The LHC's Next Frontier:
Searching for Pairs of Higgs Bosons to Understand the Standard Model and Beyond

Fermilab Wine and Cheese

Maximilian Swiatlowski

TRIUMF

ATLAS
EXPERIMENT

The LHC Context

What Do We Look For?

The Next Frontier: Higgs Pairs

Outlook

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The Standard Model

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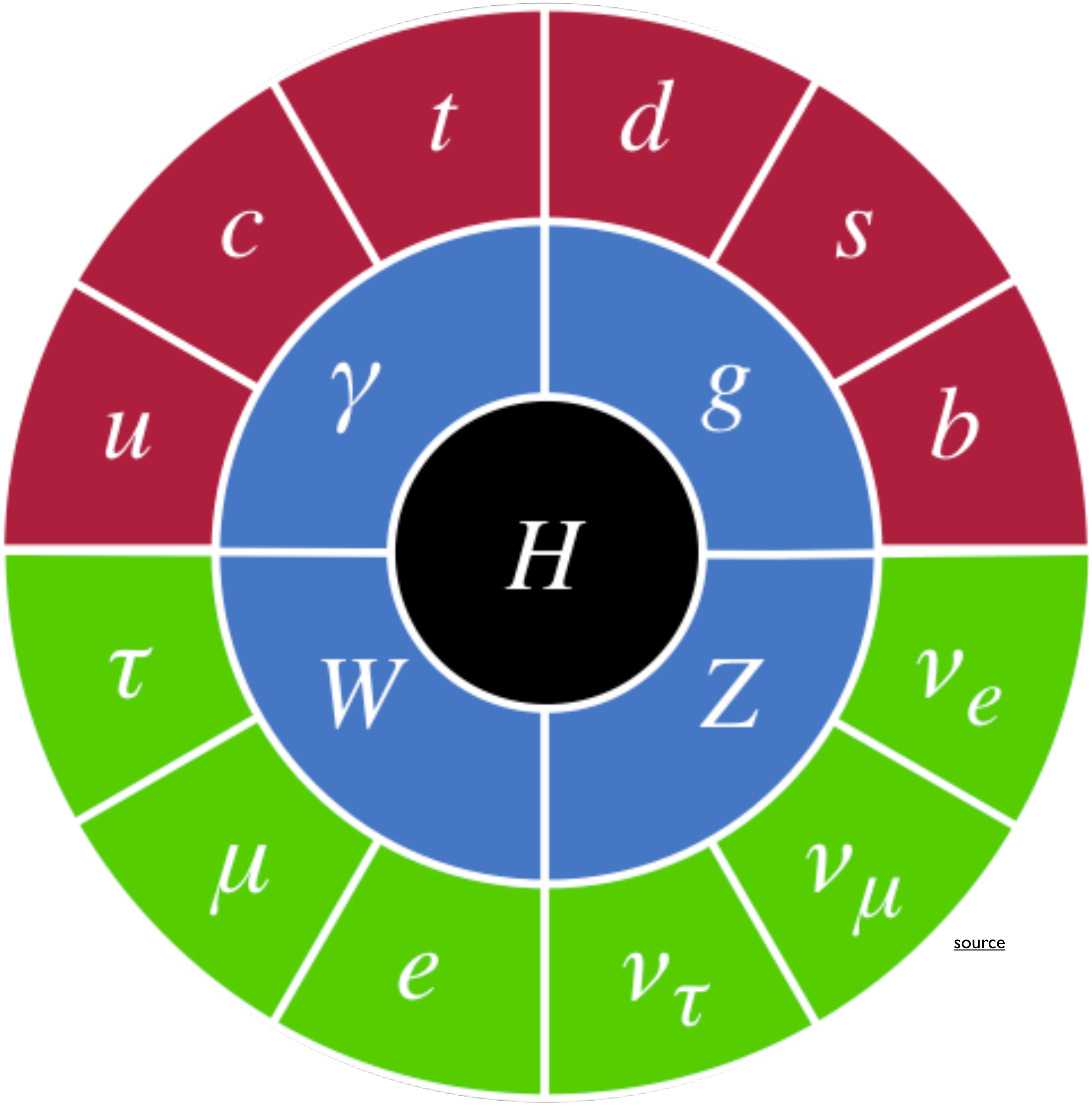

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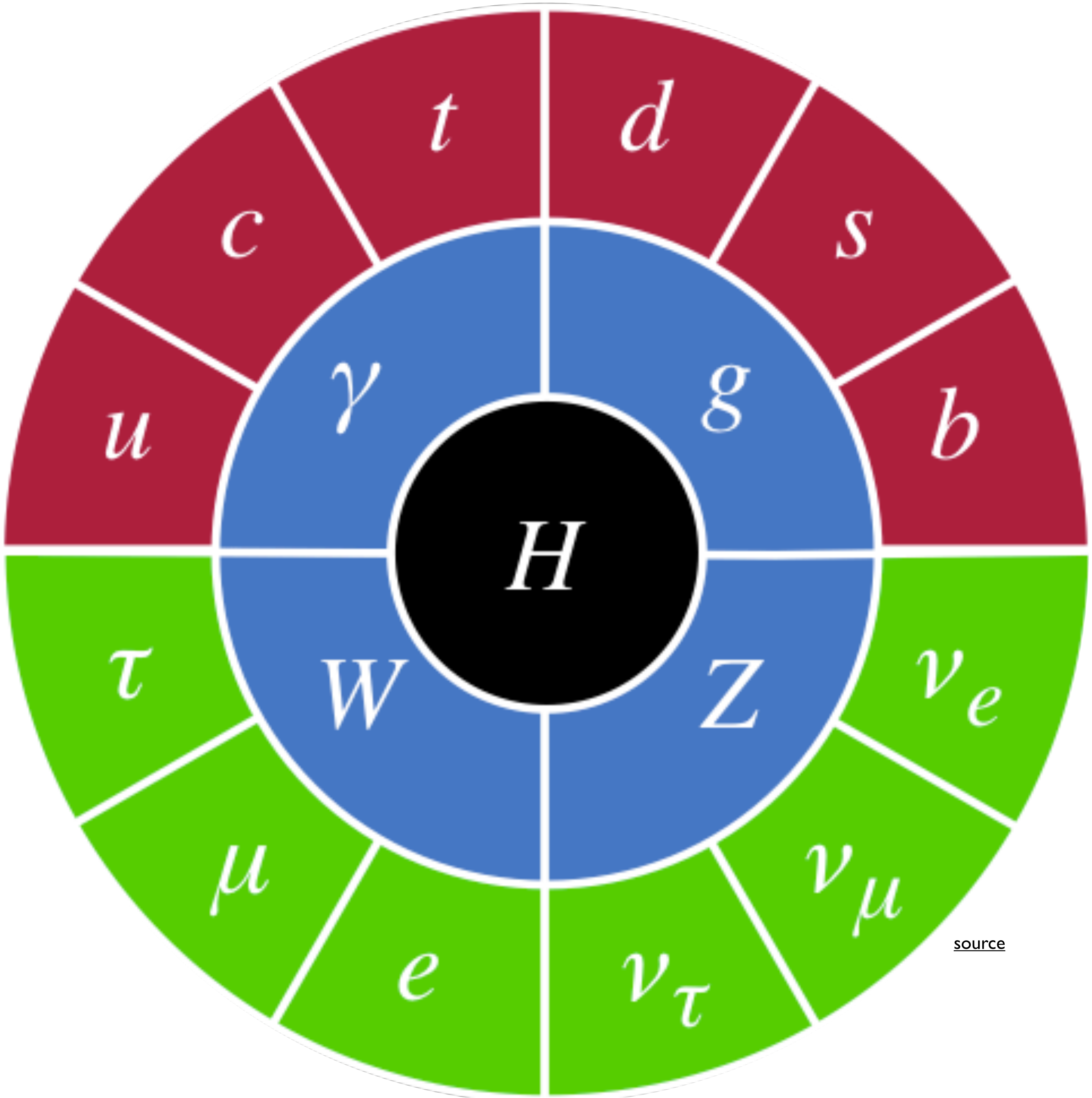

Quarks

- Matter particles
- Electroweak and strong interactions

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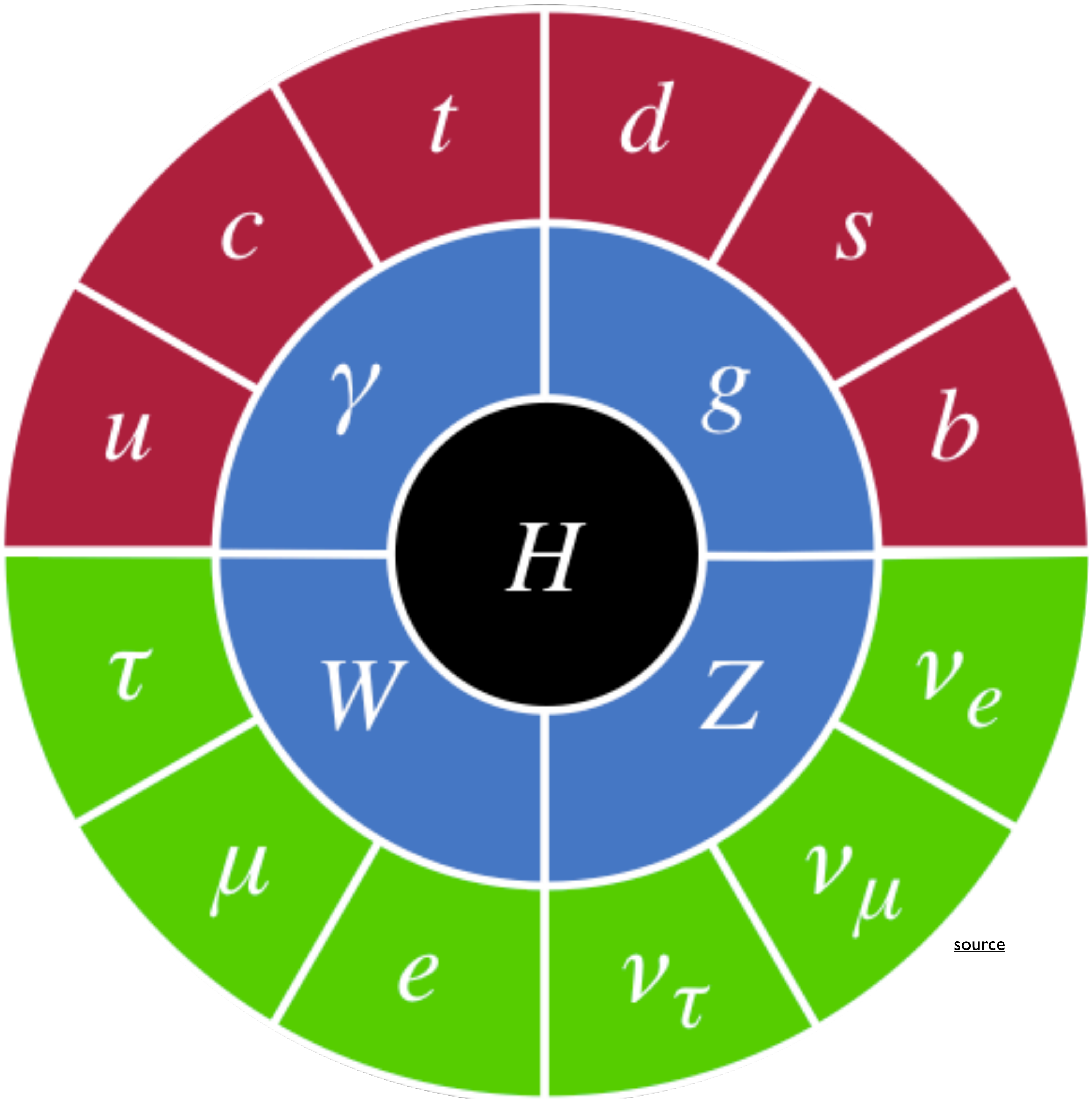

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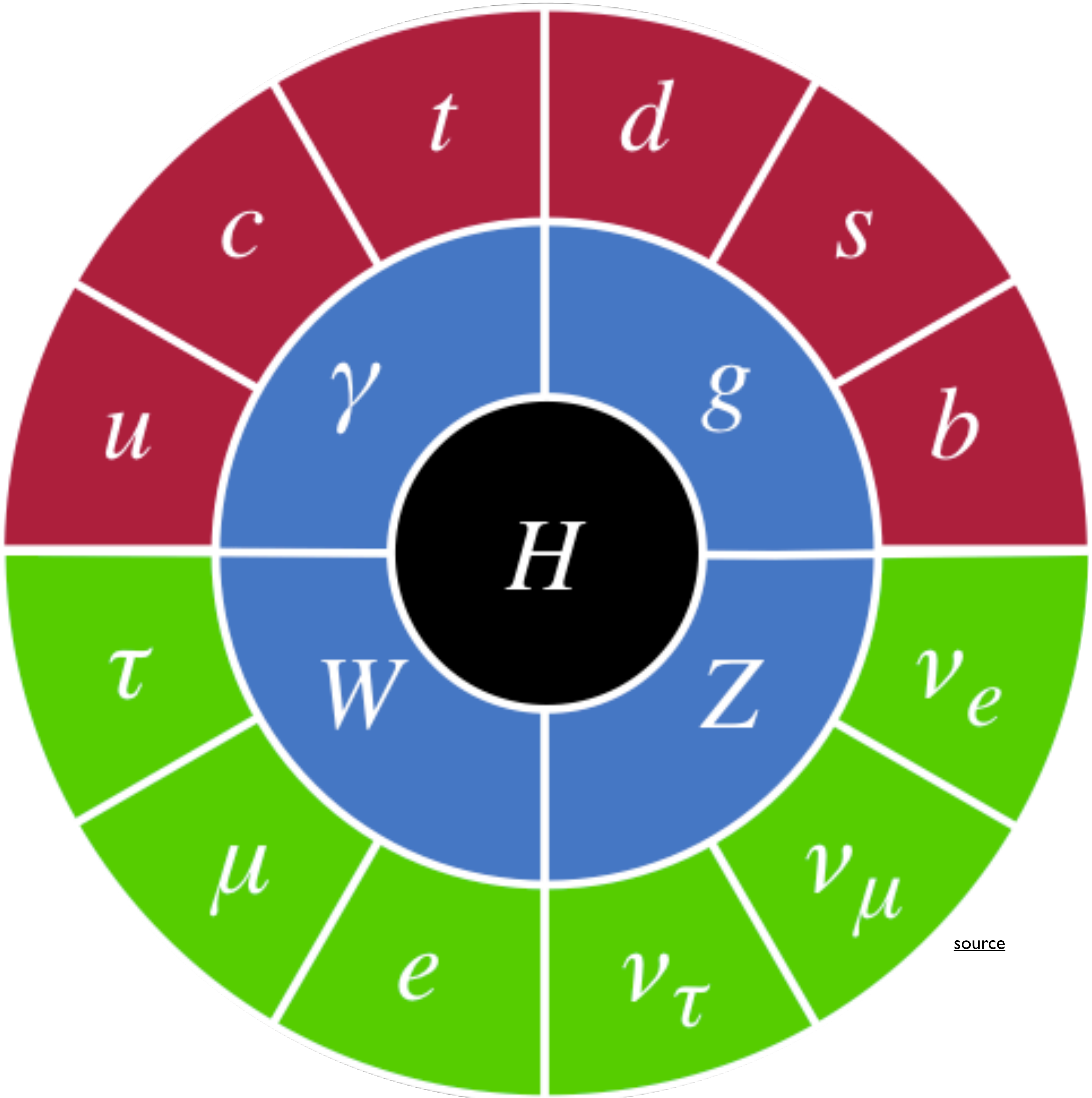

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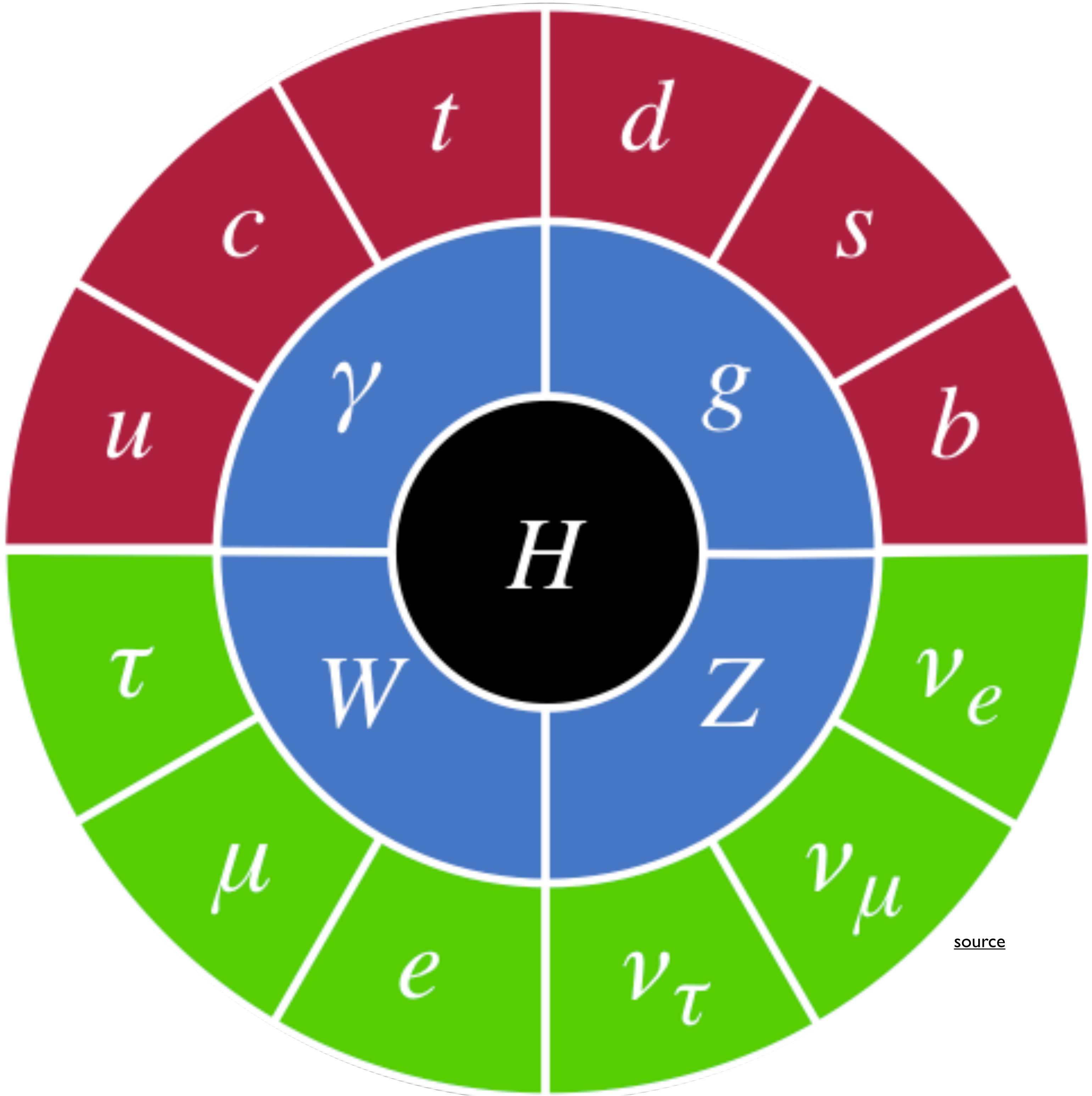

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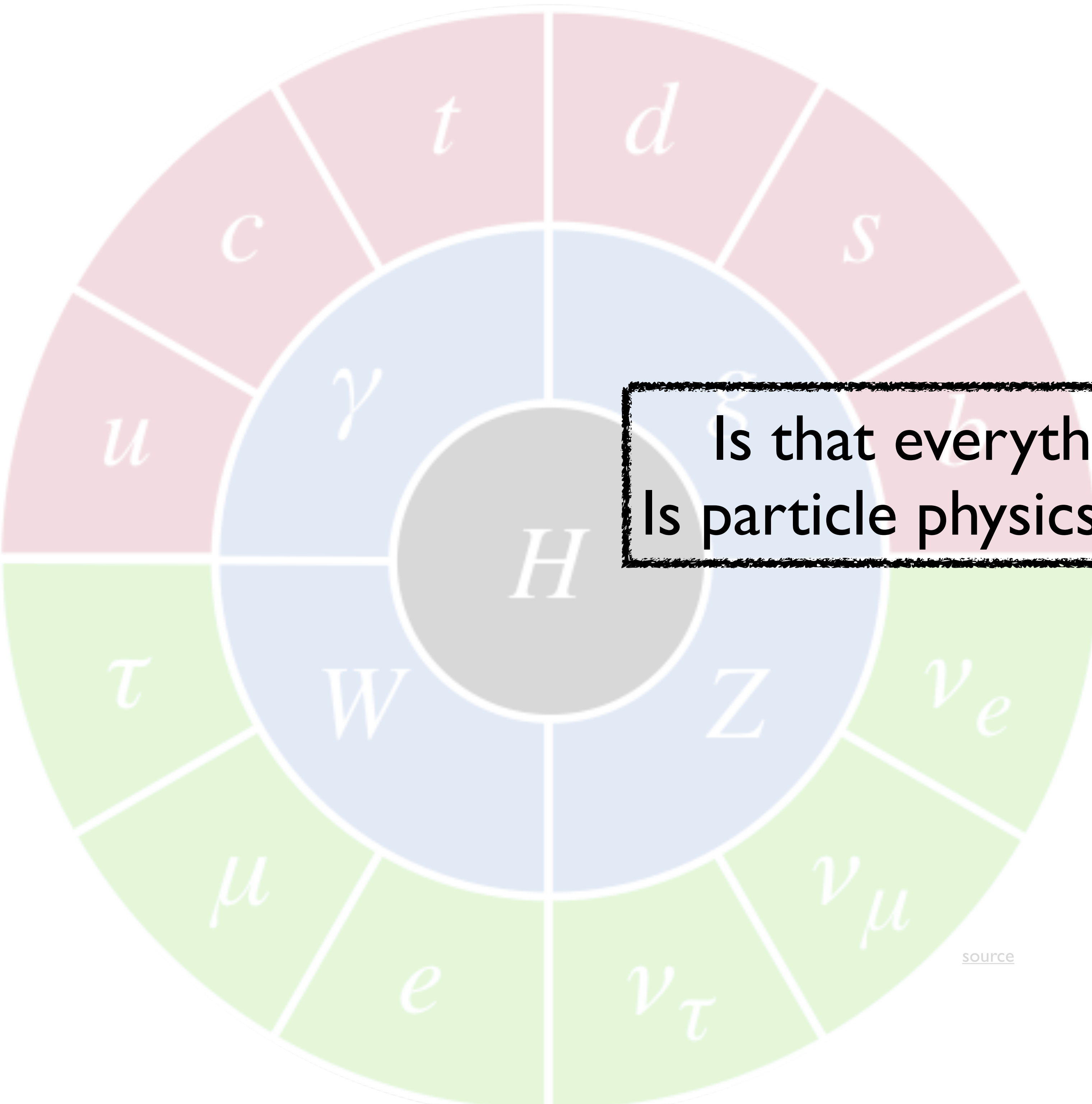

Is that everything?
Is particle physics over?

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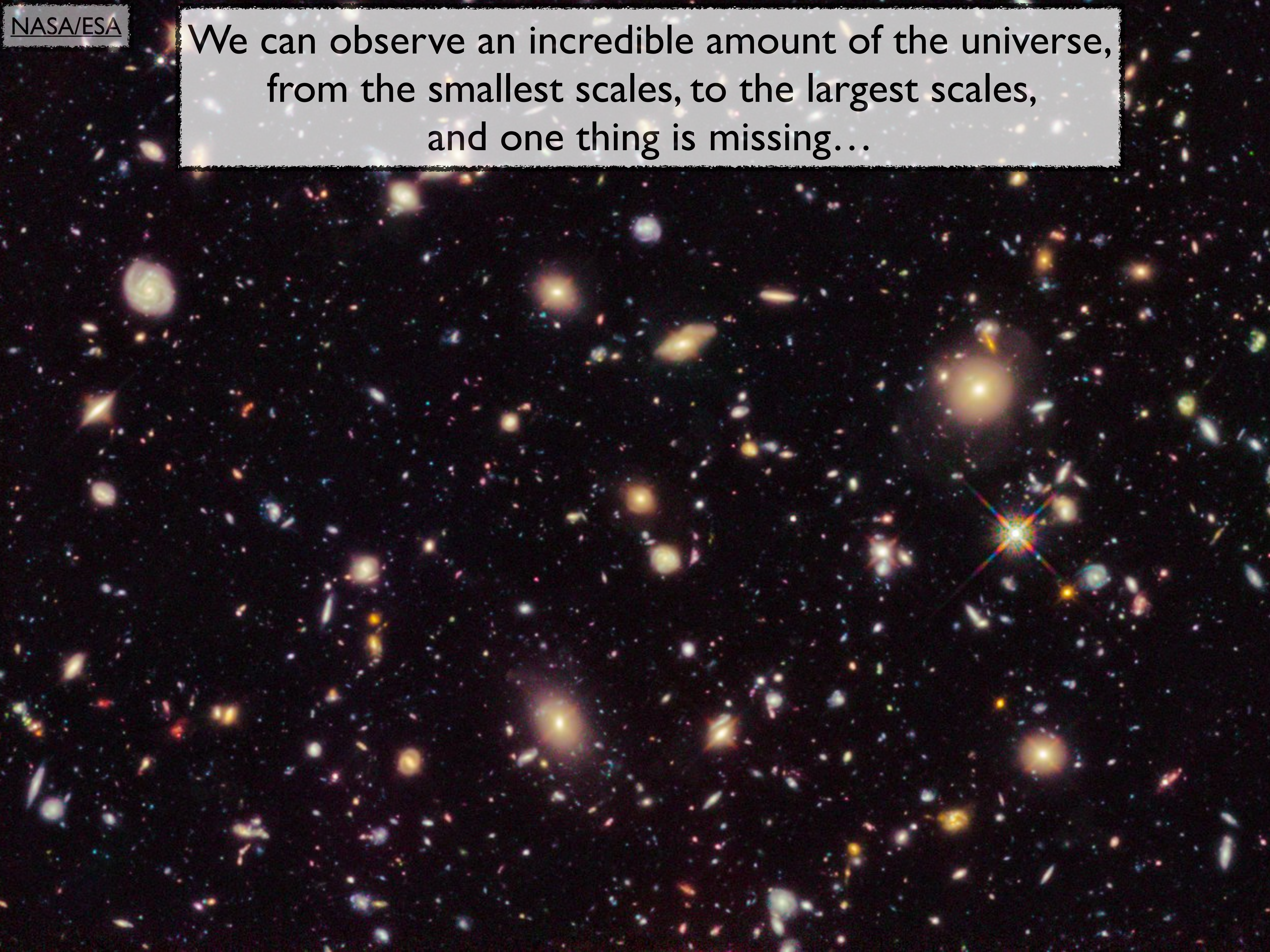
NASA/ESA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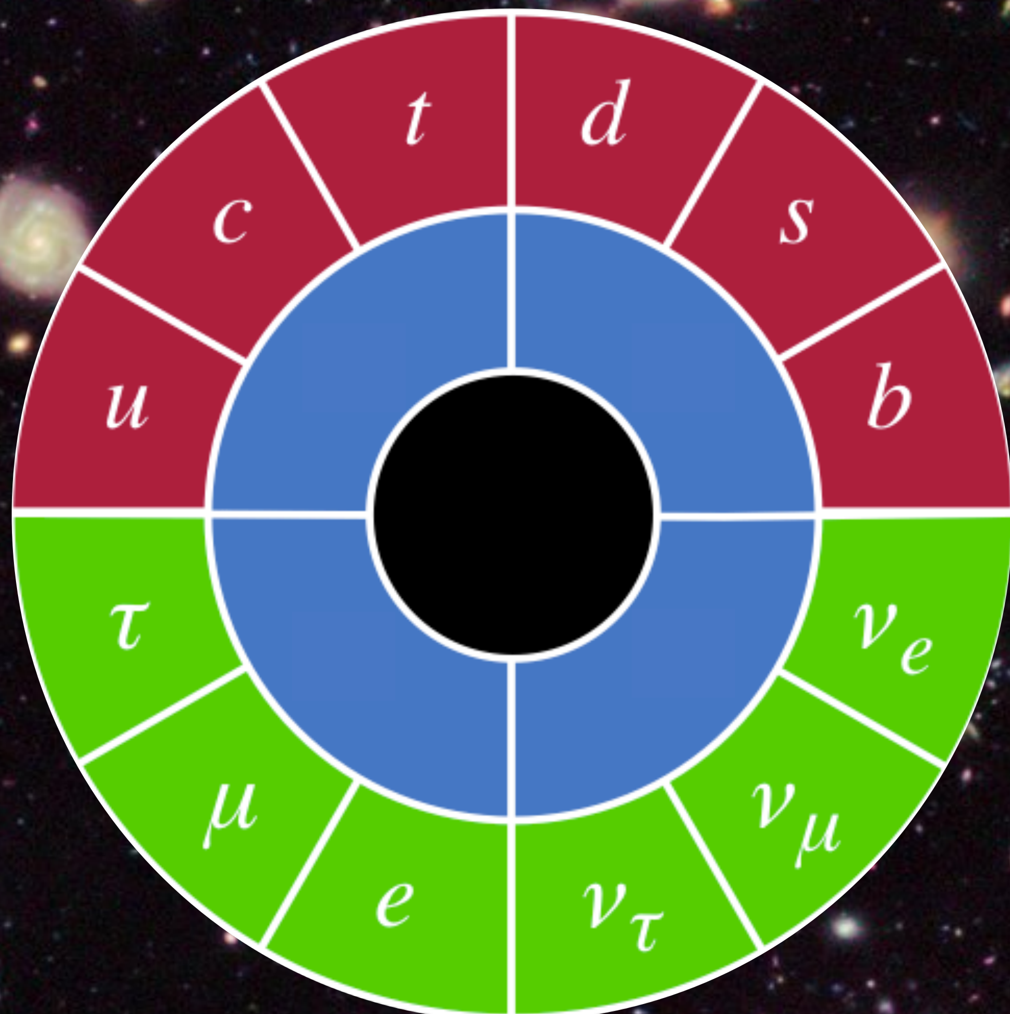

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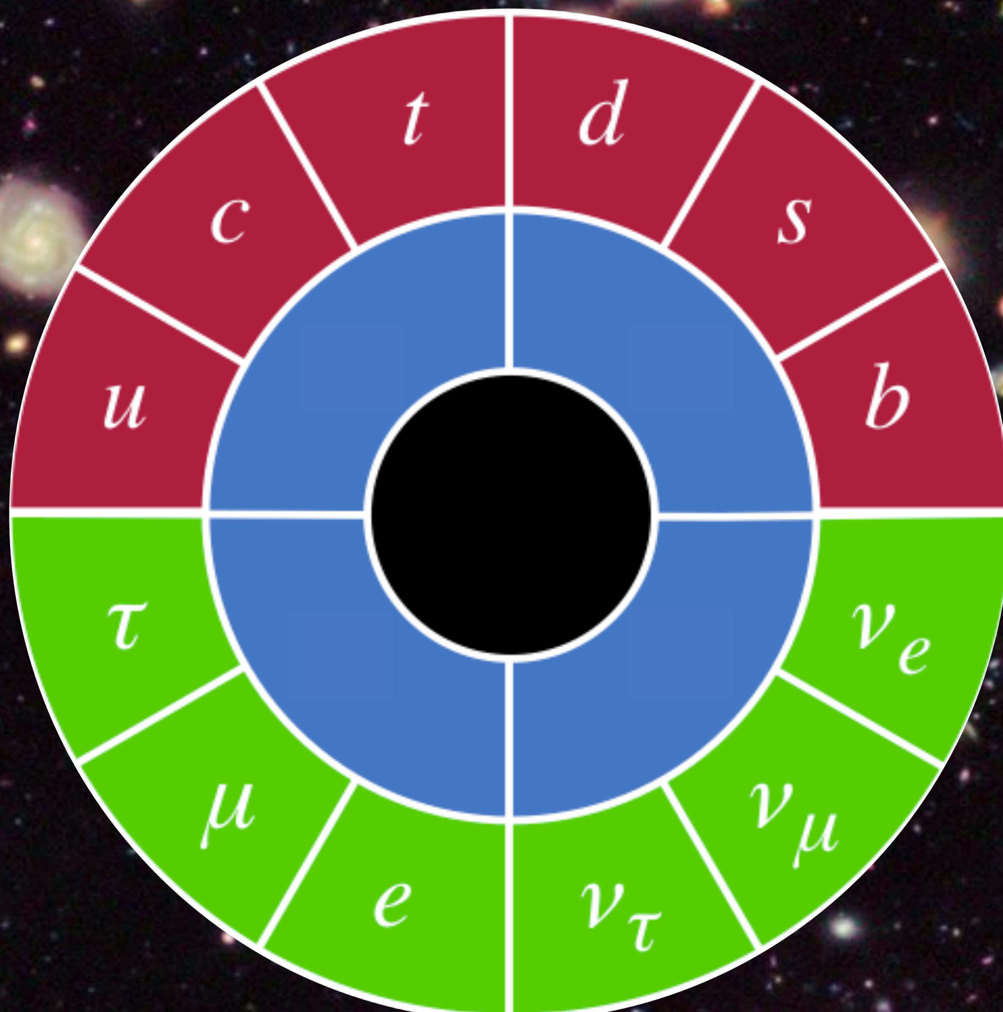

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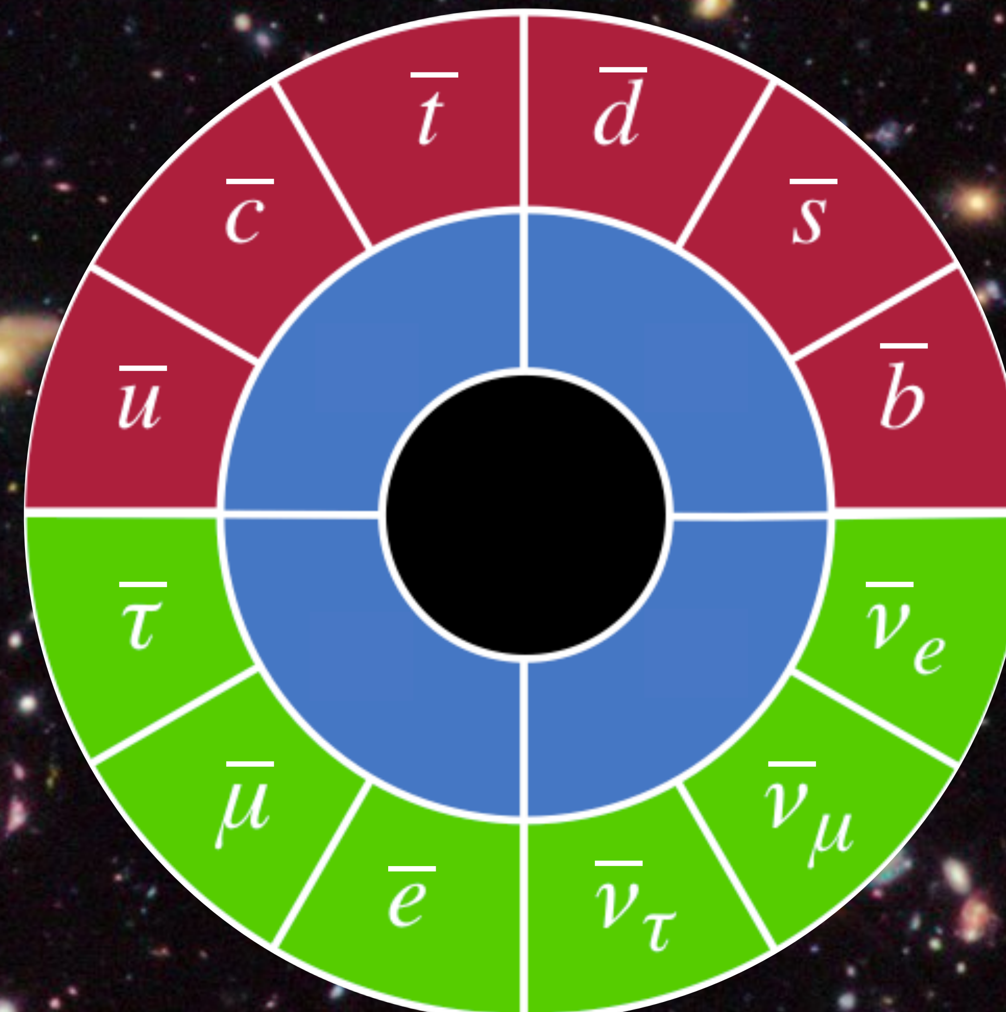

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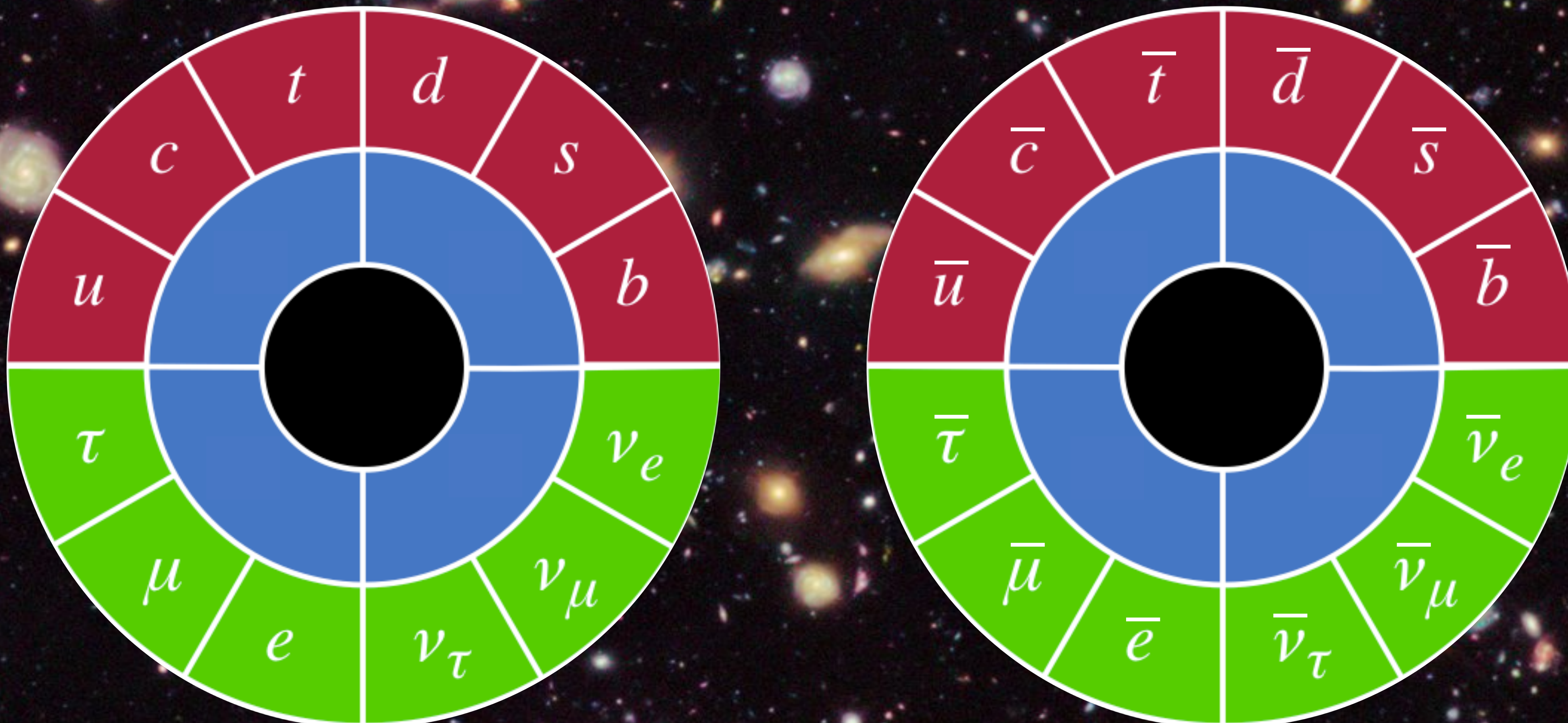

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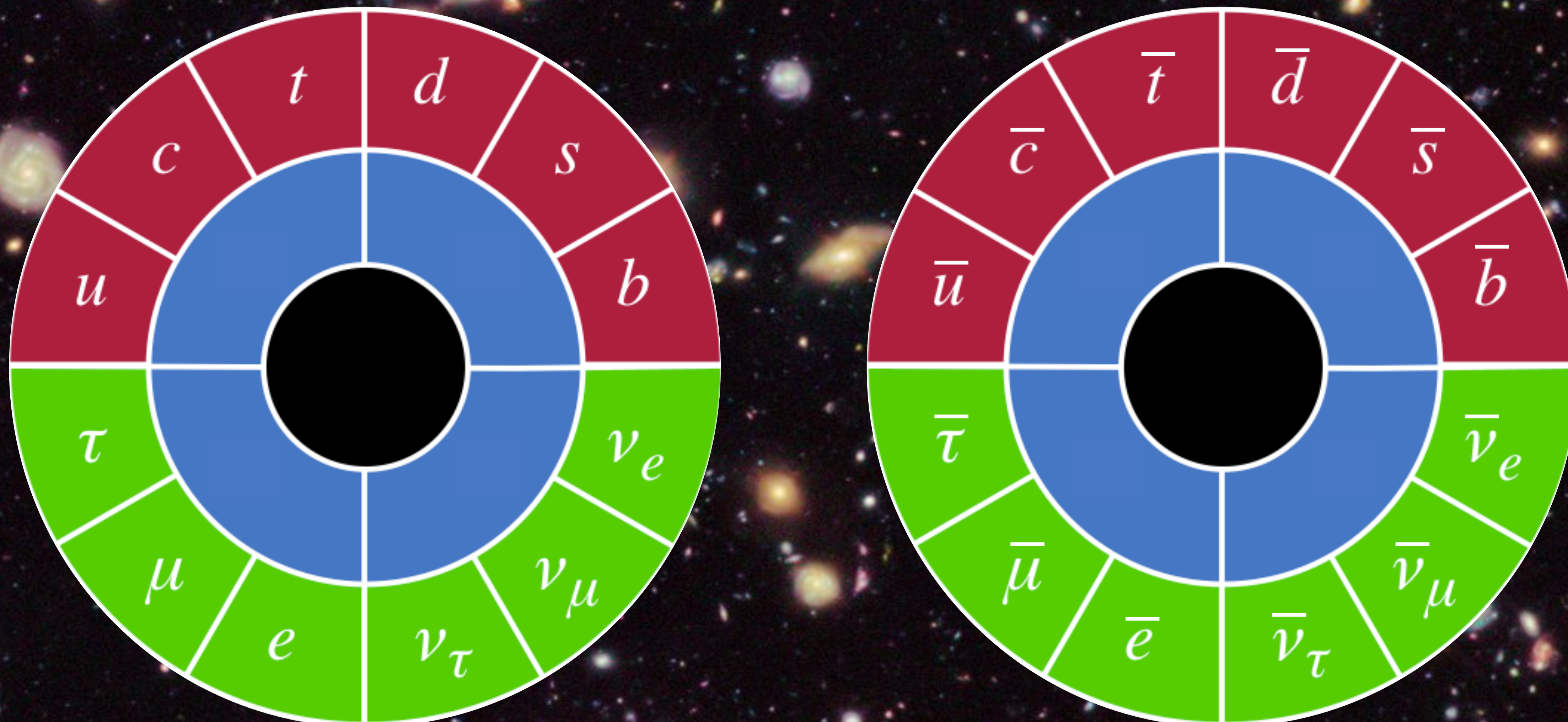

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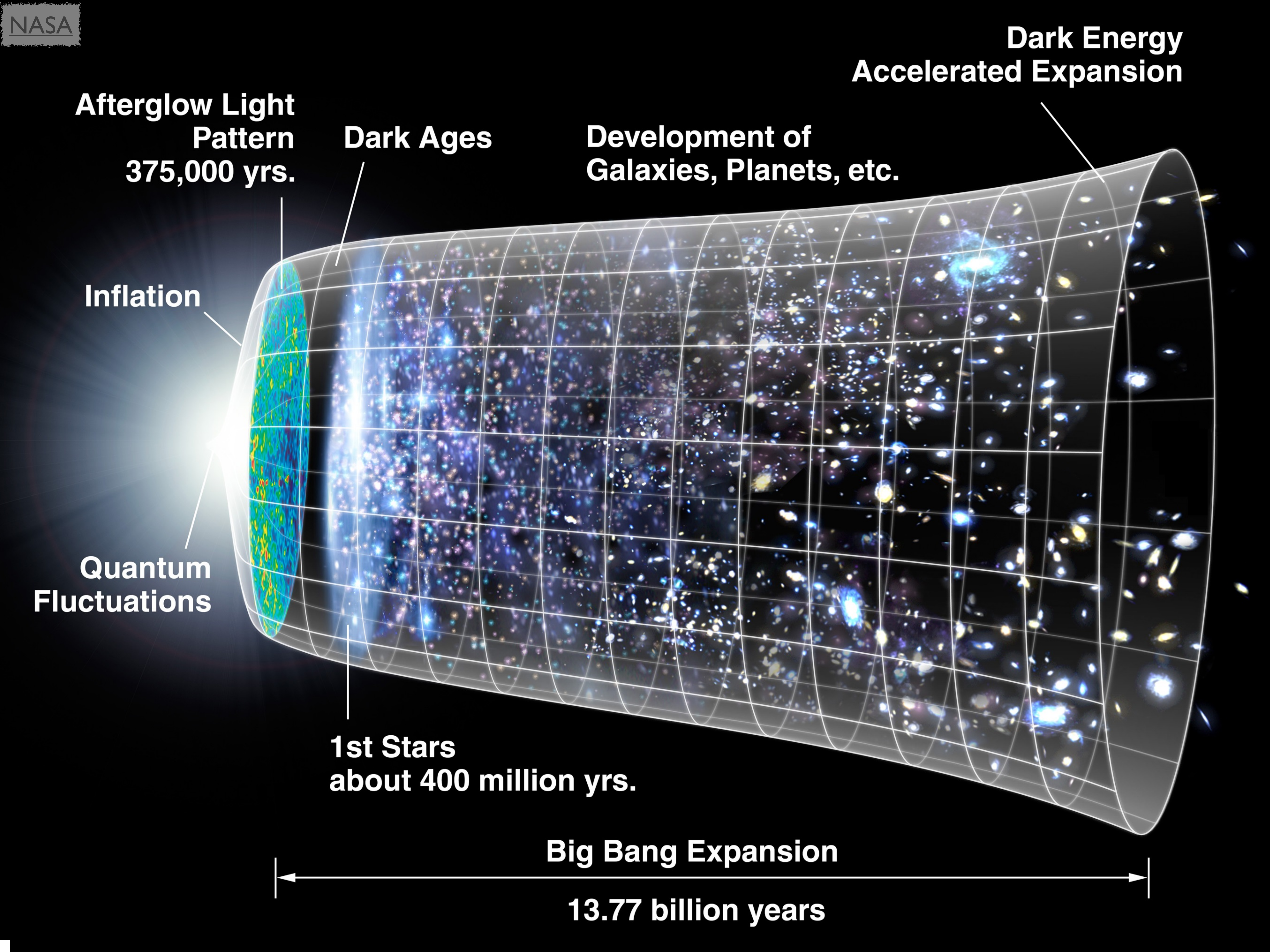
The SM cannot explain anti-matter's disappearance


NASA
Dark Energy
Accelerated Expansion
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375,000 yrs.
Dark Ages
Development of
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Big Bang Expansion
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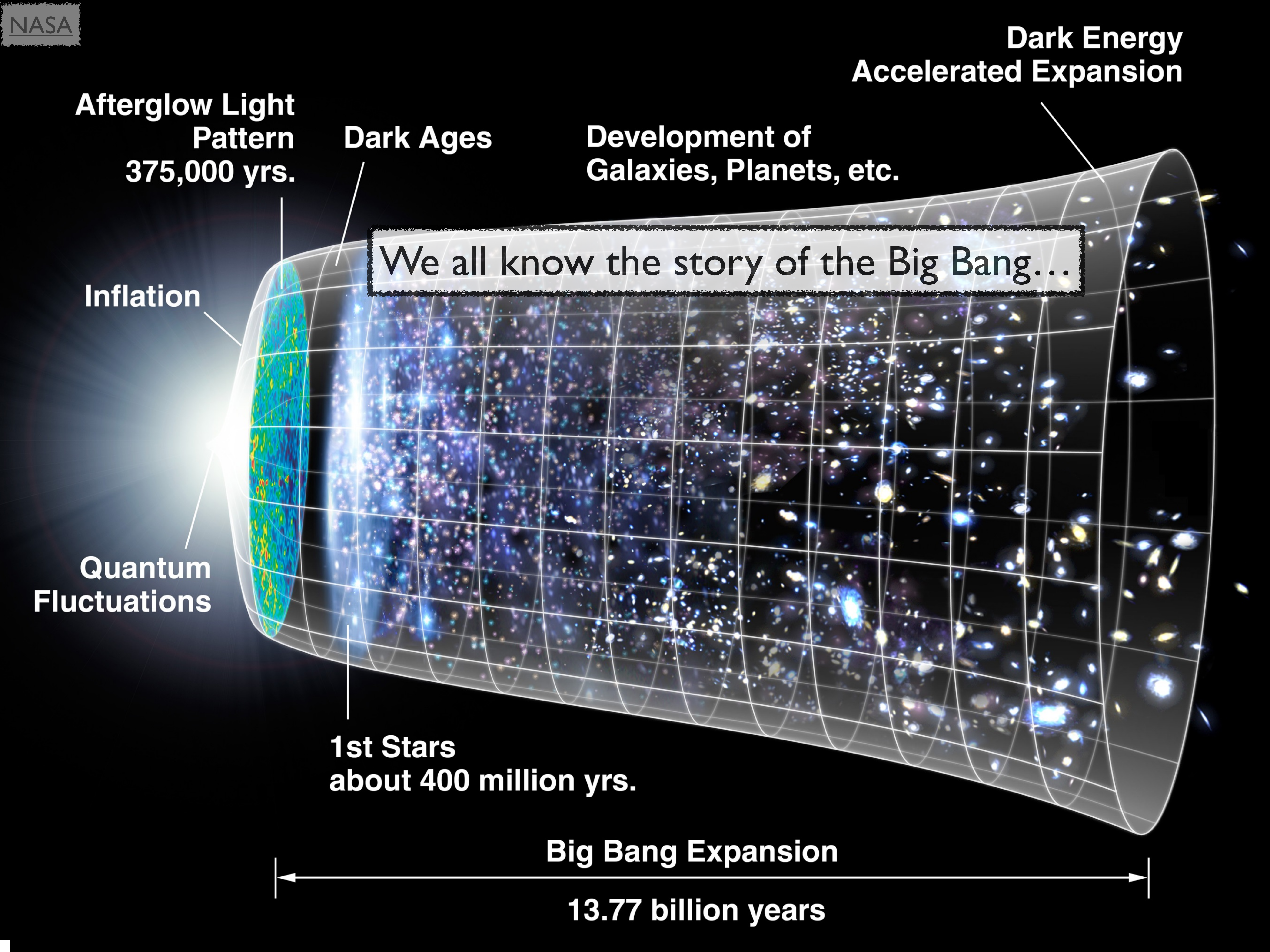

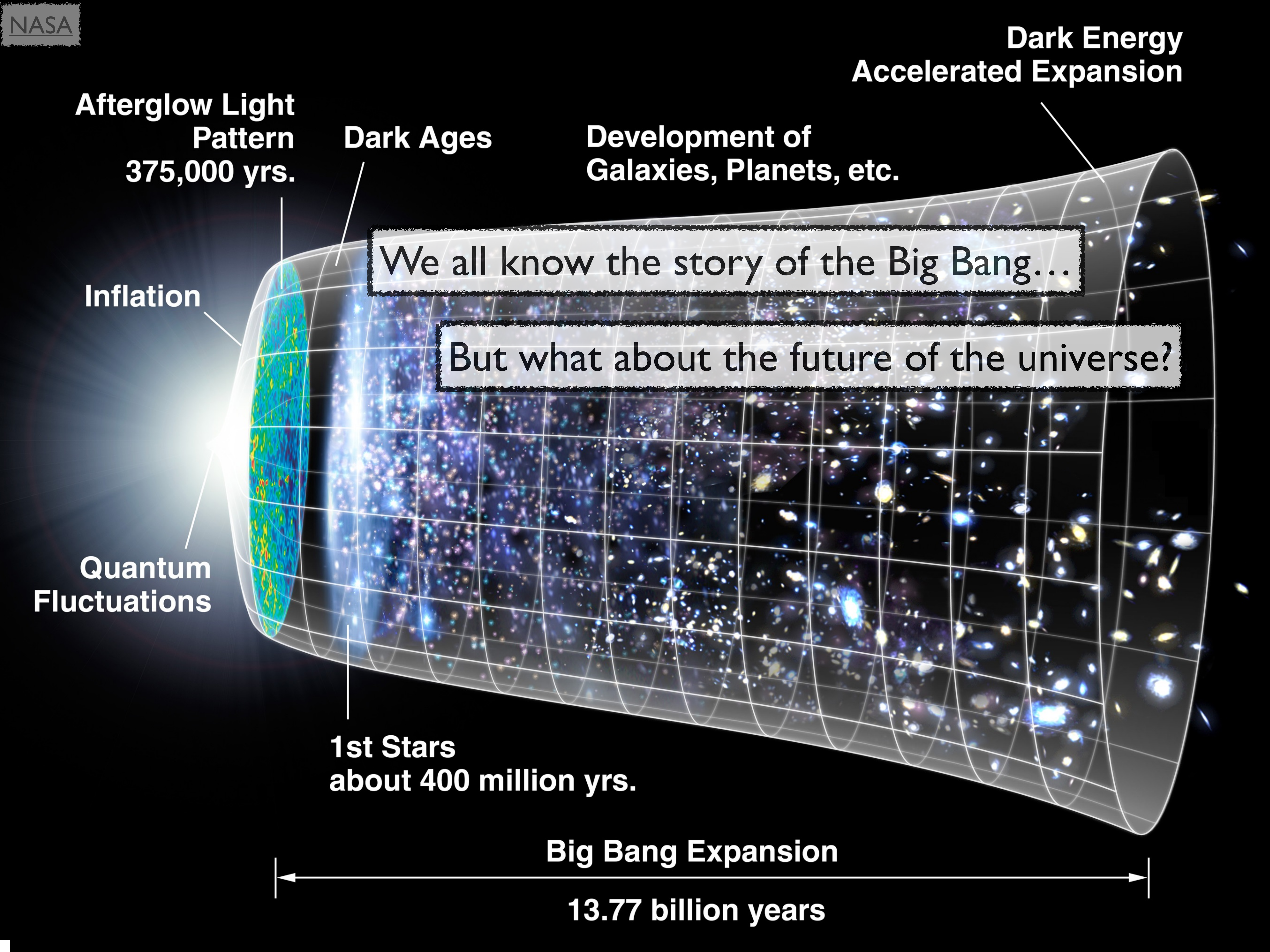
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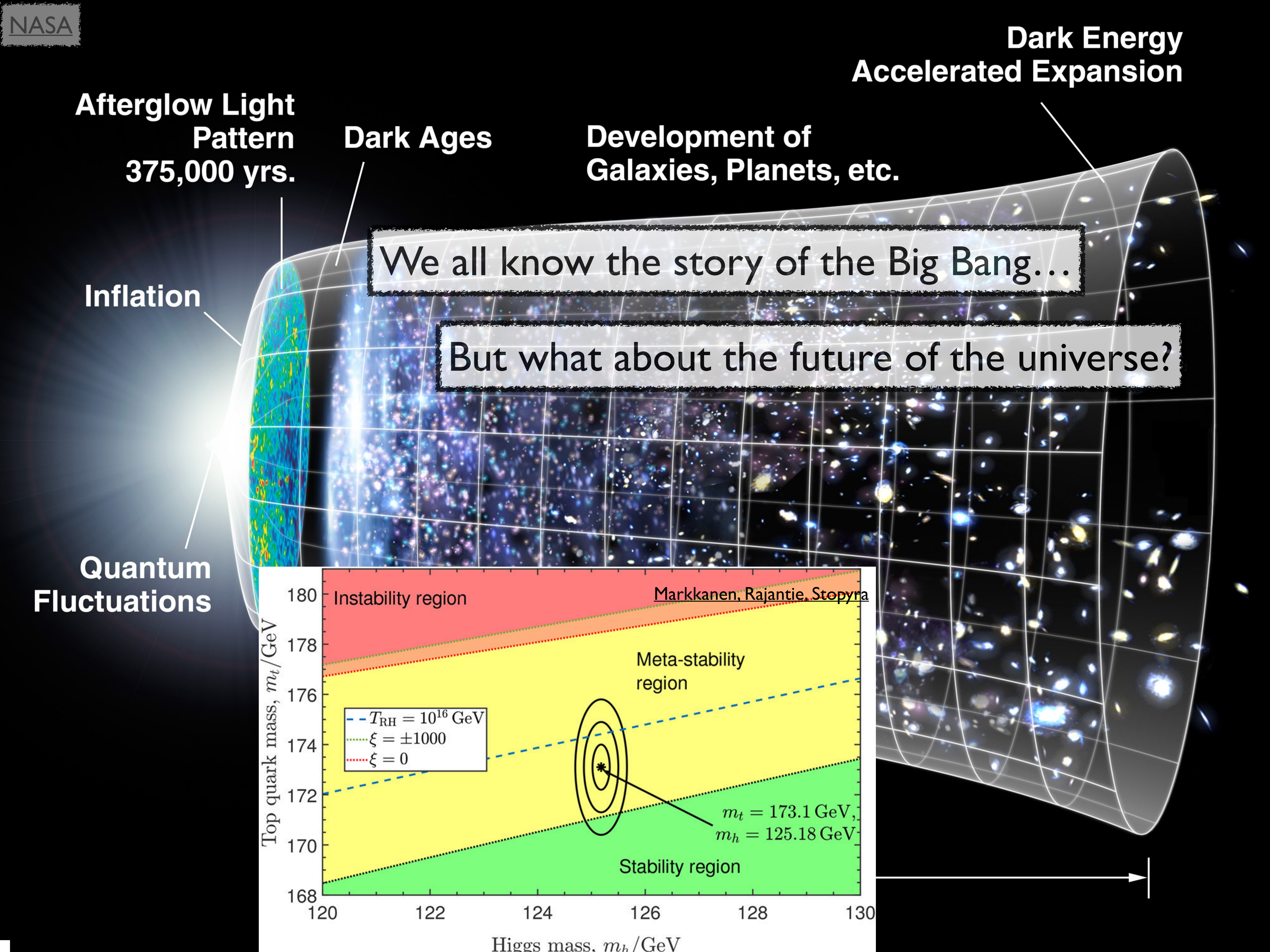

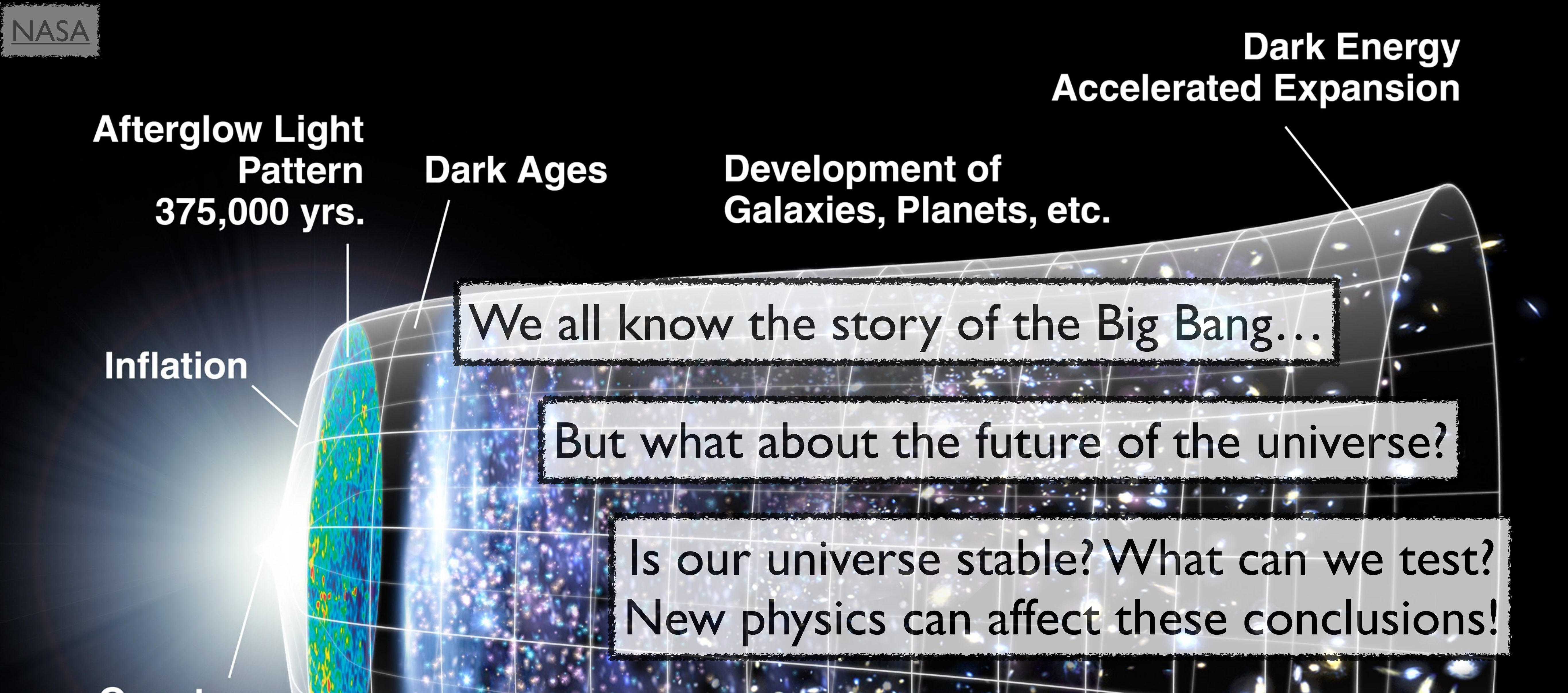

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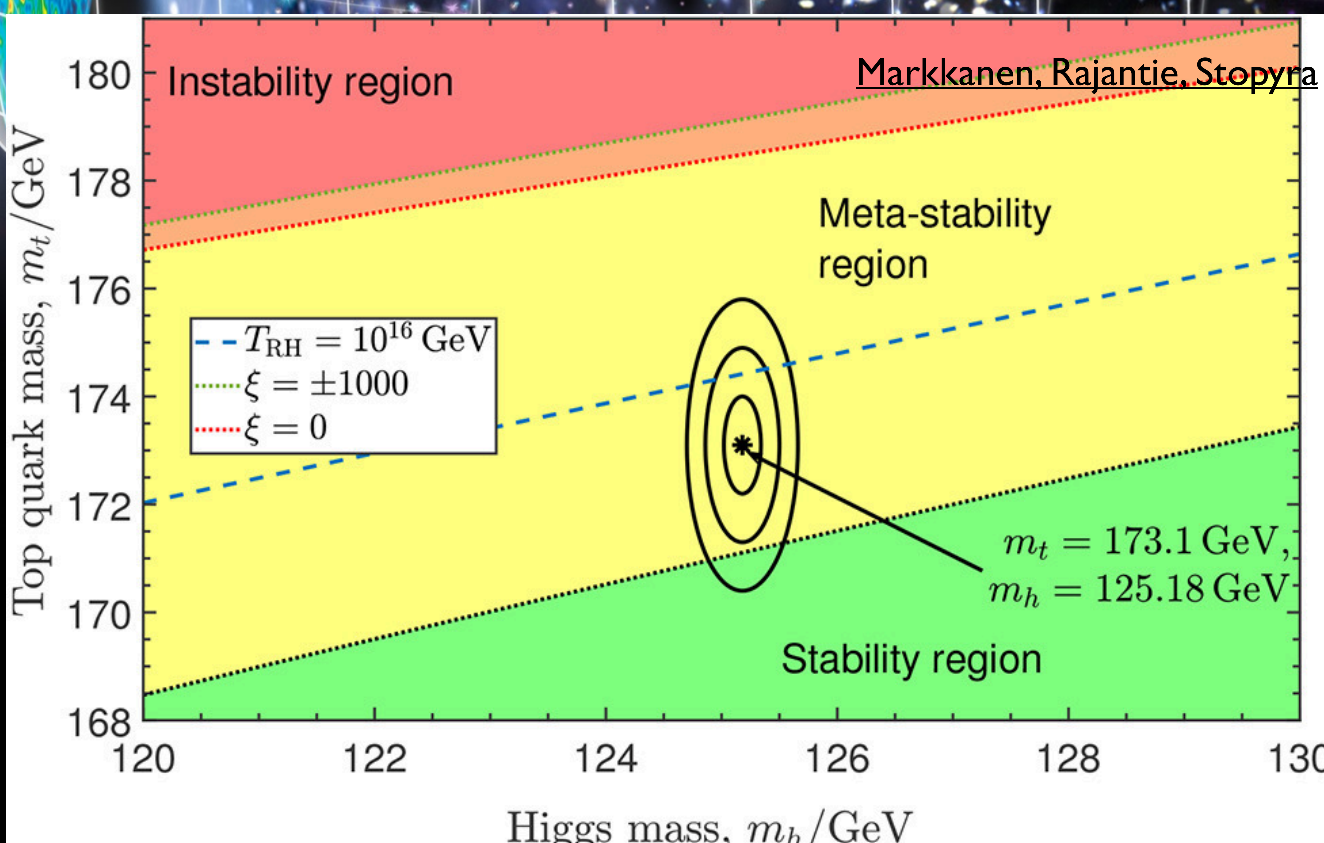
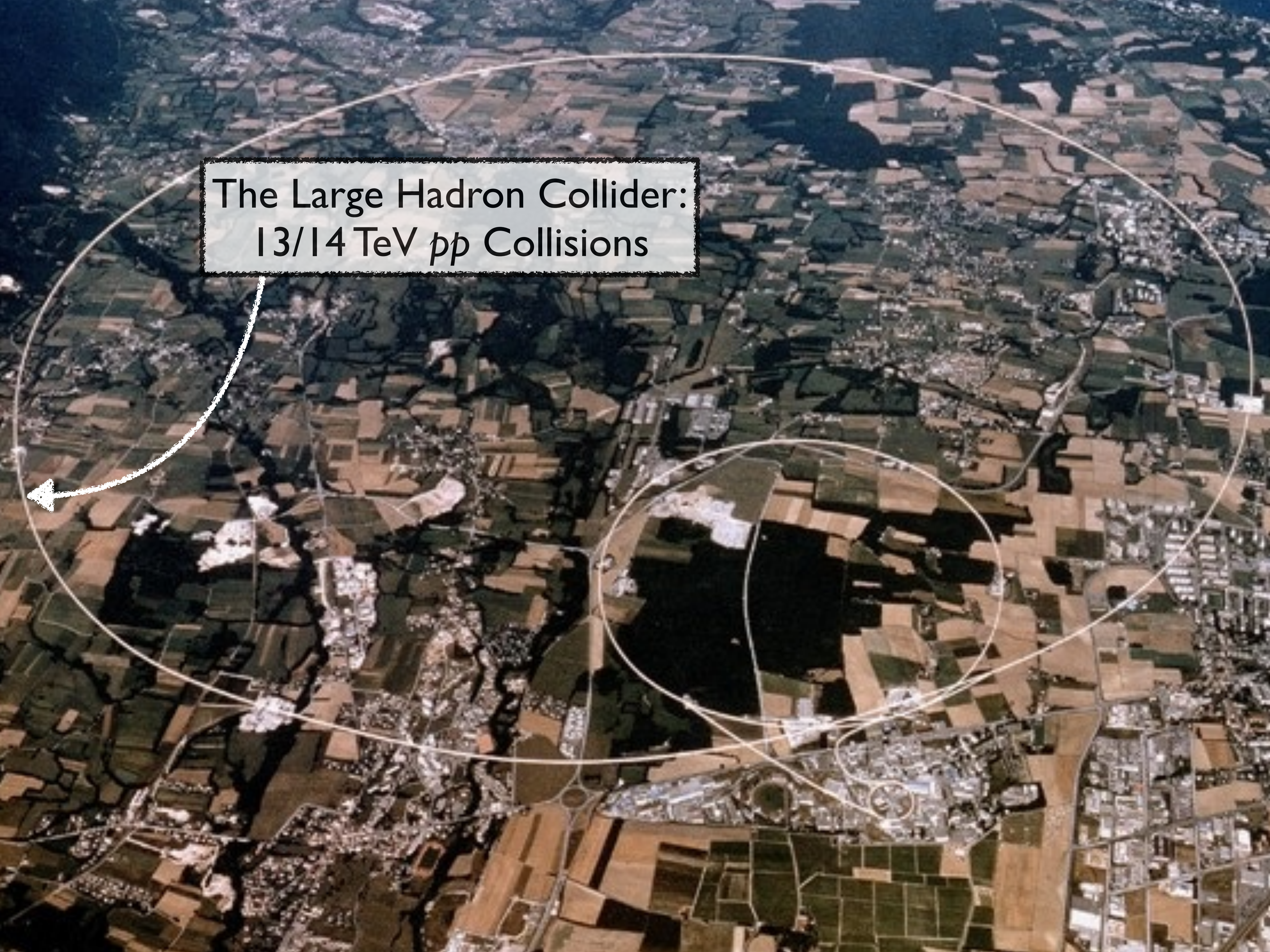
But what about the future of the universe?

Is our universe stable? What can we test?
New physics can affect these conclusions!

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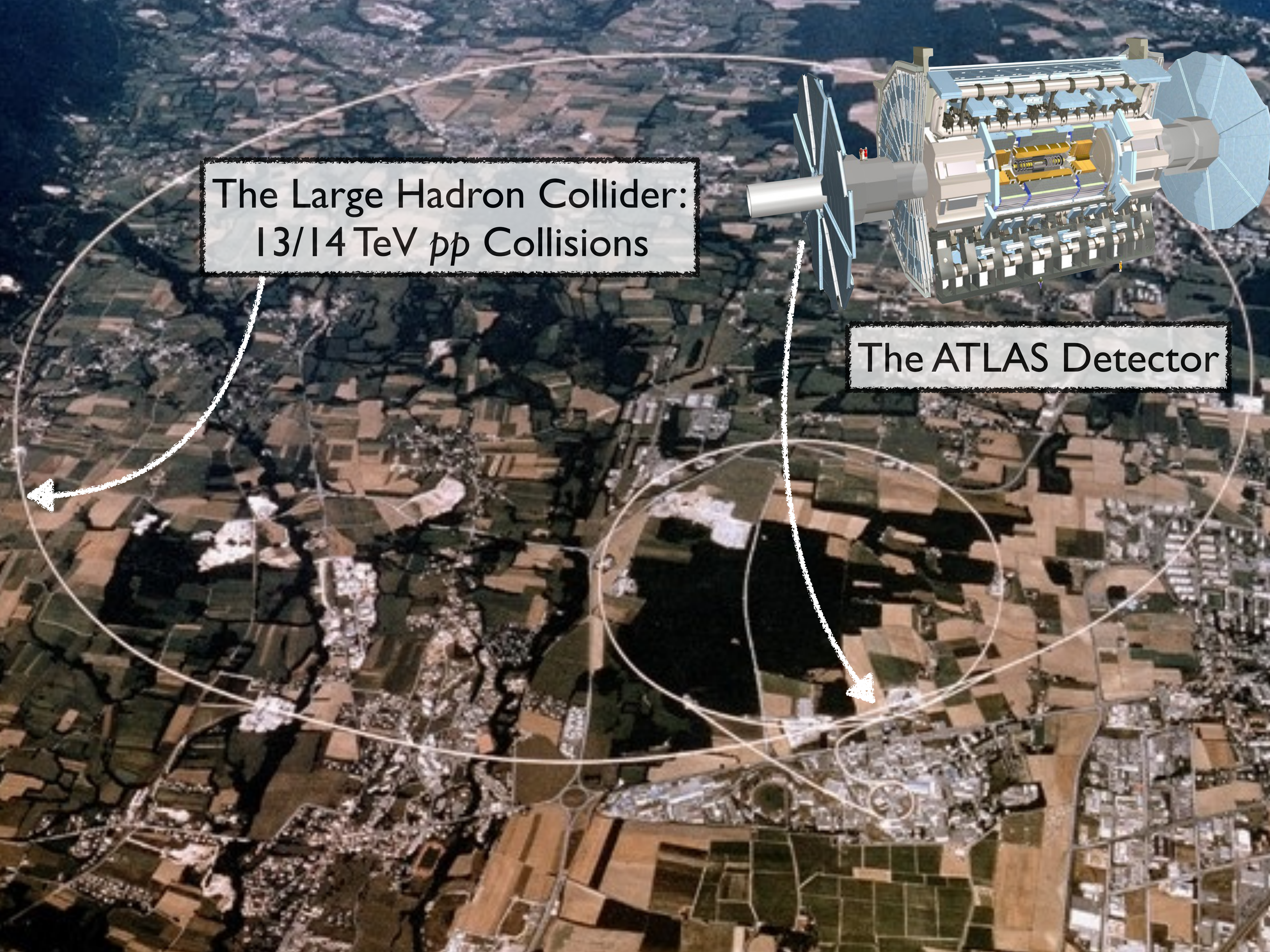
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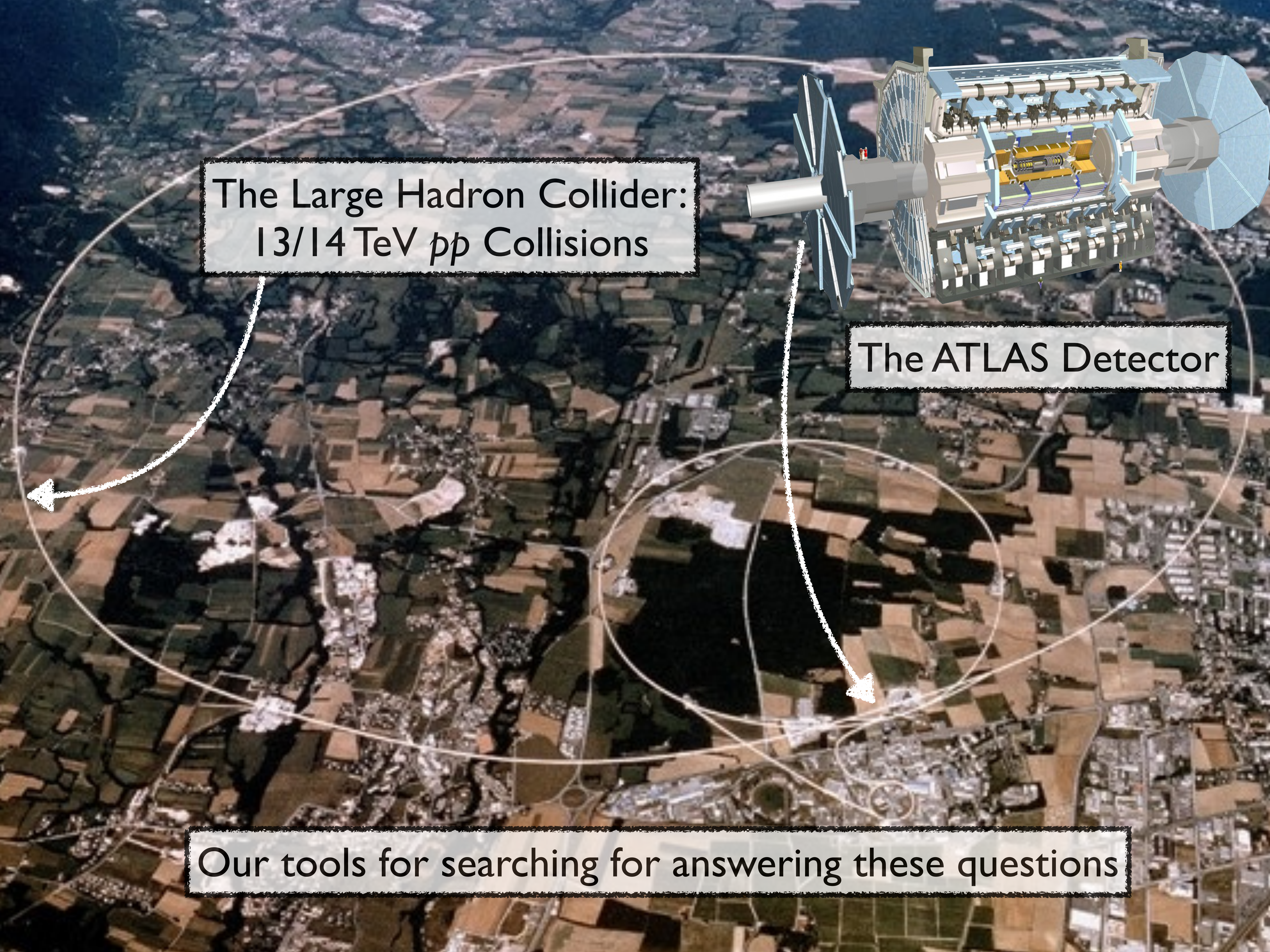
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Our tools for searching for answering these questions

What Has the LHC Taught Us?

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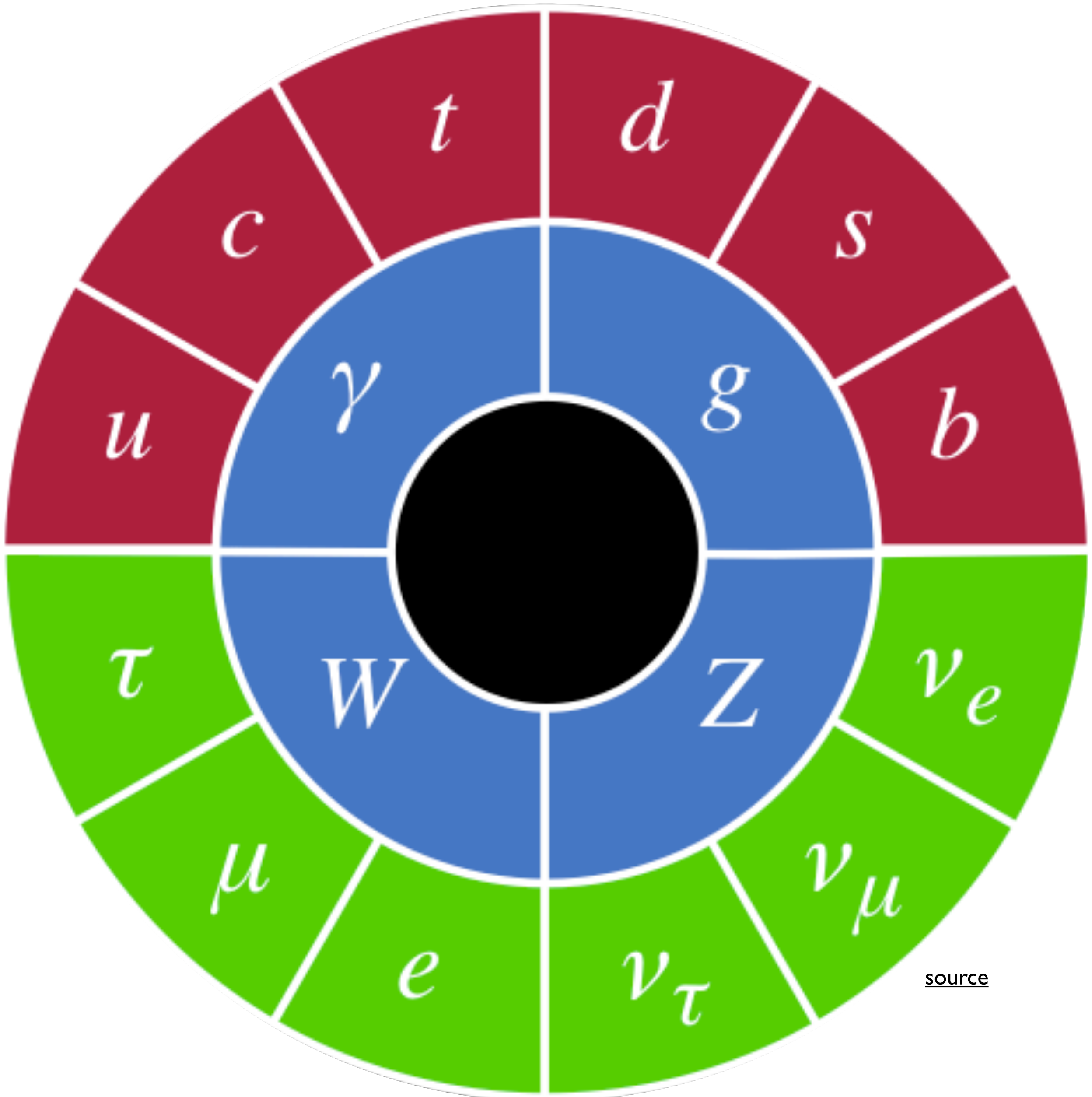

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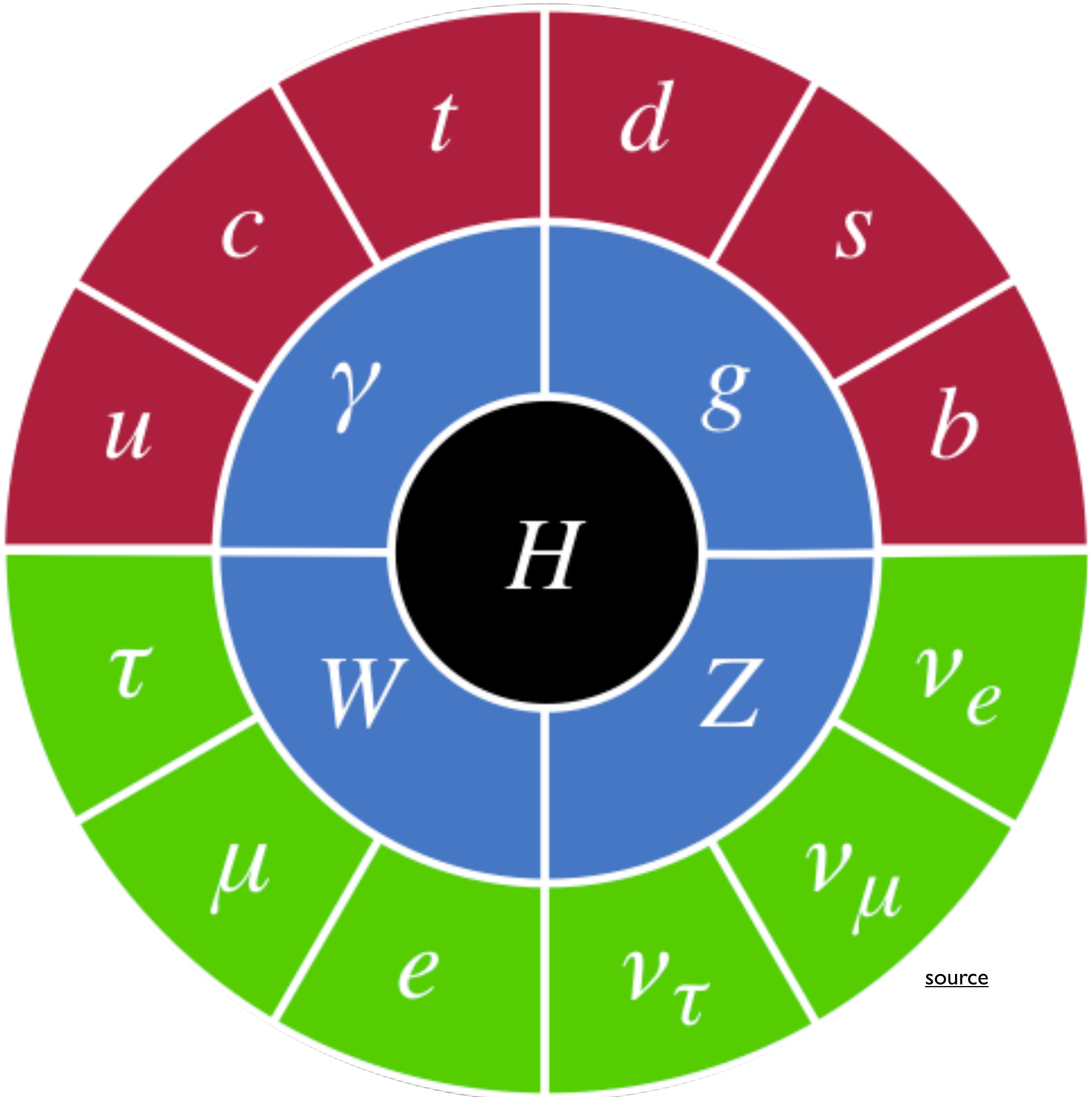

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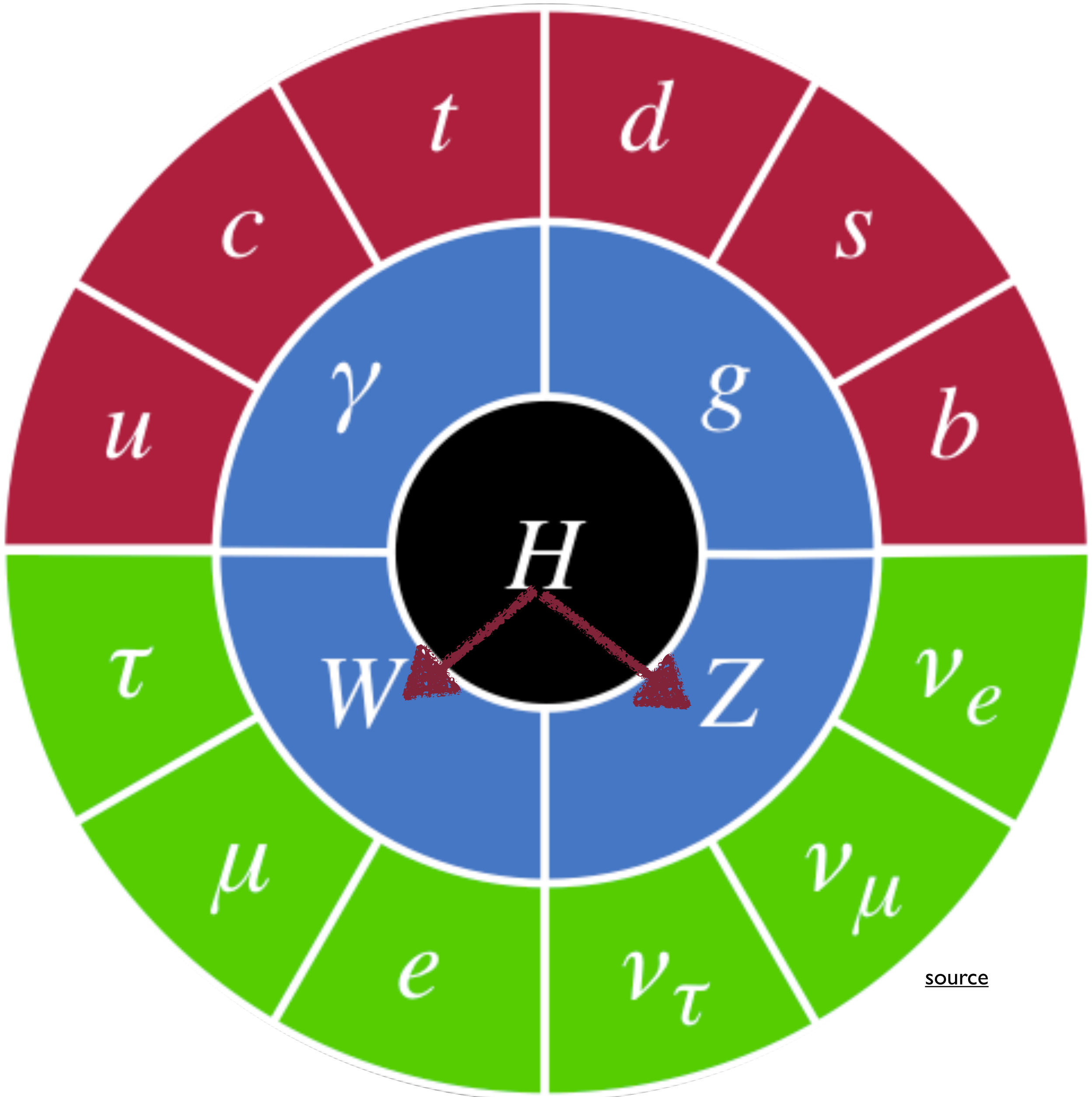

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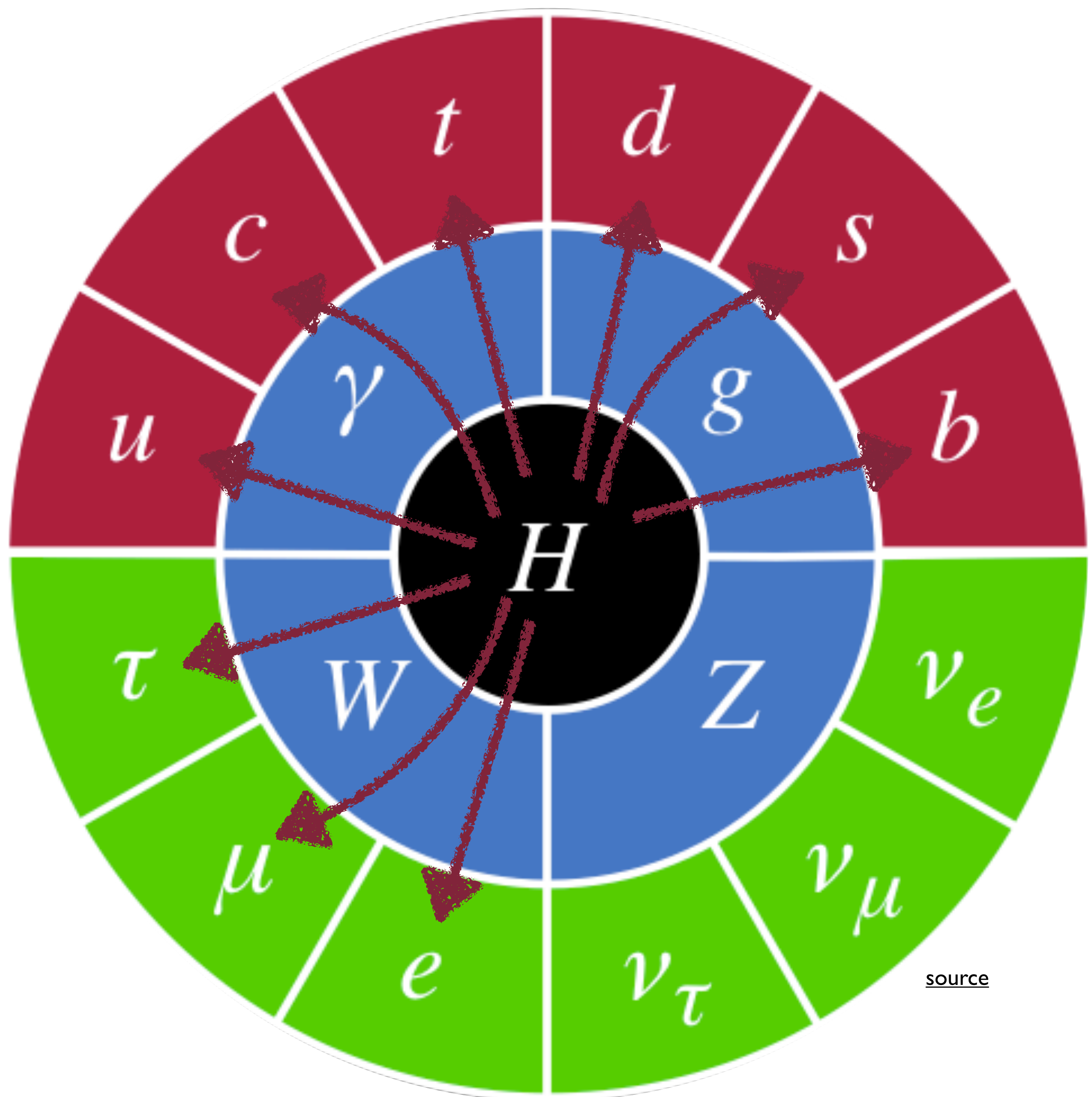

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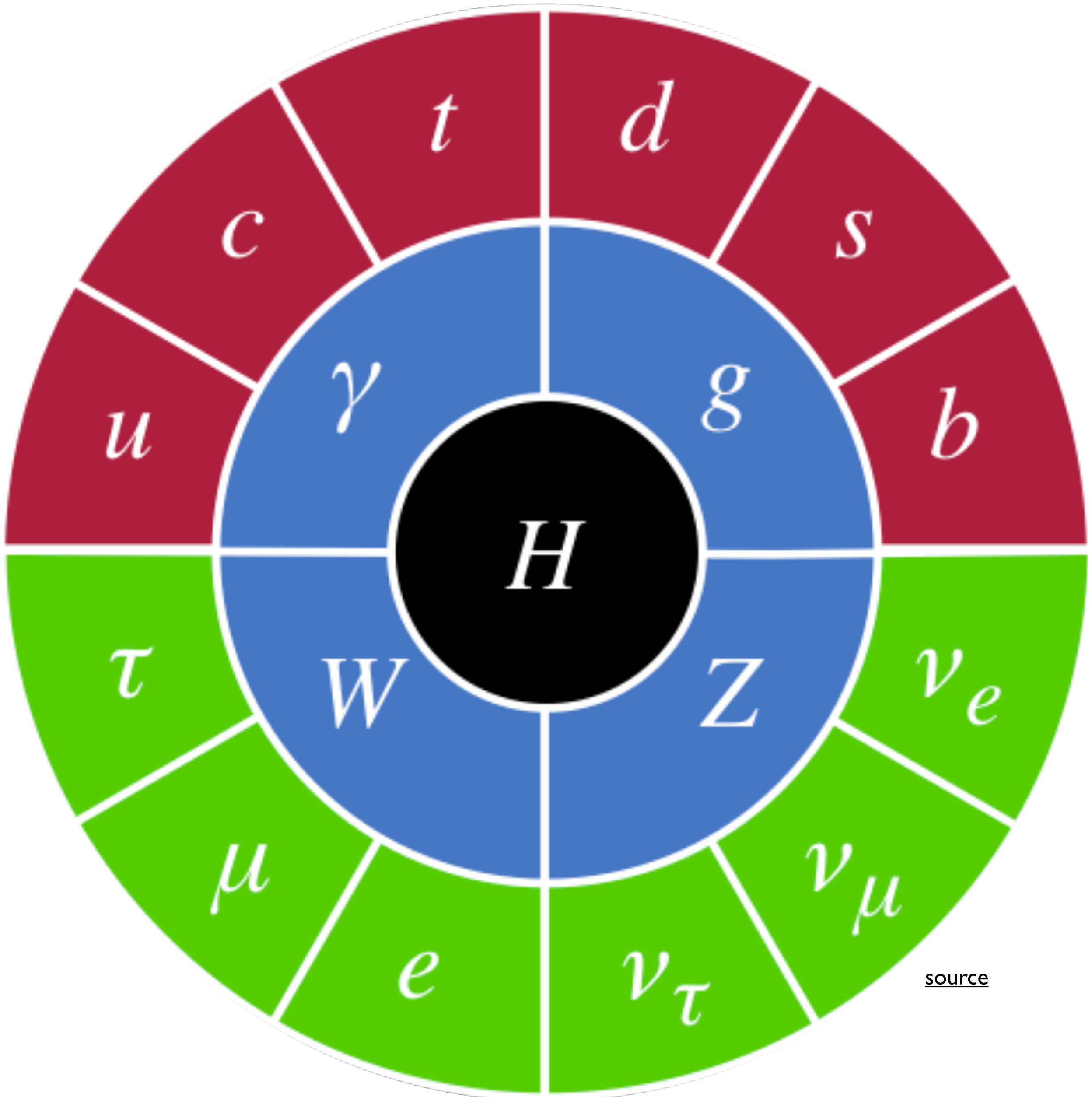

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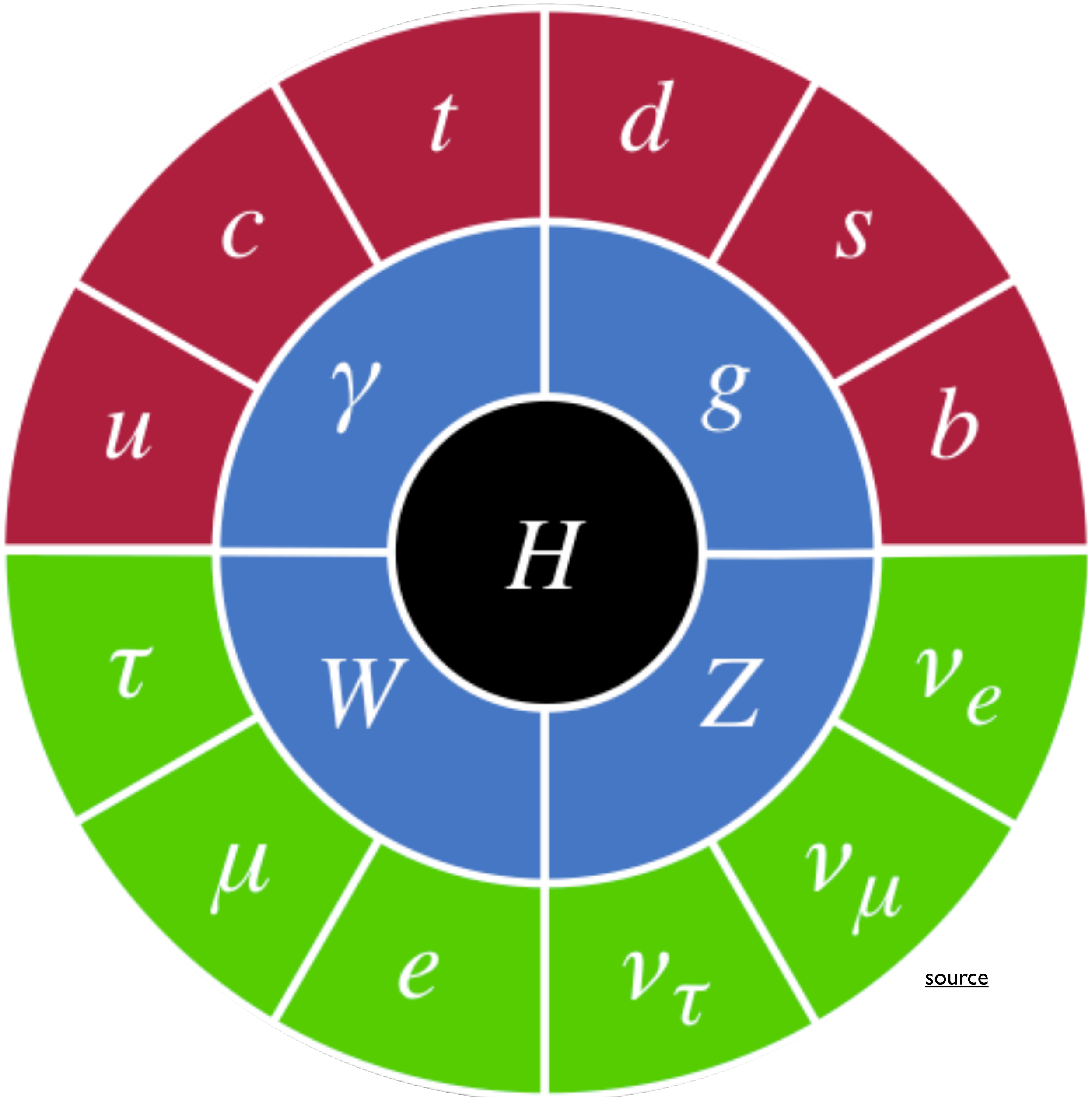

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Can the Higgs also contain hints towards BSM?

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What We Know

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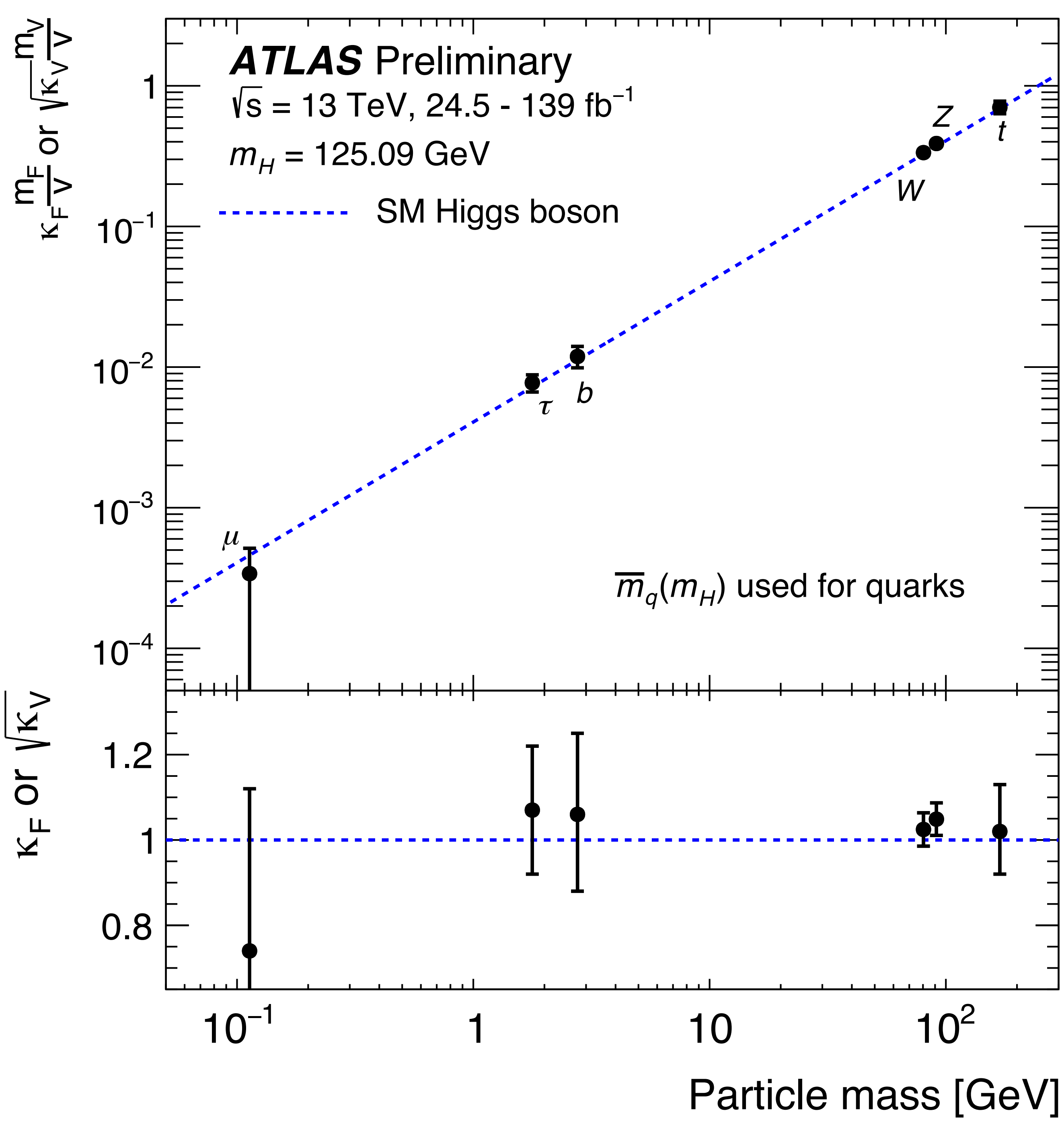

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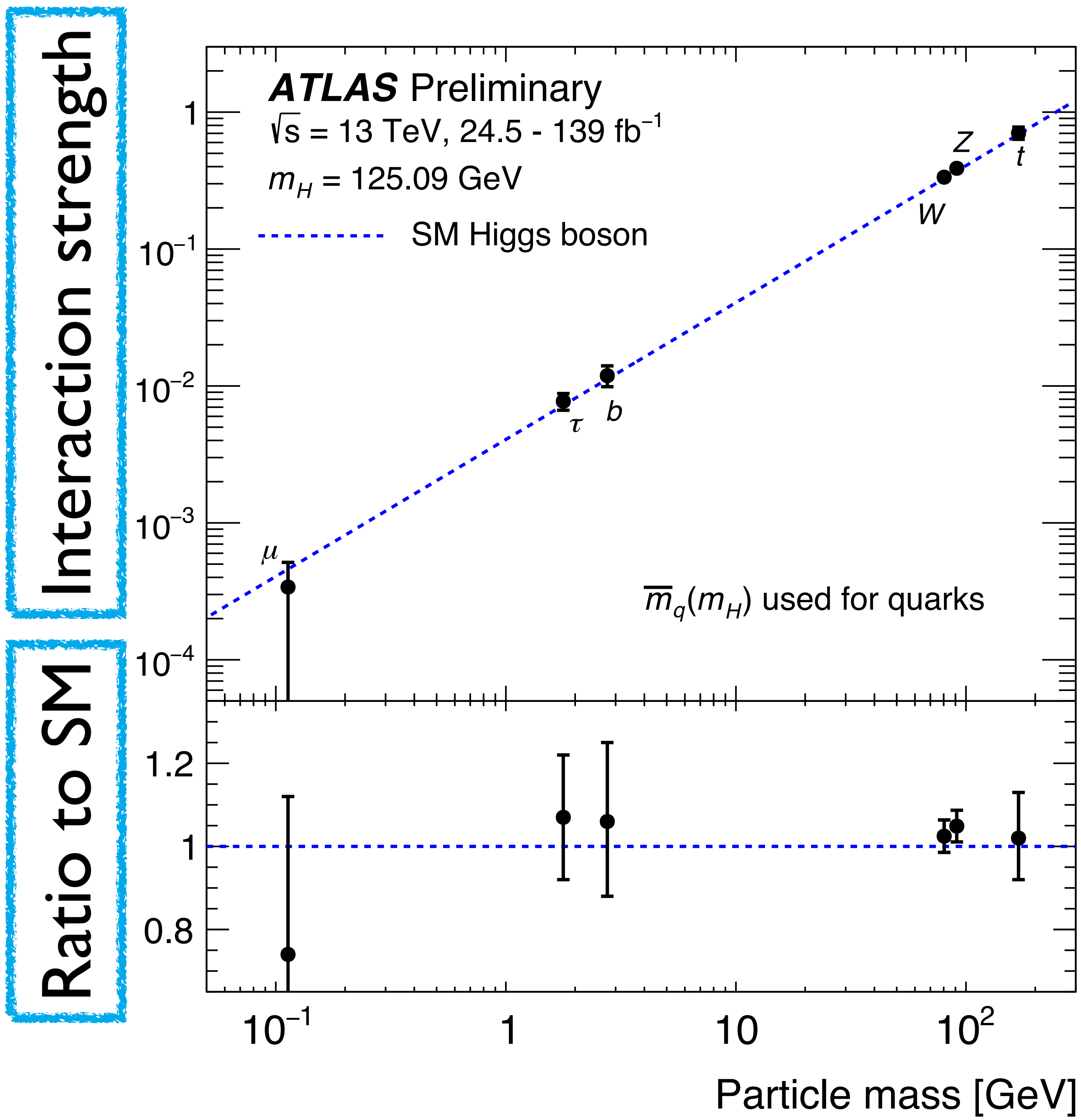

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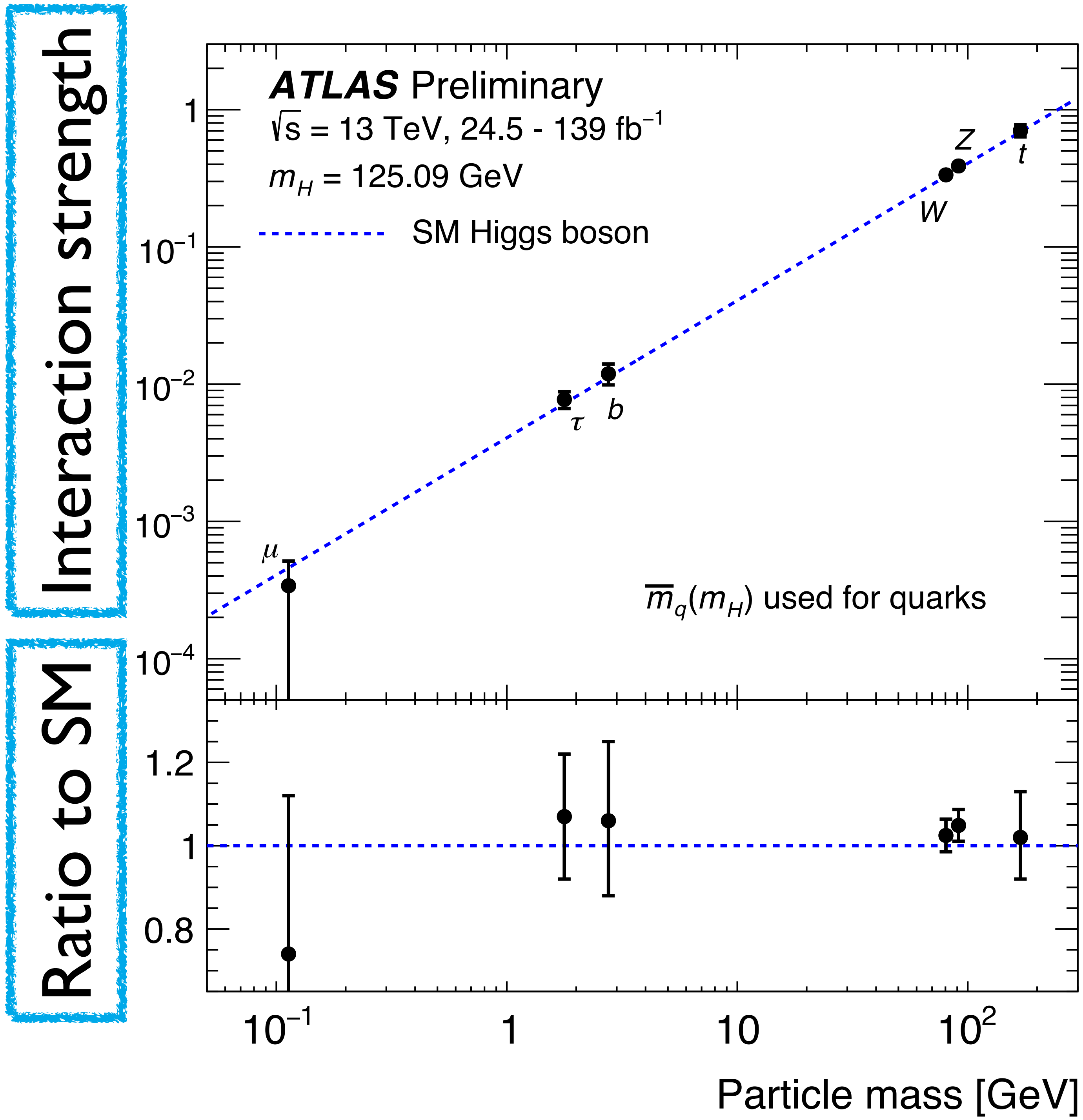

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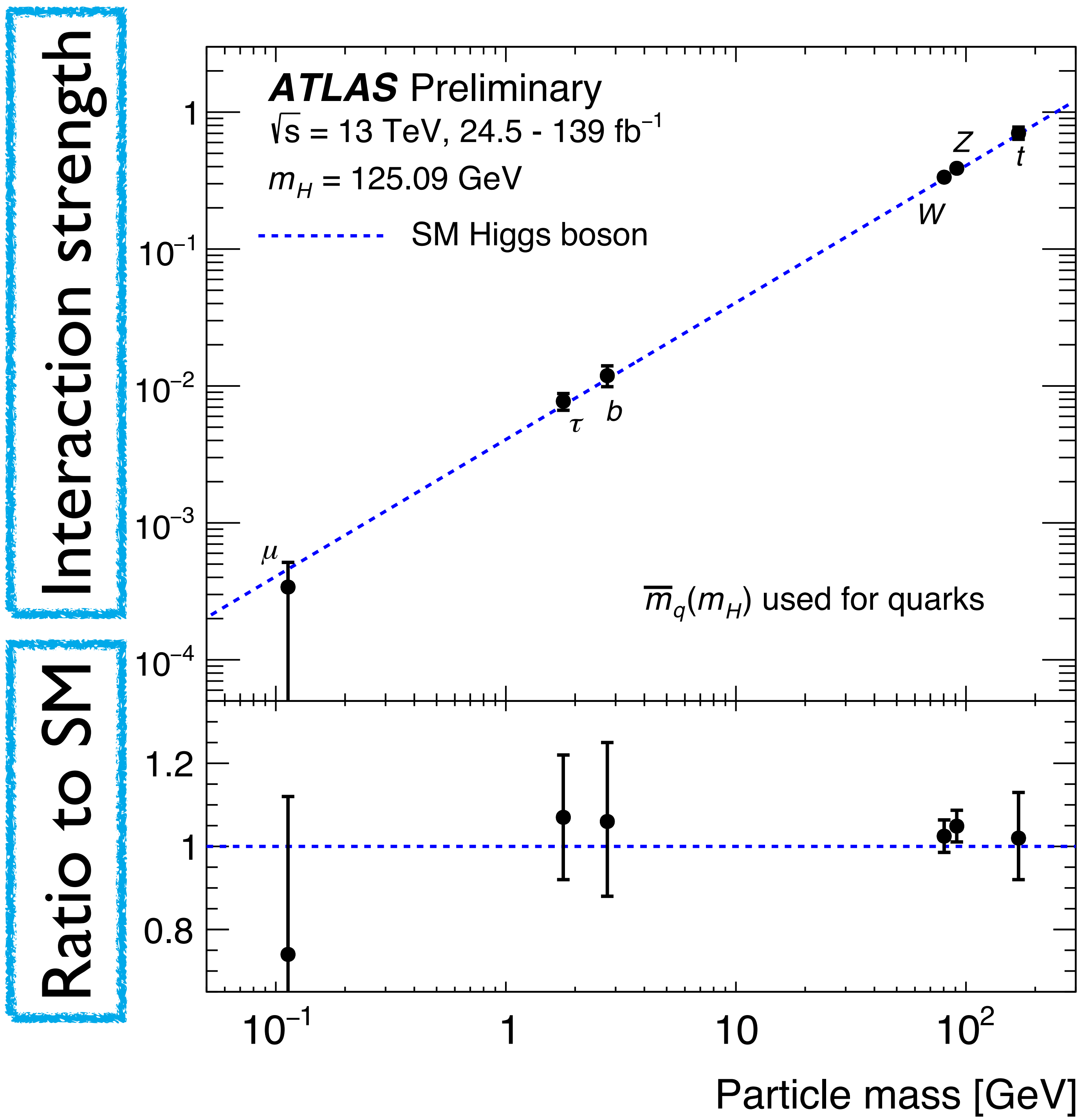

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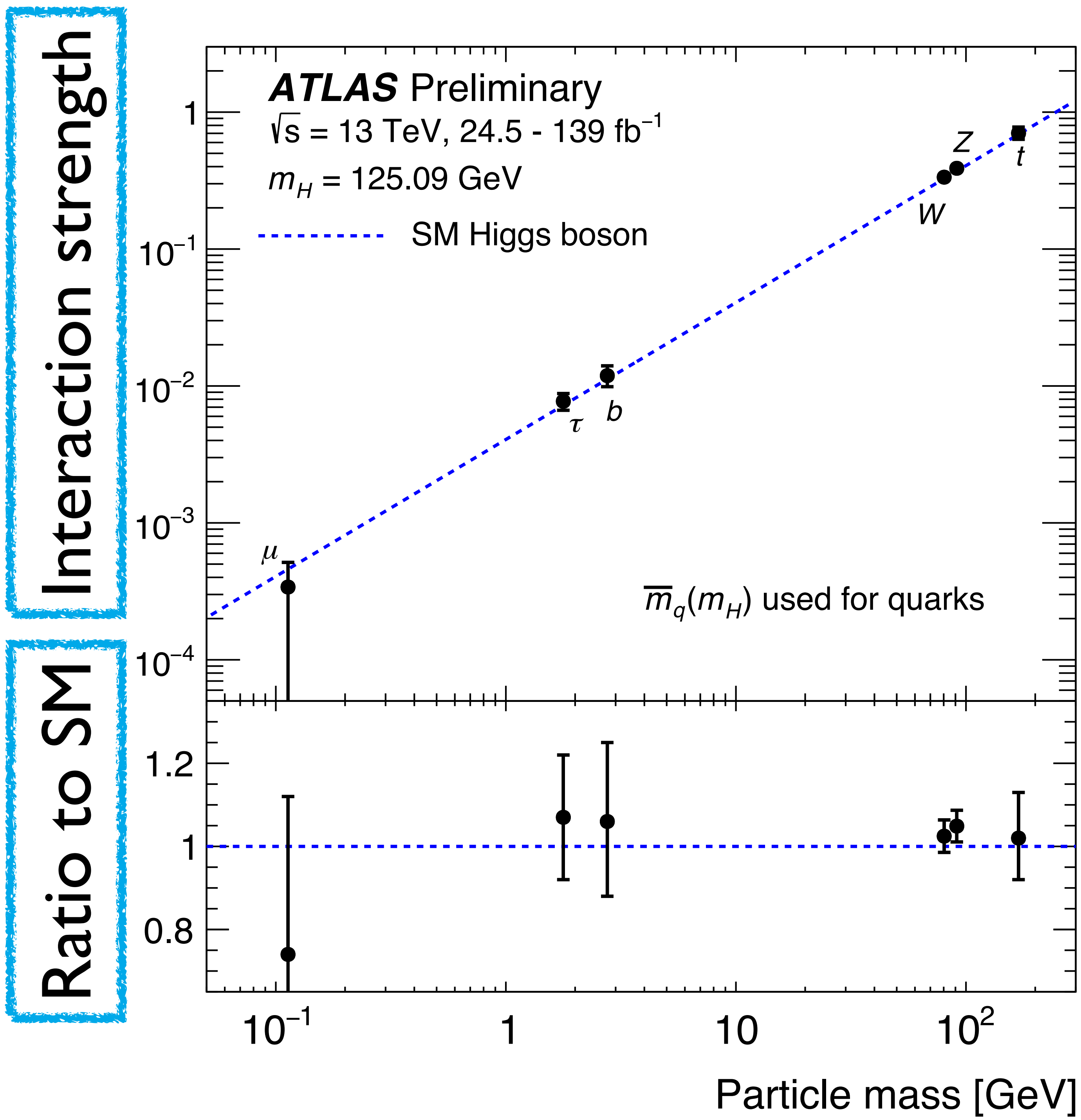

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But is there anything we don't know yet about the Higgs boson?

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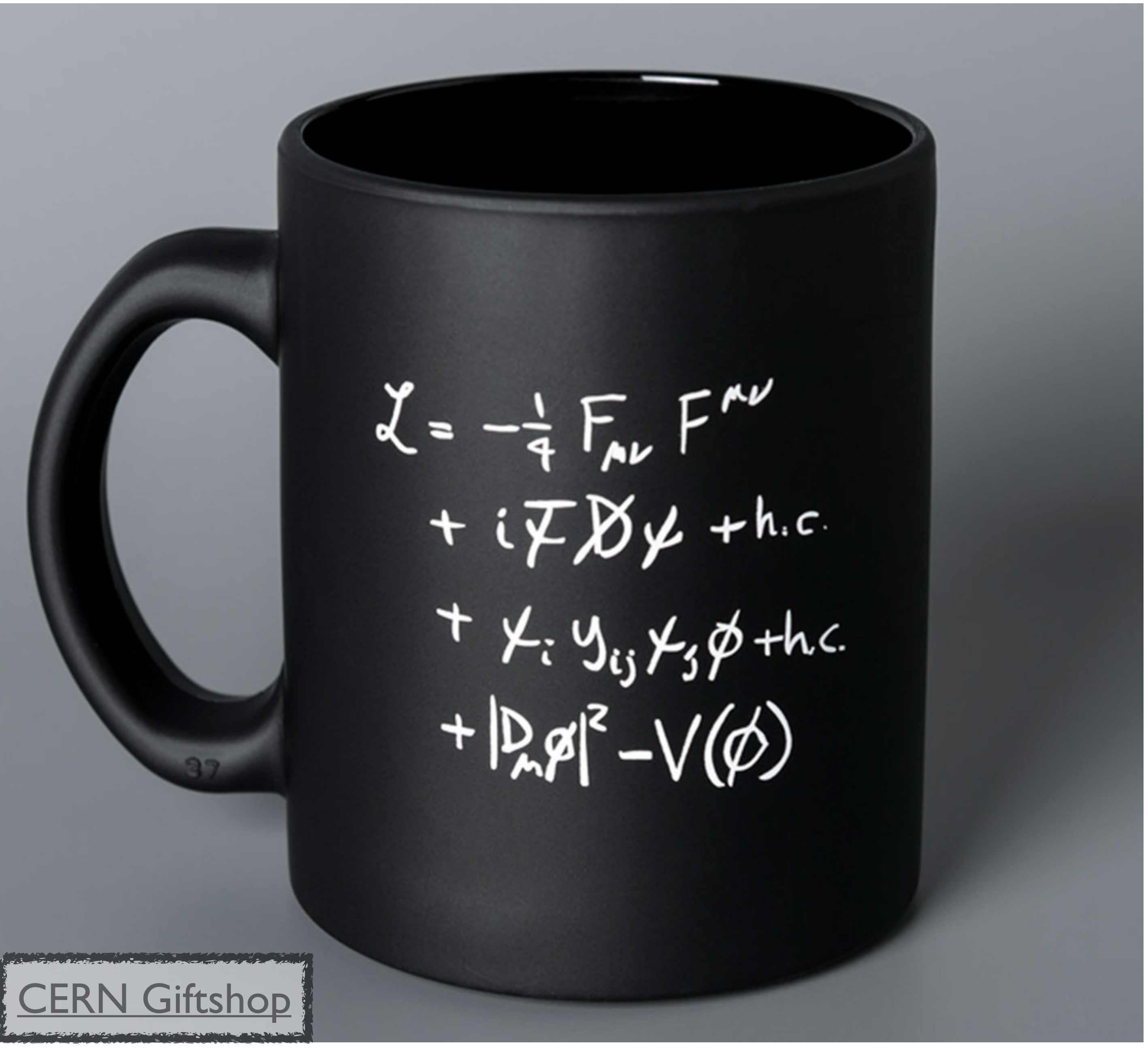

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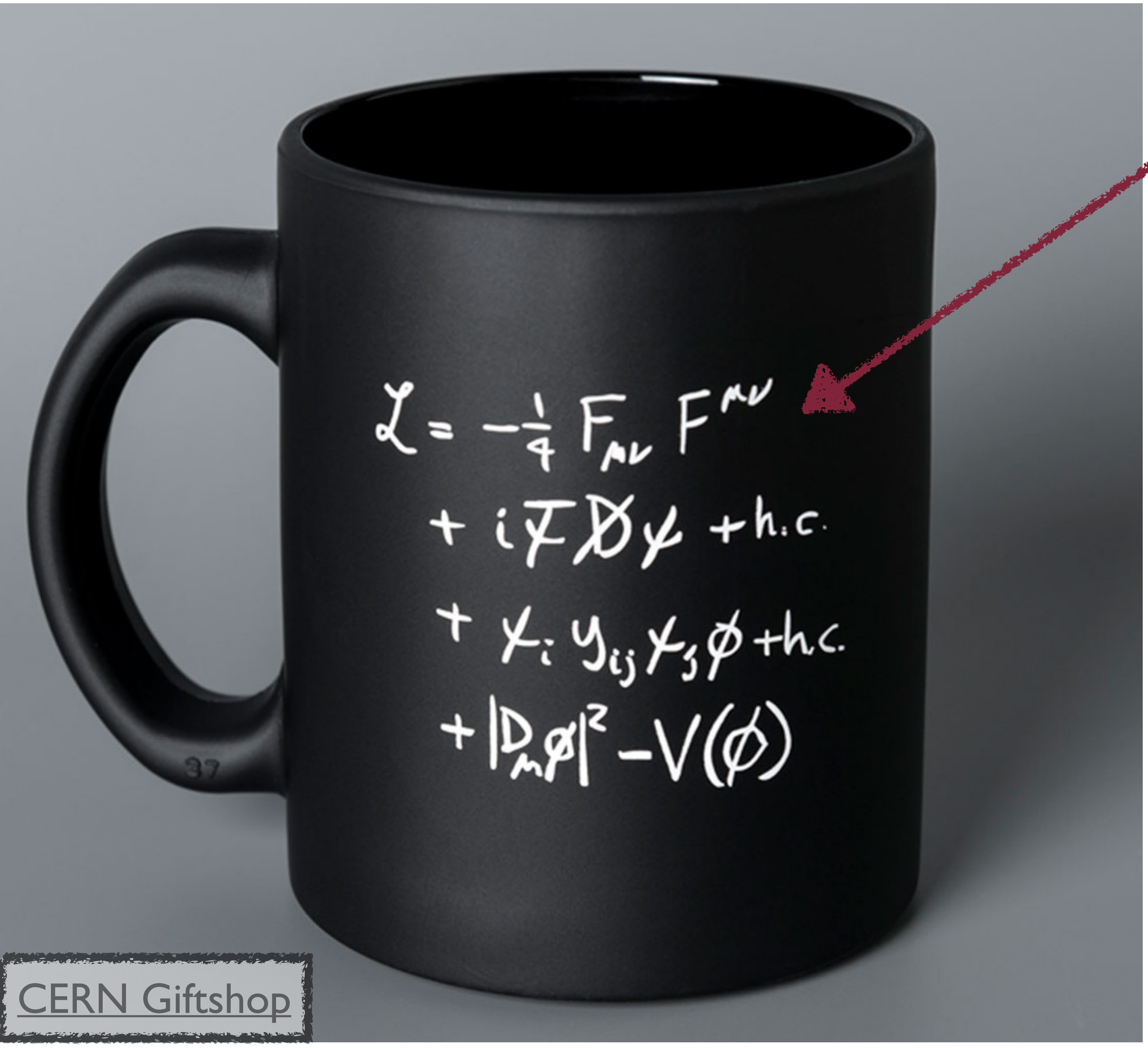

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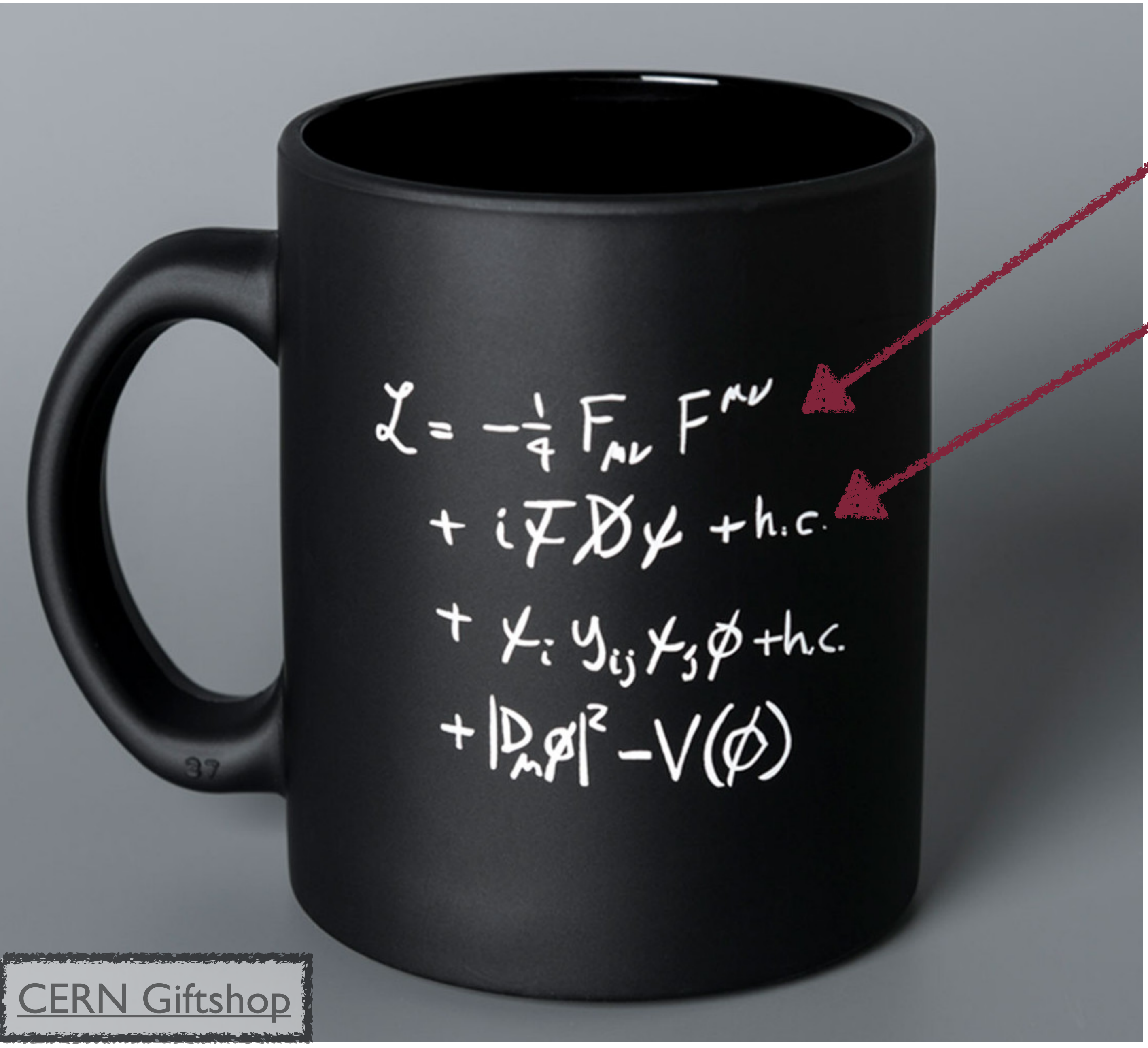

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Kinetic term for matter, and interaction with forces

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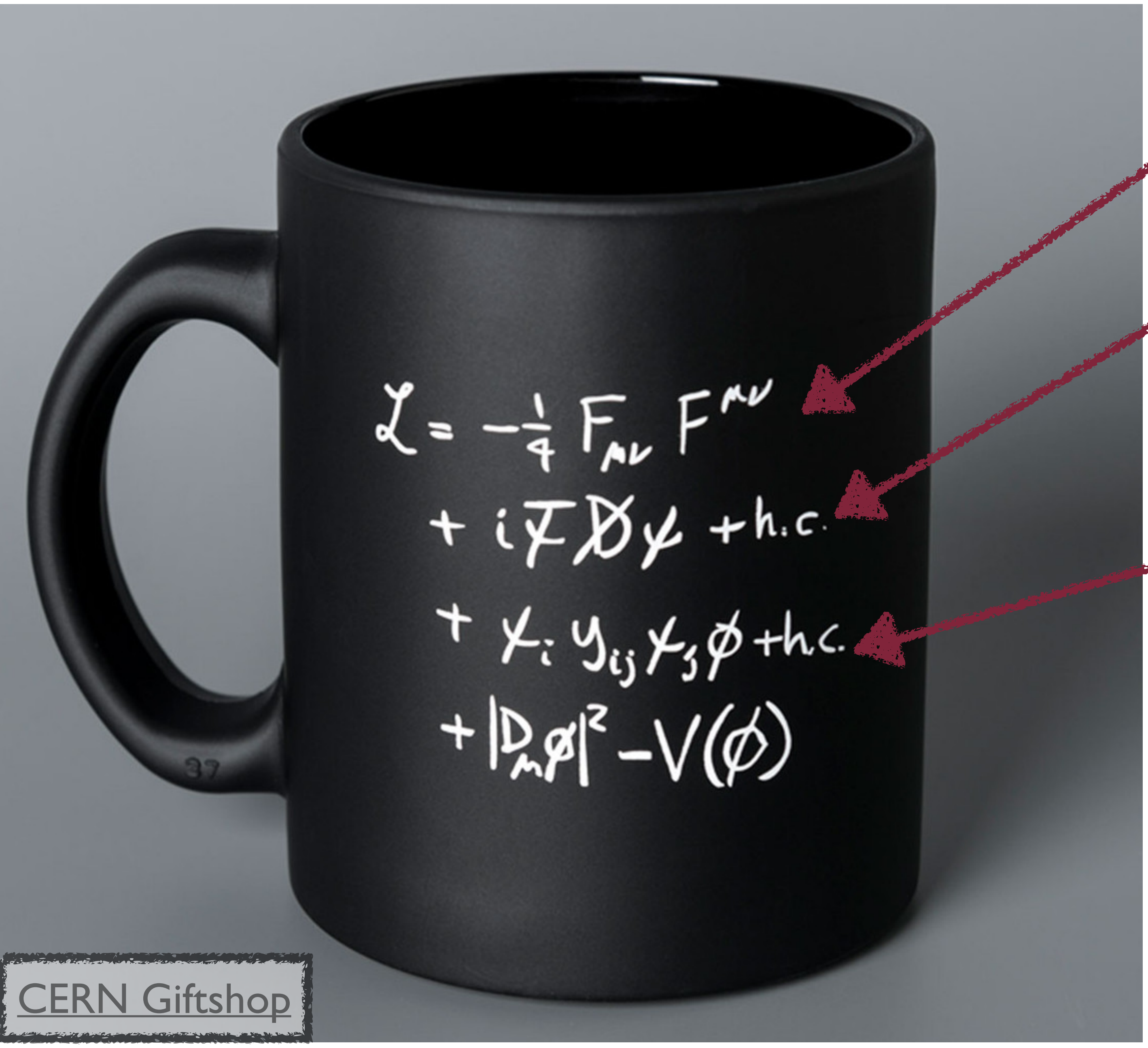

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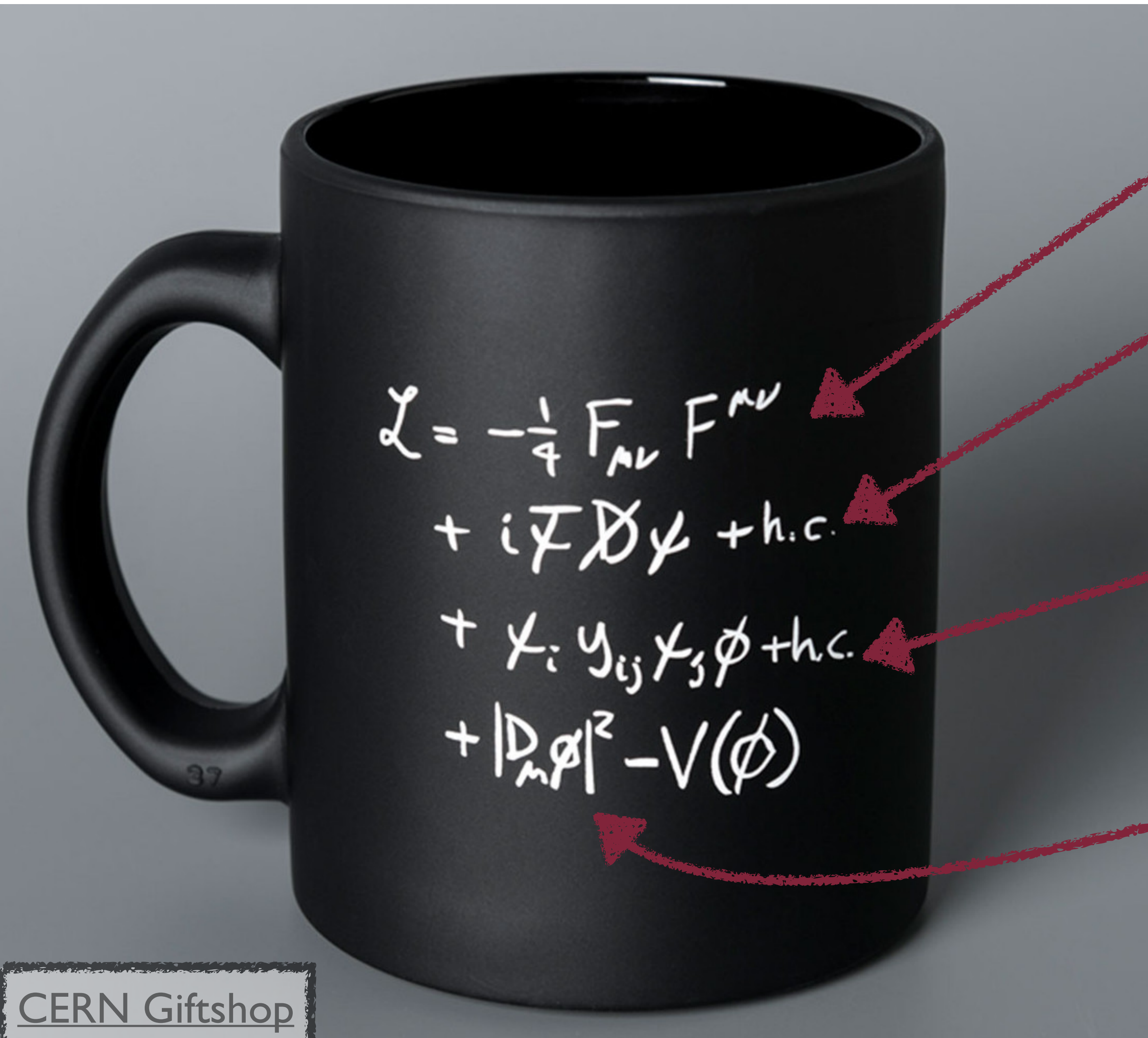

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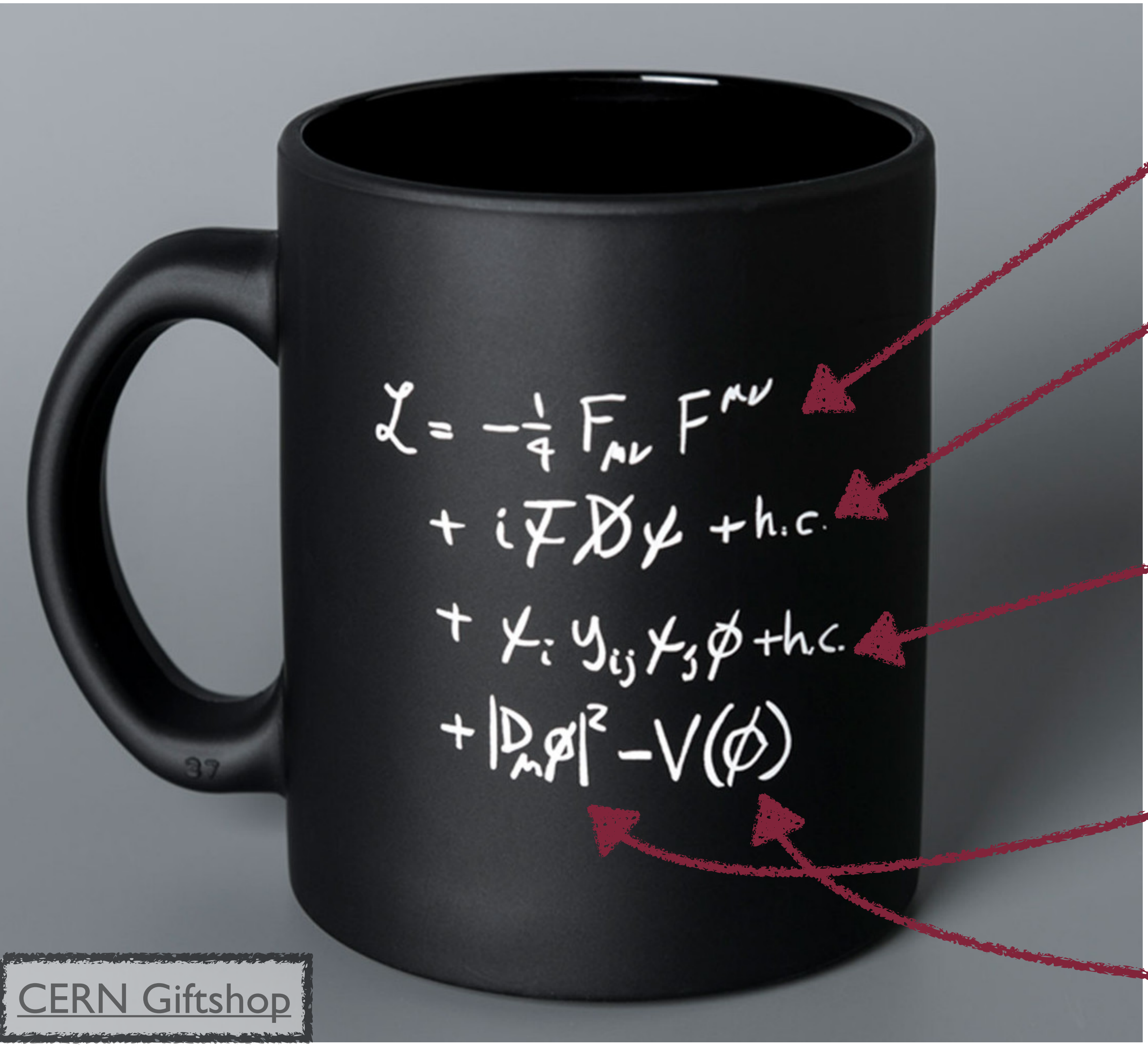

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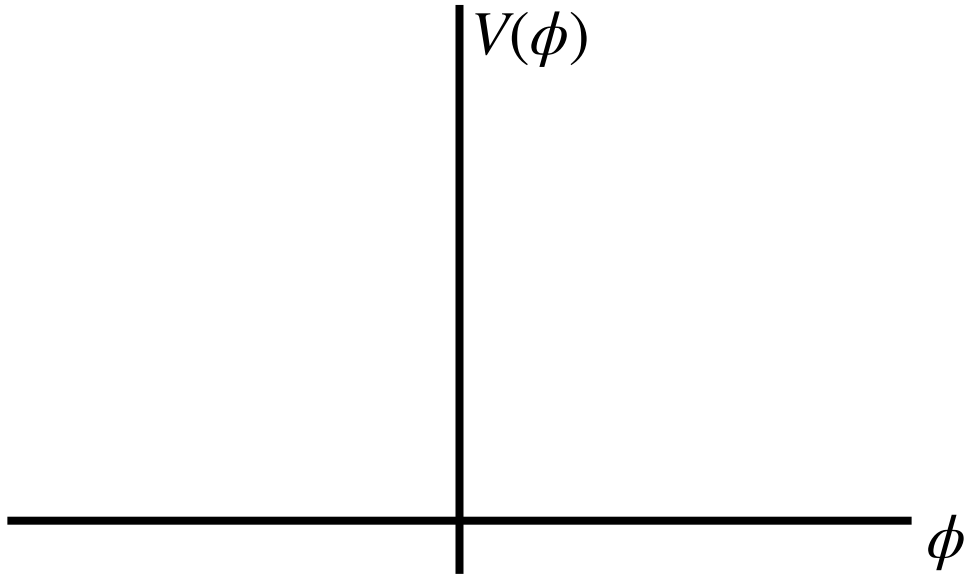

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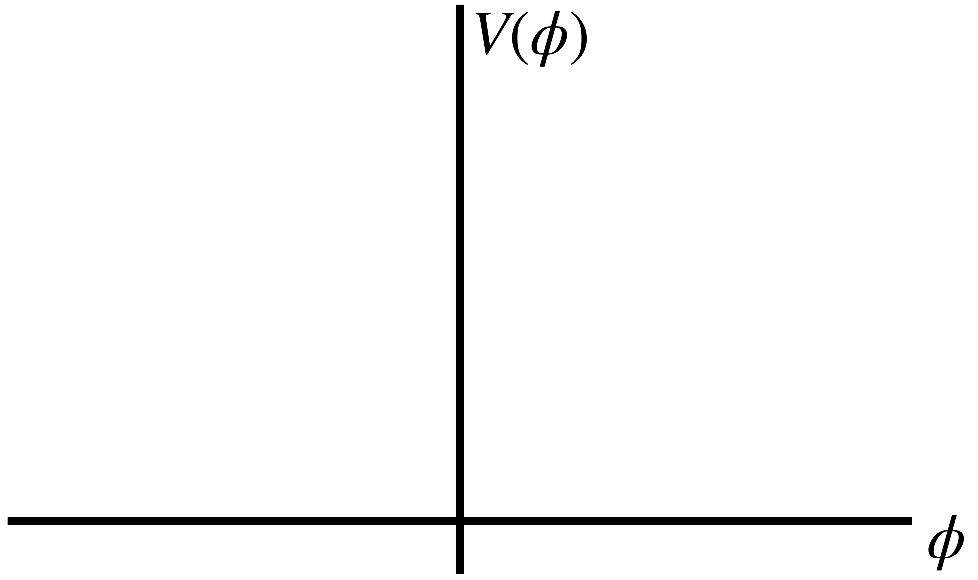
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



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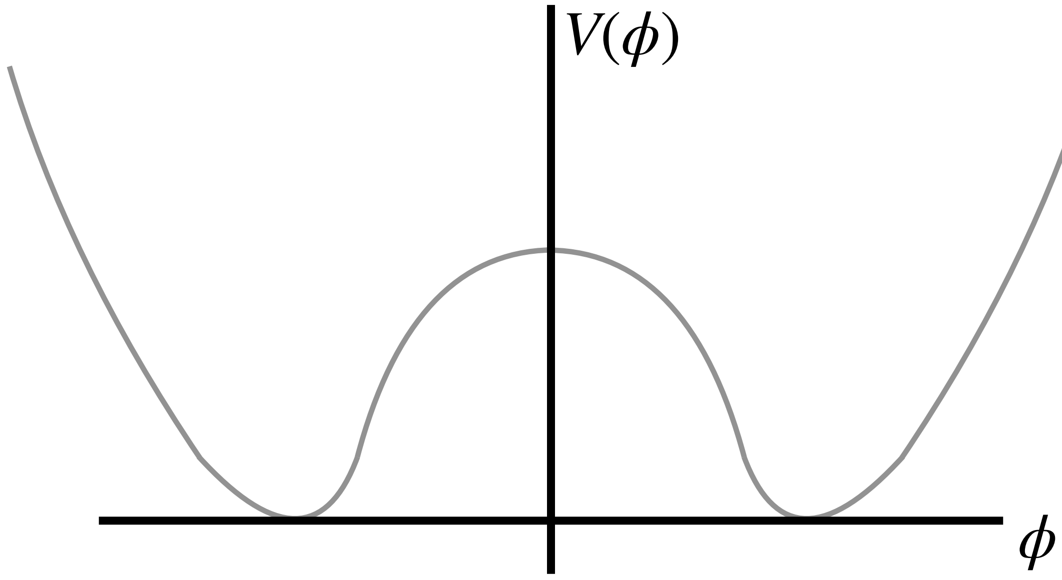

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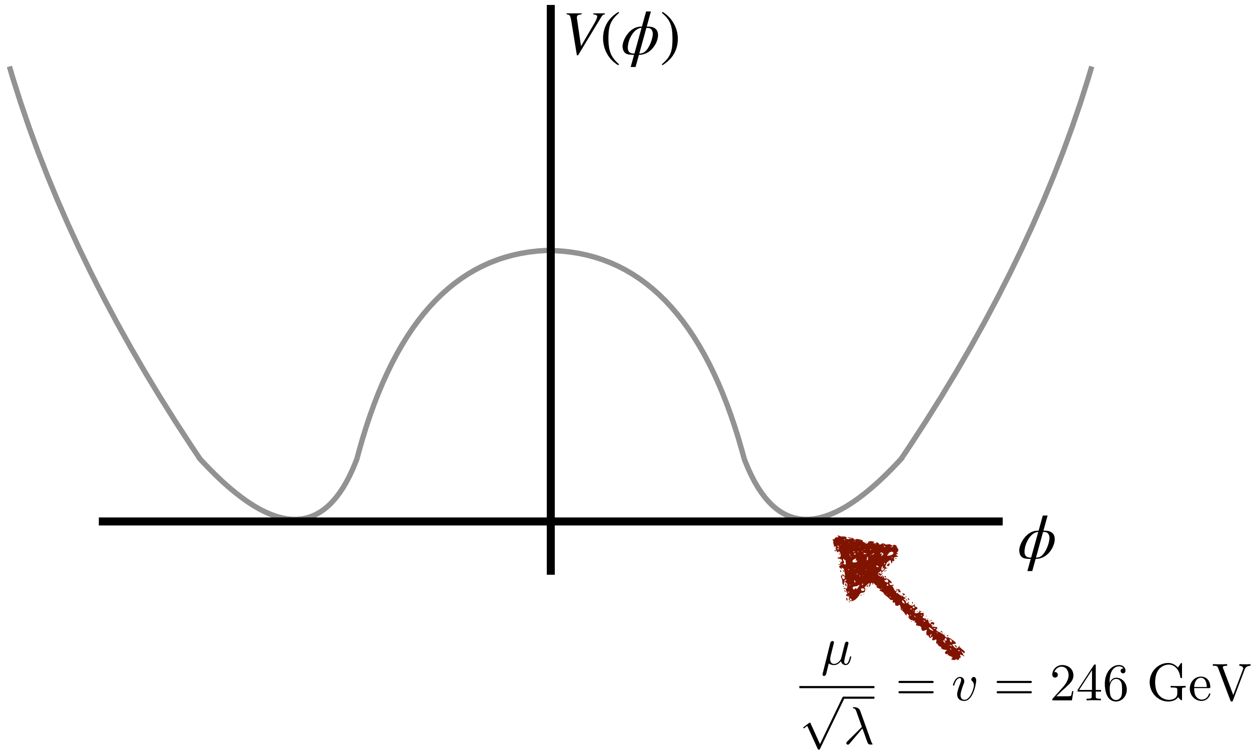

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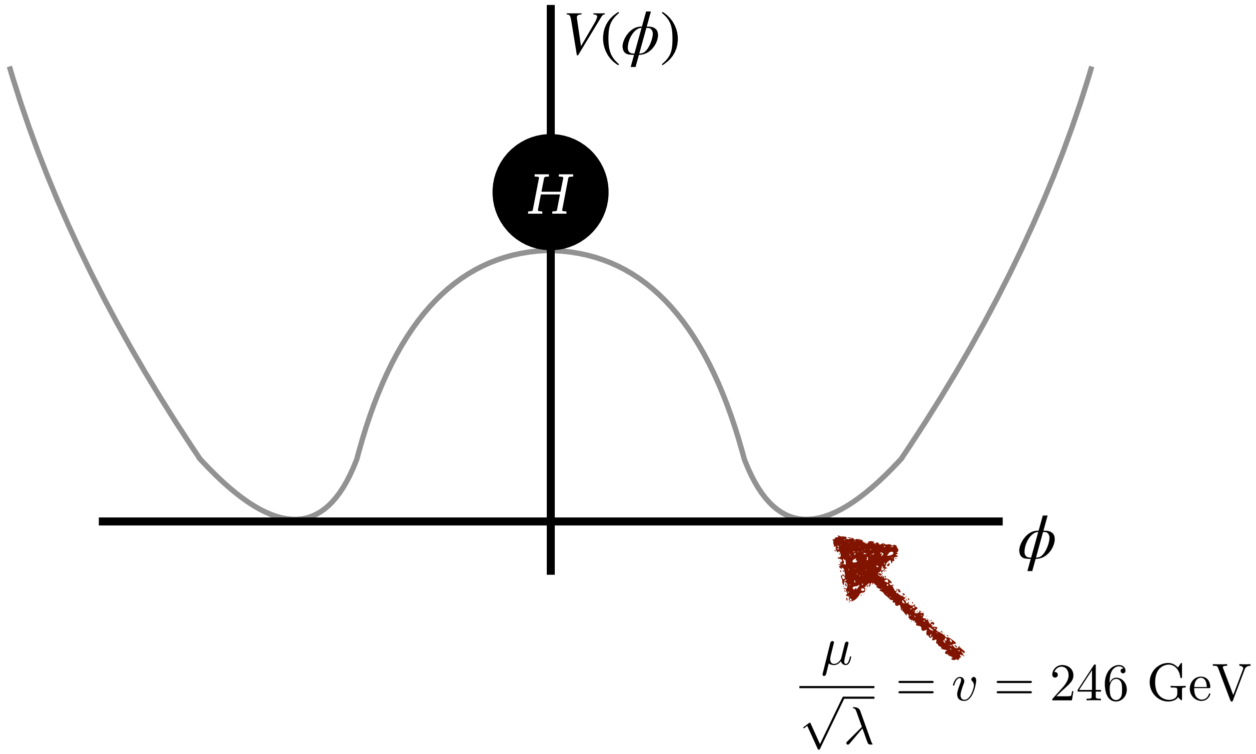

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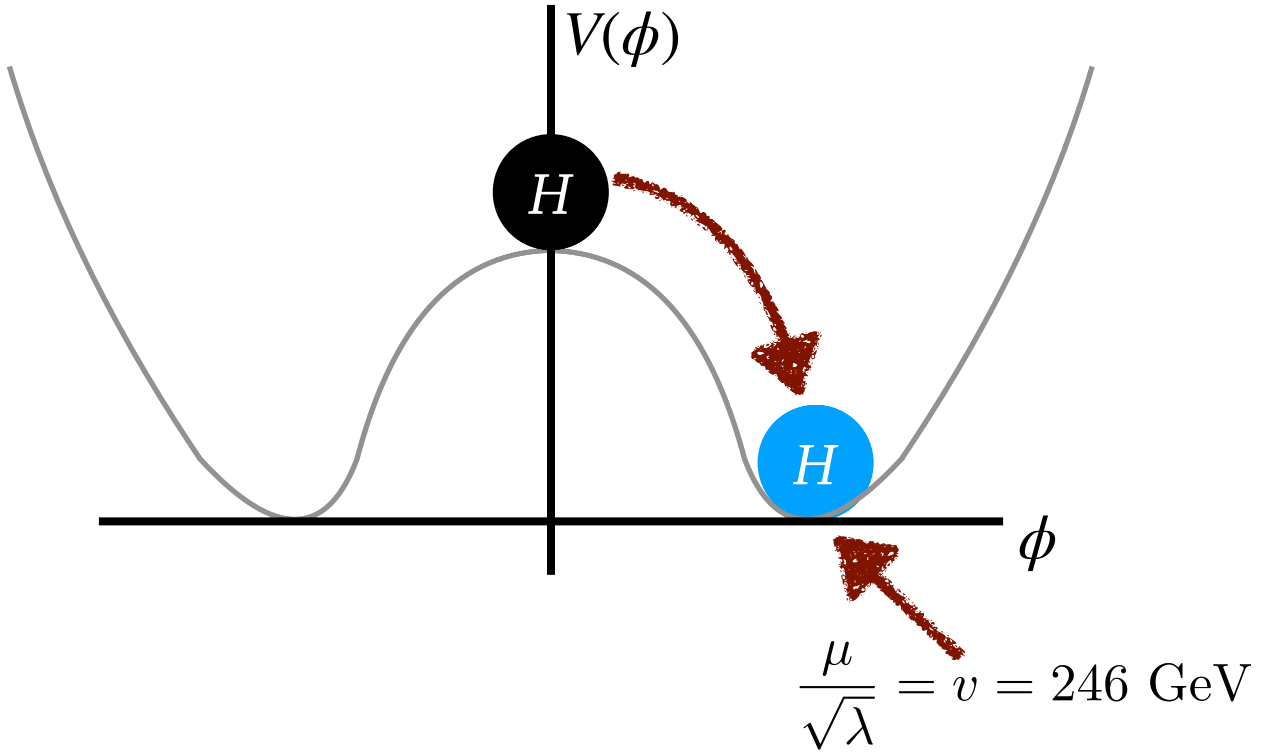

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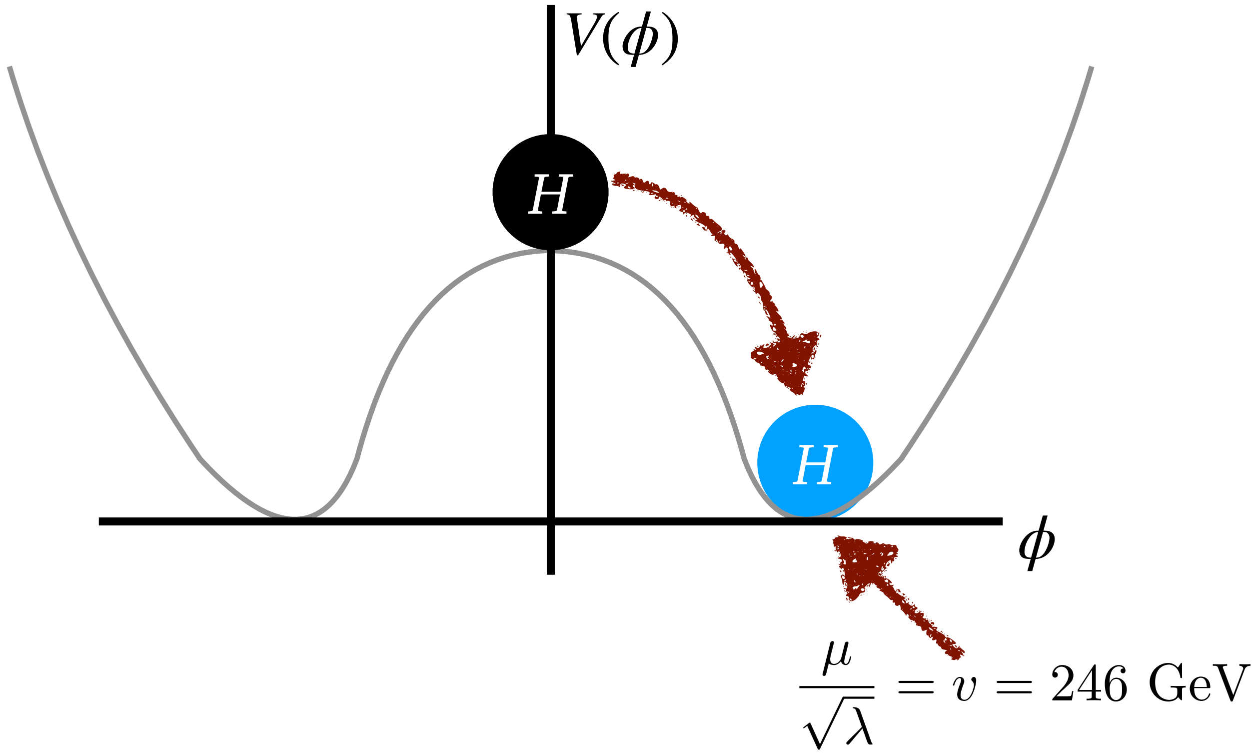

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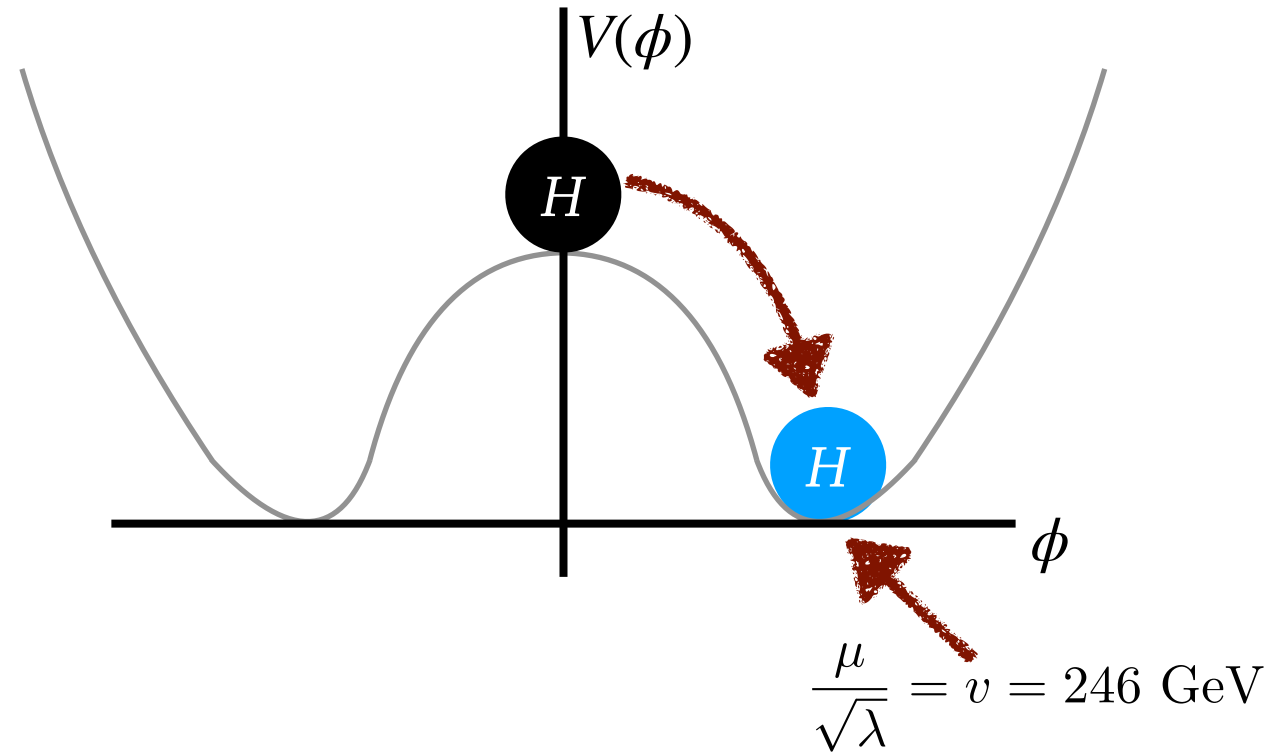

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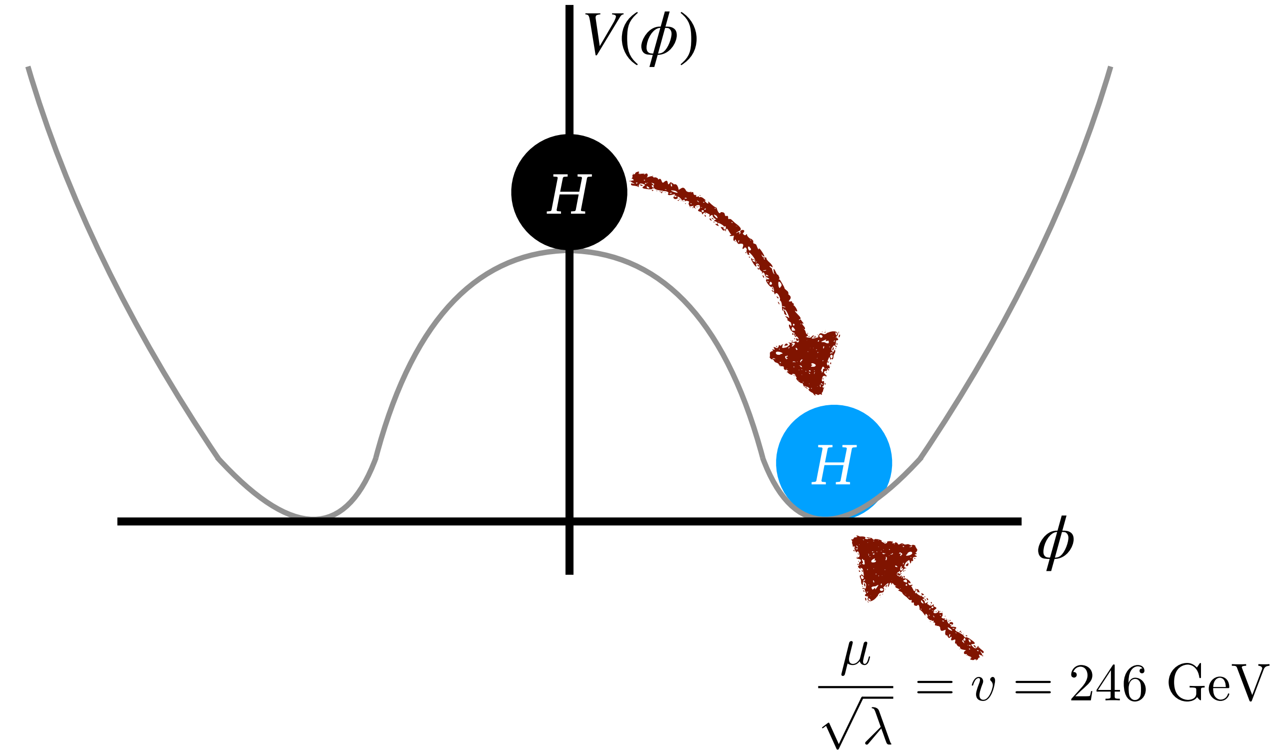

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What have we measured?

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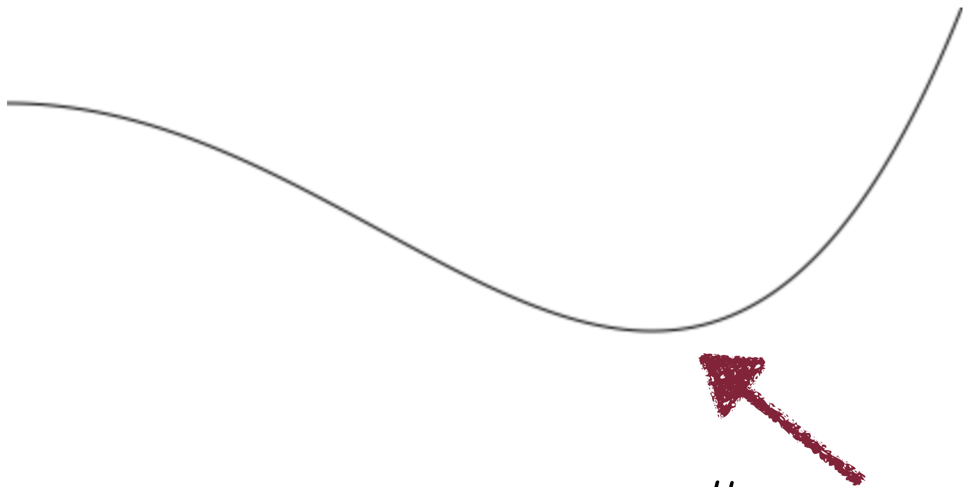

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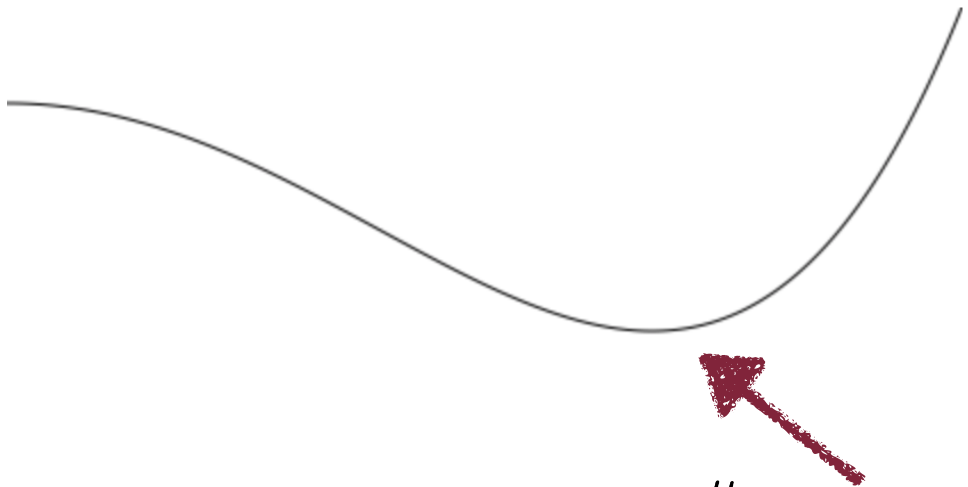

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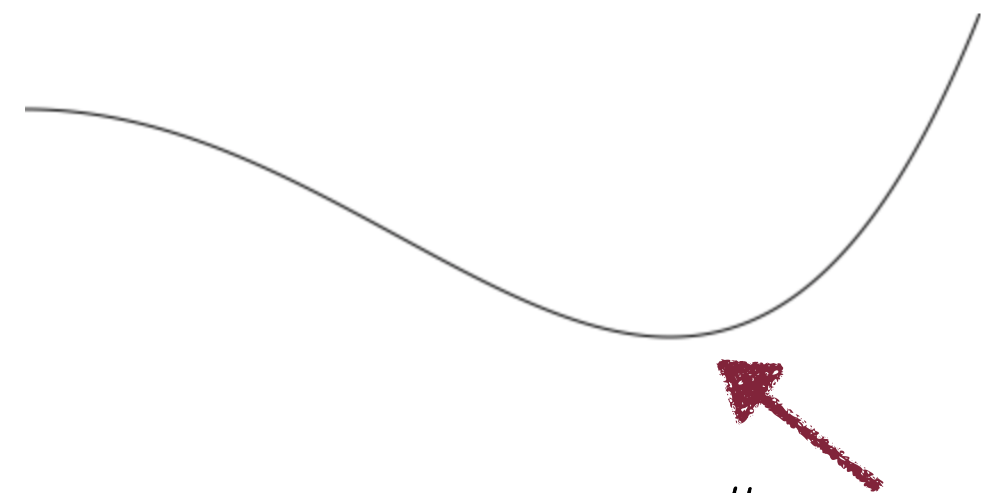

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$$\begin{aligned} V &= V_0 + \lambda v^2 h^2 + \lambda v h^3 + \ldots \\ &= V_0 + \frac{1}{2} m_H^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \ldots \end{aligned}$$

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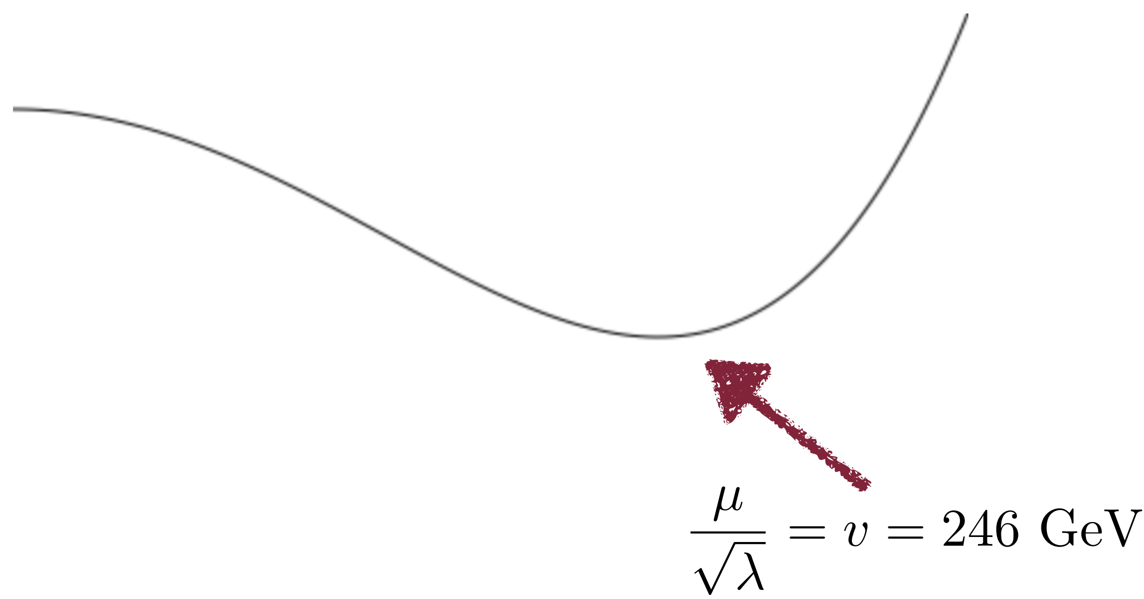

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This is a mass term!

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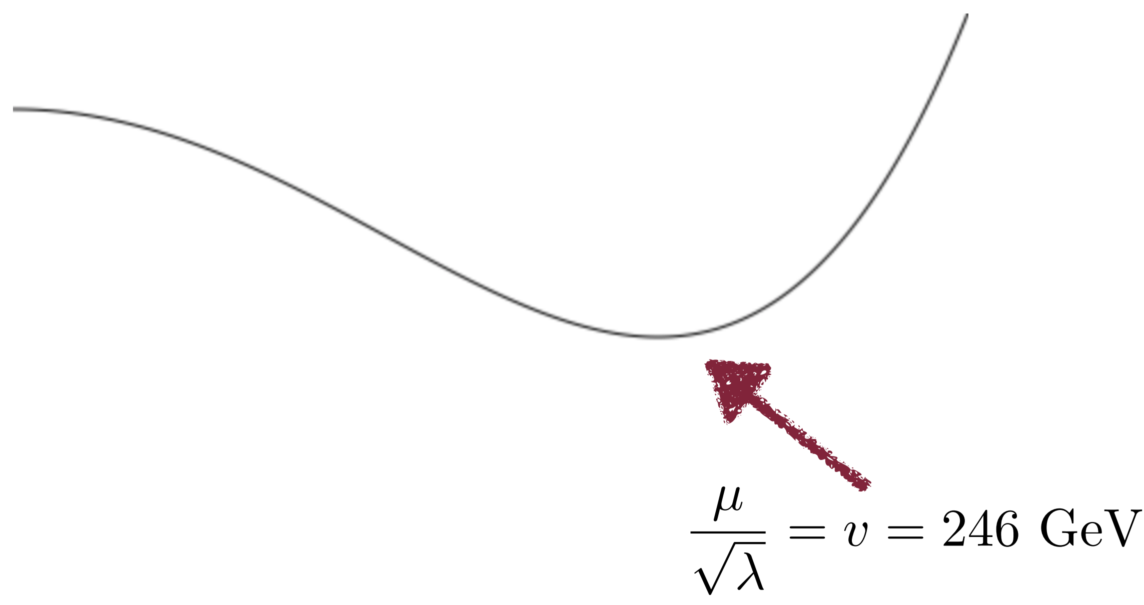

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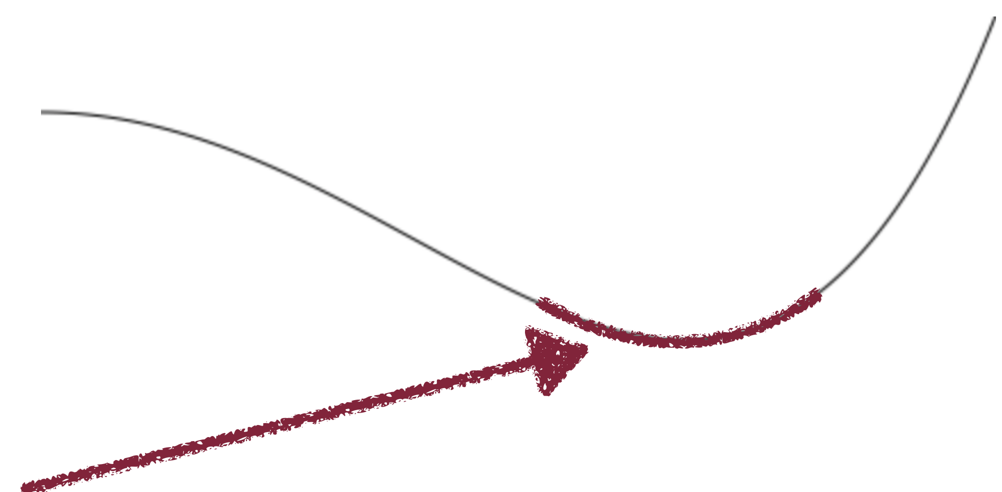
This is a mass term!



So what we've measured is the first term in this series

Measuring the Potential

The SM Higgs potential is:

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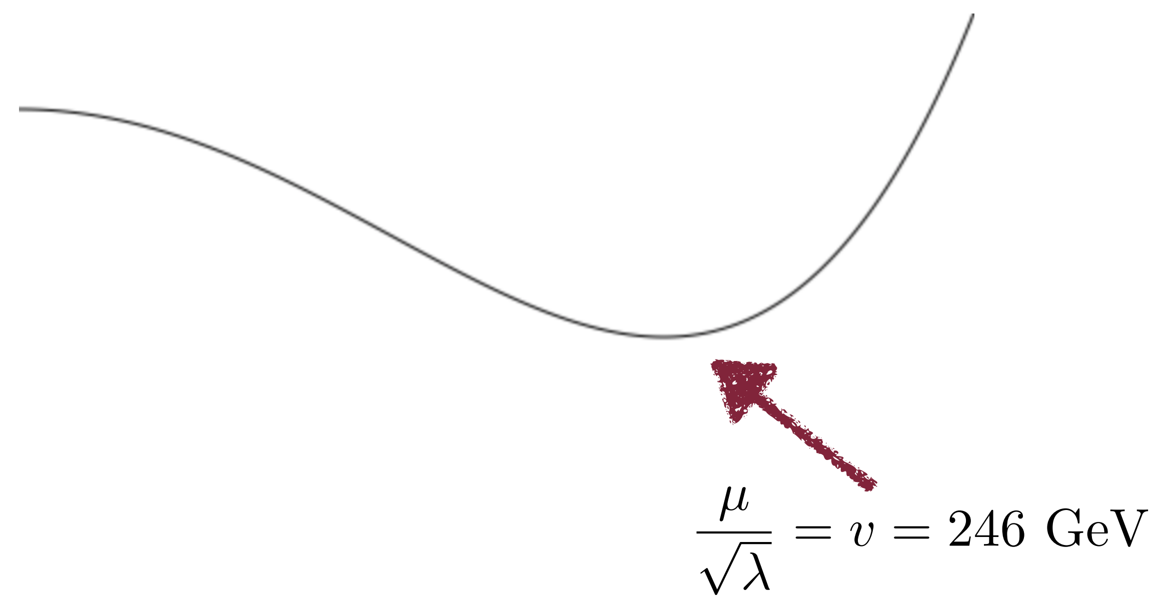

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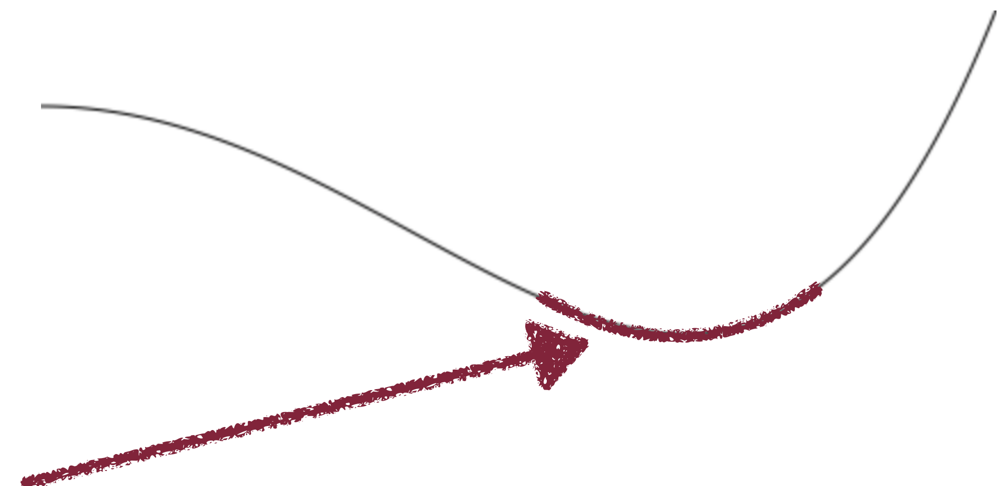

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What's next?

The Next Frontier

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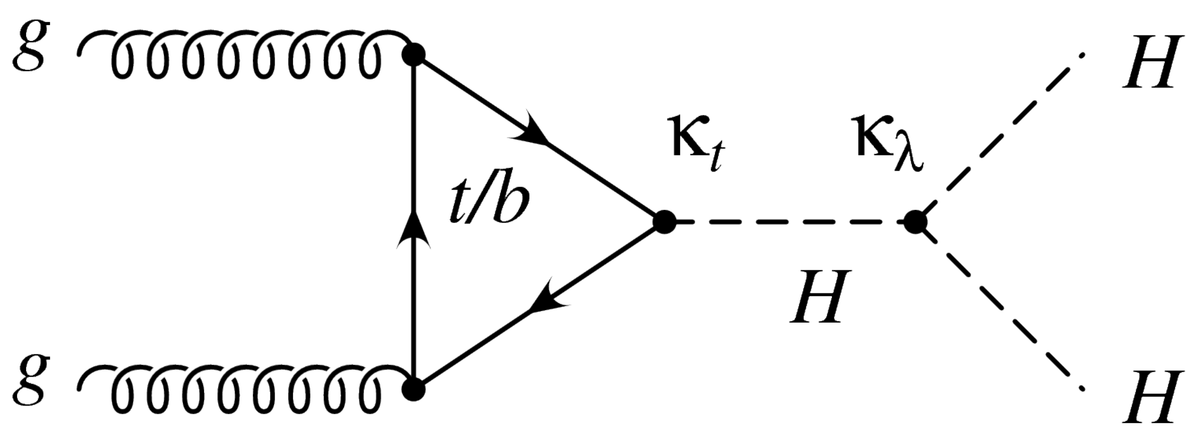

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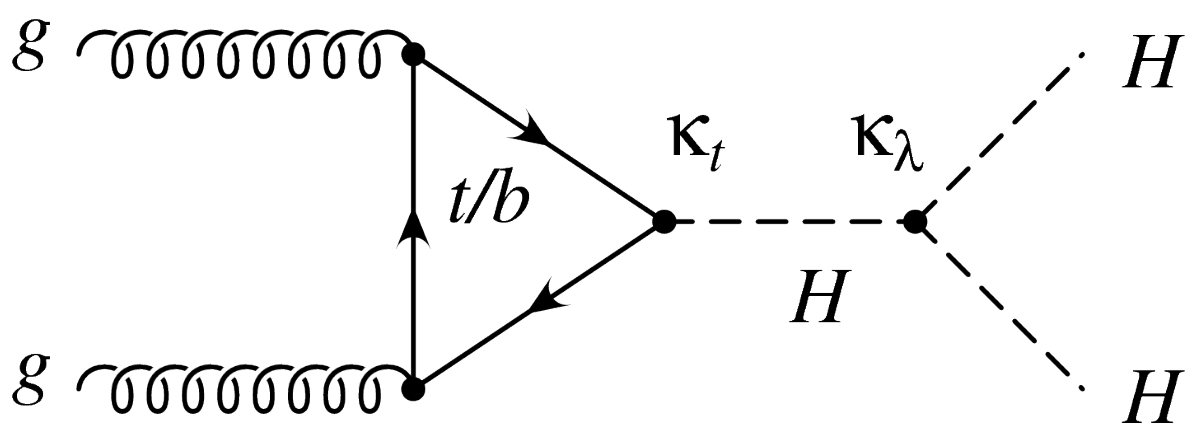

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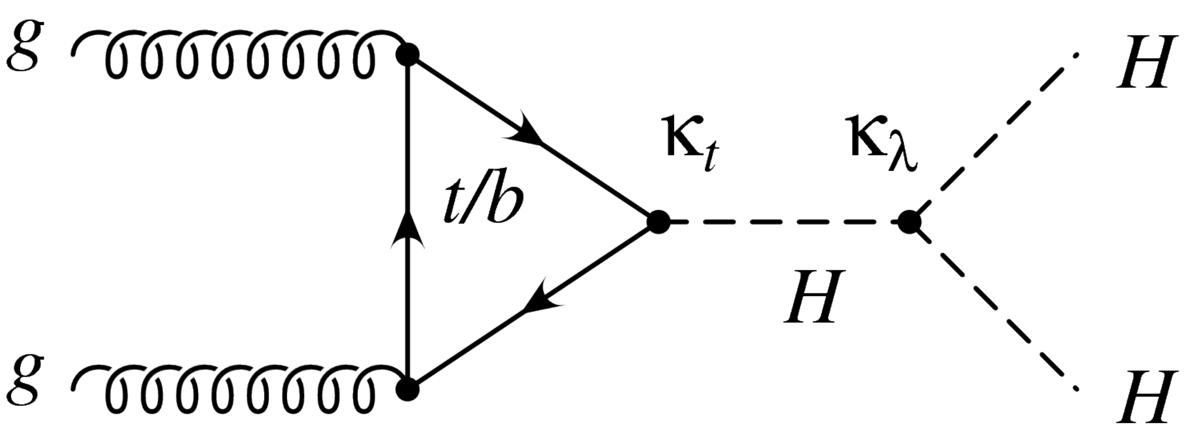

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We can measure the potential by measuring this coupling

$$\lambda_{HHH}^{SM} = \frac{m_h^2}{2v^2}$$

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

Not Quite So Easy…

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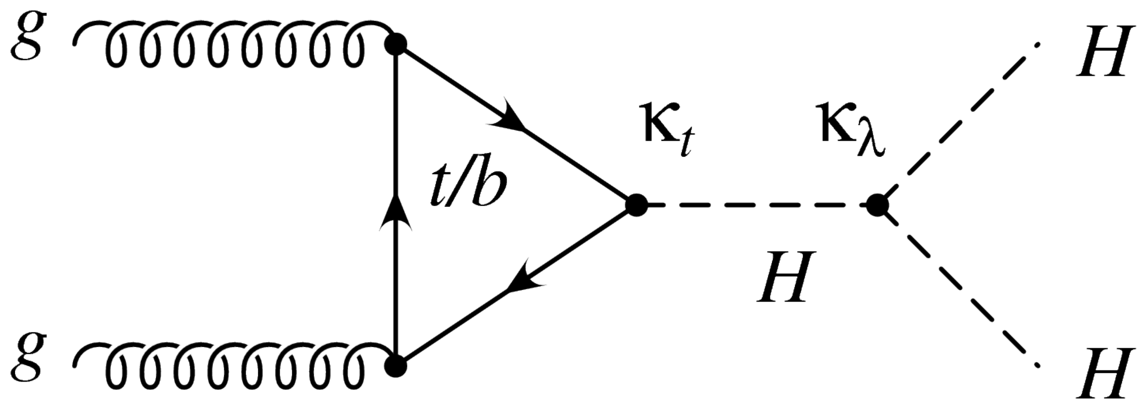

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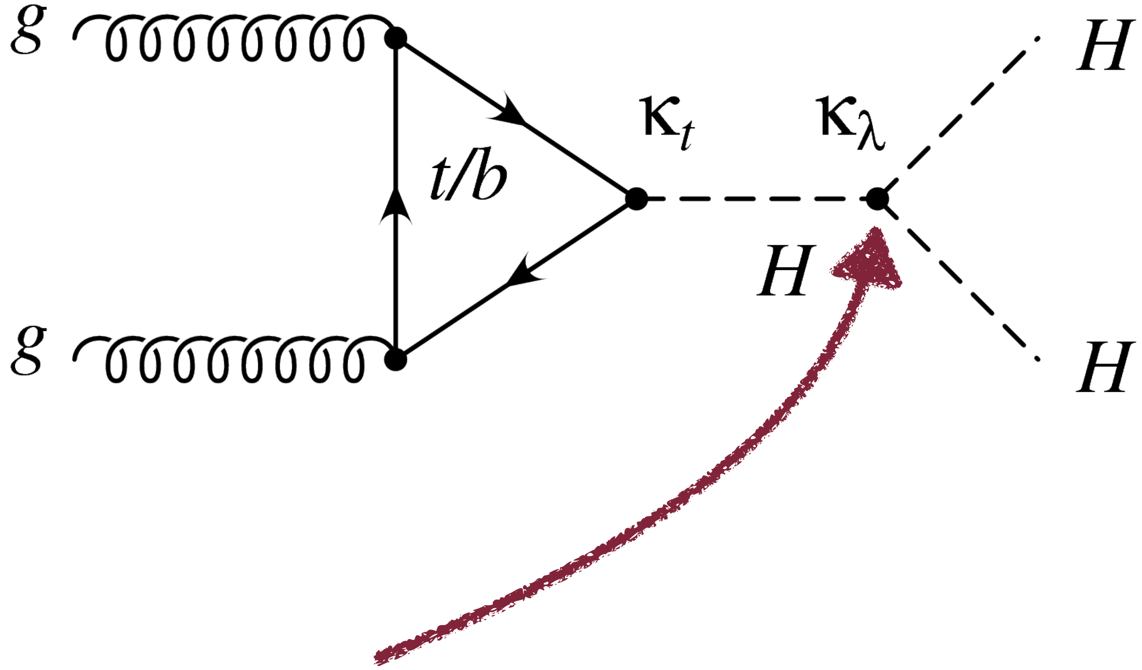

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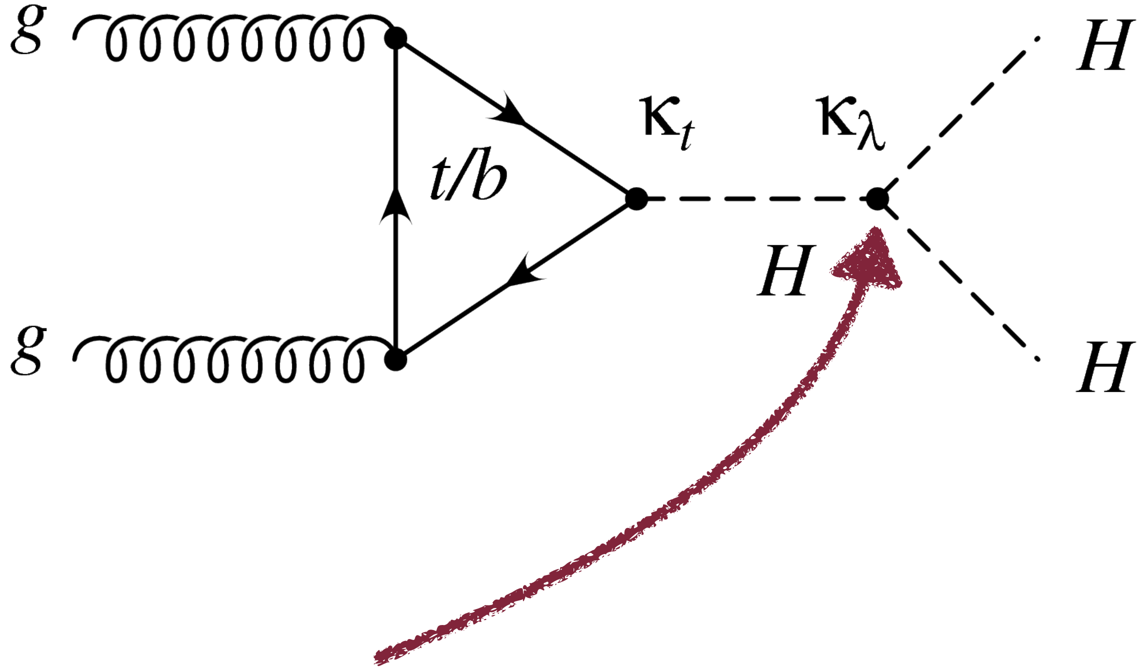

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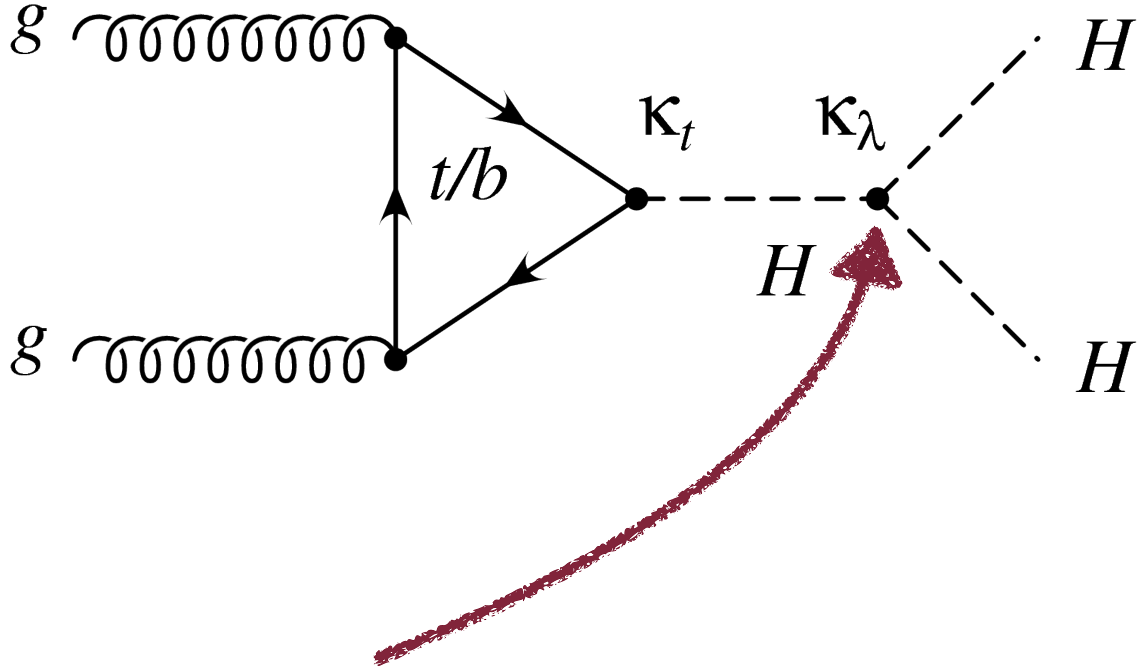

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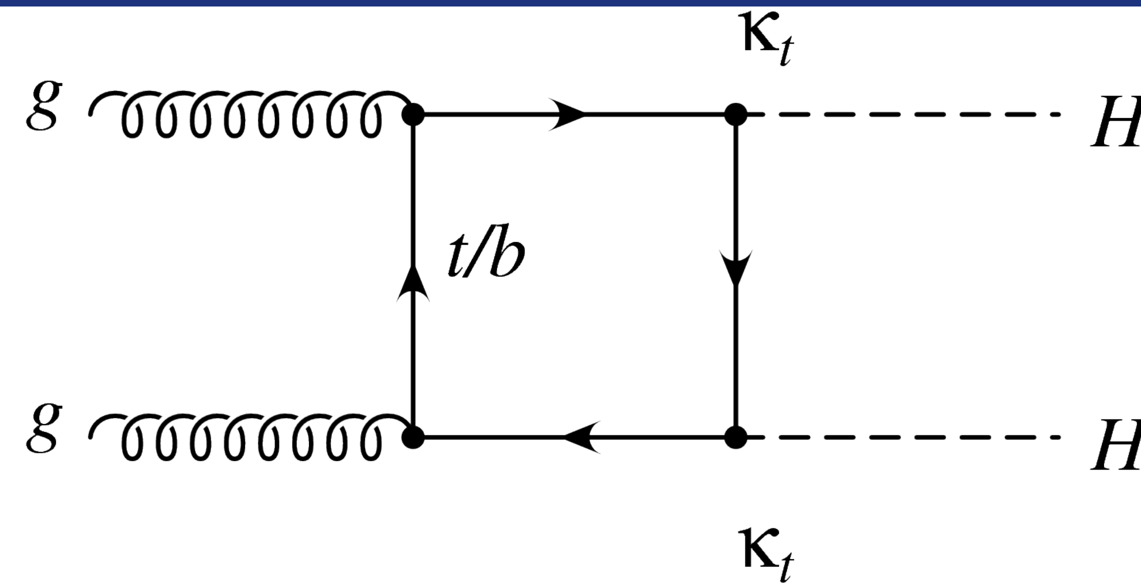

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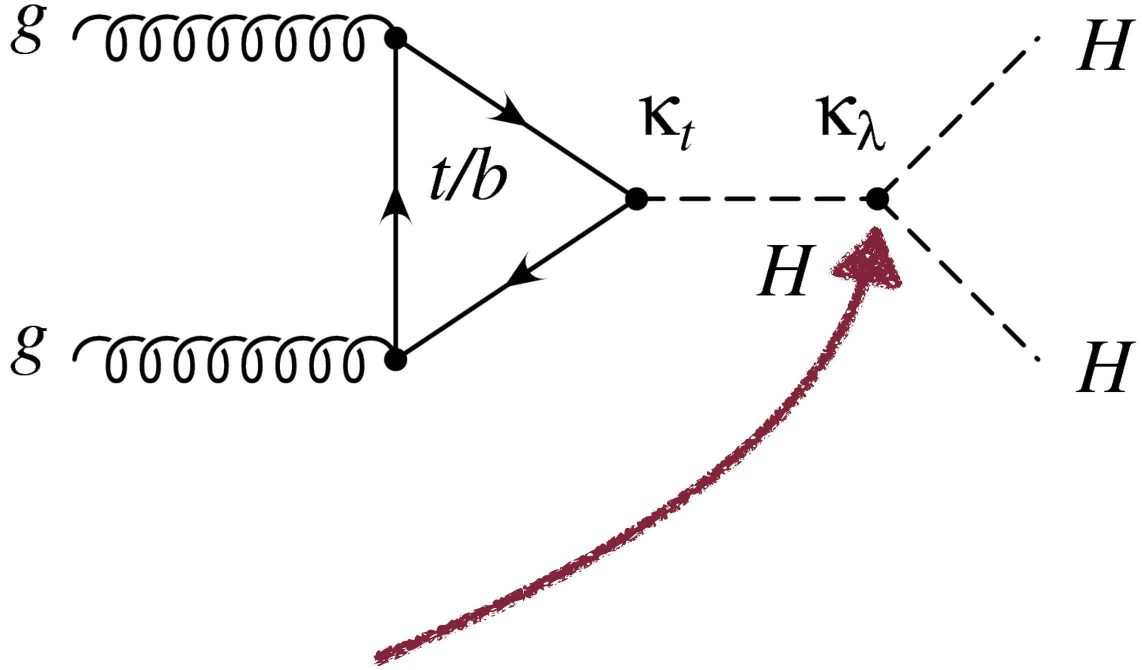

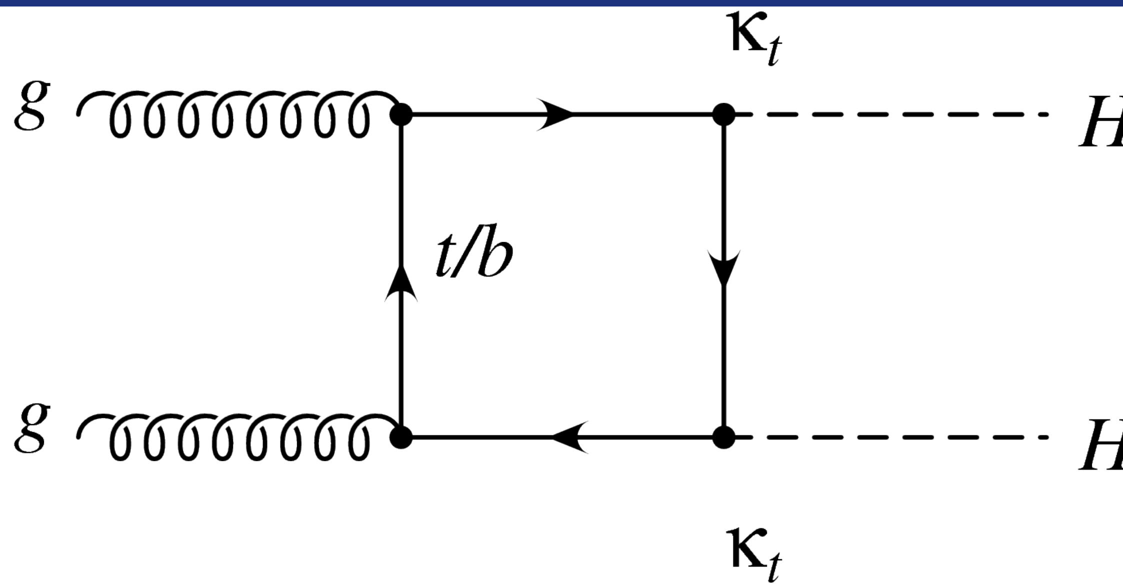

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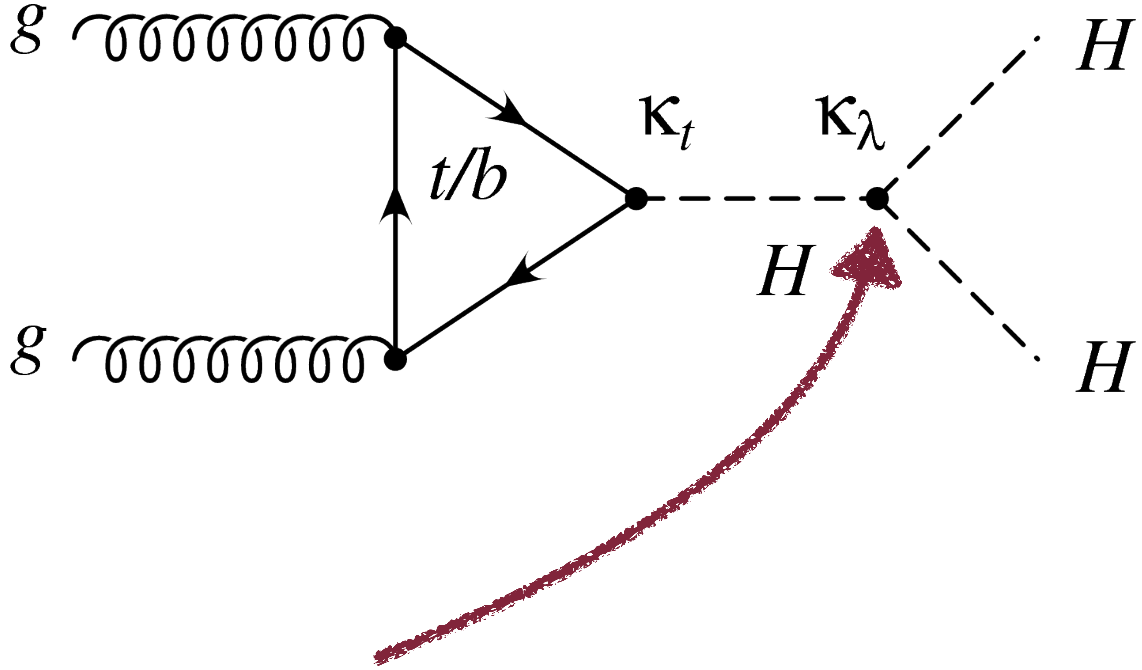

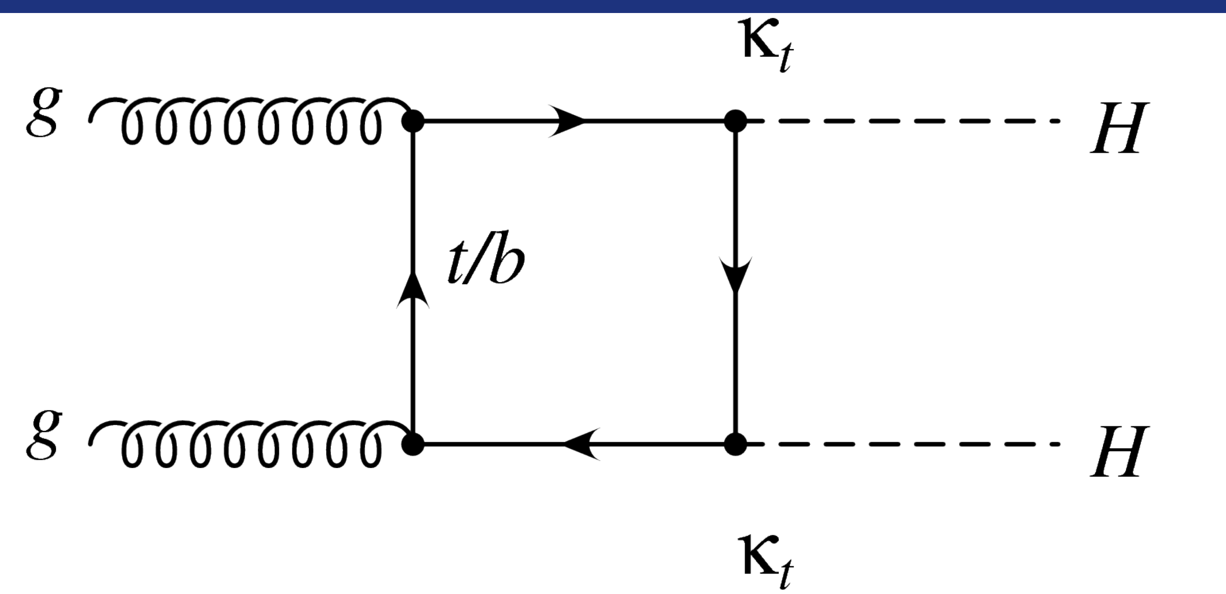

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Di-Higgs production is a **rare process**: perfect for our large datasets!

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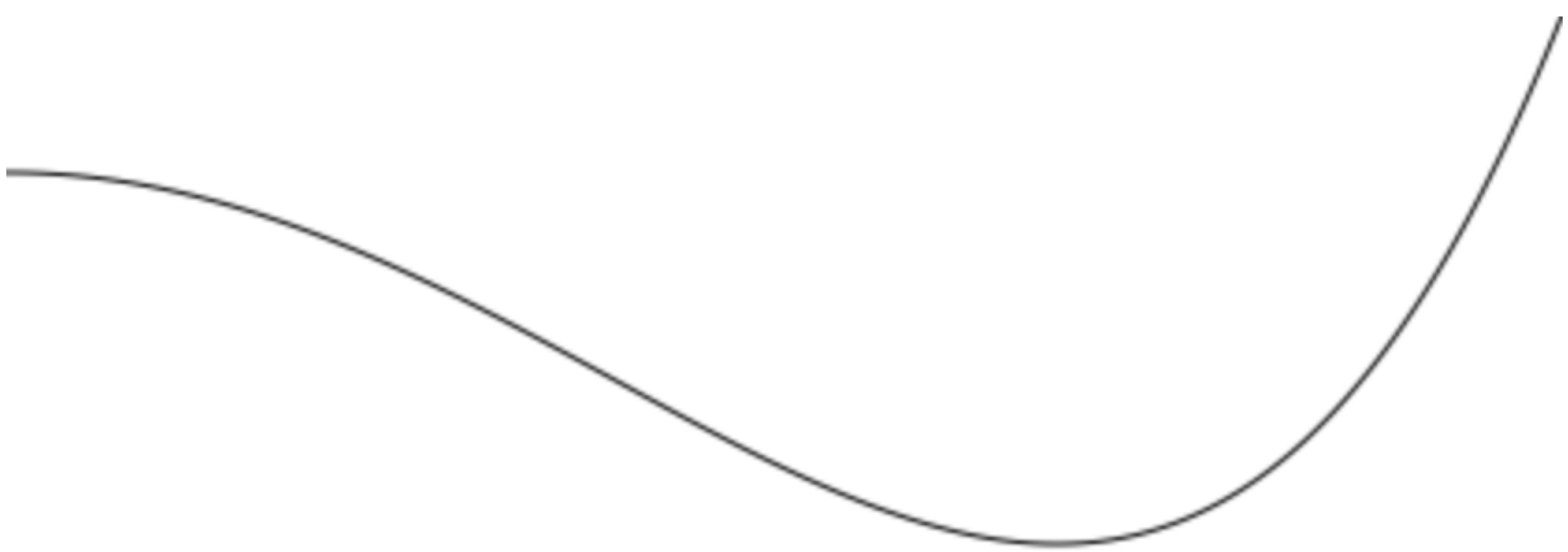

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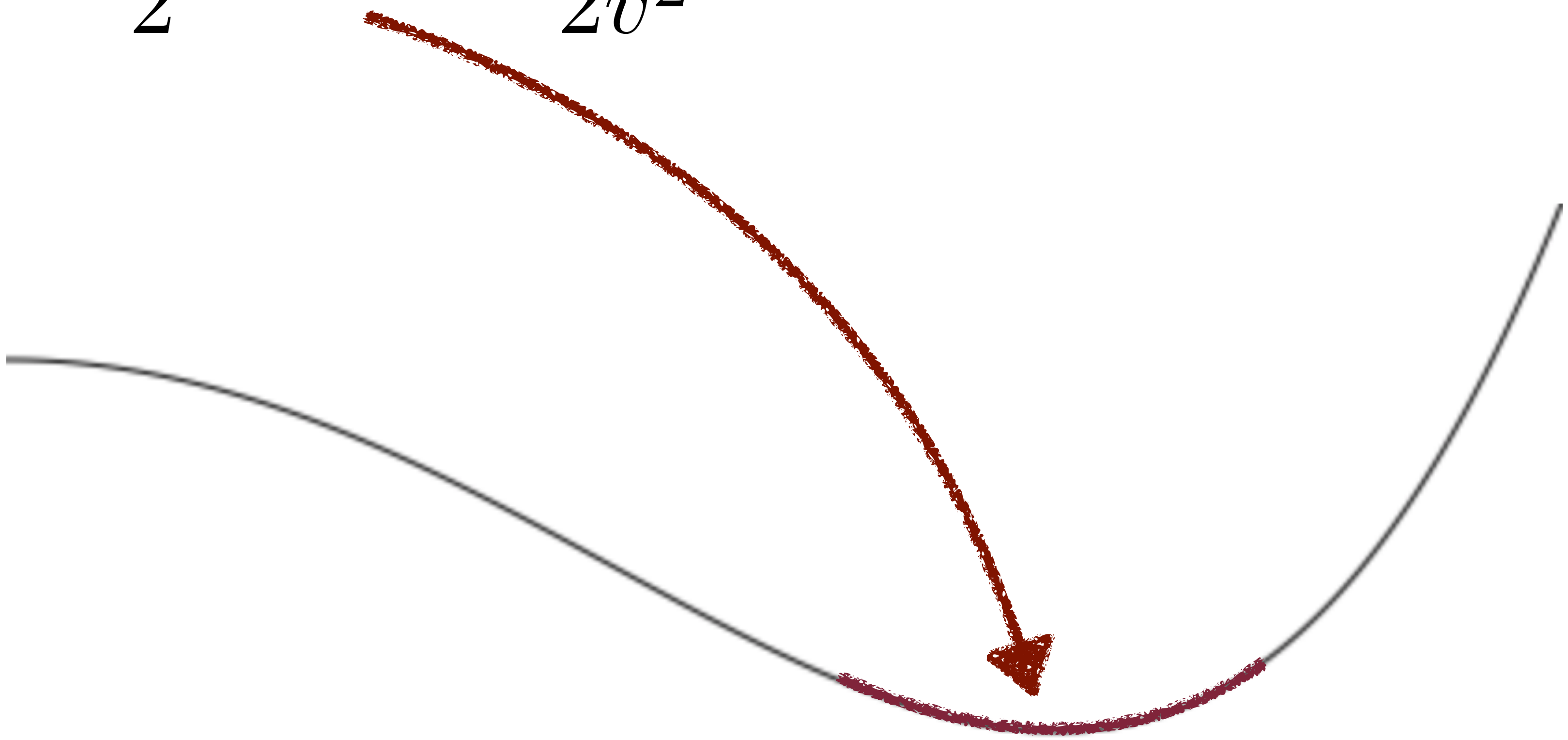

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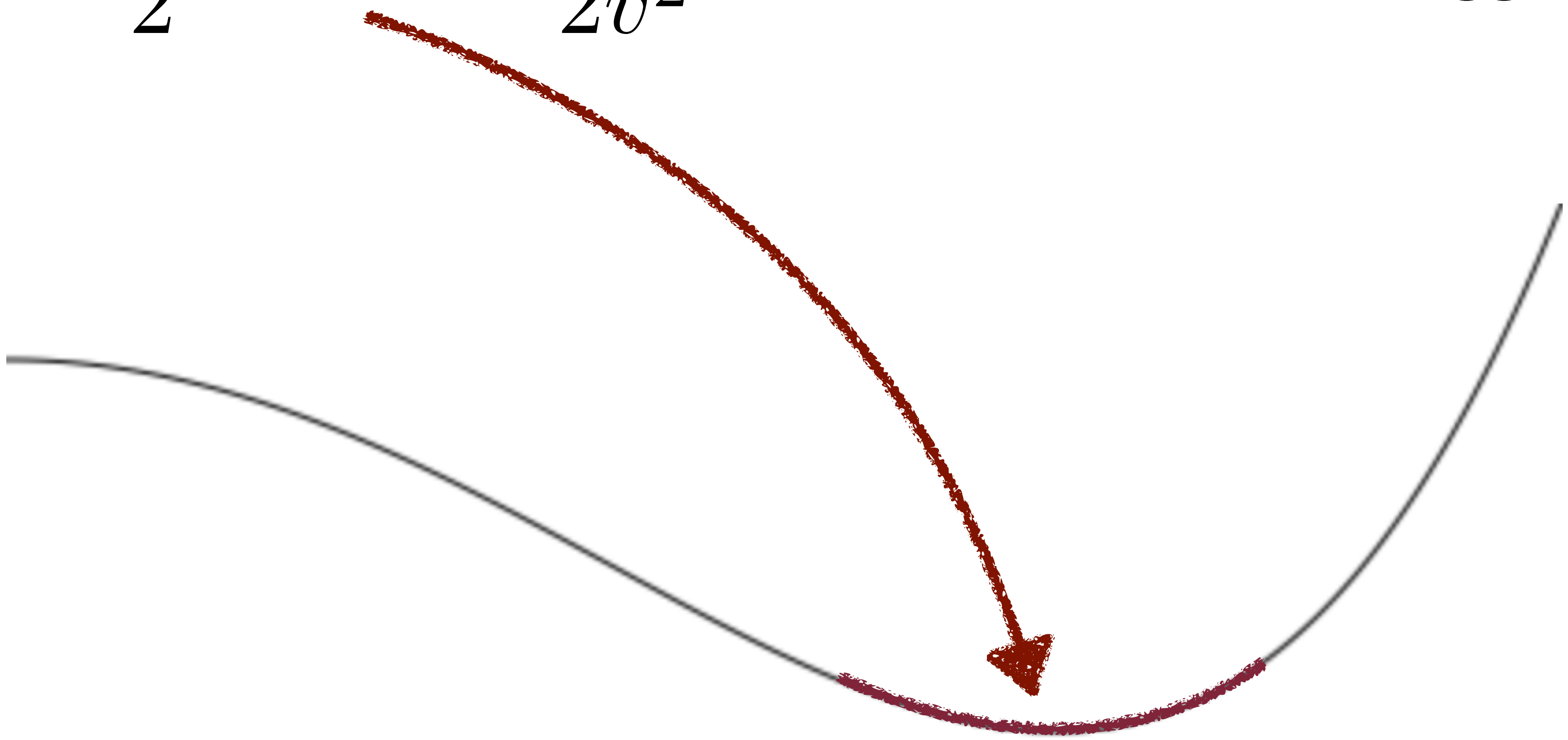
Measuring these terms helps us map out the SM's prediction for the Higgs potenial



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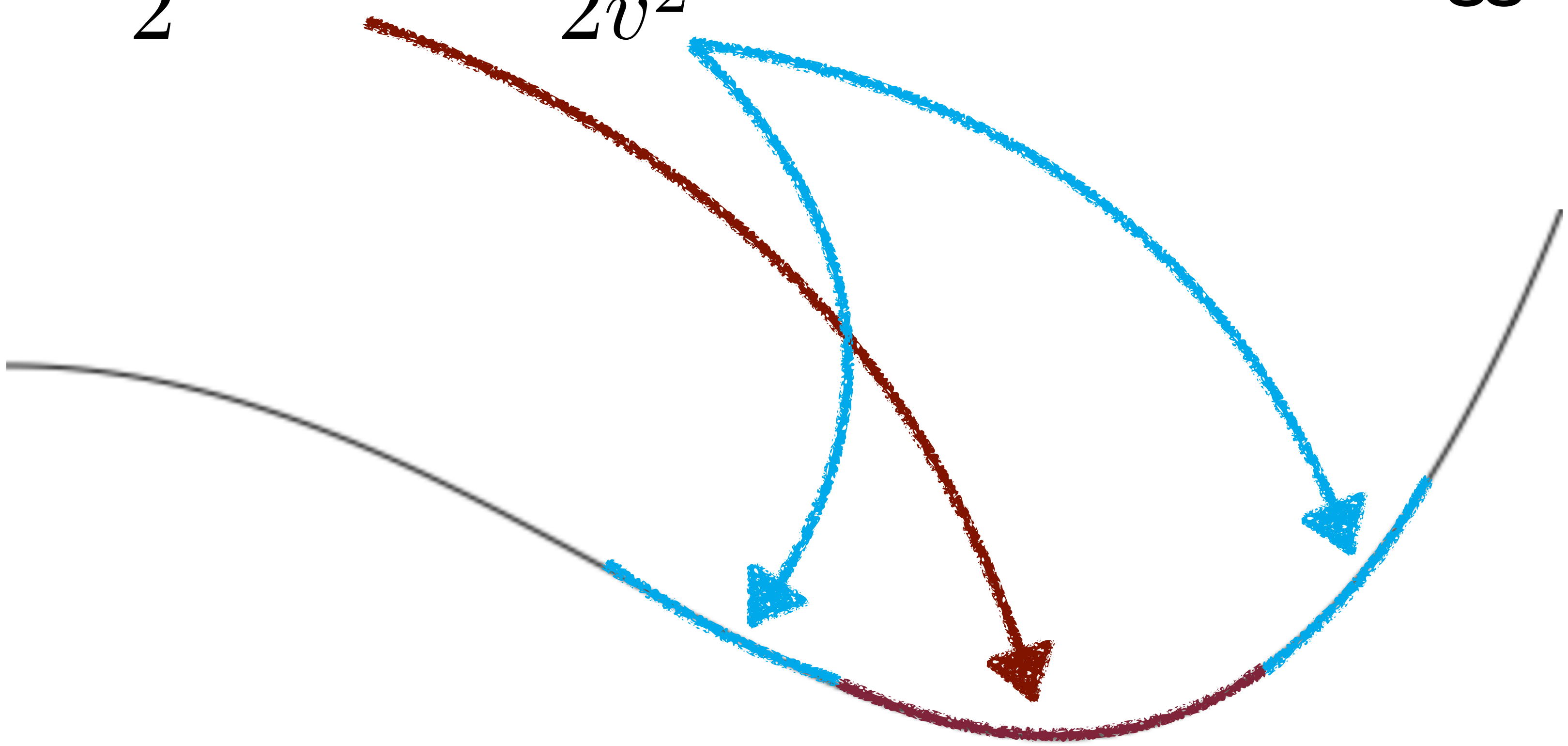

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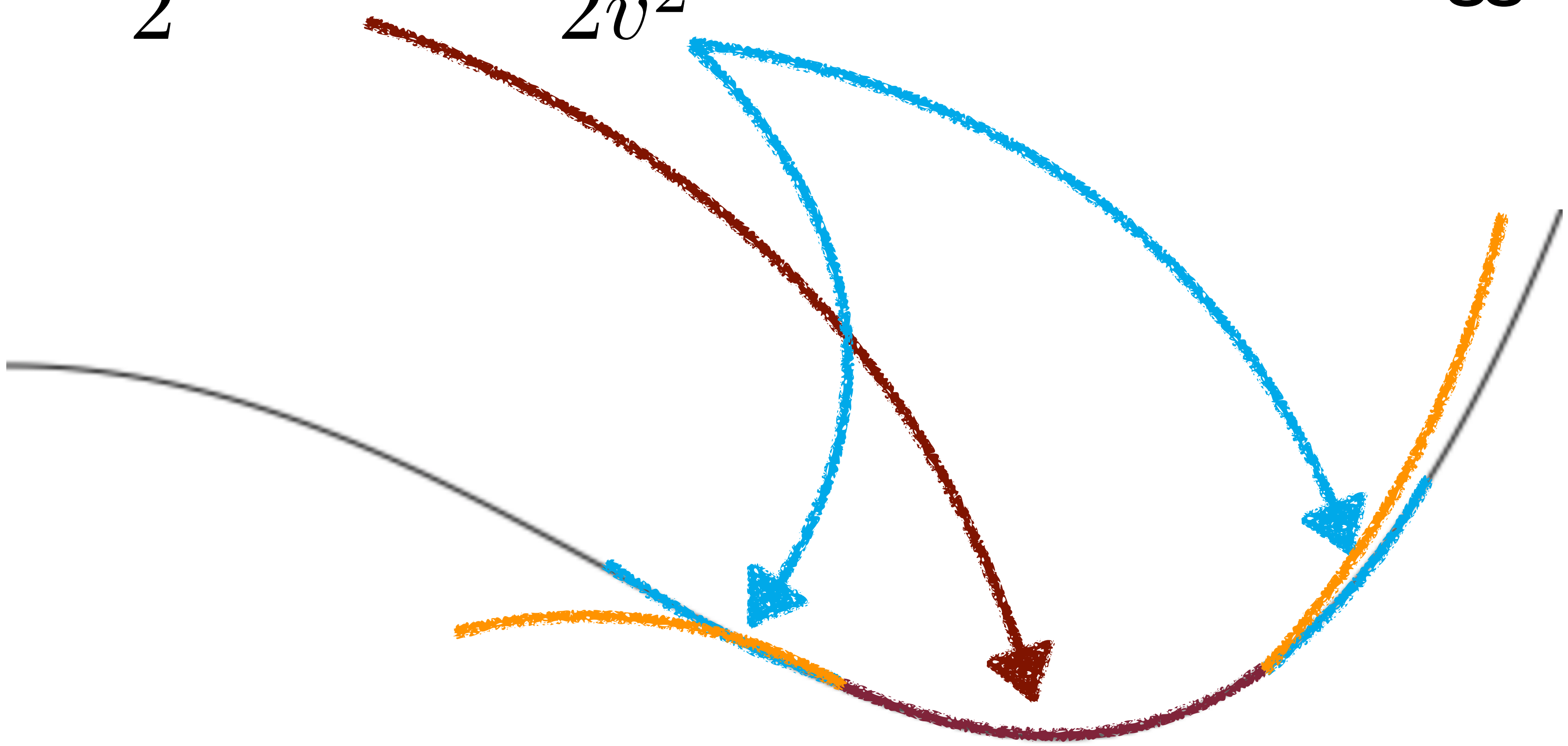

But what if we see something completely different?
What if $\kappa_\lambda = 3$?

Other Shapes?

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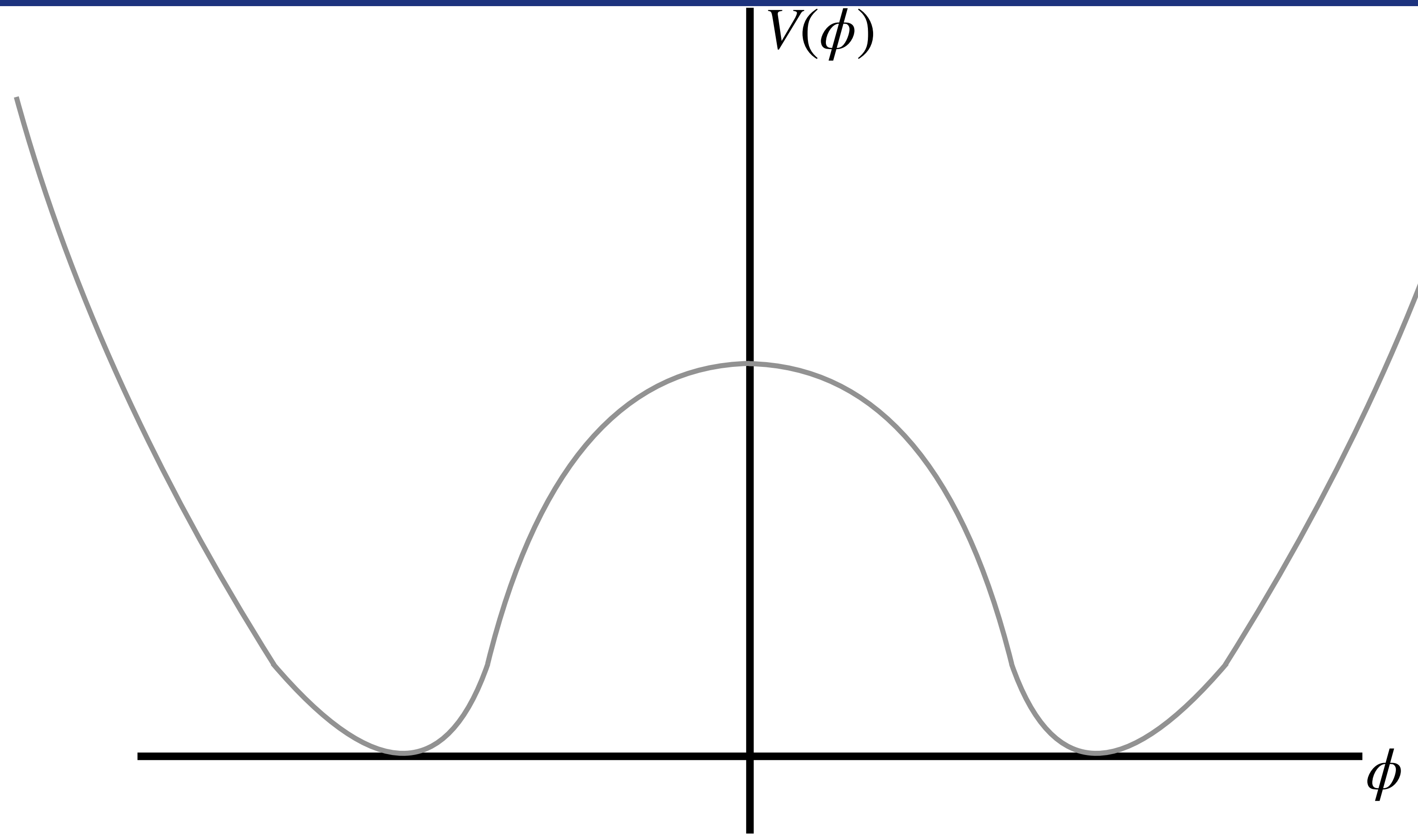

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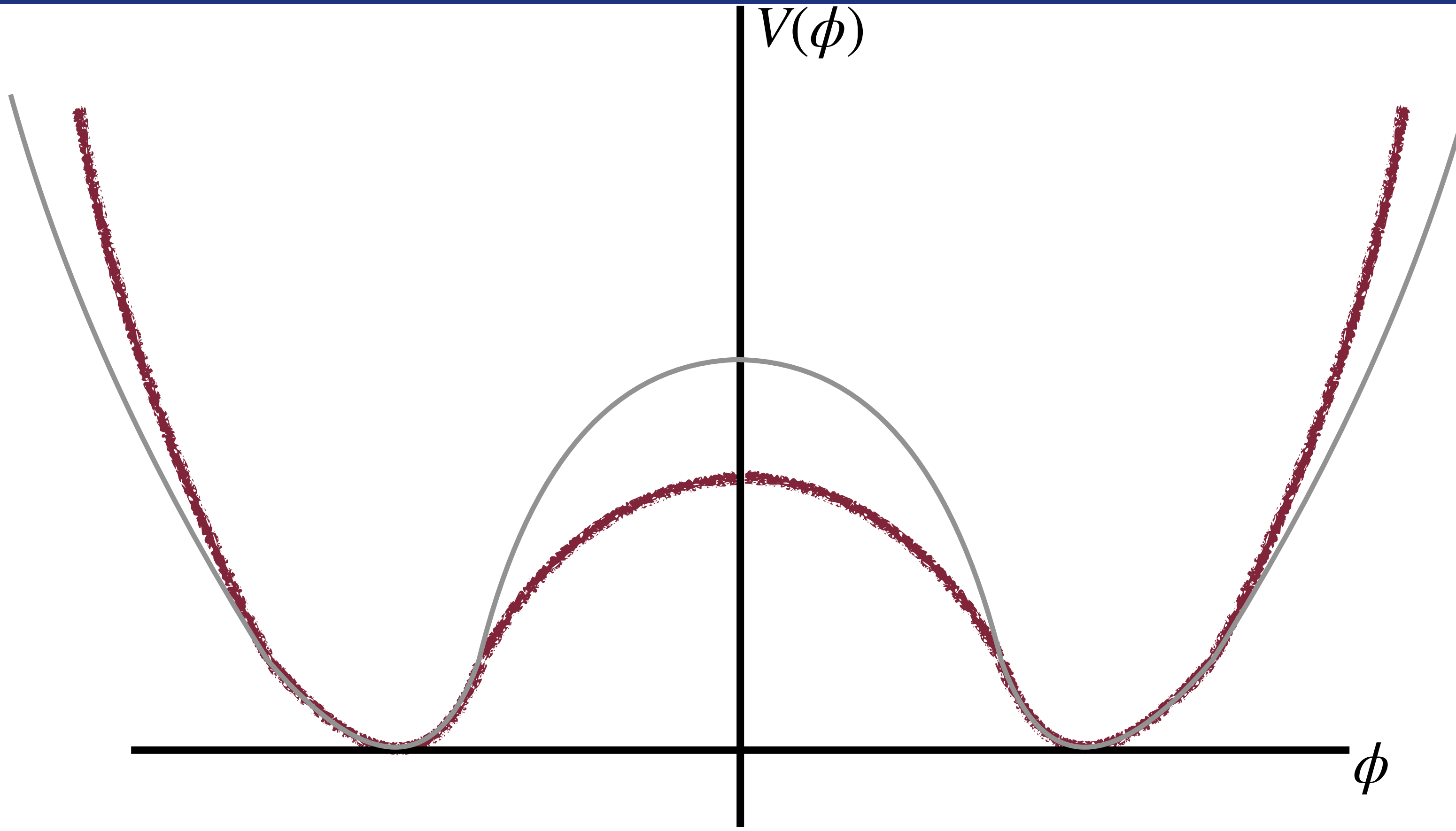

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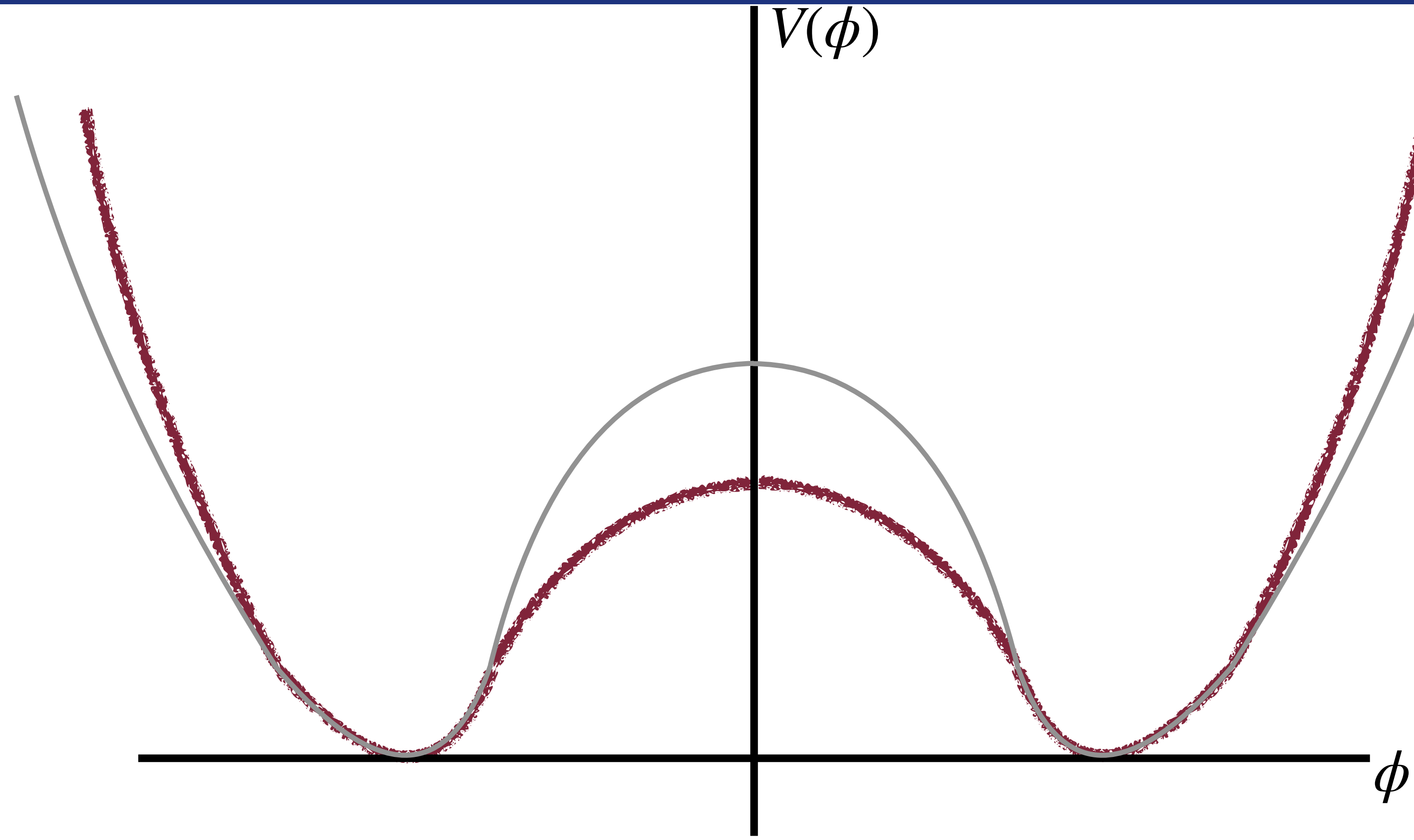

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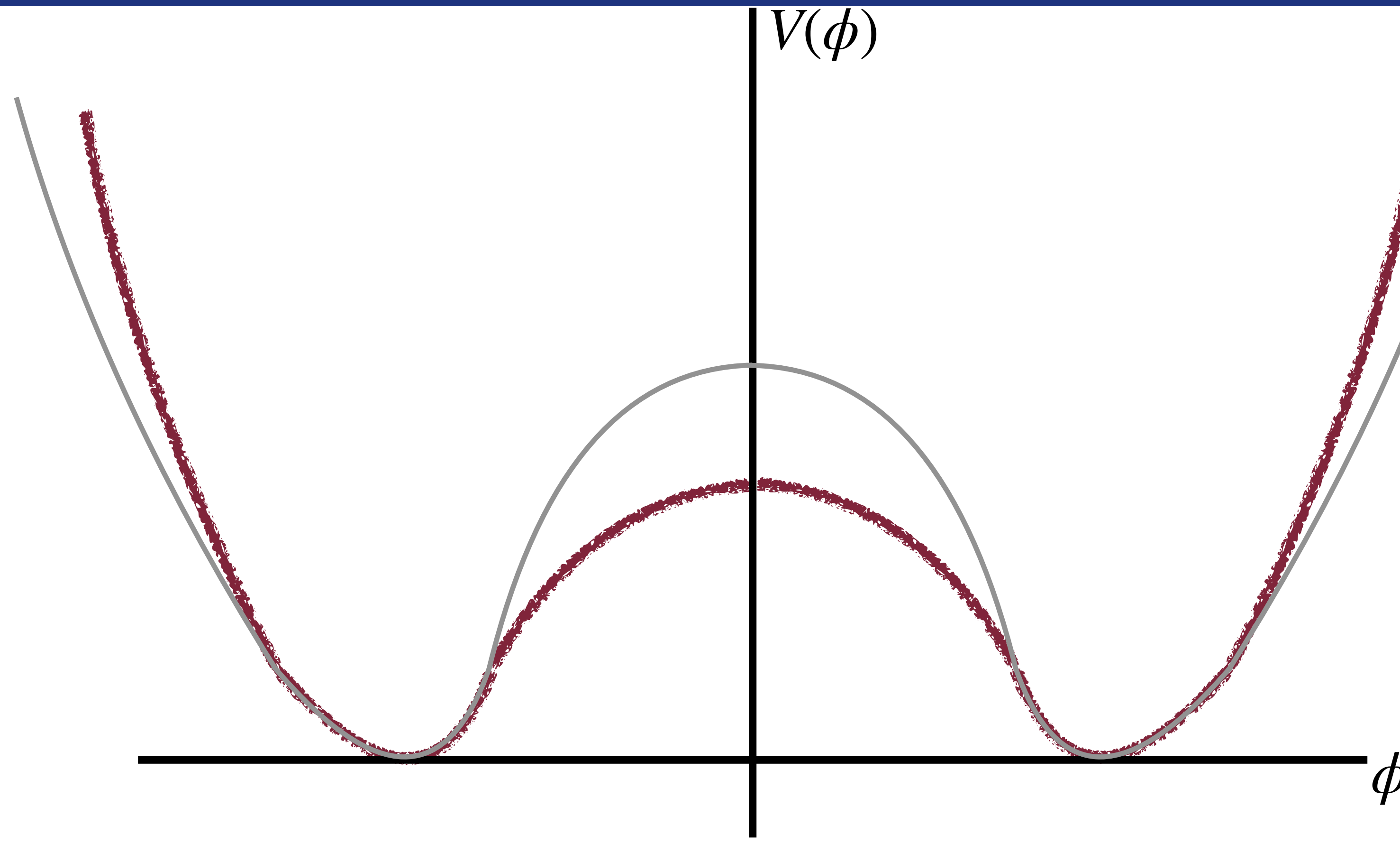

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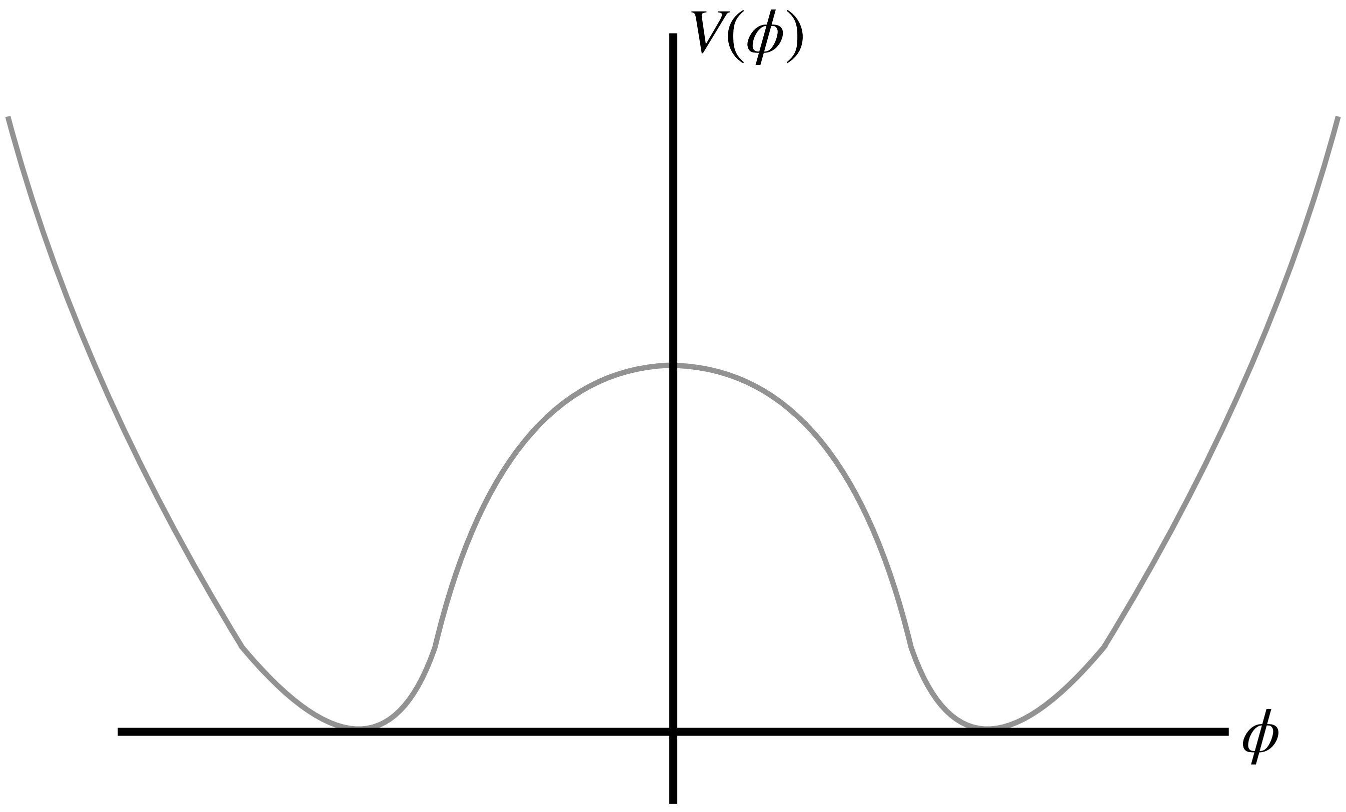
What physics could this lead to?

The Electroweak Phase Transition

Adapted from T. Tait and G. White

The Electroweak Phase Transition



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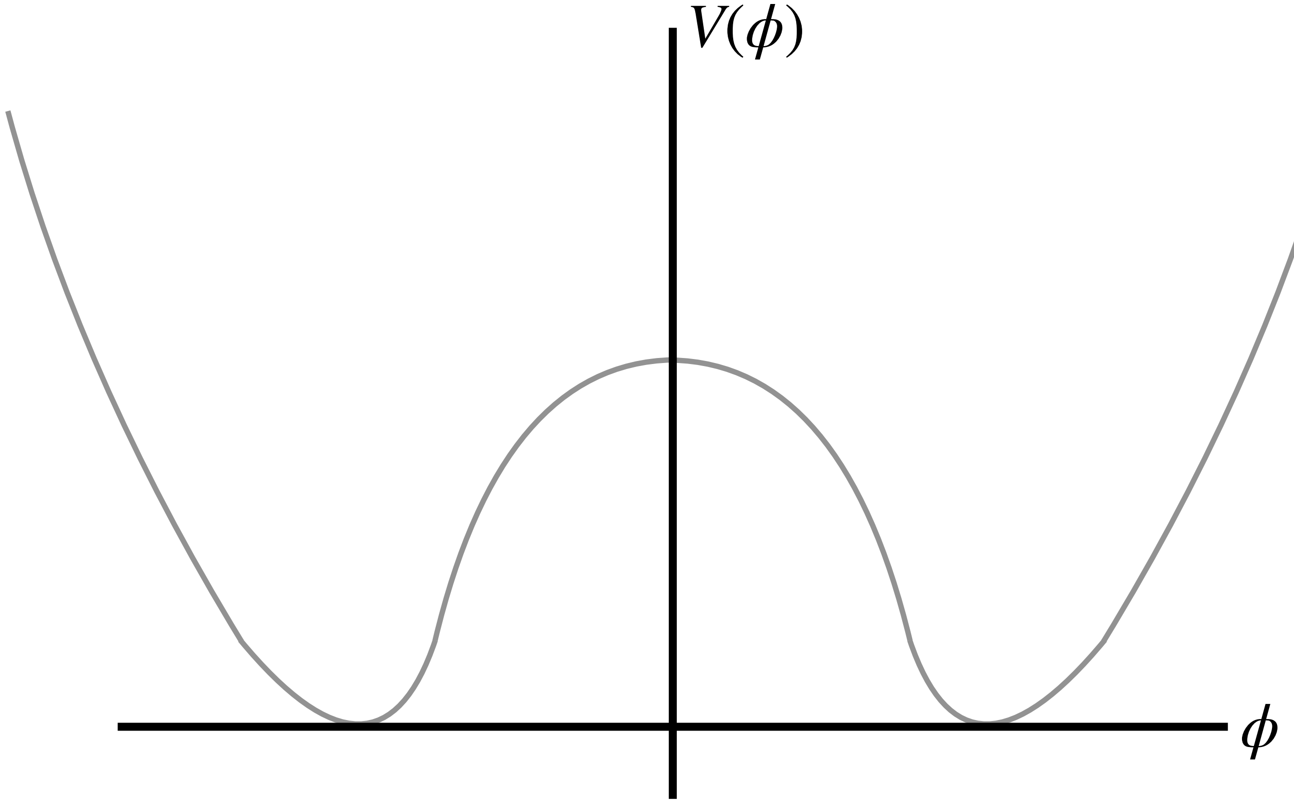

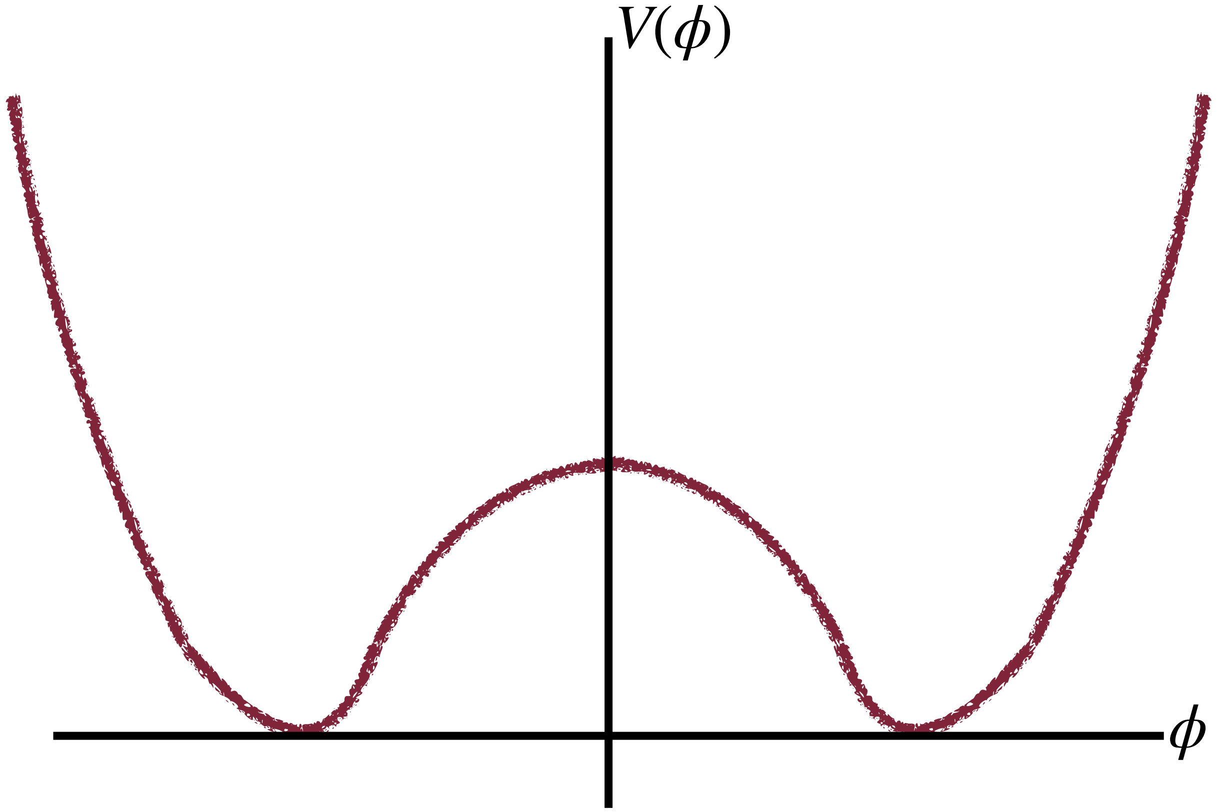

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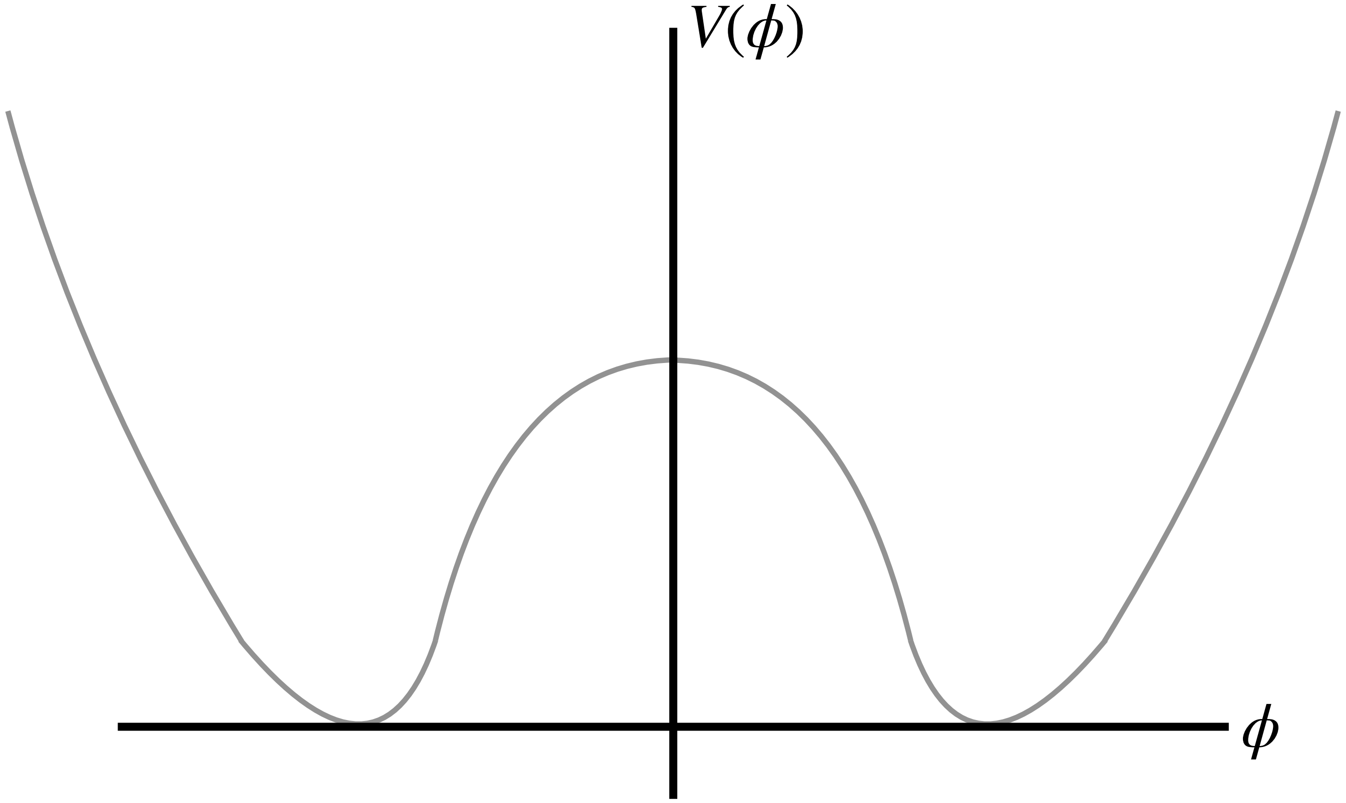

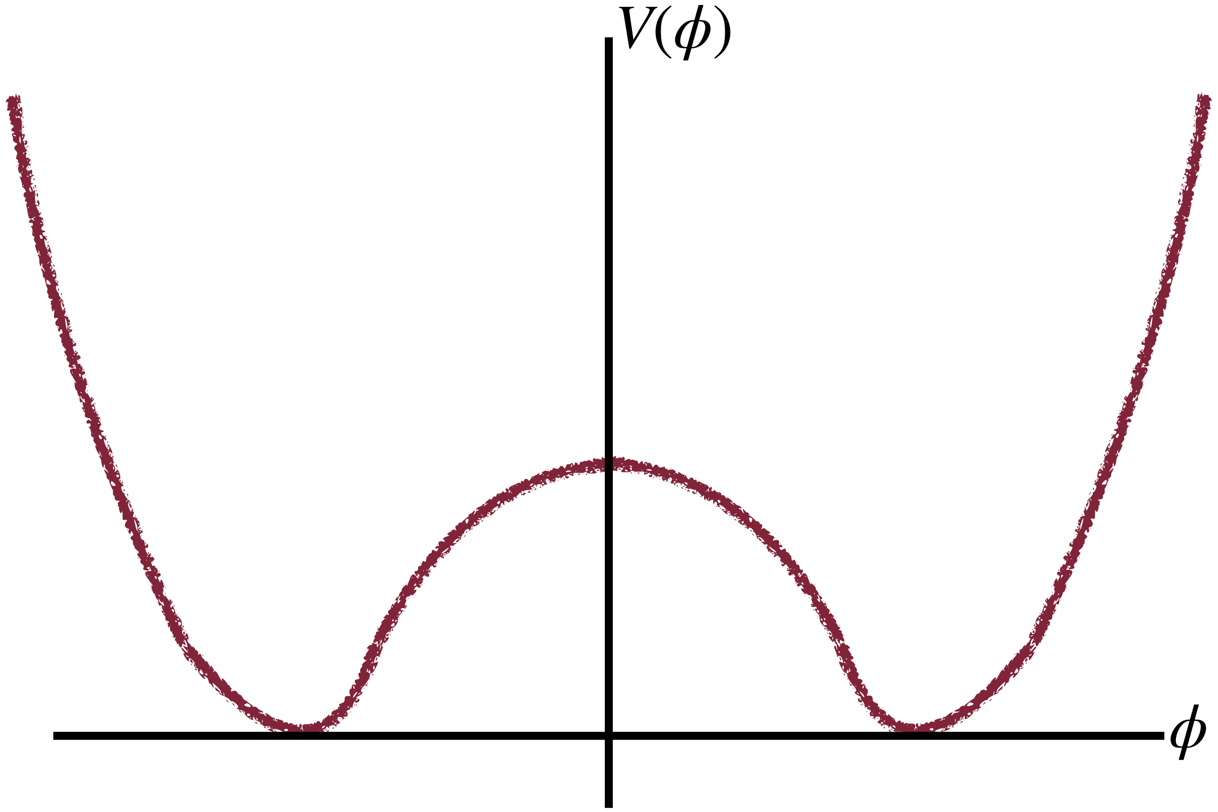

What happens as we increase the temperature:
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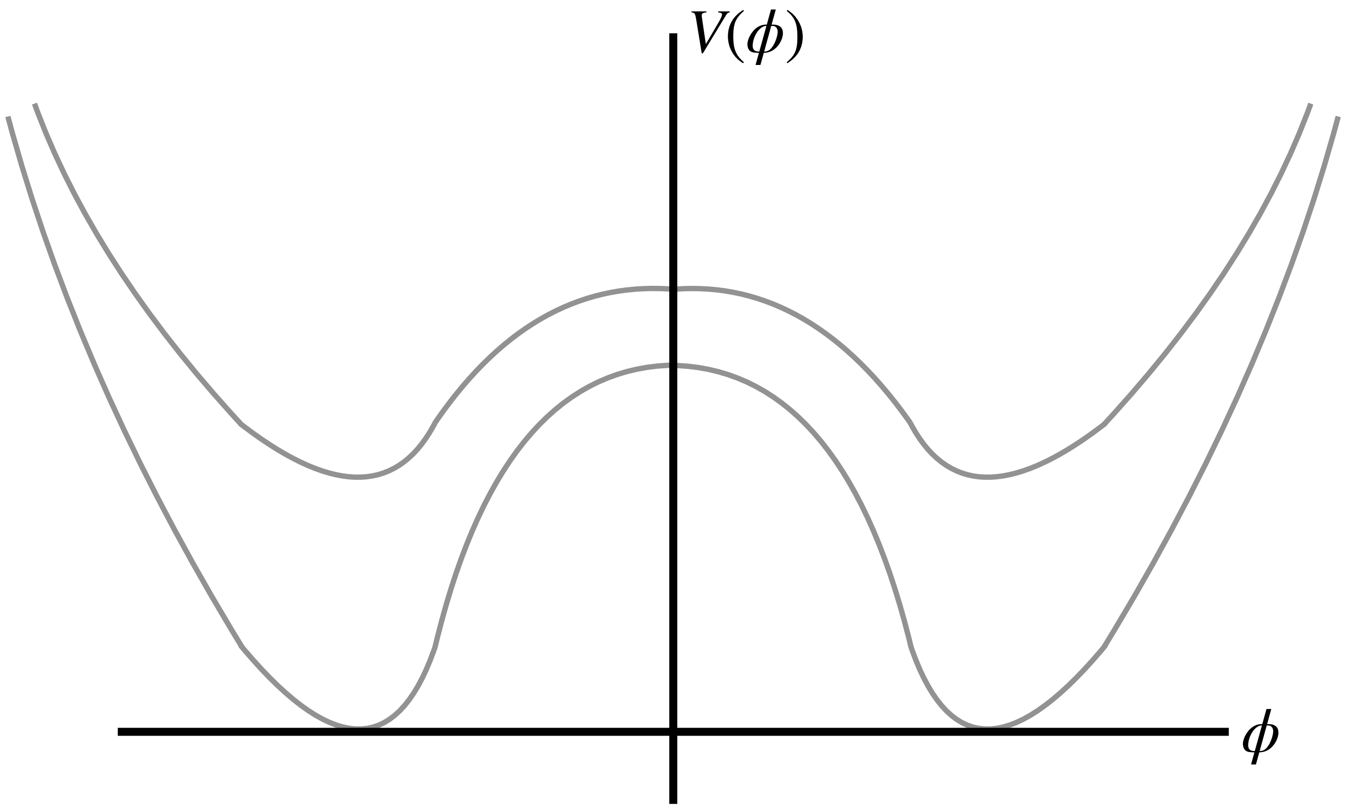

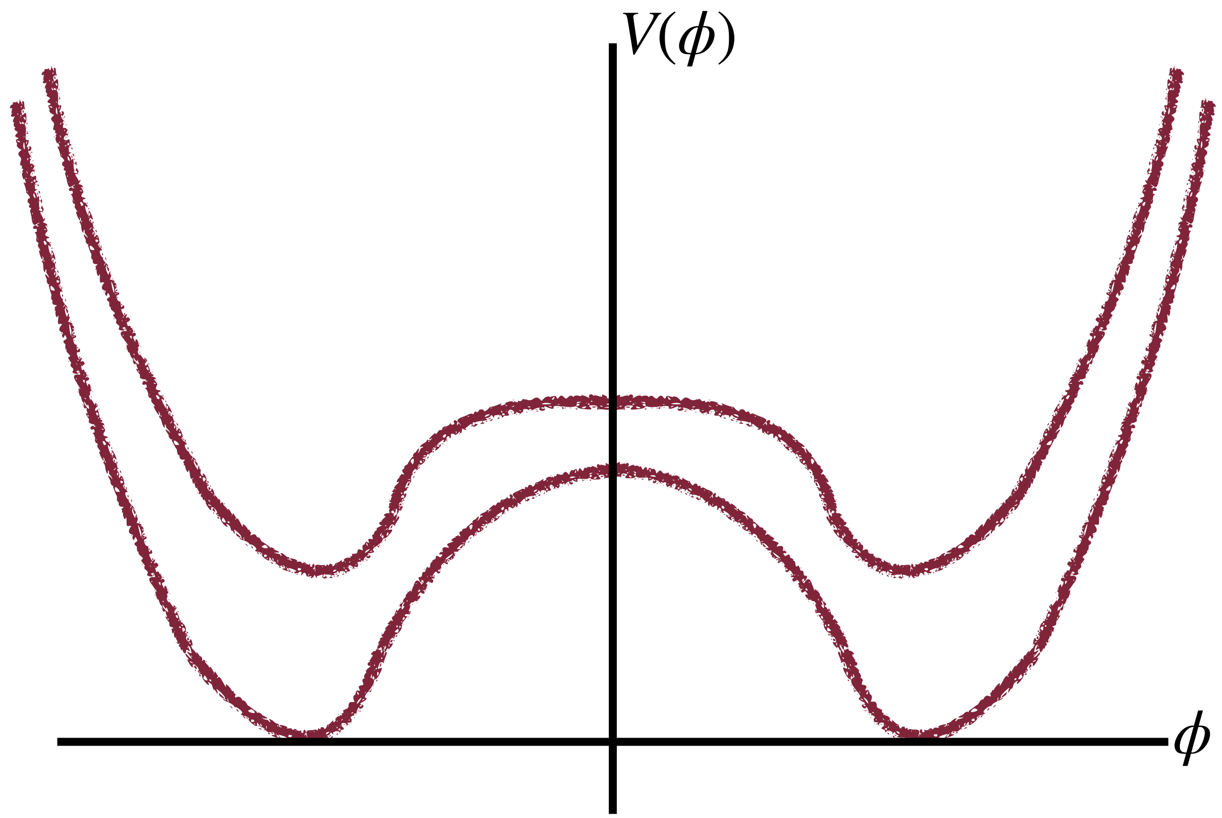

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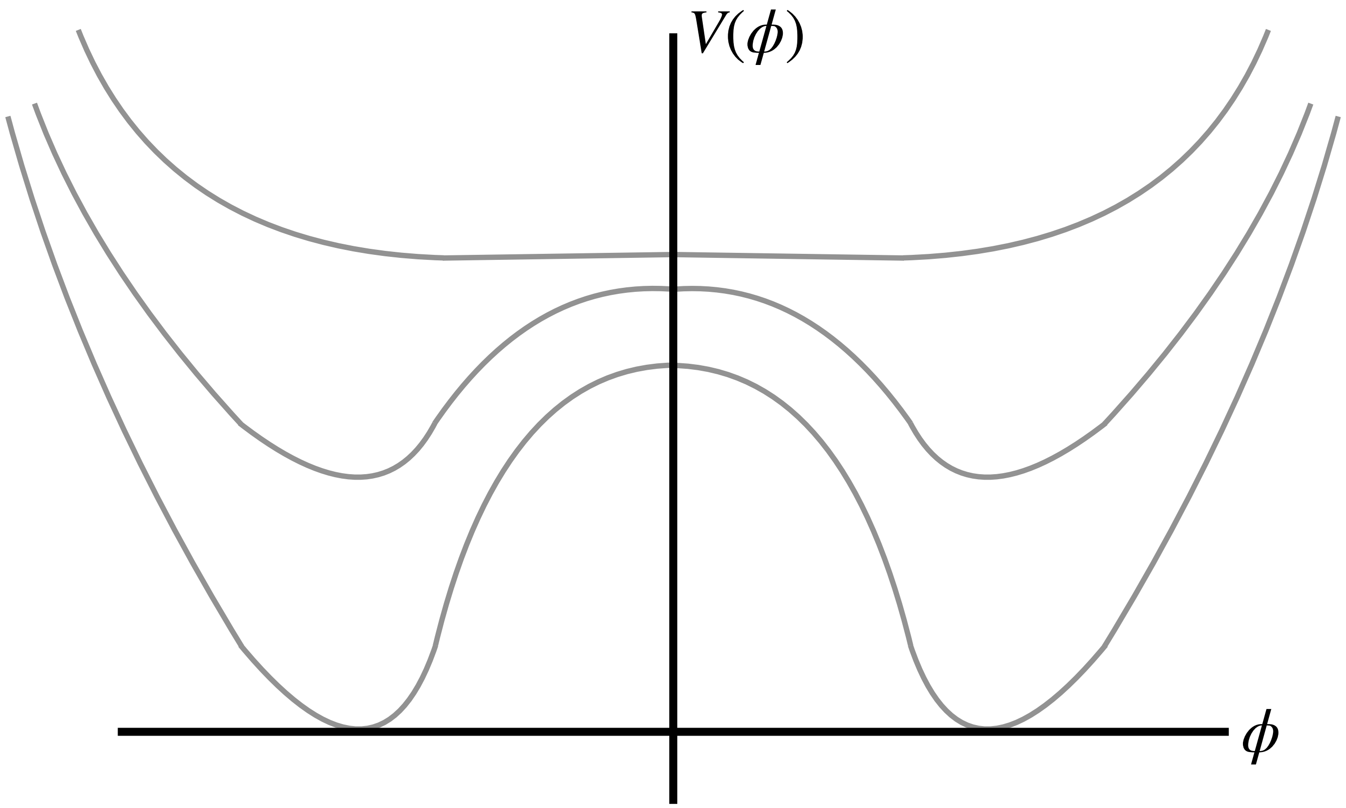

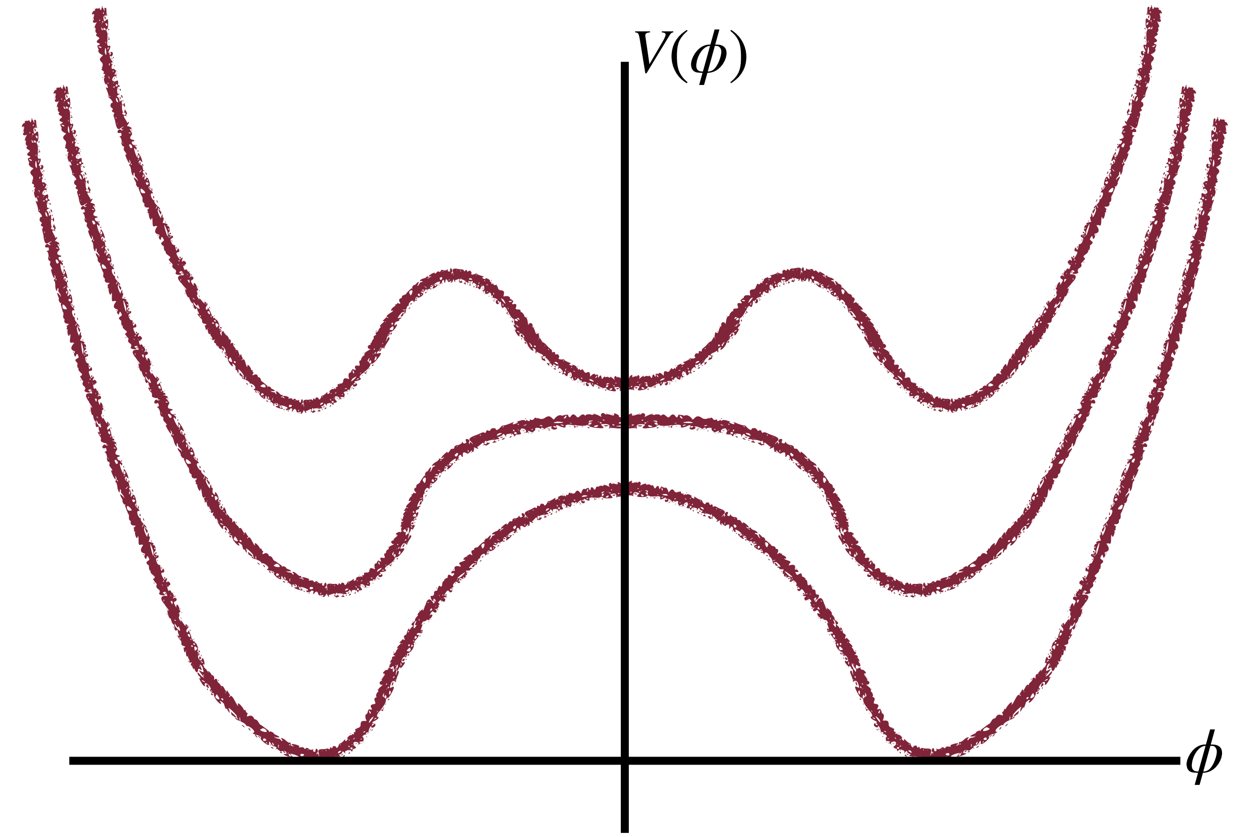

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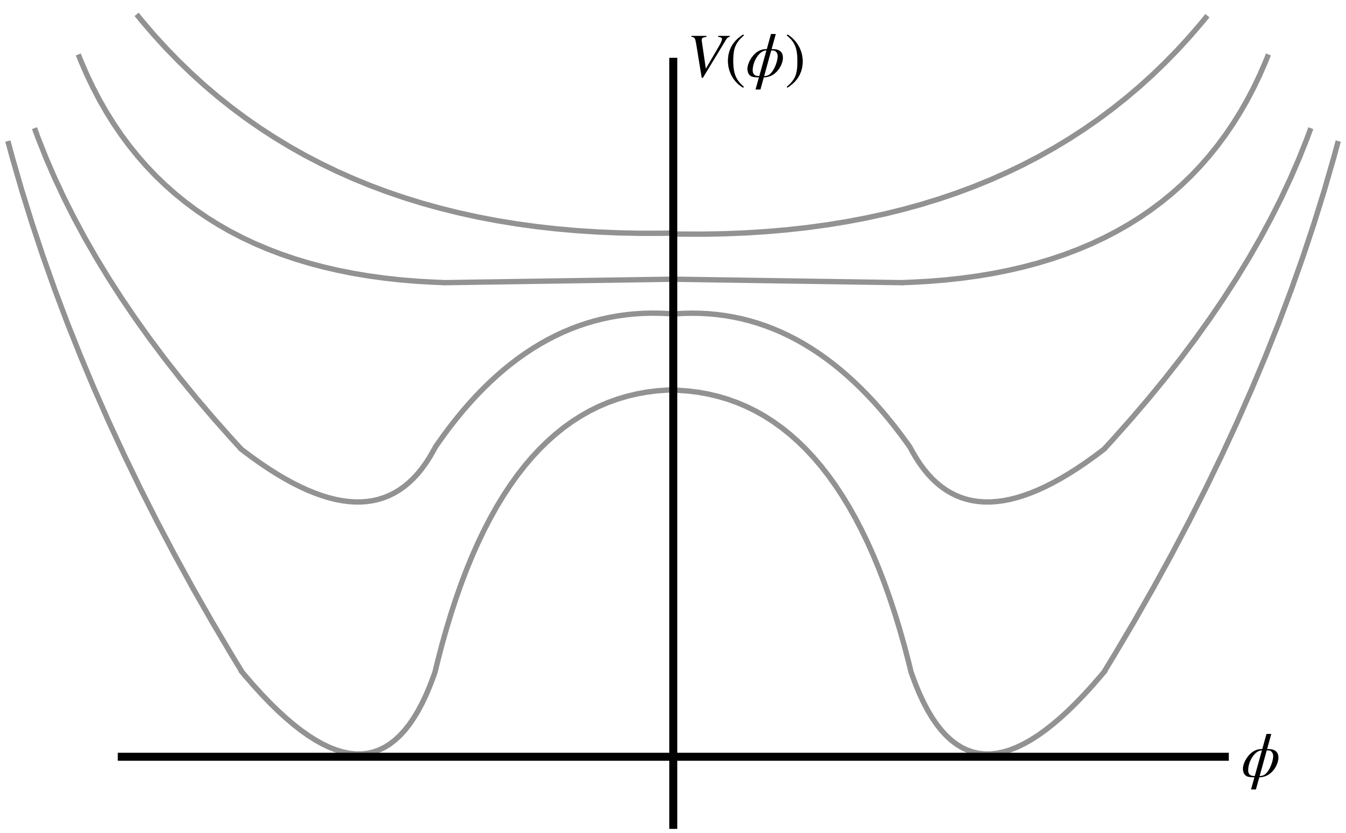

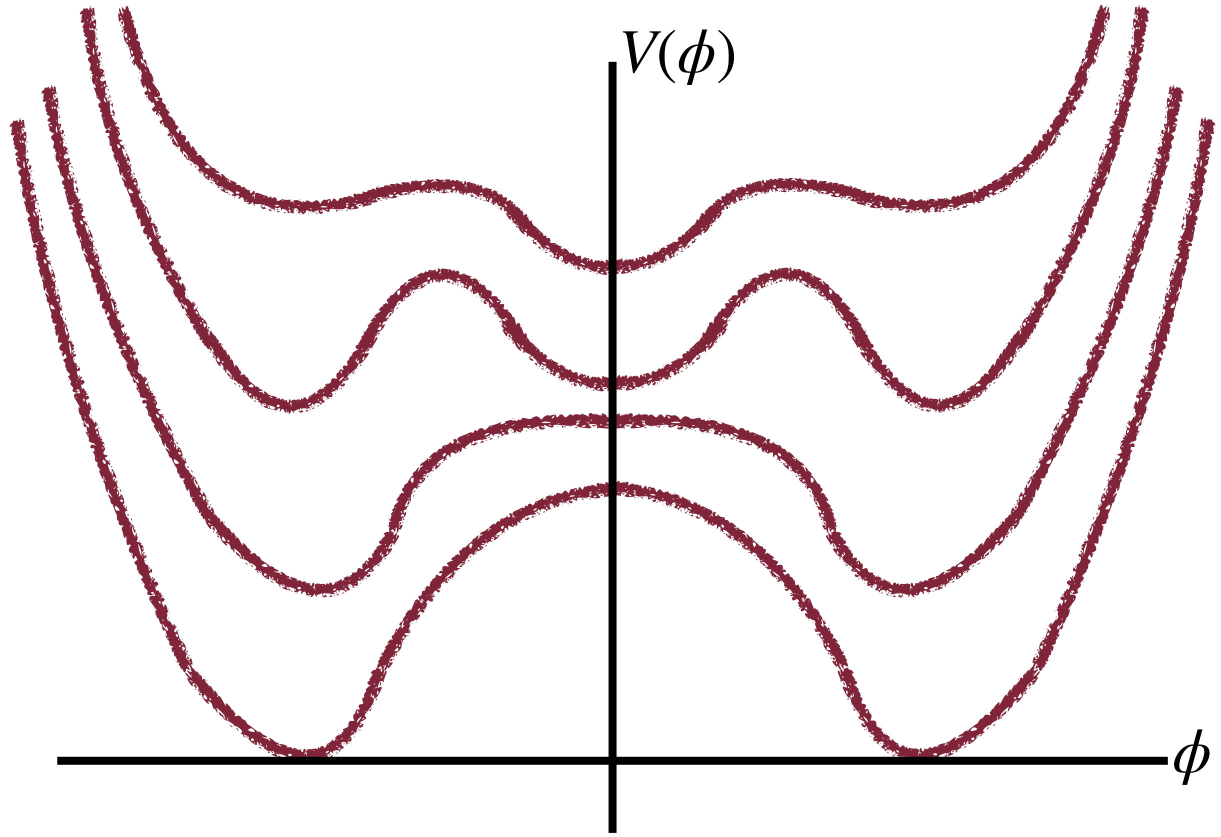

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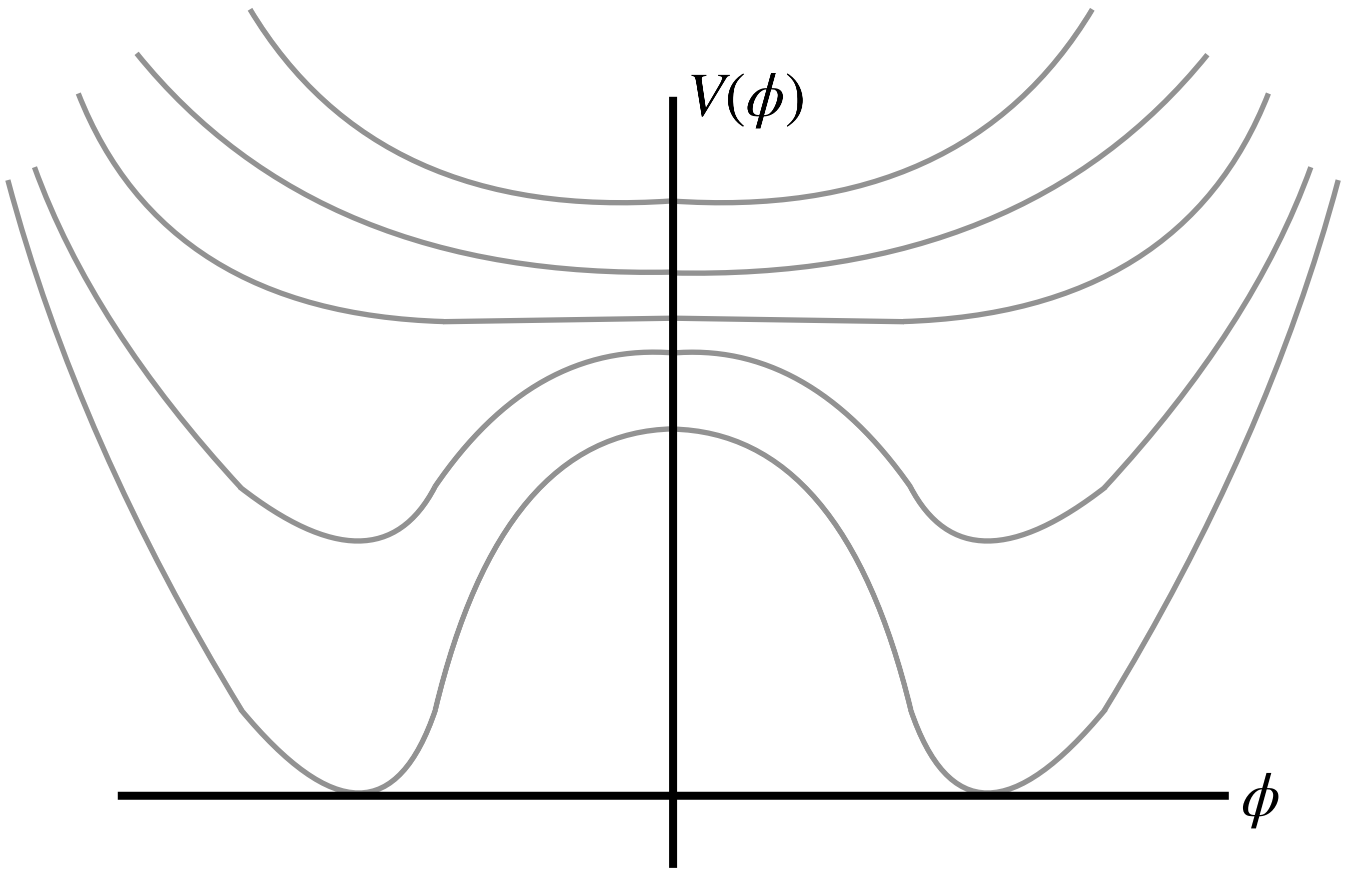

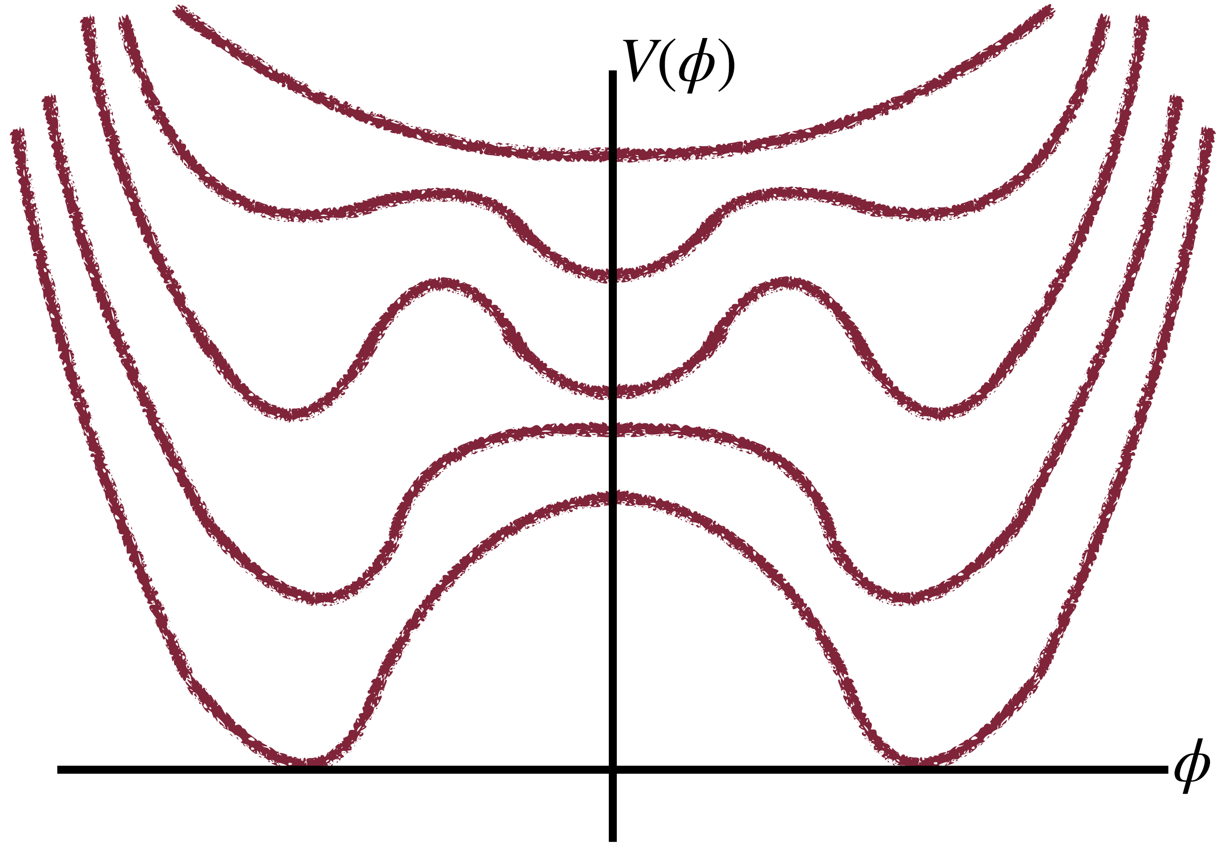

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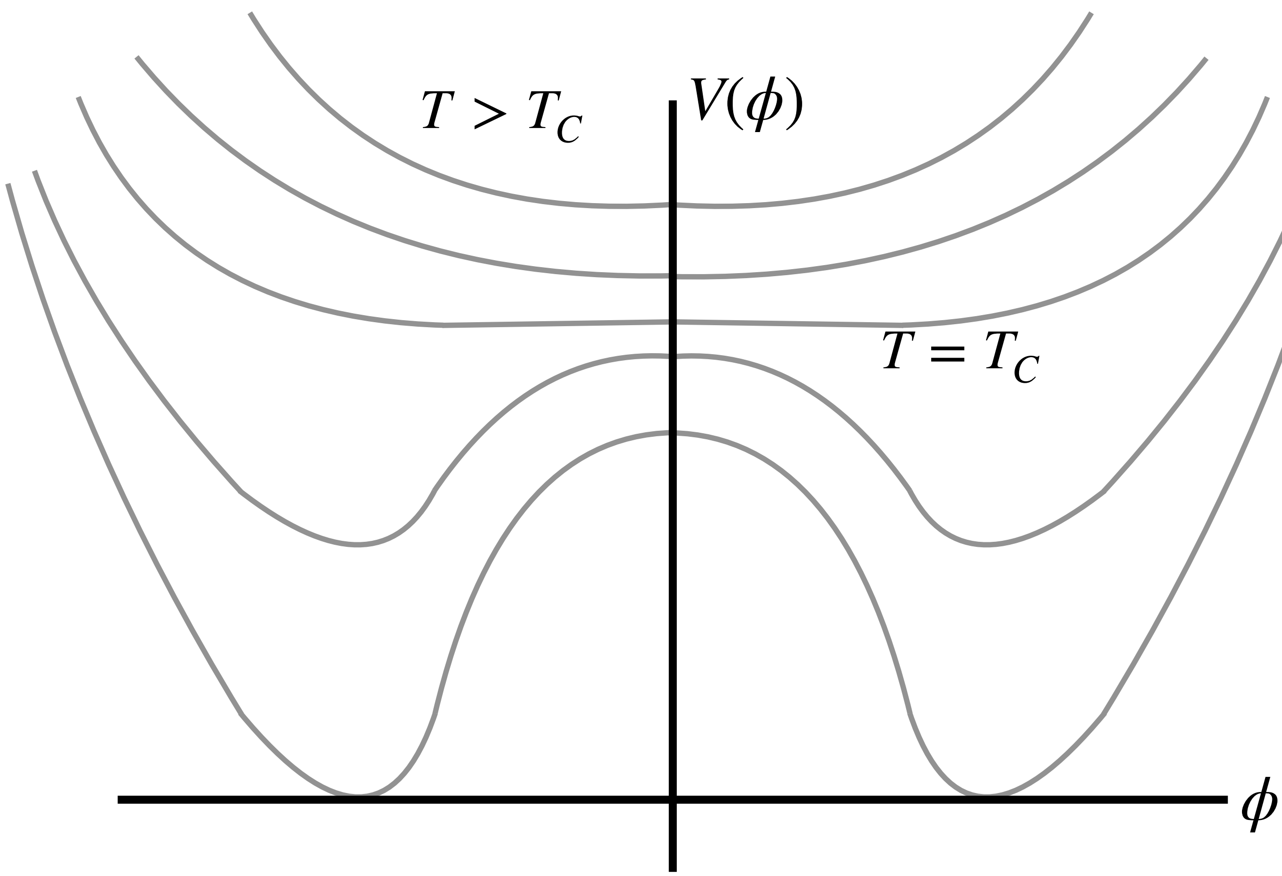

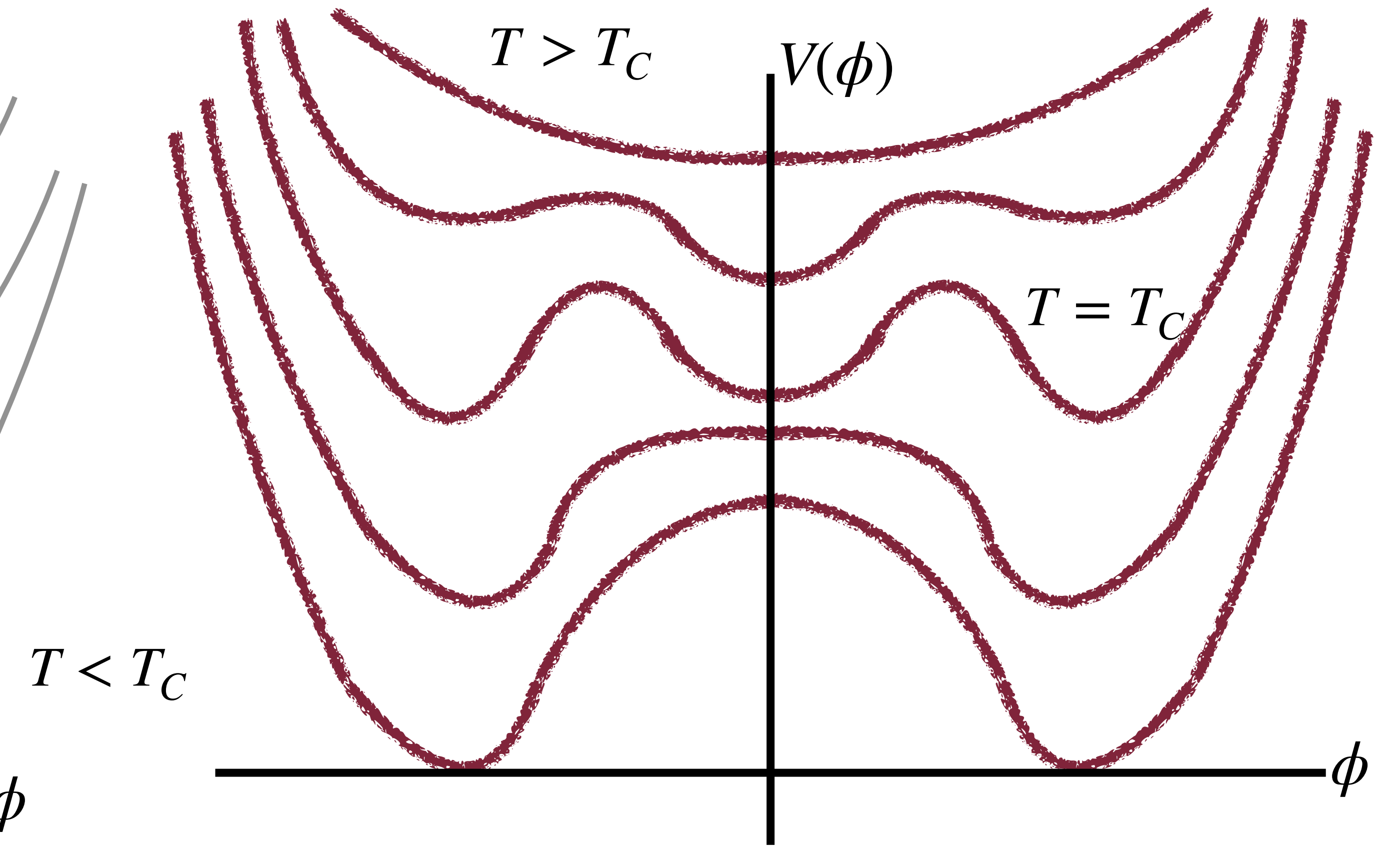

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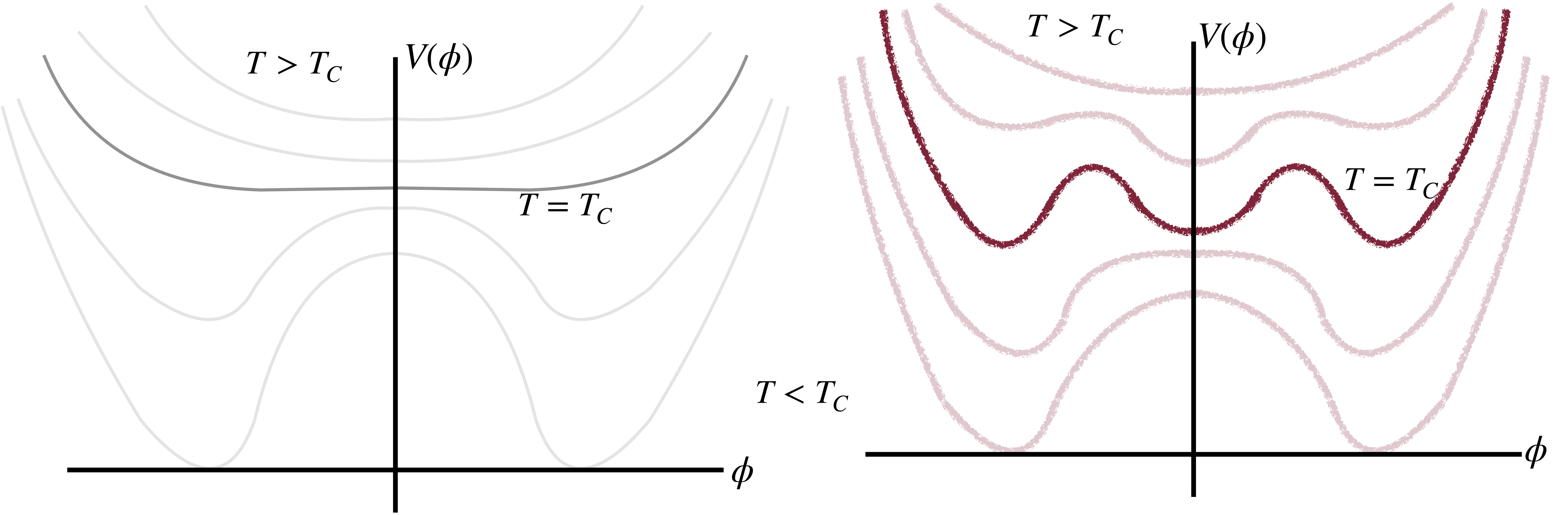

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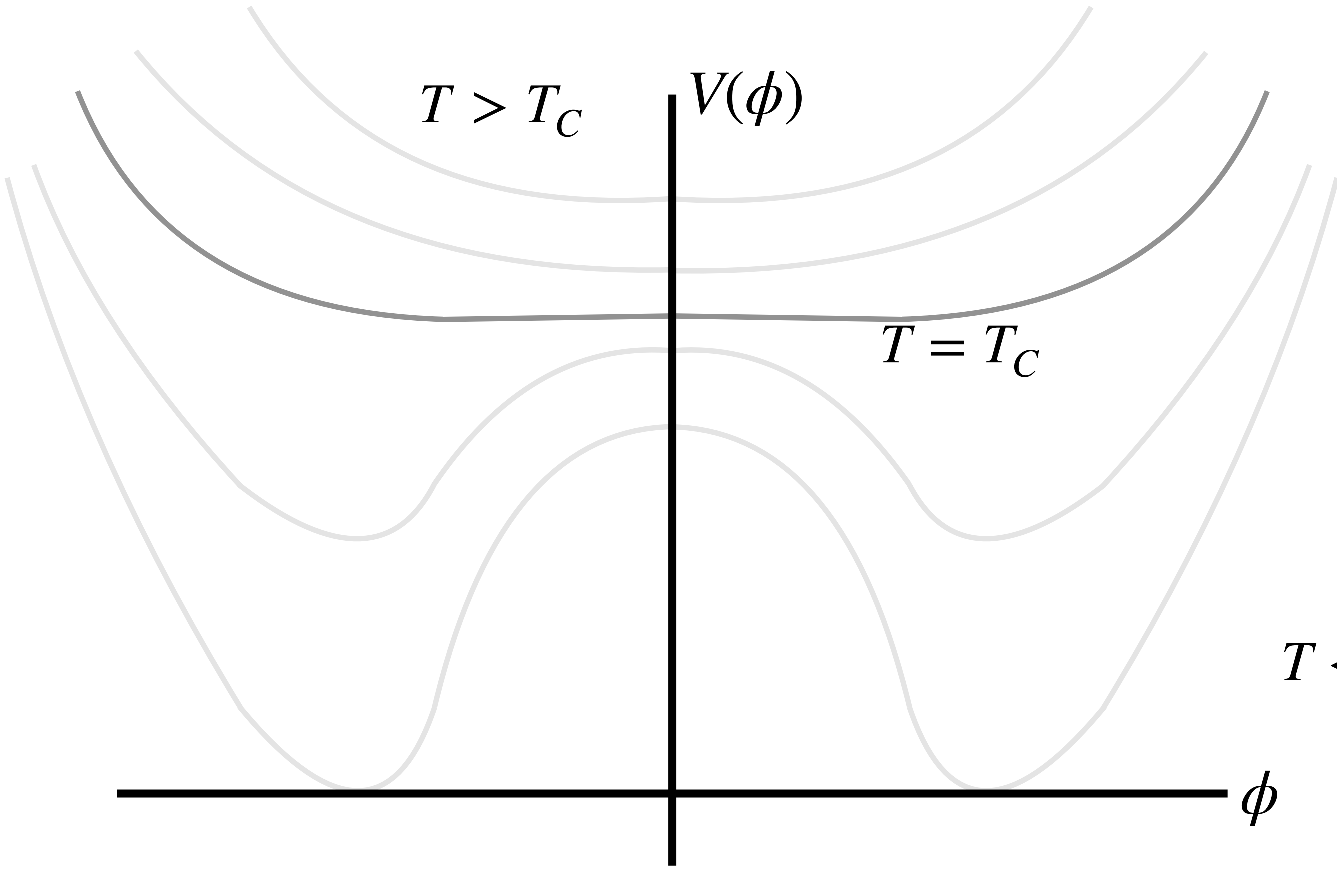

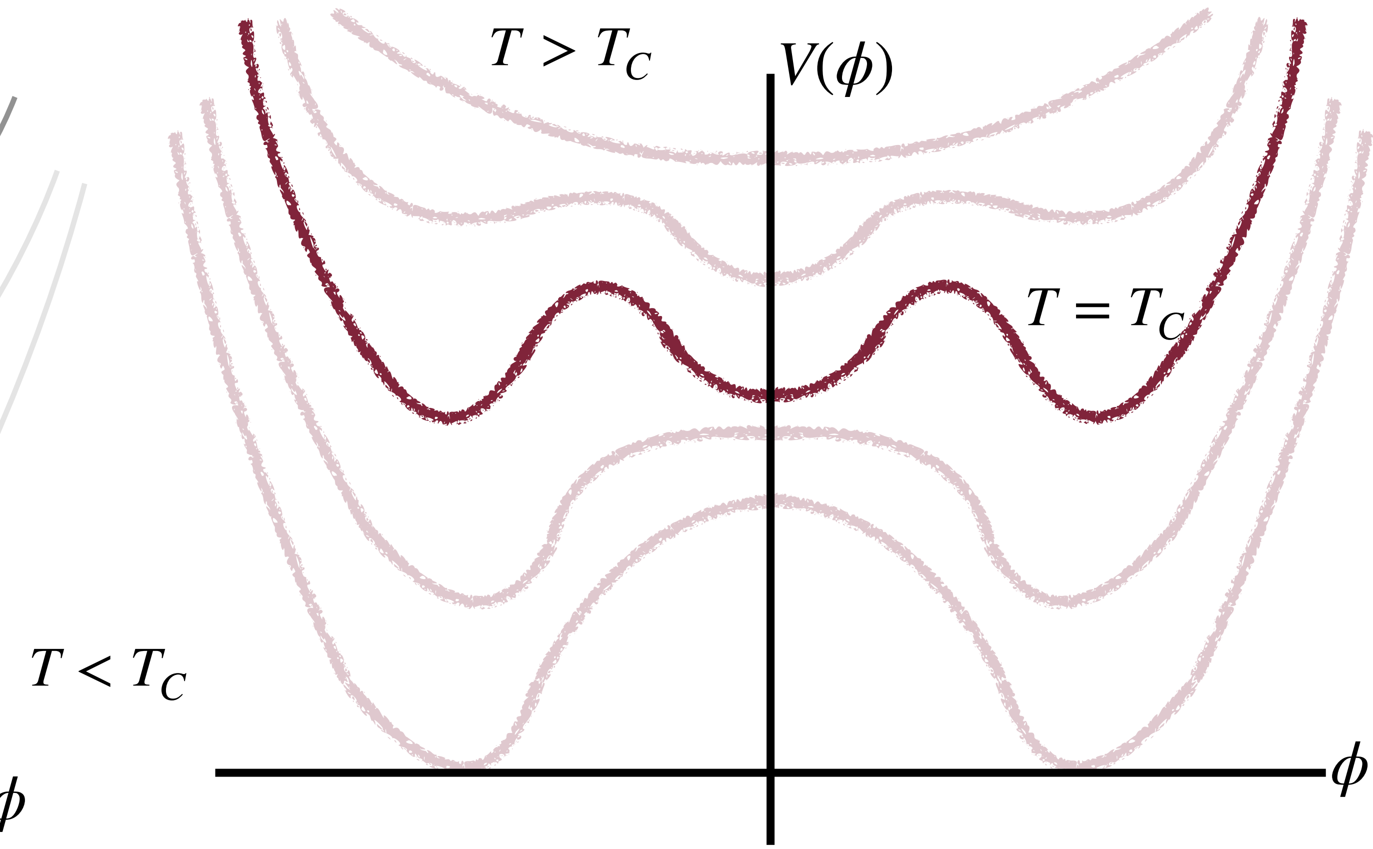

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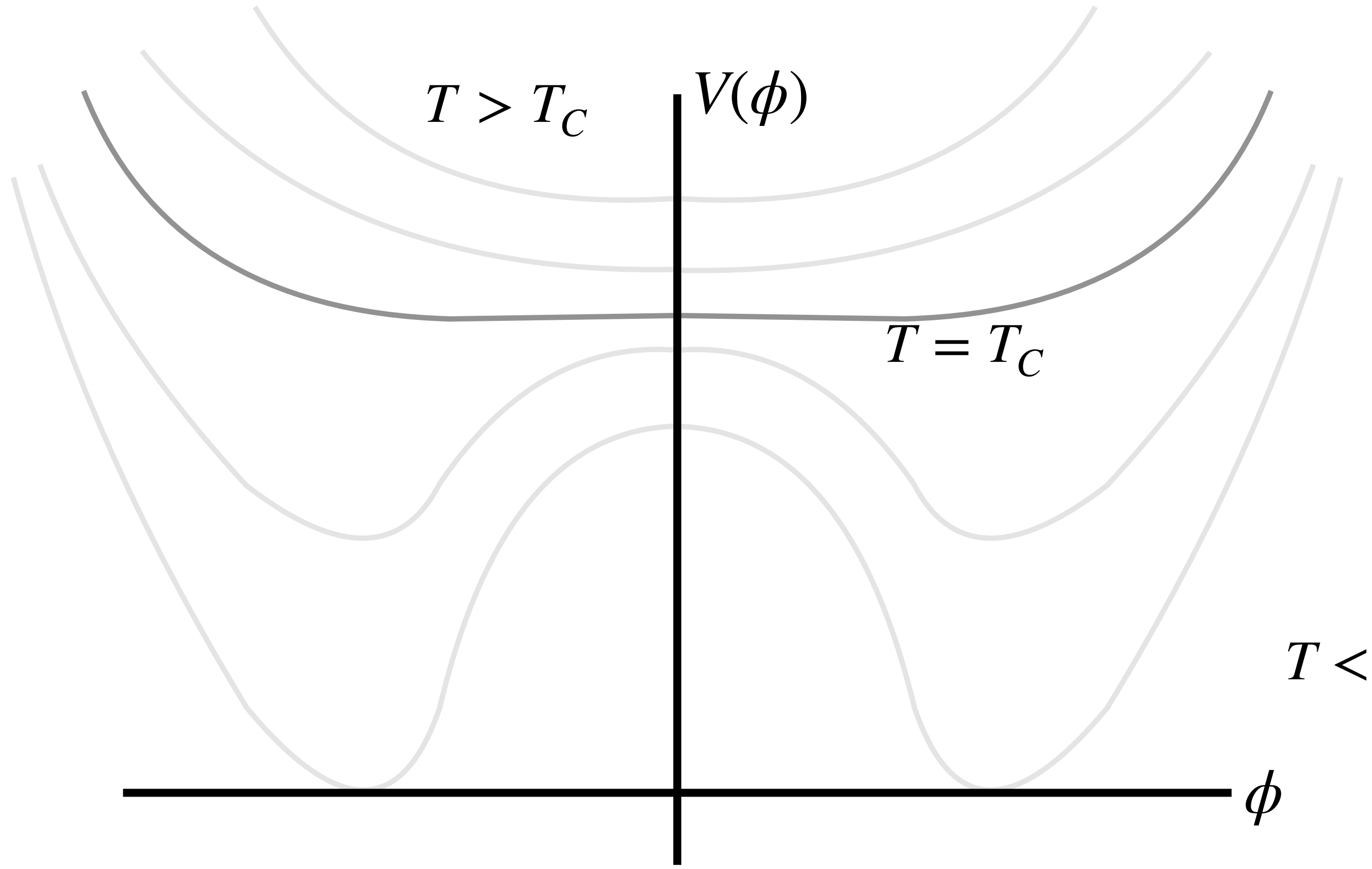

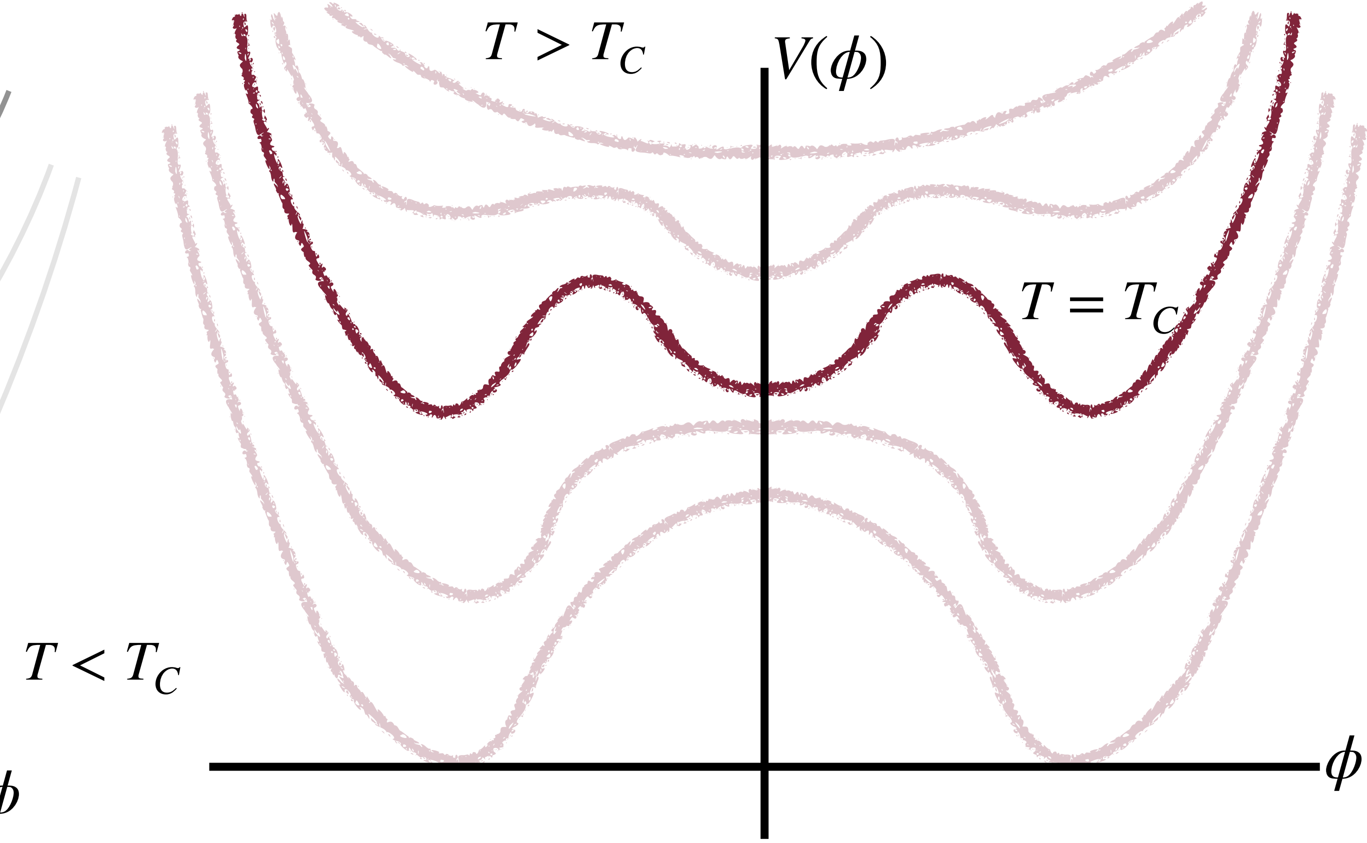

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Modified models lead to **out of equilibrium dynamics** in the early universe

Adapted from T. Tait and G. White

Broken Symmetries

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BSM models that enable this are referred
to as **Electroweak Baryogenesis**

Electroweak Baryogenesis

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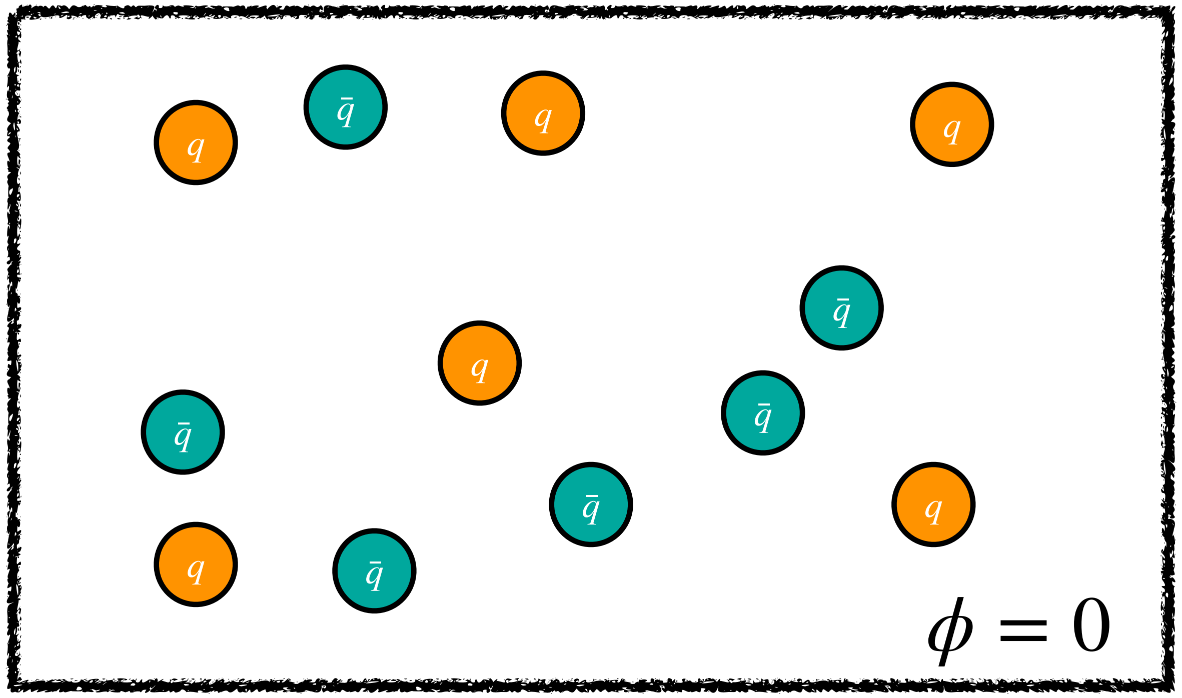

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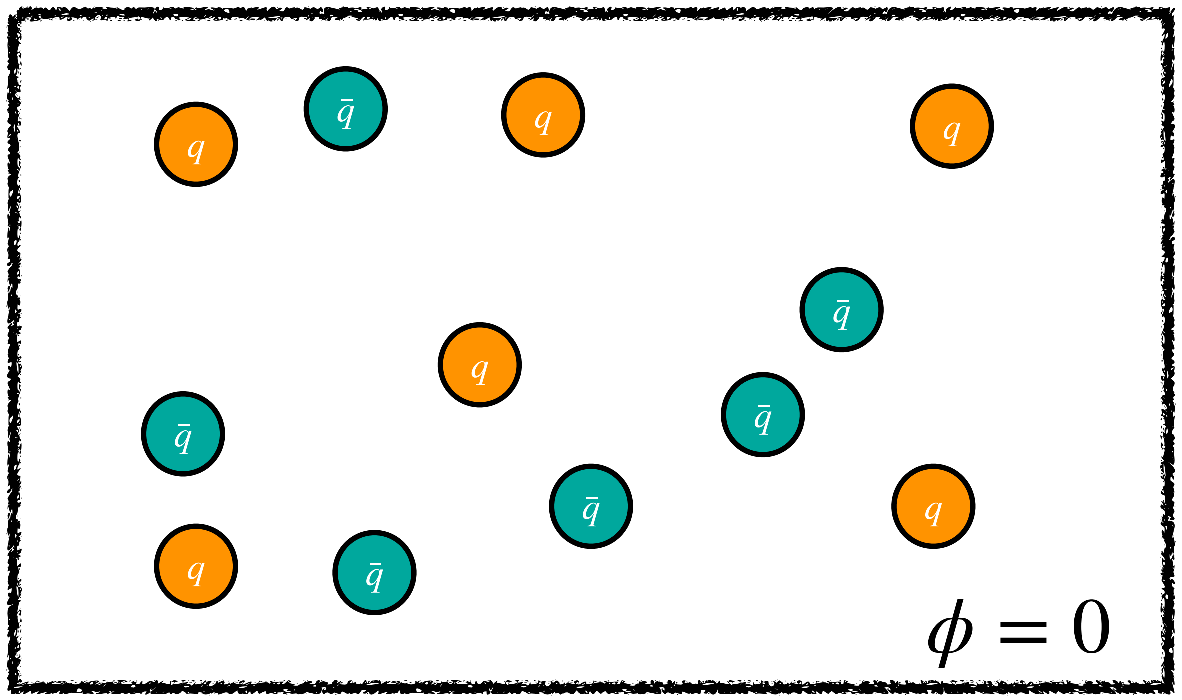

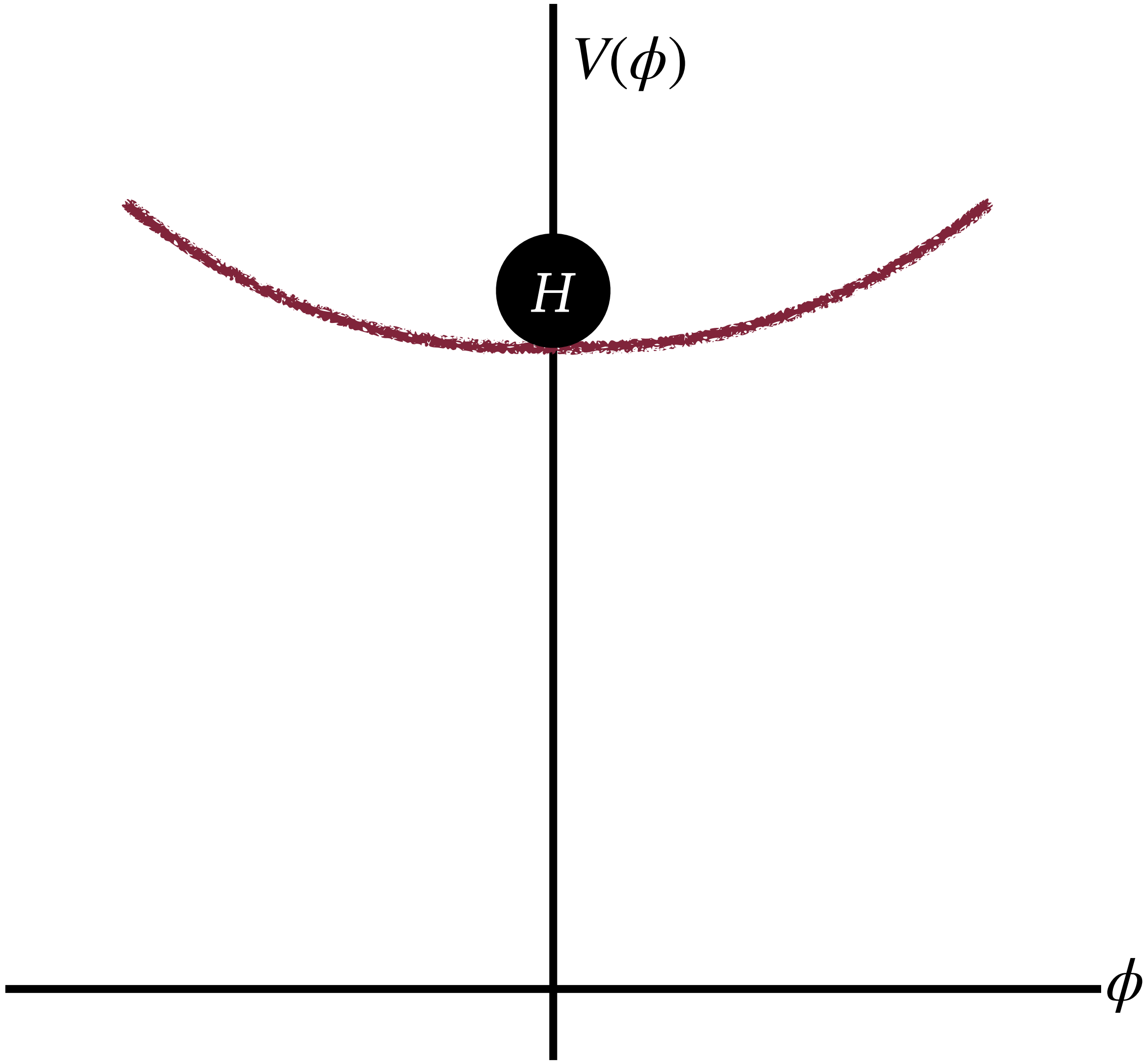

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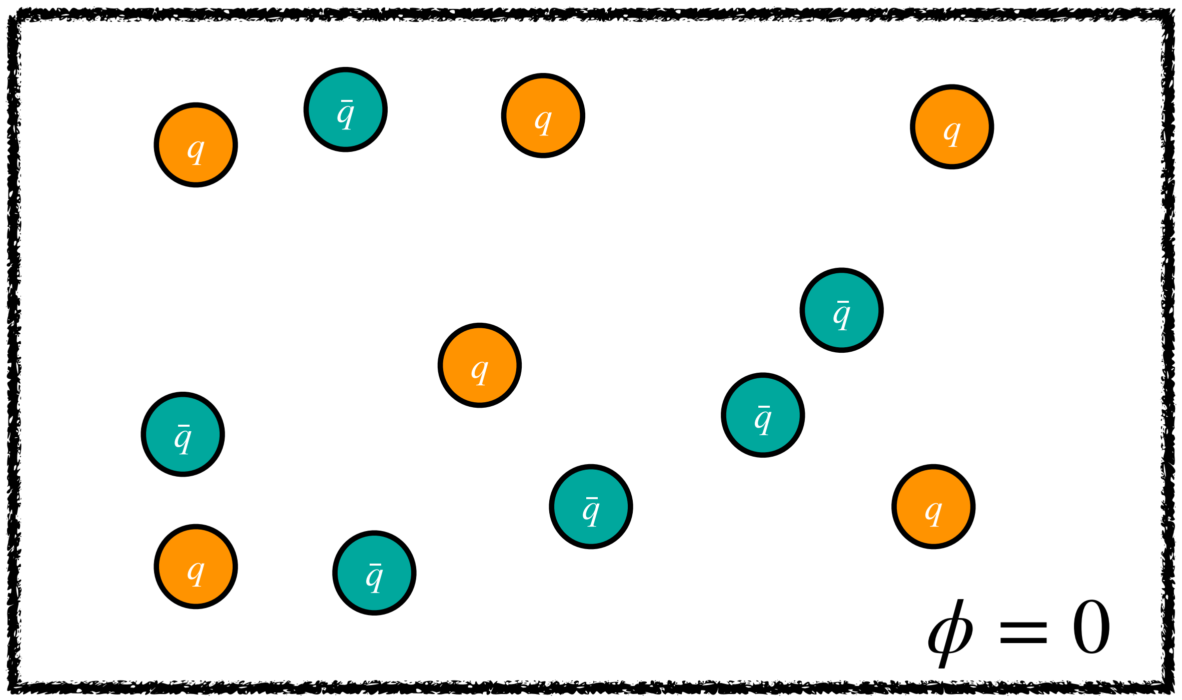
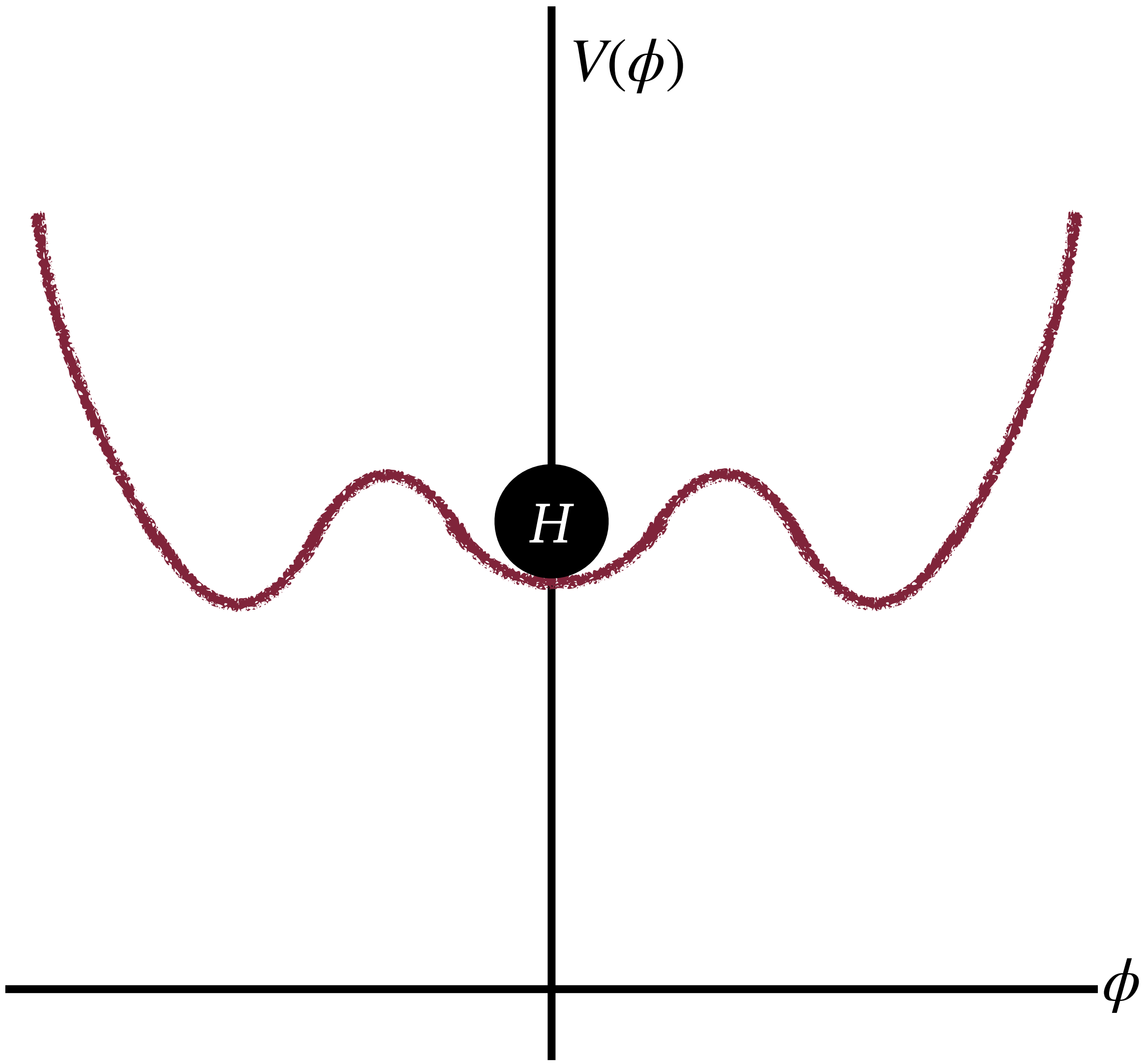
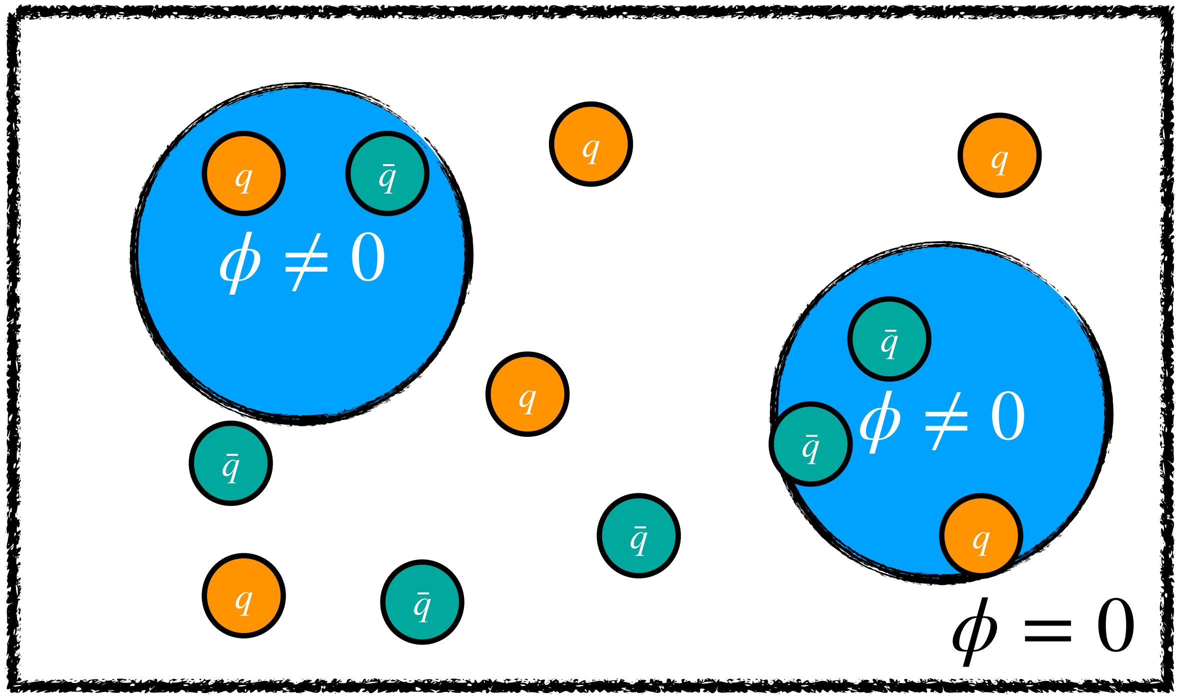


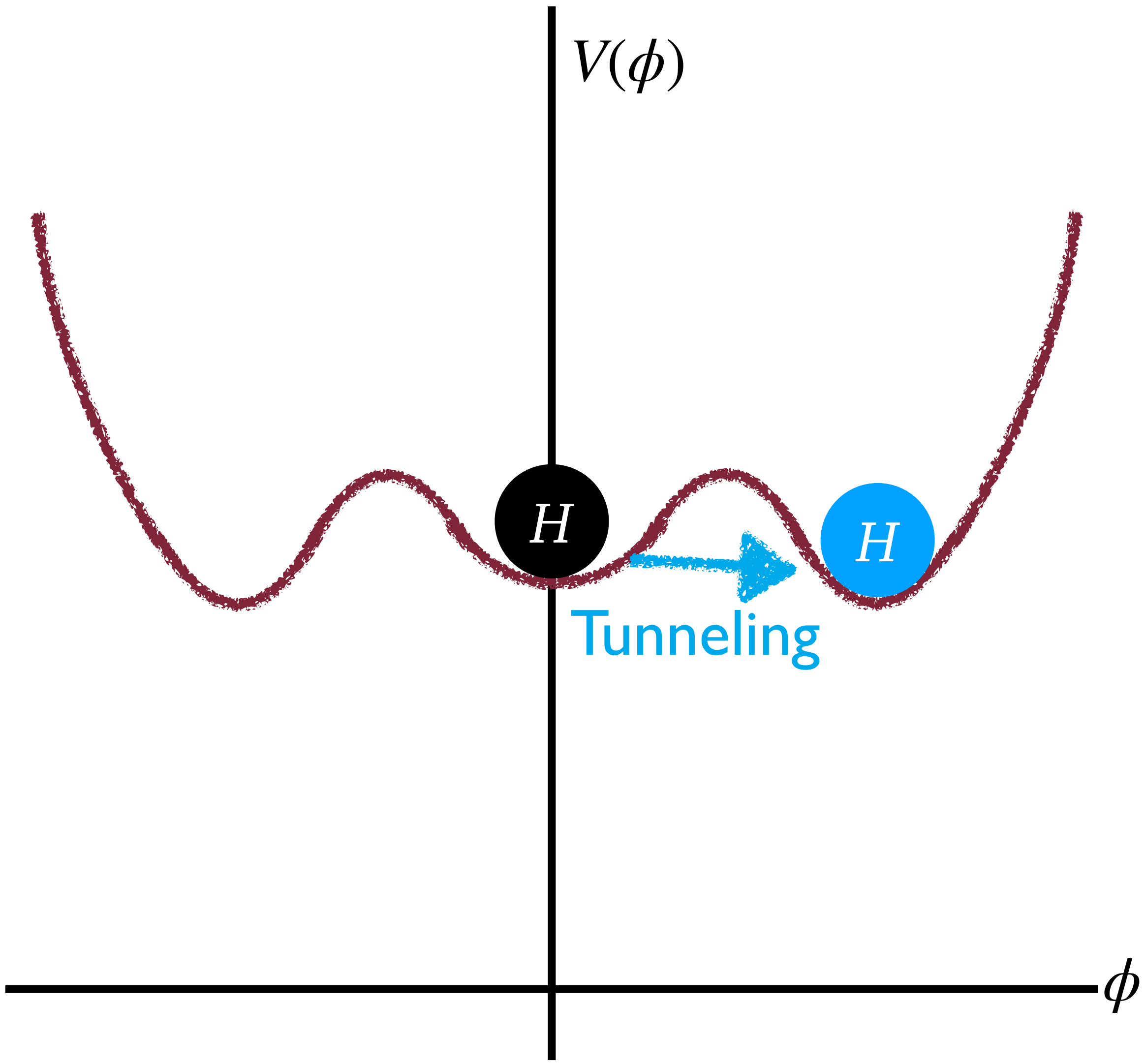


Step 0: Near the big bang, no EWSB: whole universe in $\phi = 0$ state

As the universe cools, the potential changes…

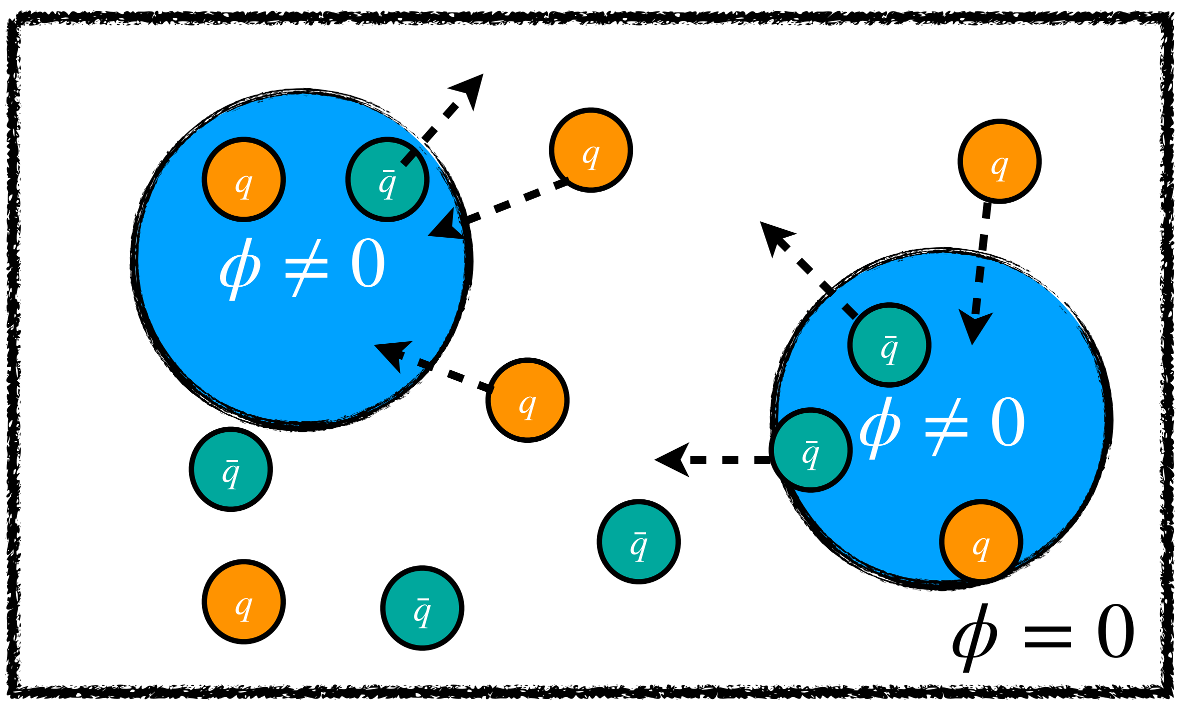
Electroweak Baryogenesis

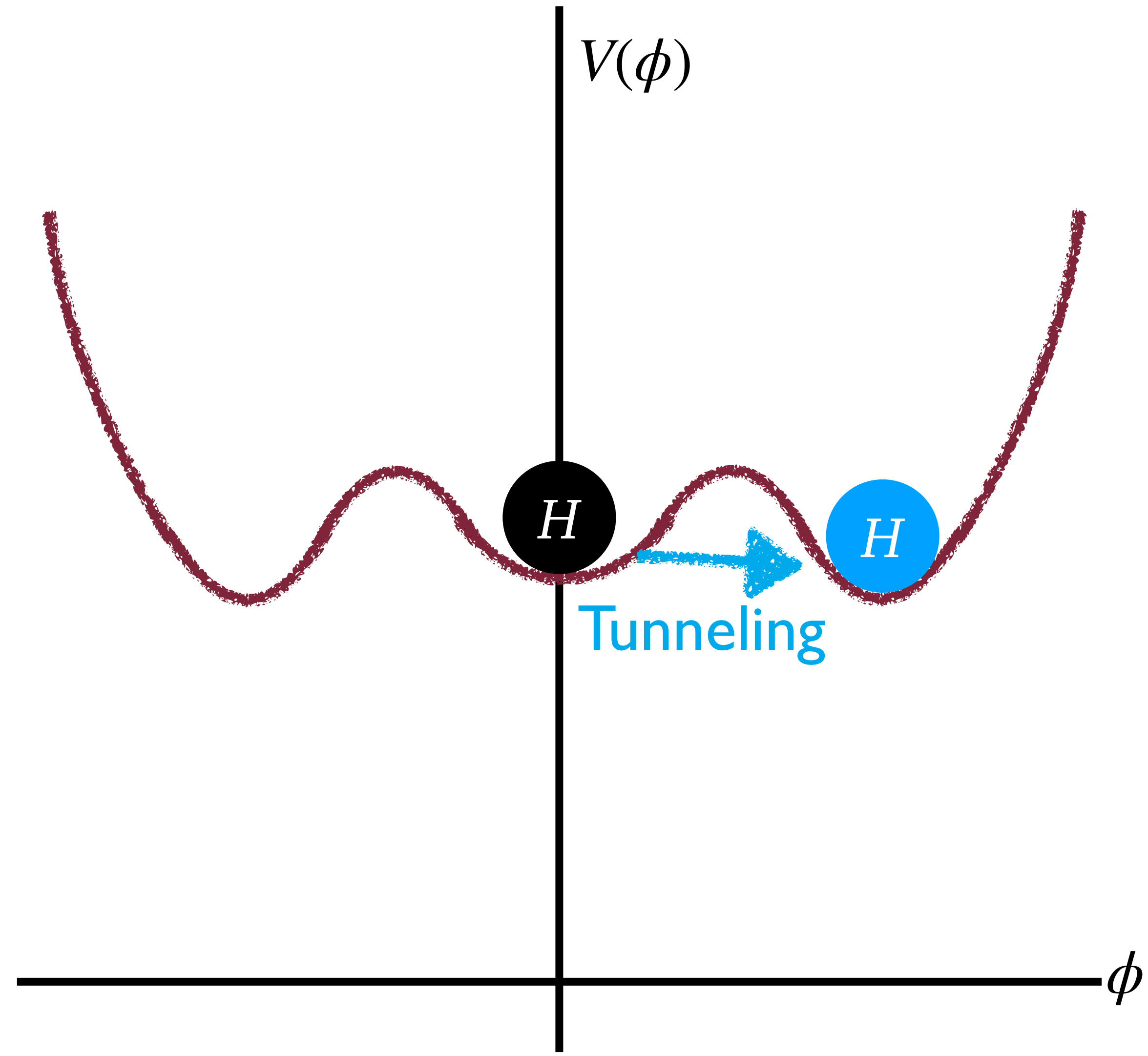




Step 1: At T_C, pockets of EWSB form via tunneling

Electroweak Baryogenesis

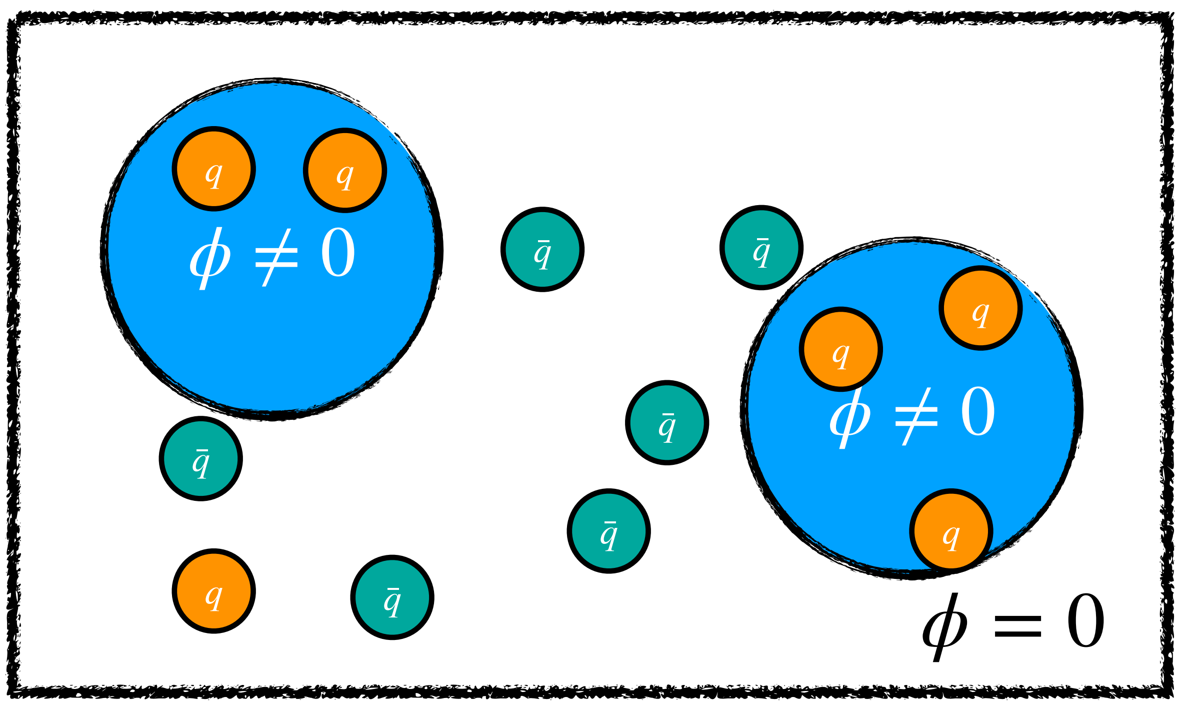


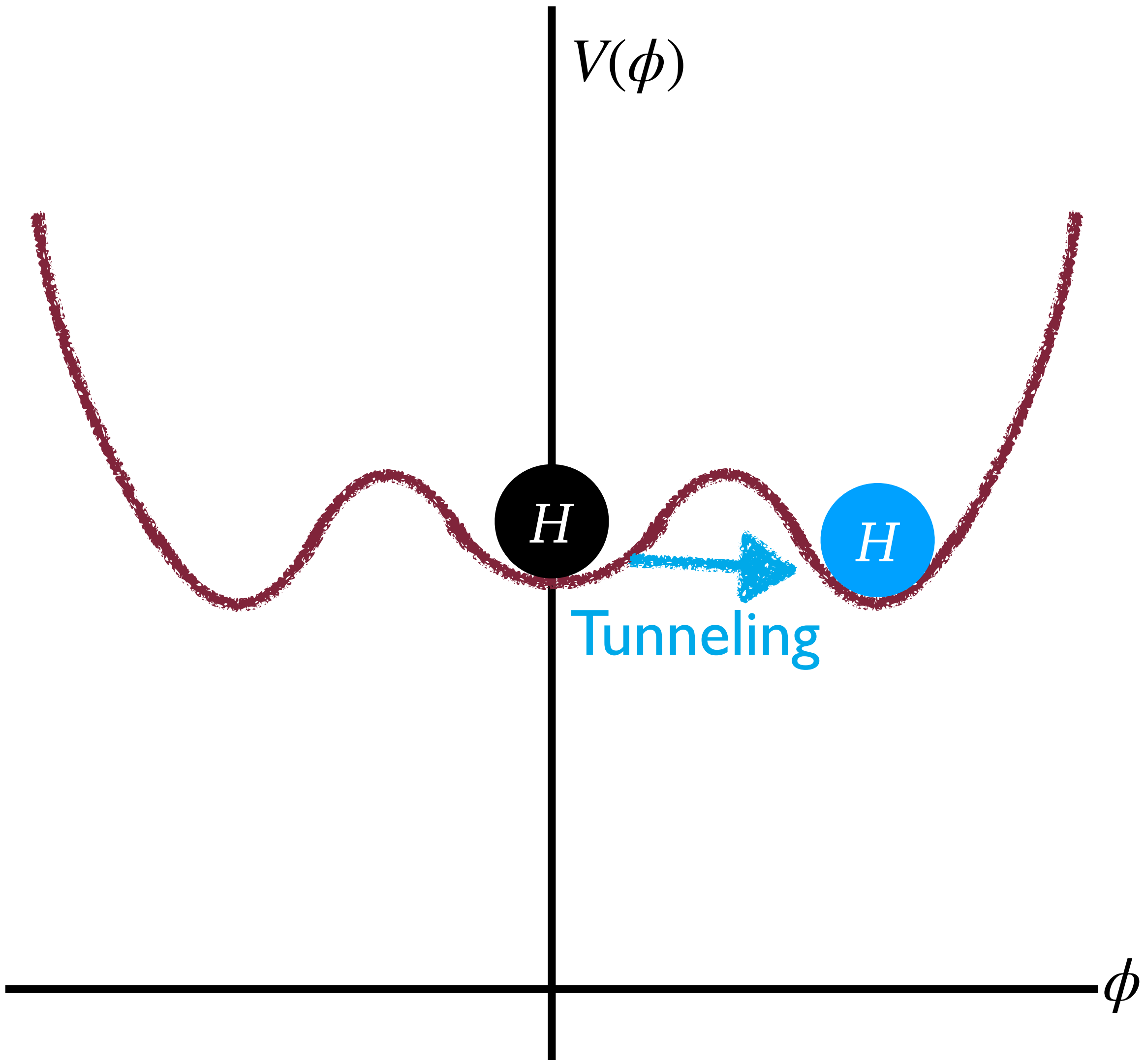


Step 2: CP Violation (*NB: requires BSM*) creates baryon flux due to interactions at the boundary

Matter and anti-matter have different transmission/reflection probabilities at the boundary

Electroweak Baryogenesis





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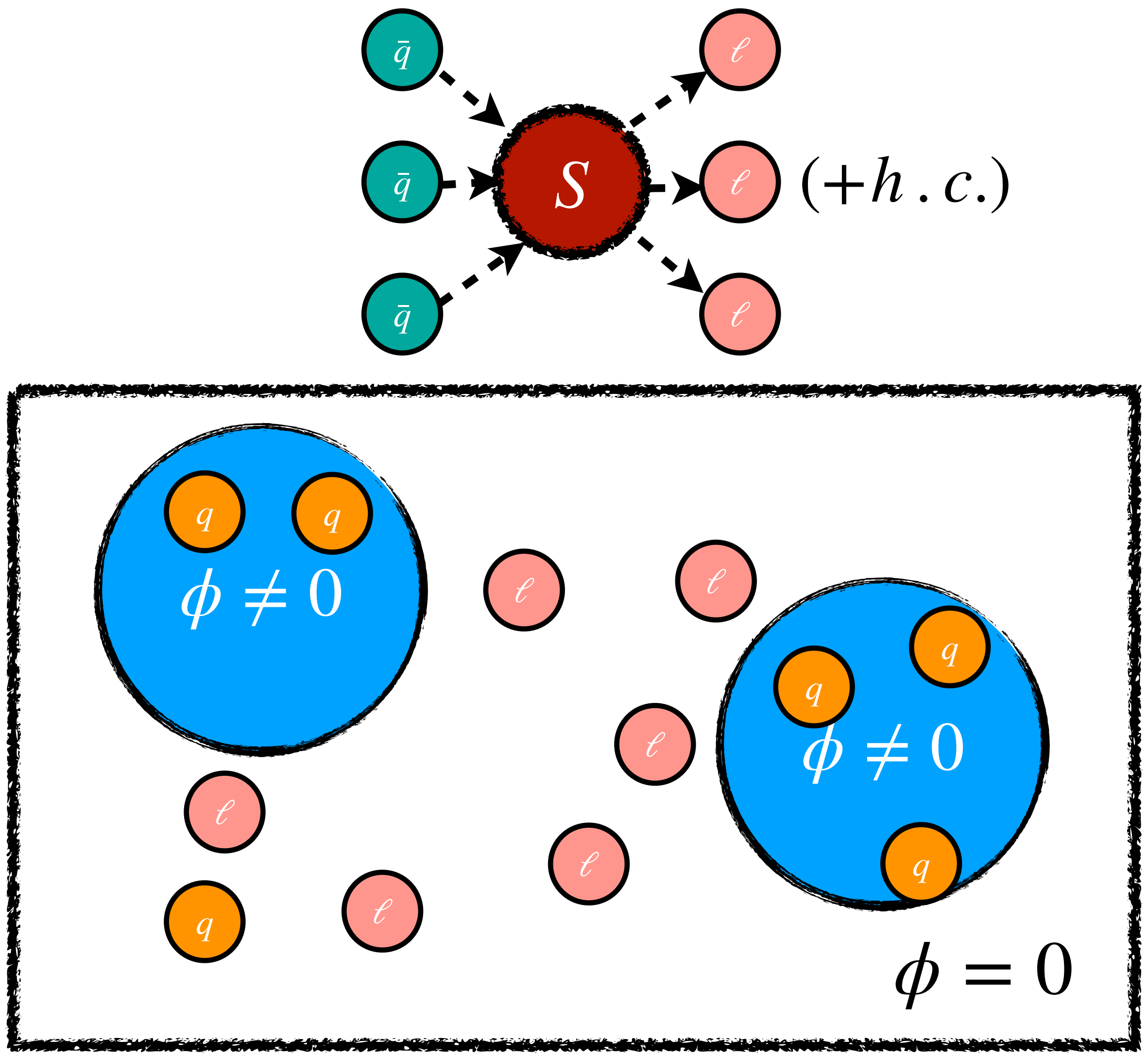
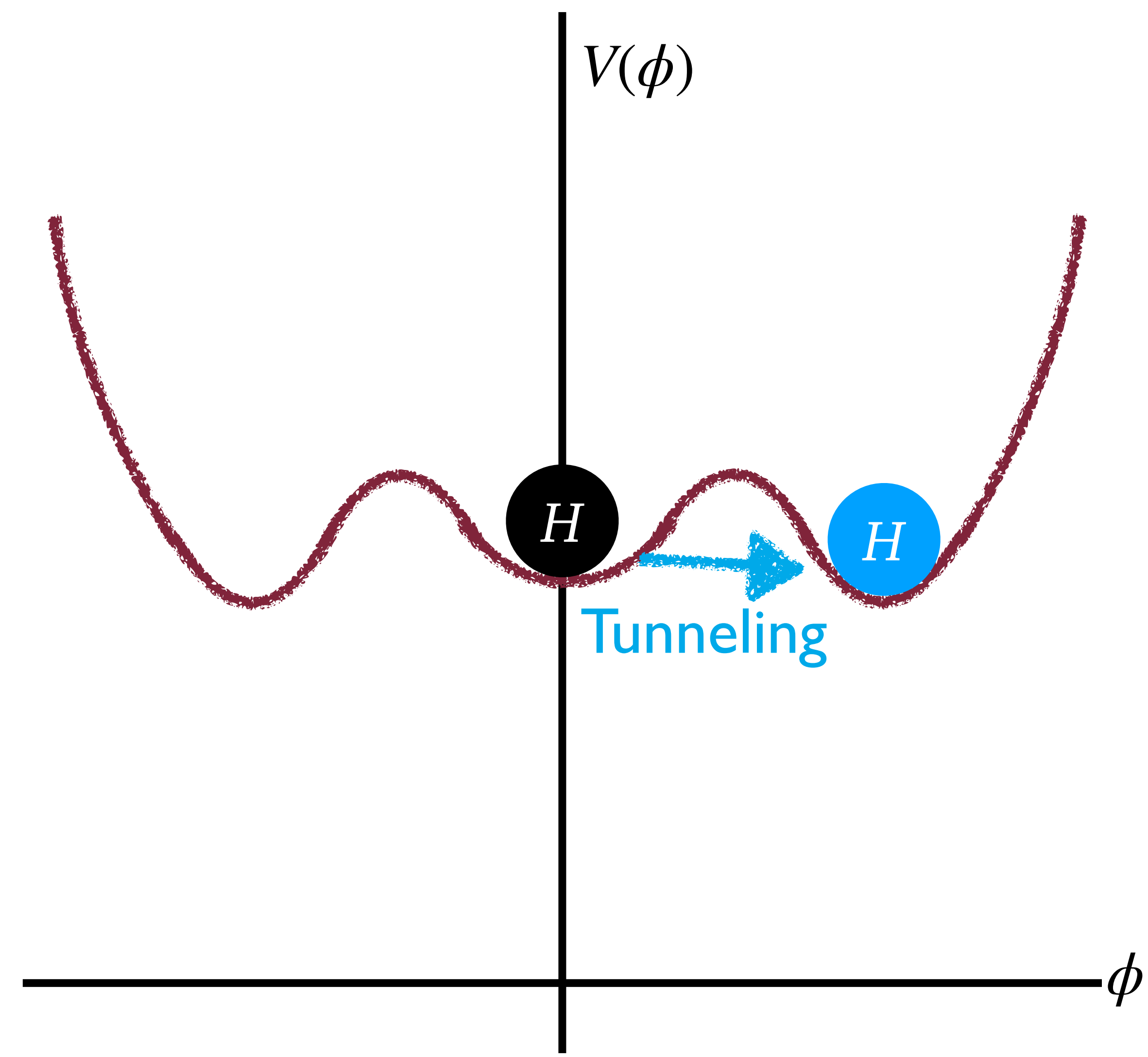
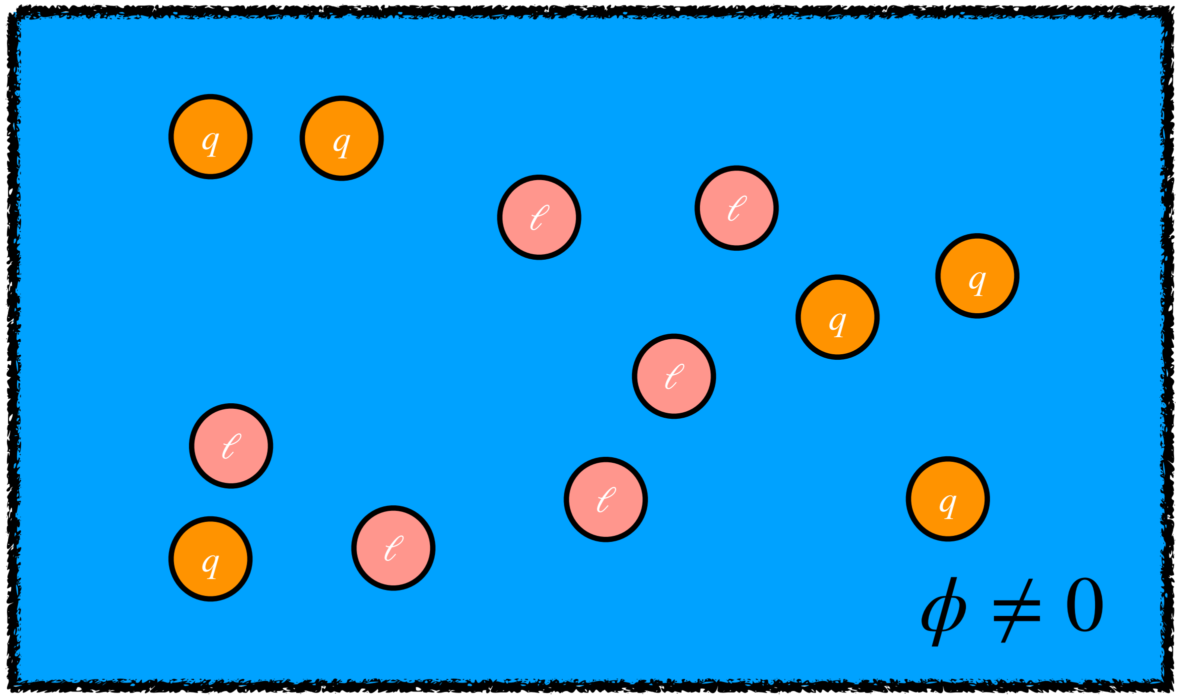


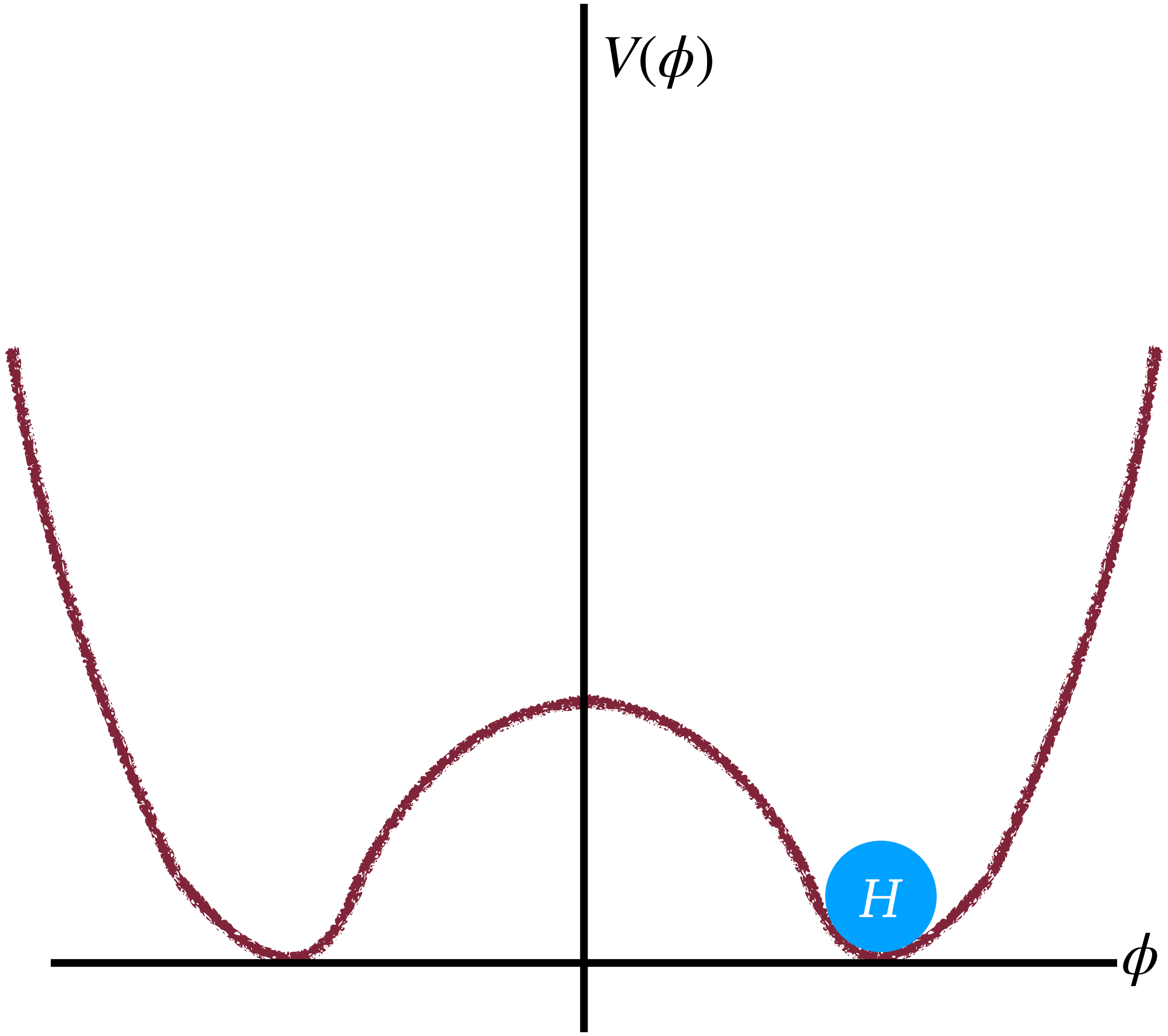


Step 3: High-temperature baryon-violating processes (*sphelarons*) at $\phi = 0$ remove anti-baryons

These processes don't occur in the $\phi \neq 0$ state: **electroweak symmetry breaking leads to matter symmetry breaking**

Electroweak Baryogenesis

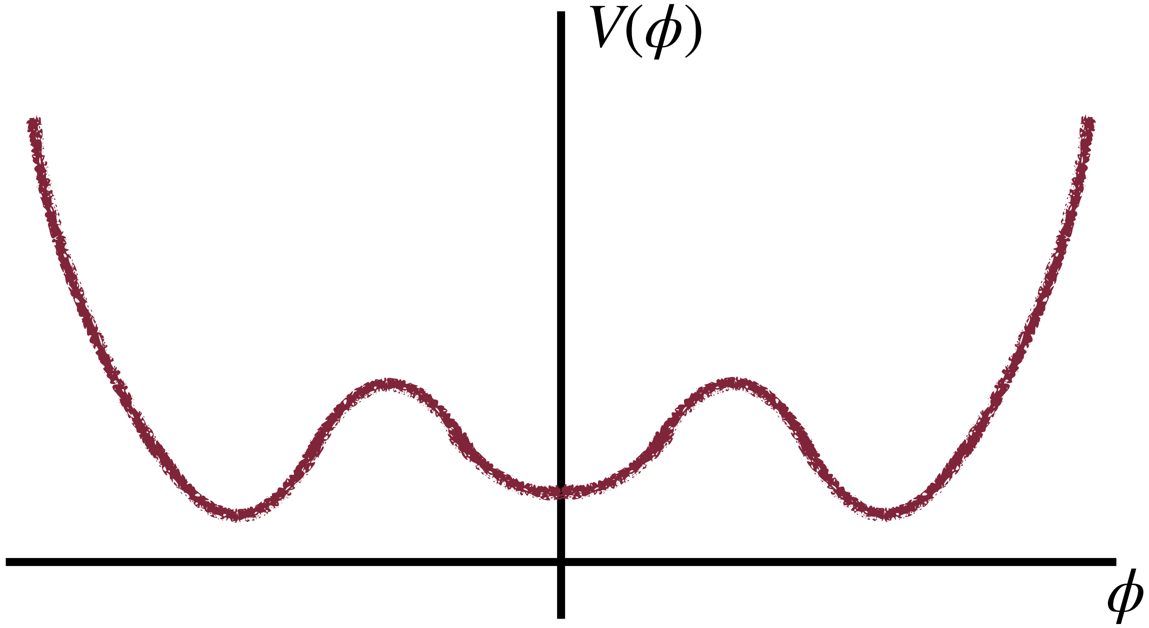




Step 4: Universe continues to cool to fully broken symmetry, but anti-baryons have been removed

The Higgs Potential and EWBG

The Higgs Potential and EWBG



The shape of the Higgs potential at T_C is critical: needs to be a first-order phase transition

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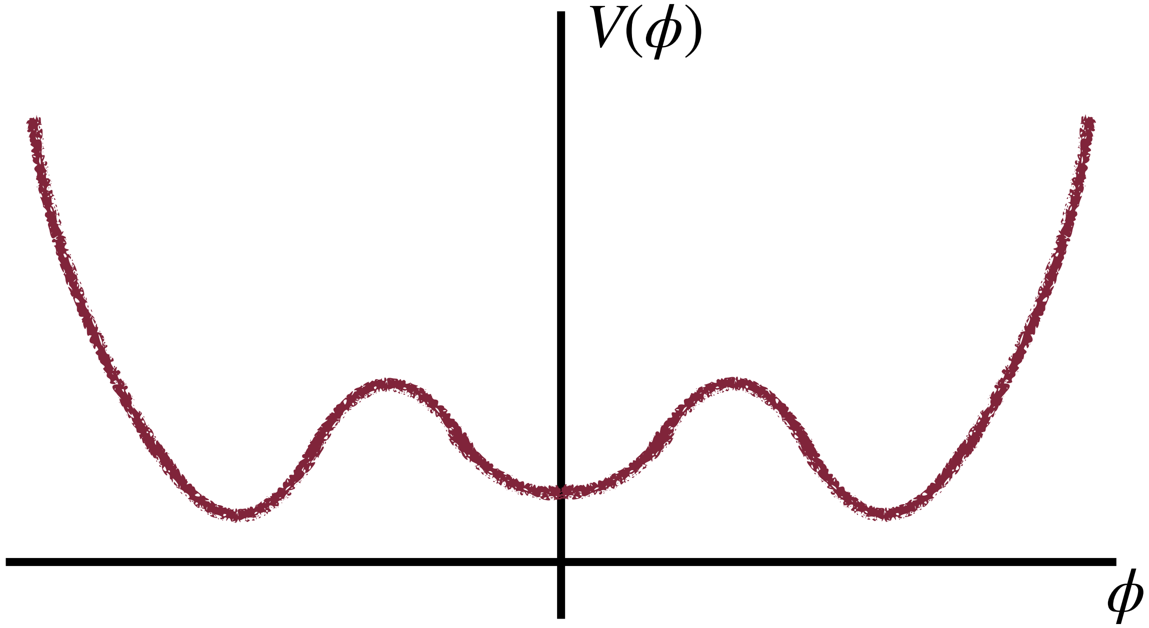

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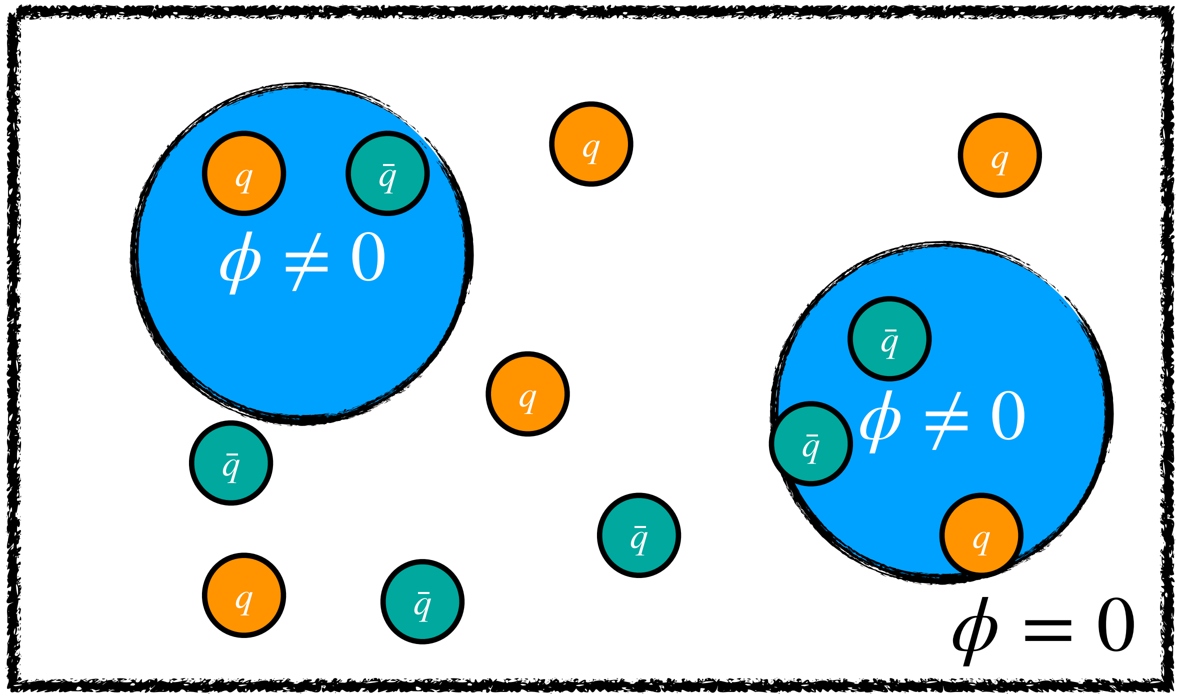

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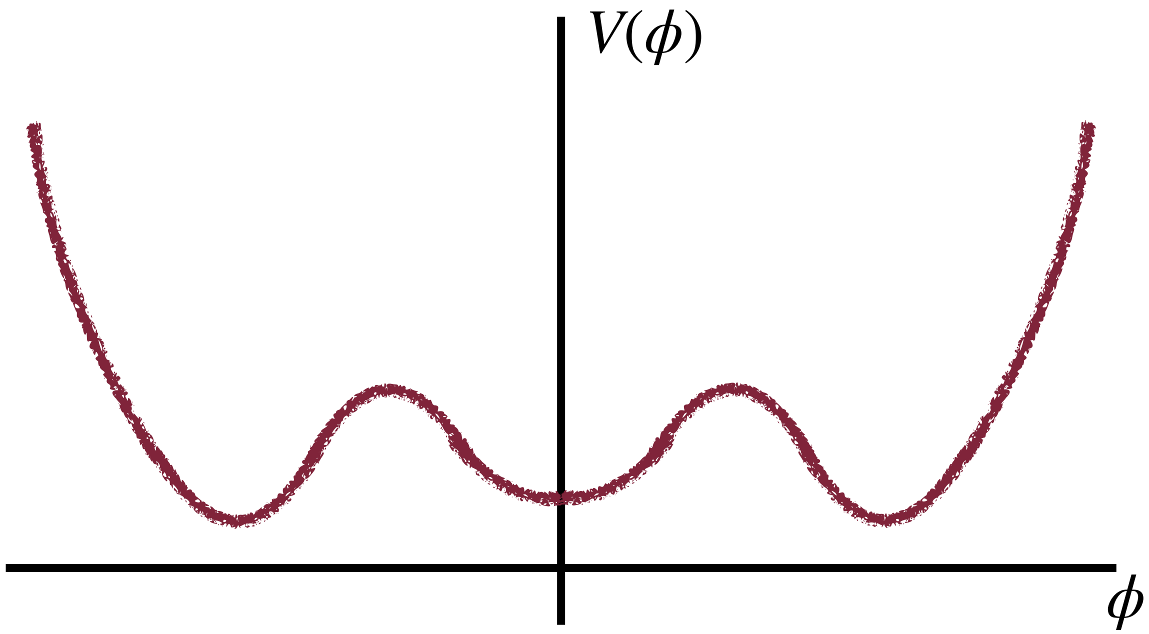

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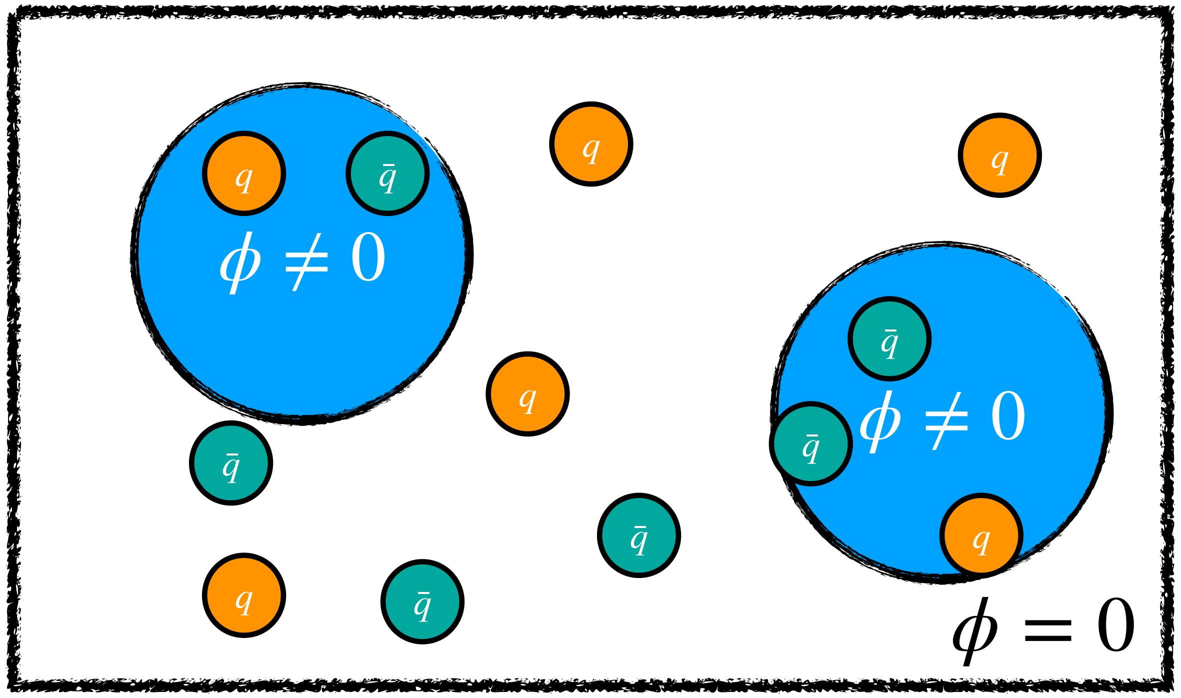

We need a modified Higgs potential to enable this first order transition: κ_λ could be between 1.2 and 6 (very roughly!)

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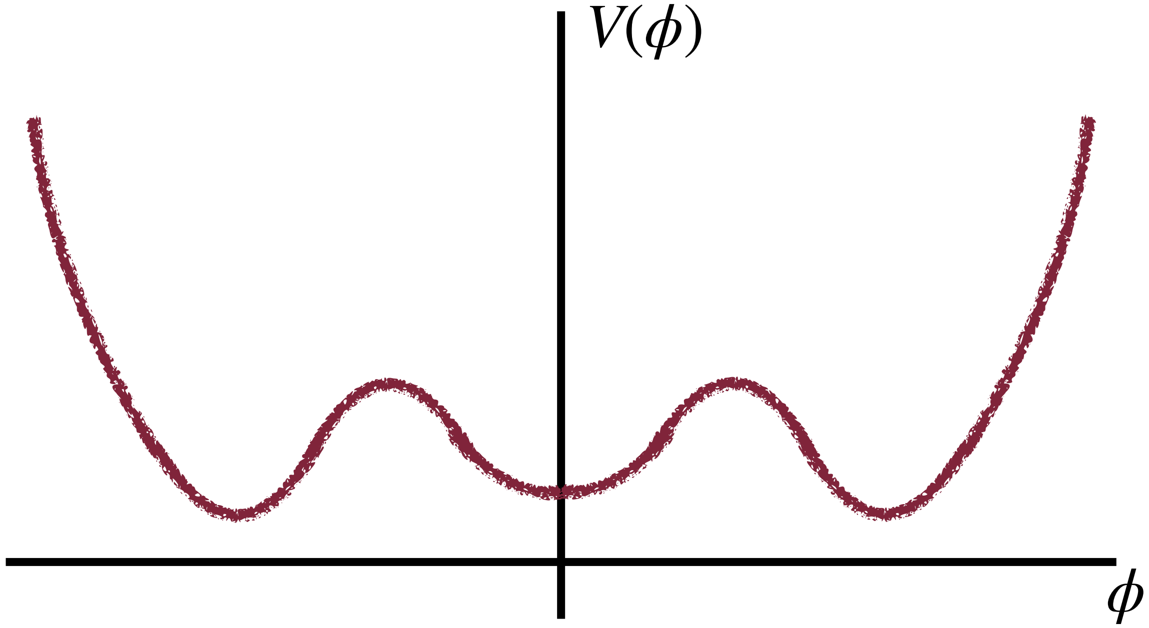

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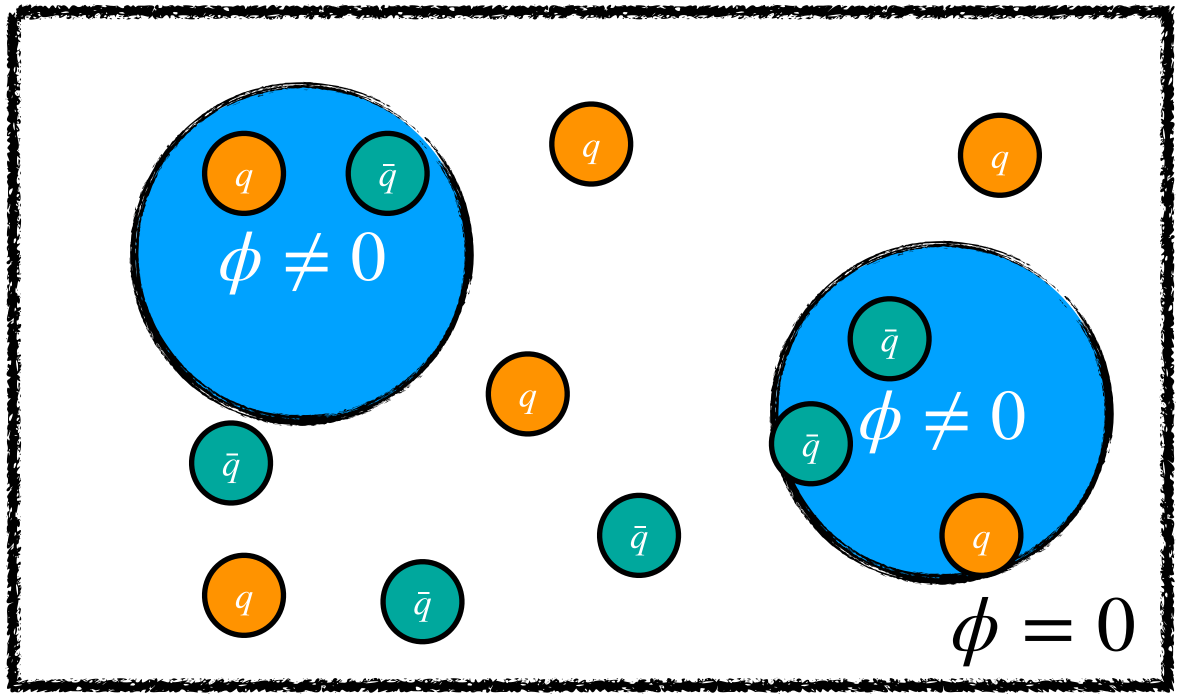

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And we could see this at the LHC with di-Higgs!

Is the Universe Stable?

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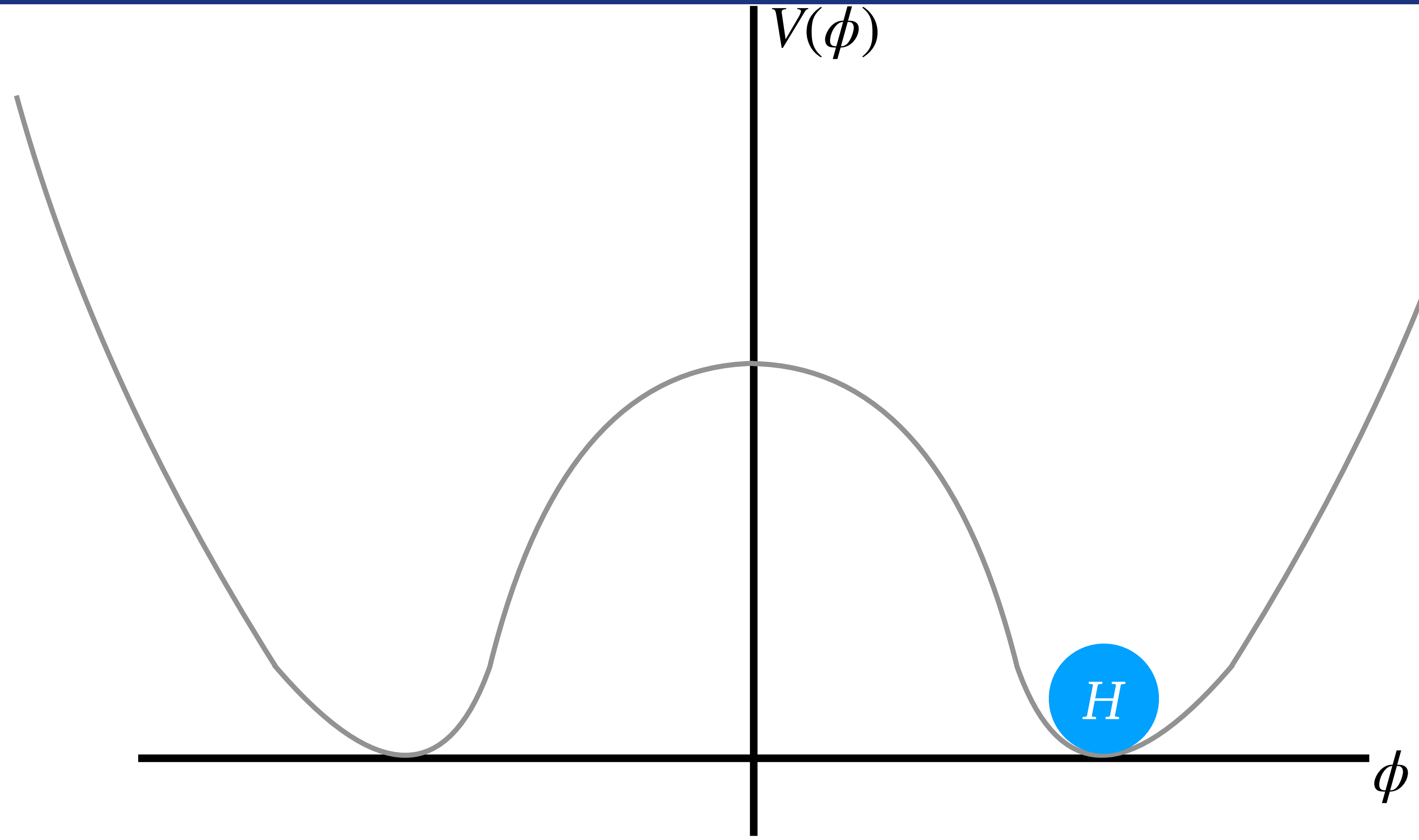

If the only field in the universe was the Higgs, an SM-like potential would be *stable*: our minimum is the global minimum

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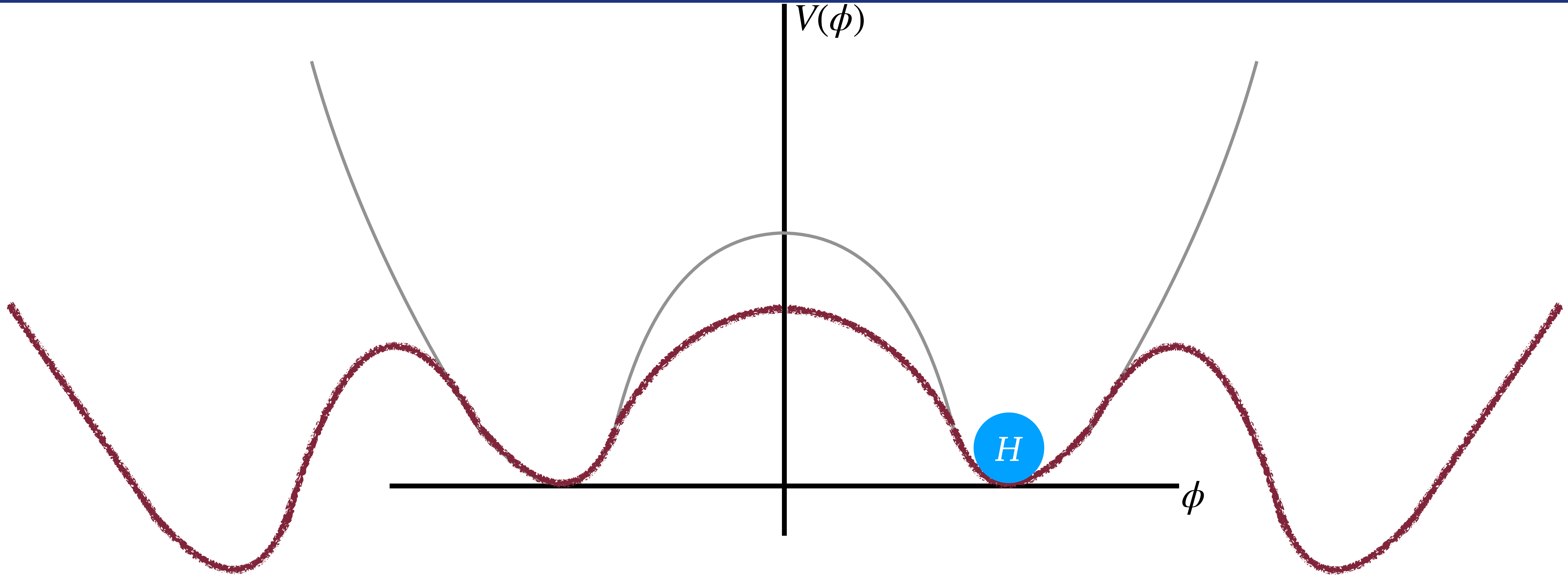

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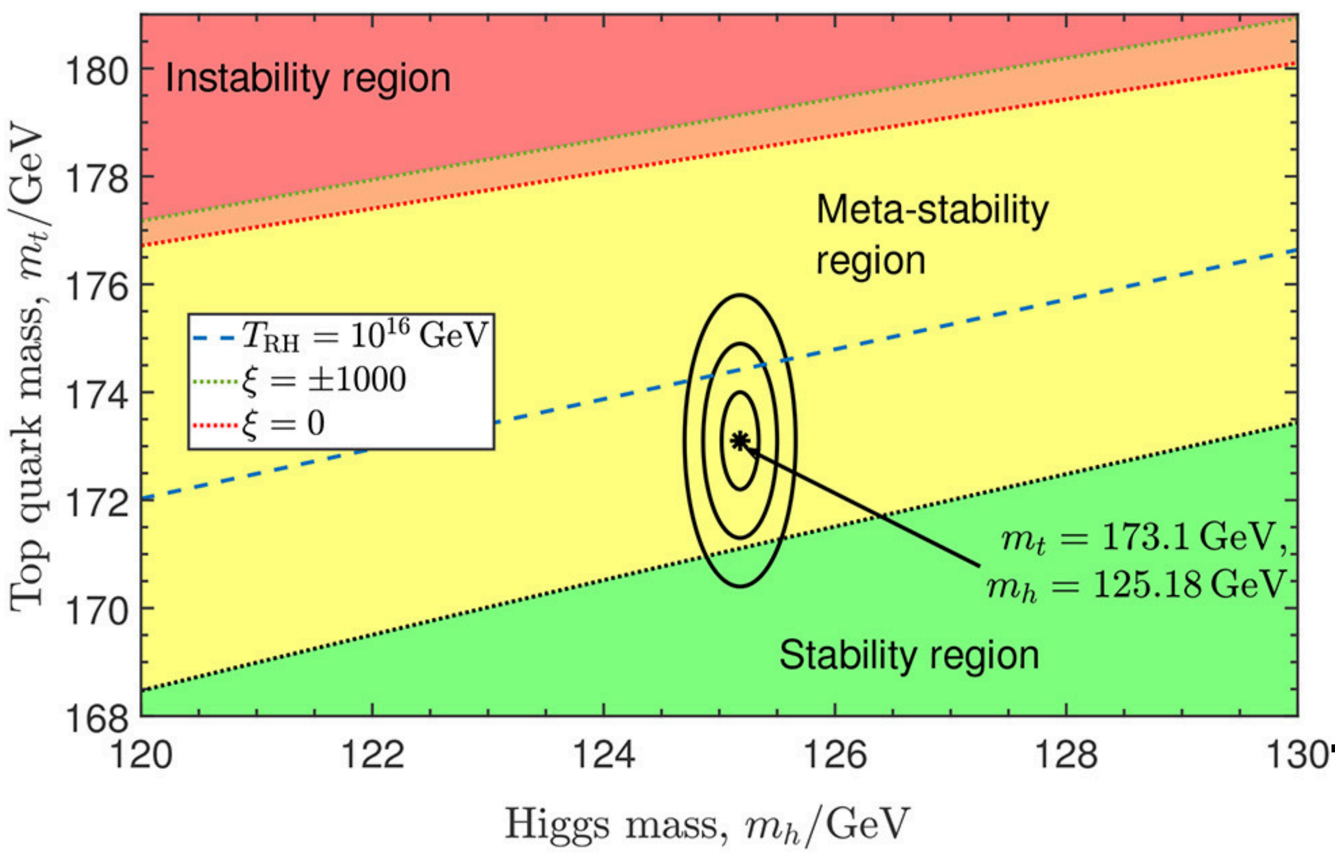
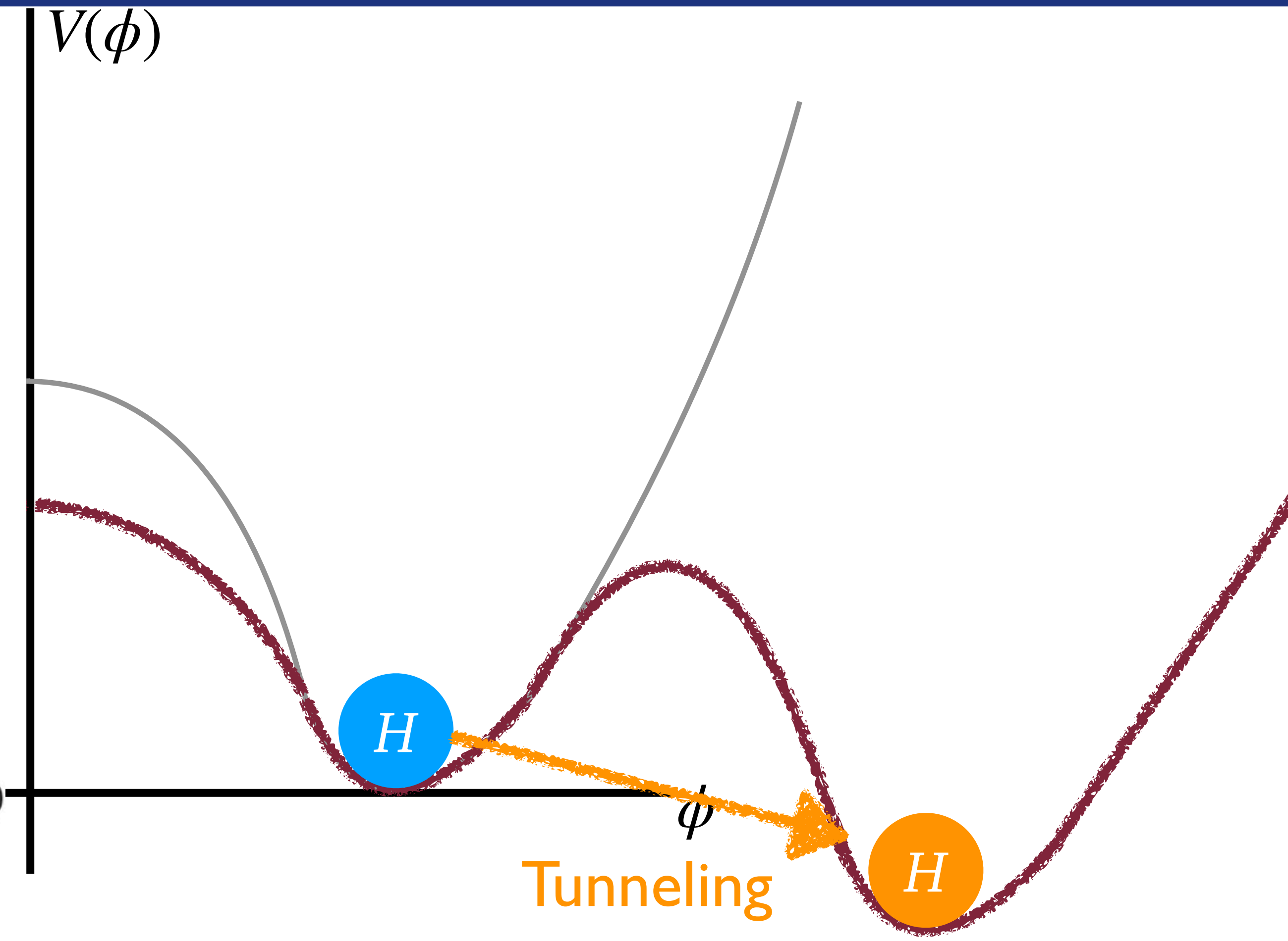
Markkanen, Rajantie, Stopyra





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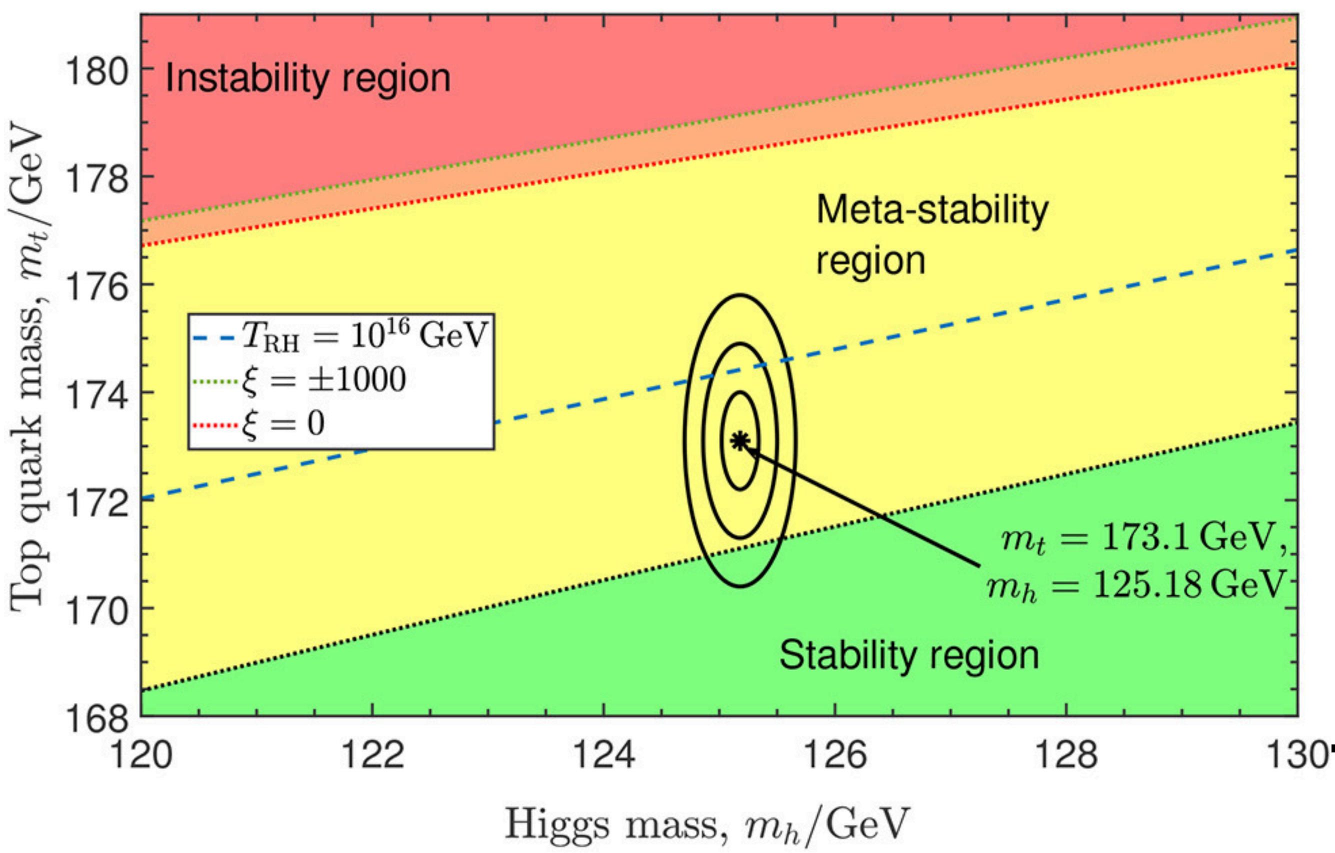

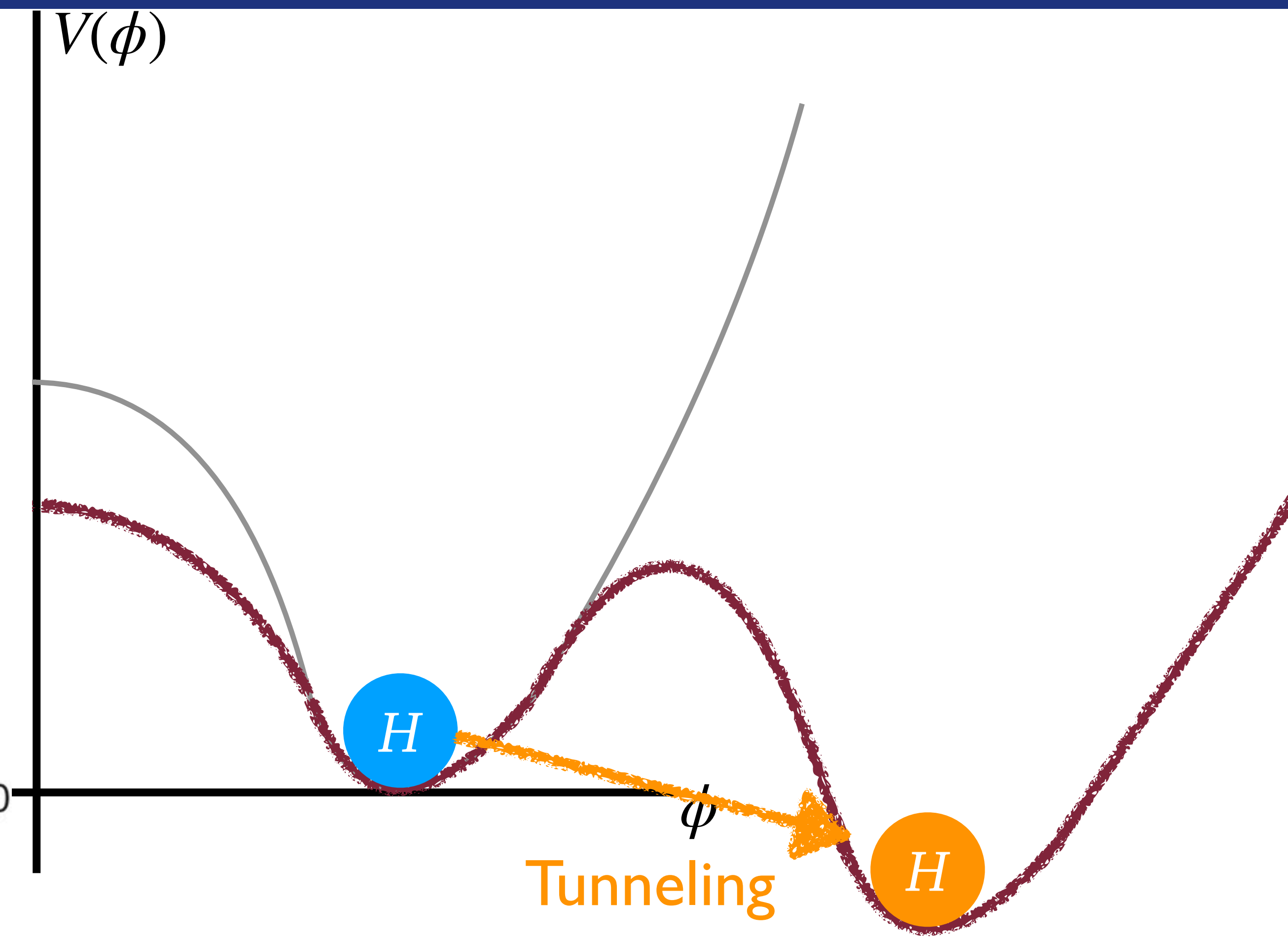

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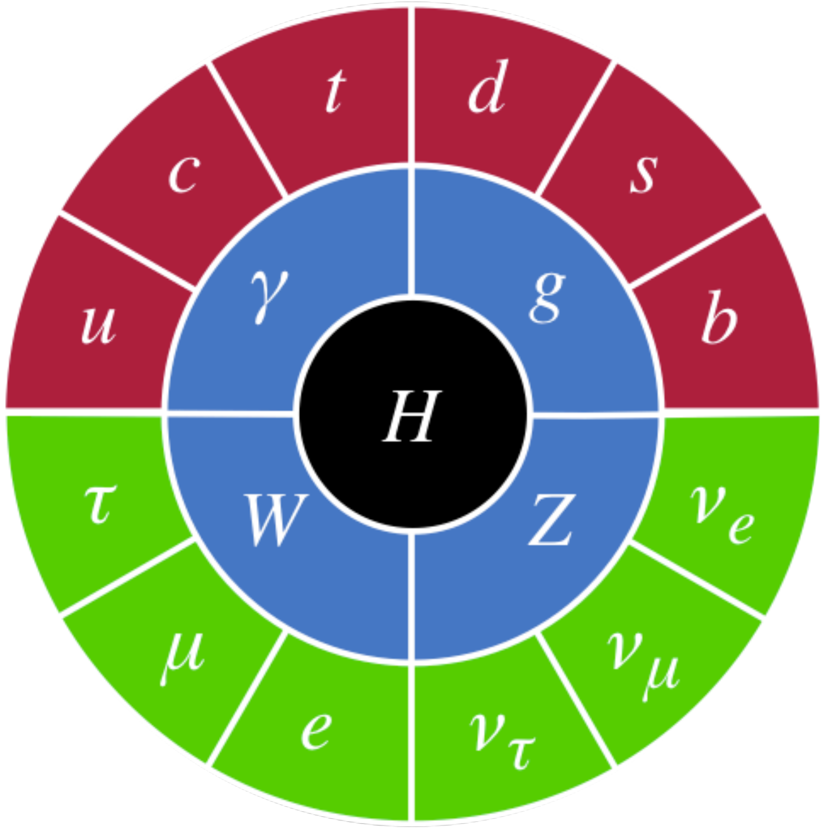
Measuring the potential as best as we can is critical: BSM physics can move our universe between stability and instability

The Higgs is still new and not fully explored



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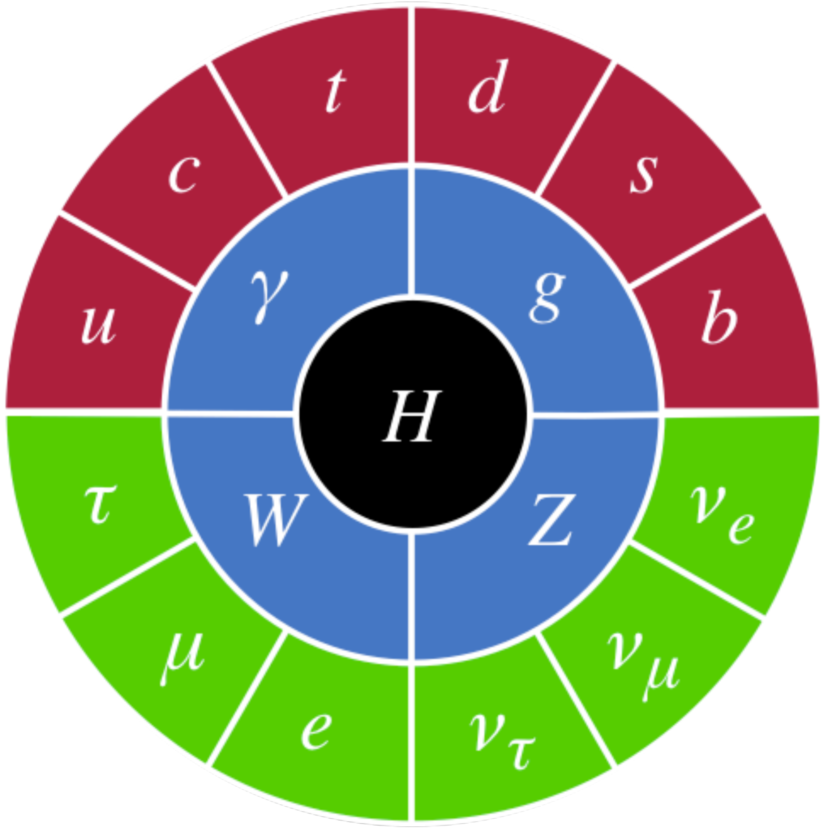
What can we learn from this new particle?



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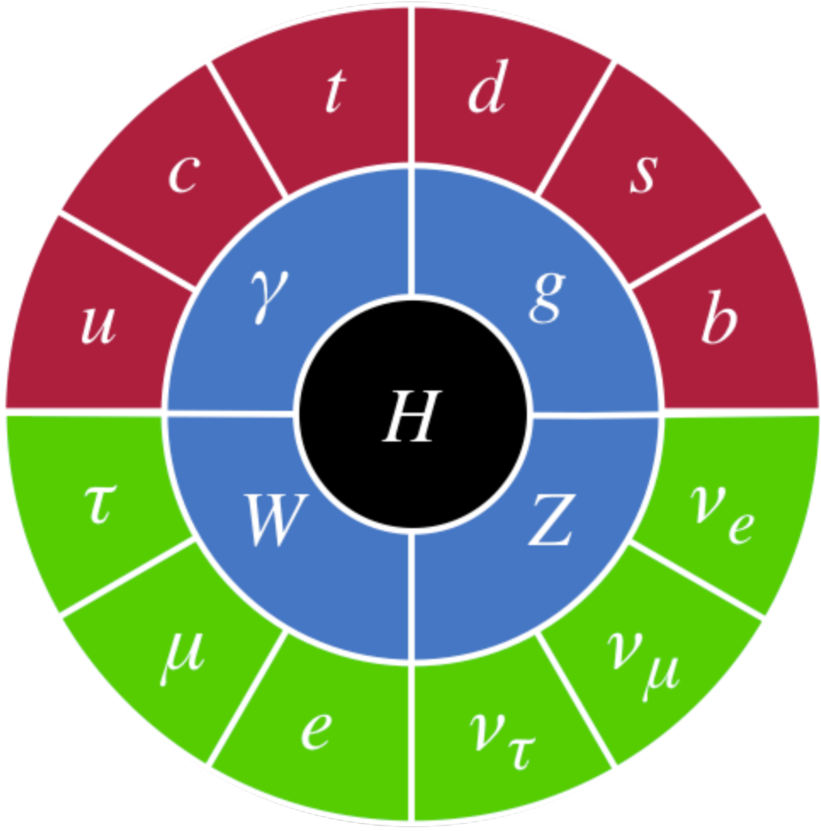

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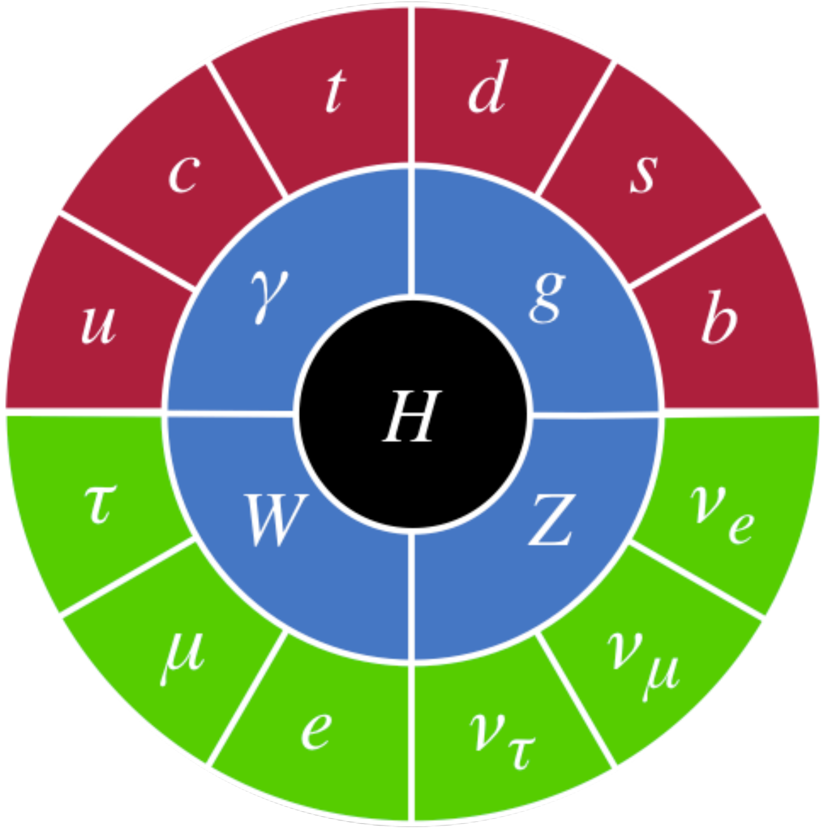

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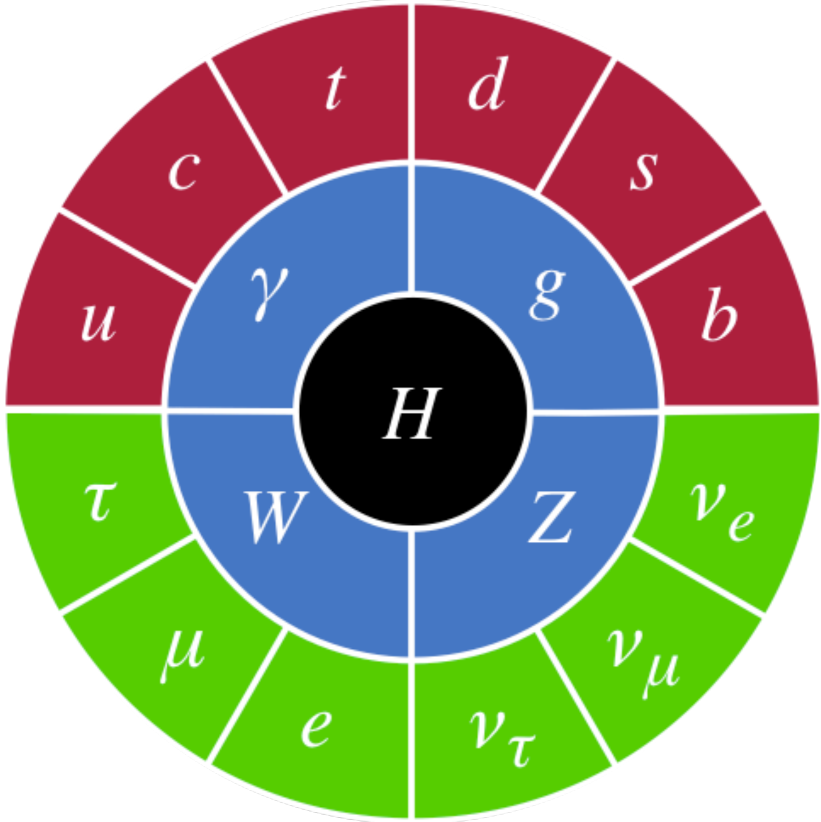

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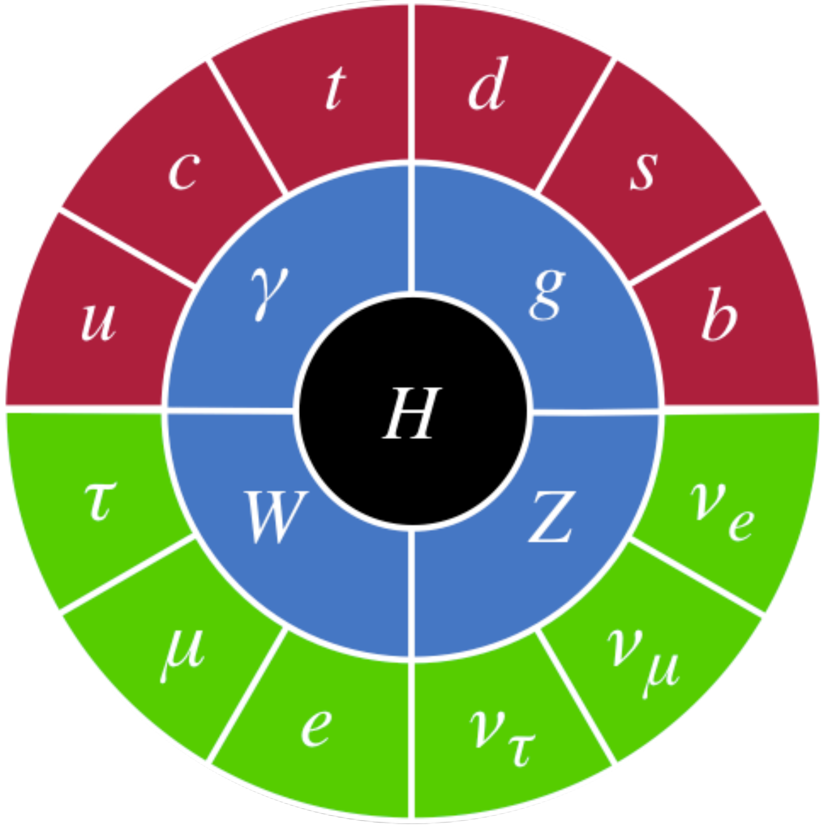

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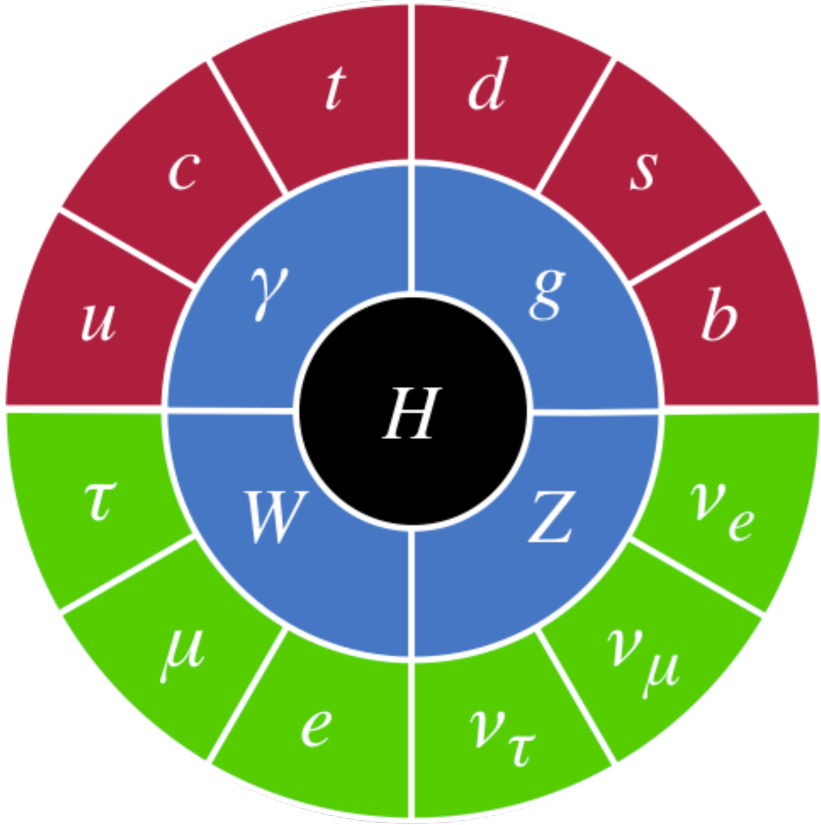

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Higgs pairs are the next frontier to understanding the Standard Model and Beyond

The LHC Context

What Do We Look For?

The Next Frontier: Higgs Pairs

Outlook

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The Next Frontier: Higgs Pairs

Outlook

What Does This Look Like?

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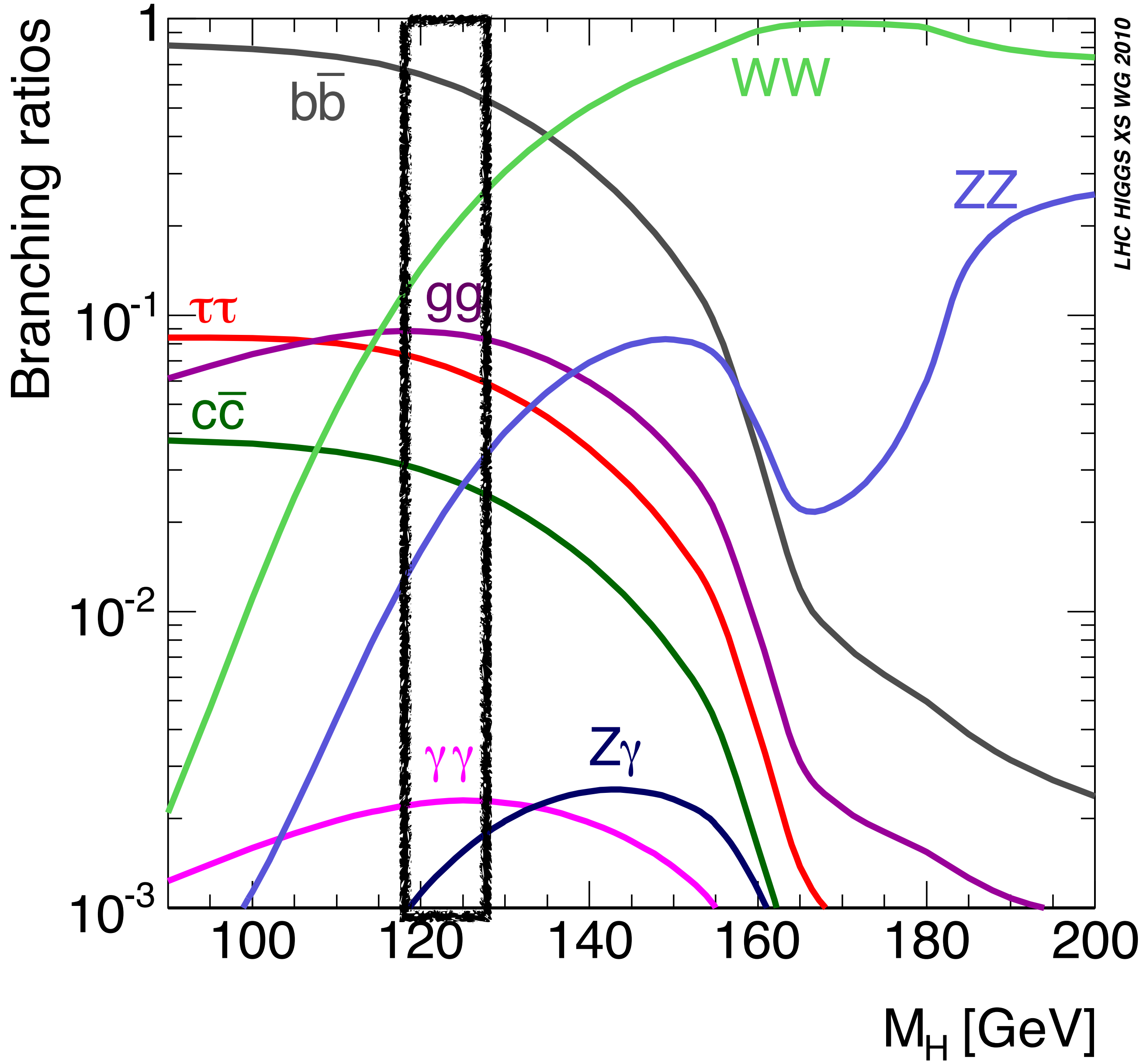

The Higgs decays instantly, to a range of particle types

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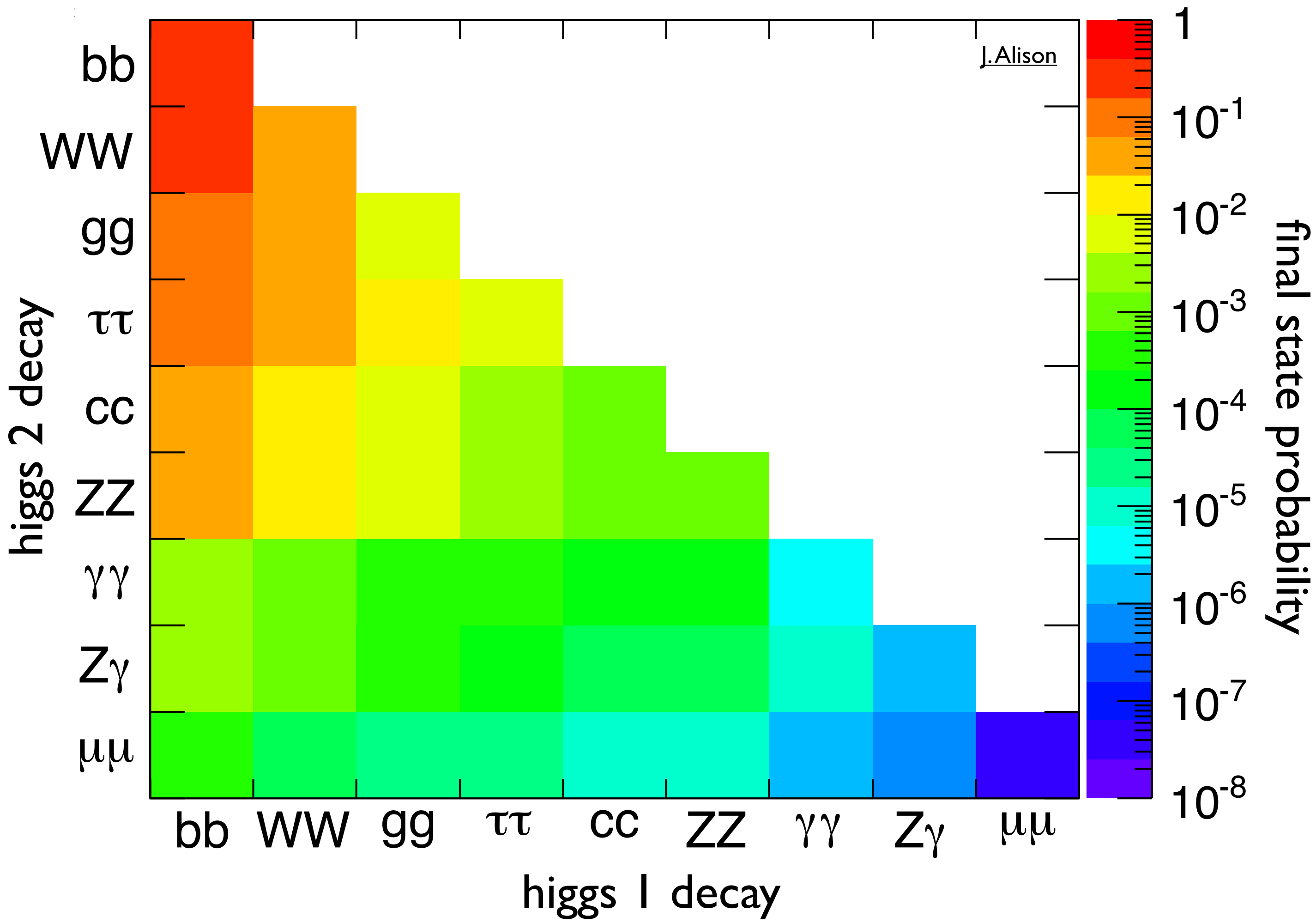

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Higgs pairs are rare, and have a hugely rich structure of final states

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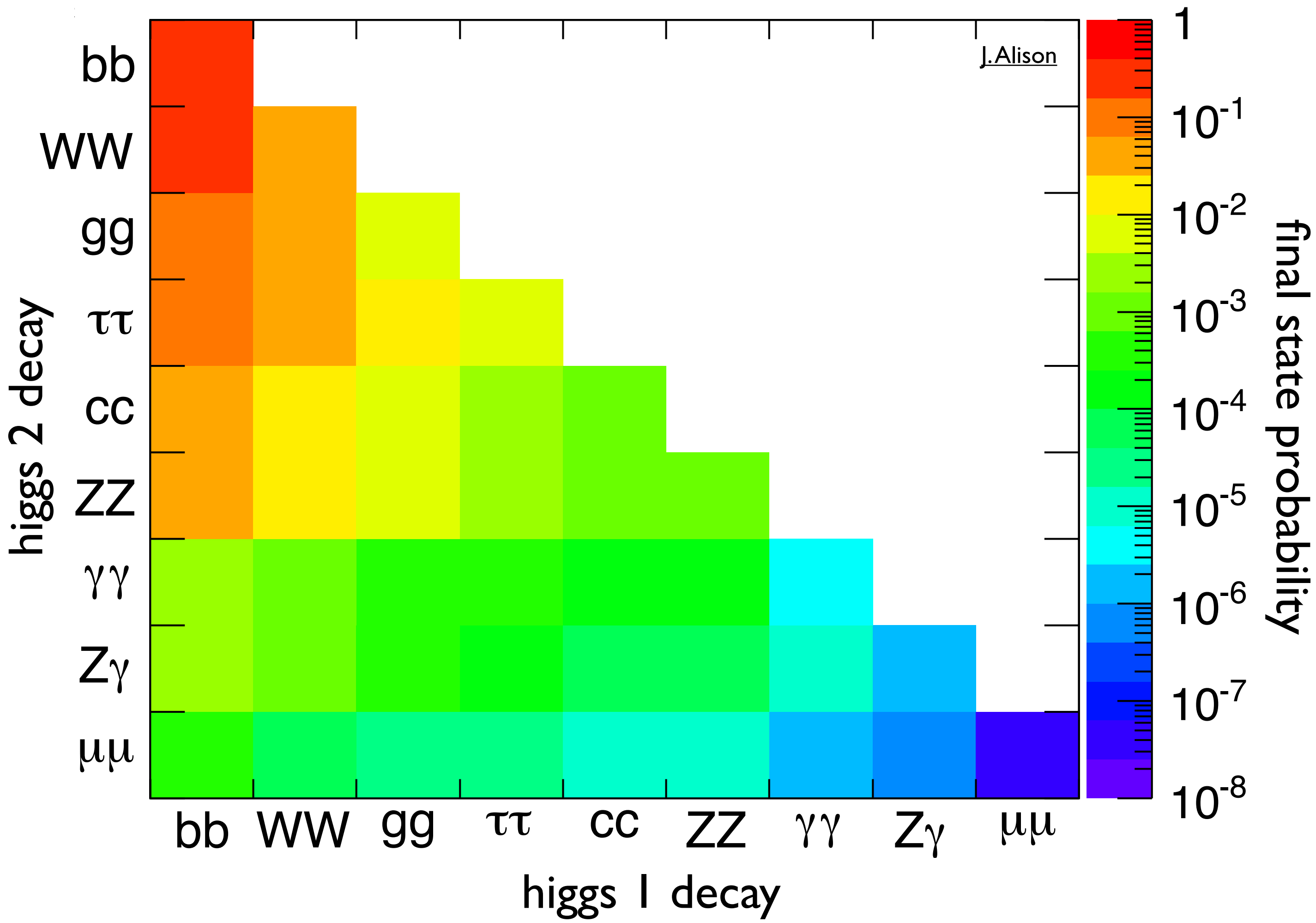

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Man on Wire, Guardian

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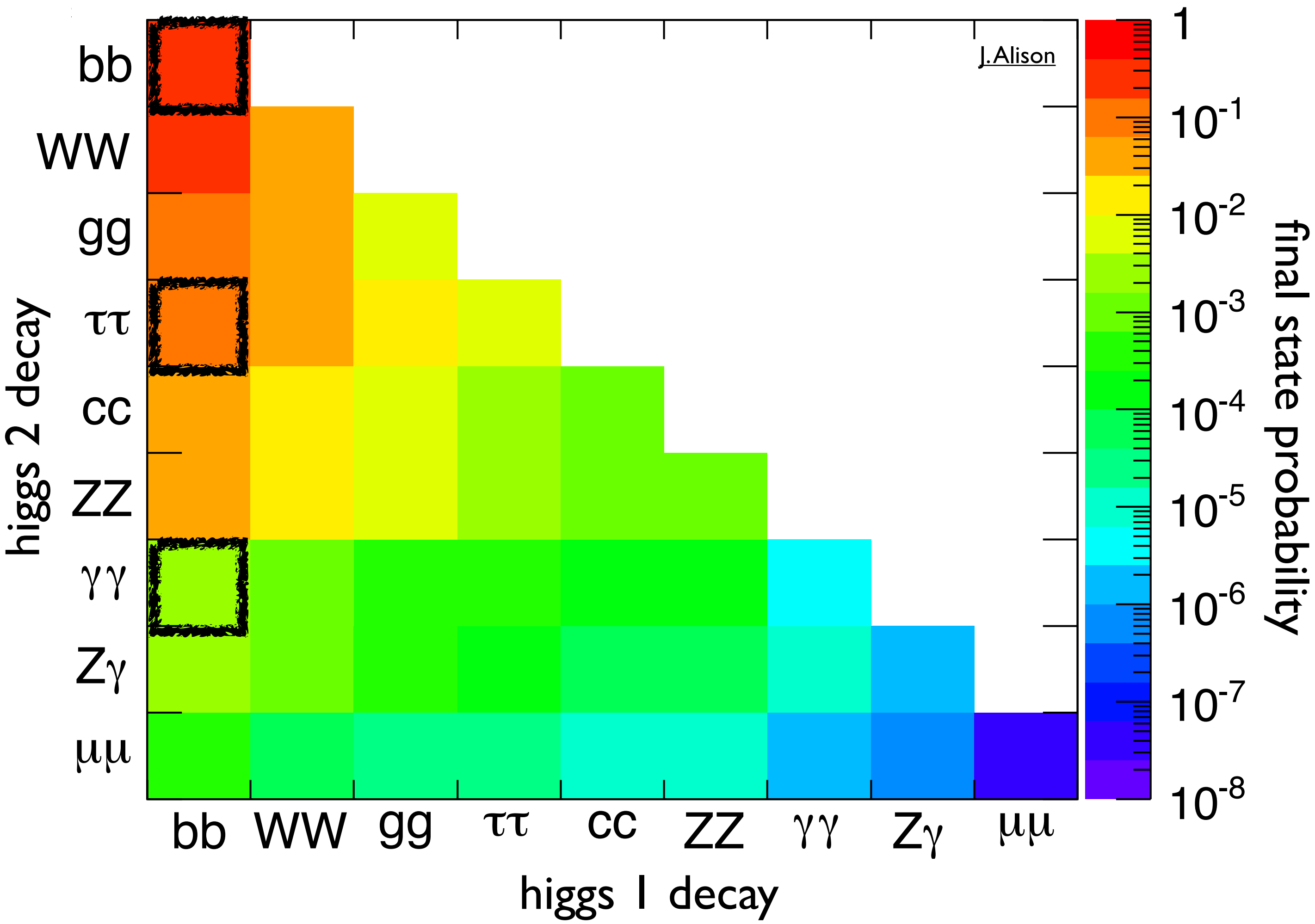

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Man on Wire, Guardian

$4b$, $b\bar{b}\tau\bar{\tau}$, and $b\bar{b}\gamma\gamma$ are the most powerful

The ATLAS Detector

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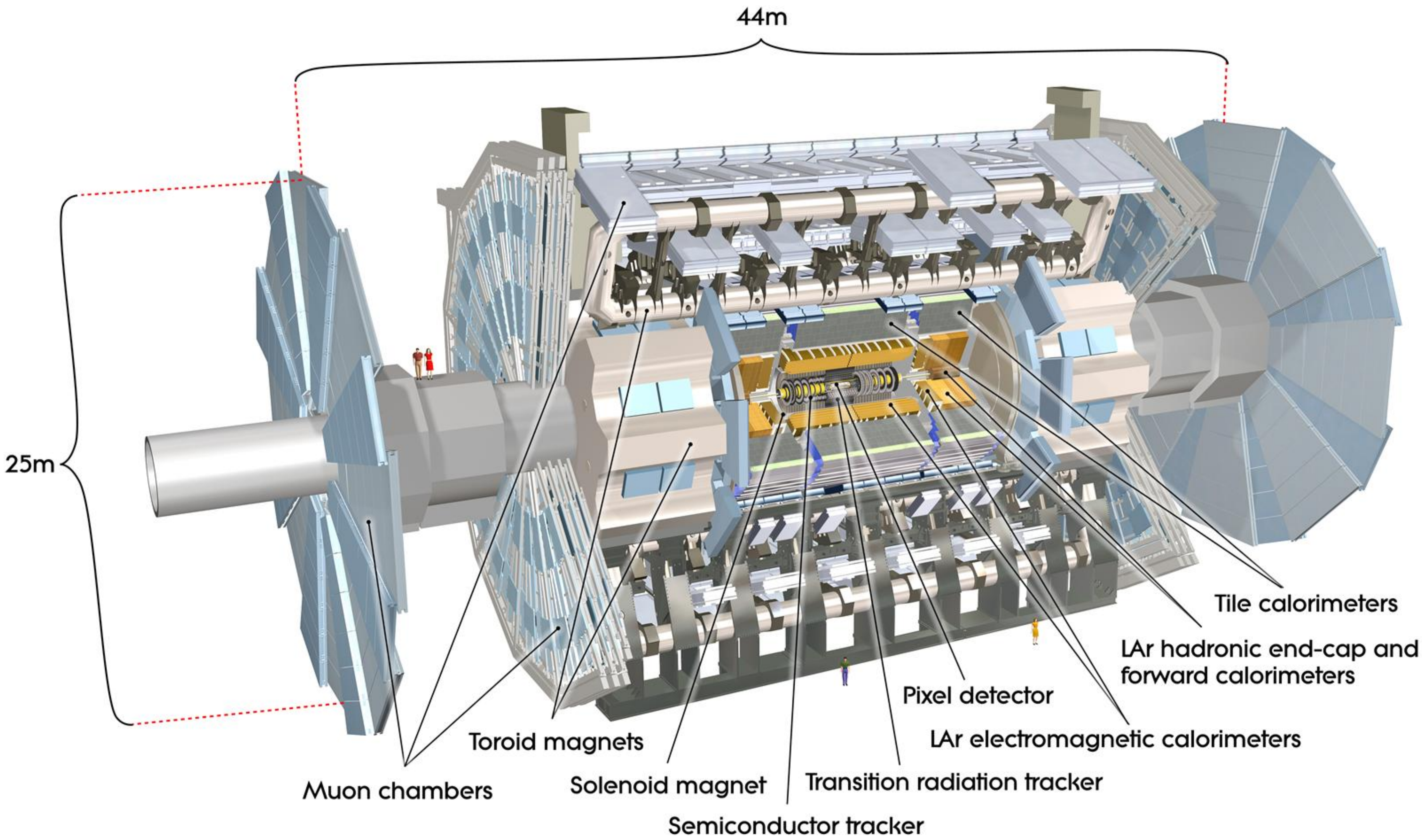

Collisions, to Physics

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LHC Collision
Rate: 40 MHz

Collide quarks and gluons accelerated in protons by the LHC

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ATLAS Hardware Trigger: 100 kHz

Collide quarks and gluons accelerated in protons by the LHC

Use coarse information and fast hardware to reduce rate by factor of 400

Collisions, to Physics

LHC Collision Rate: 40 MHz	ATLAS Hardware Trigger: 100 kHz	ATLAS Software Trigger: 1 kHz
Collide quarks and gluons accelerated in protons by the LHC	Use coarse information and fast hardware to reduce rate by factor of 400	Use more fine-grained info and software to reduce rate by factor of 100

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ATLAS
Reconstruction

LHC Collision	ATLAS Hardware Trigger	ATLAS Software Trigger	ATLAS Reconstruction
Collide quarks and gluons accelerated in protons by the LHC	Use coarse information and fast hardware to reduce rate by factor of 400	Use more fine-grained info and software to reduce rate by factor of 100	Reconstruct detector information with highest detail

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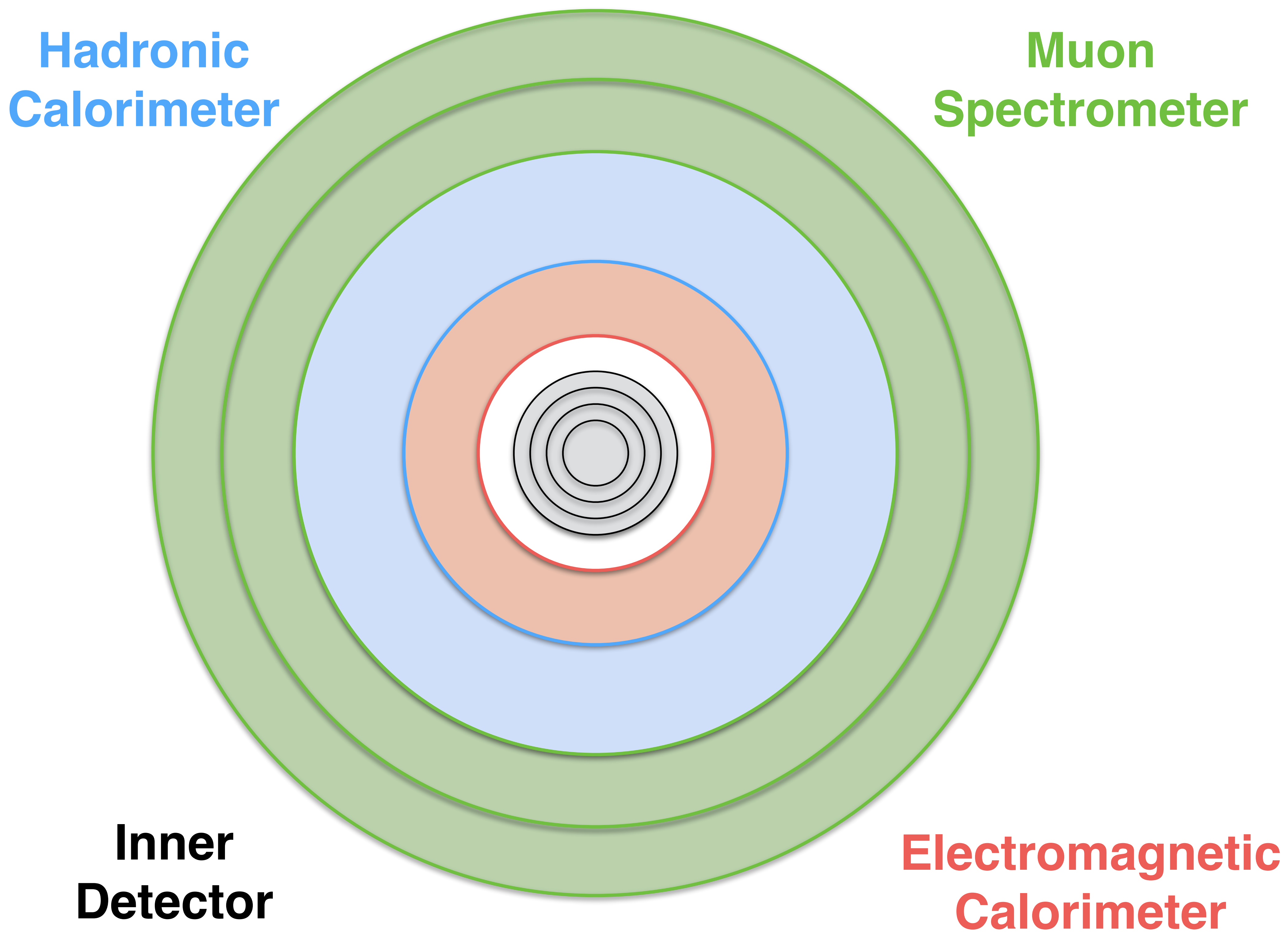
Searching with ATLAS



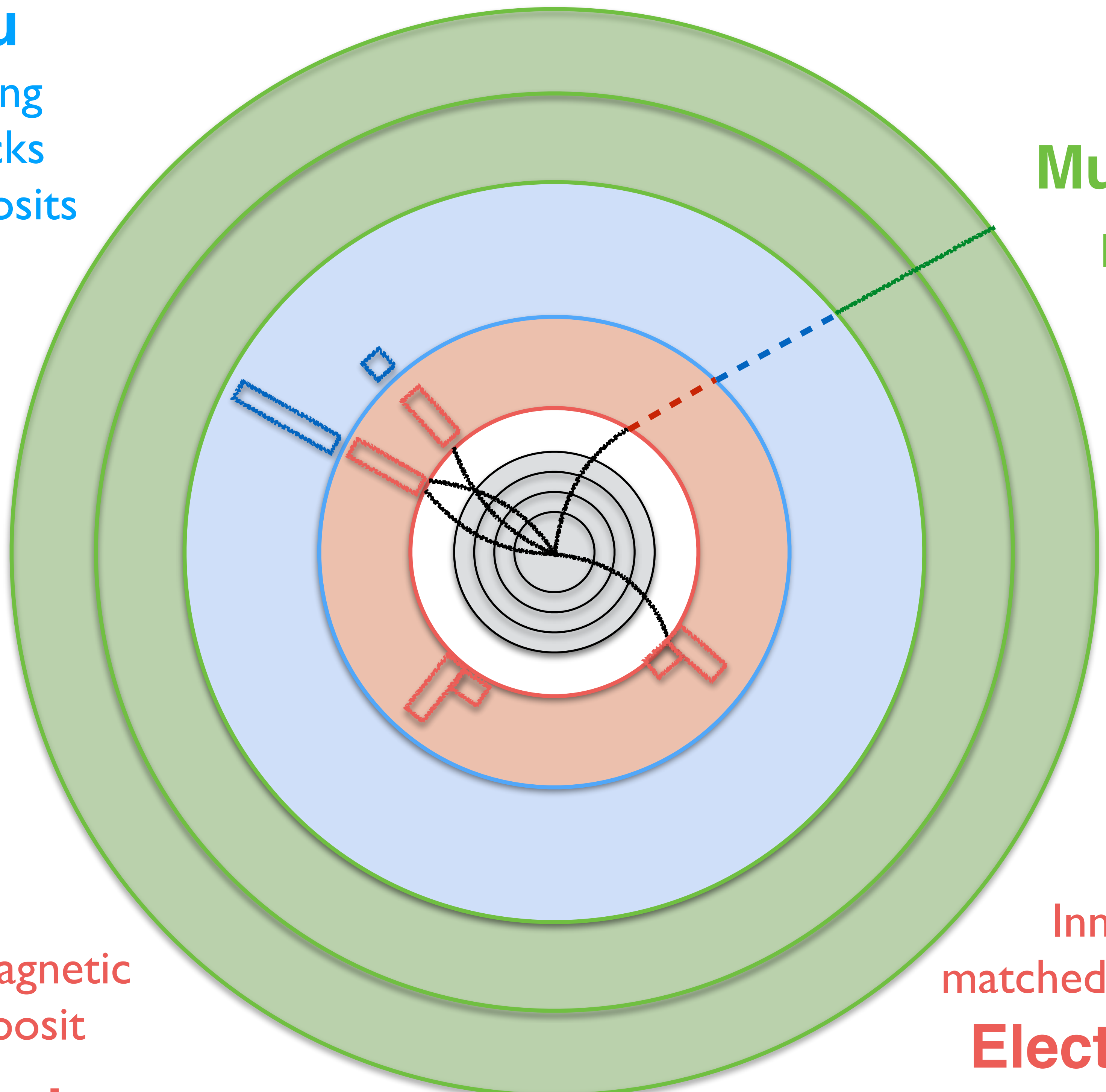
Searching with ATLAS

Tau

Single or triple prong decay to pions: tracks and calorimeter deposits

Muon

Inner detector track matched to muon spectrometer track



Isolated electromagnetic calorimeter deposit

Photon

Inner detector track matched to calorimeter deposit

Electron

An Aside: Jets

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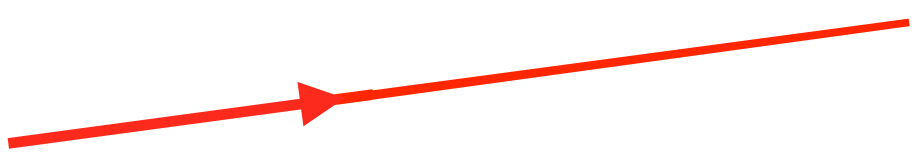
Image credit: B. Nachman

When quarks or gluons are produced during a collision…



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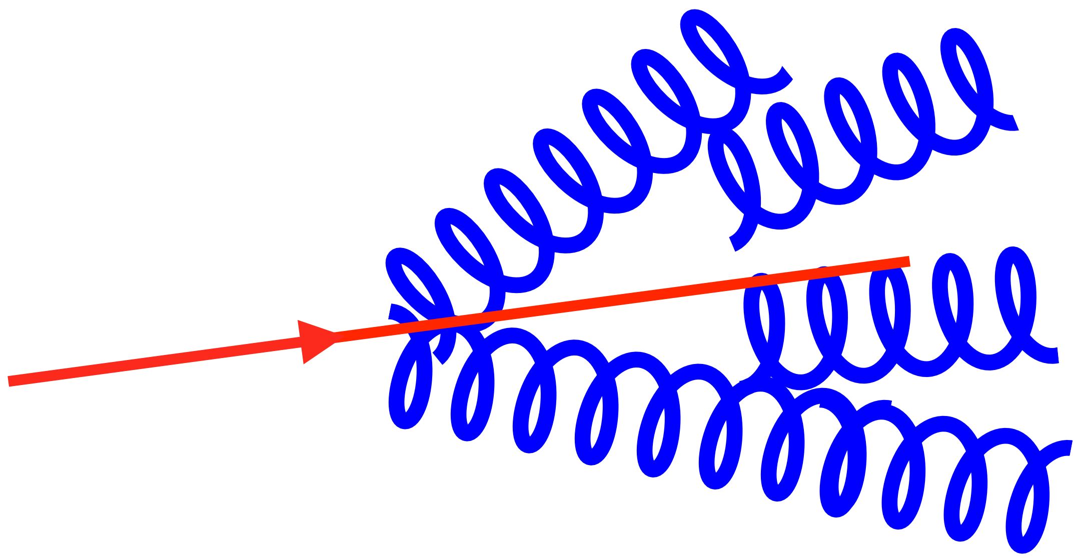

They "shower" into more gluons and quarks…

An Aside: Jets

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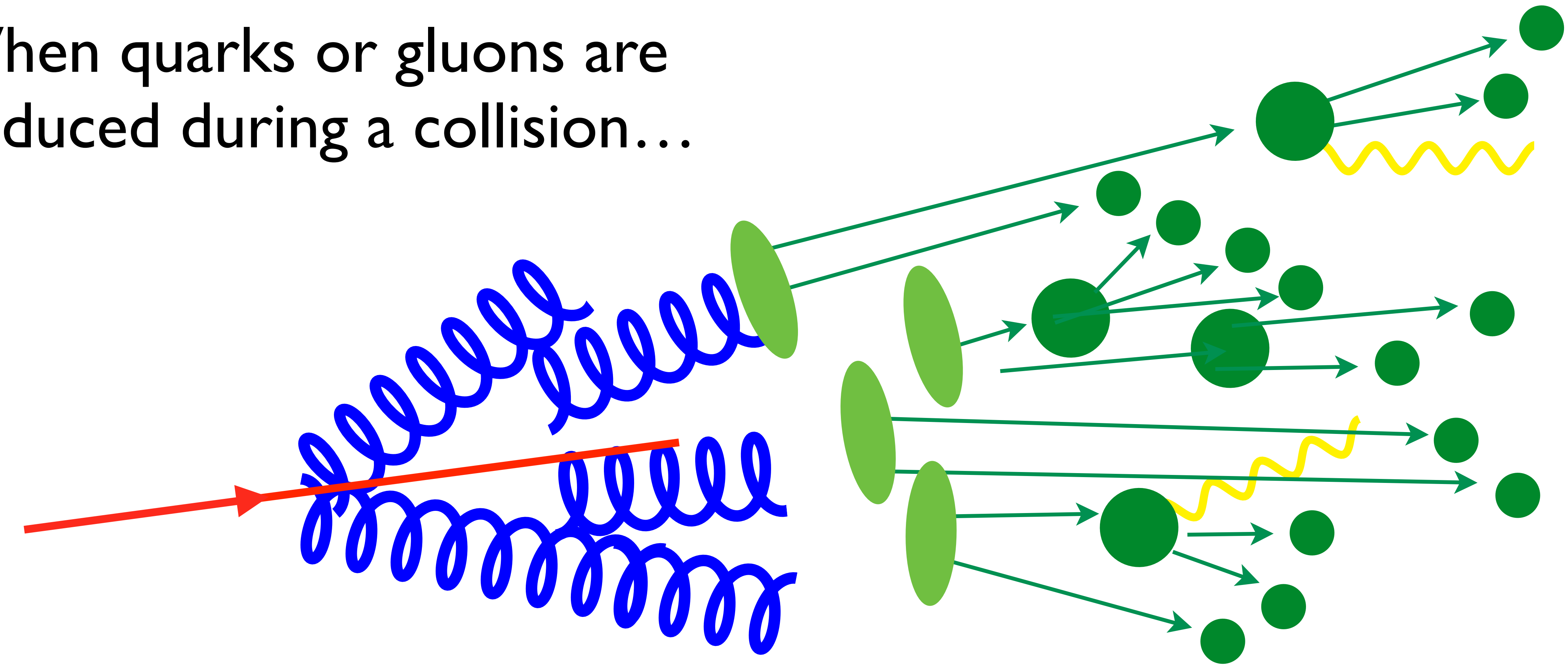

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Which "hadronize" into stable (or unstable particles)

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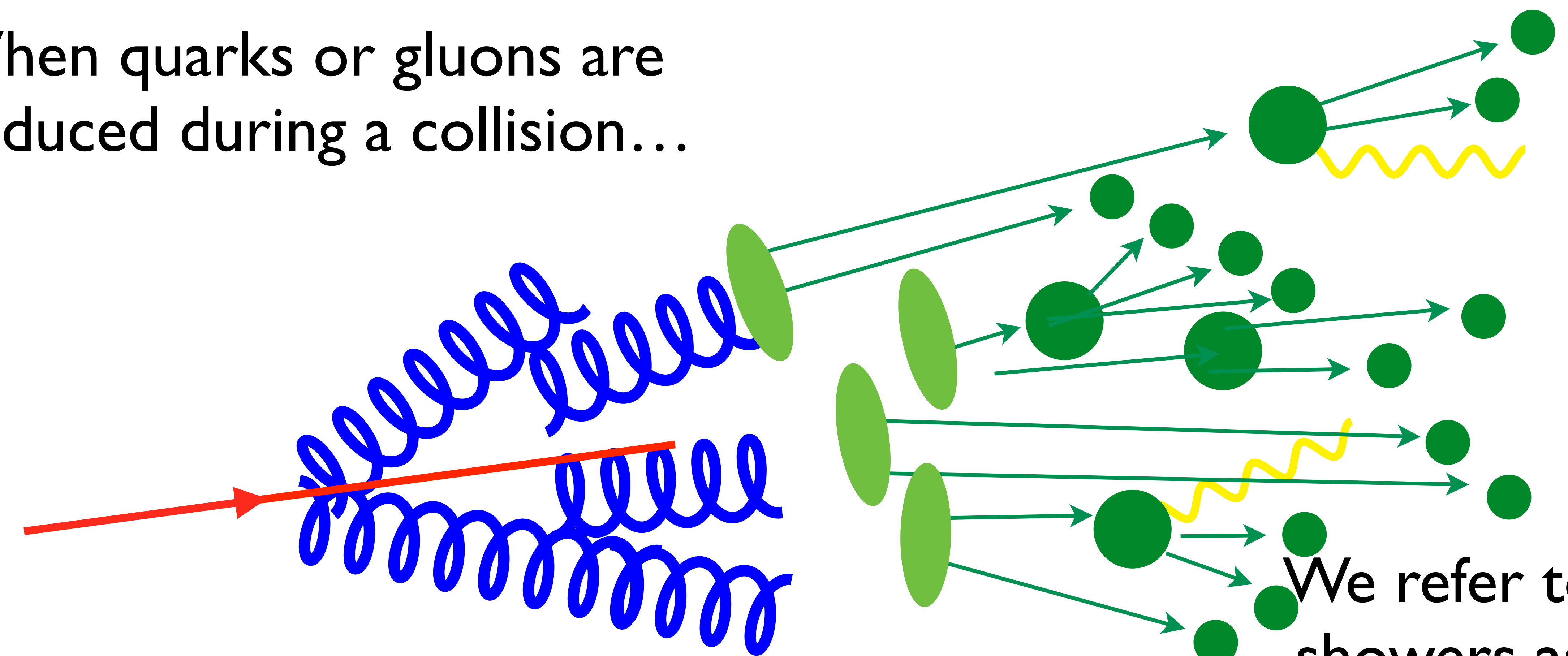


We refer to these showers as “jets”

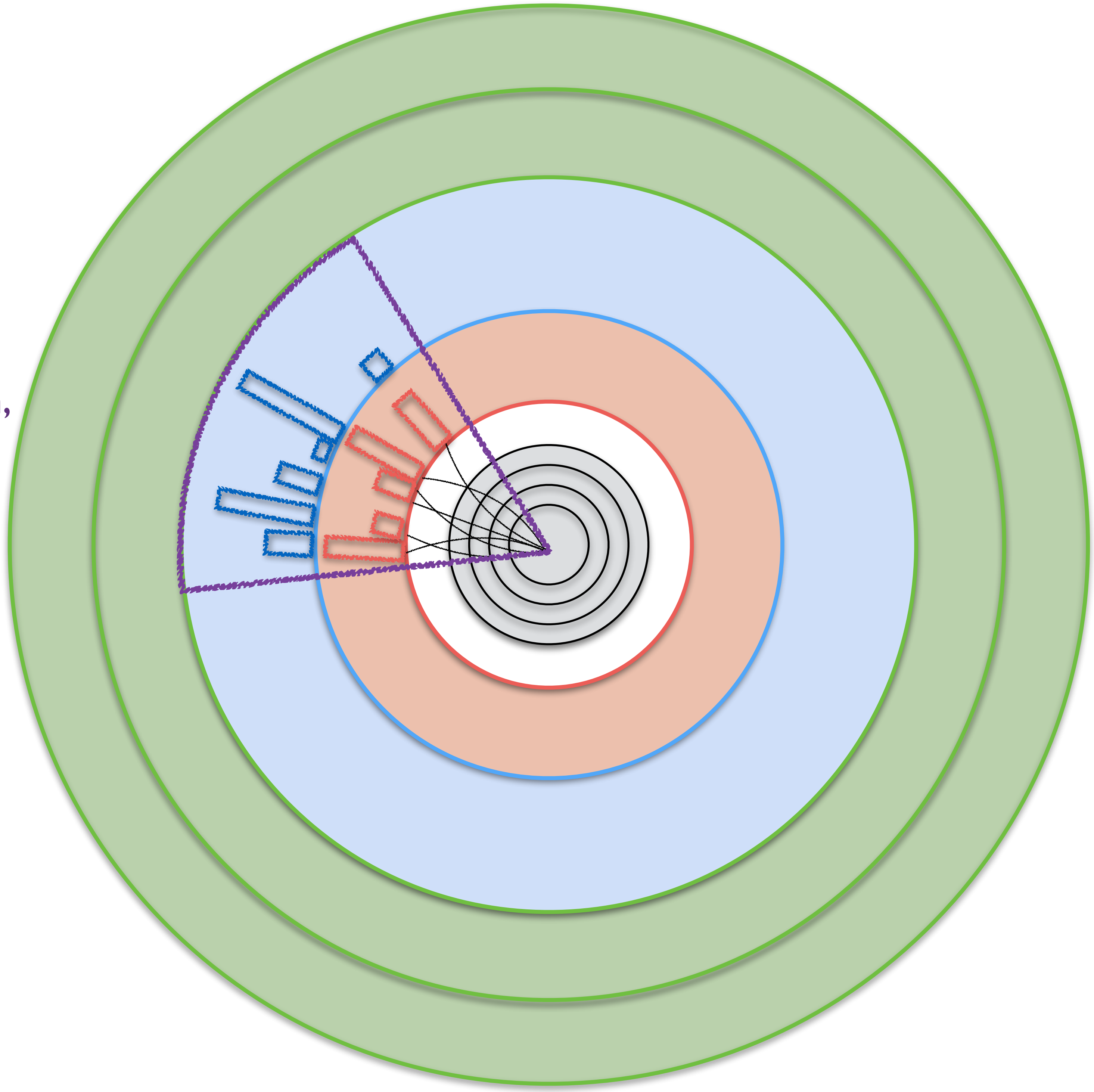
They “shower” into more gluons and quarks…

Which “hadronize” into stable (or unstable particles)

Searching with ATLAS

Jet

Spray of particles
initiated by quark or gluon,
measured in calorimeter



ATLAS Jet Performance

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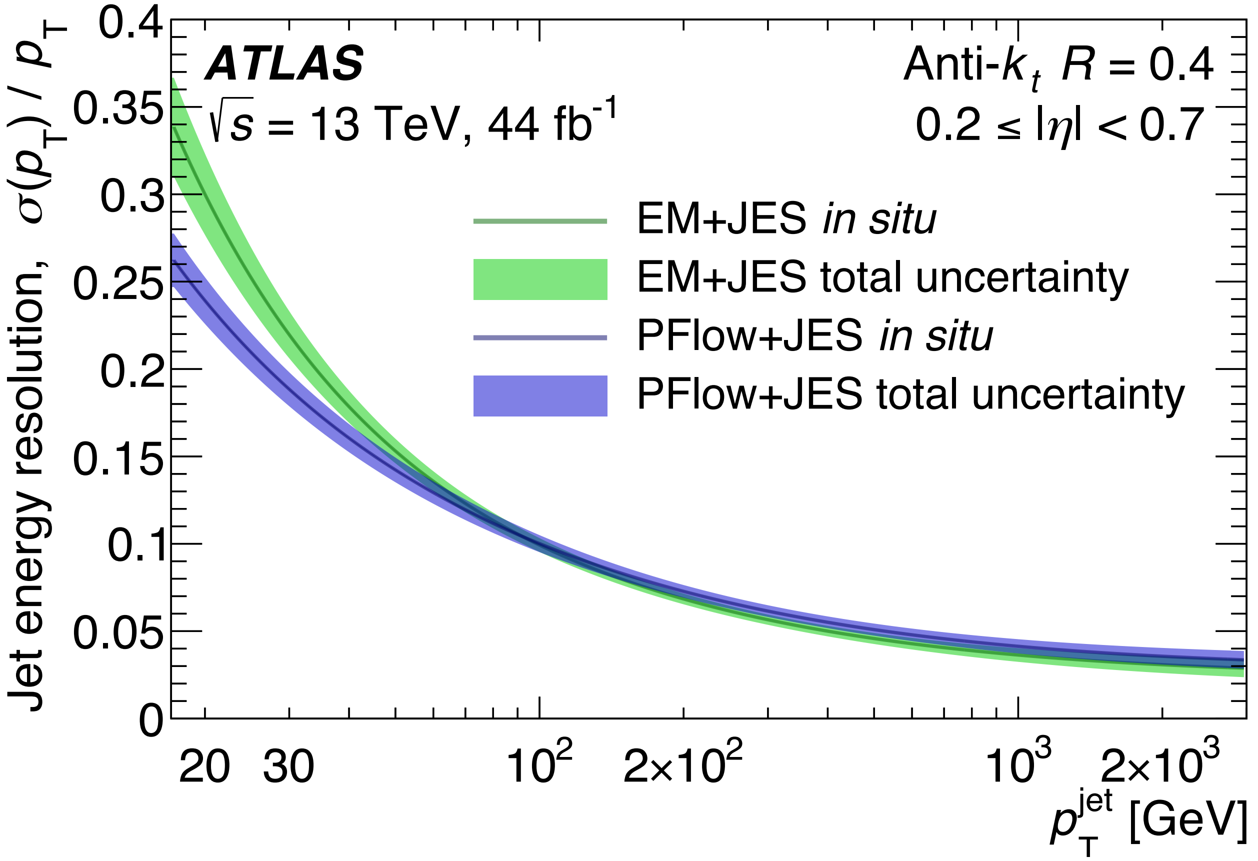
Eur. Phys. J. C 81 (2021) 689



ATLAS now utilizing PFlow reconstruction: significant resolution improvements at low p_T

ATLAS Jet Performance

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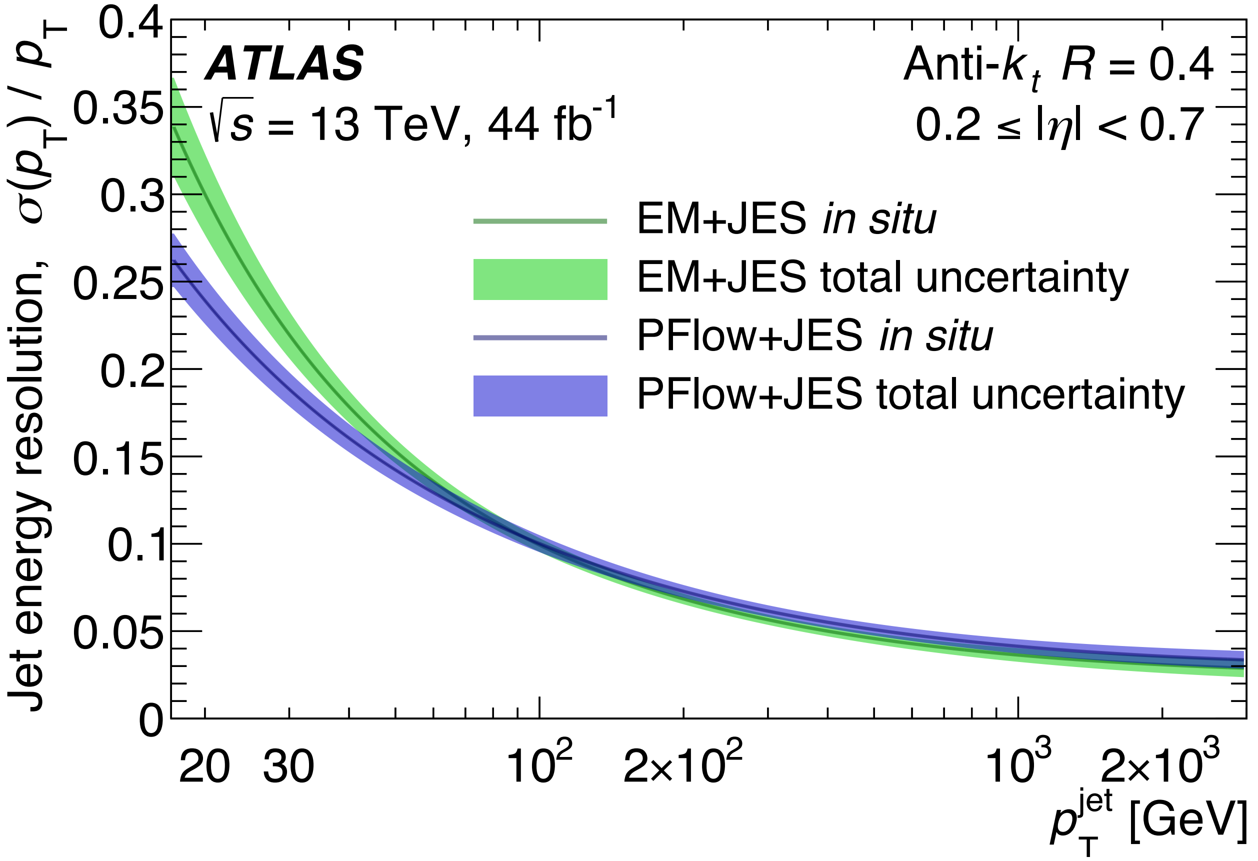

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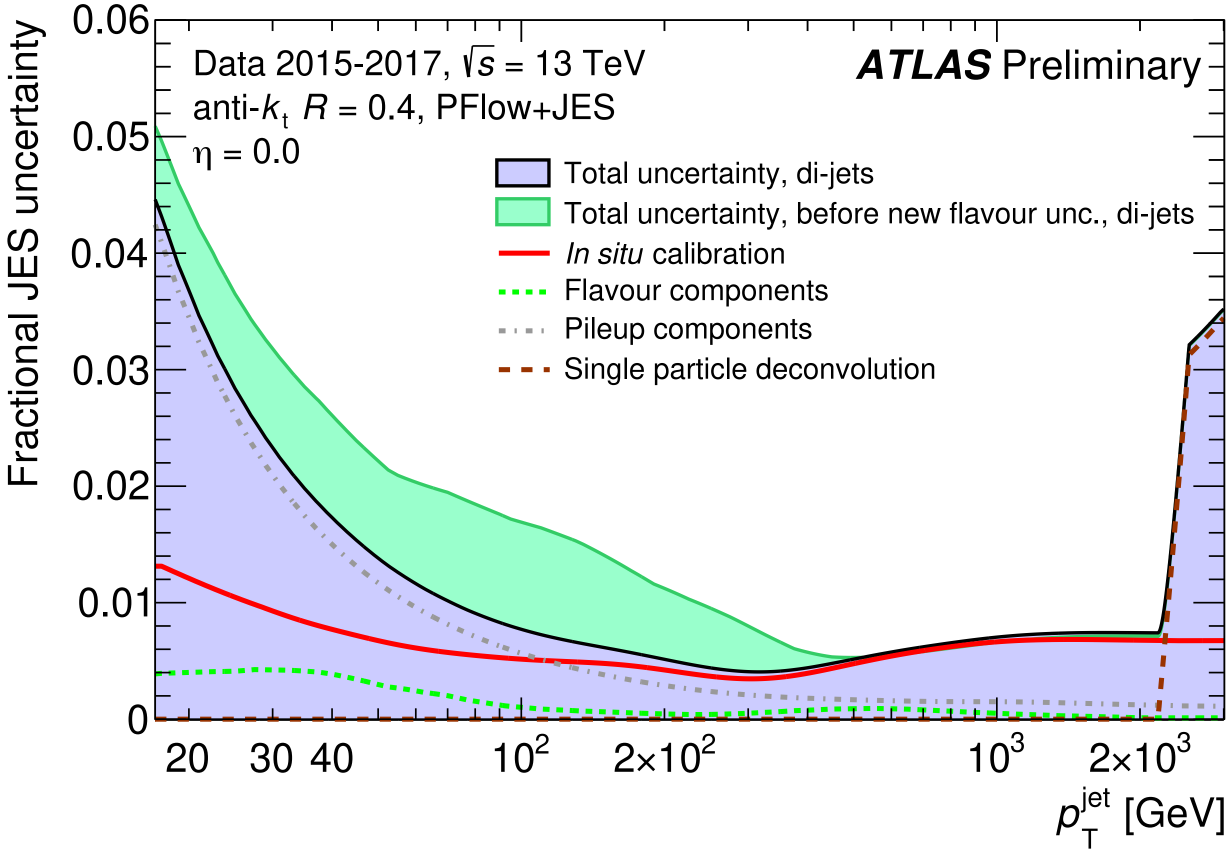
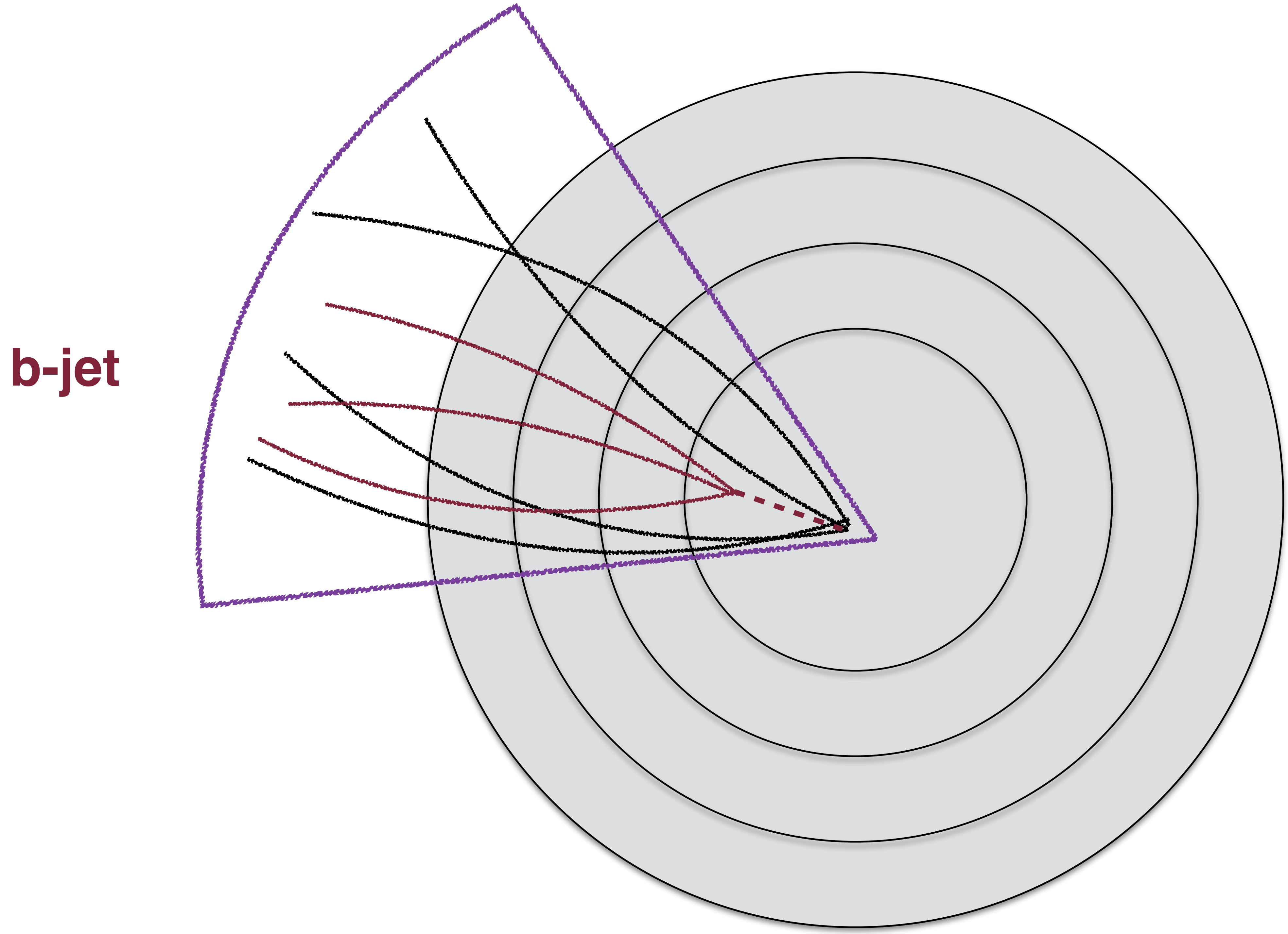
JETM-2022-005



New flavour uncertainty treatment and MC/MC calibrations lead to sub-% uncertainties above 80 GeV

Searching with ATLAS



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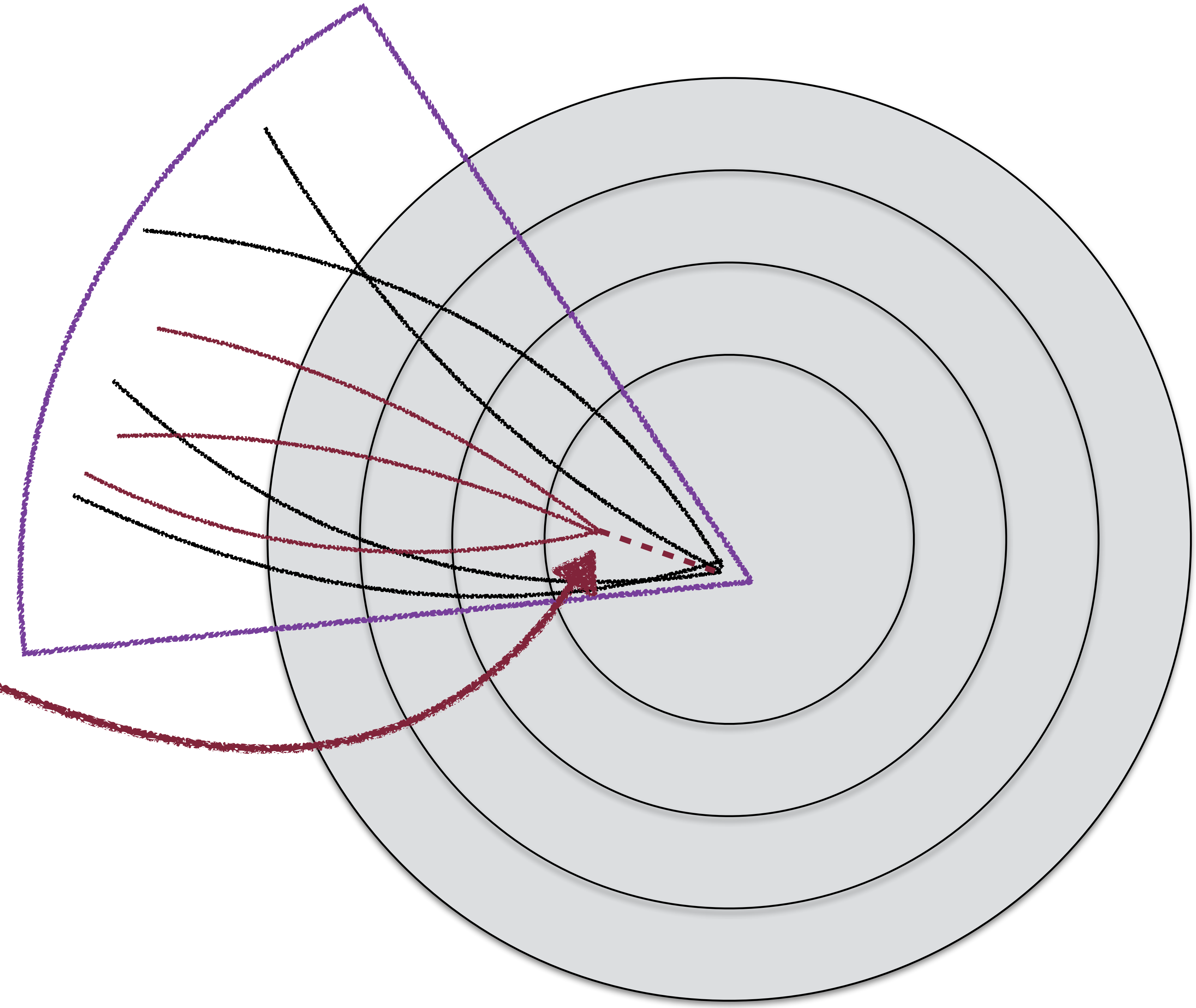
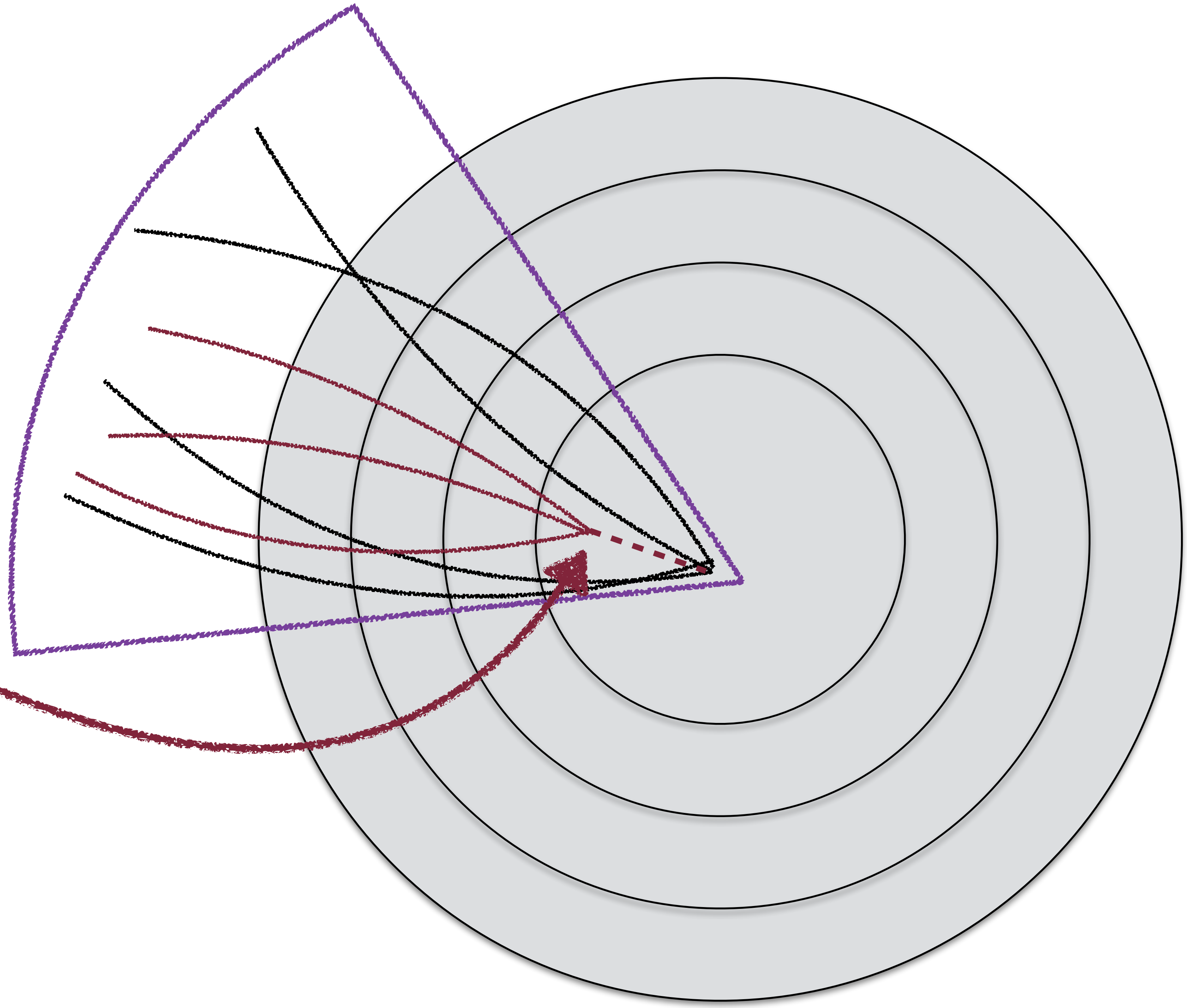


Jet initiated by a b-quark, which form B-hadrons with long lifetimes and displaced vertices

Searching with ATLAS

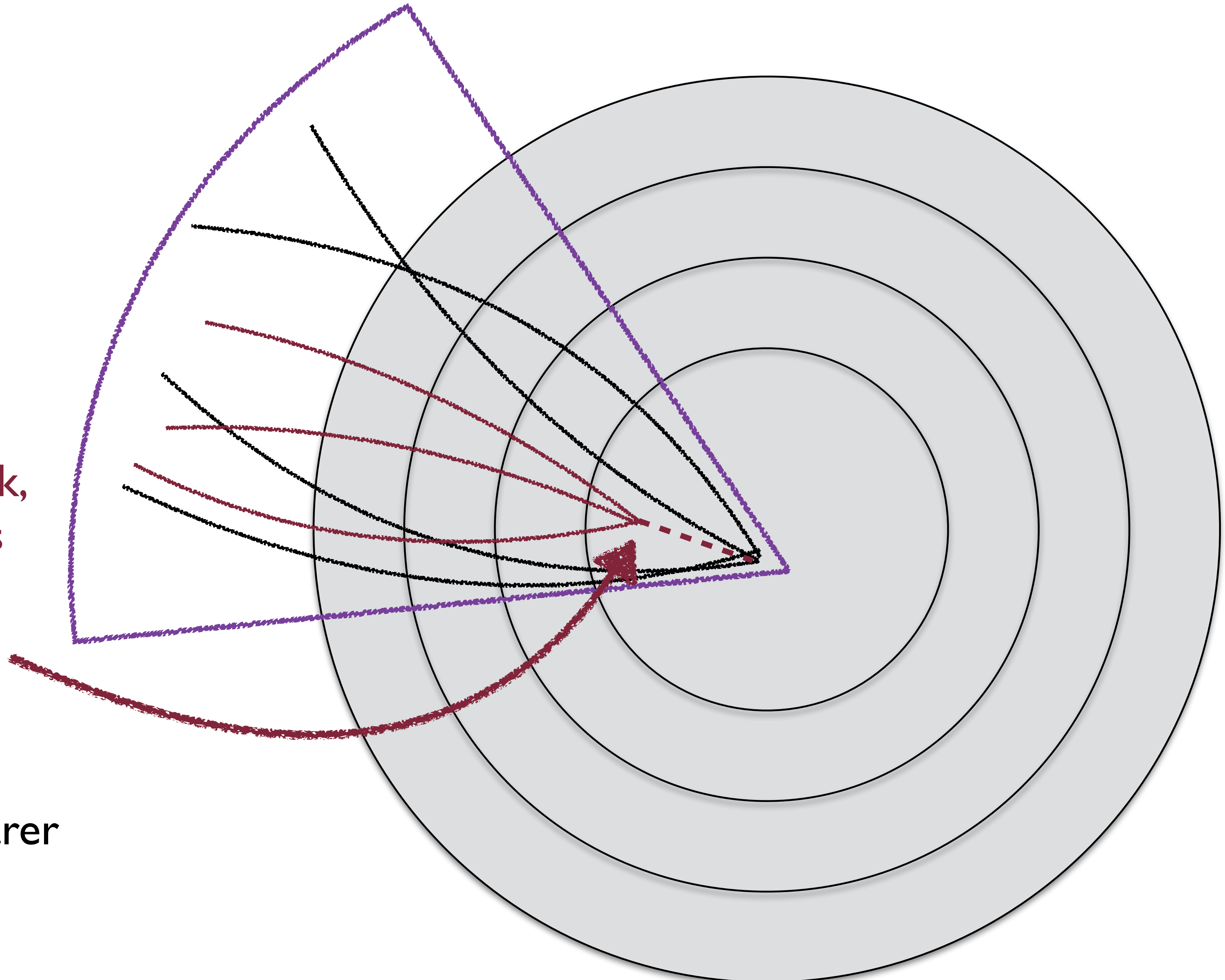


b-jet

Jet initiated by a b-quark,
which form B-hadrons
with long lifetimes
and displaced vertices

Jets are common,
but b-jets are much rarer

Searching with ATLAS



b-jet

Jet initiated by a b-quark,
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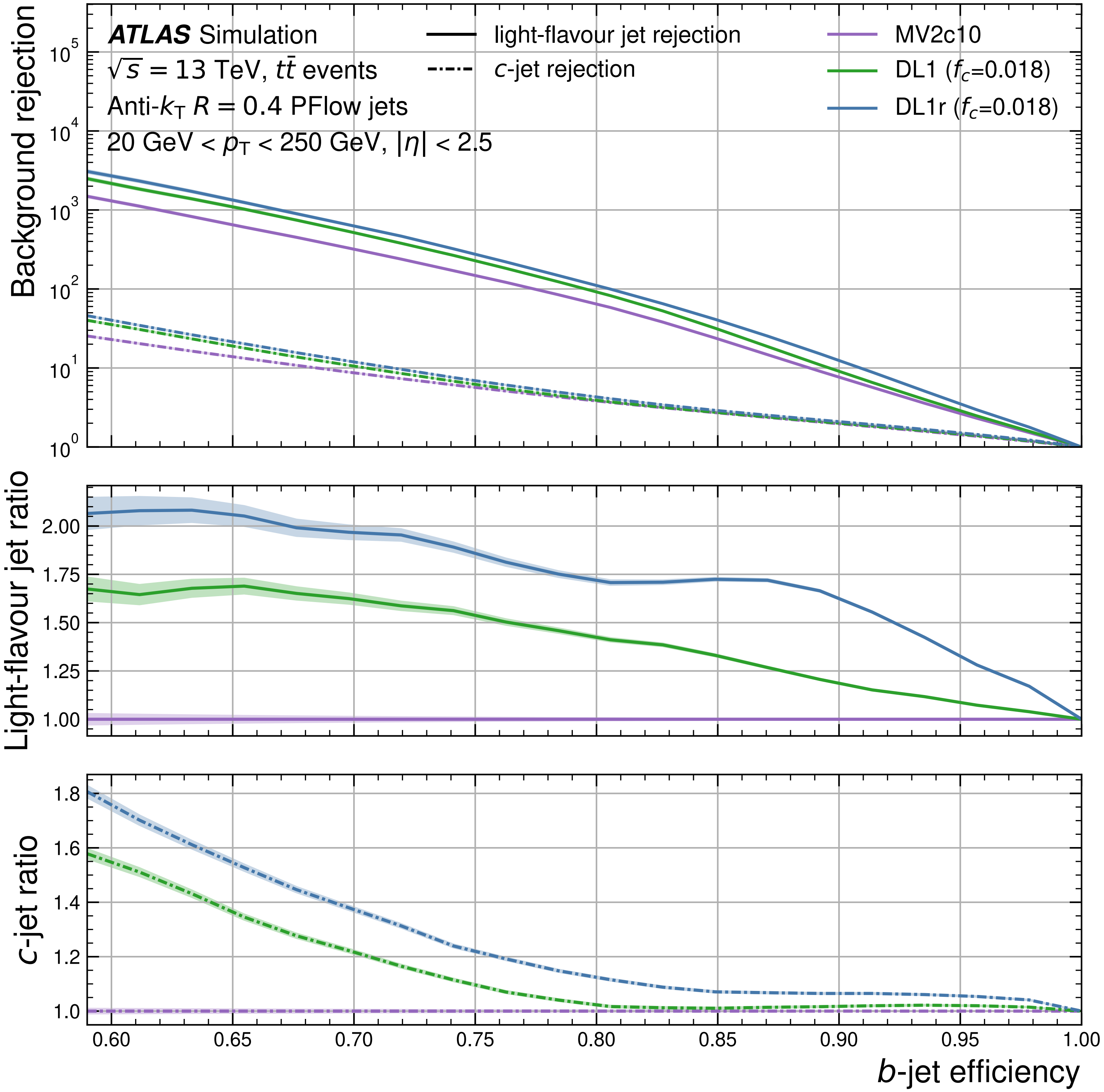
The most common
Higgs decay is to b-jets:
Can use this to find our signal!

b-Tagging Performance

b-Tagging Performance

arXiv:2211.16345



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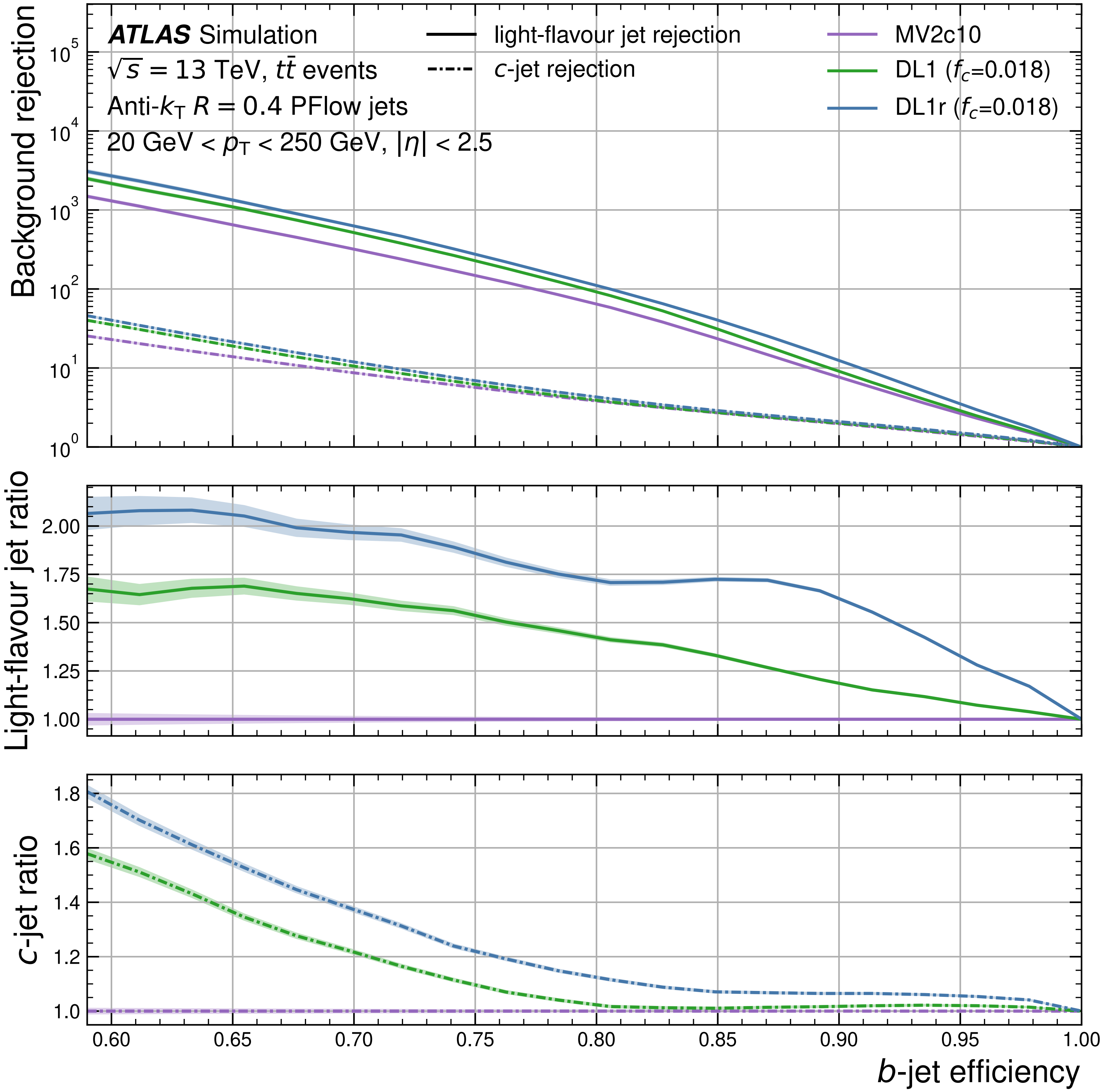
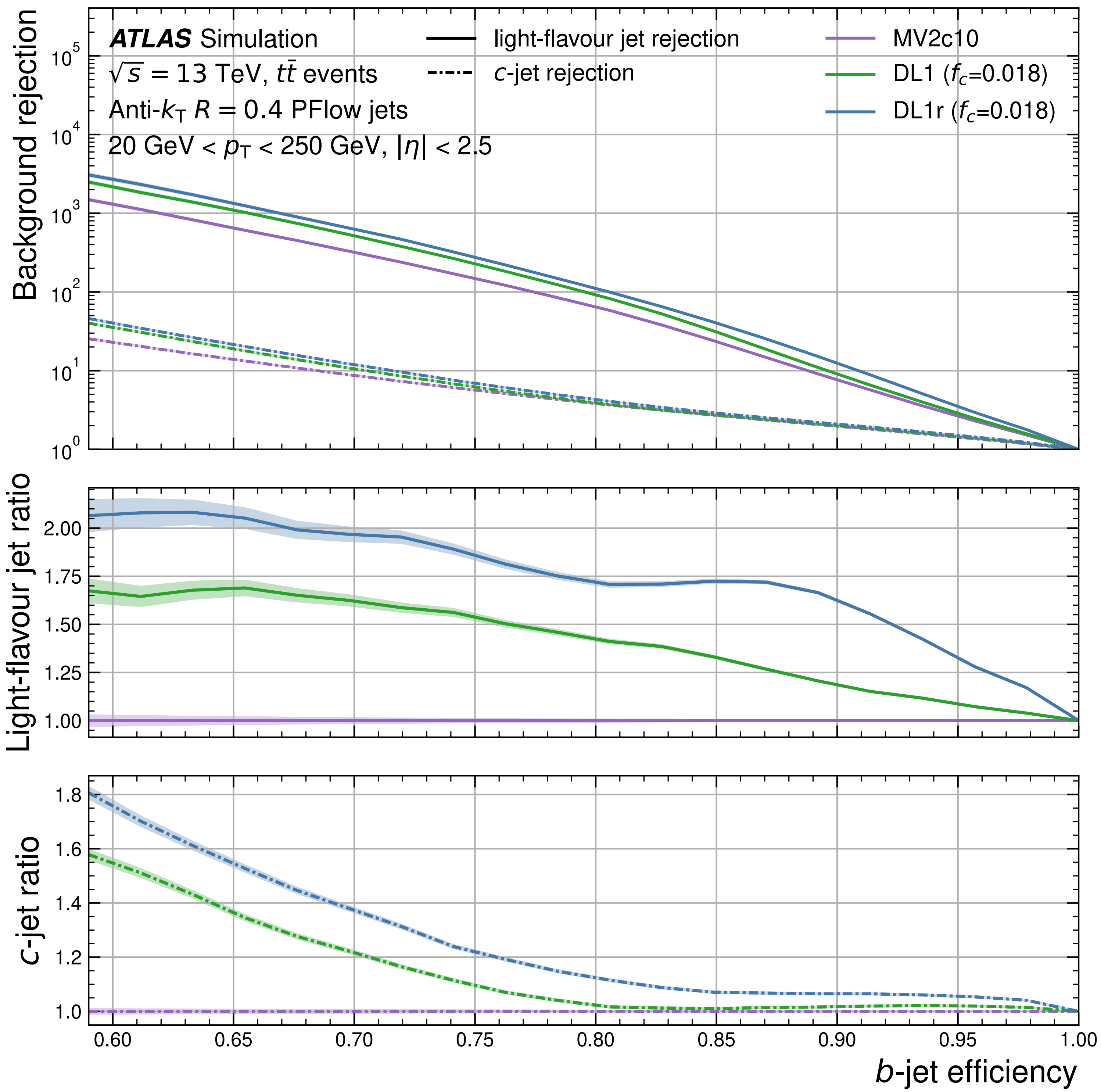


To quantify performance, show *background rejection* as a function of *b-jet efficiency*

b-Tagging Performance

arXiv:2211.16345



To quantify performance, show *background rejection* as a function of *b-jet efficiency*

DL1r is the Run2 ATLAS b-tagging algorithm: Combines several low-level vertexing inputs

b-Tagging Performance

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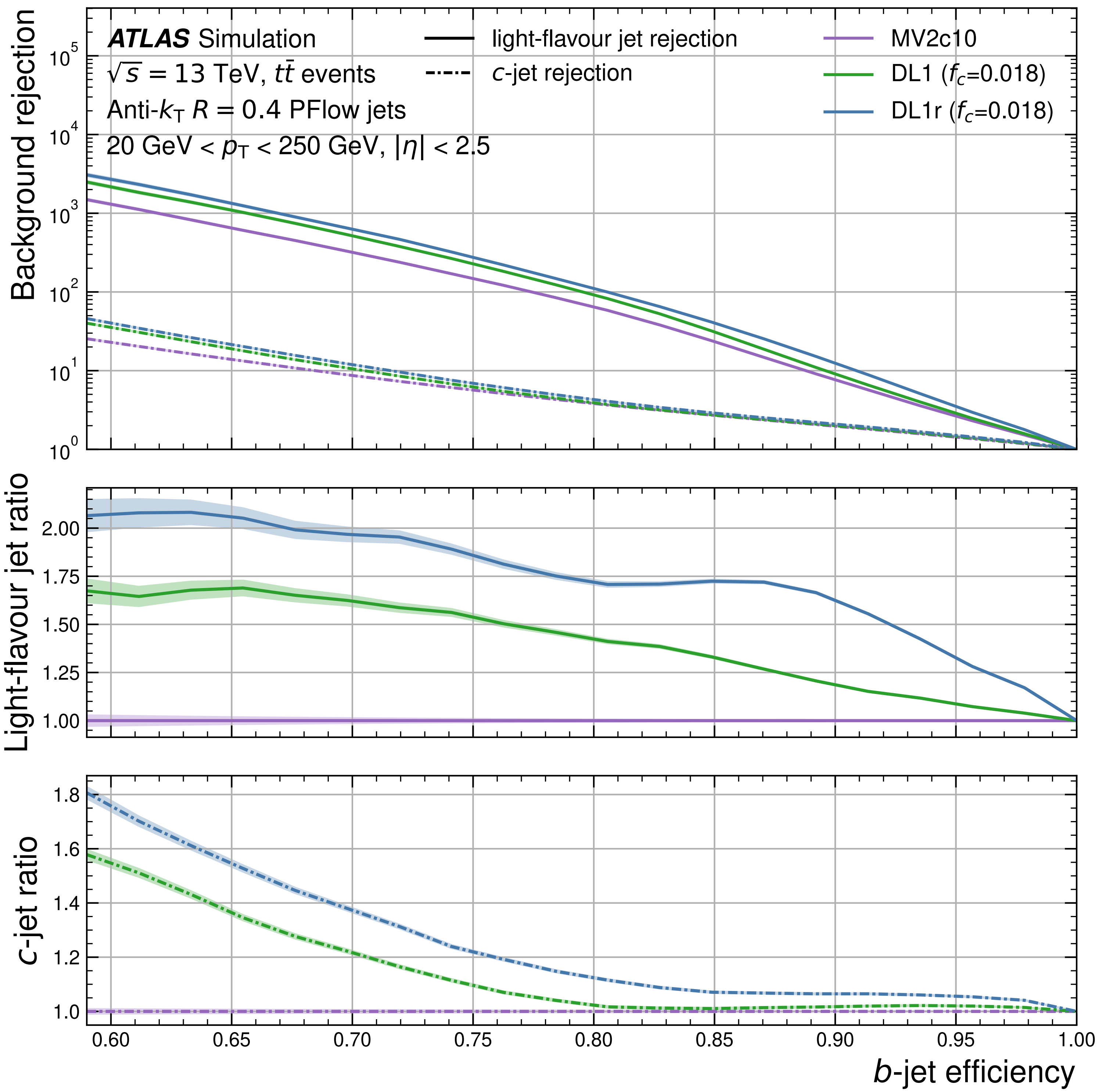

To quantify performance, show *background rejection* as a function of *b-jet efficiency*

DL1r is the Run2 ATLAS b-tagging algorithm: Combines several low-level vertexing inputs

Outperforms older BDT MV2 by nearly a factor of 2!

Searching for Higgs Pairs

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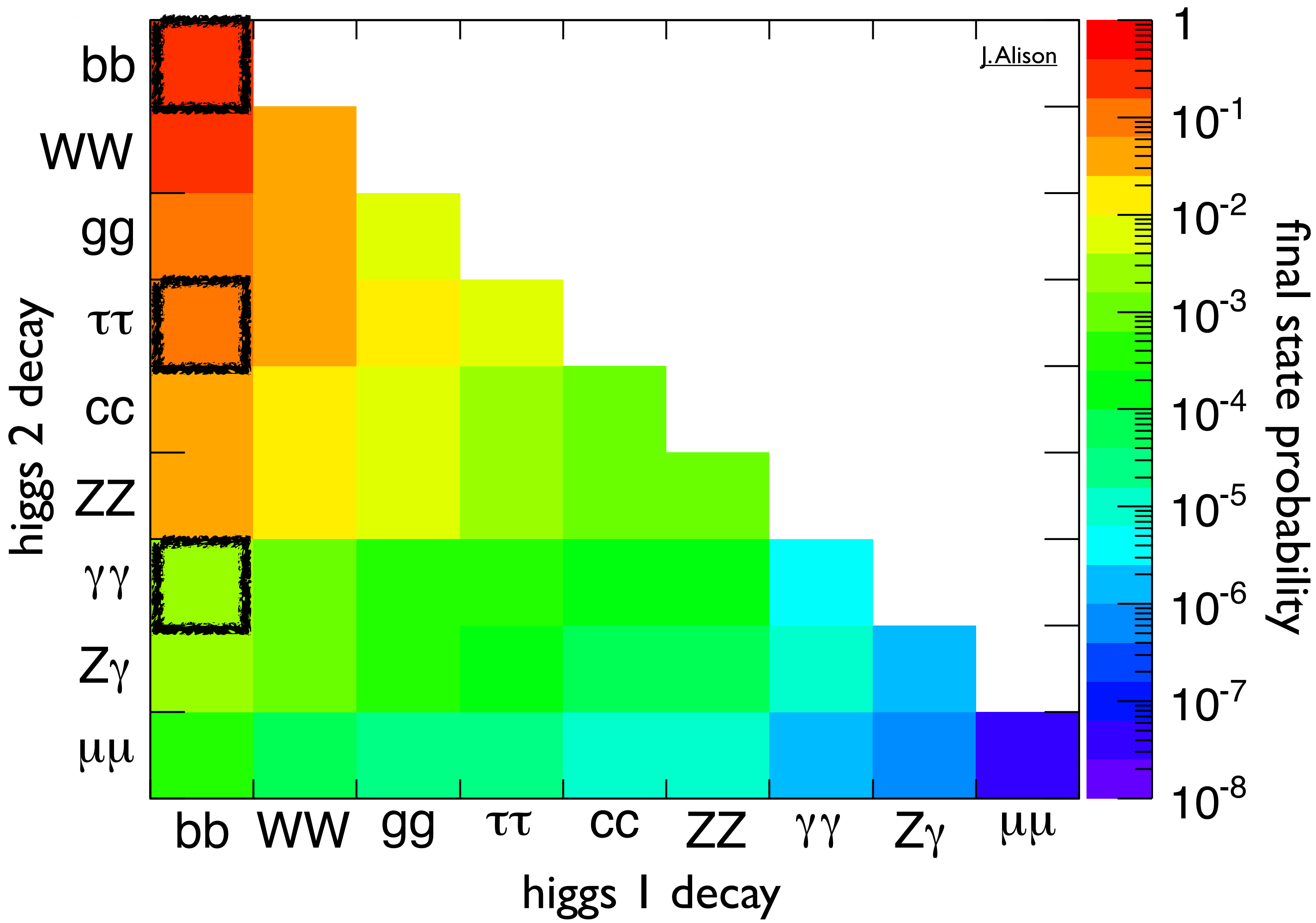

Many channels are competitive in measuring di-Higgs production:

No golden channel

Today, showing results from several recent analyses:

$HH \to b\bar{b}\gamma\gamma$

$HH \to b\bar{b}\tau\bar{\tau}$

$HH \to b\bar{b}b\bar{b}$

And their combination!

What Does κ_λ Look Like?

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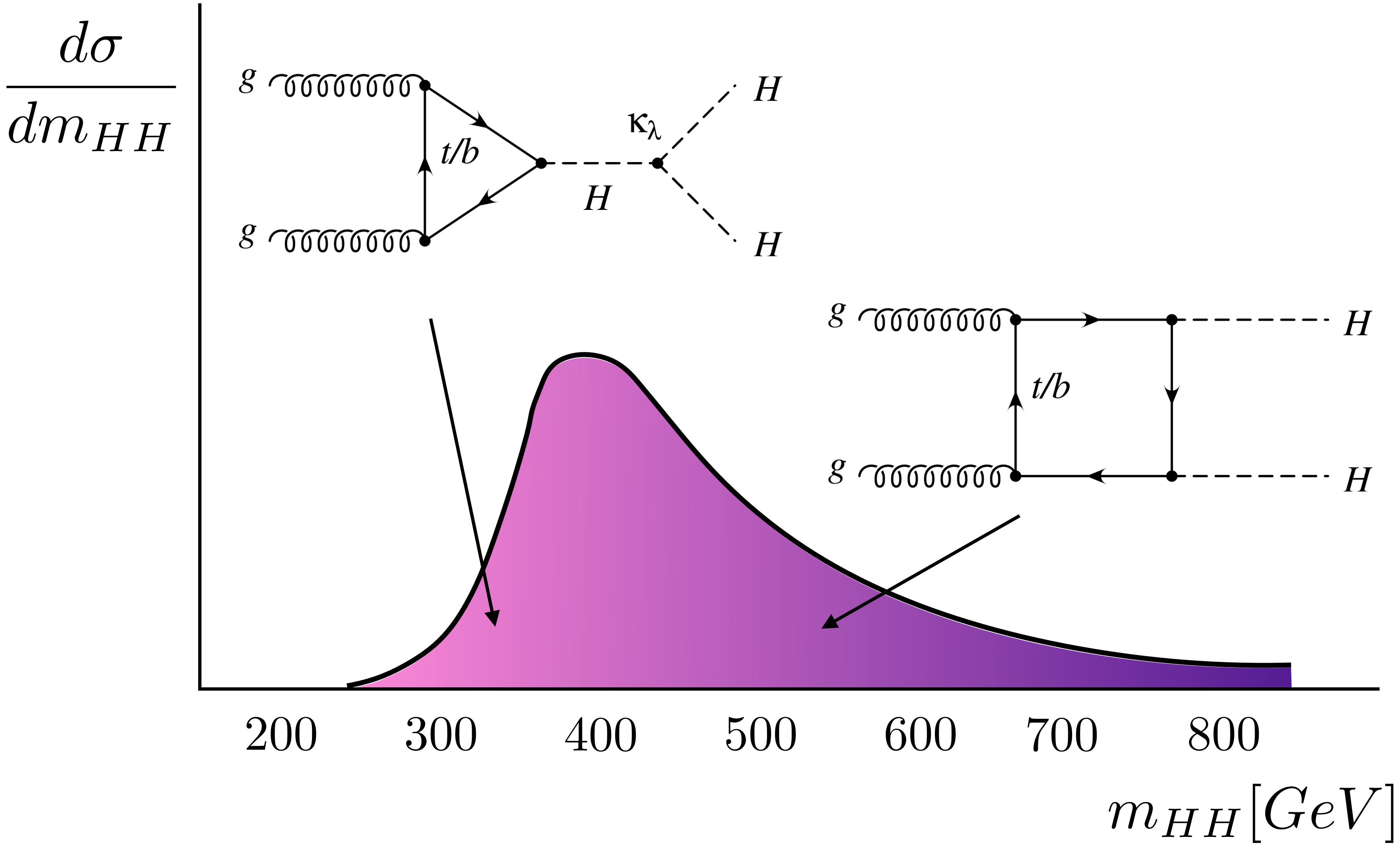

Signal distribution strongly depends on κ_λ

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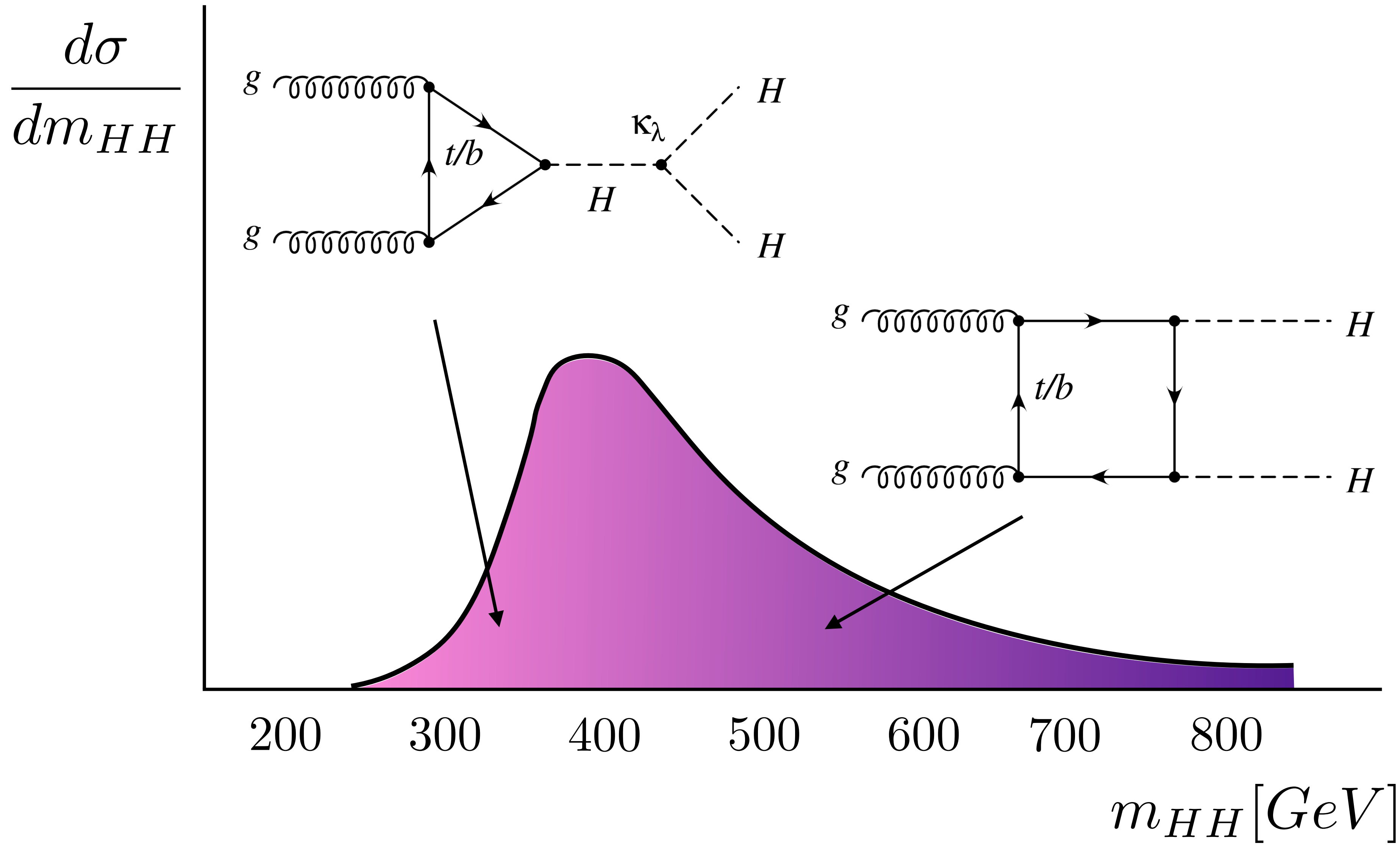

Signal distribution strongly depends on κ_λ

Increasing κ_λ leads the 'triangle diagram' to dominate:
signal peak shifts to lower m_{HH}

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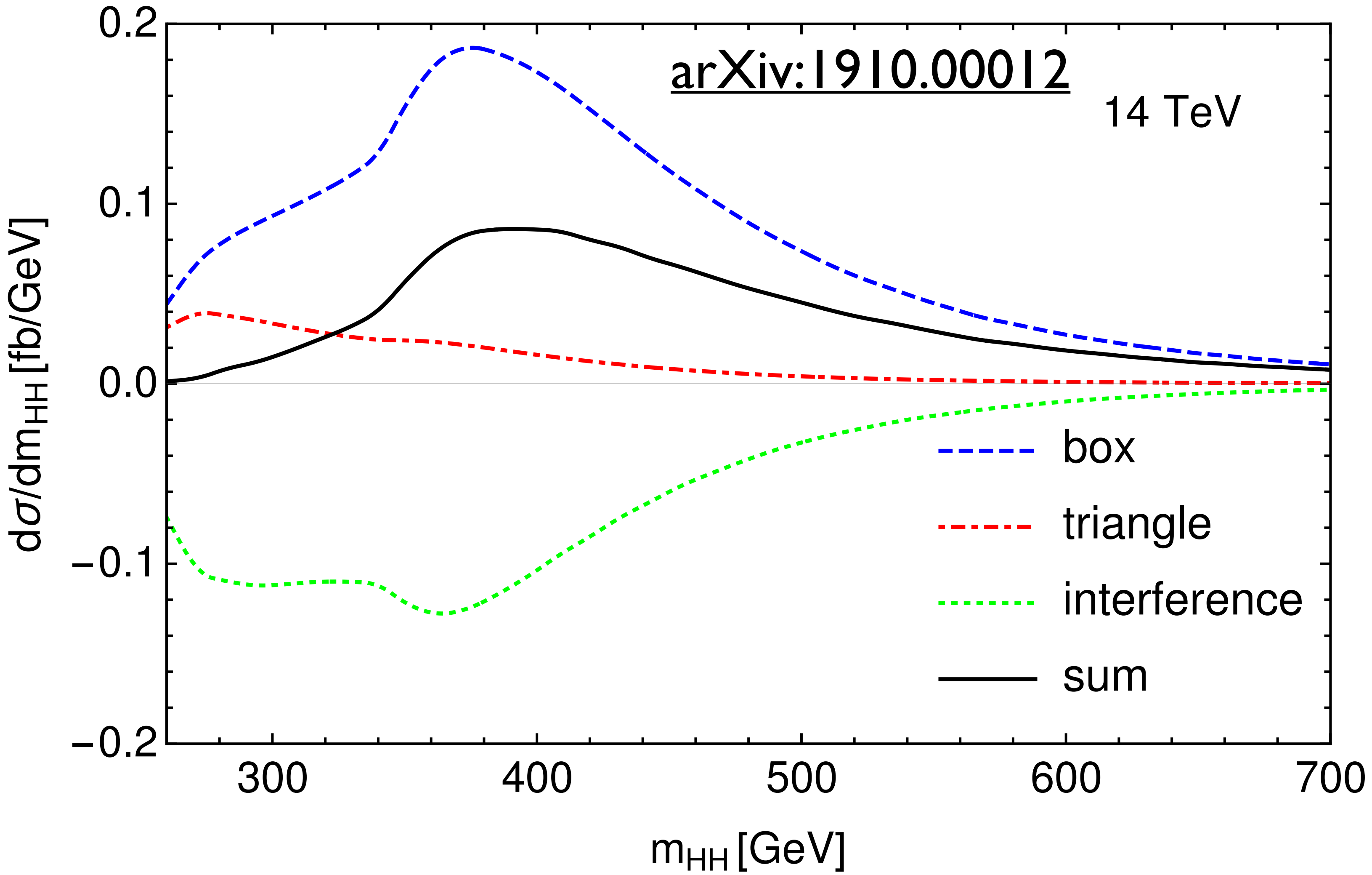

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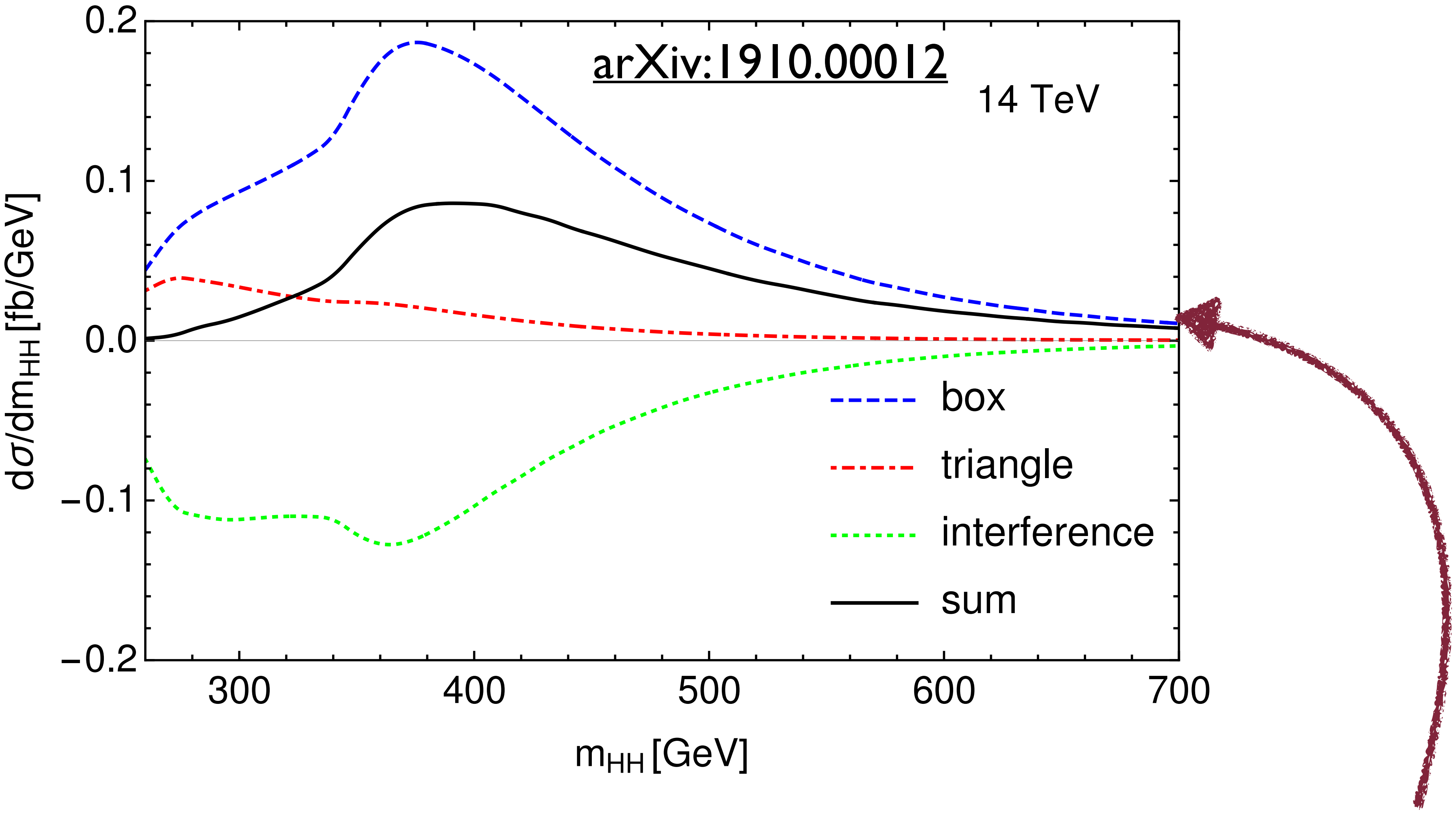

Measuring at high m_{hh} gives you sensitivity only to the box

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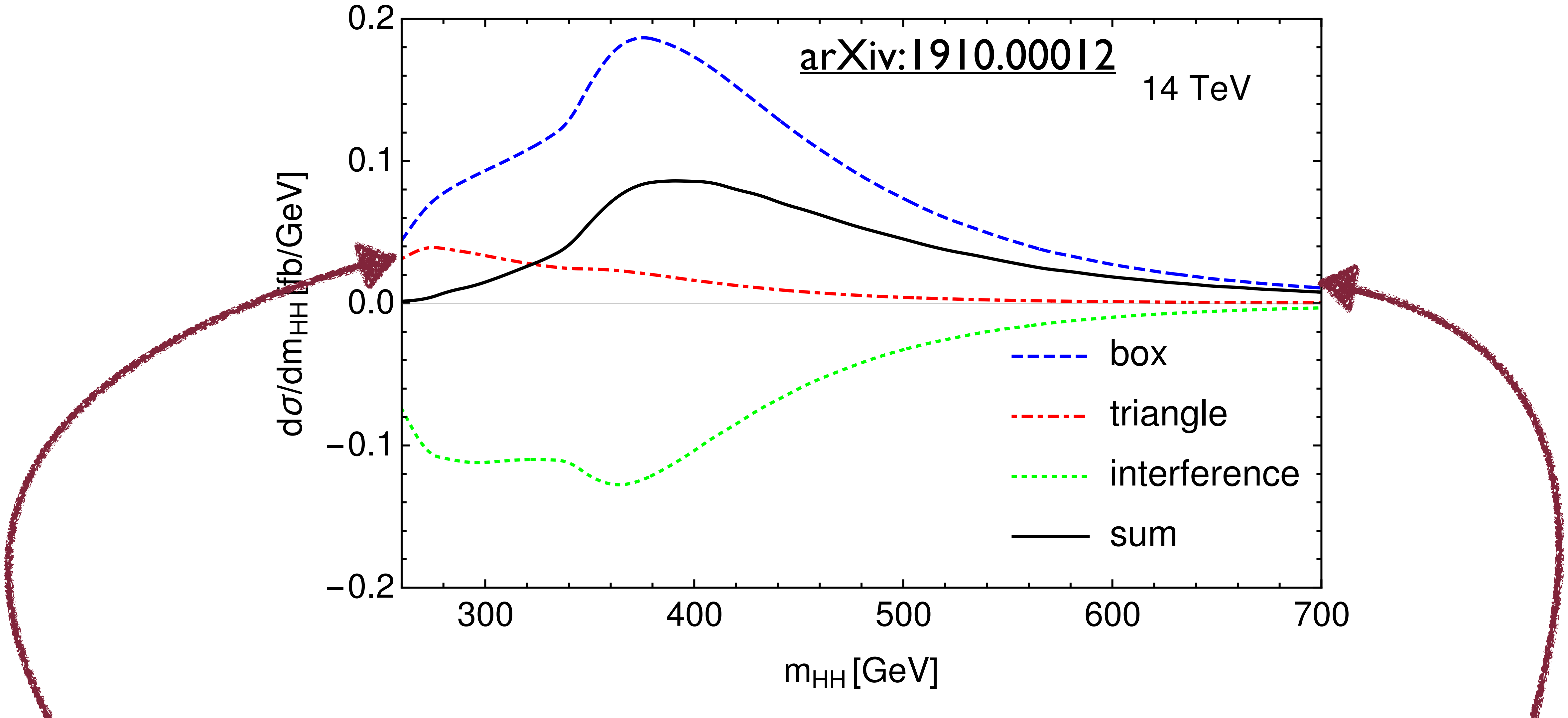

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Measuring at low m_{hh} gives access to the triangle, and κ_λ

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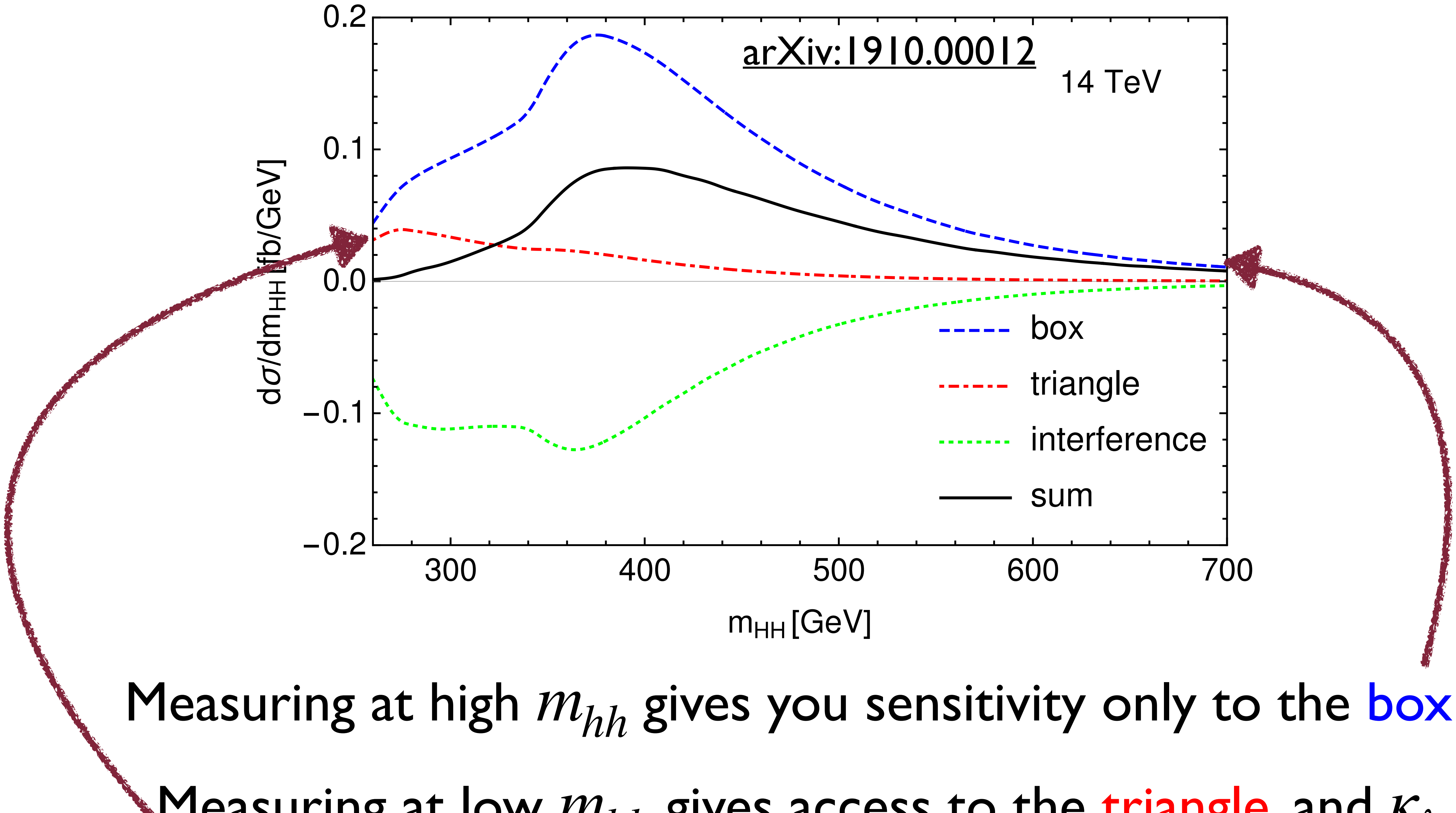
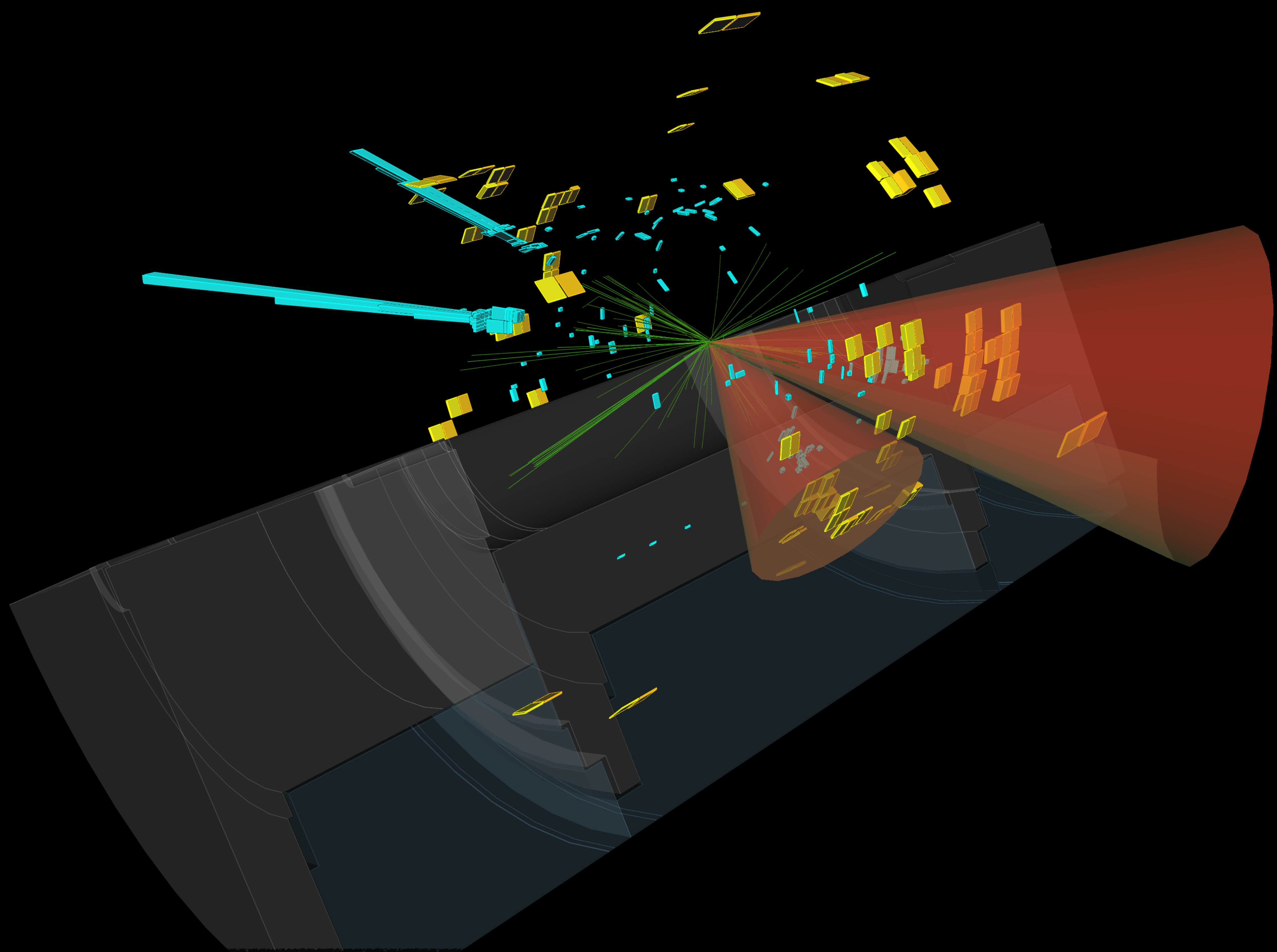


Measuring at high m_{hh} gives you sensitivity only to the box

Measuring at low m_{hh} gives access to the triangle, and κ_λ

Shapes your analysis strategy:
need low p_T triggers and shape information

$HH \rightarrow b\bar{b}\gamma\gamma$

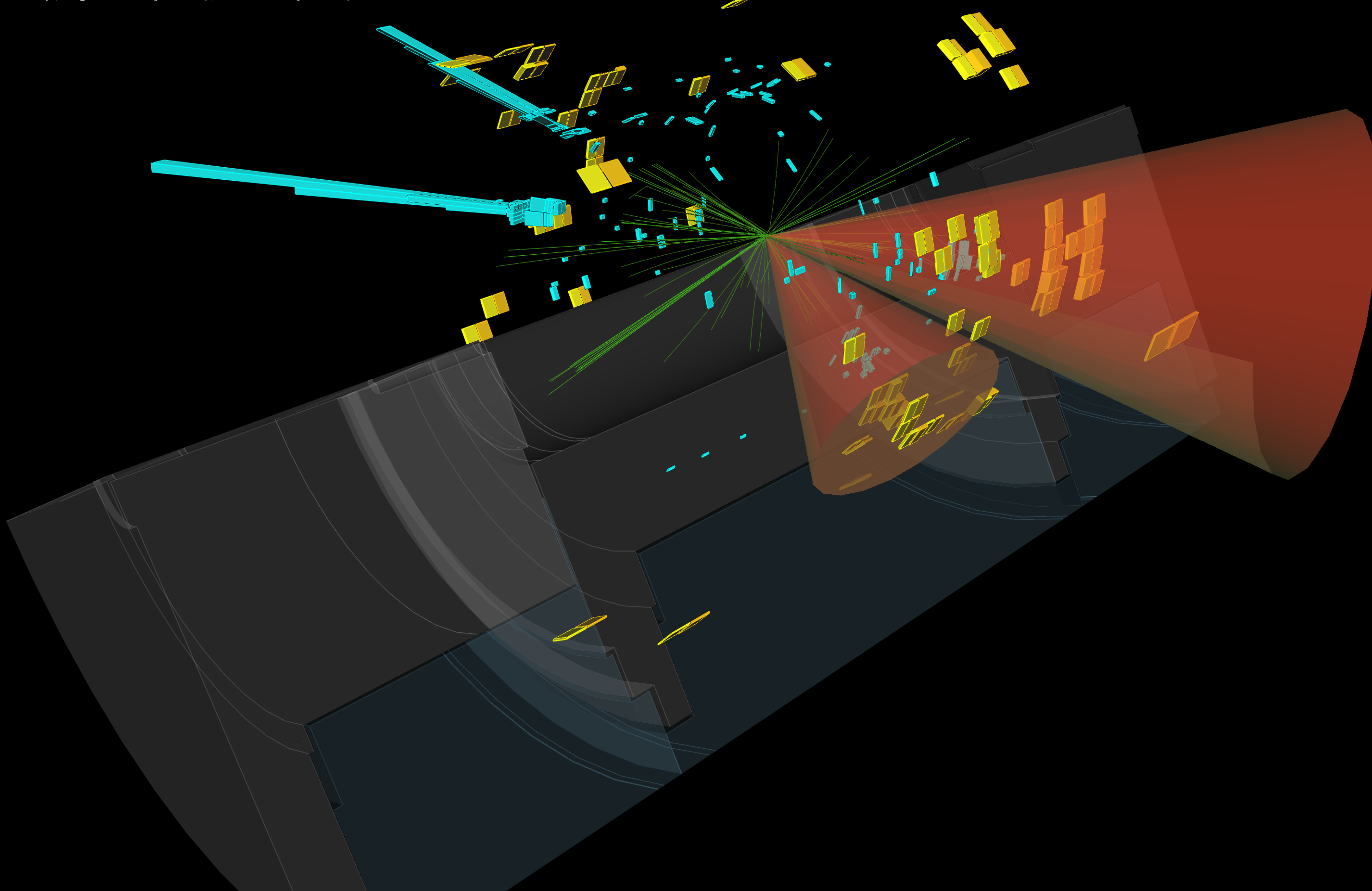


Phys. Rev. D 106 (2022) 052001

$HH \to b\bar{b}\gamma\gamma$

Trigger on diphotons

($E_T > 35{,}25$ GeV)



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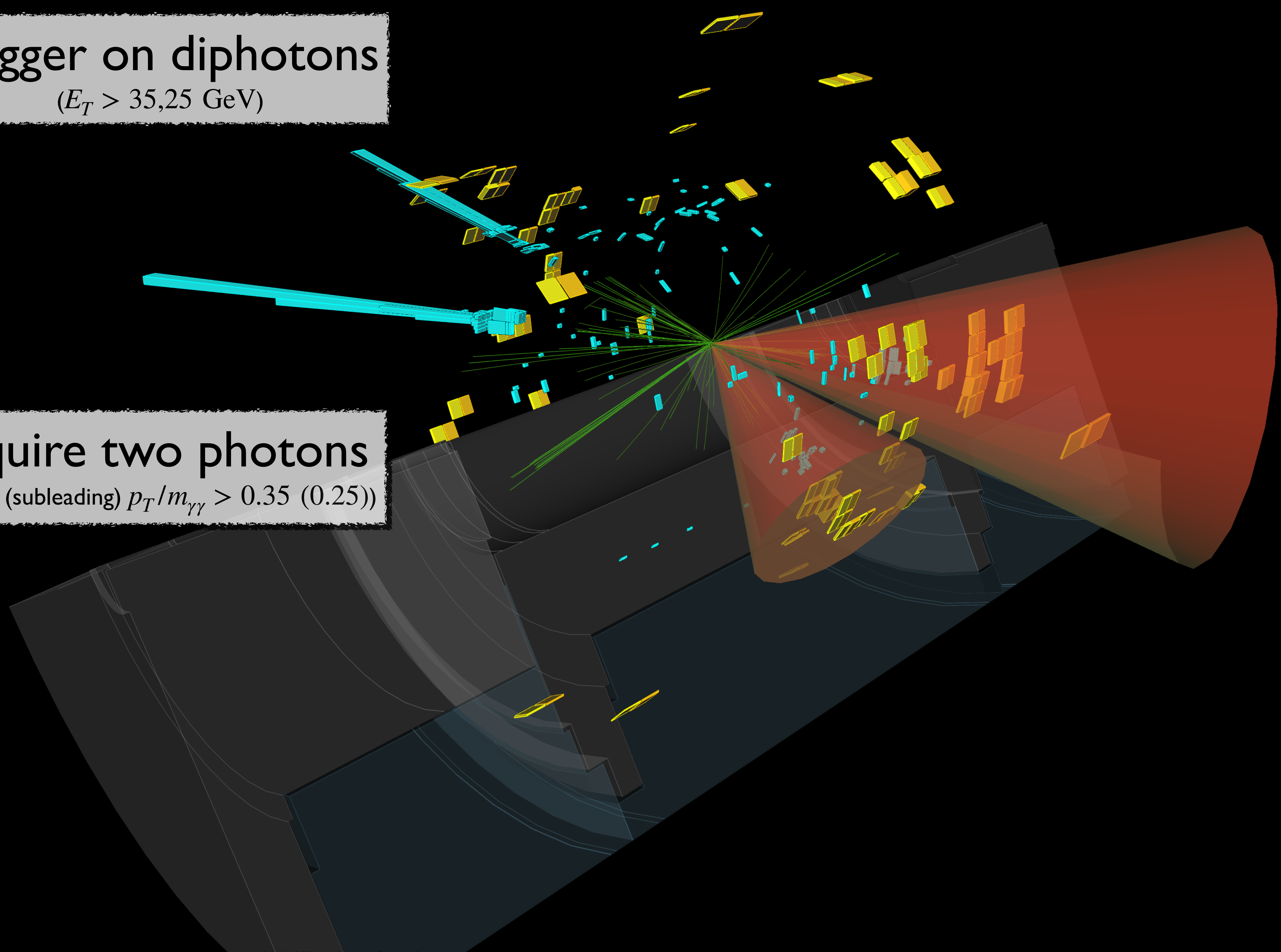

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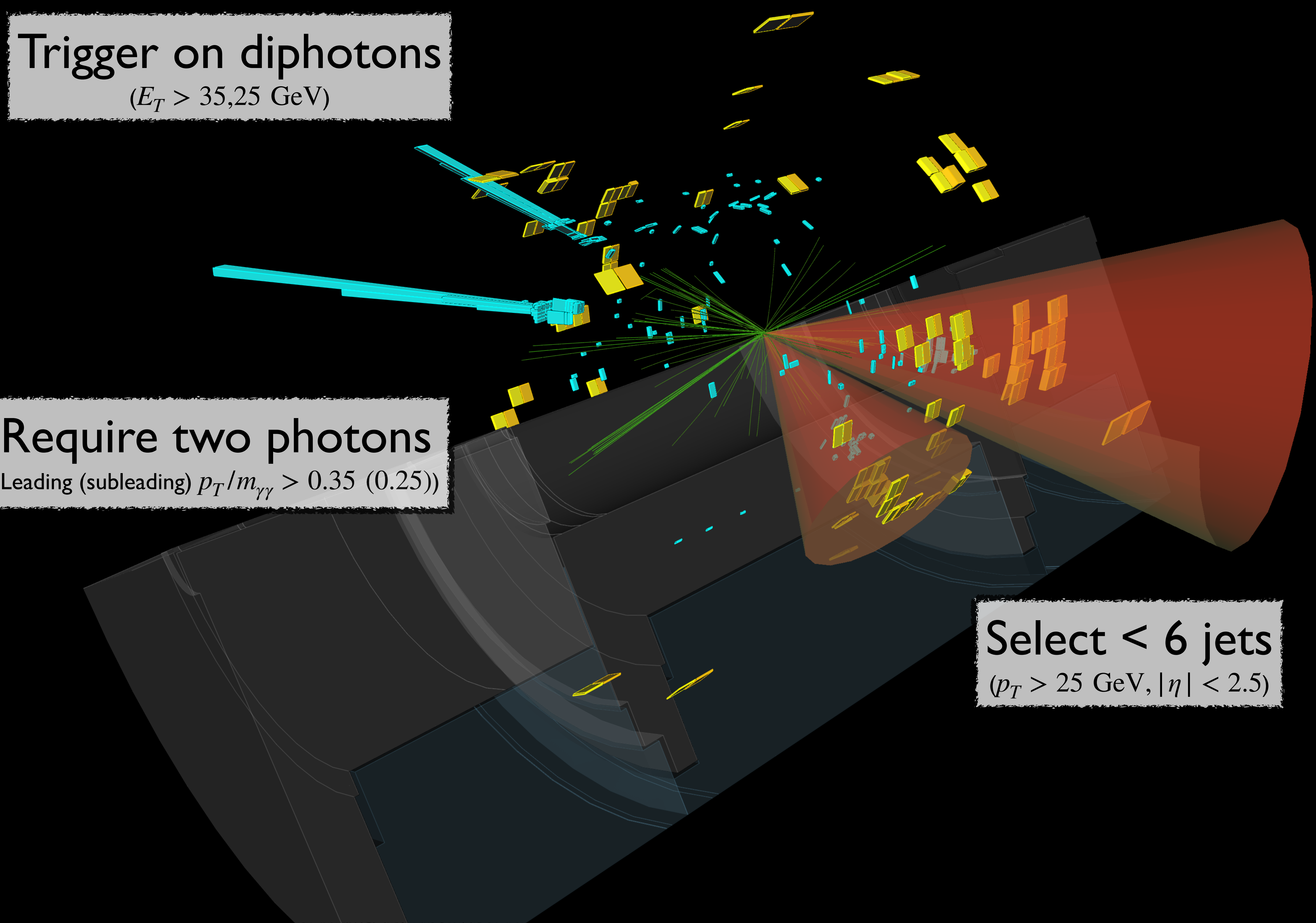

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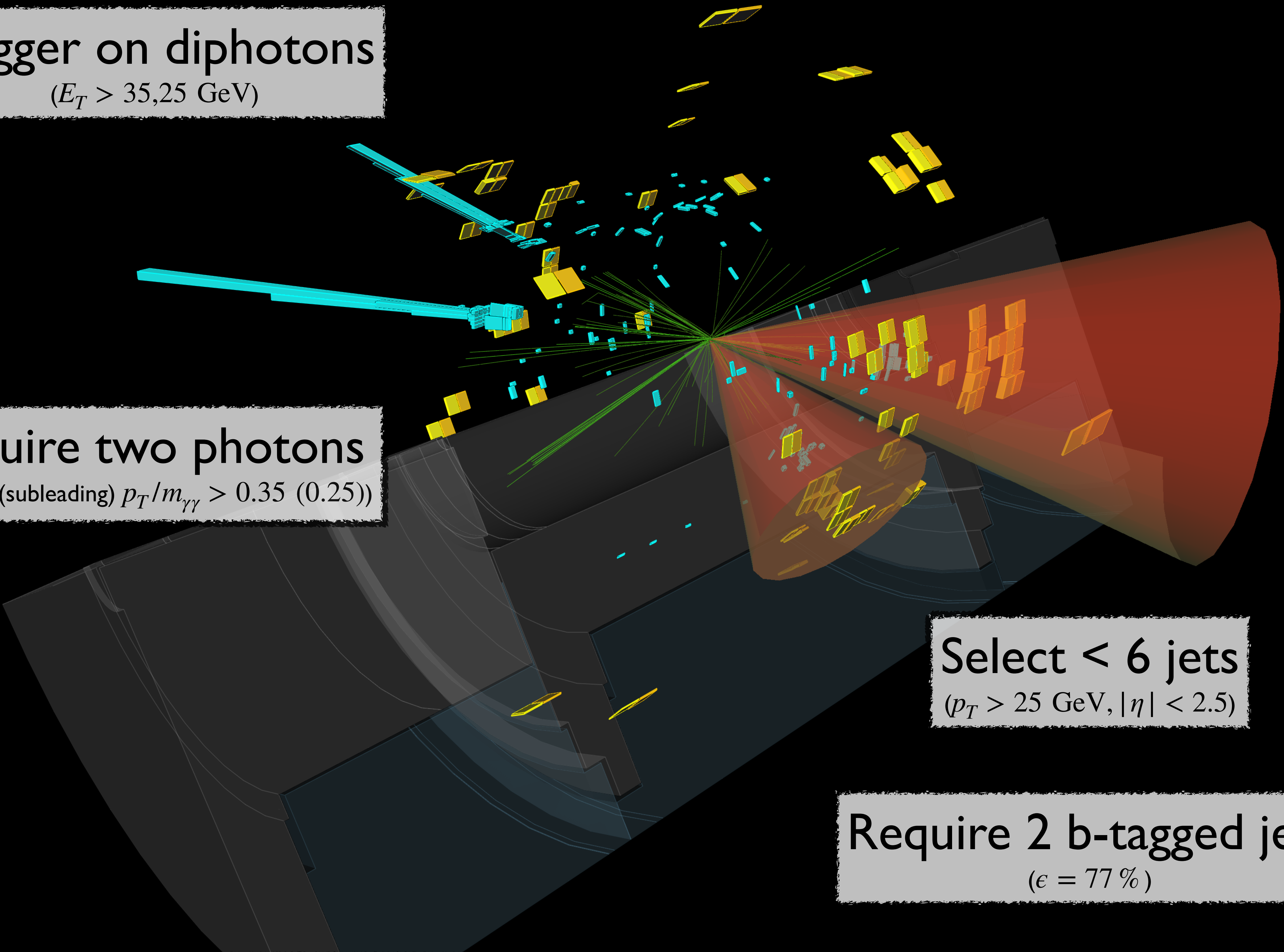

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Select < 6 jets
($p_T > 25$ GeV, $|\eta| < 2.5$)

Require 2 b-tagged jets
($\epsilon = 77\,\%$)

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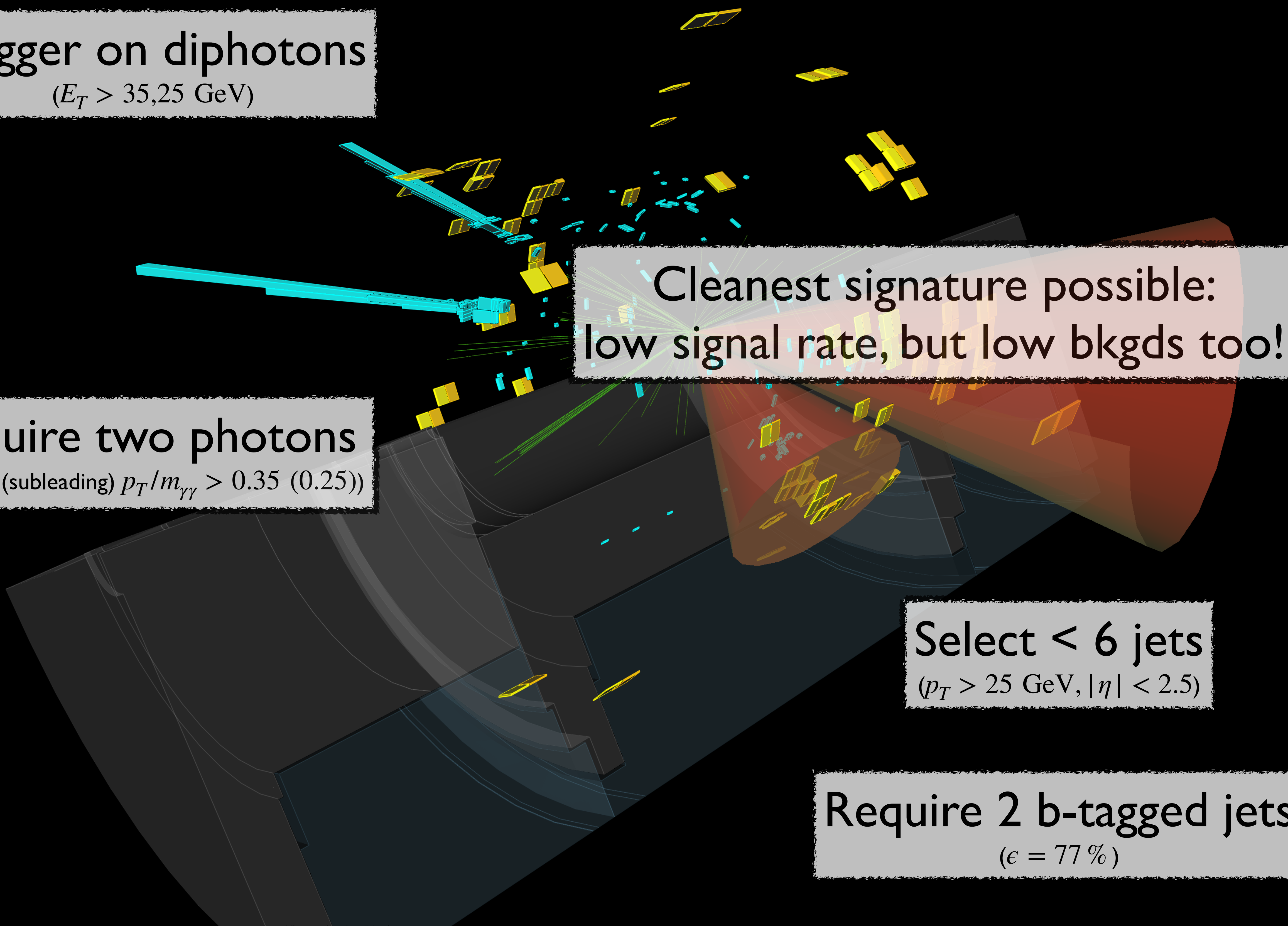
$HH \to b\bar{b}\gamma\gamma$

Trigger on diphotons
($E_T > 35{,}25$ GeV)

Cleanest signature possible:
low signal rate, but low bkgds too!

Require two photons
(Leading (subleading) $p_T/m_{\gamma\gamma} > 0.35\ (0.25)$)



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$b\bar{b}\gamma\gamma$ Analysis Strategy

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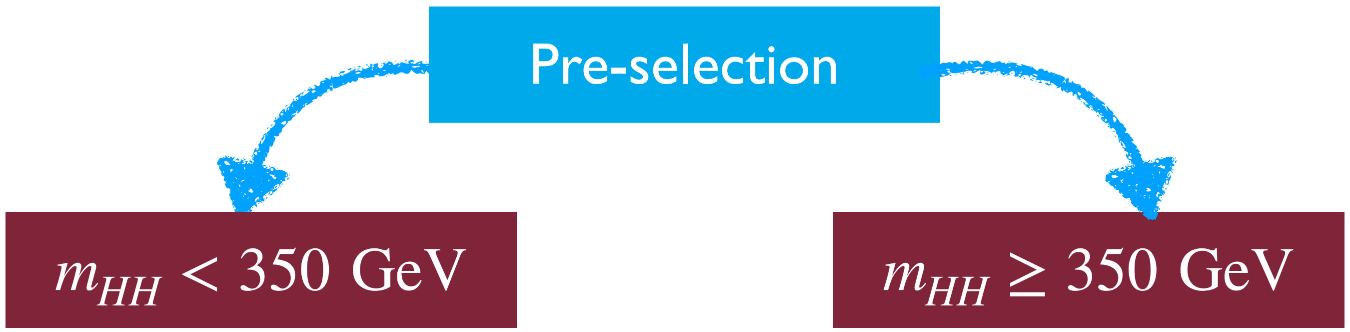

After pre-selection, split into high-mass and low-mass selections

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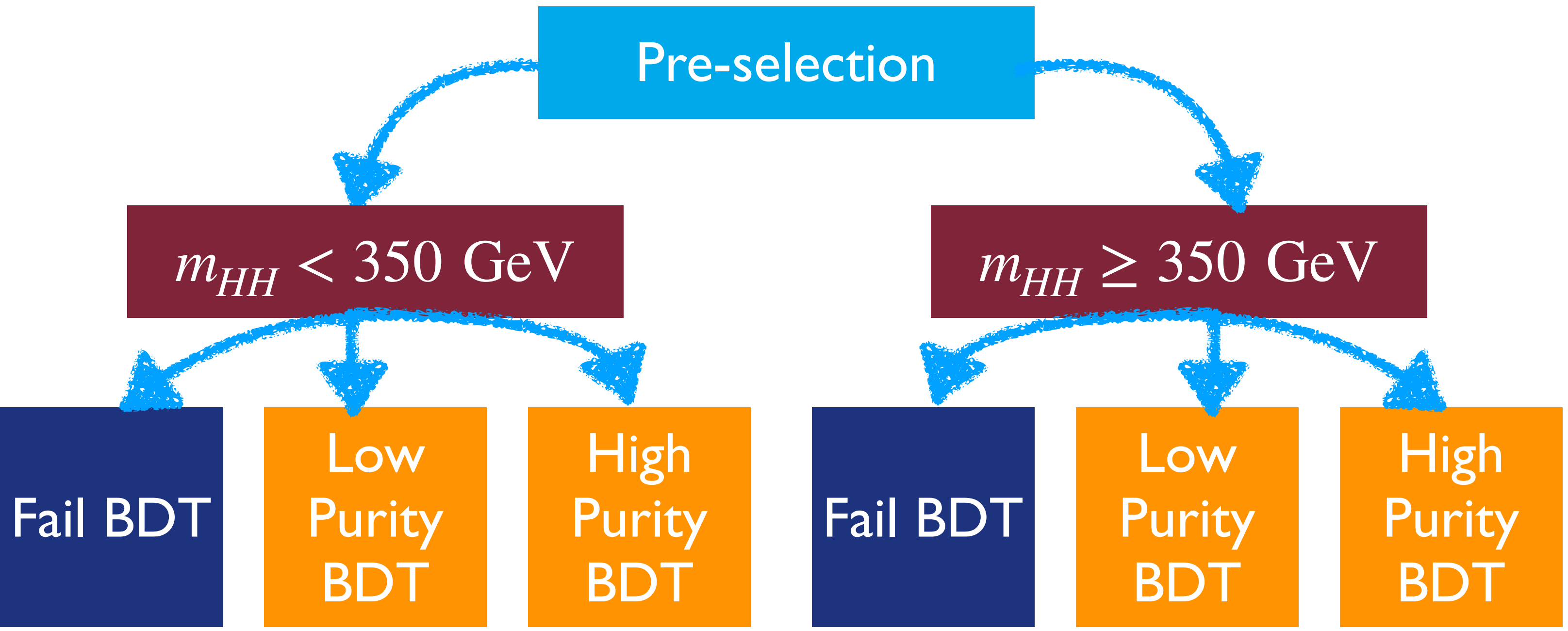

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BDT trained in each region: select low- and high-purity signal regions with BDT

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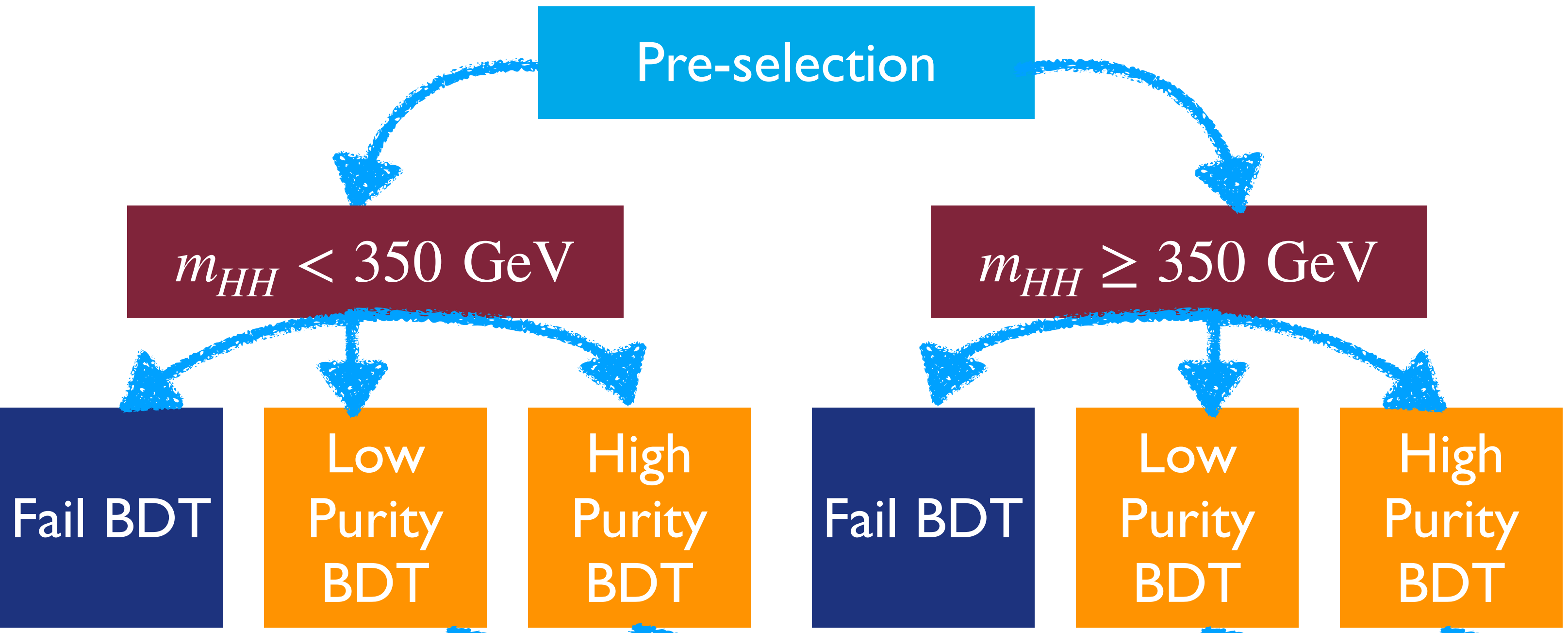

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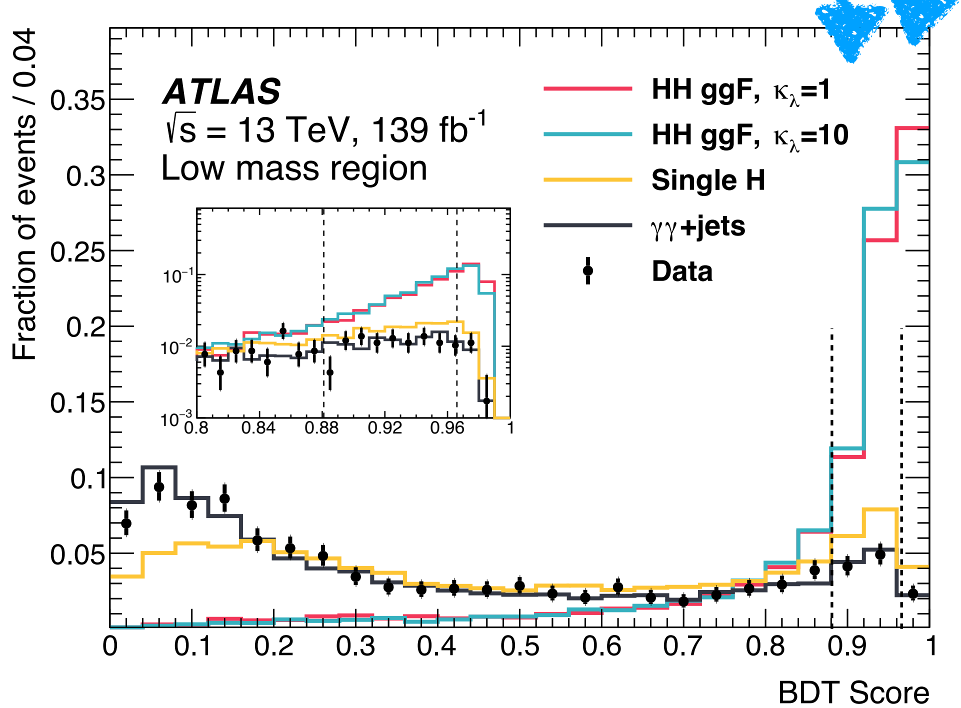

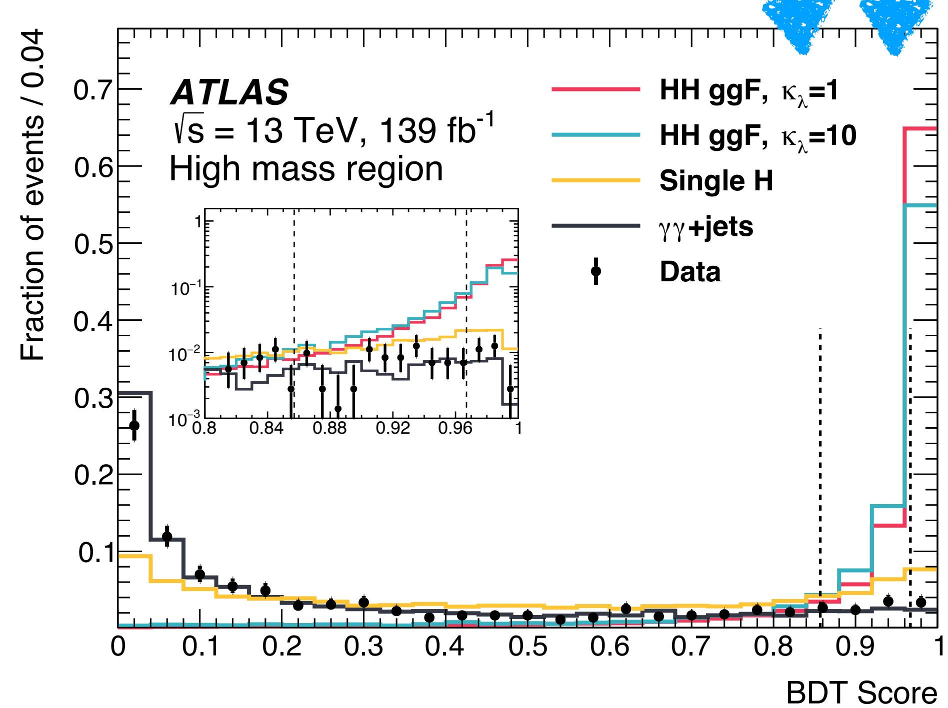

Fit $m_{\gamma\gamma}$ in 4 SR's simultaneously to extract signal

$b\bar{b}\gamma\gamma$ Background Estimate

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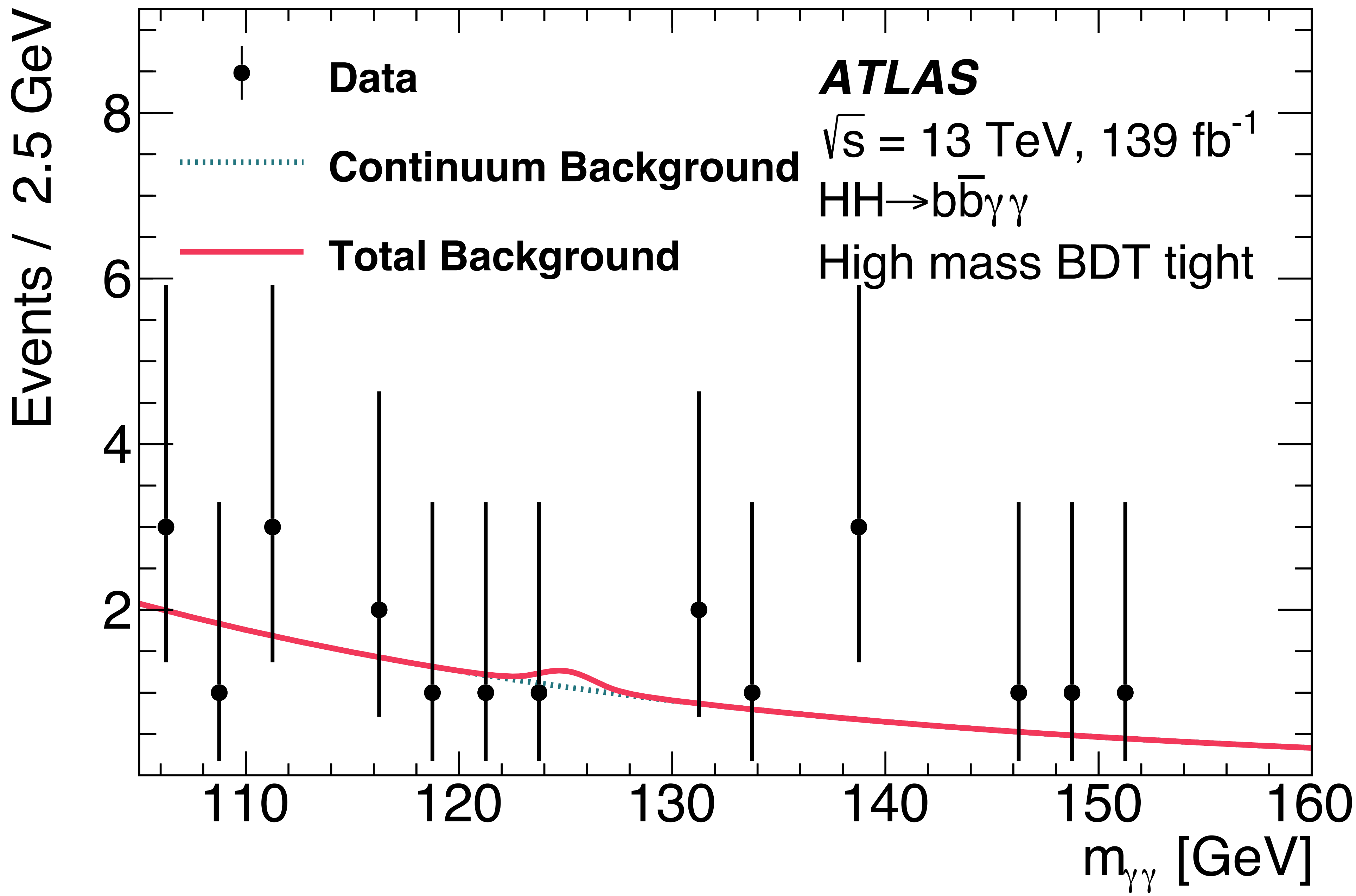

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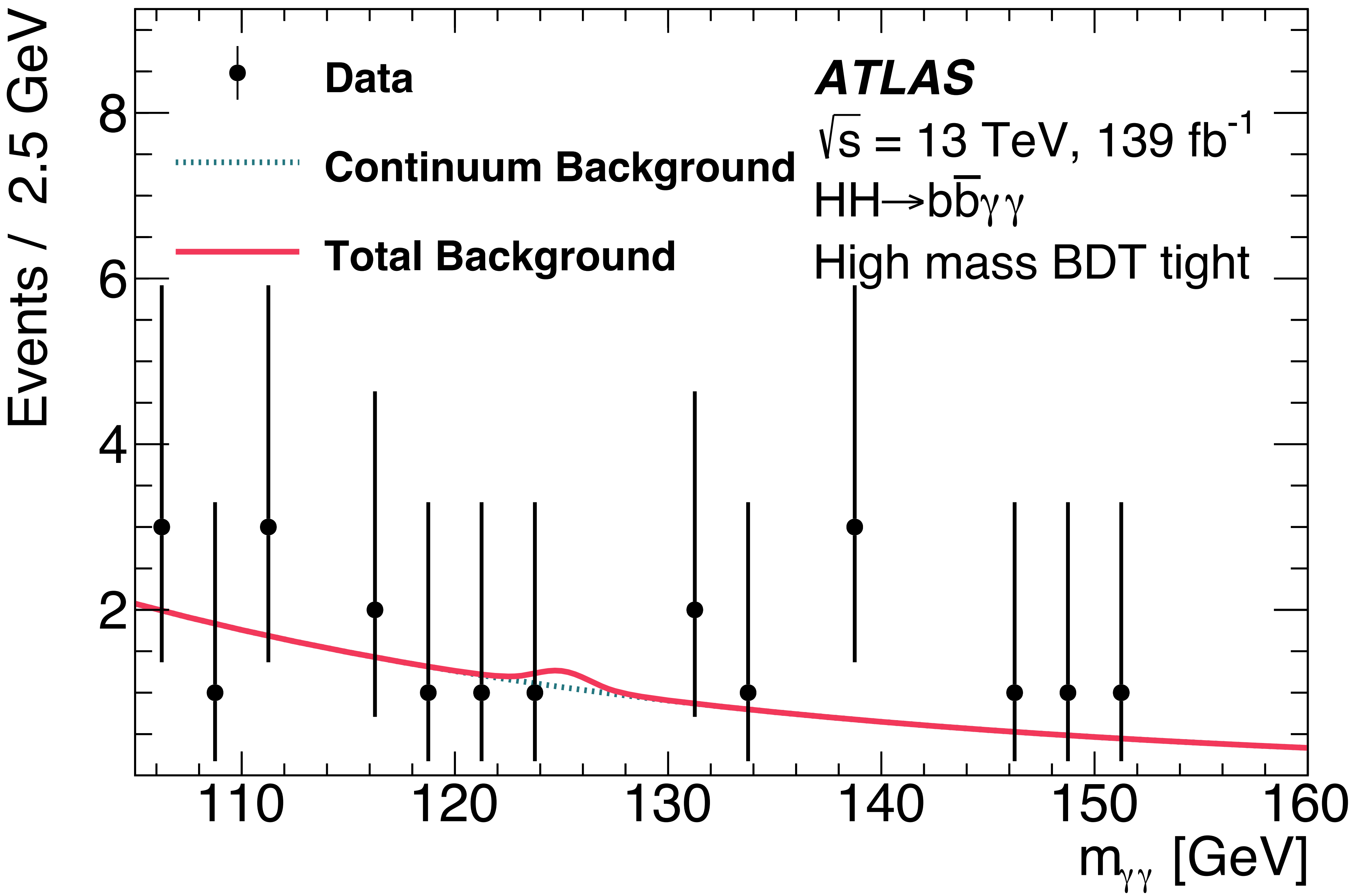

Background estimate formed on fit to $m_{\gamma\gamma}$ in different signal regions

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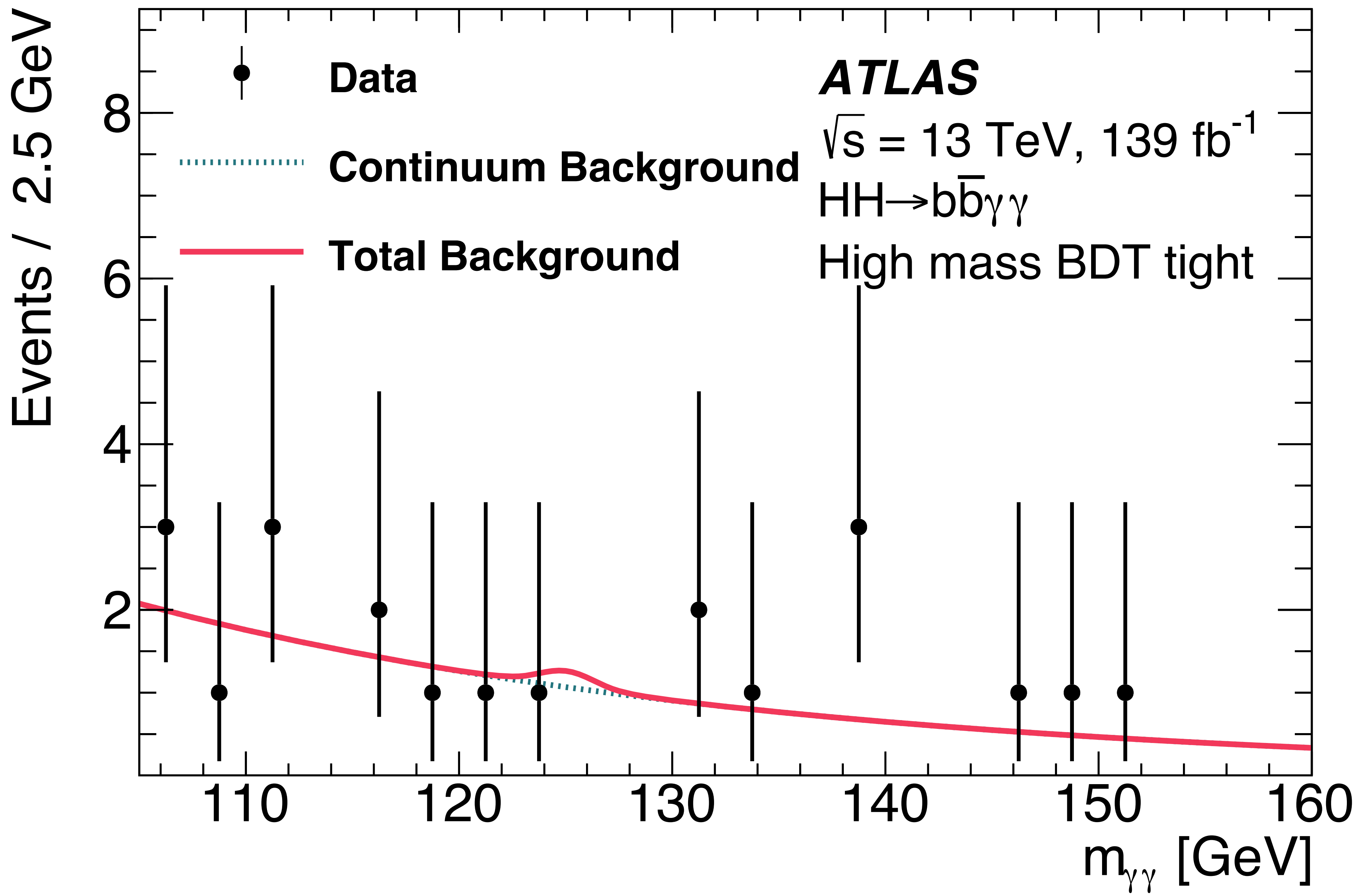
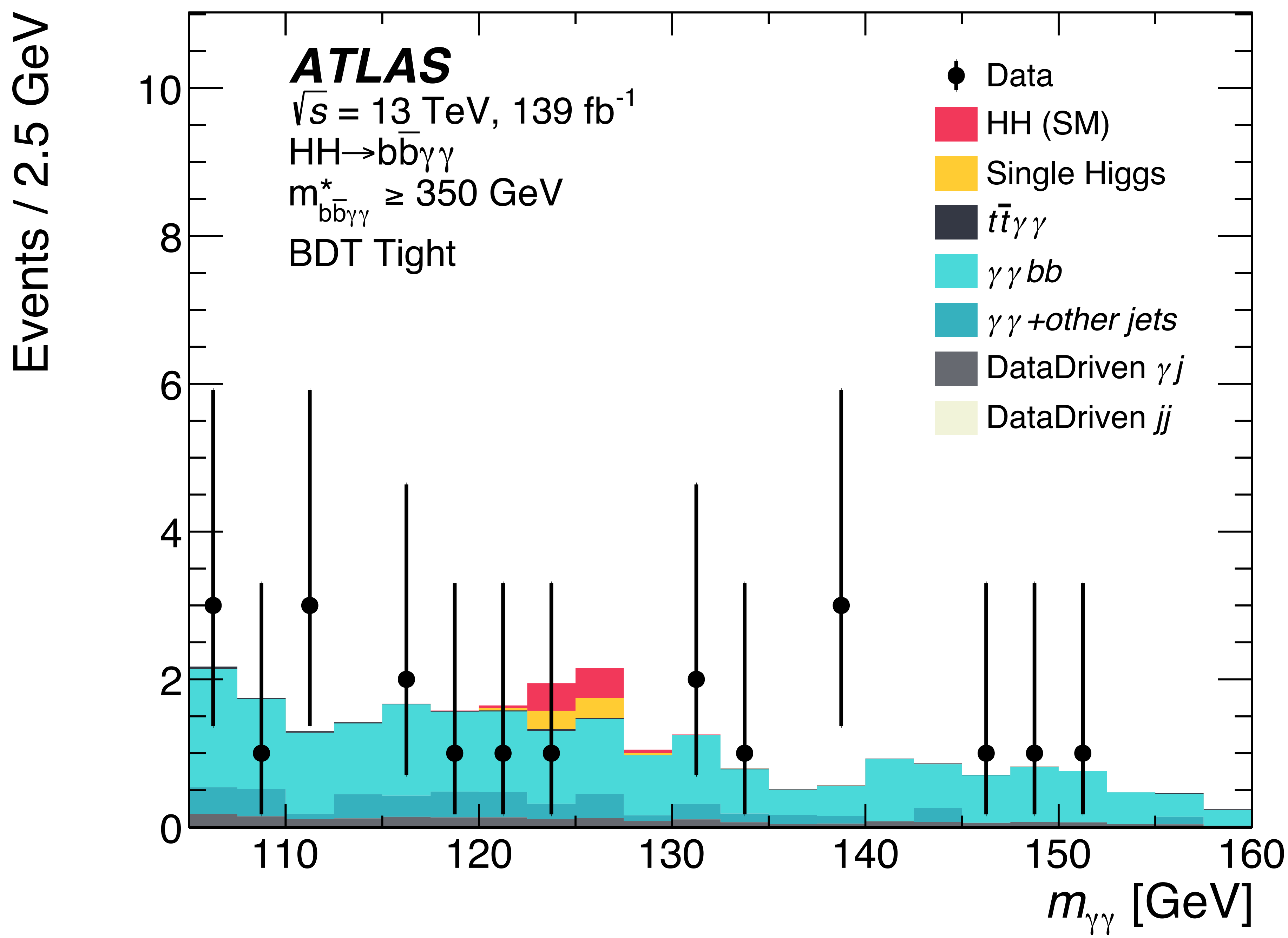


Background estimate formed on fit to $m_{\gamma\gamma}$ in different signal regions

Shape of background from MC, normalization determined from data

$b\bar{b}\gamma\gamma$ Results



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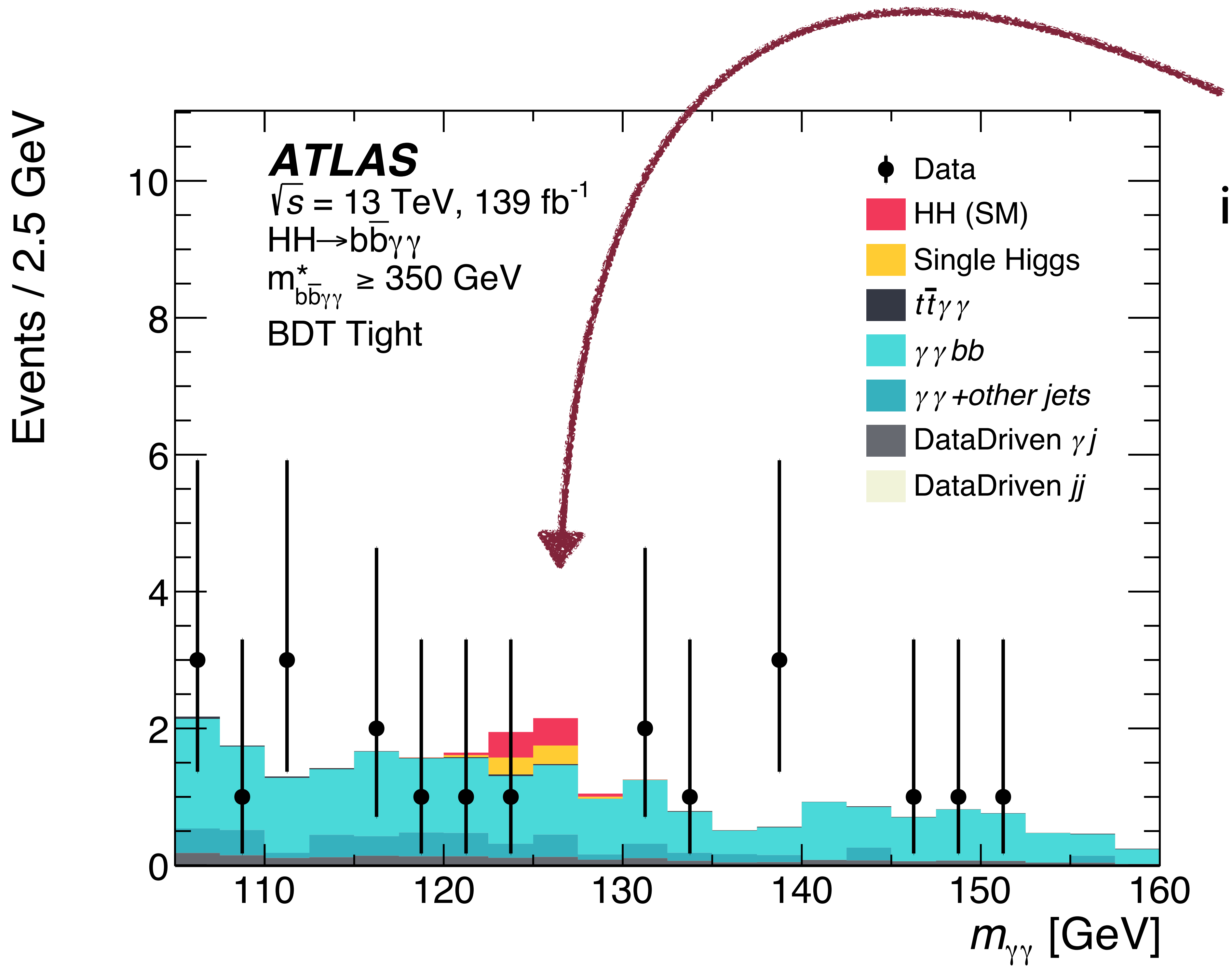
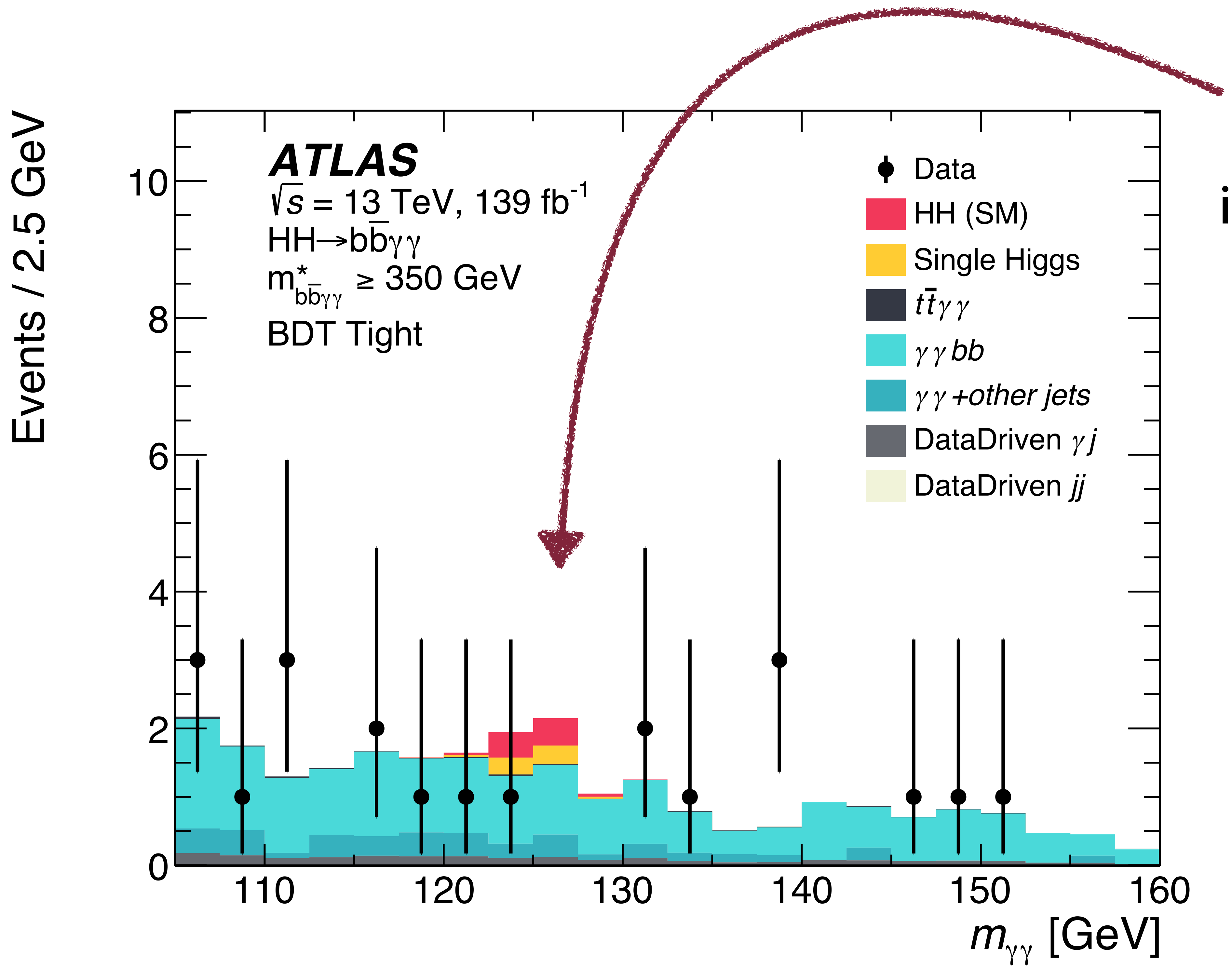


Look for a peak in the $m_{\gamma\gamma}$ spectrum near the Higgs

$b\bar{b}\gamma\gamma$ Results



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No obvious signs of new physics

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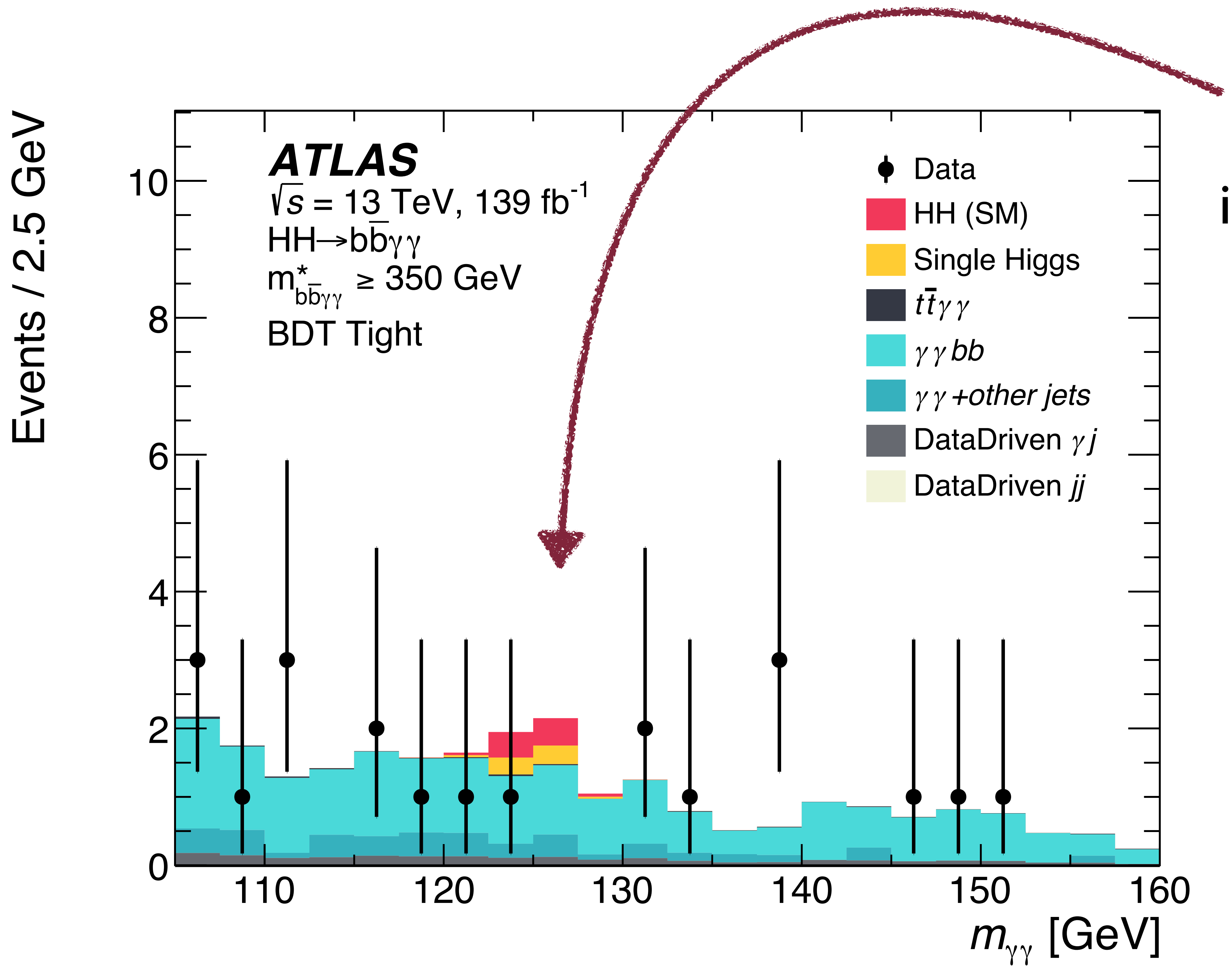

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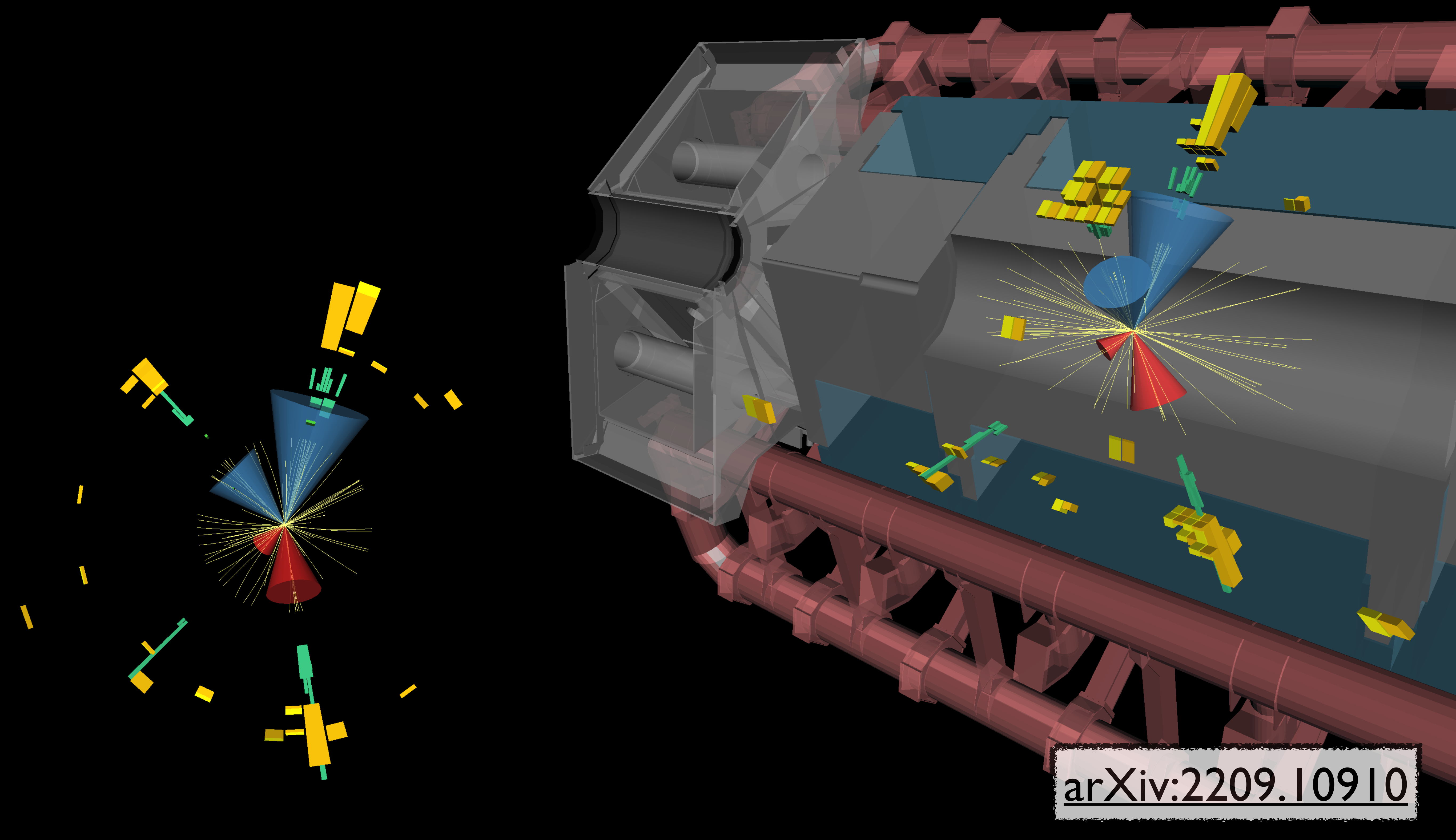
Similar results for other signal categories

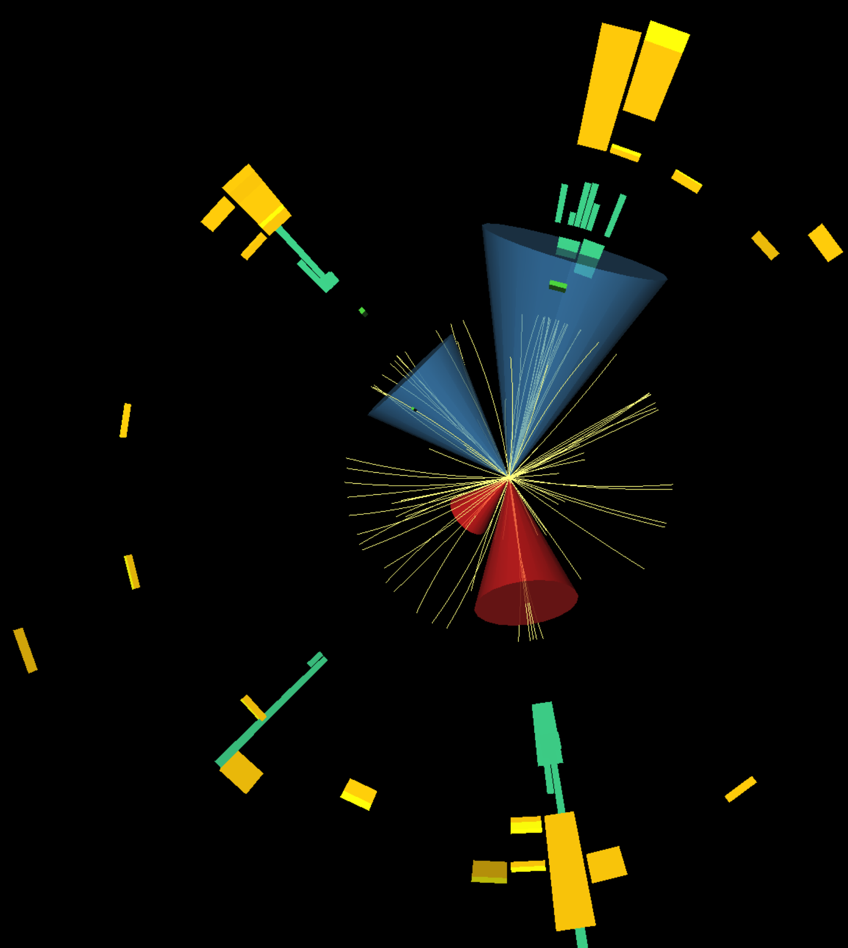
$HH \to b\bar{b}\tau\bar{\tau}$

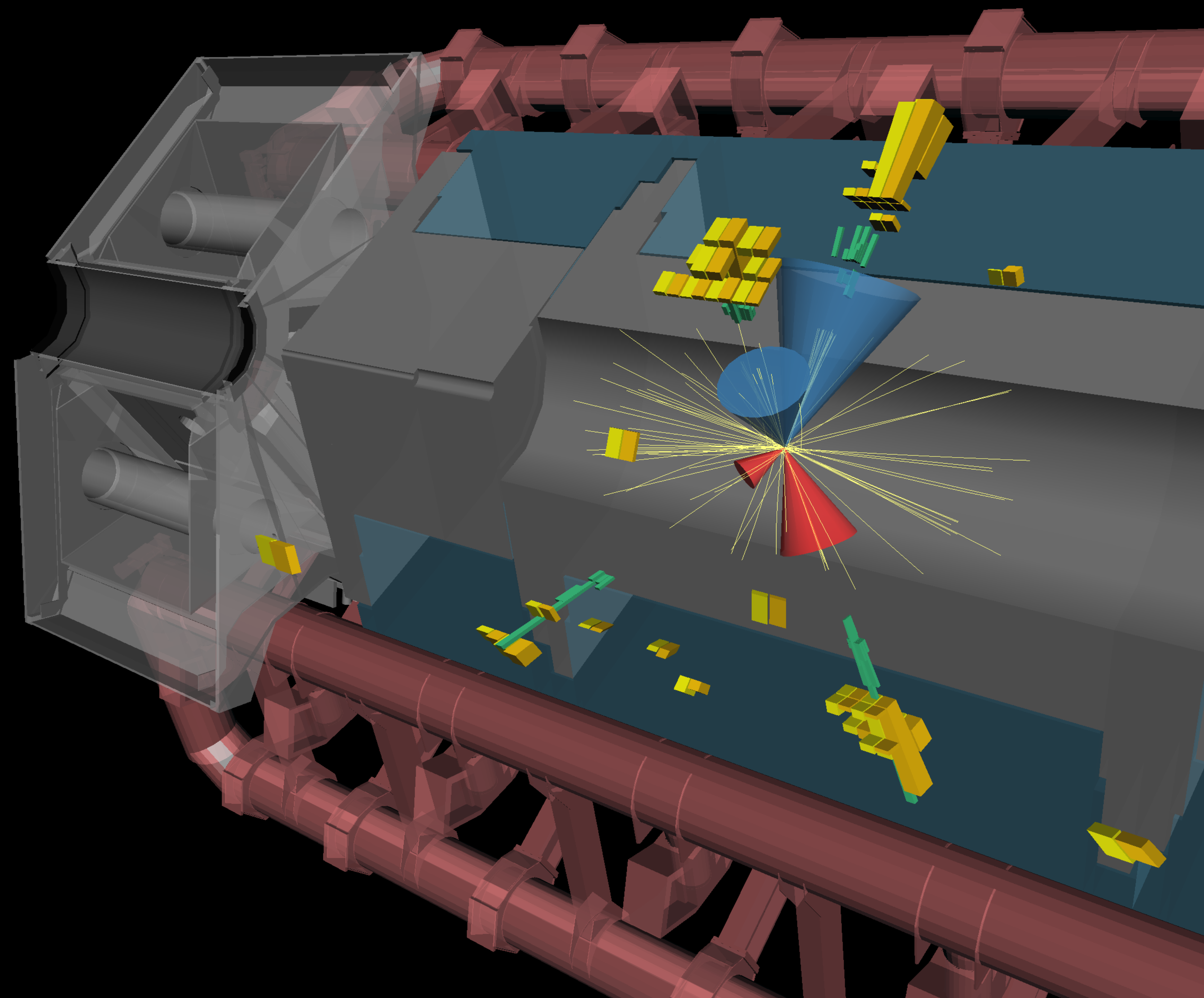


arXiv:2209.10910

$HH \rightarrow b\bar{b}\tau\bar{\tau}$

Separate into $\tau_h\tau_h$ and $\tau_\ell\tau_h$ channels





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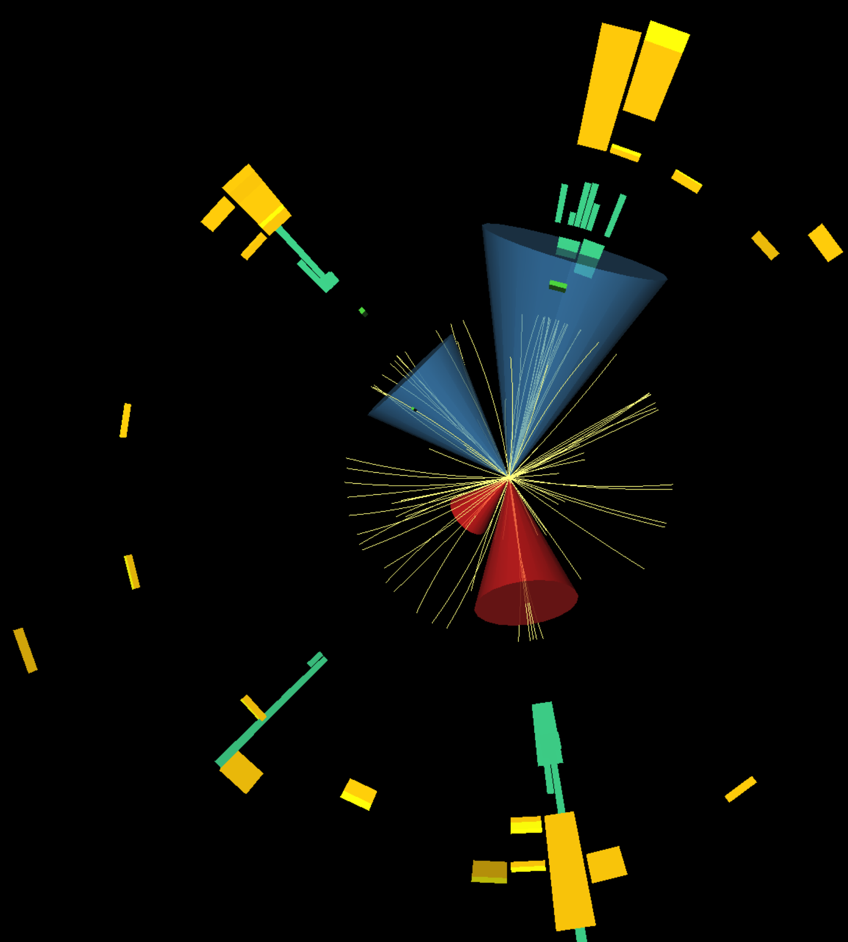
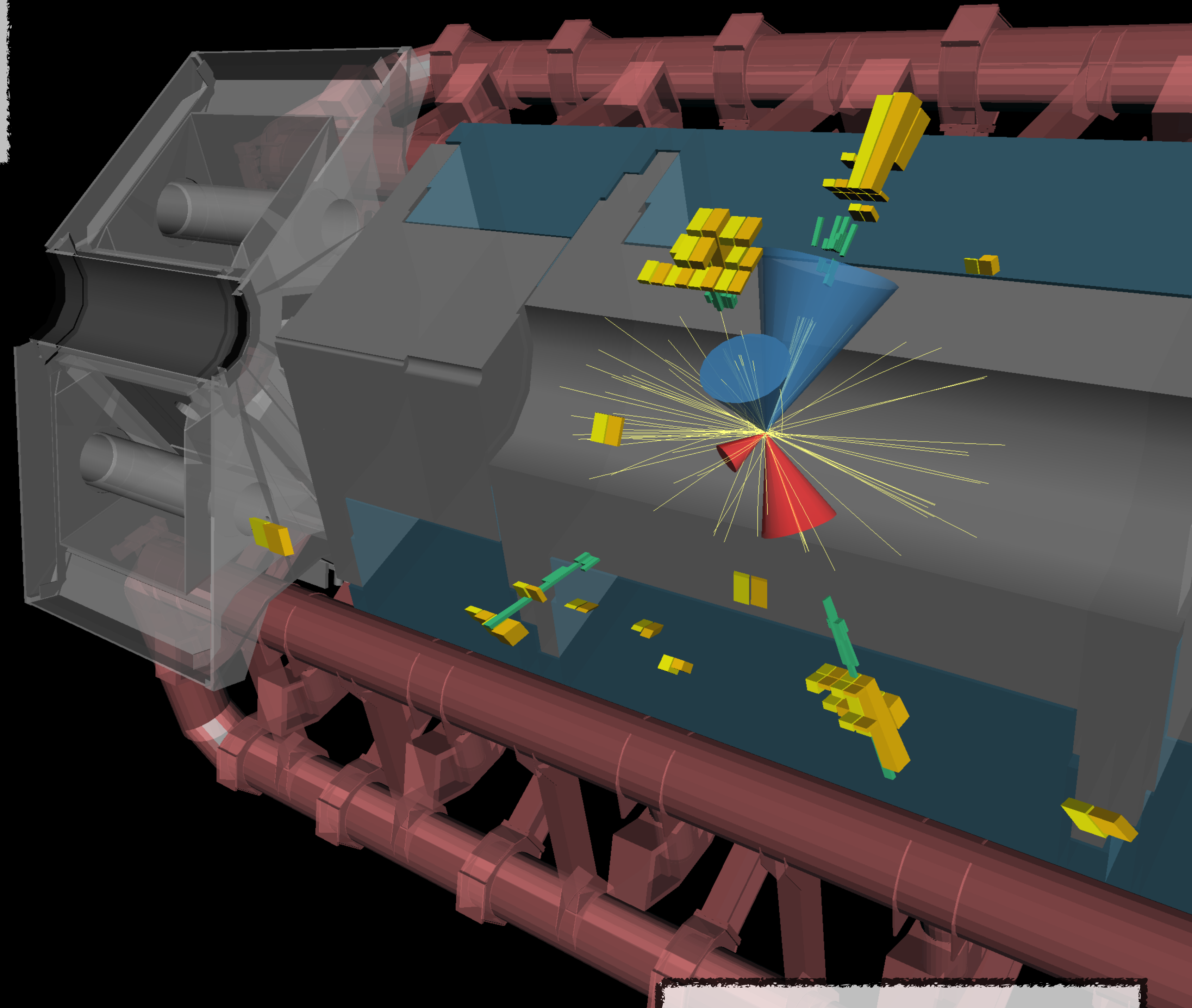
Separate into $\tau_h\tau_h$ and $\tau_\ell\tau_h$ channels

Trigger on di-τ, $\ell + \tau$, or single ℓ





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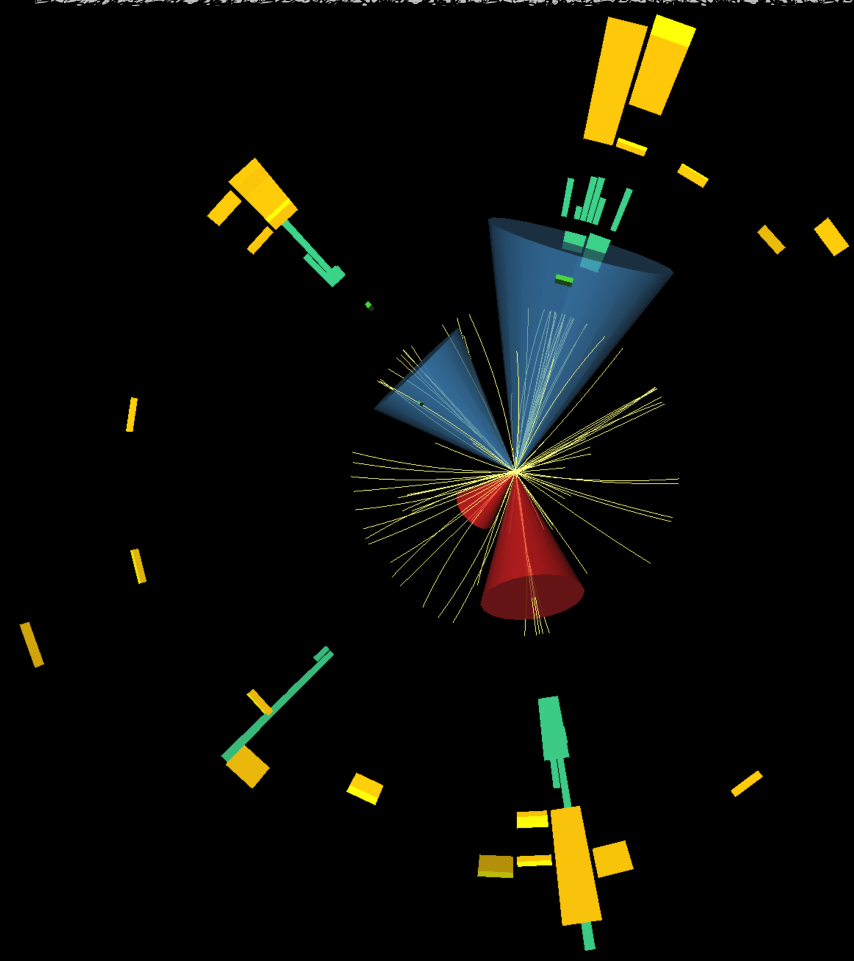
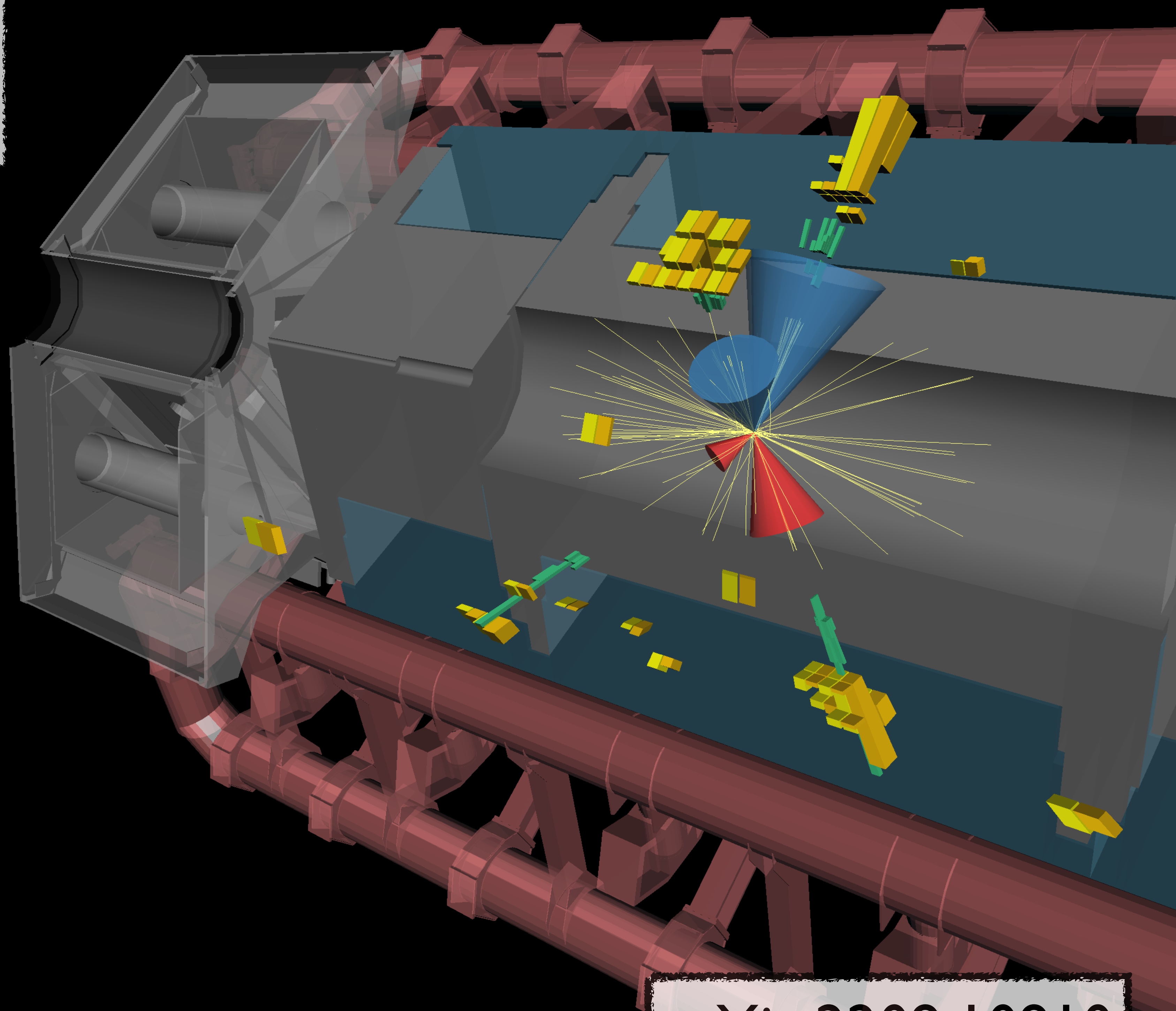
Require 1 or 2 'loose' τ: $m_{\tau\tau} > 60$ GeV





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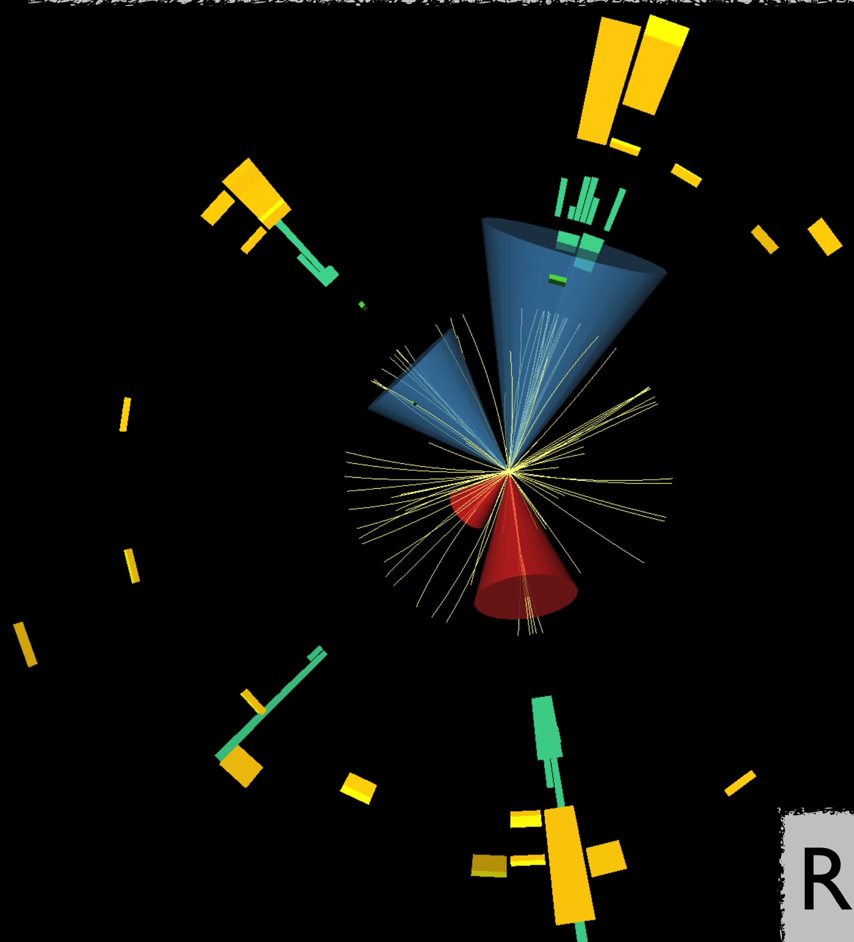

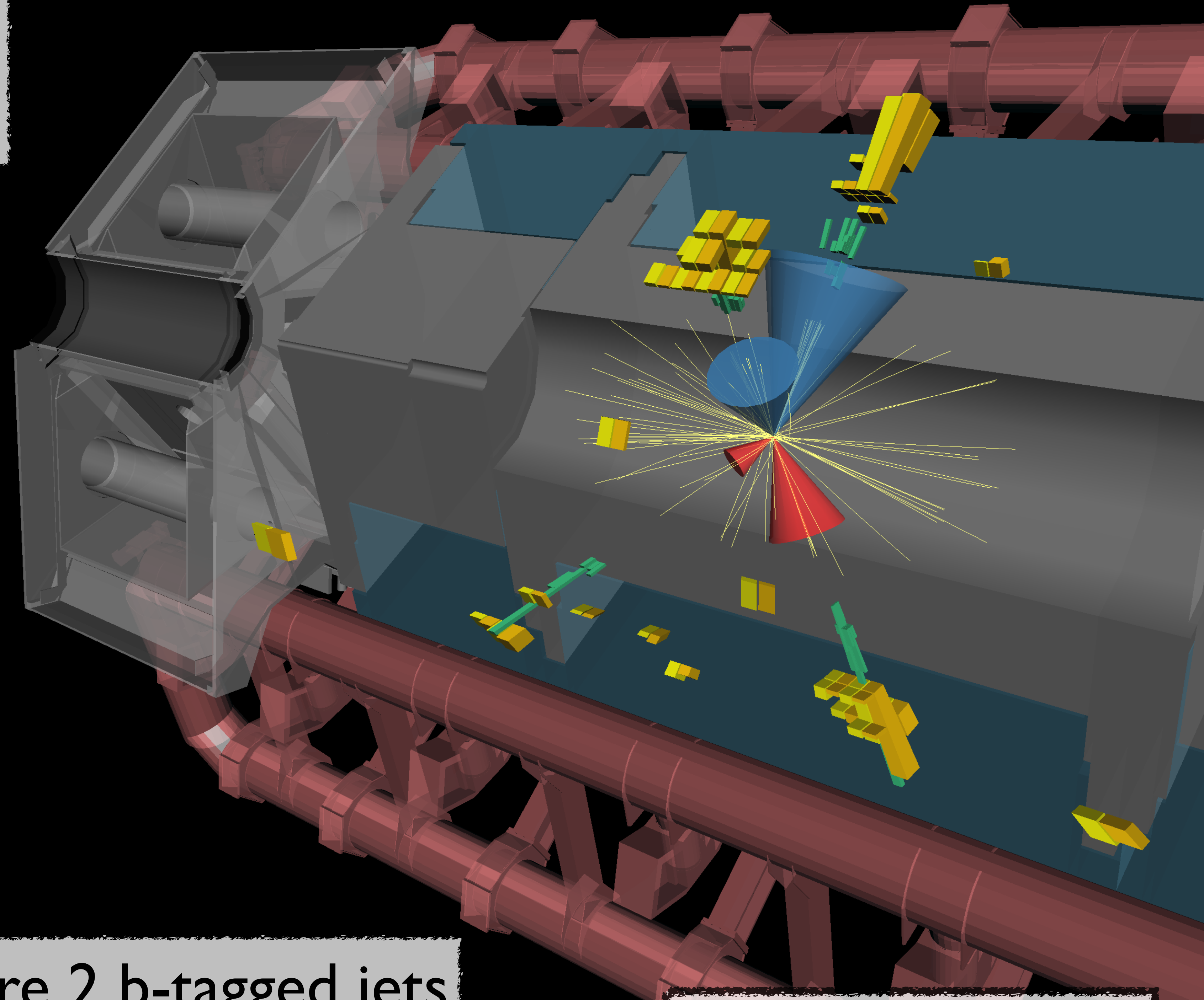

Require 2 b-tagged jets ($\epsilon = 77\,\%$)

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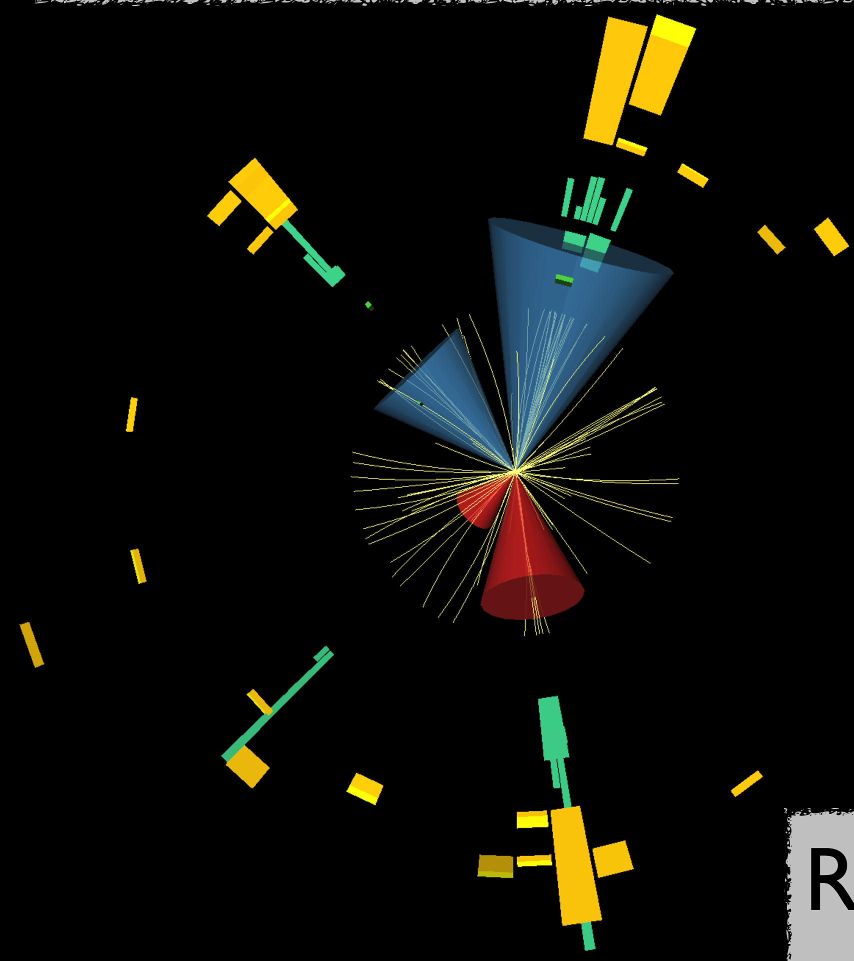

Balanced signature: τ_h allows for good bkgd suppression

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$b\bar{b}\tau\bar{\tau}$ Background Estimate

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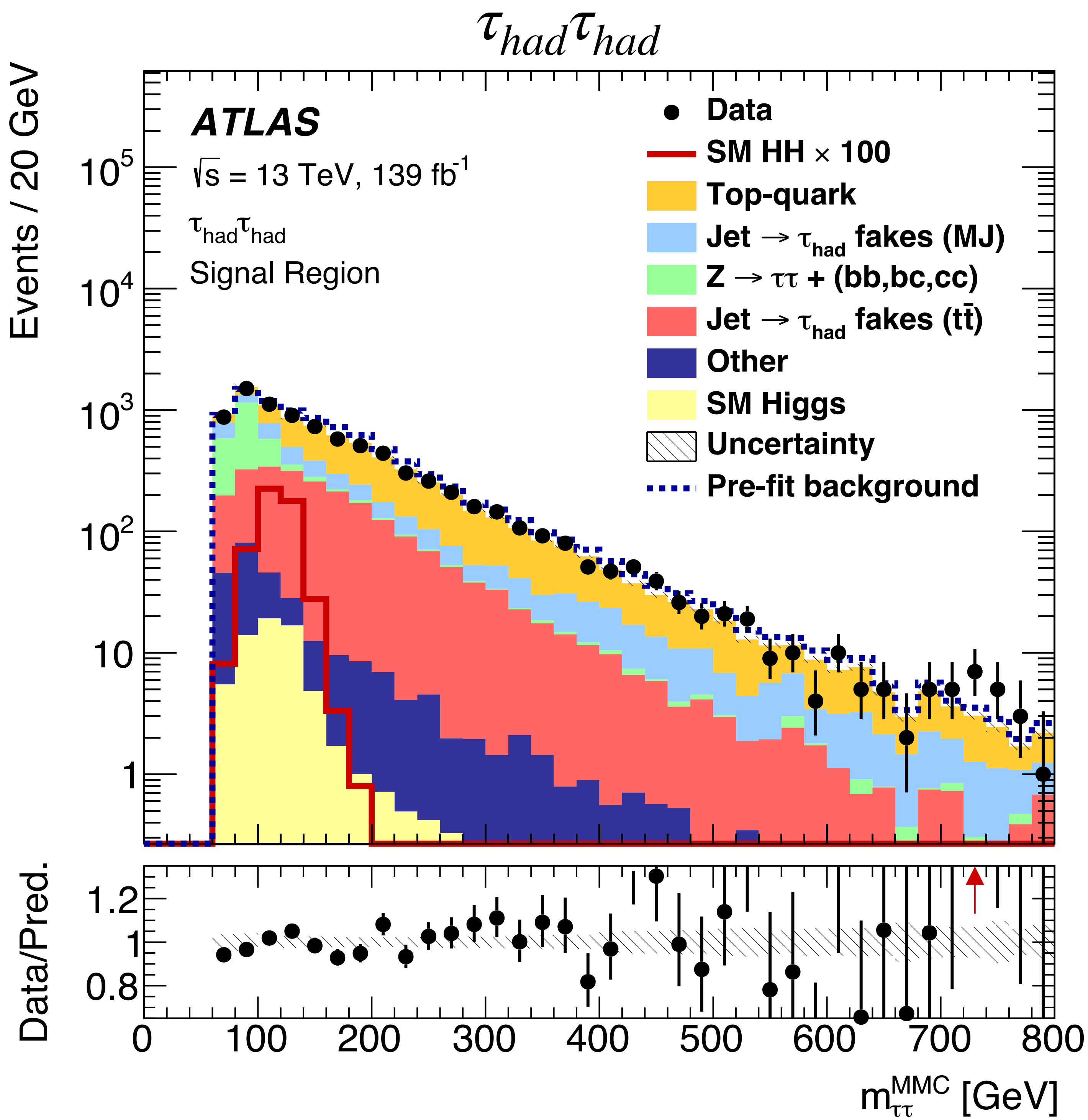

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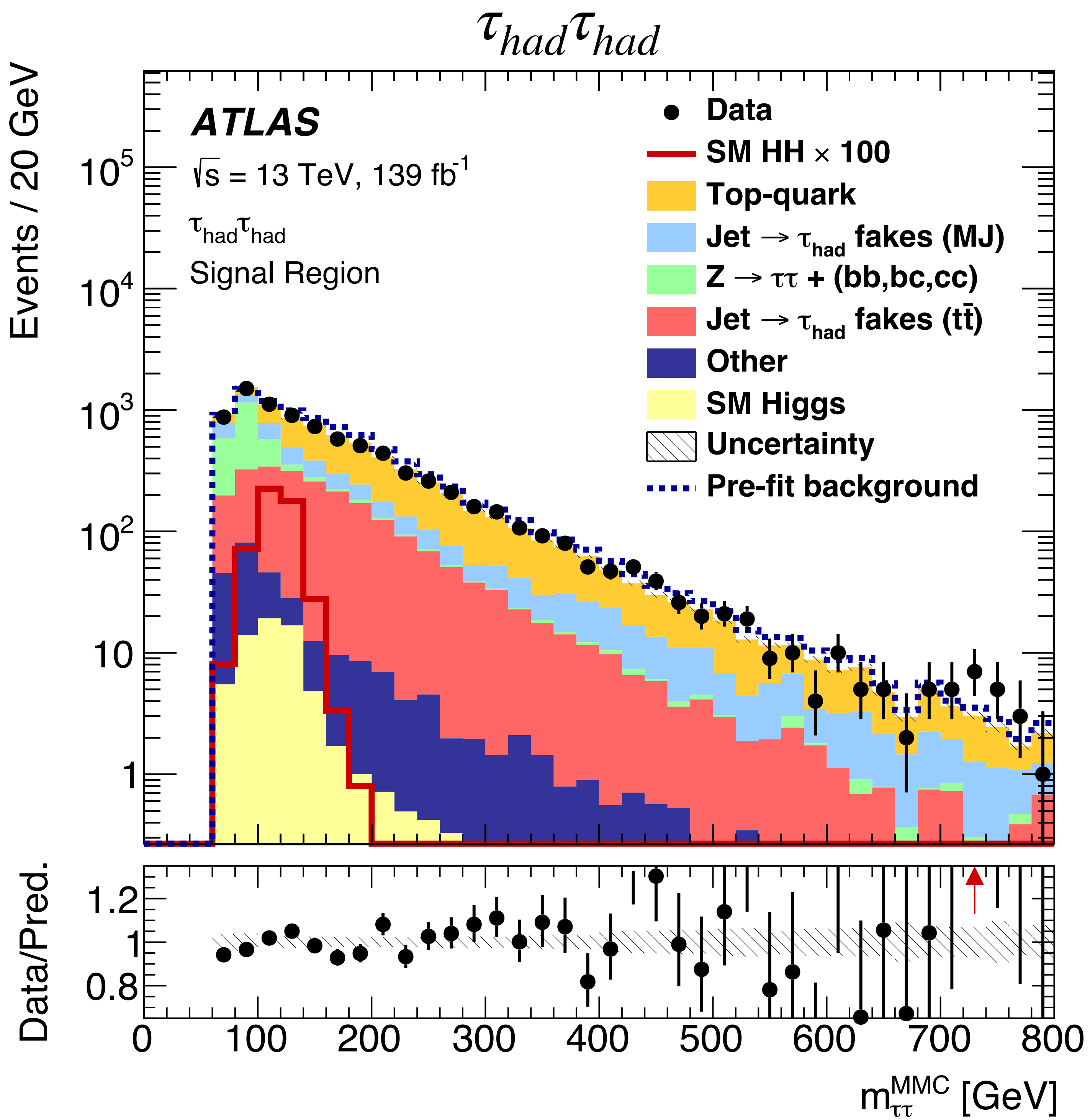

Top-quark background from MC, normalization floating in final fit

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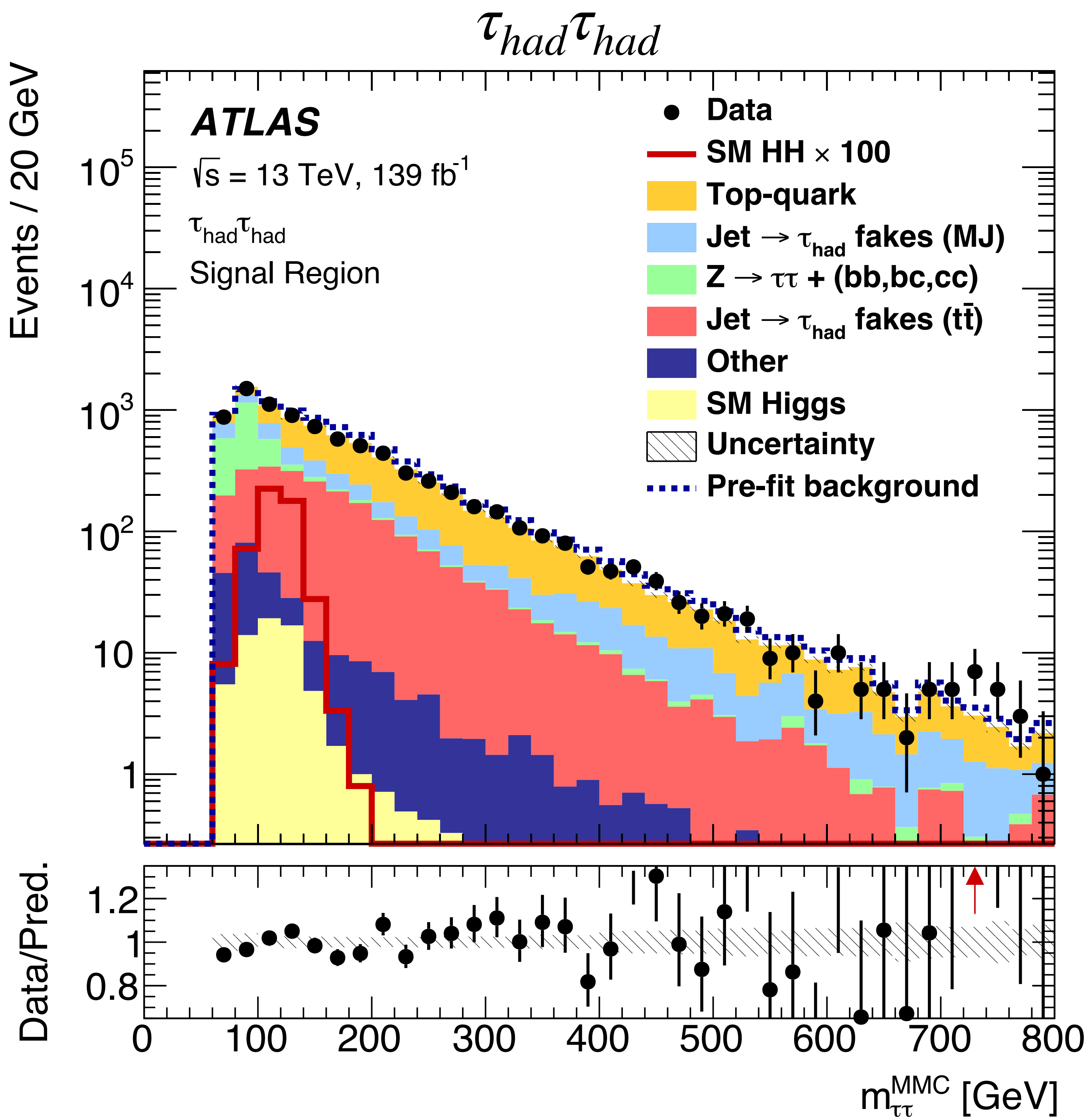

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Z+jets background from MC, normalization from leptonic CR

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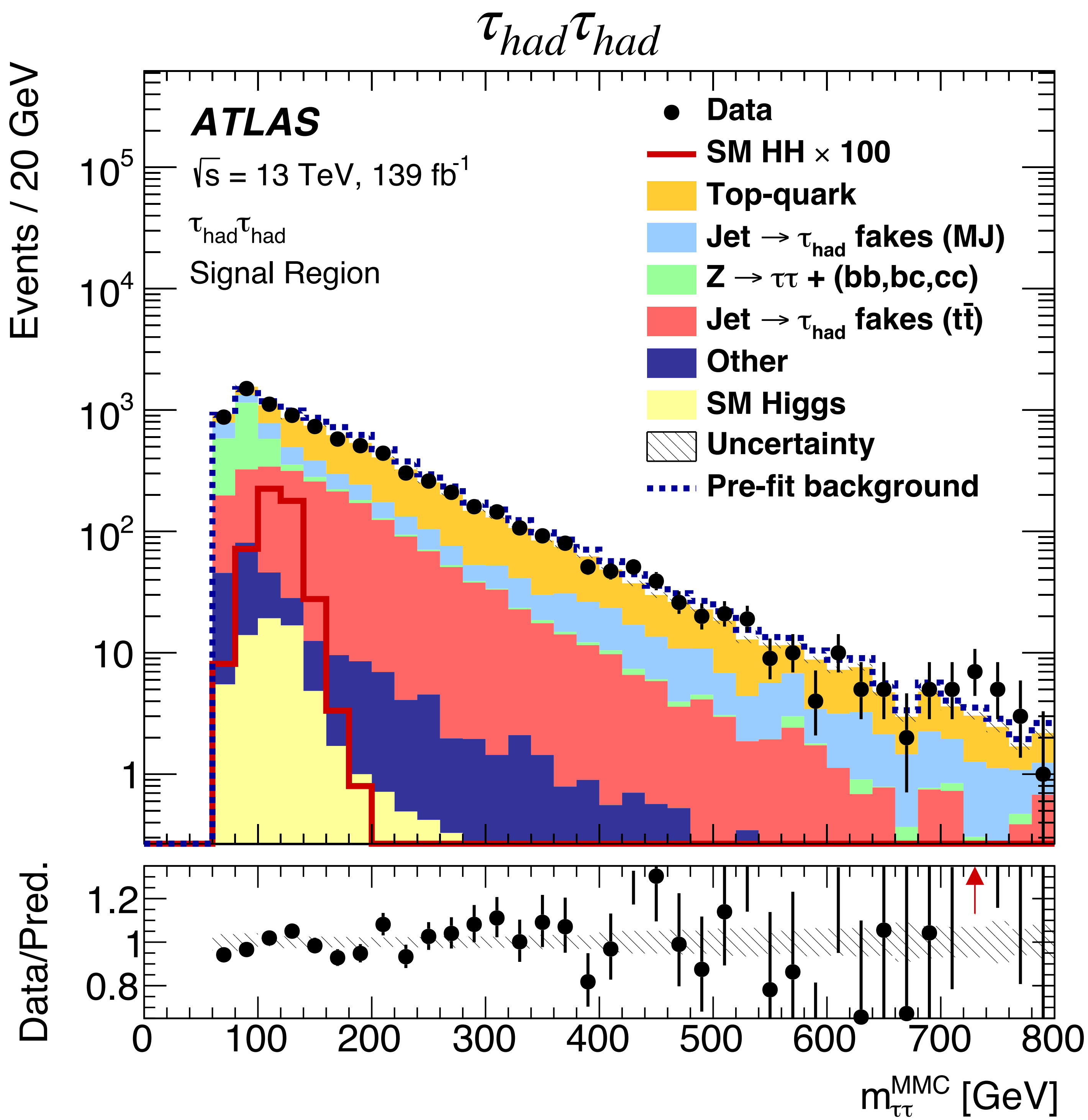

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Fake τ estimated from data using "fake factor" method

$b\bar{b}\tau\bar{\tau}$ Strategy and Results

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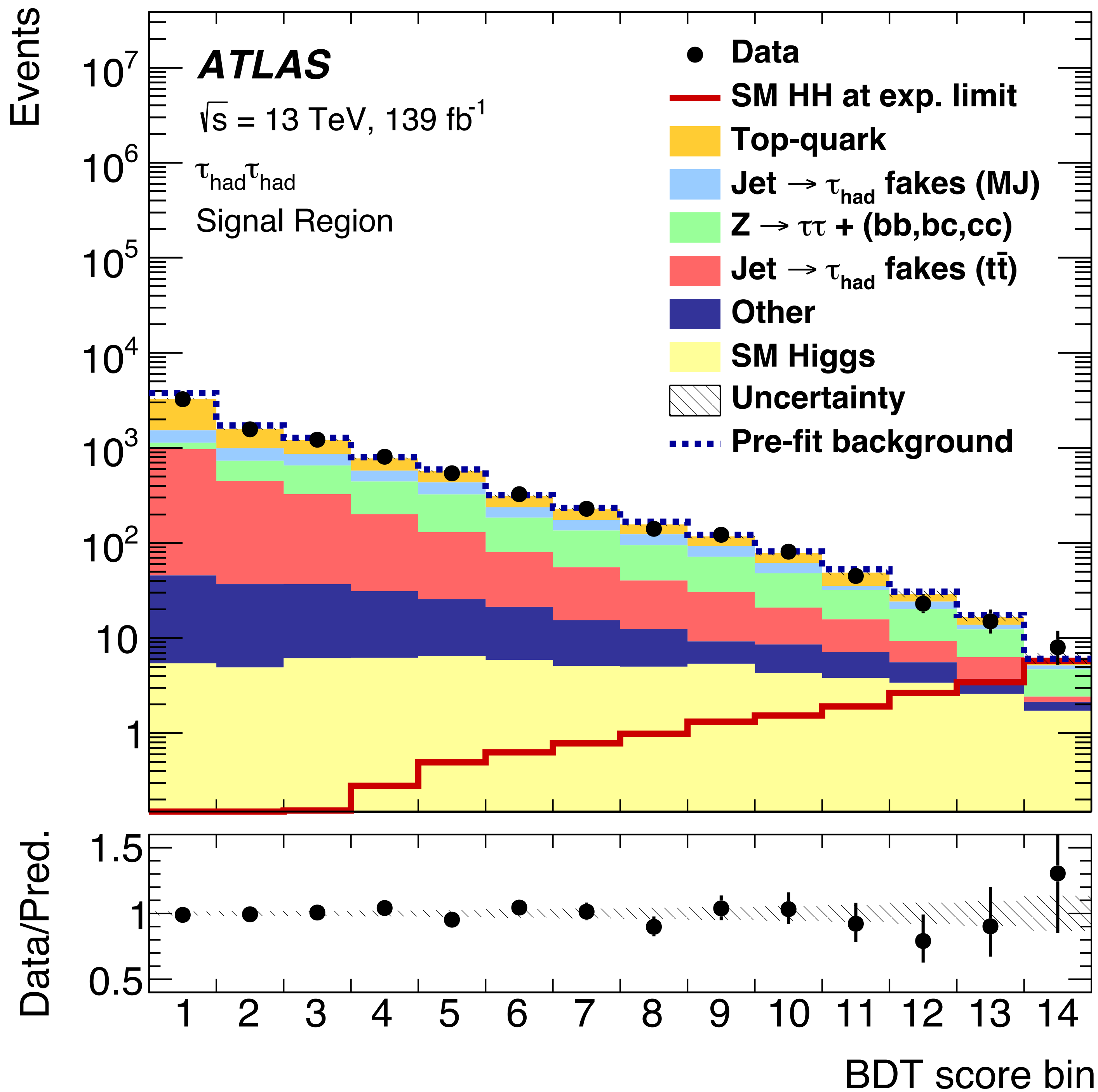

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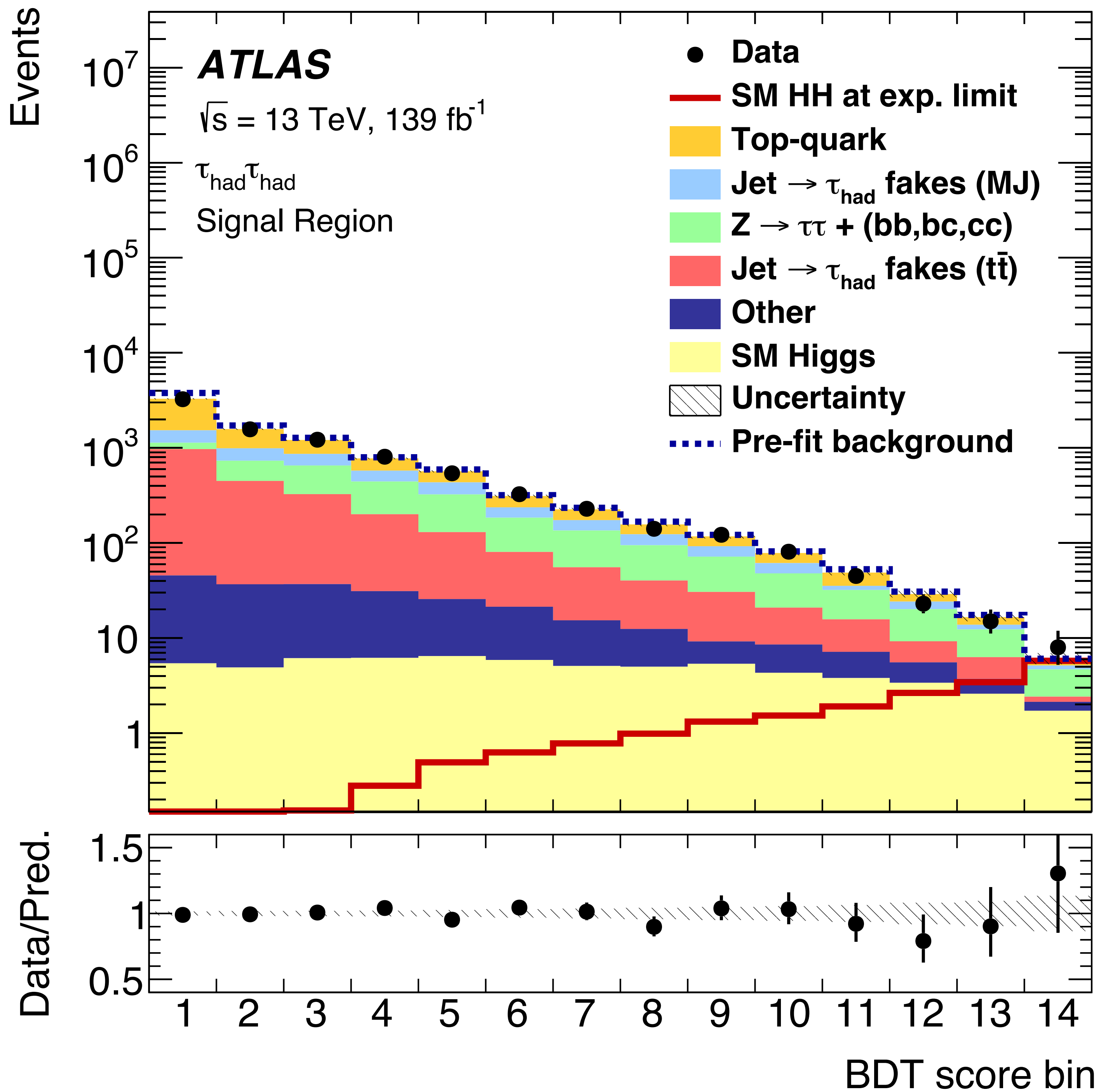

Fits to BDT/NN distribution used for final analysis

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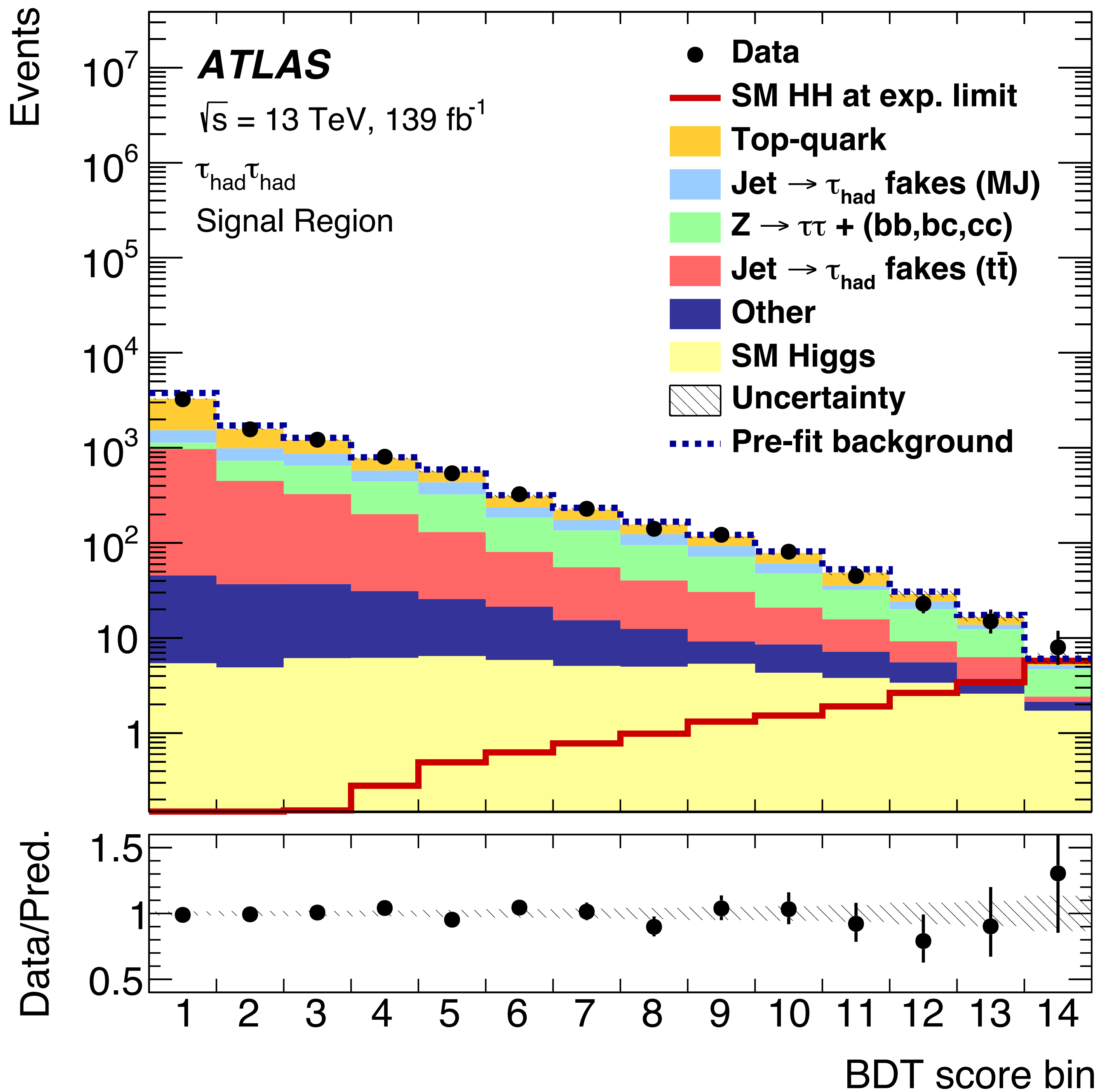

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Data agrees well with background prediction

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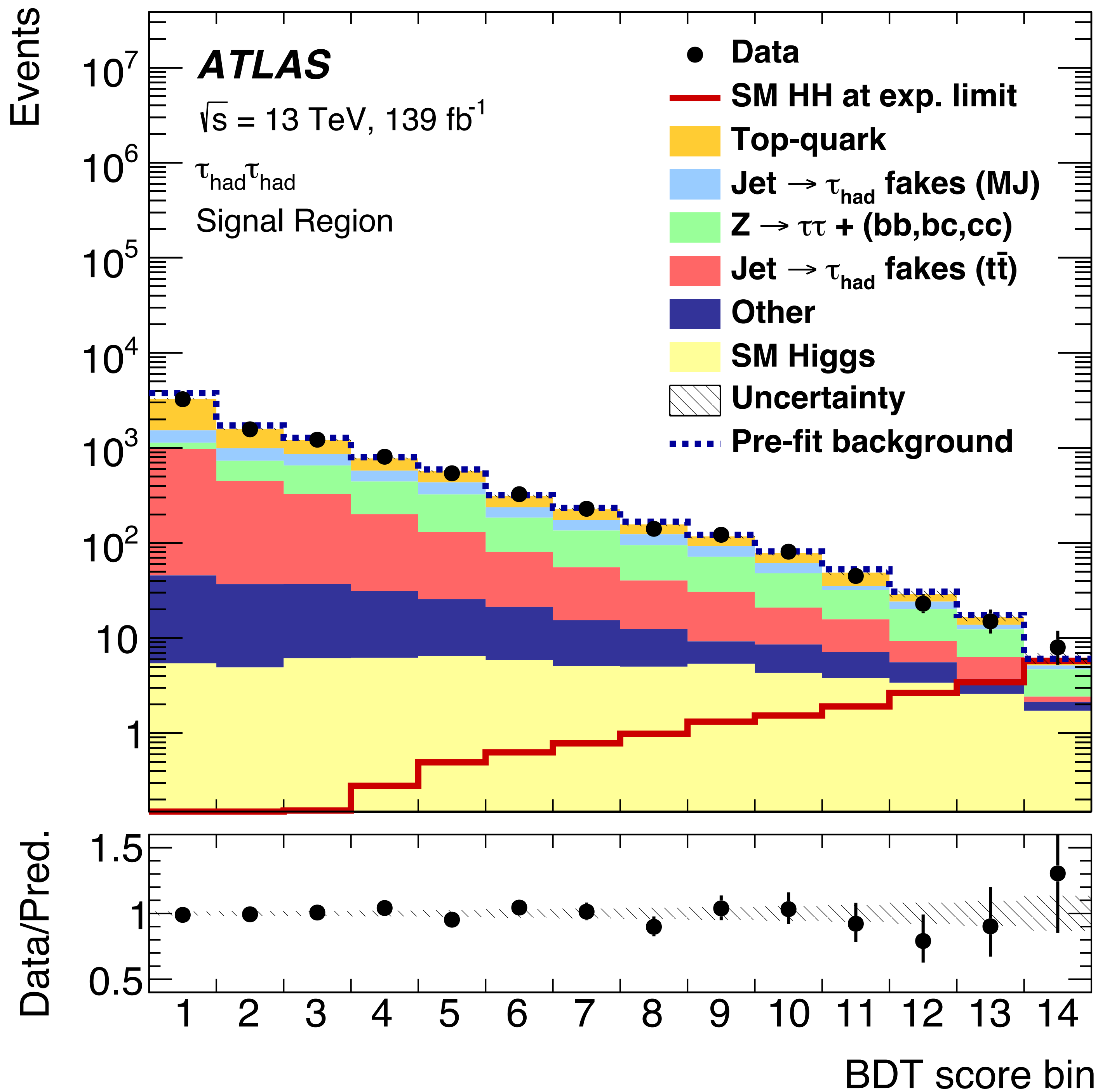


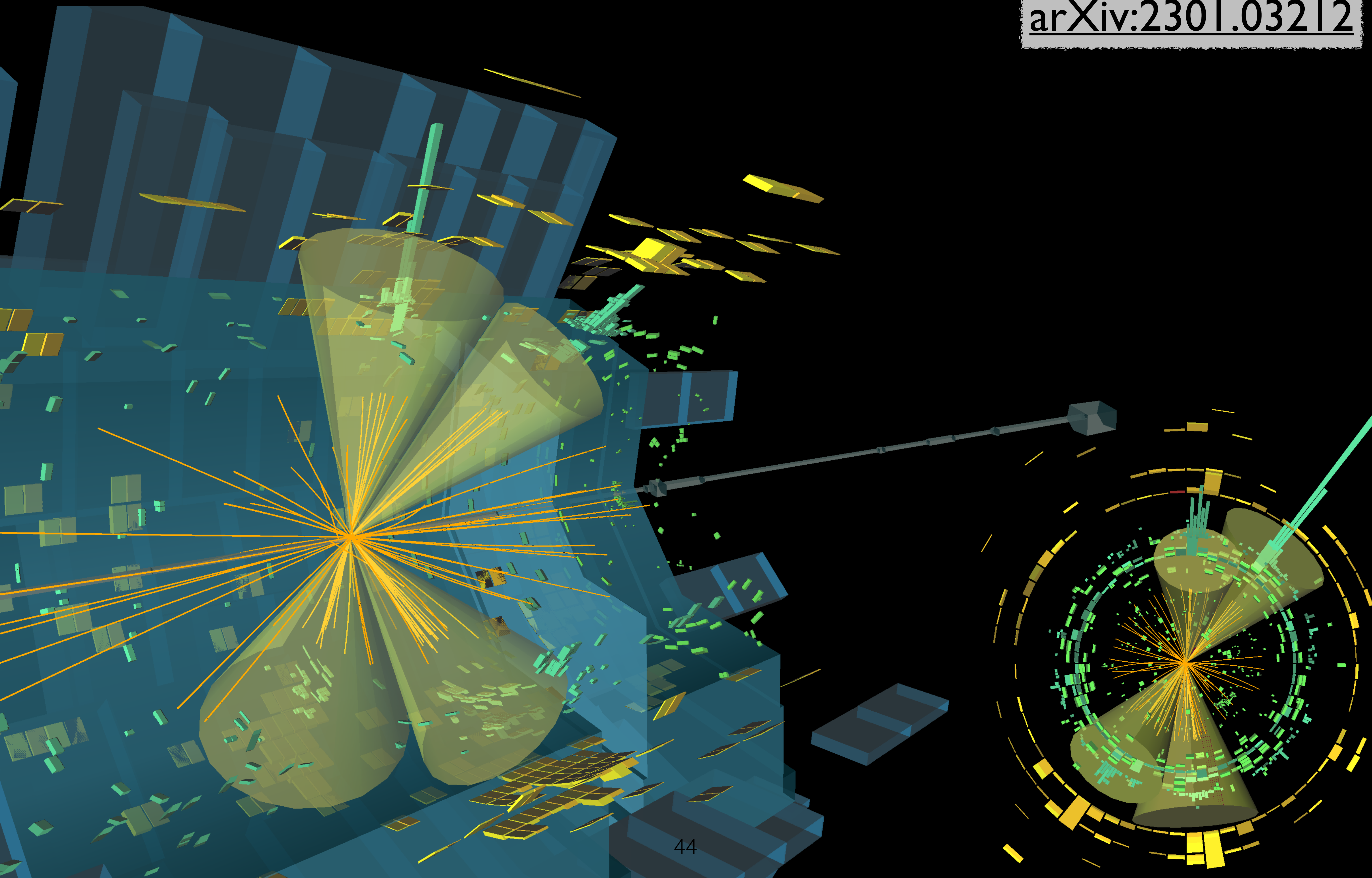
Fits to BDT/NN distribution used for final analysis

Data agrees well with background prediction

$\tau_{had}\tau_{had}$ has strongest sensitivity, but τ_{lep} channels also contribute

$HH \rightarrow b\bar{b}b\bar{b}$

arXiv:2301.03212



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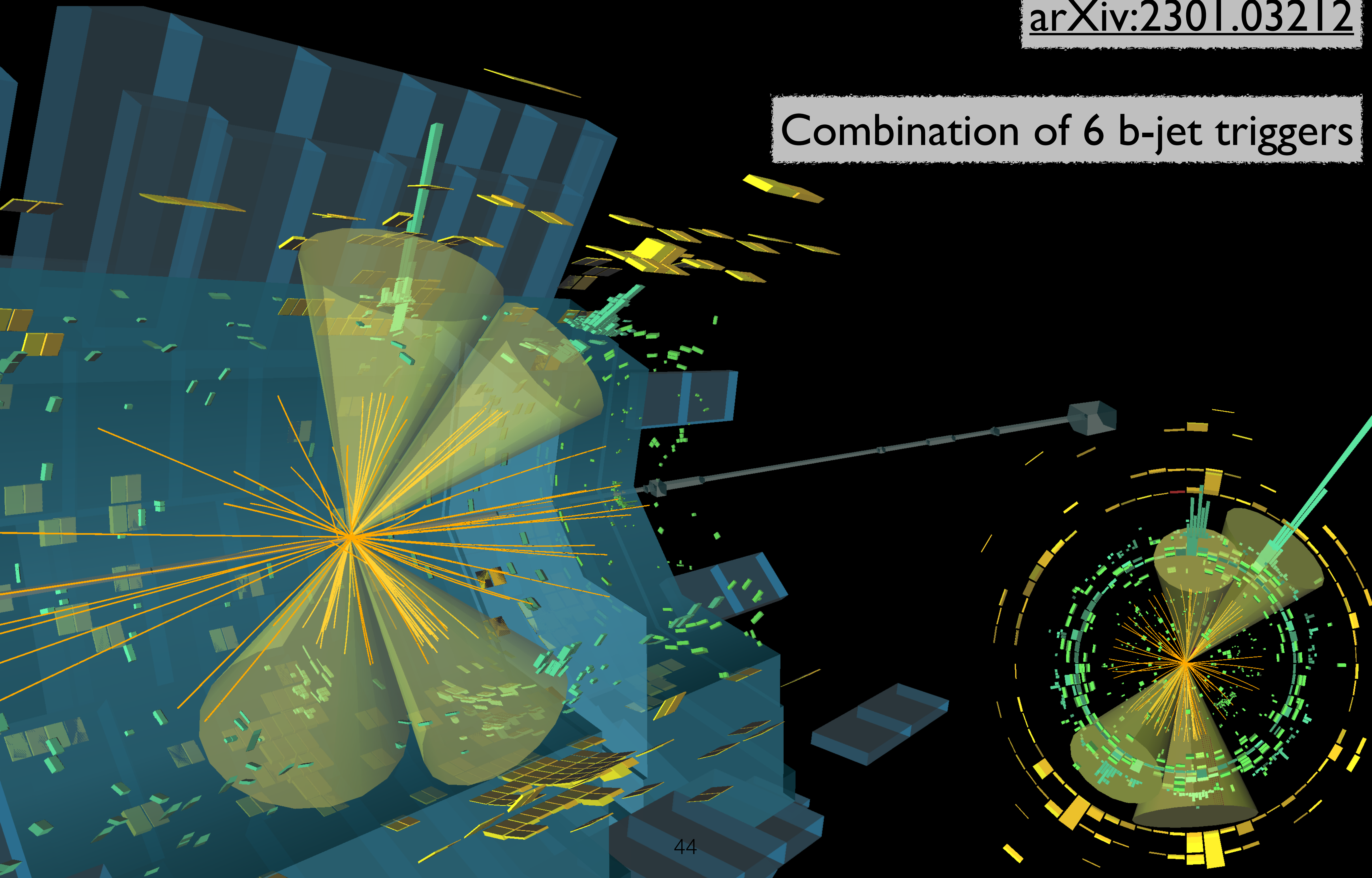
Combination of 6 b-jet triggers



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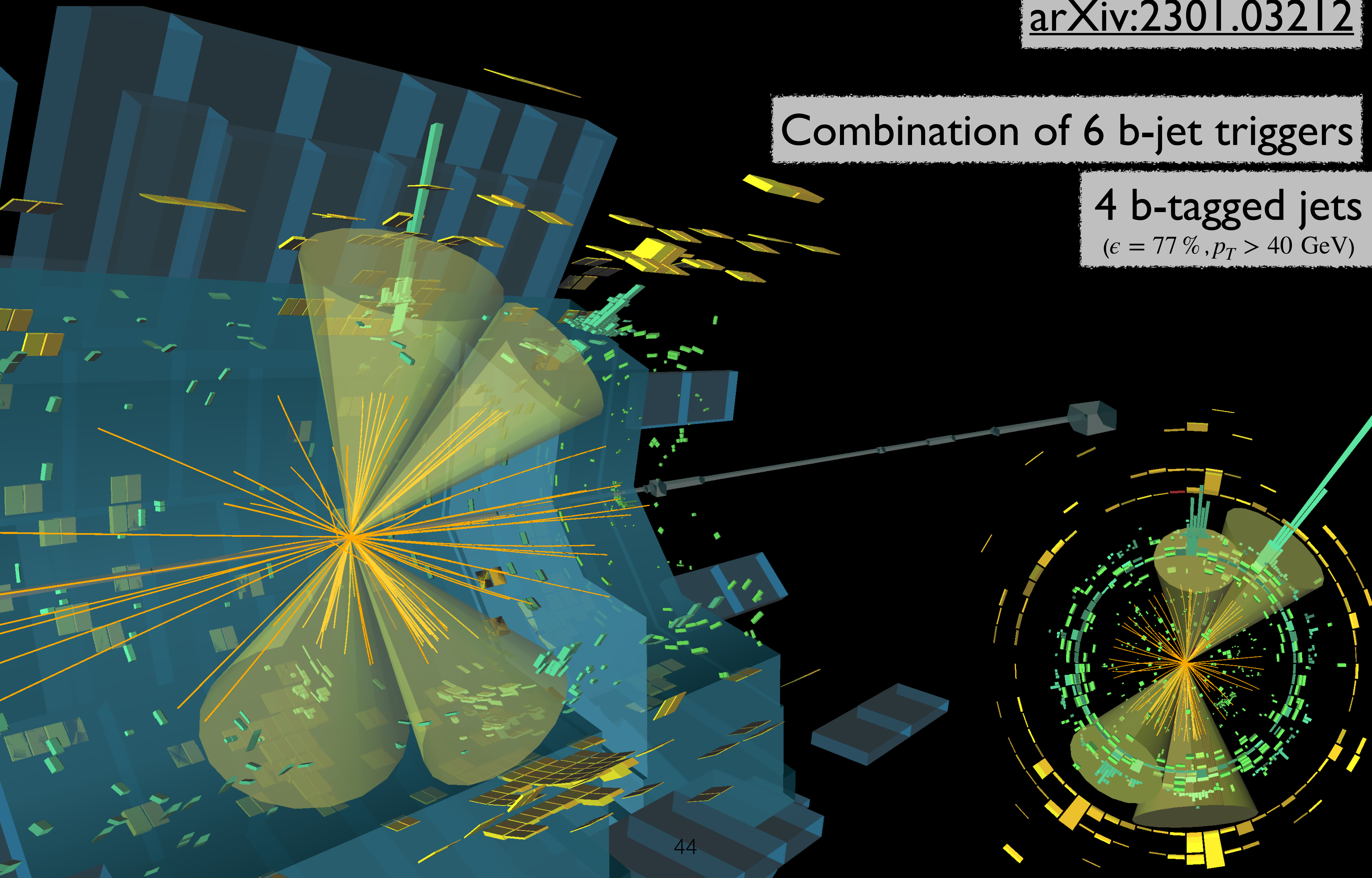
Combination of 6 b-jet triggers

4 b-tagged jets

($\epsilon = 77\,\%\,, p_T > 40$ GeV)



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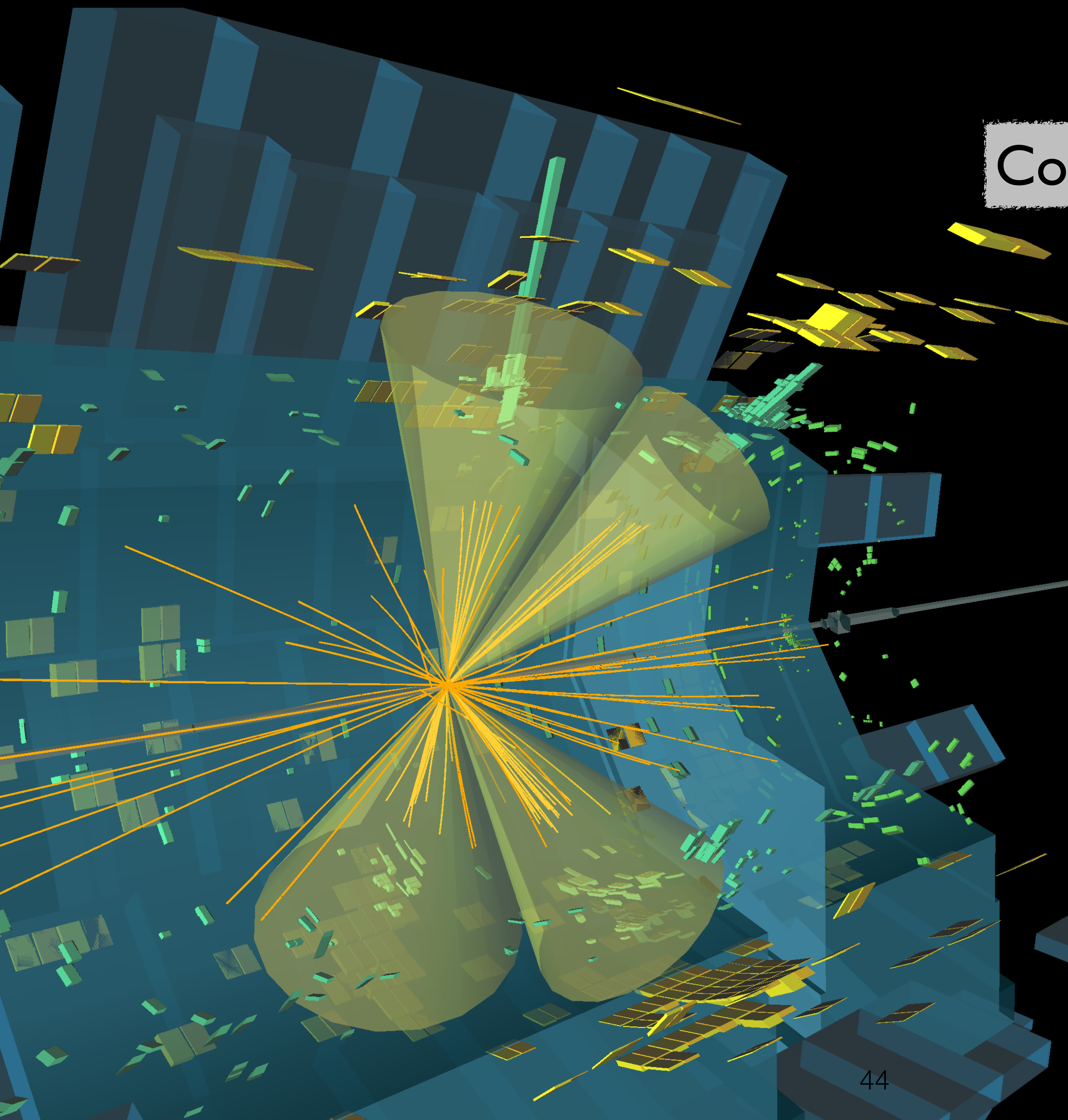
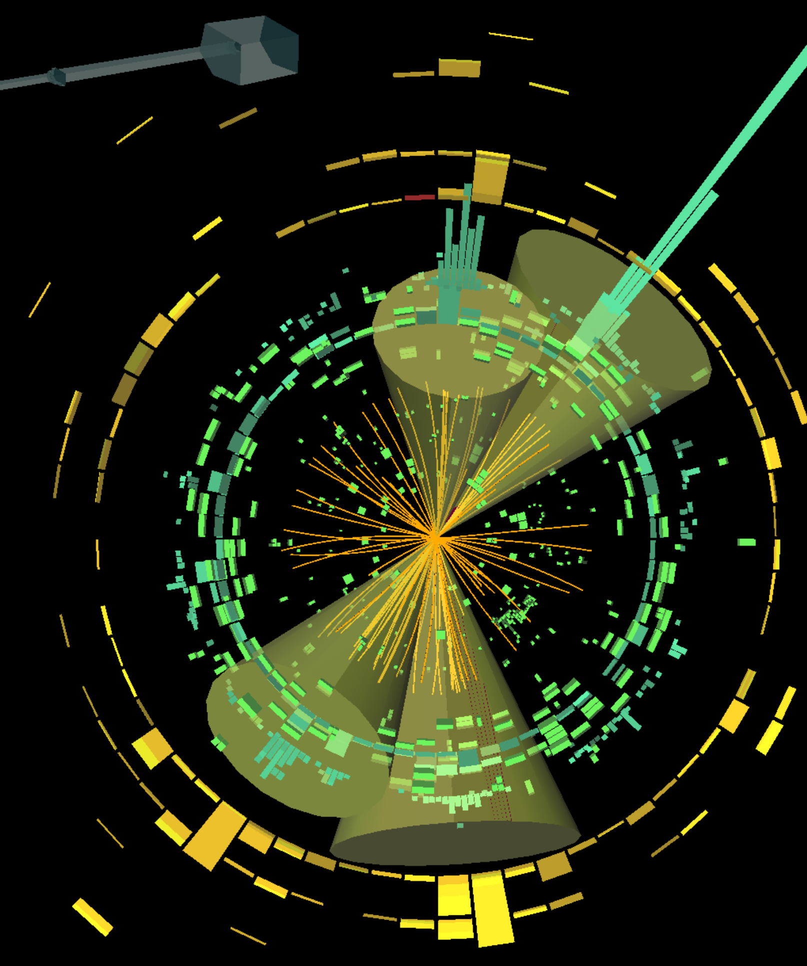
Pair “closest jets” to form Higgs candidates





$HH \to b\bar{b}b\bar{b}$

arXiv:2301.03212

Extremely challenging signature:
Large signal, but large backgrounds,
And difficult to simulate!

Combination of 6 b-jet triggers

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($\epsilon = 77\,\%\,, p_T > 40$ GeV)

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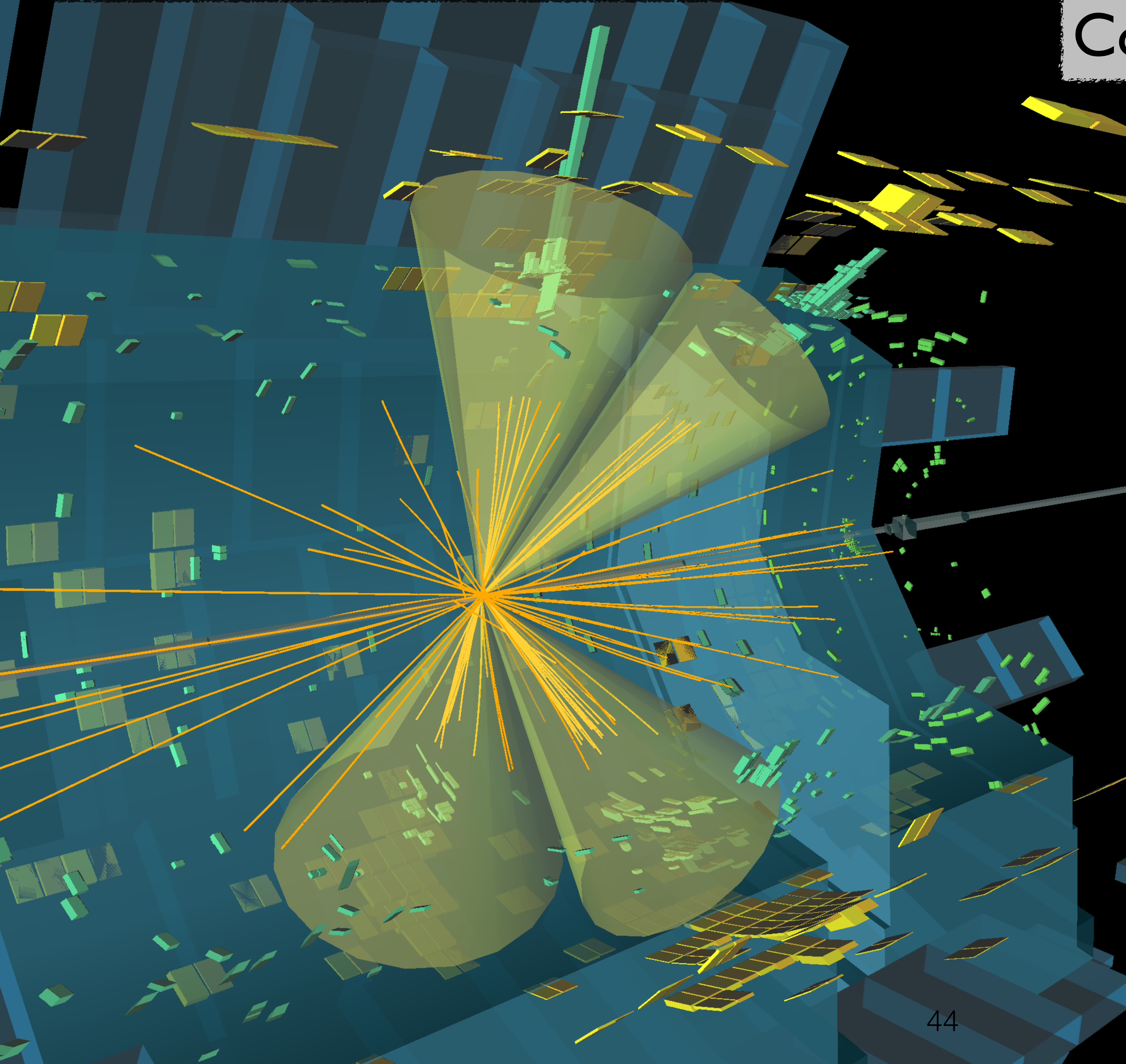
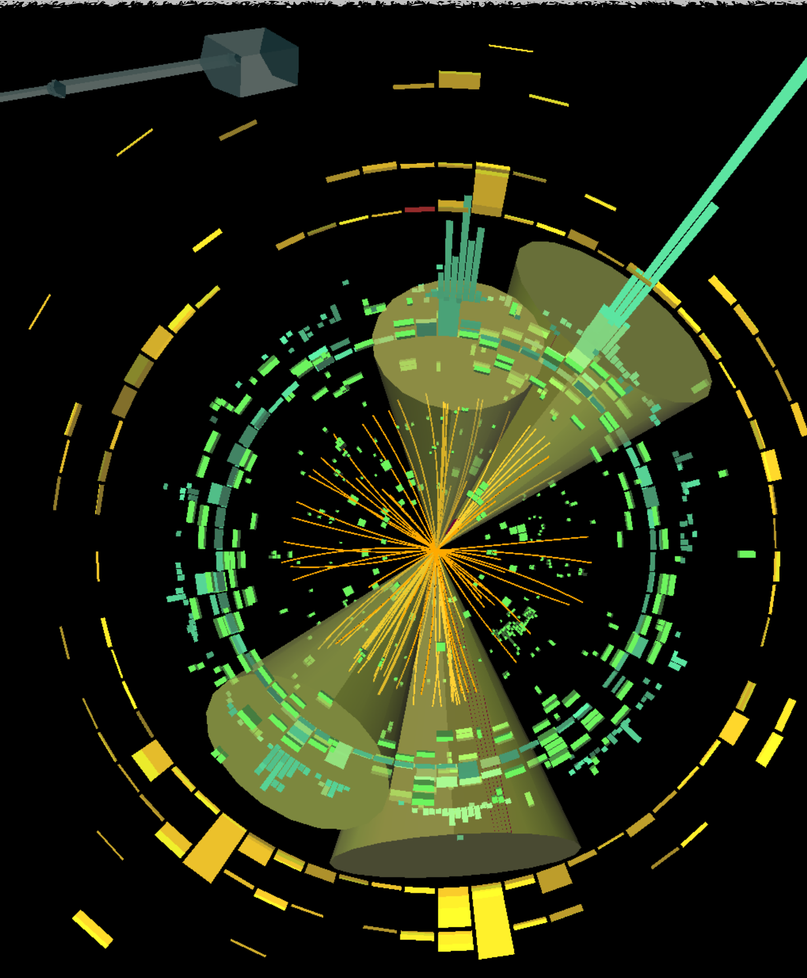




Triggering on *b*-jets

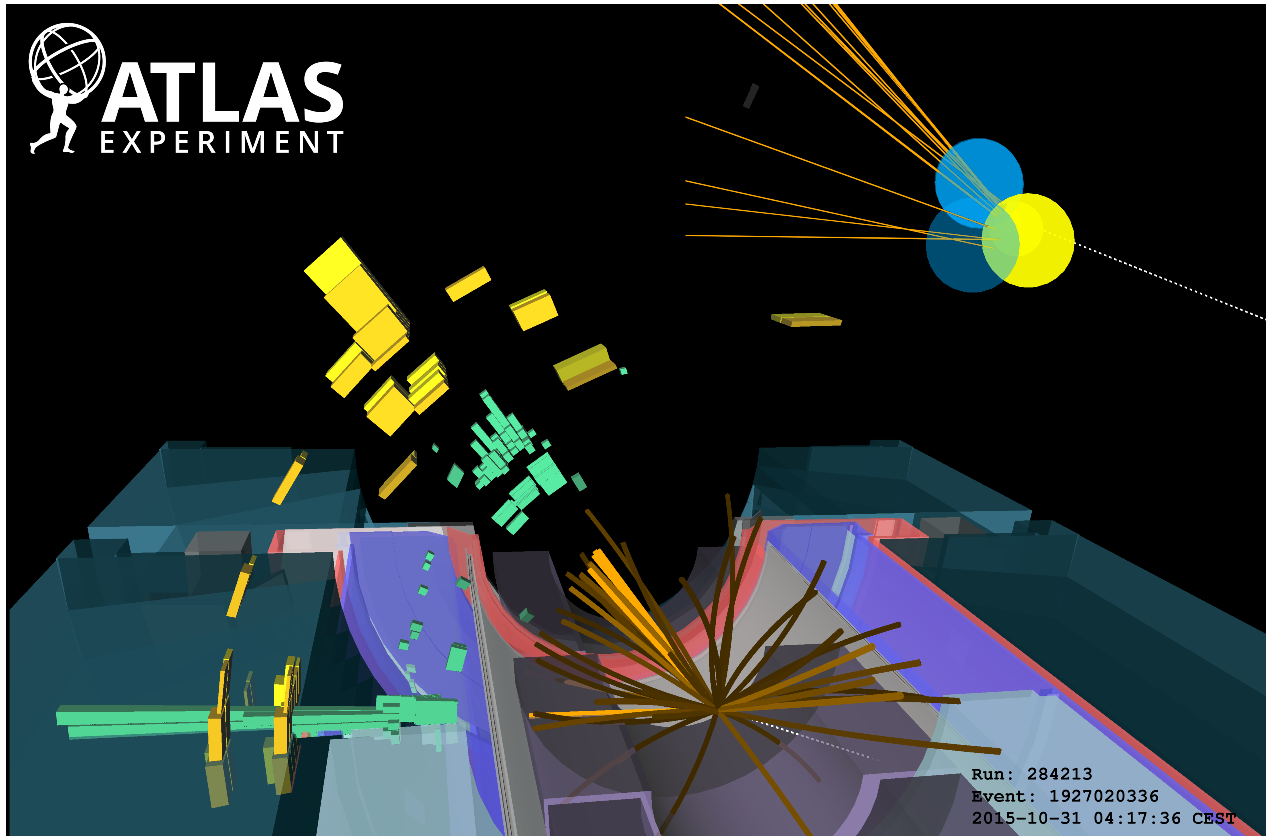
Eur. Phys. J. C 81 (2021) 1087

Triggering on b-jets

Eur. Phys. J. C 81 (2021) 1087

Multi-jet background rates are **huge**:

Utilize b-tagging in the trigger to manage the rates!



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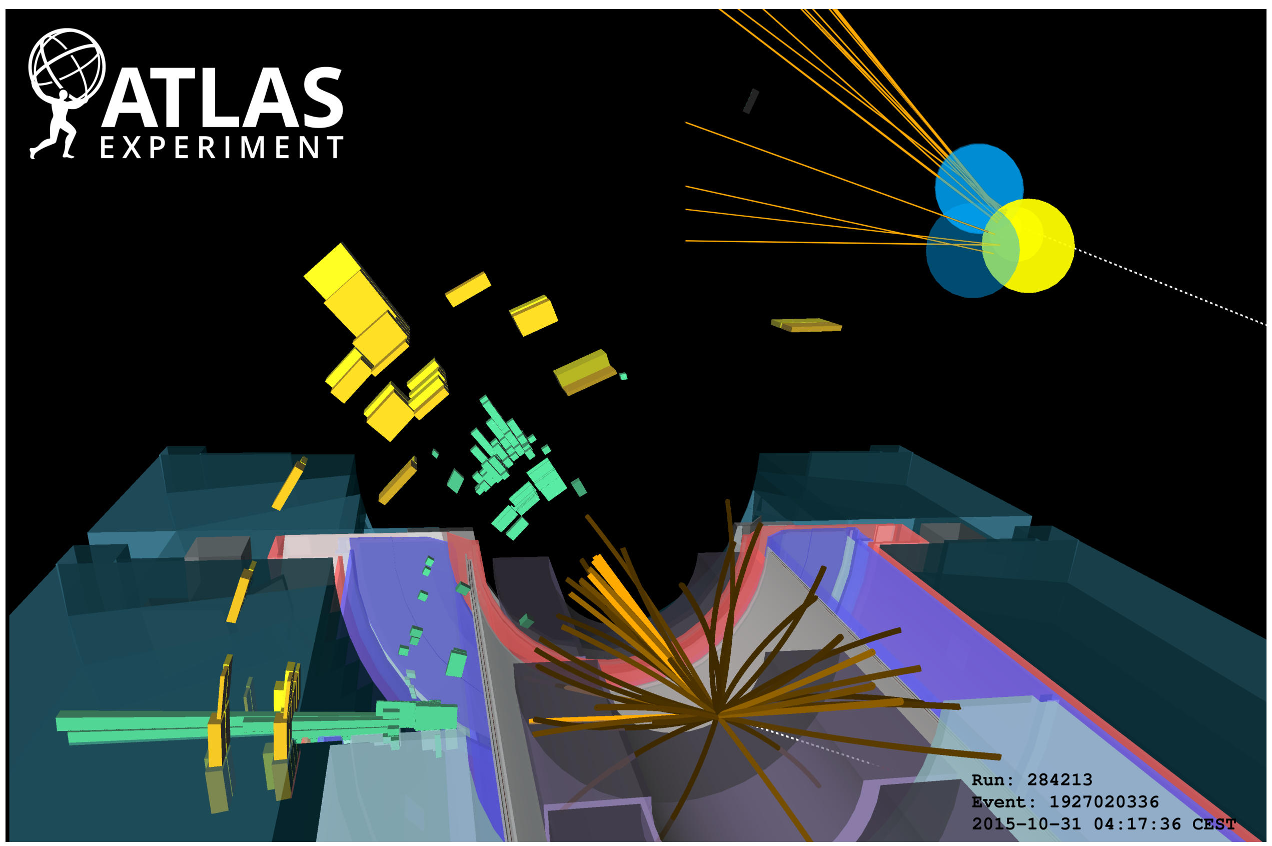

Fast b-tagging is enormously complicated: huge optimization game for speed and performance

Triggering on b-jets

Eur. Phys. J. C 81 (2021) 1087

Multi-jet background rates are **huge**:
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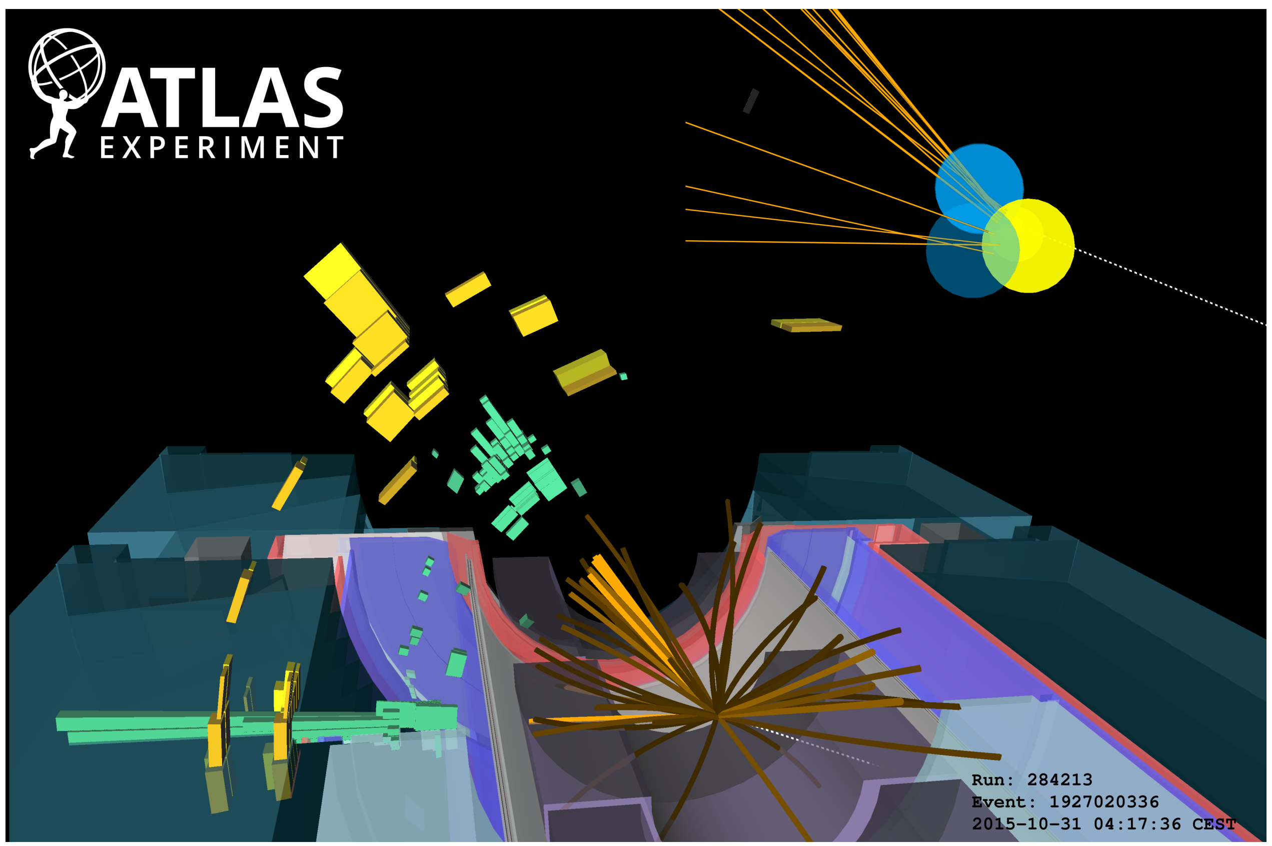

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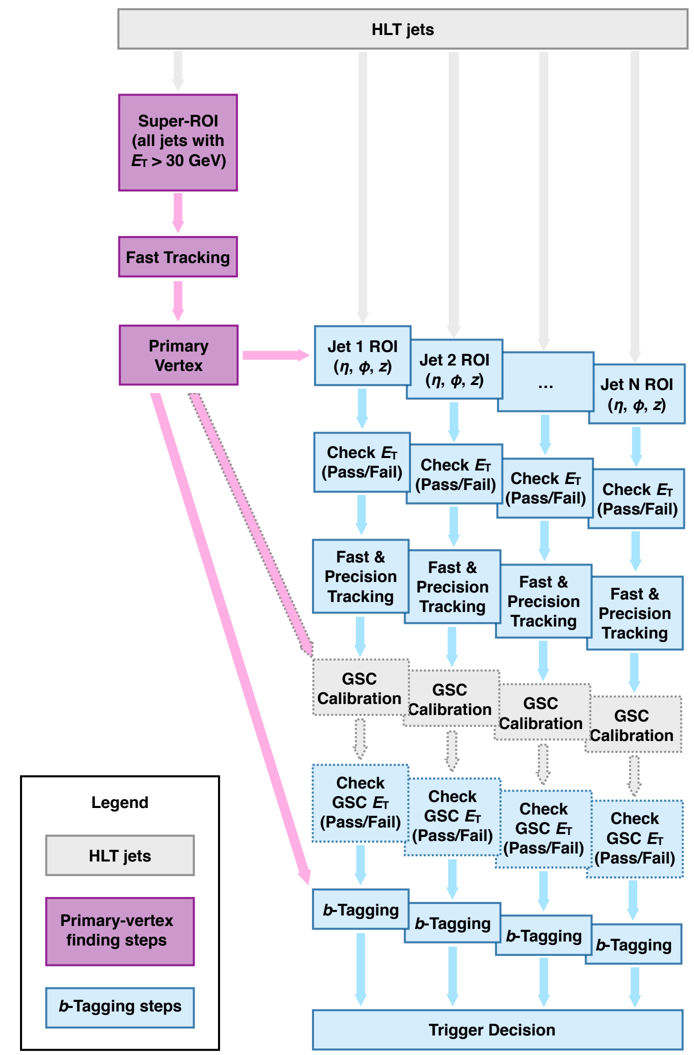

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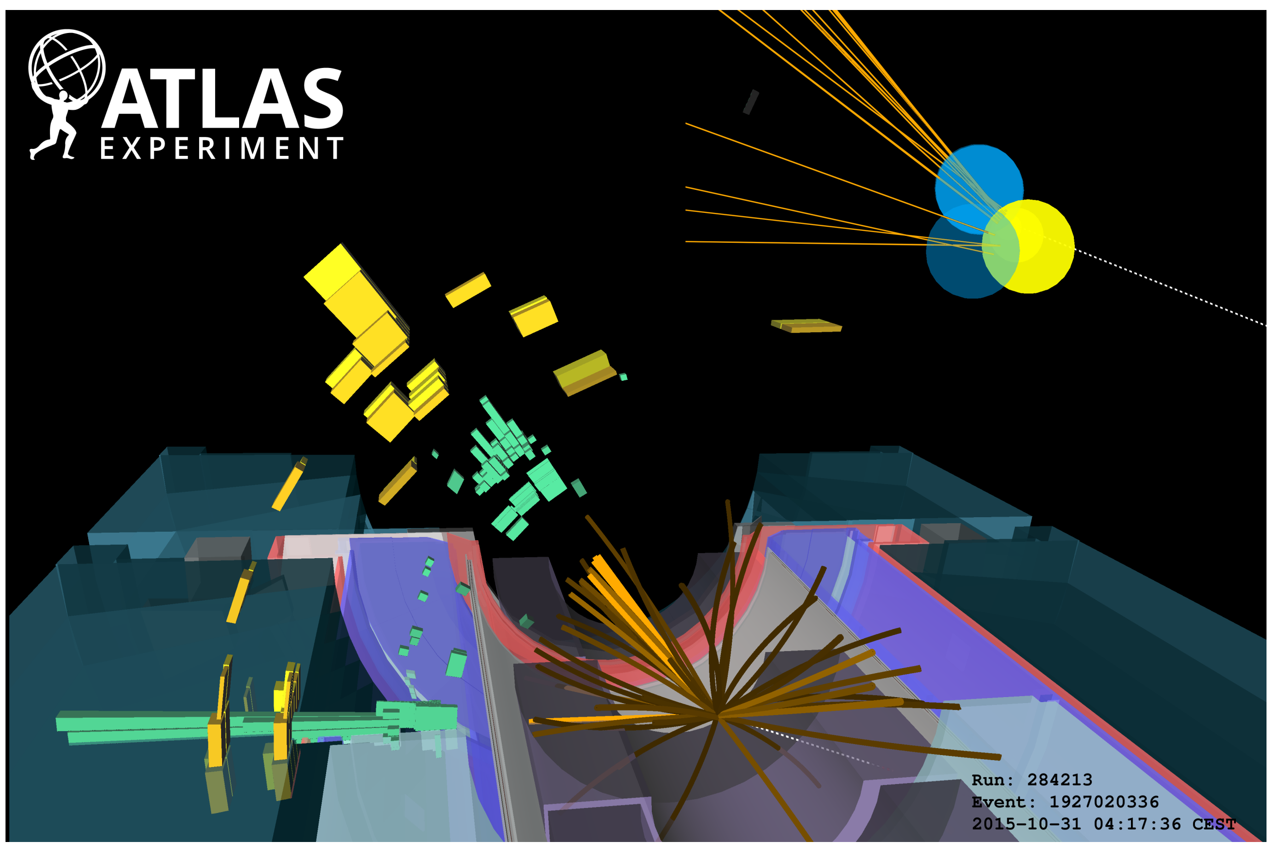

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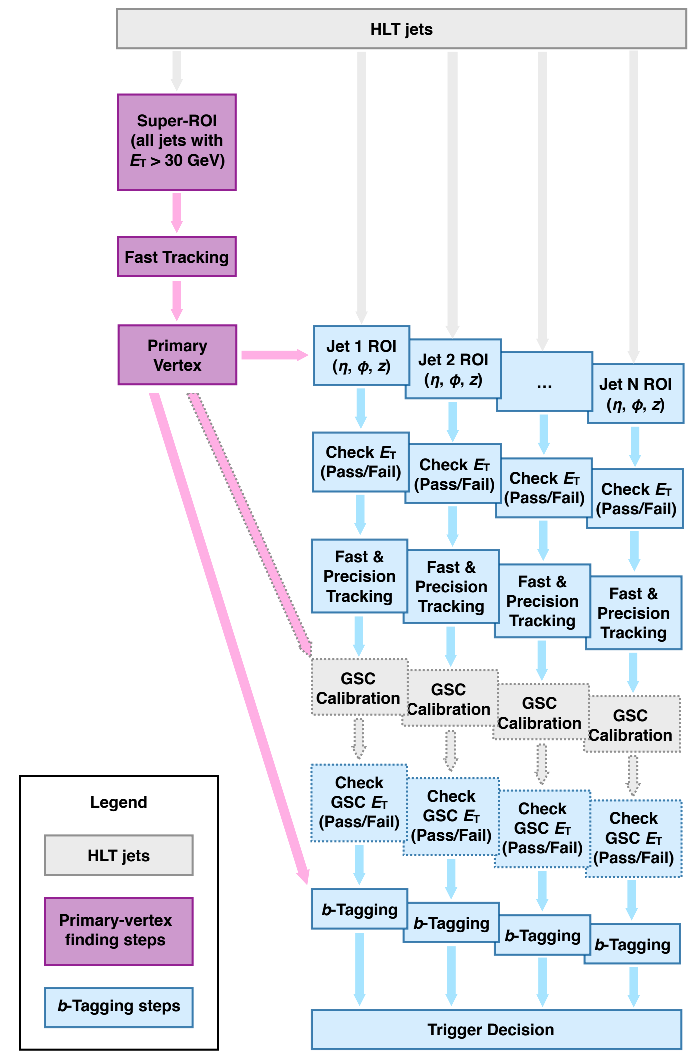
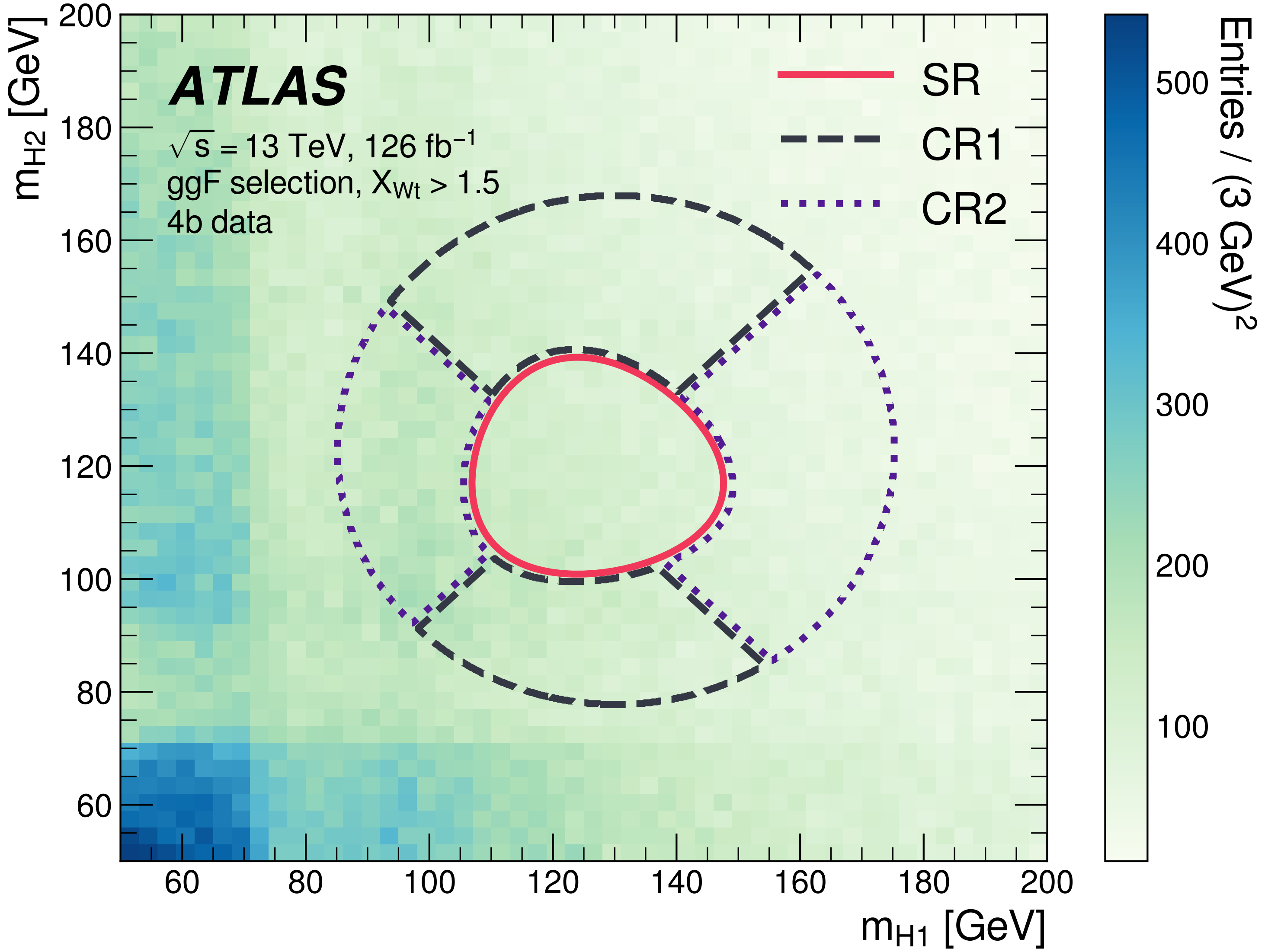


Enables efficient recording of 4 jets with $p_T > 45$ GeV,
and only 2 b-tags online

$b\bar{b}b\bar{b}$ Analysis Strategy



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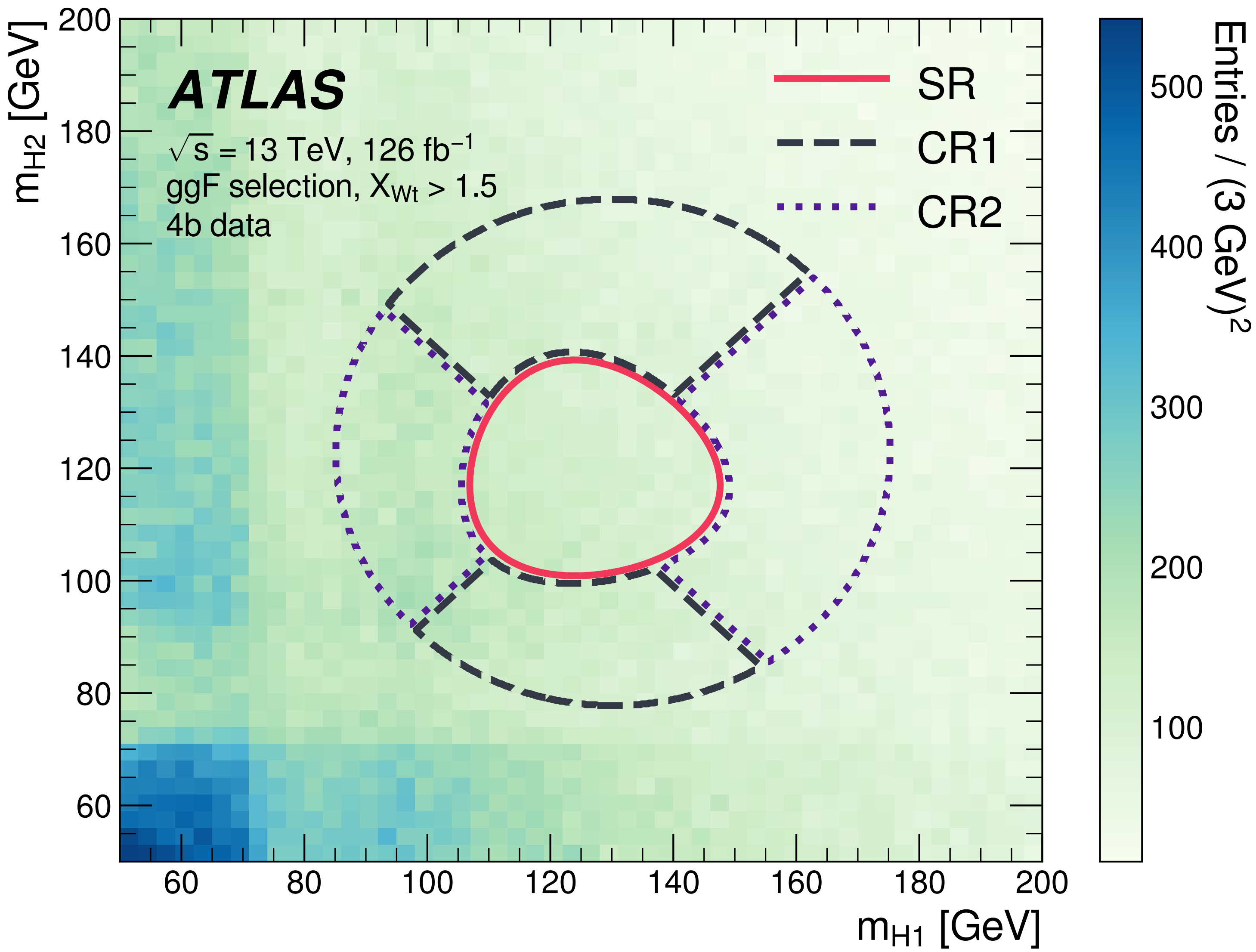

Reconstruct Higgs candidates, form "mass plane"

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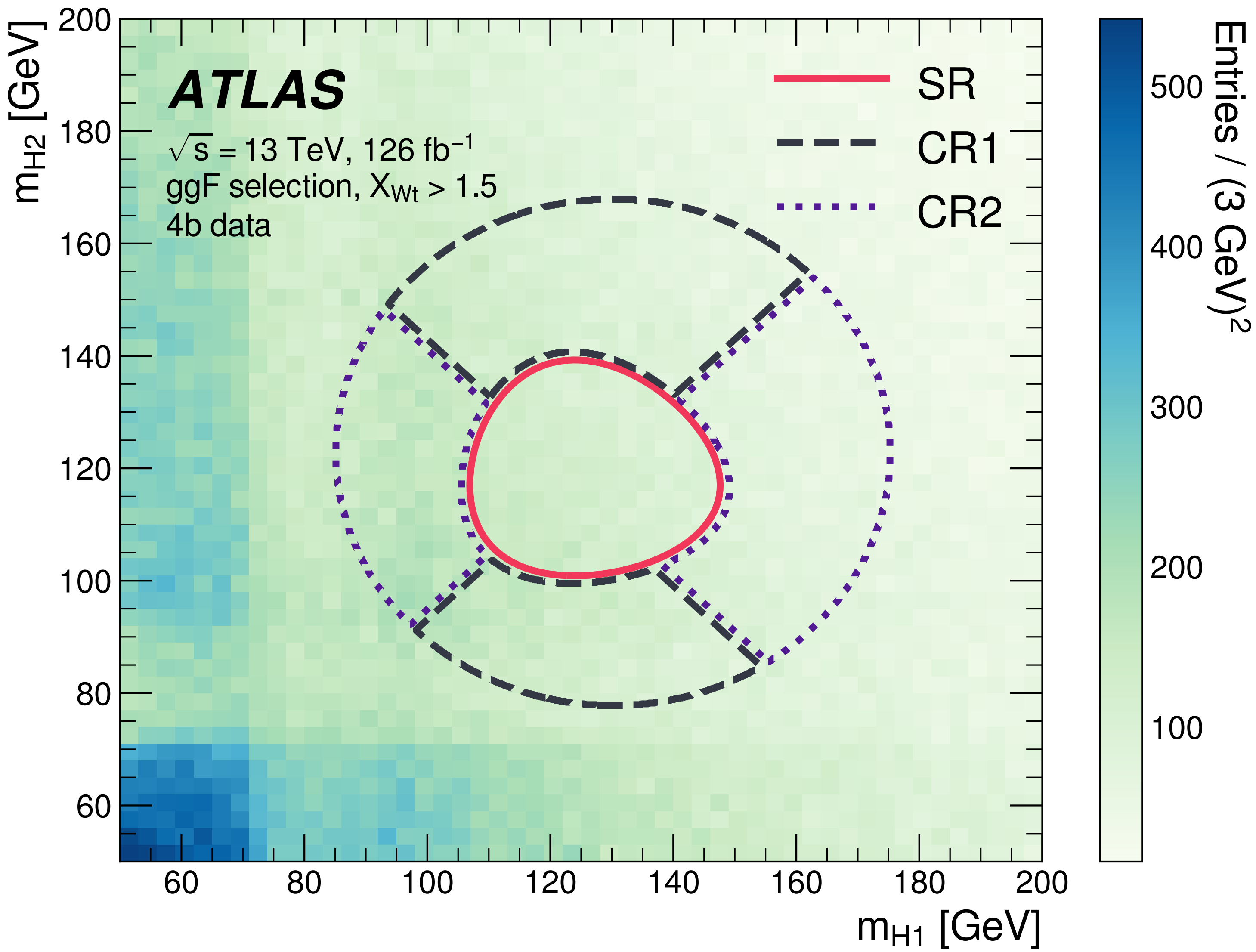

Reconstruct Higgs candidates, form "mass plane"

Center is signal-like; outer regions used for background and background validation

$b\bar{b}b\bar{b}$ Background

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Step 0: form "mass planes"
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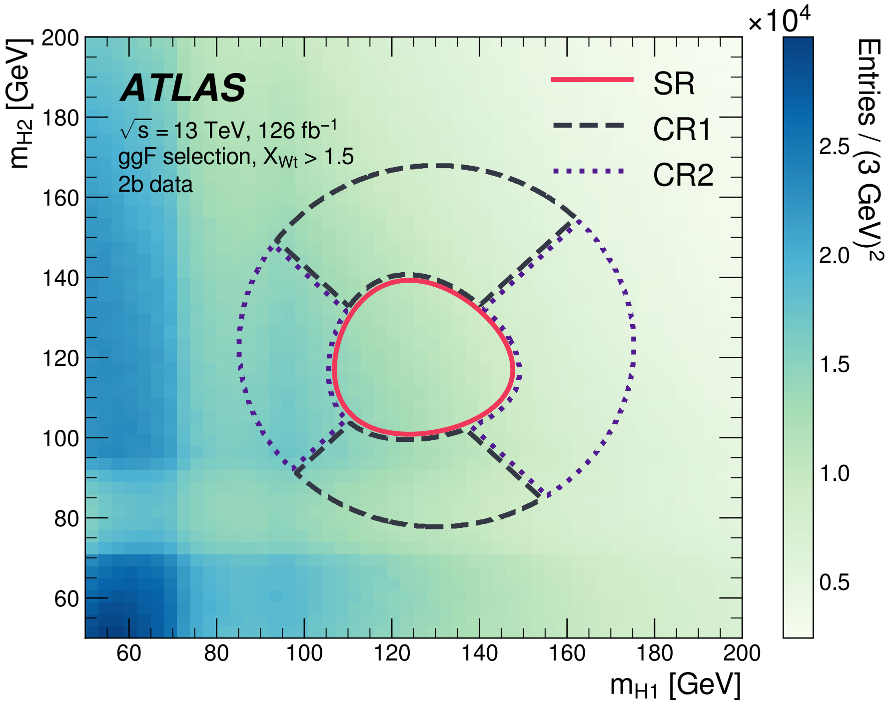

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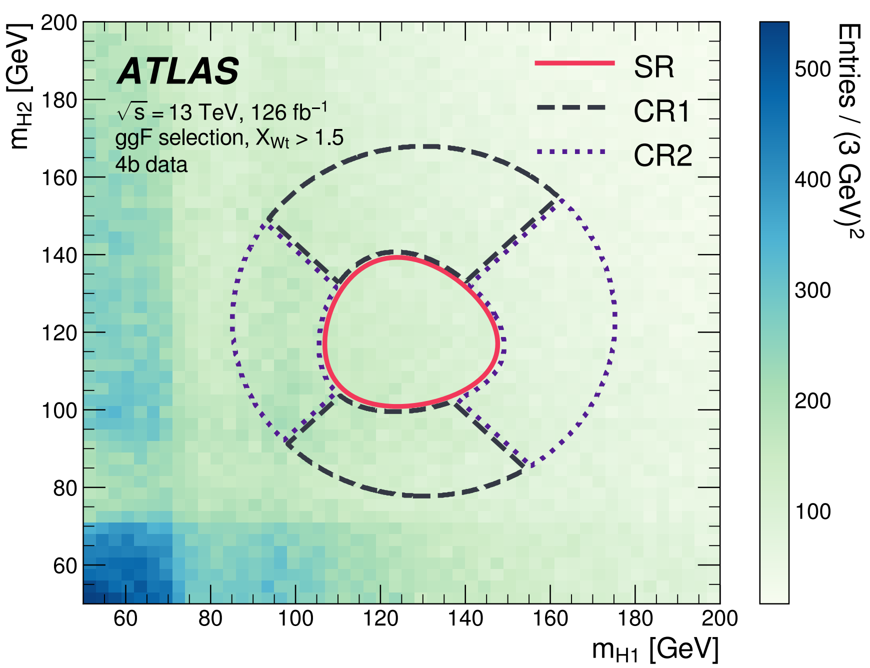

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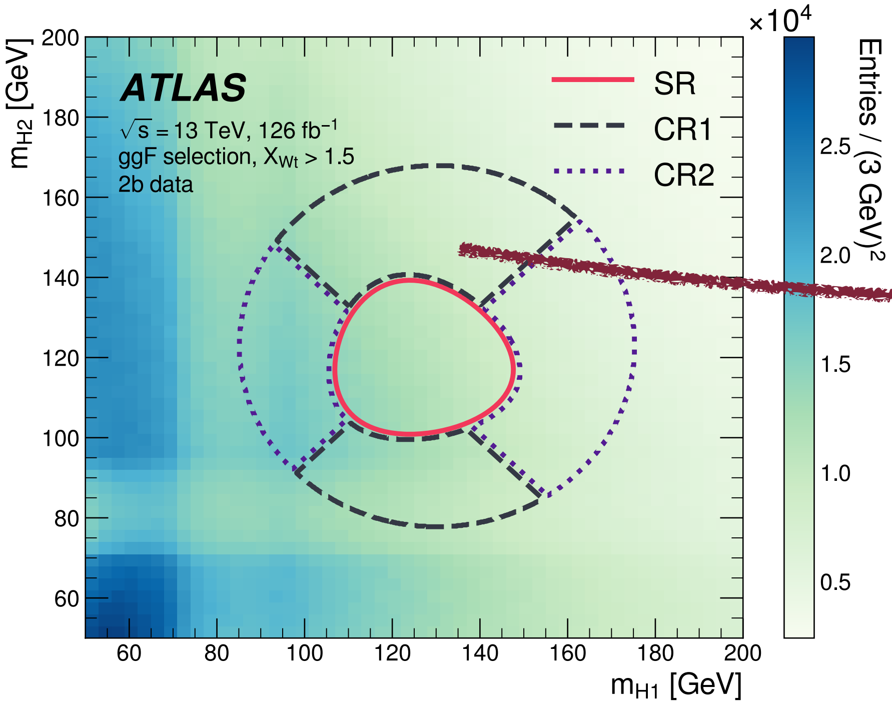

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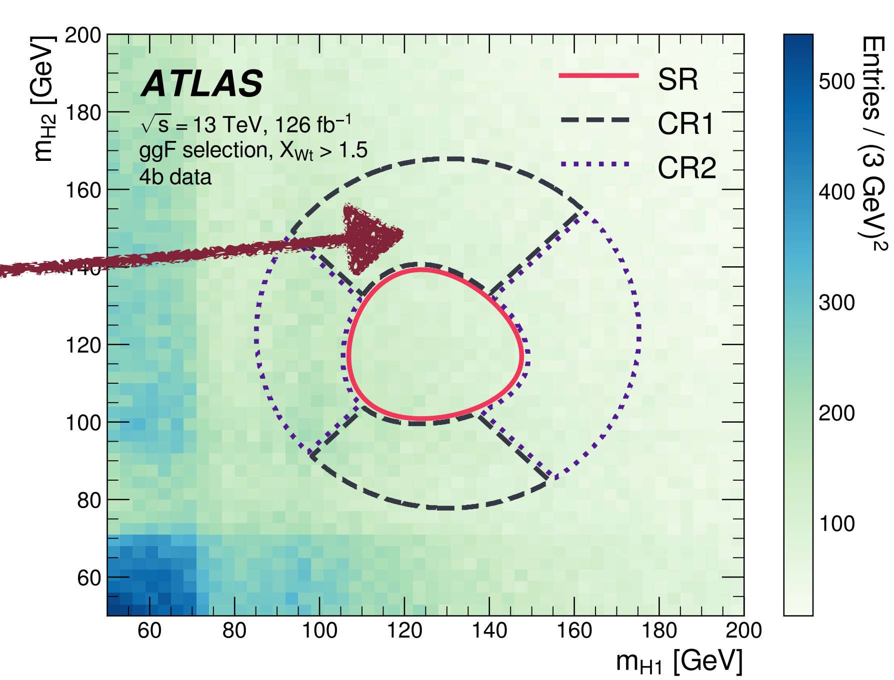

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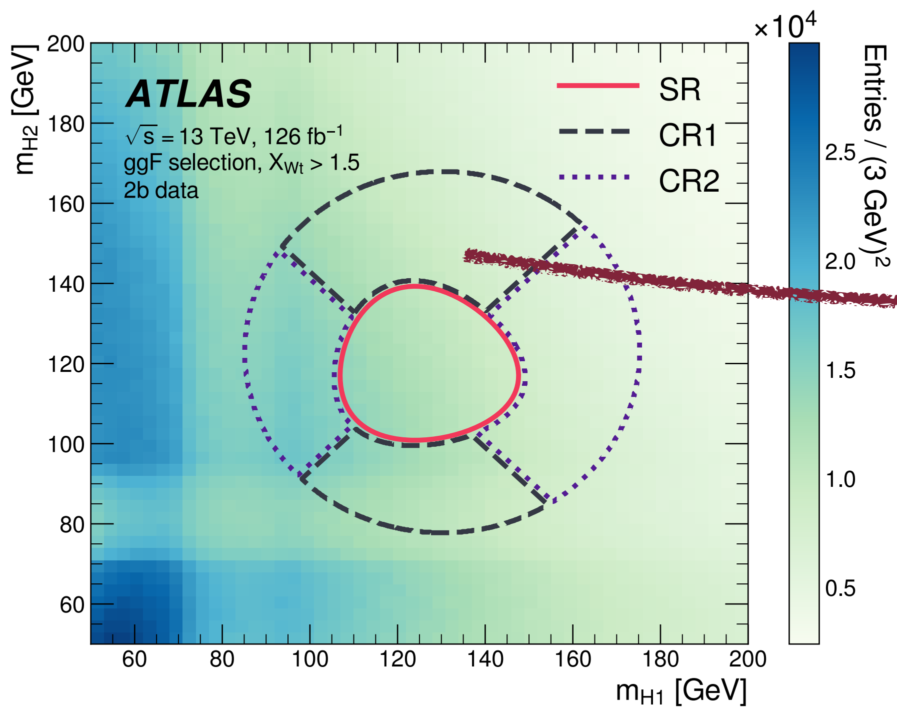

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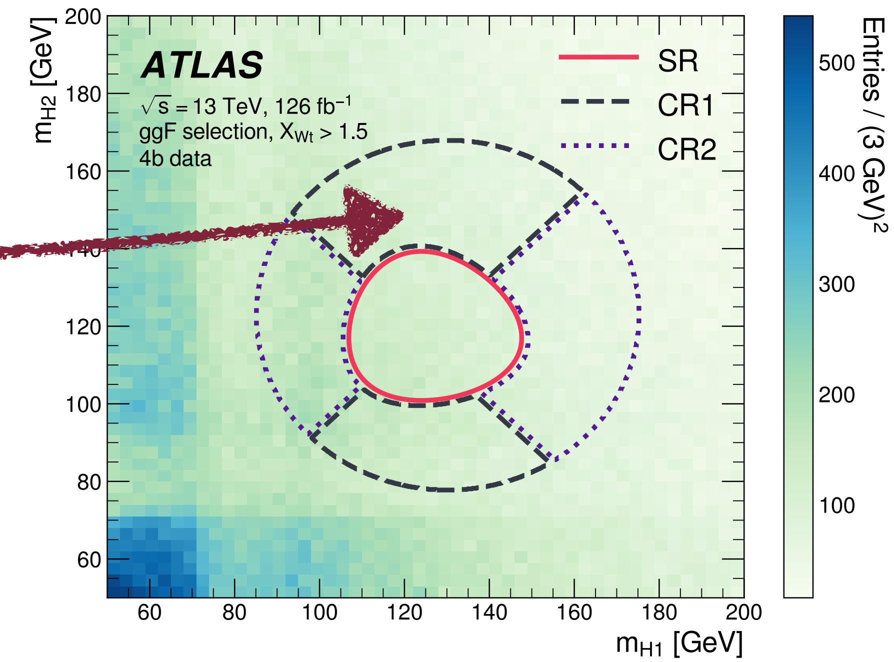

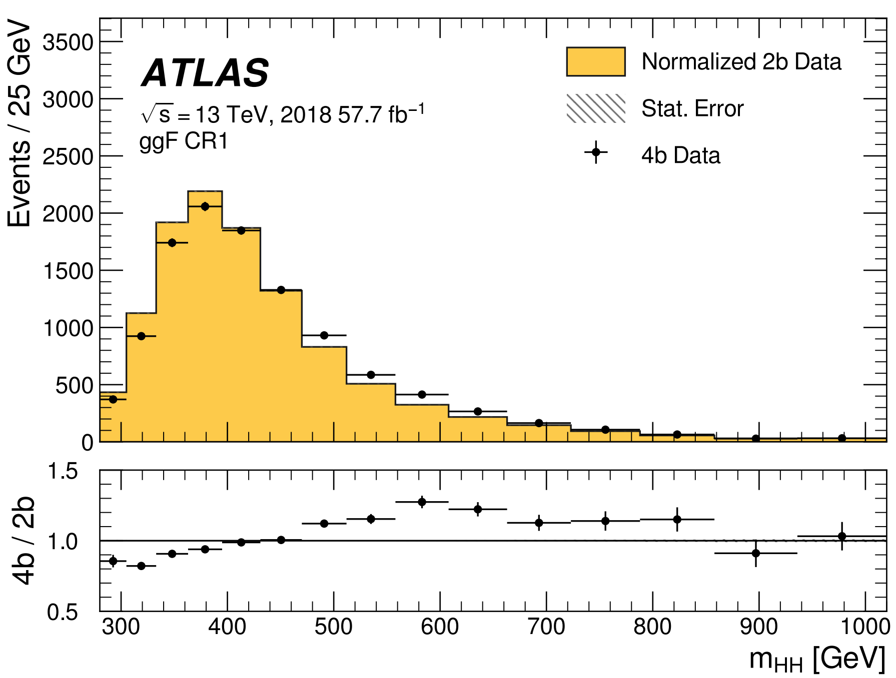

Orange histogram comes from 2b, black points from 4b

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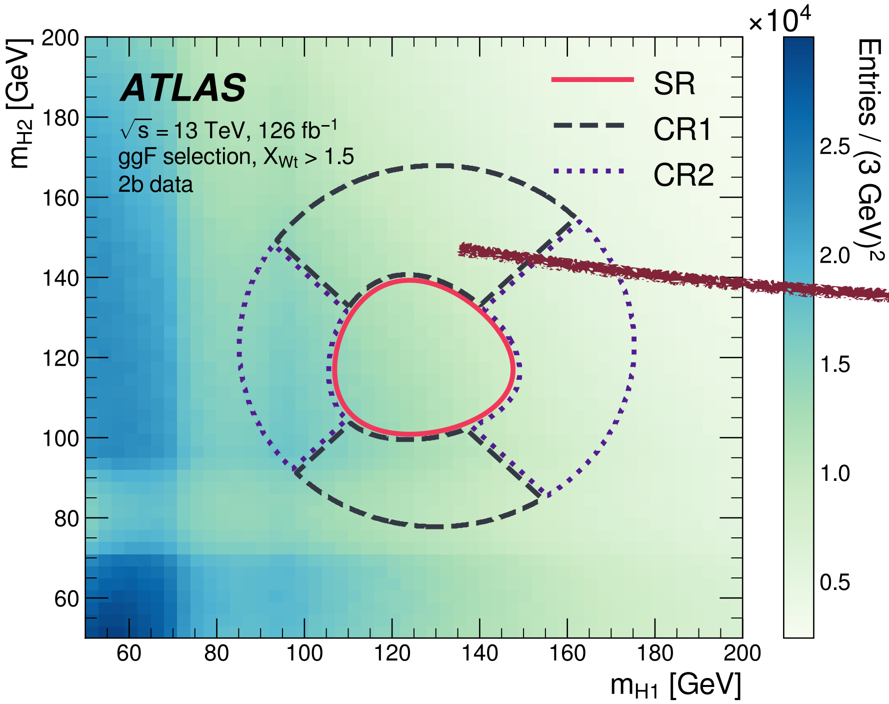

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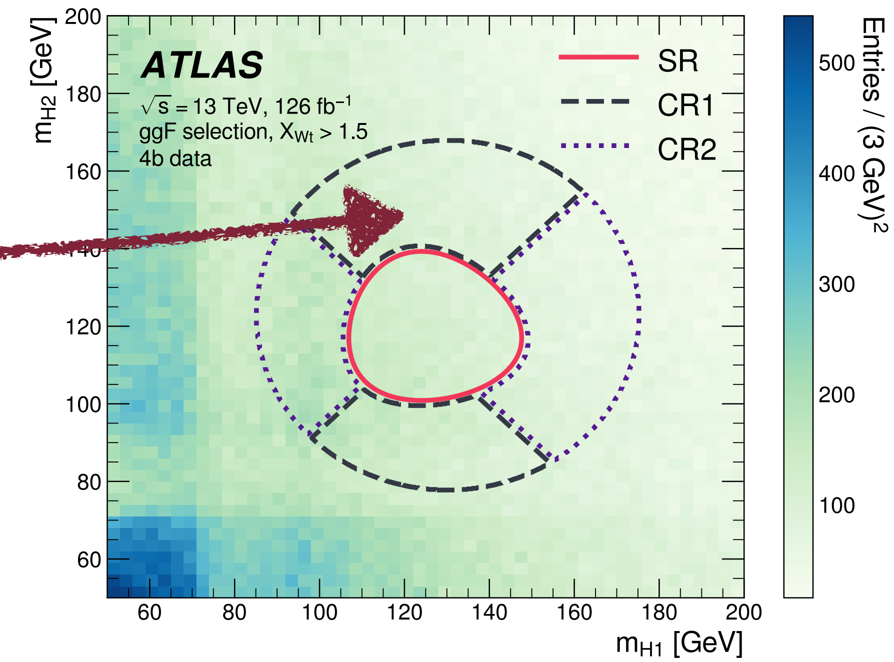

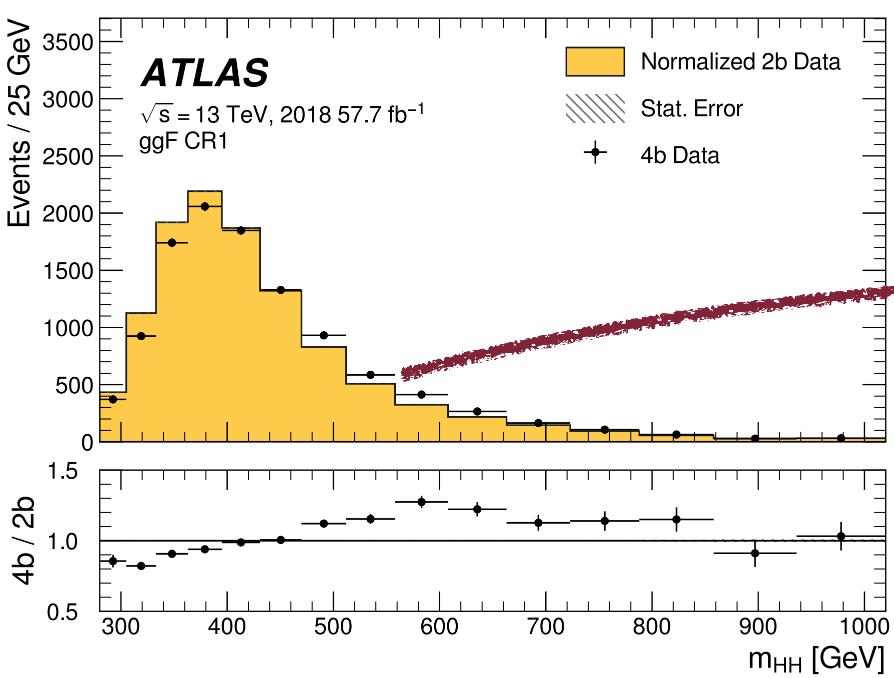

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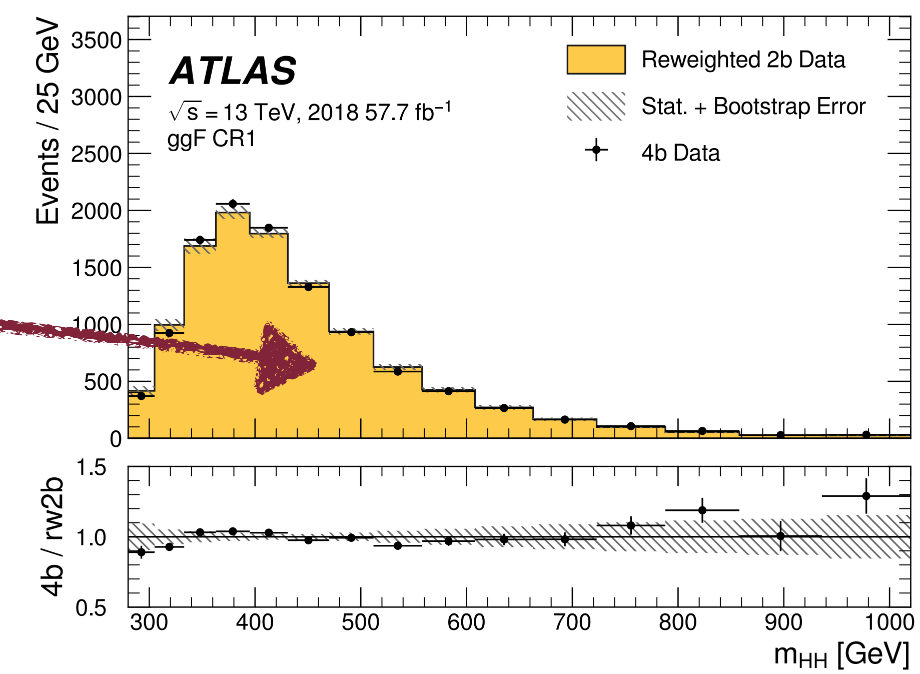
Neural network training



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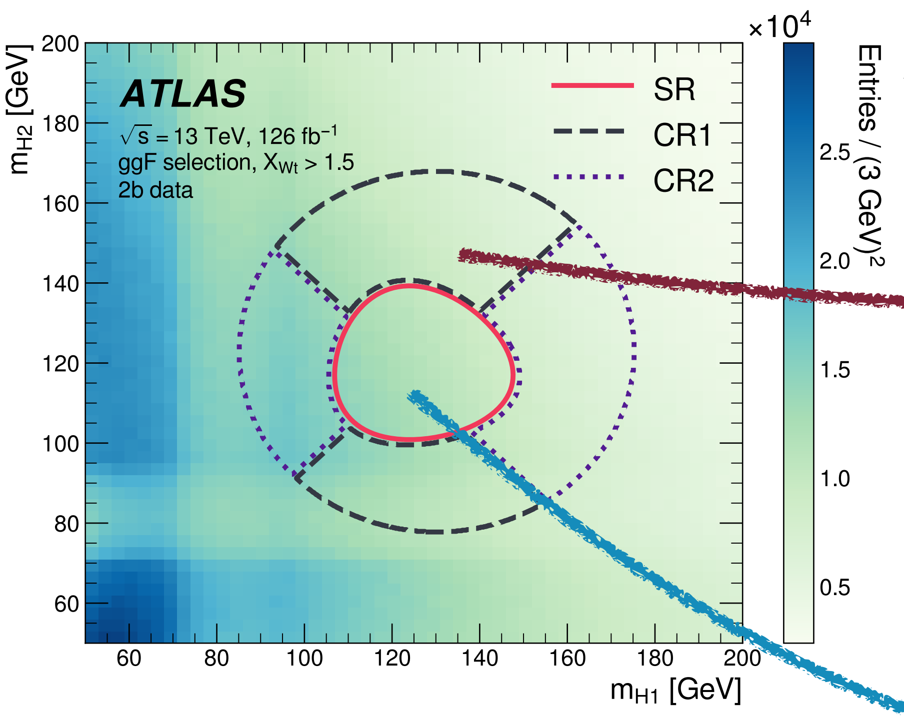

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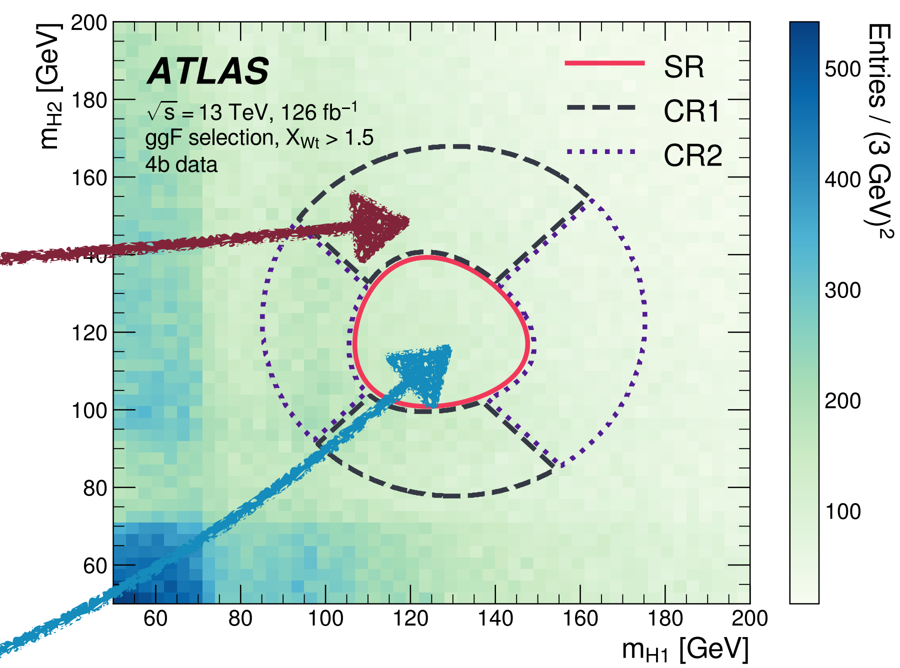

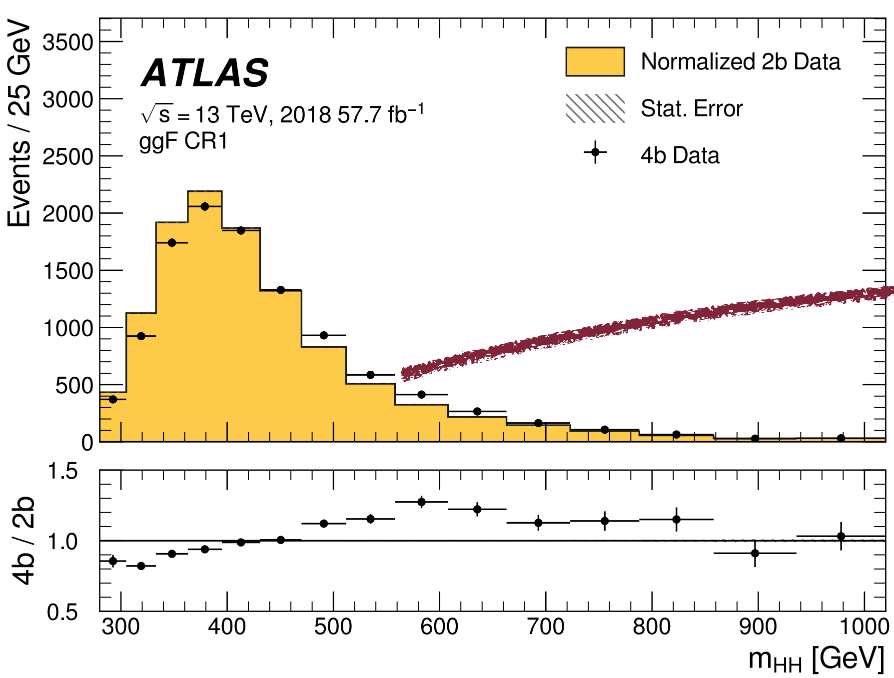

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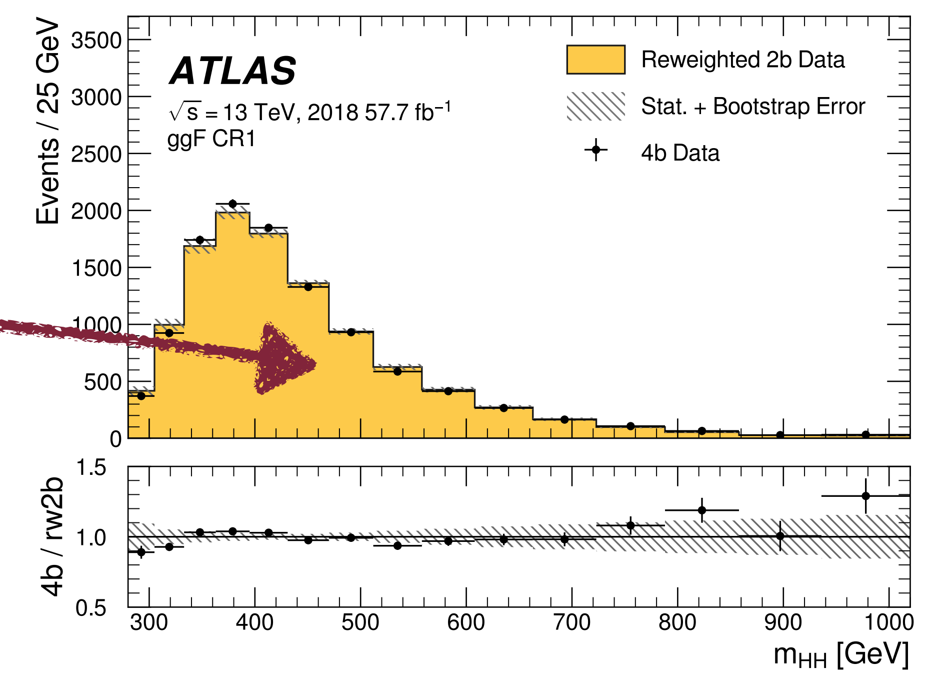

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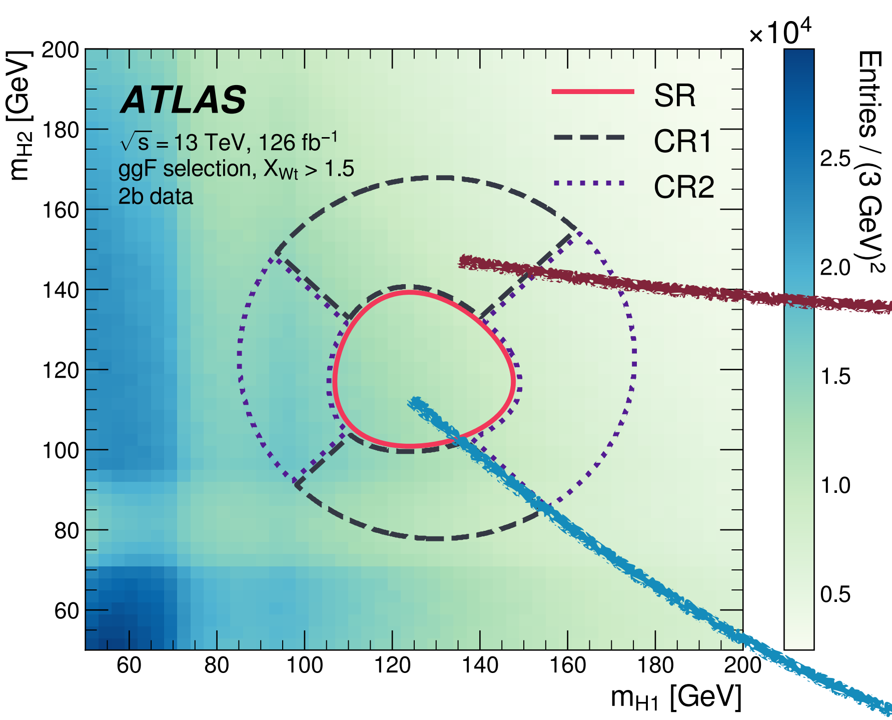

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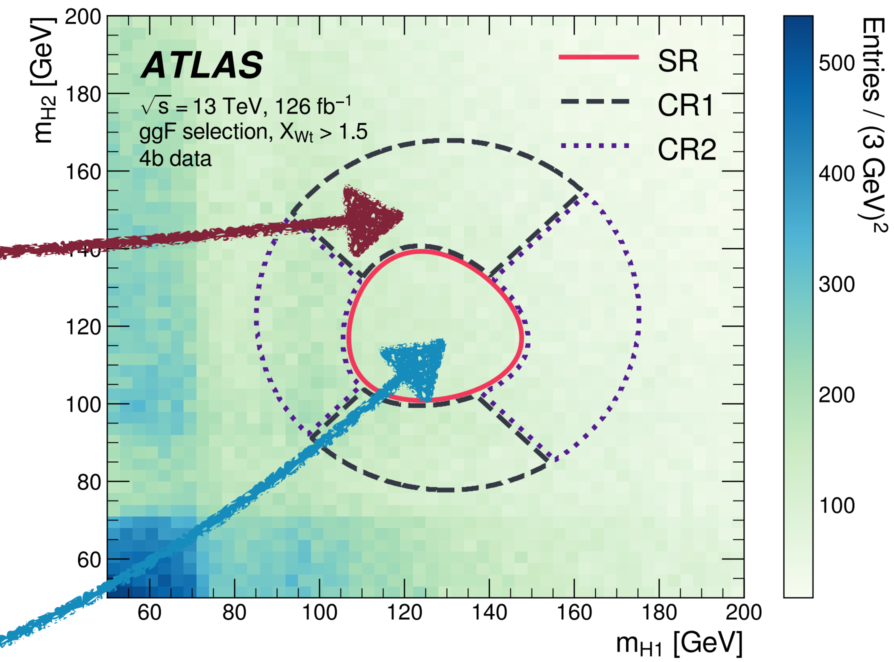

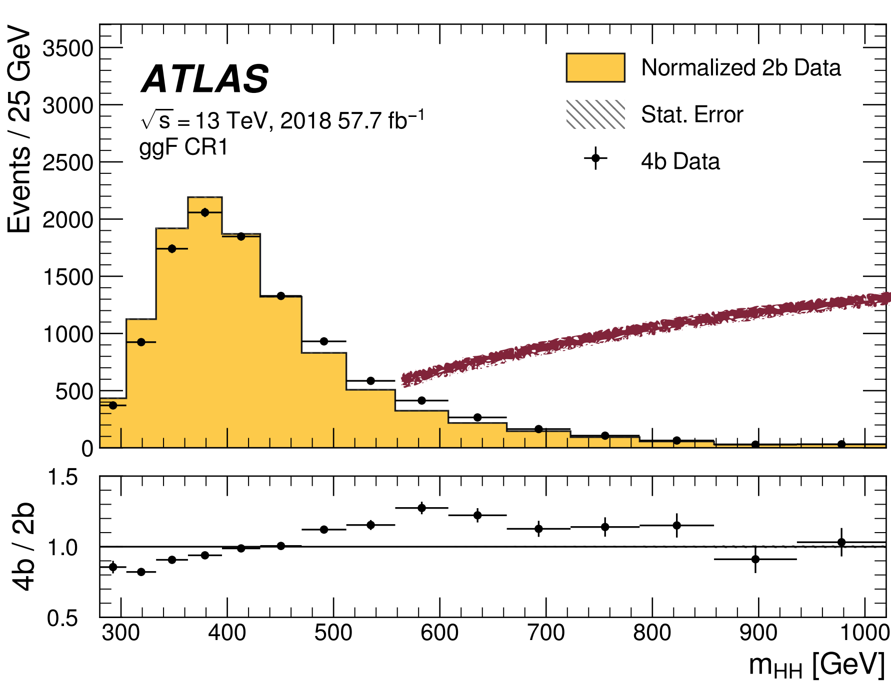

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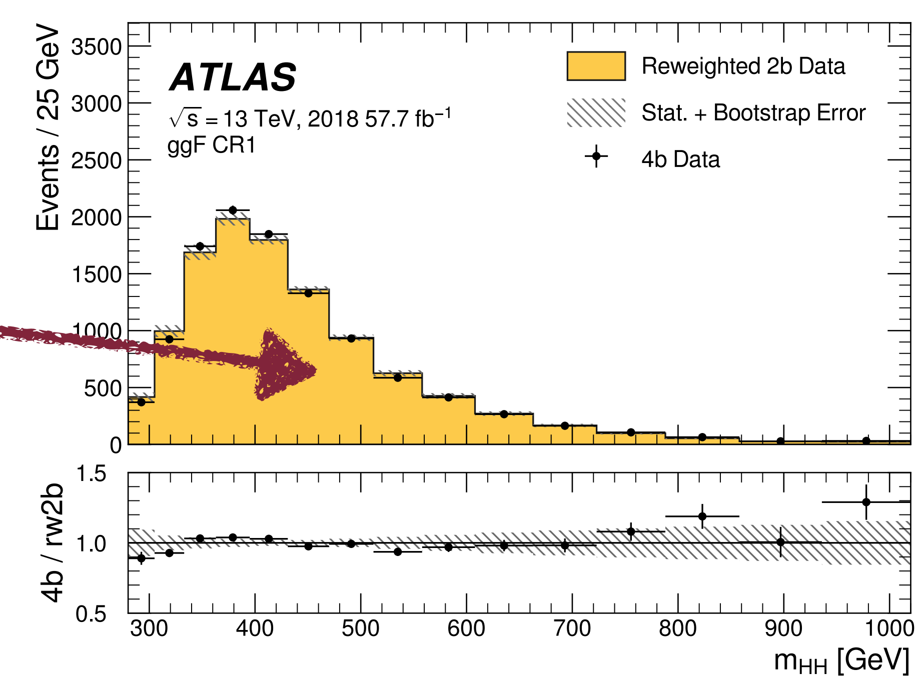
Neural network training

Systematics from alternate regions



Systematic Uncertainties

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Many usual types of uncertainties (alternate regions, etc.)

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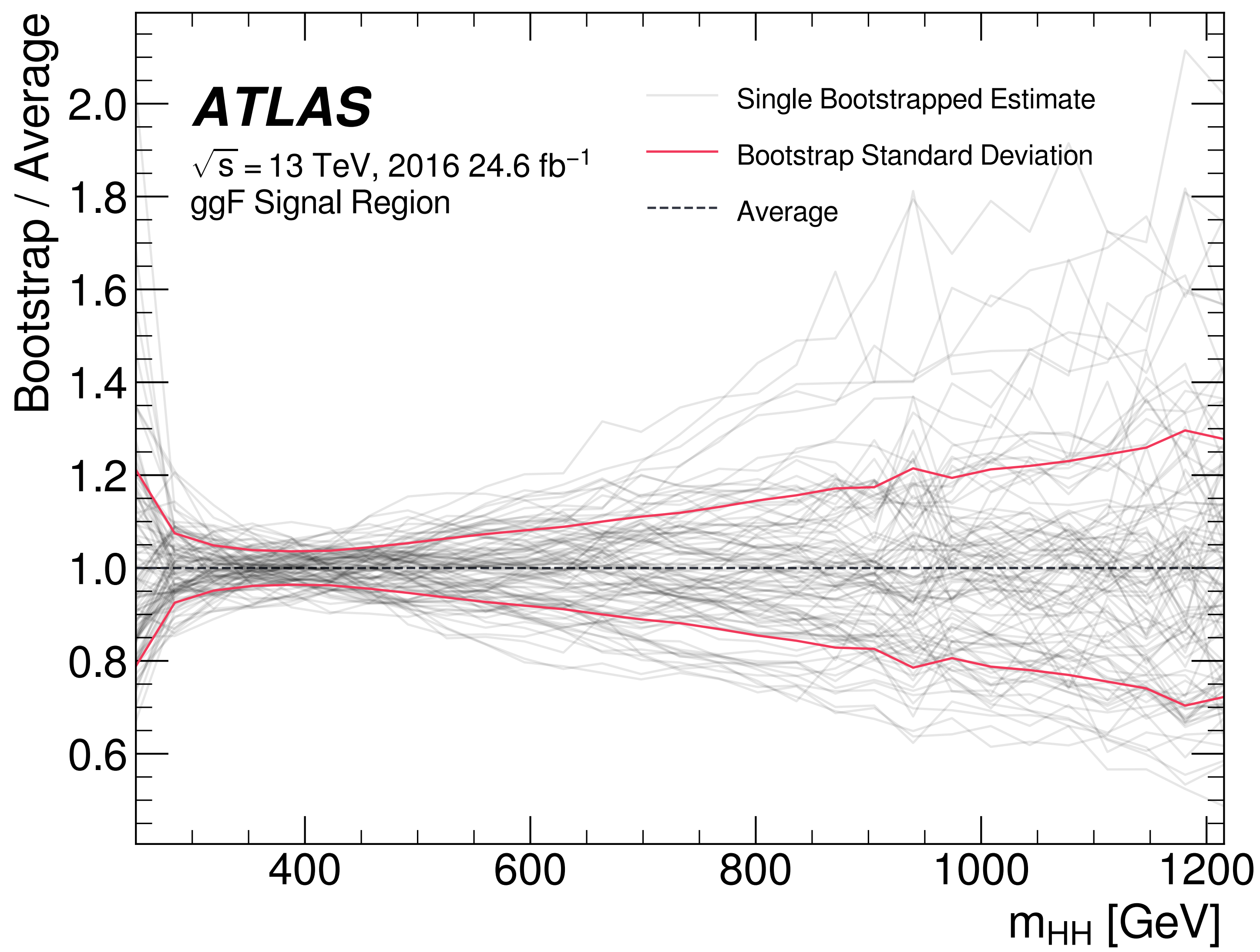

But *statistical* uncertainties play an important role as well: bkgd estimate NN very sensitive to fluctuations in training

$b\bar{b}b\bar{b}$ Results

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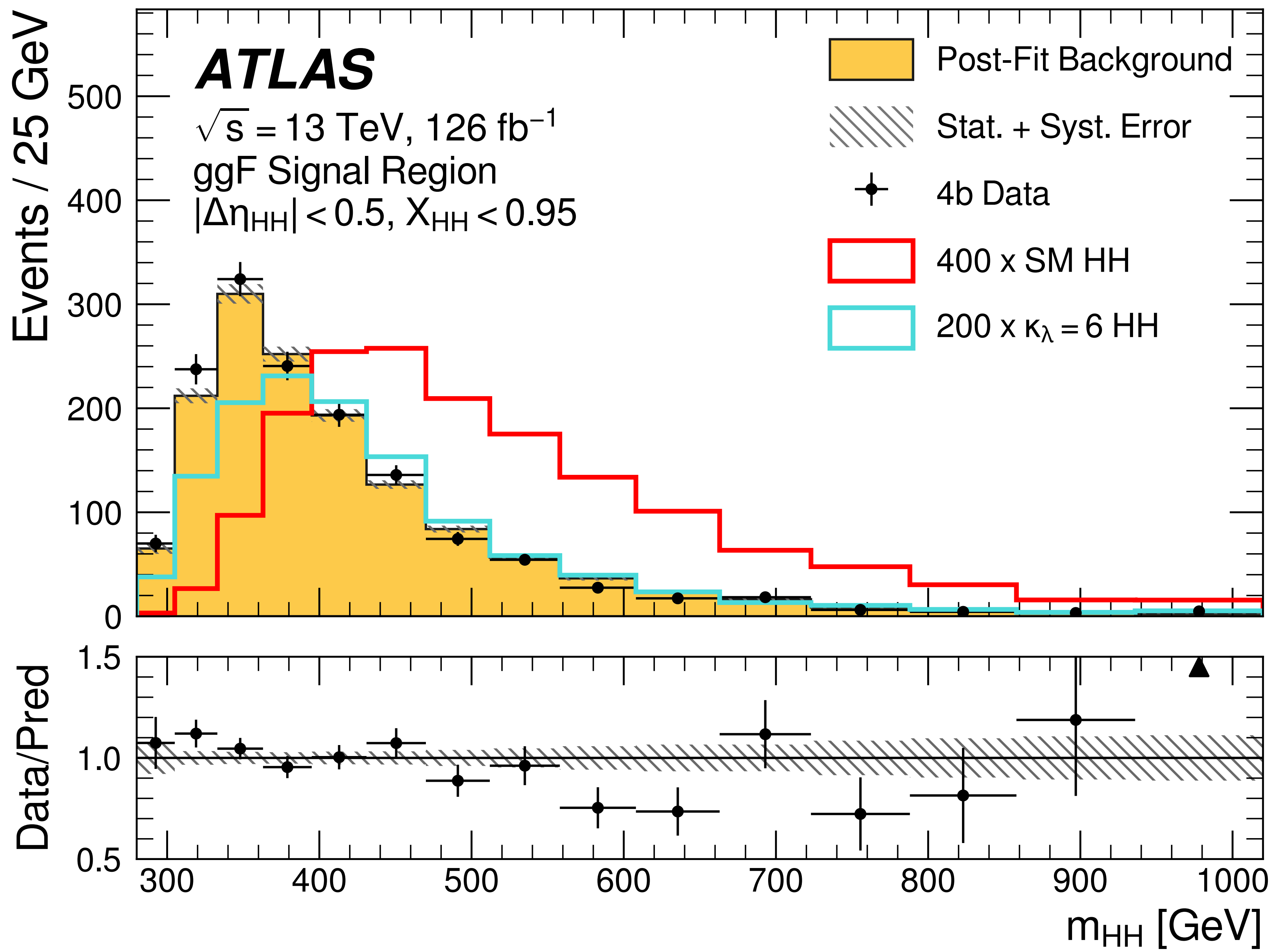

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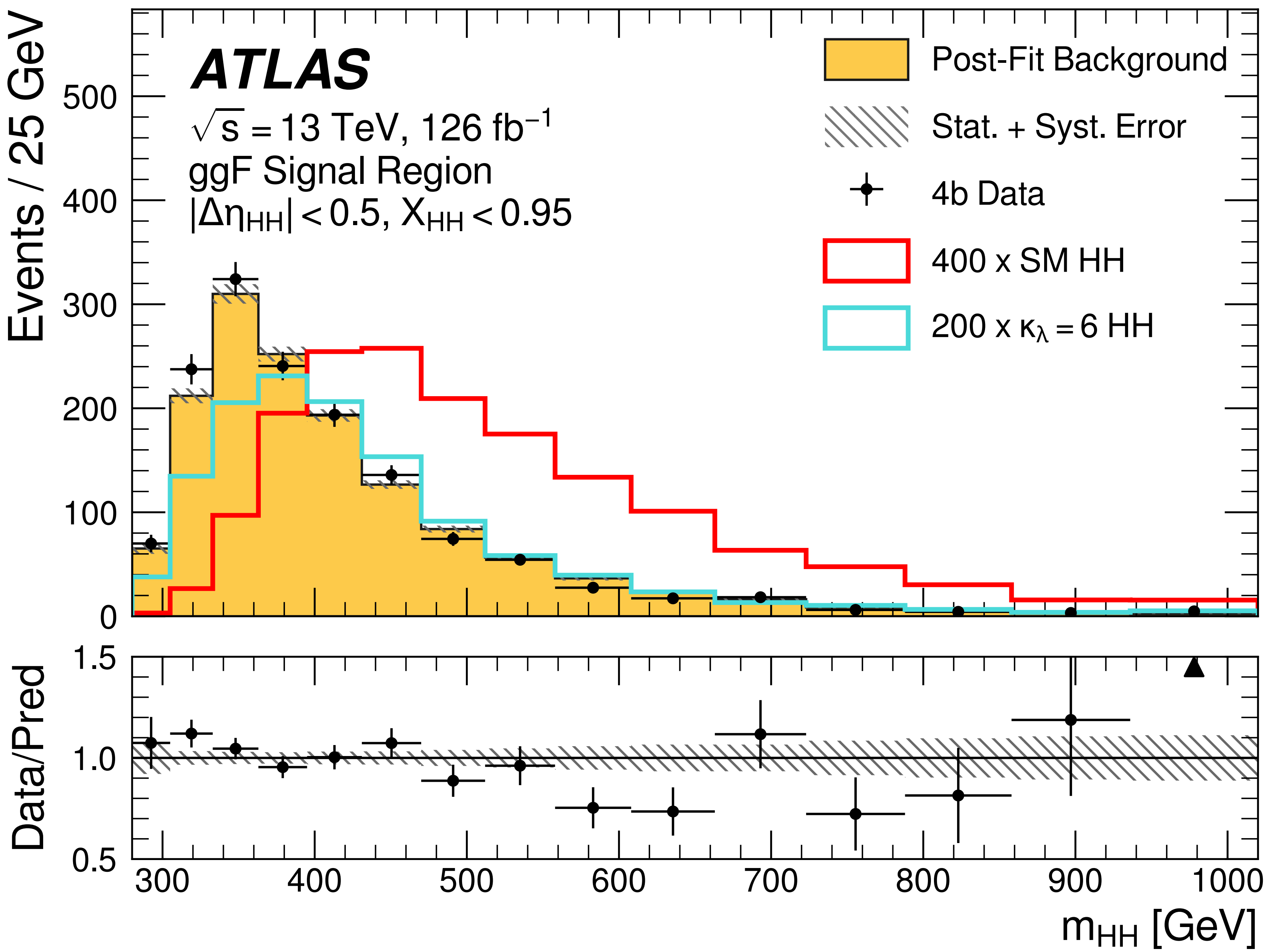

Large range of signal regions defined

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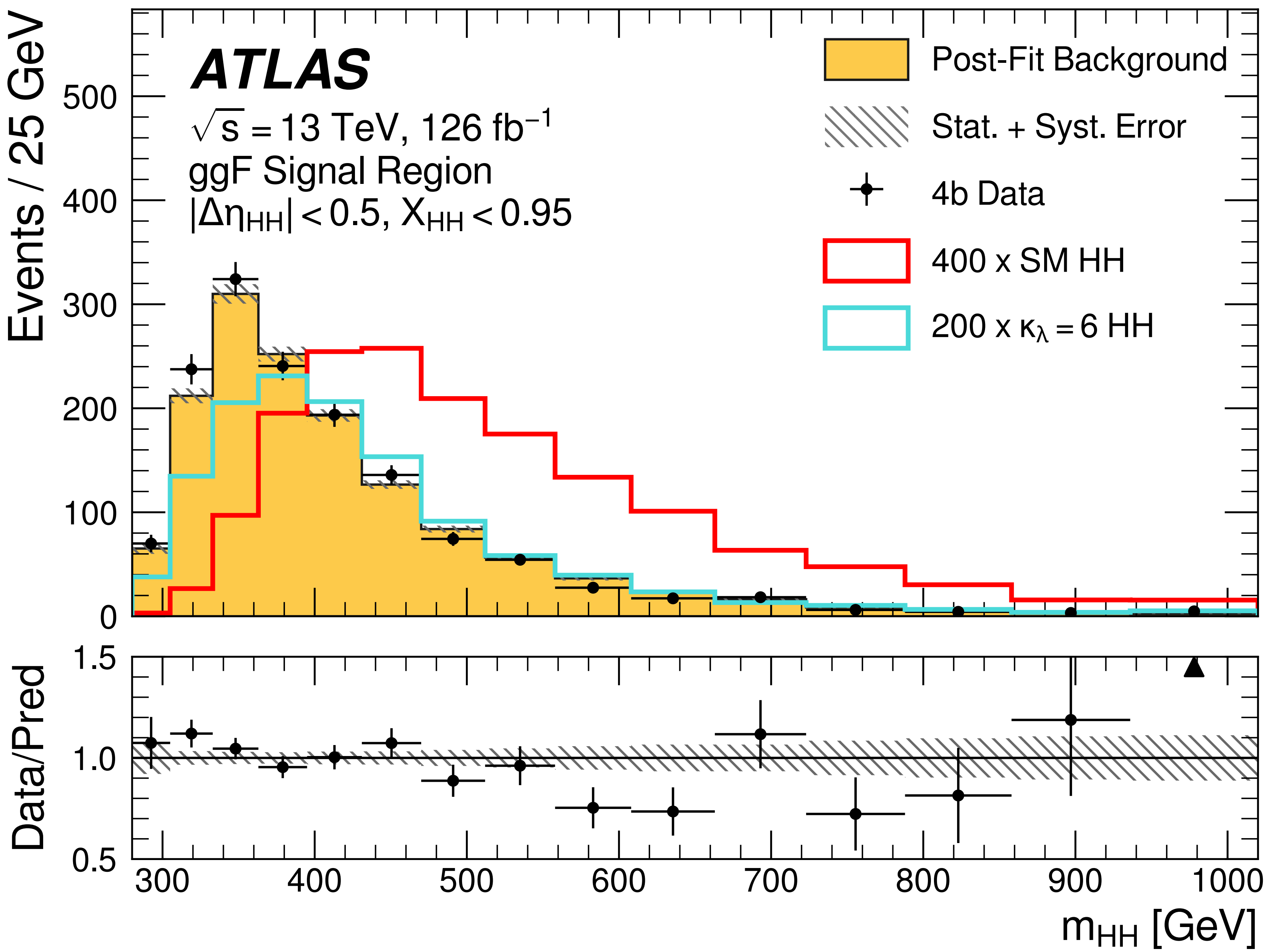

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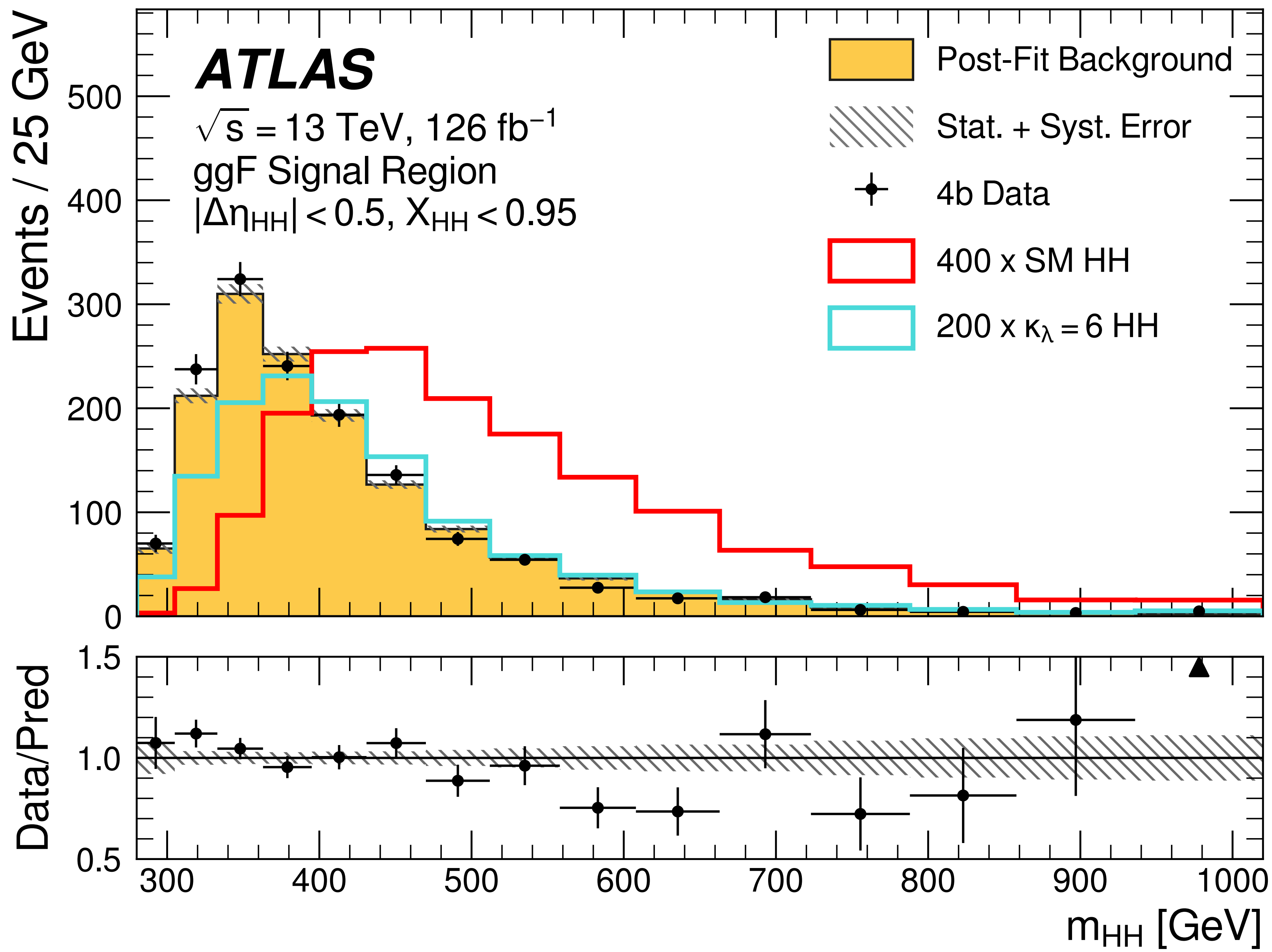

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Cover various kinematic, production regions

No excess observed

Combination

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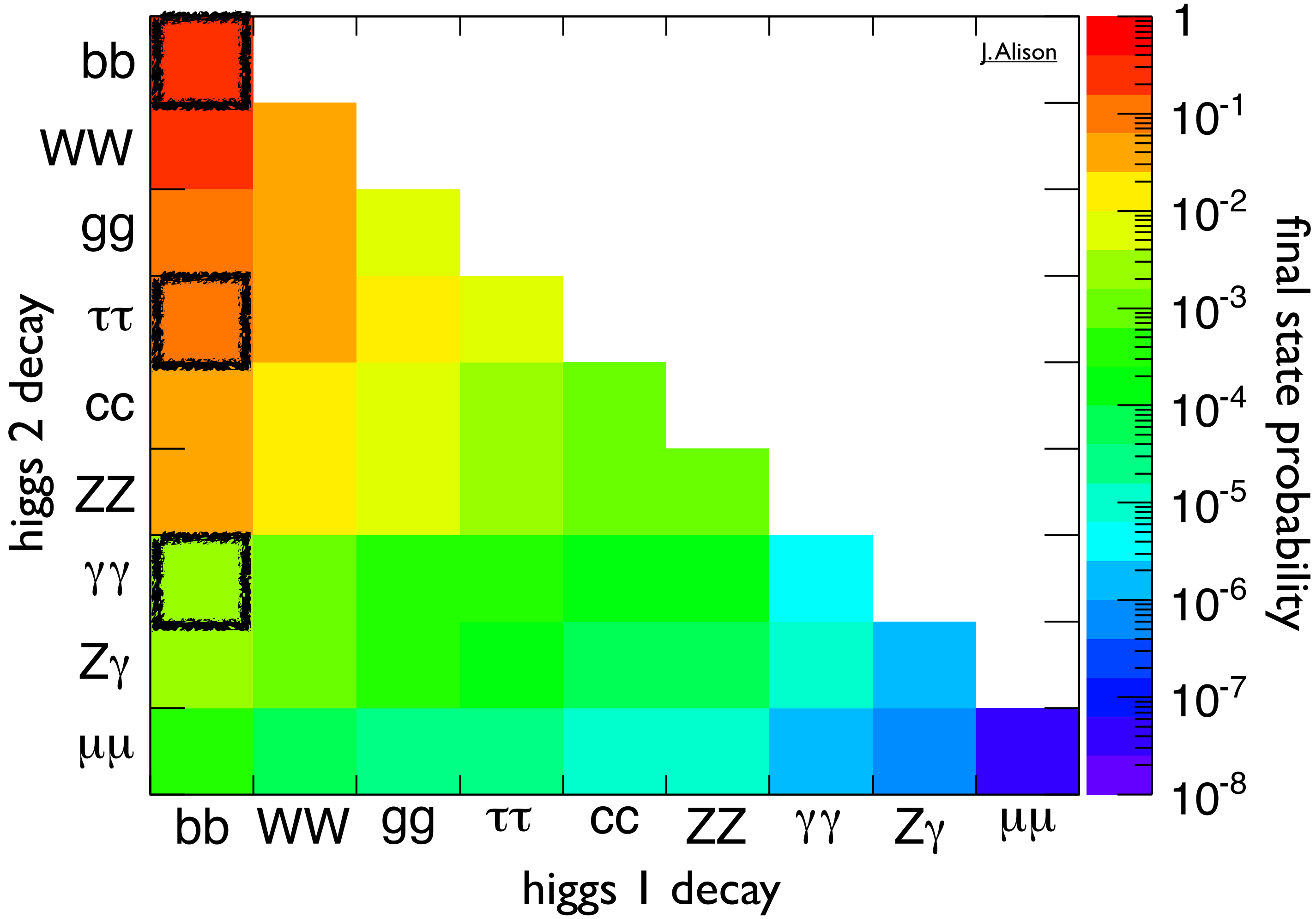

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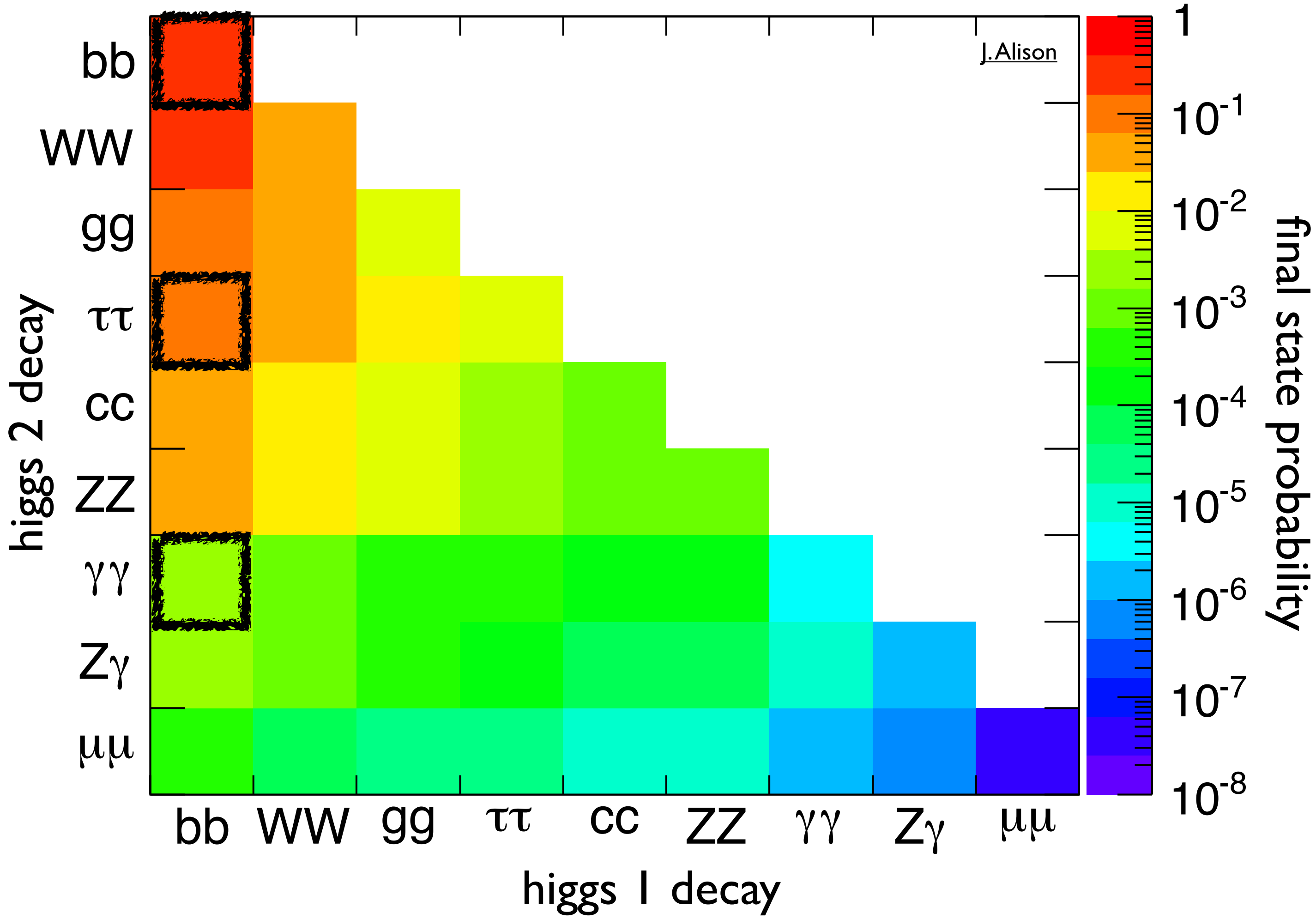

For optimal sensitivity: combine all three analyses into a single statistical interpretation

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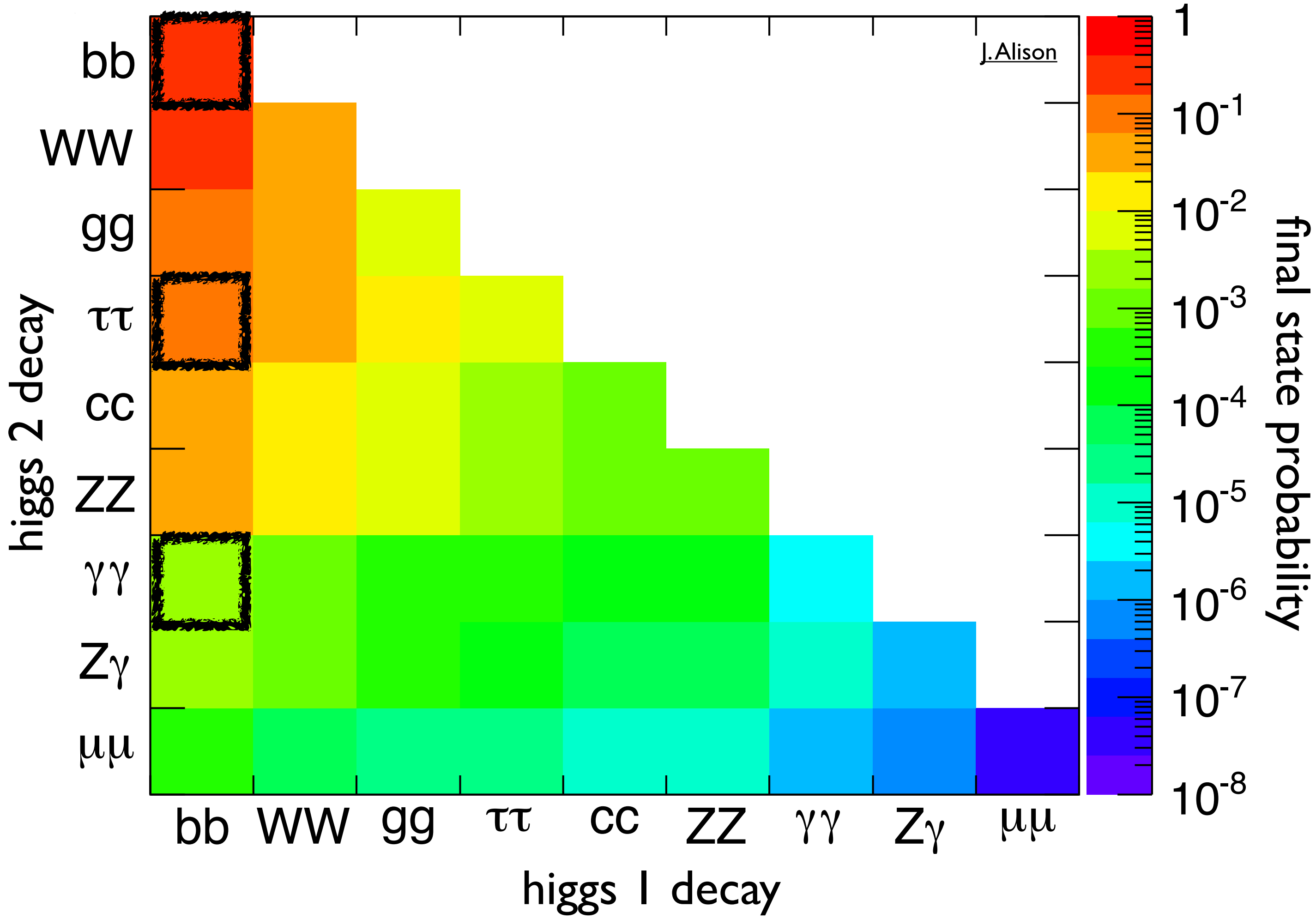

For optimal sensitivity: combine all three analyses into a single statistical interpretation

No single analysis powerful enough to measure these processes on its own!

Limits on the SM

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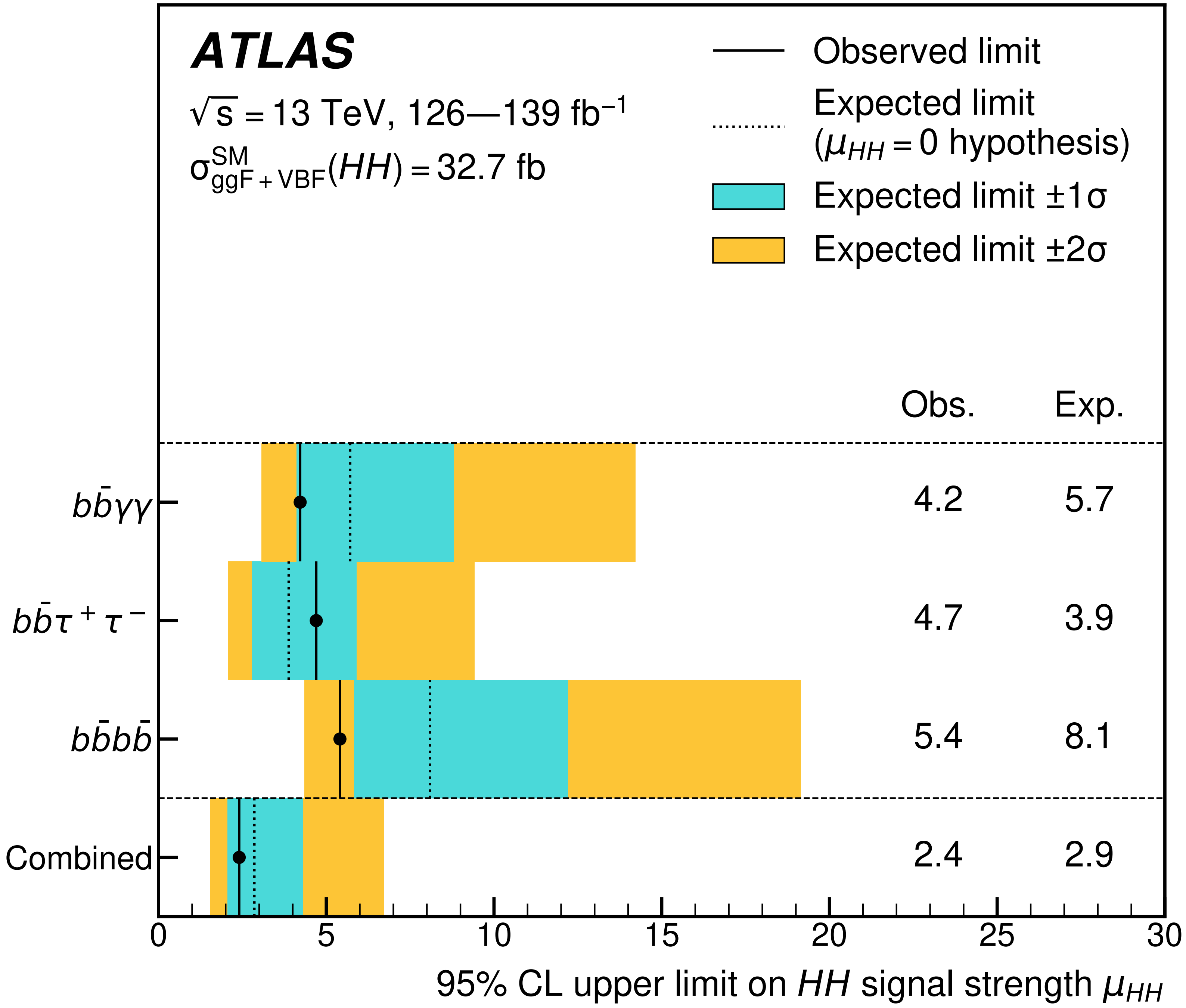
Let's put it all together:
can we see HH?

Limits on the SM



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arXiv:2211.01216

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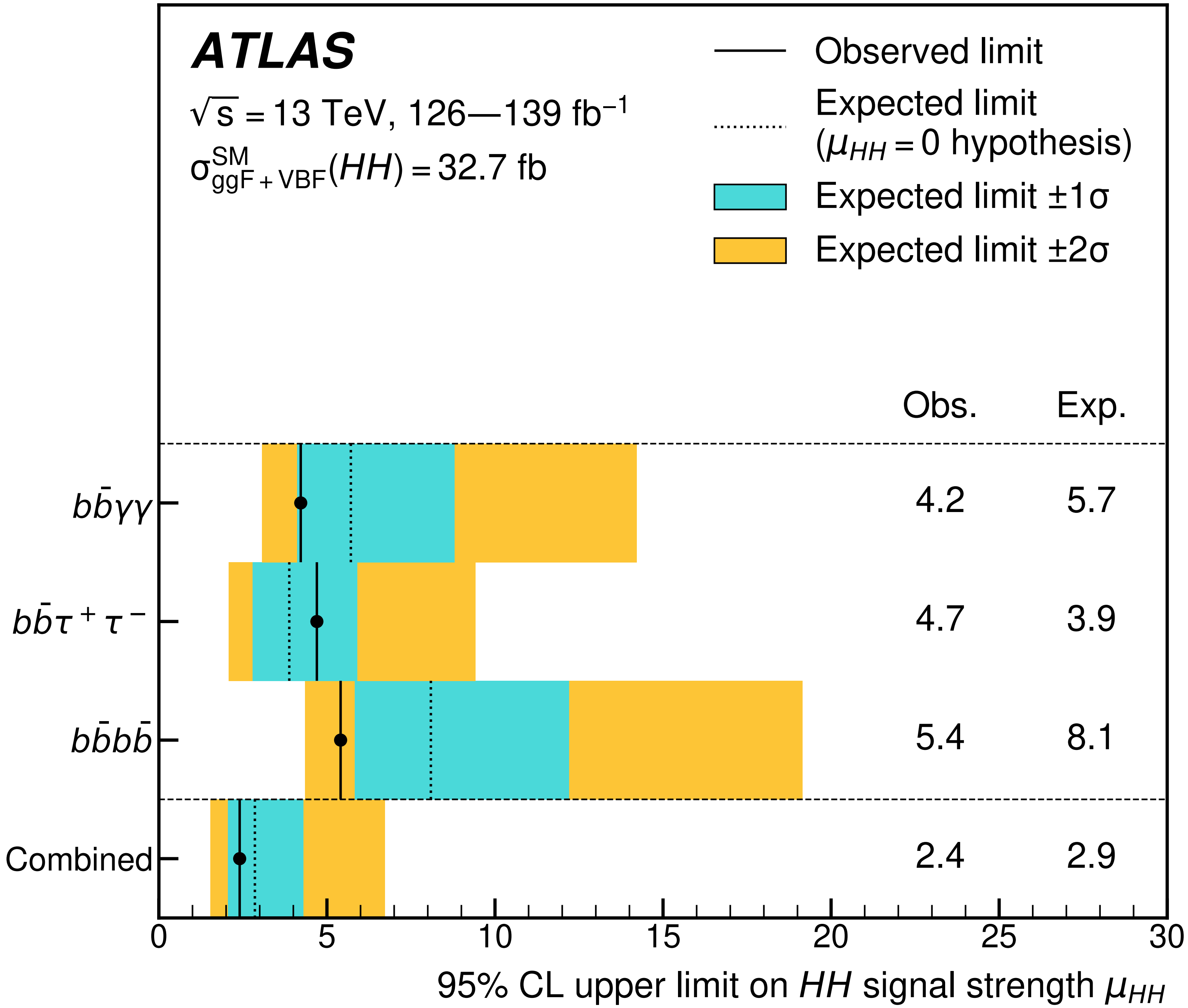

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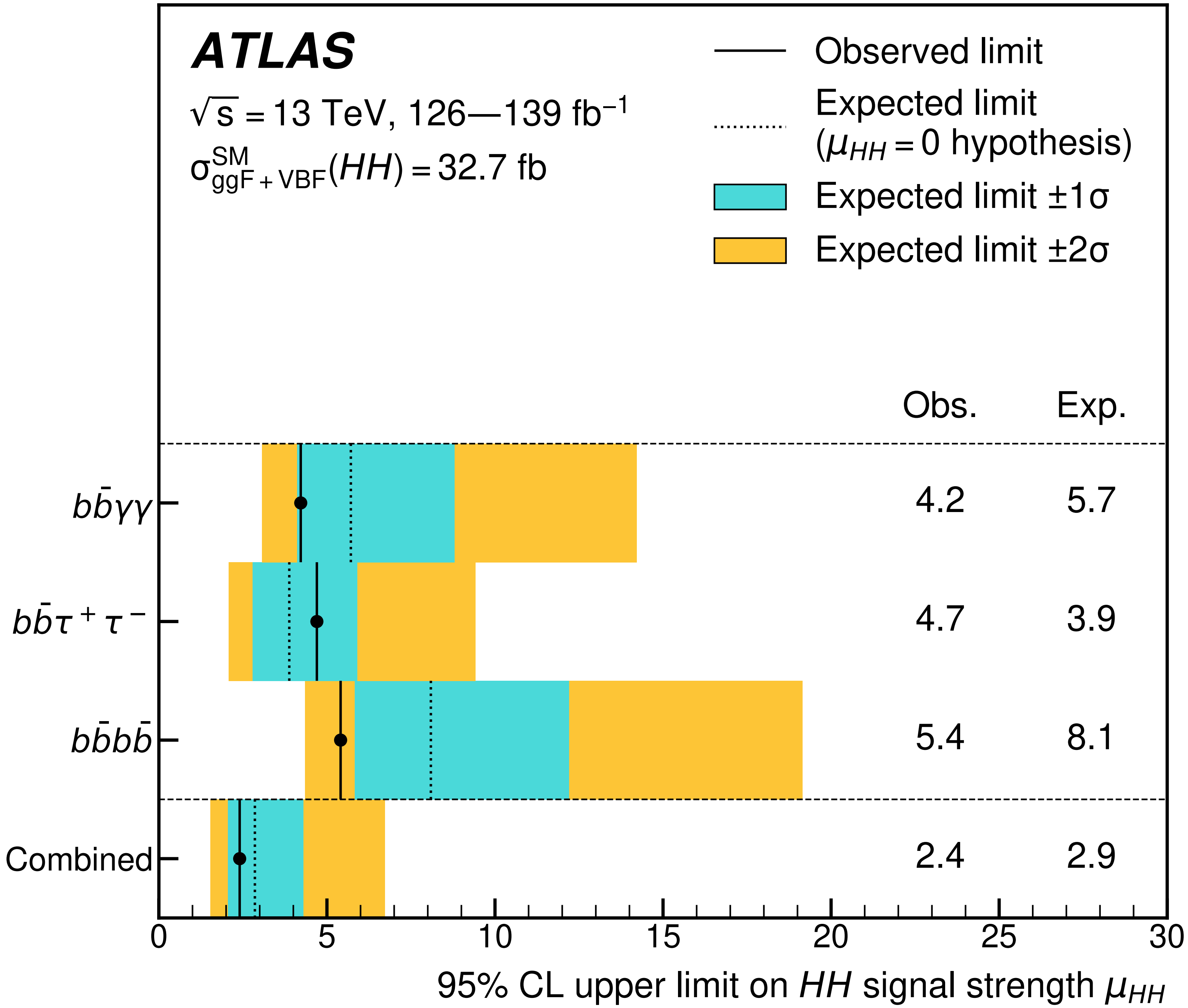

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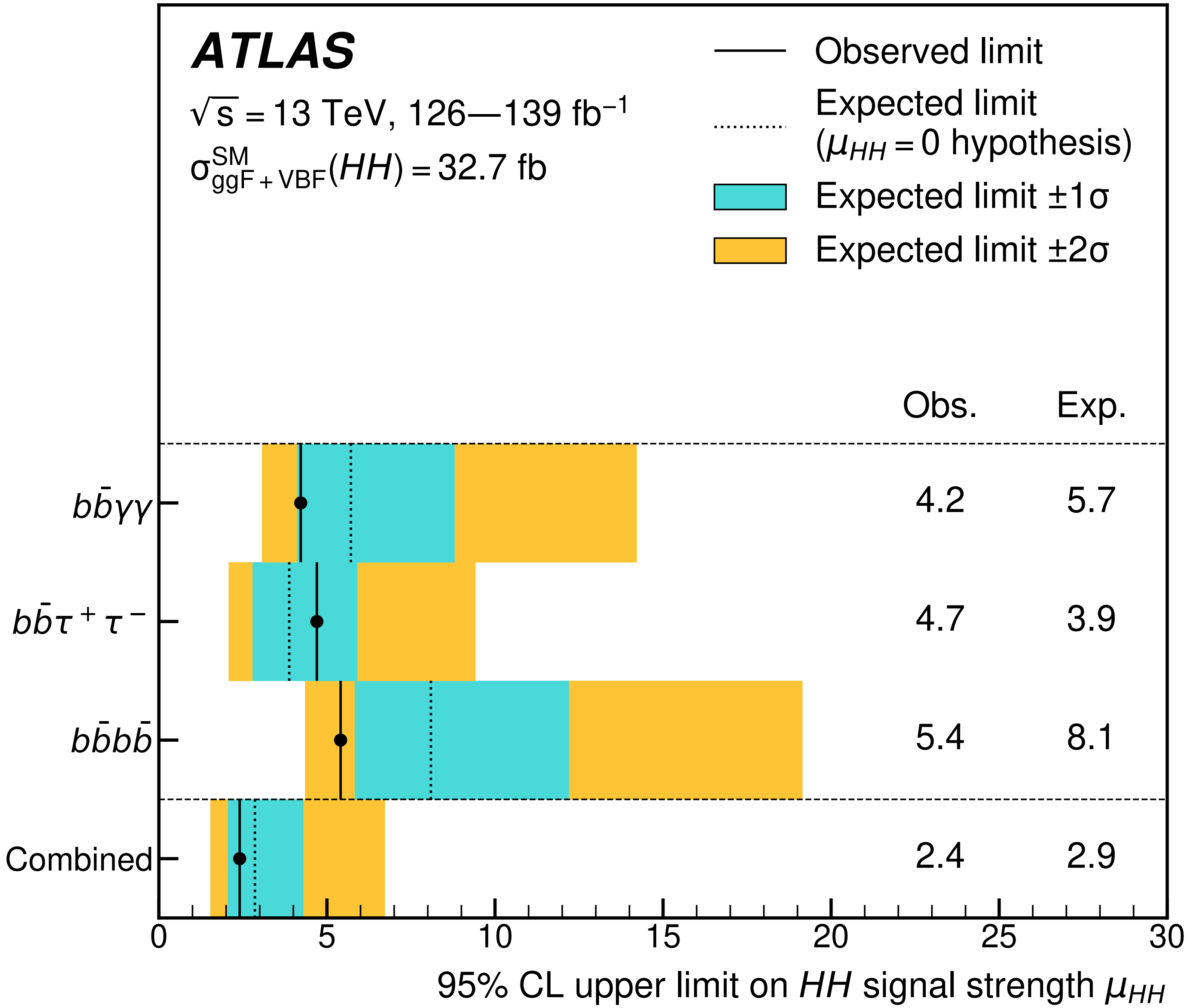

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Individual analyses set limits at ~4.5x SM

Together, set **limit at 2.4x SM**

arXiv:2211.01216

Measuring the Potential

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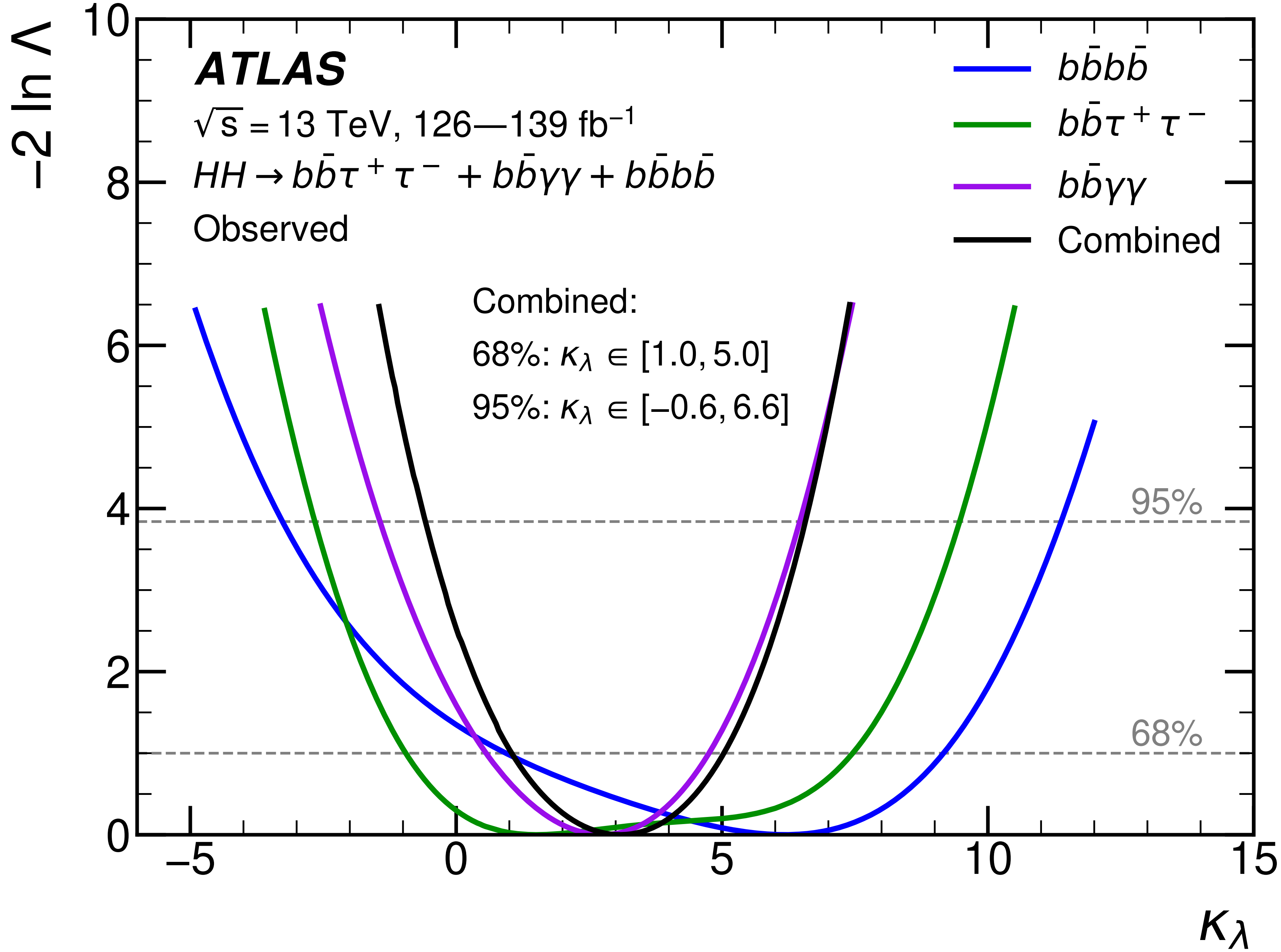
Here, show *likelihood* vs κ_λ



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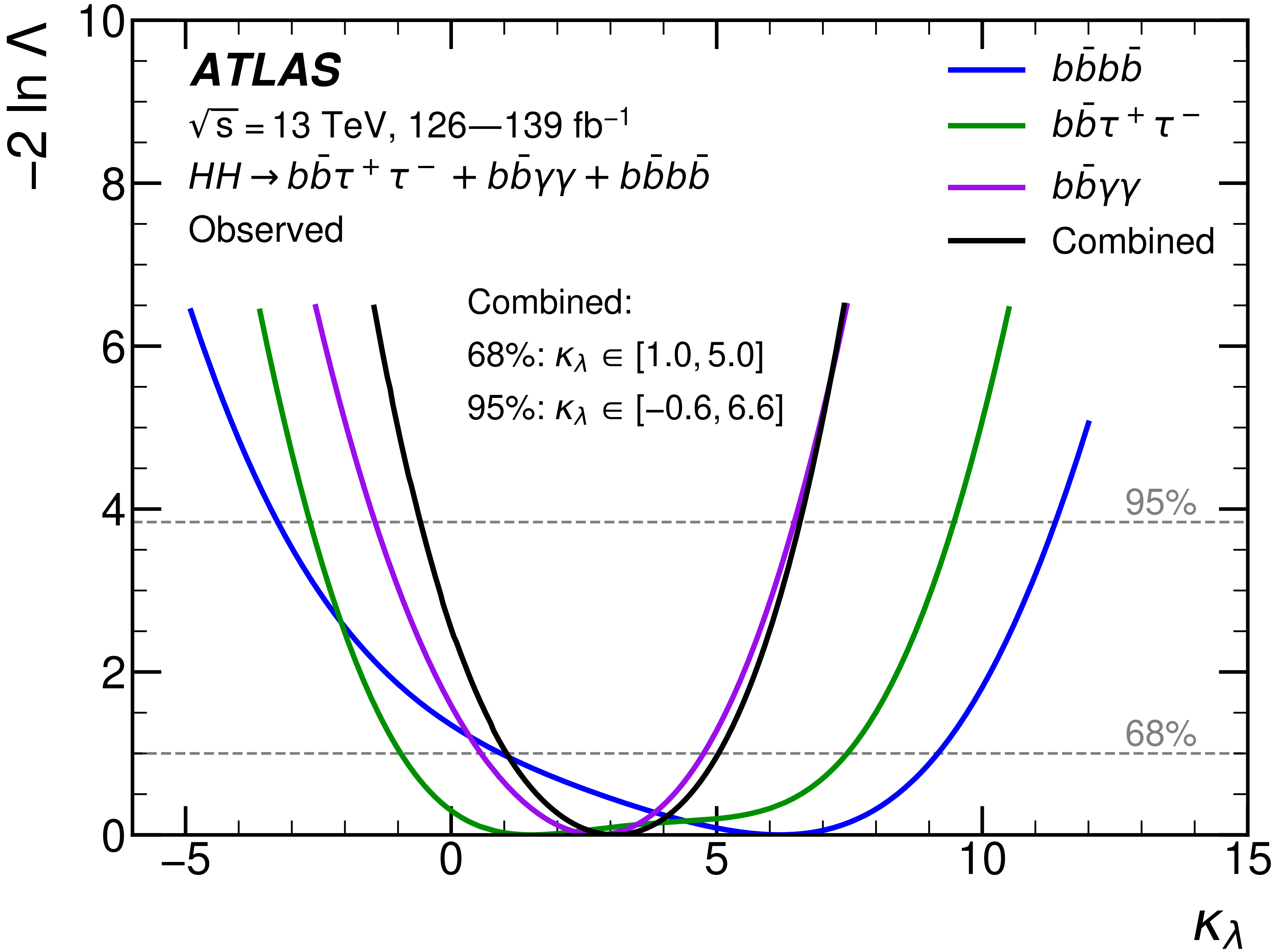

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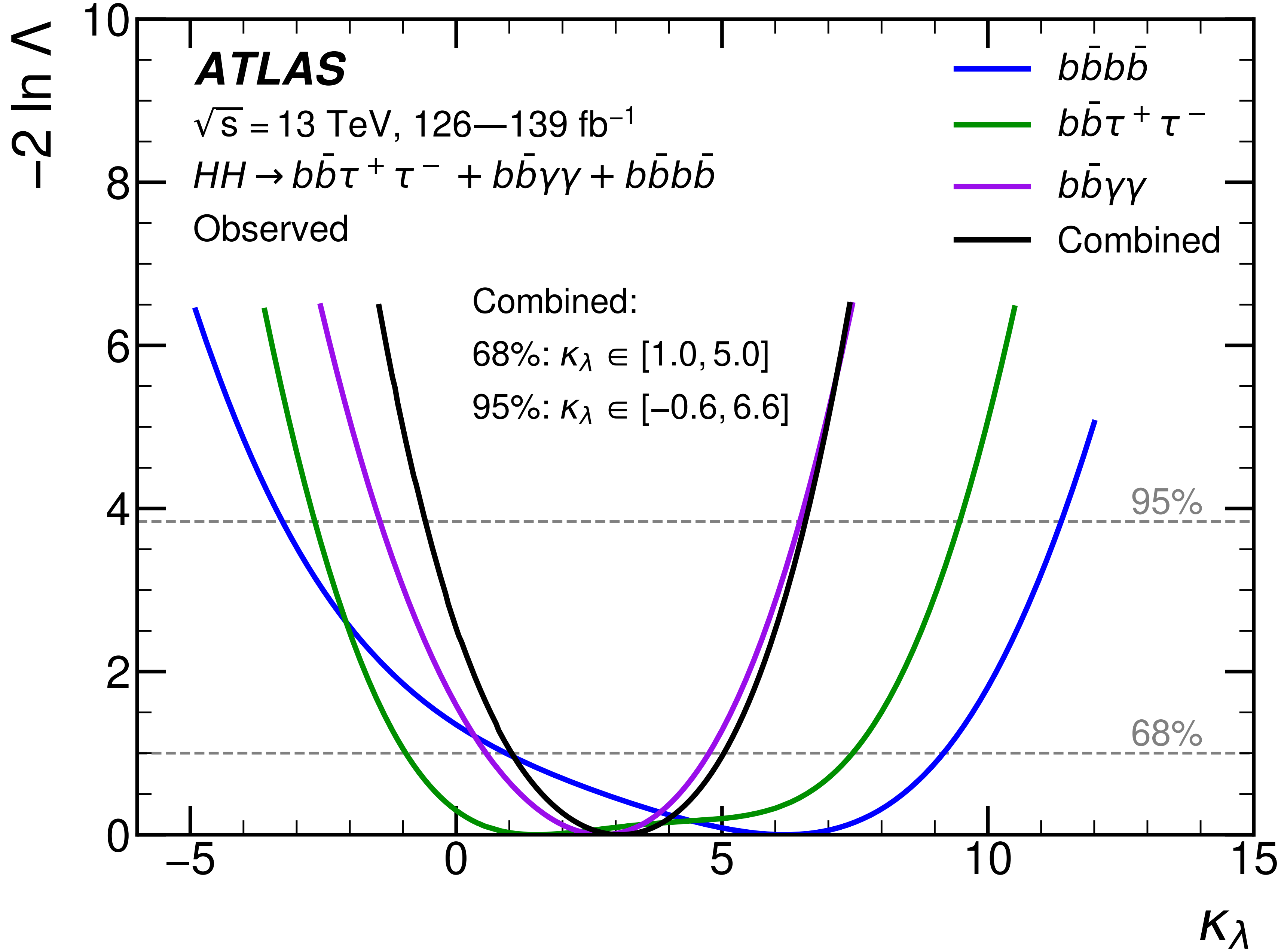

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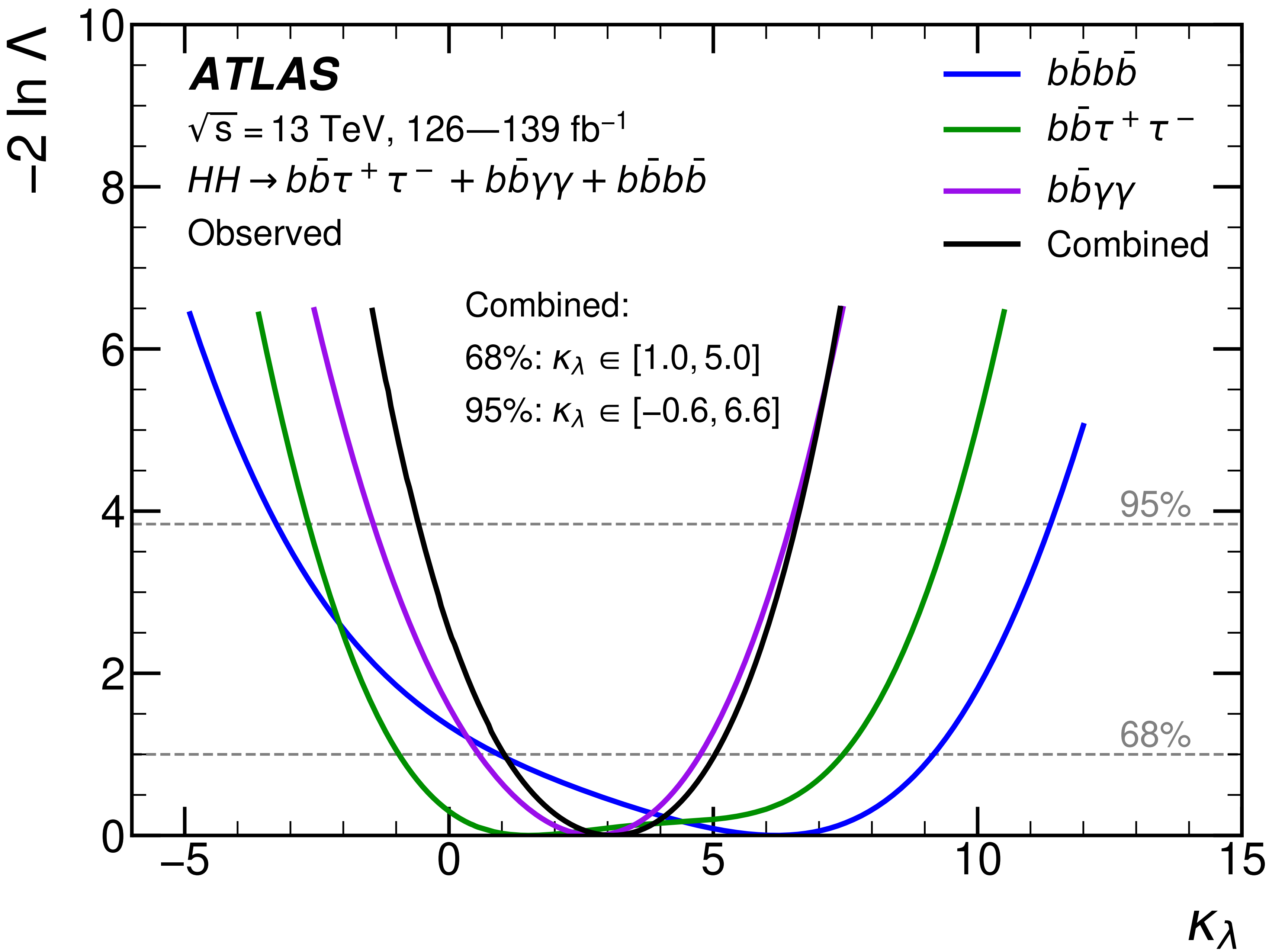

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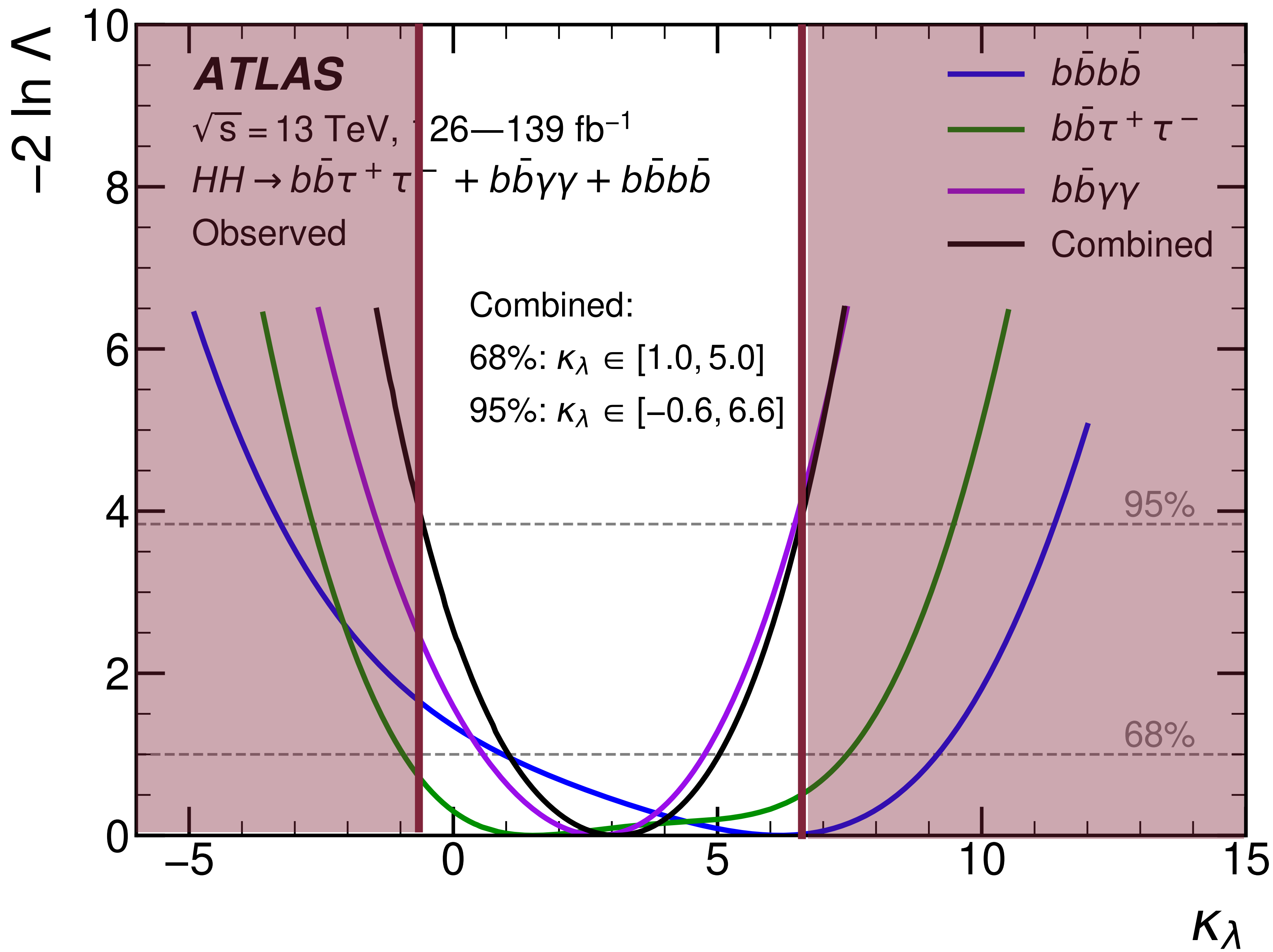

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Minimum here is the "best fit"

95% C.L. range is the "limit"

Each of the three analyses contributes to the combination

$-0.6 \leq \kappa_\lambda < 6.6$ is the allowed range: starting to probe EWBG!

Beyond κ_λ

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Focused discussion on κ_λ, but a whole host of additional BSM physics is accessible

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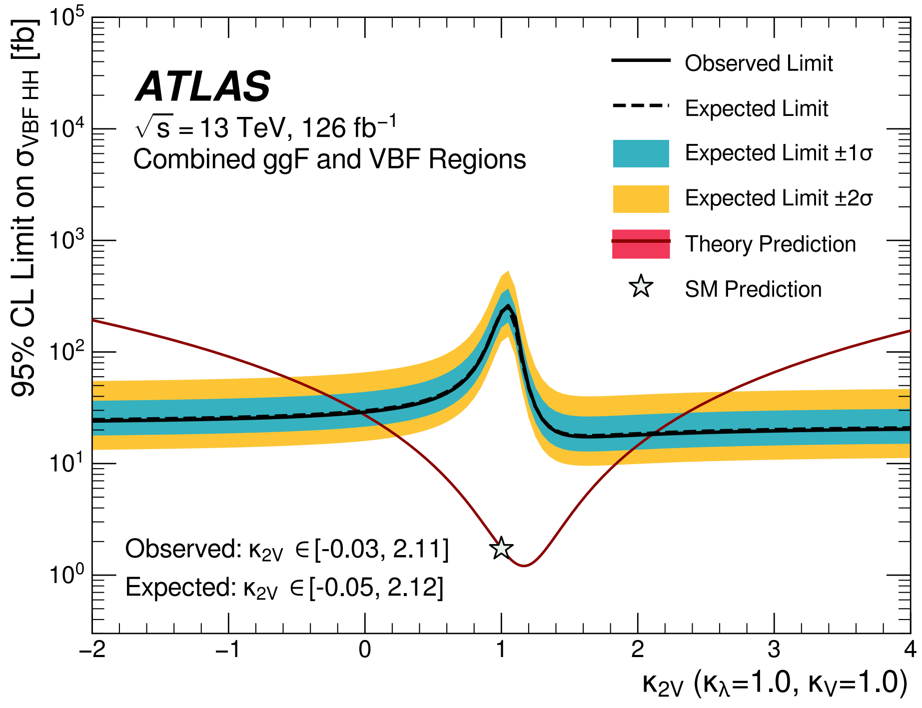

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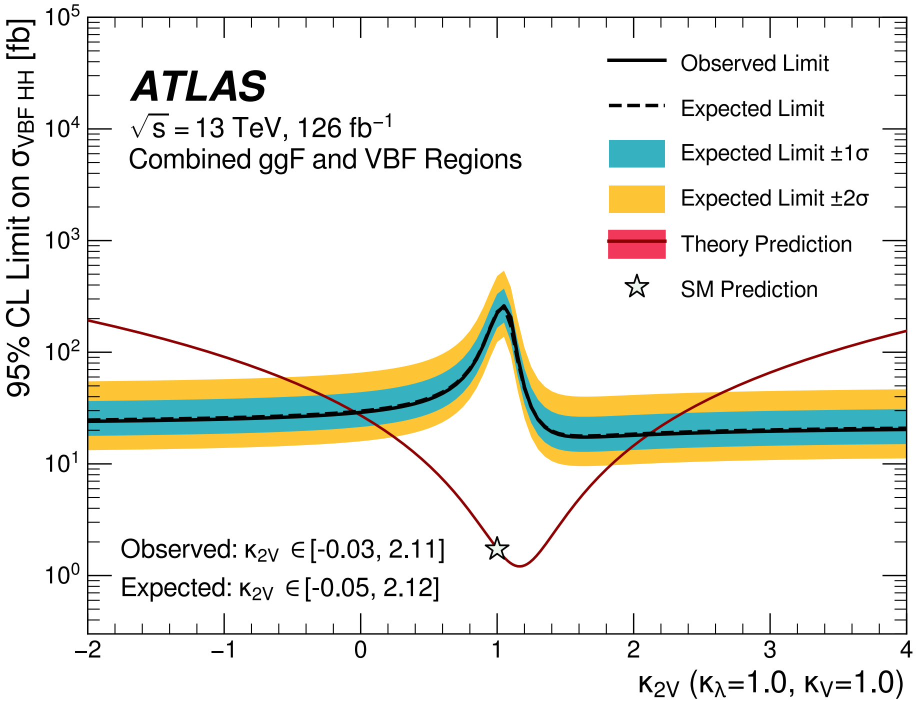

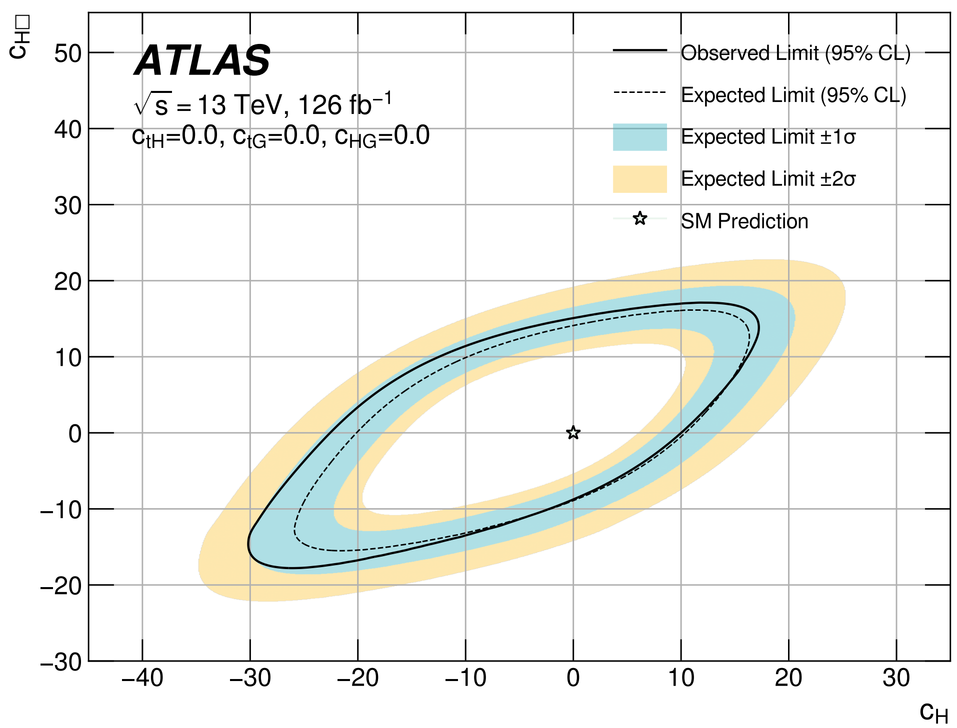

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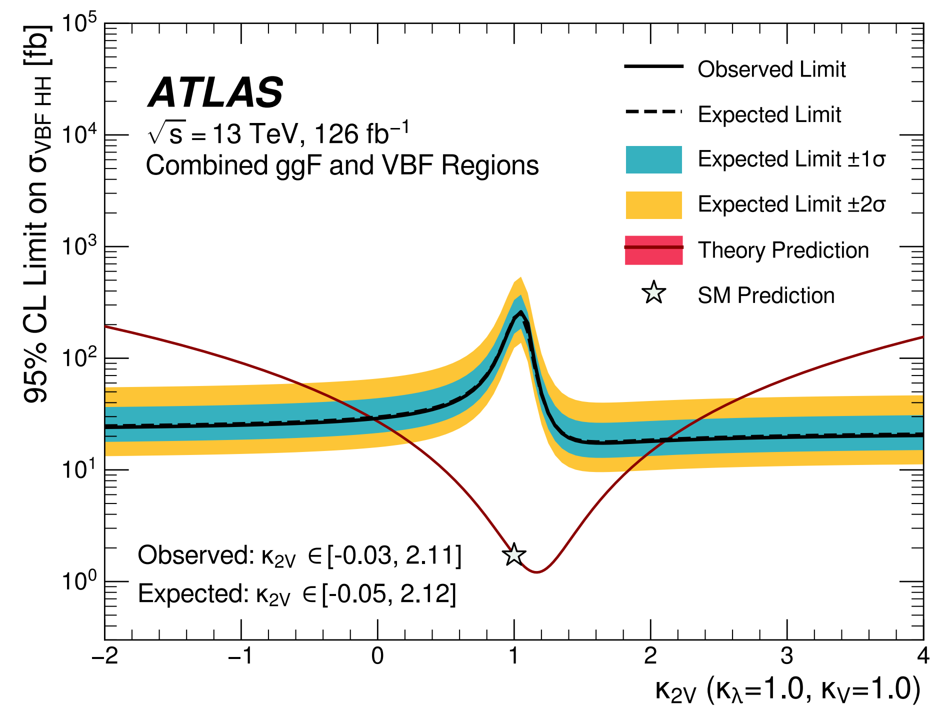
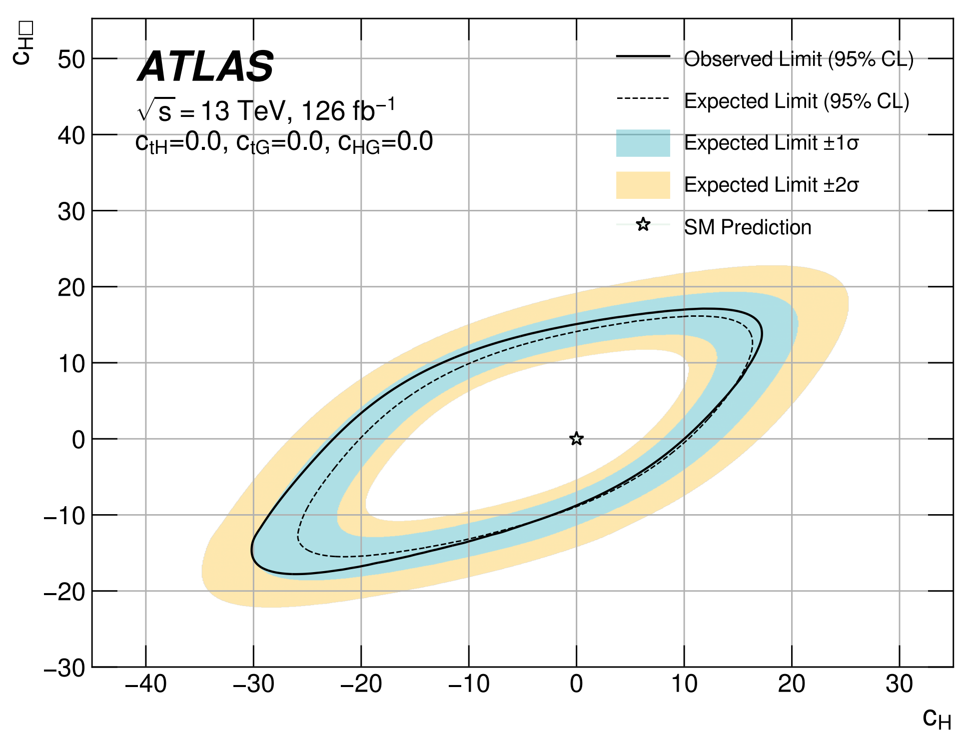
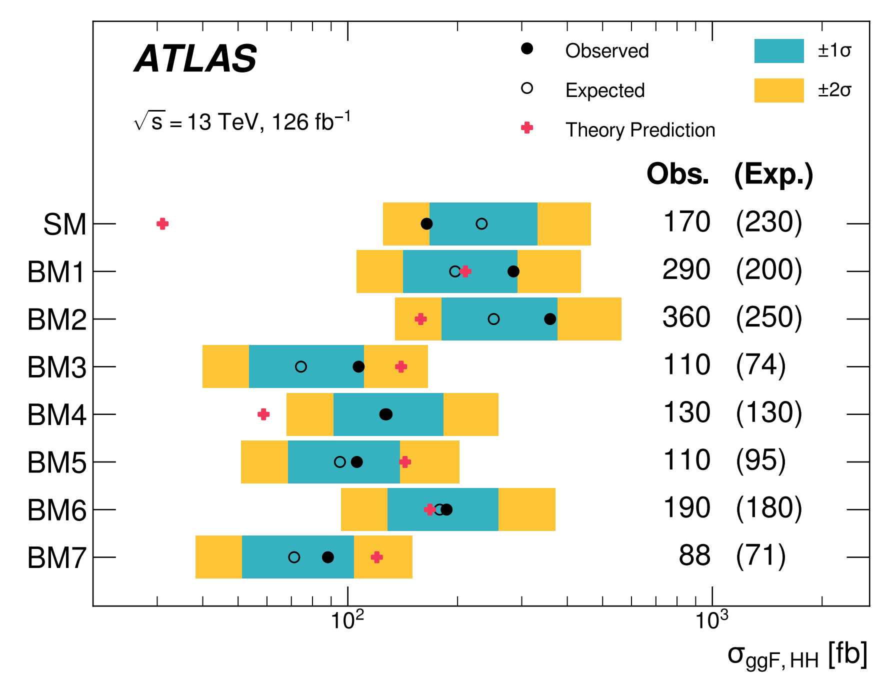


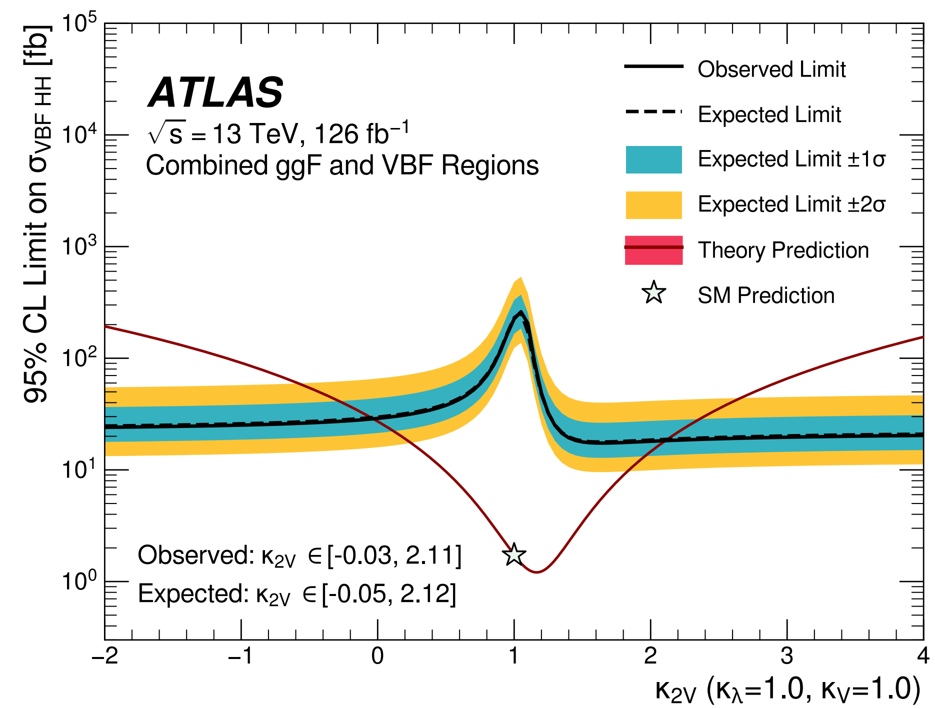


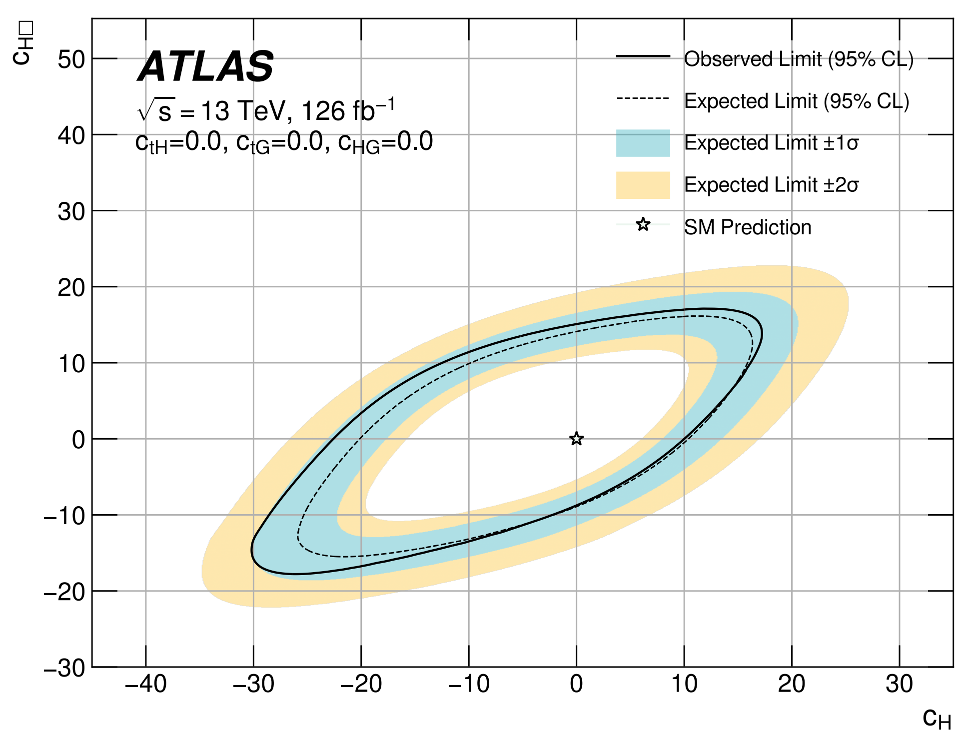


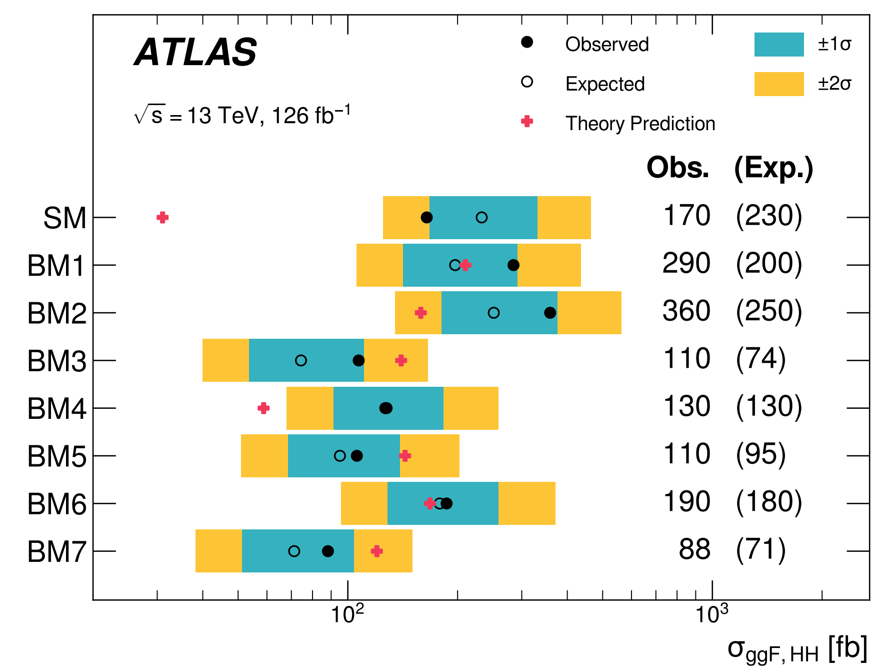
Beyond κ_λ

Focused discussion on κ_λ, but a whole host of additional BSM physics is accessible

Critical to understand degeneracies with κ_λ: are we actually measuring the Higgs potential, or other BSM?







The LHC Context

What Do We Look For?

The Next Frontier: Higgs Pairs

Outlook

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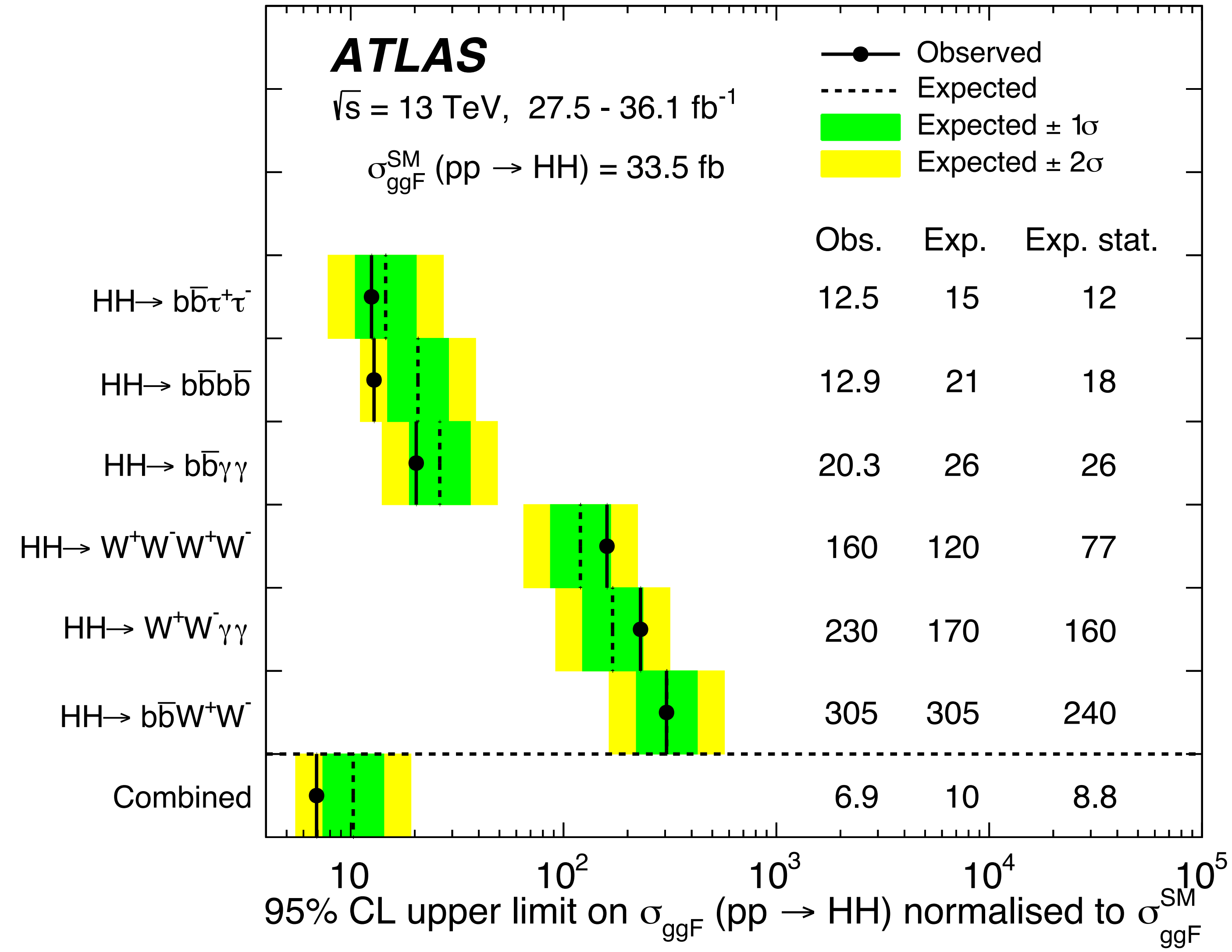


What Now?

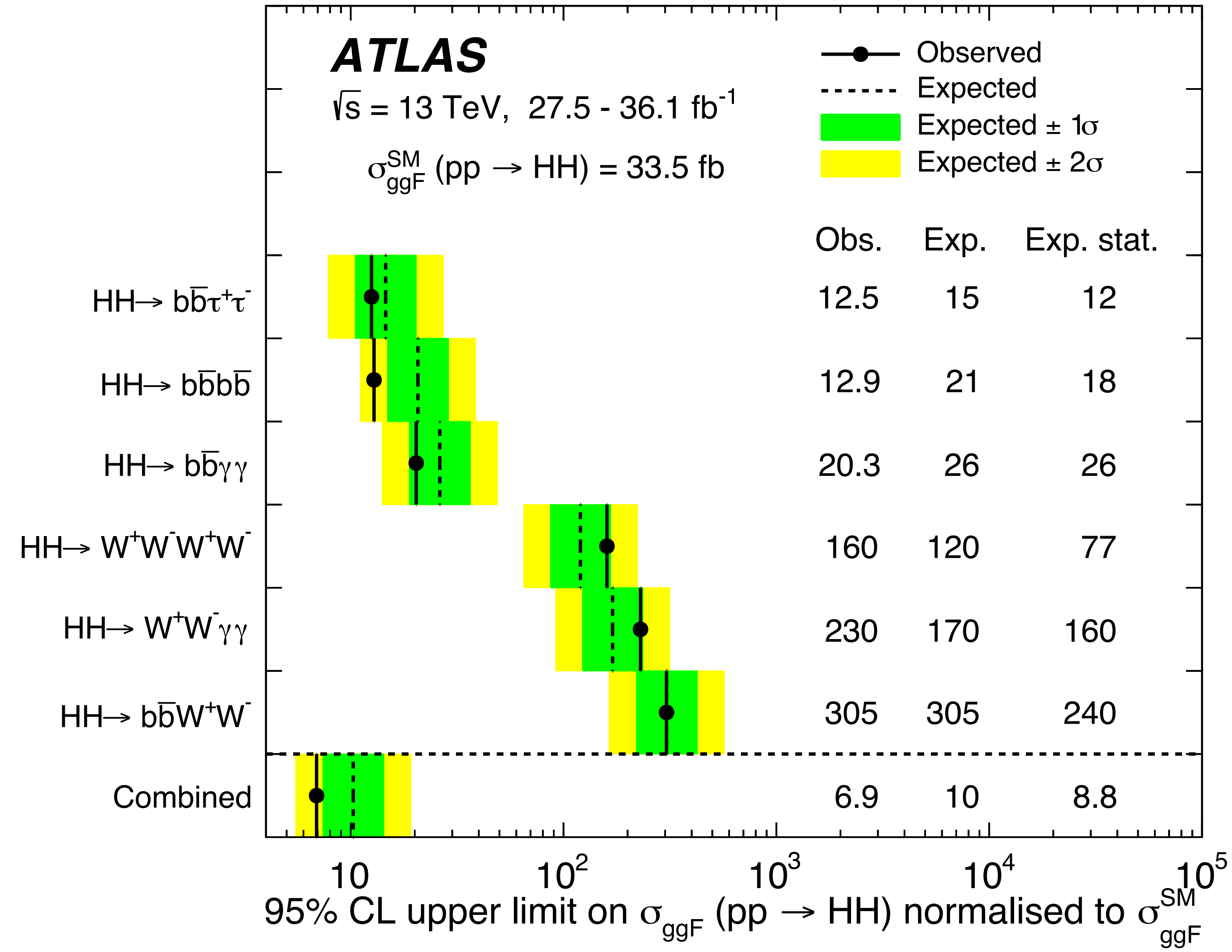
Analysis of run2 data isn't even complete!

With additional channels, can push limit to ~2x SM

No golden channel: need as much signal as possible

And combination with CMS data will get us even better!

More data from Run3 will bring us tantalizingly close to evidence of HH



What's Coming in Run3

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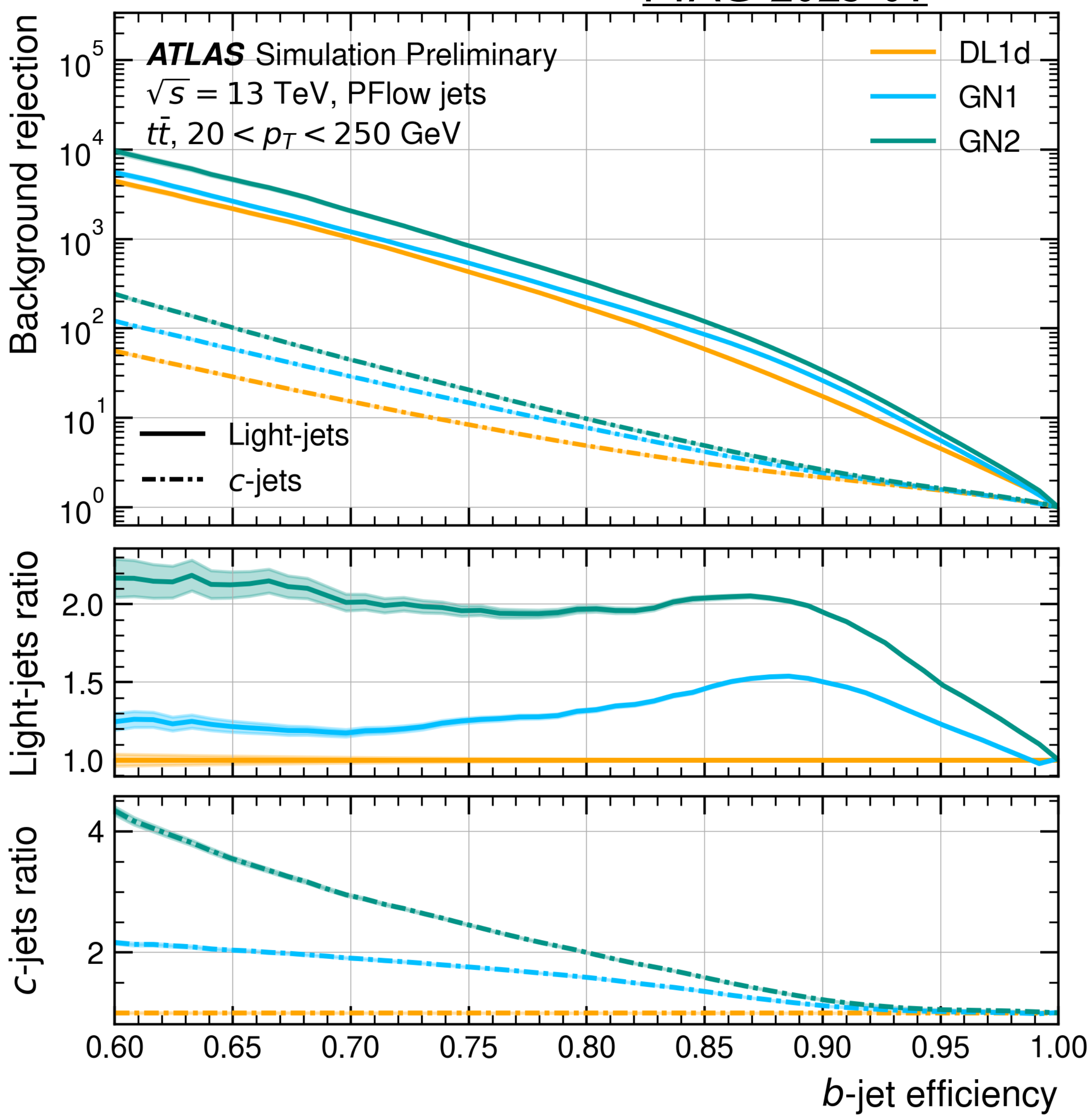
FTAG-2023-01



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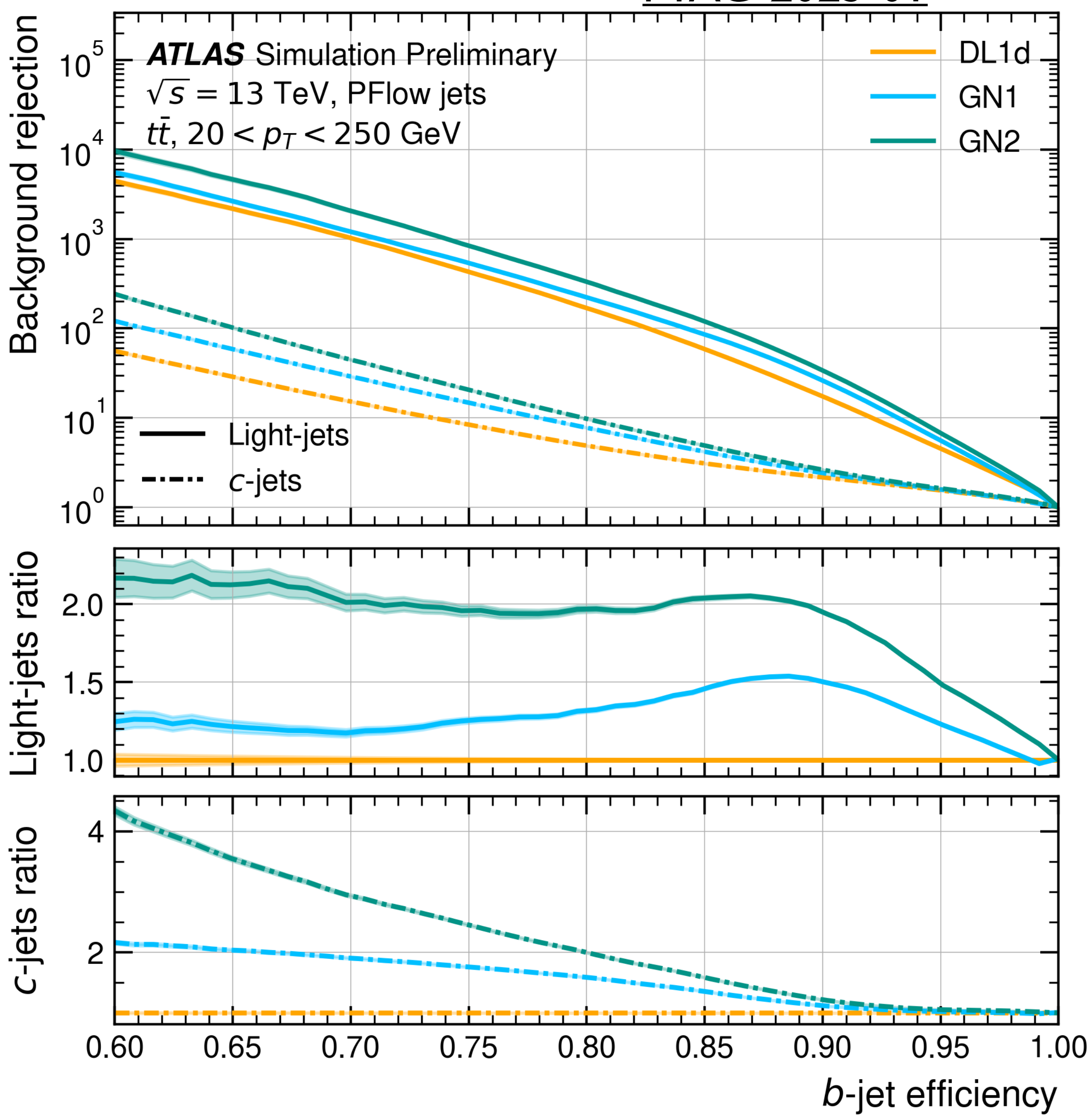

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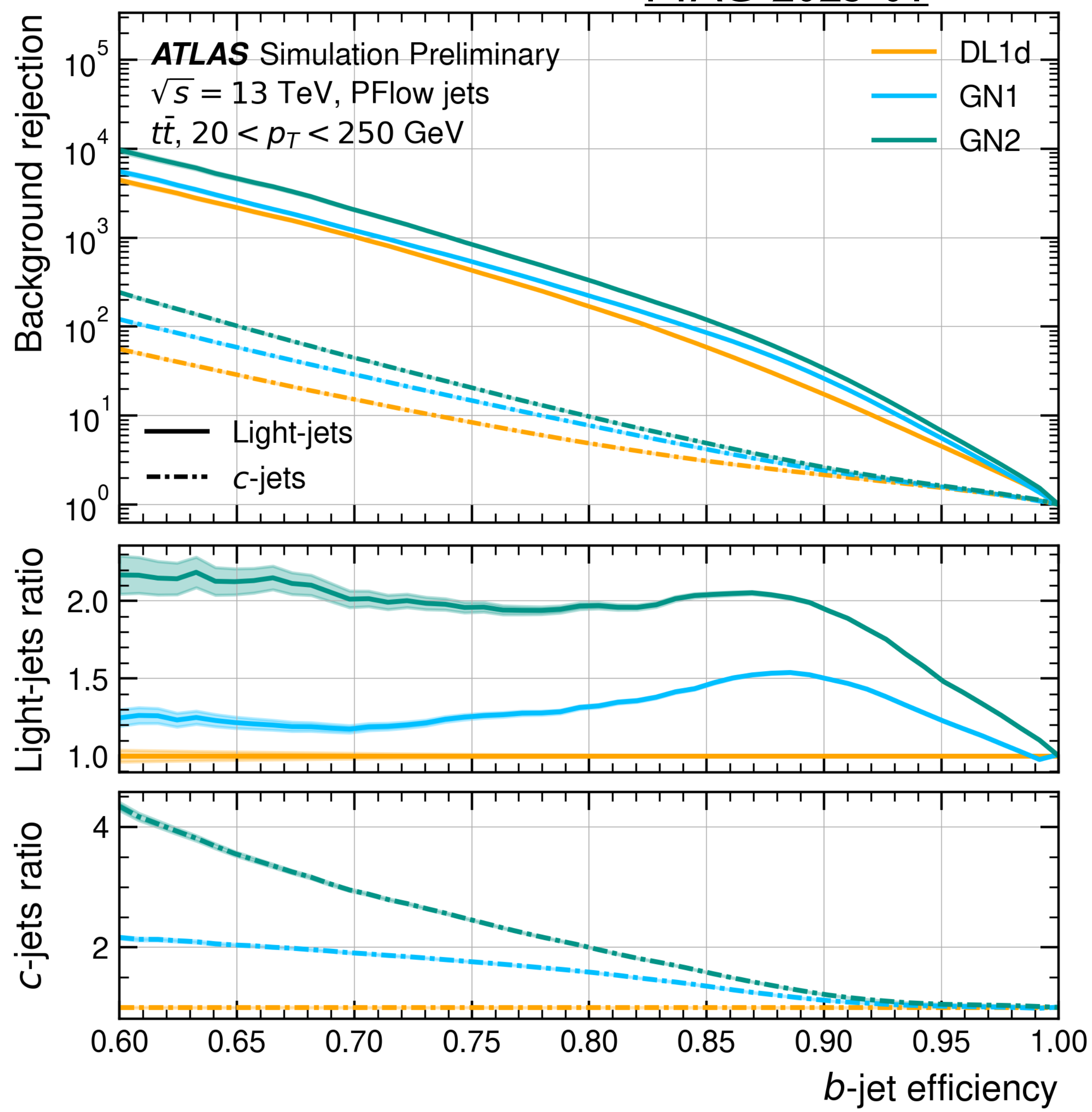

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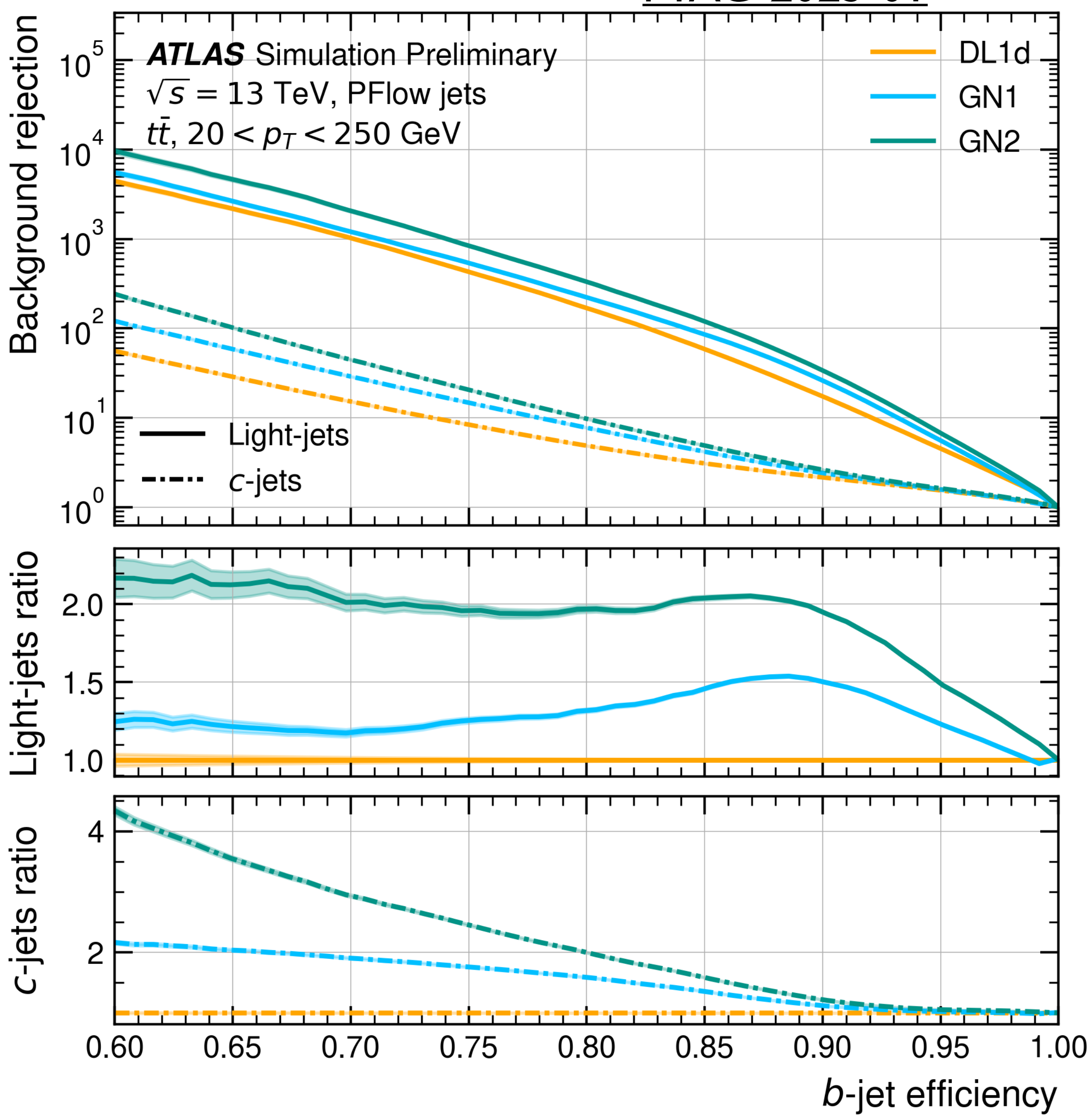
Now, GNN-based algorithms outperform DL1r(d) by **another factor of 2**!

What's Coming in Run3

FTAG-2023-01



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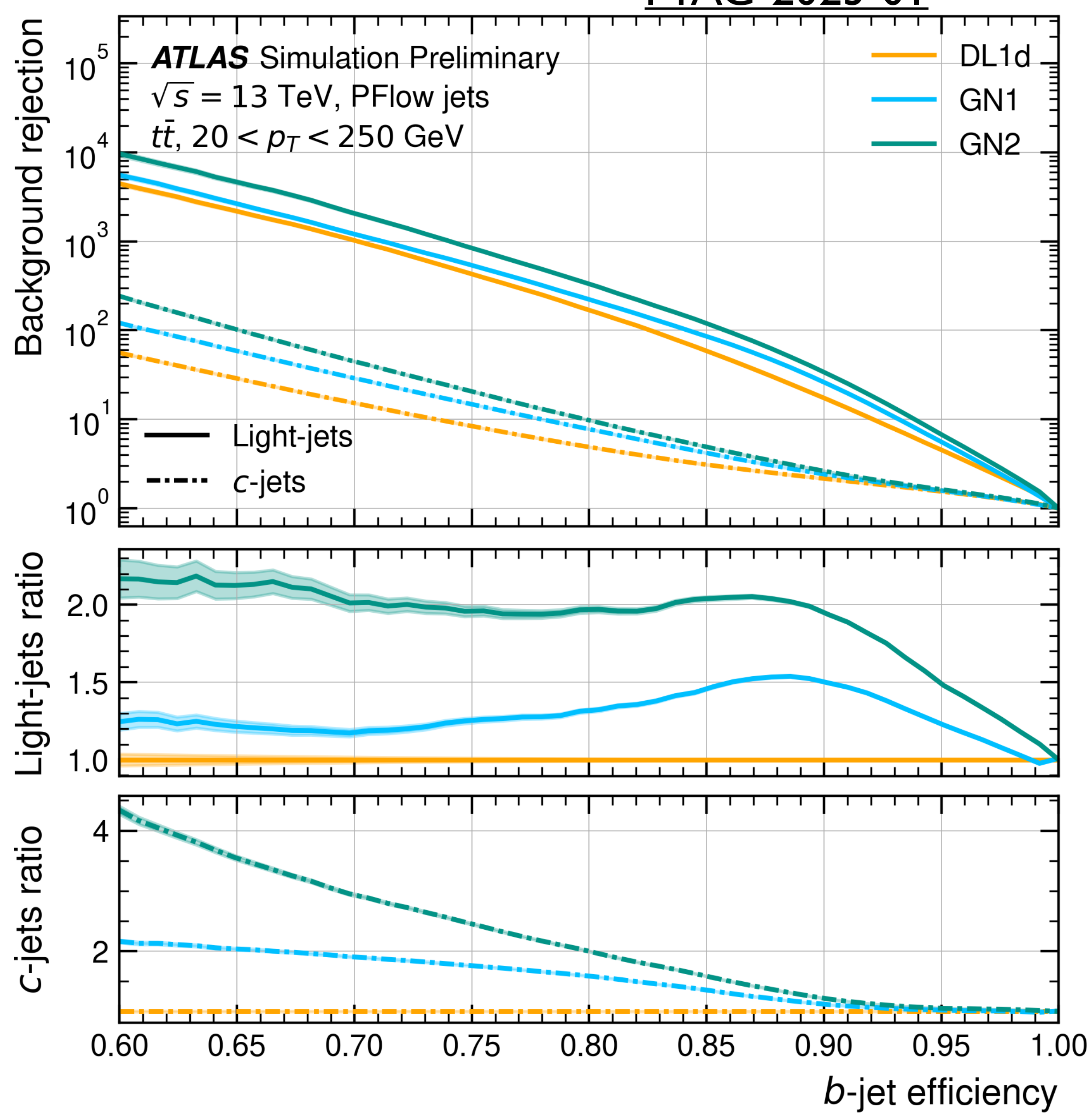

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And we can run it in the trigger, too!

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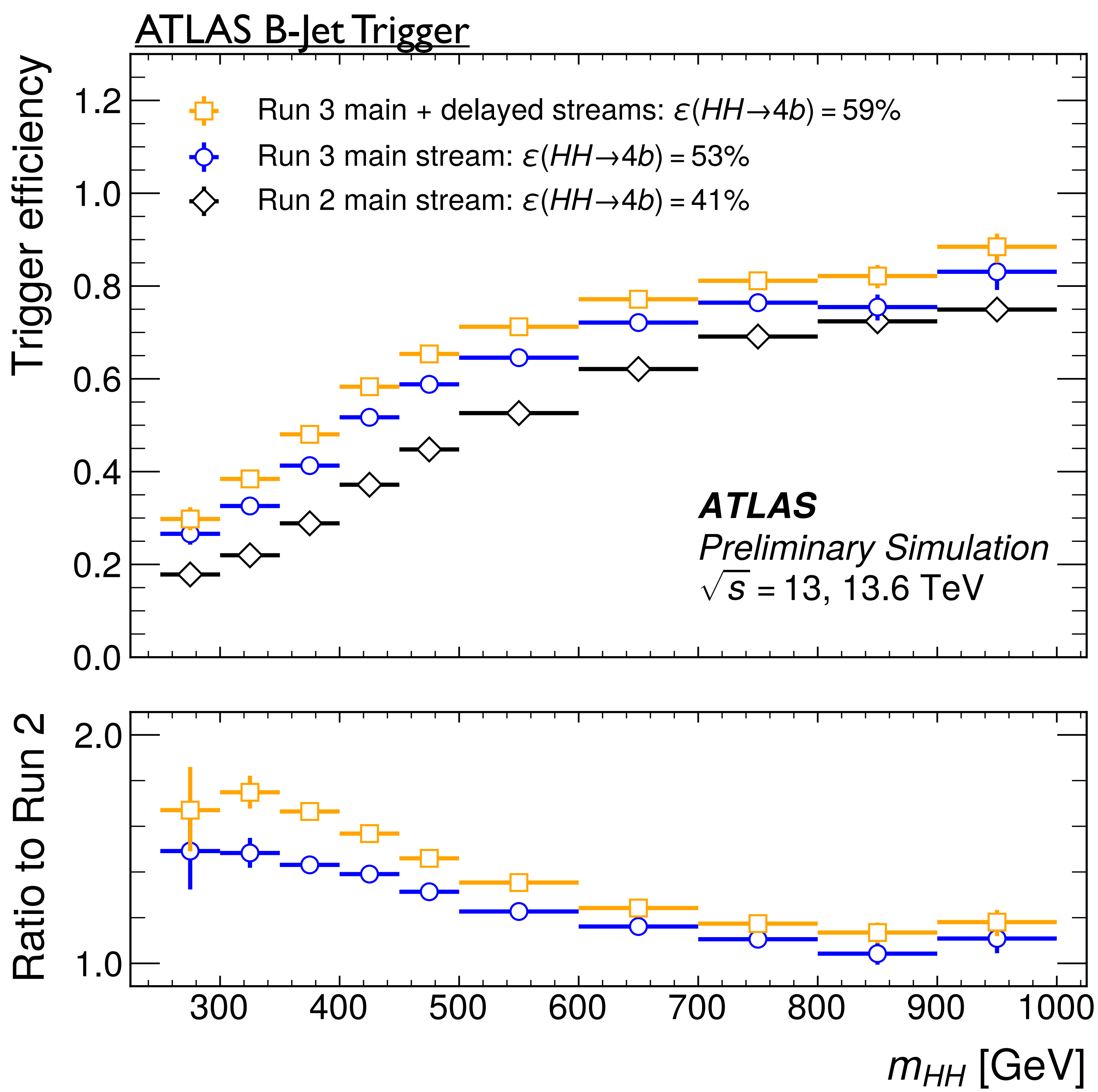

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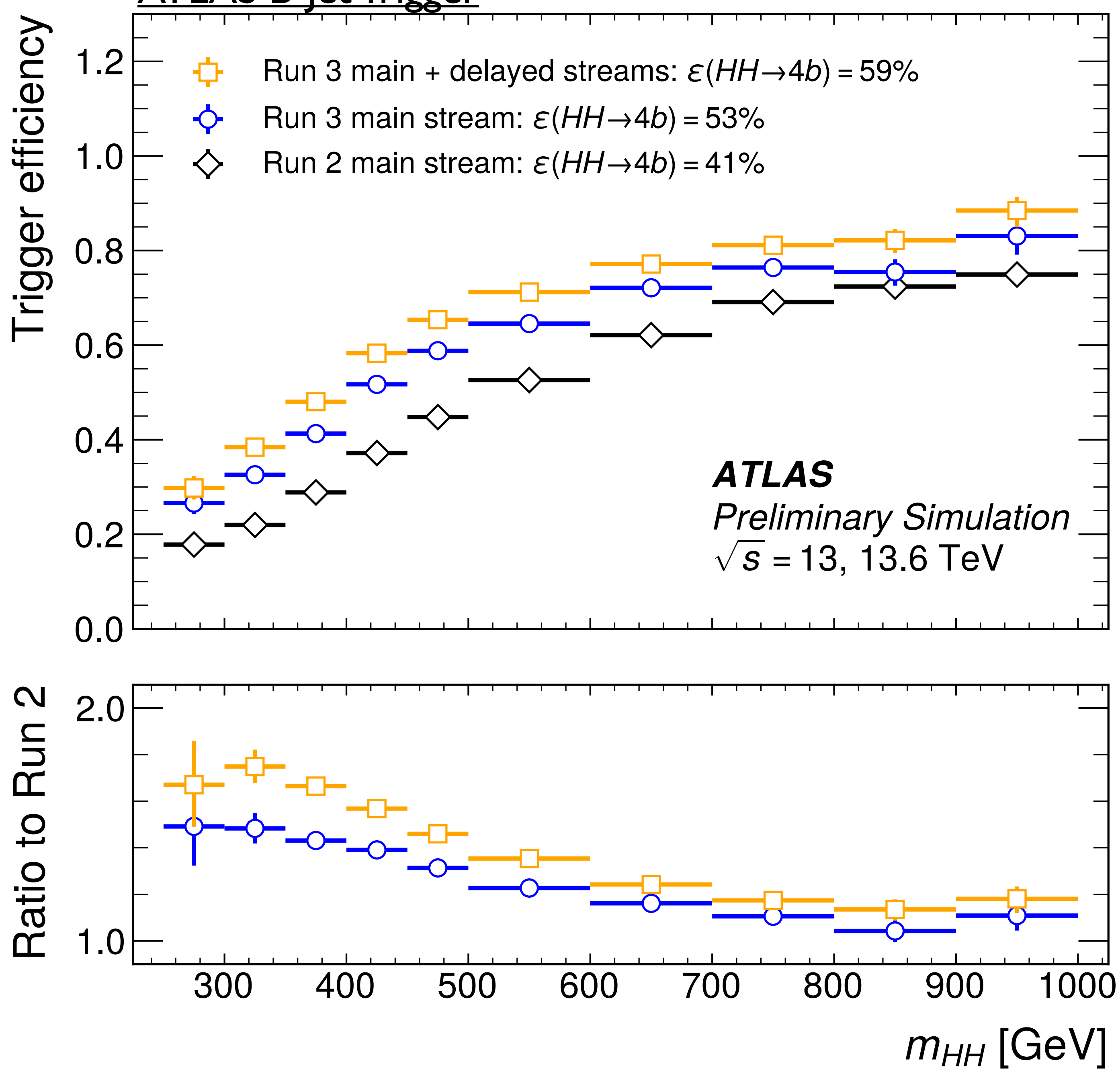
ATLAS B-Jet Trigger



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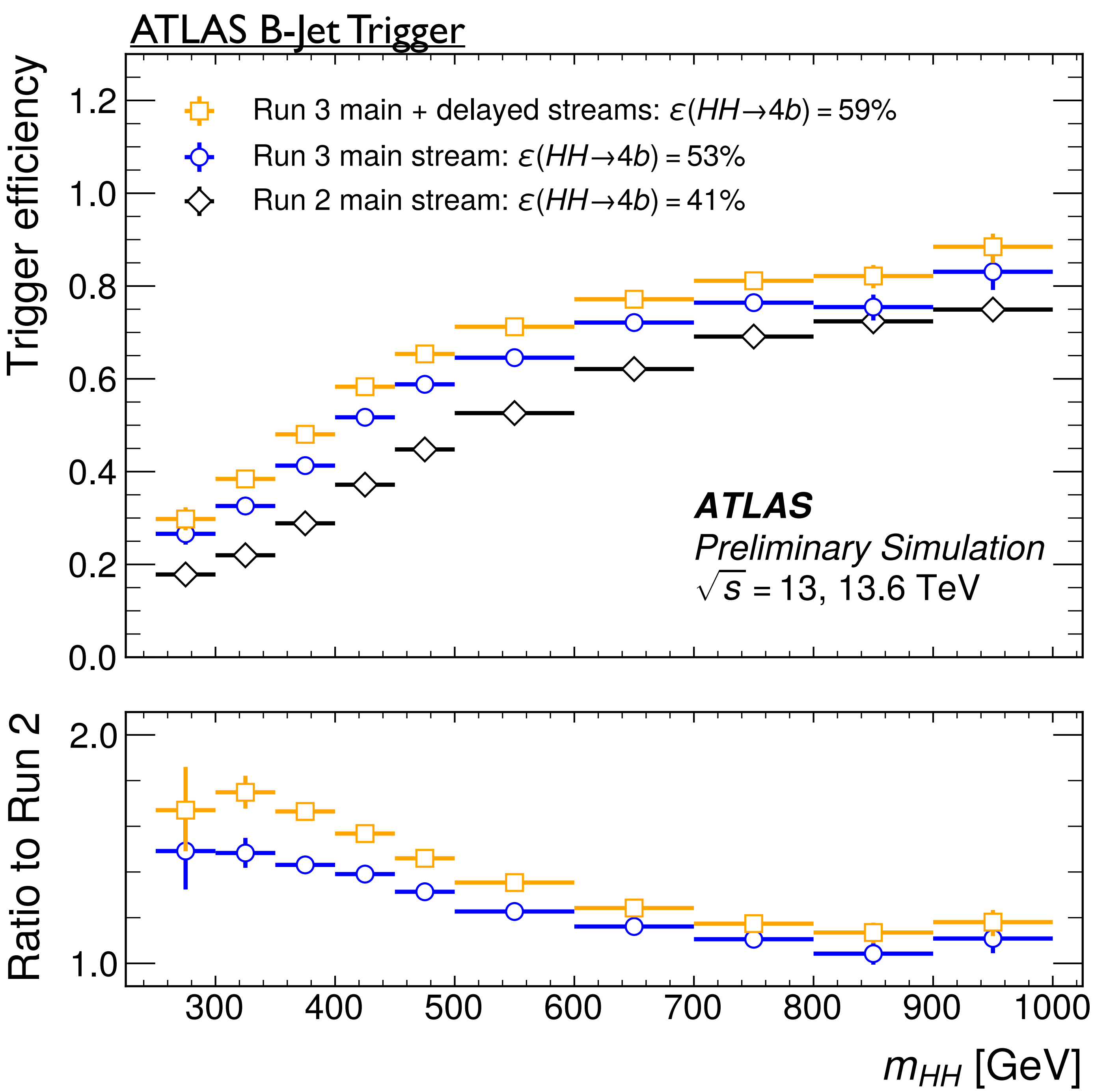

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Nearly 100% more signal at low m_{hh} for $b\bar{b}b\bar{b}$ final state!

The HL-LHC

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Huge upgrades on the way to collider and detectors to take data even faster

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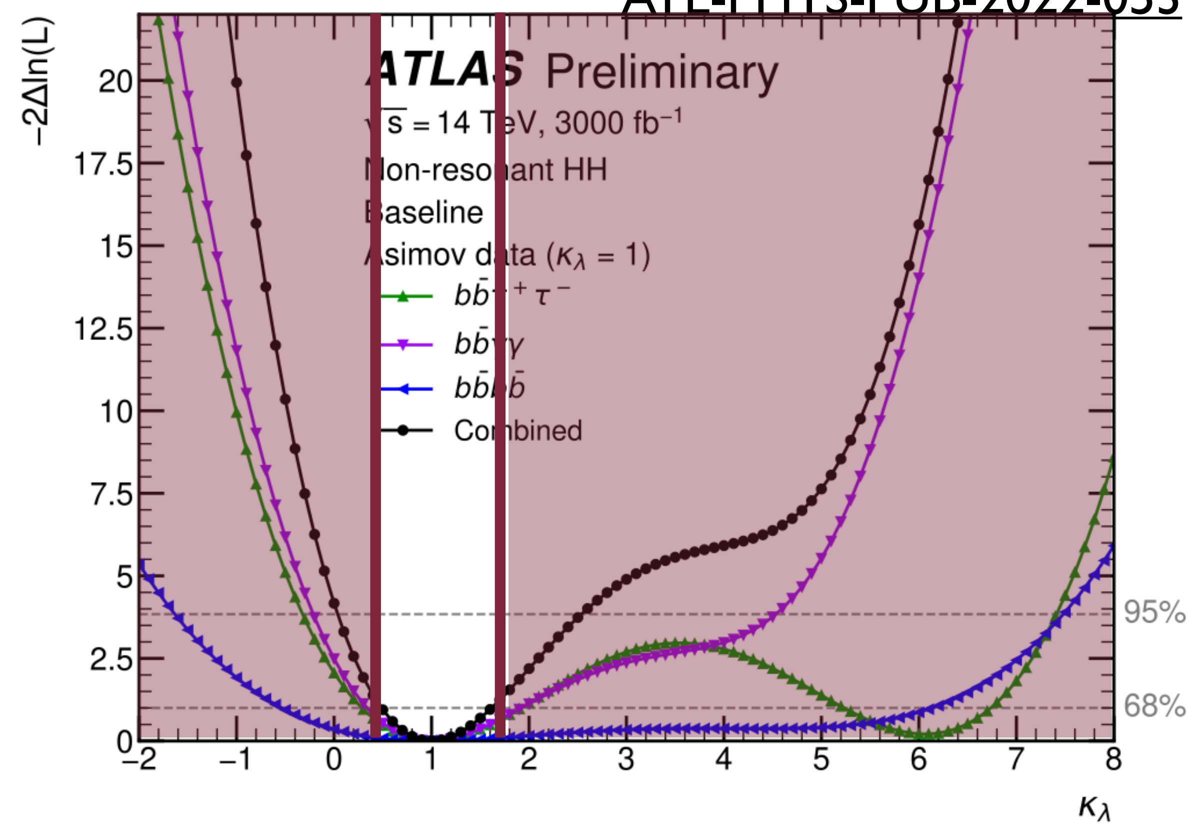
ATL-PHYS-PUB-2022-053



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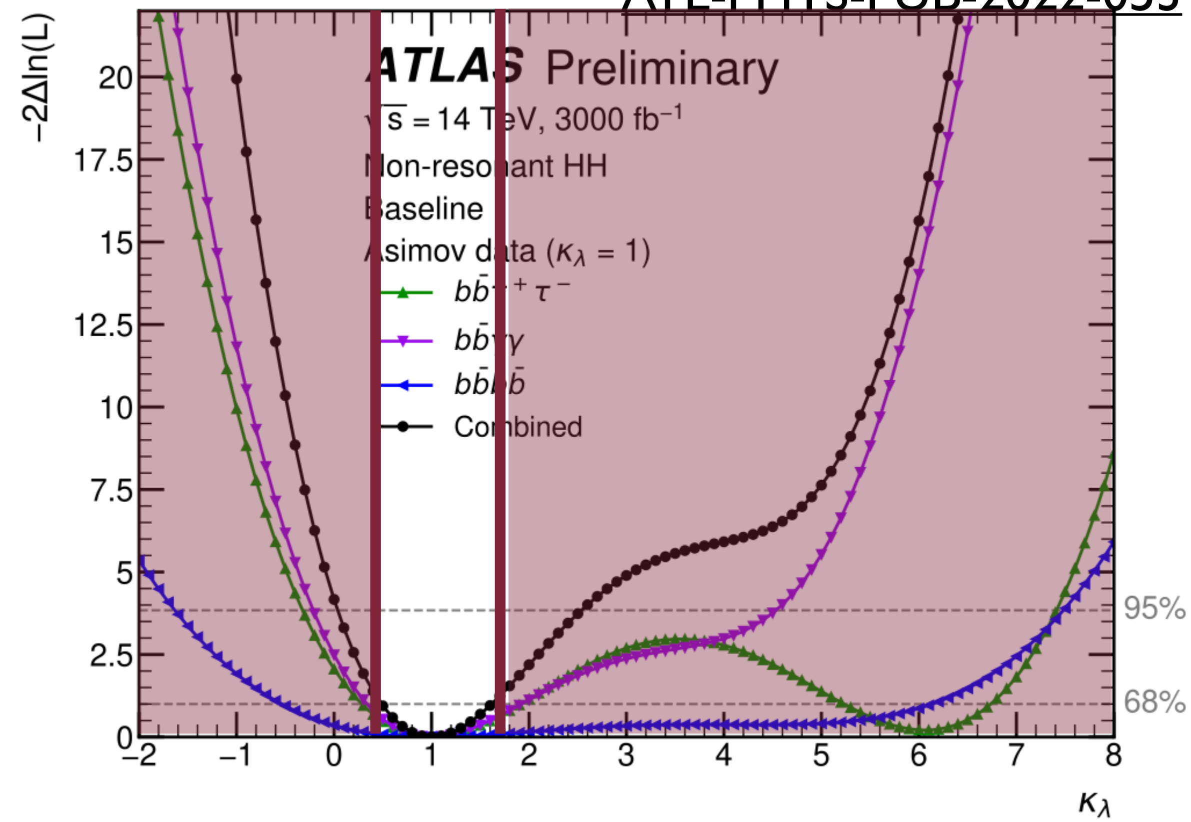

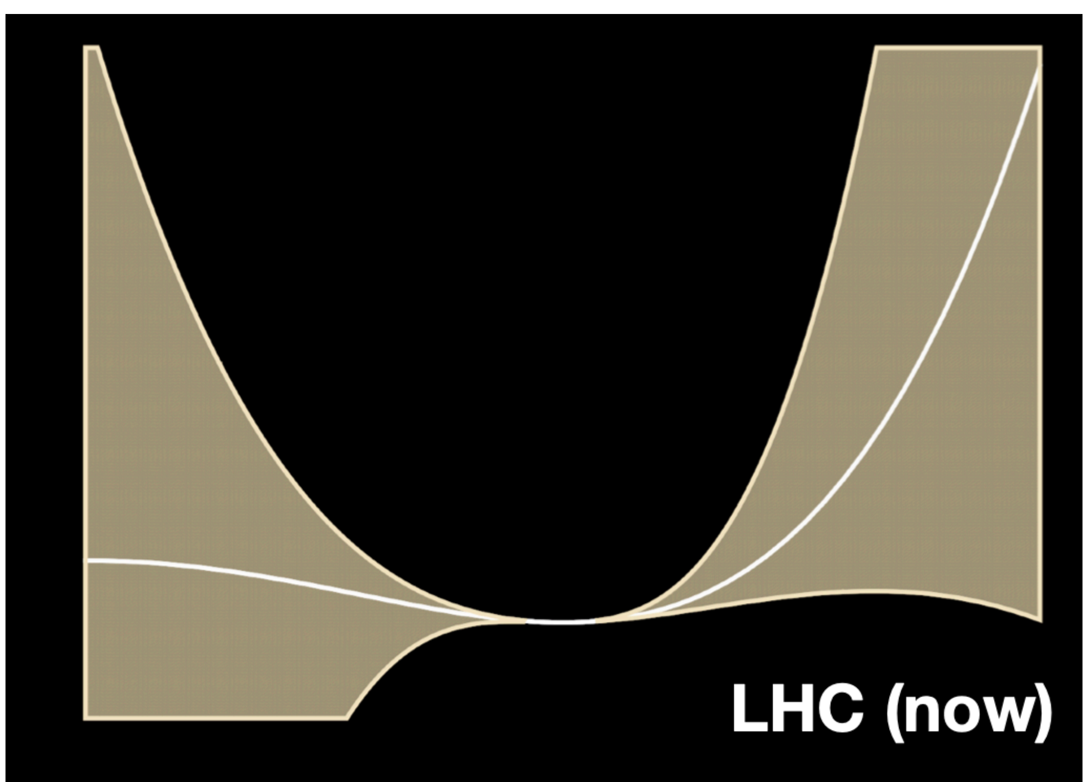

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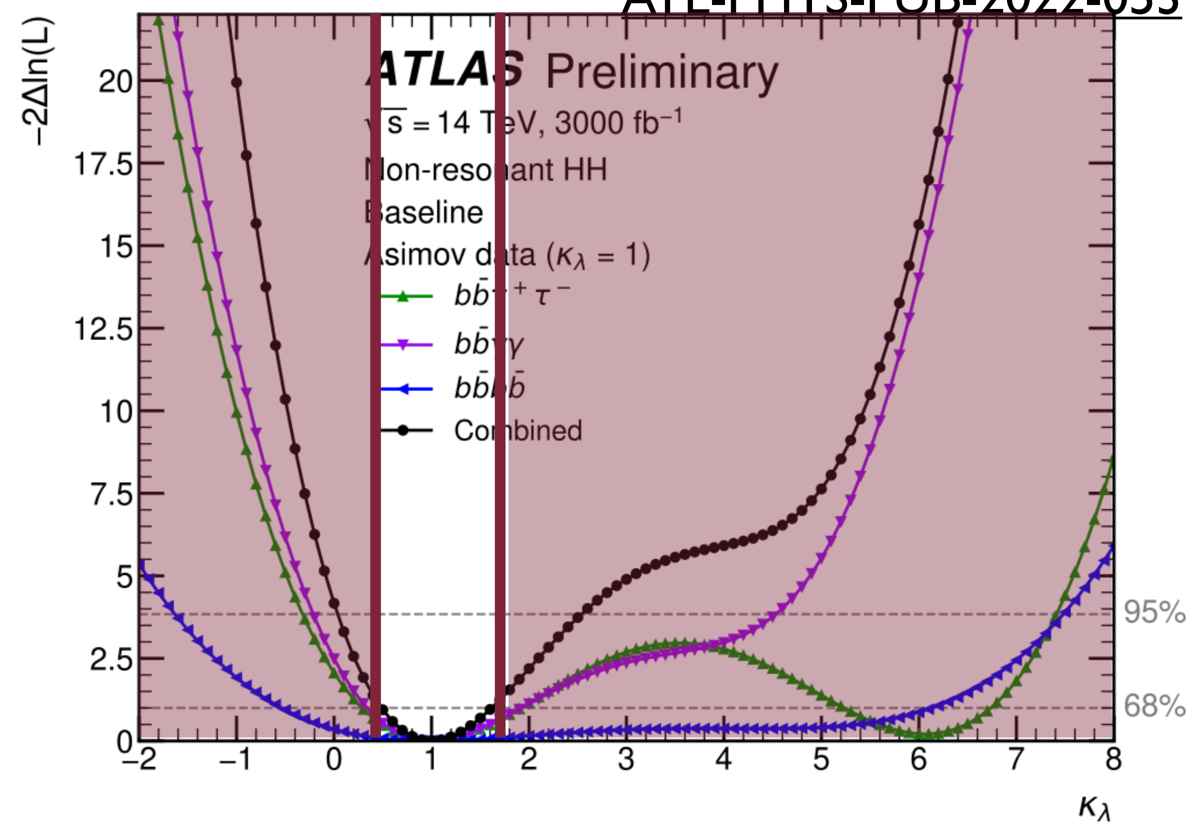
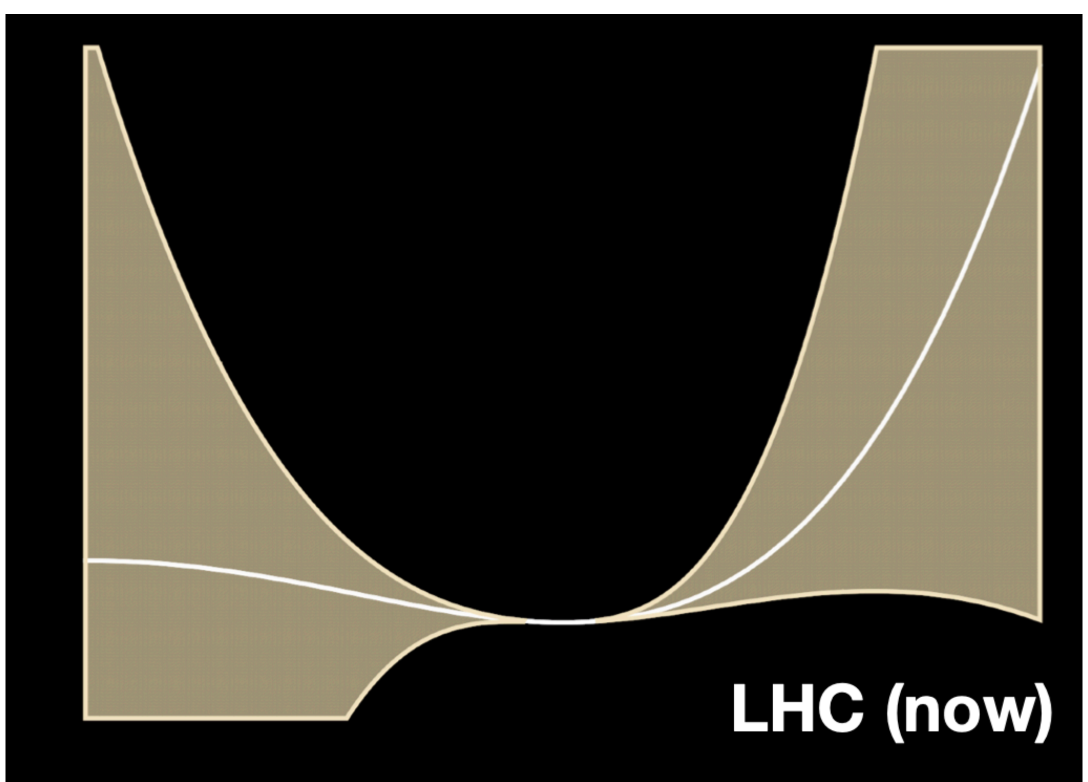
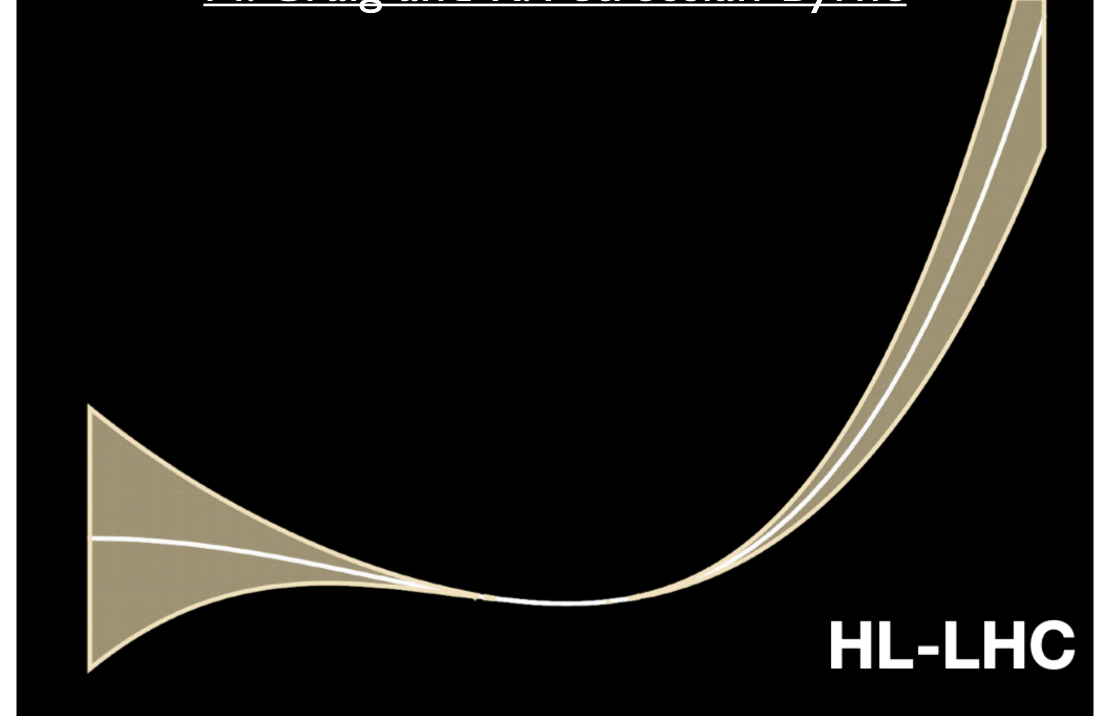




N. Craig and R. Petrossian-Byrne



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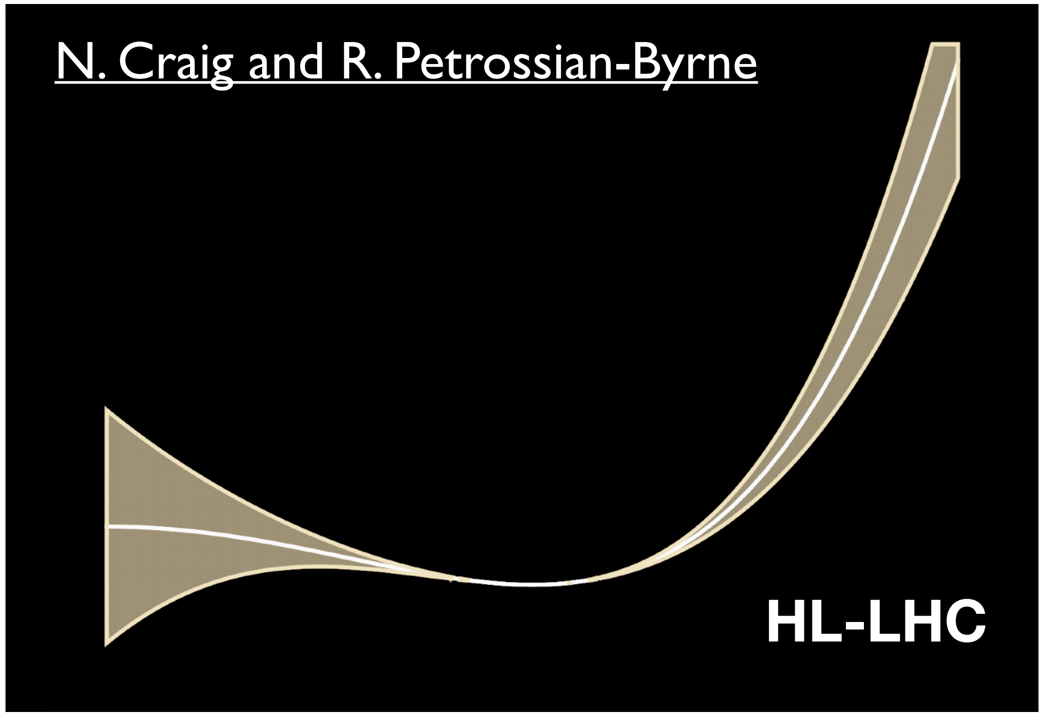

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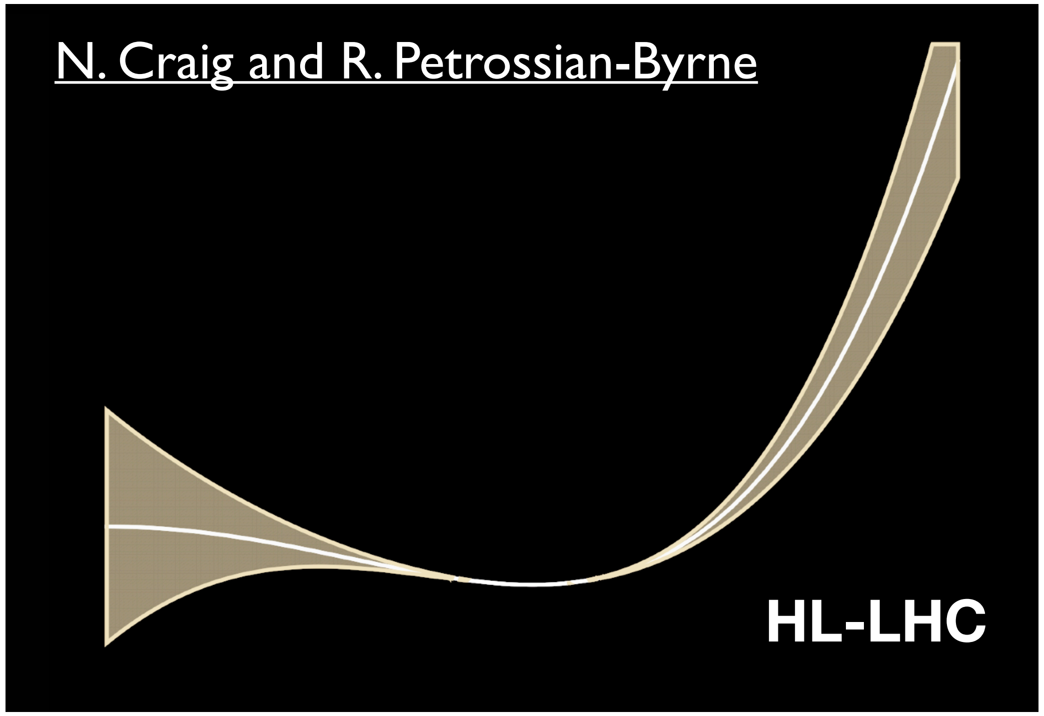

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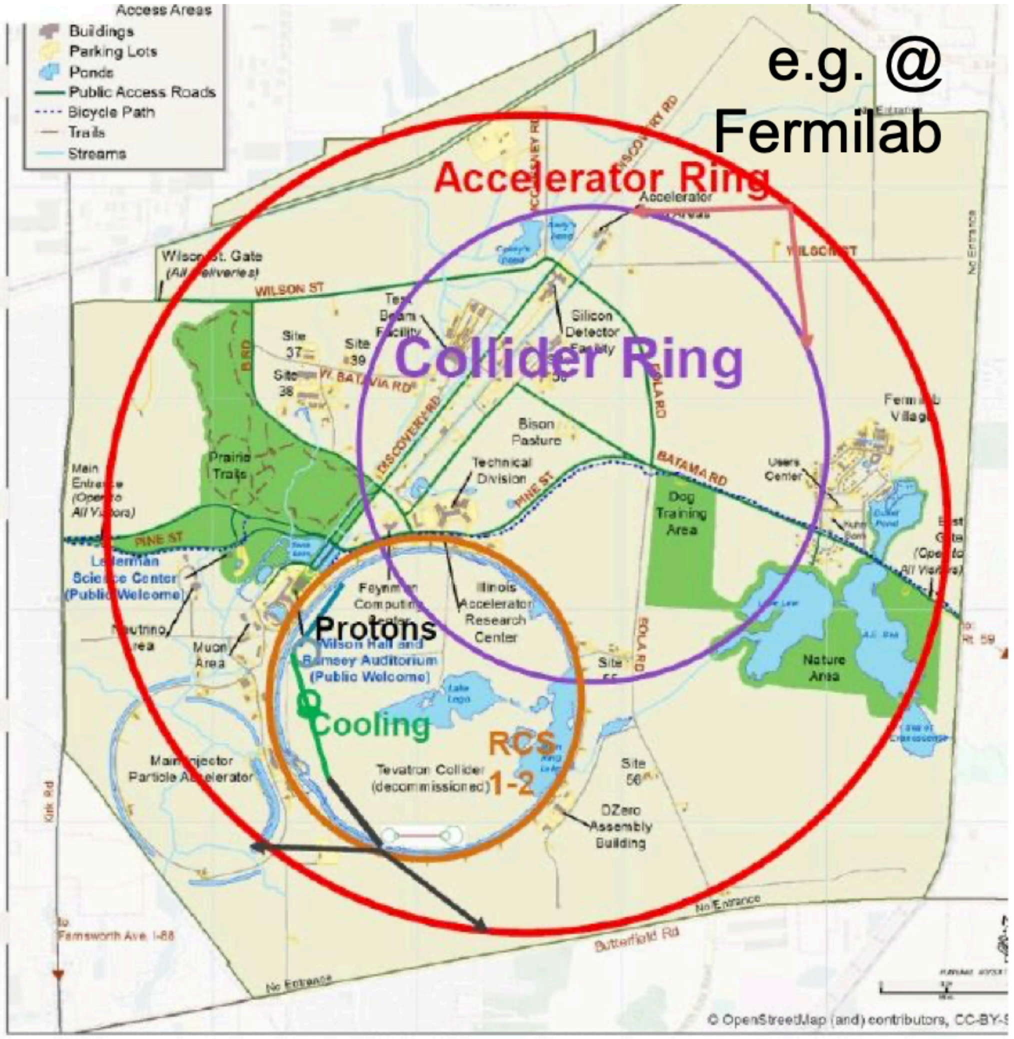

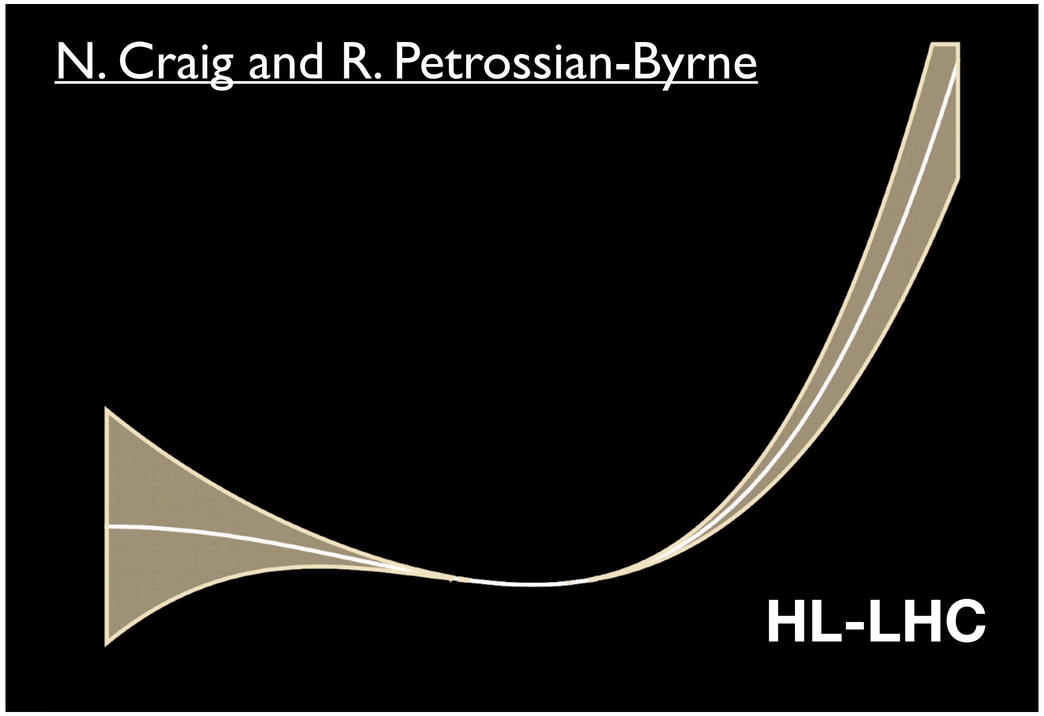

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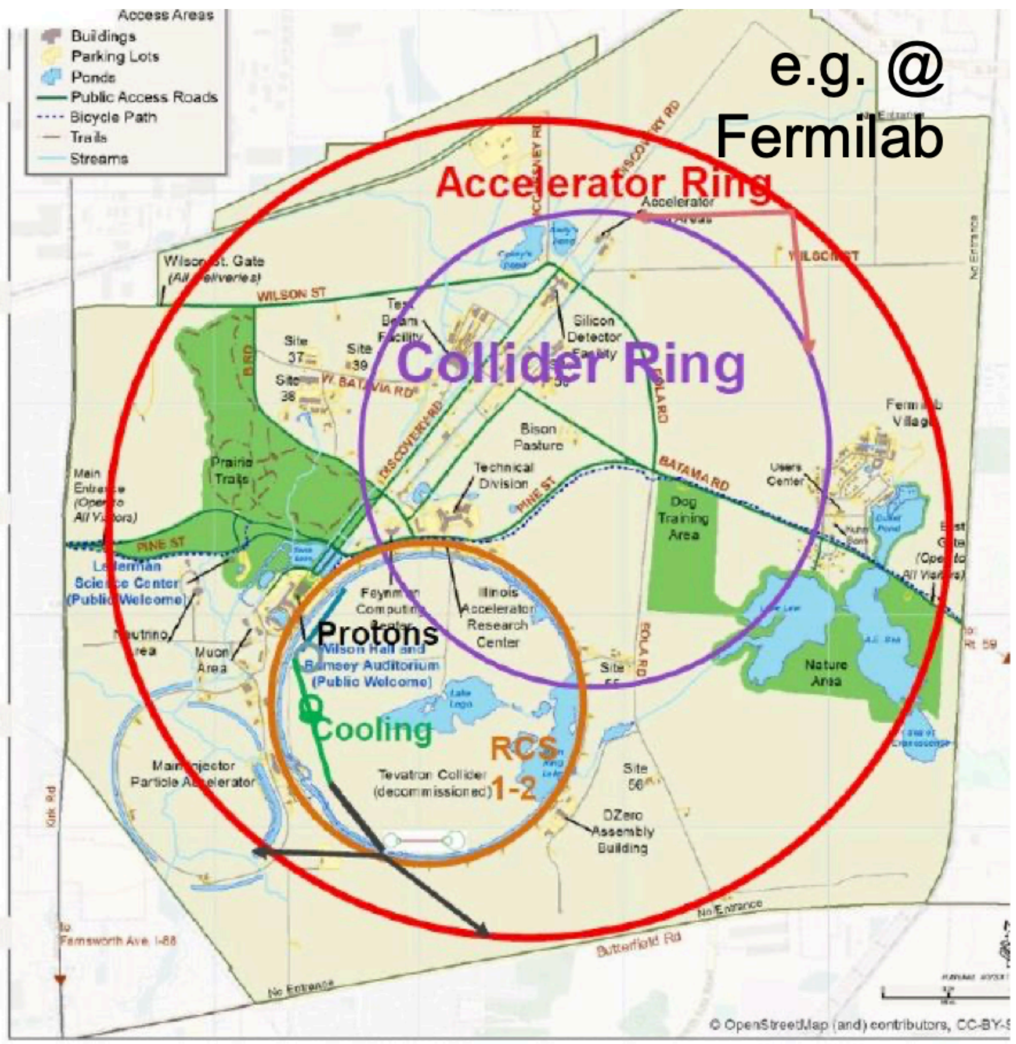

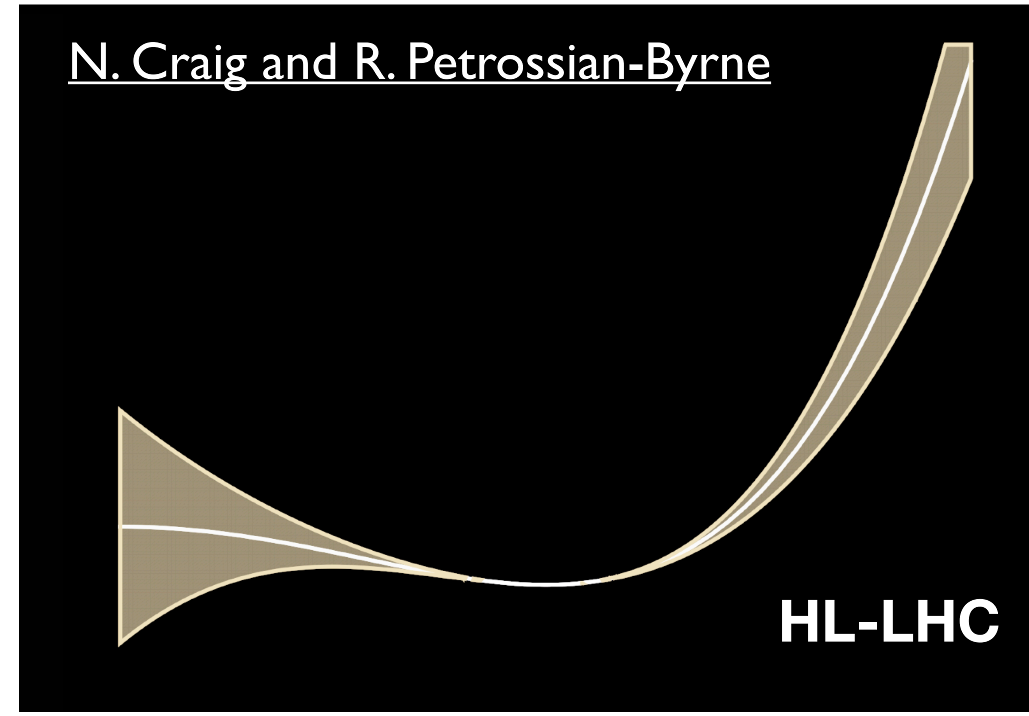

A μCollider at FNAL could do **~5%**

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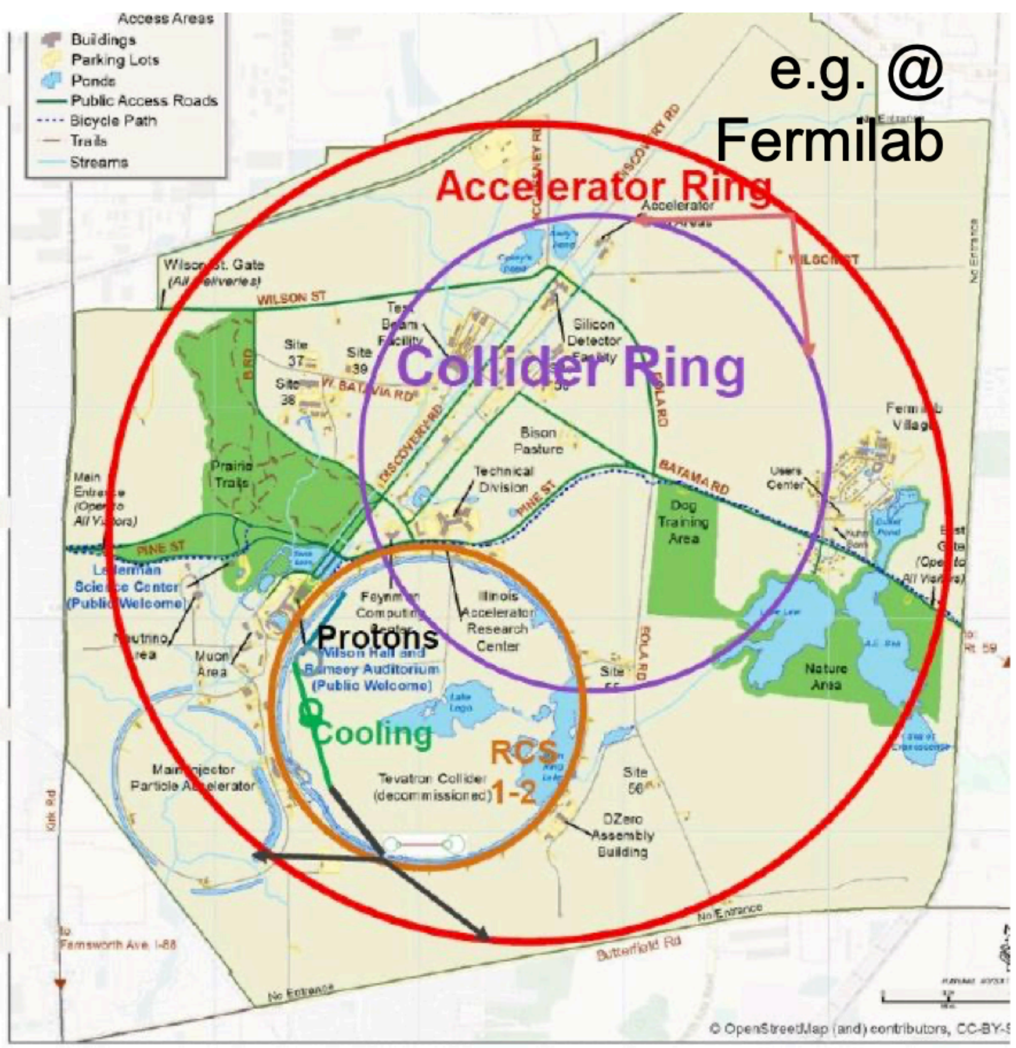

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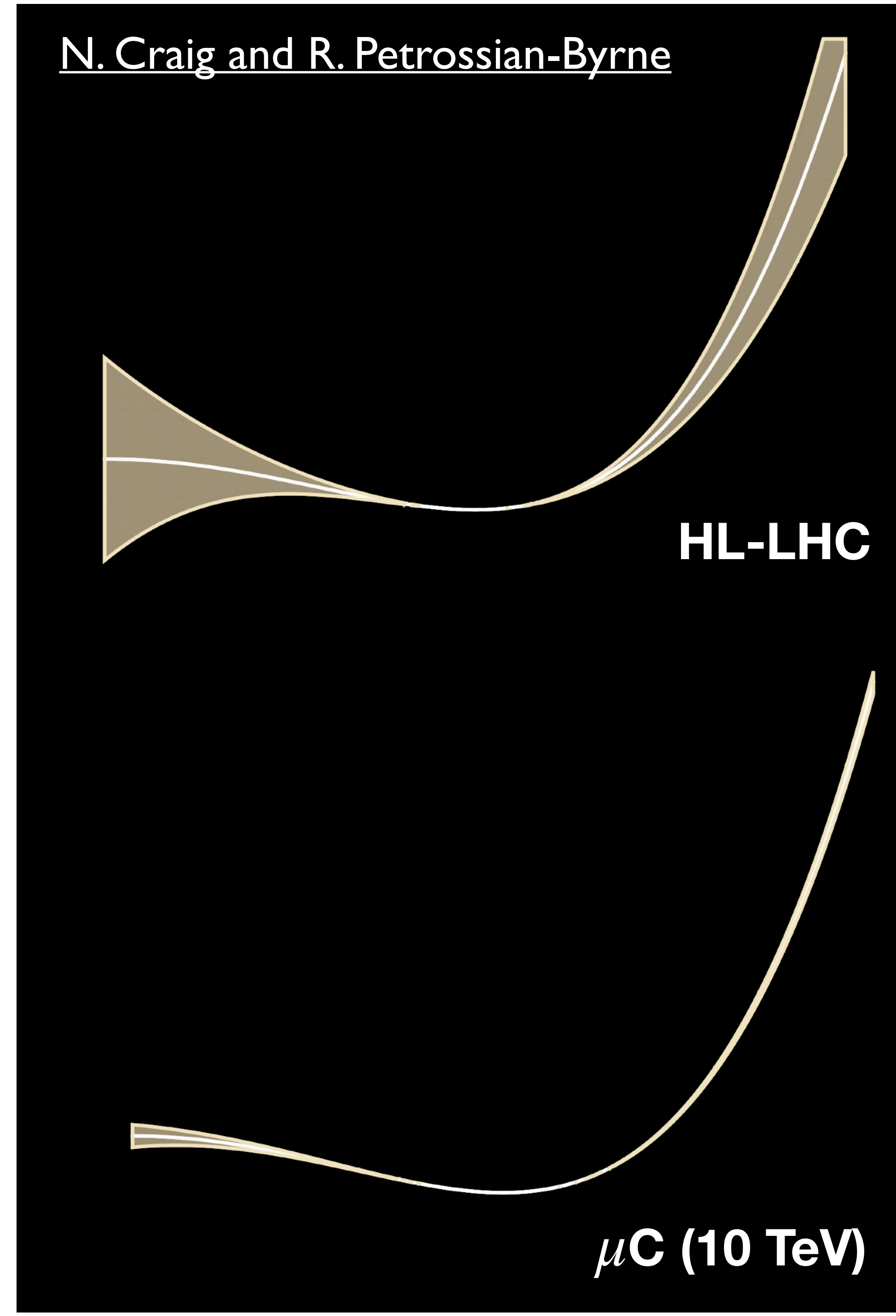

The Higgs is the center of the SM:
Measuring its potential is the
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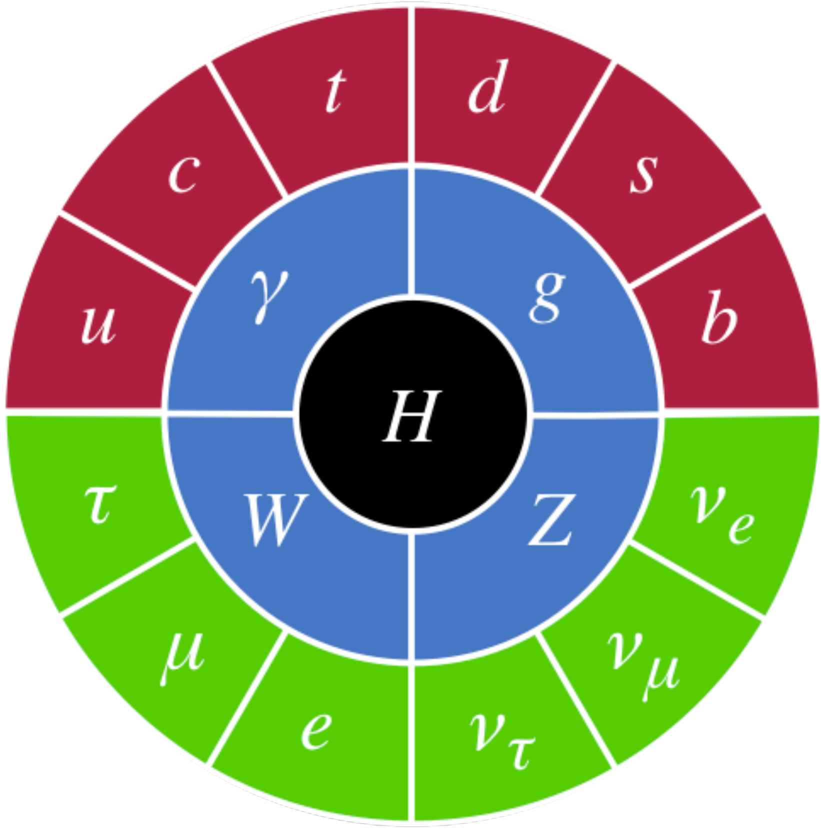

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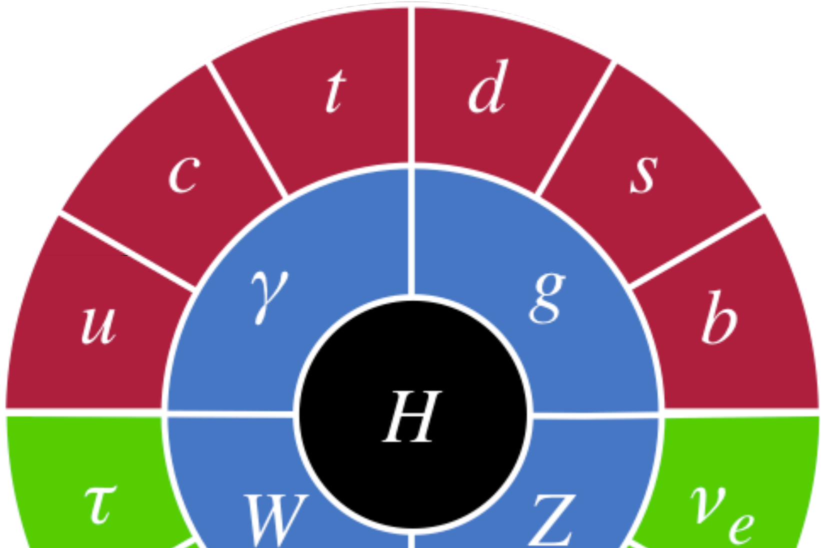
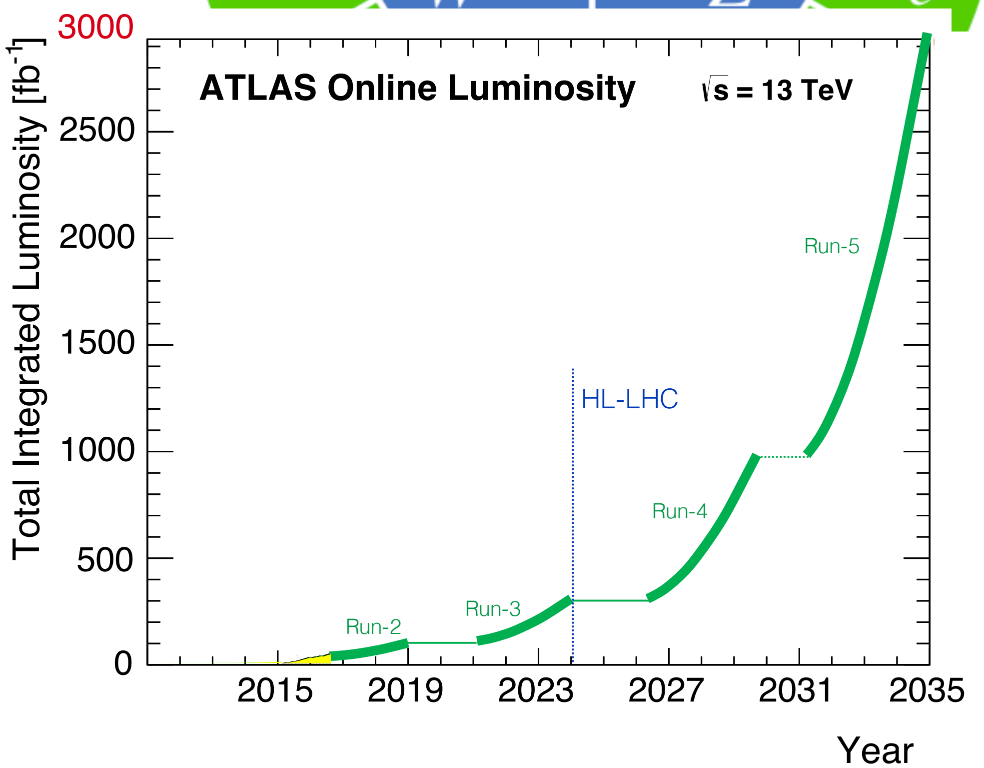


The rare signature takes advantage of the **huge LHC datasets**



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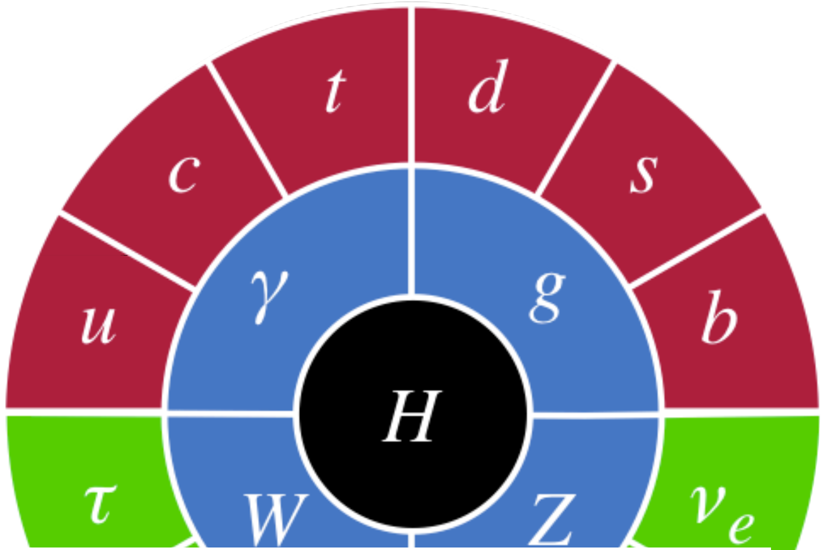

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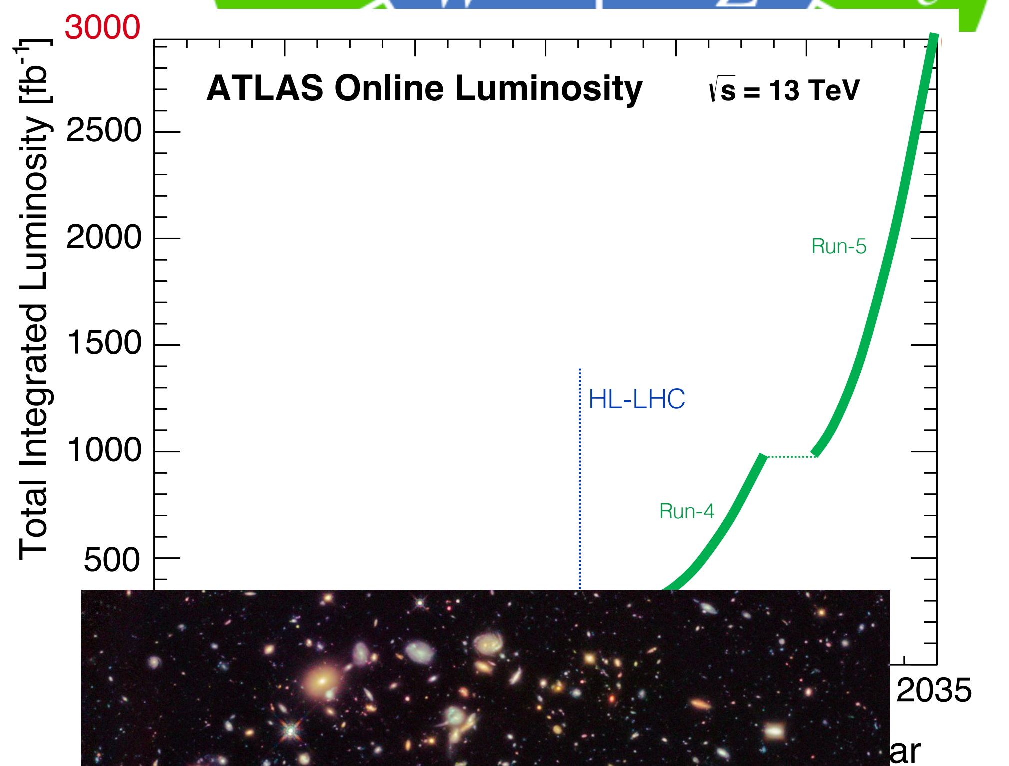

Measuring the Higgs potential
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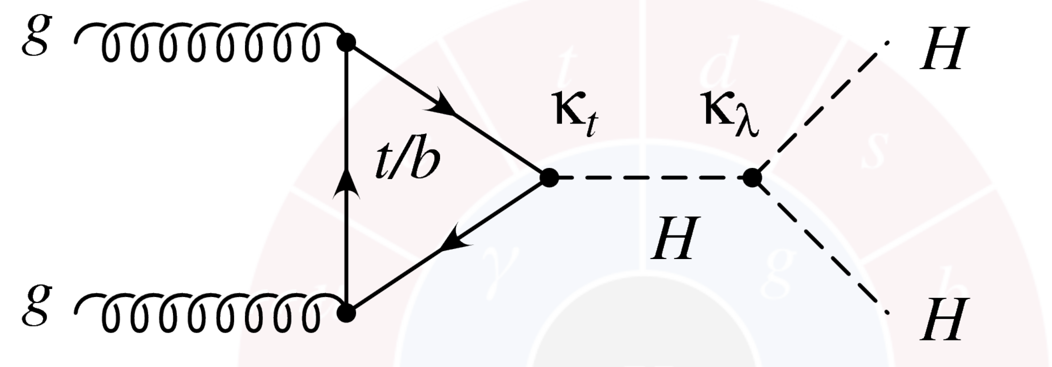
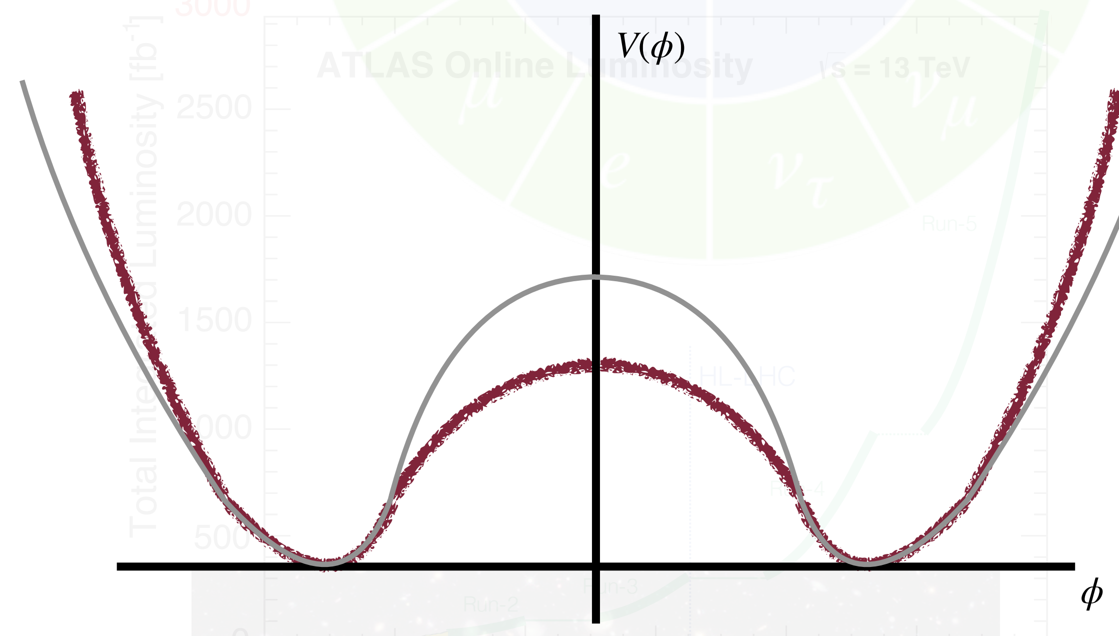
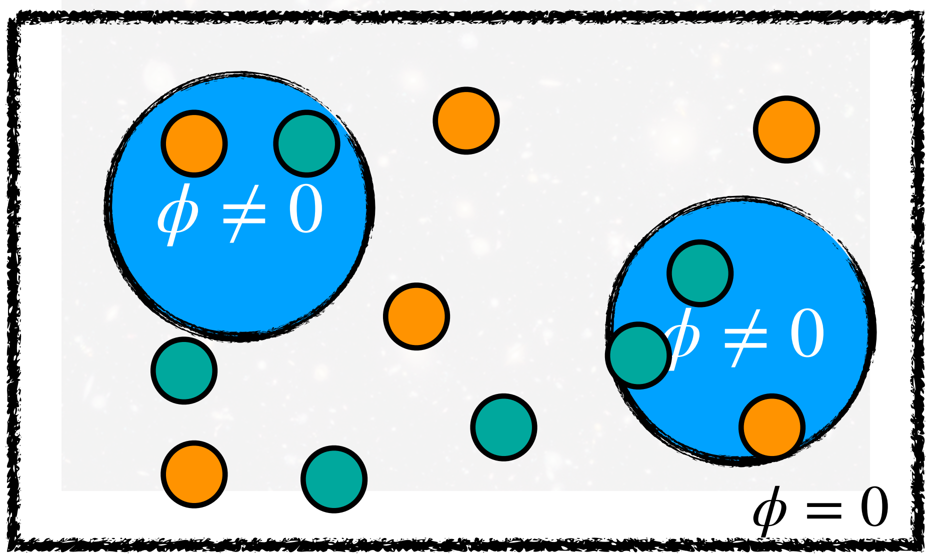
Our experimental program at ATLAS is working to overcome the challenges of the signature, to discover Higgs pair production, and to **measure the Higgs potential**







Thank you!

More in:

Phys. Rev. D 106 (2022) 052001

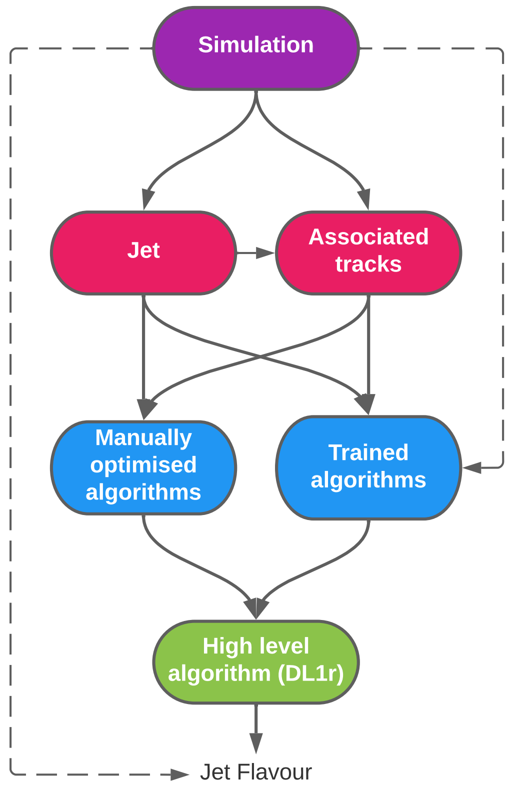
arXiv:2209.10910

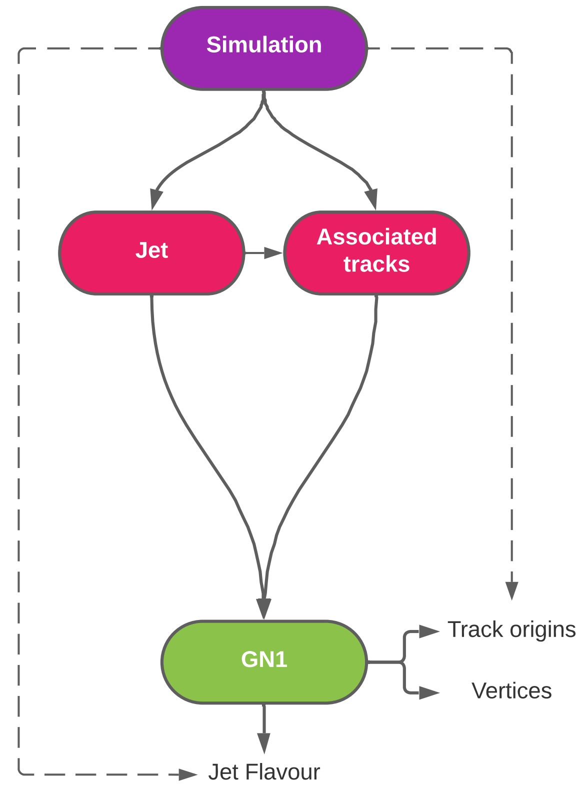
arXiv:2301.03212

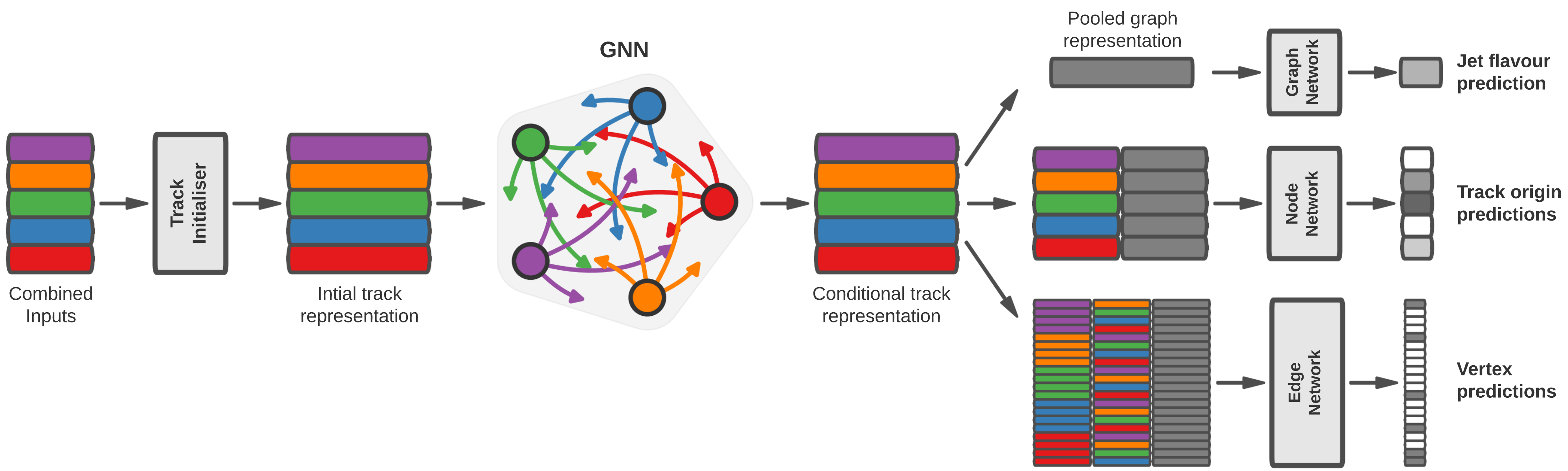
arXiv:2211.01216

Backup

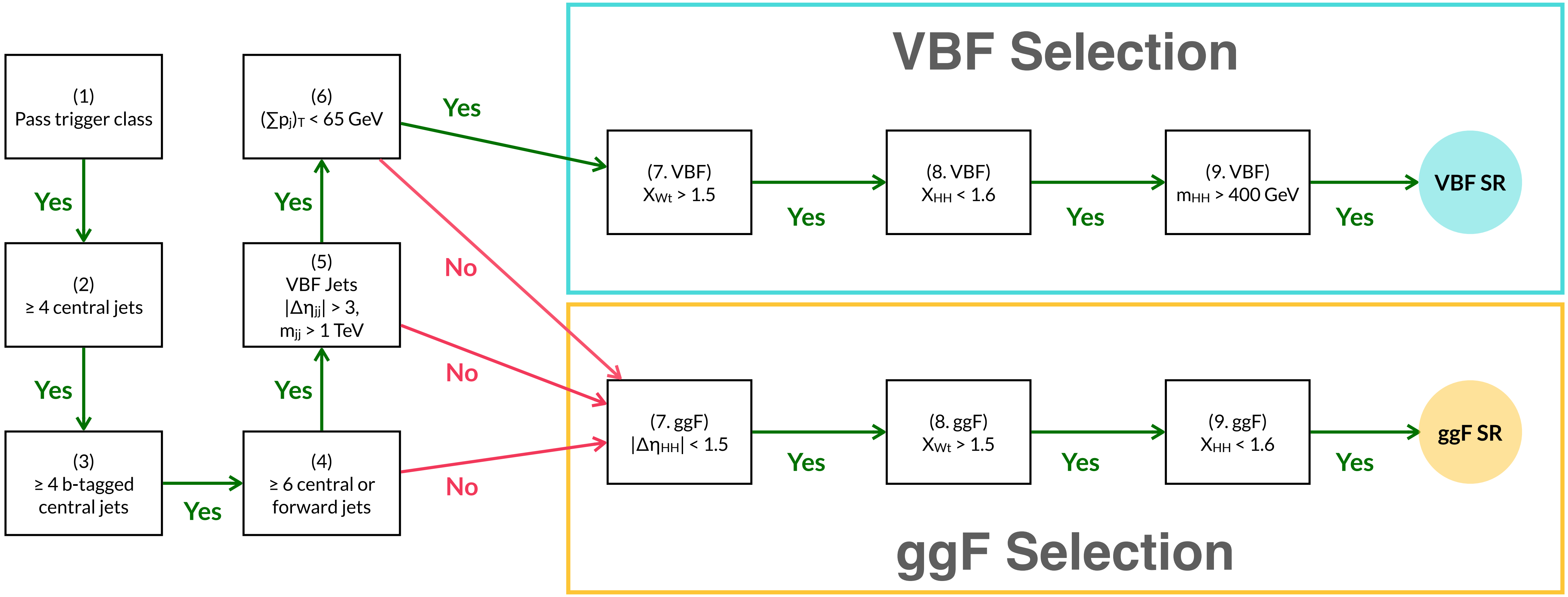
b-Tagging


Simulation
Jet
Associated tracks
Manually optimised algorithms
Trained algorithms
High level algorithm (DL1r)
Jet Flavour


Simulation
Jet
Associated tracks
GN1
Track origins
Vertices
Jet Flavour


GNN
Combined Inputs
Track Initialiser
Intial track representation
Conditional track representation
Pooled graph representation
Graph Network
Jet flavour prediction
Node Network
Track origin predictions
Edge Network
Vertex predictions

4b Analysis Flow



Resonant Searches

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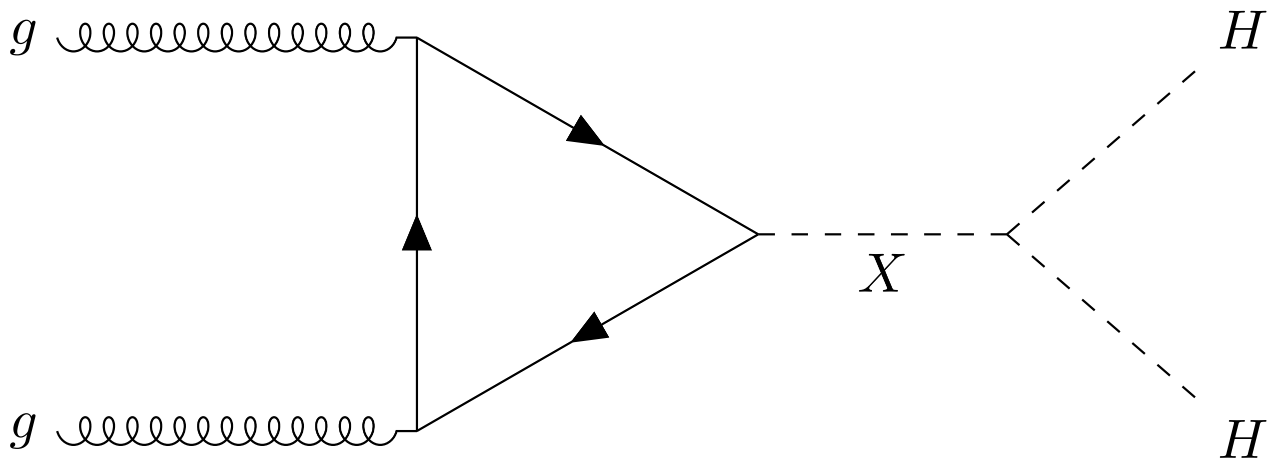
If we want to see BSM effects in the potential, can also look for BSM directly



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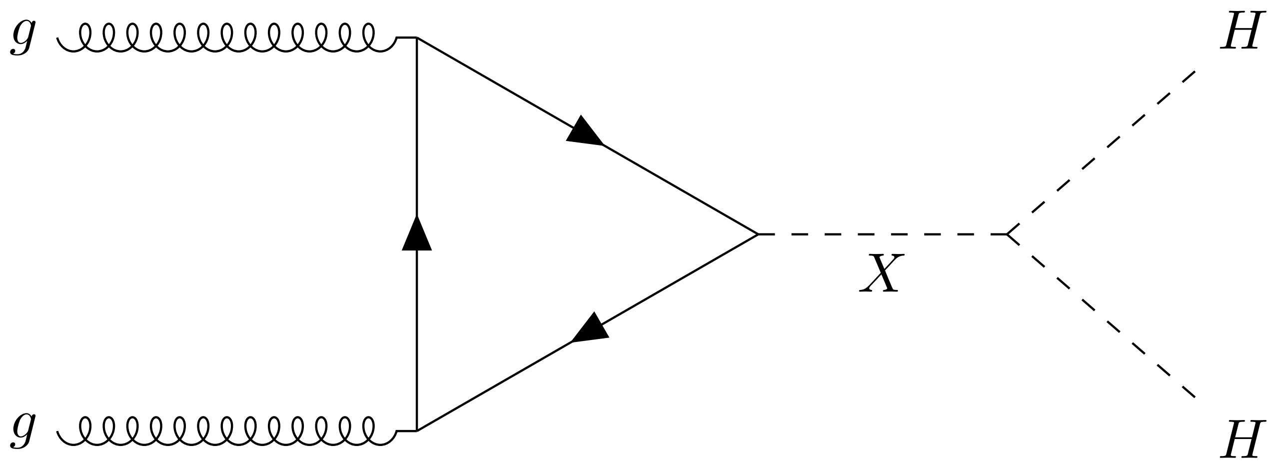

Depending on mass of X, H can have low or high momentum

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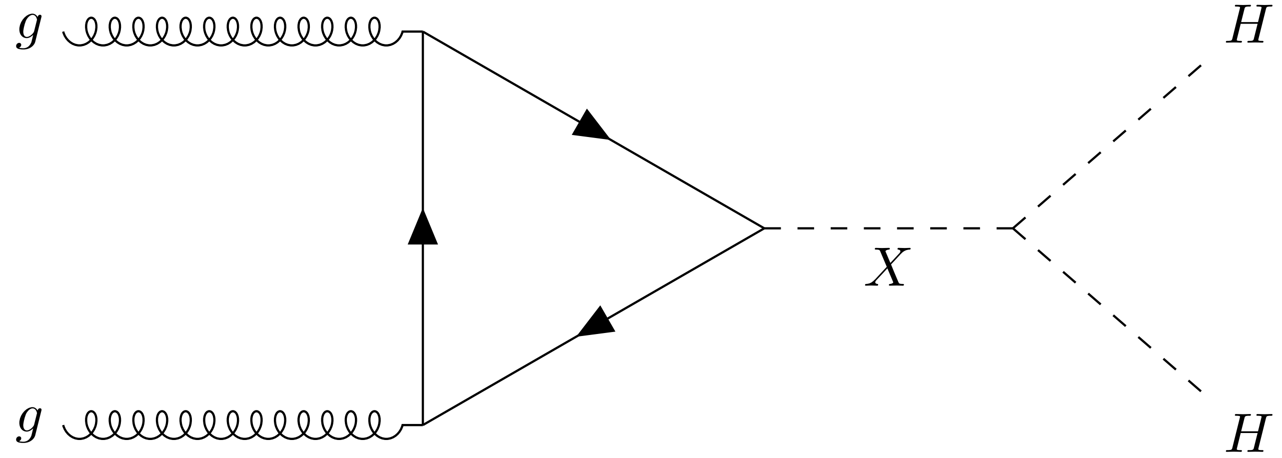

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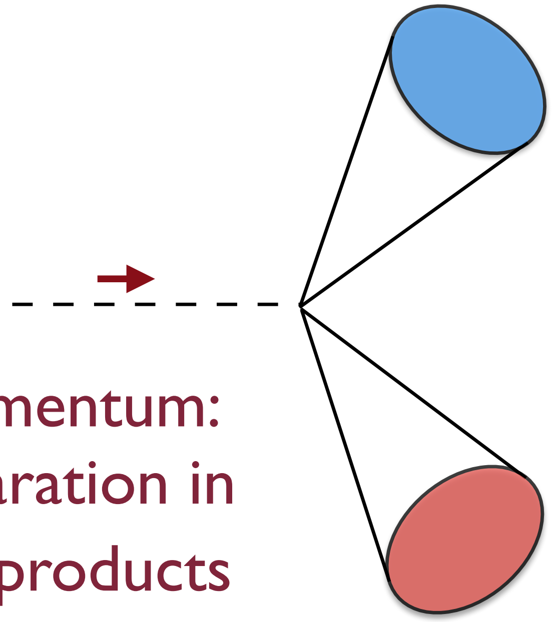

Low momentum: High separation in H decay products

Reconstruct **resolved** decay products

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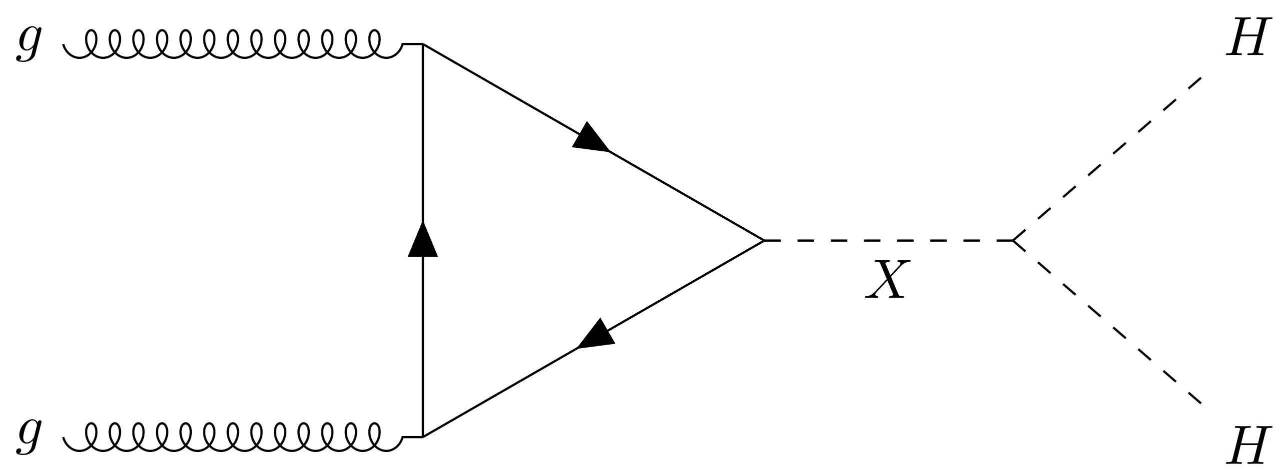

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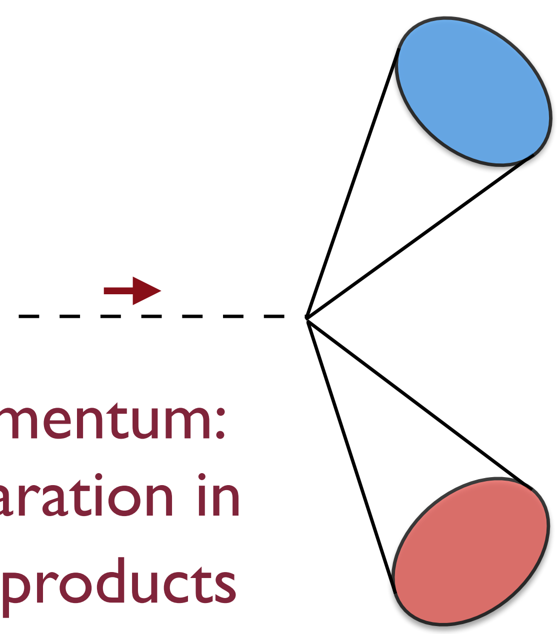

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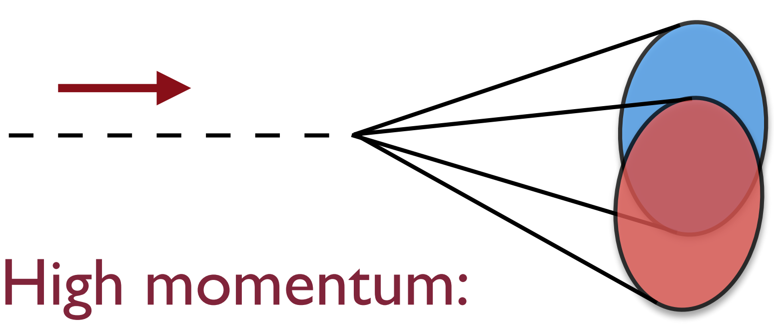

High momentum:
Low separation in
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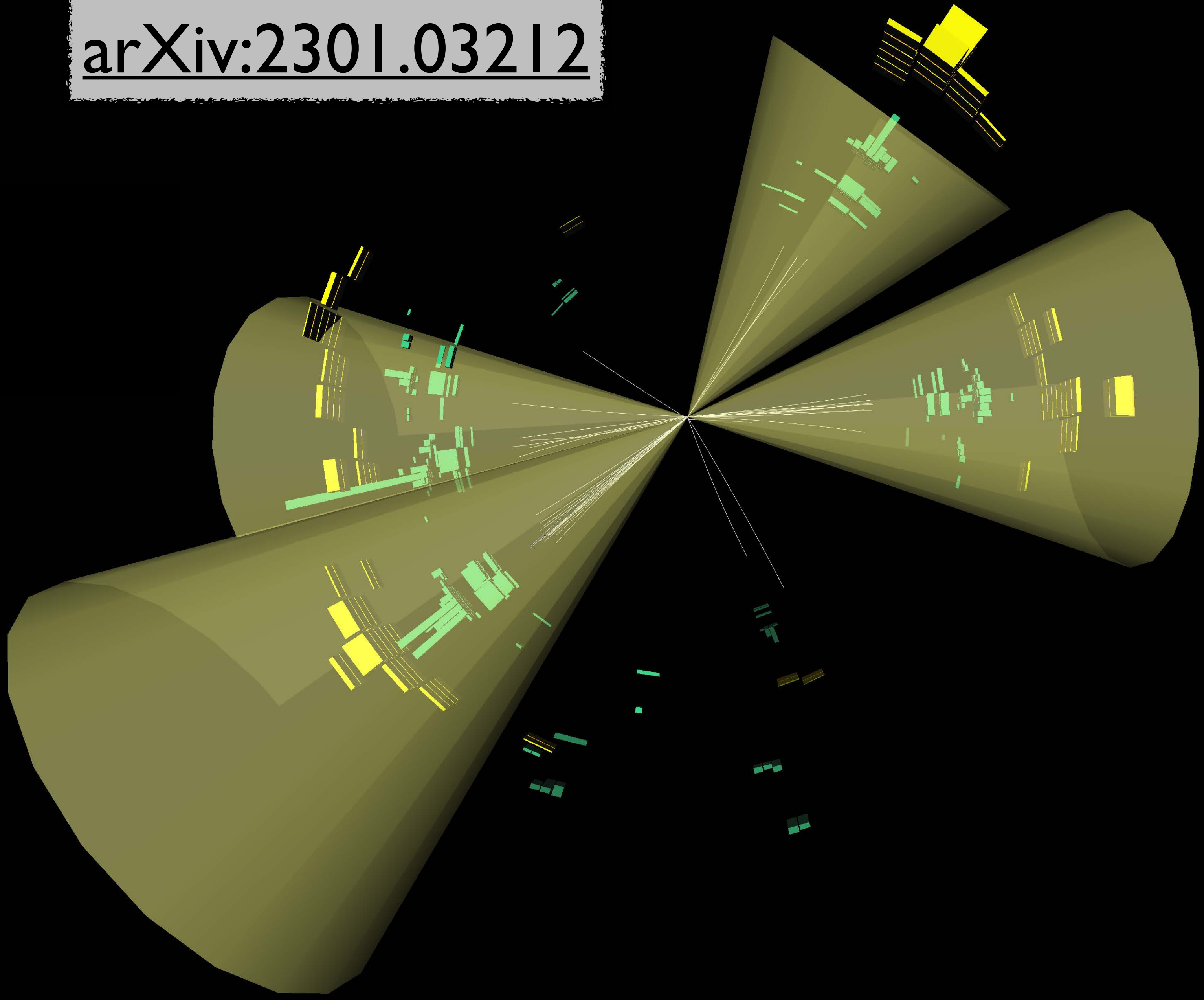
Reconstruct **resolved** decay products

Use **boost** to reconstruct single H object

$HH \to b\bar{b}b\bar{b}$ Resolved

arXiv:2301.03212



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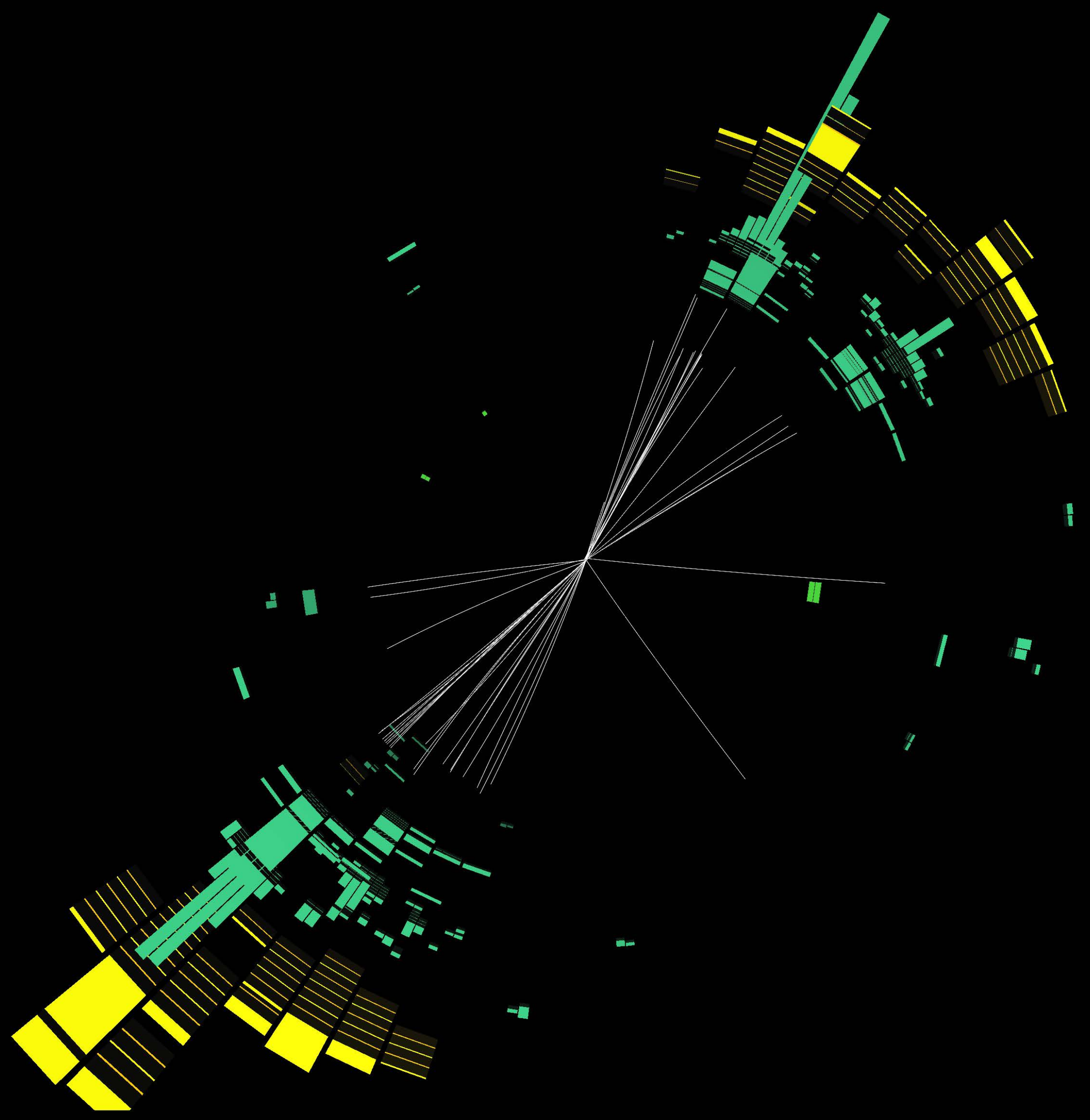

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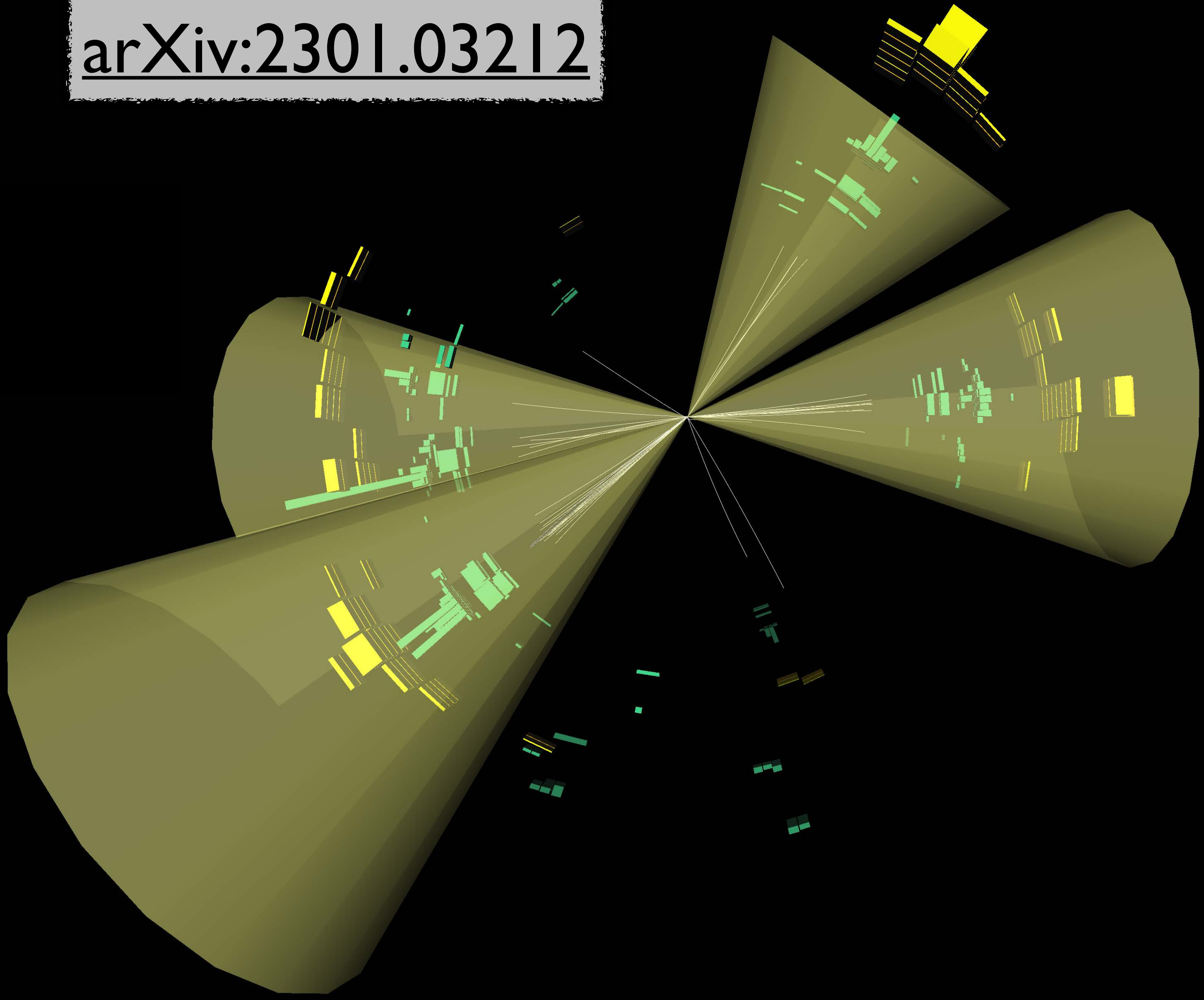
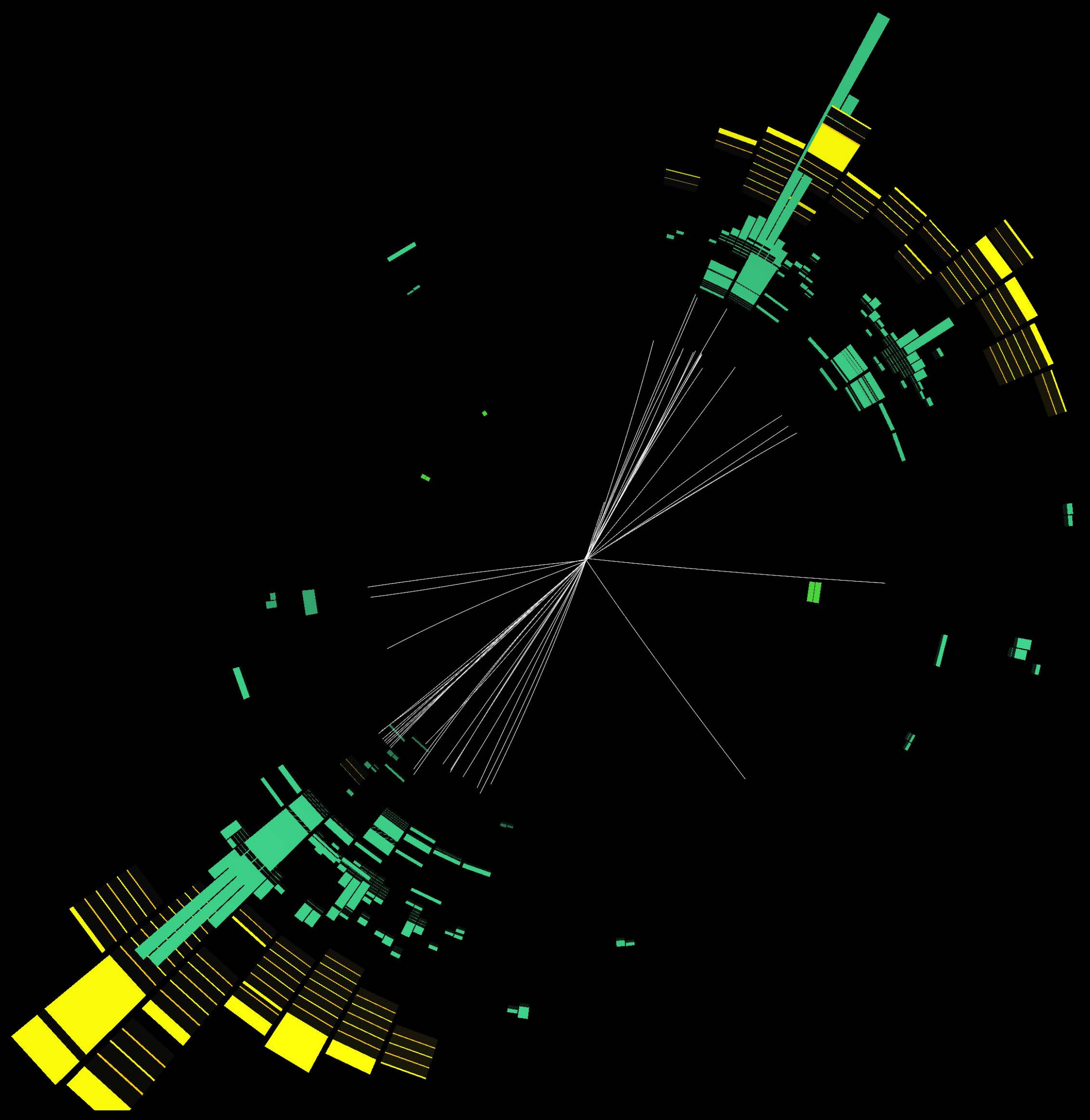


Combination of 12 b-jet triggers

$HH \rightarrow b\bar{b}b\bar{b}$ Boosted



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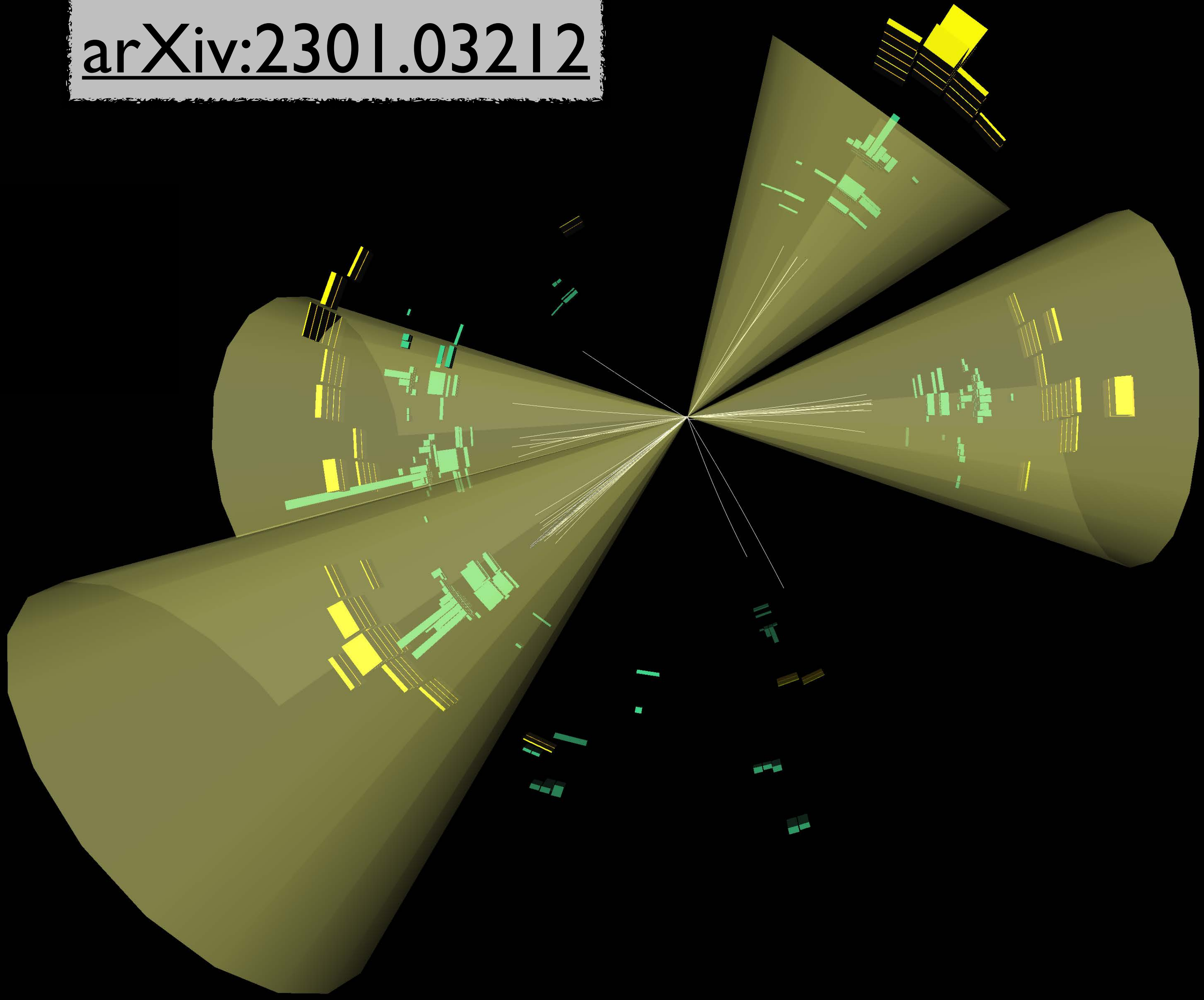

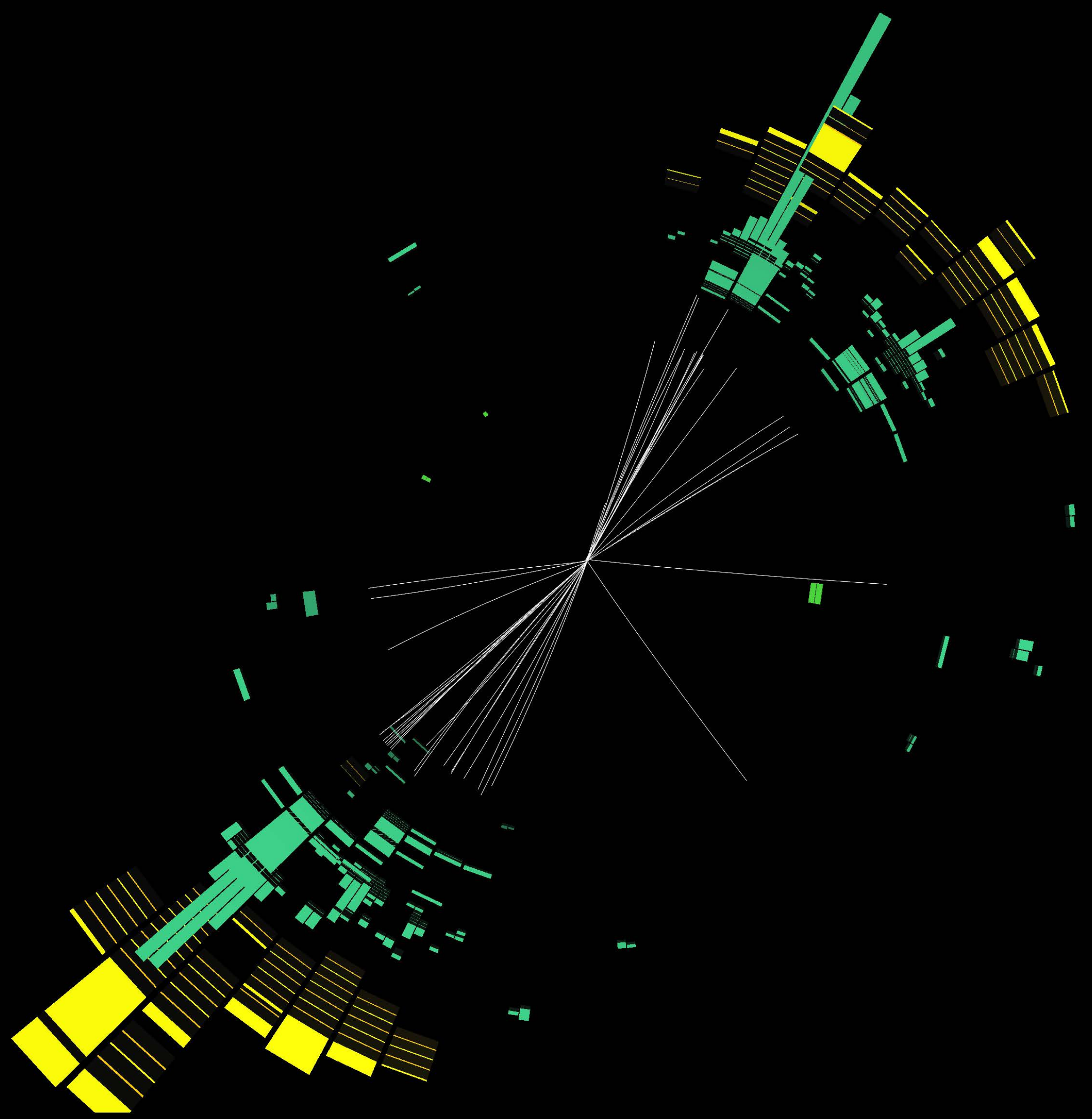

Combination of 12 b-jet triggers

4 b-tagged jets

$(\epsilon = 77\,\%\,, p_T > 40\ \mathrm{GeV})$

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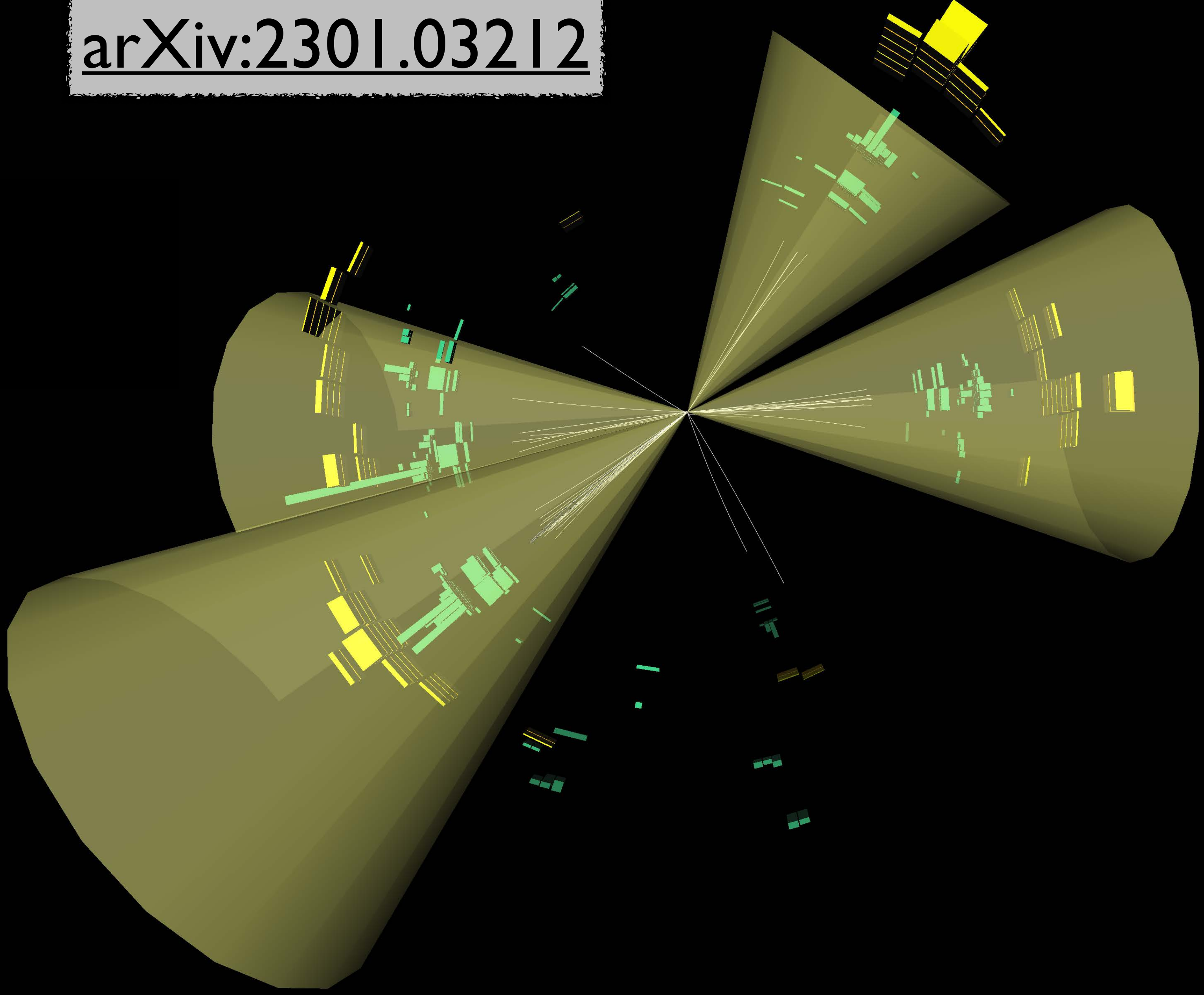

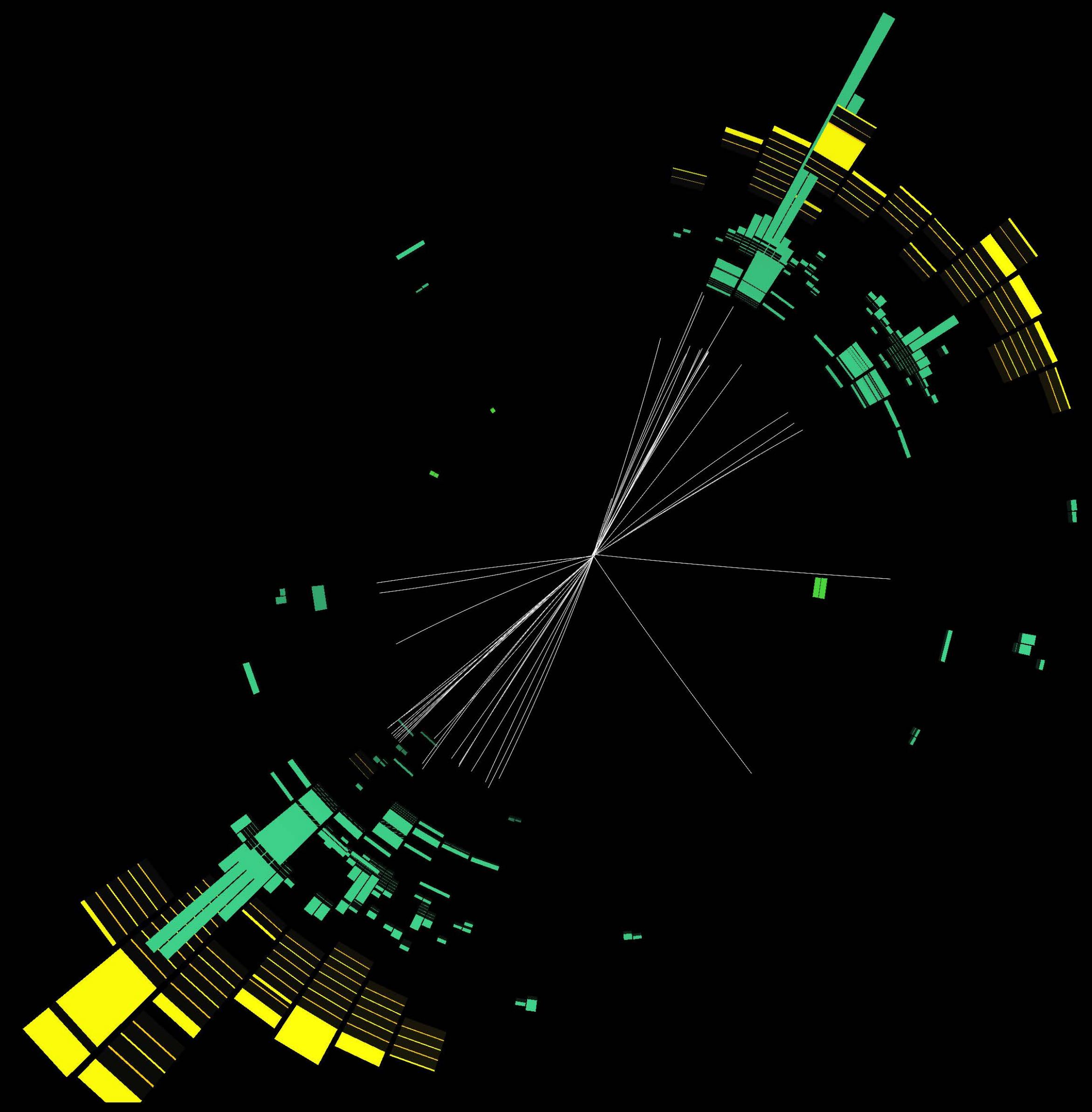

Combination of 12 b-jet triggers

4 b-tagged jets
($\epsilon = 77\,\%, p_T > 40$ GeV)

Boosted Decision Tree used to pair jets

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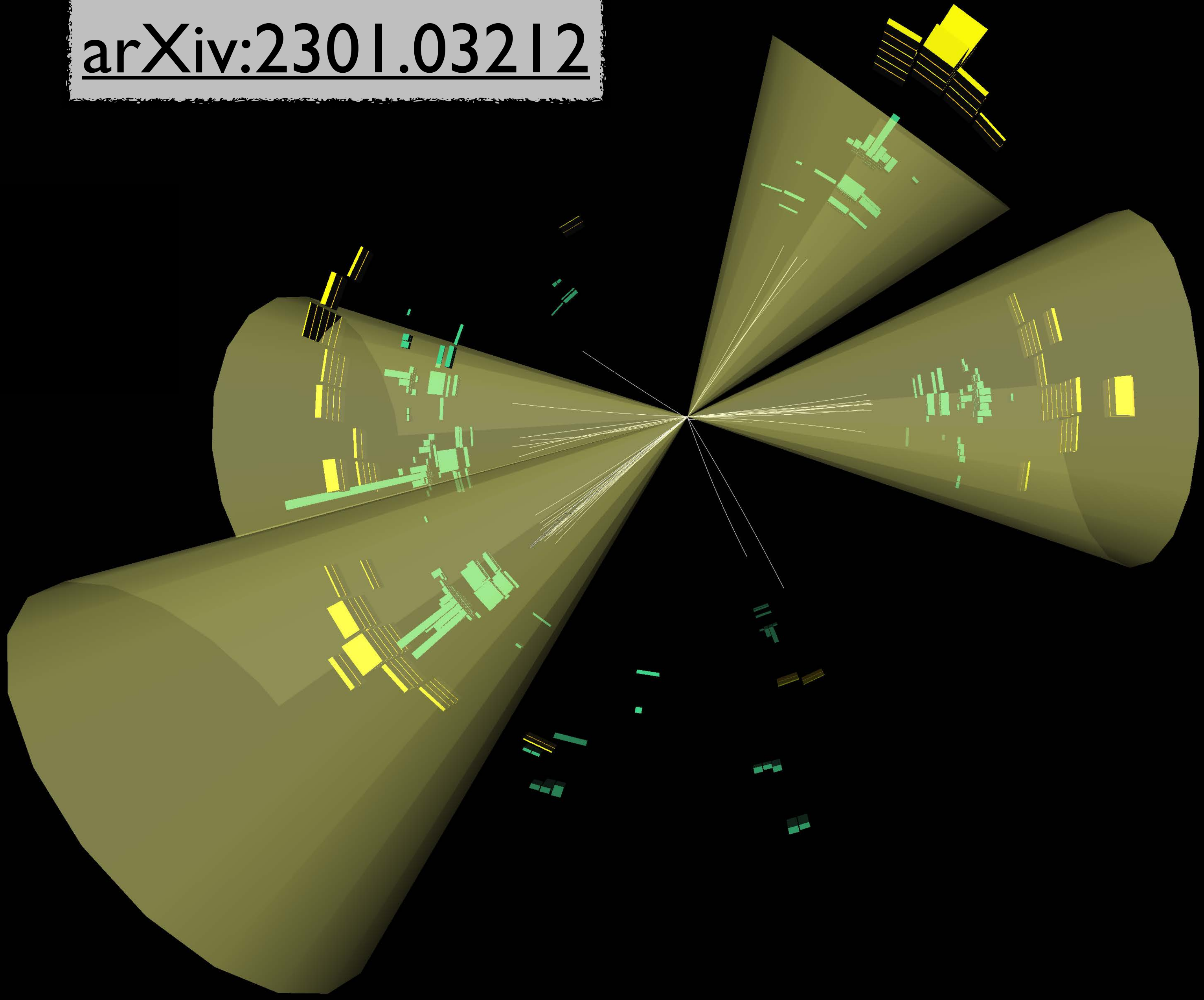

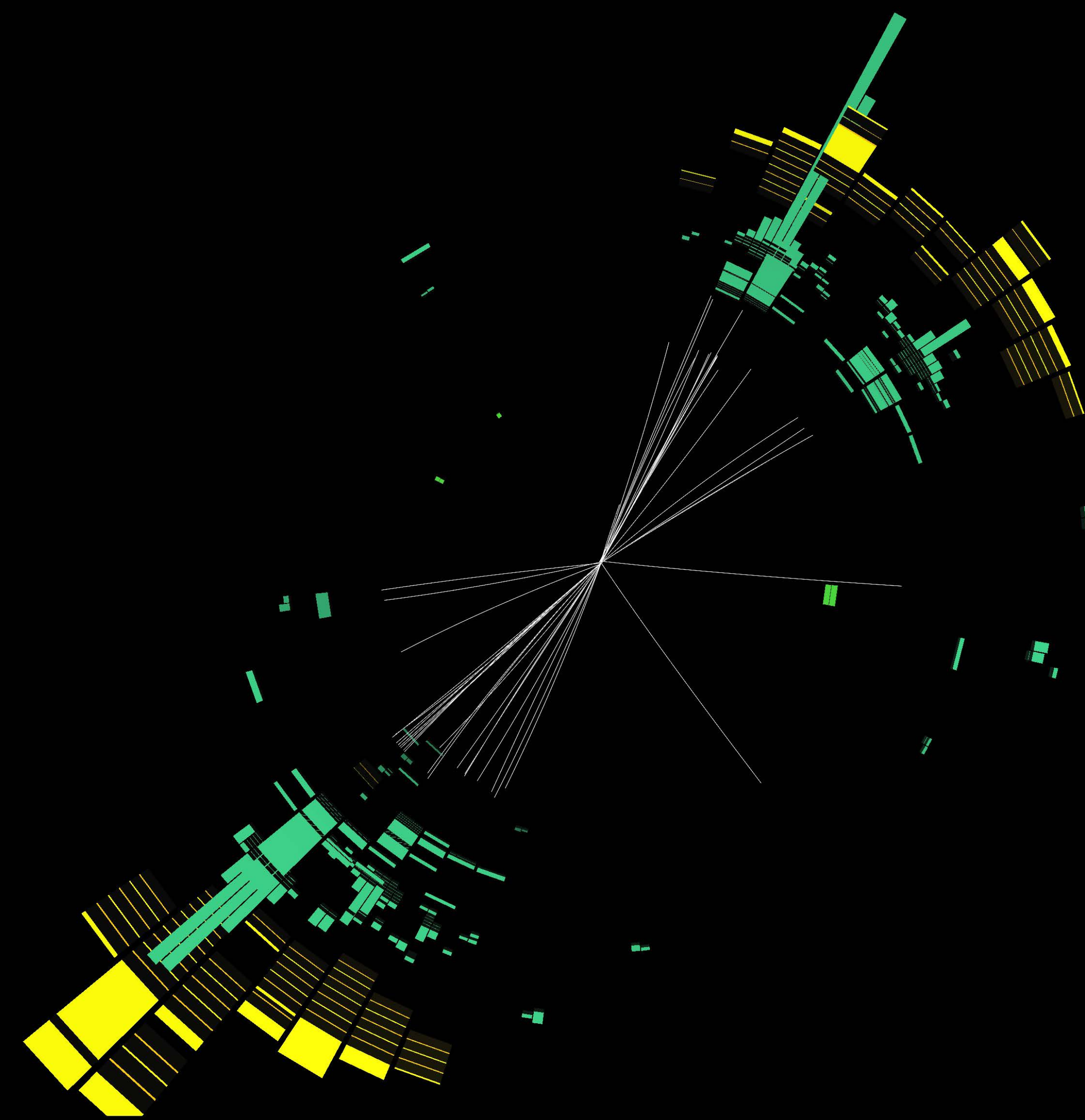

Combination of 12 b-jet triggers

Large-R jet trigger ($E_T > 450$ GeV)

4 b-tagged jets
($\epsilon = 77\,\%, p_T > 40$ GeV)

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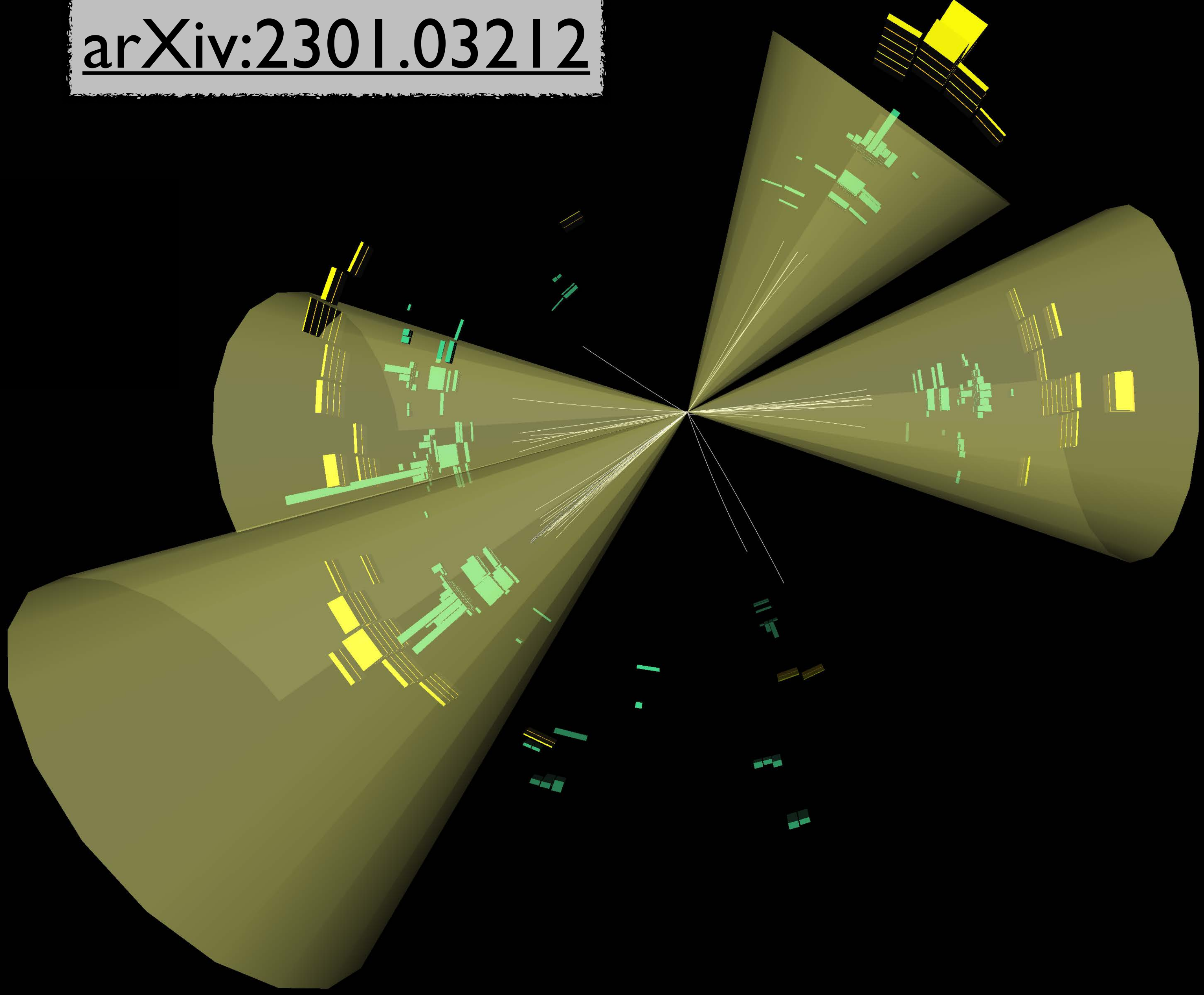

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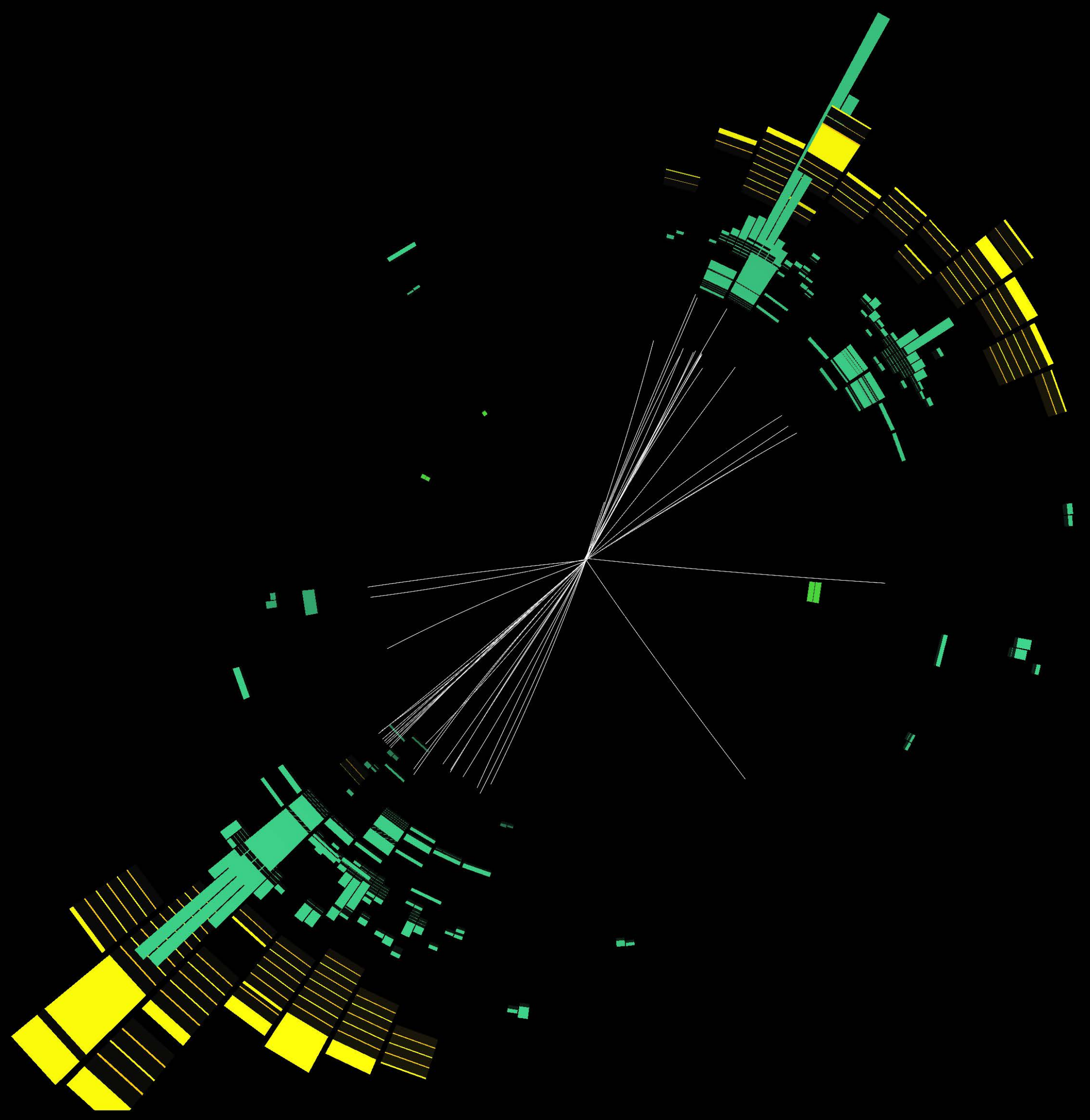

Large-R jet trigger ($E_T > 450$ GeV)

Two large-R jets

(R=1.0, $p_T > 450$ (250) GeV)

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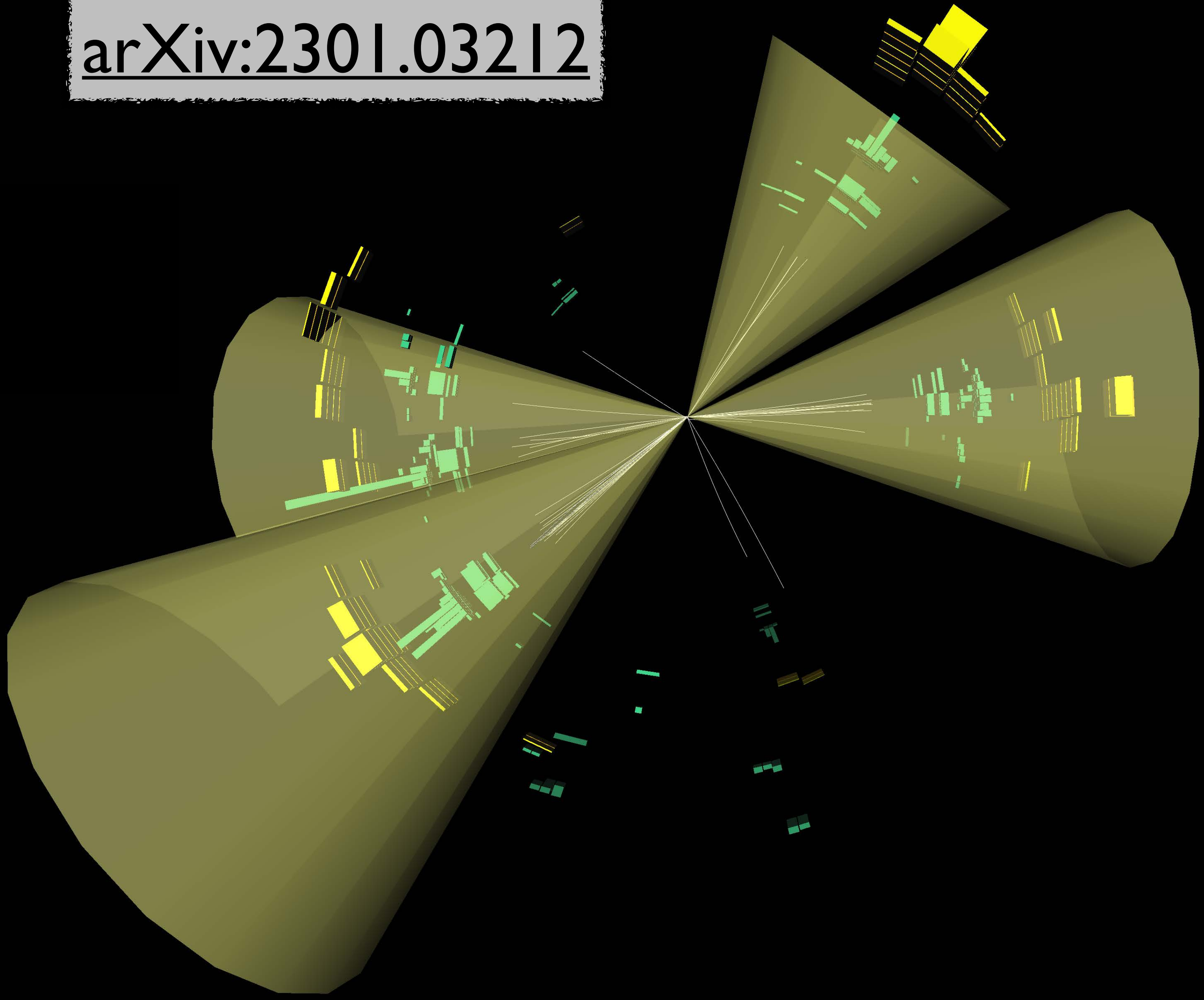
arXiv:2301.03212



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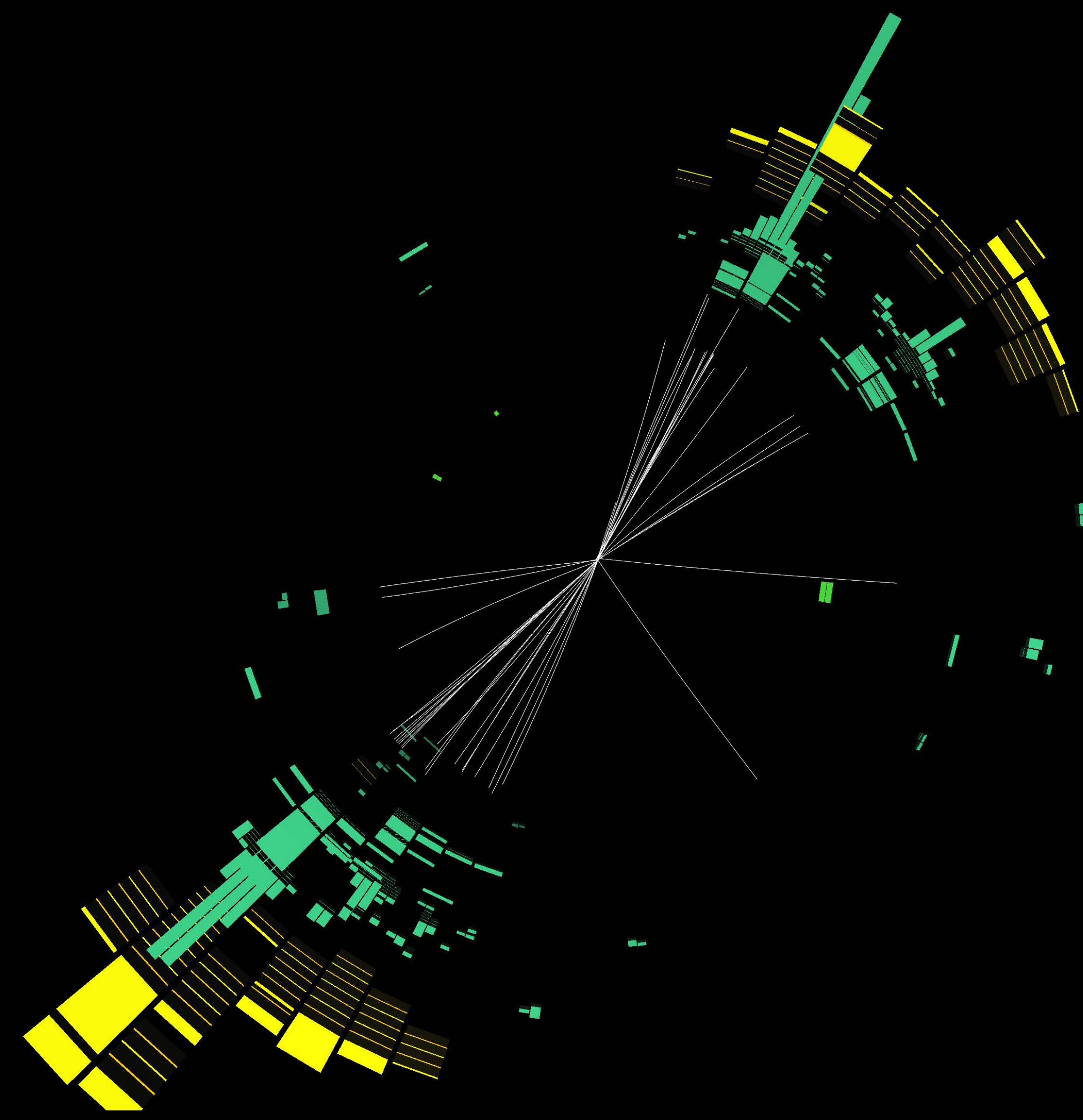

Large-R jet trigger ($E_T > 450$ GeV)

Two large-R jets
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2, 3, or 4 b-tags (via track-jets, $\epsilon = 77\,\%$)

$b\bar{b}b\bar{b}$ Analysis Strategy

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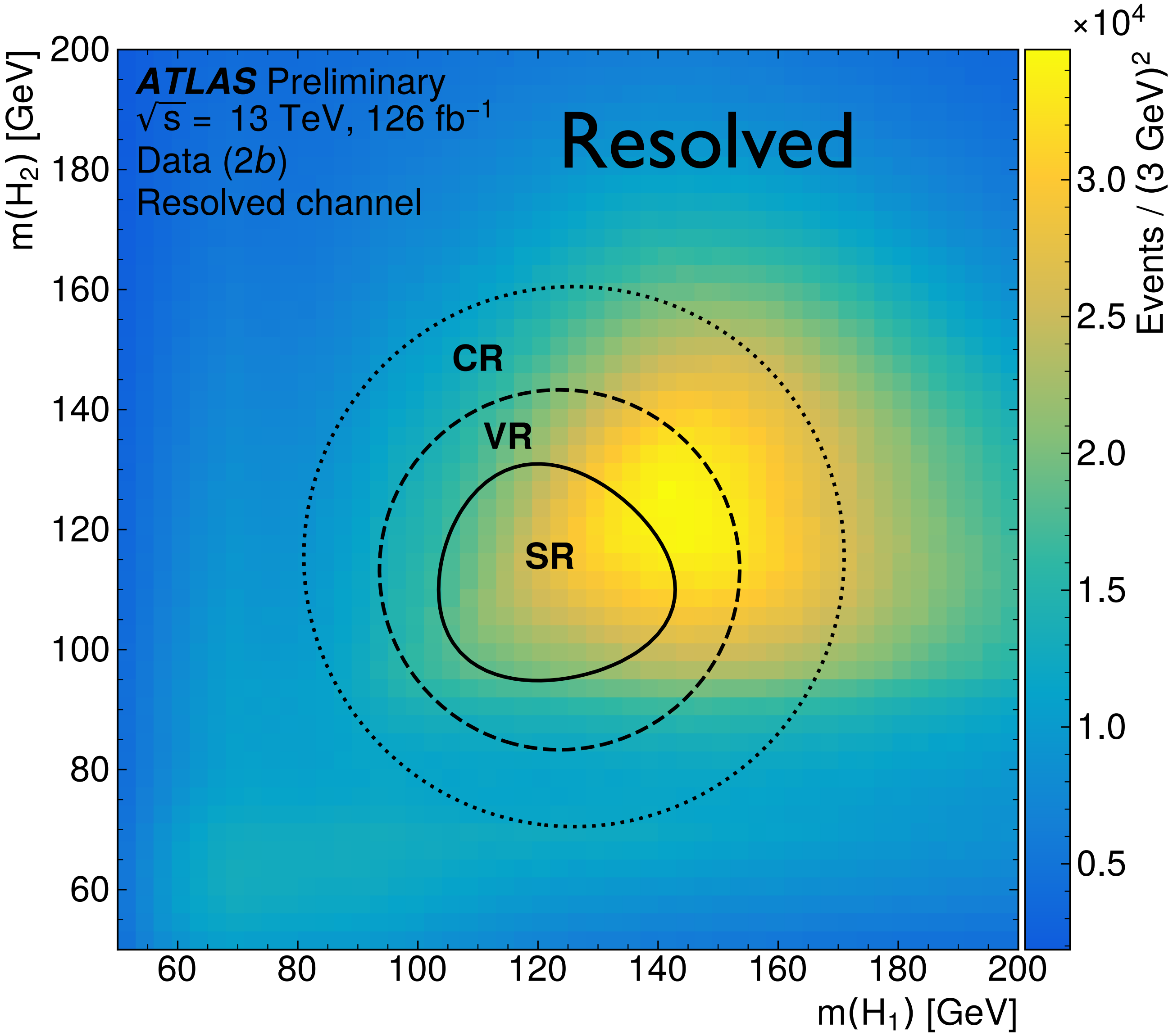
Reconstruct Higgs candidates, form “mass plane”

$b\bar{b}b\bar{b}$ Analysis Strategy



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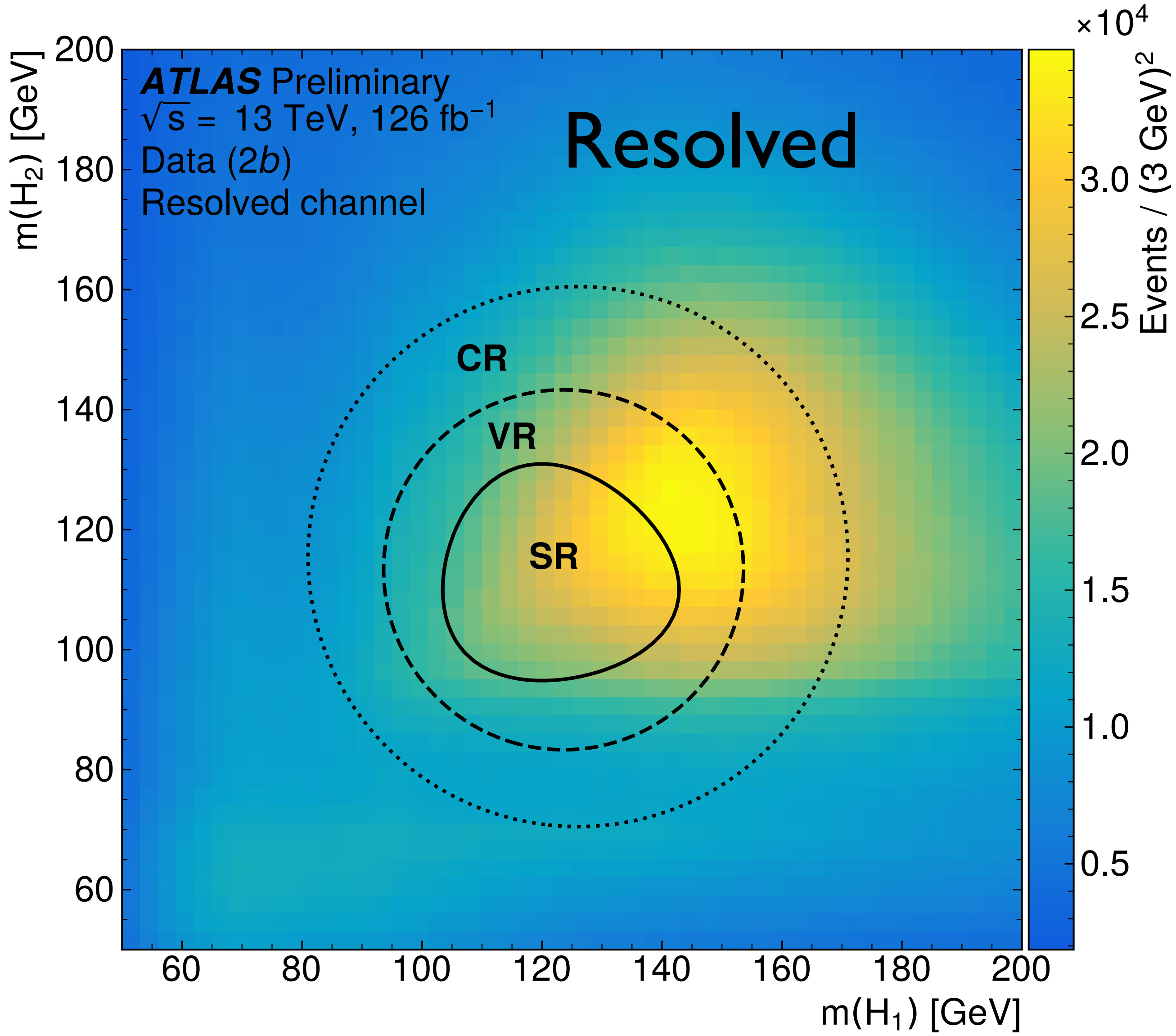
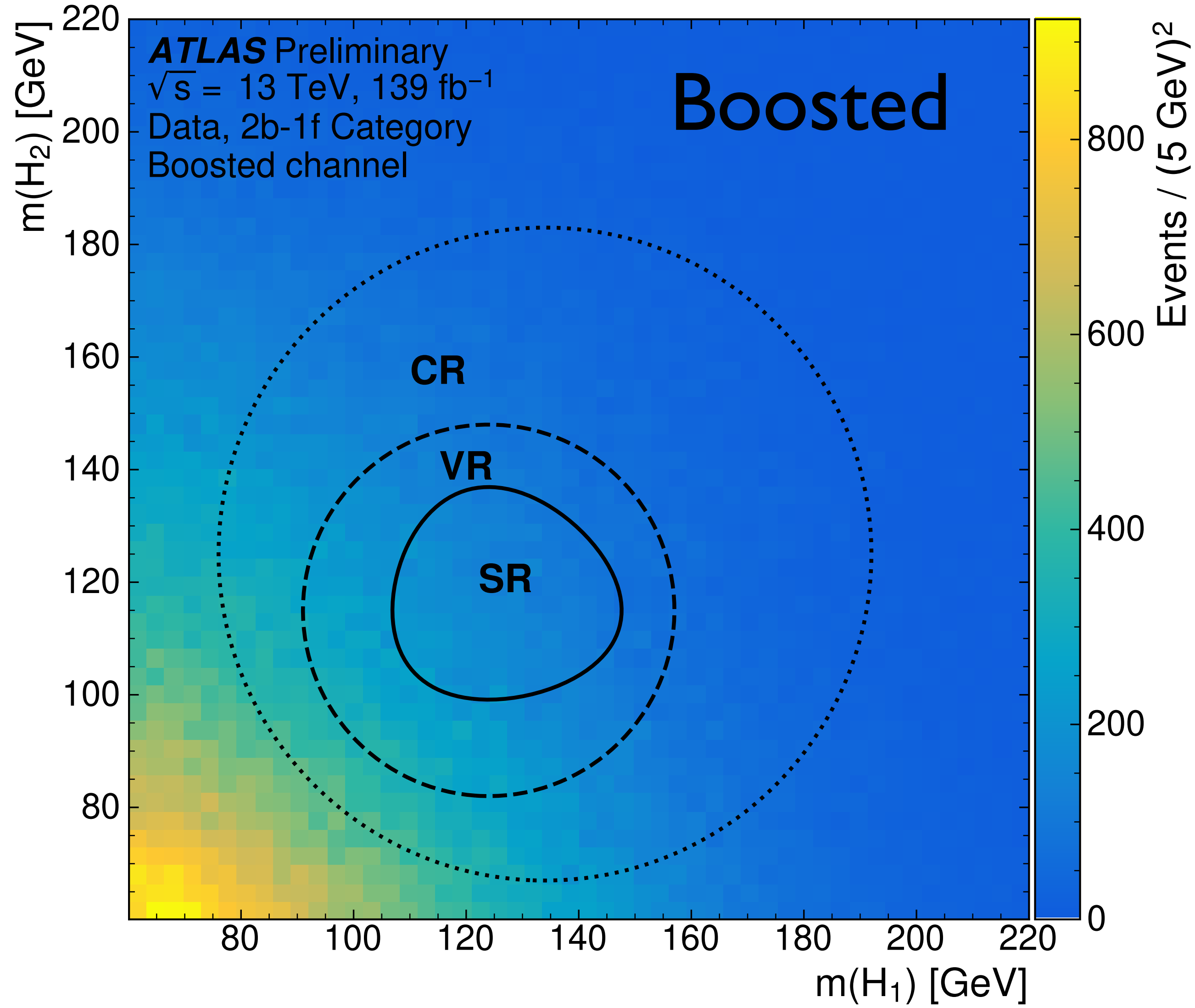
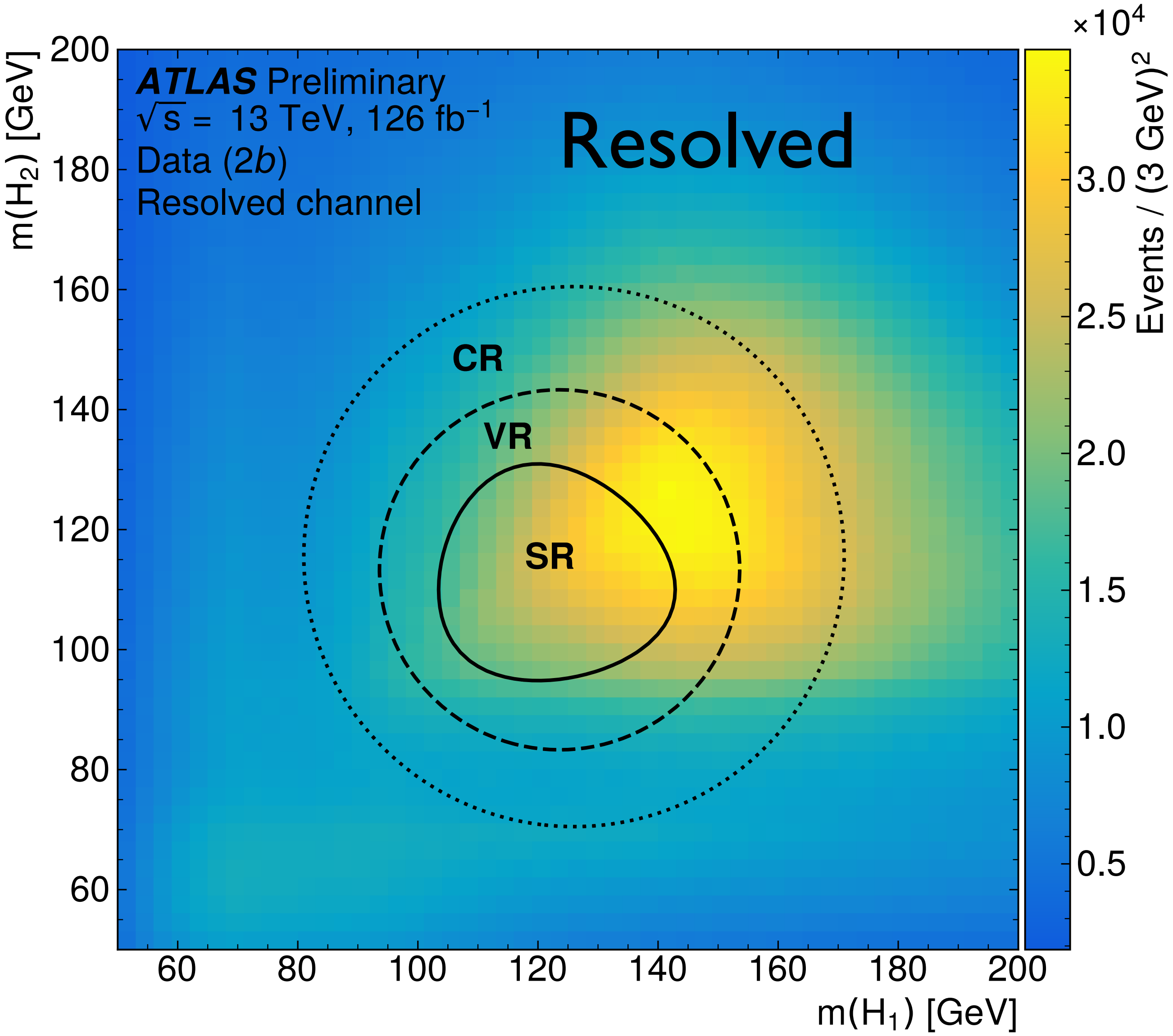
$b\bar{b}b\bar{b}$ Analysis Strategy

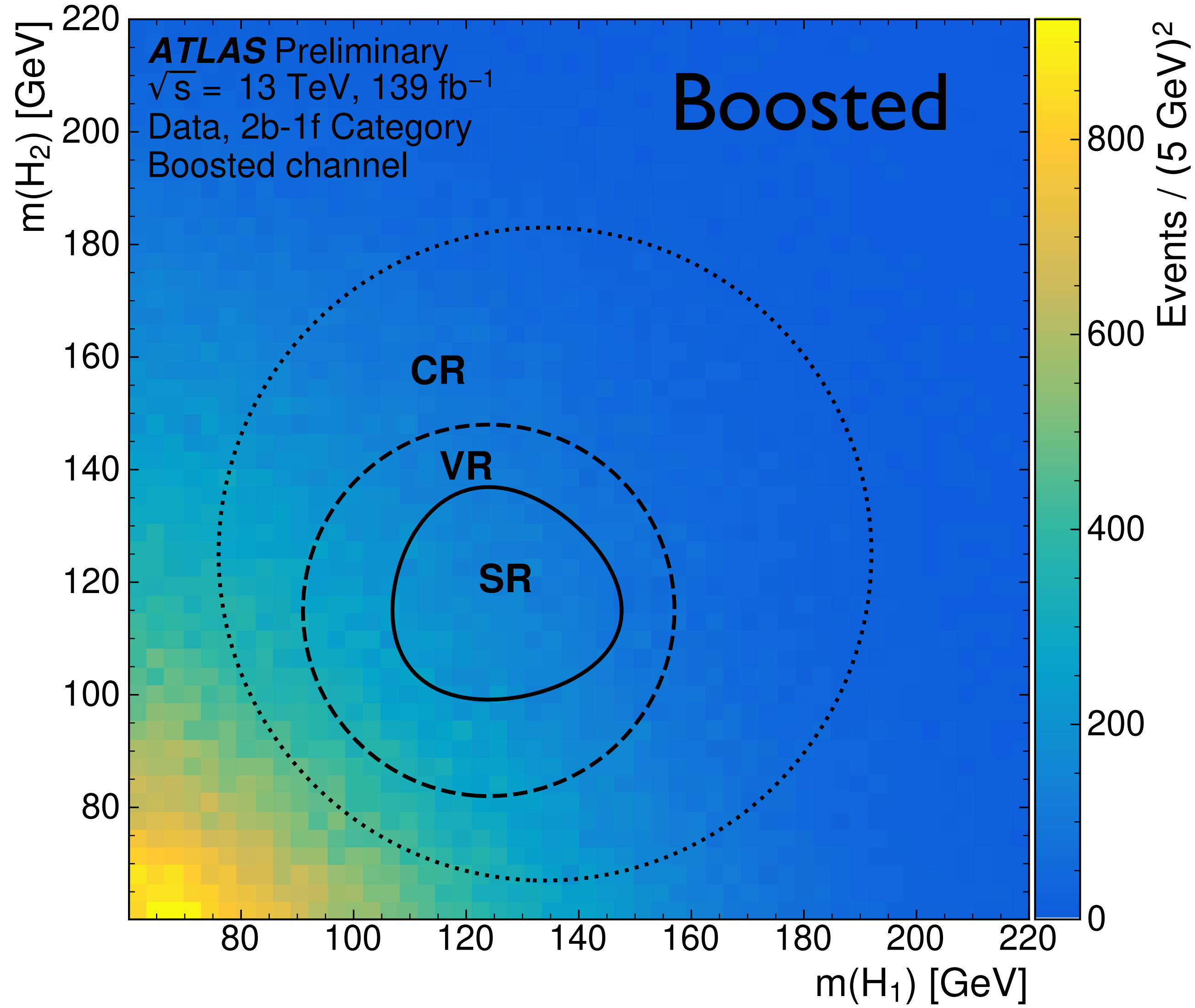




Reconstruct Higgs candidates, form “mass plane”

$b\bar{b}b\bar{b}$ Analysis Strategy





Reconstruct Higgs candidates, form "mass plane"

Center is signal-like; outer regions used for background and background validation

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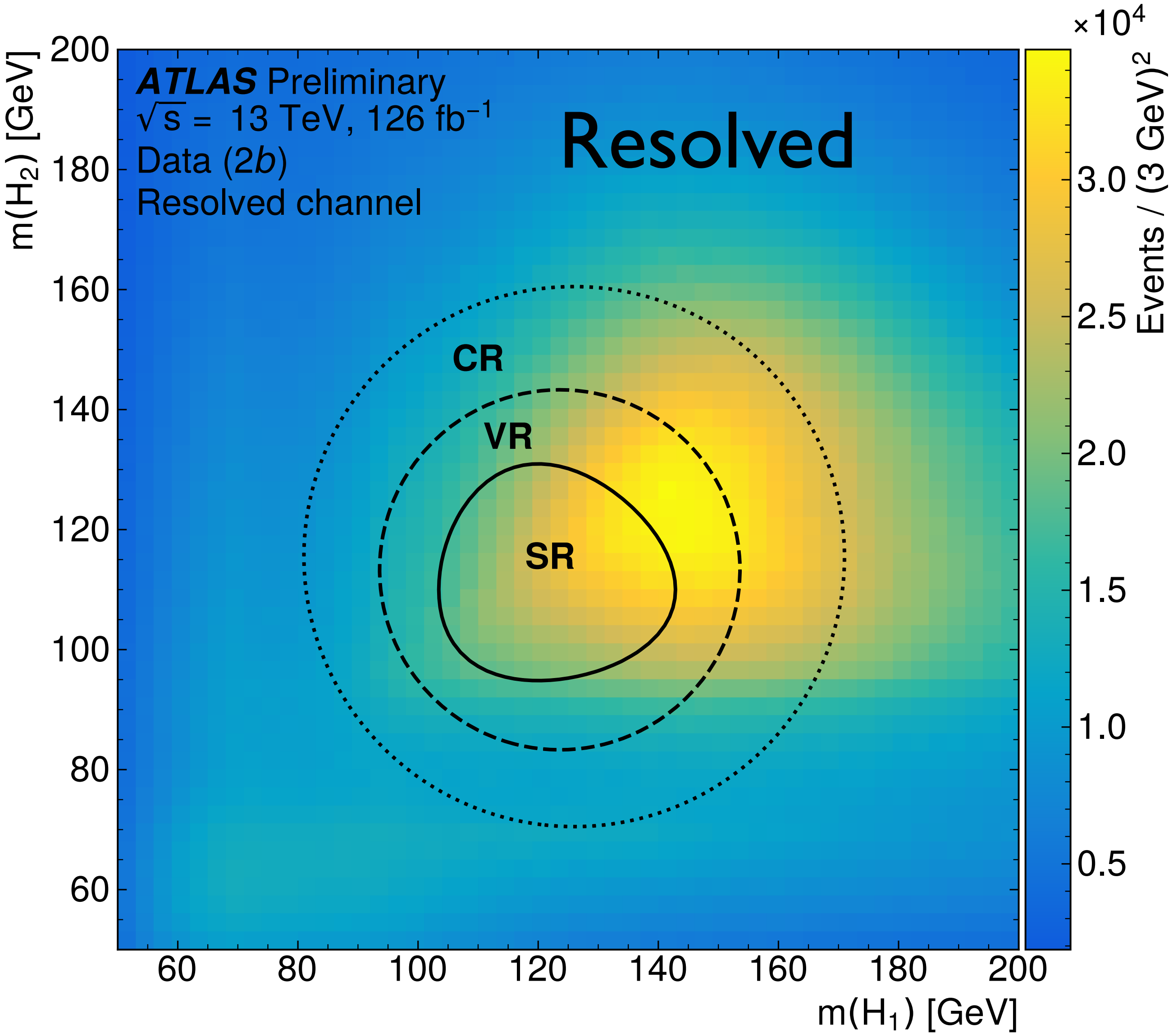

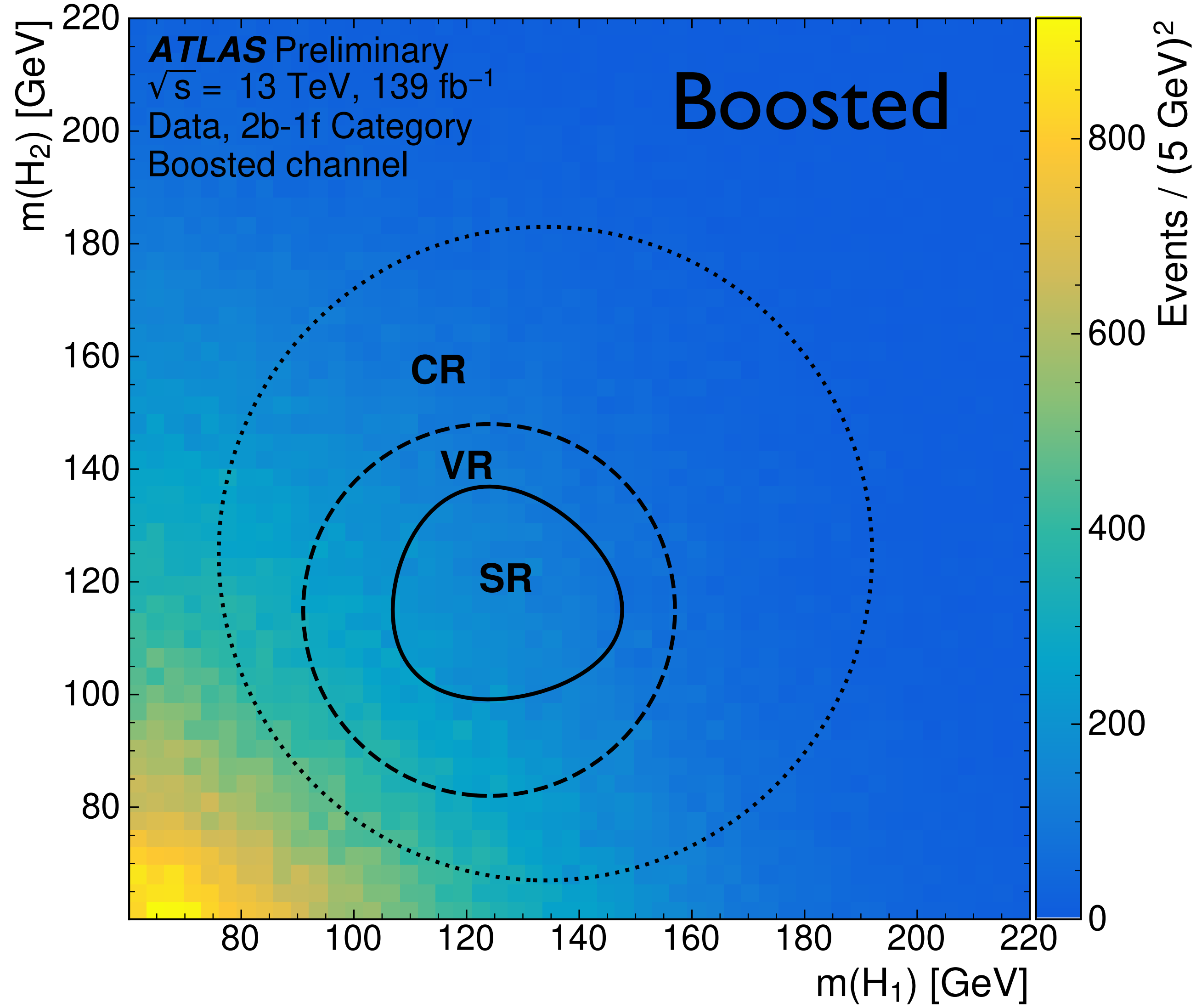

Reconstruct Higgs candidates, form "mass plane"

Center is signal-like; outer regions used for background and background validation

Fit m_{HH} in signal region for final analysis

$b\bar{b}b\bar{b}$ Resolved Background

$b\bar{b}b\bar{b}$ Resolved Background

Step 0: form "mass planes"
with leading/subleading Higgs,
for 2b and 4b events

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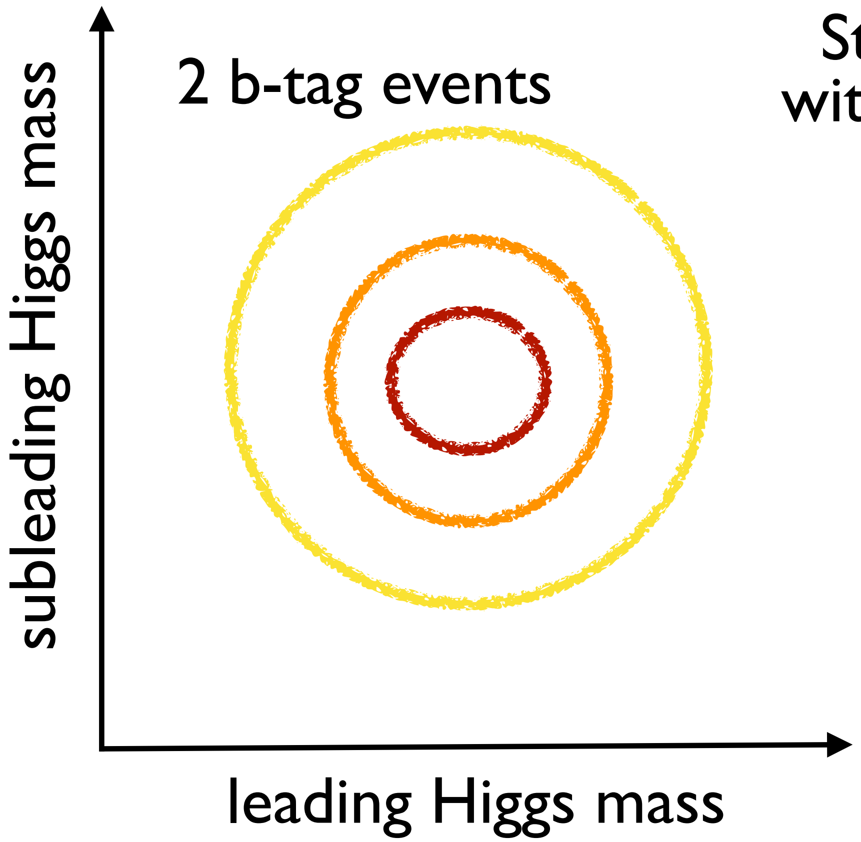

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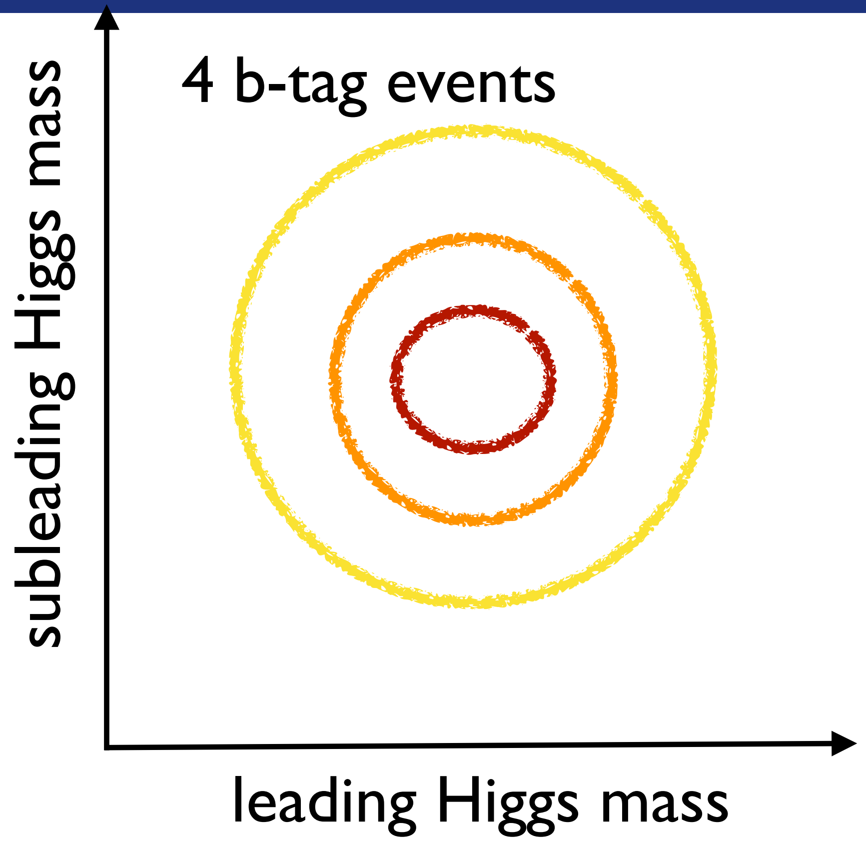
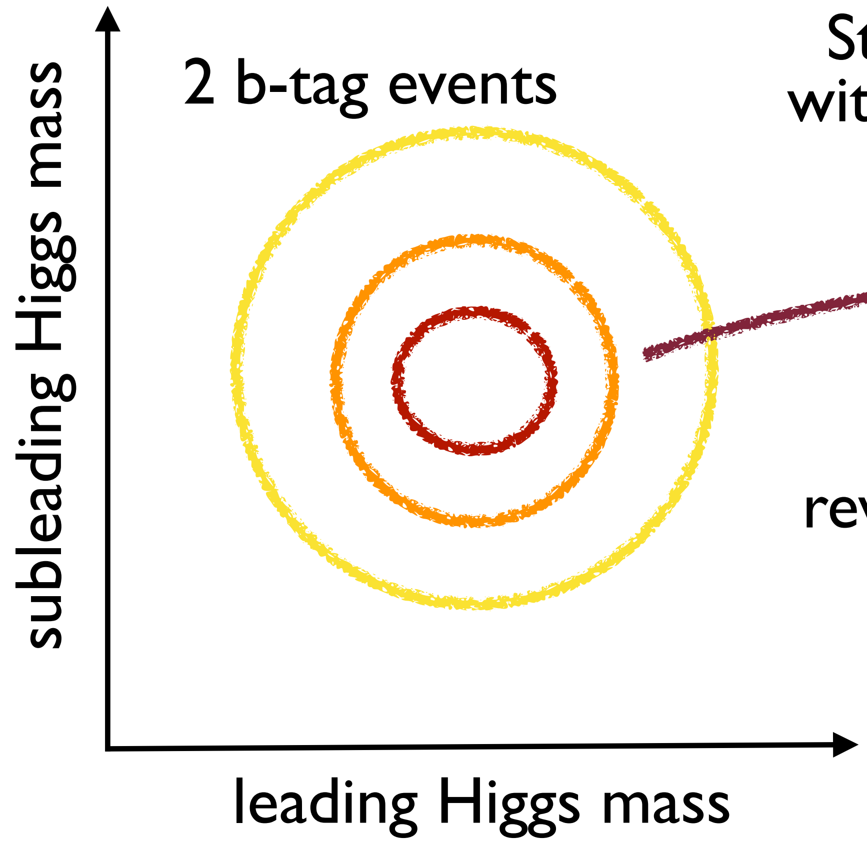
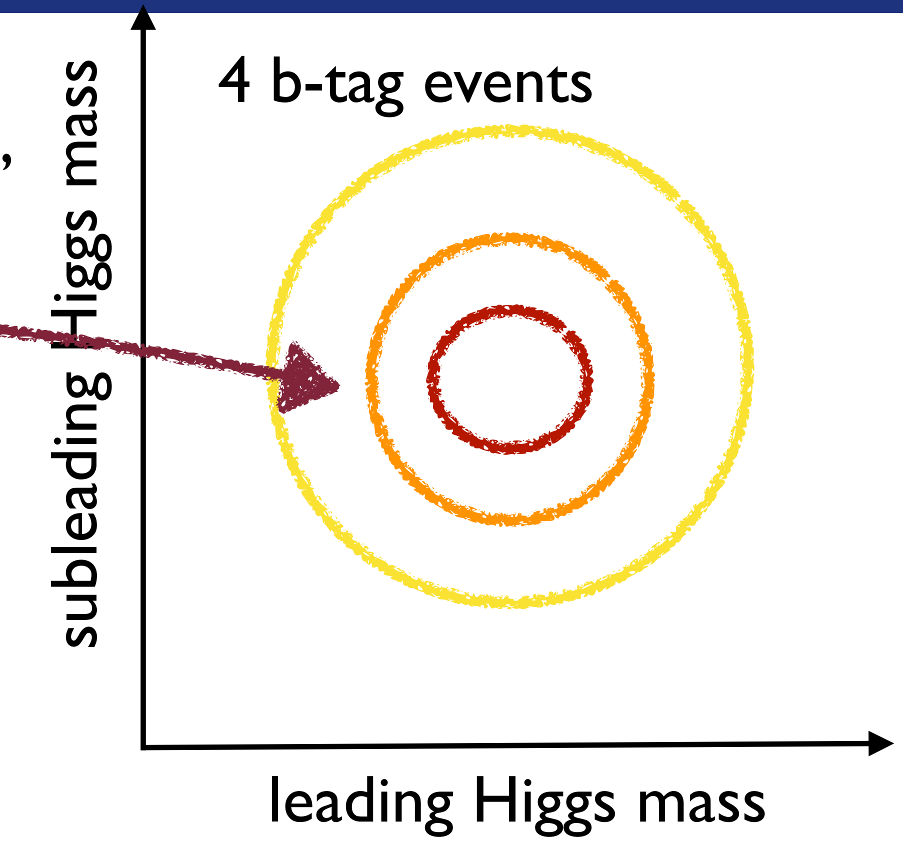


$b\bar{b}b\bar{b}$ Resolved Background

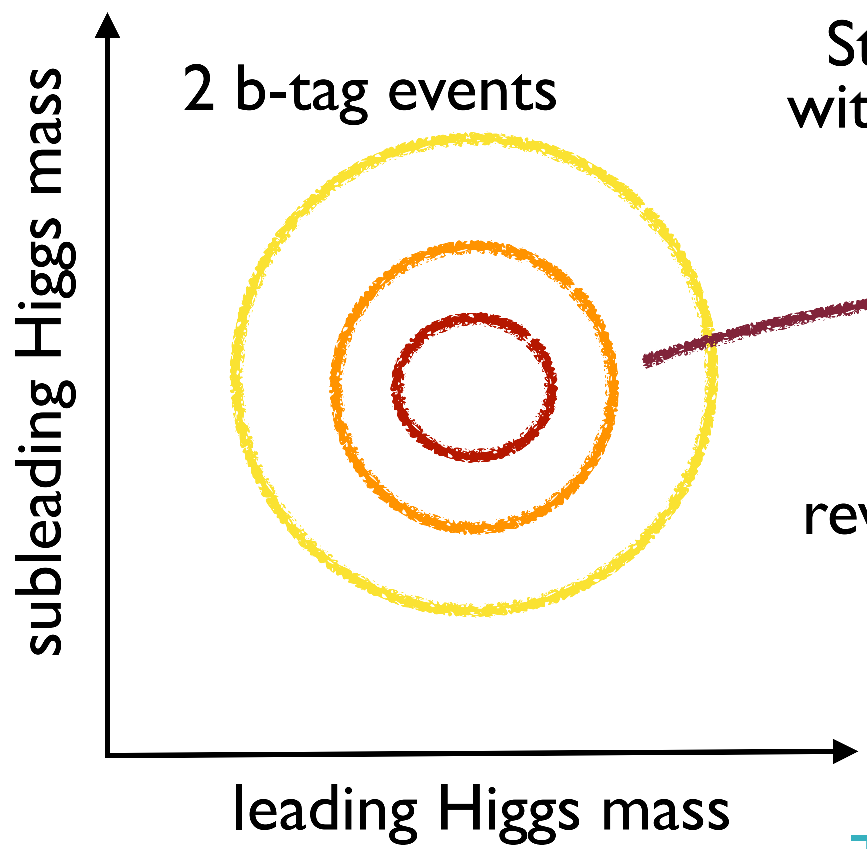


Step 0: form "mass planes" with leading/subleading Higgs, for 2b and 4b events

Step 1: use CR to train *neural network* to reweight data from 2b to 4b



$b\bar{b}b\bar{b}$ Resolved Background



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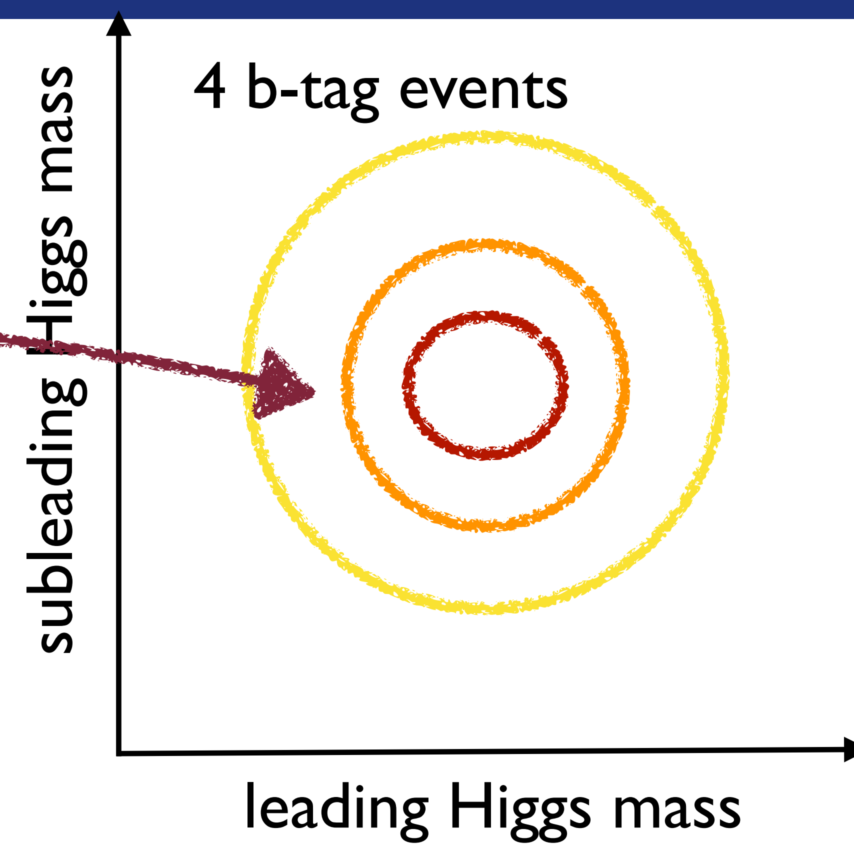
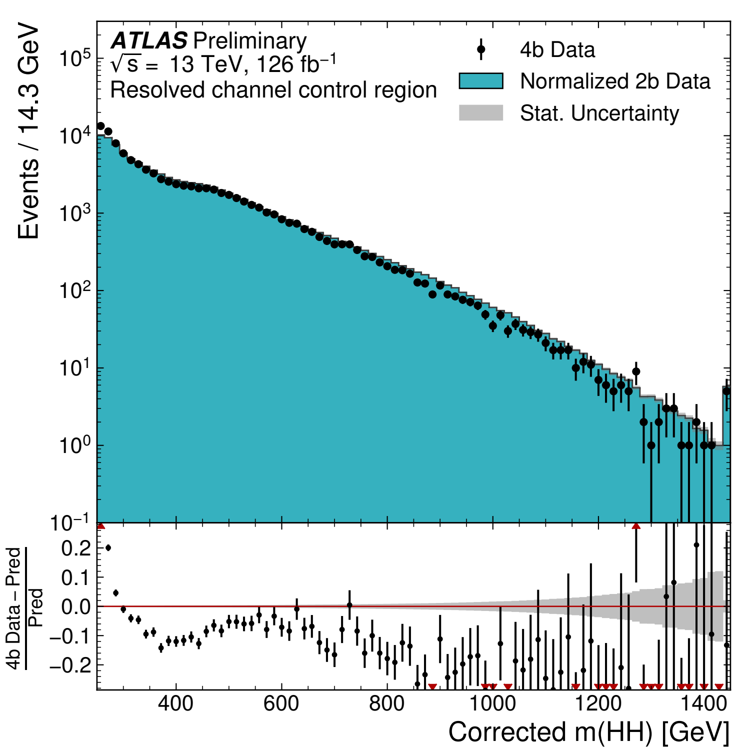
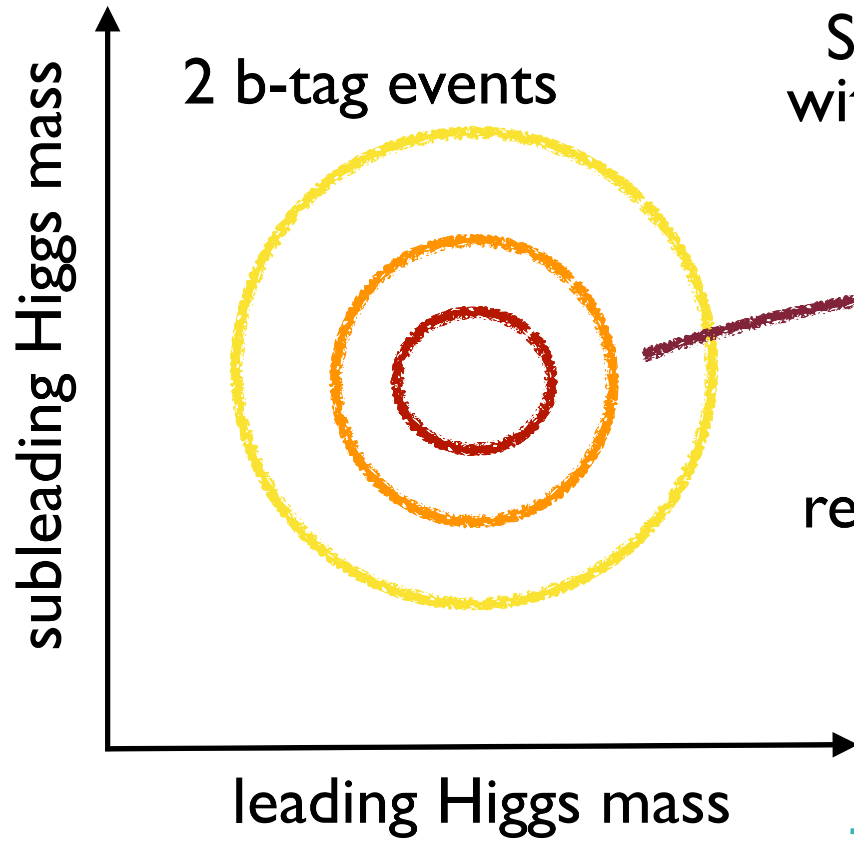




Teal histogram comes from 2b, black points from 4b

$b\bar{b}b\bar{b}$ Resolved Background



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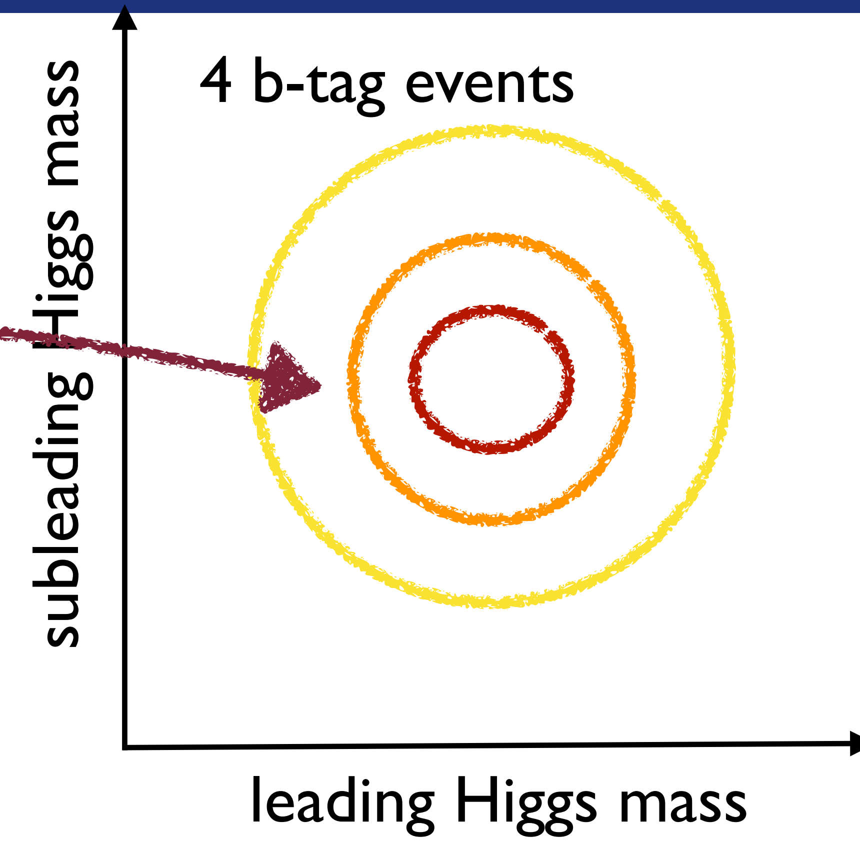

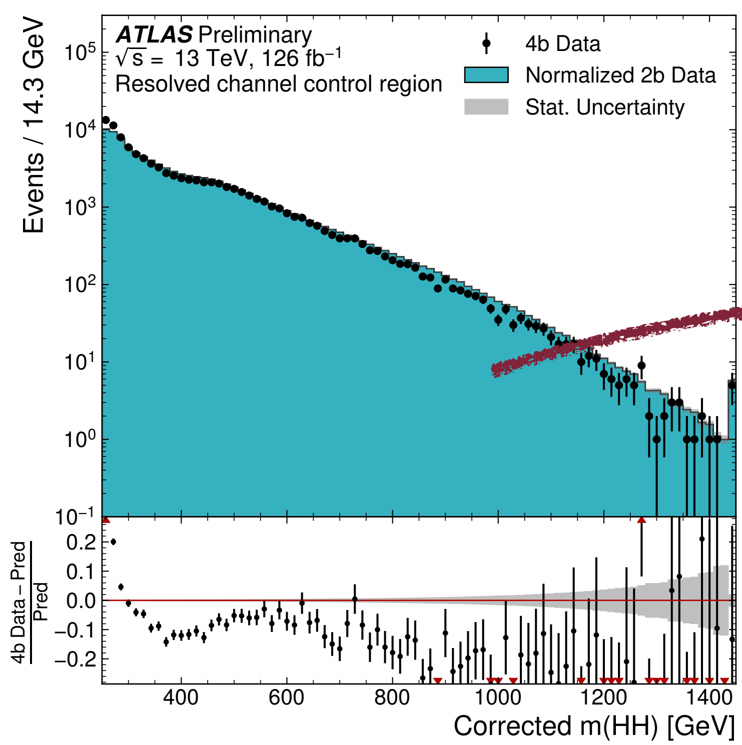

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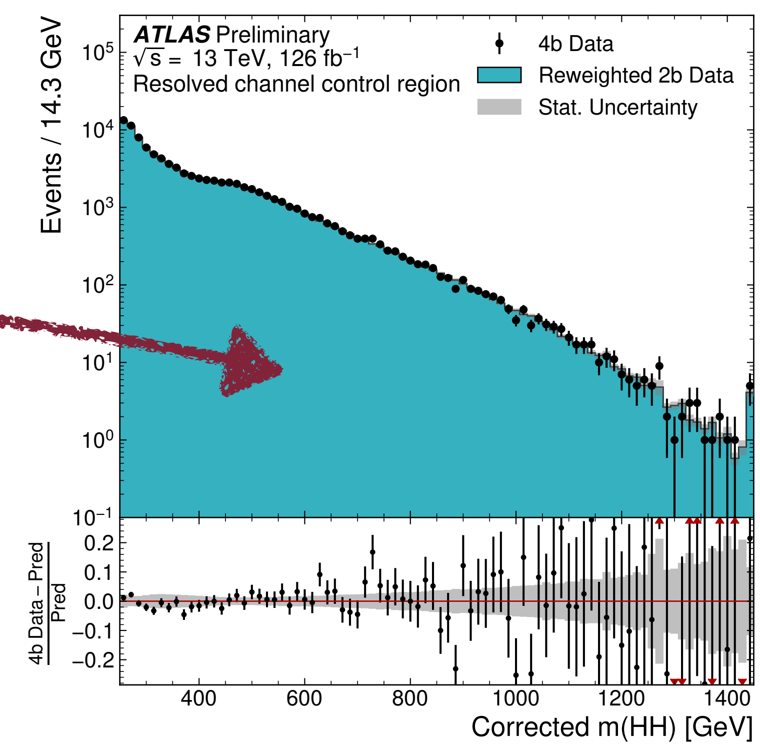
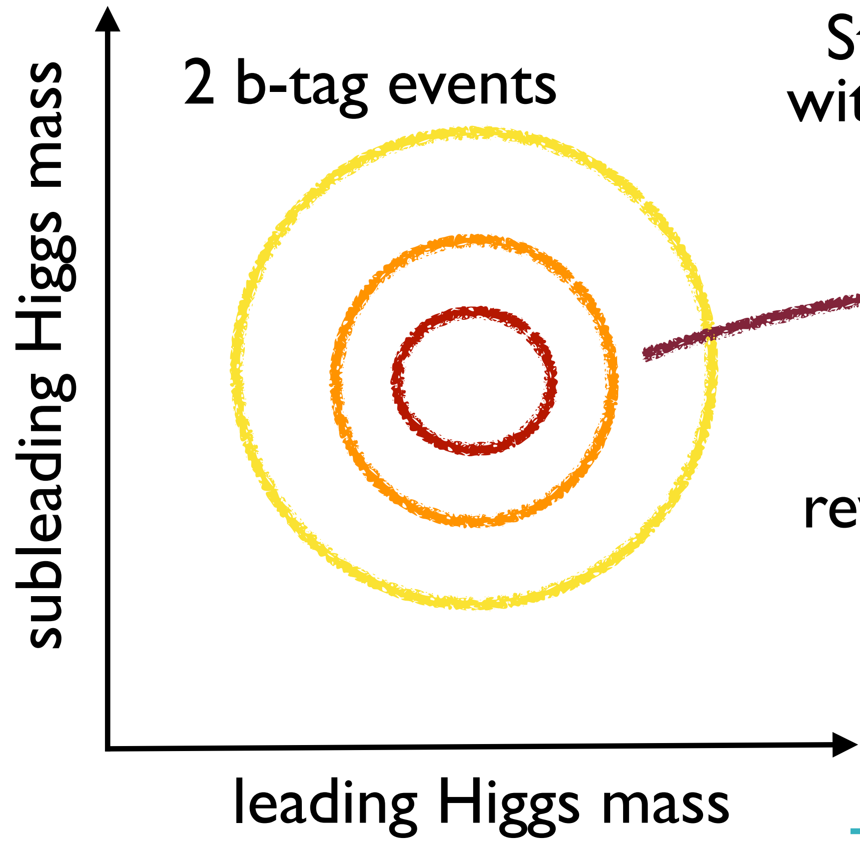
Neural network



$b\bar{b}b\bar{b}$ Resolved Background



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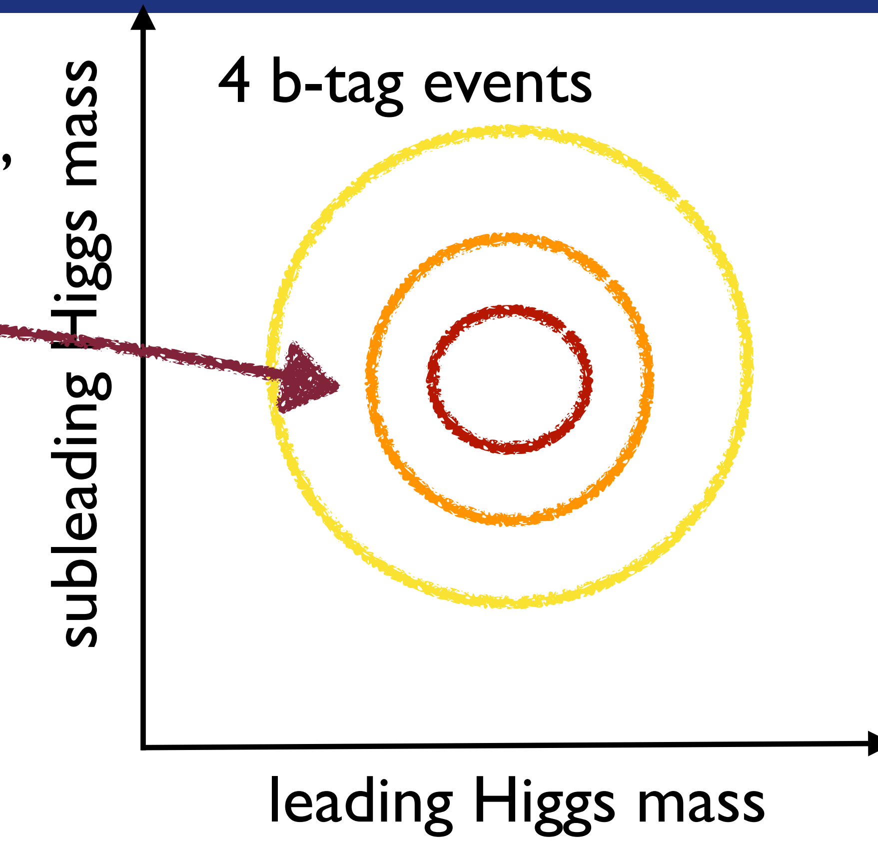

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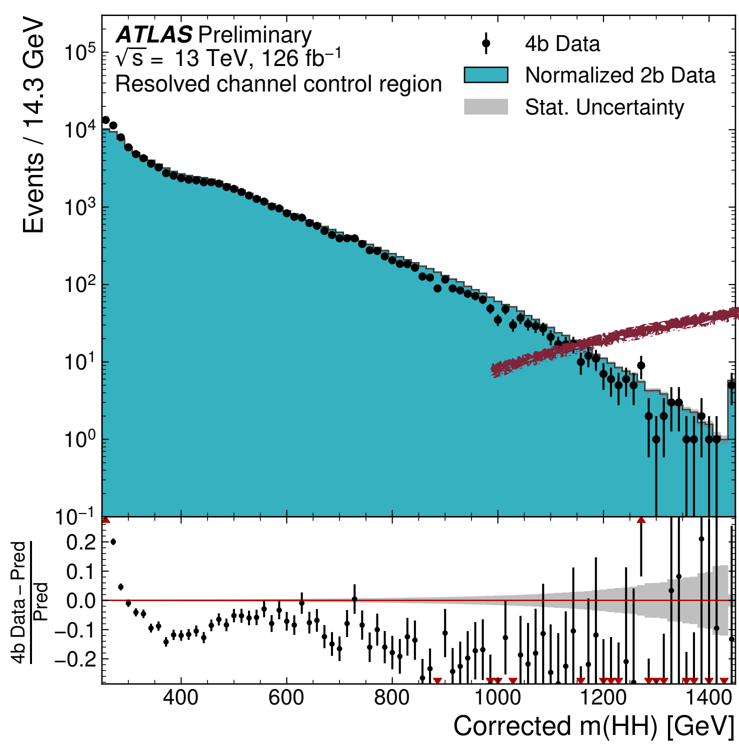
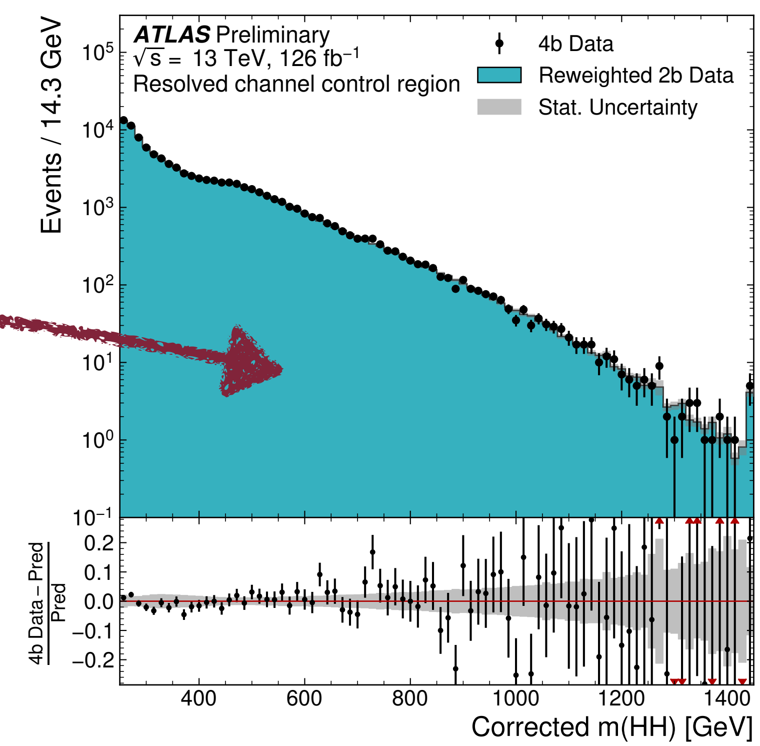


Neural network

Step 2: Apply this NN to 2b SR: prediction for 4b SR



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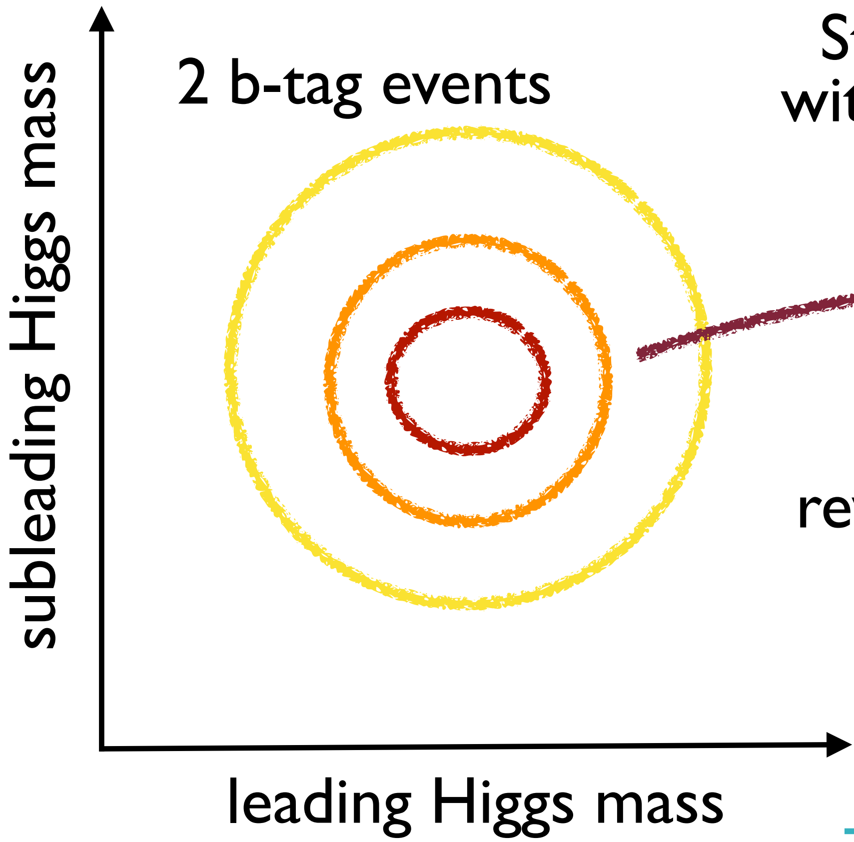

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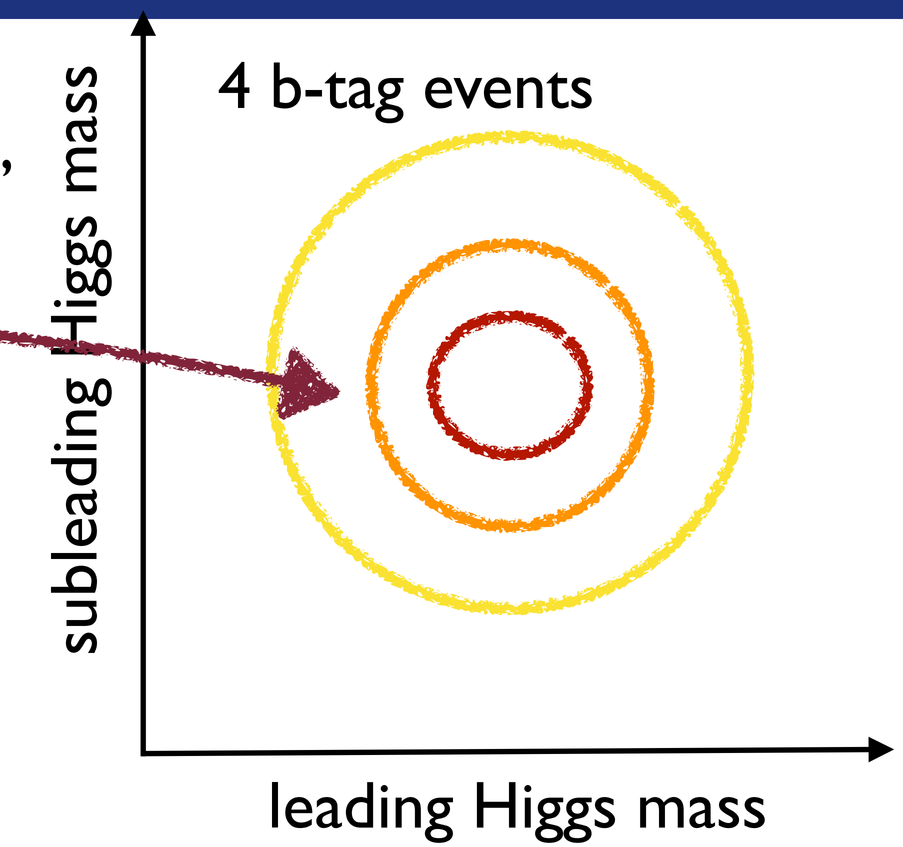

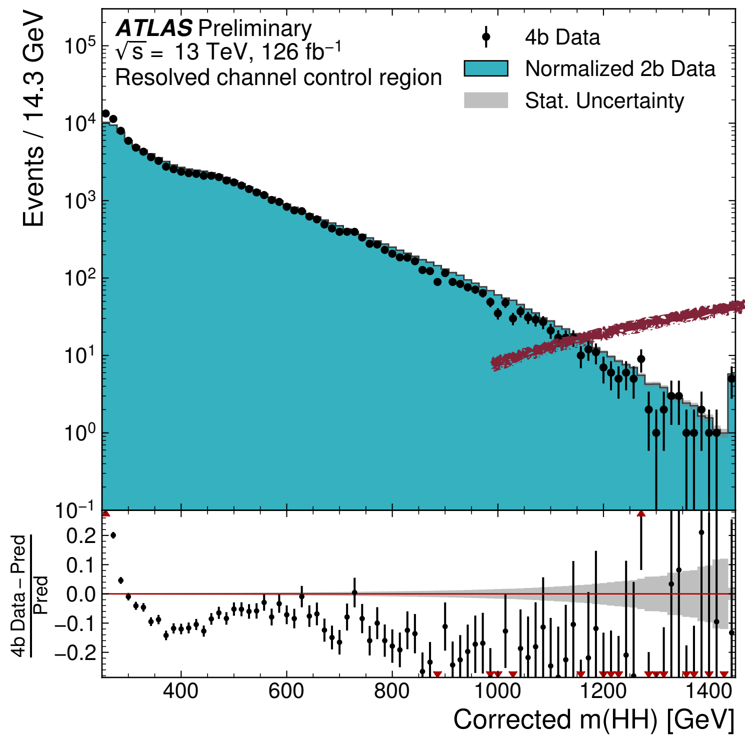

Teal histogram comes from 2b, black points from 4b

Neural network

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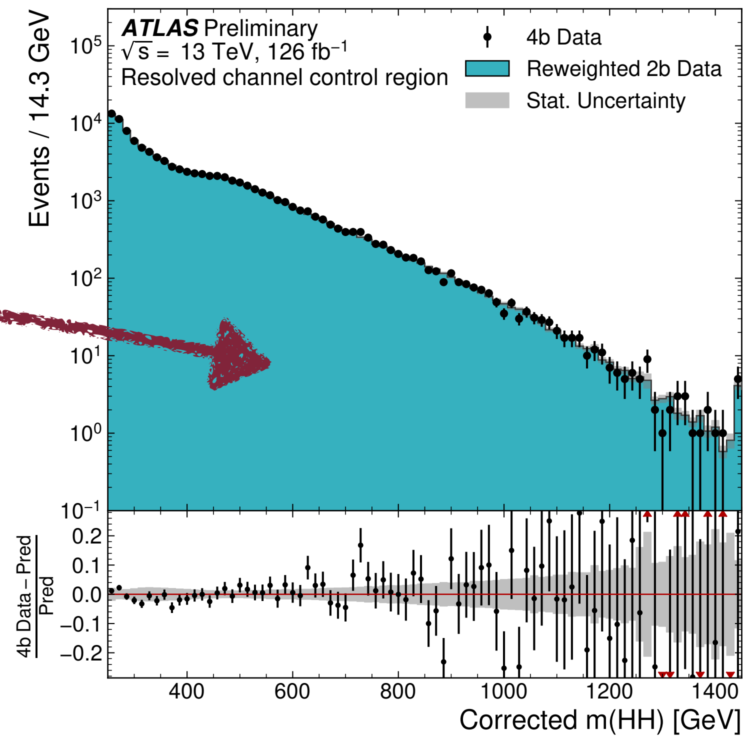
Systematics from alternate regions



Why Neural Networks?

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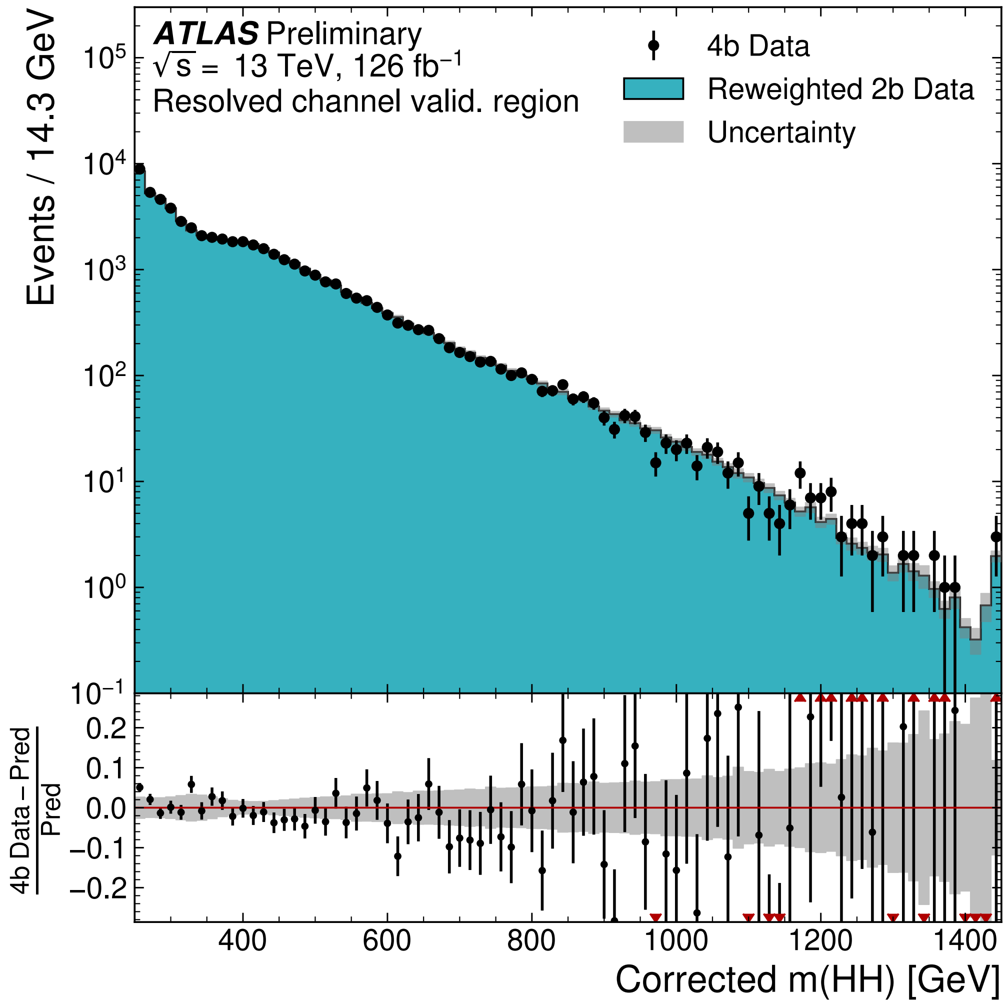
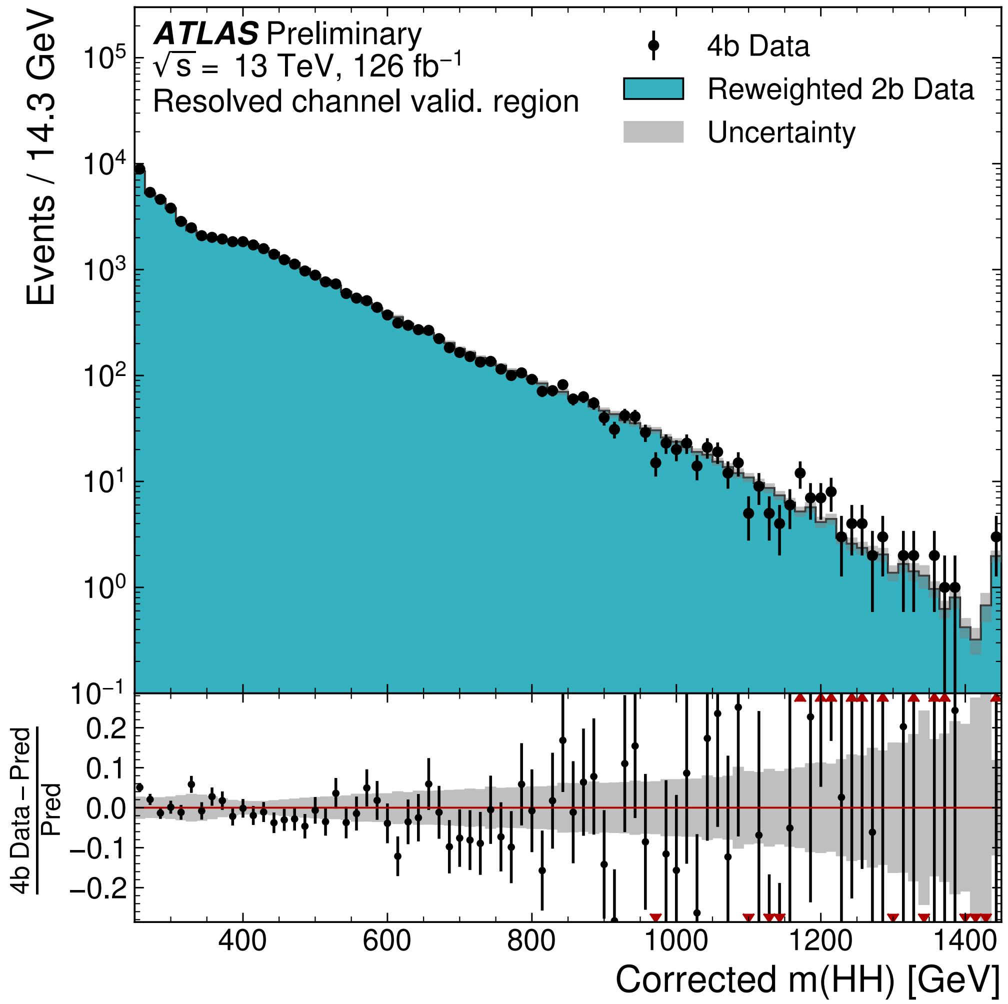


Here, apply NN to 2b data in VR

Why Neural Networks?



Here, apply NN to 2b data in VR

Works well, even on data
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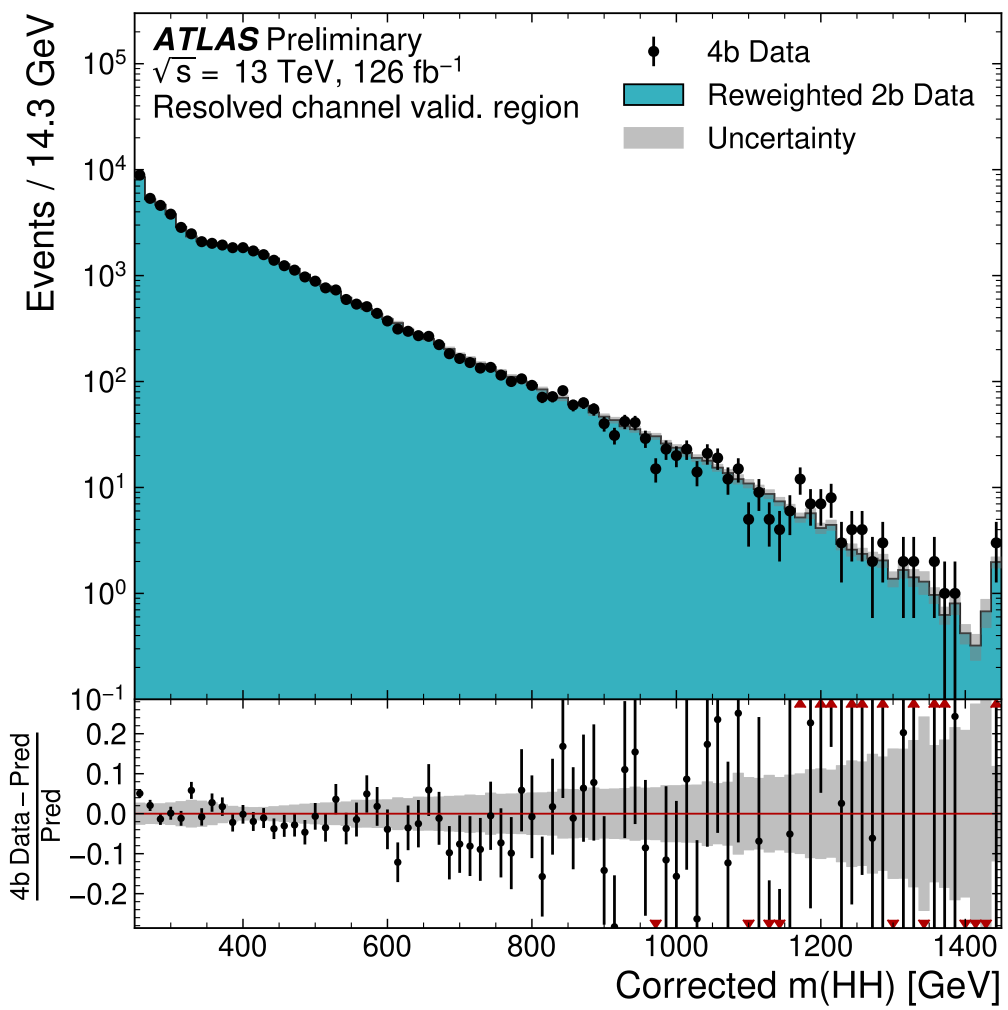

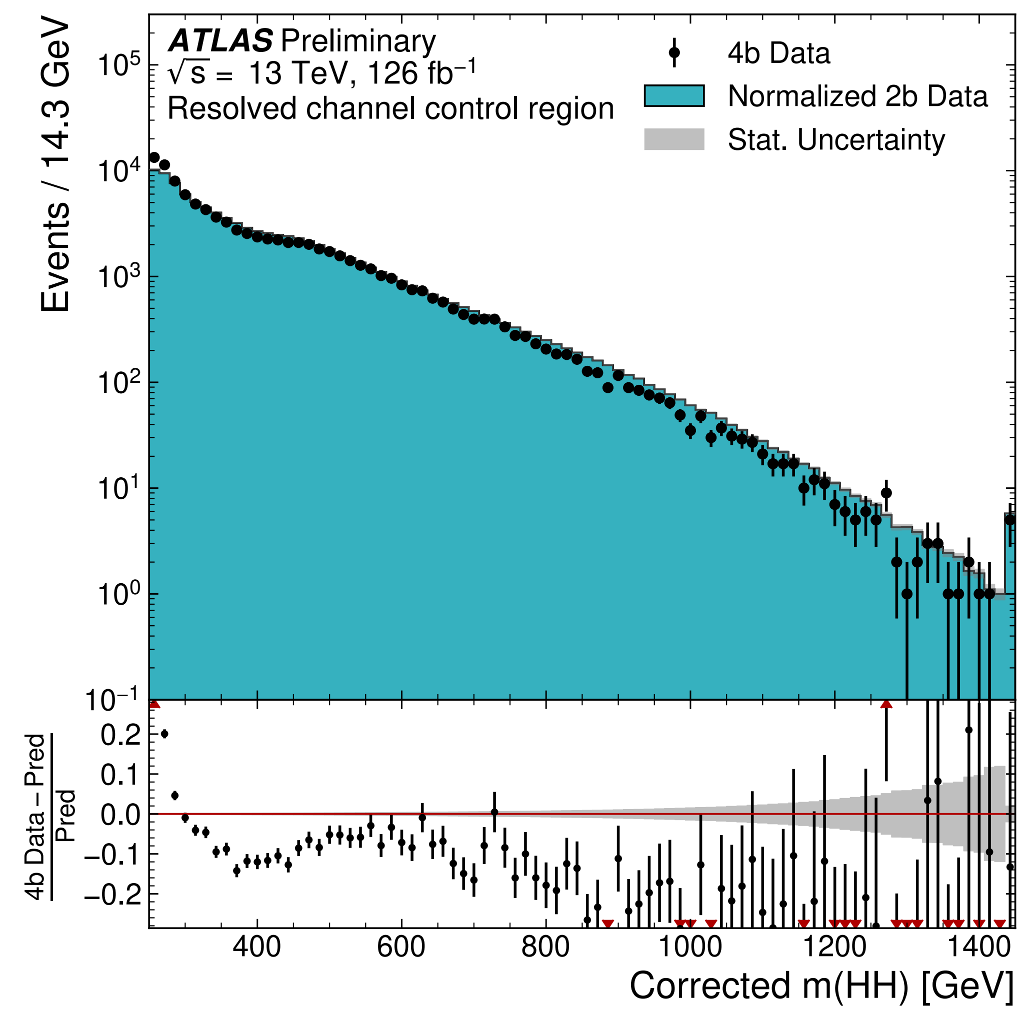

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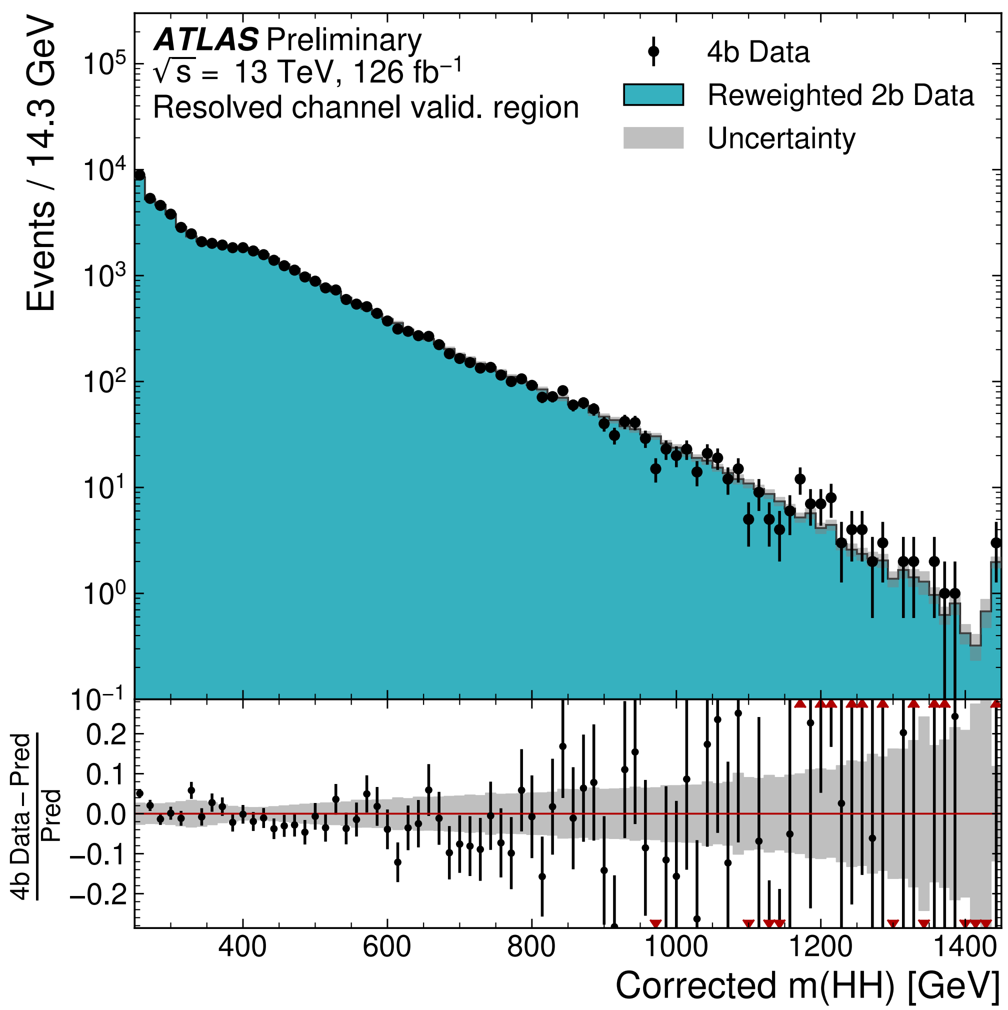
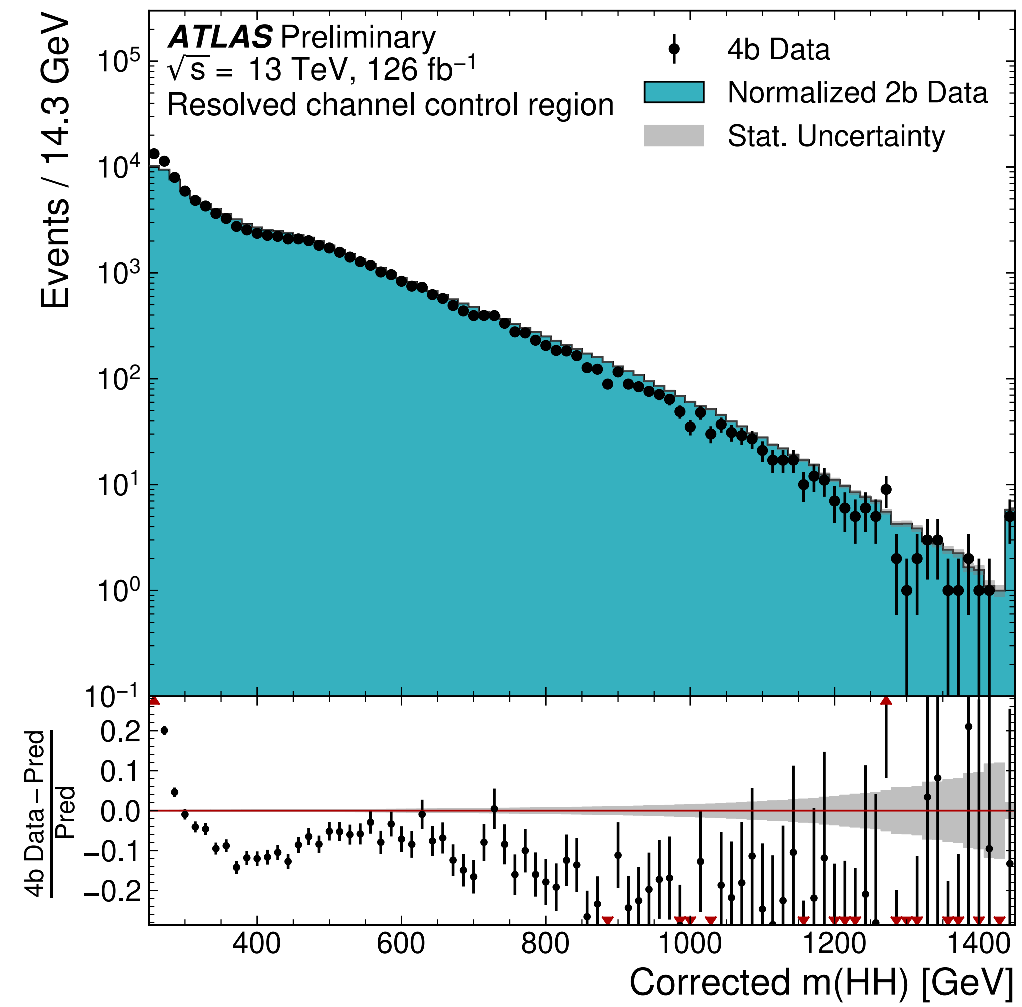
Why Neural Networks?





Here, apply NN to 2b data in VR

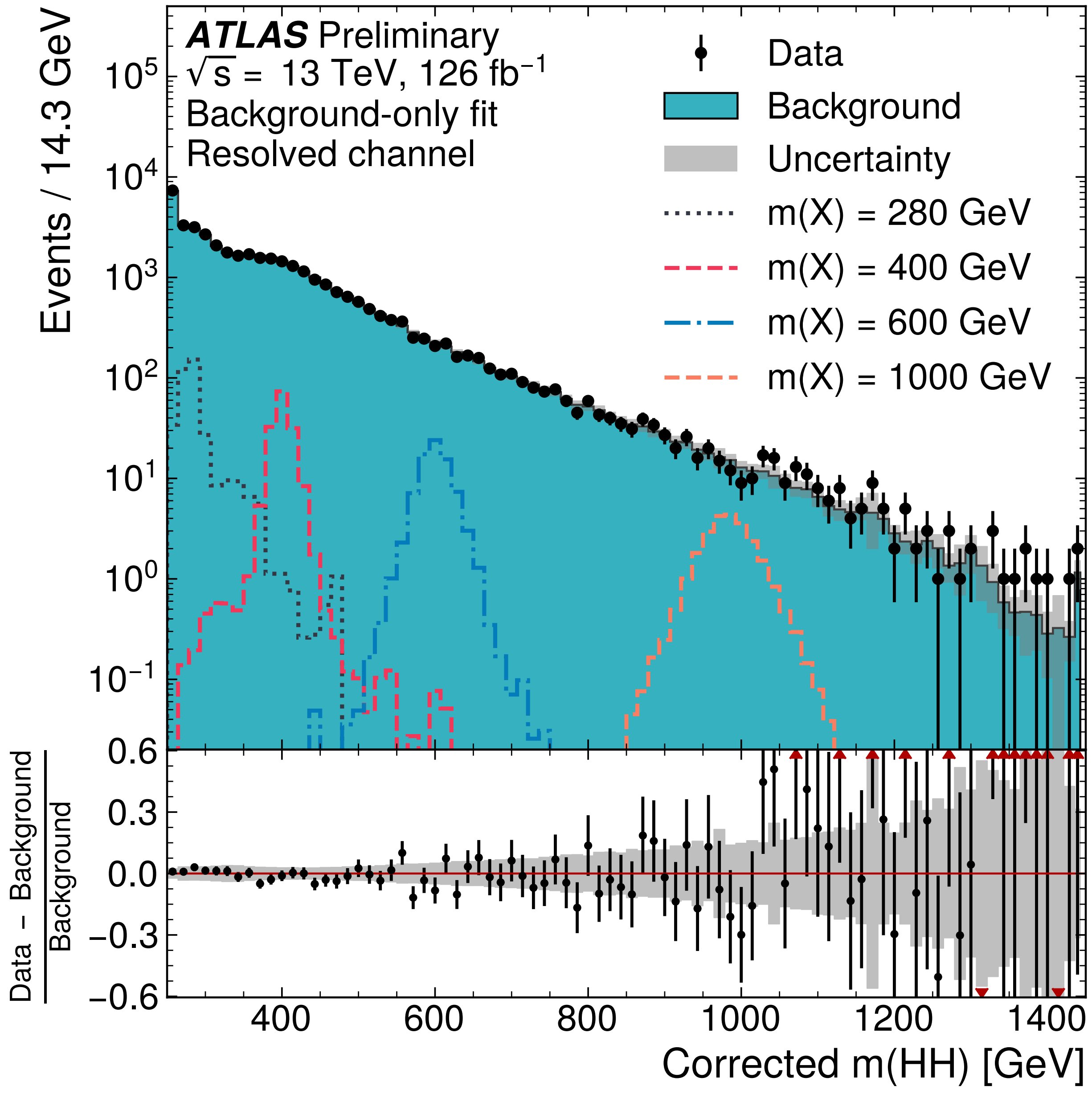
Works well, even on data that wasn't used in training!

Why does this work?

NN's learn a density ratio of two classes: normally this ratio is used to isolate a single class, but can be used to reweight classes

$b\bar{b}b\bar{b}$ Results

$b\bar{b}b\bar{b}$ Results



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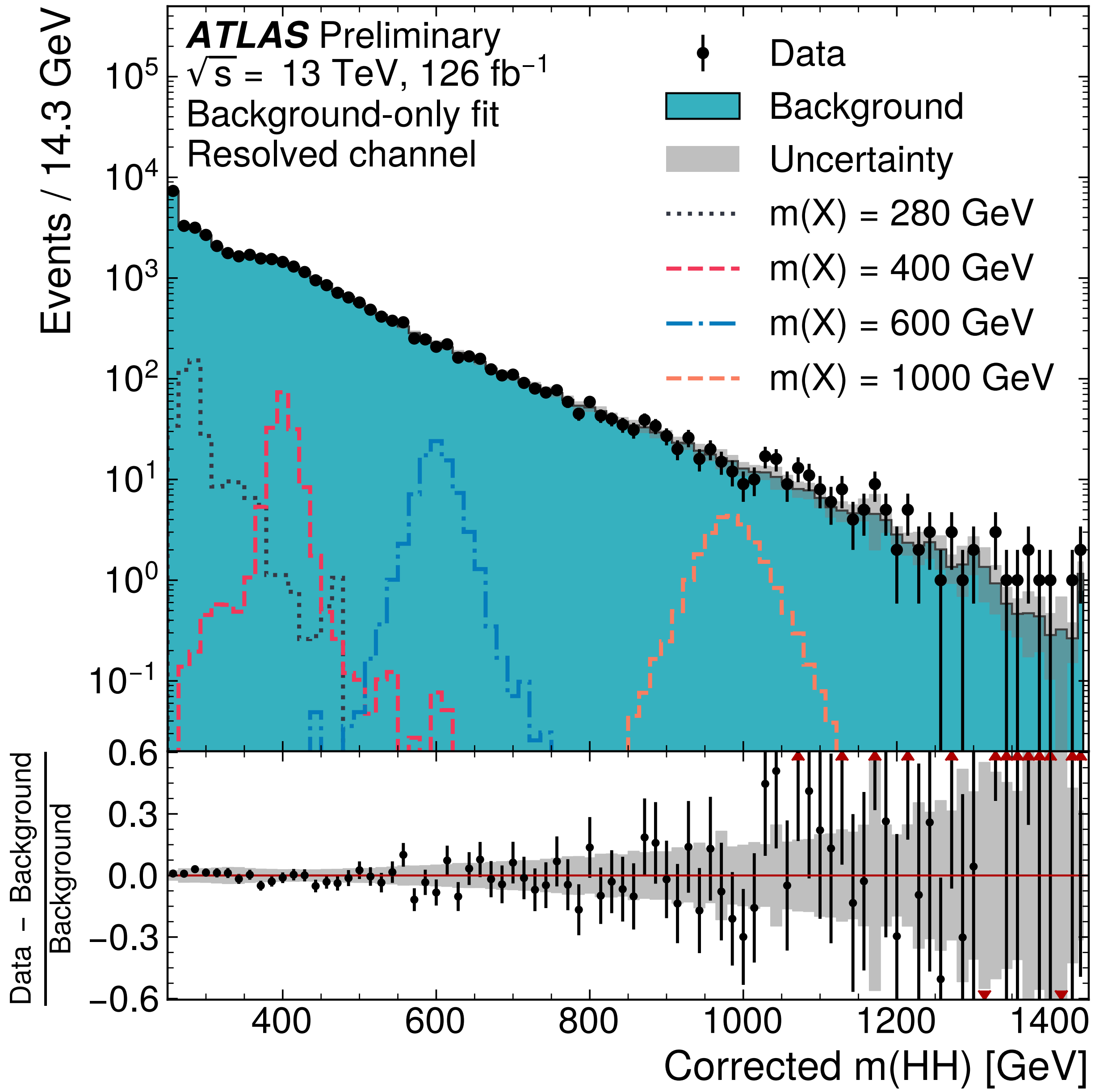
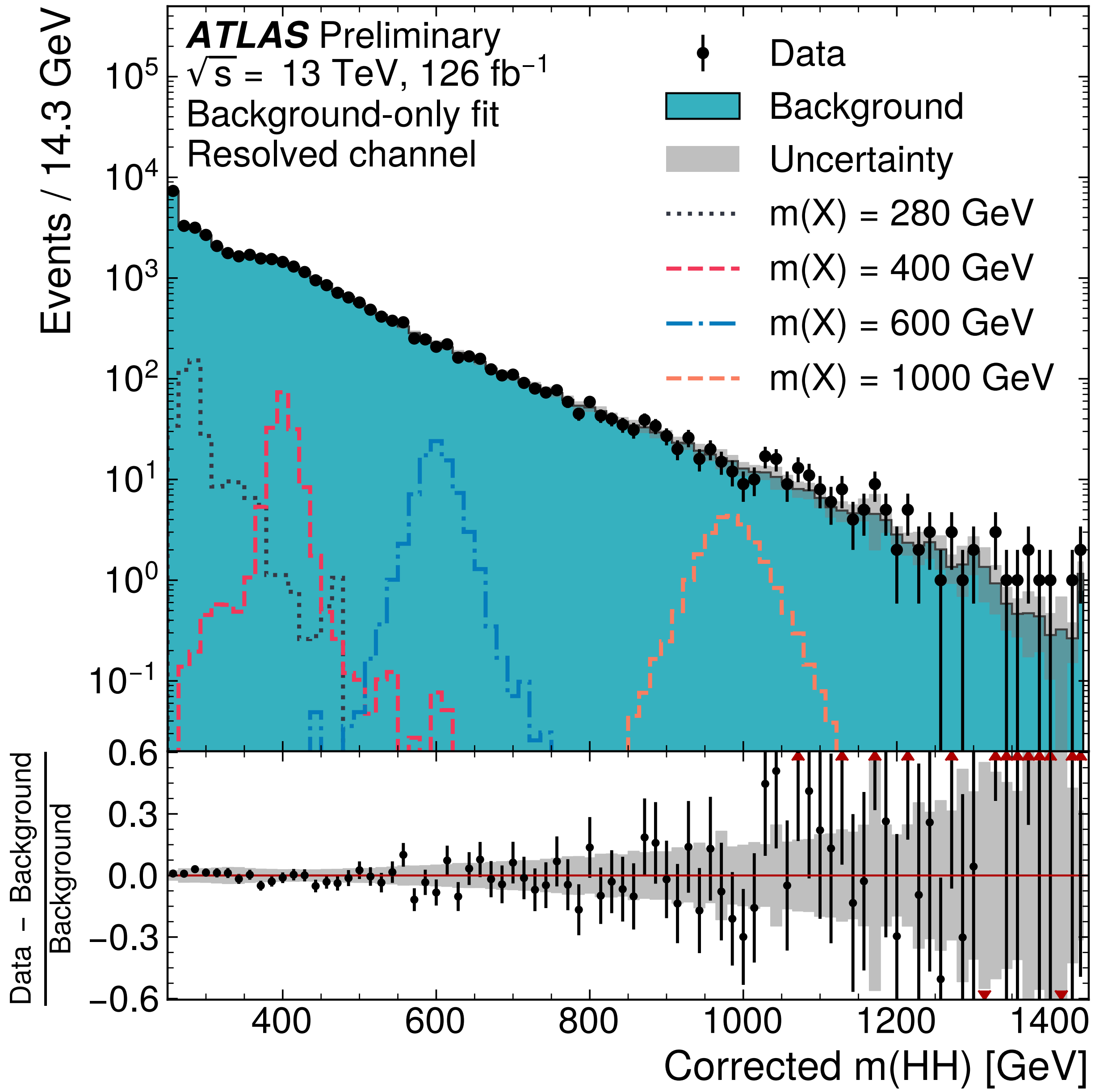
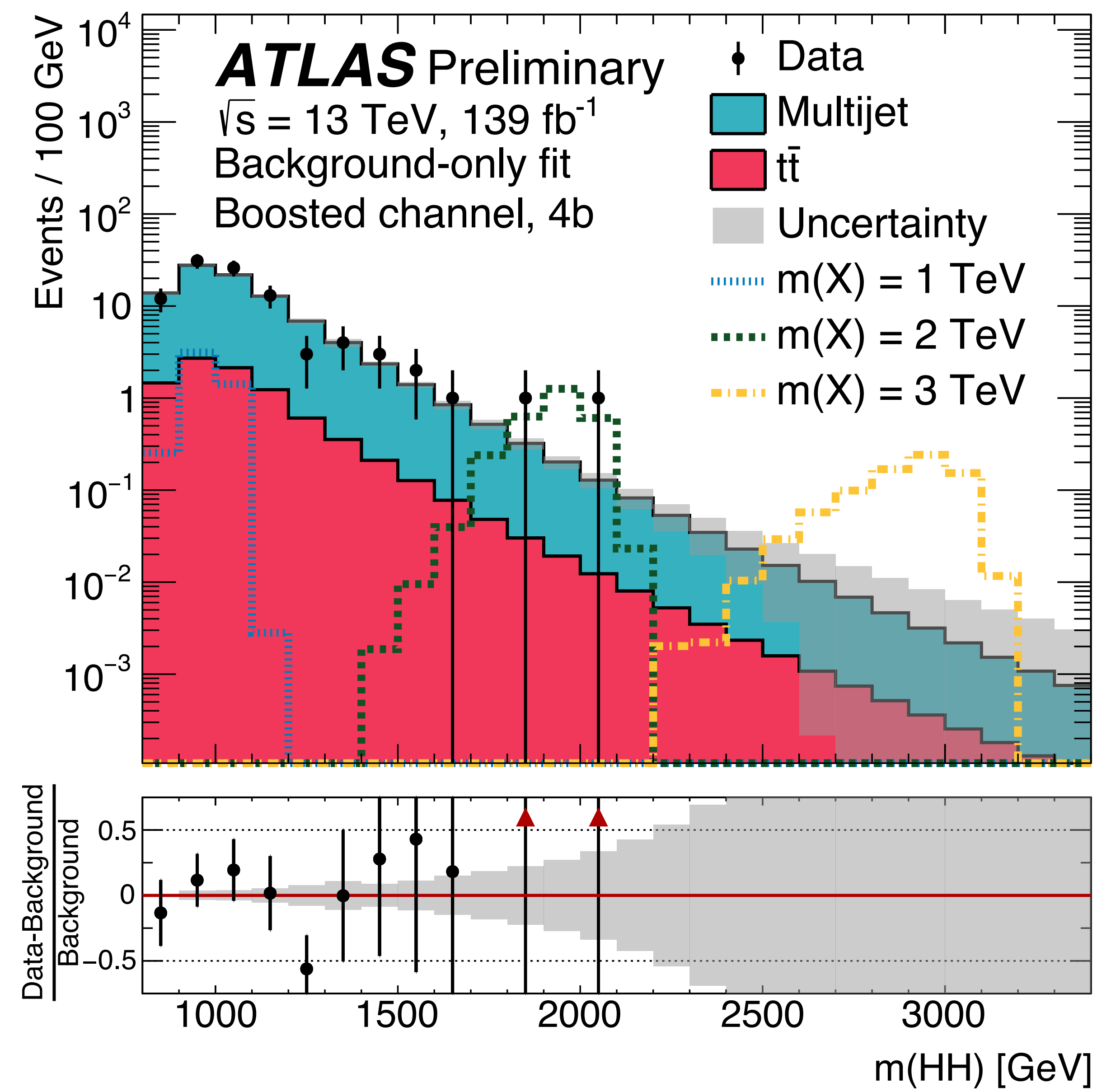


Data agrees well with background prediction

$b\bar{b}b\bar{b}$ Results





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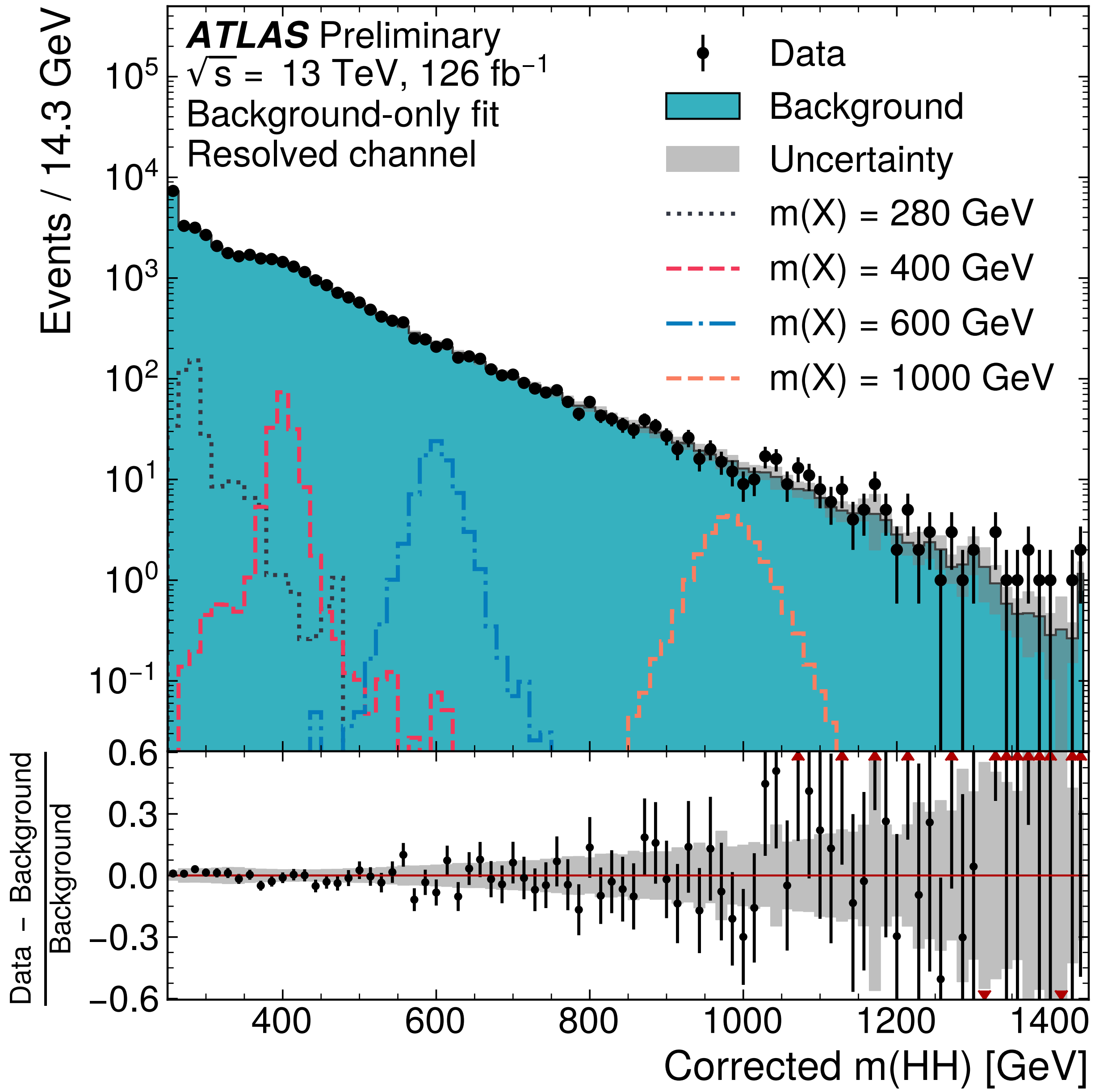

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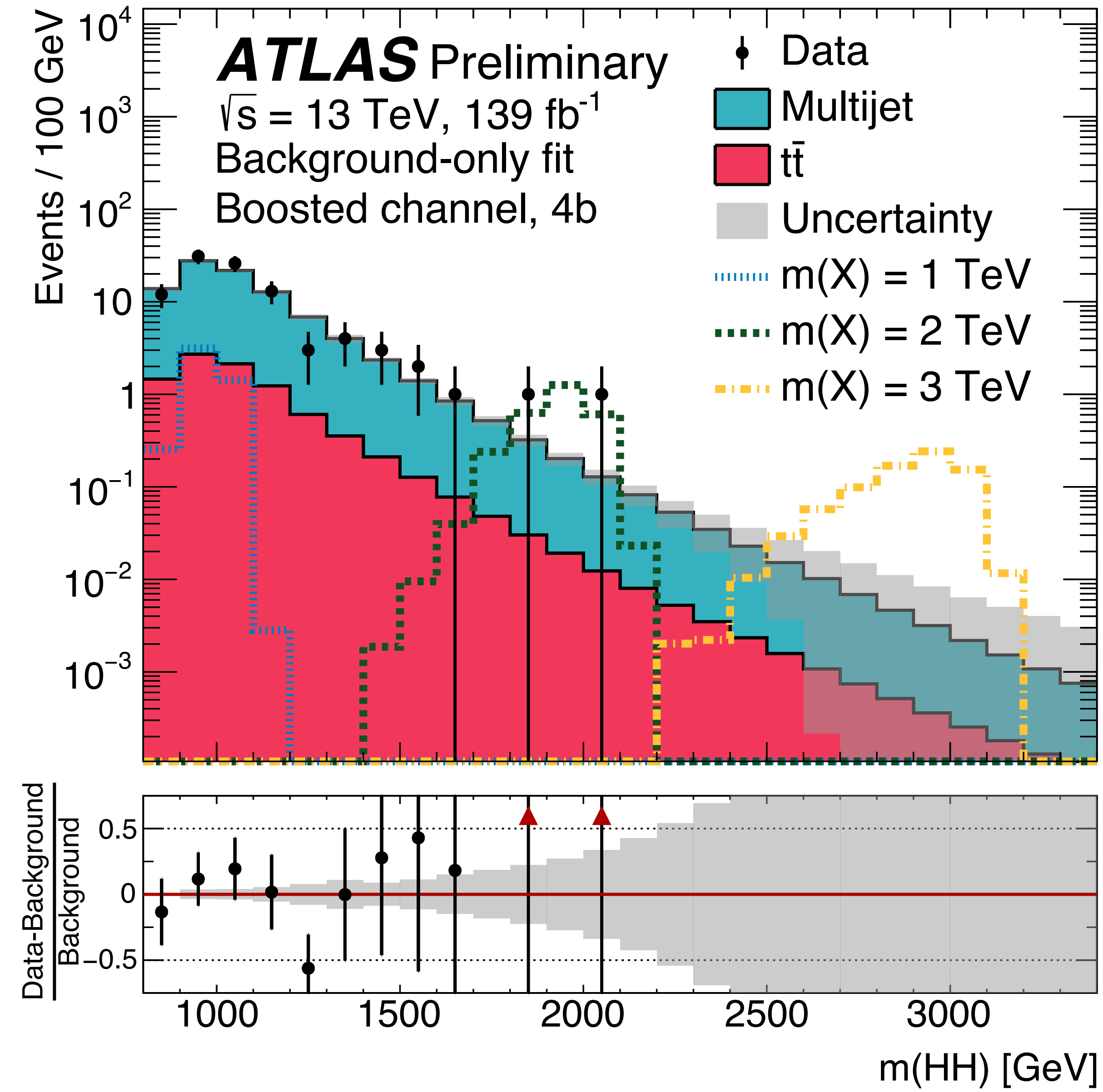

Boosted analysis is similar: simpler spline based reweighting

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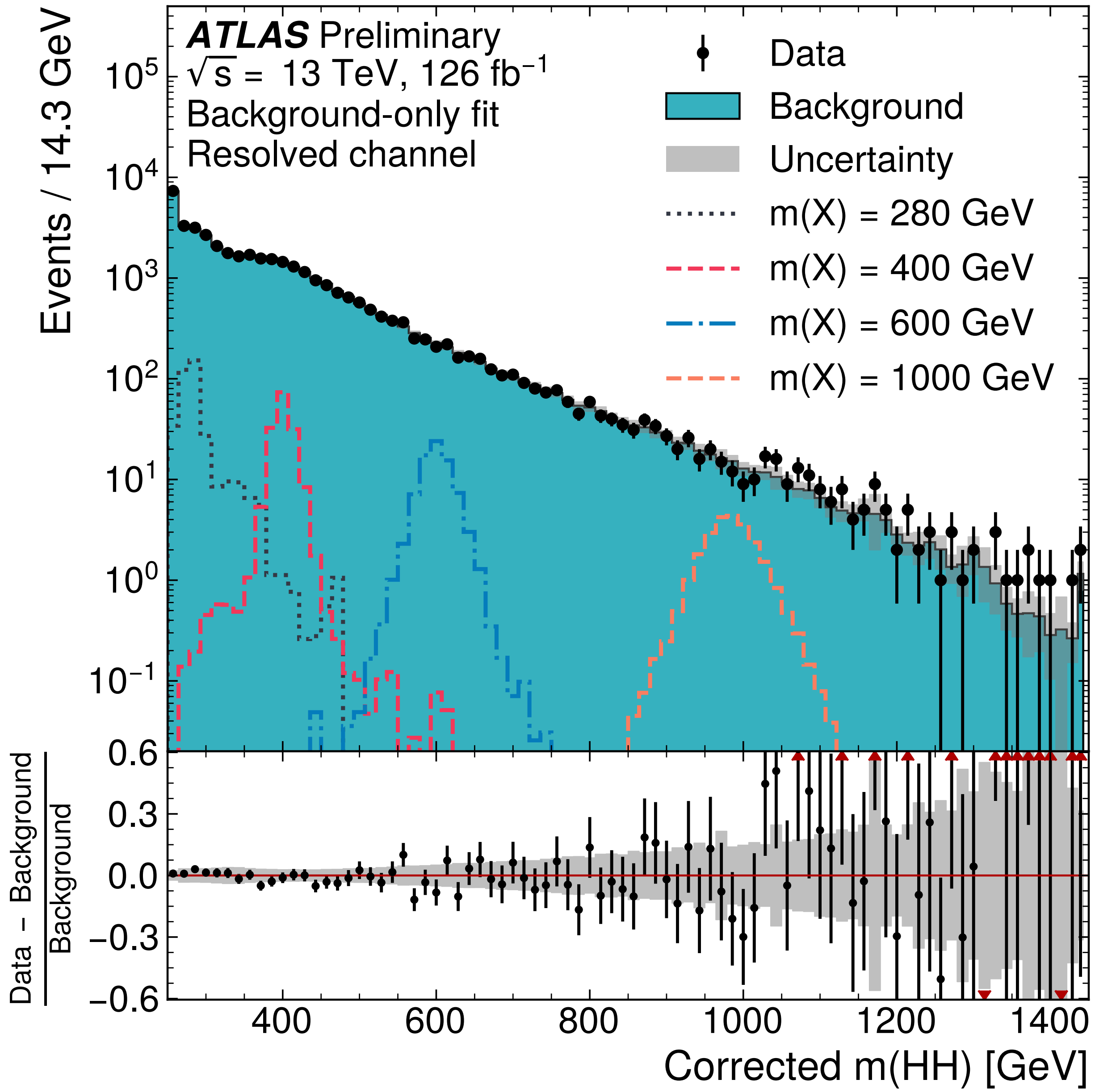
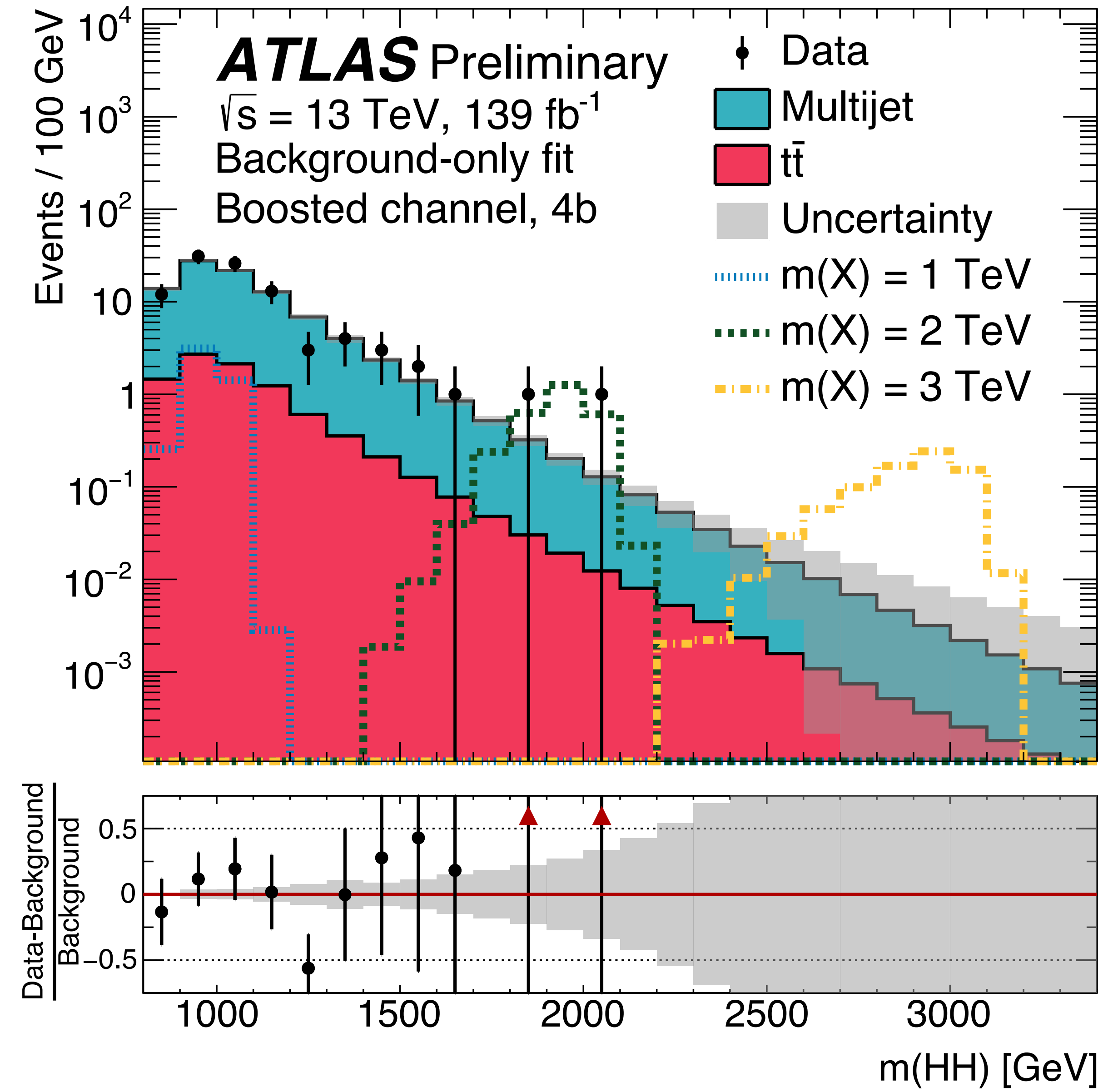




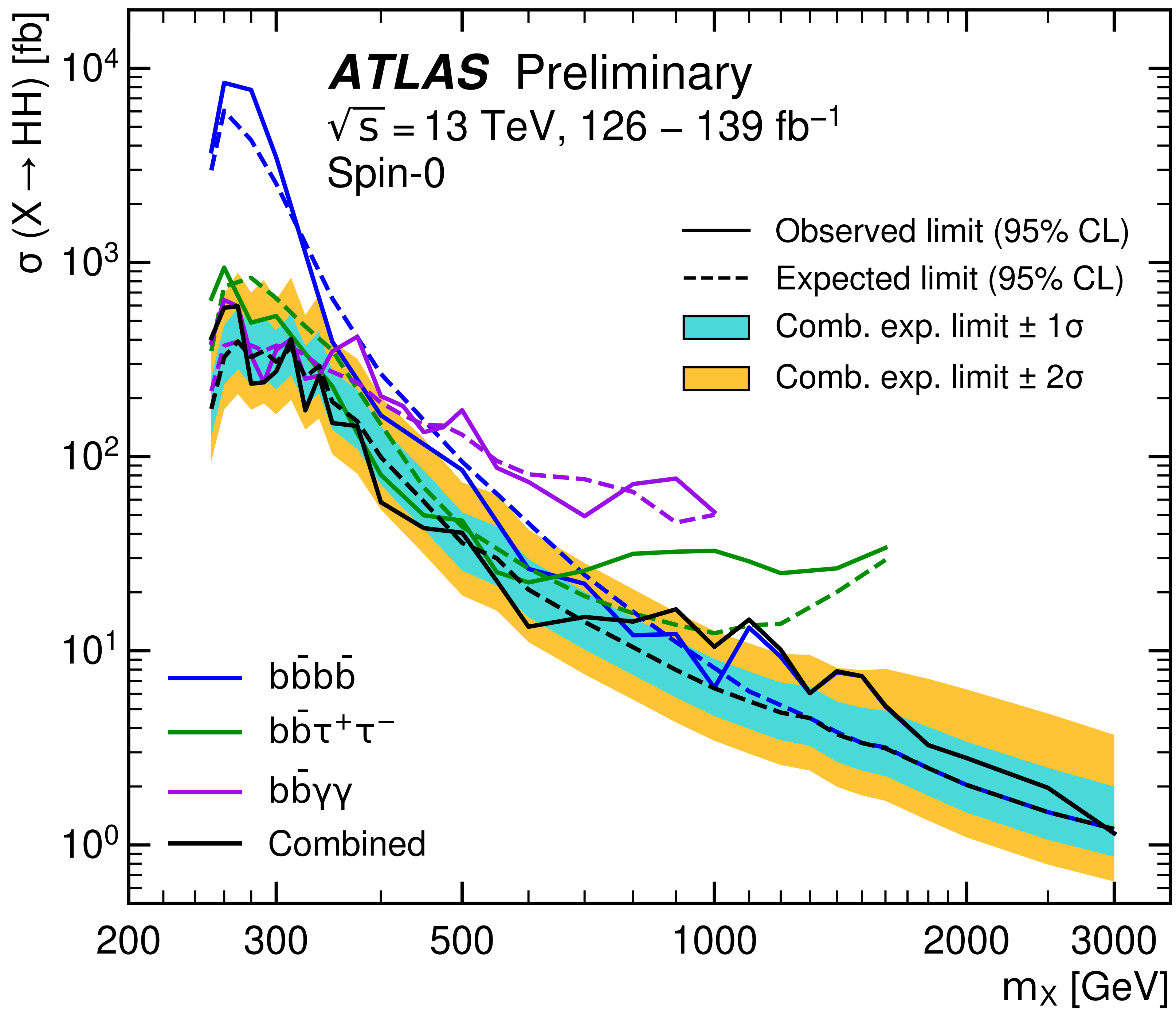
Data agrees well with background prediction

Boosted analysis is similar: simpler spline based reweighting

No excess either (also in 3b and 2b SR)

Resonant Combination

Resonant Combination



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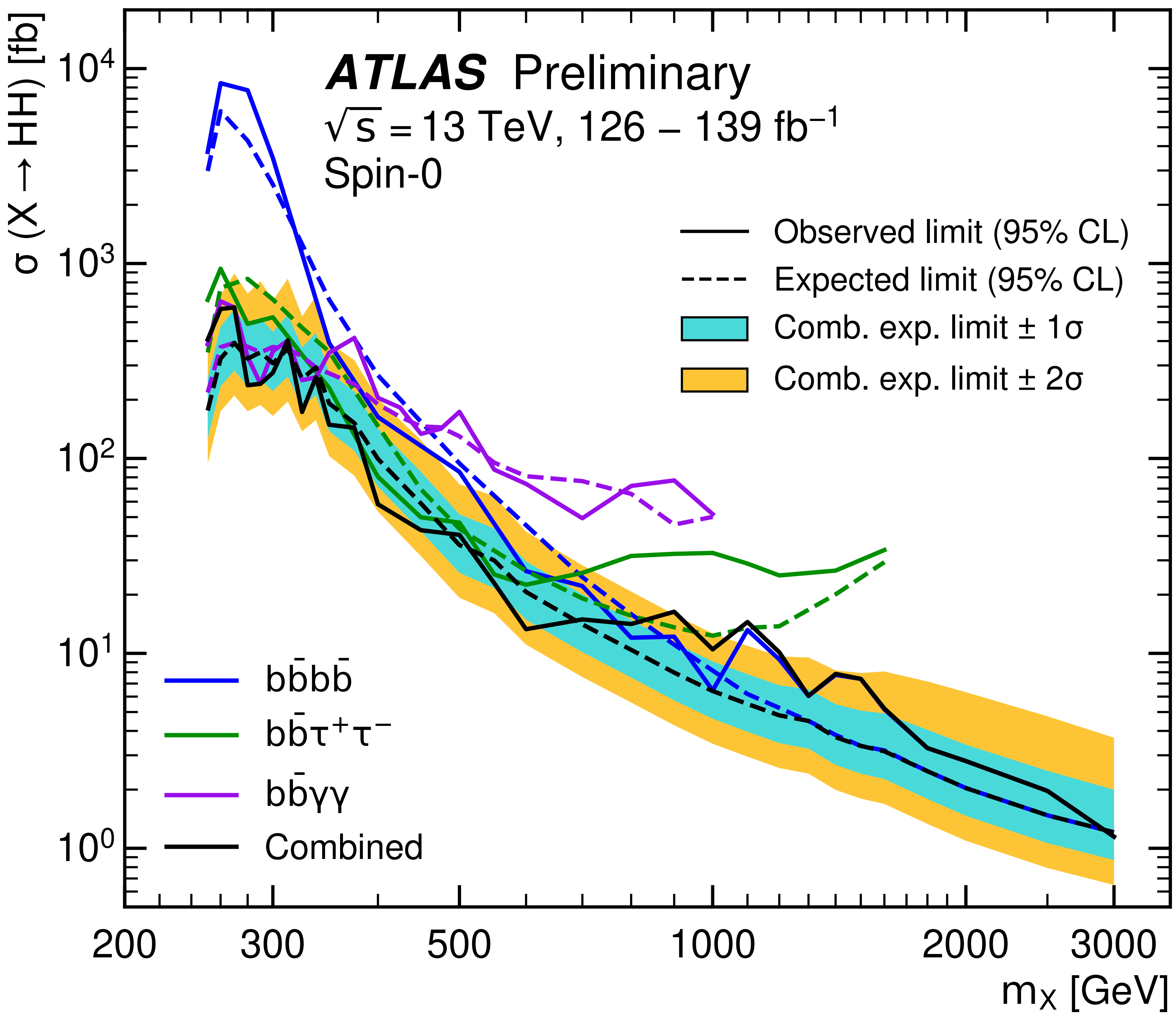
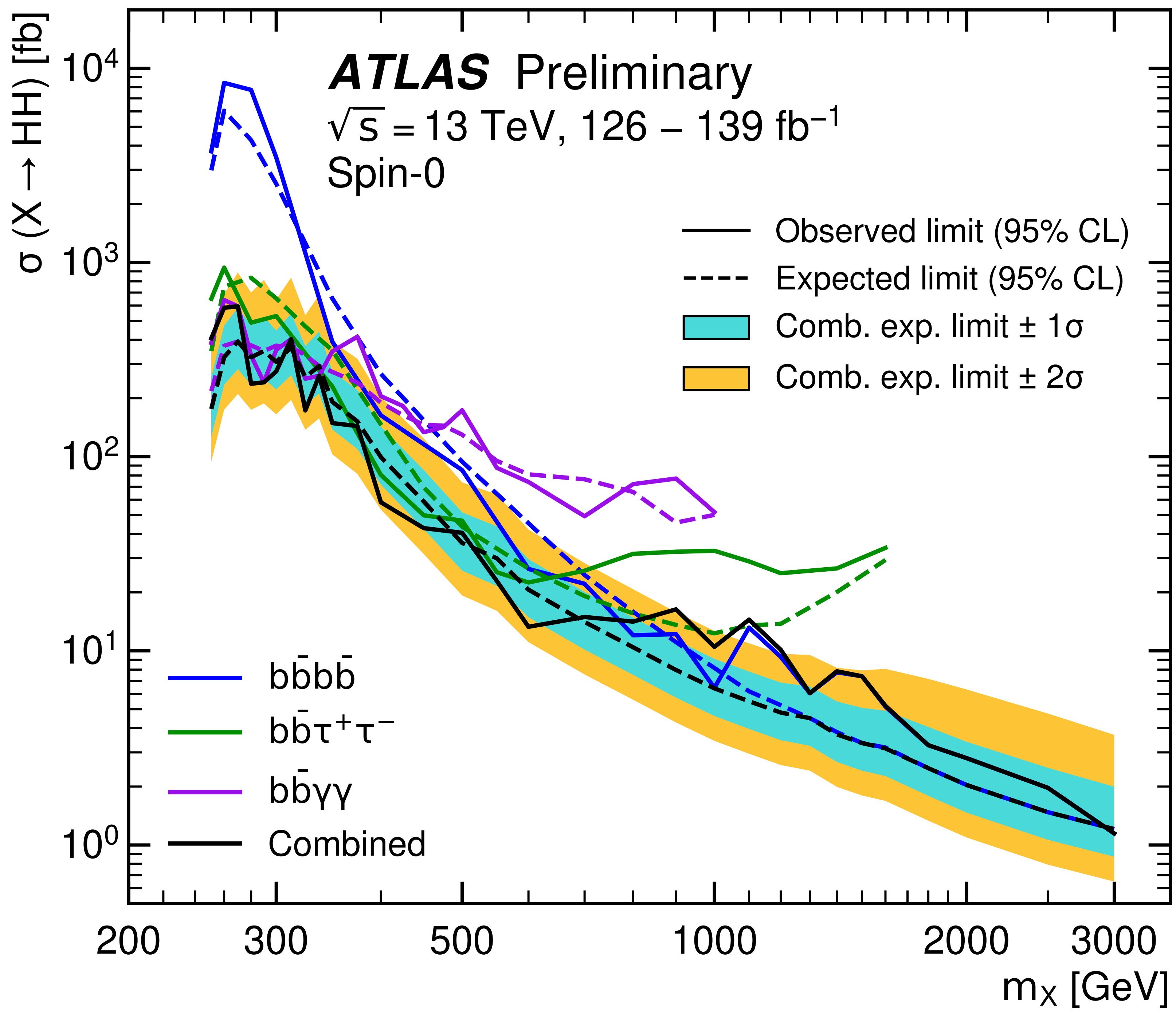


Here, show results from all three analyses

Resonant Combination



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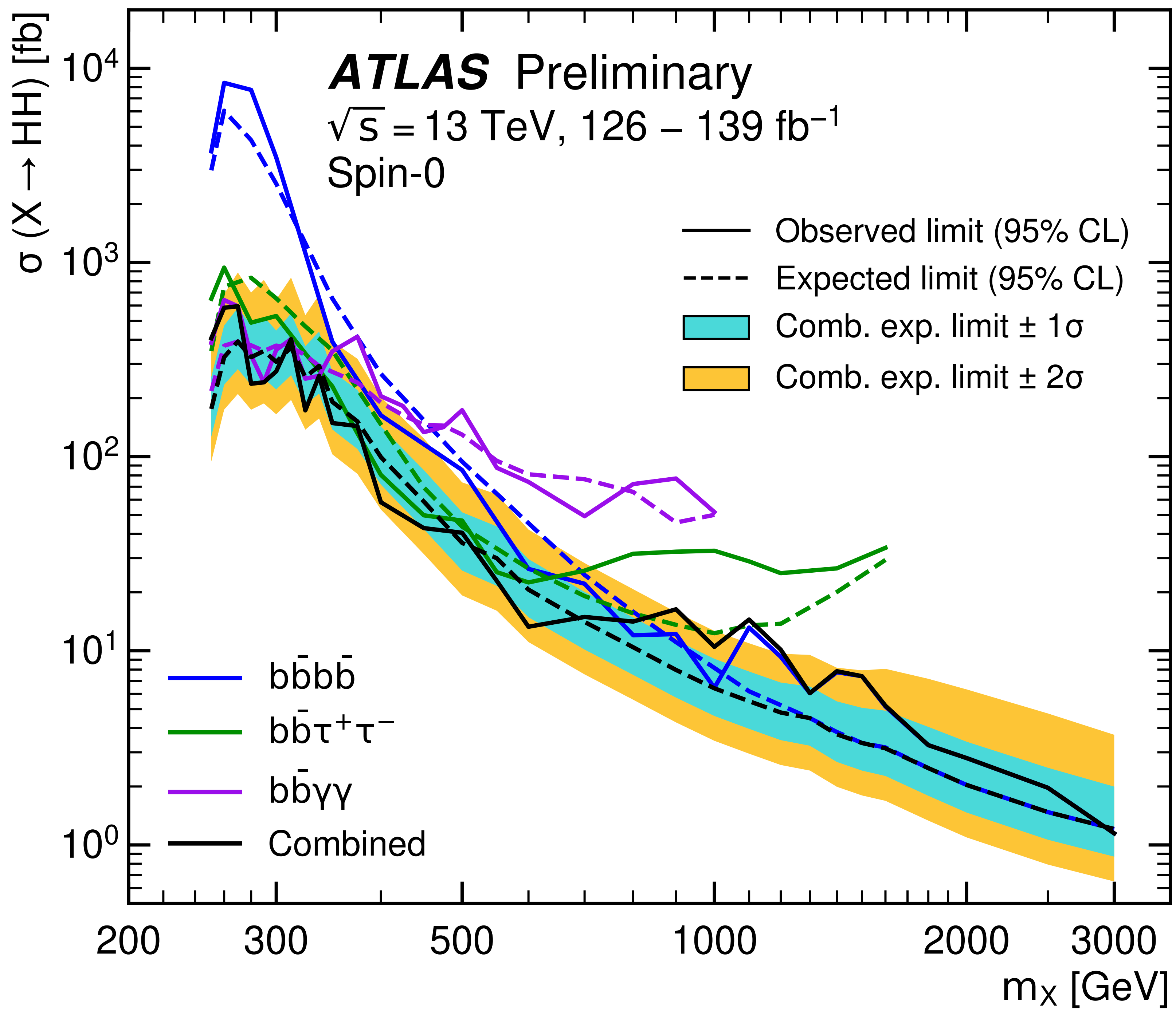
$b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\bar{\tau}$ have similar resonant-optimized searches

Resonant Combination



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($b\bar{b}\tau\bar{\tau}$ has parameterized NN for different signal mass points)

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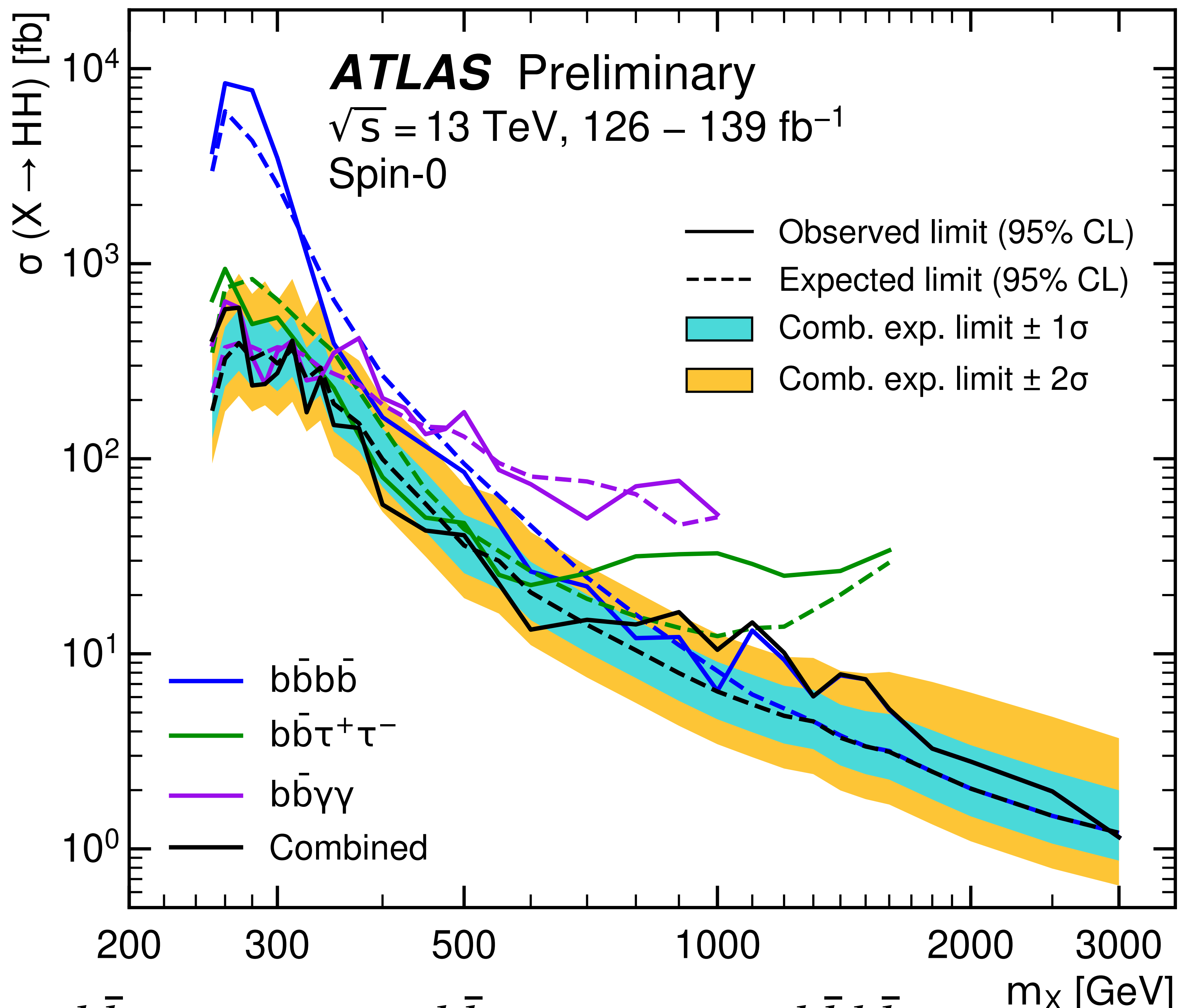


$b\bar{b}\gamma\gamma$ strongest $b\bar{b}\tau\bar{\tau}$ strongest $b\bar{b}b\bar{b}$ strongest

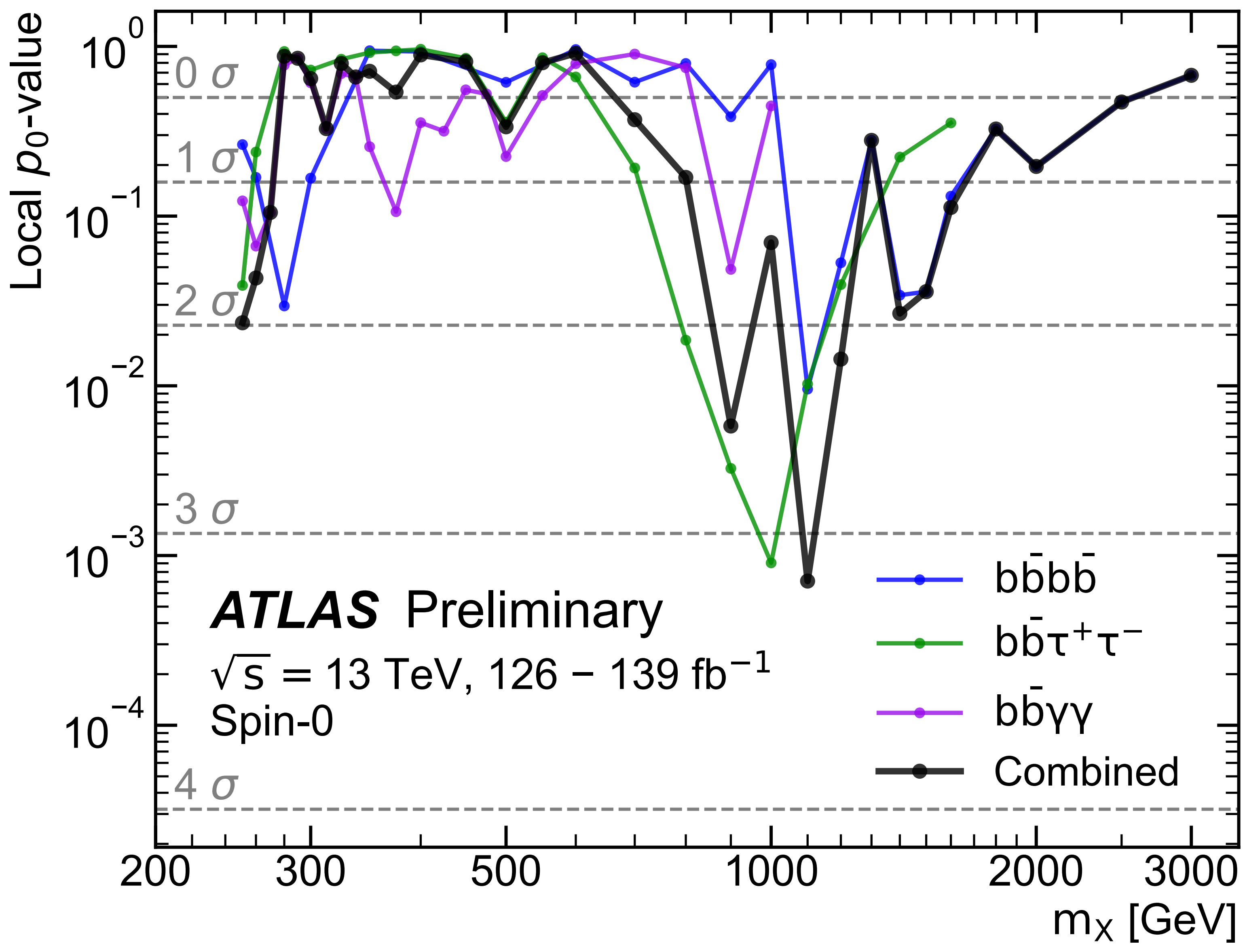
Here, show results from all three analyses

$b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\bar{\tau}$ have similar resonant-optimized searches

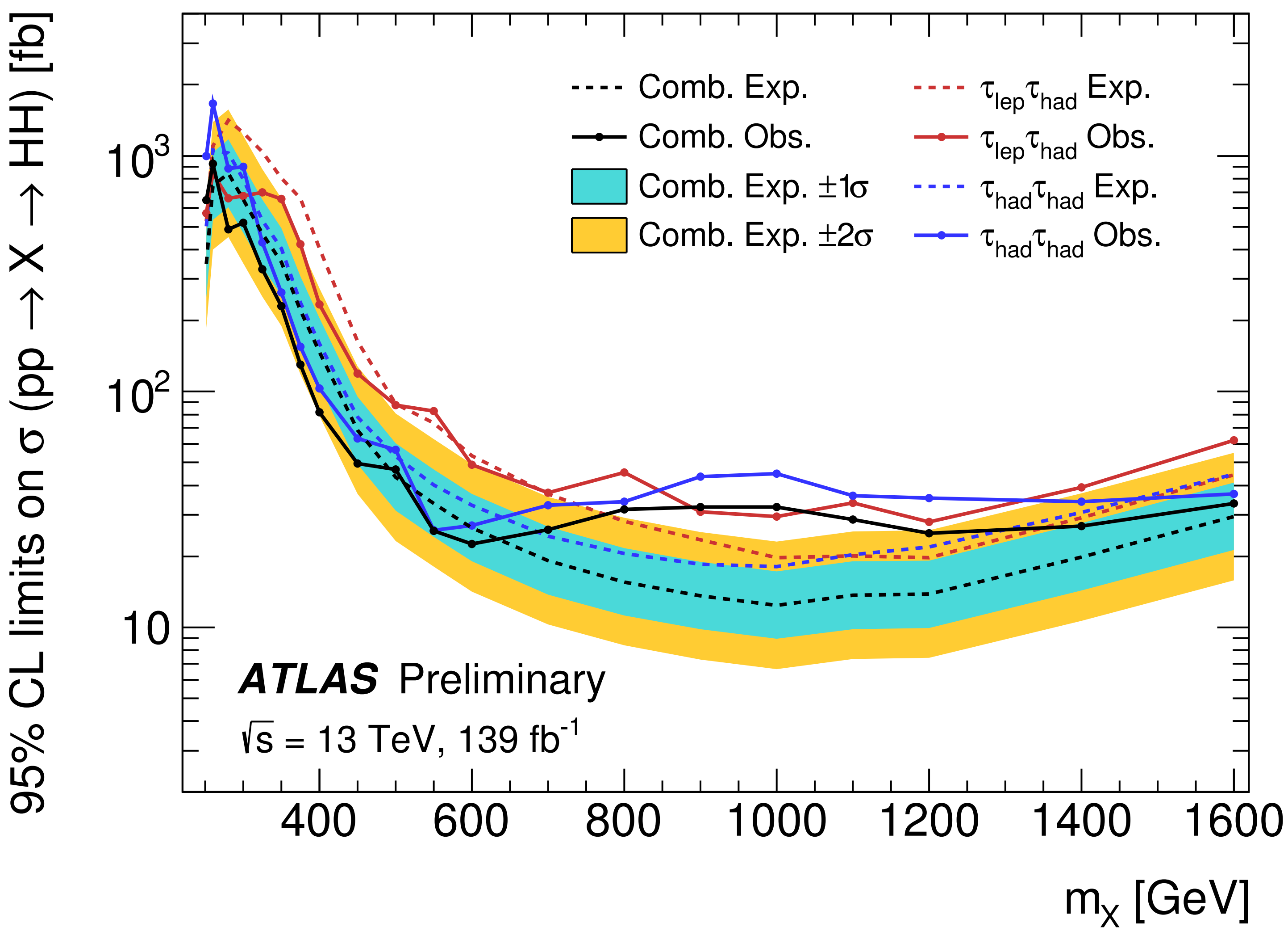
($b\bar{b}\tau\bar{\tau}$ has parameterized NN for different signal mass points)

All three analyses complementary: set best limits at different ranges

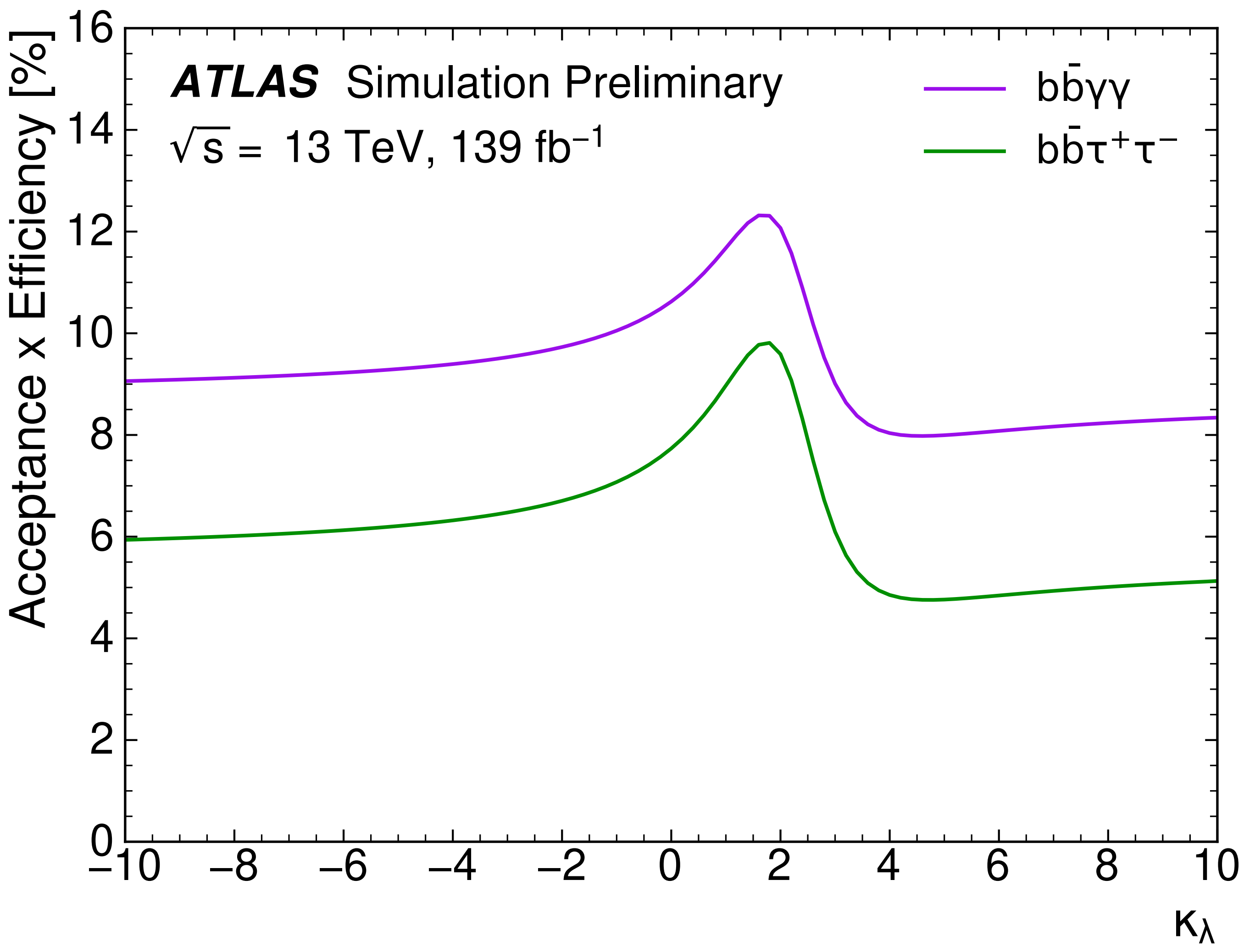
Resonant p-value



$b\bar{b}\tau\bar{\tau}$ Resonant Limits



Non-resonant Acc x Eff



Variables for MVAs

- For $b\bar{b}\gamma\gamma$: photon kinematics, b-jet kinematics, bb-system kinematics, missing energy, total energy, "top-ness"
- For $b\bar{b}\tau\bar{\tau}$: mHH, mbb, mττ, DR(b,b), DR(τ,τ), DPt(lep,τ), MET, DPhi(lepτ, bb)…
- For $b\bar{b}b\bar{b}$:

1. $\log(p_{\mathrm{T}})$ of the selected jet with the 2^{nd}-highest p_{T},
2. $\log(p_{\mathrm{T}})$ of the selected jet with the 4^{th}-highest p_{T},
3. $\log(\Delta R)$ between the two selected jets with the smallest ΔR,
4. $\log(\Delta R)$ between the other two selected jets,
5. the average $|\eta|$ of selected jets,
6. $\log(p_{\mathrm{T}})$ of the HH system,
7. ΔR between the two H candidates,
8. $\Delta\phi$ between the jets making up H_1,
9. $\Delta\phi$ between the jets making up H_2,
10. $\log(\min(X_{Wt}))$, and
11. the number of jets in the event with $p_{\mathrm{T}} > 40$ GeV and $|\eta| < 2.5$, including jets that are not selected.

$b\bar{b}\gamma\gamma$ Background Estimate

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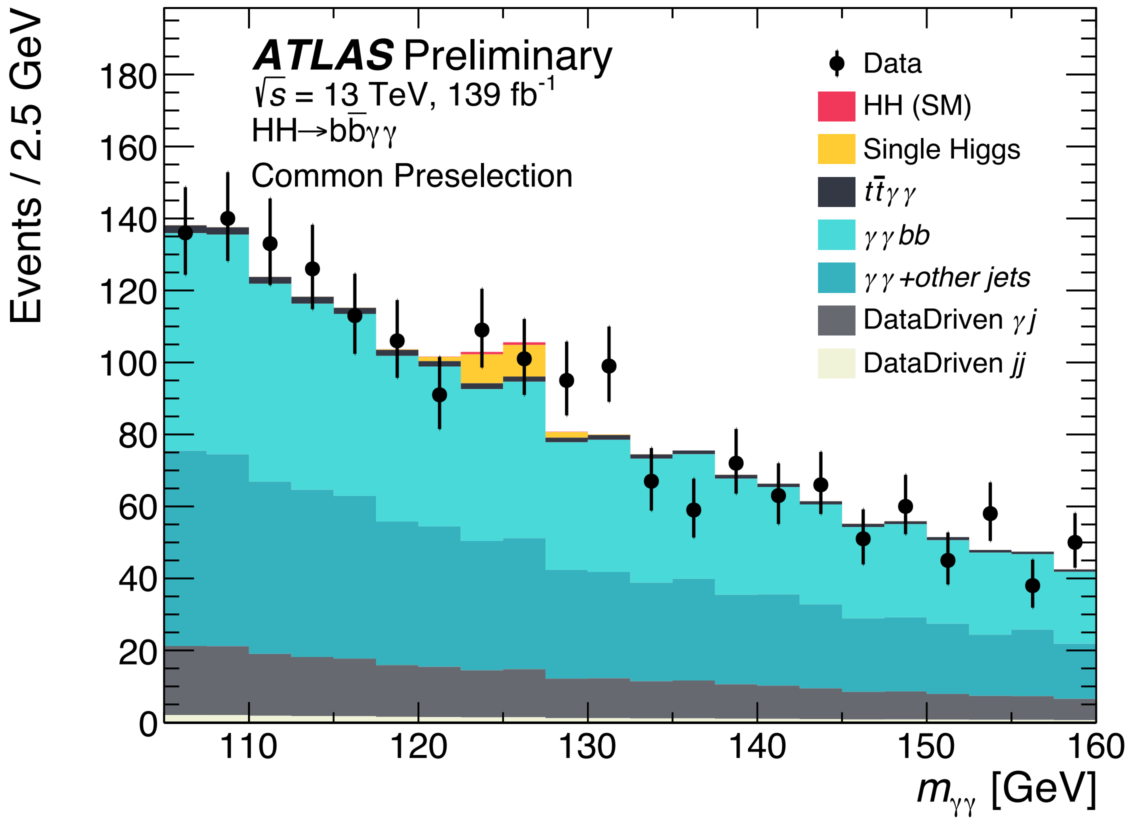
Background estimate formed on fit to $m_{\gamma\gamma}$ in different signal regions

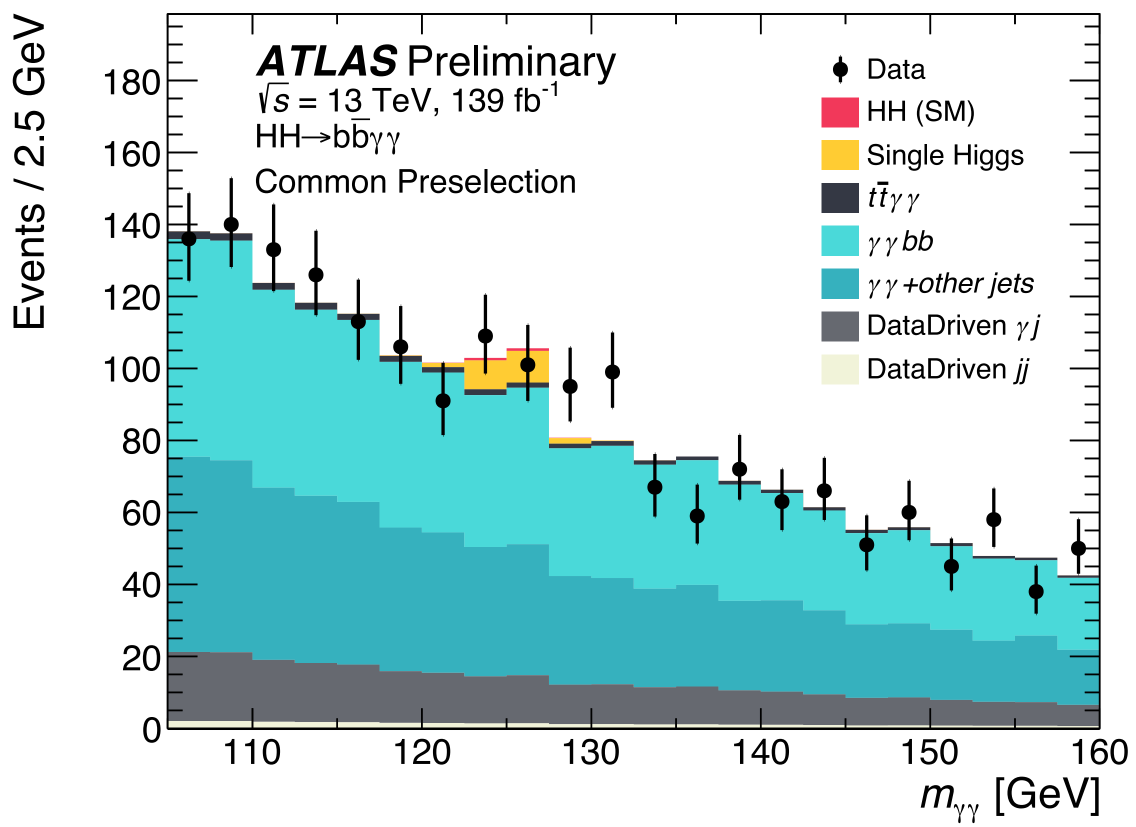
$b\bar{b}\gamma\gamma$ Background Estimate



Background estimate formed on fit to $m_{\gamma\gamma}$ in different signal regions

Shape of background function determined from MC, normalization determined from data 'sidebands'

$b\bar{b}\gamma\gamma$ Background Estimate



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Contributions from fake γ estimated from data using ABCD method

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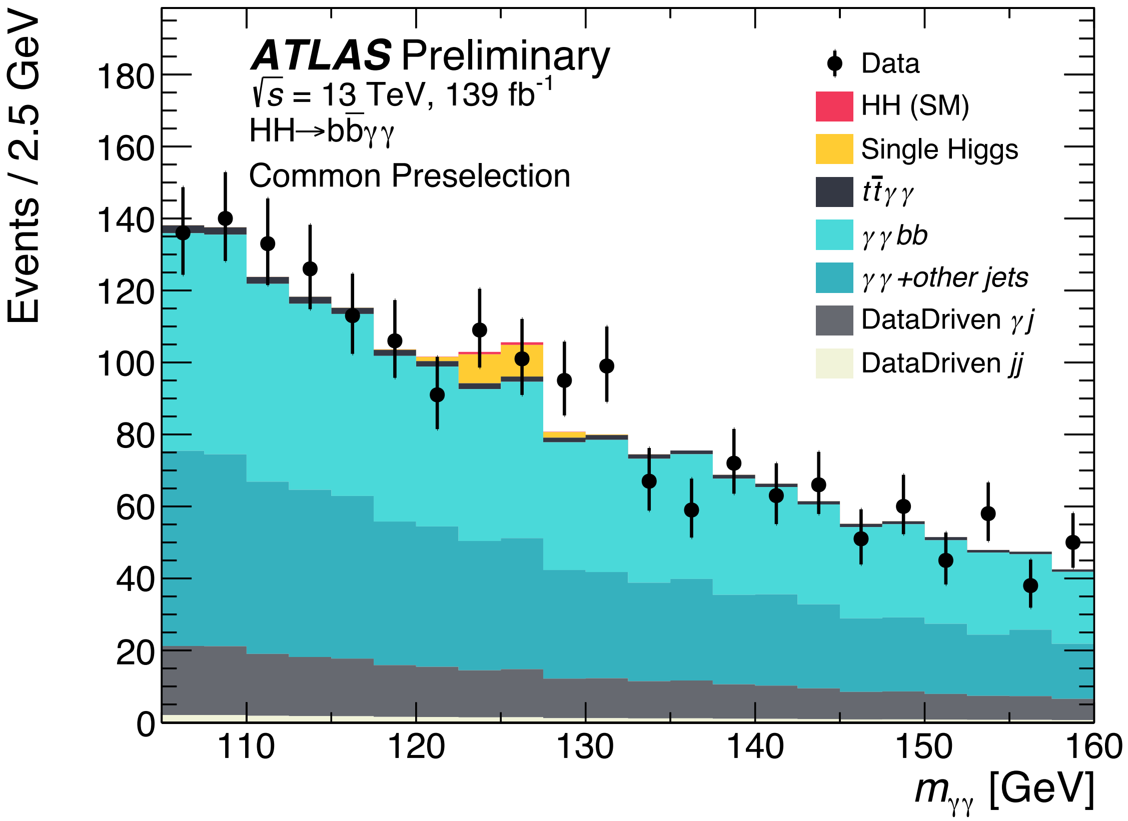

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Single Higgs background determined from MC

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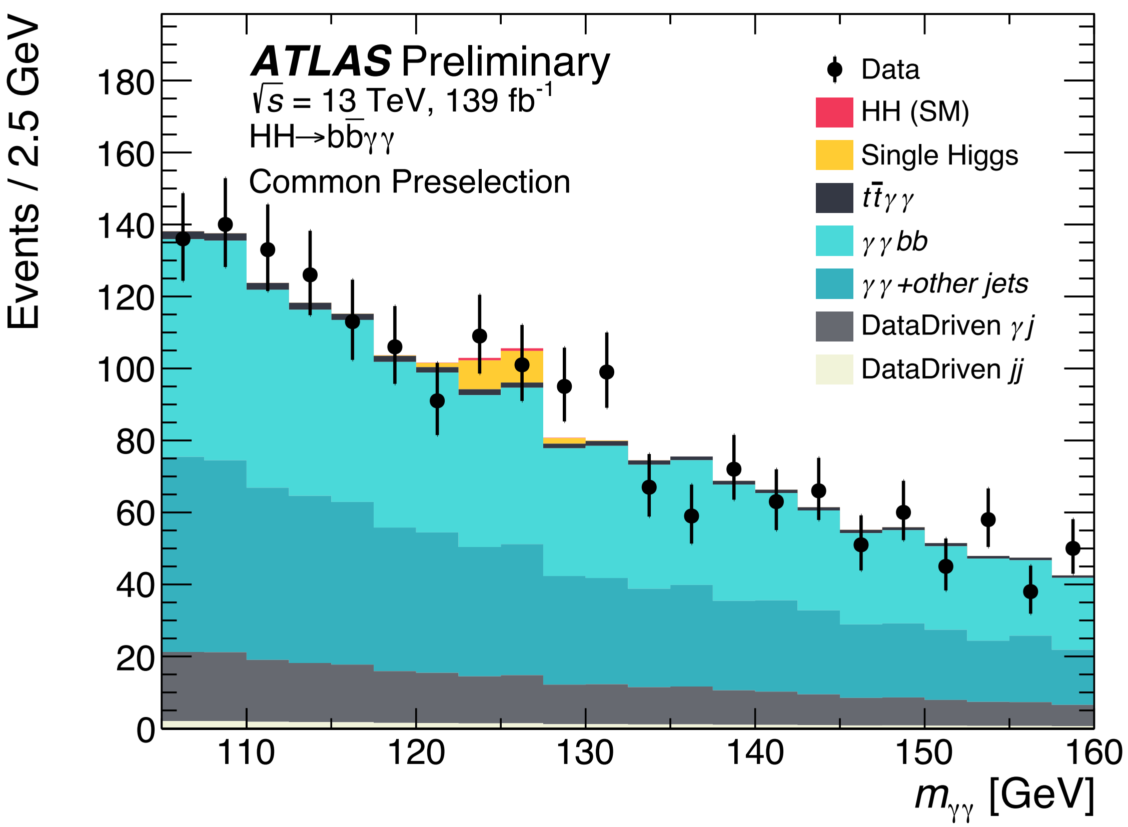

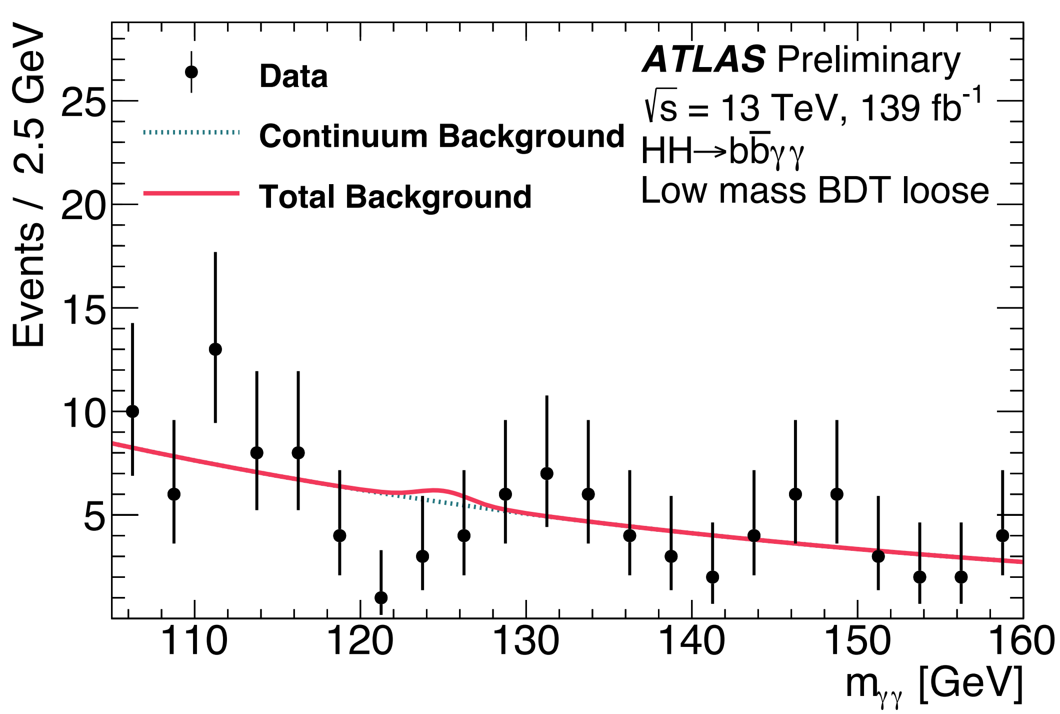

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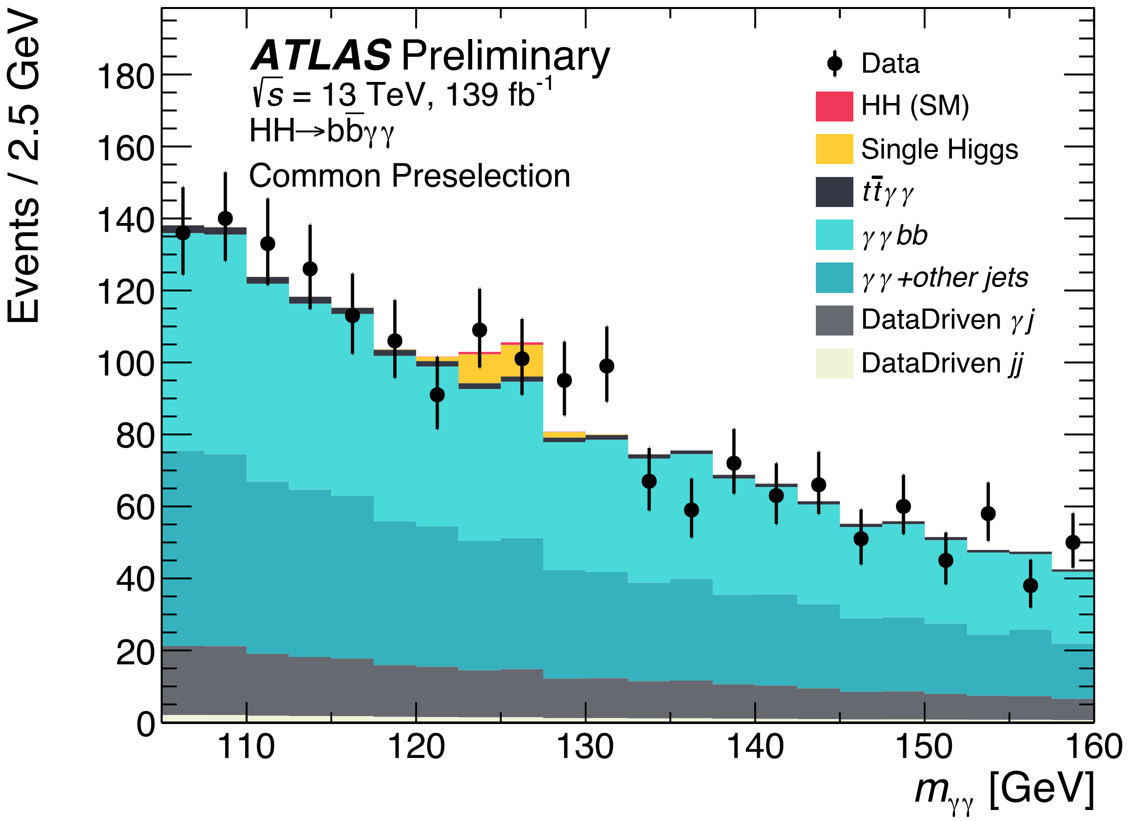

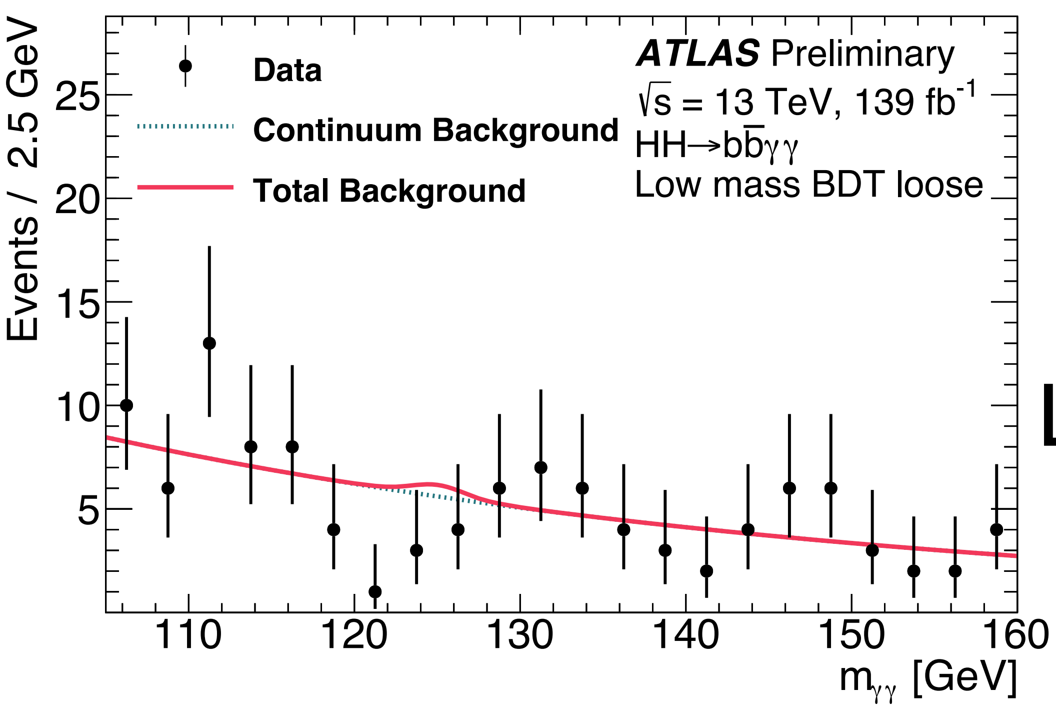

Background estimate formed on fit to $m_{\gamma\gamma}$ in different signal regions

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Contributions from fake γ estimated from data using ABCD method

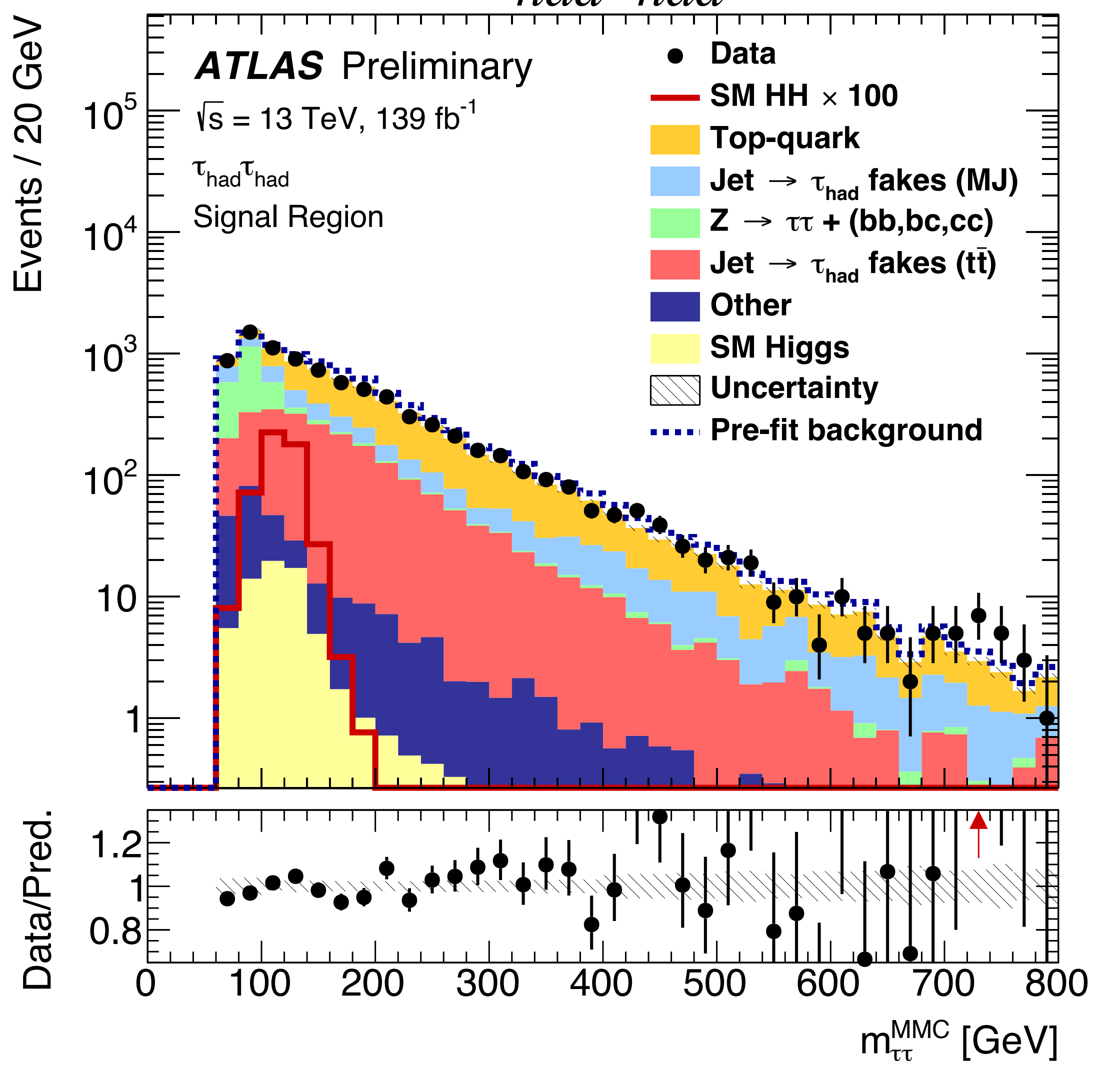
Single Higgs background determined from MC

Largest systematic from "spurious signal": fit signal + background on background-only MC template

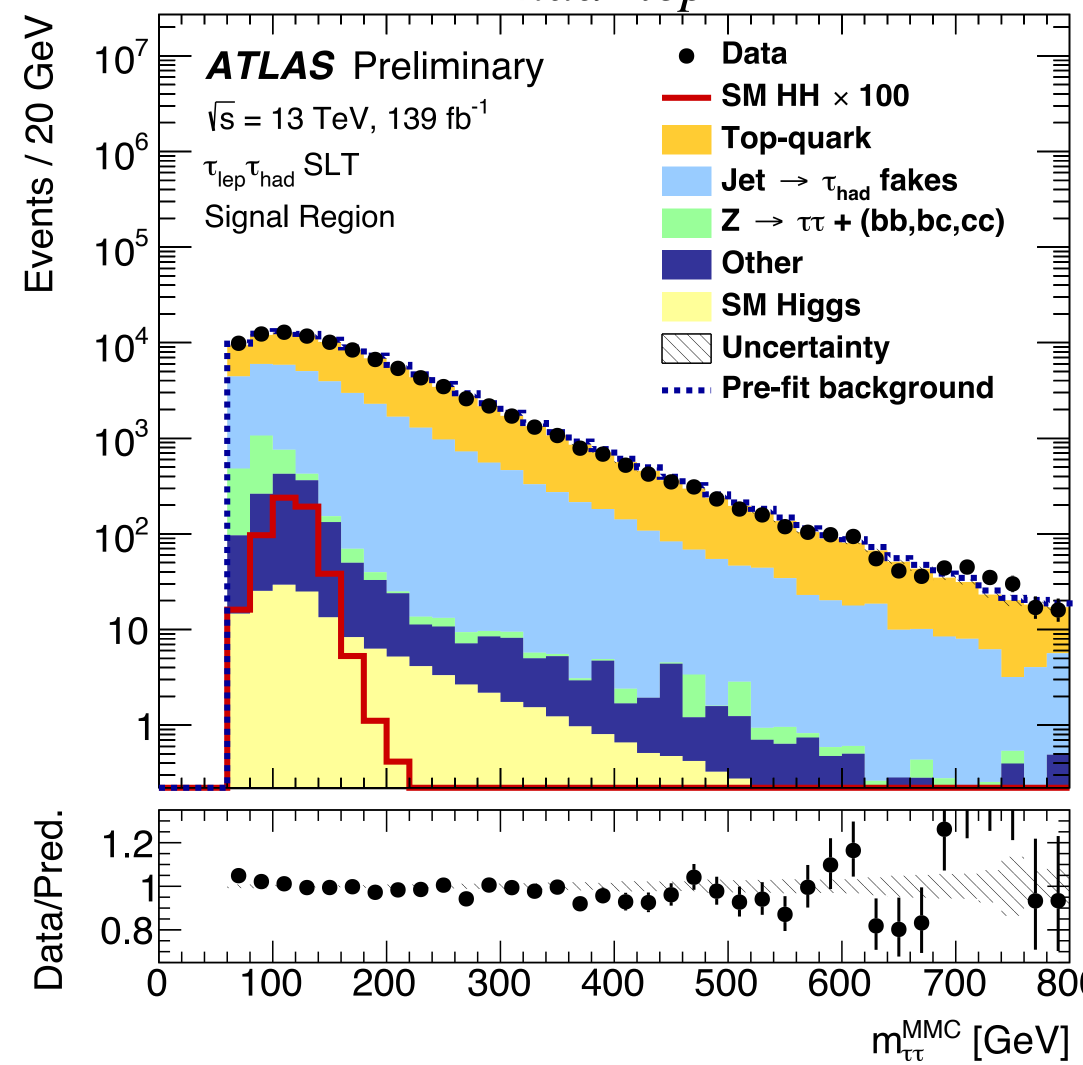
$b\bar{b}\tau\bar{\tau}$ Background Estimate

$b\bar{b}\tau\bar{\tau}$ Background Estimate

$\tau_{had}\tau_{had}$

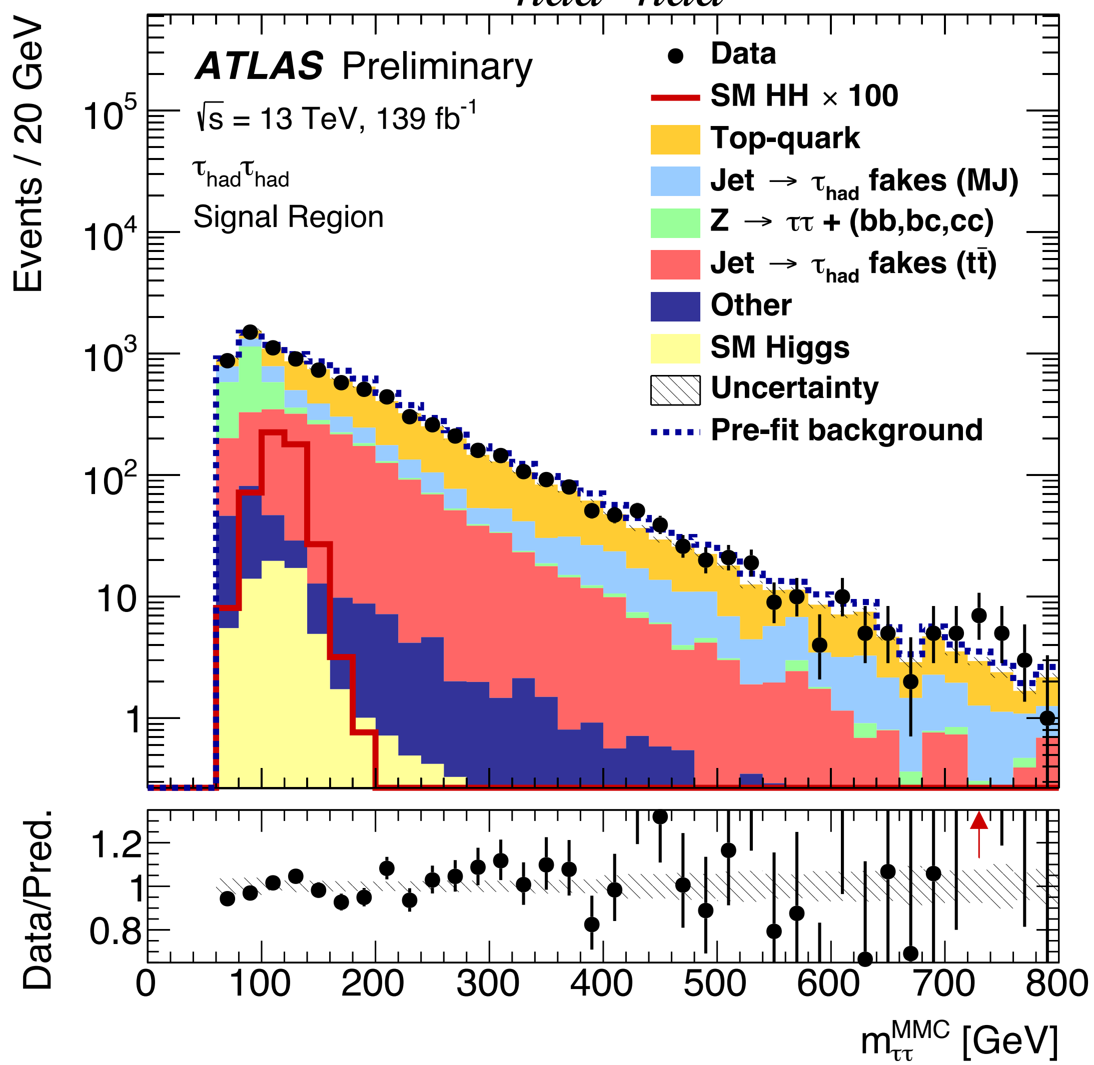


$\tau_{had}\tau_{lep}$

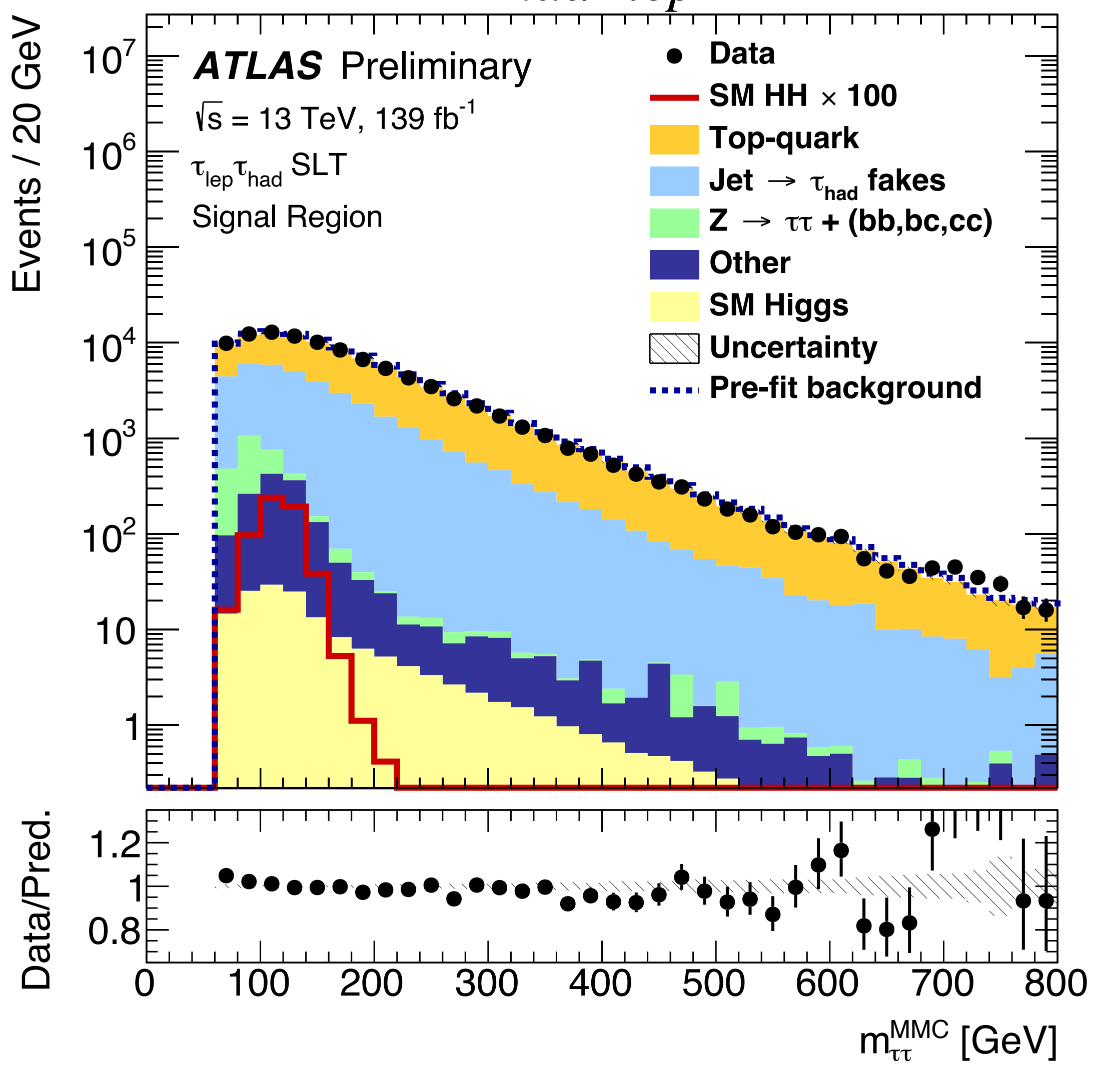


$b\bar{b}\tau\bar{\tau}$ Background Estimate

$\tau_{had}\tau_{had}$



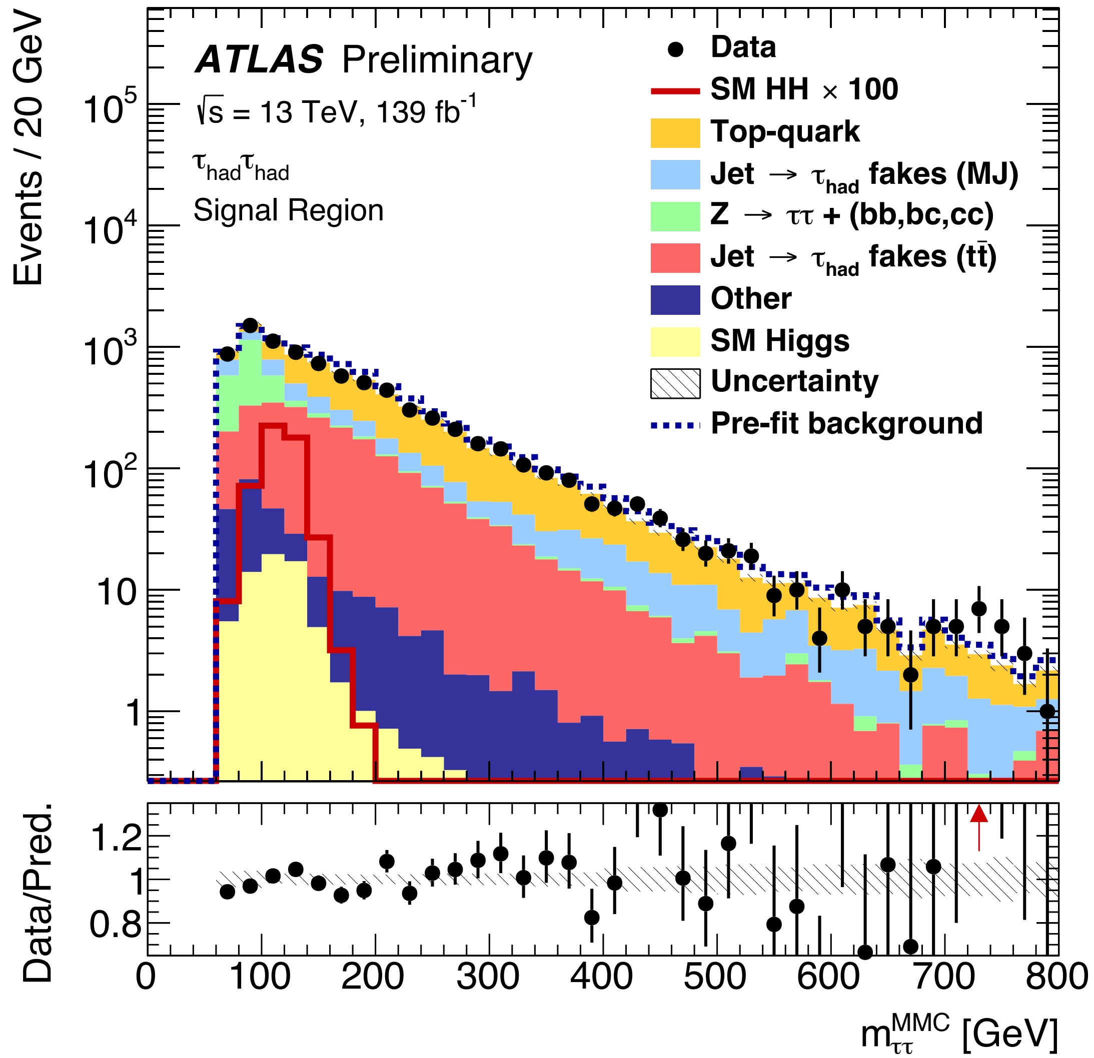
$\tau_{had}\tau_{lep}$



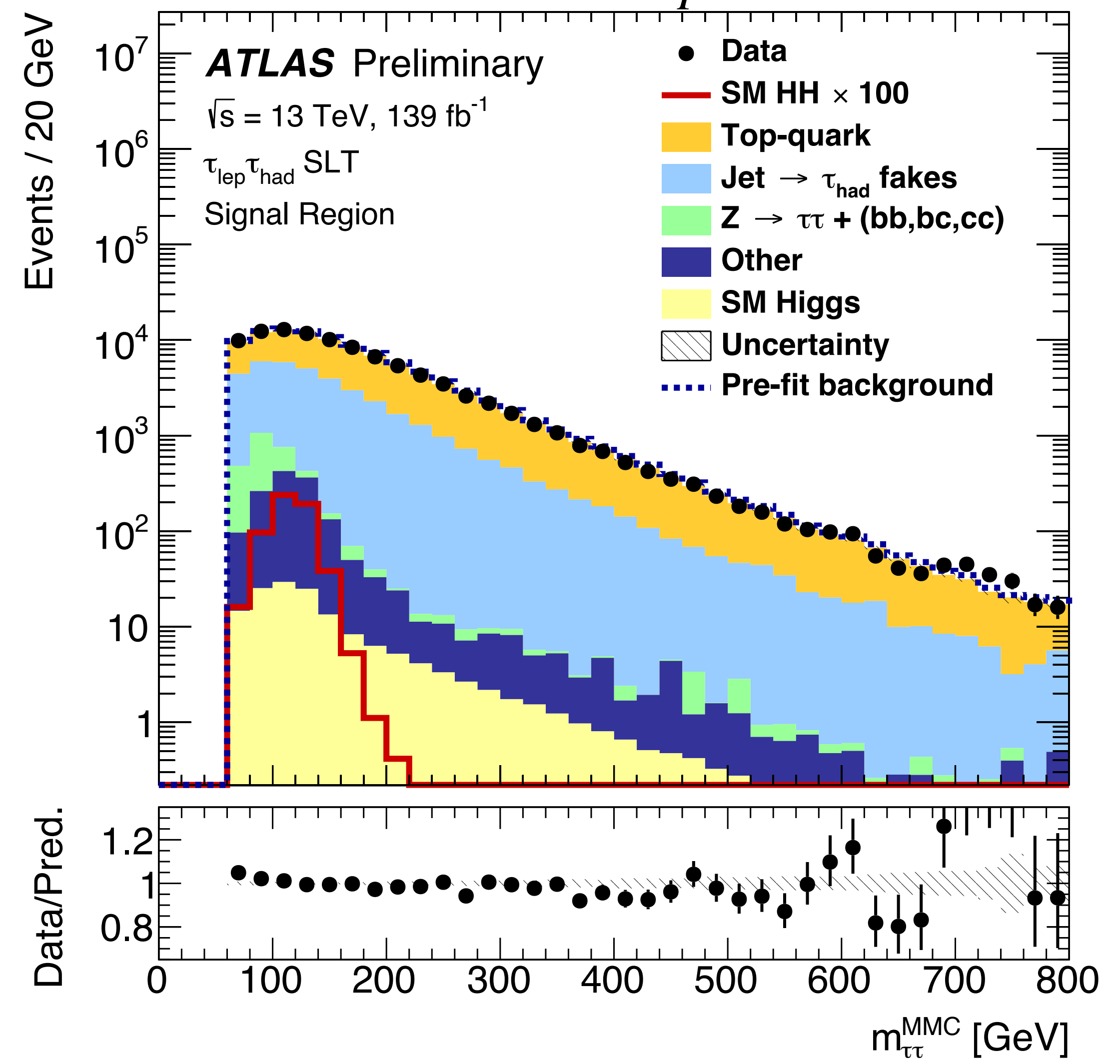
Top-quark background from MC, normalization floating in final fit

$b\bar{b}\tau\bar{\tau}$ Background Estimate

$\tau_{had}\tau_{had}$



$\tau_{had}\tau_{lep}$

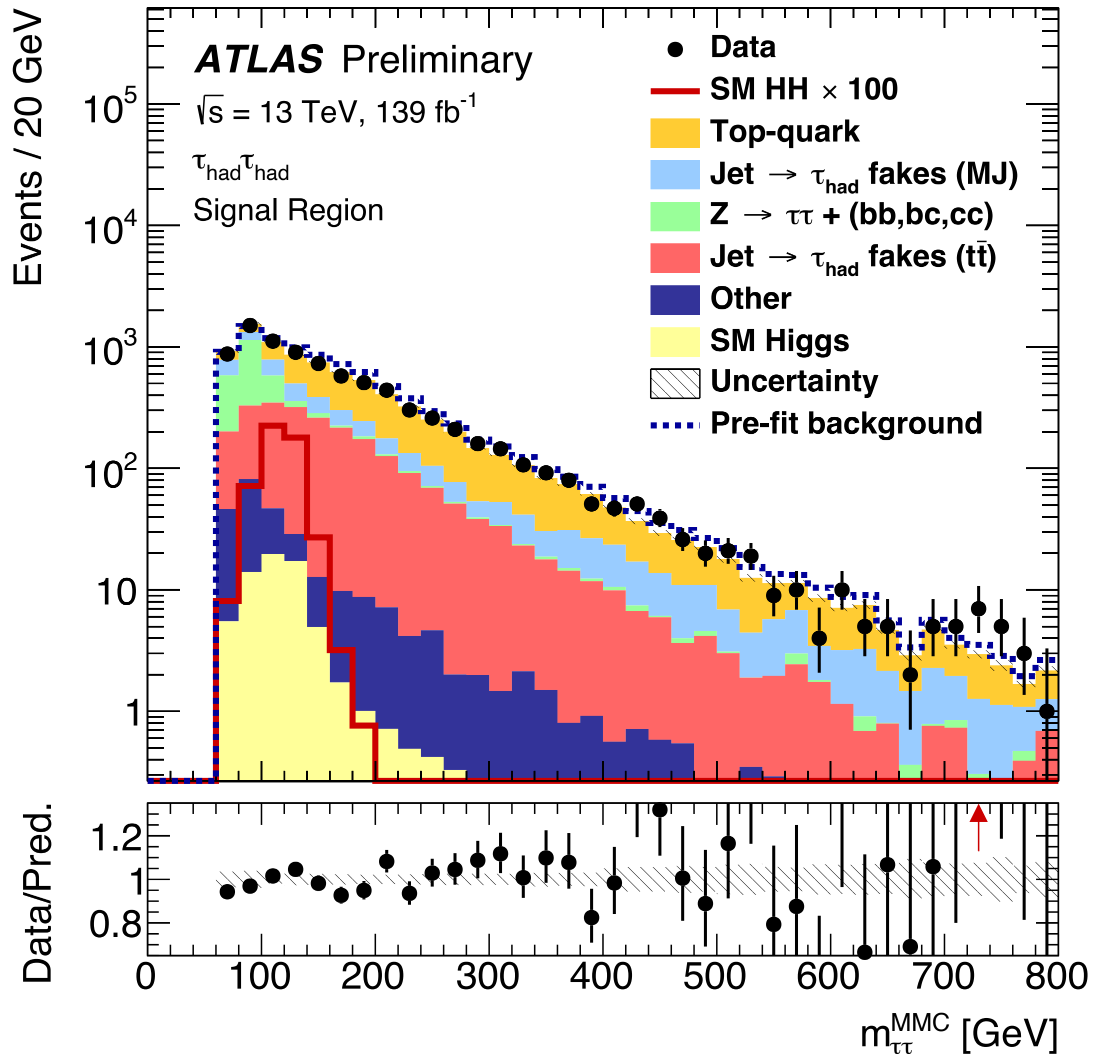


Top-quark background from MC, normalization floating in final fit

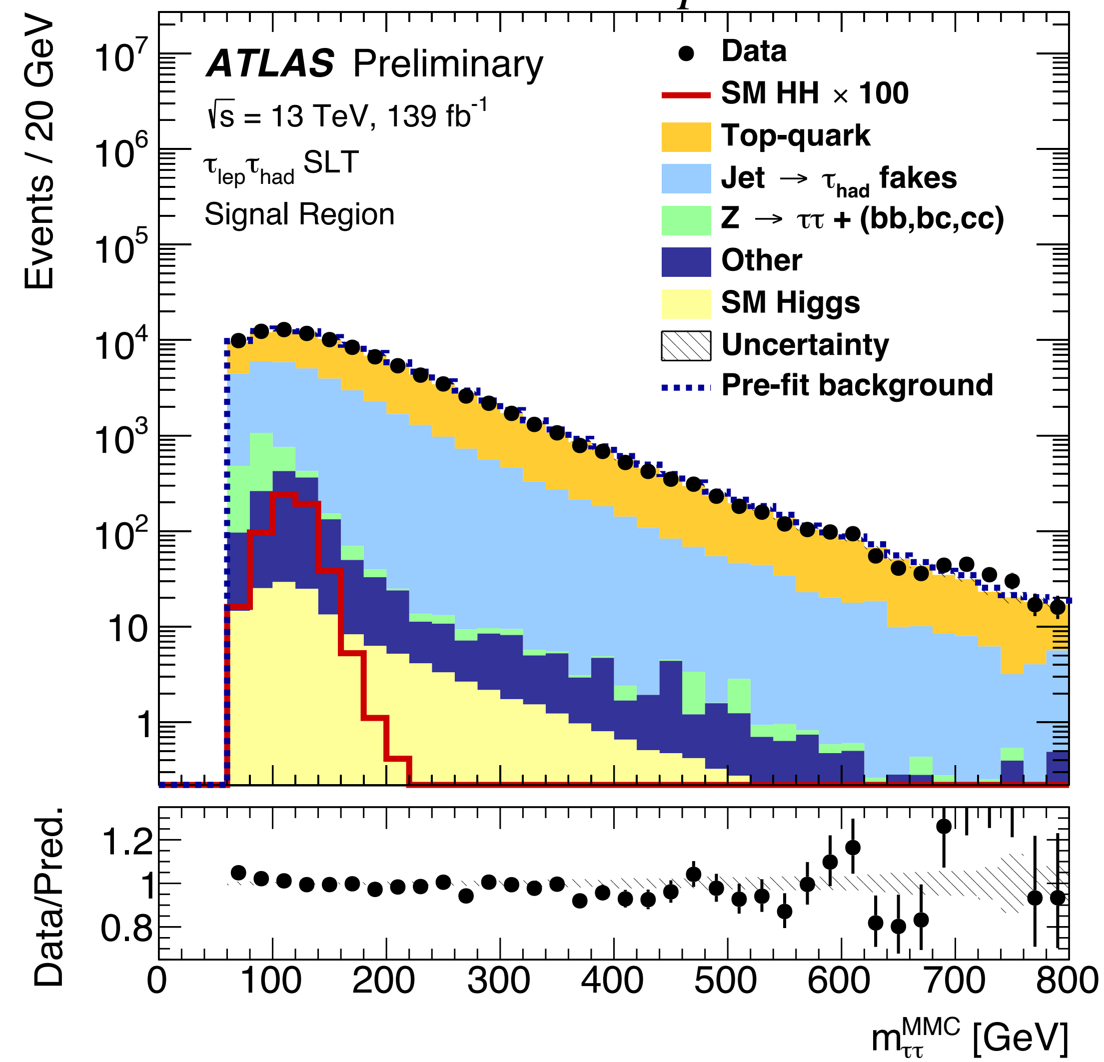
Z+jets background from MC, normalization from leptonic CR

$b\bar{b}\tau\bar{\tau}$ Background Estimate

$\tau_{had}\tau_{had}$



$\tau_{had}\tau_{lep}$



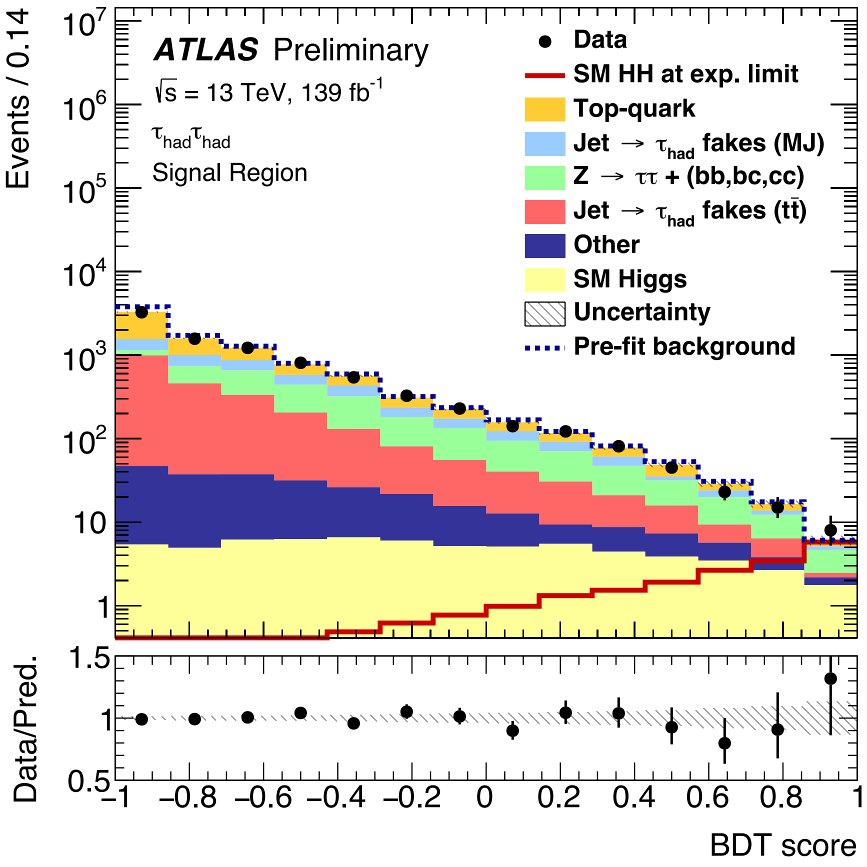
Top-quark background from MC, normalization floating in final fit

Z+jets background from MC, normalization from leptonic CR

Fake τ estimated from data using "fake factor" method

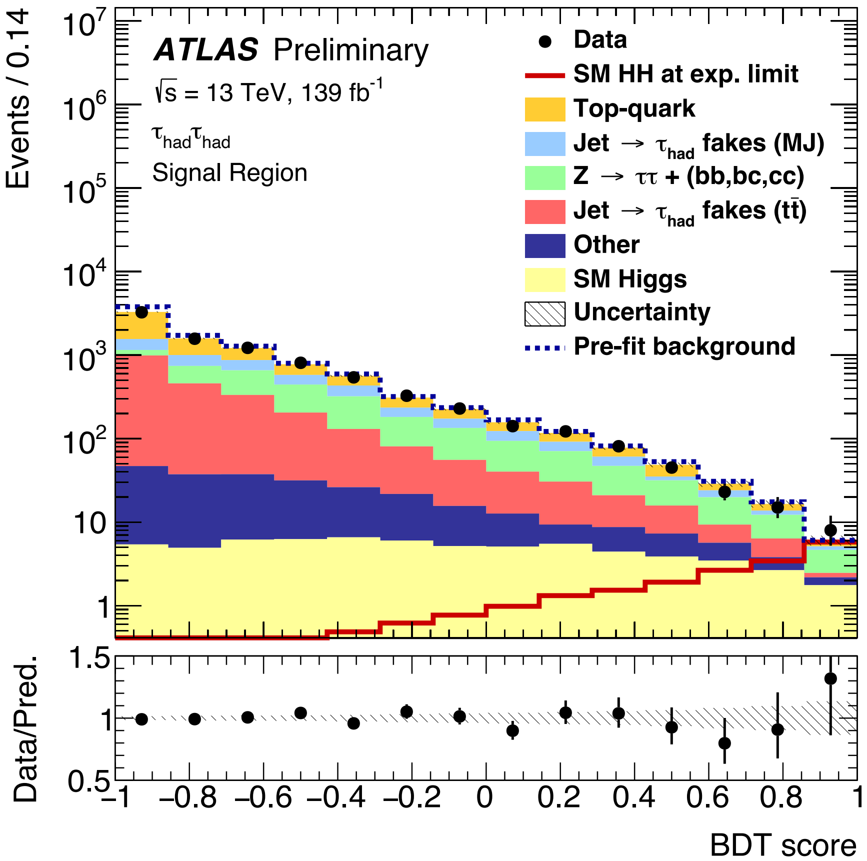
$b\bar{b}\tau\bar{\tau}$ Strategy and Results

$b\bar{b}\tau\bar{\tau}$ Strategy and Results

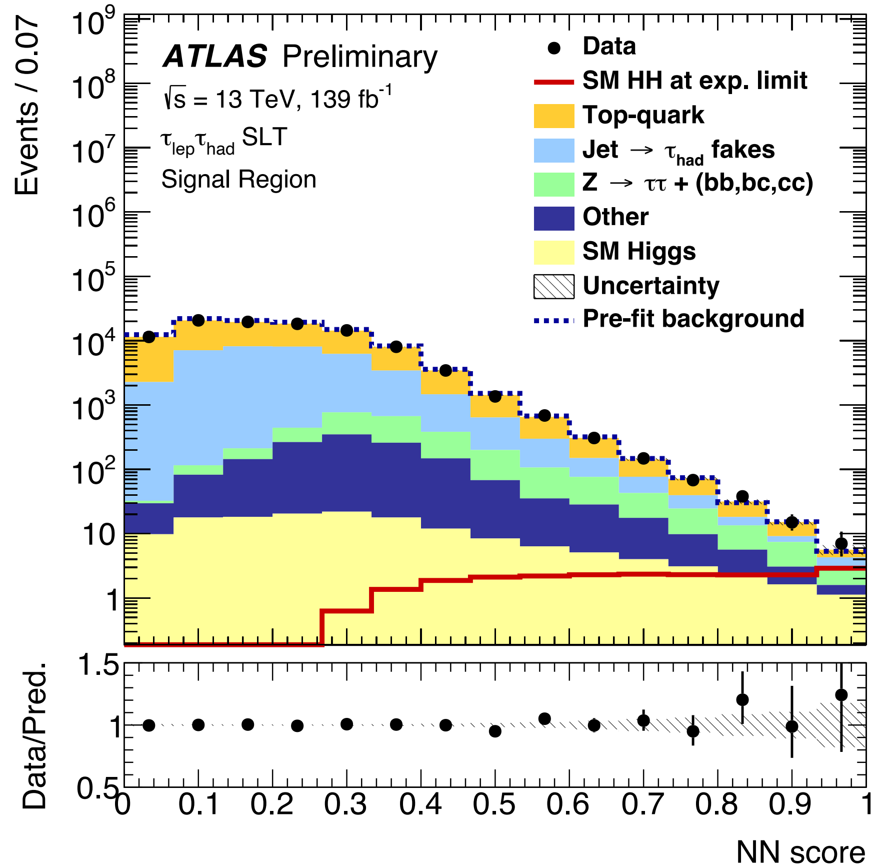


$\tau_{had}\tau_{had}$ BDT

$b\bar{b}\tau\bar{\tau}$ Strategy and Results

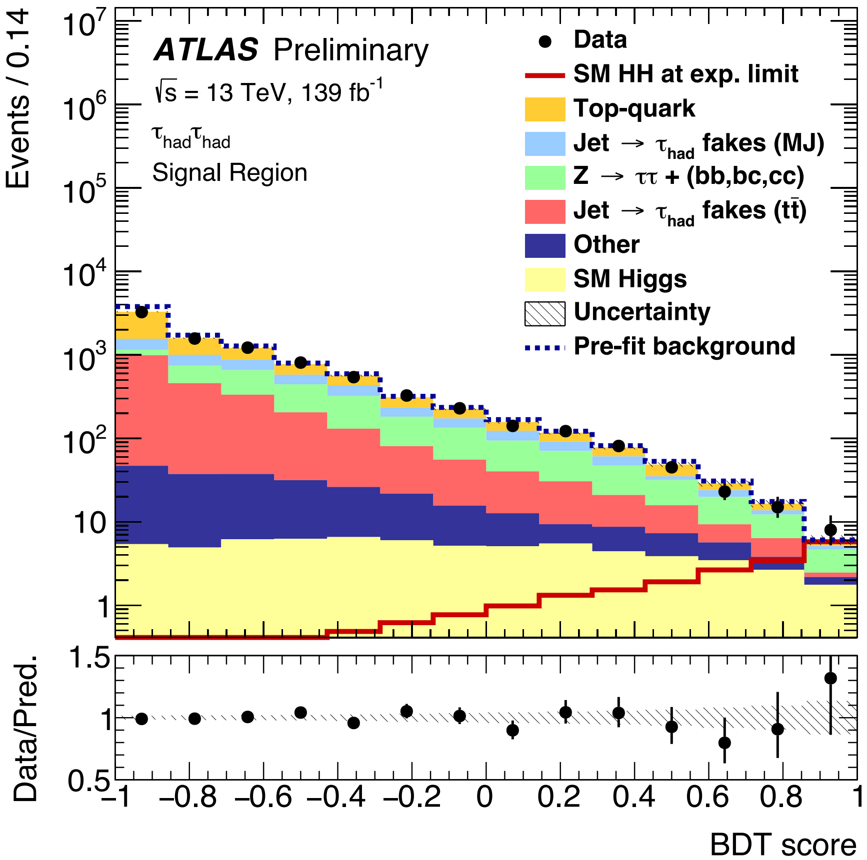


$\tau_{had}\tau_{had}$ BDT

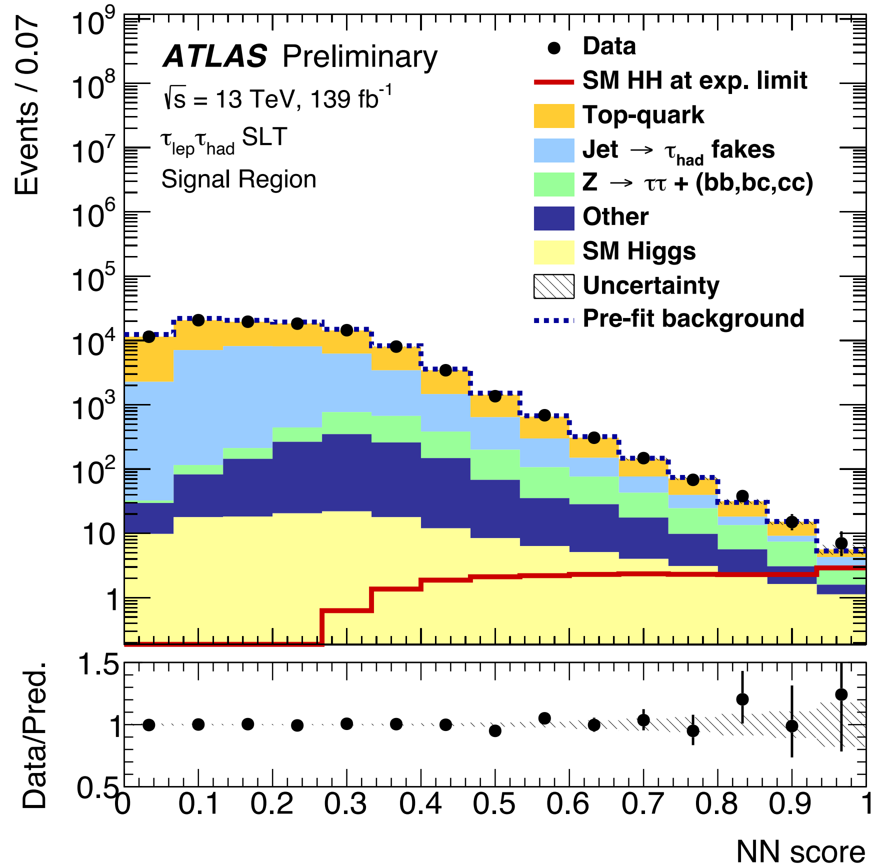


$\tau_{had}\tau_{lep}$ 1-Lepton Trigger
Neural Network

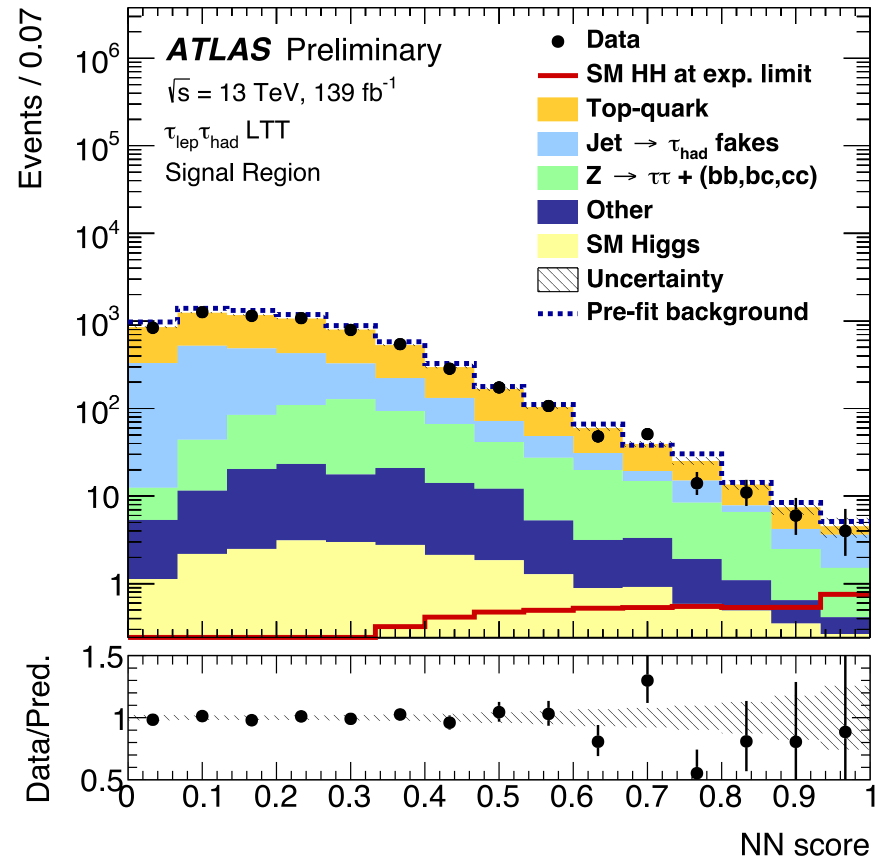
$b\bar{b}\tau\bar{\tau}$ Strategy and Results



$\tau_{had}\tau_{had}$ BDT

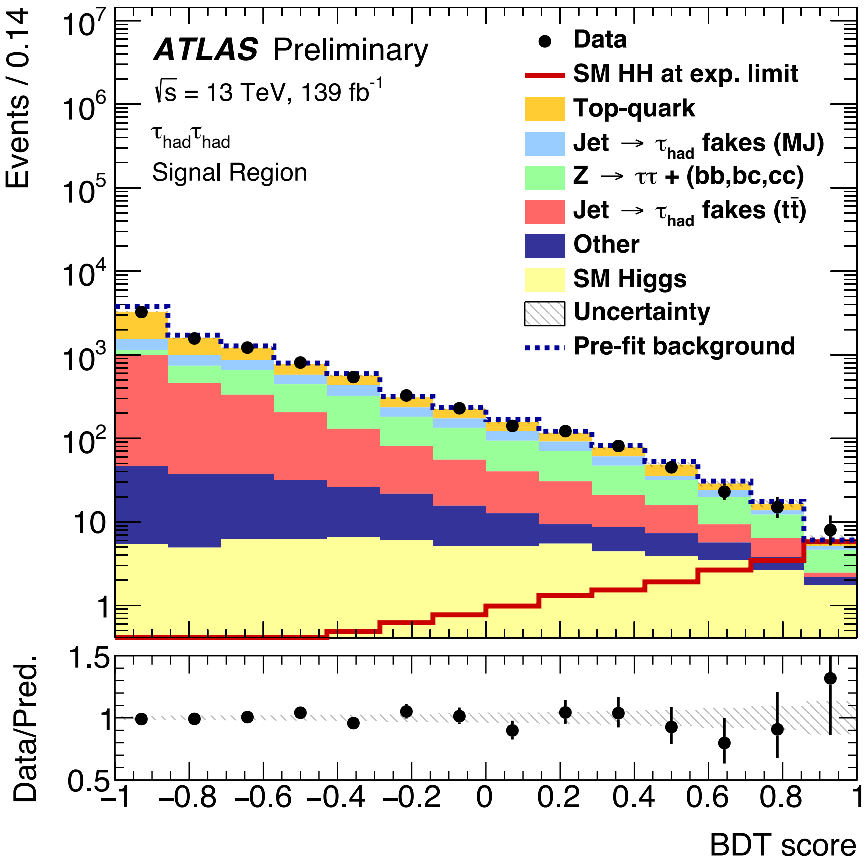


$\tau_{had}\tau_{lep}$ 1-Lepton Trigger Neural Network

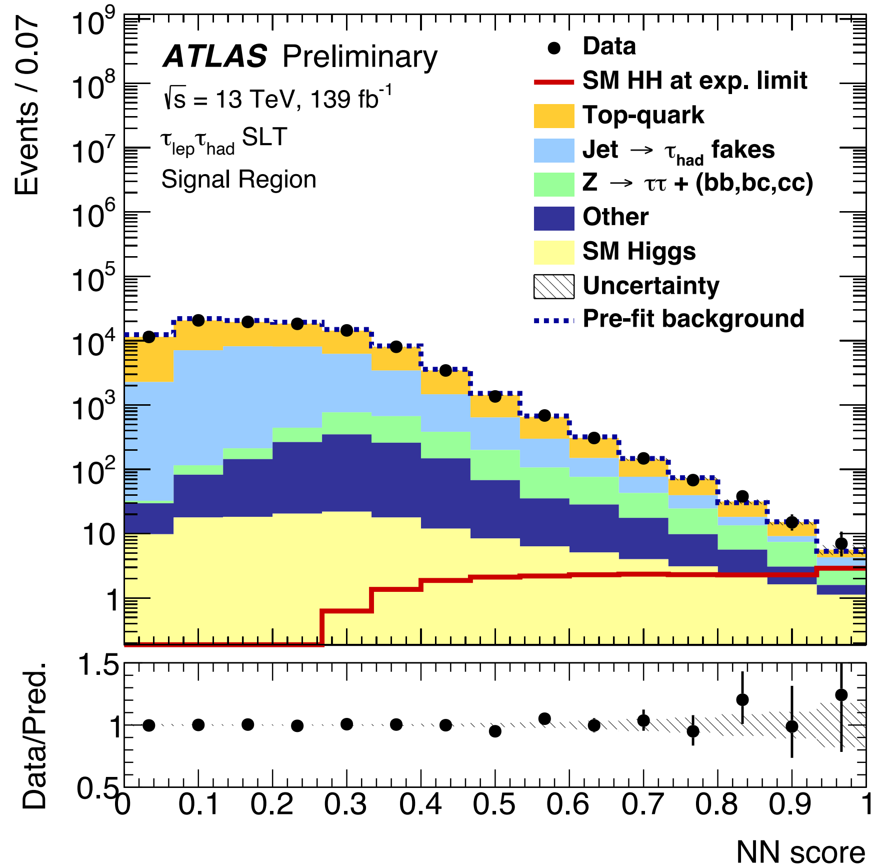


$\tau_{had}\tau_{lep}$ Lepton+Tau Neural Network

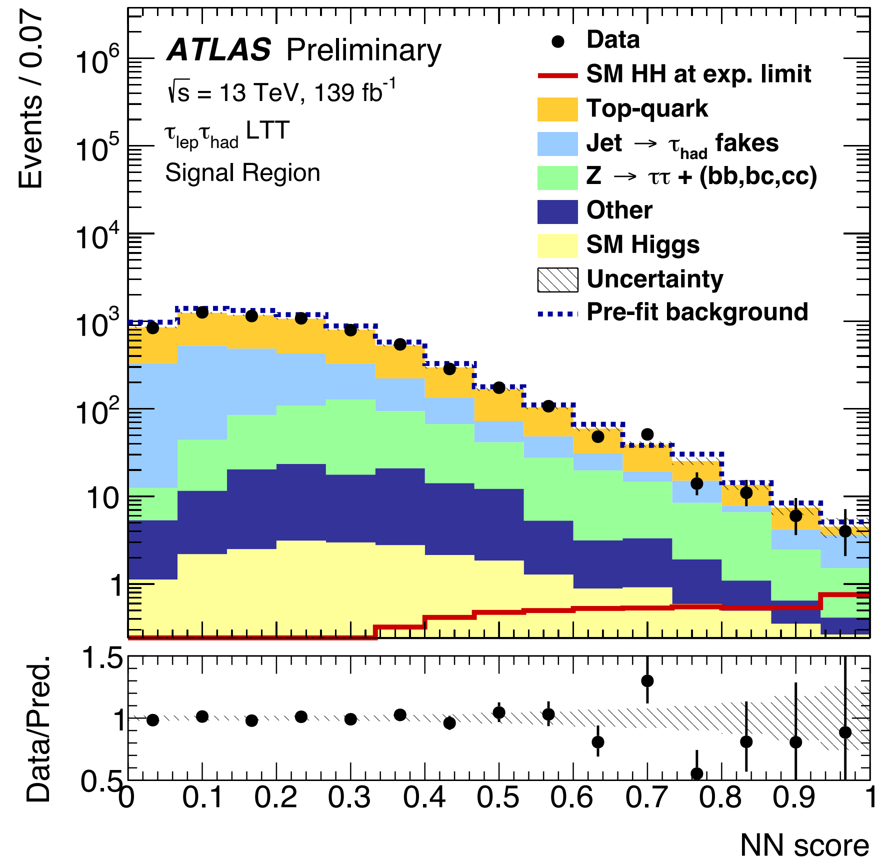
$b\bar{b}\tau\bar{\tau}$ Strategy and Results



$\tau_{had}\tau_{had}$ BDT



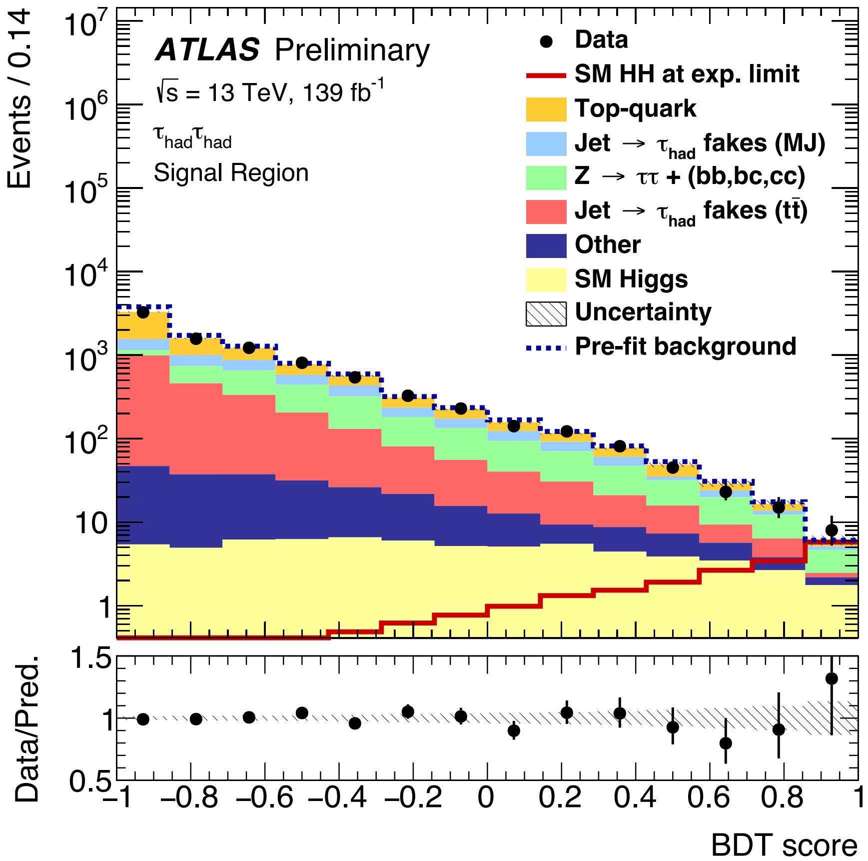
$\tau_{had}\tau_{lep}$ 1-Lepton Trigger Neural Network



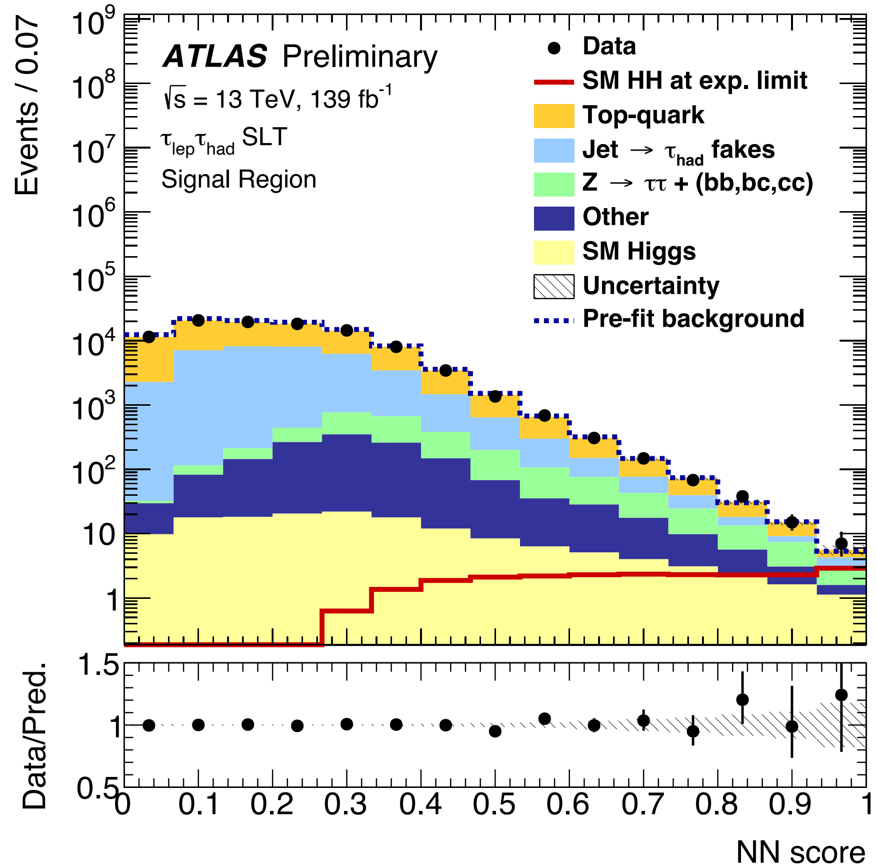
$\tau_{had}\tau_{lep}$ Lepton+Tau Neural Network

Fits to BDT/NN shape used for final analysis

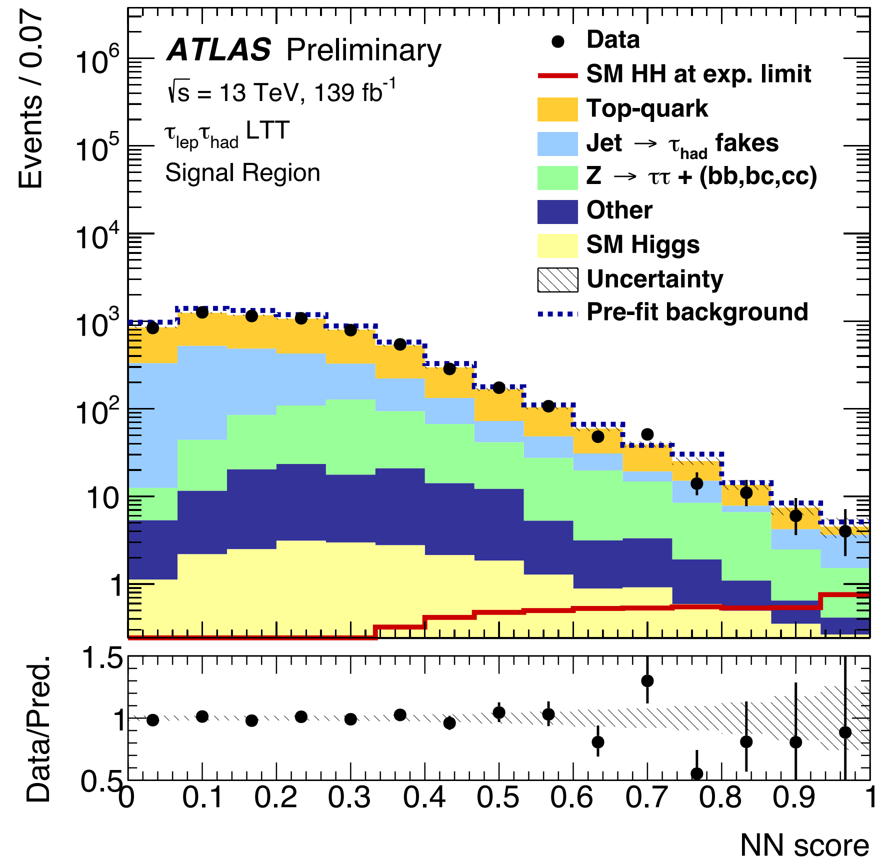
$b\bar{b}\tau\bar{\tau}$ Strategy and Results



$\tau_{had}\tau_{had}$ BDT



$\tau_{had}\tau_{lep}$ 1-Lepton Trigger Neural Network

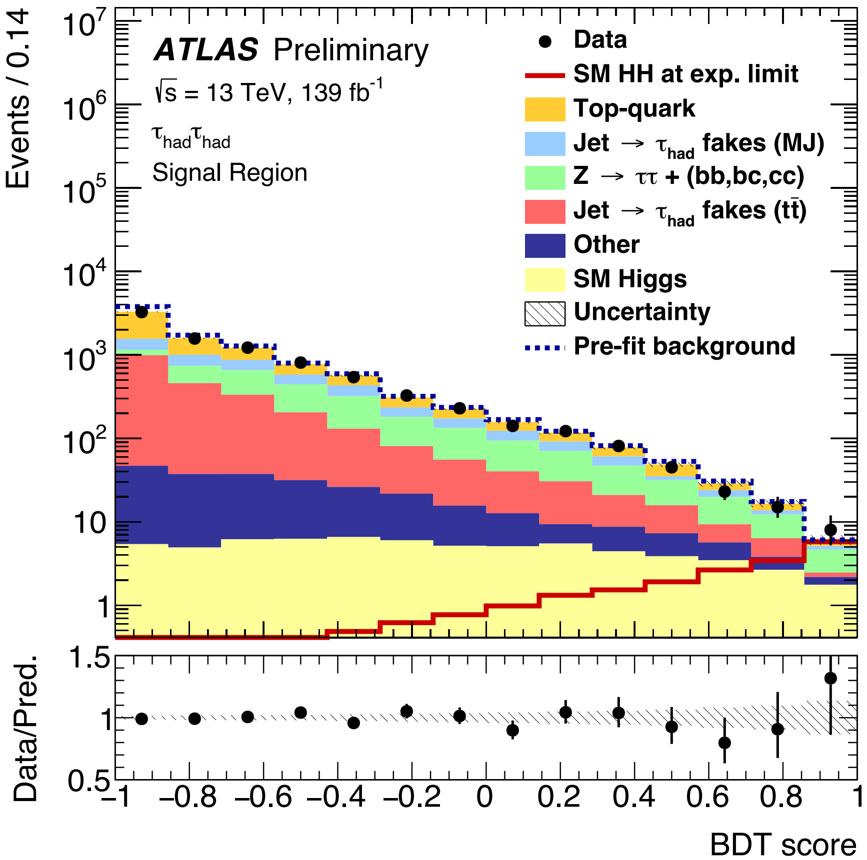


$\tau_{had}\tau_{lep}$ Lepton+Tau Neural Network

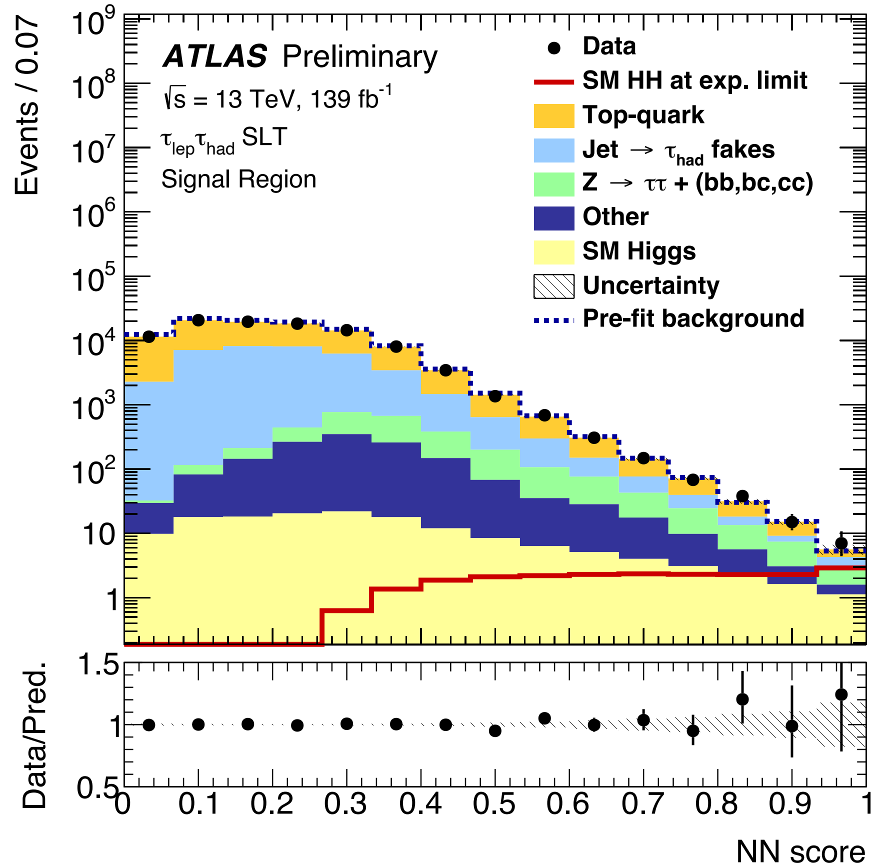
Fits to BDT/NN shape used for final analysis

Data agrees well with background prediction

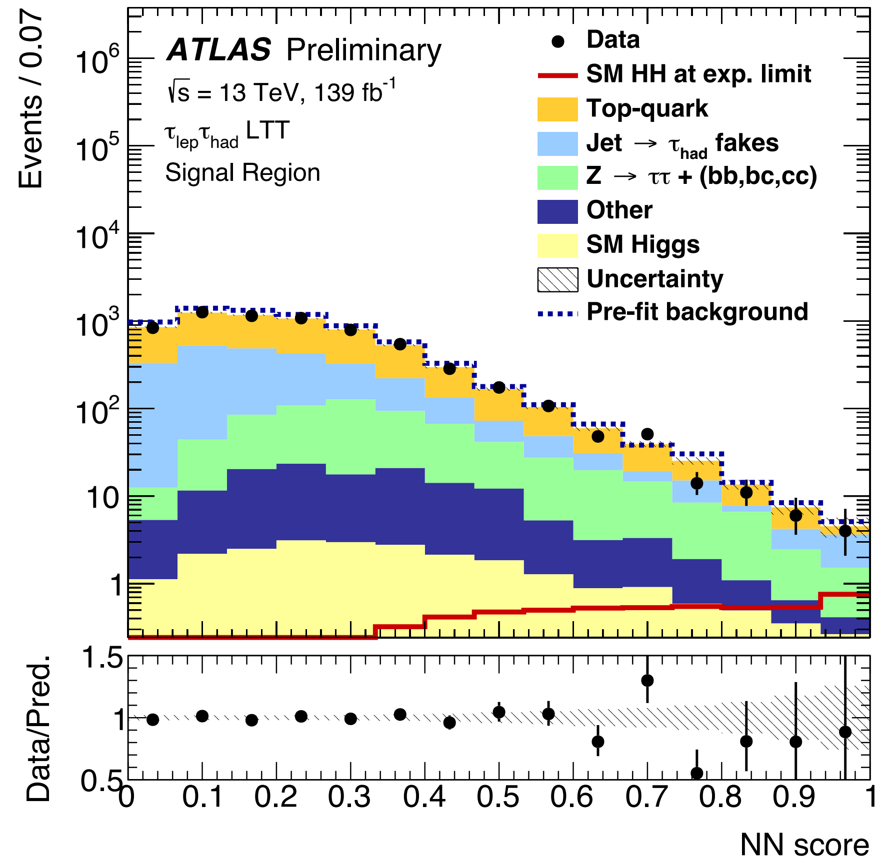
$b\bar{b}\tau\bar{\tau}$ Strategy and Results



$\tau_{had}\tau_{had}$ BDT



$\tau_{had}\tau_{lep}$ 1-Lepton Trigger Neural Network



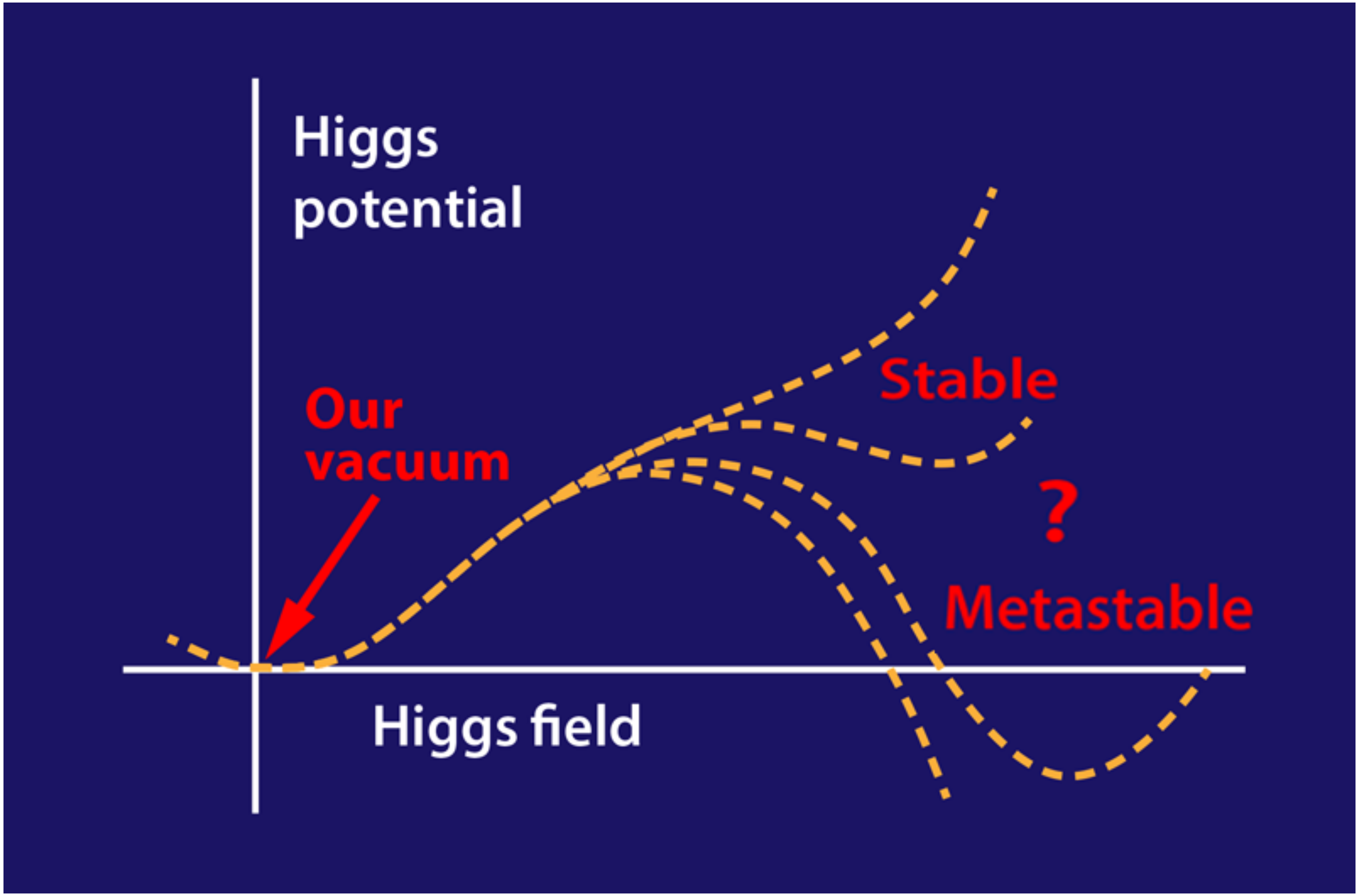
$\tau_{had}\tau_{lep}$ Lepton+Tau Neural Network

Fits to BDT/NN shape used for final analysis

Data agrees well with background prediction

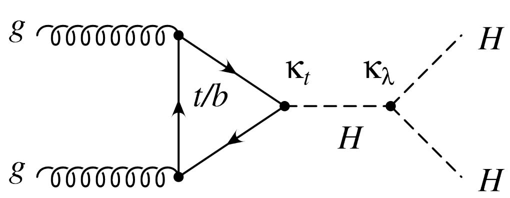
$\tau_{had}\tau_{had}$ has strongest sensitivity, but other channels also contribute

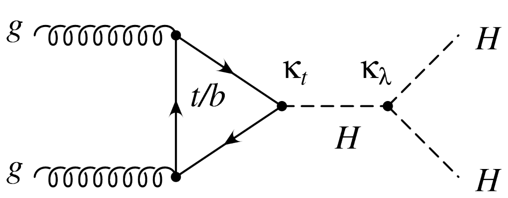
Universe Stability

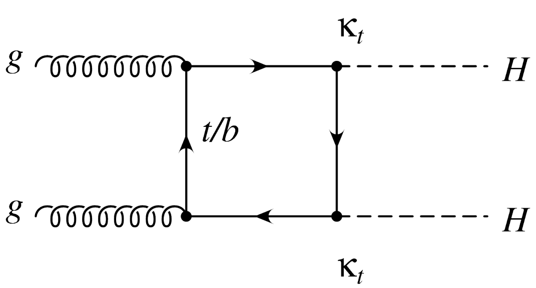


A. Kusenko

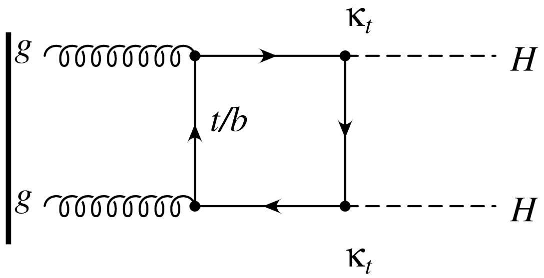
Interference

$\sigma \propto \Big|$ 

$\Big|^2 - ($ 



$+ h.c.)$

$+ \Big|$ 

$\Big|^2$