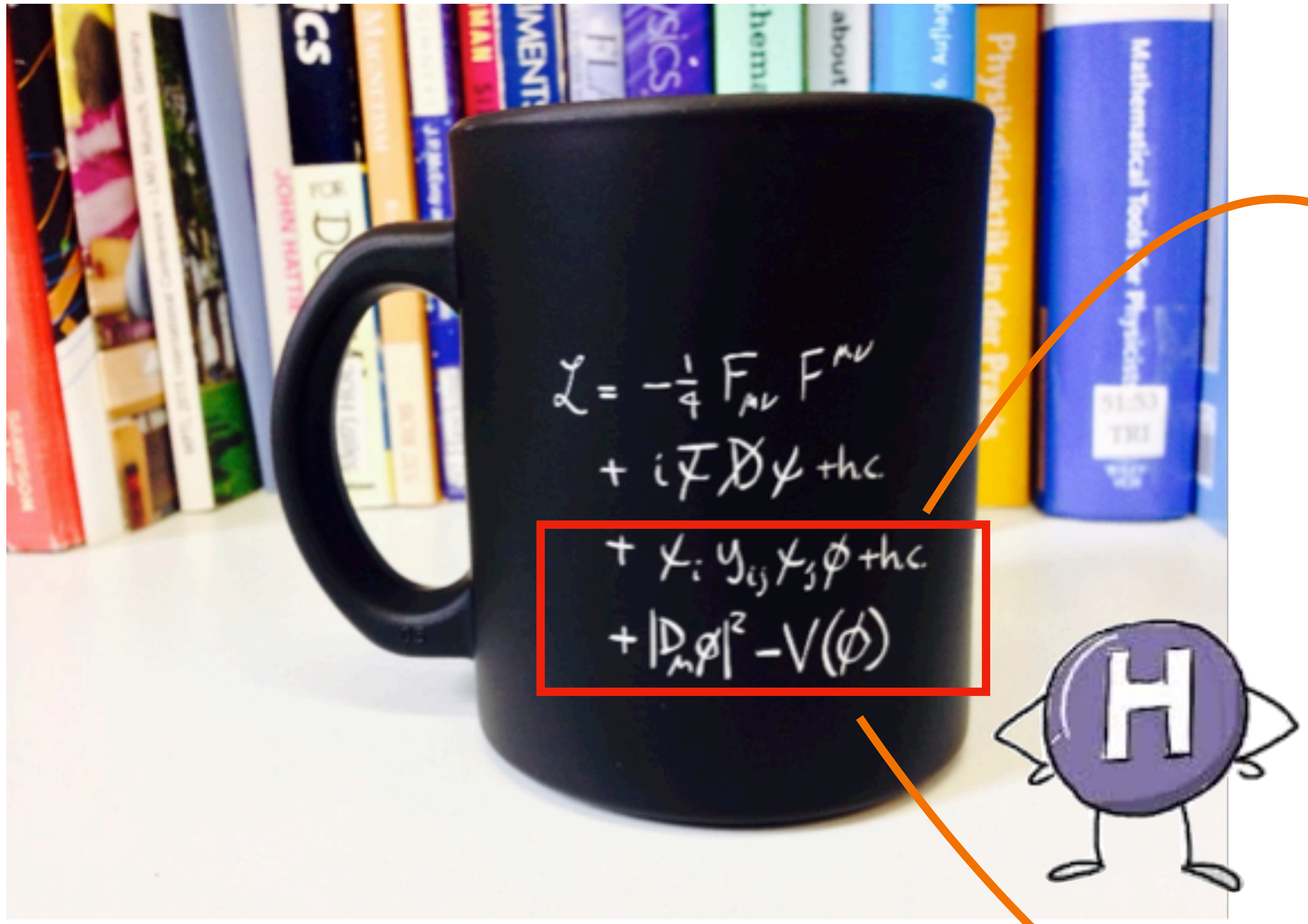
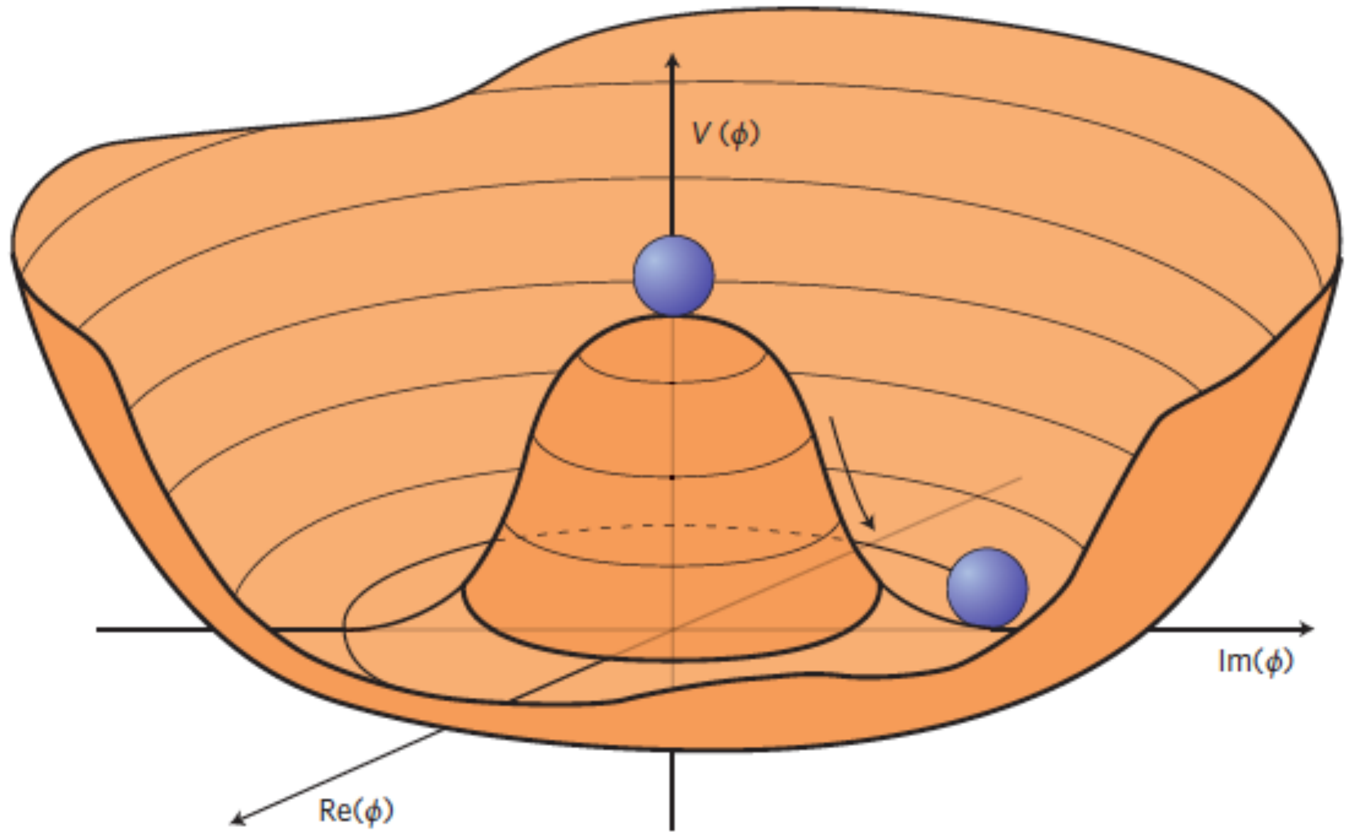
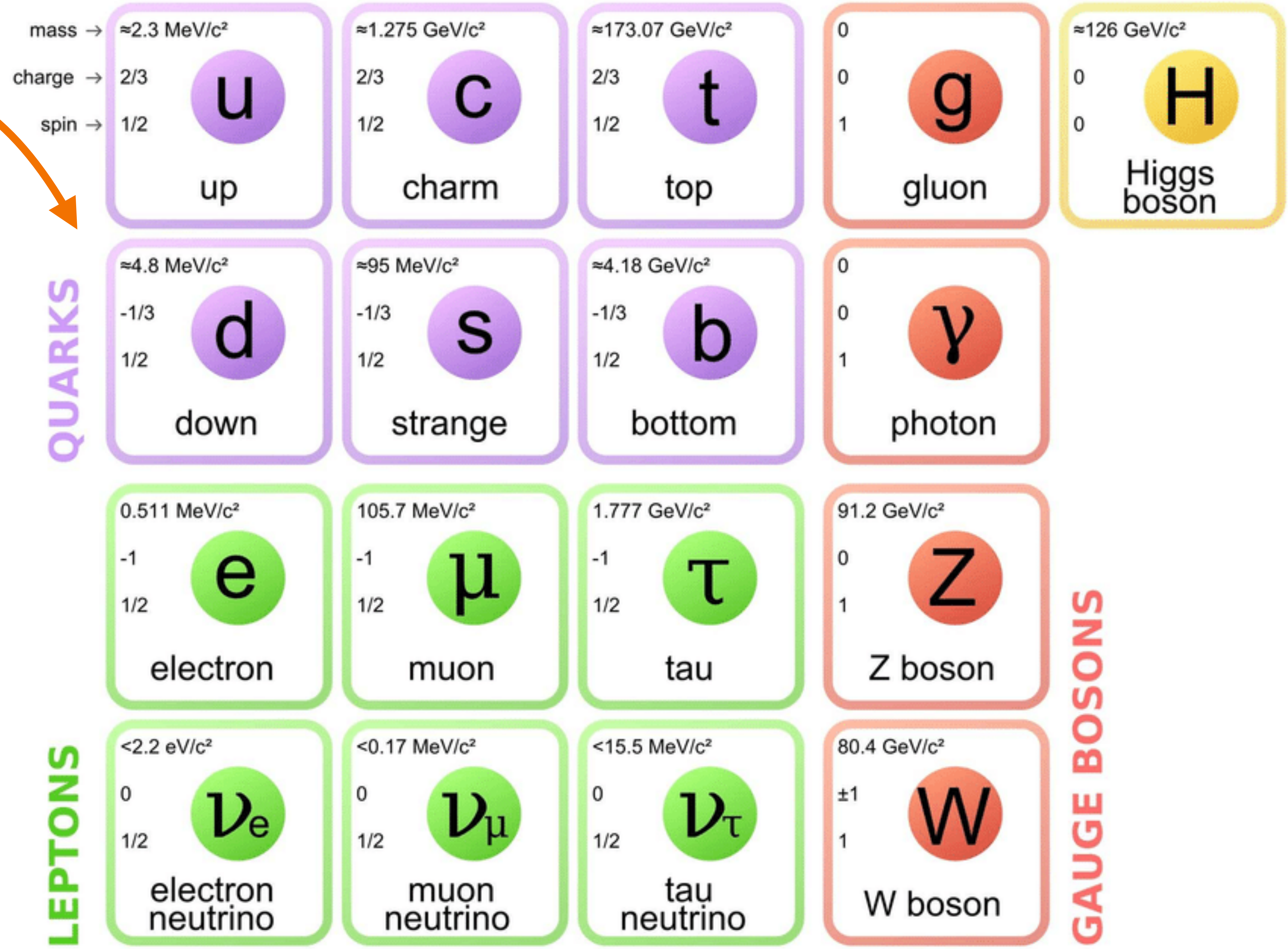
# The Higgs boson at the LHC: a journey to precision

**A. de Wit, 18.01.2024**

# The Higgs boson




**Mass! We wouldn't be here without H**

# The road to the Higgs boson discovery

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

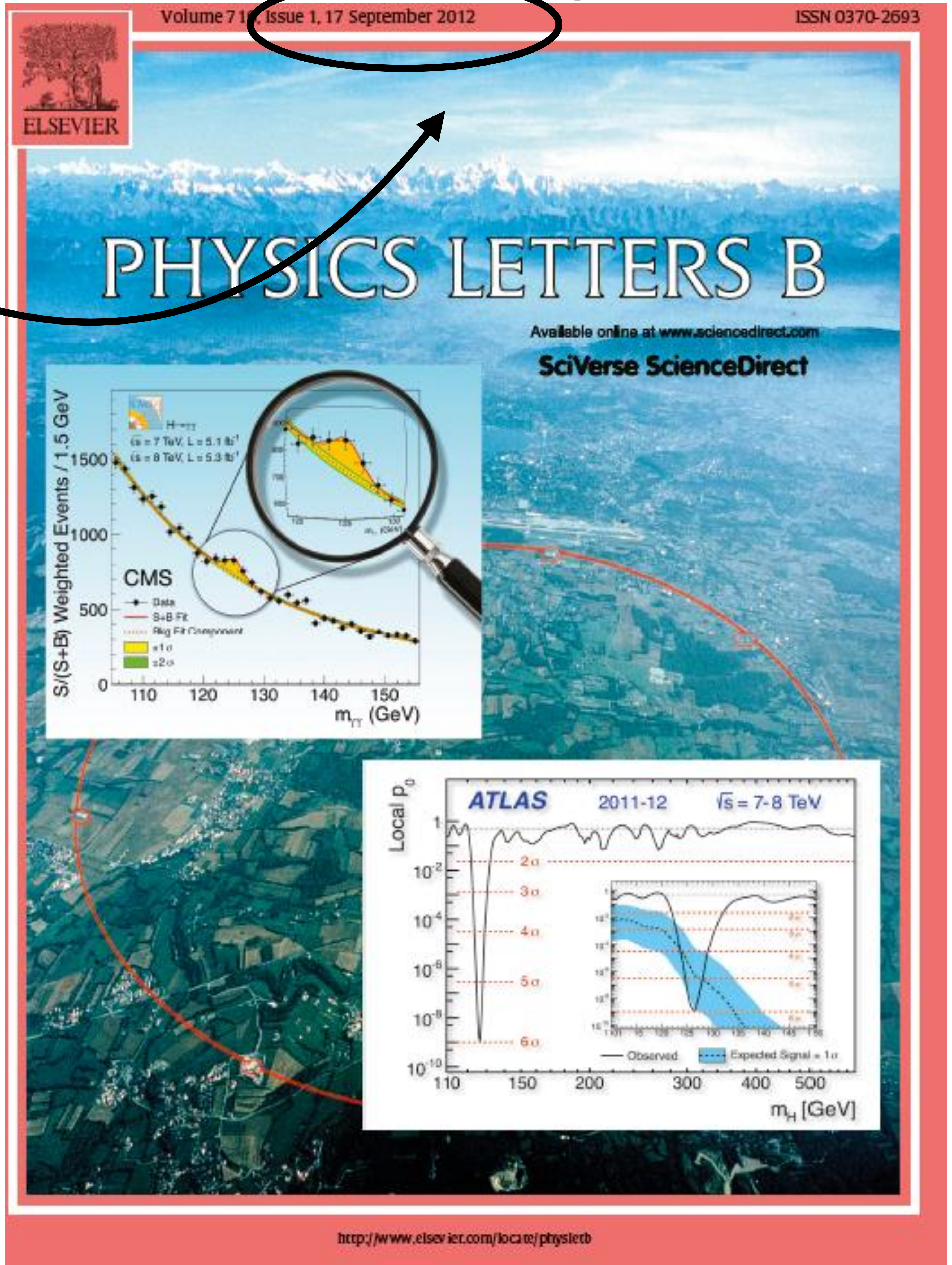
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

**48 years!**



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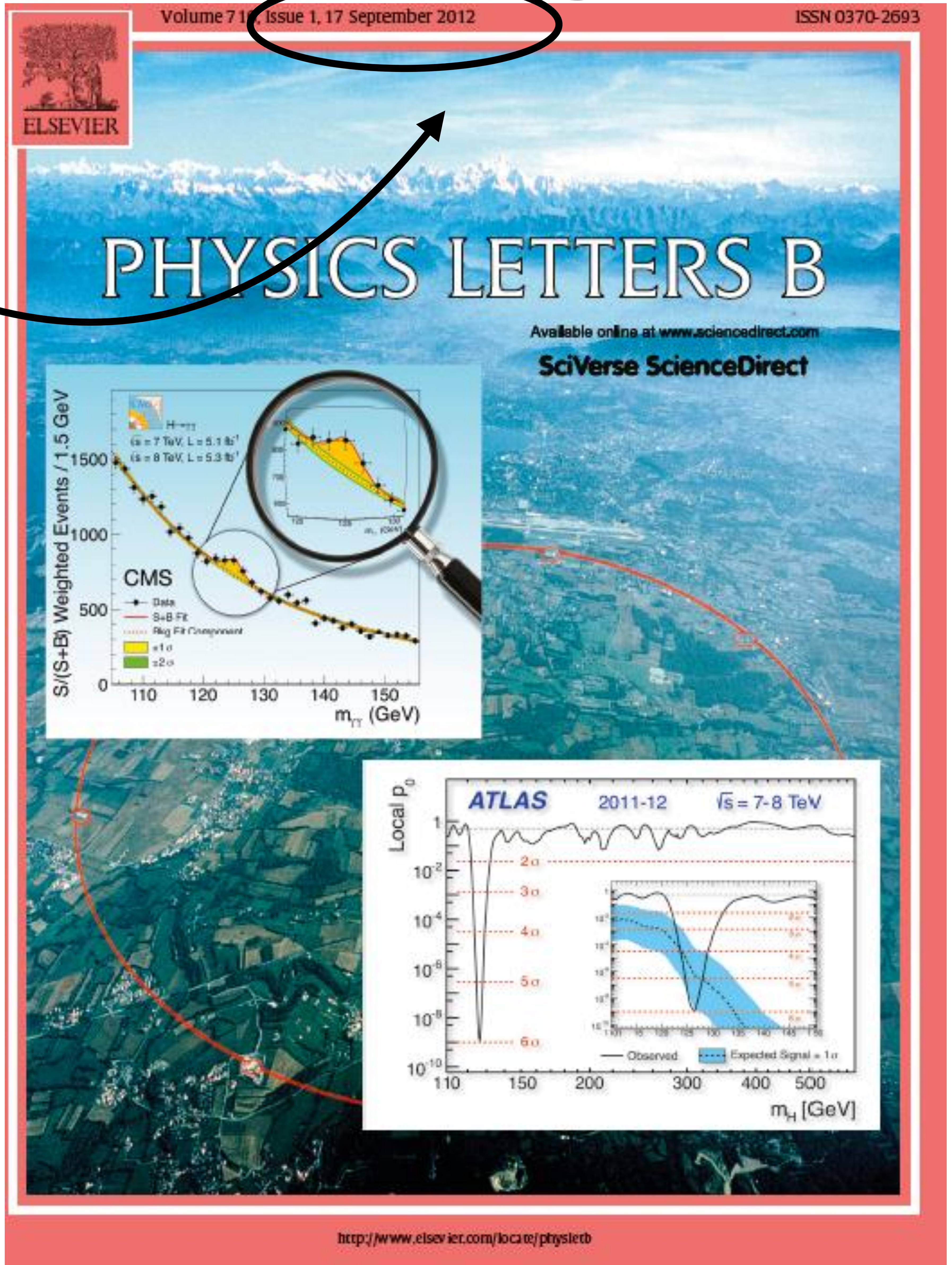


**Compare:**
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1947 Charged pion discovered

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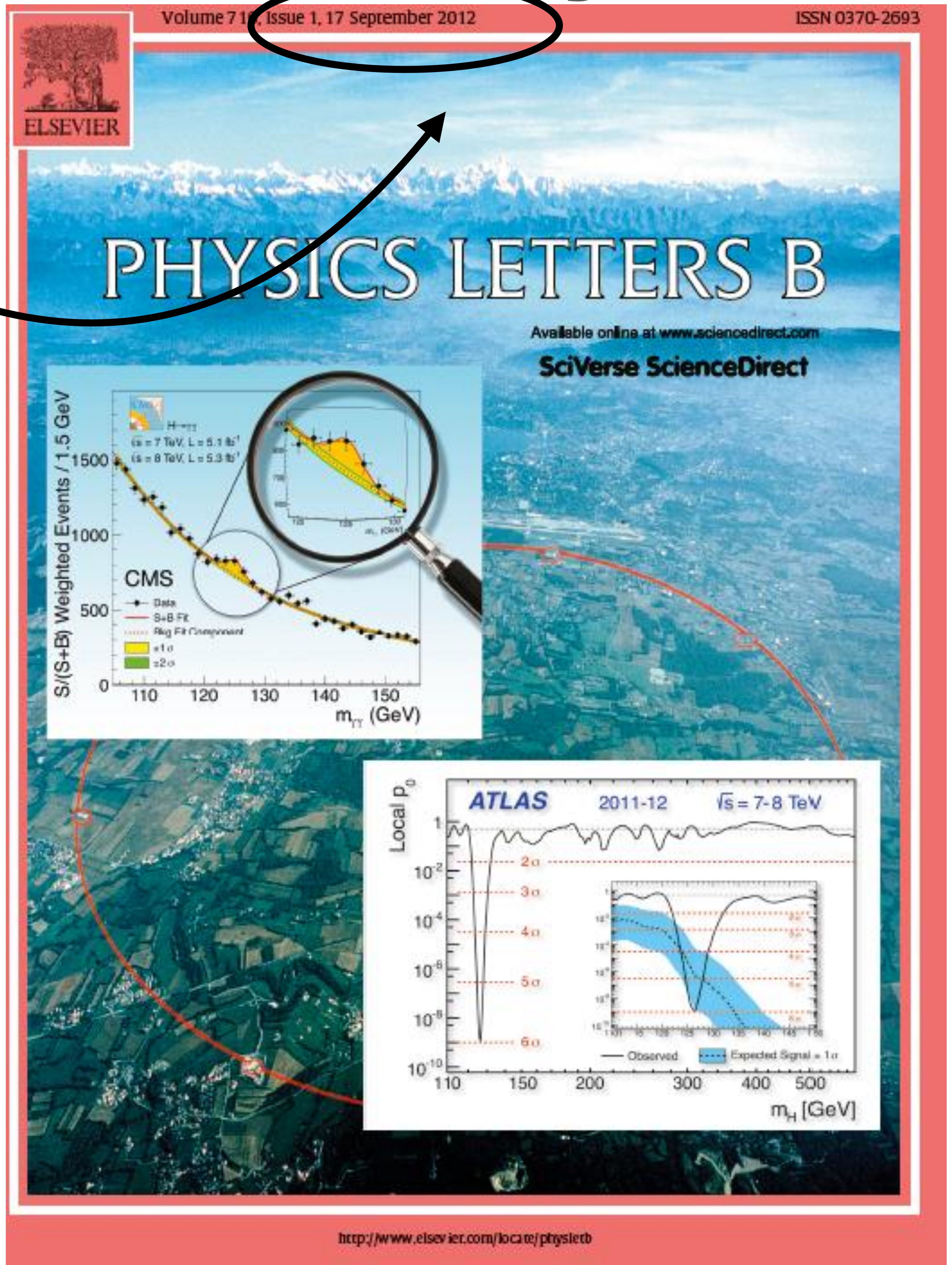


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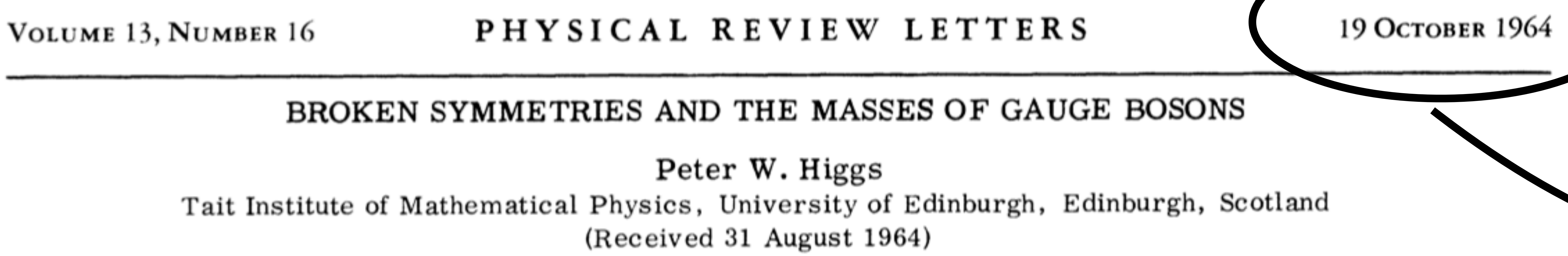
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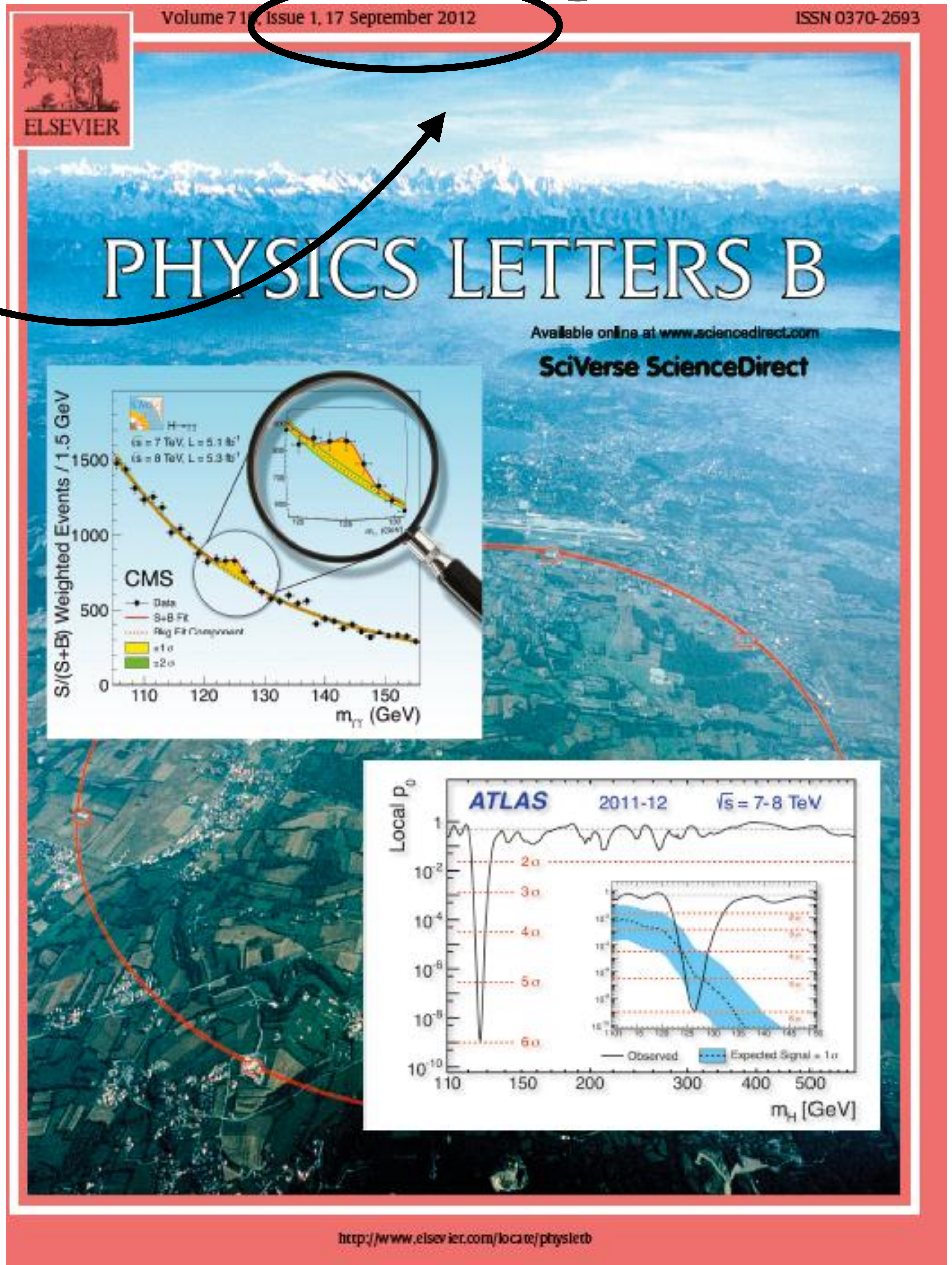


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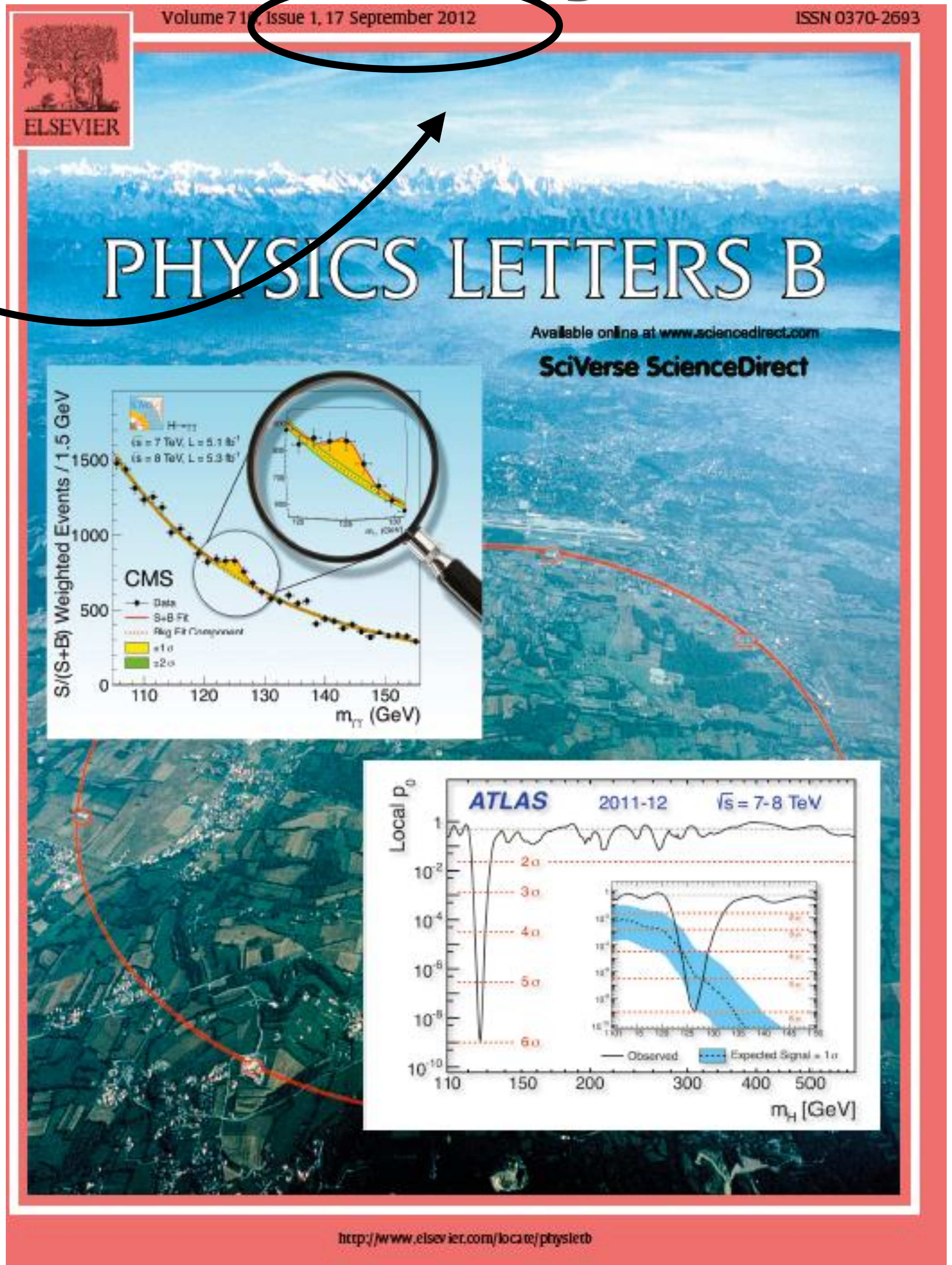


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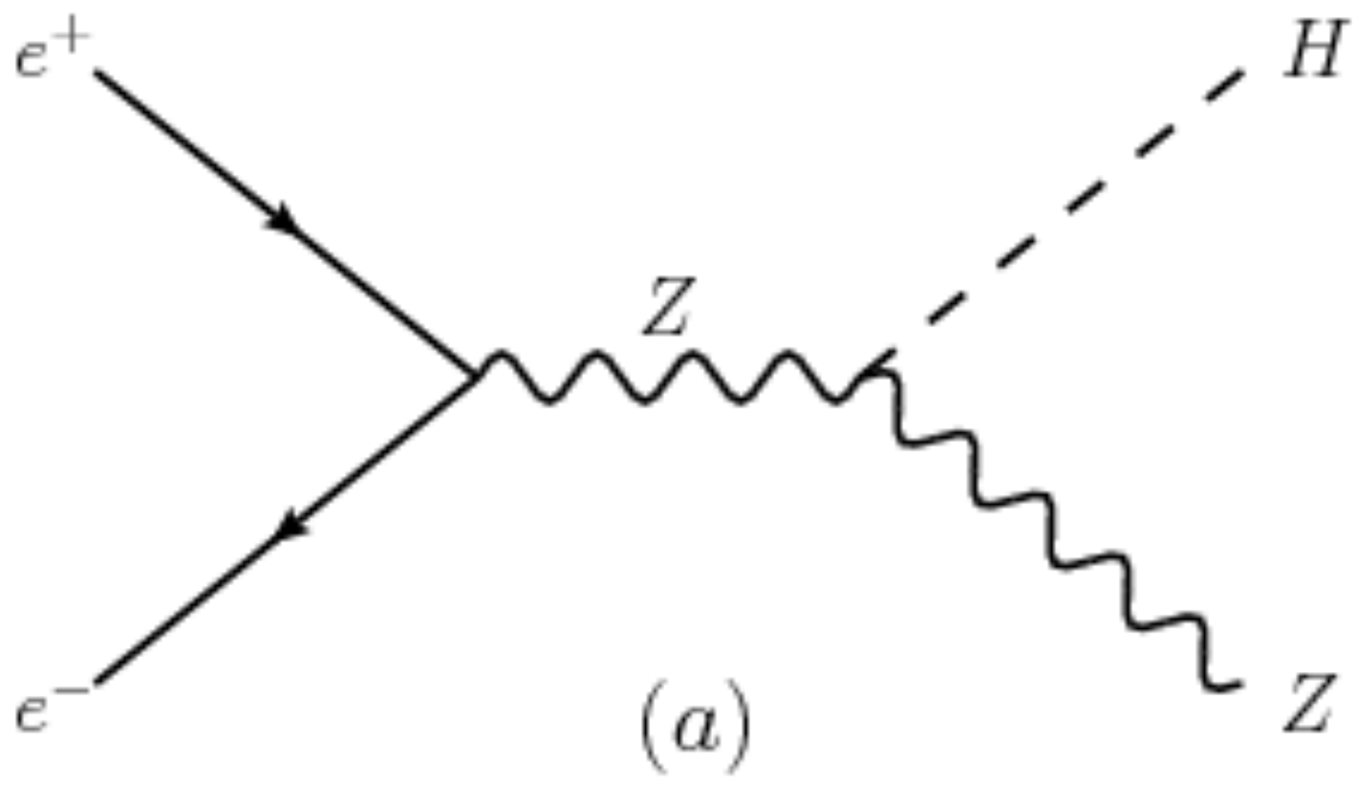
$\frac{1}{2} t_{\text{H Discovery}}$

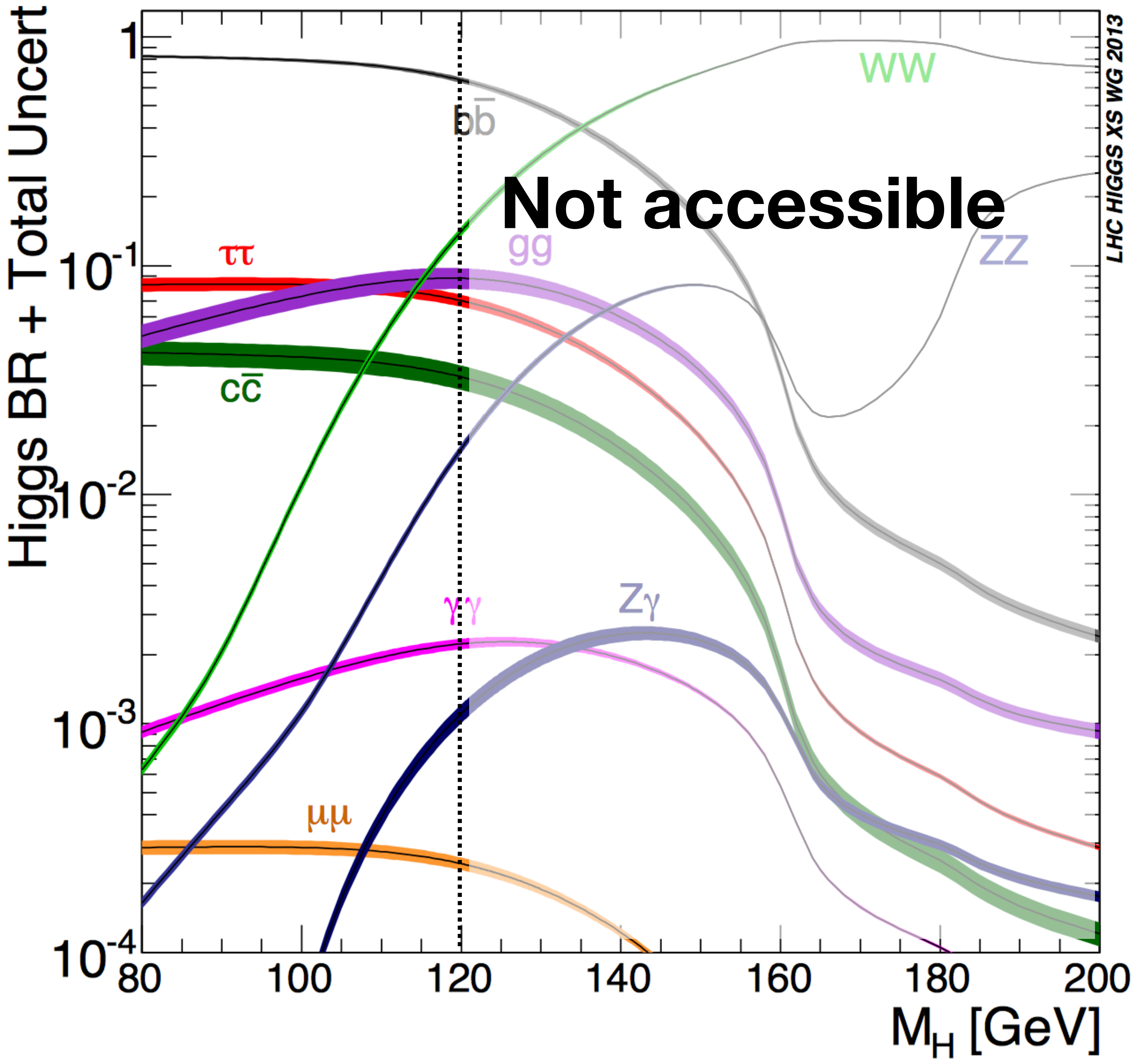
Phys.Lett.B565:61-75,2003

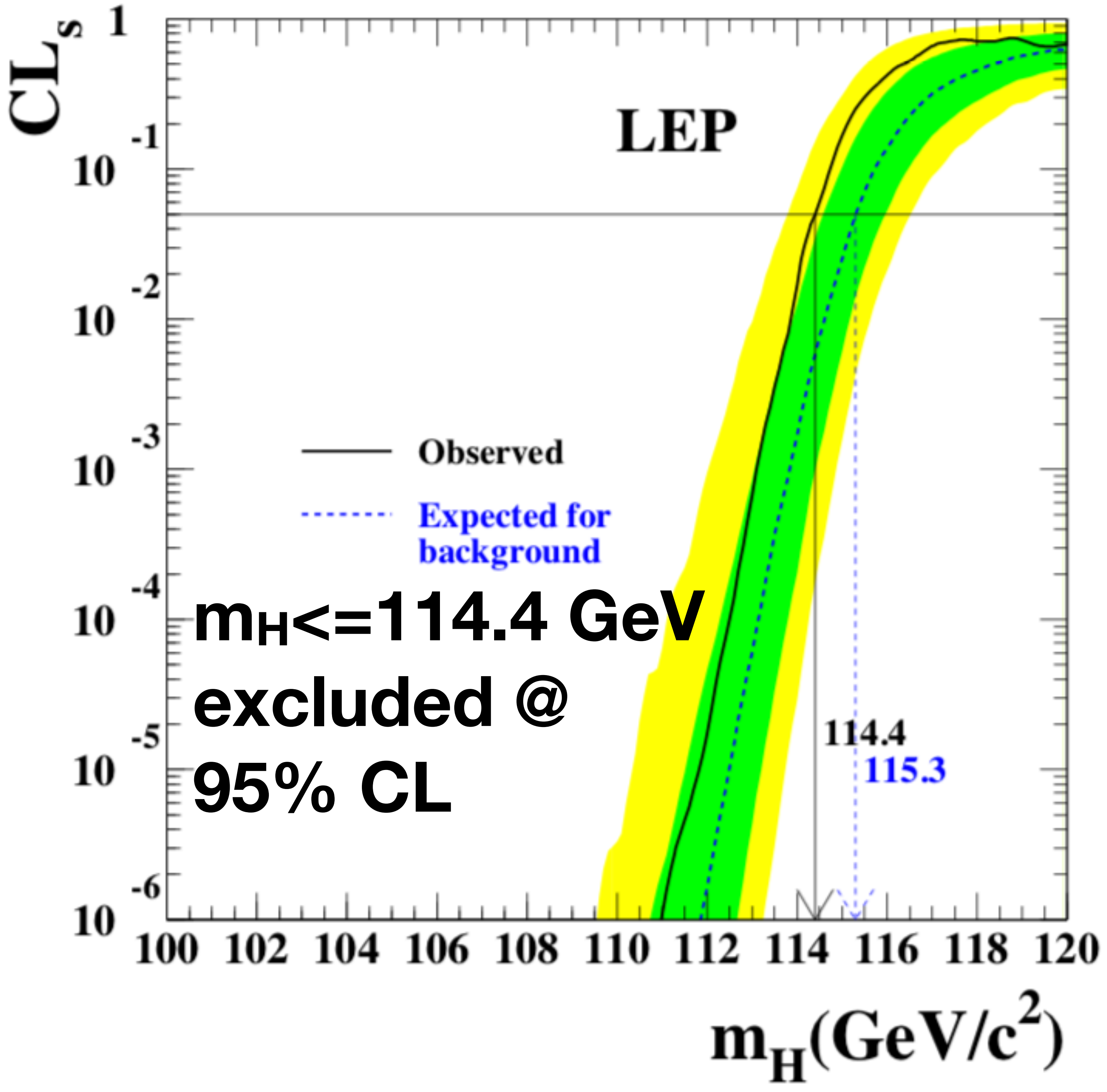
# Higgs searches at LEP

- LEP: e+e- collider ➔ main Higgs boson production mode: ZH




- Collisions at centre-of-mass energies of 189-209 GeV

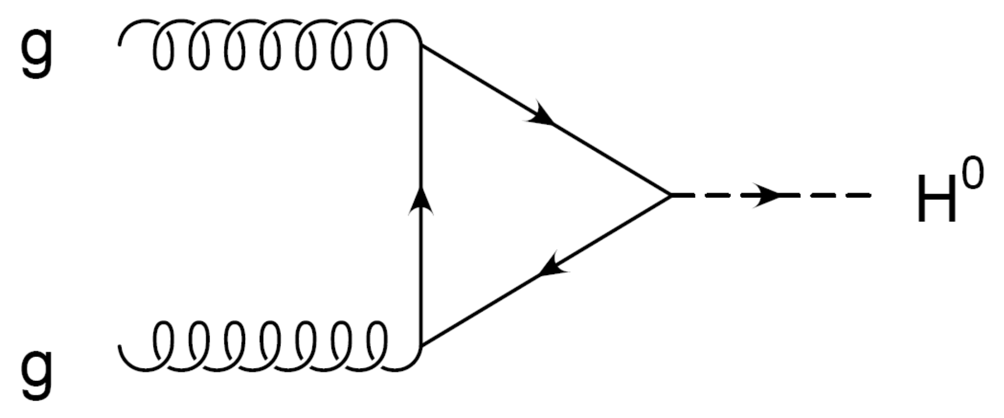


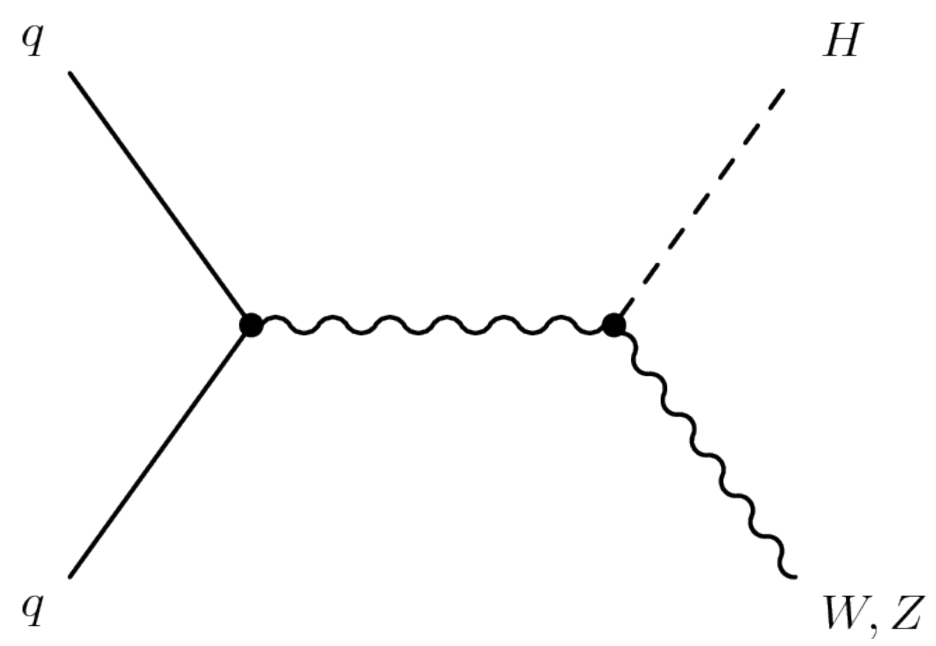



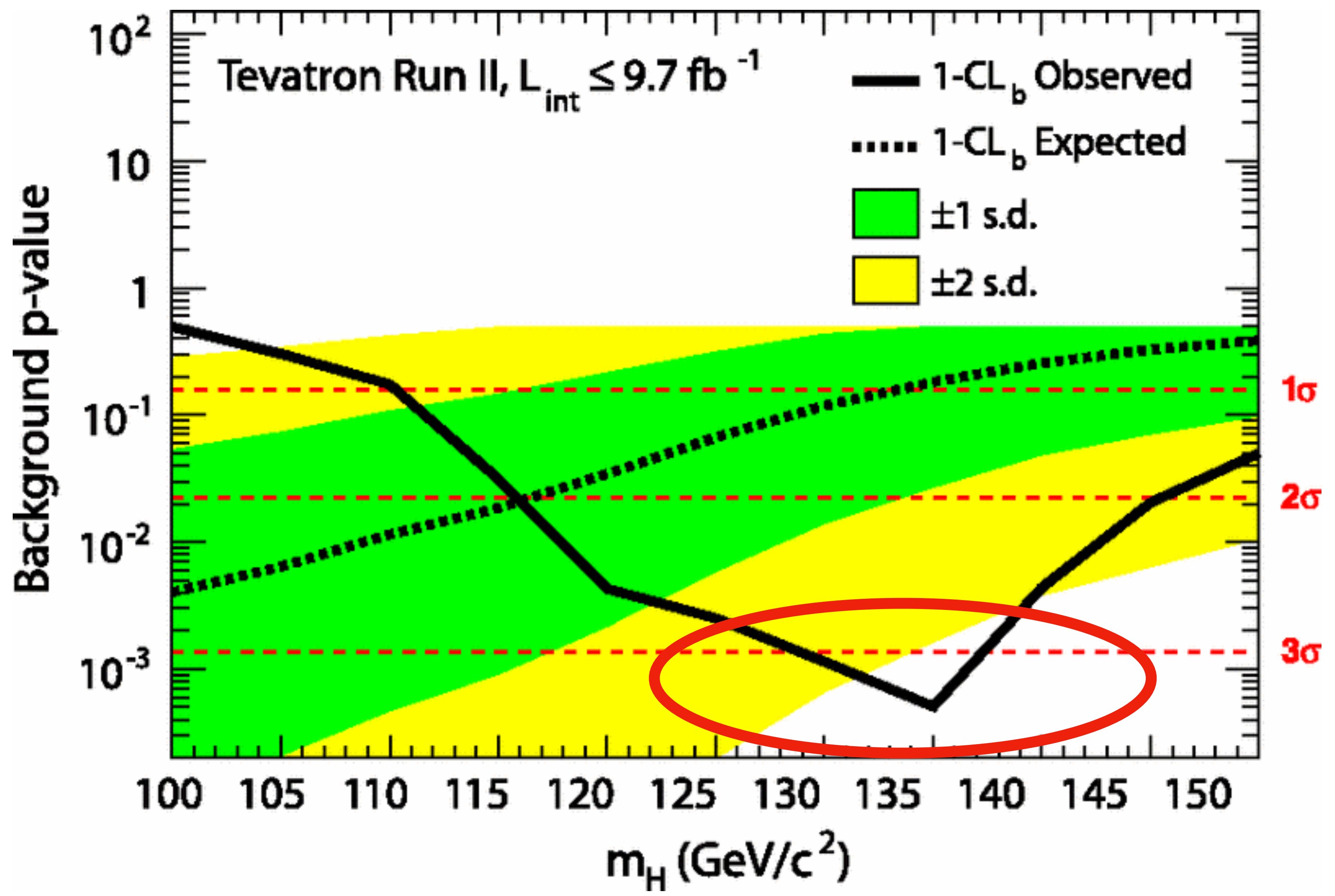
Phys. Rev. Lett. 109, 071804

# Higgs searches at Tevatron

- Tevatron: ppbar collider. Main production mode: **gluon-gluon fusion**
- Experimental sensitivity of CDF and D∅ dominated by VH, H➔bb
- Evidence for H production, July 2nd 2012

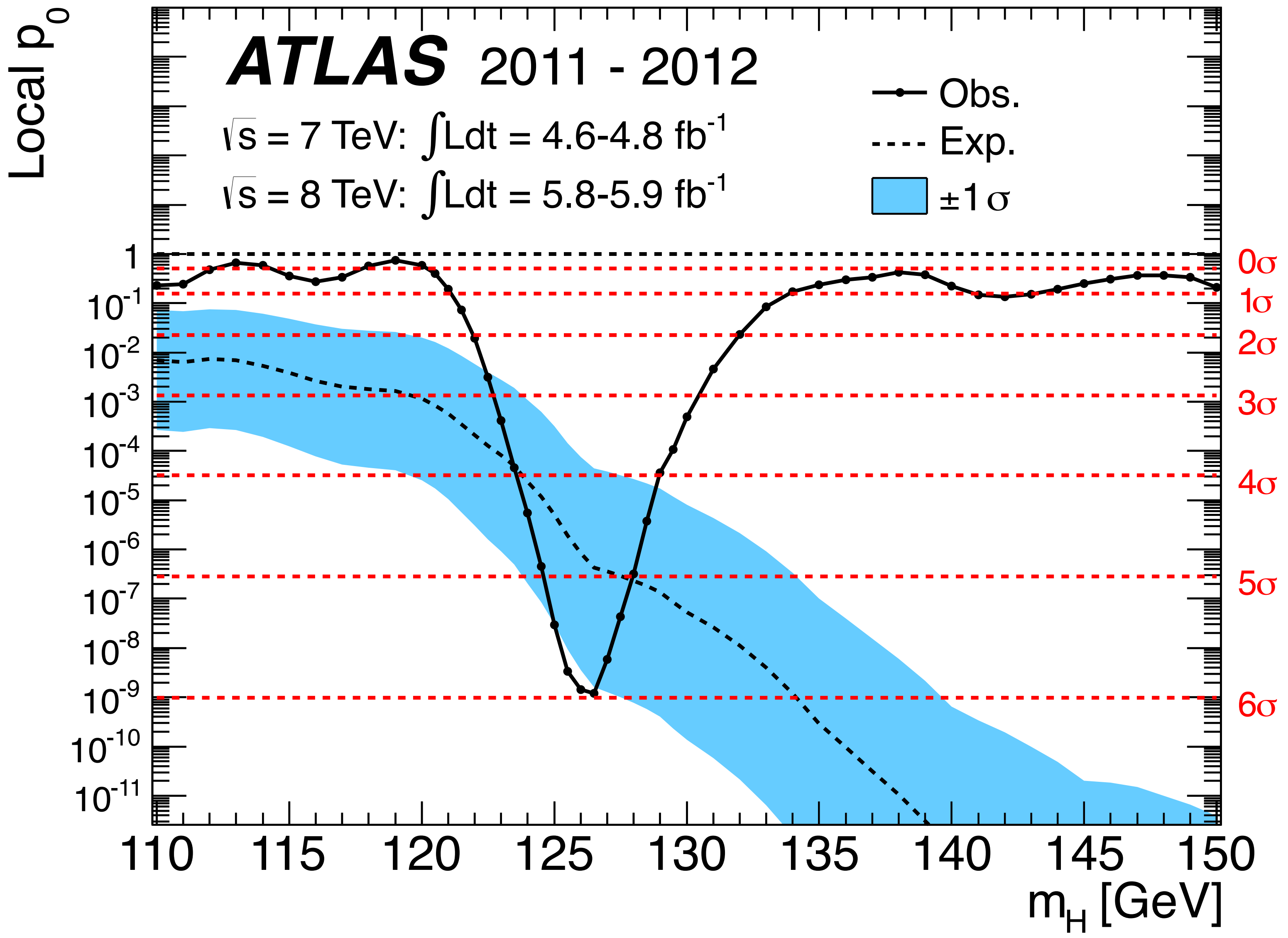


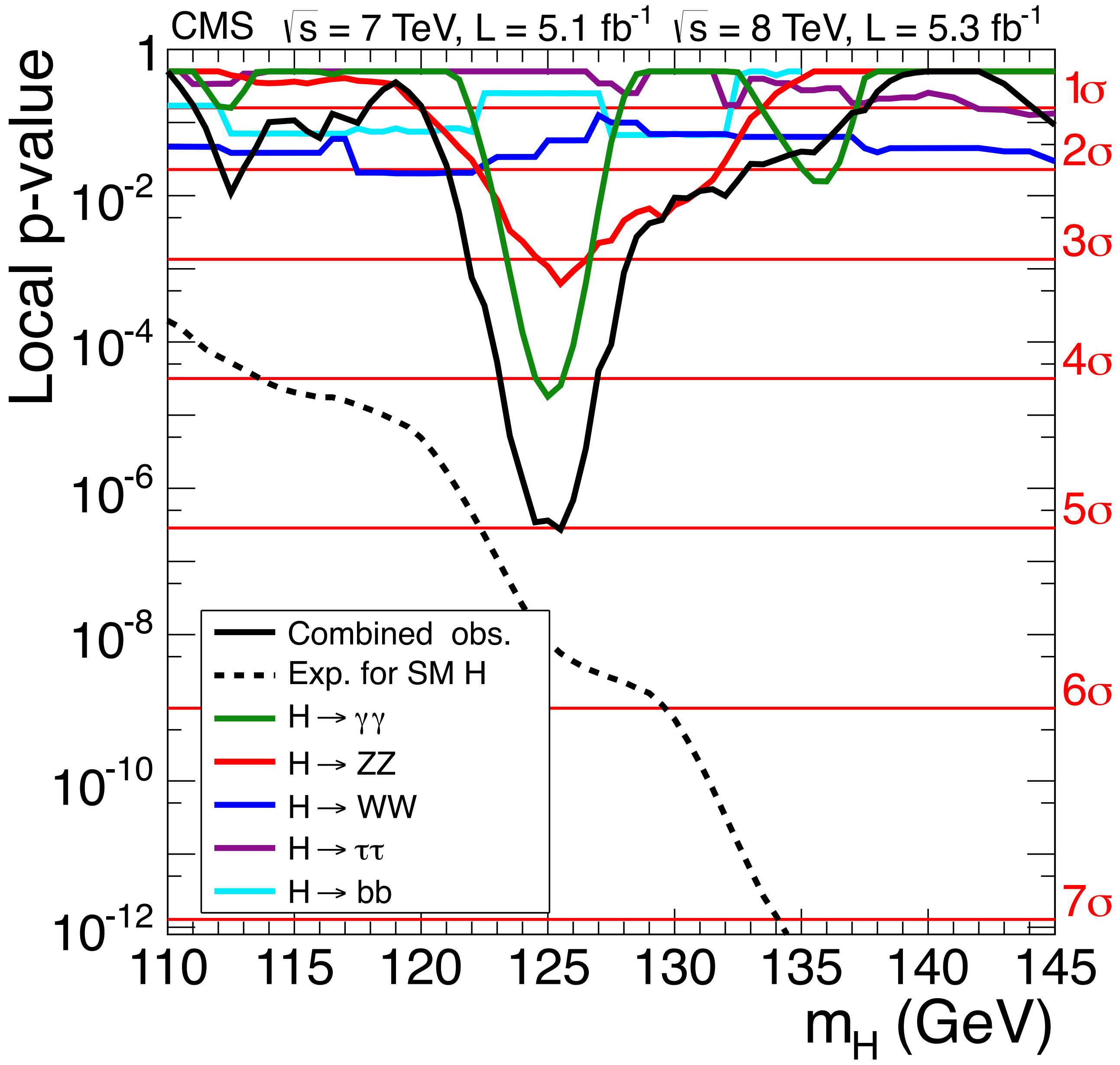



Phys. Lett. B716 (2012) 1
Phys. Lett. B716 (2012) 30

# The Higgs boson discovery



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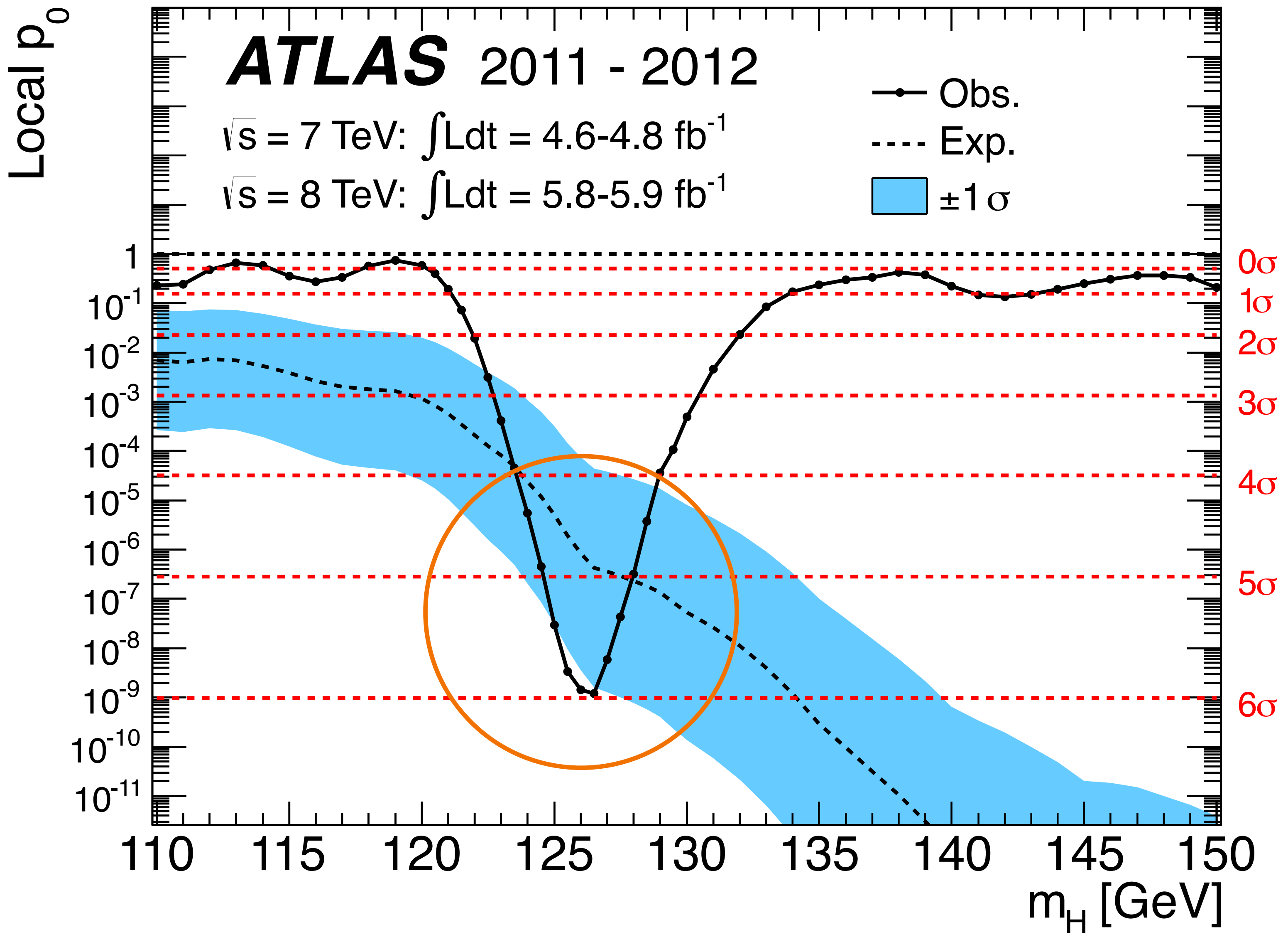


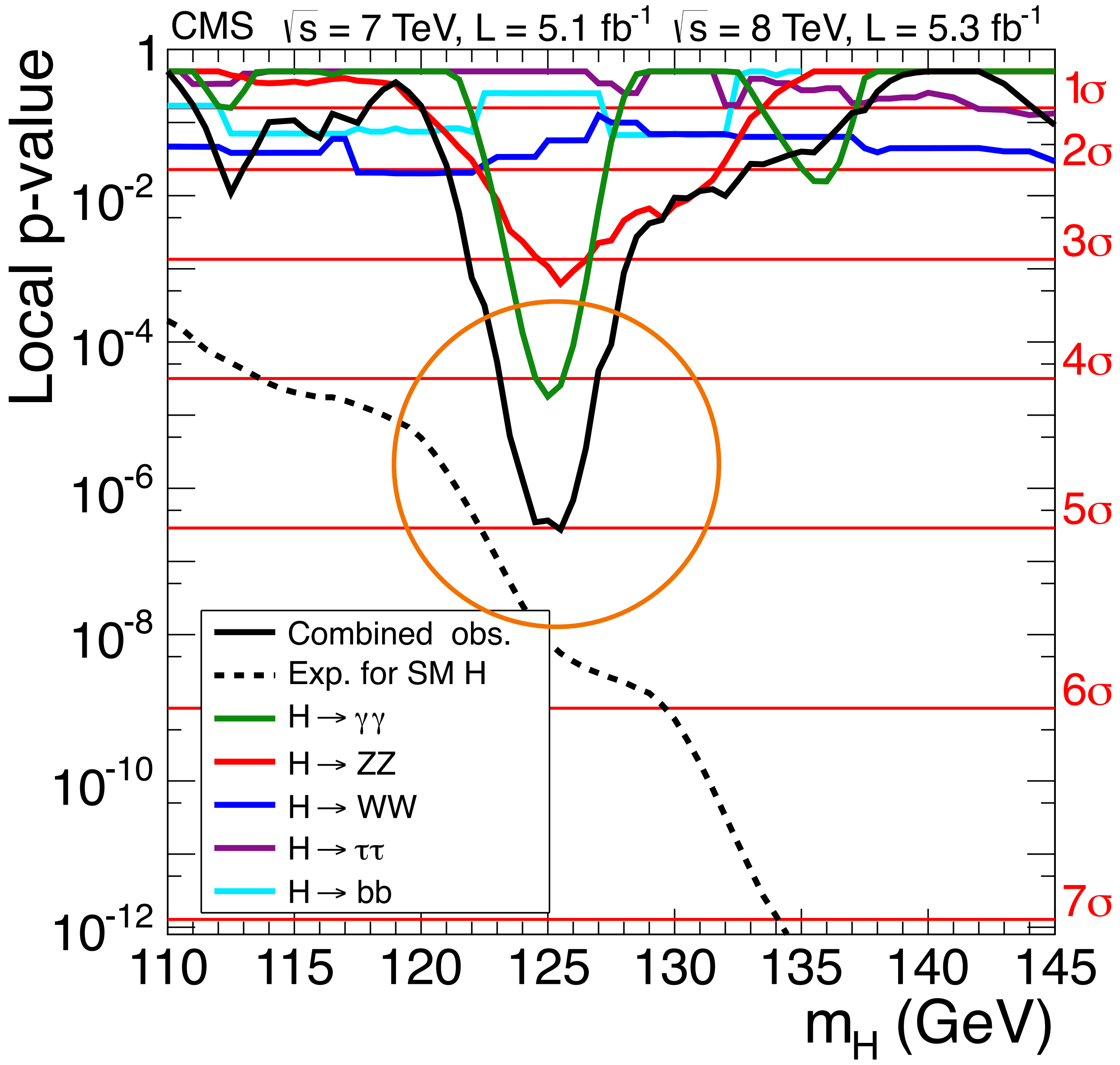

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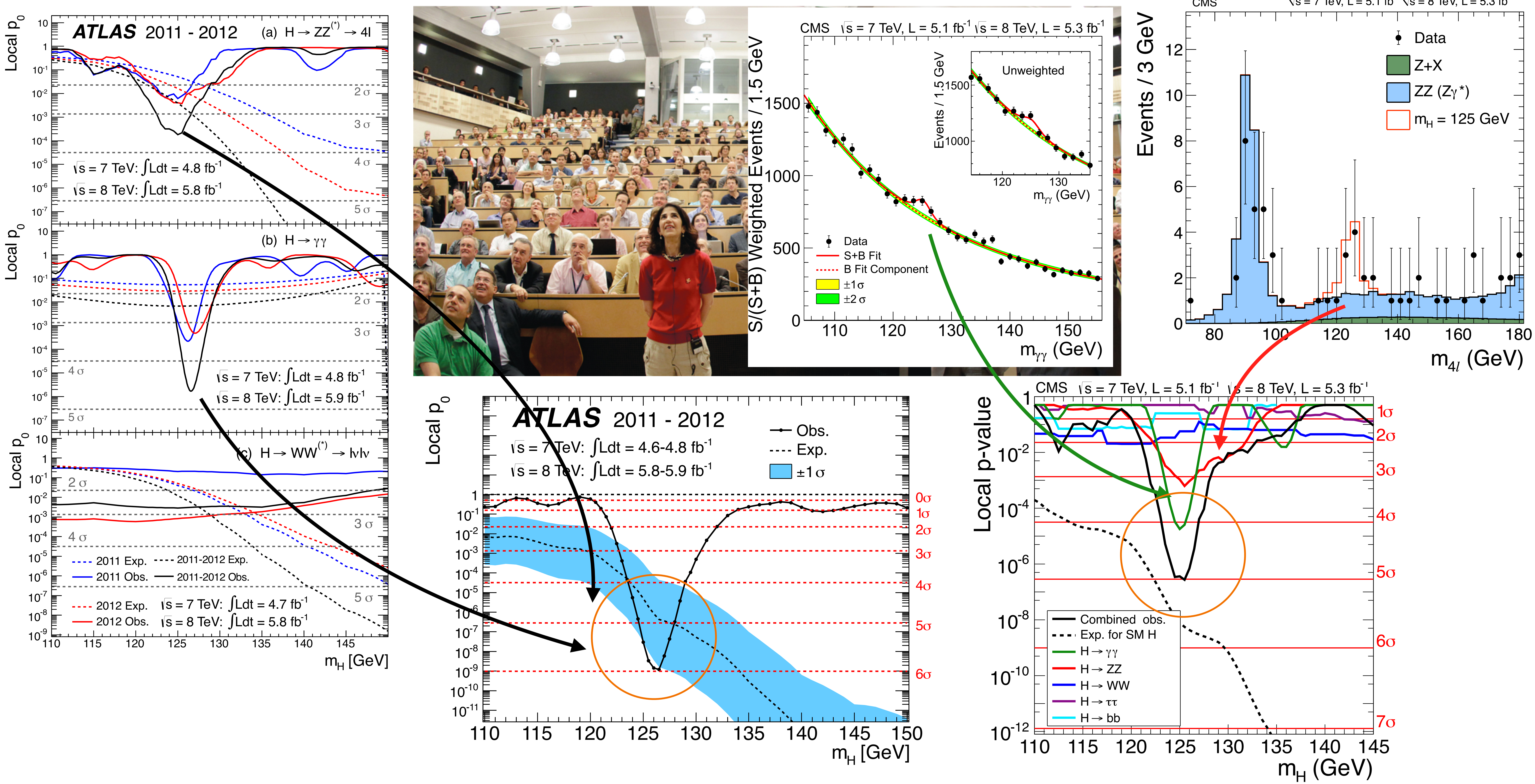

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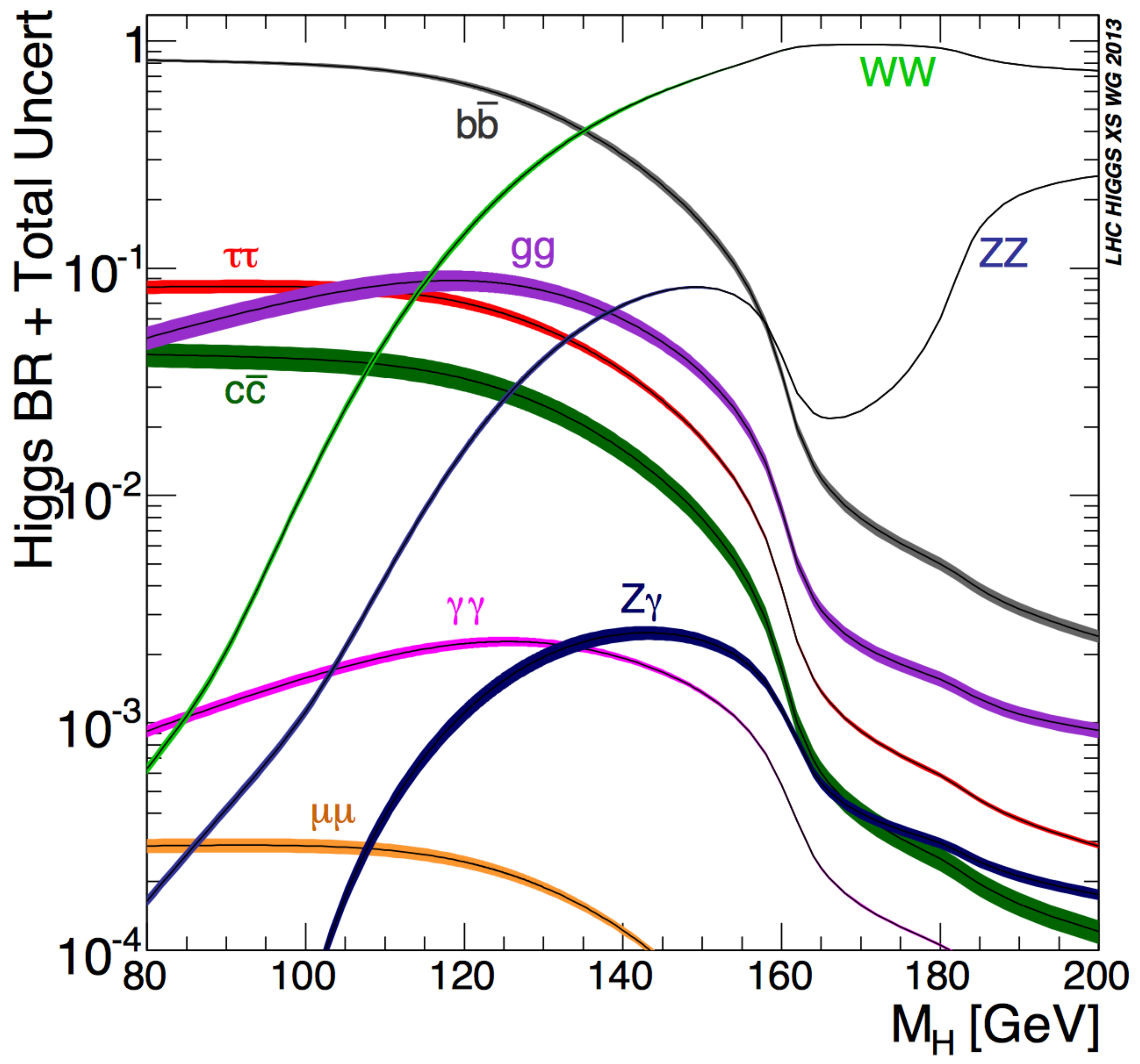

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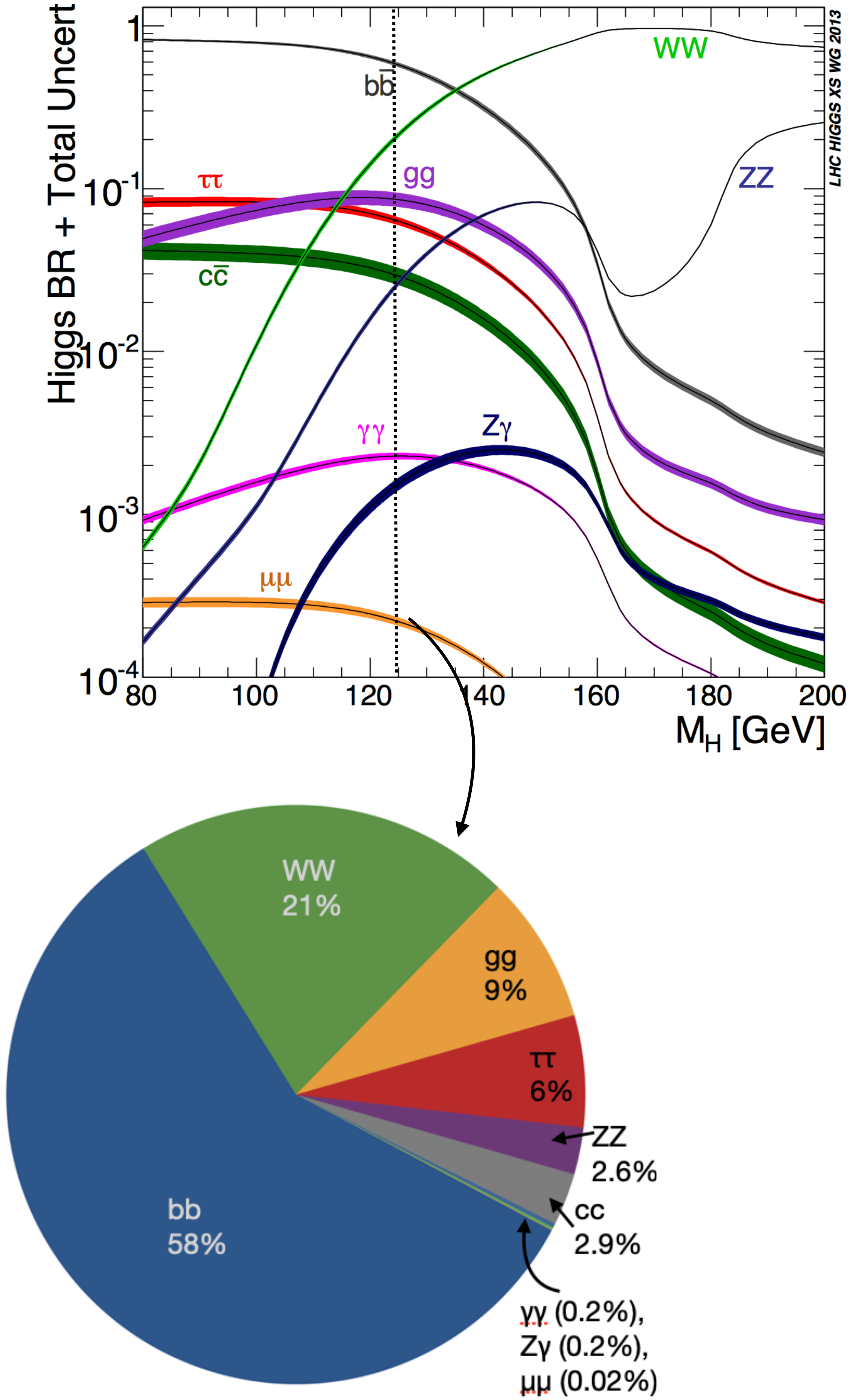

JHEP 08 (2016) 045

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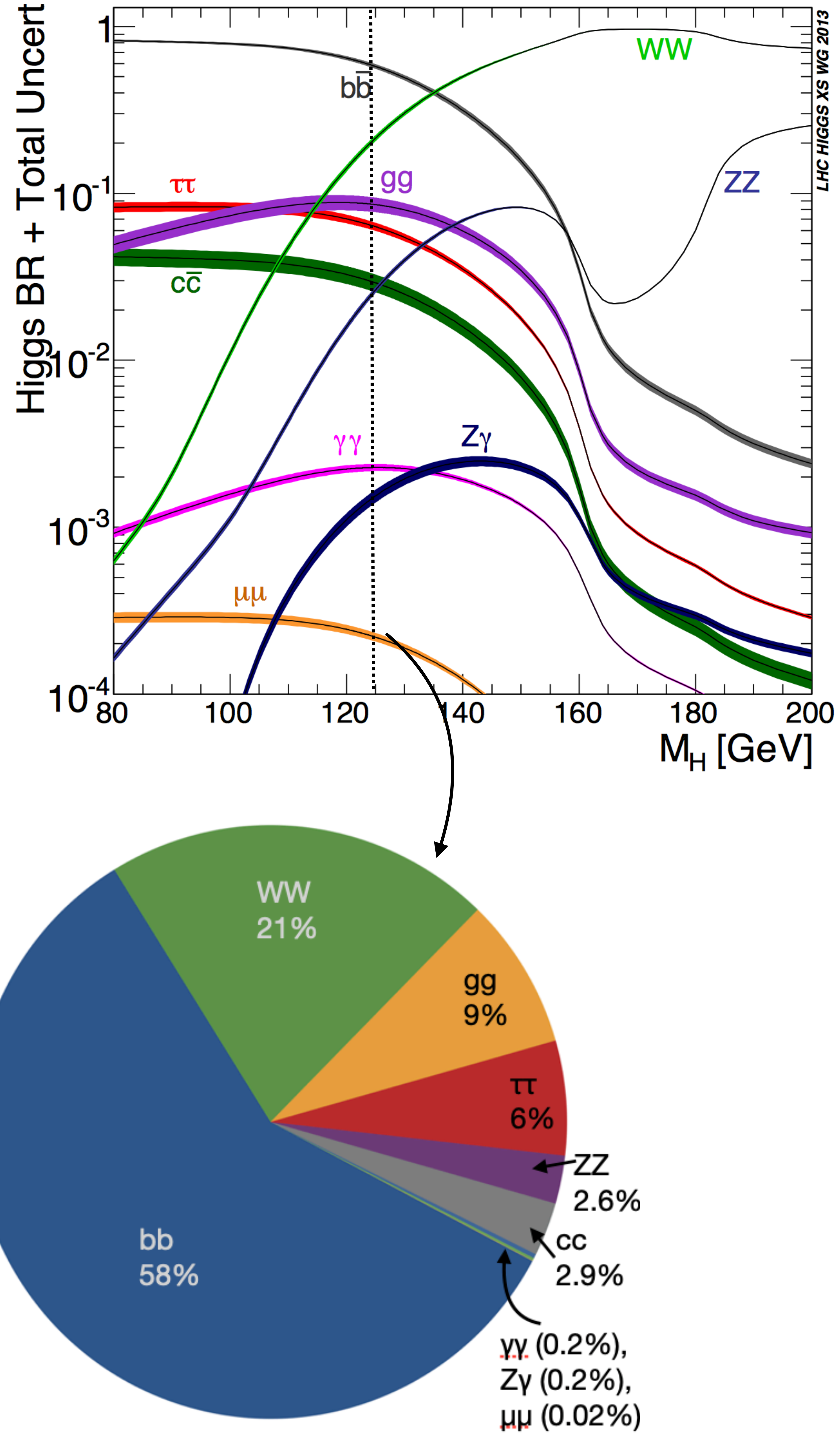


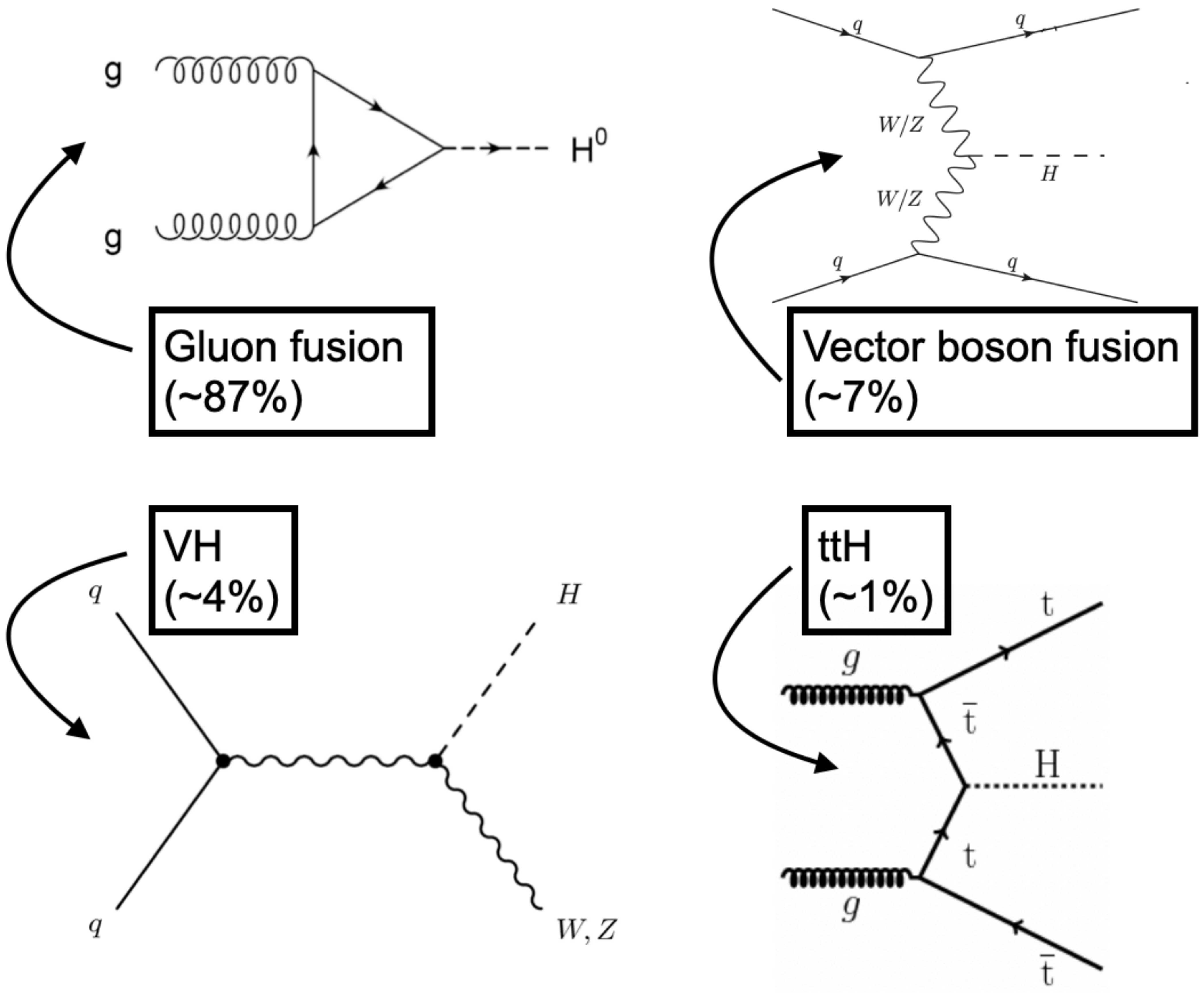

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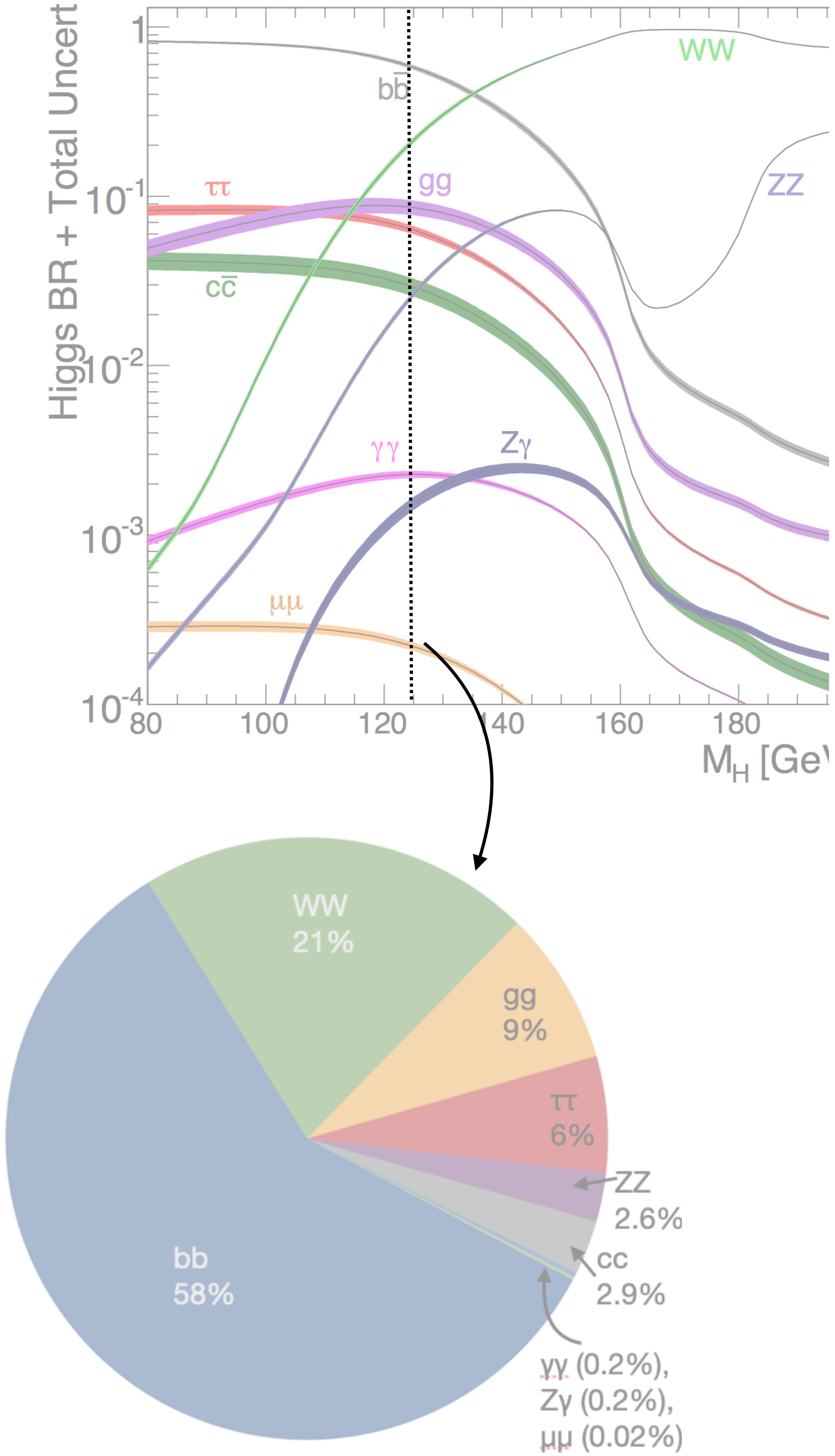


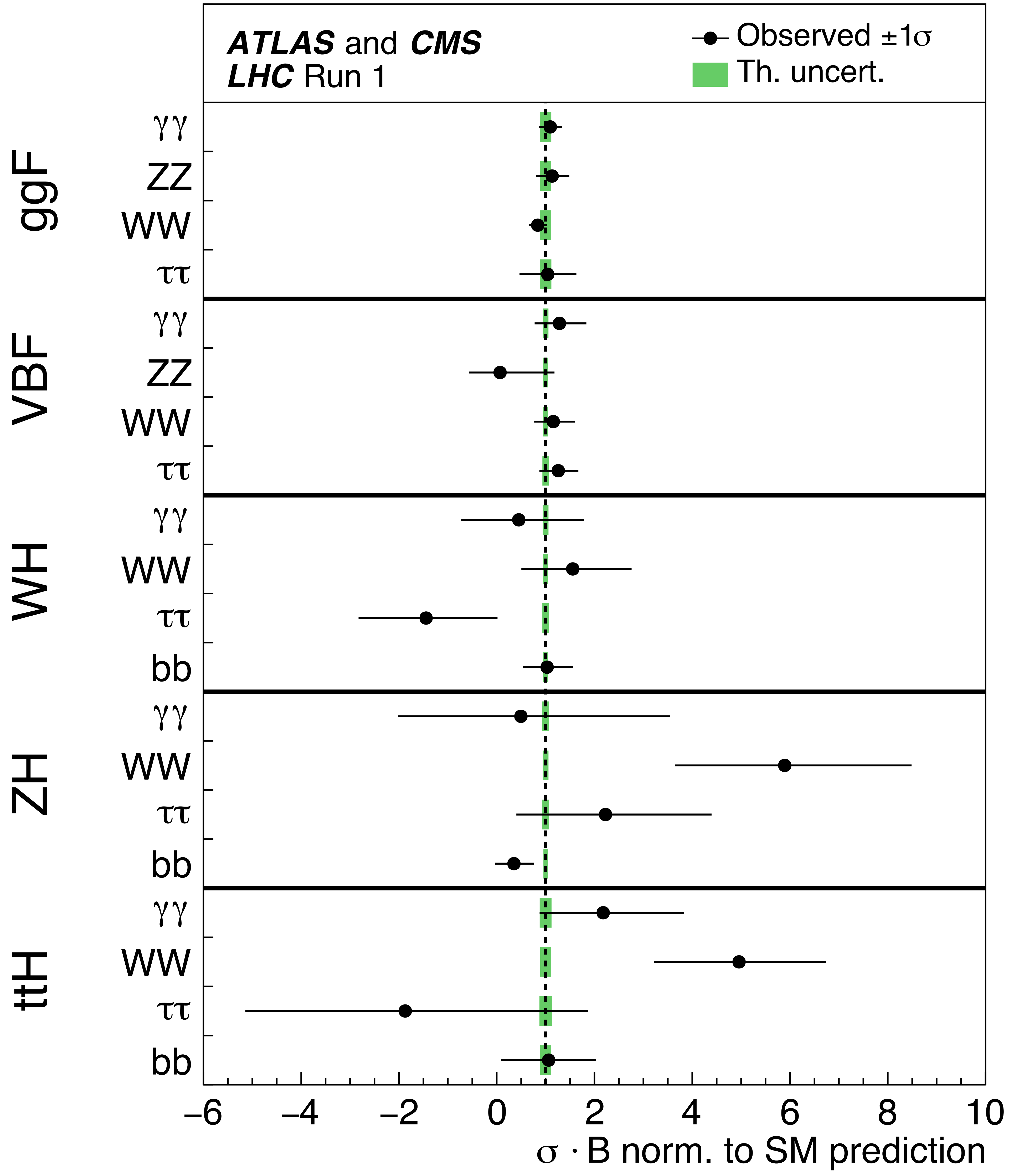

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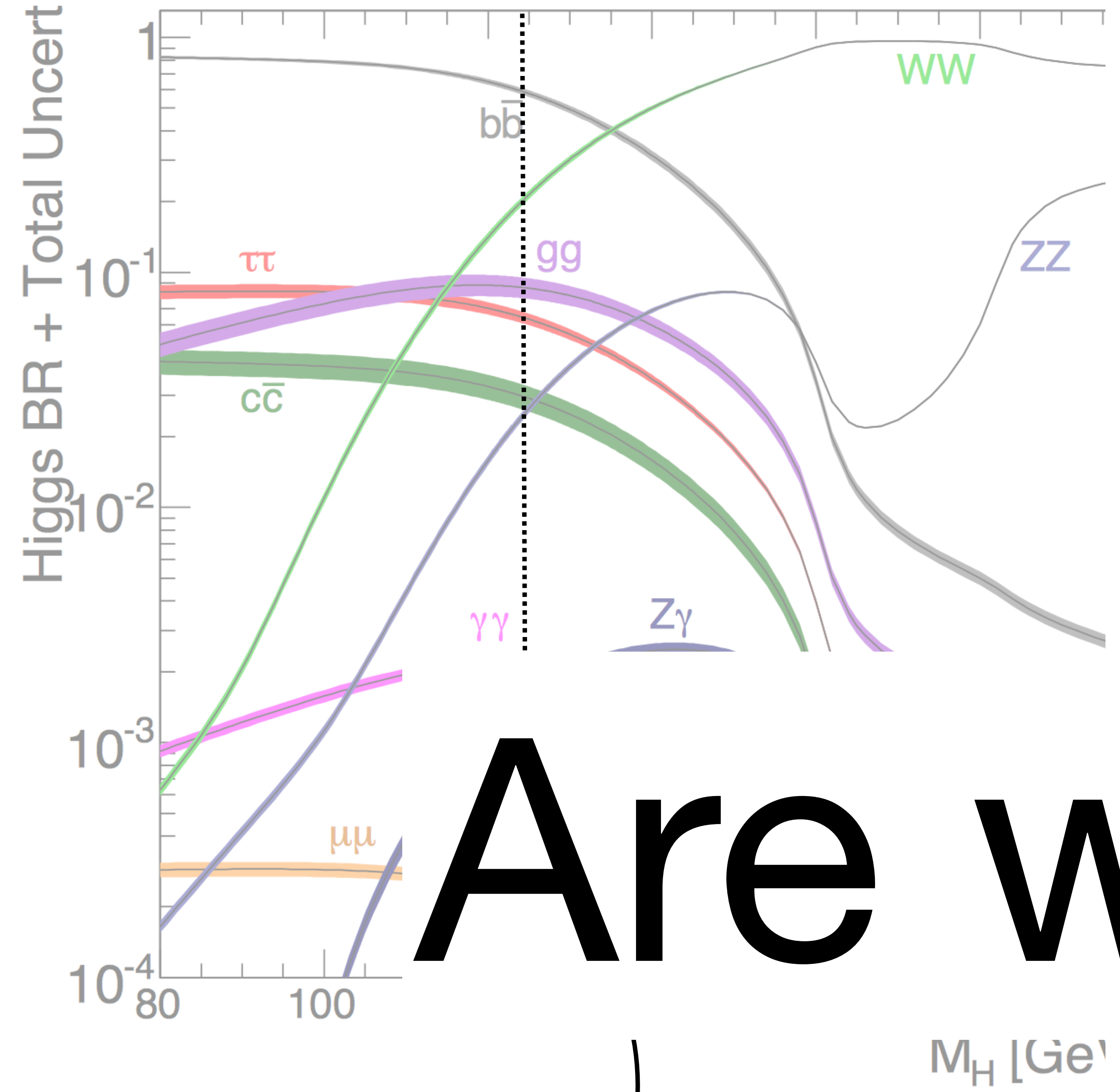


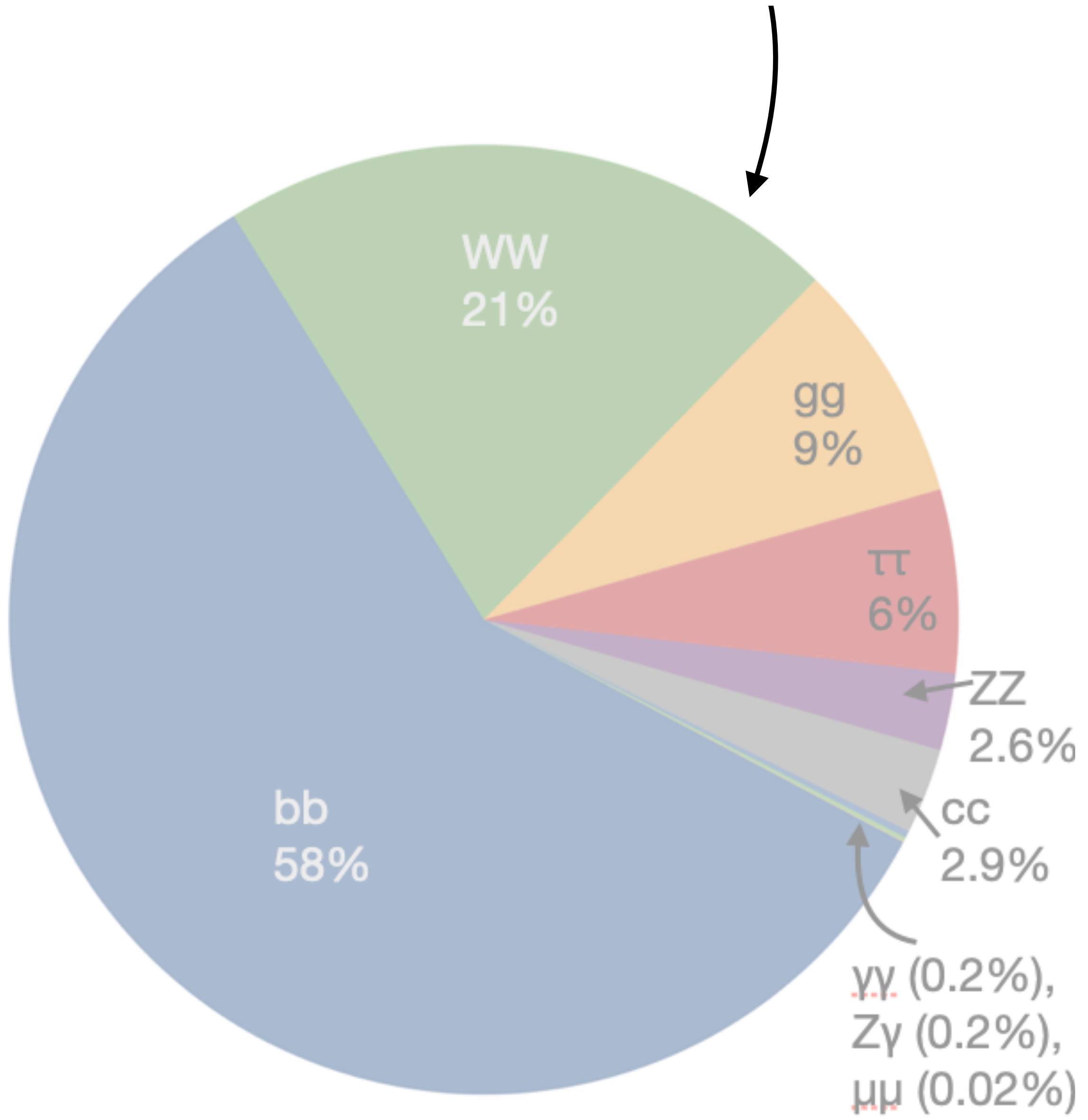


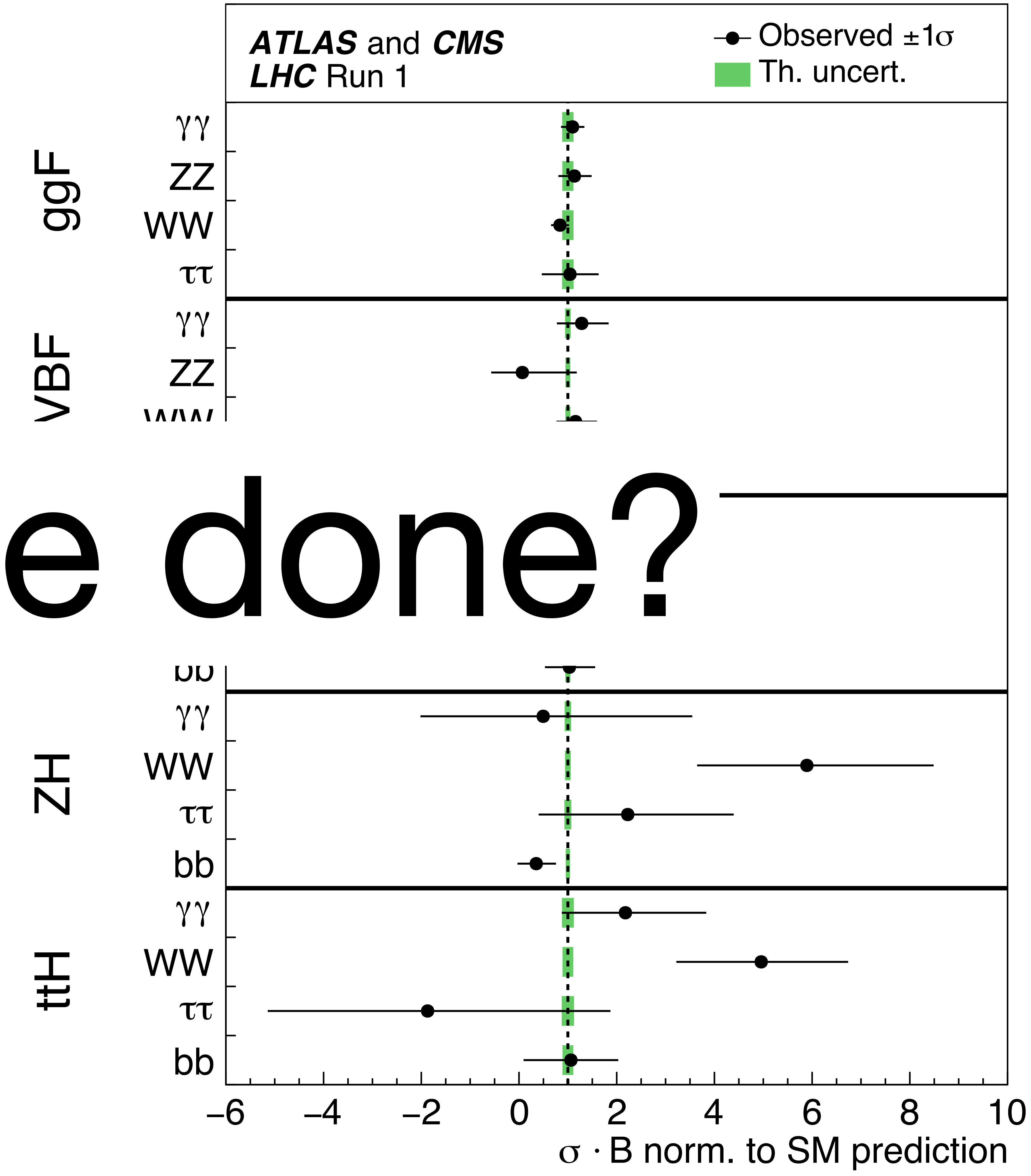


Are we done?

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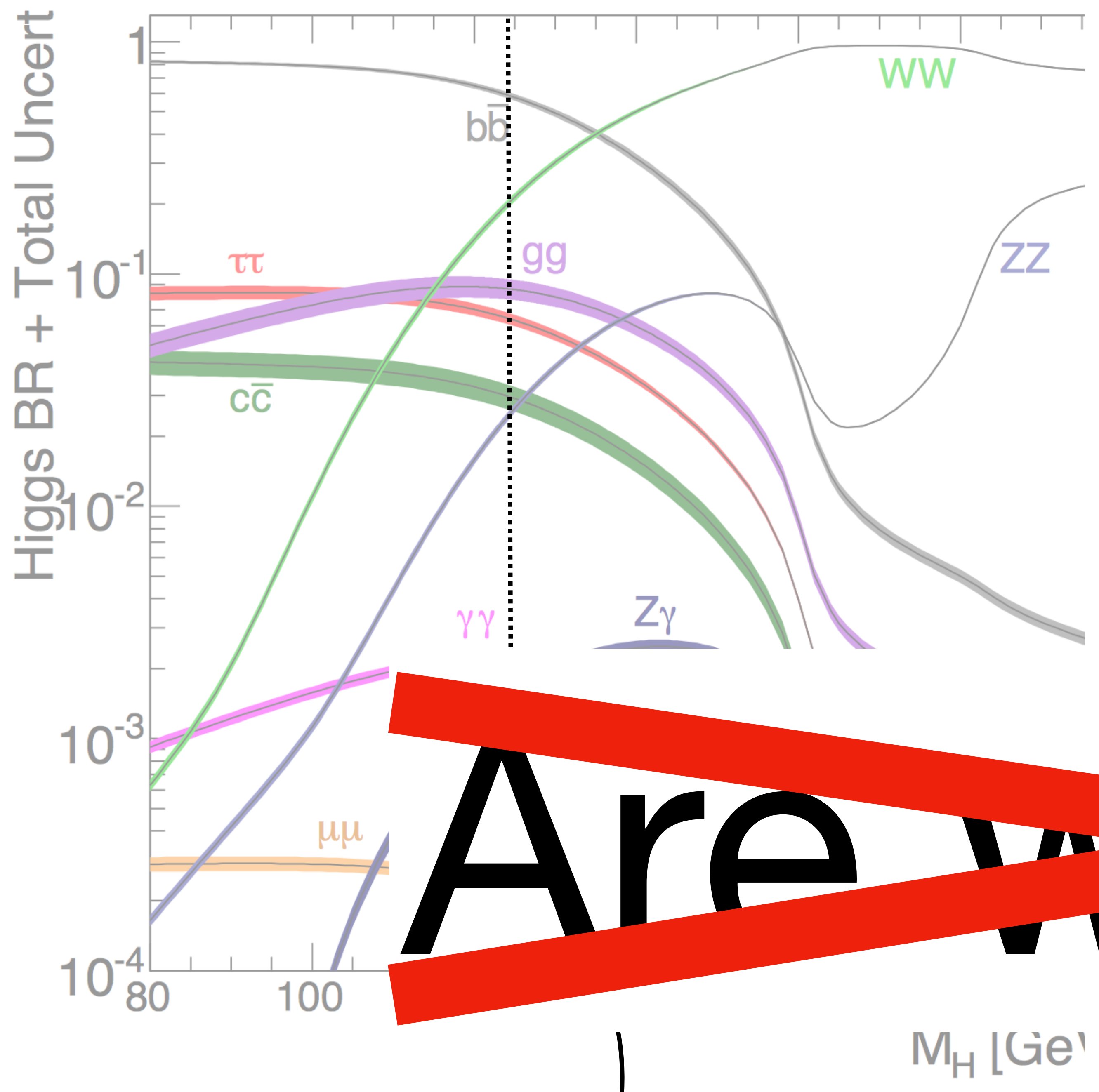


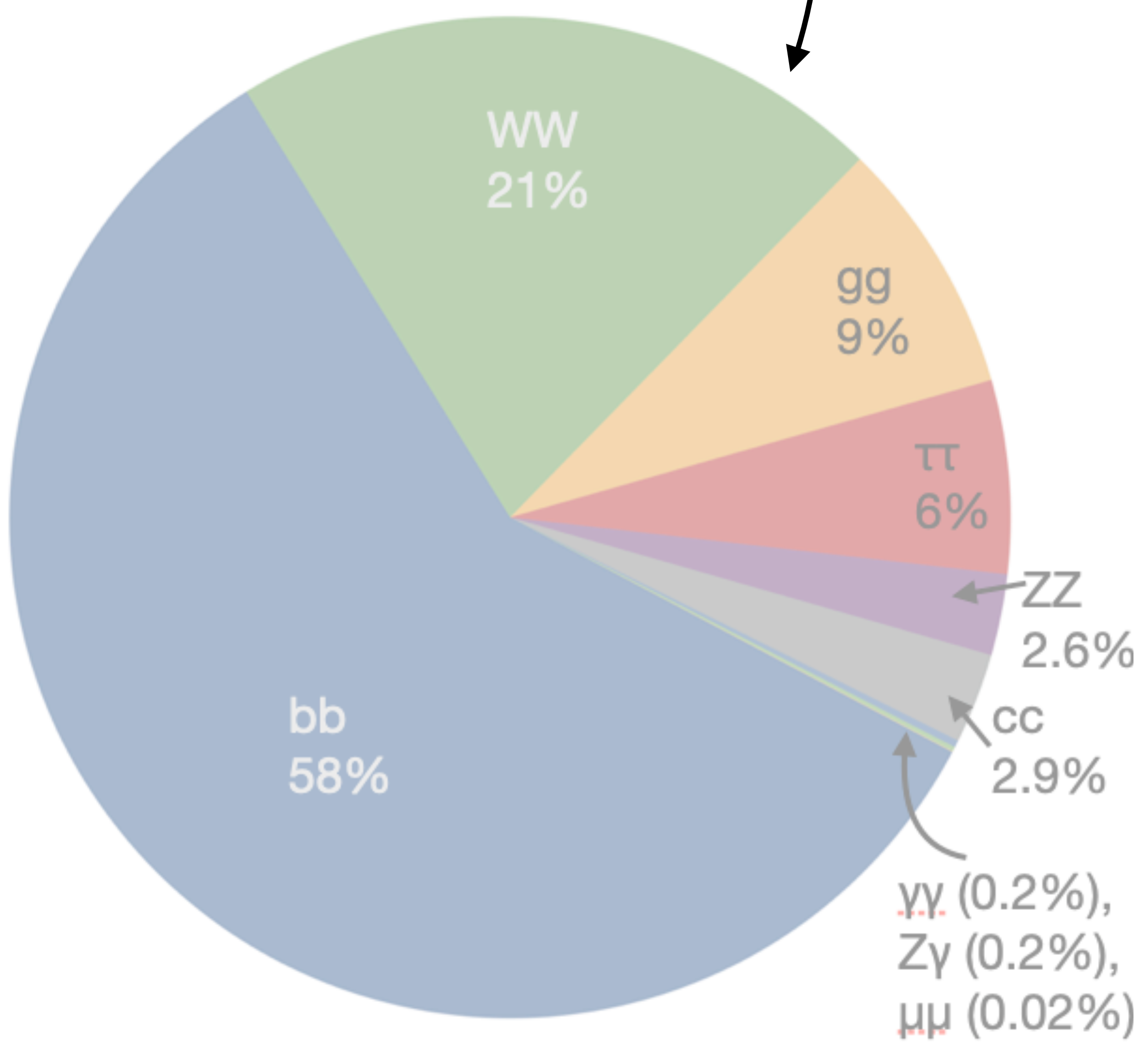


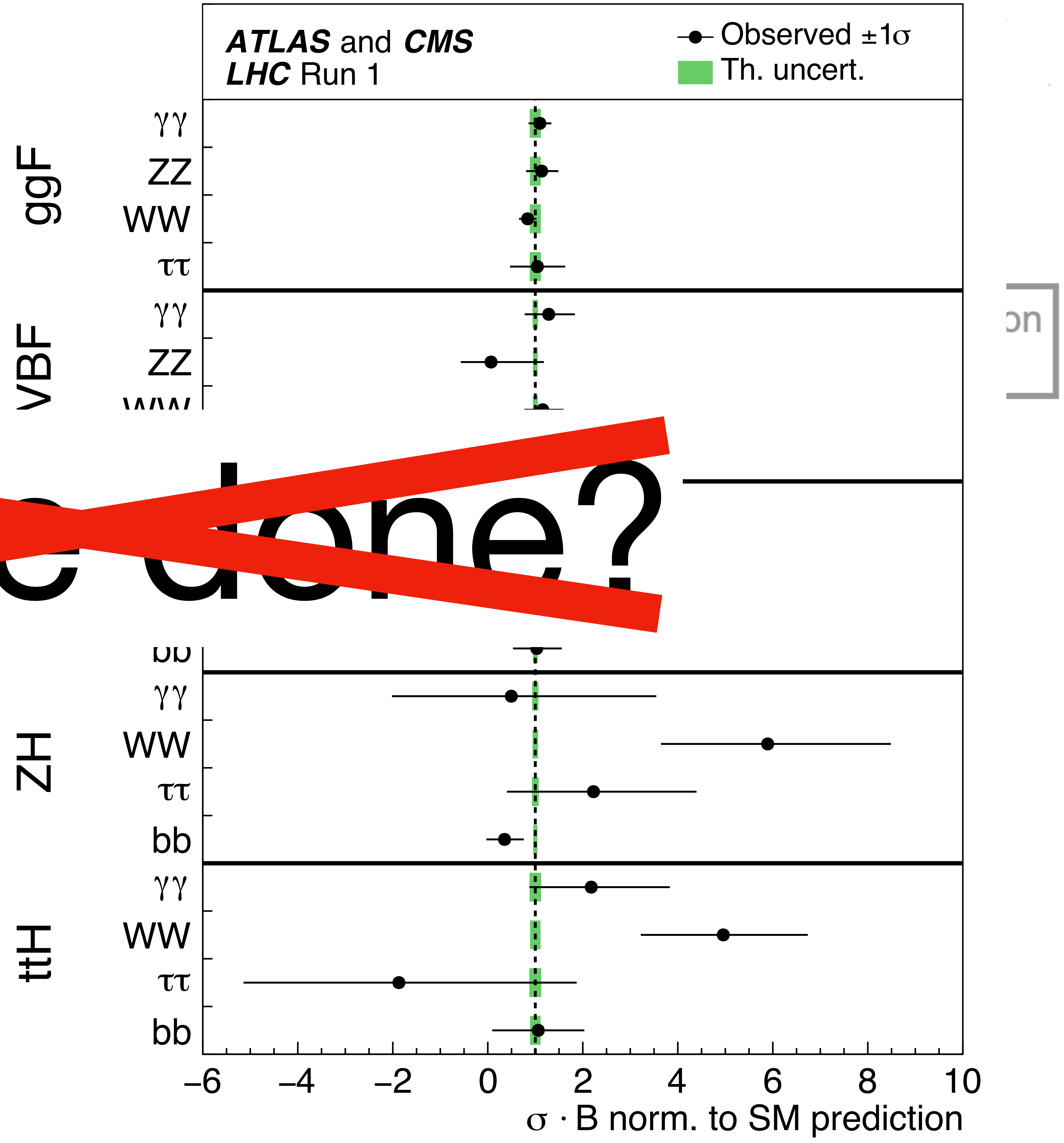


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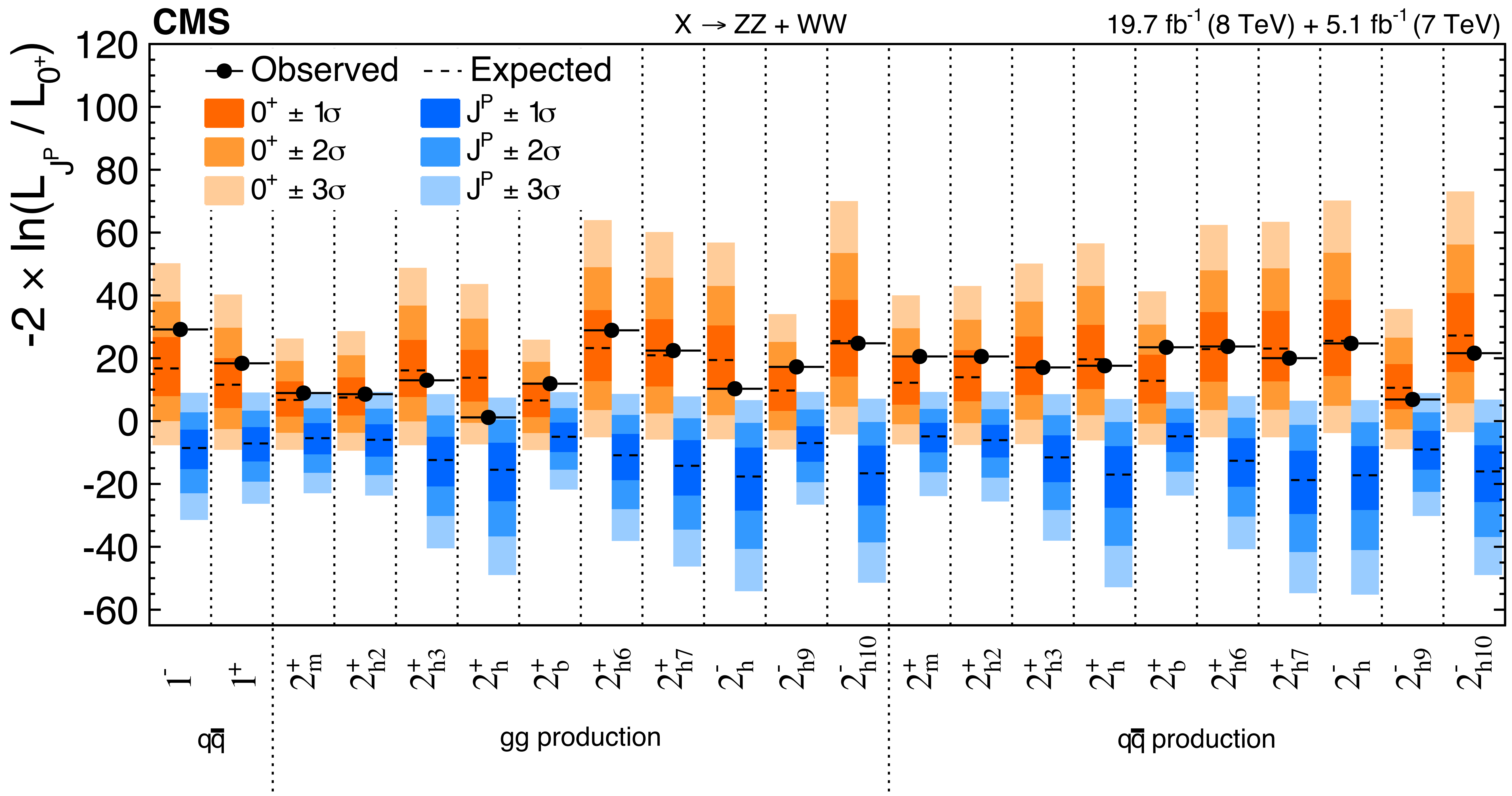
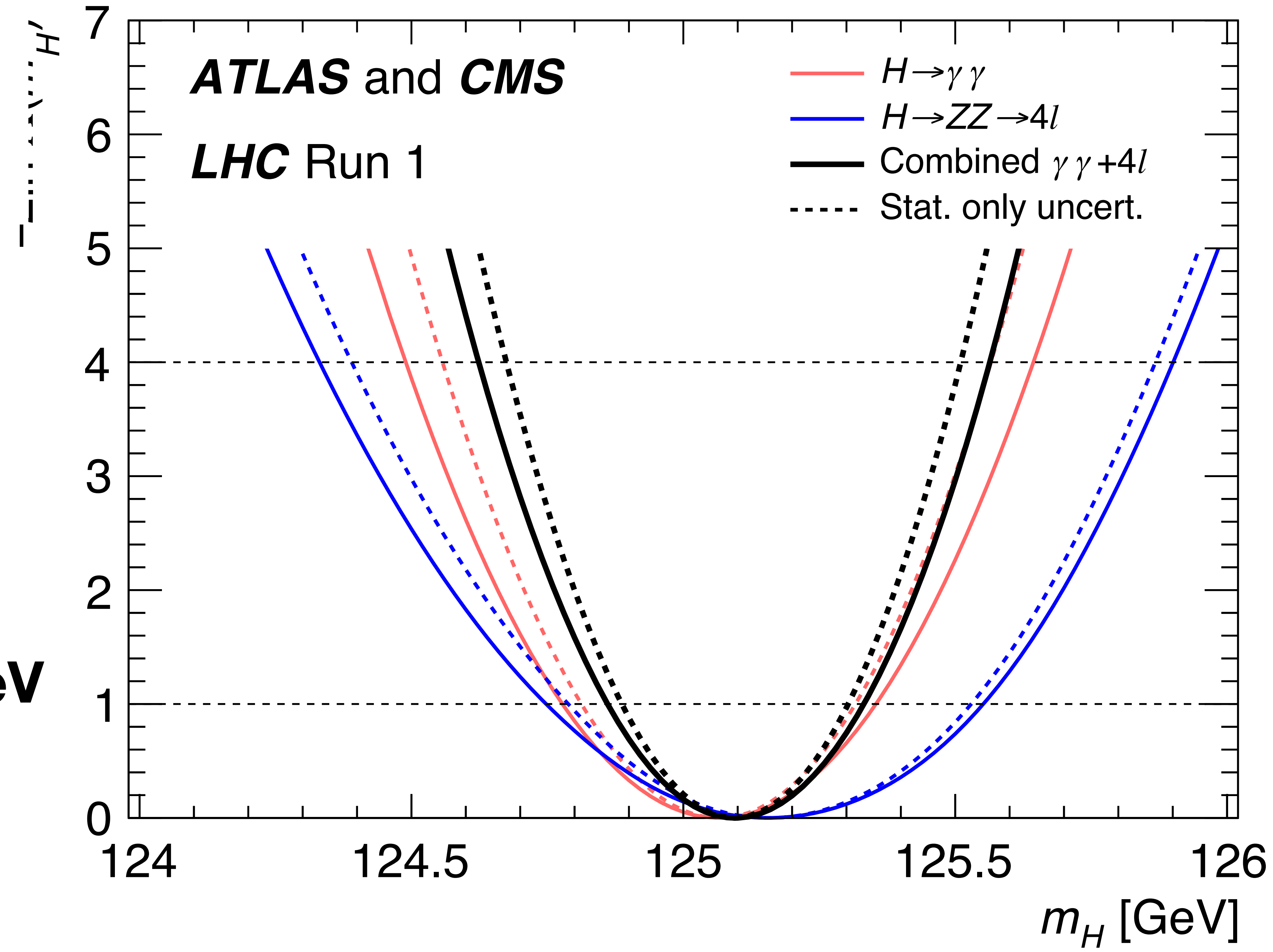
Phys. Rev. D 92 (2015) 012004




This is a spin-0 particle!

**$m_H$ = 125.09 ± 0.24 GeV**
(Run 1 ATLAS+CMS)




PRL 114 (2015) 191803

# The CMS experiment

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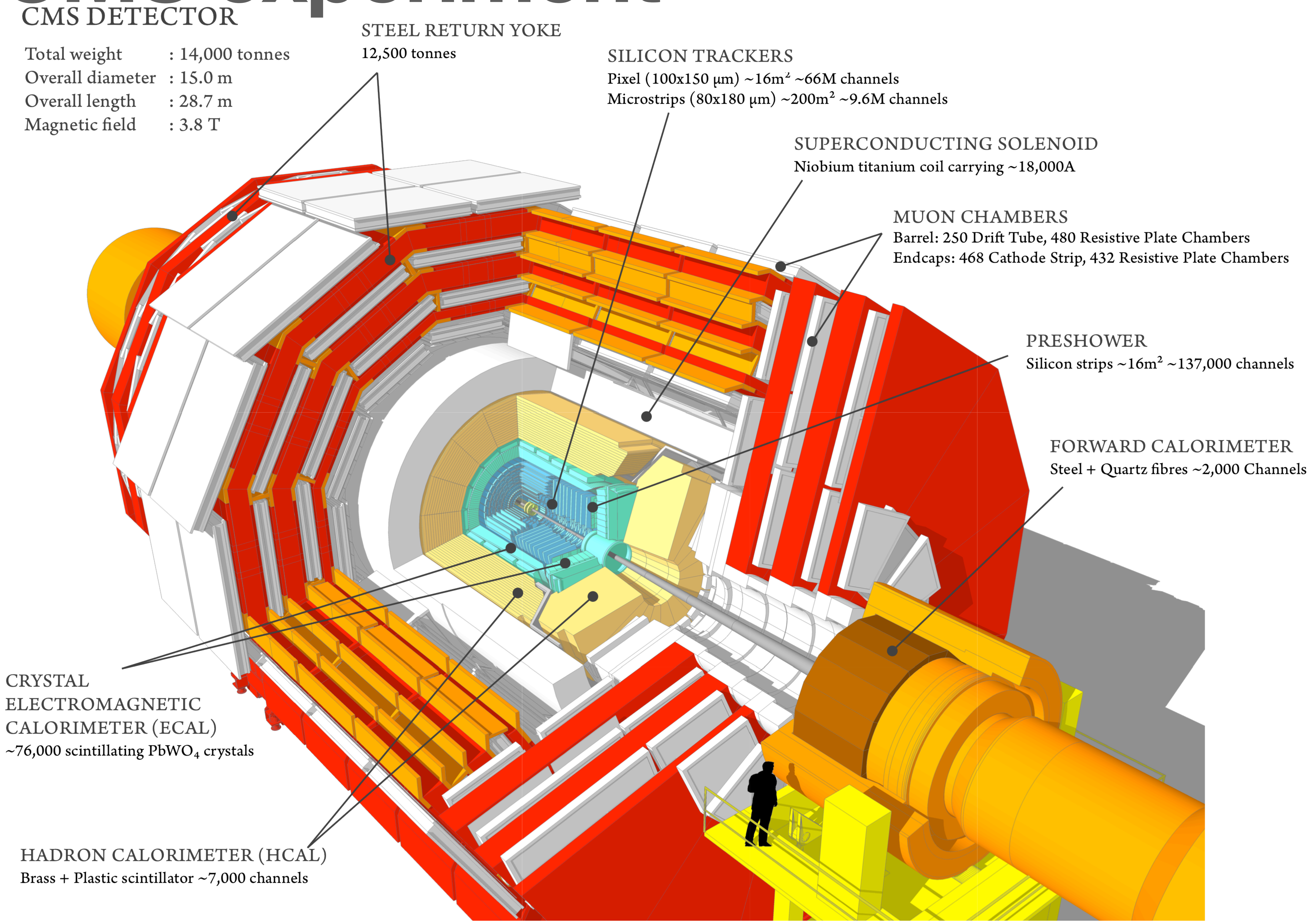
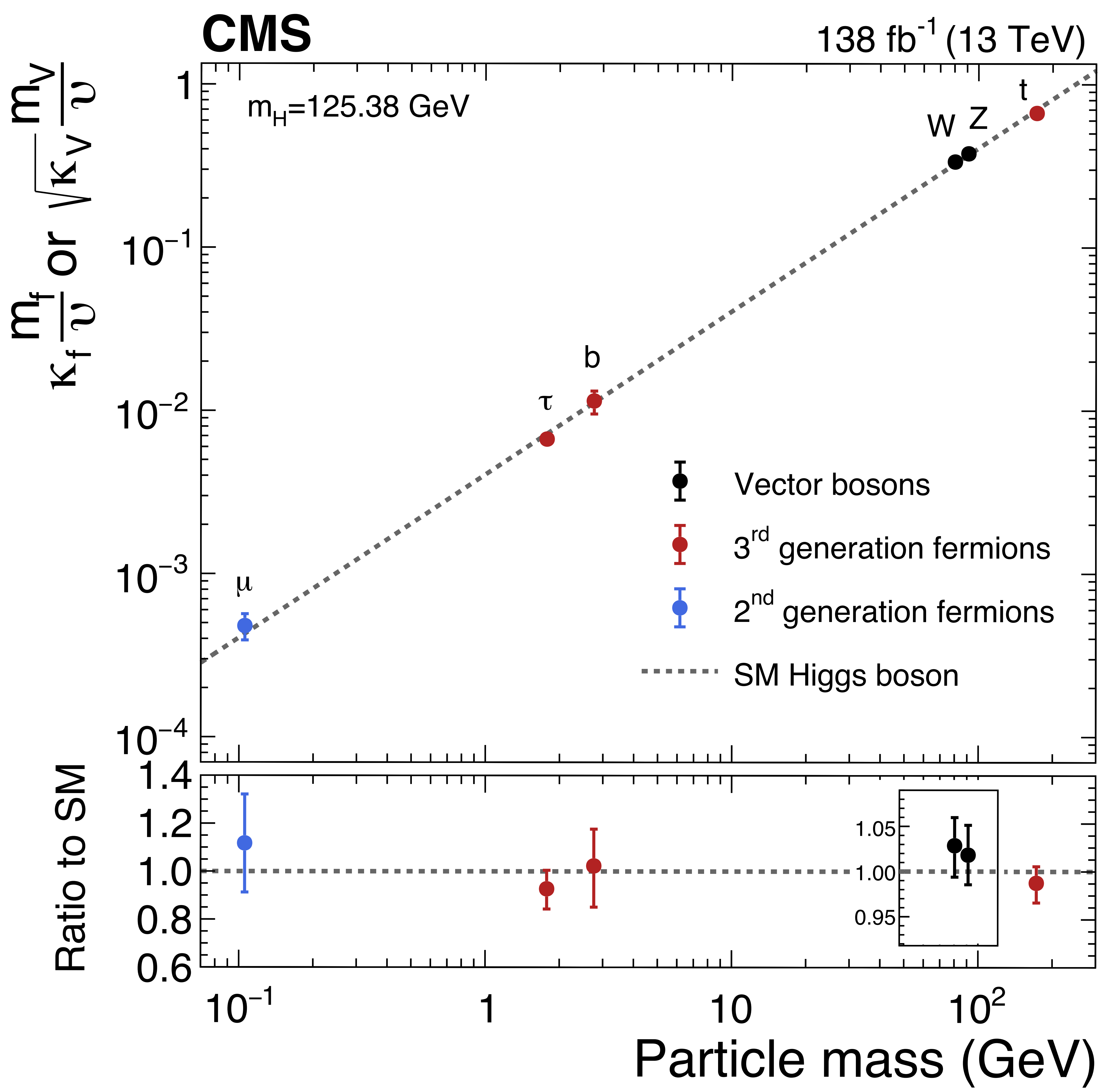


# The Higgs boson, 11 years after its discovery




- Couplings with bosons
- Mass
- Coupling structure
- Couplings with 3d generation fermions
- Couplings with 2nd generation fermions

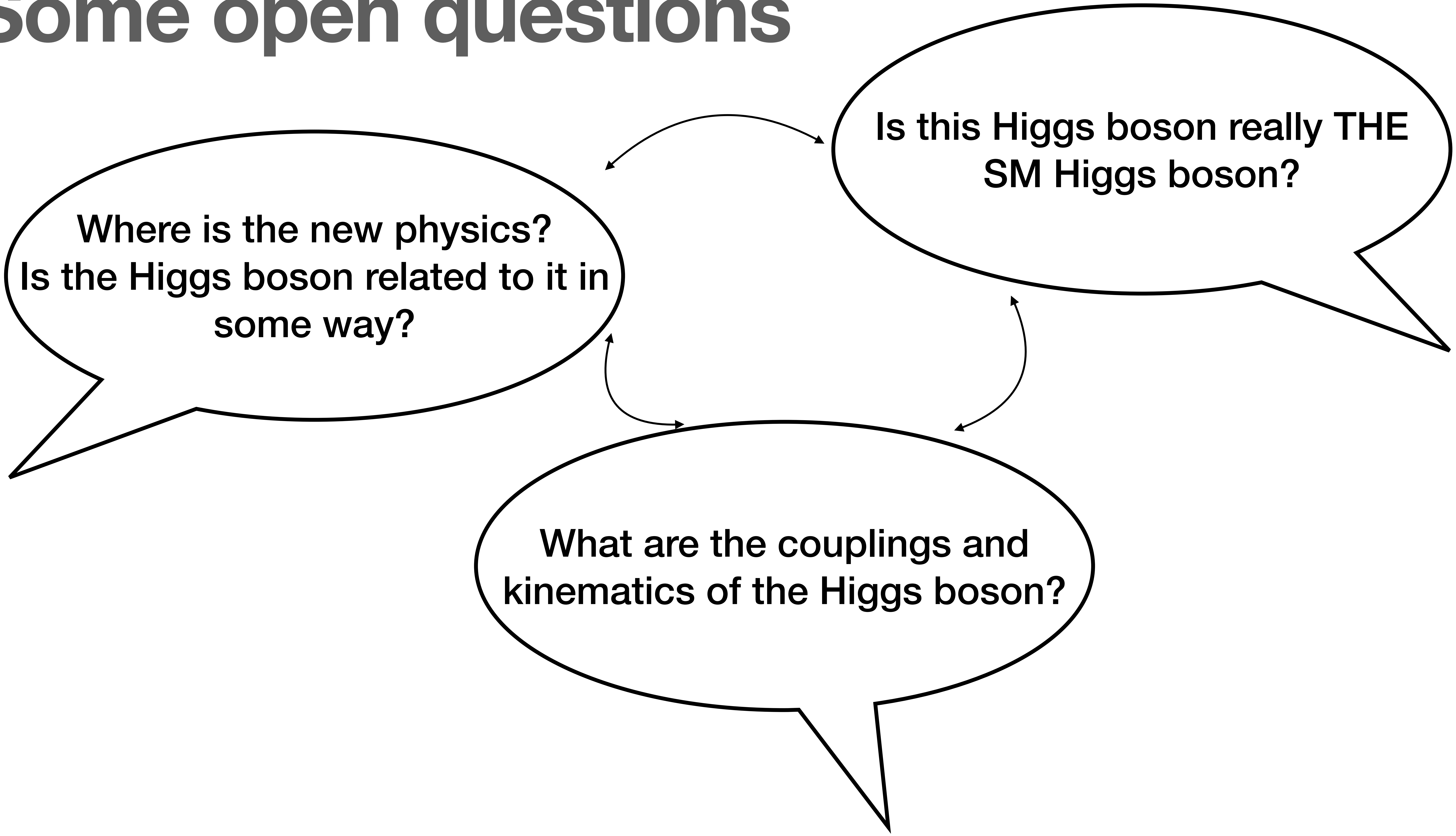
# Some open questions

Is this Higgs boson really THE
SM Higgs boson?

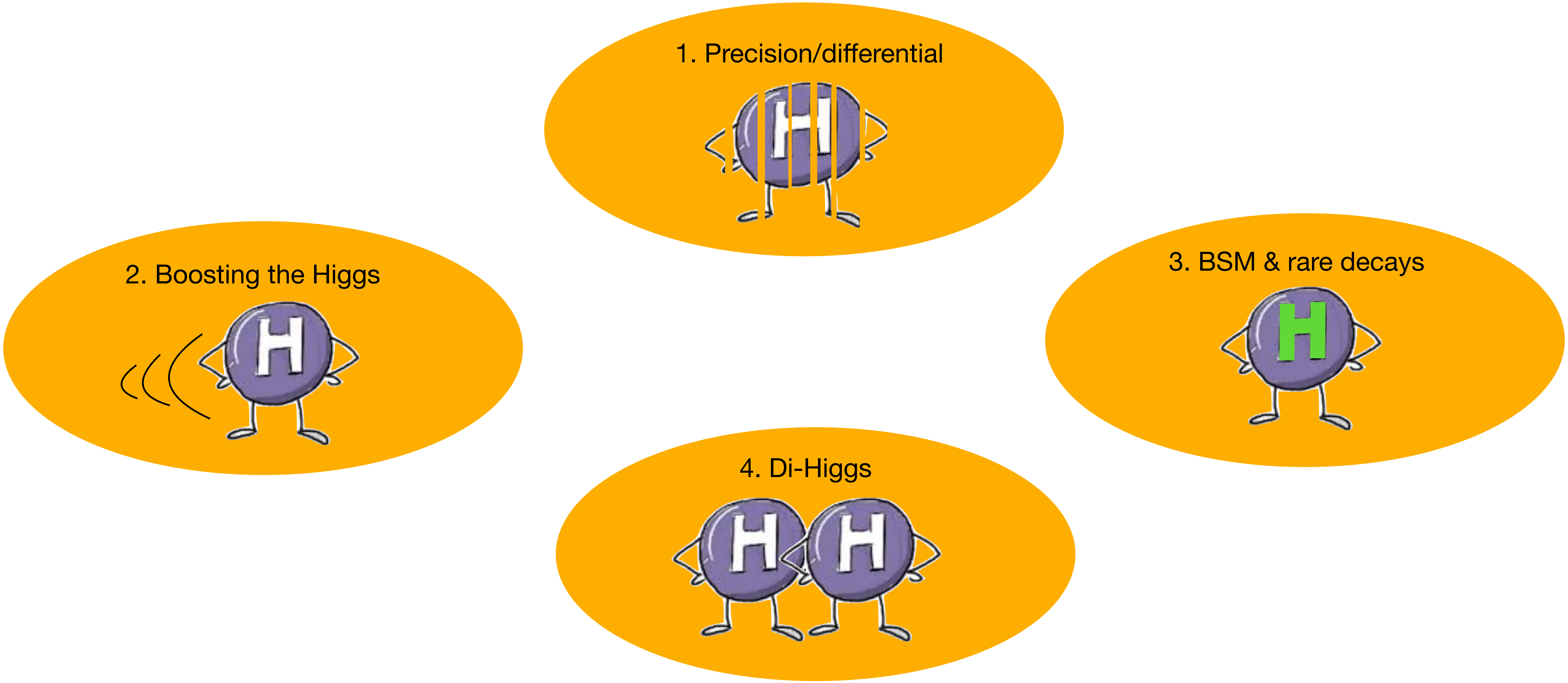
Where is the new physics?
Is the Higgs boson related to it in
some way?

What are the couplings and
kinematics of the Higgs boson?

# Some open questions



# Des questions, des réponses (?)

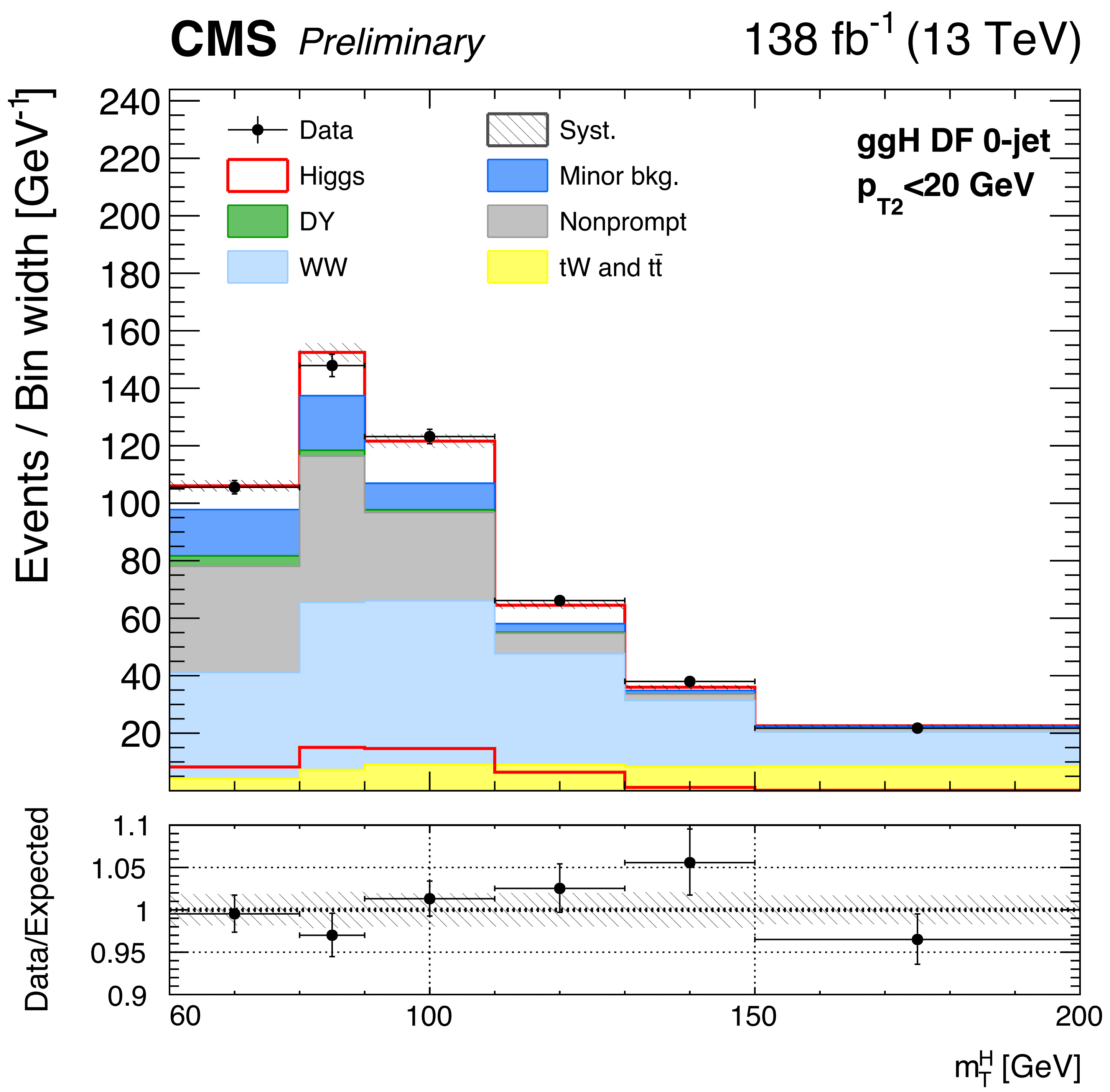


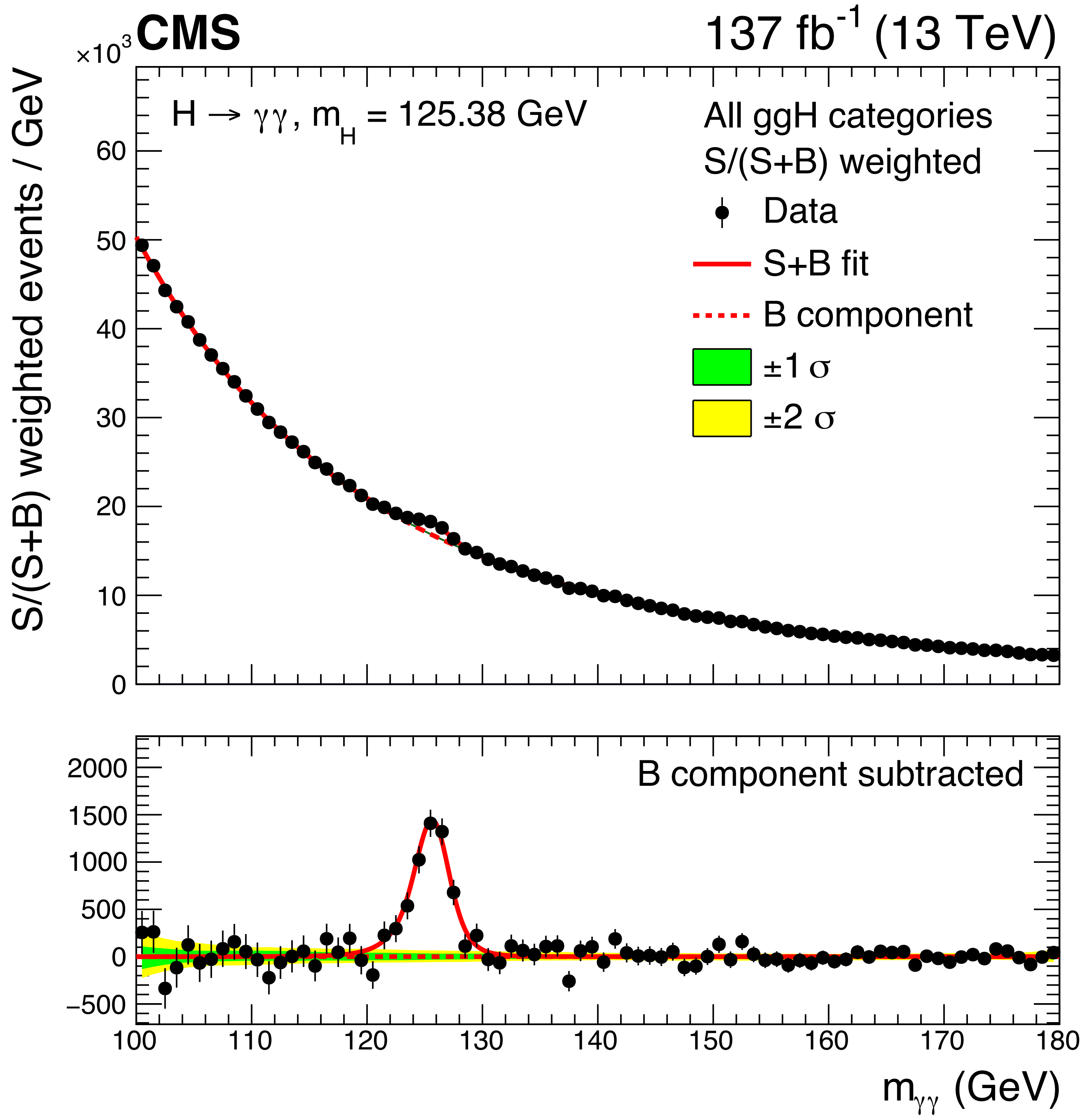
# Disclaimer

- By no means a complete picture!
- Trying to (mostly) focus on relatively recent results
- Focusing on results from CMS (consistent with ATLAS programme!)

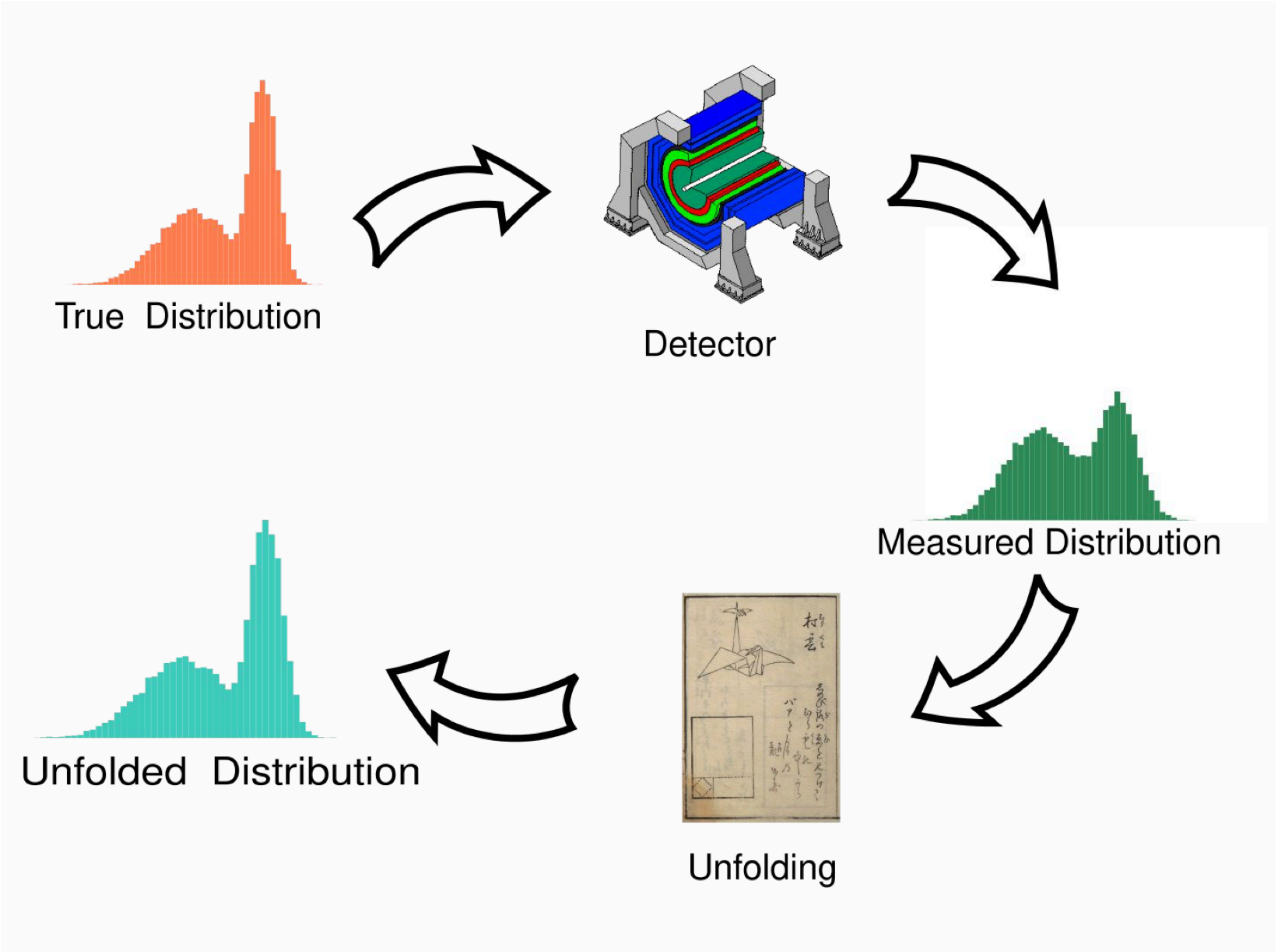
# Higgs boson analysis strategies

- Target all major decay channels (and some rare ones) + all major production modes
- Need the whole detector: γ,e,μ,τ,b,c,MET…
- Both template-based analyses + functional forms for background
  - Likelihoods!



# Brief interlude: unfolding




**Figures: K. Cormier**

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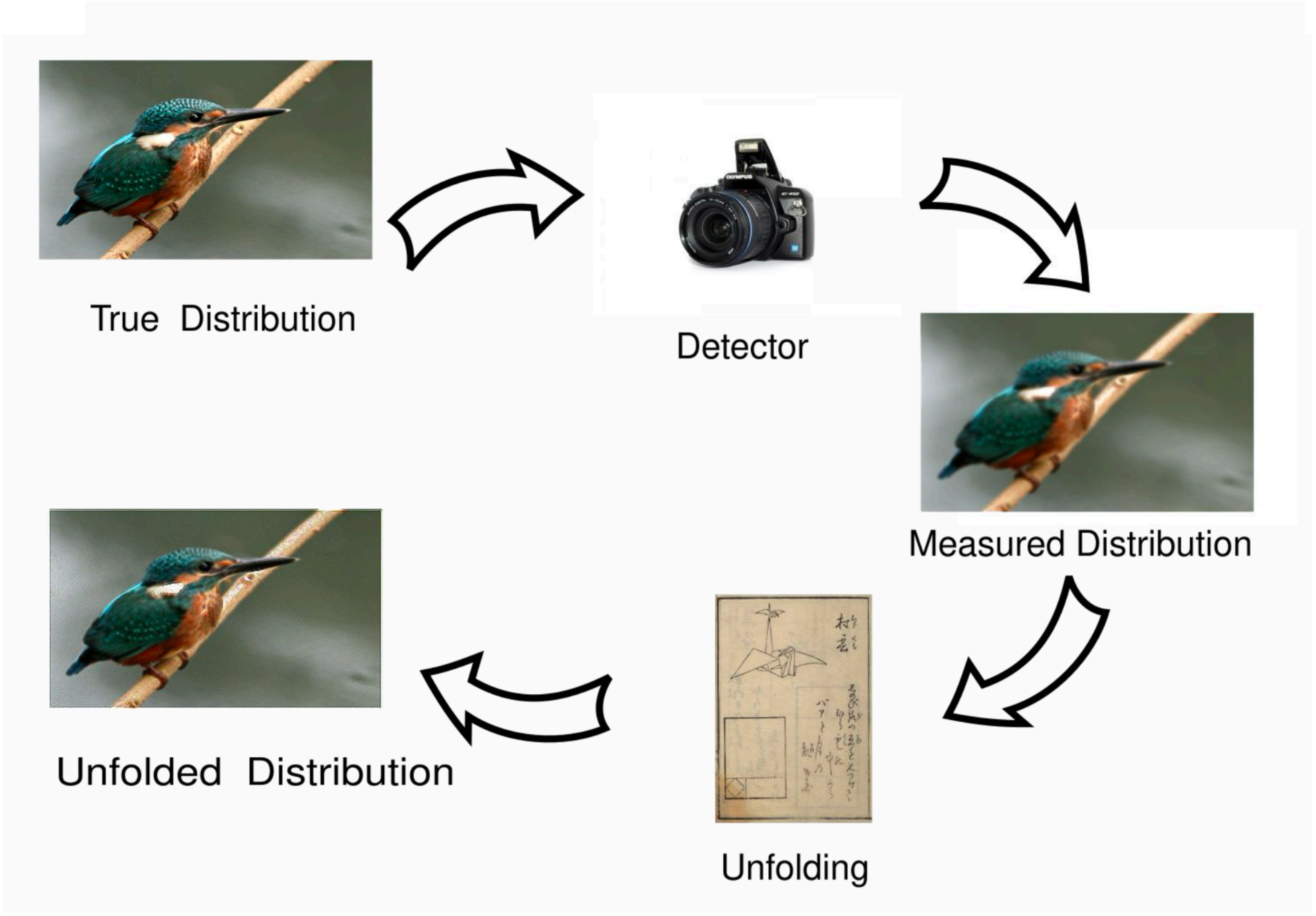


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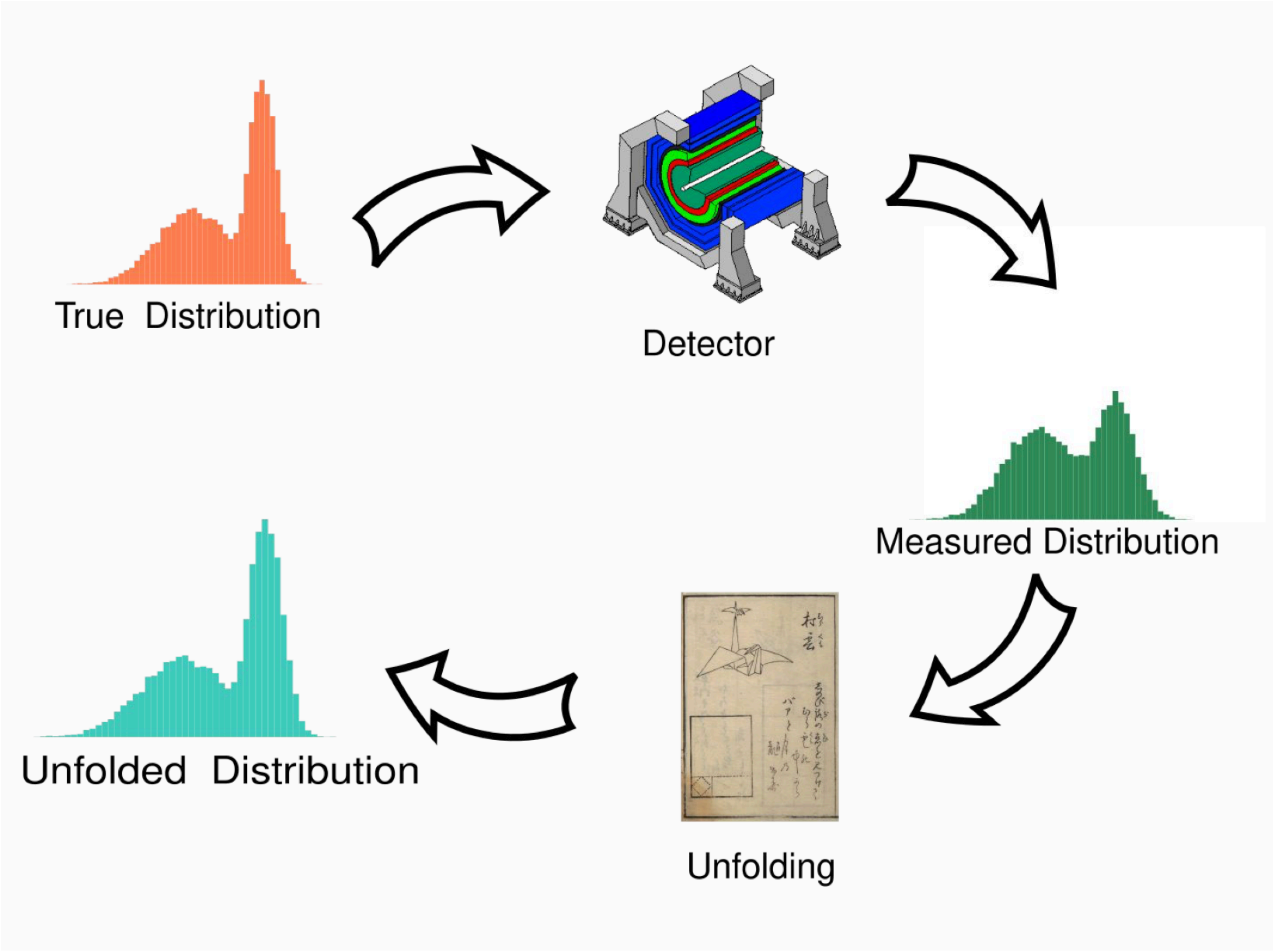
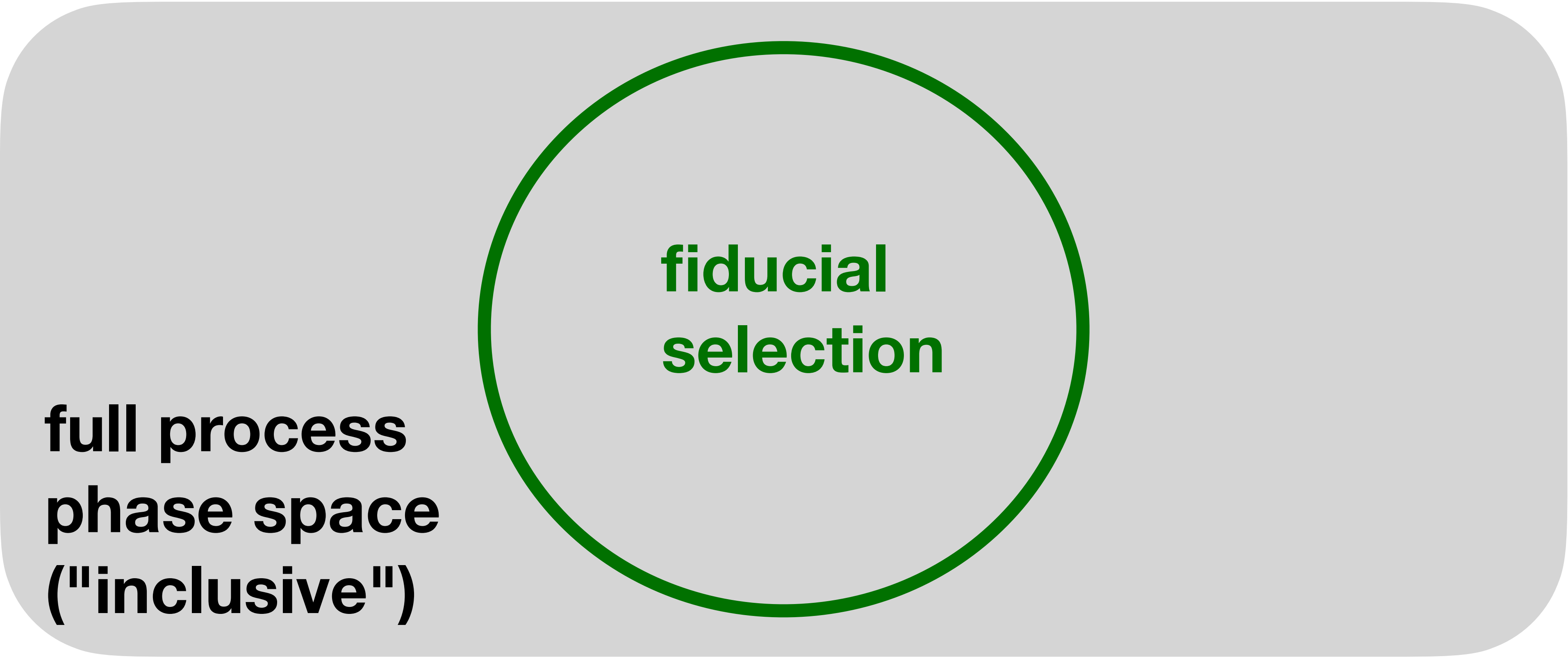



Figures: K. Cormier

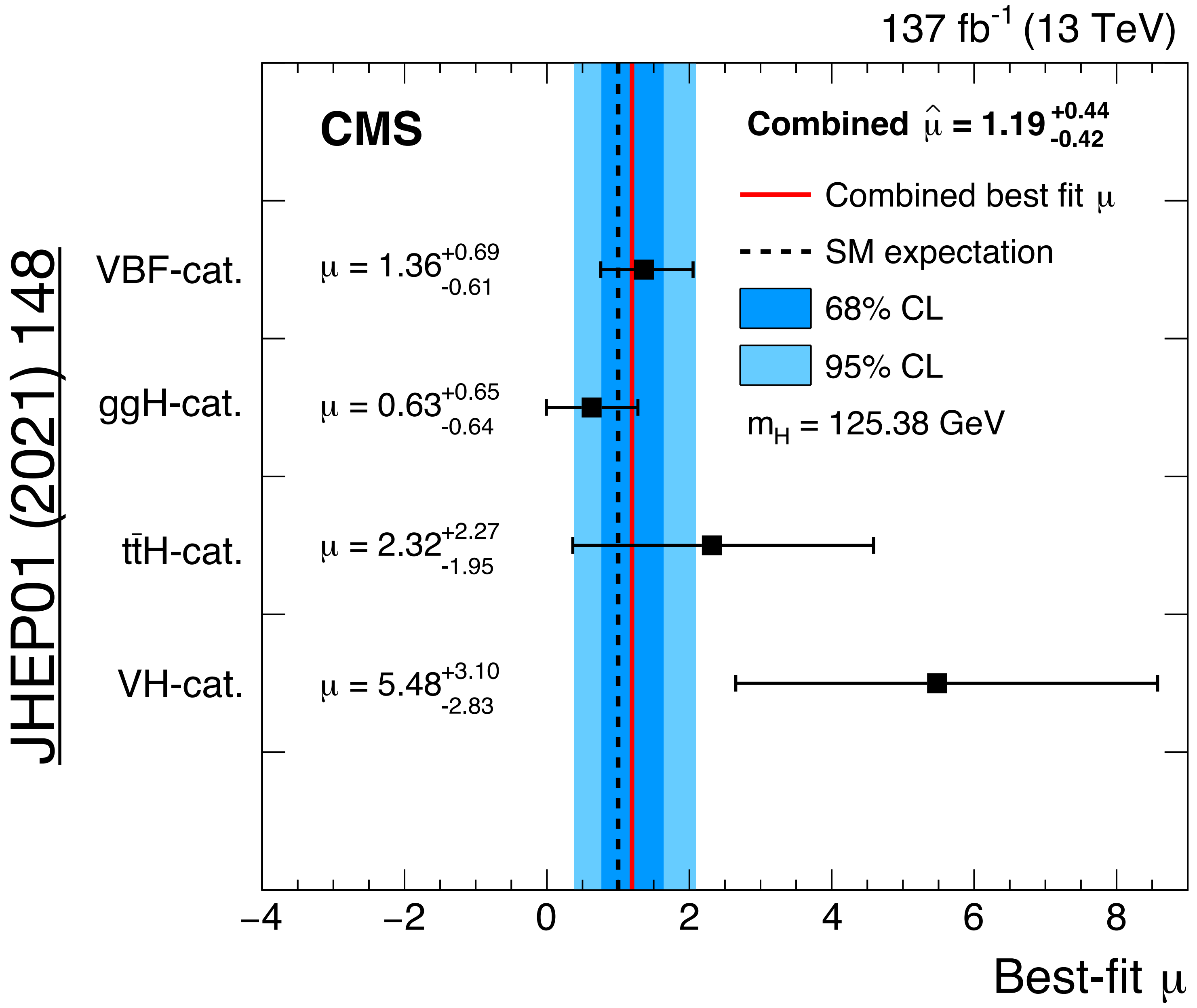
- (Almost) everything I will show today is unfolded to detector-level (general for Higgs)
- Implicit in likelihood fit
- Sometimes inclusive, sometimes fiducial



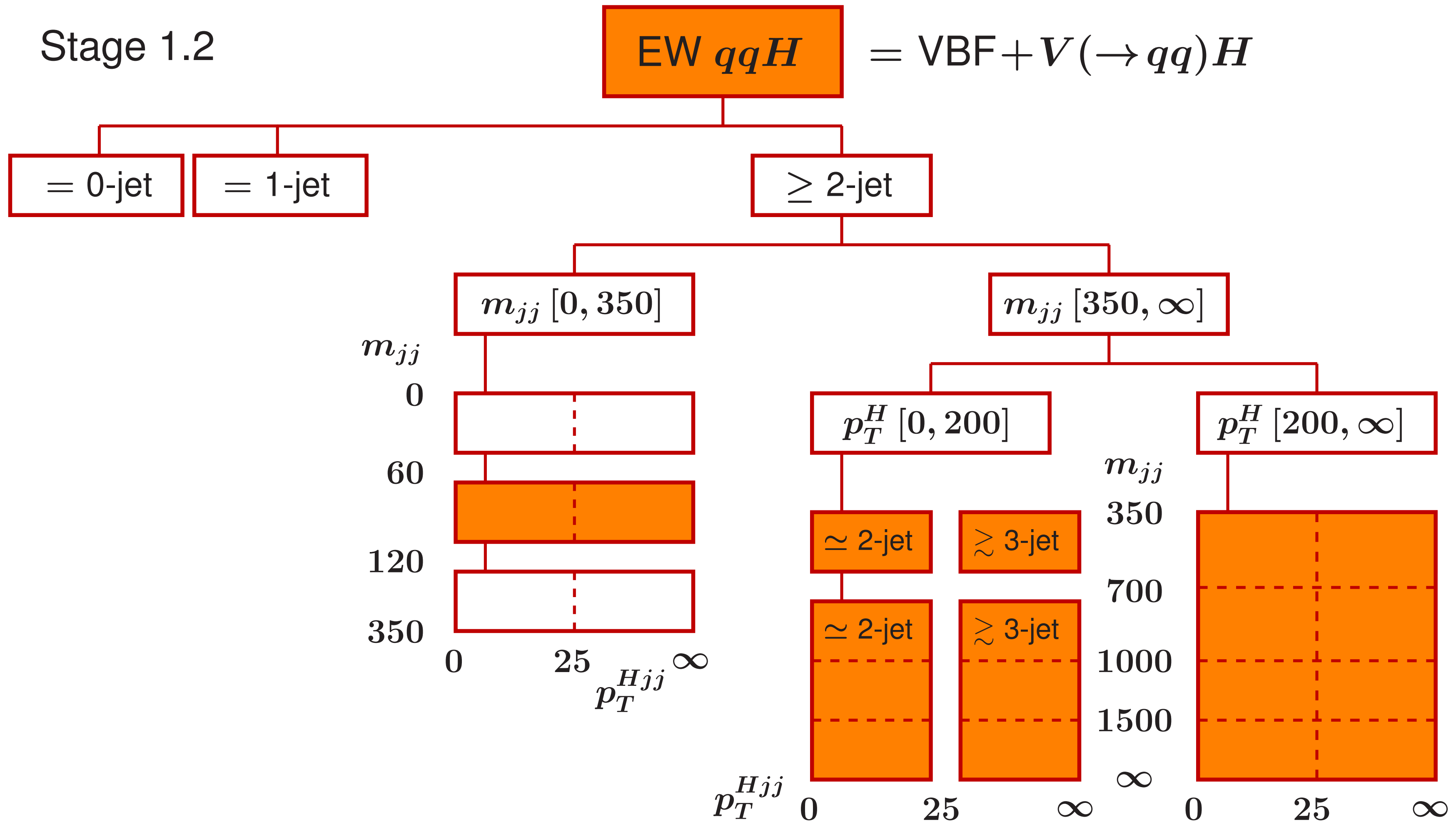
# Precision Higgs measurements

**Model dependence** ⟷ **Data needs**

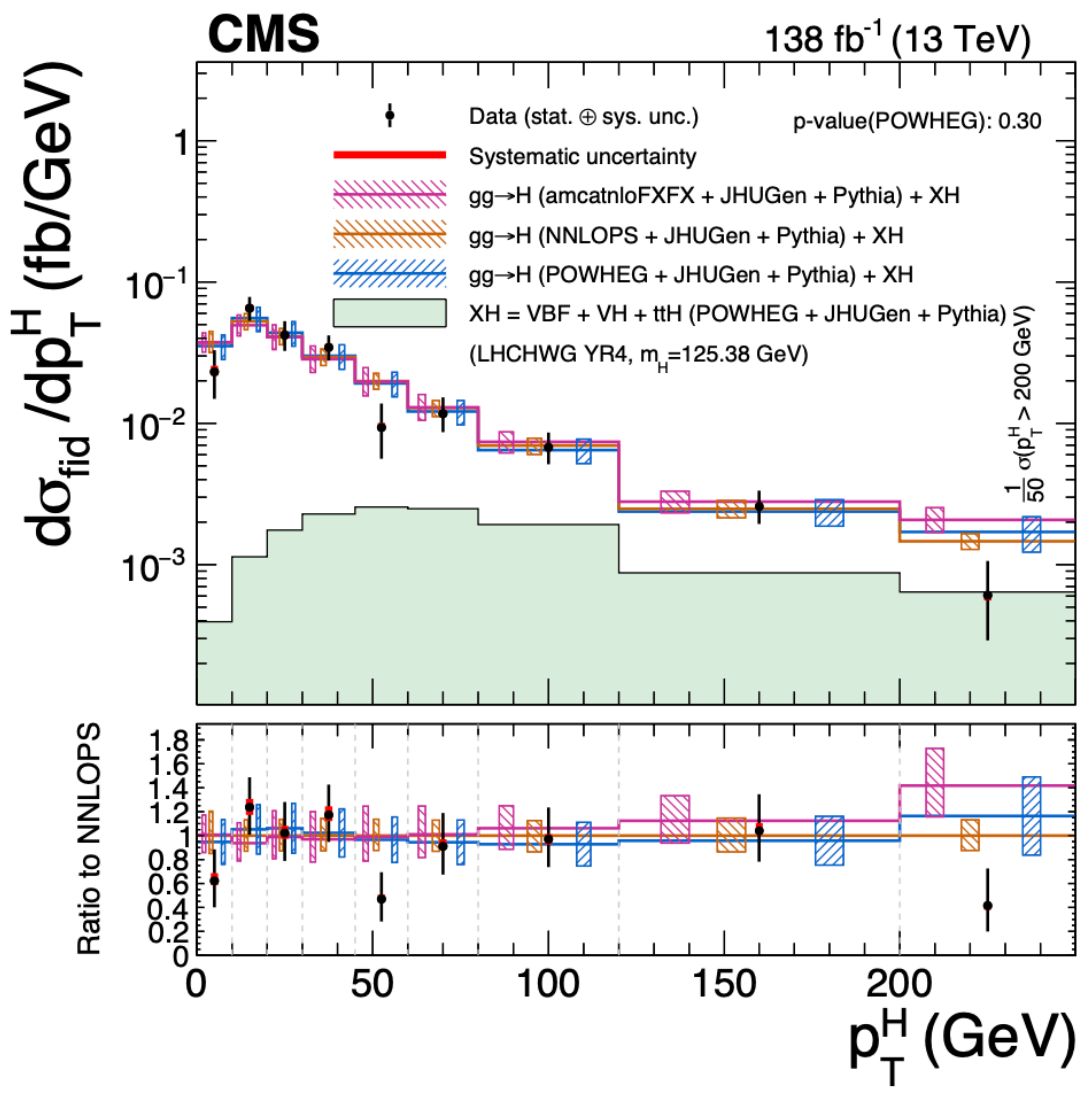
(Inclusive) signal strength or cross section




Simplified template cross sections




Differential, fiducial measurements



# Precision Higgs measurements

## Why you should care

- To satisfy our curiosity!

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arXiv:1310.8361

| Model | $\kappa_V$ | $\kappa_b$ | $\kappa_\gamma$ |
|---|---|---|---|
| Singlet Mixing | $\sim 6\%$ | $\sim 6\%$ | $\sim 6\%$ |
| 2HDM | $\sim 1\%$ | $\sim 10\%$ | $\sim 1\%$ |
| Decoupling MSSM | $\sim -0.0013\%$ | $\sim 1.6\%$ | $\sim -.4\%$ |
| Composite | $\sim -3\%$ | $\sim -(3-9)\%$ | $\sim -9\%$ |
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- BSM models predict %-level deviations in couplings ➔ need precision measurements

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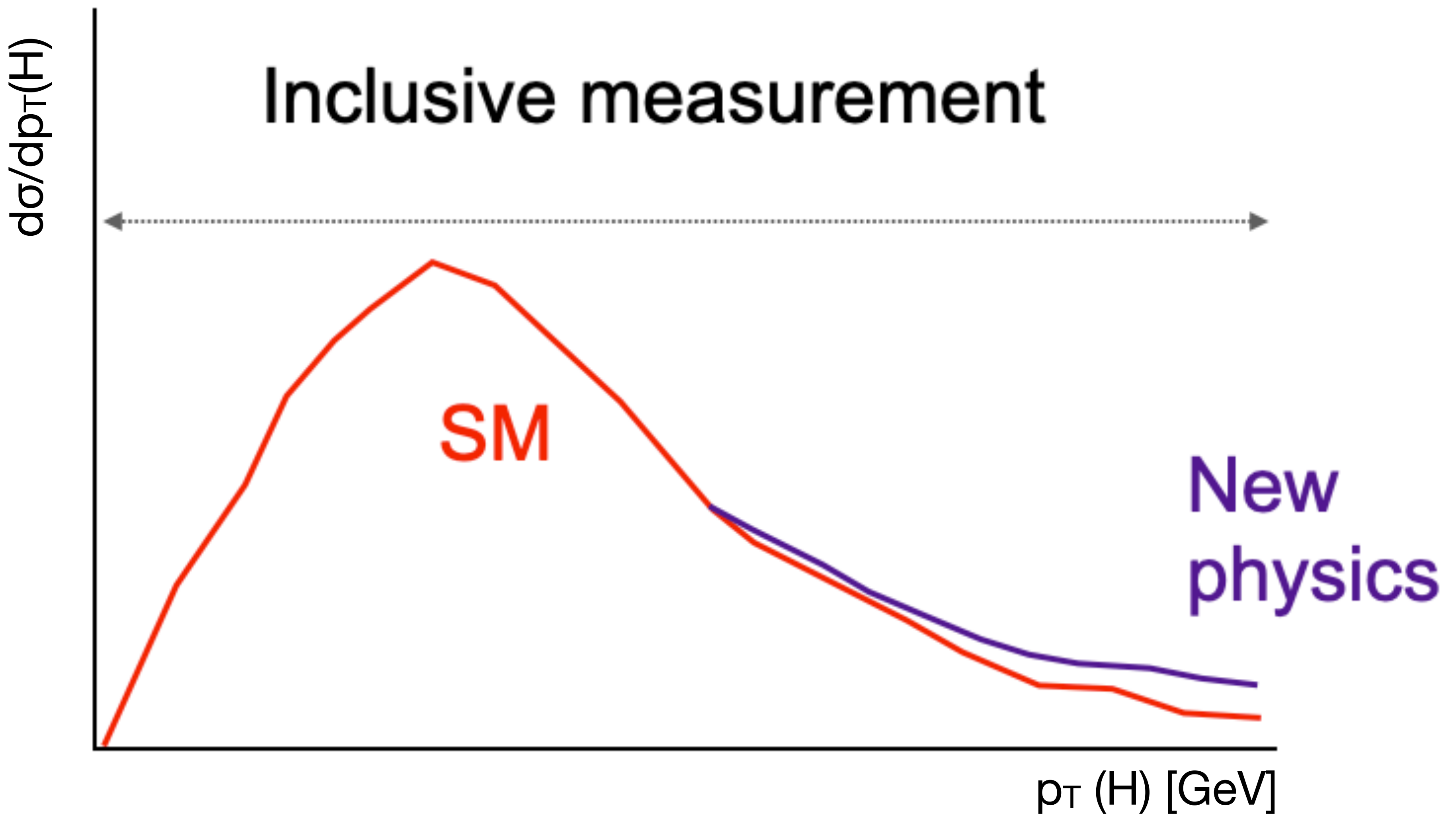

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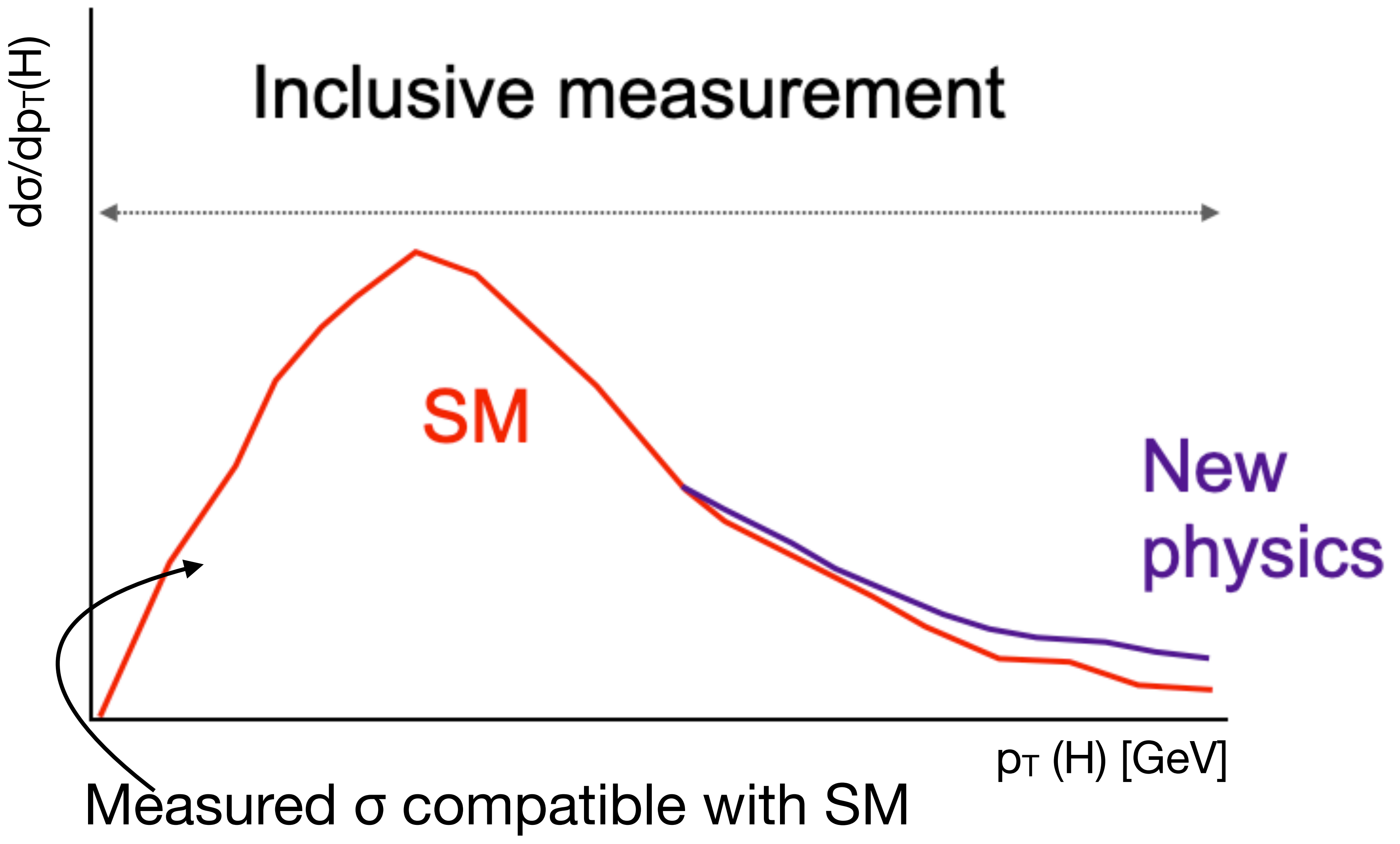

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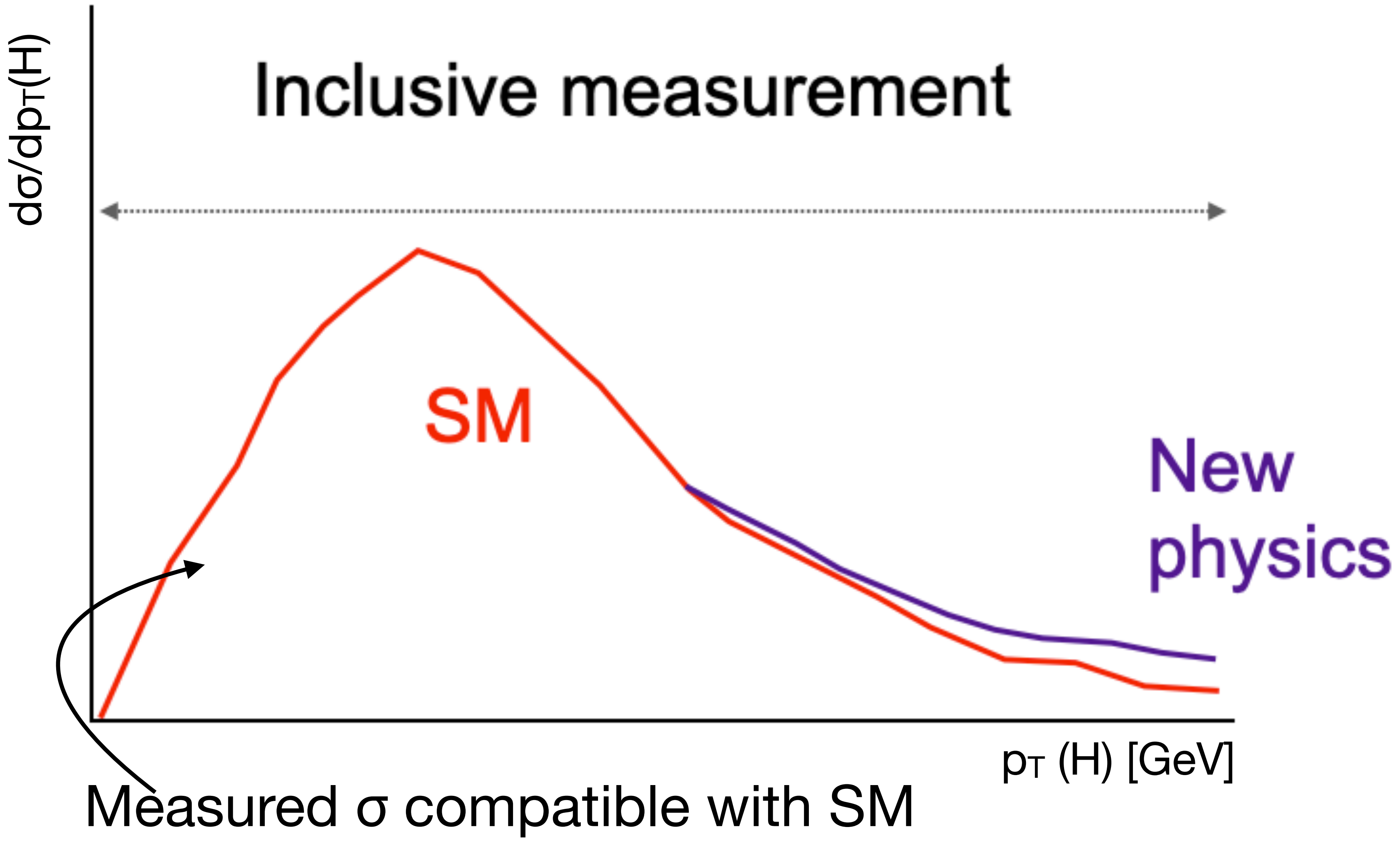


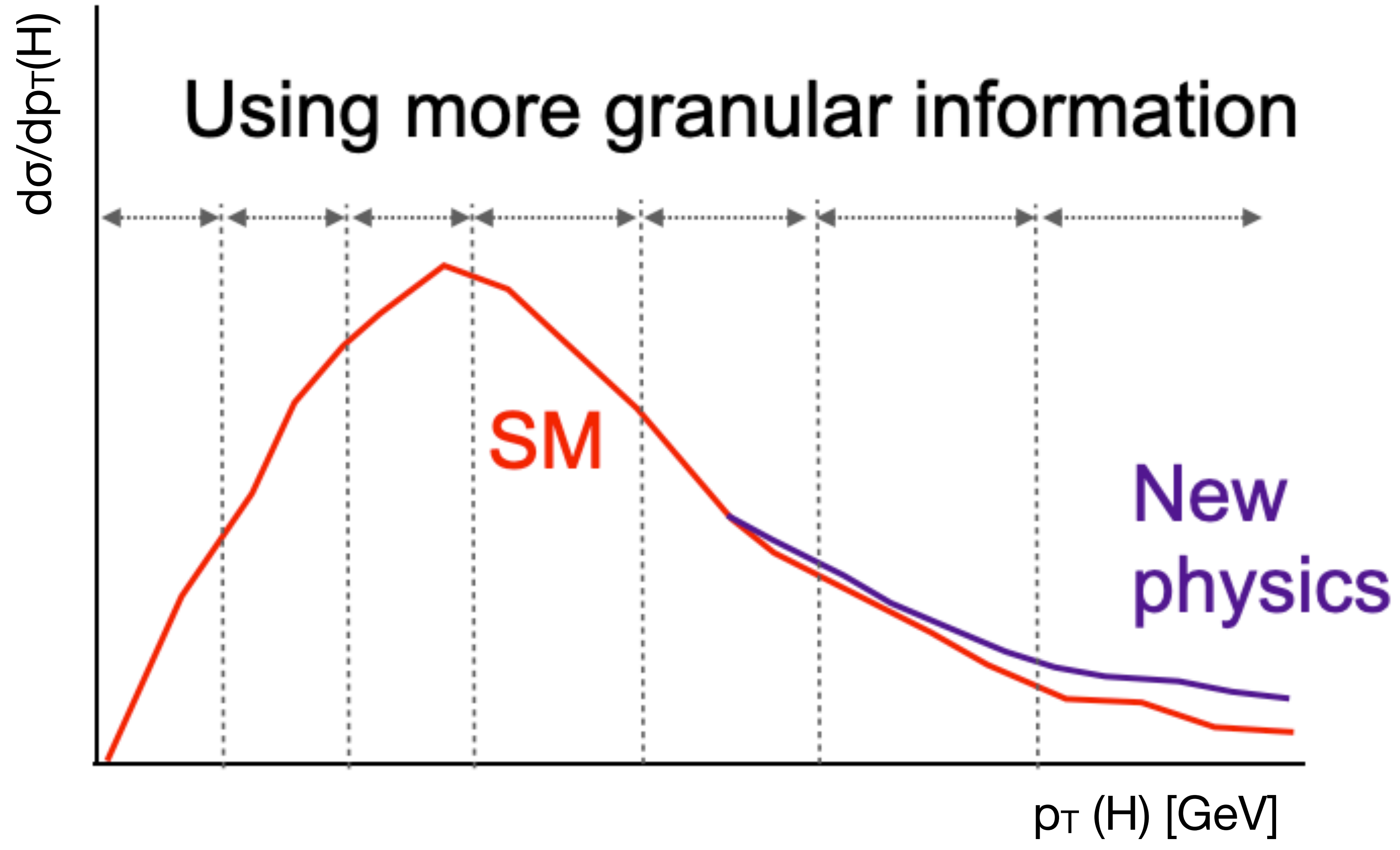

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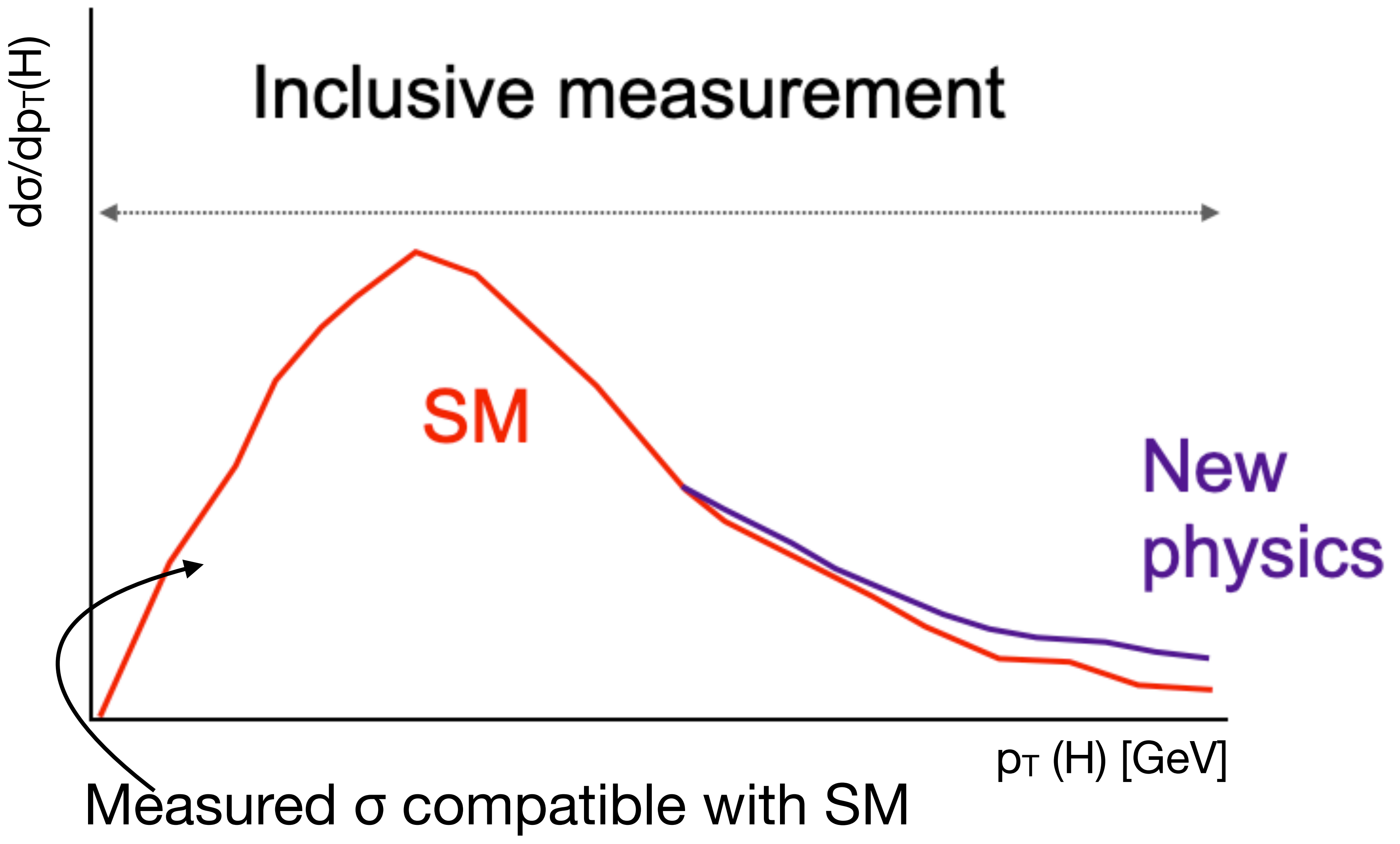


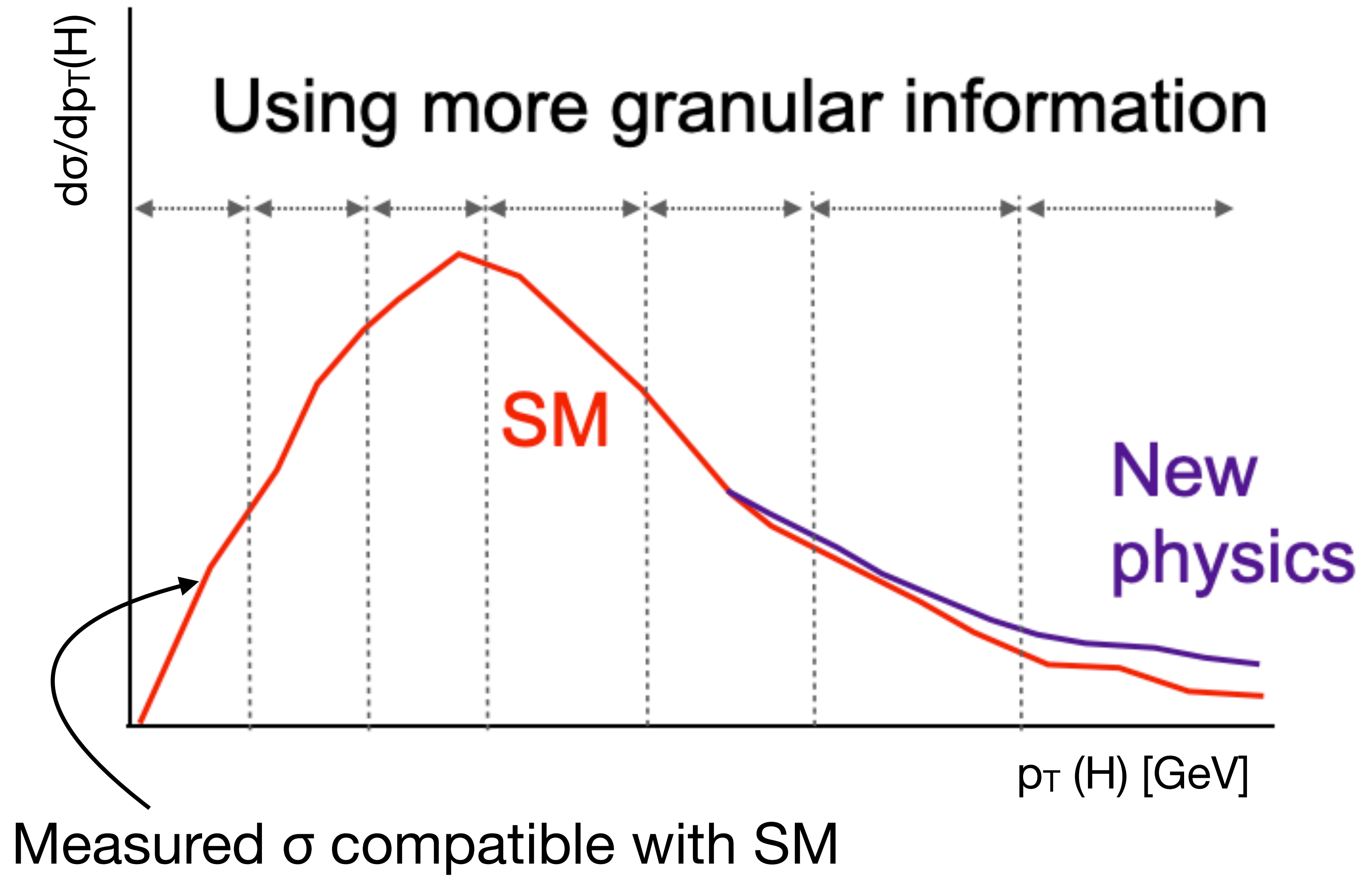

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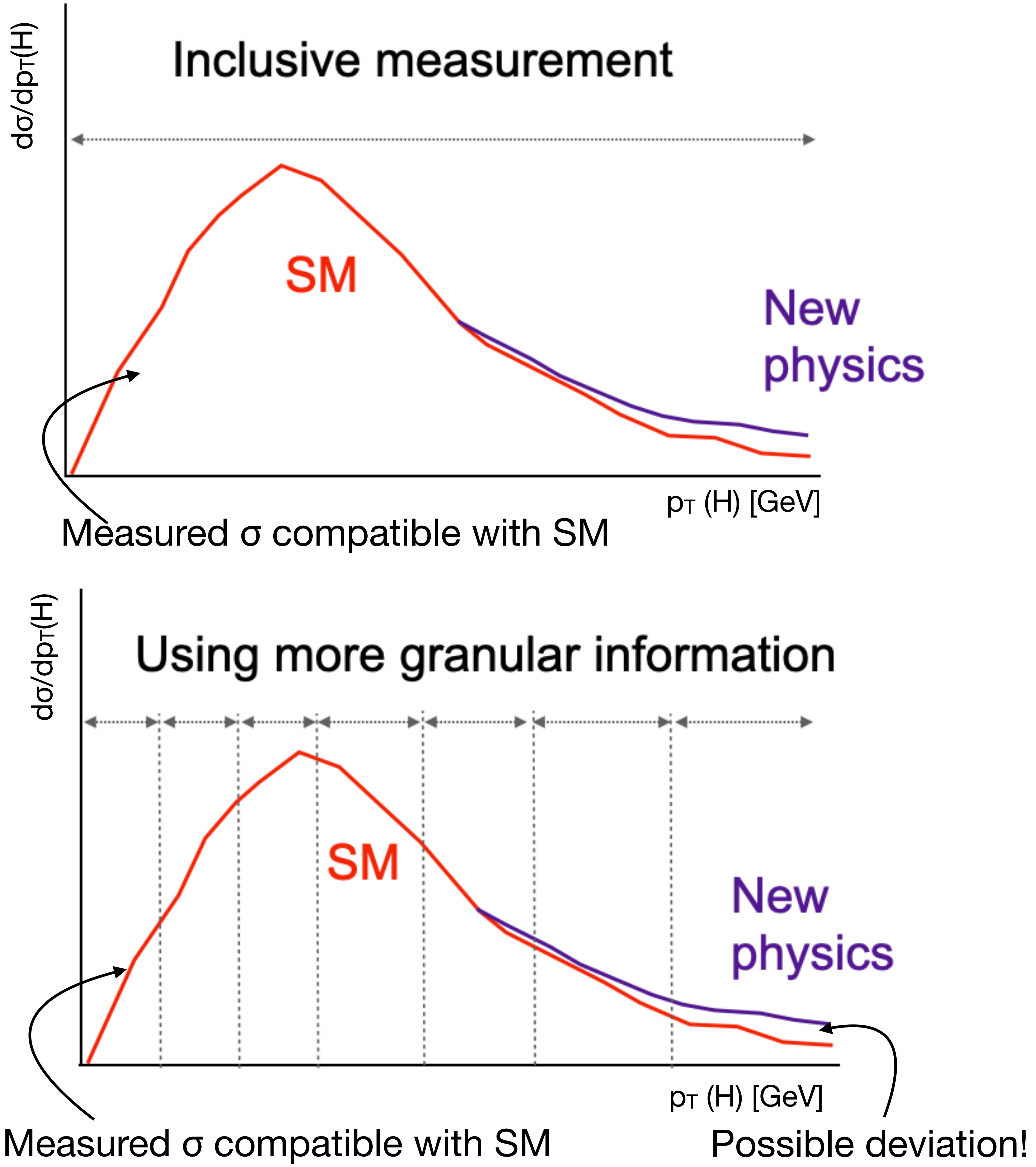
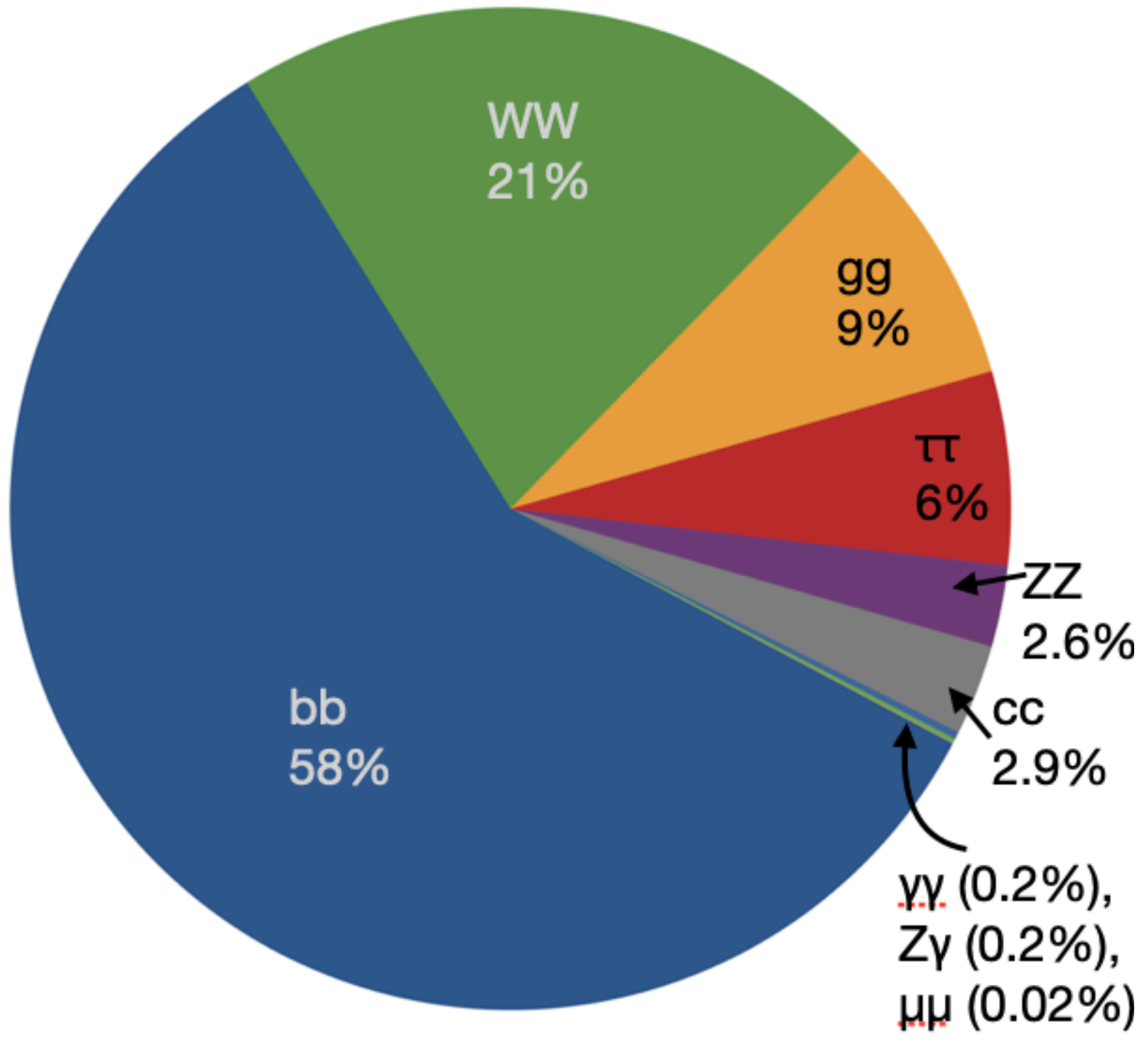
| Composite | $\sim -3\%$ | $\sim -(3-9)\%$ | $\sim -9\%$ |
| Top Partner | $\sim -2\%$ | $\sim -2\%$ | $\sim +1\%$ |

- BSM models predict %-level deviations in couplings ➔ need precision measurements



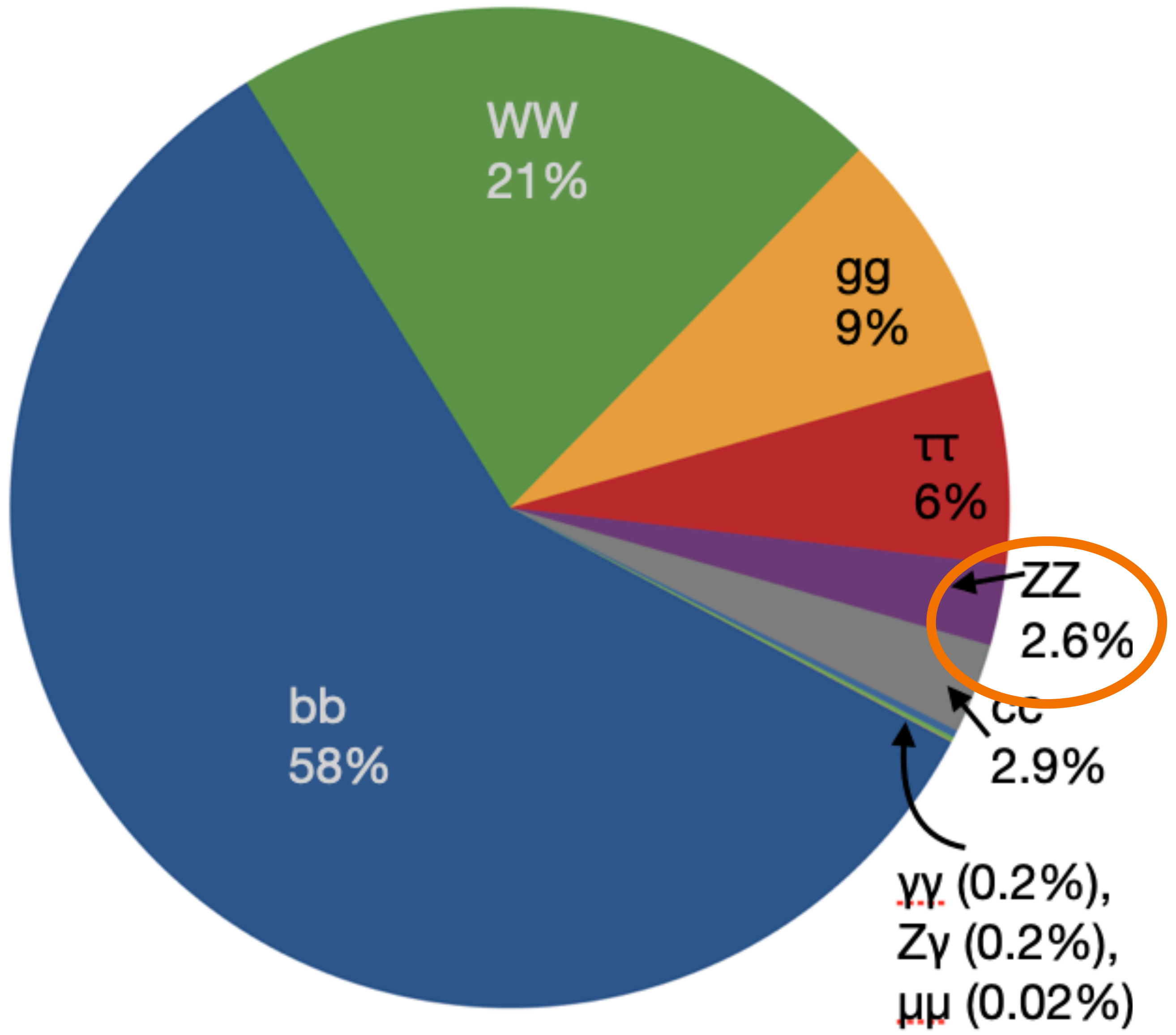
# H→bb and H→ZZ→4l




JHEP 08 (2023) 040

HIG-20-001, sub'd to PRD

# H→bb and H→ZZ→4l

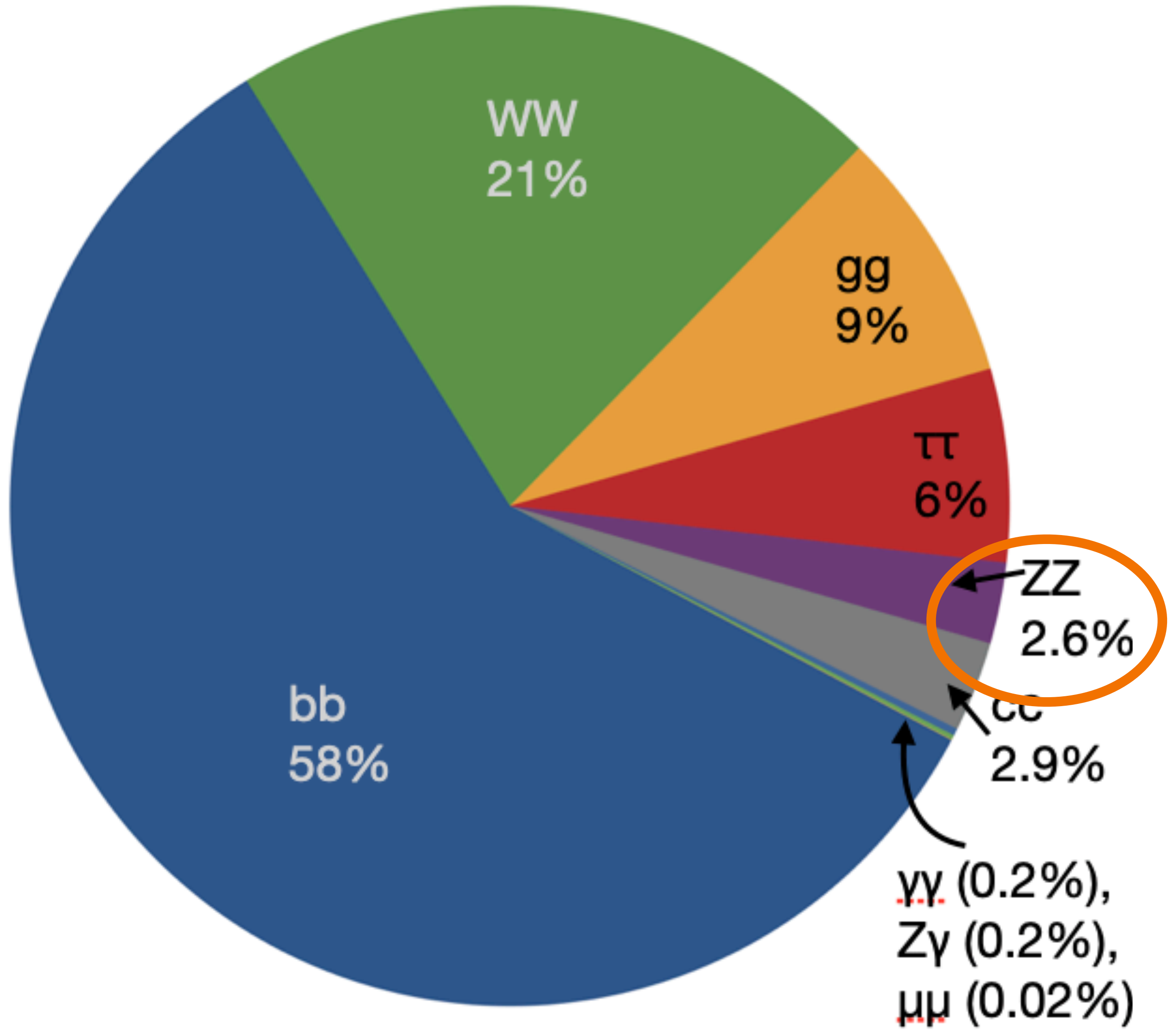



? :-(

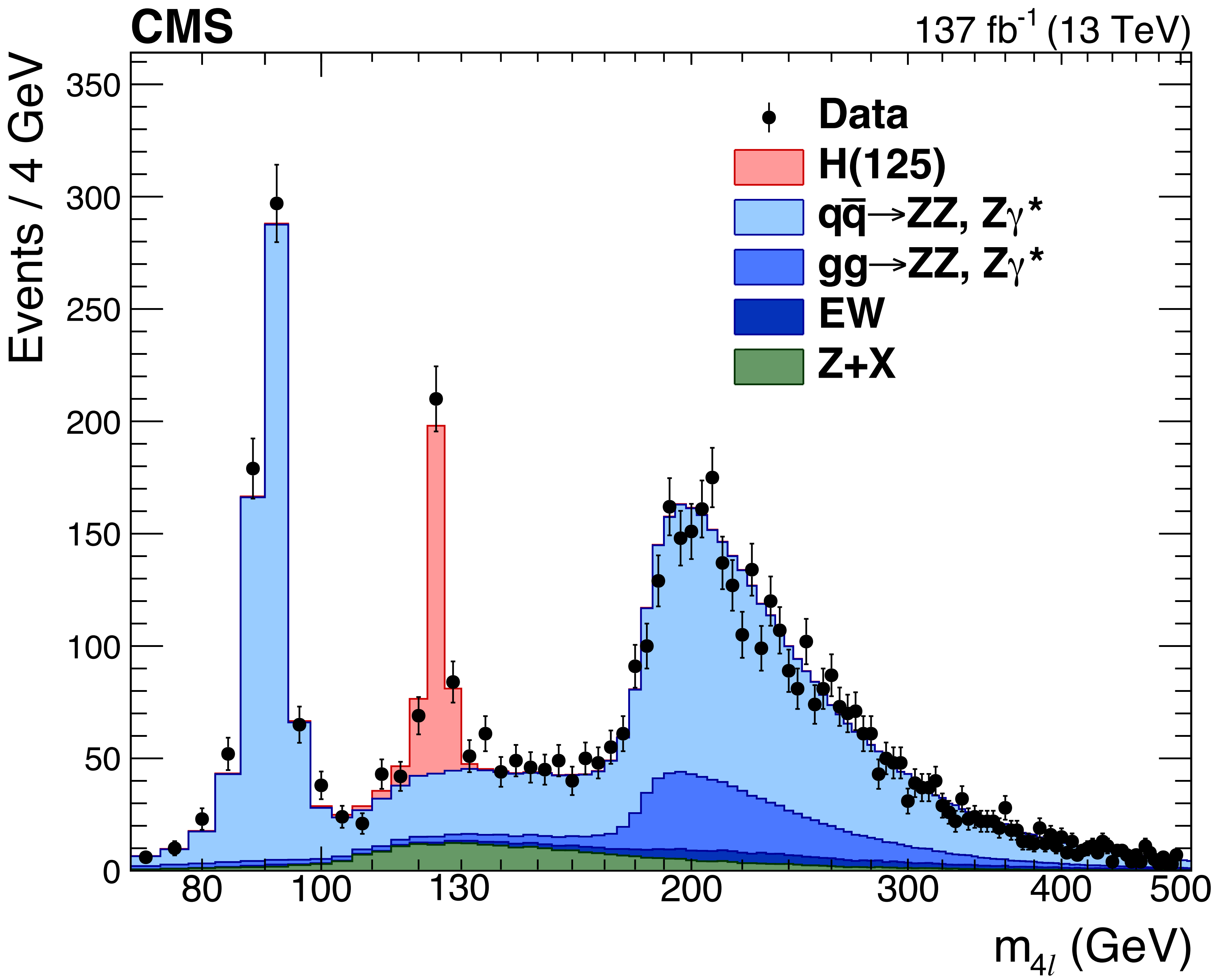
JHEP 08 (2023) 040

HIG-20-001, sub'd to PRD

# H→bb and H→ZZ→4l



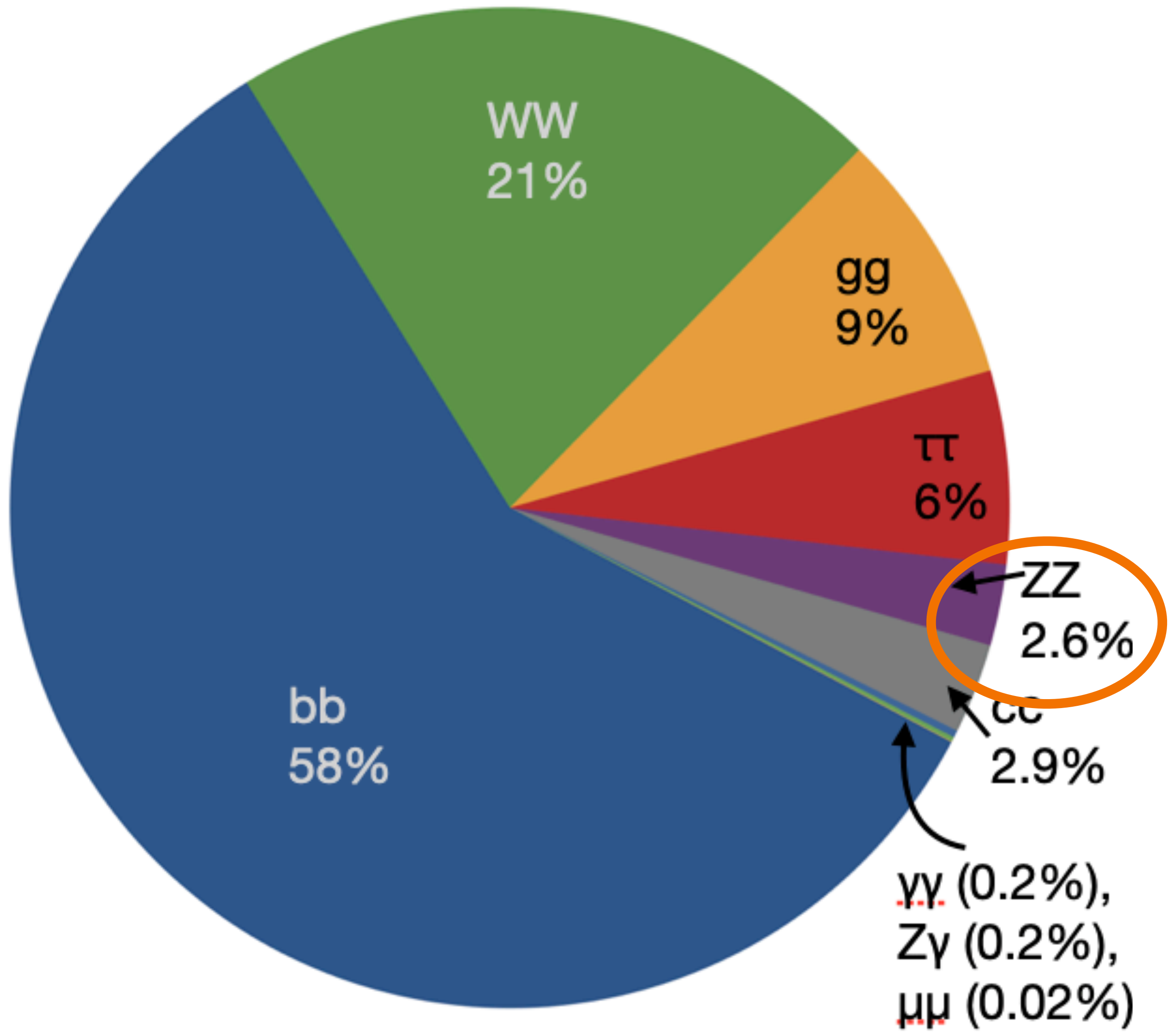

? :-(




JHEP 08 (2023) 040

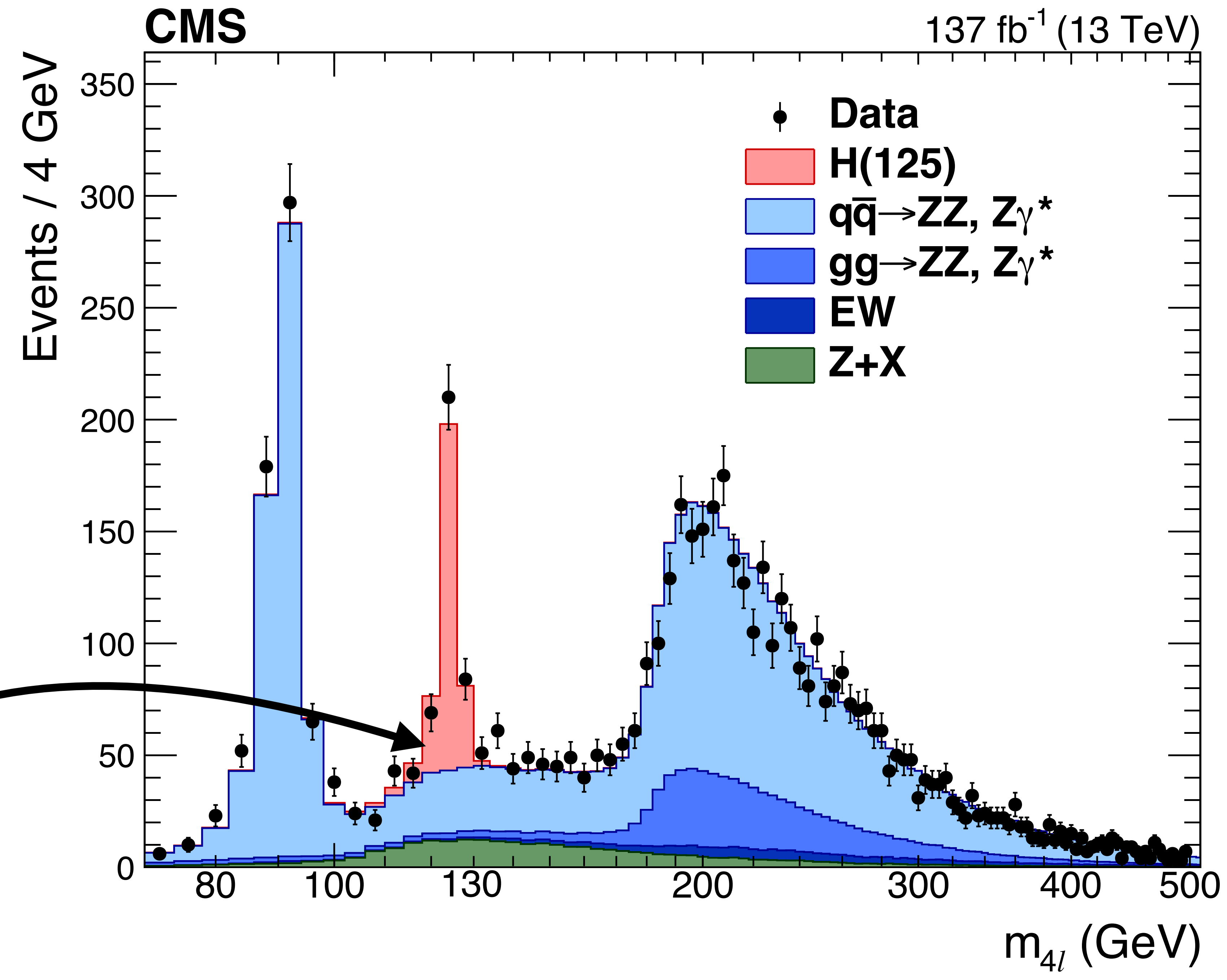
HIG-20-001, sub'd to PRD

# H→bb and H→ZZ→4l




? :-(

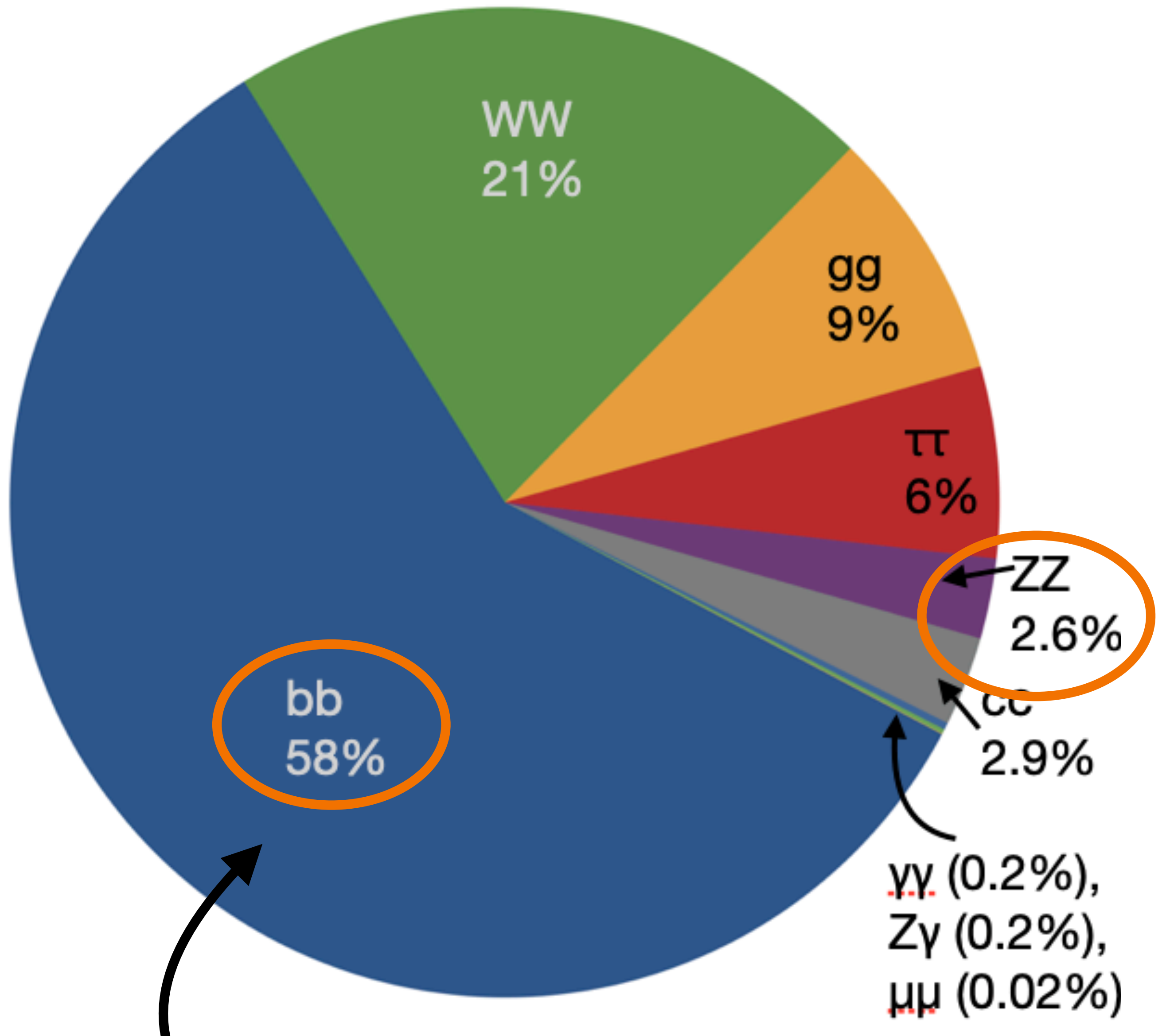
! :-)




JHEP 08 (2023) 040

HIG-20-001, sub'd to PRD

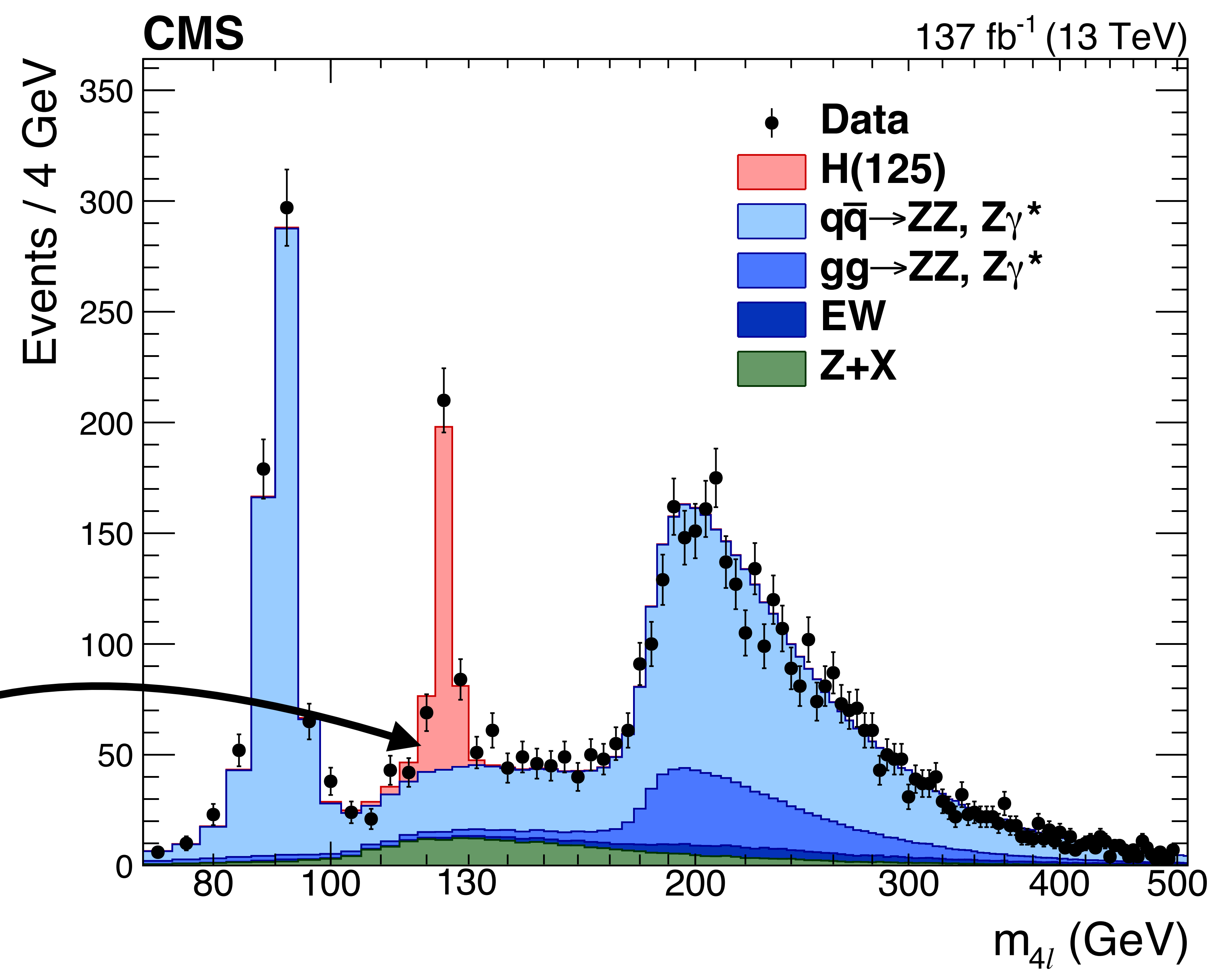
# H→bb and H→ZZ→4l




! :-)

? :-(

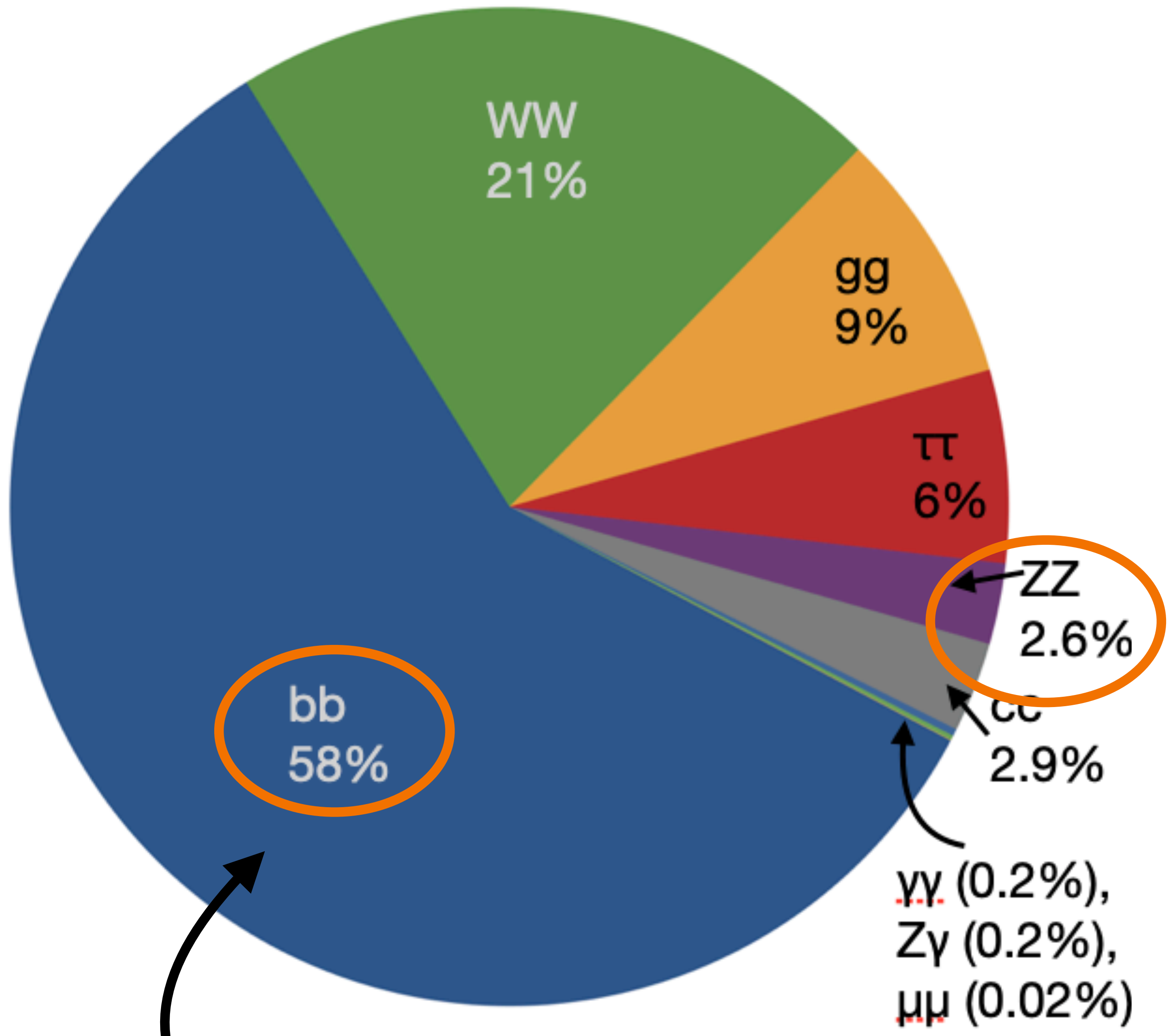
! :-)




JHEP 08 (2023) 040

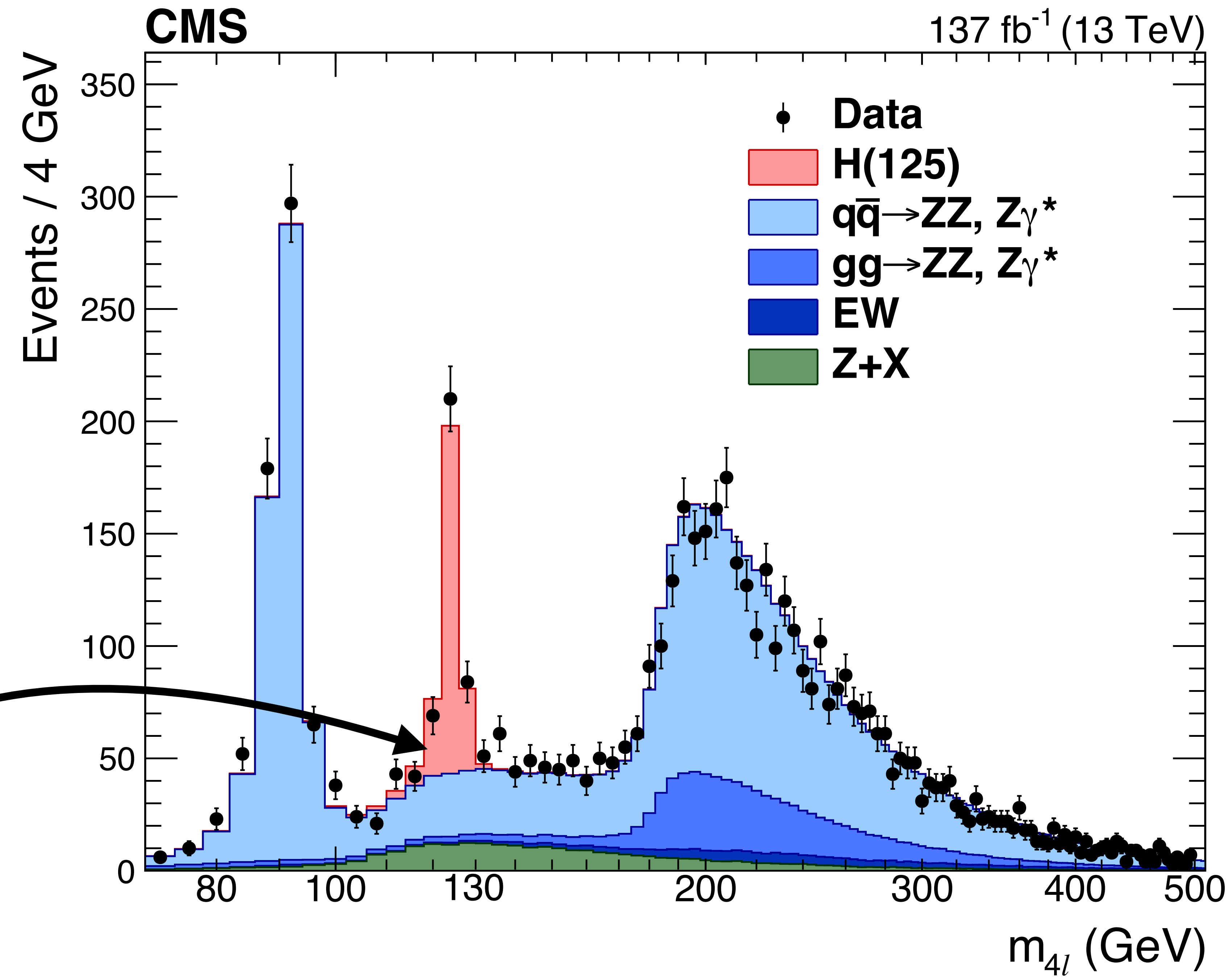
HIG-20-001, sub'd to PRD

# H→bb and H→ZZ→4l



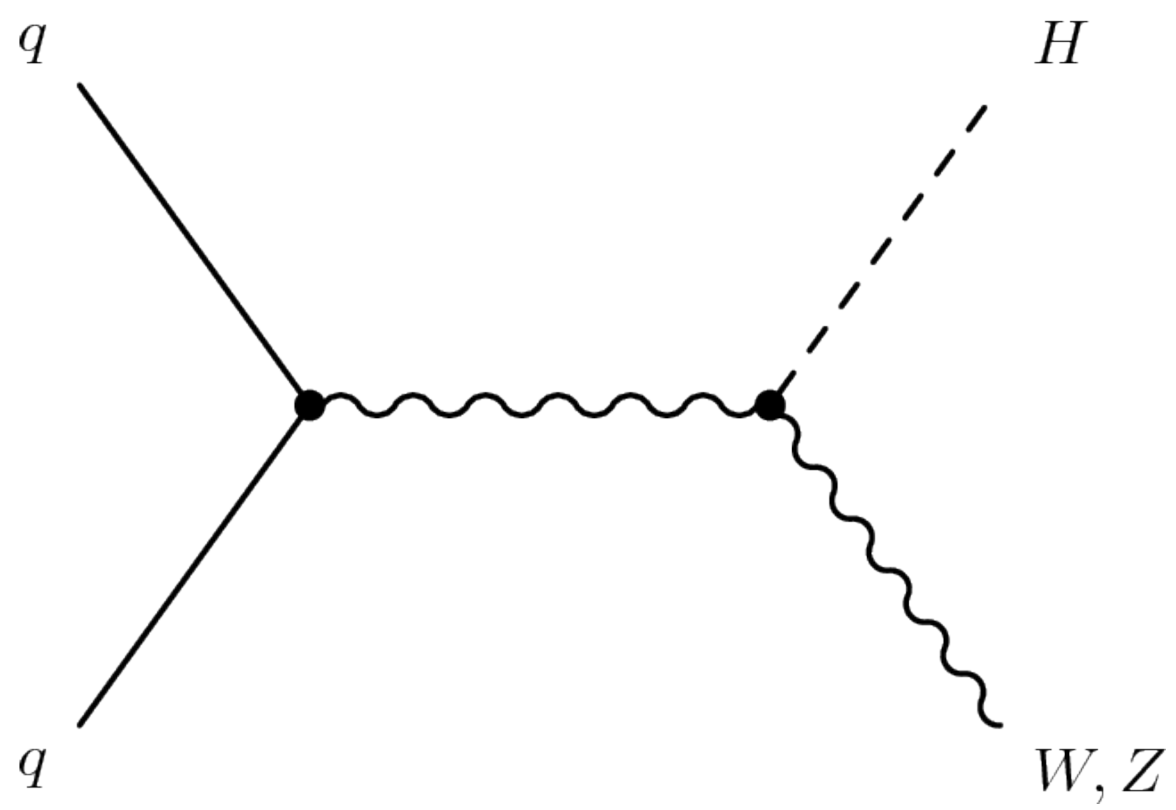

? :-(

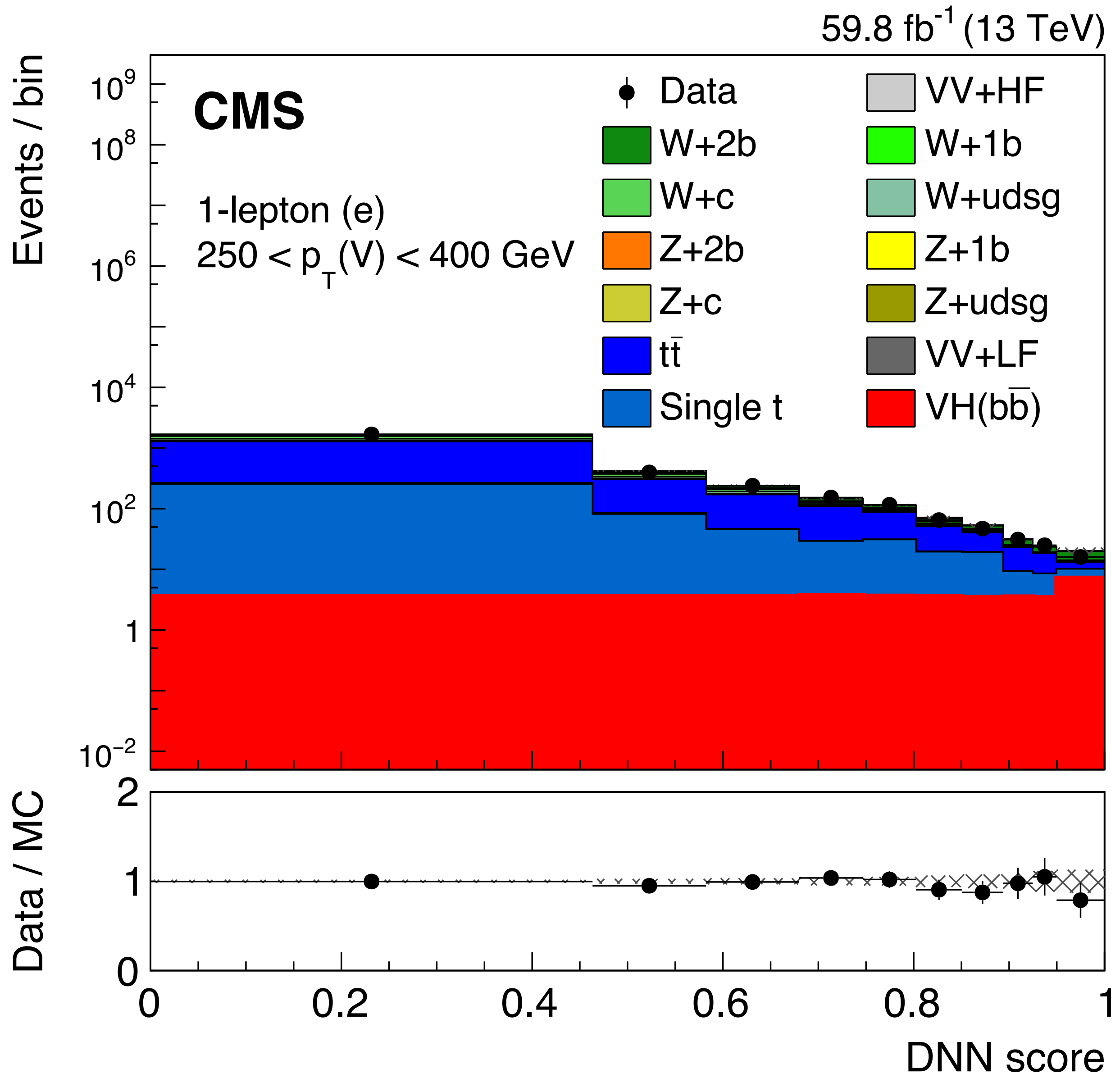
! :-)




JHEP 08 (2023) 040

! :-)

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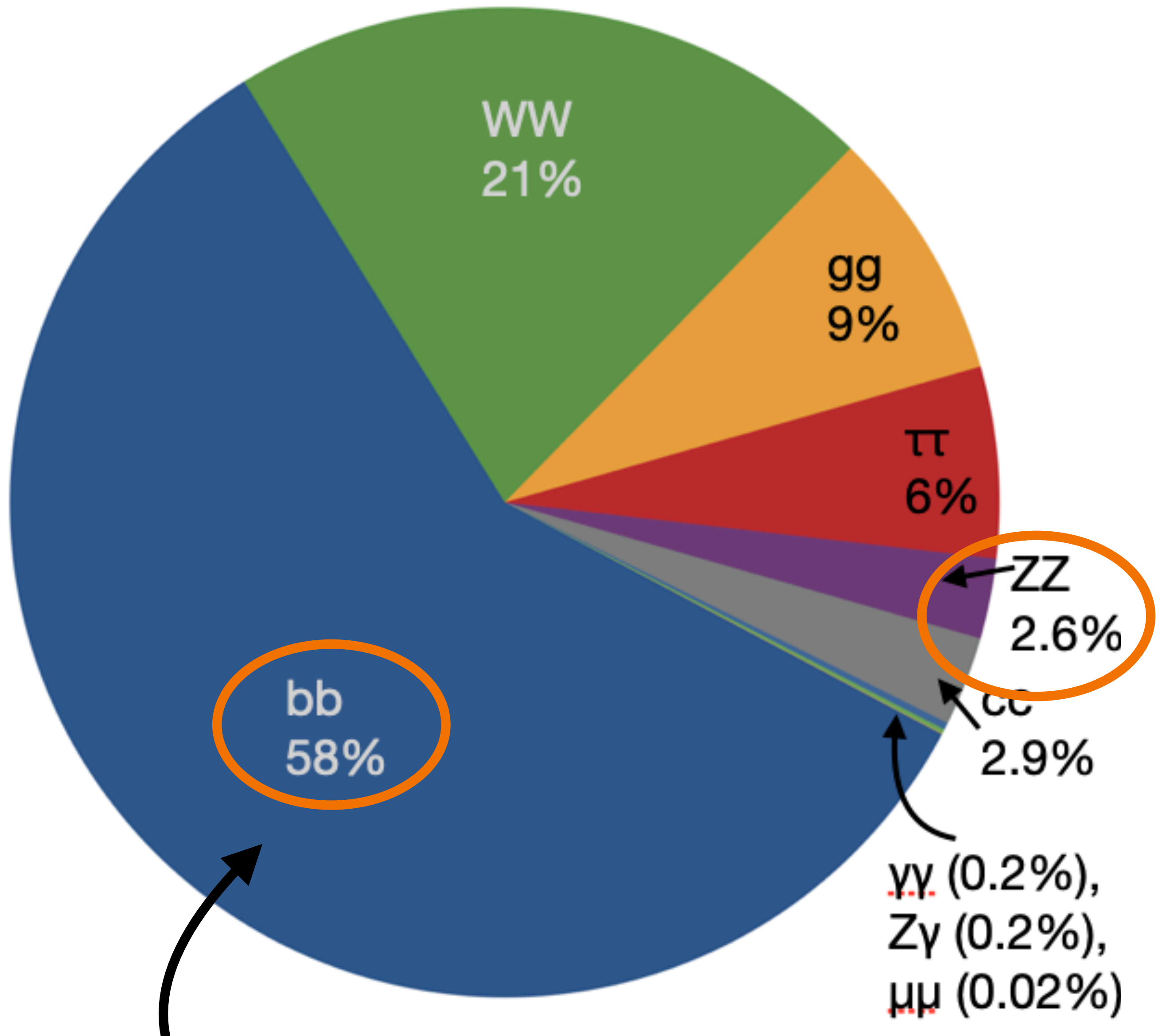
HIG-20-001, sub'd to PRD

# H→bb and H→ZZ→4l

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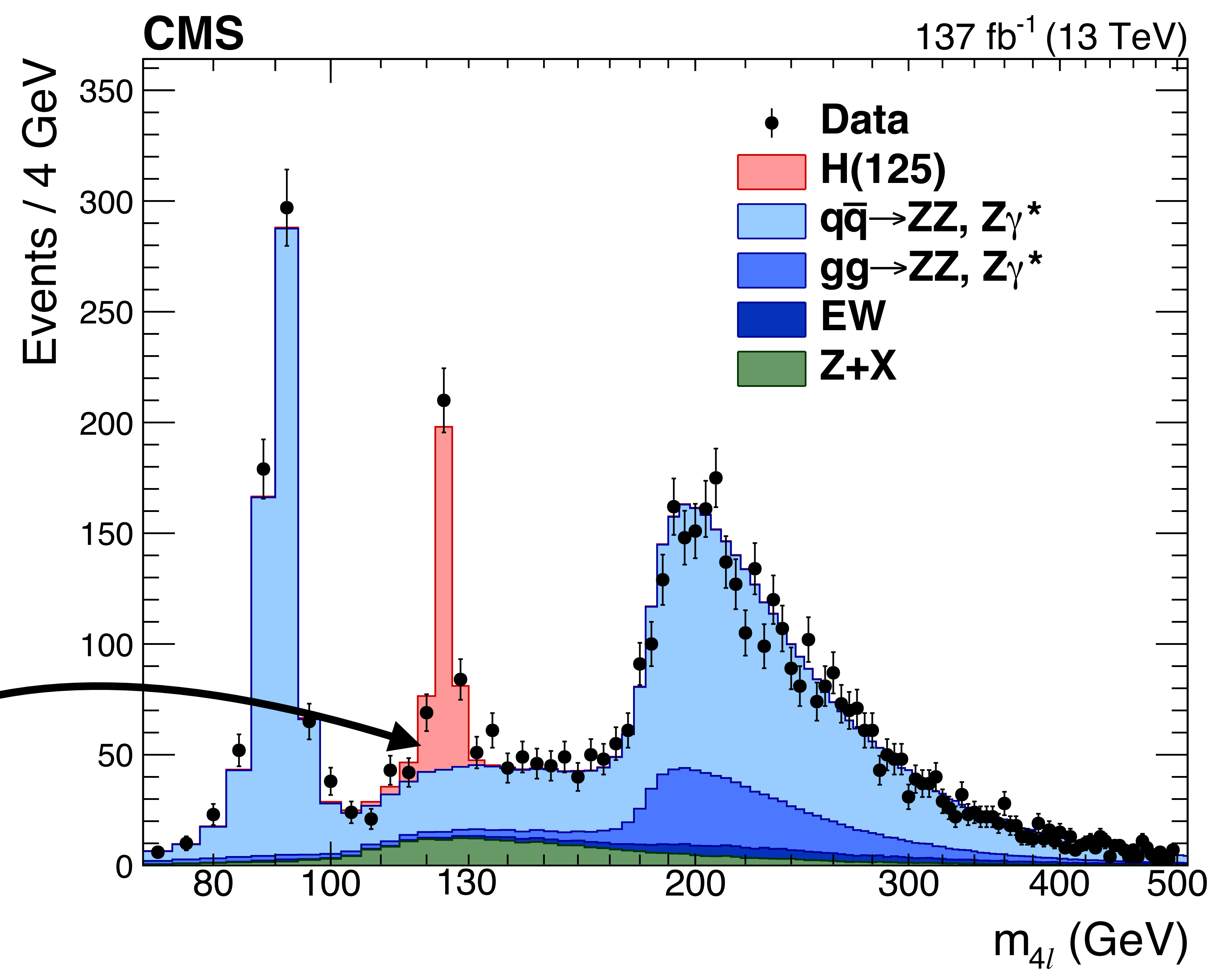
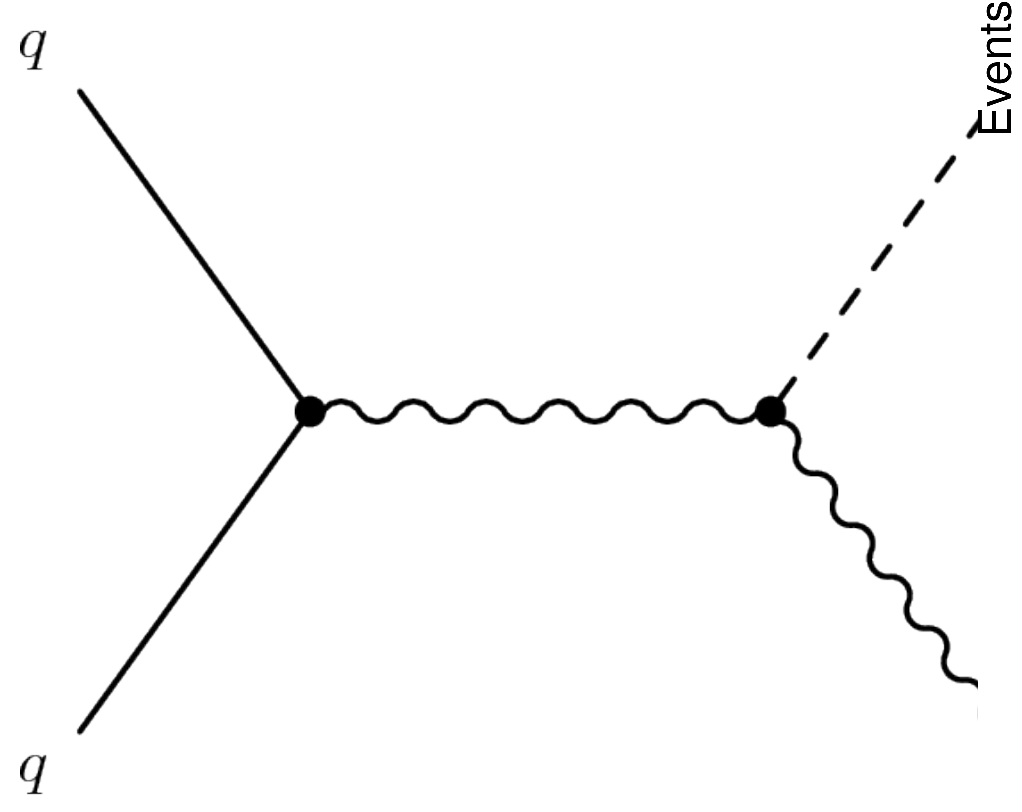
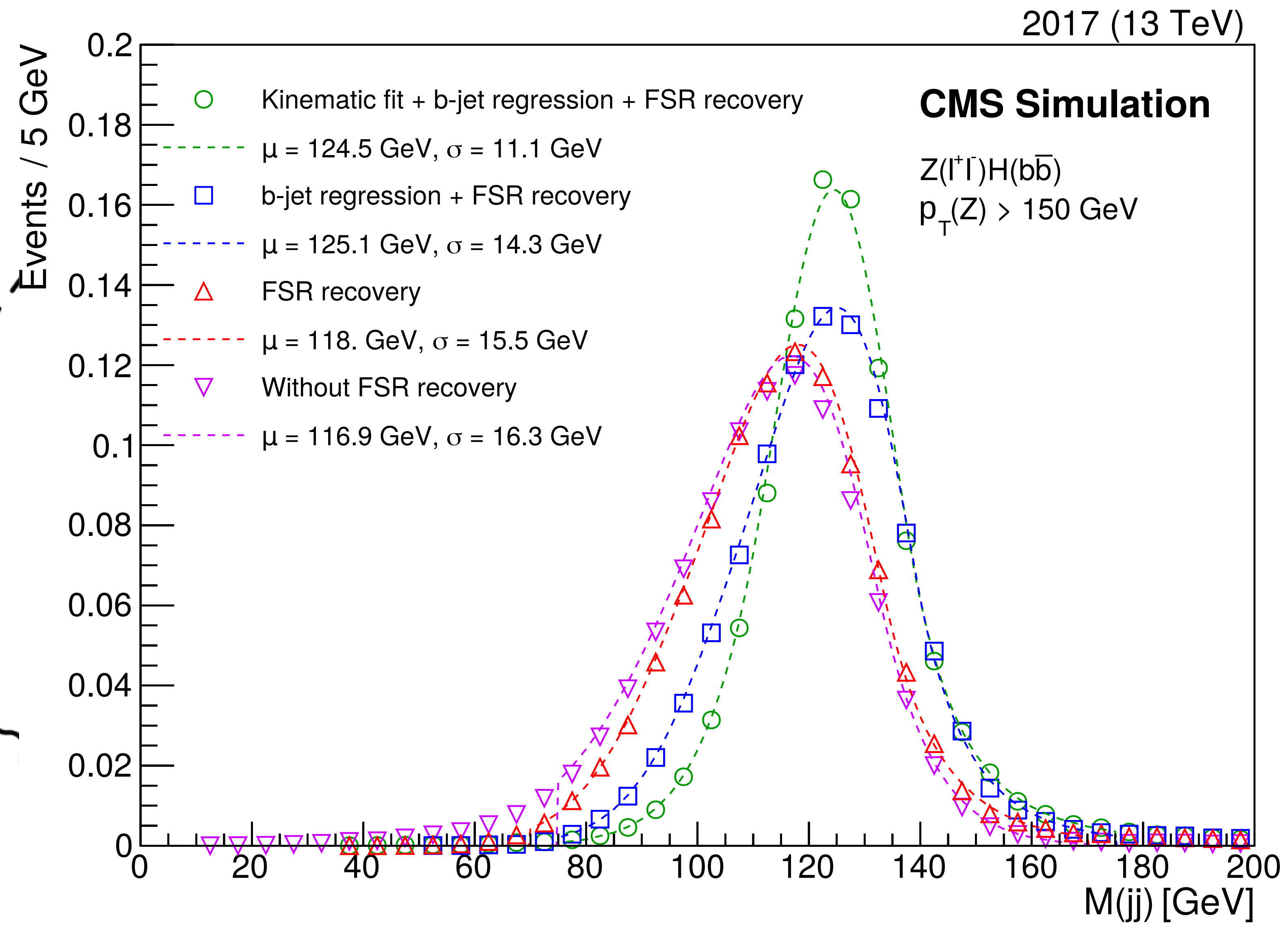
! :-)




JHEP 08 (2023) 040

! :-)

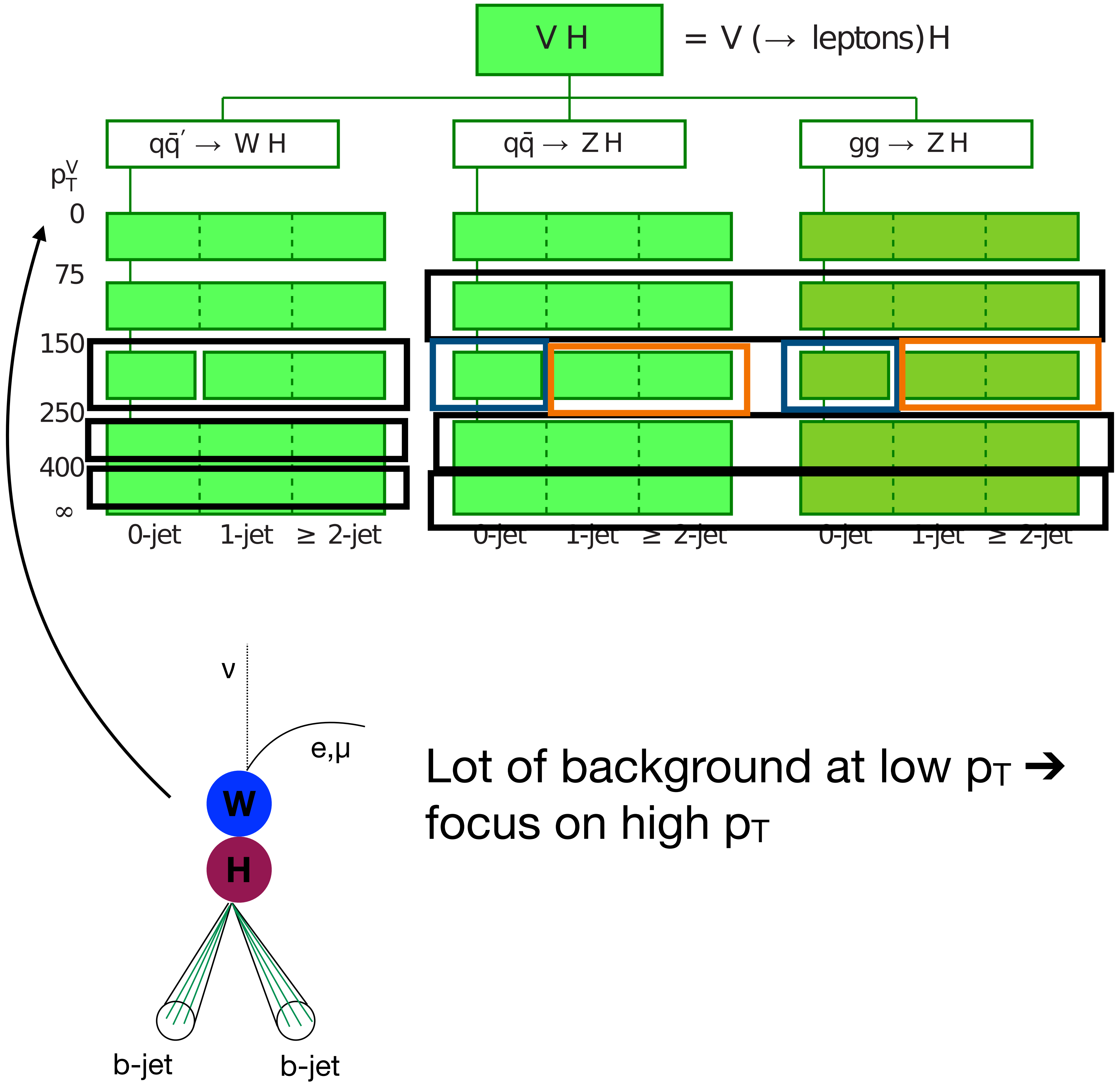



:/

HIG-20-001, sub'd to PRD

# STXS - VH, H➔bb

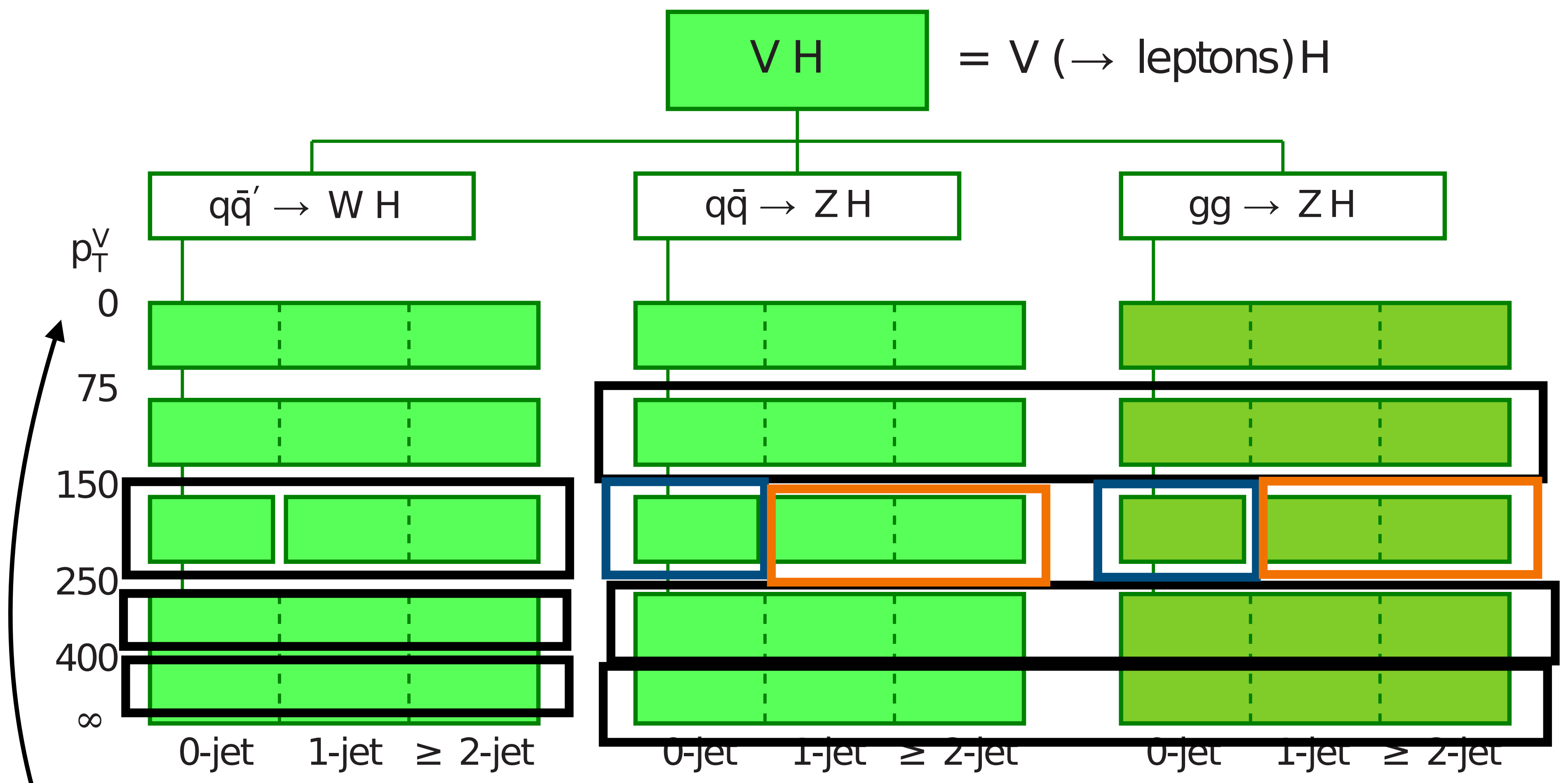


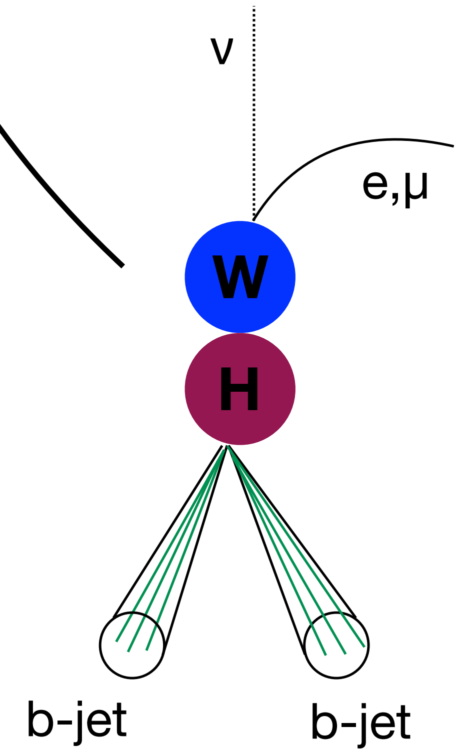

Lot of background at low $p_T$ ➔ focus on high $p_T$



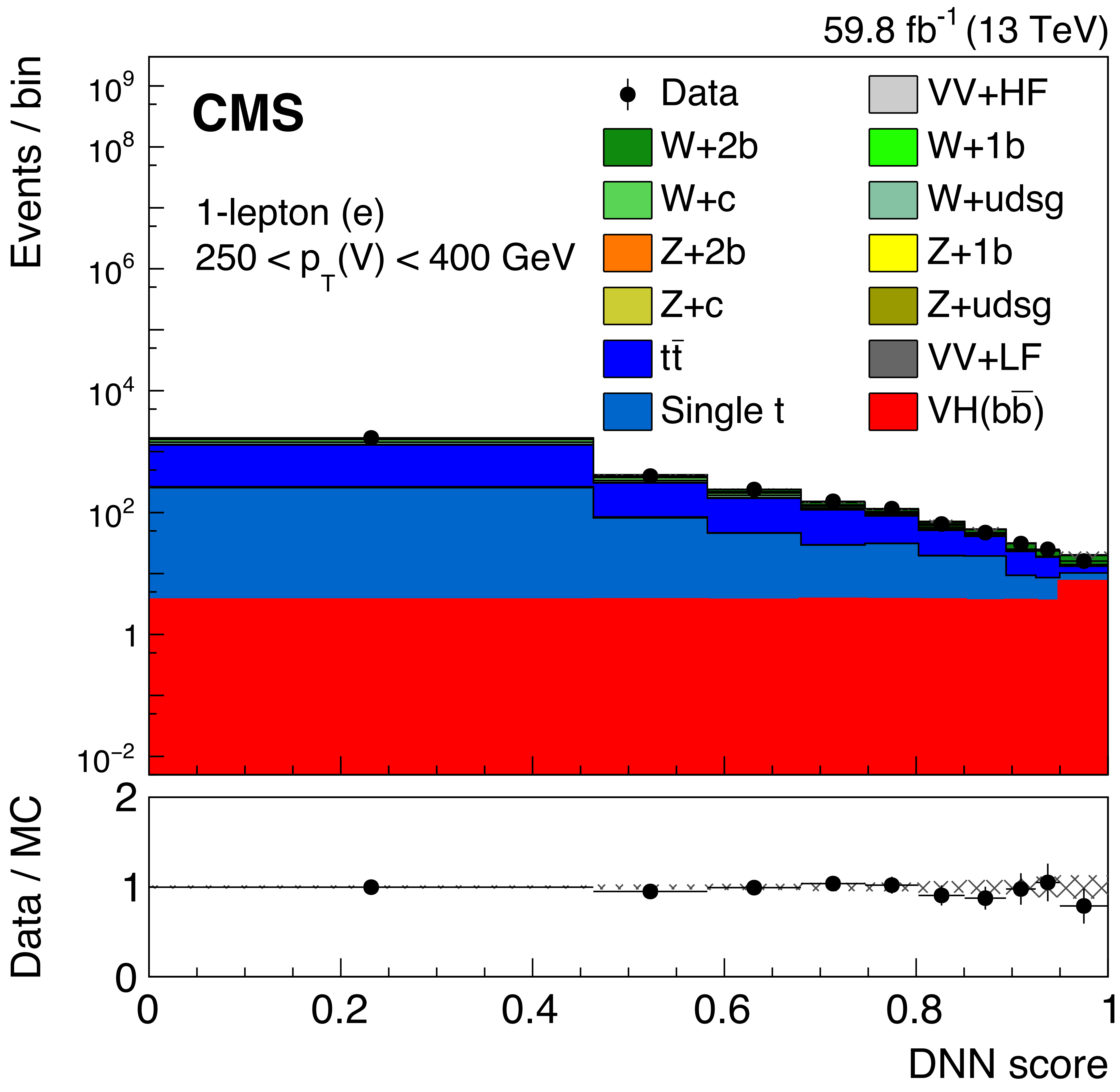
HIG-20-001, sub'd to PRD

# STXS - VH, H→bb




Lot of background at low $p_T$ ➔ focus on high $p_T$



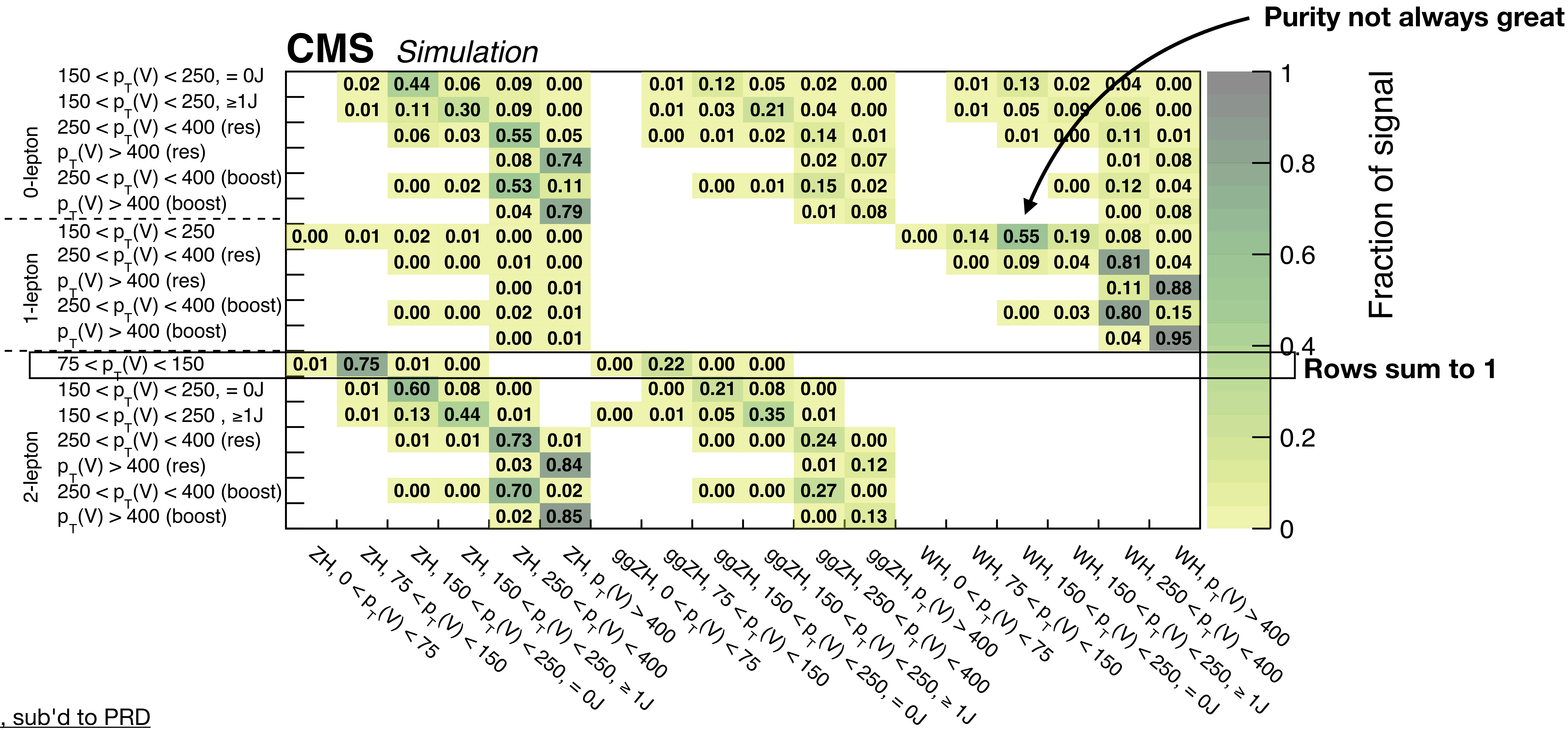

Ok, still a lot of background at high $p_T$ ➔

(1) control regions to help model ttbar, W/Z+b, W/Z+light
(2) Rely on DNN to increase sensitivity

HIG-20-001, sub'd to PRD

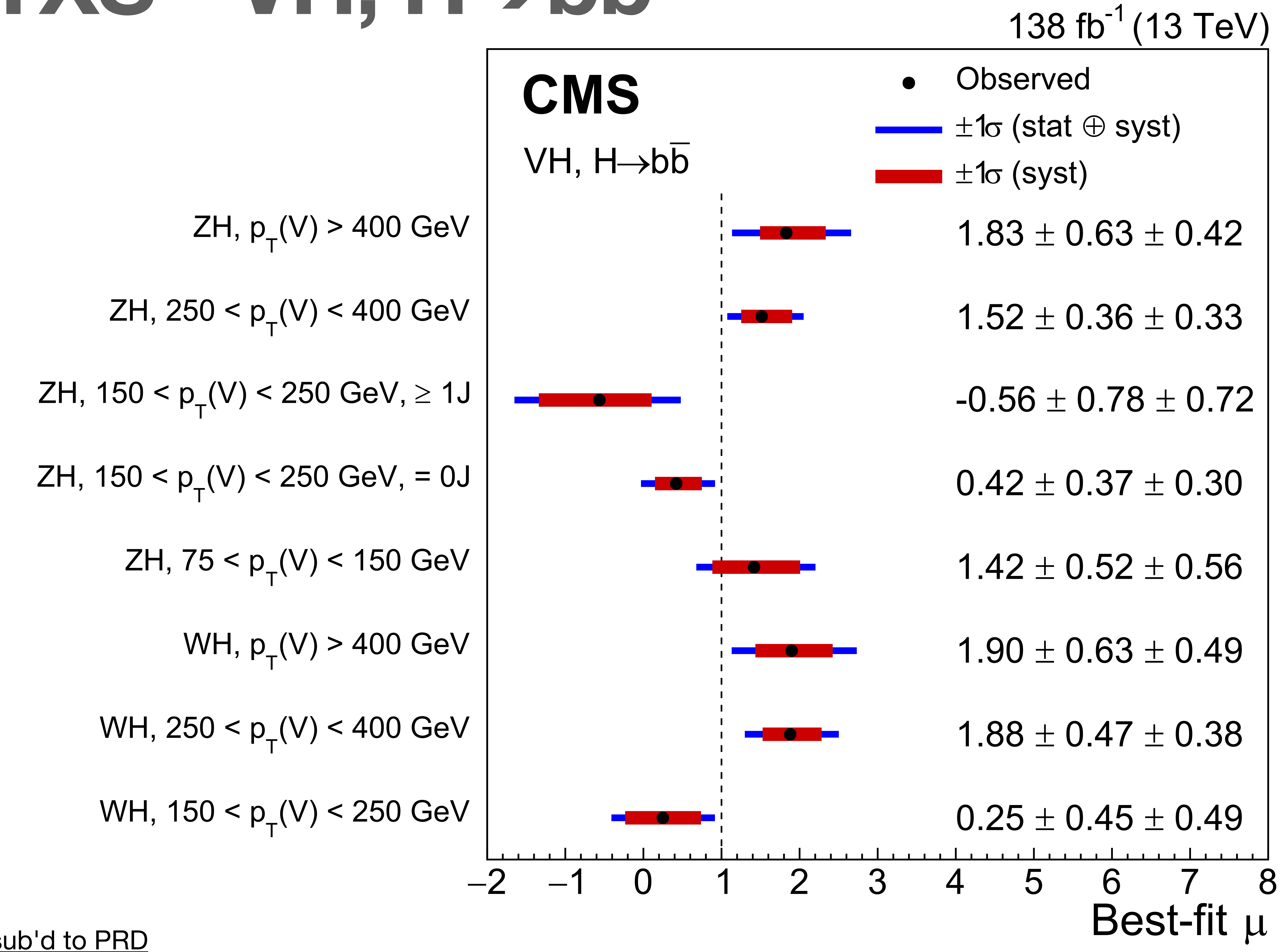
# STXS - VH, H→bb

Categorization in different reco-level categories to be able to measure STXS bins




HIG-20-001, sub'd to PRD

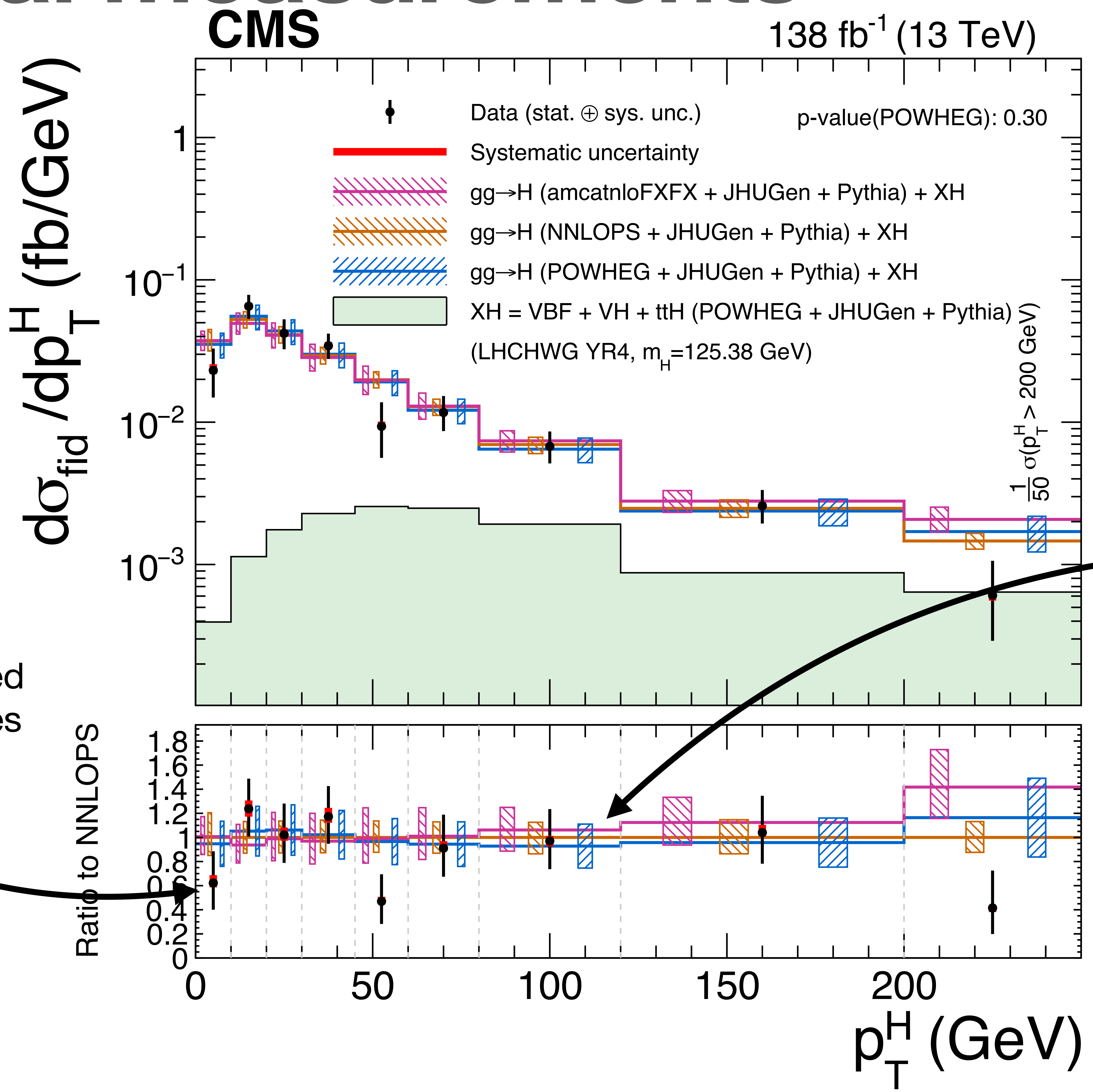
# STXS - VH, H→bb




STXS signal strengths rather than cross sections ➔ include theory uncertainties in systematic component

HIG-20-001, sub'd to PRD

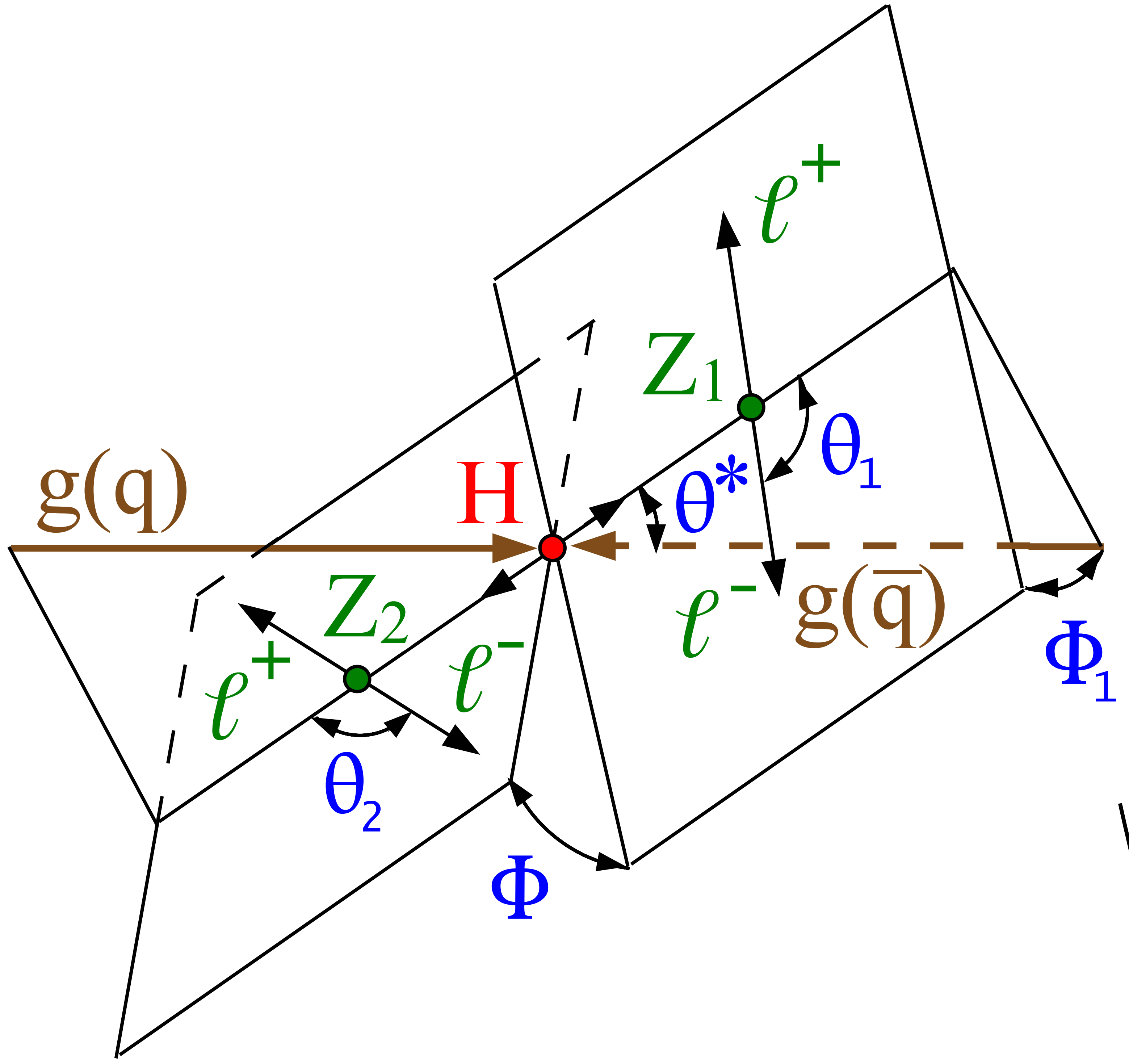
# Differential measurements




Generally good agreement with MC predictions

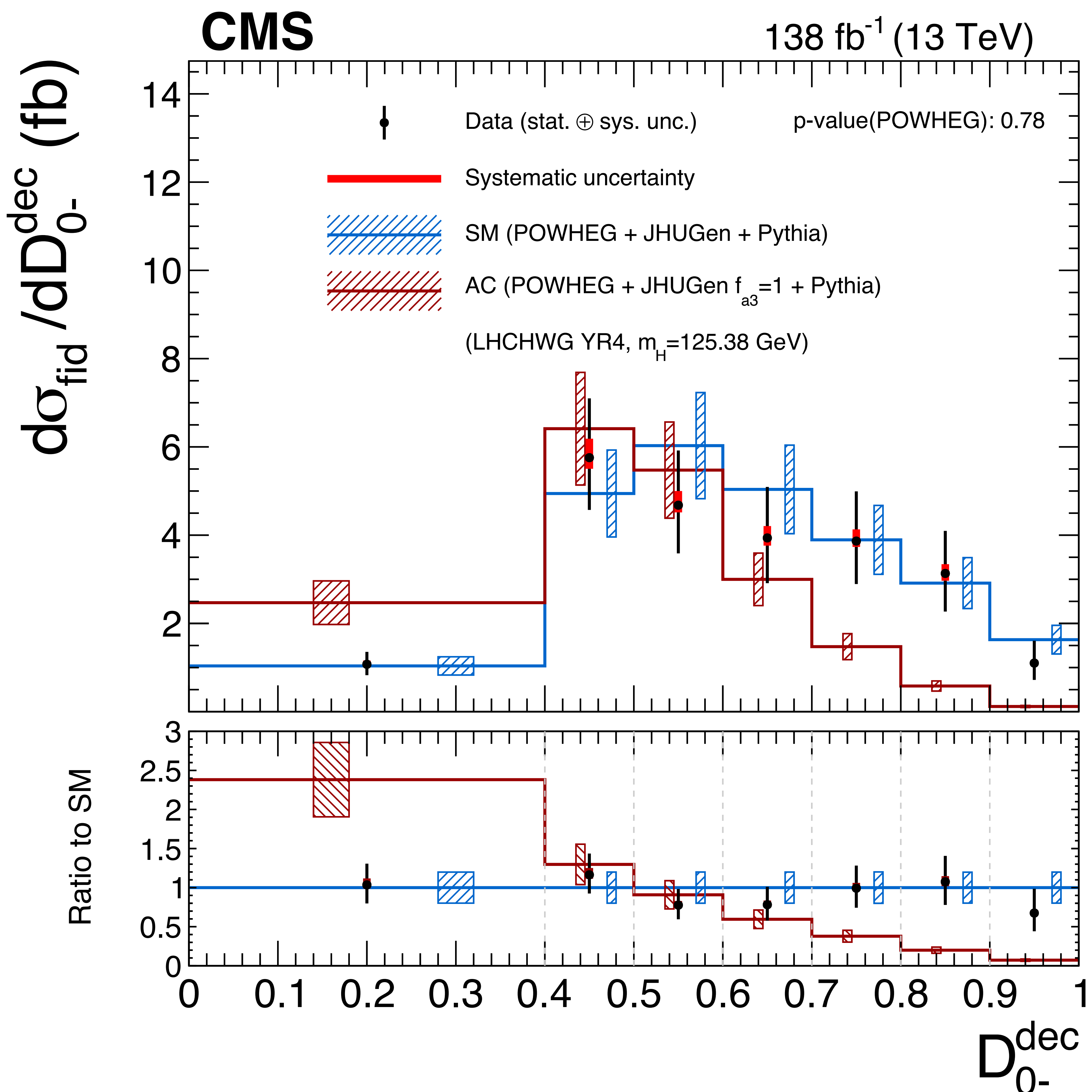
Measurements dominated by statistical uncertainties

# Differential measurements




**Probability, based on angular and kinematic properties, that event is SM-like or anomalous-like**

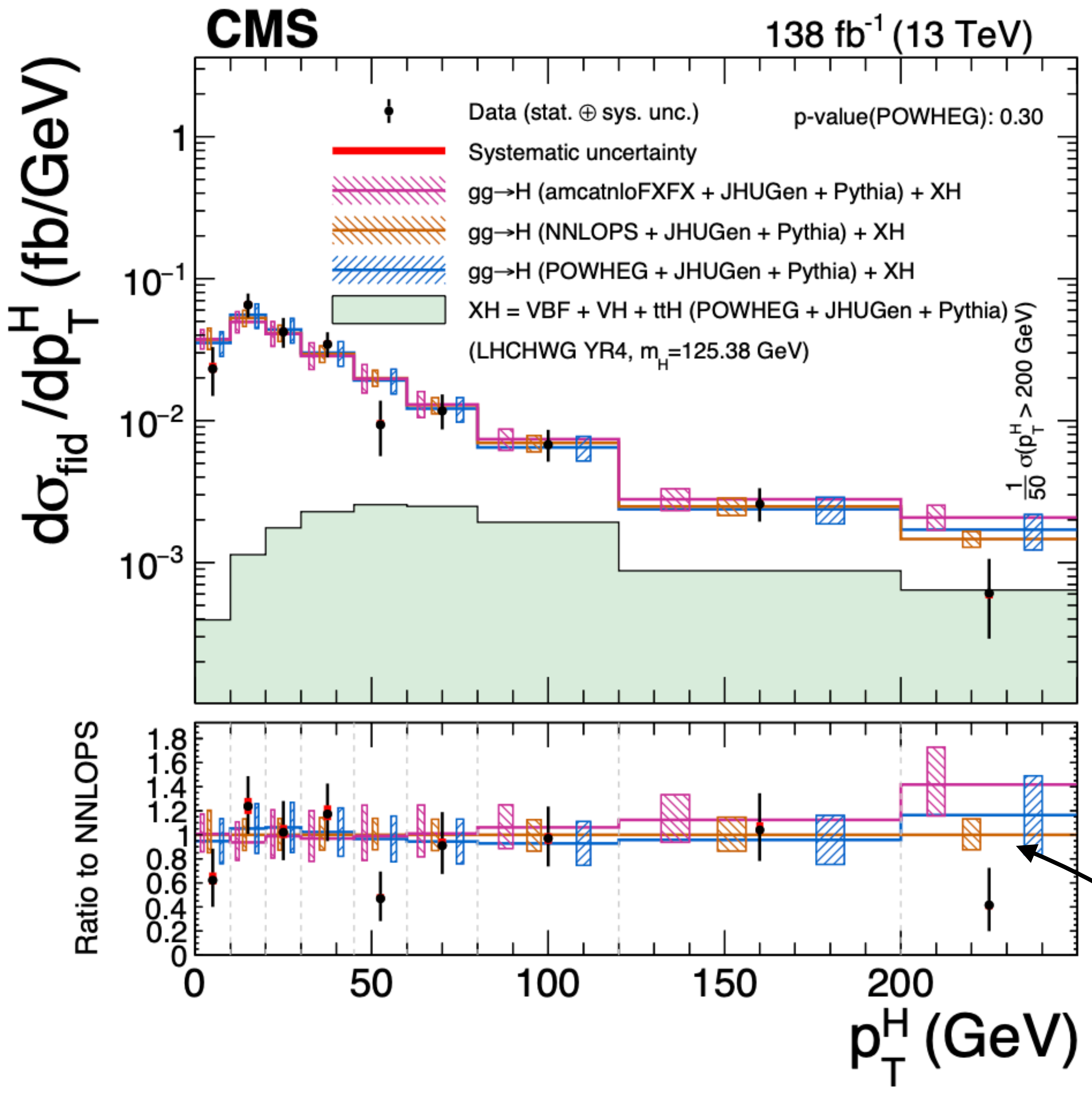
$$\mathcal{D}_{\text{alt}}\left(\vec{\Omega}\right) = \frac{\mathcal{P}_{\text{sig}}\left(\vec{\Omega}\right)}{\mathcal{P}_{\text{sig}}\left(\vec{\Omega}\right) + \mathcal{P}_{\text{alt}}\left(\vec{\Omega}\right)},$$

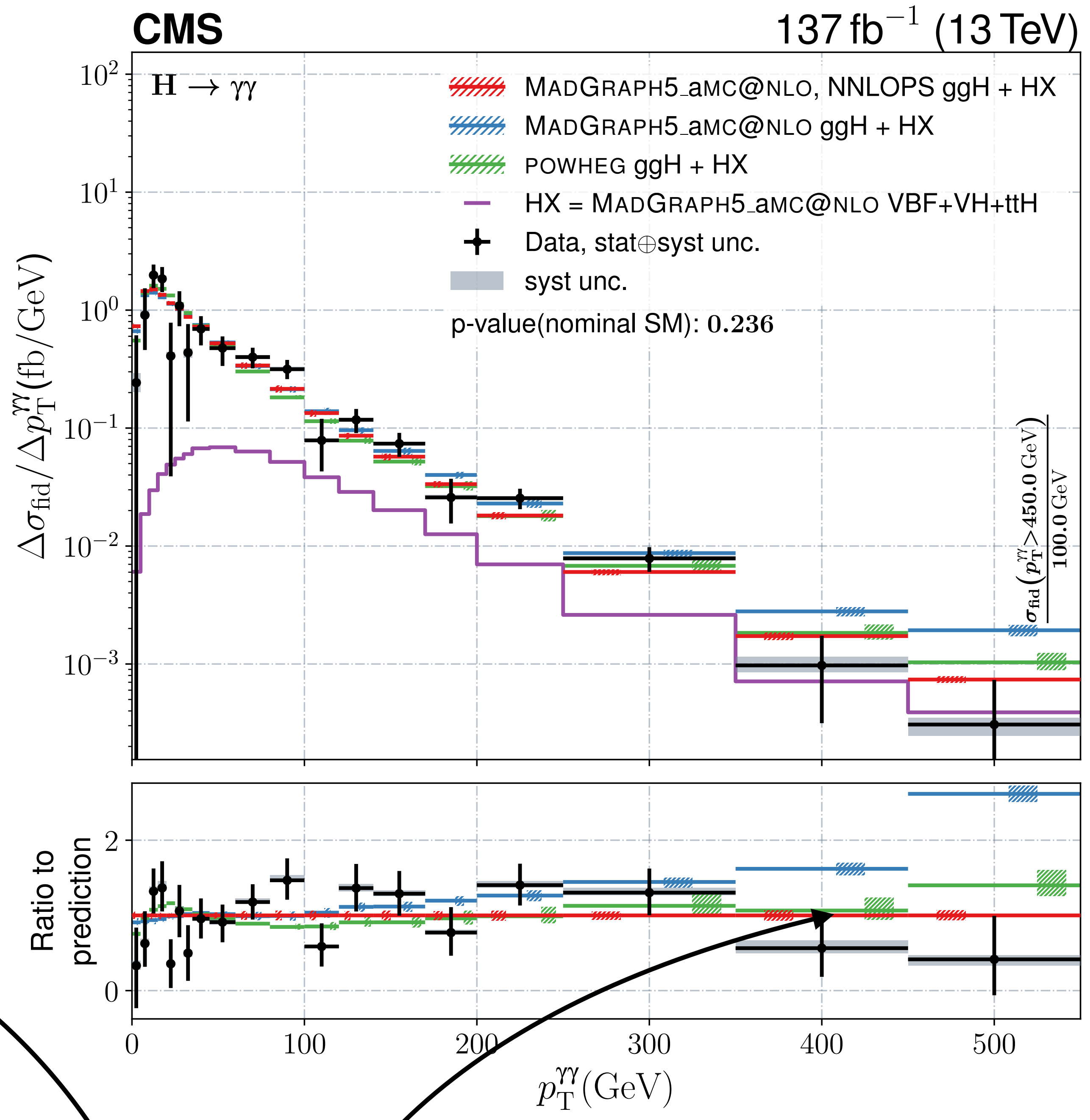


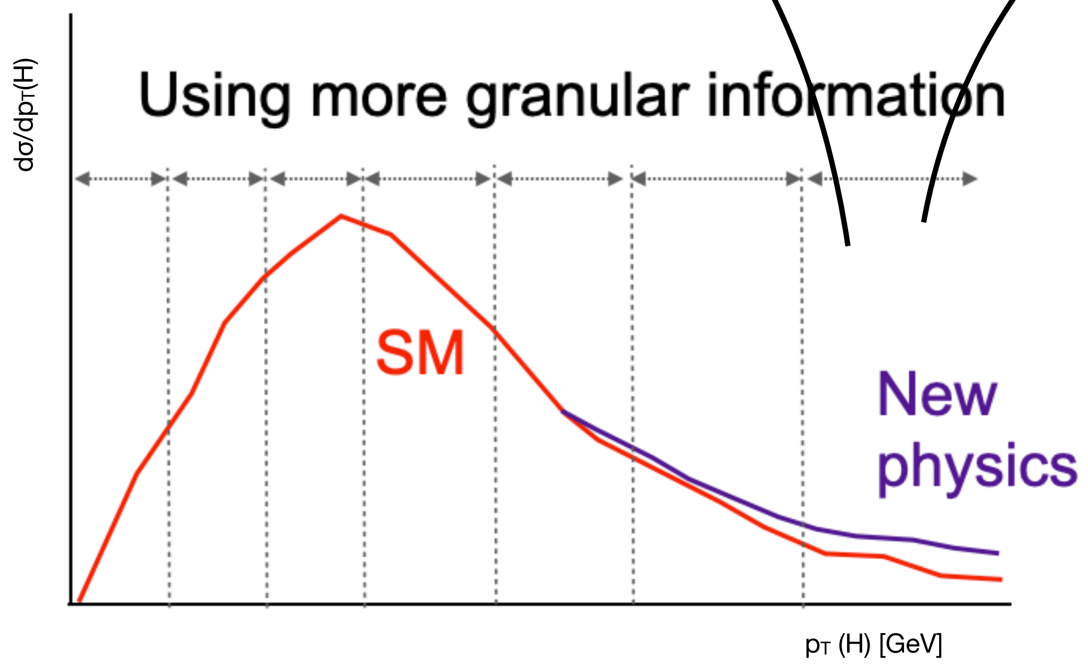

**Discriminant sensitive to anomalous interactions between the Higgs boson and vector bosons**

# Boosting the Higgs

## Why you should care

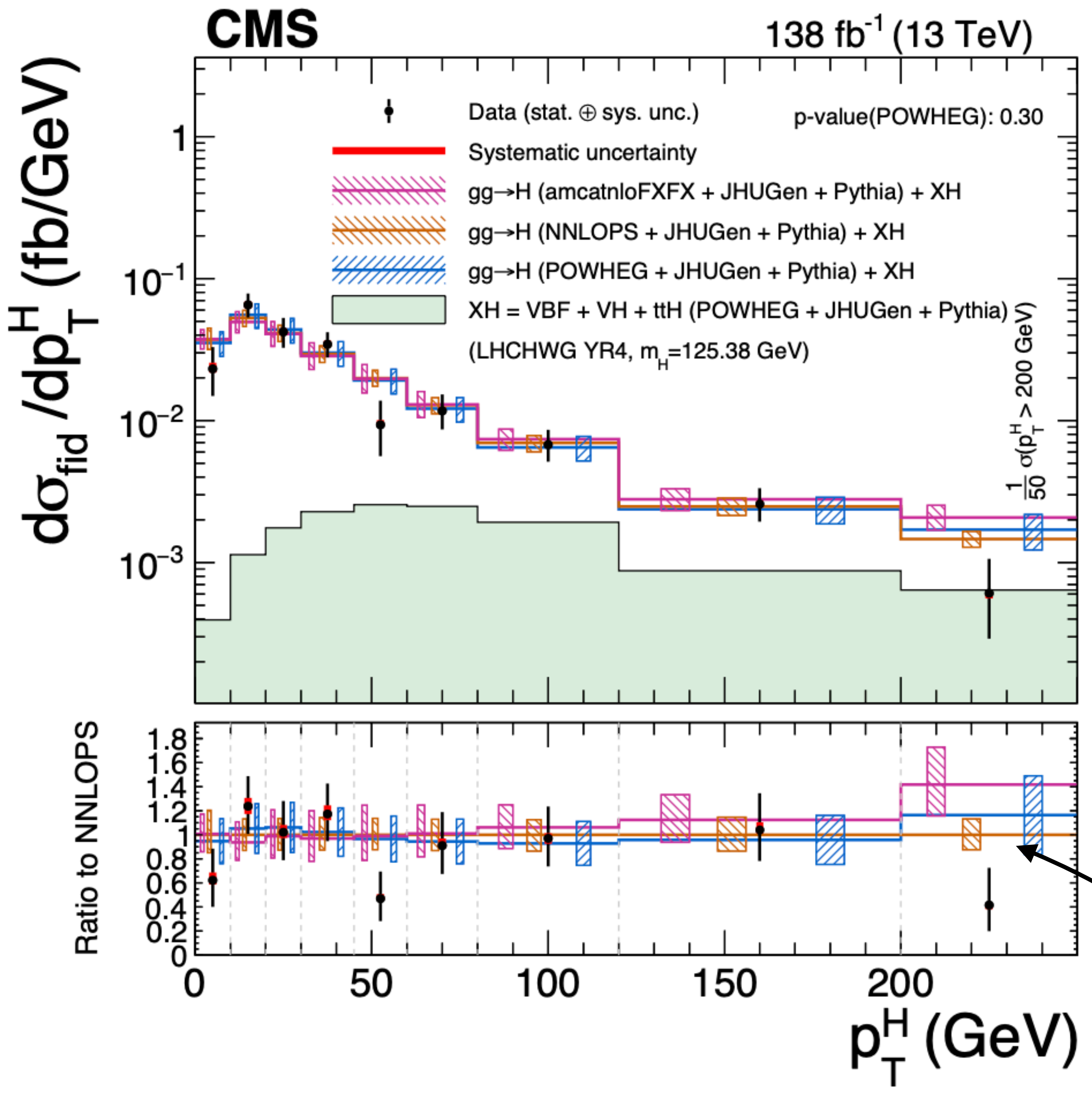


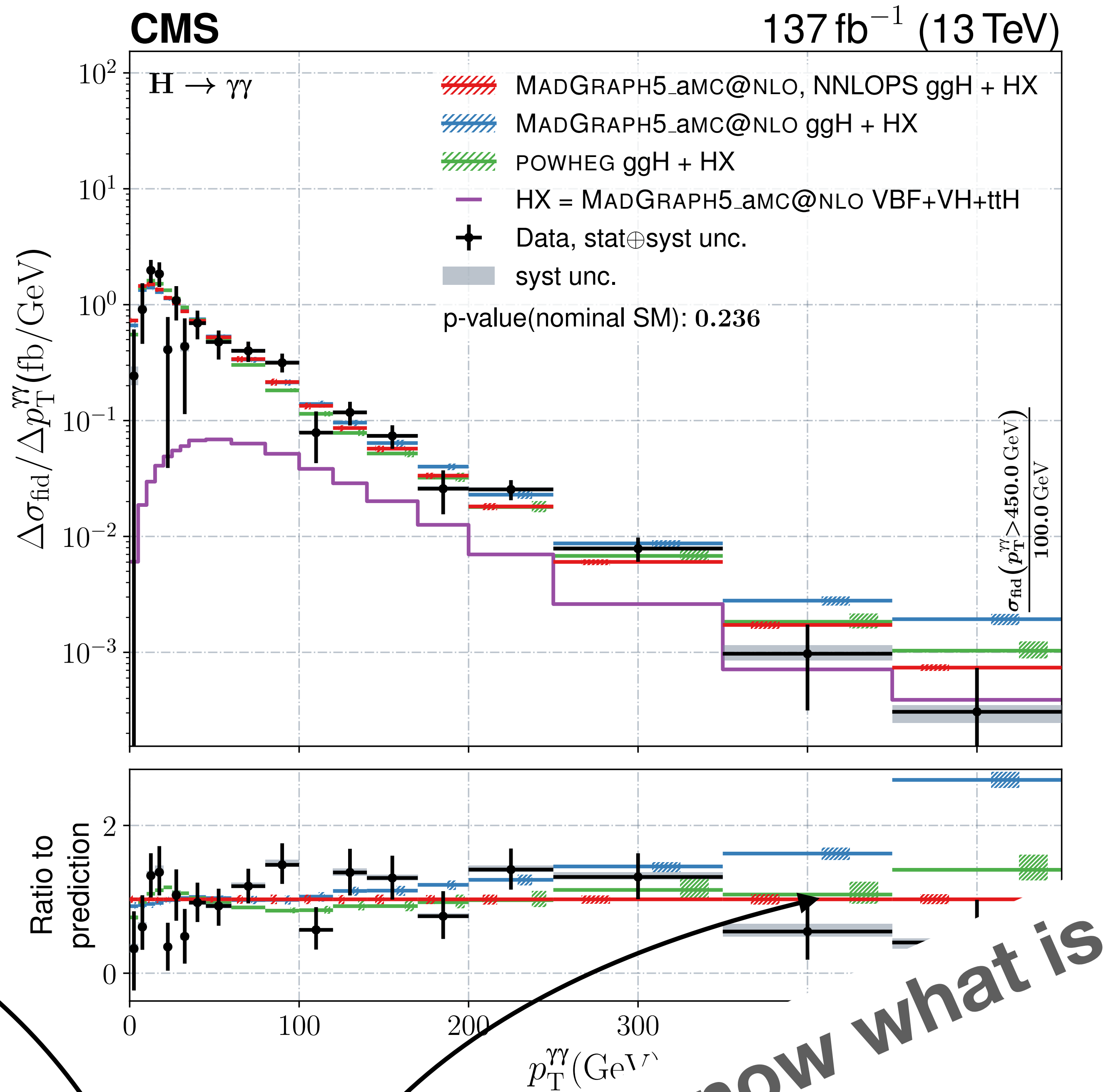



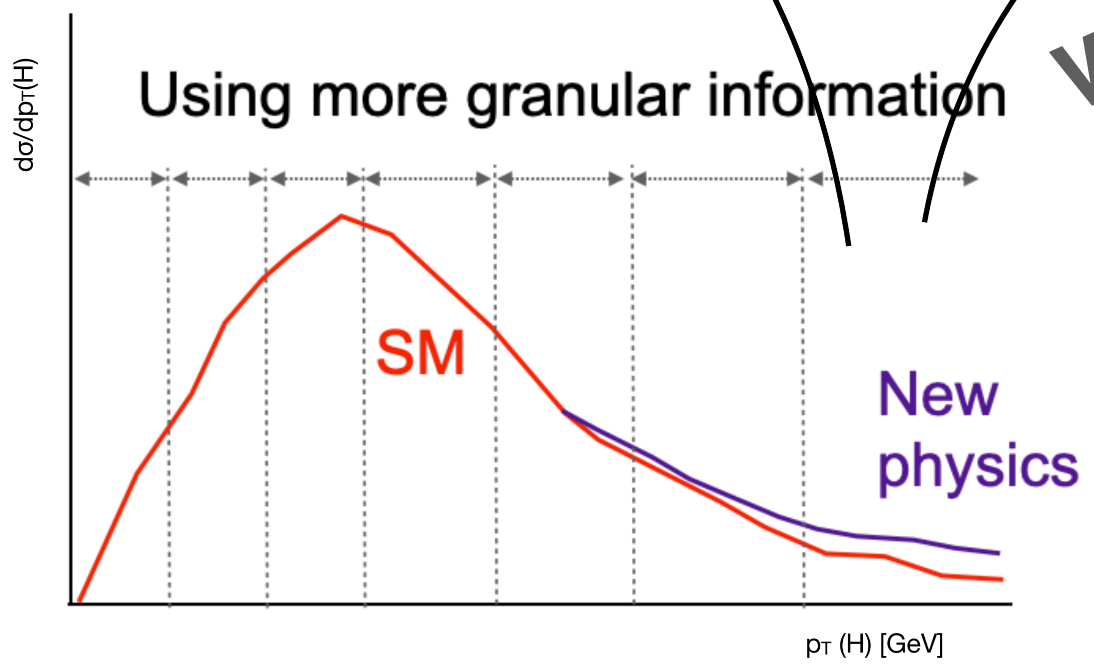



# Boosting the Higgs

## Why you should care

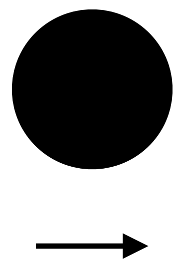


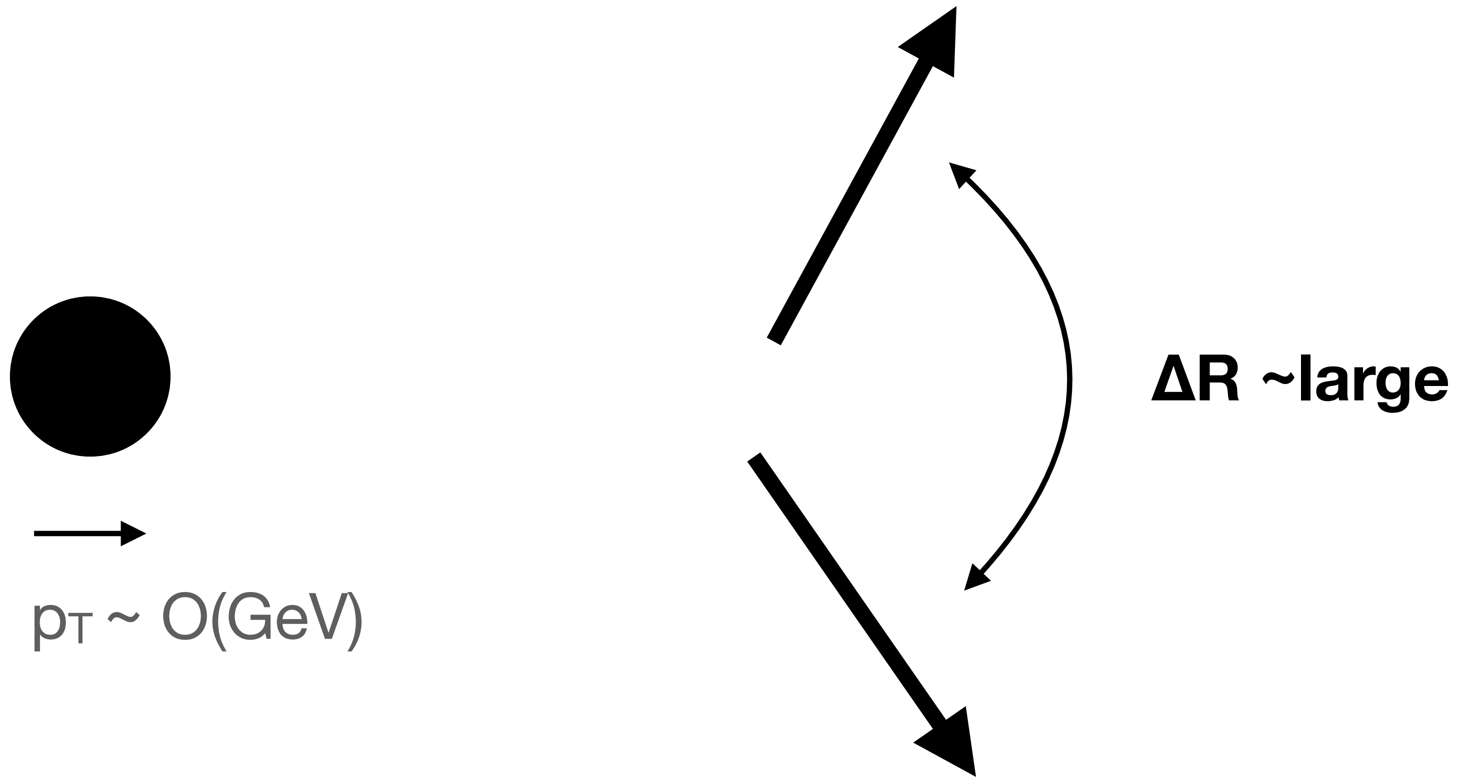

Want to know what is going on here!

# Boosting final states - challenges

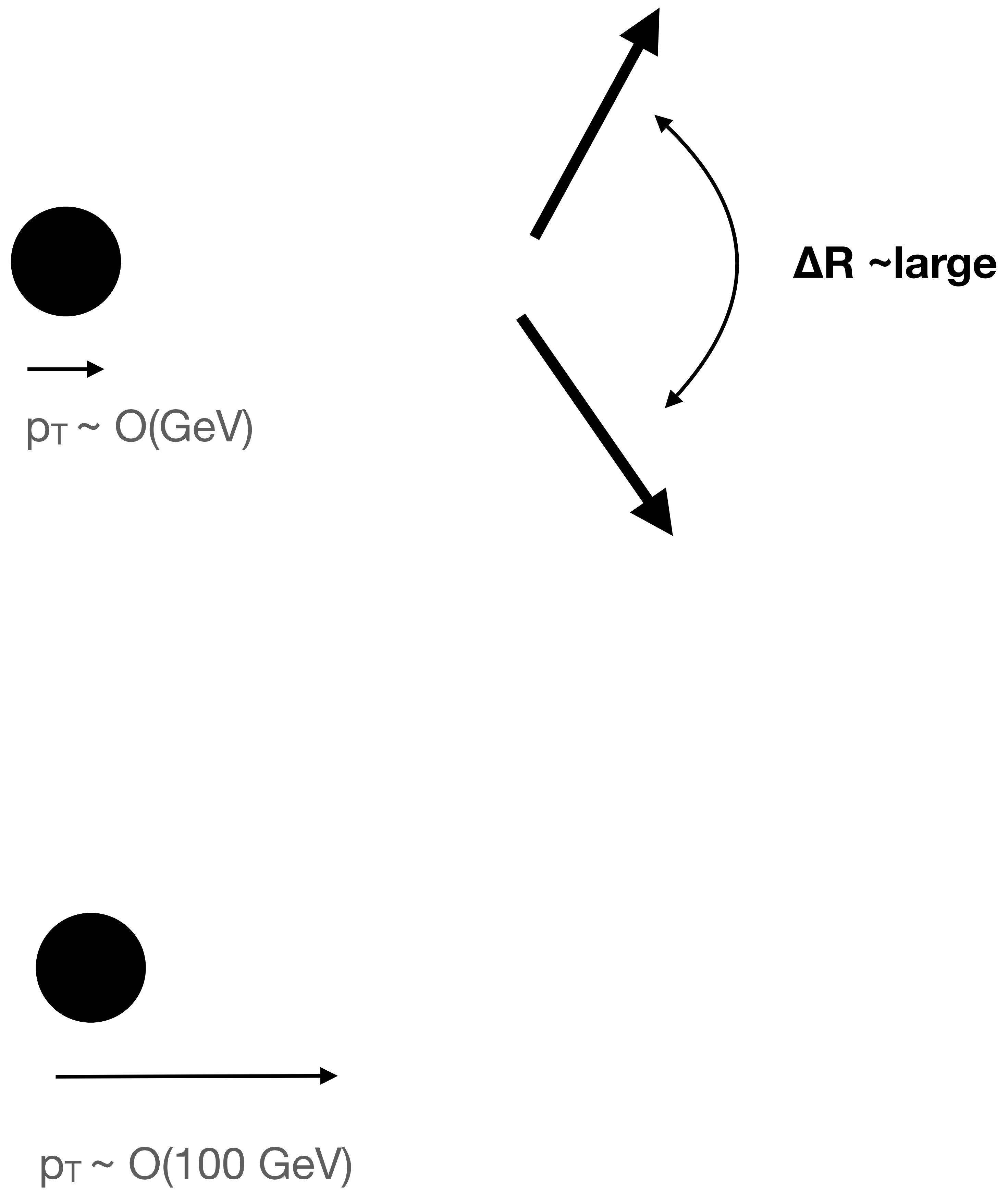


$p_T$ ~ O(GeV)

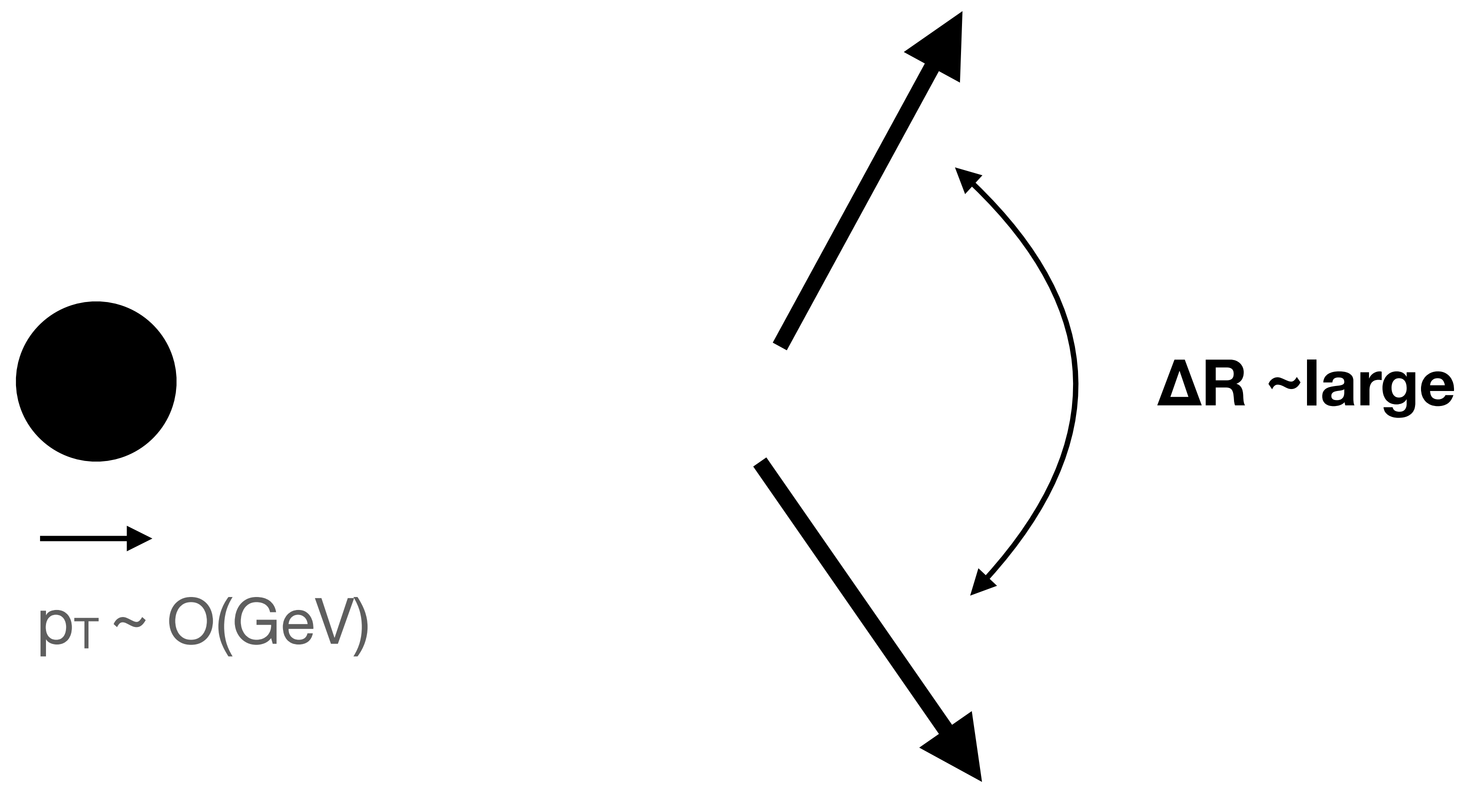
# Boosting final states - challenges

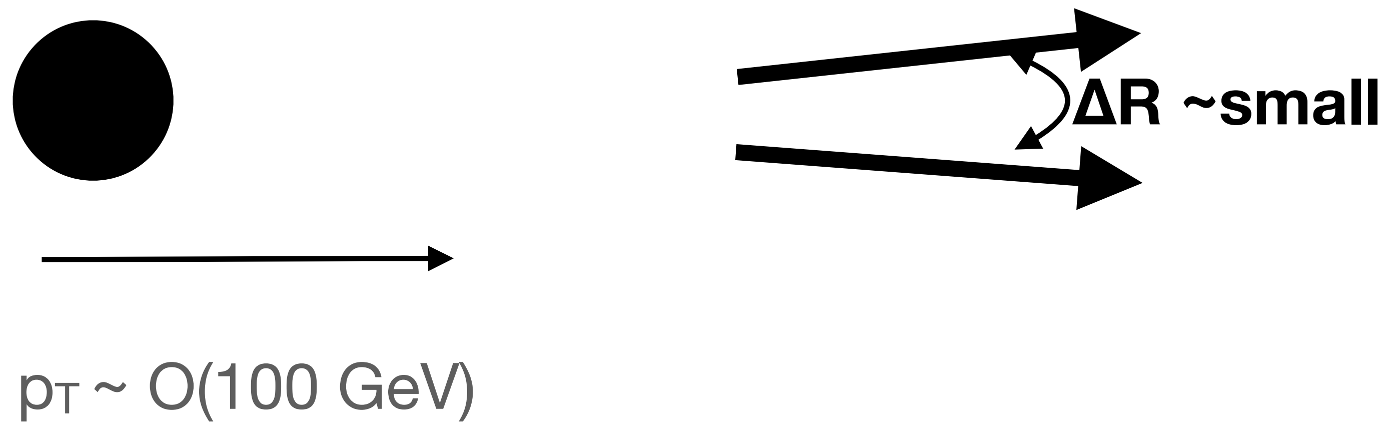


# Boosting final states - challenges

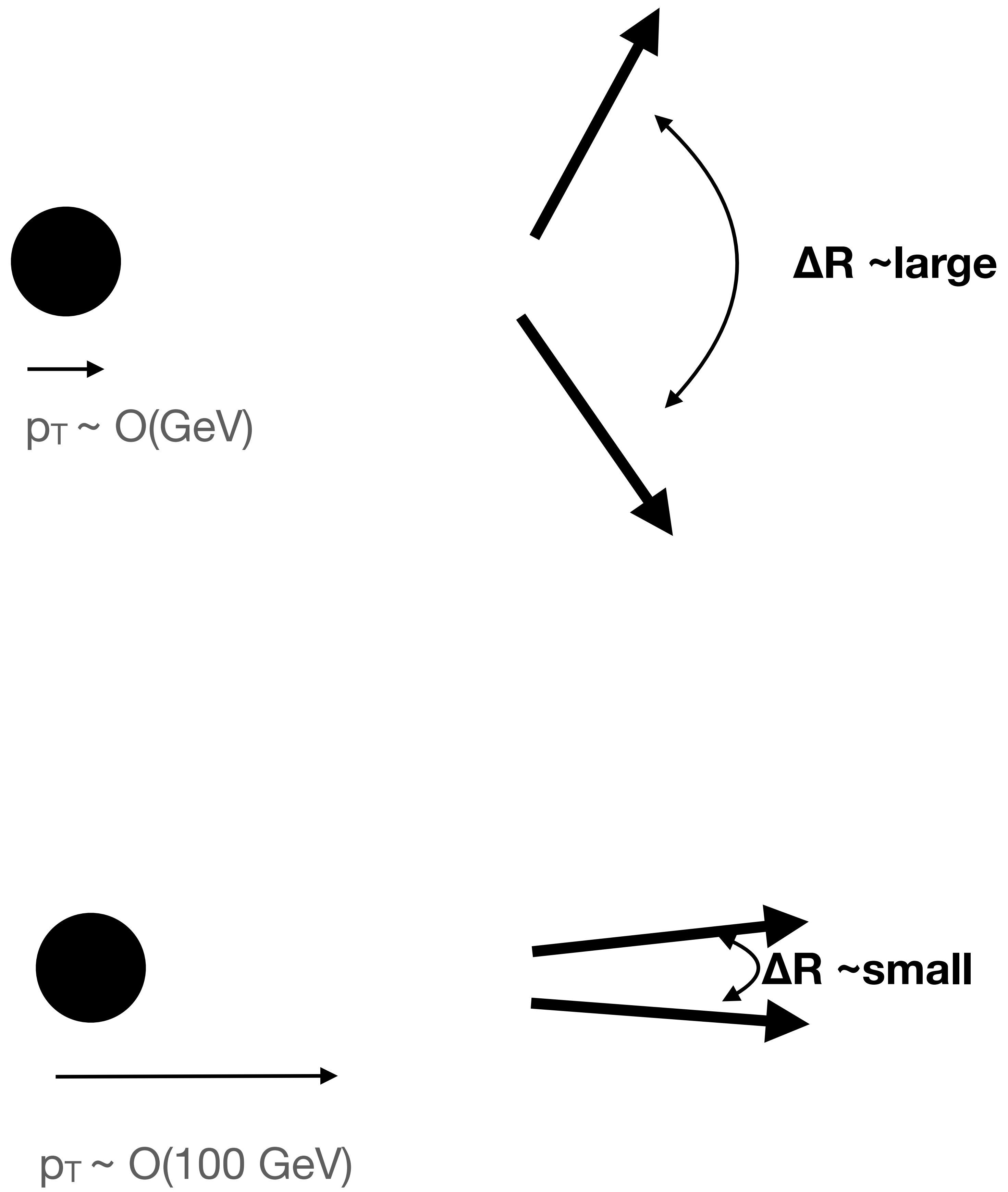


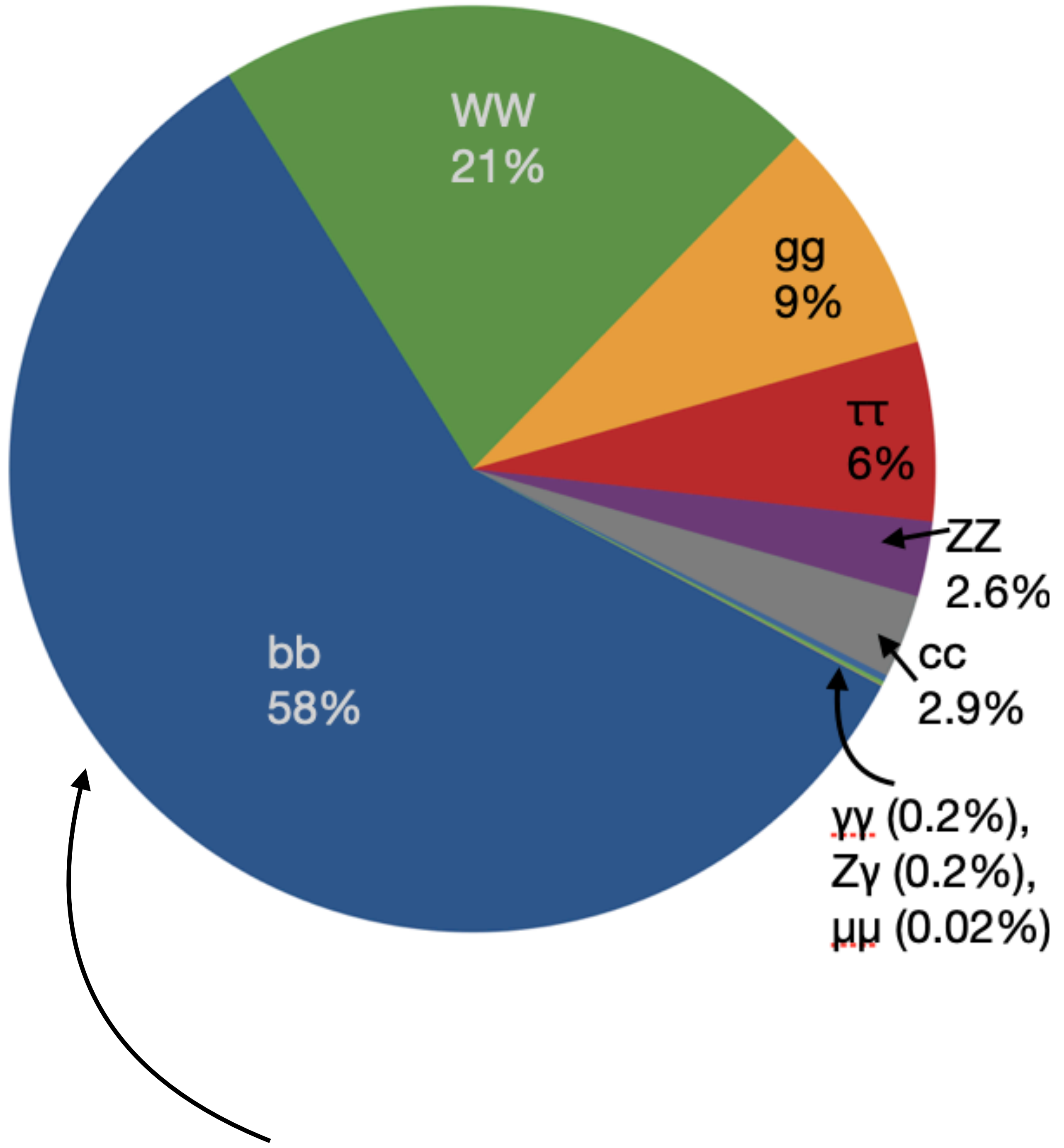
# Boosting final states - challenges



# Boosting final states - challenges



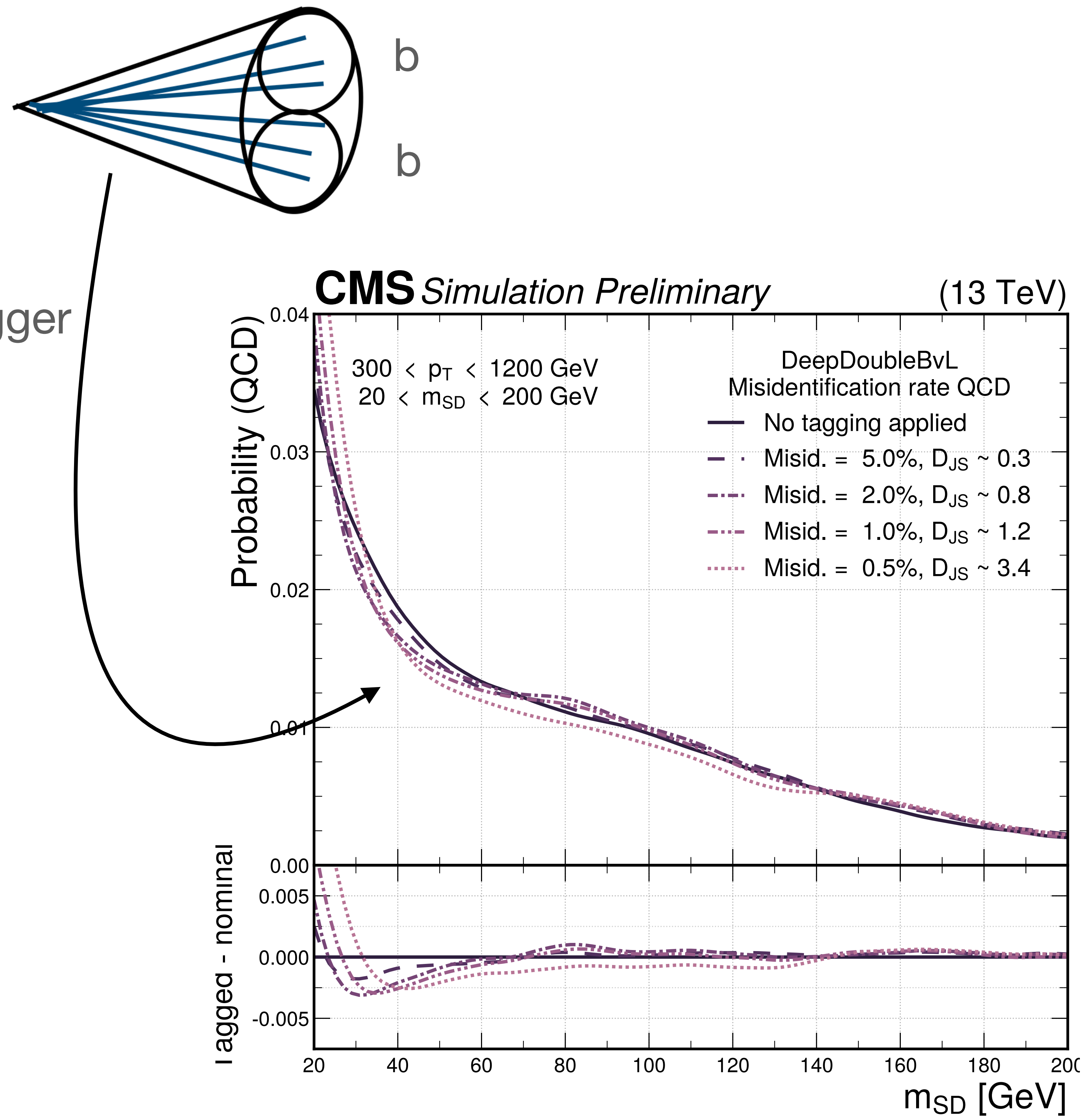




Large branching fractions are beneficial
to select sufficiently large sample of events!

# H→bb boosted

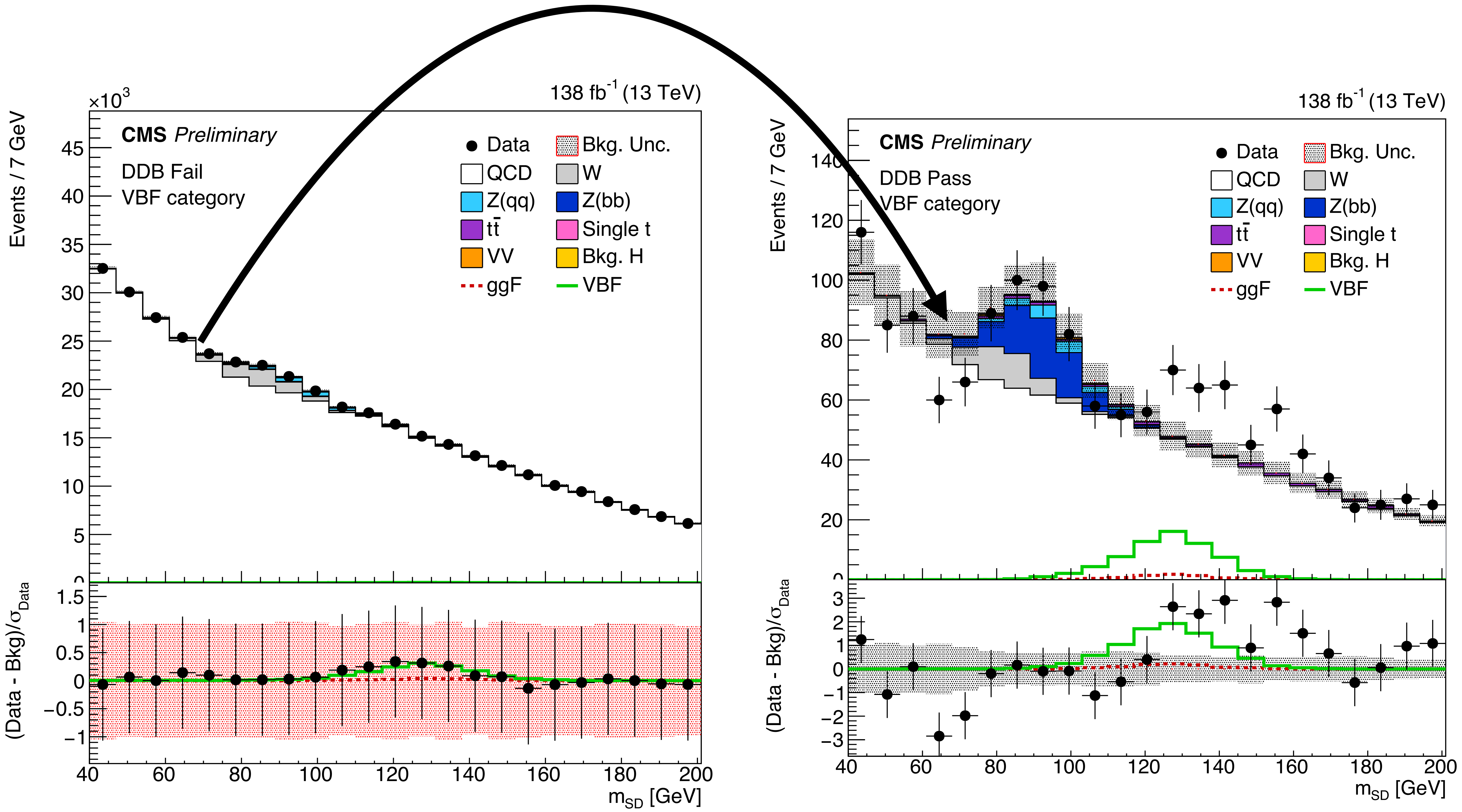
- Considering both gluon-gluon fusion and VBF production in the boosted regime (ggF less dominant @ high $p_T$)

CNN tagger



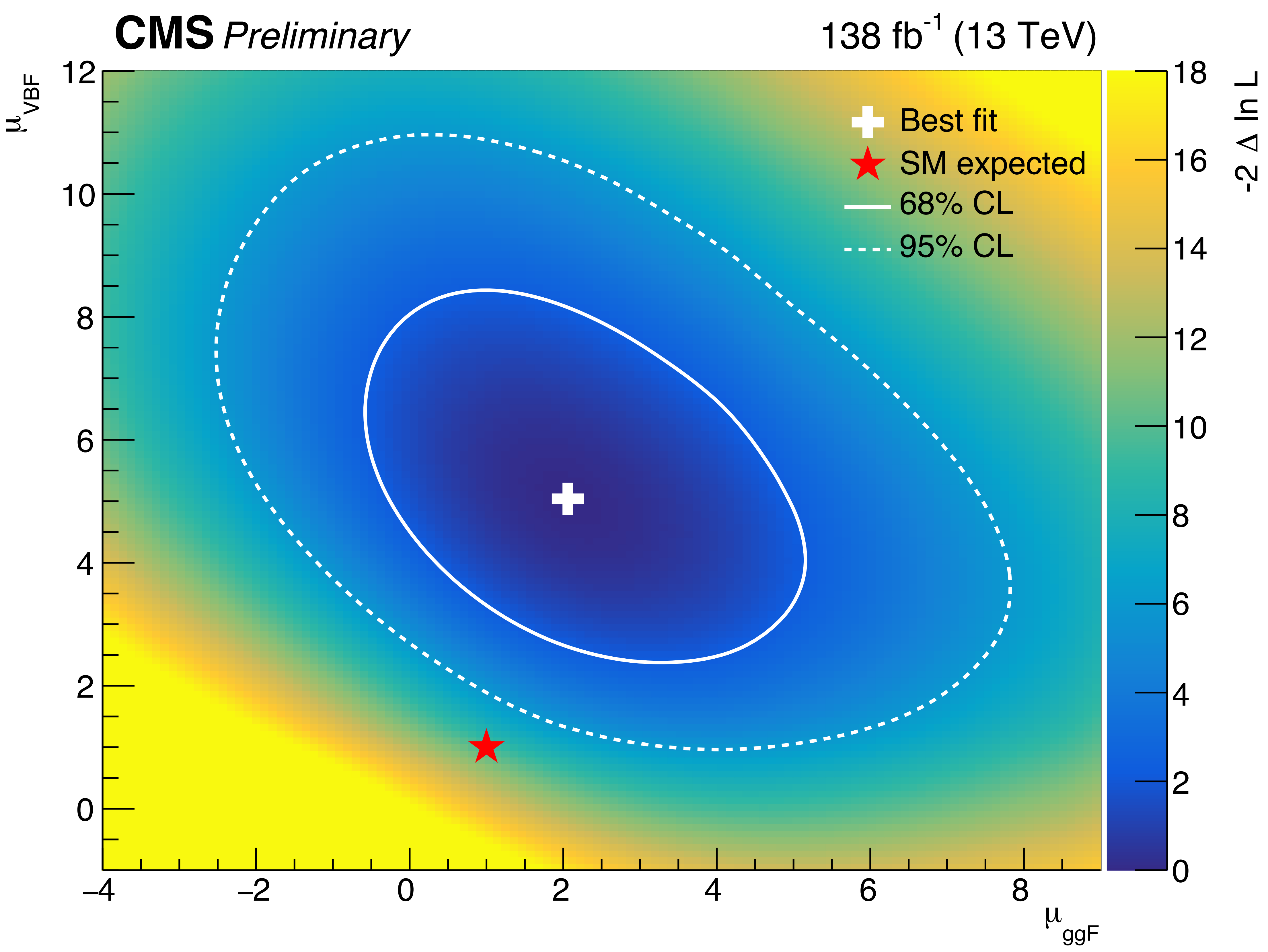

Challenge 1: reconstructing the Higgs boson

x P/F transfer factor x residual transfer factor

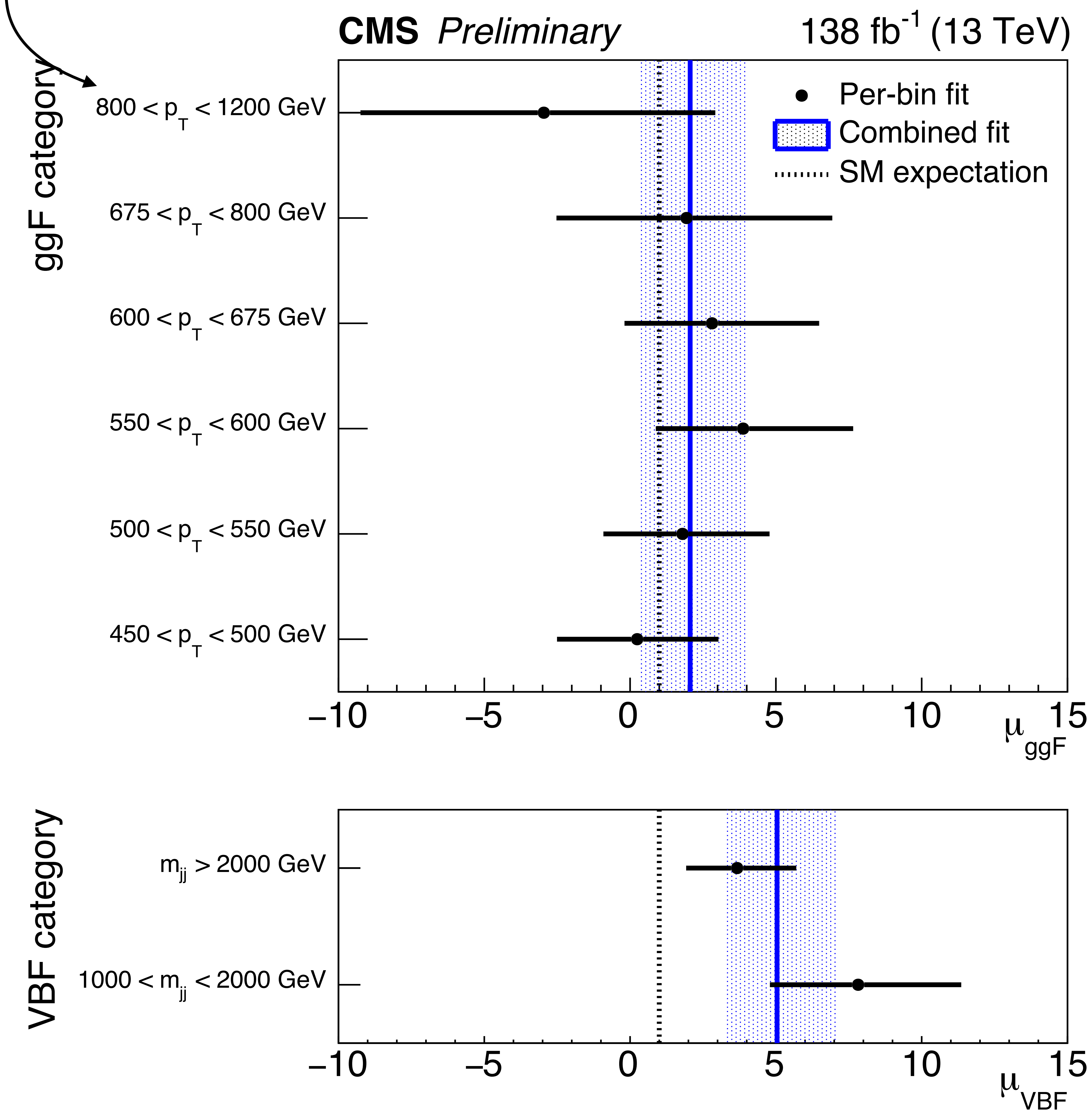



Challenge 2: multijet background

# H→bb boosted

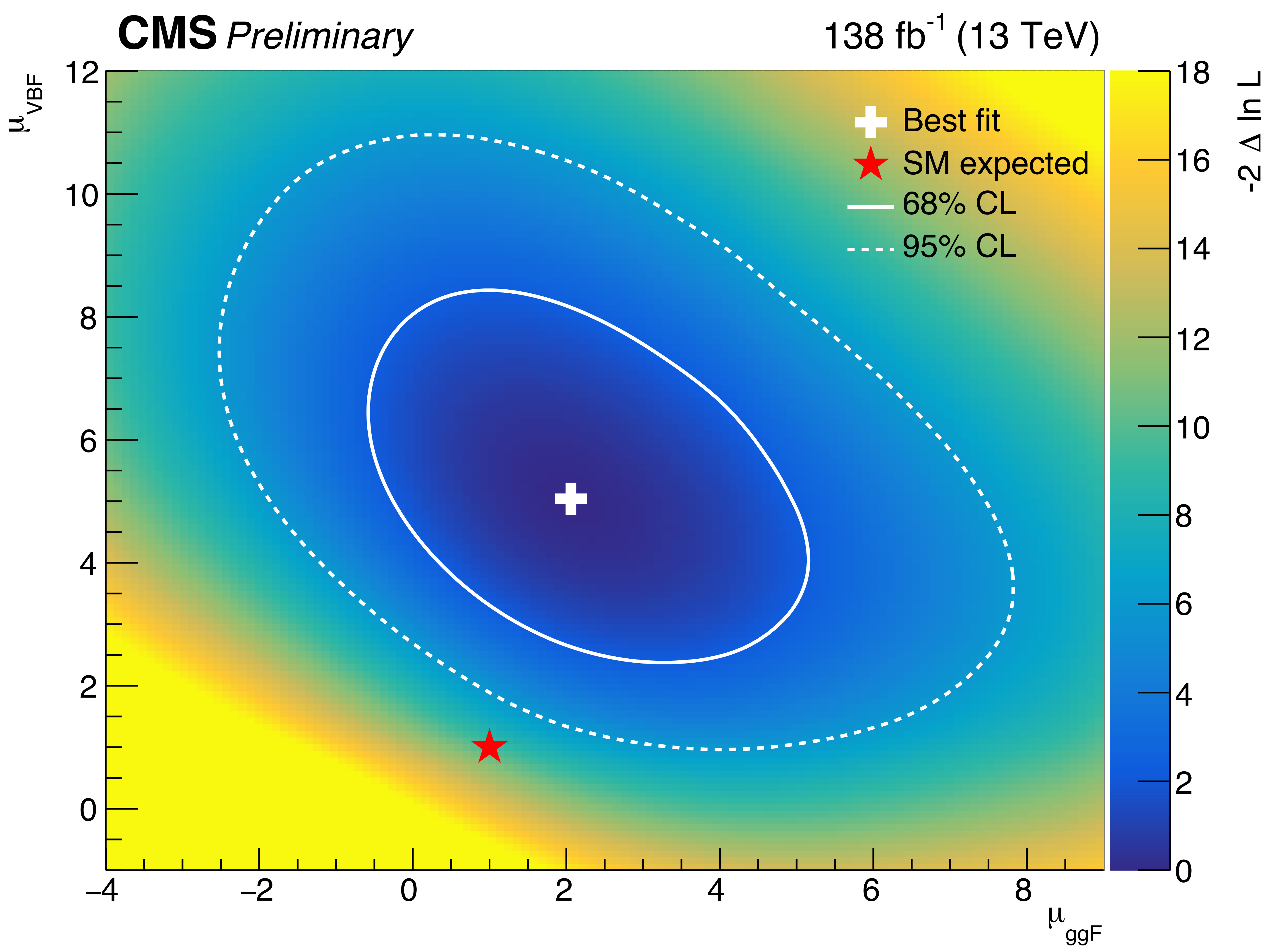



**Information up to 1.2 TeV - note: this is not unfolded to generator-level**

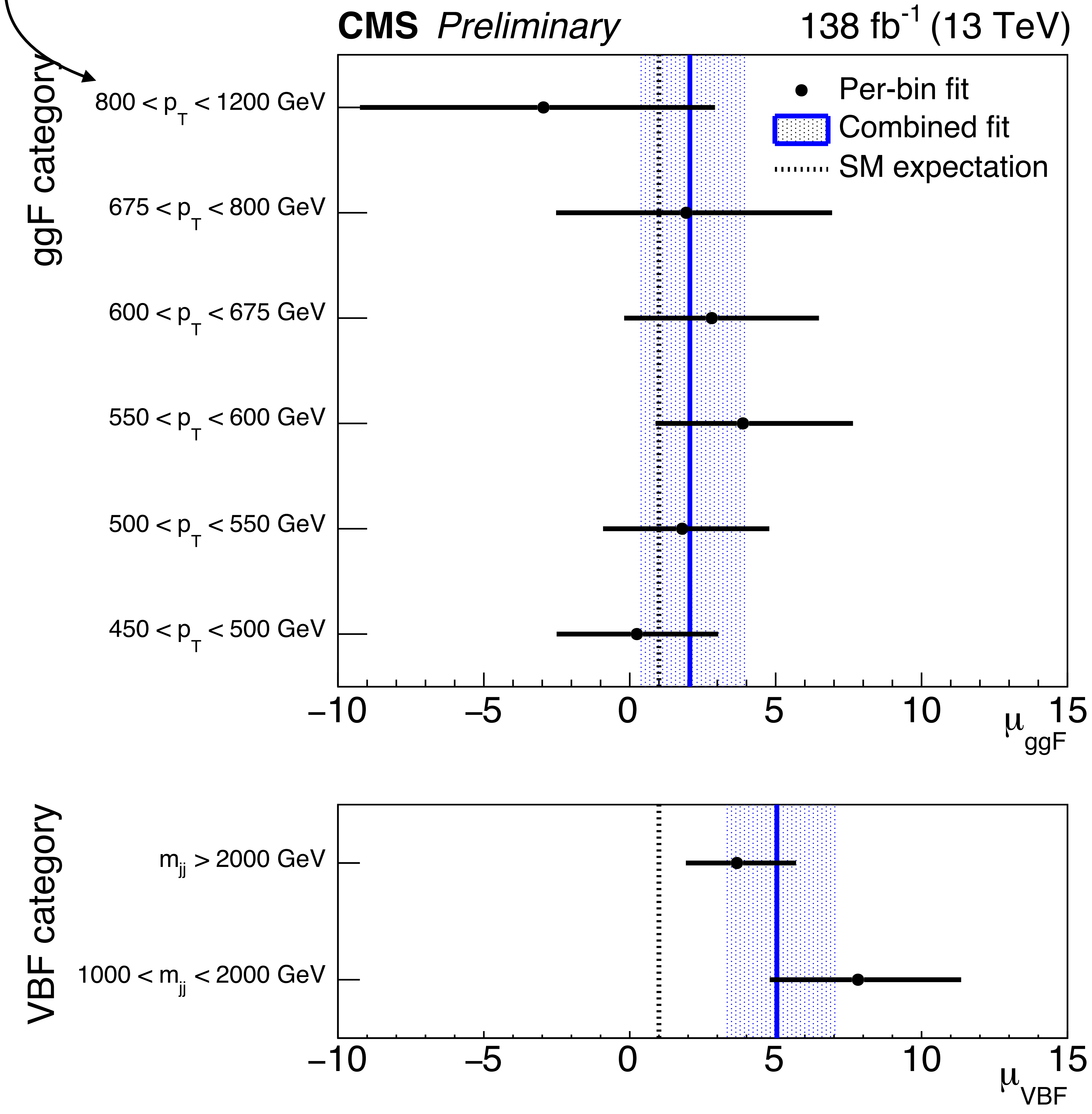



CMS-PAS-HIG-21-020

# H→bb boosted




**Information up to 1.2 TeV - note: this is not unfolded to generator-level**



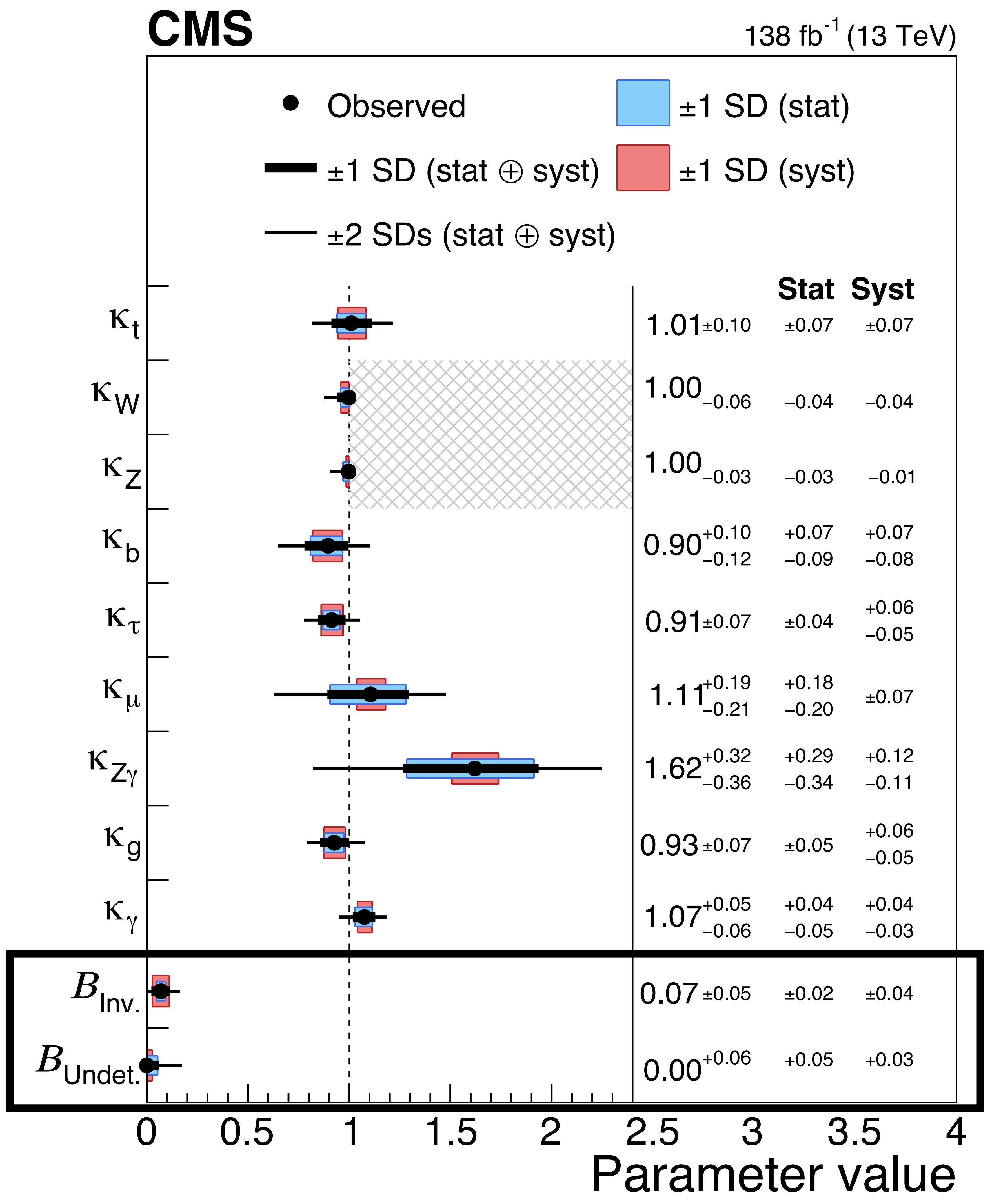

**We also study boosted H→ττ - see backup!**

CMS-PAS-HIG-21-020

# Rare & BSM Higgs decays

## Why you should care

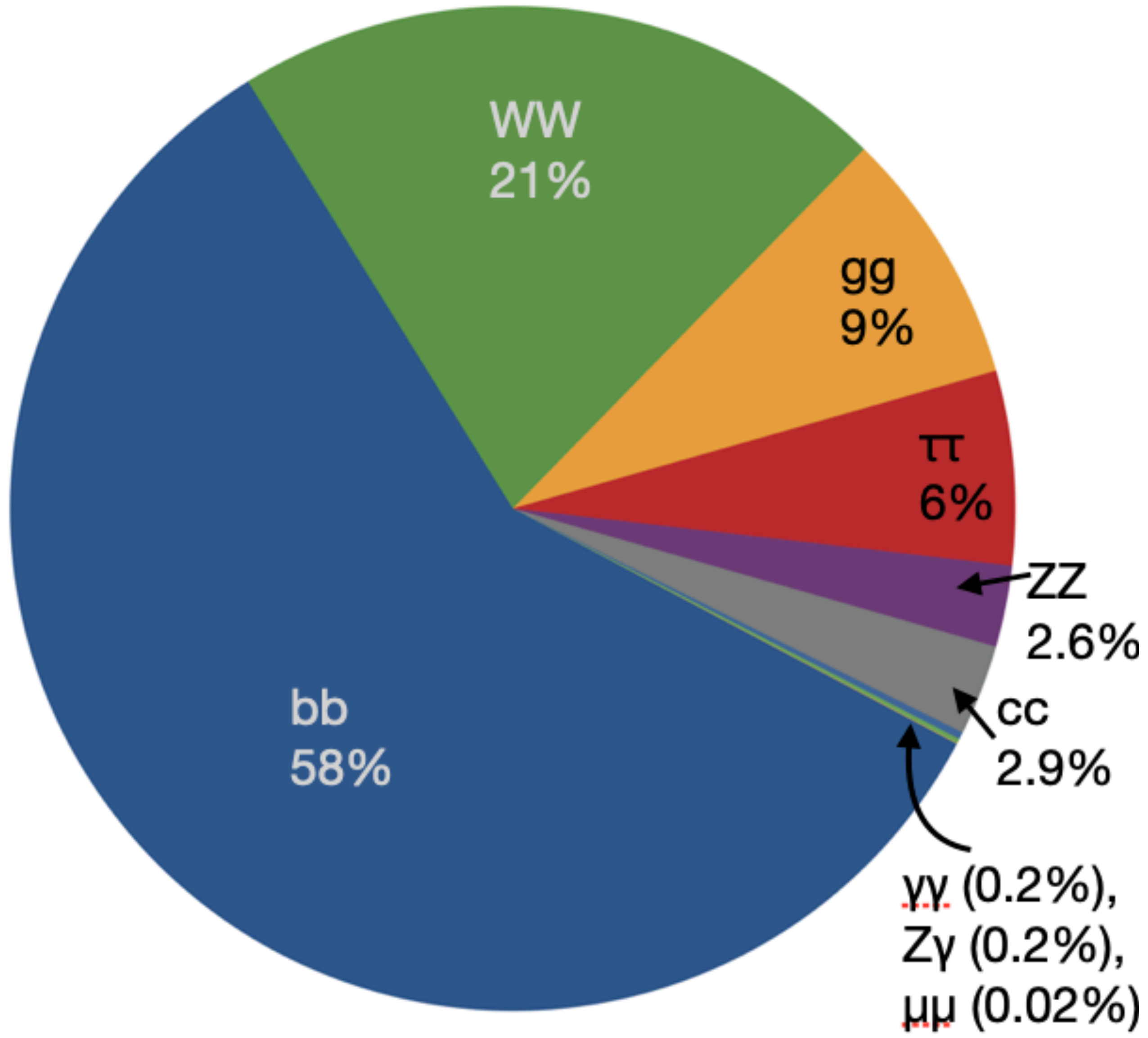
- The SM's newest particle could be a portal to new physics
- Invisible & 'other' (= not-searched-for final states) decay channels still possible
- Rare decays ➔ room for excesses




Nature 607 (2022) 60

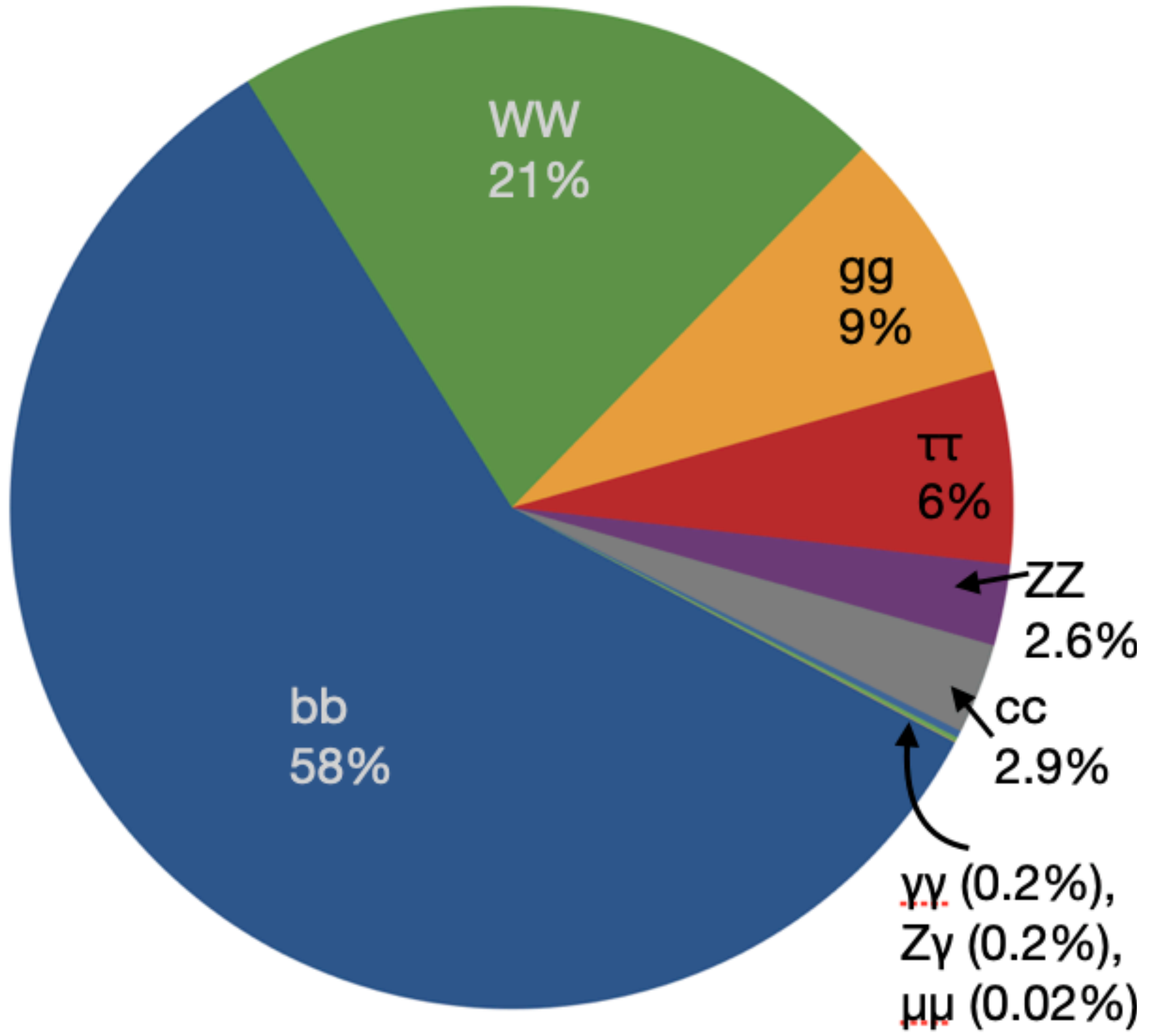
# What's in a name?

**Rare**



# What's in a name?

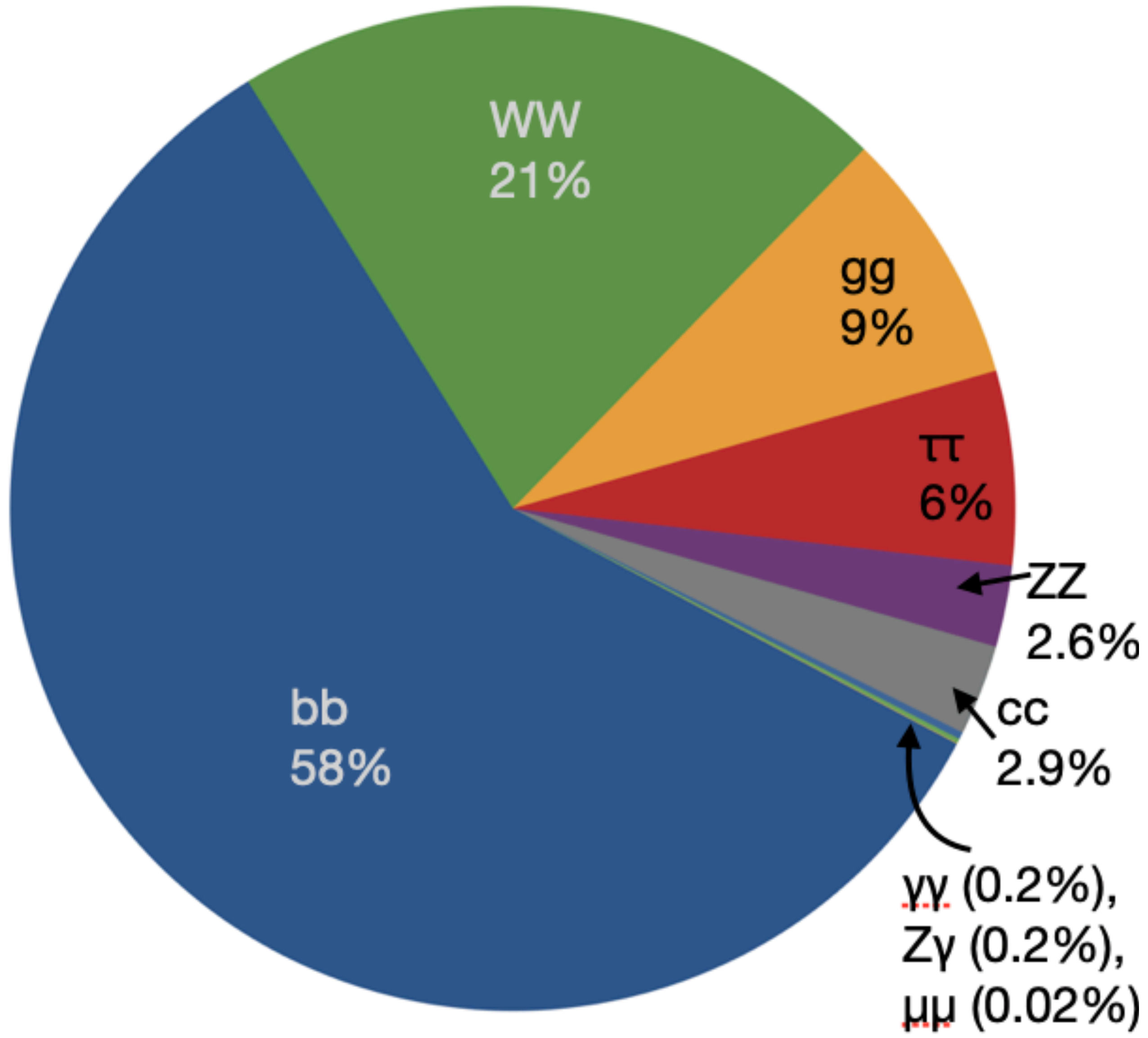
**Rare**




**H→ZZ→4l ~ 0.02% , pretty rare**

# What's in a name?

**Rare**

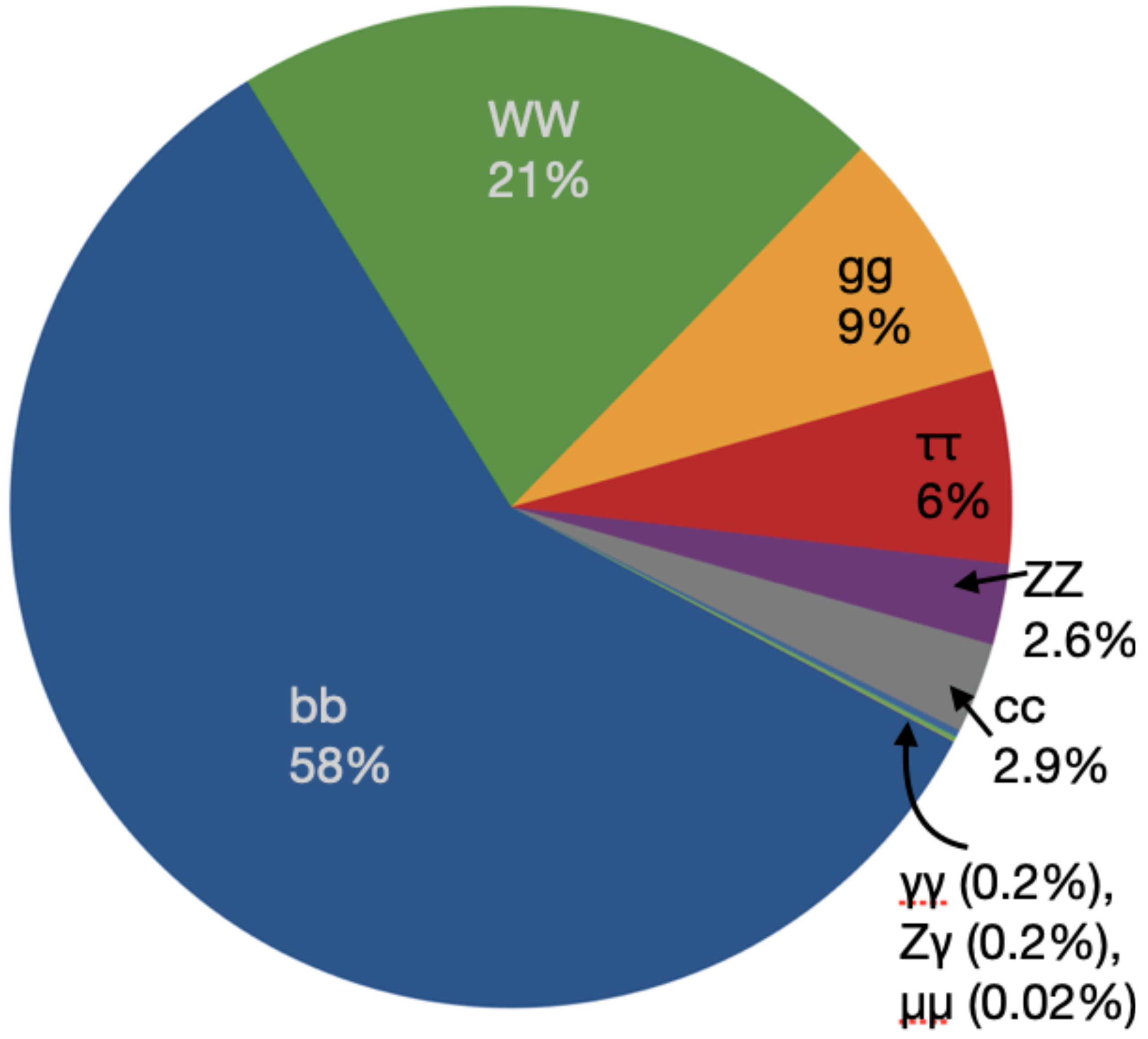



**H→ZZ→4l ~ 0.02% , pretty rare**

**H→γγ seems pretty rare too**

# What's in a name?

**Rare**



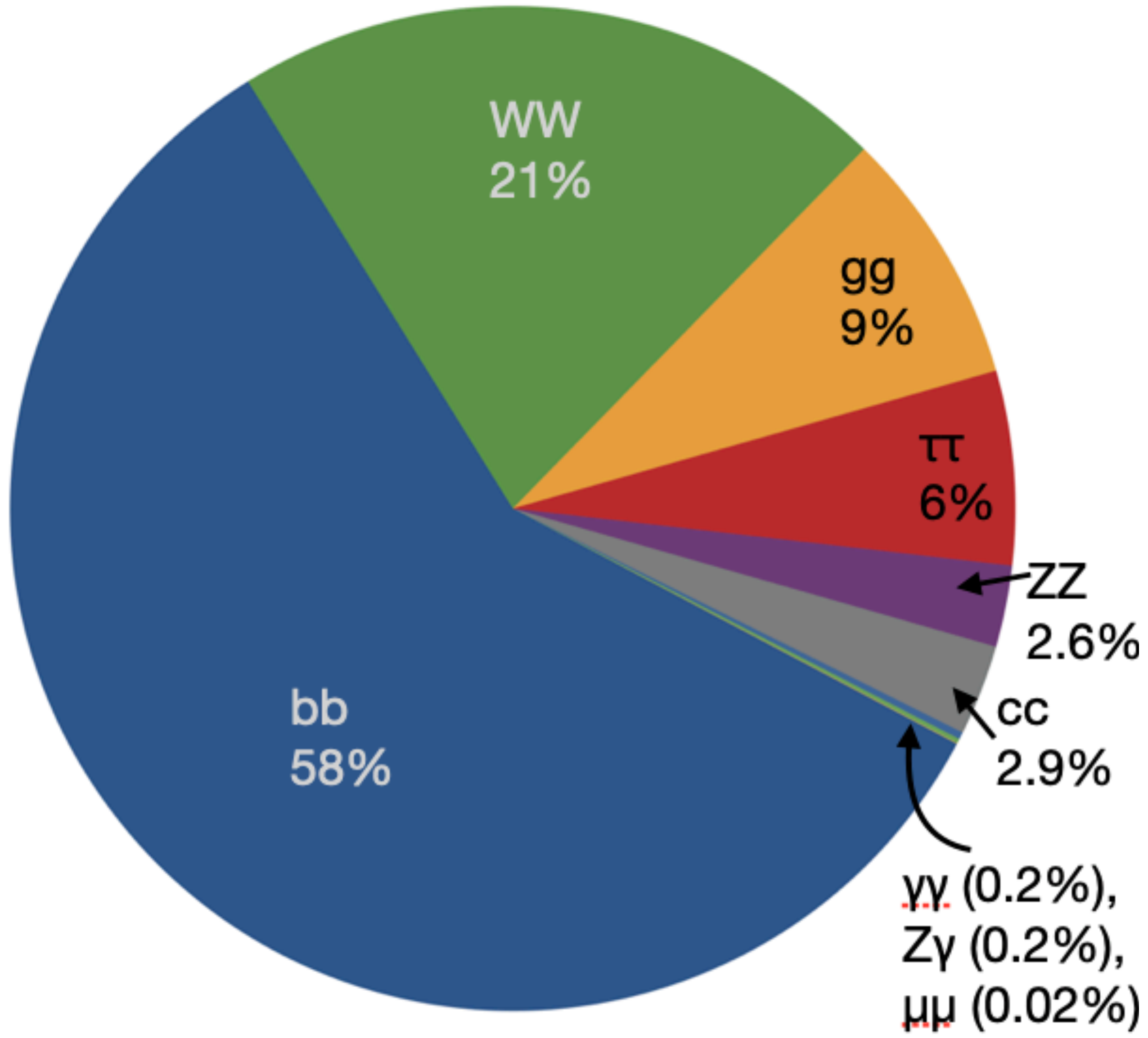

**H→ZZ→4l ~ 0.02% , pretty rare**

**H→γγ seems pretty rare too**

Typically: rare means 'small branching fraction **and** currently limited experimental sensitivity' + 'extremely small branching fractions (O($10^{-3}$ and smaller)

# What's in a name?

**Rare**




**H➔ZZ➔4l ~ 0.02% , pretty rare**

**H➔γγ seems pretty rare too**

Typically: rare means 'small branching fraction **and** currently limited experimental sensitivity' + 'extremely small branching fractions (O($10^{-3}$ and smaller)

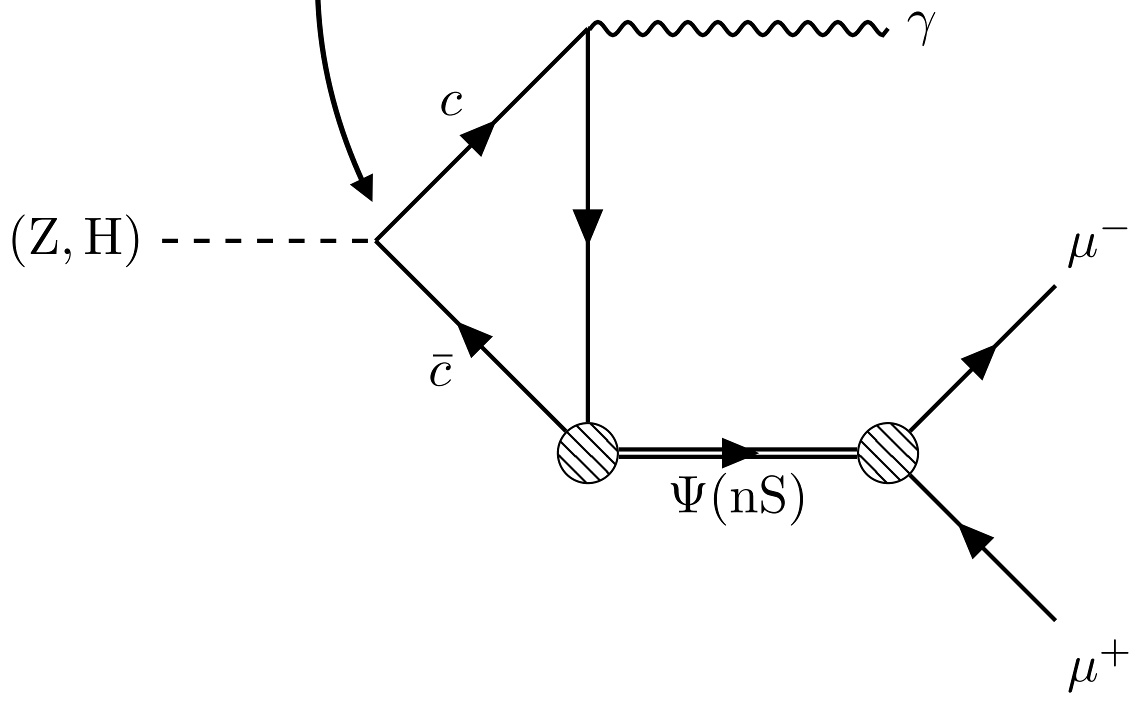
**BSM**

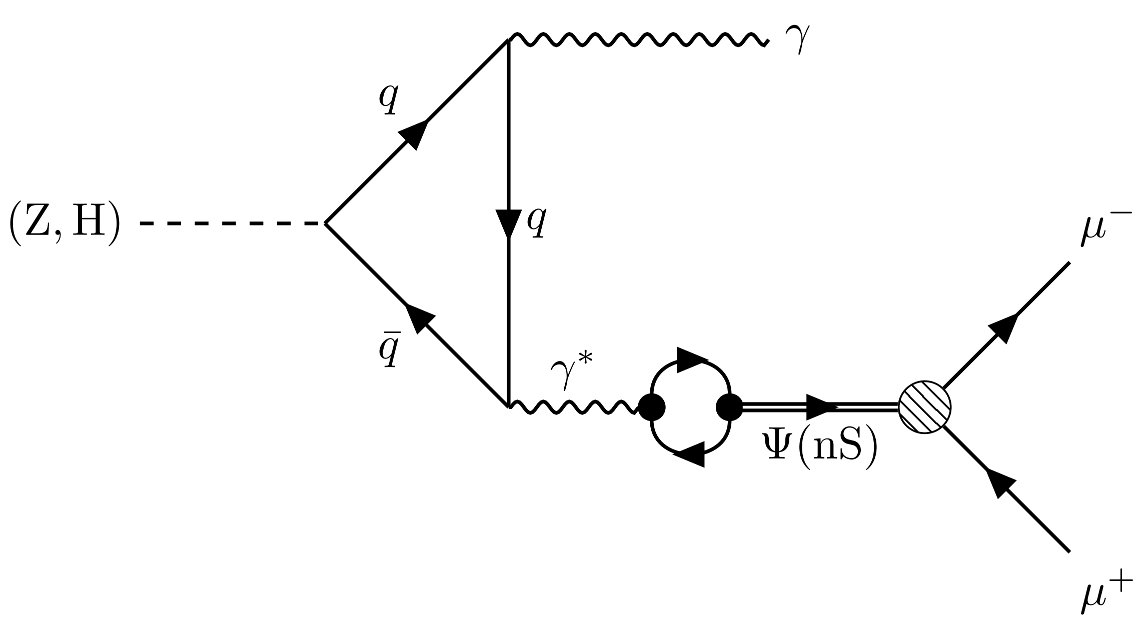
- Decay channels not allowed in the SM
- e.g. H➔invisible*, H➔light (pseudo)scalars

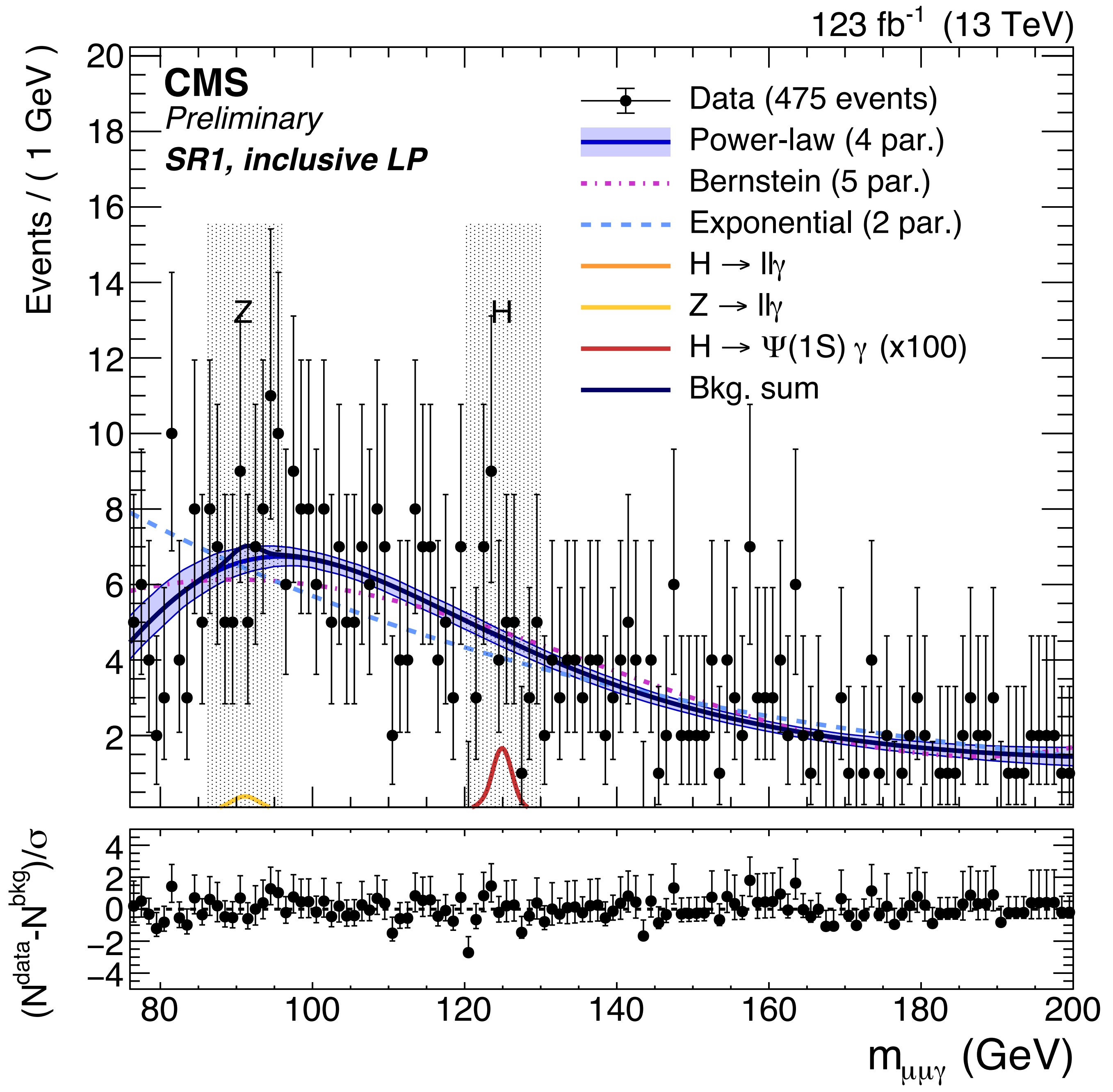
*H➔ZZ➔4ν is of course an SM process...

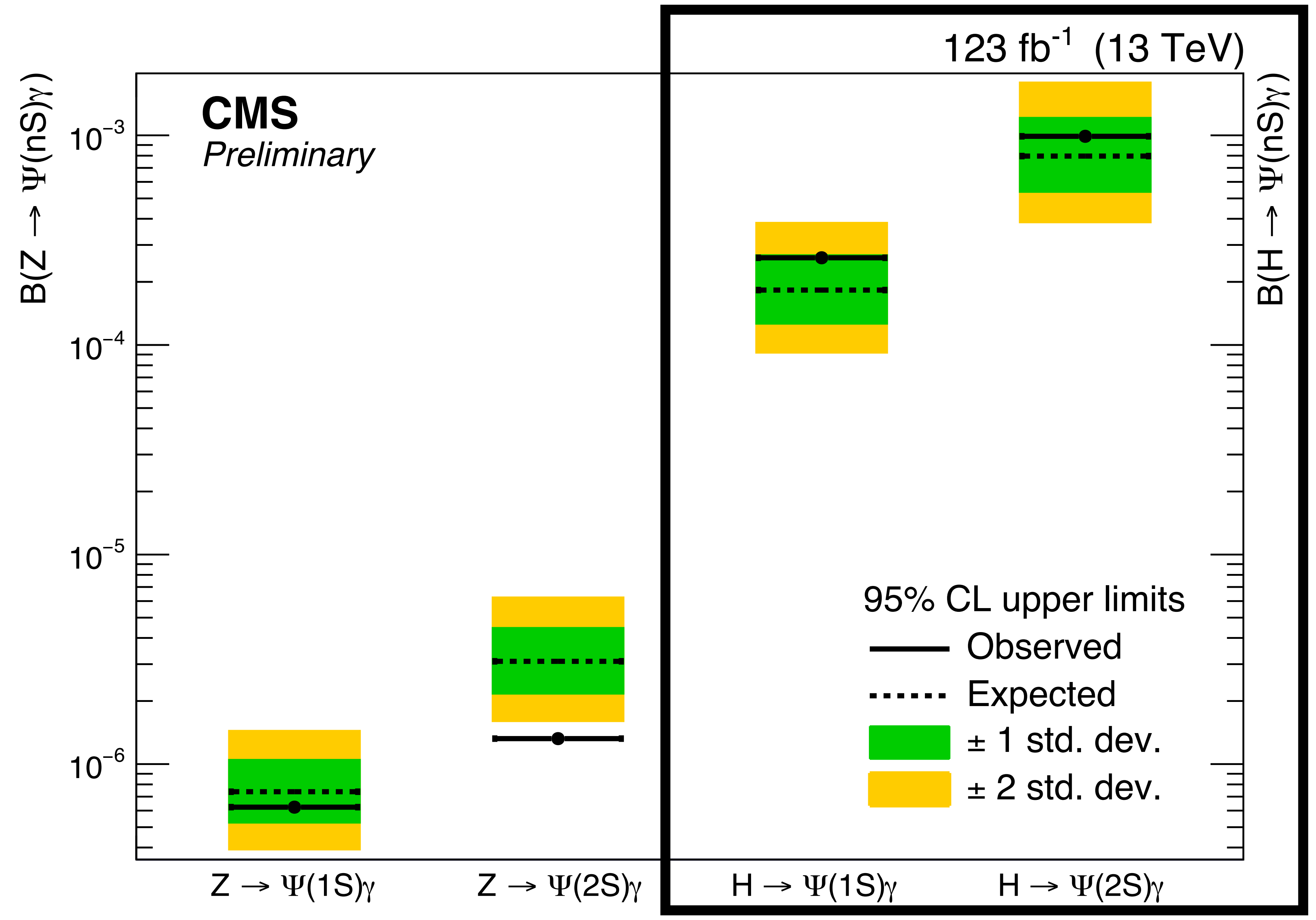
# (Super) rare decays

- Host of possible channels, e.g H➔ψ(nS)γ (recent result)
- B ~ O($10^{-6}$)
- Charmed meson ➔ possible handle on H-charm coupling



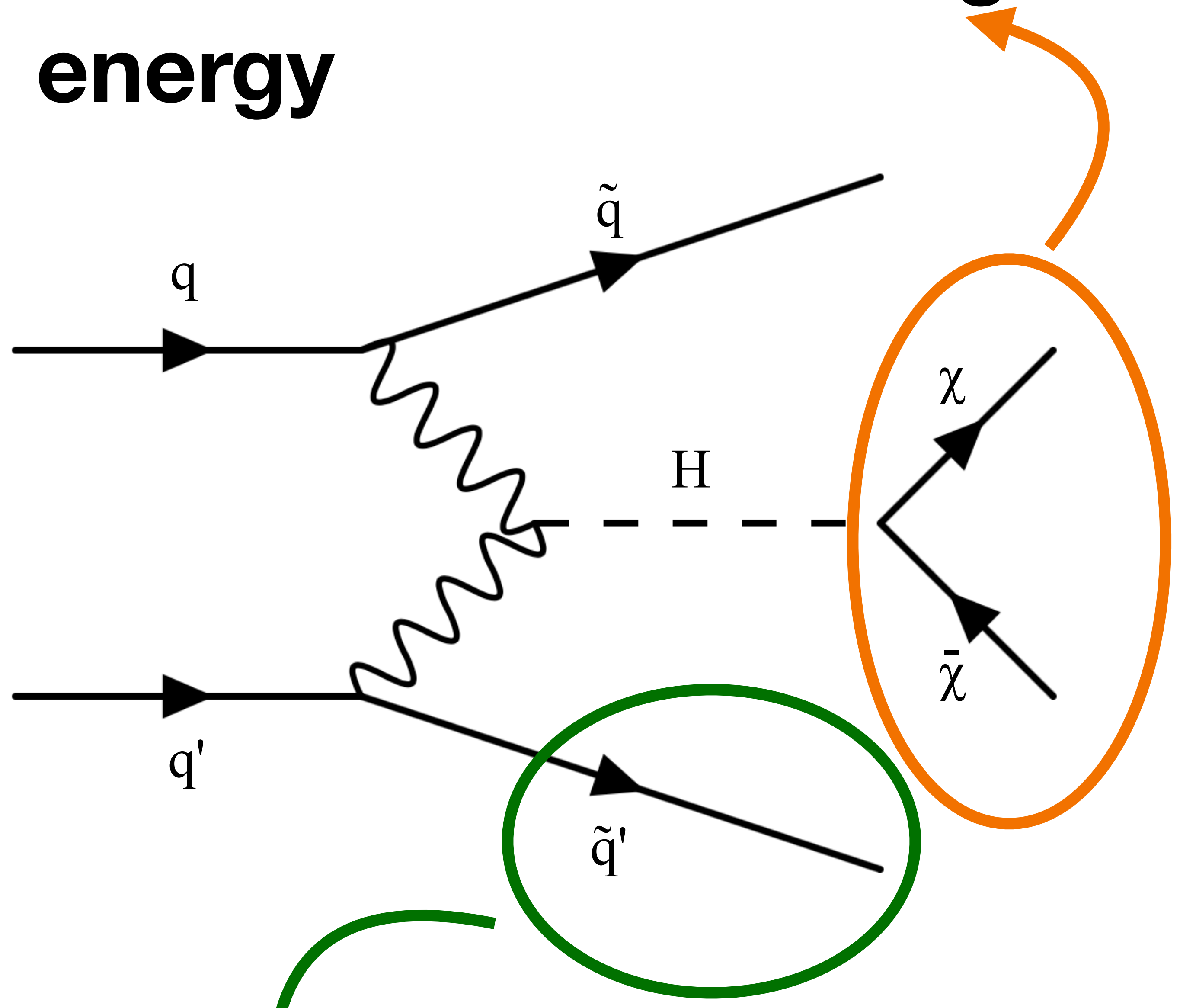



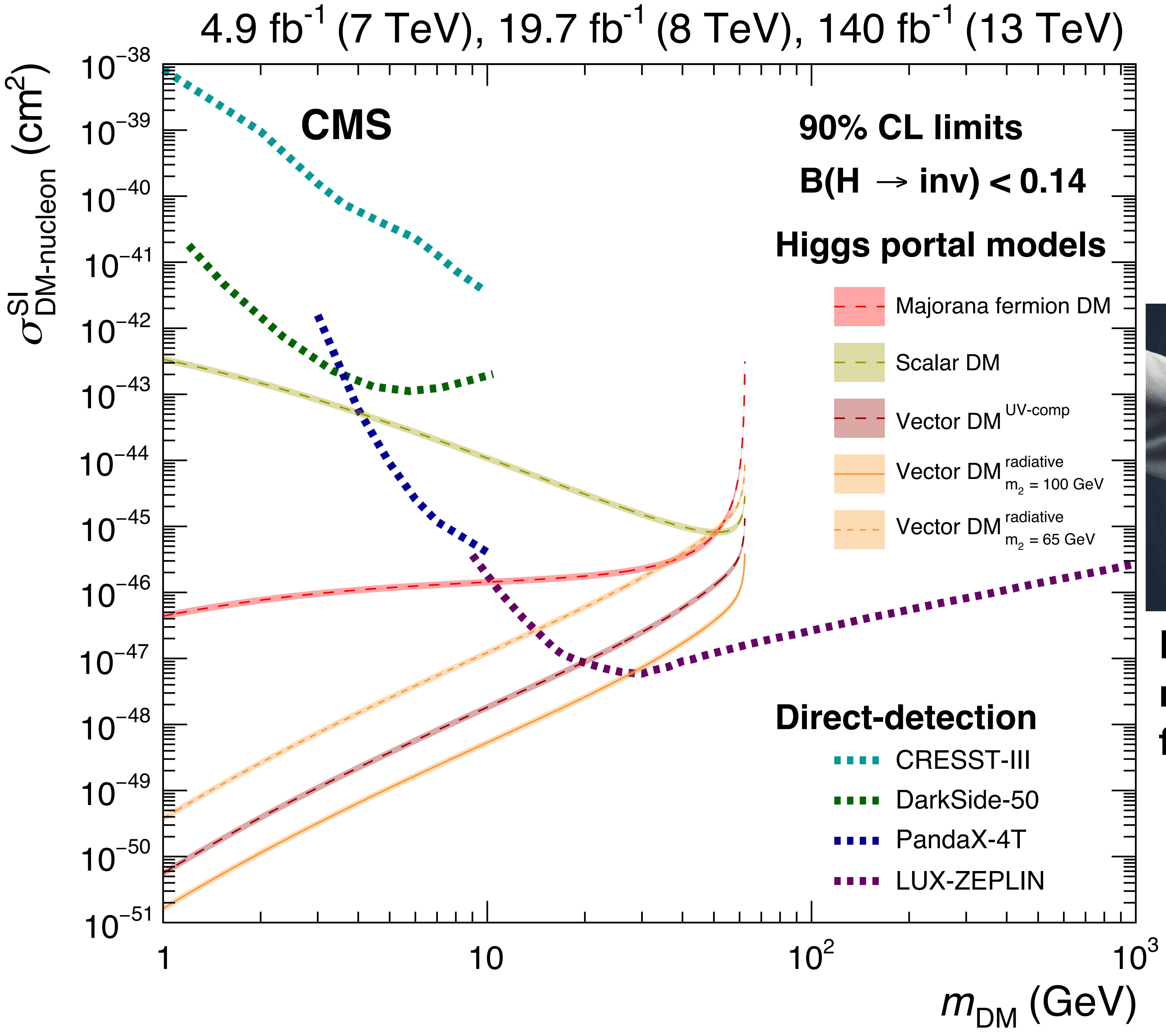
EPJC 83 (2023) 933

# BSM decays: H→invisible

**"Invisible": escape CMS undetected ➔ missing energy**



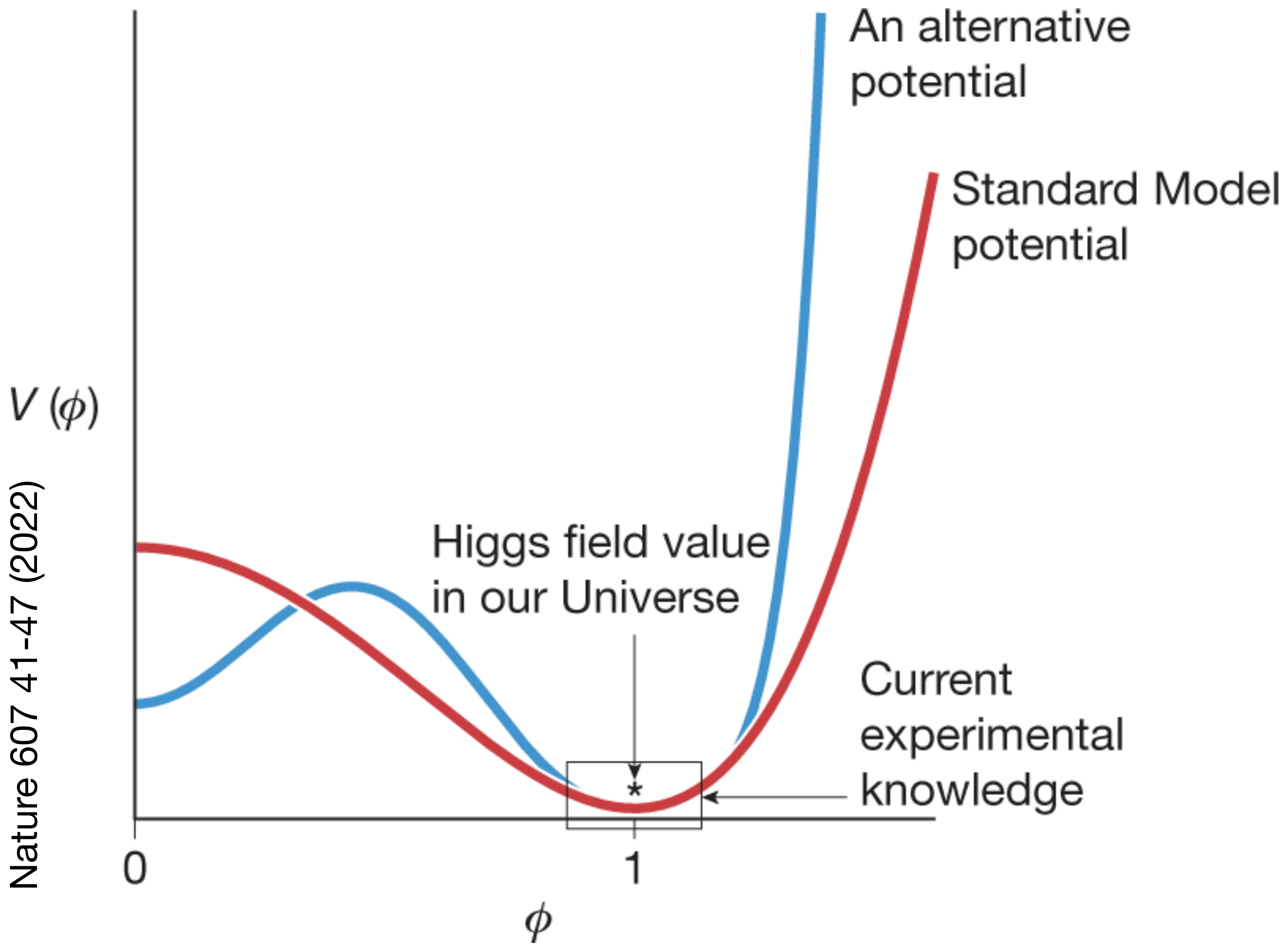

**H+something: helpful for trigger (+ backgrounds)**




**Higgs physics @ LHC and non-collider experiments join forces!**

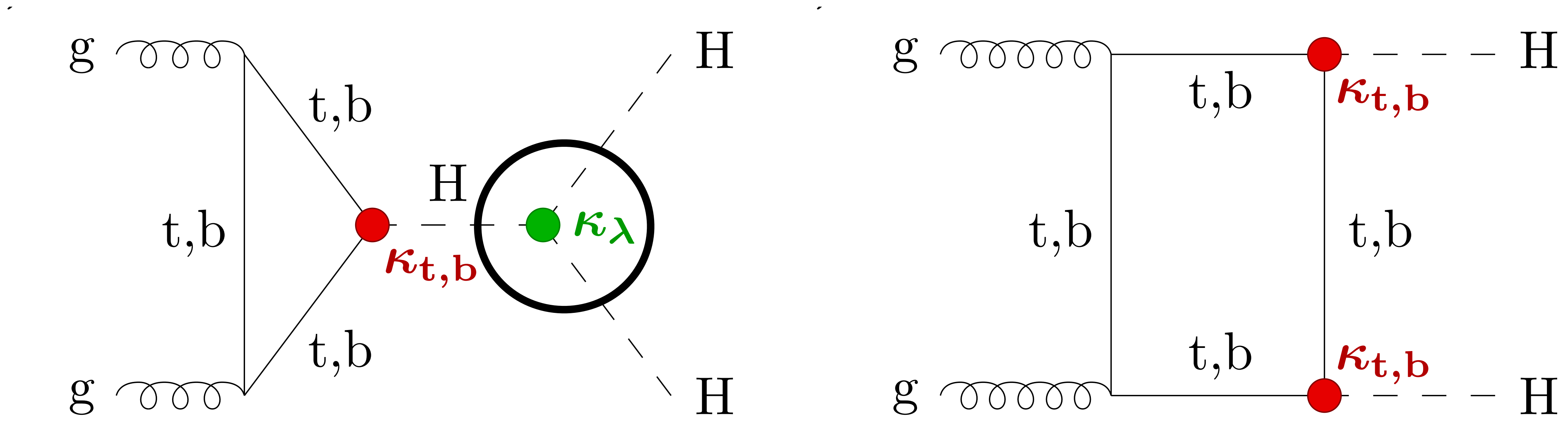
# Di-Higgs production

## Why you should care



Nature 607 41-47 (2022)

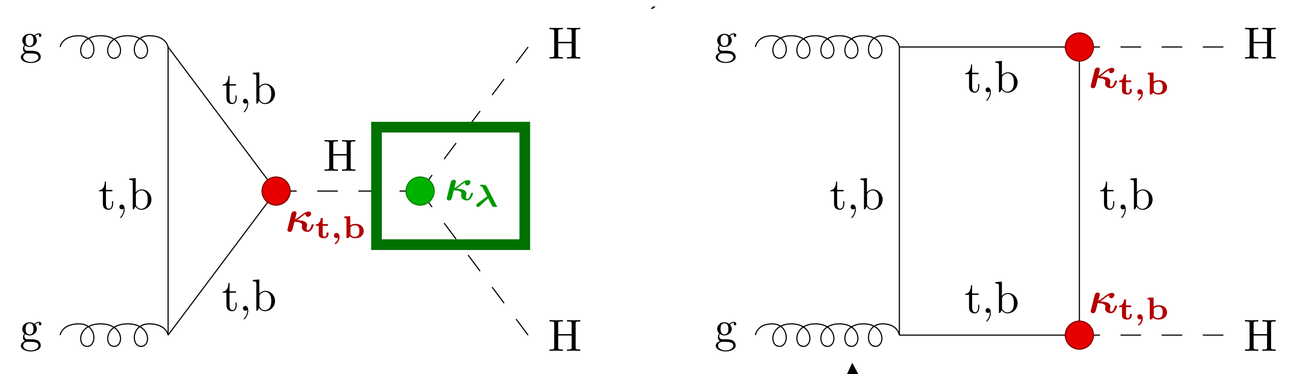
Shape of potential ➔ Higgs self-interaction
➔ di-Higgs production



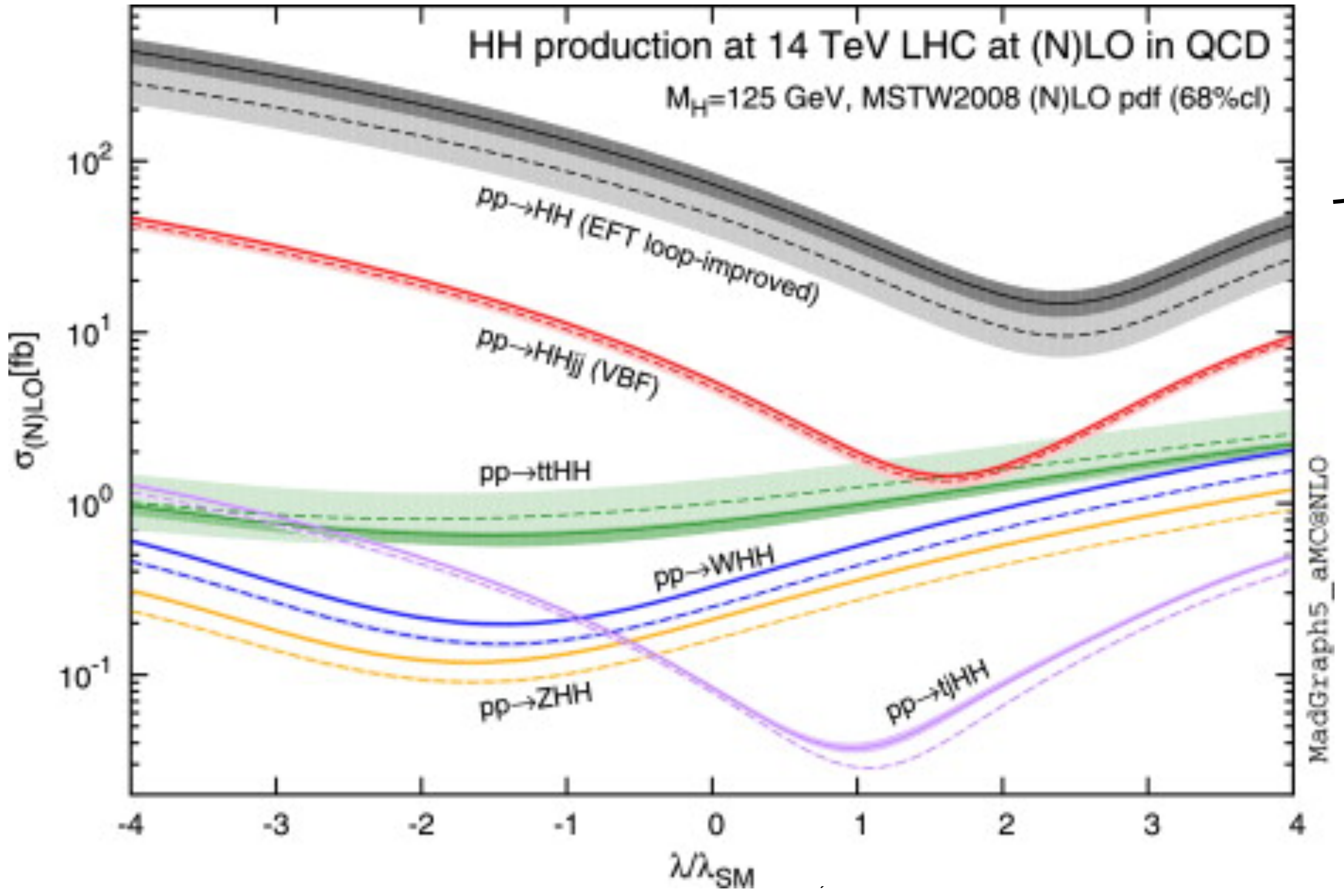
# Chasing two Higgses at the LHC

B(HH➔XXYY)
➔ No one channel dominates

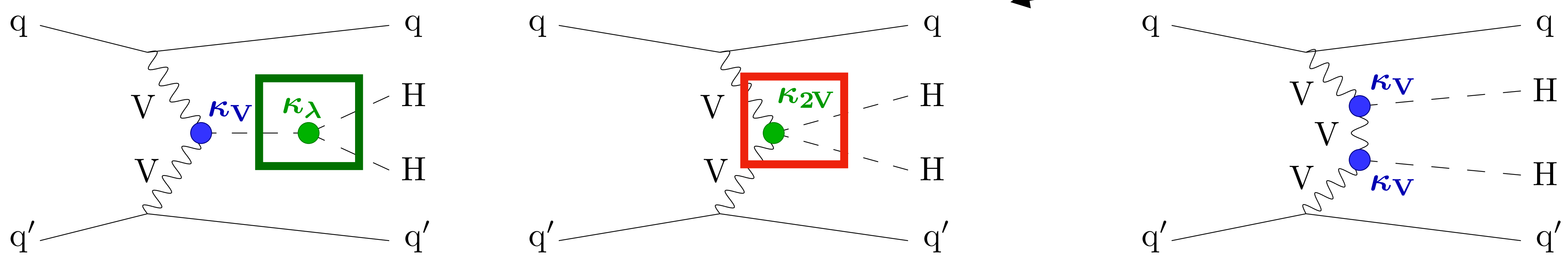
| | bb | WW | gg | ττ | ZZ | γγ |
|---|---|---|---|---|---|---|
| bb | 33.6% | | | | | |
| WW | 25.2% | 4.7% | | | | |
| gg | 9.5% | 3.5% | 0.7% | | | |
| ττ | 7.2% | 2.7% | 1.0% | 0.4% | | |
| ZZ | 3.1% | 1.2% | 0.4% | 0.3% | 0.007% | |
| γγ | 0.3% | 0.1% | 0.04% | 0.03% | 0.001% | 0.0005% |




Gluon-gluon fusion: σ ~ 31 fb



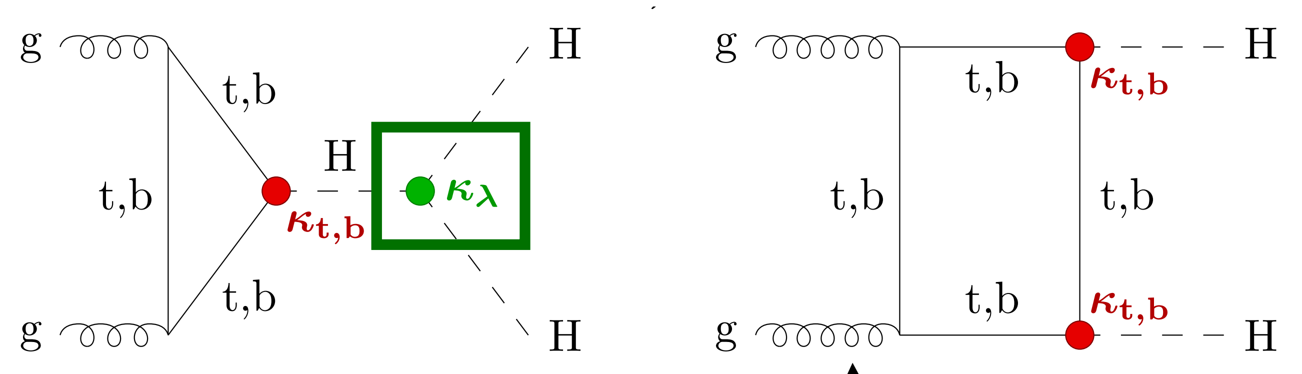

Vector boson fusion:
σ ~ 1.7 fb



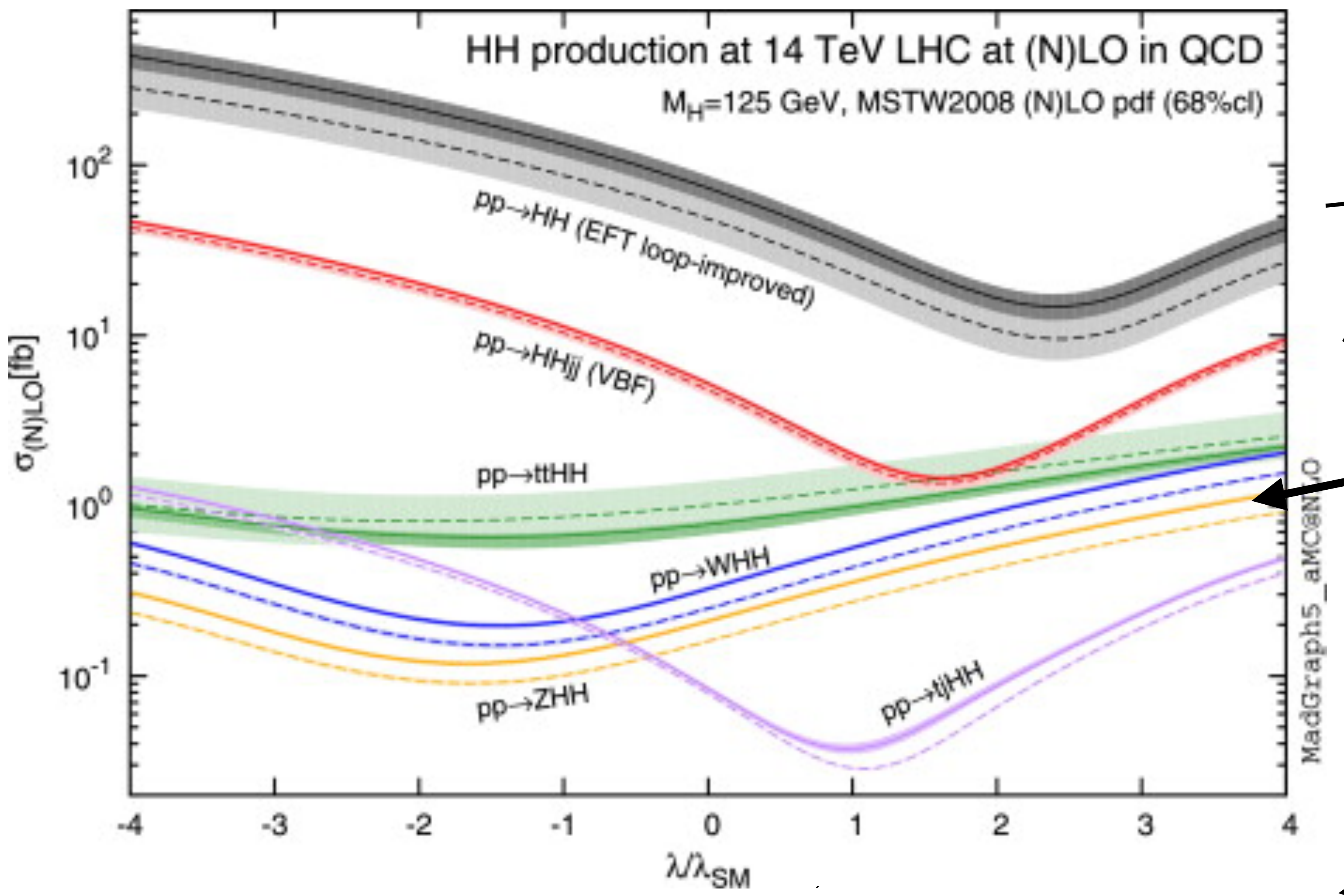
# Chasing two Higgses at the LHC

B(HH➔XXYY)
➔ No one channel dominates

| | bb | WW | gg | ττ | ZZ | γγ |
|---|---|---|---|---|---|---|
| bb | 33.6% | | | | | |
| WW | 25.2% | 4.7% | | | | |
| gg | 9.5% | 3.5% | 0.7% | | | |
| ττ | 7.2% | 2.7% | 1.0% | 0.4% | | |
| ZZ | 3.1% | 1.2% | 0.4% | 0.3% | 0.007% | |
| γγ | 0.3% | 0.1% | 0.04% | 0.03% | 0.001% | 0.0005% |

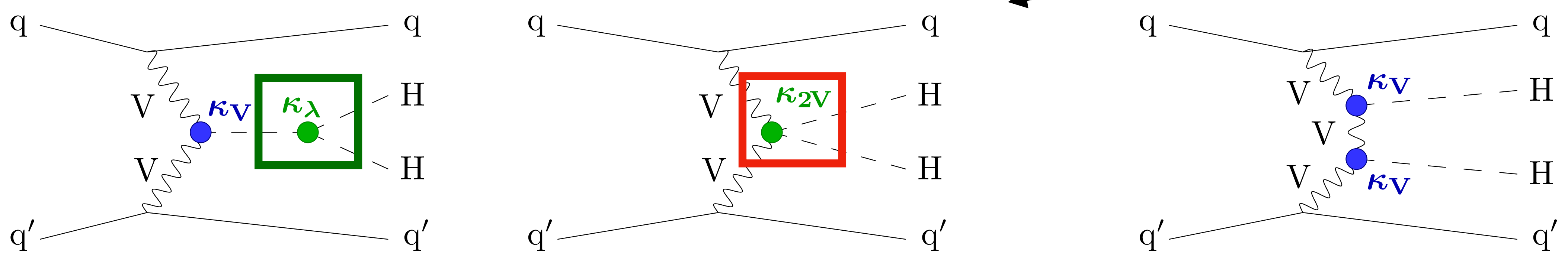



Gluon-gluon fusion: σ ~ 31 fb

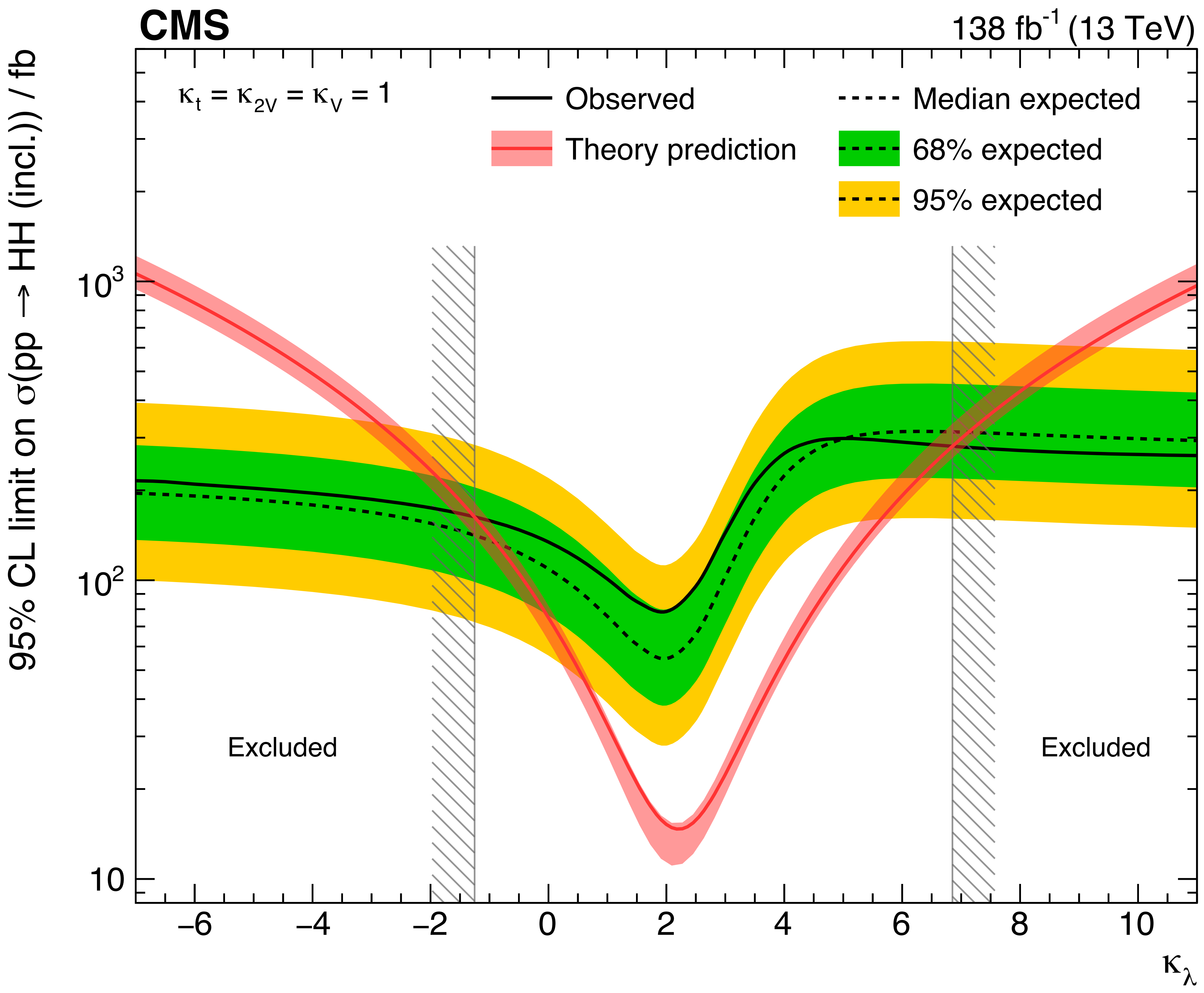



We also look here (WWH,ZZH)

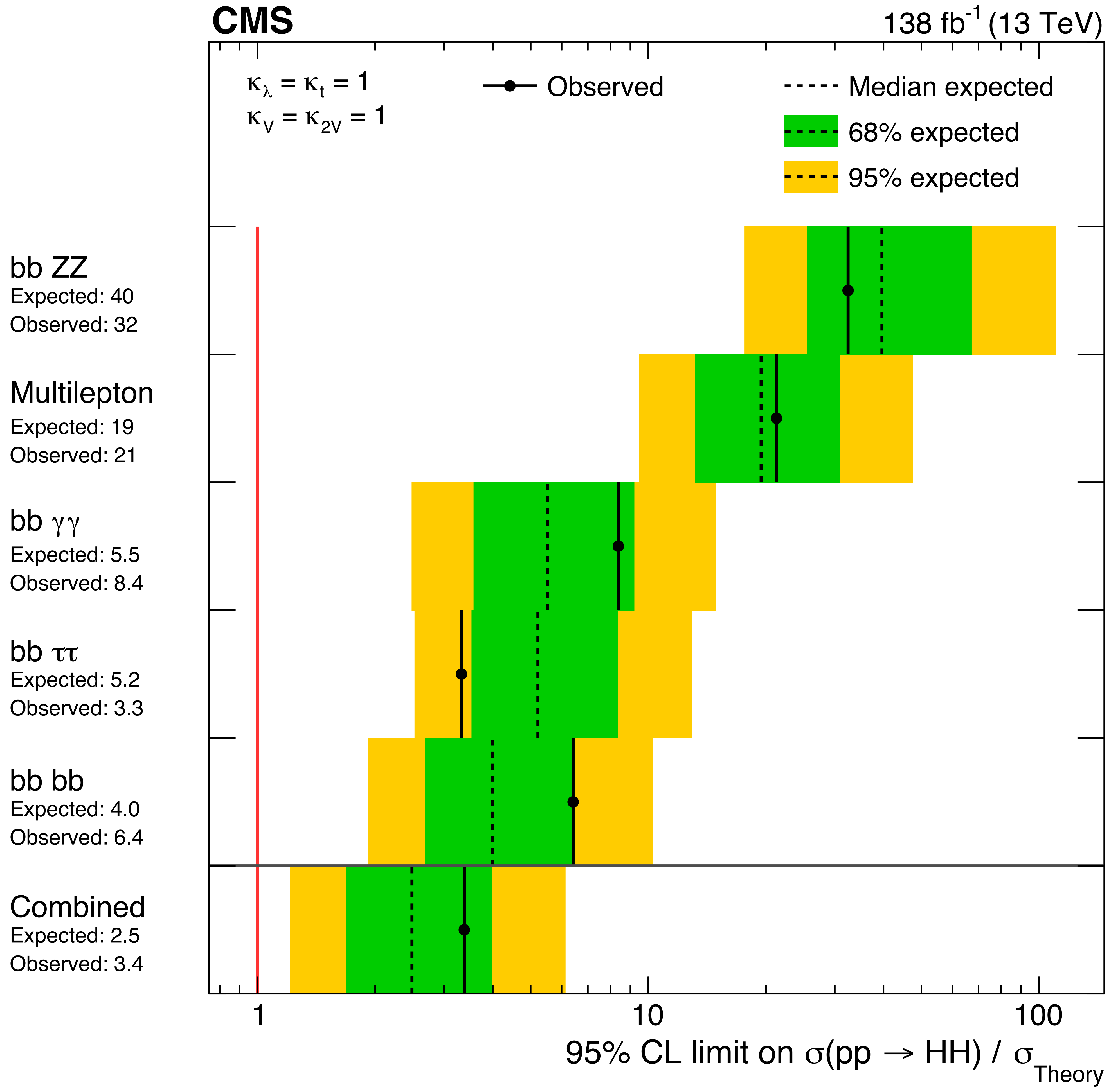
Vector boson fusion: σ ~ 1.7 fb



# Status of HH analyses

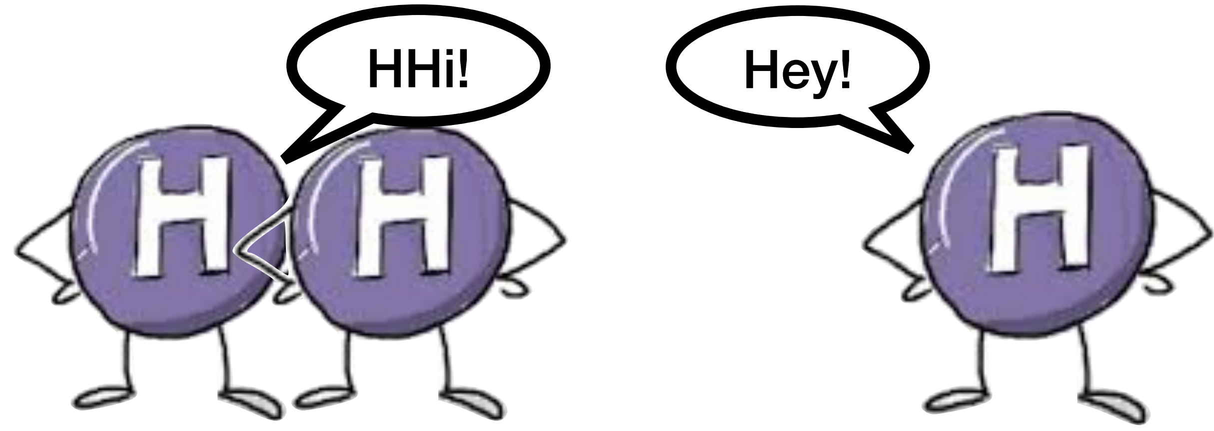



**-1.24 < κλ <6.49**



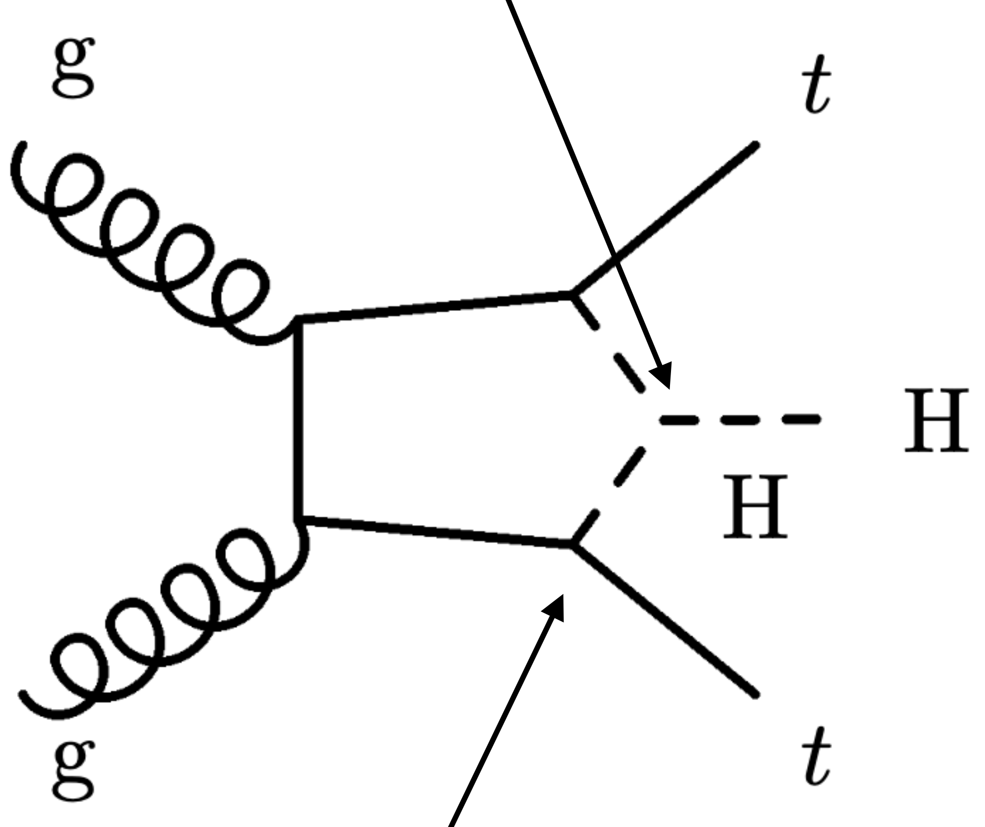

+bbWW, VHH(4b), etc.

Nature 607 (2022) 60

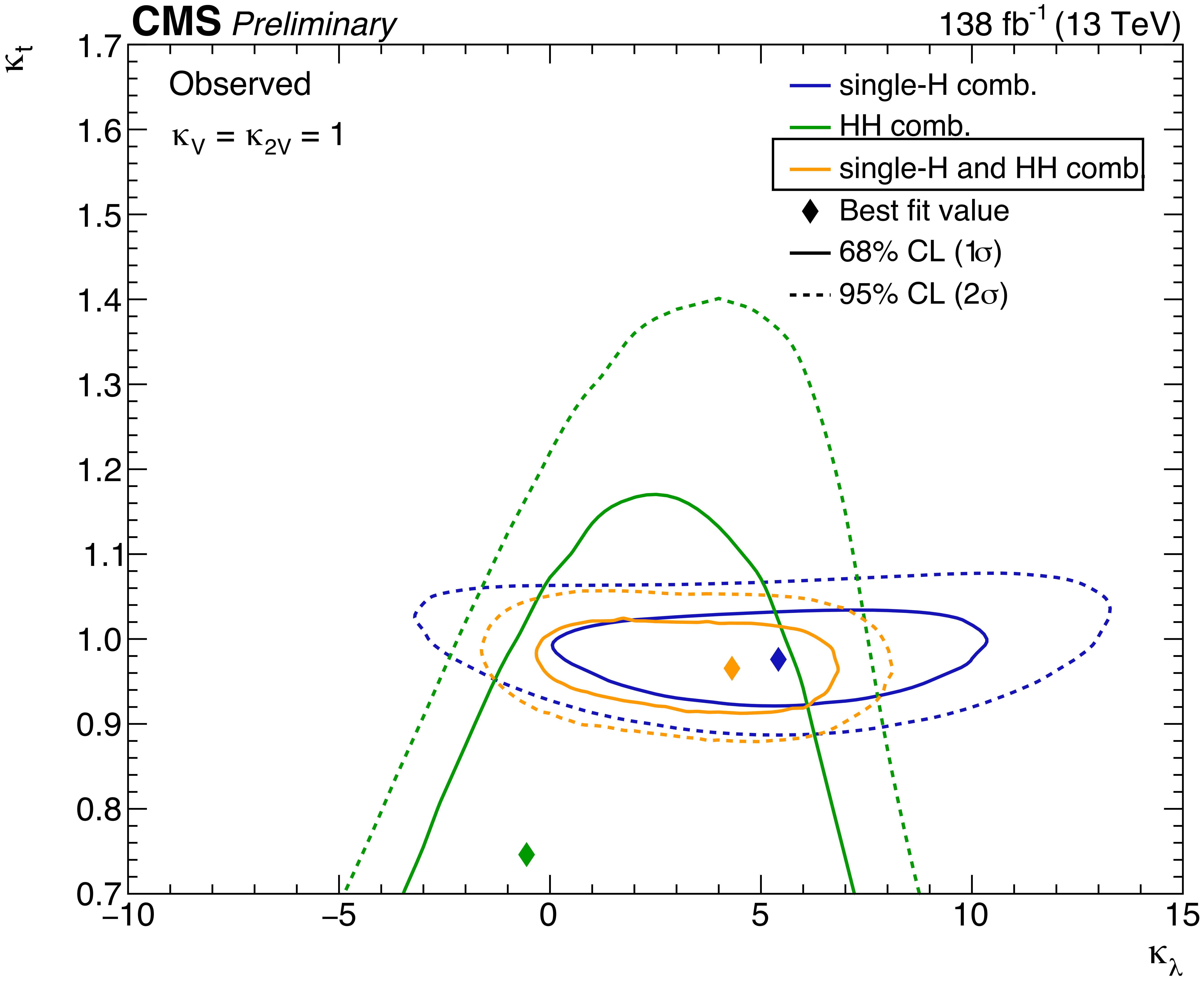



# Single H meets HH

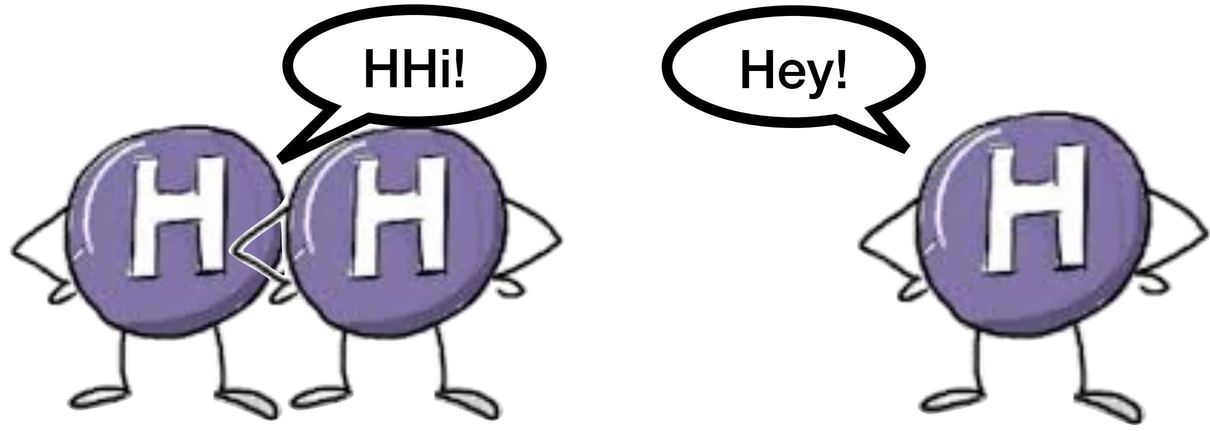
NLO EW contributions from Higgs self-coupling in single H processes

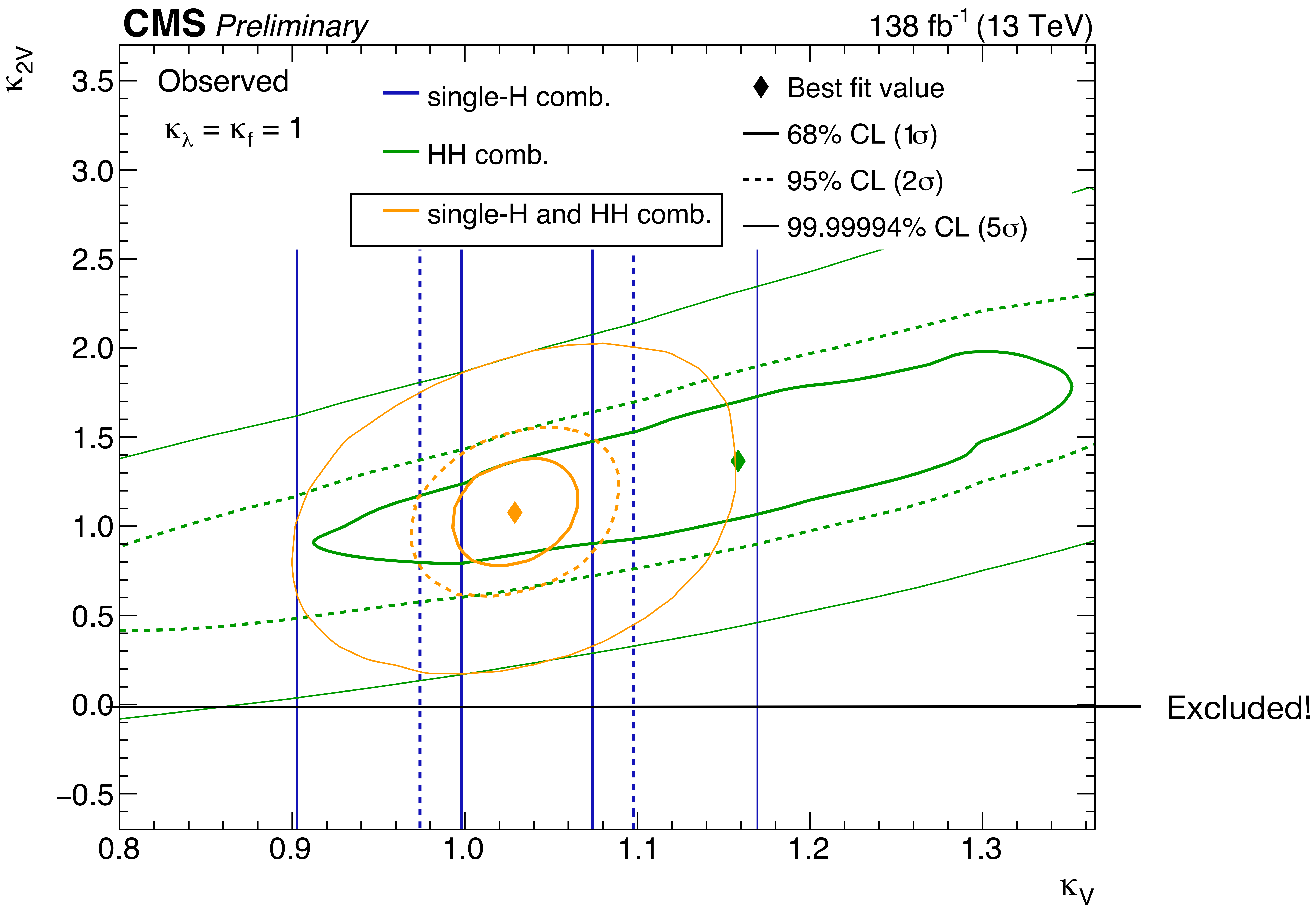



Other Higgs couplings of course still enter!

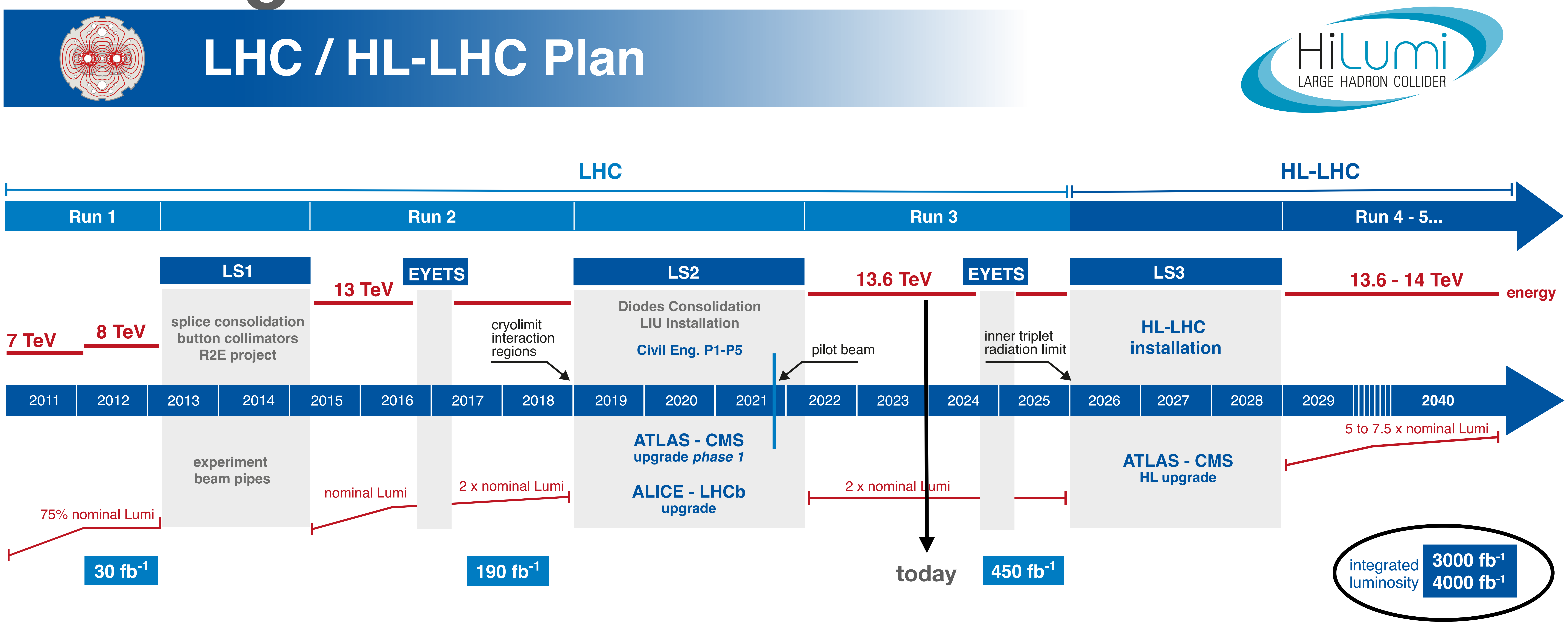


# Single H meets HH



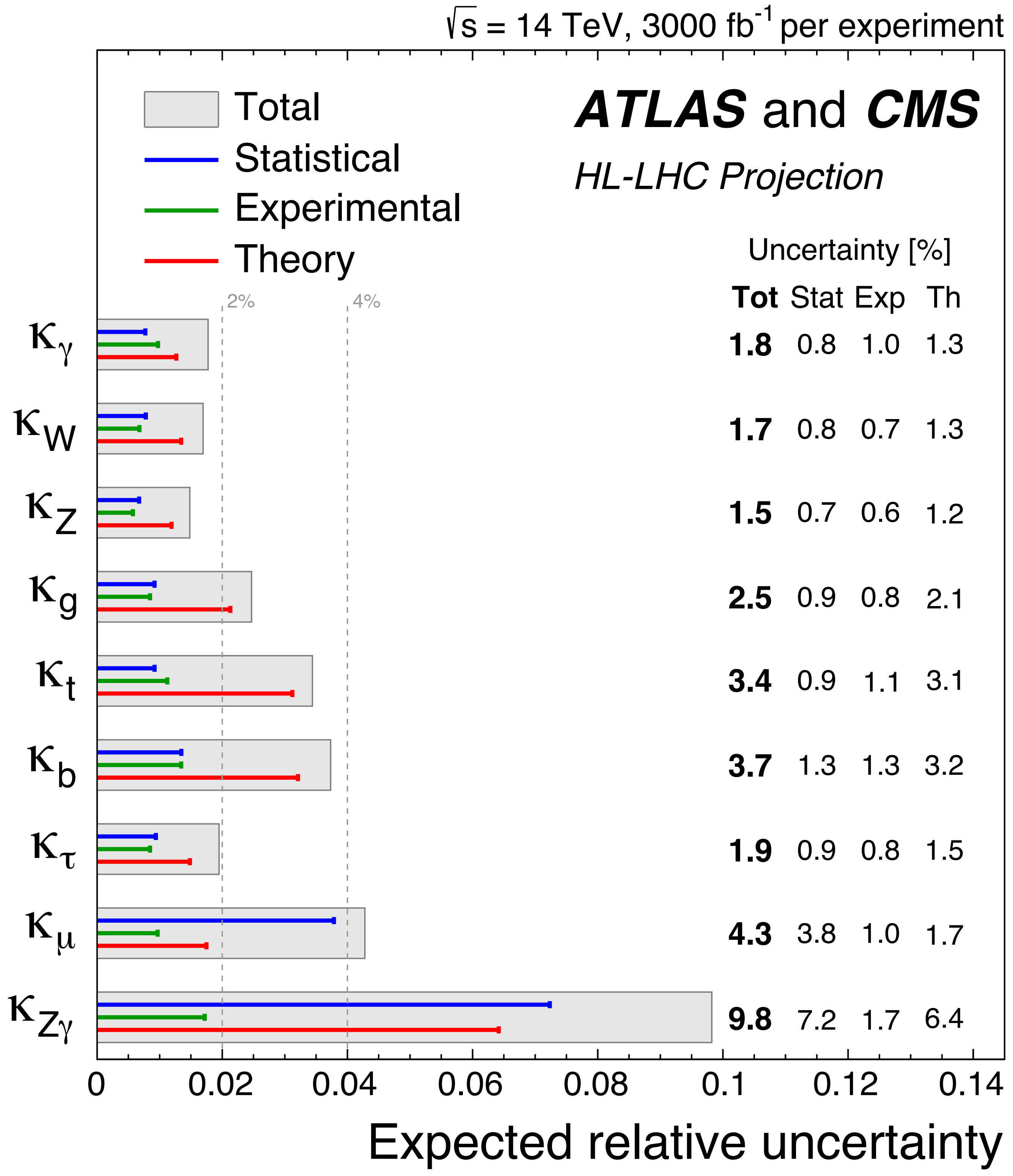
# Looking ahead




Much more data to come in the next decades!
(Relying on the upgrades)

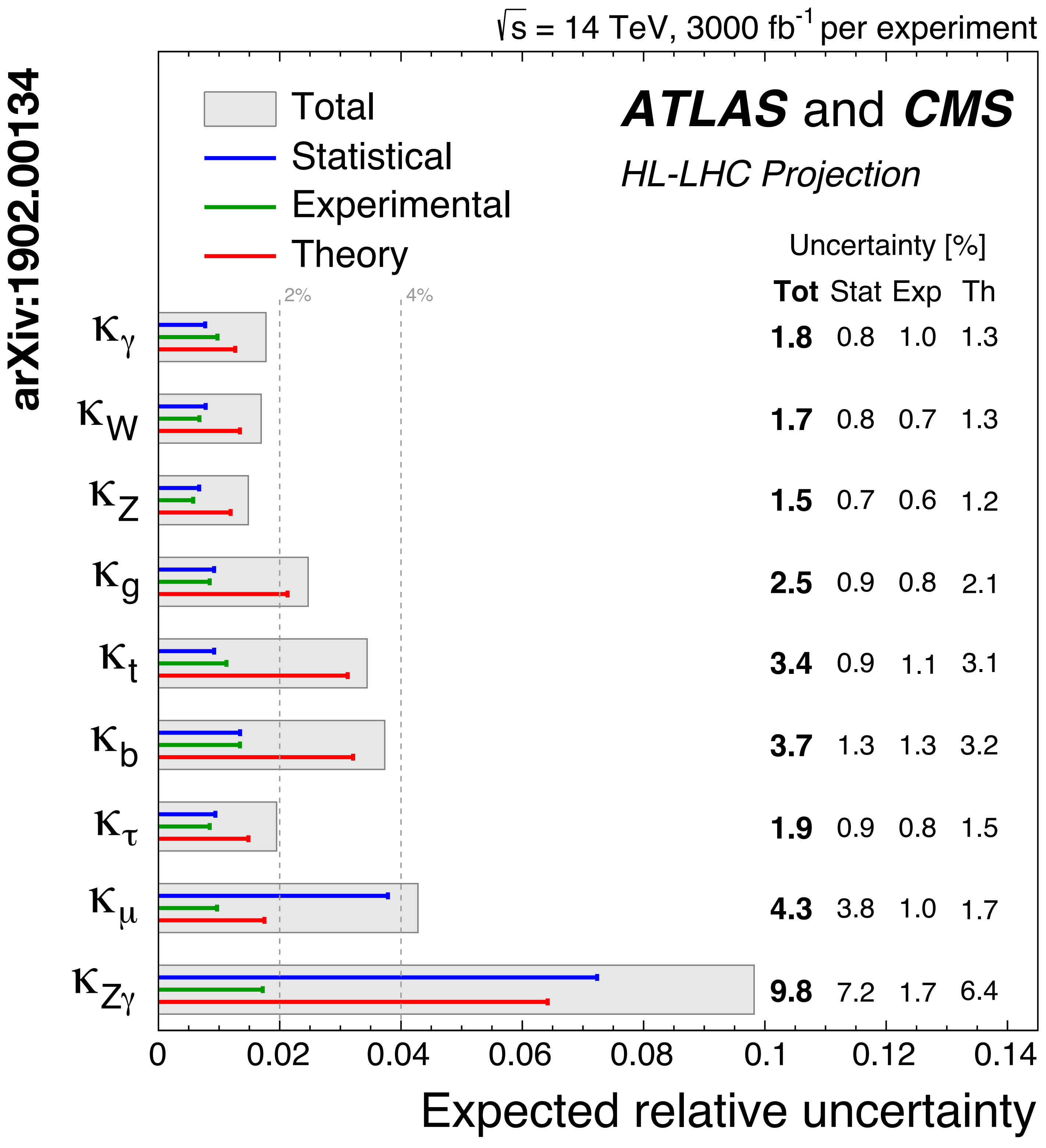
# Higgs prospects at the HL-LHC

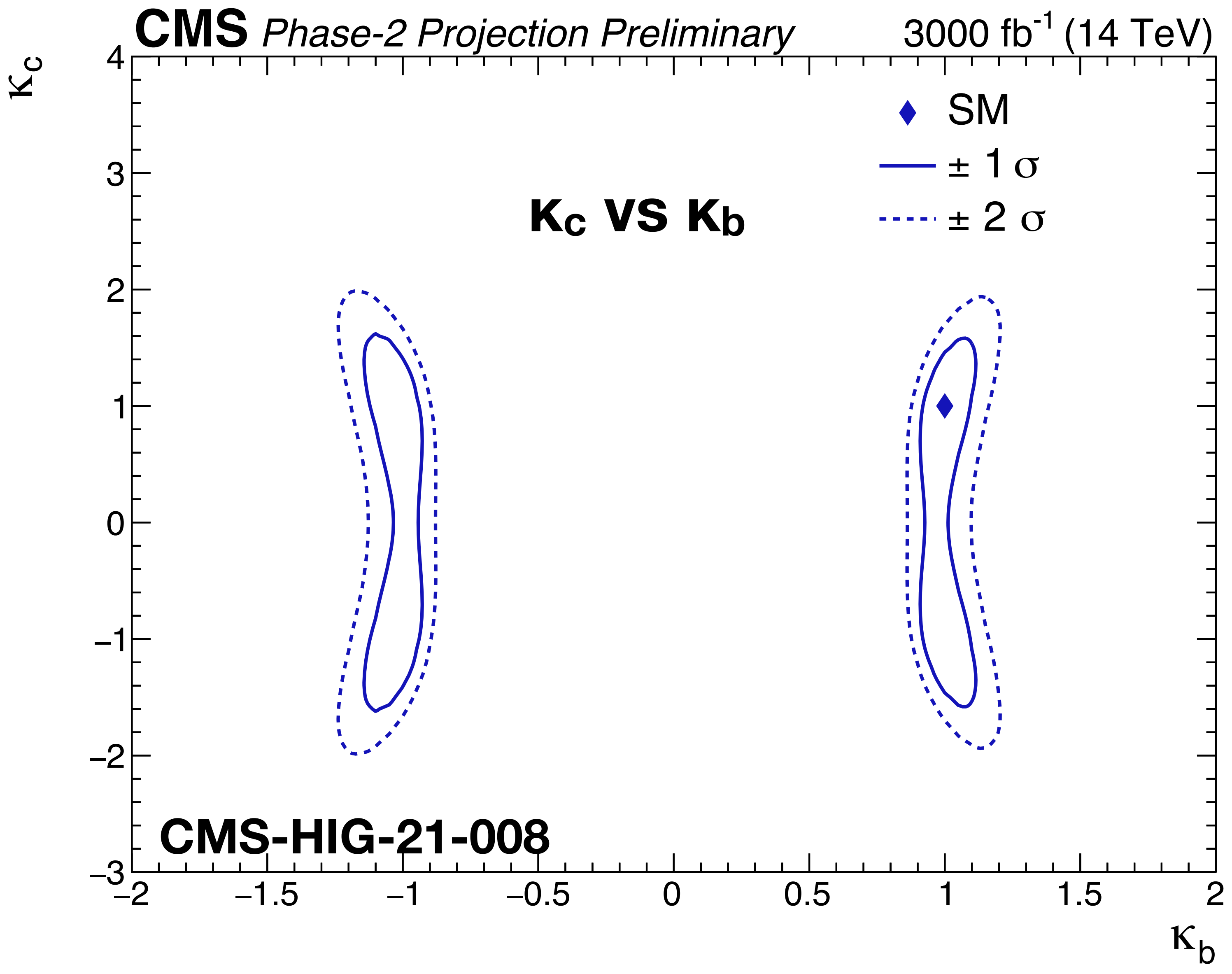
arXiv:1902.00134




Per-cent level precision on most Higgs couplings, **dominated by theory uncertainties**

# Higgs prospects at the HL-LHC

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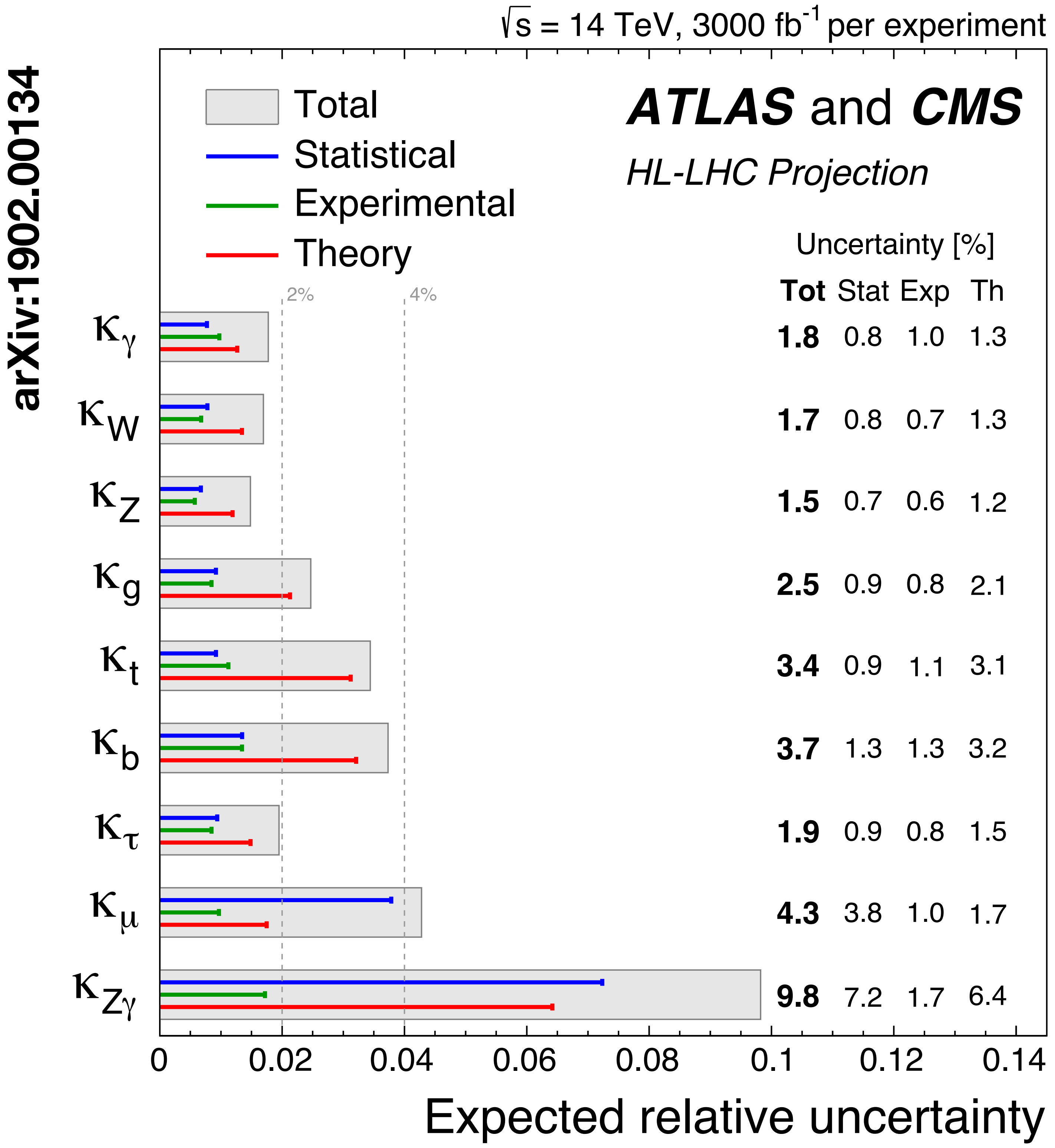
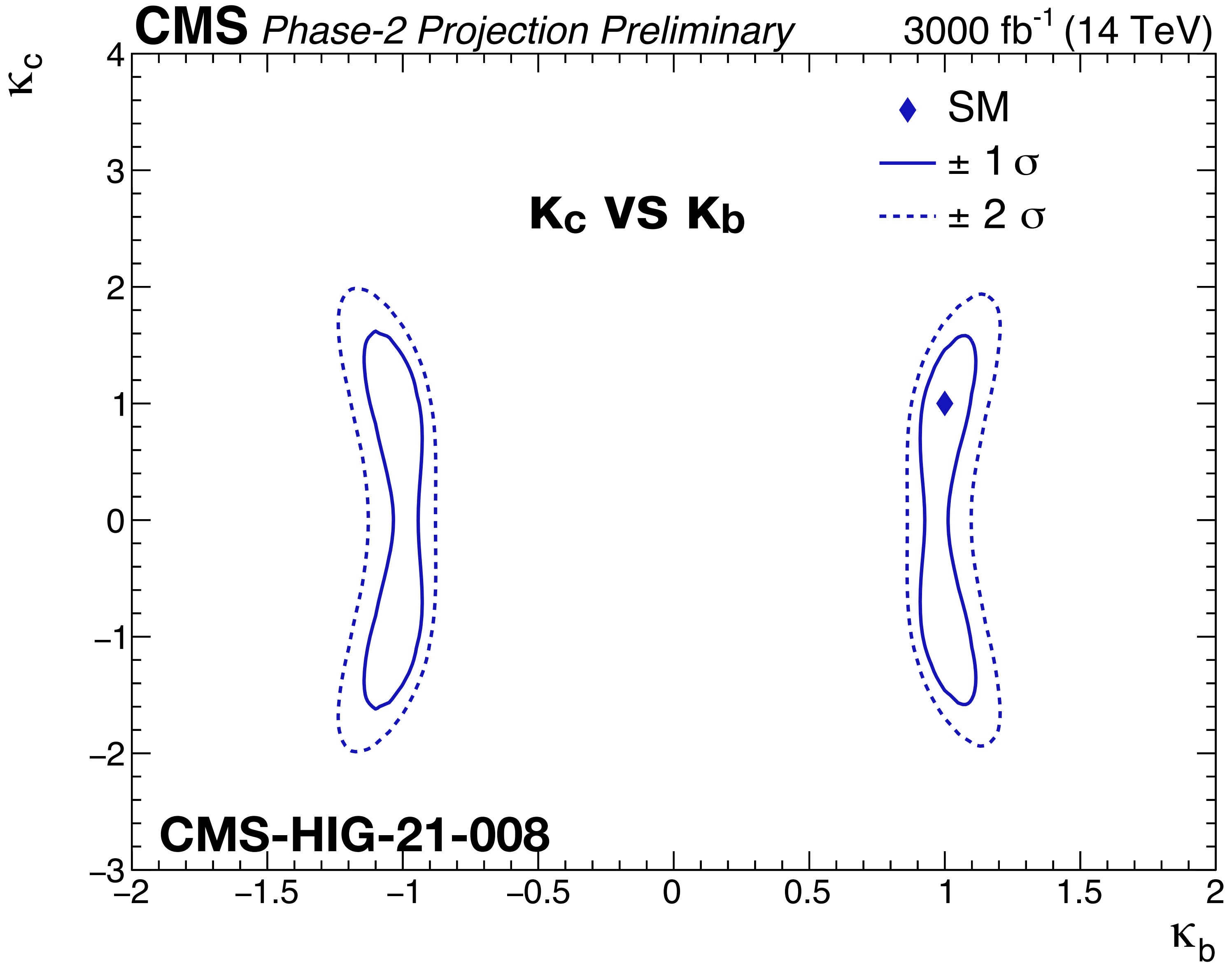
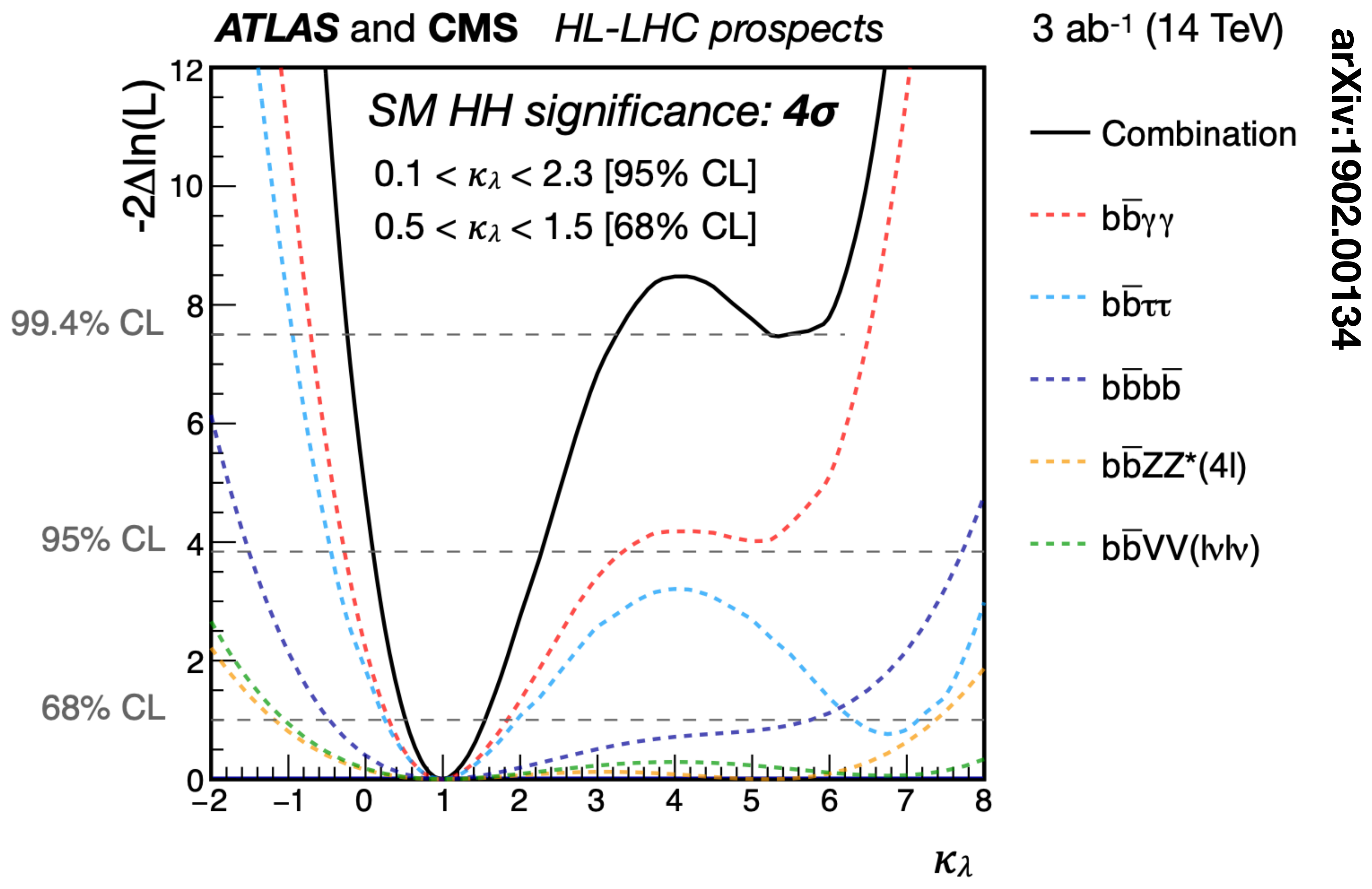



Per-cent level precision on most Higgs couplings, **dominated by theory uncertainties**

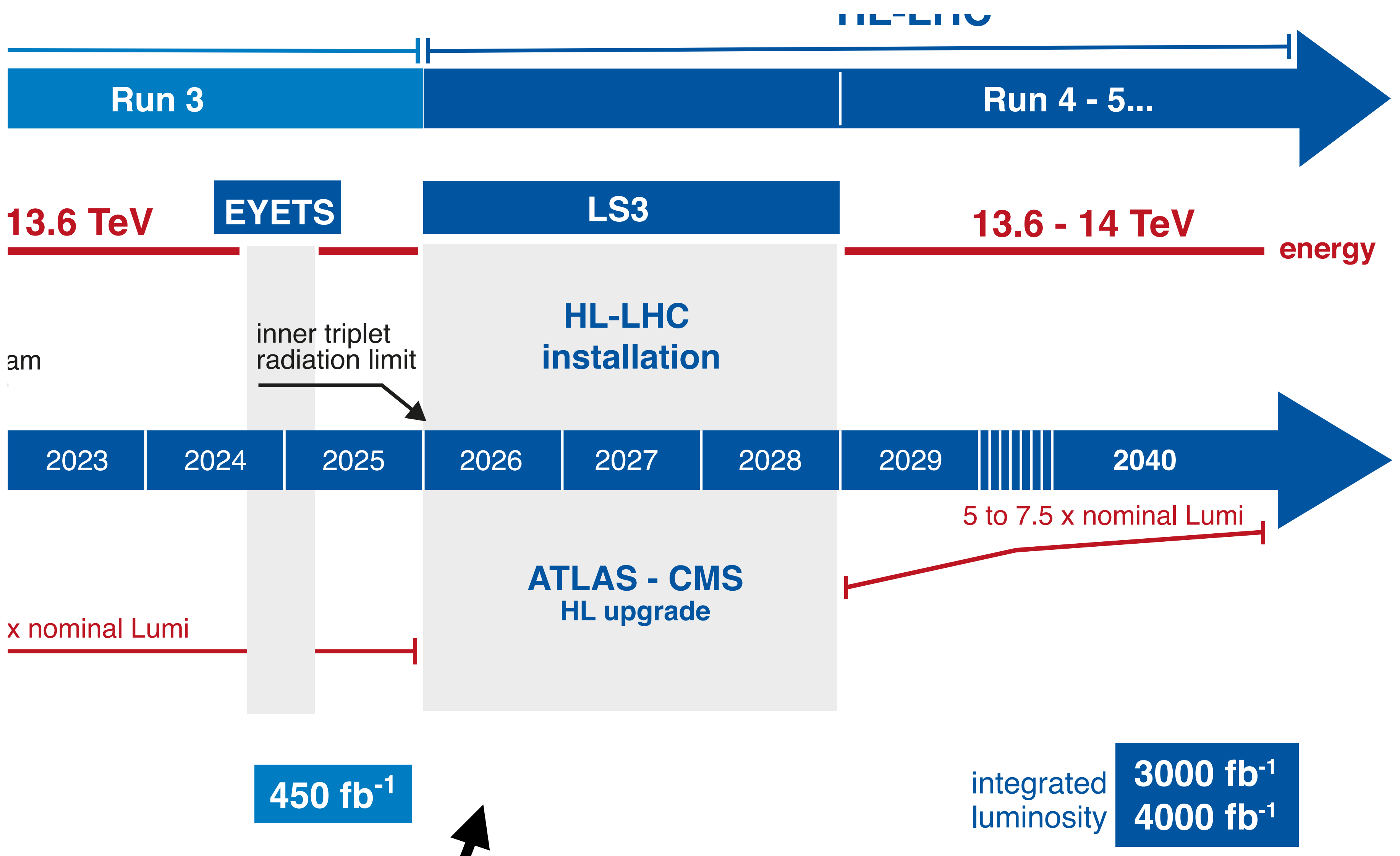


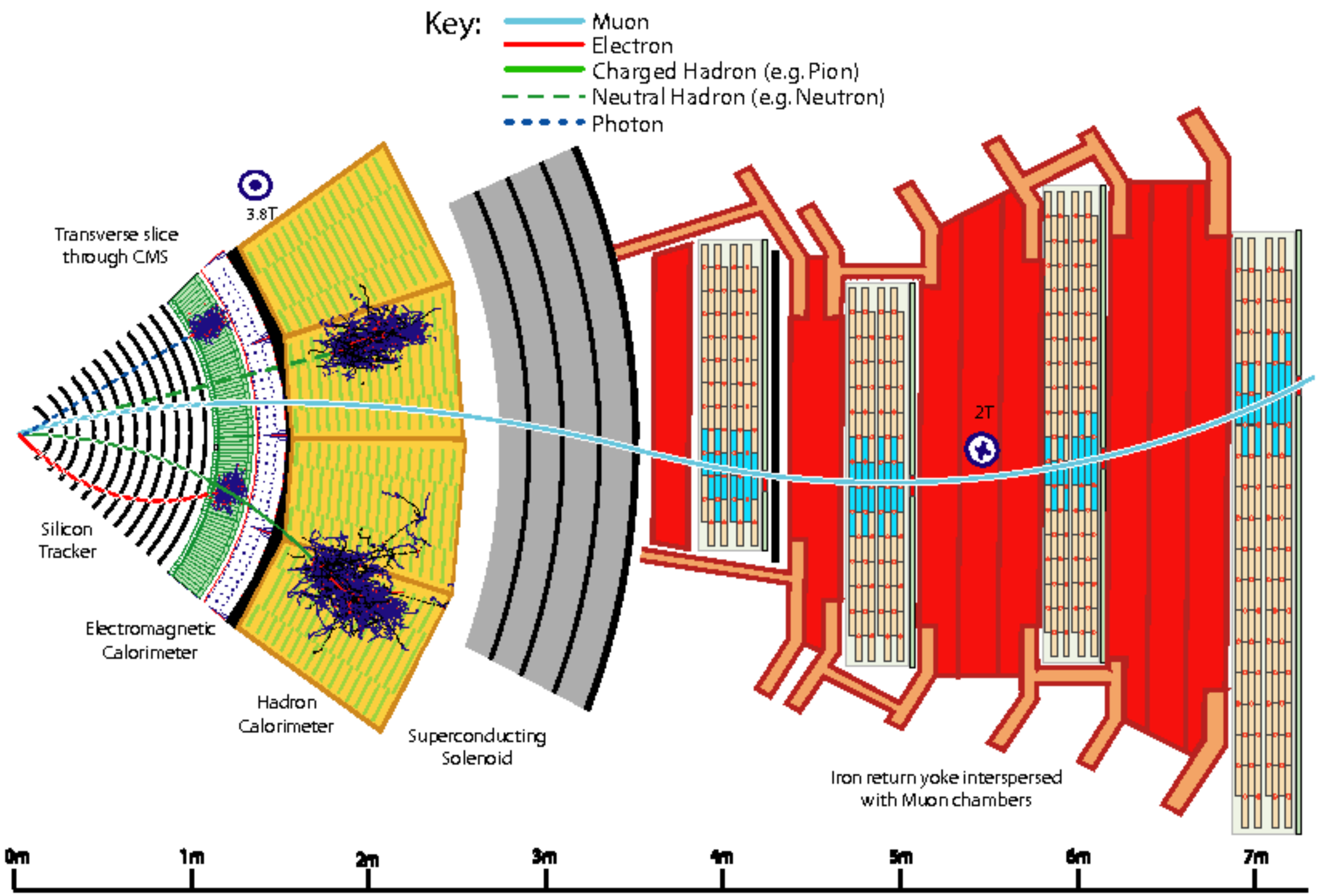

NB projection already "outdated"
➔ analysis methods for full Run 2 improved wrt 2016!

# Summary

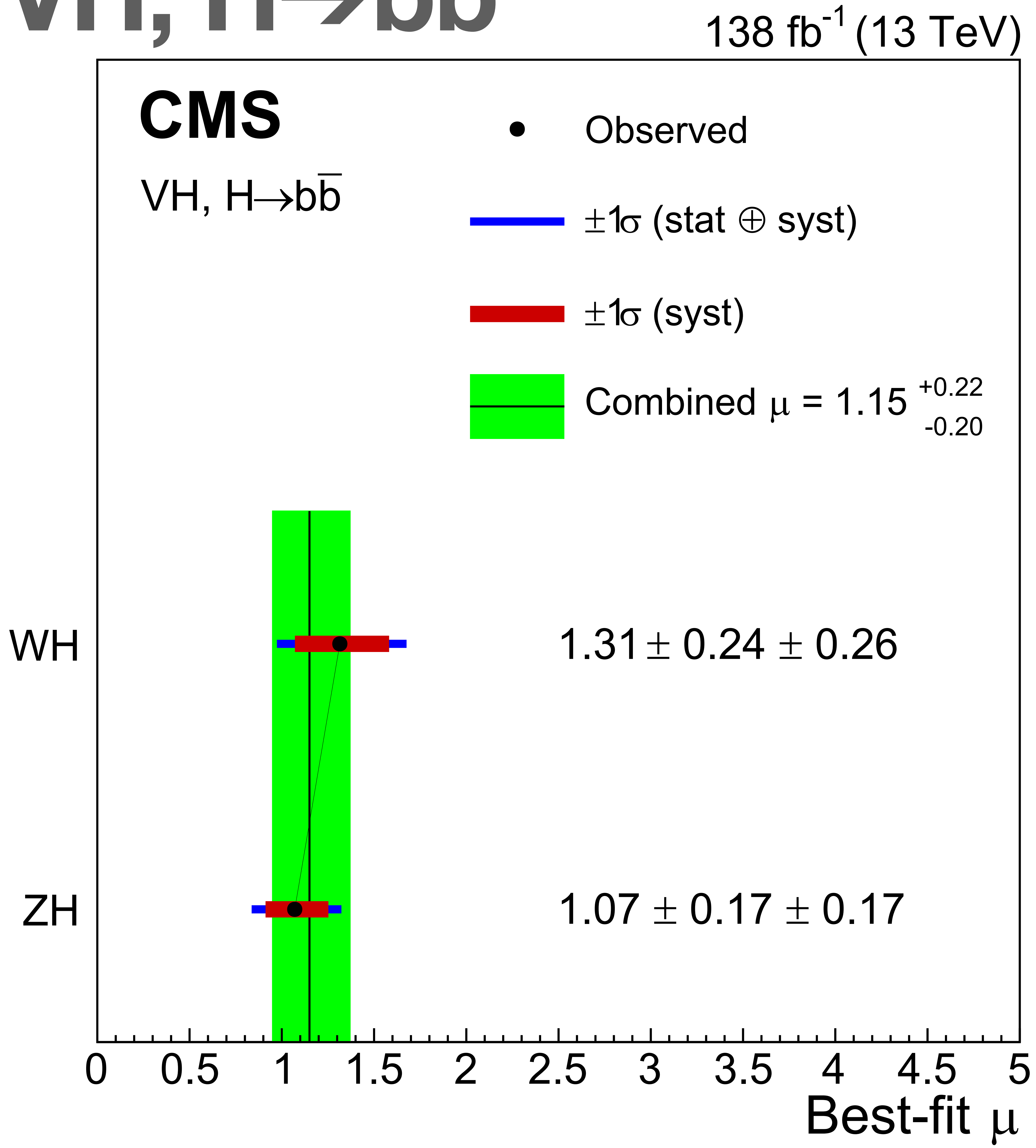
- (Biased) overview of recent advances in Higgs physics at CMS
- In 11 years since the Higgs boson discovery, tremendous progress has been made
- Much more to measure, understand, and (hopefully) discover about the Higgs boson with Run 3 and HL-LHC data!



# Particle ID @ CMS

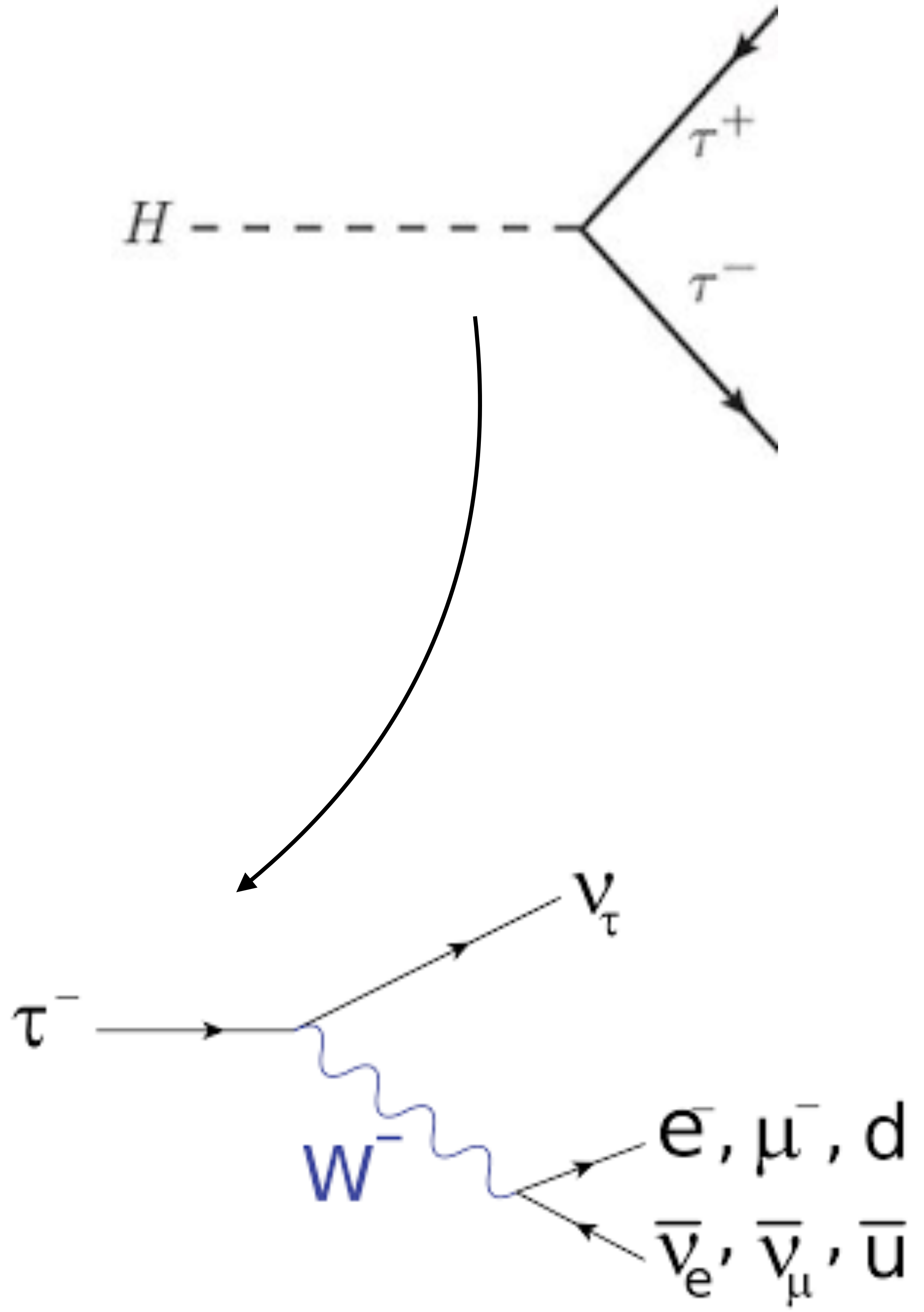


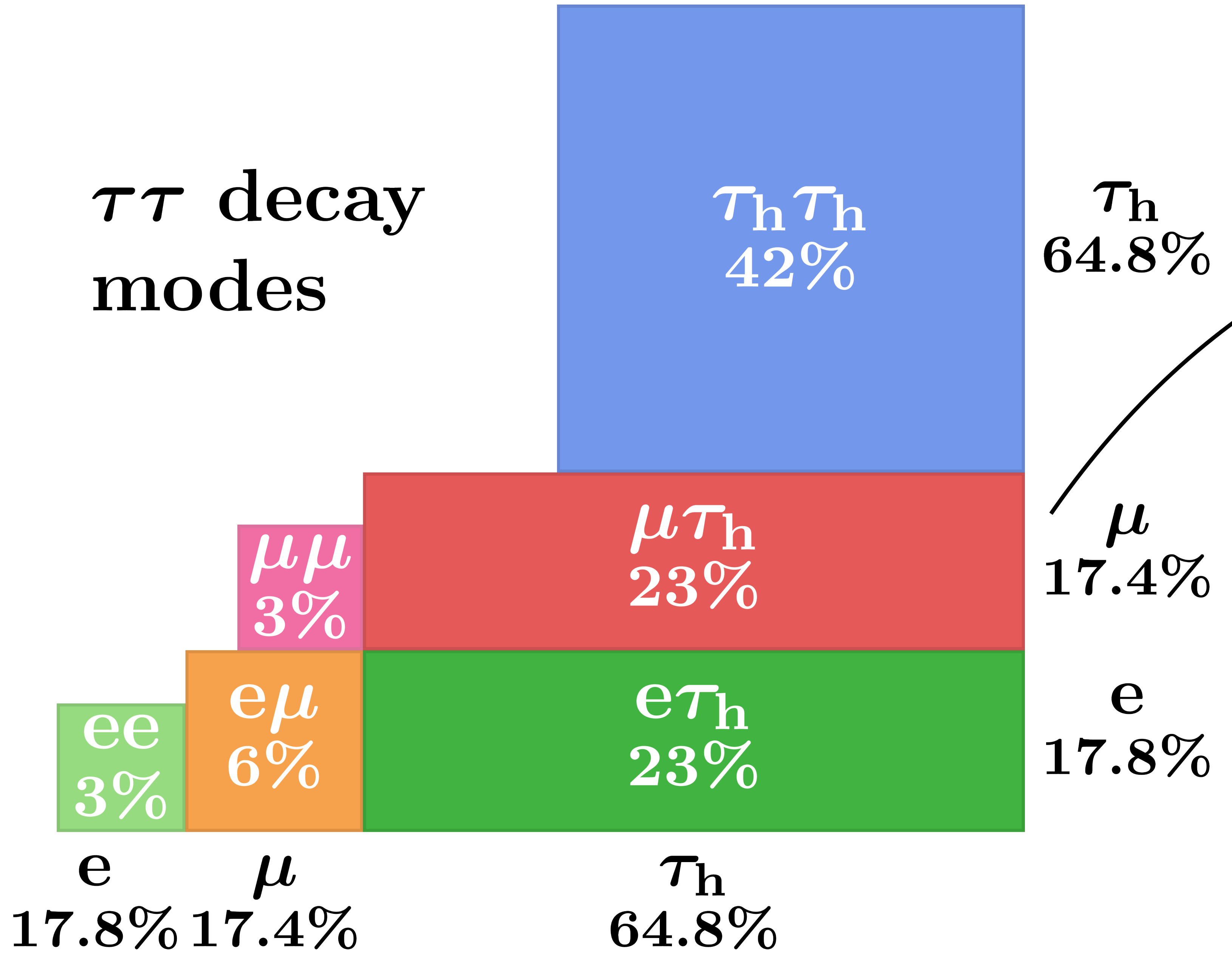
# STXS - VH, H→bb

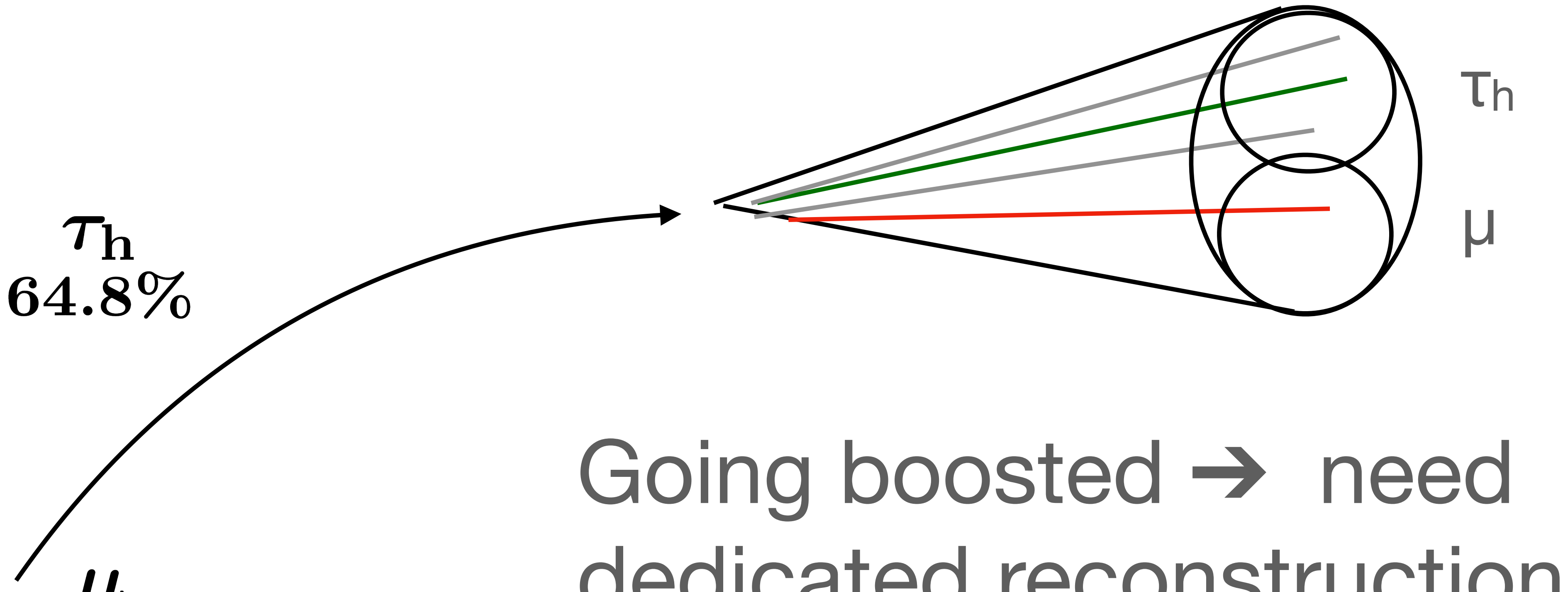



HIG-20-001, sub'd to PRD

# H→ττ boosted



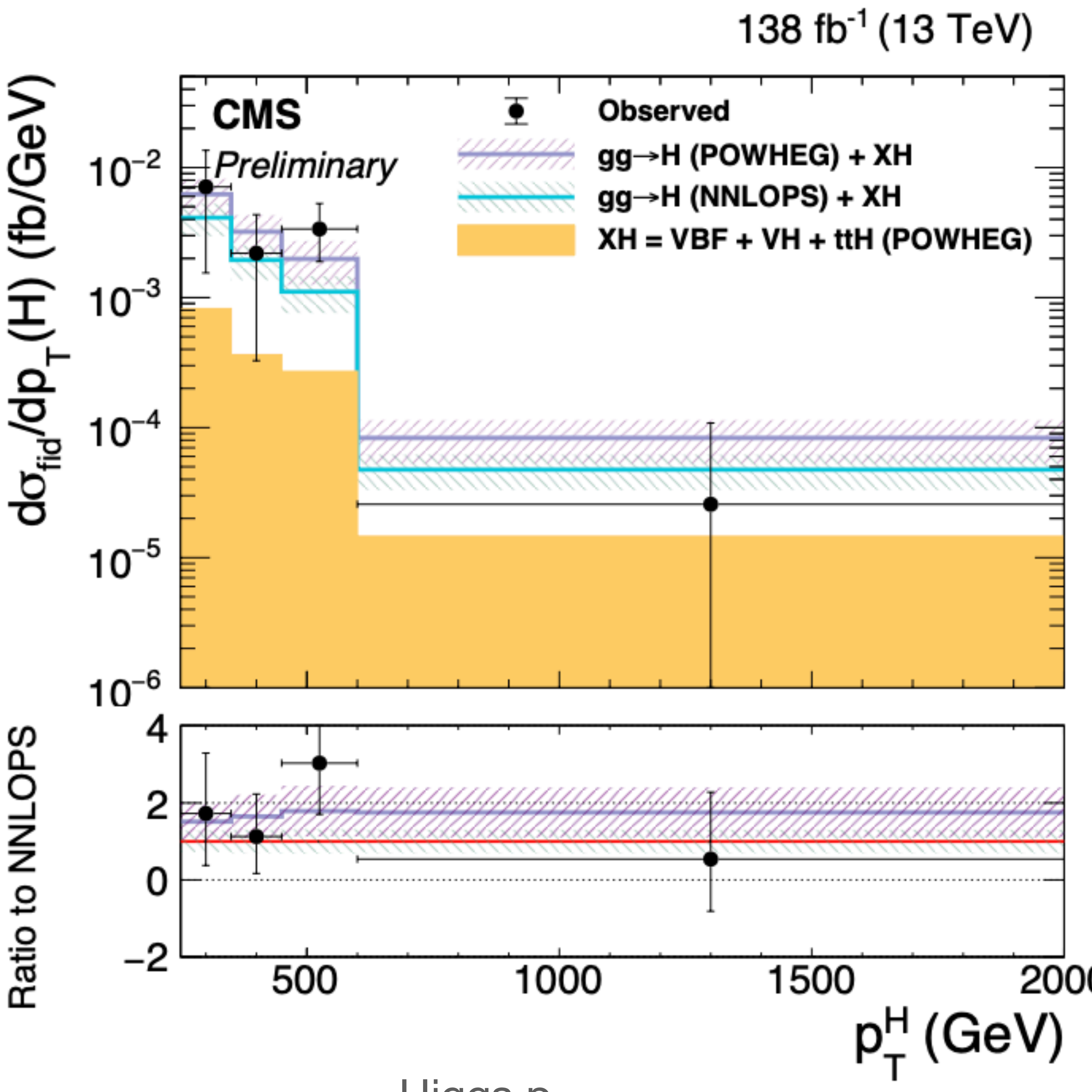



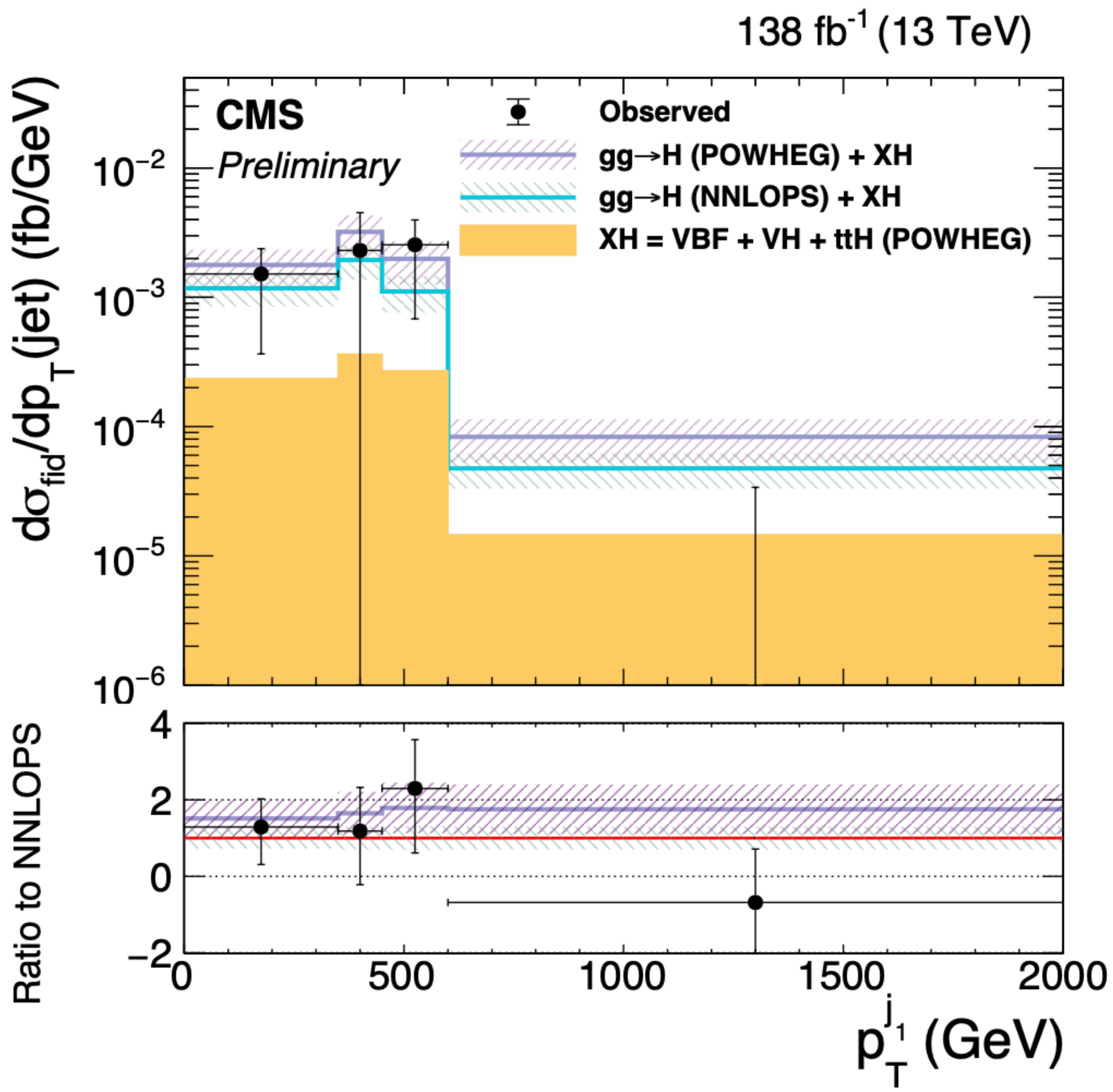

Going boosted ➔ need dedicated reconstruction (isolation)

Many H→ττ decay modes possible!

# H→ττ boosted




Higgs $p_T$



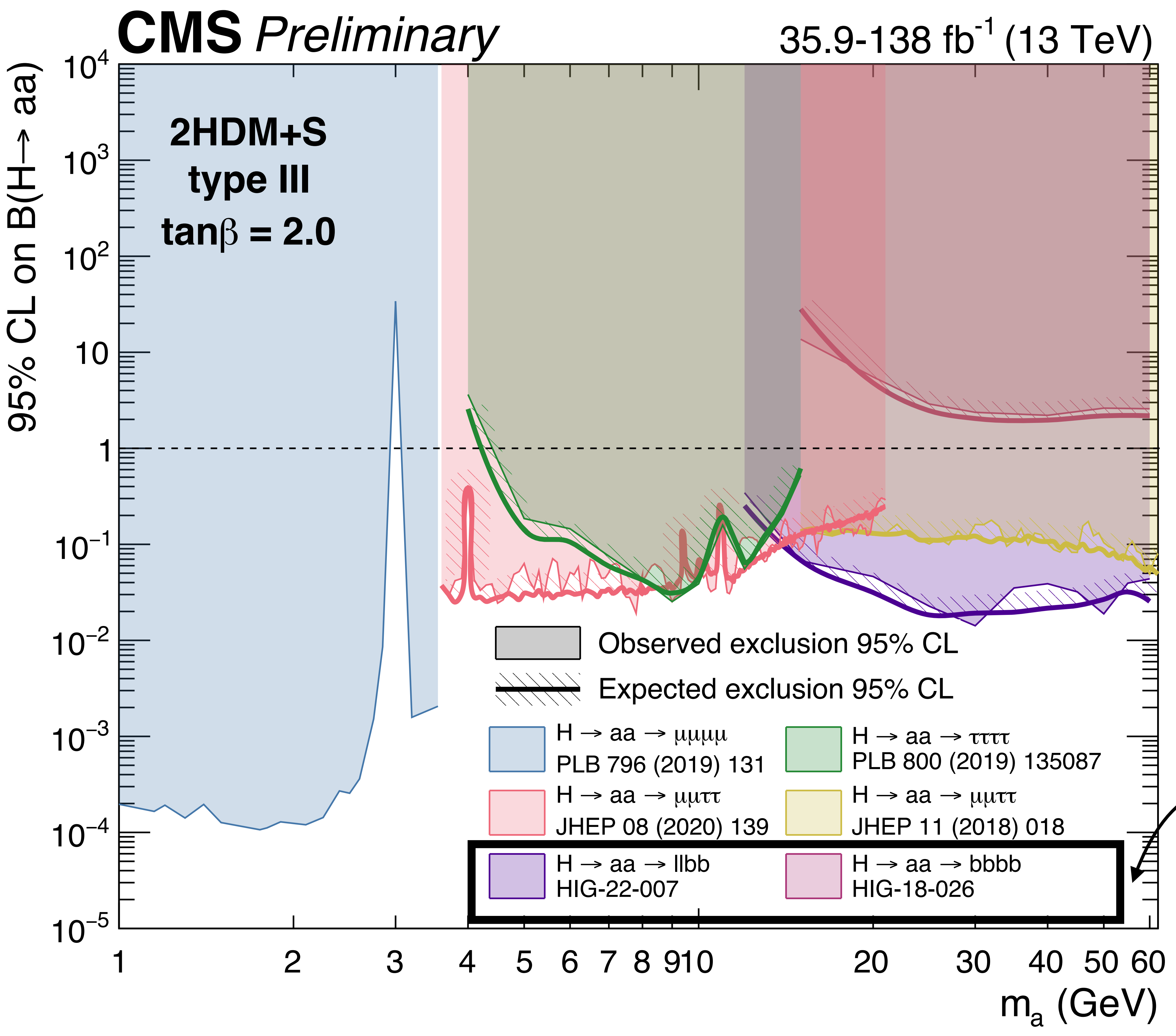

Jet $p_T$

**Probing fewer bins than bb, still interesting additional information at very high $p_T$**

**Adds a (still imprecise) measurement of associated jet $p_T$**

# BSM decays: H→aa

- Extended Higgs sectors ➔ BSM Higgs decays possible
- E.g. models with two Higgs doublets + scalar singlet
- 2HDM: 5 Higgs bosons
    - H(125) does not decay to the others
- 2HDM+S: 7 Higgs bosons, incl. light 'a'




Lower masses accessible e.g. merged 4γ search

Higher masses not kinematically allowed

Only 2 full Run 2 results, much more to come!

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2

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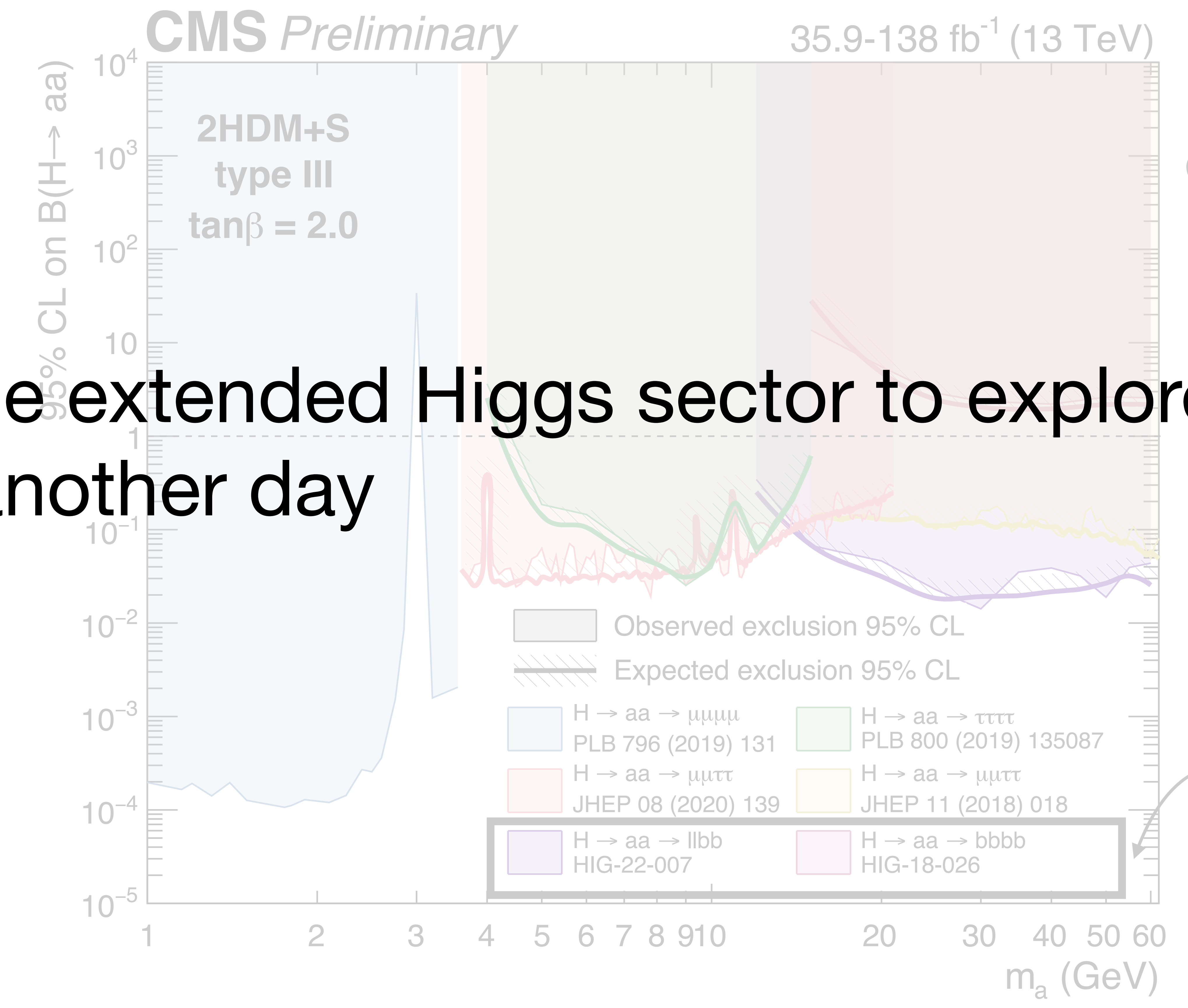
There's a whole extended Higgs sector to explore!
➔ a story for another day

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