Higgs Self-Coupling Measurements

SM@LHC@FNAL

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On behalf of ATLAS
TRIUMF

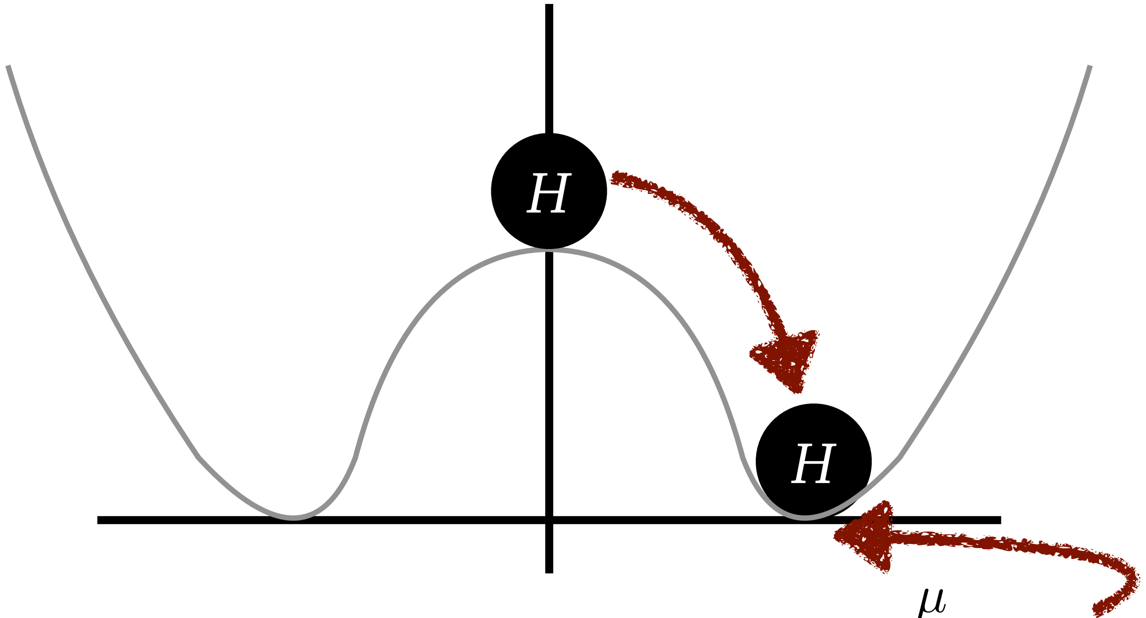
(Organizational Note)

- First, my apologies
- This talk was intended to also include CMS results, but due to organizational complications the speaker invitation went out extremely late
- I was not able to include the excellent CMS results on this topic (or attend the conference): my apologies
- Please check these great results at your leisure!
  - Thankfully, Daniel provided a great overview already yesterday!
    - Especially check out the great boosted 4b result he highlights
  - See also Ana's talk on EFT's: many relevant results in that talk
- And many thanks to Pier Paolo for the introduction!

The Higgs Potential

The *SM* Higgs potential is:

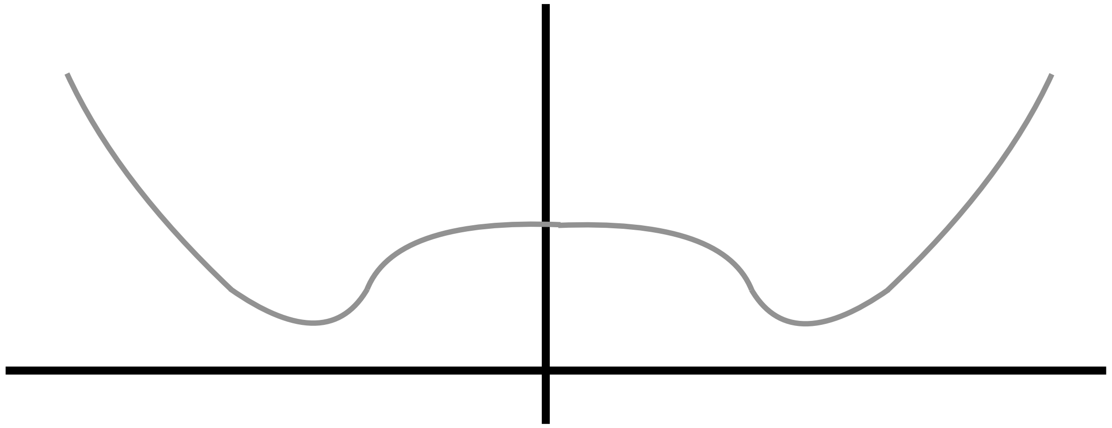
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



$$\frac{\mu}{\sqrt{\lambda}} = v = 246 \text{ GeV}$$

The field "rolls" into a lower energy state, the initial symmetry is broken, the field acquires a non-zero vacuum expectation value

But many other shapes could have caused the same physics



We have no knowledge of the actual shape: just some of its properties

Why does this matter?

Why Measure the Potential?

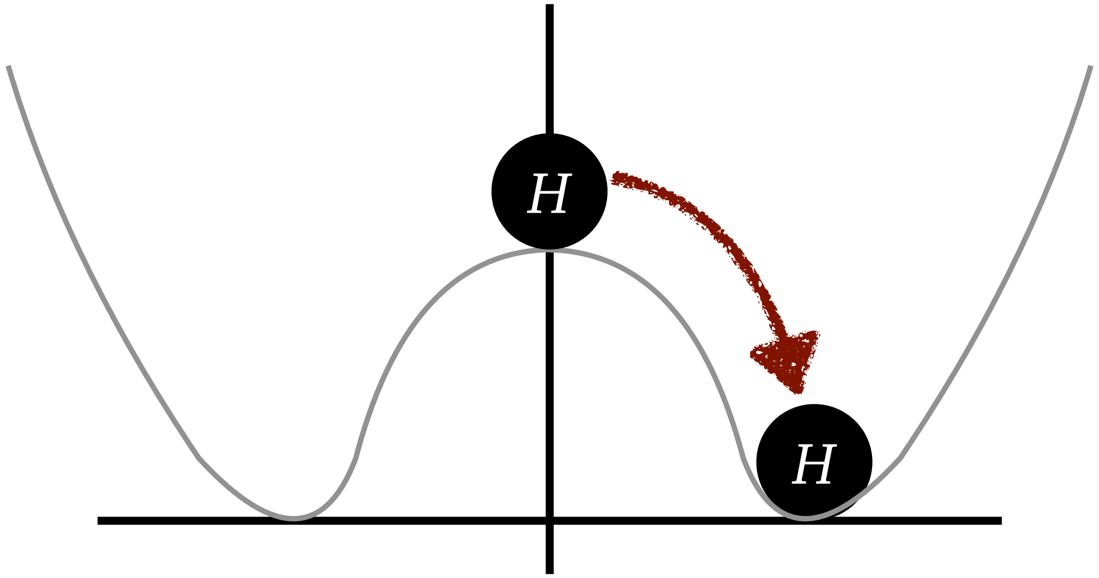
Many models alter the Higgs potential

Models of "electroweak baryogenesis" have the Higgs potential undergo a phase transition, which could explain matter-antimatter asymmetry

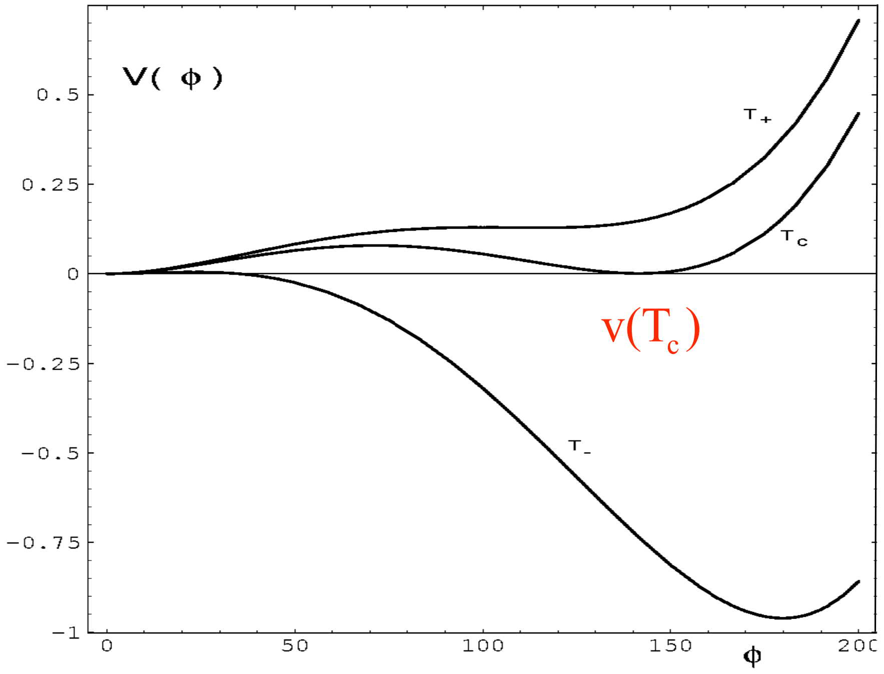
This phase transition requires modifications to the SM potential!

And generically: it's hard to alter only the potential, and not change any other Higgs couplings!

If we can measure the shape of the potential, we can find hints of fundamental, critical new physics!



C.Wagner



How to Measure the Potential

The SM Higgs potential is:

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

$$\frac{\mu}{\sqrt{\lambda}} = v = 246 \text{ GeV}$$

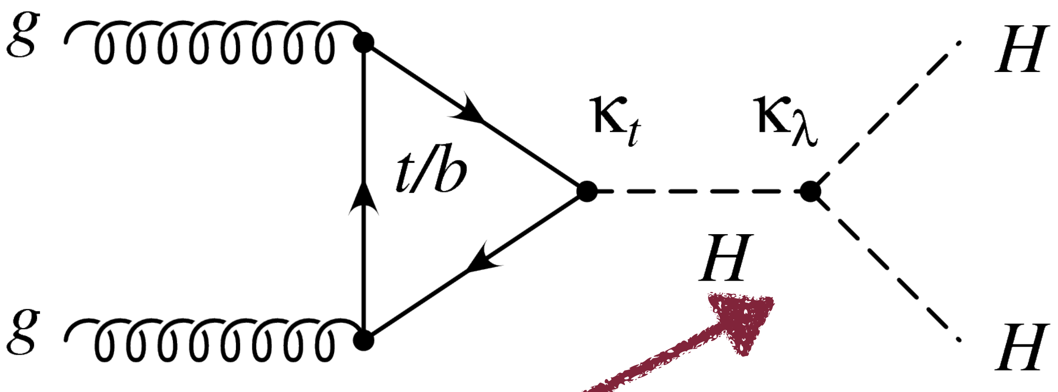
Expand around the minimum, get:

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \ldots$$

$$= V_0 + \frac{1}{2}m_H^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \ldots$$

This is the mass: well measured

This term is the Higgs self-coupling



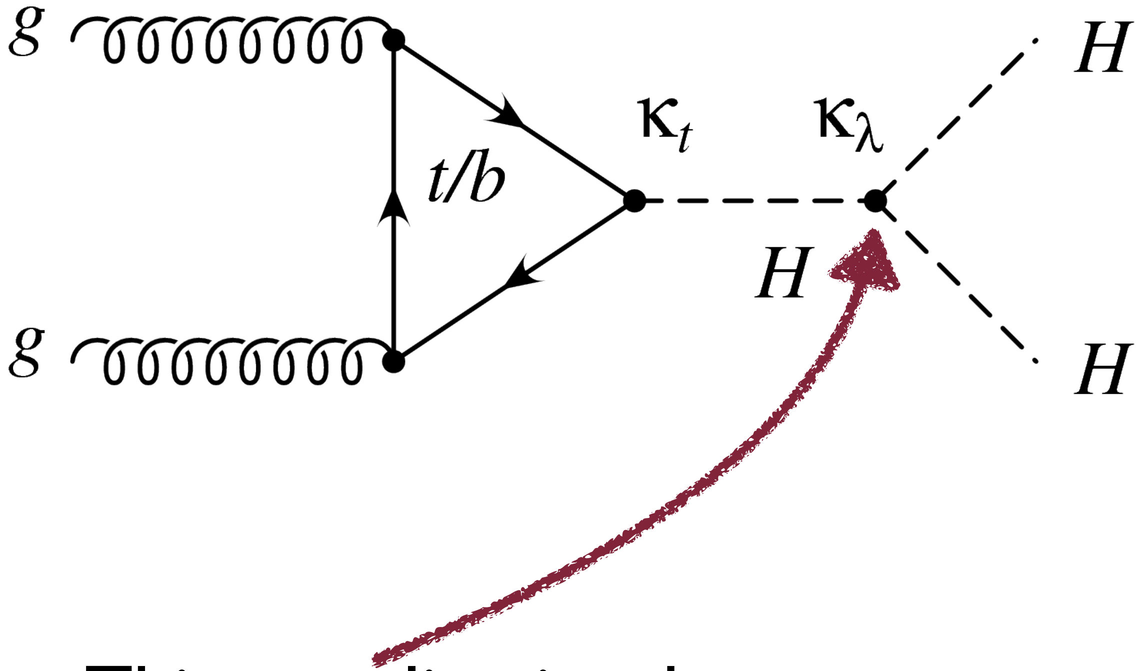
The SM predicts di-Higgs production

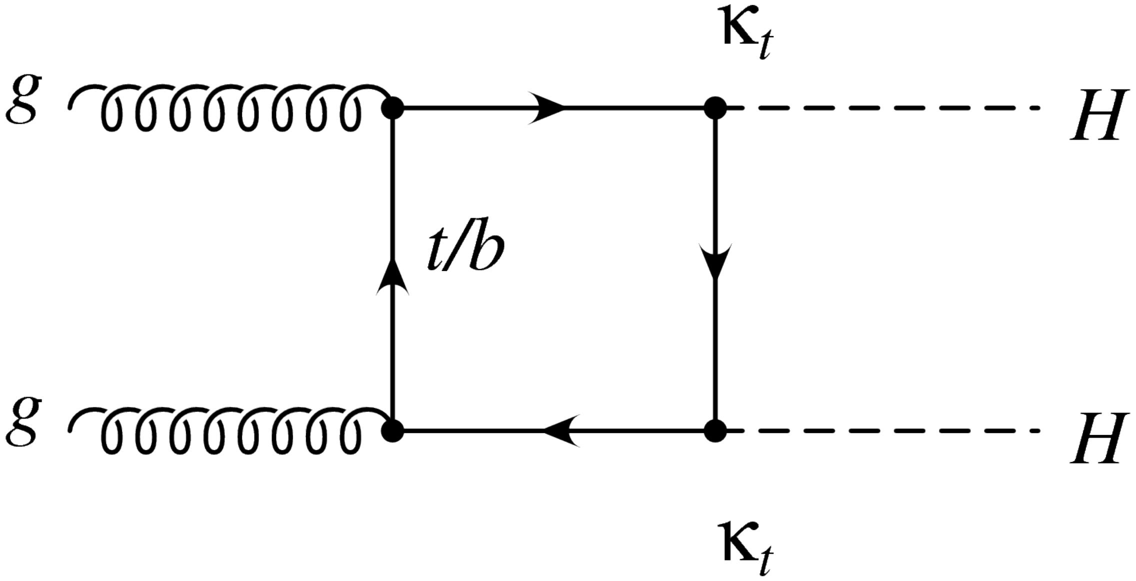
$$\lambda_{HHH}^{SM} = \frac{m_h^2}{2v^2}$$

This higher-order term tells us more about the shape of the potential!

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

Self-Coupling with Di-Higgs





This coupling is what we want to measure

This tells us about the shape of the Higgs potential

This process has the same final state, but κ_λ doesn't appear: no information about the Higgs potential

These two processes destructively interfere in the SM, leading to **very low cross section**

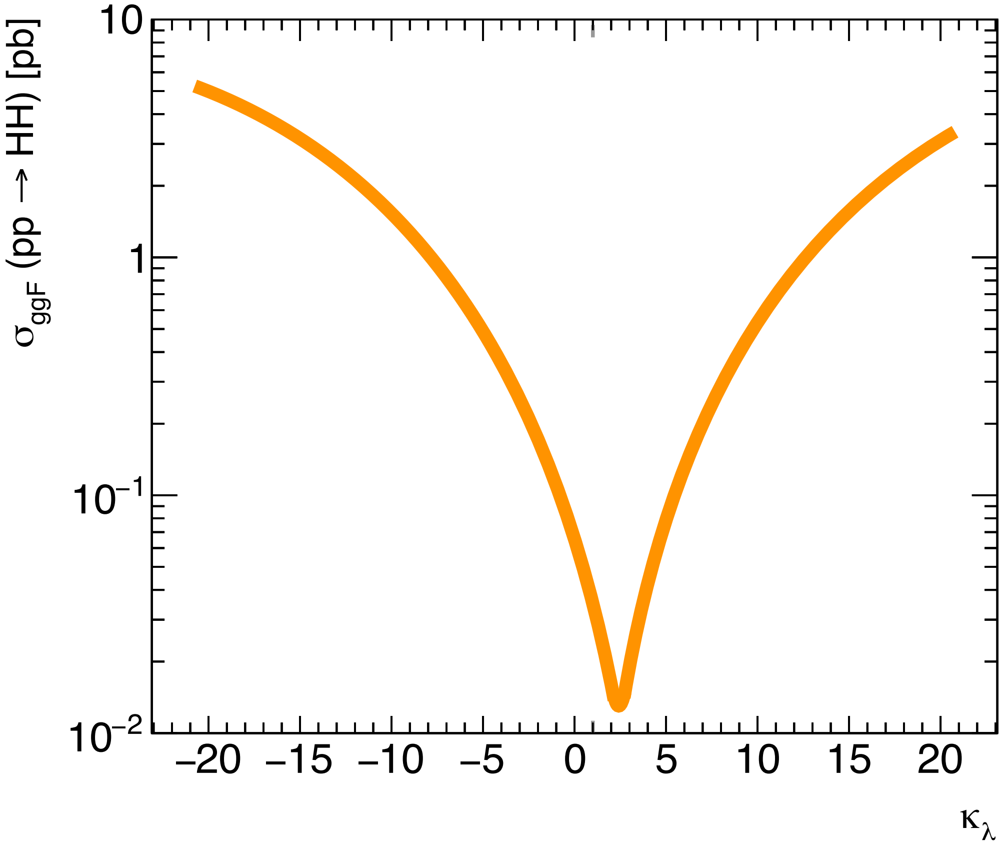
Also important: κ_λ always appears with κ_t: sensitivity can change if κ_t allowed to float

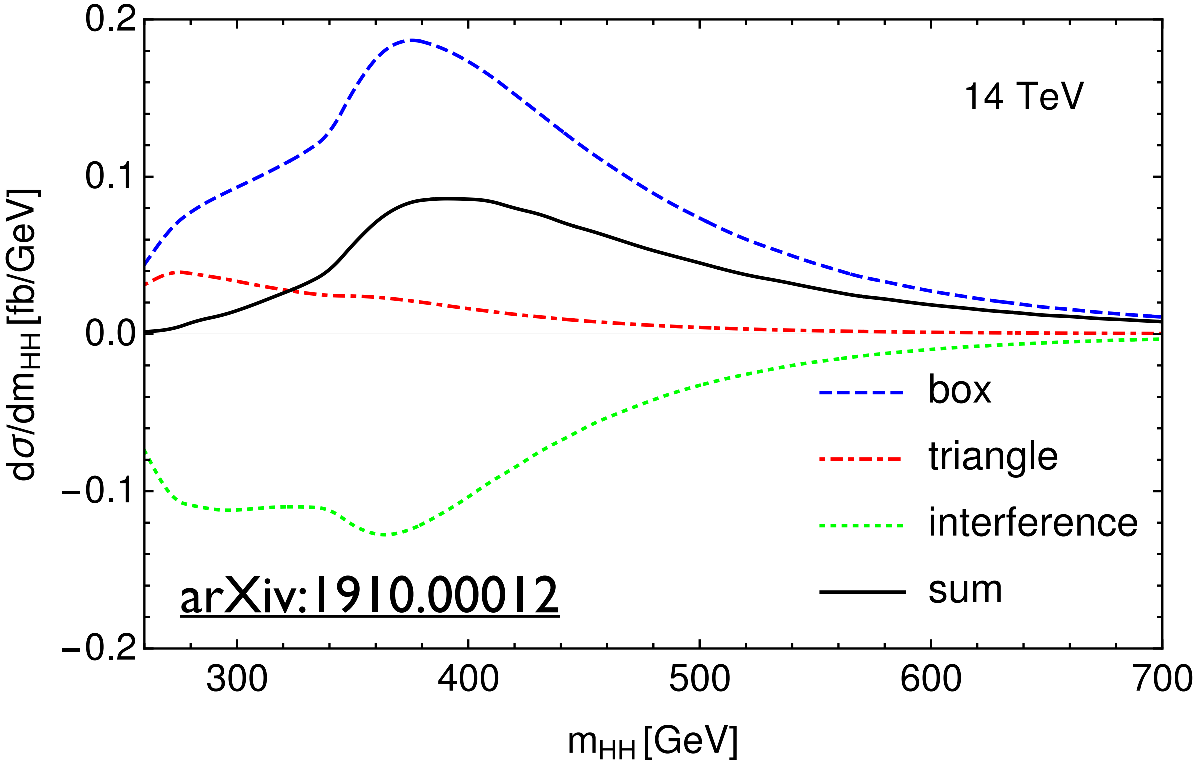
Measuring with Di-Higgs

If κ_λ isn't the SM value interference diminishes: larger cross section!

But while the cross section can increase, the **lowest m_{HH} component** is what is most enhanced

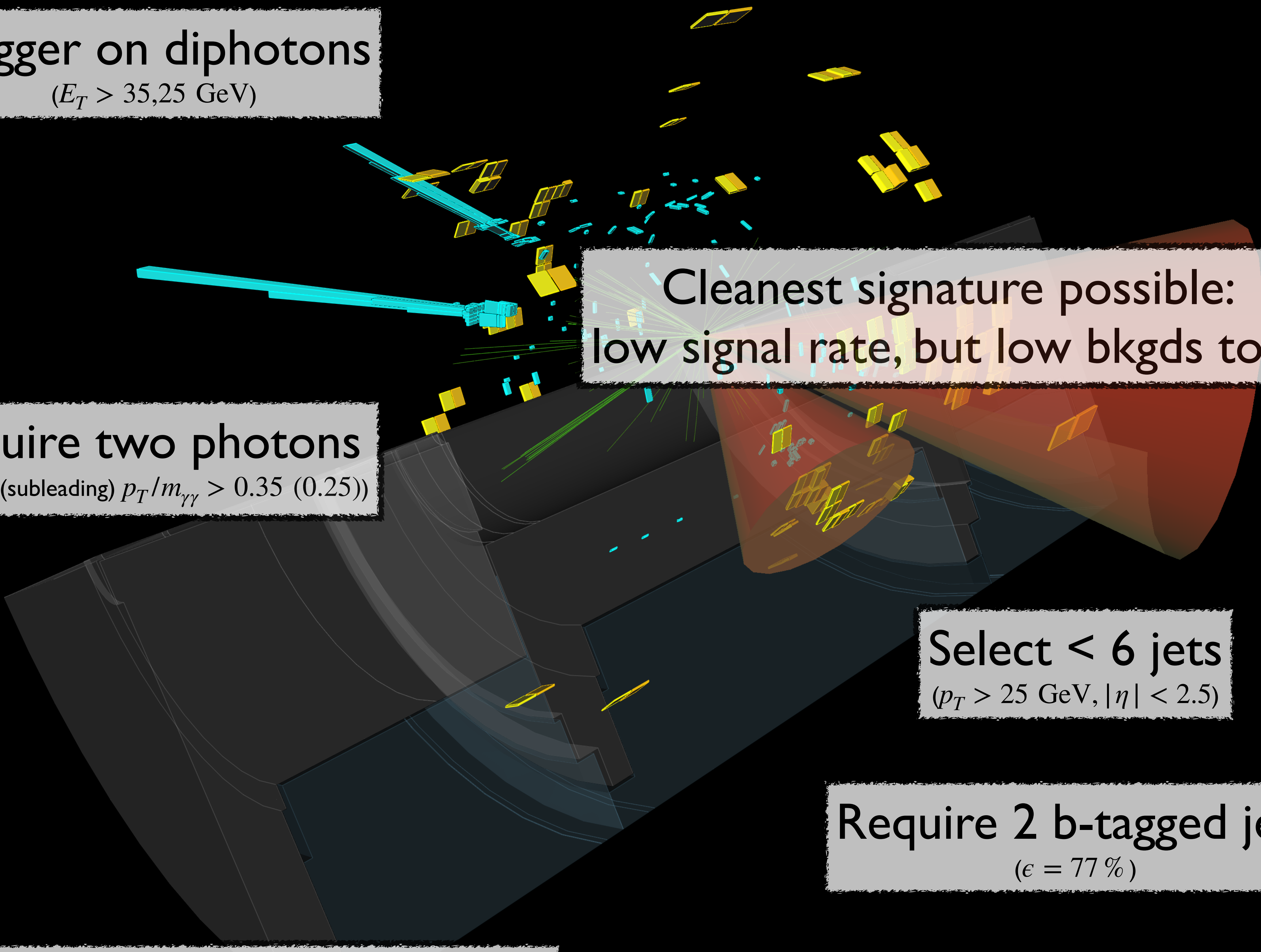
Measuring κ_λ is challenging: need both rate and shape information for best constraints





arXiv:1910.00012

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



Trigger on diphotons

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

Require two photons

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

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

Select < 6 jets

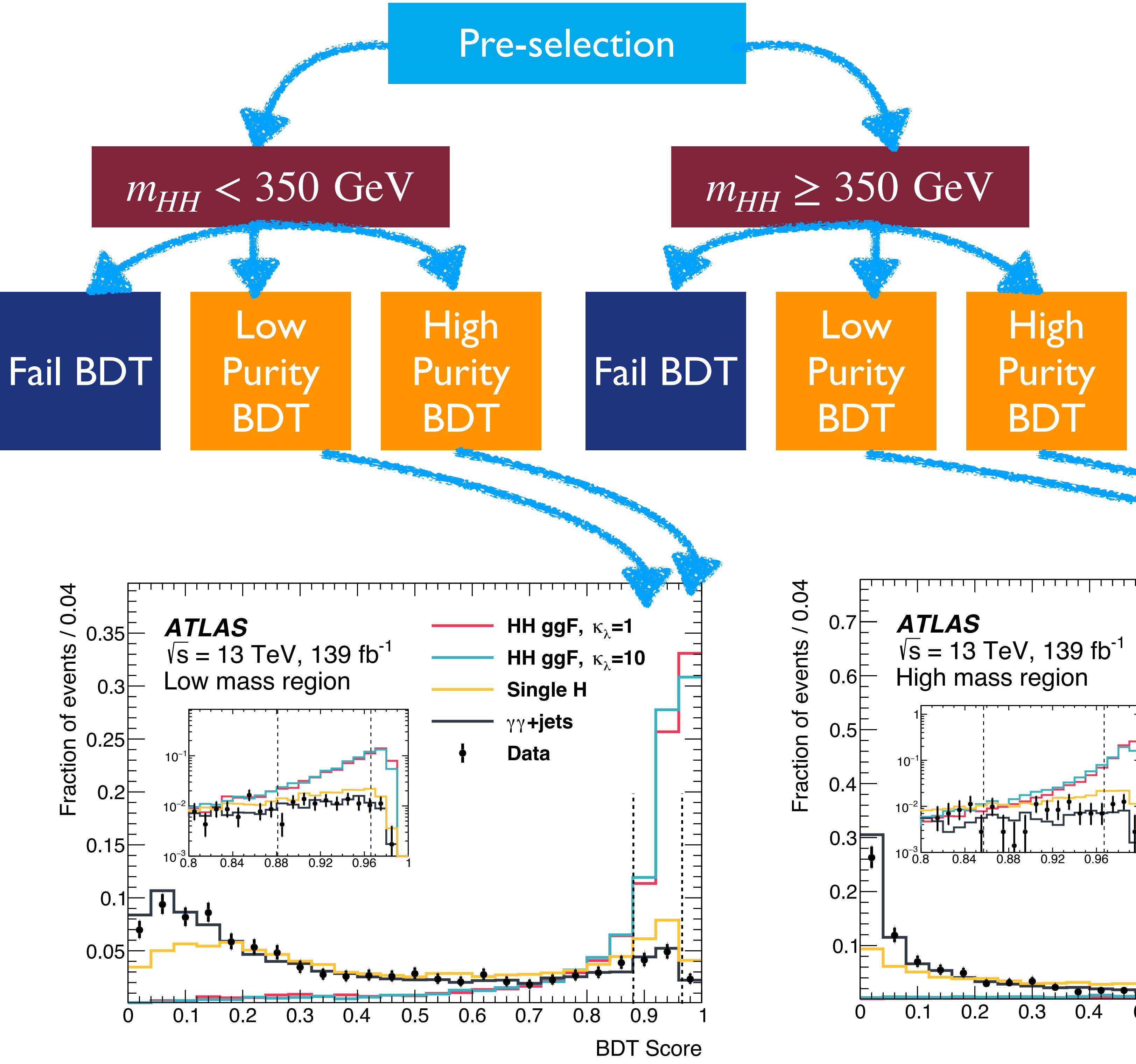
($p_T > 25$ GeV, $|\eta| < 2.5$)

Require 2 b-tagged jets

($\epsilon = 77\,\%$)

Phys. Rev. D 106 (2022) 052001

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



Pre-selection

$m_{HH} < 350$ GeV

$m_{HH} \geq 350$ GeV

Fail BDT

Low Purity BDT

High Purity BDT

Fail BDT

Low Purity BDT

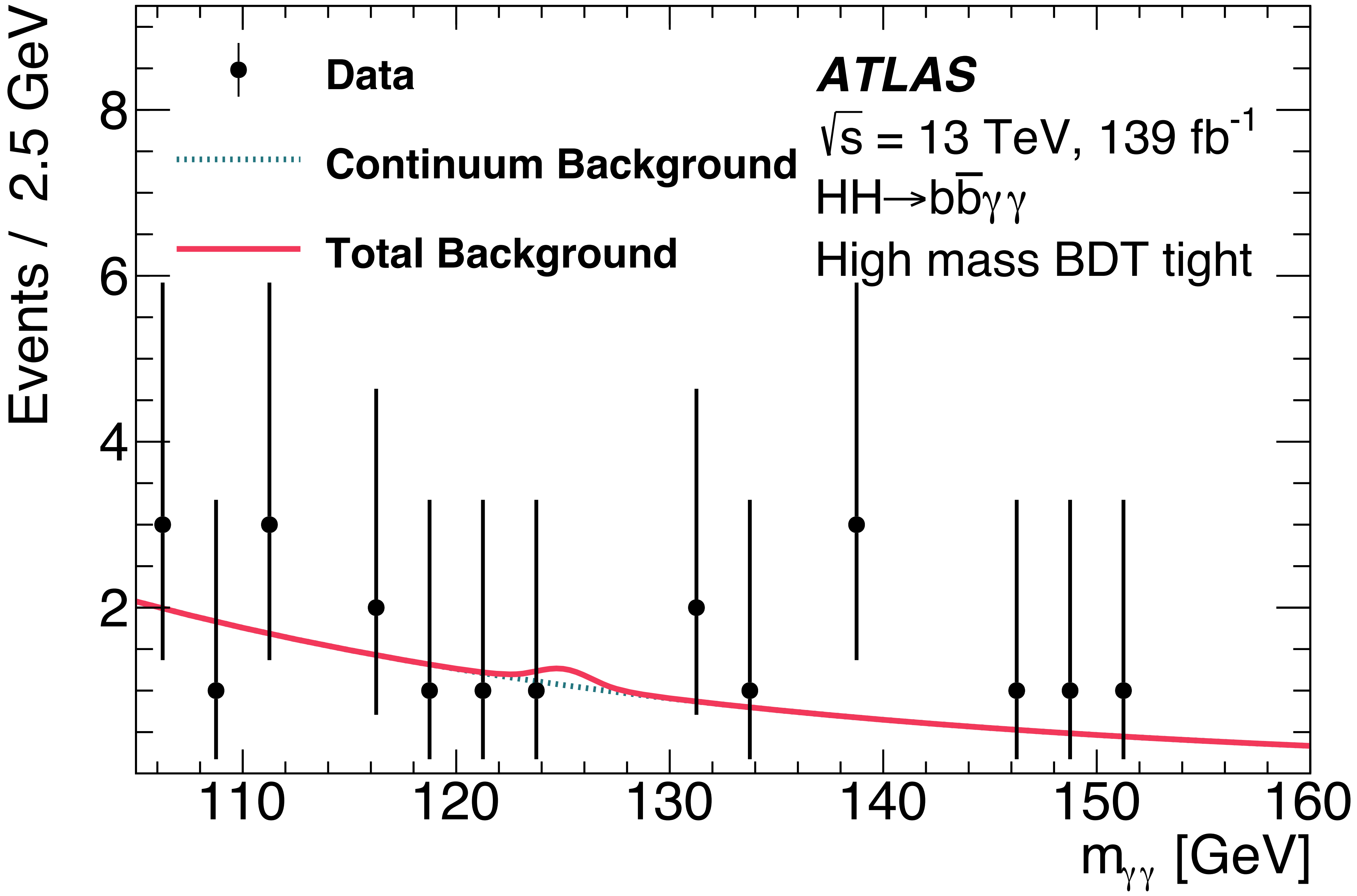
High Purity BDT

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

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

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

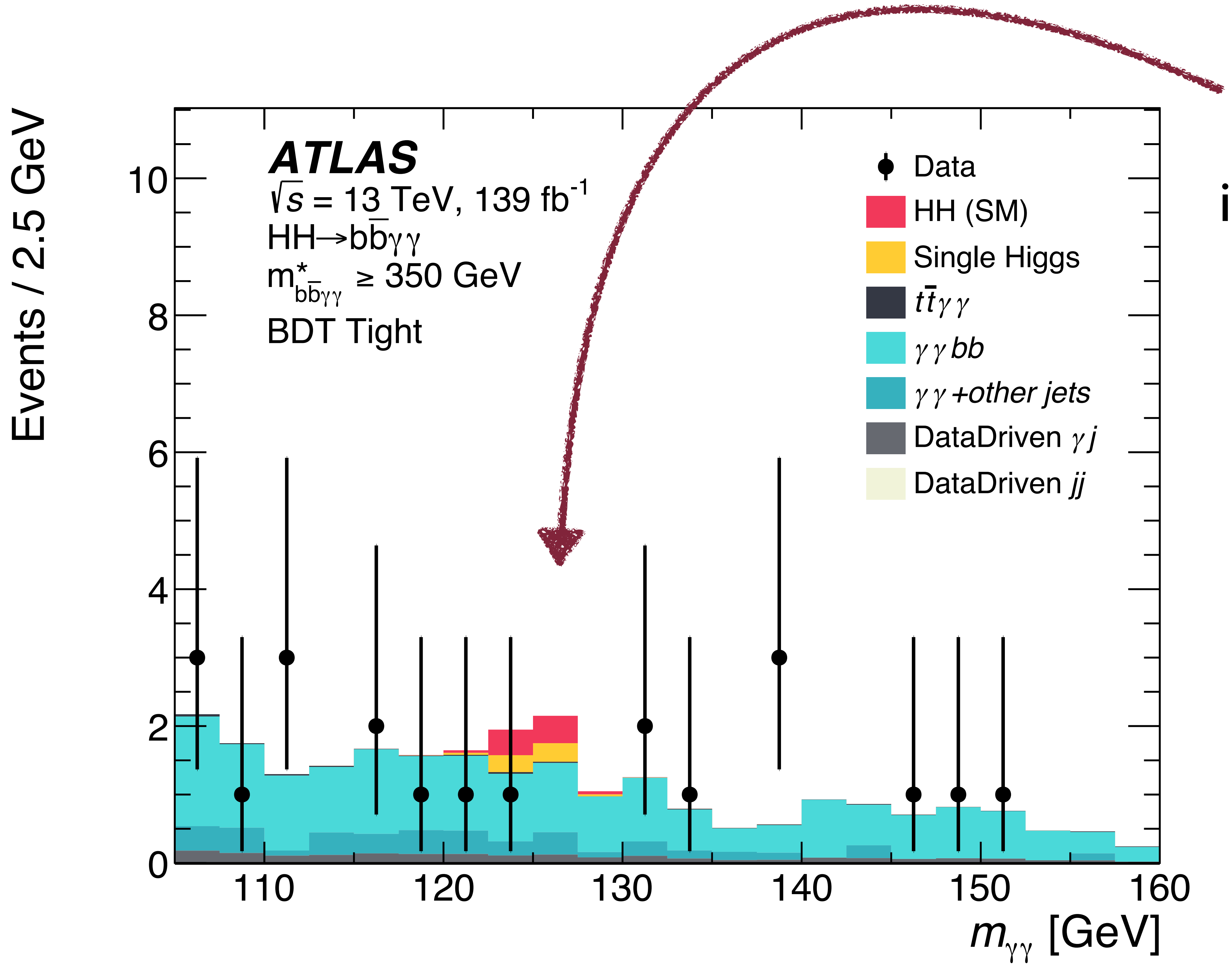
$b\bar{b}\gamma\gamma$ Background Estimate



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



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

No obvious signs
of new physics

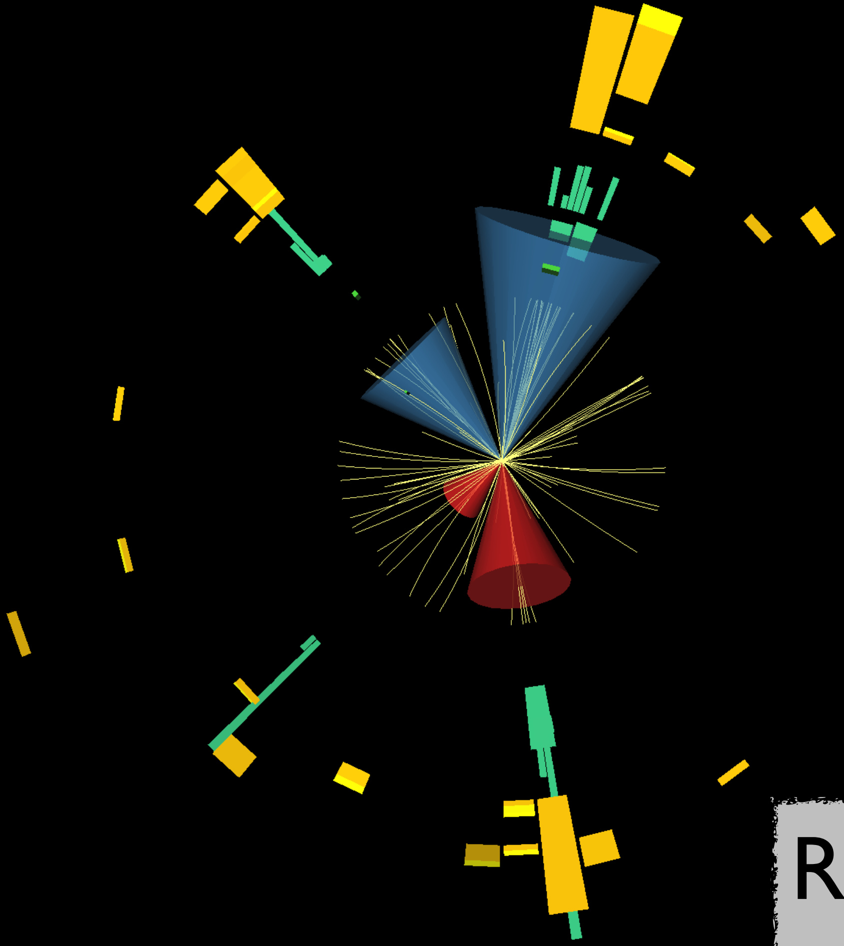
Similar results for
other signal
categories

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

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

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

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

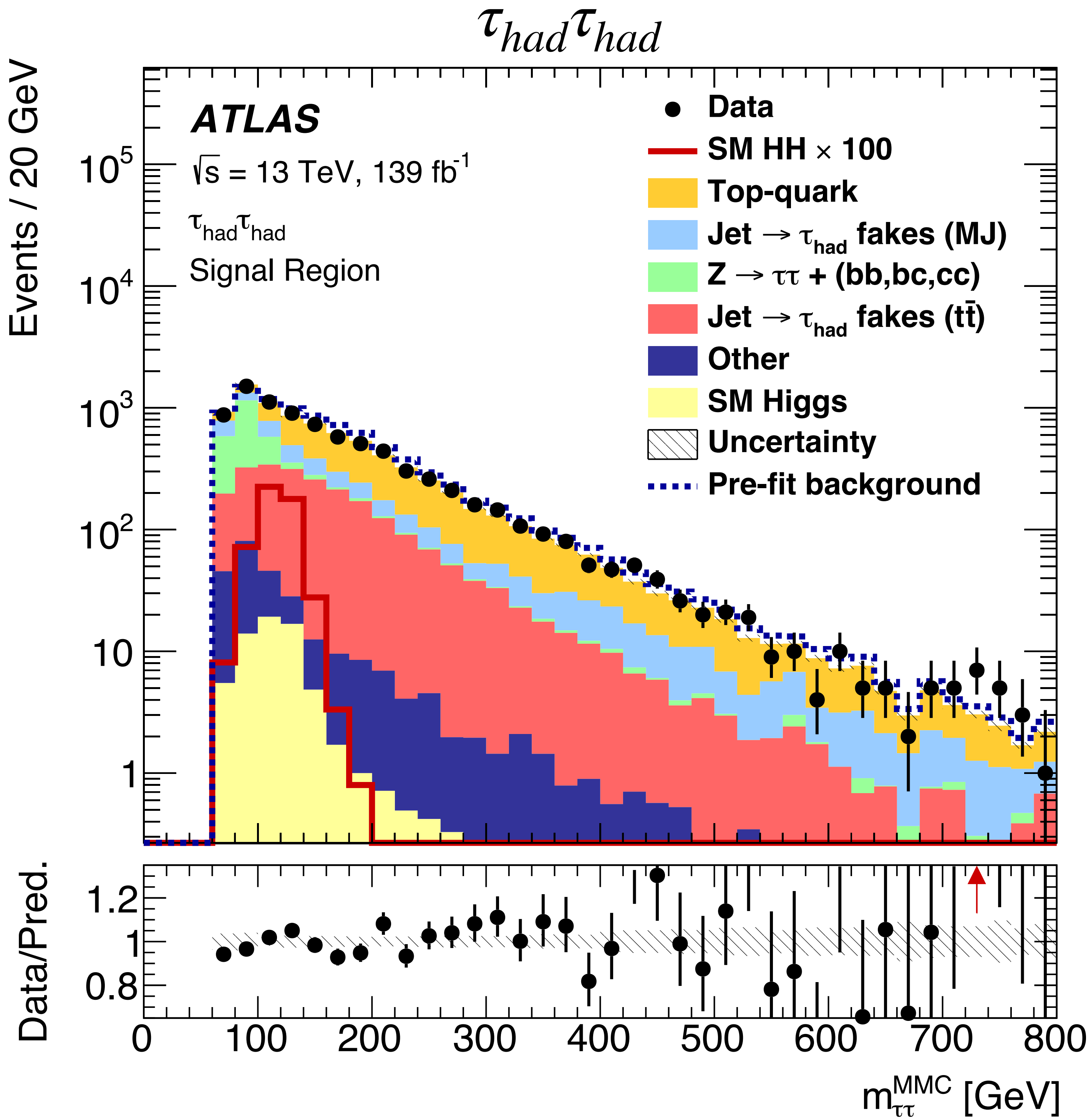


Balanced signature: τ_h allows for good bkgd suppression

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

JHEP 07 (2023) 040

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

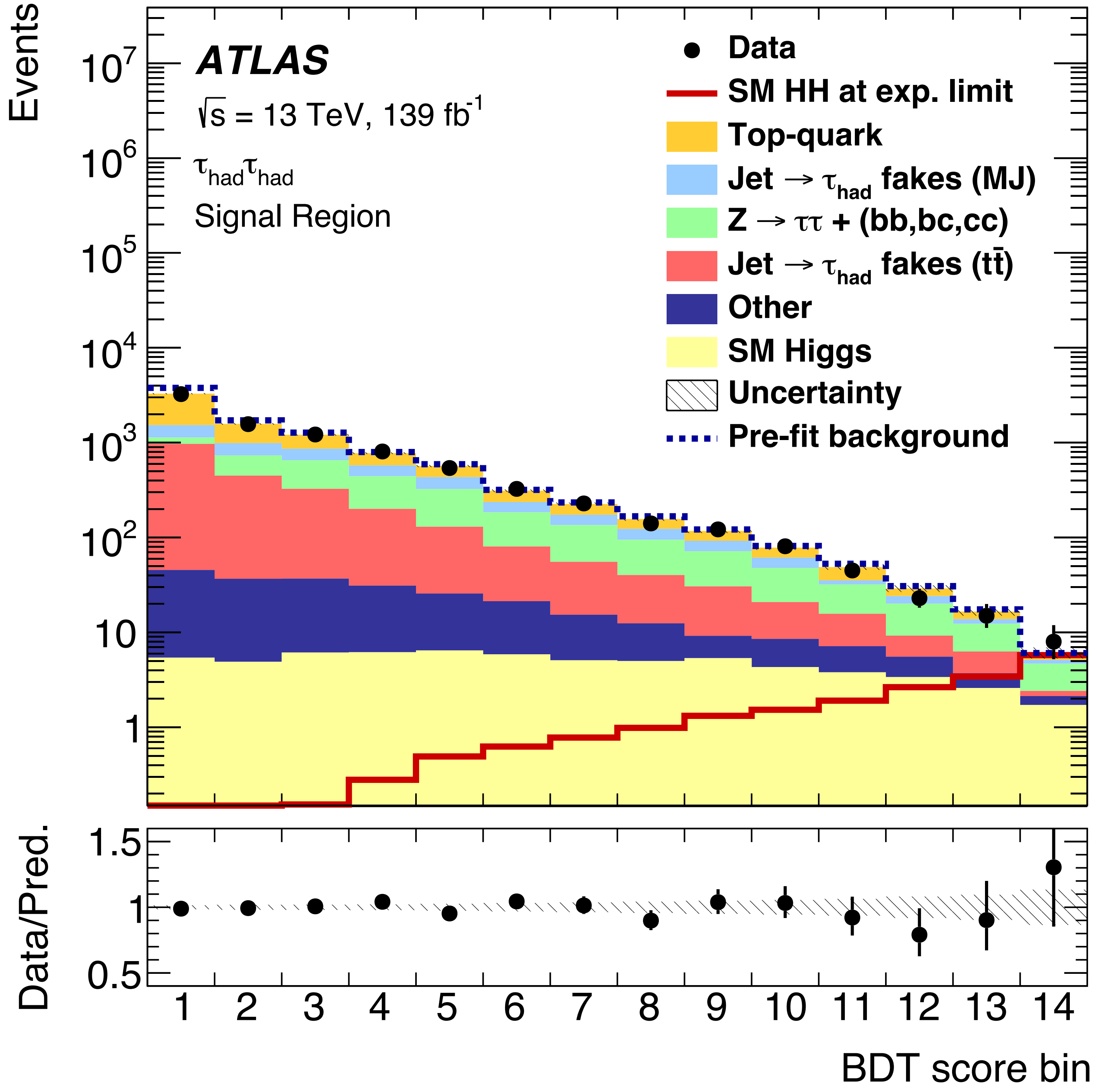


Top-quark background from MC, normalization floating in final fit

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



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

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

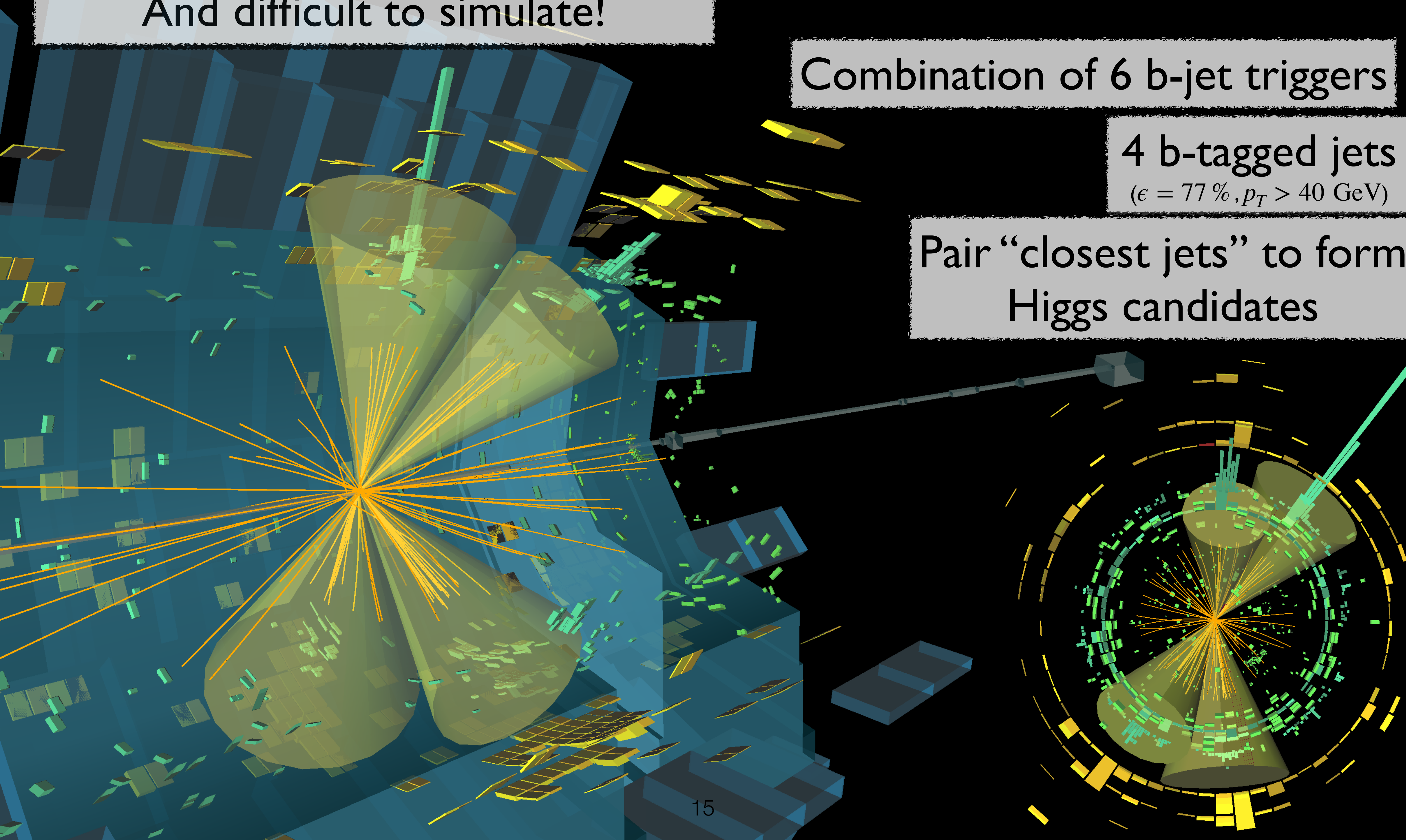
Extremely challenging signature:
Large signal, but large backgrounds,
And difficult to simulate!

arXiv:2301.03212

Combination of 6 b-jet triggers

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

Pair "closest jets" to form
Higgs candidates

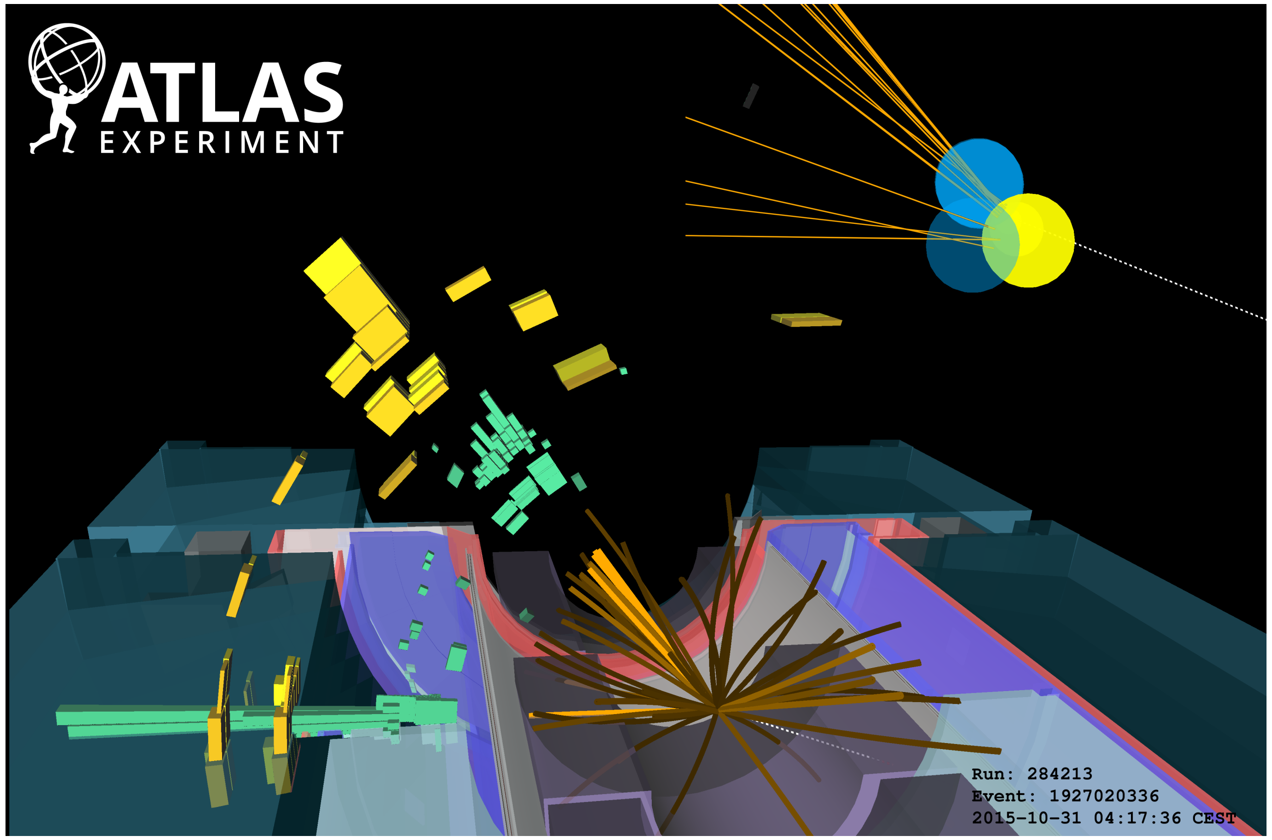


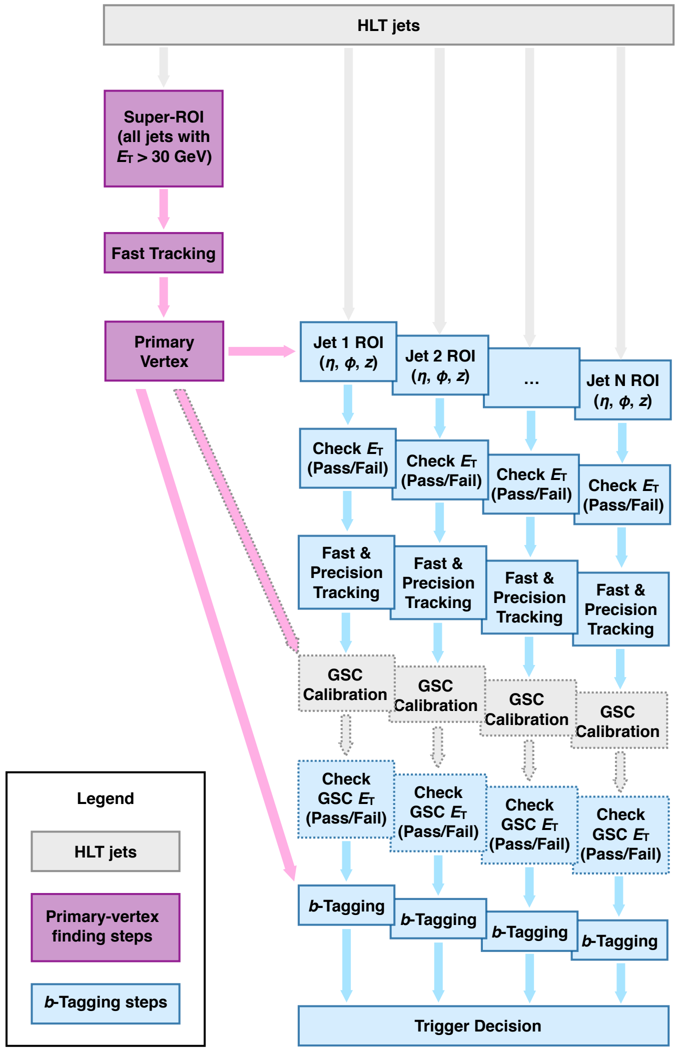
Triggering on b-jets

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

Multi-jet background rates are **huge**:
Utilize b-tagging in the trigger
to manage the rates!

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




HLT jets

Super-ROI (all jets with $E_T > 30$ GeV)

Fast Tracking

Primary Vertex

Jet 1 ROI (η, ϕ, z)
Jet 2 ROI (η, ϕ, z)
...
Jet N ROI (η, ϕ, z)

Check E_T (Pass/Fail)

Fast & Precision Tracking

GSC Calibration

Check GSC E_T (Pass/Fail)

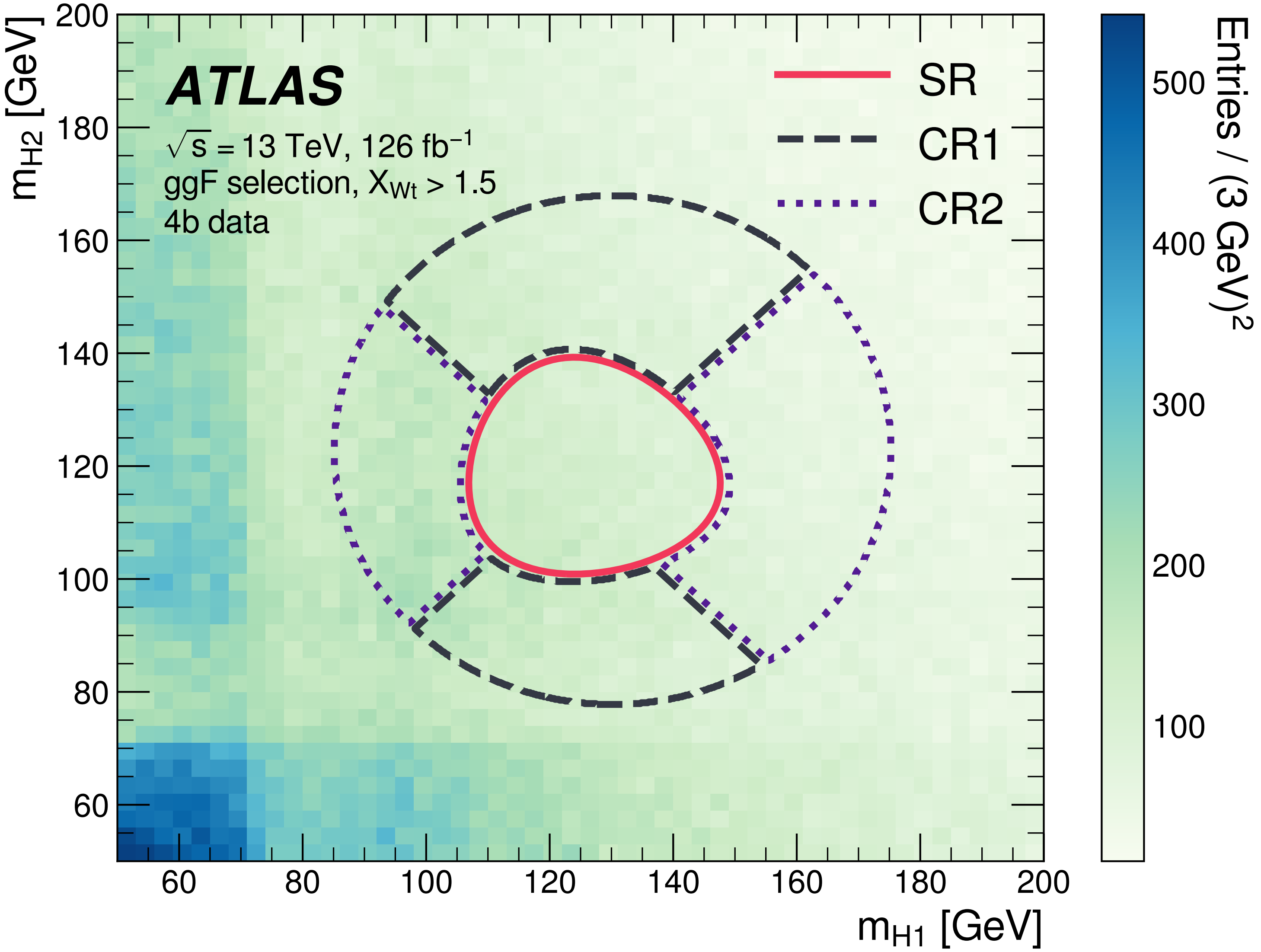
b-Tagging

Trigger Decision

Legend
HLT jets
Primary-vertex finding steps
b-Tagging steps

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

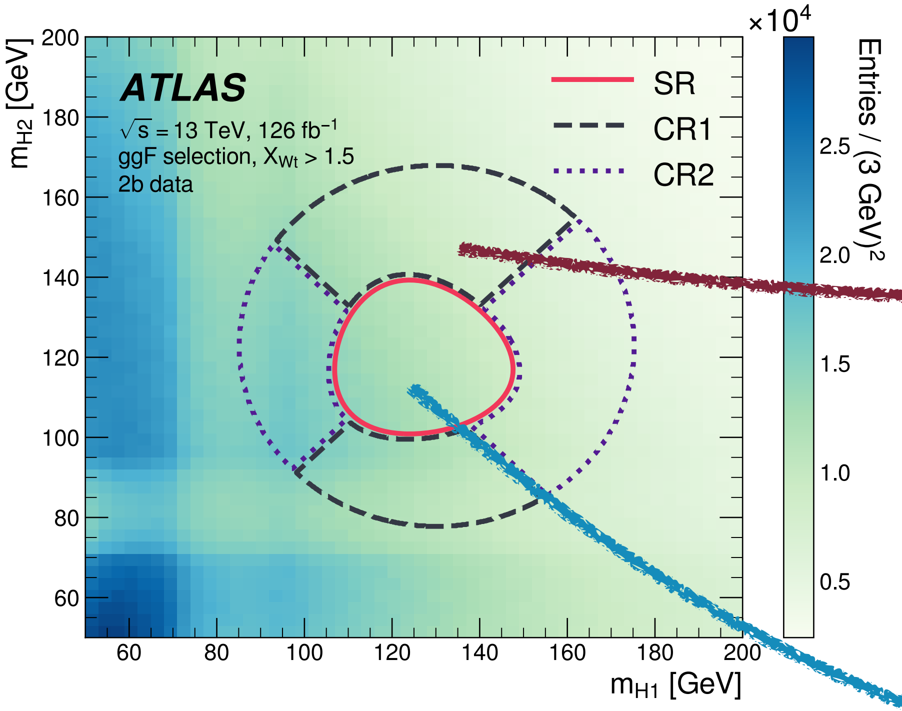
$b\bar{b}b\bar{b}$ Analysis Strategy



Reconstruct Higgs candidates, form "mass plane"

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

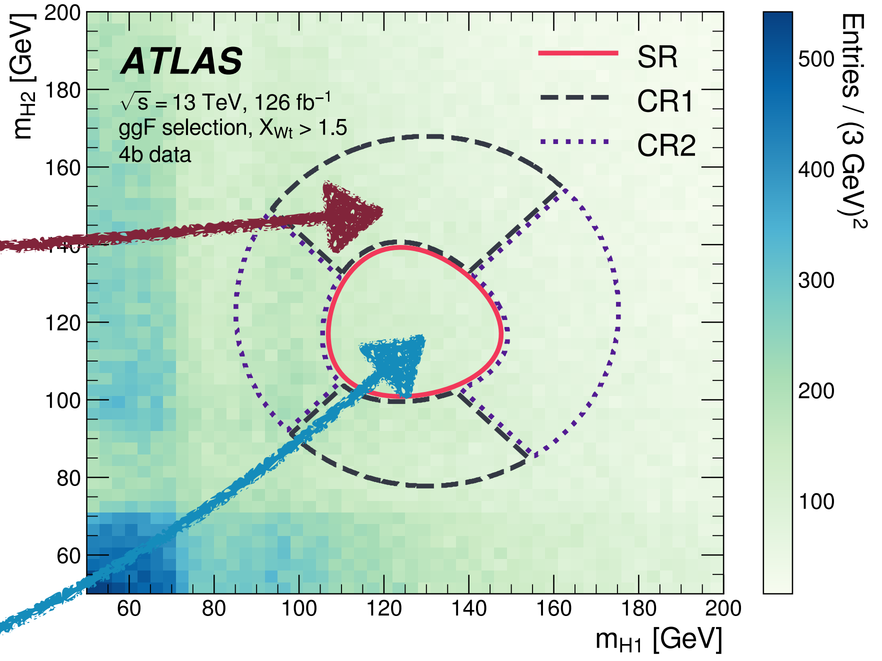
$b\bar{b}b\bar{b}$ Background

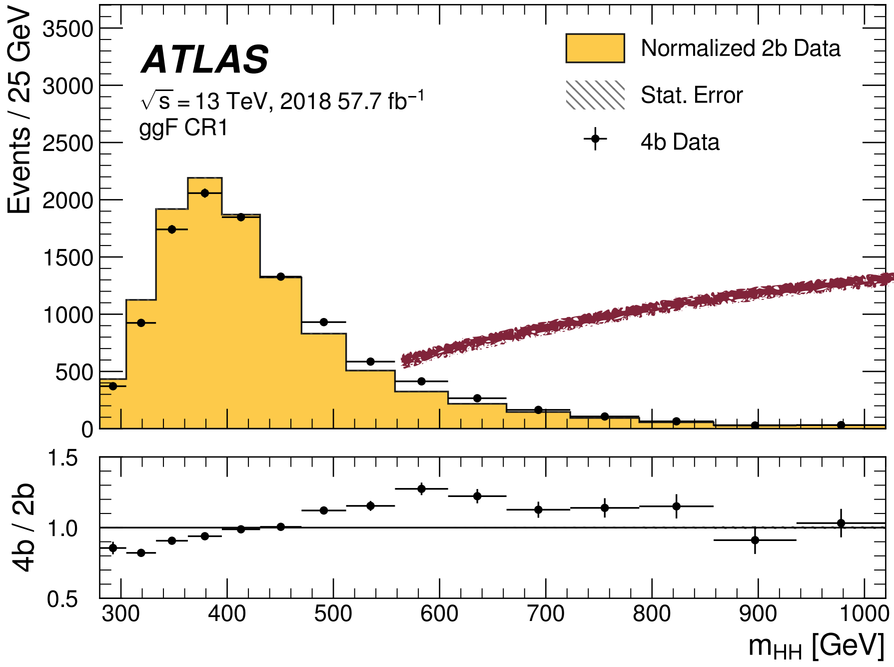


Step 0: form "mass planes" with leading/subleading Higgs, for 2b and 4b events

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

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

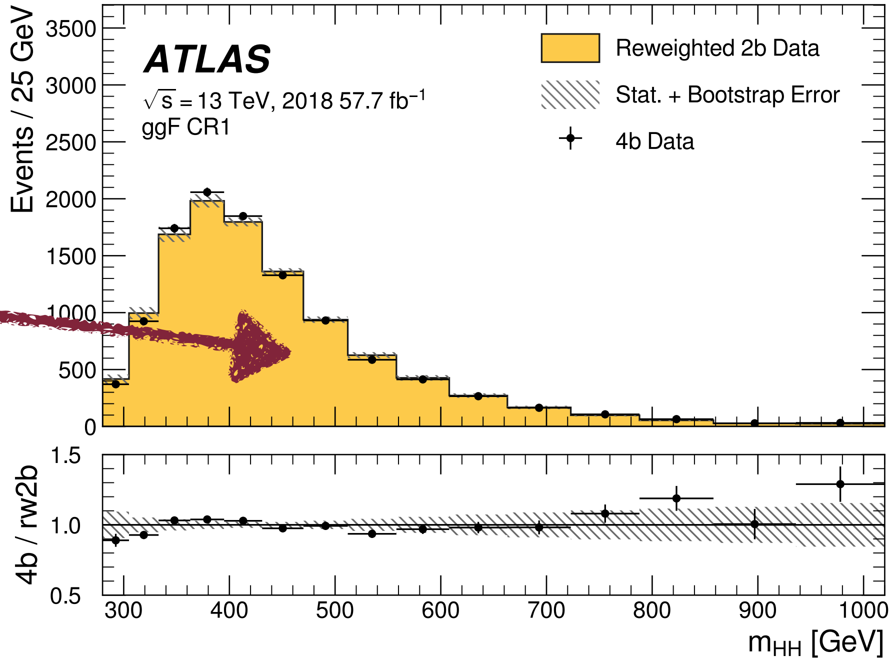




Orange histogram comes from 2b, black points from 4b

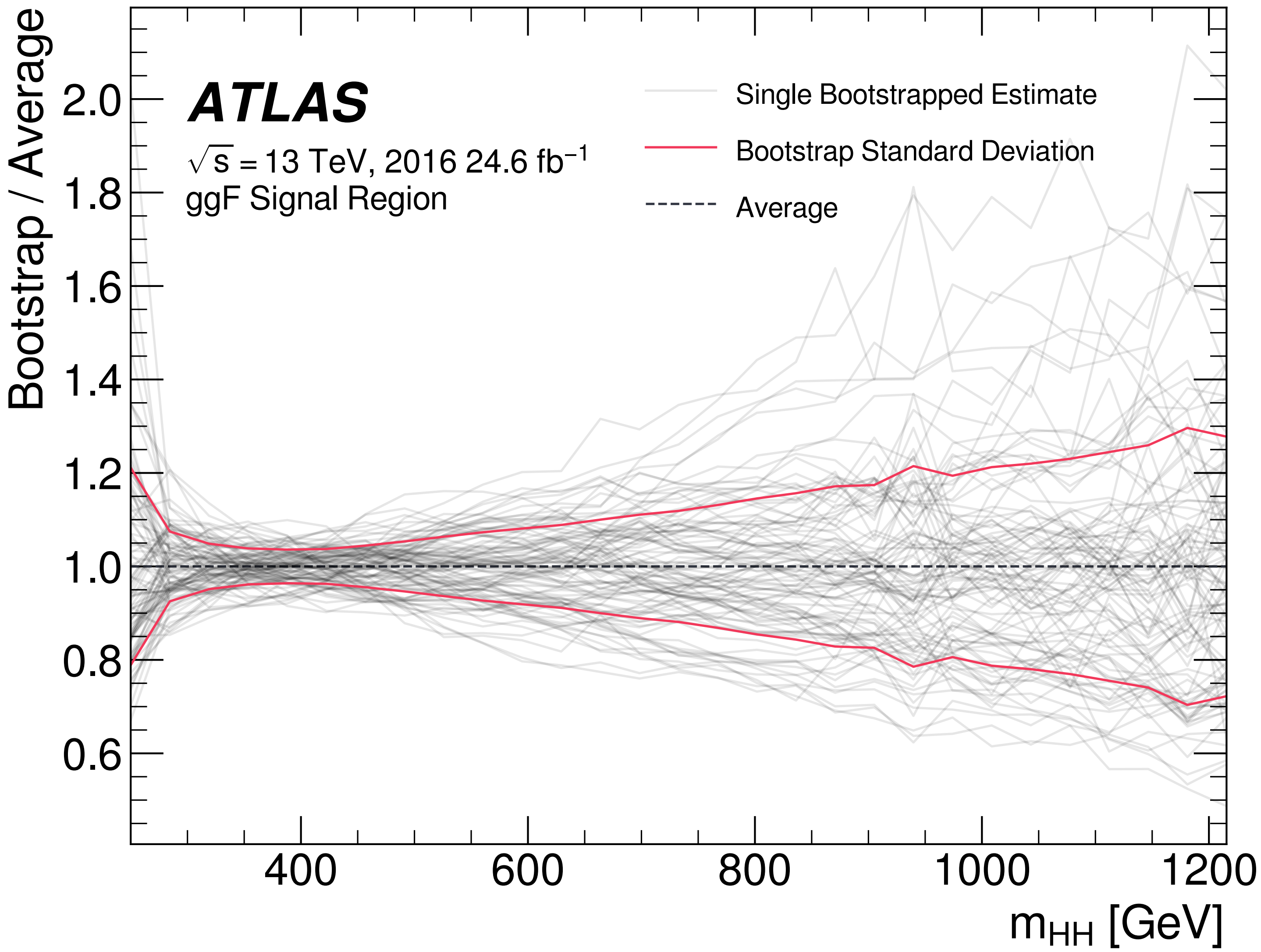
Neural network training

Systematics from alternate regions



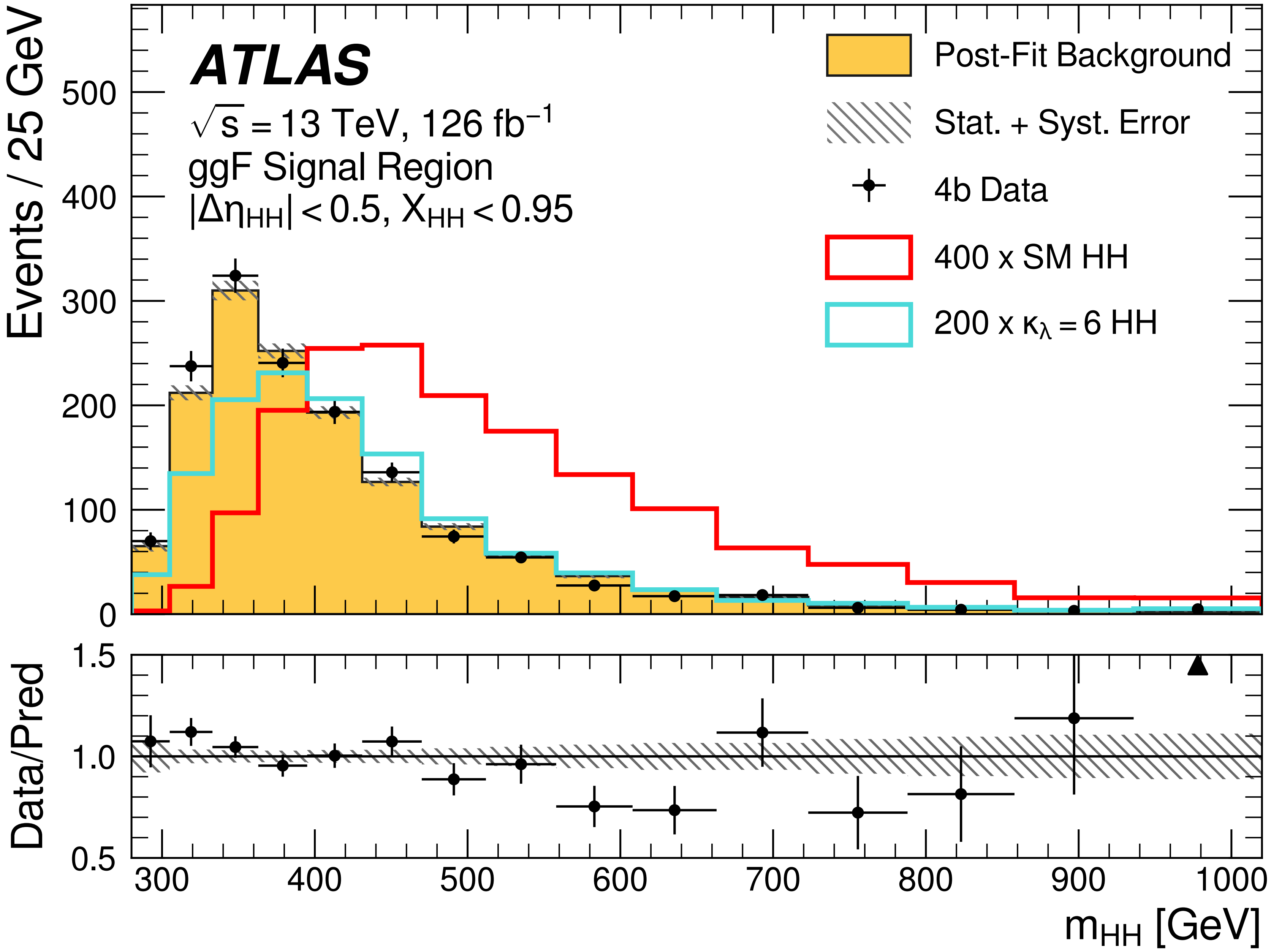
Systematic Uncertainties

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



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

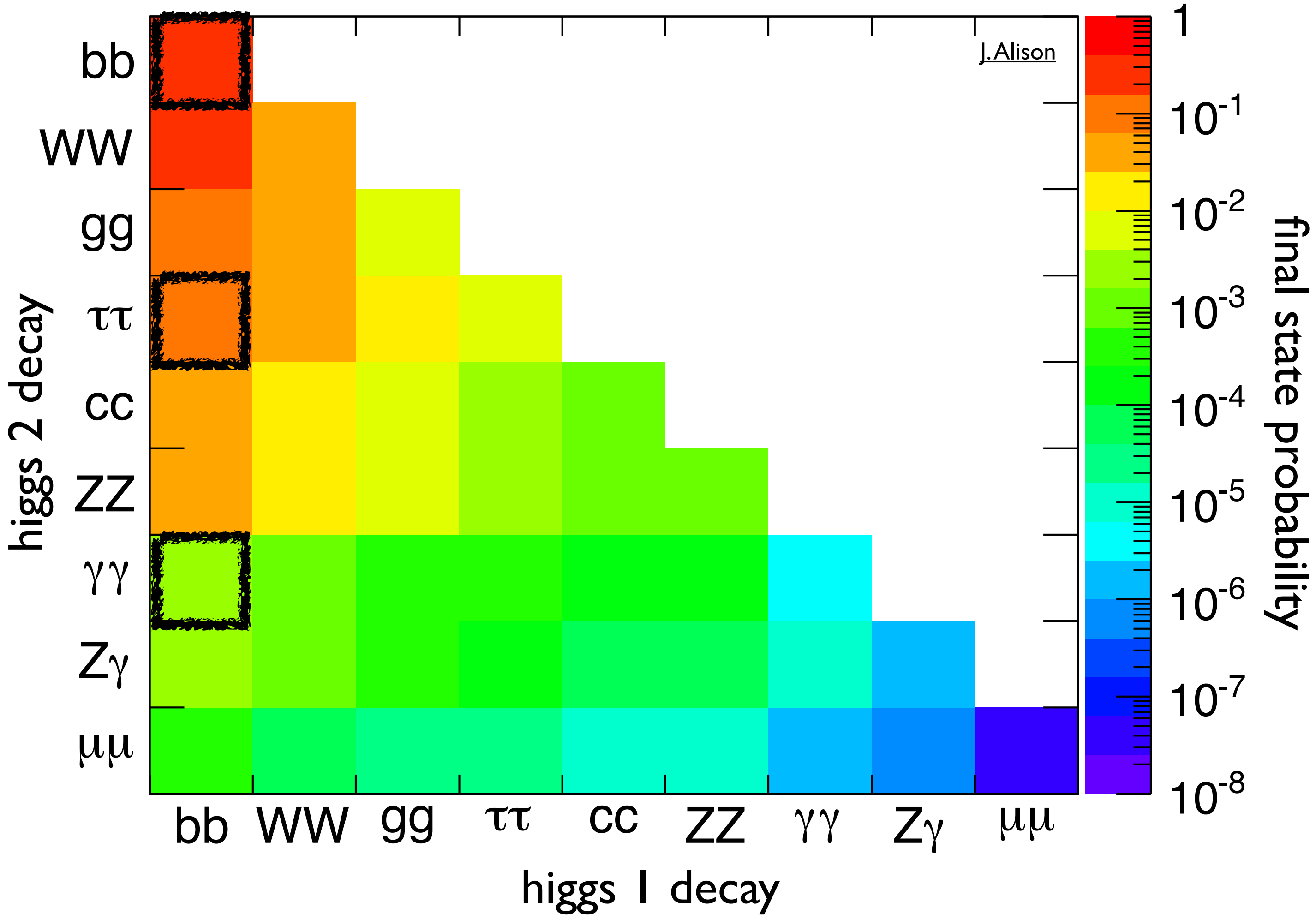


Large range of signal regions defined

Cover various kinematic, production regions

No excess observed

Combination

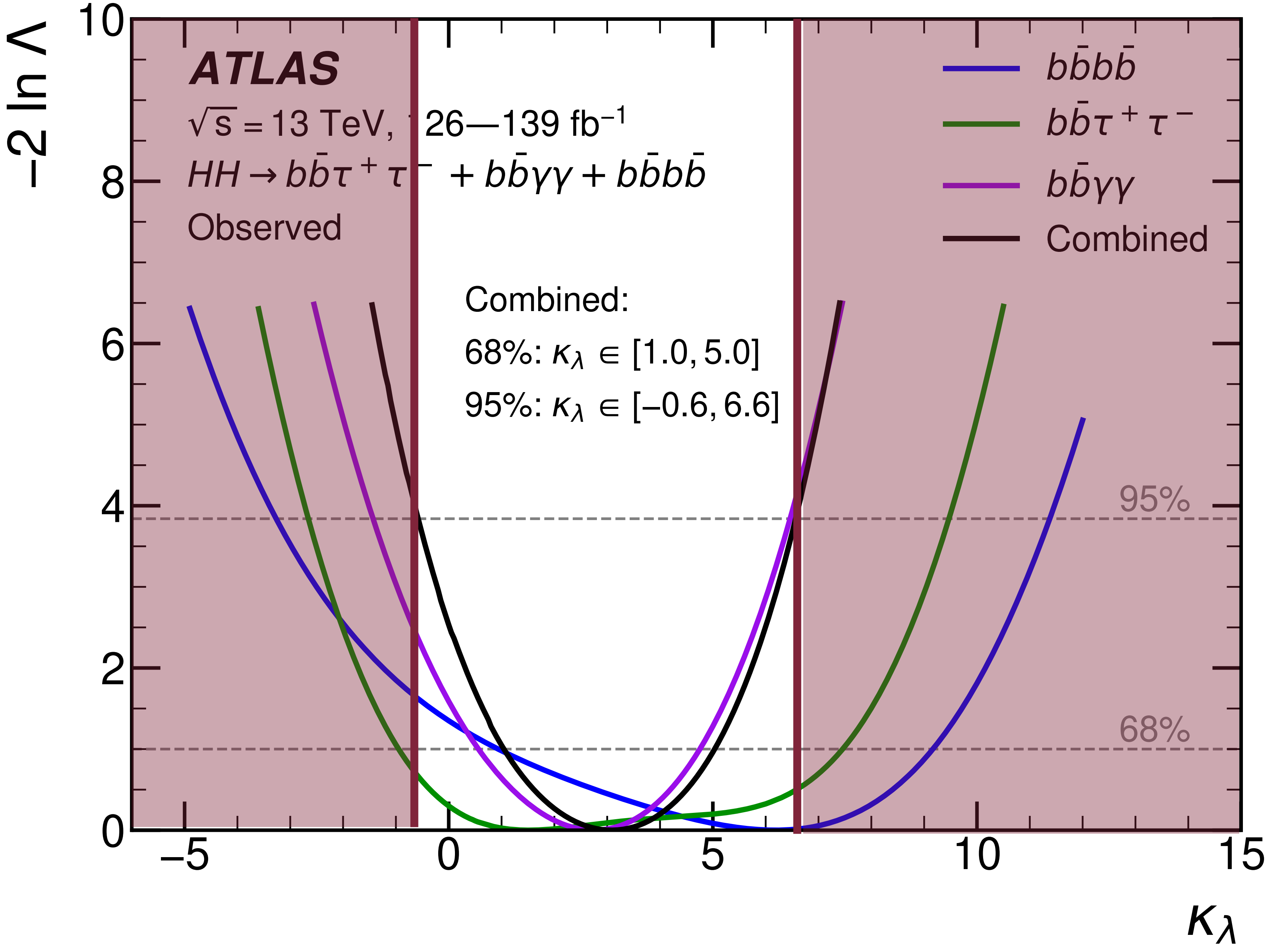


For optimal sensitivity: combine all three analyses into a single statistical interpretation

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

Phys. Lett. B 843 (2023) 137745

Measuring the Potential



Here, show *likelihood* vs κ_λ

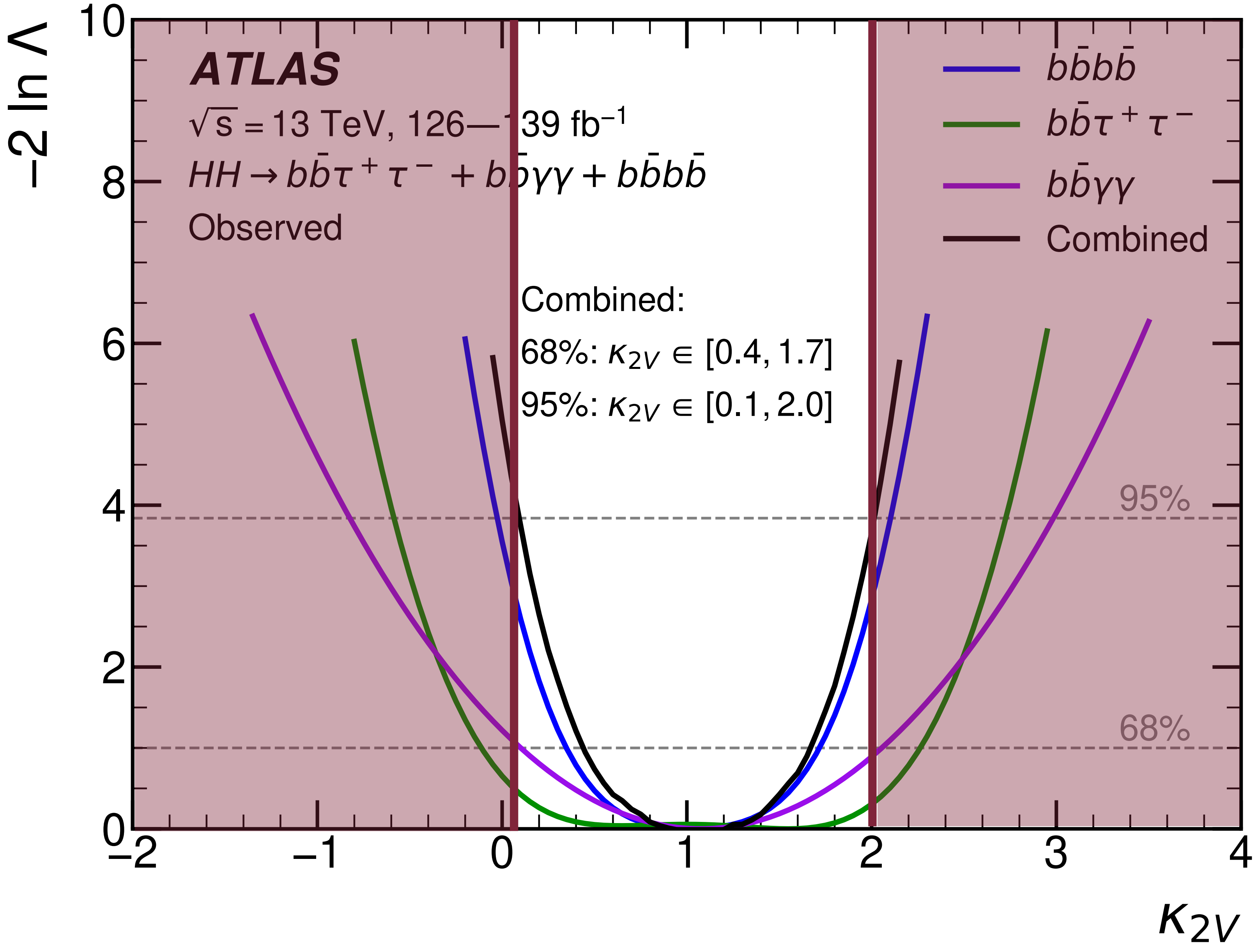
Minimum here is the "best fit"

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

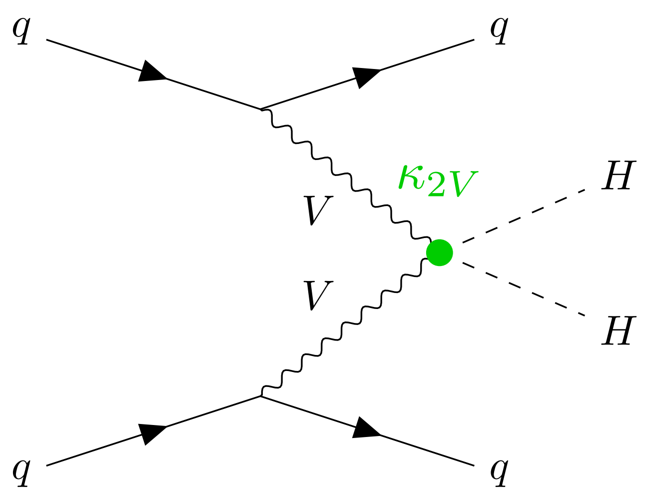
Each of the three analyses contributes to the combination

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

Other Couplings



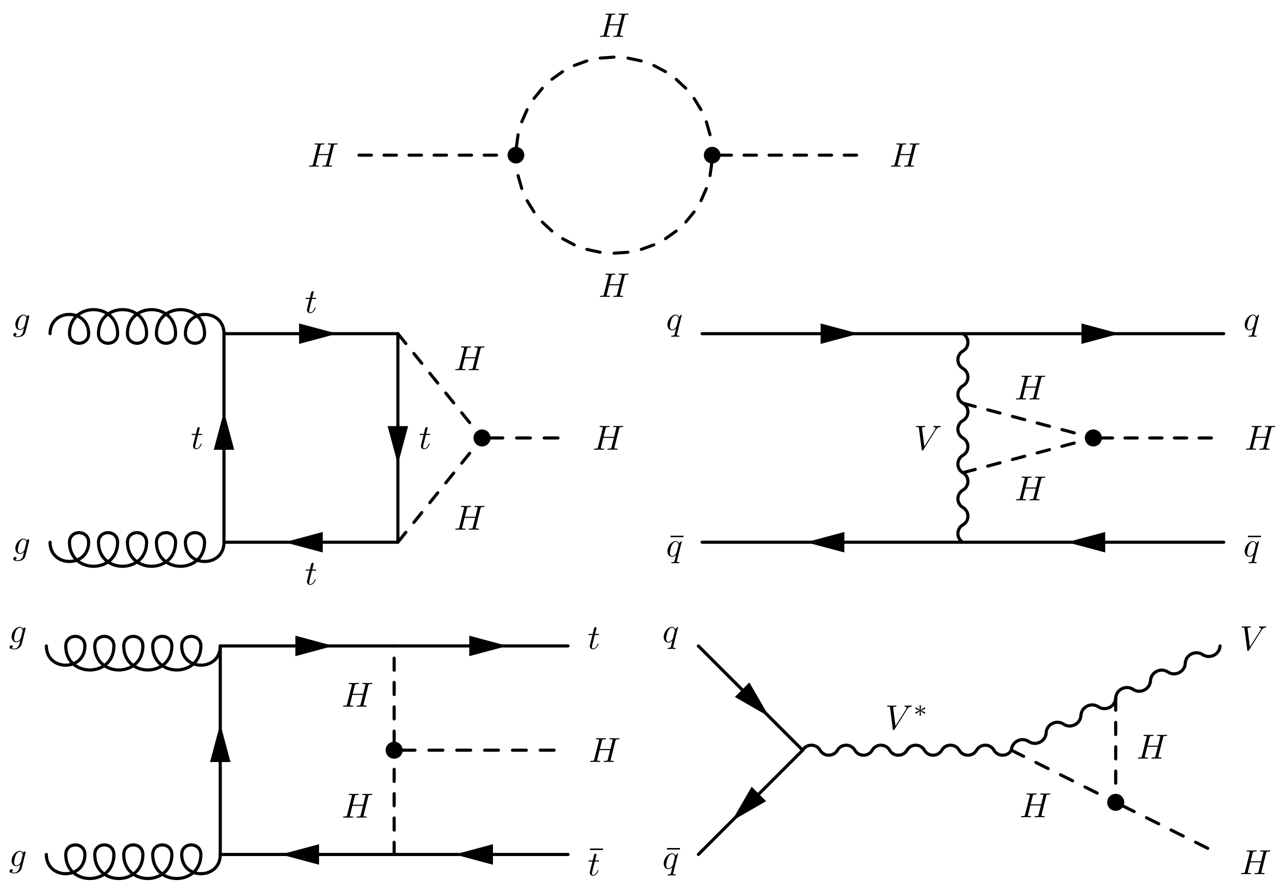
Via dedicated vector-boson fusion channels, can also measure the $VVHH$ coupling

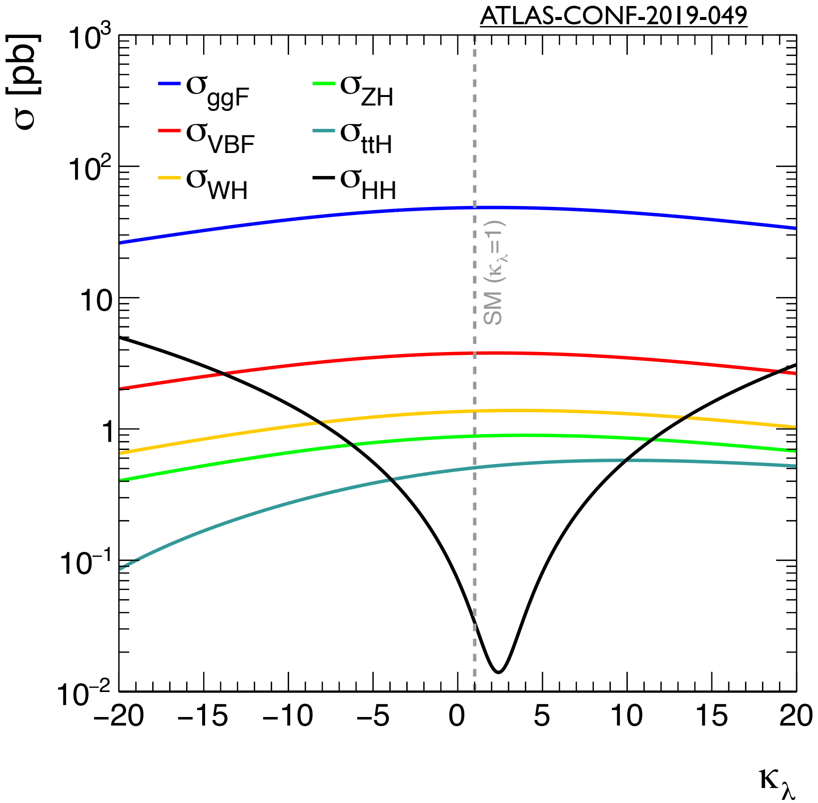


Limits set at

$$0.1 < \kappa_{2V} < 2.0$$

Measuring with Single Higgs

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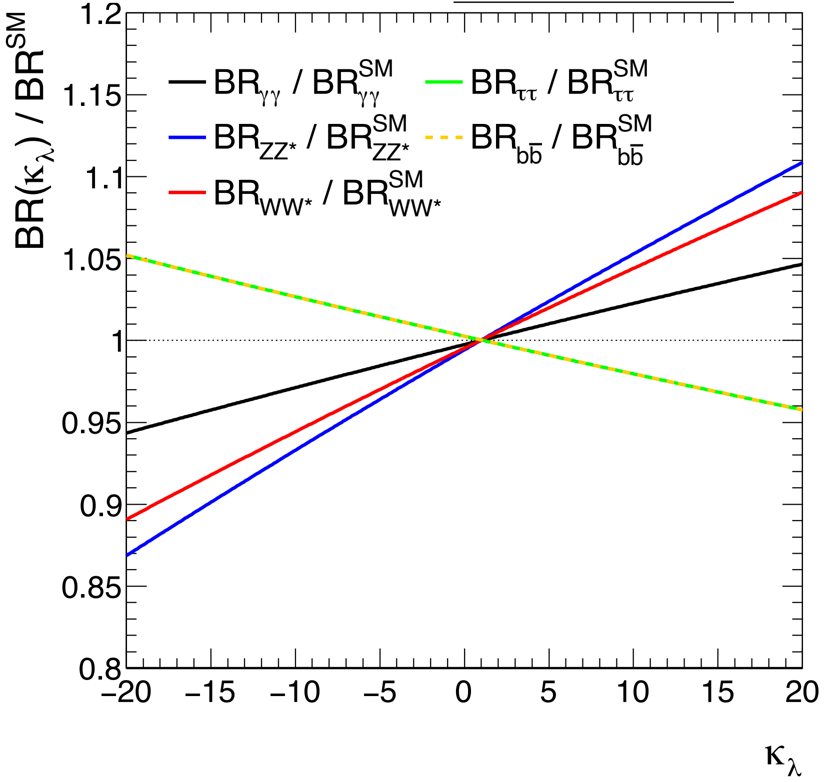
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Single Higgs final states can also be sensitive to κ_λ

NLO EW corrections give Higgs cross-section, branching ratios, and kinematics dependence on κ_λ

Combining Single and Double

Channel	Integrated luminosity [fb^{-1}]	Ref.
$HH \to b\bar{b}\gamma\gamma$	139	[17]
$HH \to b\bar{b}\tau^+\tau^-$	139	[18]
$HH \to b\bar{b}b\bar{b}$	126	[19]
$H \to \gamma\gamma$	139	[58]
$H \to ZZ^* \to 4\ell$	139	[59]
$H \to \tau^+\tau^-$	139	[60]
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)	139	[61]
$H \to b\bar{b}$ (VH)	139	[62]
$H \to b\bar{b}$ (VBF)	126	[63]
$H \to b\bar{b}$ $(t\bar{t}H)$	139	[64]

Can perform a combined analysis, using single and double Higgs!

Single Higgs analysis use STXS template fits
for VBF and VH measurements

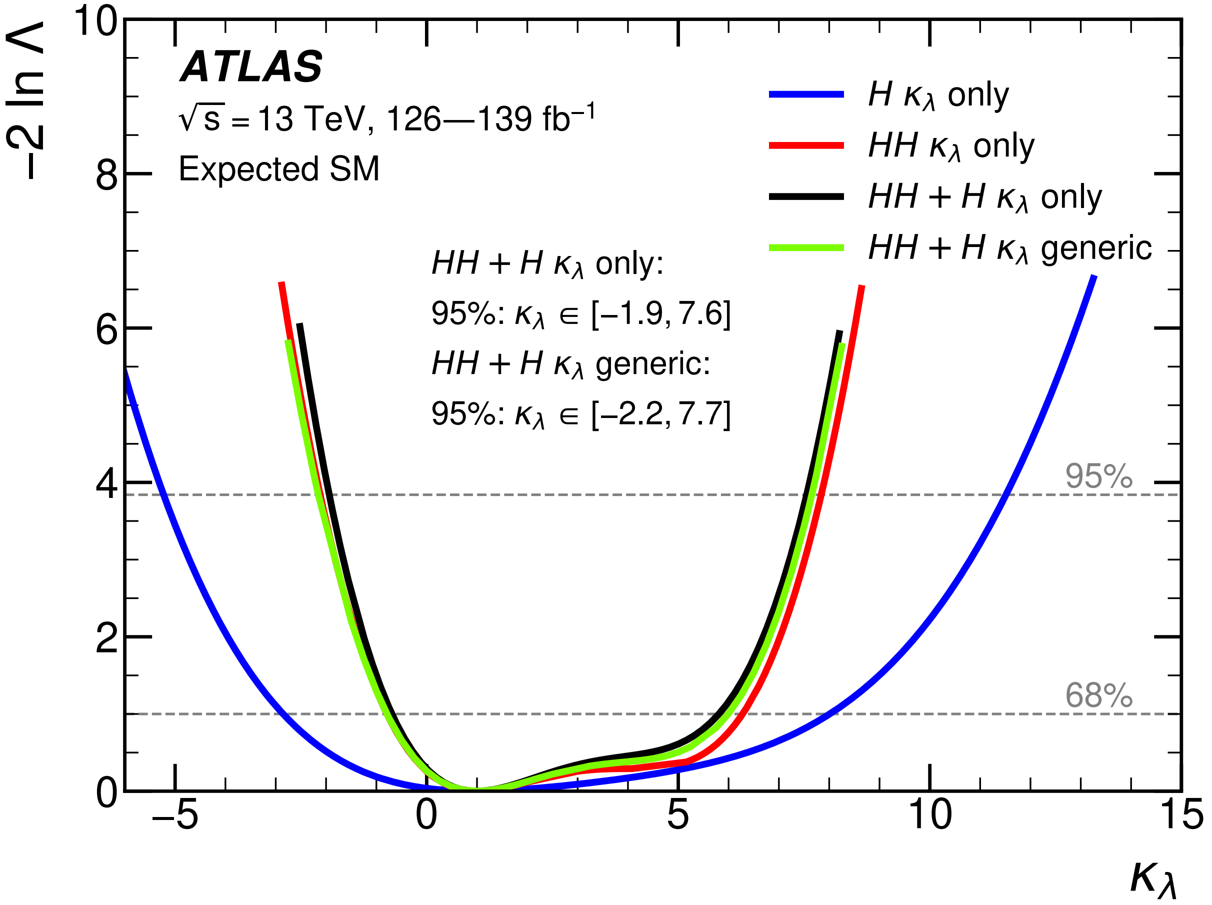
Explicit checks for overlap: remove $t\bar{t}H \to \gamma\gamma$ due to $b\bar{b}\gamma\gamma$ overlap

Perform two types of interpretations:

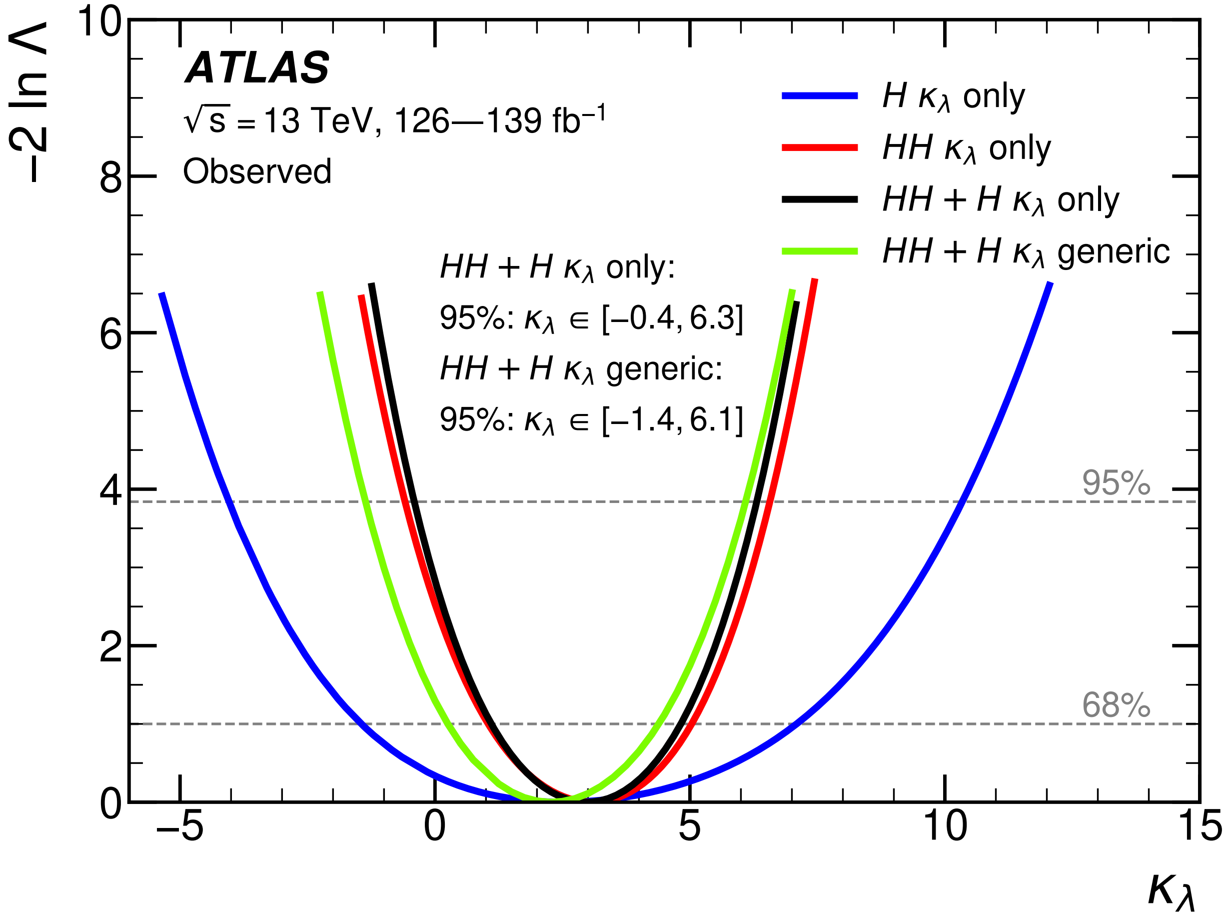
1. New physics only in κ_λ
2. New physics in any κ coupling

Results: κ_λ

Expected



Observed

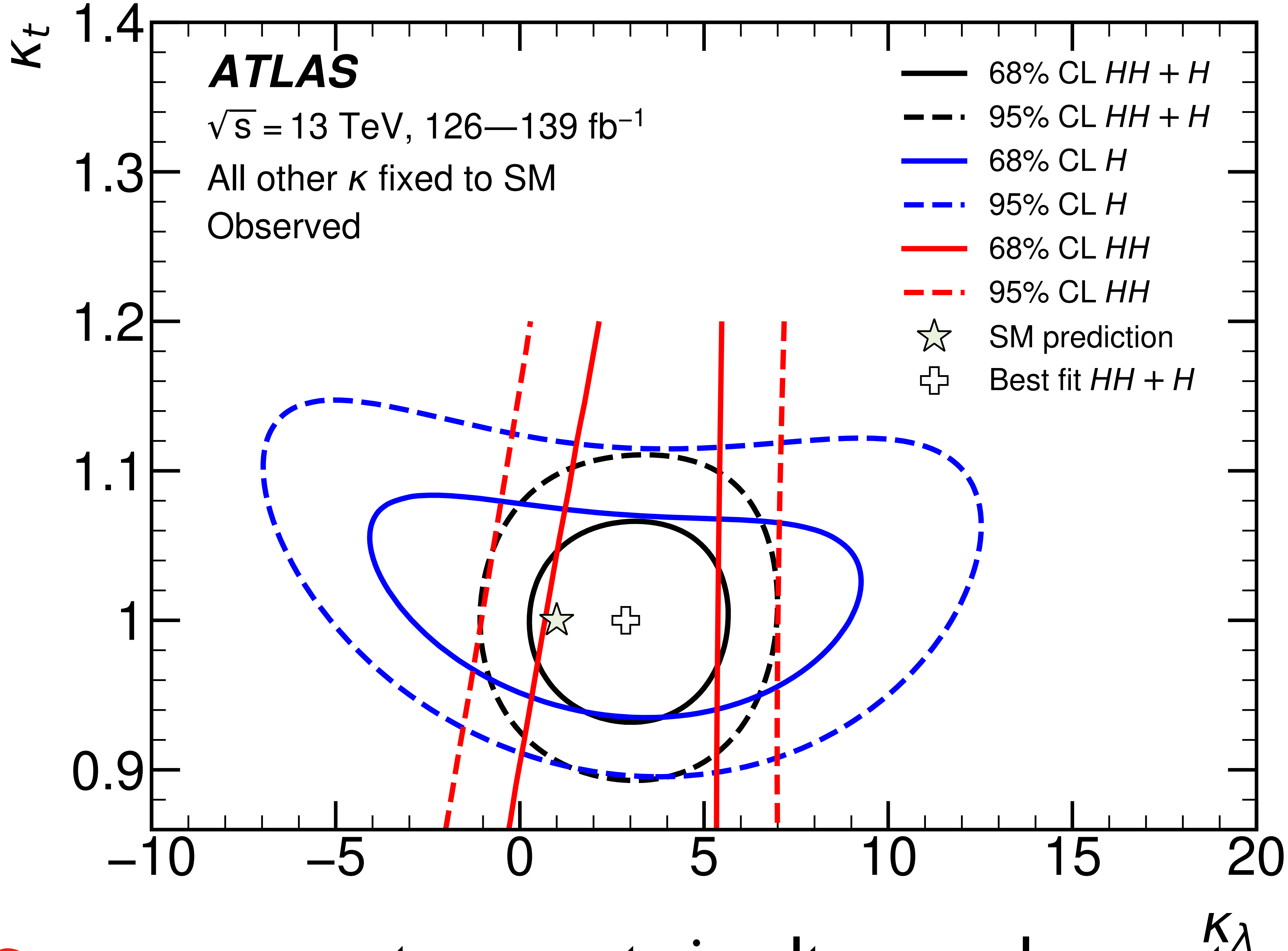


Di-Higgs provides stronger limits, but **Single-Higgs** helps!

Combination provides strongest limits

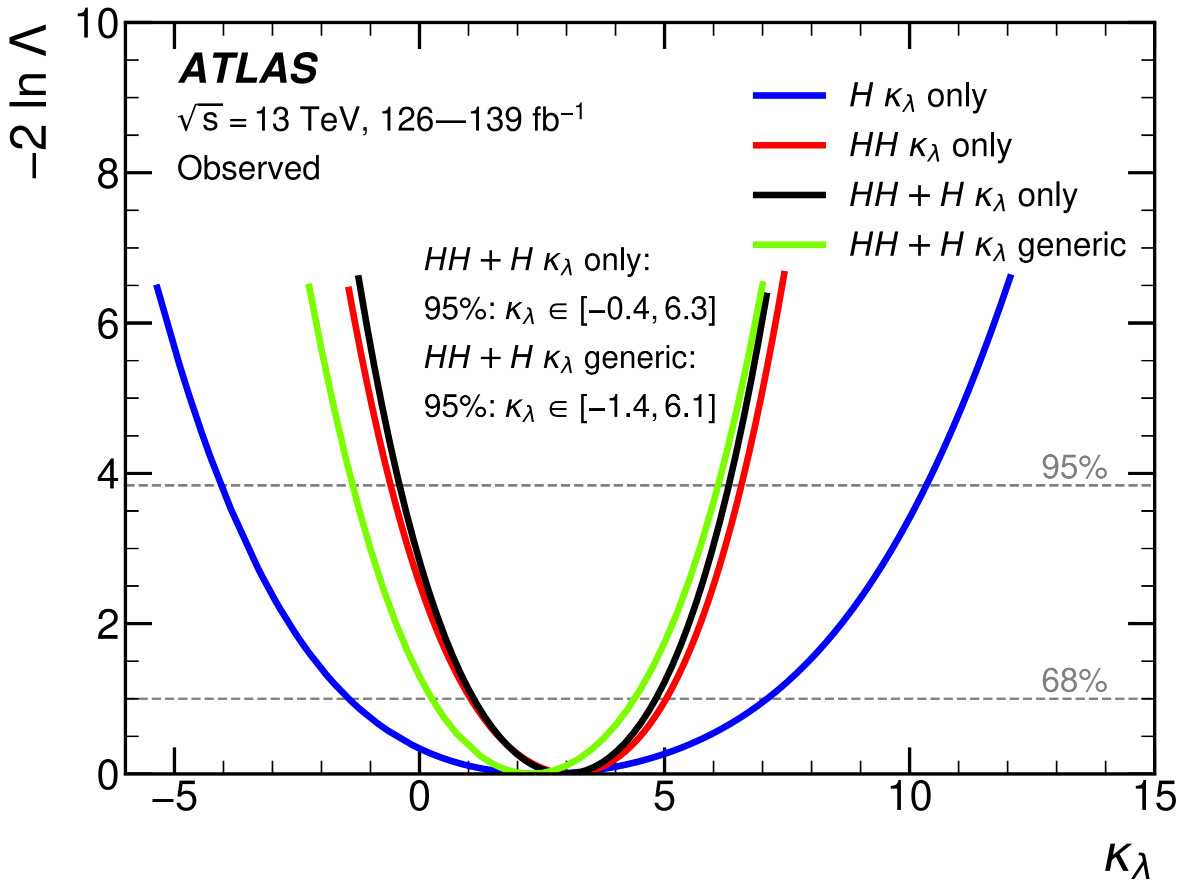
Generic interpretation allows other κ values to float:
Would be dramatically worse without Single Higgs!

Relaxing Constraints



Di-Higgs measurements cannot simultaneously constrain κ_λ and κ_t
Single Higgs allows the **Combinations** to be sensitive to variations in both parameters

Conclusions



$$-0.4 < \kappa_\lambda < 6.3$$

$$-1.4 < \kappa_\lambda < 6.1$$

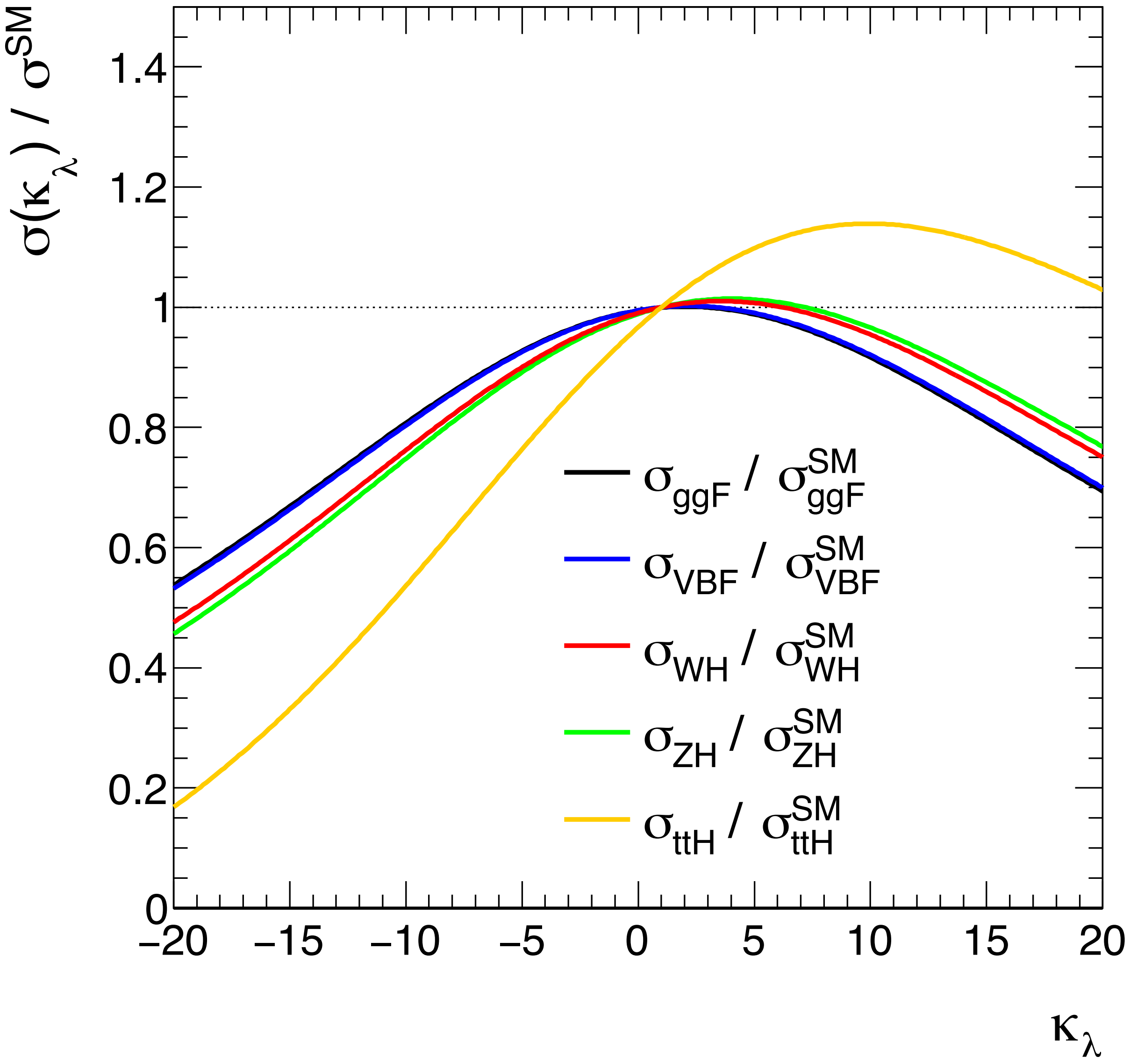
ATLAS has performed a unique, new measurement combining single and di-Higgs final states to measure the Higgs self-coupling

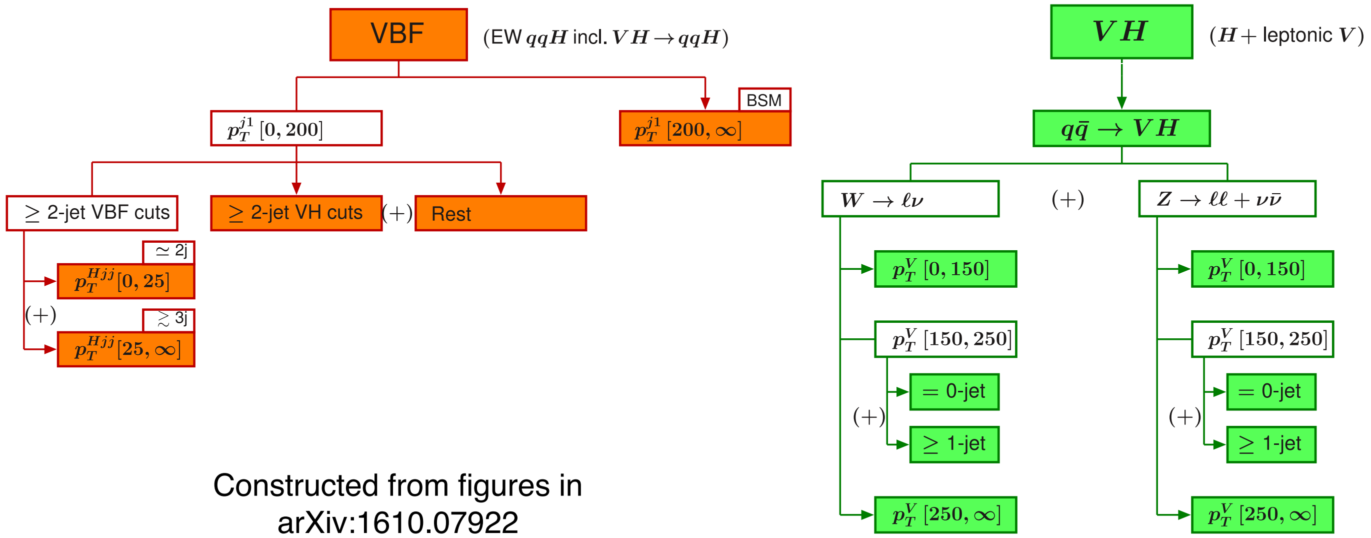
With more physics constraints, we can relax the model assumptions and test more 'realistic' deviations from the SM

This combination provides the **most precise**, and **most general**, constraints on the Higgs self-coupling

Thank You!

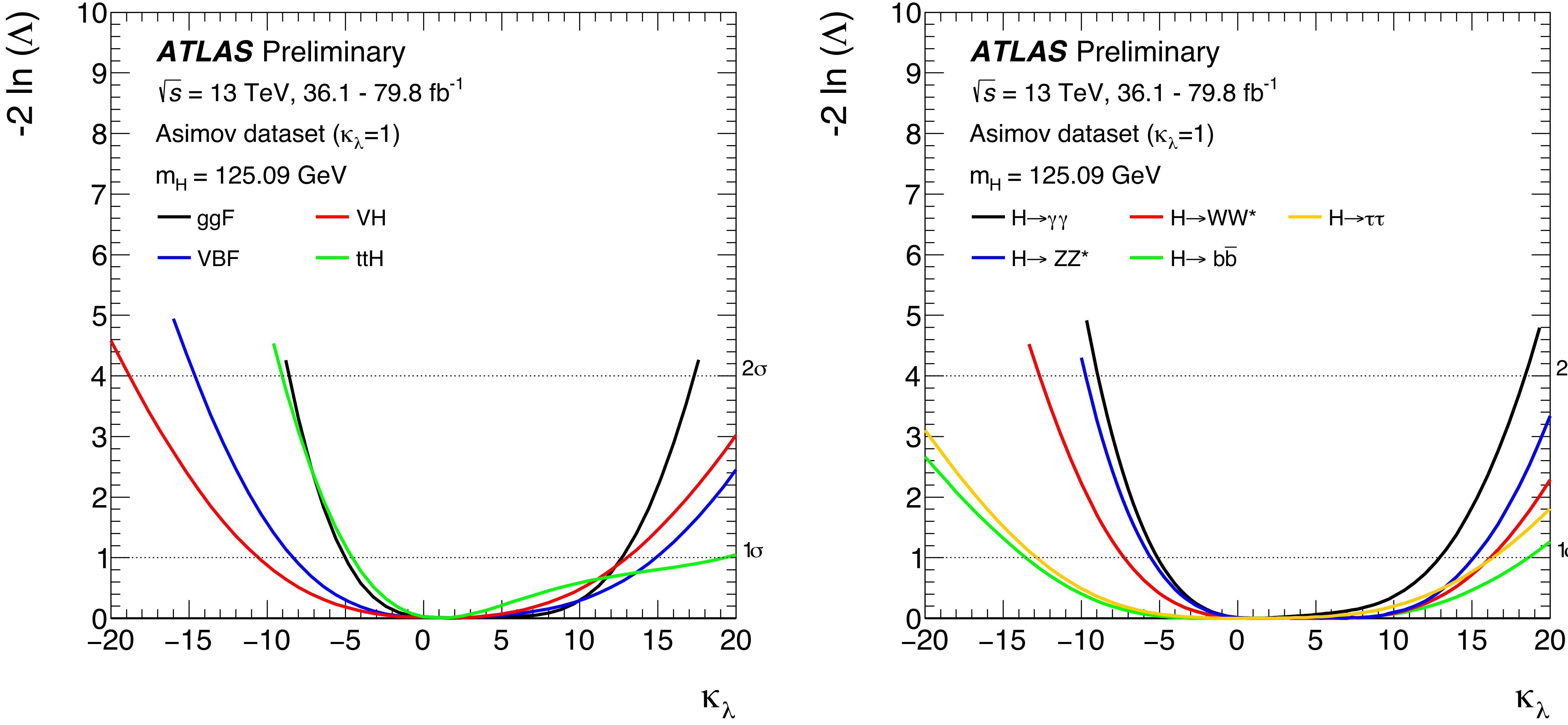
More on Single Higgs



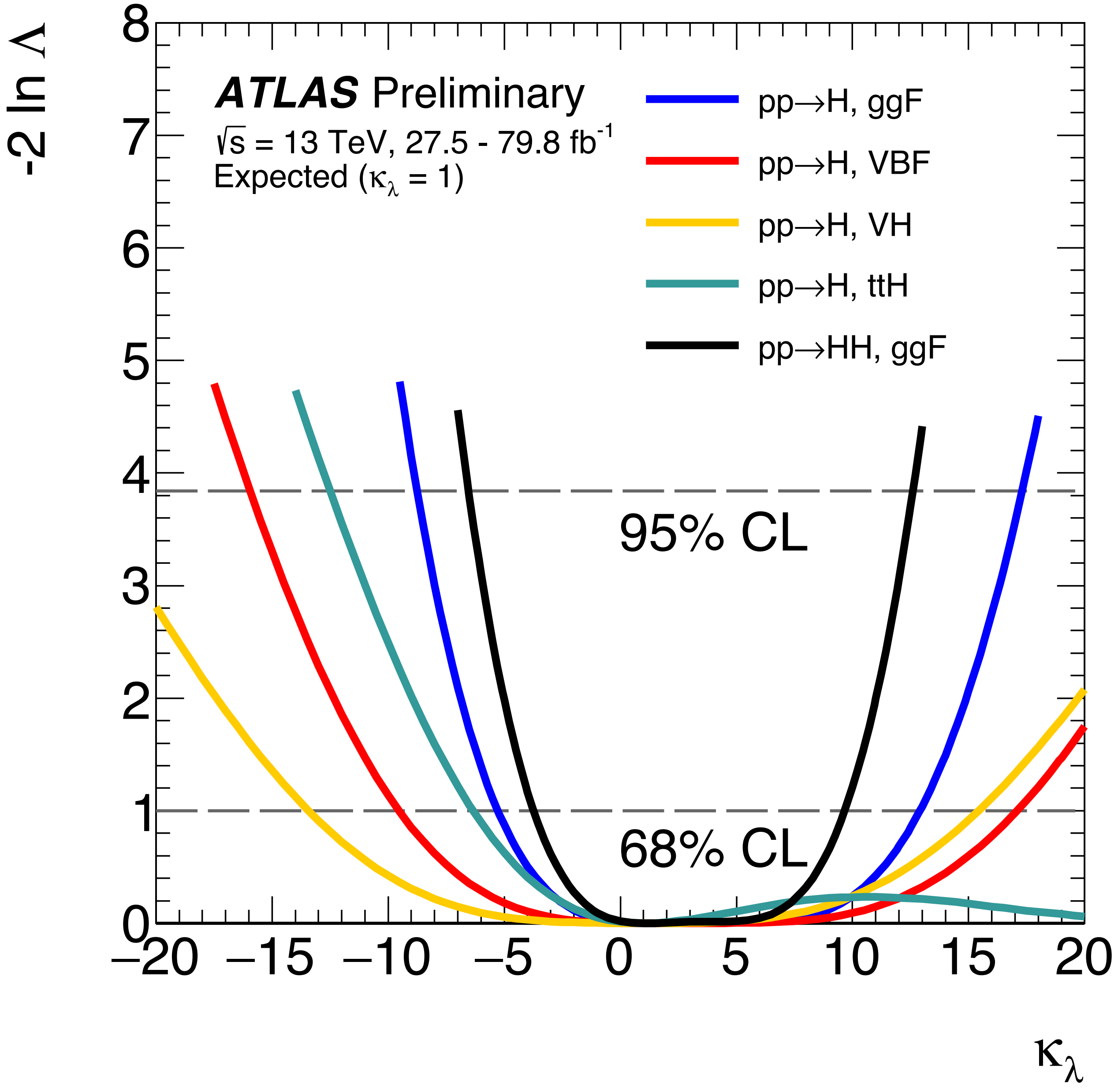


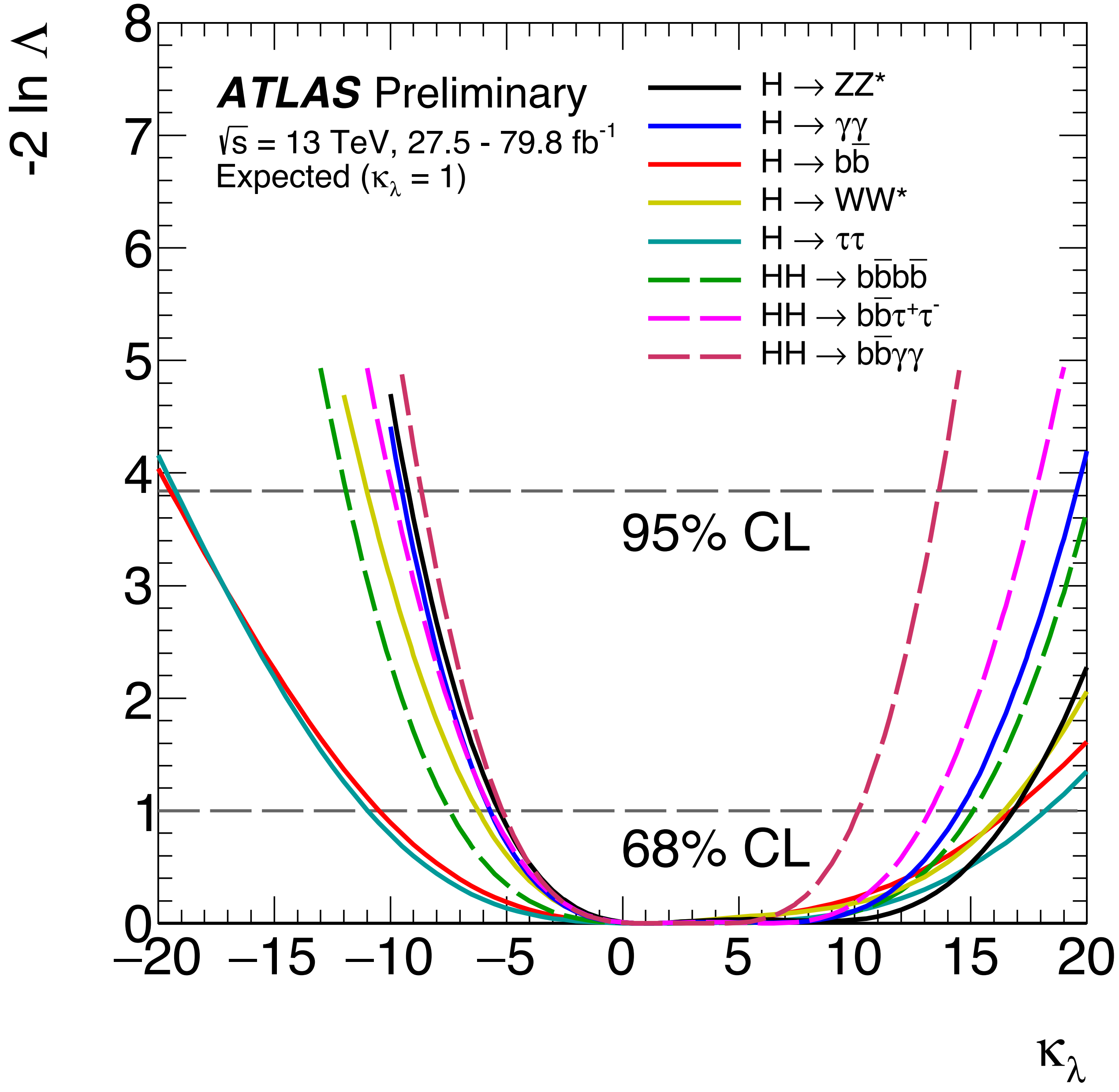
Constructed from figures in
arXiv:1610.07922

More on Single Higgs



More on Combination





Generalized Limits on κ_λ

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$