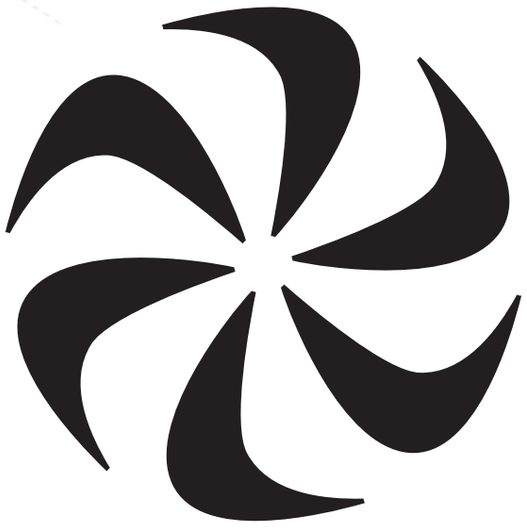
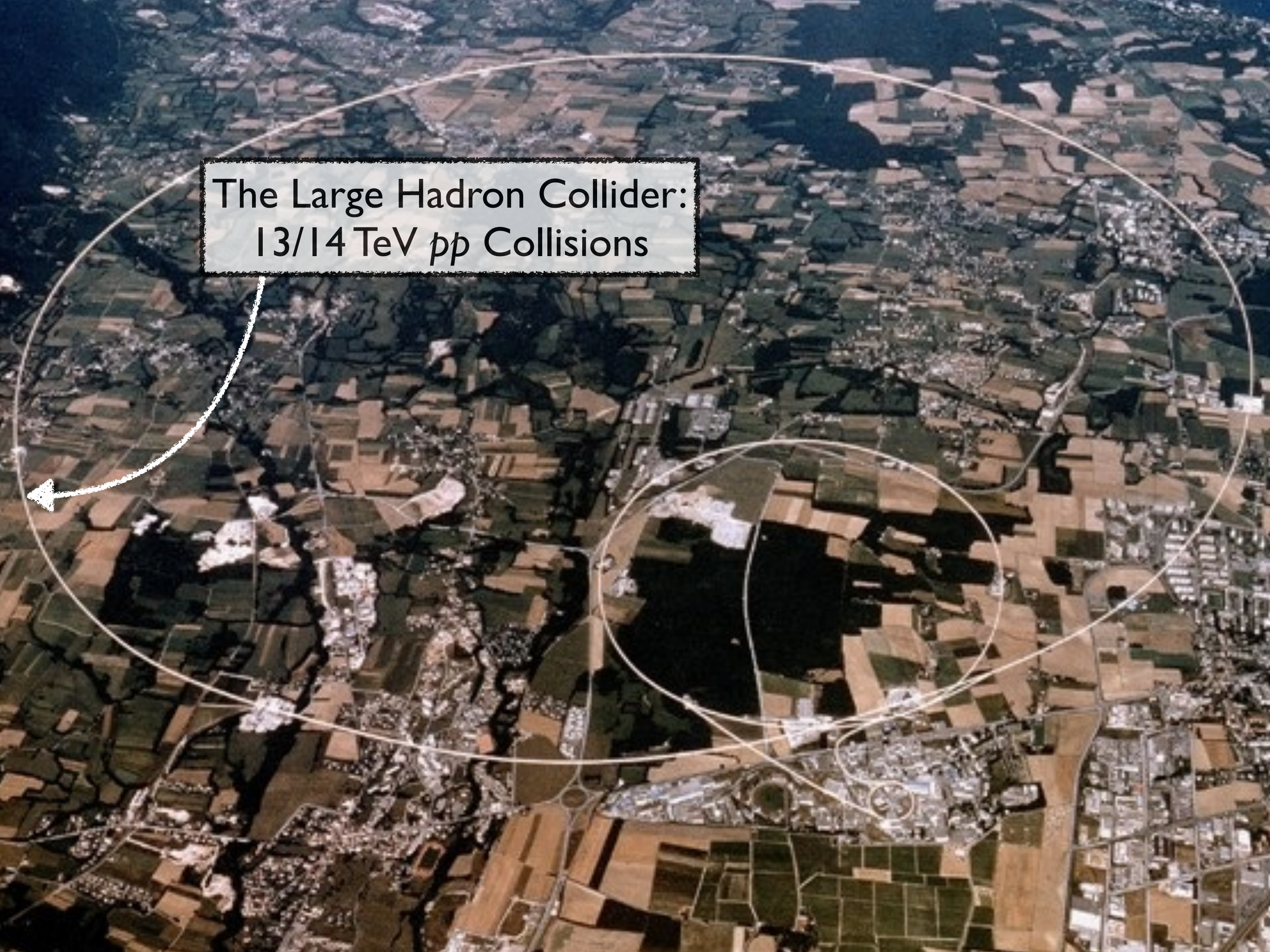
Probing the nature of electroweak symmetry breaking with Higgs boson pair-production at ATLAS

Lake Louise Winter Institute 2024

Maximilian Swiatlowski

TRIUMF





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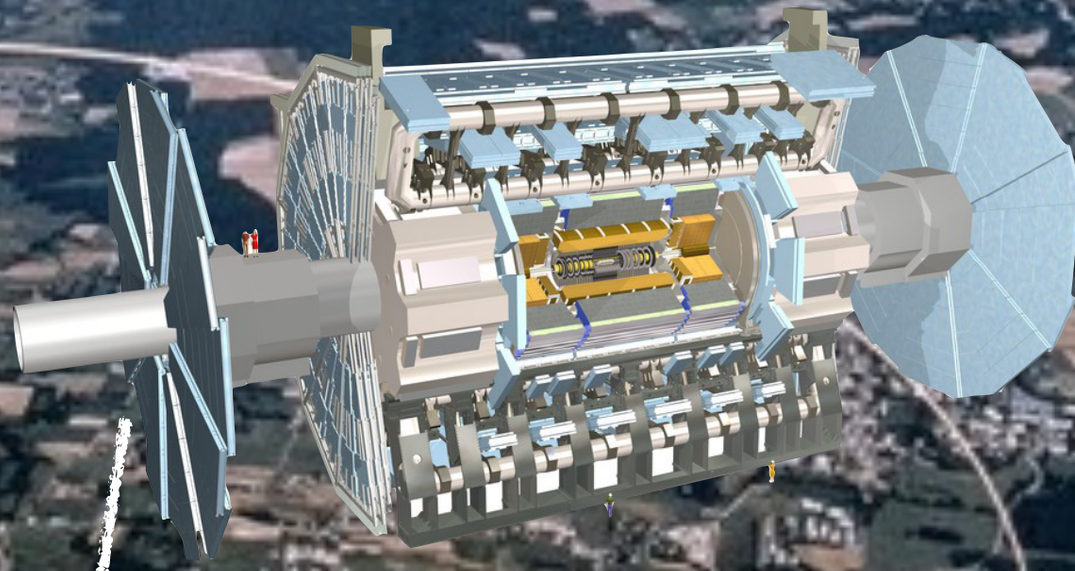

The ATLAS Detector

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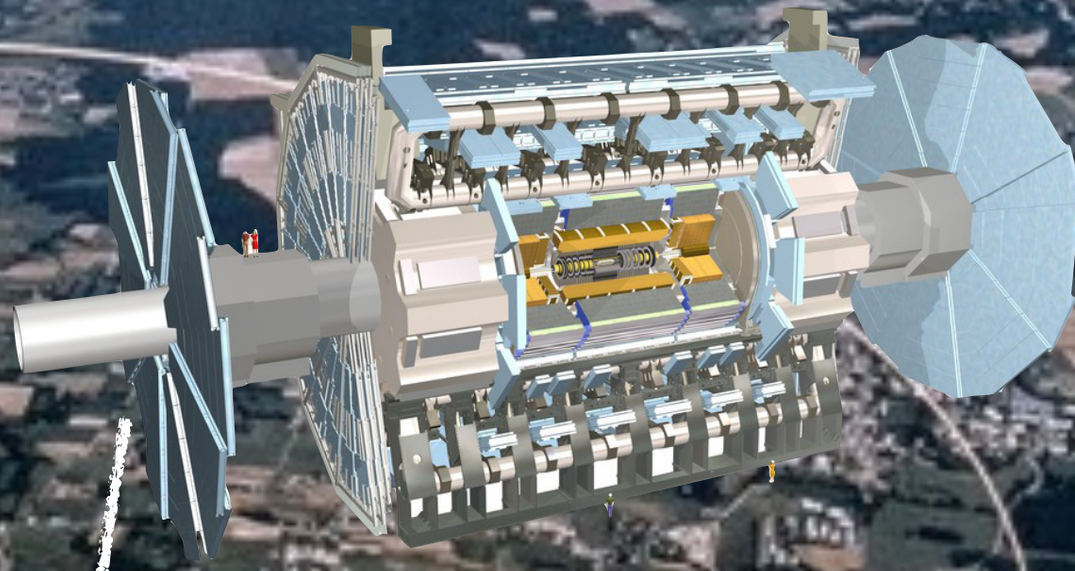


The ATLAS Detector

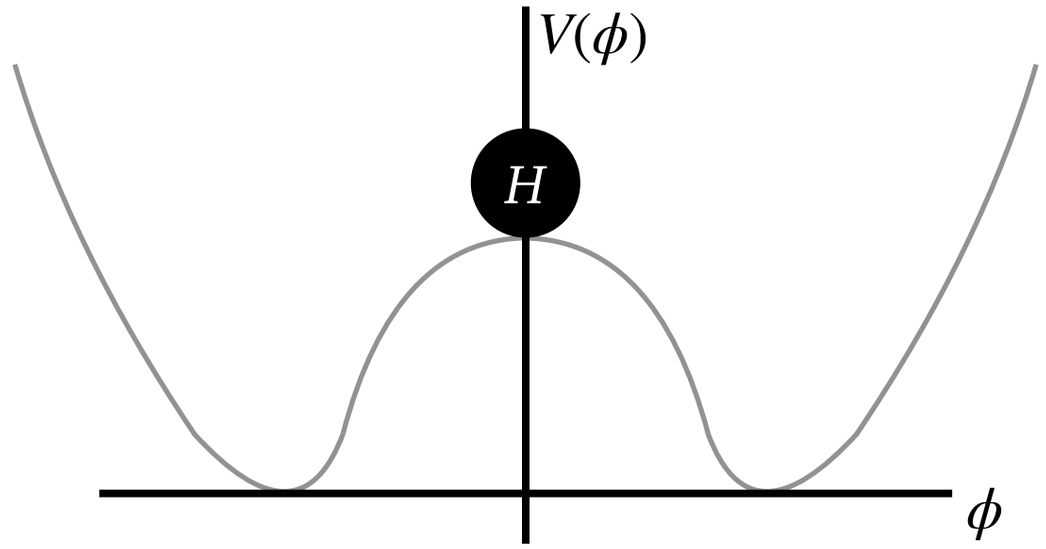
Our tools for measuring the Higgs potential

The Higgs Potential

The Higgs Potential

The SM Higgs potential is:

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



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Our universe lives in the minimum:

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

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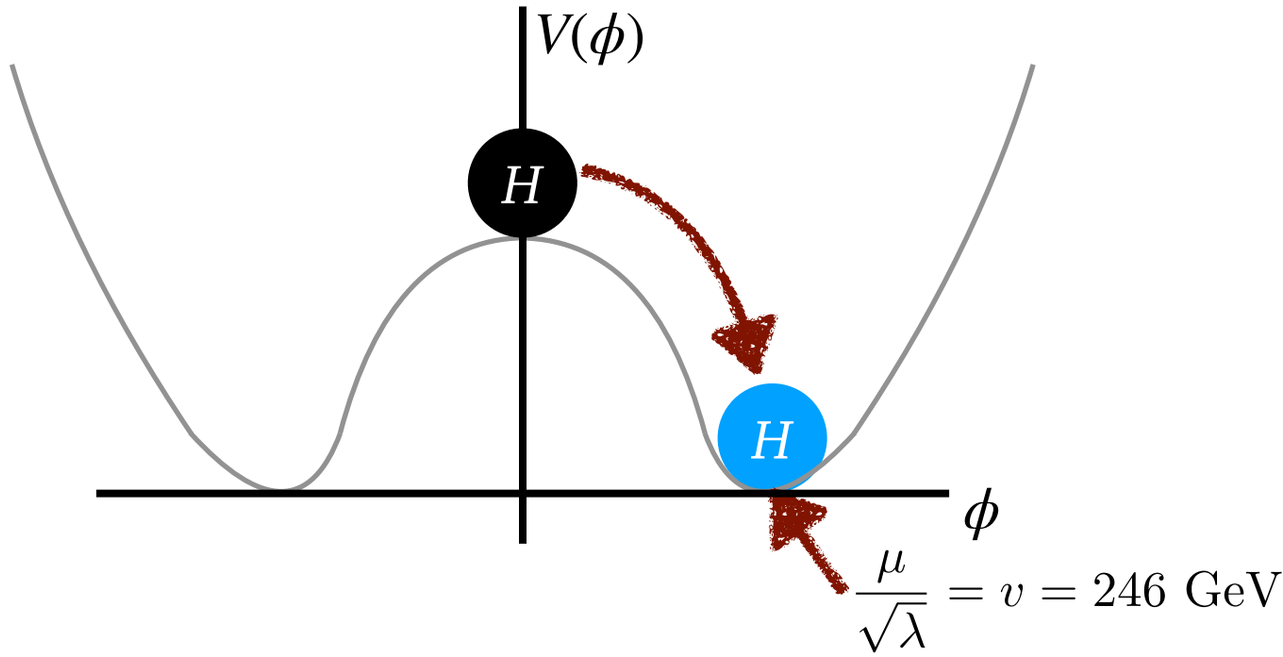

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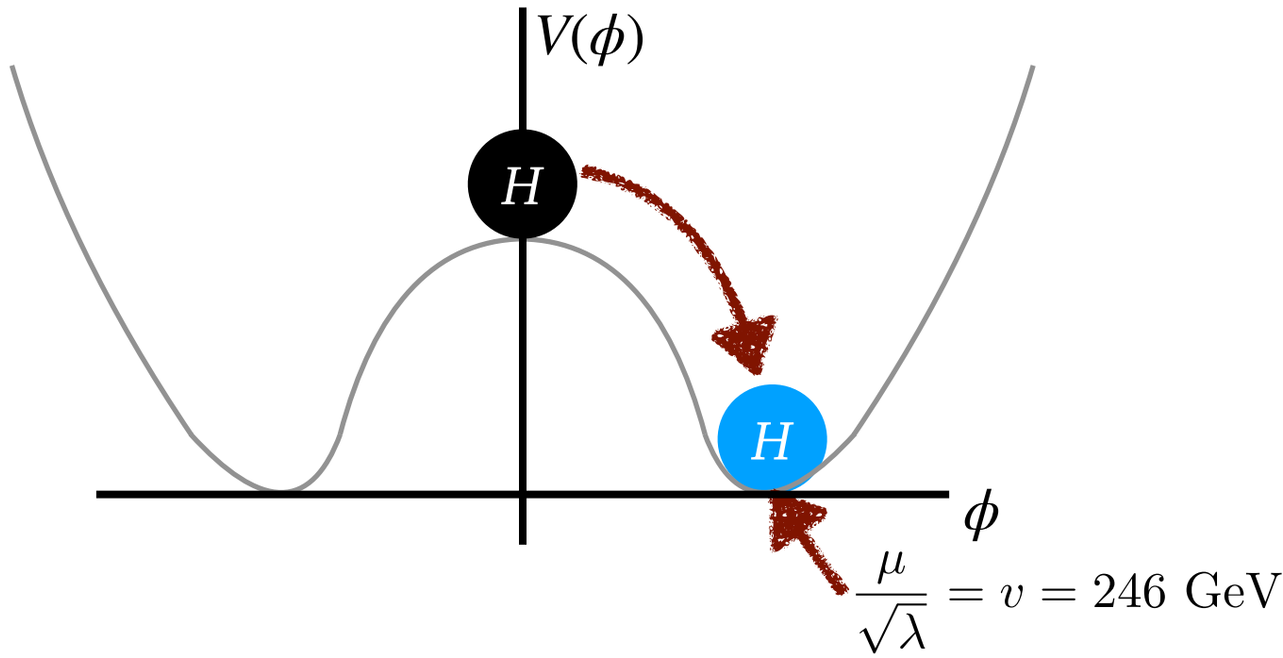

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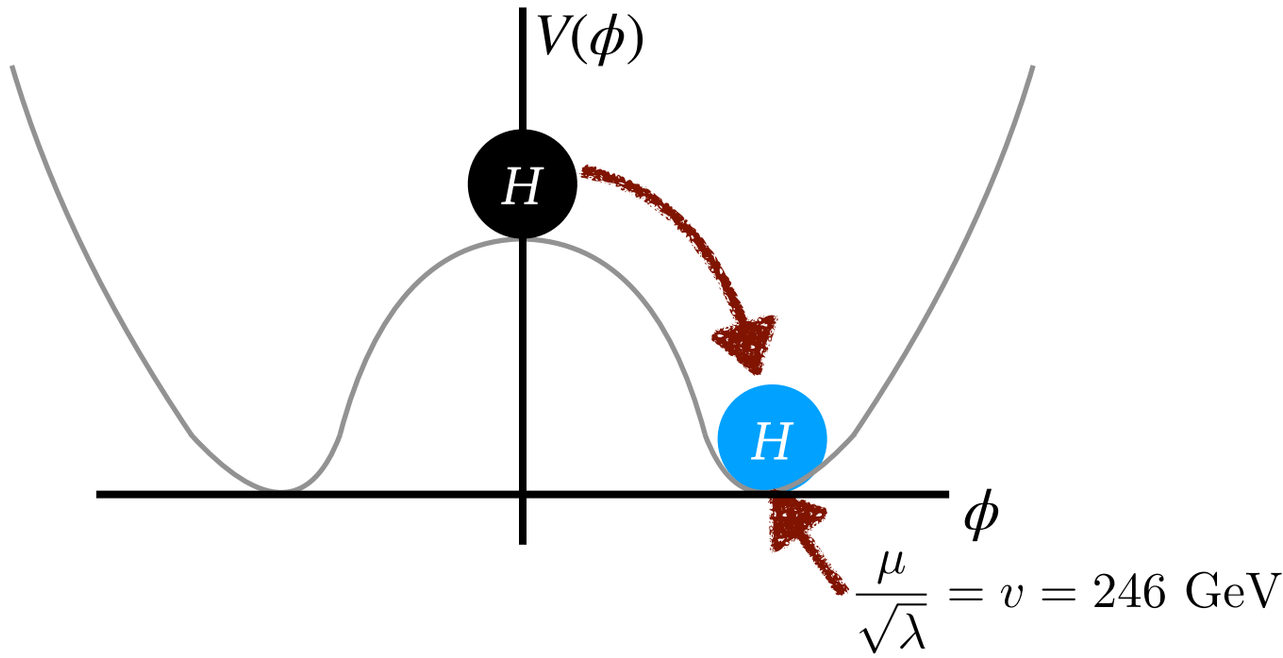
Self-interaction



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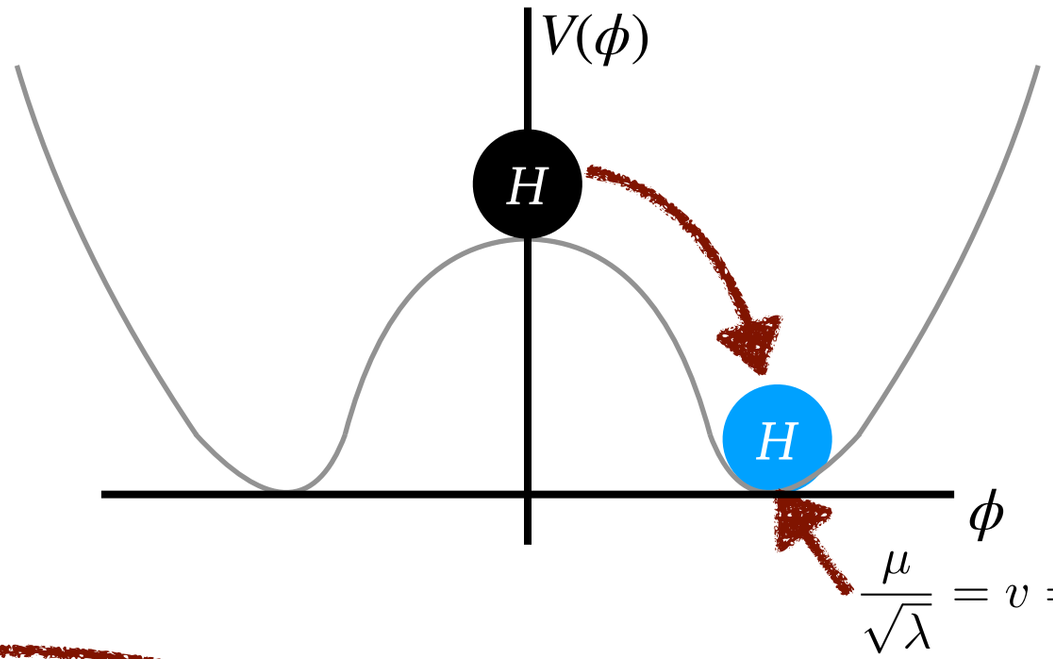

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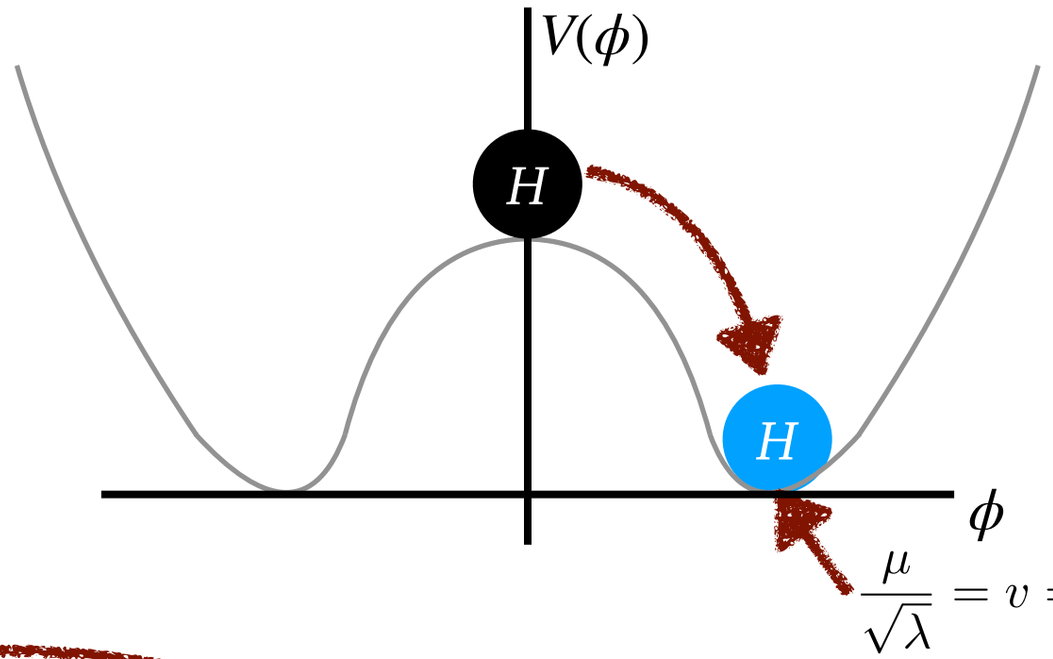

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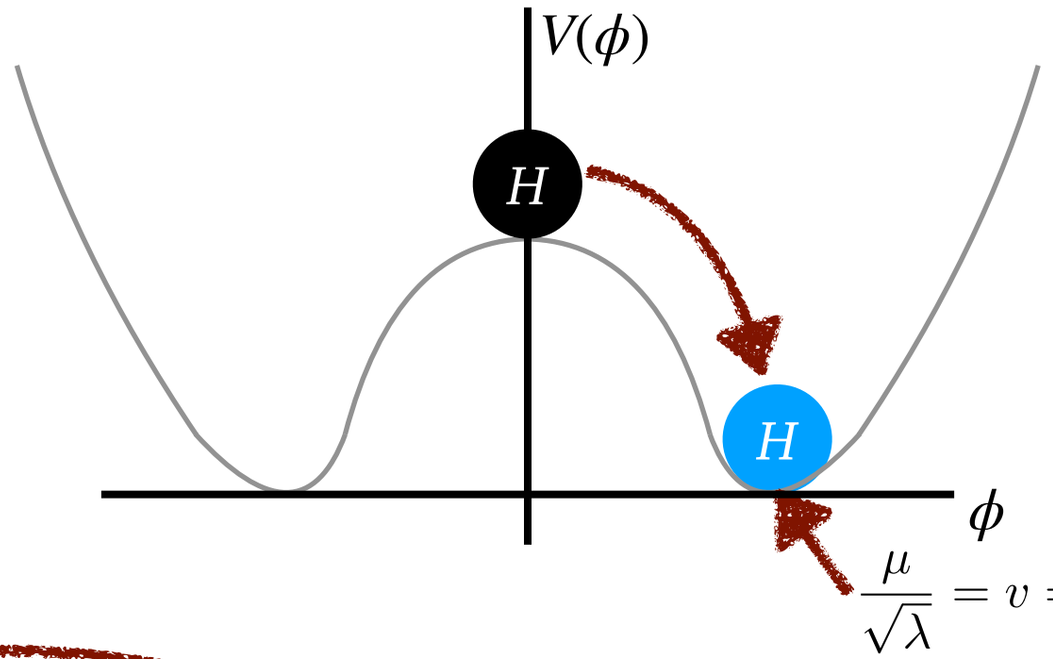

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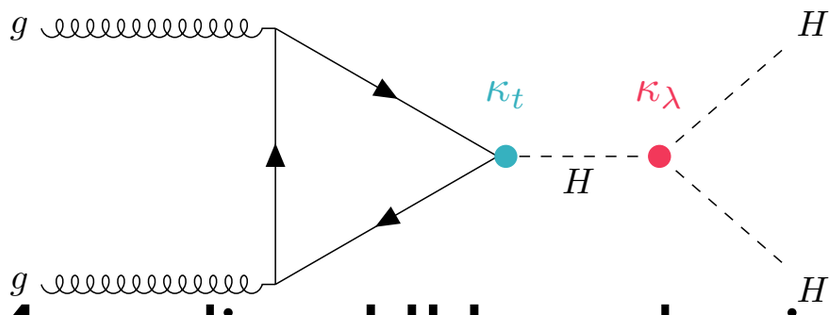

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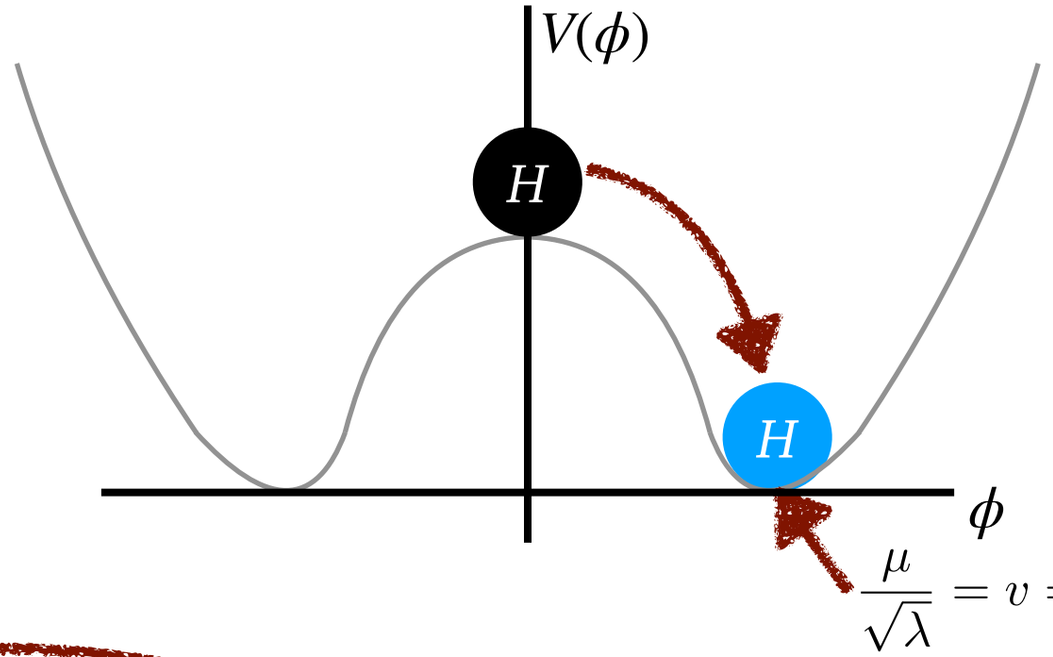

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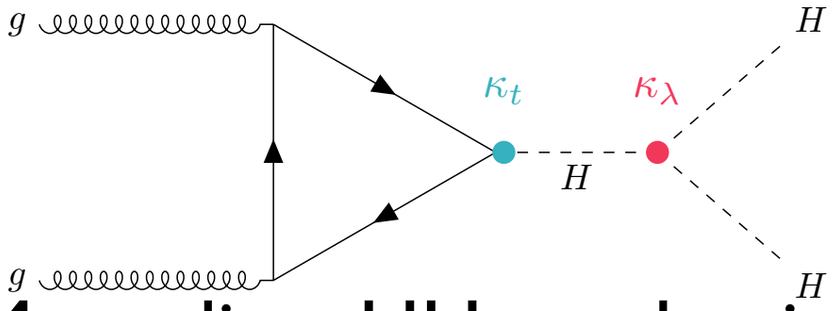

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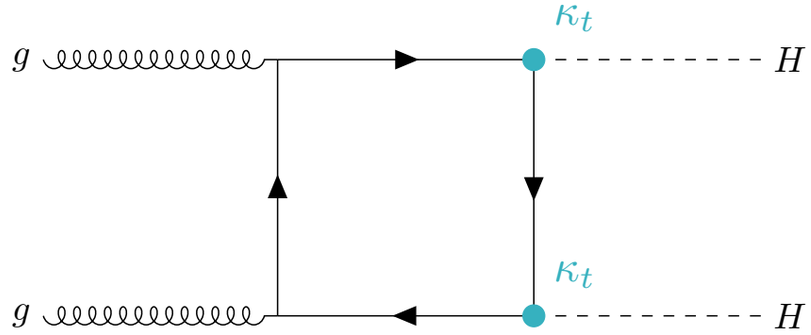

But interference means x-sec is very low

Potential Higgs Potentials

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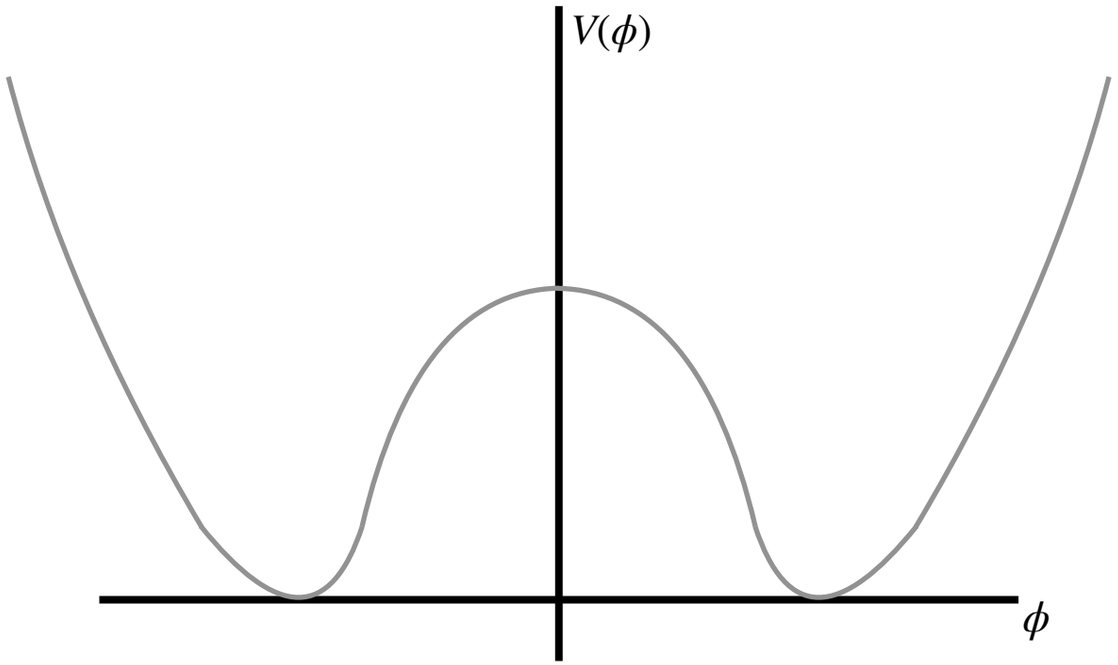

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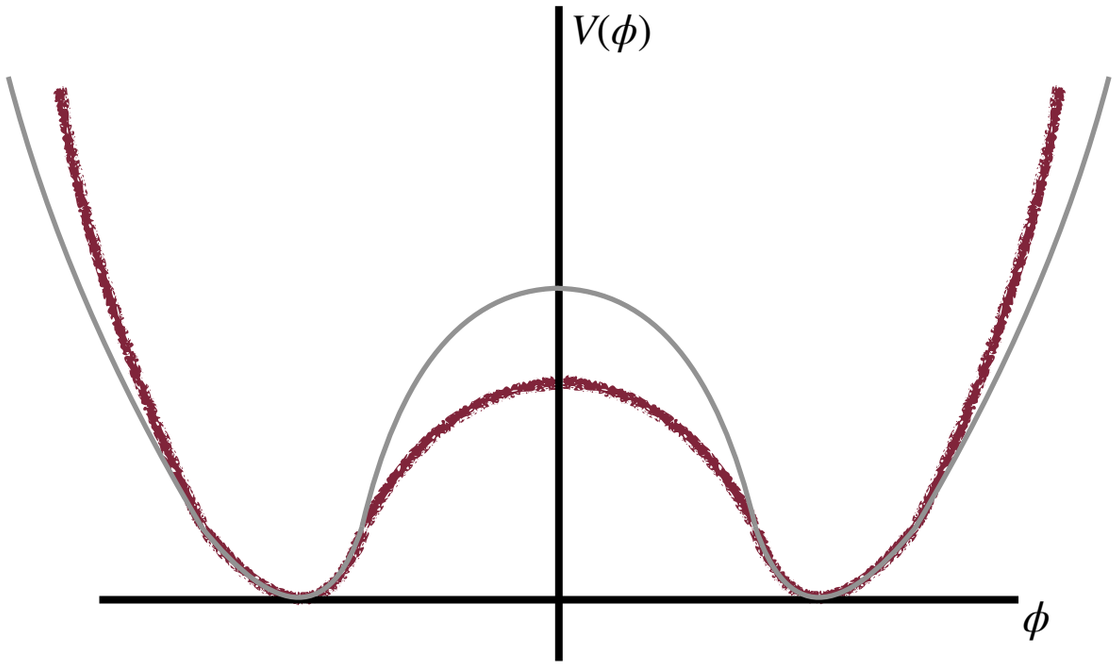

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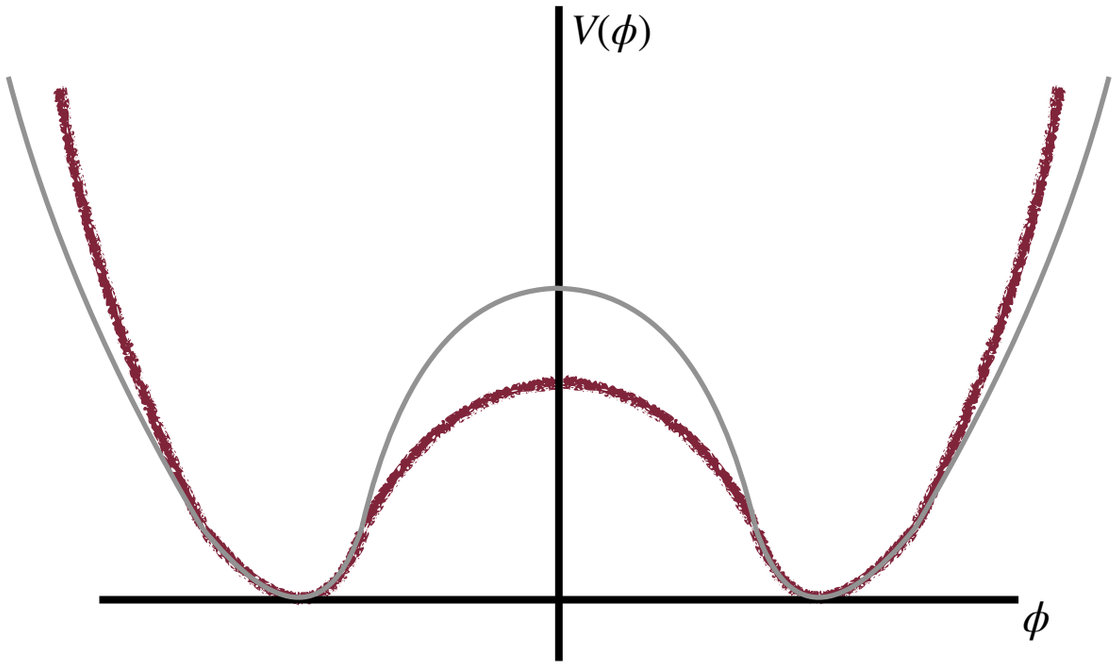

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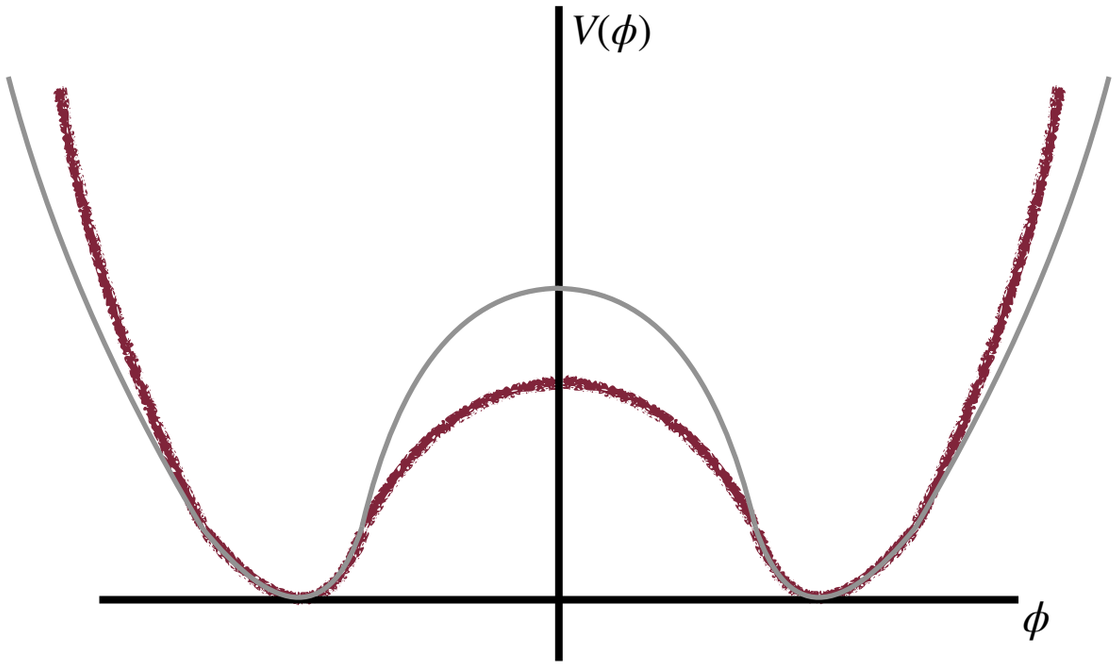
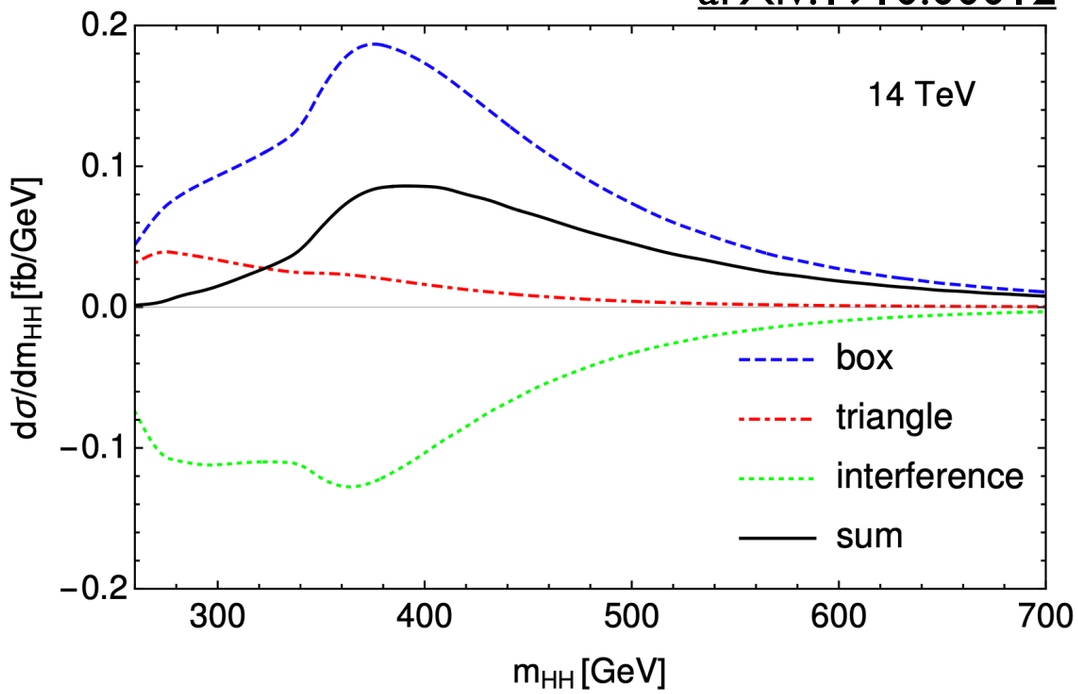


arXiv:1910.00012



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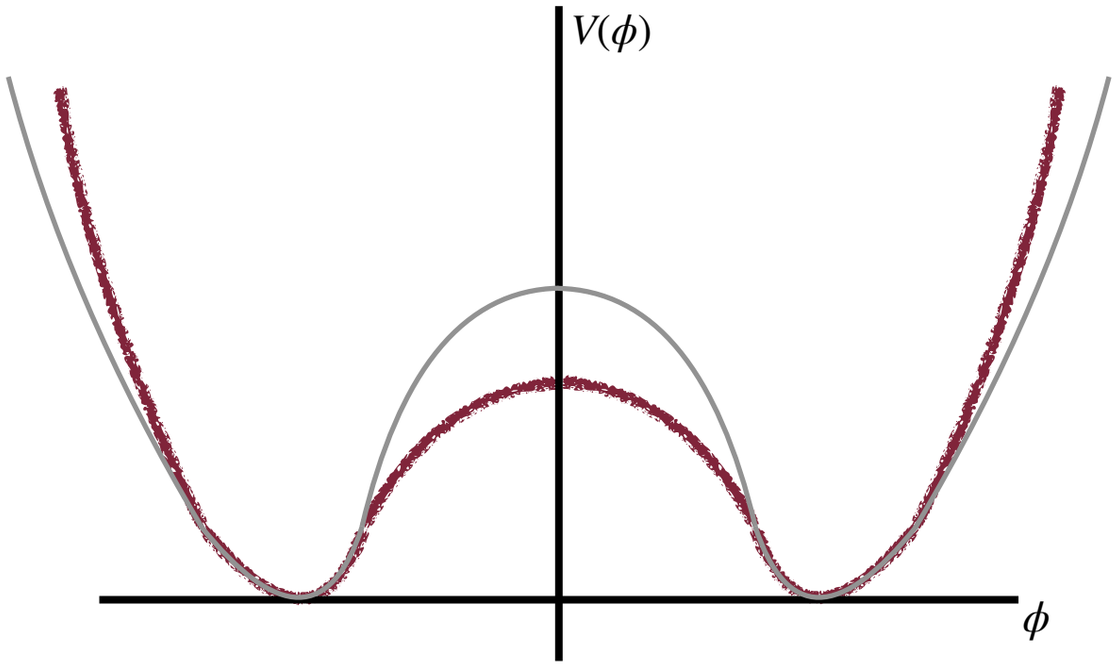

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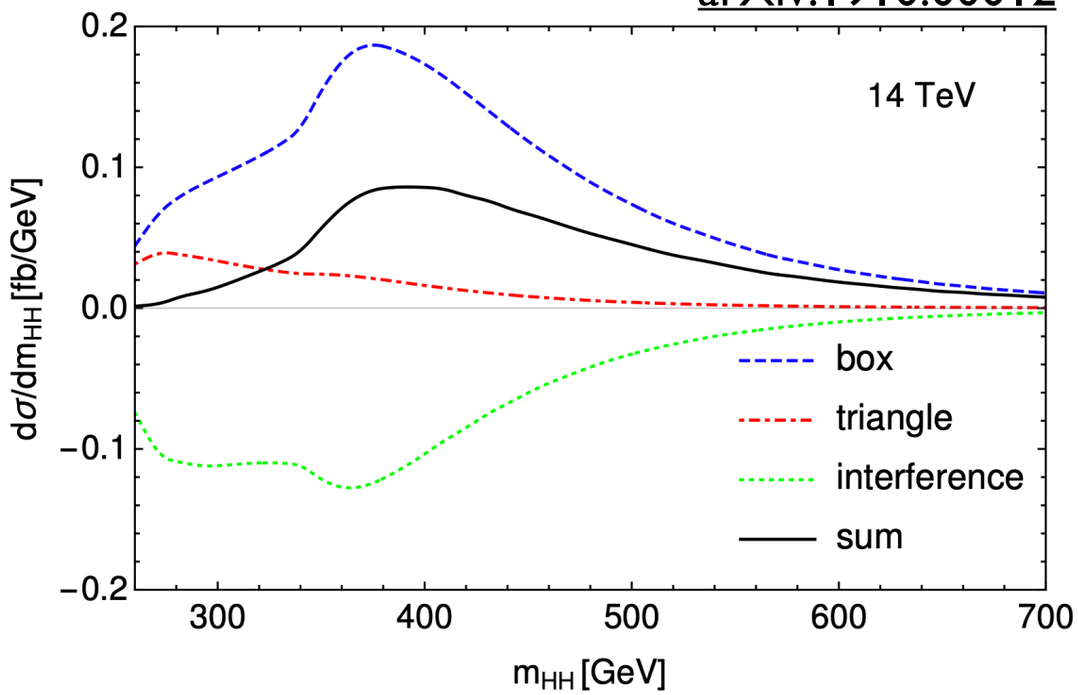

Signal distribution strongly depends on κ_λ

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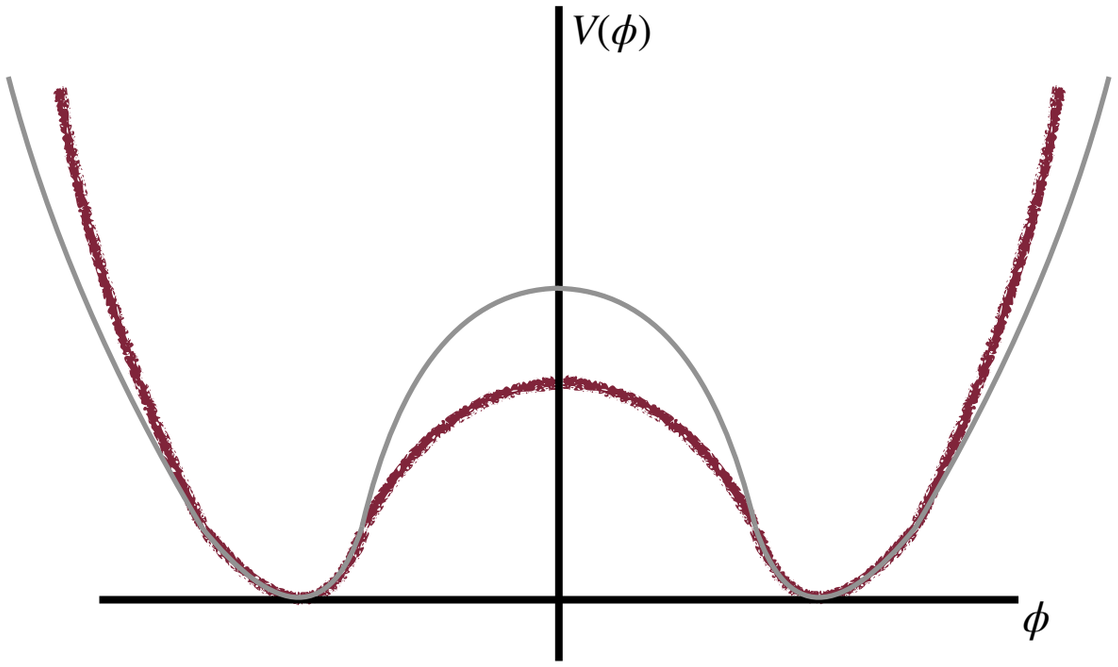

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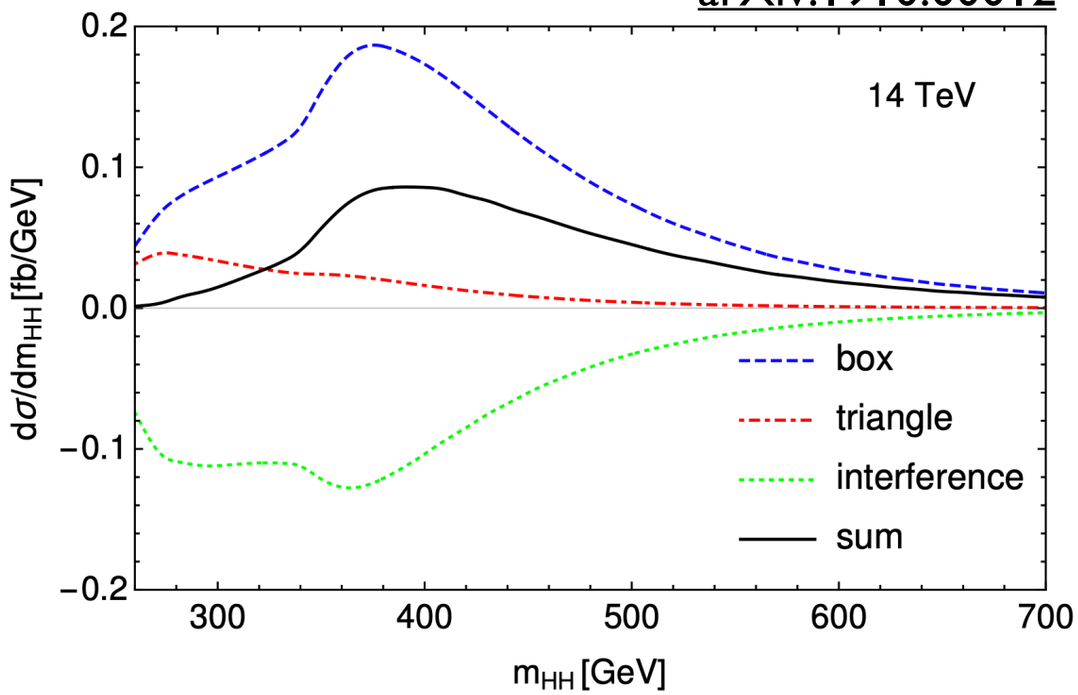

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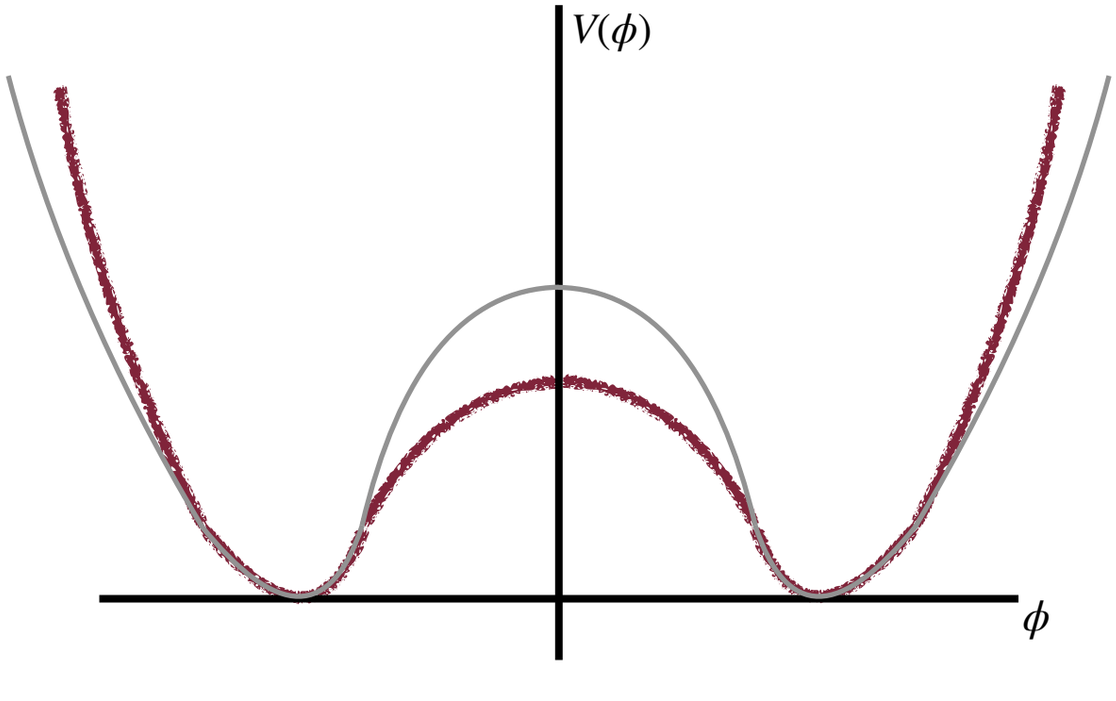

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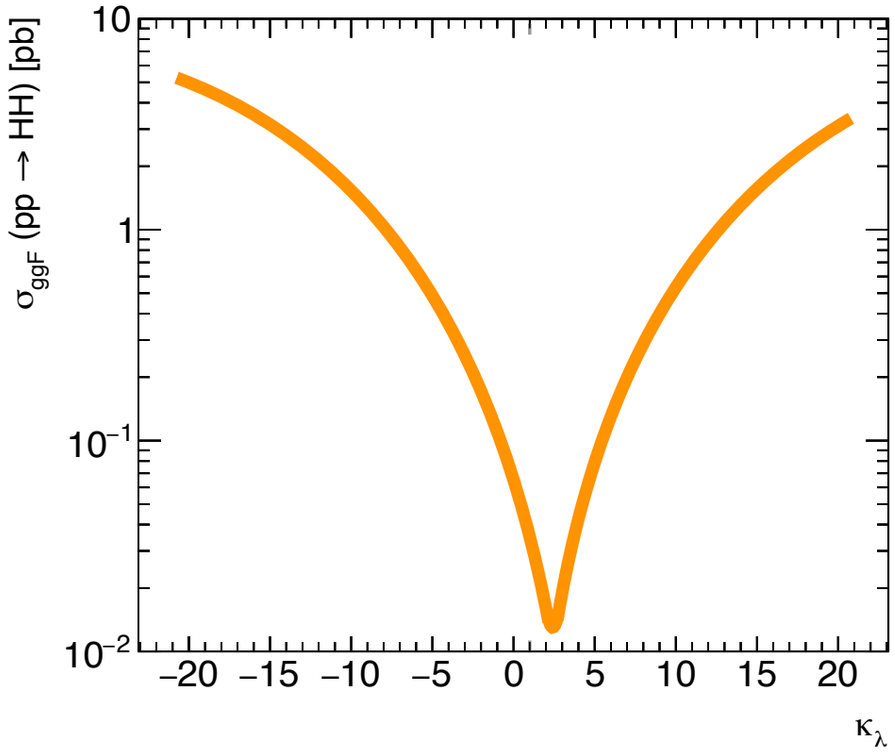

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Cross-section also depends on κ_λ: discoverable now!

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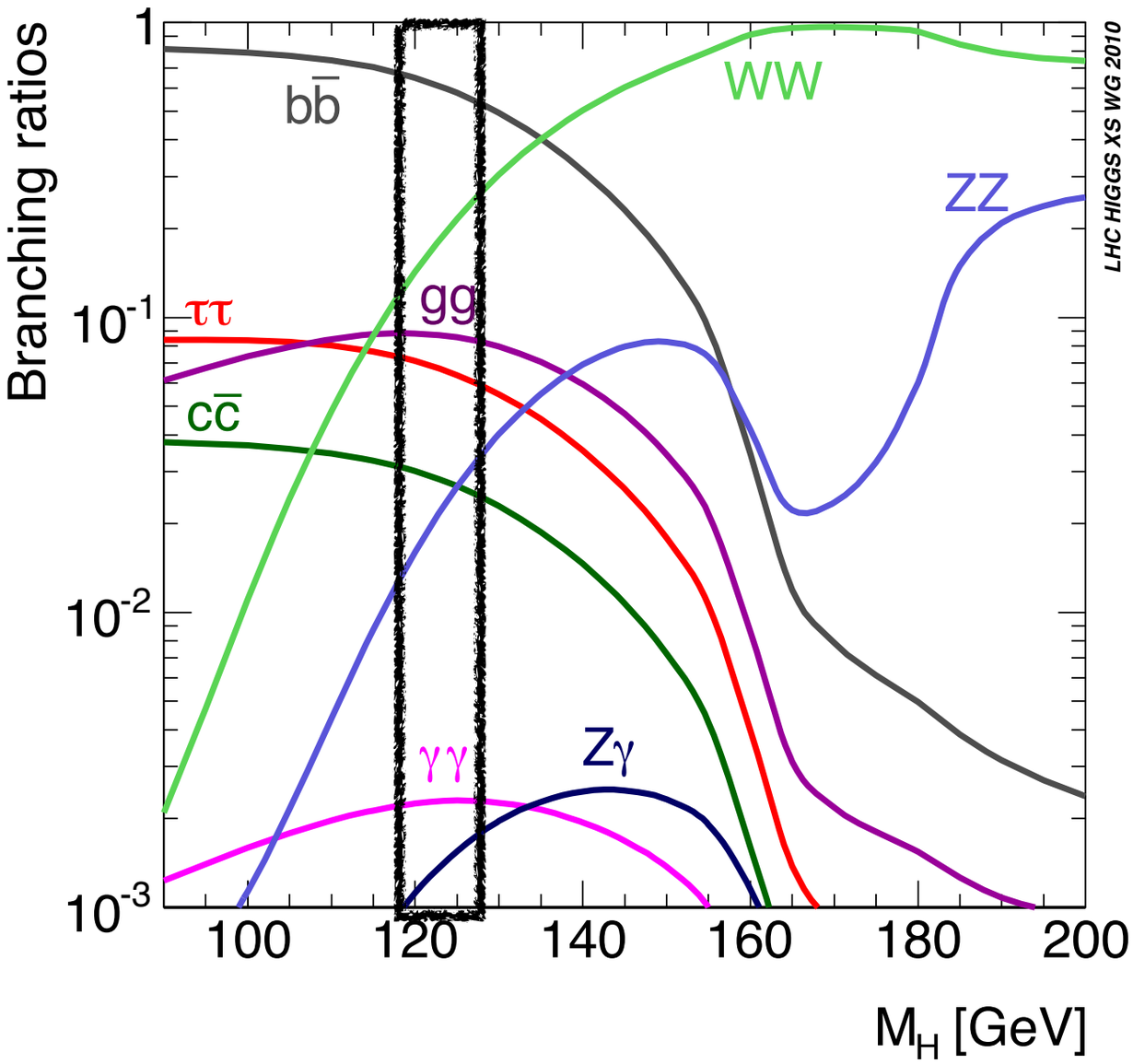
The Higgs decays instantly, to a range of particle types



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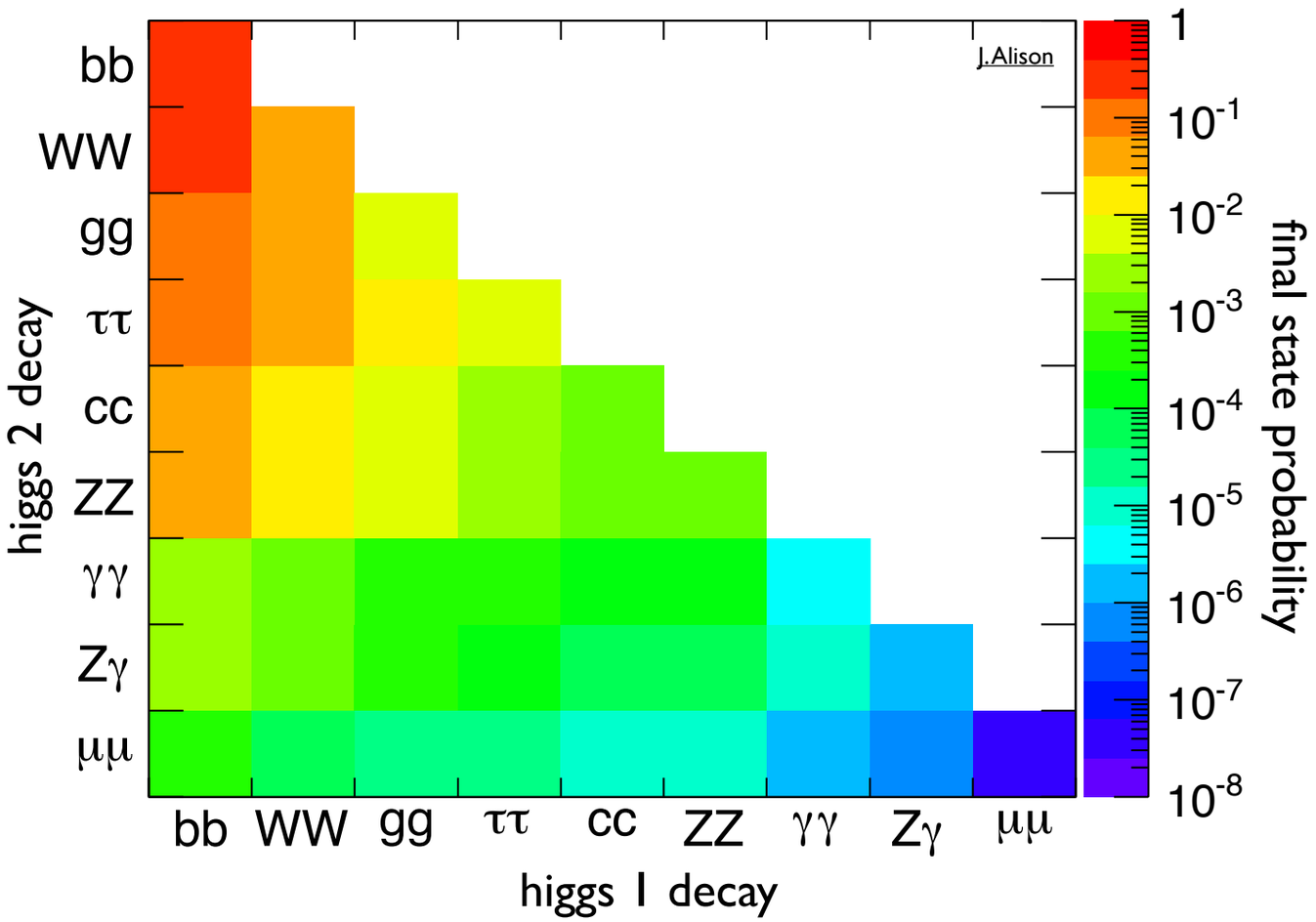

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Higgs pairs are rare, and have a hugely rich structure of final states

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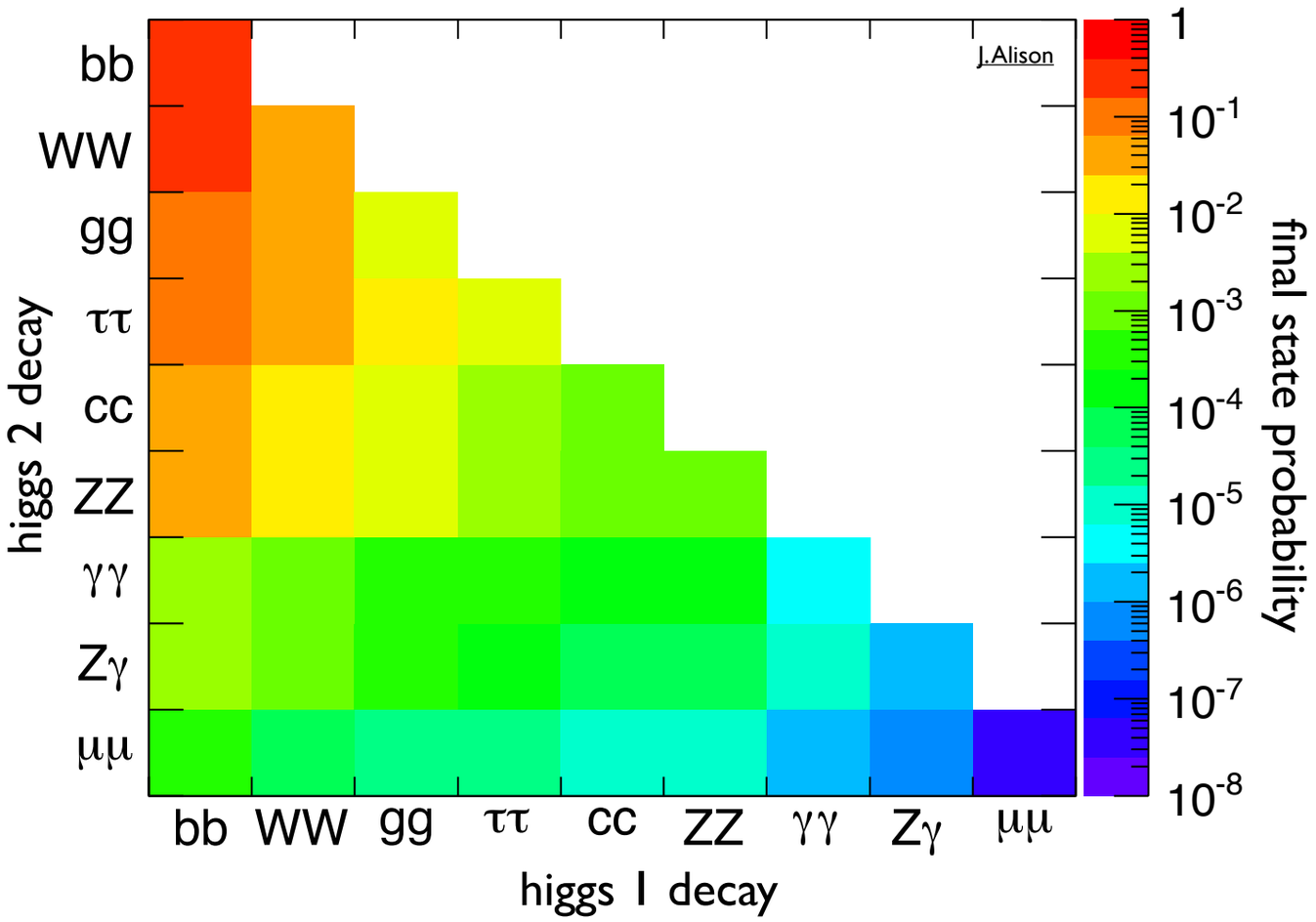

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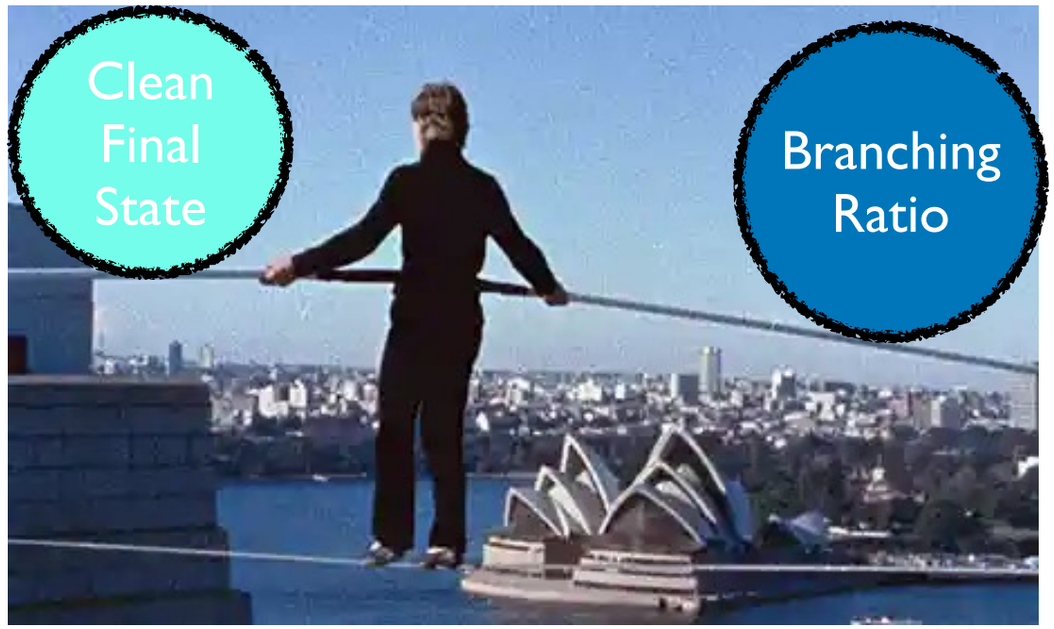

Man on Wire, Guardian

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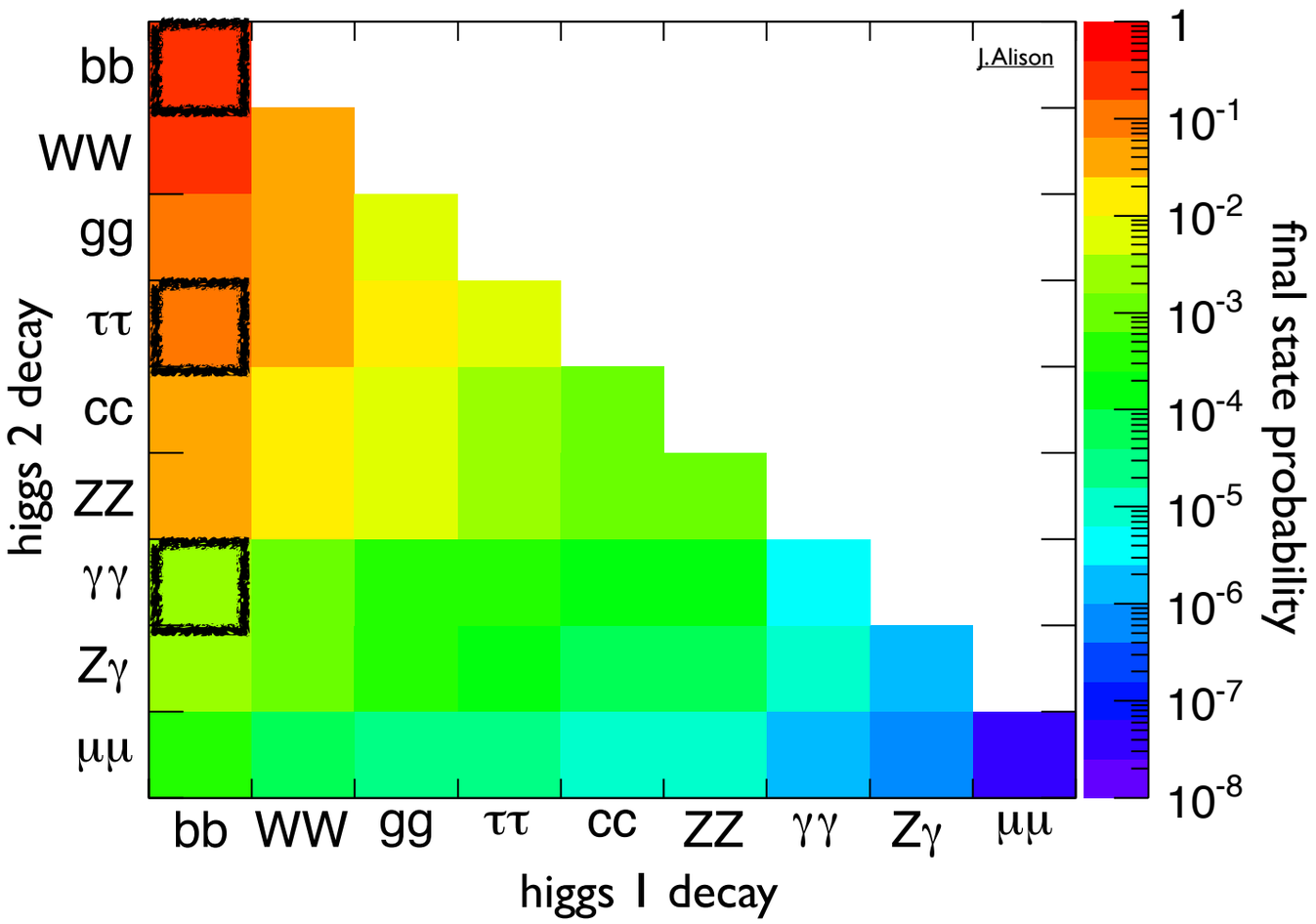

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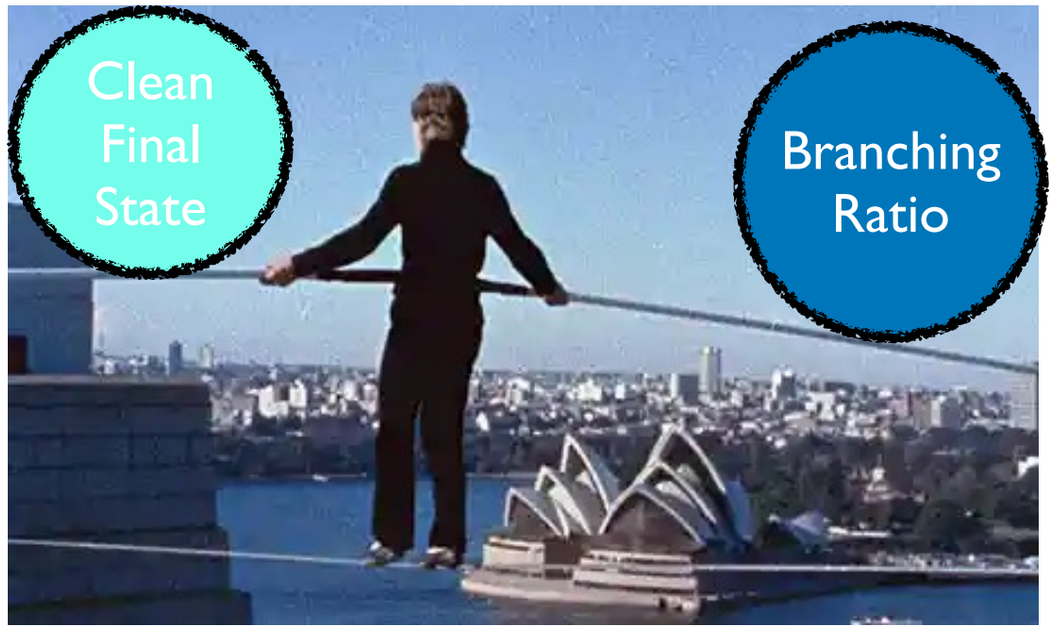

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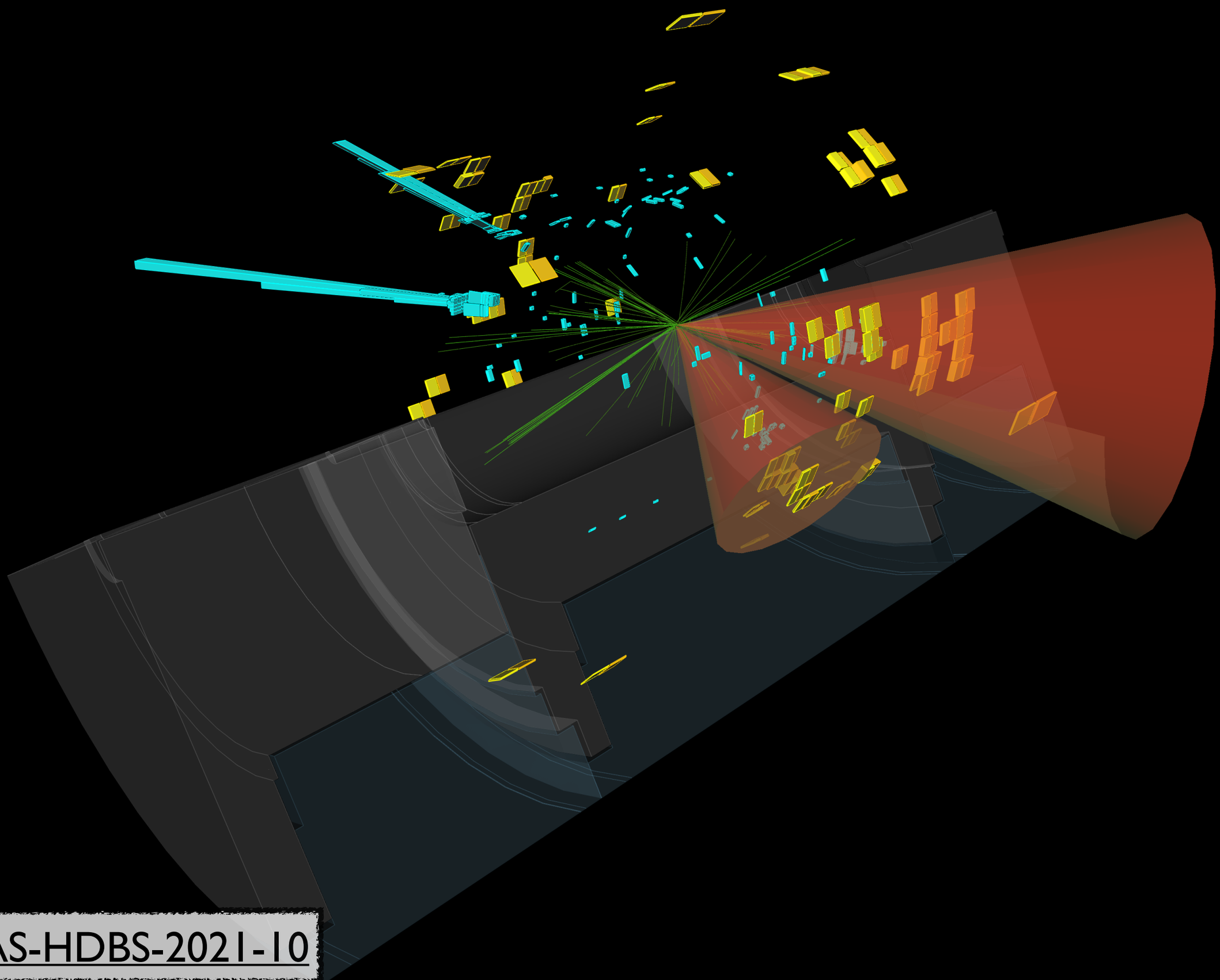
$4b$, $b\bar{b}\tau\bar{\tau}$, and $b\bar{b}\gamma\gamma$ are the most powerful

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

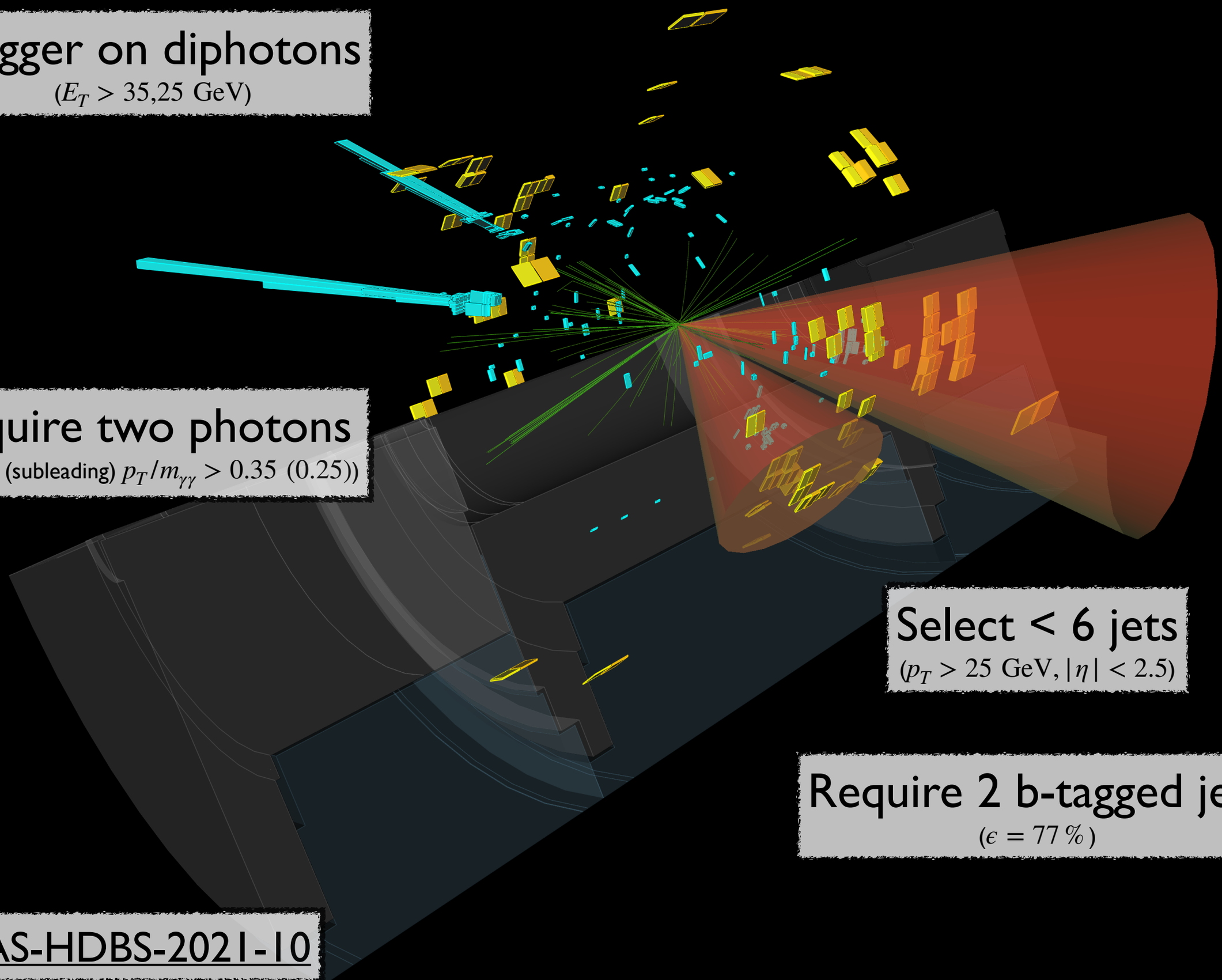


ATLAS-HDBS-2021-10

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

Trigger on diphotons

(E_T > 35,25 GeV)



Require two photons

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

Select < 6 jets

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

Require 2 b-tagged jets

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

ATLAS-HDBS-2021-10

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

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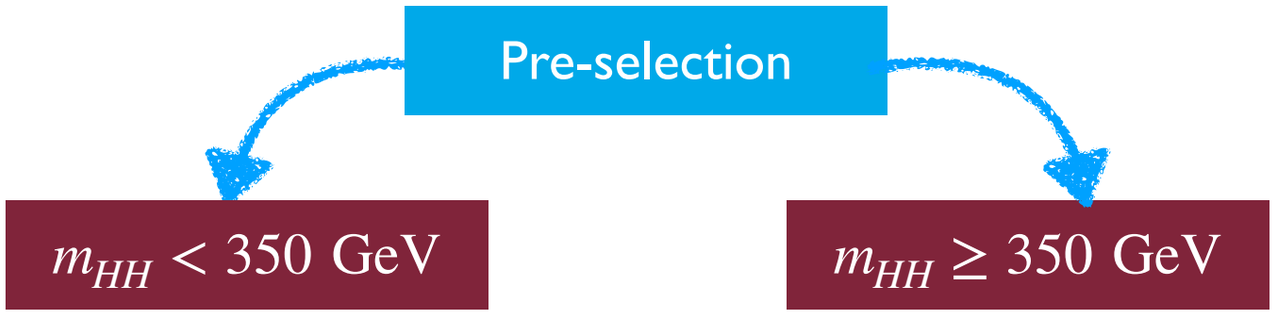

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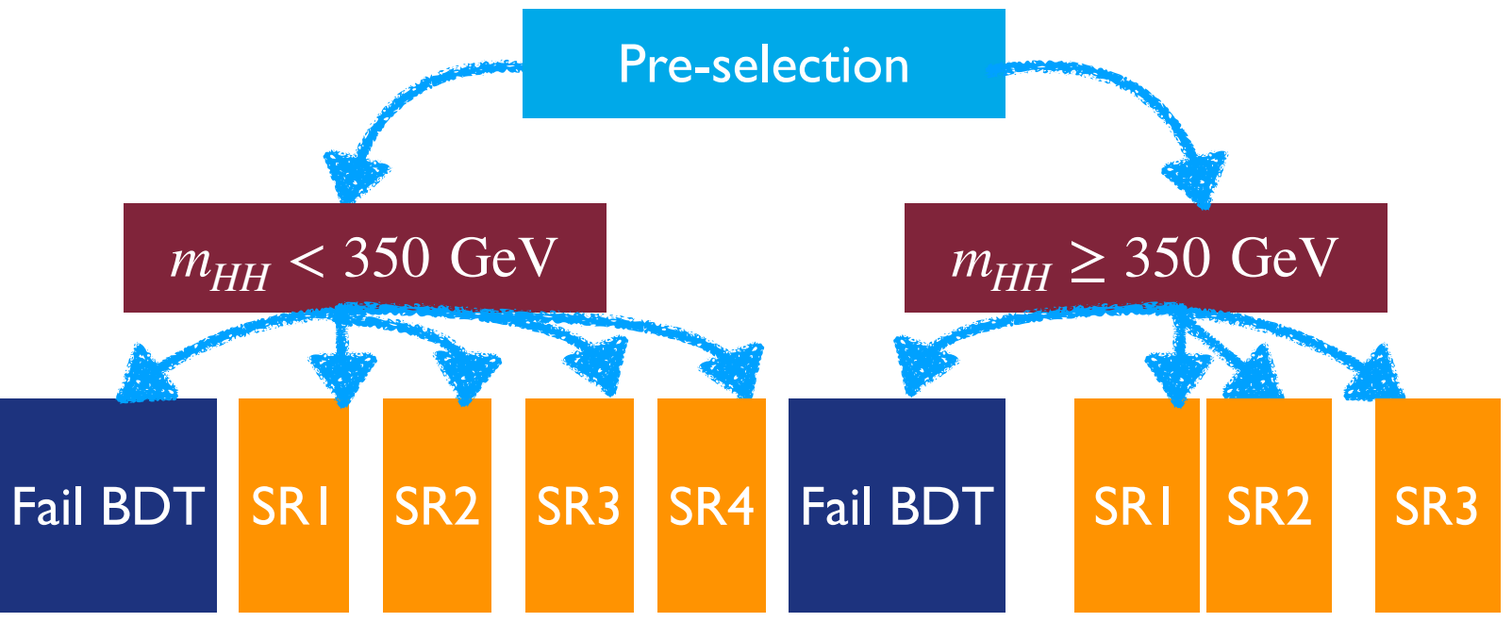

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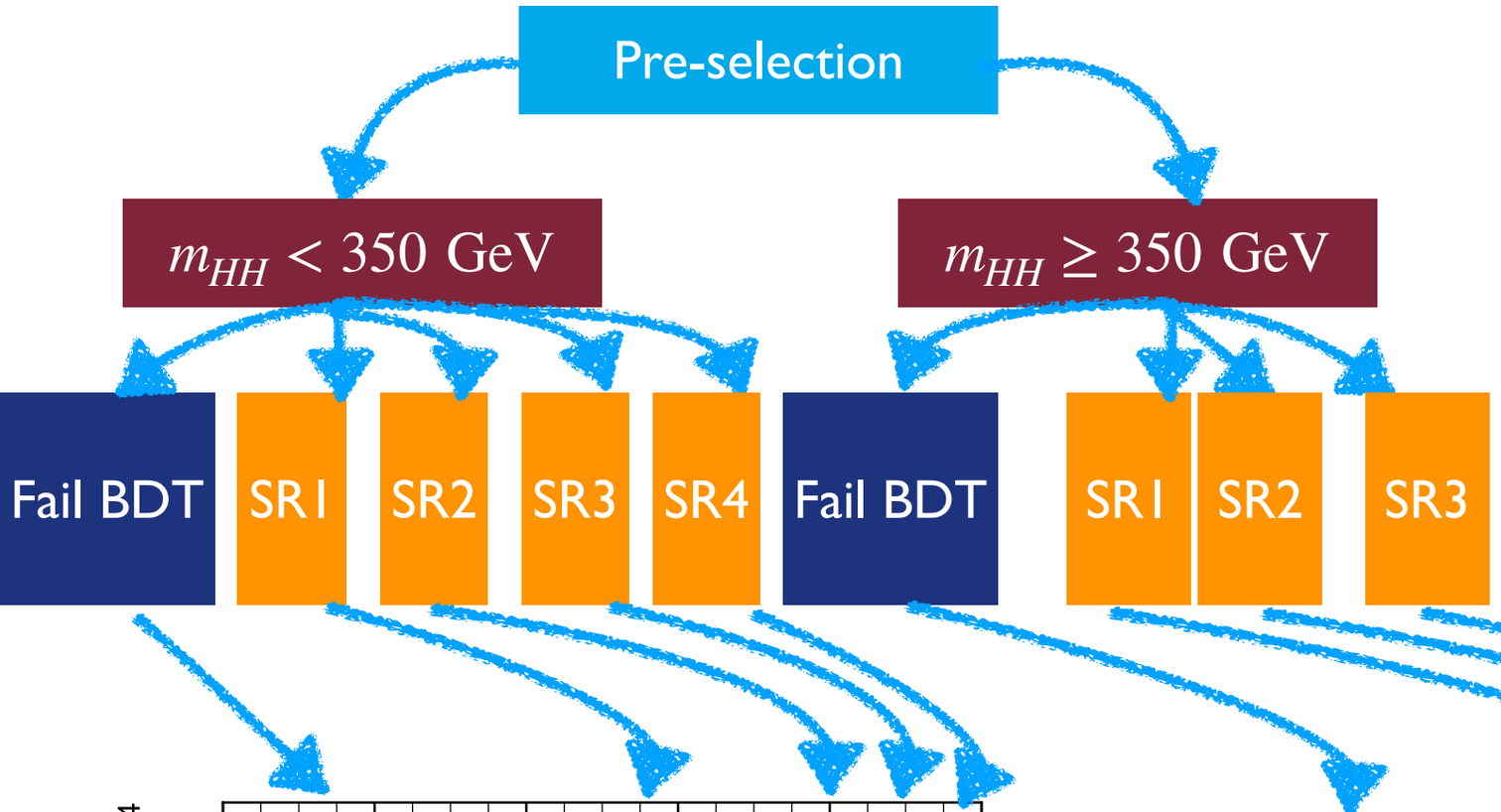

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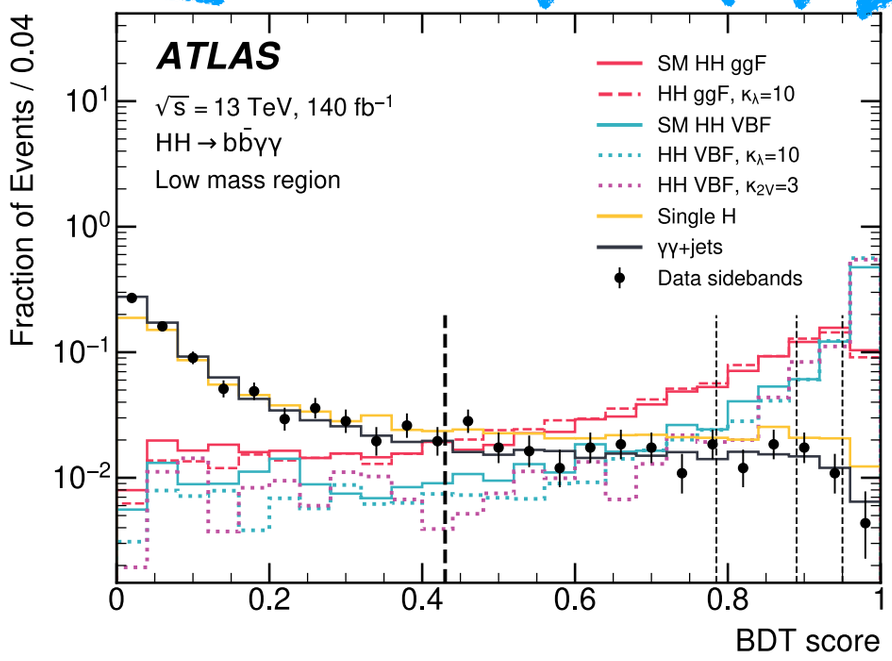

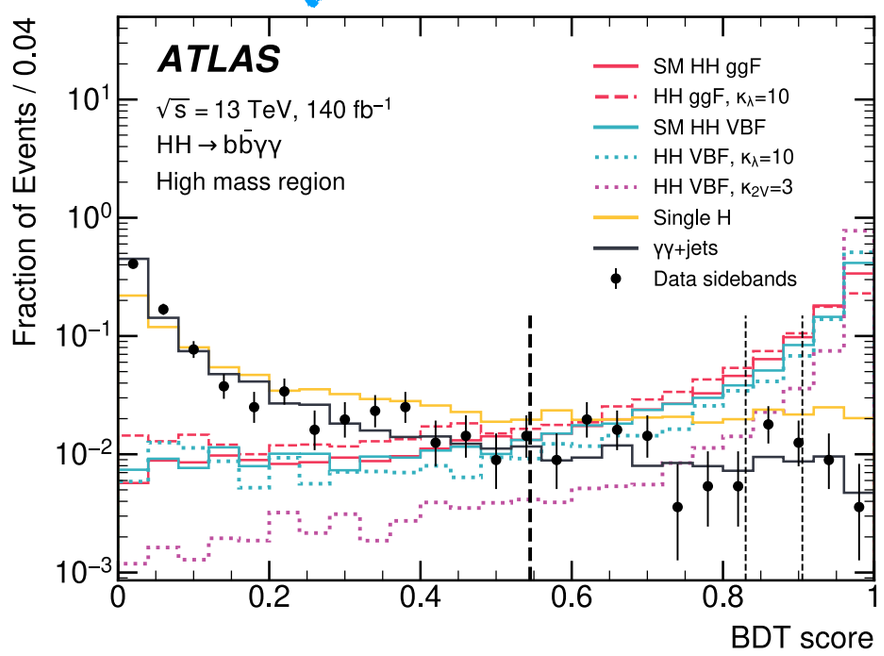

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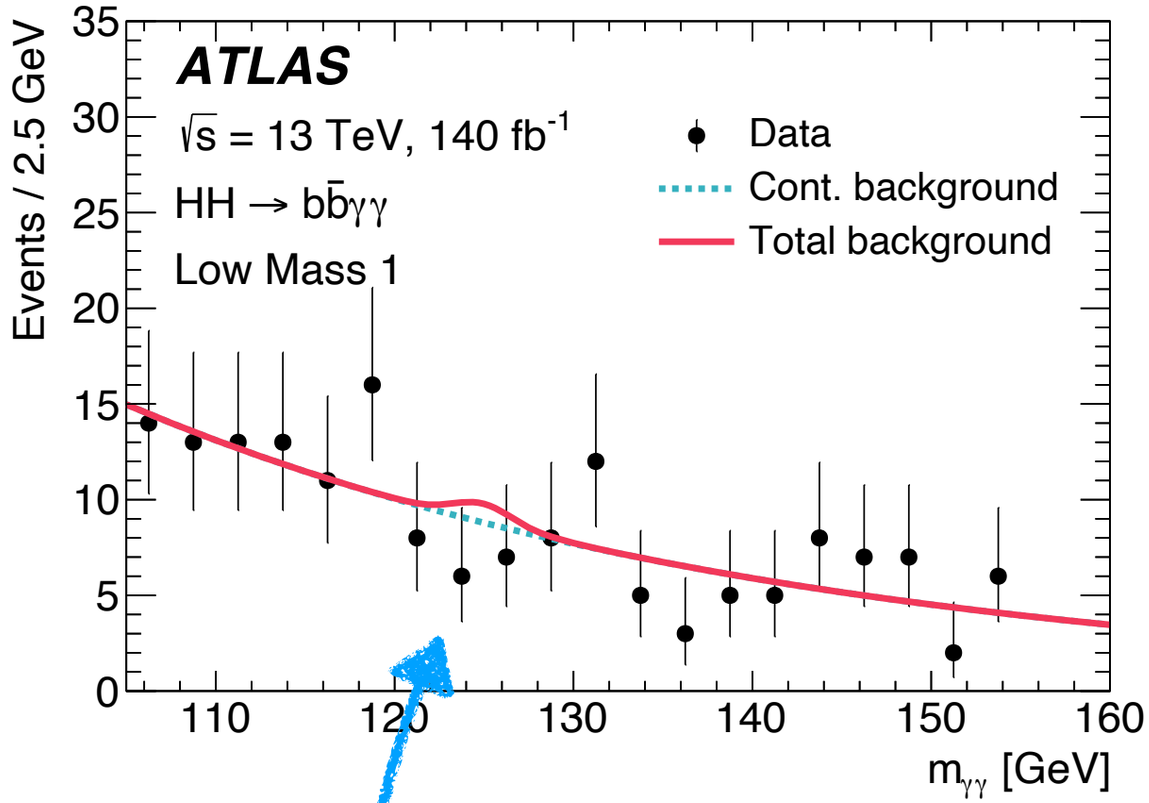

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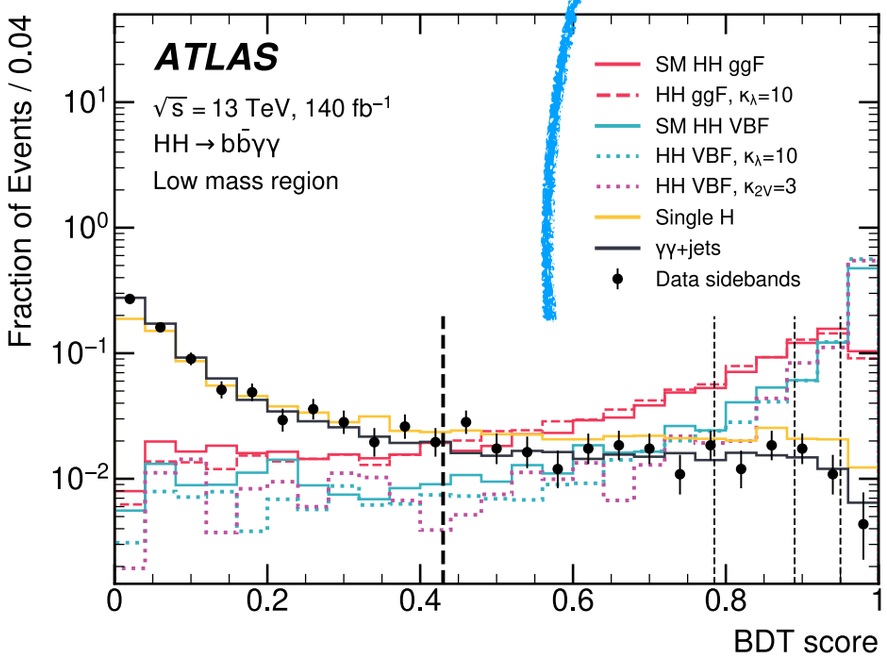
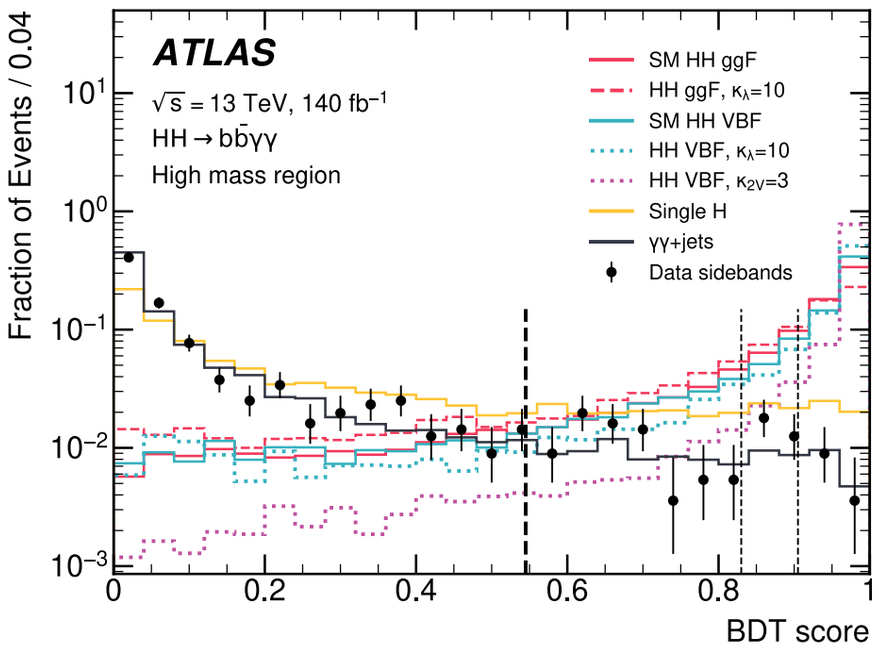
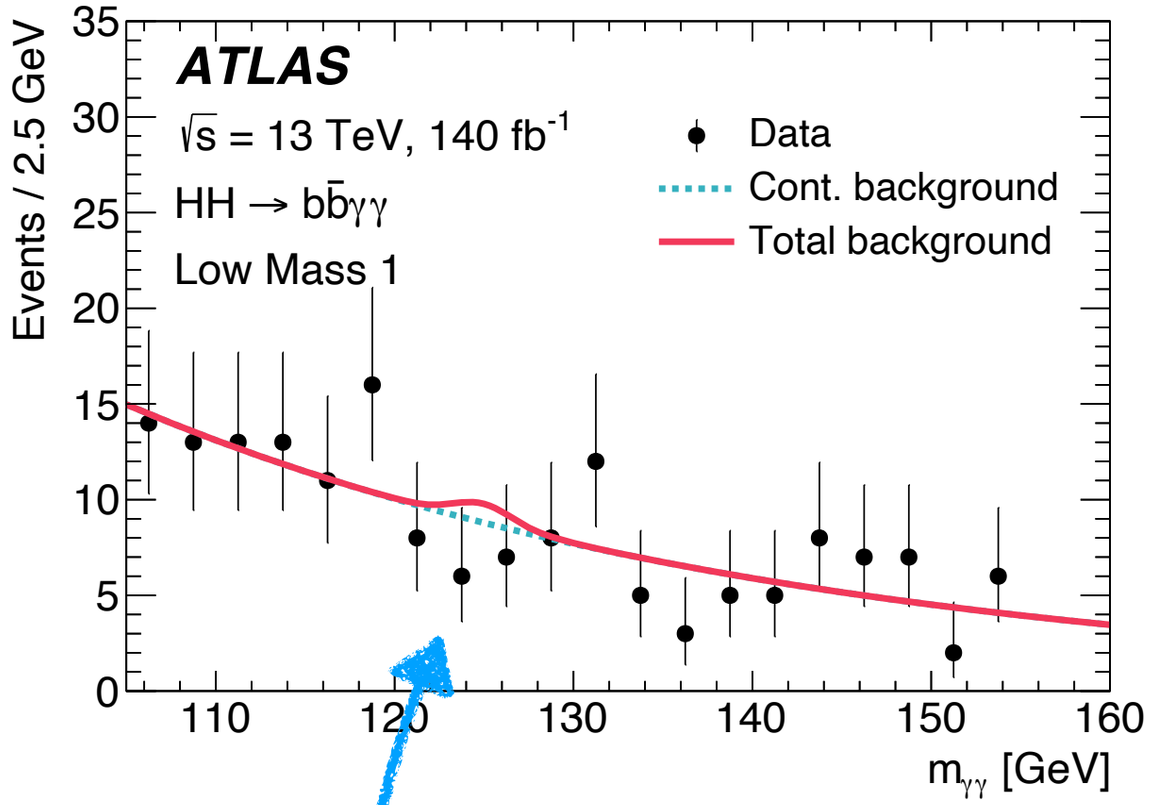




Fit $m_{\gamma\gamma}$ in 7 SR's simultaneously to extract signal

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



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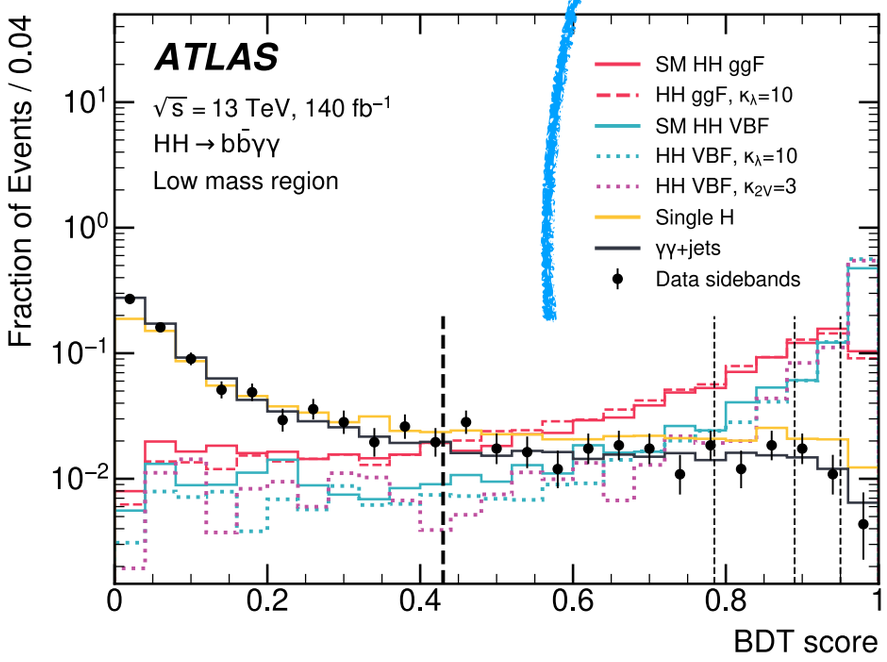
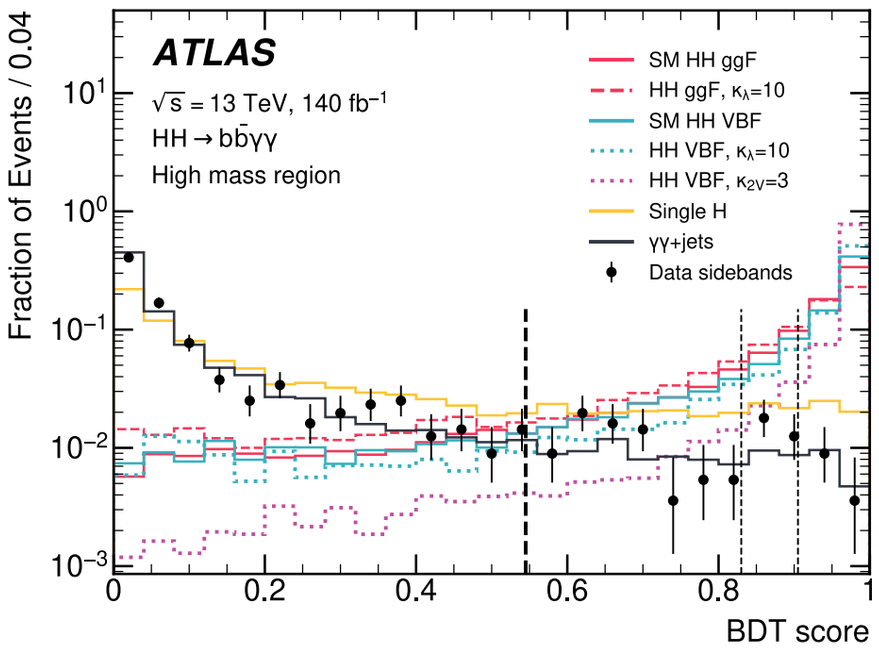
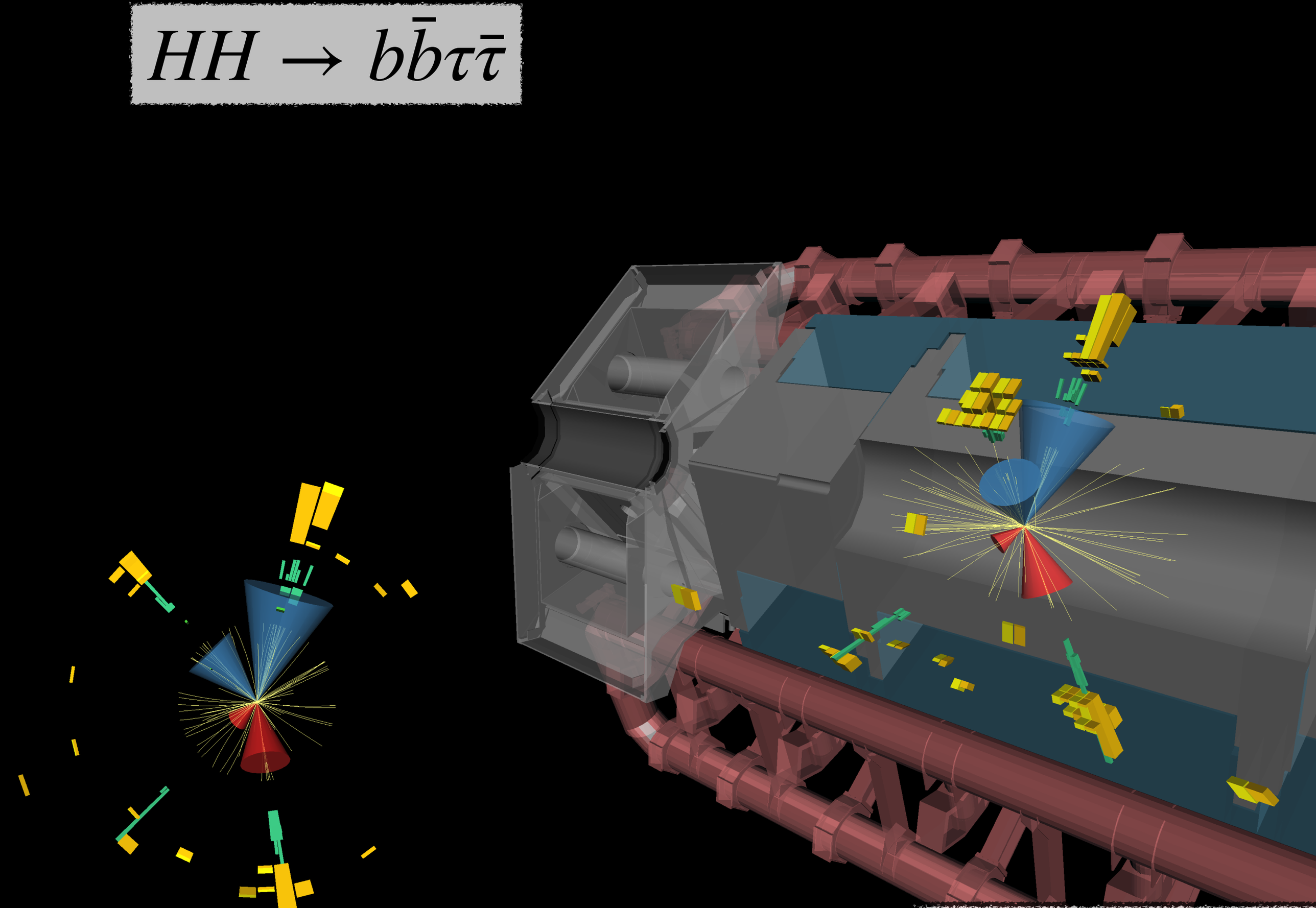




Fit $m_{\gamma\gamma}$ in 7 SR's simultaneously to extract signal

No signs of new physics

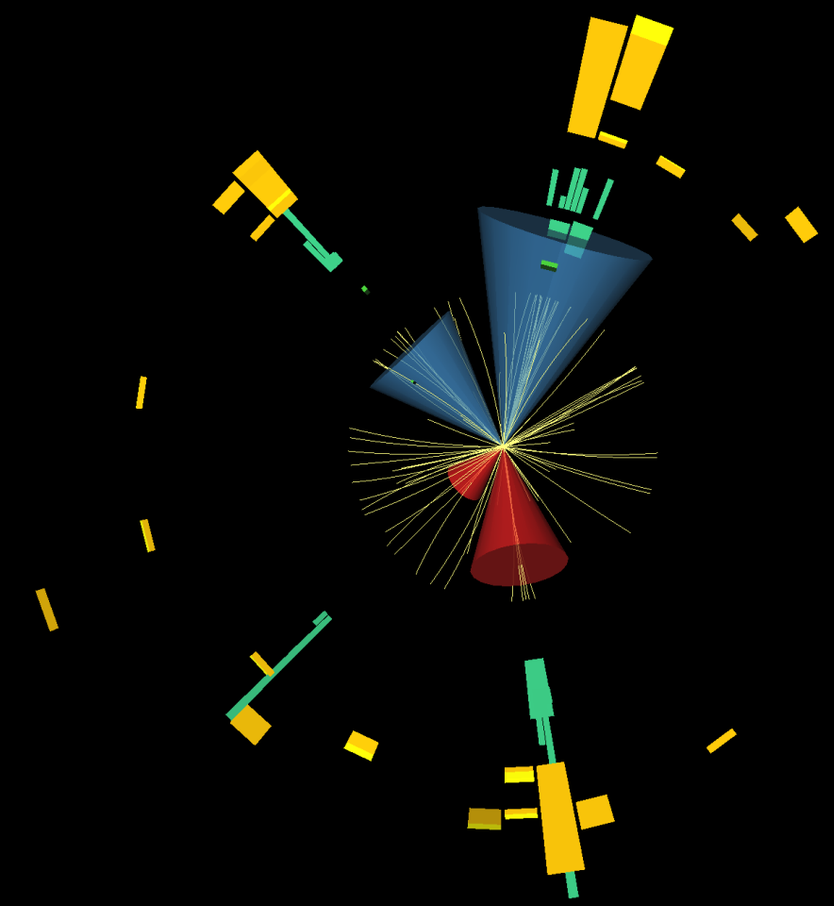
$HH \to b\bar{b}\tau\bar{\tau}$

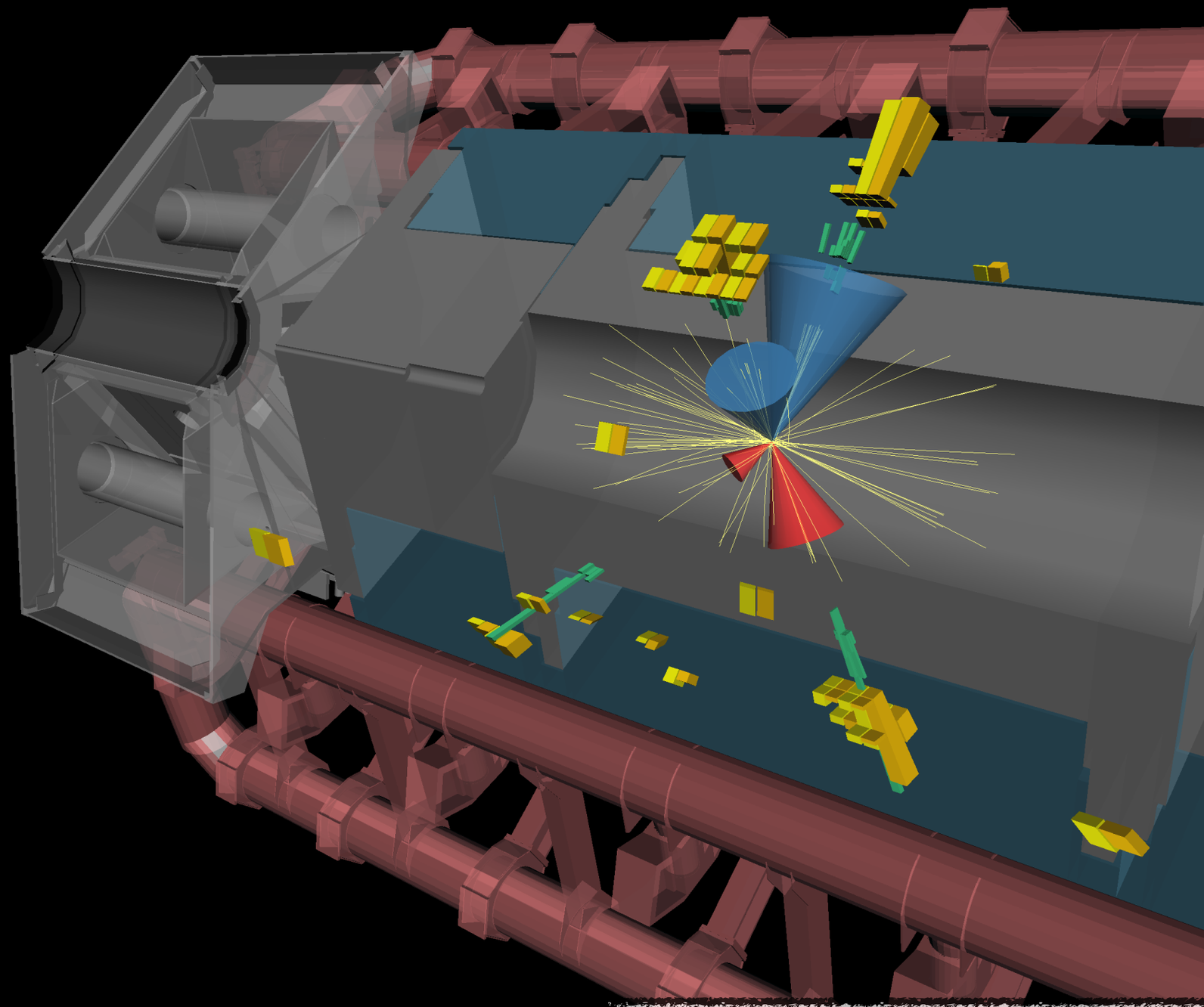


ATLAS-CONF-2023-071

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

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



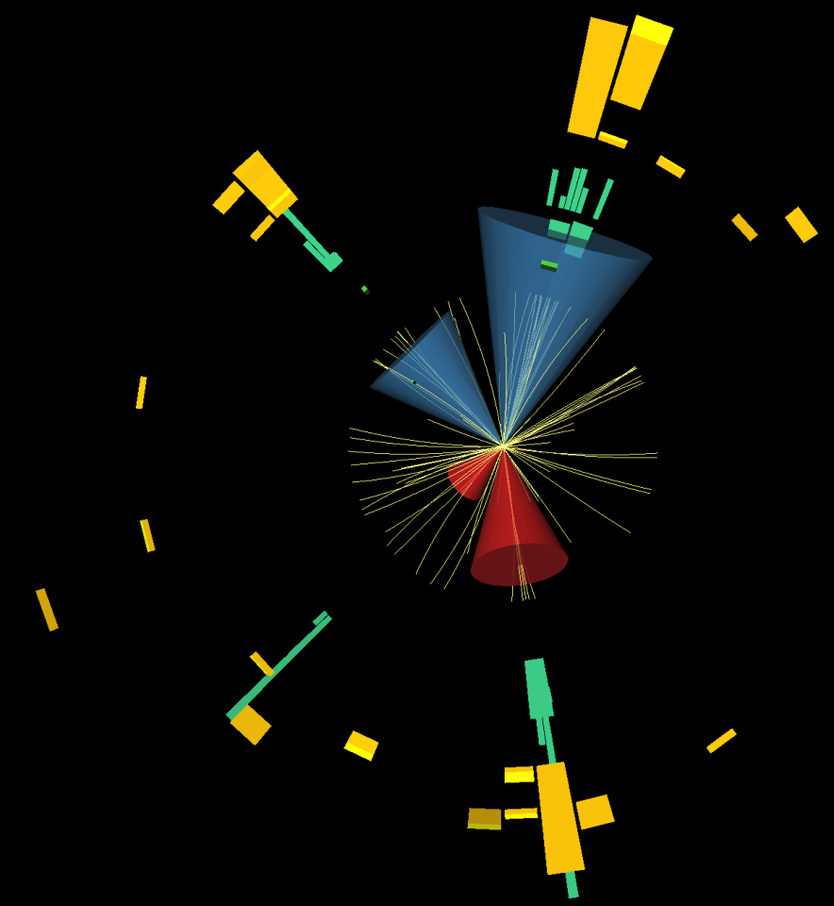


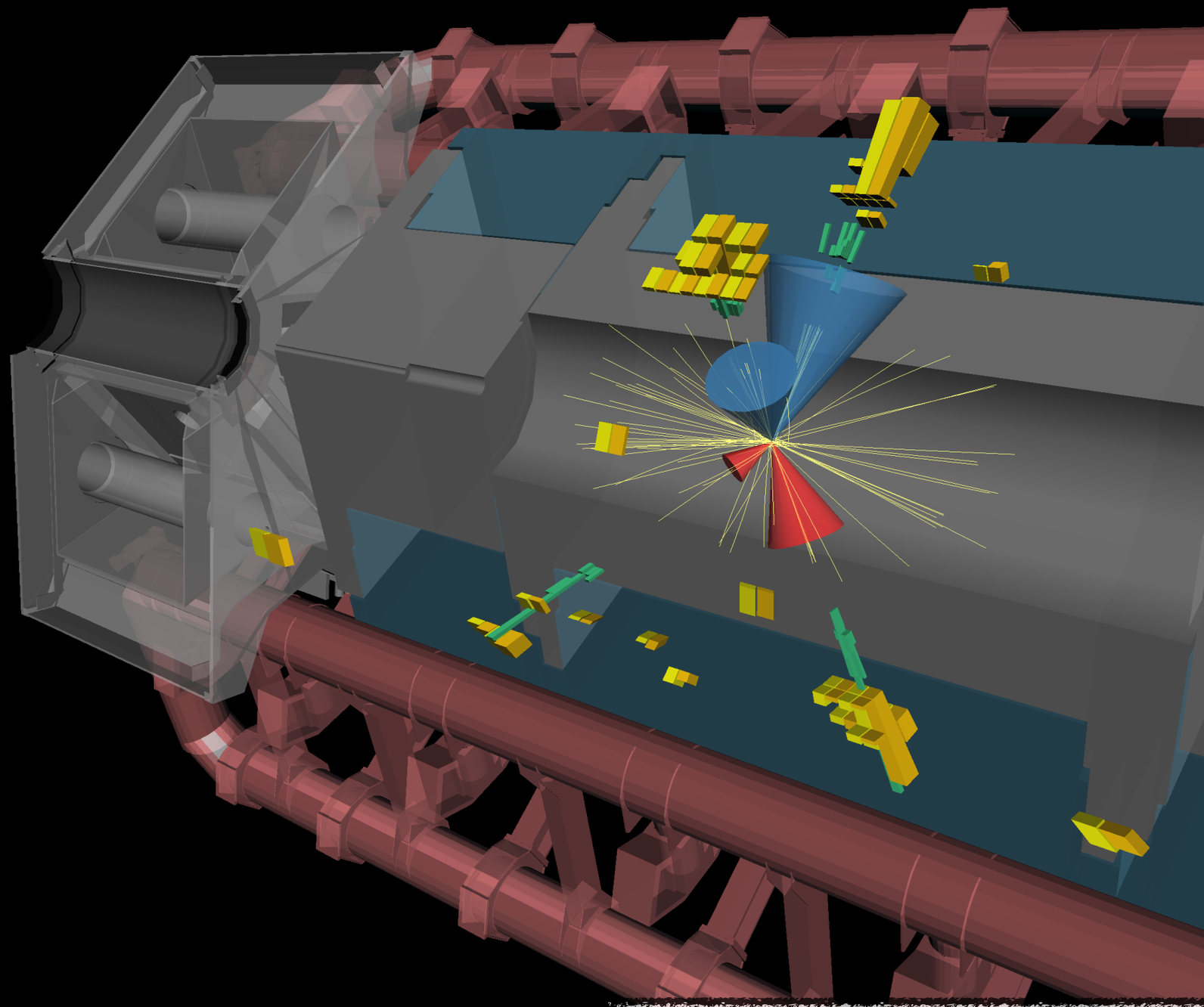
ATLAS-CONF-2023-071

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

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

τ_h, τ_ℓ = (hadronically, leptonically) decaying τ





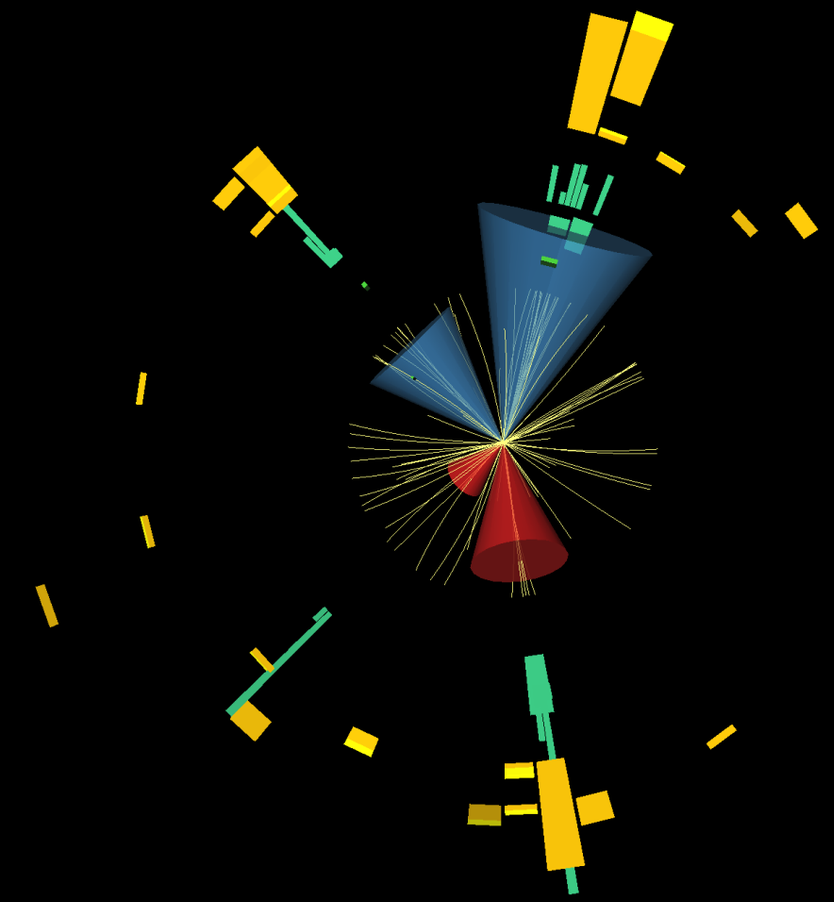
ATLAS-CONF-2023-071

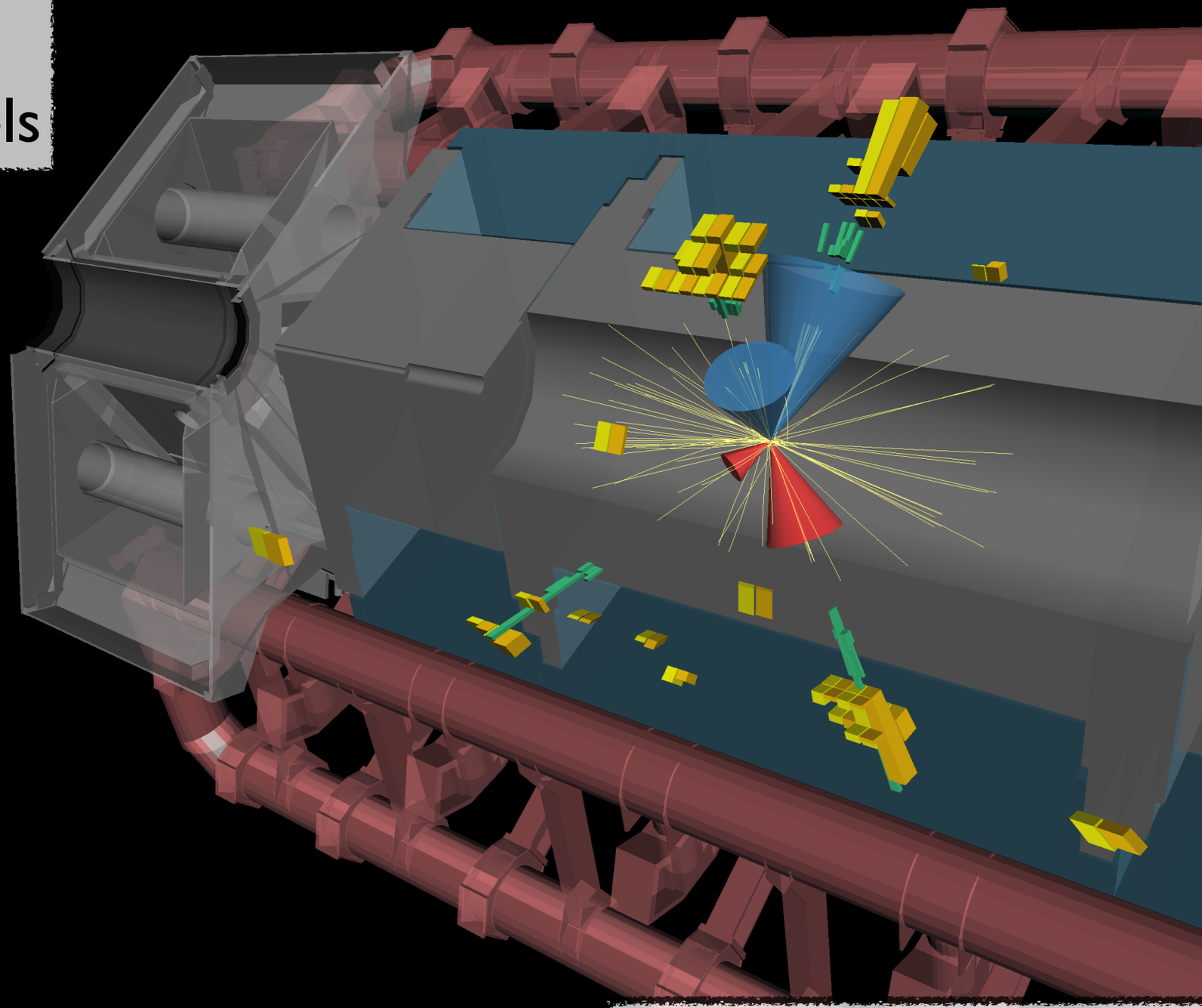
$HH \to b\bar{b}\tau\bar{\tau}$

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

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

τ_h, τ_ℓ = (hadronically, leptonically) decaying τ





ATLAS-CONF-2023-071

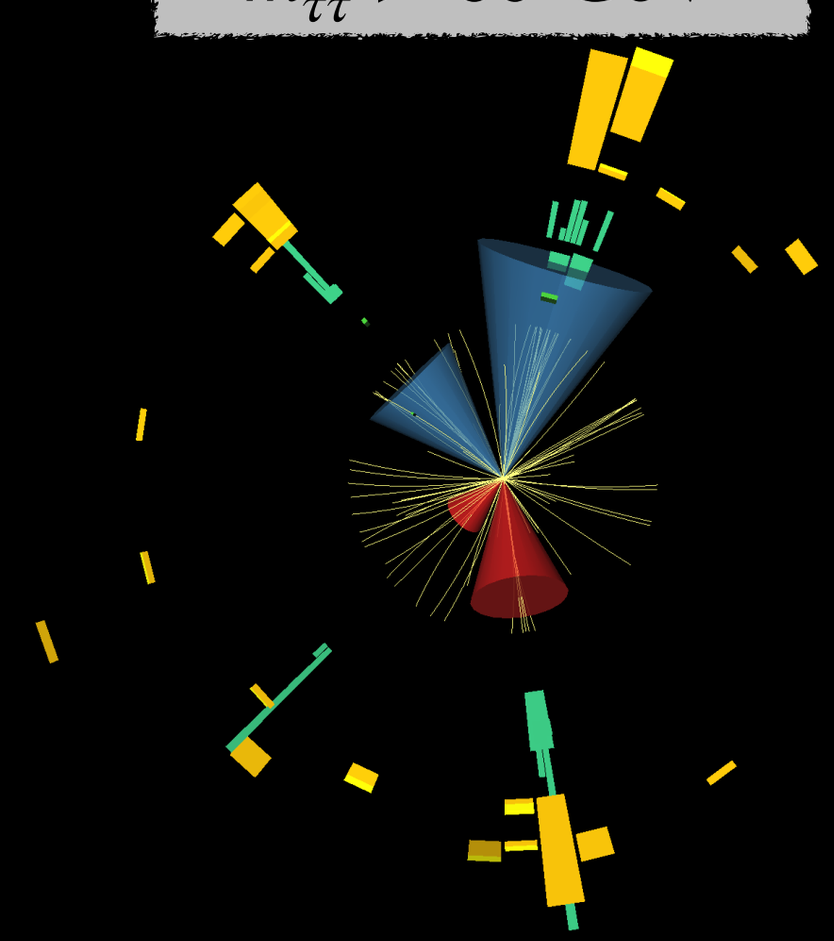
$HH \to b\bar{b}\tau\bar{\tau}$

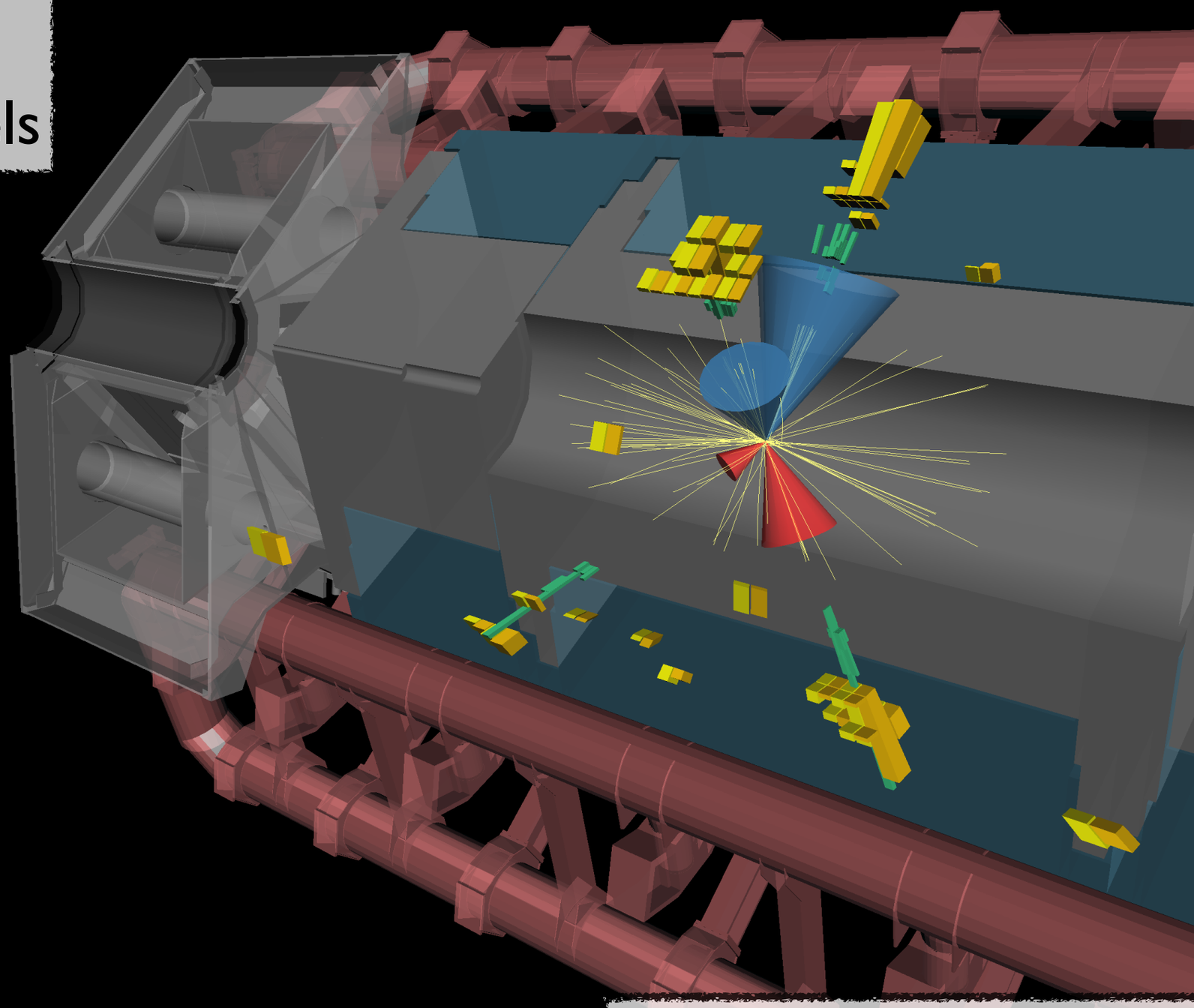
Separate into $\tau_h\tau_h$ and $\tau_\ell\tau_h$ channels

τ_h, τ_ℓ = (hadronically, leptonically) decaying τ

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

Require 1 or 2 τ_h: $m_{\tau\tau} > 60$ GeV





ATLAS-CONF-2023-071

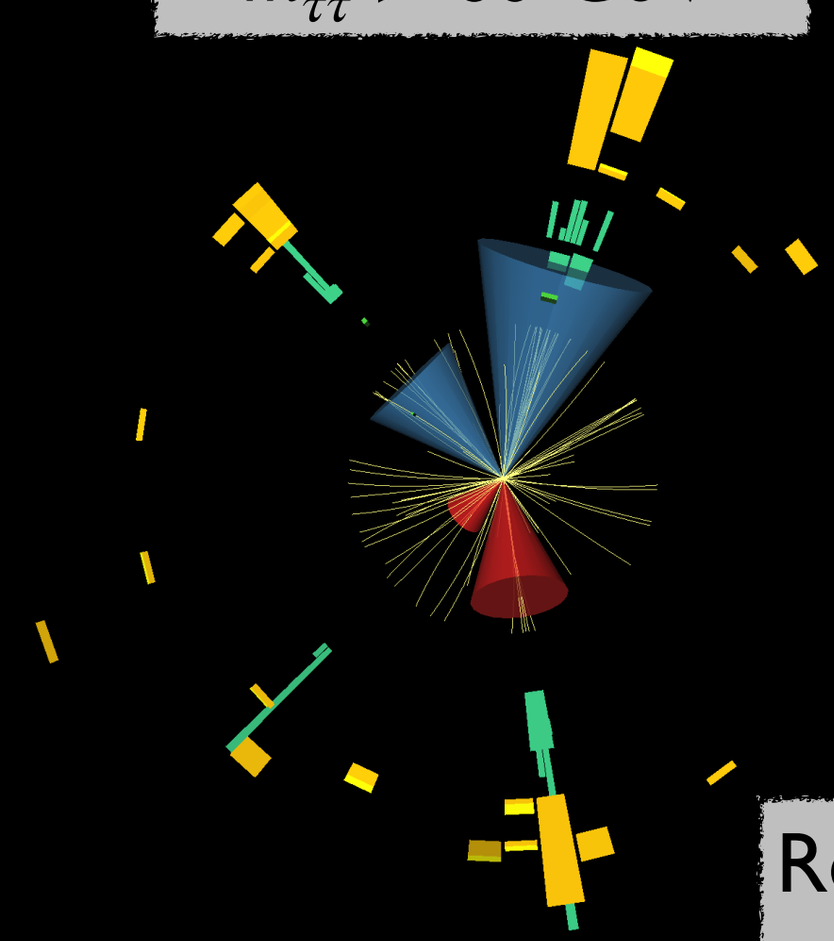
$HH \to b\bar{b}\tau\bar{\tau}$

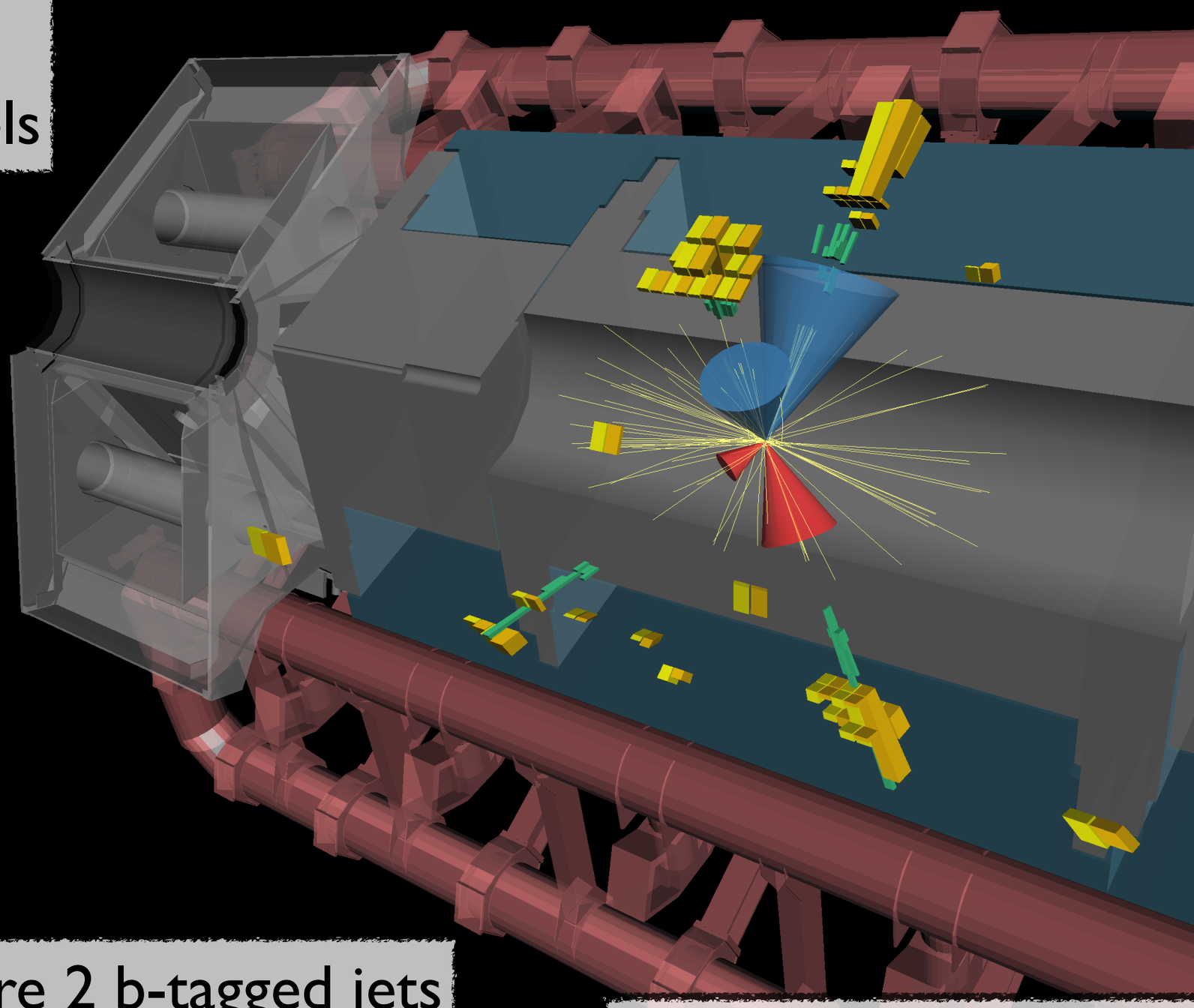
Separate into $\tau_h\tau_h$ and $\tau_\ell\tau_h$ channels

τ_h, τ_ℓ = (hadronically, leptonically) decaying τ

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

Require 1 or 2 τ_h: $m_{\tau\tau} > 60$ GeV





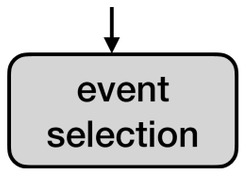
Require 2 b-tagged jets

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

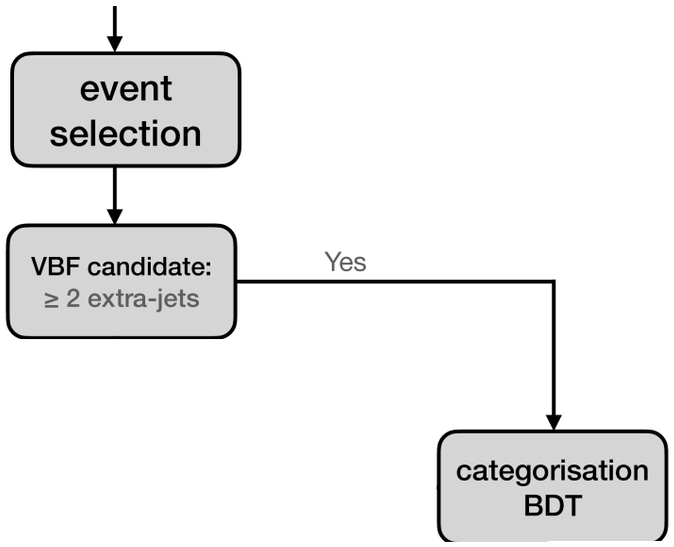
ATLAS-CONF-2023-071

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

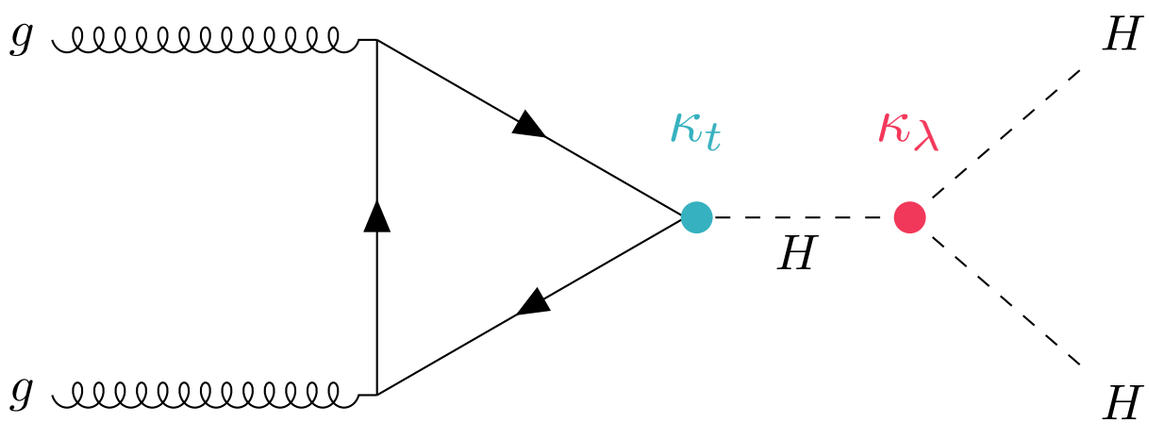
$b\bar{b}\tau\bar{\tau}$ Strategy

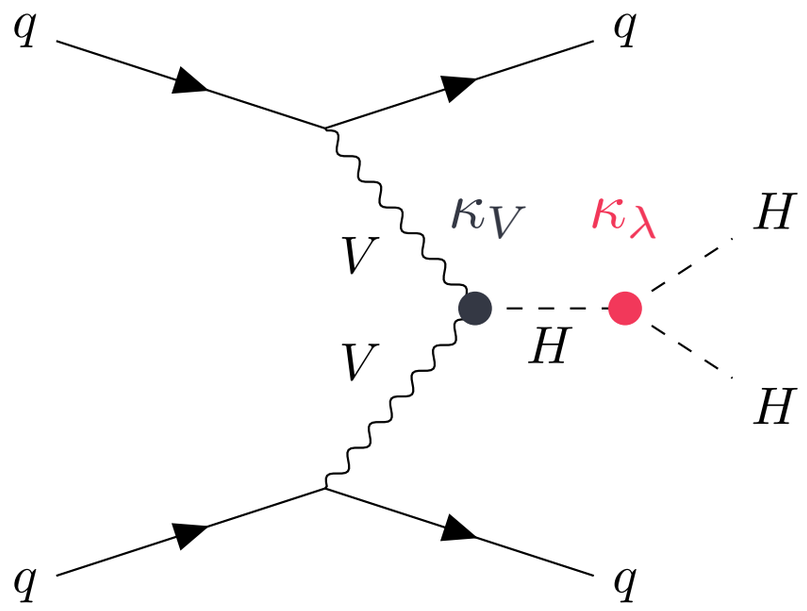


$b\bar{b}\tau\bar{\tau}$ Strategy

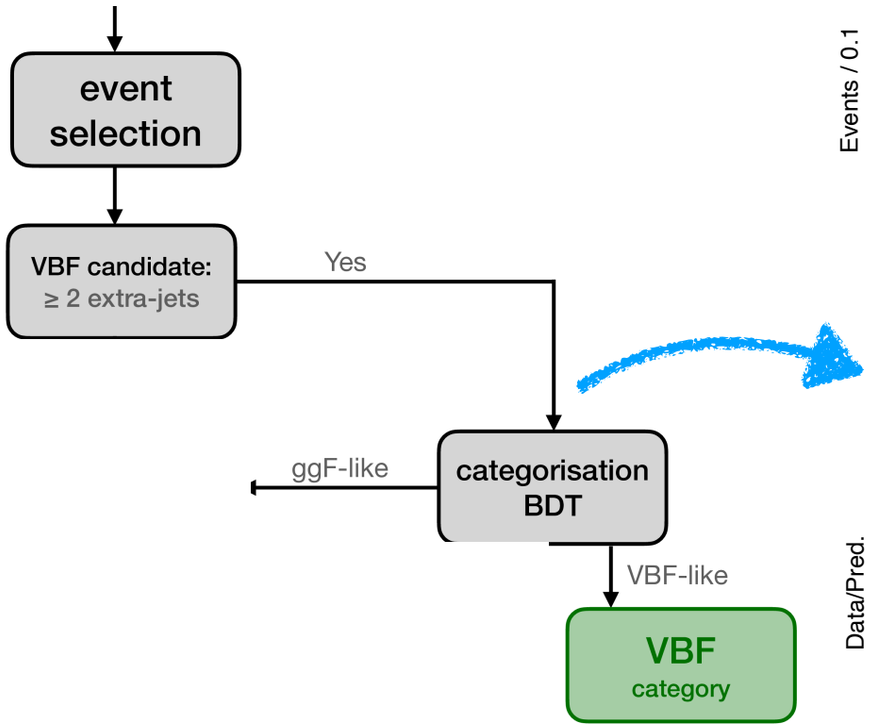


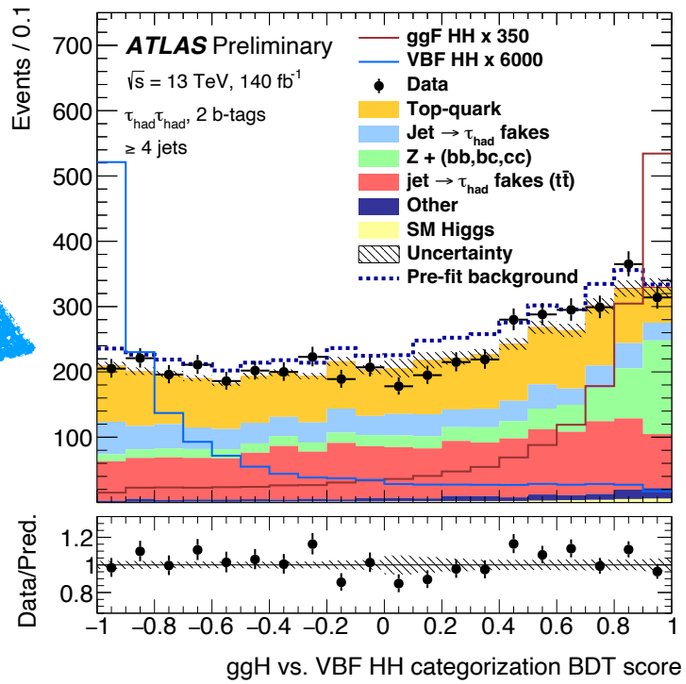
Categorize events by Higgs production: ggF or VBF



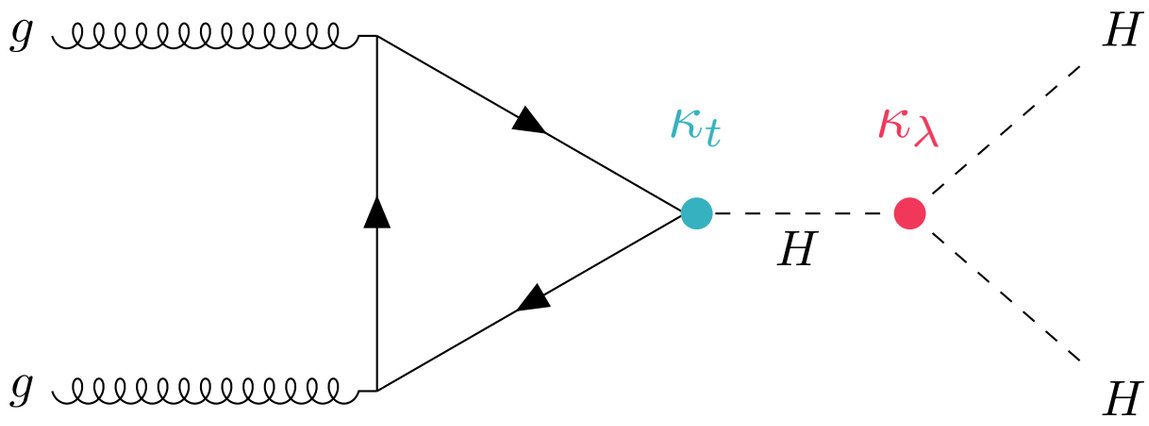


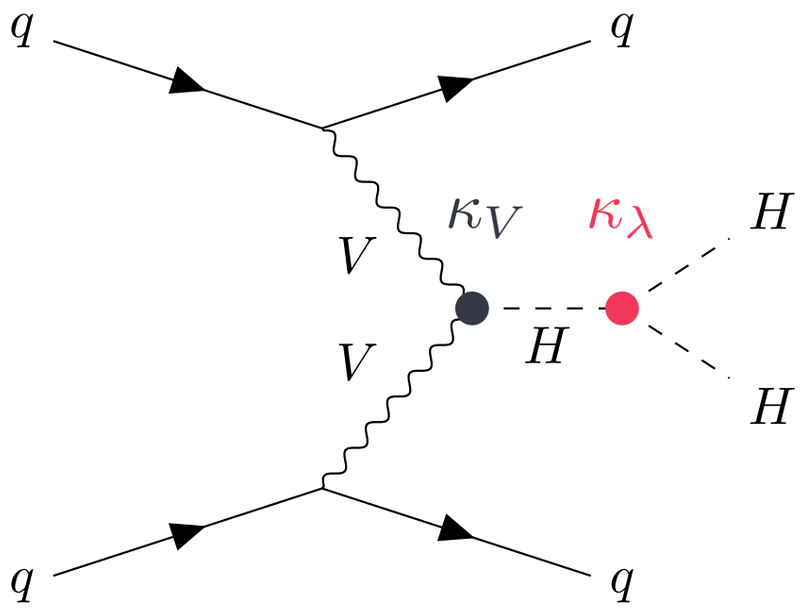
$b\bar{b}\tau\bar{\tau}$ Strategy



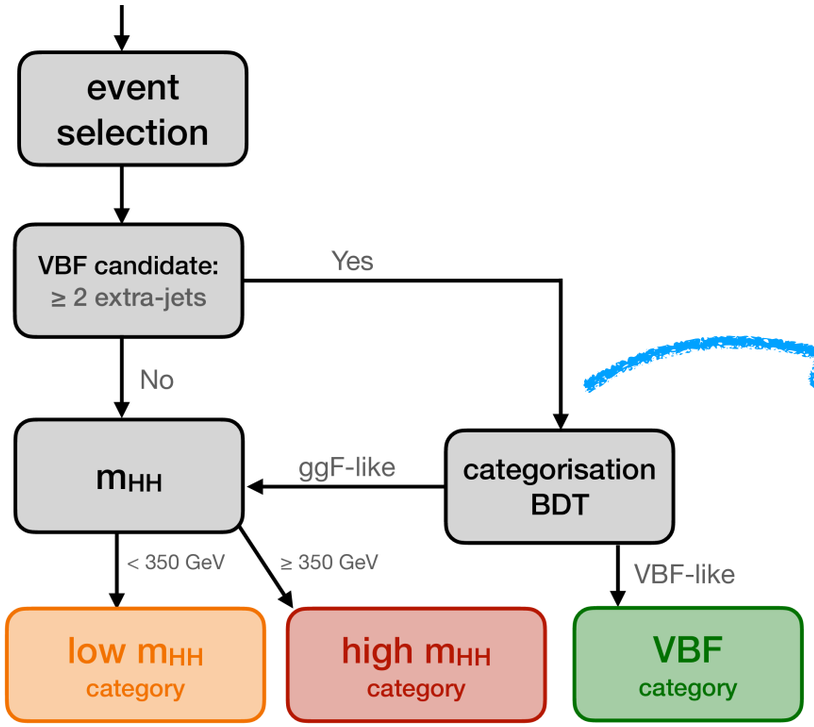


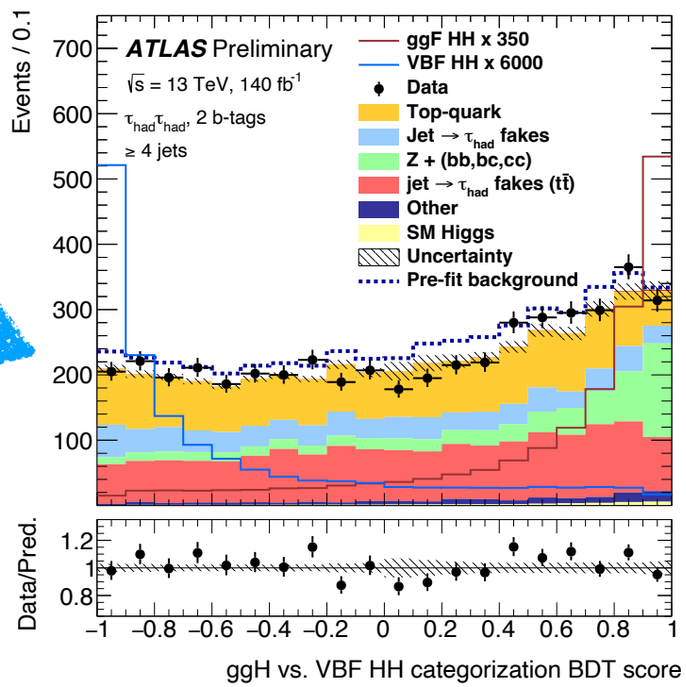
Categorize events by Higgs production: ggF or VBF





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

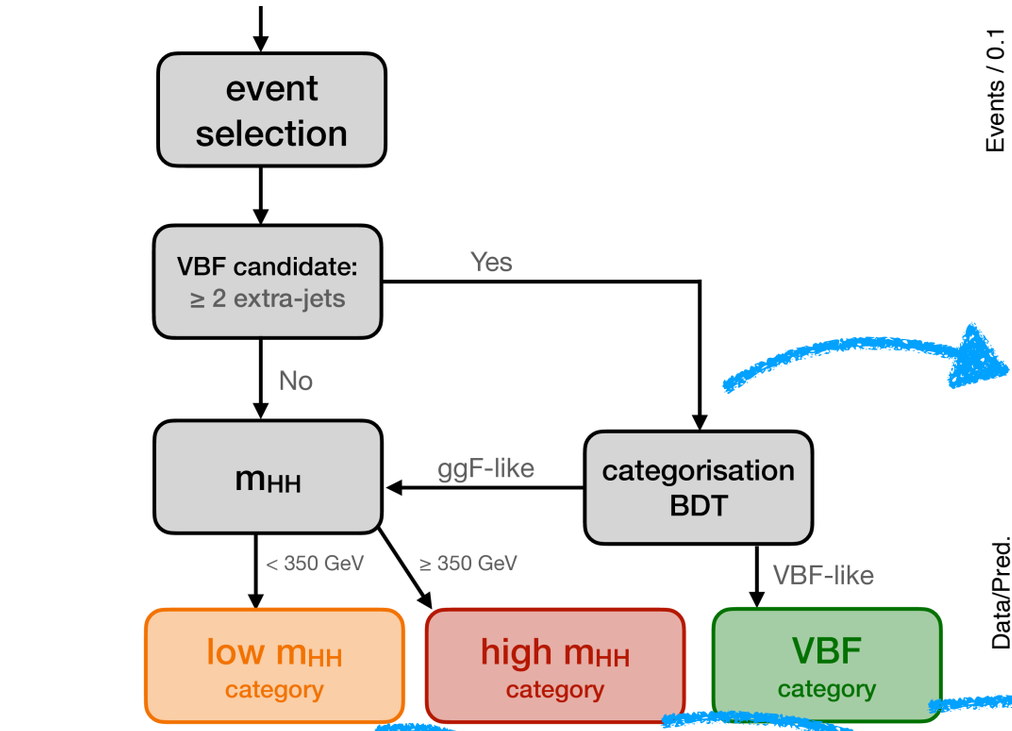


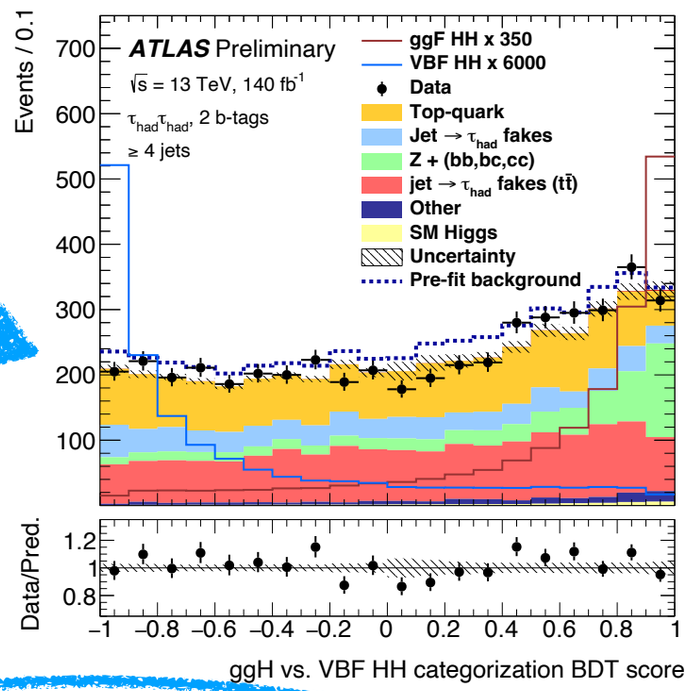


Categorize events by Higgs production: ggF or VBF

Split ggF by m_{HH}

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

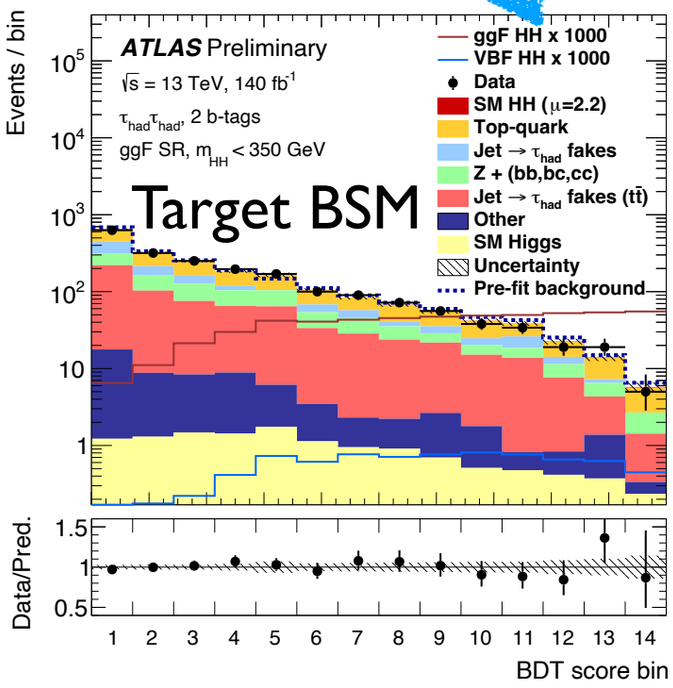


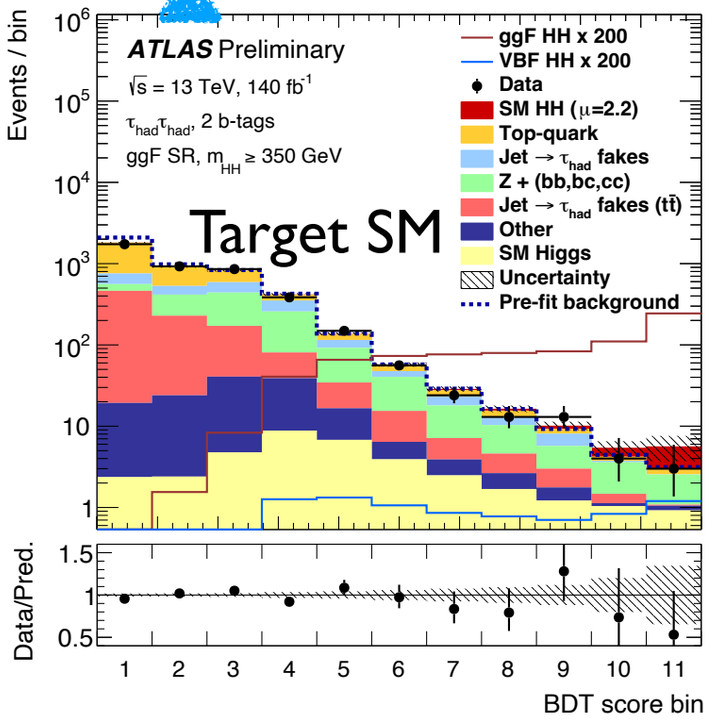


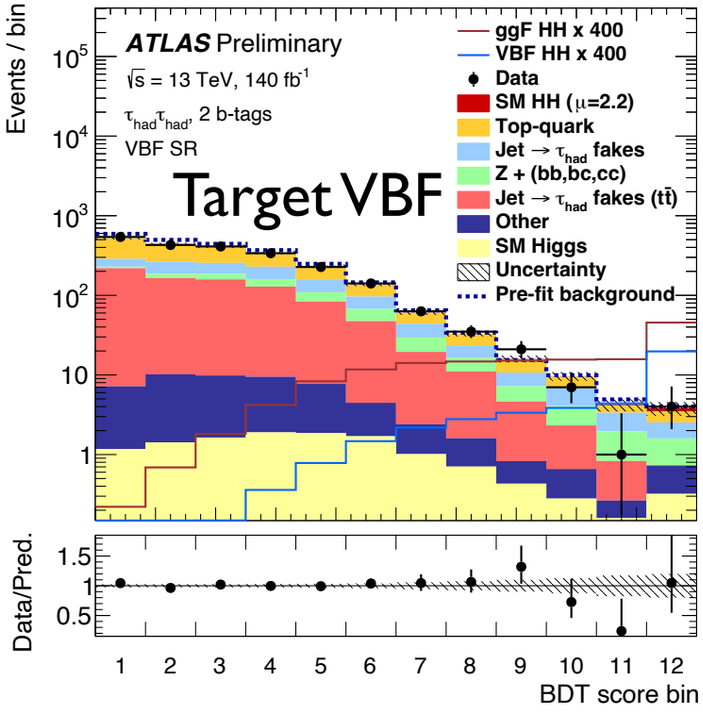
Categorize events by Higgs production: ggF or VBF

Split ggF by m_{HH}

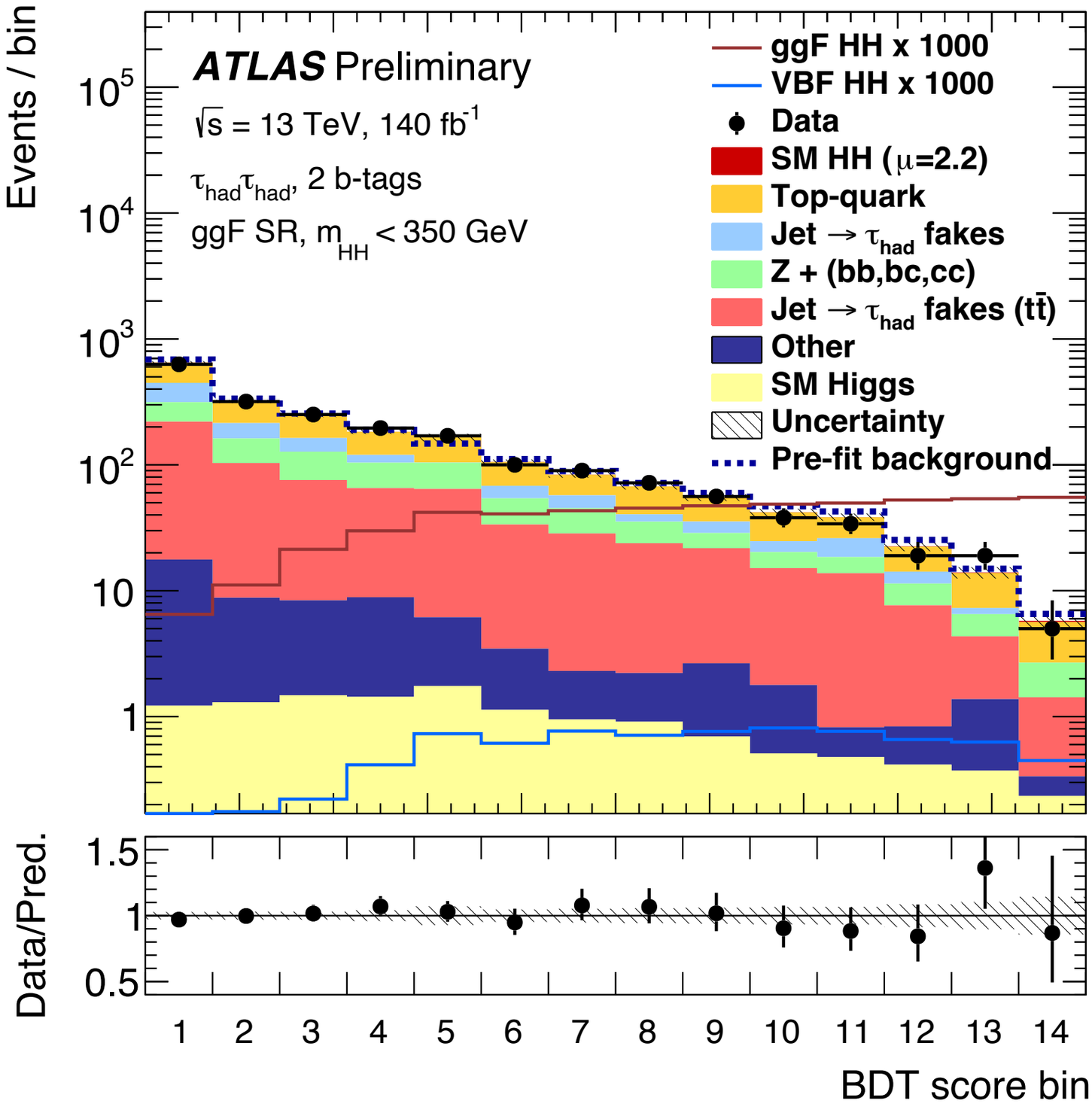
Train BDT in each SR







$bb\tau\tau$ Strategy



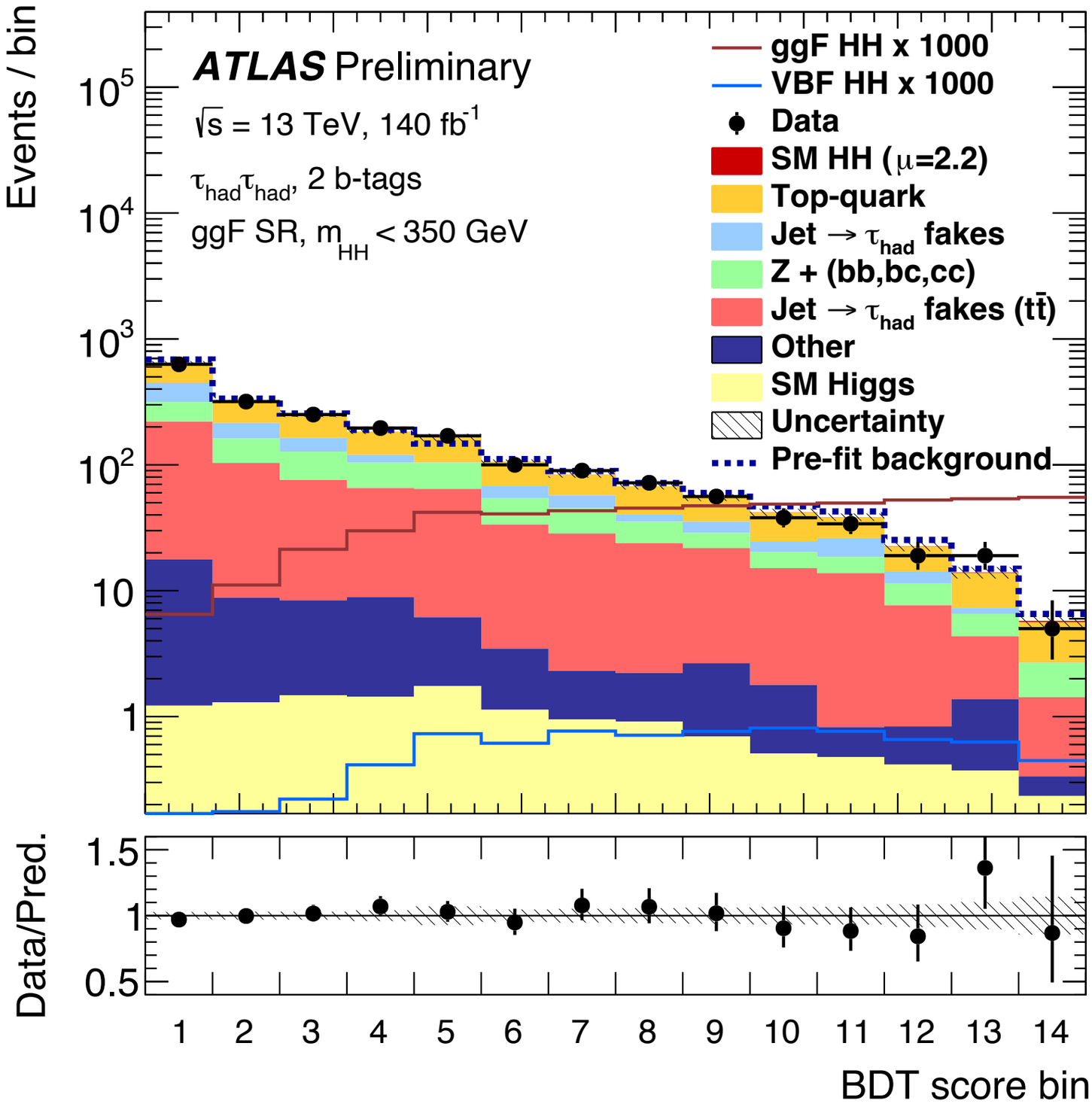
Categorize events by Higgs production: ggF or VBF

Split ggF by m_{HH}

Train BDT in each SR

No significant excess

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



Categorize events by Higgs production: ggF or VBF

Split ggF by m_{HH}

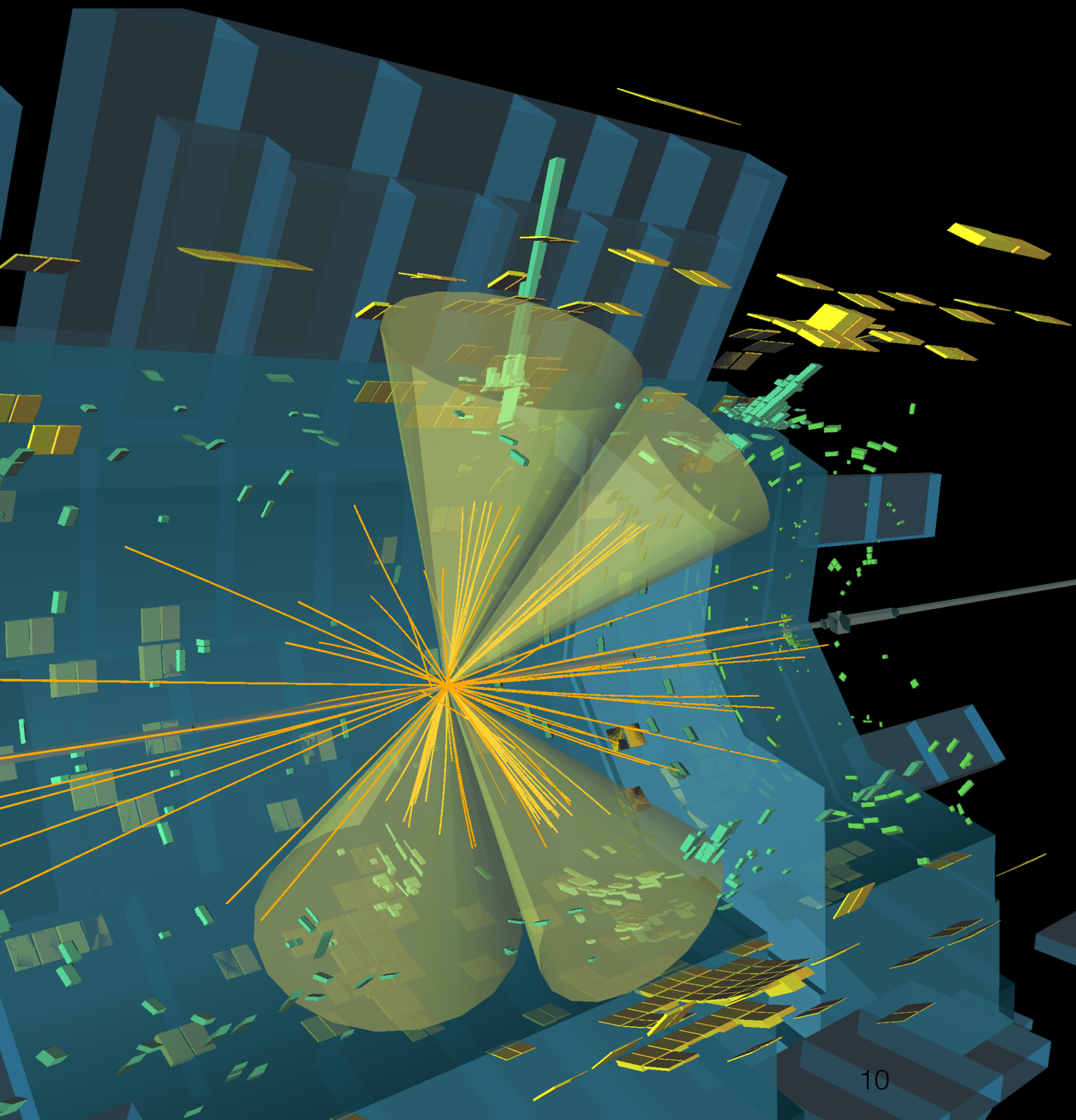
Train BDT in each SR

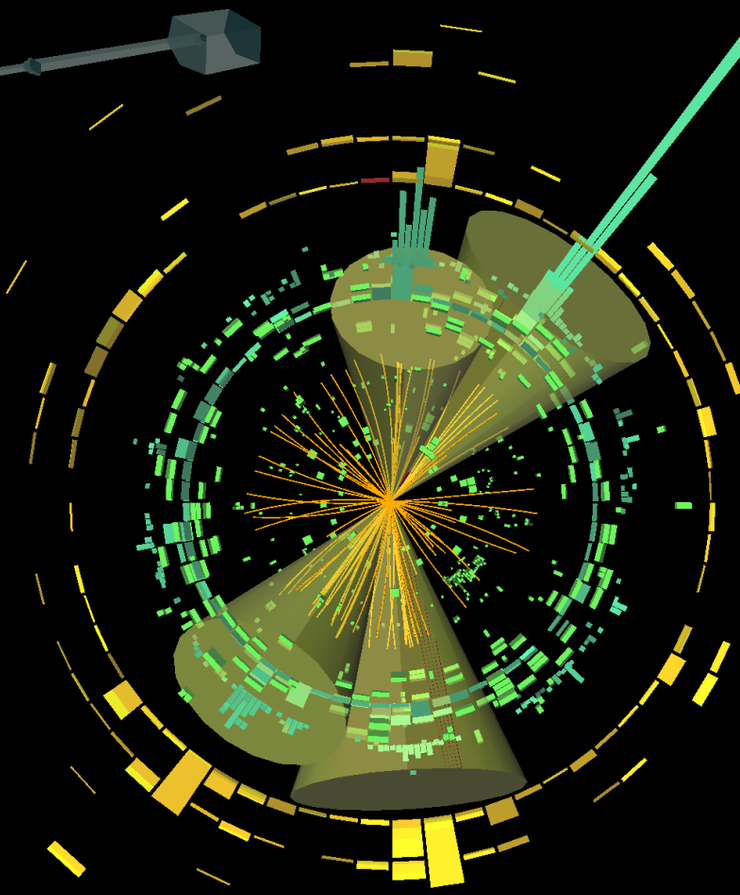
No significant excess

(Backgrounds mostly from simulation, normalized in control regions and in final fit)

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

HDBS-2019-29

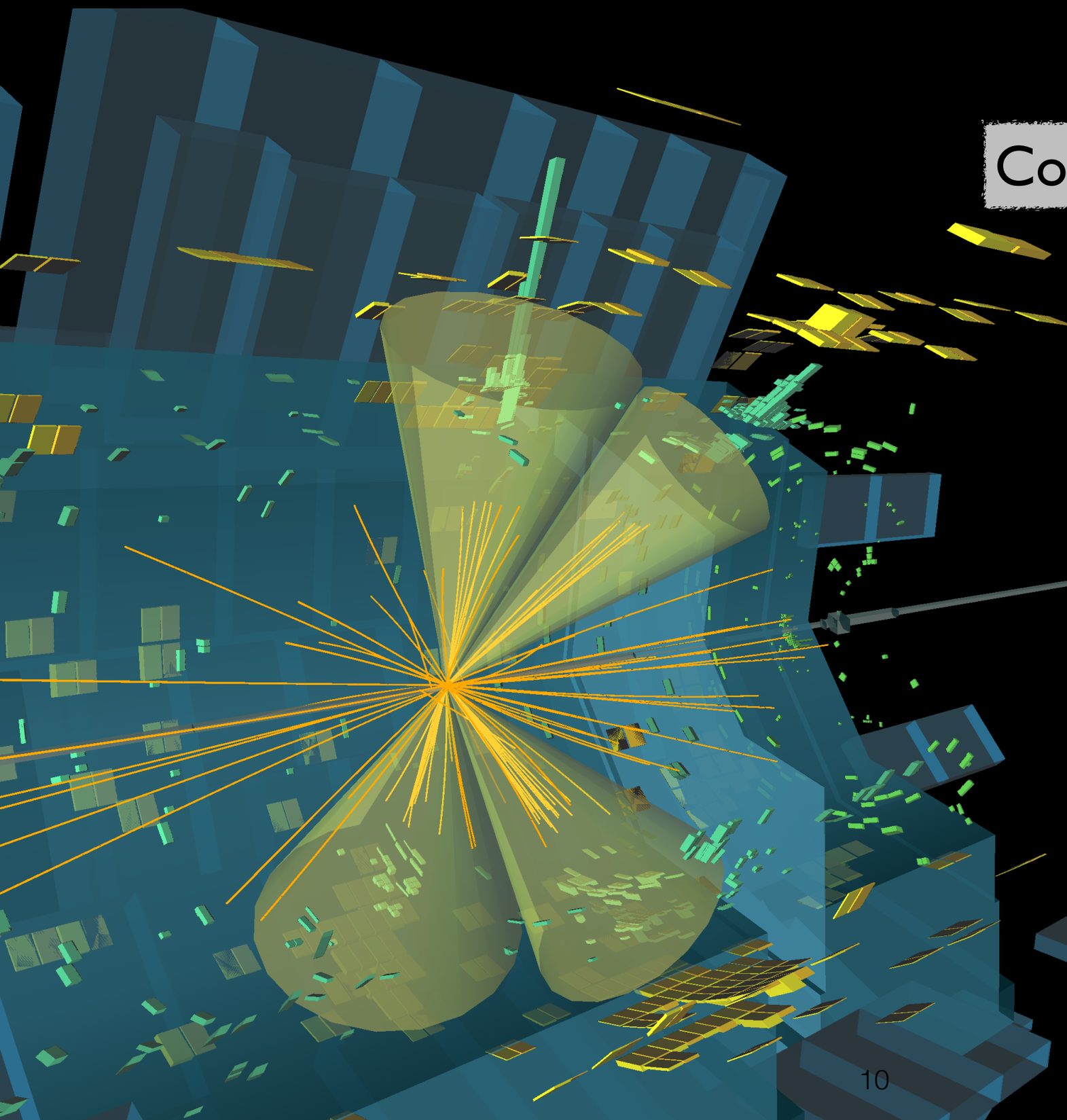


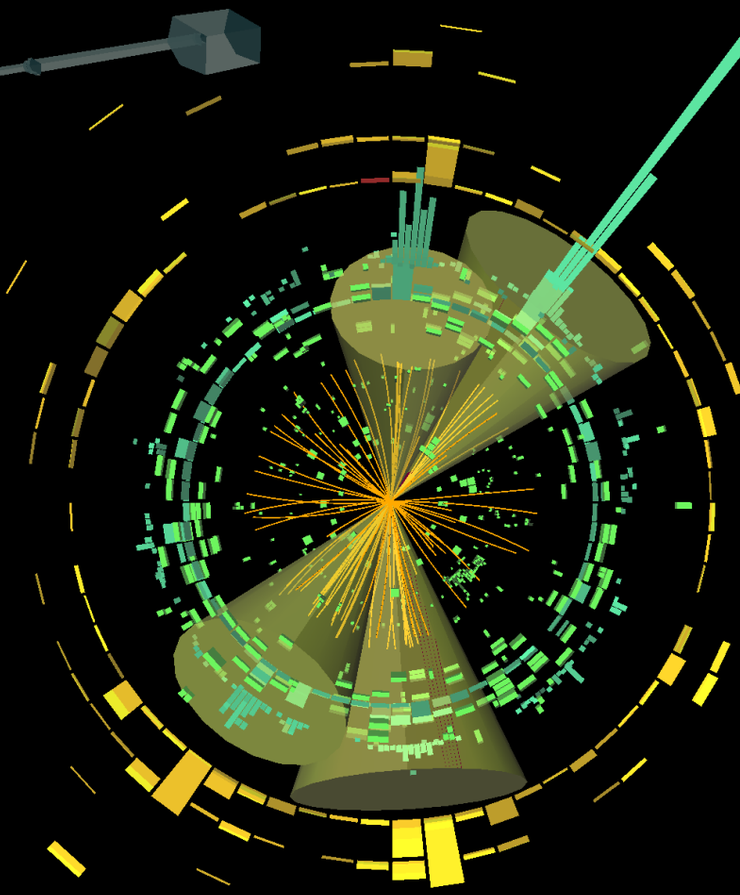


$HH \to b\bar{b}b\bar{b}$

HDBS-2019-29

Combination of 6 b-jet triggers





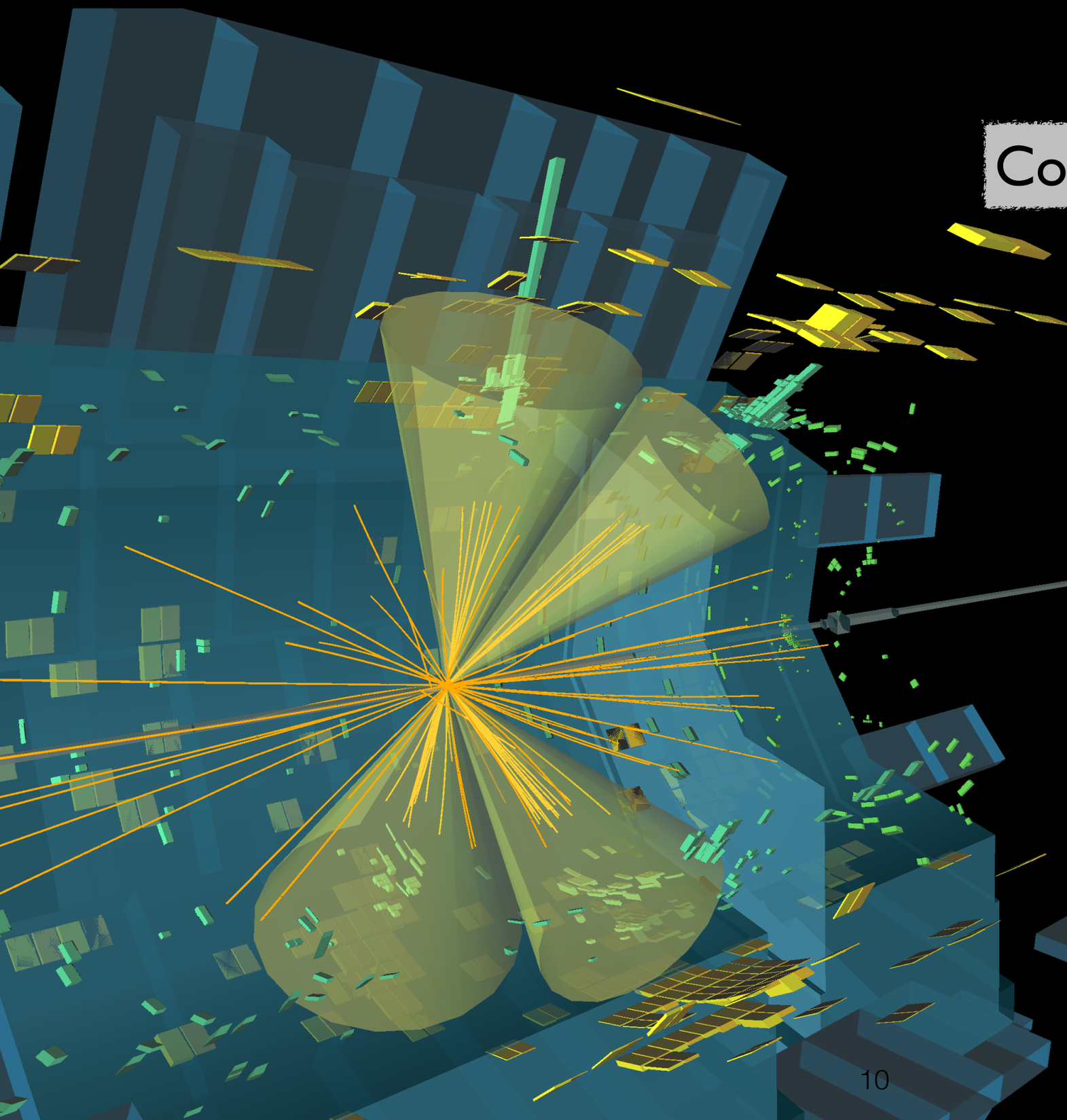
$HH \to b\bar{b}b\bar{b}$

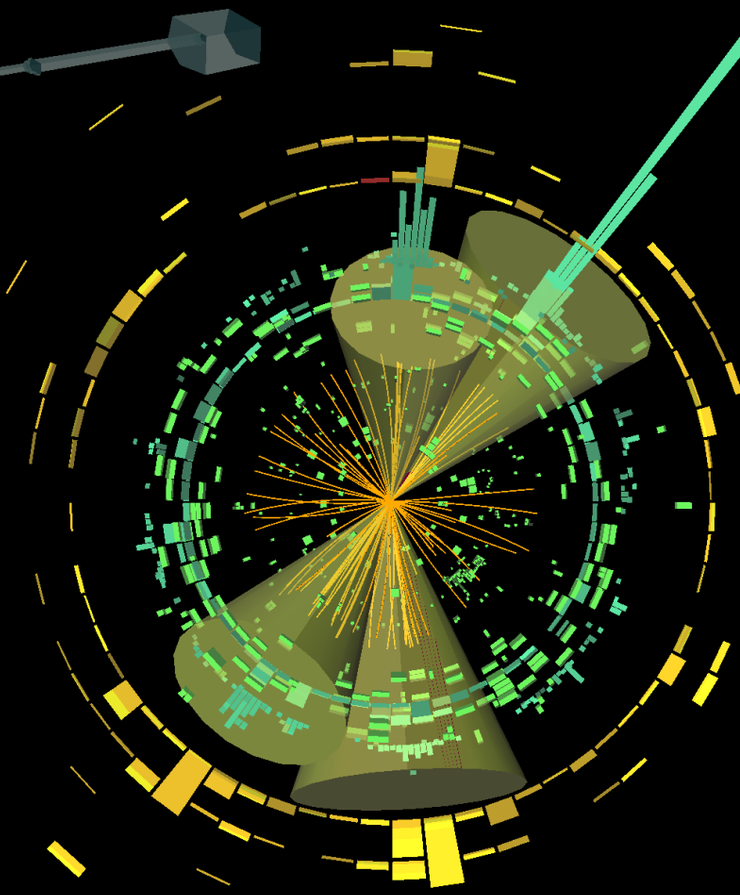
HDBS-2019-29

Combination of 6 b-jet triggers

4 b-tagged jets

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





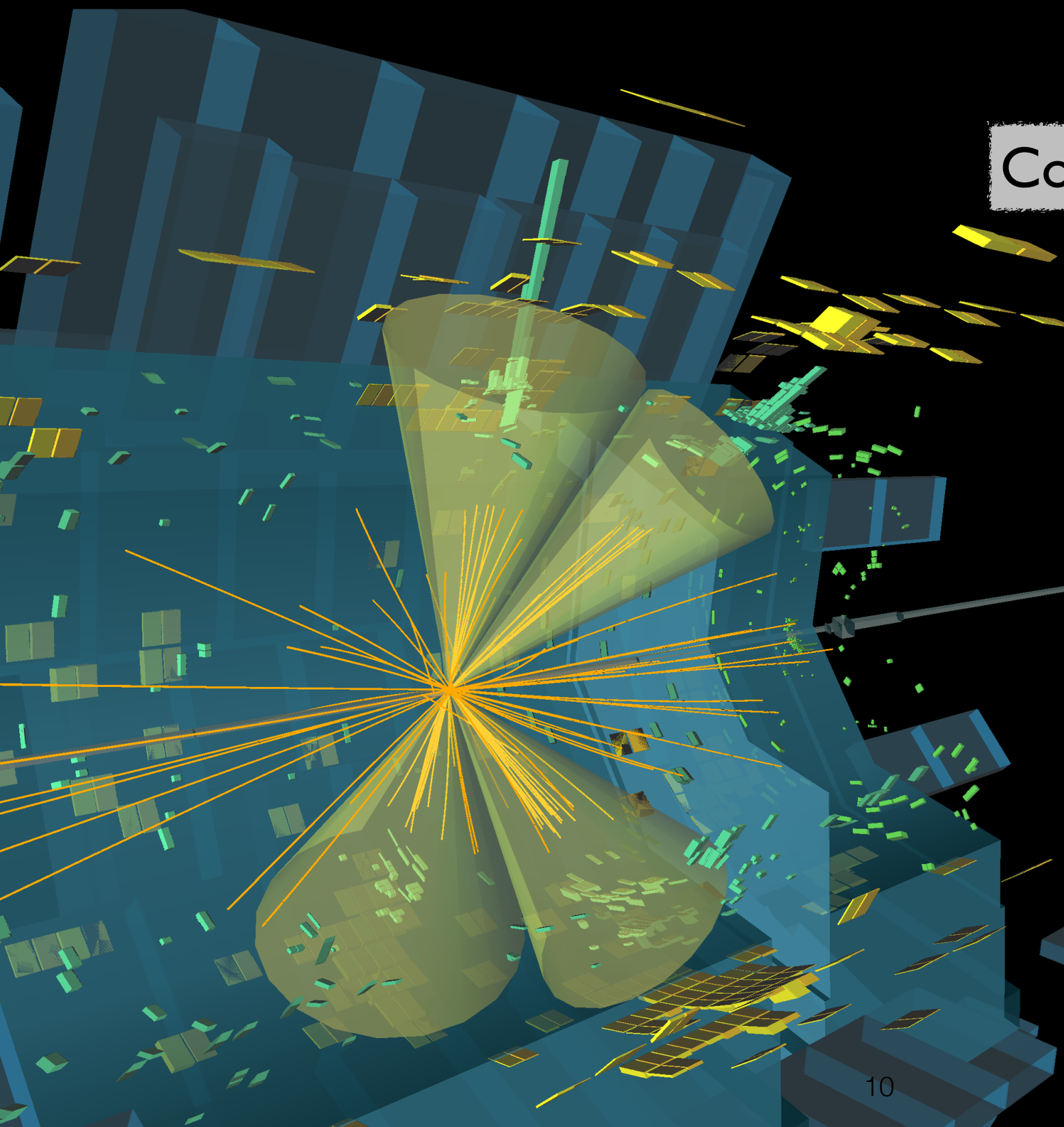
$HH \to b\bar{b}b\bar{b}$

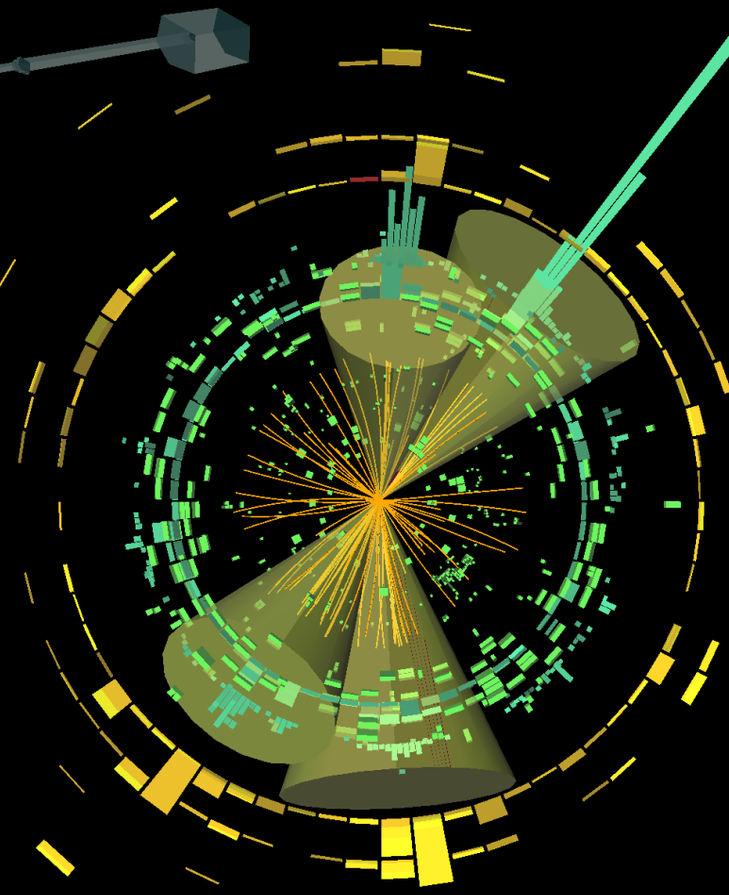
HDBS-2019-29

Combination of 6 b-jet triggers

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

Pair "closest jets" to form Higgs candidates





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

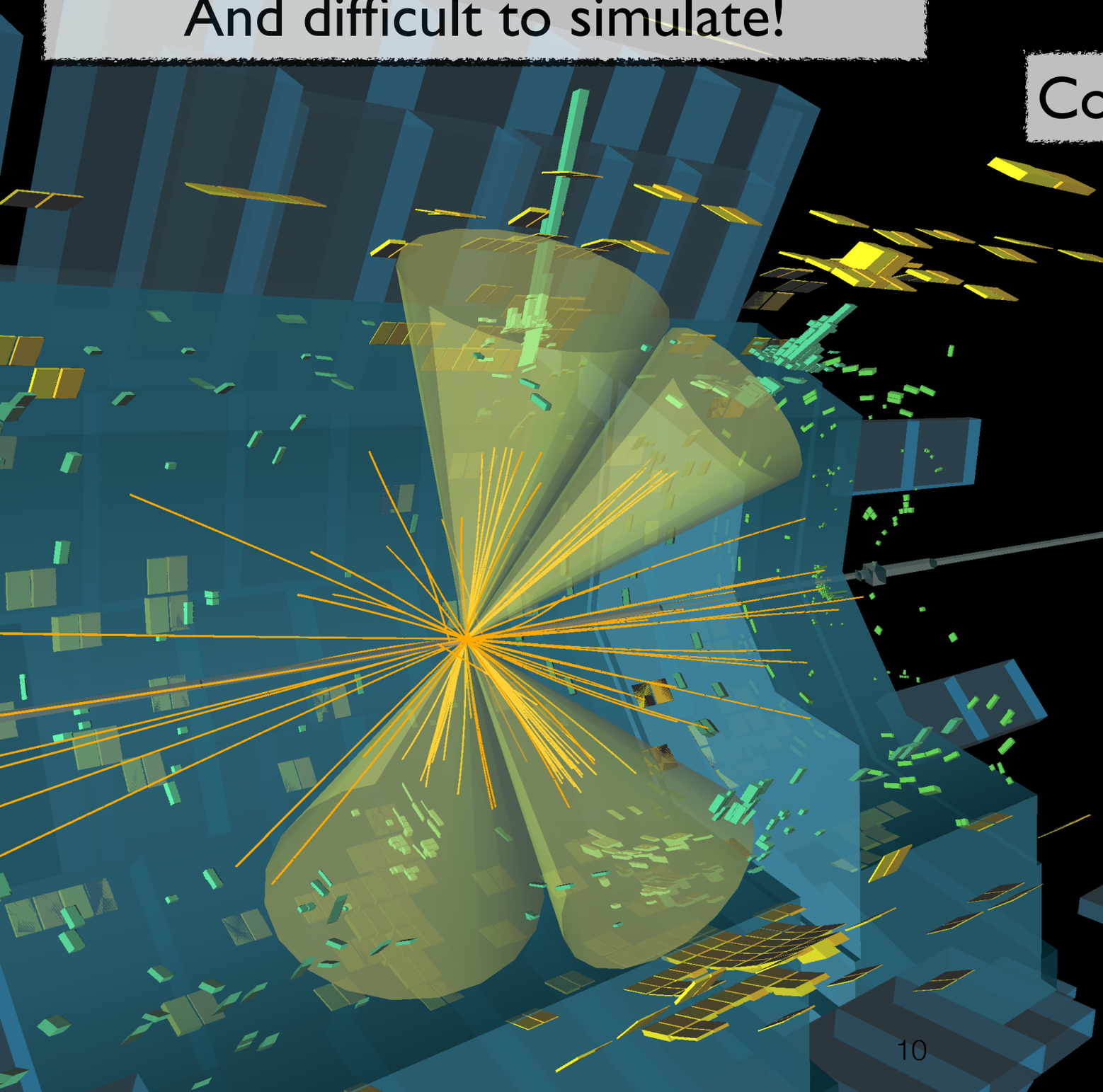
Extremely challenging signature:
Large signal, but large backgrounds,
And difficult to simulate!

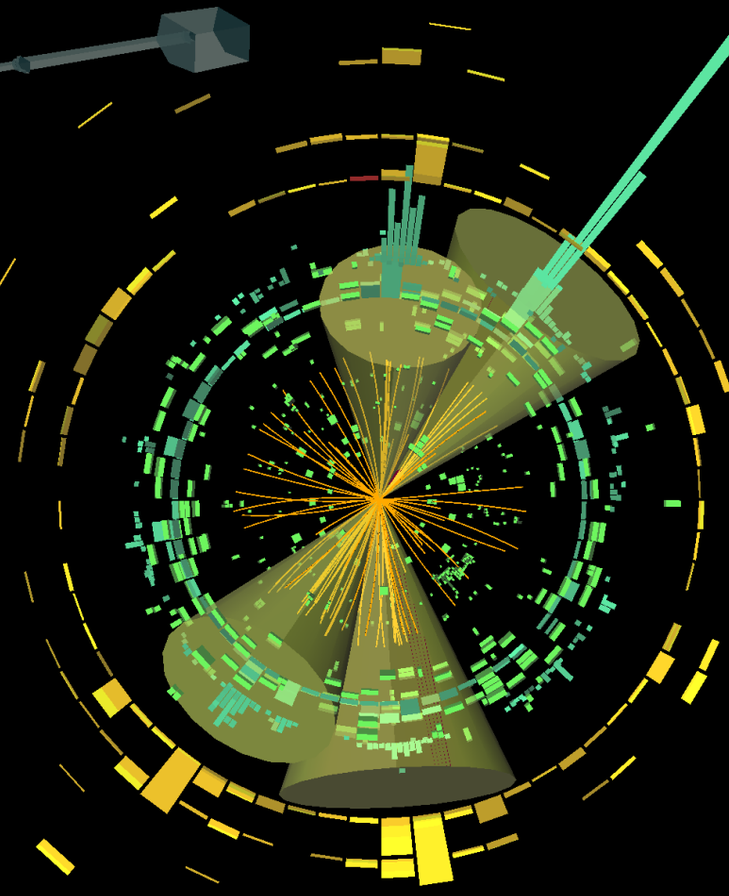
HDBS-2019-29

Combination of 6 b-jet triggers

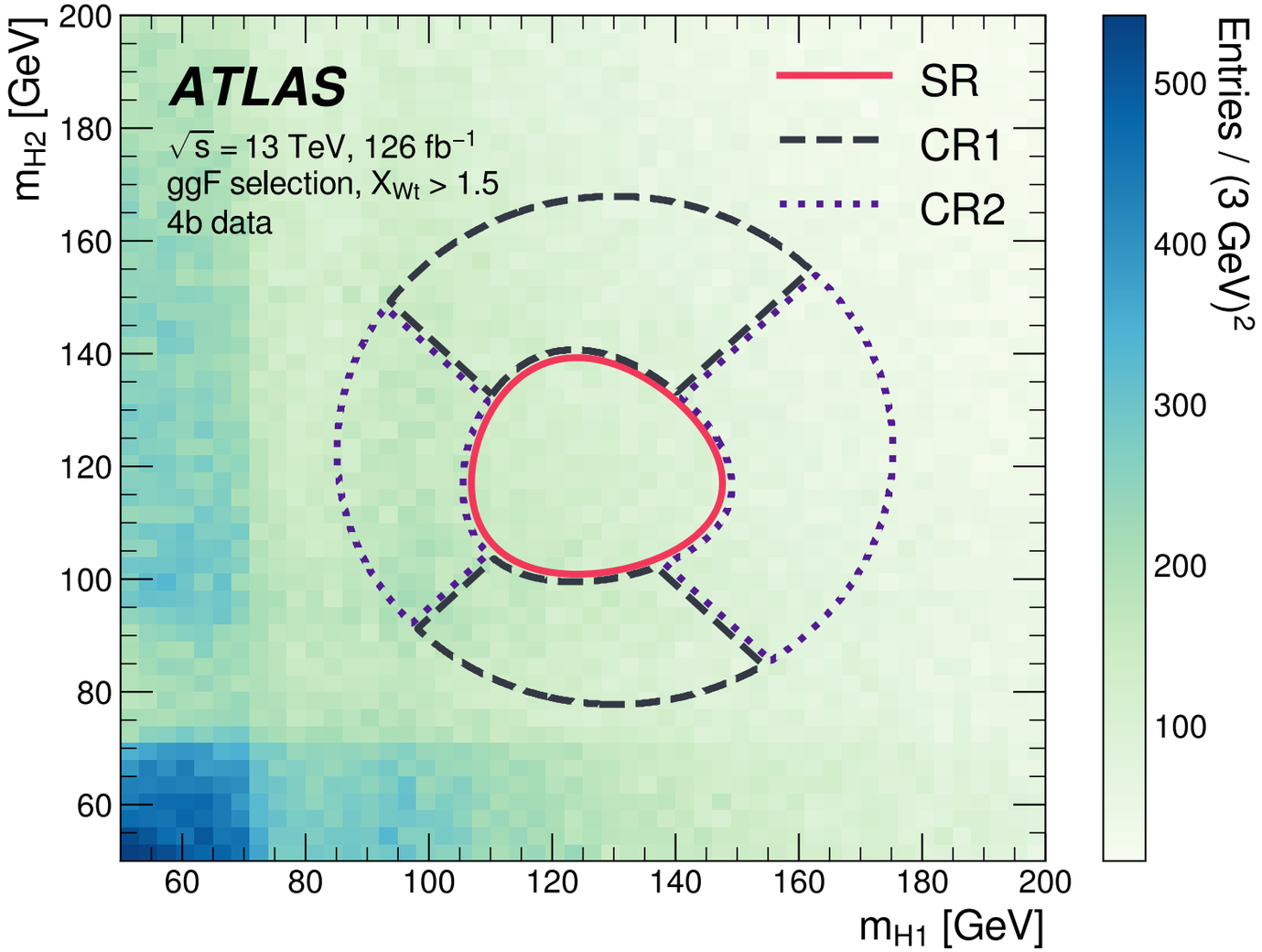
4 b-tagged jets
($\epsilon = 77\,\%, p_T > 40$ GeV)

Pair "closest jets" to form
Higgs candidates

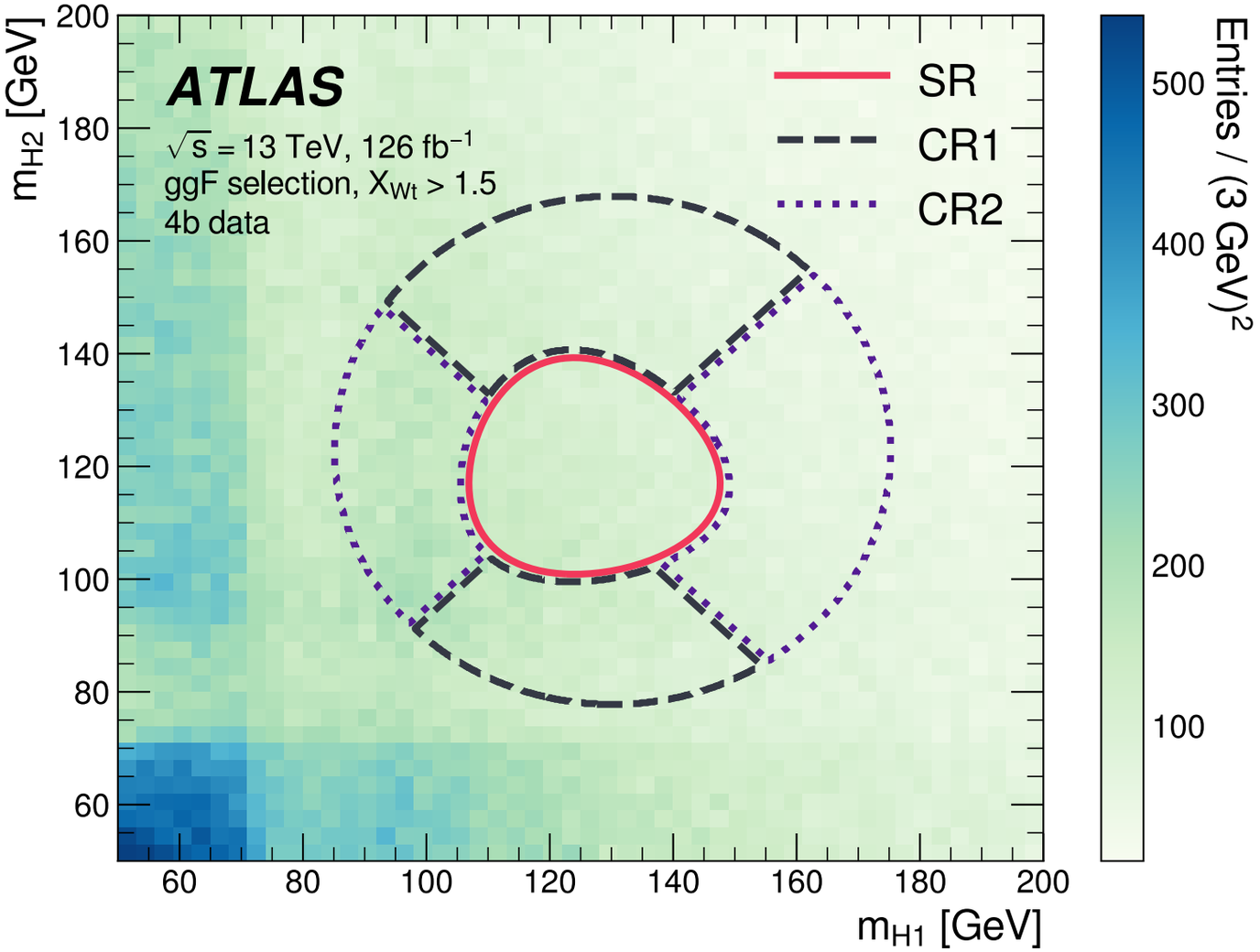




$b\bar{b}b\bar{b}$ Analysis Strategy

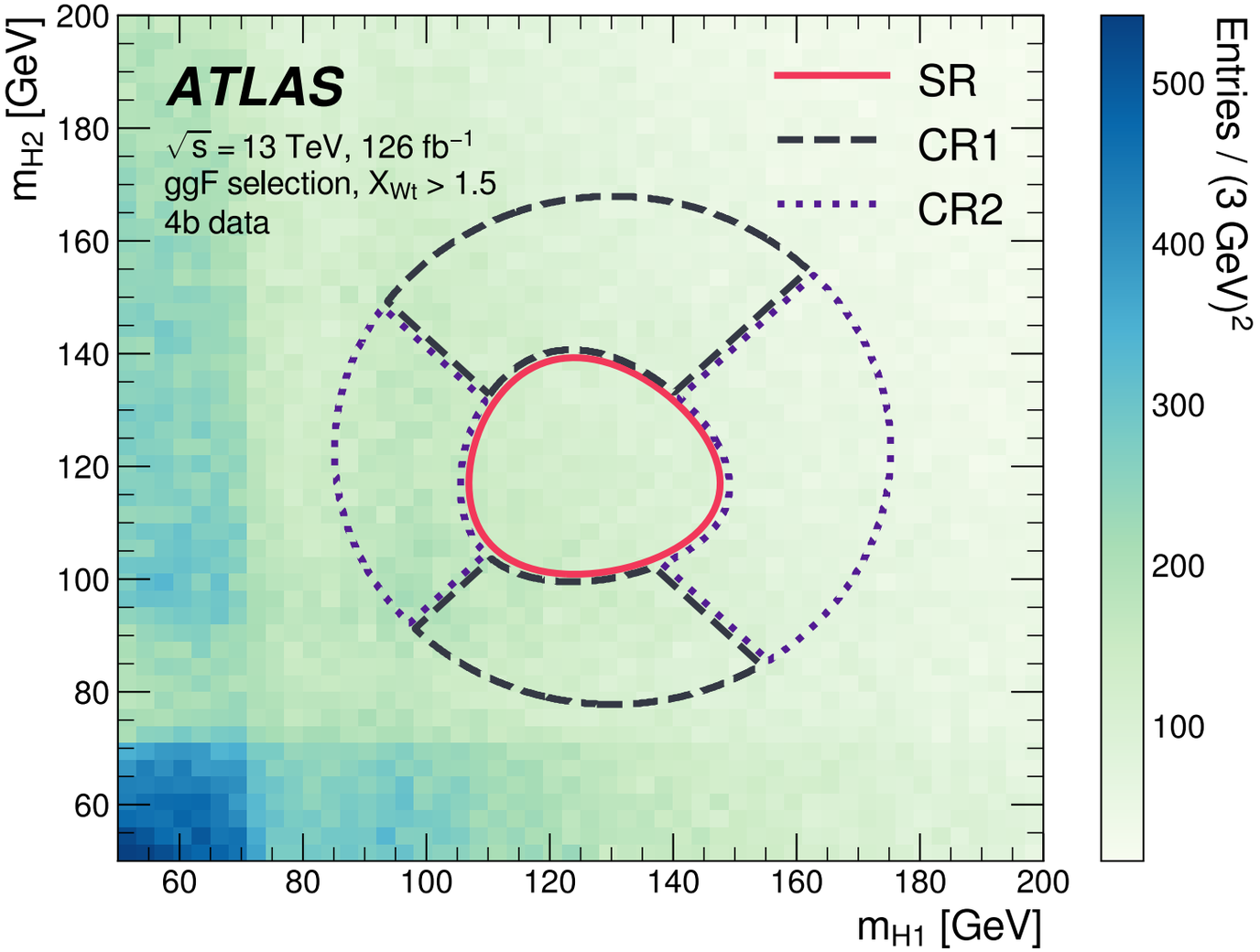


$b\bar{b}b\bar{b}$ Analysis Strategy



Reconstruct Higgs candidates, form "mass plane"

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



Reconstruct Higgs candidates, form "mass plane"

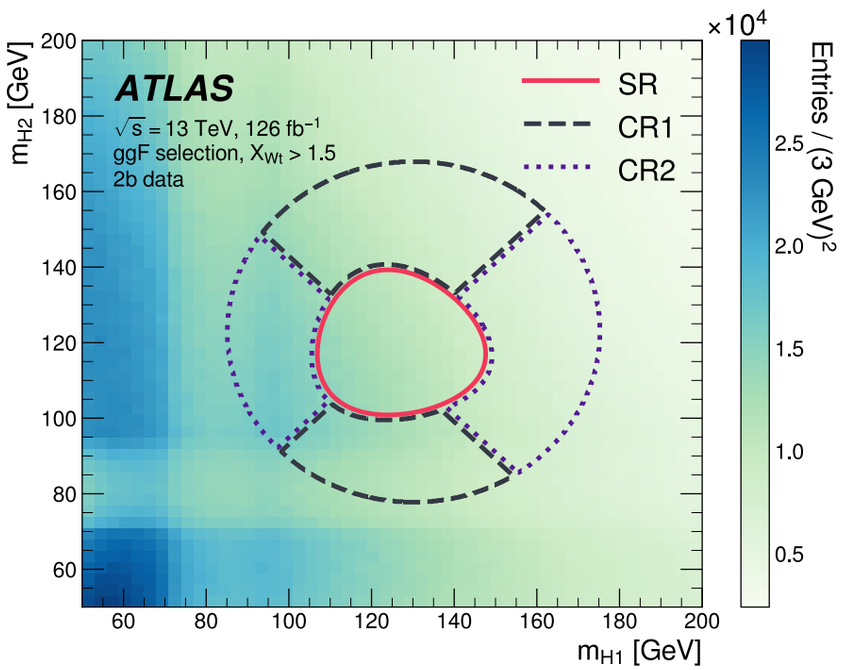
Center is signal-like; outer regions used for background and background validation

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

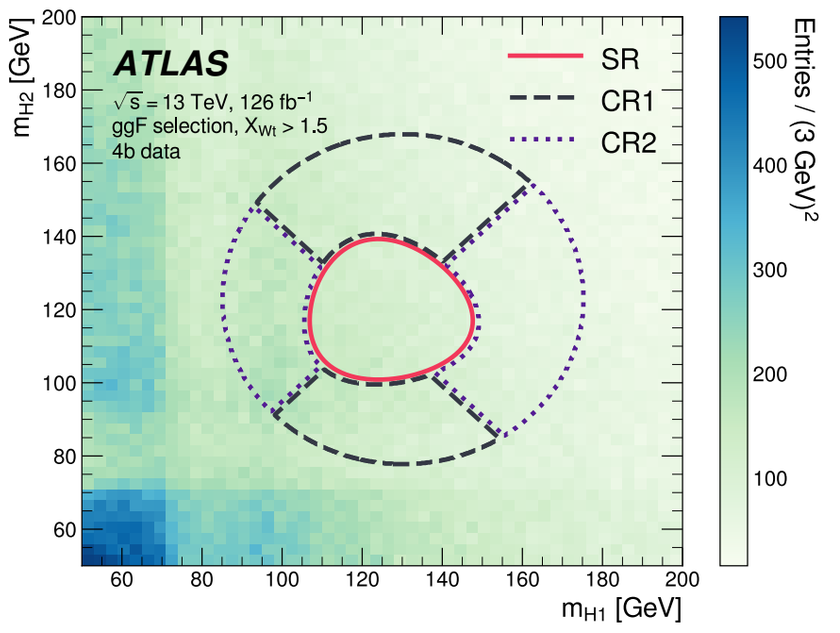
$b\bar{b}b\bar{b}$ Background

Step 0: form "mass planes" for
2b (control region, no signal)
and 4b events

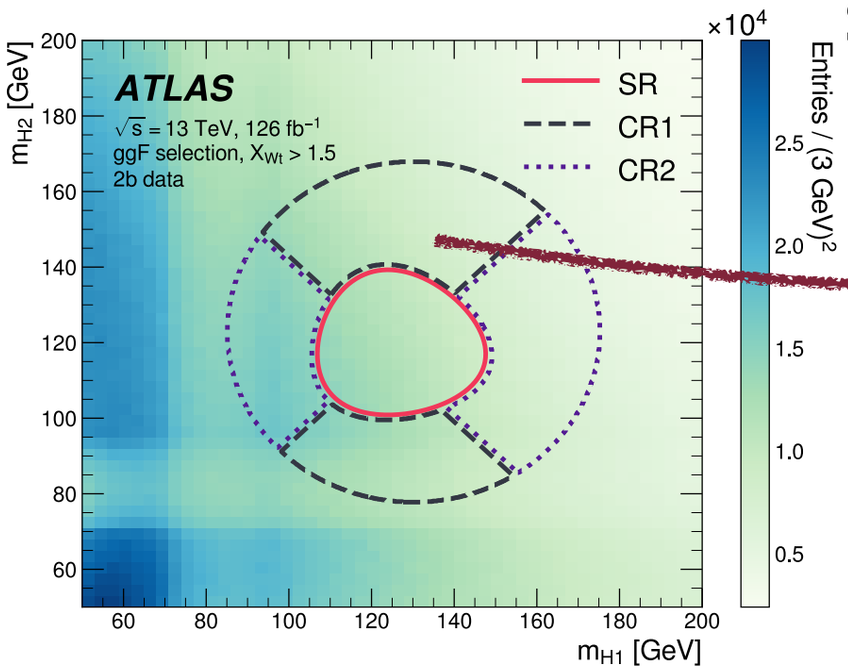
$b\bar{b}b\bar{b}$ Background



Step 0: form "mass planes" for 2b (control region, no signal) and 4b events

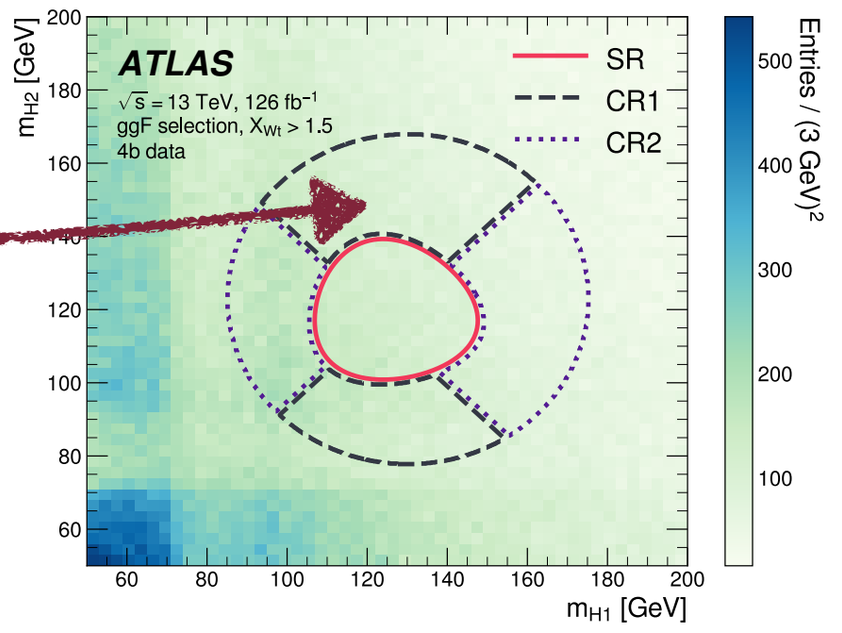


$b\bar{b}b\bar{b}$ Background

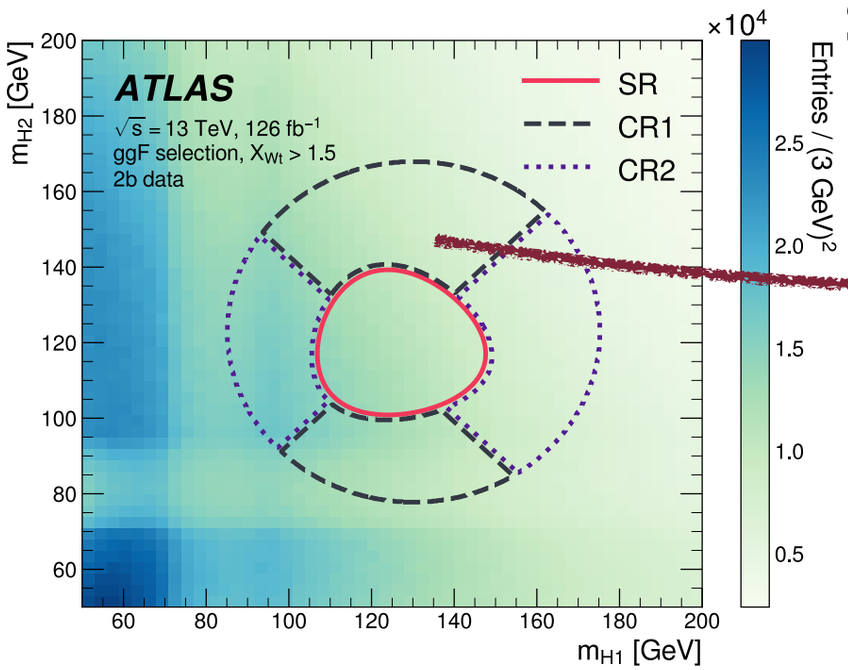


Step 0: form "mass planes" for 2b (control region, no signal) and 4b events

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



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



Step 0: form "mass planes" for 2b (control region, no signal) and 4b events

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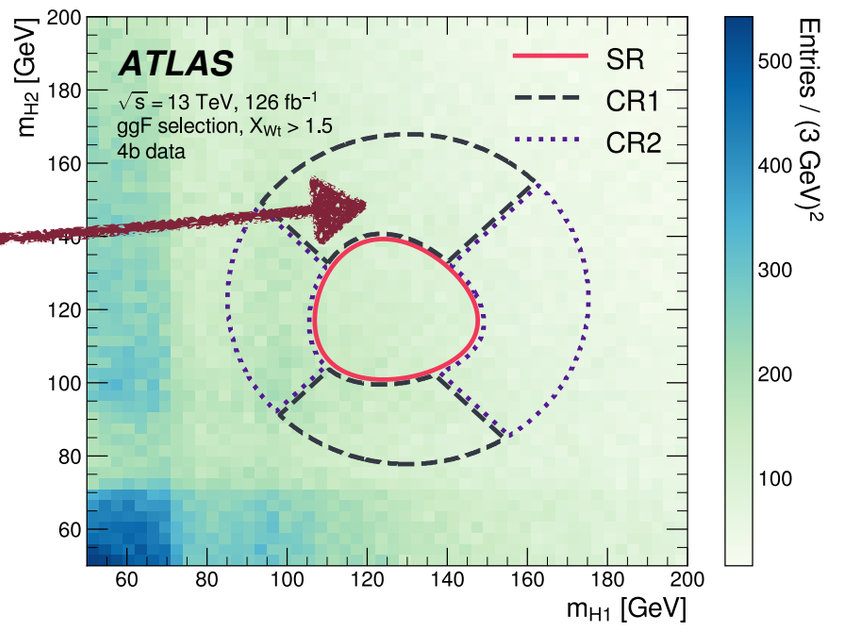
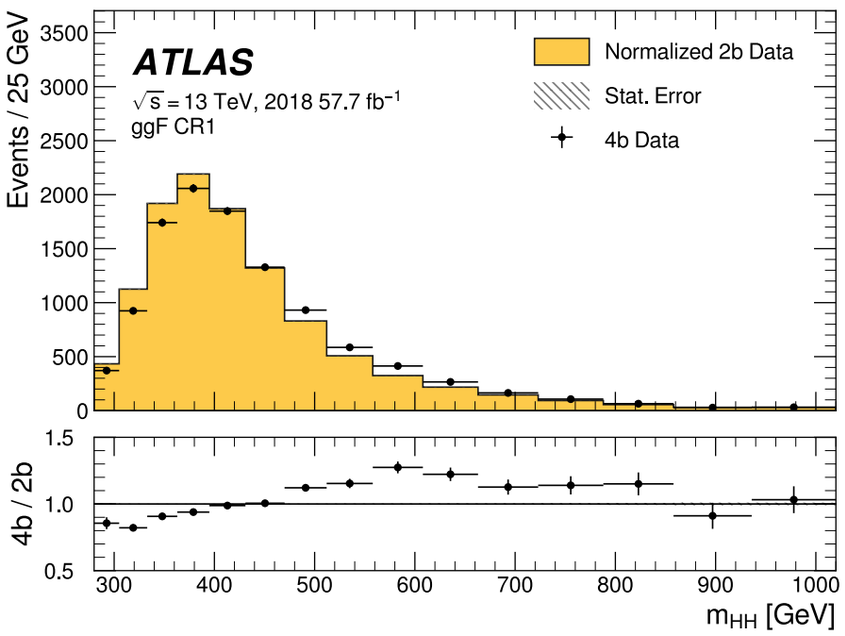
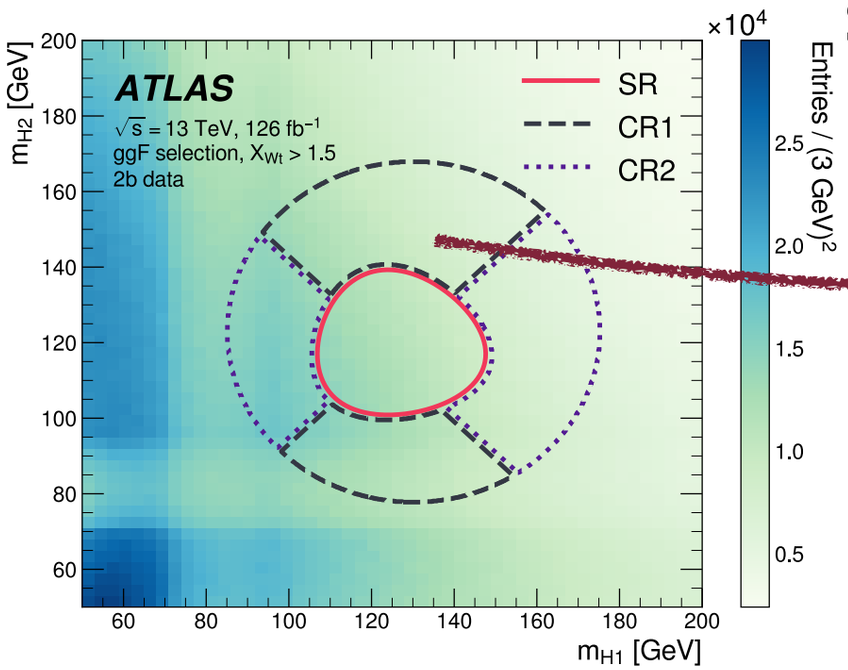




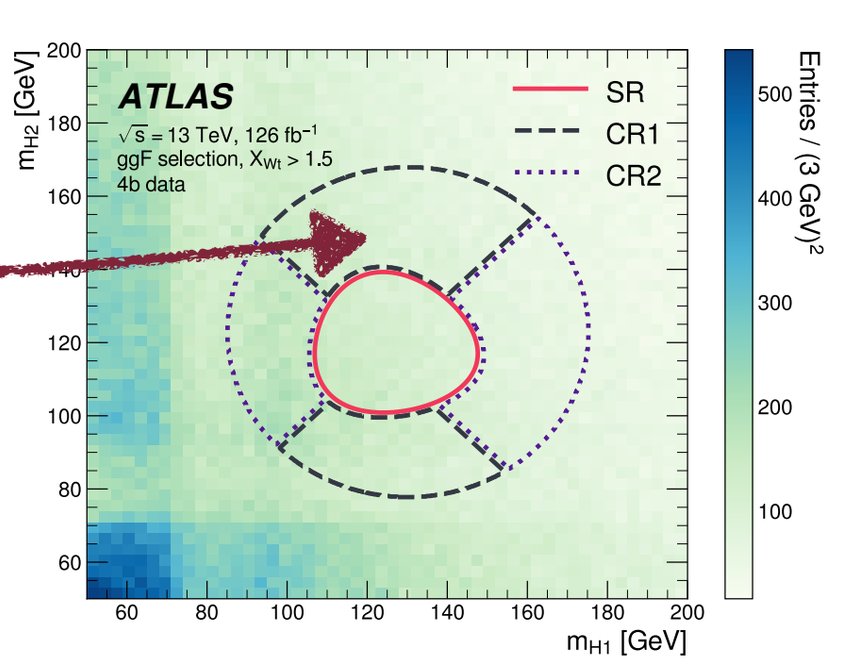
Orange histogram comes from 2b, black points from 4b

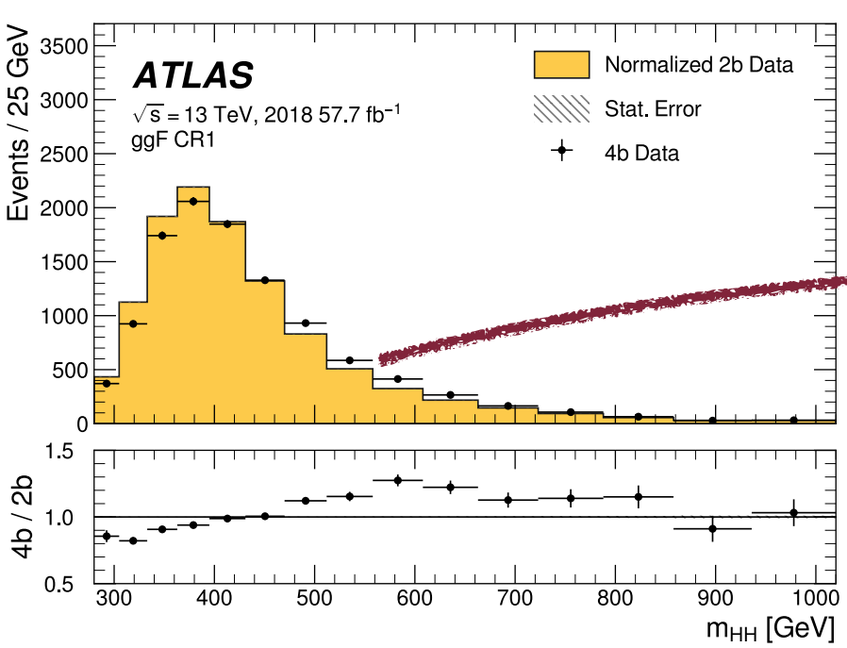
$b\bar{b}b\bar{b}$ Background



Step 0: form "mass planes" for 2b (control region, no signal) and 4b events

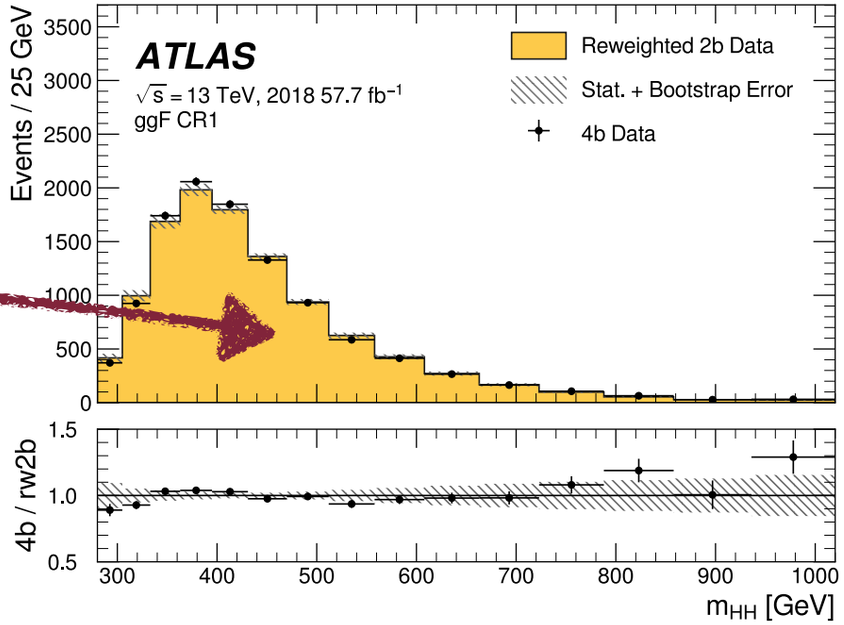
Step 1: use CR to train *neural network* to reweight data from 2b to 4b



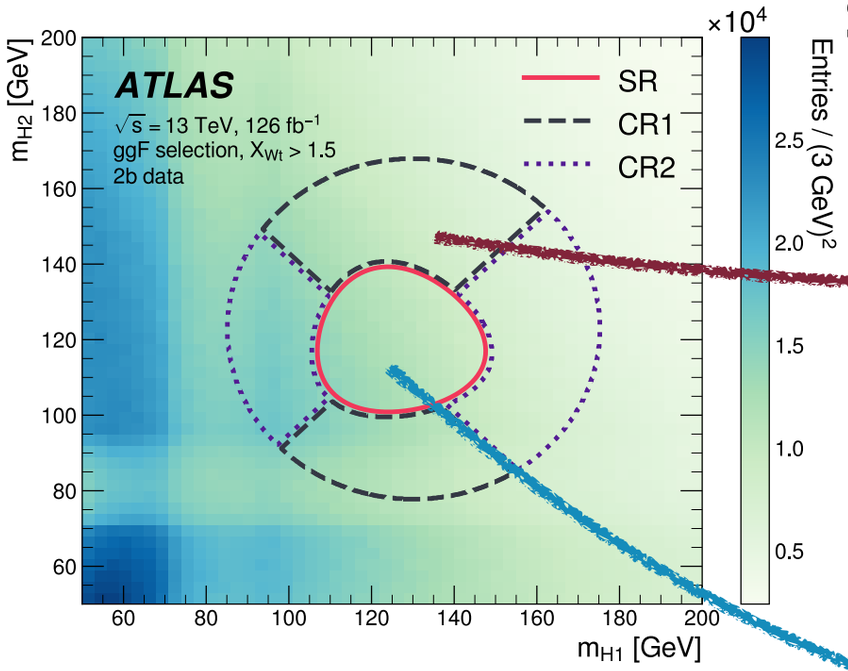


Orange histogram comes from 2b, black points from 4b

Neural network training



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



Step 0: form "mass planes" for 2b (control region, no signal) and 4b events

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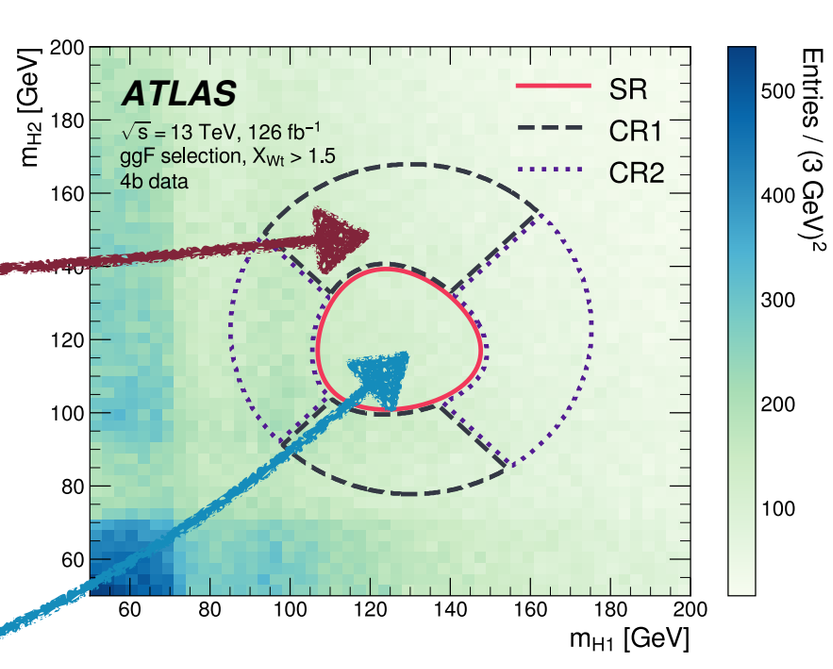

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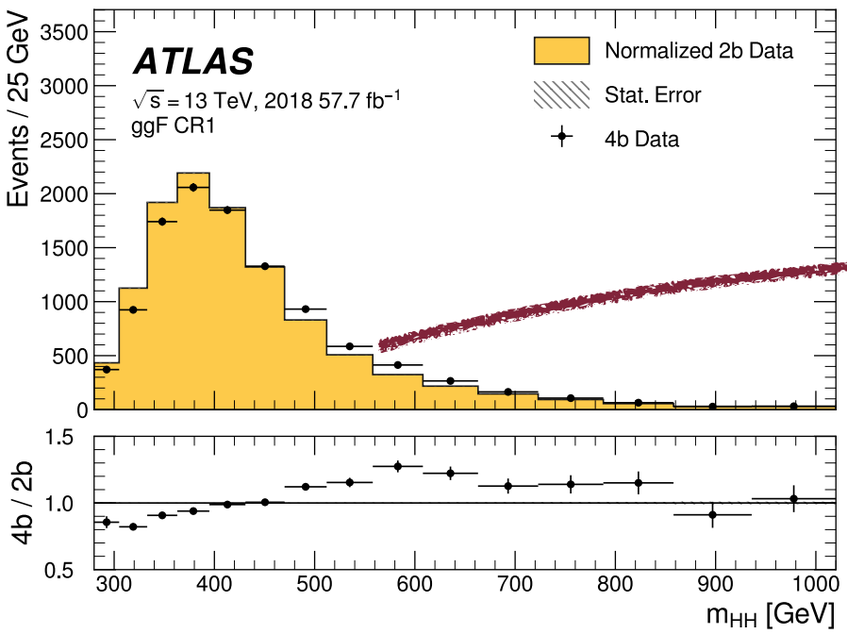

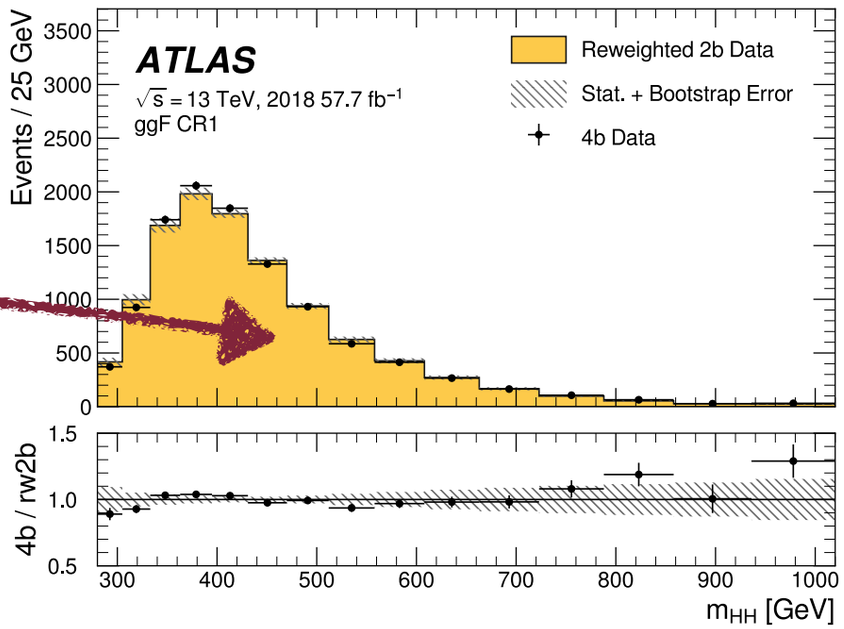

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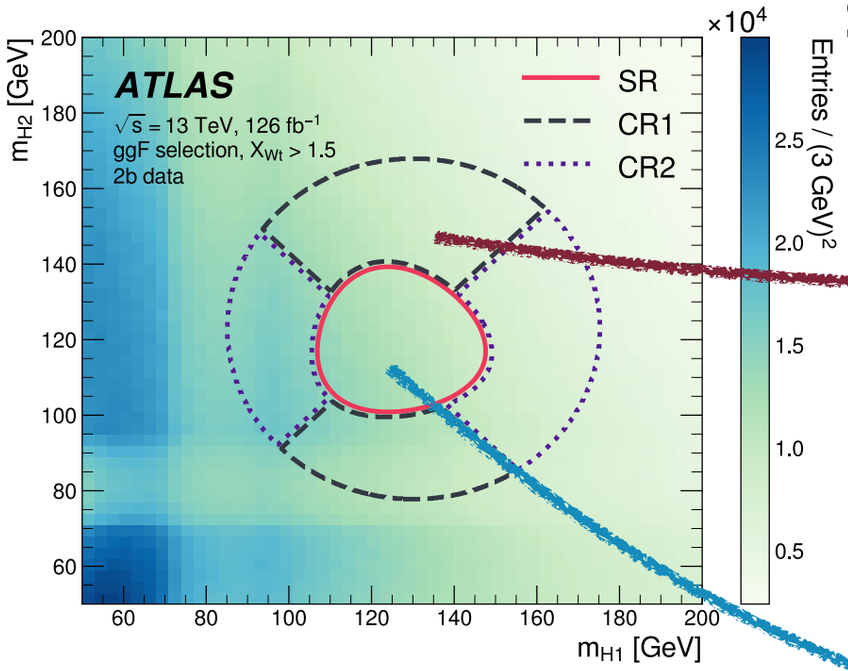

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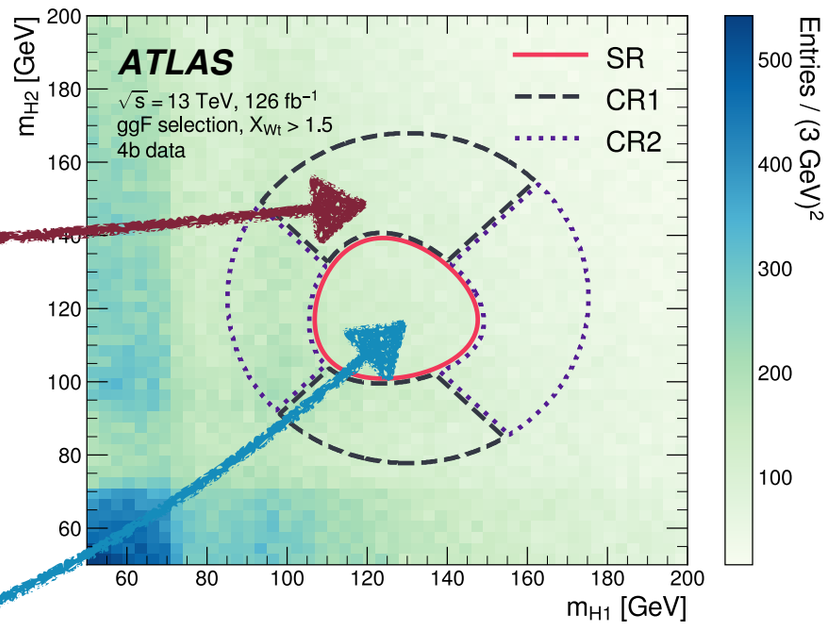
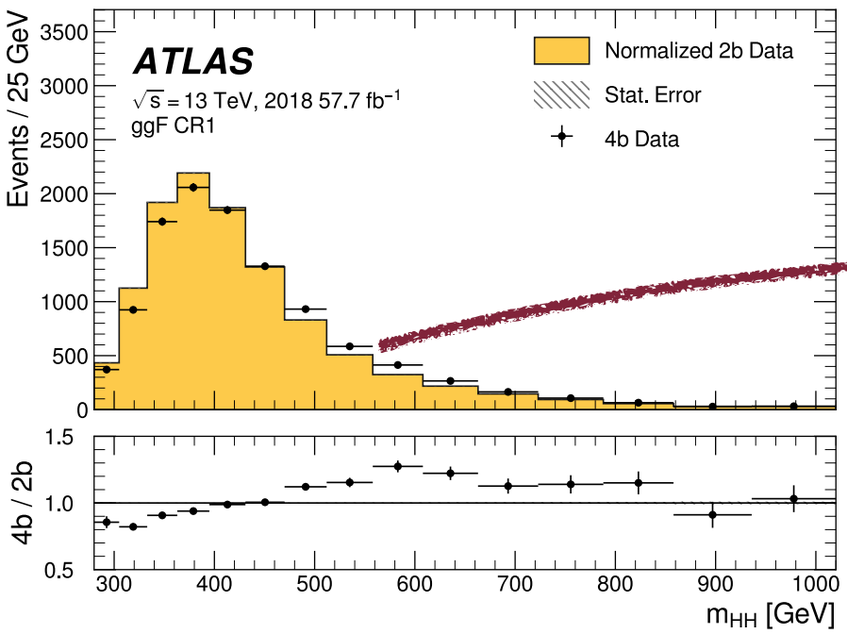
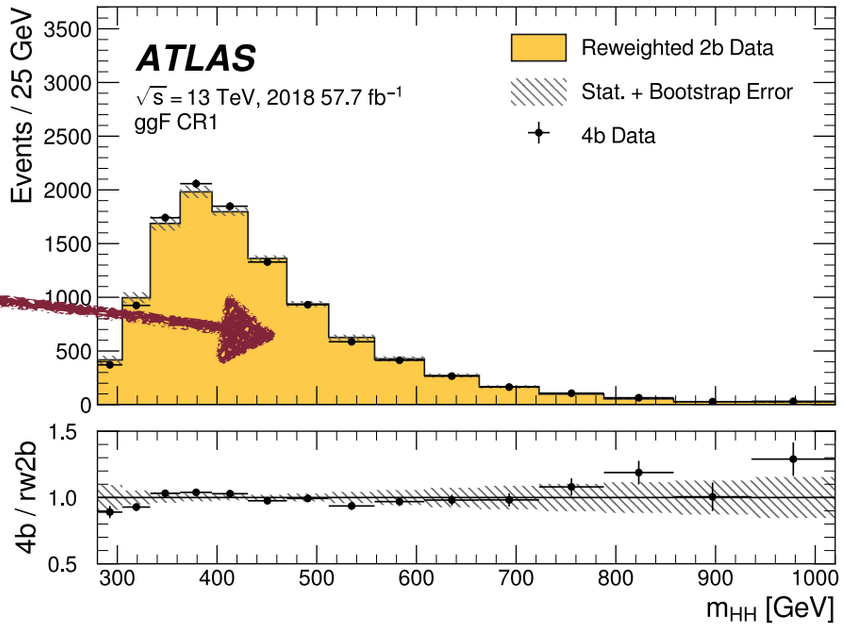




Orange histogram comes from 2b, black points from 4b

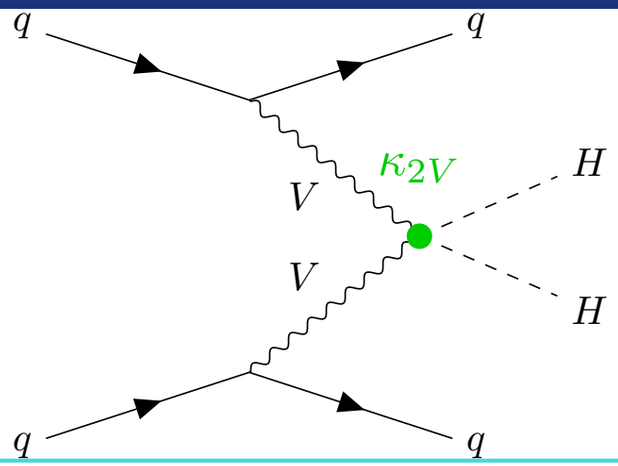
Neural network training

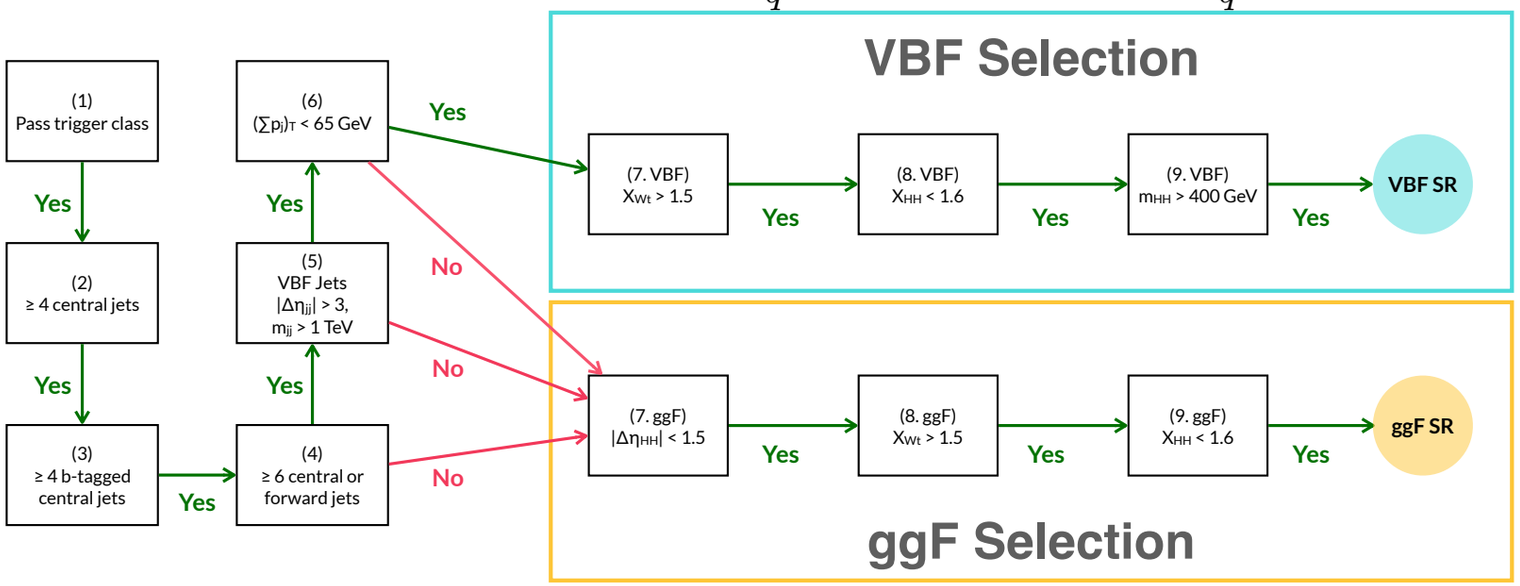
Systematics from alternate regions

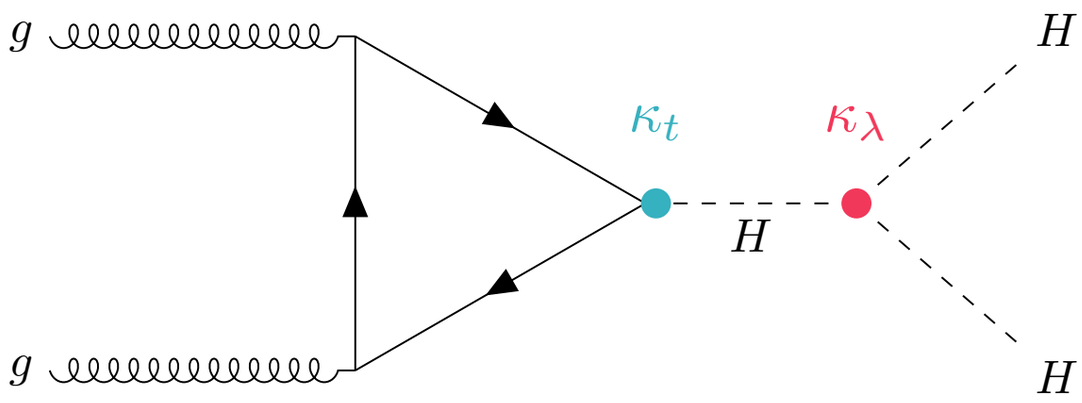


$b\bar{b}b\bar{b}$ Results

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

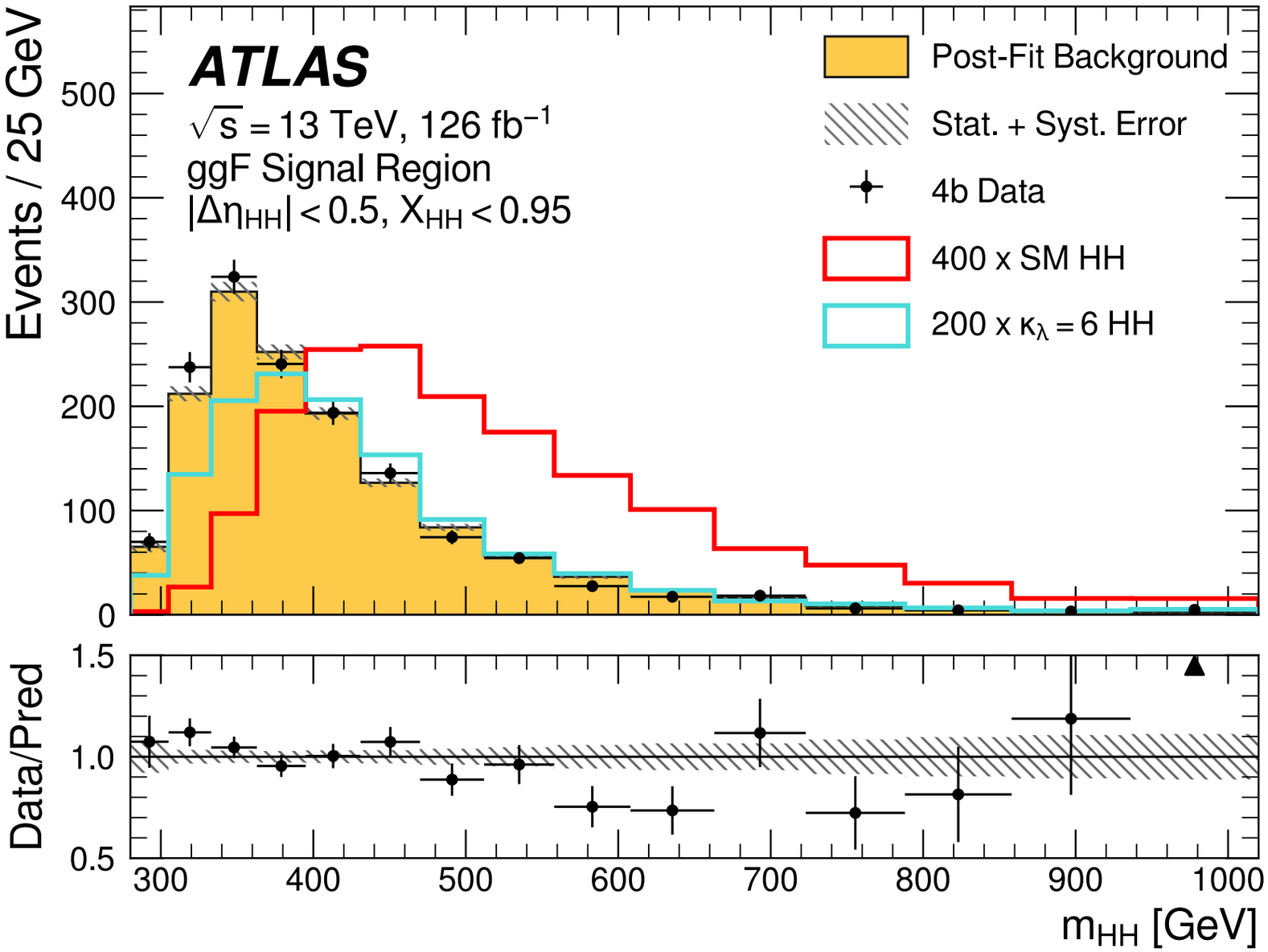






Both VBF and ggF signal regions defined

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



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Signal regions divided by kinematic properties

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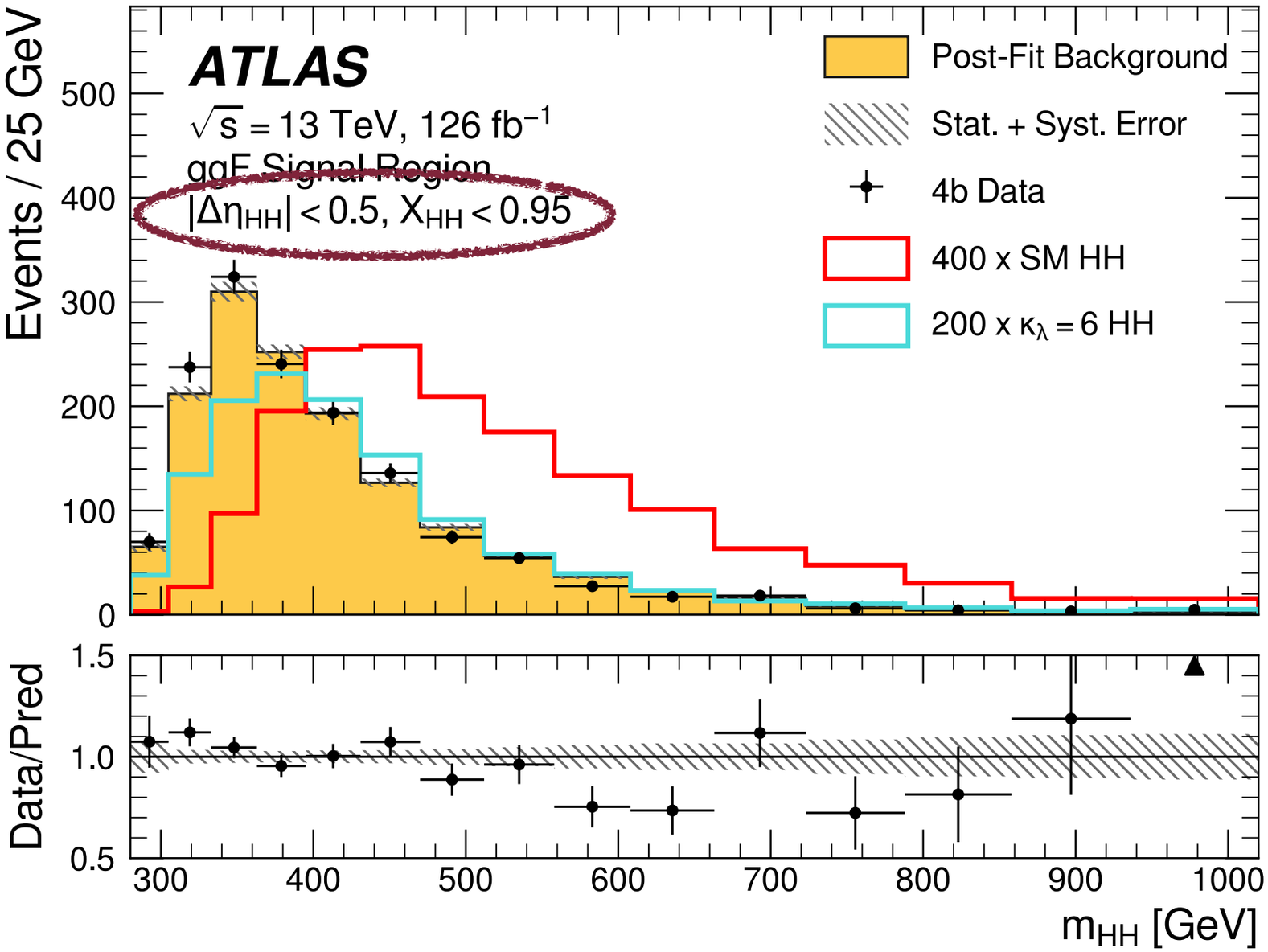

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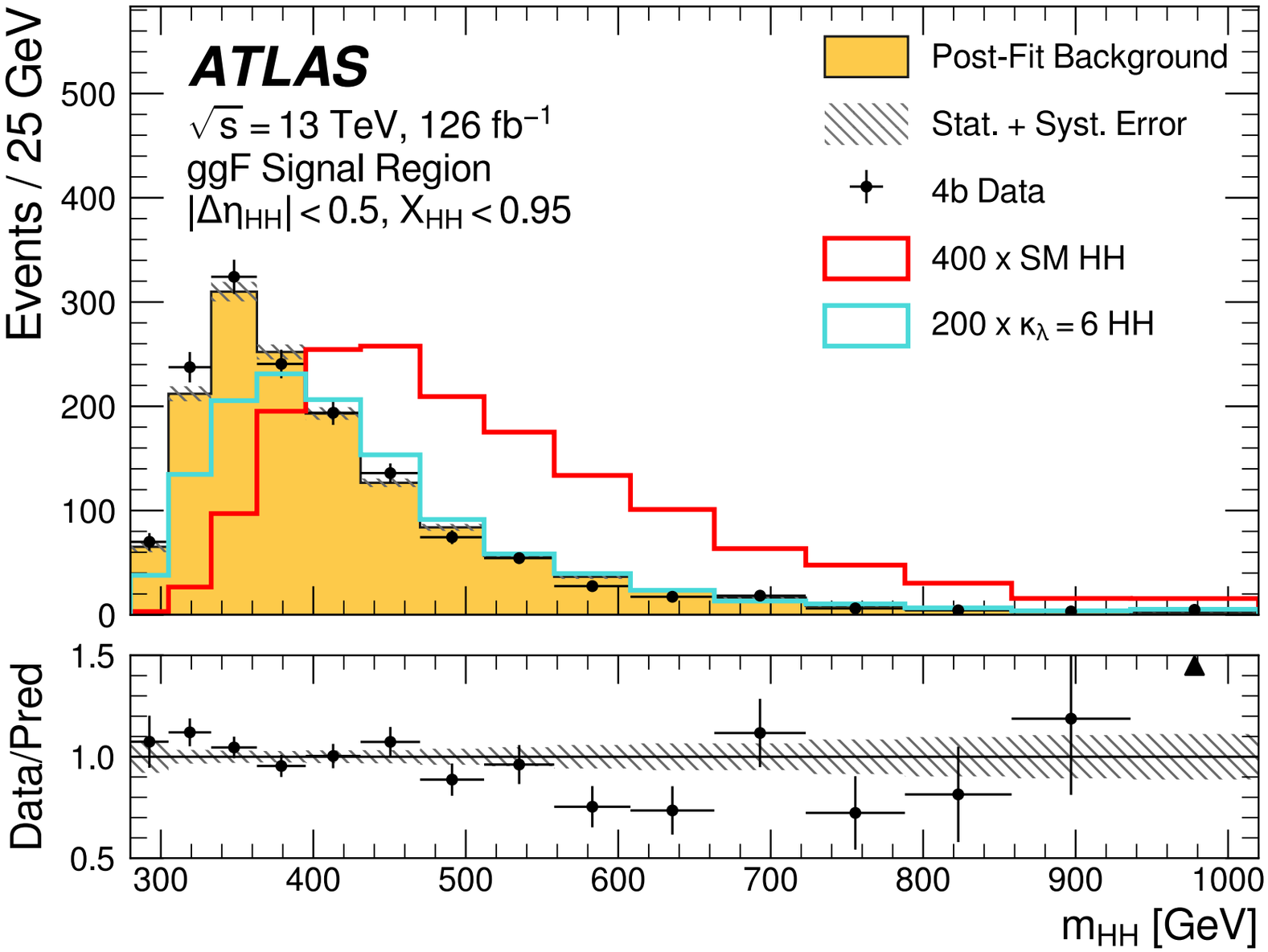

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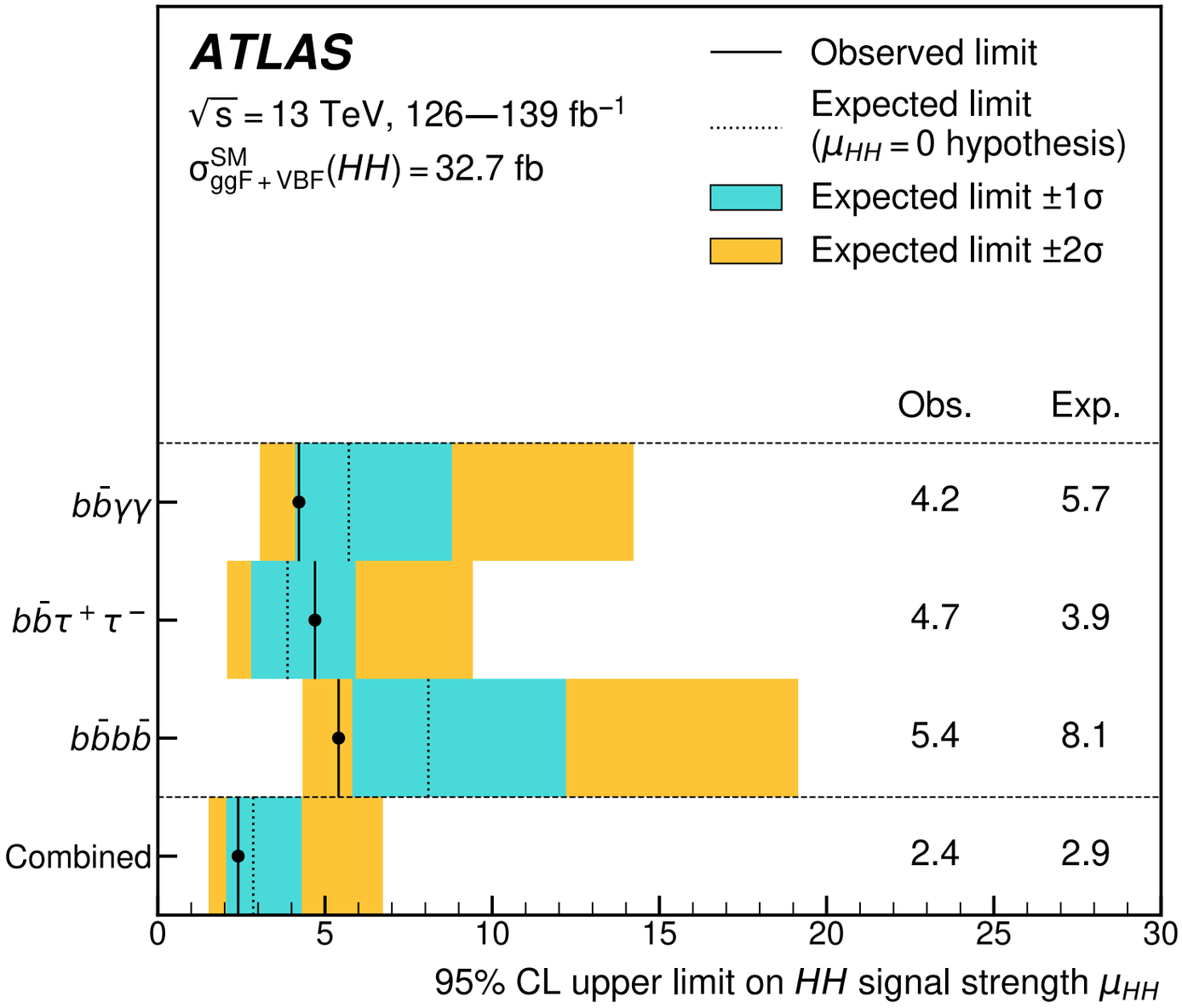
No excess observed

Limits on the SM

Limits on the SM

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

Limits on the SM



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

ATLAS-HDBS-2022-03

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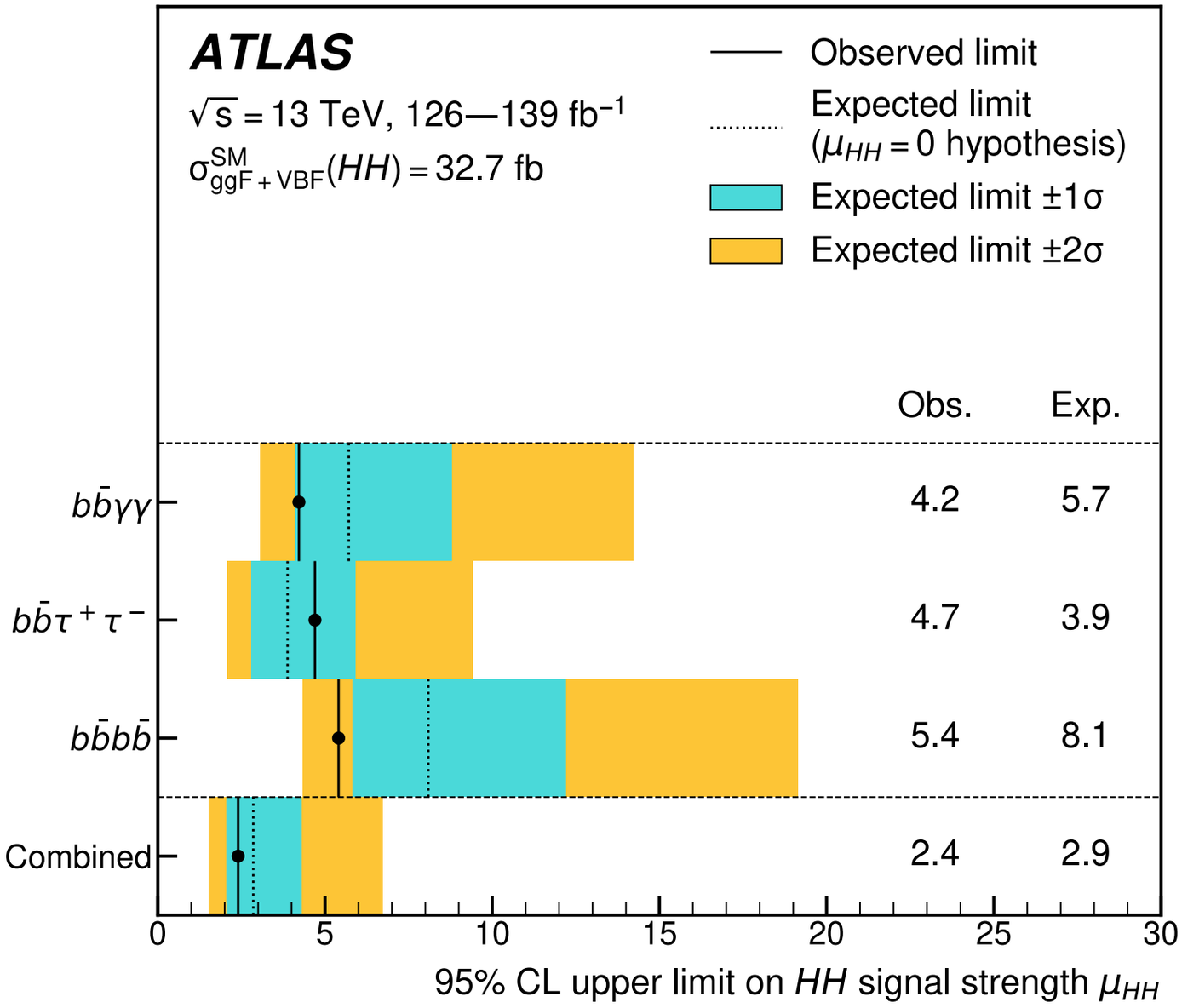

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Individual analyses set limits at ~4.5x SM

ATLAS-HDBS-2022-03

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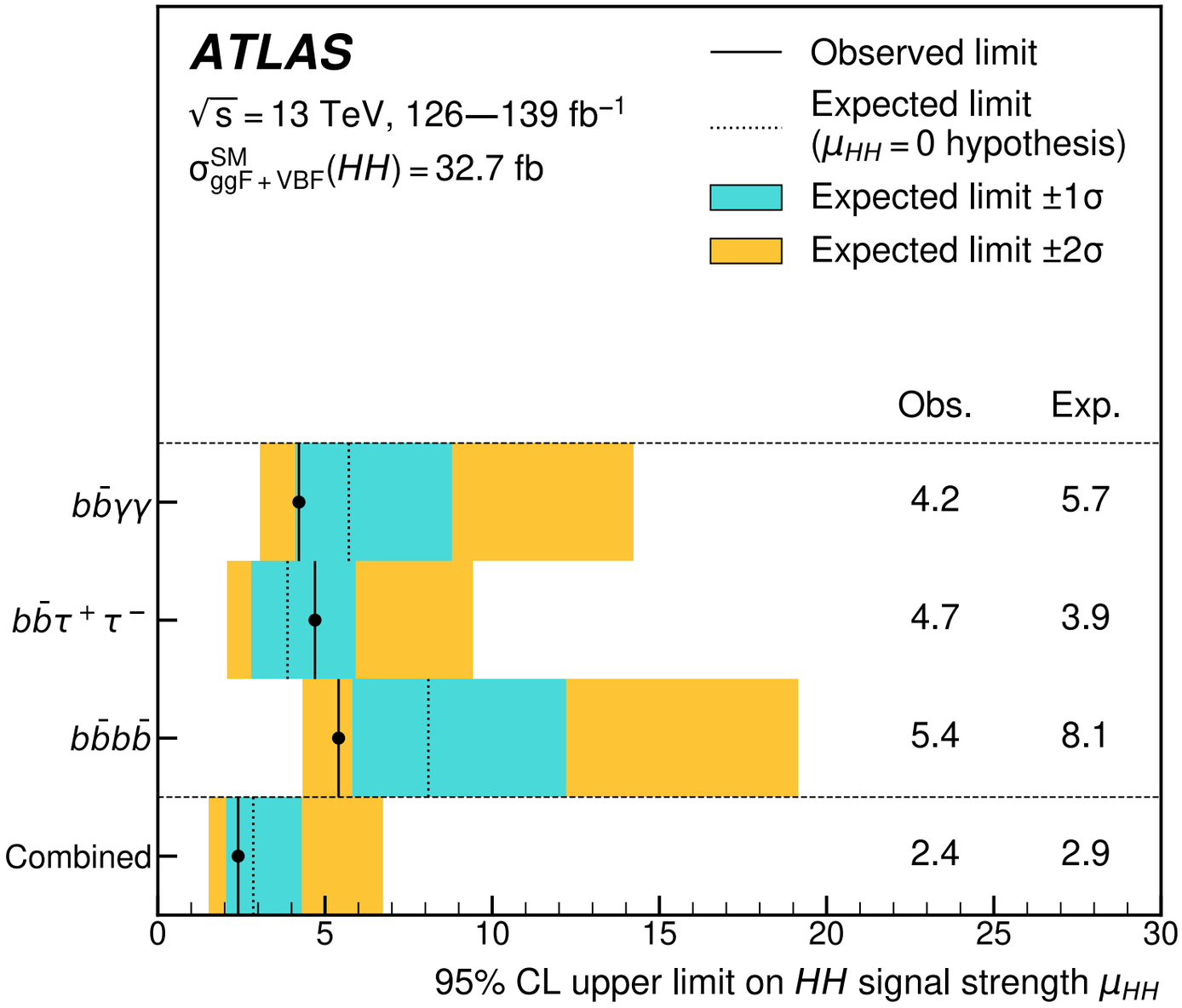

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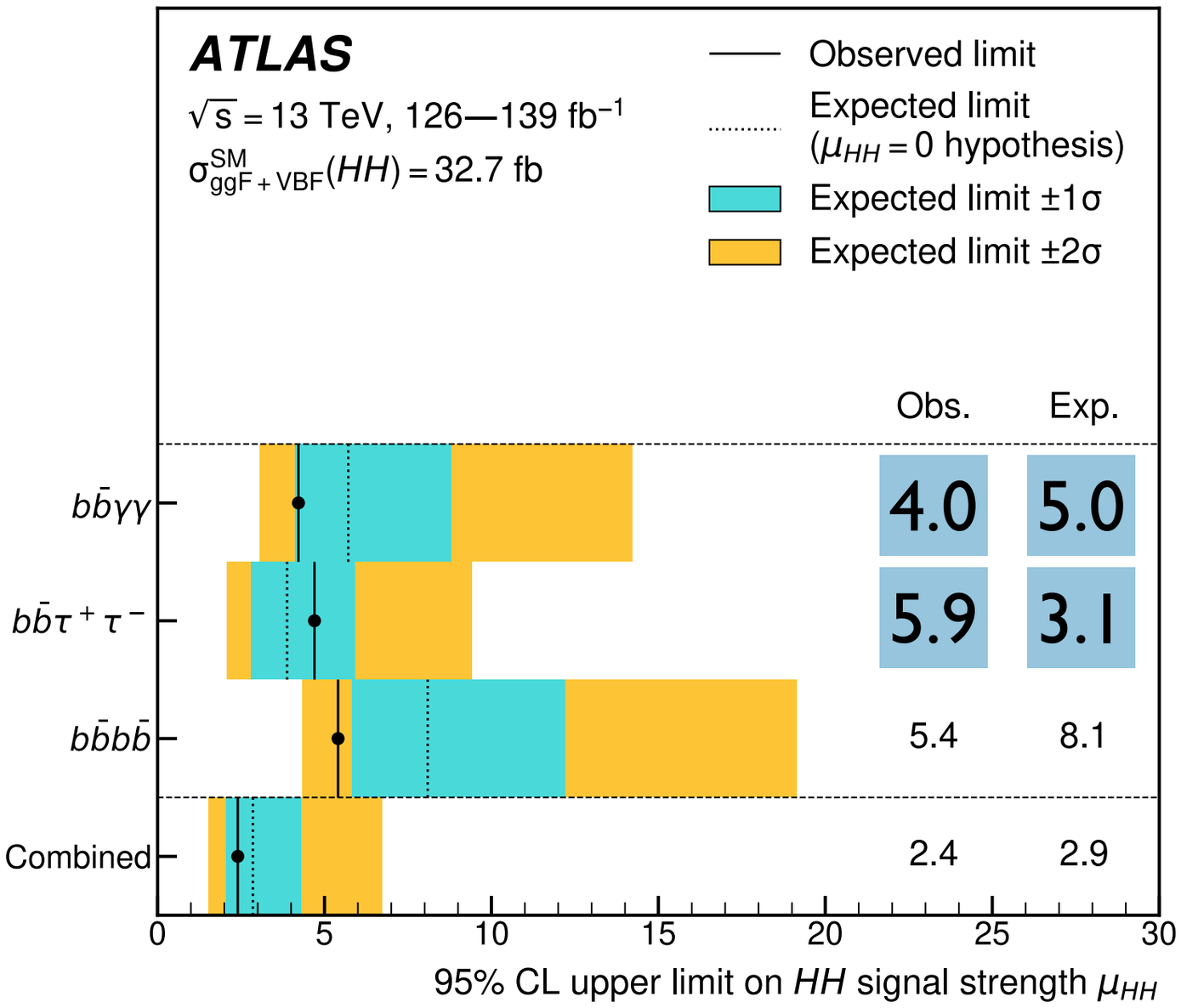
ATLAS-HDBS-2022-03

Limits on the SM



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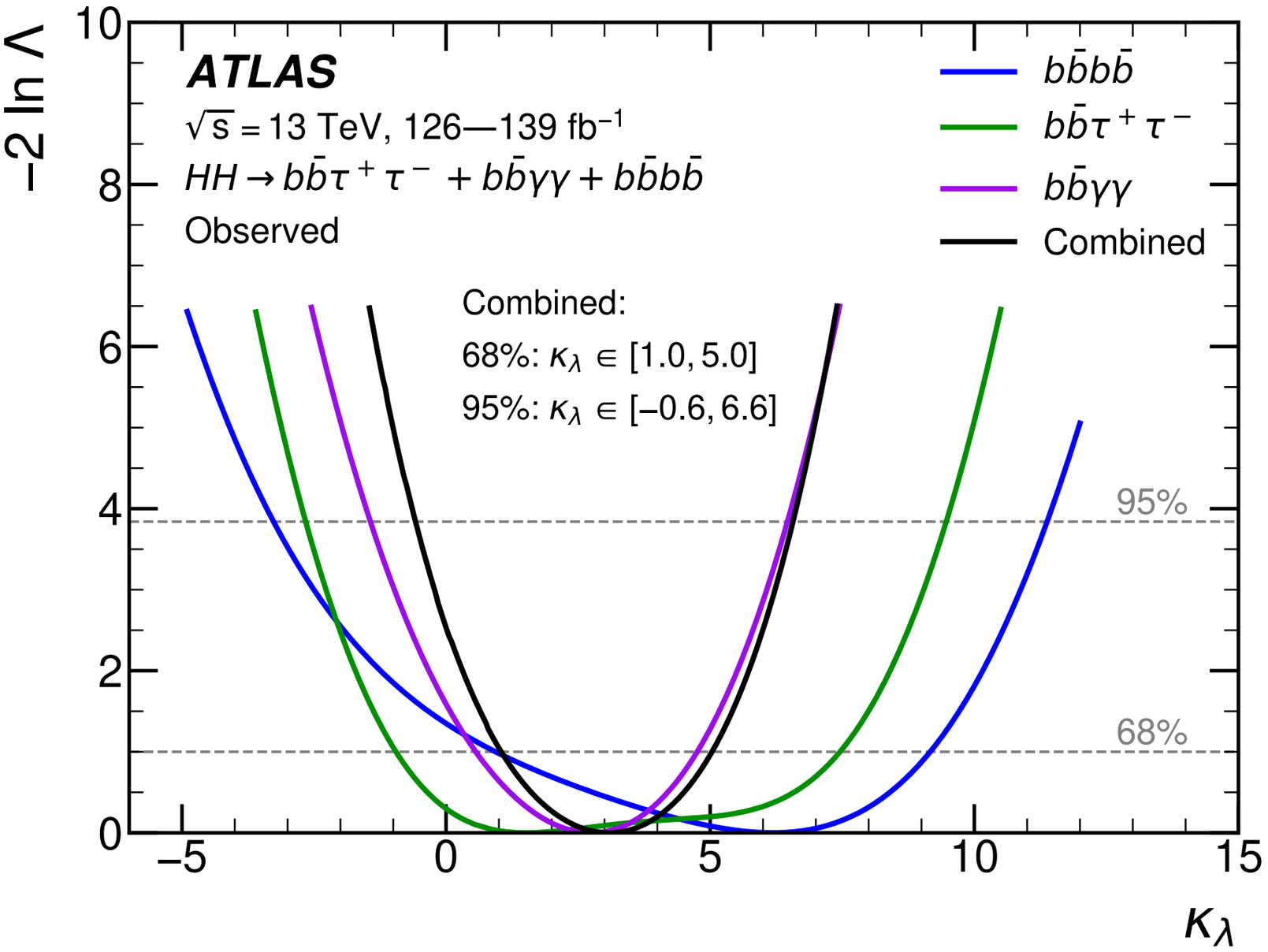
NB: not yet including **latest** $b\bar{b}\gamma\gamma, b\bar{b}\tau\bar{\tau}, b\bar{b}\ell\bar{\ell}$ results

ATLAS-HDBS-2022-03

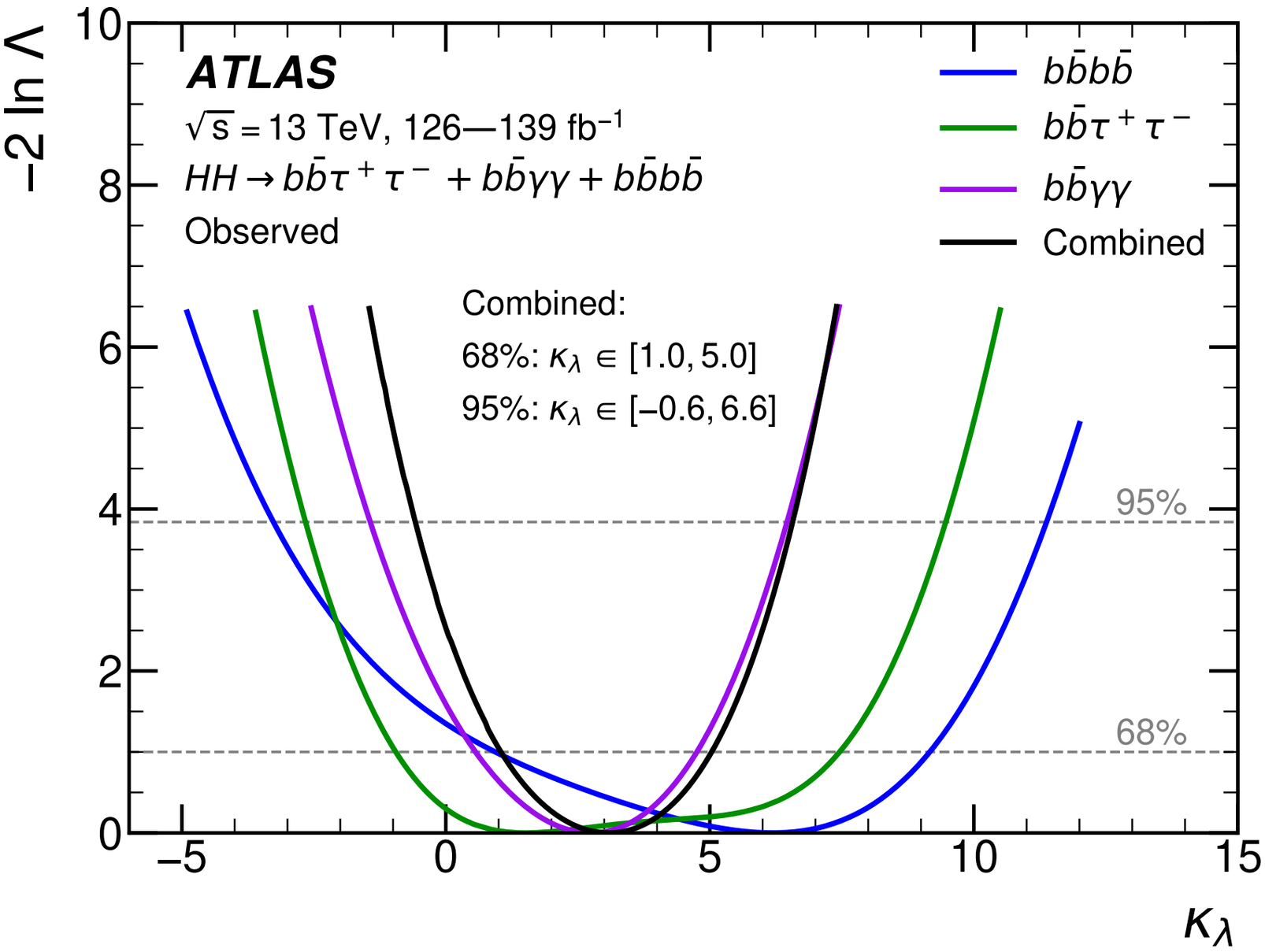
Measuring the Potential

Measuring the Potential

Here, show *likelihood* vs κ_λ



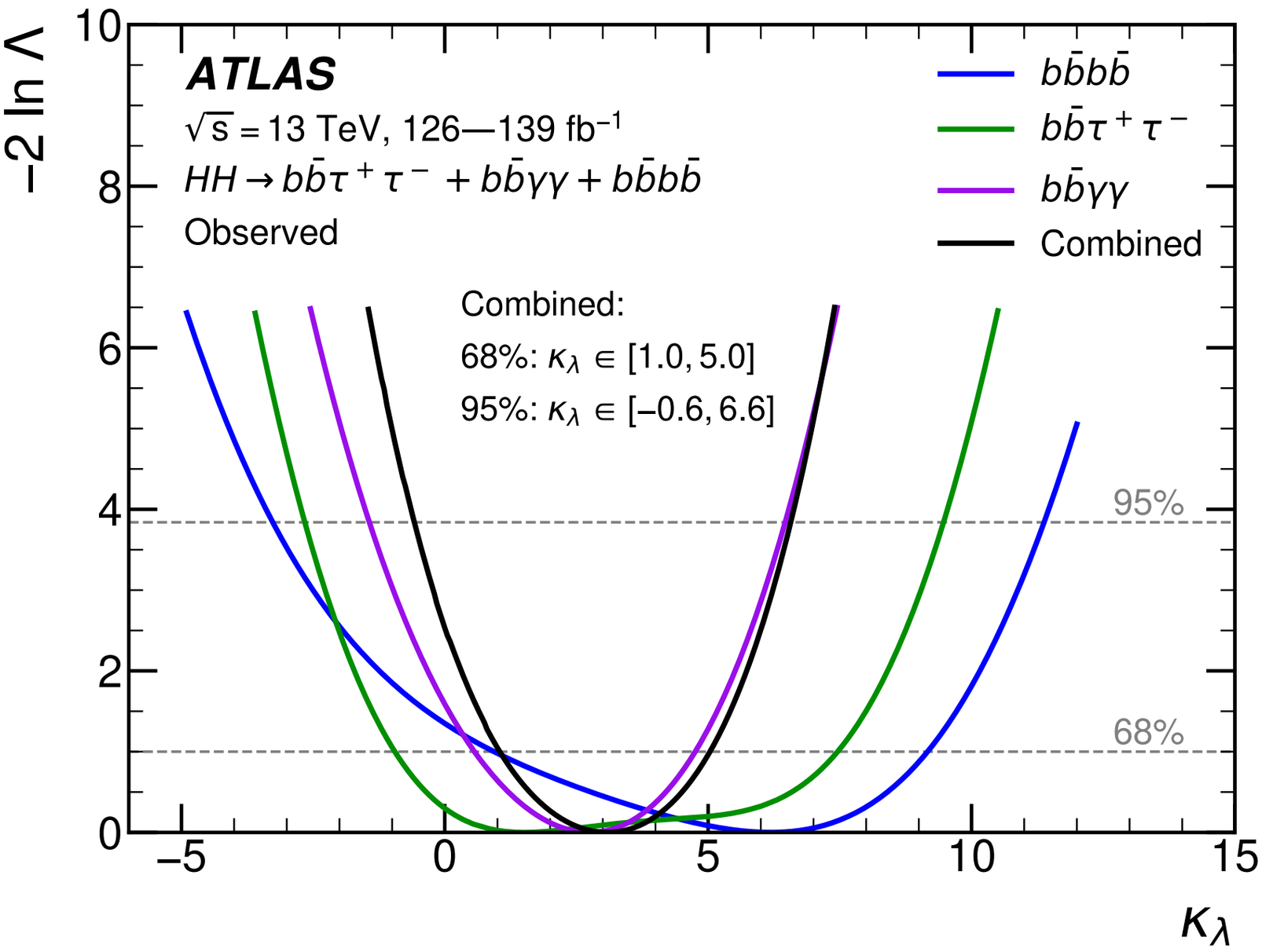
Measuring the Potential



Here, show *likelihood* vs κ_λ

Minimum here is the "best fit"

Measuring the Potential



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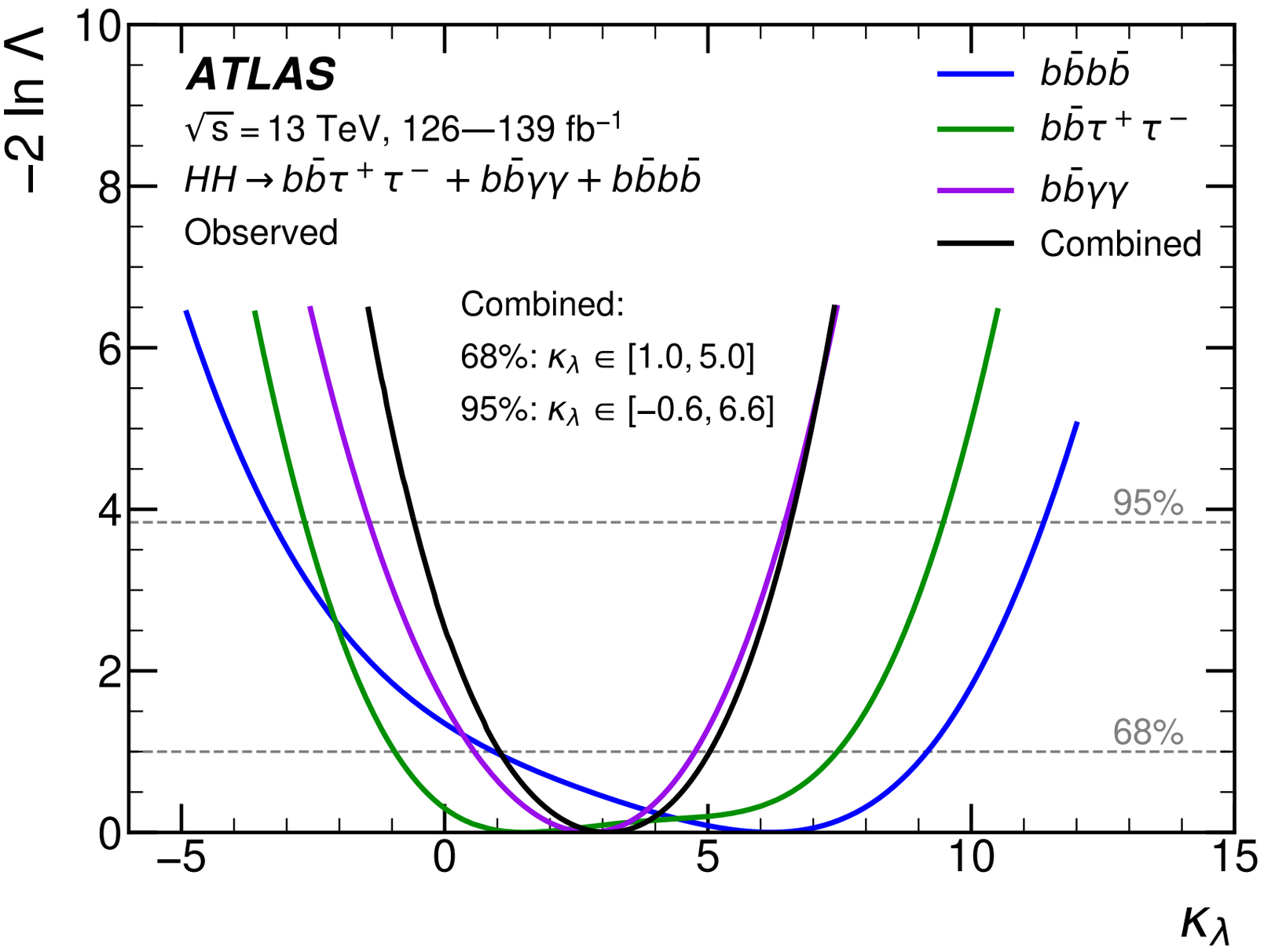

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Each of the three analyses contributes to the combination

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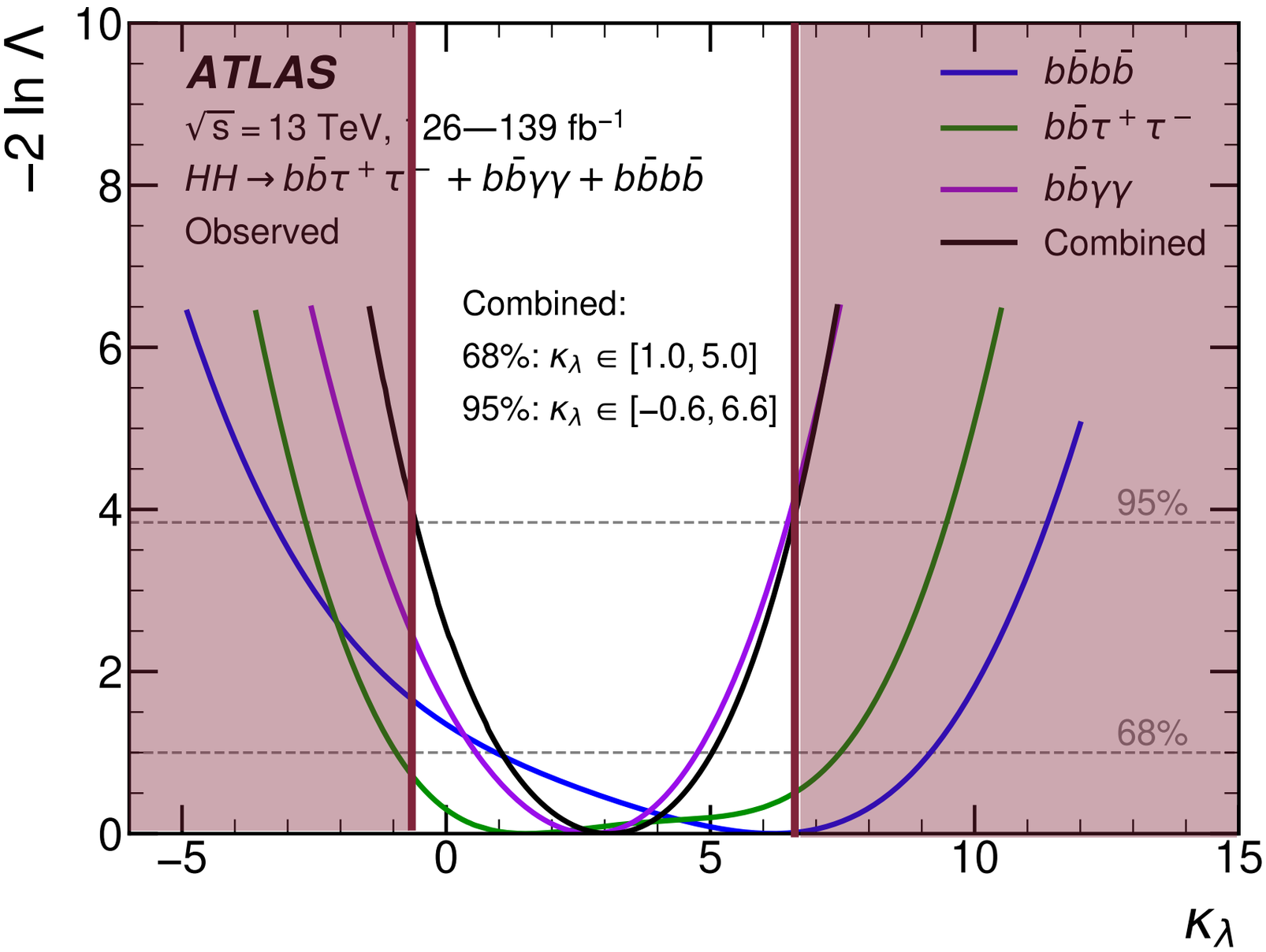

Here, show *likelihood* vs κ_λ

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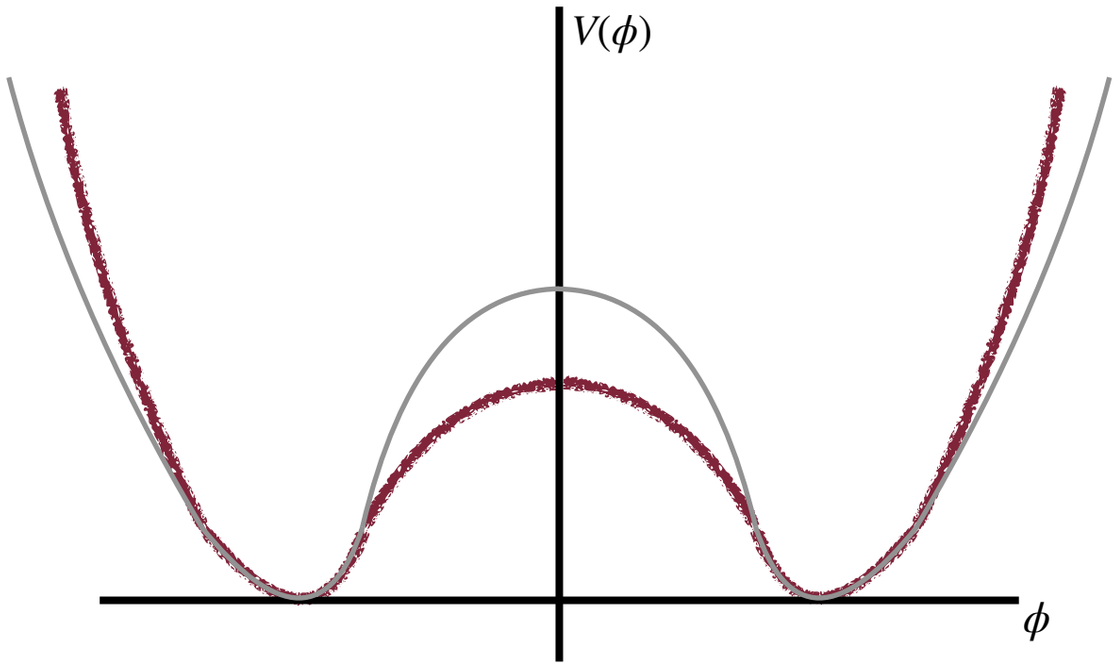
Each of the three analyses contributes to the combination

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

Conclusions

Conclusions

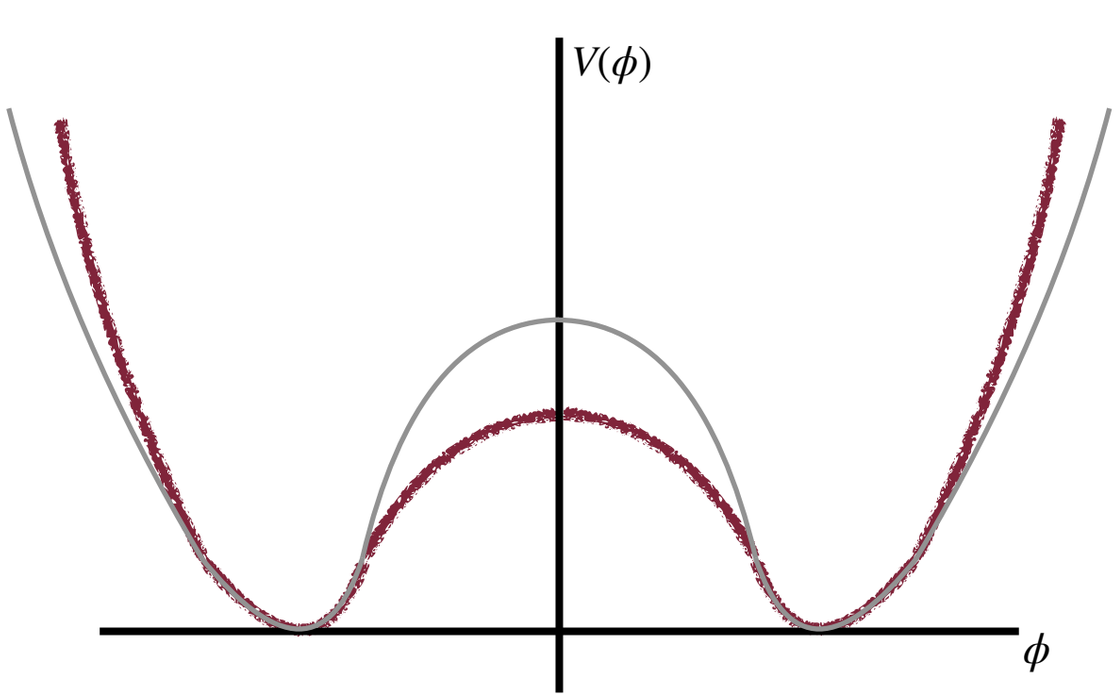
Higgs pair measurements let us directly probe the shape of the Higgs potential

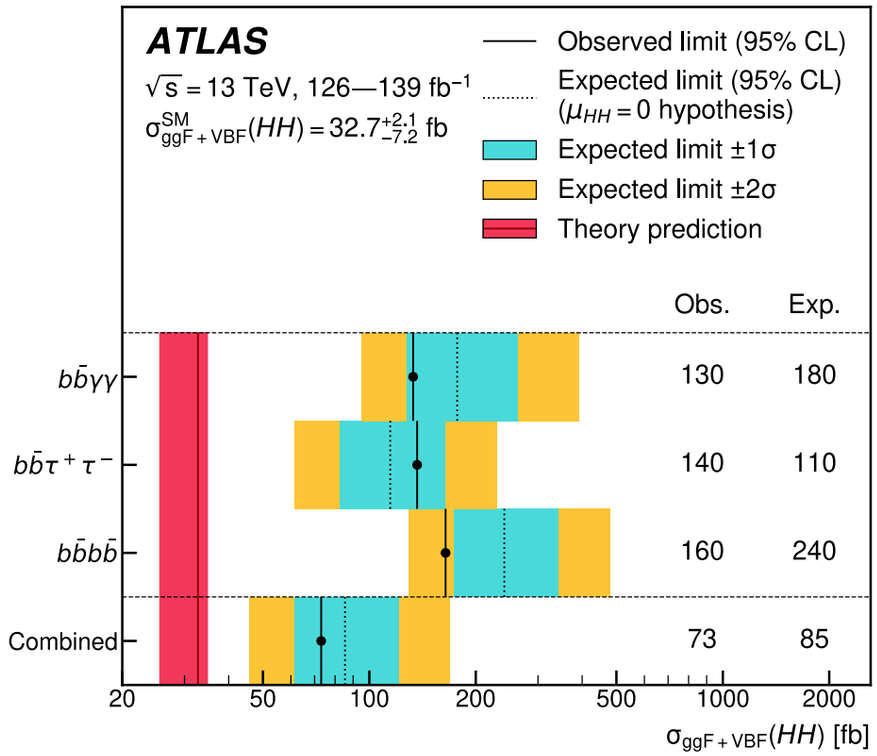


Conclusions

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

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



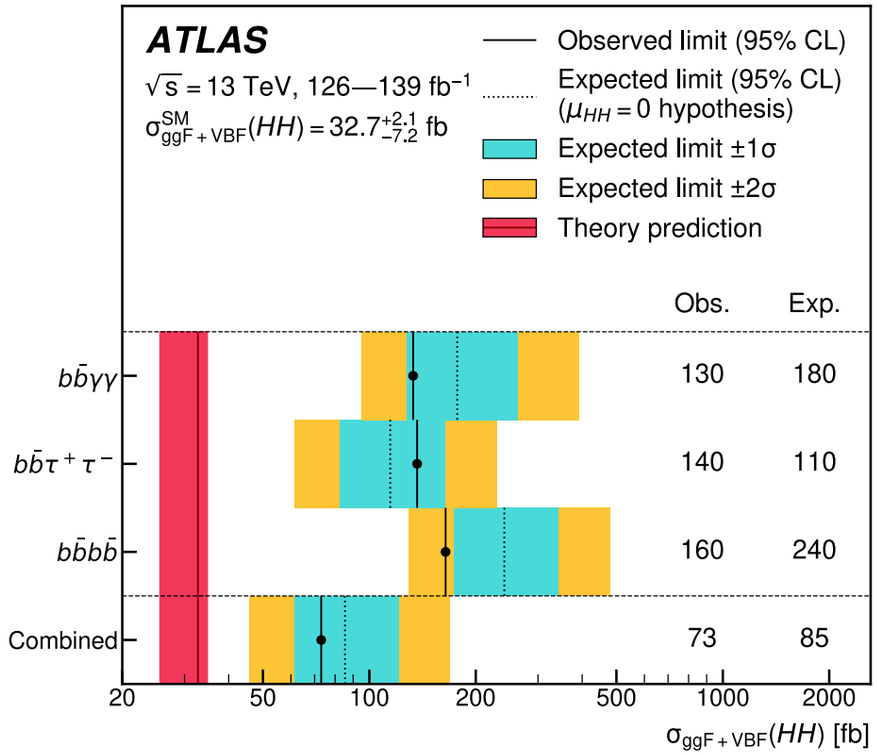


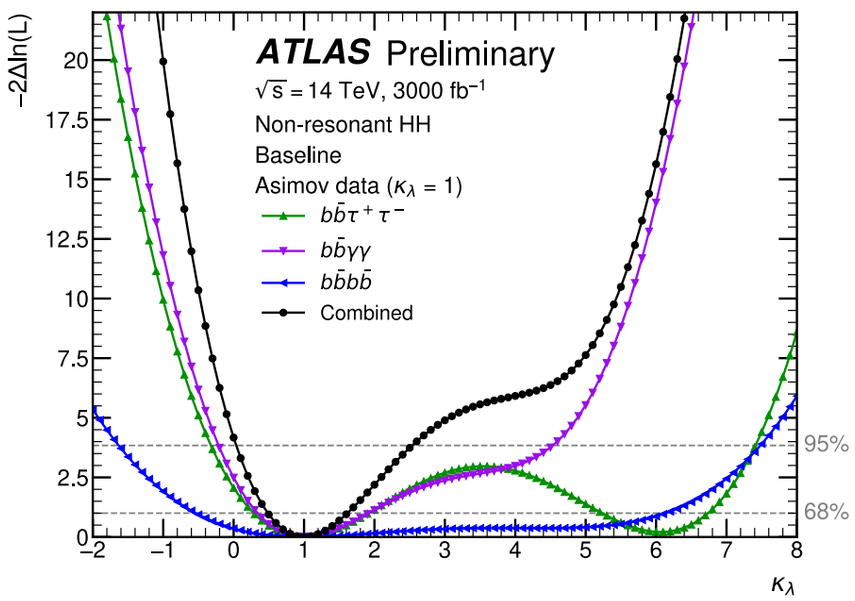
Conclusions

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

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-2022-053

Thank you!

More in:

ATLAS-HDBS-2021-10

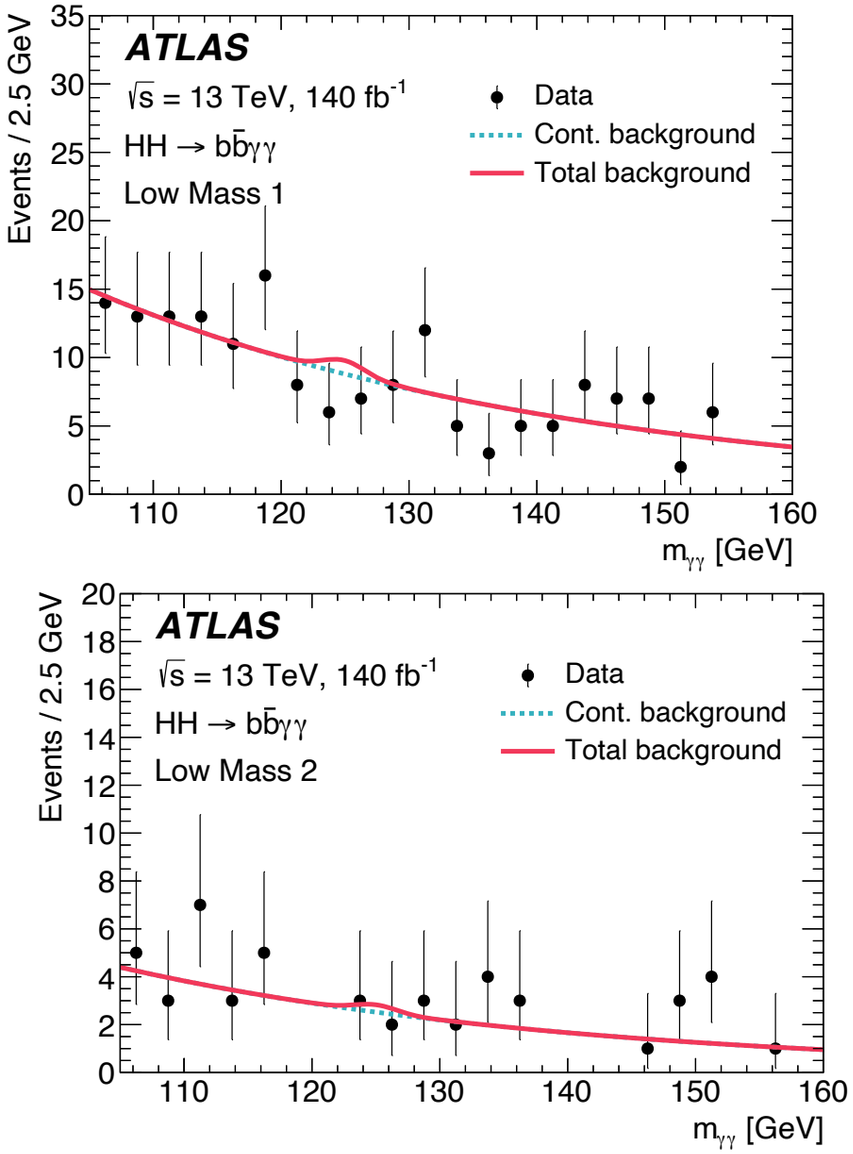
ATLAS-CONF-2023-071

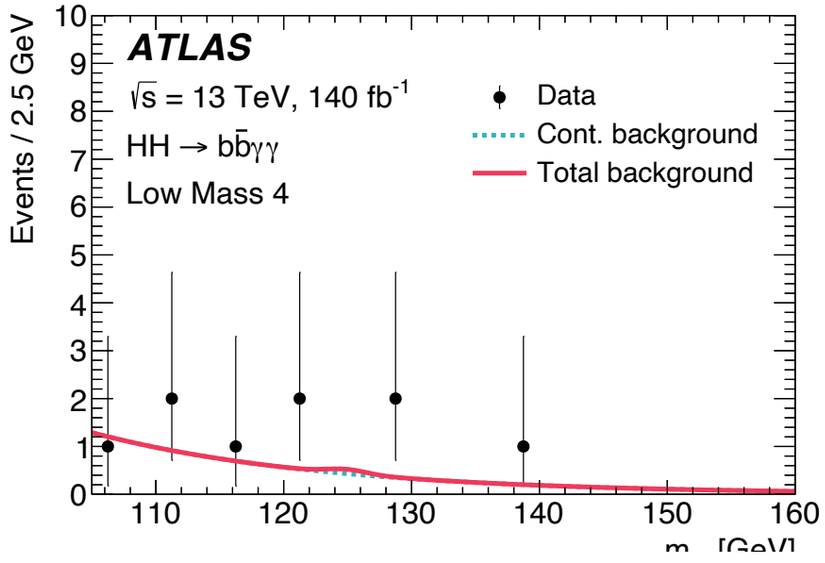
ATLAS-HDBS-2019-29

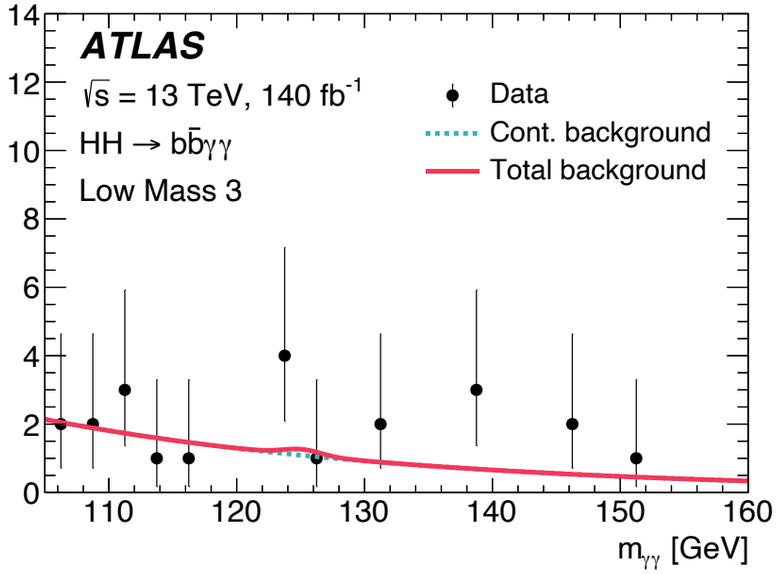
ATLAS-CONF-2022-03

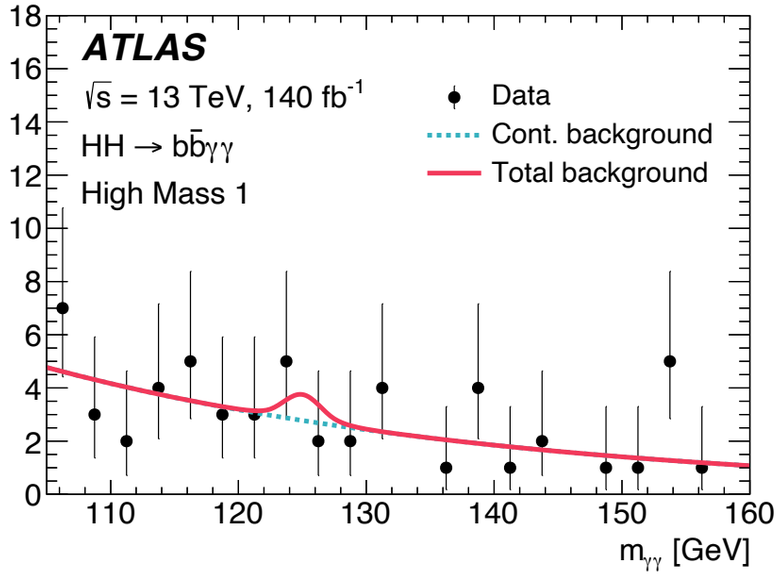
Backup

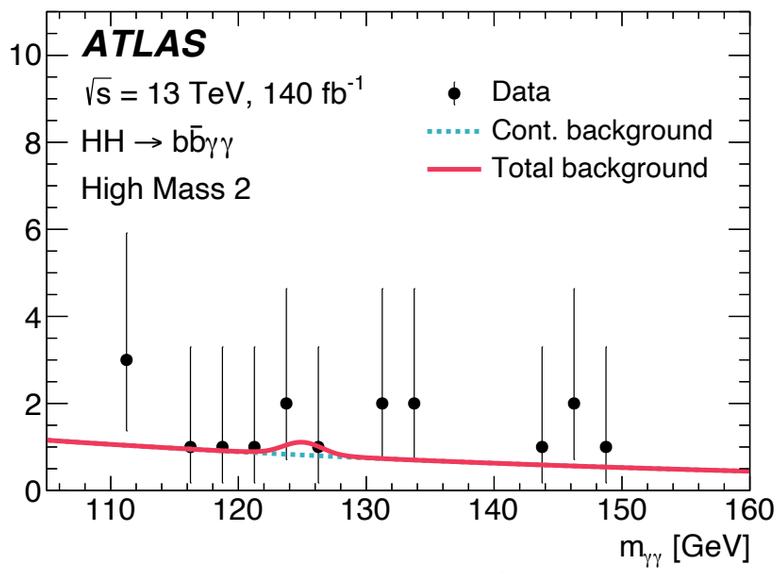
$b\bar{b}\gamma\gamma$ Results

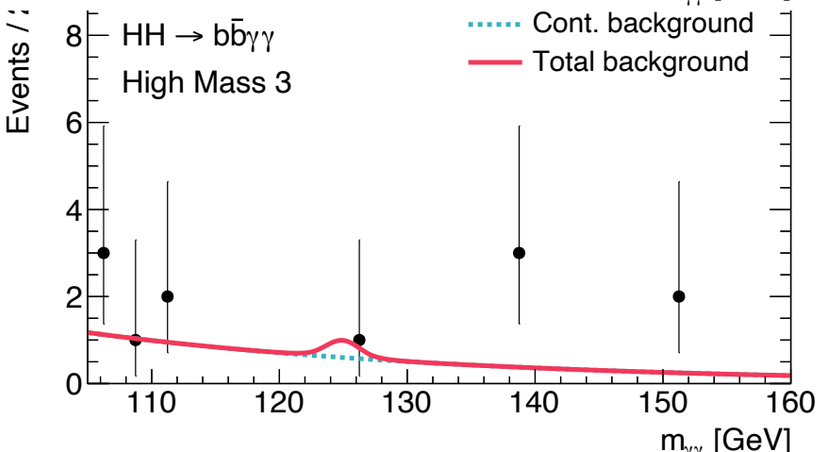




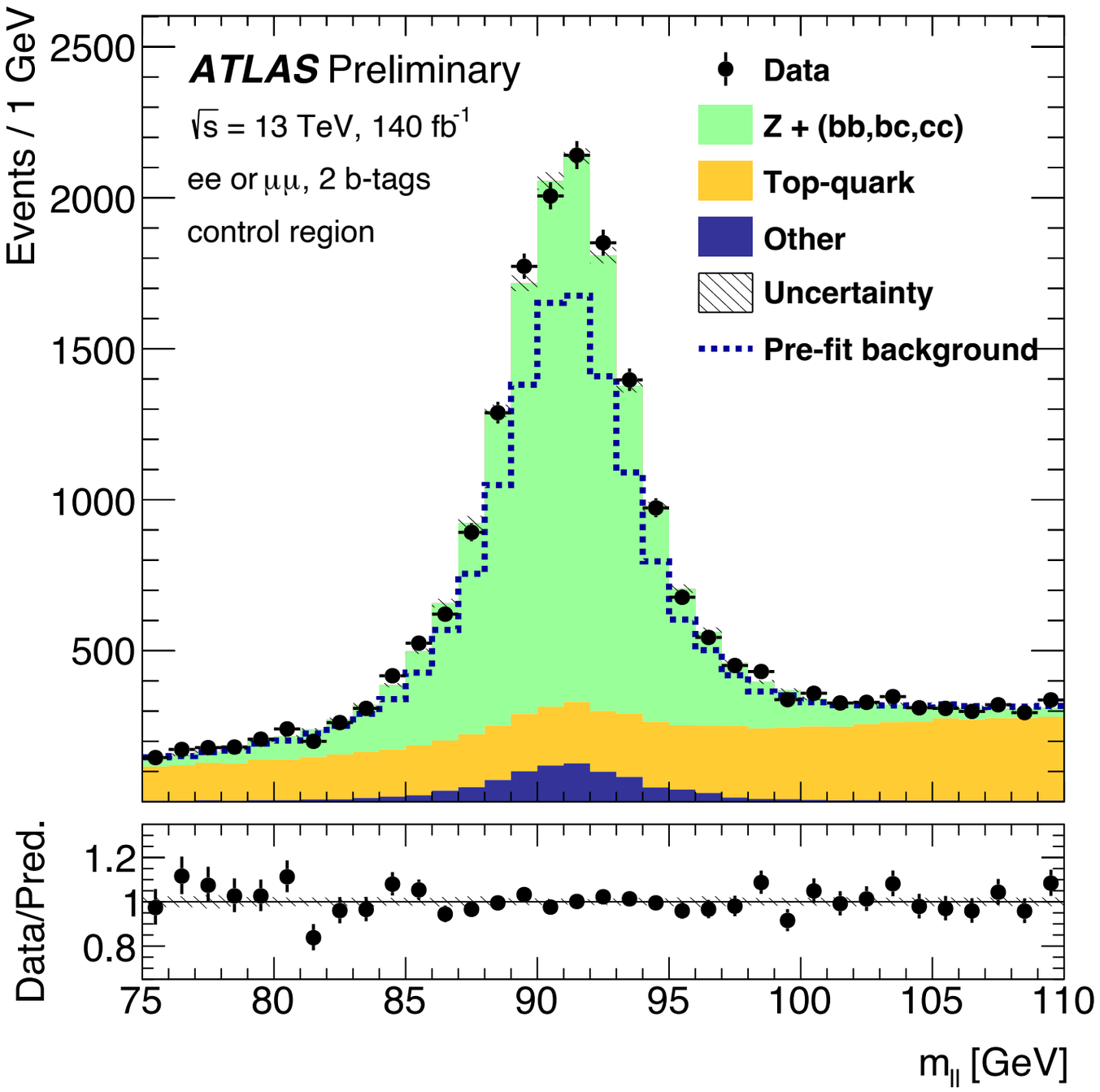








$b\bar{b}\tau\bar{\tau}$ Background Estimate

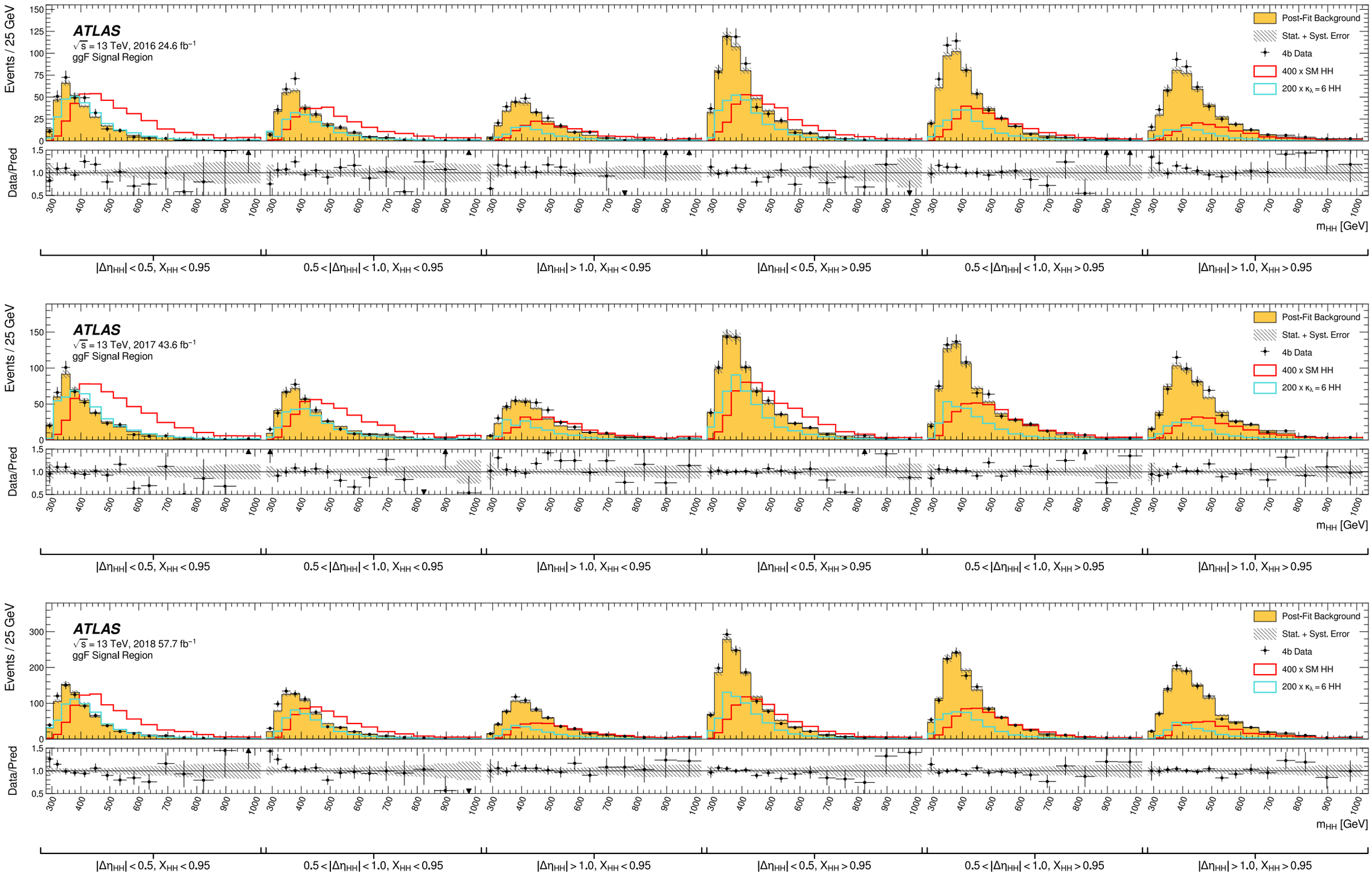


Top-quark background from MC, normalization floating in final fit

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

Fake τ estimated from data

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



Variables for MVAs

- For $b\bar{b}\gamma\gamma$: photon kinematics, b-jet kinematics, bb-system kinematics, missing energy, total energy, "top-ness"

- For $b\bar{b}b\bar{b}$:

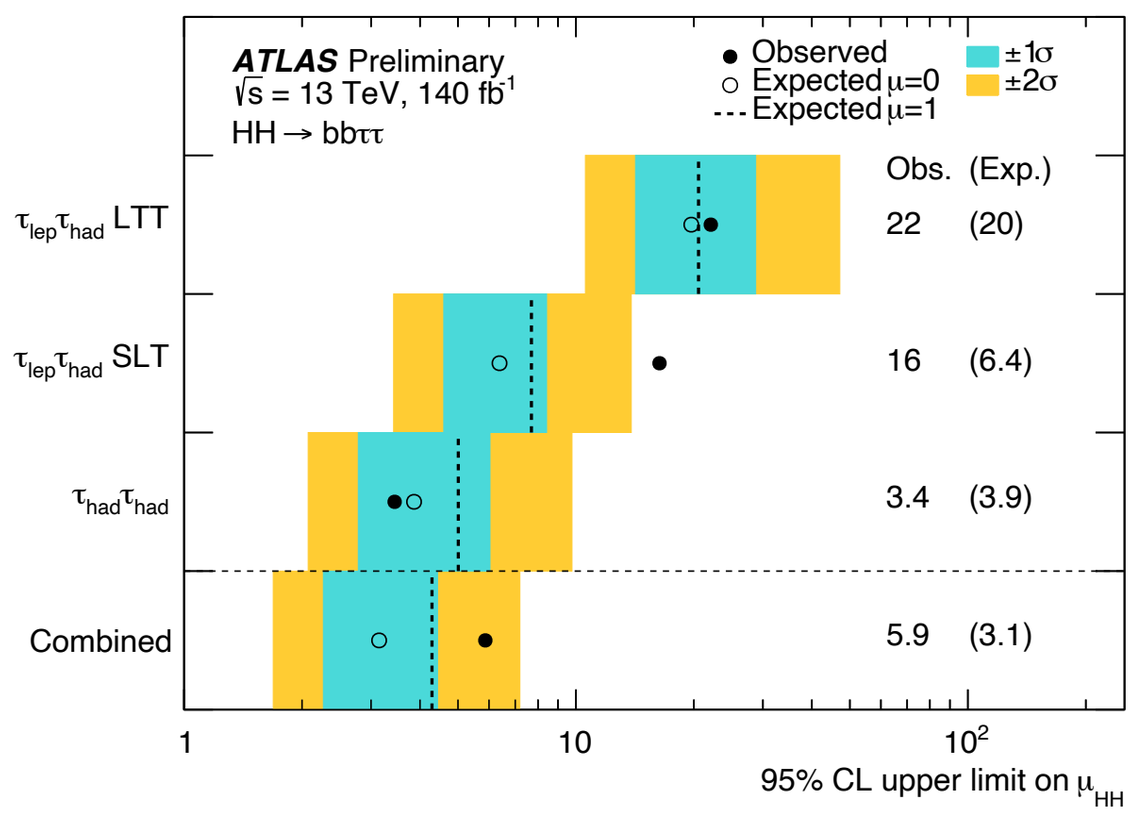
1. $\log(p_{\mathrm{T}})$ of the selected jet with the 2^{nd}-highest p_{T},
2. $\log(p_{\mathrm{T}})$ of the selected jet with the 4^{th}-highest p_{T},
3. $\log(\Delta R)$ between the two selected jets with the smallest ΔR,
4. $\log(\Delta R)$ between the other two selected jets,
5. the average $|\eta|$ 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 $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $|\eta| < 2.5$, including jets that are not selected.

Variables for bbττ

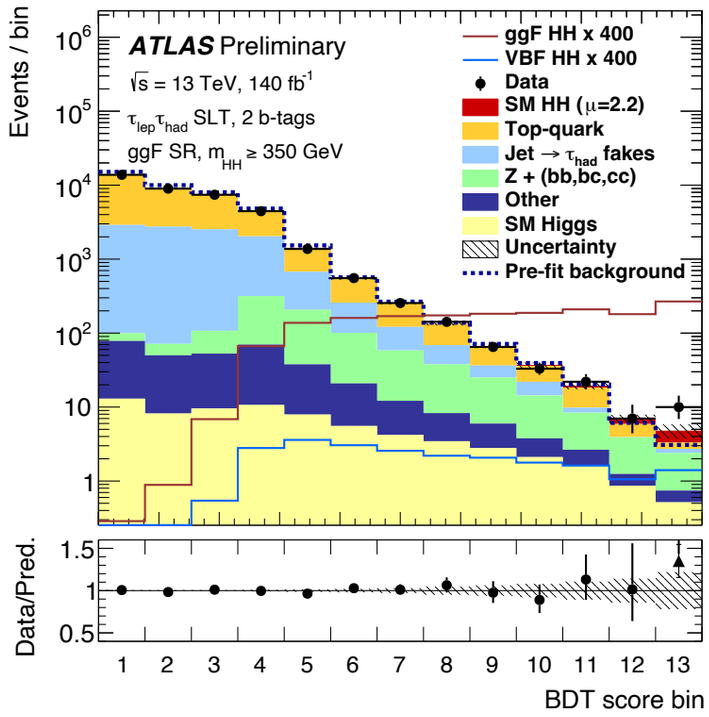
Variable	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{had}}$ SLT	$\tau_{\text{lep}}\tau_{\text{had}}$ LTT
m_{jj}^{VBF}	✓	✓	✓
$\Delta\eta_{jj}^{\text{VBF}}$	✓	✓	✓
VBF $\eta_0 \times \eta_1$	✓	✓	
$\Delta\phi_{jj}^{\text{VBF}}$	✓		
$\Delta R_{jj}^{\text{VBF}}$		✓	✓
$\Delta R_{\tau\tau}$	✓		
m_{HH}	✓		
f_2^a	✓		
C^a		✓	✓
m_{Eff}^a		✓	✓
f_0^c		✓	
f_0^a			✓
h_3^a			✓

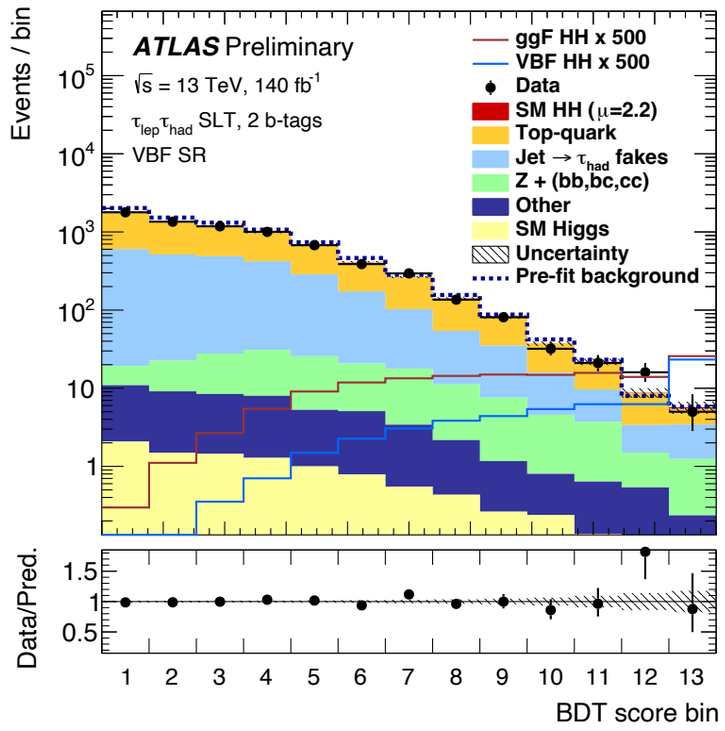
Limits for bbττ

		μ_{HH}	μ_{ggF}	μ_{VBF}	μ_{ggF} (μ_{VBF}=1)	μ_{VBF} (μ_{ggF}=1)
$\tau_{\text{had}}\tau_{\text{had}}$	observed	3.4	3.6	87	3.5	80
	expected	3.9	4.0	103	3.9	101
$\tau_{\text{lep}}\tau_{\text{had}}$ SLT	observed	16.4	16.9	133	16.7	155
	expected	6.4	6.6	128	6.5	125
$\tau_{\text{lep}}\tau_{\text{had}}$ LTT	observed	22	18	767	21	731
	expected	20	21	323	20	317
Combined	observed	5.9	5.8	91	5.9	94
	expected	$3.1^{+1.3}_{-0.9}$	$3.2^{1.7}_{0.9}$	72^{+32}_{-20}	$3.2^{+1.7}_{-0.9}$	71^{+31}_{-20}



bbττ


ATLAS Preliminary
√s = 13 TeV, 140 fb-1
τlepτhad SLT, 2 b-tags
ggF SR, mHH ≥ 350 GeV
ggF HH x 400
VBF HH x 400
Data
SM HH (μ=2.2)
Top-quark
Jet → τhad fakes
Z + (bb,bc,cc)
Other
SM Higgs
Uncertainty
Pre-fit background
Events / bin
Data/Pred.
BDT score bin


ATLAS Preliminary
√s = 13 TeV, 140 fb-1
τlepτhad SLT, 2 b-tags
VBF SR
ggF HH x 500
VBF HH x 500
Data
SM HH (μ=2.2)
Top-quark
Jet → τhad fakes
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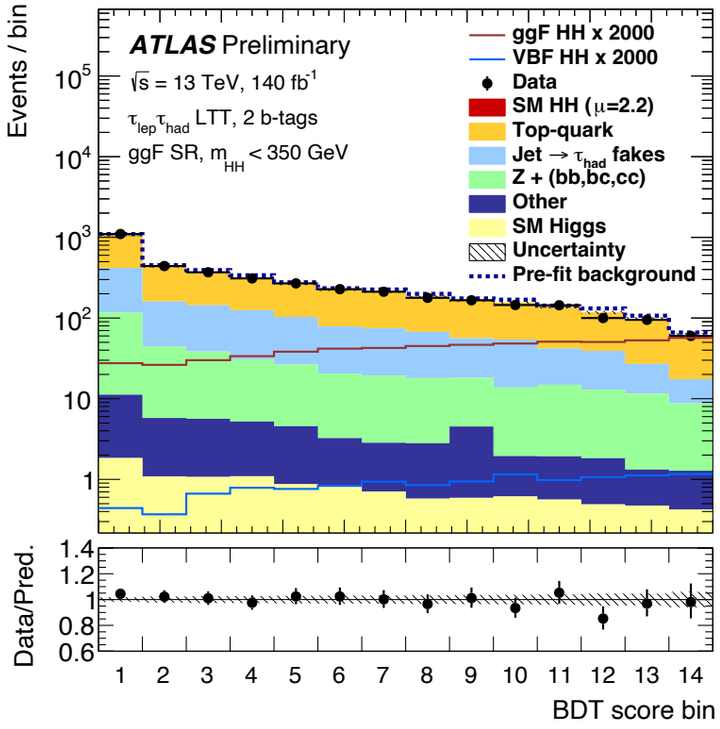
ATLAS Preliminary
√s = 13 TeV, 140 fb-1
τlepτhad LTT, 2 b-tags
ggF SR, mHH < 350 GeV
ggF HH x 2000
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SM HH (μ=2.2)
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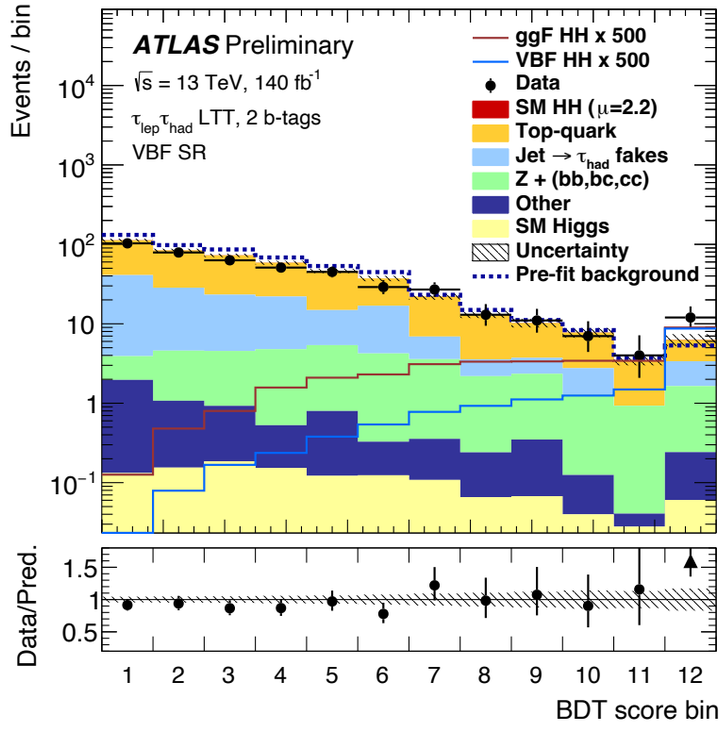
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√s = 13 TeV, 140 fb-1
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Resonant Searches

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

The SM's potential only choice that
is *gauge invariant, renormalizable*

Resonant Searches

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

The SM's potential only choice that is *gauge invariant, renormalizable*

$$V(\phi) = -m^2\phi^2 + \lambda\phi^4 + C\phi^6 + D\phi^8 + \ldots$$

If we want modifications like these

C and D terms: they have to emerge from new physics

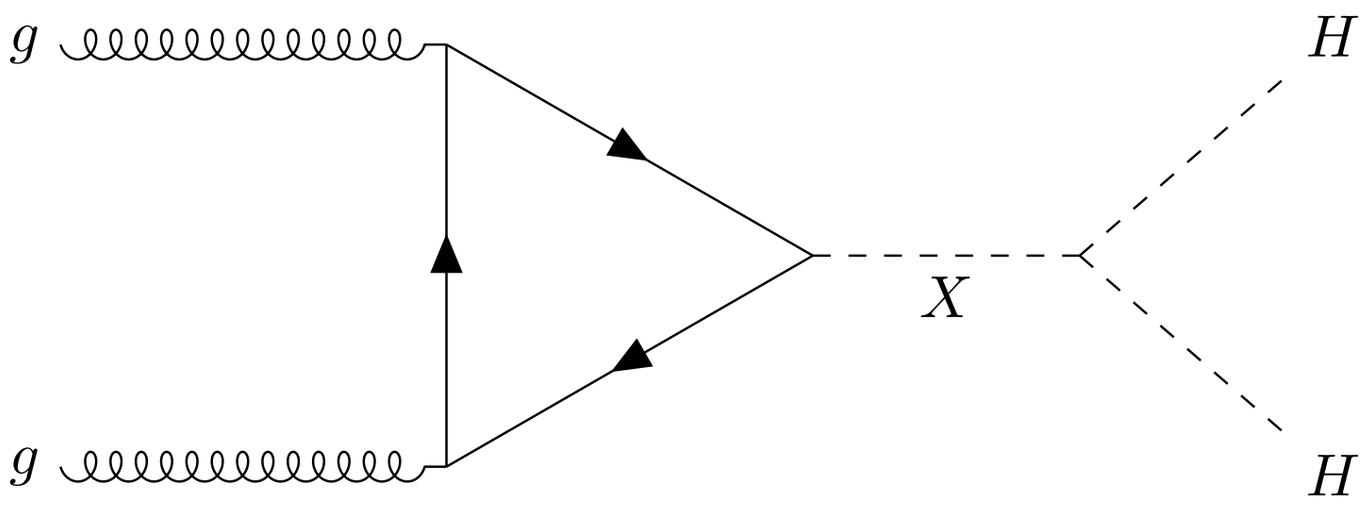
Resonant Searches

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

The SM's potential only choice that
is *gauge invariant, renormalizable*

$$V(\phi) = -m^2\phi^2 + \lambda\phi^4 + C\phi^6 + D\phi^8 + \ldots$$

If we want modifications like these
C and D terms: they have to
emerge from new physics

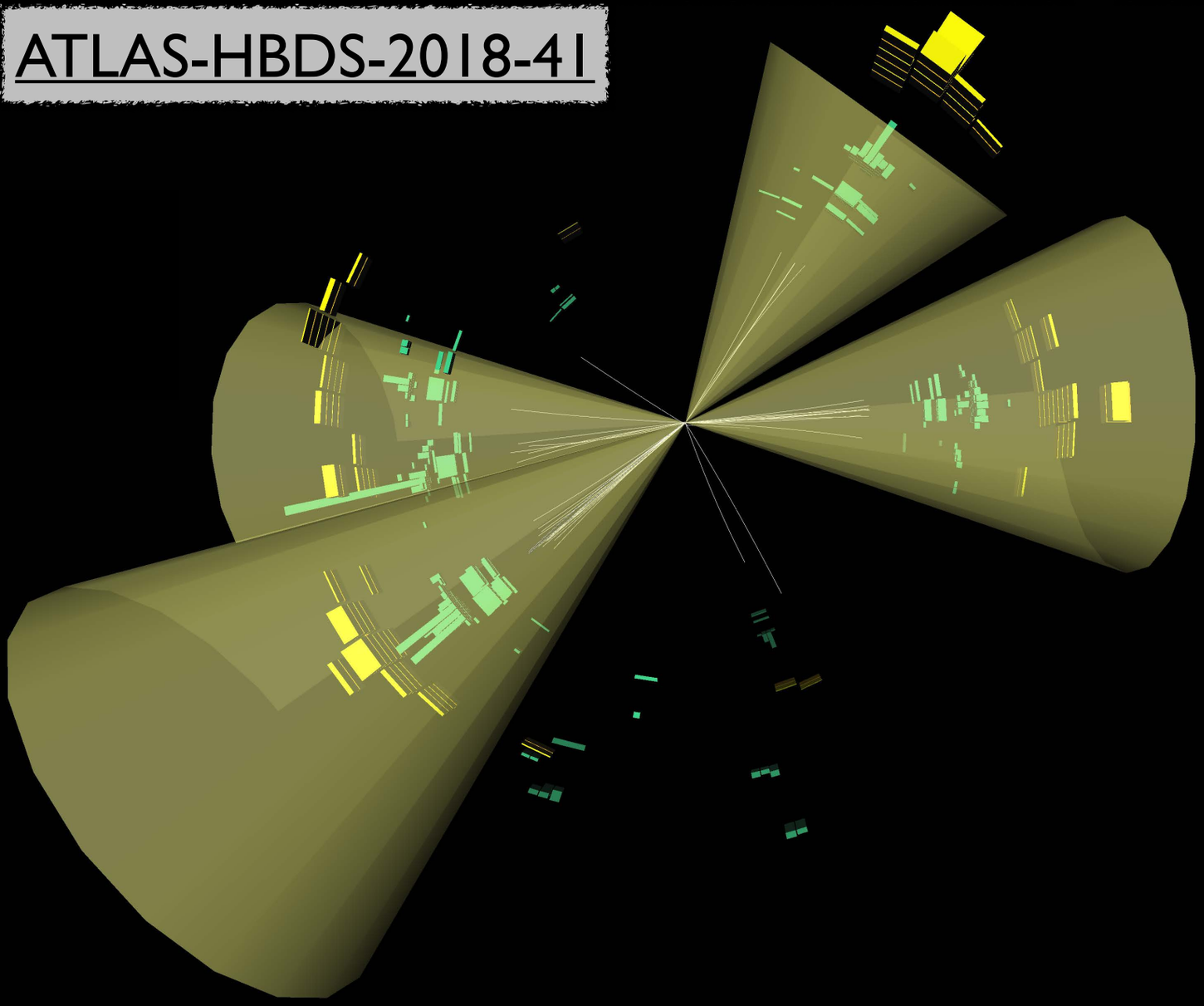


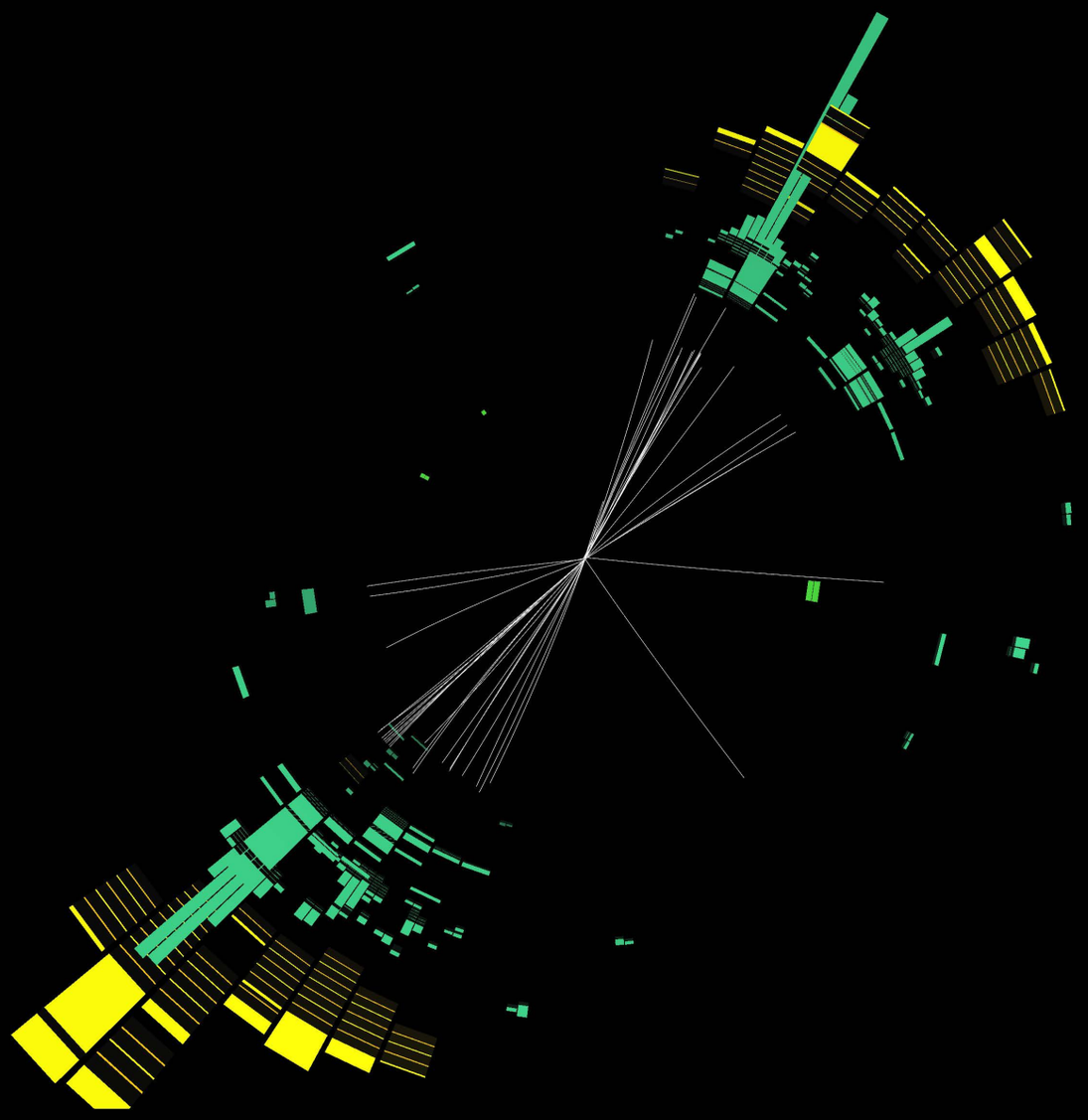
Like a new resonance!

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

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

ATLAS-HBDS-2018-41





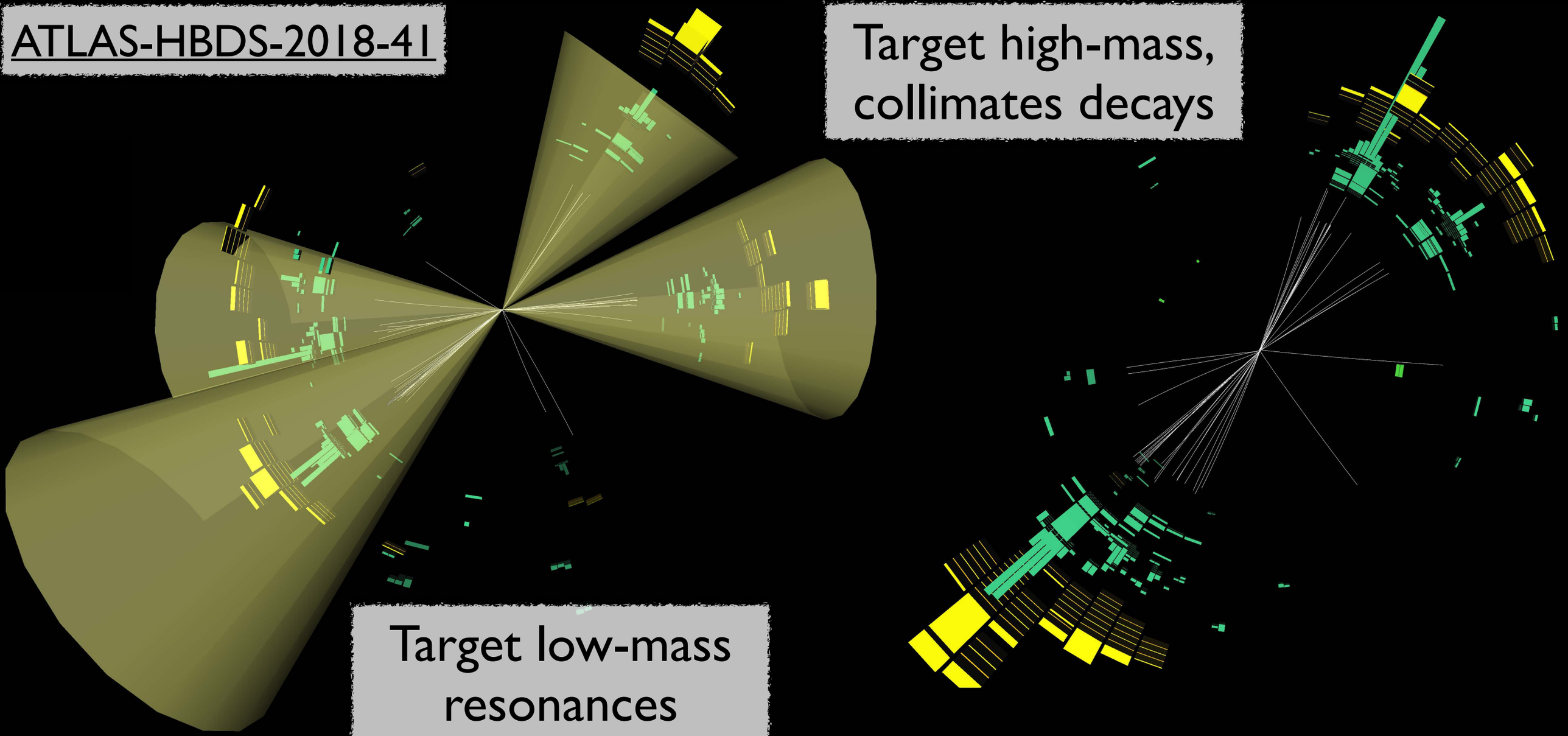
$HH \to b\bar{b}b\bar{b}$ Resolved

ATLAS-HBDS-2018-41

Target low-mass resonances

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

Target high-mass, collimates decays



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

ATLAS-HBDS-2018-41

Target low-mass resonances

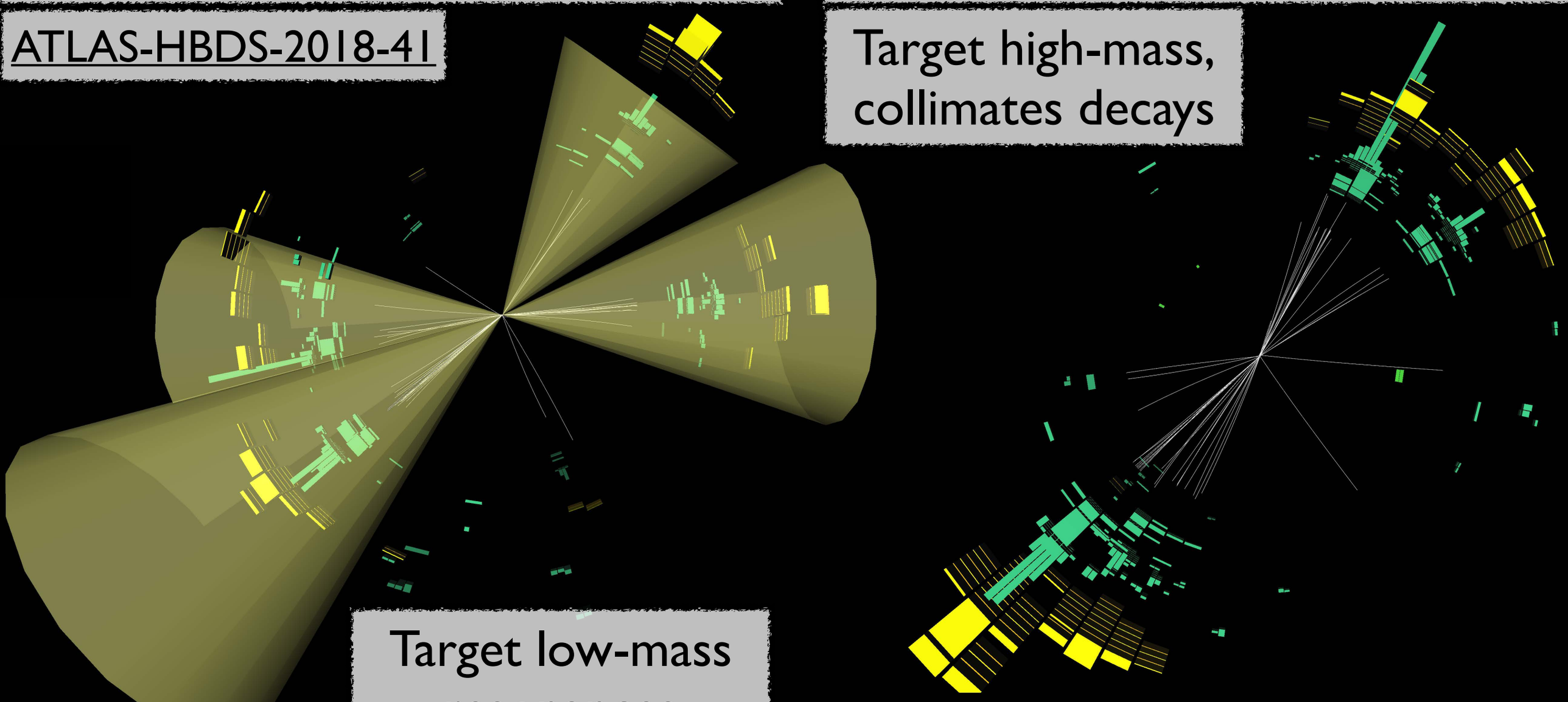
Combination of ~4 b-jet triggers

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

Boosted Decision Tree used to pair jets

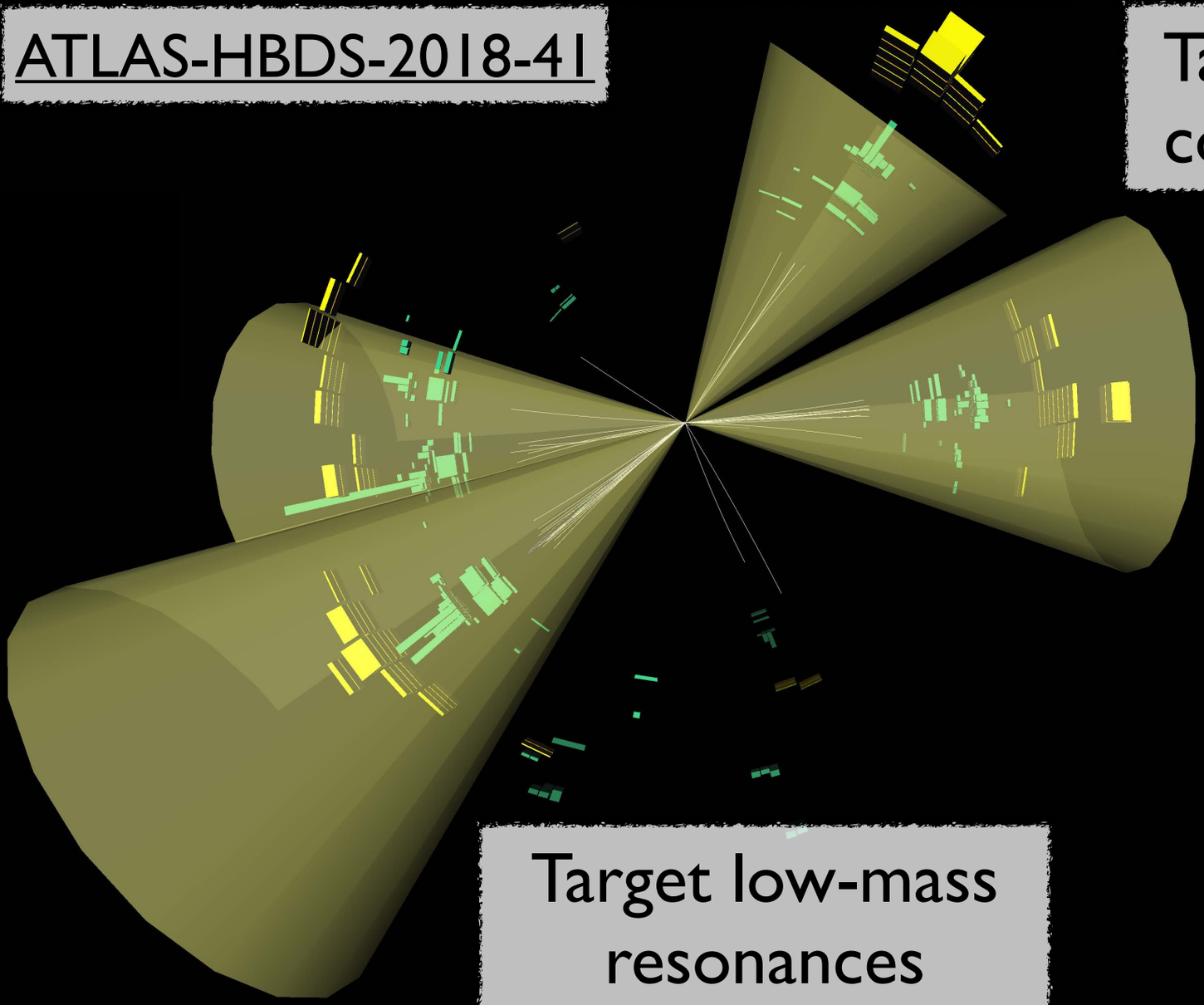
$HH \to b\bar{b}b\bar{b}$ Boosted

Target high-mass, collimates decays



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

ATLAS-HBDS-2018-41



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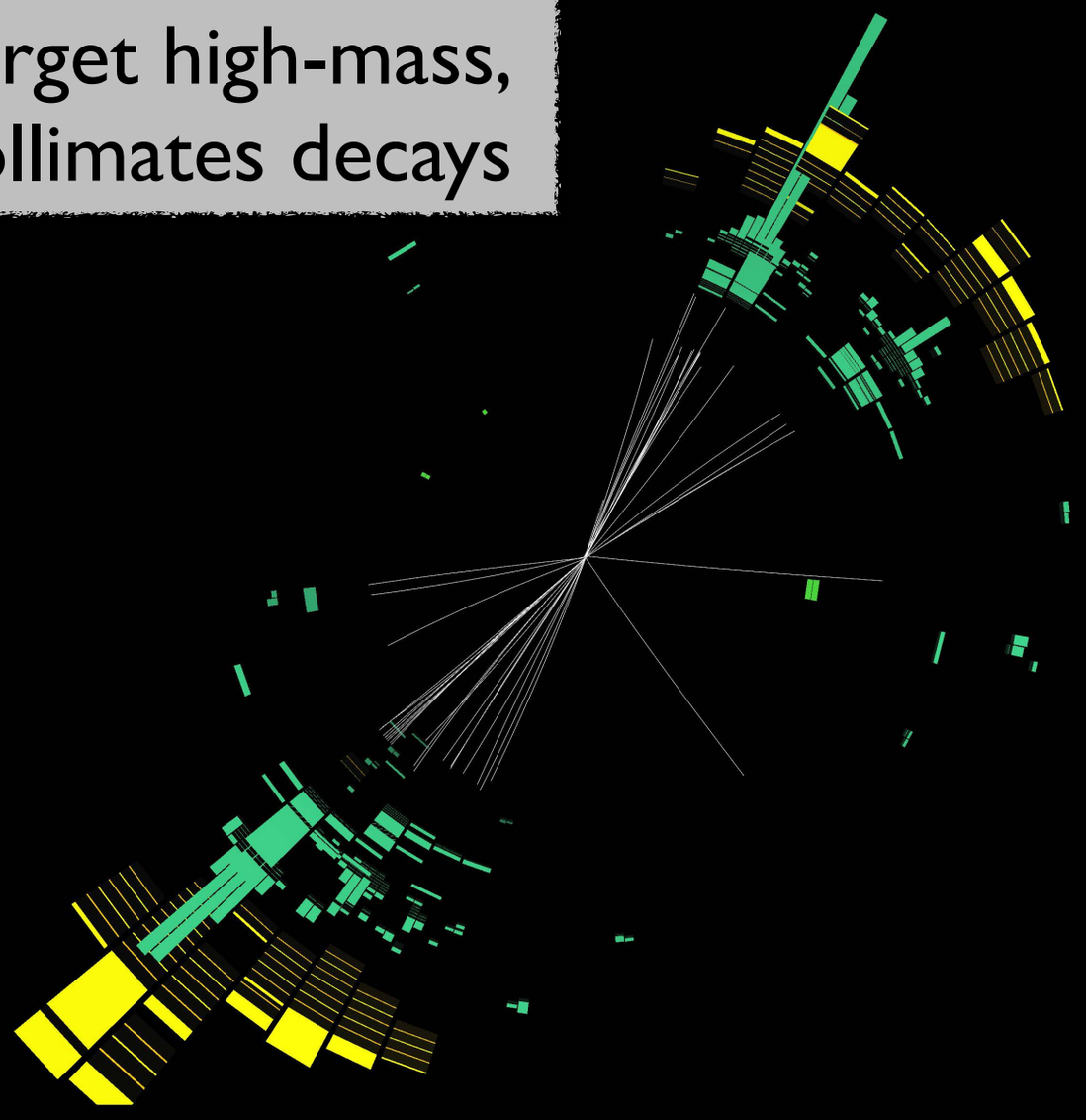


Large-R jet trigger ($E_T > 450$ GeV)

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

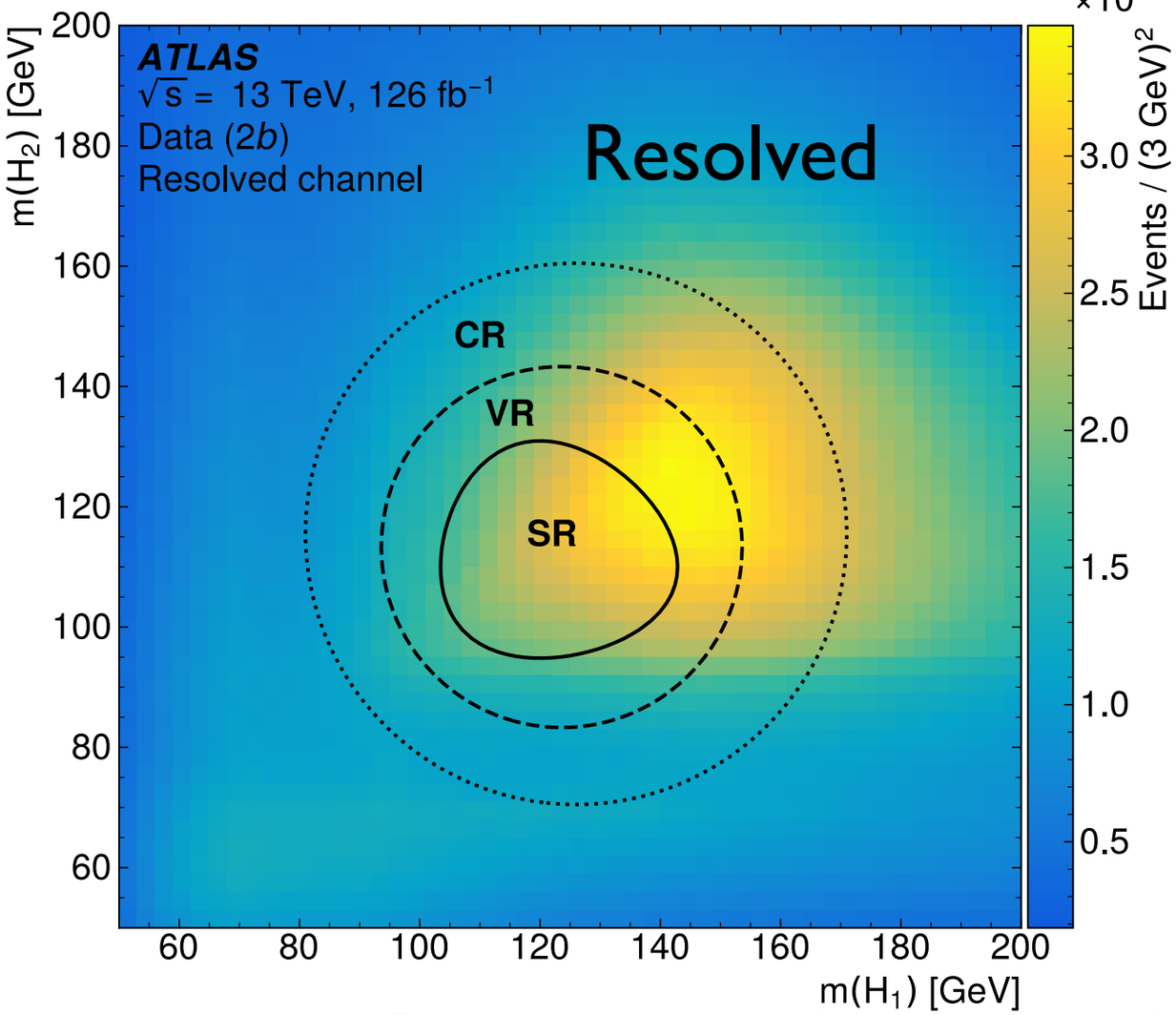
2, 3, or 4 b-tags (via track-jets, $\epsilon = 77\,\%$)

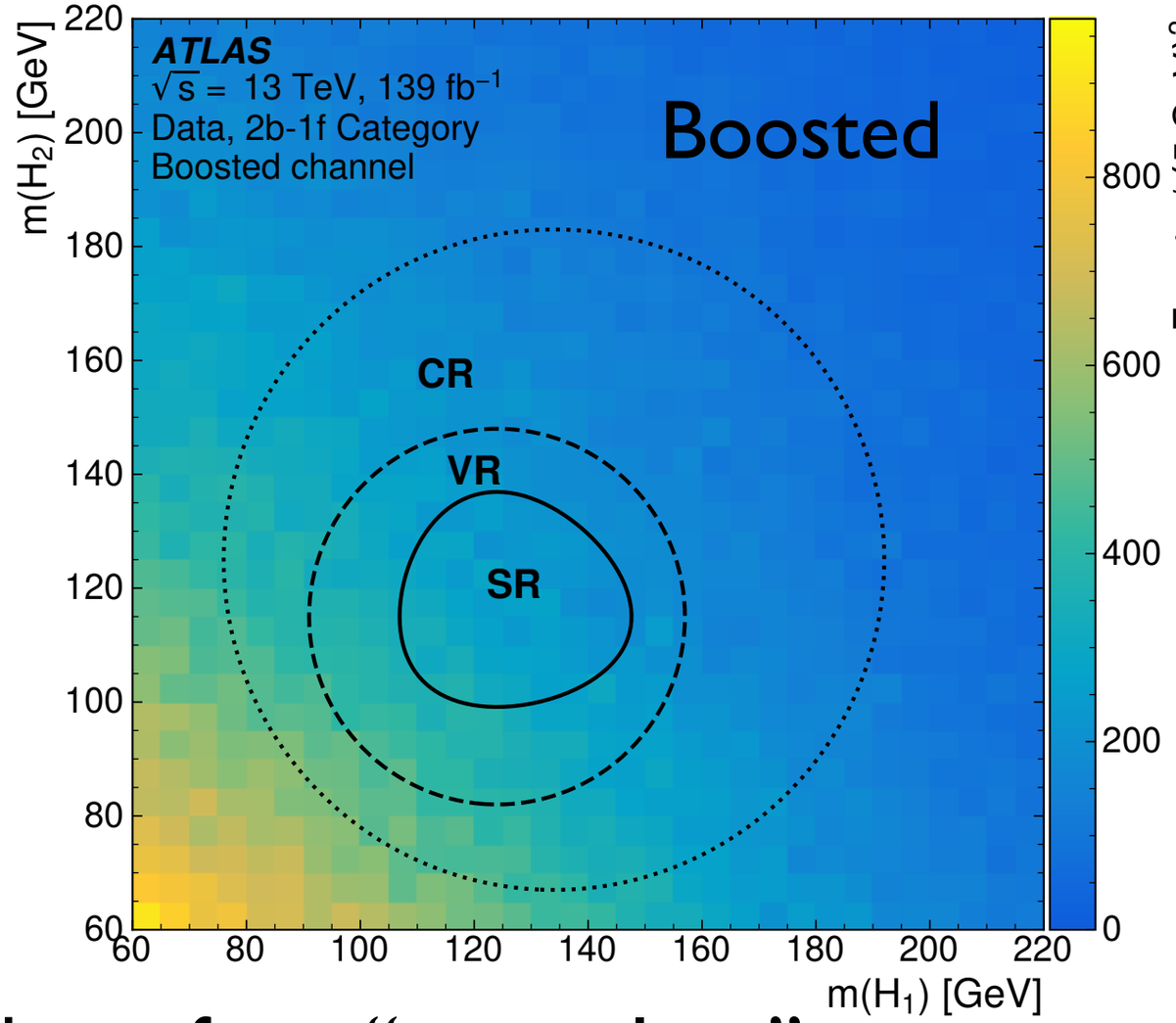
$b\bar{b}b\bar{b}$ Analysis Strategy

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

Reconstruct Higgs candidates, form “mass plane”

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





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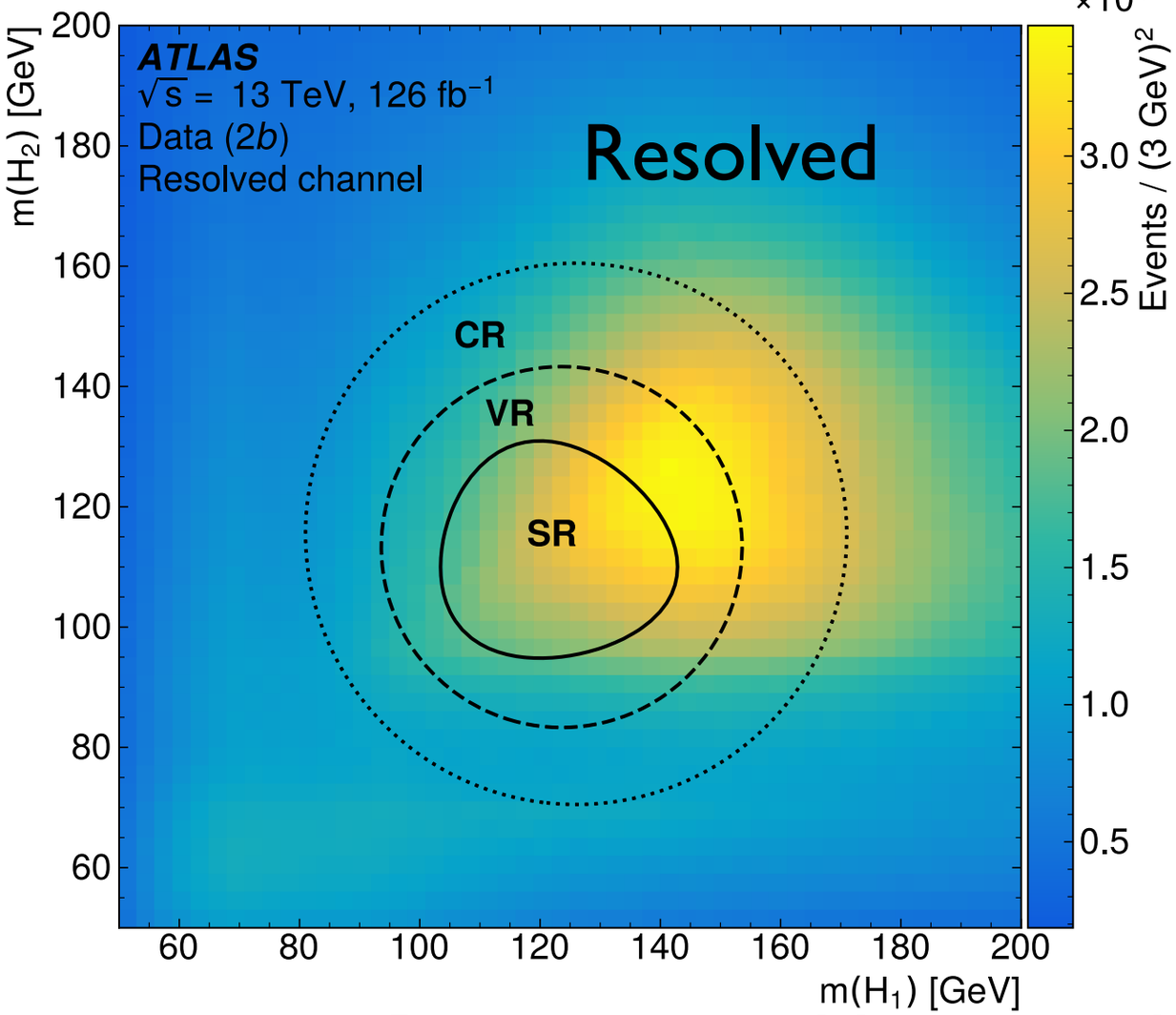
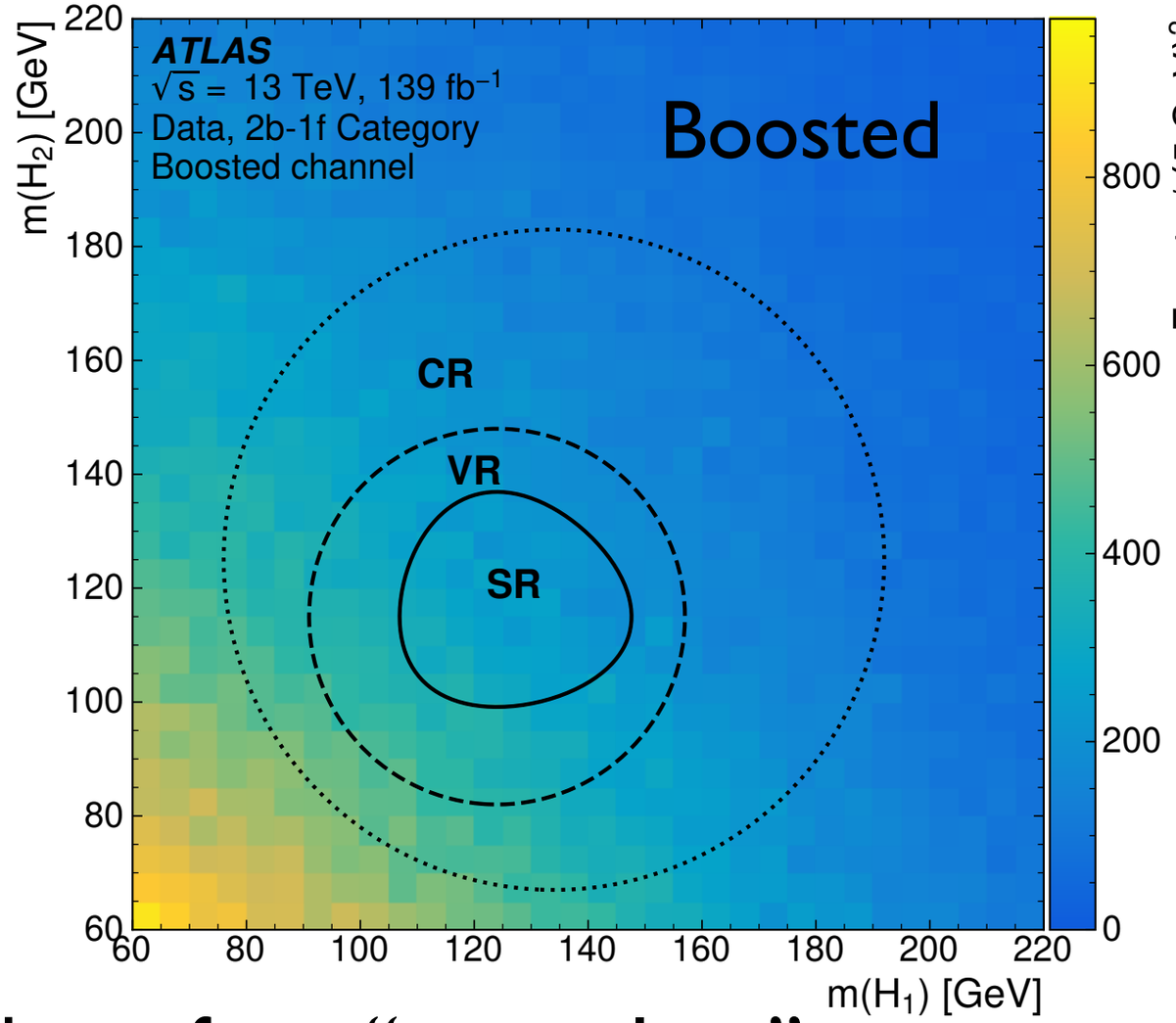
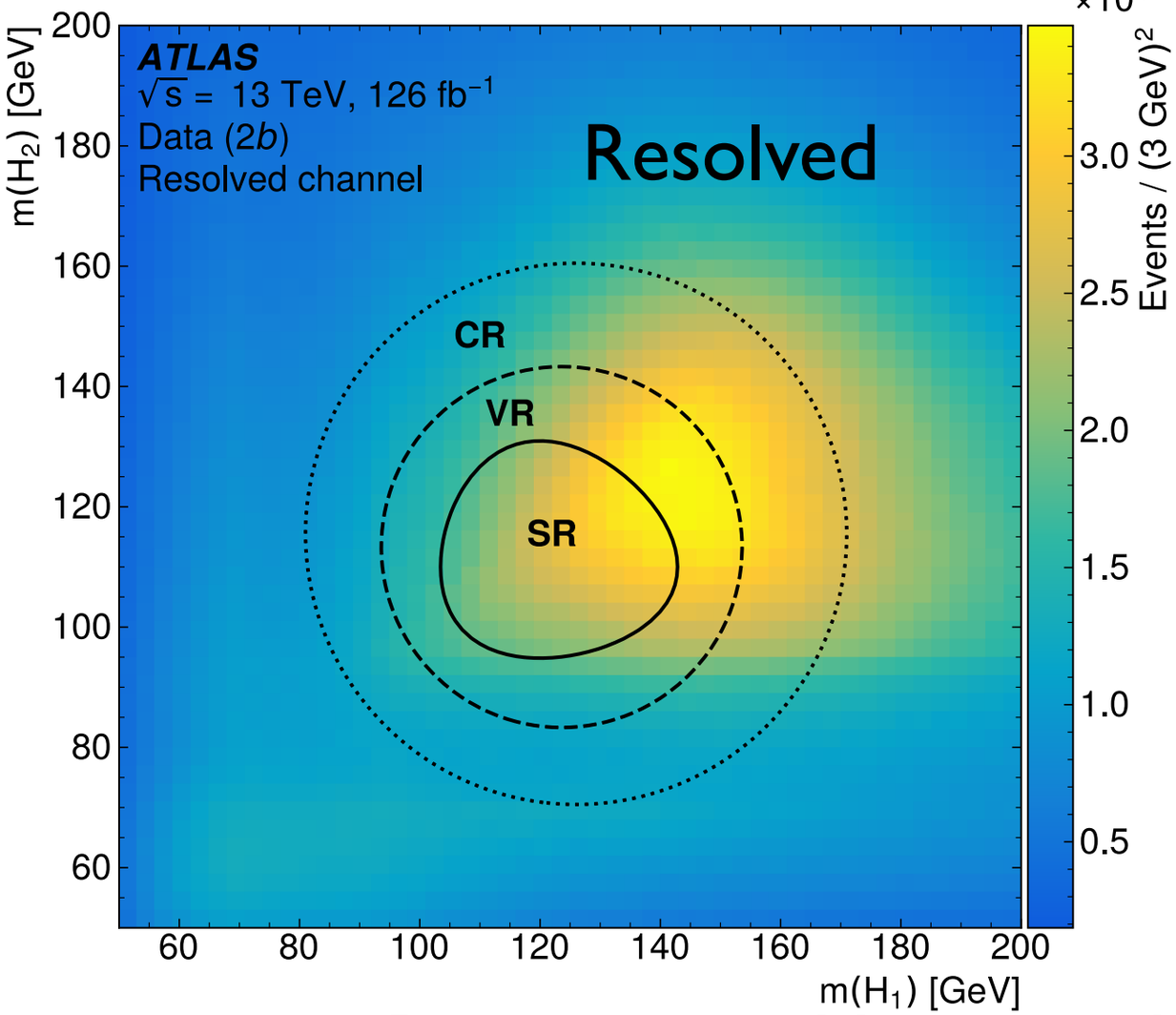


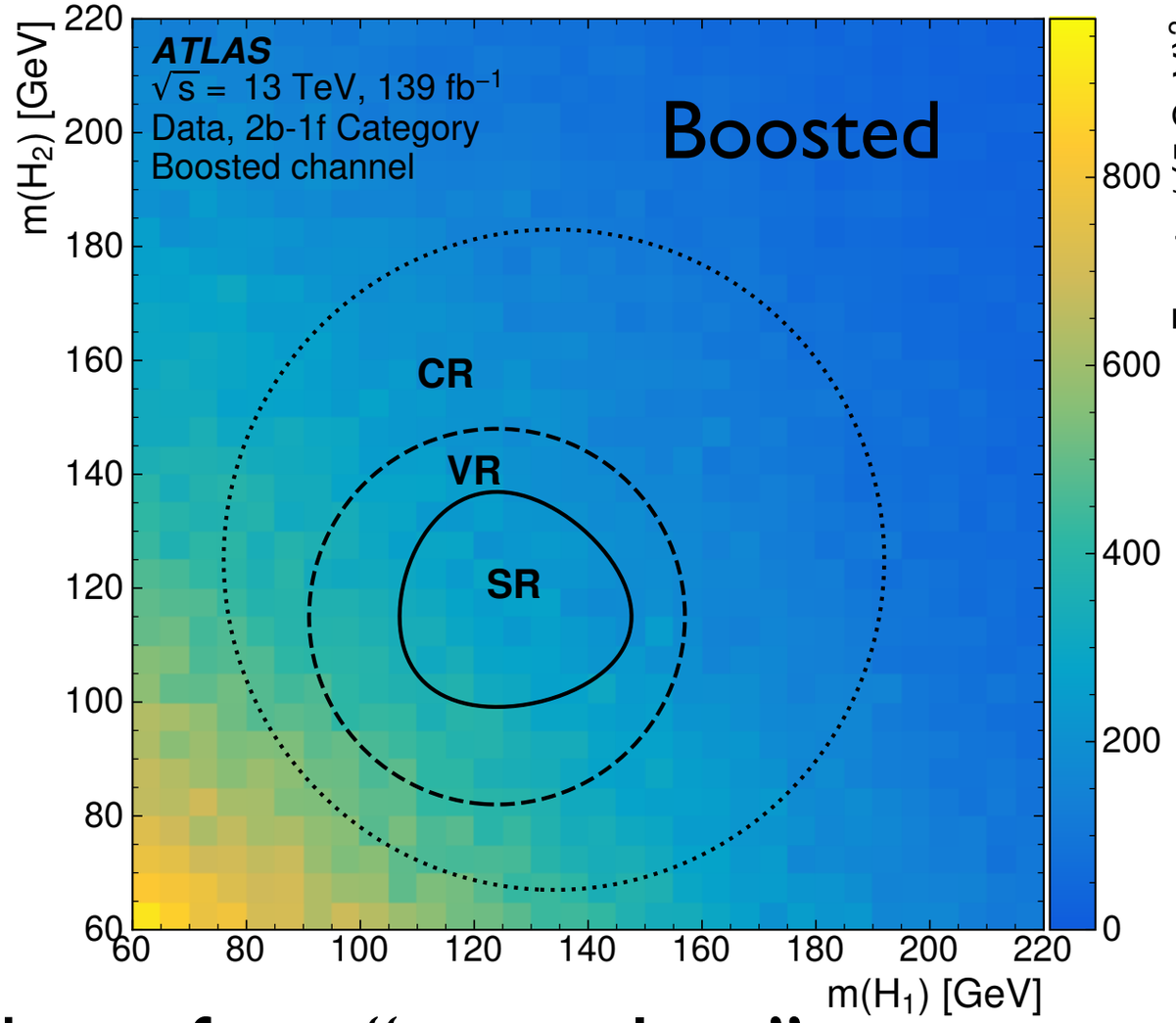


Reconstruct Higgs candidates, form "mass plane"

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

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





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

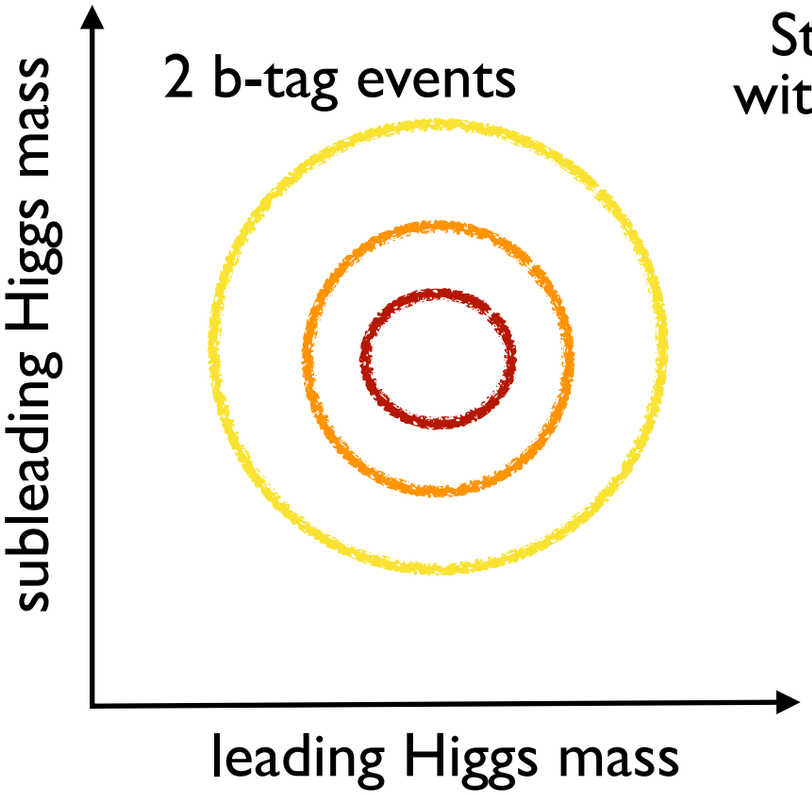
$b\bar{b}b\bar{b}$ Resolved Background

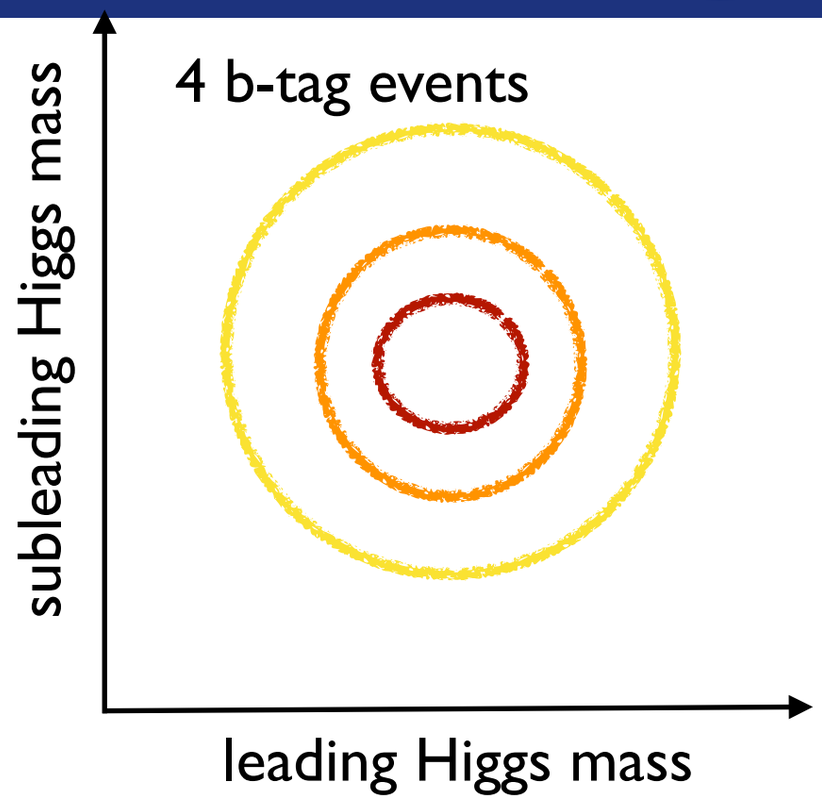
$b\bar{b}b\bar{b}$ Resolved Background

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

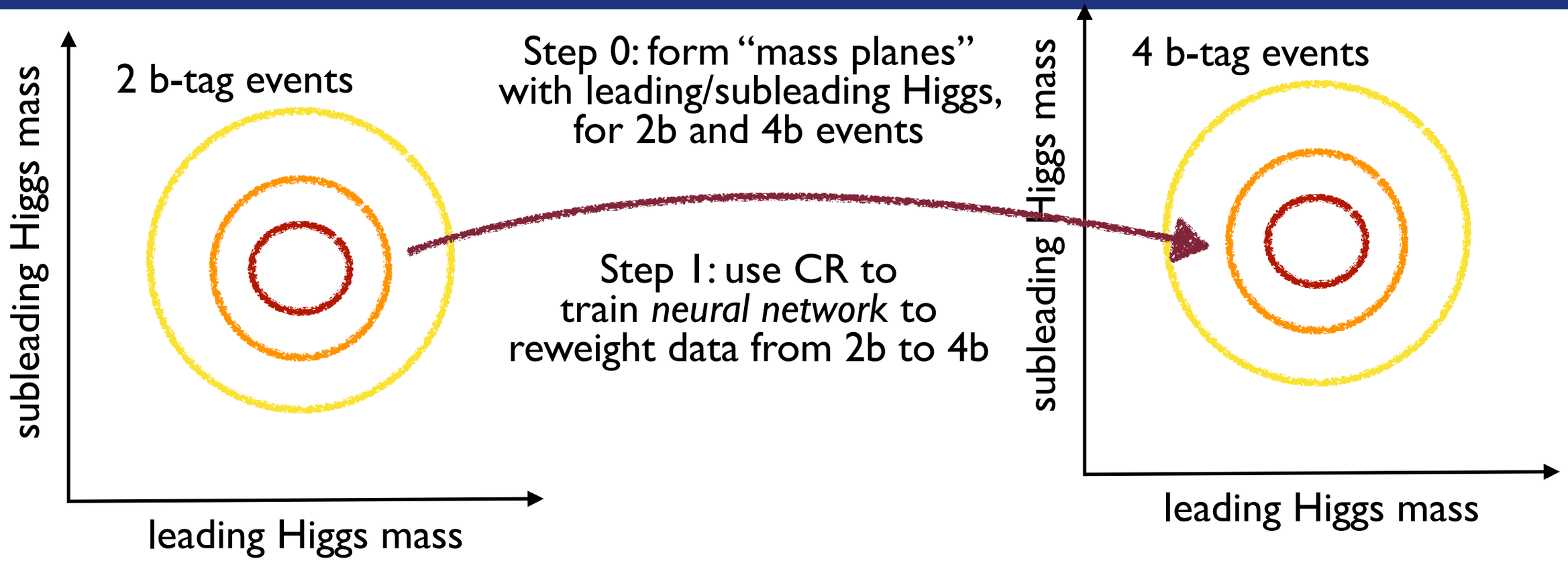
$b\bar{b}b\bar{b}$ Resolved Background

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

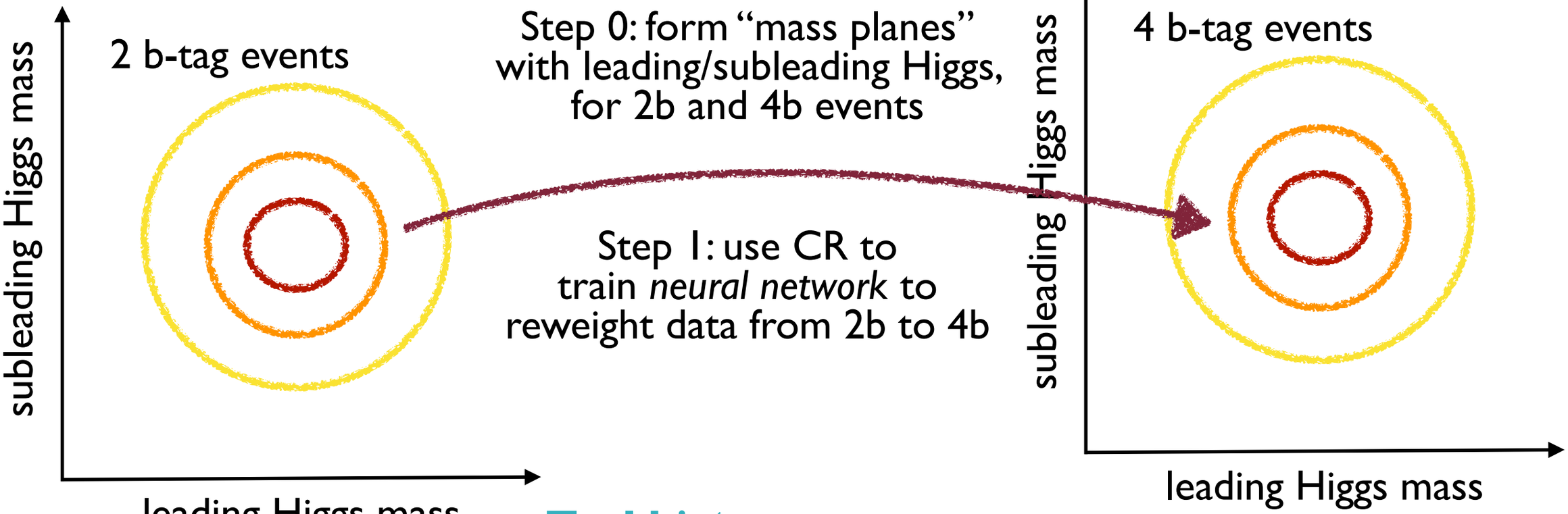


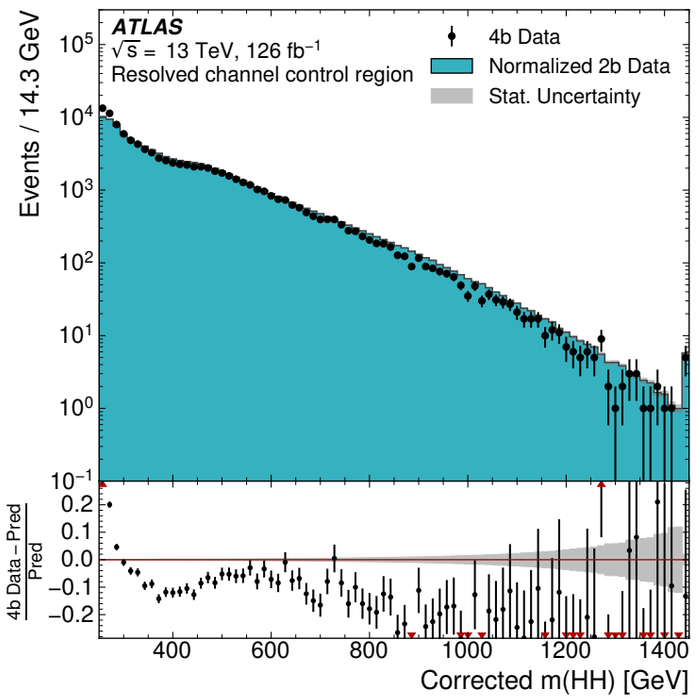


$b\bar{b}b\bar{b}$ Resolved Background



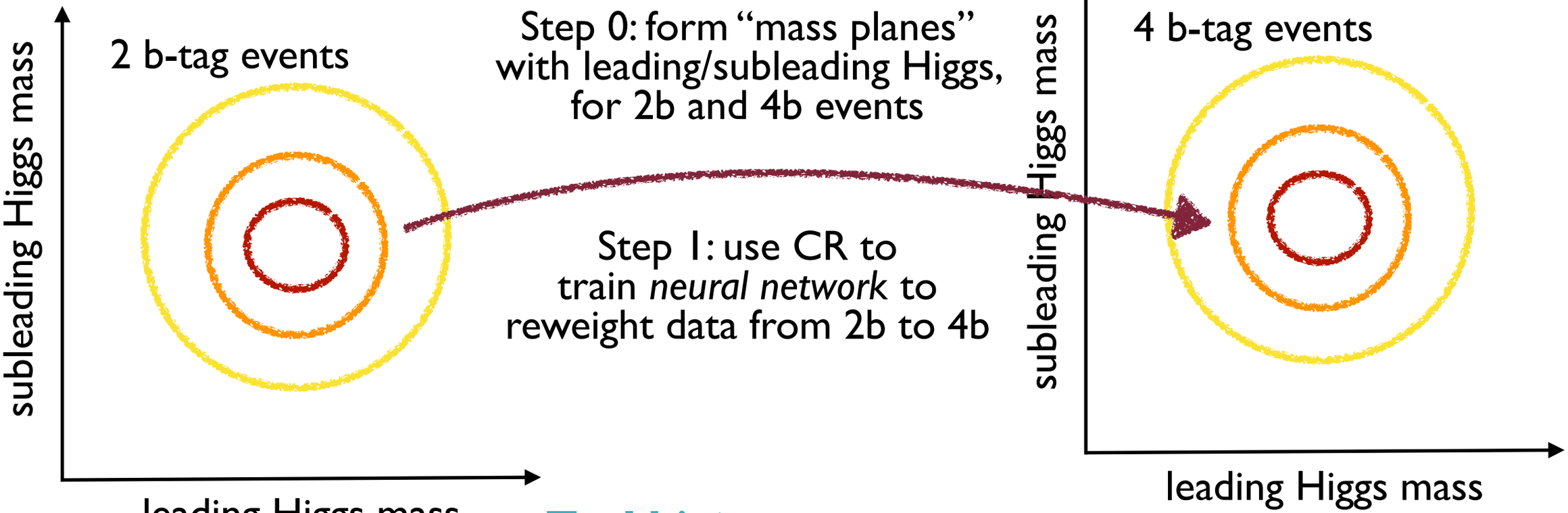
$b\bar{b}b\bar{b}$ Resolved Background





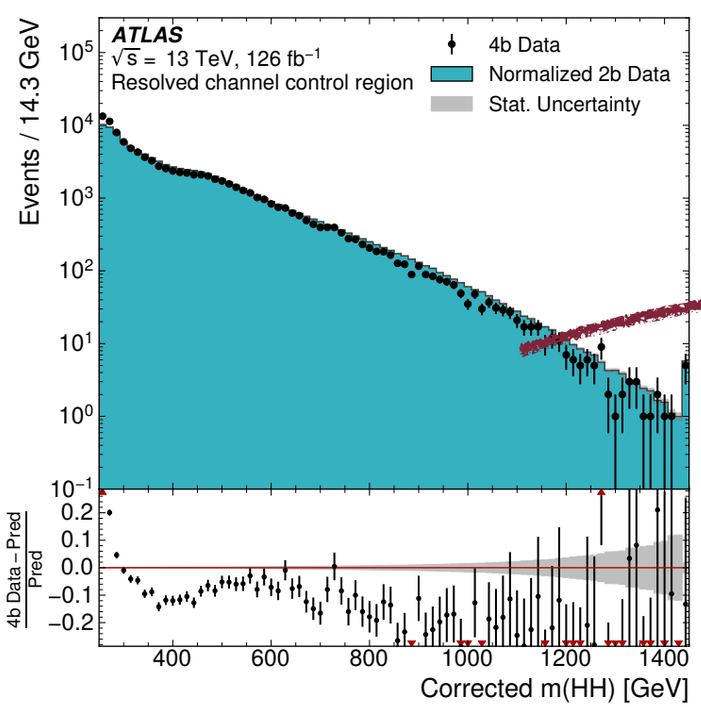
Teal histogram comes from 2b, **black points** from 4b

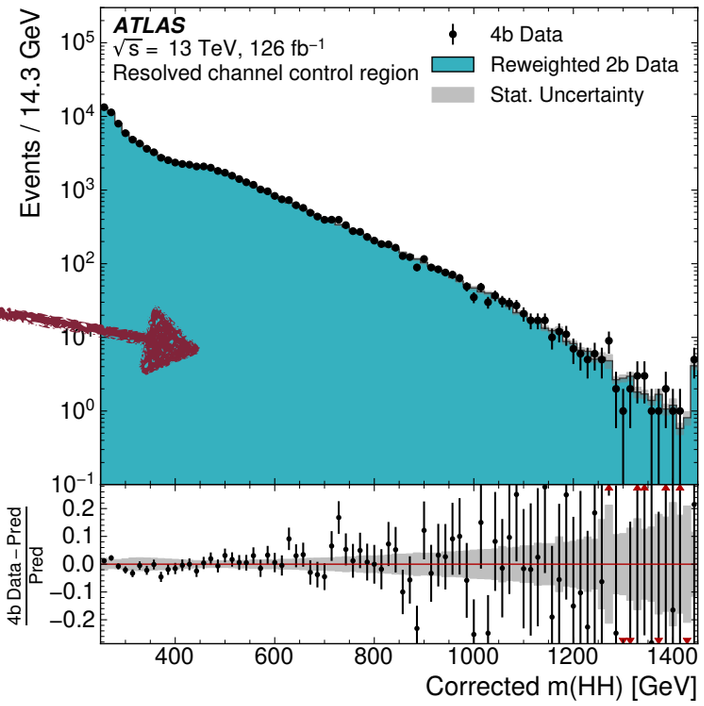
$b\bar{b}b\bar{b}$ Resolved Background



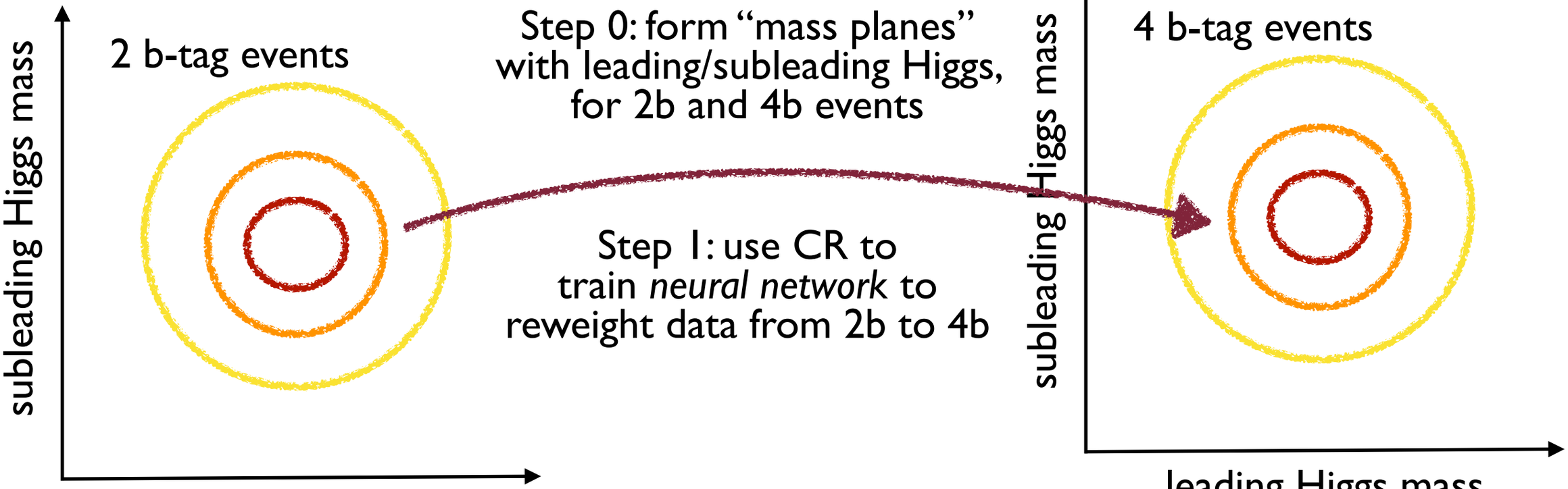
Teal histogram comes from 2b, **black points** from 4b

Neural network





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



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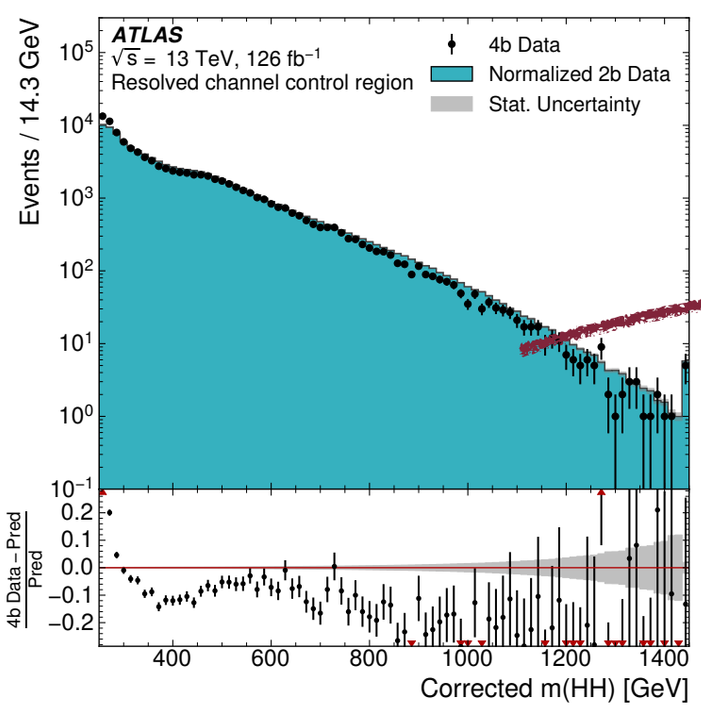
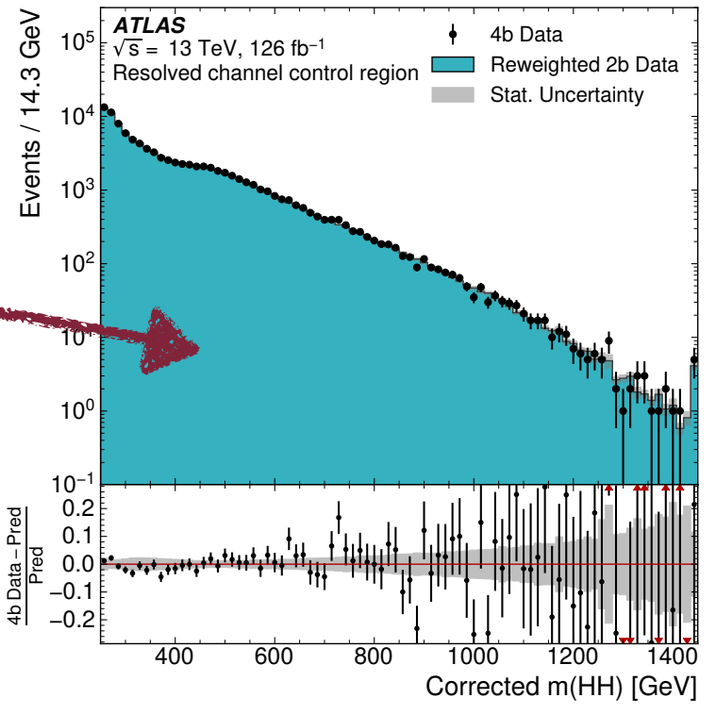
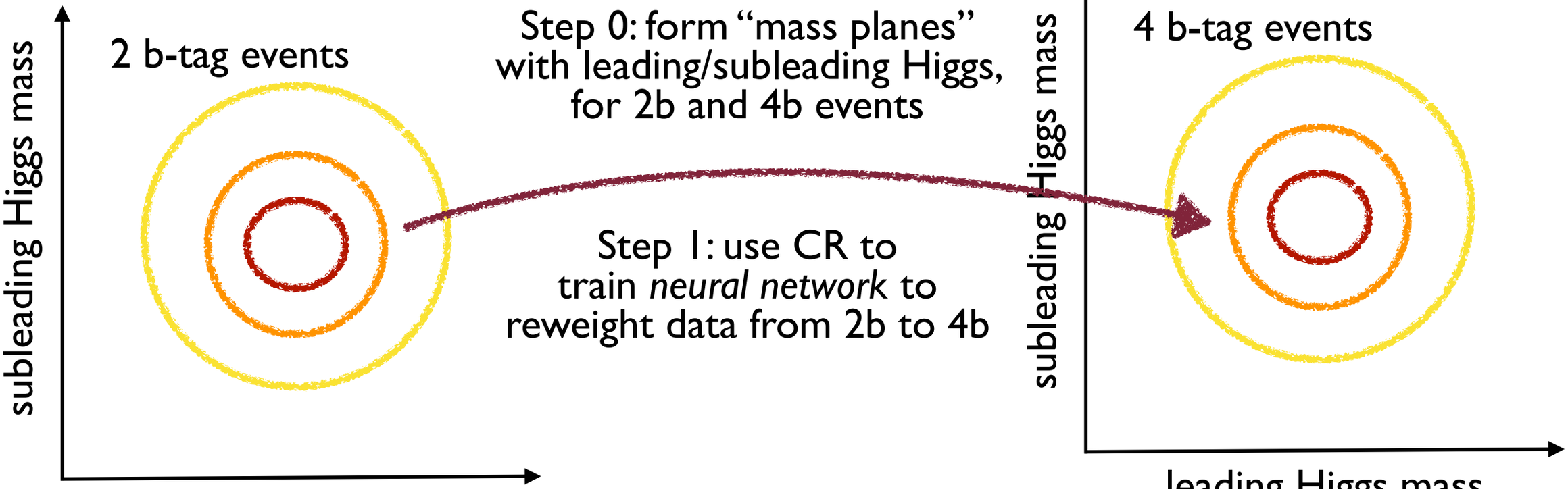
Neural network

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





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



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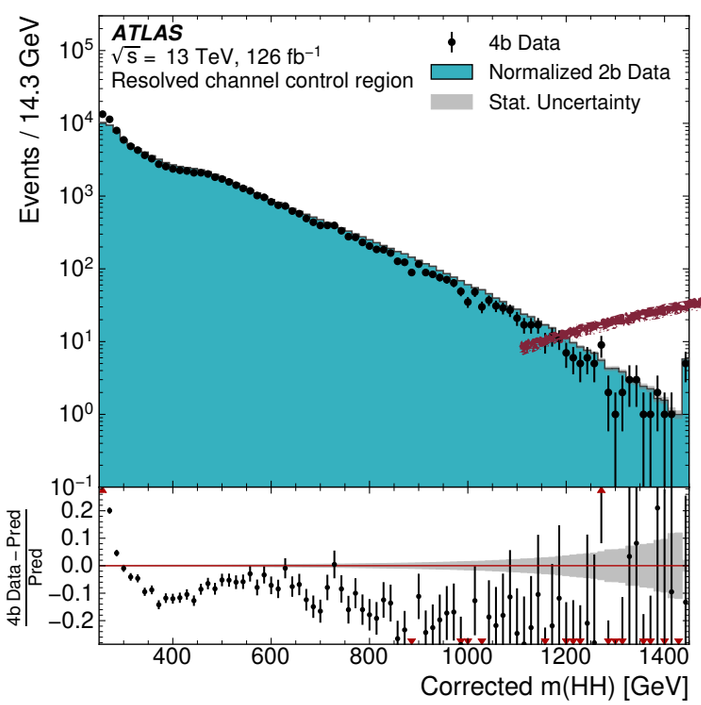
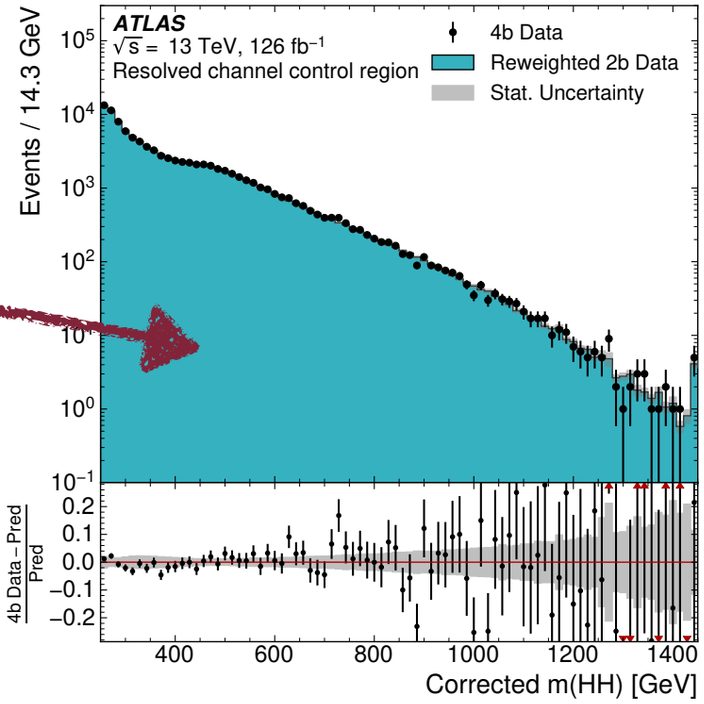
Neural network

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

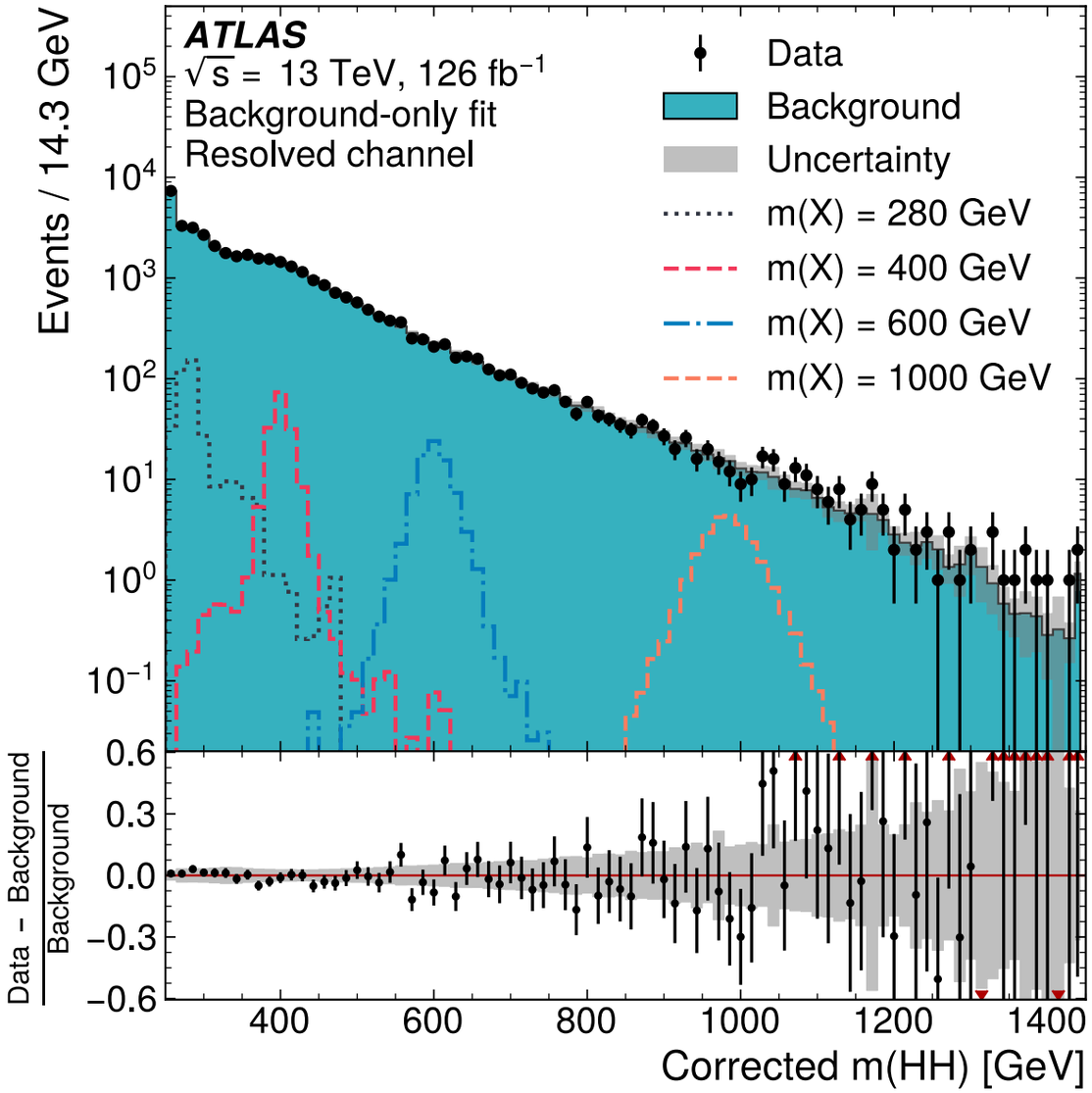
Systematics from alternate validation region





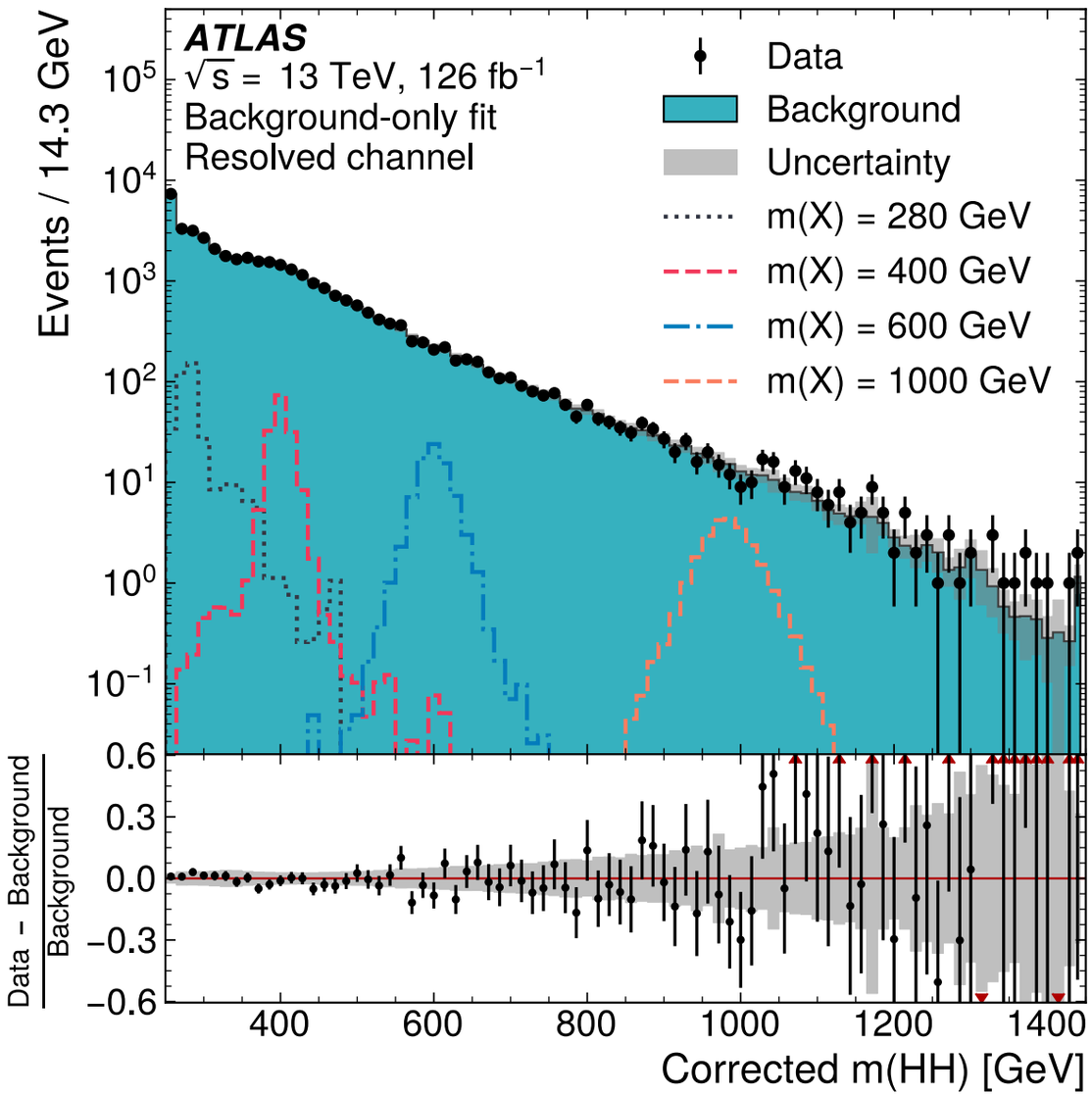
$b\bar{b}b\bar{b}$ Results

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



Data agrees well with background prediction

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



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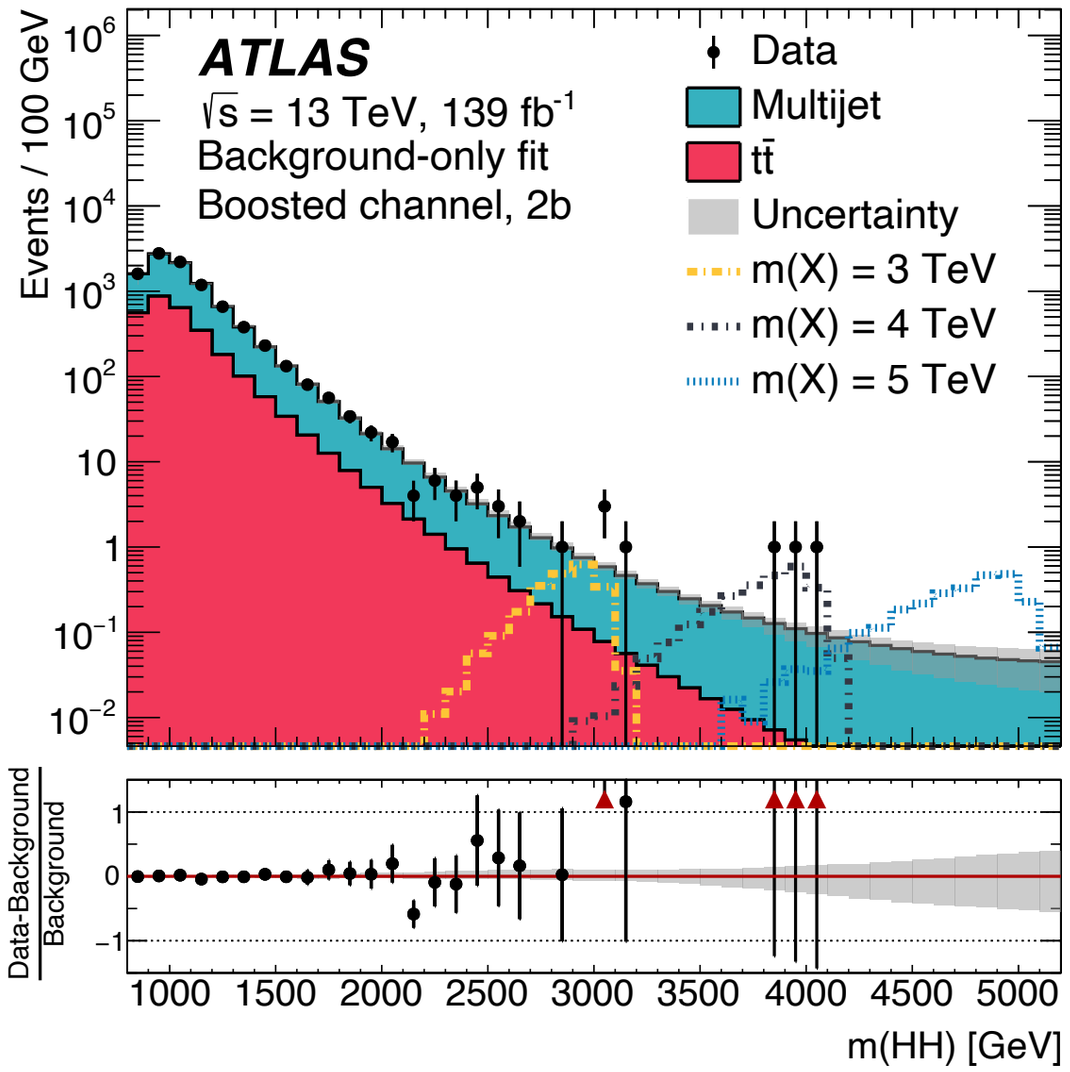


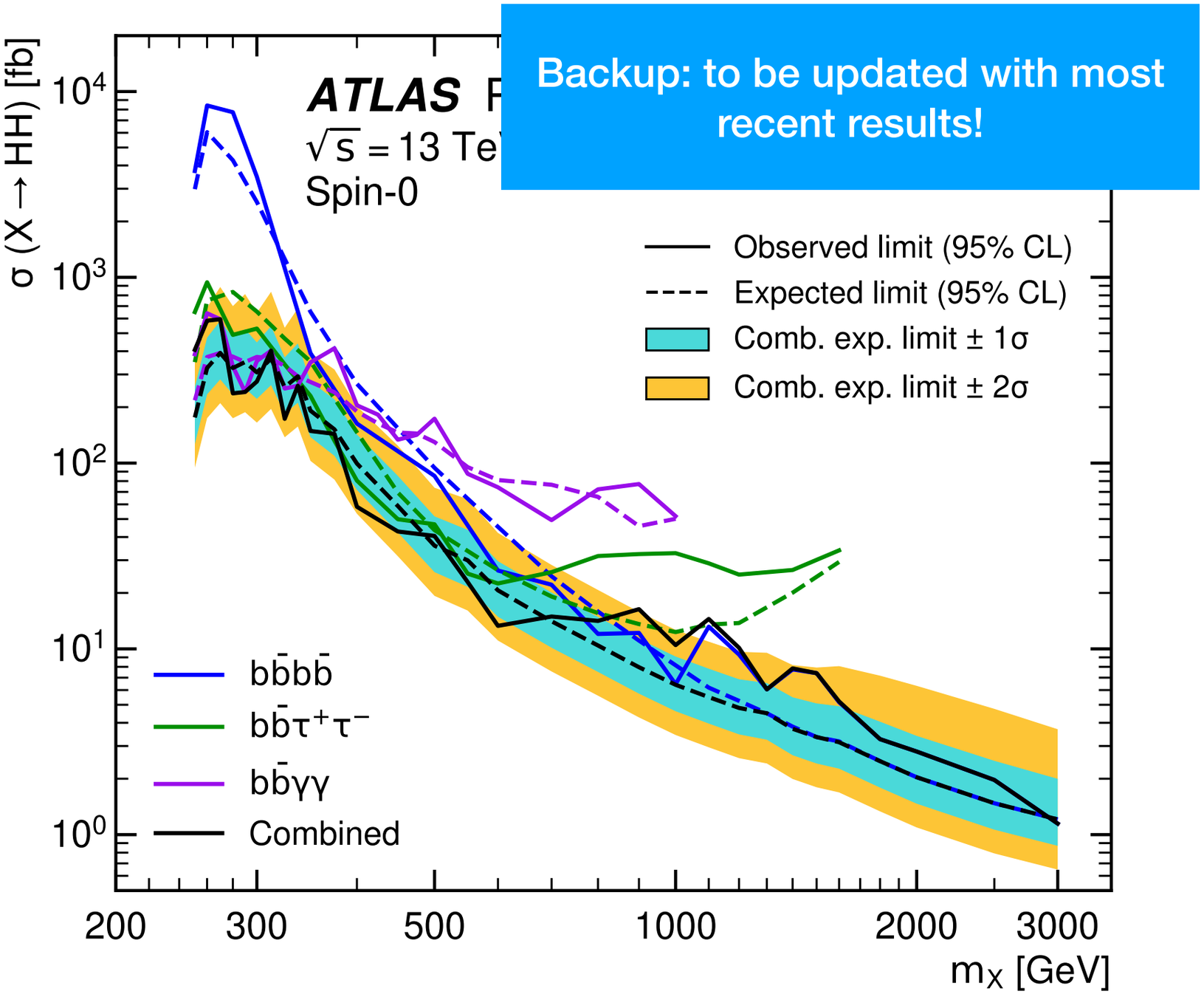
Boosted analysis is similar: simpler spline based reweighting

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

Resonant Combination

Backup: to be updated with most recent results!

Resonant Combination



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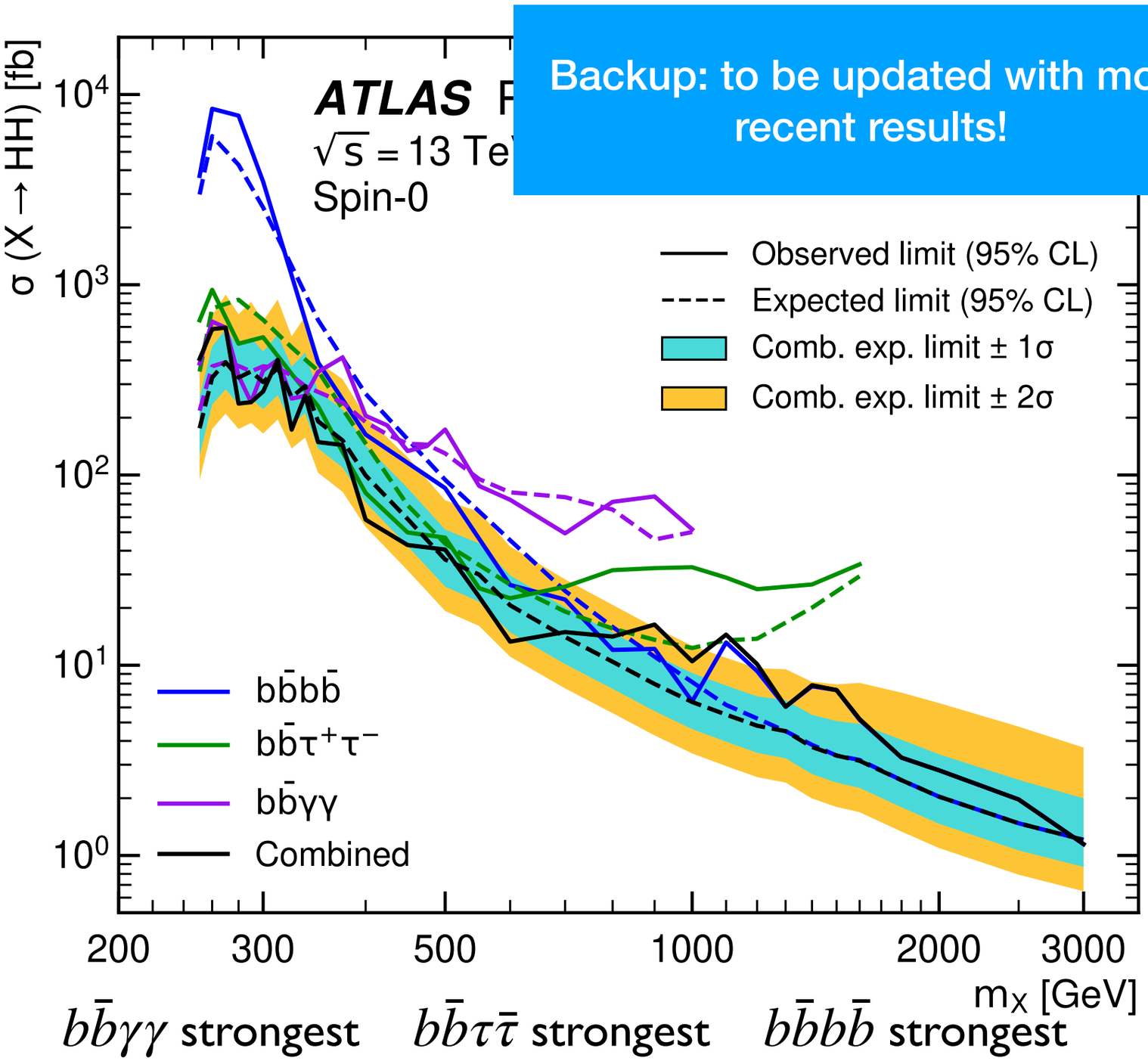


Backup: to be updated with most recent results!

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

Here, show results from all three analyses

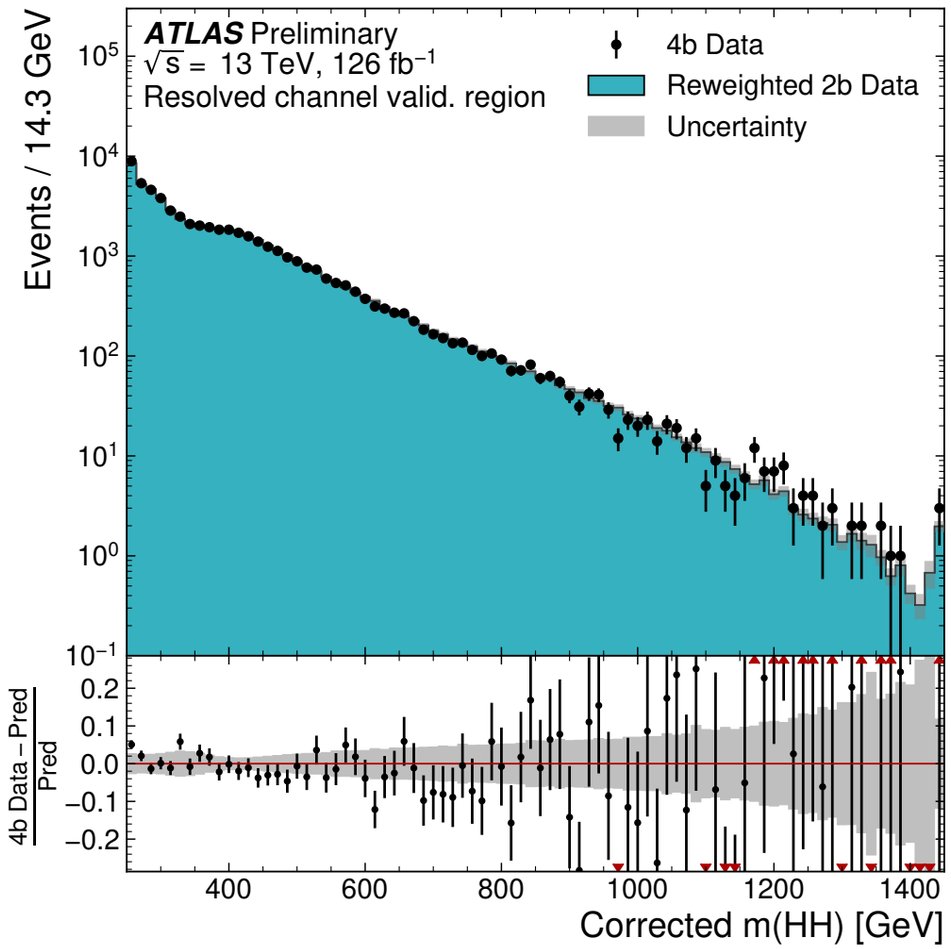
$b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\bar{\tau}$ have similar resonant-optimized searches

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

All three analyses complementary: set best limits at different ranges

Why Neural Networks?

Why Neural Networks?



Here, apply NN to 2b data in VR

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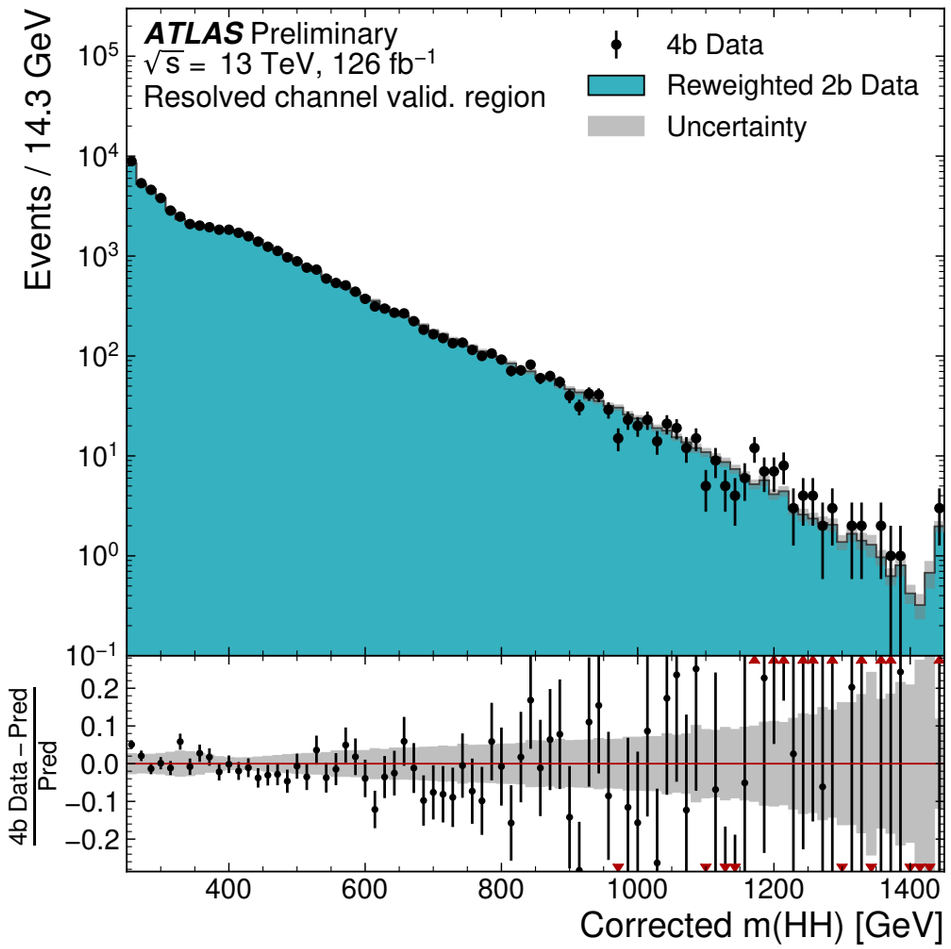

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Works well, even on data that wasn't used in training!

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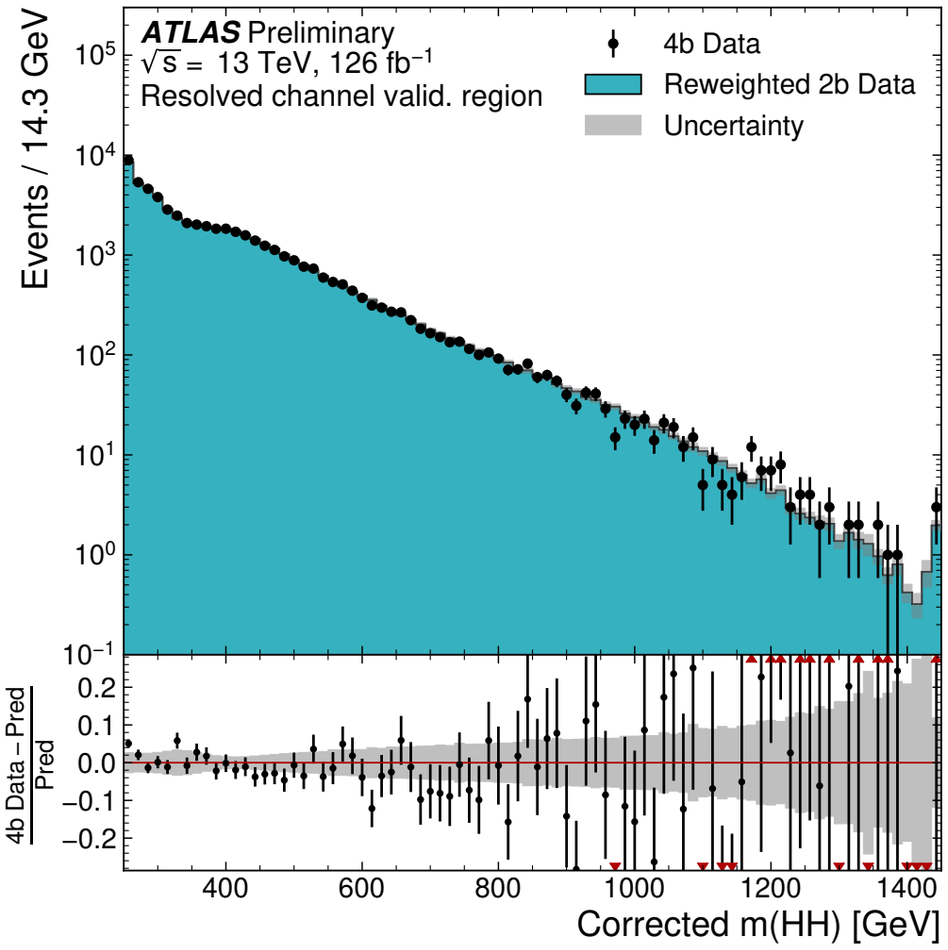

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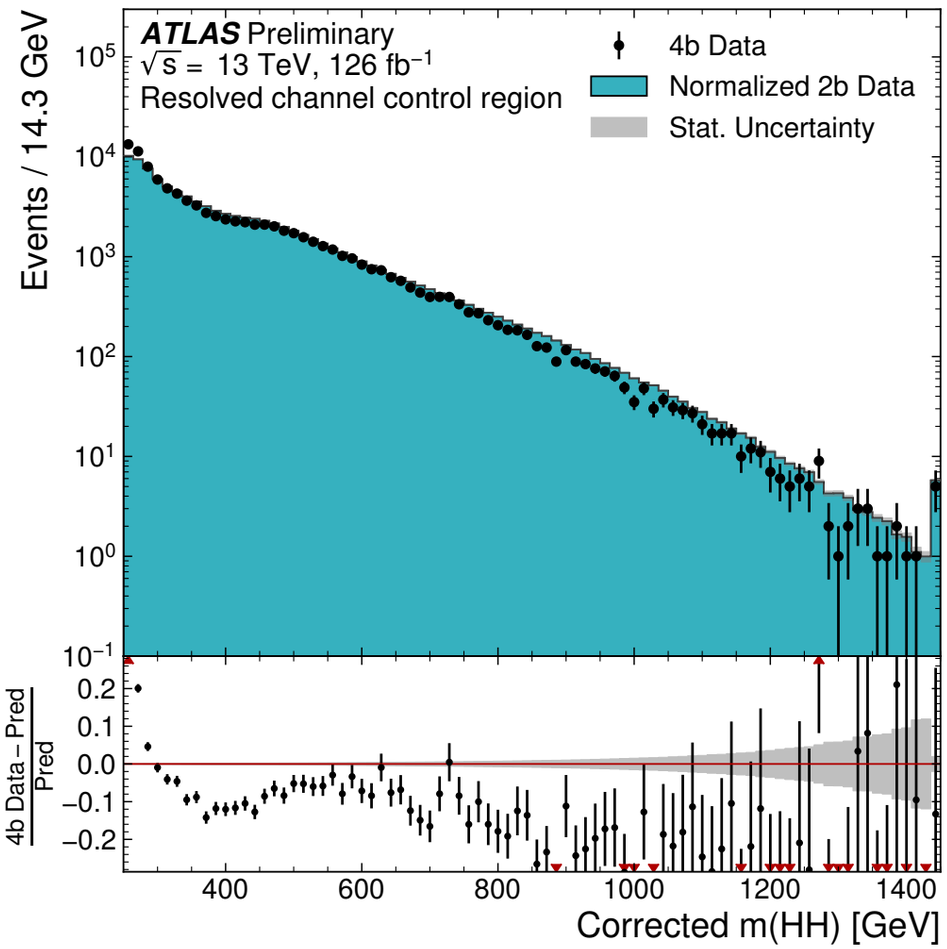

Why does this work?

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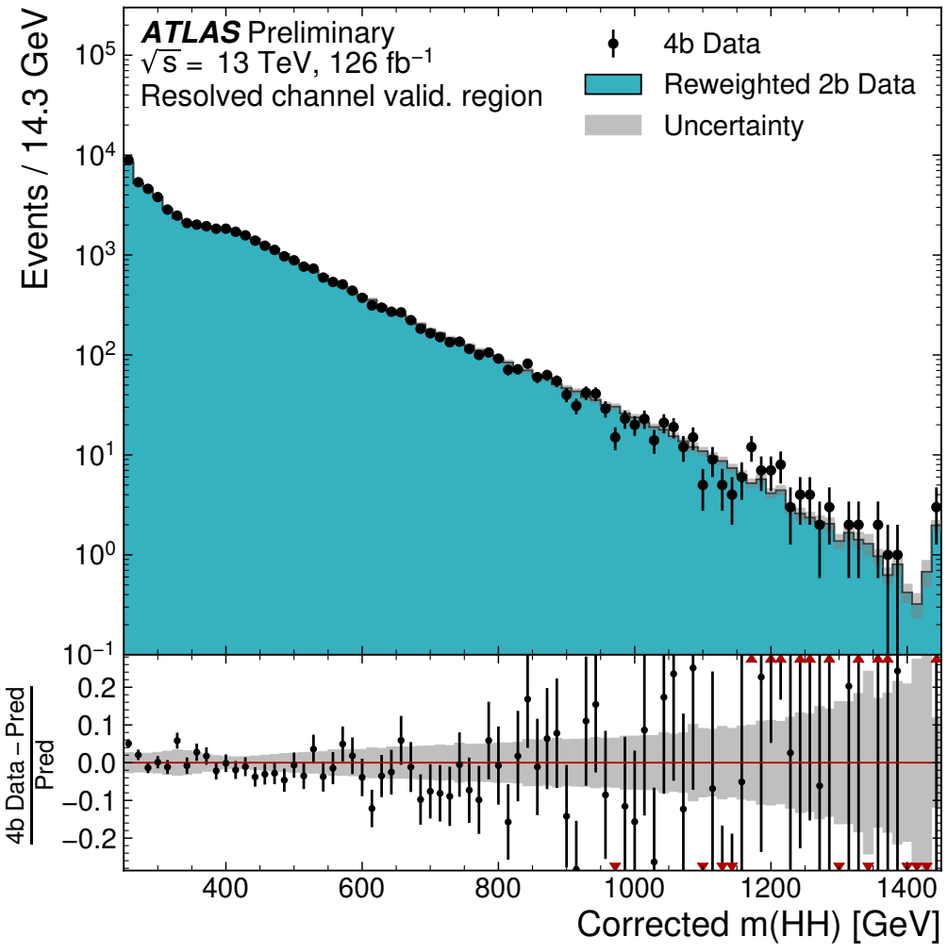

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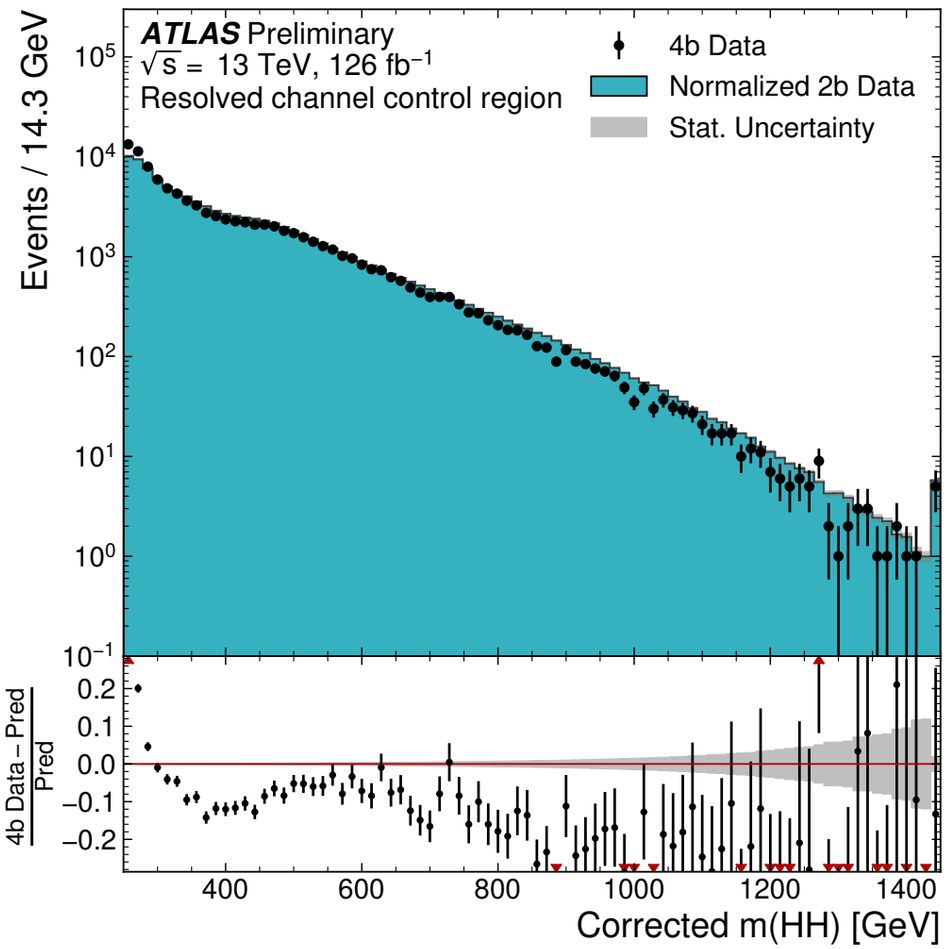
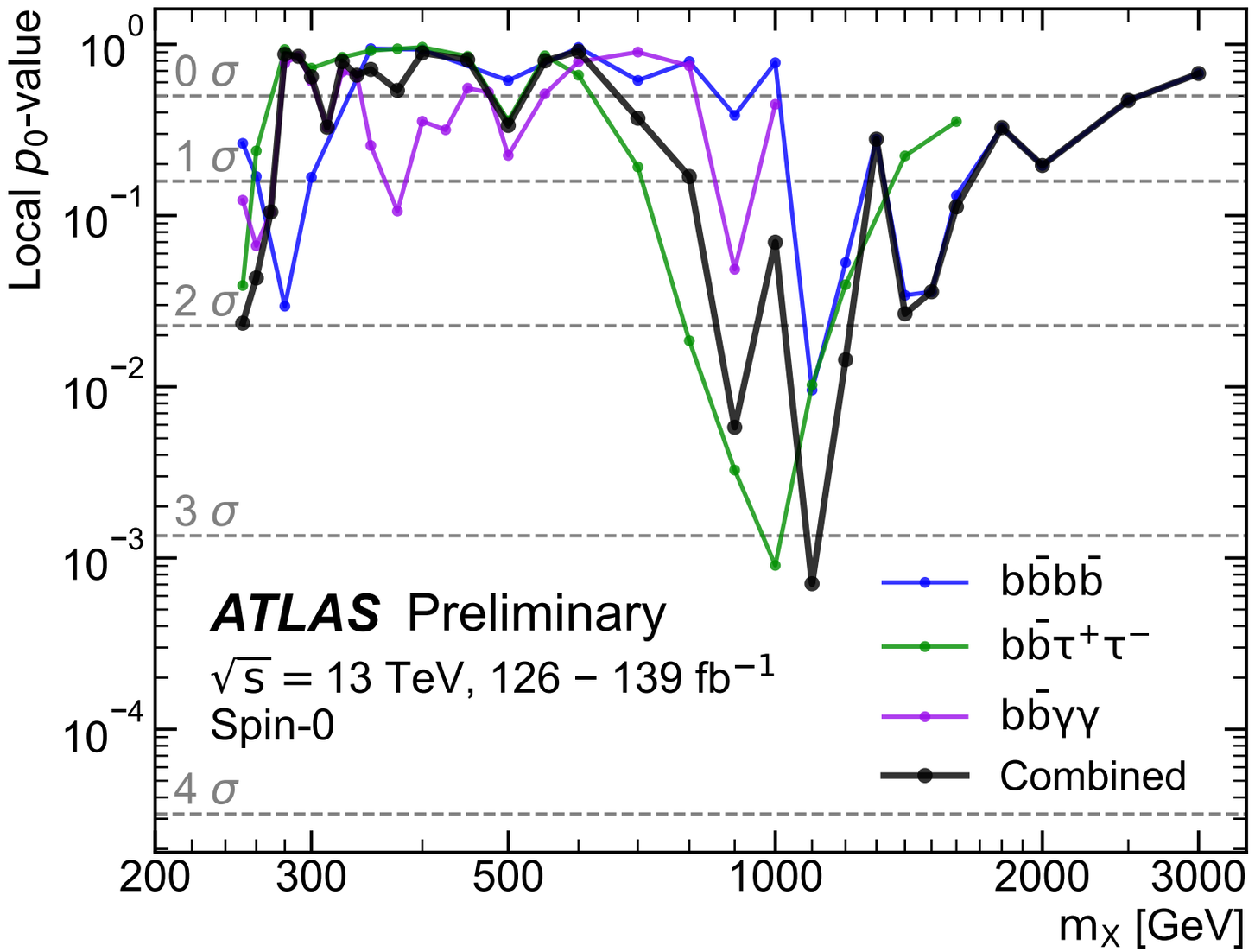


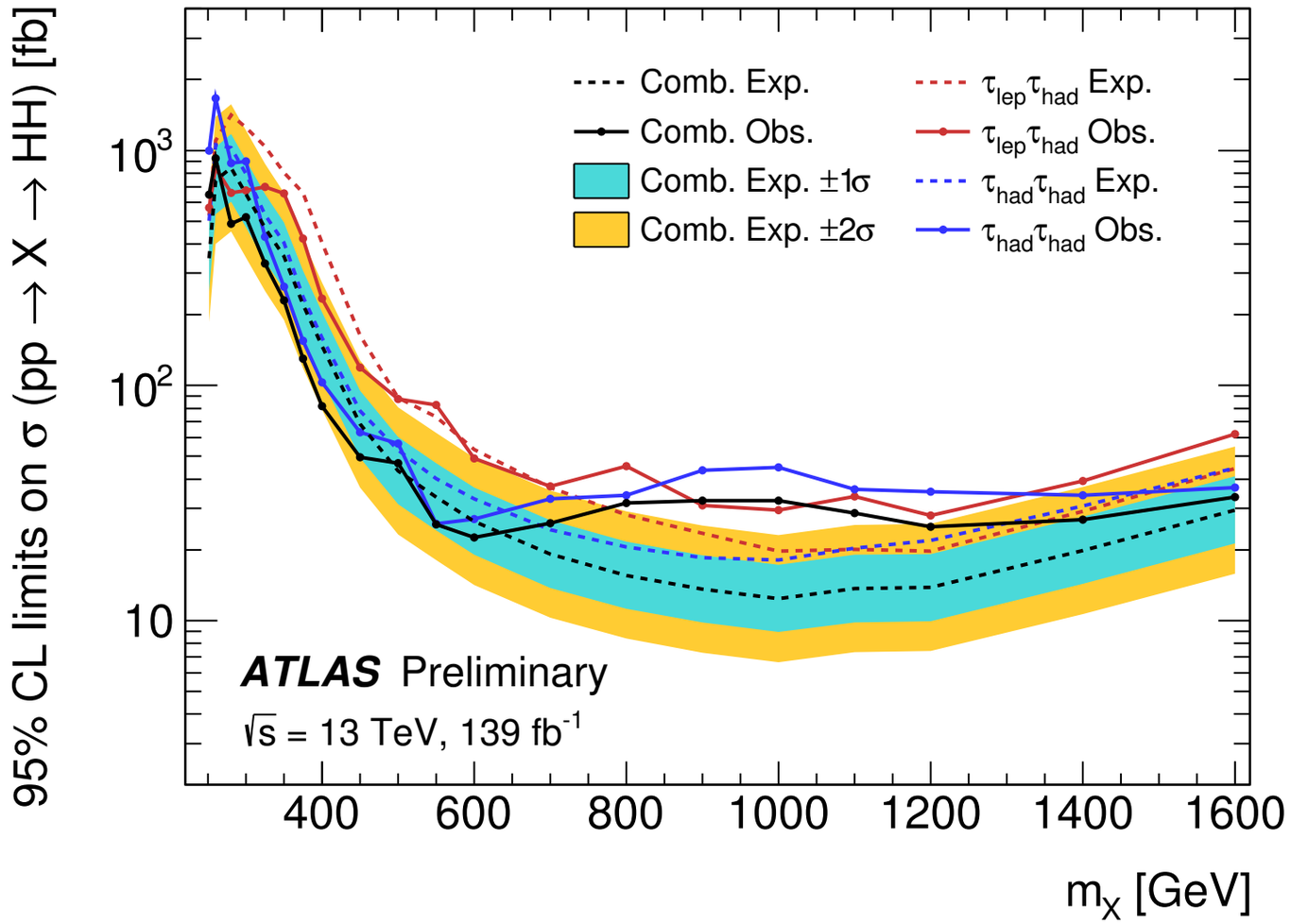
Why does this work?

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

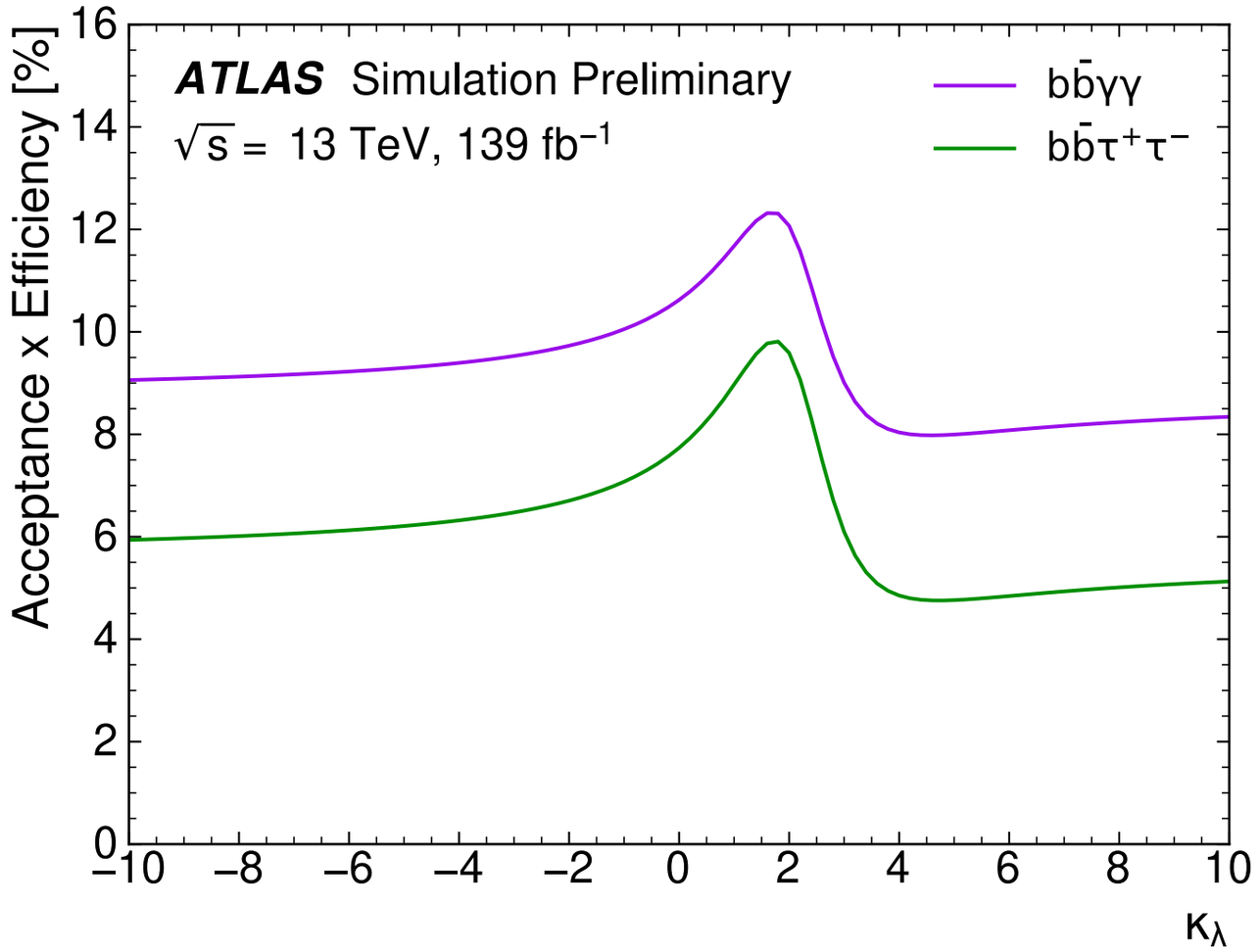
Resonant p-value



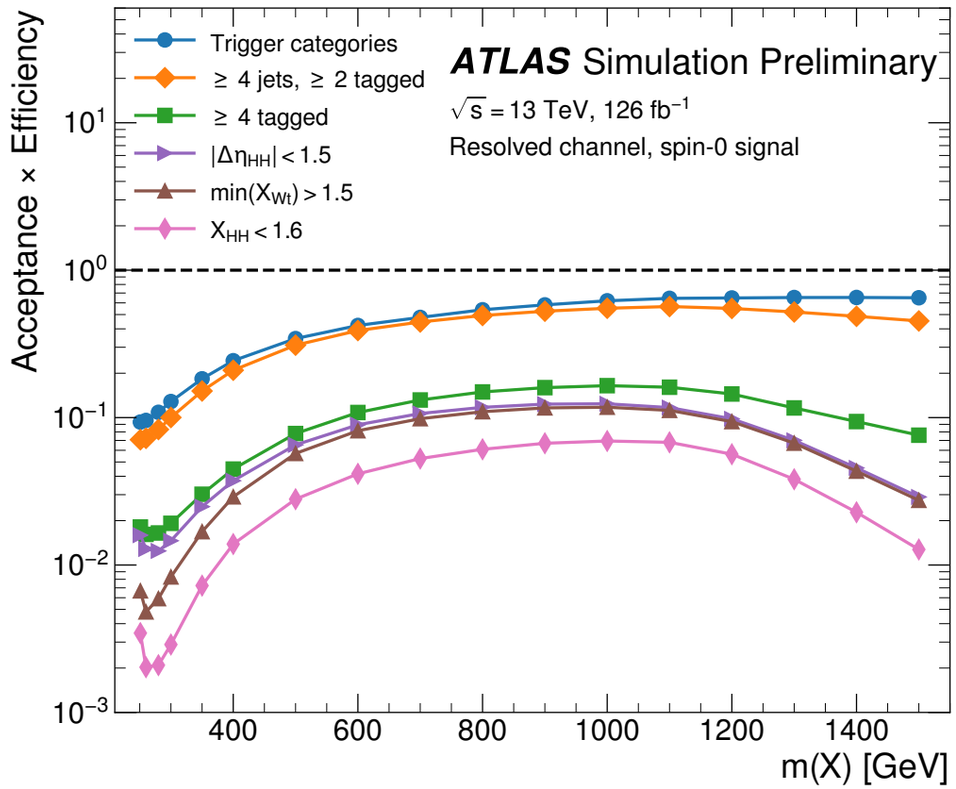
$b\bar{b}\tau\bar{\tau}$ Resonant Limits

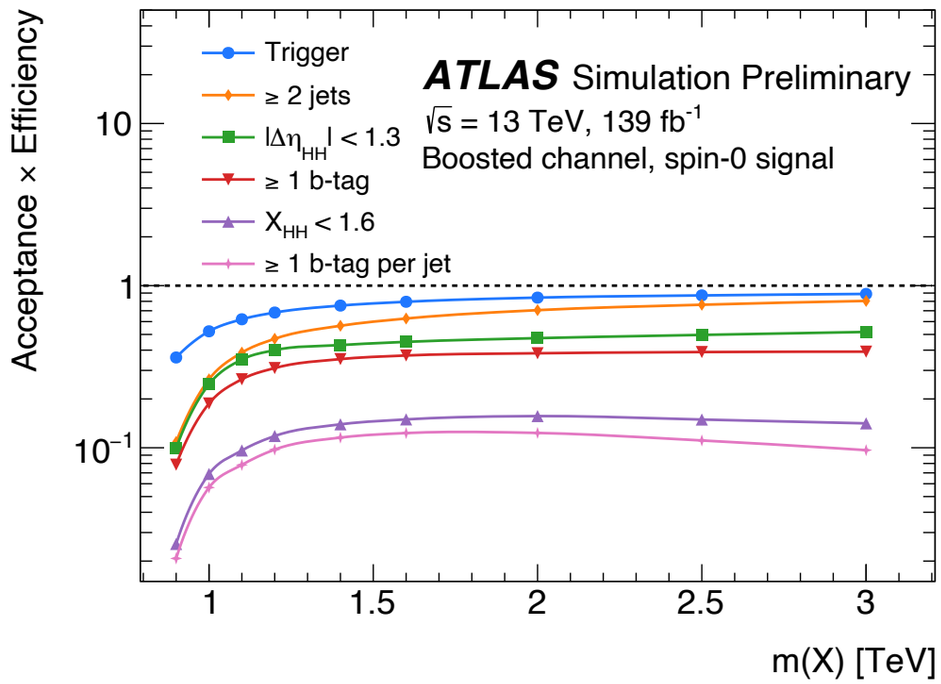


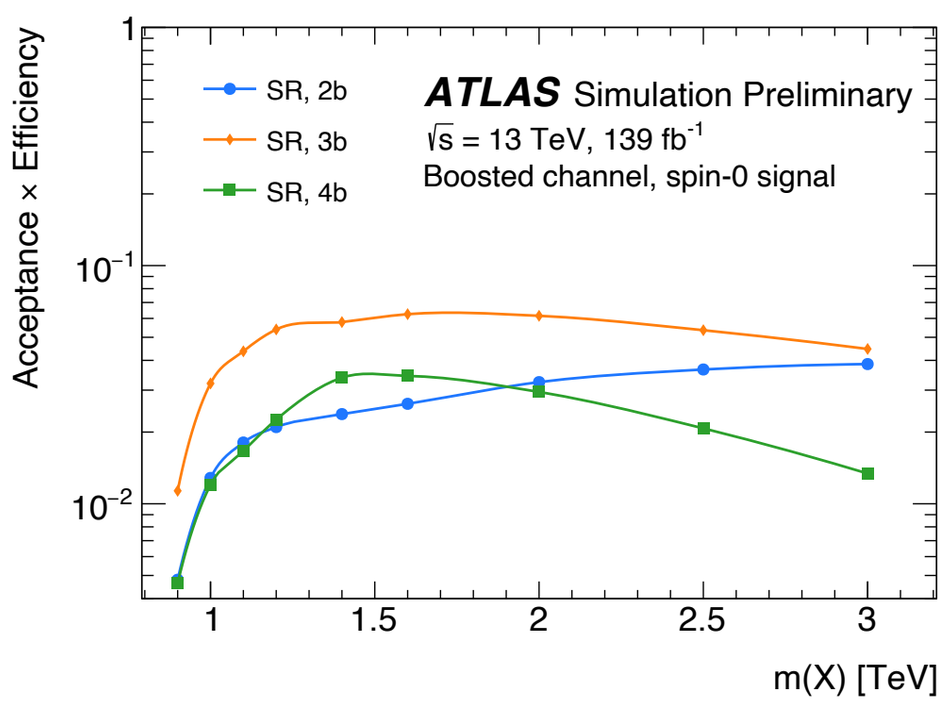
Non-resonant Acc x Eff



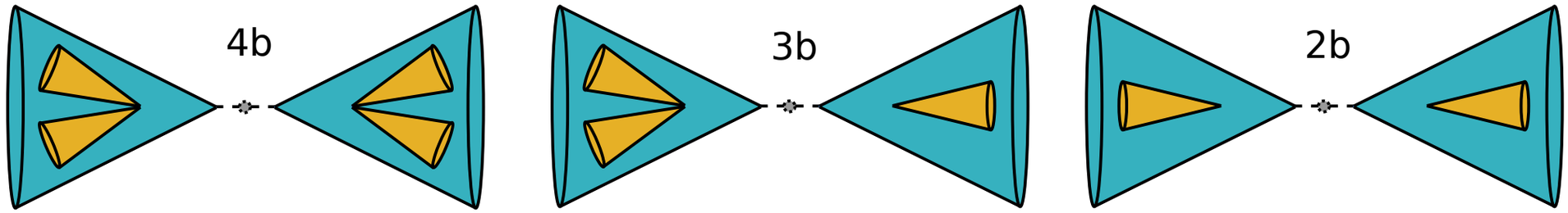
Acceptance x Eff $b\bar{b}b\bar{b}$

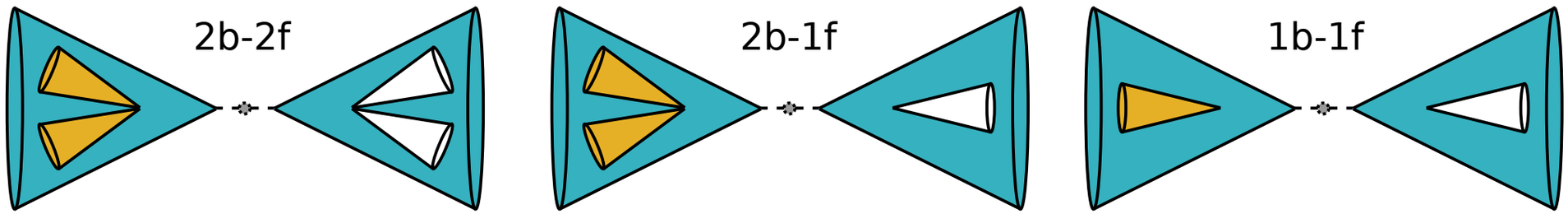


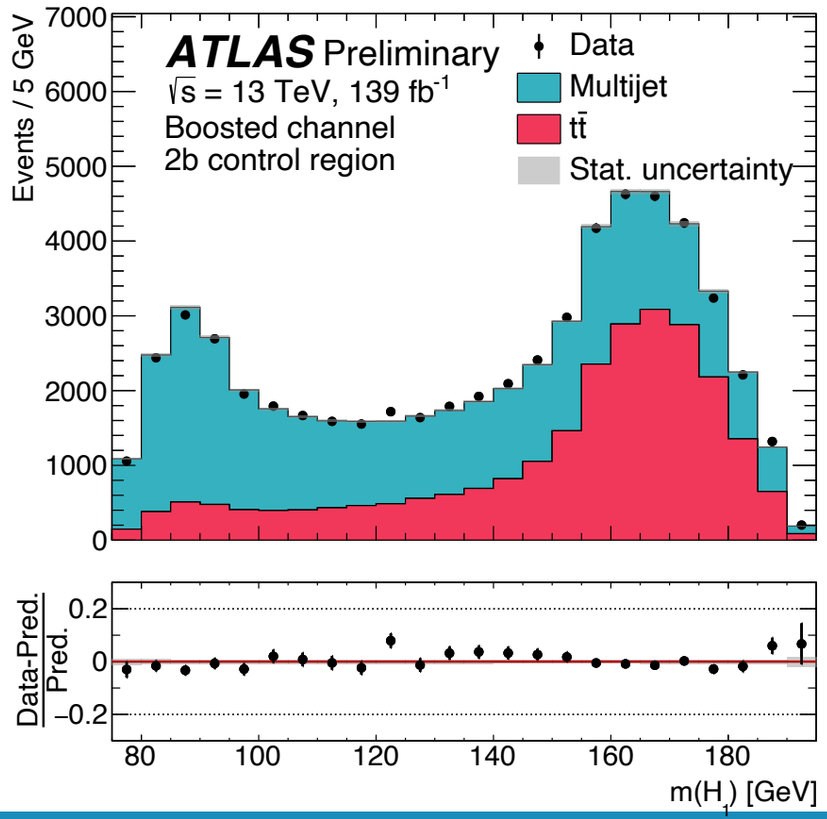


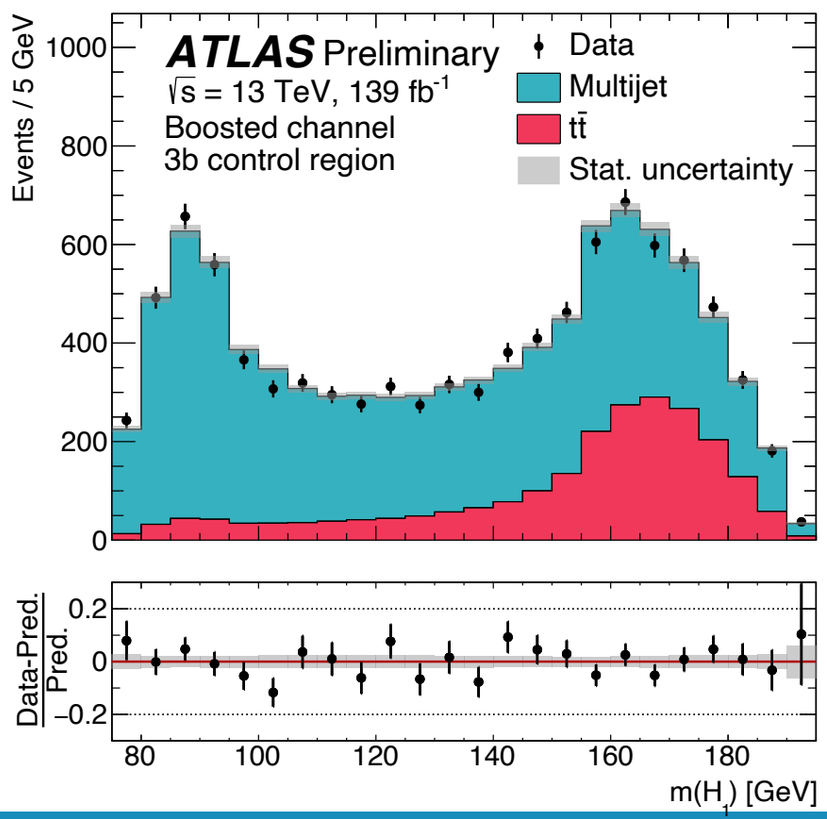


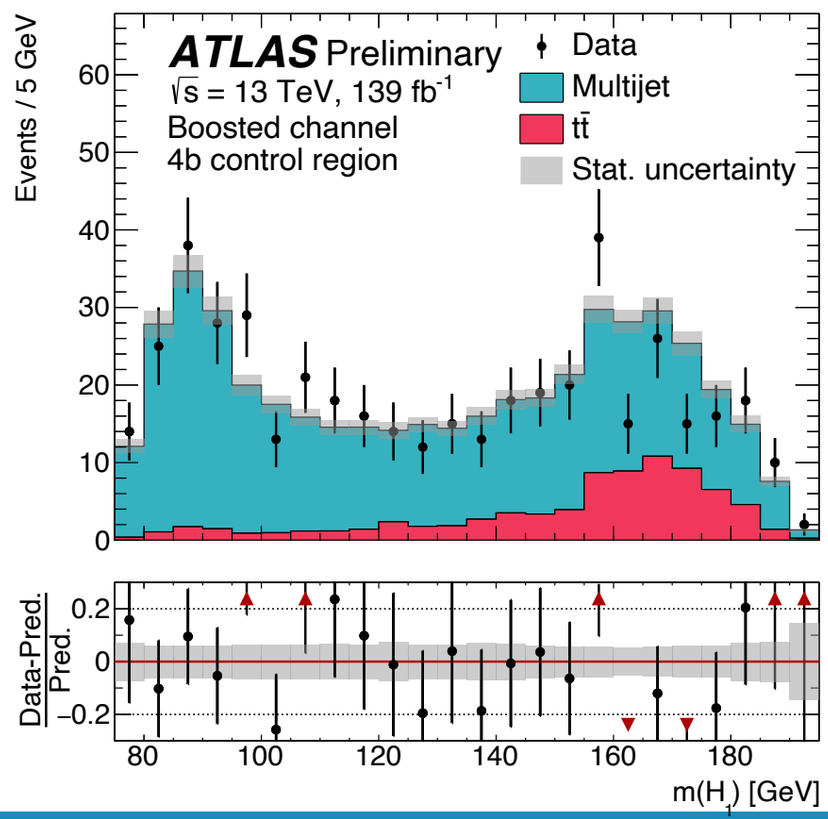
Boosted Backgrounds



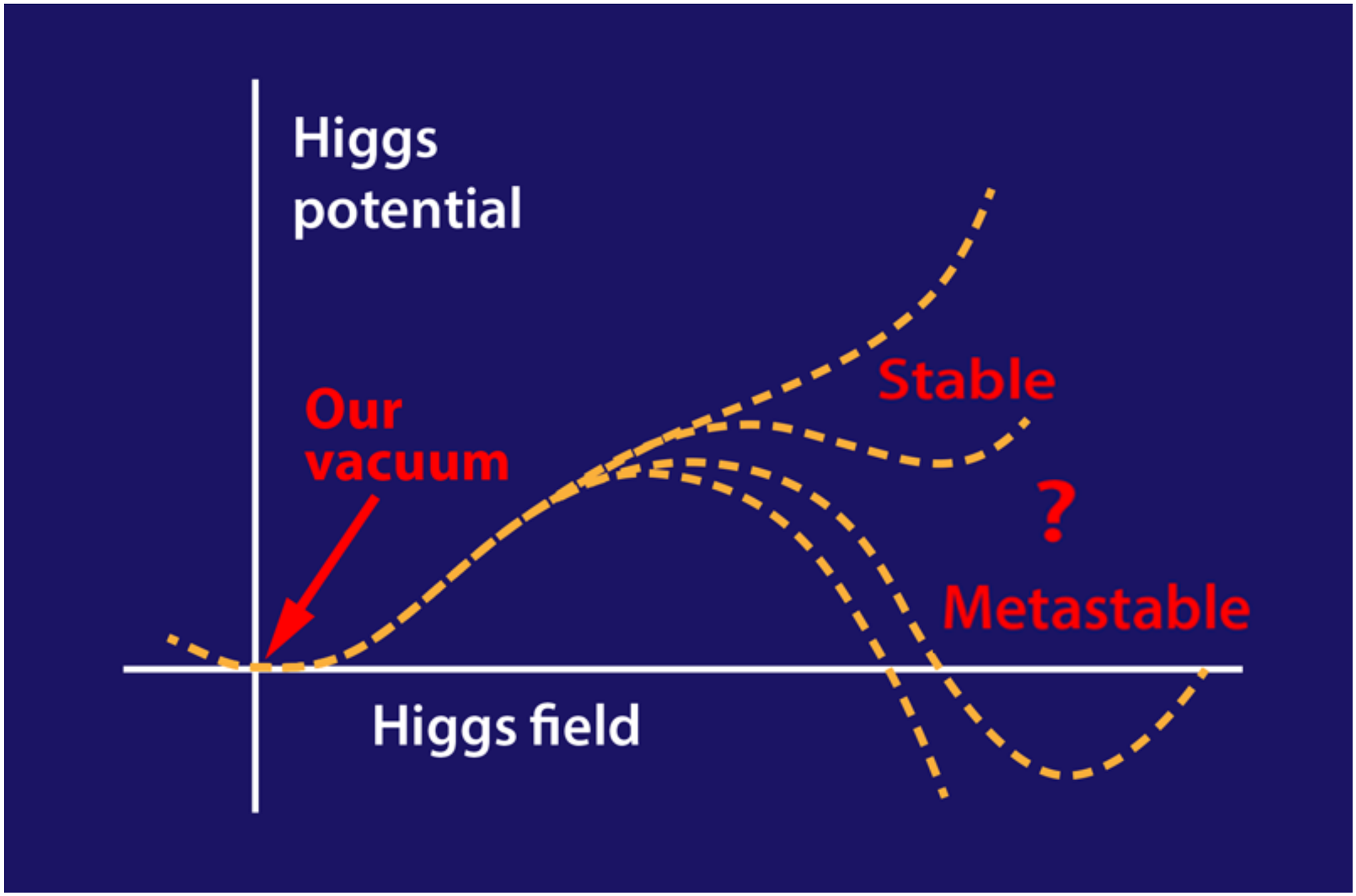








Universe Stability



A. Kusenko

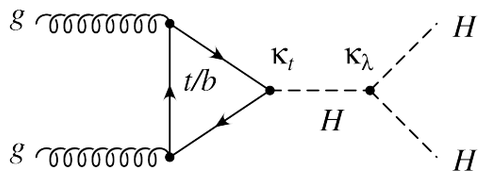
Interference

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

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

Interference

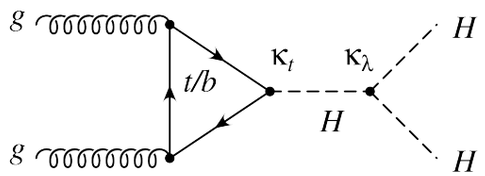
$$\sigma \propto \left| \quad \right|^2 - (\quad \kappa_t \quad \kappa_\lambda \quad + h.c.)$$



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

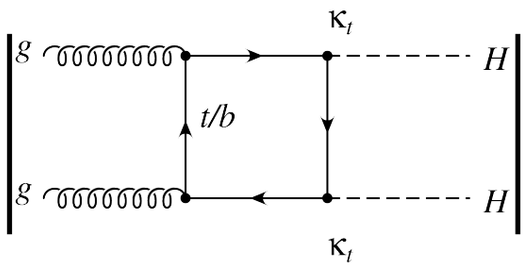
Interference

$$\sigma \propto \left| \right|^2 - ($$



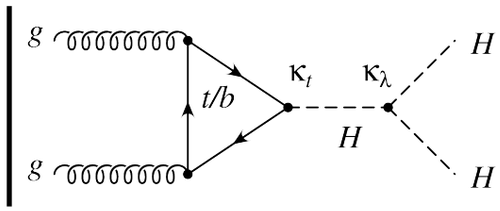
$$+ h.c.)$$

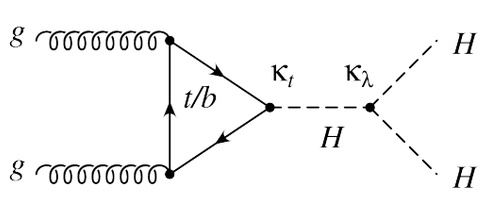
$$+ \left| \right|^2$$



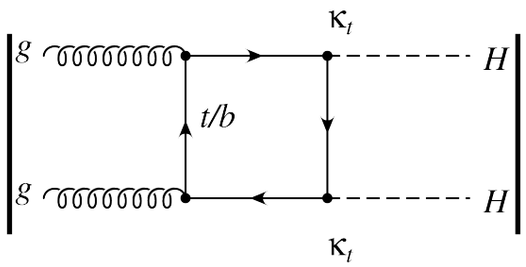
Interference

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



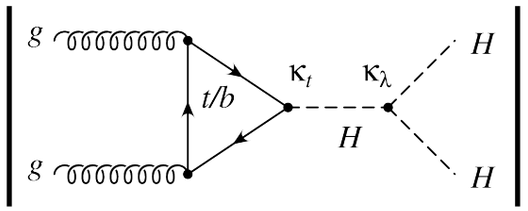


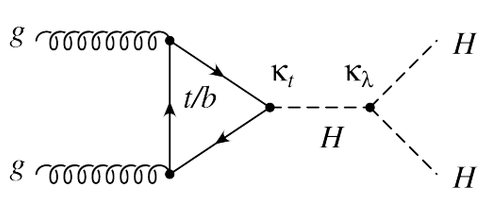
$$+ \left| \quad \right|^2$$

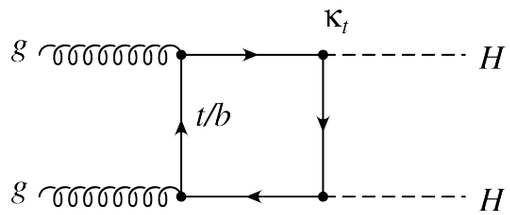


Interference

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







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