Probing the nature of electroweak symmetry breaking with Higgs boson pair-production at ATLAS

Lake Louise Winter Institute 2022

Maximilian Swiatlowski

TRIUMF

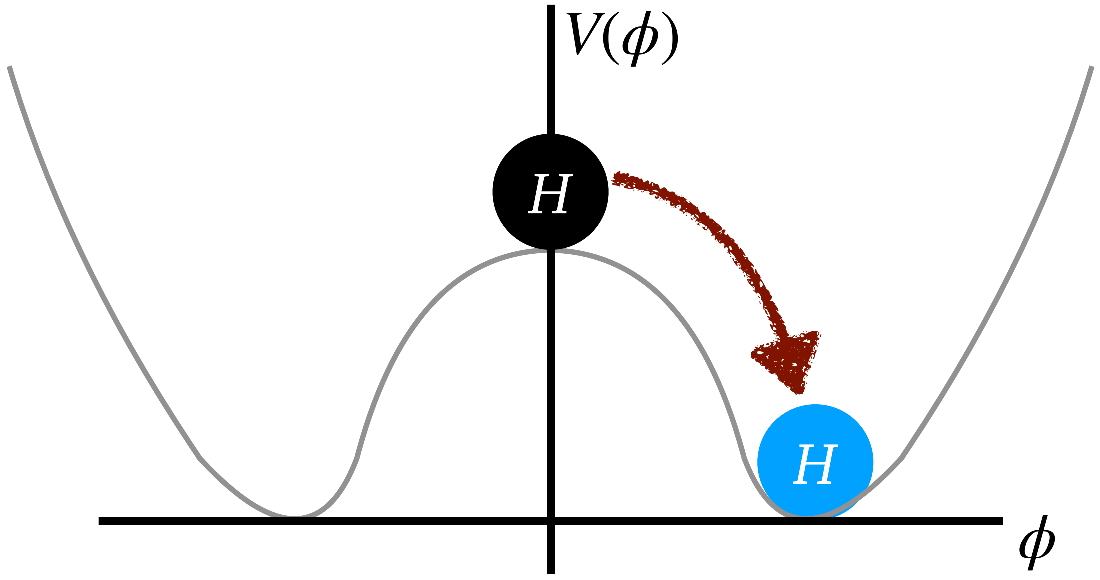
ATLAS EXPERIMENT

The Higgs Potential

The Higgs Potential

The SM Higgs potential is:

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



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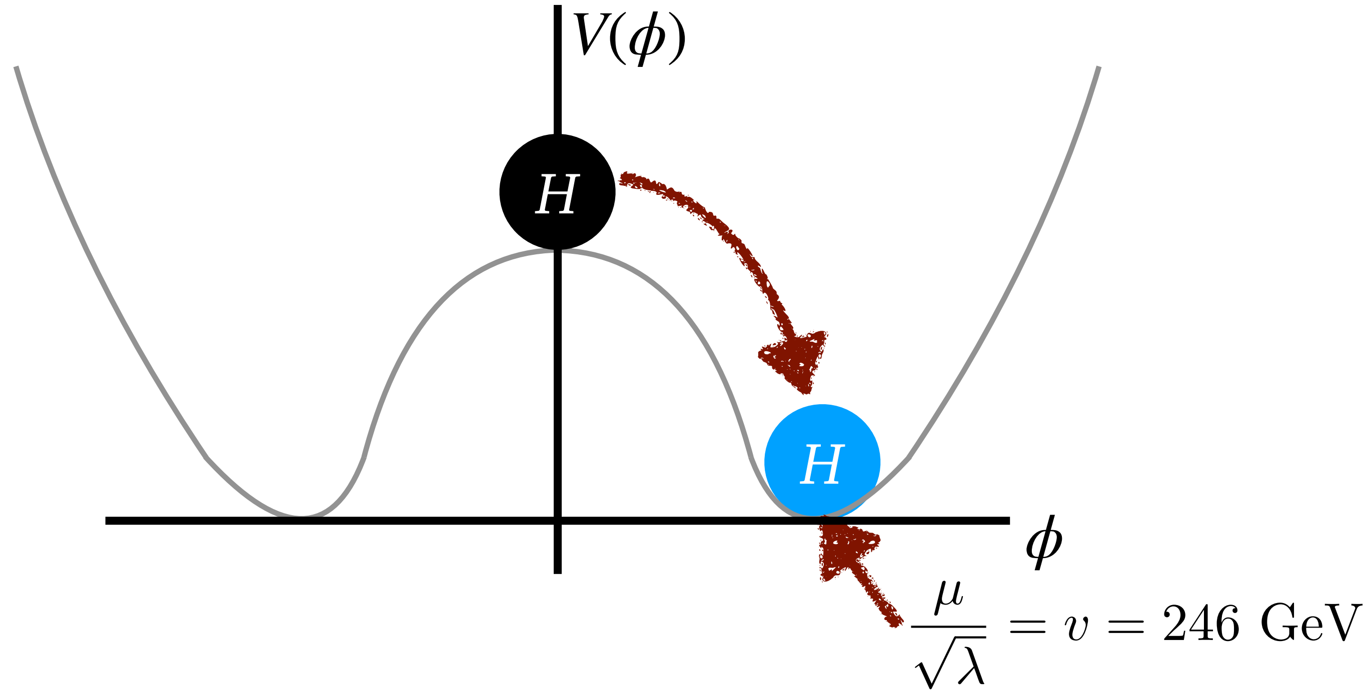

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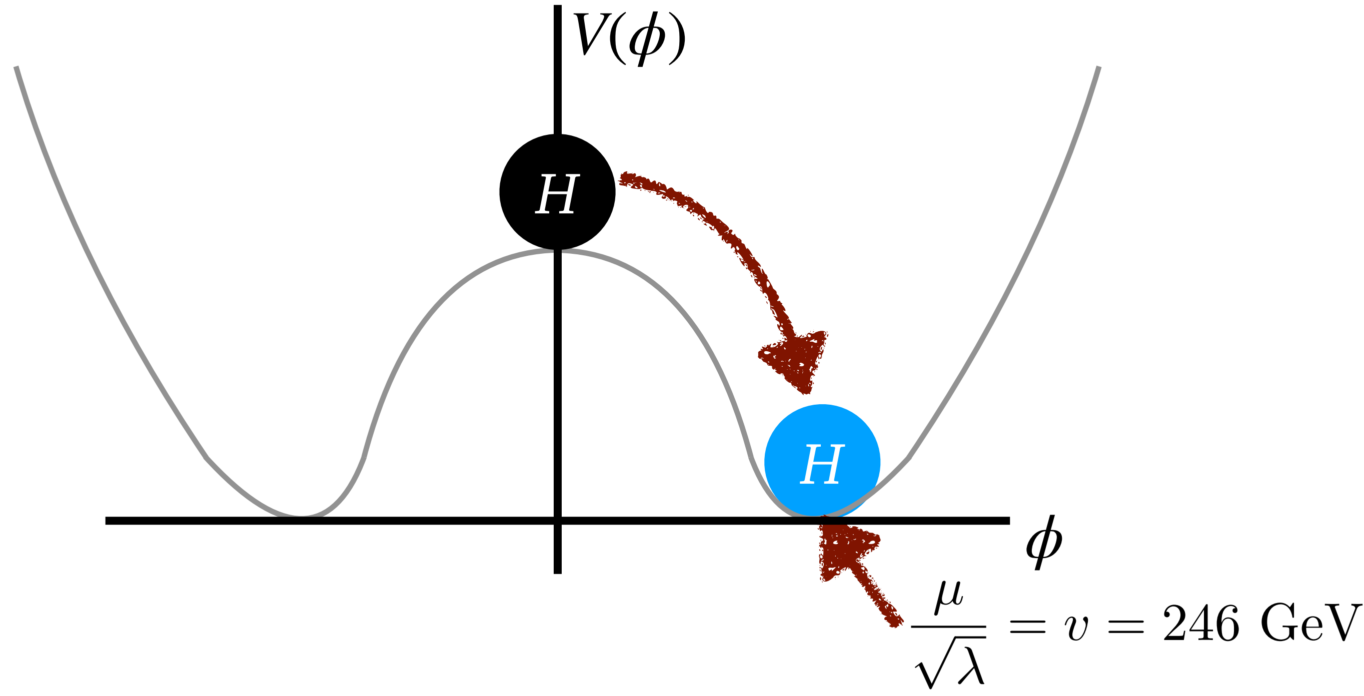

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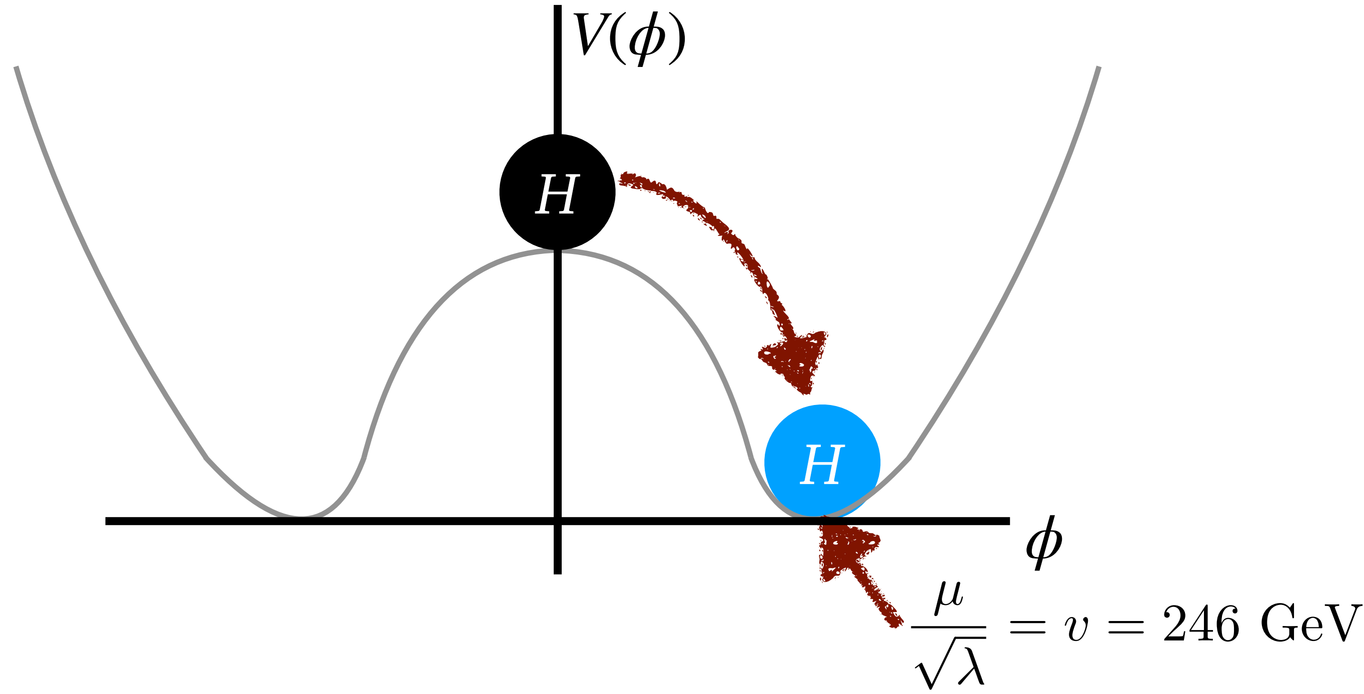

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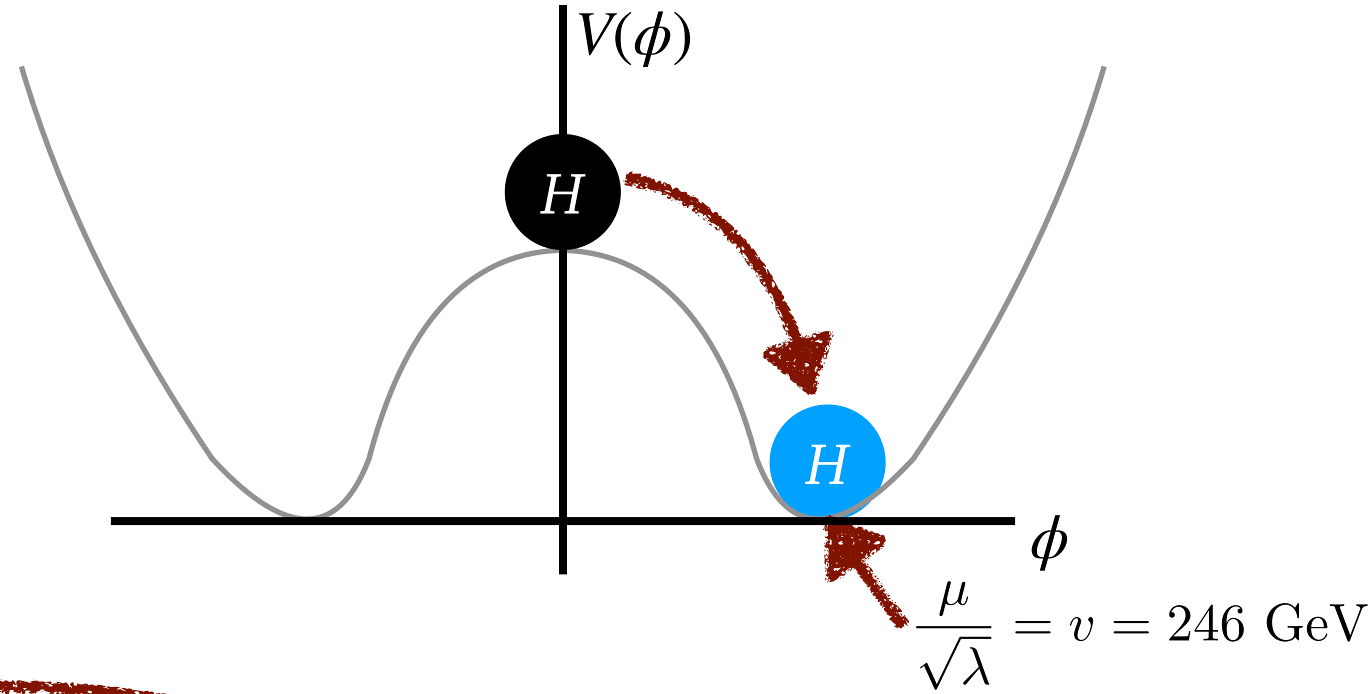

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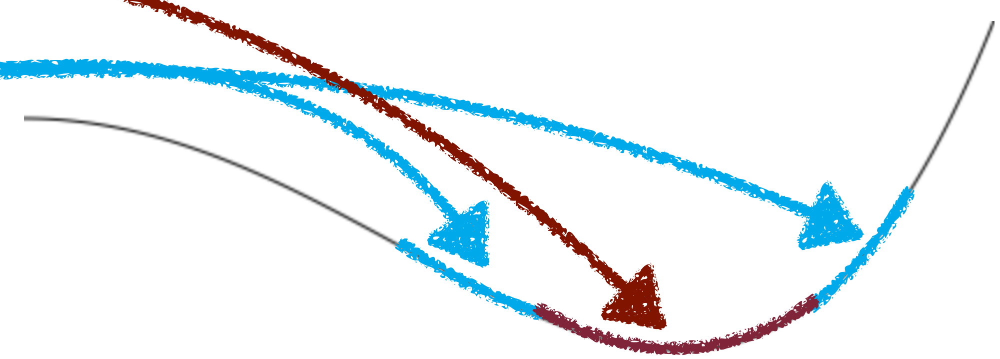

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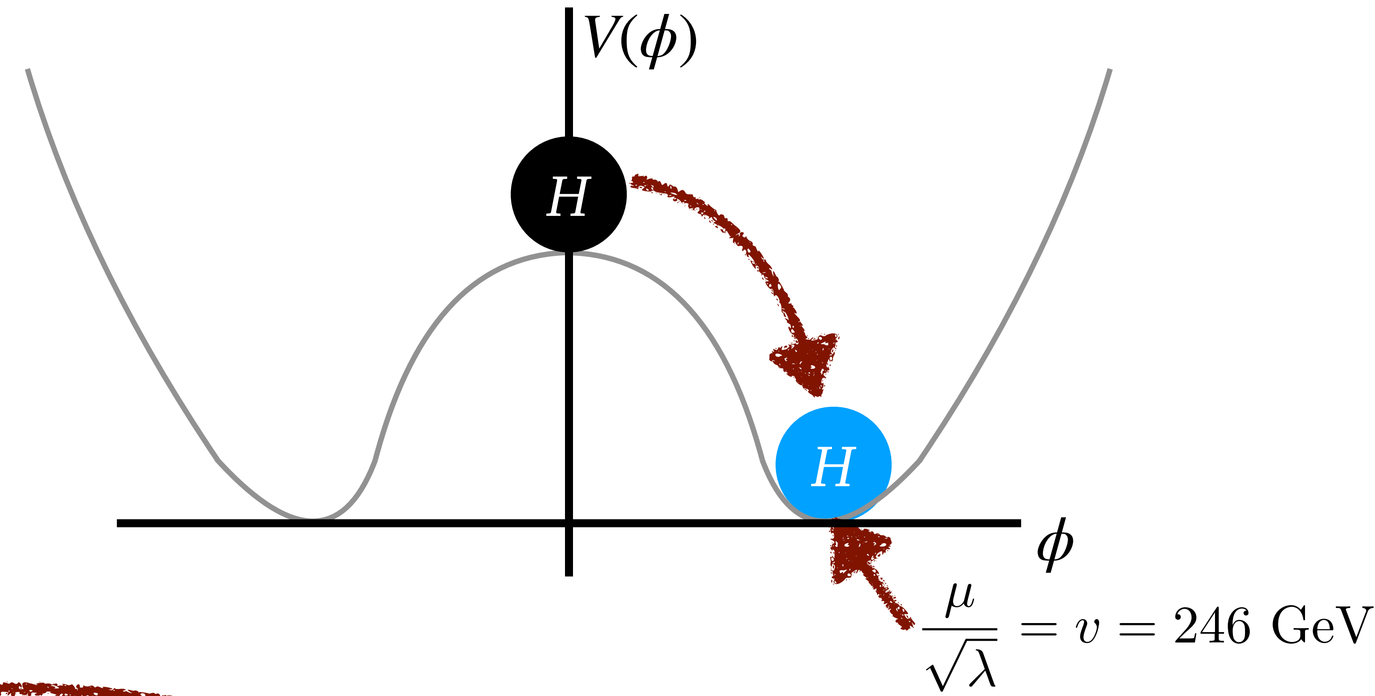

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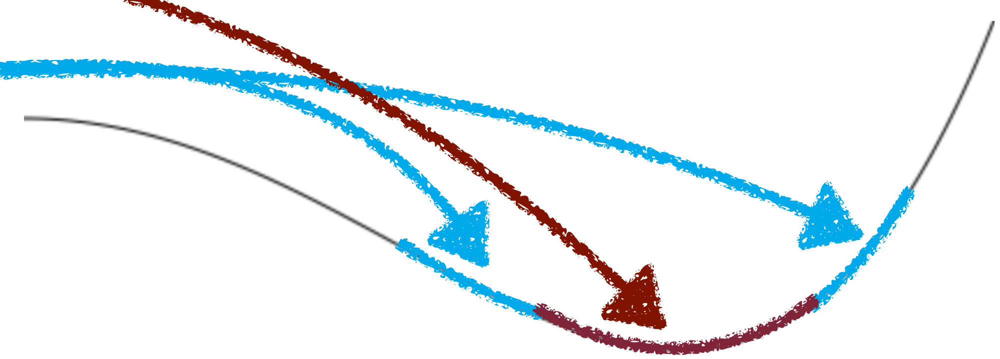

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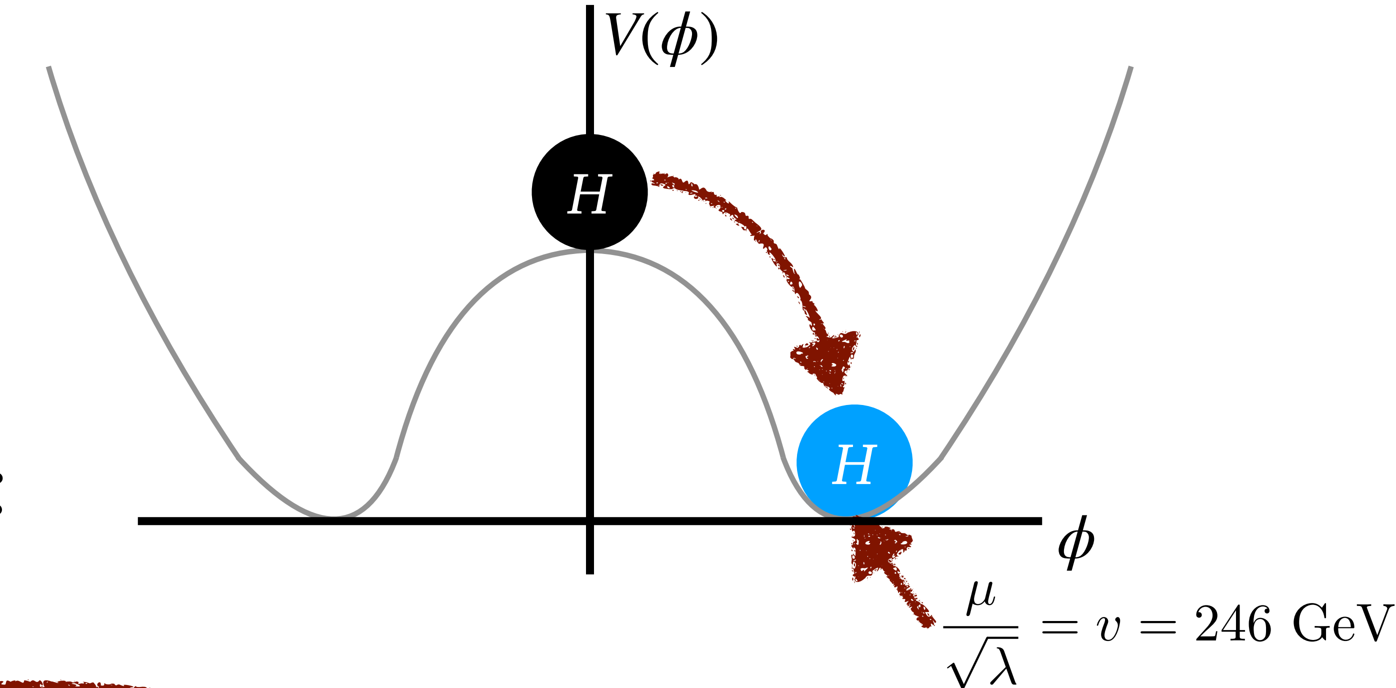

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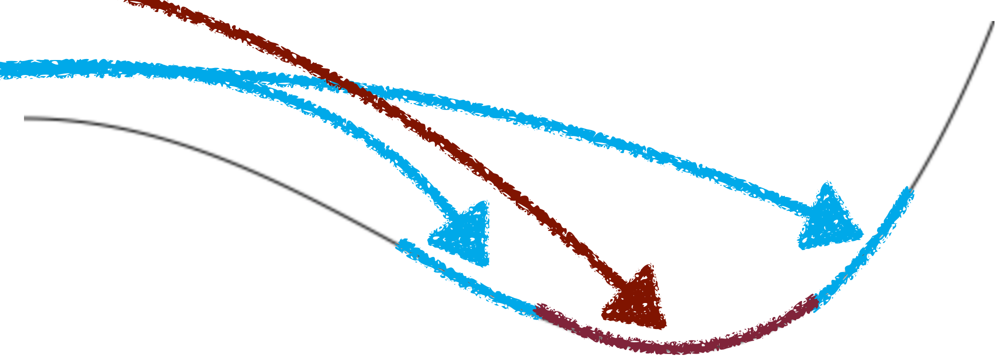

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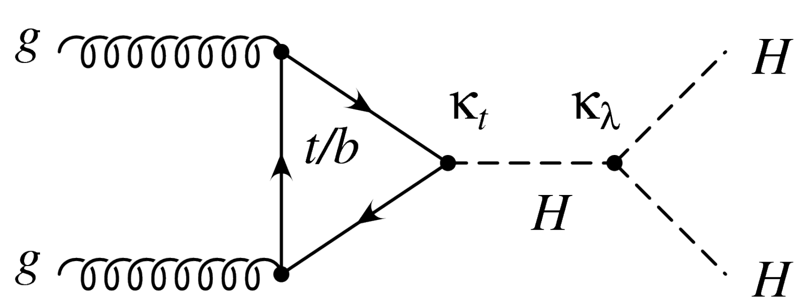

SM predicts HH production, and gives measures potential

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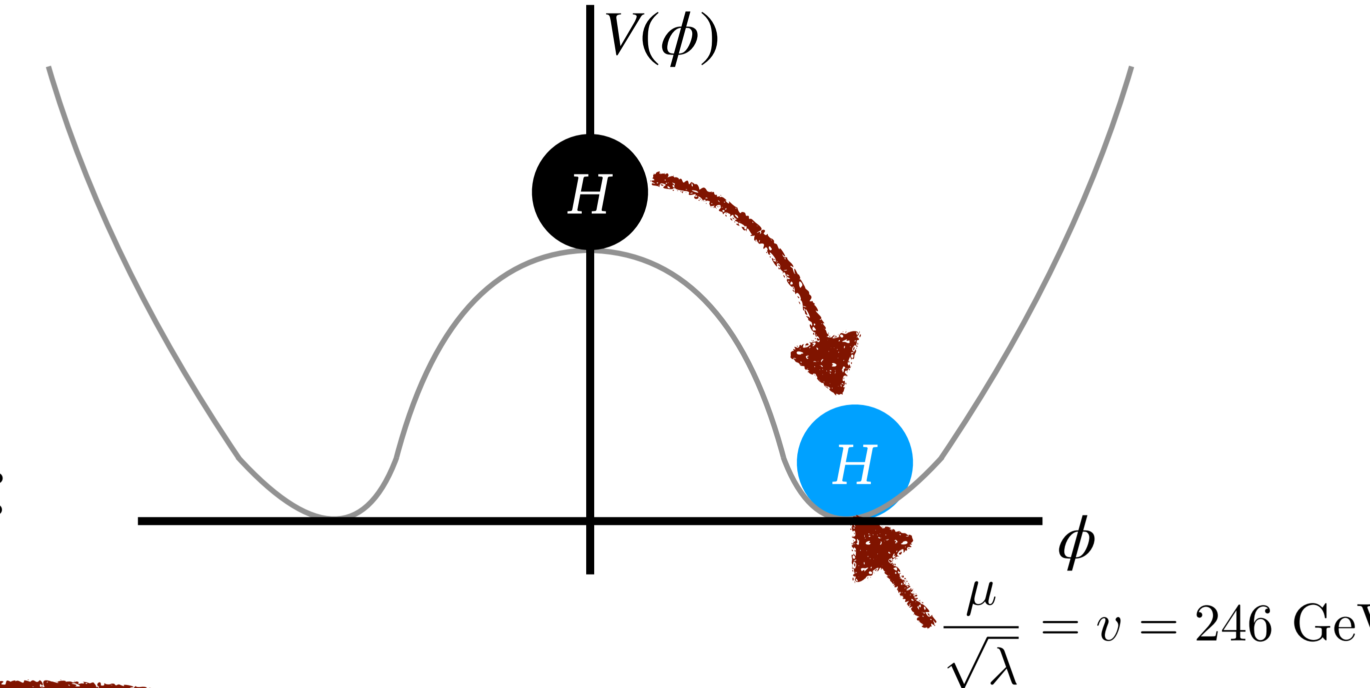

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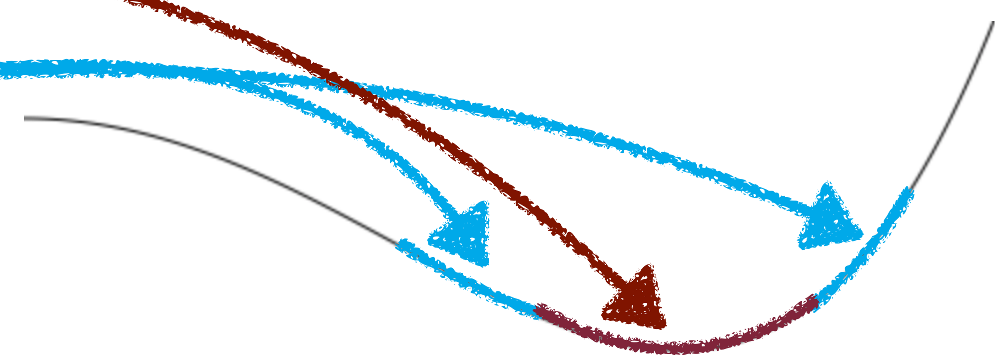

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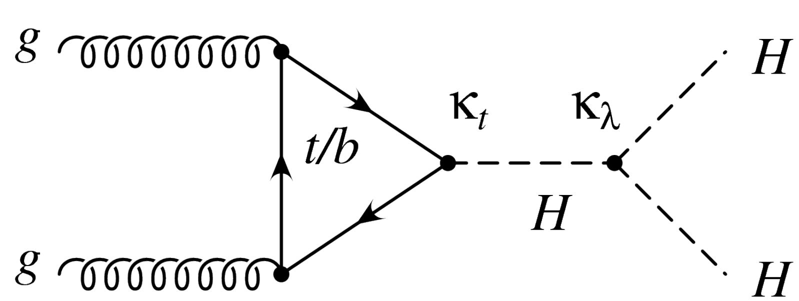

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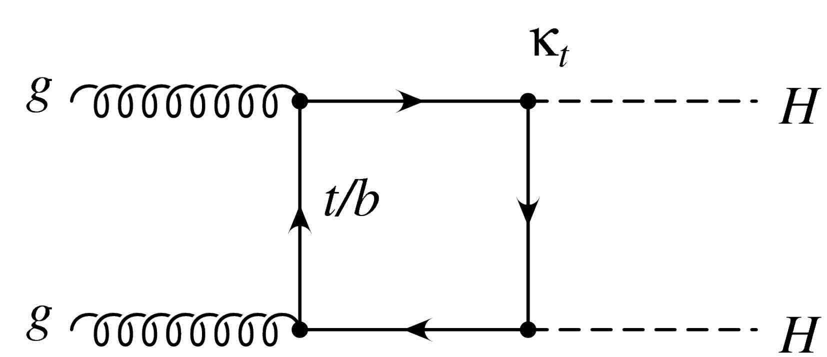

But interference means x-sec is very low

Potential Higgs Potentials

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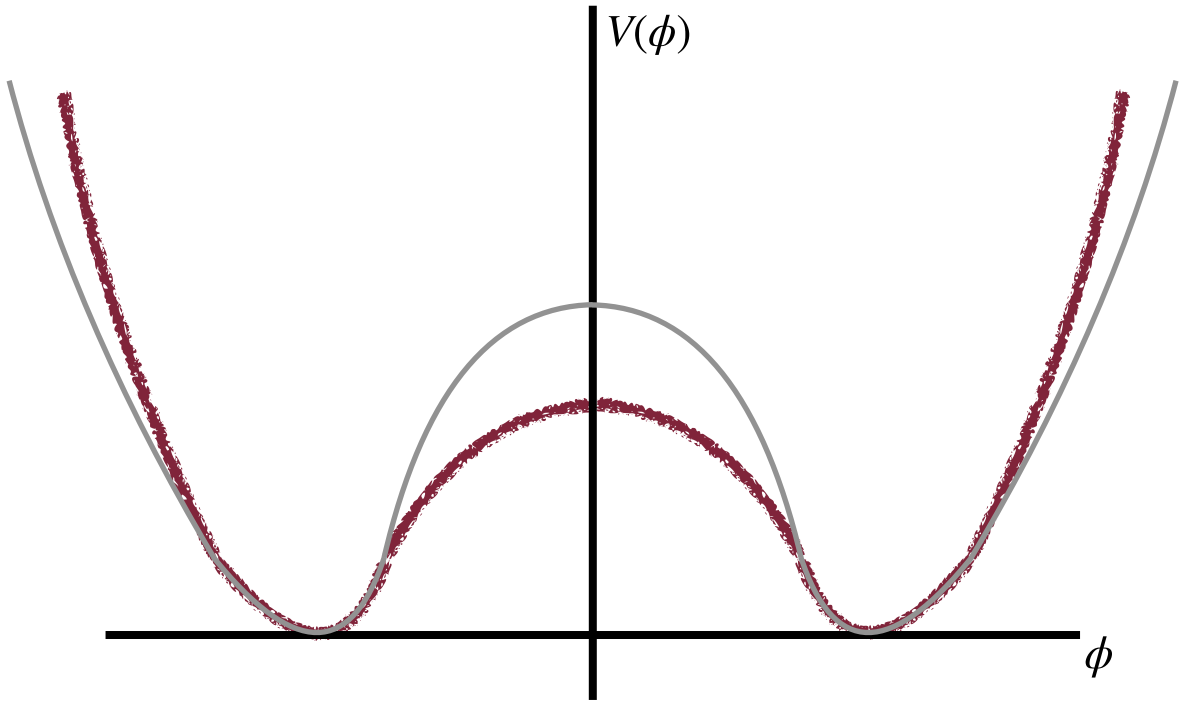

We have a prediction for the shape from the SM…

But other shapes of the potential still allow for Electroweak Symmetry Breaking

Other shapes could reveal evidence for *Electroweak Baryogenesis*, or hints to vacuum stability

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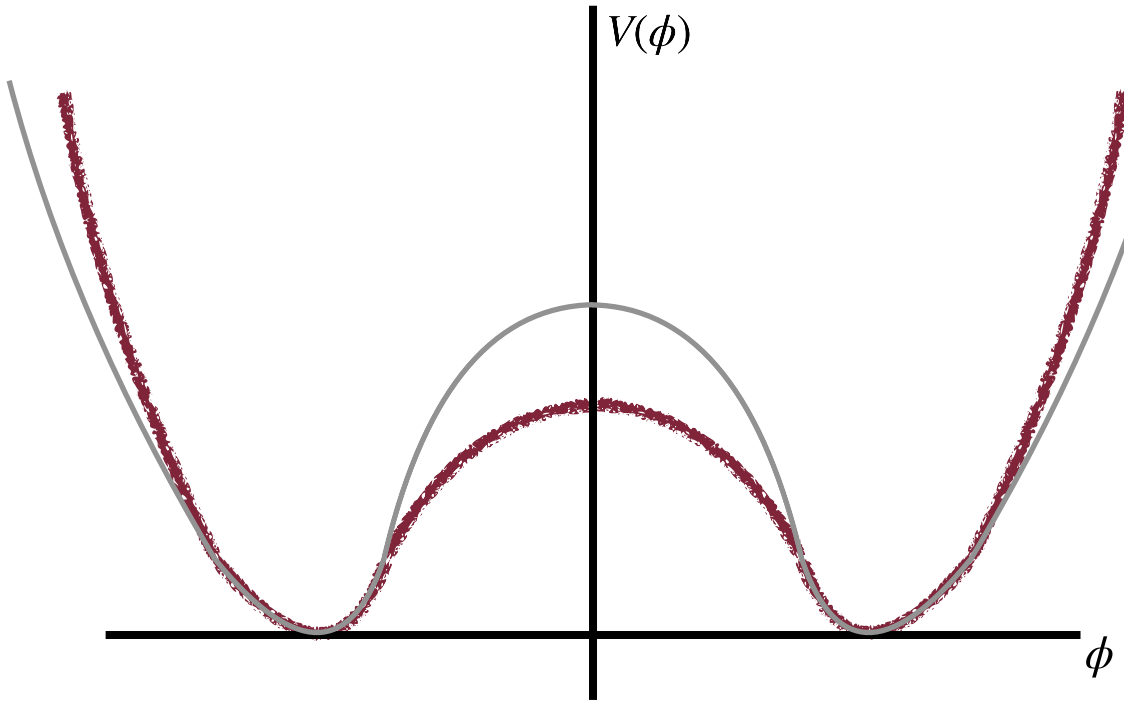
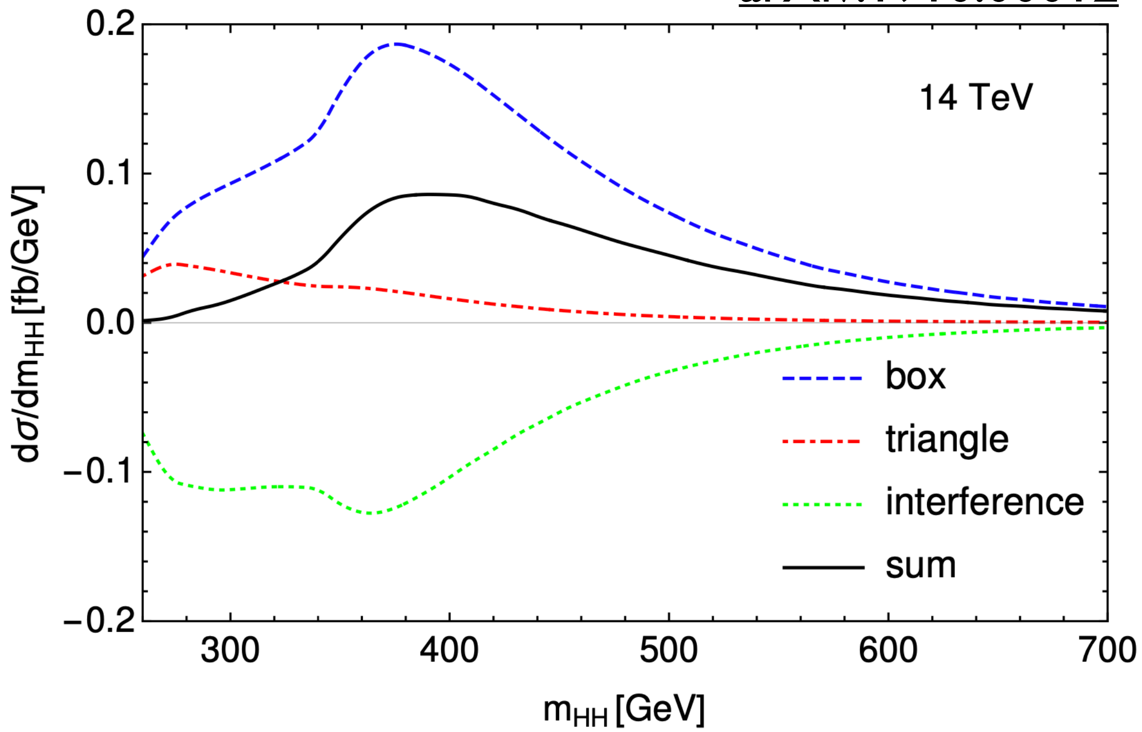


arXiv:1910.00012



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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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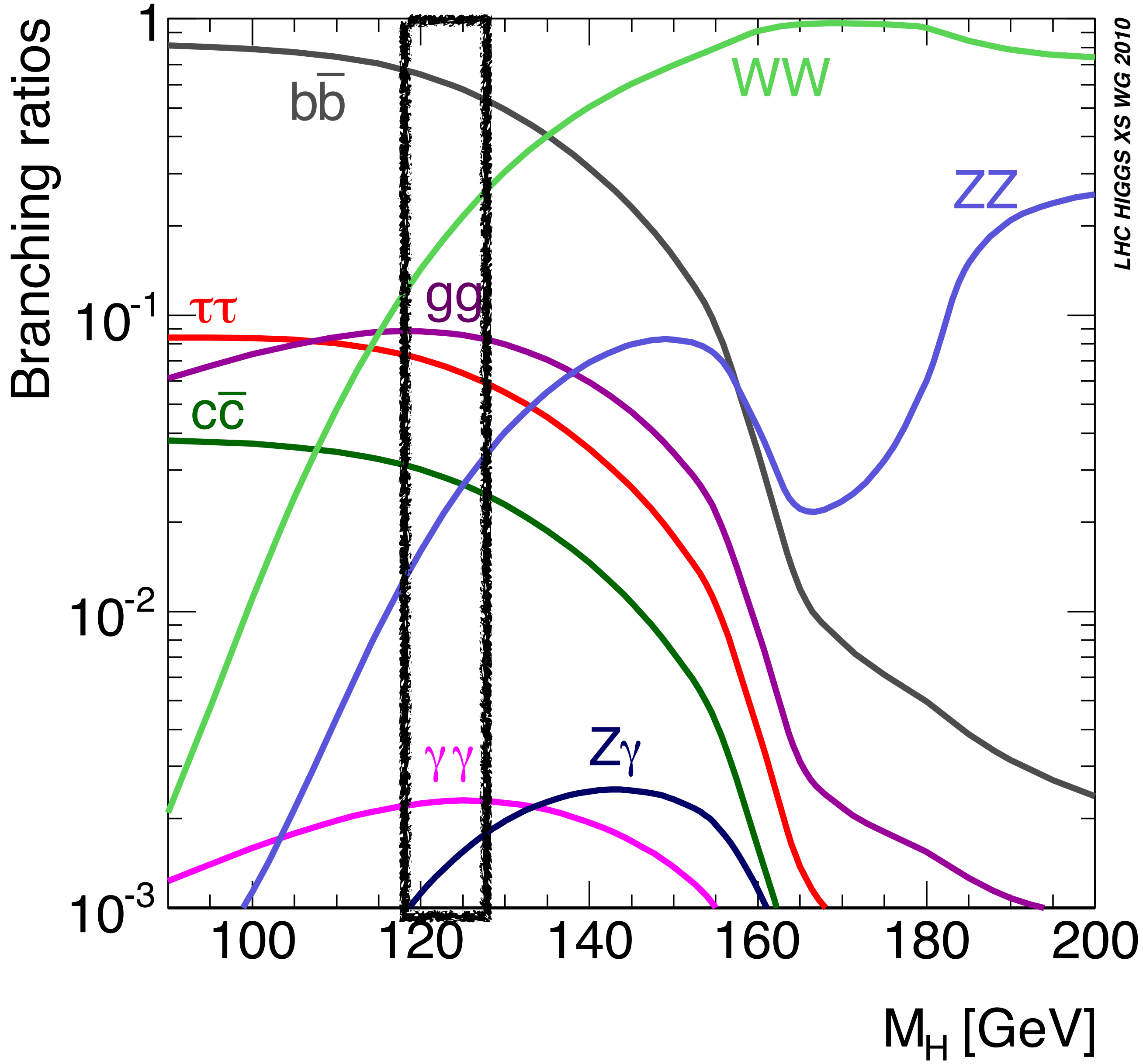
The Higgs decays instantly, to a range of particle types



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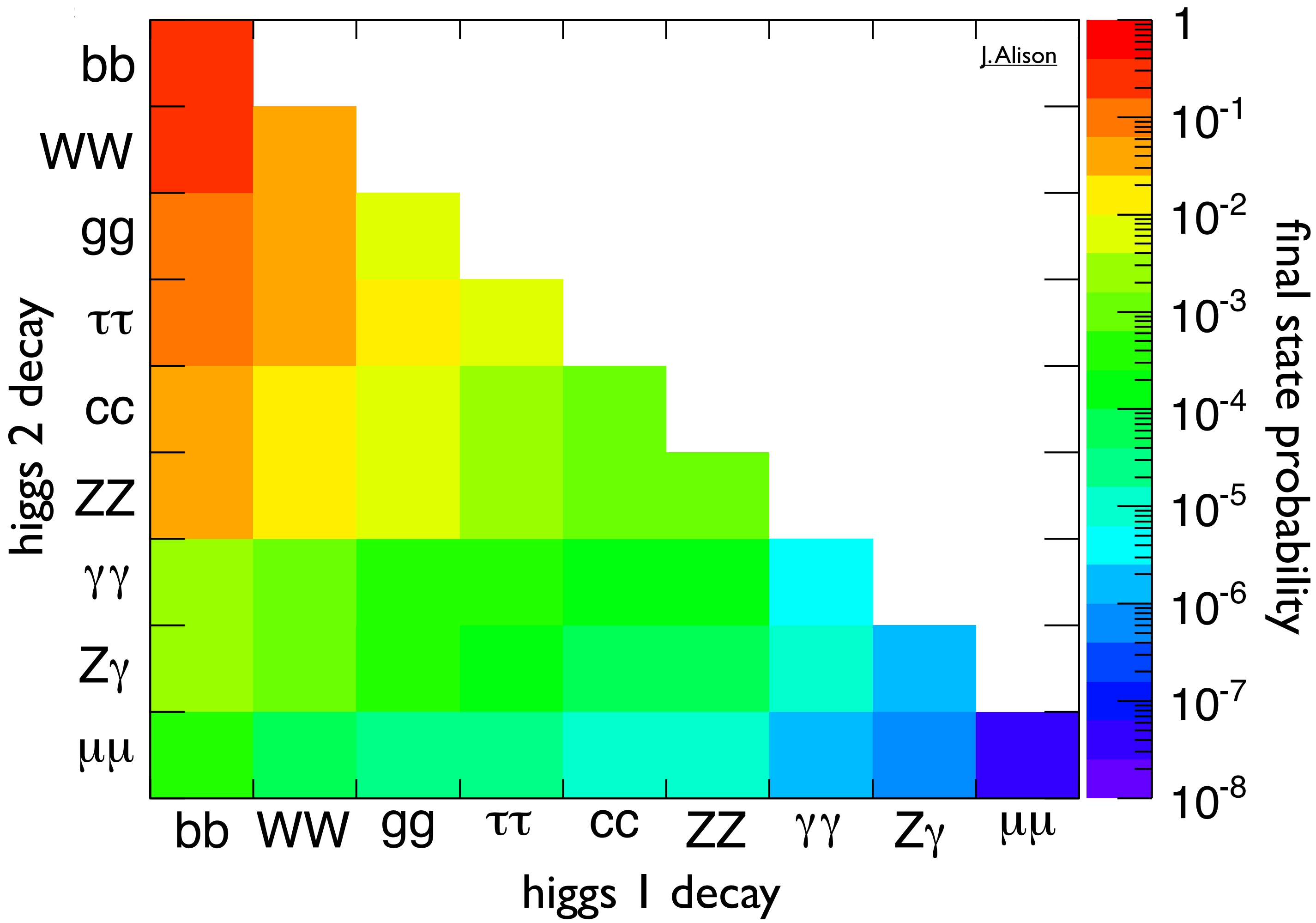

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Higgs pairs are rare, and have a hugely rich structure of final states

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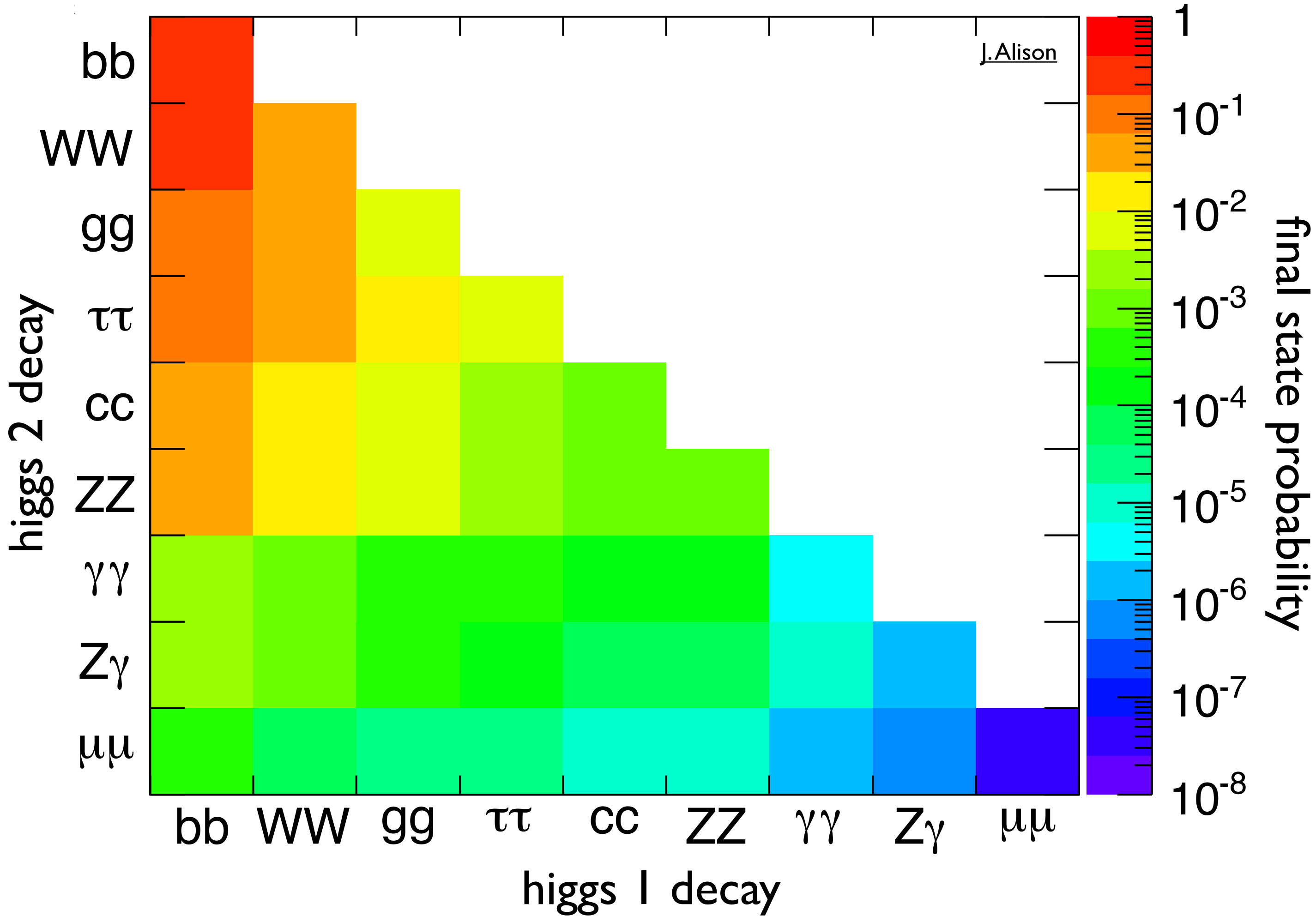

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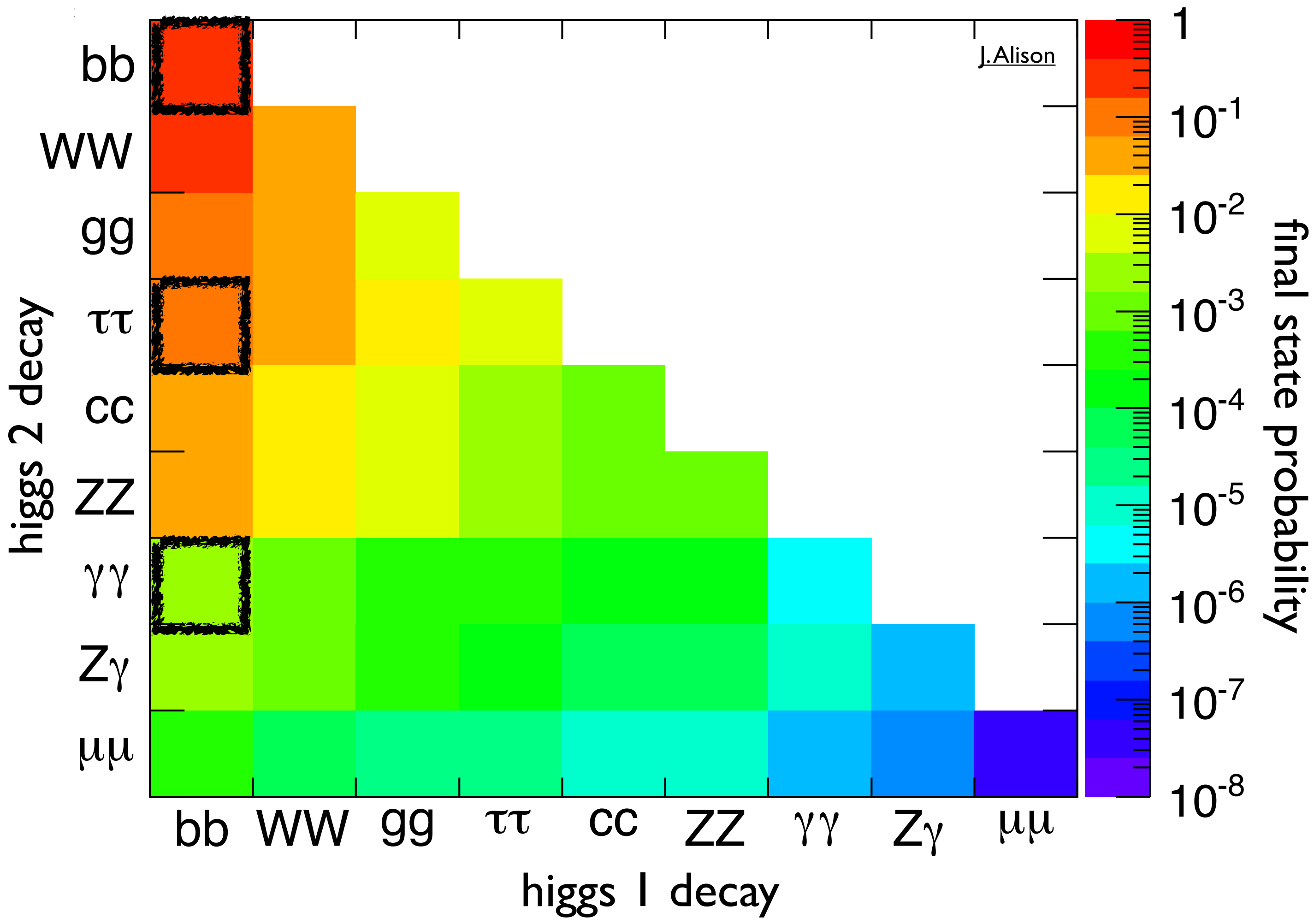

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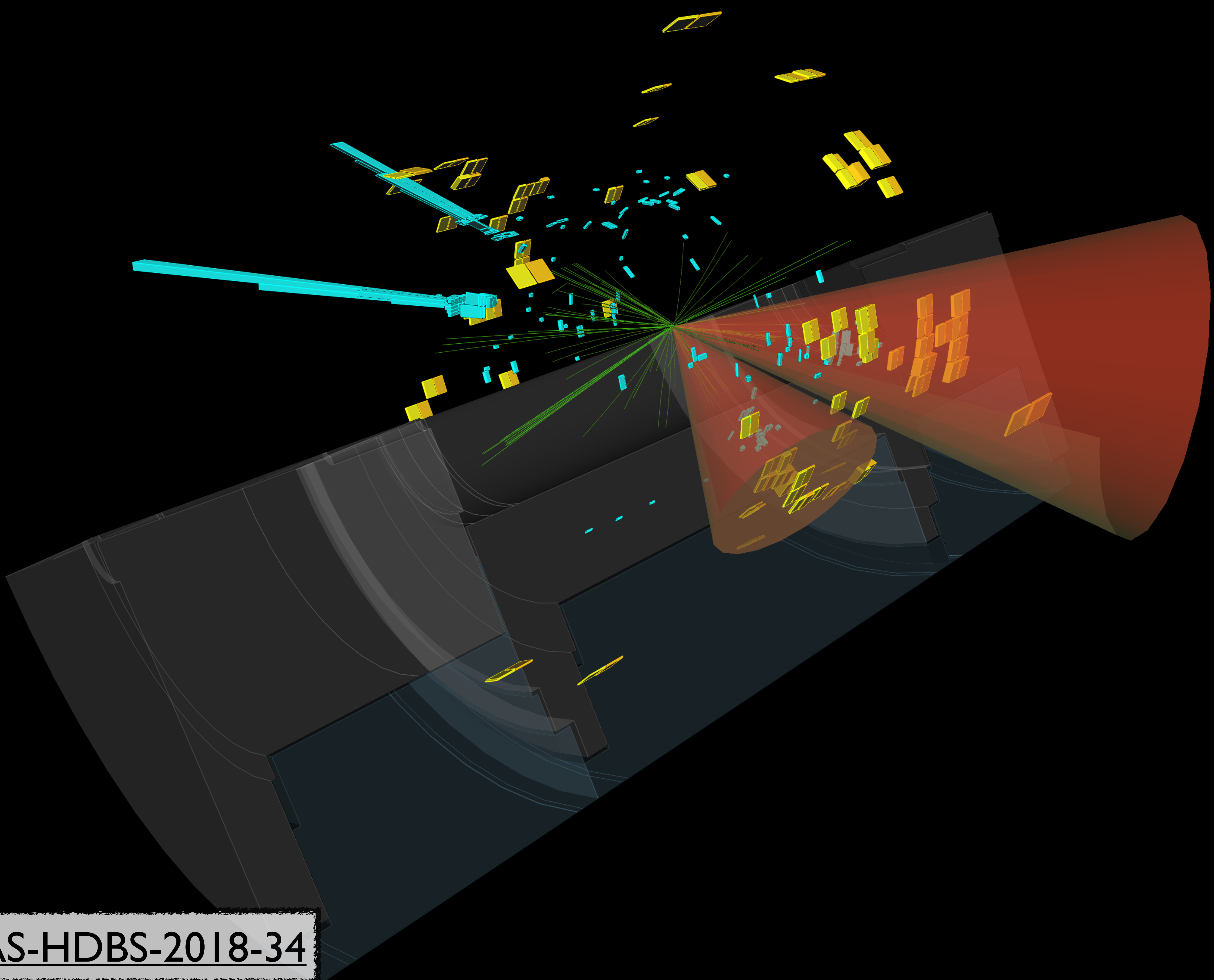
$4b$, $b\bar{b}\tau\bar{\tau}$, and $b\bar{b}\gamma\gamma$ are the most powerful

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



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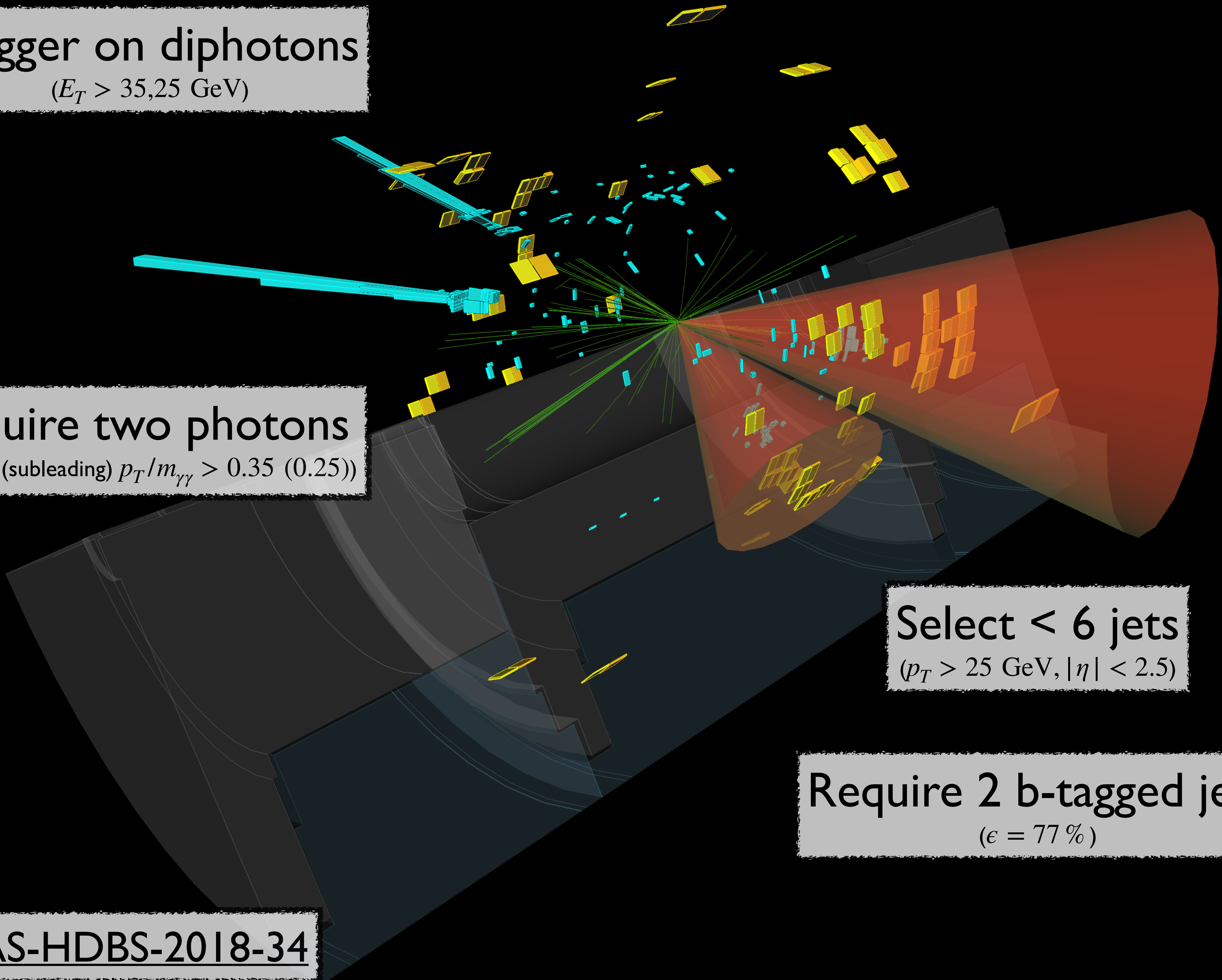


Trigger on diphotons
($E_T > 35{,}25$ GeV)

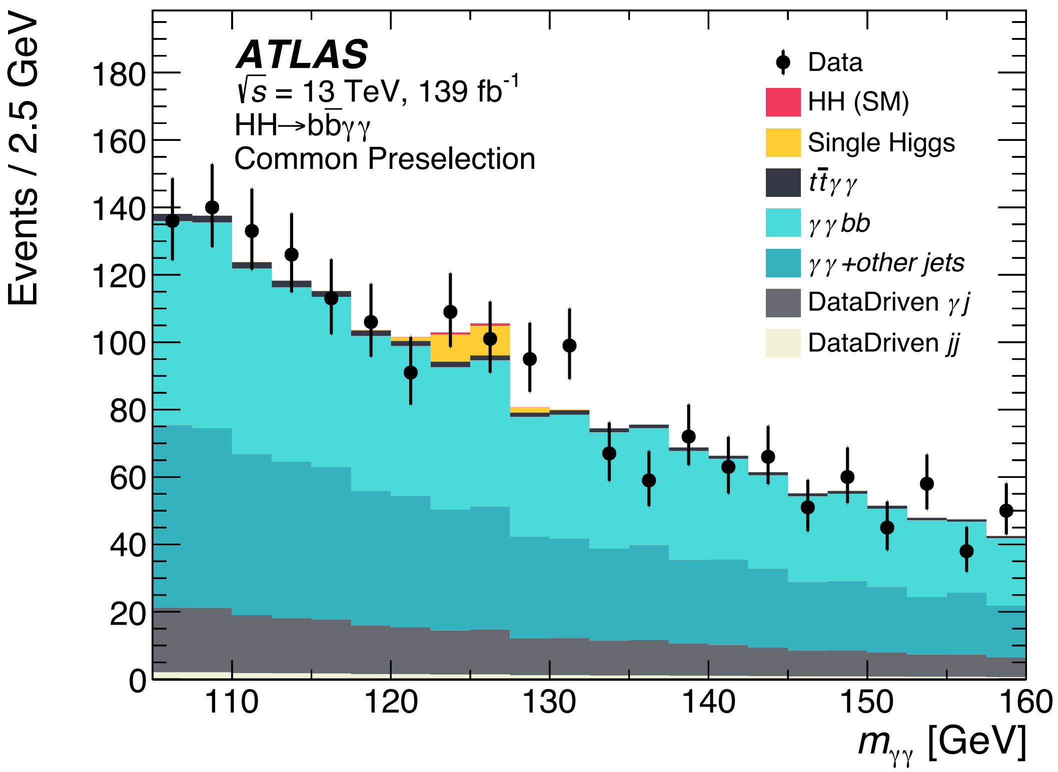
Require two photons
(Leading (subleading) $p_T/m_{\gamma\gamma} > 0.35$ (0.25))

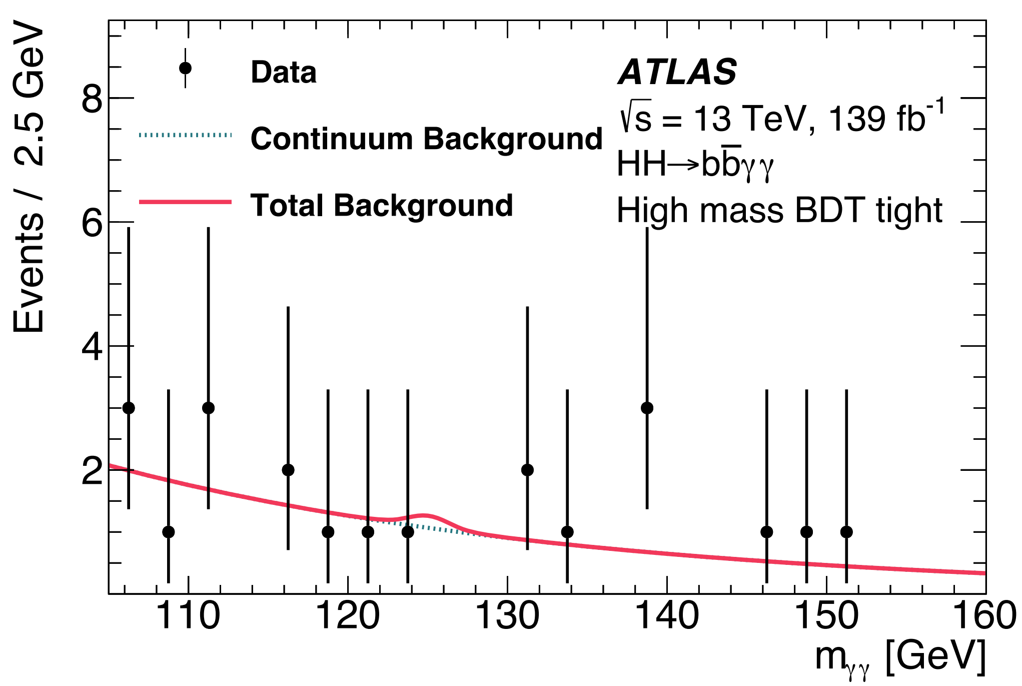
Select < 6 jets
($p_T > 25$ GeV, $|\eta| < 2.5$)

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

<u>ATLAS-HDBS-2018-34</u>

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





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

Shape of background function determined from simulation, norm determined from data 'sidebands'

Contributions from fake γ estimated using data-driven method

Single Higgs background determined from simulation

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

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

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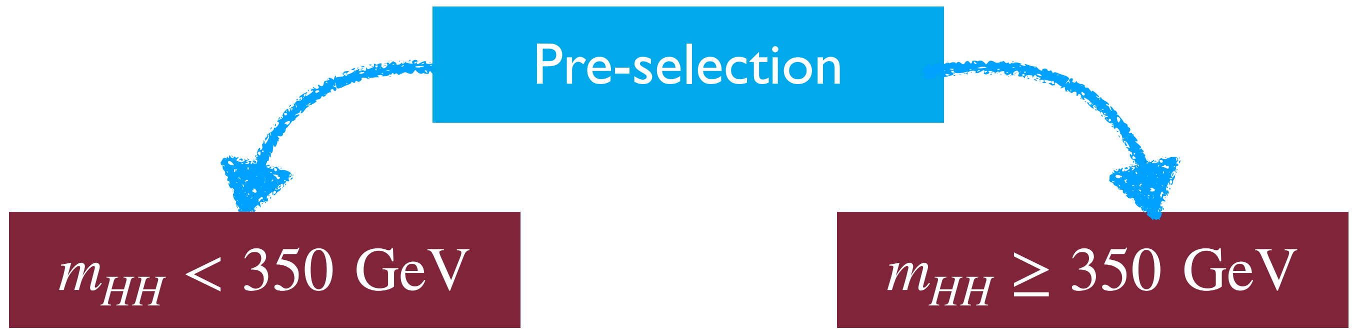

After pre-selection, split into high-mass and low-mass selections

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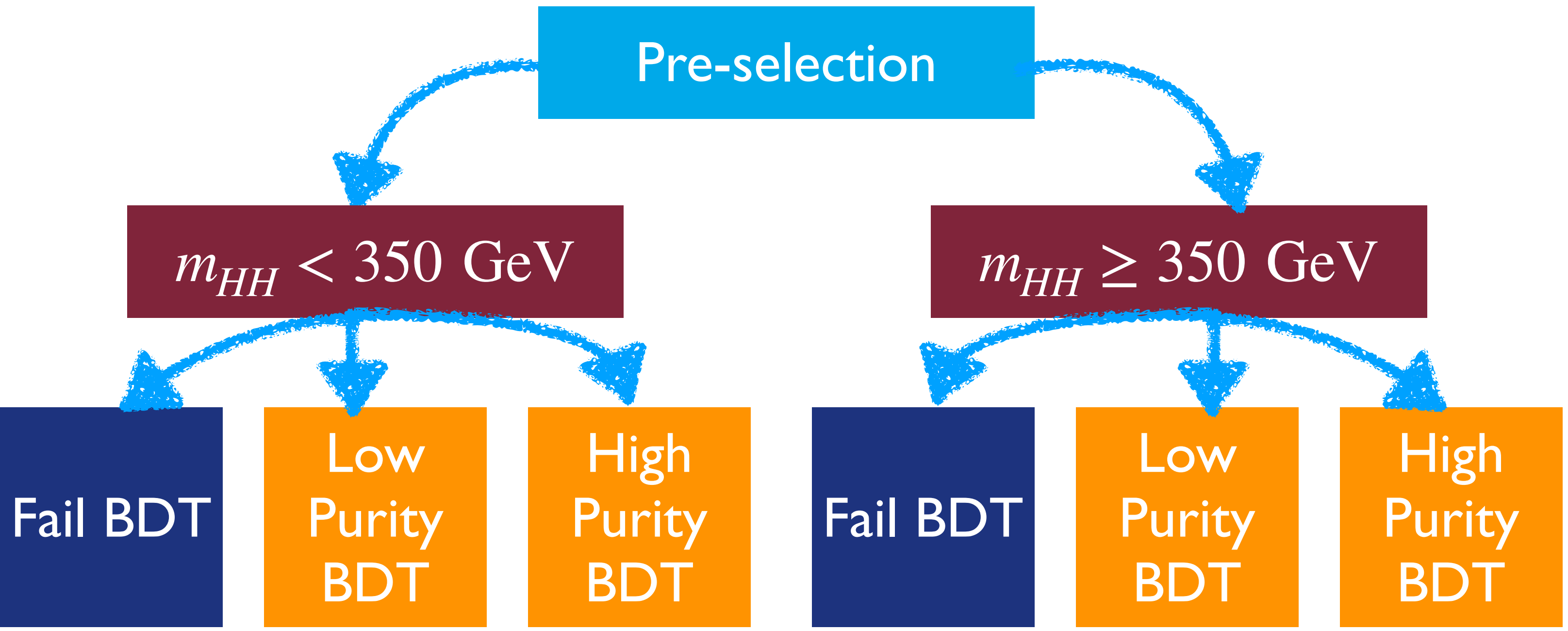

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BDT trained in each region: select low- and high-purity signal regions with BDT

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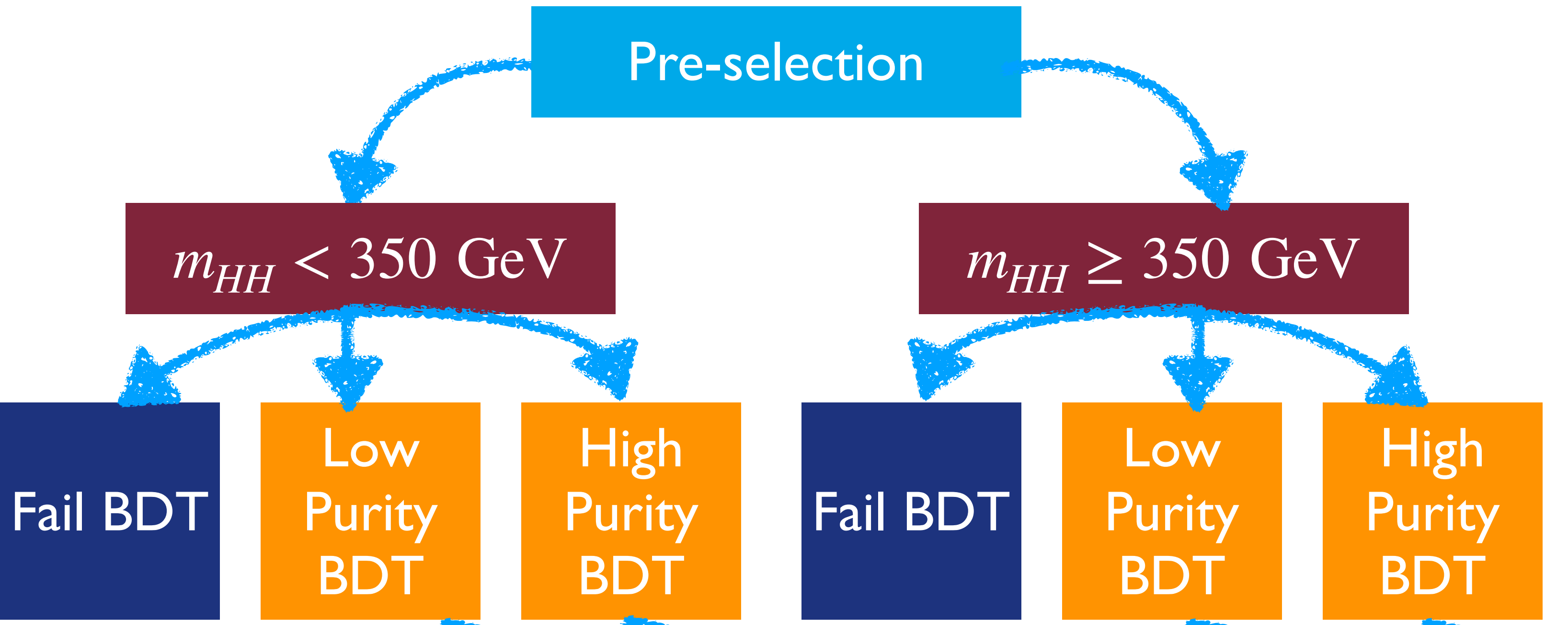

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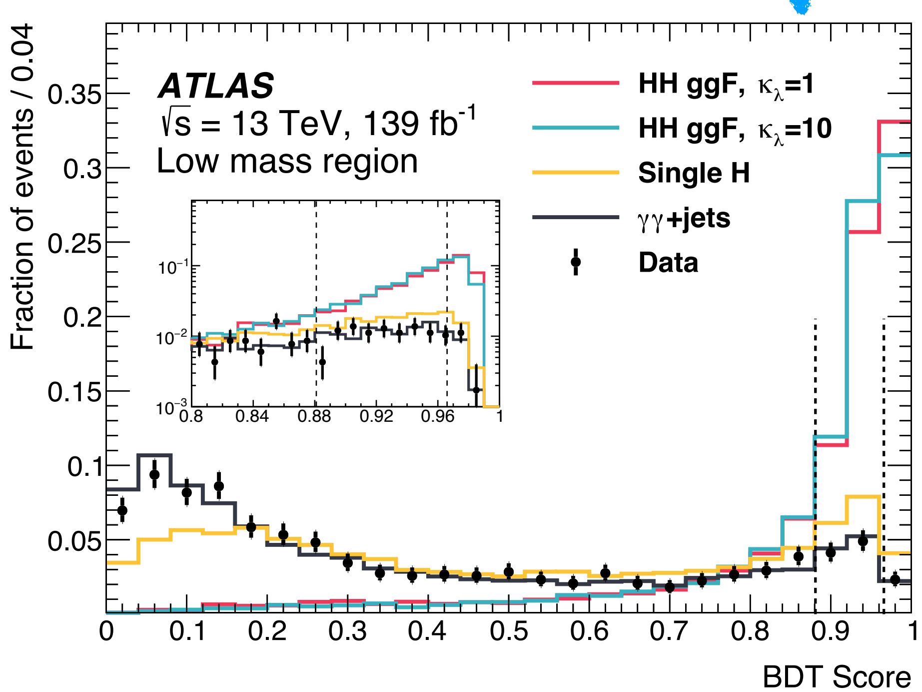

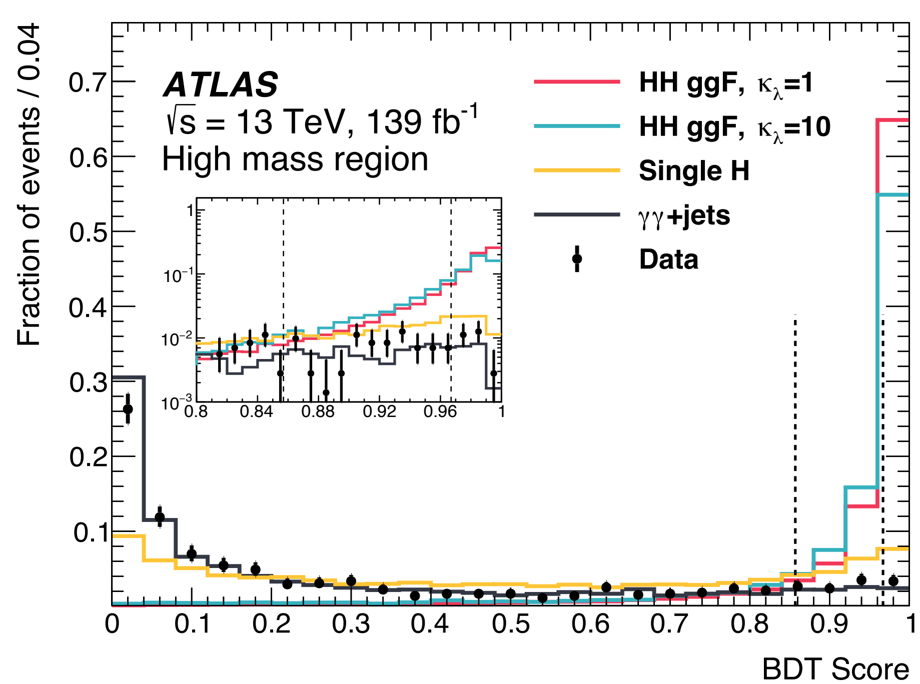

Fit $m_{\gamma\gamma}$ in 4 SR's simultaneously to extract signal

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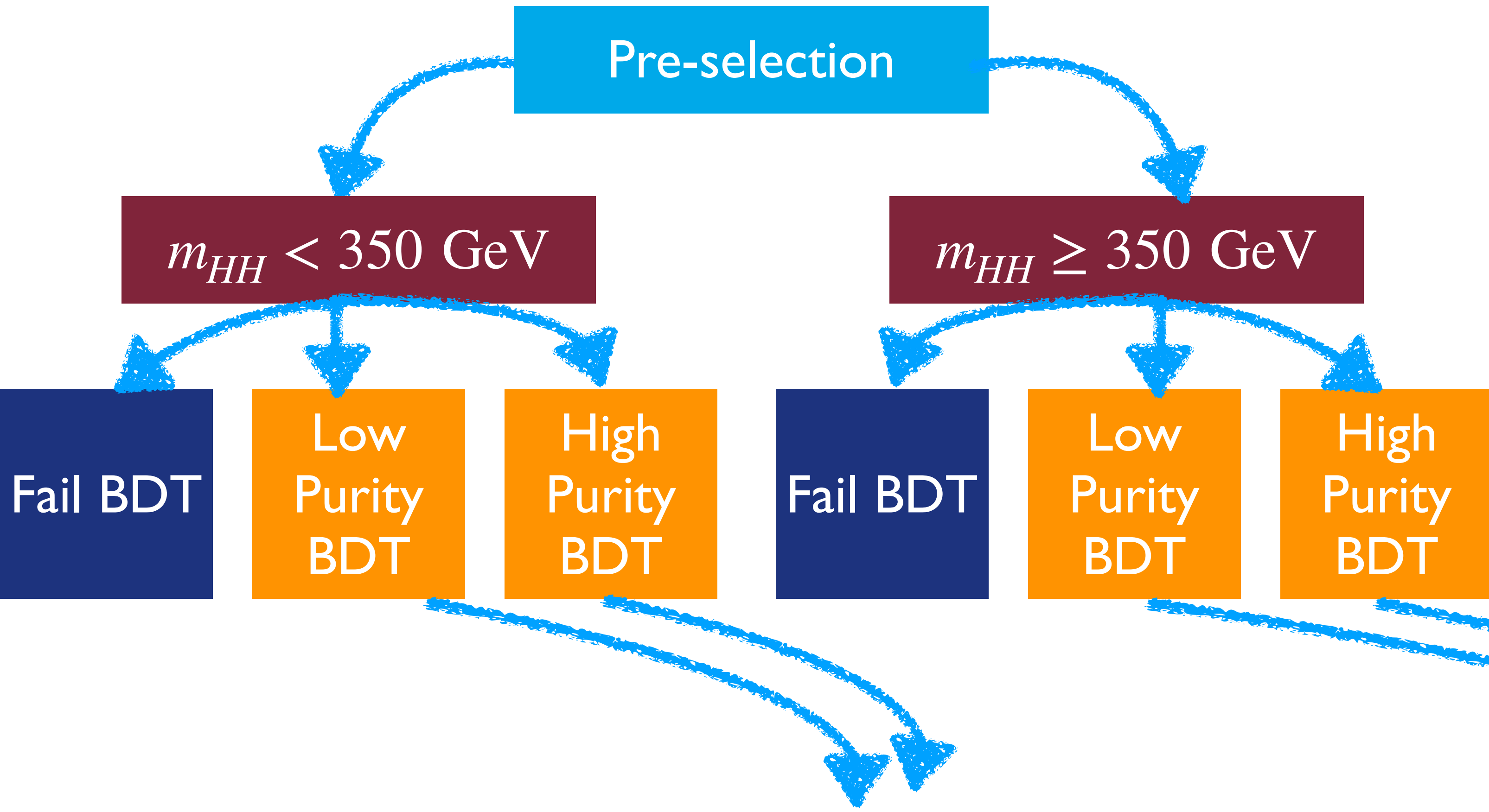

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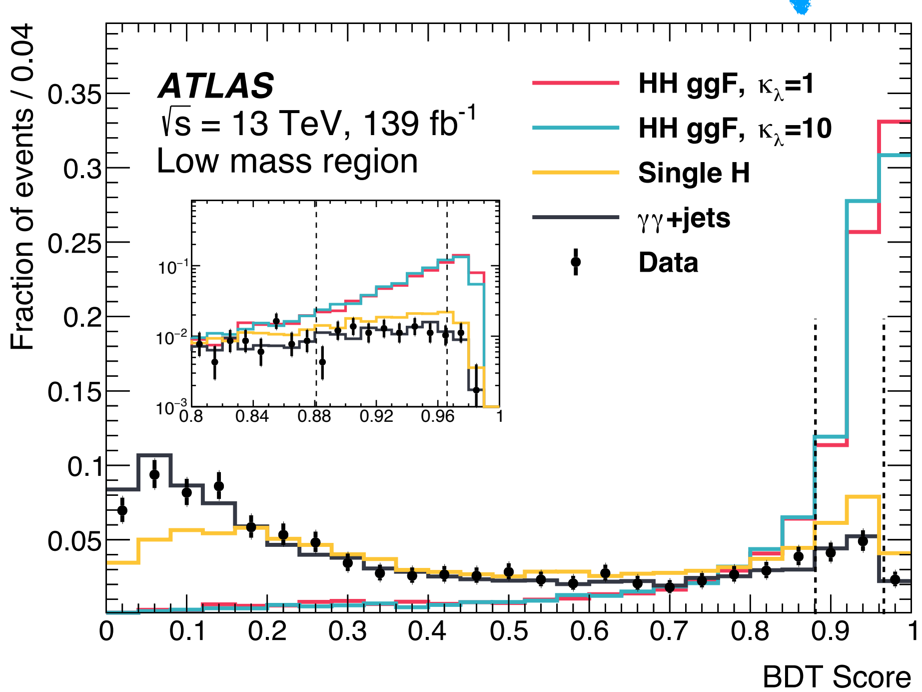
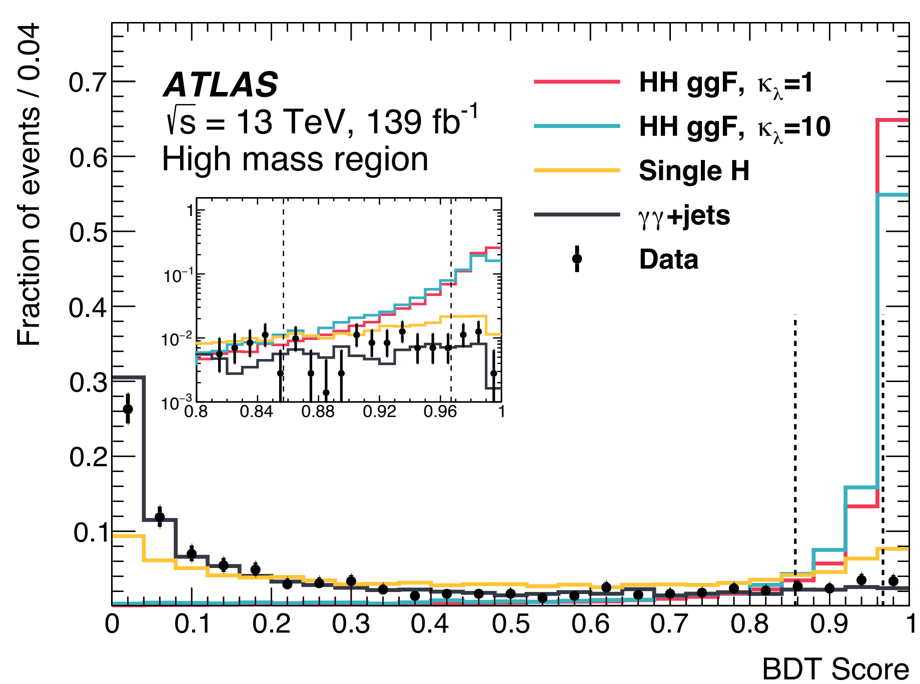
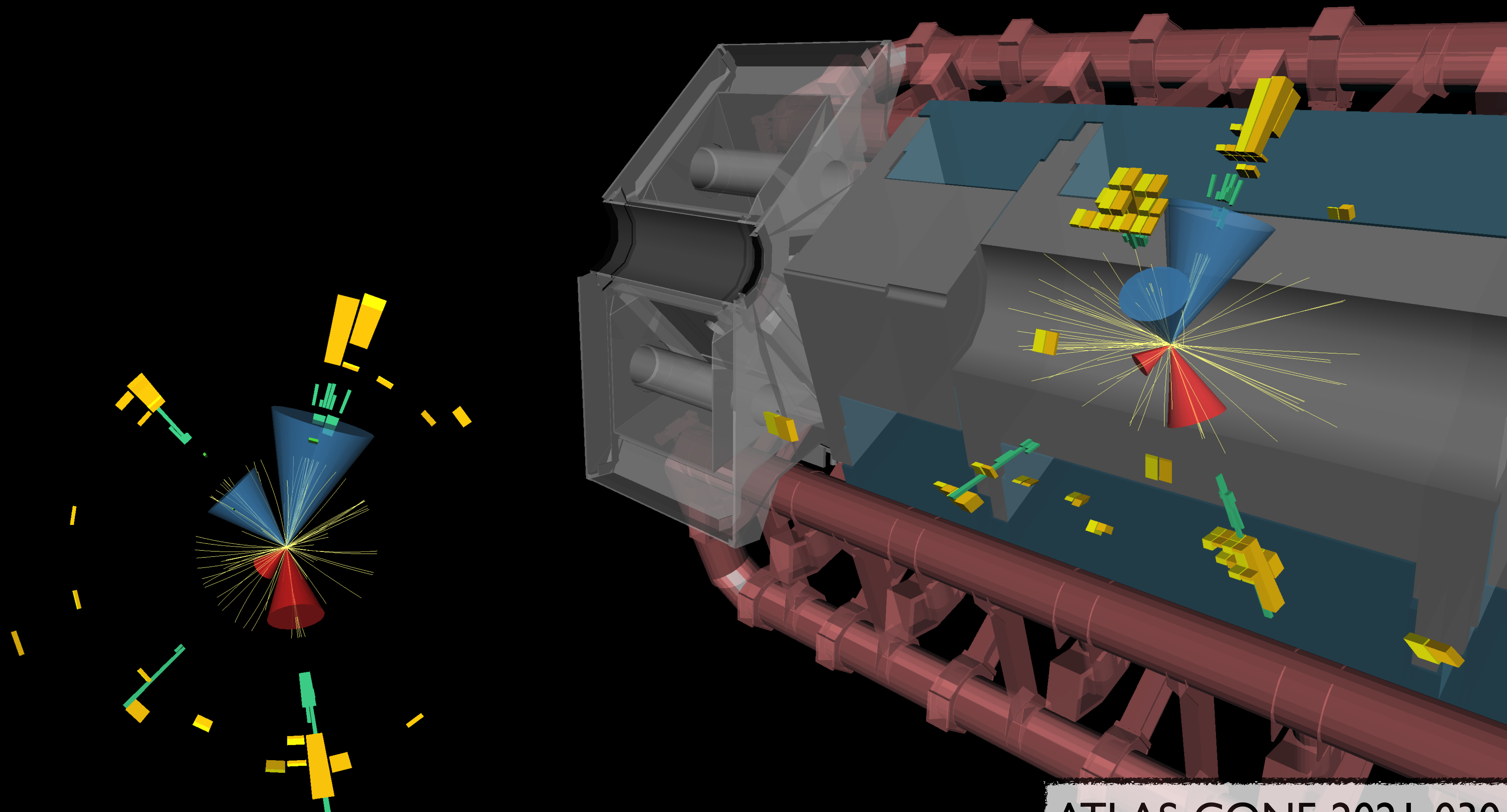




Fit $m_{\gamma\gamma}$ in 4 SR's simultaneously to extract signal

No obvious signs of new physics

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



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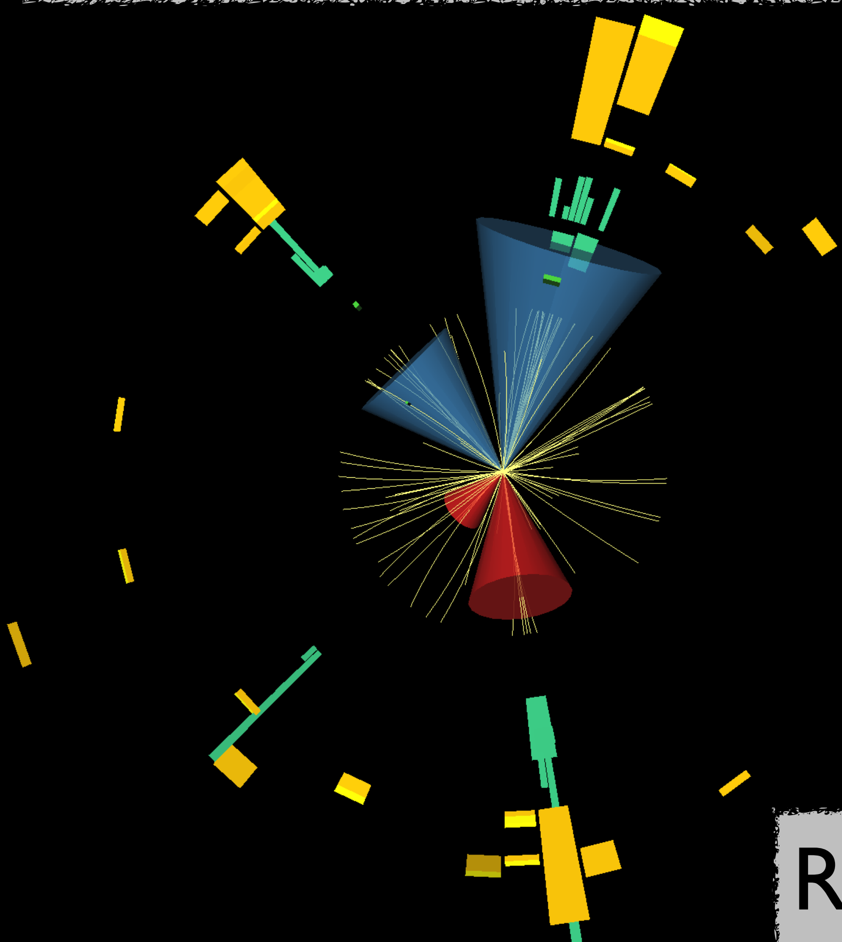
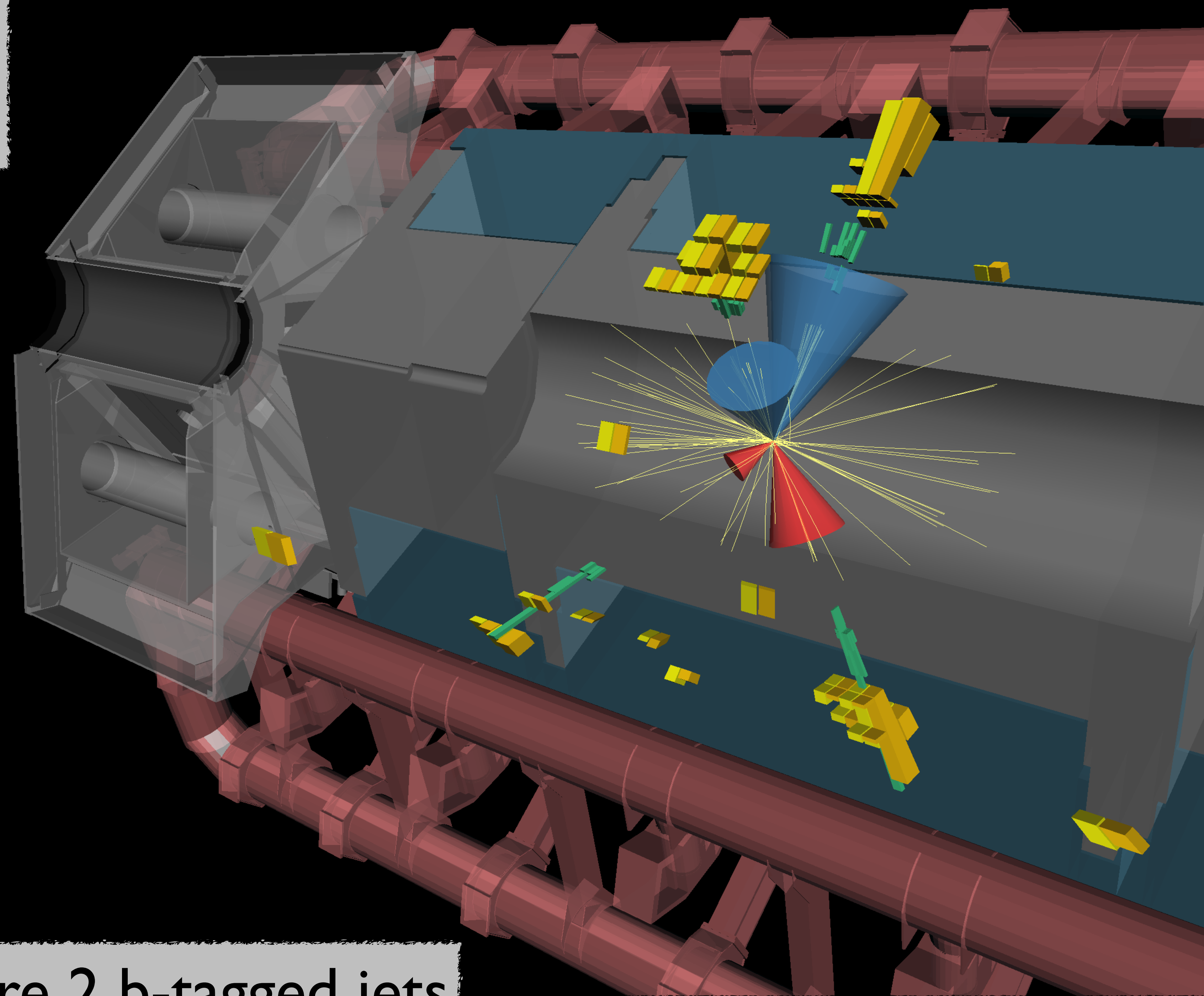
$HH \to b\bar{b}\tau\bar{\tau}$

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





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

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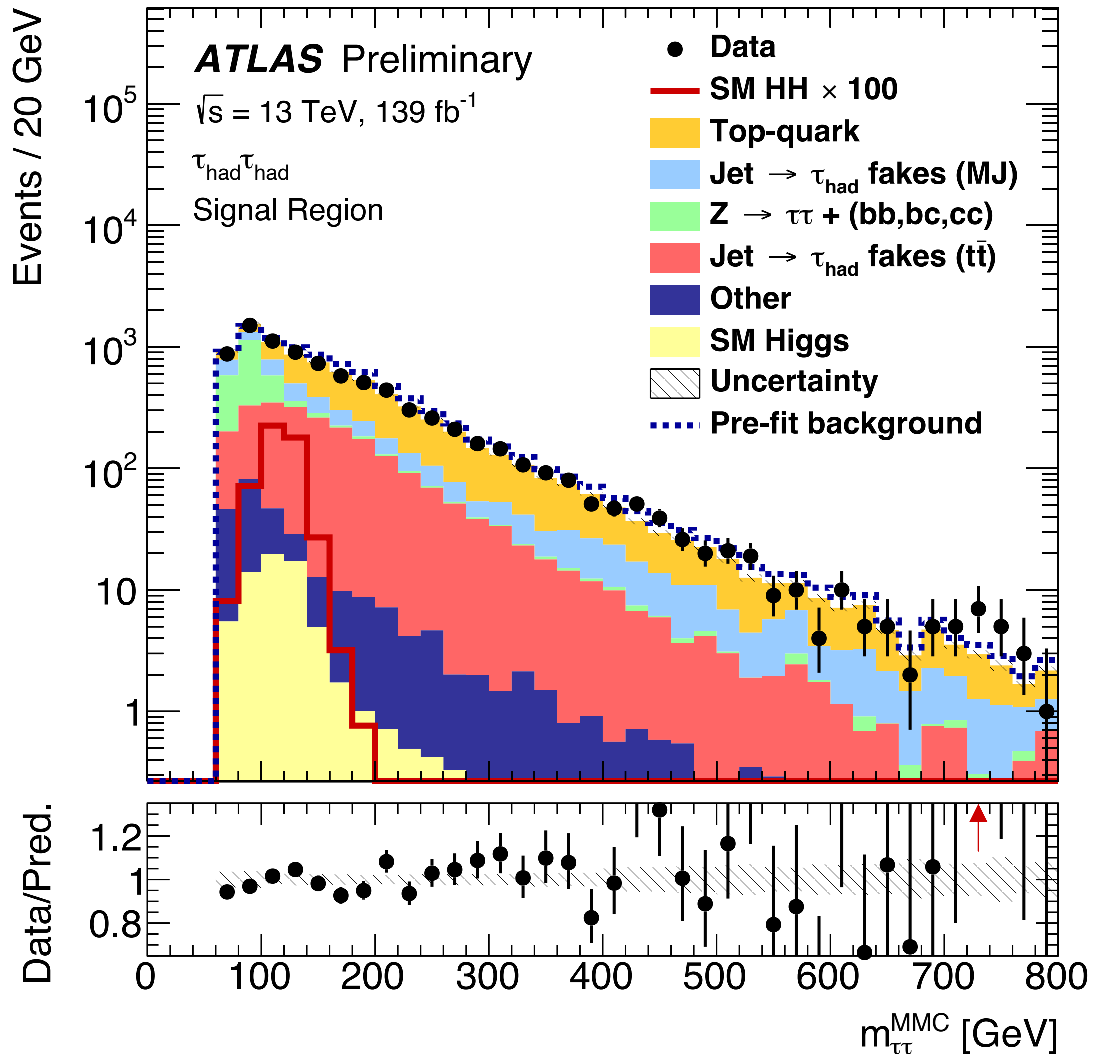
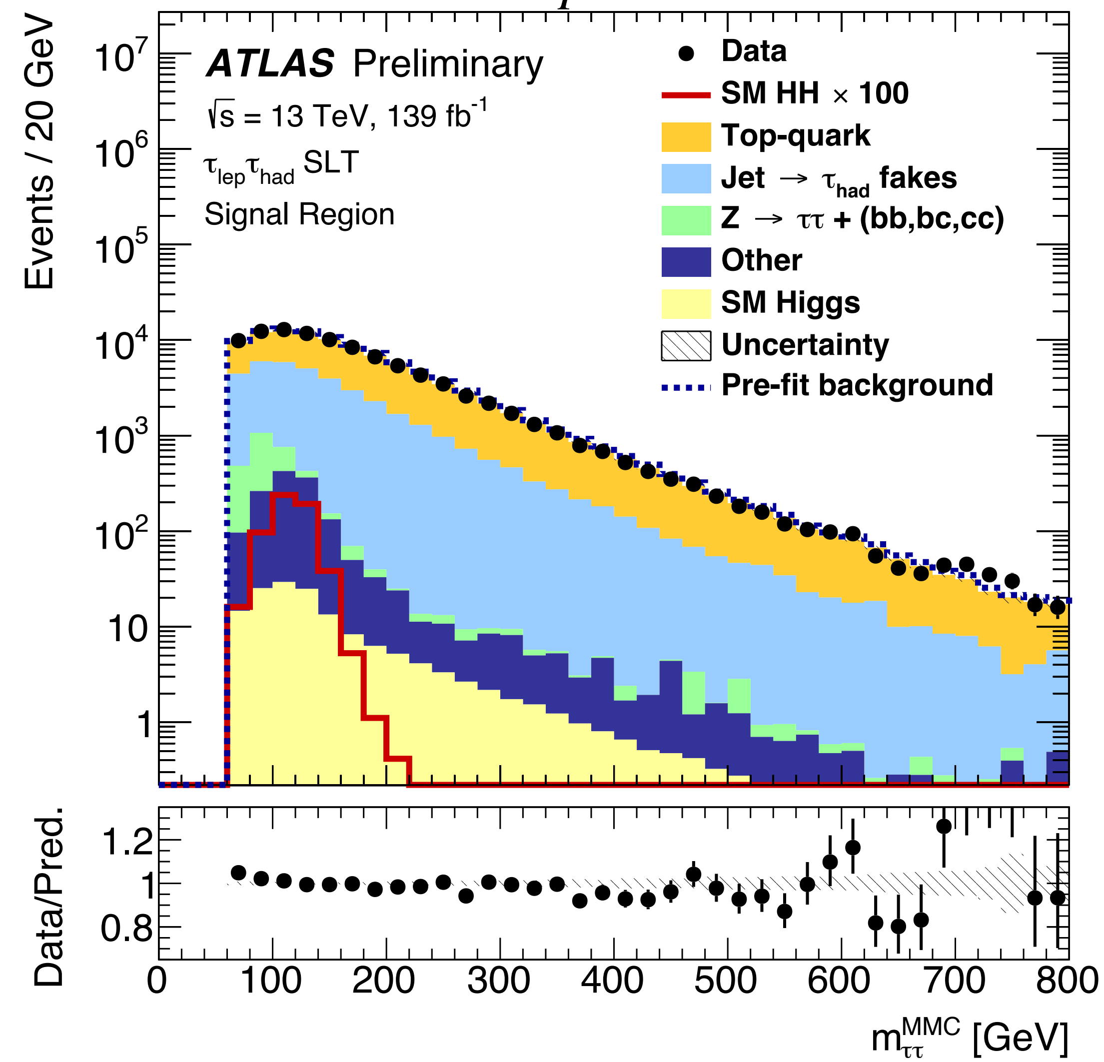
$b\bar{b}\tau\bar{\tau}$ Background Estimate

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



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



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

Z+jets background from MC, normalization from leptonic control region

Fake τ estimated from data

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

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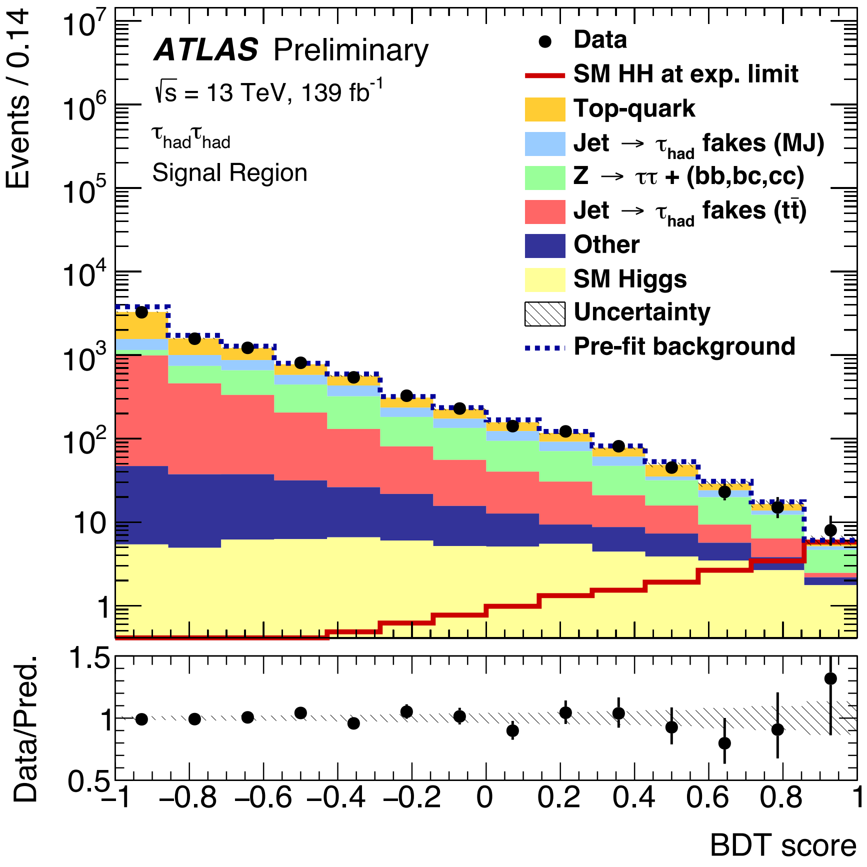

$\tau_{had}\tau_{had}$ BDT

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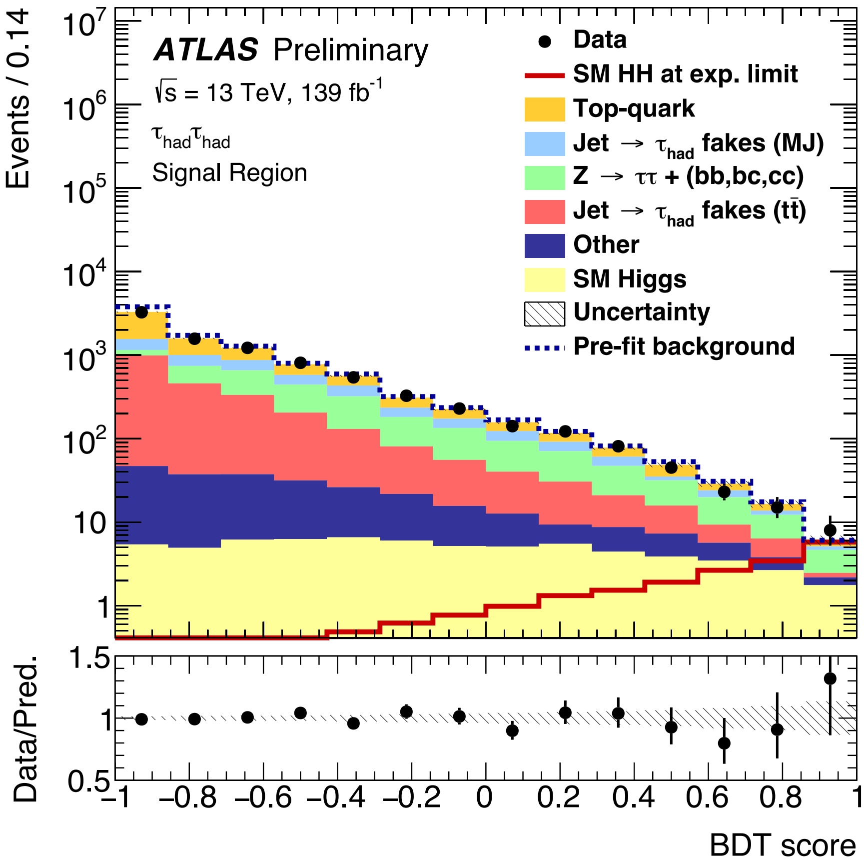

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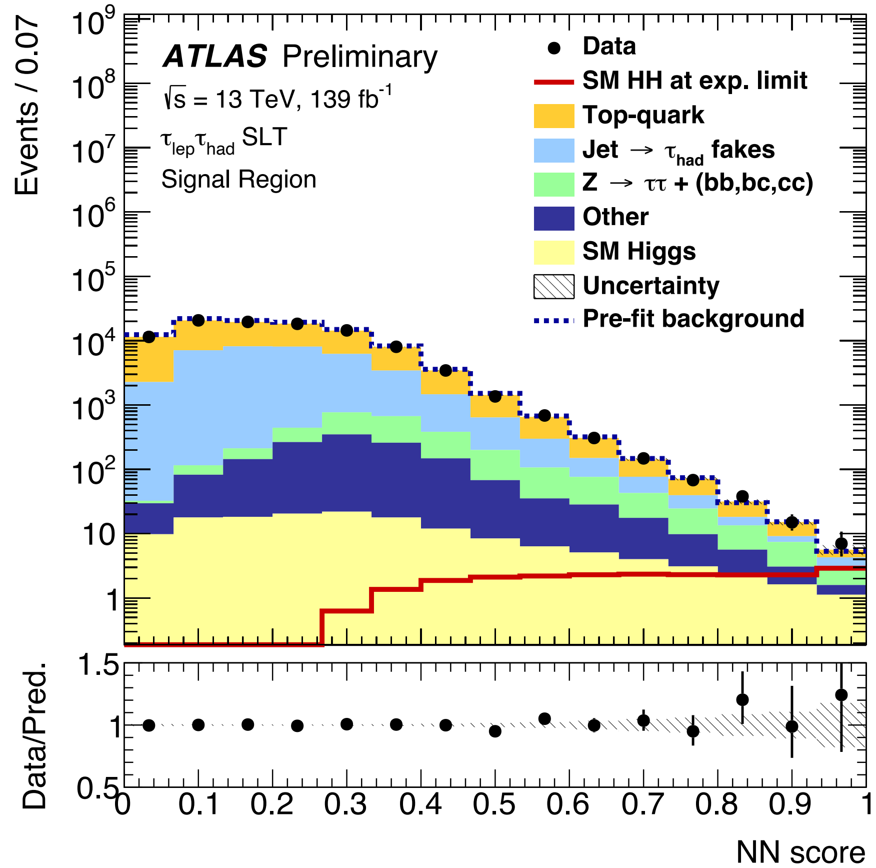

$\tau_{lep}\tau_{had}$ 1-Lepton Trigger
Neural Network

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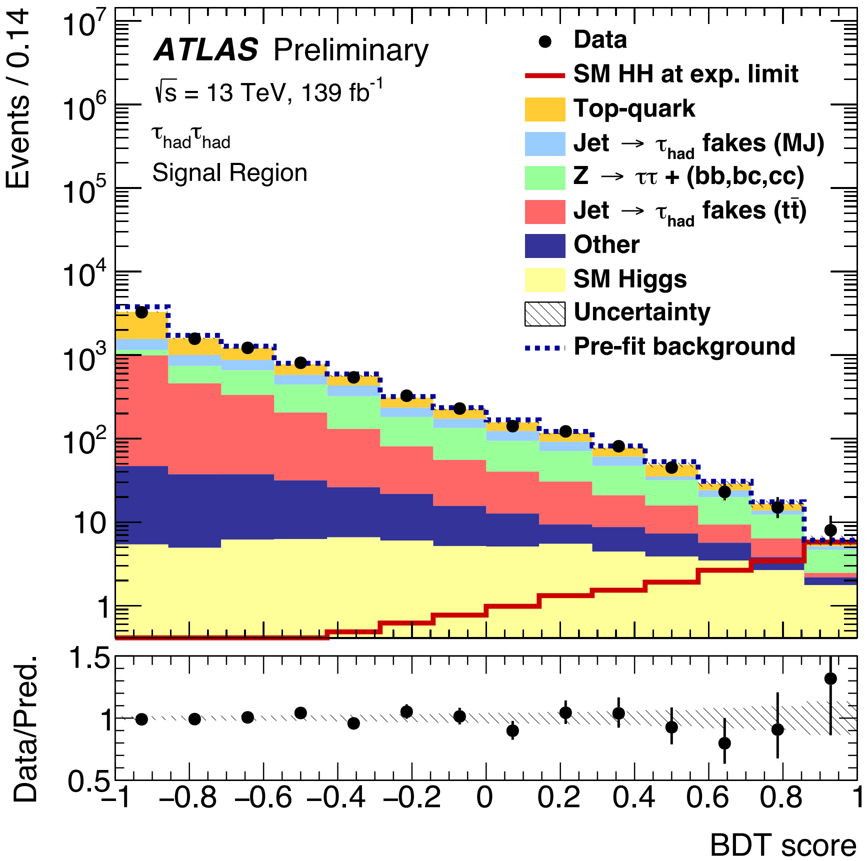

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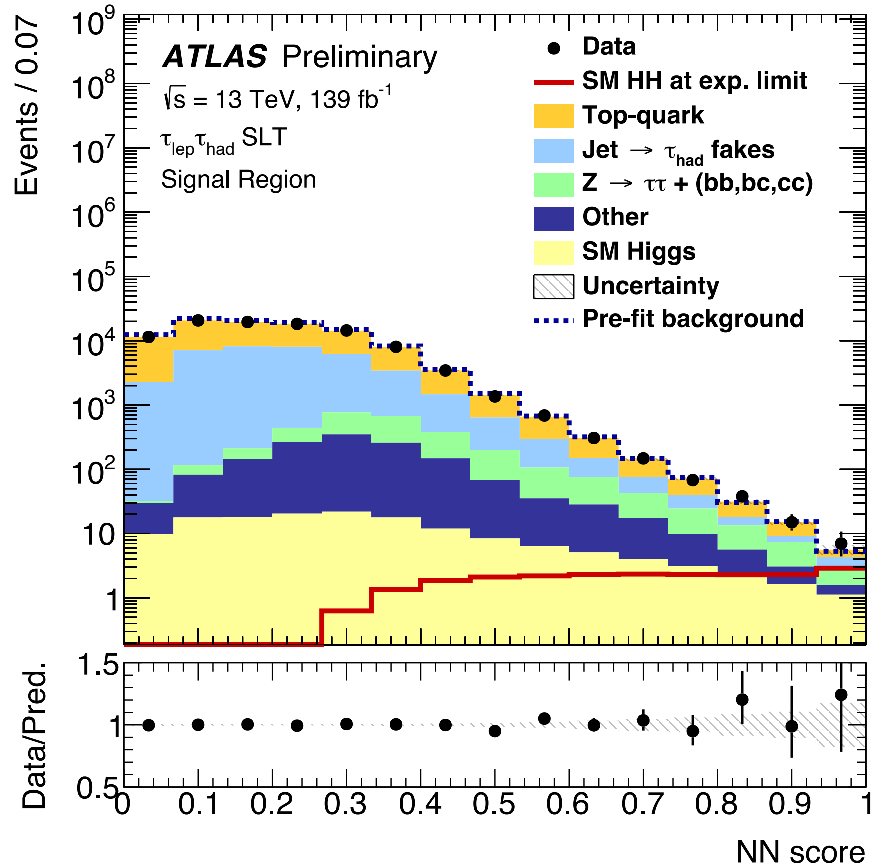

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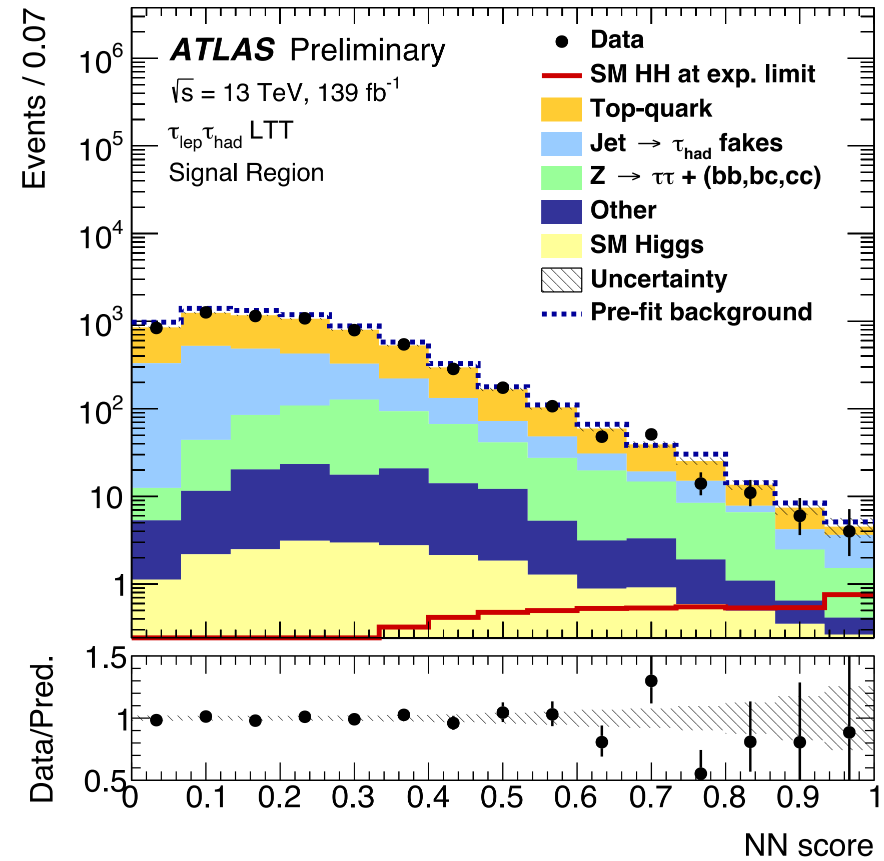

$\tau_{lep}\tau_{had}$ Lepton+Tau Neural Network

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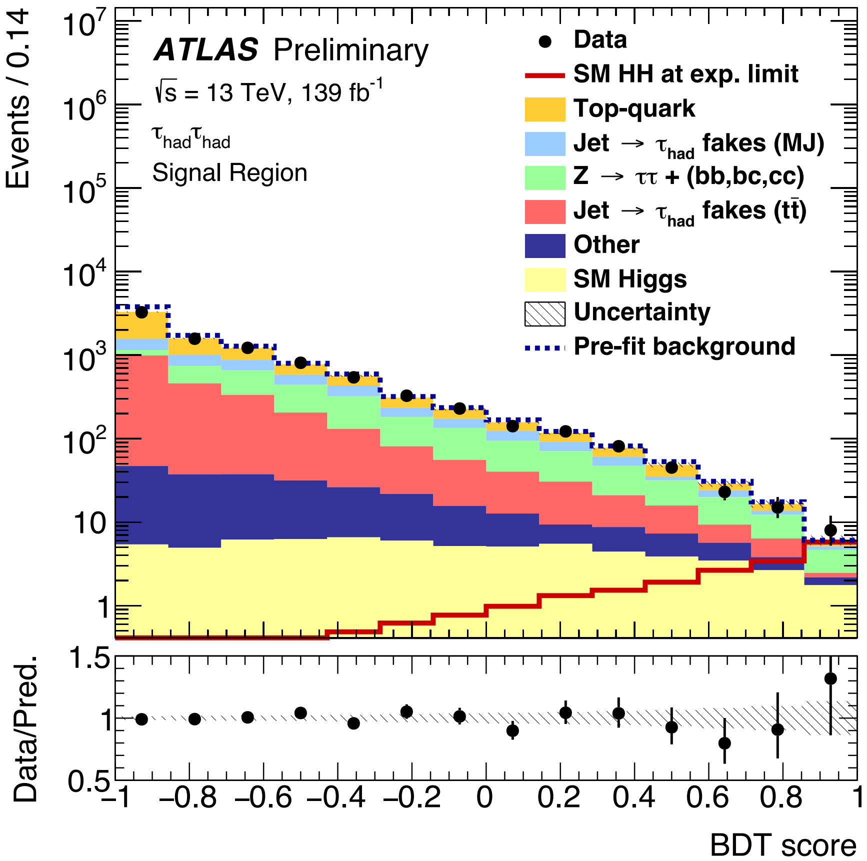

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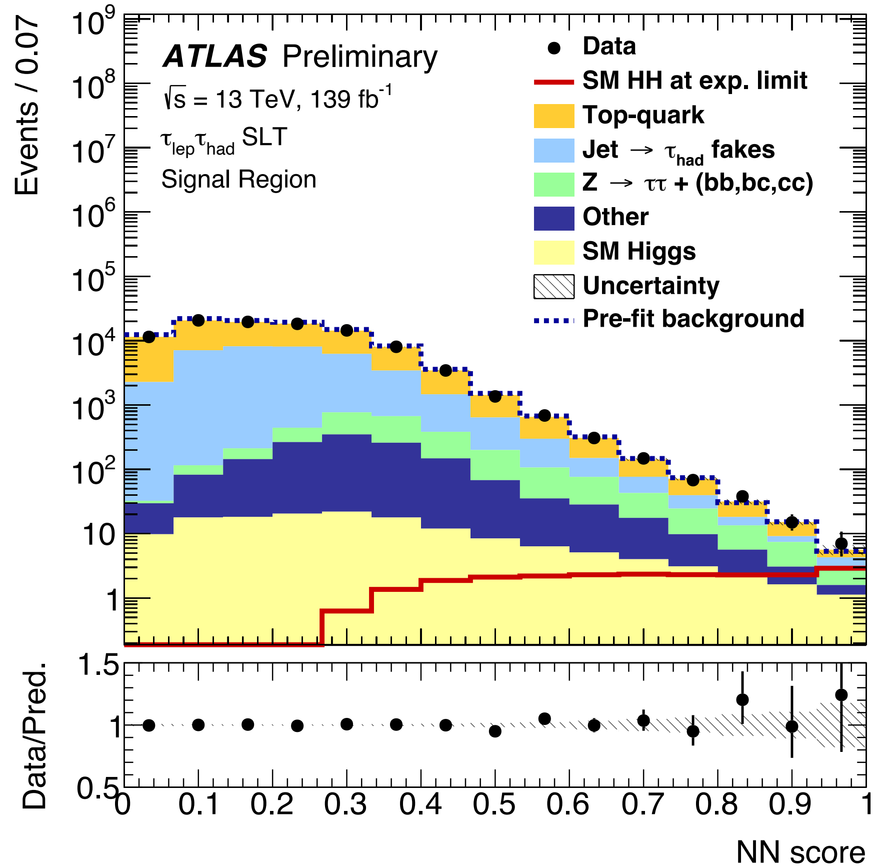

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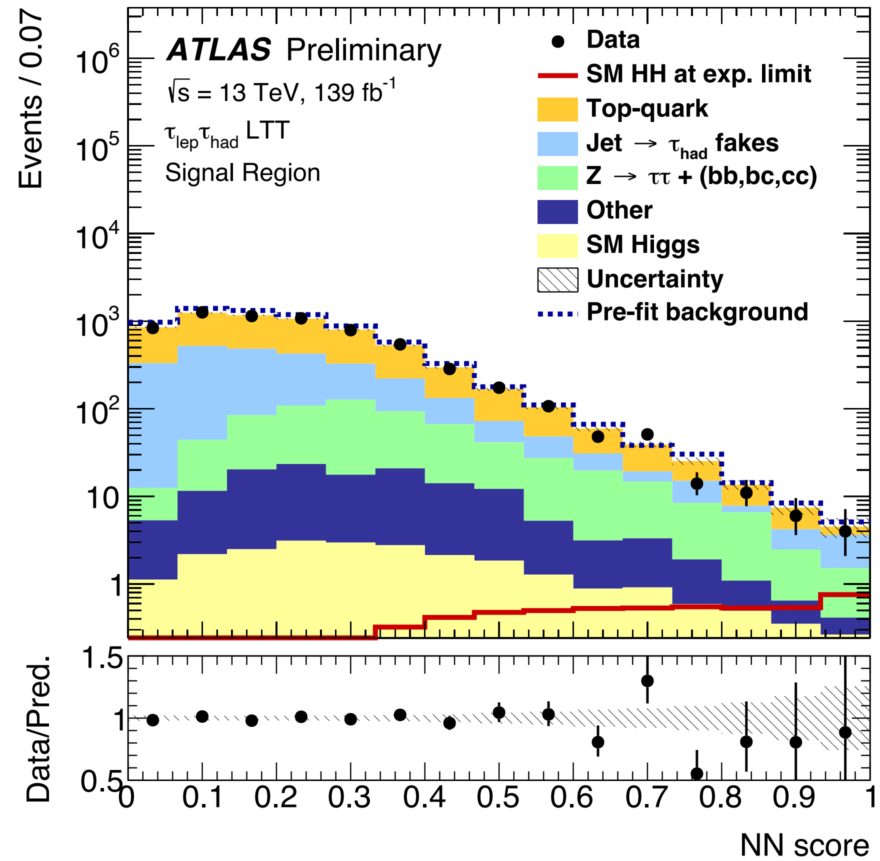

$\tau_{lep}\tau_{had}$ Lepton+Tau Neural Network

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

Limits on the SM

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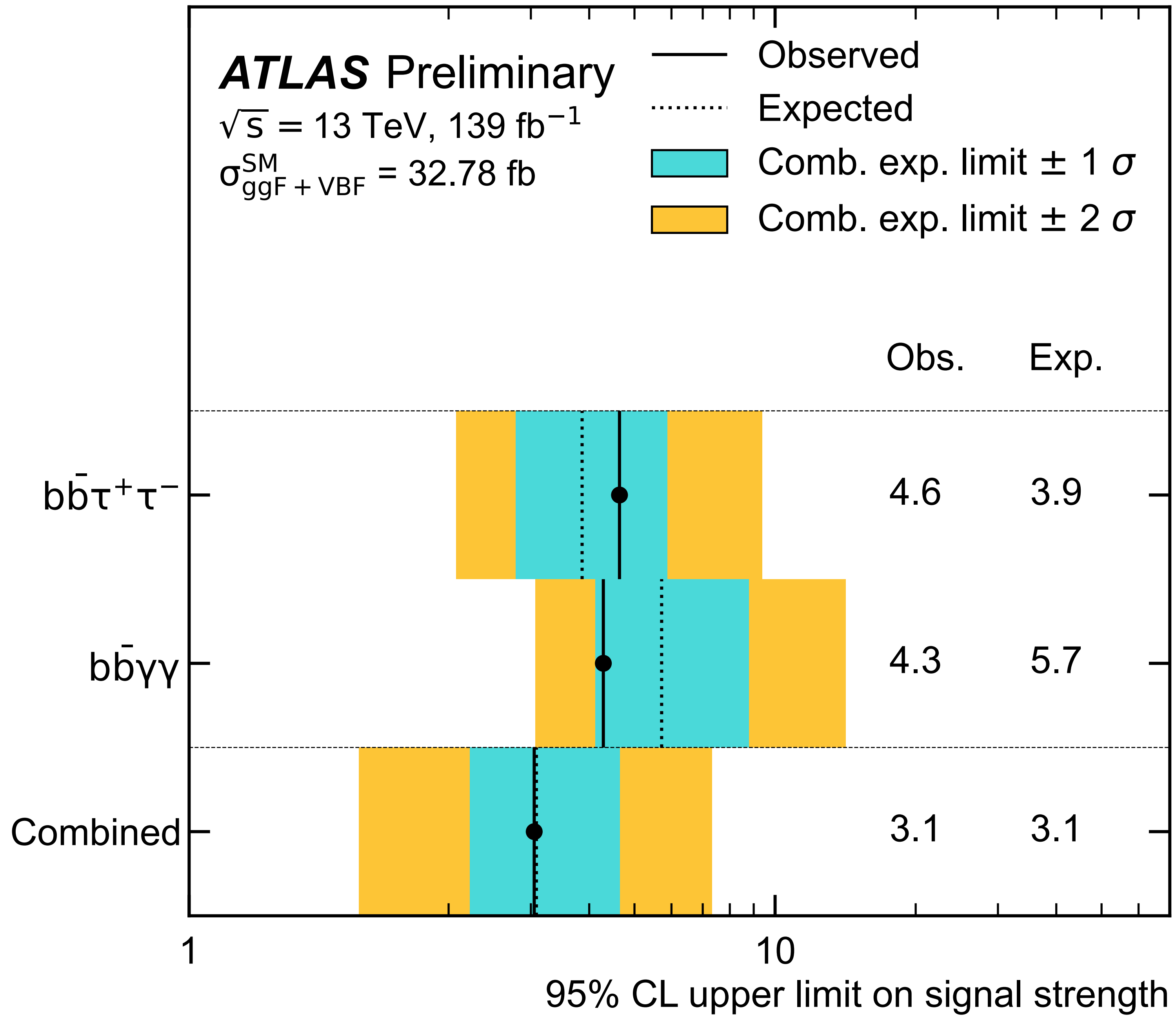
Let's put it all together:
can we see HH?

Limits on the SM



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

Here, show sensitivity to SM signal: what factor larger would the signal have to be, for us to be sensitive?

Individual analyses set limits at ~4.5x SM

Together, set **limit at 3.1x SM**

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Measuring the Potential

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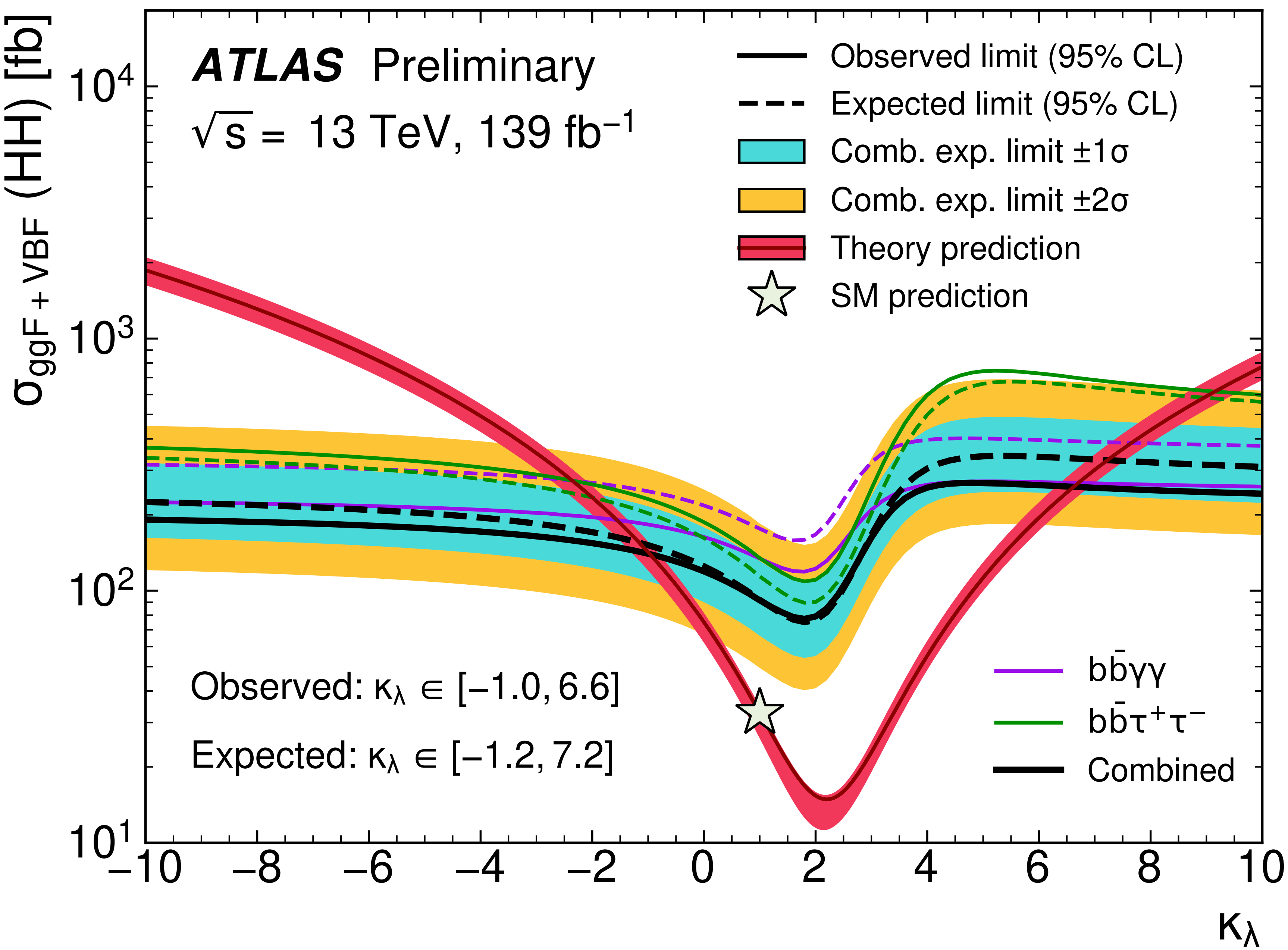

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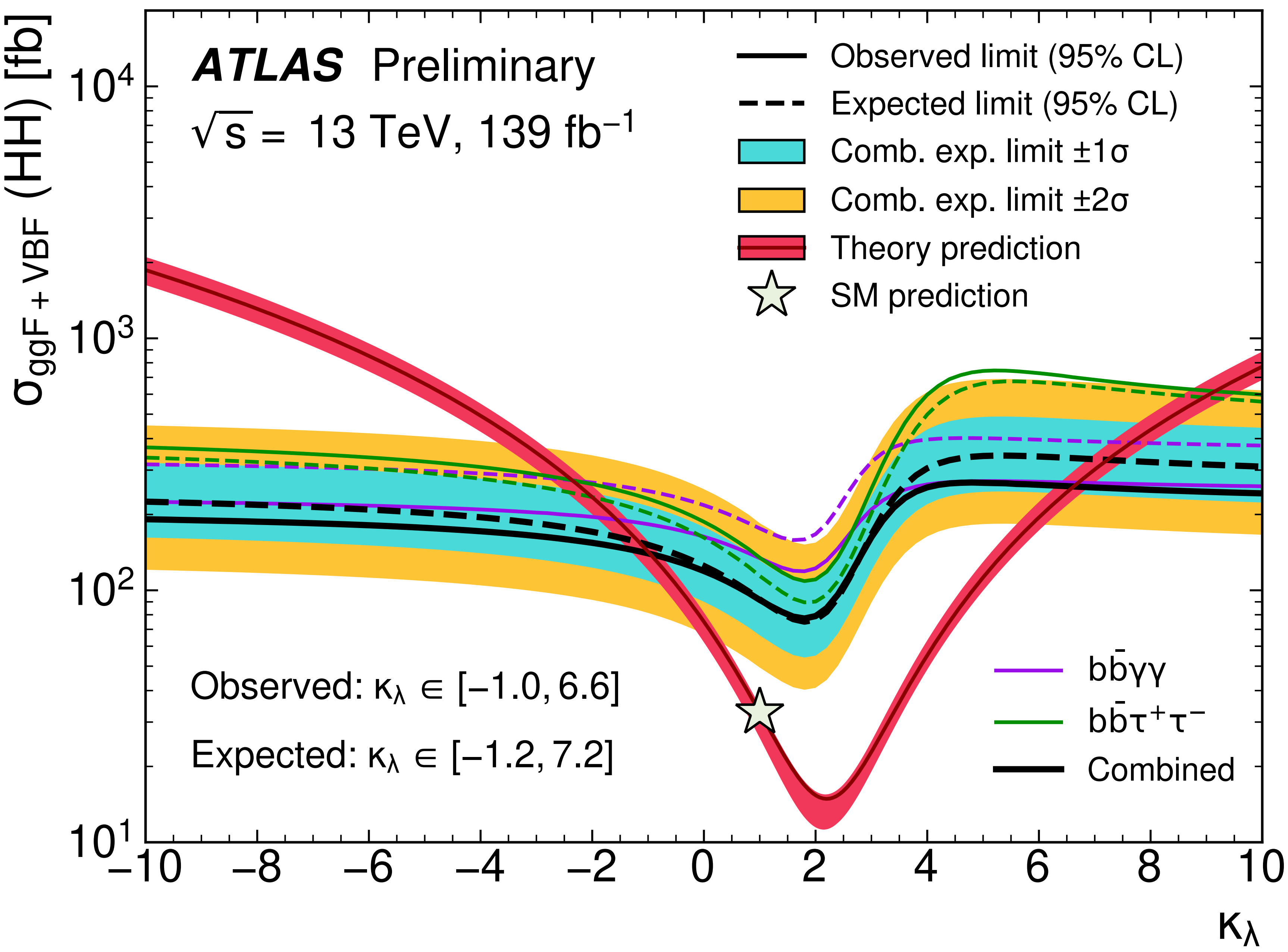

Signal σ goes *up* for extreme κ_λ: produce more signal

Limits also go up at extreme κ_λ: signal is growing, but is concentrated at low m_{HH}, same as backgrounds

Both analyses contribute to combination!

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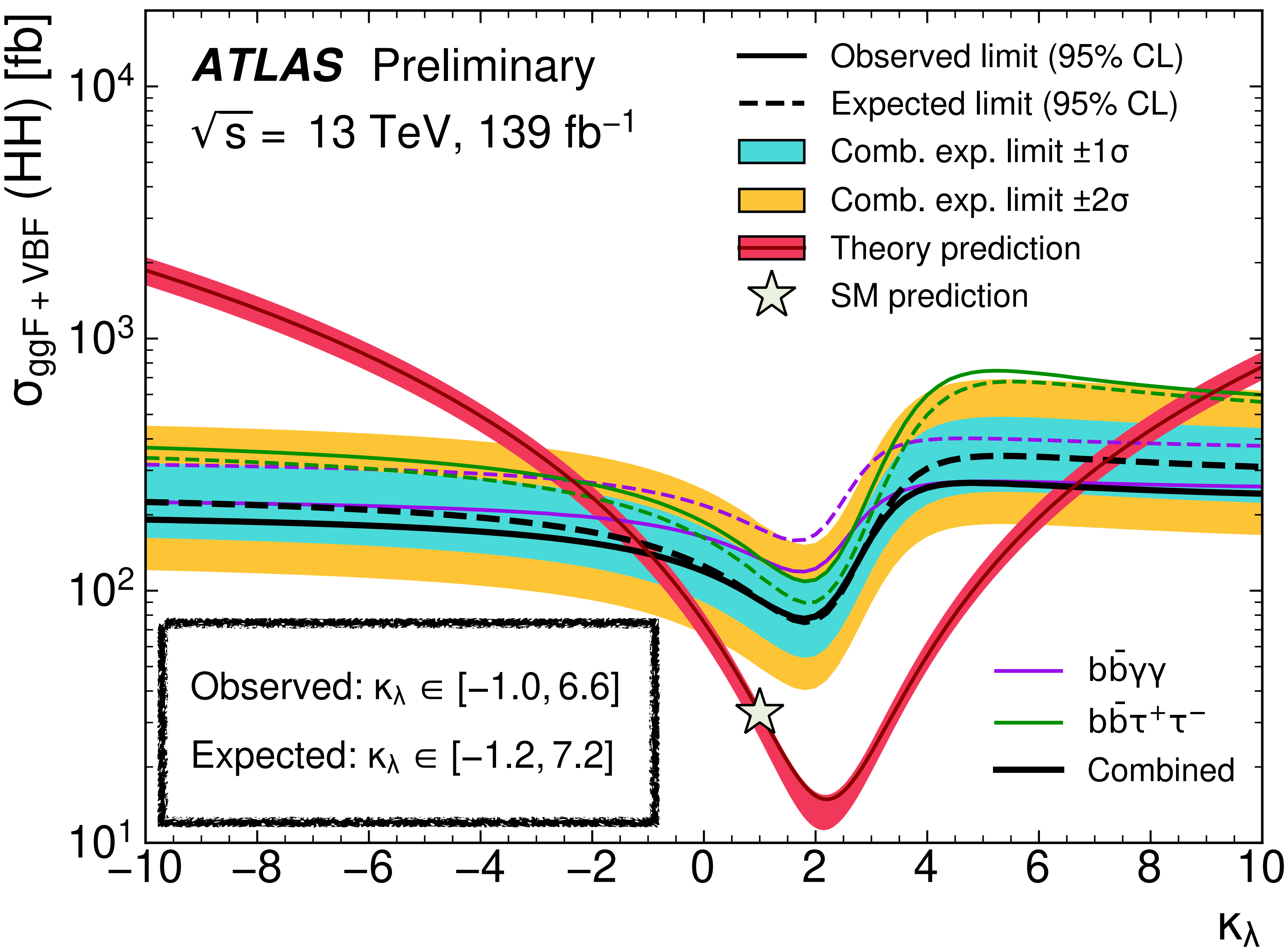

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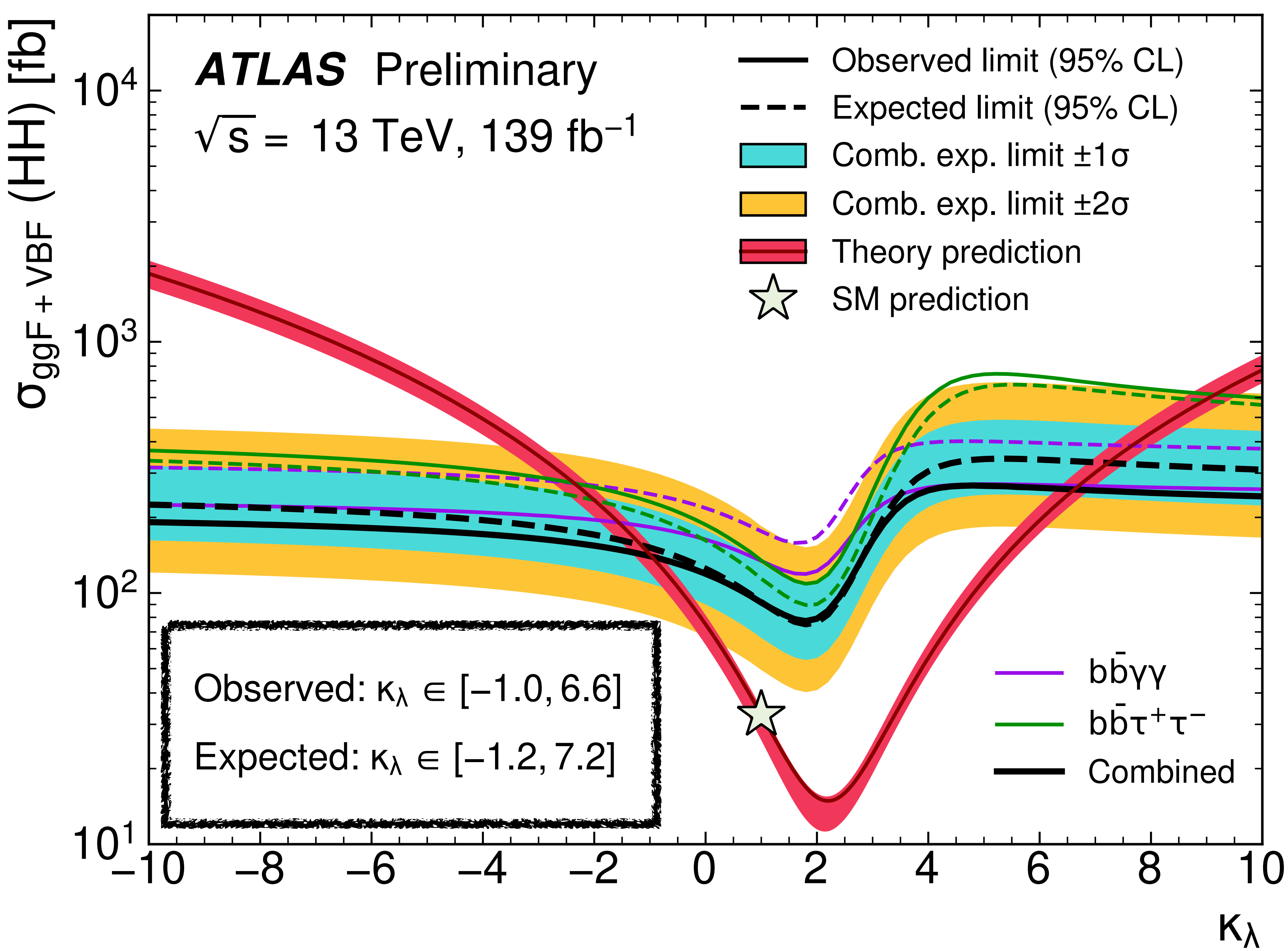
Both analyses contribute to combination!

Allowed range:
$-1.0 < \kappa_\lambda \leq 6.6$

Measuring the Potential



Significantly improved compared to mid-Run2: $-5.0 < \kappa_\lambda \leq 12.0$

Signal σ goes *up* for extreme κ_λ: produce more signal

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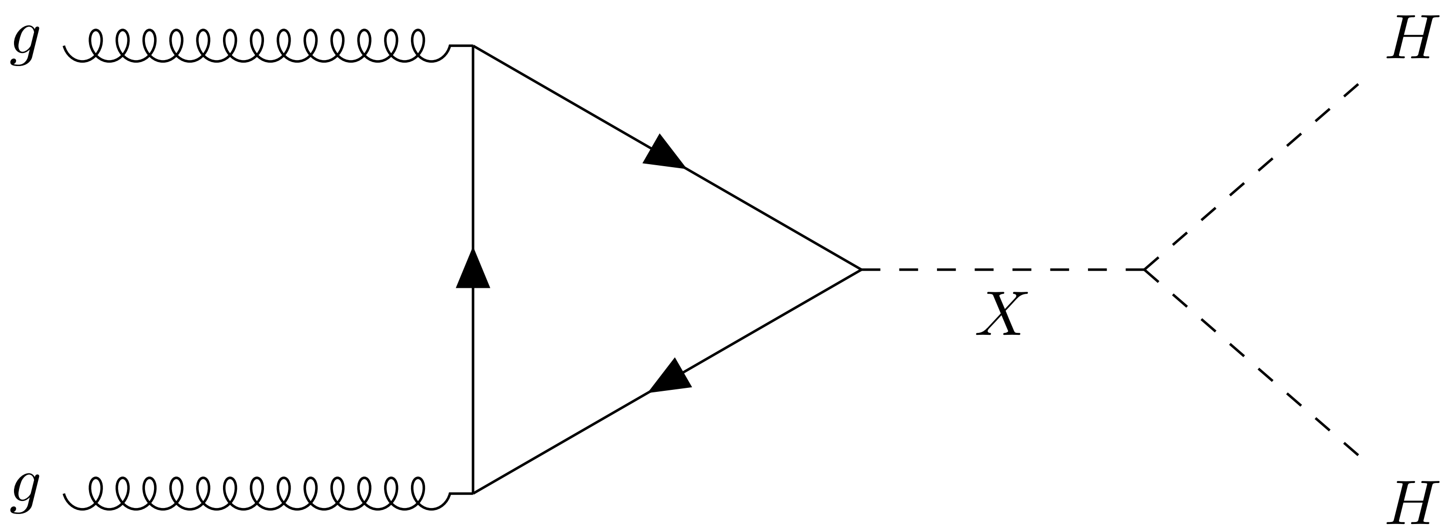
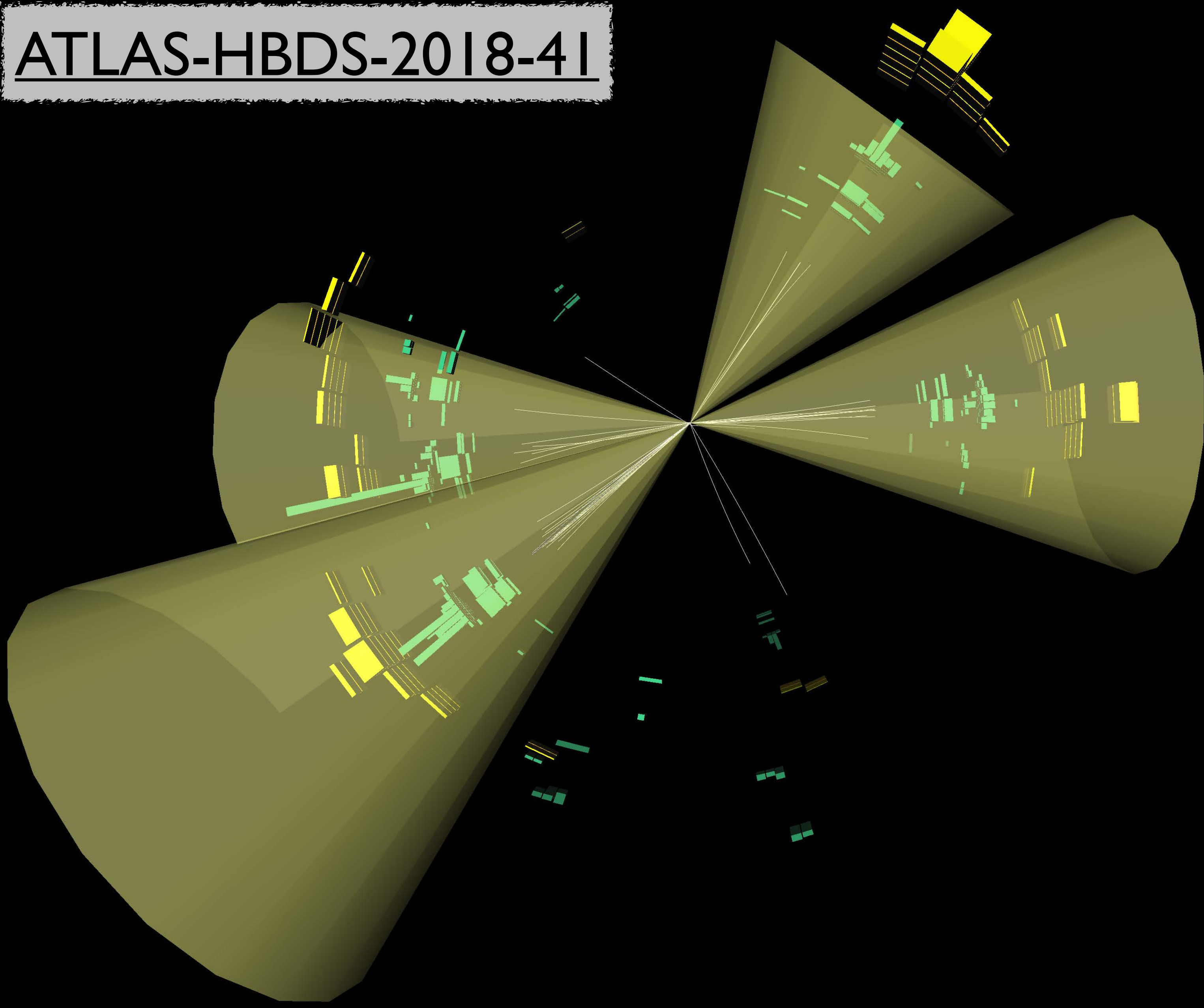


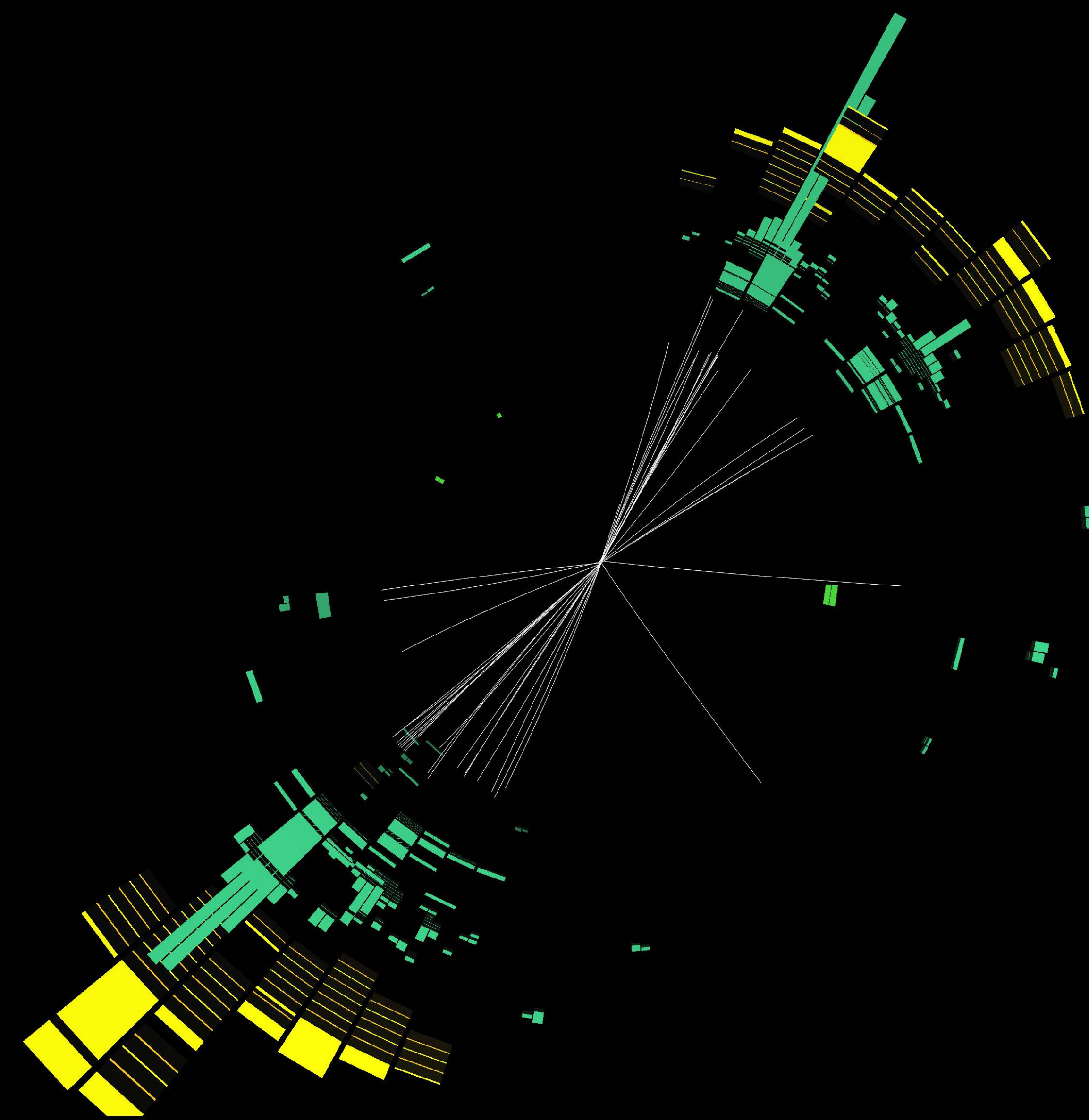
Like a new resonance!

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

ATLAS-HBDS-2018-41



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



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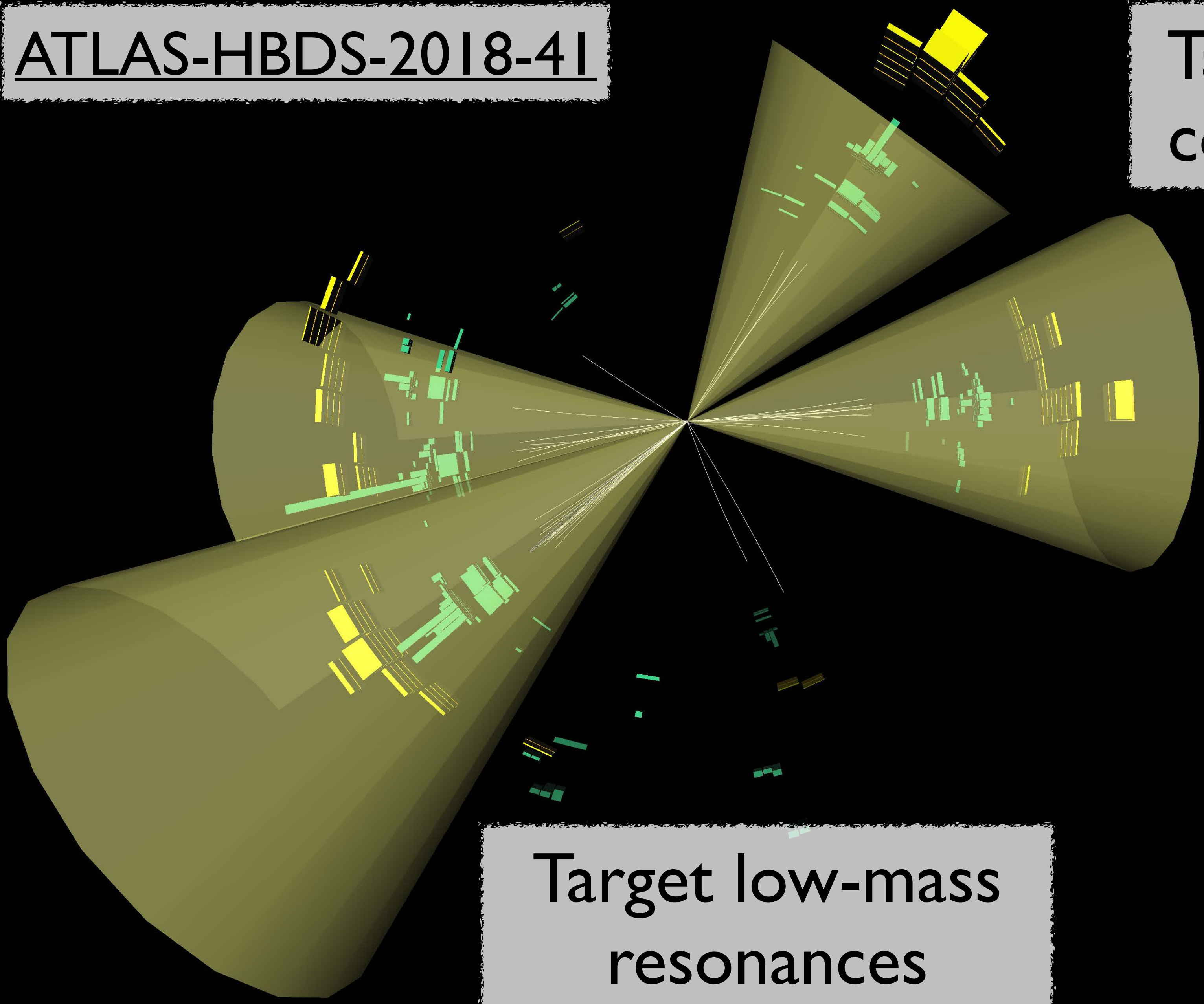
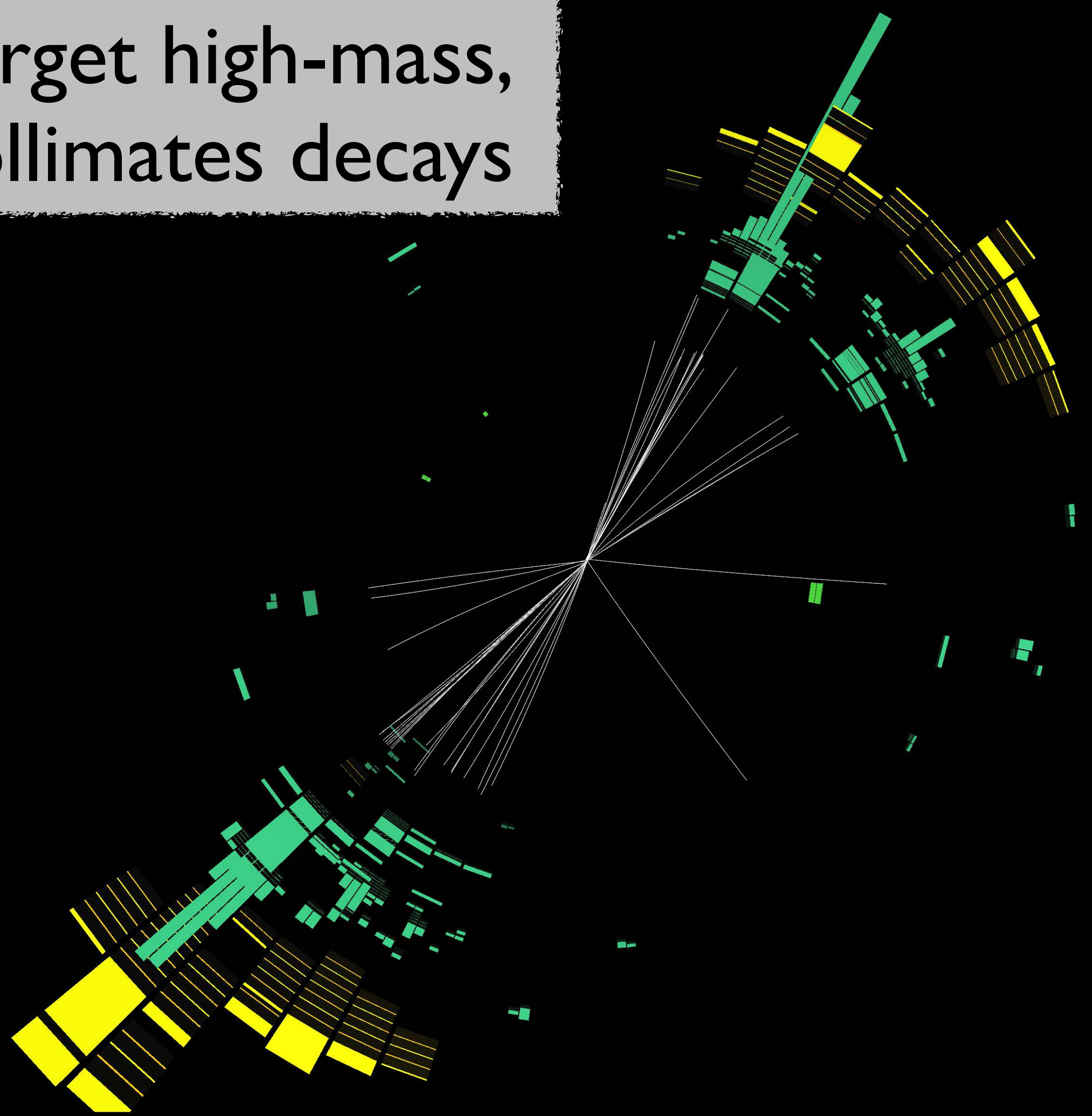


Target low-mass resonances

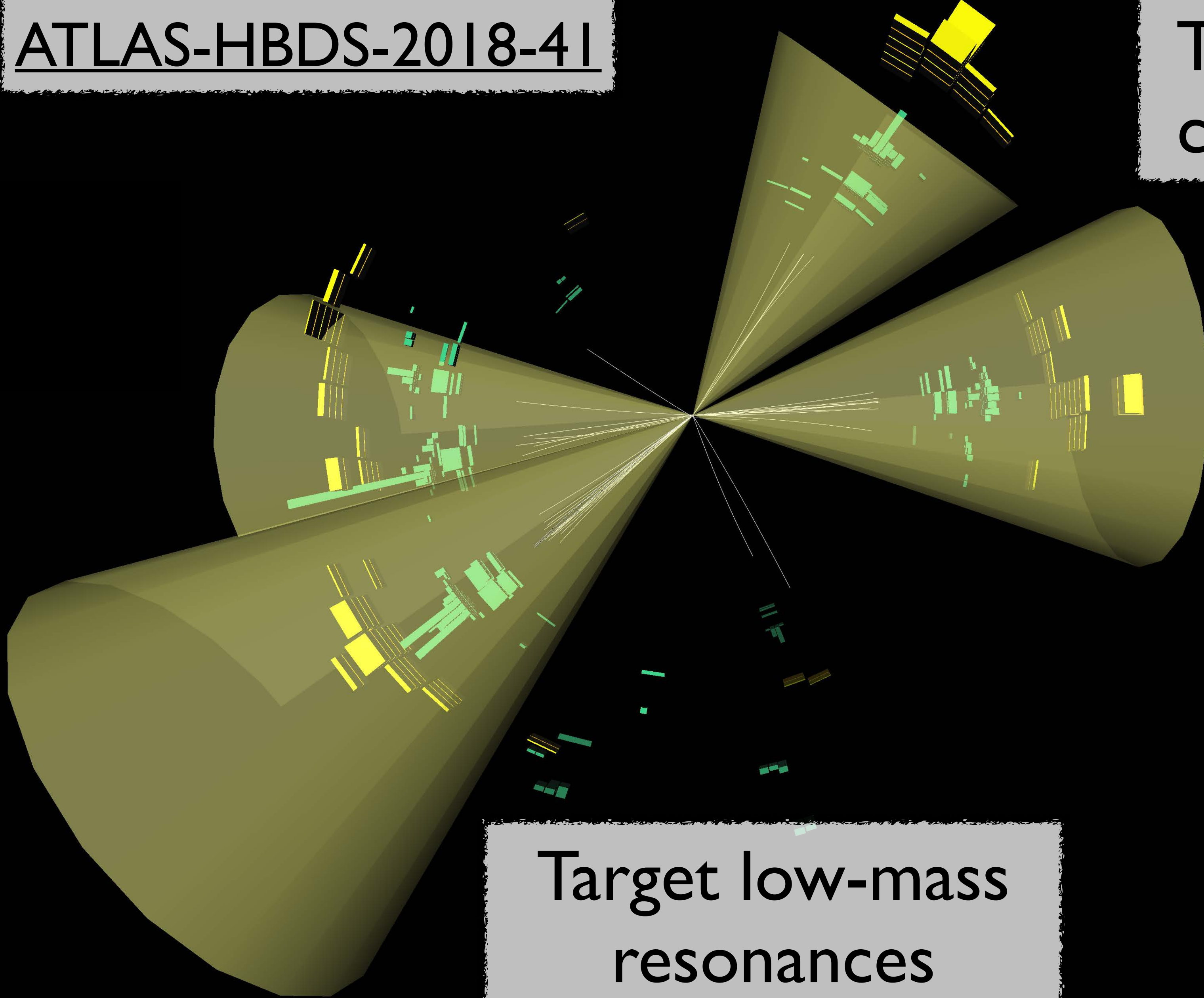
$HH \to b\bar{b}b\bar{b}$ Boosted

Target high-mass, collimates decays



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

ATLAS-HBDS-2018-41



Target low-mass resonances

Combination of ~4 b-jet triggers

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

Boosted Decision Tree used to pair jets

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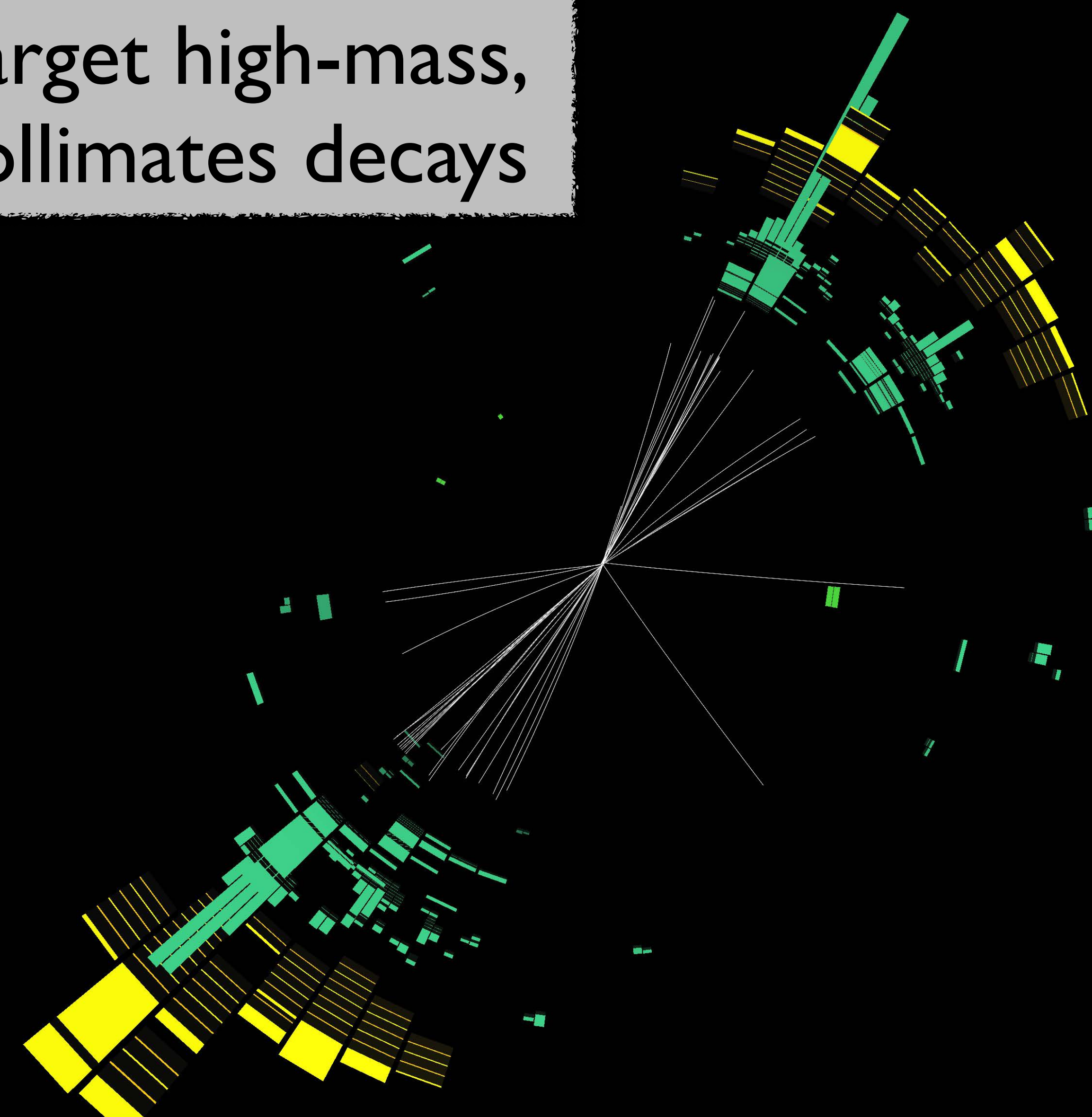

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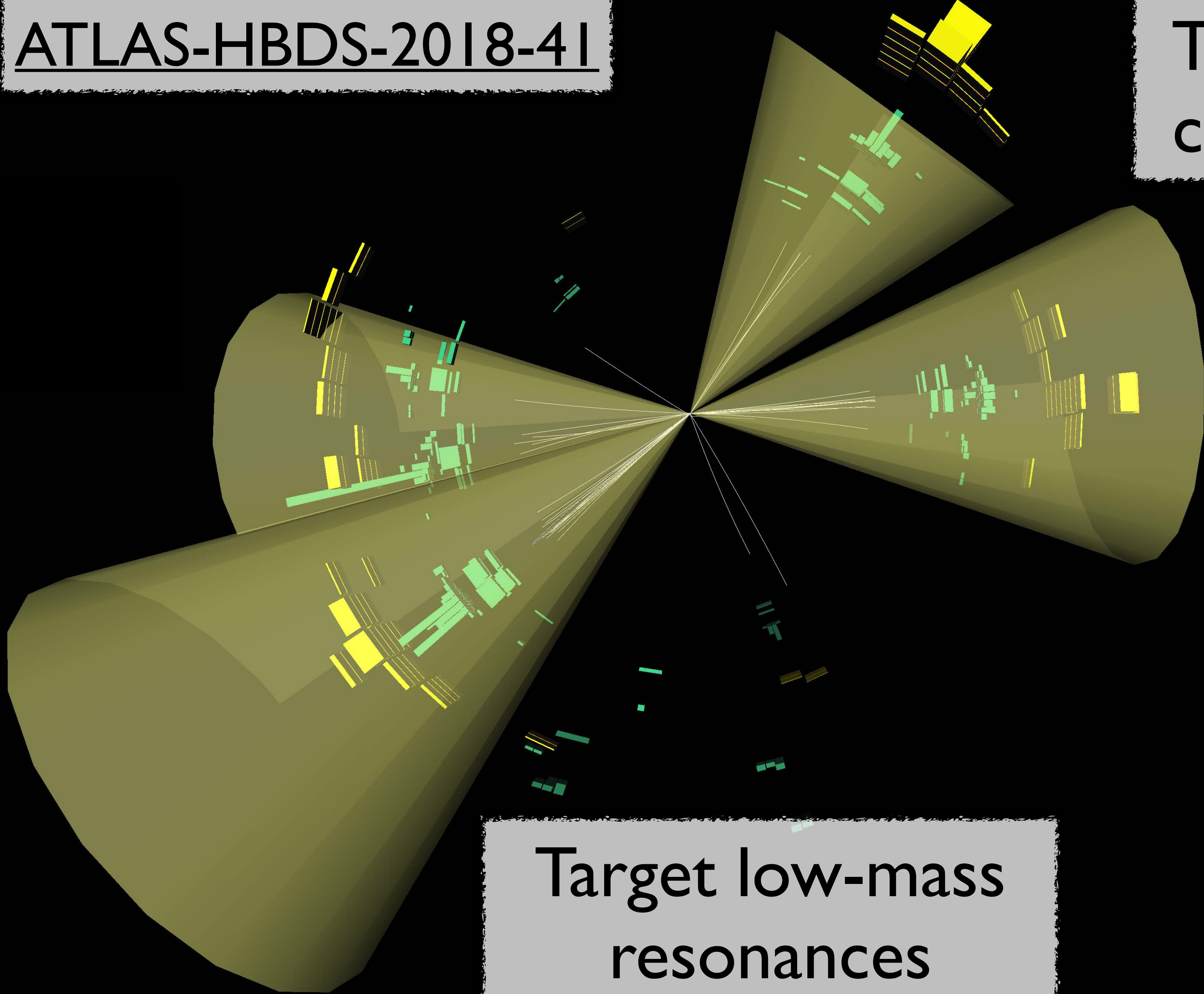

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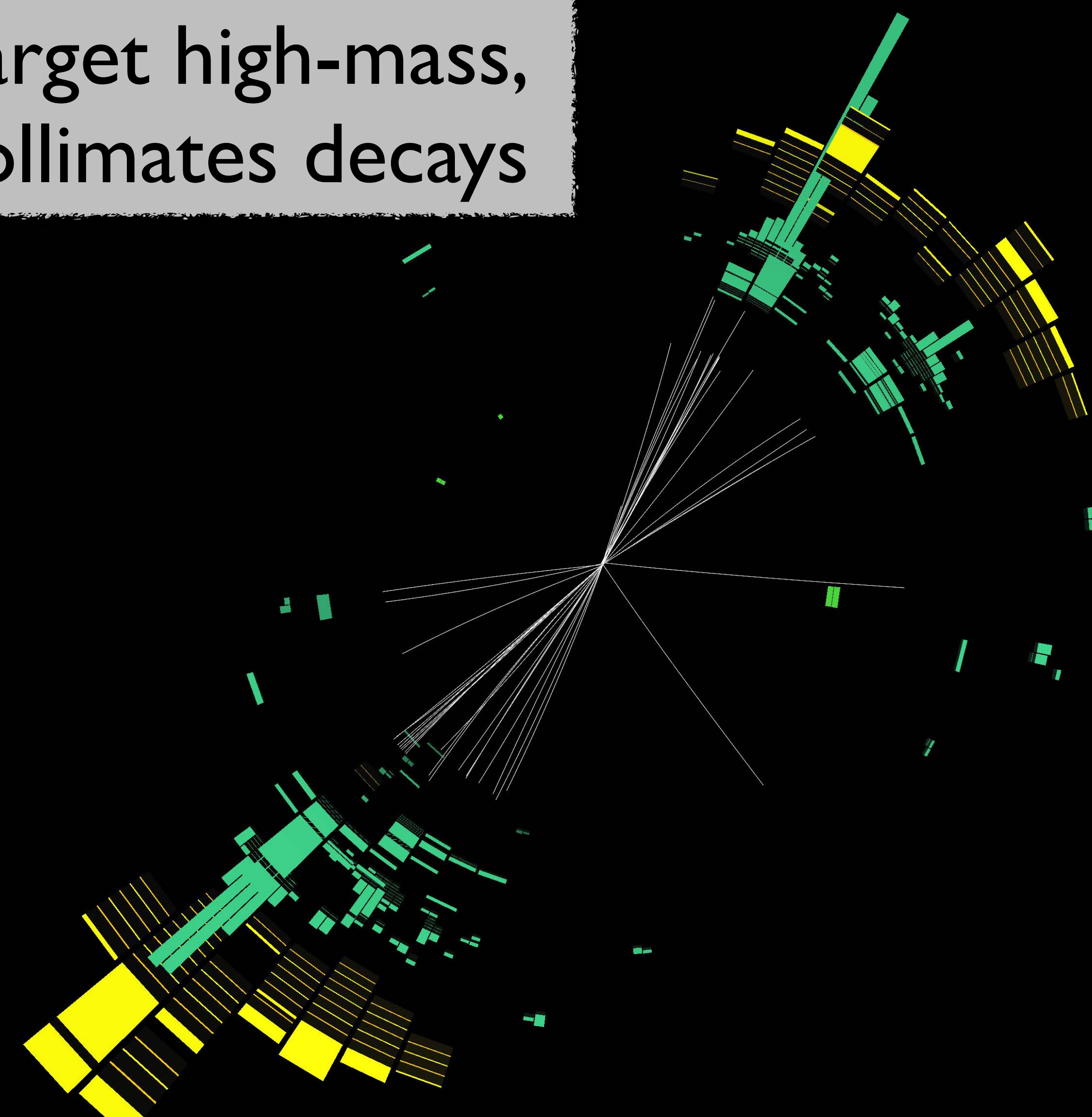

Large-R jet trigger ($E_T > 450$ GeV)

Two large-R jets
(R=1.0, $p_T > 450$ (250) GeV)

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

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

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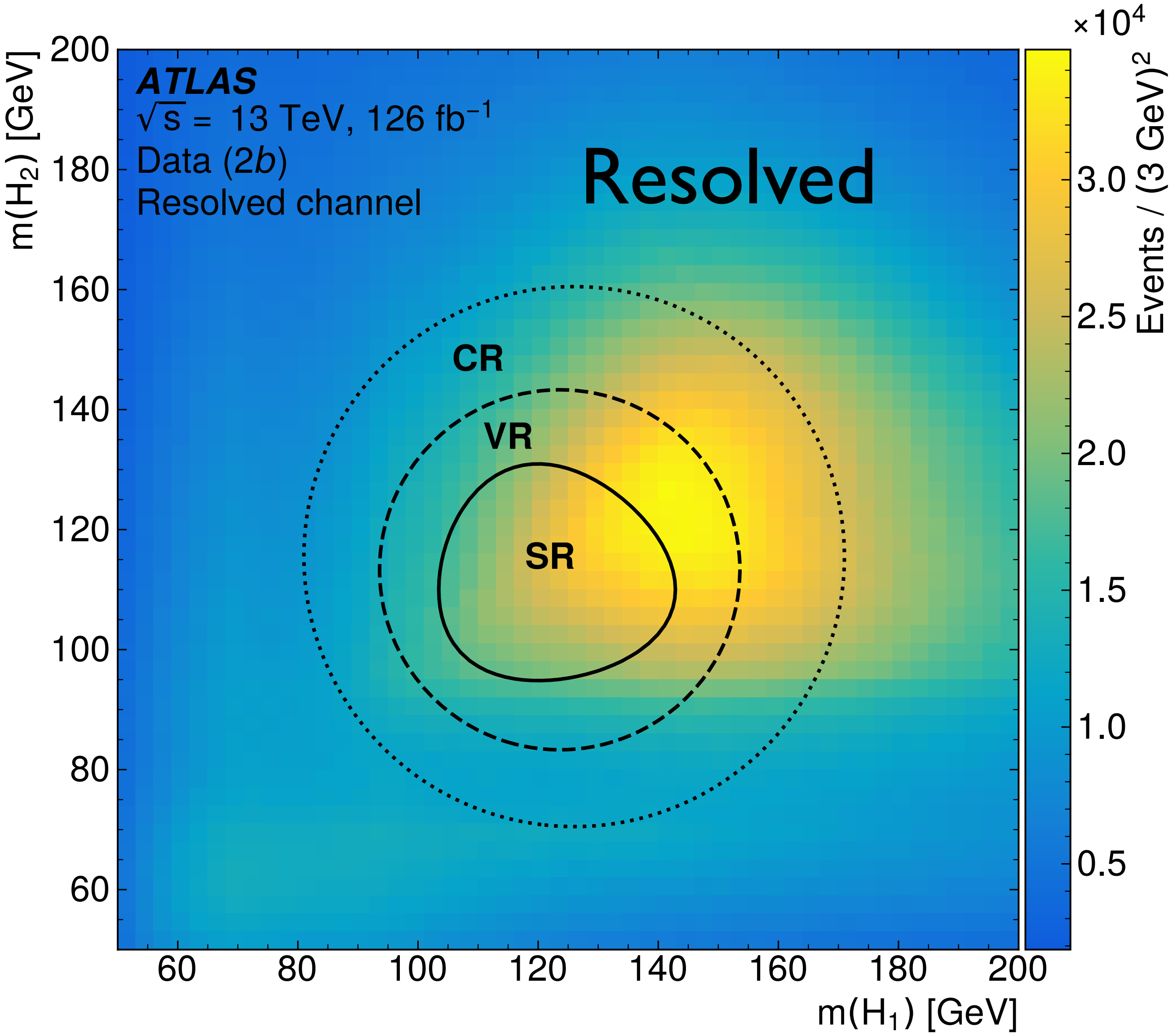
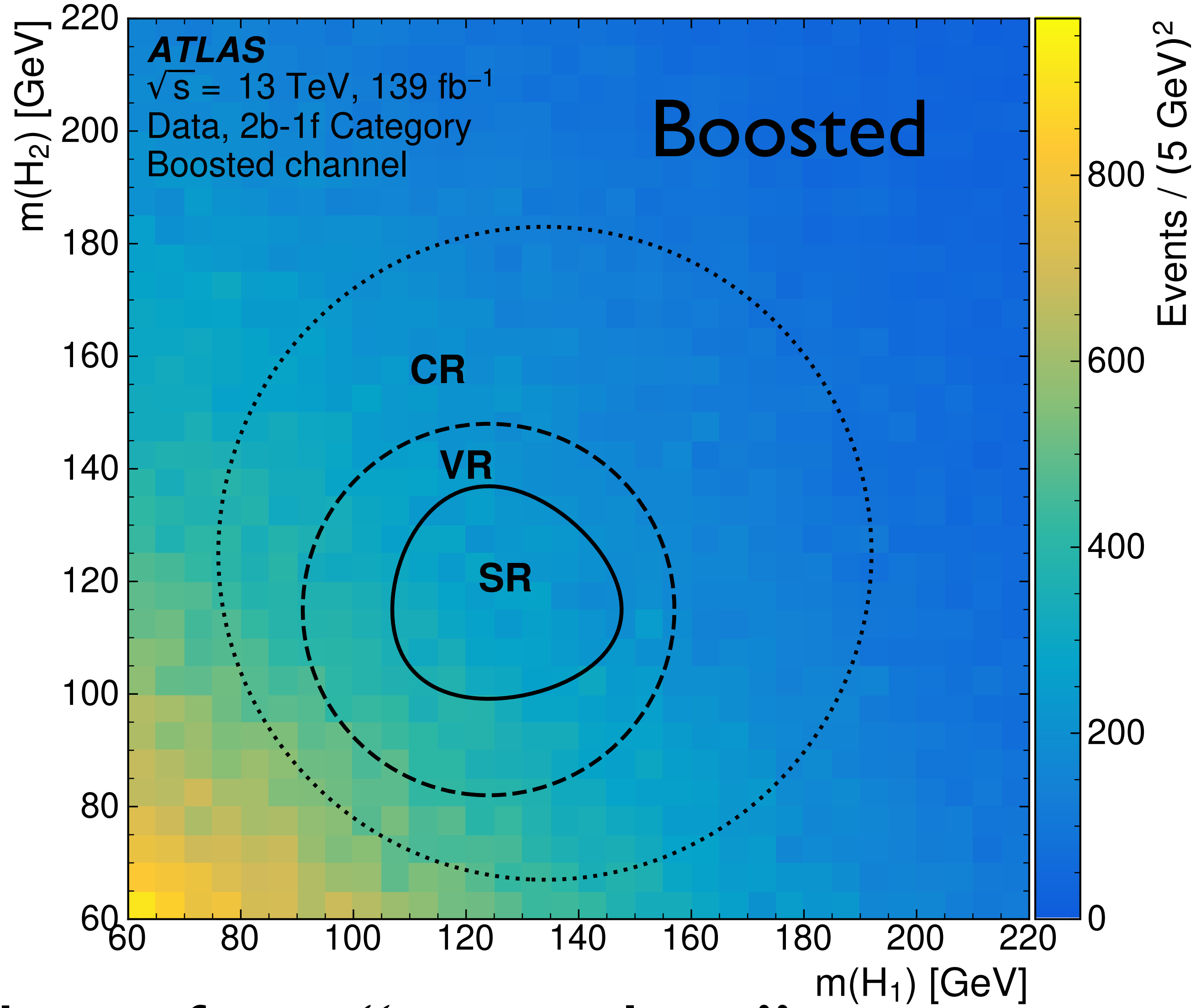
Reconstruct Higgs candidates, form “mass plane”

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





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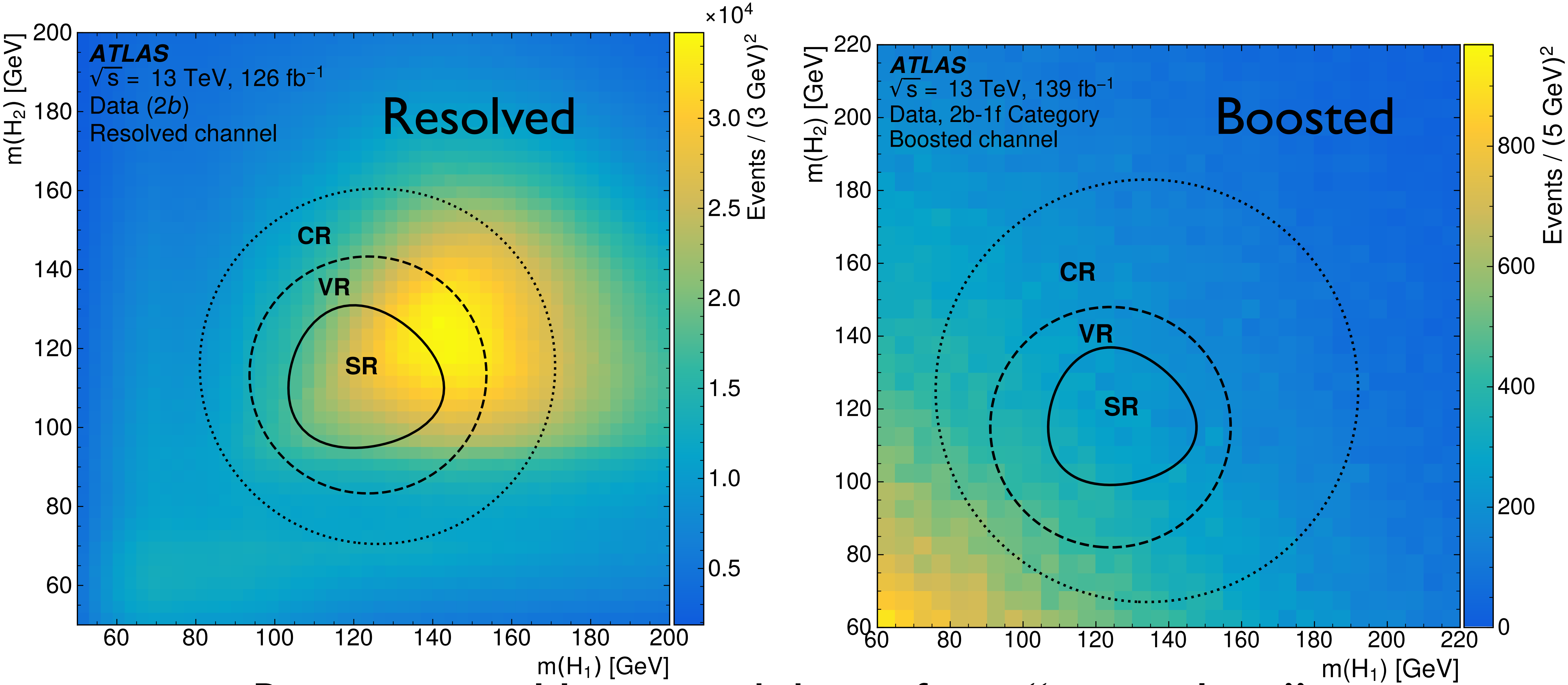

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Center is signal-like; outer regions used for background estimation and validation

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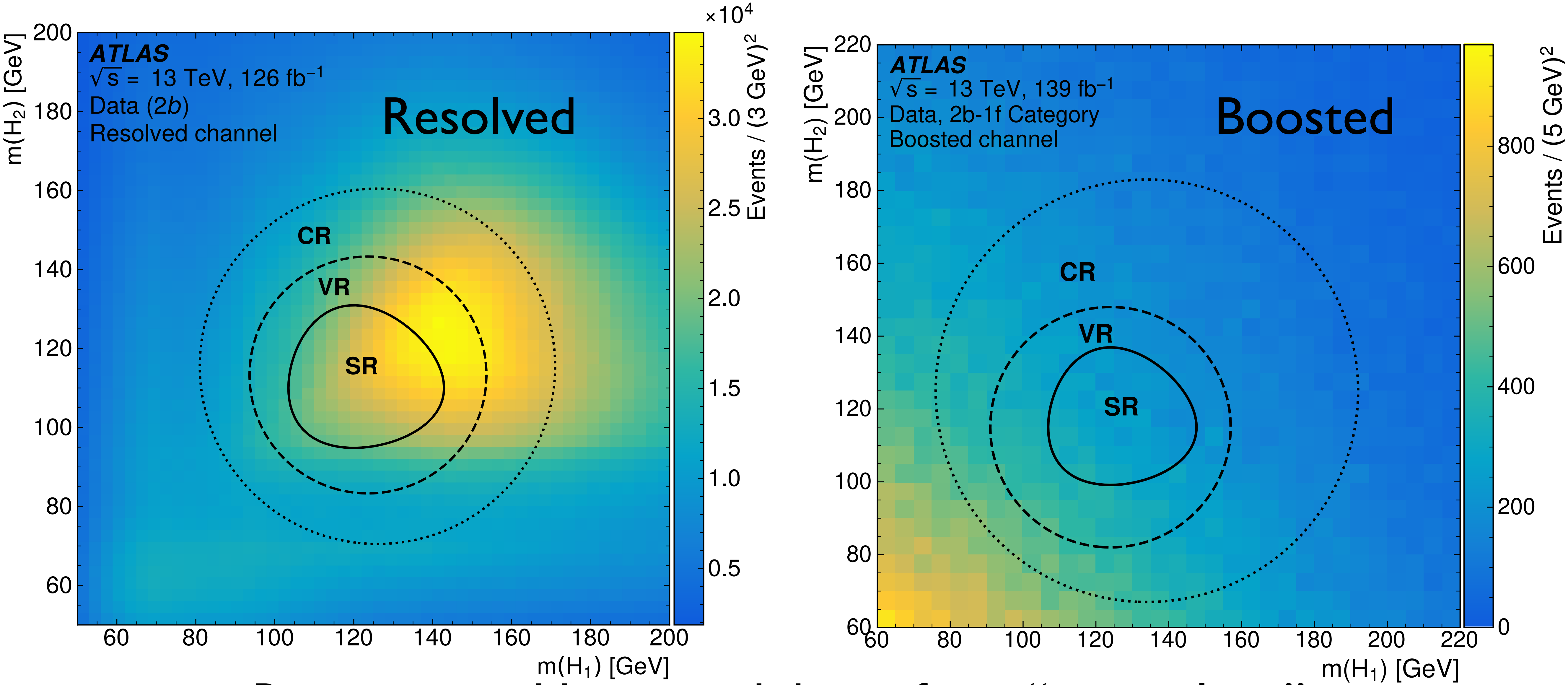

Reconstruct Higgs candidates, form “mass plane”

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

Fit m_{HH} in signal region for final analysis

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

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Step 0: form "mass planes"
with leading/subleading Higgs,
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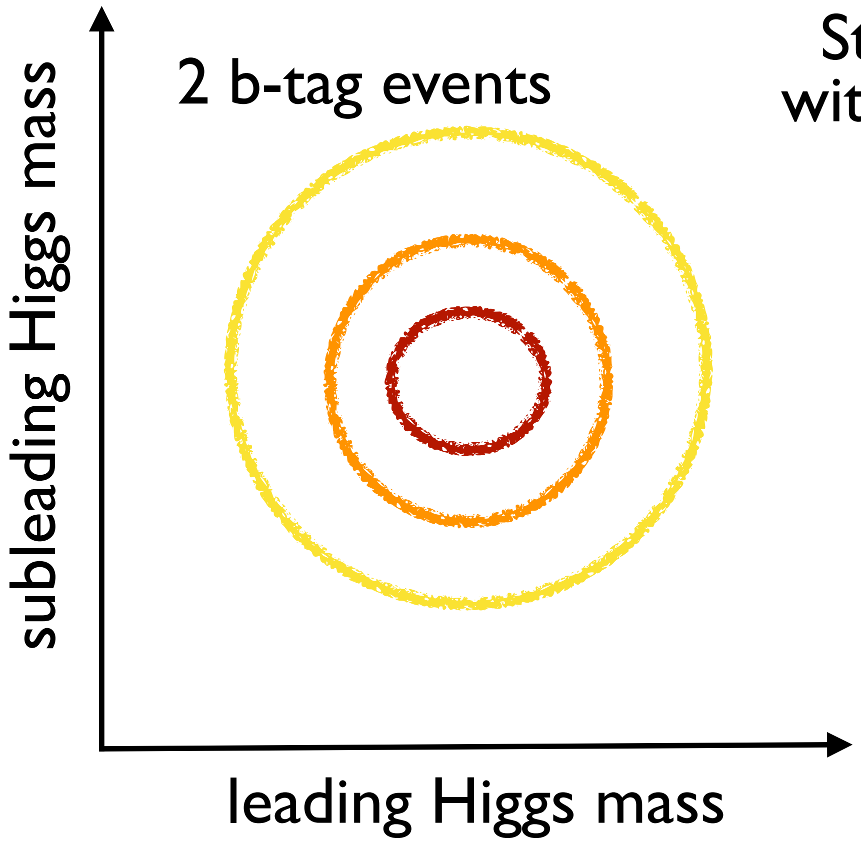

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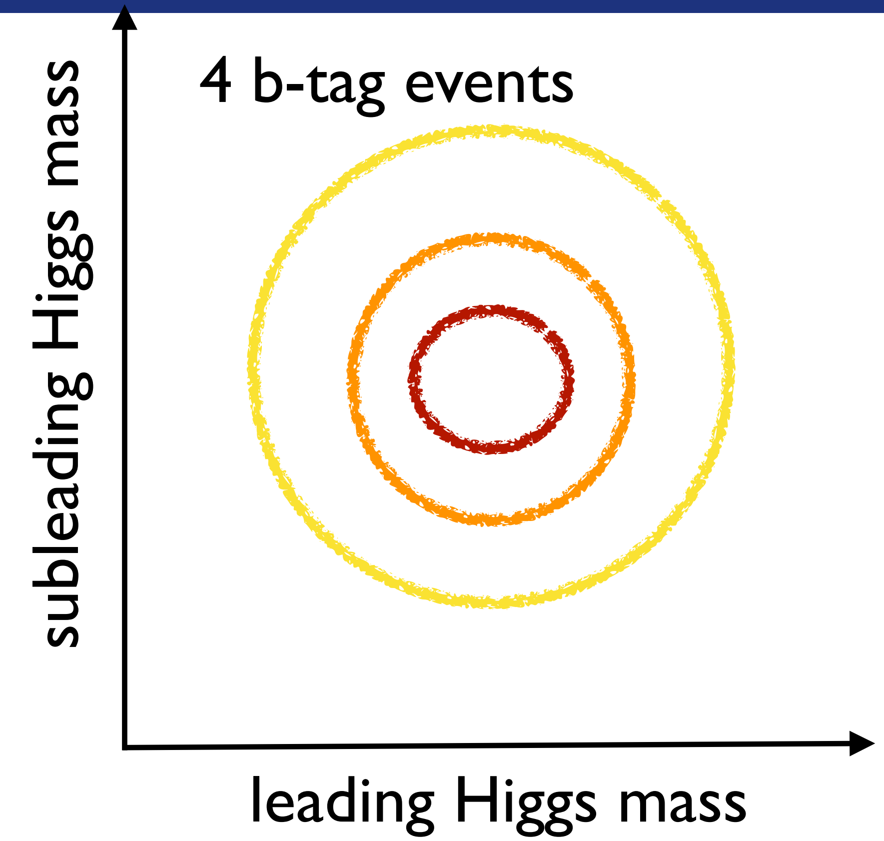

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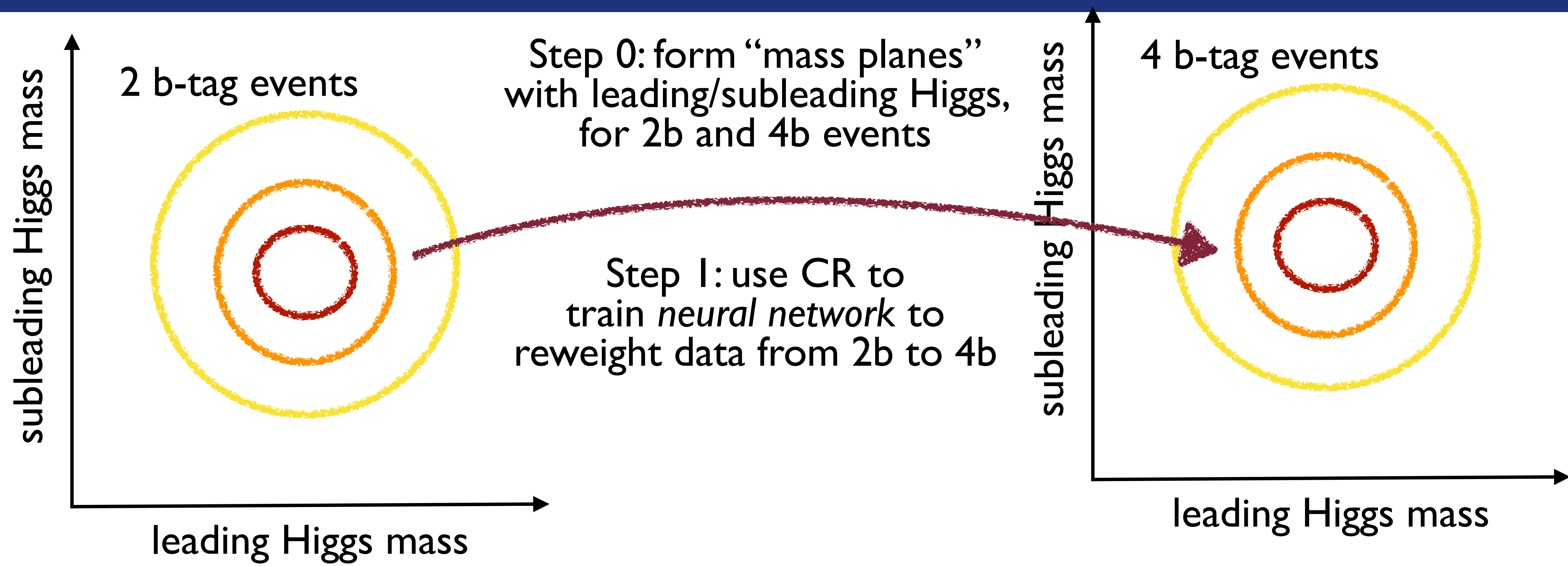

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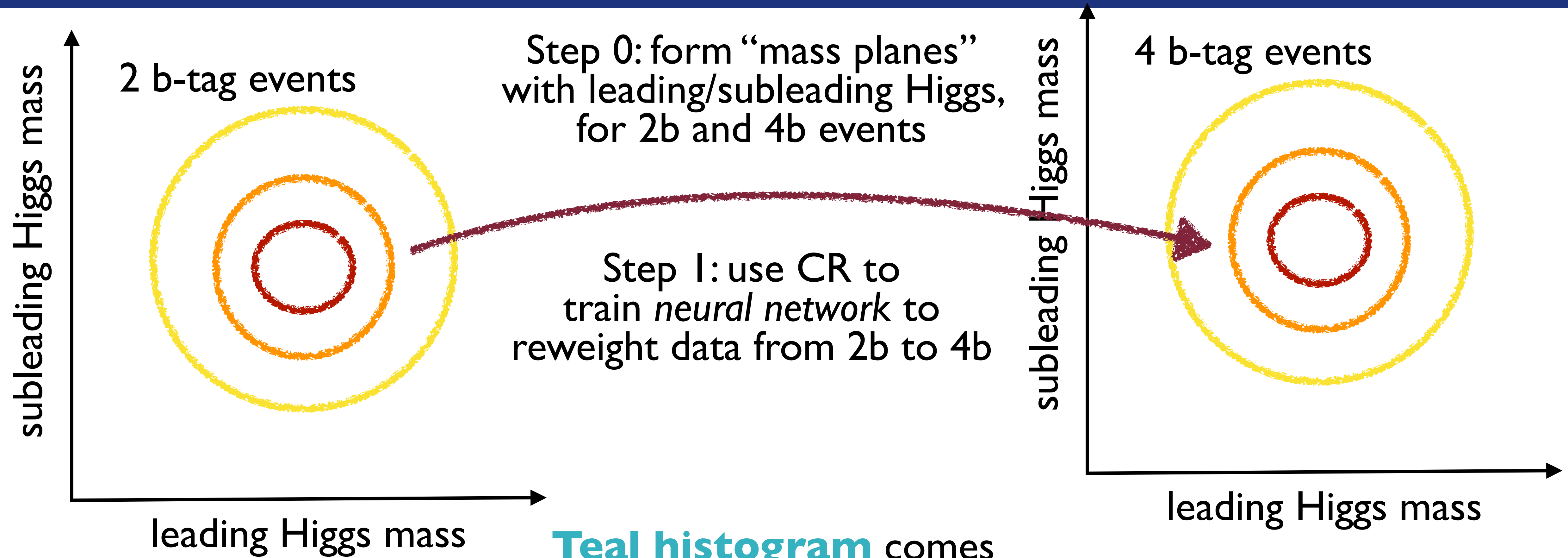

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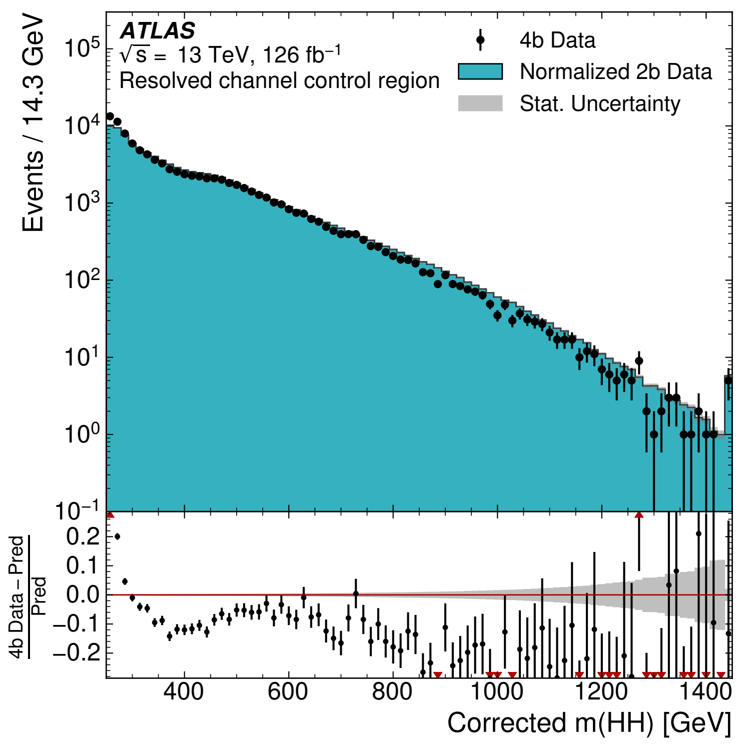
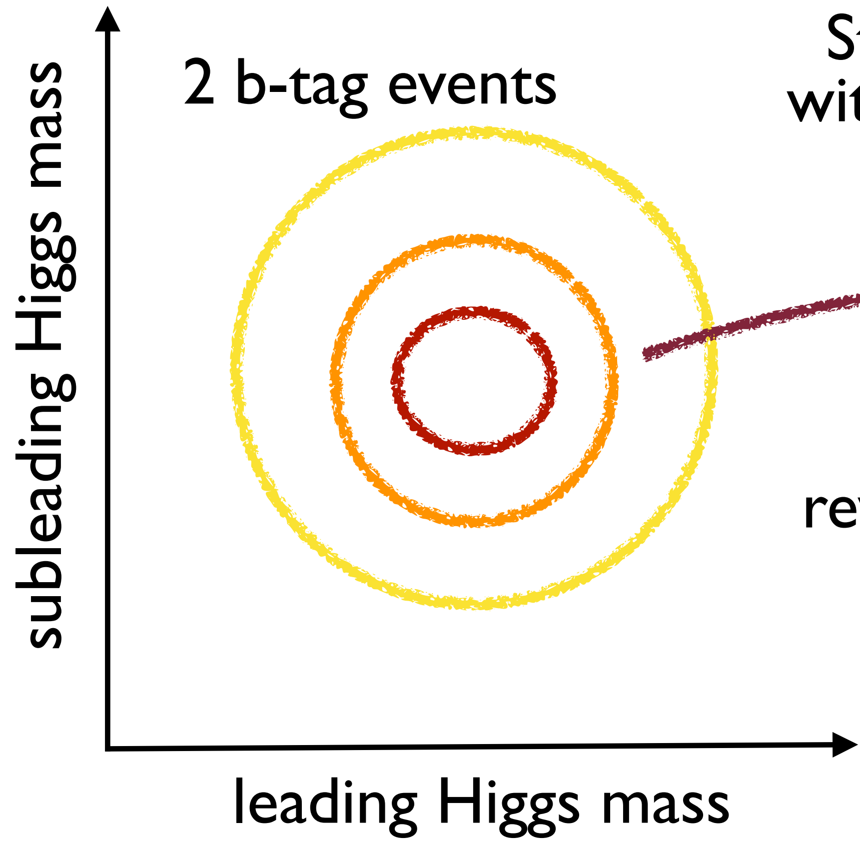
Step 1: use CR to train *neural network* to reweight data from 2b to 4b



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

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



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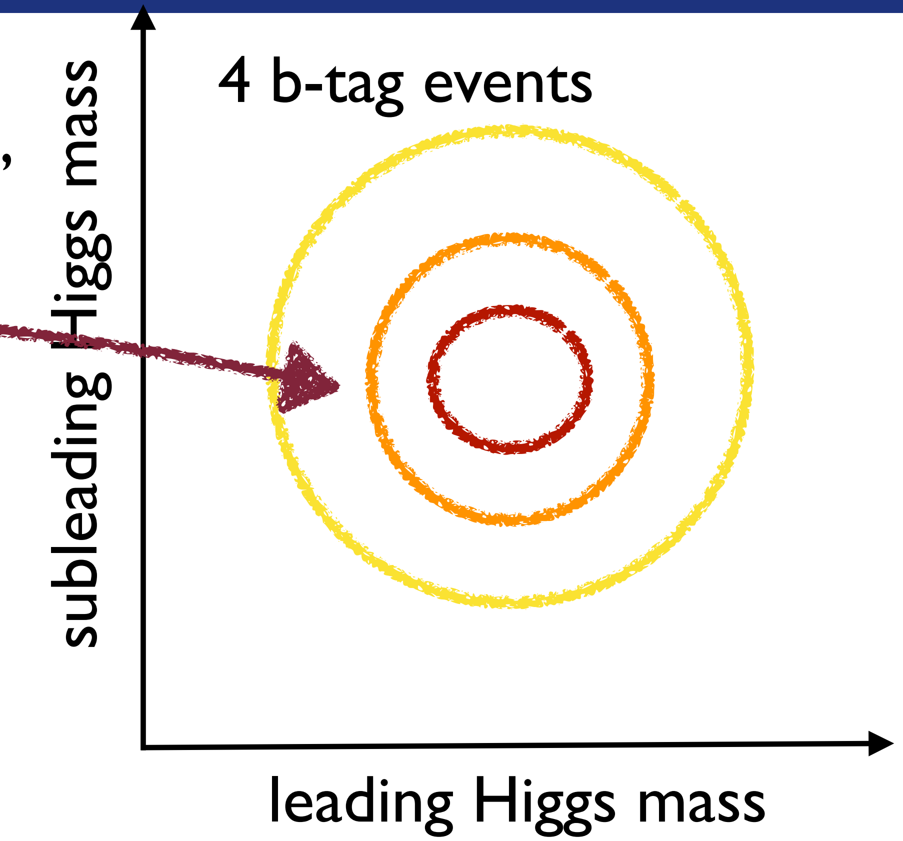

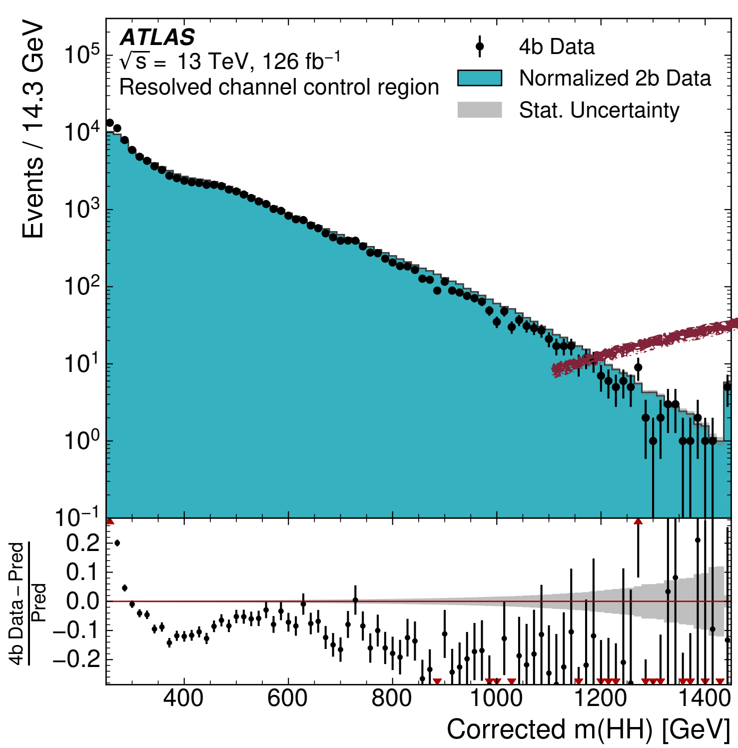

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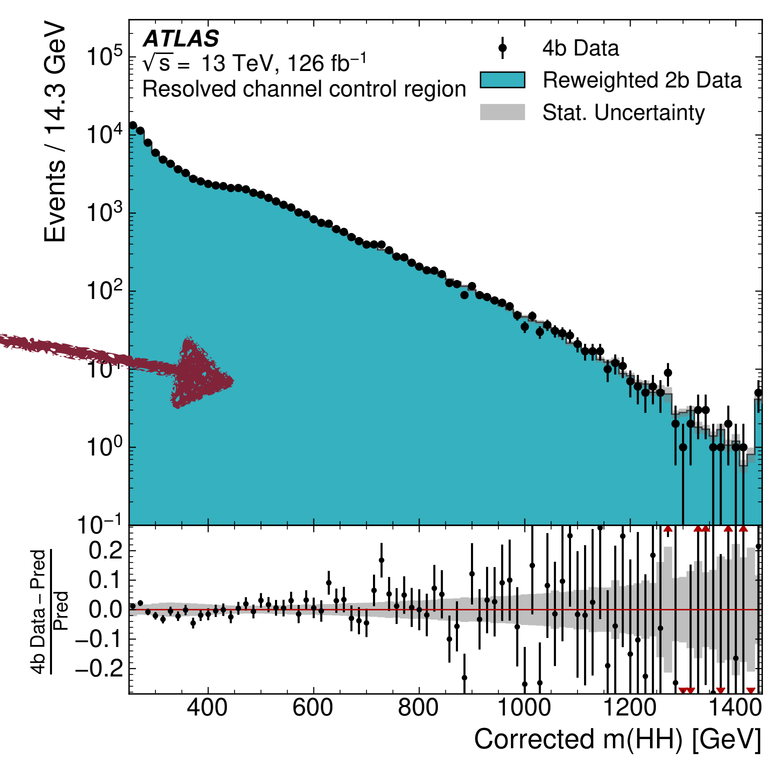
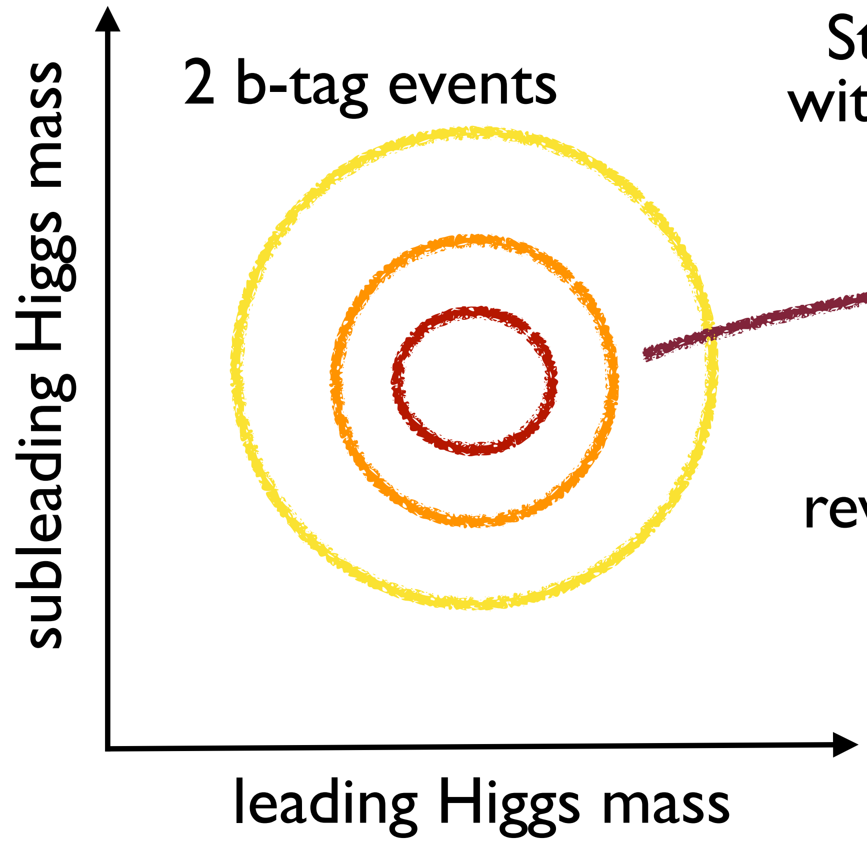
Neural network



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



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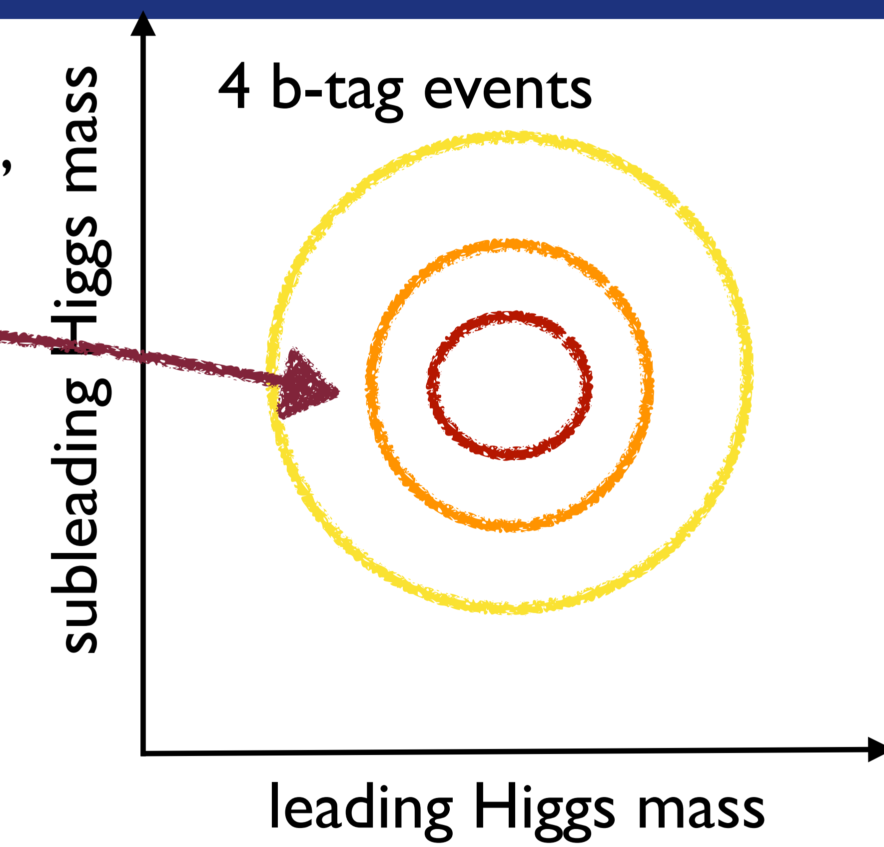

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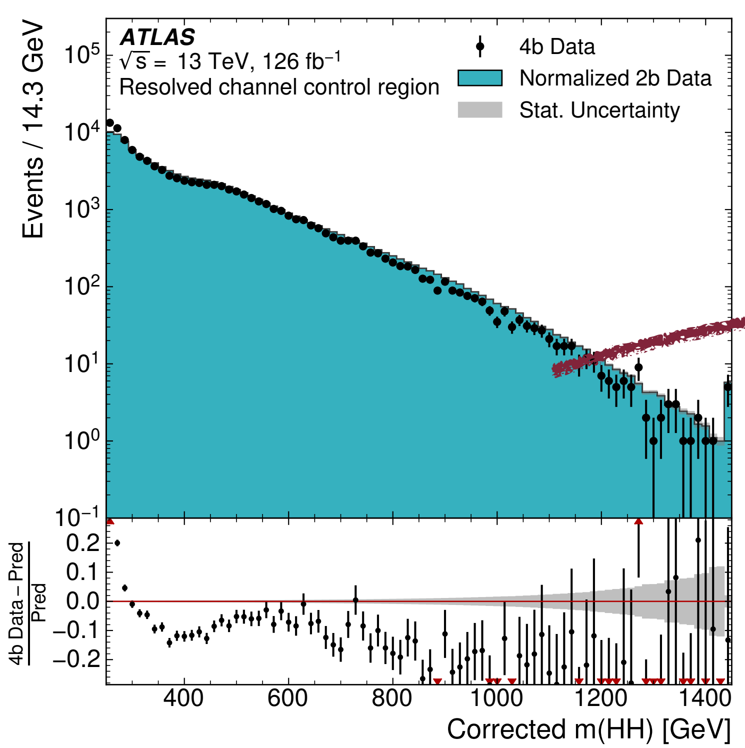

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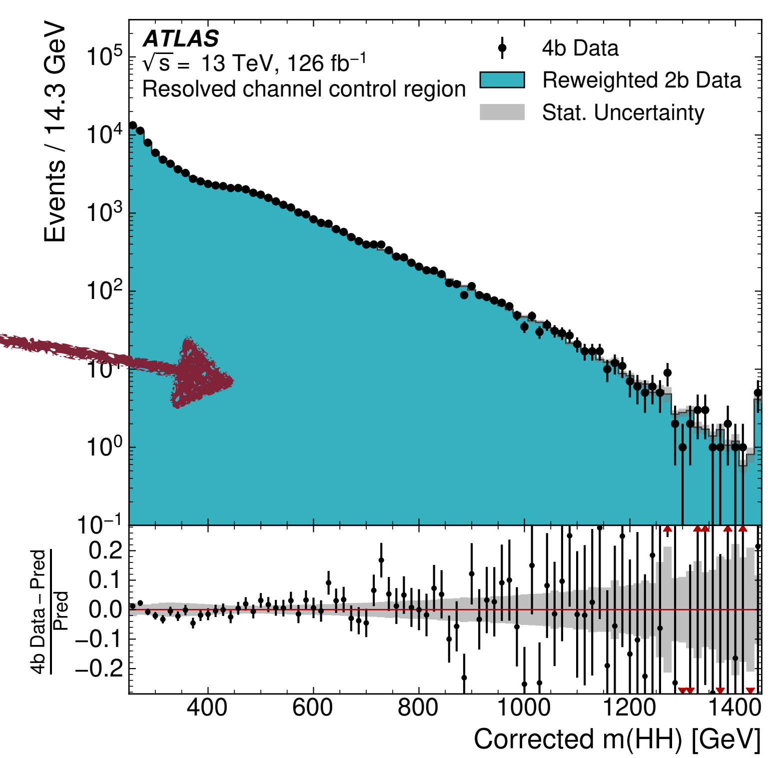
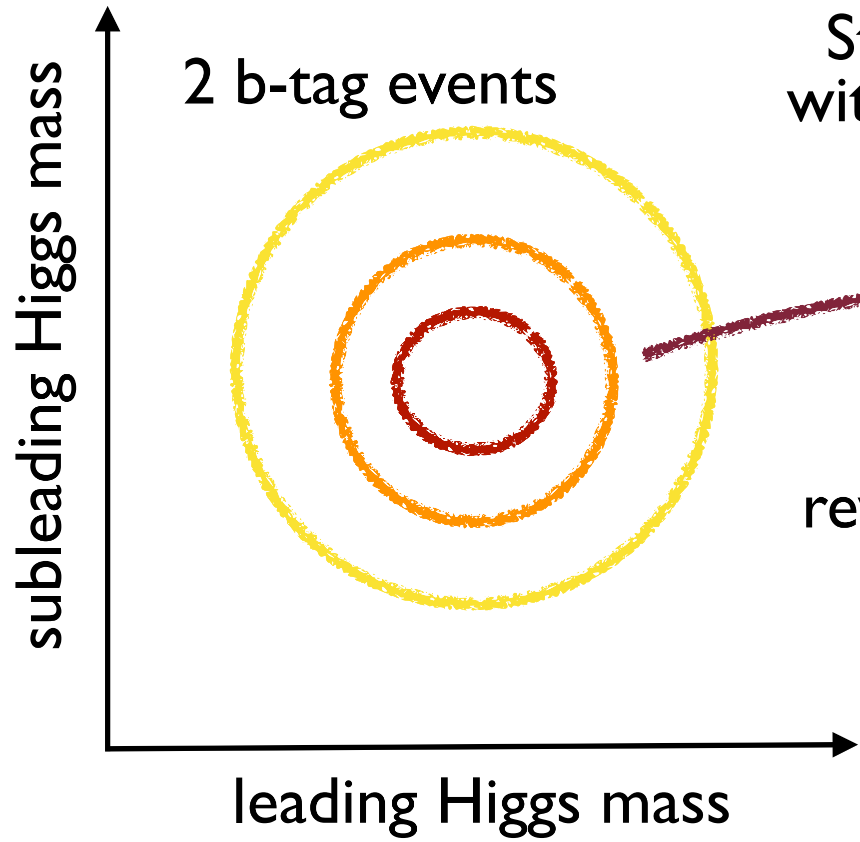


Step 2: Apply this NN to 2b SR: prediction for 4b SR

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



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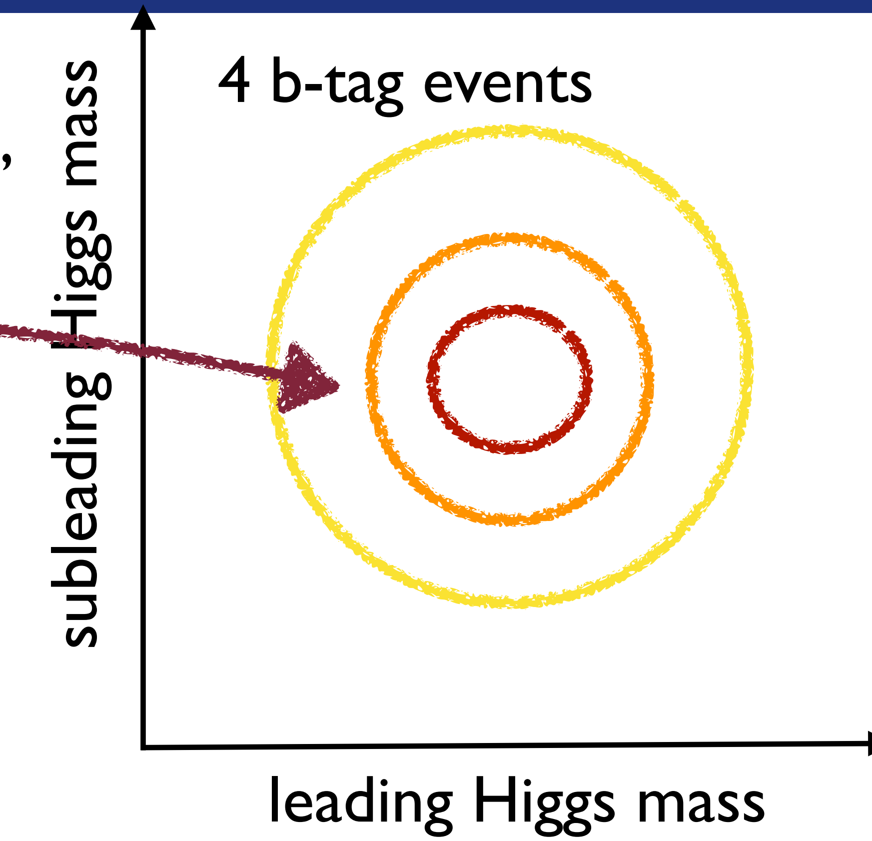

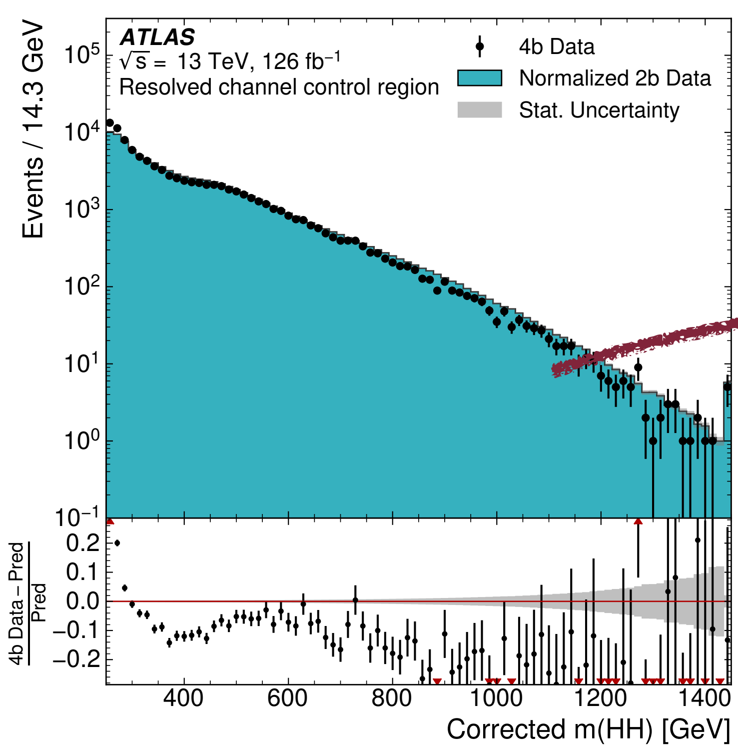

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Neural network

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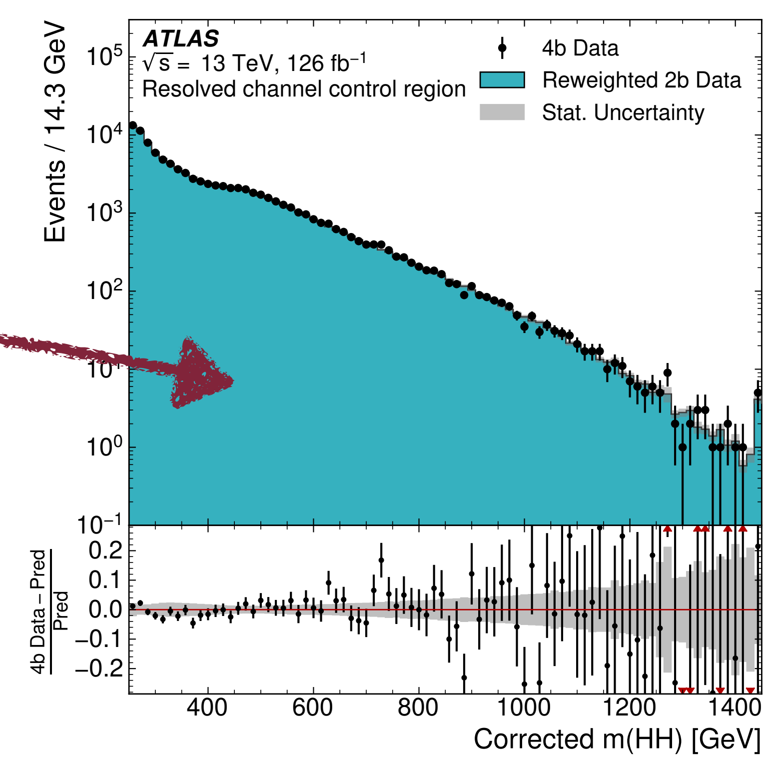
Systematics from alternate validation region



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

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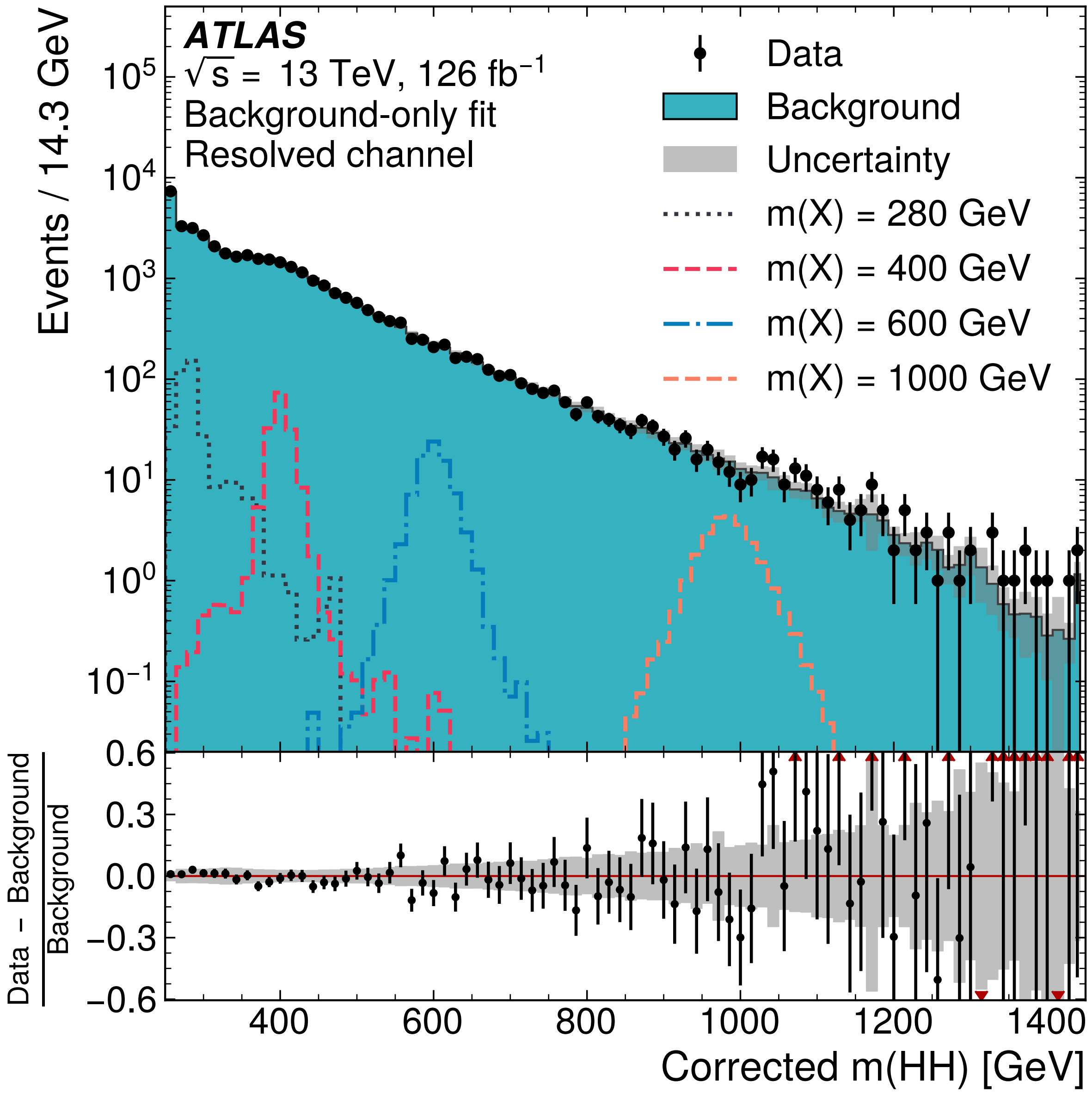
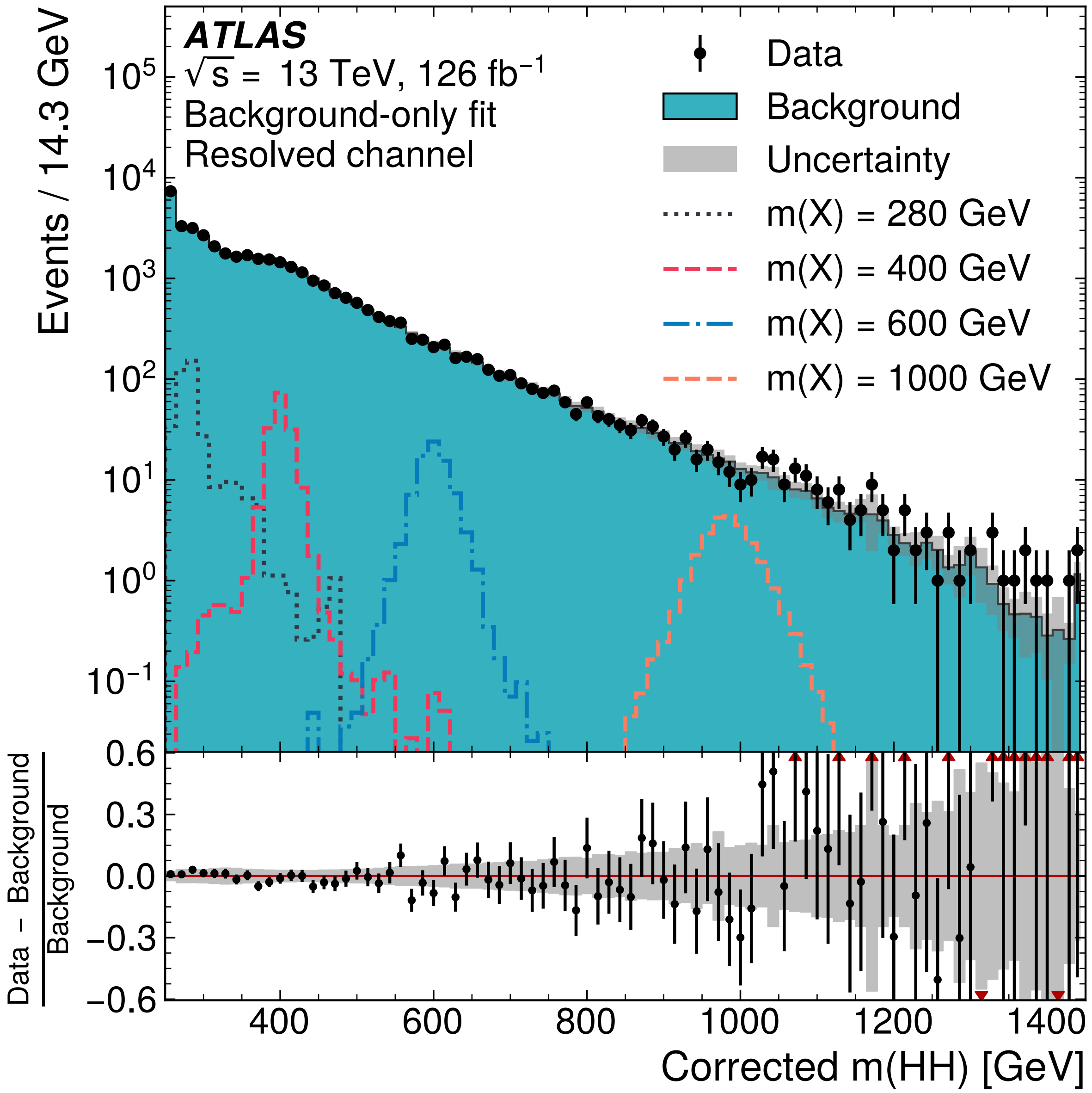


Data agrees well with background prediction

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



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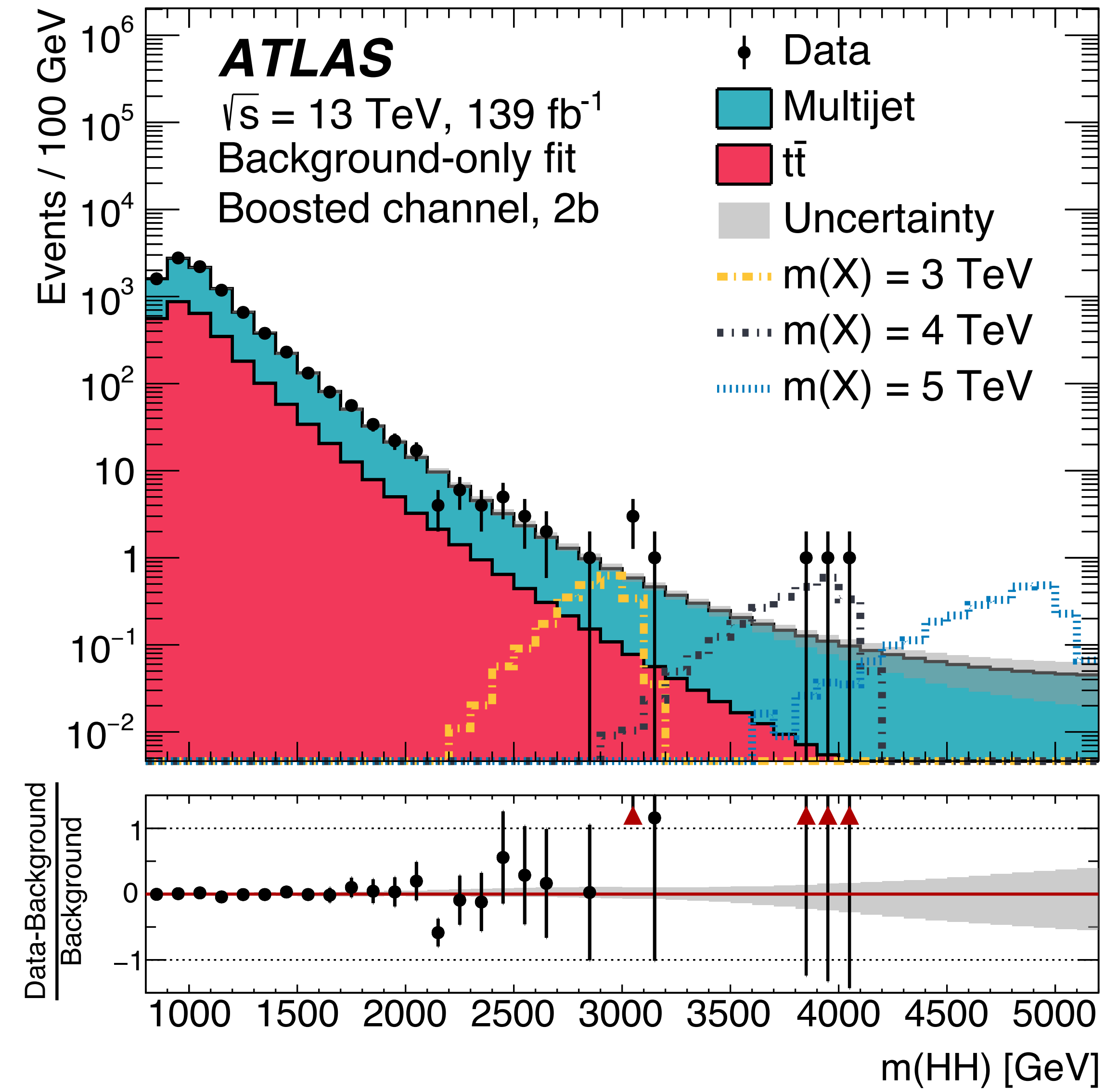
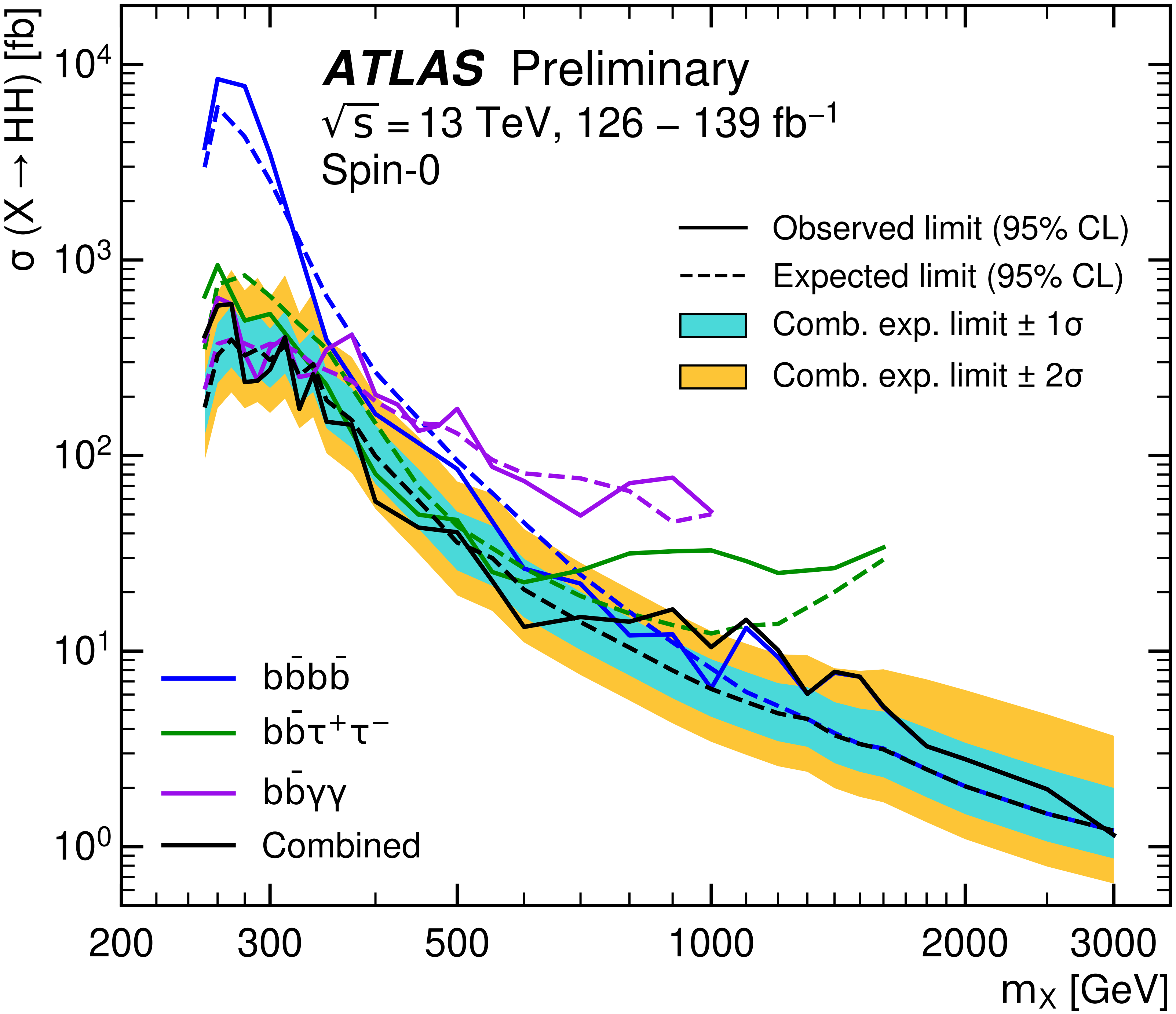


Boosted analysis is similar: simpler spline based reweighting

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

Resonant Combination

Resonant Combination



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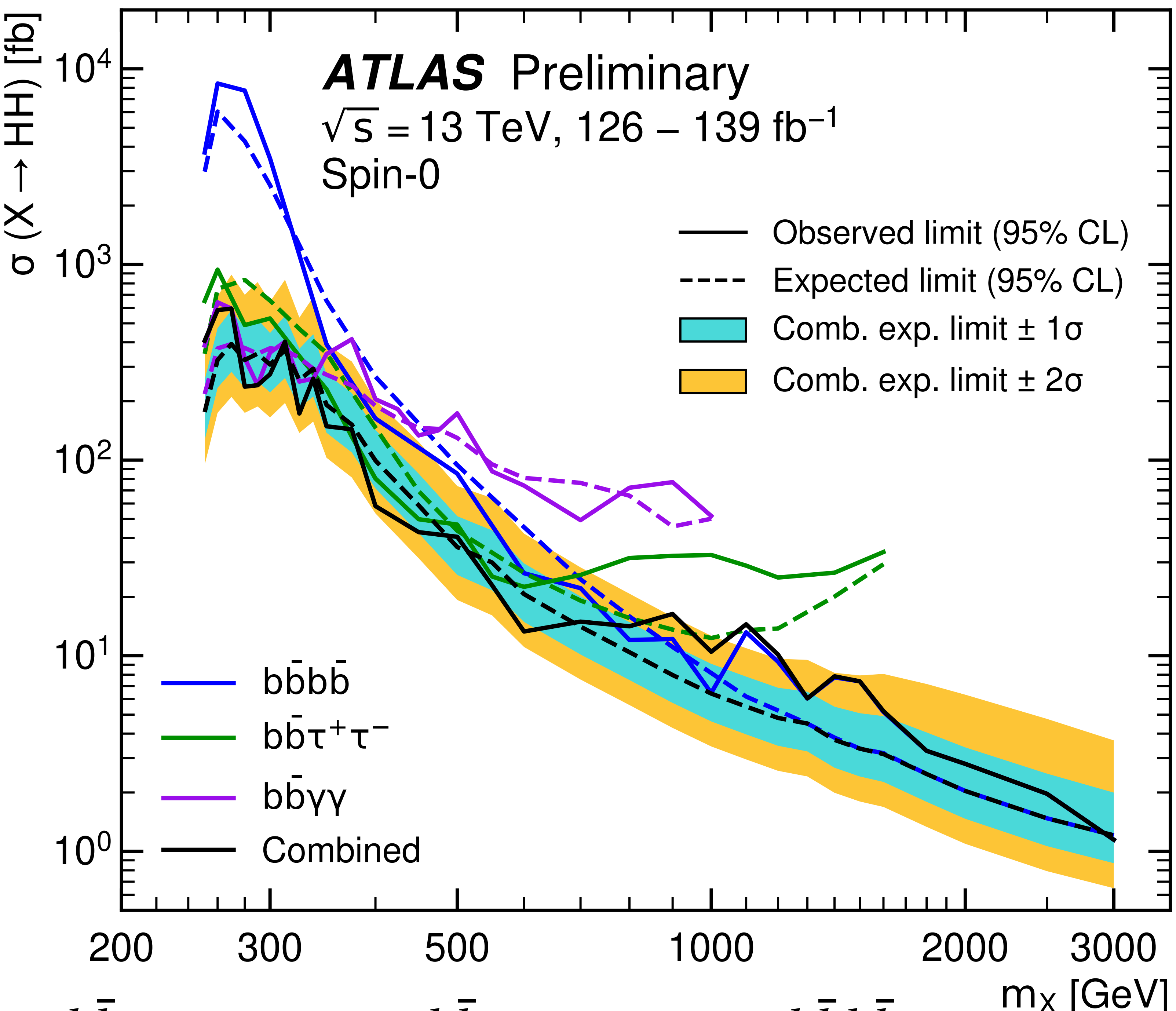

$b\bar{b}\gamma\gamma$ strongest $b\bar{b}\tau\bar{\tau}$ strongest $b\bar{b}b\bar{b}$ strongest

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

Conclusions

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Higgs pair measurements let us directly probe the shape of the Higgs potential

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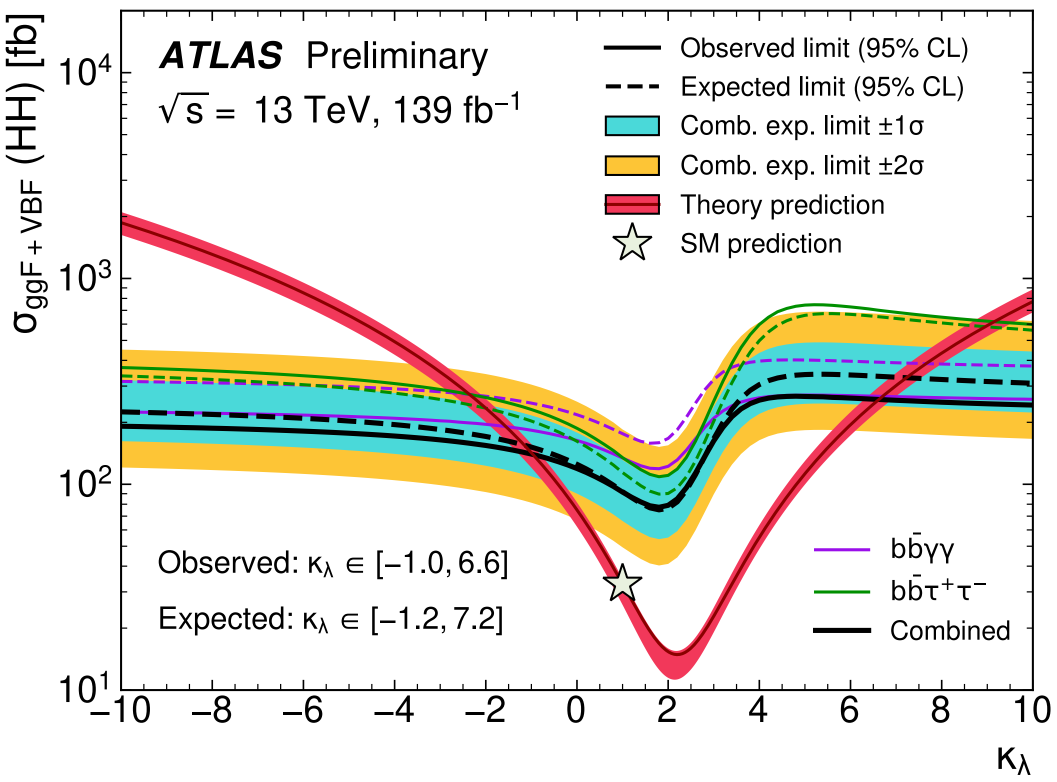
Rapidly approaching sensitivity to even the rare SM x-sec!



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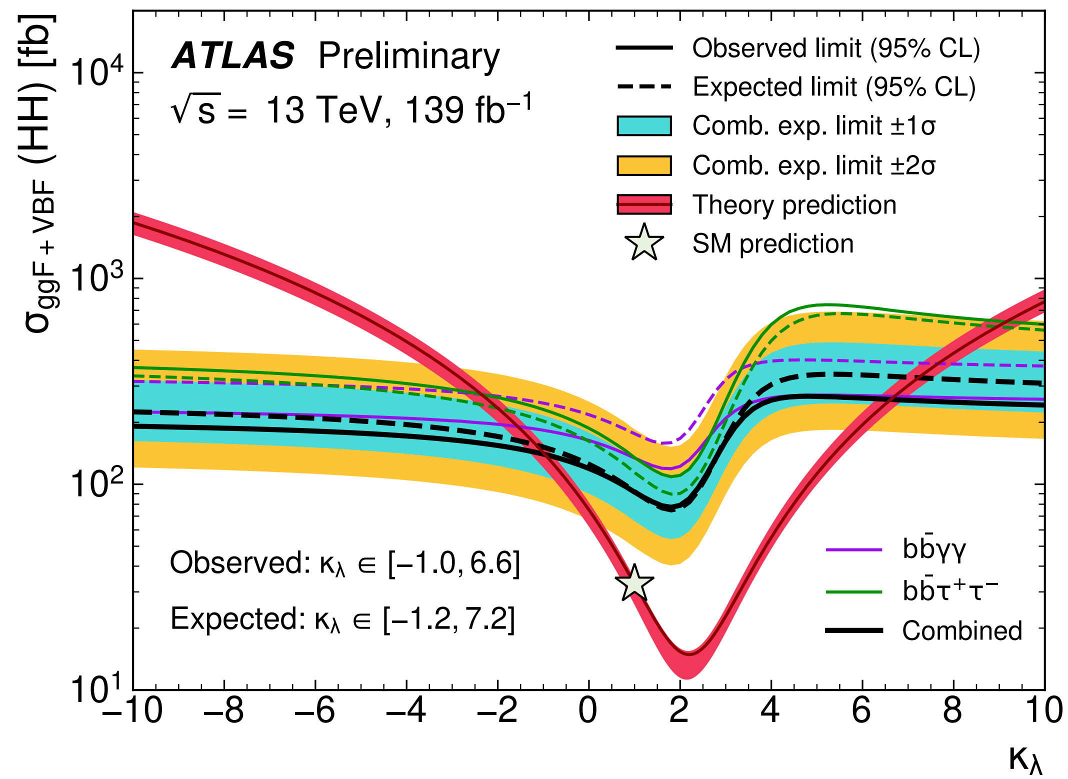
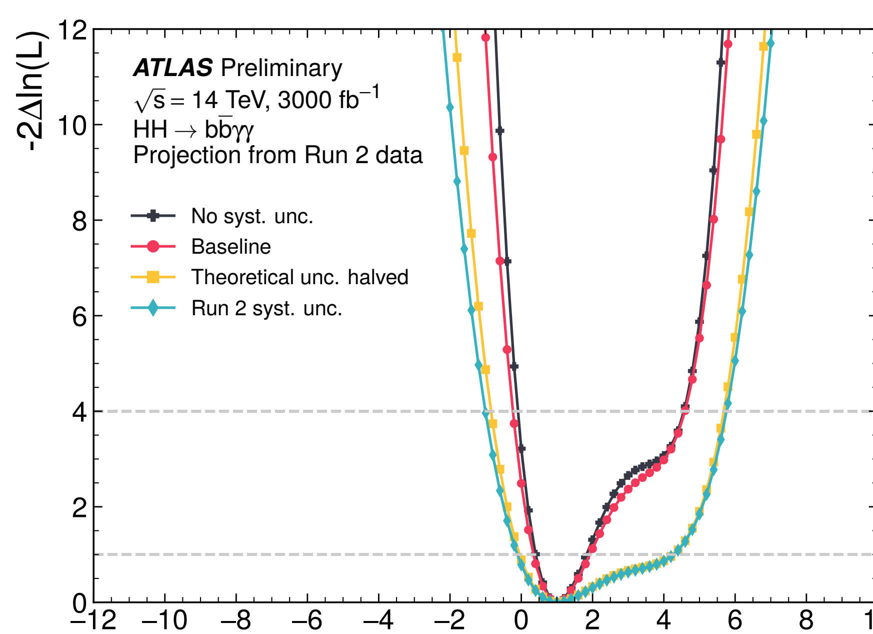
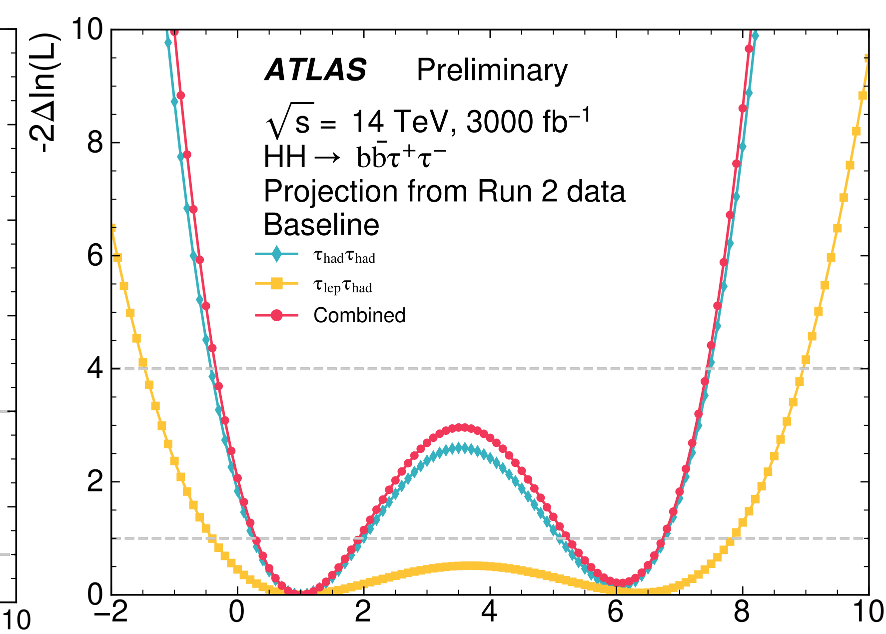


Rapidly approaching sensitivity to even the rare SM x-sec!

Projections for HL-LHC rapidly improving as analyses are optimized: many exciting years of analysis remain!



ATL-PHYS-PUB-2022-001/



ATL-PHYS-PUB-2021-044

Thank you!

More in:

ATLAS-HDBS-2018-34

ATLAS-CONF-2021-030

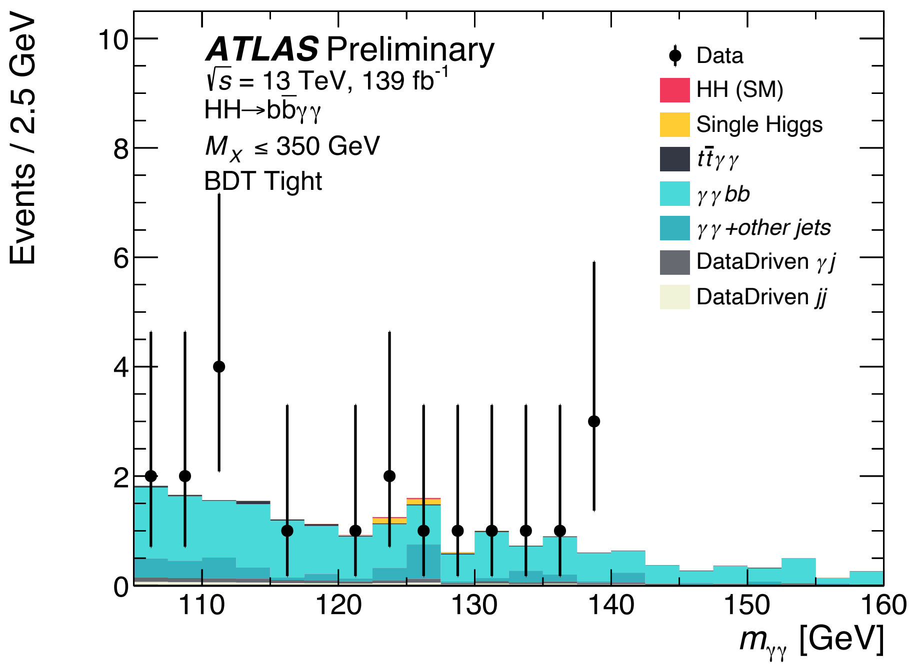
ATLAS-HDBS-2018-41

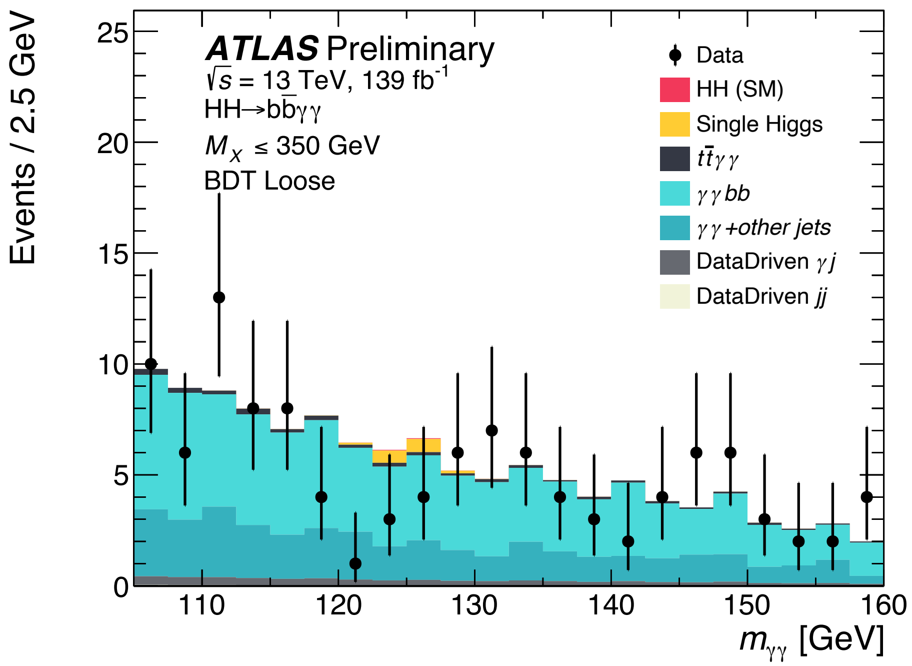
ATLAS-CONF-2021-052

Backup

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

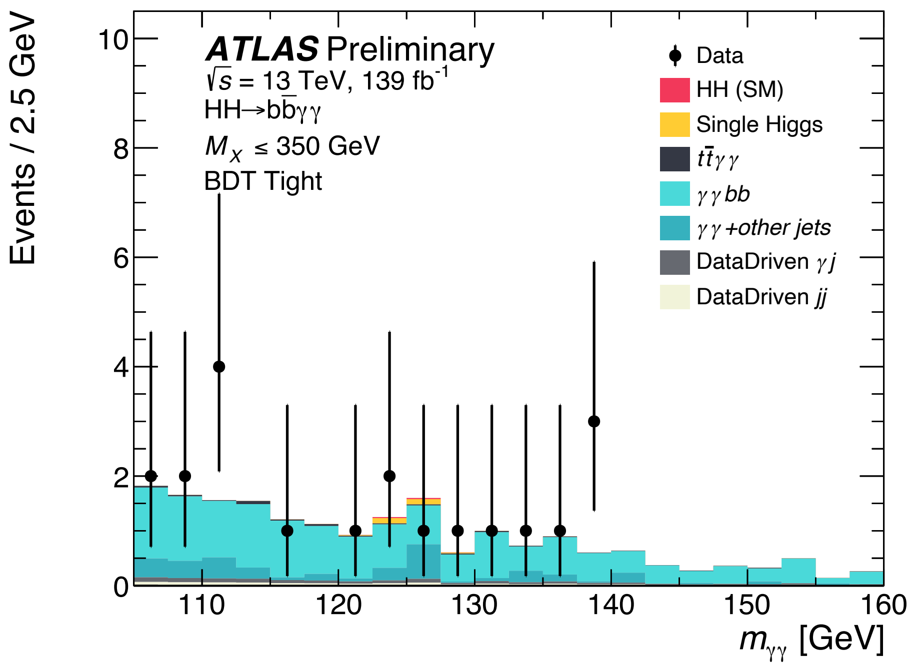
$b\bar{b}\gamma\gamma$ Results

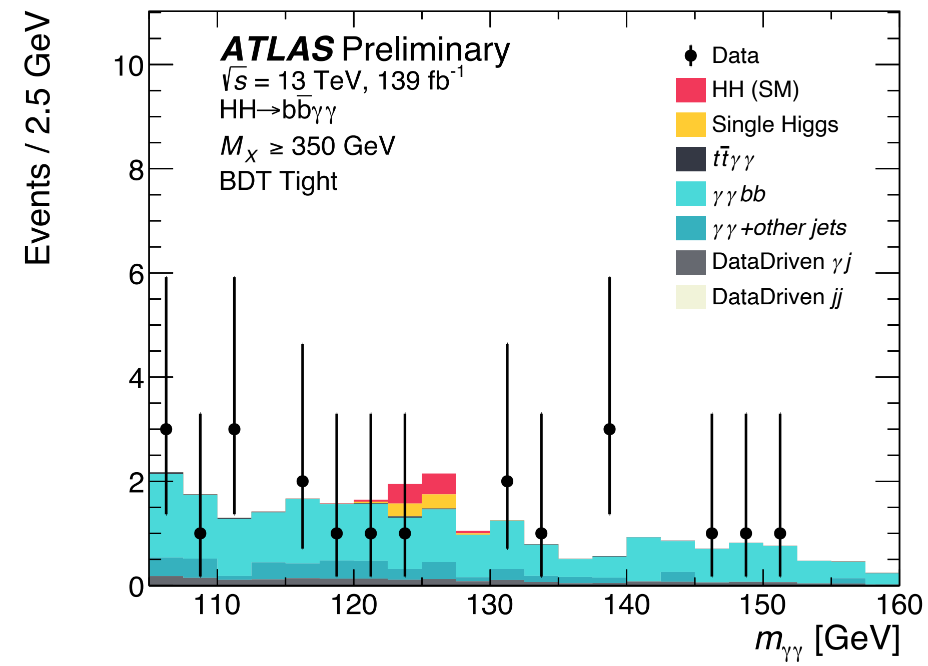


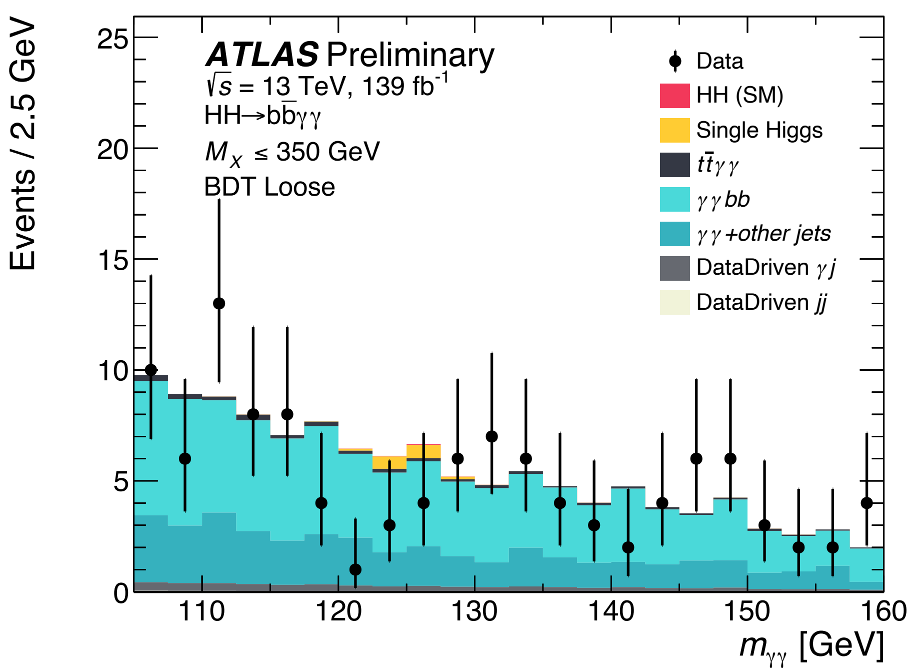


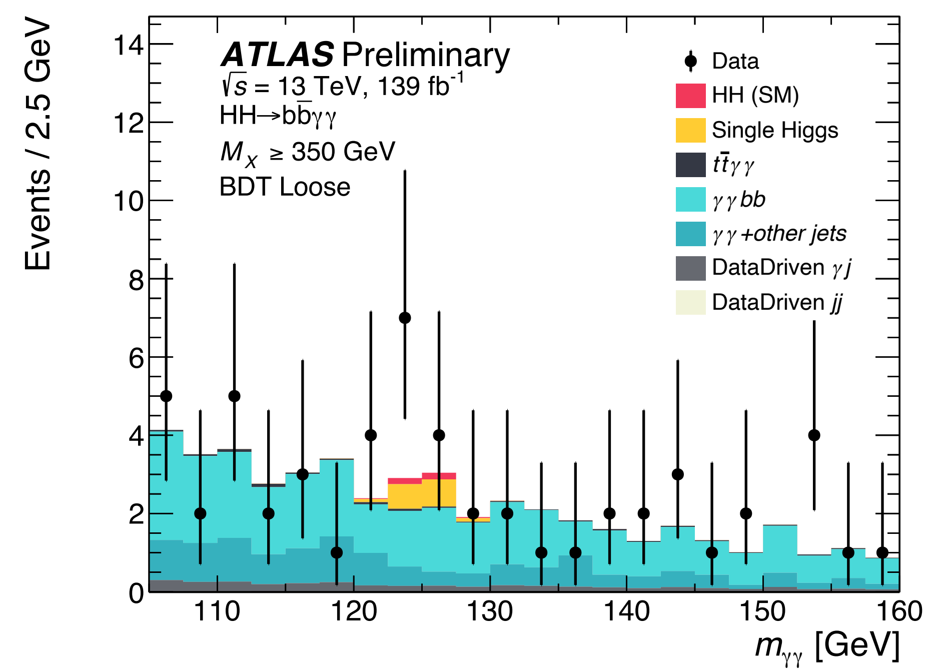
Low mass: sensitive to κ_λ

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









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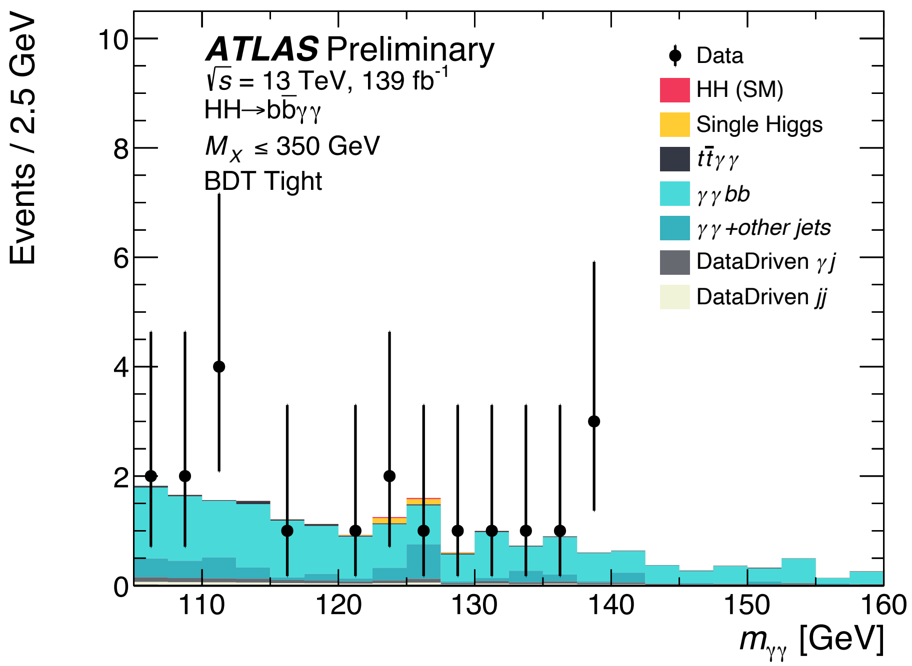
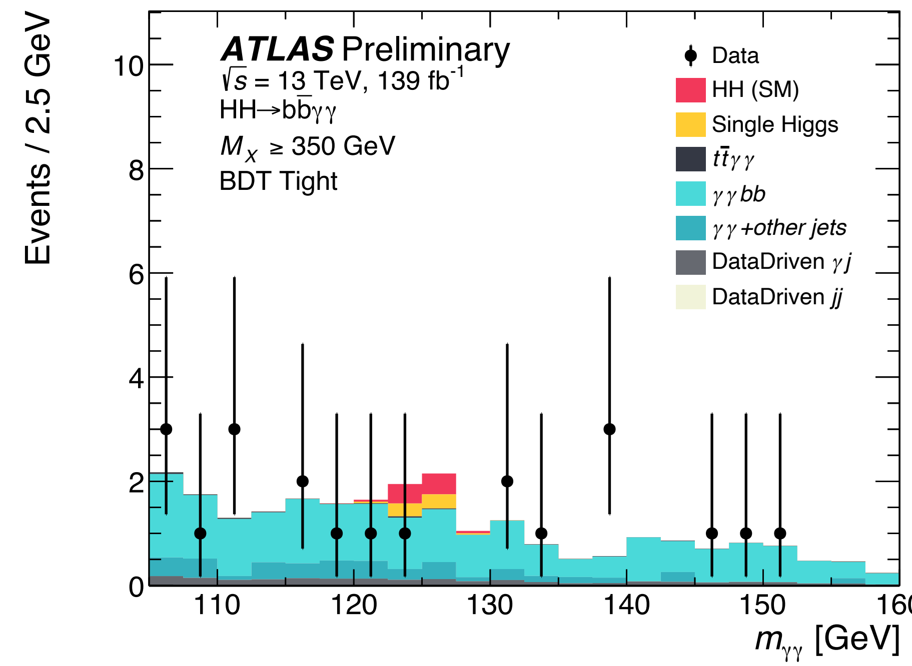
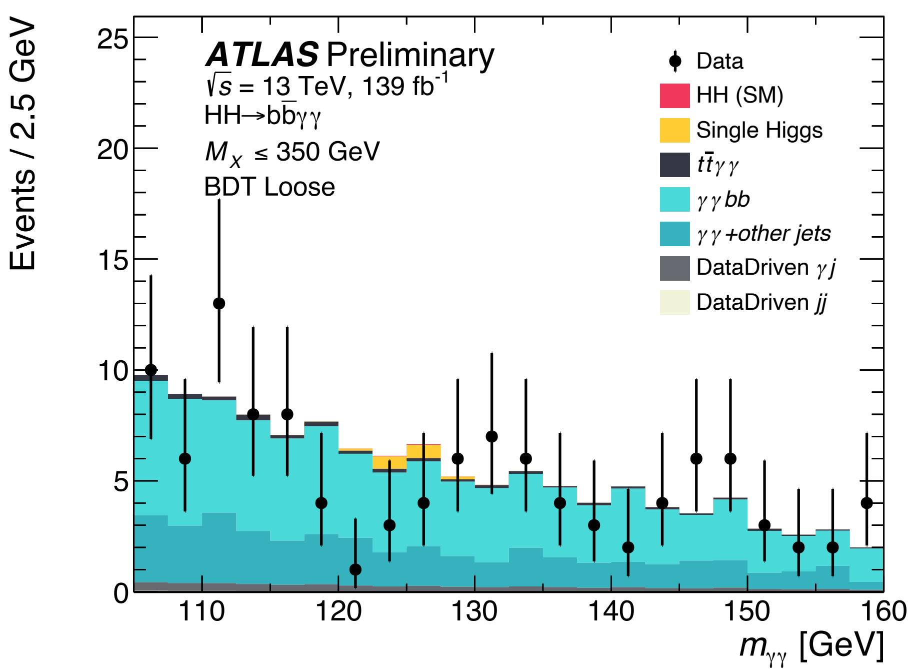
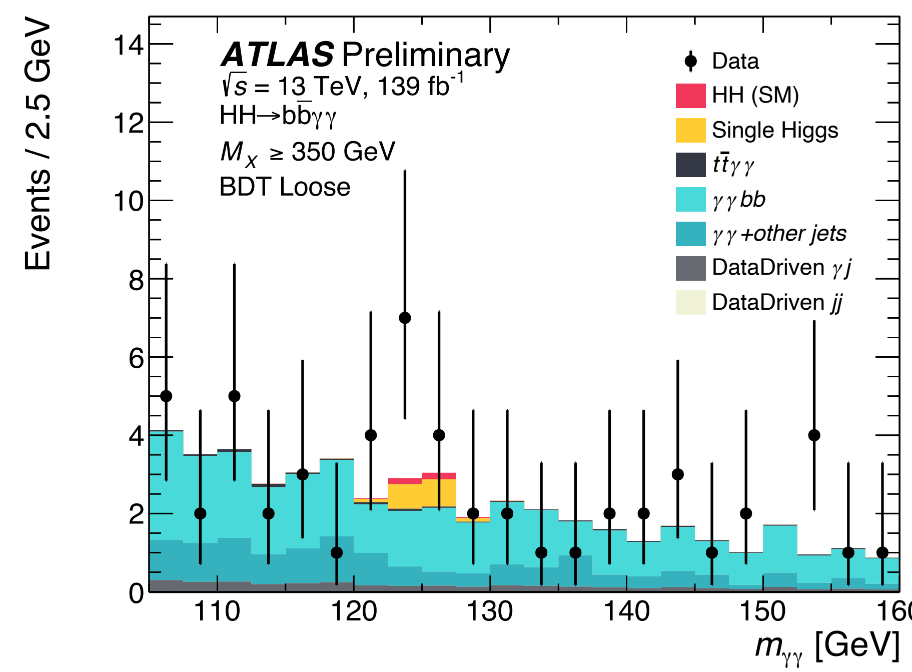


No obvious signs of new physics!







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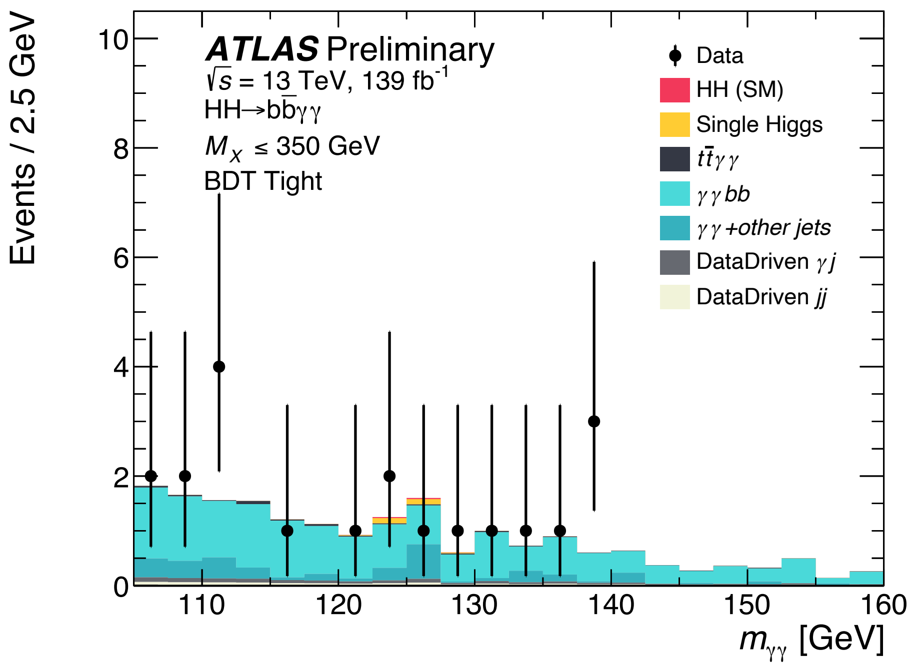

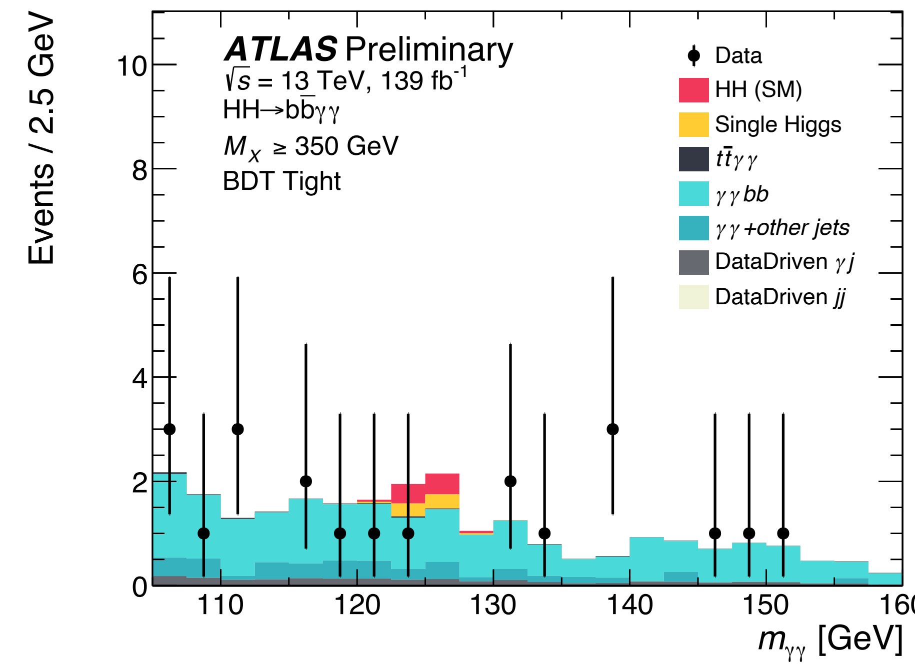

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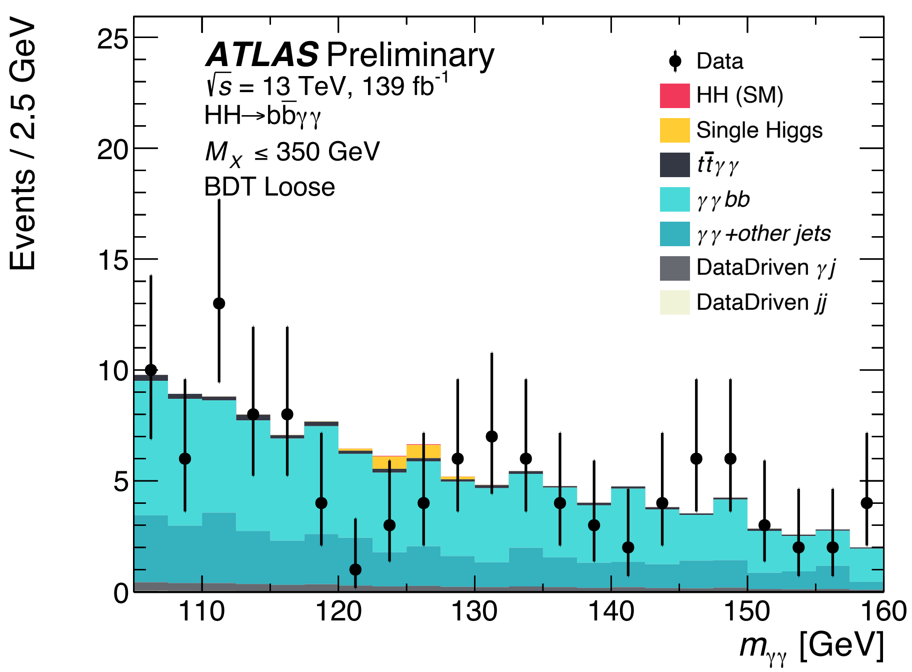

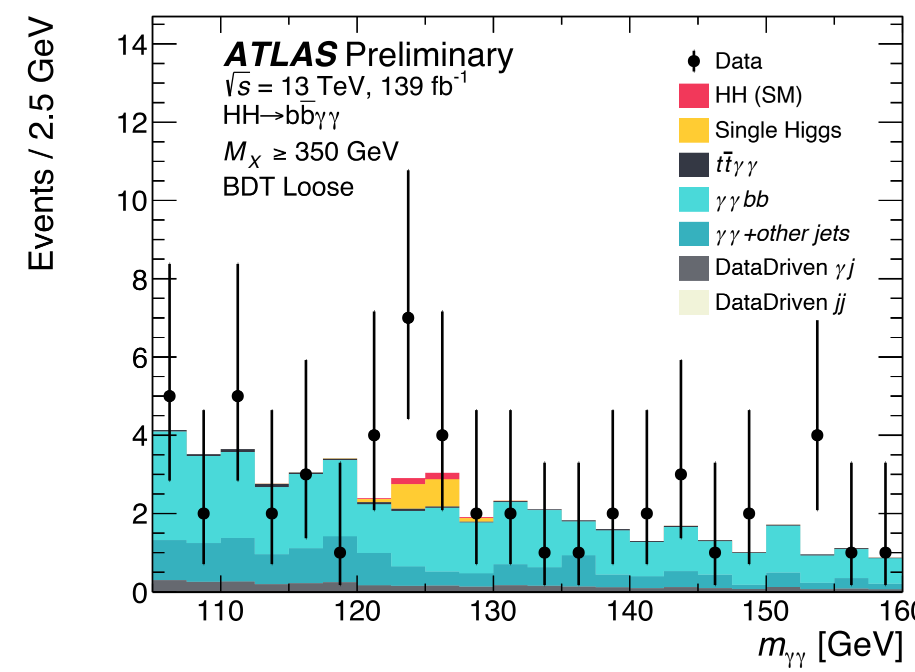

But some of the best sensitivity to HH ever…

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Why Neural Networks?

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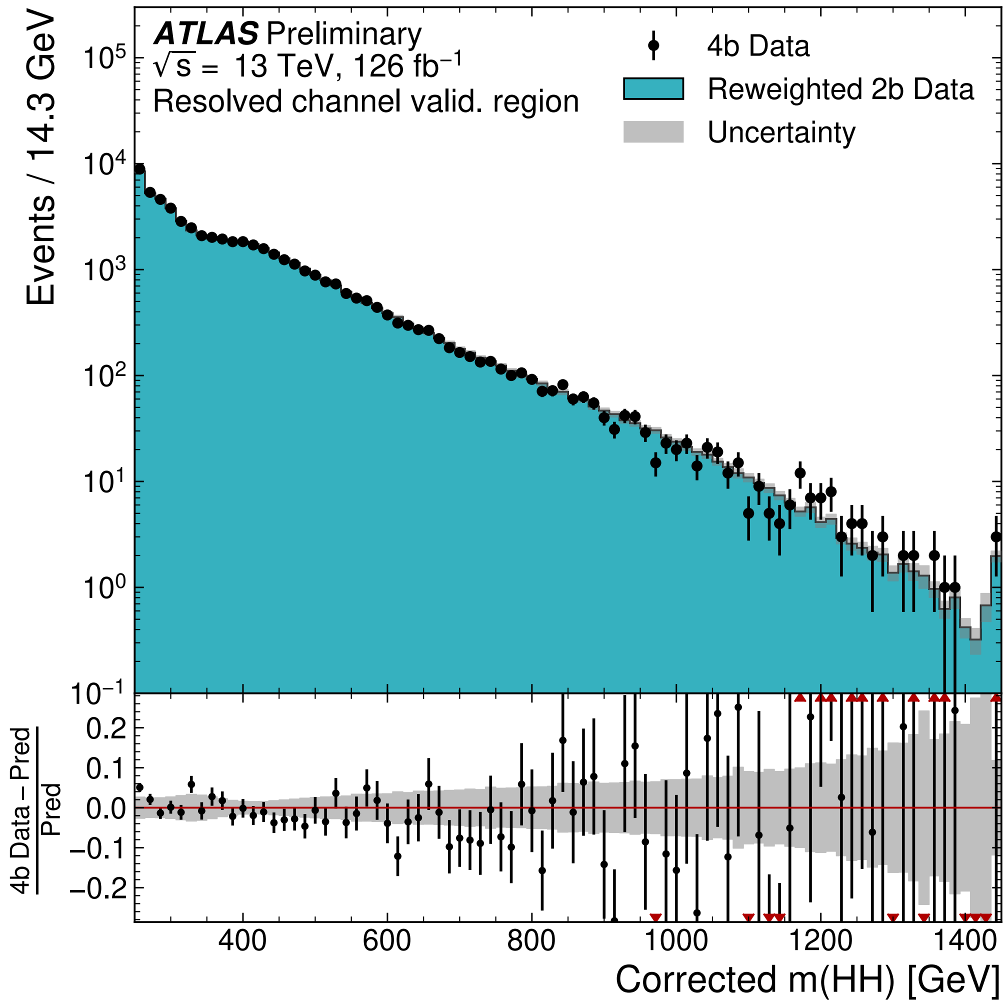

Here, apply NN to 2b data in VR

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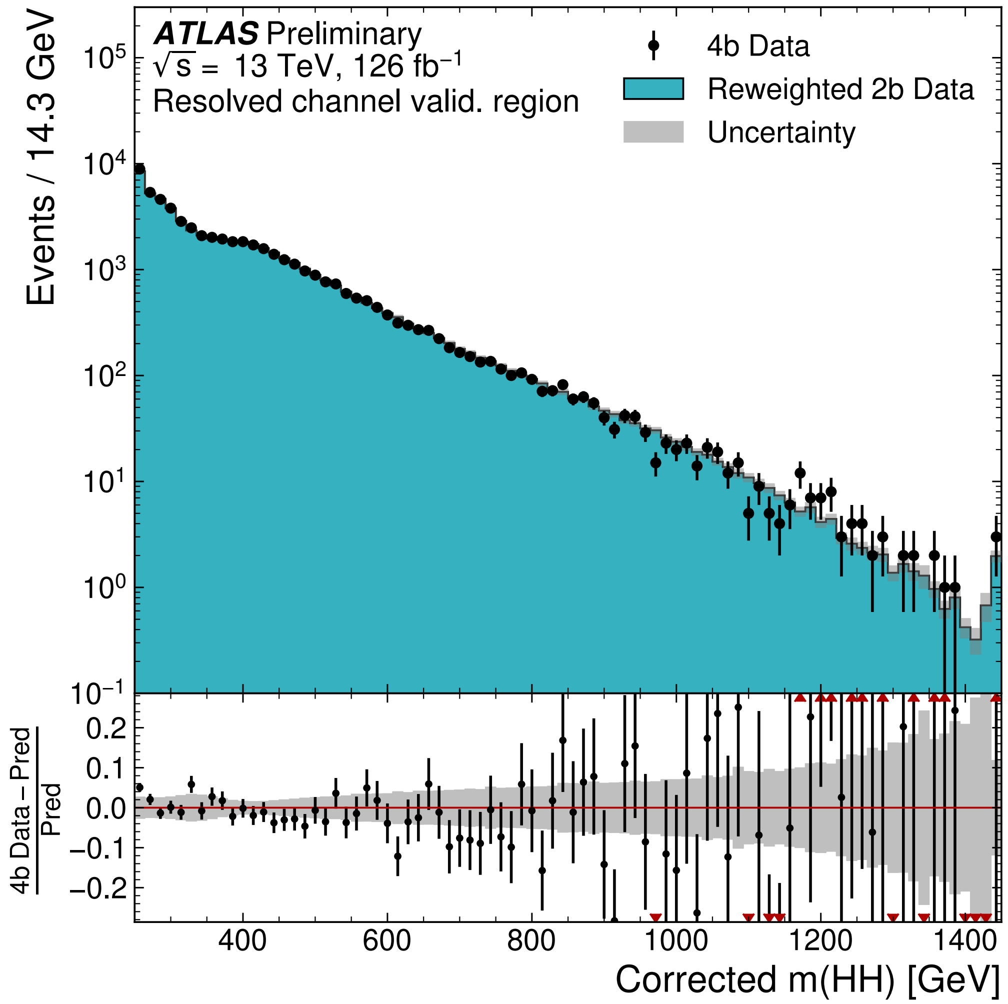
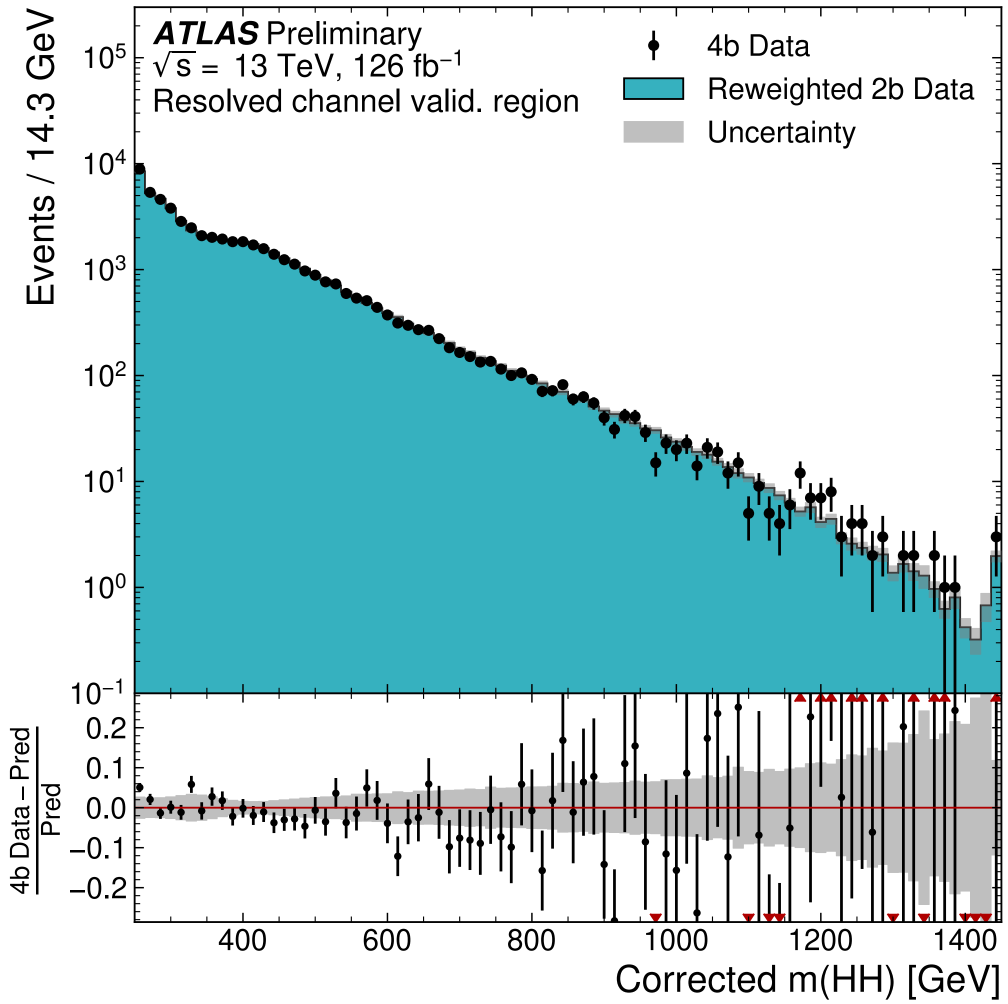


Here, apply NN to 2b data in VR

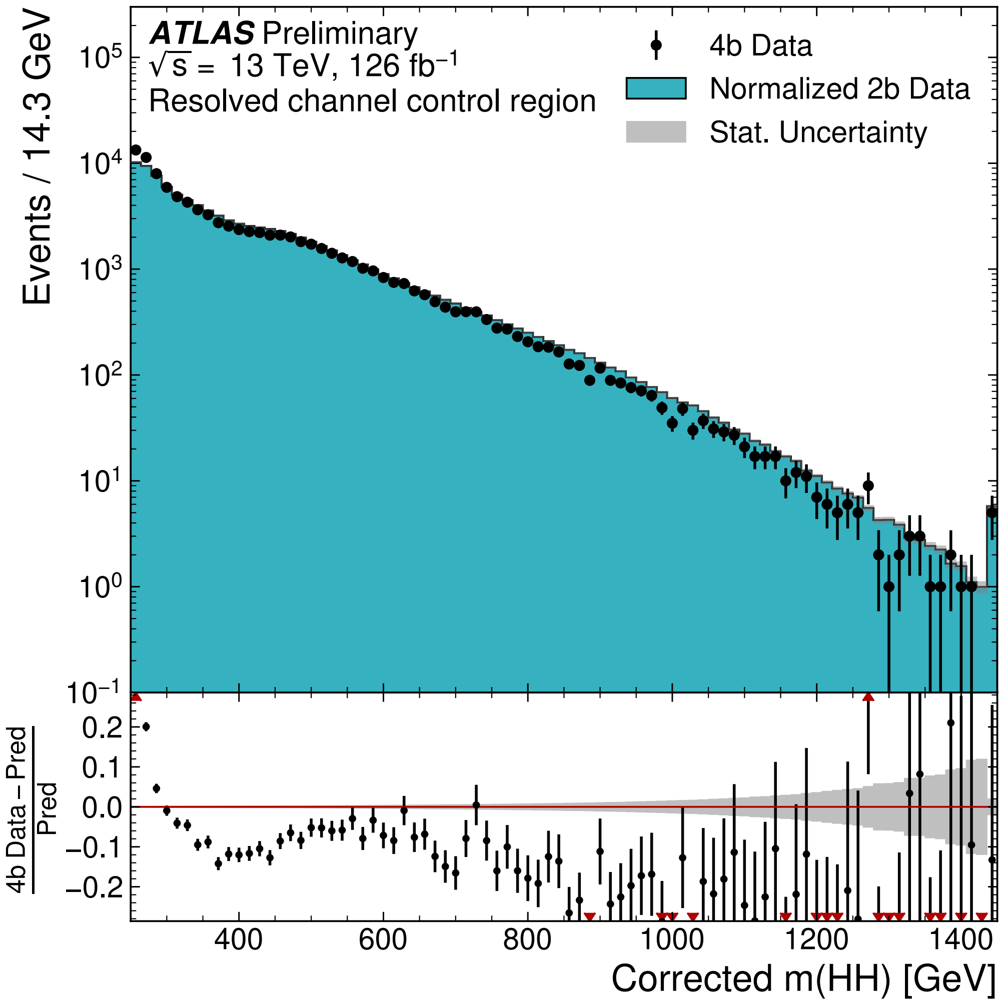
Works well, even on data that wasn't used in training!

Why Neural Networks?



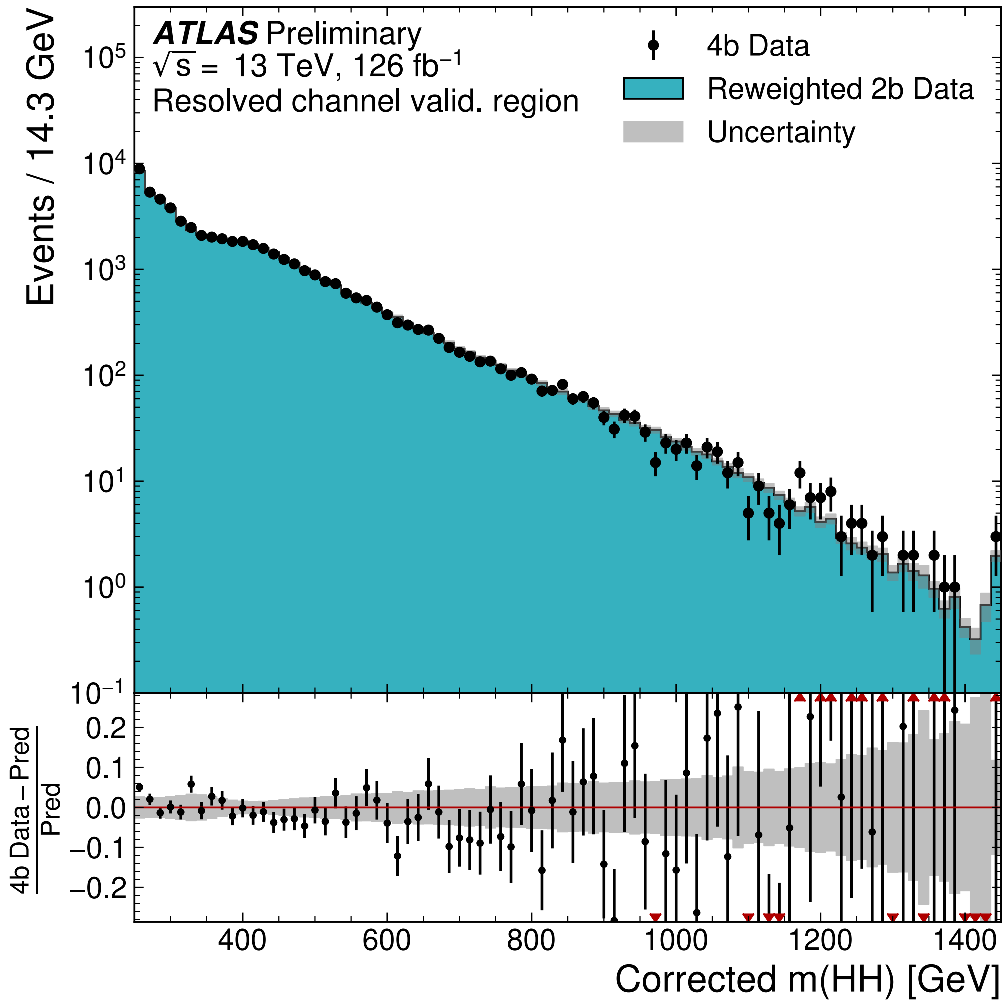
Here, apply NN to 2b data in VR

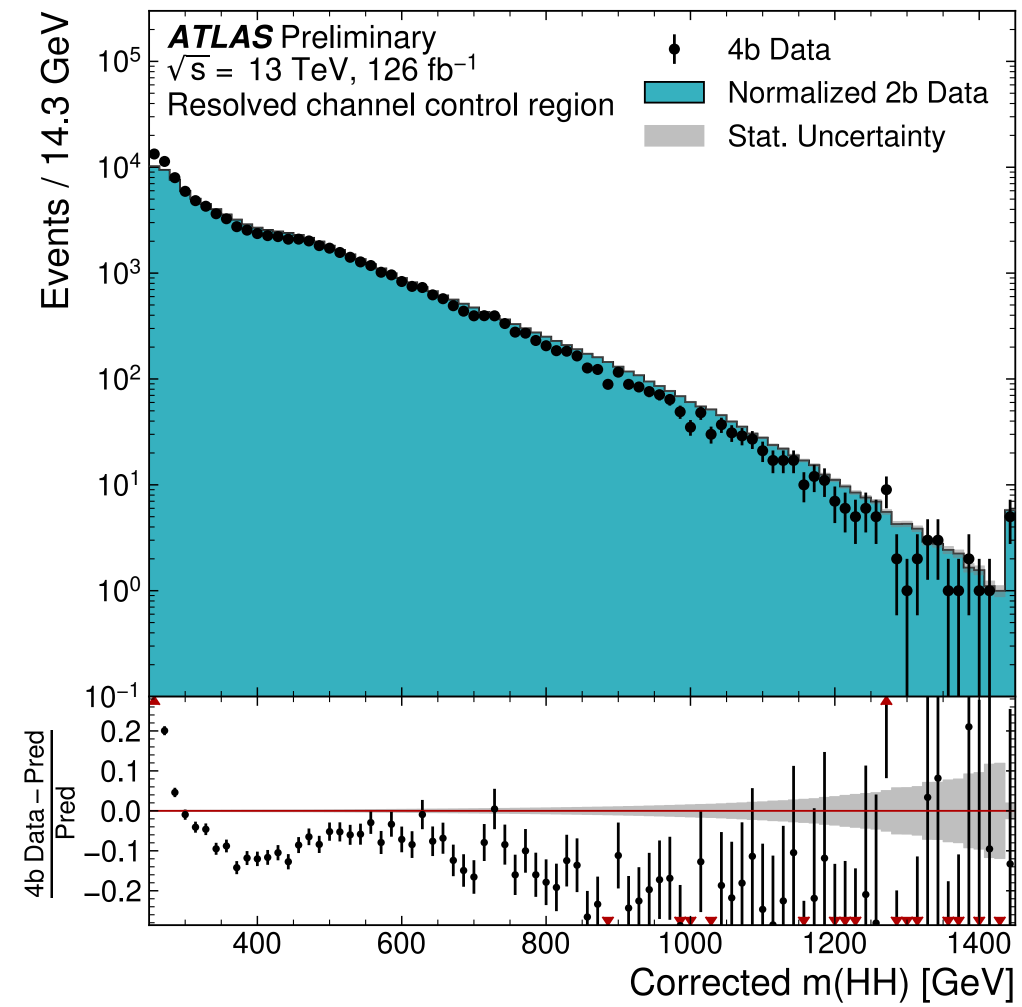
Works well, even on data
that wasn't used in training!



Why does this work?

Why Neural Networks?





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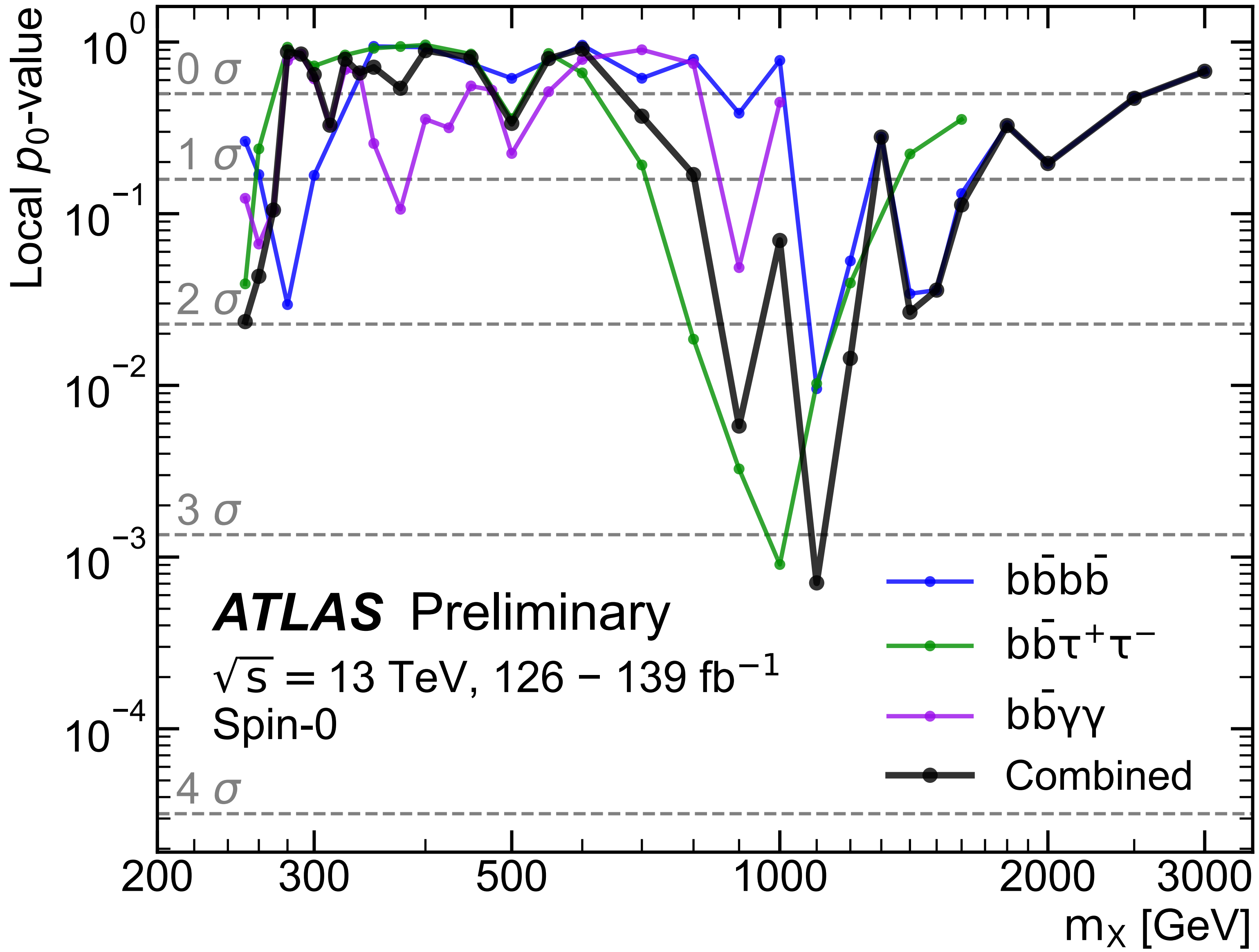
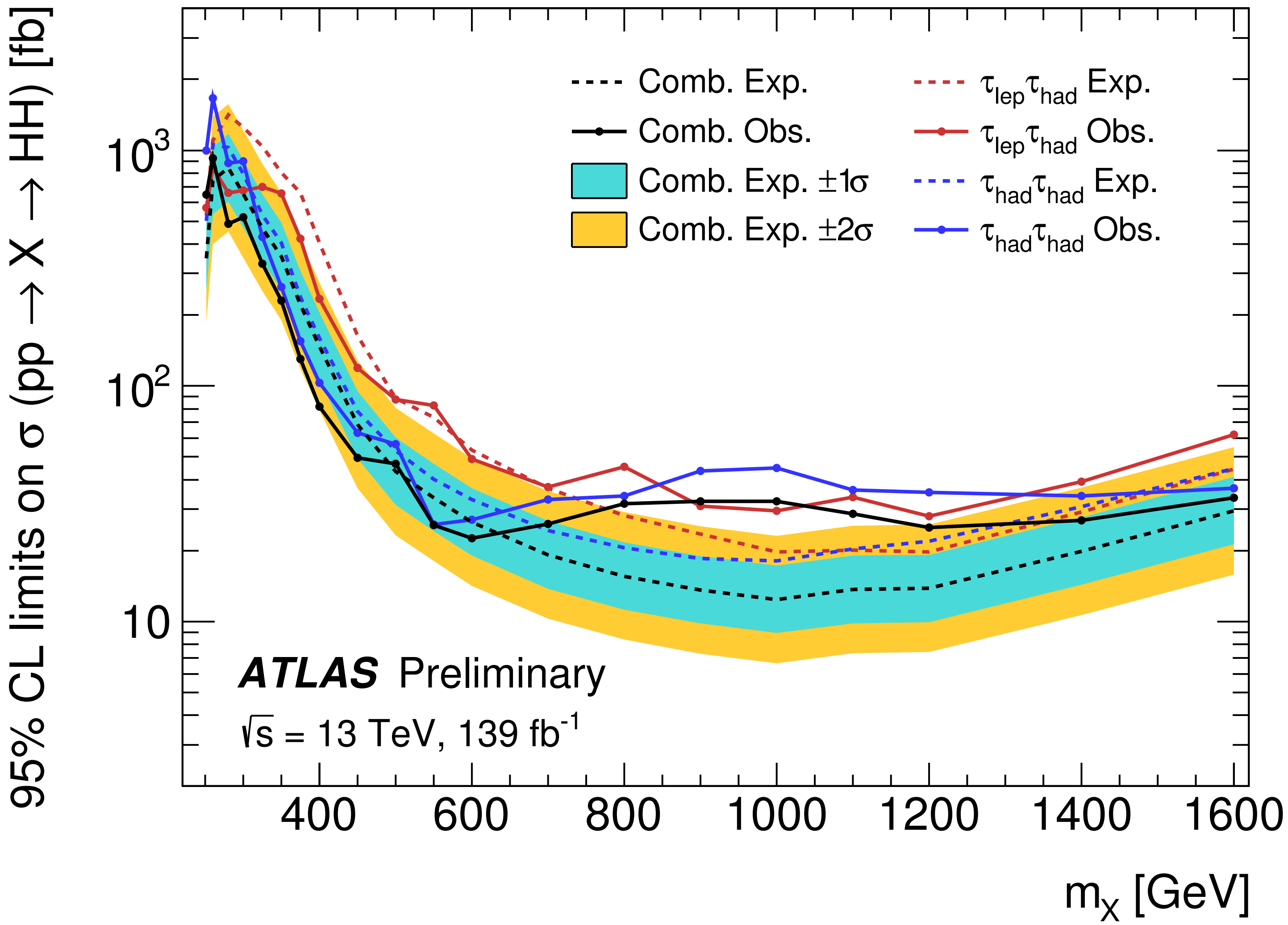
Why does this work?

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

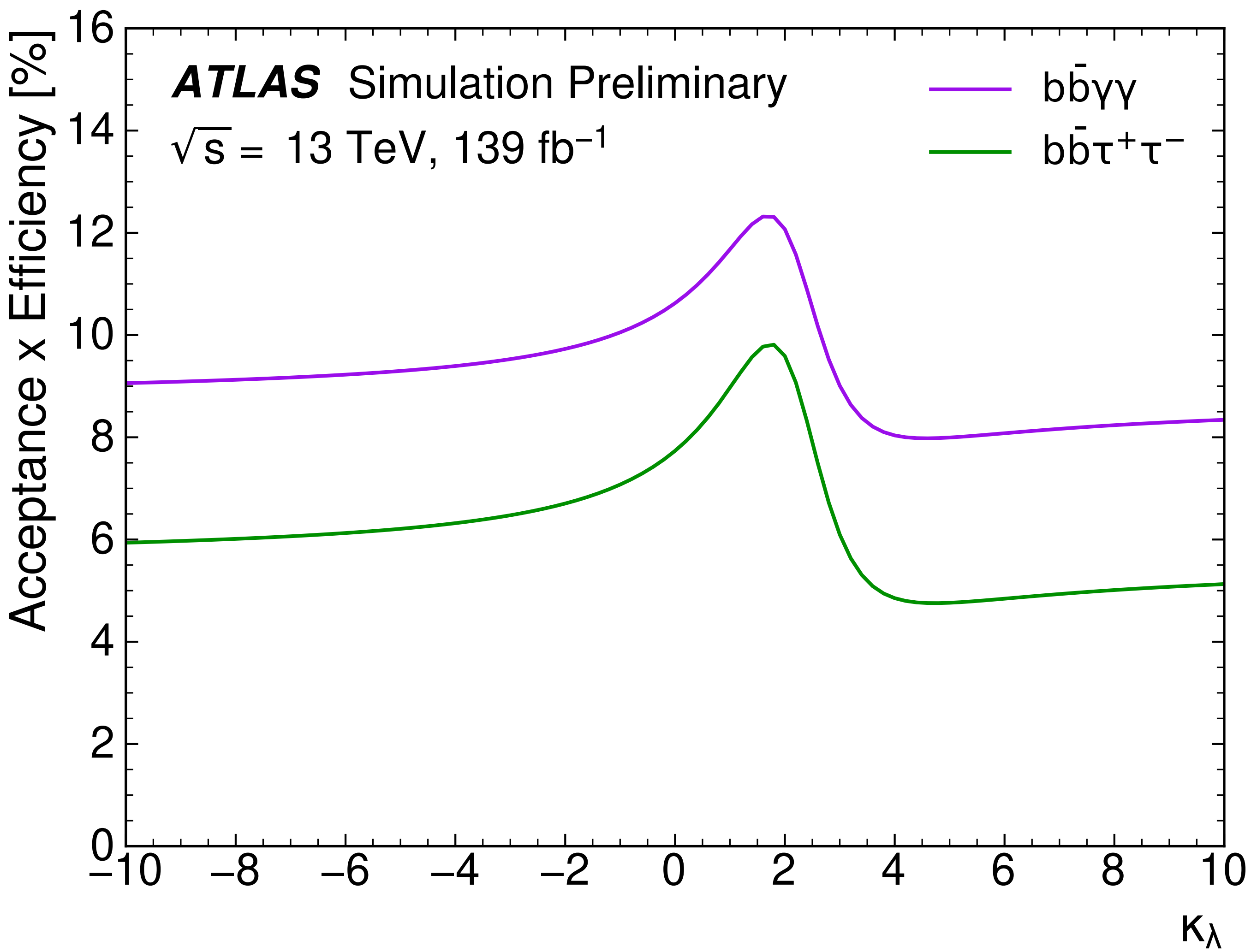
Resonant p-value



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



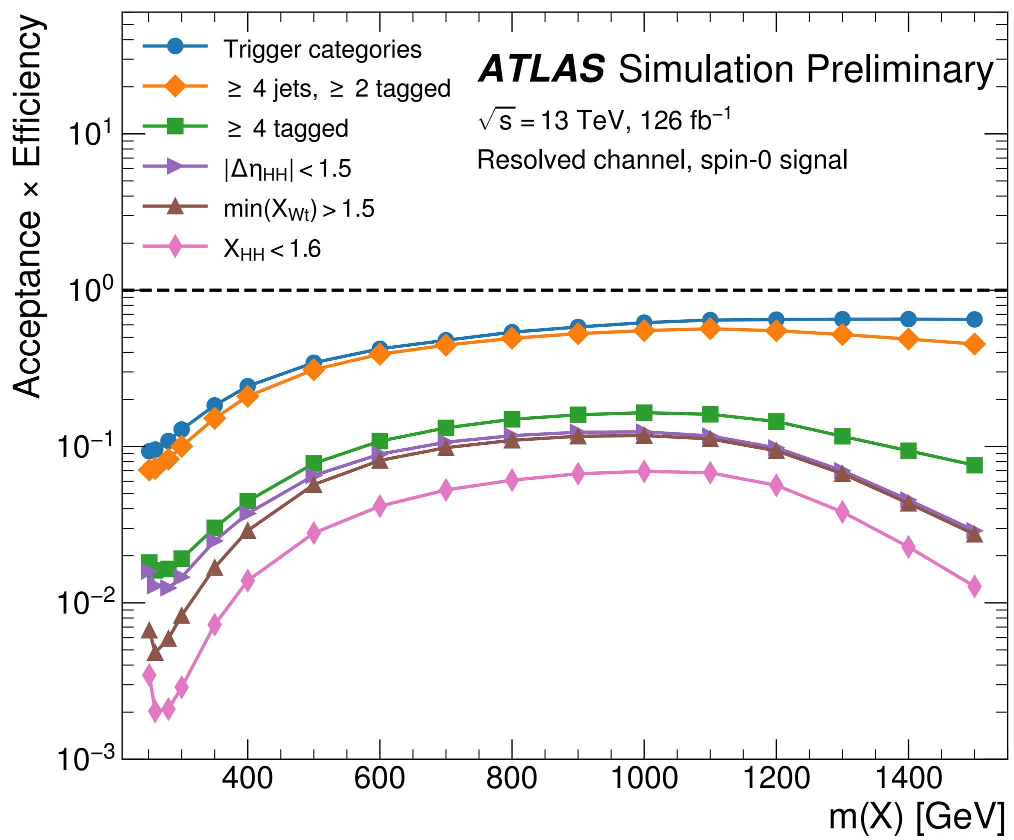
Non-resonant Acc x Eff

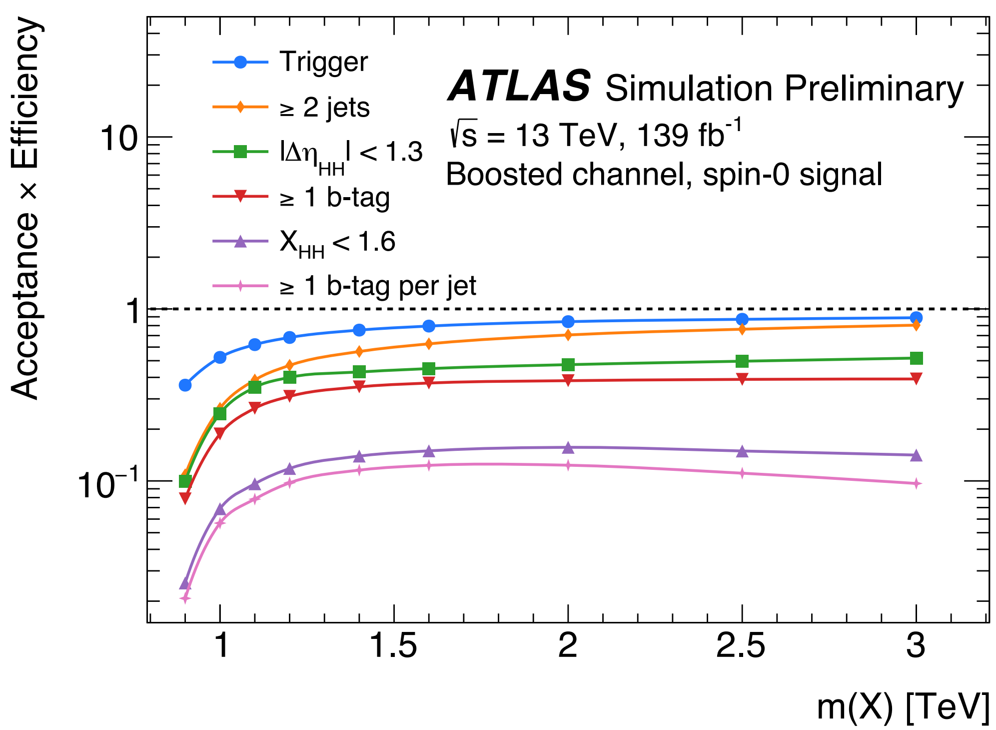


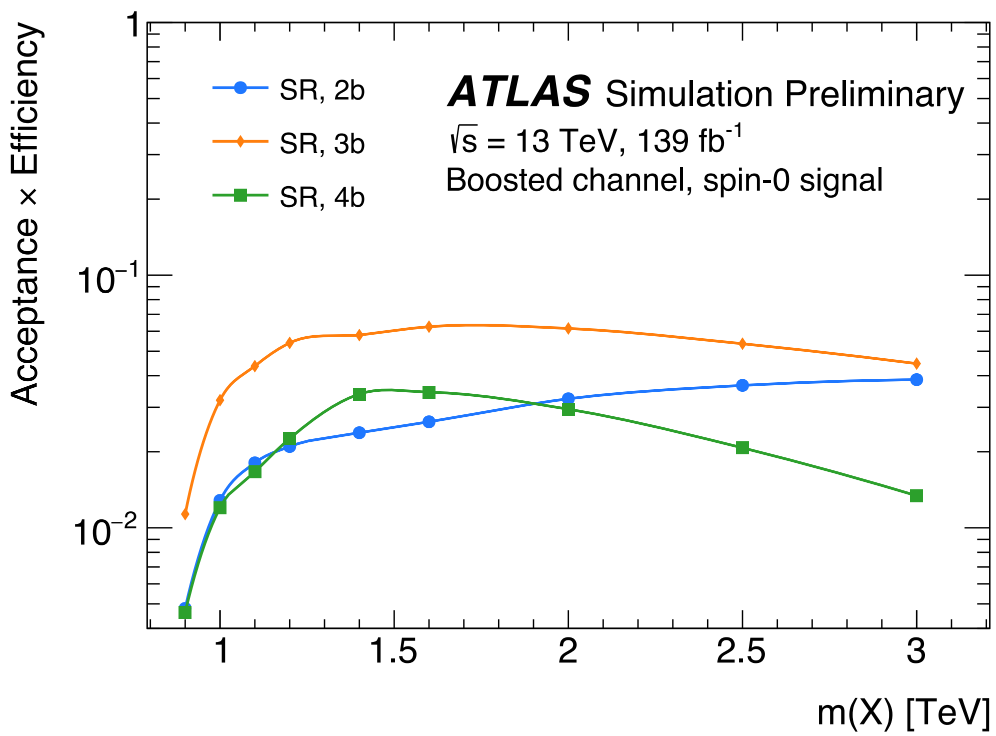
Variables for MVAs

- 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. $\log(p_T)$ of the selected jet with the 2$^{\text{nd}}$-highest p_T,
  2. $\log(p_T)$ of the selected jet with the 4$^{\text{th}}$-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. $\log(p_T)$ 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 $p_T > 40$ GeV and $|\eta| < 2.5$, including jets that are not selected.

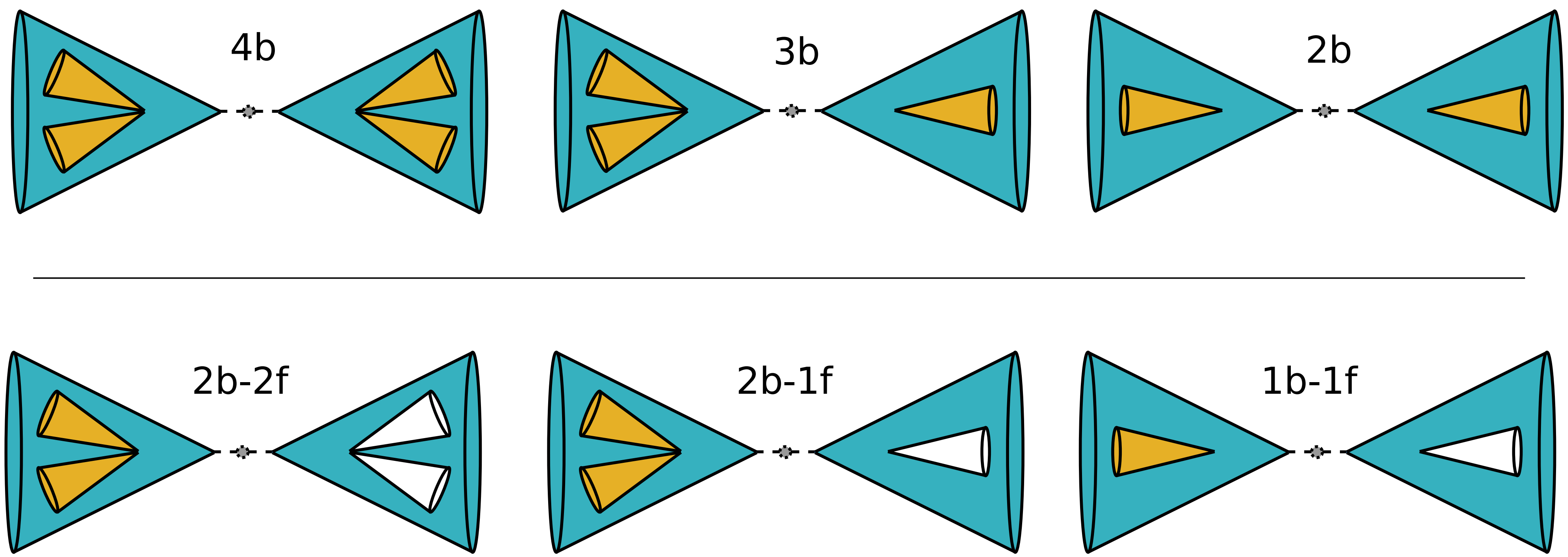
Acceptance x Eff $b\bar{b}b\bar{b}$

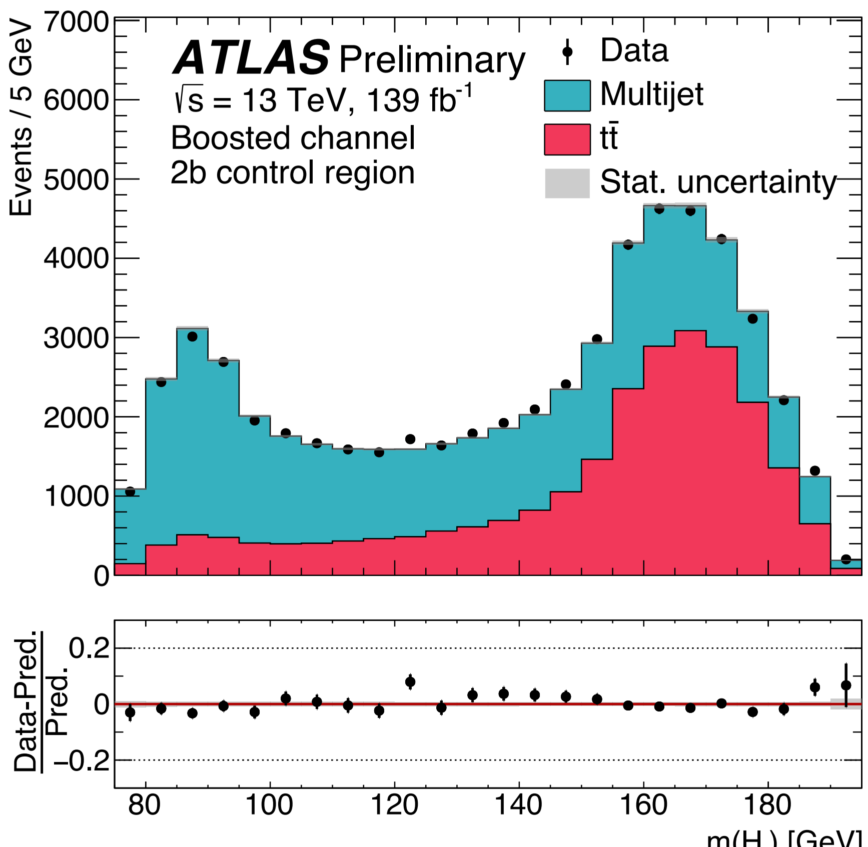


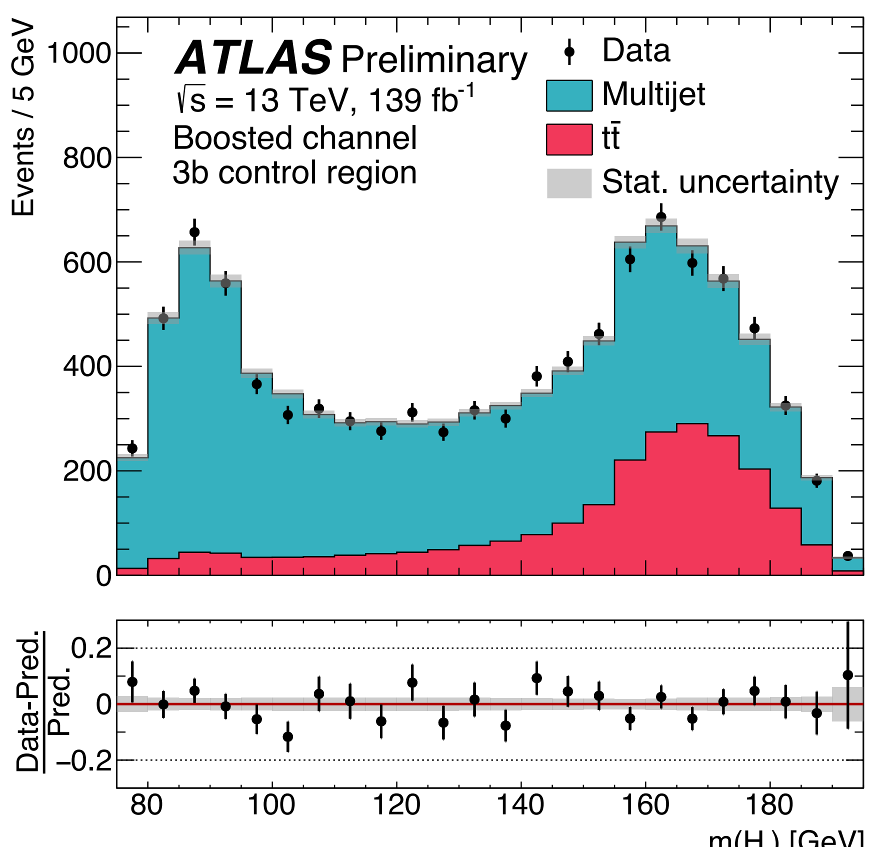


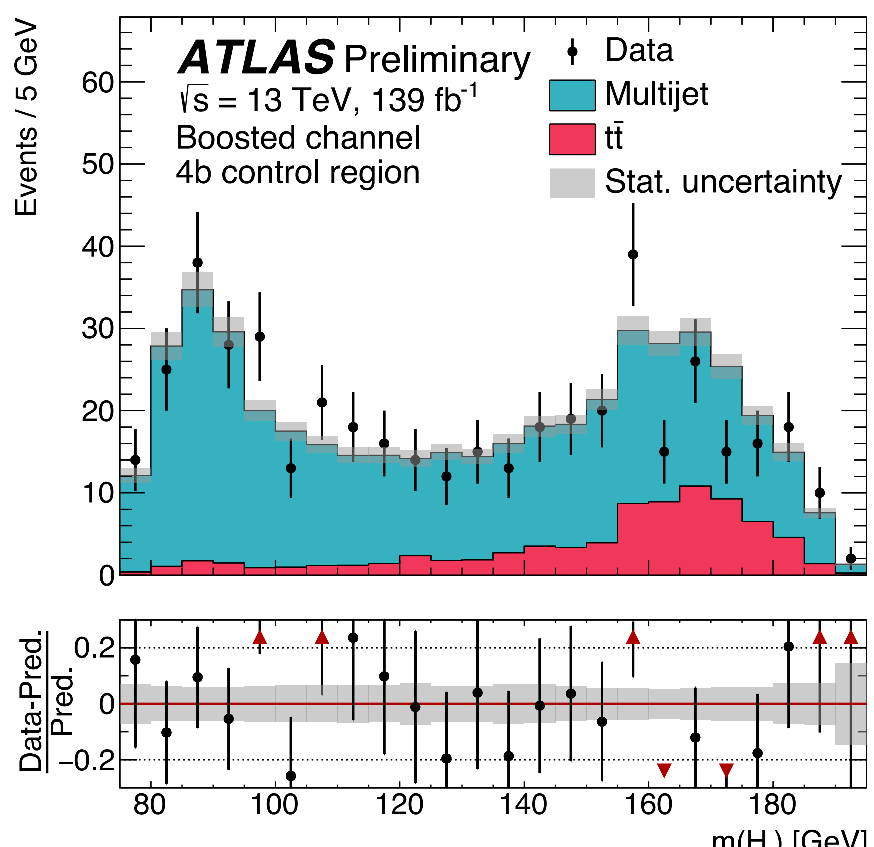


Boosted Backgrounds









From Limits, to Discovery

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From Limits, to Discovery

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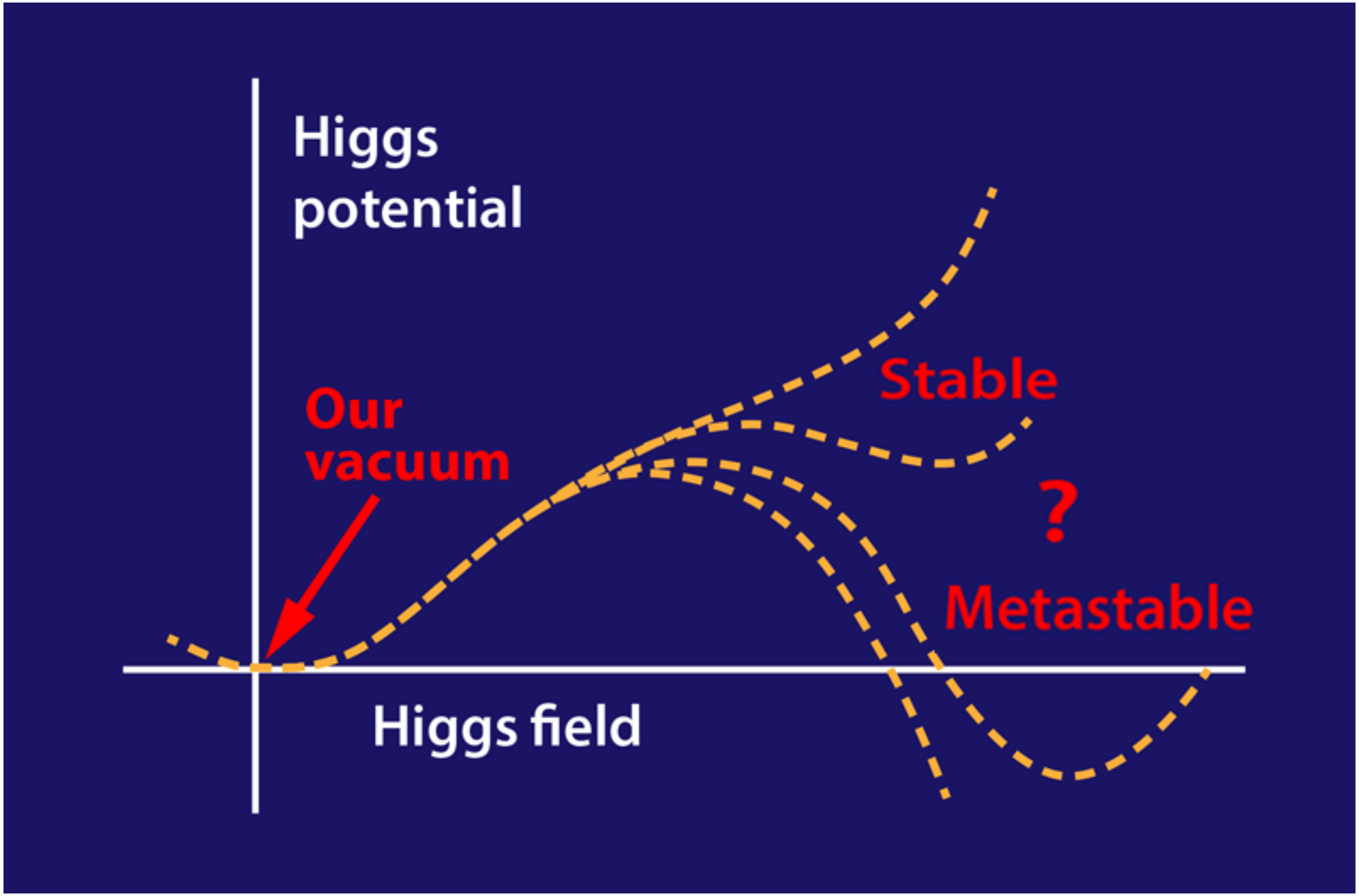
- **Jet reconstruction**
- **Jet triggering**
- A common theme to these problems: how to use **more information**
  - And a common solution to many: **machine learning**

Universe Stability



A. Kusenko

Interference

$$\sigma \propto \left| \qquad \right|^2 - (\qquad + h.c.)$$

$$+ \left| \qquad \right|^2$$

Interference

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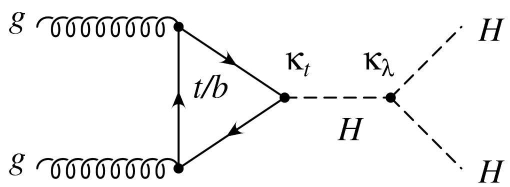

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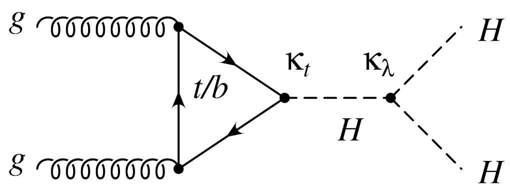

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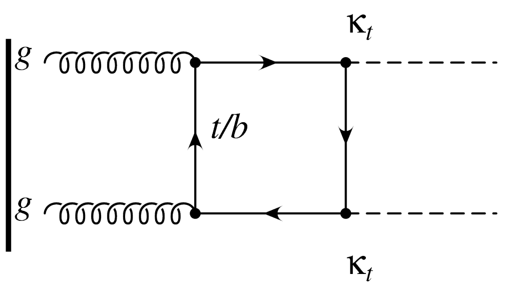

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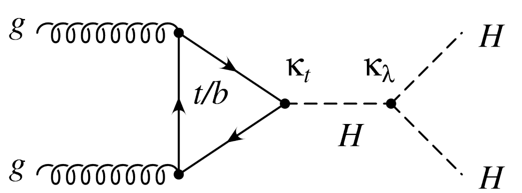
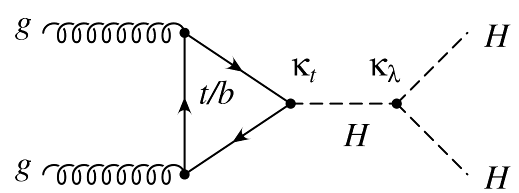
$\sigma \propto \Big|$ 

$\Big|^2 - \Big($ 

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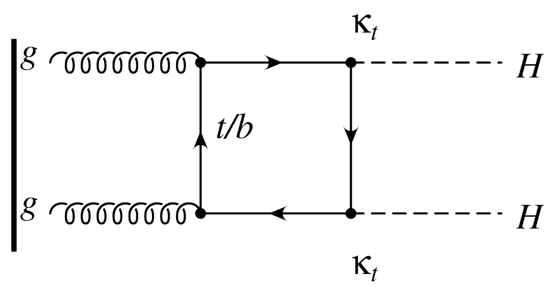
$+ \Big|$ 

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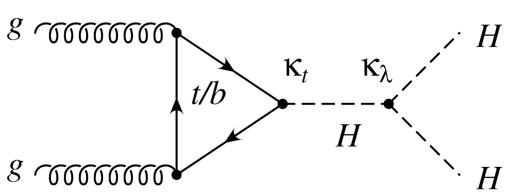
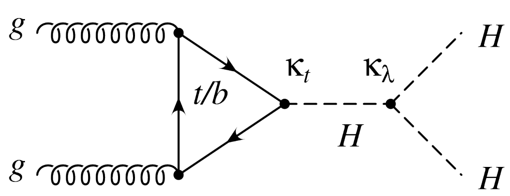
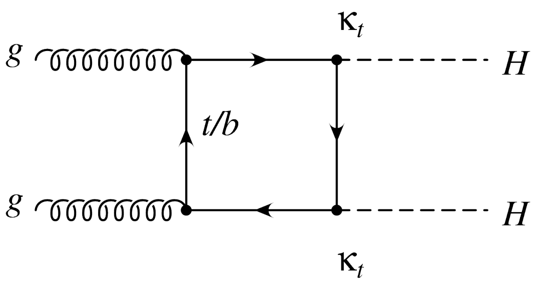
$\sigma \propto \Big|$ 

$\Big|^2 - \big($ 



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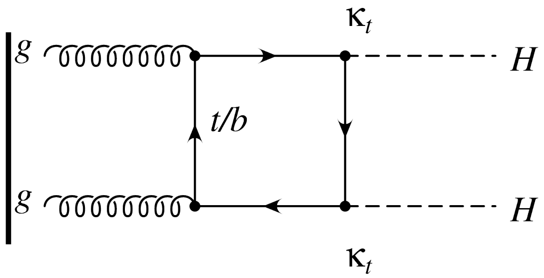
$+ \Big|$ 

$\Big|^2$