



**Carnegie  
Mellon  
University**

# Di-Higgs Production at the LHC

**John Alison**

*Carnegie Mellon University*

for the ATLAS and CMS Collaborations

**LHCP 2024**

# Outline

Introduction

HH Phenomenology

Production

Decay

Survey of Current Analyses

Emphasis on the big three channels:  $4b$  /  $bb\tau\tau$  /  $bb\gamma\gamma$

Current Sensitivity

Past and Future of HH

# Outline

Introduction

HH Phenomenology

Production

Decay

Survey of Current Analyses

Emphasis on the big three channels:  $4b7s$

Current Sensitivity

Past and Future of HH

Disclaimer:

*A Lot of interesting HH physics I will not cover:*  
VBF-HH / V-HH /  $X \rightarrow HH$  /  $X \rightarrow YH$  / ...  
See other talks at this conference:

non-Resonant HH at CMS

*Dutta*

non-Resonant HH at ATLAS

*Cortes*

Rare Higgs and BSM Higgs

*Hirose*

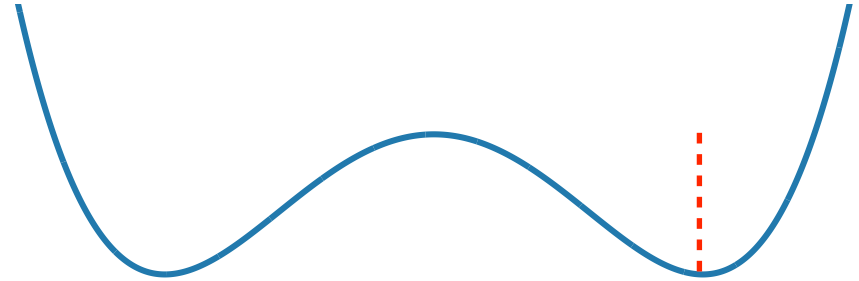
Resonant searches

*Portales*

# HH Production in SM

Higgs potential:

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

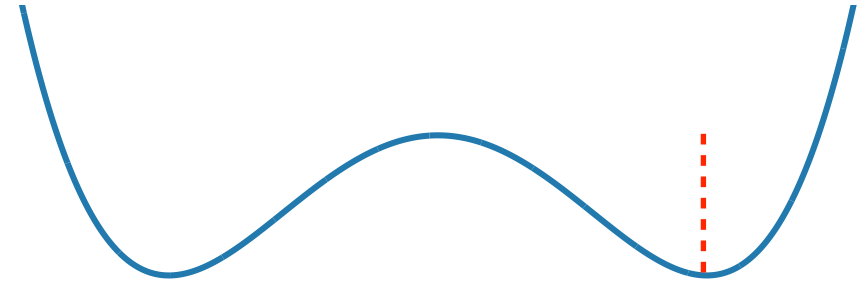


$$\frac{\mu}{\sqrt{\lambda}} \equiv v \quad 246 \text{ GeV}$$

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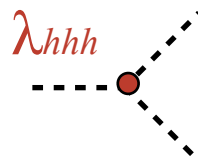


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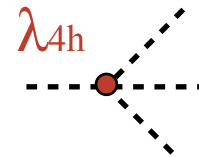
Expanding about minimum:  $V(\phi) \rightarrow V(v + h)$

$$V = V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$$

Higgs mass term



HH-production

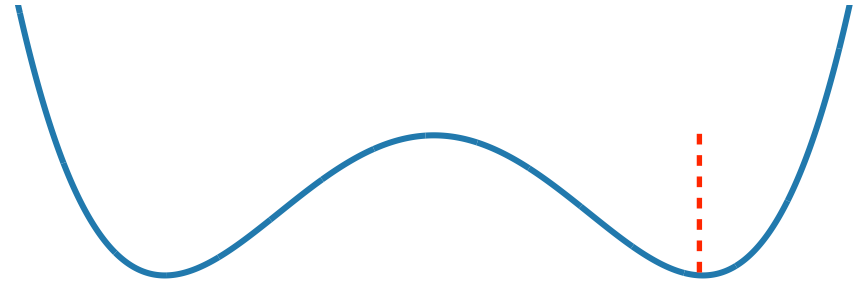


HHH-production

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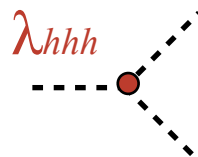


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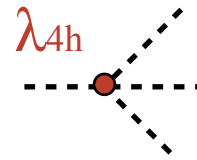
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Higgs mass term



HH-production



HHH-production

Shape of potential gives relationship between  $\lambda_{hhh}$  and  $m_h, v$

Standard Model:

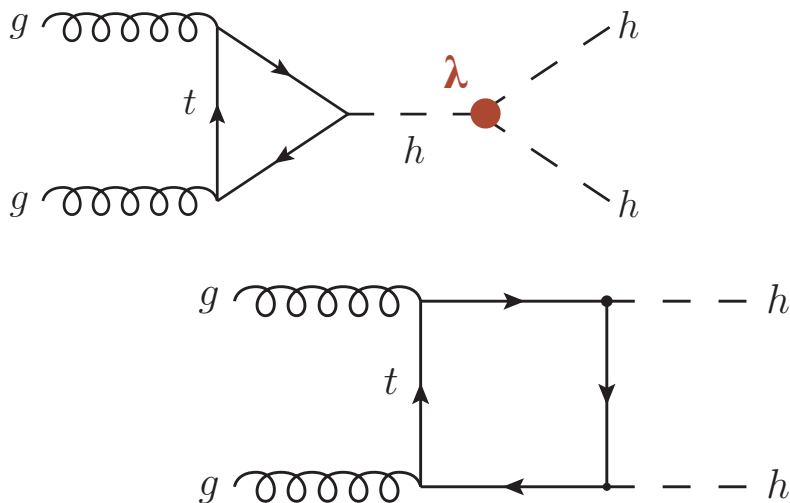
$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

# SM HH Production at the LHC

## Small in Standard Model.

- HH production higher order in  $\alpha_{\text{EWK}}$
- Reduced phase space: 2 heavy particles in final state.
- Destructive interference among diagrams

### Example Diagrams *ggF-HH:*

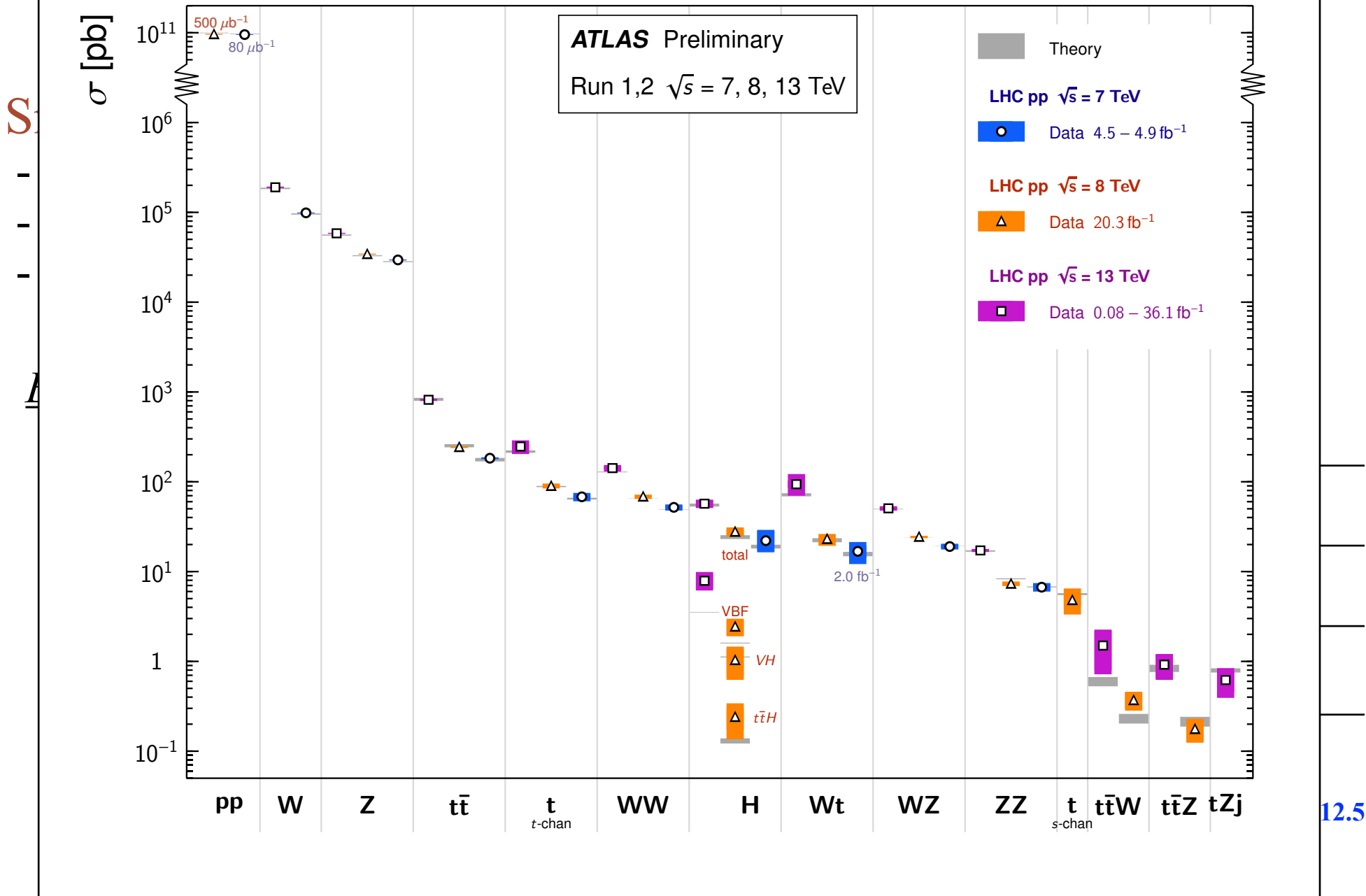


Production mode	Cross section (13 TeV)
ggF-HH	31 fb
VBF-HH	1.7 fb
V-HH	0.87 fb
tt-HH	0.76 fb

[arXiv:1212.5581](https://arxiv.org/abs/1212.5581)

# Standard Model Total Production Cross Section Measurements

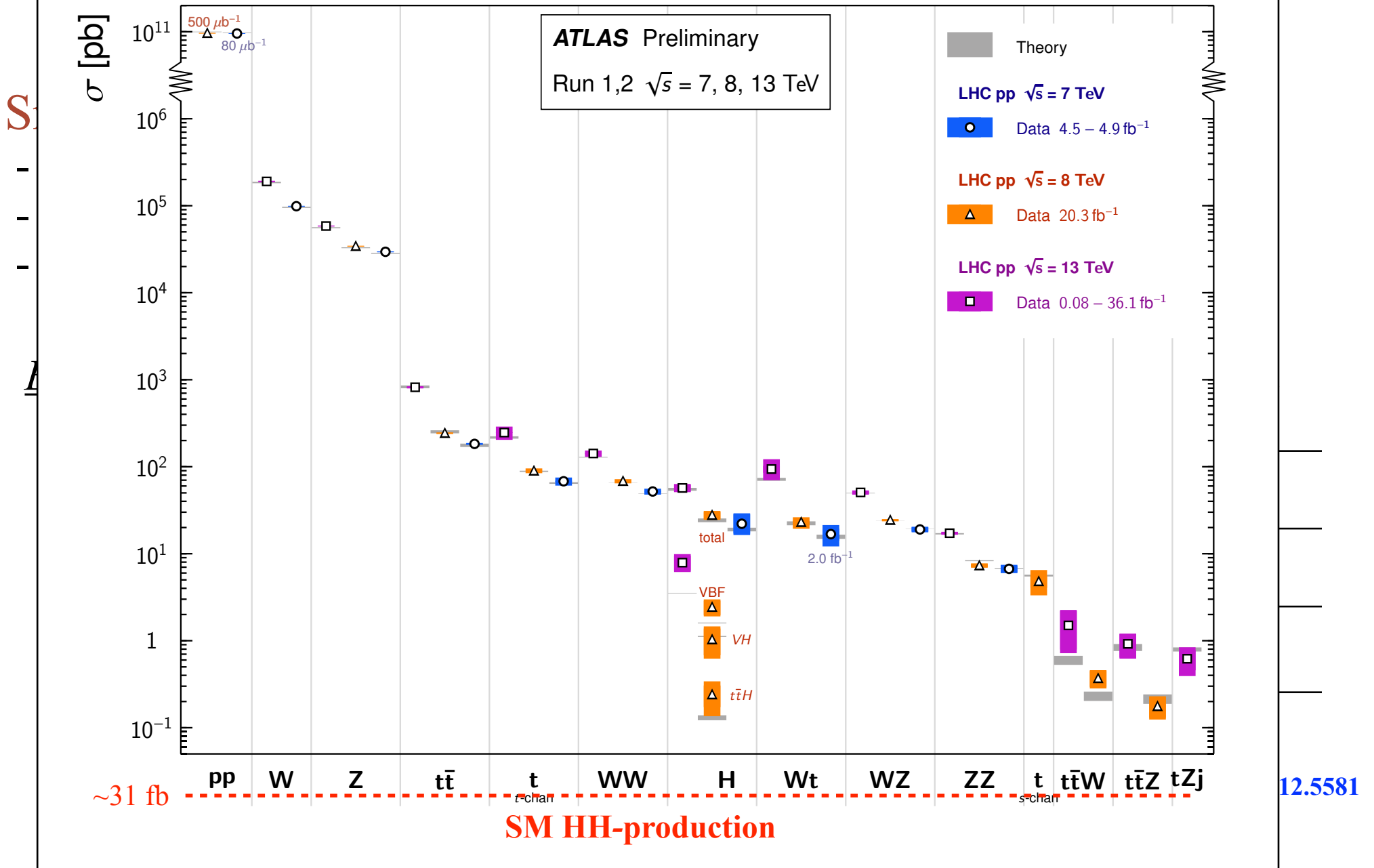
Status: July 2017





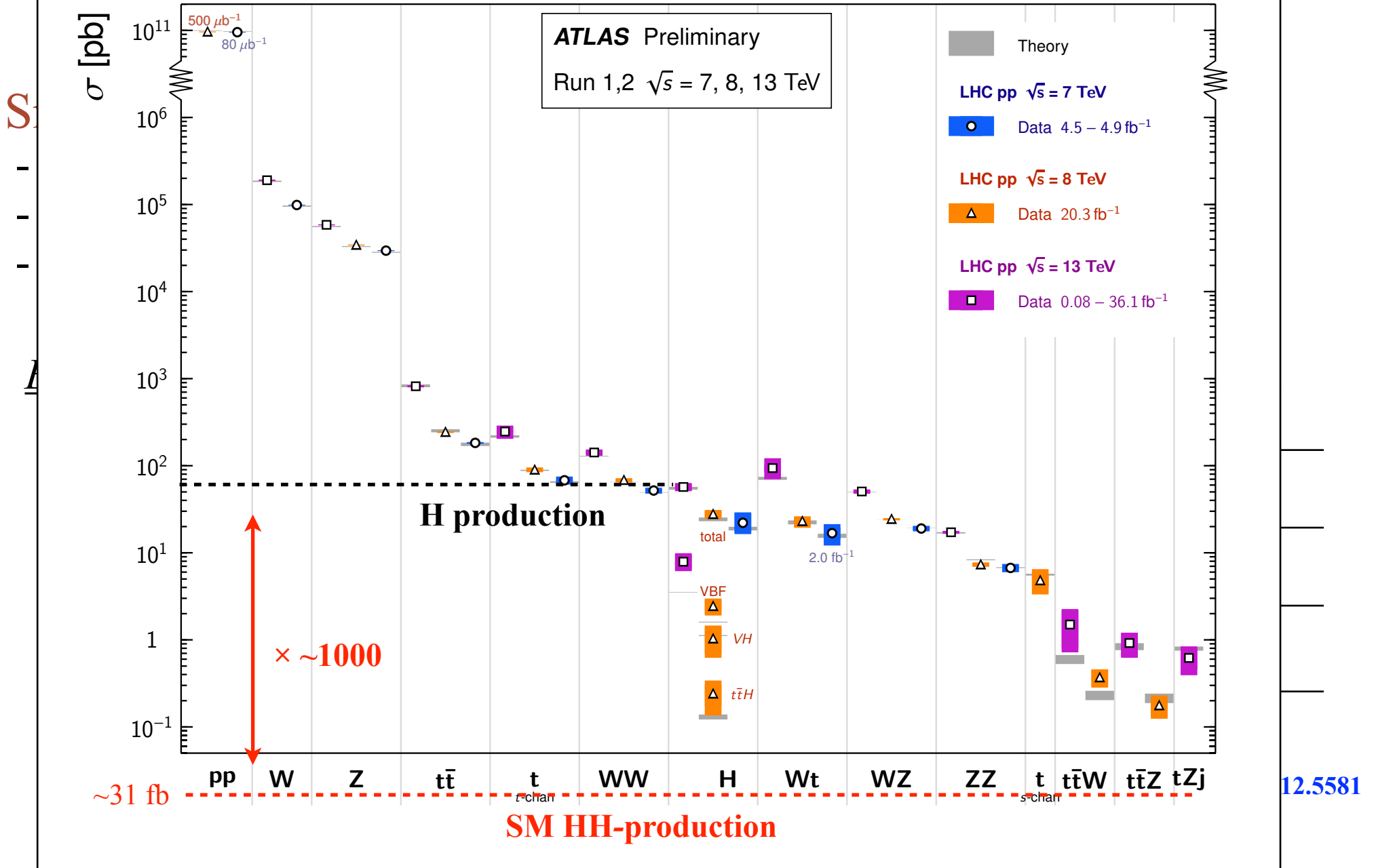
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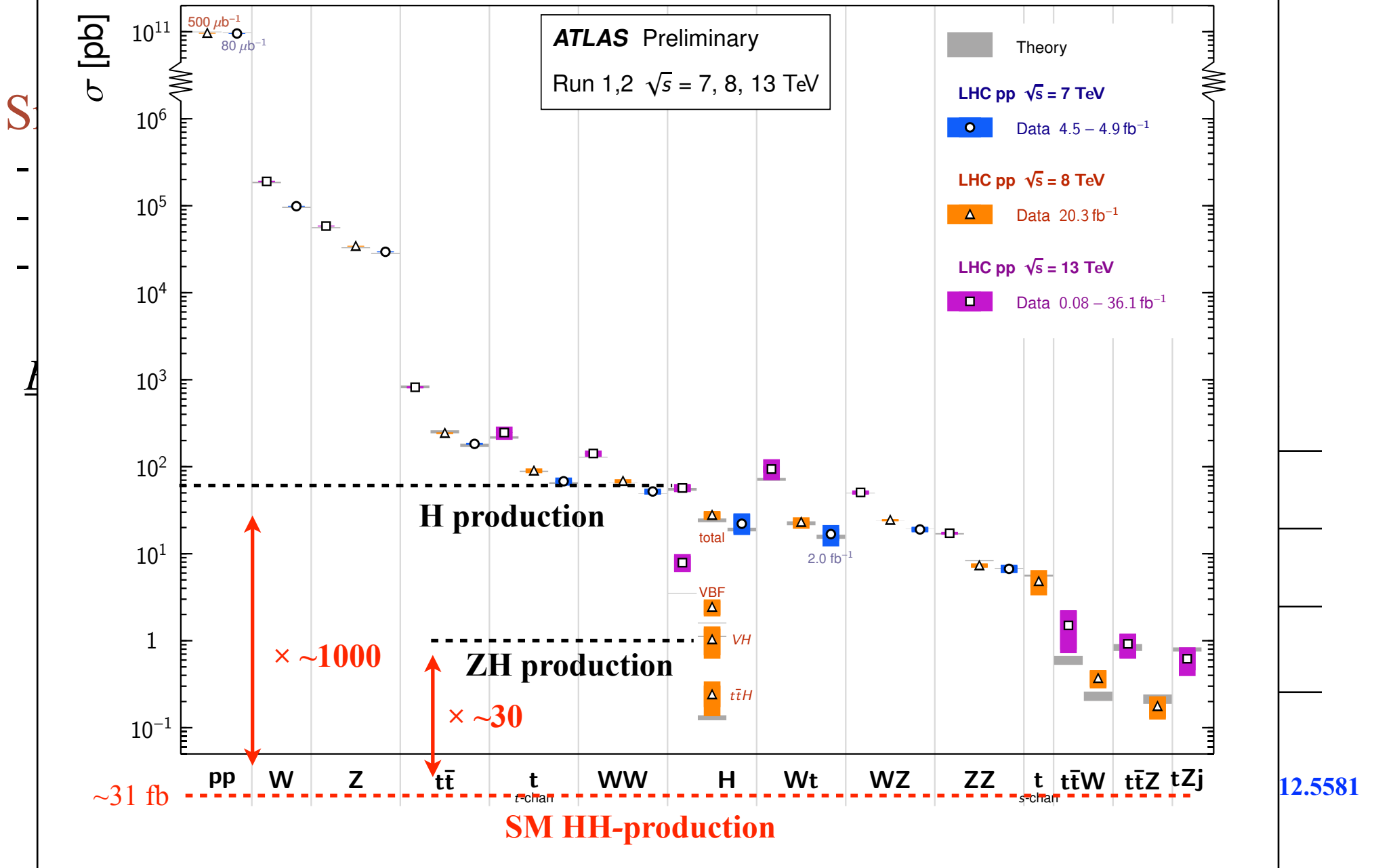
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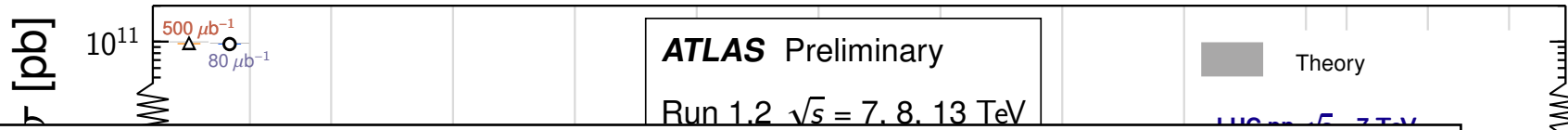
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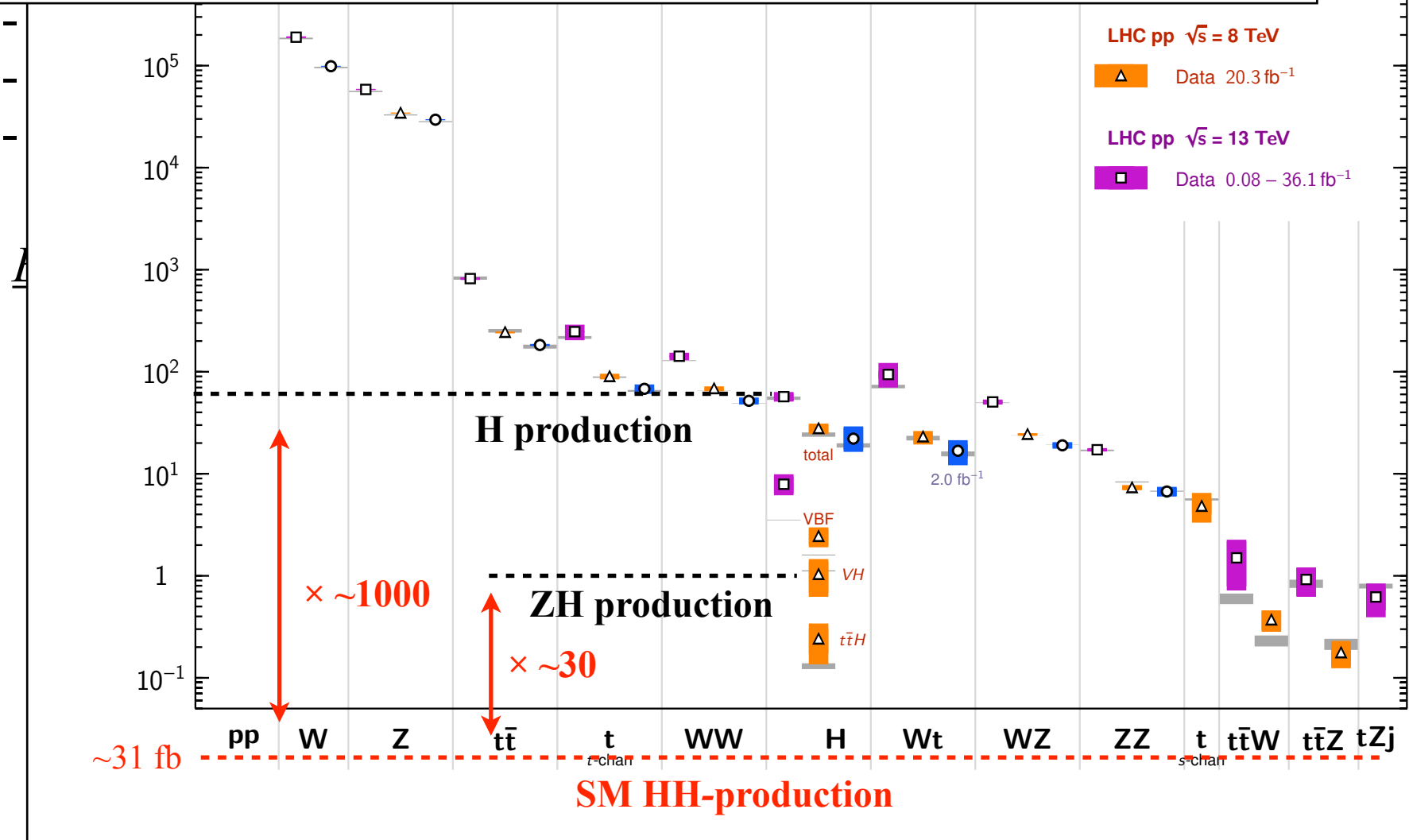


# Standard Model Total Production Cross Section Measurements

Status: July 2017



Sensitivities interesting w/full HL-LHC dataset (more on this later)



12.5581

# BSM HH Production

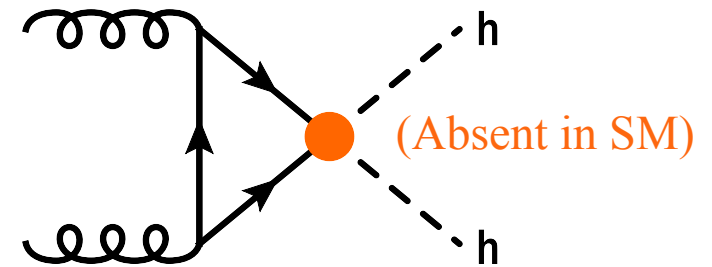
HH production significantly enhanced in many BSM models.

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HH production significantly enhanced in many BSM models.

## Non-resonant HH enhancement:

- Generic in many BSM models  
(composite higgs / little higgs /... )
- Significant enhancements wrt SM
- **Modify**  $\lambda_{hhh}$  or activate new vertices

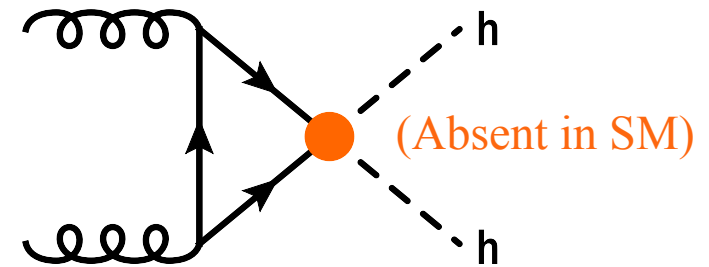


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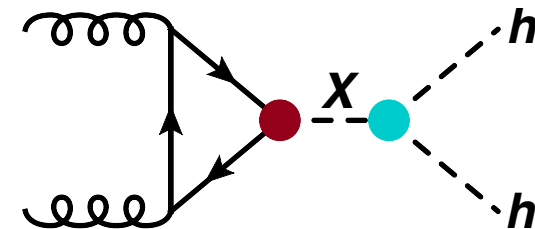
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## Resonant HH production:

- Generically expected. ("*Higgs Portal*")
- Host of models (KK-gravitons /2HDM/....)
- Significant cross-section enhancement on resonance (up to pb)
- Exploit  $m_X$  to reduce (and to model) backgrounds

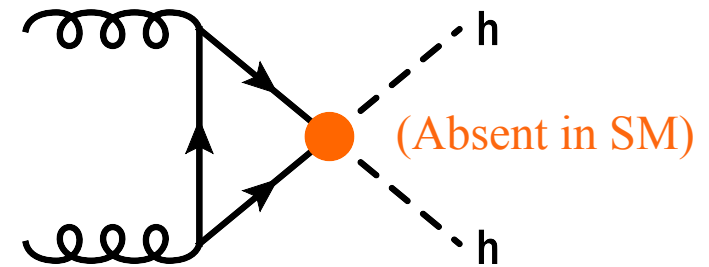


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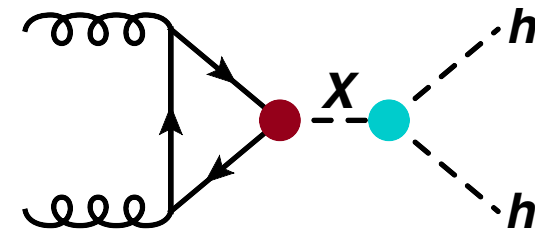
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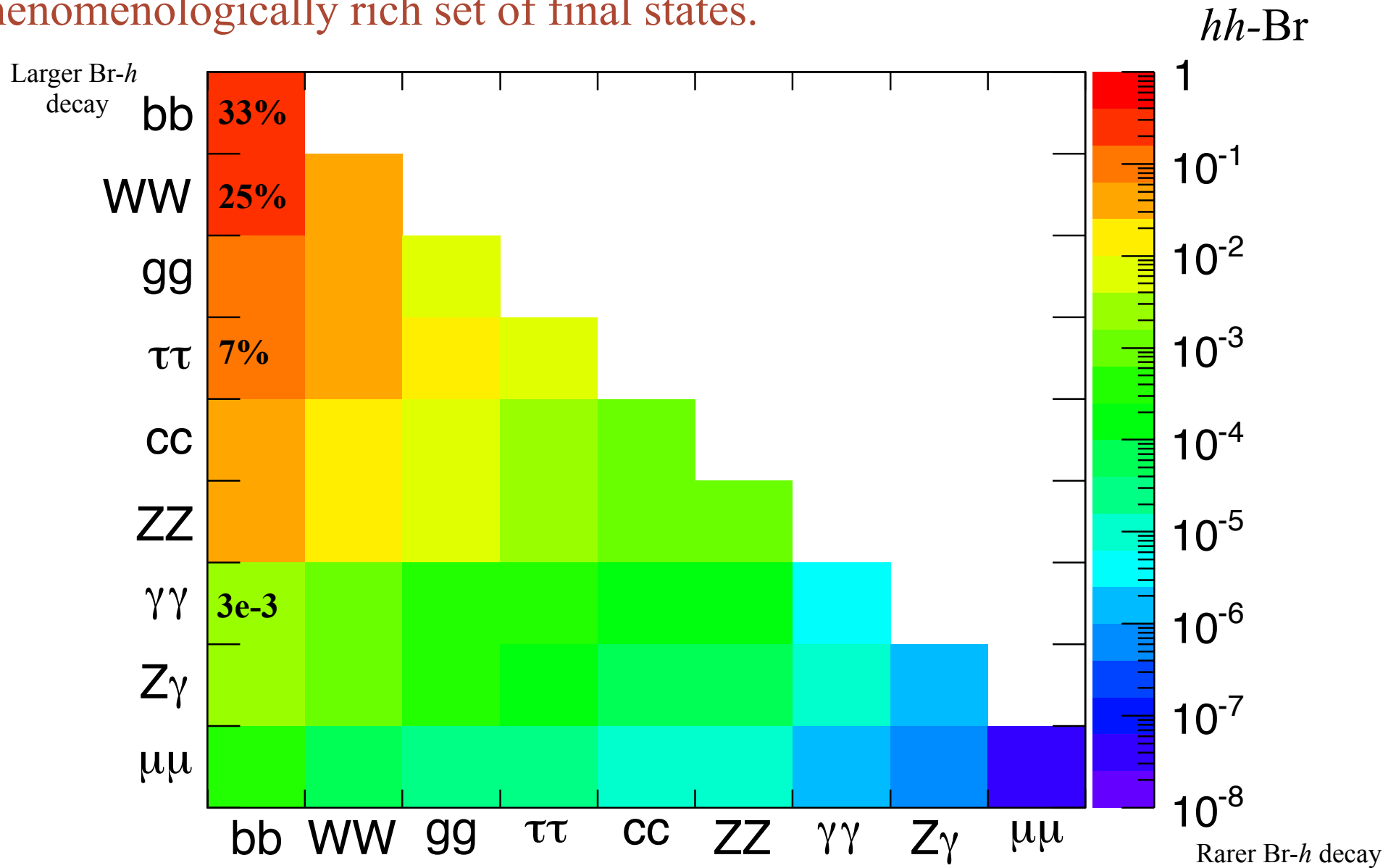


Sensitivities interesting already / Continue as dataset grows



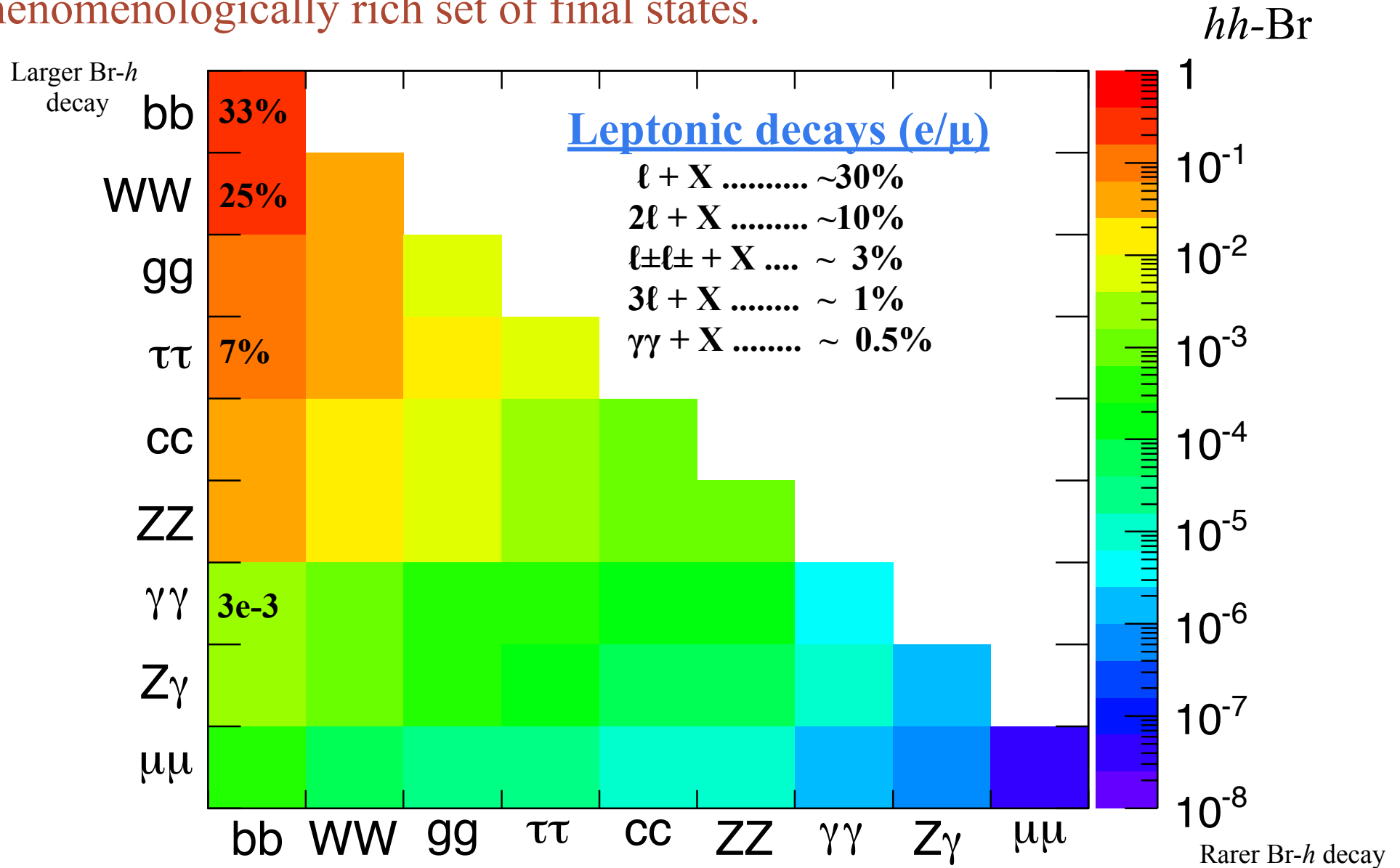
# HH Decay

Phenomenologically rich set of final states.



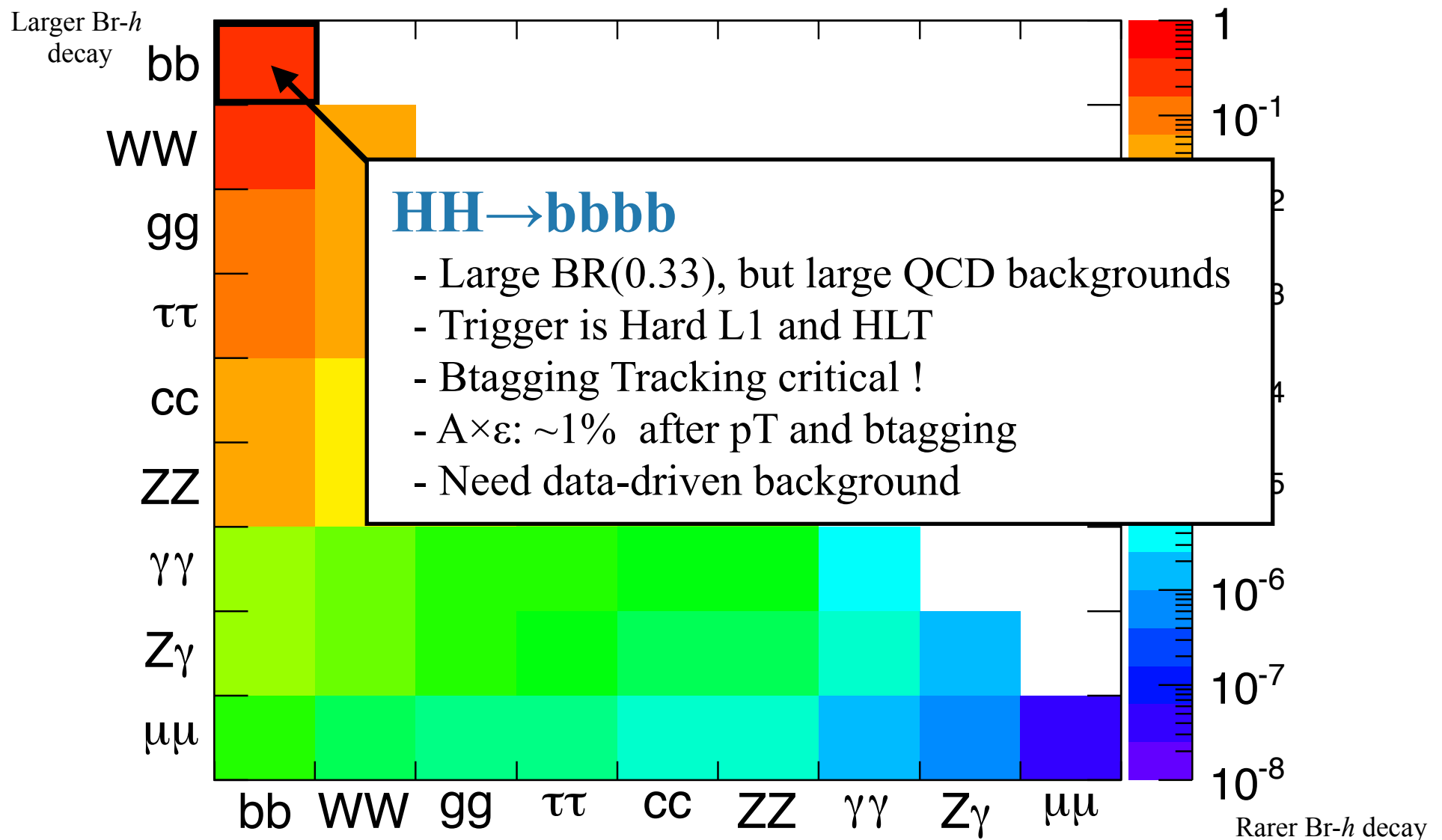
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# Survey of “Big 3” HH Analyses

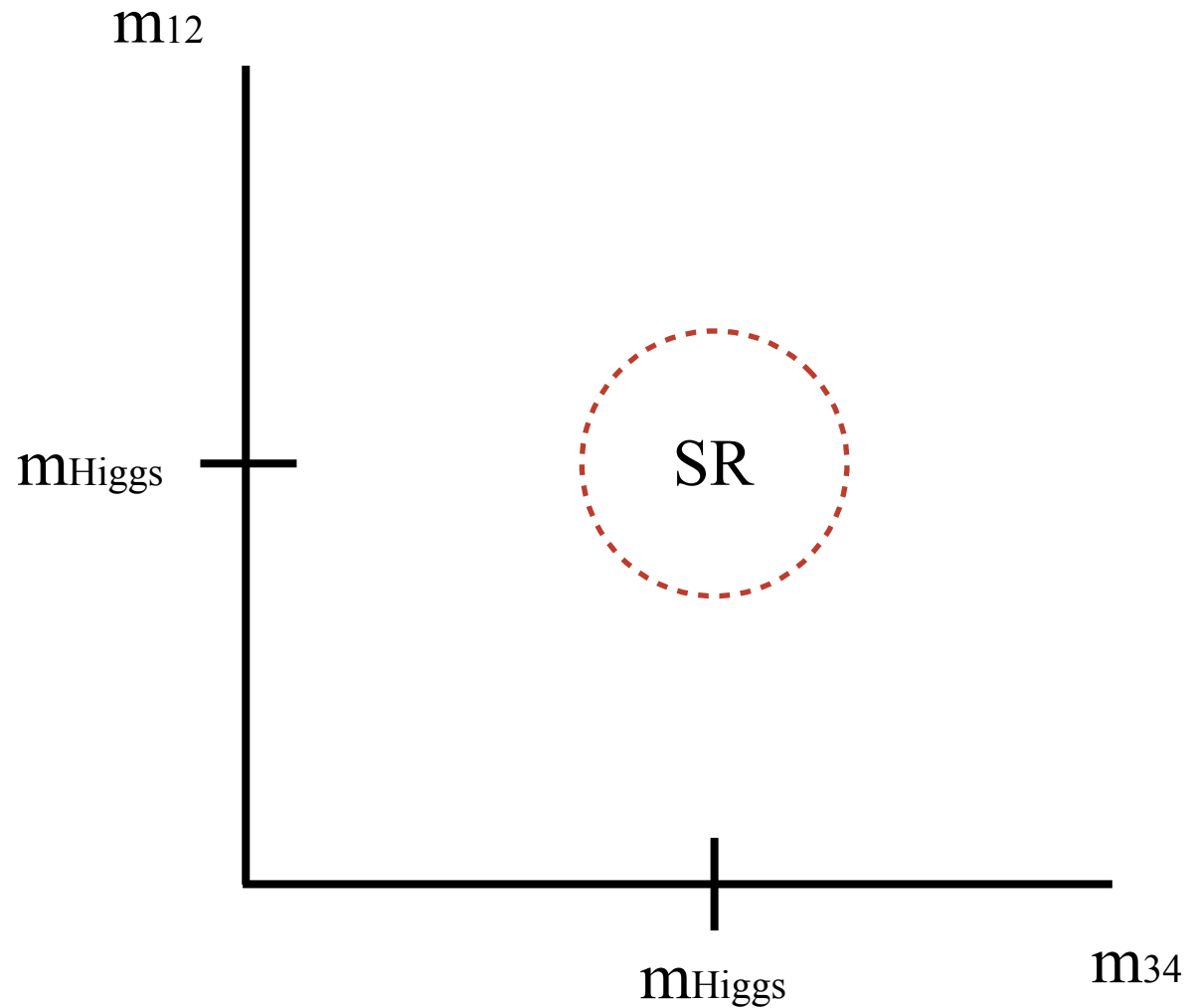
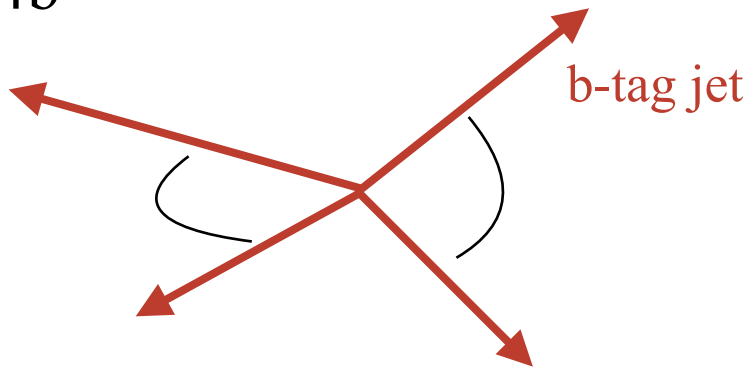
# Survey of “Big 3” HH Analyses



# HH $\rightarrow$ 4b

Resolved and merged-jet channels both important: *focus here on resolved*

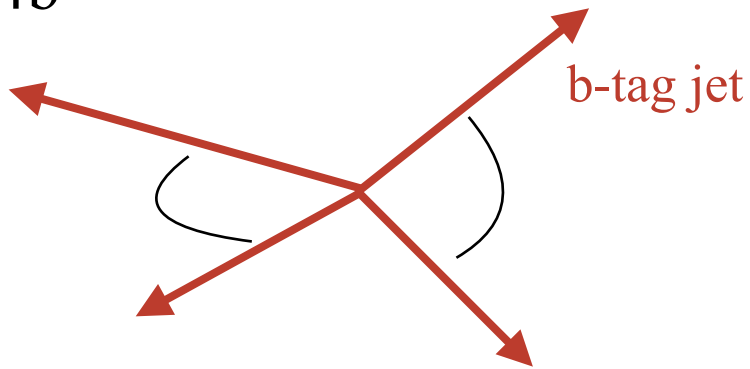
“4b”



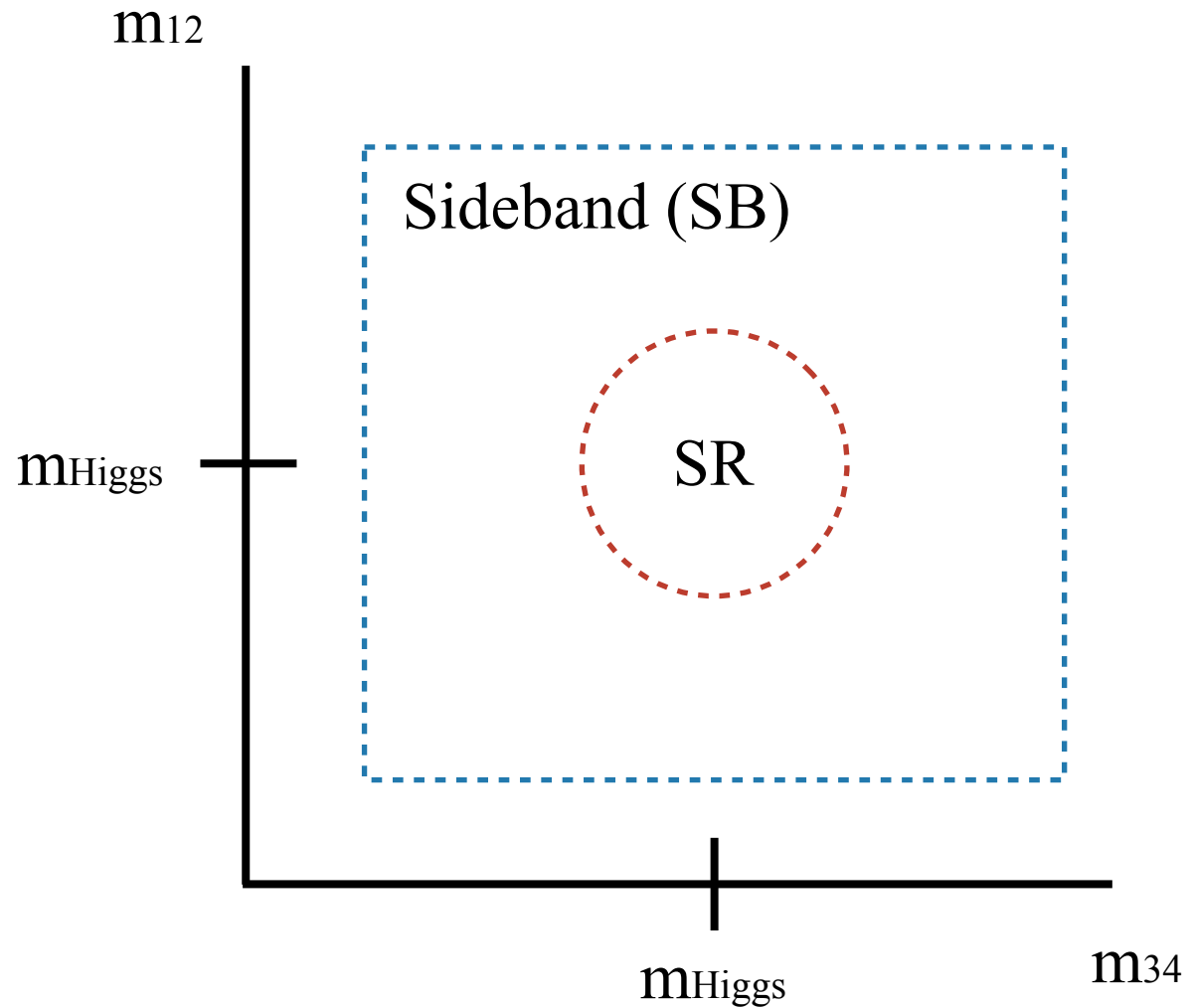
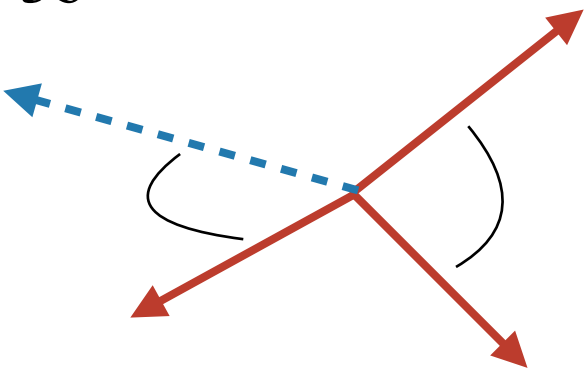
# HH $\rightarrow$ 4b

Resolved and merged-jet channels both important: *focus here on resolved*

“4b”



“3b”



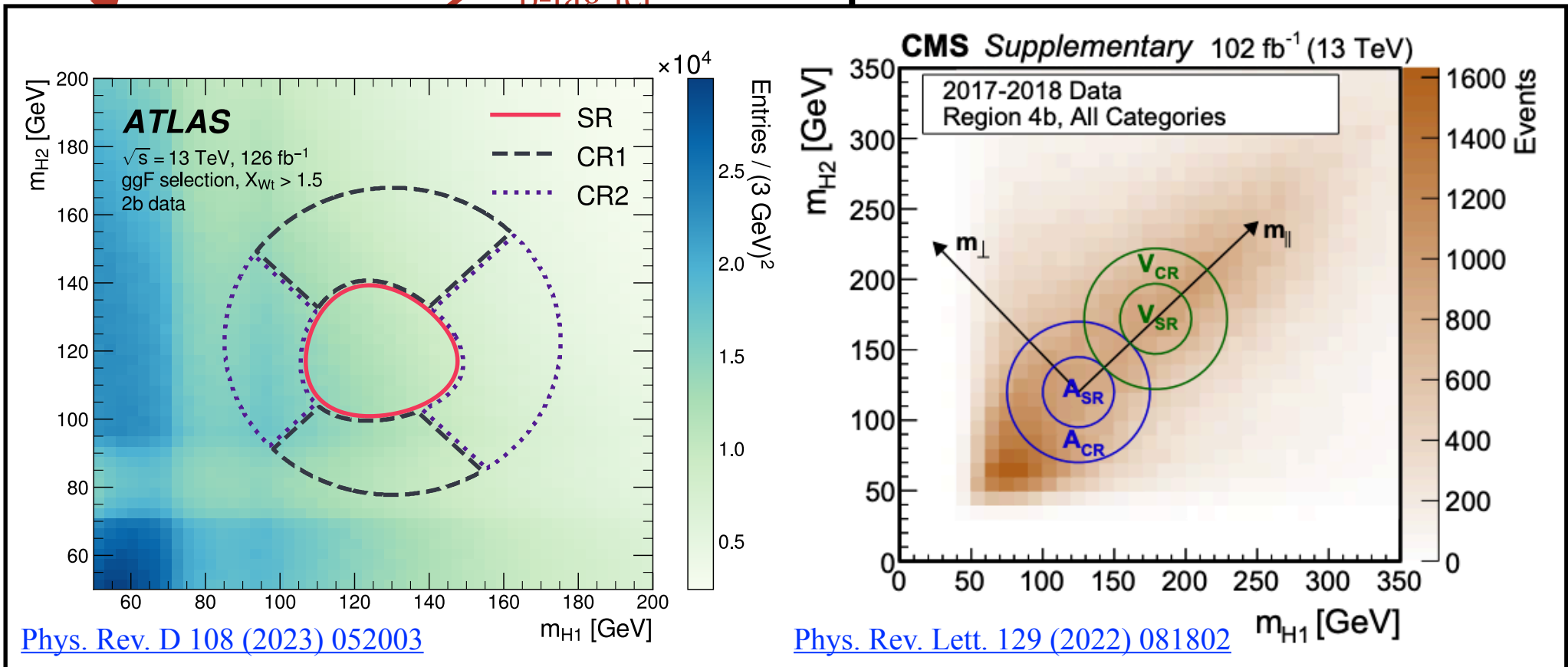
# HH $\rightarrow$ 4b

Resolved and merged-jet channels both important: *focus here on resolved*

“4b”

$m_{12}$

b-tag jet



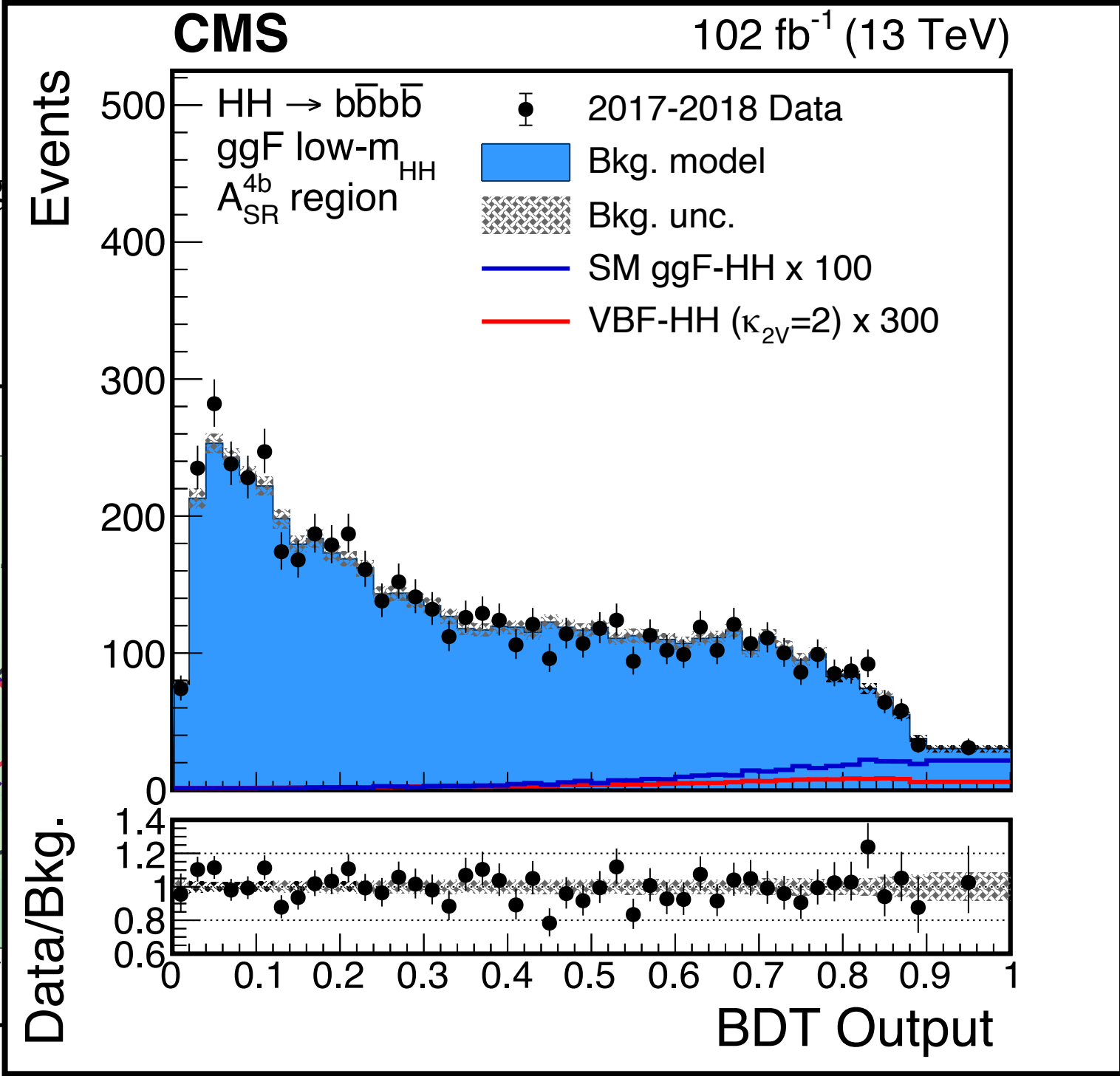
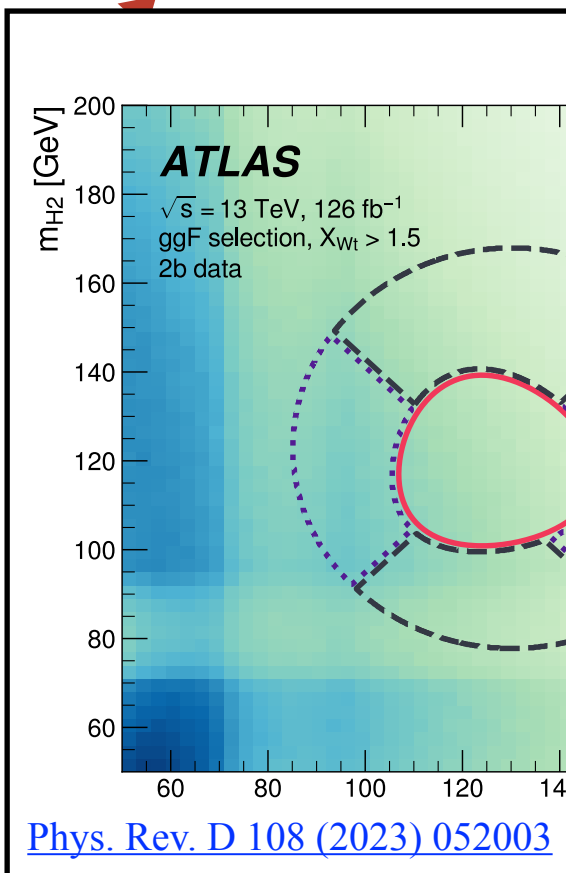
[Phys. Rev. D 108 \(2023\) 052003](#)

[Phys. Rev. Lett. 129 \(2022\) 081802](#)

HHiggs

Resolved and merged

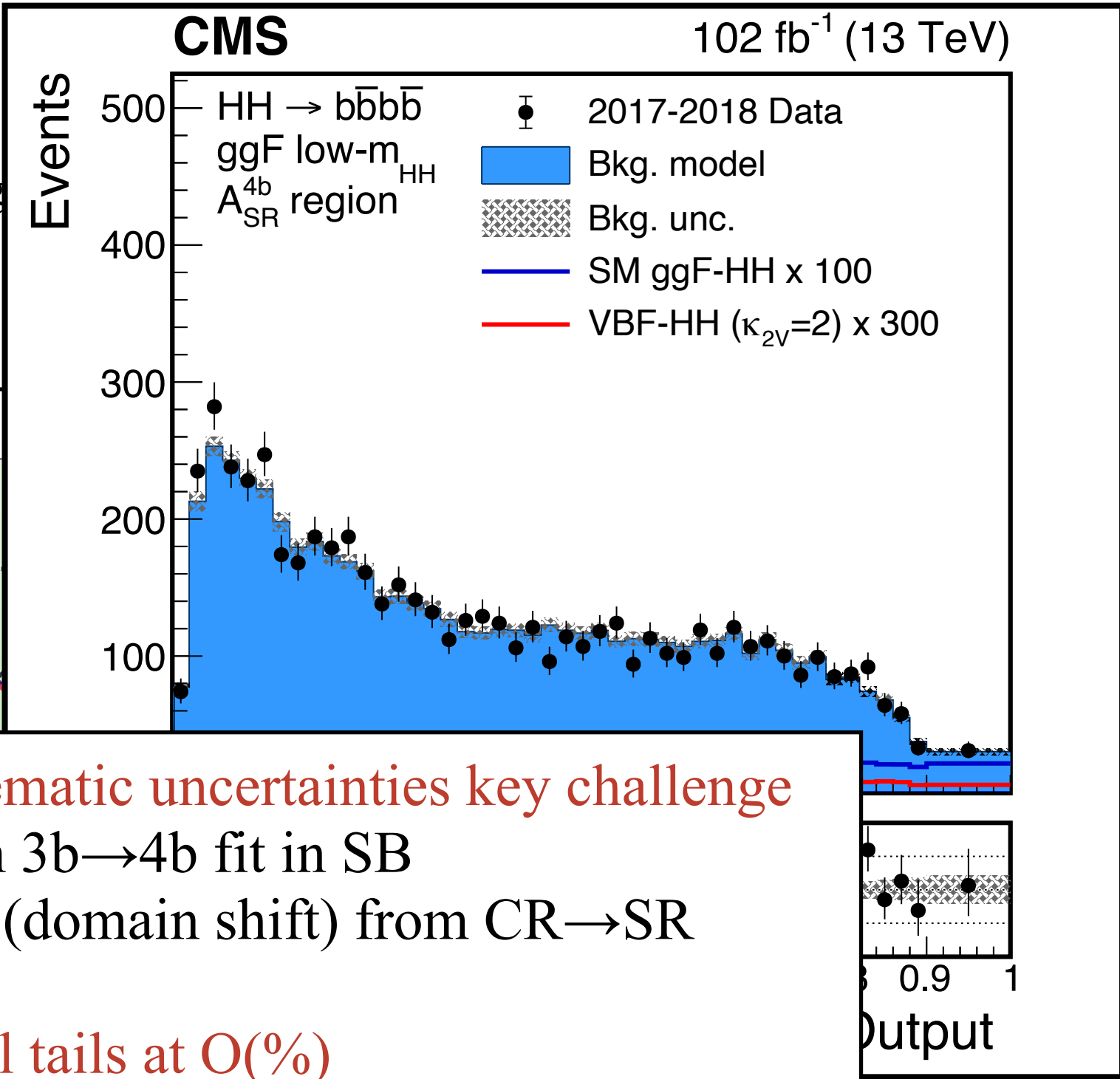
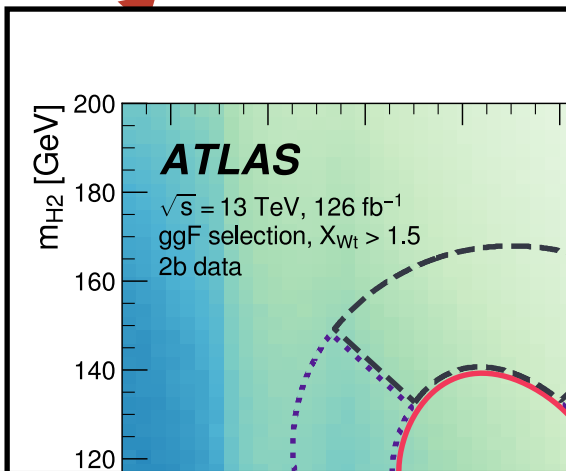
“4b”





Resolved and merged

“4b”



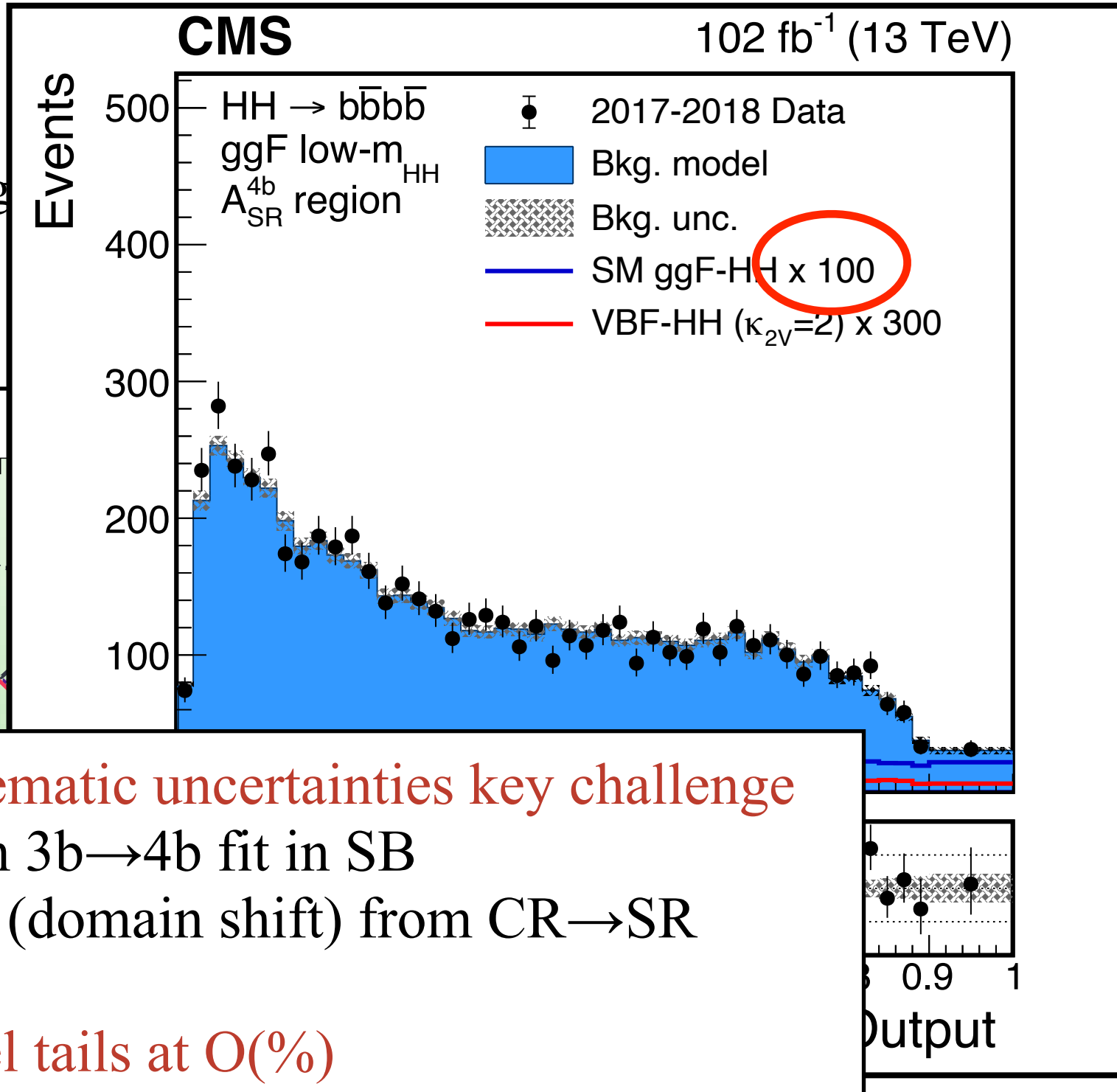
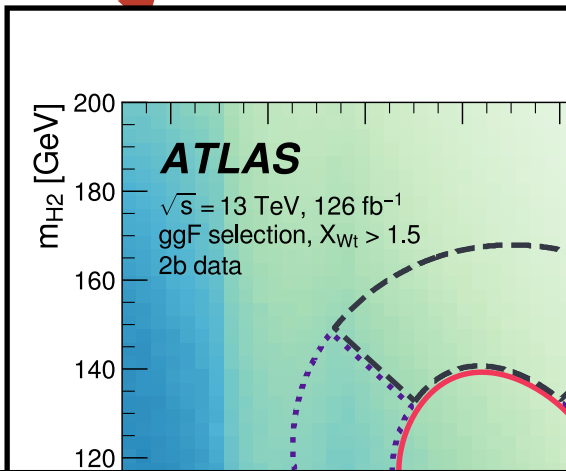
## Controlling Systematic uncertainties key challenge

- Uncertainty in 3b→4b fit in SB
- Extrapolation (domain shift) from CR→SR
- ...

We need to model tails at O(%)

Resolved and merged

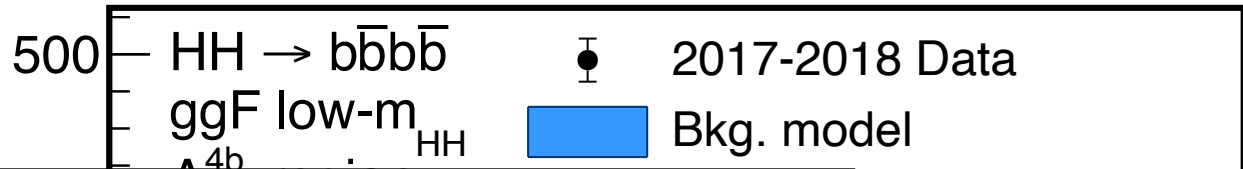
“4b”



CMS

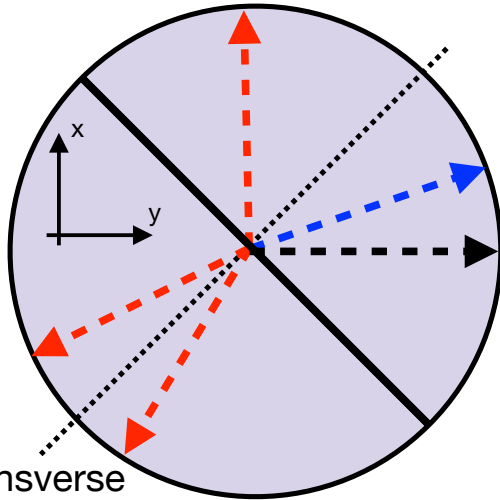
102 fb<sup>-1</sup> (13 TeV)

vents

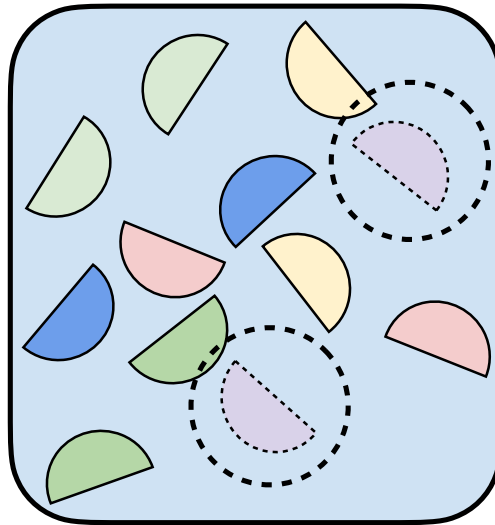


# Synthetic Datasets from Event Mixing: [Submitted to Eur. Phys. J. C](#)

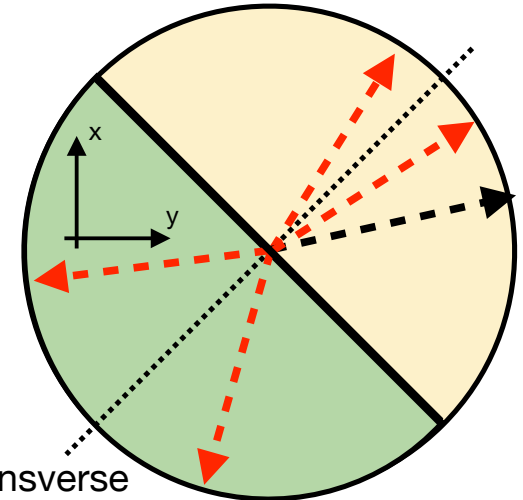
Original three-tag event split into two hemispheres



Hemisphere library made from four-tag events filled in 1<sup>st</sup> pass, queried on 2<sup>nd</sup>



Mixed Event using replaced hemispheres

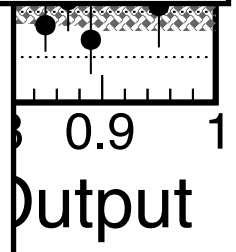


- - - - - ▶ b-tagged jets    
 - - - - - ▶ pseudo-tagged jets    
 - - - - - ▶ non b-tagged jets

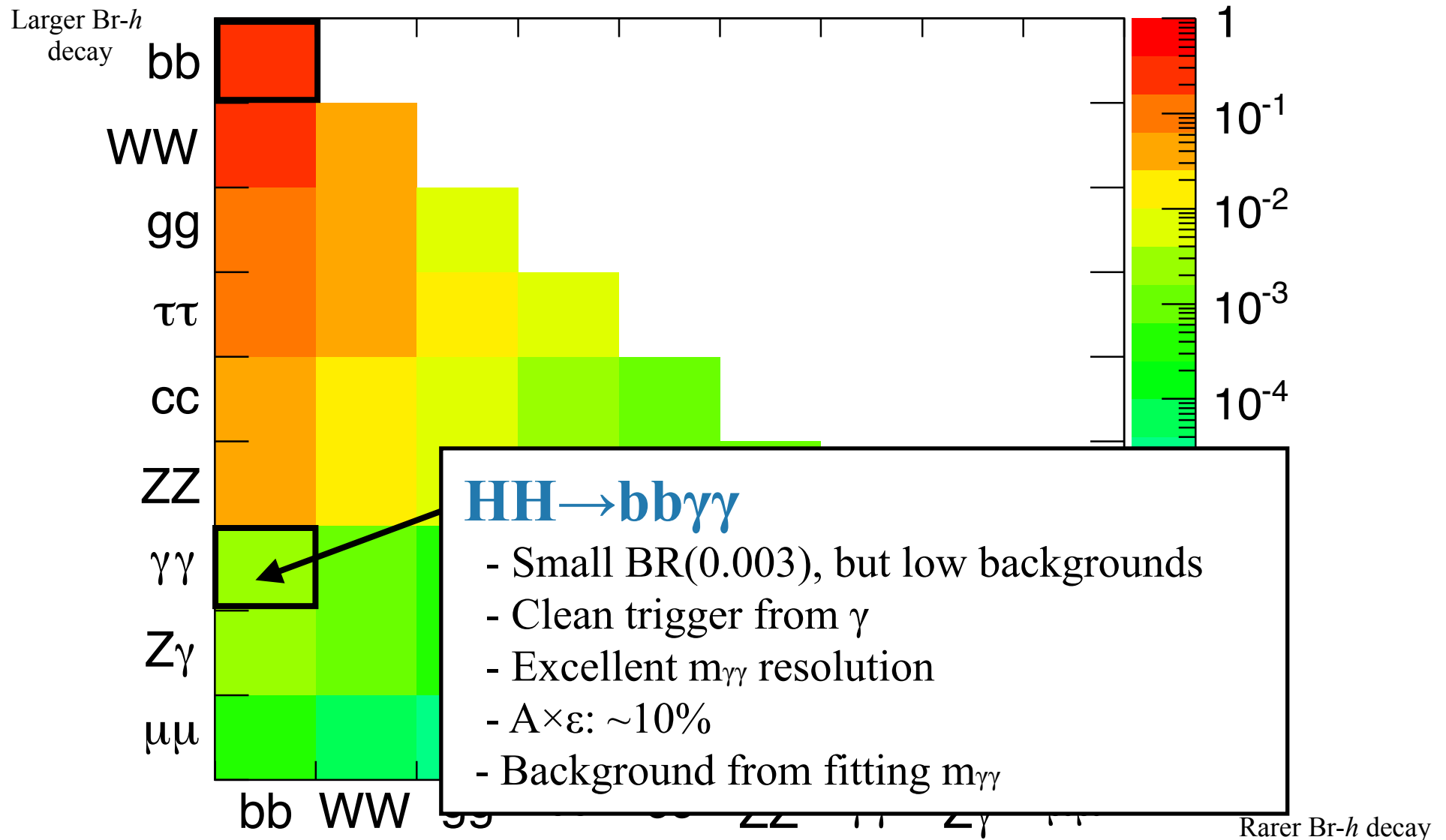
- Extrapolation (domain shift) from CR → SR

- ...

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# “Big 3” HH Analyses

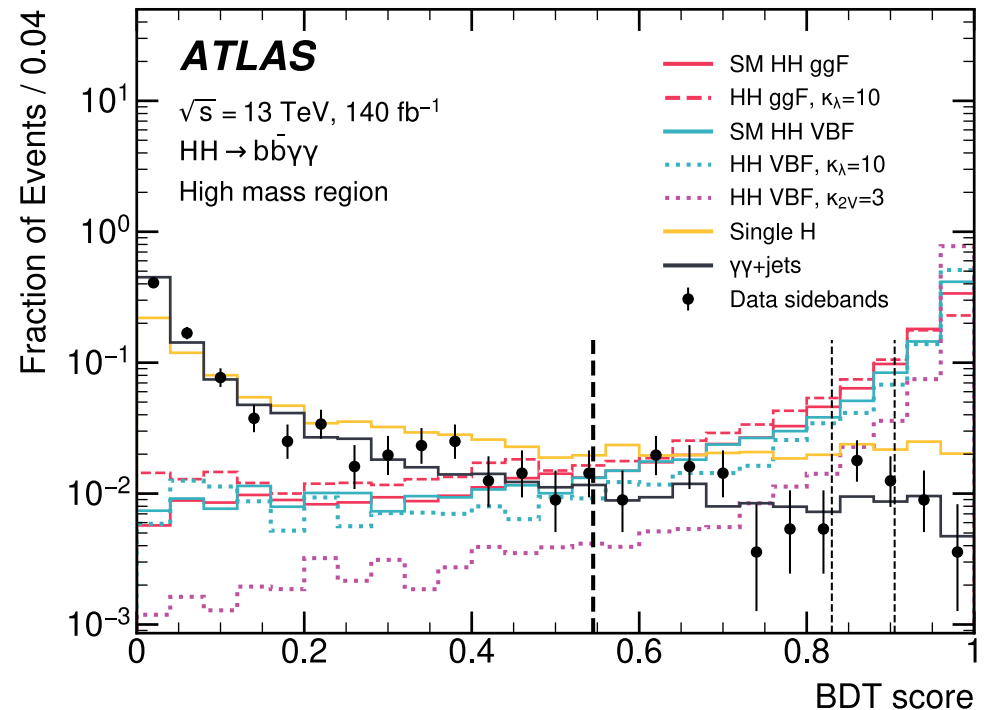
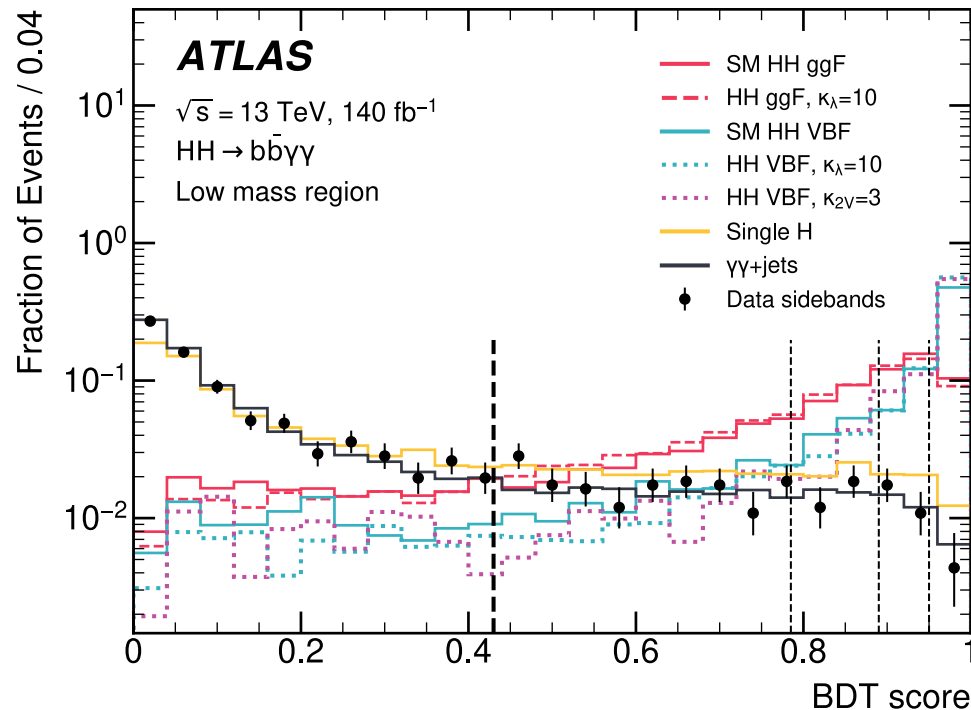


# HH $\rightarrow$ $b\bar{b}\gamma\gamma$

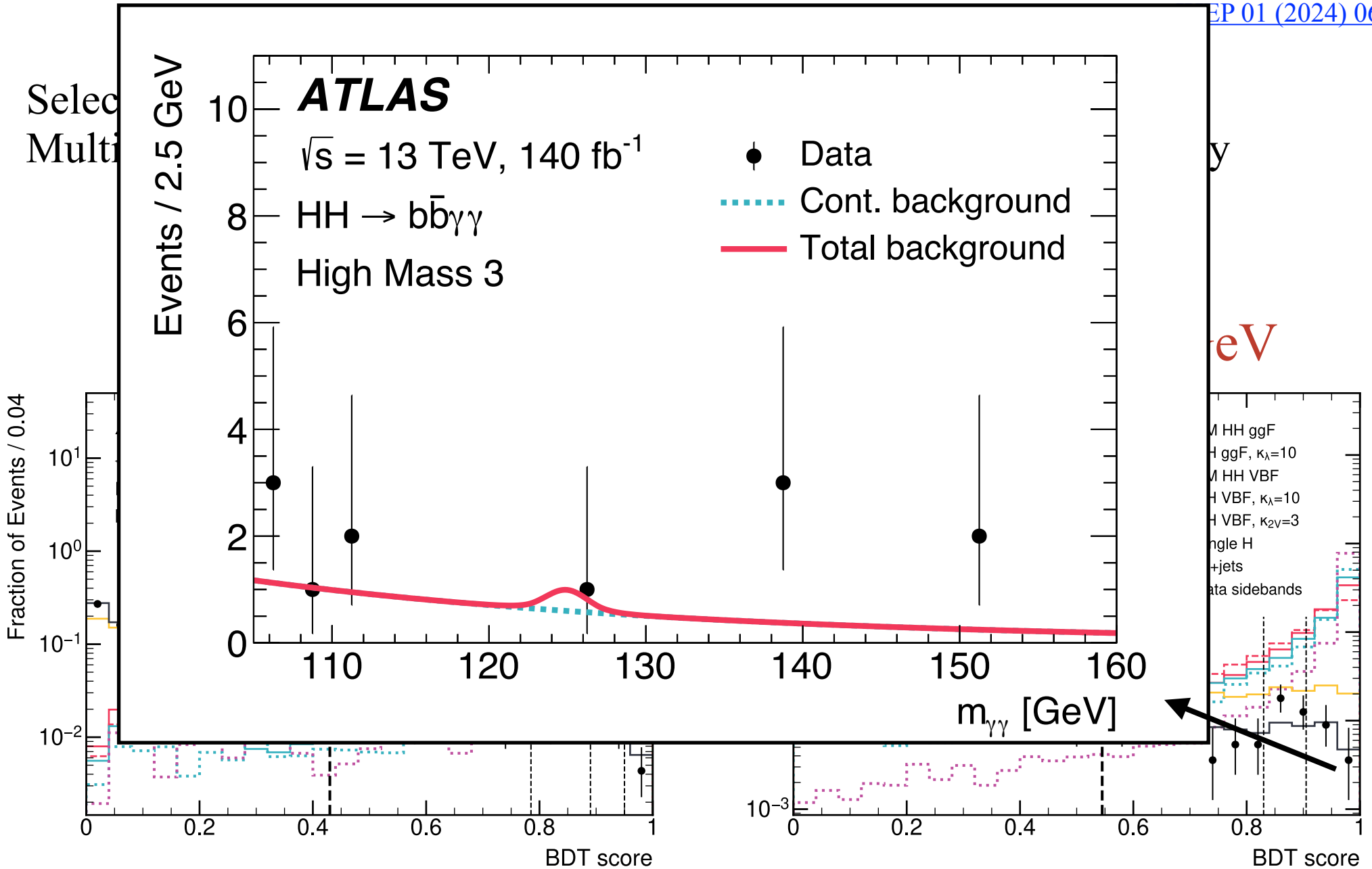
Selection follows  $H \rightarrow \gamma\gamma$  + additional b-tagged jets  
BDT targeting low and high mass regions separately

$m_{HH} < 350$  GeV

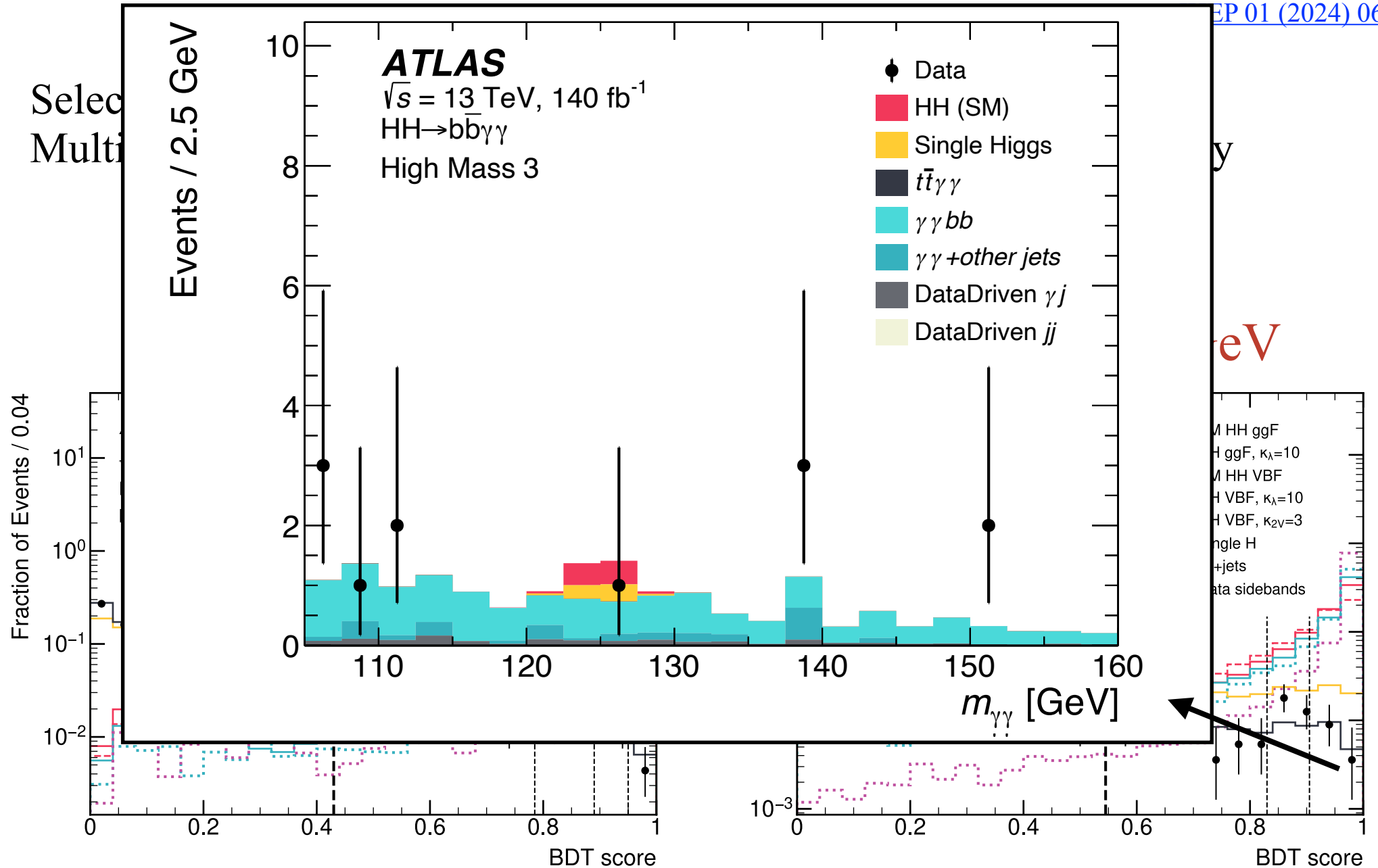
$m_{HH} \geq 350$  GeV



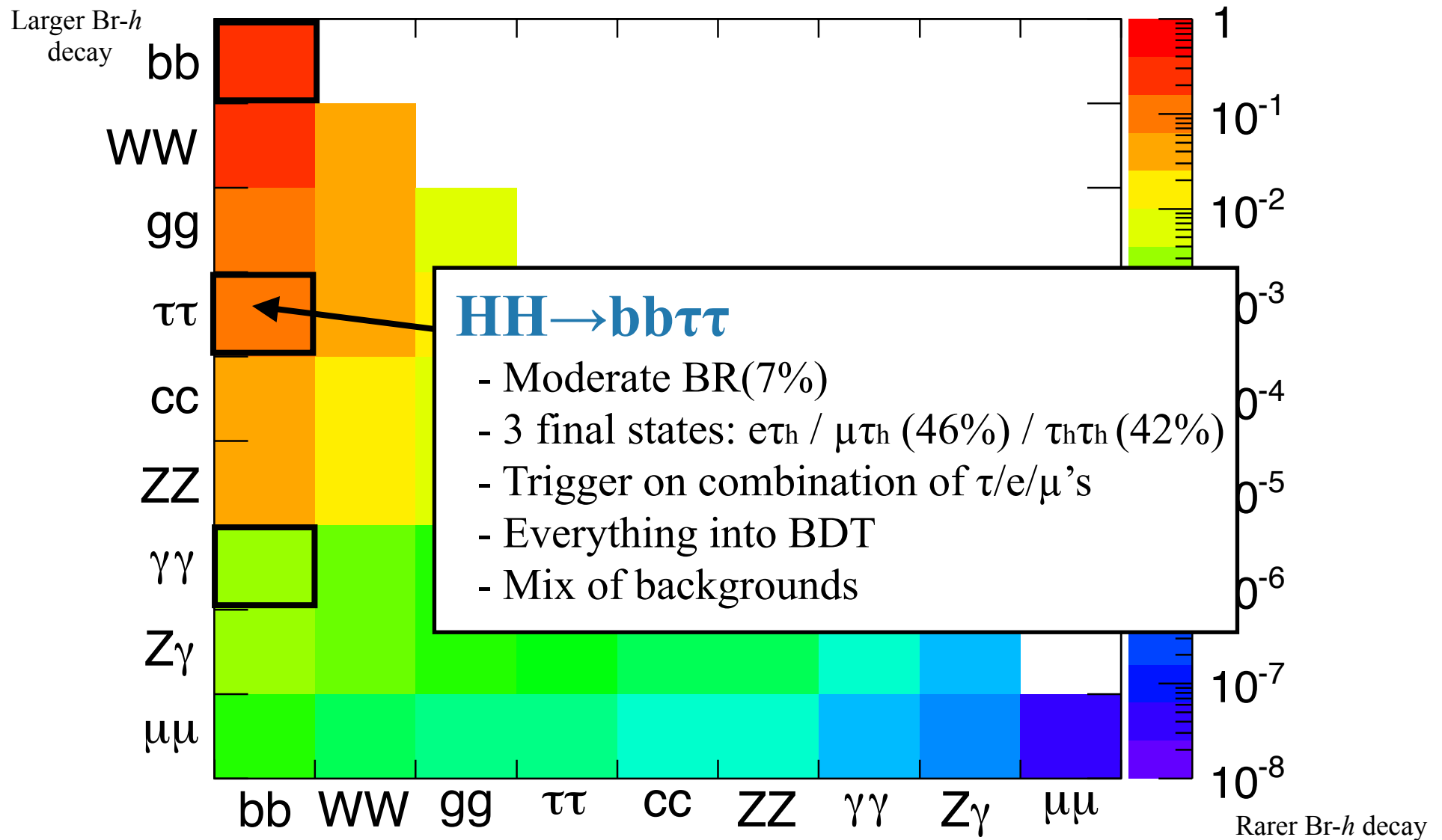
# HH $\rightarrow$ $b\bar{b}\gamma\gamma$



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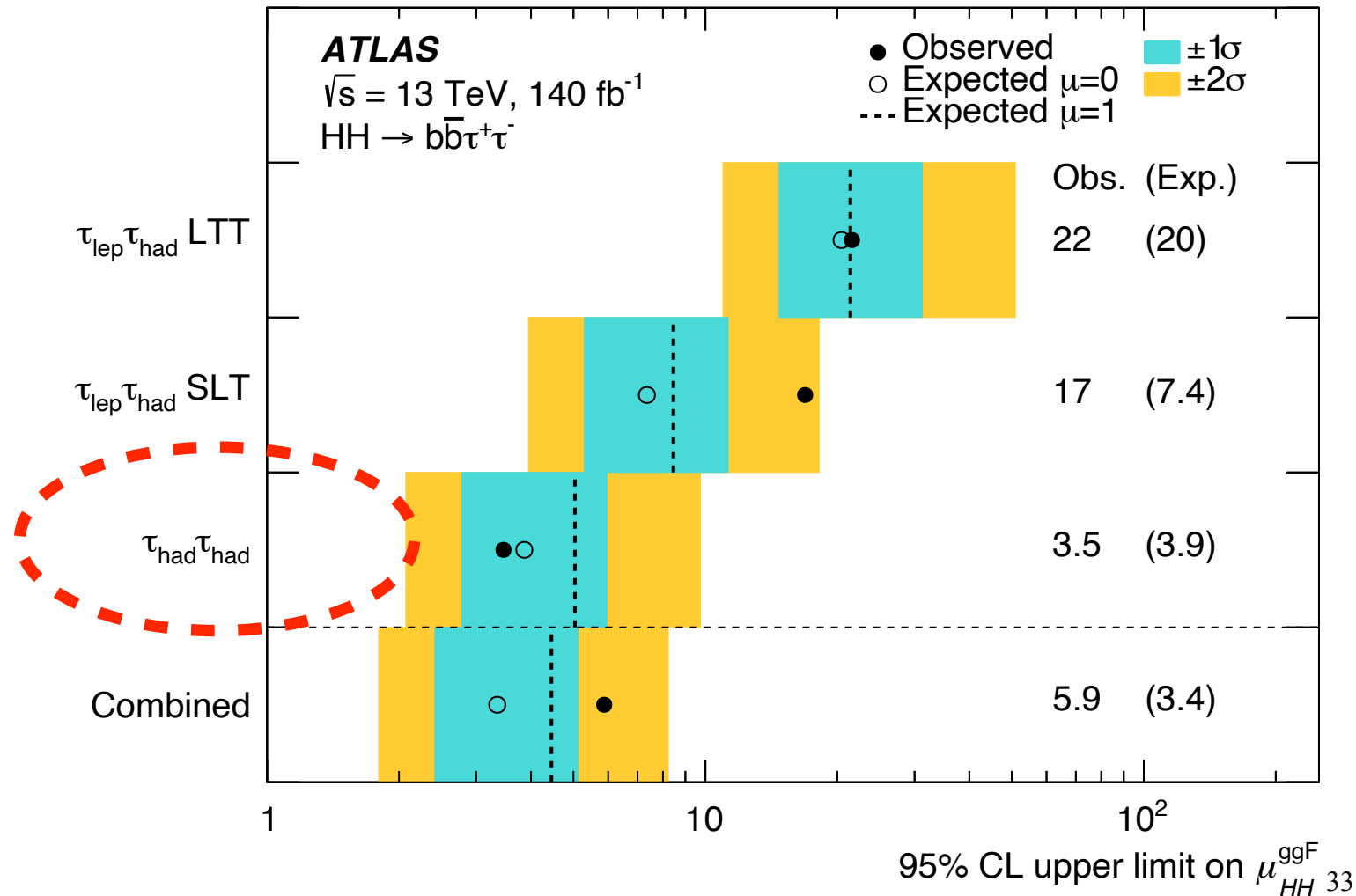




# HH $\rightarrow$ bb $\tau\tau$

Combination of three driven by  $\tau\tau$  decays:  $e\tau / \mu\tau / \tau\tau$   
 Sensitivity driven by  $\tau\text{th}\tau$   $\Rightarrow$  di- $\tau$  triggers critical !

[arXiv:2404.12660](https://arxiv.org/abs/2404.12660)



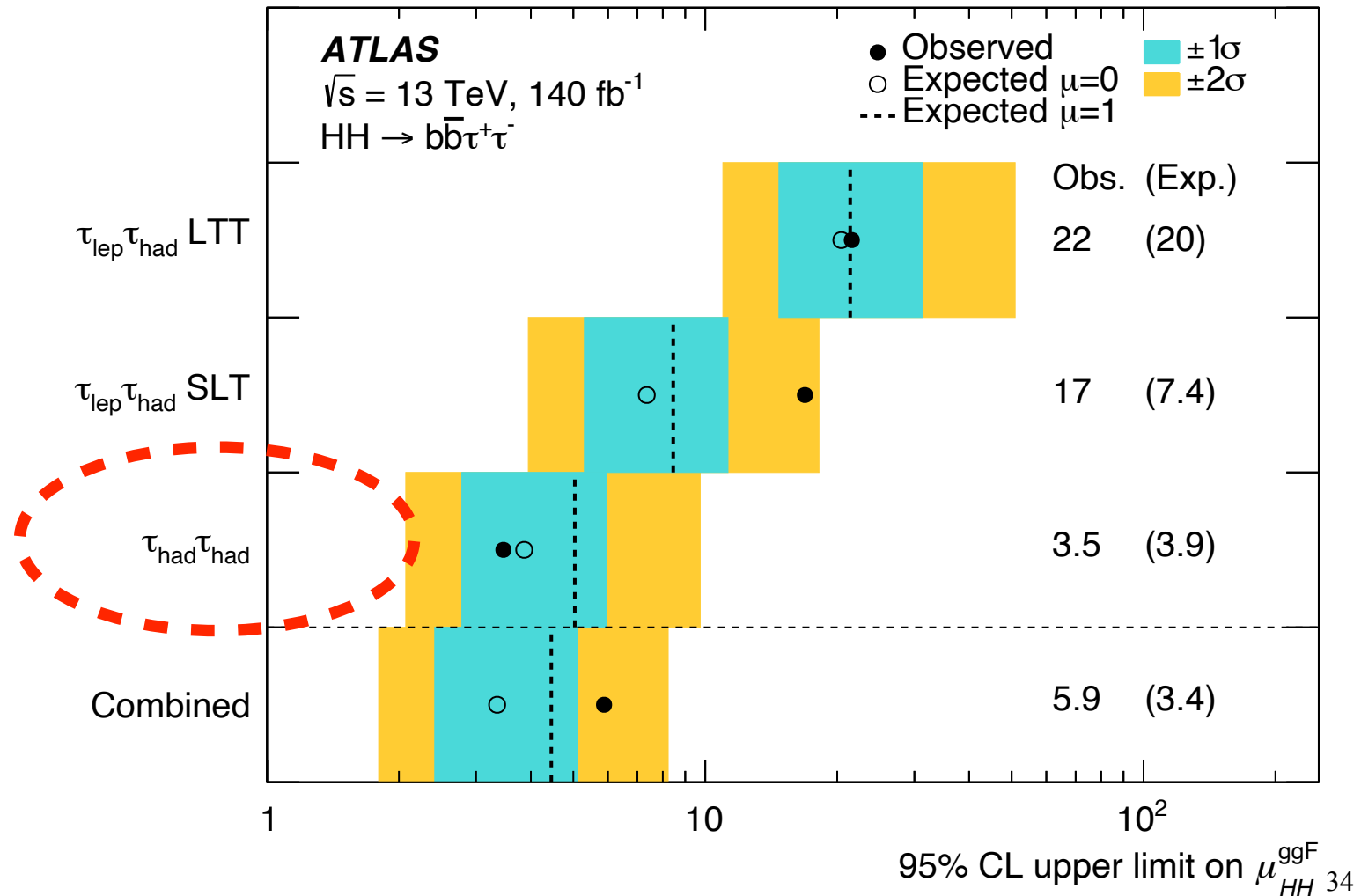
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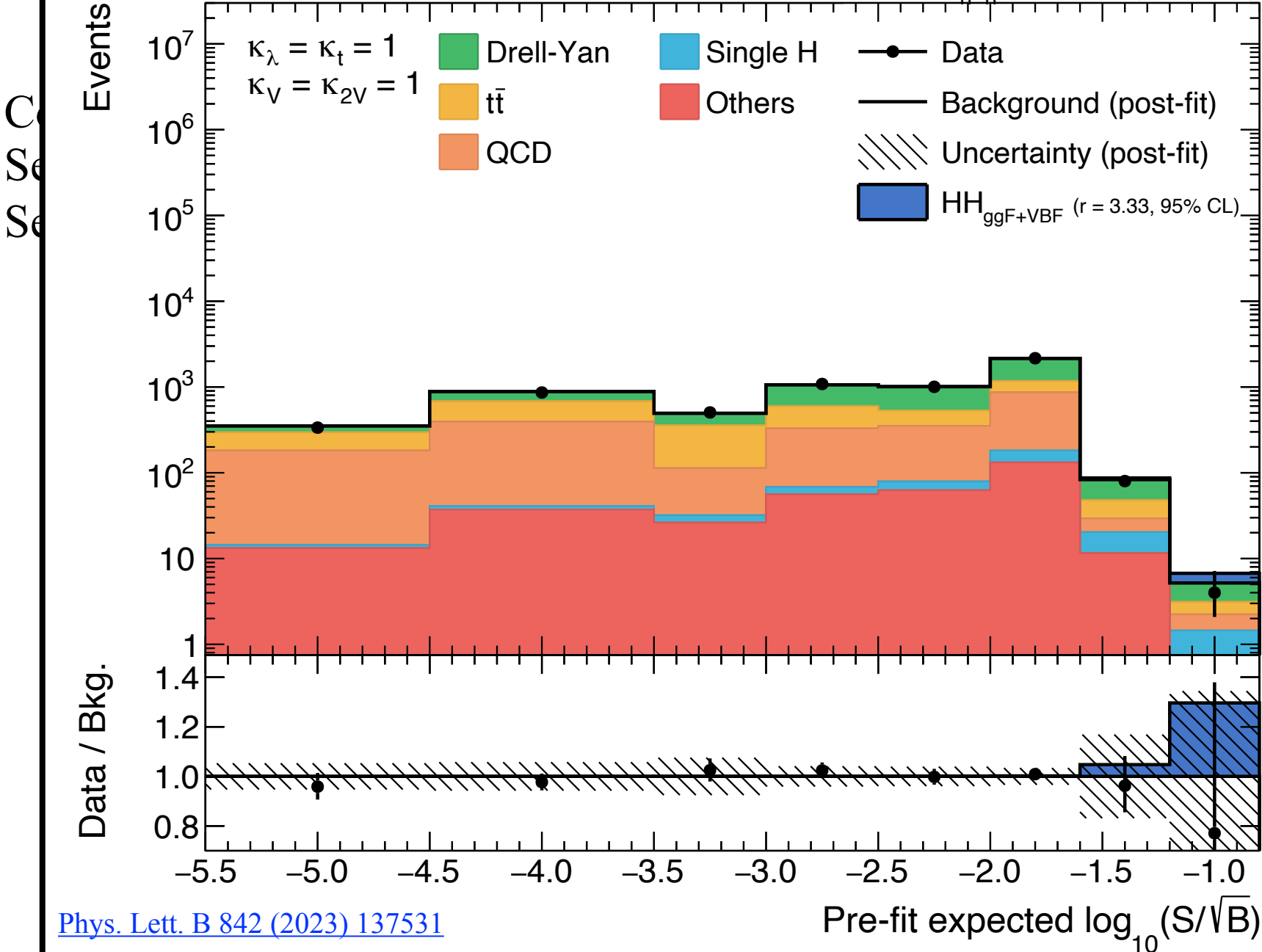
Several backgrounds important

[arXiv:2404.12660](https://arxiv.org/abs/2404.12660)

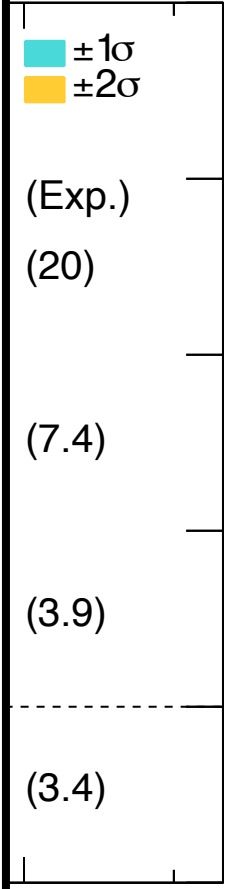


CMS

$bb\tau_h\tau_h$ , 138 fb<sup>-1</sup> (13 TeV)



[arXiv:2404.12660](https://arxiv.org/abs/2404.12660)

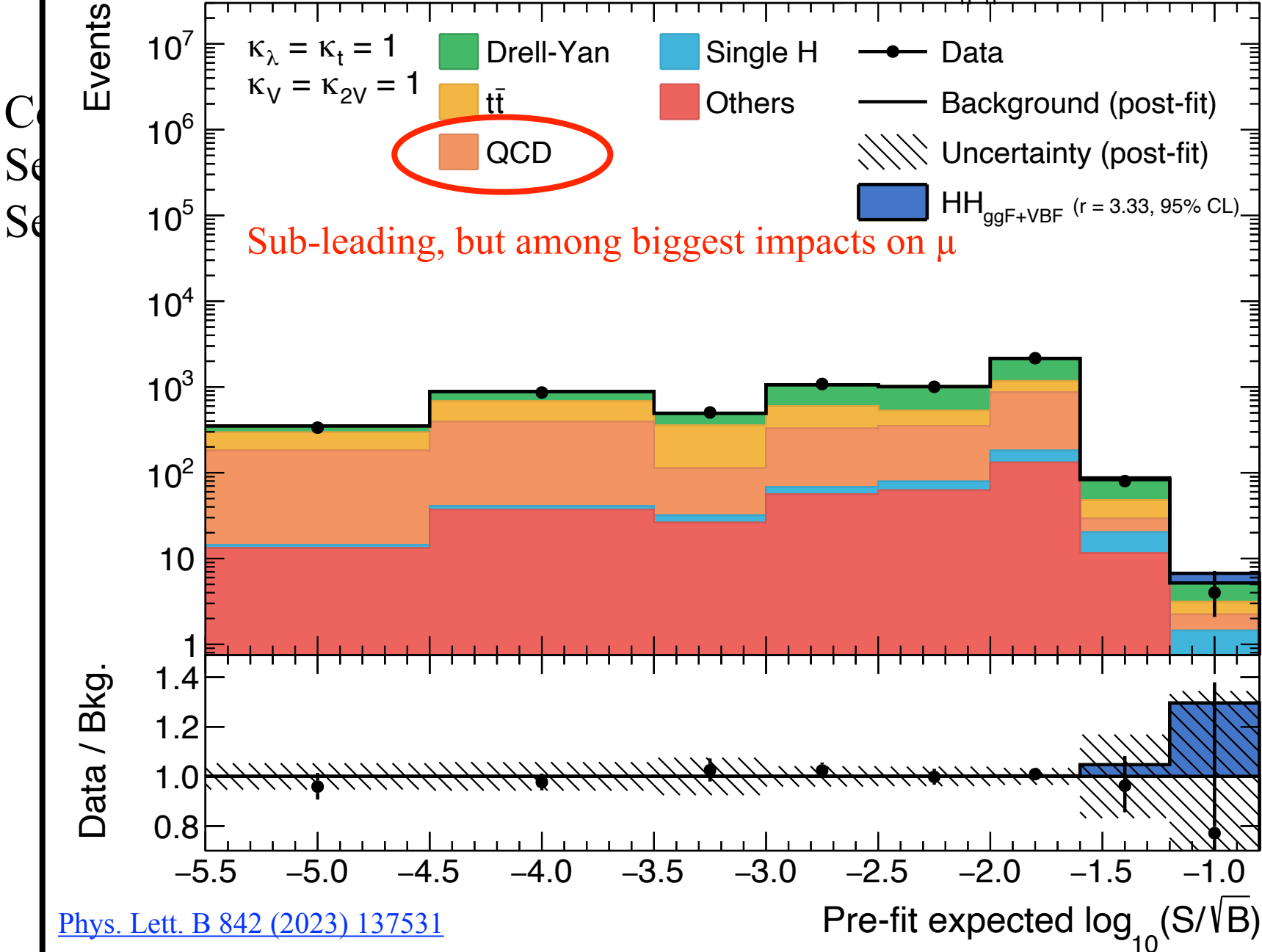


[Phys. Lett. B 842 \(2023\) 137531](https://arxiv.org/abs/2404.12660)

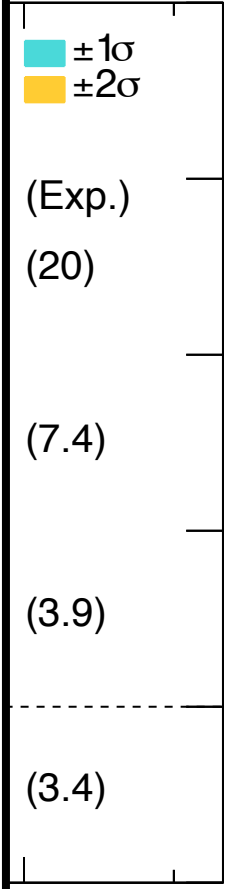
95% CL upper limit on  $\mu_{HH}^{ggF}$  35

CMS

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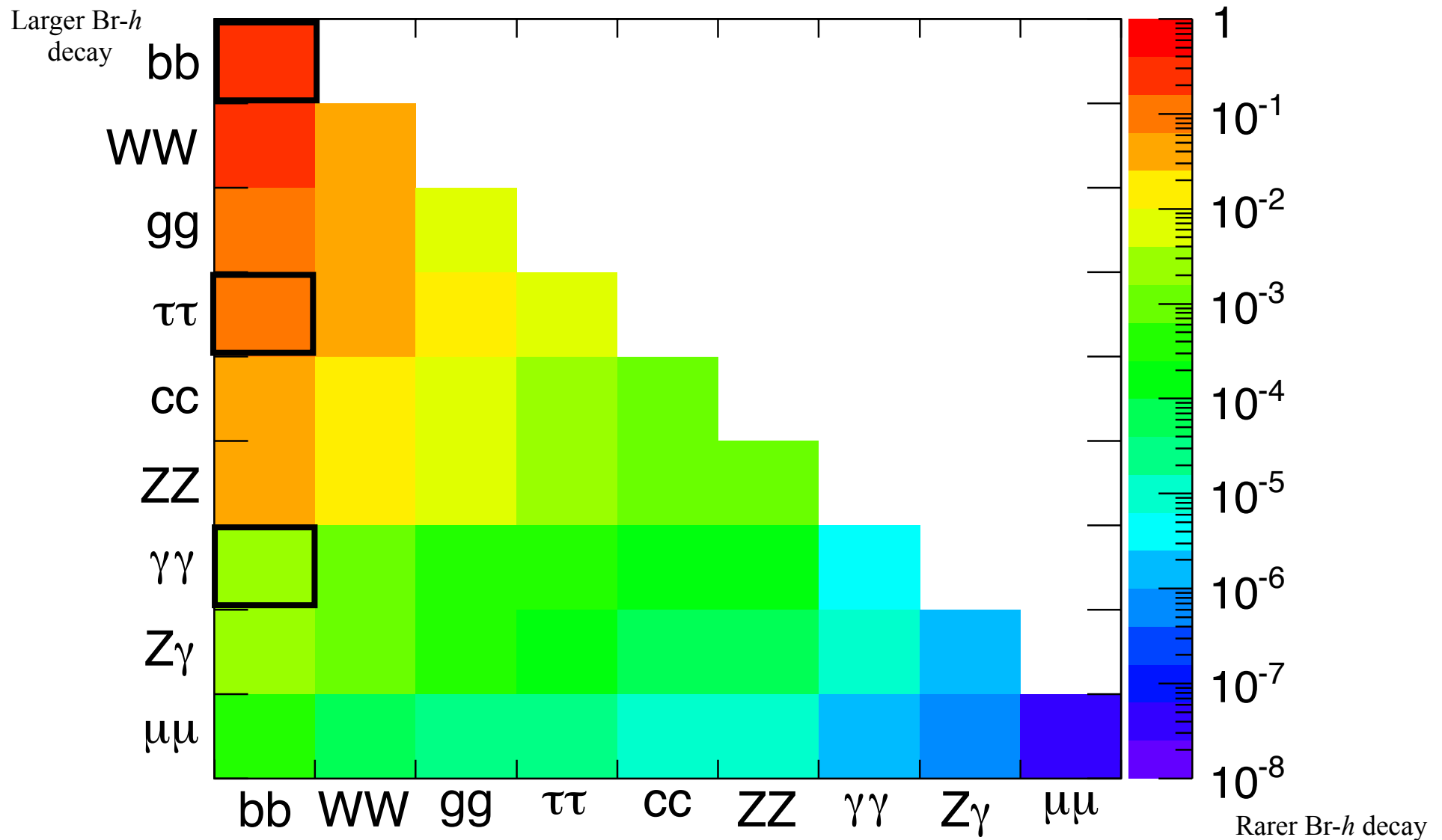
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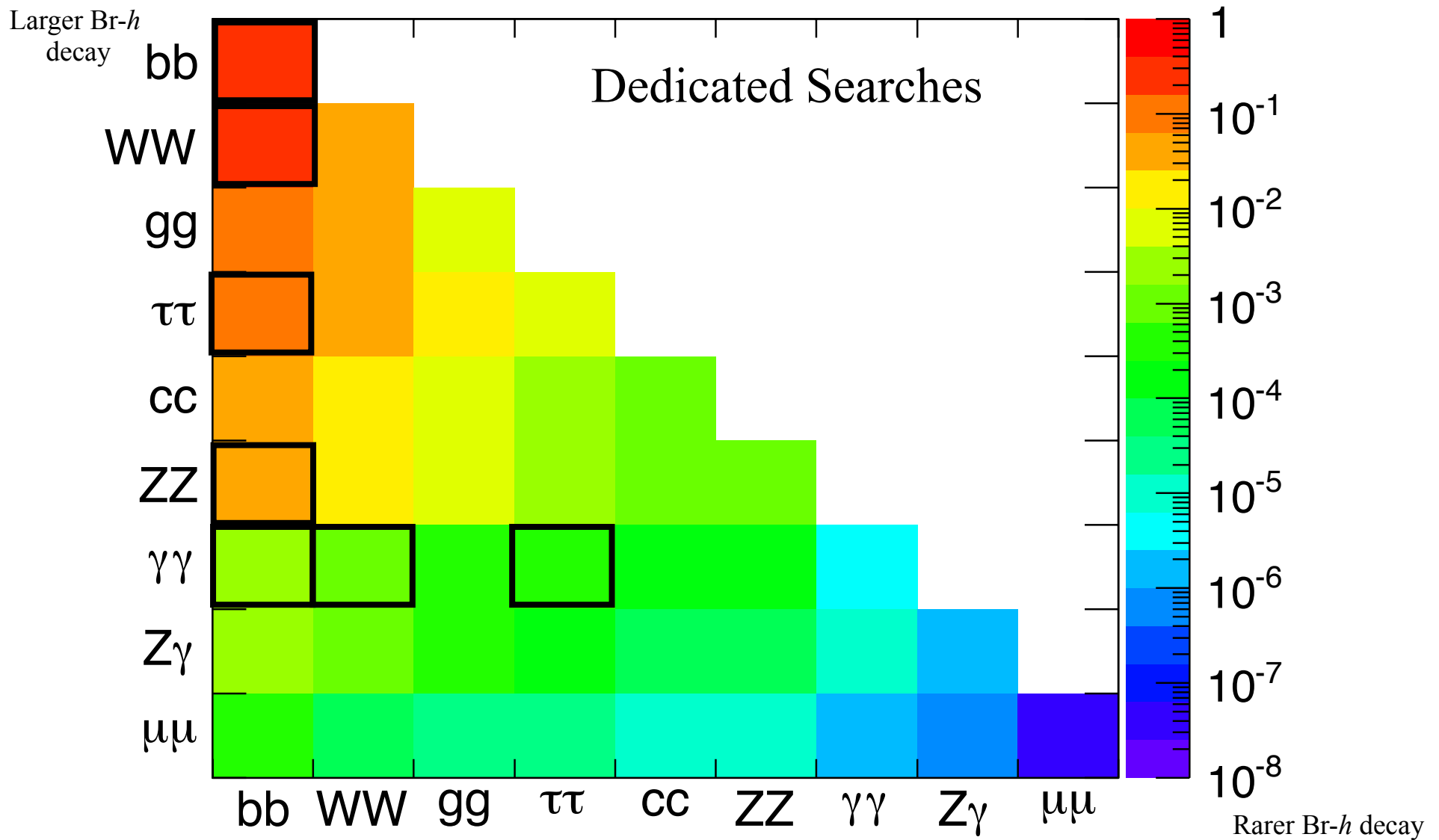
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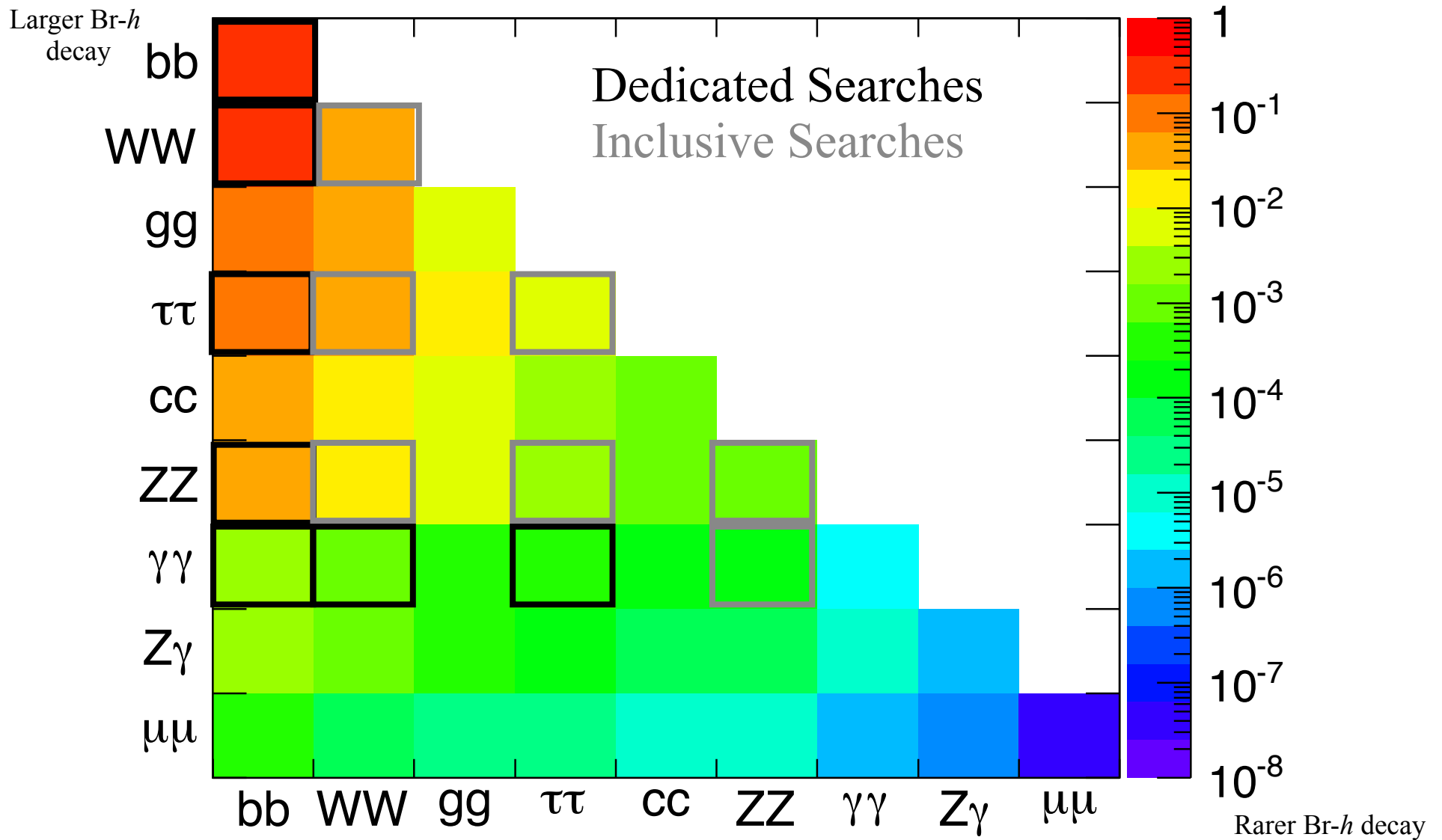
# Survey of Other HH Analyses



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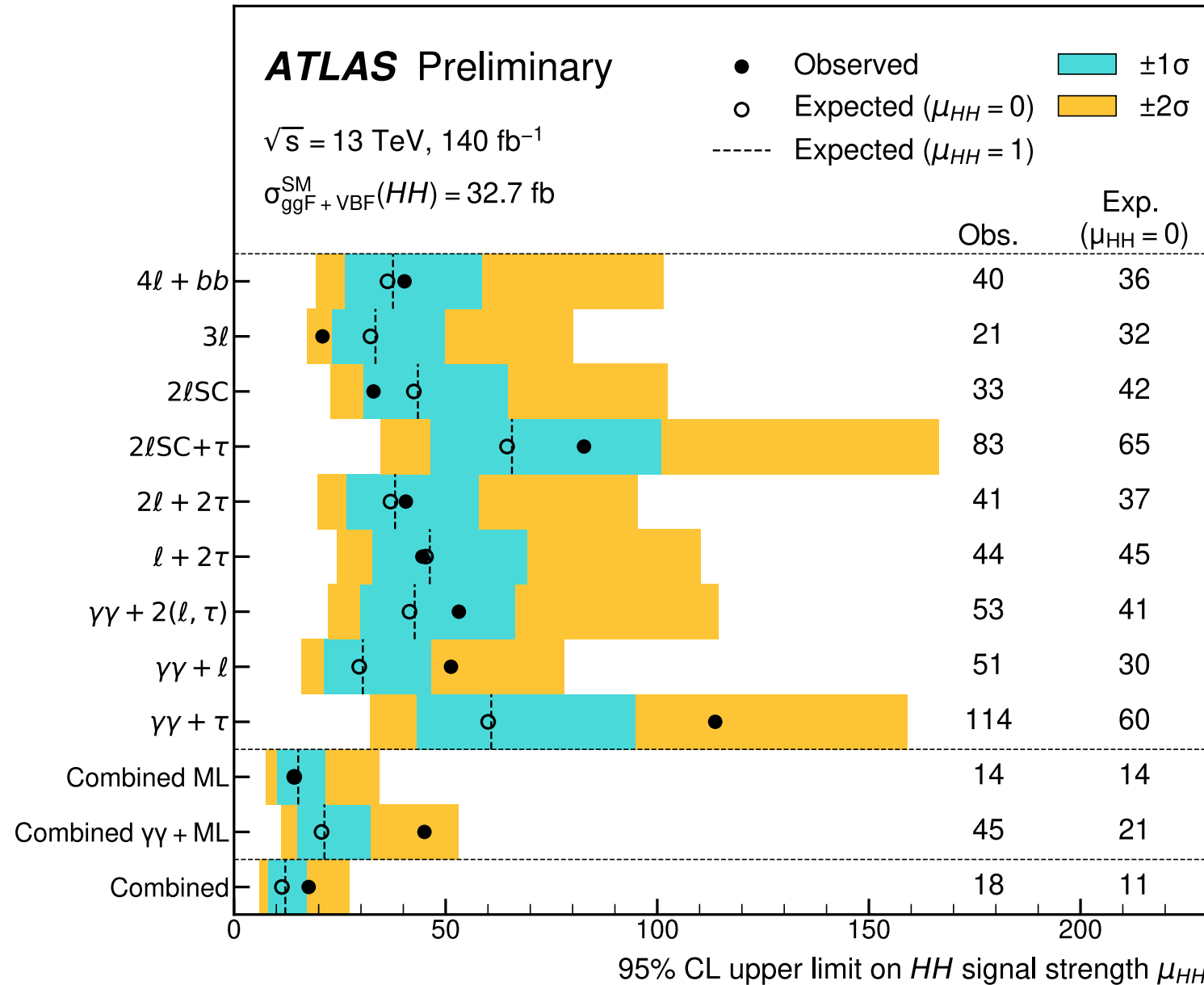
# Survey of Other HH Analyses

$$HH \rightarrow \ell / \tau / \gamma\gamma + X$$

Submitted to J. High Energy Phys.

Larger Br- $h$   
decay

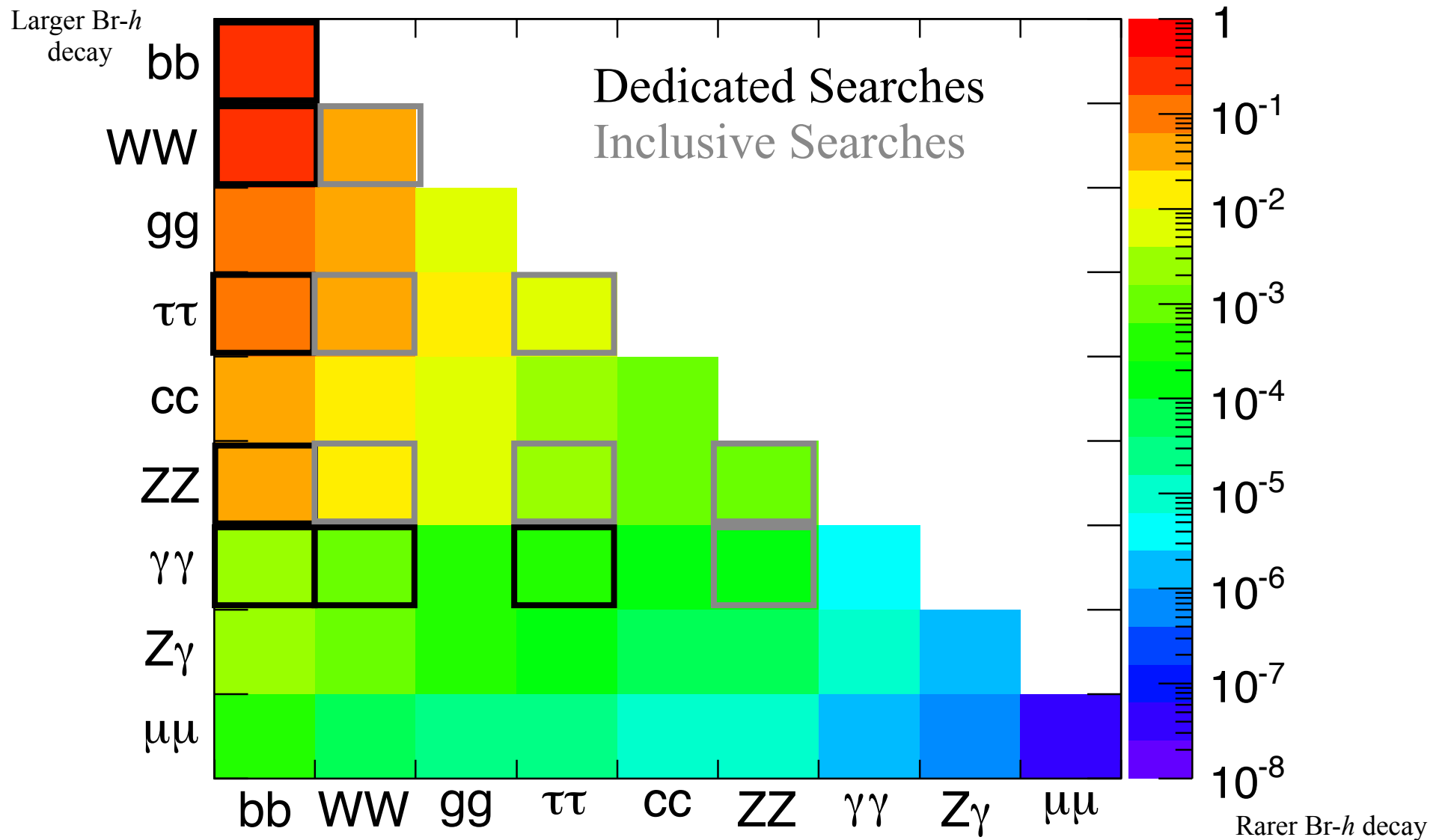
W



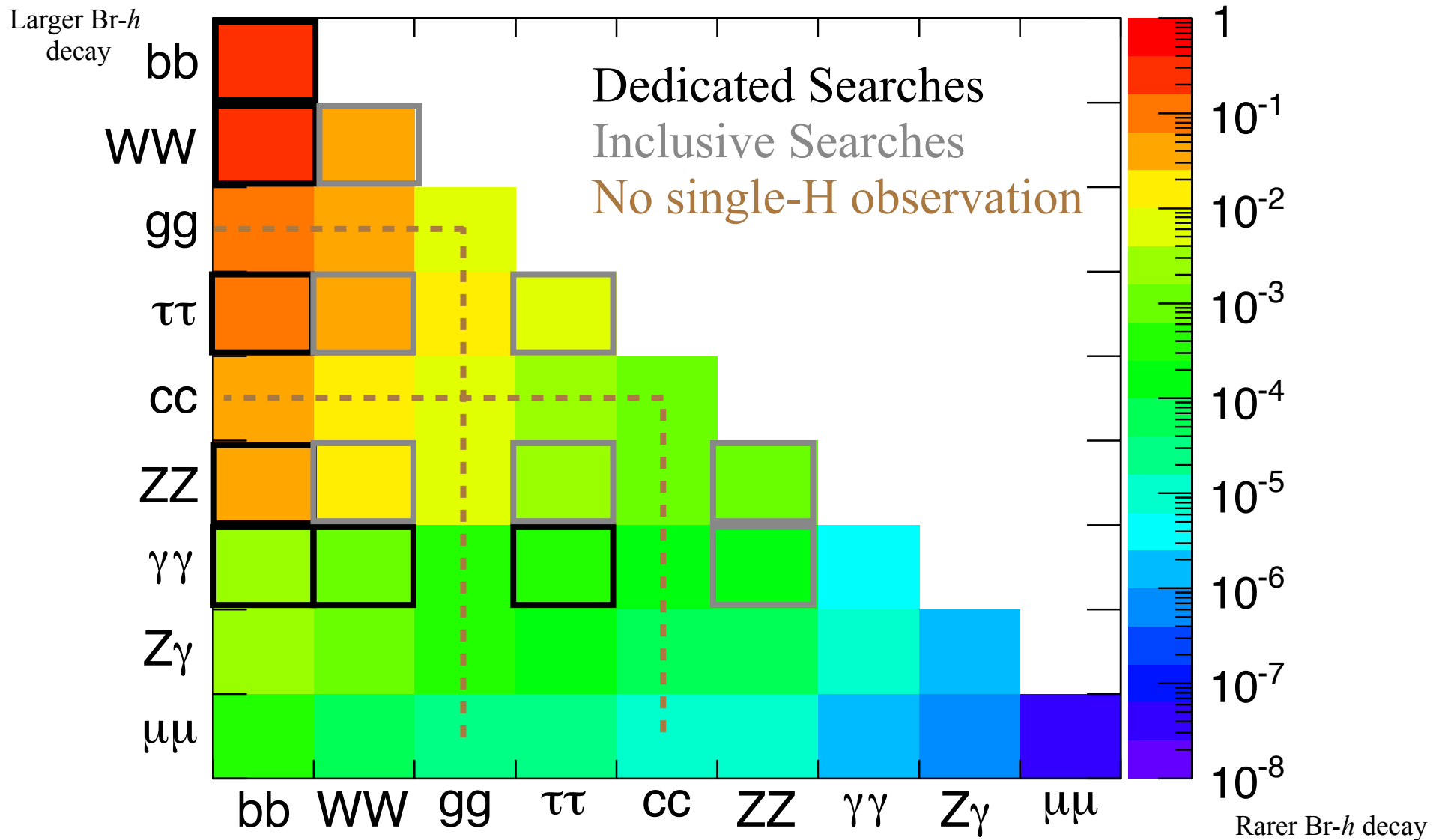
Br- $h$  decay



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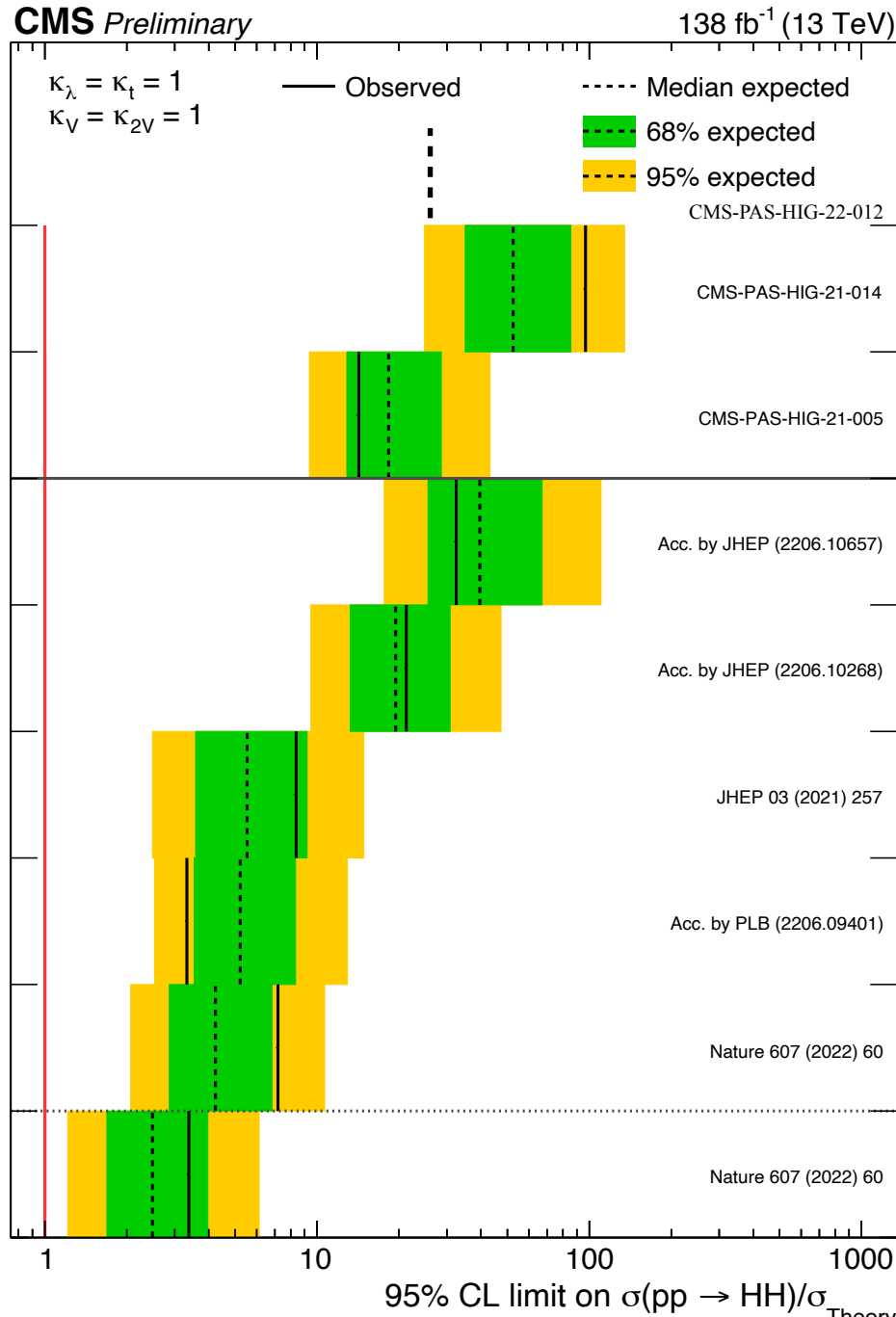


# Survey of Other HH Analyses



# Relative HH Sensitivities

[CMS: Summary plots](#)

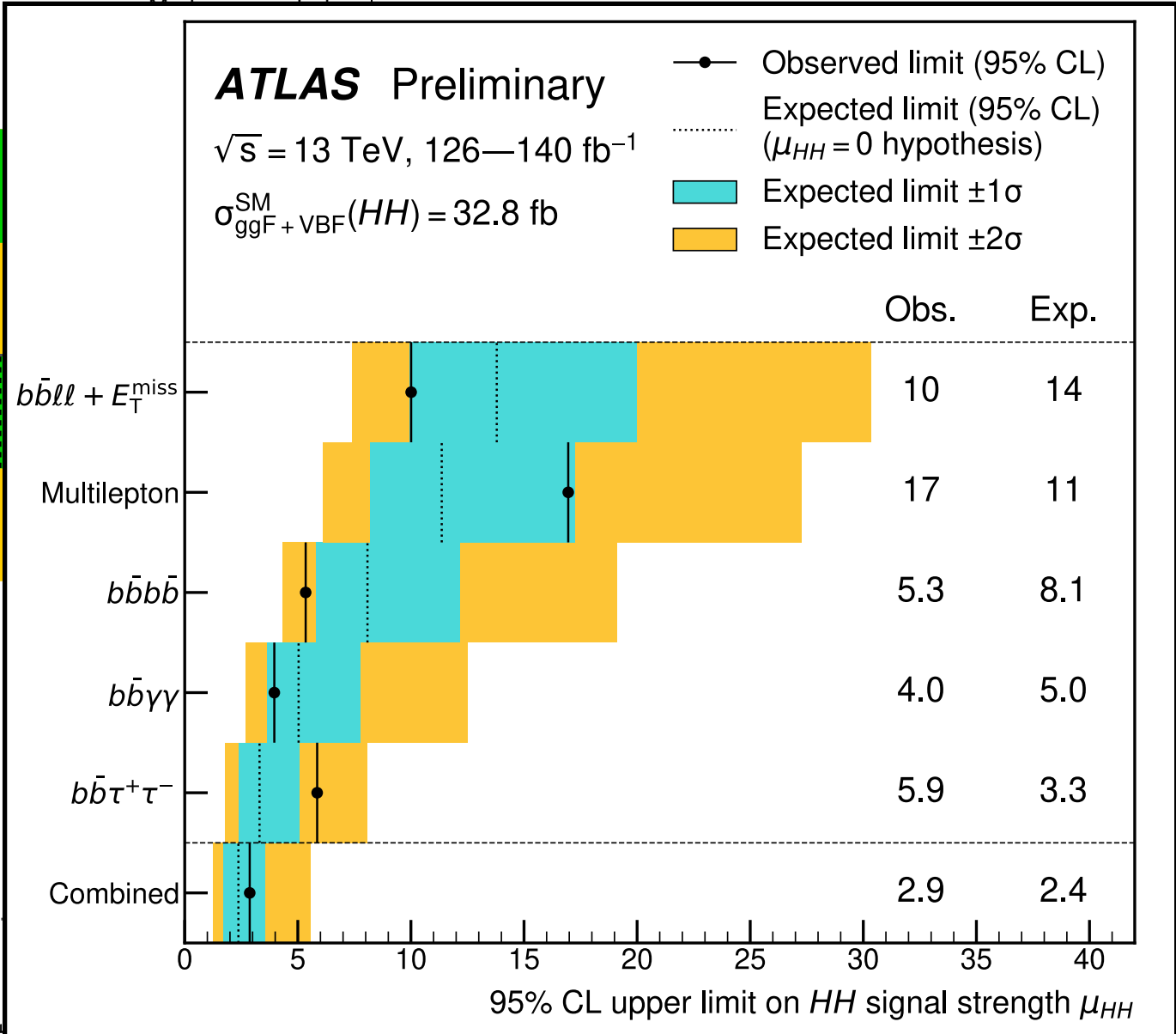
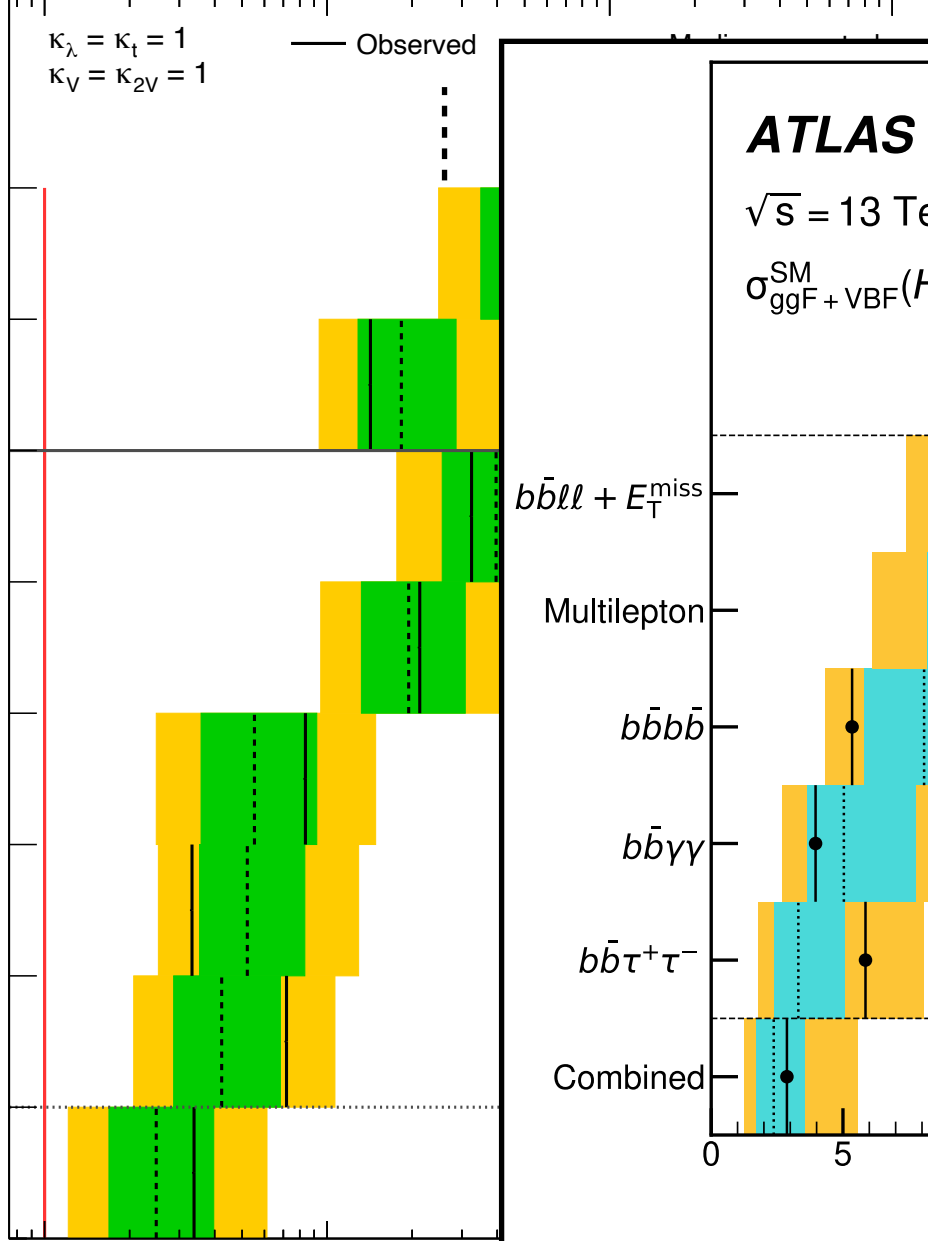


# Relative HH Sensitivities

[CMS: Summary plots](#)

[ATLAS-CONF-2024-006](#)

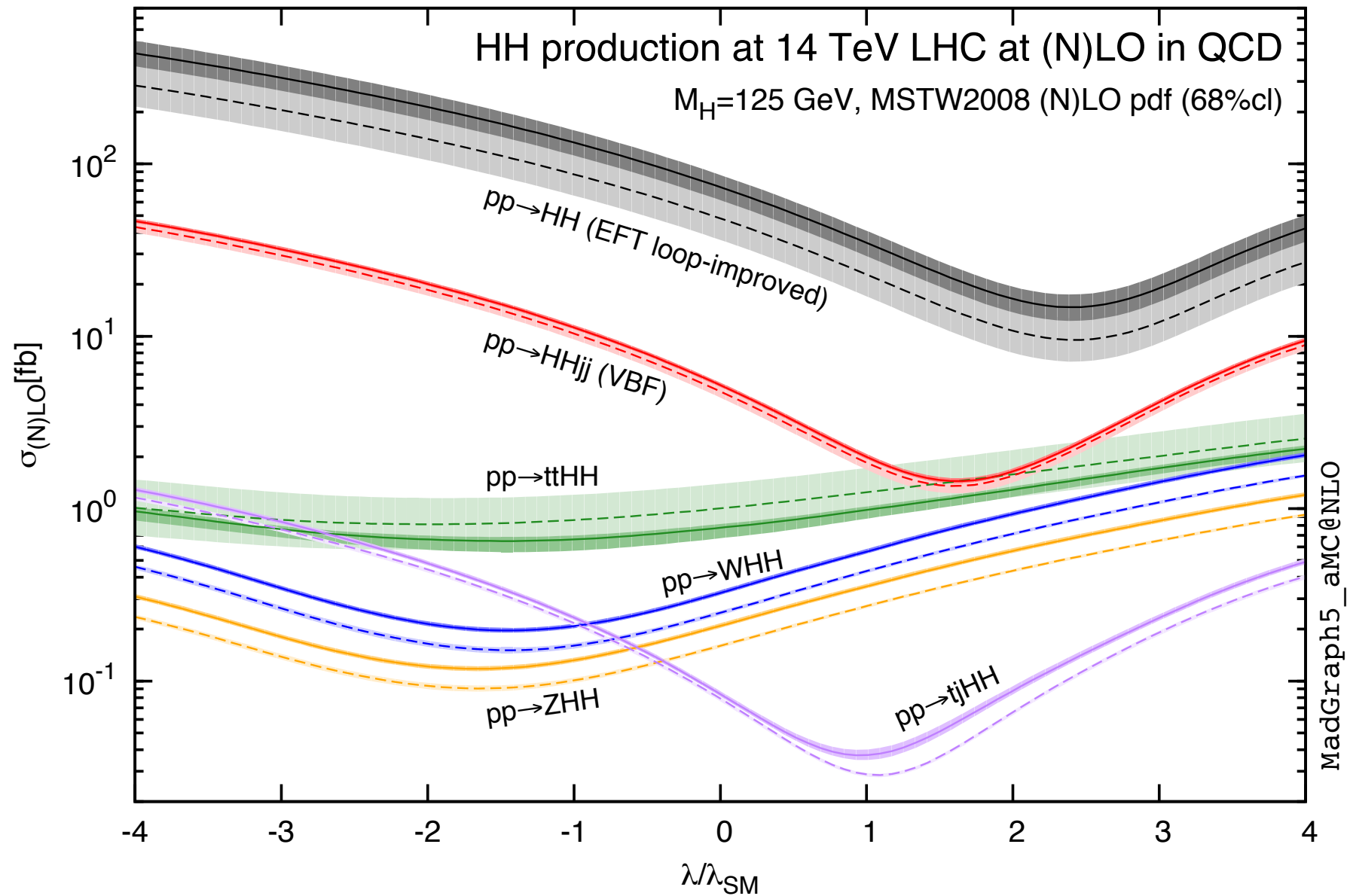
**CMS Preliminary** 138 fb<sup>-1</sup> (13 TeV)



95% CL limit on  $\sigma(pp \rightarrow HH)/\sigma_{\text{Theory}}$

# Measuring $\lambda_{hhh}$

arXiv:1401.7340

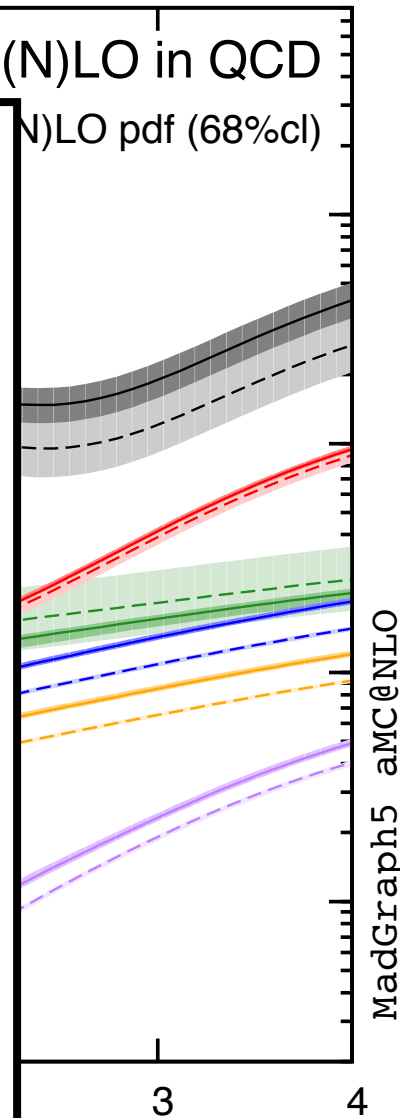
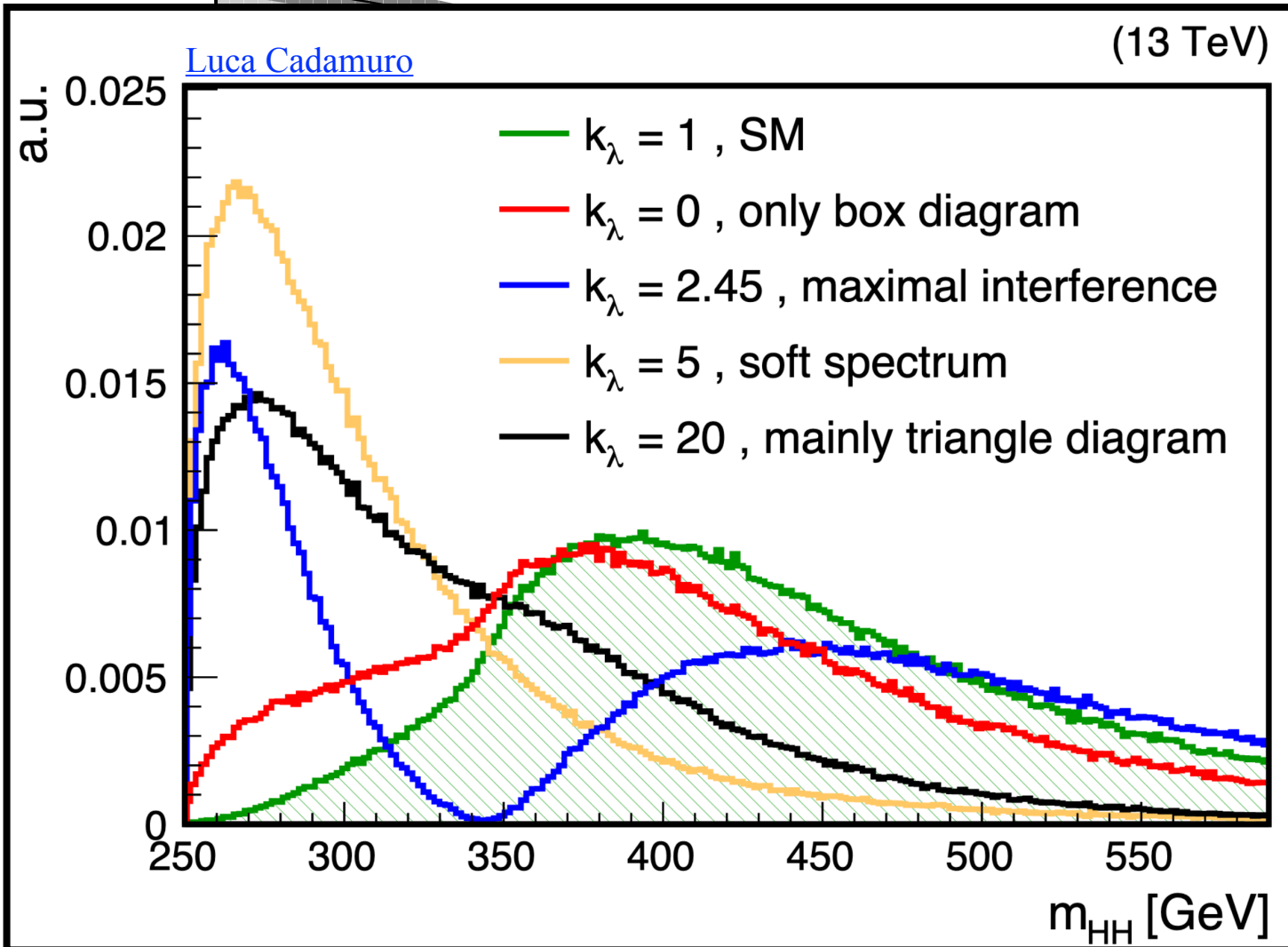


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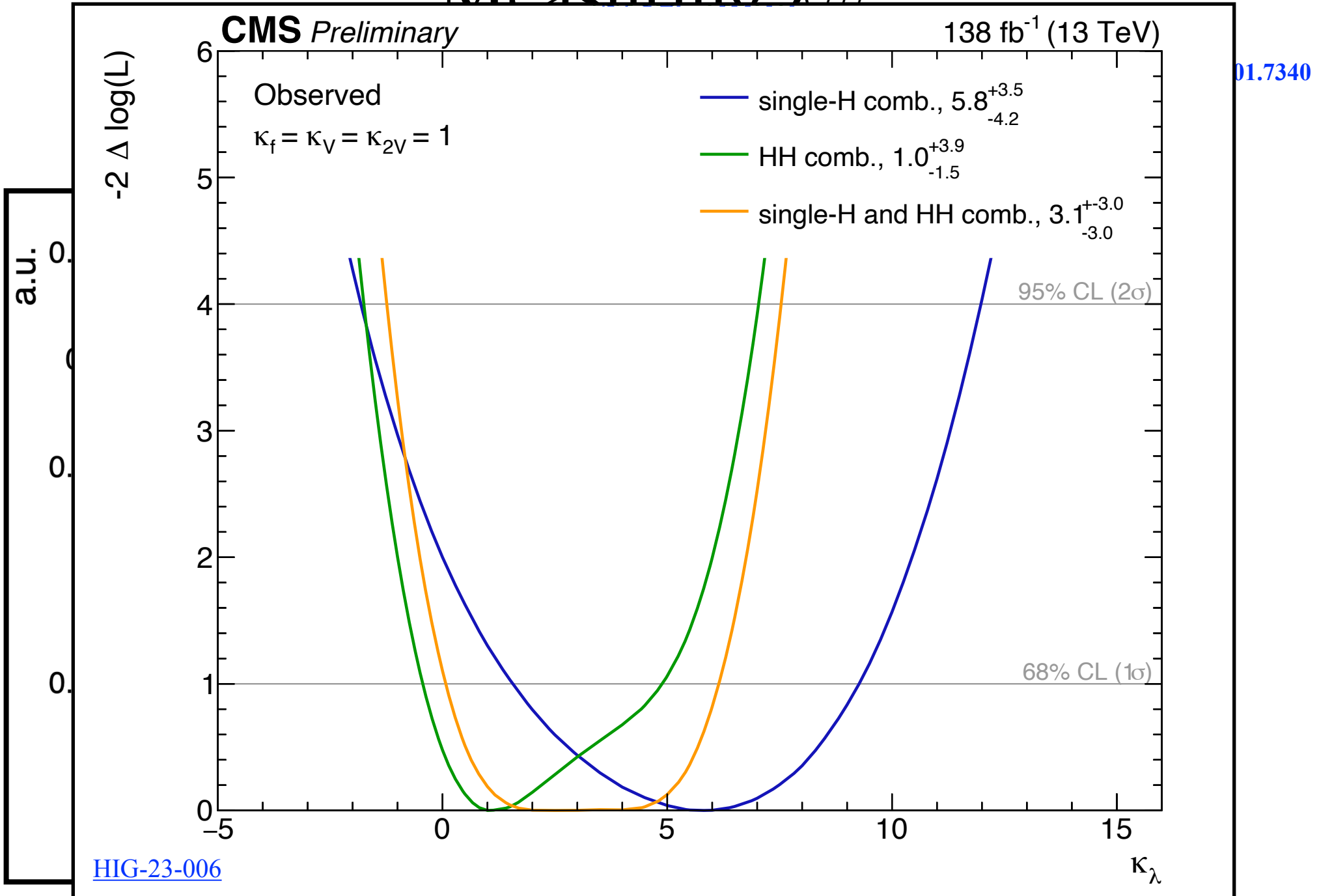
arXiv:1401.7340

HH production at 14 TeV LHC at (N)LO in QCD

(13 TeV) (N)LO pdf (68%cl)

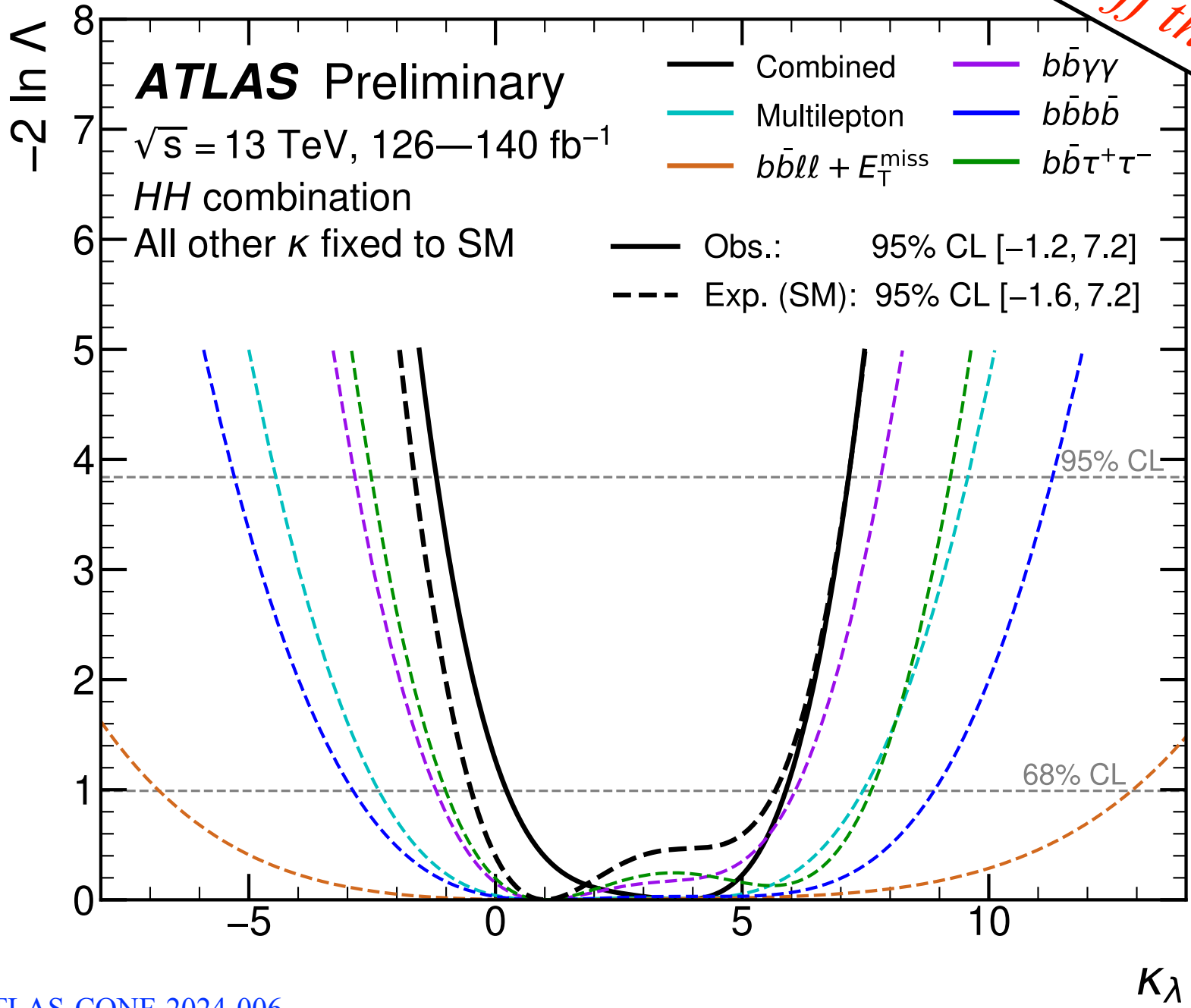


# Measuring $\lambda_{HH}$



# Measuring $\lambda_{tt}$

*Hot off the press!*





# Future of HH ?

# Future of HH ?

## Predicting future is an easy way to embarrass yourself:

*"The Americans have need of the telephone, but we do not. We have plenty of messenger boys."*

- Chief Engineer of the British Post Office, 1876

*"The horse is here to stay, but the automobile is only a novelty—a fad."*

- Advisor to Henry Ford's lawyer, 1903

*"I think there is a world market for maybe five computers."*

- President of IBM, 1943

*"Our children will enjoy in their homes electrical energy too cheap to meter."*

- Chairman of the U.S. Atomic Energy Commission, 1954

*"Nuclear-powered vacuum cleaners will probably be a reality in 10 years."*

- President of Lewyt Corporation, 1955

*"Man will never reach the moon, regardless of all future scientific advances."*

- Inventor of the vacuum tube, 1957

*"There is practically no chance communications space satellites will be used to provide better telephone, telegraph, television or radio service inside the United States."*

- FCC Commissioner, 1961

*"The Japanese auto industry isn't likely to carve out a big slice of the U.S. market for itself."*

- Business Week, 1968

*"We will never make a 32-bit operating system."*

- Bill Gates, 1989

*"Bitcoin is a fraud."*

- CEO of JPMorgan Chase, 2017 (Now offering Bitcoin to clients)

*Past*

~~Future of HH ?~~



# Experimental Studies of $hh$

*John Alison*

*University of Chicago*

for the ATLAS and CMS Collaborations

Higgs Couplings 2014

# *Past* ~~Future~~ of HH ?

HH 10 years ago...

No  $b\bar{b}\tau\tau$

**4b**: resolved only / resonant only /  $m_{HH} > 500$  GeV  
O(100) events in SR

**$b\bar{b}\gamma\gamma$** : 4 events in SR /  $\mu < 240$  (!)

No MVAs

$X \rightarrow HH$  limits end at 1 TeV

No  $\lambda$  limits

Only ggF

Projections focused on the “Big-Two” HH analyses  
(non-resonant 4b thought impossible)

...



udies of  $hh$

ago

and CMS Collaborations  
Higgs Couplings 2014

# *Past* ~~Future~~ of HH ?

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No  $\lambda$  limits

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Projections focused on the “Big-Two” HH analyses  
(non-resonant 4b thought impossible)

...

*Spectacular progress in last 10 years !* 4

$\sim 100 \times$  gain in HH sensitivity



udies of  $hh$

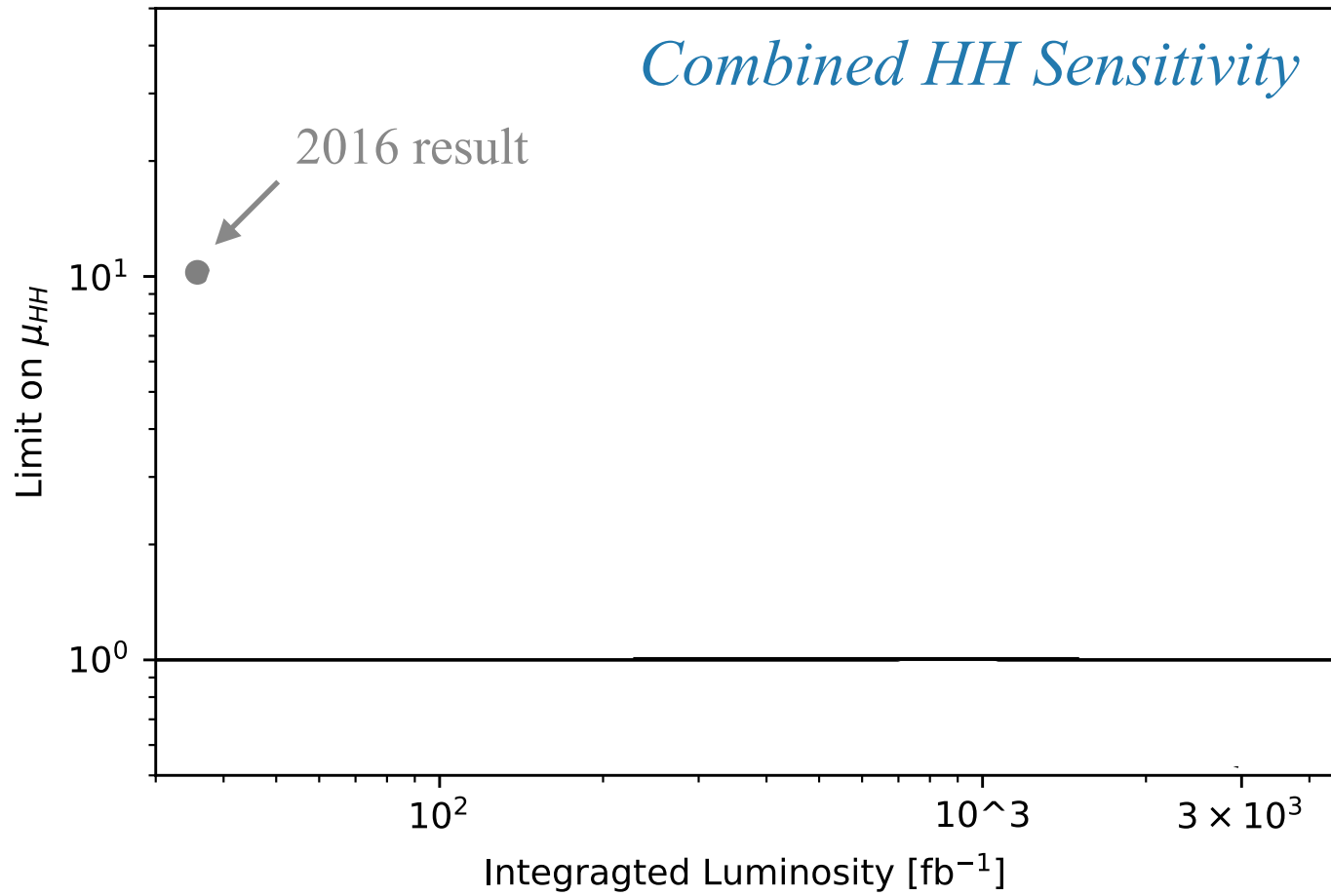
ago

and CMS Collaborations

# Future of HH ?

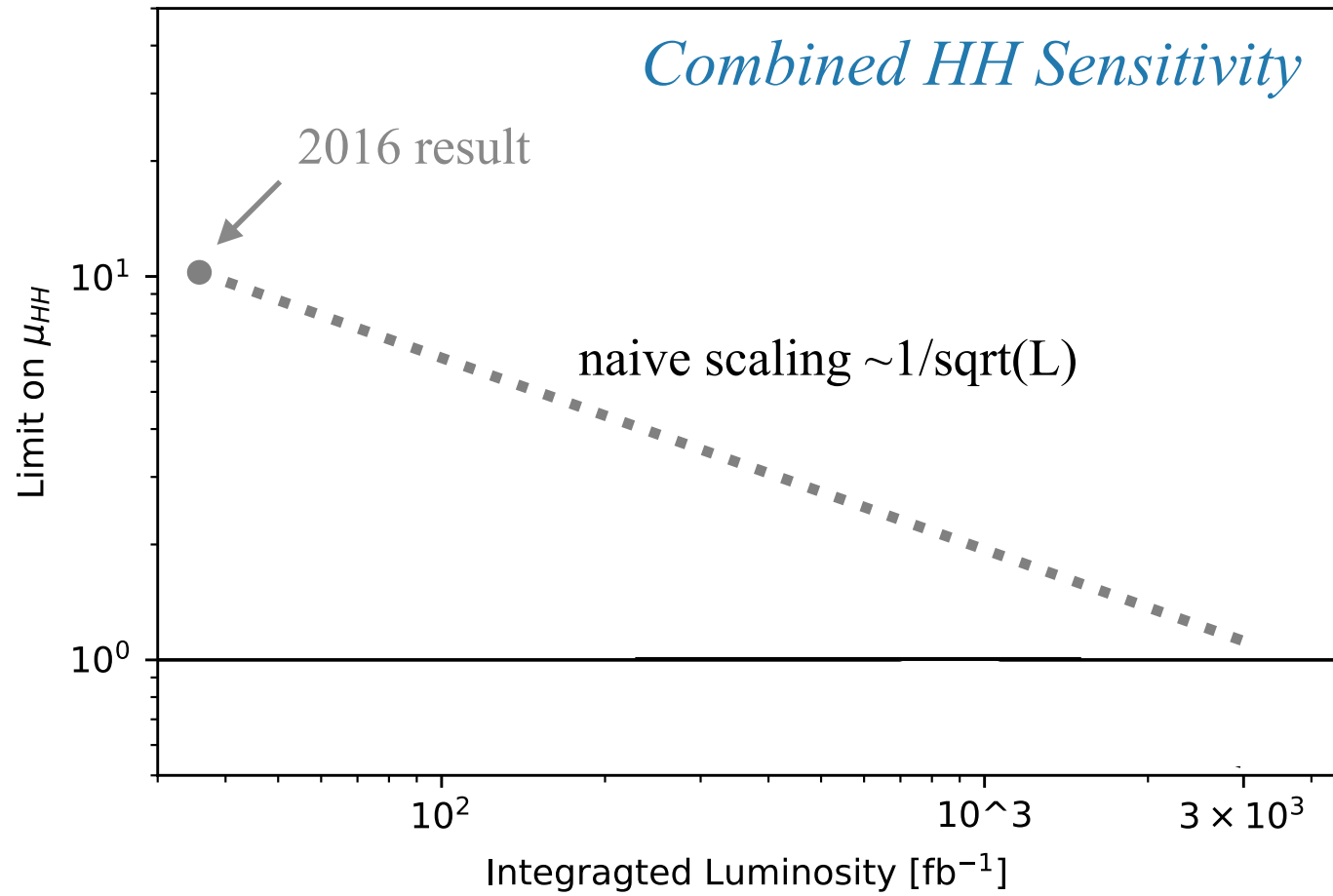
# Future of HH ?

[Nature 607, 60–68 \(2022\).](#)



# Future of HH ?

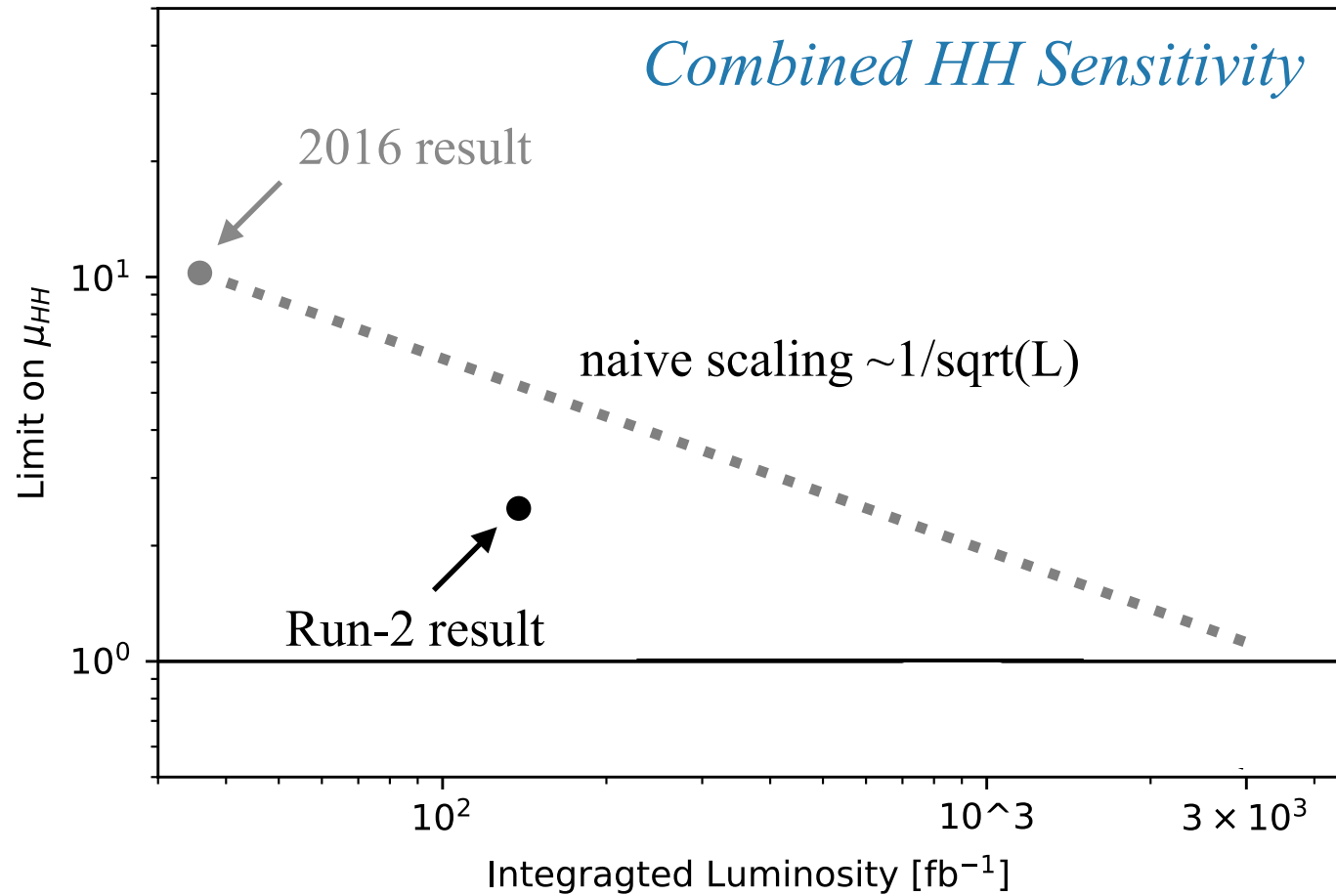
[Nature 607, 60–68 \(2022\).](#)





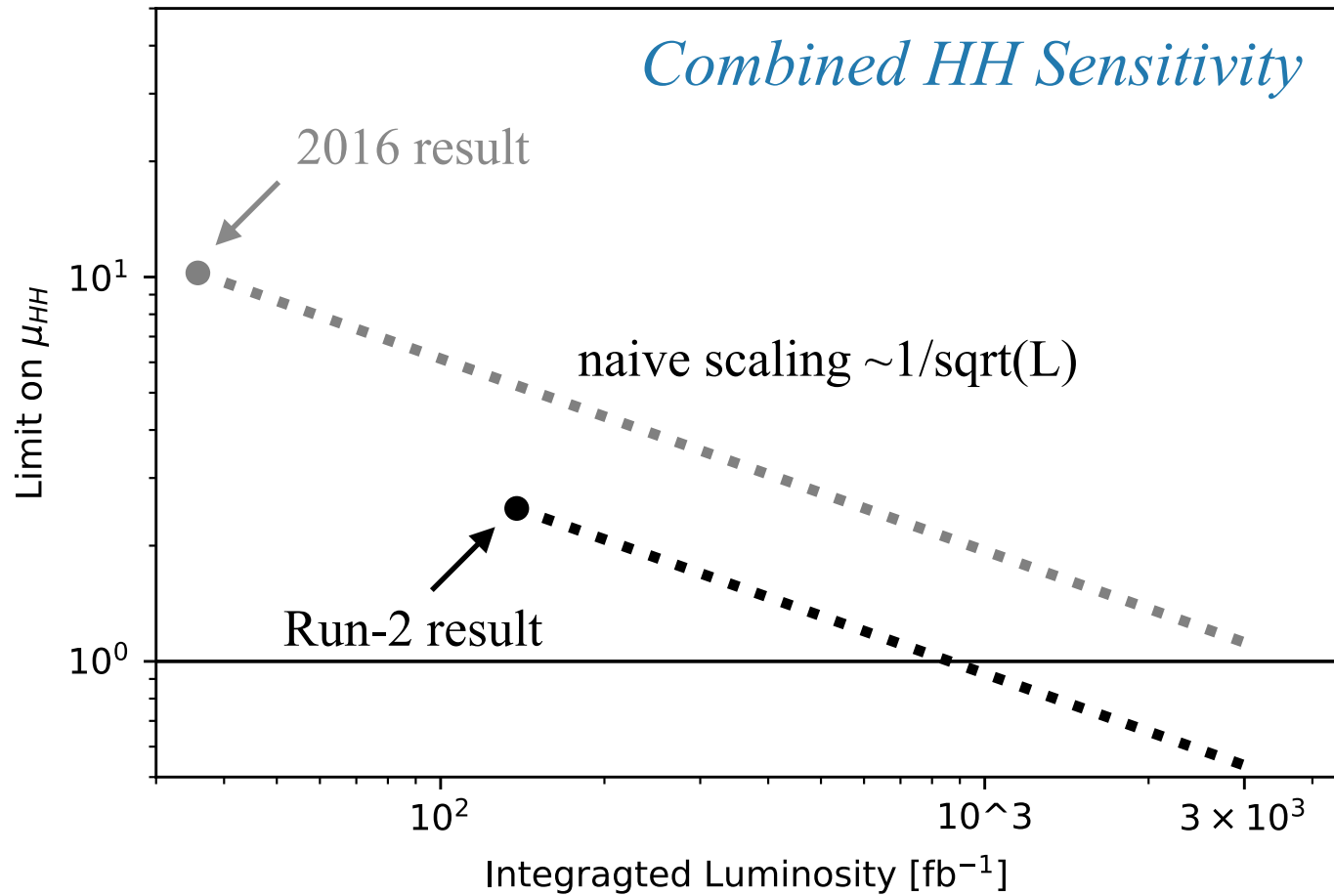
# Future of HH ?

[Nature 607, 60–68 \(2022\).](#)



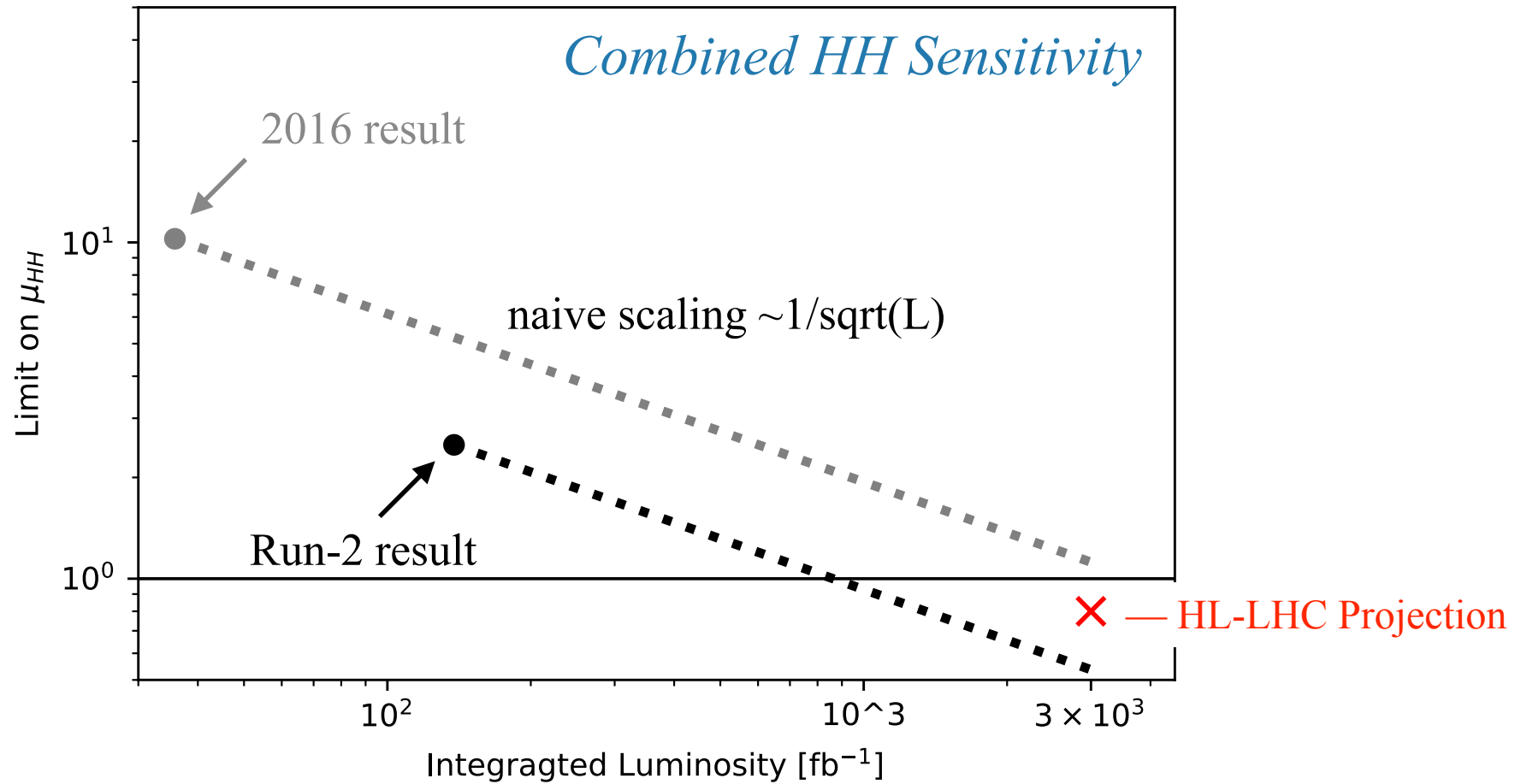
# Future of HH ?

[Nature 607, 60–68 \(2022\).](#)



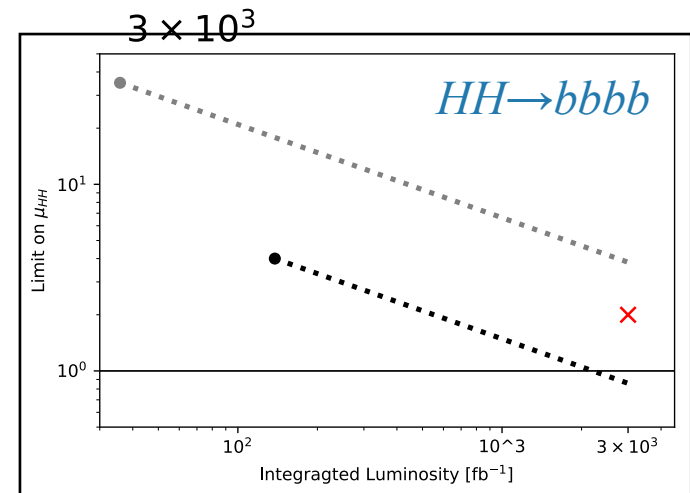
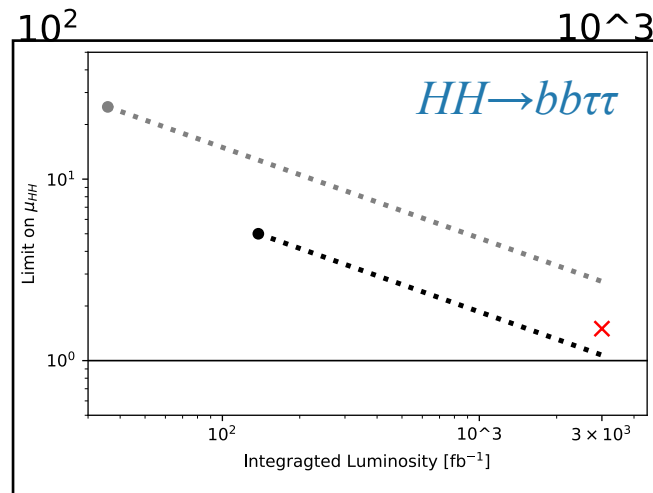
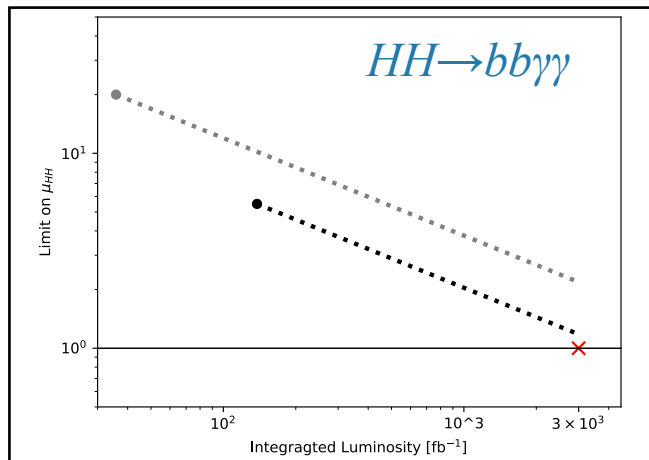
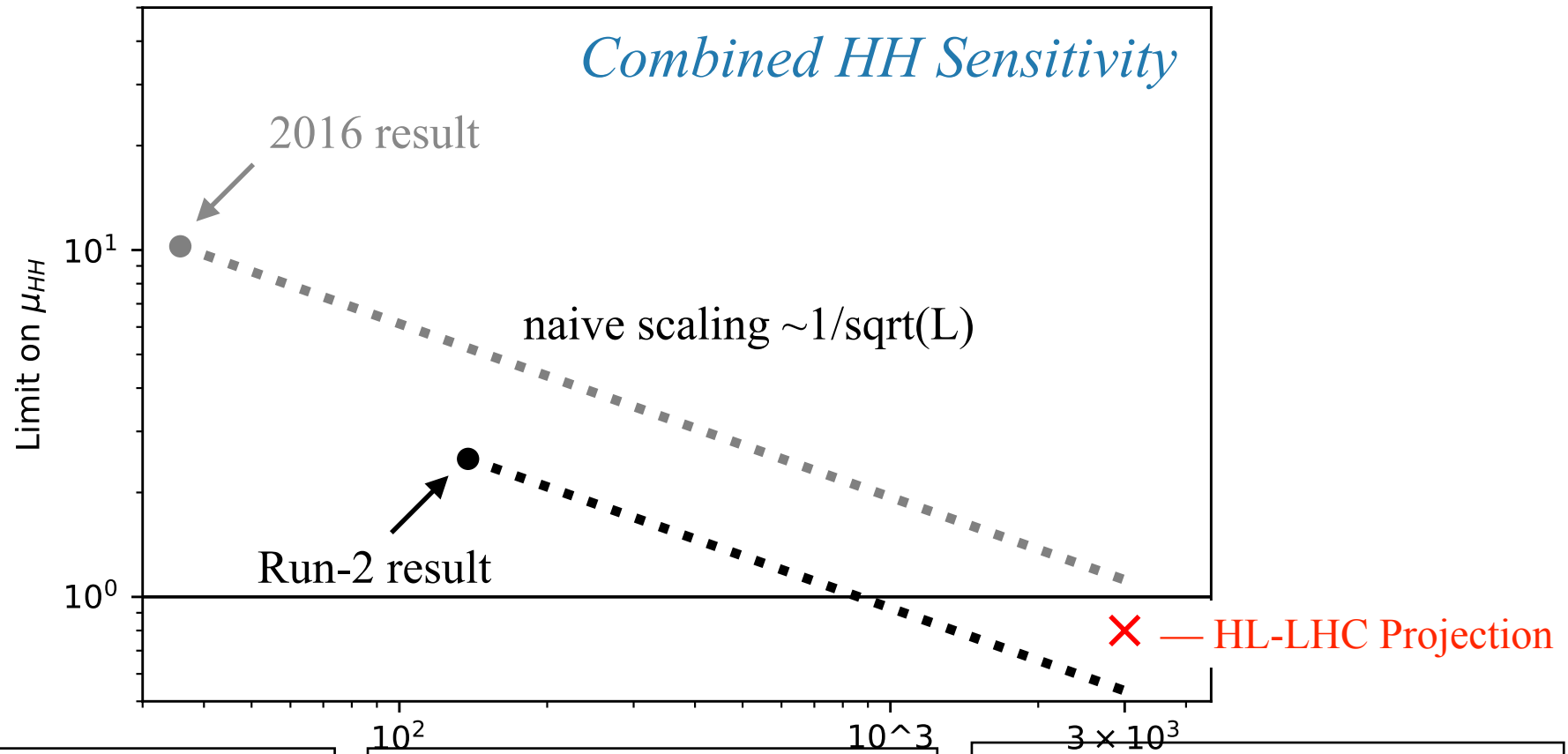
# Future of HH ?

[Nature 607, 60–68 \(2022\).](#)



# Future of HH ?

[Nature 607, 60–68 \(2022\).](#)

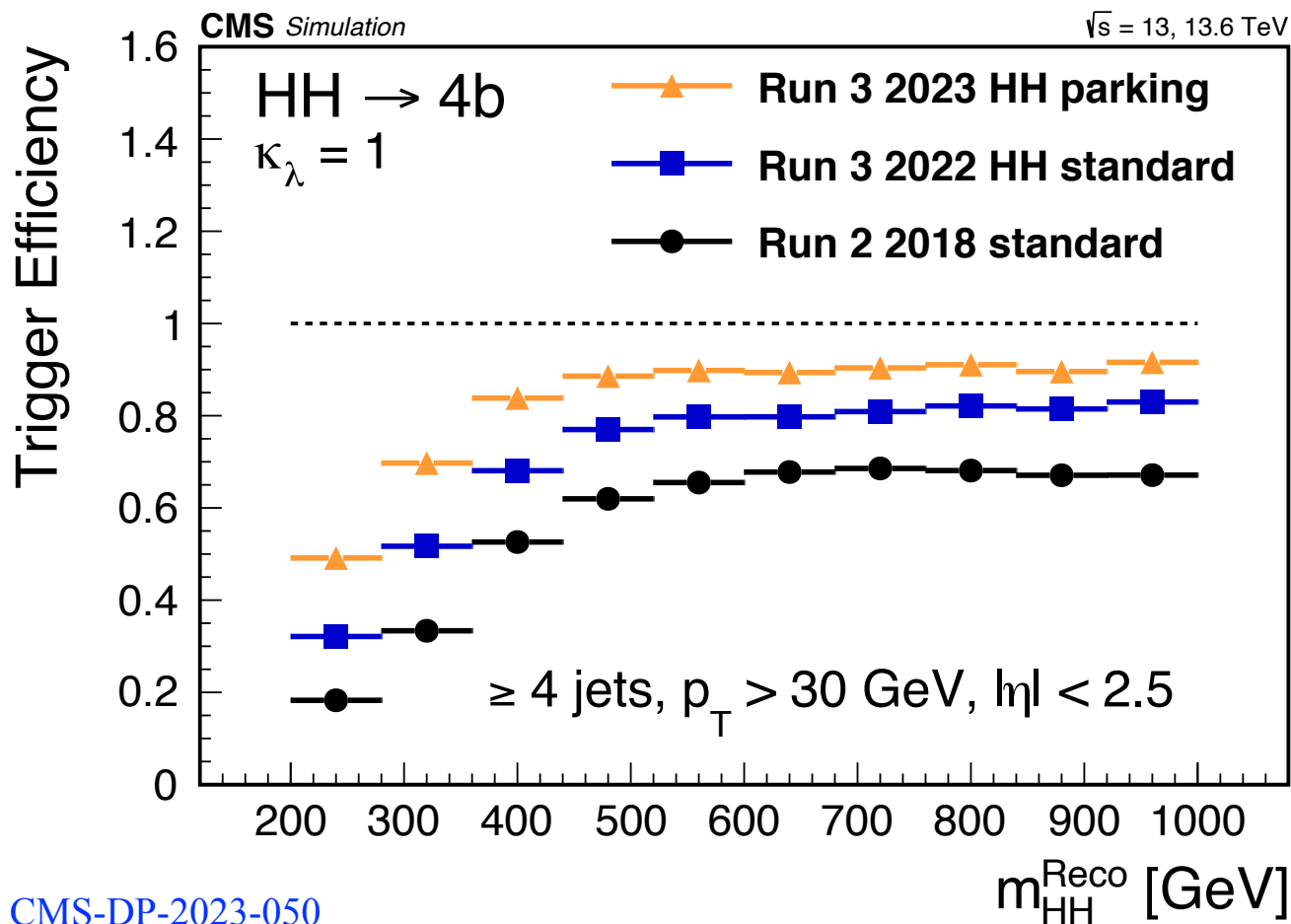


# Future of HH ?

[Nature 607, 60–68 \(2022\).](#)

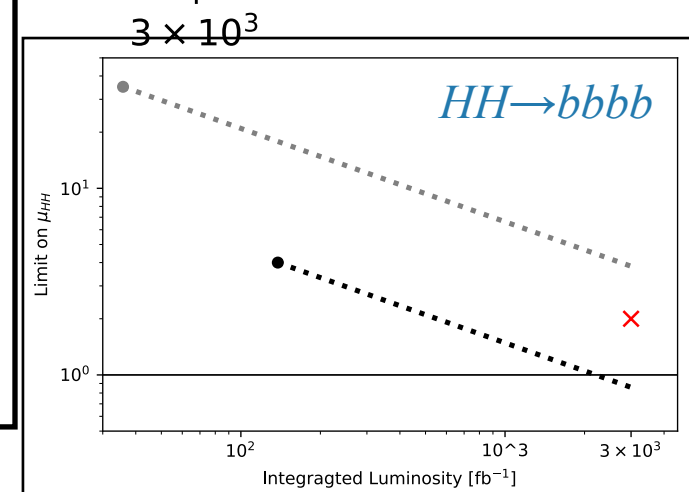
## Combined HH Sensitivity

2016 result



[CMS-DP-2023-050](#)

X — HL-LHC Projection



$10^2$   $10^3$   $3 \times 10^3$   
Integrated Luminosity [ $\text{fb}^{-1}$ ]

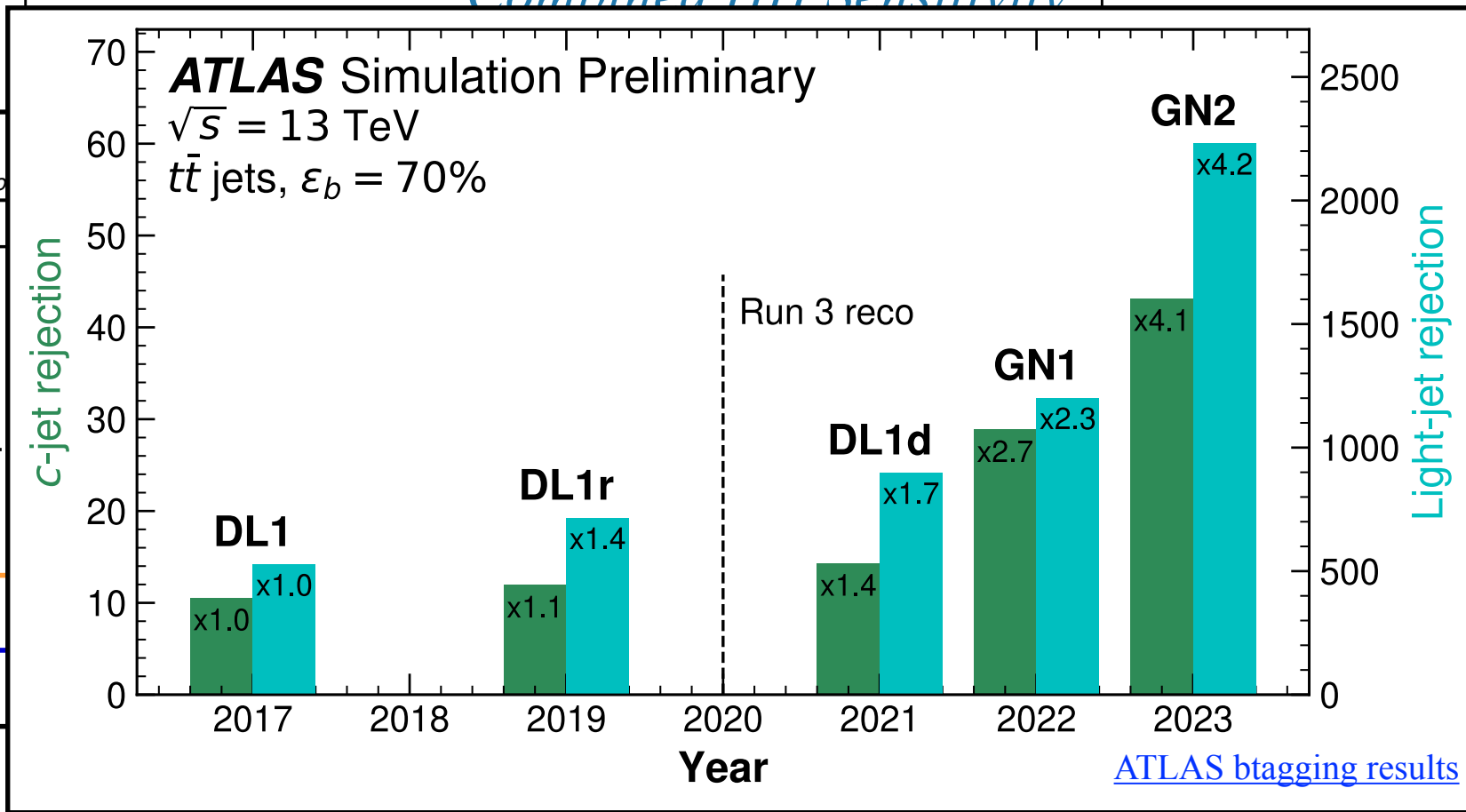
$10^2$   $10^3$   $3 \times 10^3$   
Integrated Luminosity [ $\text{fb}^{-1}$ ]

$10^2$   $10^3$   $3 \times 10^3$   
Integrated Luminosity [ $\text{fb}^{-1}$ ]

# Future of HH ?

[Nature 607, 60–68 \(2022\).](#)

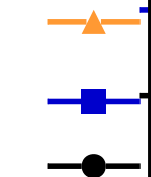
## Combined HH Sensitivity



Trigger Efficiency

CMS Simulation

HH  
 $\kappa_\lambda = 1$

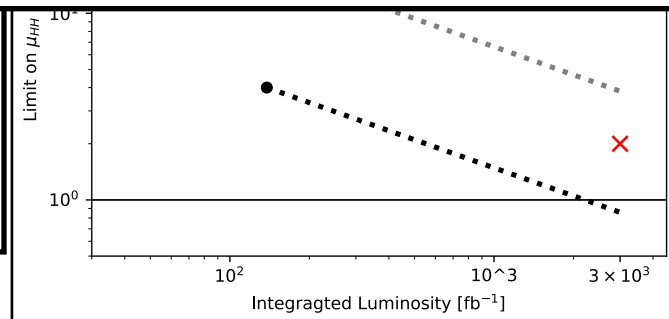


c-jet rejection

Light-jet rejection

[CMS-DP-2023-050](#)

$m_{HH}^{Reco}$  [GeV]



Integrated Luminosity [ $fb^{-1}$ ]

Integrated Luminosity [ $fb^{-1}$ ]

Integrated Luminosity [ $fb^{-1}$ ]

# Conclusions

Study of HH production has a long and rich future

BSM sensitivity interesting already

- Searches in essentially all relevant HH final states
- Constraints on non-resonant production as low as  $2.5 \times \sigma_{hh}$

Will continue to be exciting with remainder of Run-3 Data

Lots I couldn't cover: VBF-HH / V-HH /  $X \rightarrow YH$  / ...

Measurement of  $\lambda_{hhh}$  flagship of HL-LHC

- Big-three well-established, will continue to improve
- Predictions suggest combined sensitivity marginal at HL-LHC
- Critical to get hadronic triggers right:  $4b$  /  $\tau h \tau h$
- Really nice to have “Big-Four” ( $bbWW$  ? / “ $\ell\tau\gamma\gamma$ ” ? / *others* ?)

# Bonus



# References



[ATLAS: 4b](#)

[ATLAS: 4b boosted VBF](#)

[ATLAS: 4b VHH](#)

[ATLAS:  \$bb\gamma\gamma\$](#)

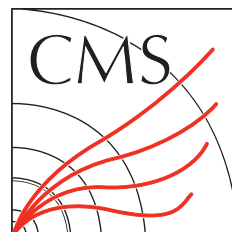
[ATLAS:  \$bb\tau\tau\$](#)

[ATLAS:  \$bb + ll + \text{MeT}\$](#)

[ATLAS: leptons +  \$\tau s + \gamma s\$](#)

[ATLAS: H + HH Combination](#)

[ATLAS: VHH](#)



[CMS: 4b](#)

[CMS: ZZ ZH->4b](#)

[CMS: 4b VHH](#)

[CMS:  \$bbWW\$](#)

[CMS:  \$bb\tau\tau\$](#)

[CMS:  \$bb\gamma\gamma\$](#)

[CMS: Multilepton](#)

[CMS:  \$bbZZ\$](#)

[CMS:  \$WW\gamma\gamma\$](#)

[CMS:  \$\tau\tau\gamma\gamma\$](#)

[CMS: Higgs Run-2 summary](#)

[CMS: H + HH Combination](#)

[CMS: VHH](#)

# Validating 4b Background Model

Lot of recent work on techniques to validate data-drive background

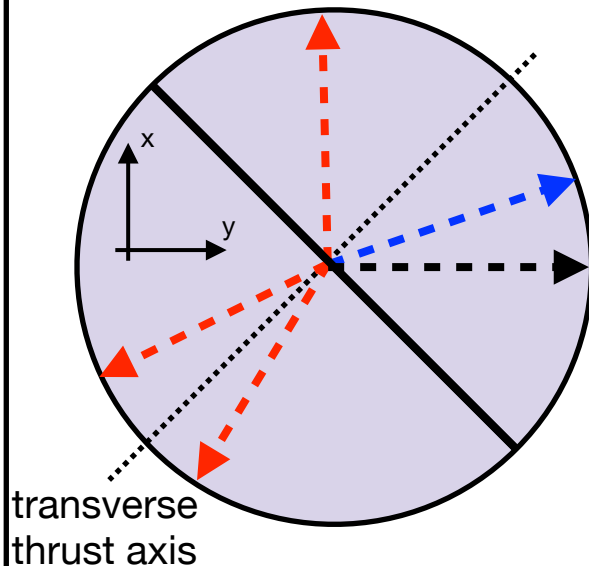
**ATLAS:** Nice k-folding studies [Phys. Rev. D 108 \(2023\) 052003](#)

**CMS:** Validation SR extrapolation with Synthetic datasets

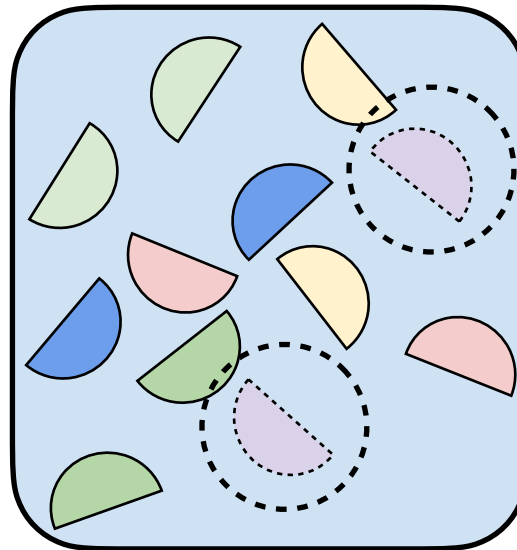
[Submitted to Eur. Phys. J. C](#)

## Synthetic Datasets from Mixing

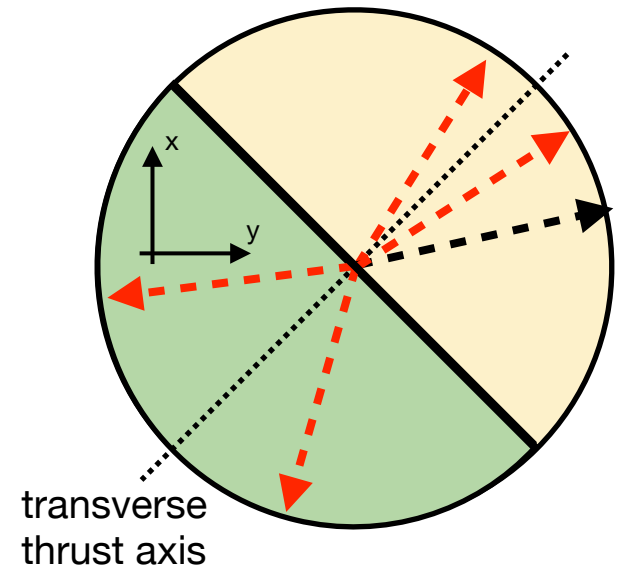
**Original three-tag event**  
split into two hemispheres



**Hemisphere library**  
made from four-tag events  
filled in 1<sup>st</sup> pass, queried on 2<sup>nd</sup>



**Mixed Event**  
using replaced hemispheres

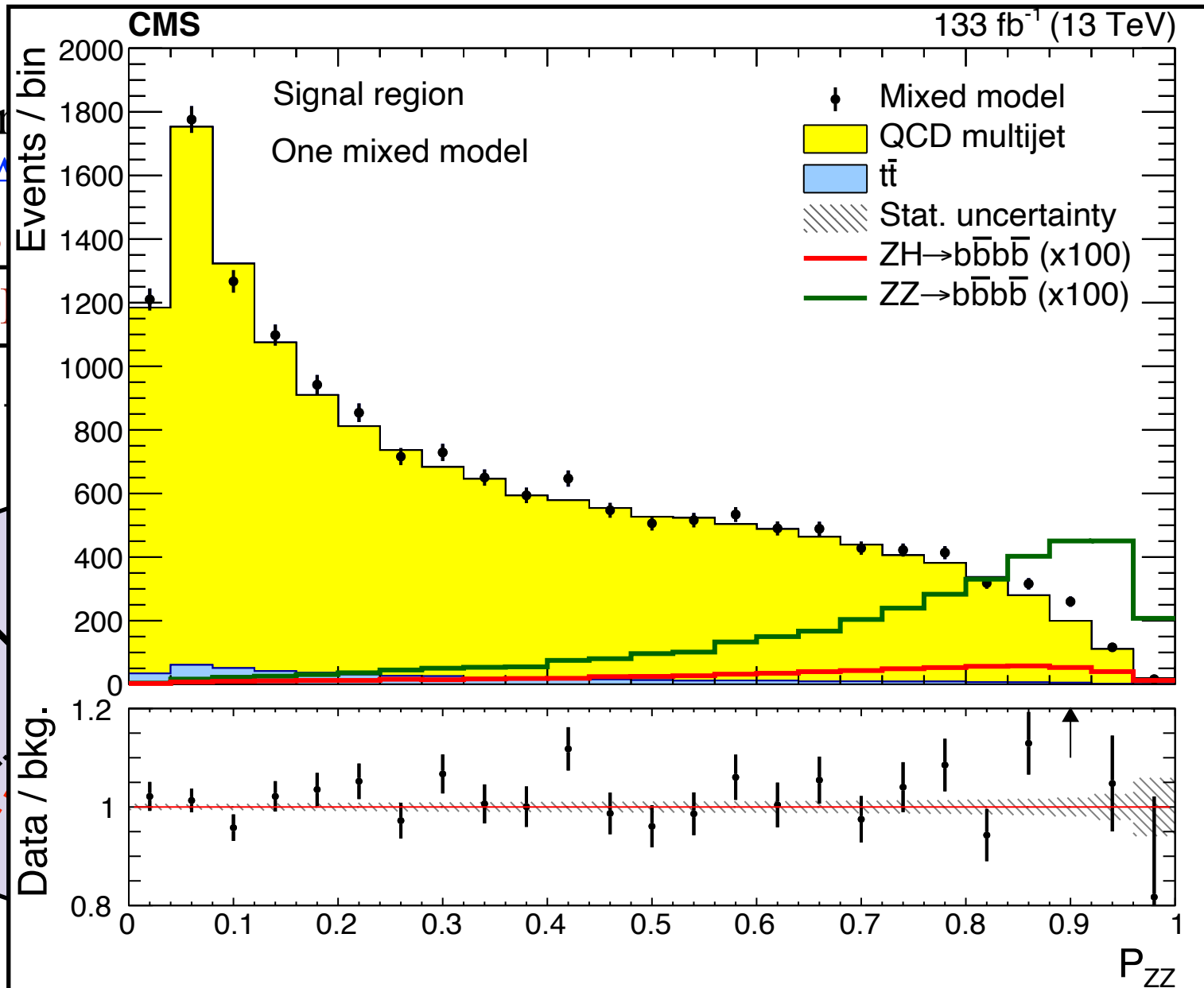


---▶ b-tagged jets

---▶ pseudo-tagged jets

---▶ non b-tagged jets

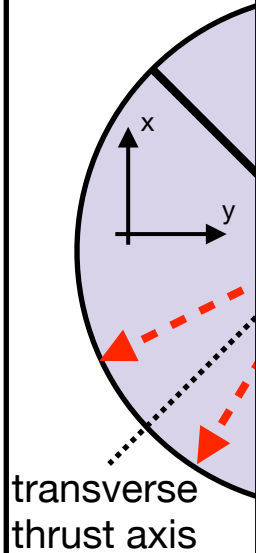
# Validating 4b Background Model



Lot of 1  
ATLAS  
CMS

Synthetic

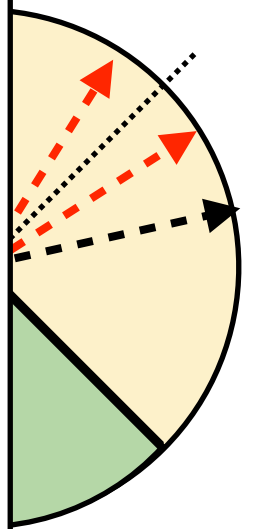
Original  
split into



und

[HIG-22-011](#)

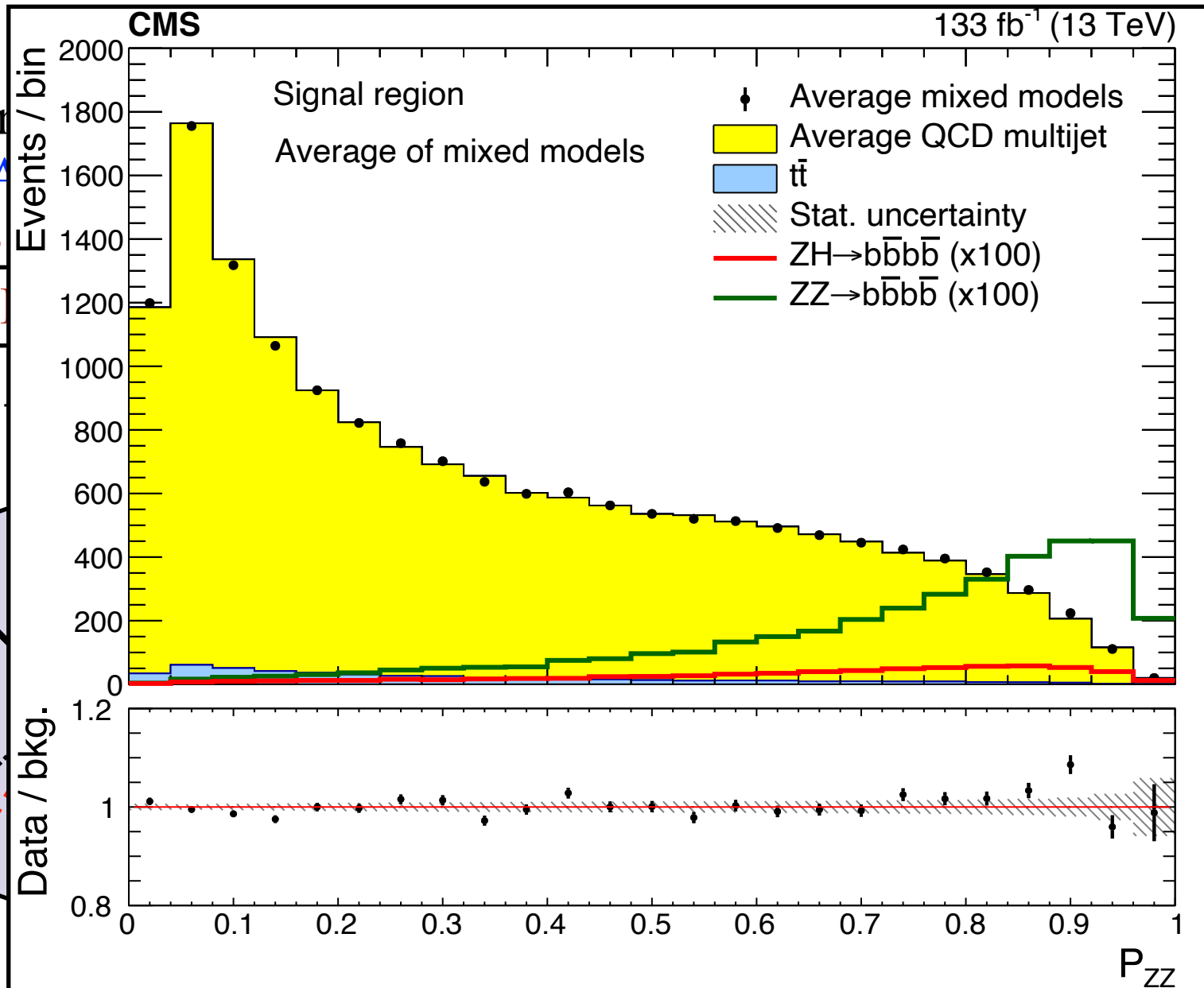
nt  
hisphe



- - - - - - - - - - - - - - -

▶ b-tagged jets   
 ▶ pseudo-tagged jets   
 ▶ non b-tagged jets

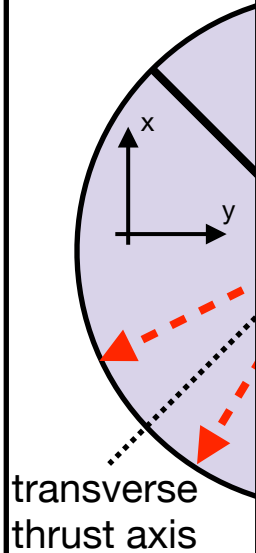
# Validating 4b Background Model



Lot of 1  
ATLAS  
CMS

Synthetic

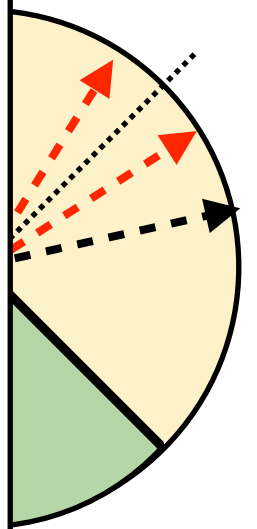
Original  
split into



und

[HIG-22-011](#)

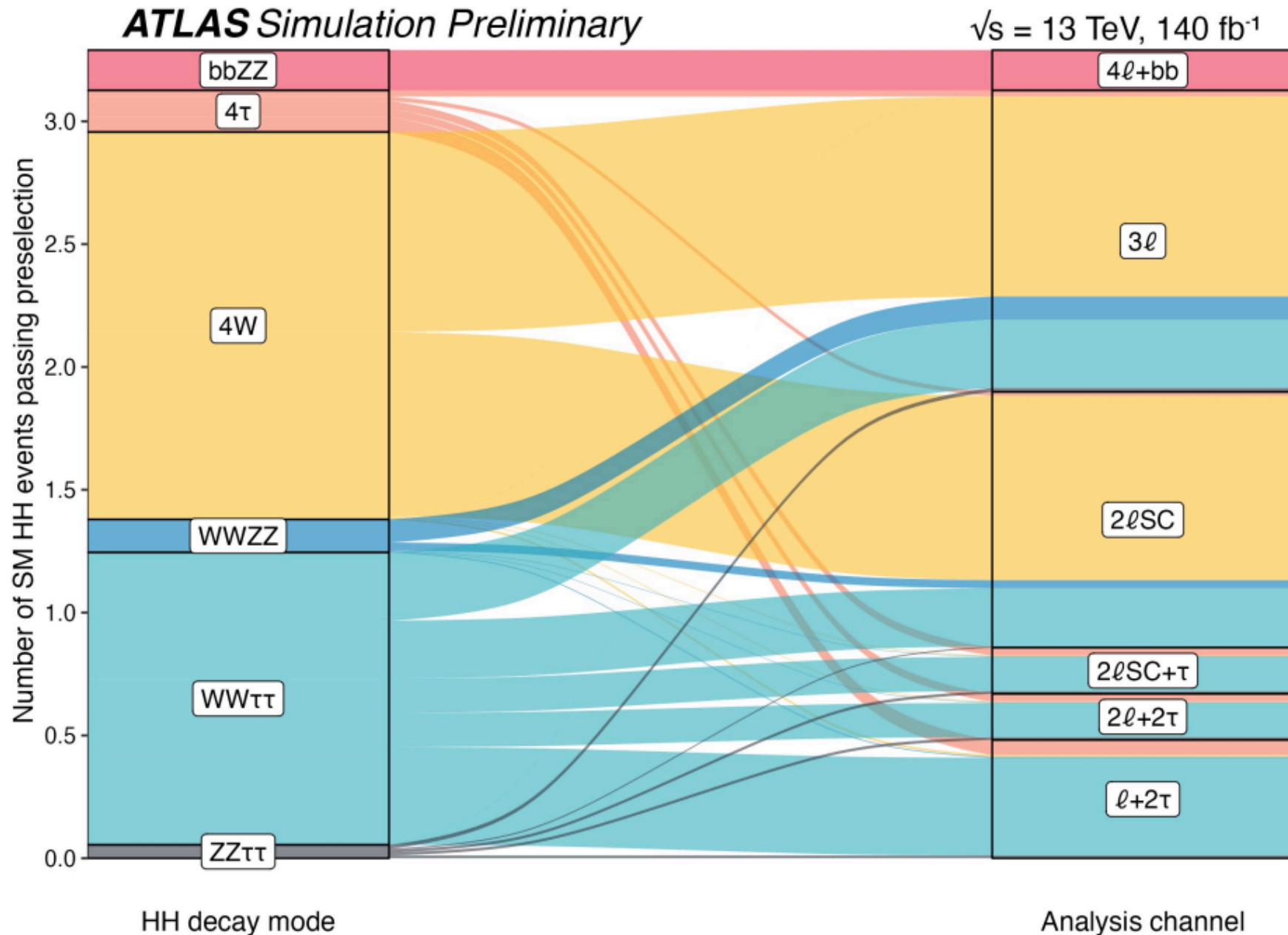
nt  
hisphe



—•— b-tagged jets    —•— pseudo-tagged jets    —•— non b-tagged jets

# ATLAS: $\ell\tau\gamma\gamma$

[Submitted to J. High Energy Phys.](#)

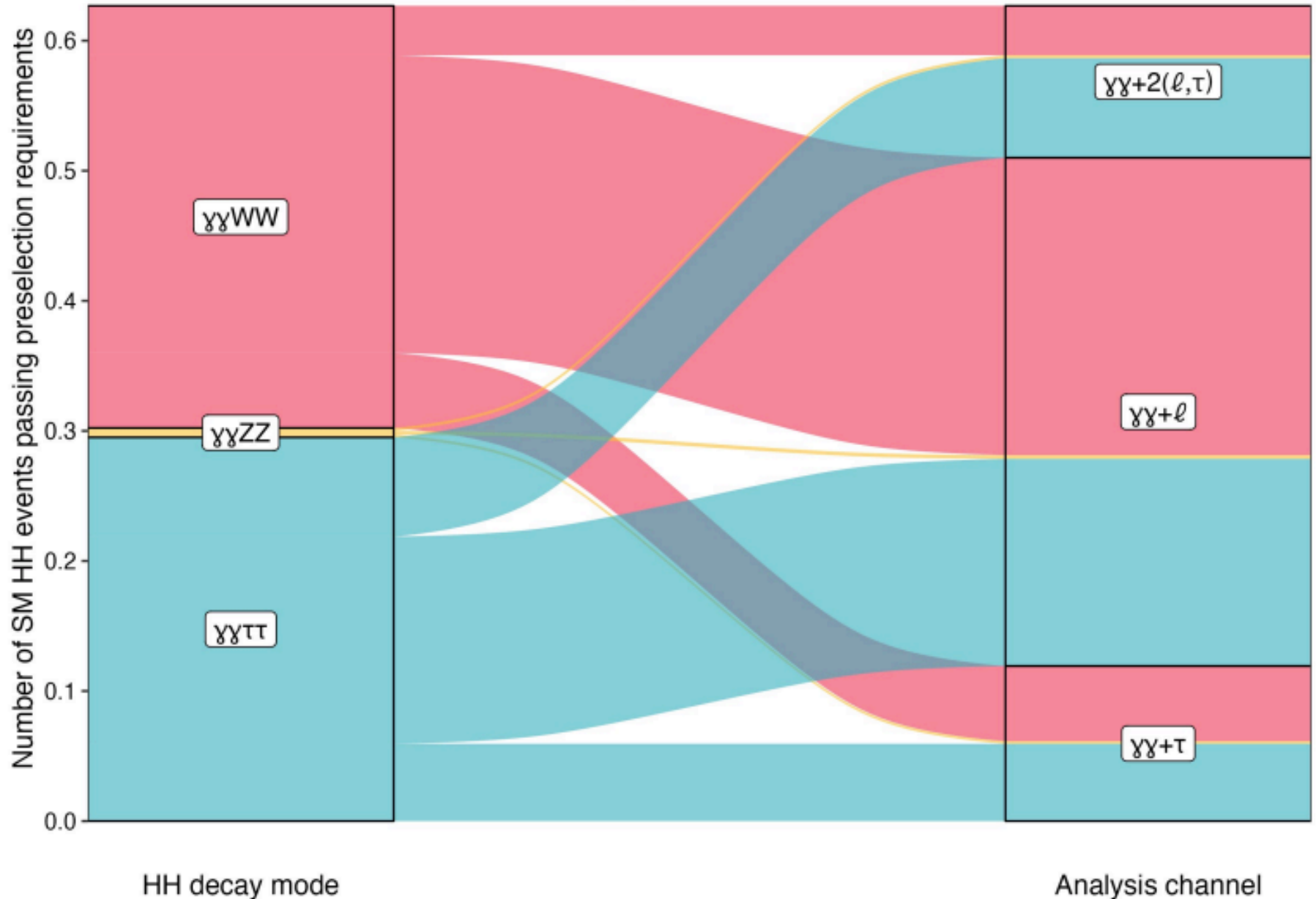


# ATLAS: $\ell\tau\gamma\gamma$

[Submitted to J. High Energy Phys.](#)

**ATLAS Simulation Preliminary**

$\sqrt{s} = 13 \text{ TeV}, 140 \text{ fb}^{-1}$



# CMS: $HH \rightarrow bbWW$

[Submitted to J. High Energy Phys.](#)

**CMS**

138 fb<sup>-1</sup> (13 TeV)

$$\begin{aligned} \kappa_\lambda &= \kappa_t = 1 \\ \kappa_V &= \kappa_{2V} = 1 \end{aligned}$$

— Observed

— ± 1 σ expected

----- Median expected

— ± 2 σ expected

**bbWW**

dilepton

Expected: 27

Observed: 19

single-lepton

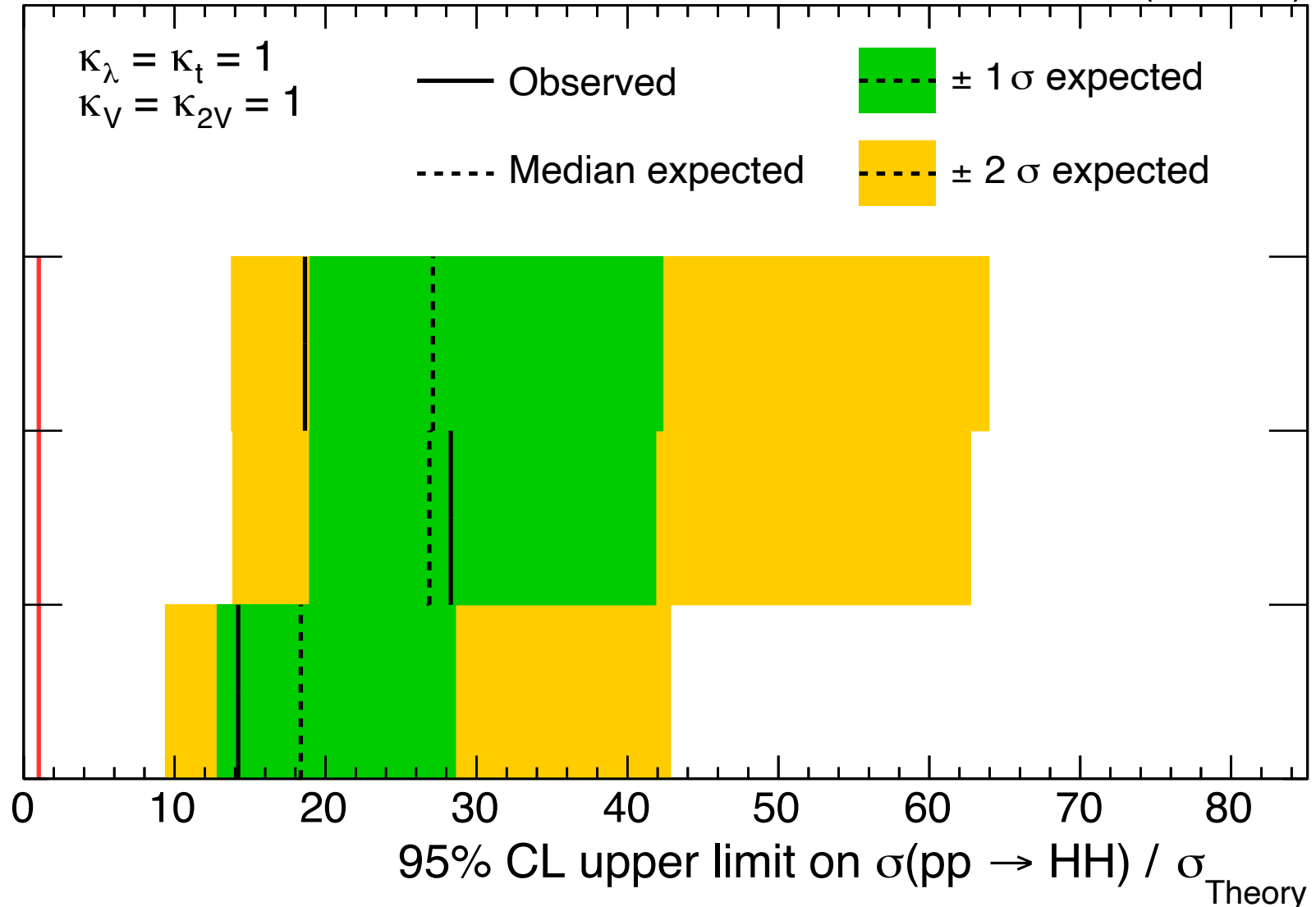
Expected: 27

Observed: 28

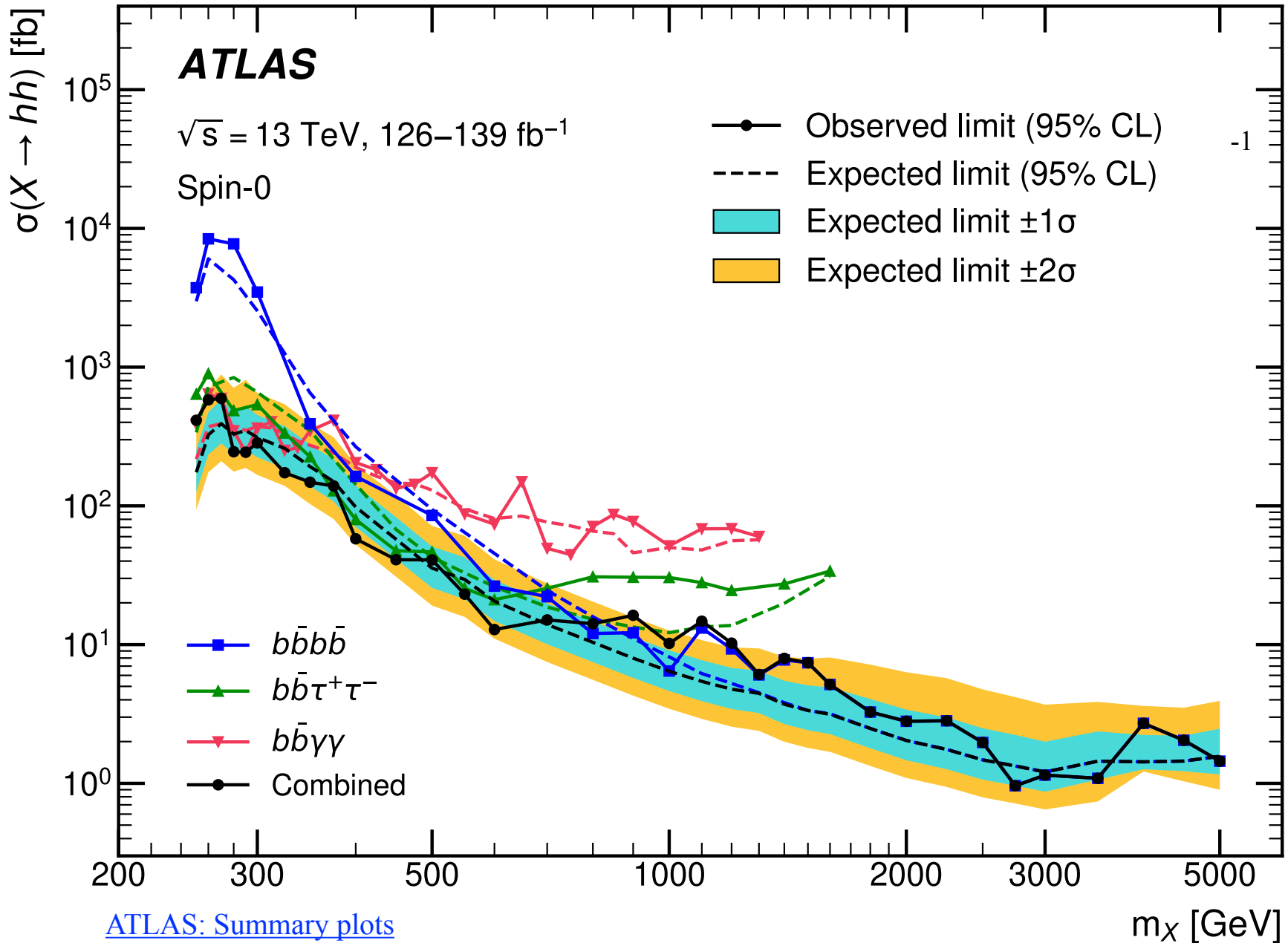
Combined

Expected: 18

Observed: 14



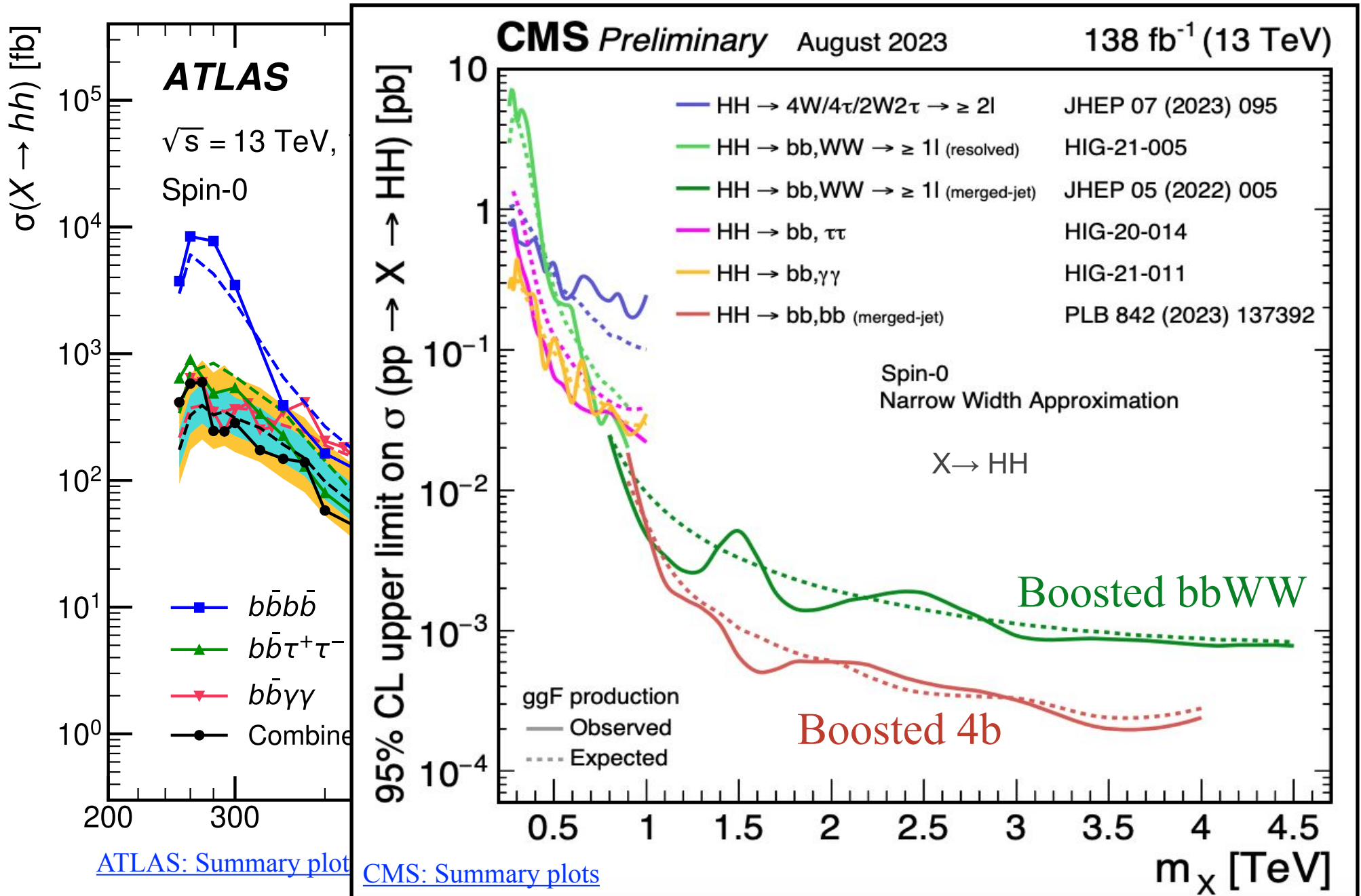
# Relative HH Sensitivities



[ATLAS: Summary plots](#)



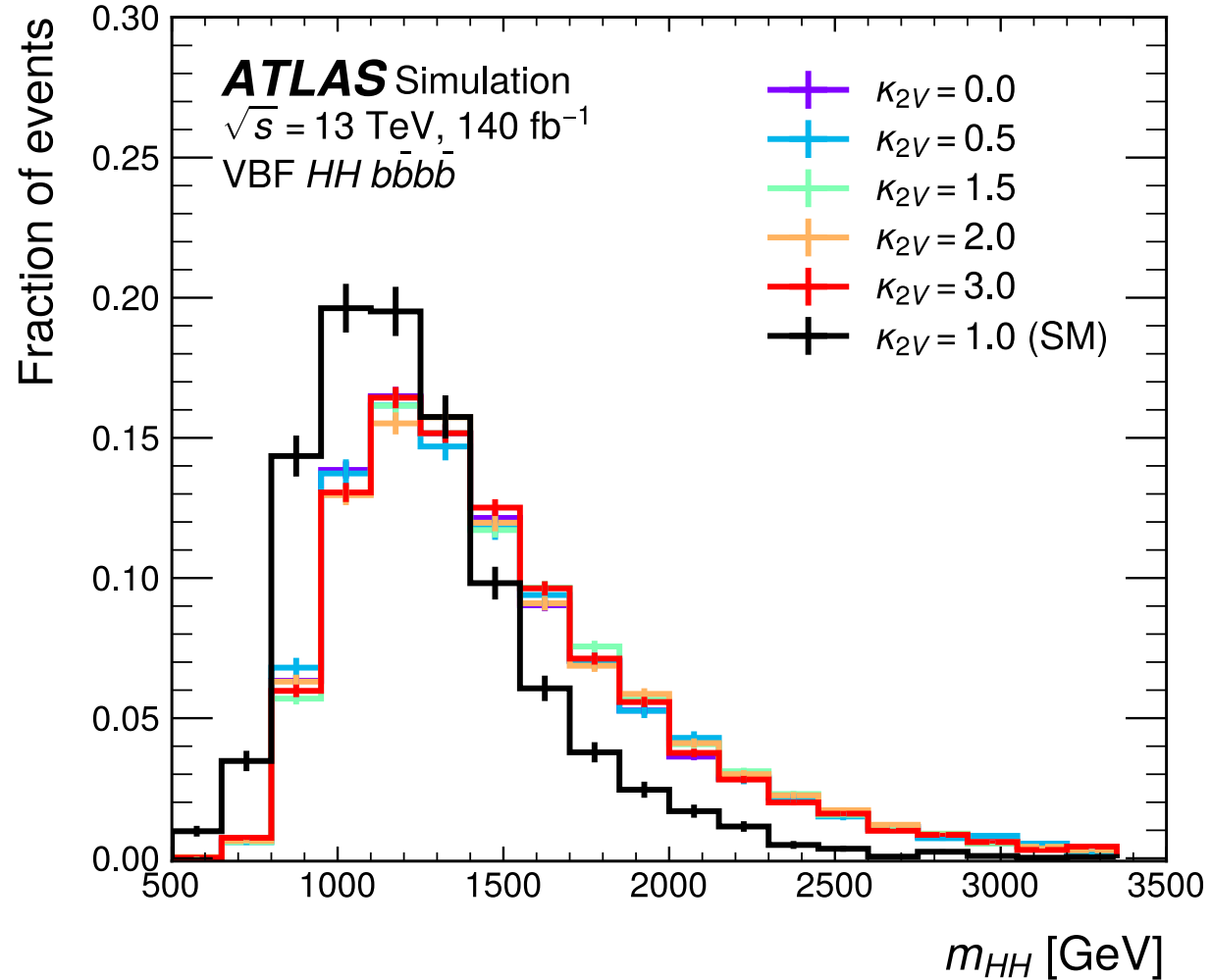
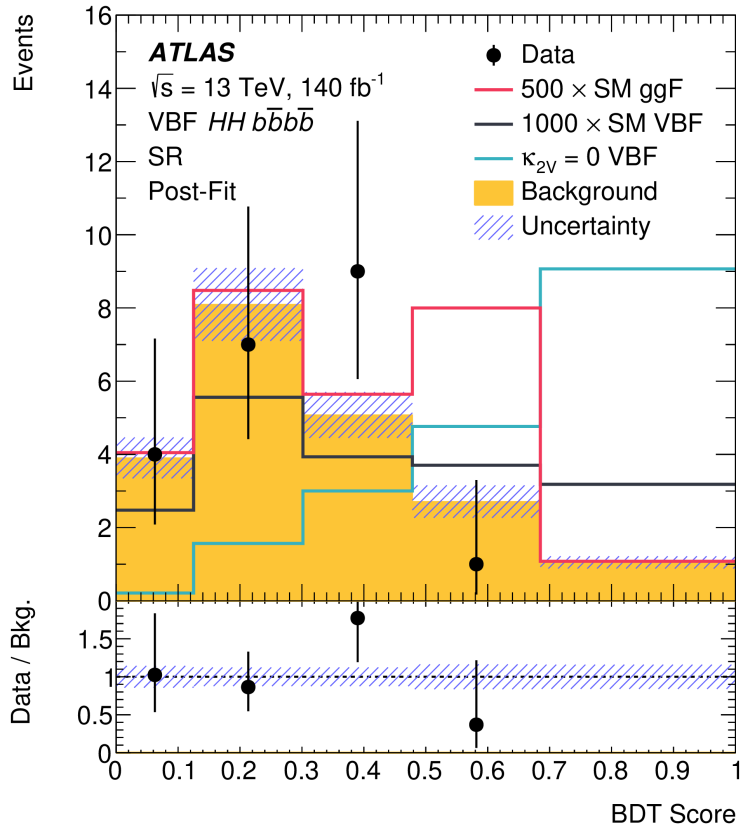
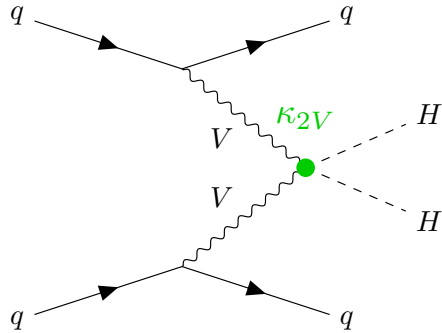
# Relative HH Sensitivities



# VBF Constraints

Submitted to: Phys. Lett. B.

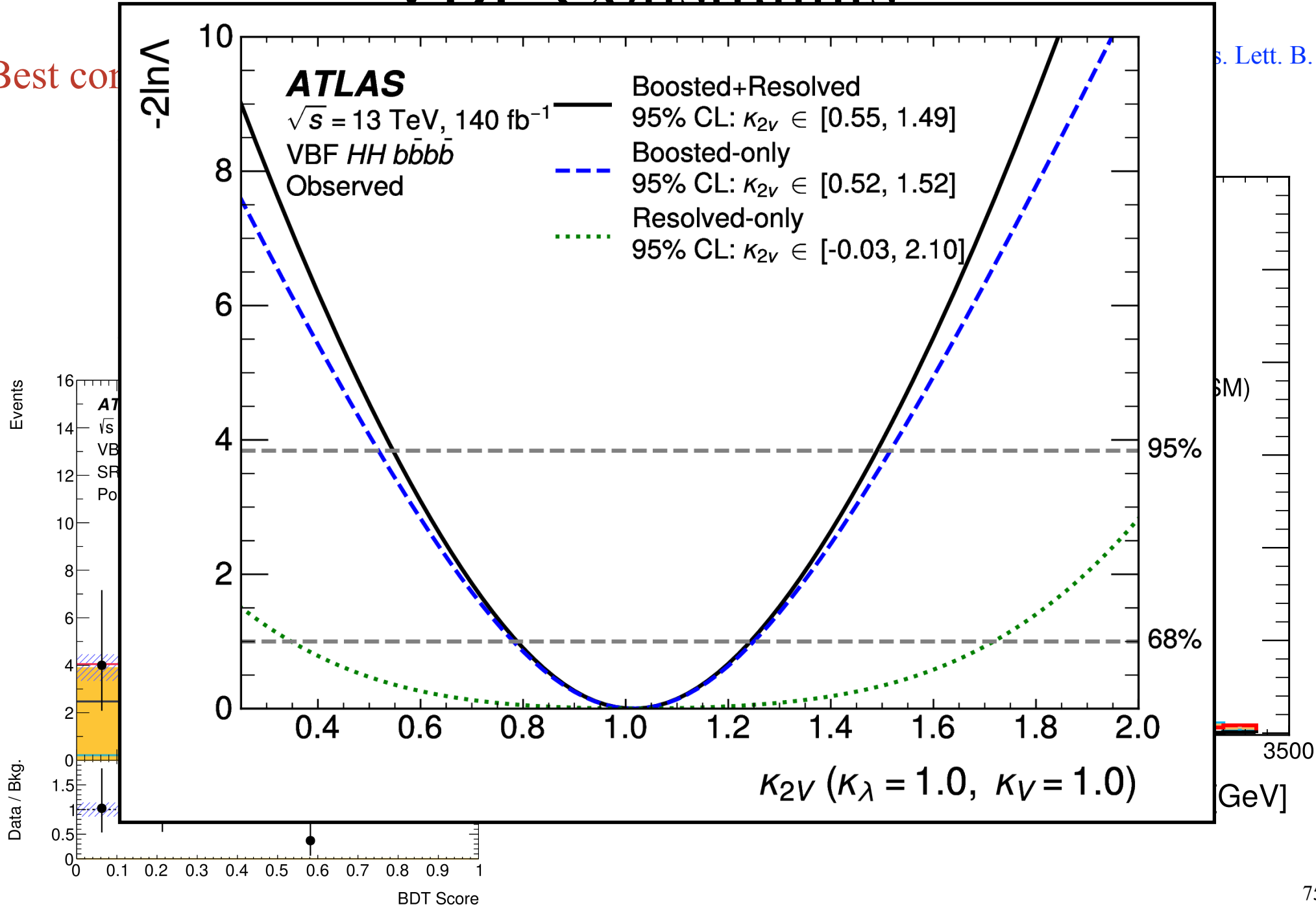
Best constraints on  $\kappa_{2V}$  from VBF  $HH \rightarrow 4b$



# VBF Constraints

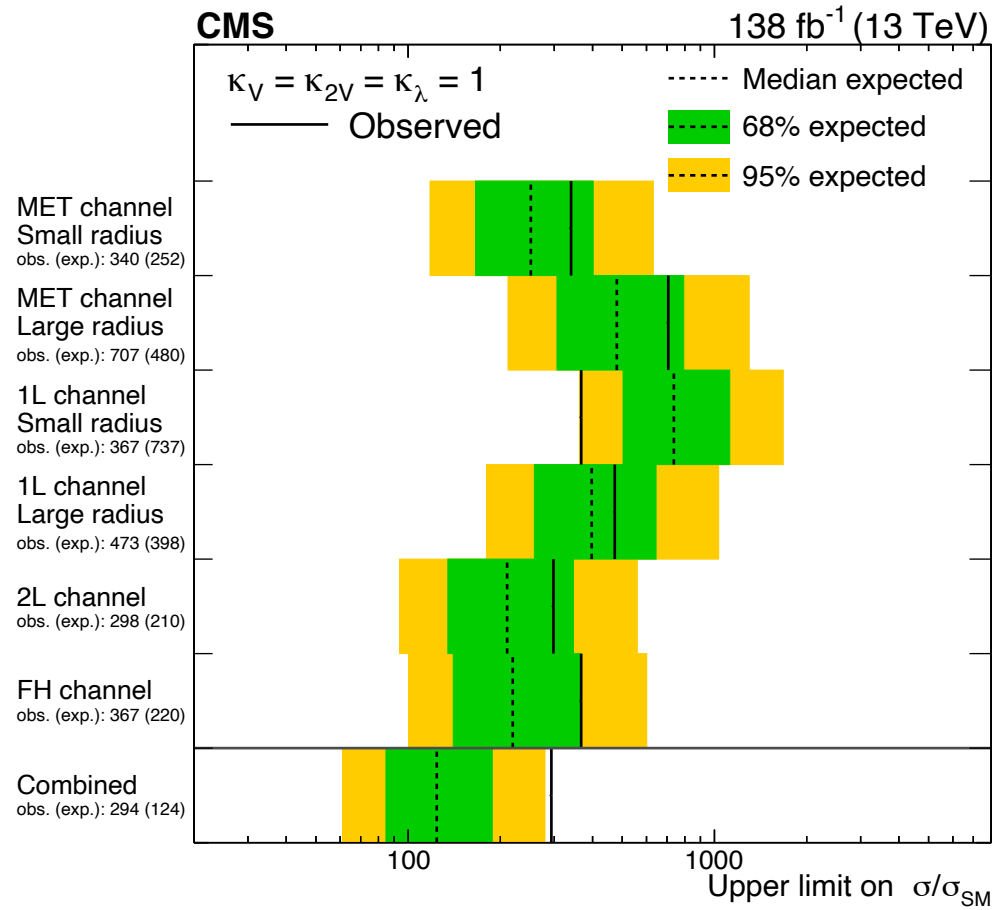
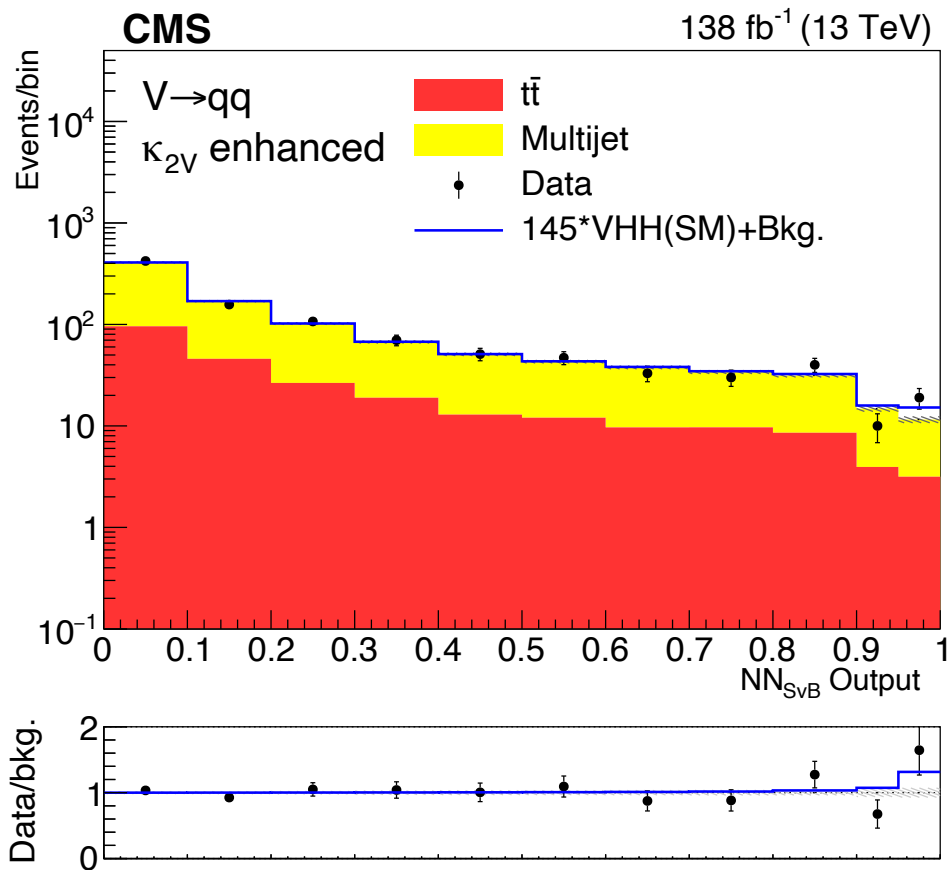
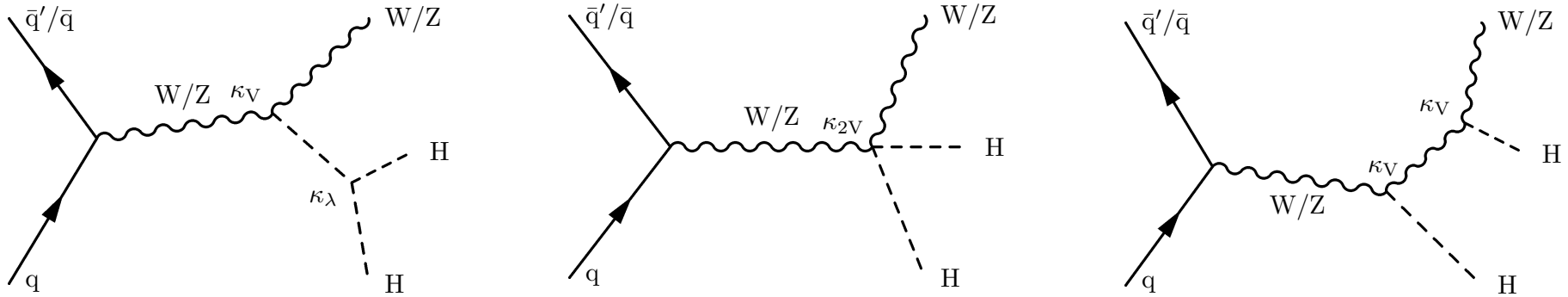
Best con

s. Lett. B.

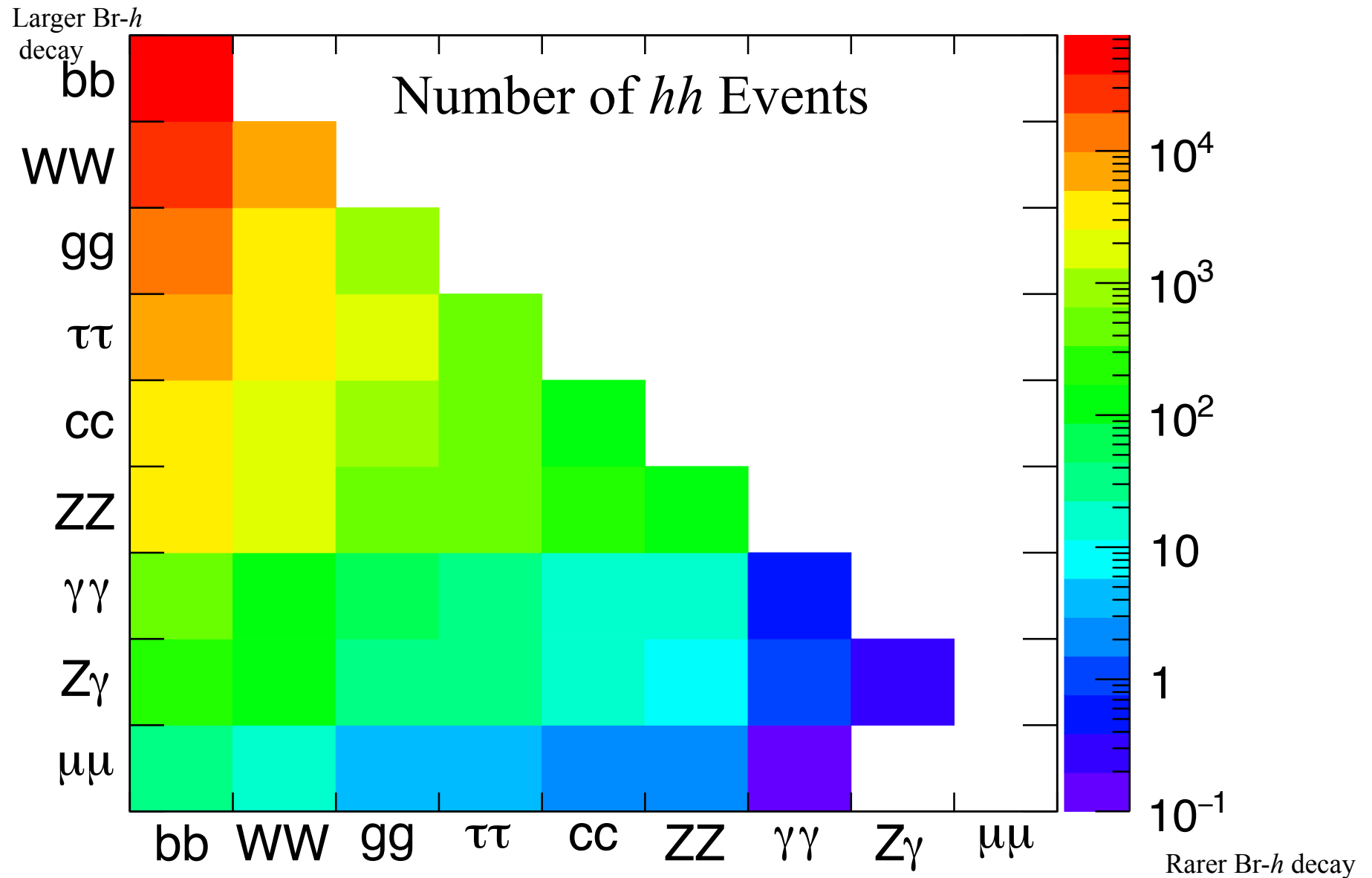


# VHH $\rightarrow$ 4b

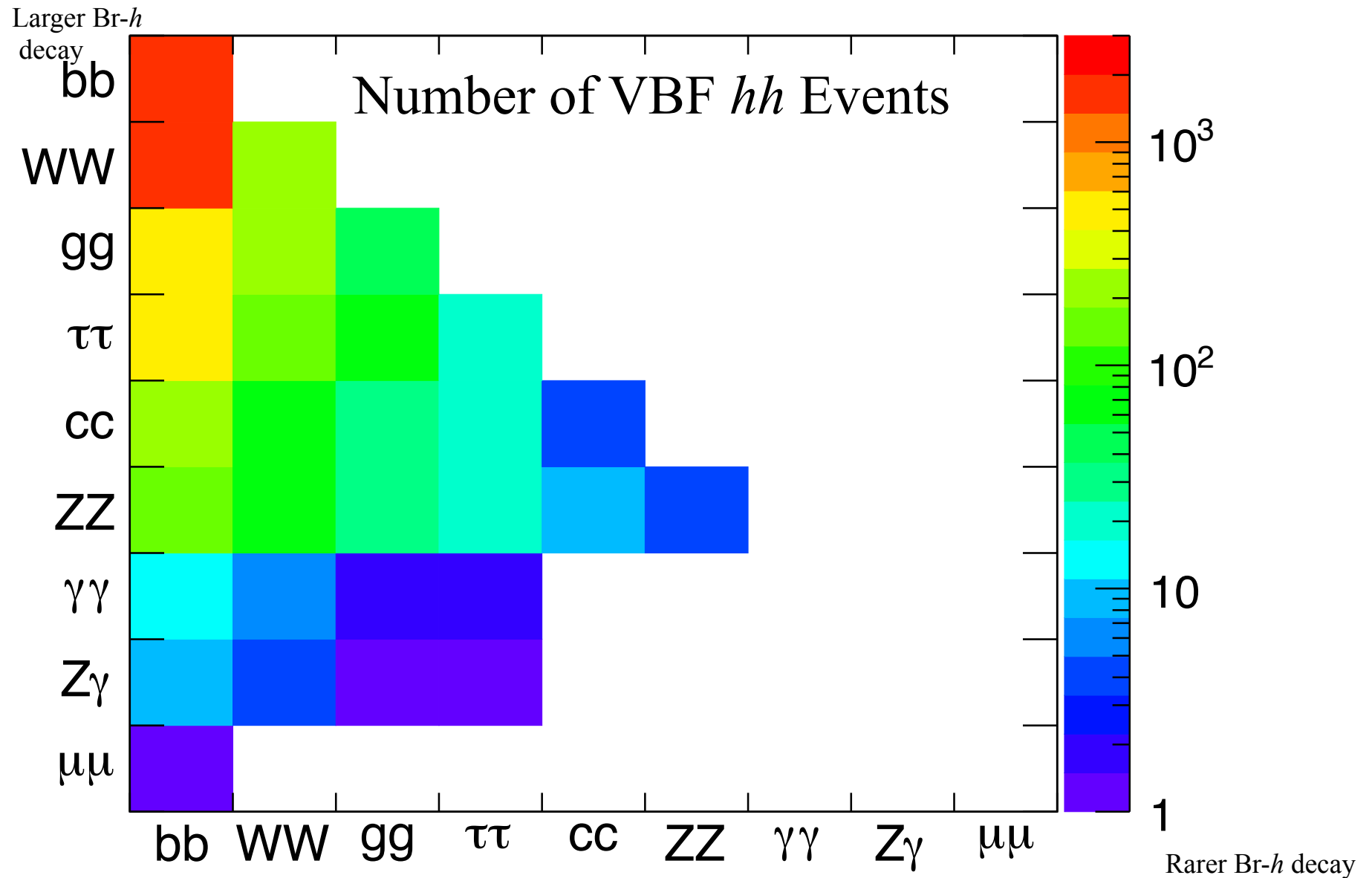
Submitted to JHEP



# Event Yields ( $\mathcal{L} = 3000 \text{ fb}^{-1}$ )<sup>1</sup>



# Event Yields ( $\mathcal{L} = 3000 \text{ fb}^{-1}$ )<sup>1</sup>



# Event Yields ( $\mathcal{L} = 3000 \text{ fb}^{-1}$ )<sup>1</sup>

