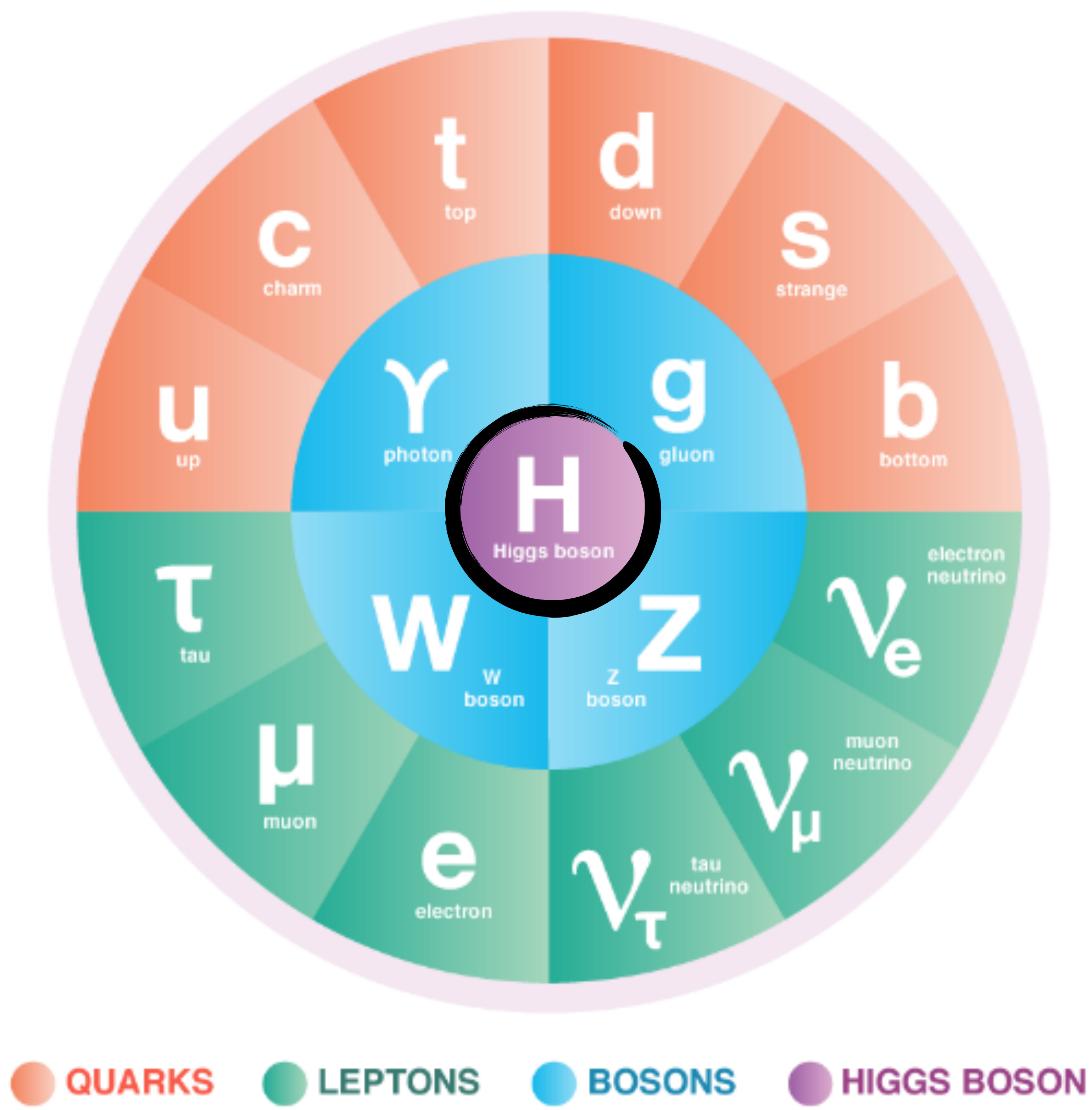
Measurements of the Higgs potential at the LHC

Brendon Bullard
Research Associate @ SLAC

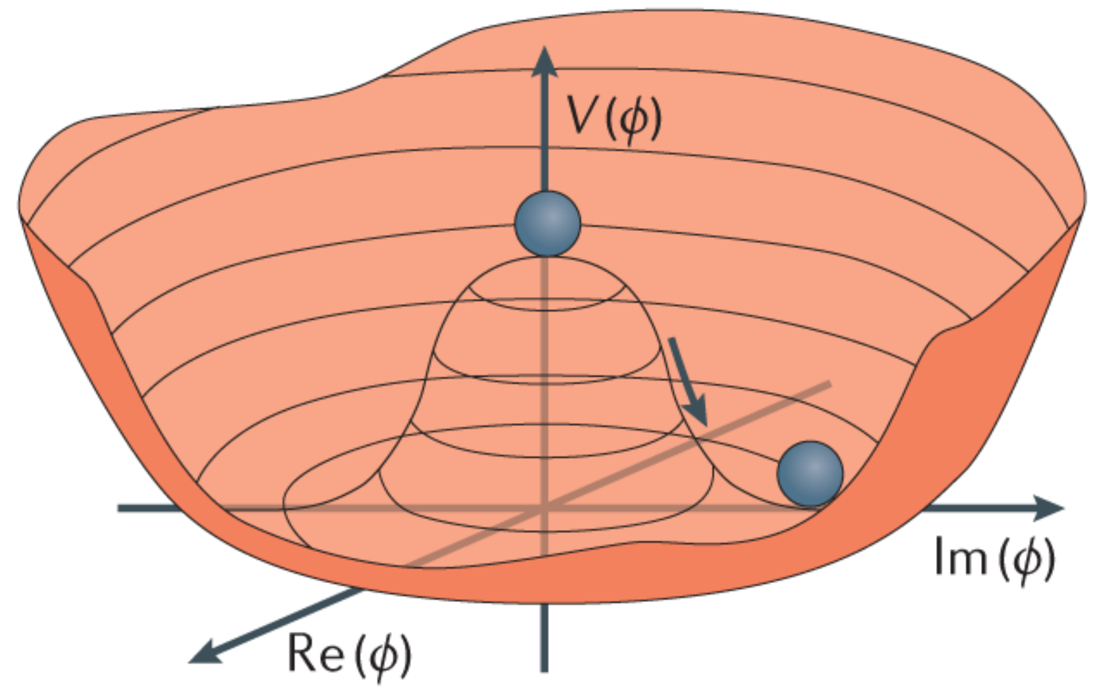
US-LUA Lightning Talk
December 15, 2023

ATLAS EXPERIMENT

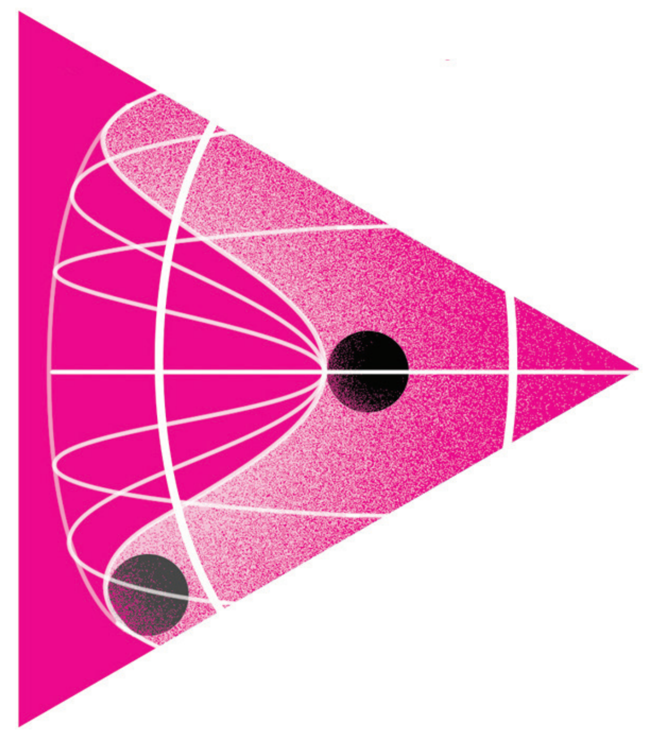
SLAC NATIONAL ACCELERATOR LABORATORY



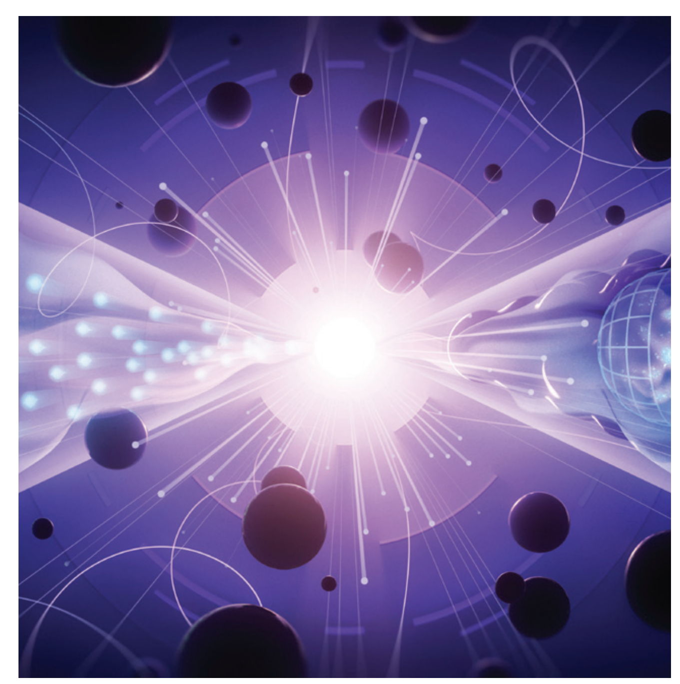
→ Higgs is **central** in the SM



Higgs potential drives the generation of mass

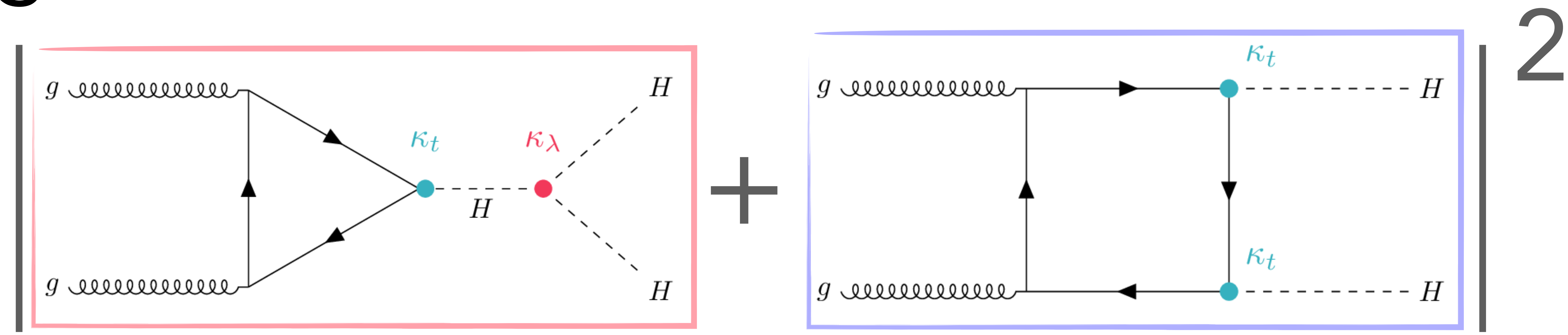


Experimental **verification of its shape** is a high priority goal for HL-LHC!

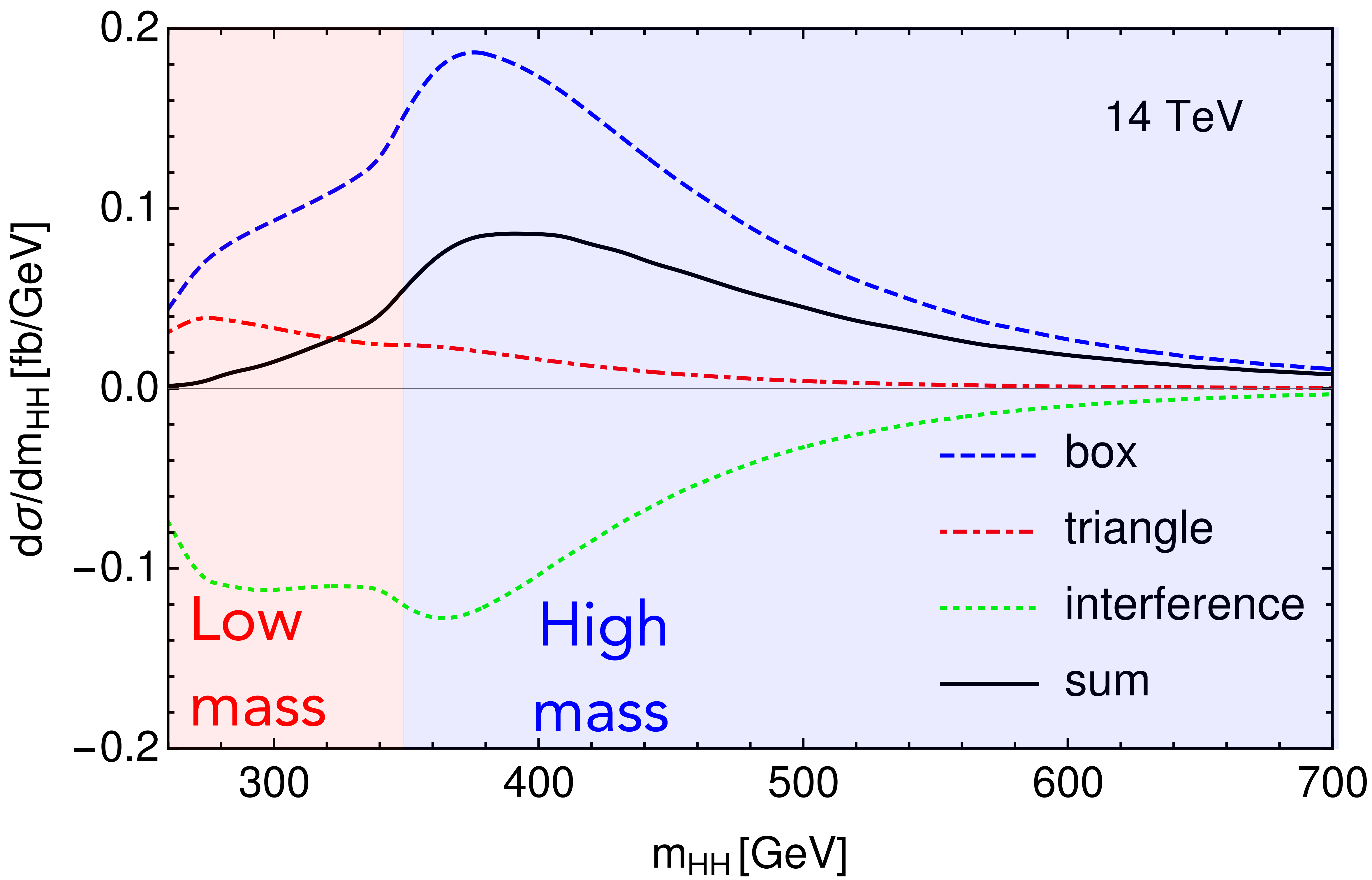


BSM physics can imply *first order phase transition* in early universe → **baryogenesis**

Producing HH

$\sigma =$ 

→ Interference pattern limits sensitivity to $\kappa_\lambda = \lambda_{obs}/\lambda_{SM}$



Focus: the ATLAS Run 2 search for non-resonant *HH* production in the $b\bar{b}\gamma\gamma$ final state

arXiv:2310.12301

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

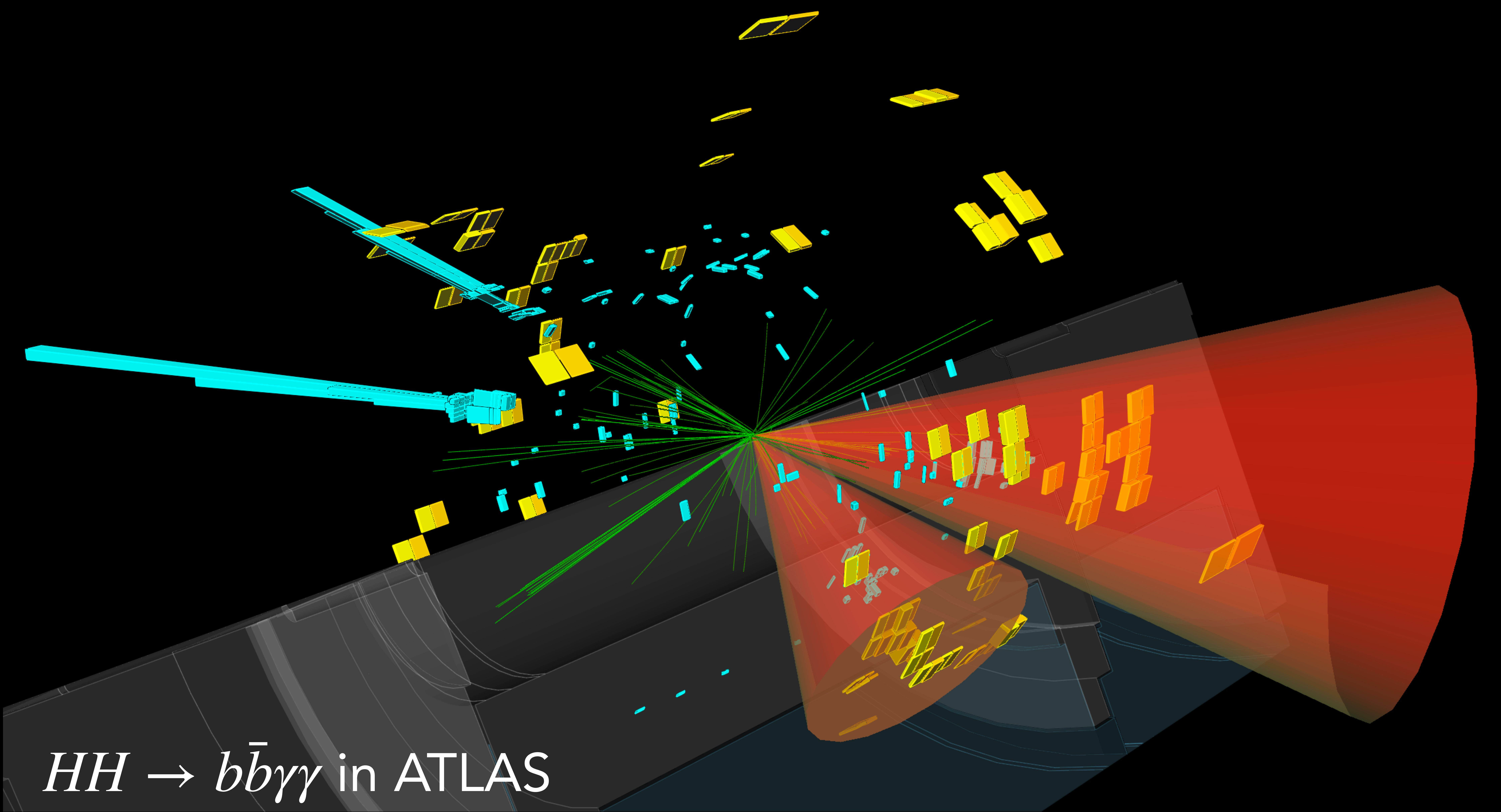
Submitted to: JHEP

CERN-EP-2023-206
20th October 2023

Studies of new Higgs boson interactions through nonresonant HH production in the $b\bar{b}\gamma\gamma$ final state in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

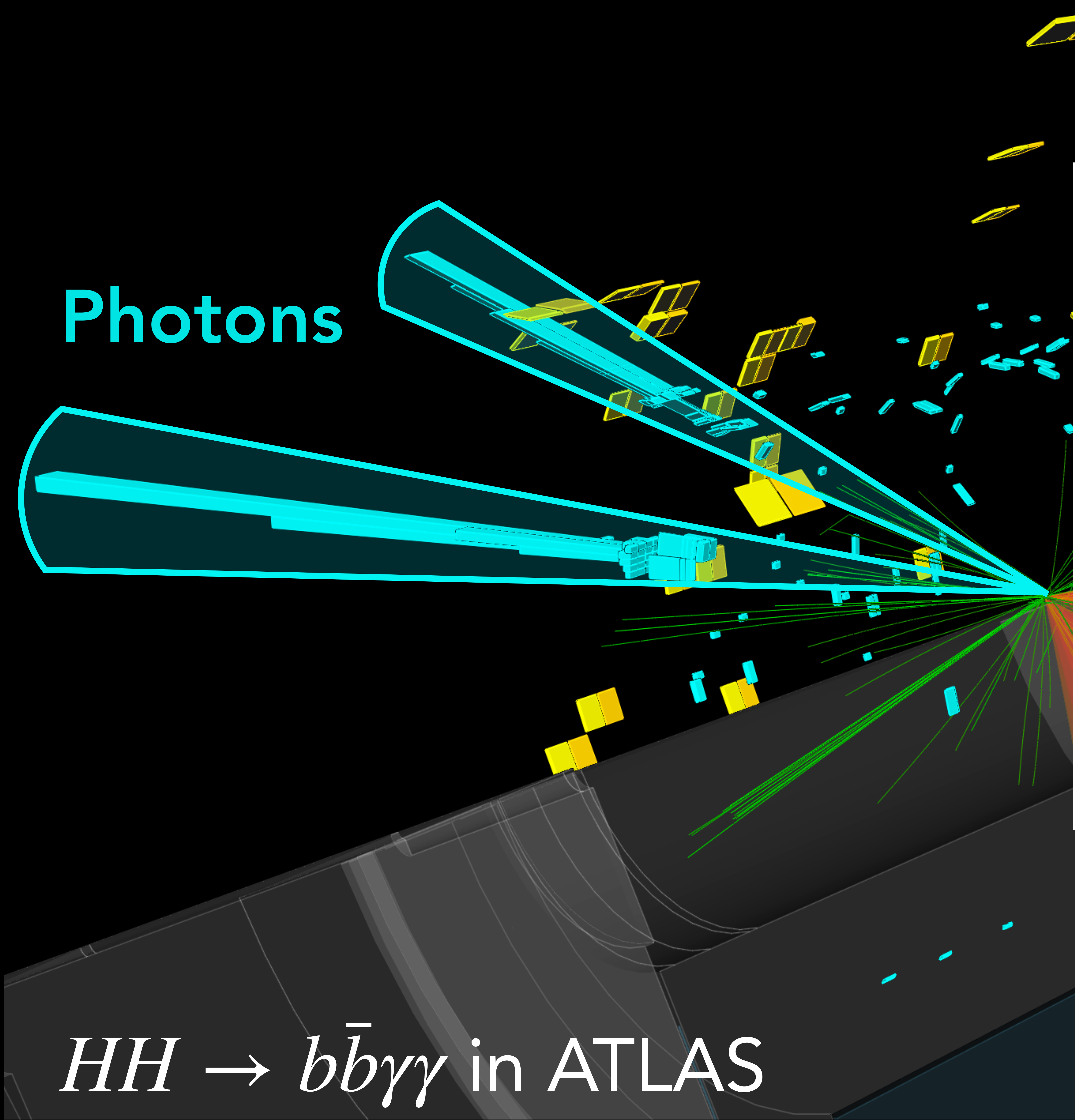
The ATLAS Collaboration

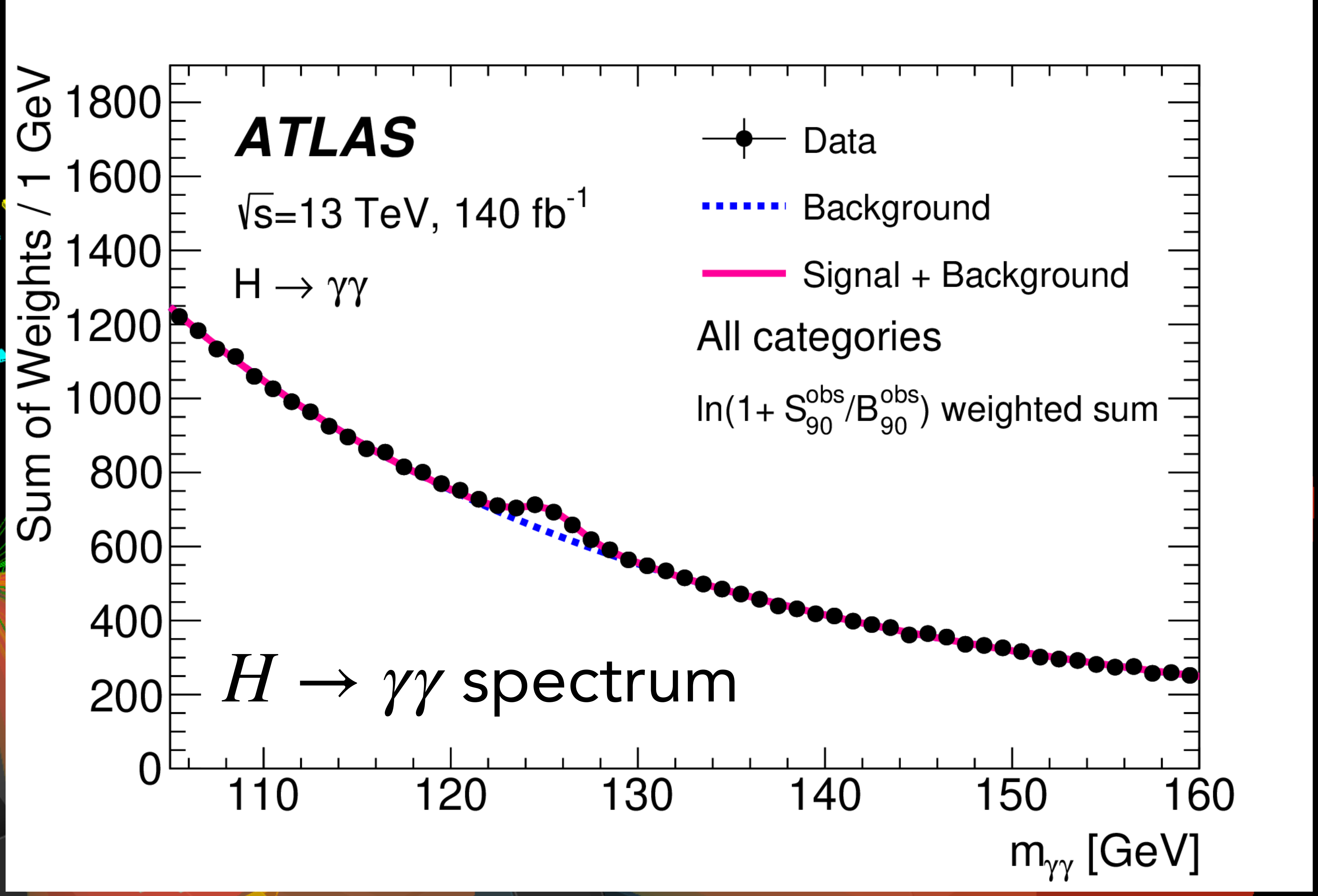
A search for nonresonant Higgs boson pair production in the $b\bar{b}\gamma\gamma$ final state is performed using 140 fb^{-1} of proton–proton collisions at a centre-of-mass energy of 13 TeV recorded by the ATLAS detector at the CERN Large Hadron Collider. This analysis supersedes and expands upon the previous nonresonant ATLAS results in this final state based on the same data sample. The analysis strategy is optimised to probe anomalous values not only of the Higgs (H) boson self-coupling modifier κ_λ but also of the quartic $HHVV$ ($V = W, Z$) coupling modifier κ_{2V}. No significant excess above the expected background from Standard Model processes is observed. An observed upper limit $\mu_{HH} < 4.0$ is set at 95% confidence level on the Higgs boson pair production cross-section normalised to its Standard Model prediction. The 95% confidence intervals for the coupling modifiers are $-1.4 < \kappa_\lambda < 6.9$ and $-0.5 < \kappa_{2V} < 2.7$, assuming all other Higgs boson couplings except the one under study are fixed to the Standard Model predictions. The results are interpreted in the Standard Model effective field theory and Higgs effective field theory frameworks in terms of constraints on the couplings of anomalous Higgs boson (self-)interactions.



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

Excellent $p_T(\gamma)$, $m_{\gamma\gamma}$ resolution

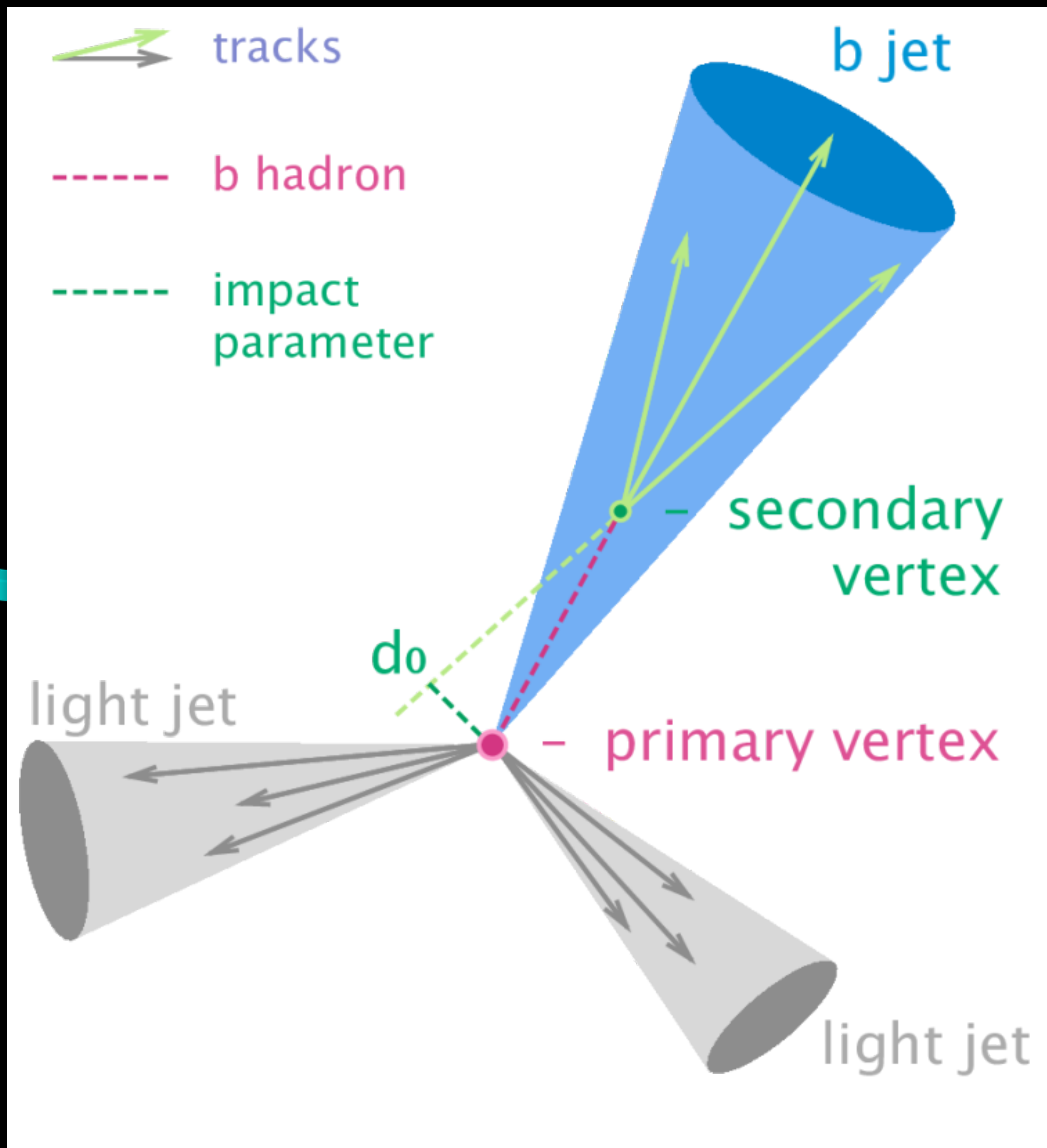


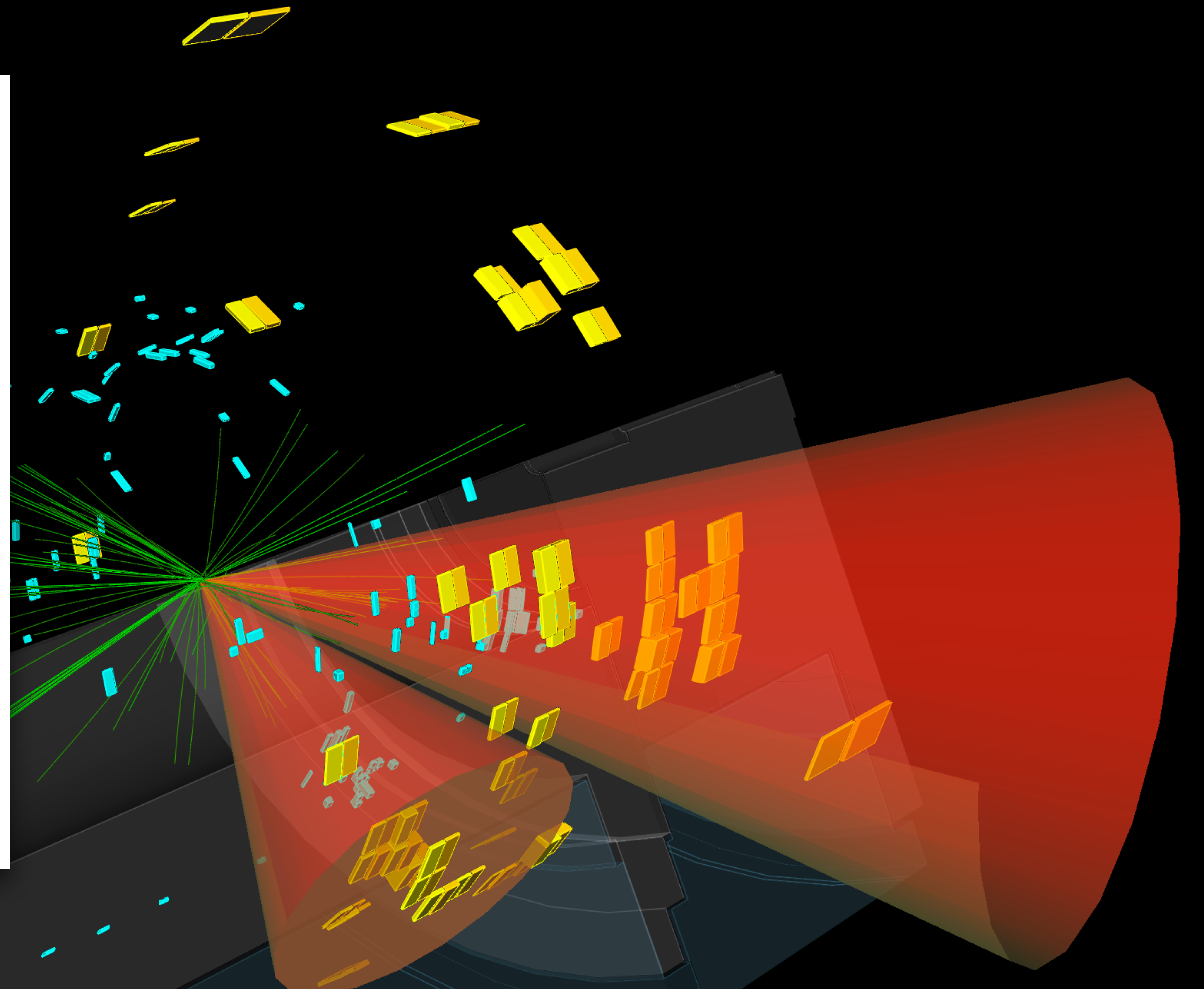


arXiv:2308.07216

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

Jet flavor tagging





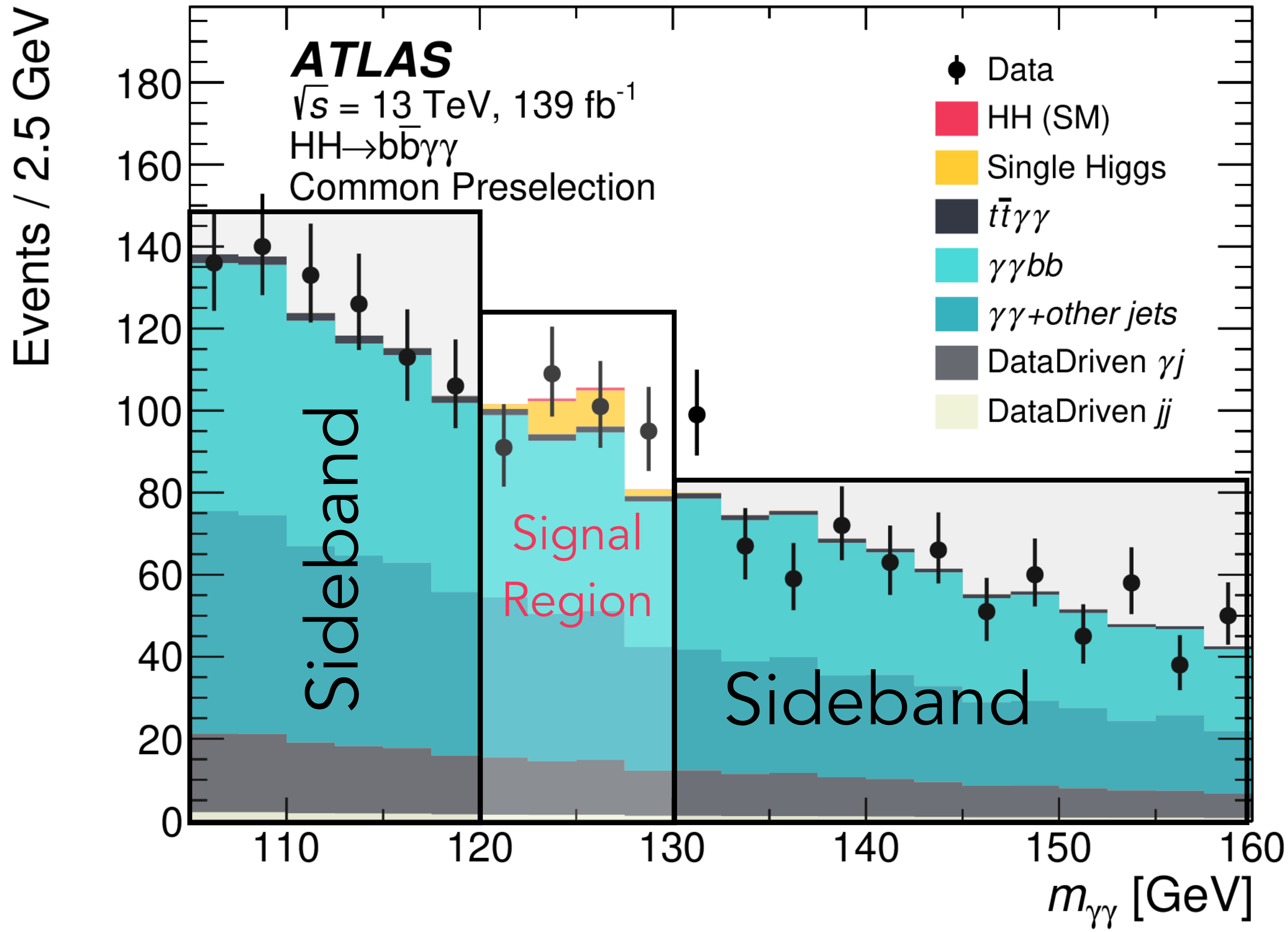
$HH \rightarrow b\bar{b}\gamma\gamma$ in ATLAS

b-tagged jets (DL1r 77% eff)

Backgrounds

- Key variable: $m_{\gamma\gamma}$
  - Define signal region
- Very small signal!
- Single Higgs production is a background 🤯!

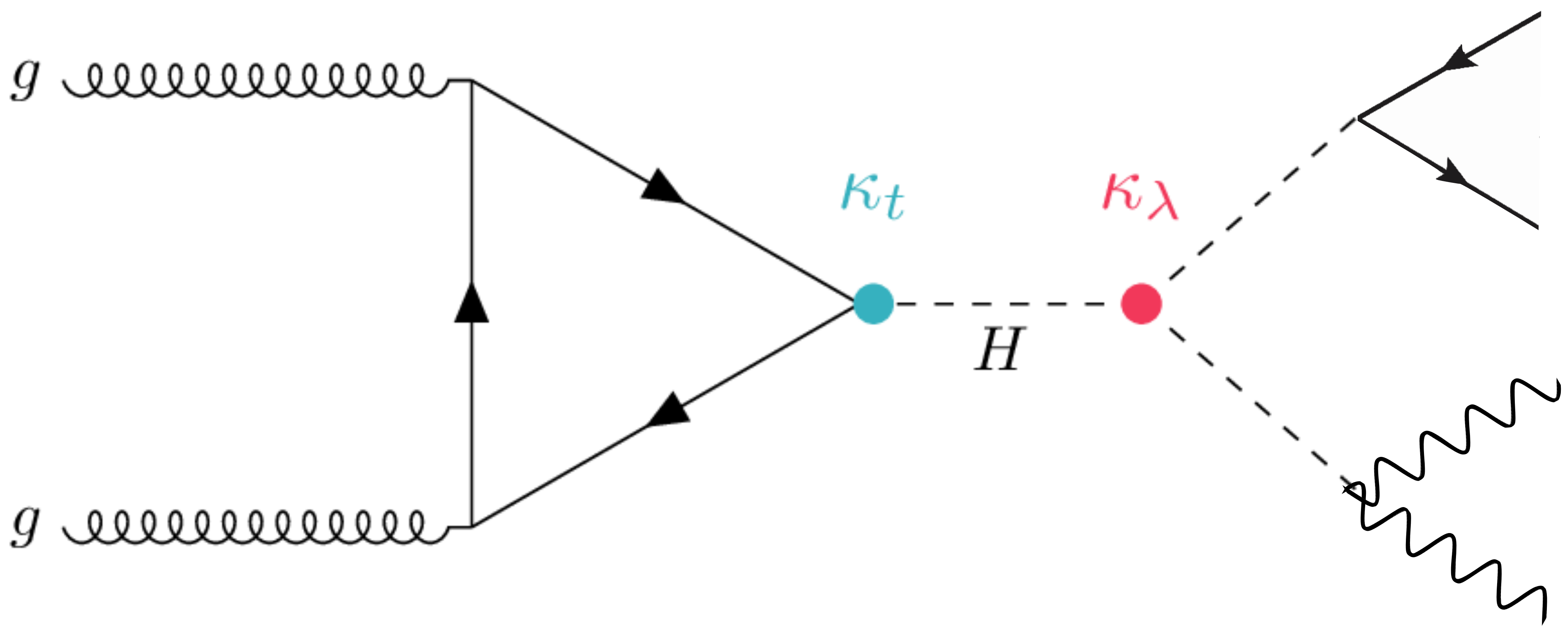
*plot from previous publication



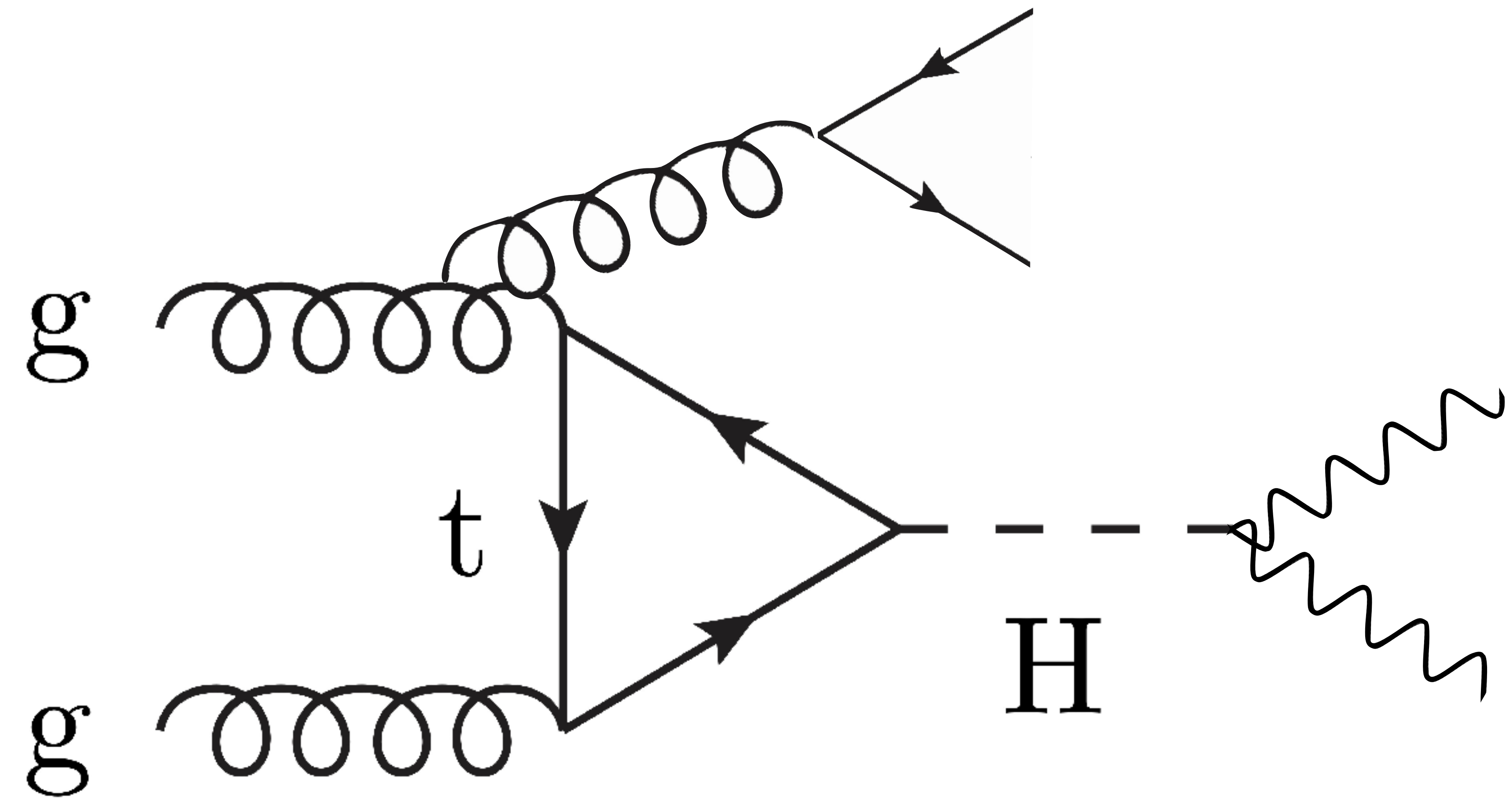
Kinematic information

- Single Higgs backgrounds are important
  - Primarily from gluon-gluon fusion (ggF) and ttH

HH signal

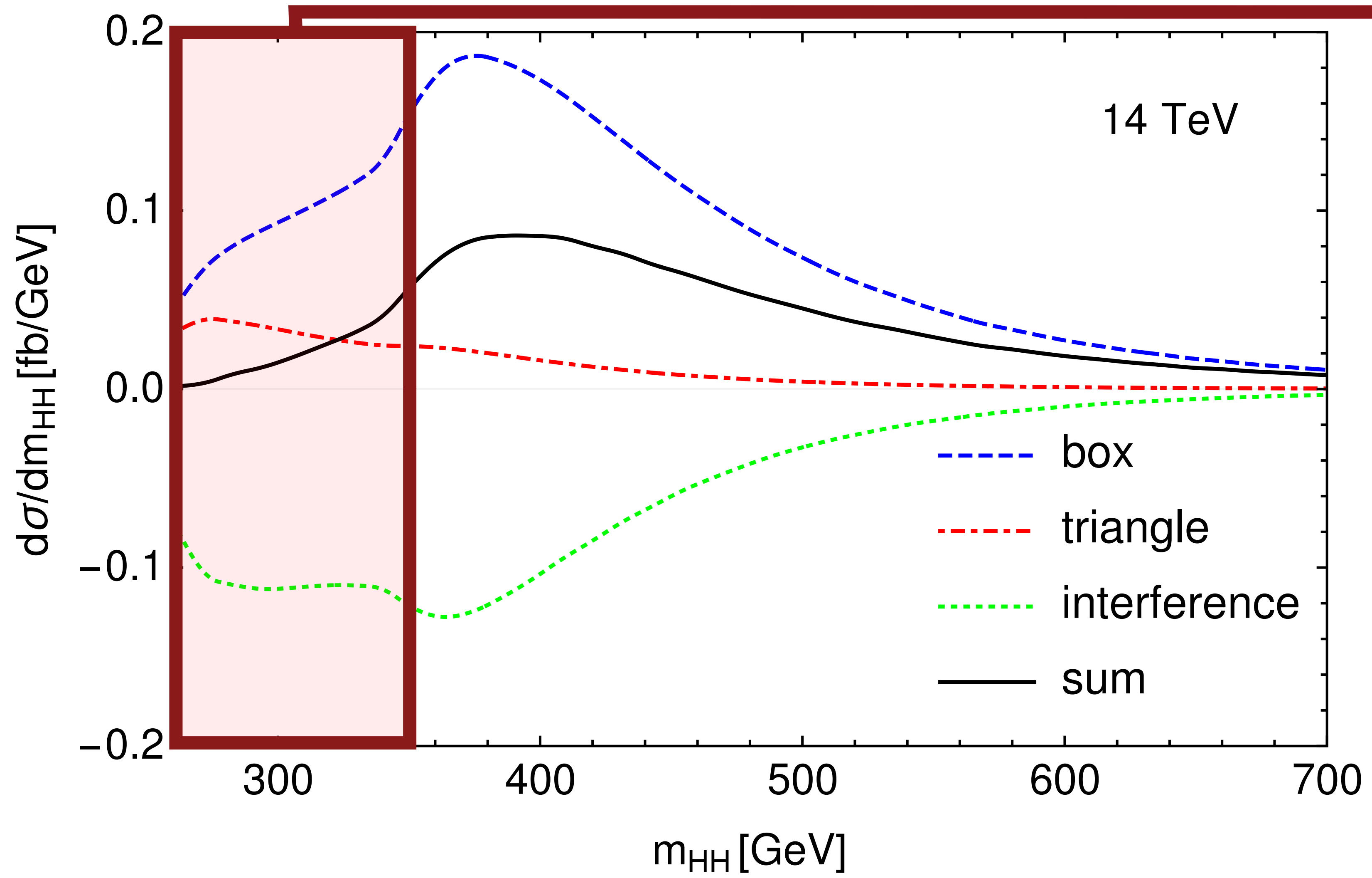


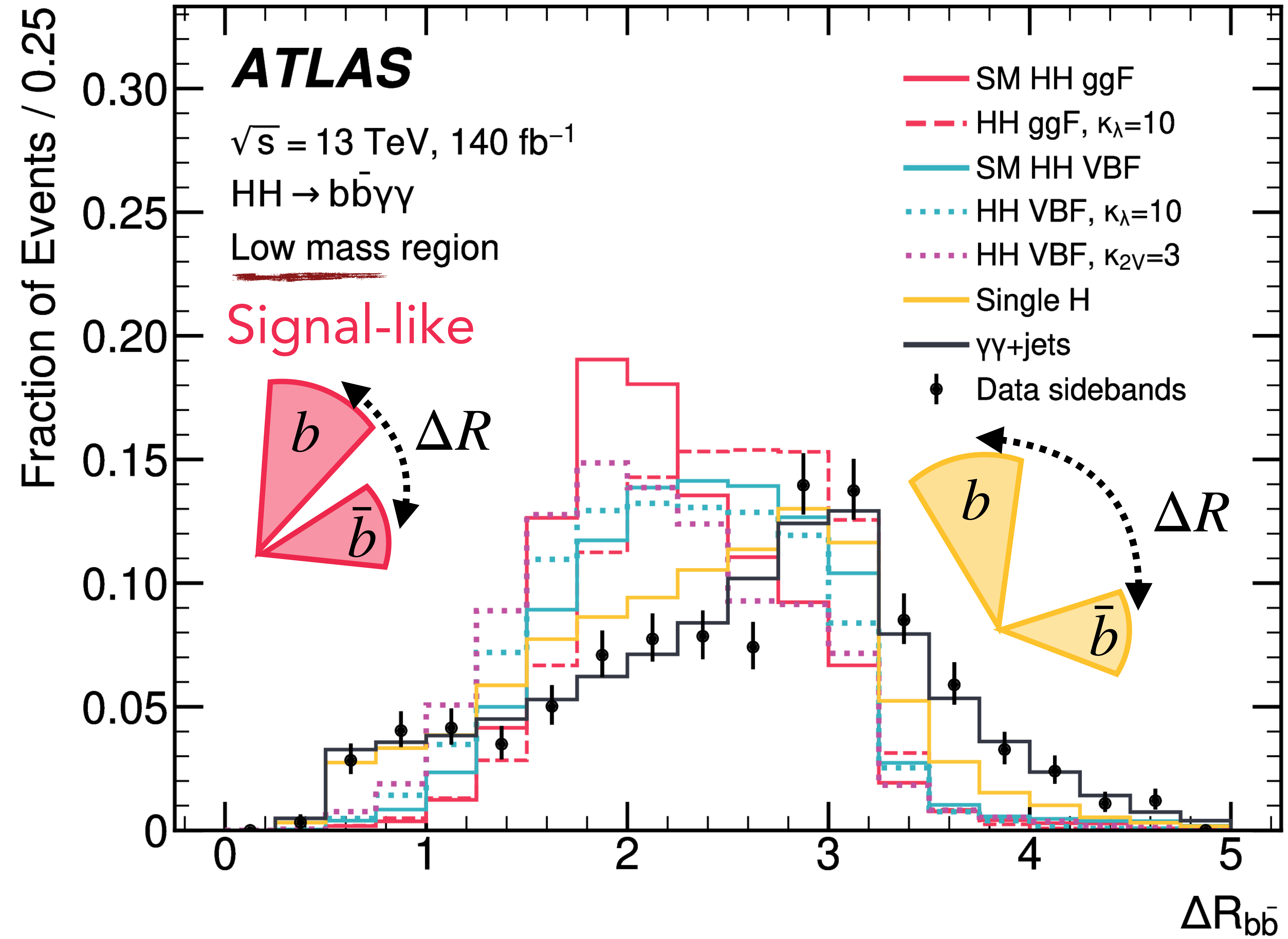
ggF + $b\bar{b}$ background



Exploit ***kinematics*** *to reduce backgrounds*

Event categorization

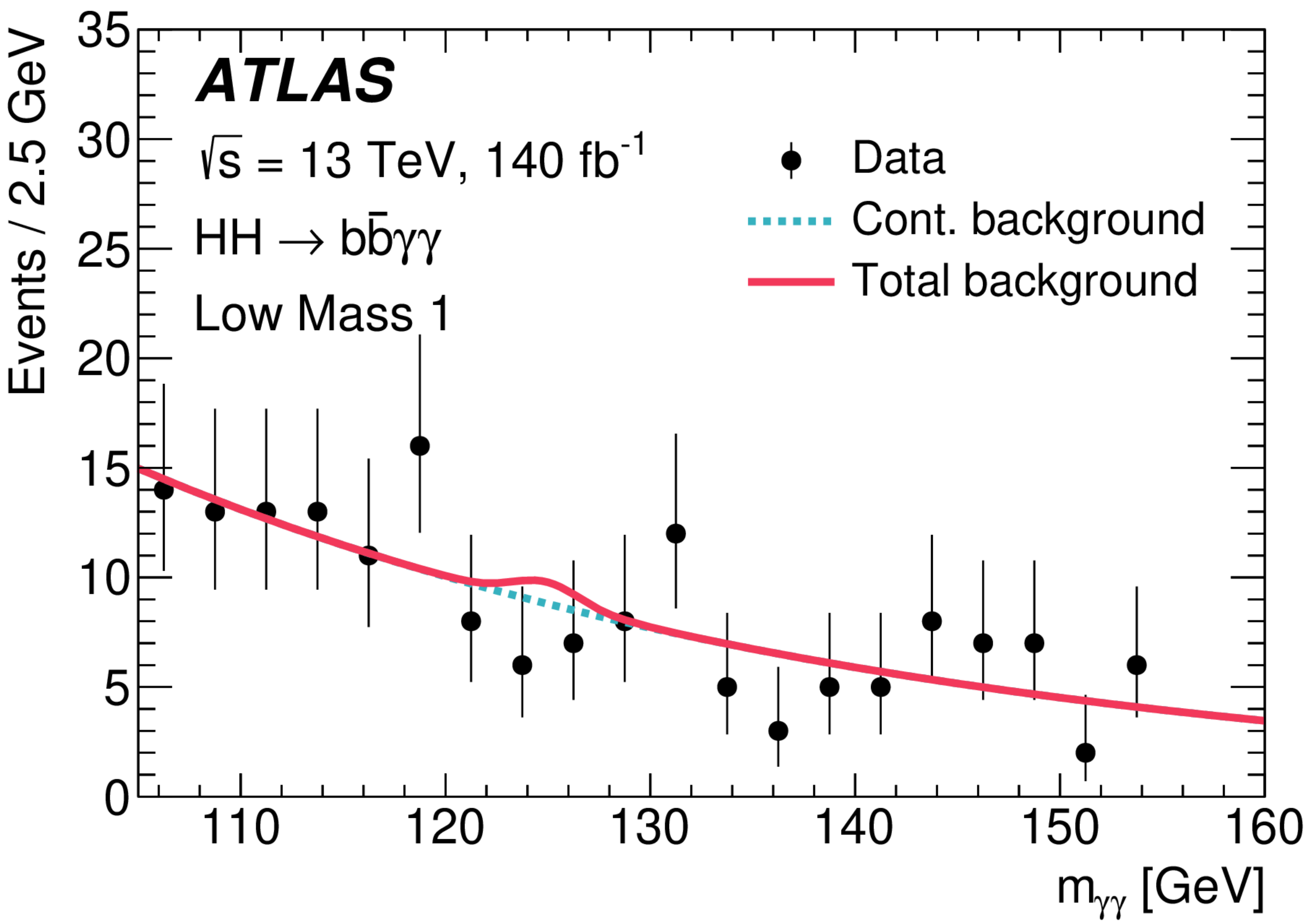




- Train **boosted decision trees** to combine kinematic info
  - Form analysis regions with varying S/B!
- **B-jet information** key for single Higgs!

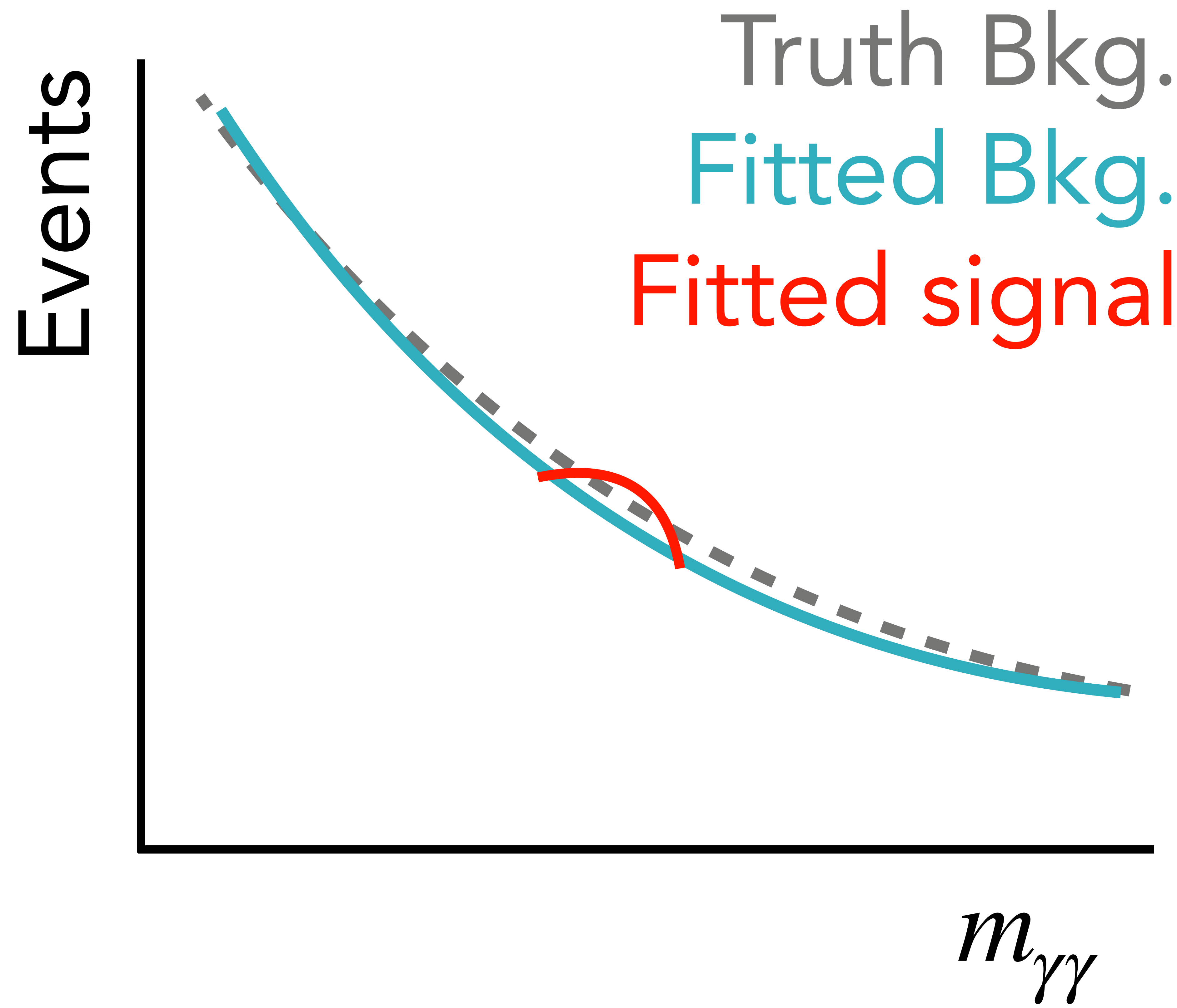
Fit strategy

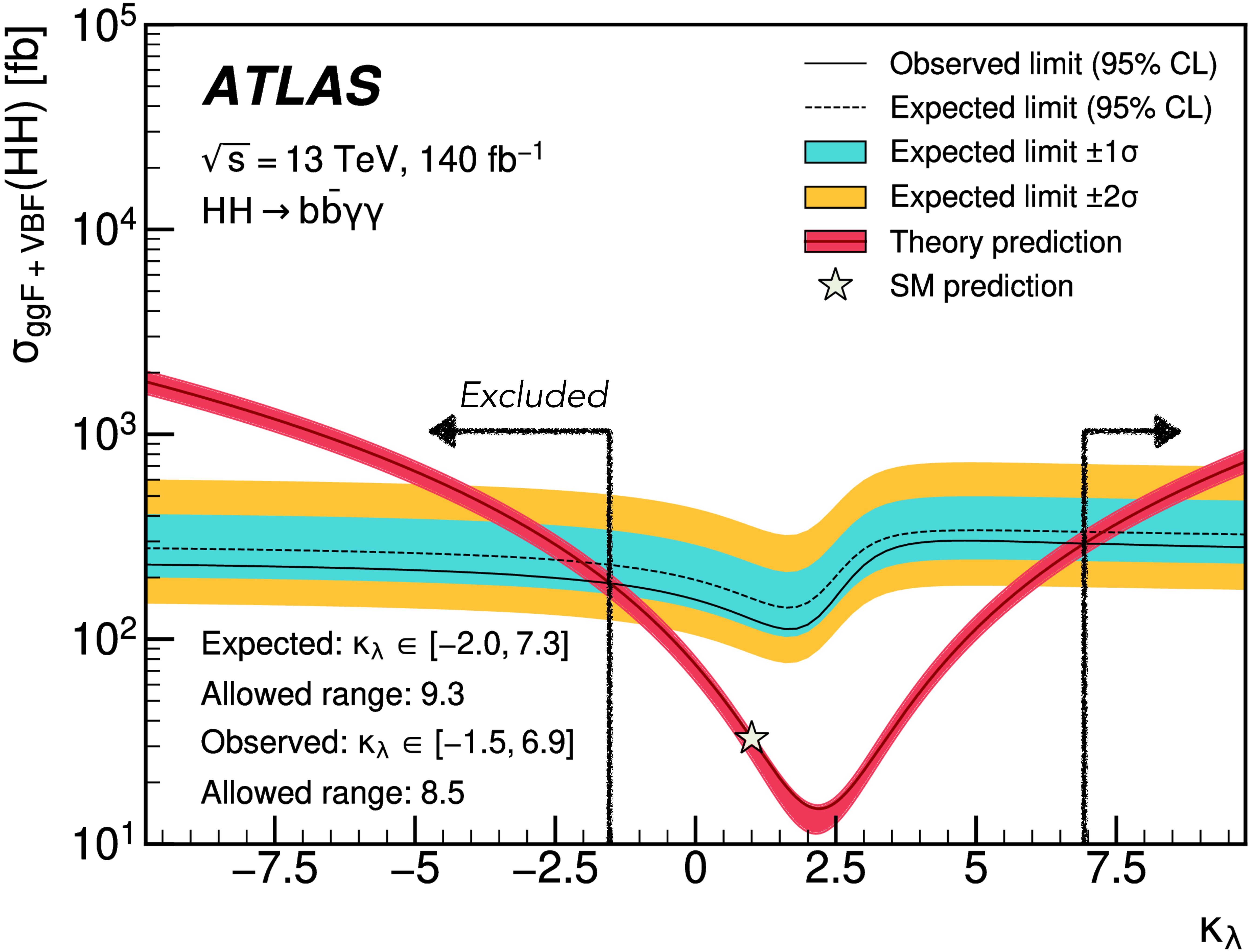
Fit data to exponential function in sidebands, **interpolate into SR**



Fit in all categories **simultaneously**

Possibility that background estimate is incorrect → **spurious signal**



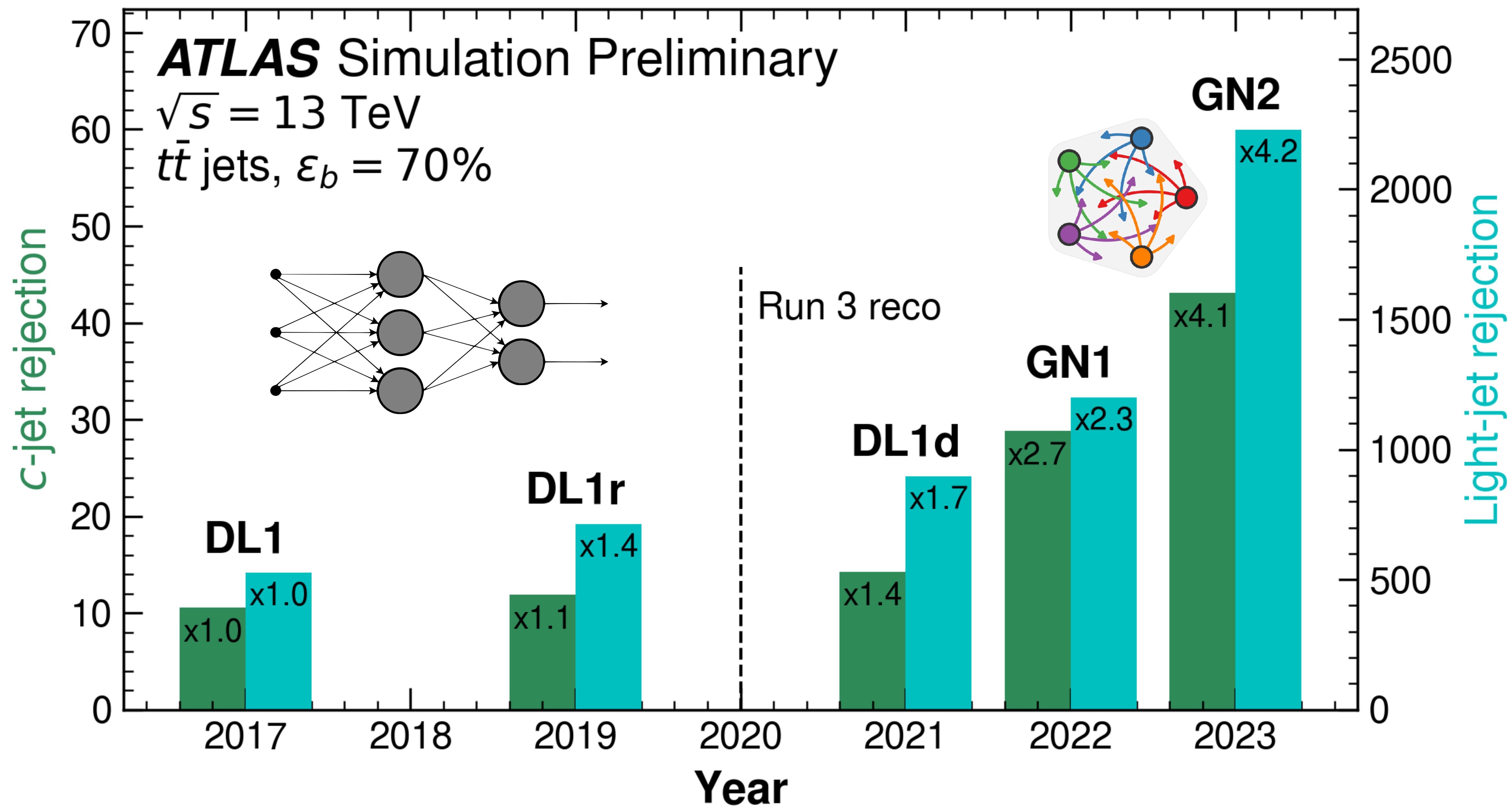


Wide range of BSM scenarios still possible!

Next steps

Can we do anything besides take **more data**?

B-tagging dramatically improved with **graph neural networks**



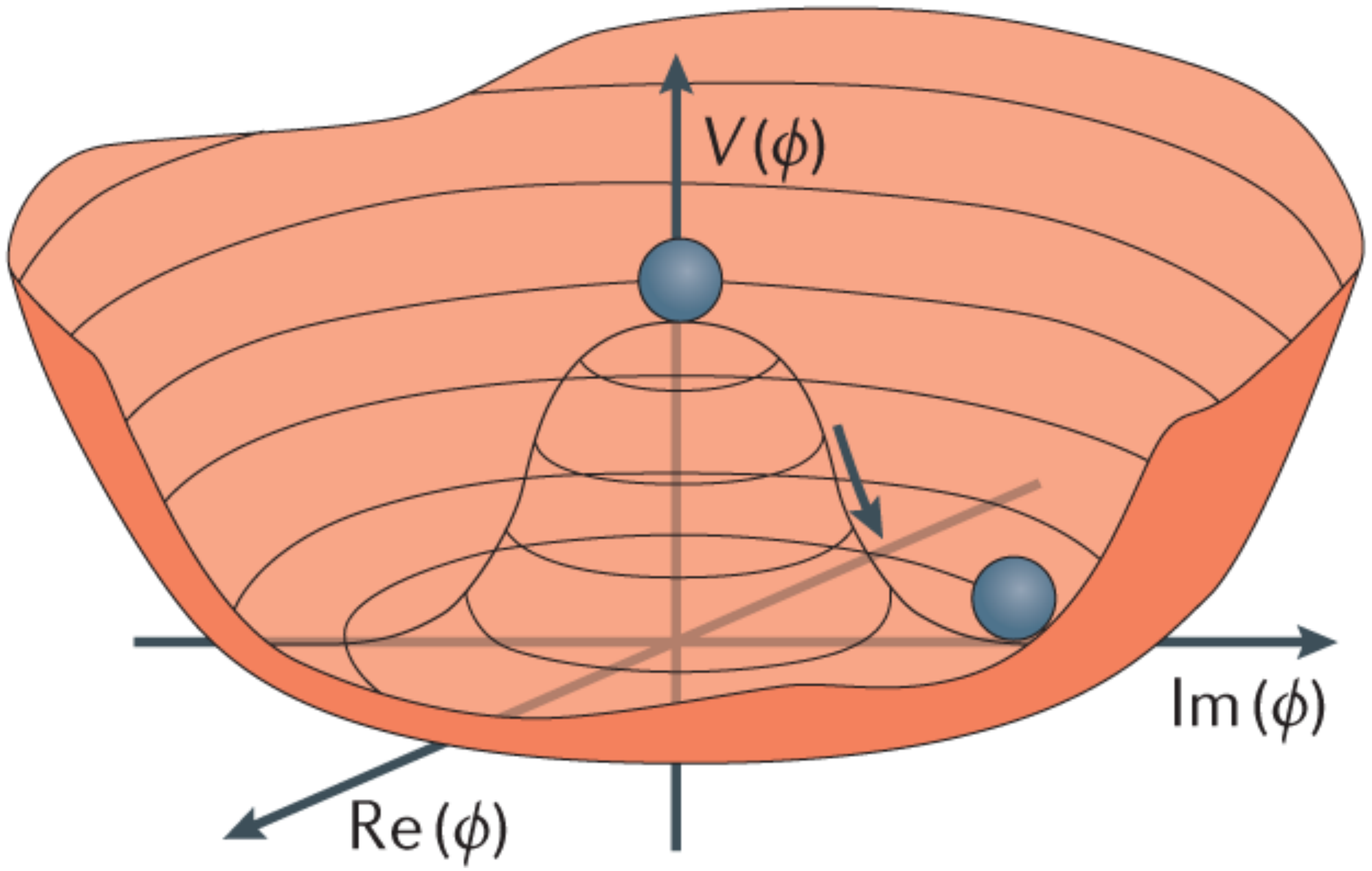
→ apply GNN to the task of **b-jet p_T regression**

Thanks for your attention!

Backup

The Higgs self-coupling

→ How to measure the **shape**?



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

In vacuum, $\phi = v + h$:

$$V(h) = -\frac{1}{2}m_h^2 h^2 \quad \text{(mass)}$$

$$-\underbrace{\frac{m_h^2}{2v^2}}_{\lambda_{hhh}} vh^3 + \underbrace{\frac{m_h^2}{8v^2}}_{\lambda_{hhhh}} h^4$$

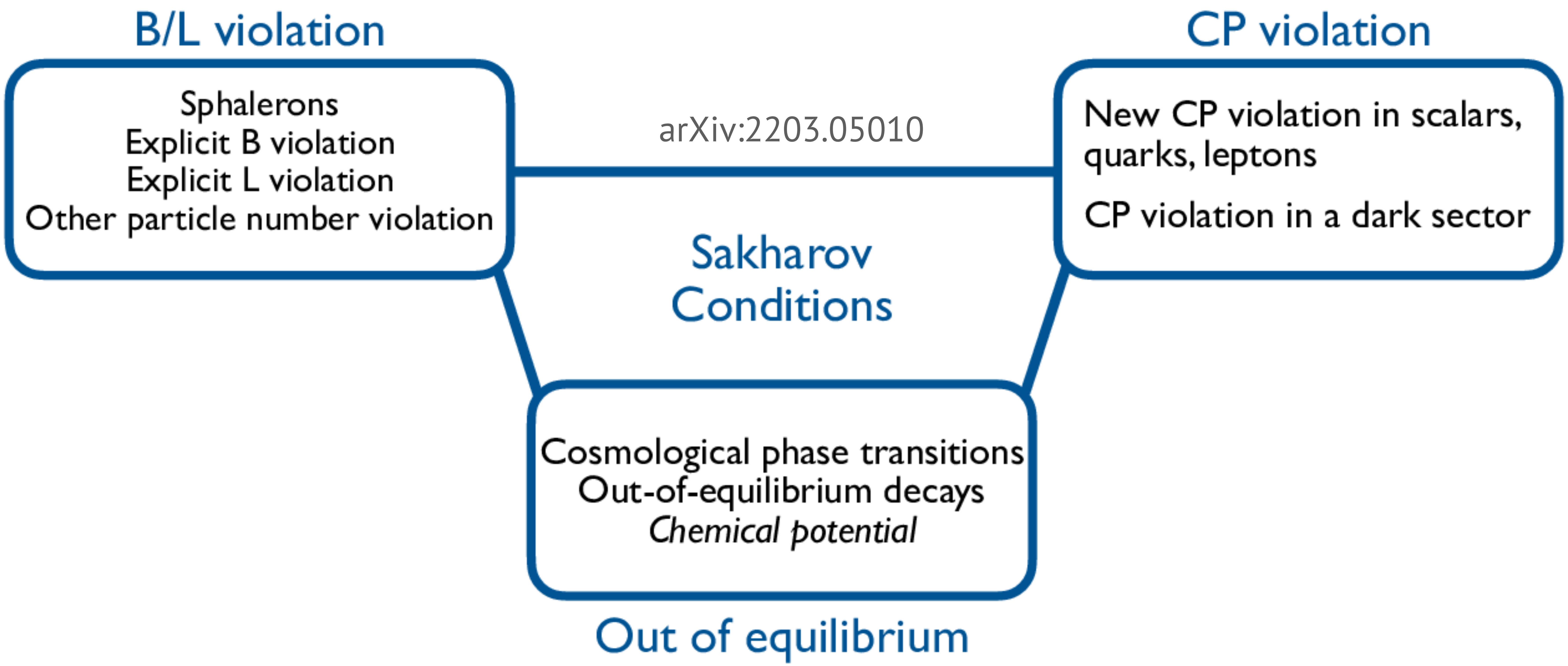
→ Measure the trilinear Higgs **self-coupling**

Baryogenesis

If universe began with equal matter/antimatter,
three basic conditions are required

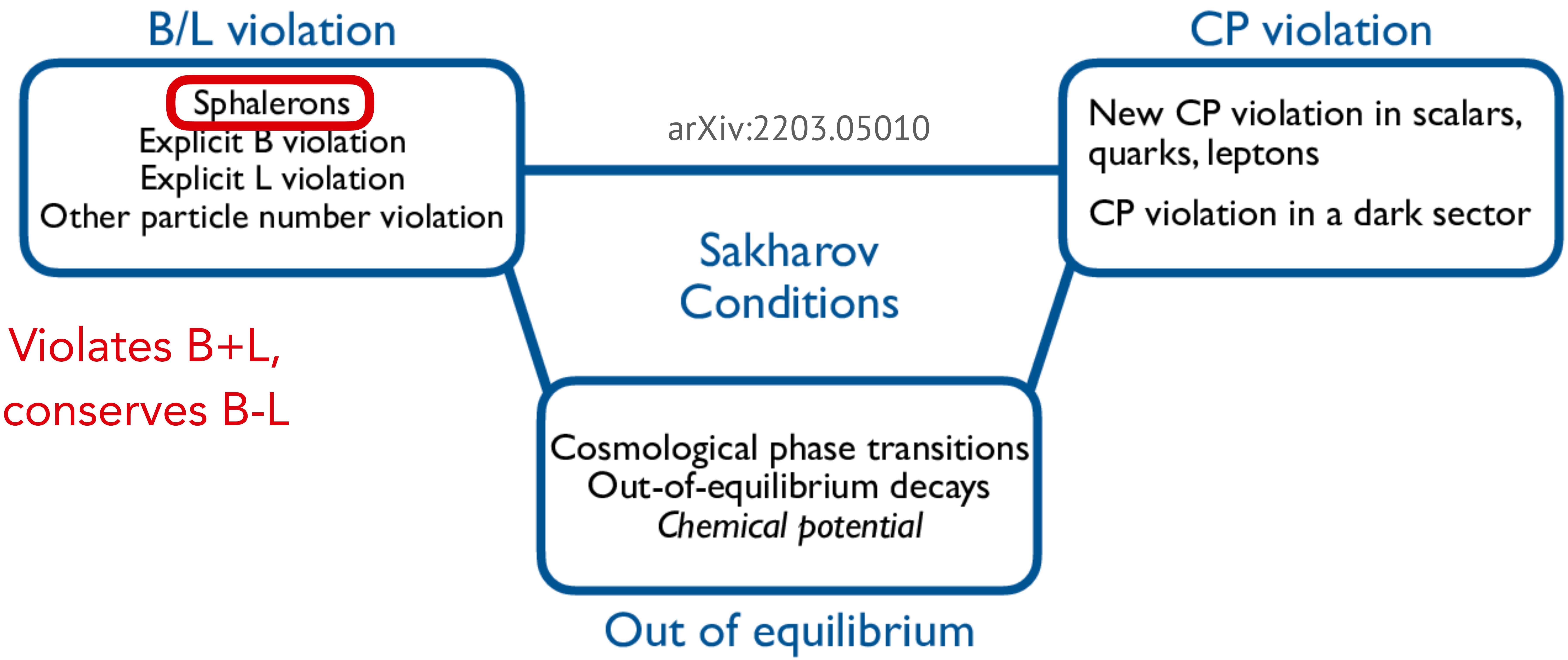
Baryogenesis

If universe began with equal matter/antimatter,
three basic conditions are required



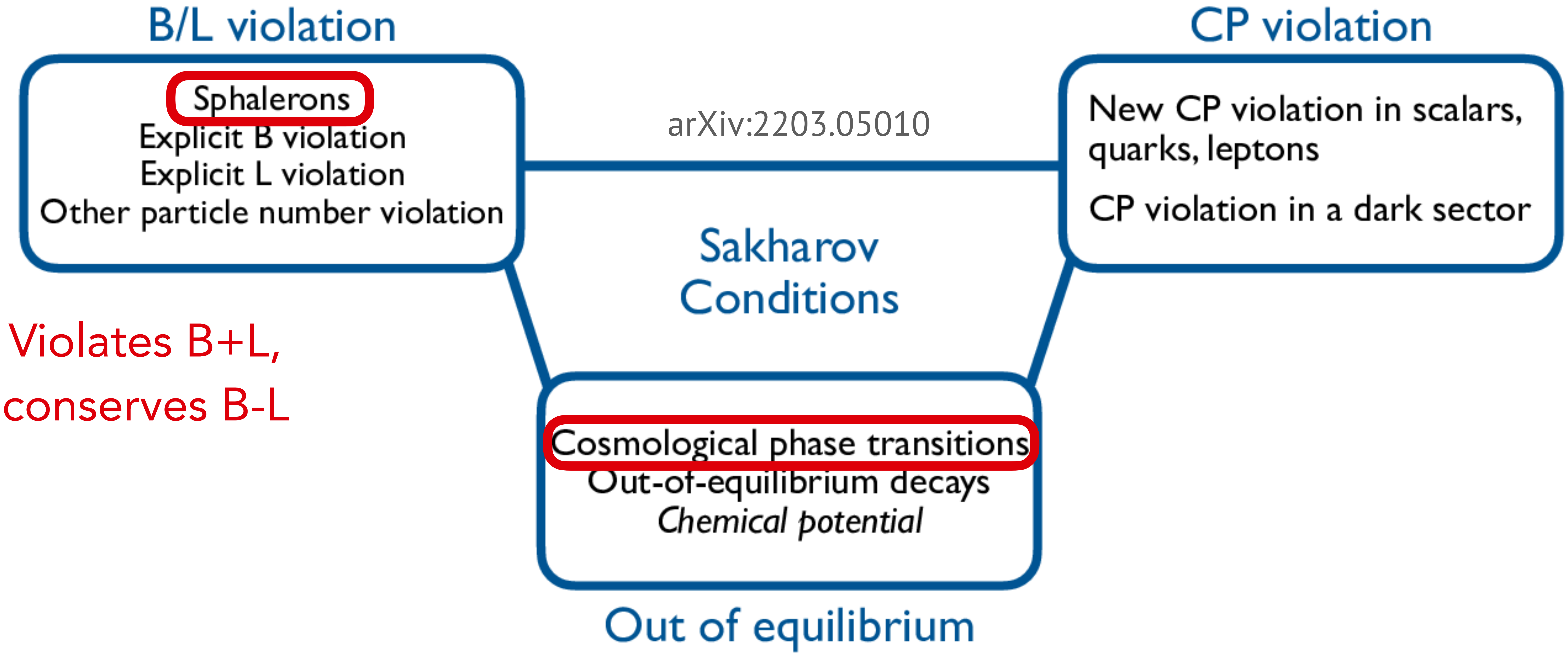
Baryogenesis

If universe began with equal matter/antimatter,
three basic conditions are required



Violates B+L,
conserves B-L

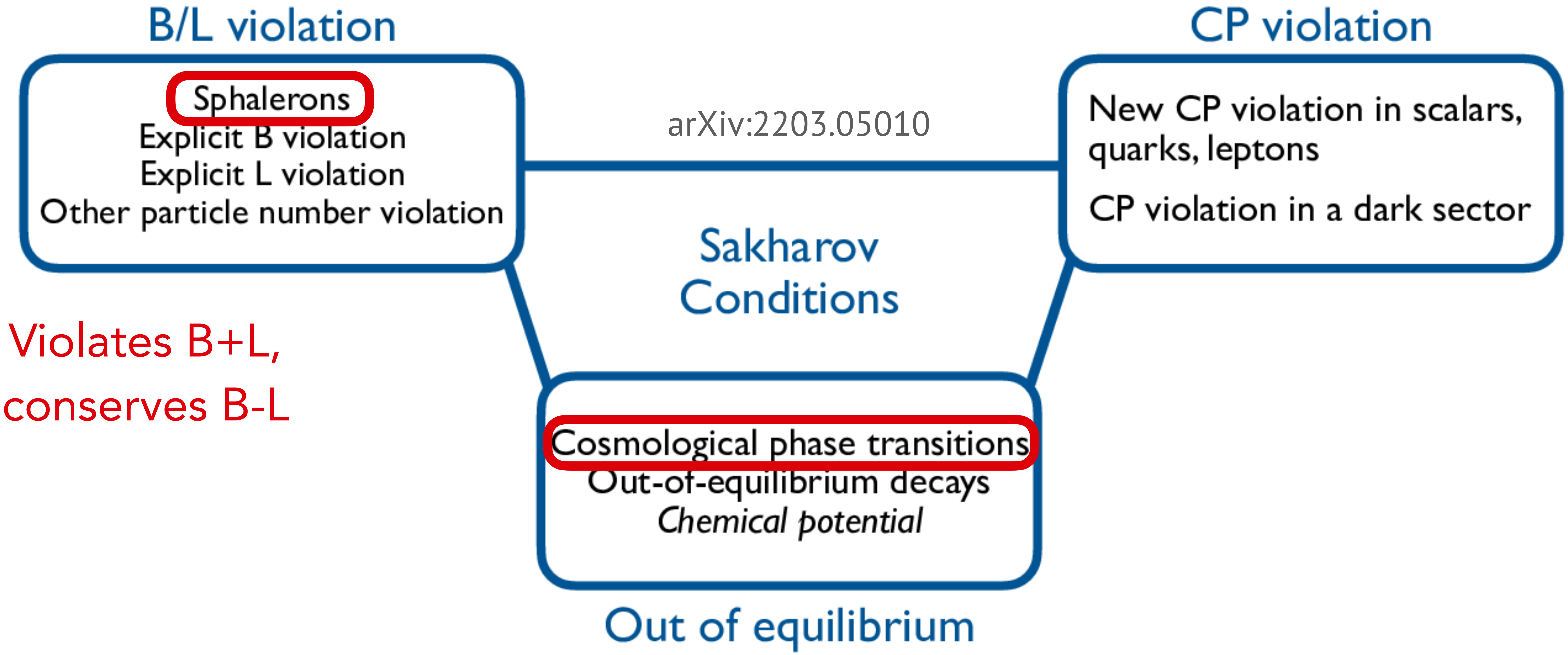
If universe began with equal matter/antimatter, three basic conditions are required



Violates B+L, conserves B-L

Baryogenesis

If universe began with equal matter/antimatter,
three basic conditions are required

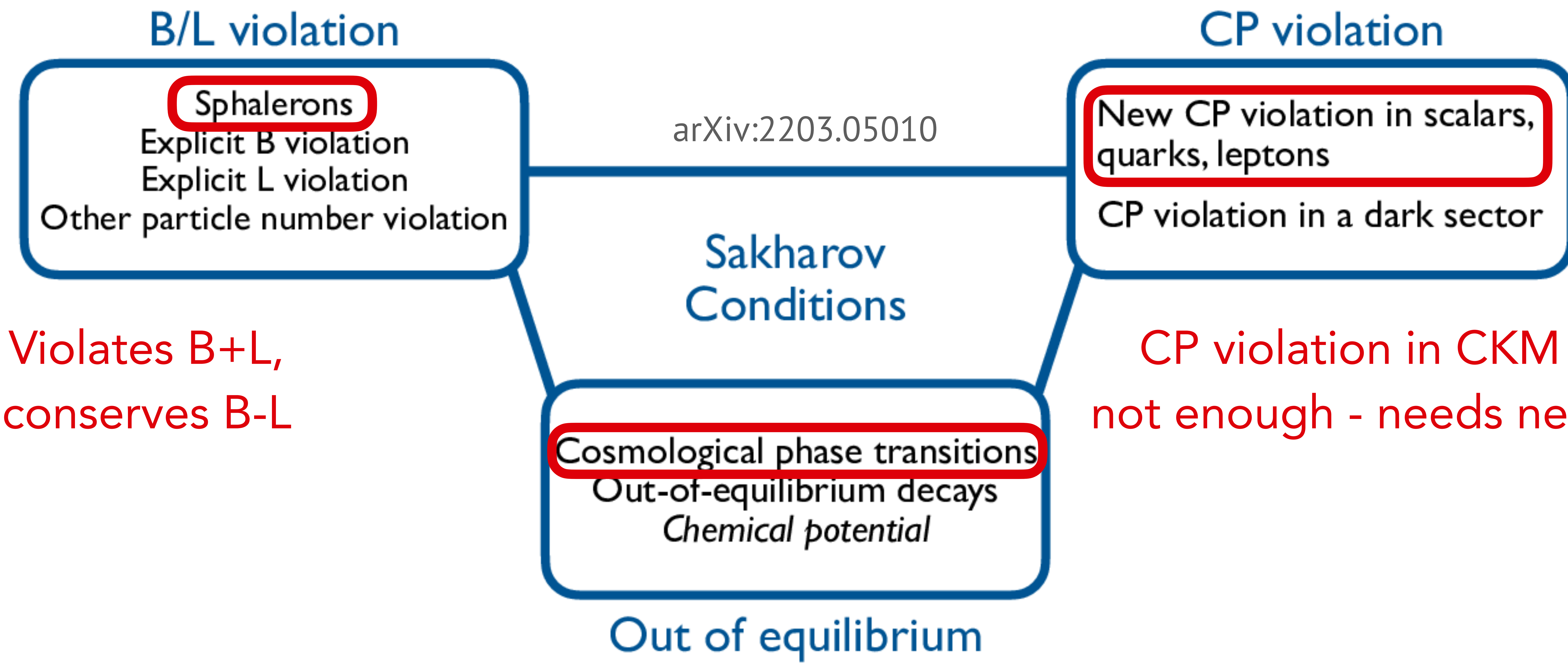


Violates B+L,
conserves B-L

First order phase transition
(EW phase transition is 2nd order, needs new physics)

Baryogenesis

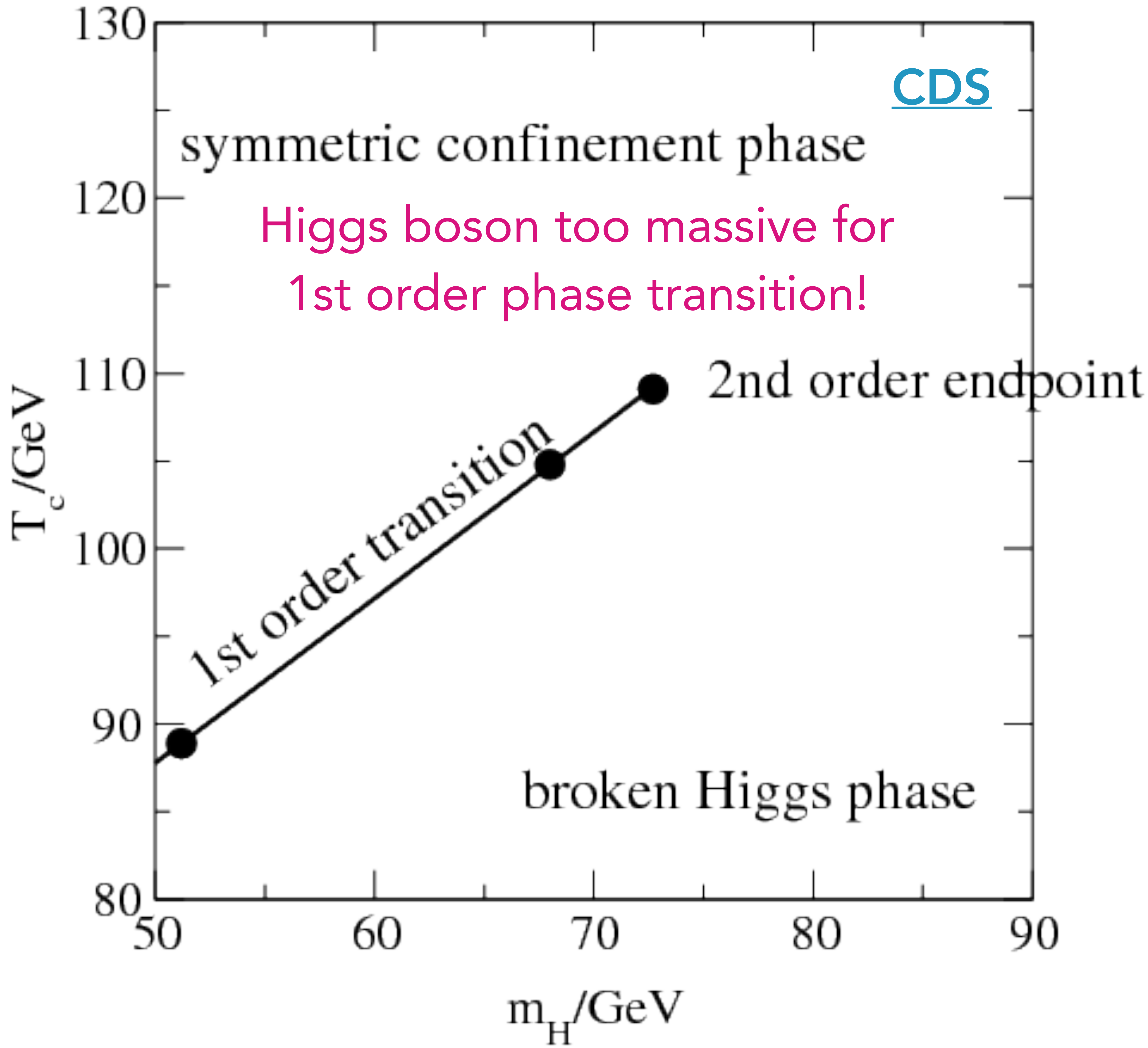
If universe began with equal matter/antimatter,
three basic conditions are required



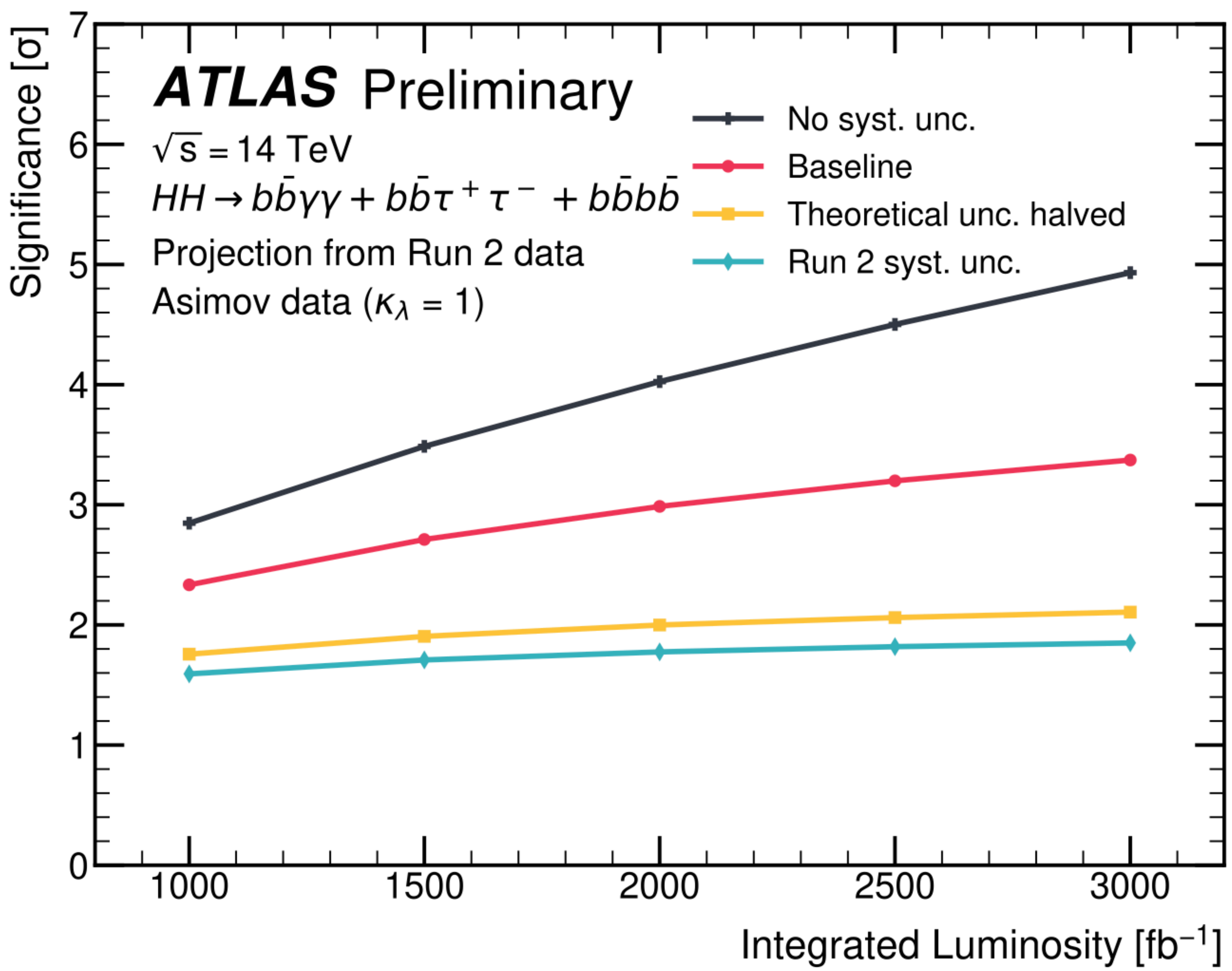
Violates B+L,
conserves B-L

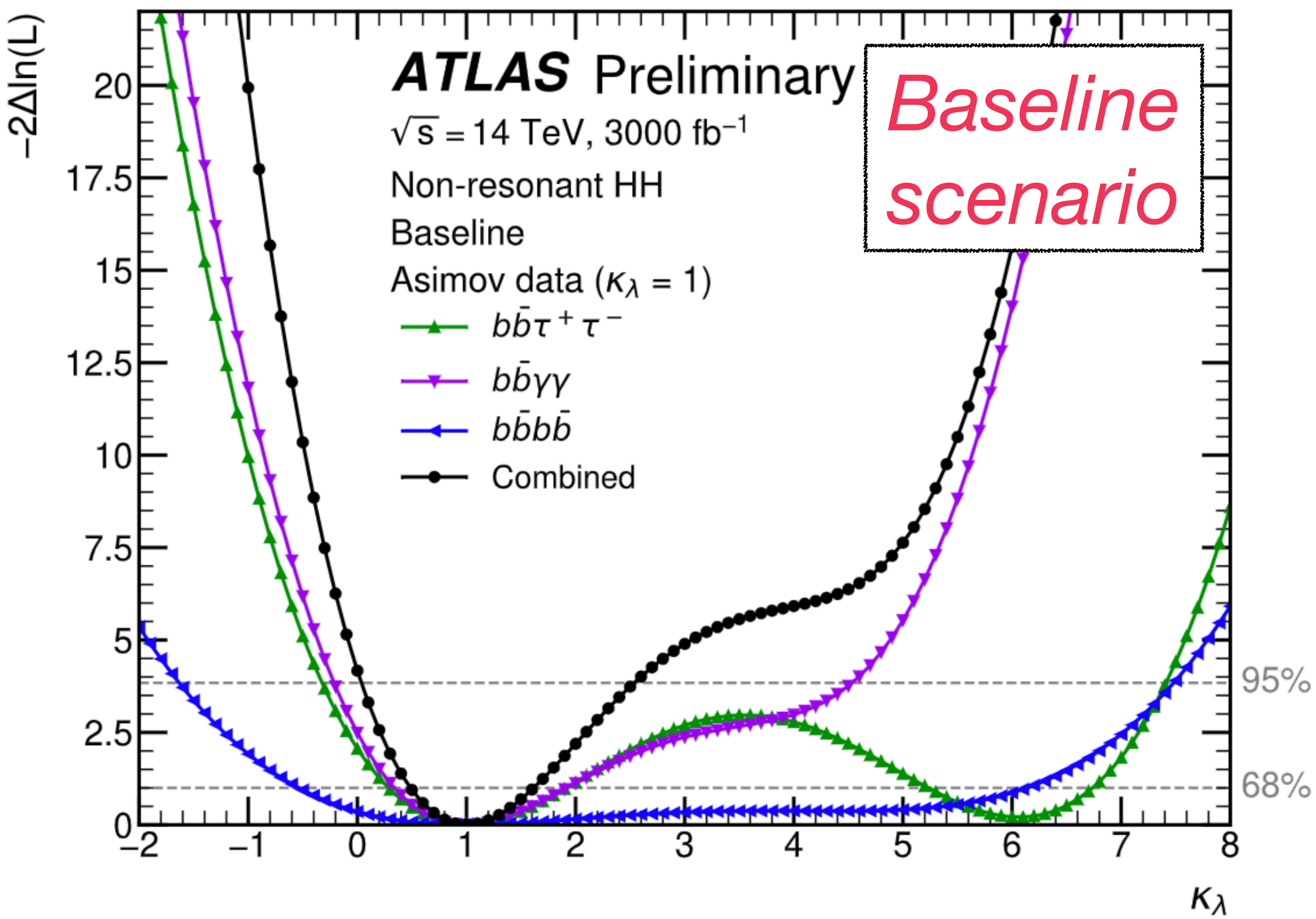
CP violation in CKM matrix,
not enough - needs new physics

First order phase transition
(EW phase transition is 2nd order, needs new physics)

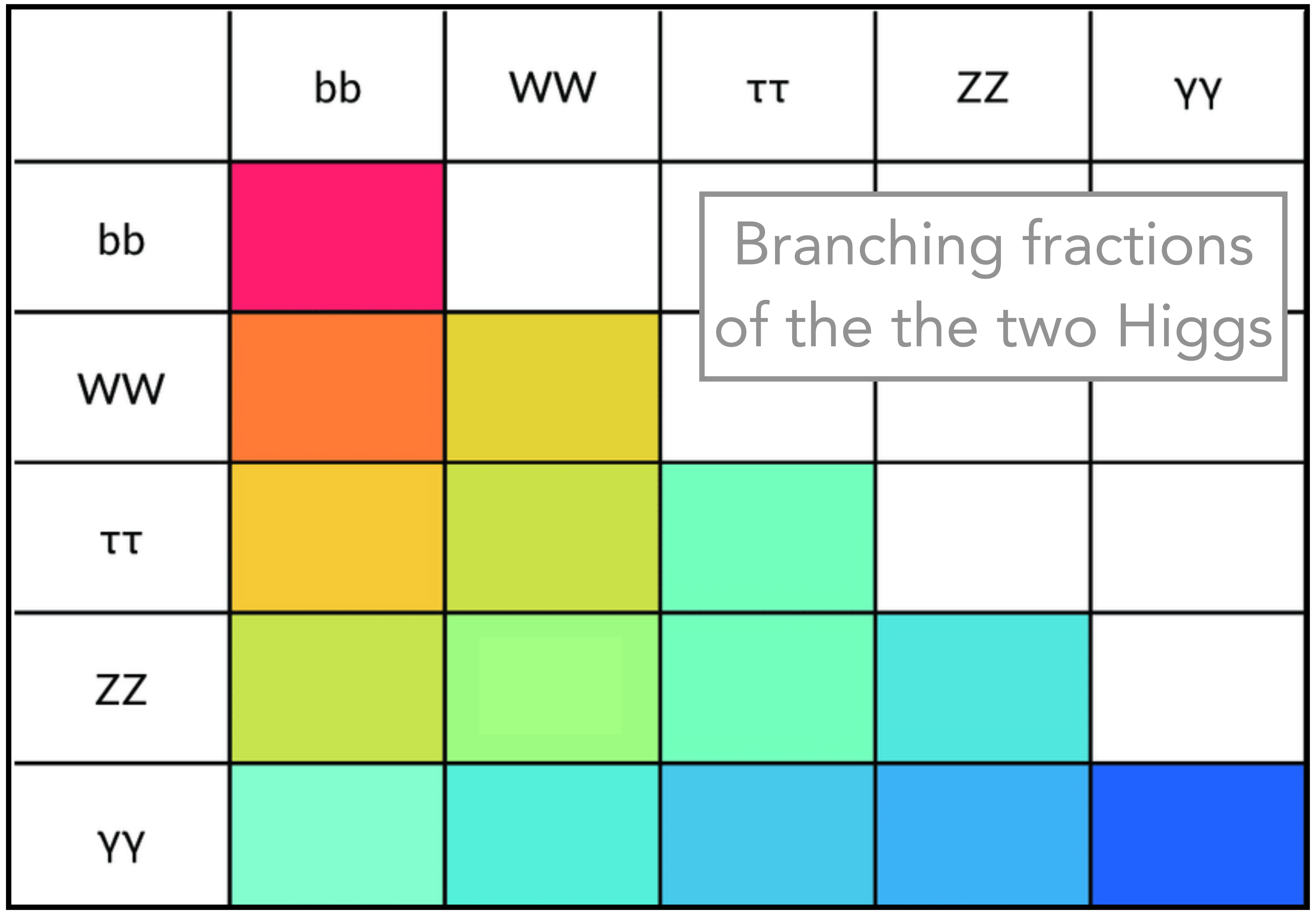

CDS
symmetric confinement phase
Higgs boson too massive for
1st order phase transition!
2nd order endpoint
1st order transition
broken Higgs phase
T_c/GeV
130
120
110
100
90
80
50
60
70
80
90
m_H/GeV

Observation of HH production will be challenging

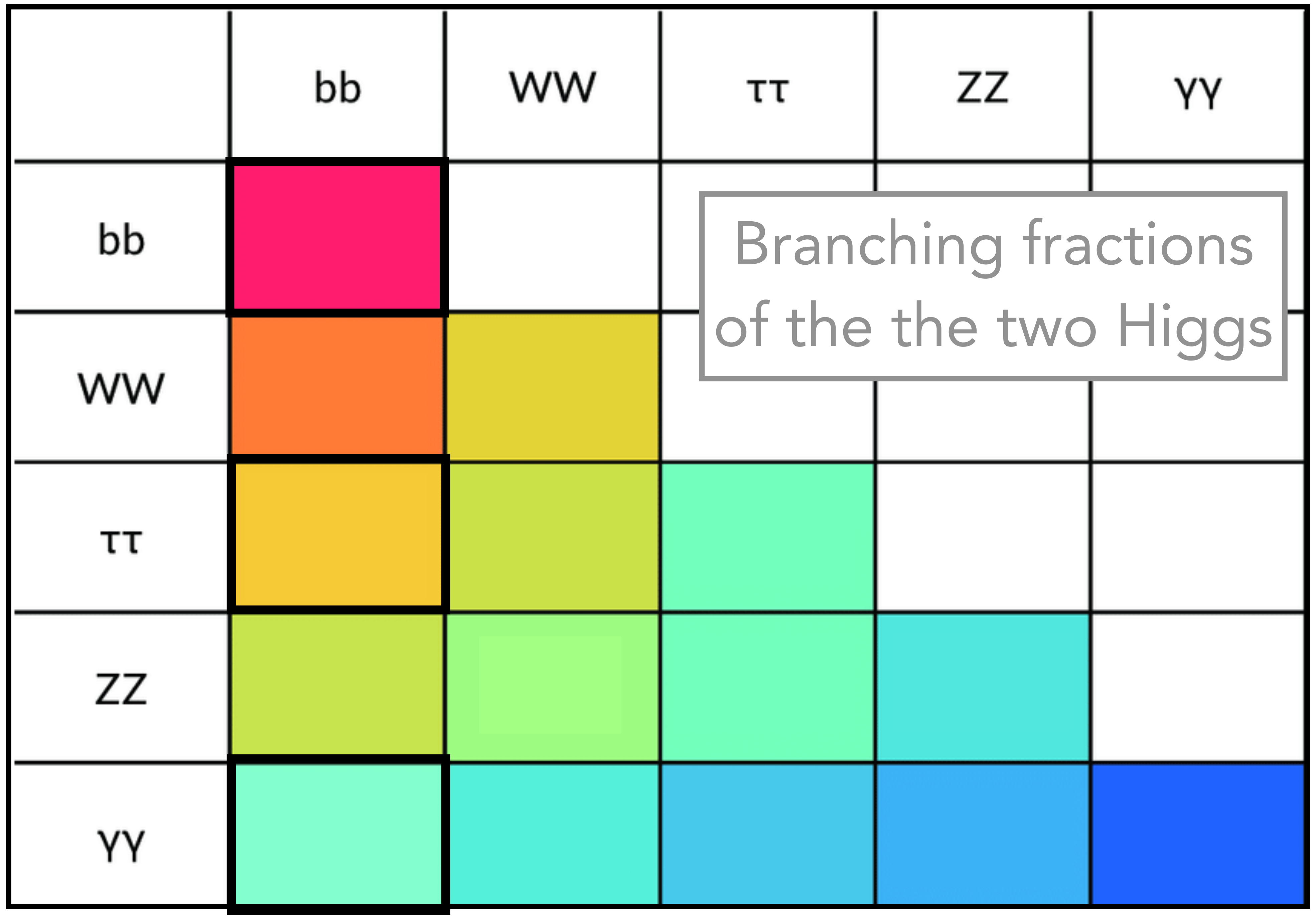




Primary channels



Primary channels

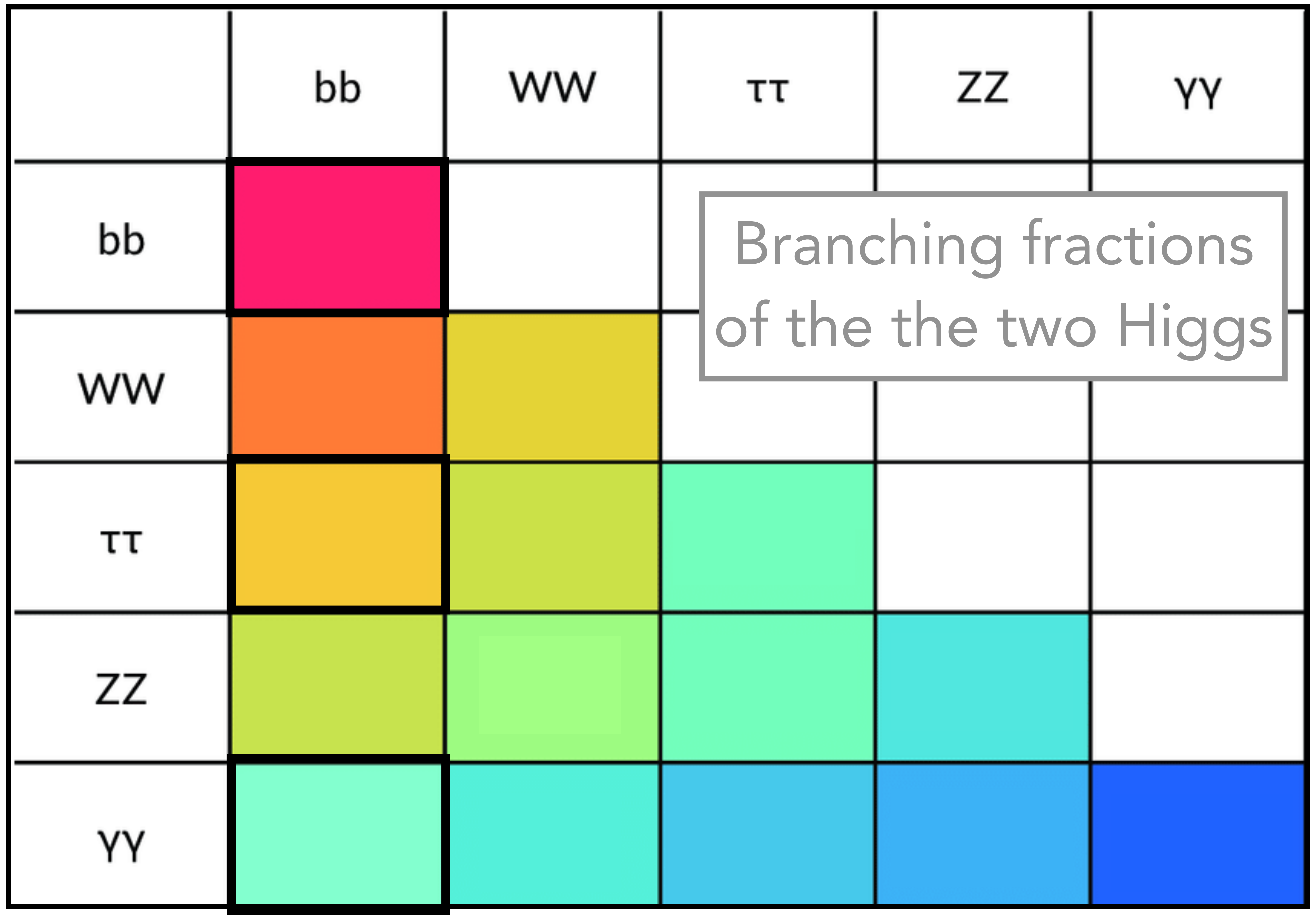


$b\bar{b}\gamma\gamma$

$b\bar{b}\tau\tau$

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

Primary channels

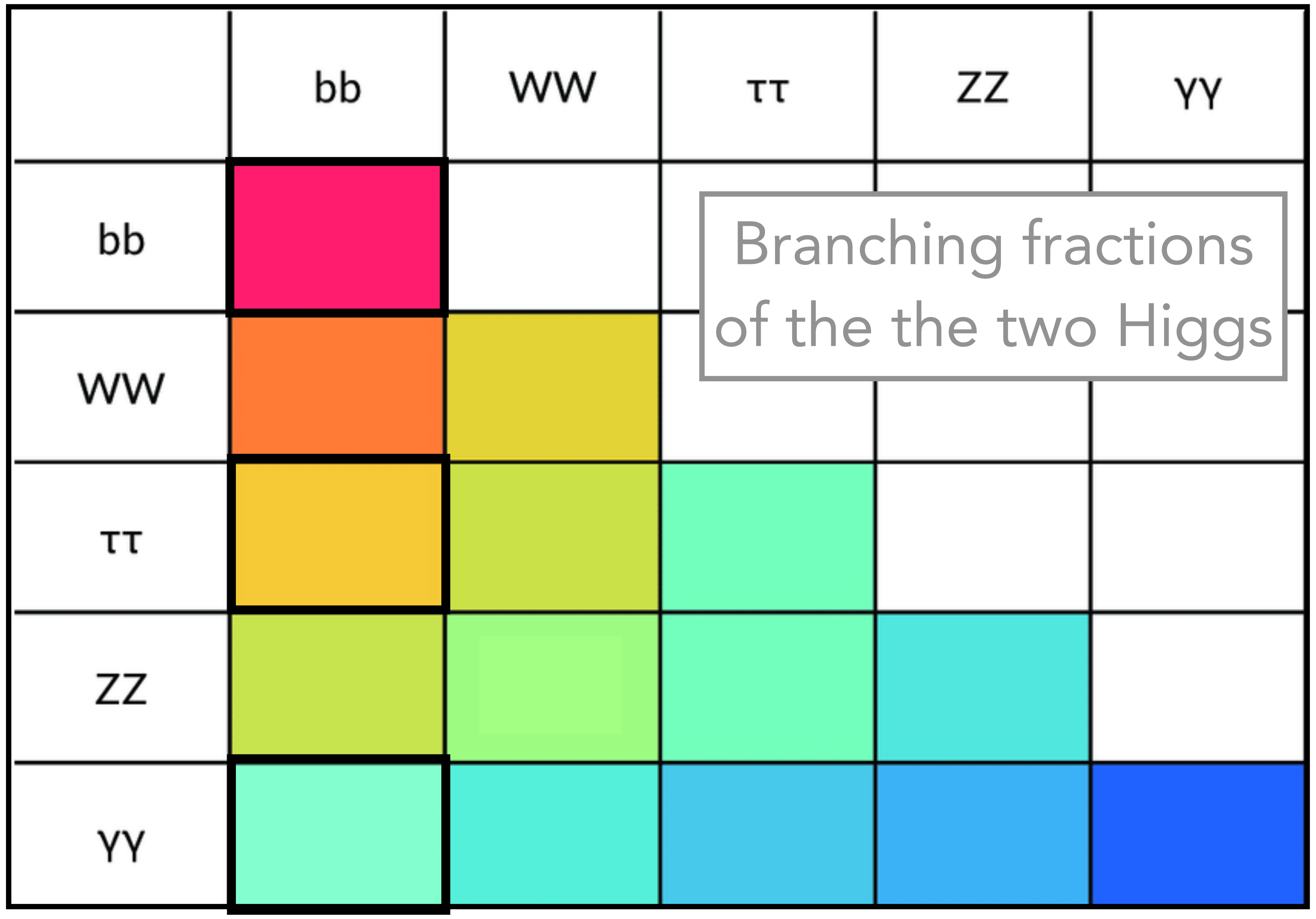


Larger branching fraction

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

Smaller S/B

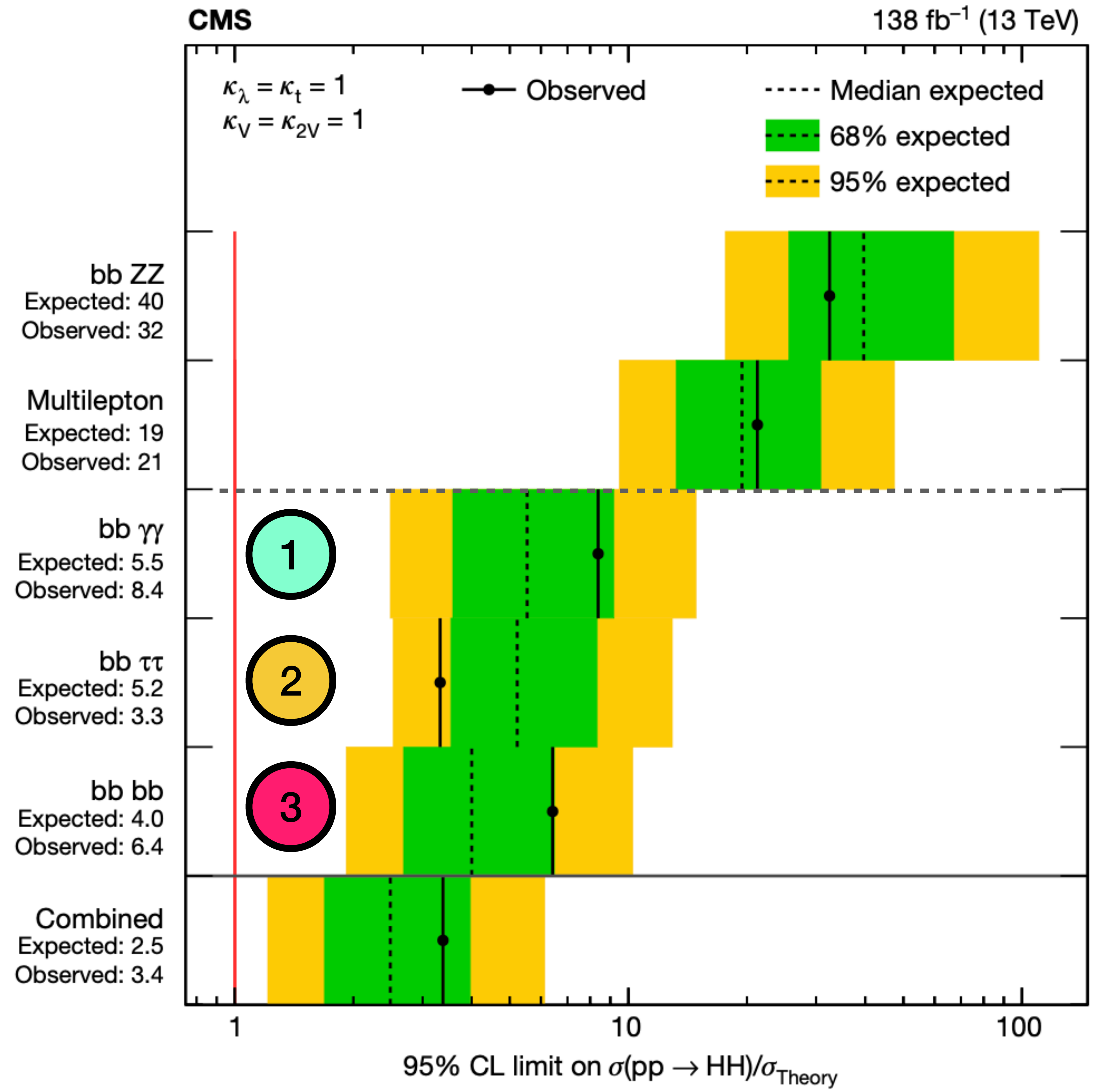
Primary channels



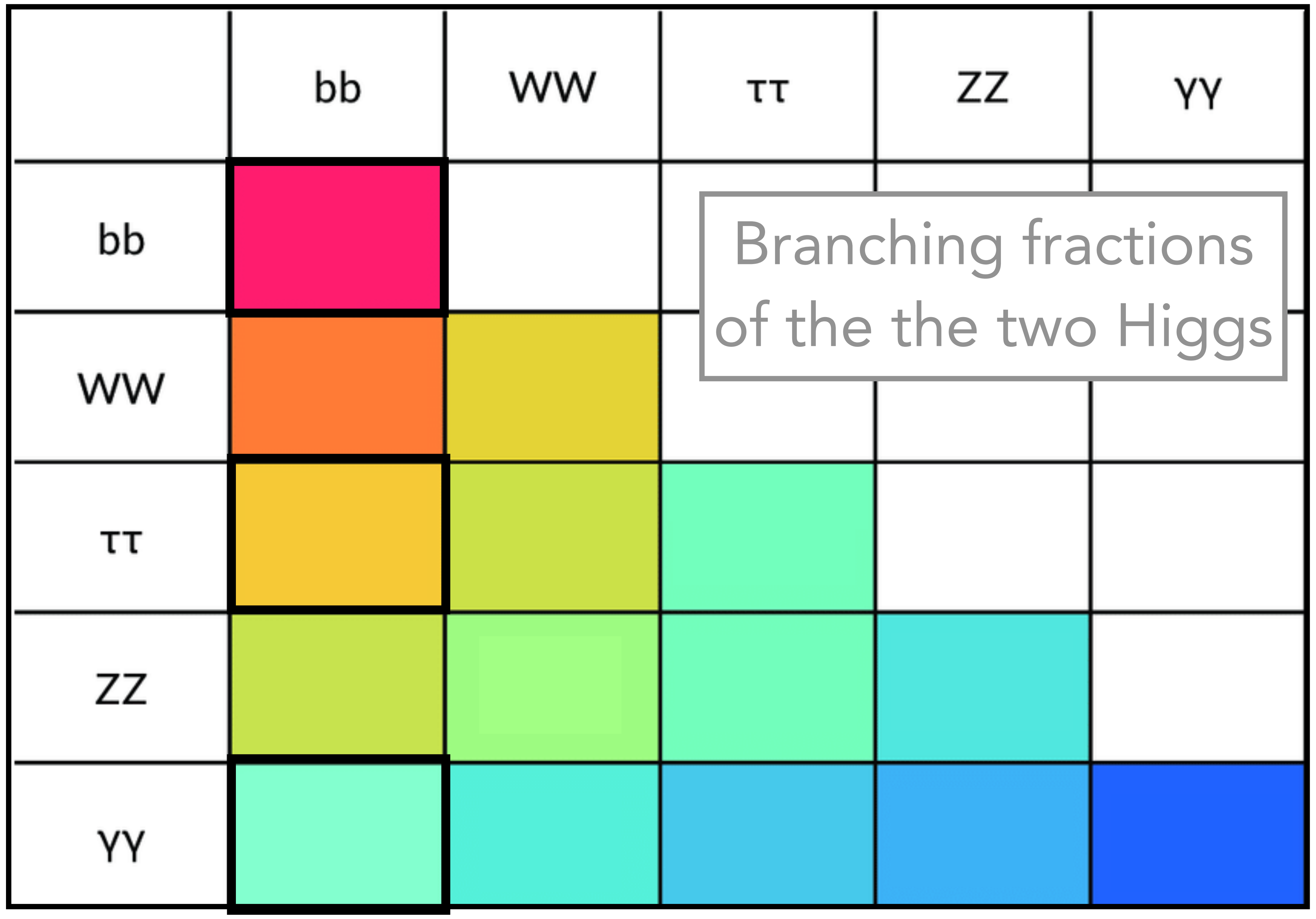
Larger branching fraction

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

Smaller S/B



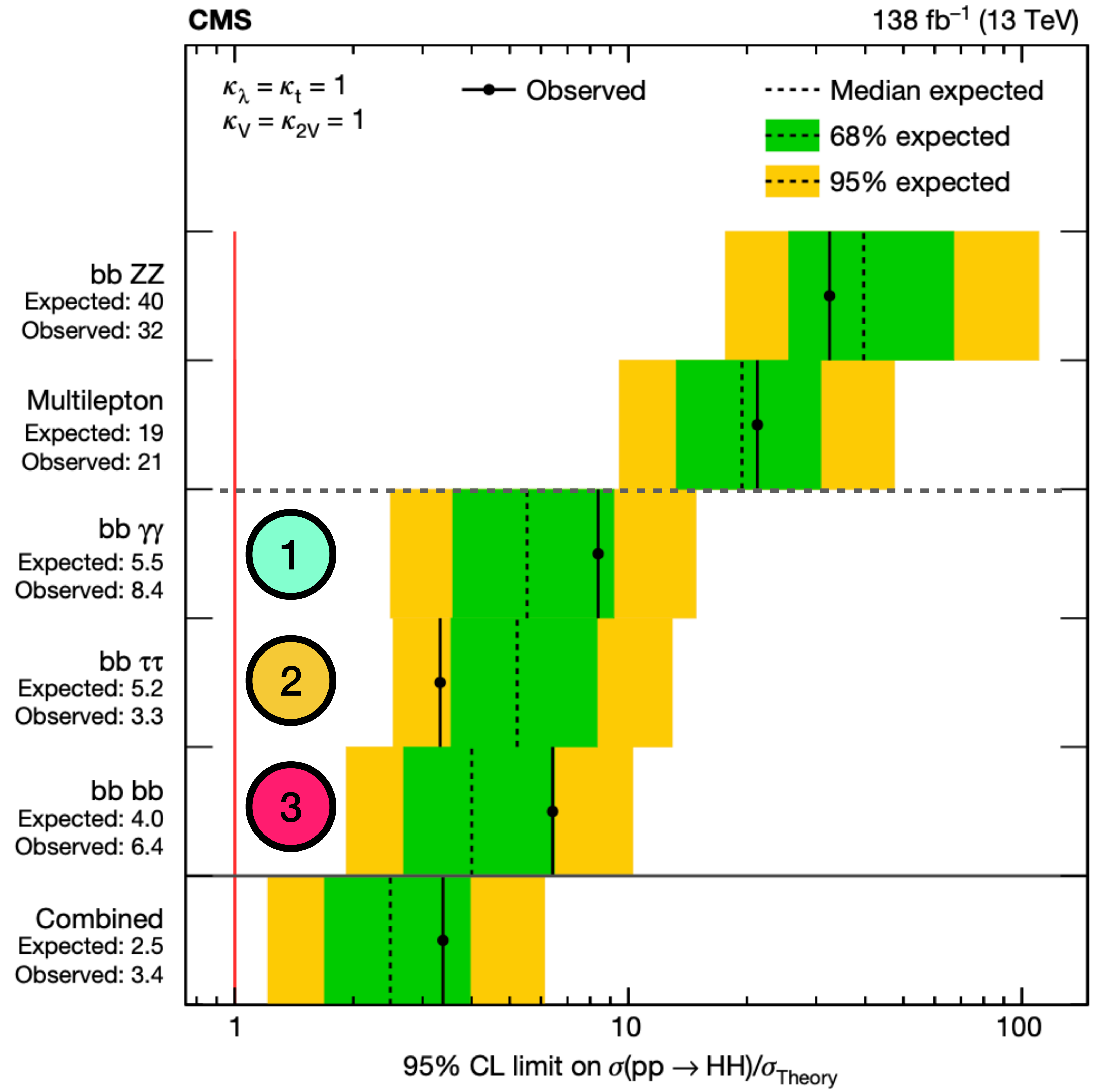
Primary channels



Larger branching fraction

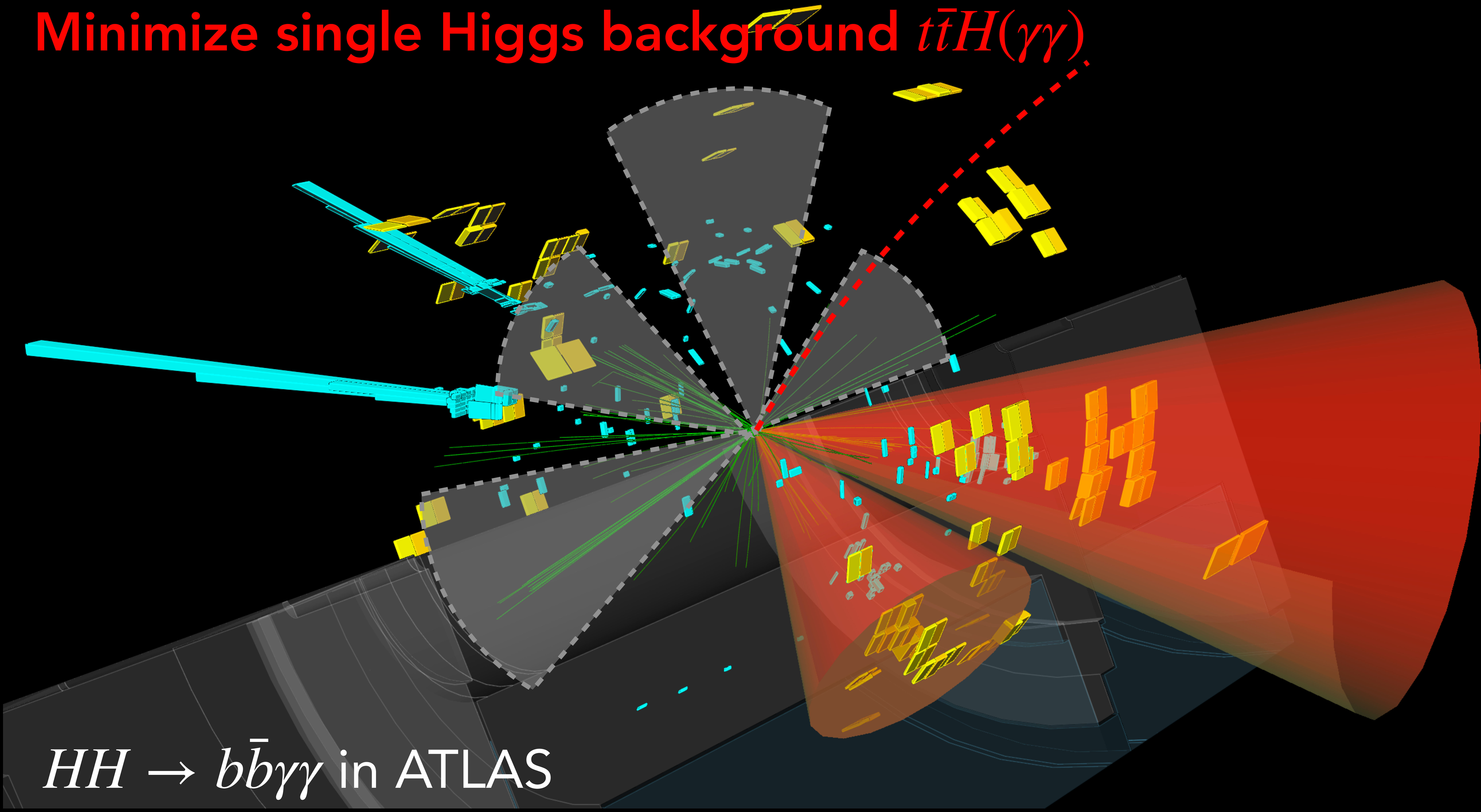
$b\bar{b}\gamma\gamma$ $b\bar{b}\tau\tau$ $b\bar{b}b\bar{b}$

Smaller S/B



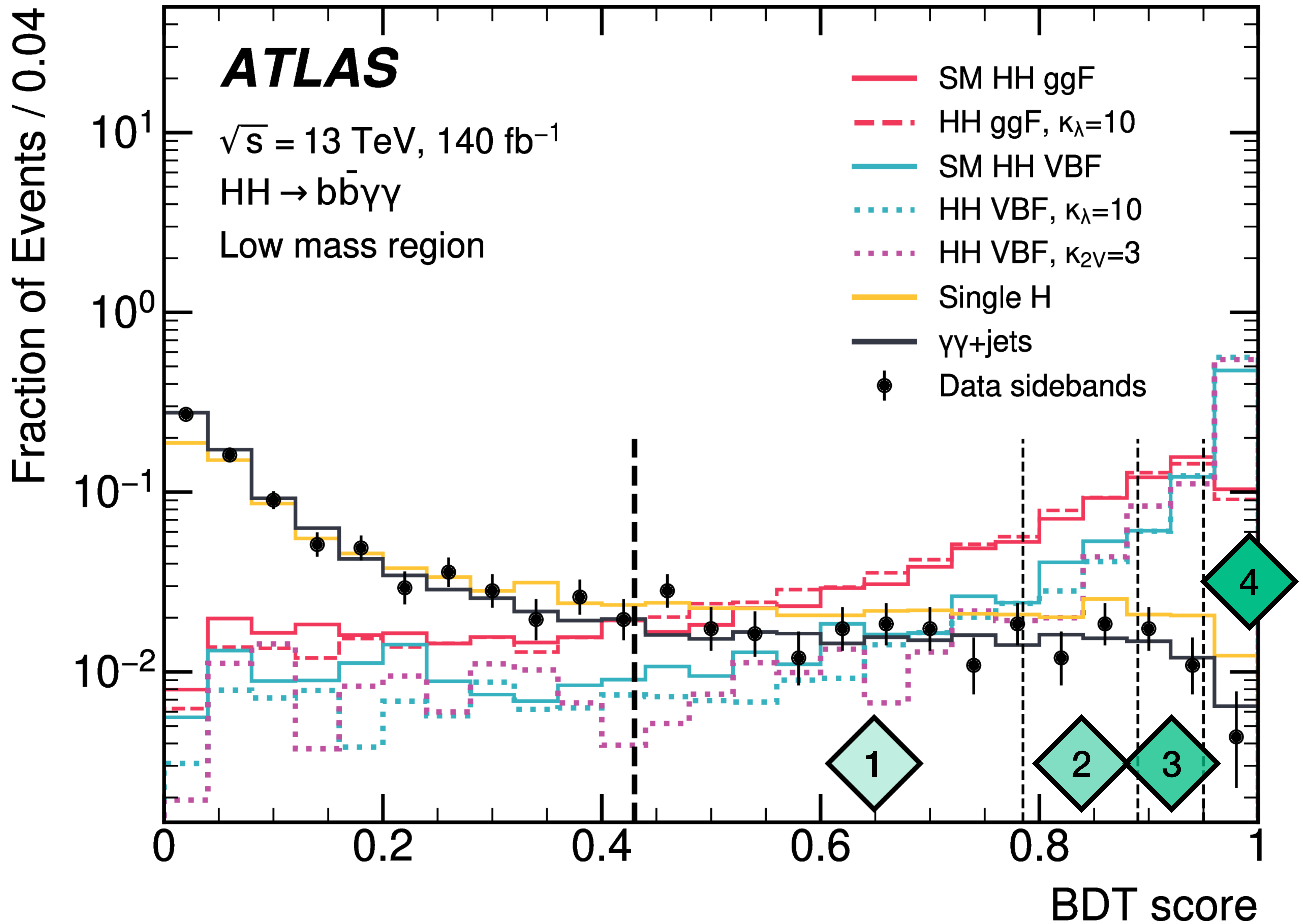
Veto events with e/μ or >5 jets

Minimize single Higgs background $t\bar{t}H(\gamma\gamma)$



BDT Categorization

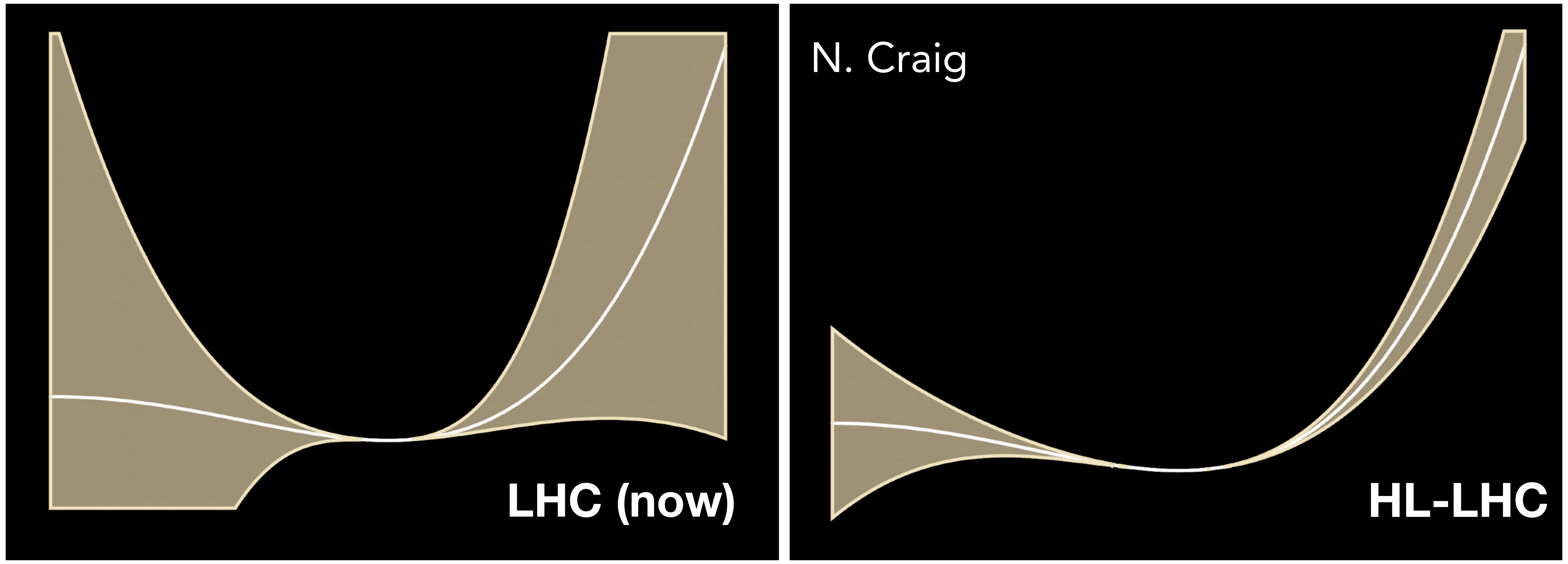
Train on Kinematics



Define analysis categories based on BDT scores

High luminosity LHC

Need **more data**!



Inner system of the ATLAS Tracker upgrade being **built @ SLAC**!