Beyond the Standard Model Searches at Colliders

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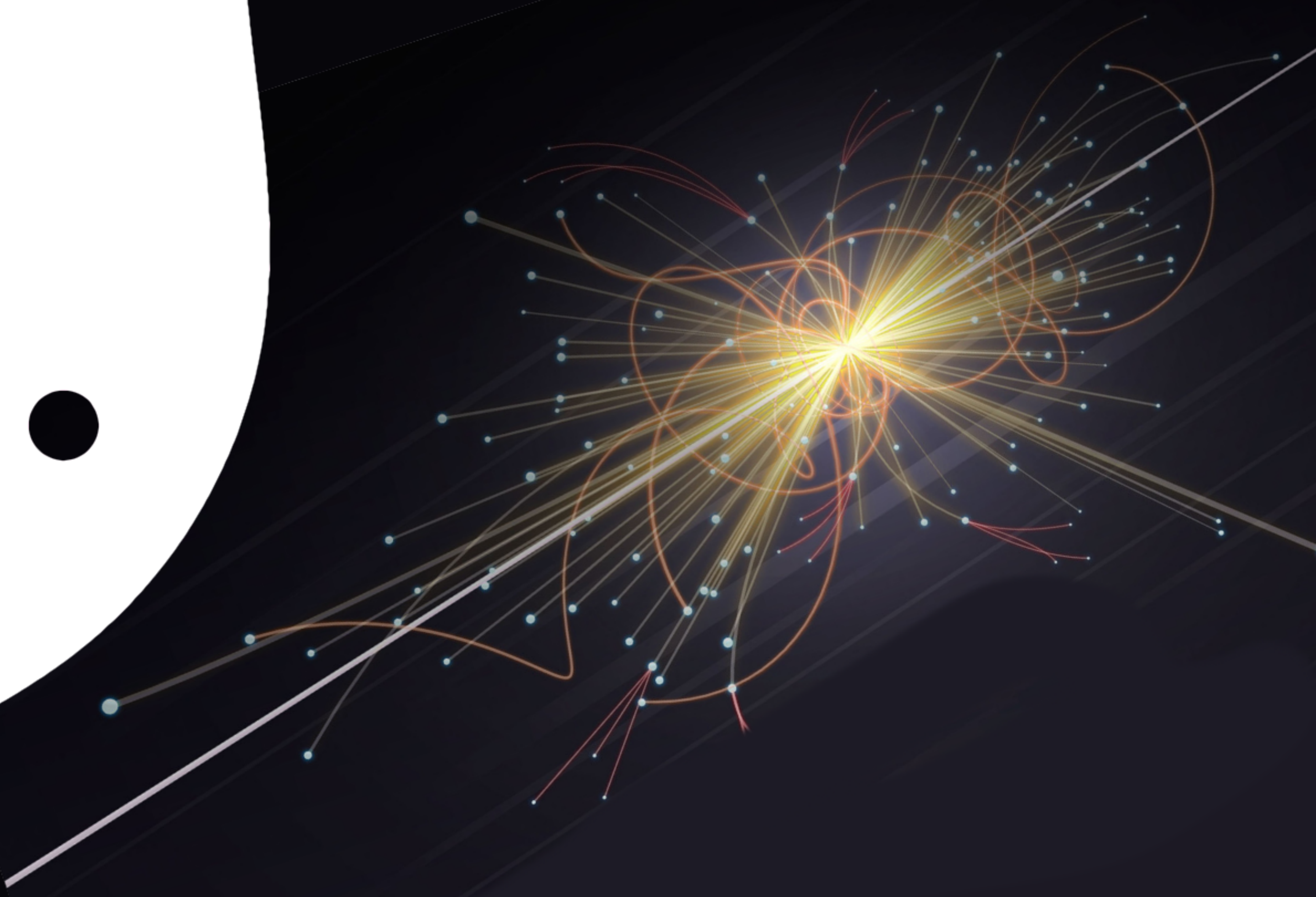
Southern Methodist University, Dallas, Texas, US

25th May 2022



Outline

Yesterday: Why and how we look for BSM physics

- Why are we looking beyond the Standard Model?
- How do we search for new physics?
- Anomaly-driven searches.

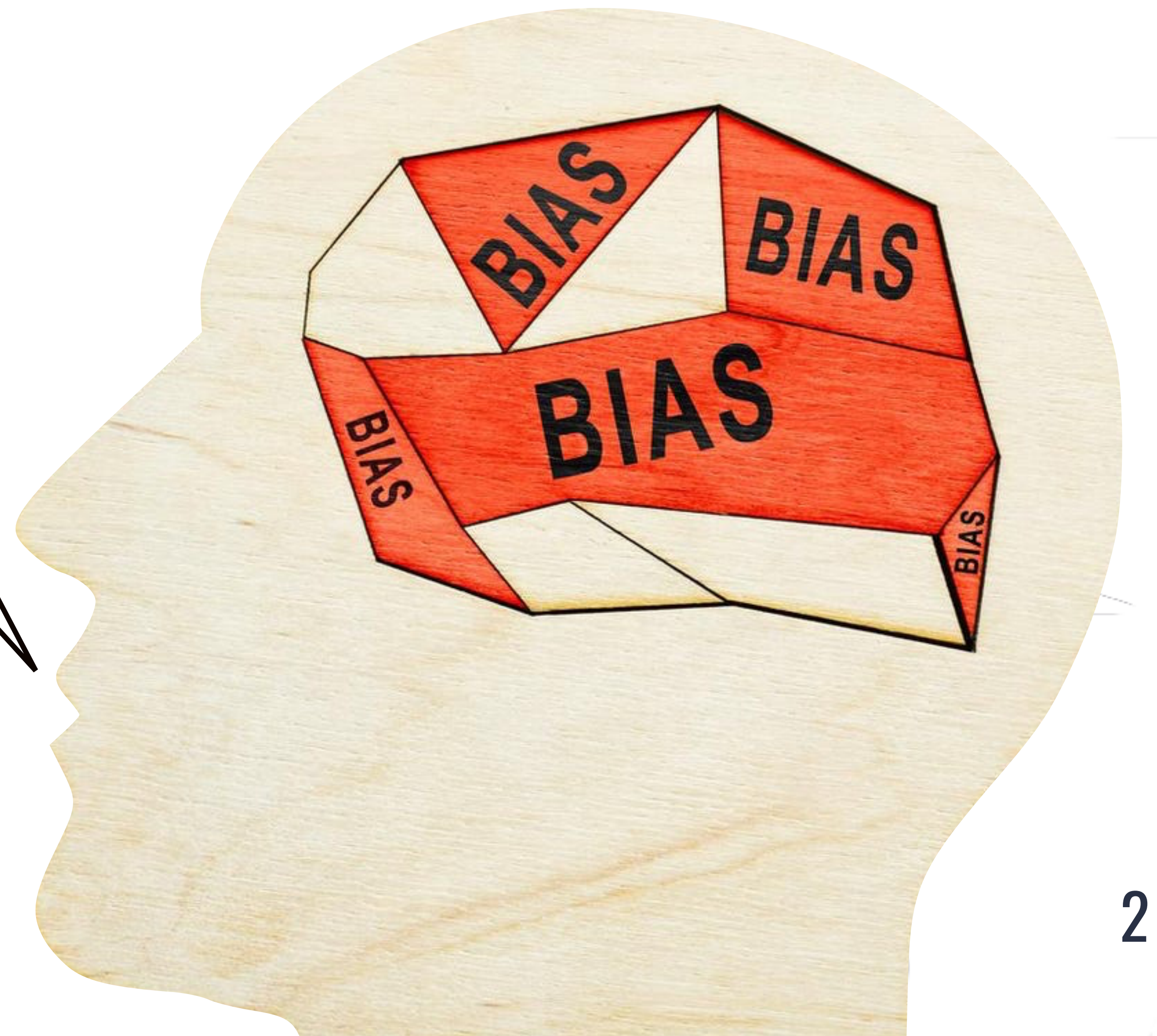
Today: New physics in the scalar sector

- Additional Higgs bosons.
- Using the Standard Model Higgs boson as a tool to search for new physics.
  - Exotic decays of the Higgs boson
  - Higgs self-coupling as a probe of new physics.

Disclaimer

BSM searches at colliders covers a vast amount of experimental and theoretical work - not possible to cover everything in two 40 minute talks!

There is also a lot of personal bias in this talk! Due to the limited time I have chosen to focus more on areas I personally find interesting (and/or have expertise in).



The Higgs boson as a portal to new physics

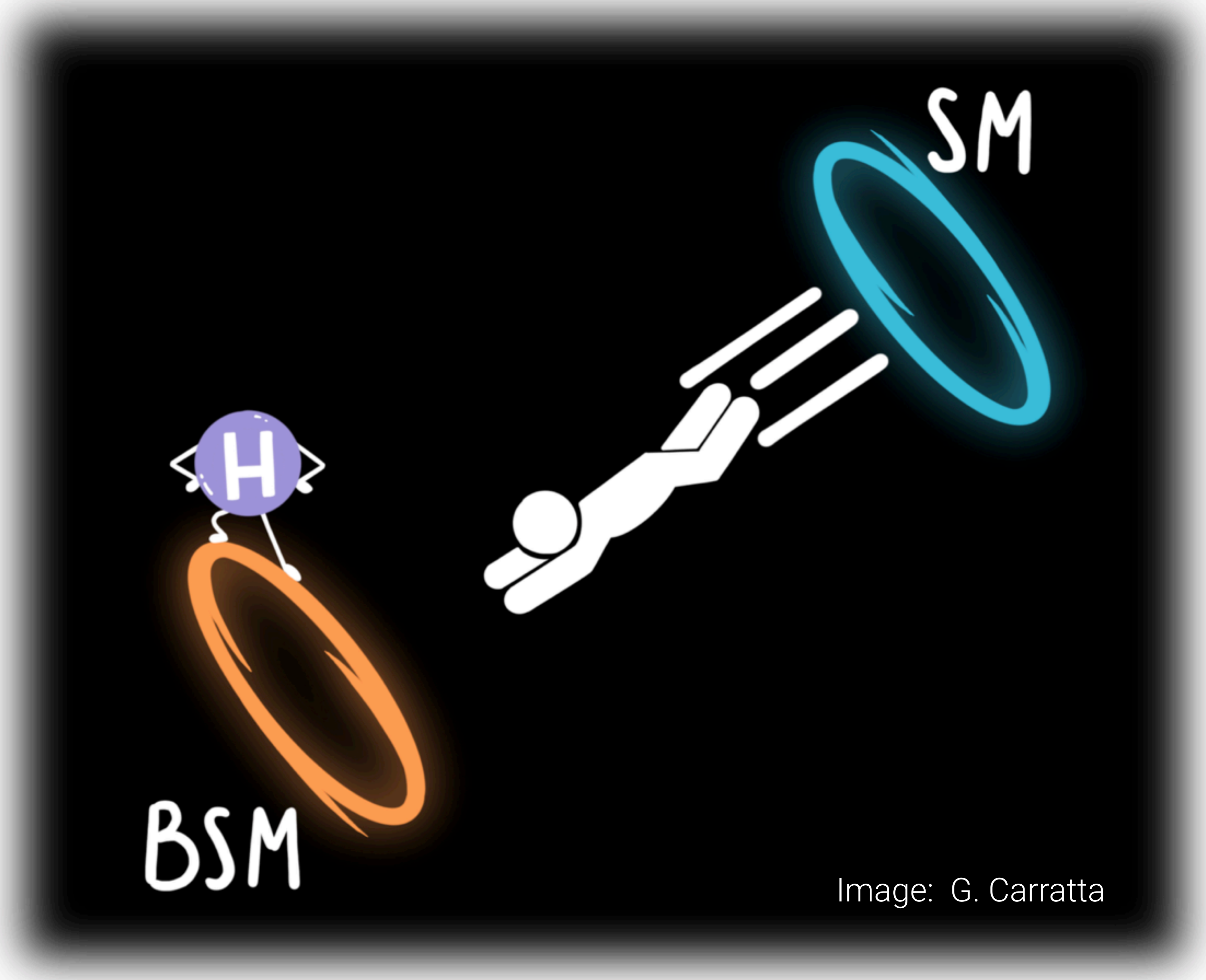
We're fairly certain that there must be new physics at some scale, but if this new physics doesn't interact with the weak, strong, or EM forces, then it may only be detectable in the Higgs sector.

- Additional Higgs bosons.
- Exotic decays of the Higgs boson, e.g. to dark matter.
- Non-SM couplings of the Higgs boson.
  - Impact on the Higgs self-coupling.

Higgs couples to mass

→ different interaction strengths across quark-lepton generations

→ possible link to flavour anomalies?



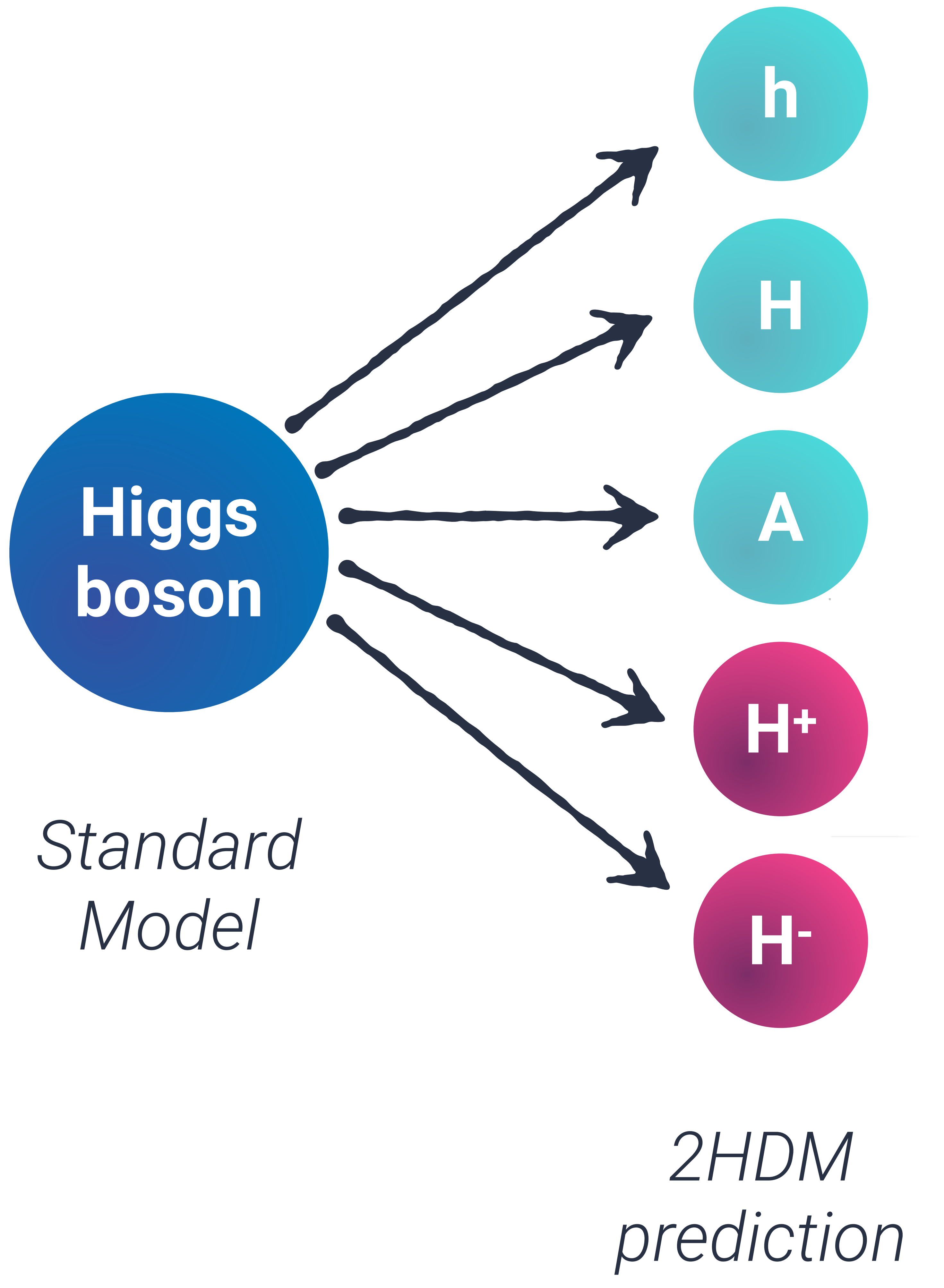
Additional Higgs bosons

Extended Higgs sector

Extend the SM to have two Higgs doublets instead of one.
- 2 Higgs Doublet Model (2HDM)

Additional Higgs doublet yields five physical Higgs bosons:
- Two CP-even Higgs bosons, h, and H (one is the 125 GeV Higgs).
- CP-odd pseudoscalar, A.
- Two charged Higgs bosons, H^+ and H^-.

Describe in terms of six parameters:
- Four Higgs masses: m_h, m_H m_A, $m_{H\pm}$
- Ratio of the two vacuum expectation values of the doublets: $\tan\beta$
- Mixing angle (parametrises the mixing between the CP-even neutral Higgs): $\sin\alpha$

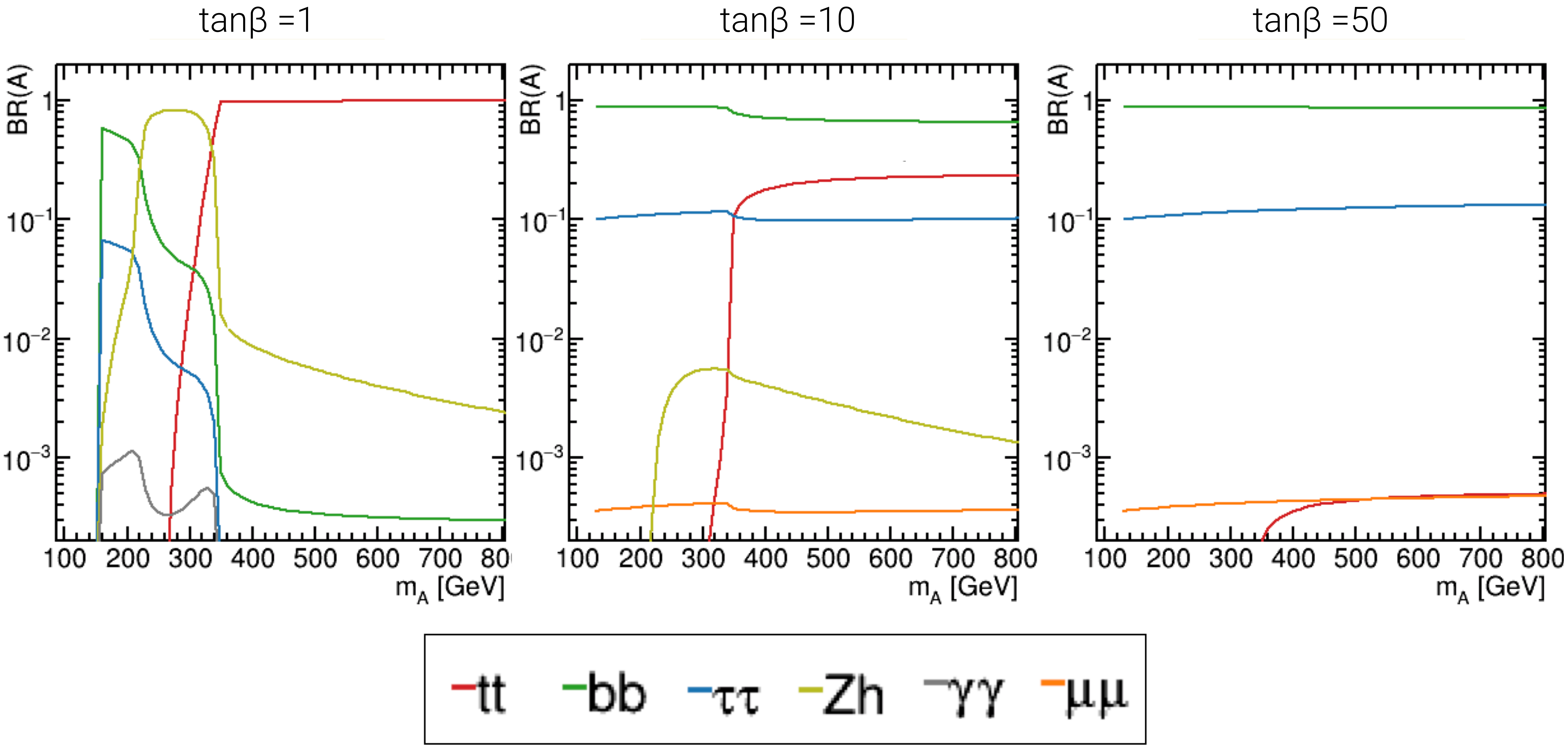


Flavours of 2HDMs

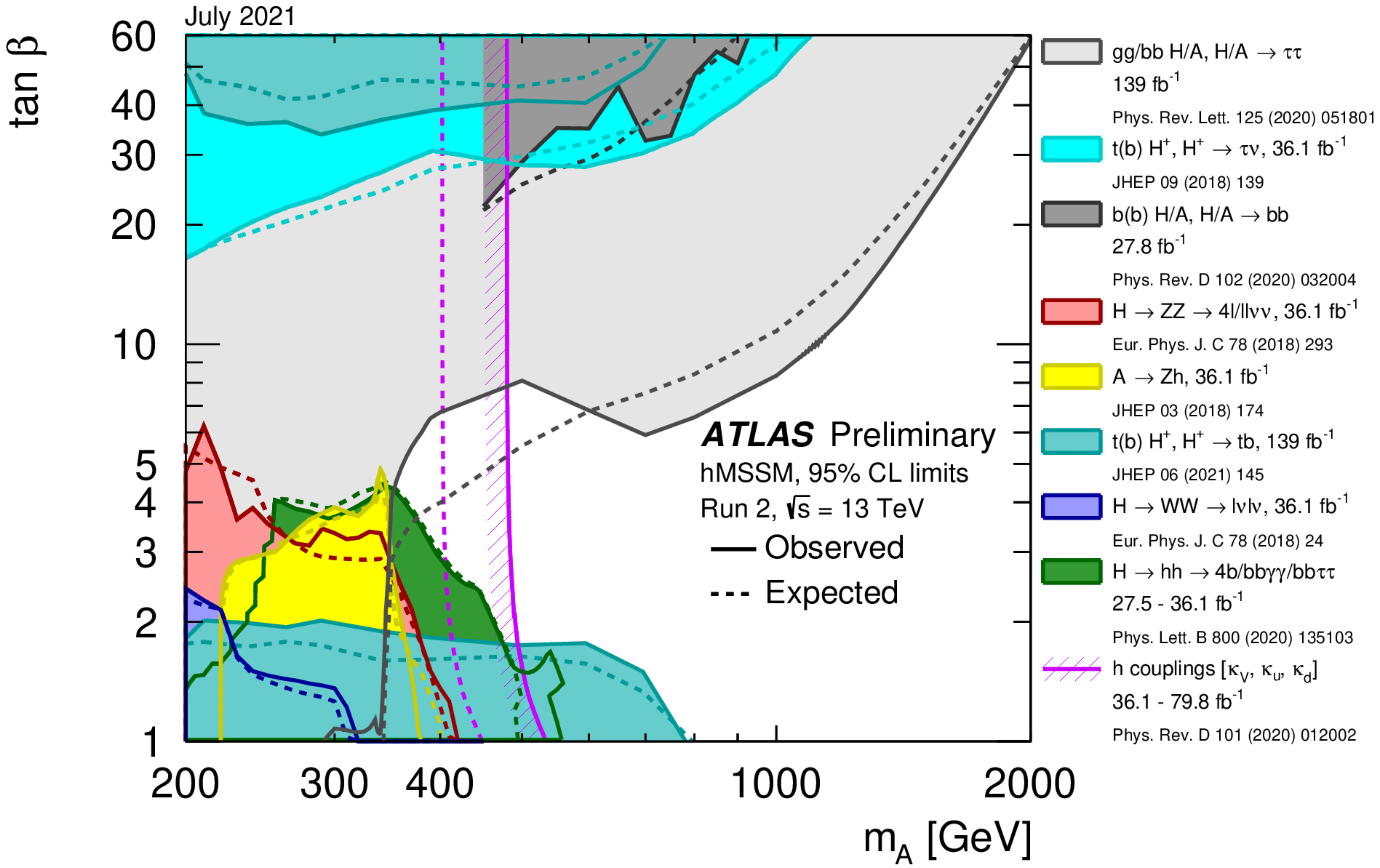
Different types of 2HDM, depending on which types of fermions couple of which Higgs doublet.

Add a third Higgs doublet (3HDM) → get doubly-charged Higgs bosons, H^{++} and H^{--} as well.

Example: A boson decay in hMSSM



Searches for additional Higgs bosons



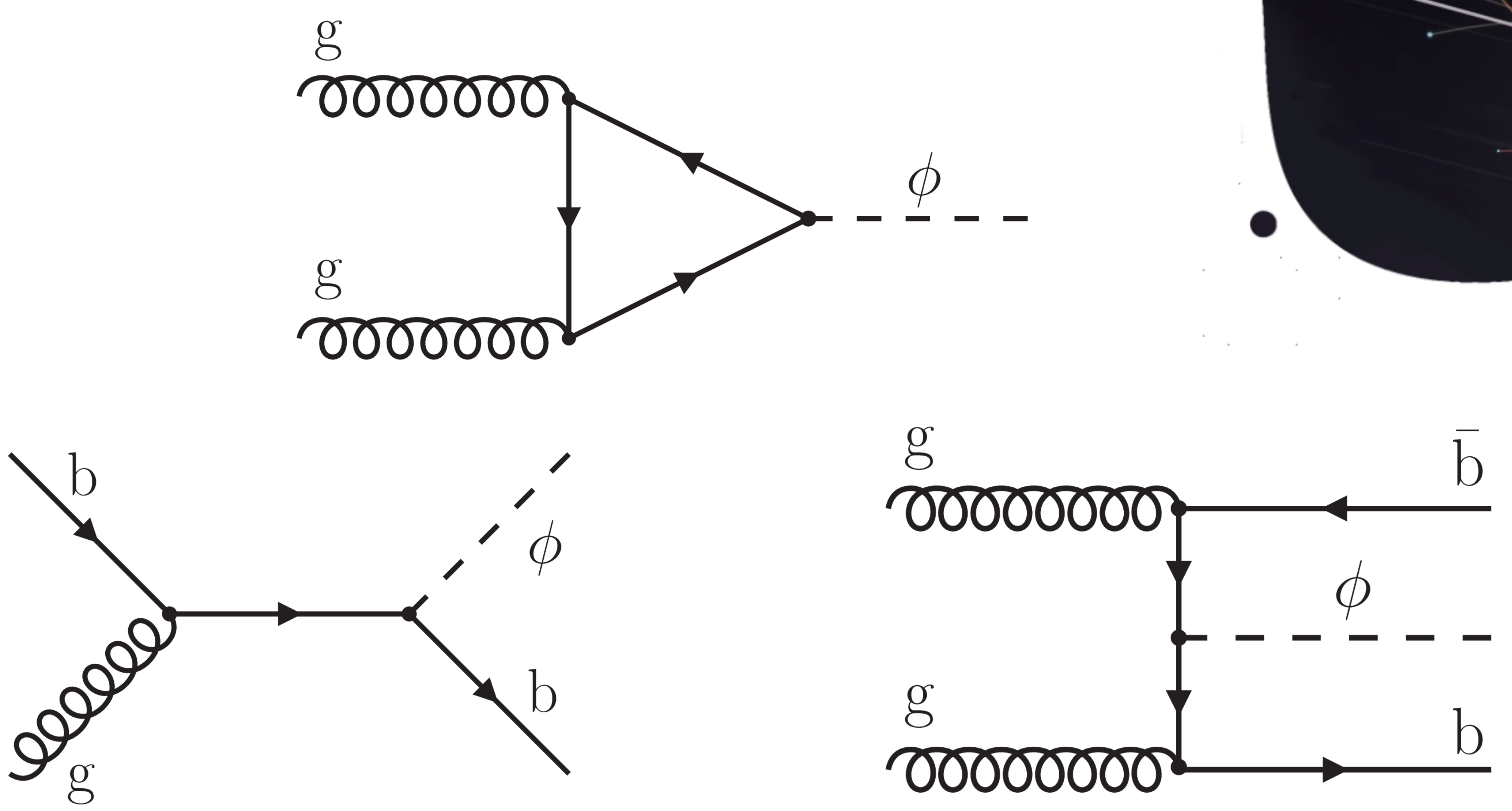
Similar set of results from CMS

A/H→ττ

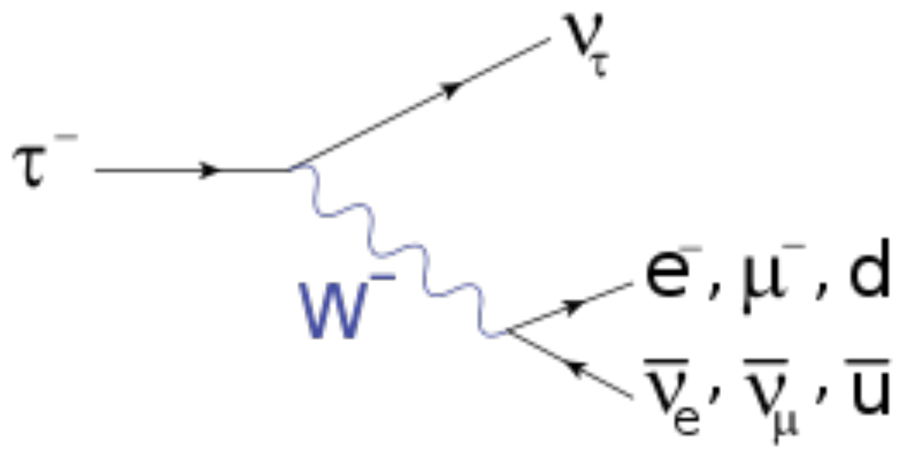
CMS-PAS-HIG-21-001

Recent CMS result searching for a new particle decaying to a pair of taus.

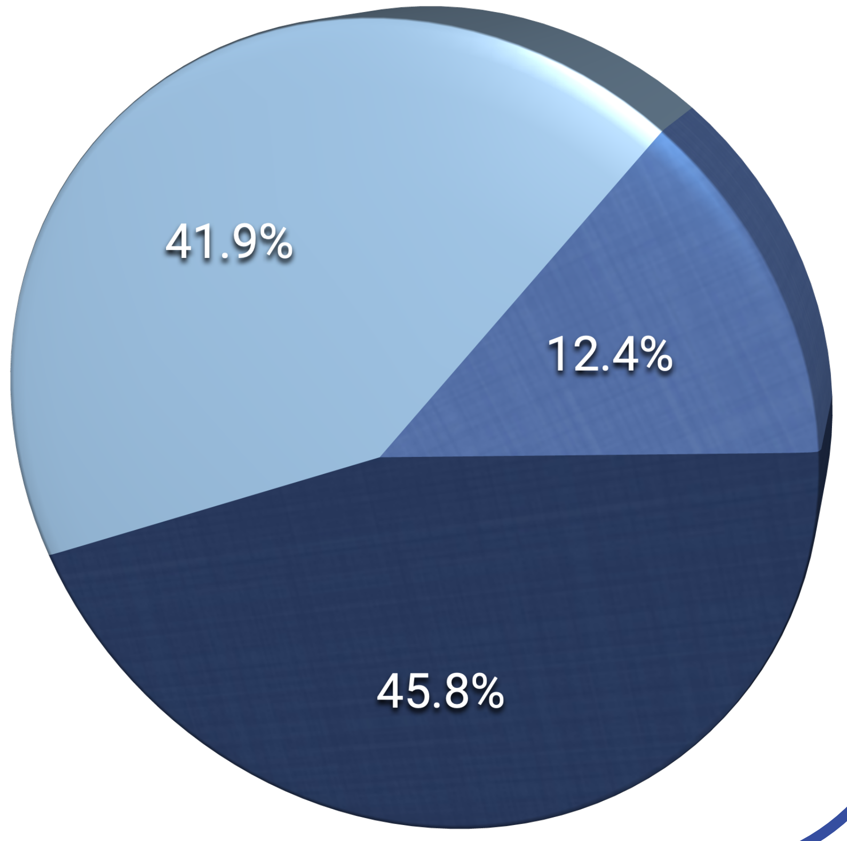
- Gluon fusion production.
- Produced in association with one or two b-quarks.

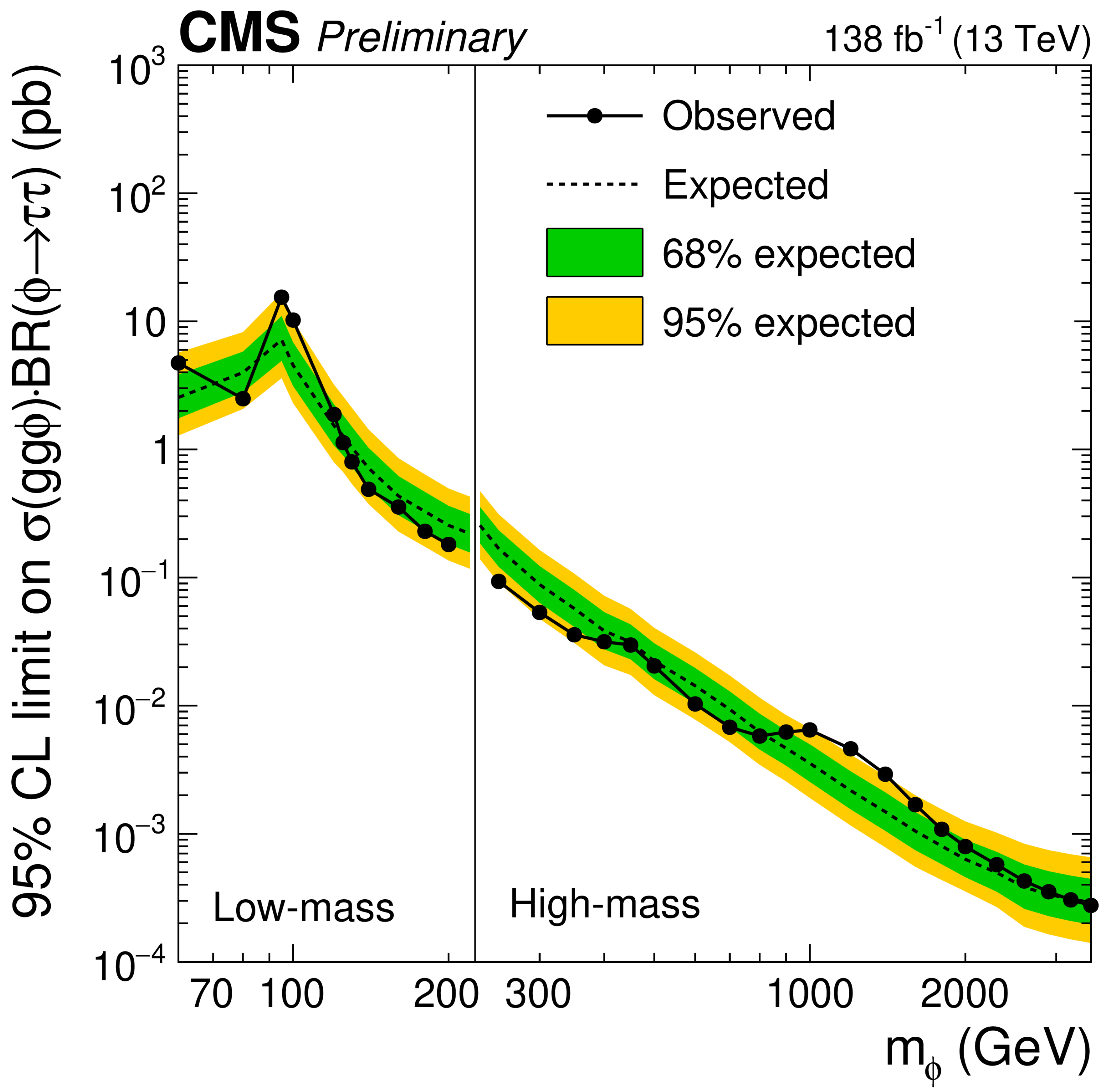


Tau decay



τ-τ decay channels





Two mild excesses:
- 95 GeV (2.6σ)
- 1.2 TeV (2.8σ)

To note:
- Significances reduce to 2.3σ and 2.4σ once the "look-elsewhere effect" is taken into account.
- 1.2 TeV excess is not observed by ATLAS.
- ATLAS has not done this analysis in the "low mass region".

$H^+ \rightarrow tb$

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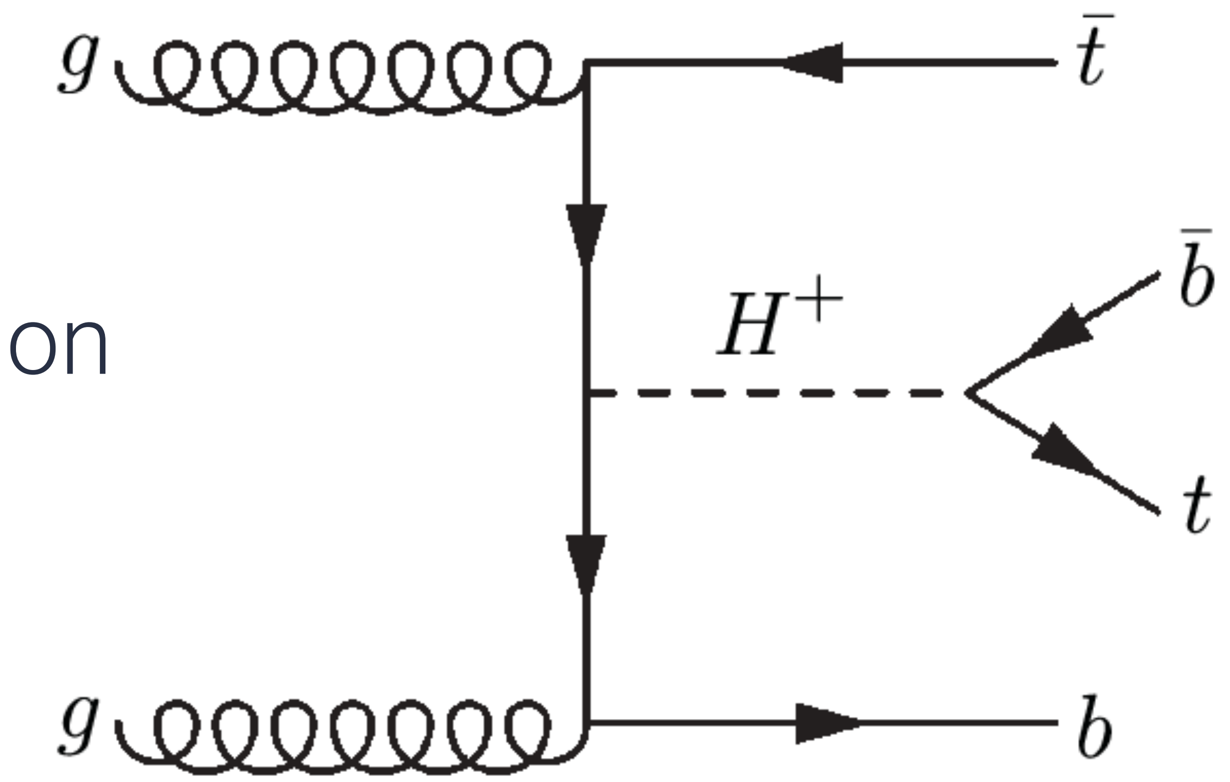


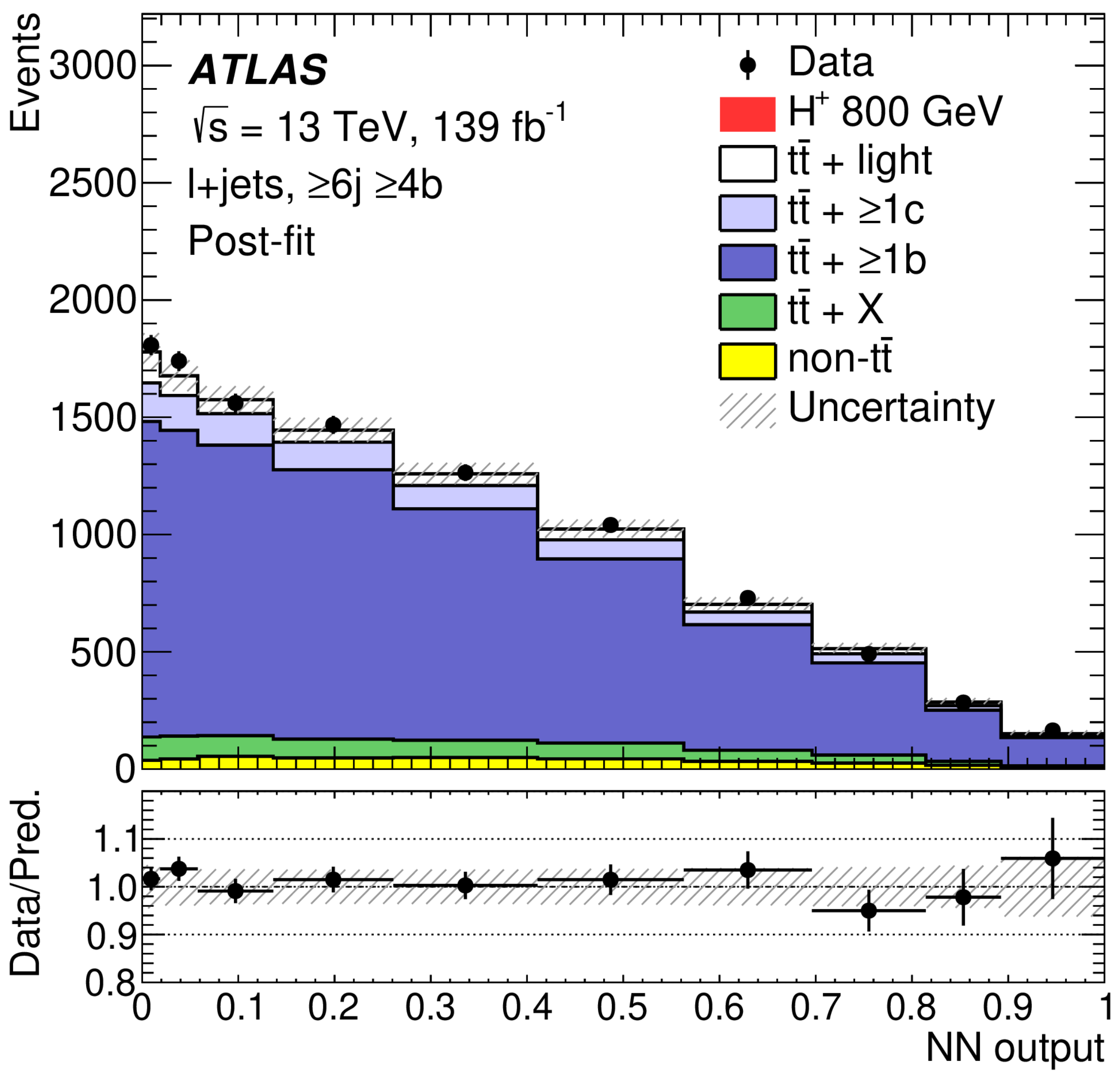
Charged Higgs produced in association with a top quark and a b-quark.

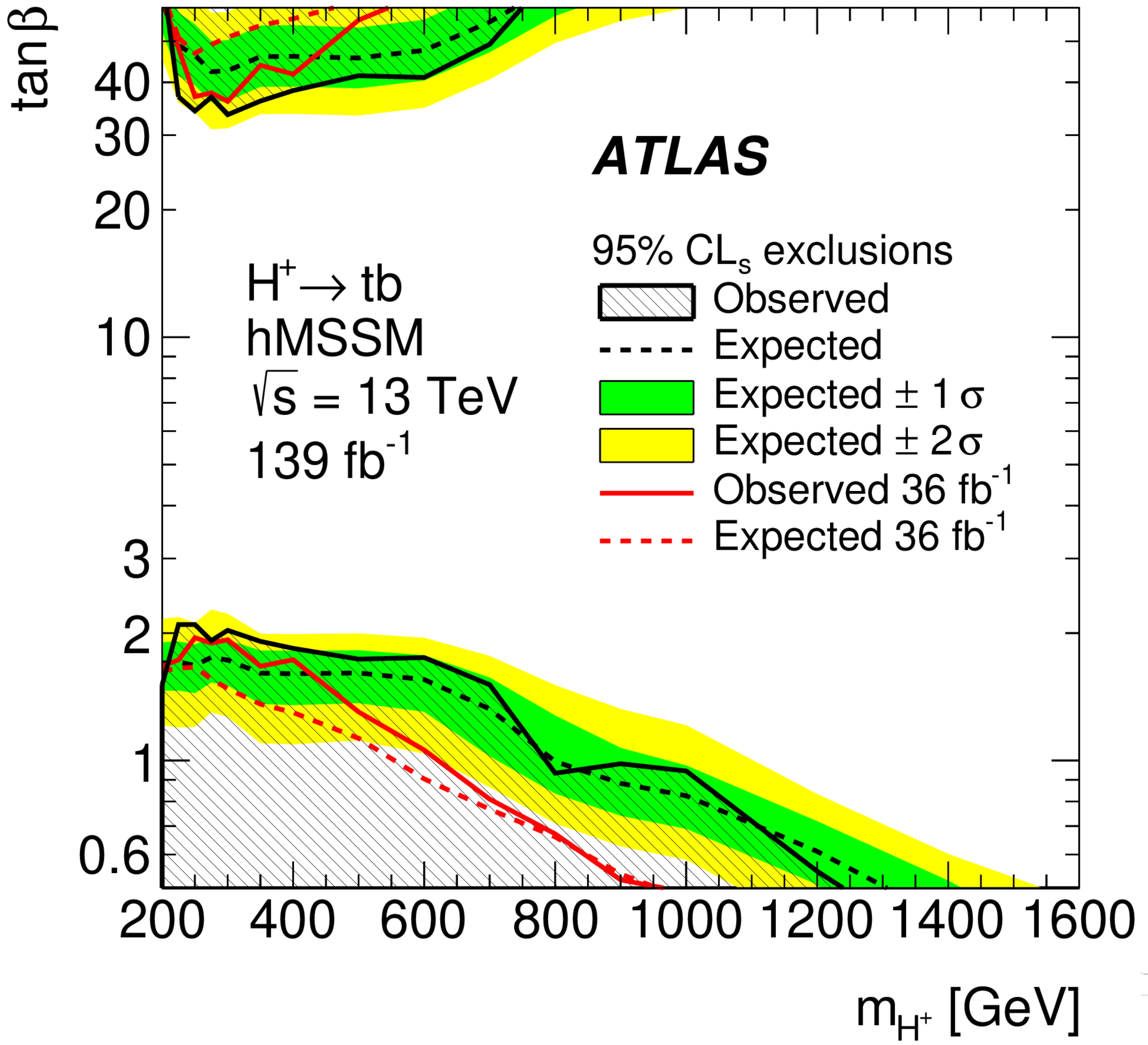
- H+ → tb.
- Both top quarks → Wb.
- One W → ℓν.
- Other W → qq.

Final state with one e/μ, missing E_T, 4 b-jets and 2 additional jets!

ATLAS analysis uses neural networks to separate signal from background.

- Dominant background process is ttbar produced in association with additional jets.



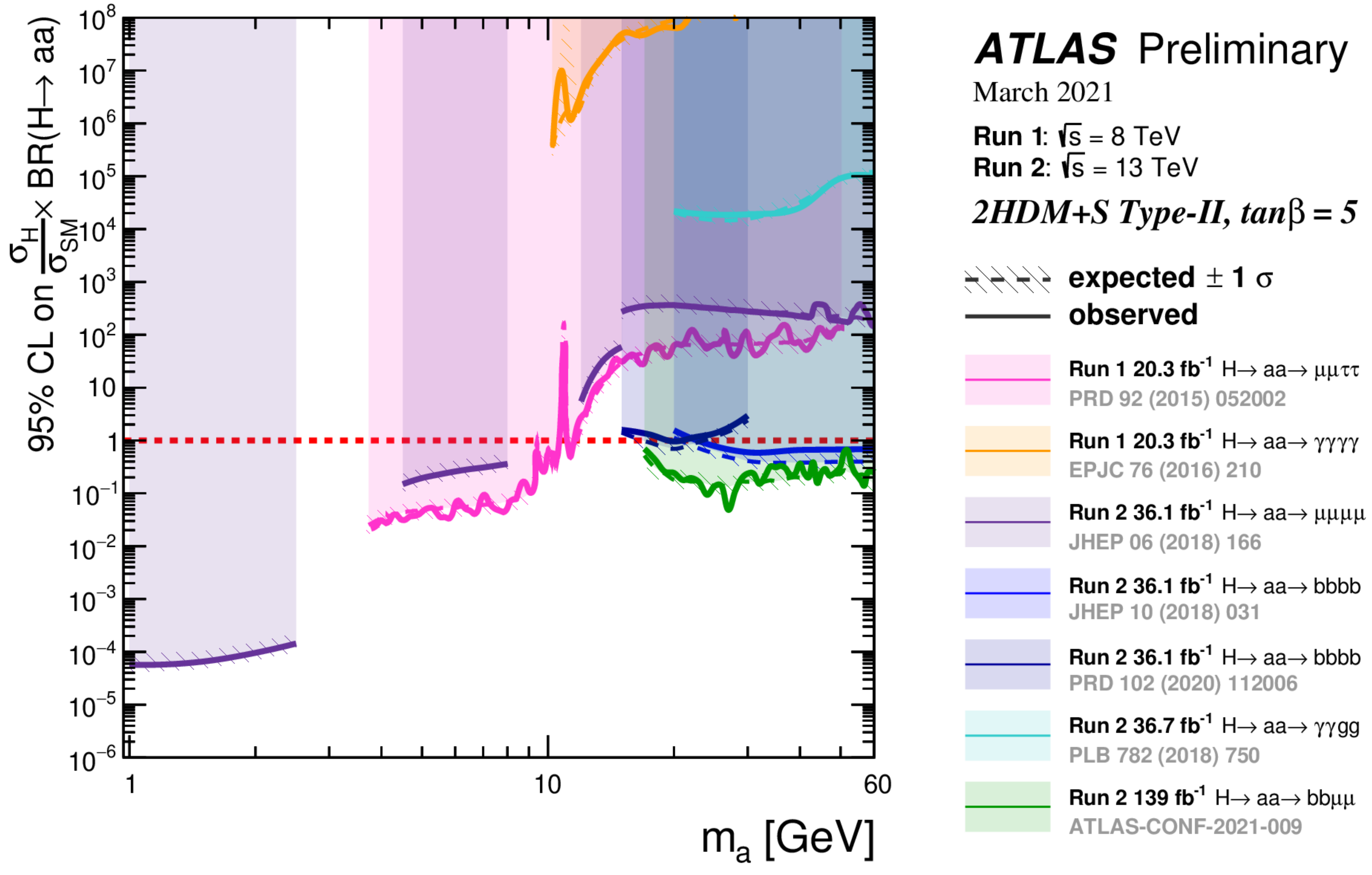


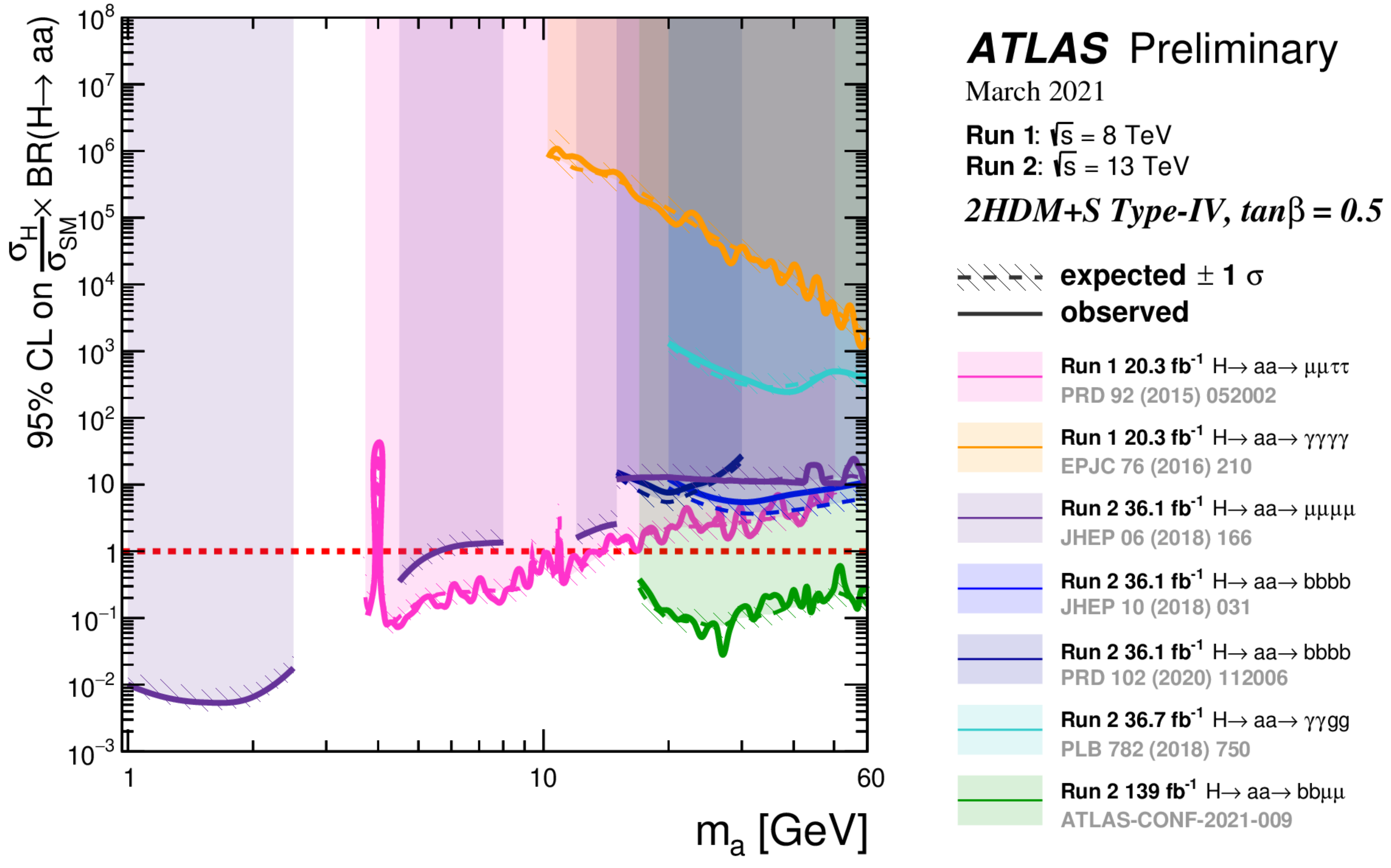
Exotic decays of the Higgs

Further extending 2HDMs

- 2HDM+S: Popular class of models where an additional scalar singlet, S, is introduced to the 2HDM.
- S couples only to the two Higgs doublets, and gives rise to a light pseudoscalar, a.
- Different predictions for how the new pseudoscalar, a, couples to SM particles → interpret results in different models to rule out regions of phase space.

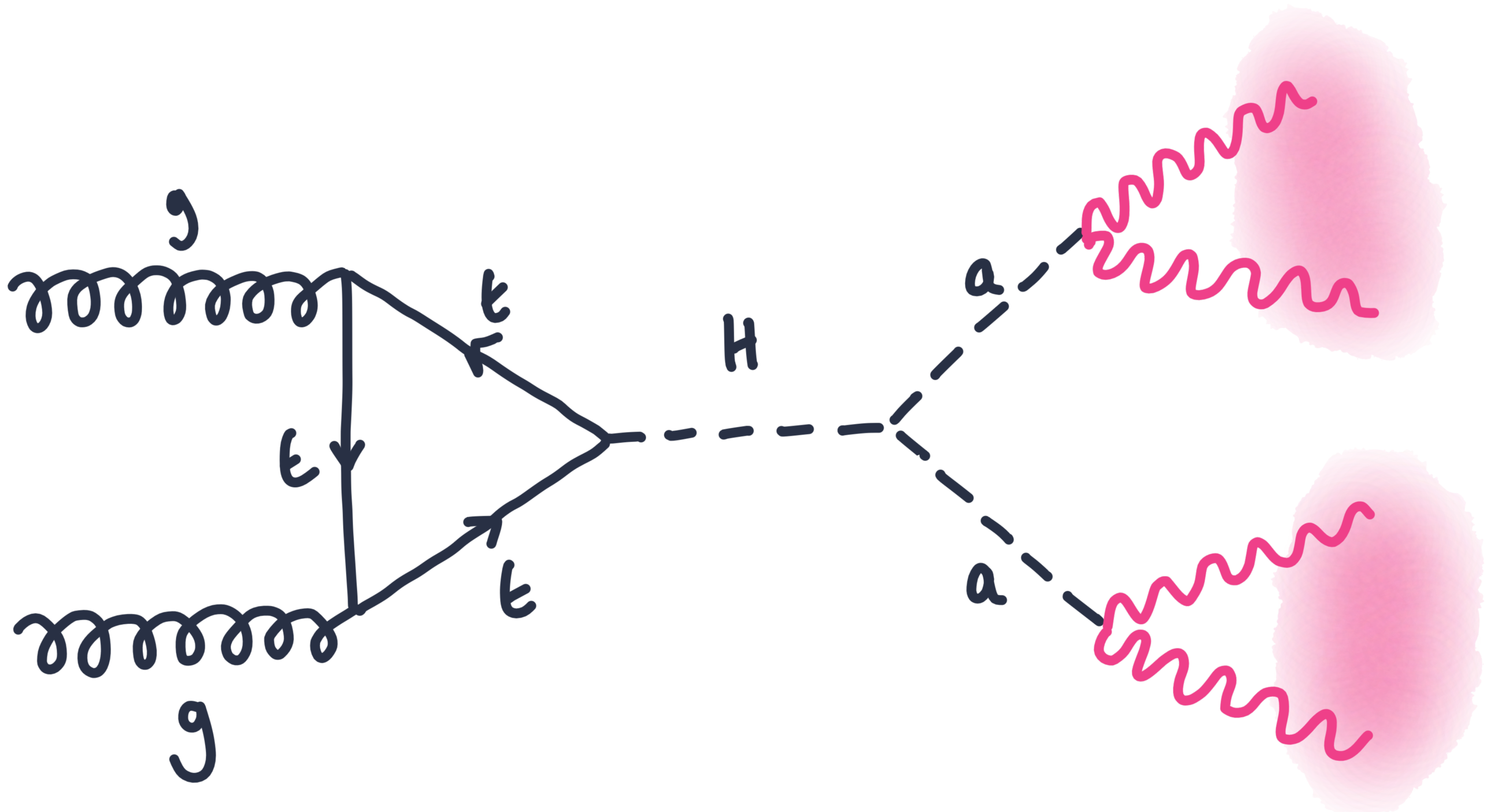
Similar set of results from CMS

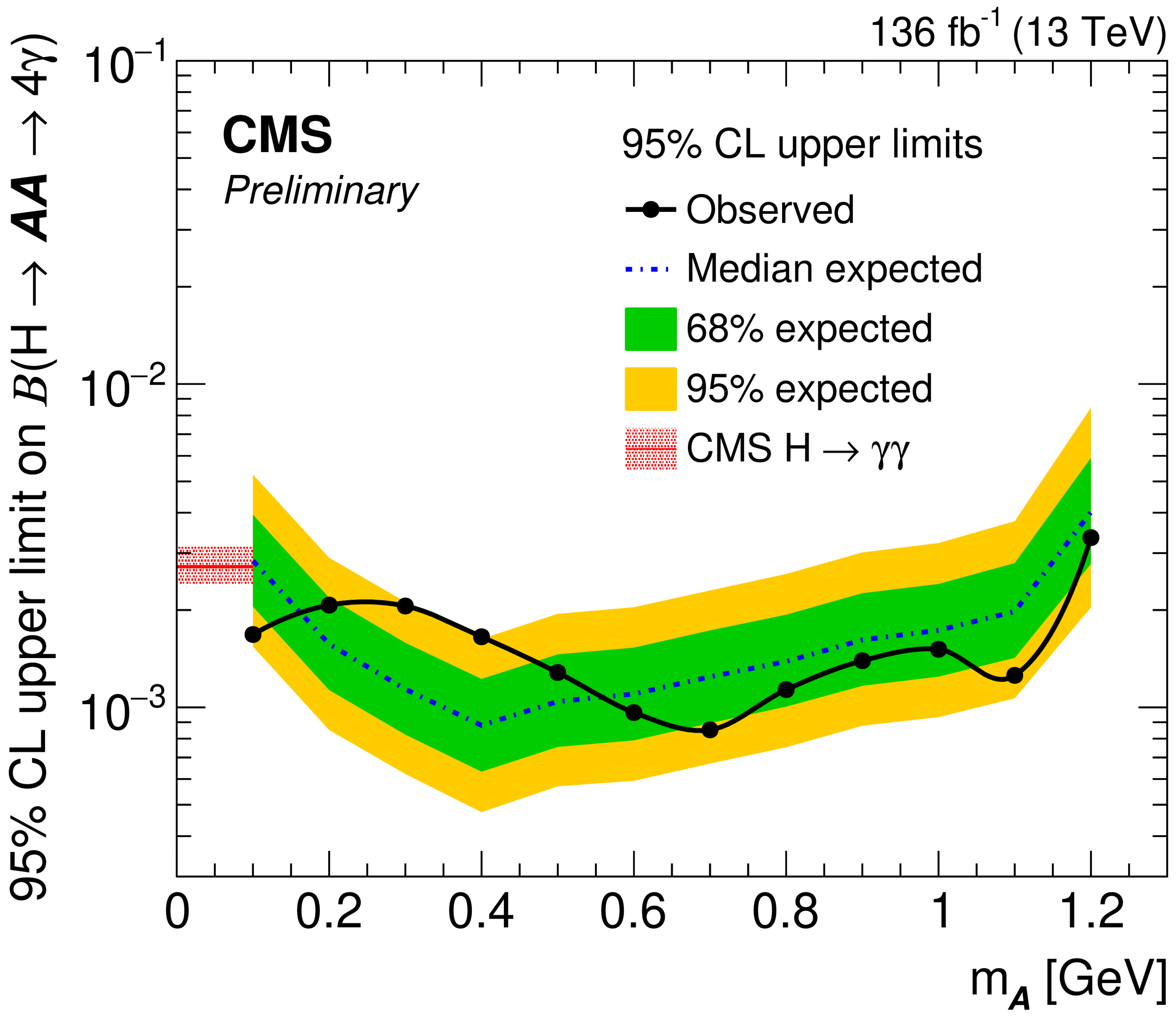




H→aa→4γ

CMS analysis probing extremely low mass pseudoscalars ($0.1 < m_a < 1.2$ GeV).





γγ pairs merged in calorimeter

- Normal photon identification algorithms inefficient.
- Developed specialised tagging algorithm to identify these merged photons.

H→aa→bbμμ

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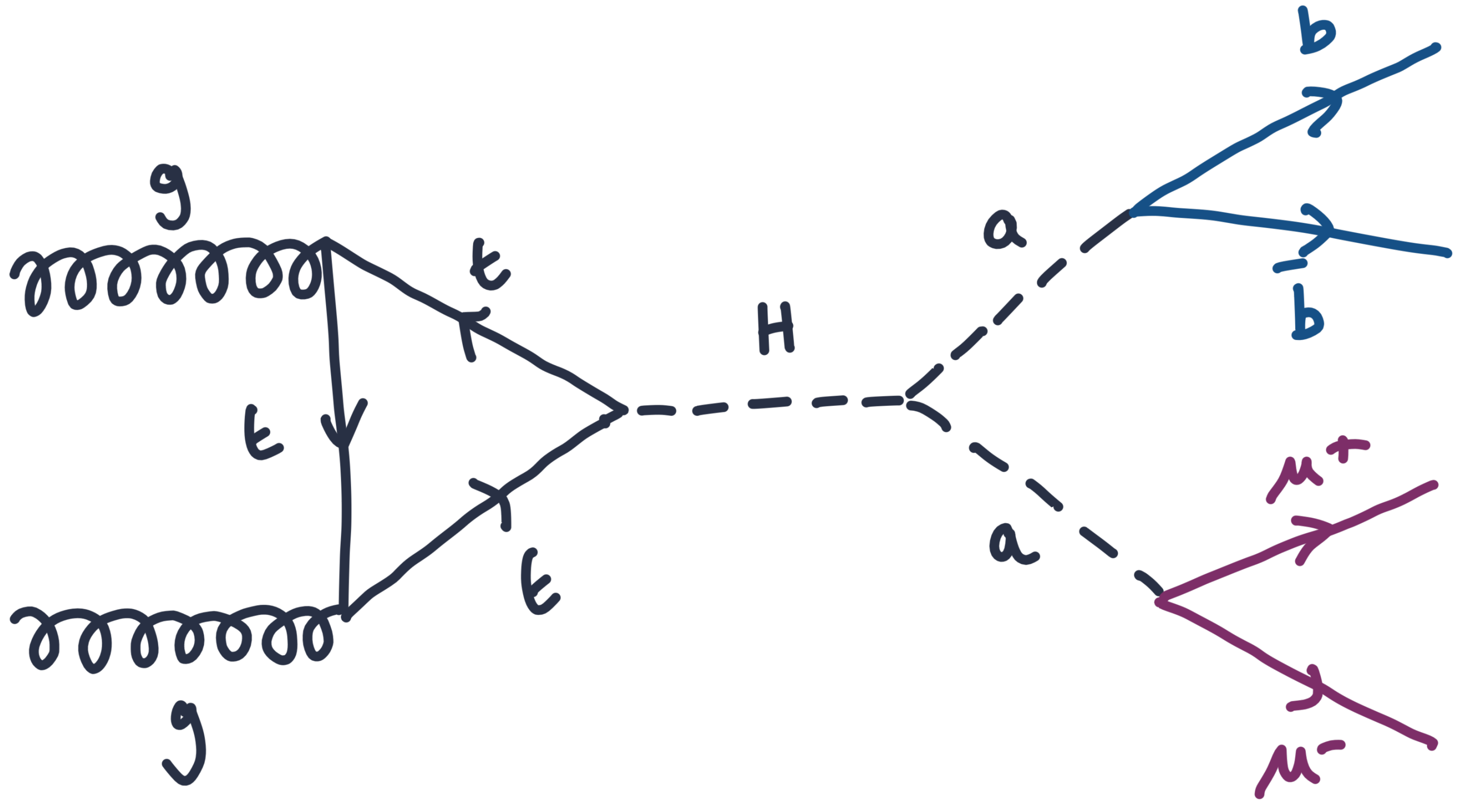
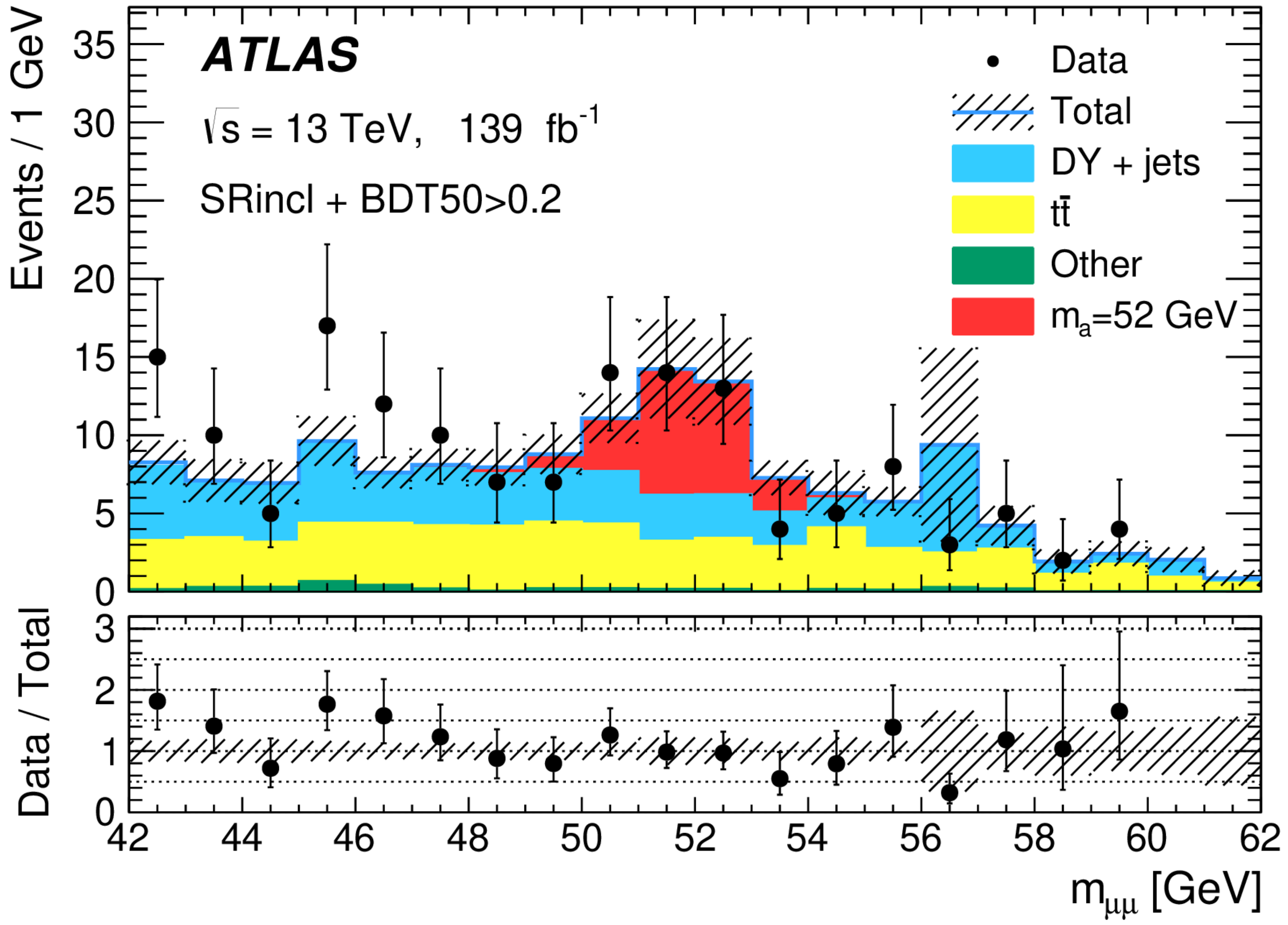
ATLAS search for events with two b-jets and two muons.

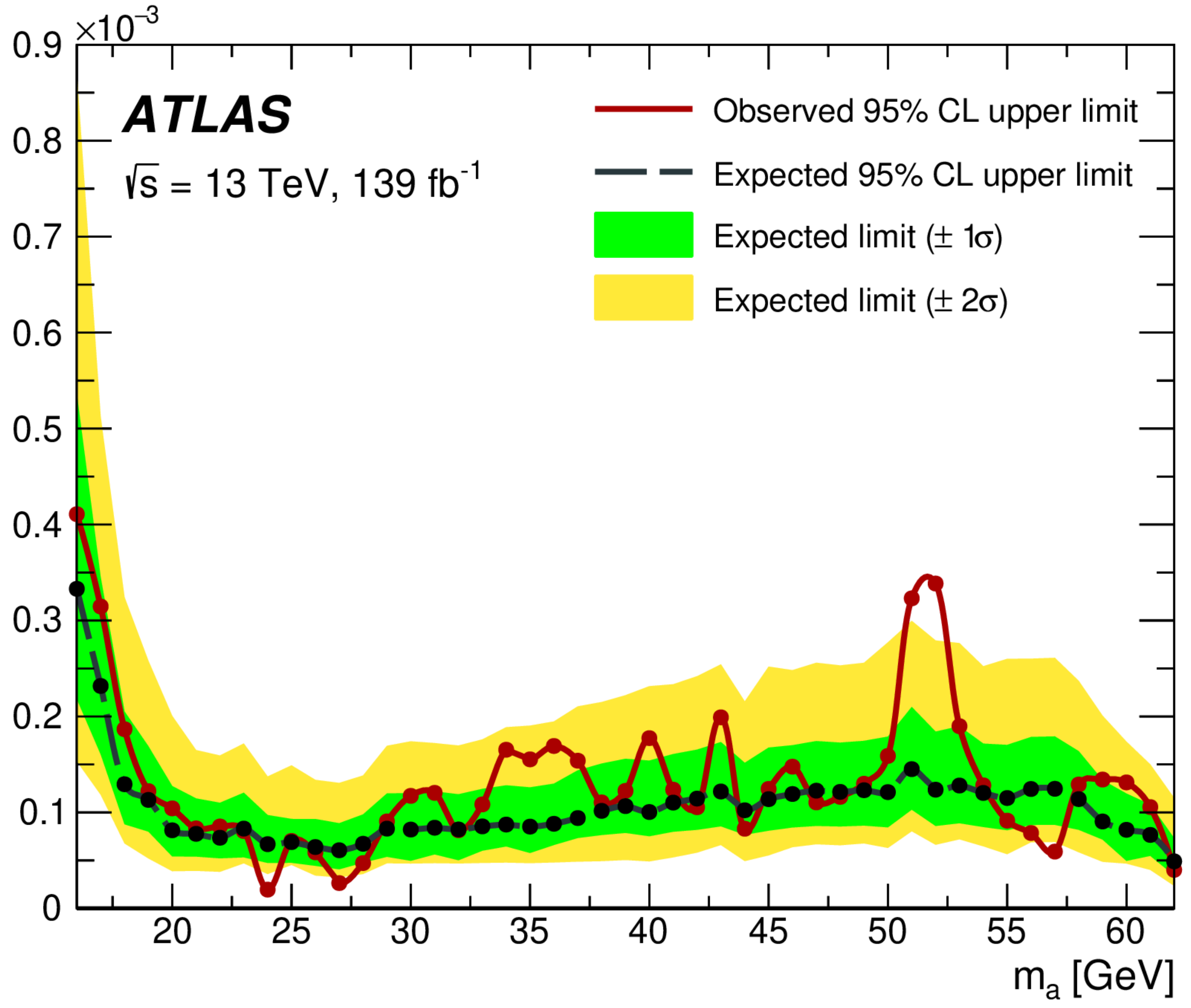
- $m_{bb} \approx m_{\mu\mu}$
- Invariant mass of bbμμ system compatible with coming from the Higgs.
- Use BDTs to improve separation of signal from backgrounds.



3.3σ excess at m_a = 52 GeV.

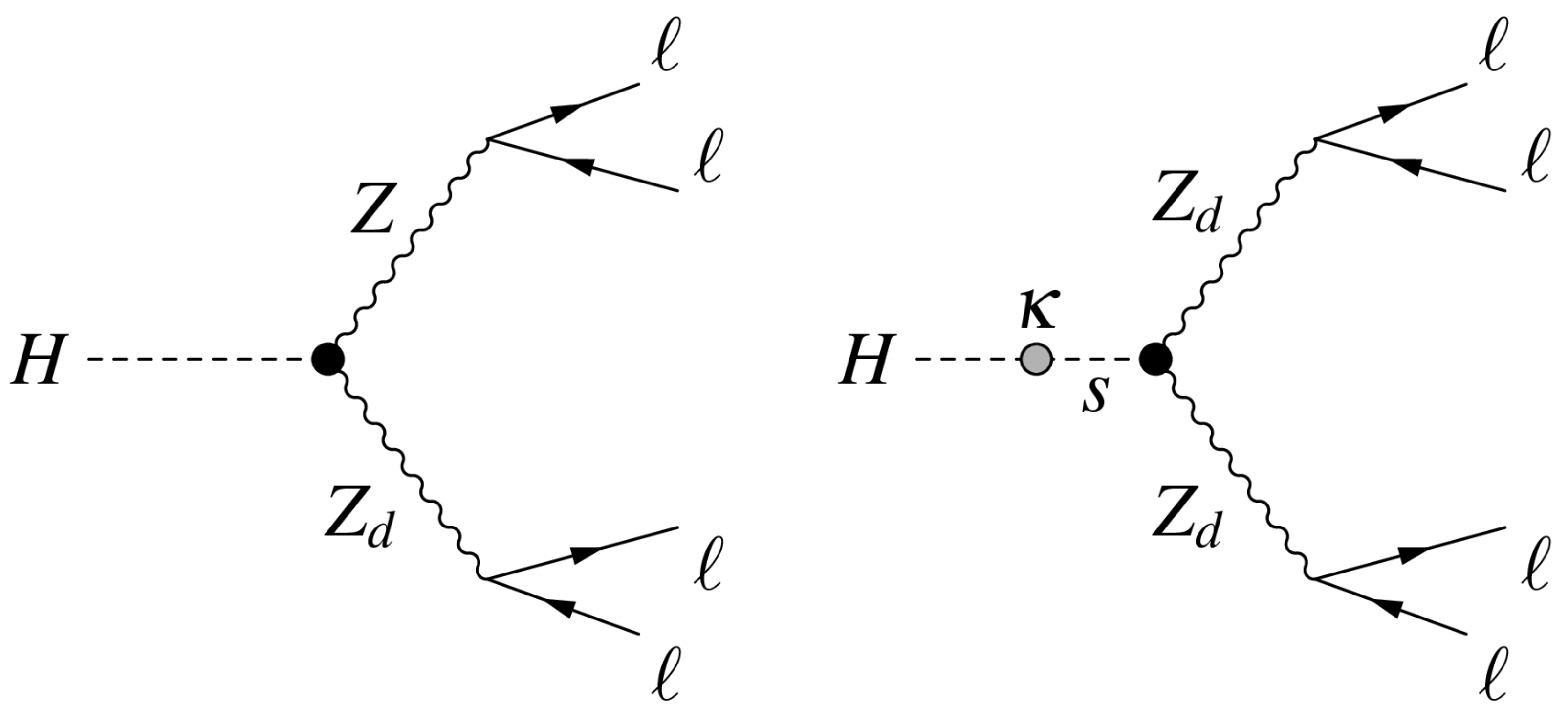
- Reduces to 1.7σ when accounting for the look-elsewhere effect.

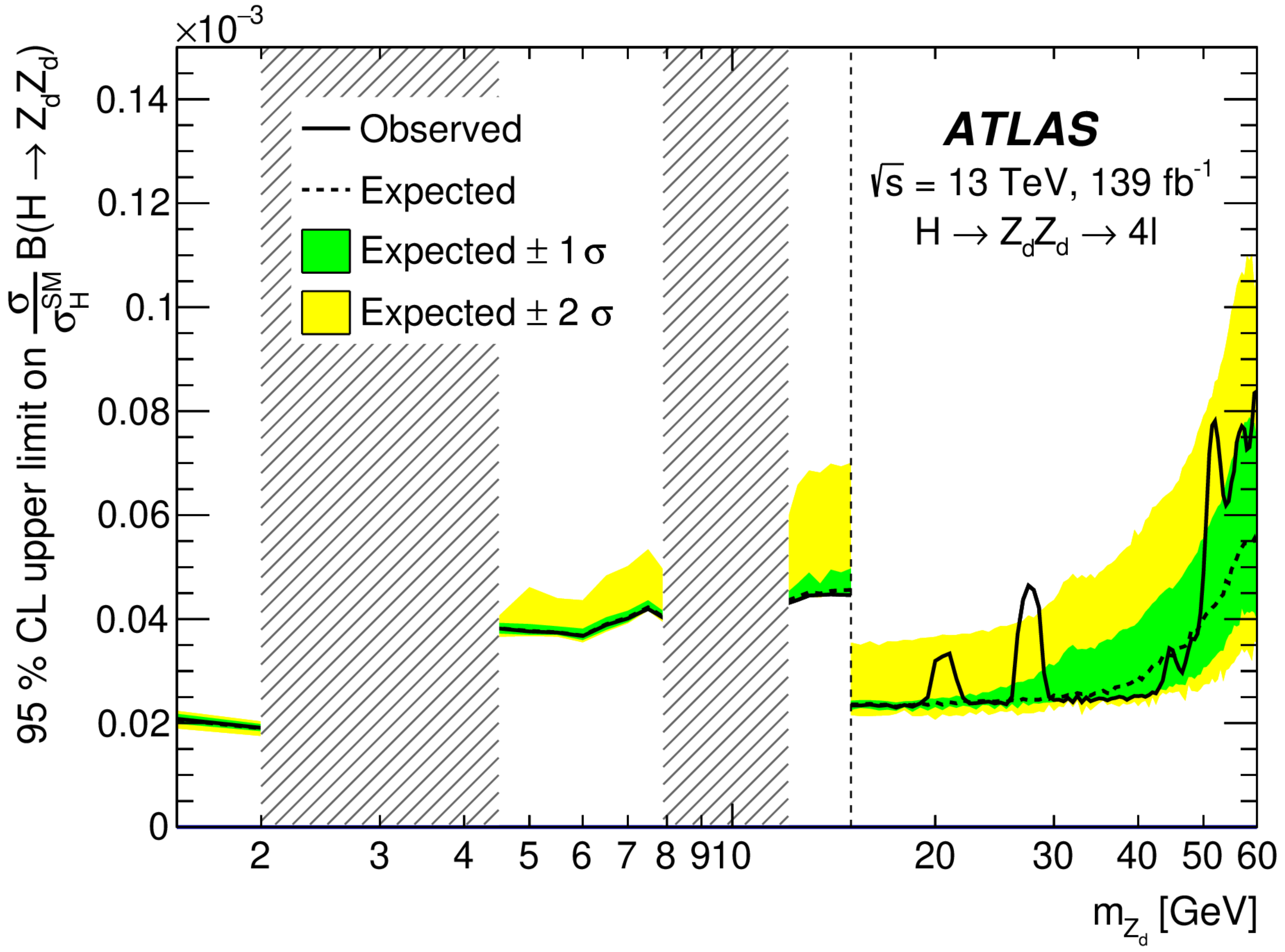




$H \to Z_{(d)}Z_d \to 4\ell$

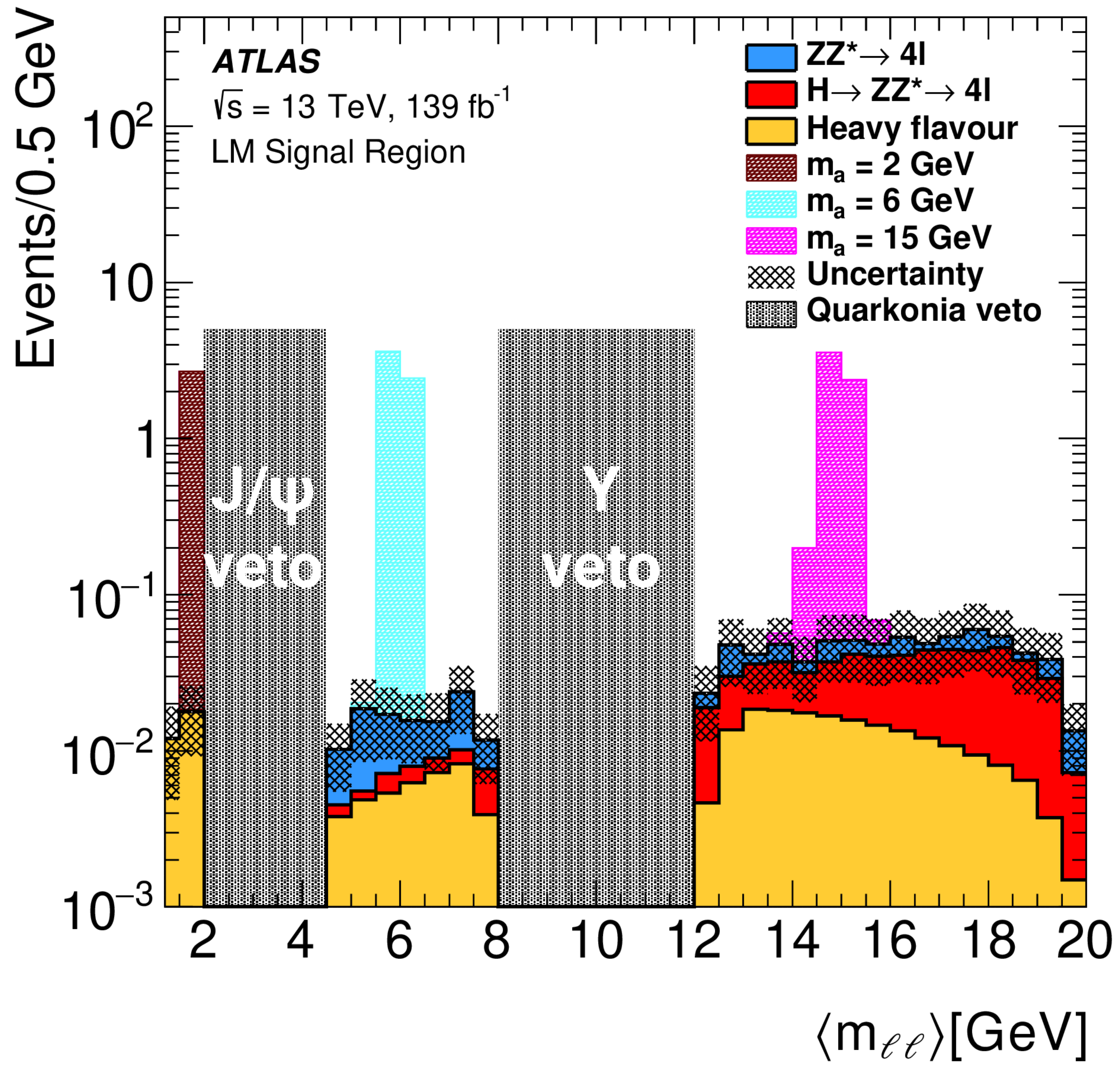
HDBS-2018-55

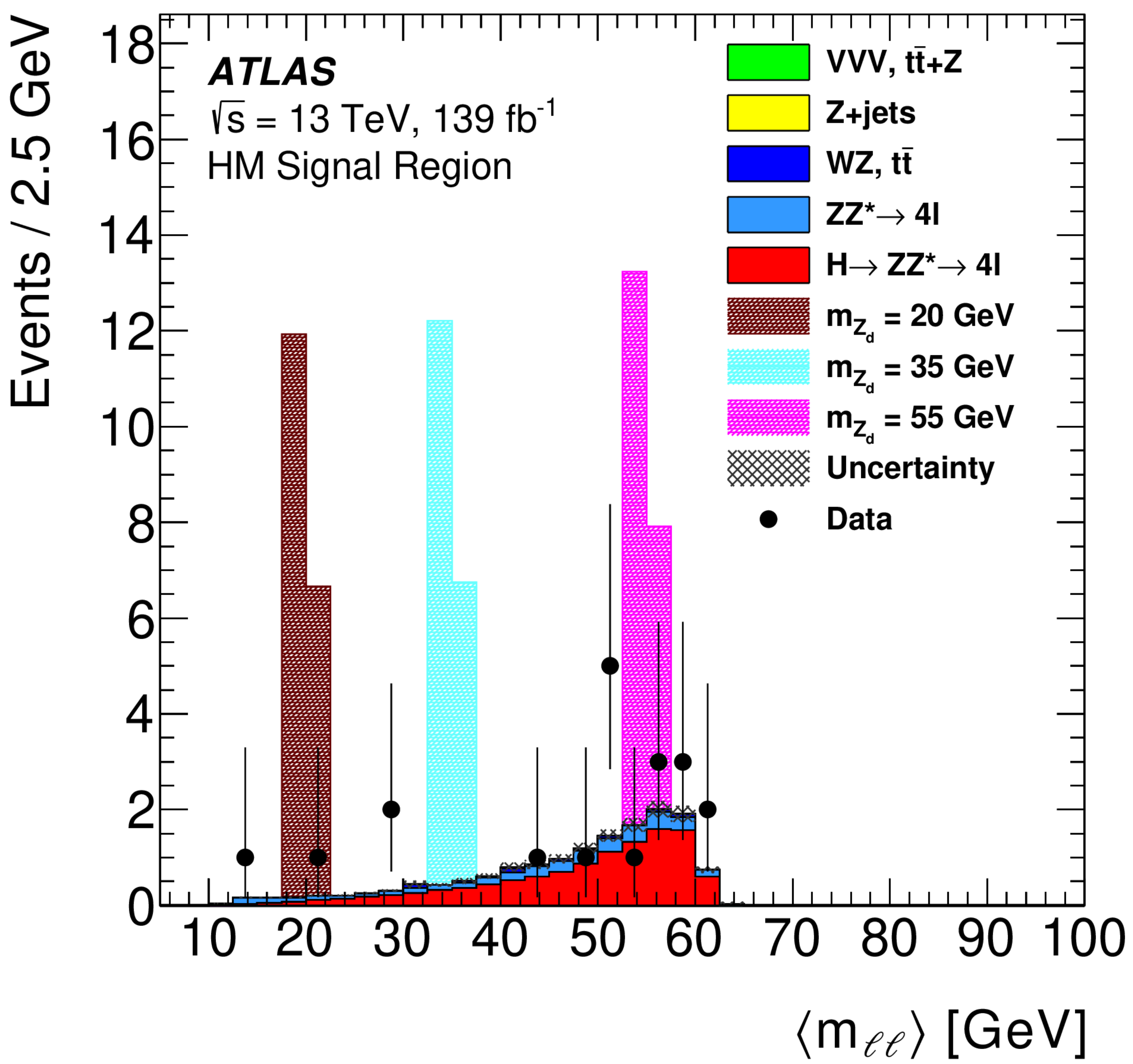




ATLAS analysis probing Higgs decay to dark vector gauge bosons (mediating interactions between dark matter and SM particles).

- 4 lepton final state very clean.
  - Remember $H \to ZZ \to 4\ell$ was one of the two Higgs discovery channels!
- Explore 1 GeV < m_{Zd} < 60 GeV.

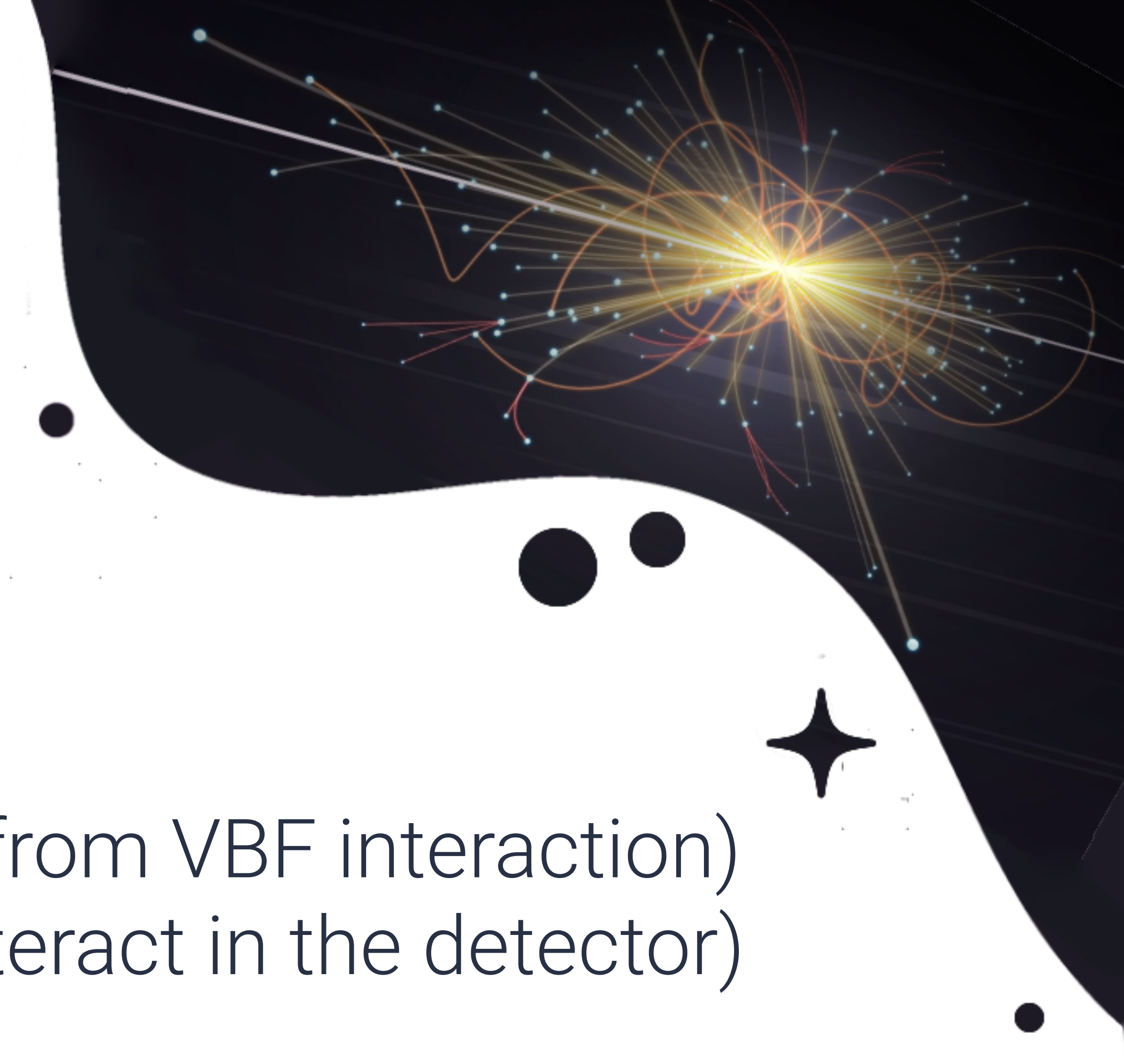




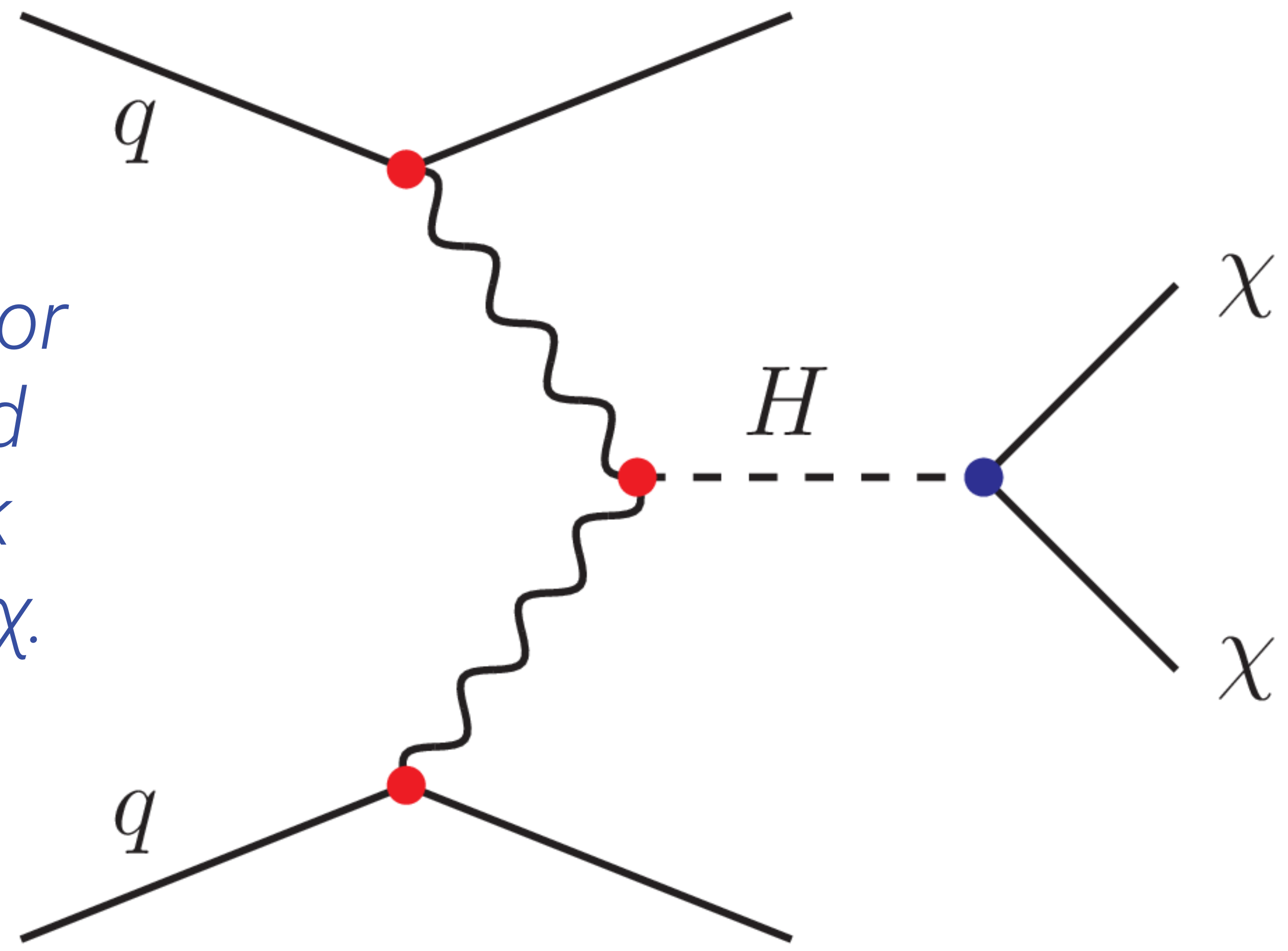
Higgs and dark matter

ATLAS-CONF-2020-052

https://arxiv.org/abs/2202.07953

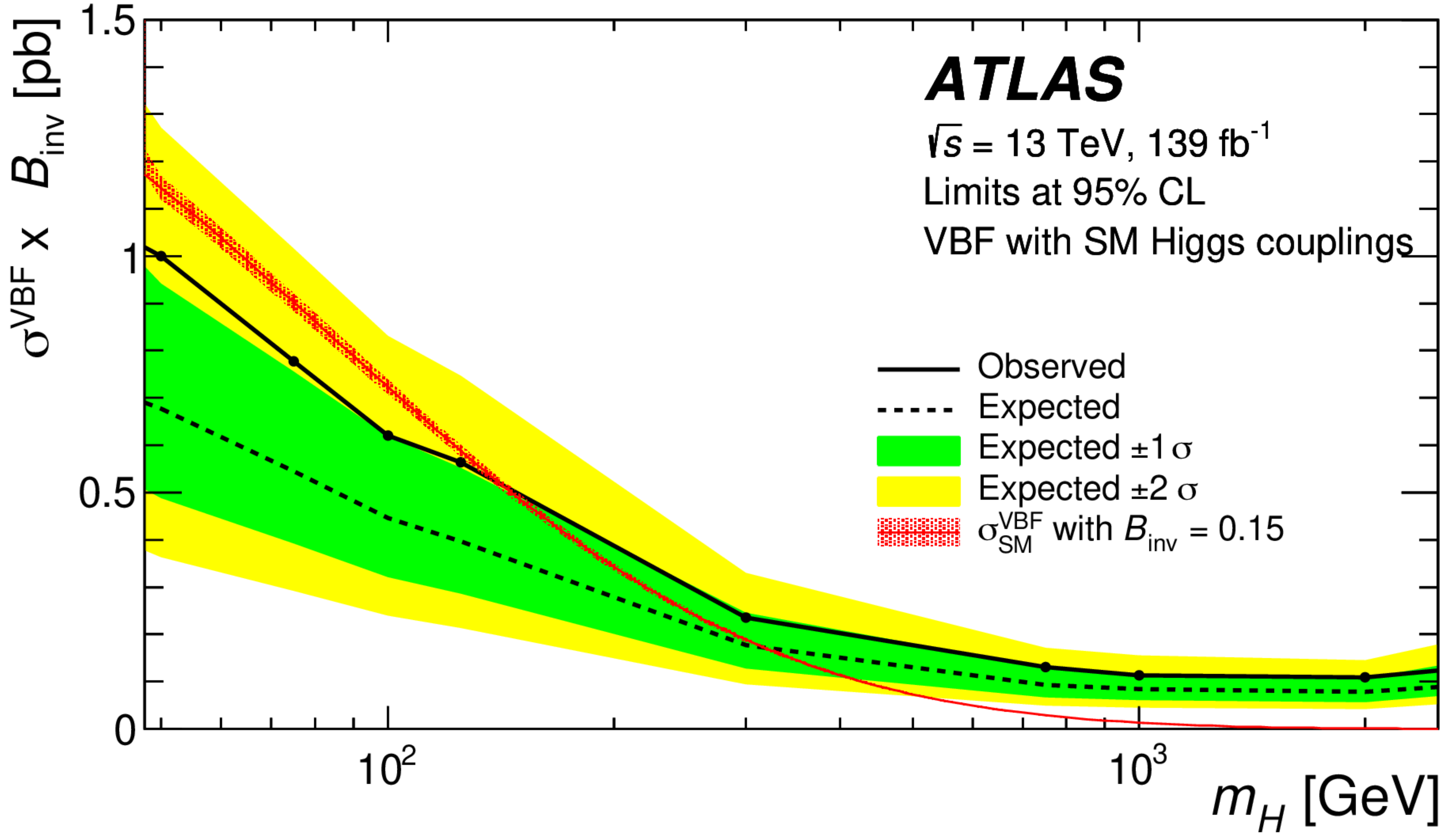


Example: Higgs produced via vector boson fusion and decaying to dark matter particles, χ.



Signature:

- Two forward jets (proton remnants from VBF interaction)
- Large missing energy (χ does not interact in the detector)



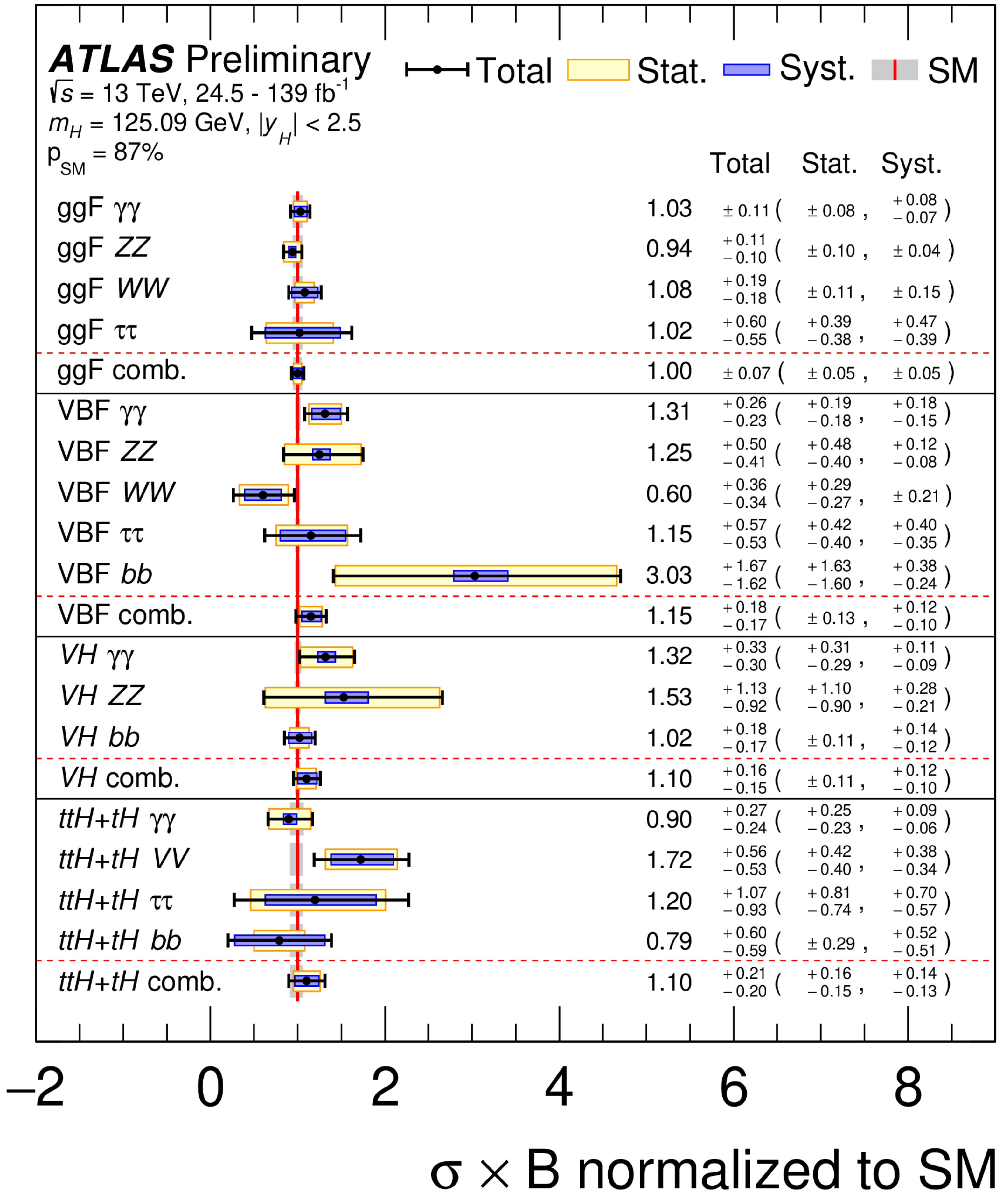
- Constrain BR(H→invisible) to be < 14.5%.
  - Similar analysis from CMS: BR < 18%.
- Also consider scenarios where the "H" in the diagram is a BSM Higgs boson.
  - 50 GeV < m_H < 2 TeV.

BSM couplings of the Higgs

Constraints from Higgs measurements

Precise predictions from the SM about how the Higgs boson should be produced and decay.
→ Measure these processes!

- New physics may be subtle.
- Detect it by looking for new types of interactions.
- New physics would yield new interactions, with different theoretical models having different effects on different couplings.
- Test how new couplings can be accommodated within the precision our measurements allow.
- If there are high-mass phenomena far beyond the reach of the LHC's collision energy these sorts of techniques may be the only way we can detect them.



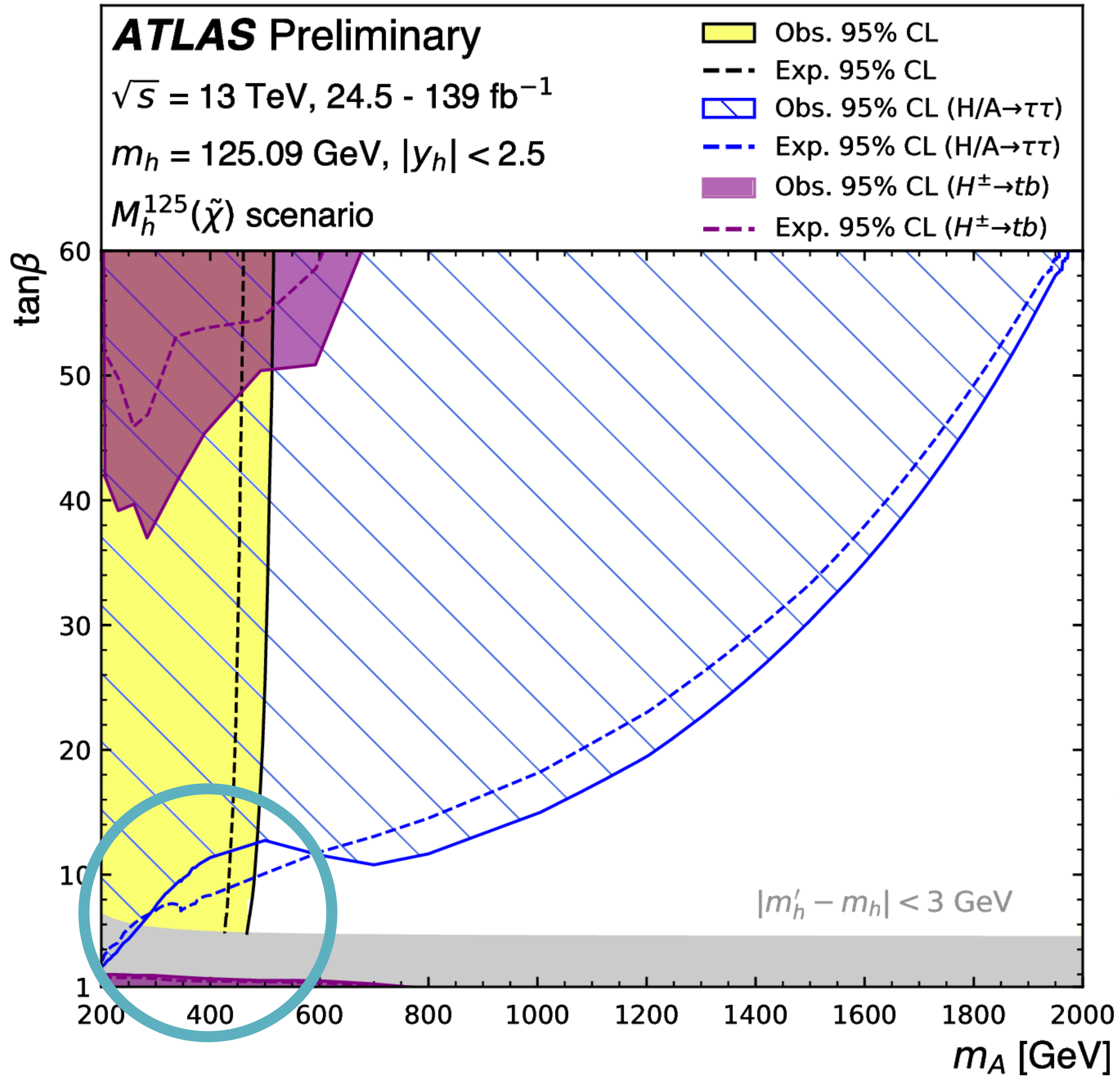
Constraints from Higgs measurements

Constraints from fits to SM Higgs couplings:

- BR(H→invisible) < 9%
  - Higgs decays identified with missing E_T signature.
- BR(H→undetected) < 19%
  - Decays to which we are not sensitive, e.g. to light quarks or undetected BSM particles that don't have large missing E_T in the final state.

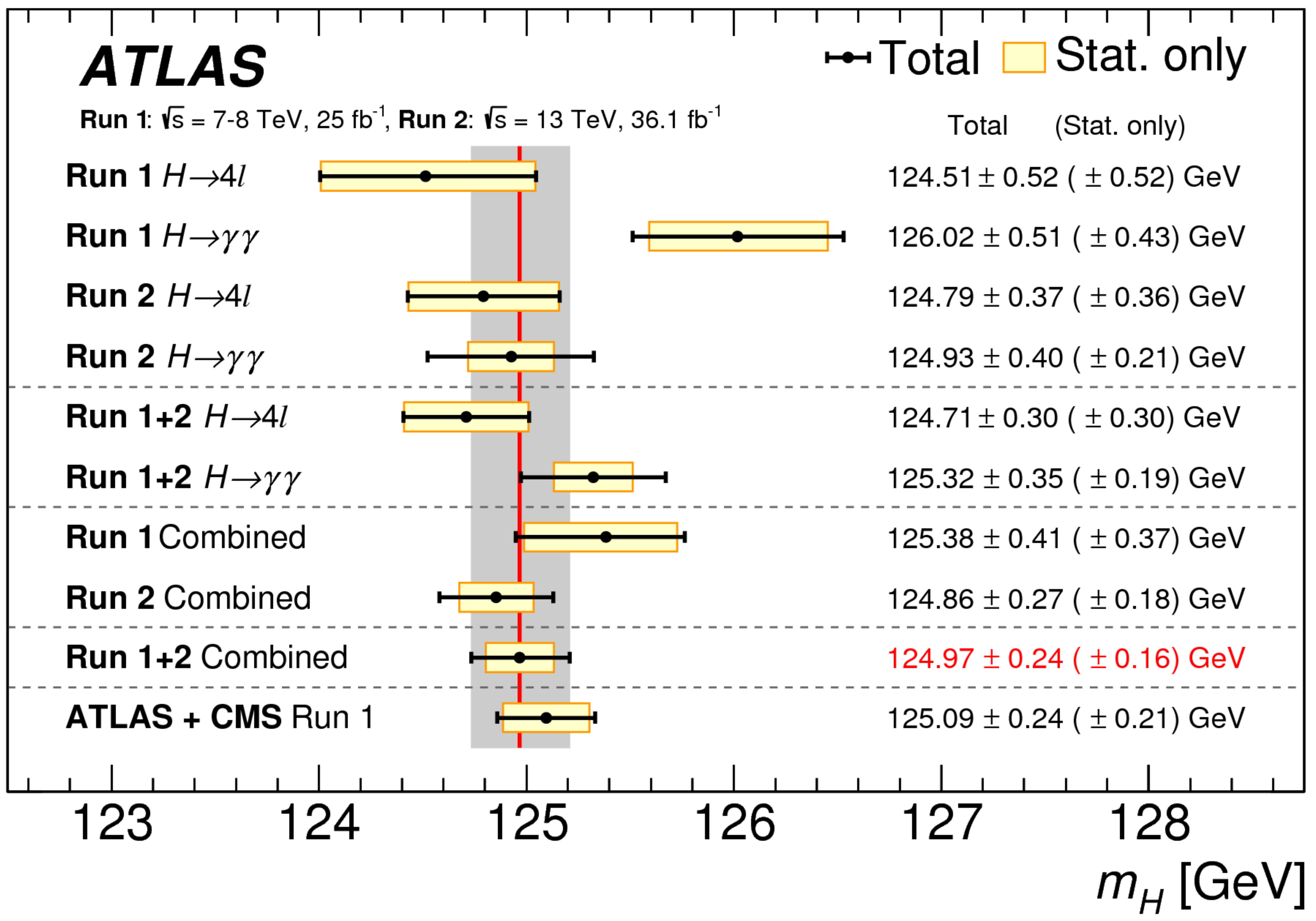
Complementary to direct searches → sometimes able to rule out regions of parameter space that direct searches are not sensitive to.

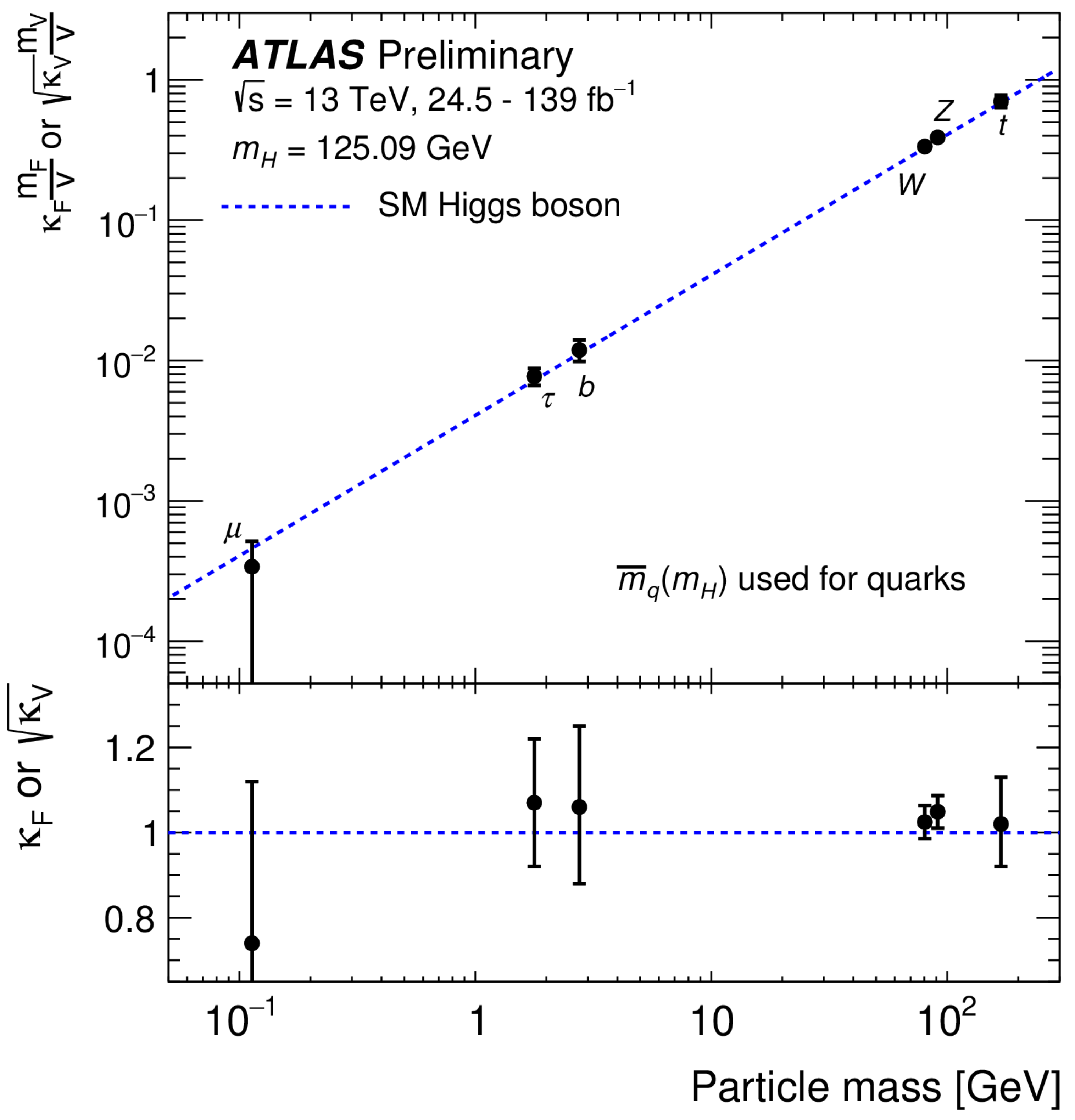
ATLAS-CONF-2020-027
ATLAS-CONF-2020-052
ATLAS-CONF-2020-053



Probing Higgs properties

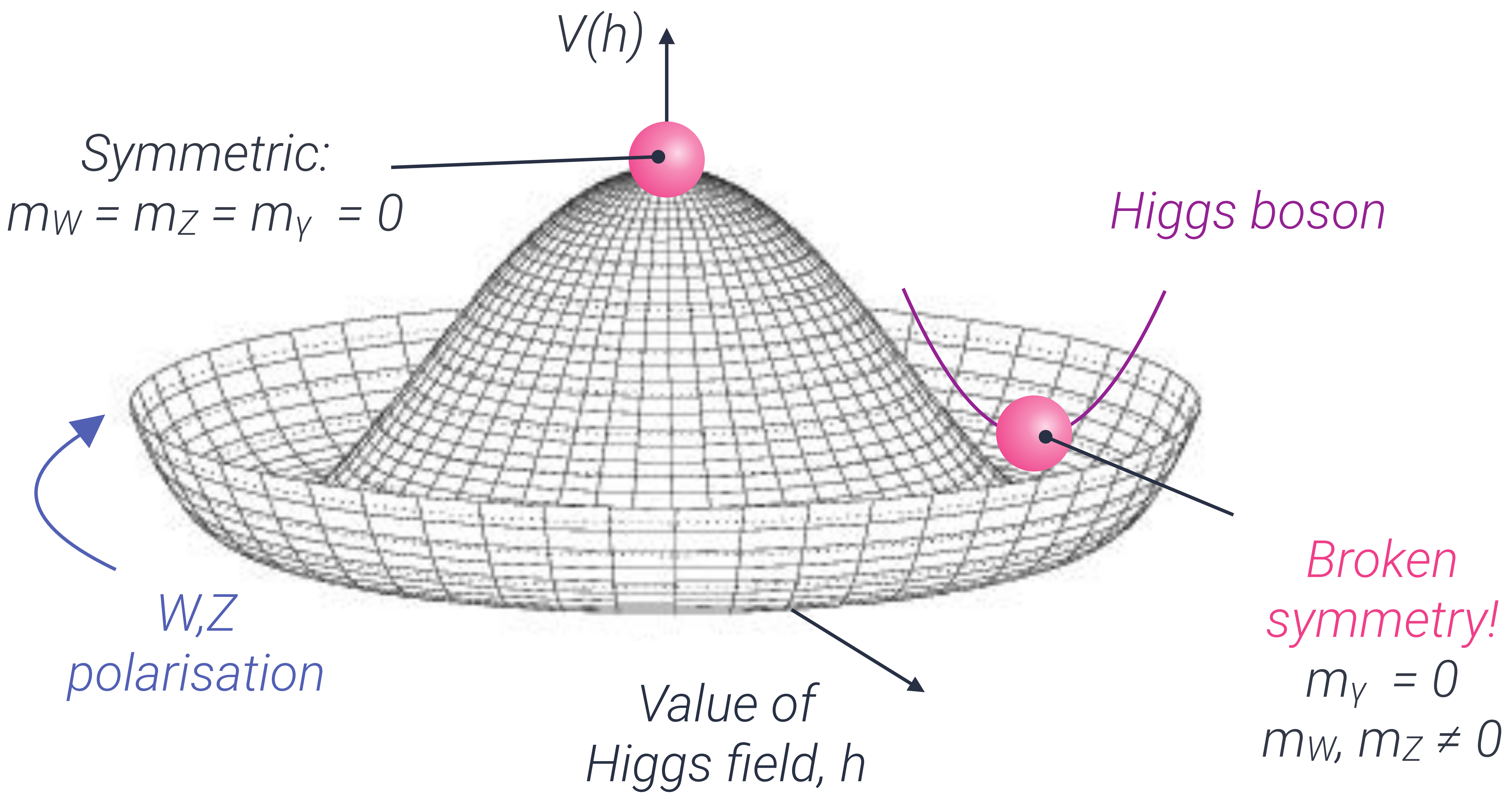
Tremendous advances in our understanding of the Higgs boson since its discovery in 2012…





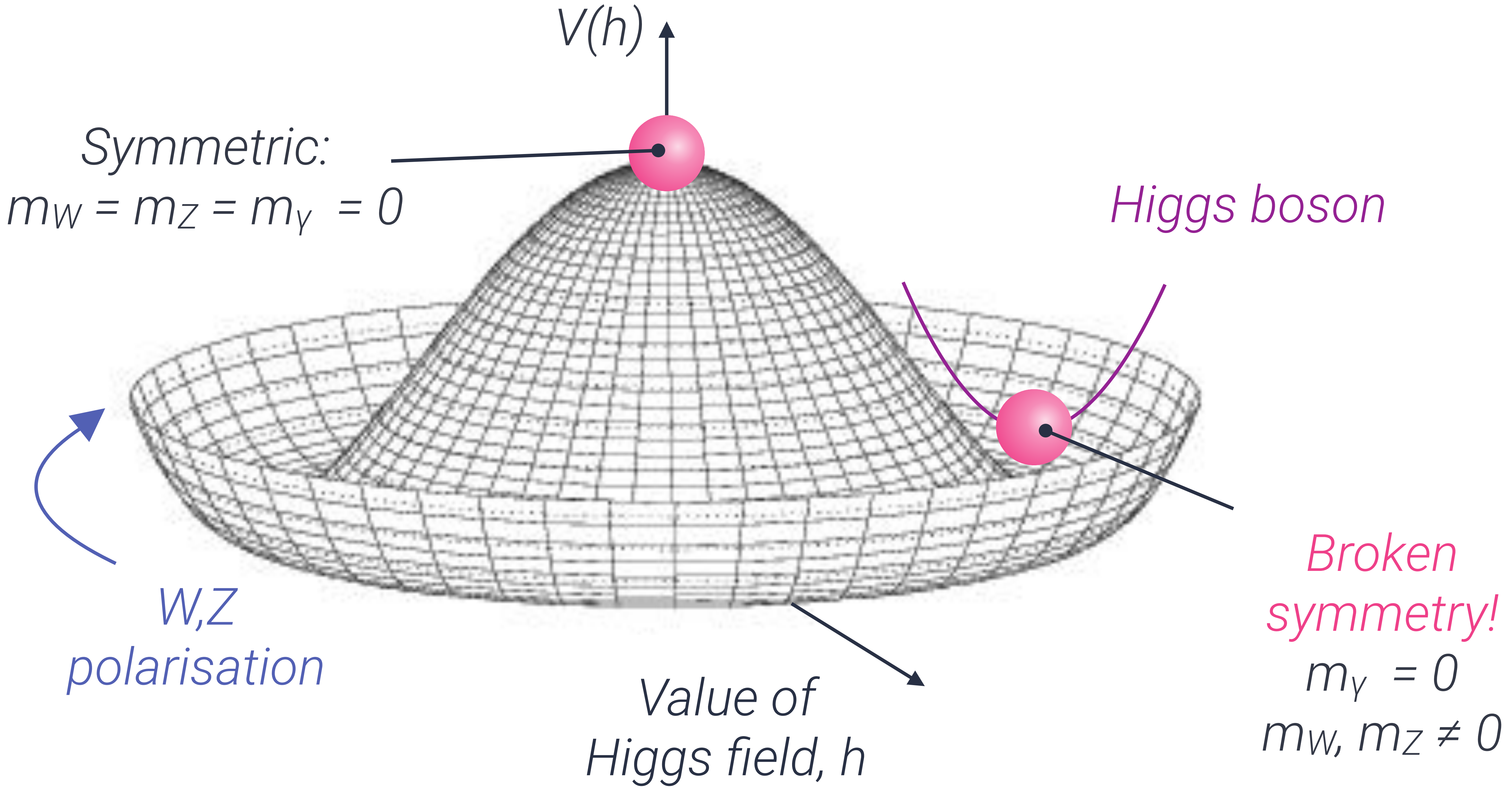
… but still very little knowledge about the shape of the Higgs potential.

Electroweak Symmetry Breaking



$$V(h) \simeq \frac{1}{2}m_H^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

Electroweak Symmetry Breaking



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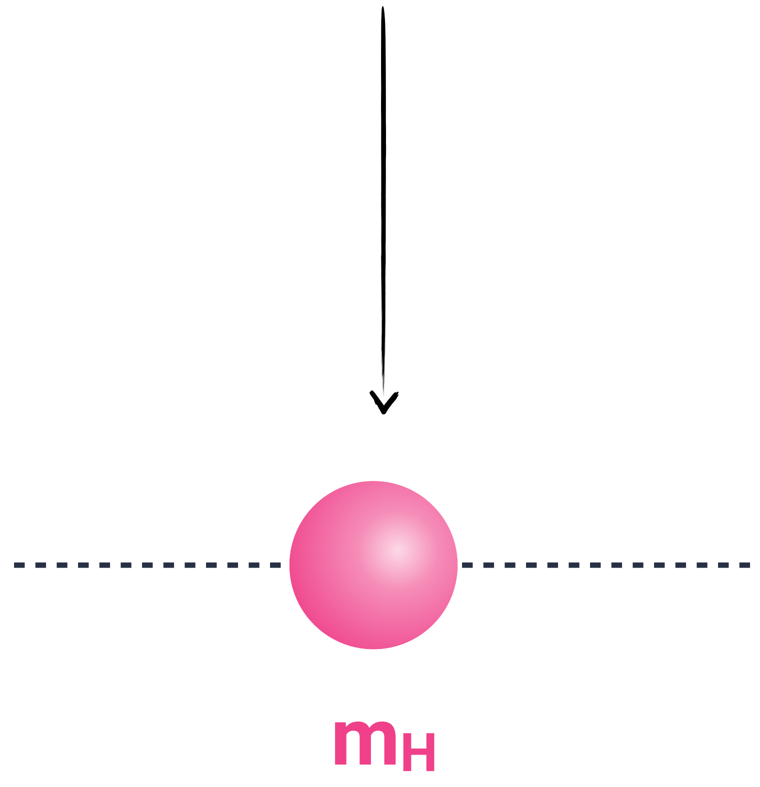
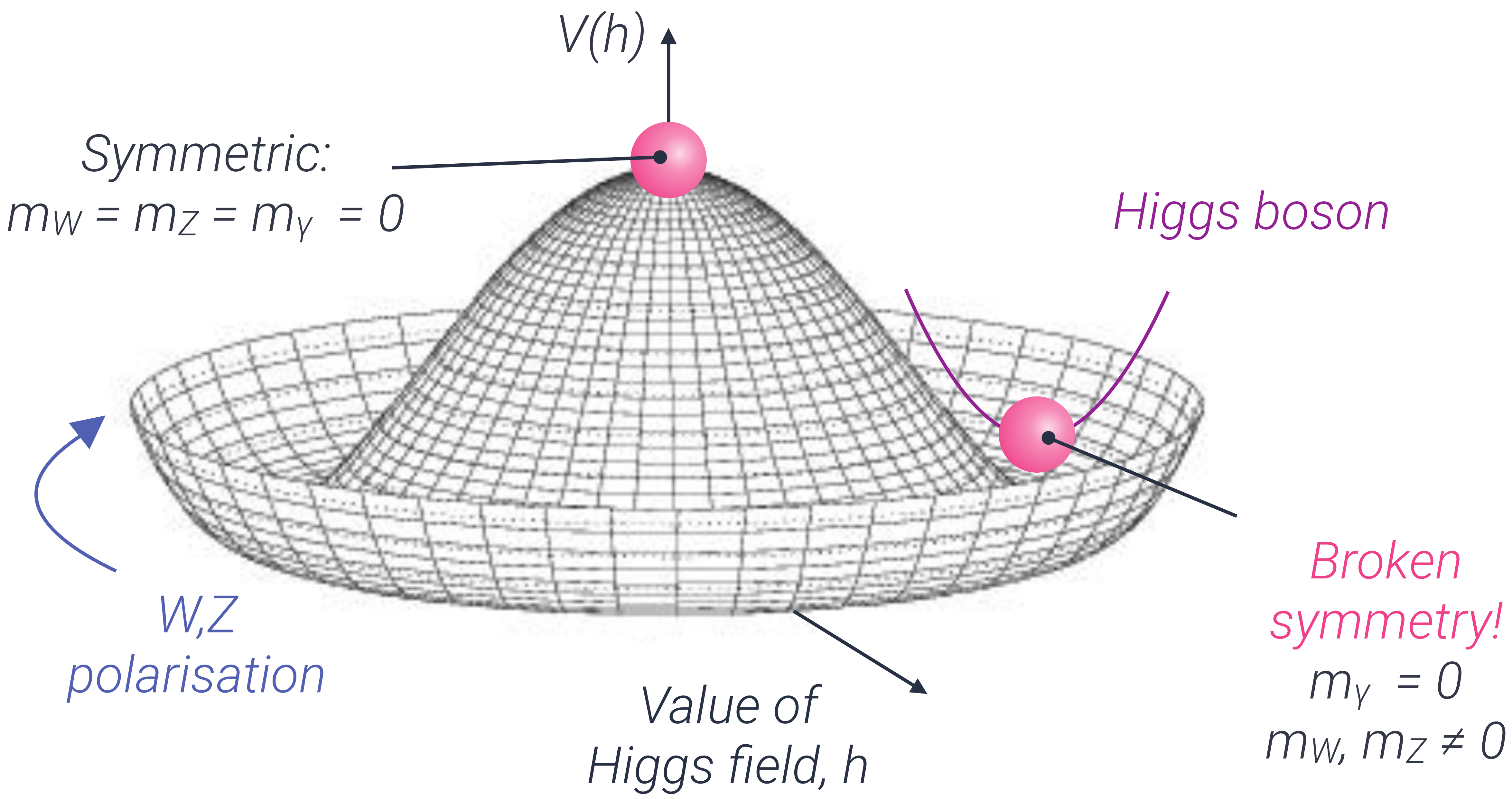


Minimum of the potential

$$m_H = \sqrt{2\lambda v} \approx 125 \text{ GeV}$$

$$\lambda_{SM} \approx 0.13$$

Electroweak Symmetry Breaking



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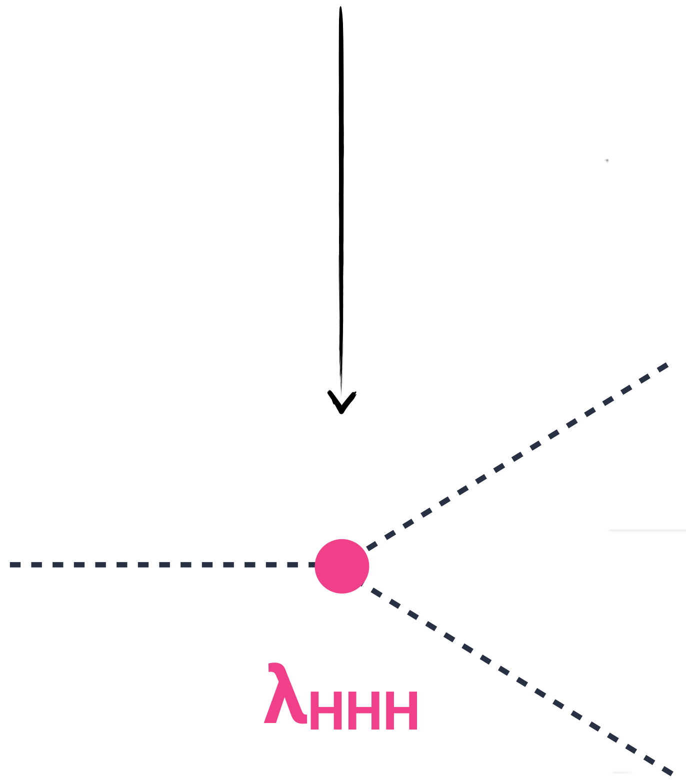
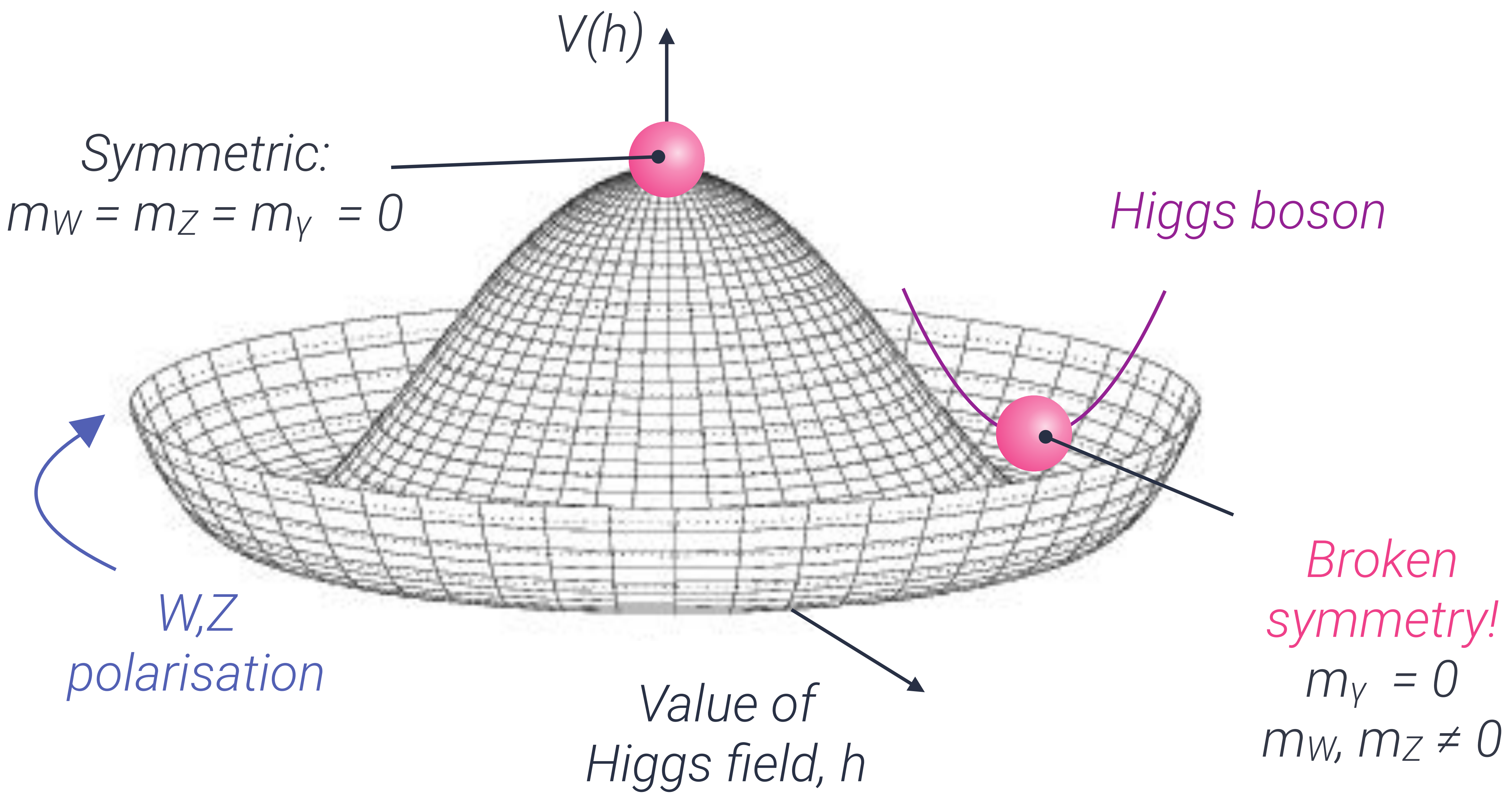


Directly measure λ_{HHH} via HH production

Electroweak Symmetry Breaking



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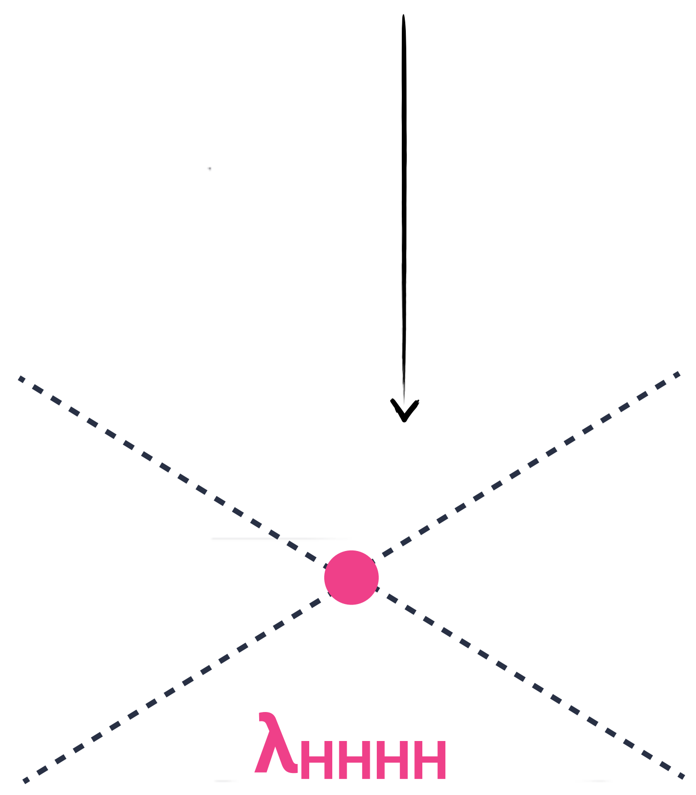
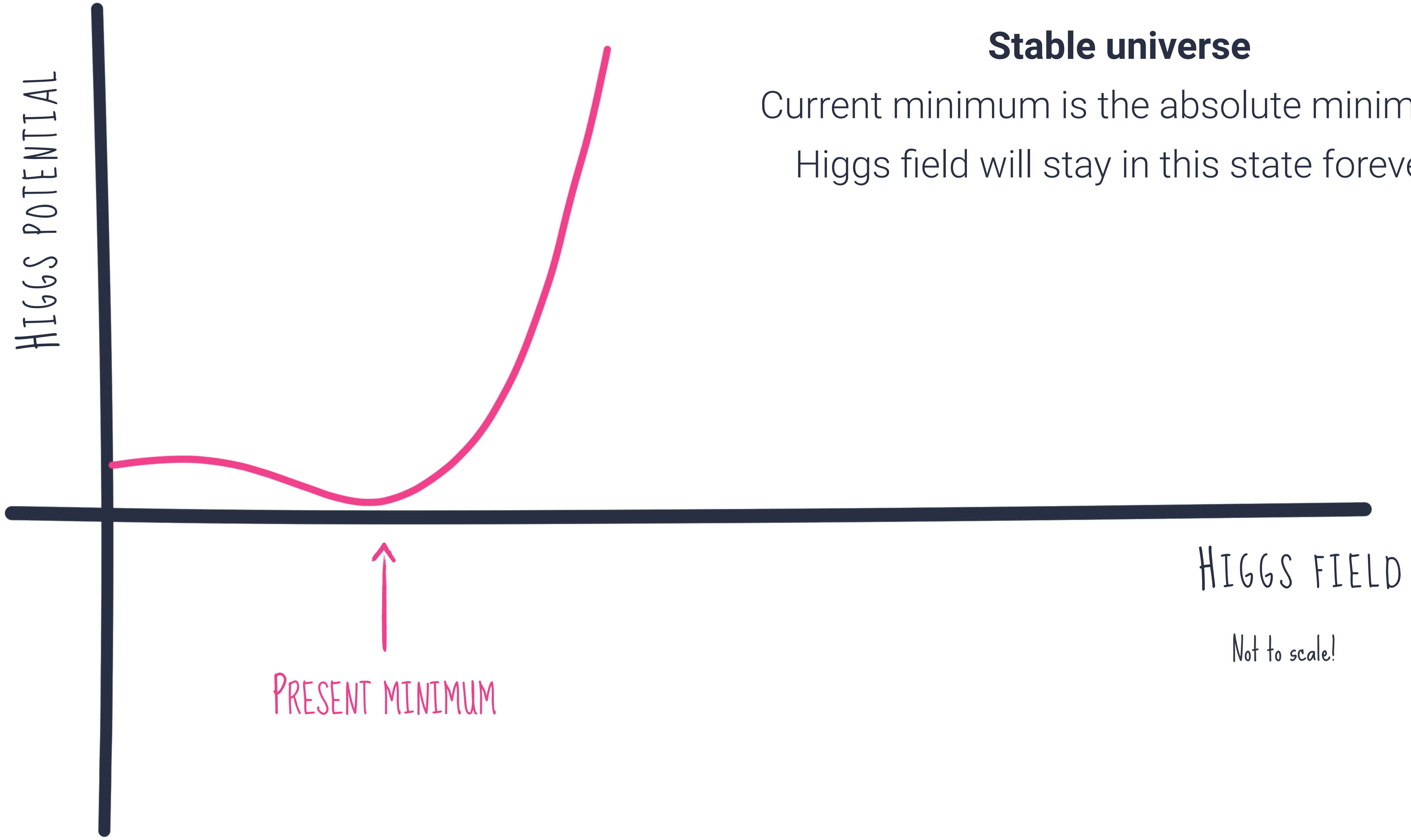


Out of reach for HL-LHC...

... probably...

Stability of the Universe



Stable universe

Current minimum is the absolute minimum.

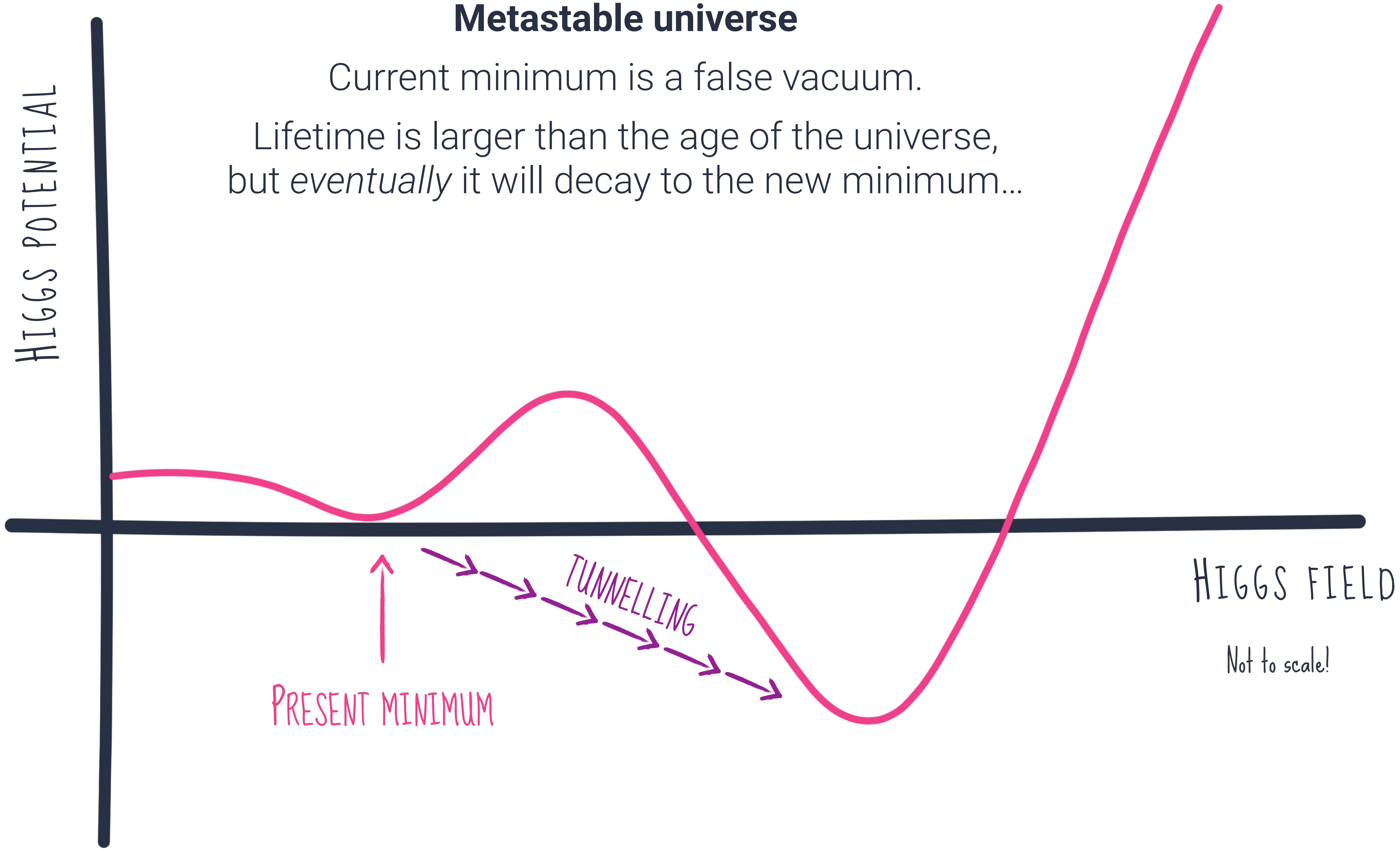
Higgs field will stay in this state forever.

Stability of the Universe

Metastable universe

Current minimum is a false vacuum.

Lifetime is larger than the age of the universe, but *eventually* it will decay to the new minimum…



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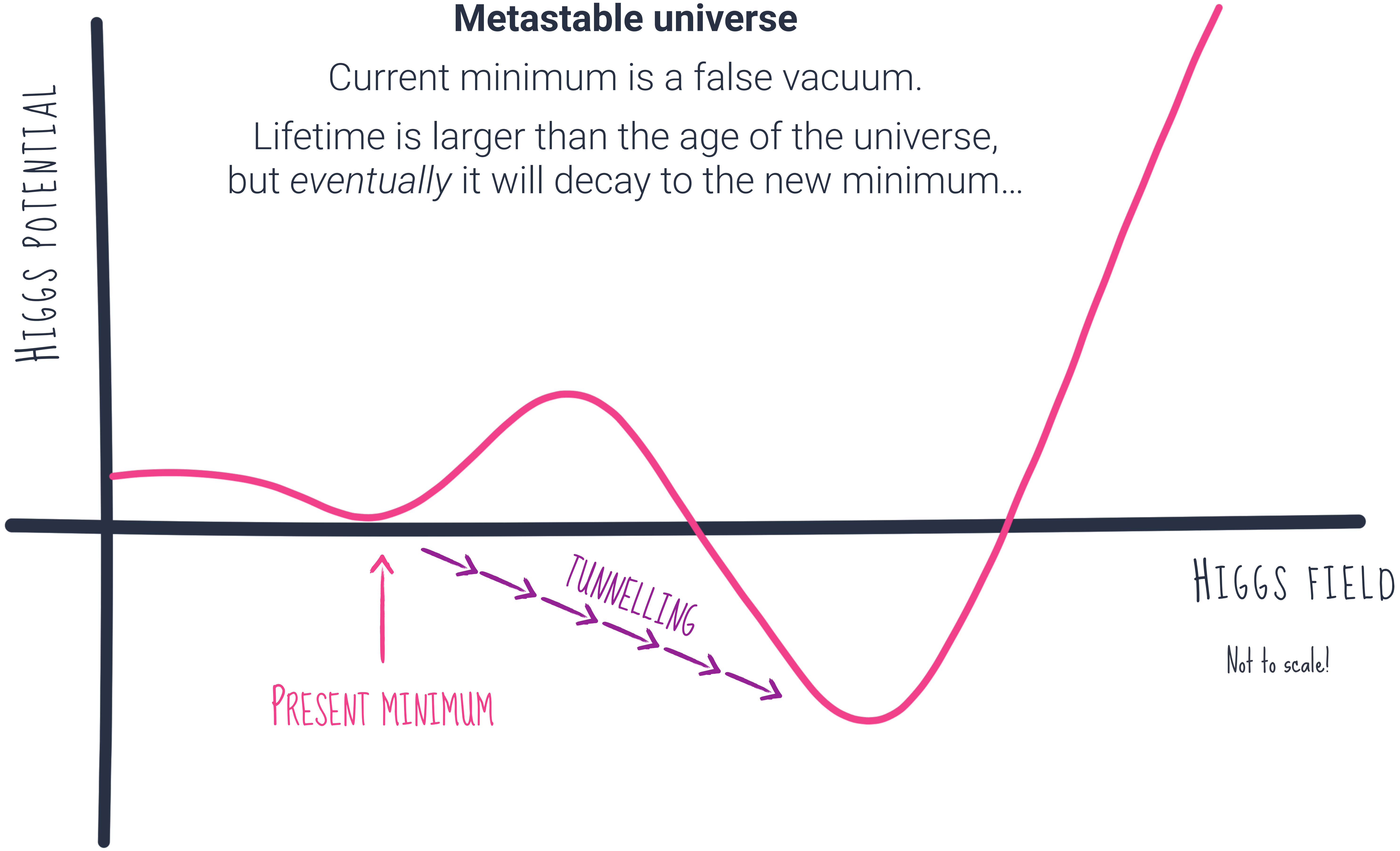
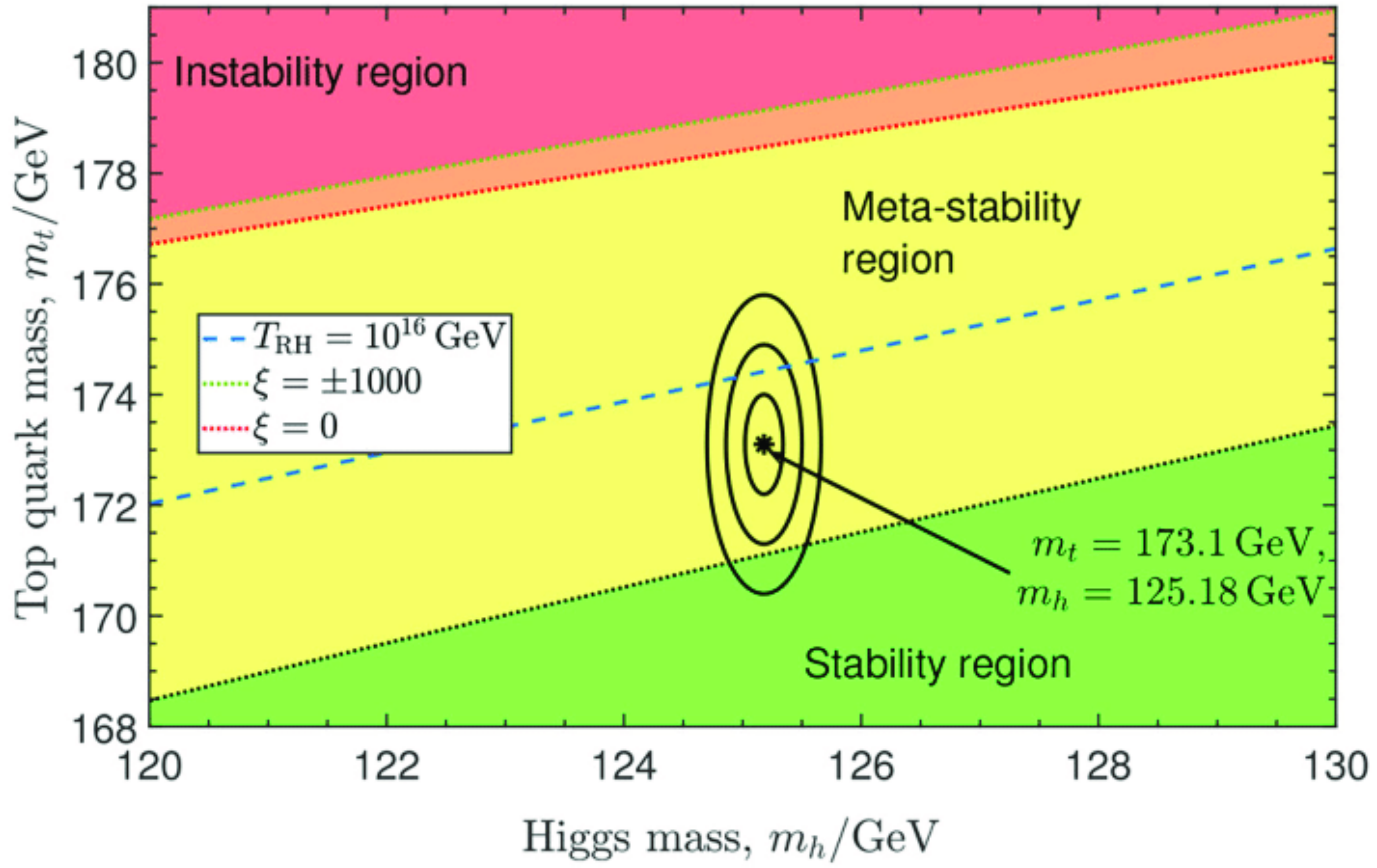


Markkanen, Rajantie, Stopyra



The Higgs Boson and the Early Universe

Nature of electroweak phase transition is unknown…

Baryogenesis *requires* a first order electroweak phase transition.

First-order electroweak phase transition *requires* new physics that interacts with the Higgs boson.

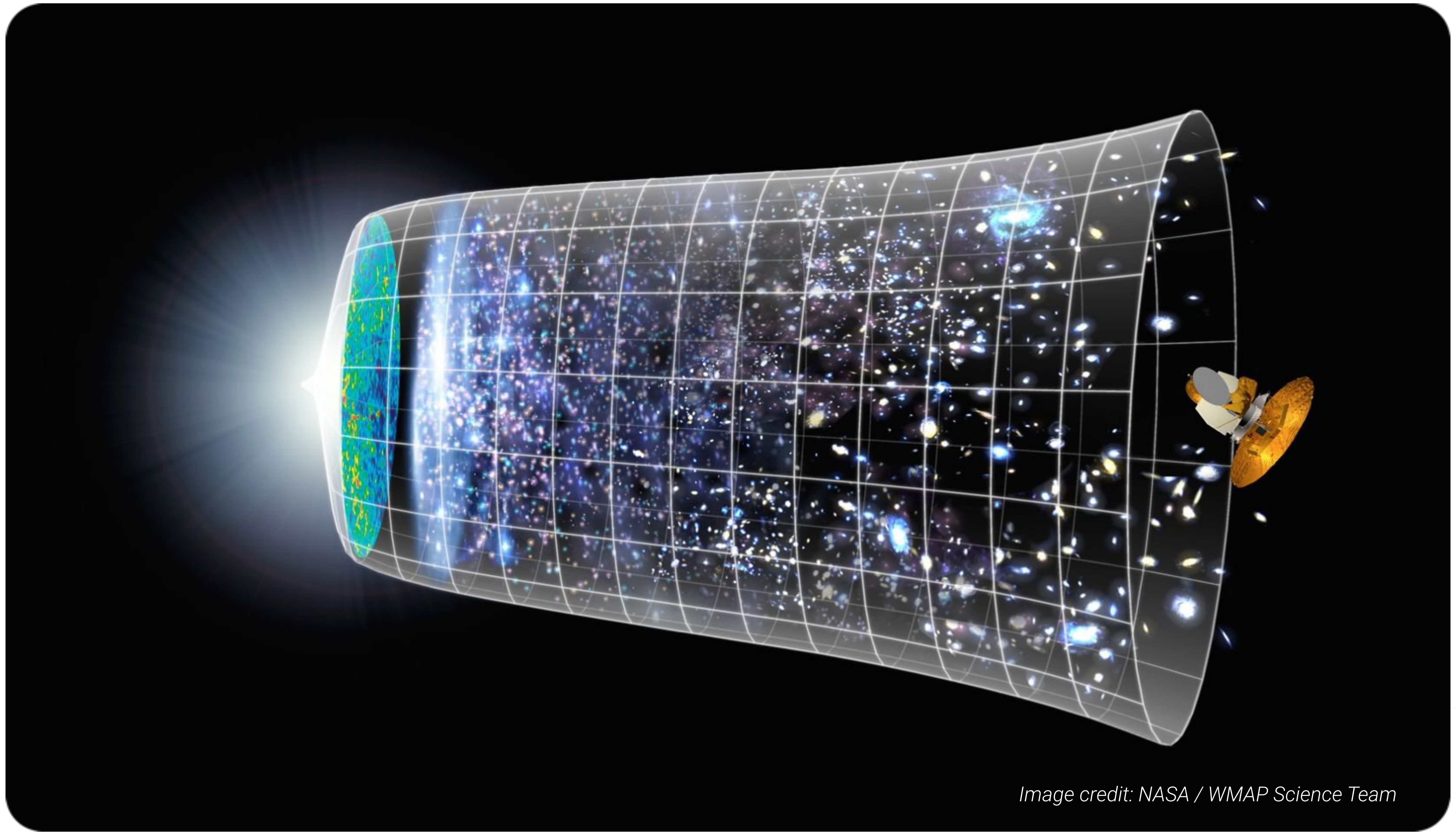
→ Leads to a large ($\mathcal{O}1$) modification to the Higgs self-coupling.

Noble, Perelstein

Some inflation models require that the Higgs couples to gravity.

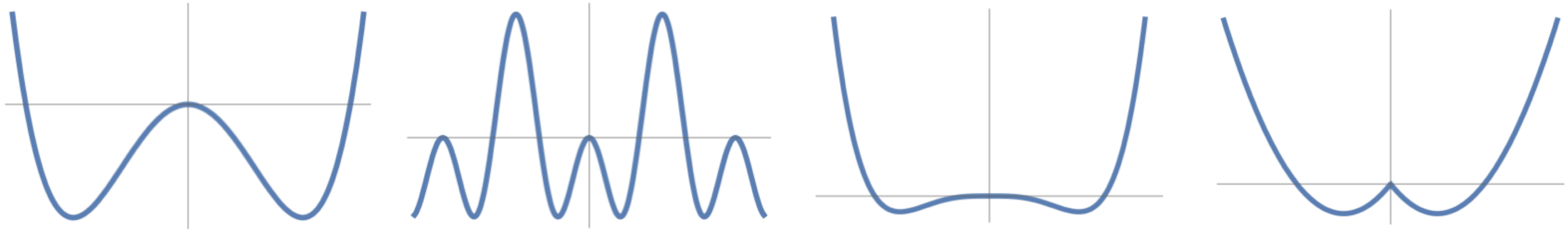
→ Modifies the shape of the potential.

Bezrukov, Shaposhnikov



Shape of the Higgs Potential

Measurements of HH can provide discrimination between different scenarios and models…



Landau-Ginzburg Higgs (SM) | **Nambu-Goldstone Higgs** | **Coleman-Weinberg Higgs** | **Tadpole-Induced Higgs**

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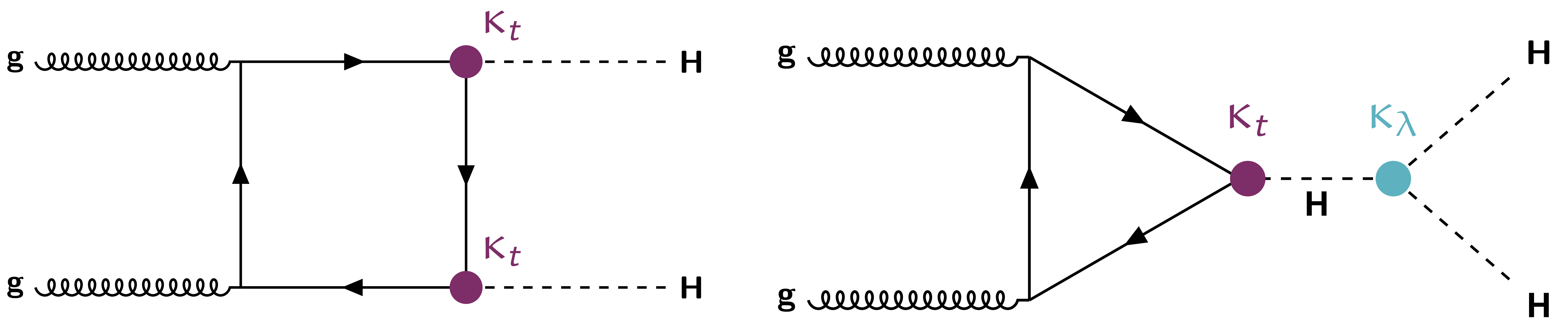
… but measuring triple-Higgs production at a future collider (e.g. 100 TeV machine) will be needed to really pin down the exact shape of the potential.

HH production at the LHC

Cross-section ~1000x smaller than single Higgs

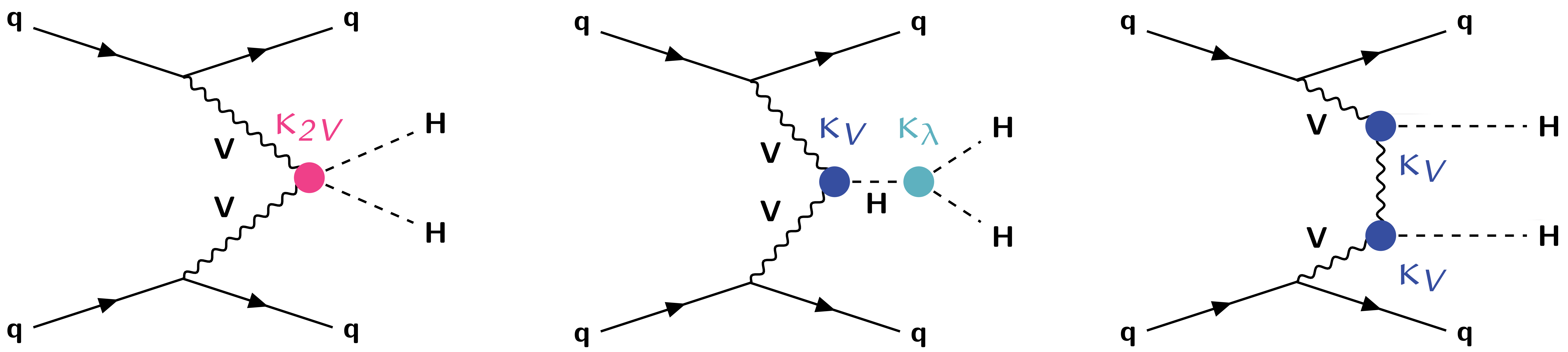
gluon-fusion

$\sigma_{ggF}(pp \rightarrow HH) = 31.05$ fb



VBF

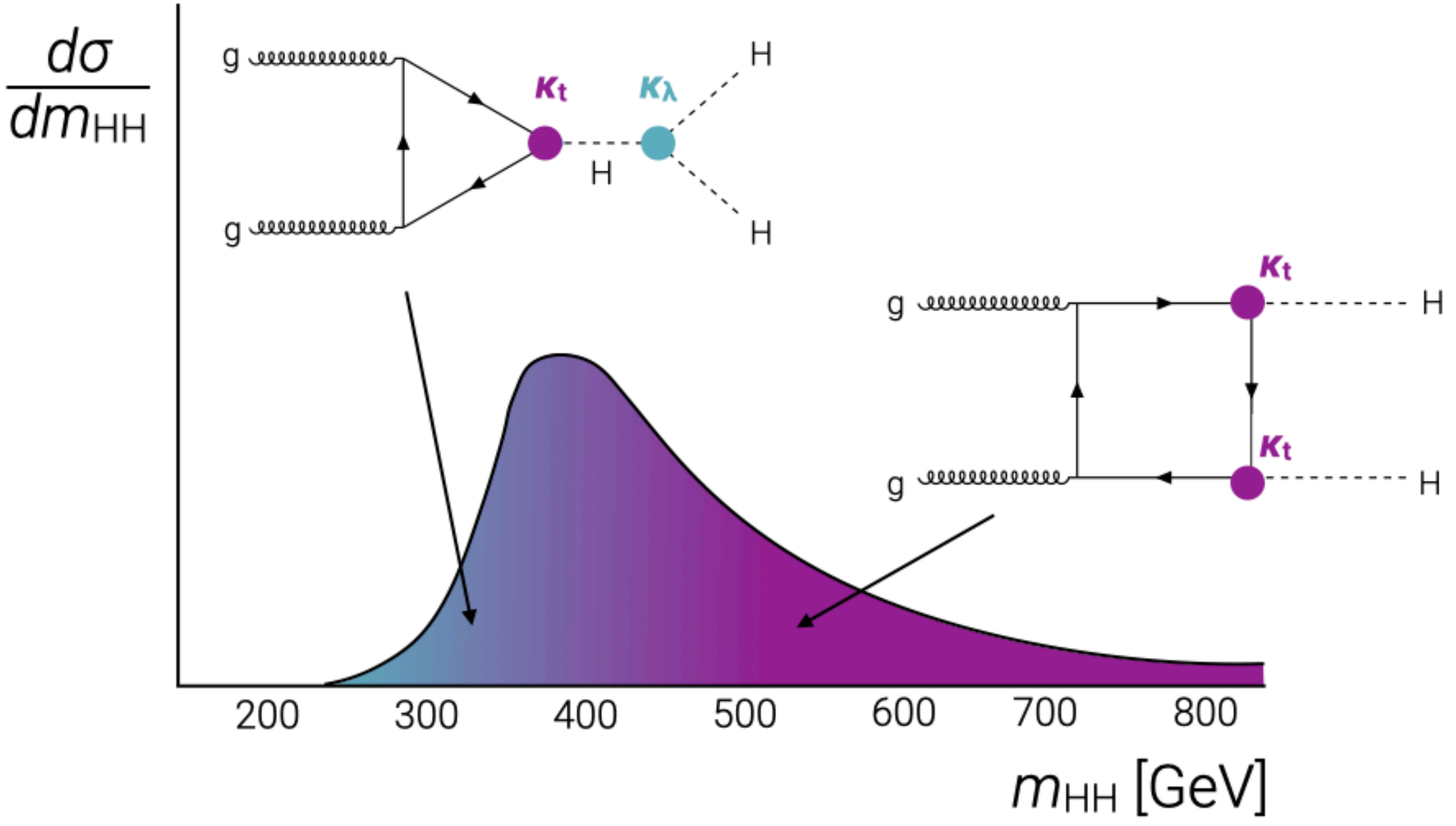
$\sigma_{VBF}(pp \rightarrow HH) = 1.726$ fb

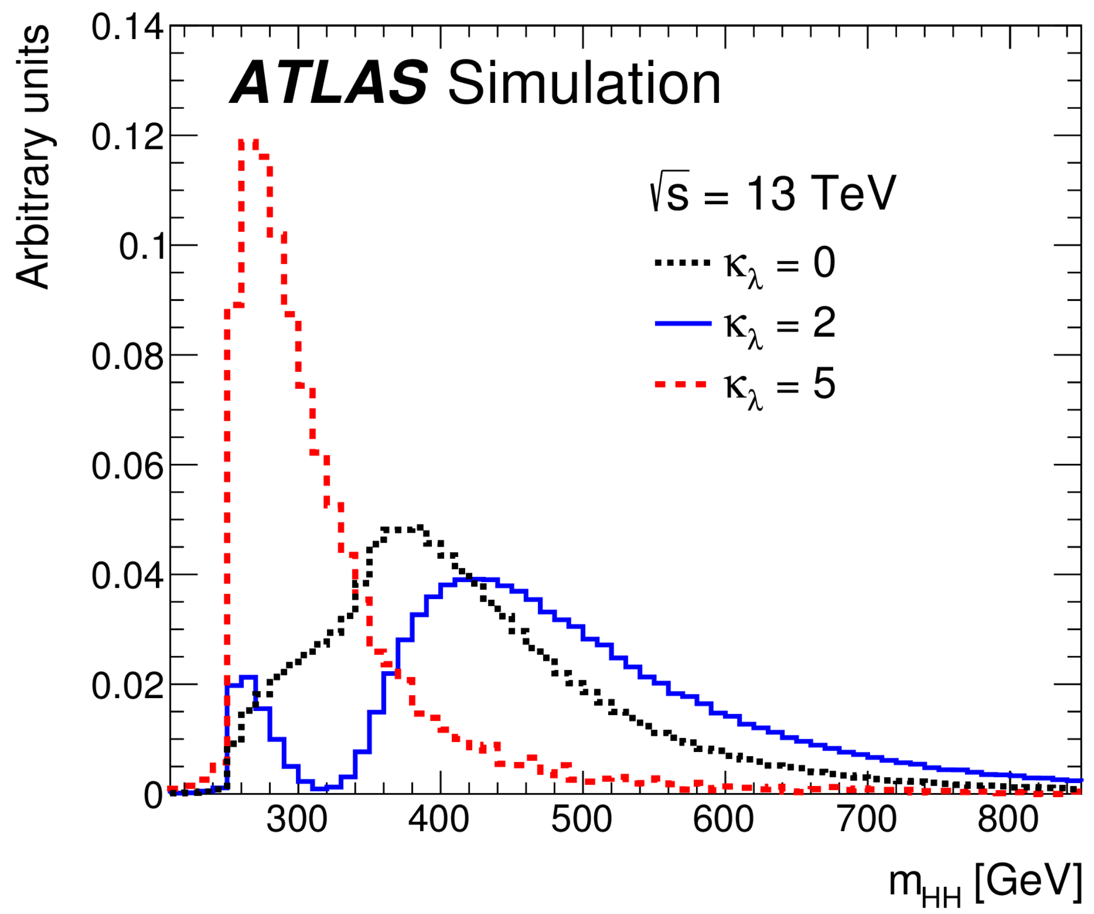


The Unbearable Lightness of m_{HH}

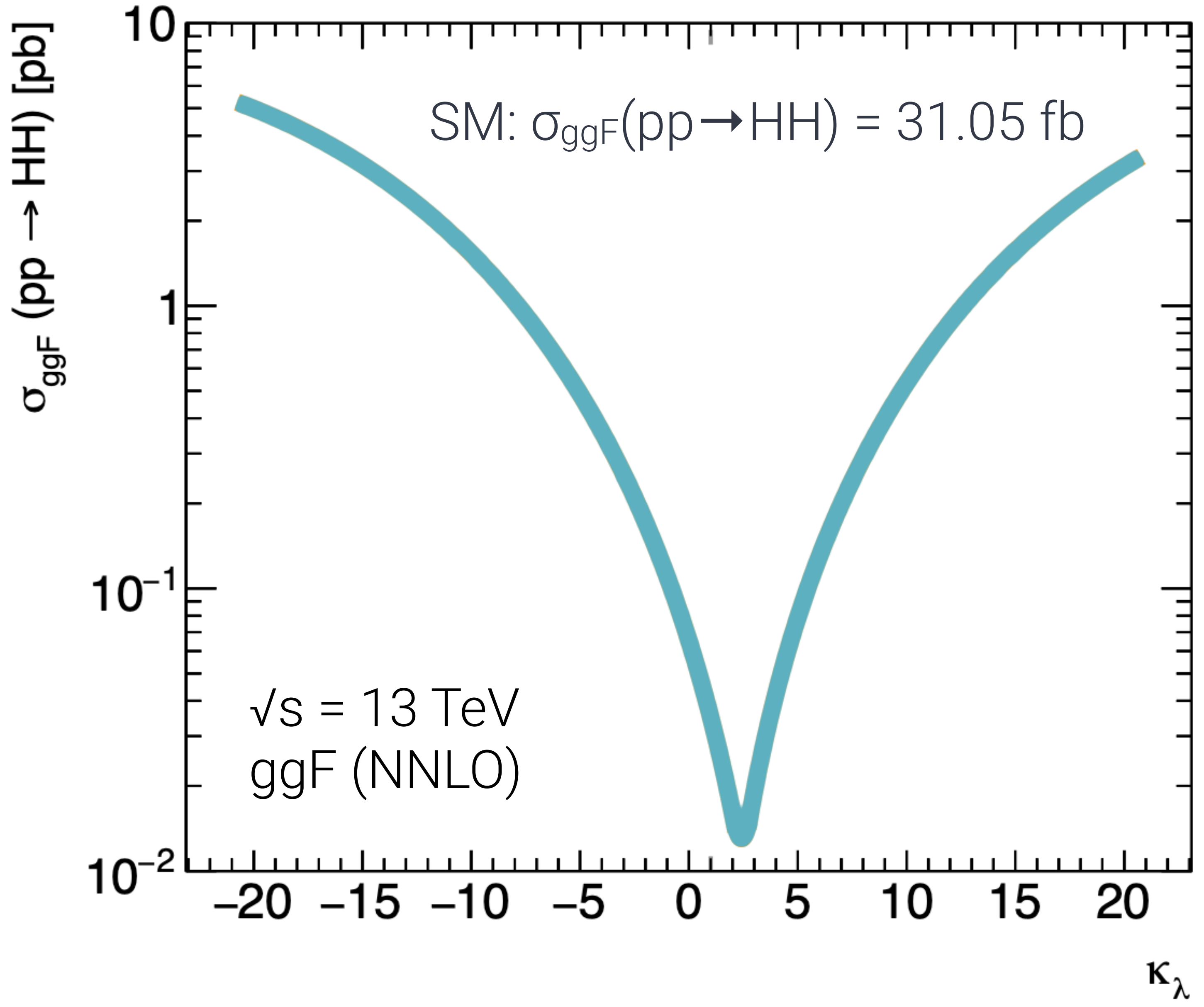
Cross-section and shape of m_{HH} distribution changes with the self-coupling strength κ_λ (= λ/λ_{SM})

Destructive interference between the 'triangle' and `box' diagrams





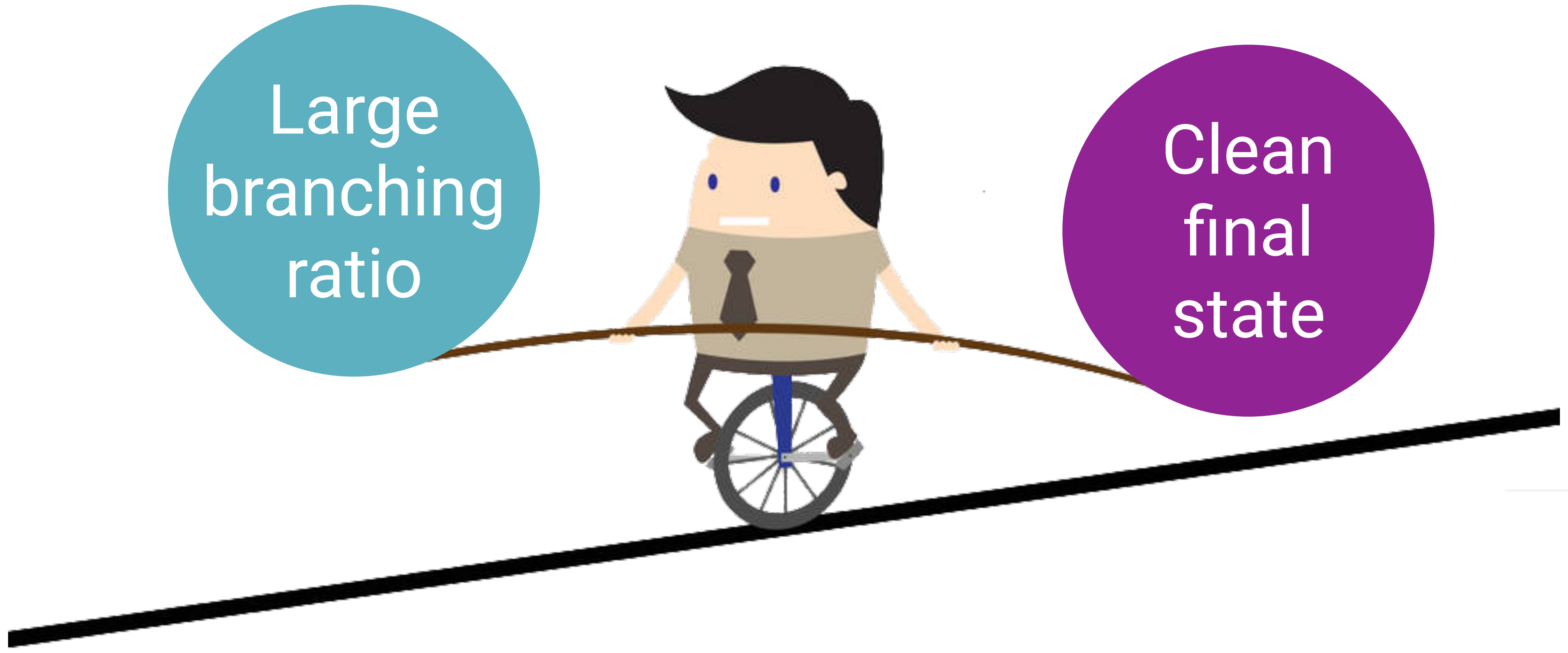
JHEP 05 (2018) 059 and others



HH Decay Modes

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

All channels have trade-offs between branching ratio vs final state



No single 'golden channel'

HH Decay Modes

	bb	WW	ττ	ZZ	γγ
bb	34%				
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ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

HH→bbbb

- Largest branching ratio
- Challenging multi-jet backgrounds

ATLAS-CONF-2021-035

HH Decay Modes

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

HH→bbττ

- Moderate branching fraction.
- Presence of hadronic taus (and light lepton in $\tau_\ell\tau_h$ channel) effective at rejecting multi-jet backgrounds.
- EW and top backgrounds mimic signal.

ATLAS-CONF-2021-030

HH Decay Modes

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

HH→bbγγ

- Tiny branching fraction.
- Very clean final state.
- Excellent di-photon mass resolution.

ATLAS-CONF-2021-016

ATLAS HH→bbγγ

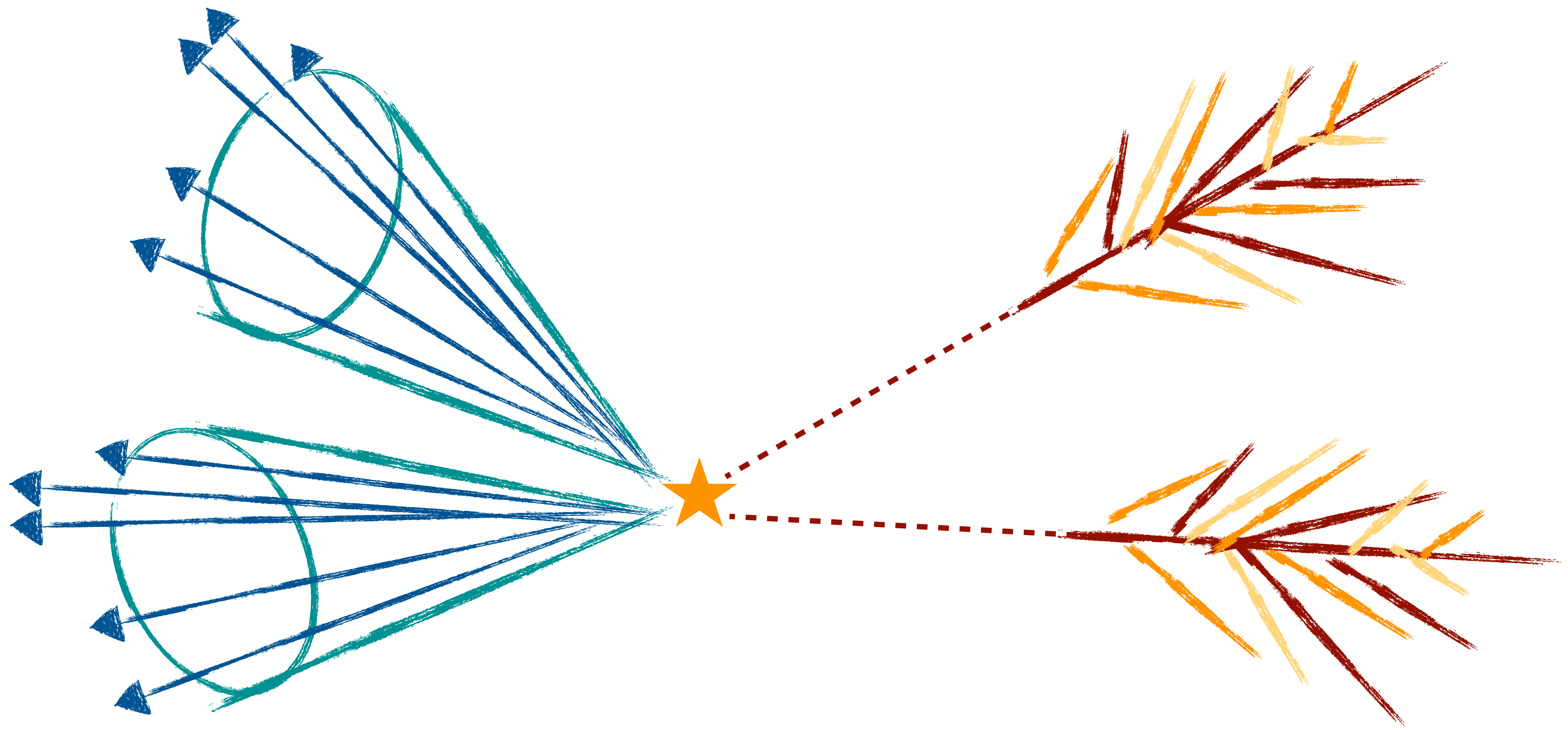
ATLAS-CONF-2021-016

Branching ratio HH→bbγγ : 0.26%

See also CMS HH→bbγγ result:
JHEP 03 (2021) 257

< 6 jets
(p_T > 25 GeV, |η| < 2.5)

Two b-tagged jets (ε=77%)



At least 2 photons

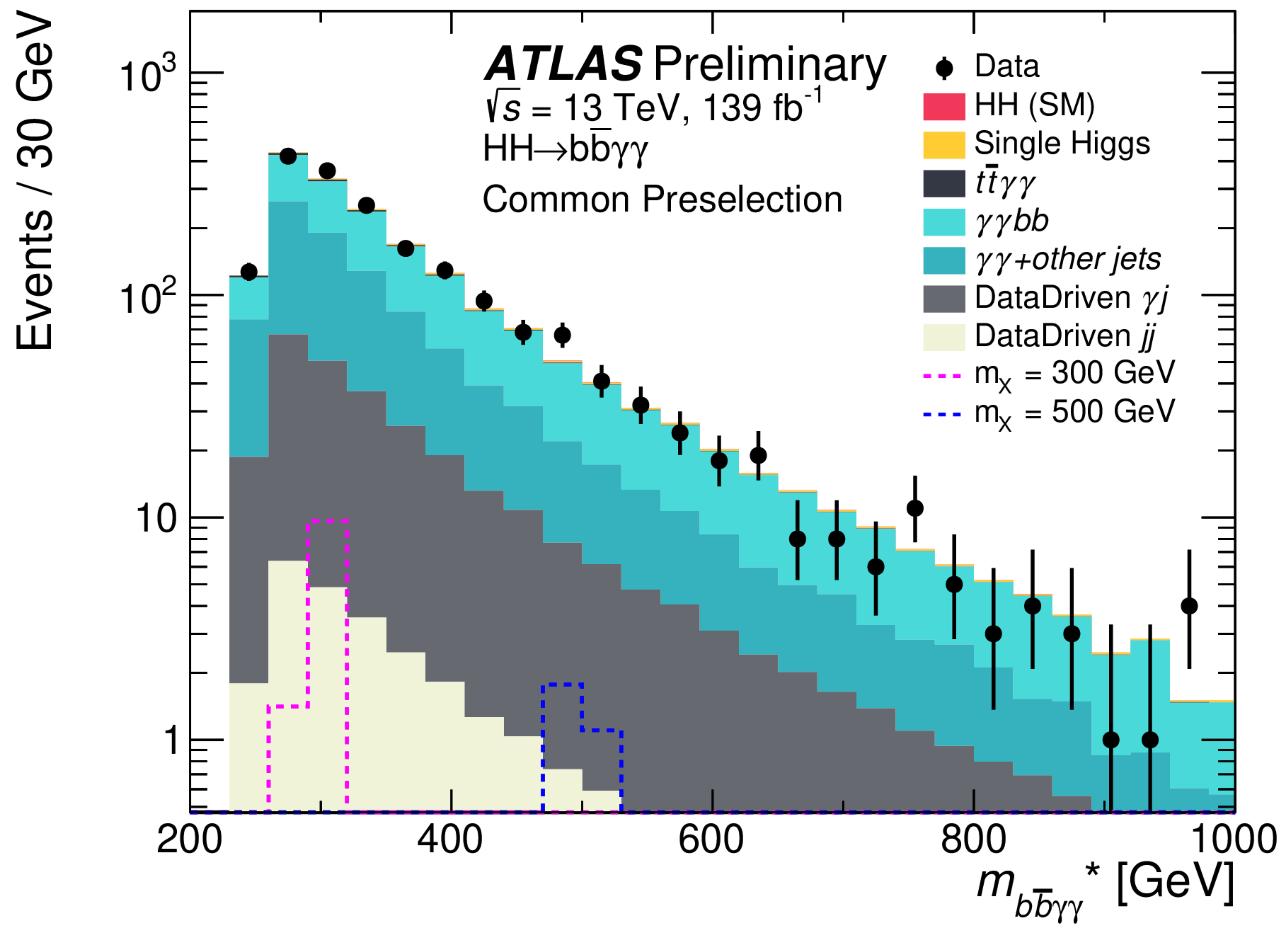
105 GeV < $m_{\gamma\gamma}$ < 160 GeV

No e/μ in the event

ATLAS HH→bbγγ

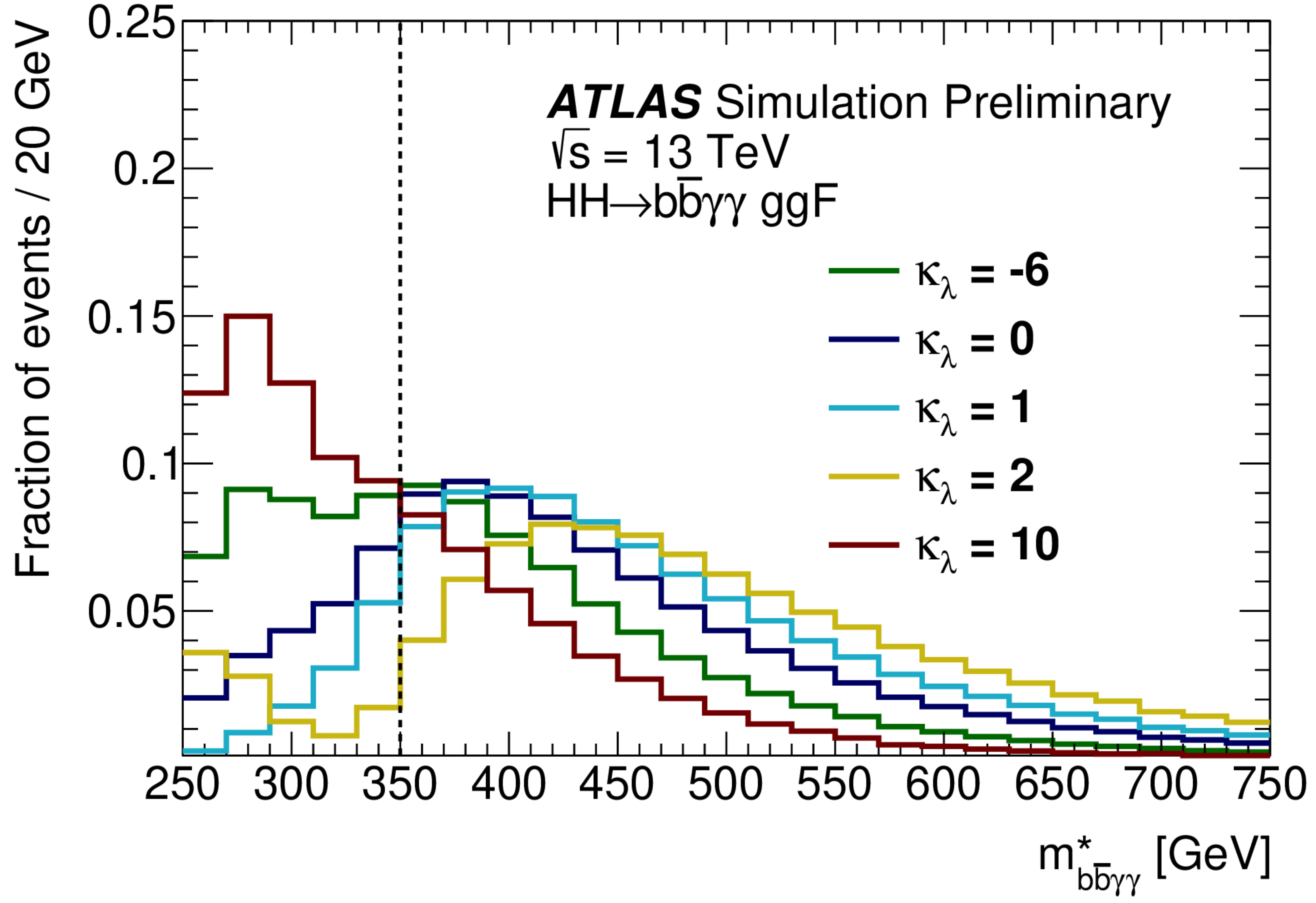
BDTs to separate signal from backgrounds.

Low and high mass regions targeted separately.



$$m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250 \text{ GeV}$$

→ *improves 4-body resolution*



Targets BSM κλ

Most sensitive for SM

ATLAS HH→bbττ

ATLAS-CONF-2021-030

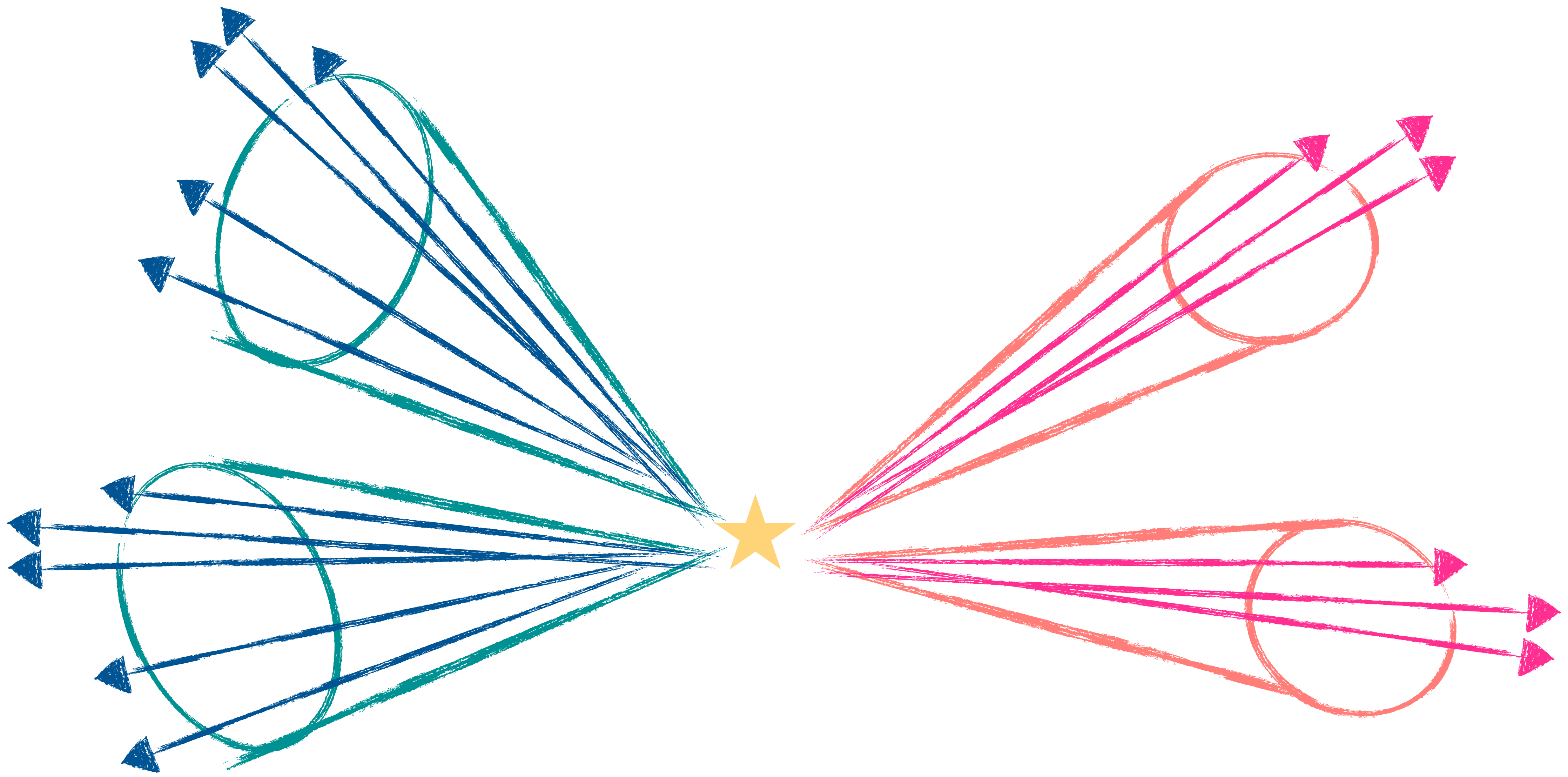
Branching ratio HH→bbττ : 7.3%

See also CMS HH→bbττ result:
CMS-PAS-HIG-20-010

Fully hadronic channel

$BR(\tau_h\tau_h) = 42.0\%$

Two b-tagged jets (ε=77%)



Two hadronic taus

No e/μ in the event

$m_{\tau\tau} > 60$ GeV

ATLAS HH→bbττ

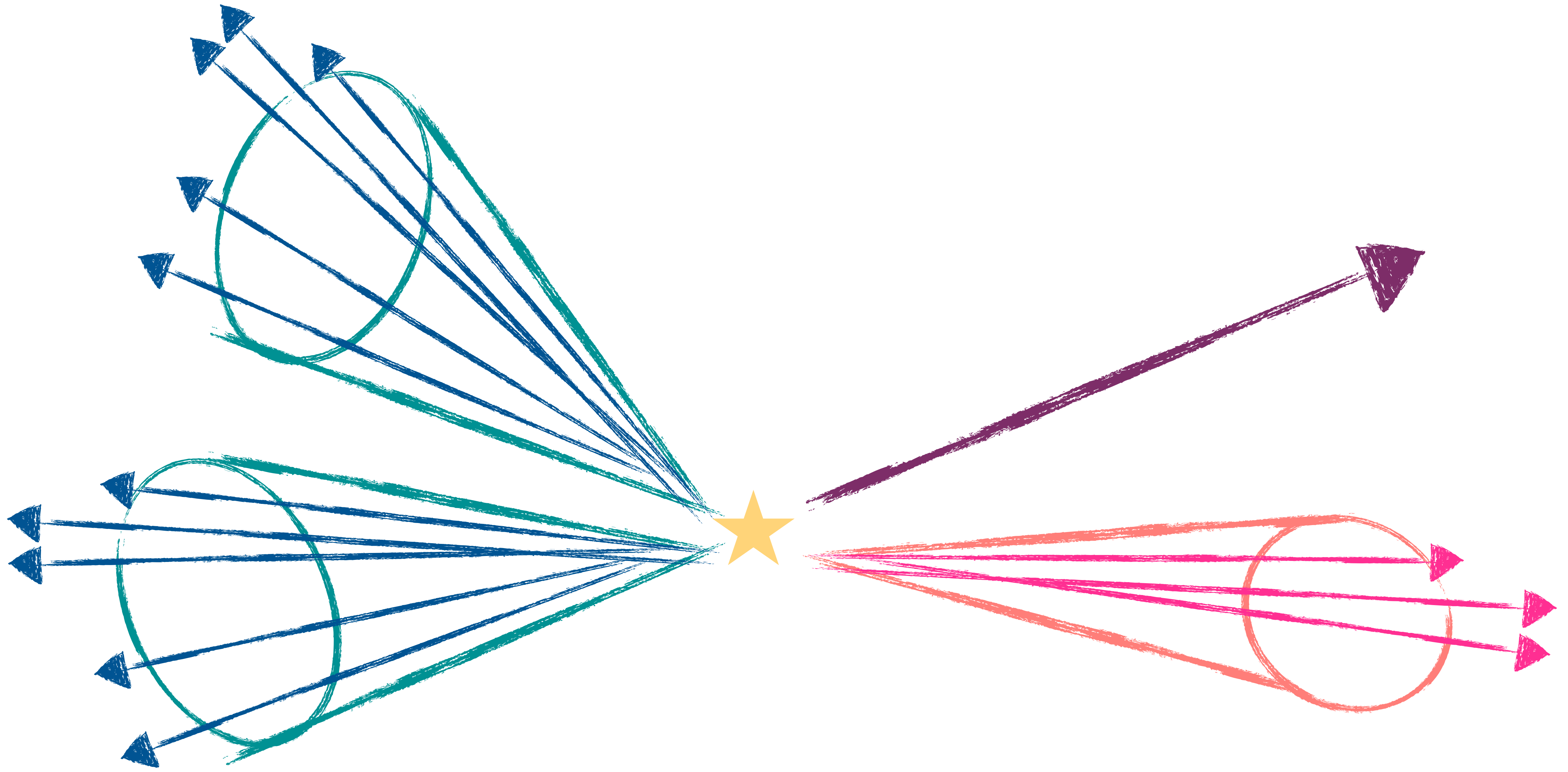
ATLAS-CONF-2021-030

Branching ratio HH→bbττ : 7.3%

See also CMS HH→bbττ result:
CMS-PAS-HIG-20-010

Semi-leptonic channel

BR($\tau_\ell\tau_h$) = 45.6%



Two b-tagged jets (ε=77%)

m_{bb} < 150 GeV

One electron or muon

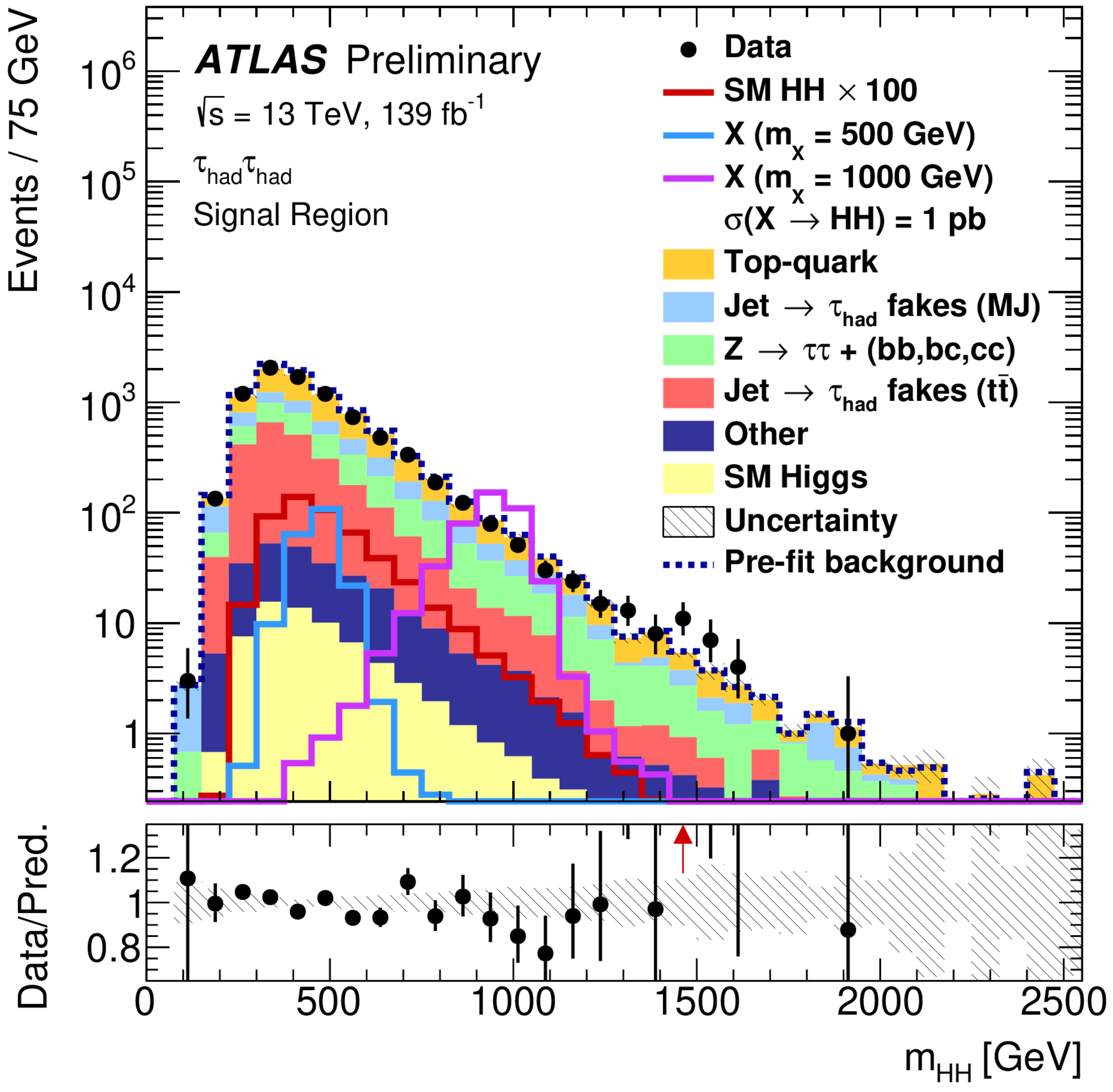
One hadronic tau

(trigger-dependent p_T thresholds)

$m_{\tau\tau}$ > 60 GeV

ATLAS HH→bbττ

Use BDTs and NNs to separate signal from backgrounds.

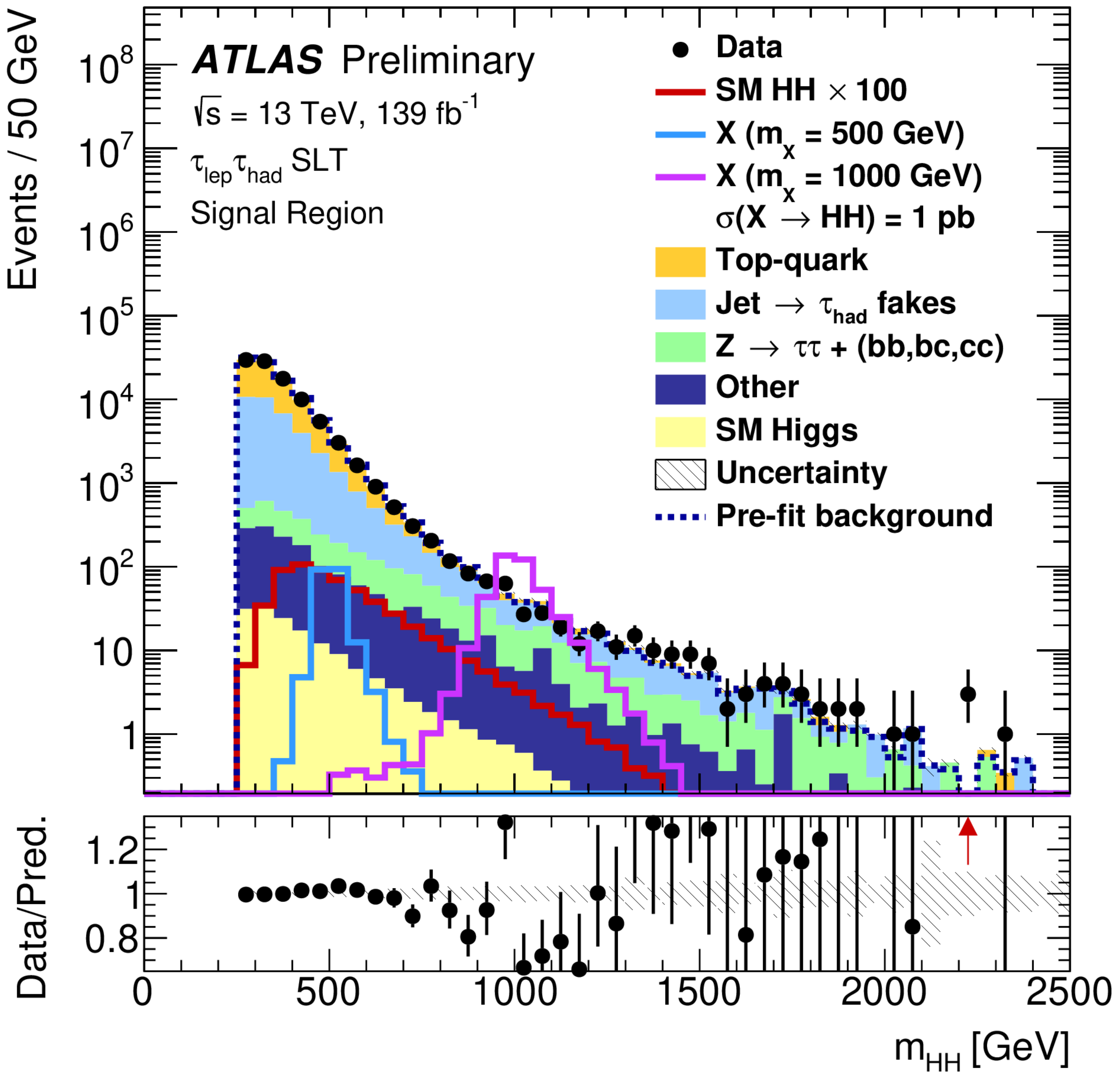


Top quark processes (true taus):
Shape from MC, normalisation from fit.

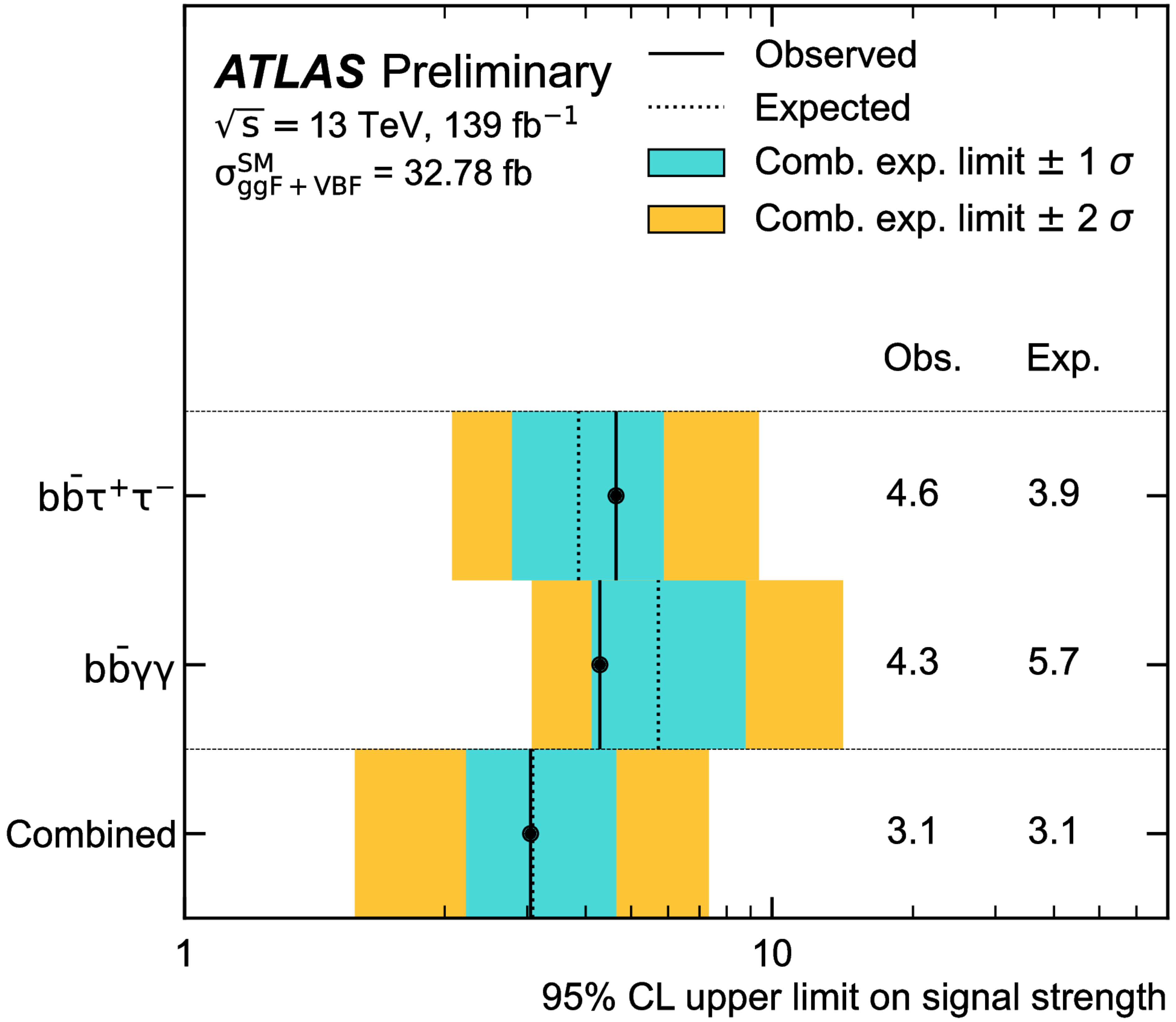
Z→ττ + heavy flavour:
Shape from MC, normalisation from Z→ee/μμ + heavy flavour control region.

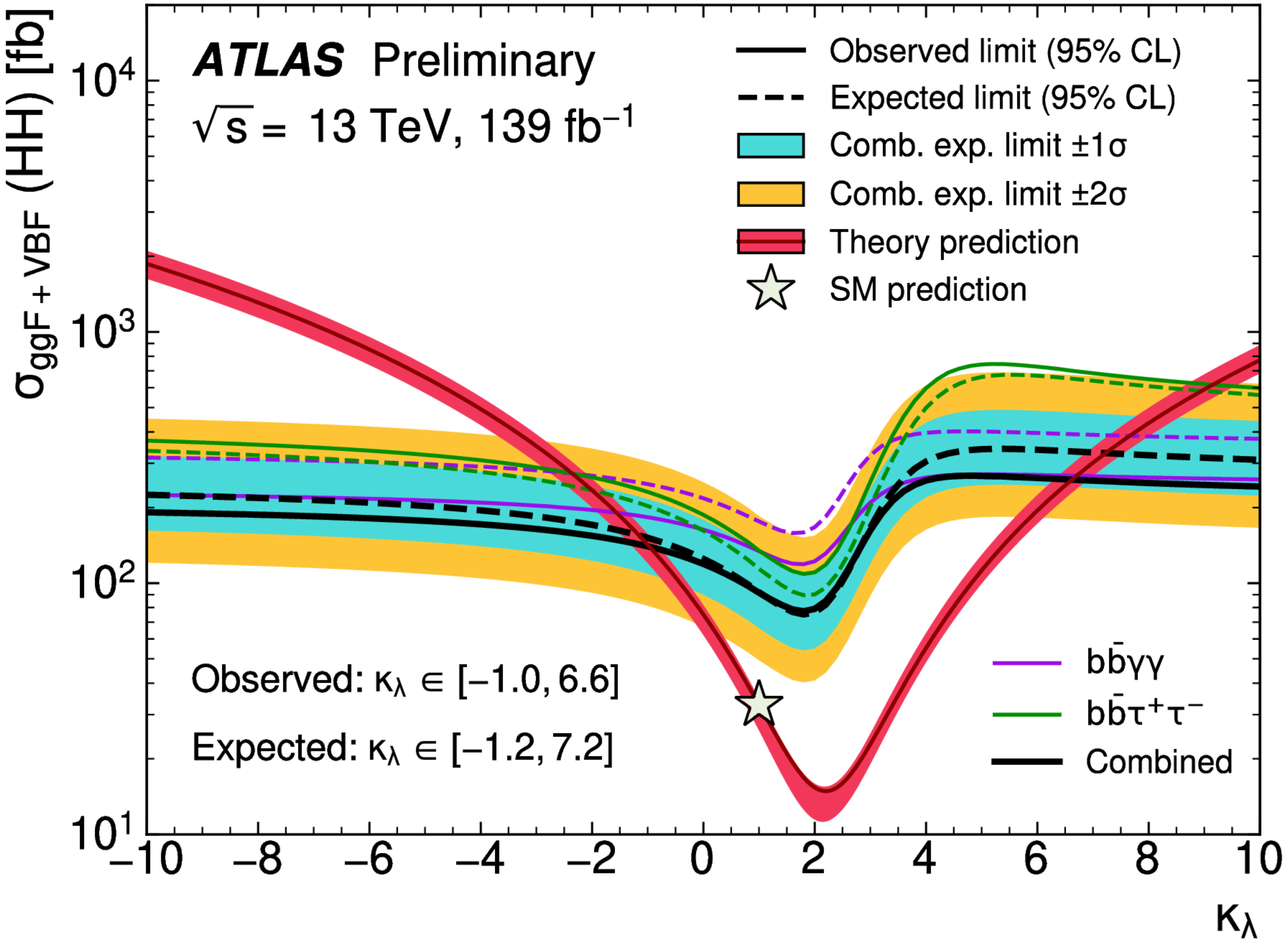
Single Higgs & others
Estimated from MC

Fake tau backgrounds
Estimate rate for jets to fake taus from data.



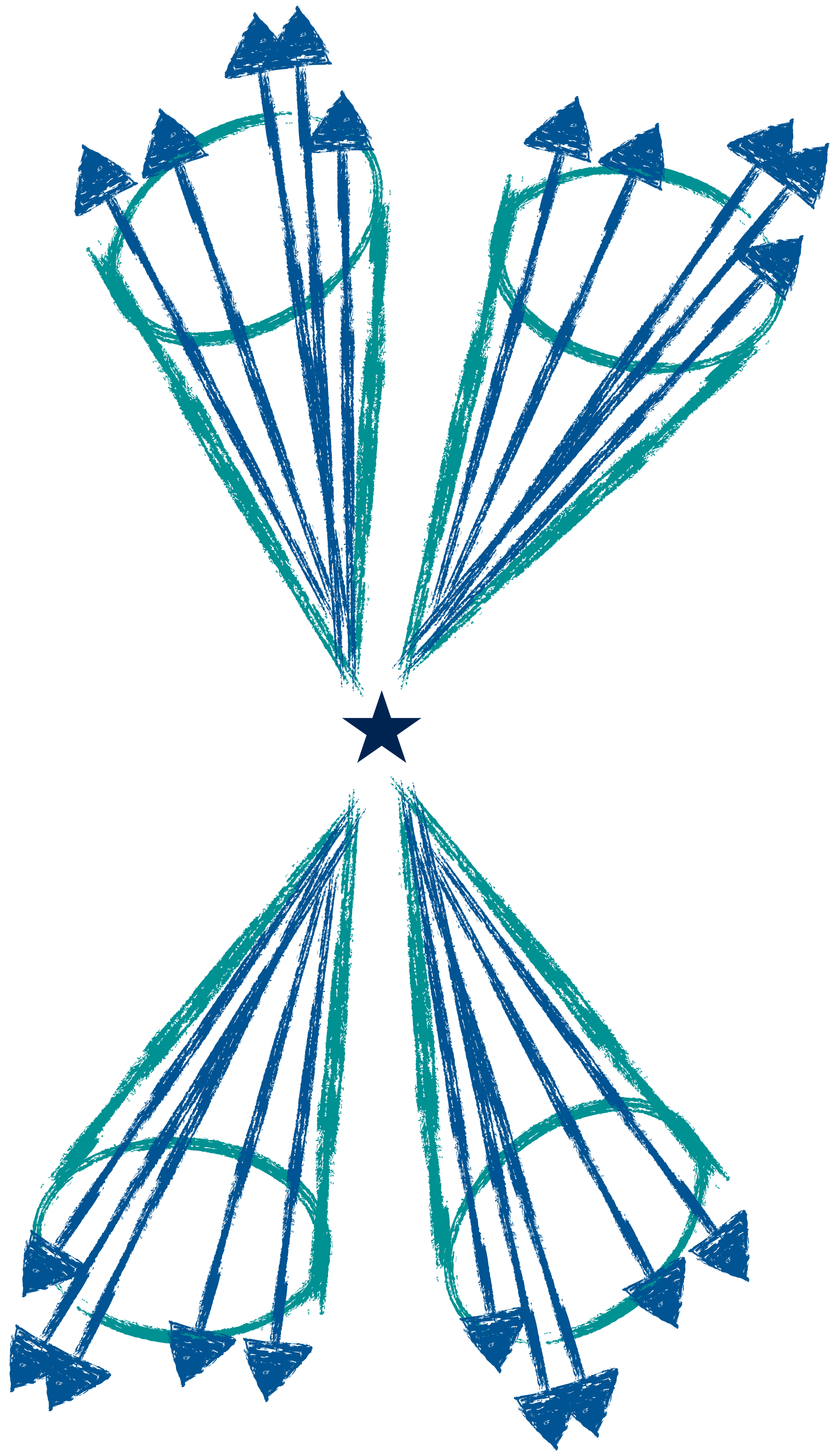
ATLAS combination (HH→bbγγ, bbττ)

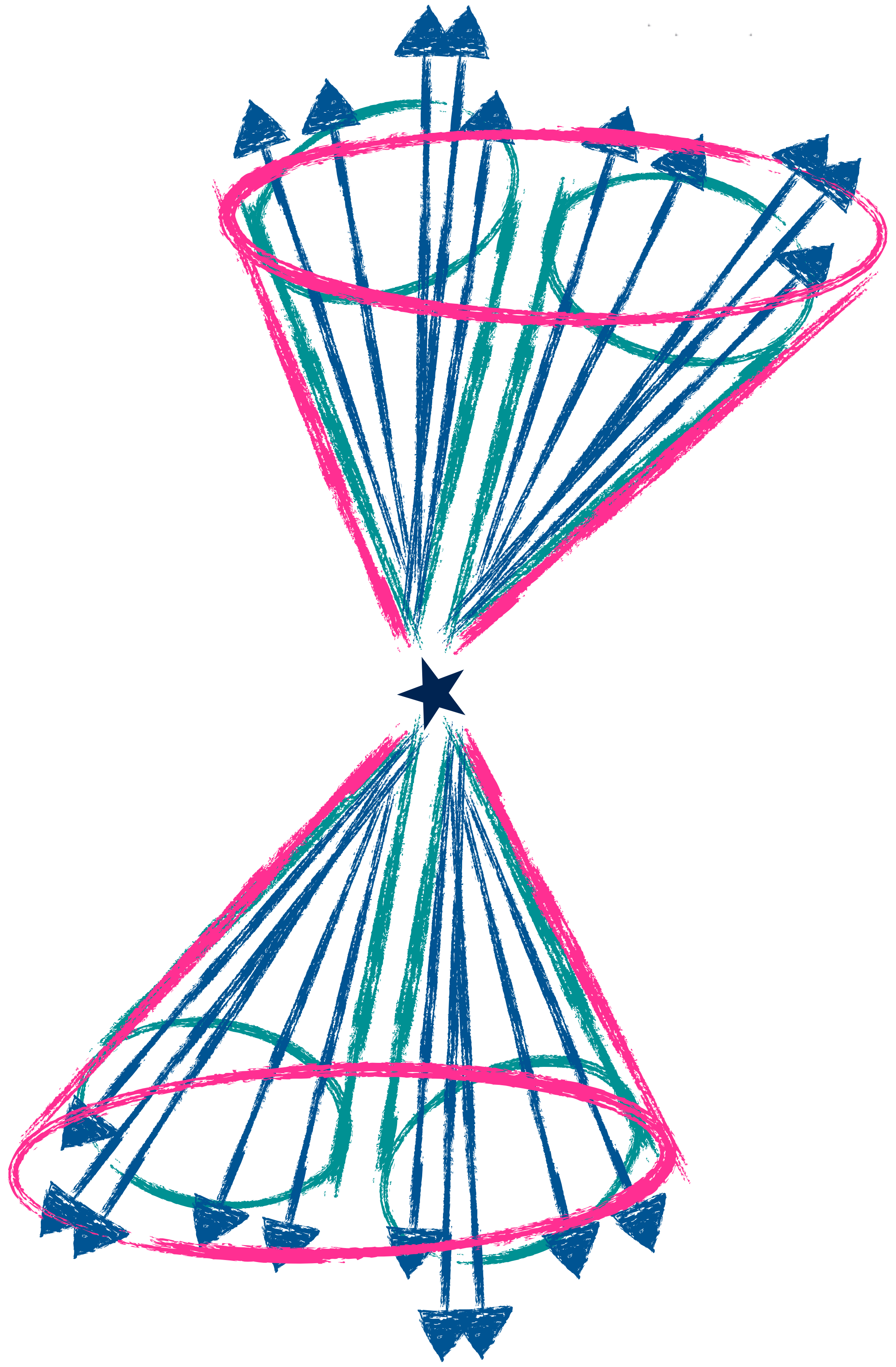




CMS HH→bbbb

[CMS-HIG-20-005](CMS-HIG-20-005)
[CMS-B2G-22-003](CMS-B2G-22-003)



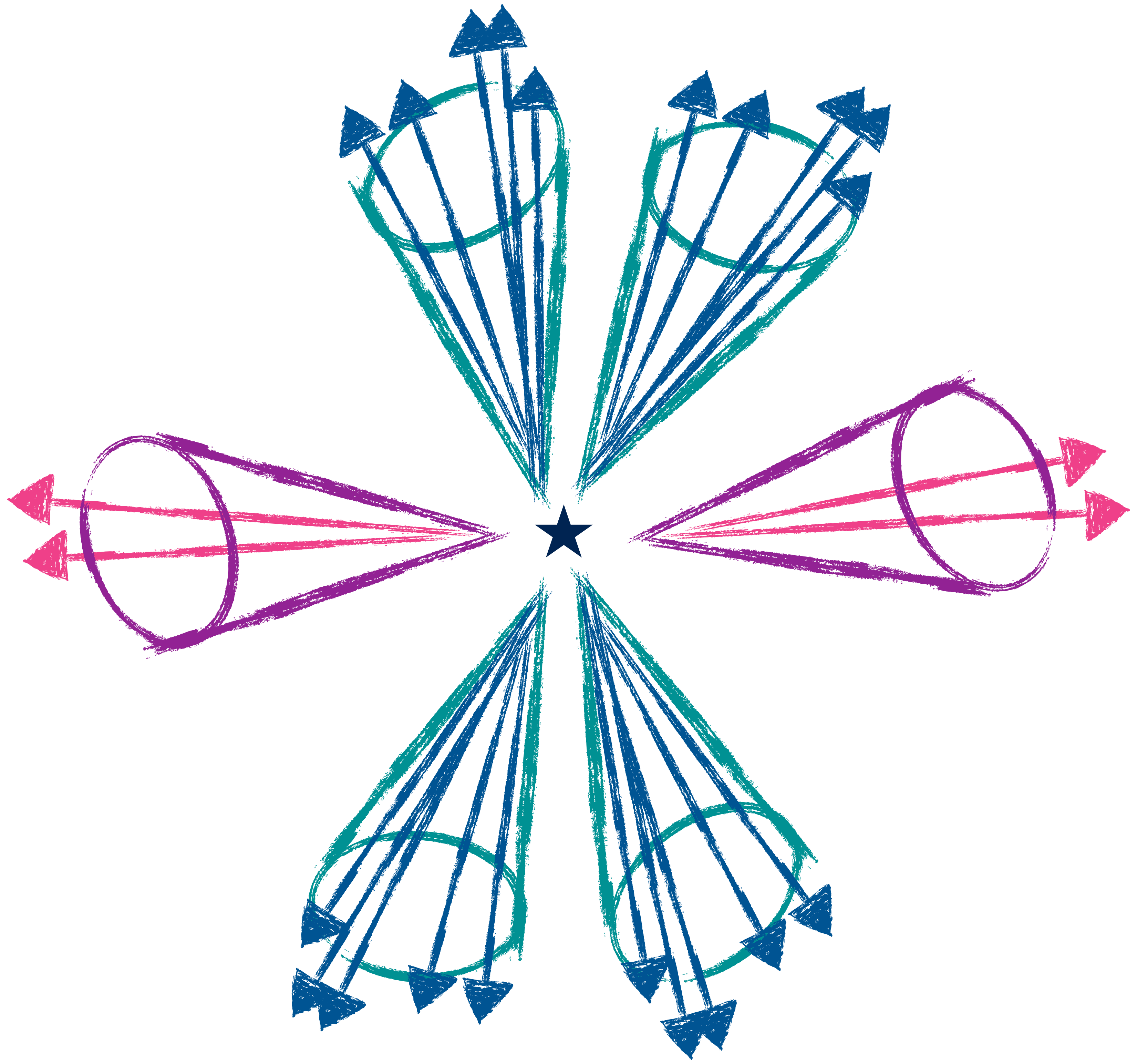


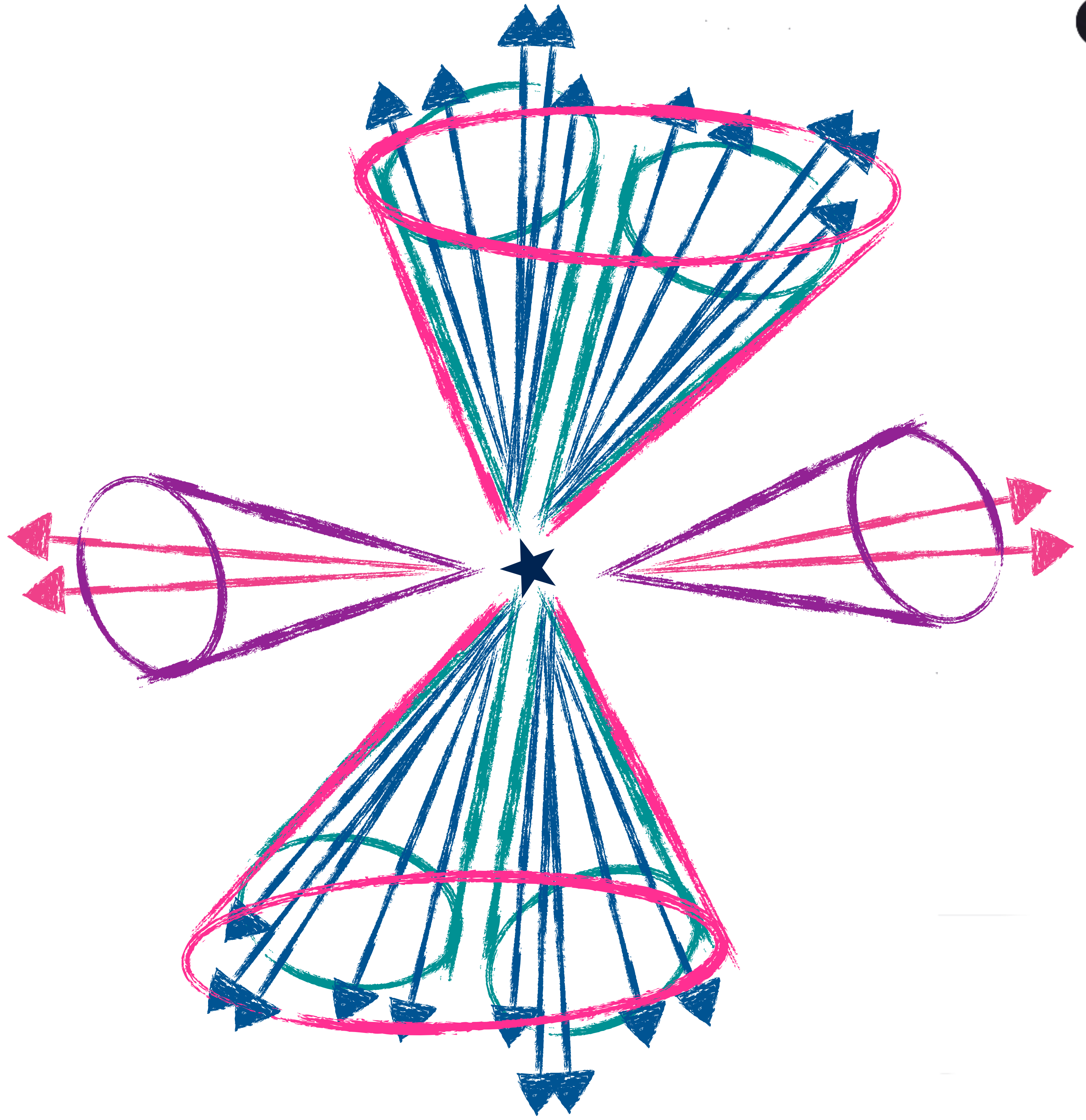
Resolved analysis
Higgs bosons have low-moderate p_T and the b-jets can be resolved into individual jets using standard jet reconstruction algorithms

Boosted analysis
Higgs bosons have high p_T so the decay products (b-jet pair) are close together - reconstruct both in a “large radius” jet

CMS HH→bbbb

[CMS-HIG-20-005](#)
[CMS-B2G-22-003](#)





VBF channels

Use BDTs to separate gluon fusion and vector boson fusion production modes.
(VBF events typically characterised by two high p_T jets, with large m_{jj} and large $\Delta\eta$.)

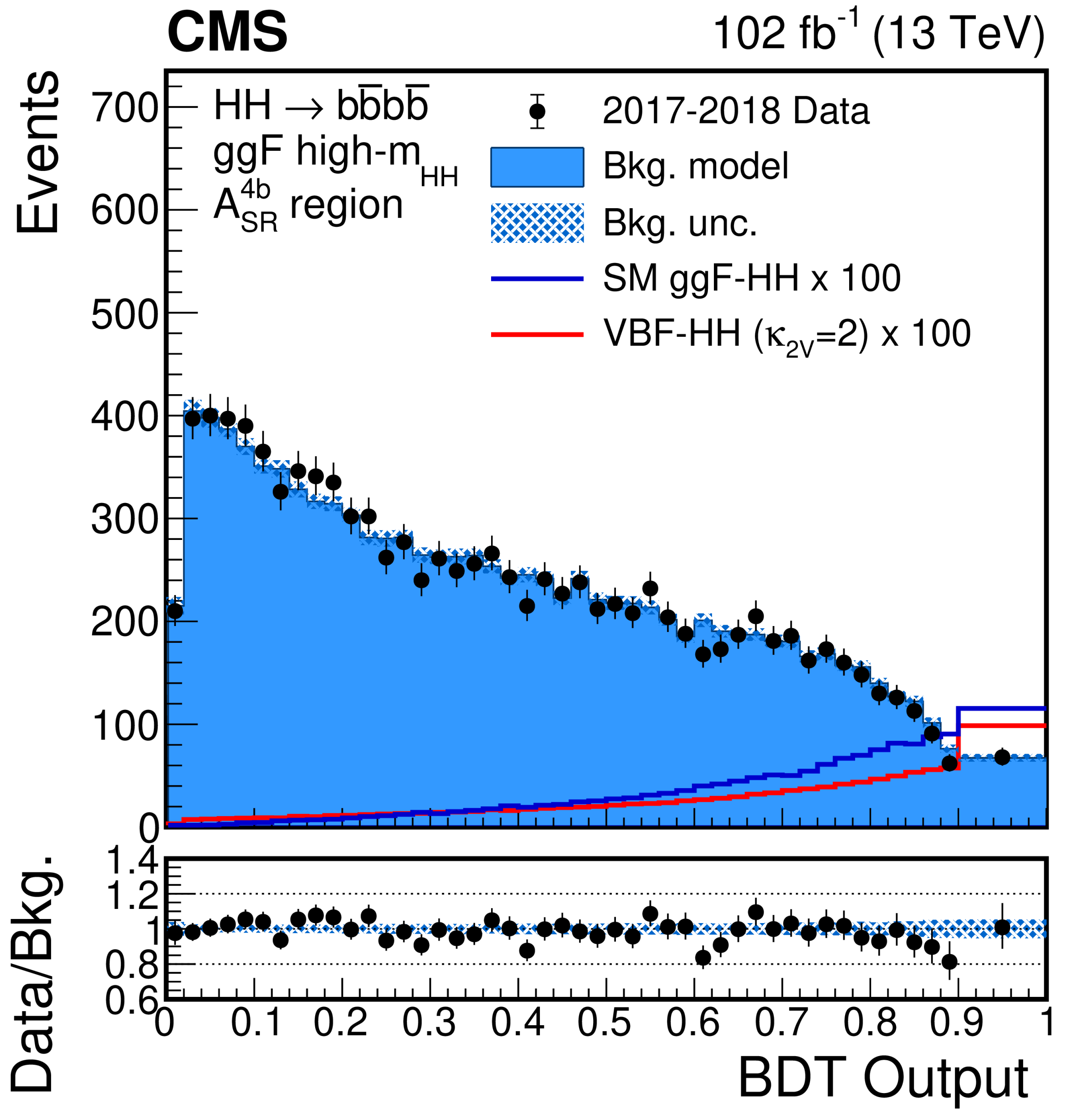
CMS HH→bbbb

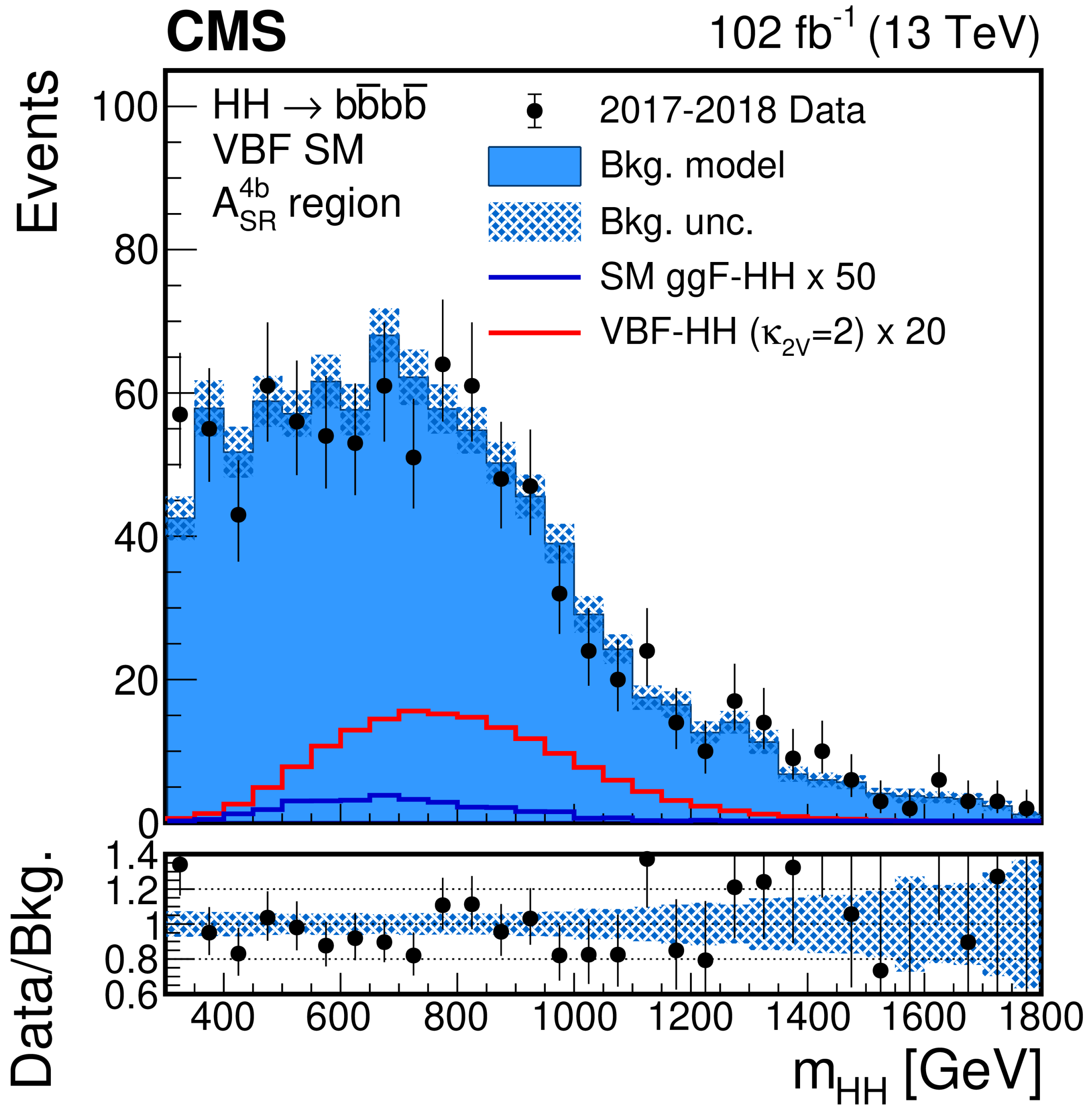
CMS-HIG-20-005
CMS-B2G-22-003

Use BDTs to separate signal from backgrounds in different analyses/ channels.

Main challenges:

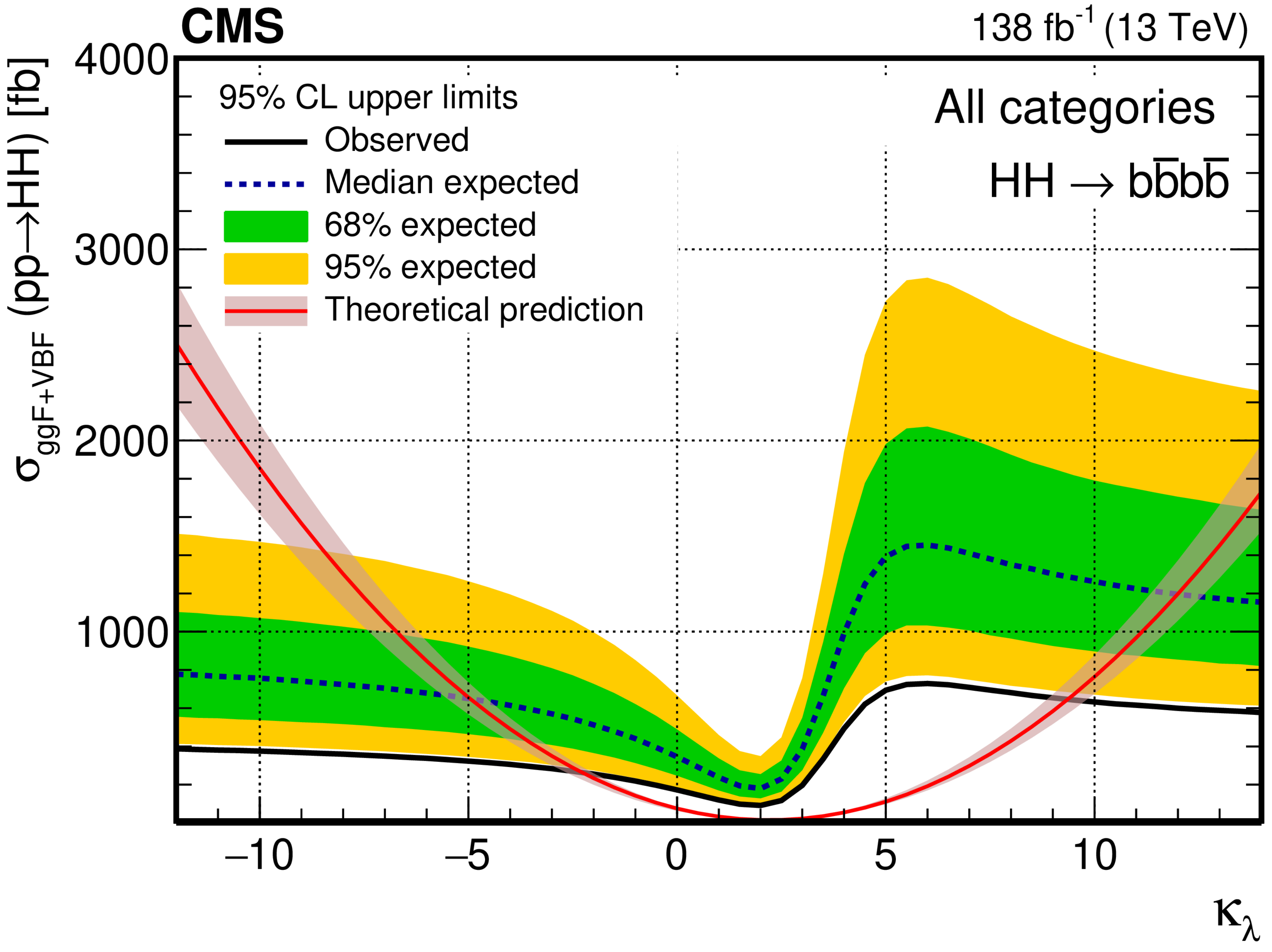
- Pairing b-jets into Higgs candidates - difficult to do this without sculpting background to look like signal.
- Estimate large multijet background - re-weight data with 3 b-jets to look like 4 b-jet data - hard to model accurately (large uncertainties).





Resolved analysis

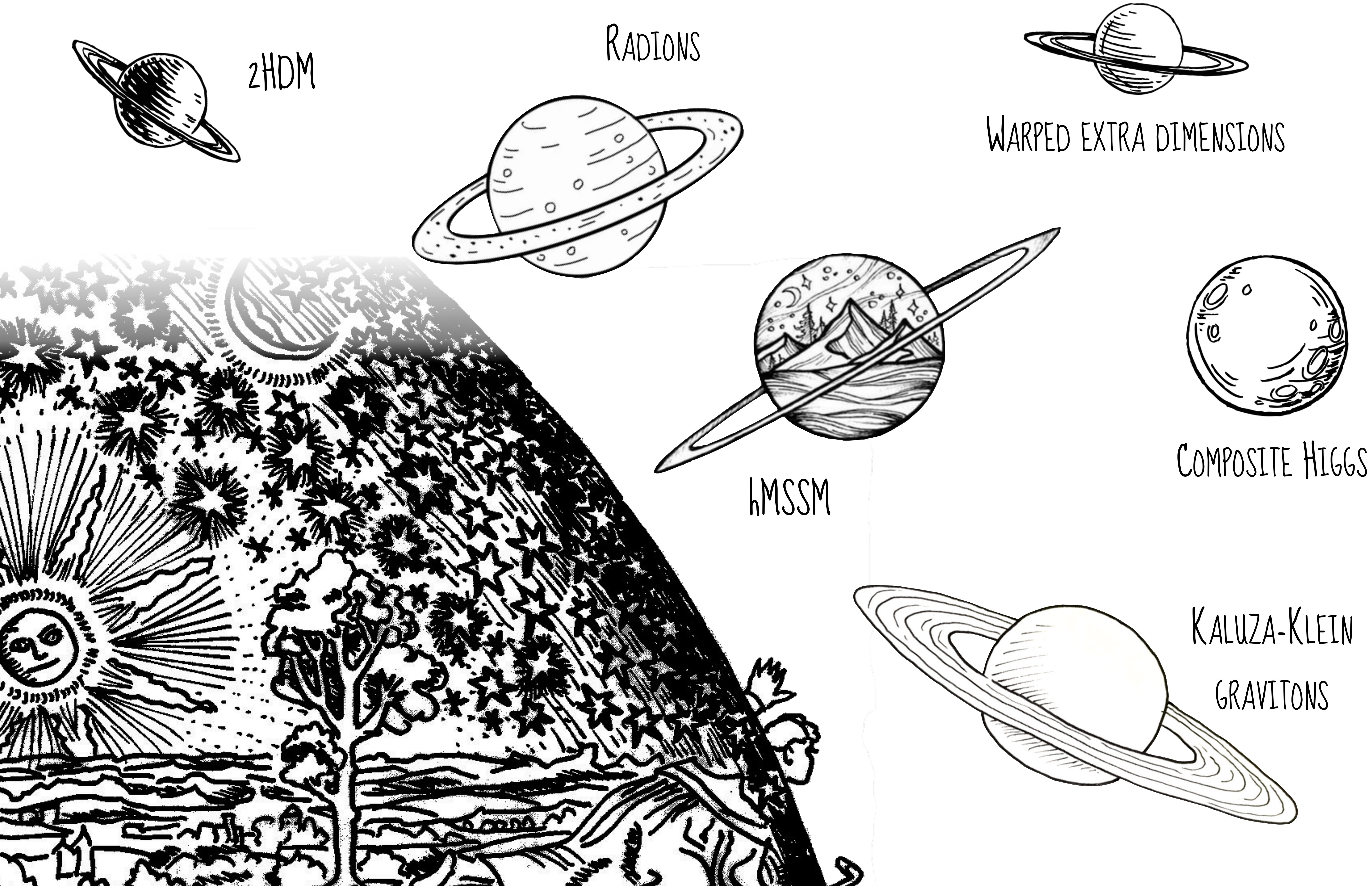
Observed (expected) limit at 95% confidence level: 3.9 (7.8) x SM prediction.

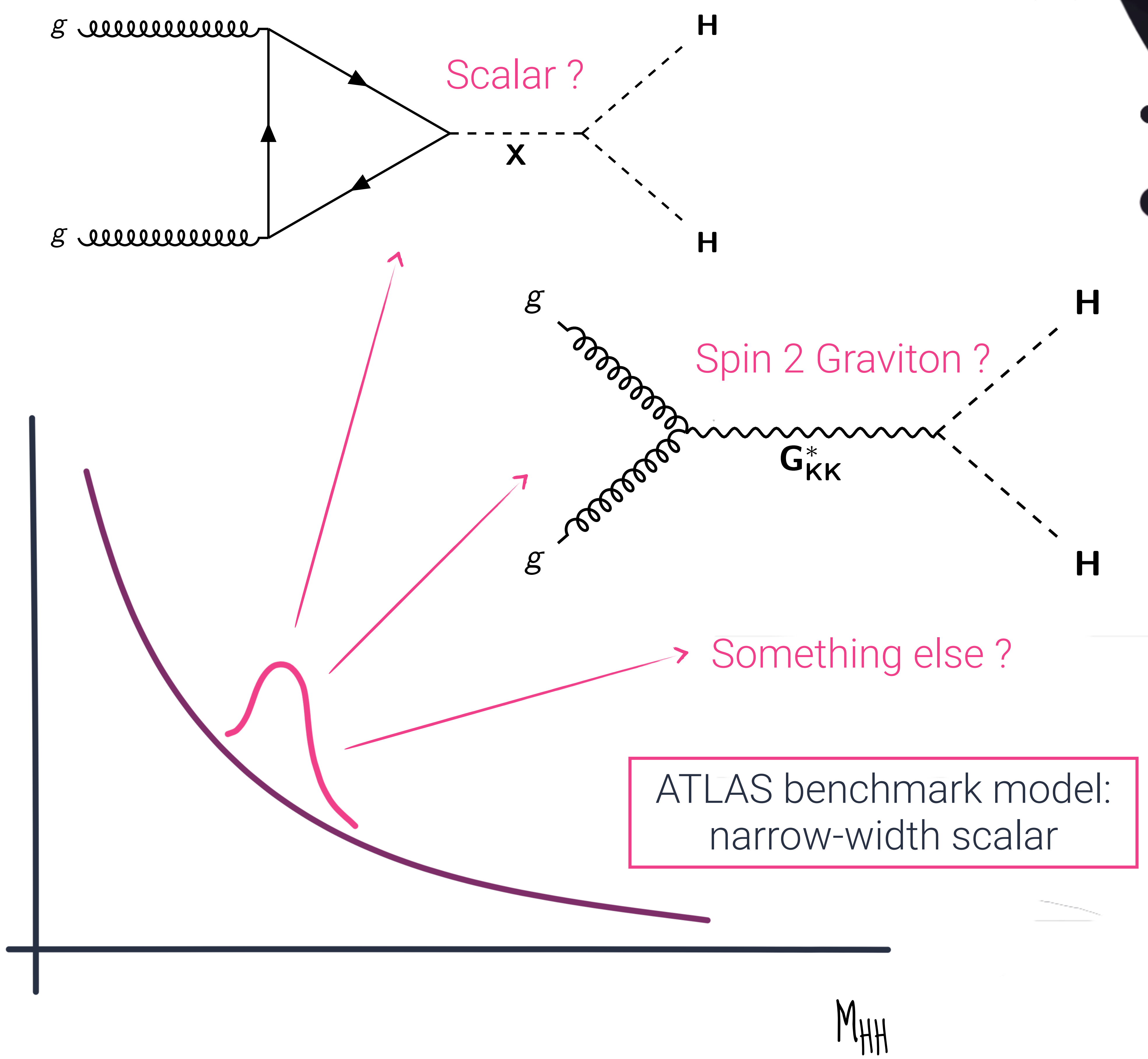


Resonant Higgs Pair Production

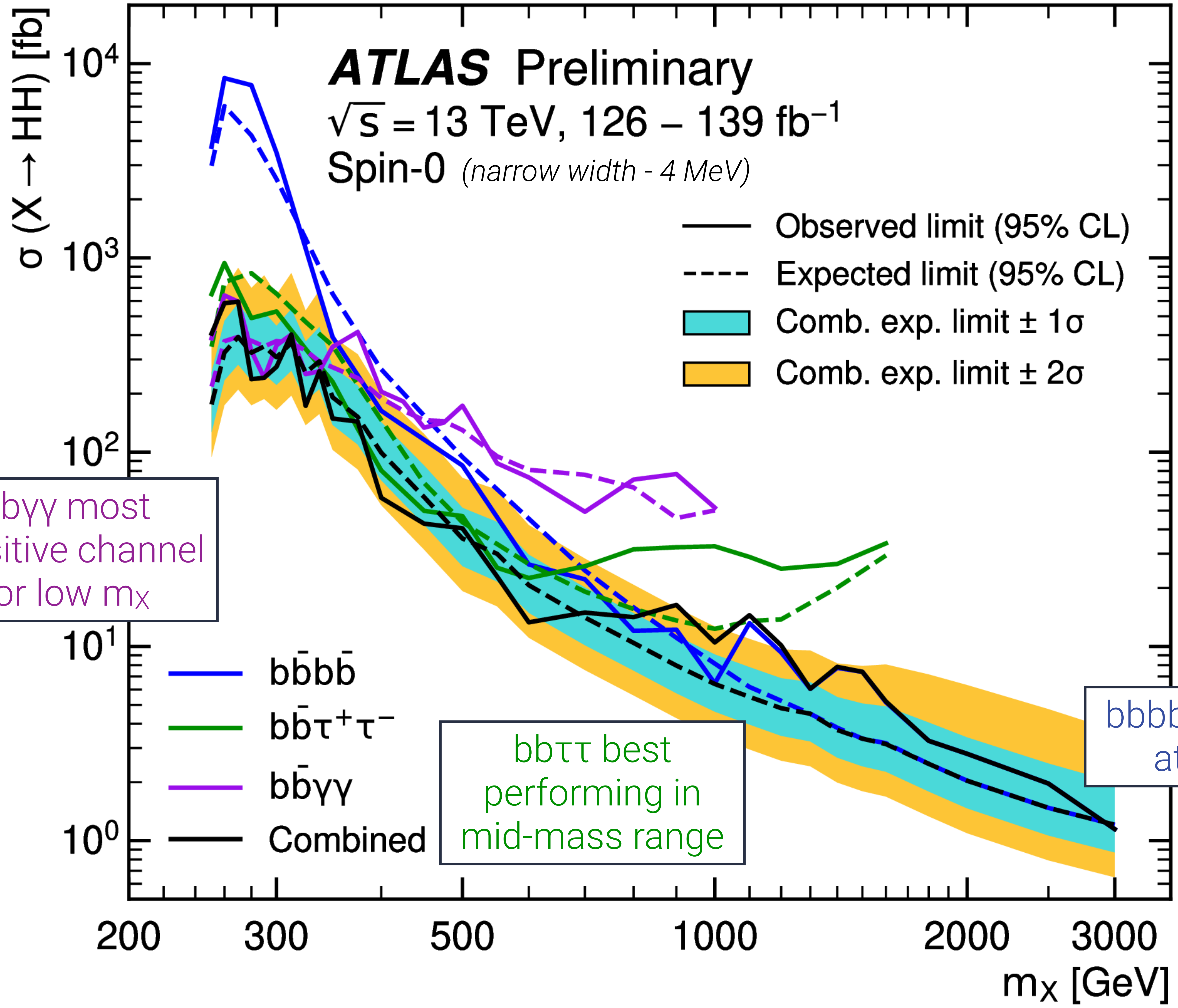
New physics is *required* if $\kappa_\lambda \neq 1$

Many beyond the Standard Model theories predict new particles that can decay to a pair of Higgs bosons





ATLAS resonant HH (bbγγ, bbττ, bbbb)



bbγγ most sensitive channel for low m_X

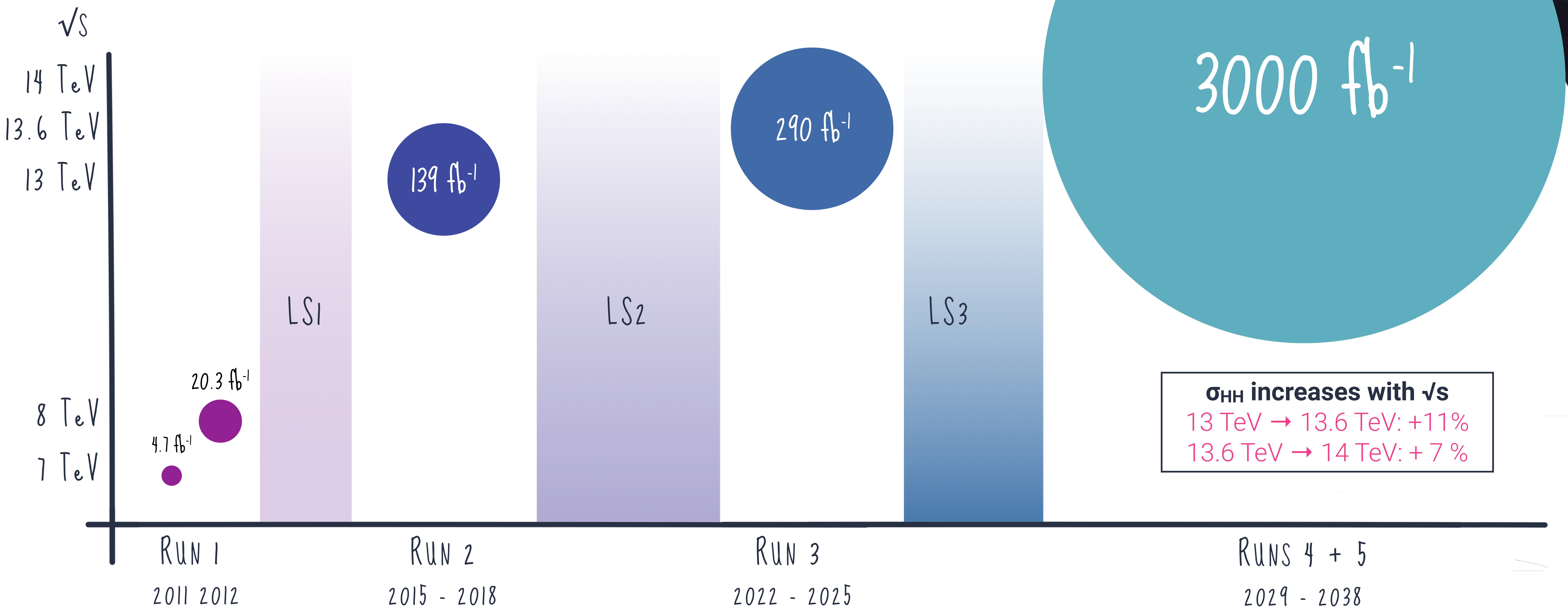
bbττ best performing in mid-mass range

bbbb dominates at high m_X

The future of searches

HL-LHC

Expect ~20x the current dataset with the HL-LHC

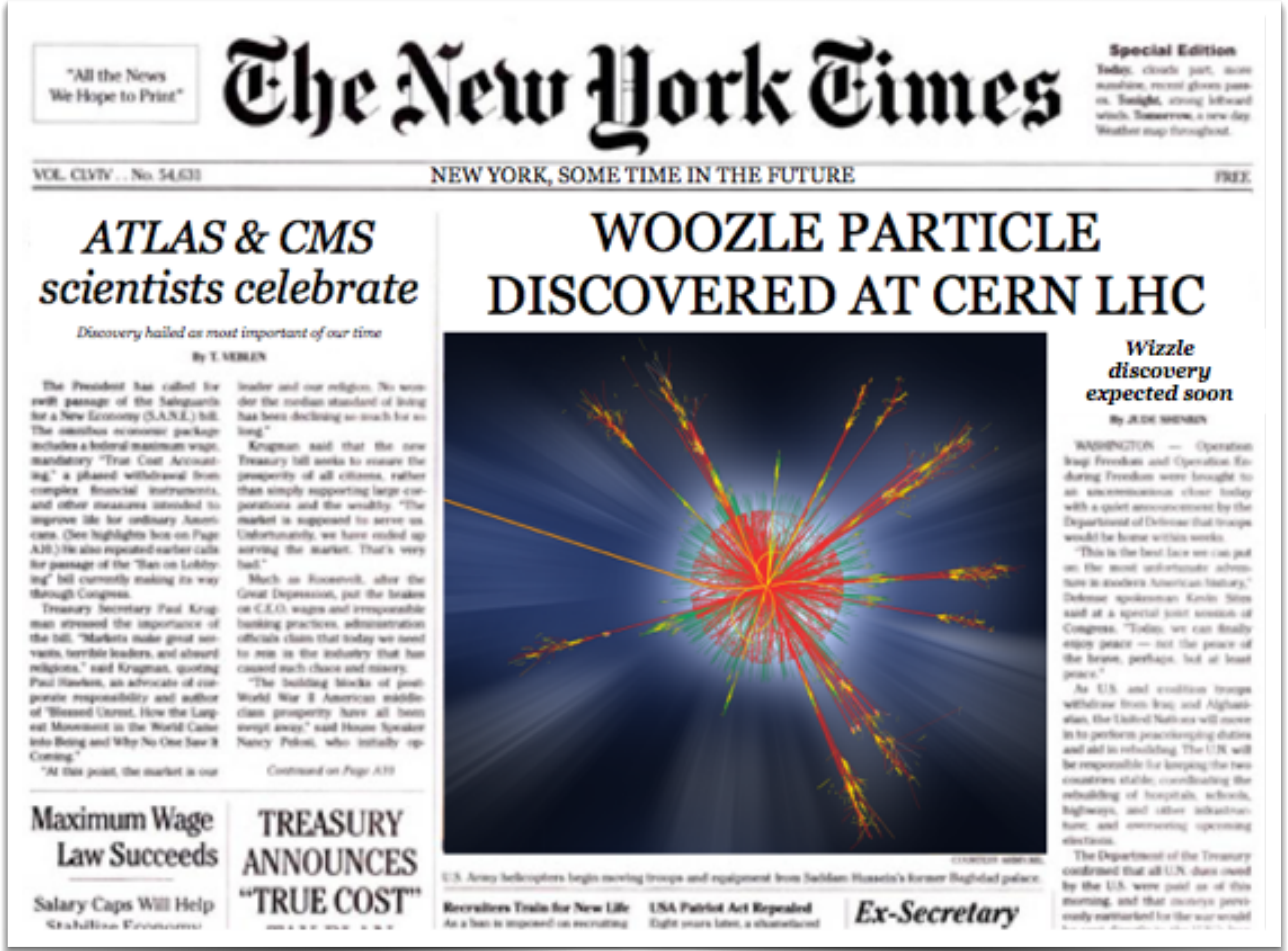


σ_{HH} increases with √s

13 TeV → 13.6 TeV: +11%

13.6 TeV → 14 TeV: + 7 %

Summary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The New York Times

Special Edition

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WOOZLE PARTICLE DISCOVERED AT CERN LHC

ATLAS & CMS scientists celebrate

Discovery hailed as most important of our time

Wizzle discovery expected soon

Maximum Wage Law Succeeds

Salary Caps Will Help

TREASURY ANNOUNCES "TRUE COST"

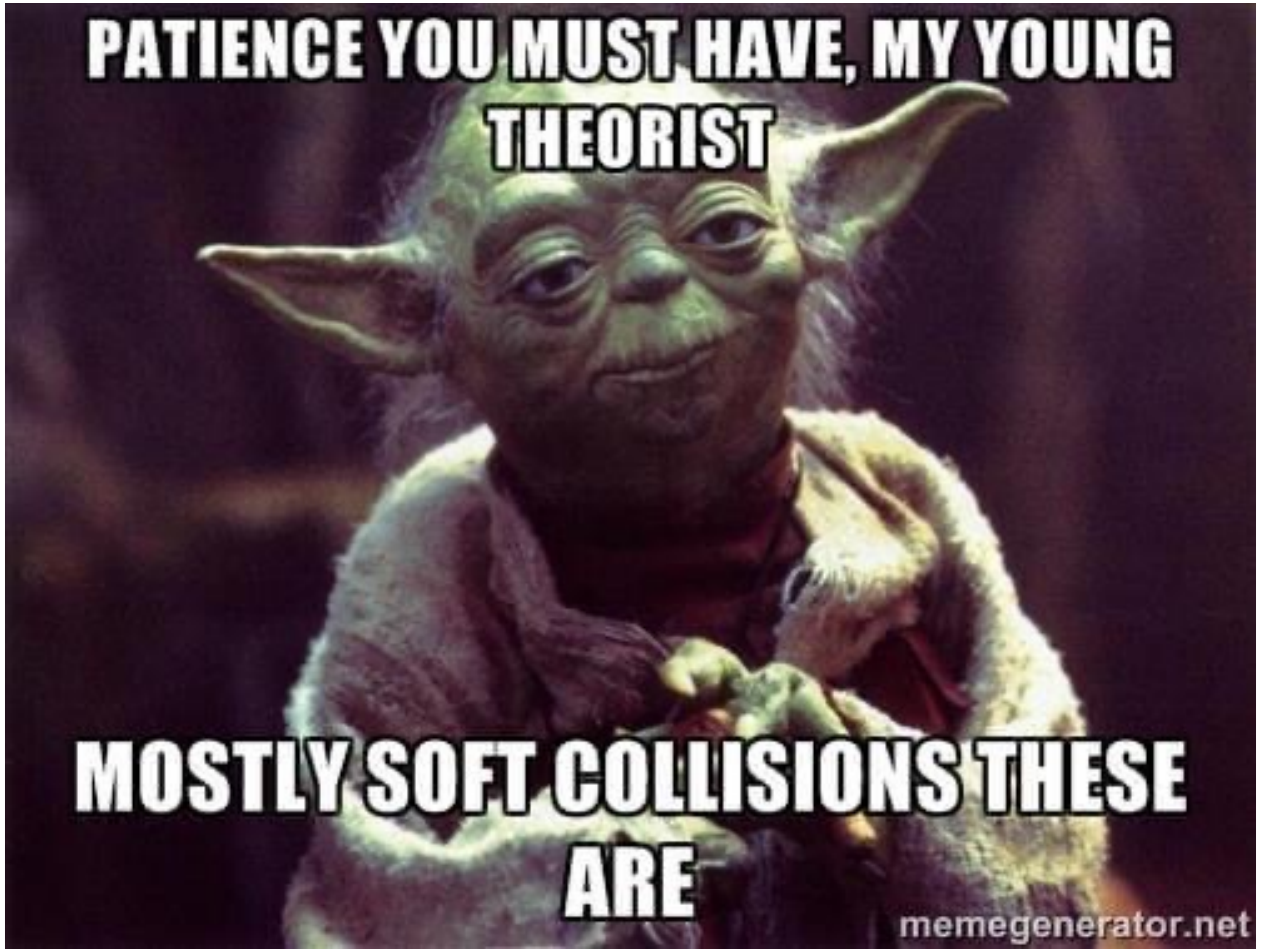
Recruiters Train for New Life

USA Patriot Act Repealed

Ex-Secretary

Back Up

Why haven’t we found anything yet?



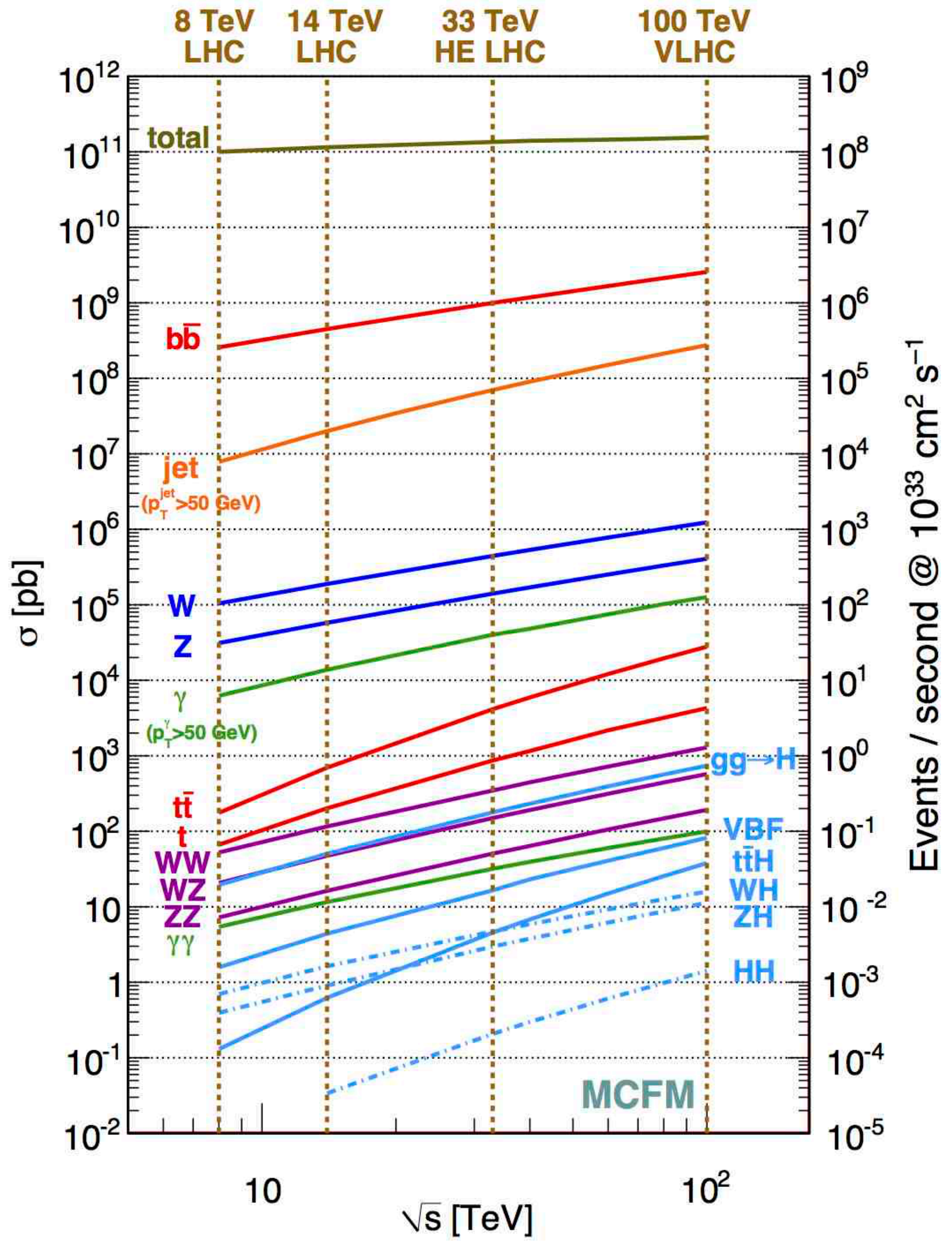
How can we make more new particles?

1. Increase the collision energy.

The LHC is the “energy frontier” .

Many new physics searches done at ATLAS and CMS are searching for increasingly heavier particles.

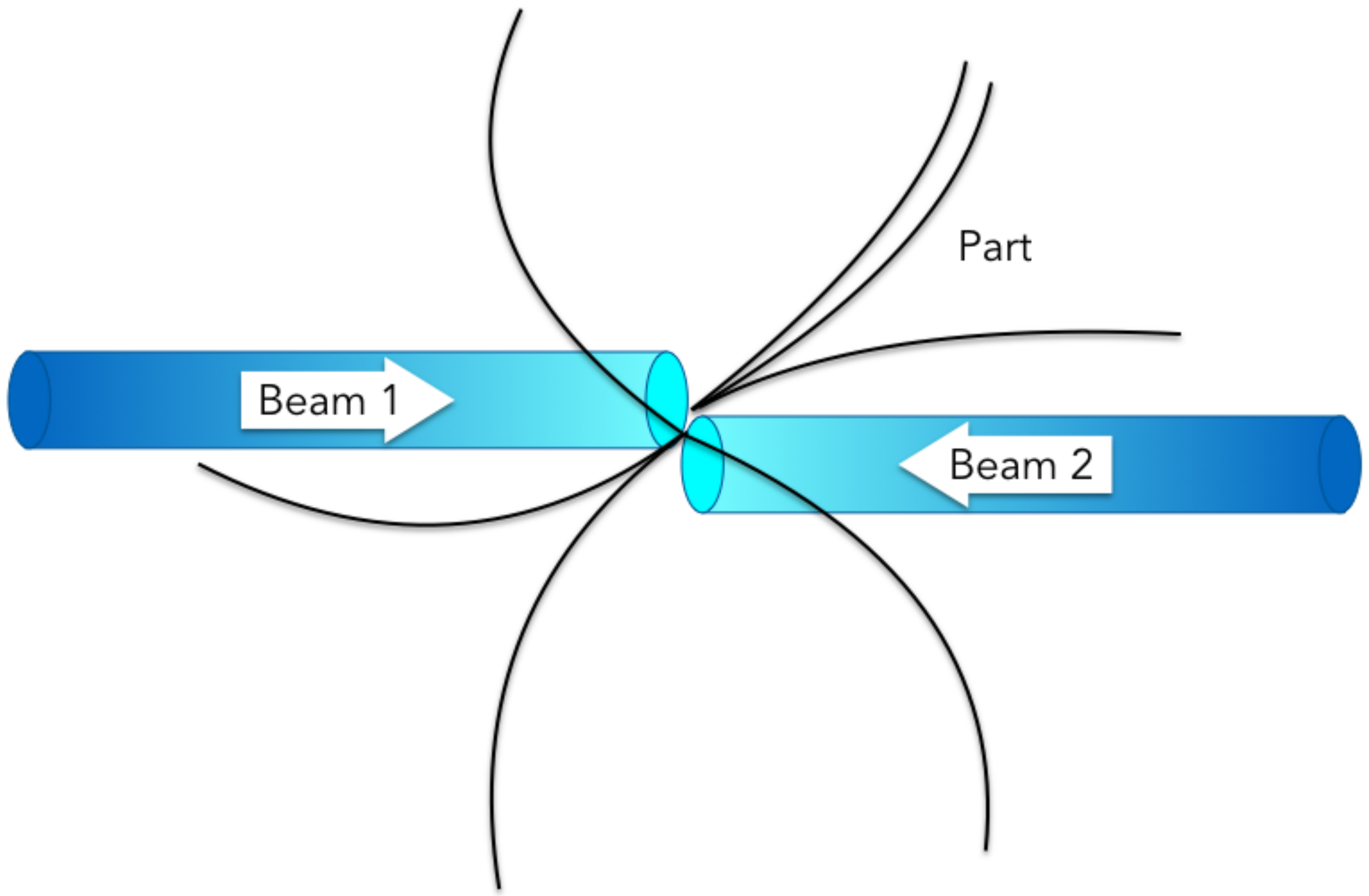
If we put more energy into the collisions then it’s easier to create them (E = mc2).



How can we make more new particles?

1. Increase the intensity of the collisions

More proton-proton collisions per second per unit area (even at lower energies) means more interactions and more chances to make new BSM particles (if they exist!)

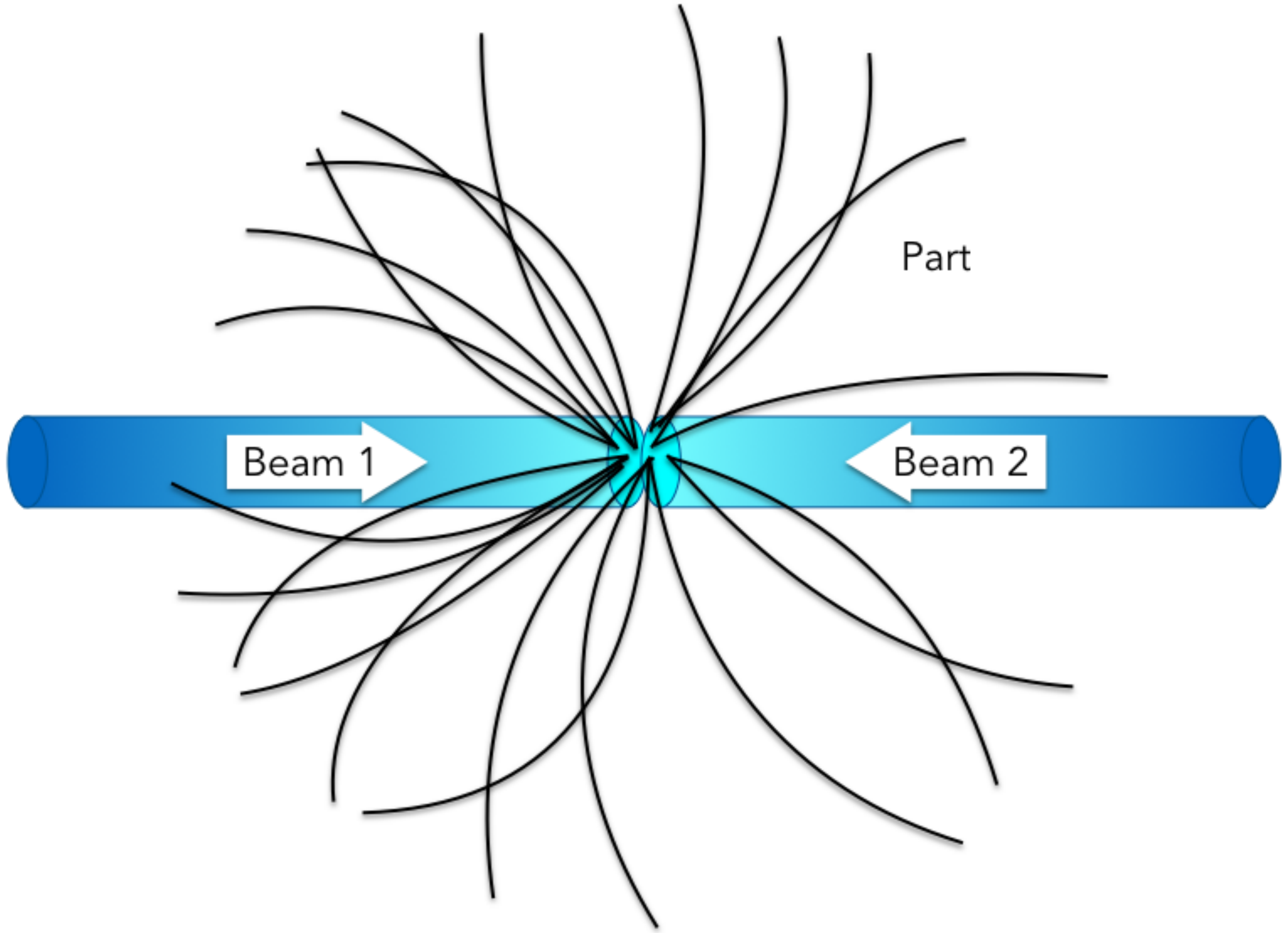


a). When the proton beams only overlap slightly there are few interactions and

How can we make more new particles?

1. Increase the intensity of the collisions

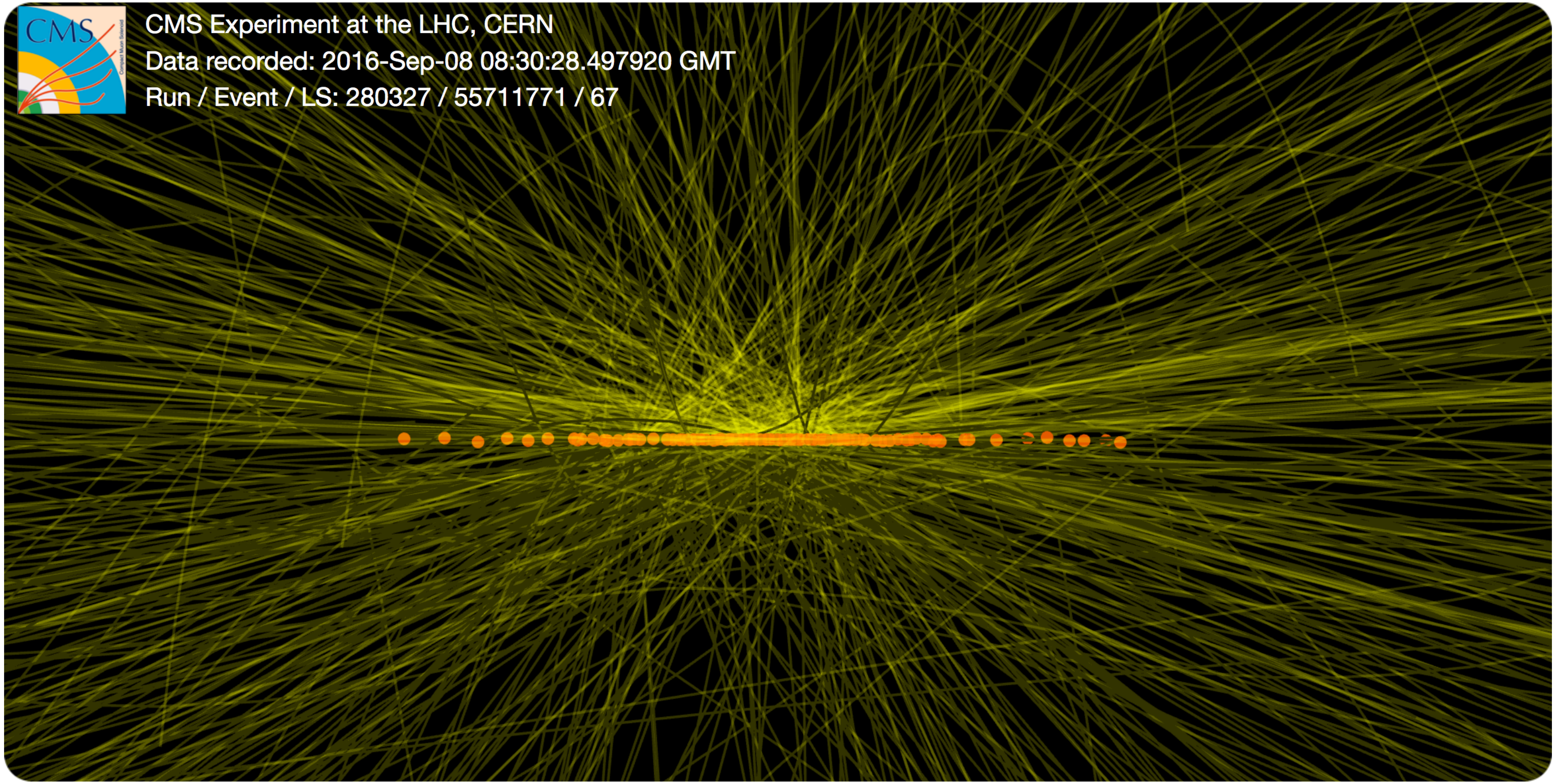
More proton-proton collisions per second per unit area (even at lower energies) means more interactions and more chances to make new BSM particles (if they exist!)



b). When the two beams overlap completely there are many interactions and m

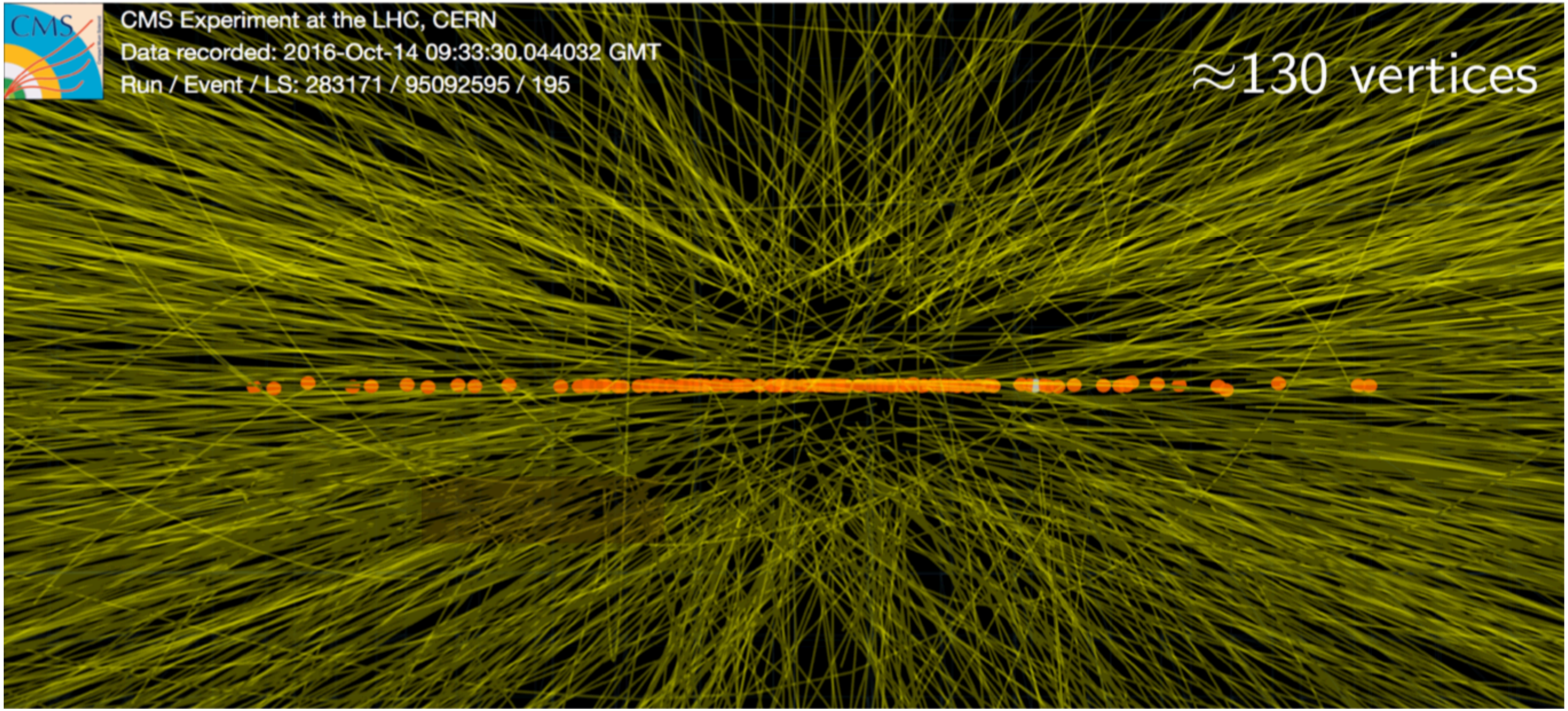
HL-LHC

Average of 60 proton collisions per bunch crossing during Run 2



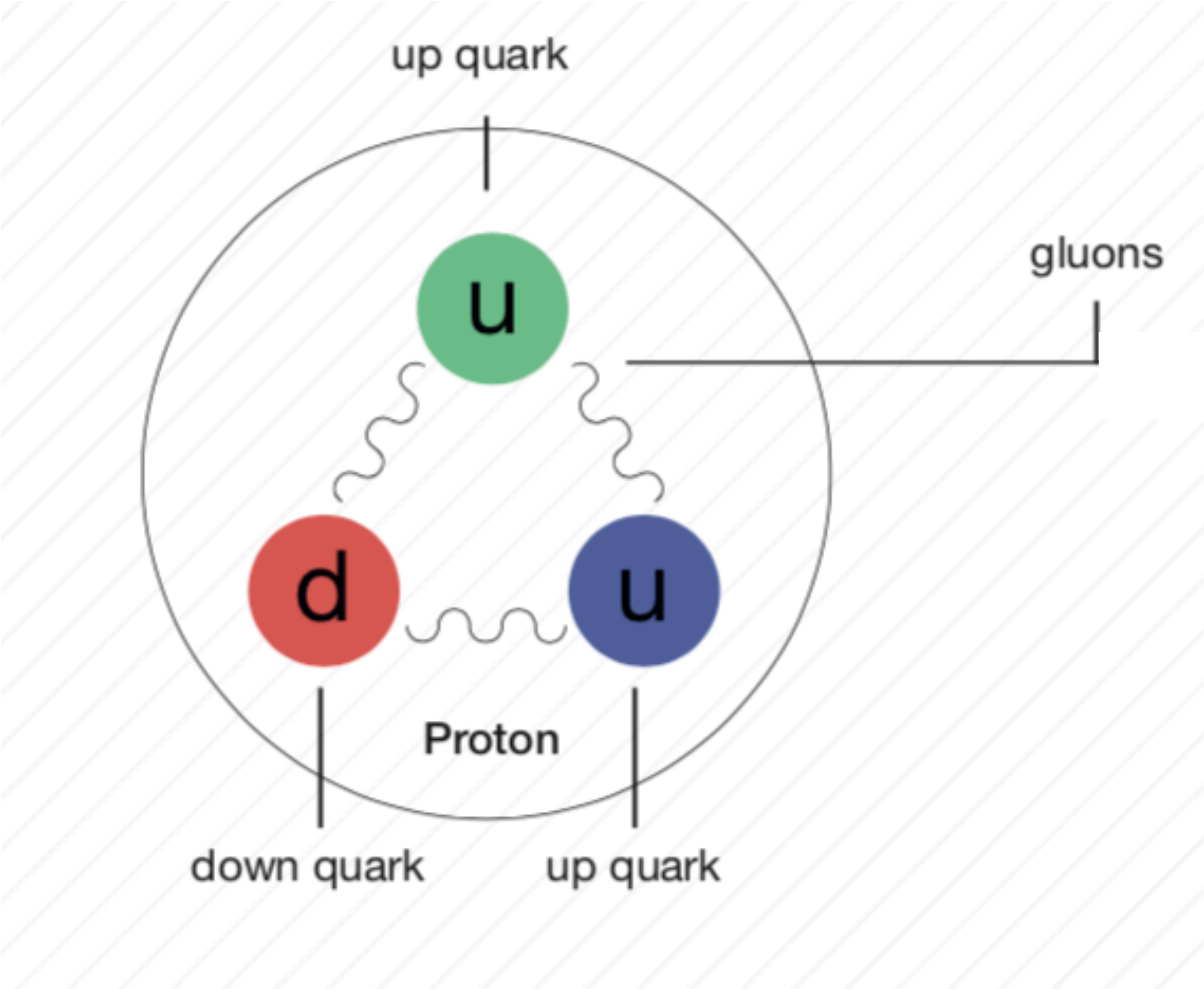
HL-LHC

Increasing to <μ> ~130 in Run 4, and eventually even higher (<μ> ~300) in Run 5.



Revisiting the proton

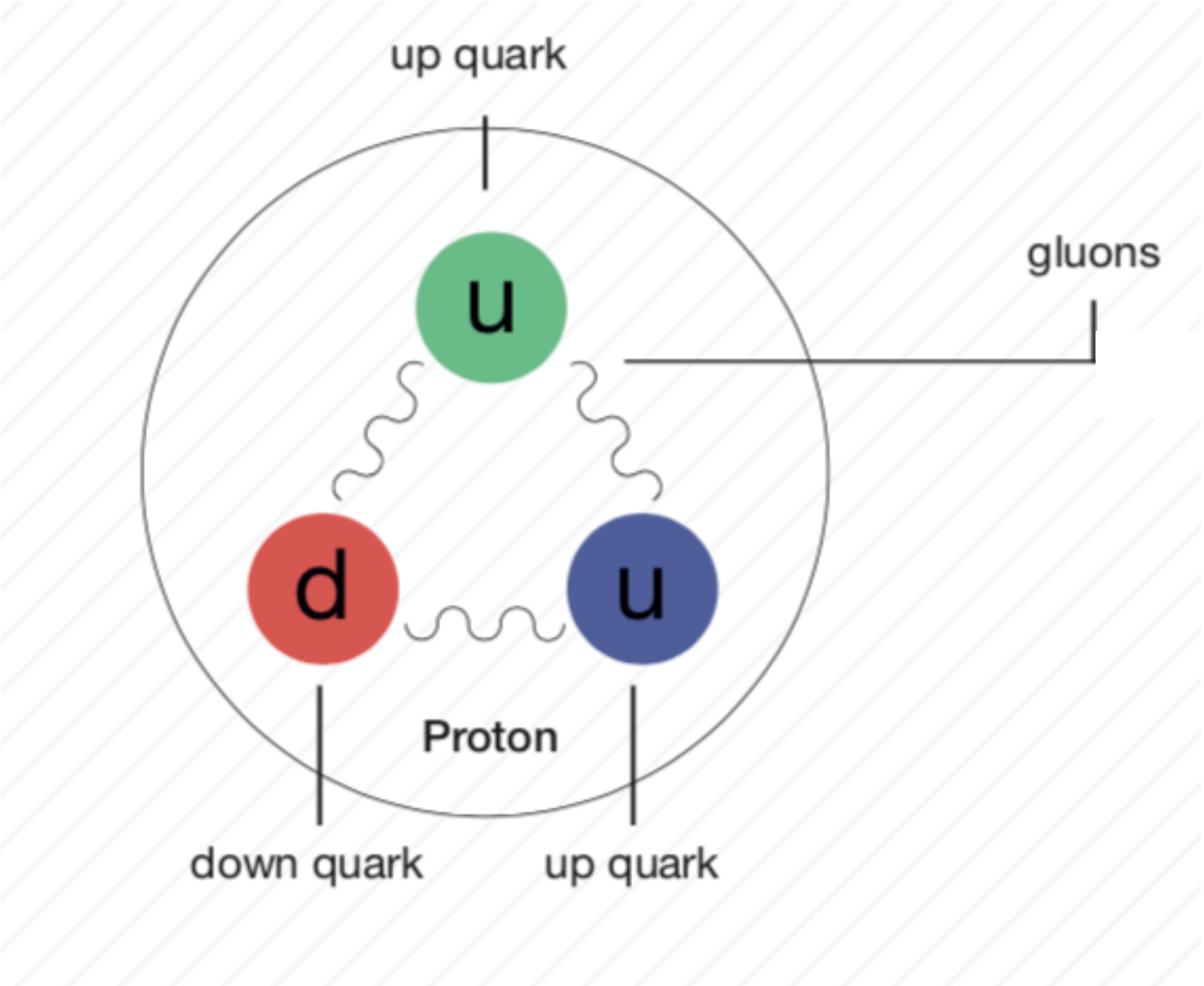
Simplified picture of a proton:



- 3 primary quarks
    - 2 up-quarks
    - 1 down-quark
- Quarks are bound together by the strong force (carried by gluons)

Revisiting the proton

Simplified picture of a proton:

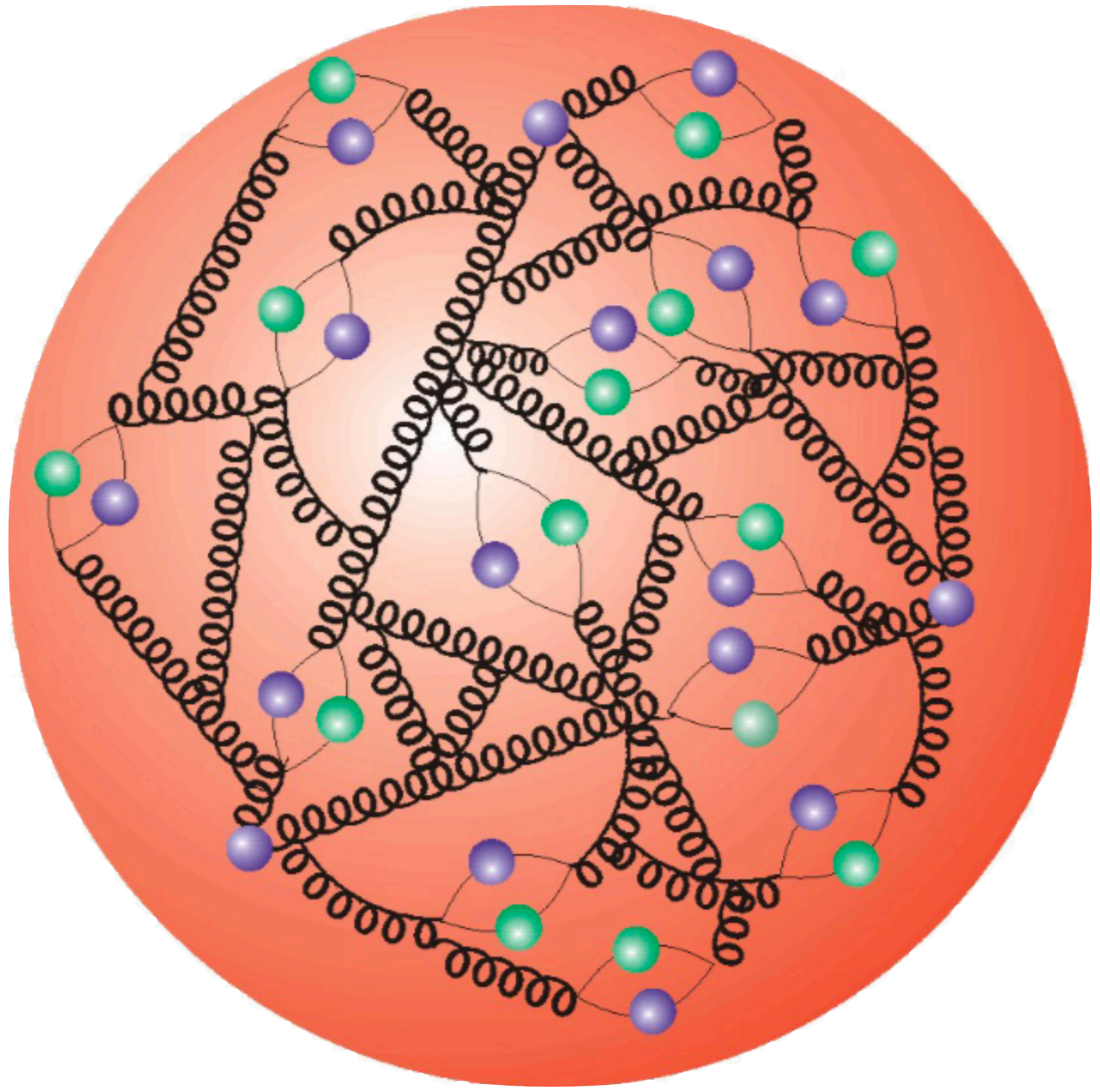


- 3 primary quarks
  - 2 up-quarks
  - 1 down-quark
- Quarks are bound together by the strong force (carried by gluons)

This picture is otherwise horribly wrong!

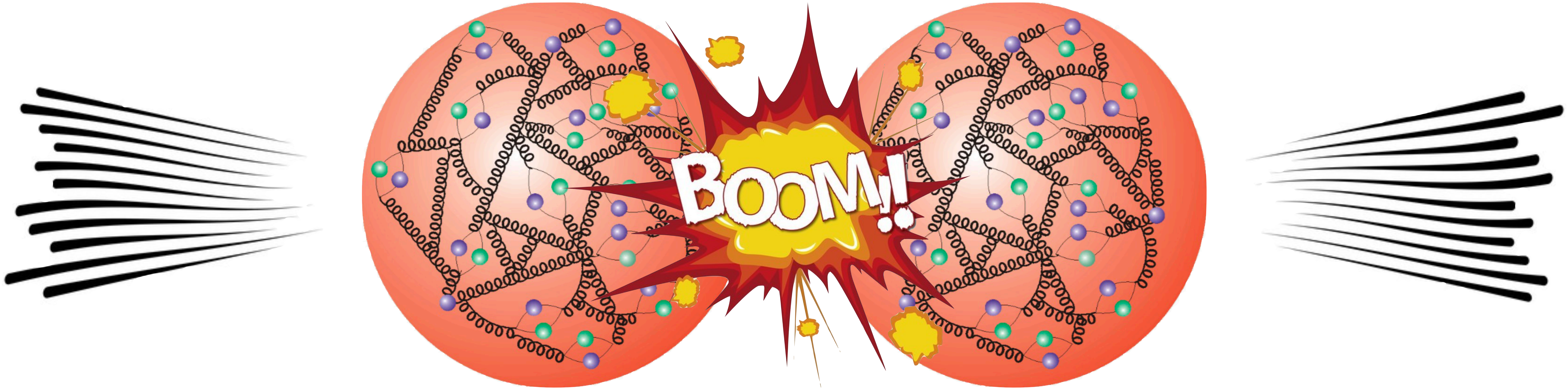
Revisiting the proton

(Slightly) more accurate picture of a proton:



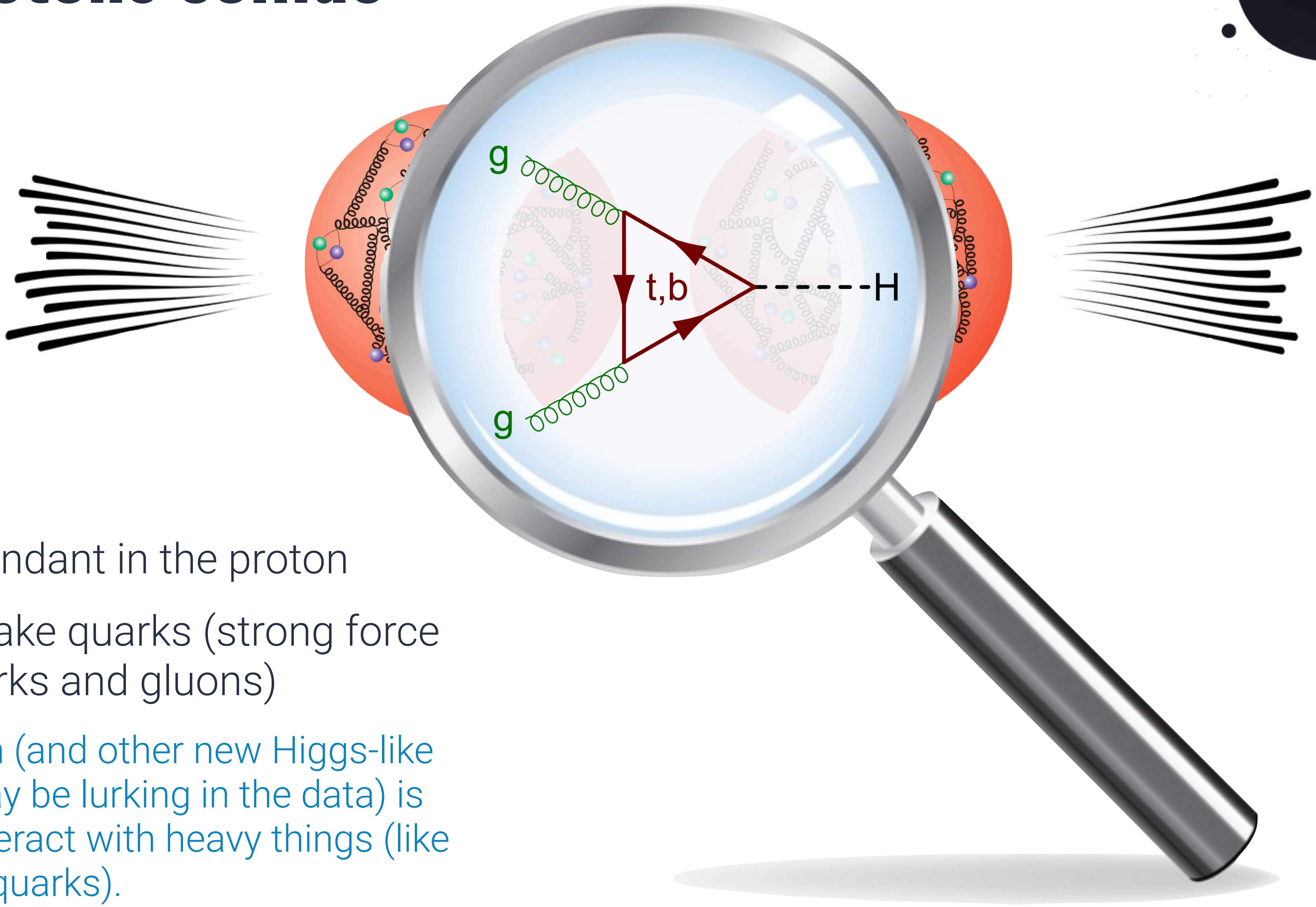
Most of the proton's structure comes from the activity of the gluons, and the fact that virtual quark—anti-quark pairs are popping in and out of existence (thanks to the strong energy field).

When protons collide



The energy carried by all of the quarks and gluons inside the proton can be used to create new heavy particles.

When protons collide



Gluons are abundant in the proton

They love to make quarks (strong force couples to quarks and gluons)

The Higgs boson (and other new Higgs-like particles that may be lurking in the data) is most likely to interact with heavy things (like top and bottom quarks).

Jokes

The bartender says, “We don’t serve tachyons in here.”

A tachyon walks into a bar.

A bar walks into a man… oops, wrong reference frame.

A neutrino walks through a bar.

What did one photon say to the other photon?

"I’m sick and tired of your interference."

What is blue and smells like red paint?

Red paint moving very fast towards you.

Schrodinger and Heisenberg were out driving together when they were pulled over by a policeman.

The policeman walks up to the window and asks, “Sir, do you know how fast you were going?”

Heisenberg replies, “No, but I know exactly where I was.”

The policeman is unamused and orders the physicists to open their car boot. He looks in and sees a dead cat.

“Do you know there is a dead cat in your trunk?”

Schrodinger replies, “Well, I do now!”