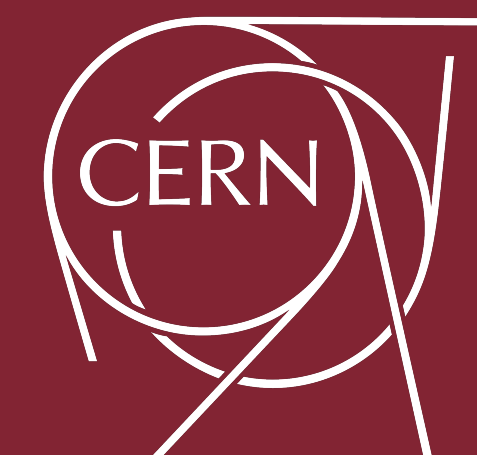
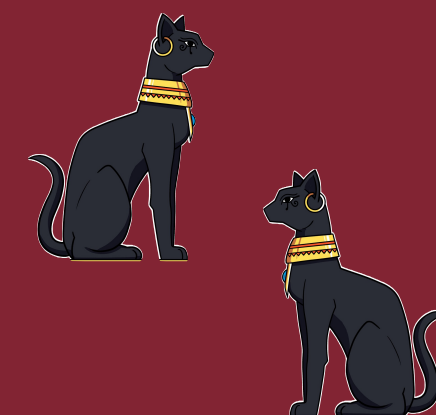




Higgs self-coupling and HH measurements ATLAS

Lorenzo Santi
on behalf of ATLAS
l.santi@cern.ch

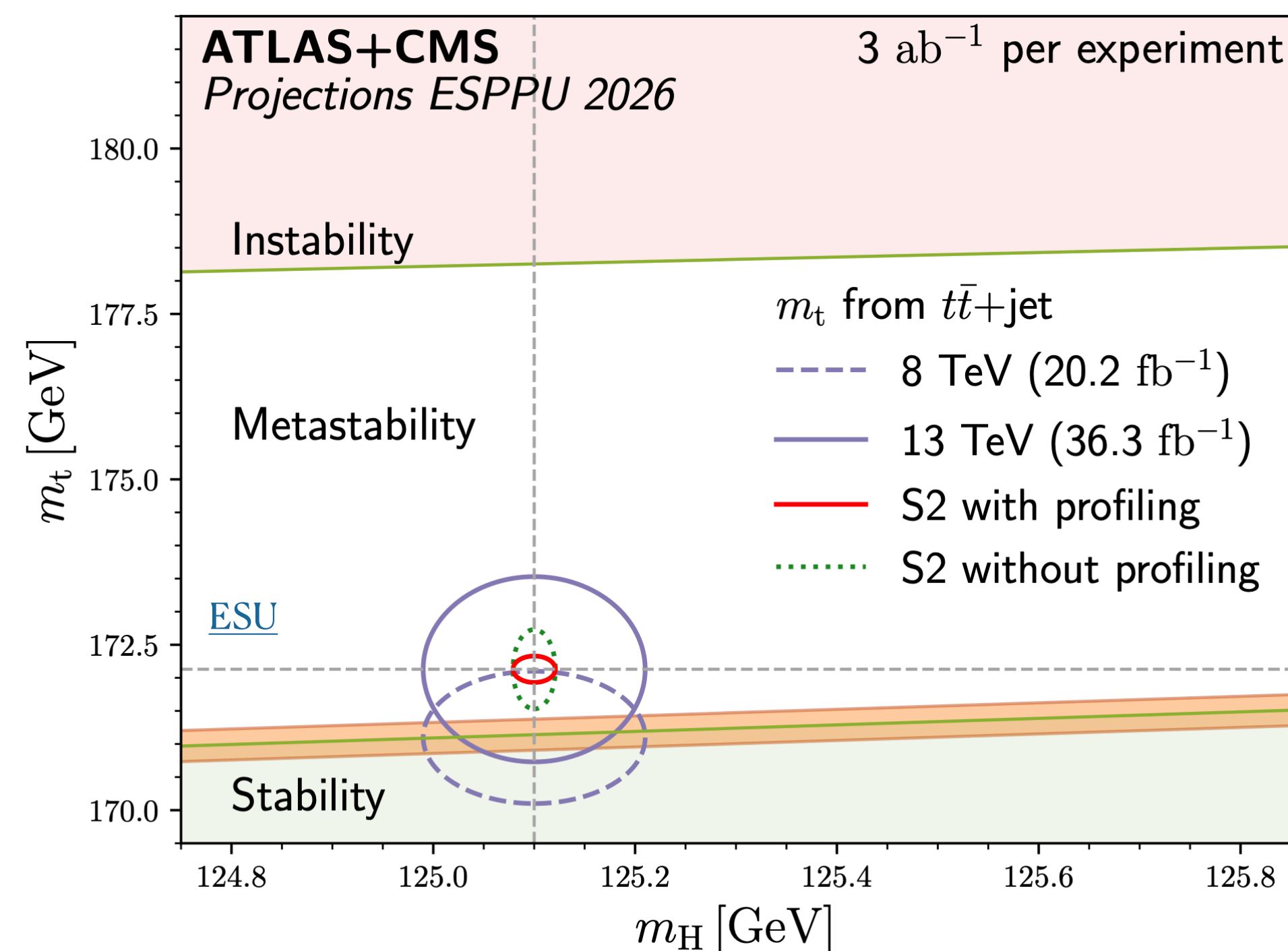
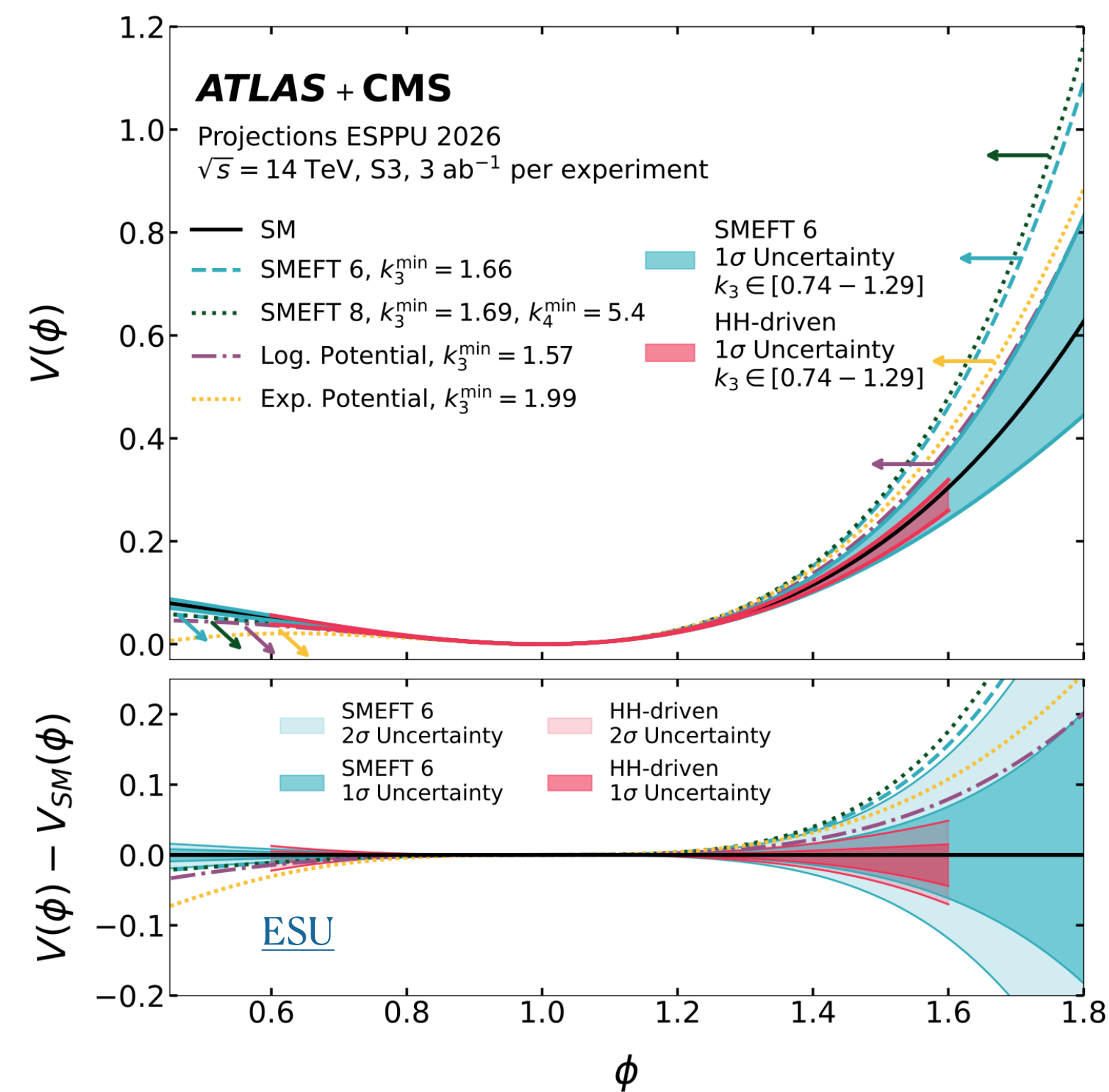
Higgs Hunting 2025
15/07/2025
Paris



Introduction

Direct evidence of Higgs self-coupling (λ) remains one of the major **missing pieces** of Standard Model

Huge implications on the **Higgs potential shape**: EW stability, Phase Transition, Baryogenesis etc.



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

$$\xrightarrow[\phi \rightarrow H + v]{\text{SSB}}$$

$$V(H) = \frac{m_H^2}{2} H^2 + \lambda v H^3 + \frac{\lambda H^4}{4}$$

Introduction

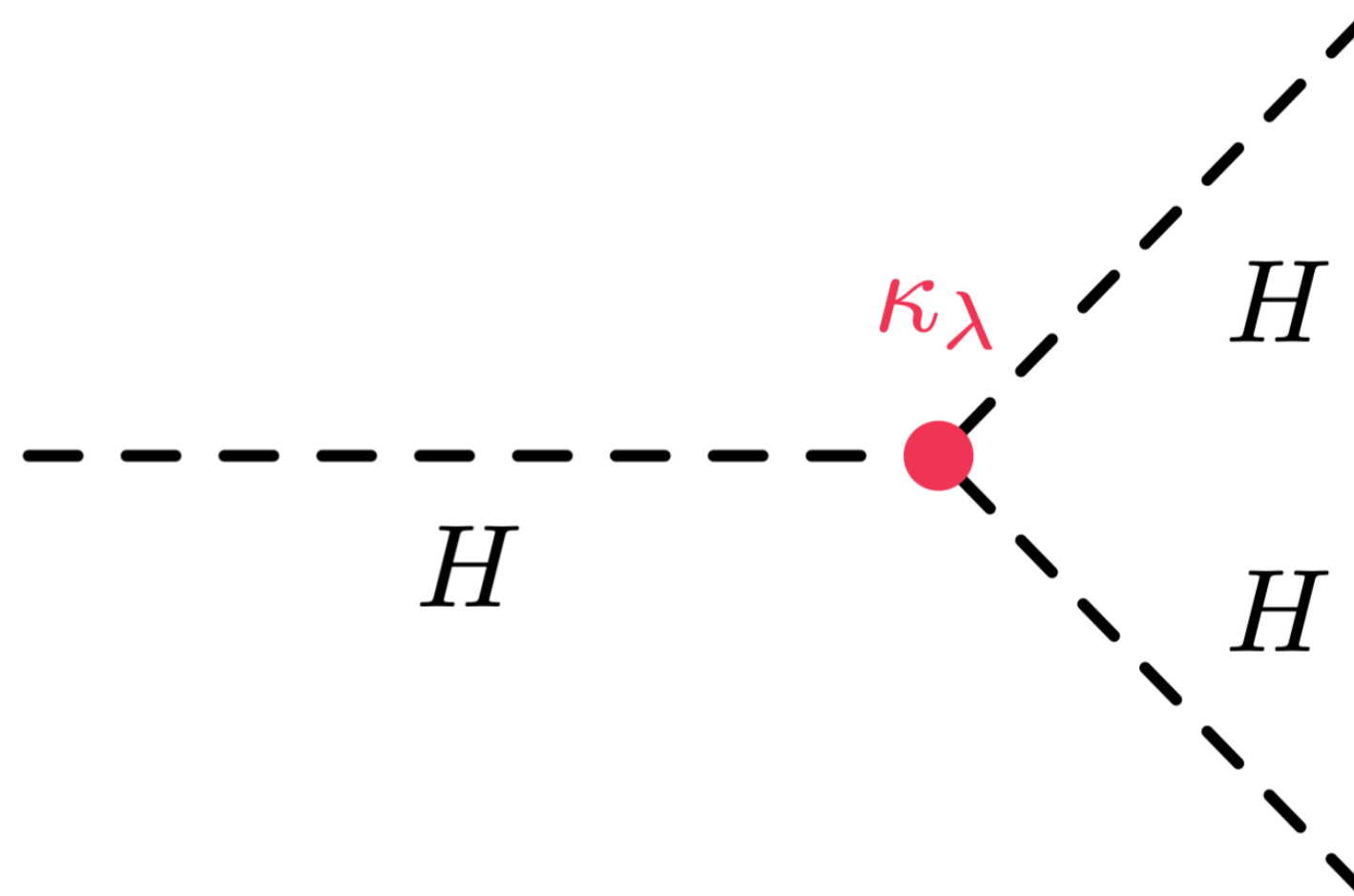
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Results are provided in **upper limits on the signal-strength** μ_{HH}

Or in the κ -framework where we aim to measure $\kappa_\lambda = \lambda/\lambda_{SM}$



Introduction

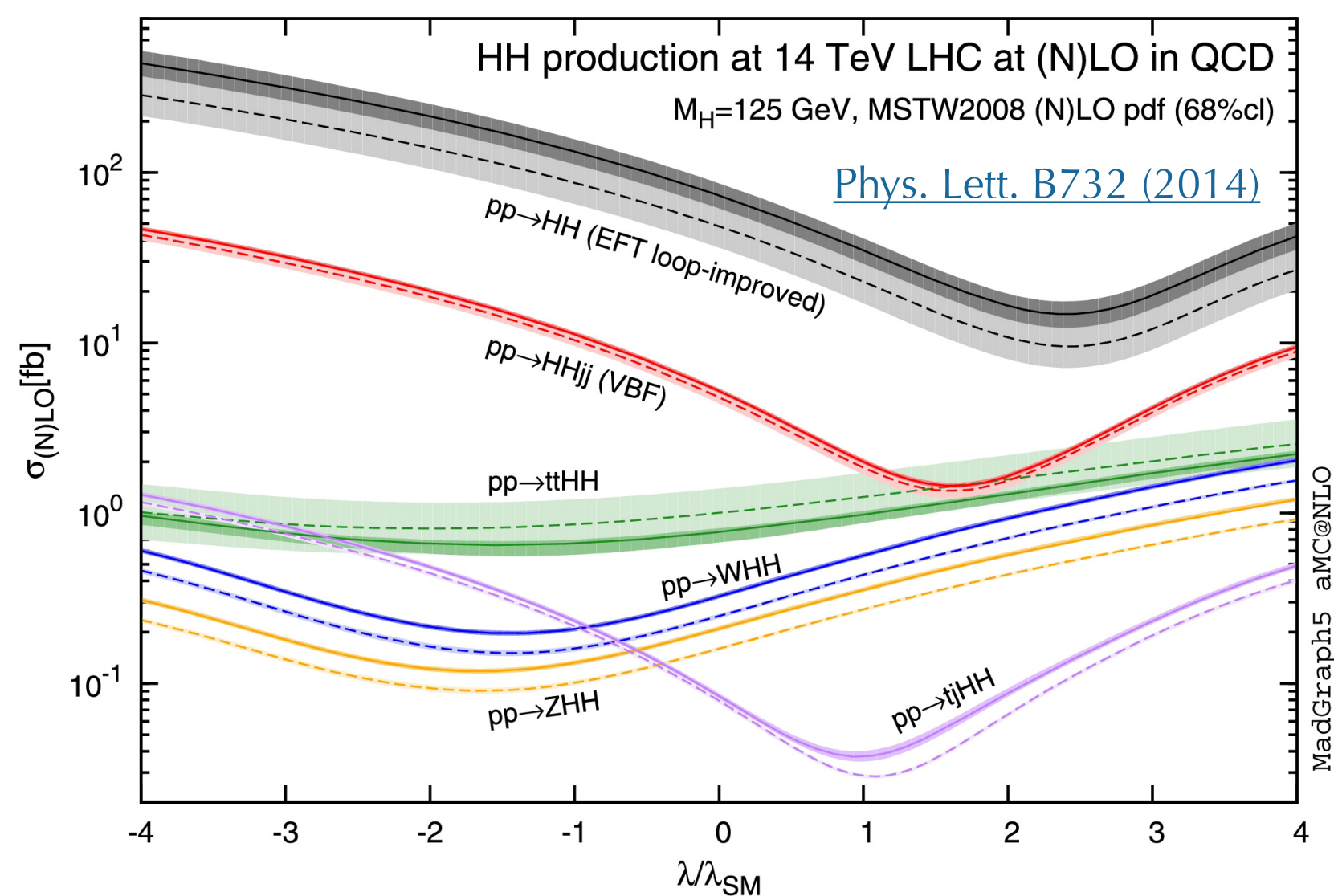
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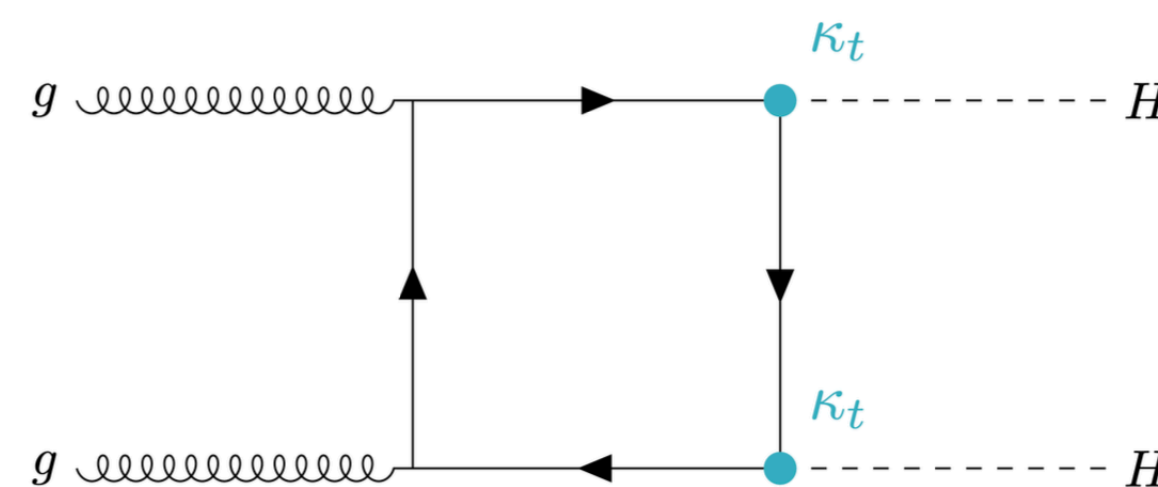
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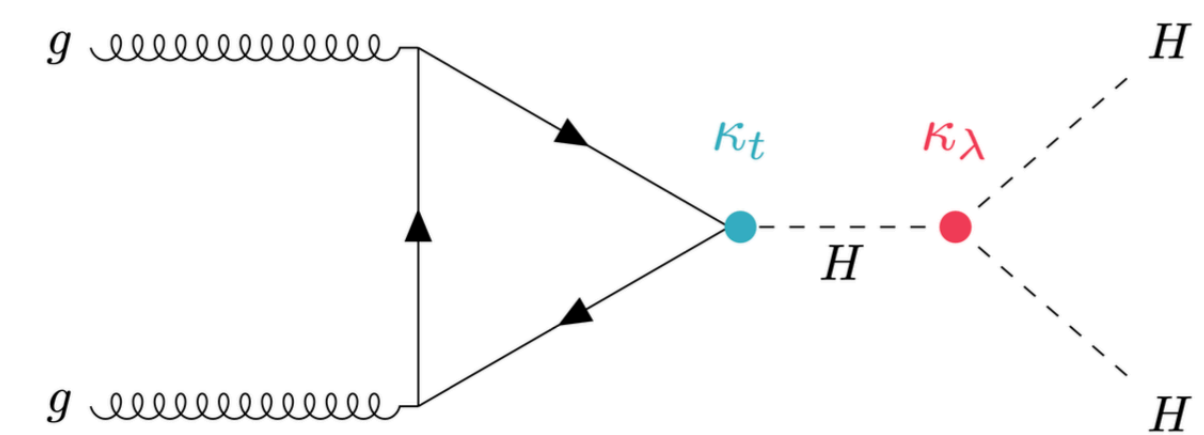


gluon-gluon Fusion (ggF) leading production mode @ LHC

$$\sigma_{ggF}^{SM}(SM) = 30.8_{-7.1}^{+2.0} fb @ 13 TeV$$



(a) Box Diagram



(b) Triangle Diagram

Introduction

$$V(H) = \frac{m_H^2}{2}H^2 + \lambda v H^3 + \frac{\lambda H^4}{4}$$

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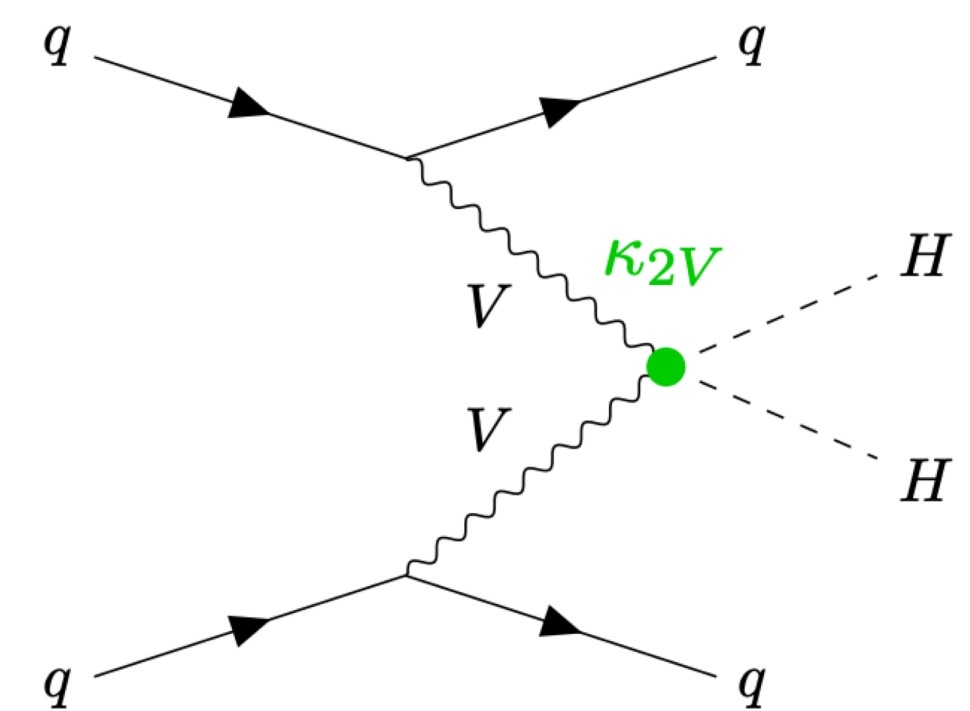
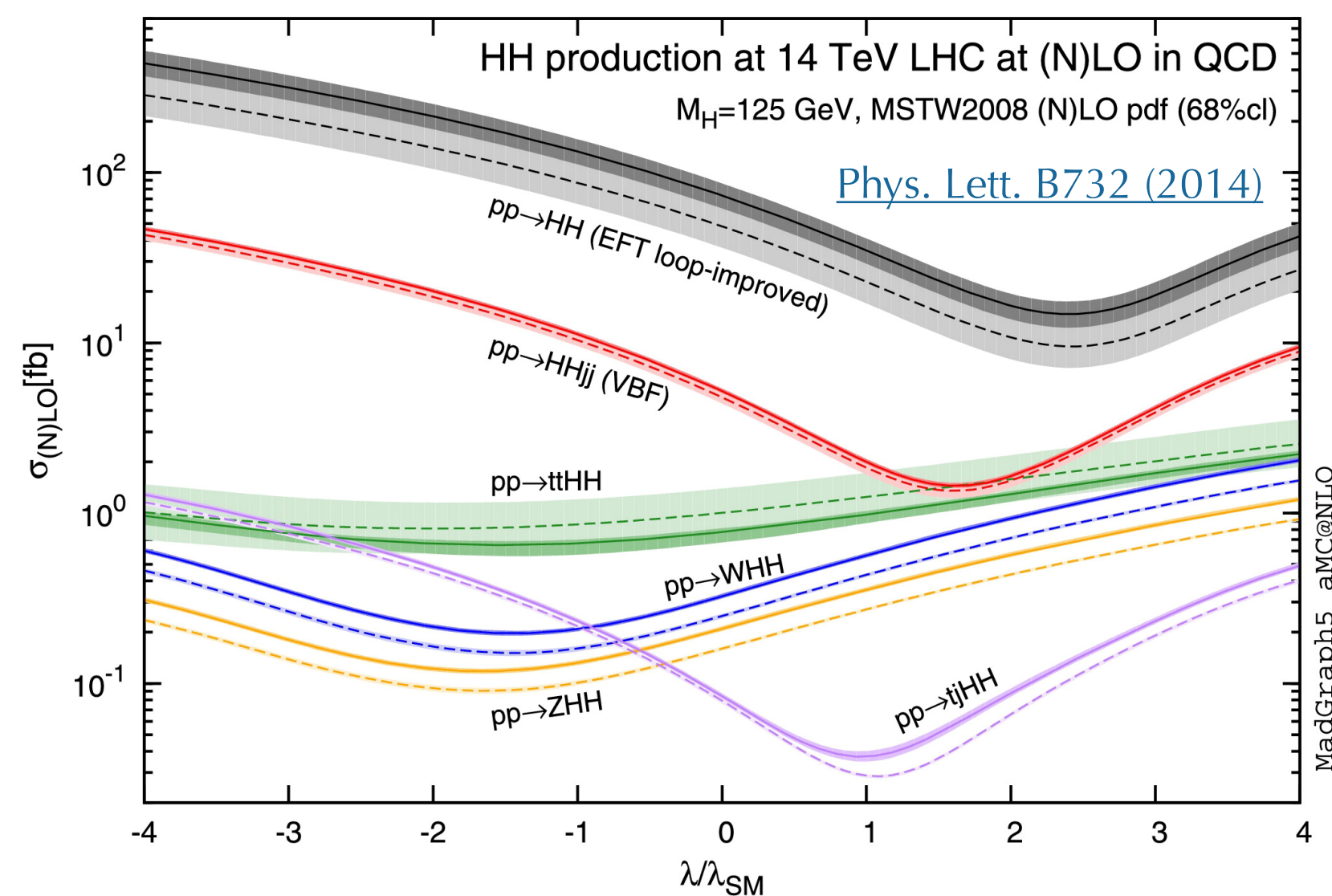
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Results are provided in **upper limits on the signal-strength** μ_{HH}

Or in the κ -framework where we aim to measure $\kappa_\lambda = \lambda/\lambda_{SM}$

Vector Boson Fusion (VBF) second production mode @ LHC

- $\sigma_{VBF}^{SM}(SM) = 1.69 \pm 0.05 \text{ fb @ 13 TeV}$
- sensitive to the $\kappa_{2V} = g_{VVHH}/g_{VVHH}^{SM}$



HH Decay Channels

Several decay channels are combined together to maximize the sensitivity!

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

HH Decay Channels

Several decay channels are combined together to maximize the sensitivity!

Main channels discussed today:

- $HH(b\bar{b}b\bar{b})$

Pros: Very large Branching Ratio (34%)

Cons: overwhelming QCD background

	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%

HH Decay Channels

Several decay channels are combined together to maximize the sensitivity!

Main channels discussed today:

- $HH(b\bar{b}b\bar{b})$
- $HH(b\bar{b}\tau^+\tau^-)$

Pros: Good compromise between Branching Ratio (7.3%) and background

Cons: Complex object reconstruction and modelling

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
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Several decay channels are combined together to maximize the sensitivity!

Main channels discussed today:

- $HH(b\bar{b}b\bar{b})$
- $HH(b\bar{b}\tau^+\tau^-)$
- $HH(b\bar{b}\gamma\gamma)$

Pros: Very clean signature to trigger

Cons: Extremely small BR (0.26%)

	bb	WW	$\tau\tau$	ZZ	$\Upsilon\Upsilon$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
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HH Decay Channels

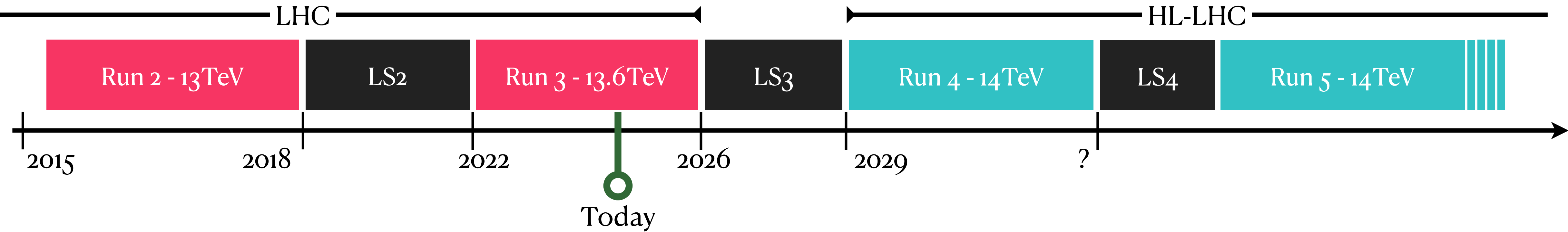
Several decay channels are combined together to maximize the sensitivity!

In the combination we also include channels with smaller sensitivity:

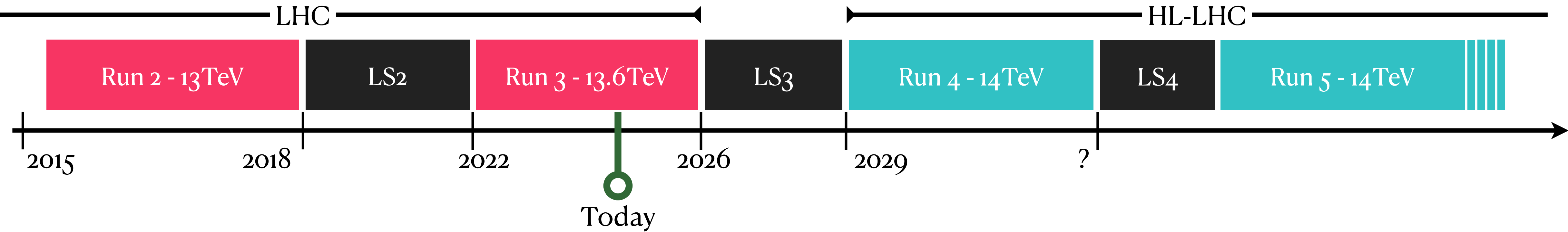
- $b\bar{b}ll + E_T^{miss}$
- Multilepton

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

Outline

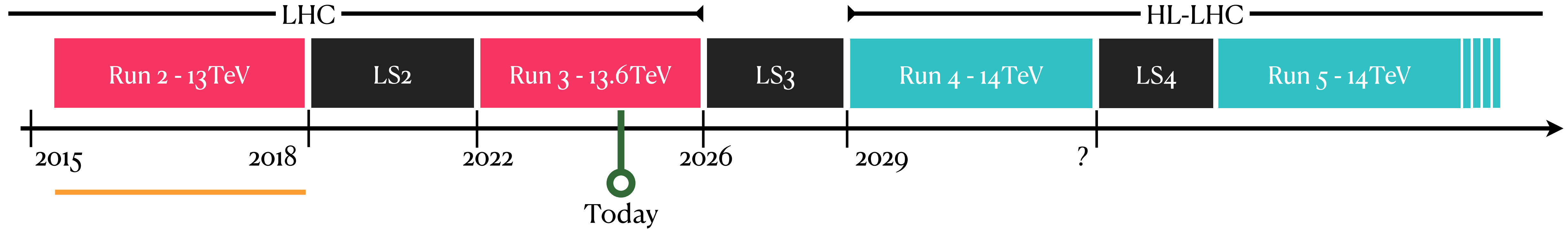


Outline



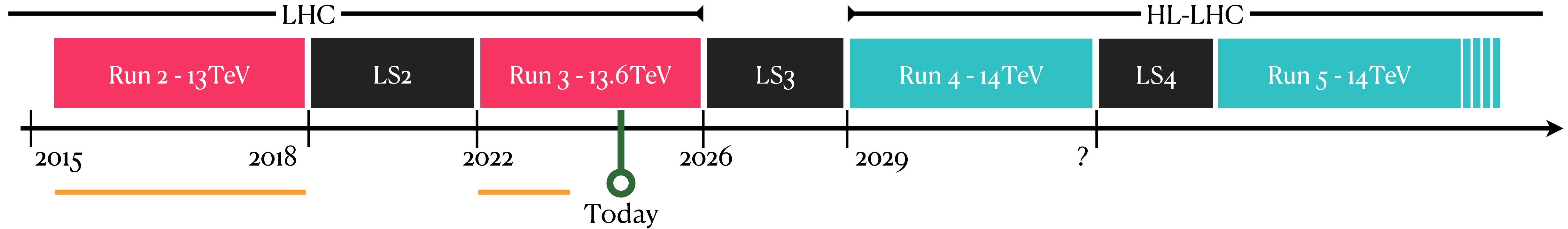
Note: I will present only a sub-set of all the results!

ATLAS HH analyses



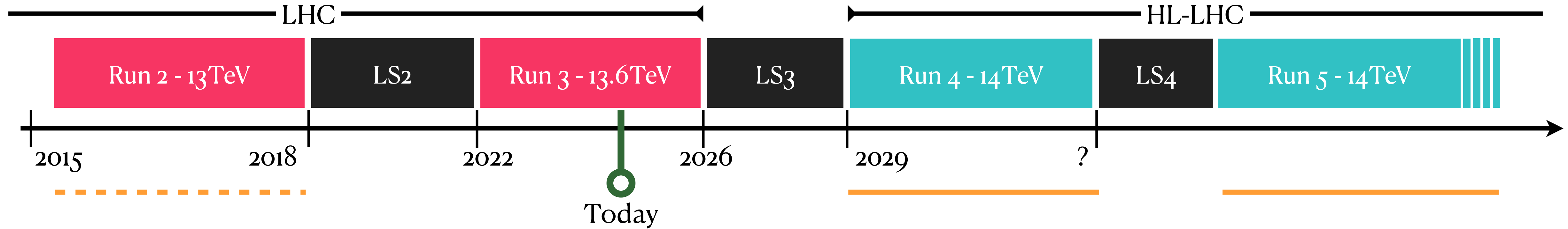
- **Run 2 analyses** and their combination with 140 fb^{-1} collected data
 - HH Combination: [Phys. Rev. Lett. 133 \(2024\) 101801](#)
 - $\text{HH}(b\bar{b}\tau\tau)$: [Phys. Rev. D 110 \(2024\) 032012](#)
 - $\text{HH}(b\bar{b}\gamma\gamma)$: [JHEP 01 \(2024\) 066](#)
 - $\text{HH}(b\bar{b}b\bar{b})$: [Phys. Rev. D 108 \(2023\) 052003](#) (Resolved), [Phys. Lett. B 858 \(2024\) 139007](#) (Boosted)
 - HH+H ATLAS Combination: [Phys. Lett. B 843 \(2023\) 137745](#)

ATLAS HH analyses



- Run 2 analyses and their combination with 140 fb^{-1} collected data
- **First HH analysis with partial Run 3** data-taking using 308 fb^{-1} data
 - $\text{HH}(b\bar{b}\gamma\gamma)$ Run 2 + partial (22-24) Run 3: [Arxiv:2507.0349](https://arxiv.org/abs/2507.0349)

ATLAS HH analyses



- Run 2 analyses and their combination with 140 fb^{-1} collected data
- First HH analysis with partial Run 3 data-taking using 308 fb^{-1} data
- **Run 2 results extrapolation to HL-LHC** 3000 fb^{-1} from Run 2 results input to [ESU](#):
 - $\text{HH}(b\bar{b}\tau\tau)$: [ATL-PHYS-PUB-2024-016](#)
 - $\text{HH}(b\bar{b}\gamma\gamma)$: [ATL-PHYS-PUB-2025-001](#)
 - $\text{HH}(b\bar{b}b\bar{b})$: [ATL-PHYS-PUB-2022-053](#) (ggF), [ATL-PHYS-PUB-2025-005](#) (VBF)
 - HH Combination: [ATL-PHYS-PUB-2025-006](#)

Run 2 HH Combination

Improvements in the combination:

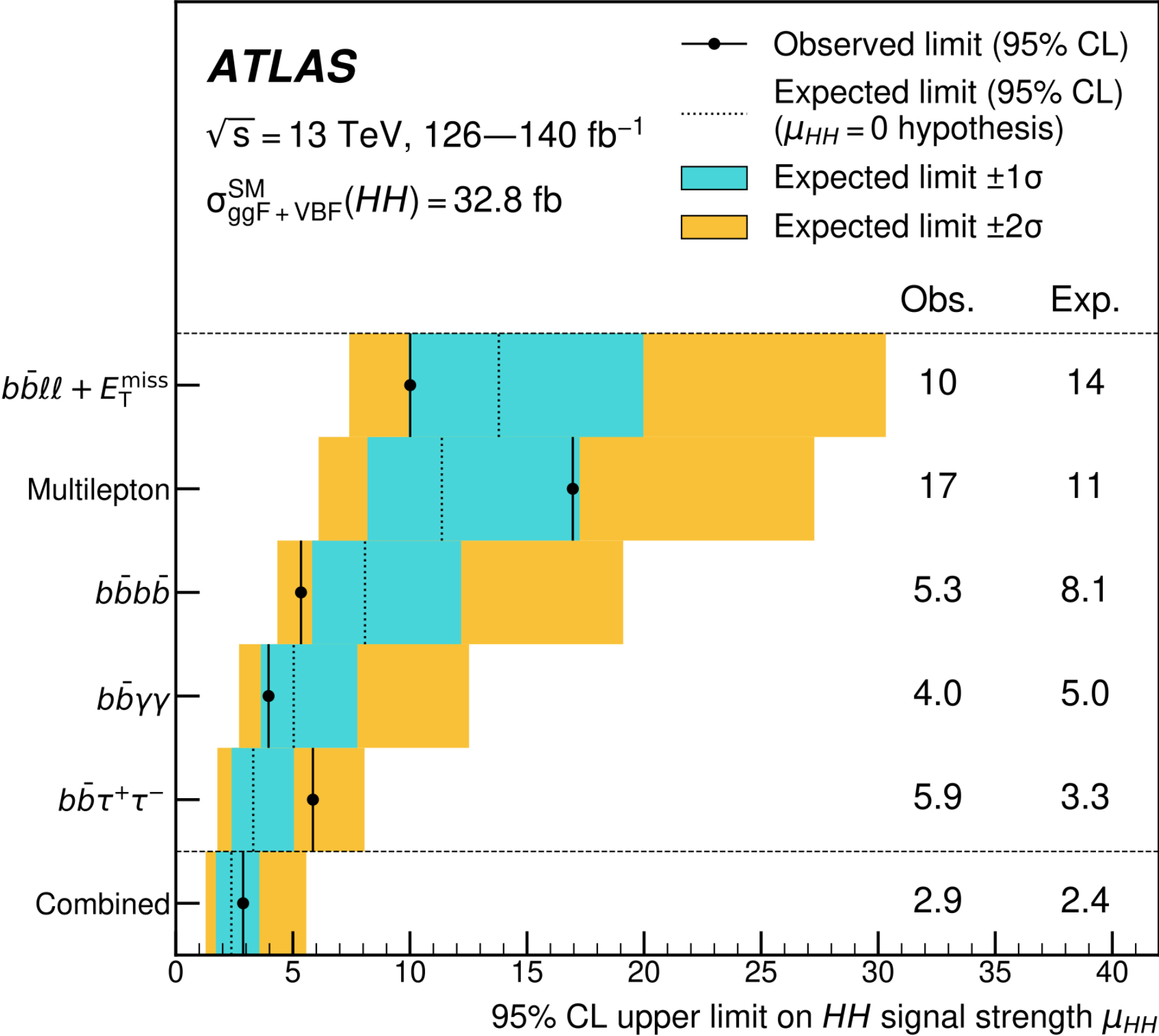
- Reanalysis of Run 2 for $HH(b\bar{b}\tau^+\tau^-)$ and $HH(b\bar{b}\gamma\gamma)$
- New boosted VBF $HH(b\bar{b}b\bar{b})$
- Added extra channels

Observed (Expected) upper limits @ 95% CL

on μ_{HH} : $2.9(2.4) \times SM$

17% improvement wrt previous result:

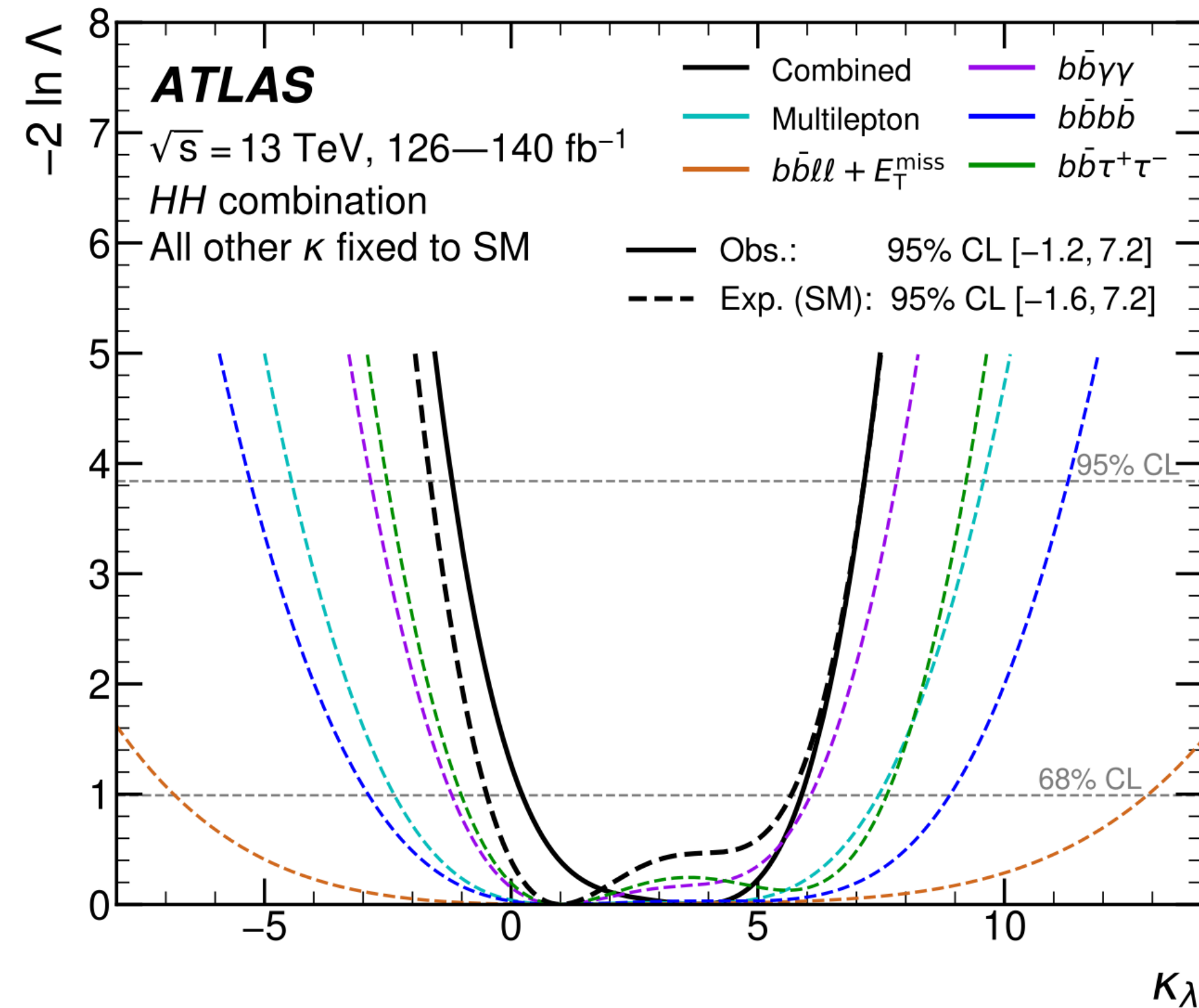
- 13% leading channels
- 4% other channels



Observed HH SM Significance: 0.4σ

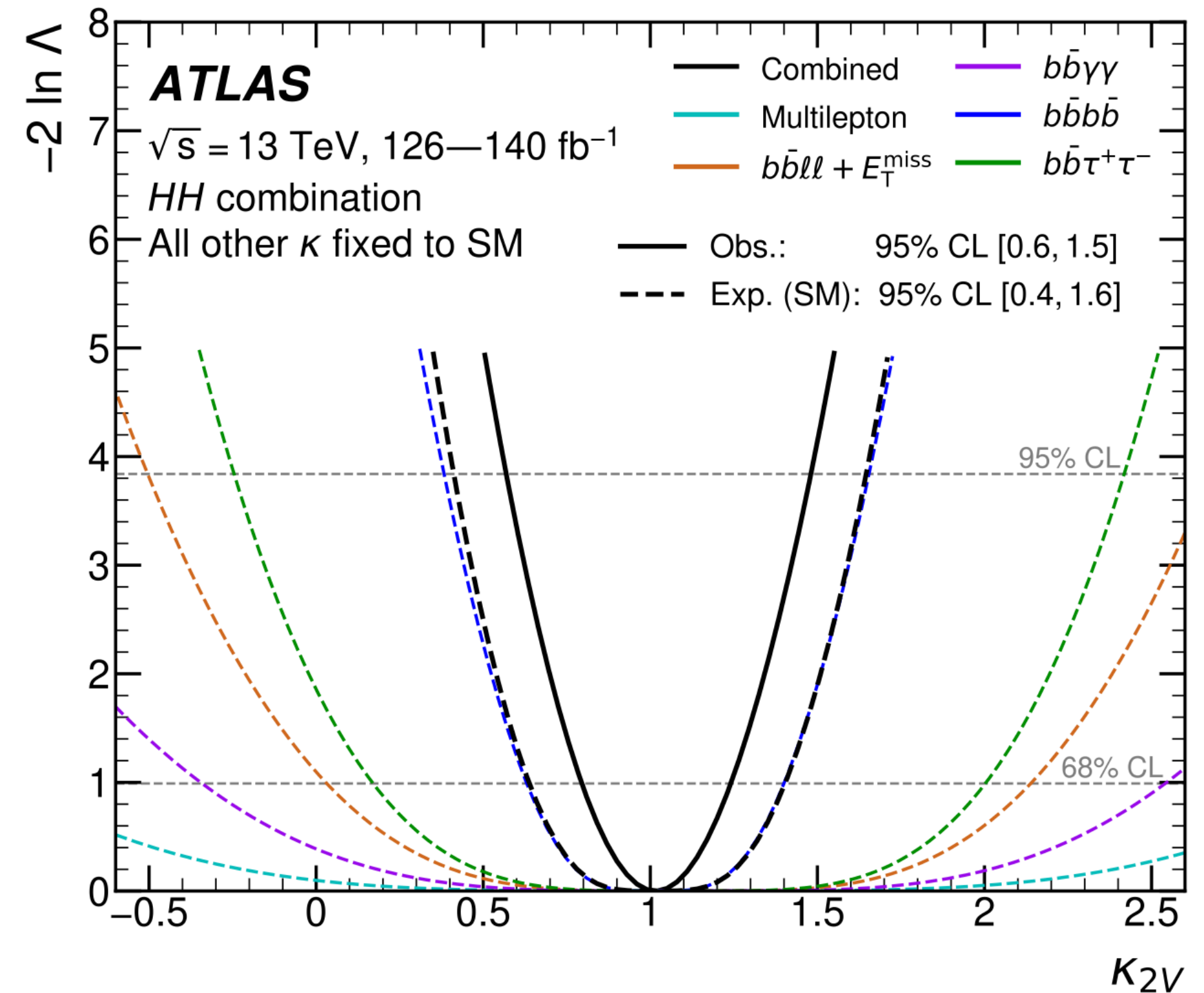
Expected HH SM Significance: 1.0σ

Run 2 HH Combination



Observed (Expected) limits @ 95% CL:

$$\kappa_\lambda \in [-1.2, 7.2]([-1.6, 7.2])$$

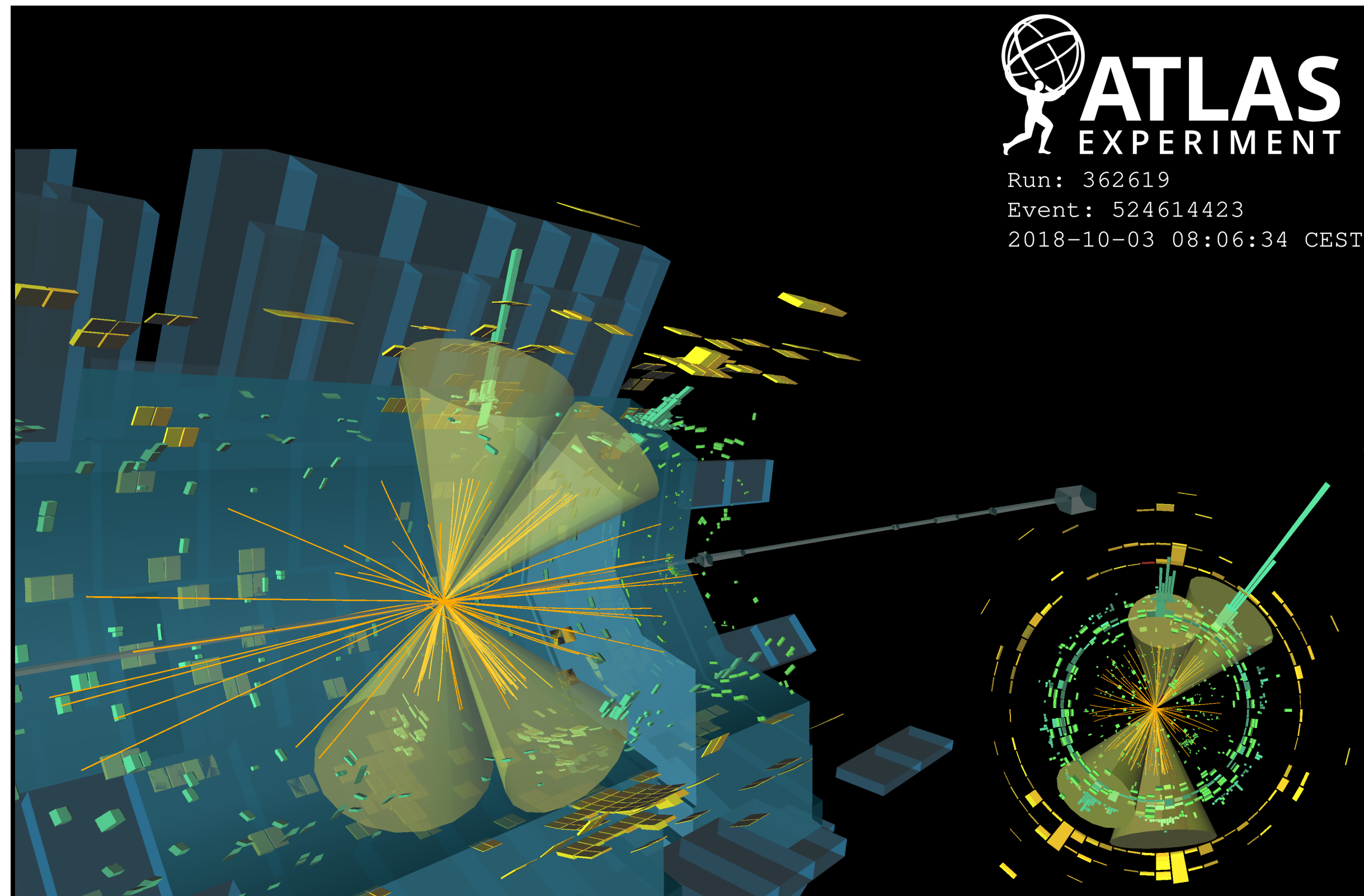


Observed (Expected) limits @ 95% CL:

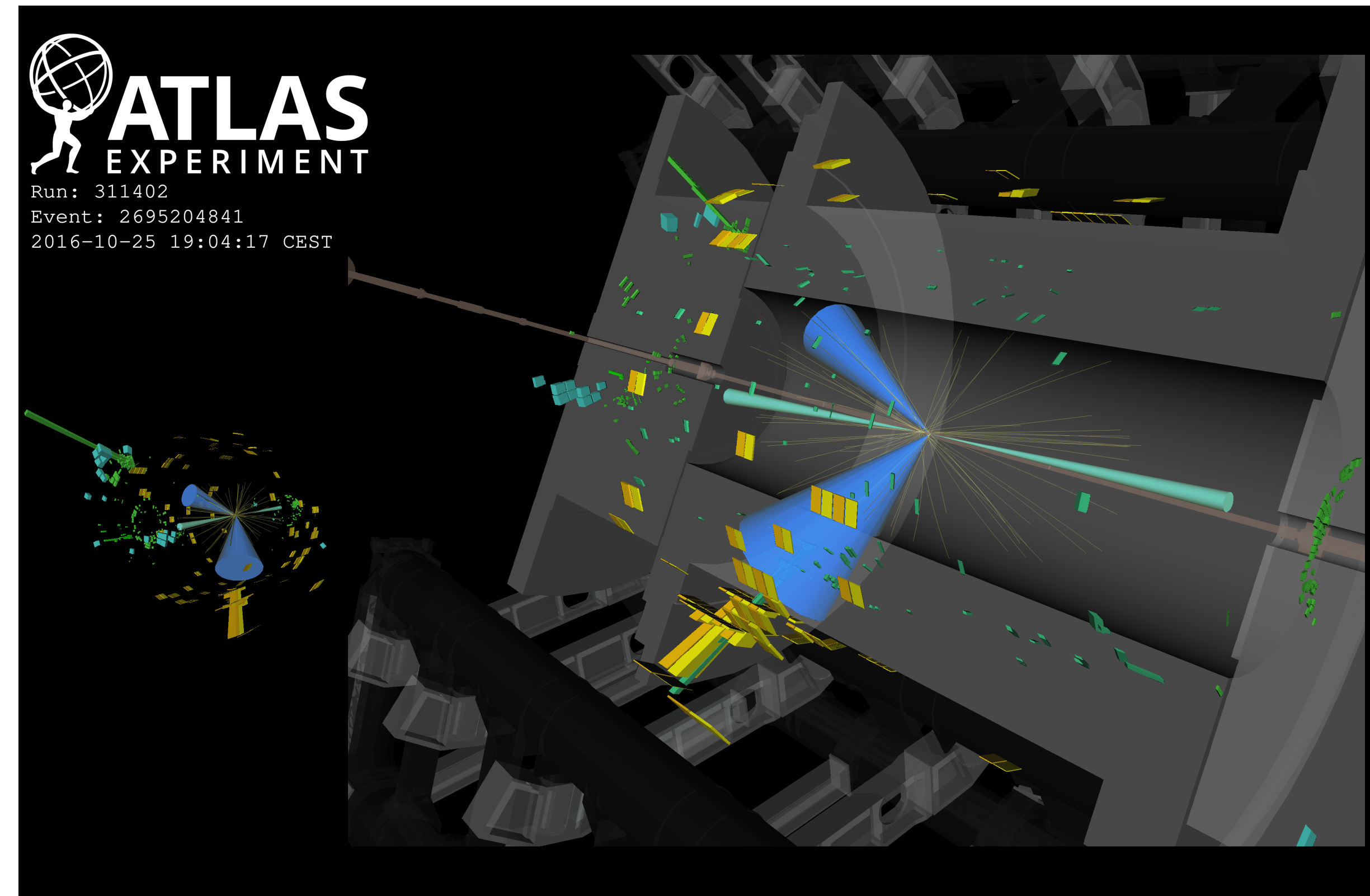
$$\kappa_{2V} \in [0.6, 1.5]([0.4, 1.6])$$

Run 2 HH(bb $\bar{b}\bar{b}$)

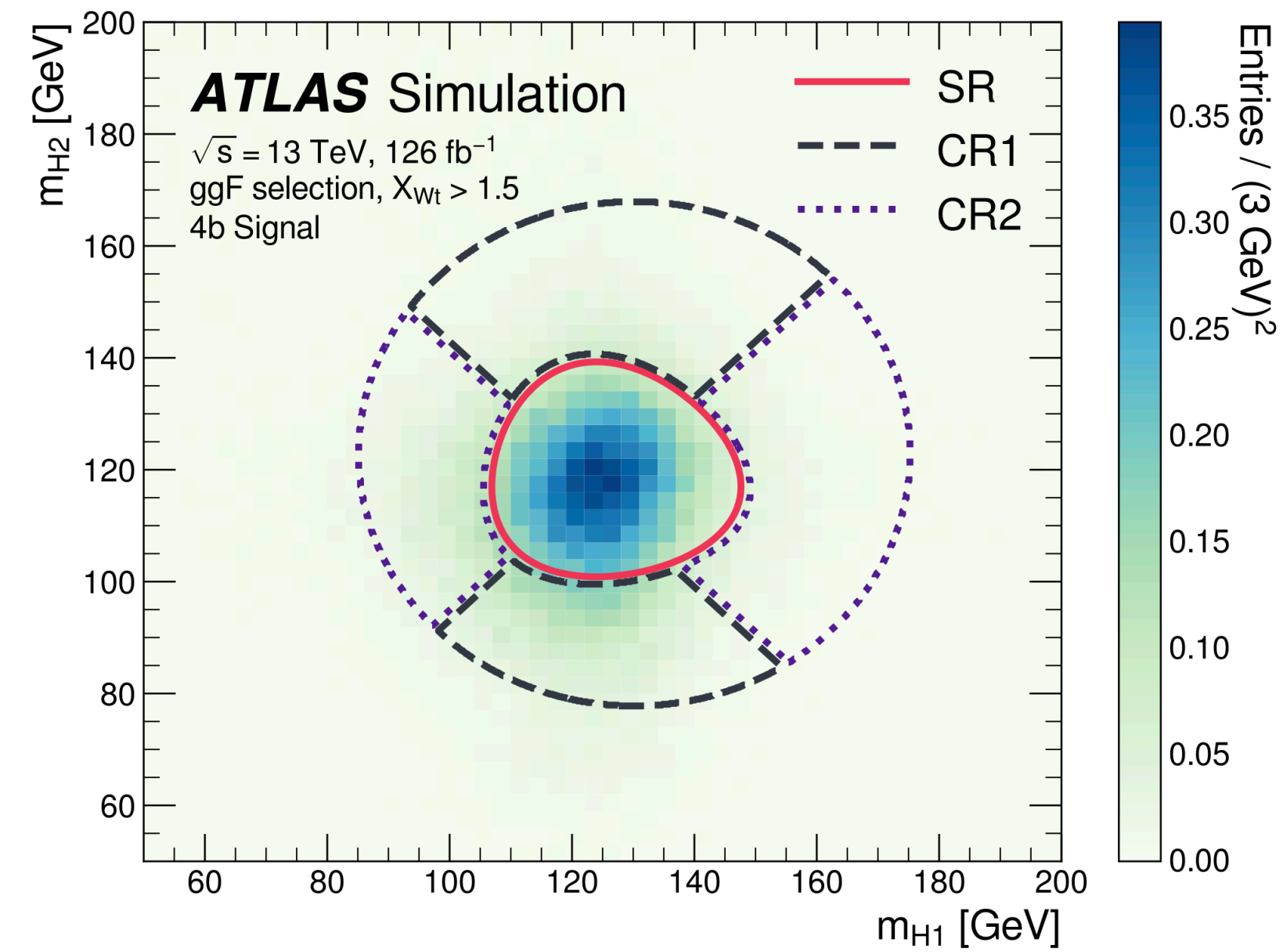
Resolved Topology



VBF Boosted Topology

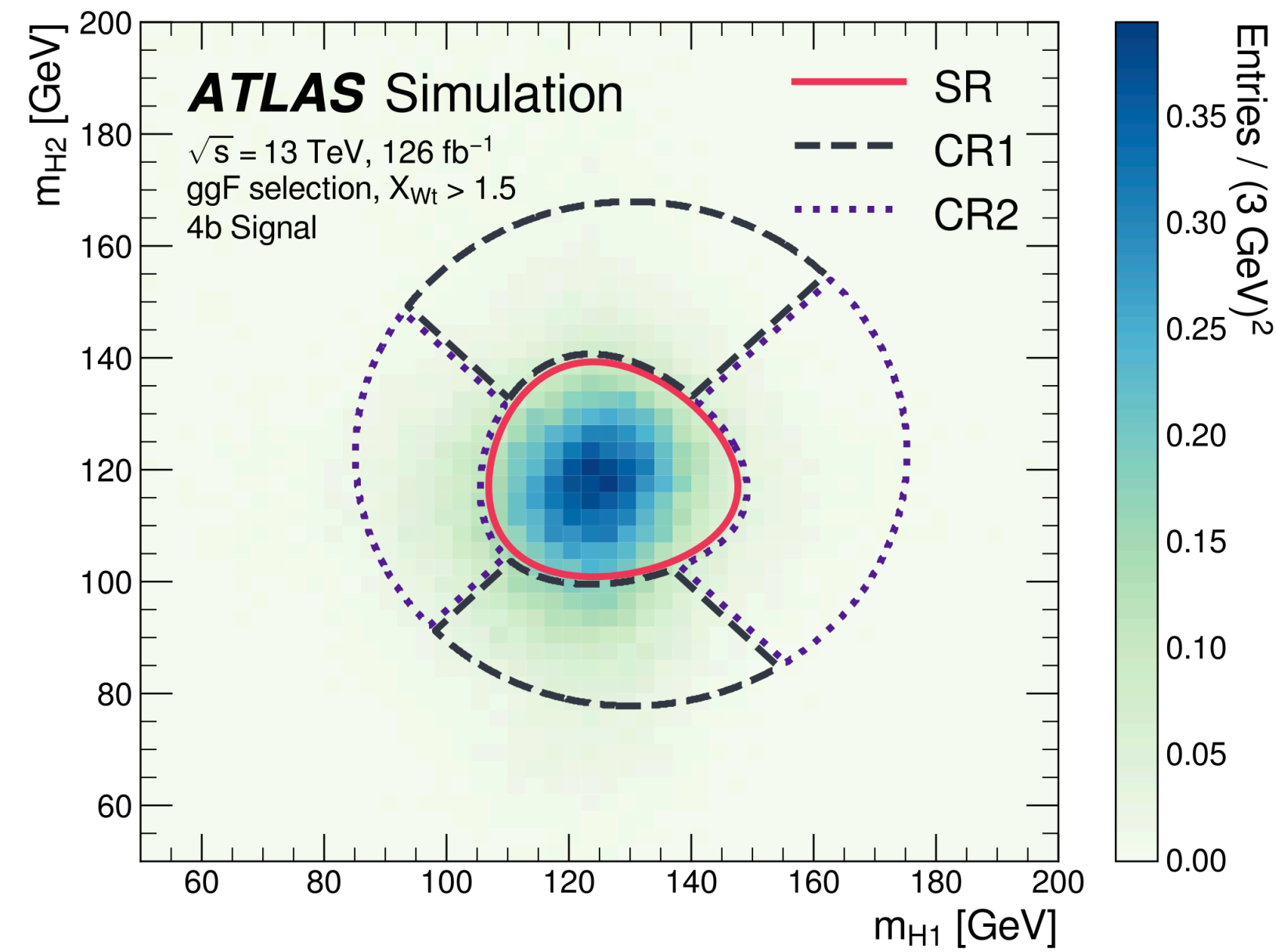


Run 2 HH(bb $\bar{b}\bar{b}$): Resolved

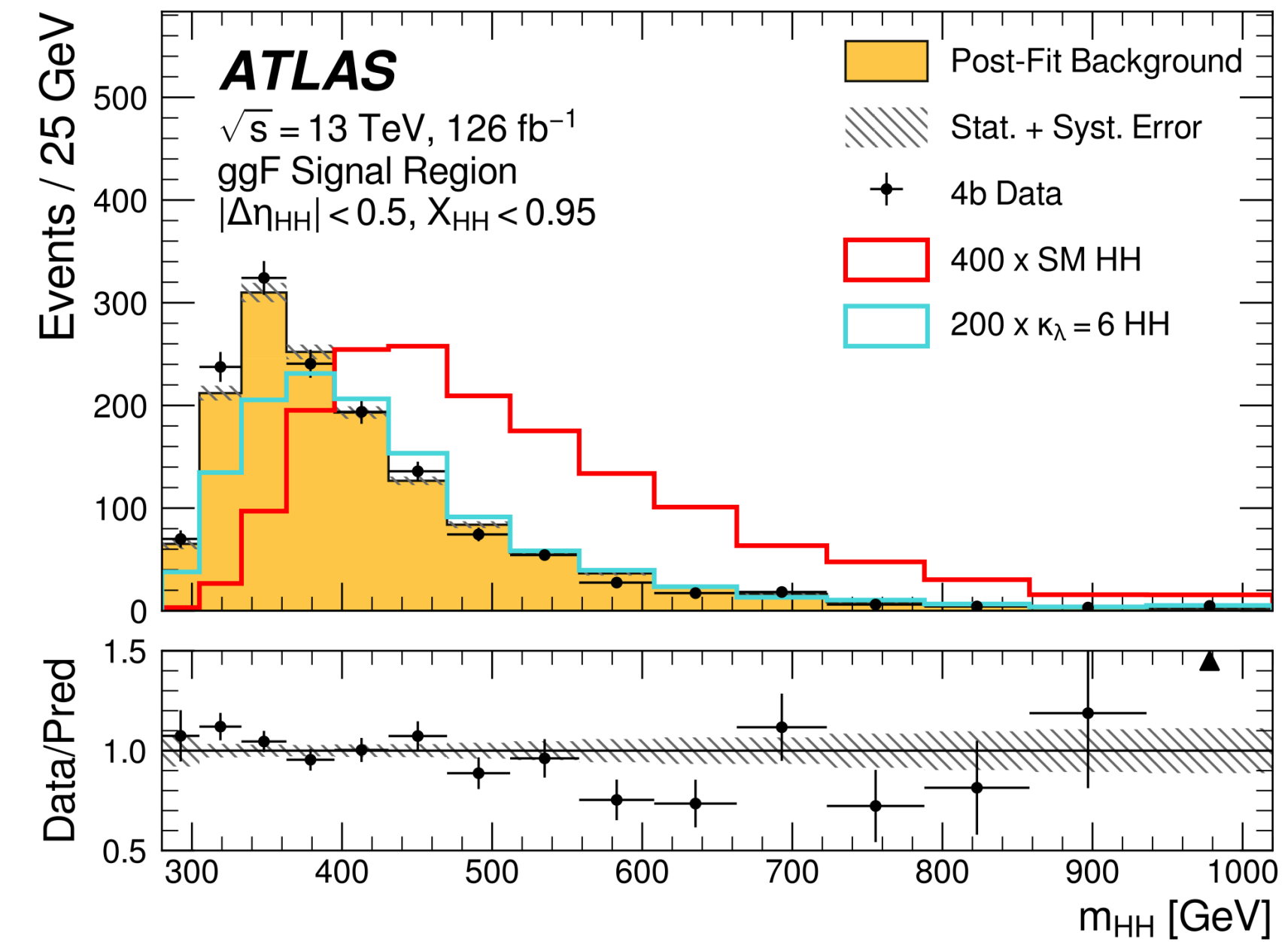


SR and CR defined based on m_H of the pairs
Reweighting CR1 and Interpolation from CR2

Run 2 HH(bb $\bar{b}\bar{b}$): Resolved

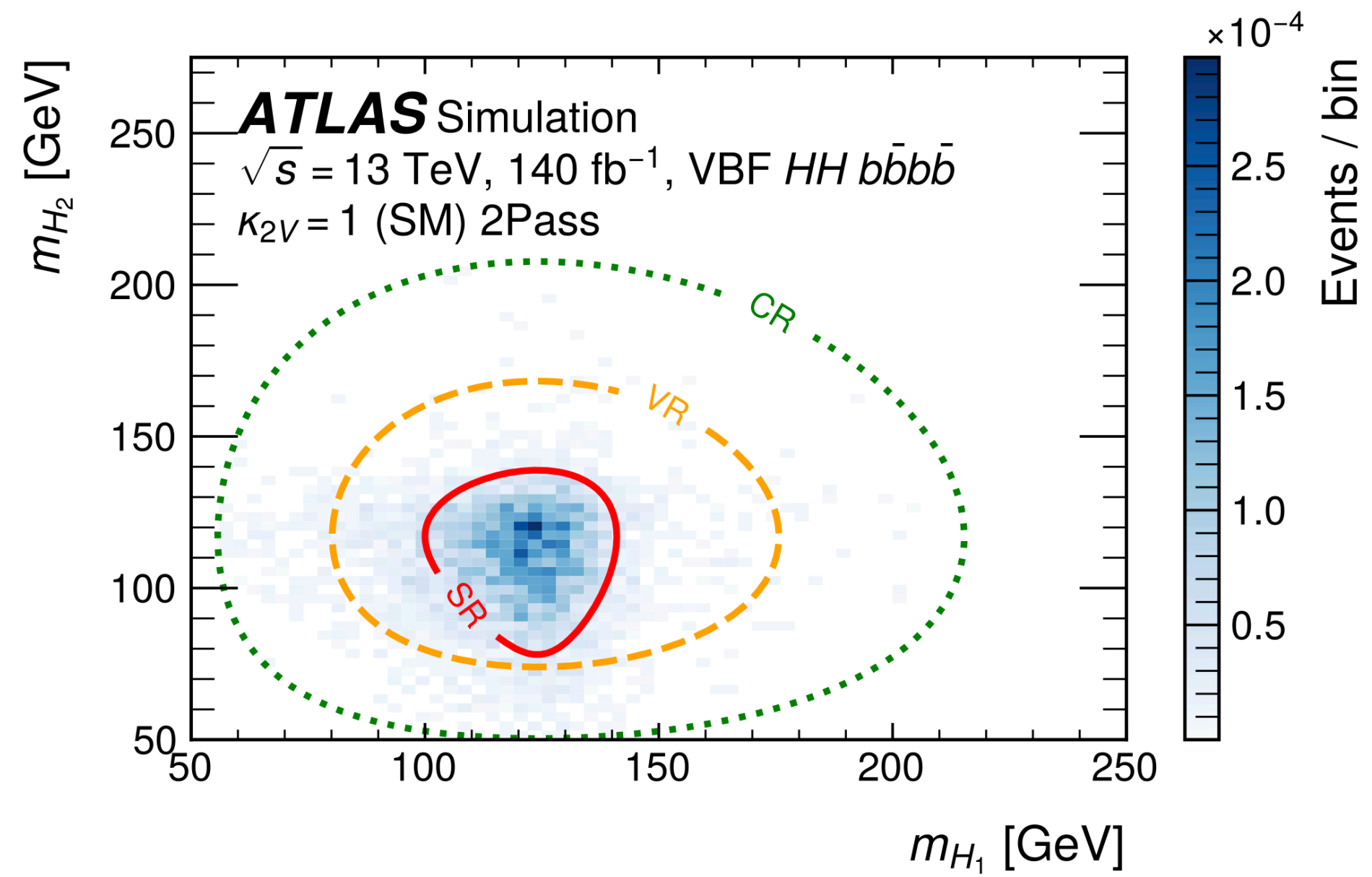


SR and CR defined based on m_H of the pairs
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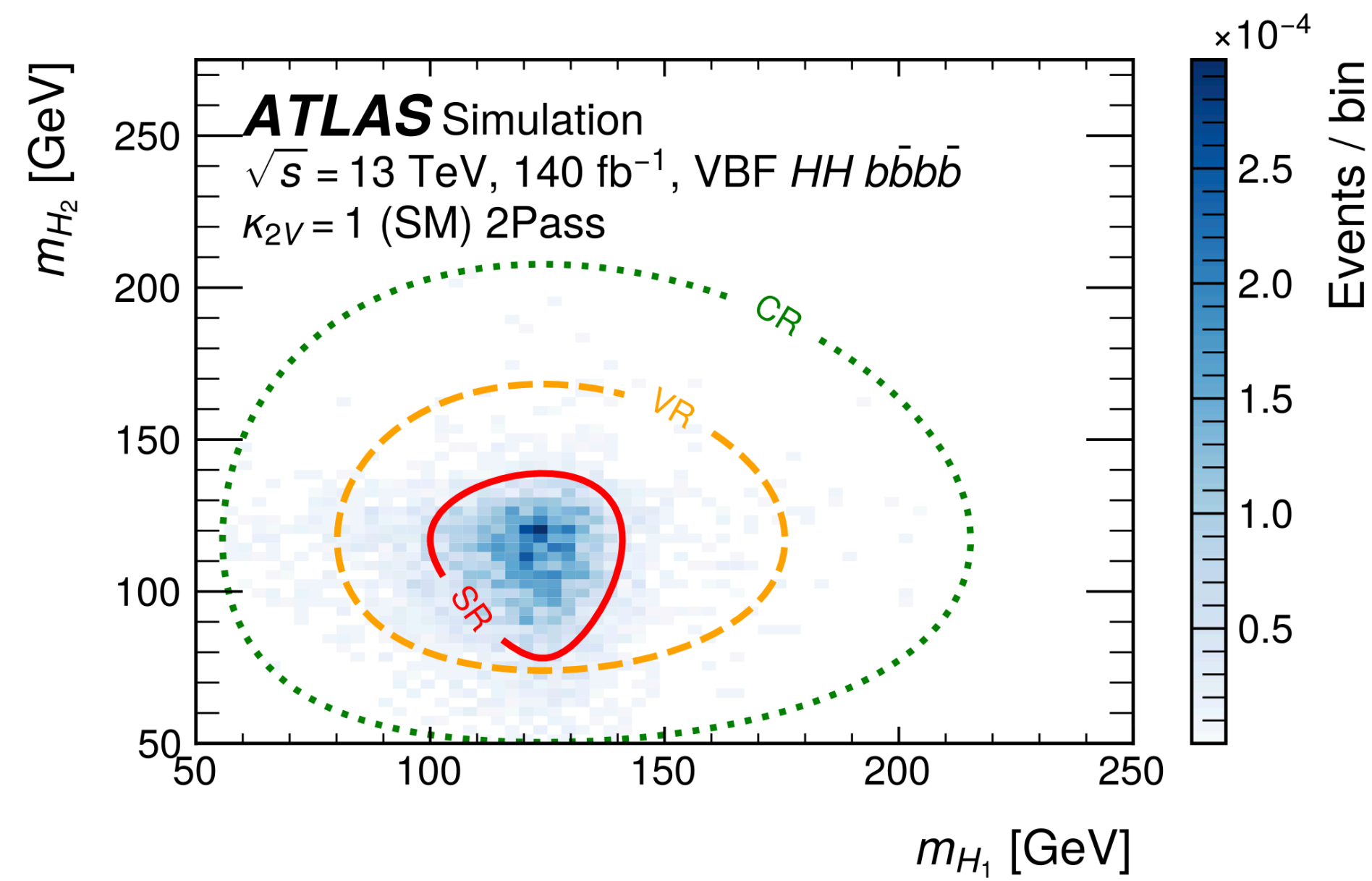
Fit performed in bins of m_{HH} and $|\Delta\eta_{HH}|$
Observed (Expected) upper limits @ 95% CL
on μ_{HH} : $5.4(8.1) \times SM$
 $\kappa_\lambda \in [-3.9, 11.1]([-4.6, 10.8])$

Run 2 HH(bb $\bar{b}\bar{b}$): Boosted

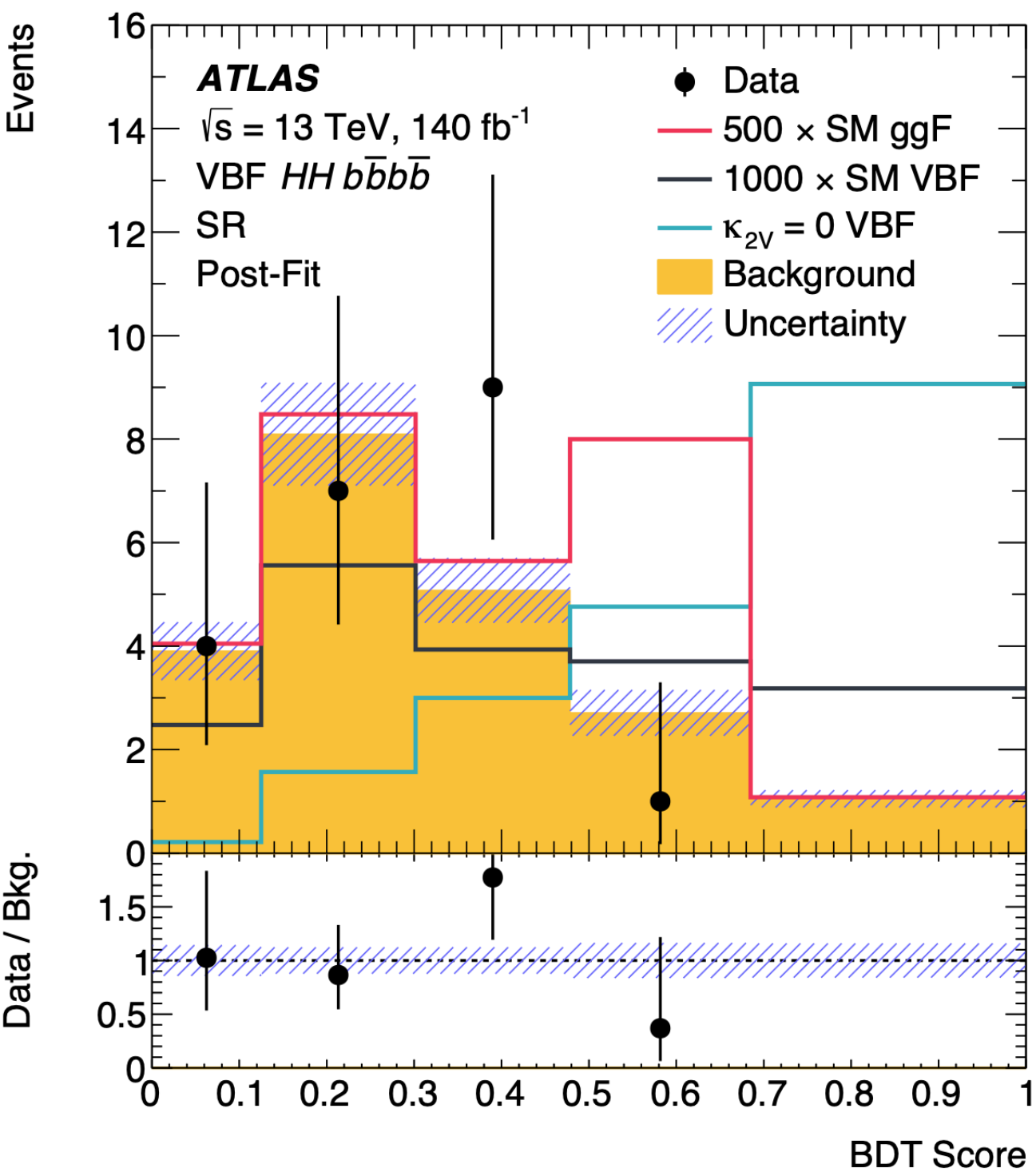


Similar procedure as Resolved
SR, VR and CR

Run 2 HH(bb $\bar{b}\bar{b}$): Boosted



Similar procedure as Resolved
SR, VR and CR

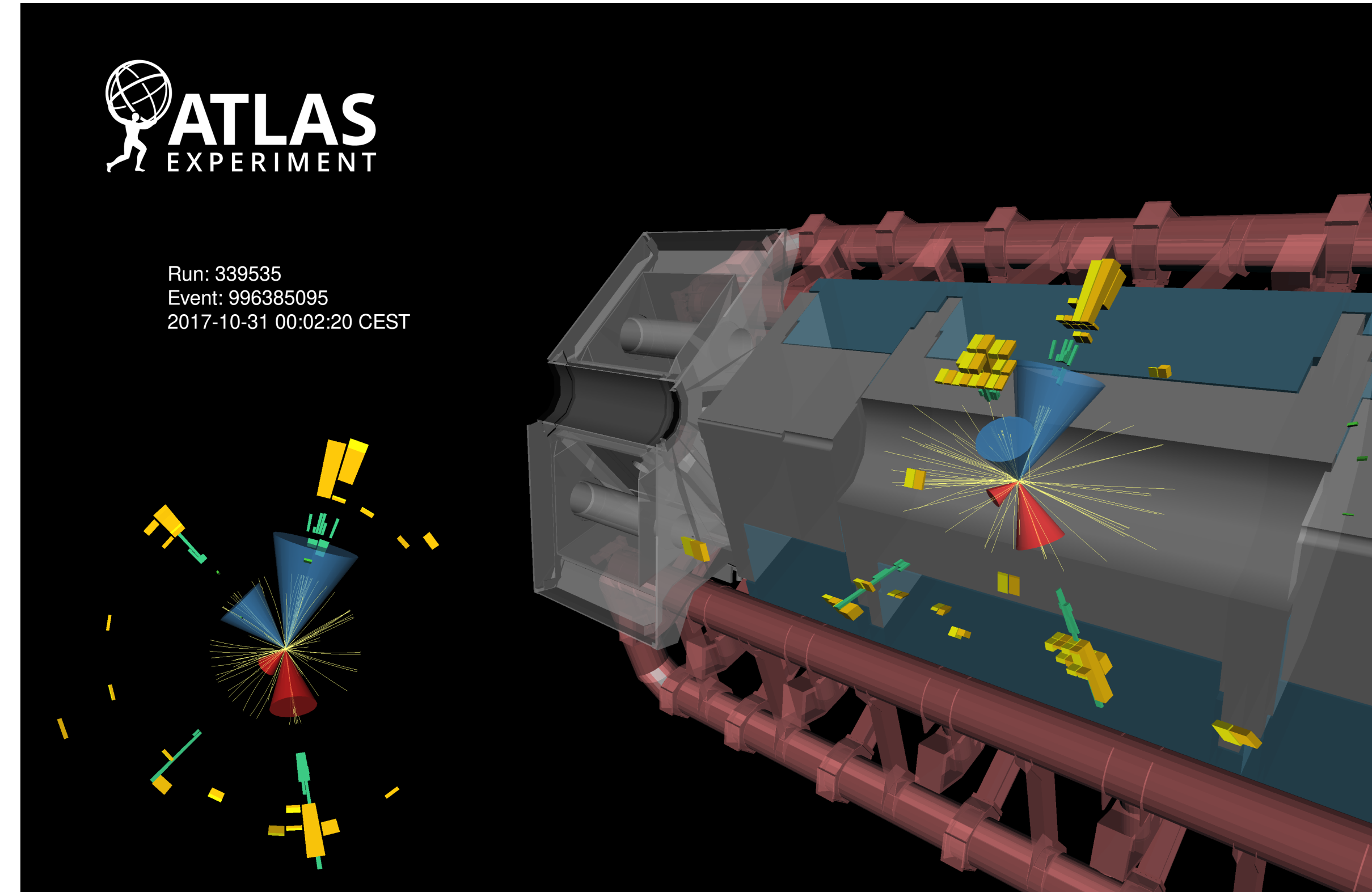


Fit performed on BDT score
Observed (Expected) limits @ 95% CL:
 $\kappa_{2V} \in [-0.55, 1.49]([-0.37, 1.67])$ ✨

Run 2 HH($bb\tau\tau$)

Target two different final state depending on the τ

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

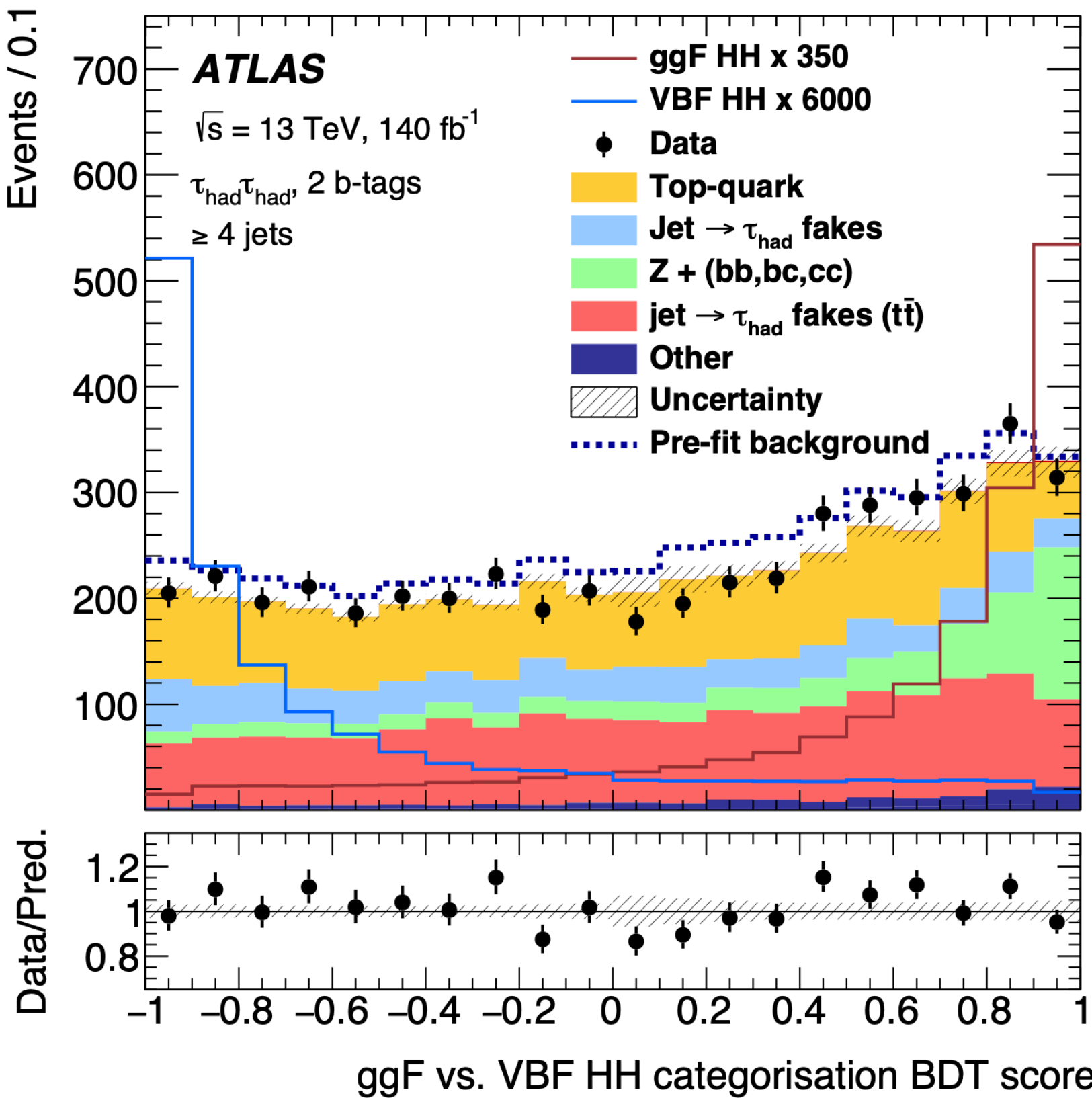


Run 2 HH($bb\tau\tau$)

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BDT score to discriminate ggF from VBF



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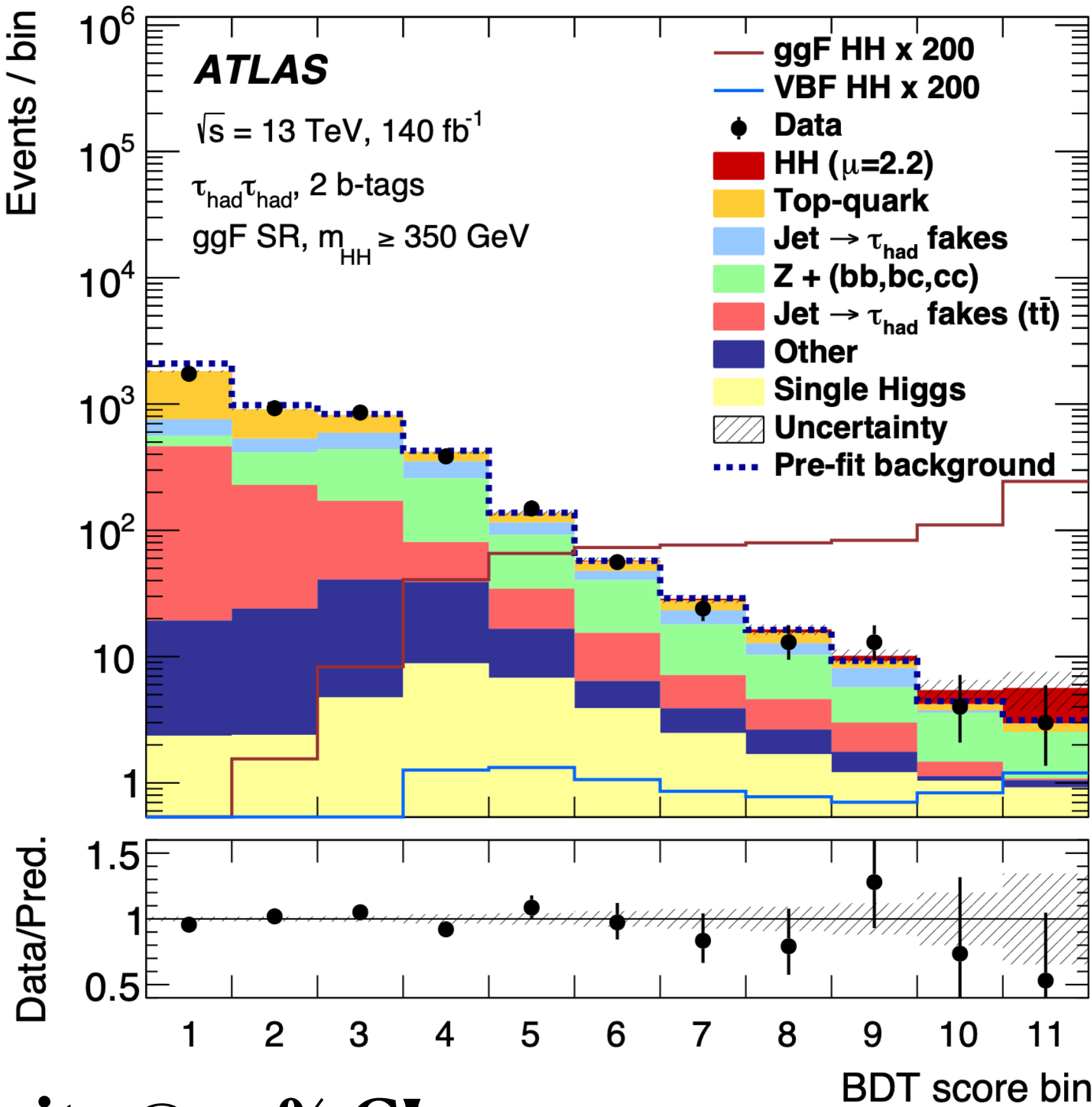
Fit performed in 3 categories:

- ggF low- m_{HH}
- ggF high- m_{HH}
- VBF

Observed (Expected) upper limits @ 95% CL

on μ_{HH} : $5.4(3.3) \times SM$ ✨

$\kappa_\lambda \in [-3.1, 9.0]([-2.5, 9.3])$



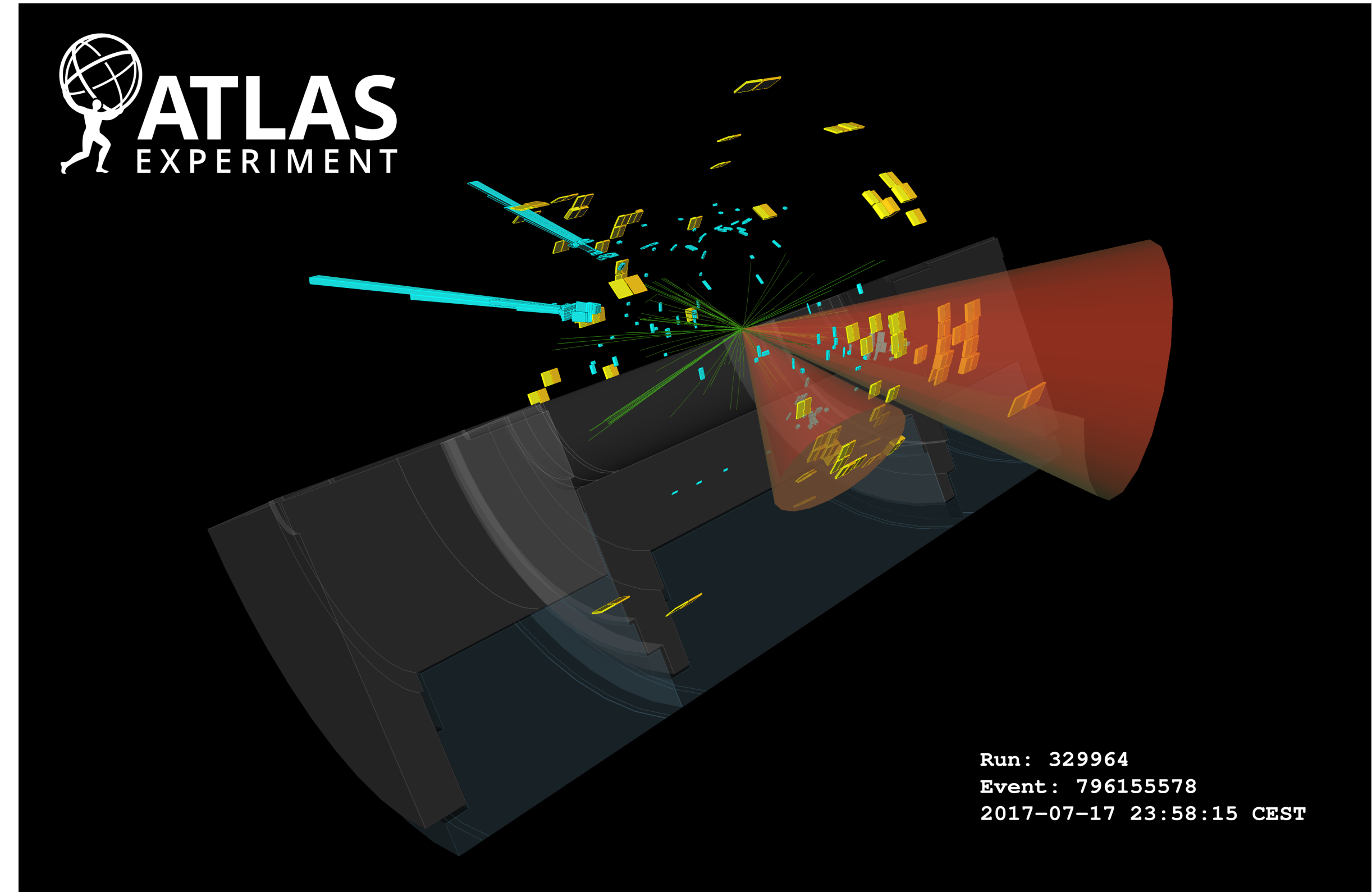
Run 2 HH($bb\gamma\gamma$)

JHEP 01 (2024) 066

Extremely pure and stat limited channel

BDT to discriminate HH from non-resonant bkg.

separate in low- m_{HH} and high- m_{HH}



Run 2 HH($bb\gamma\gamma$)

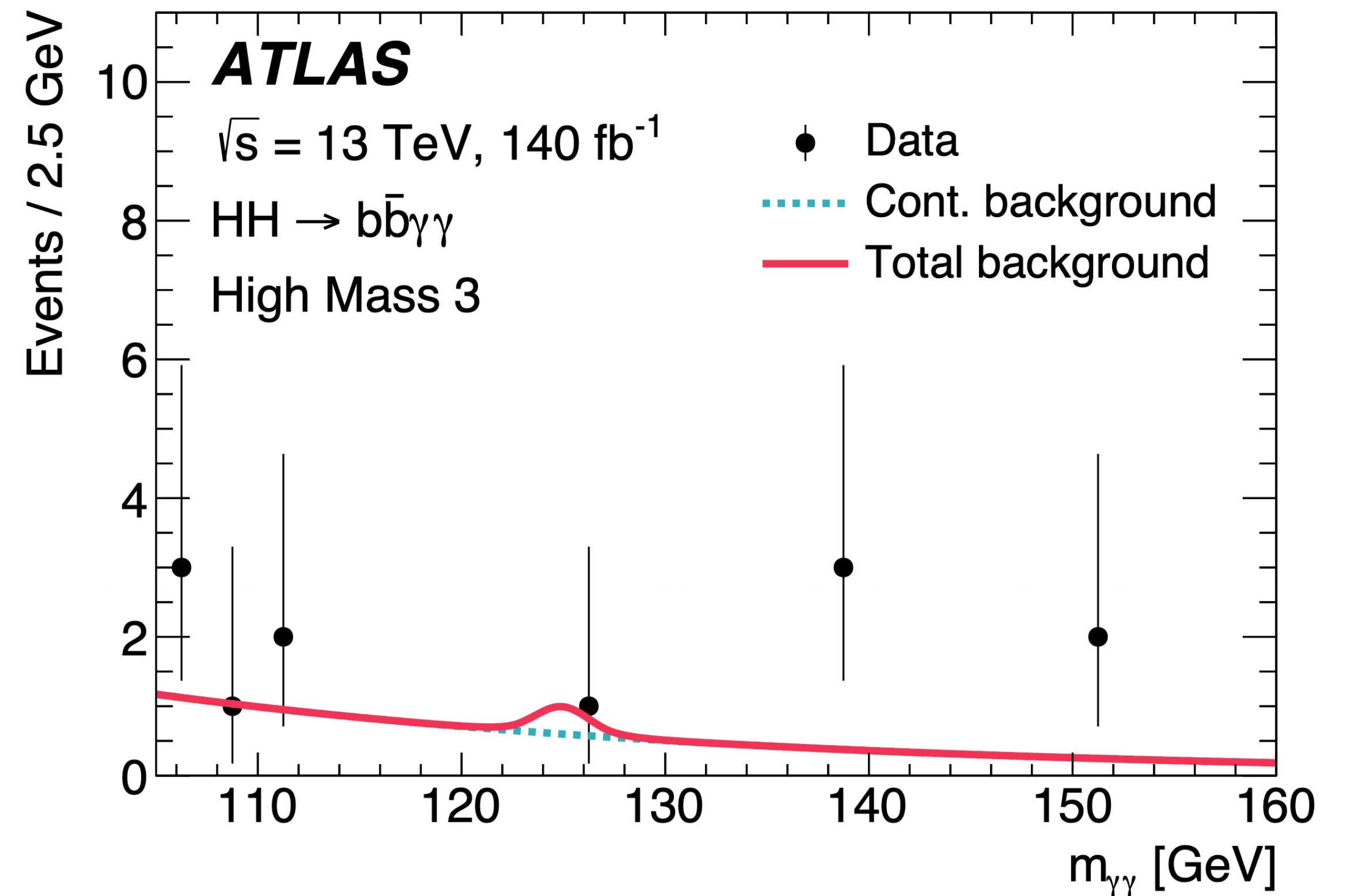
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Categorization performed to maximize the significance

Then a simultaneous unbinned fit on $m_{\gamma\gamma}$ is performed



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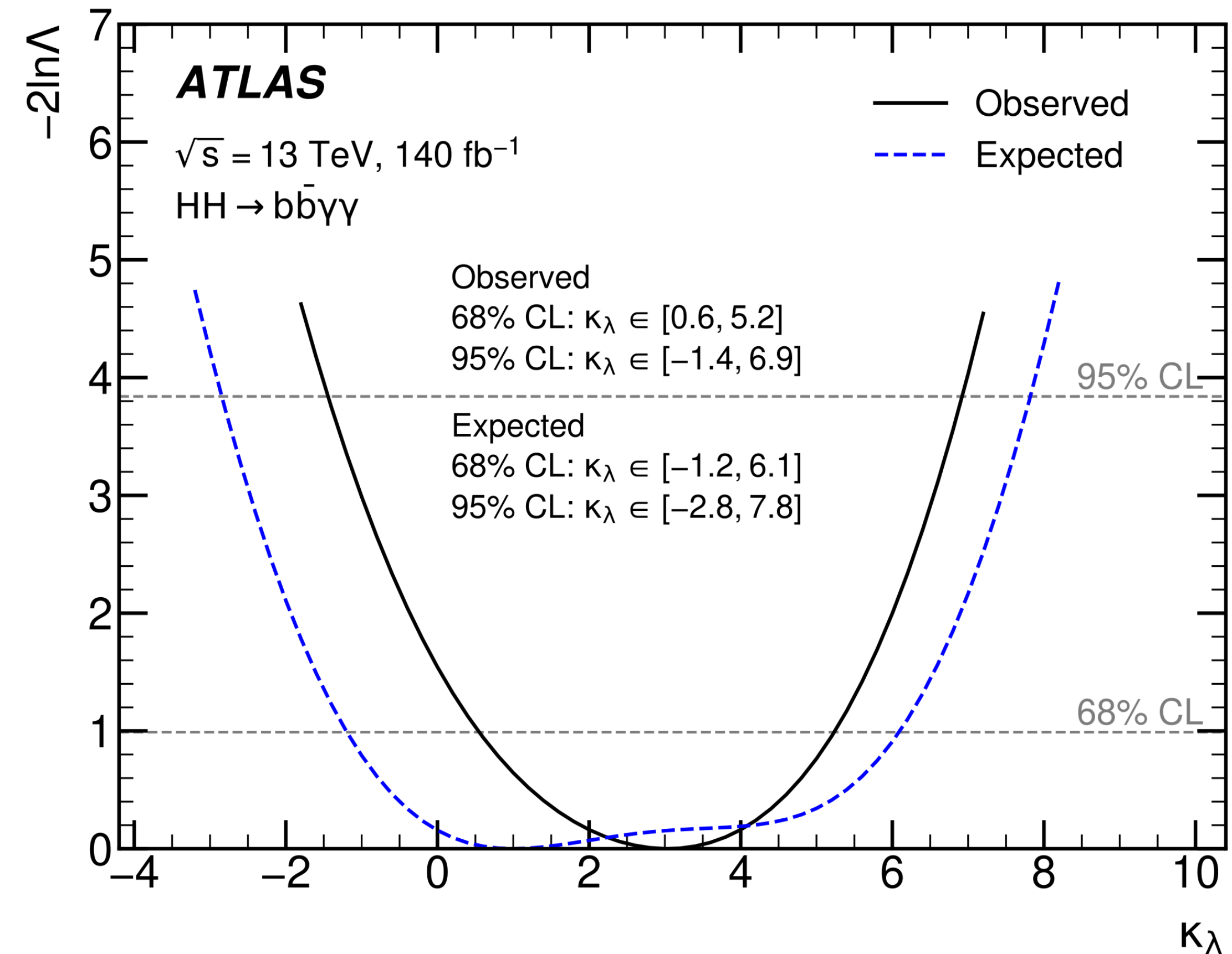
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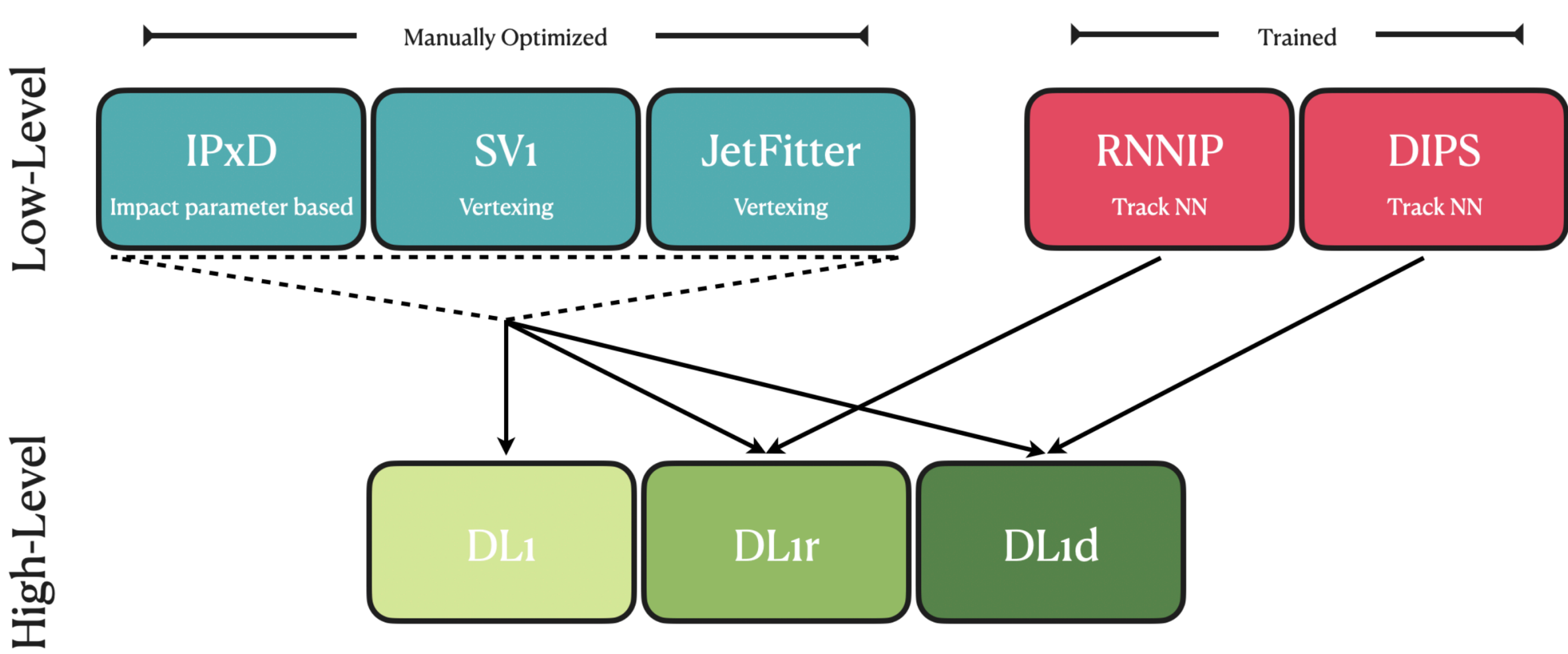
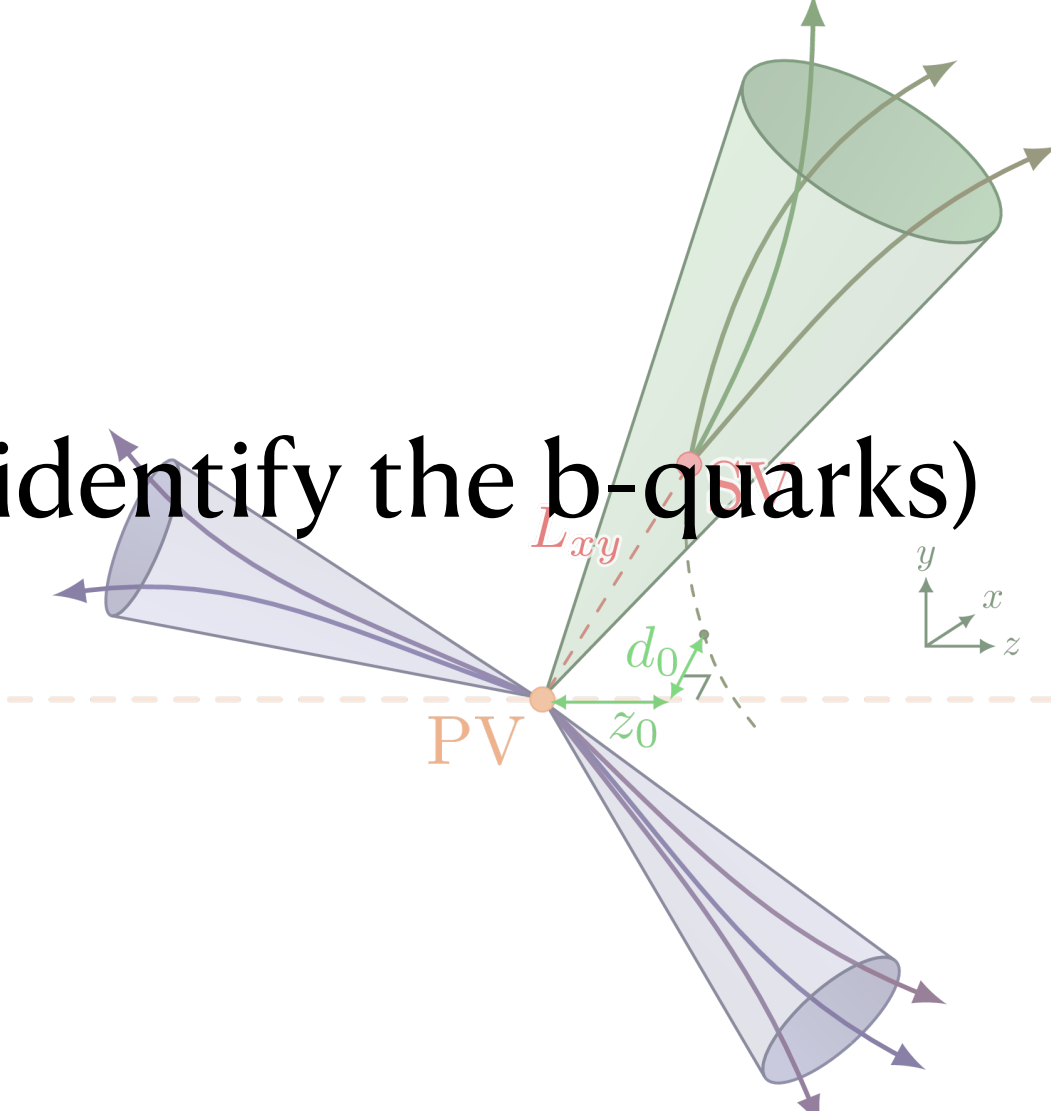
on μ_{HH} : 4.0(5.0) $\times SM$

$\kappa_\lambda \in [1.4, 6.9]([2.8, 7.8])$ ✨



Transforming Flavour Tagging

All the presented analyses heavily rely on Flavour Tagging (a.k.a. the ability to identify the b -quarks)
All the Run 2 analyses have been performed using DL1r



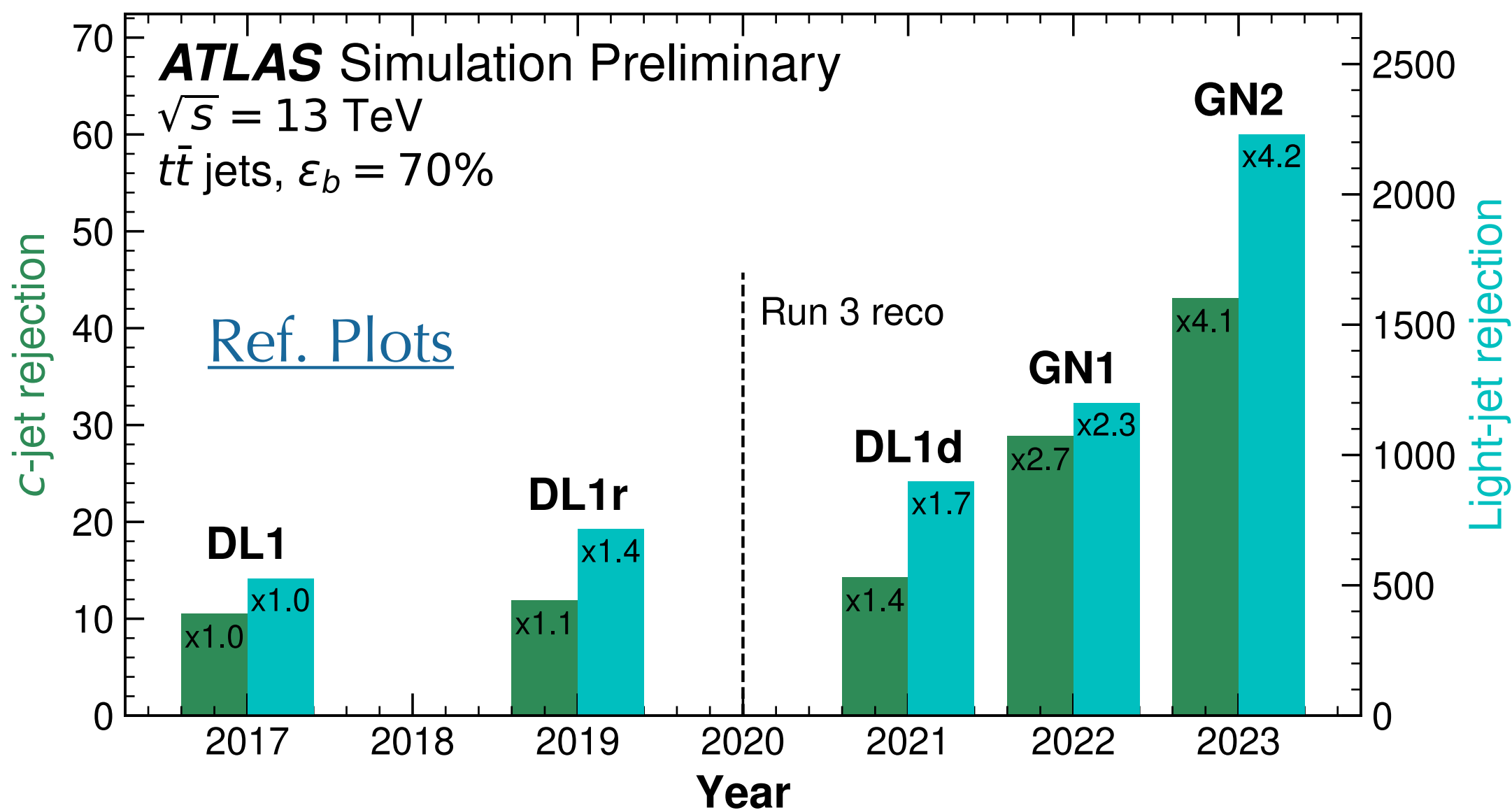
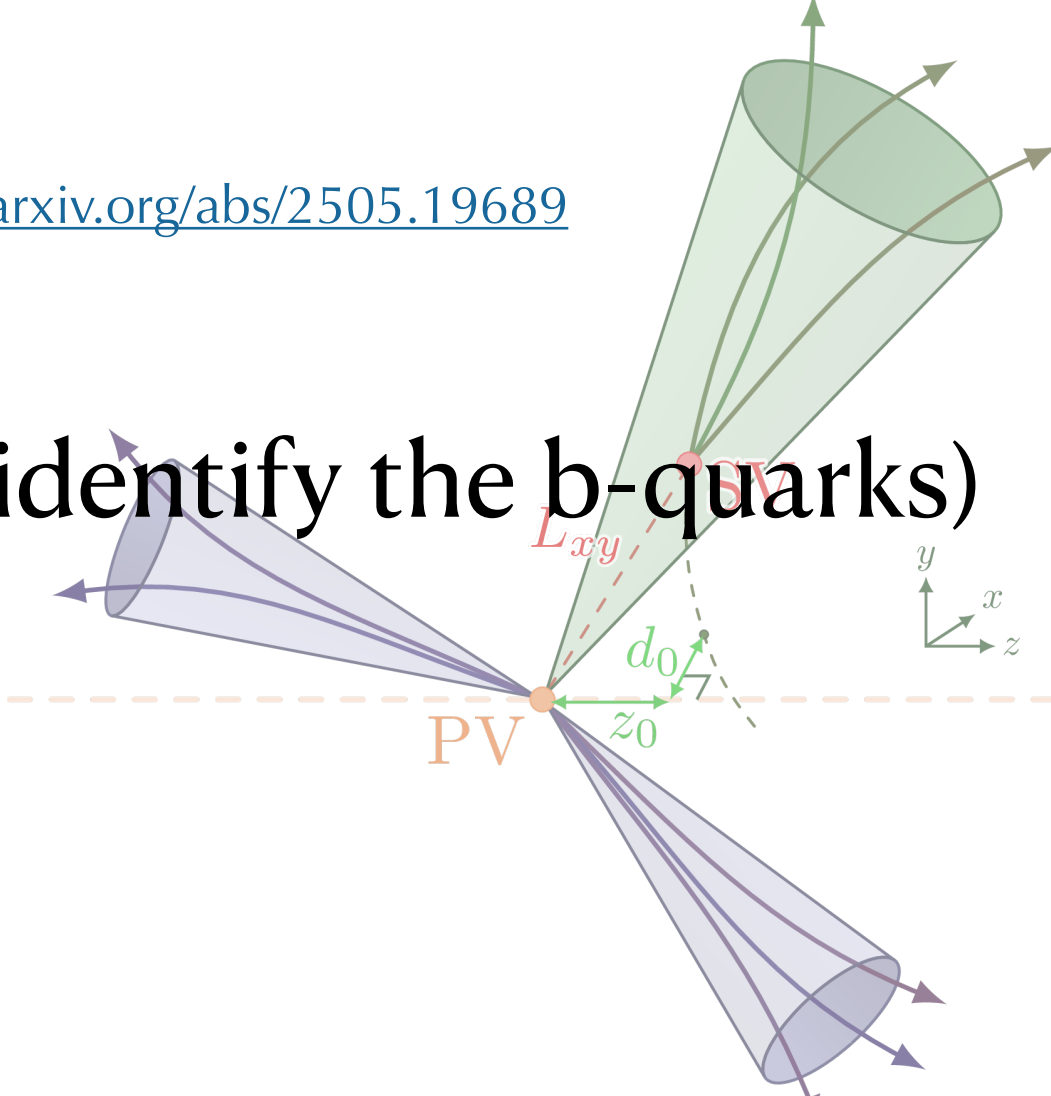
The Flavour Tagging beauty story:
- Originally simple taggers based on the **track impact parameters** and **secondary vertices finding** were developed

Transforming Flavour Tagging

<https://arxiv.org/abs/2505.19689>

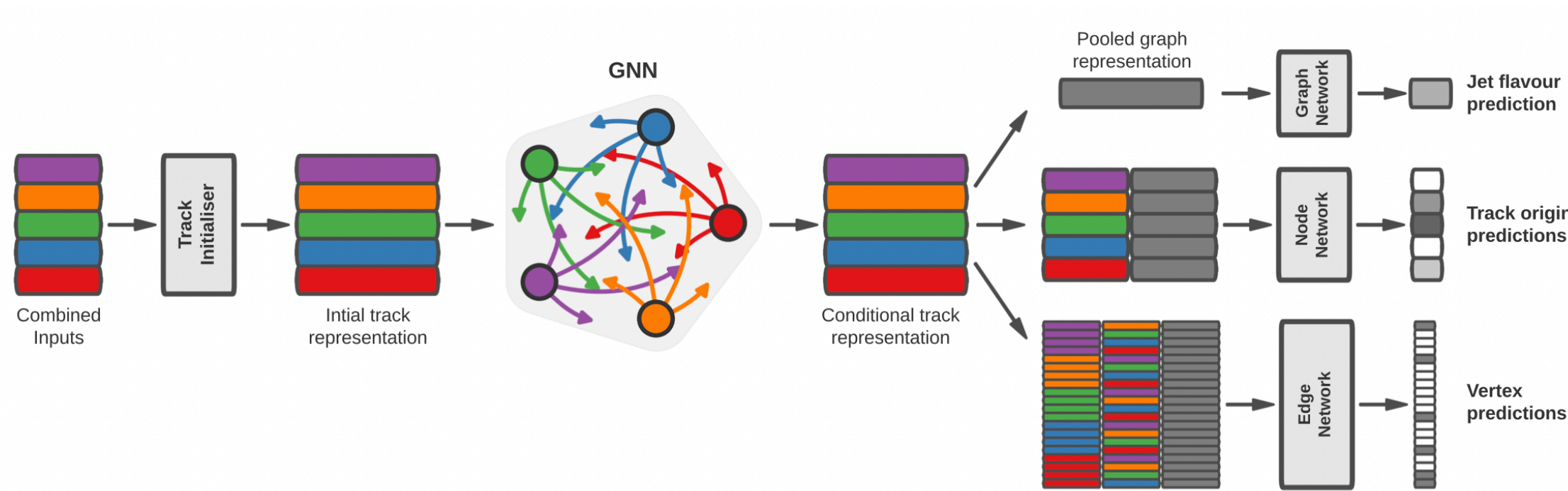
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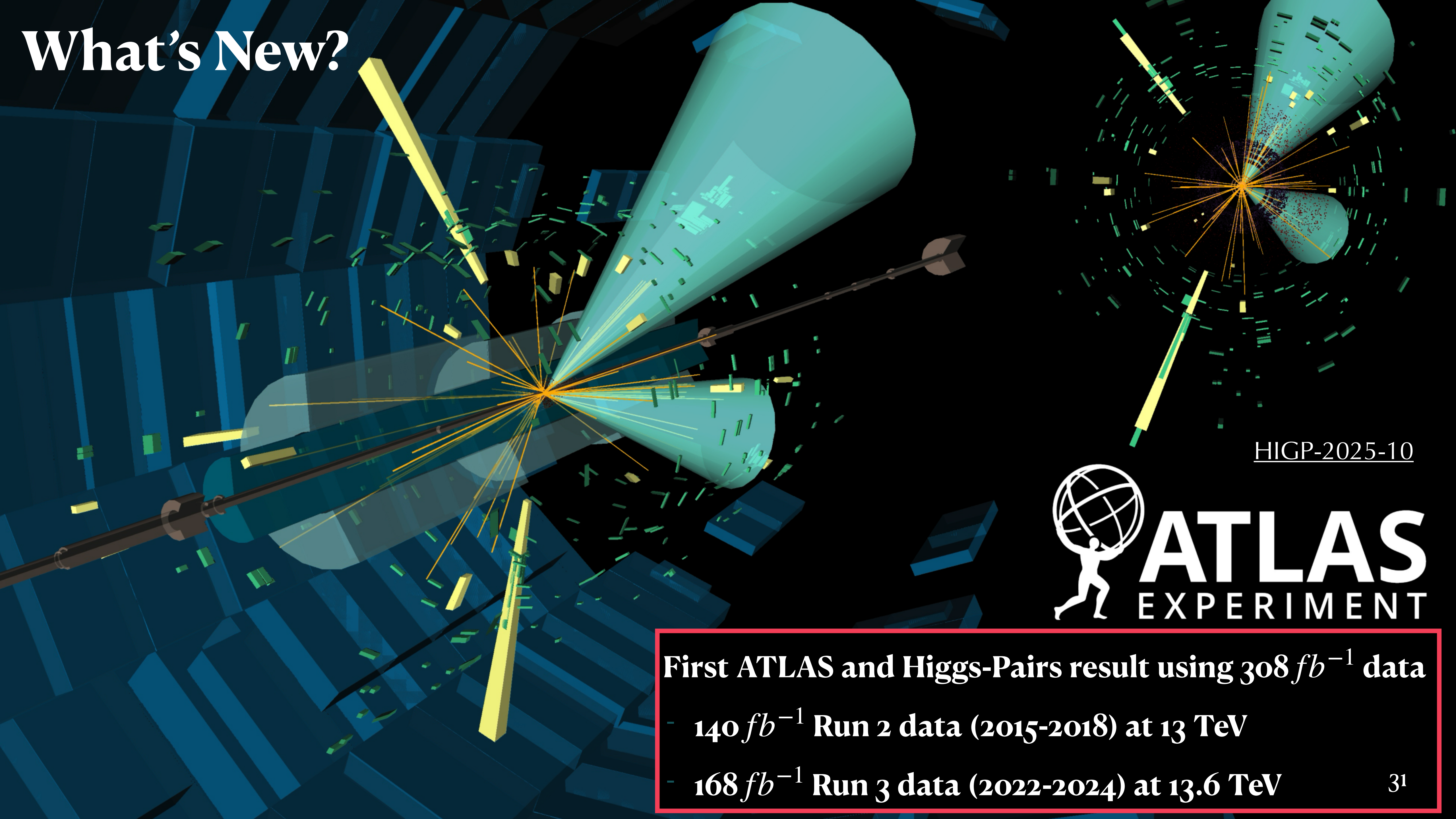


The Flavour Tagging beauty story:

- Originally simple taggers based on the **track impact parameters** and **secondary vertices finding** were developed
- With **Deep Learning** development new advanced algorithms have been developed **based directly on tracks 4-vectors**



What's New?



HIGP-2025-10



First ATLAS and Higgs-Pairs result using 308 fb^{-1} data

- 140 fb^{-1} Run 2 data (2015-2018) at 13 TeV

- 168 fb^{-1} Run 3 data (2022-2024) at 13.6 TeV

Run 2 + partial Run 3 HH($bb\gamma\gamma$)

Several improvements performed to enhance the sensitivity!

$$\sigma_{ggF}^{SM}(SM) = 34.1_{-7.9}^{+2.2} \text{ fb @ 13.6 TeV (+10% wrt 13 TeV)}$$

- Selection improved requiring ≥ 2 b-jets with GN2 $\epsilon_b = 85 \%$

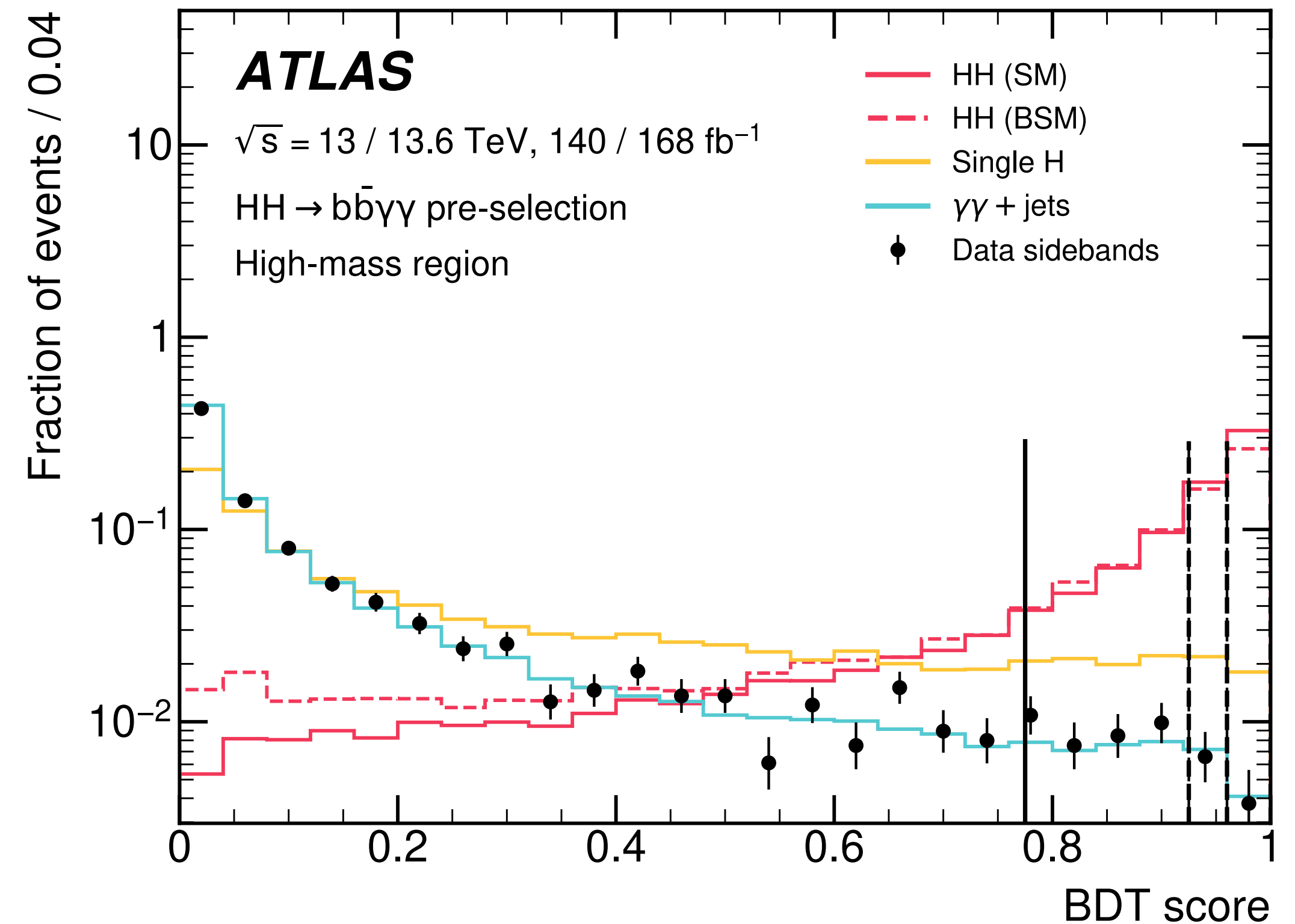


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- Training simultaneous in Run 2 and Run 3 exploiting the correlation to categorize tighter

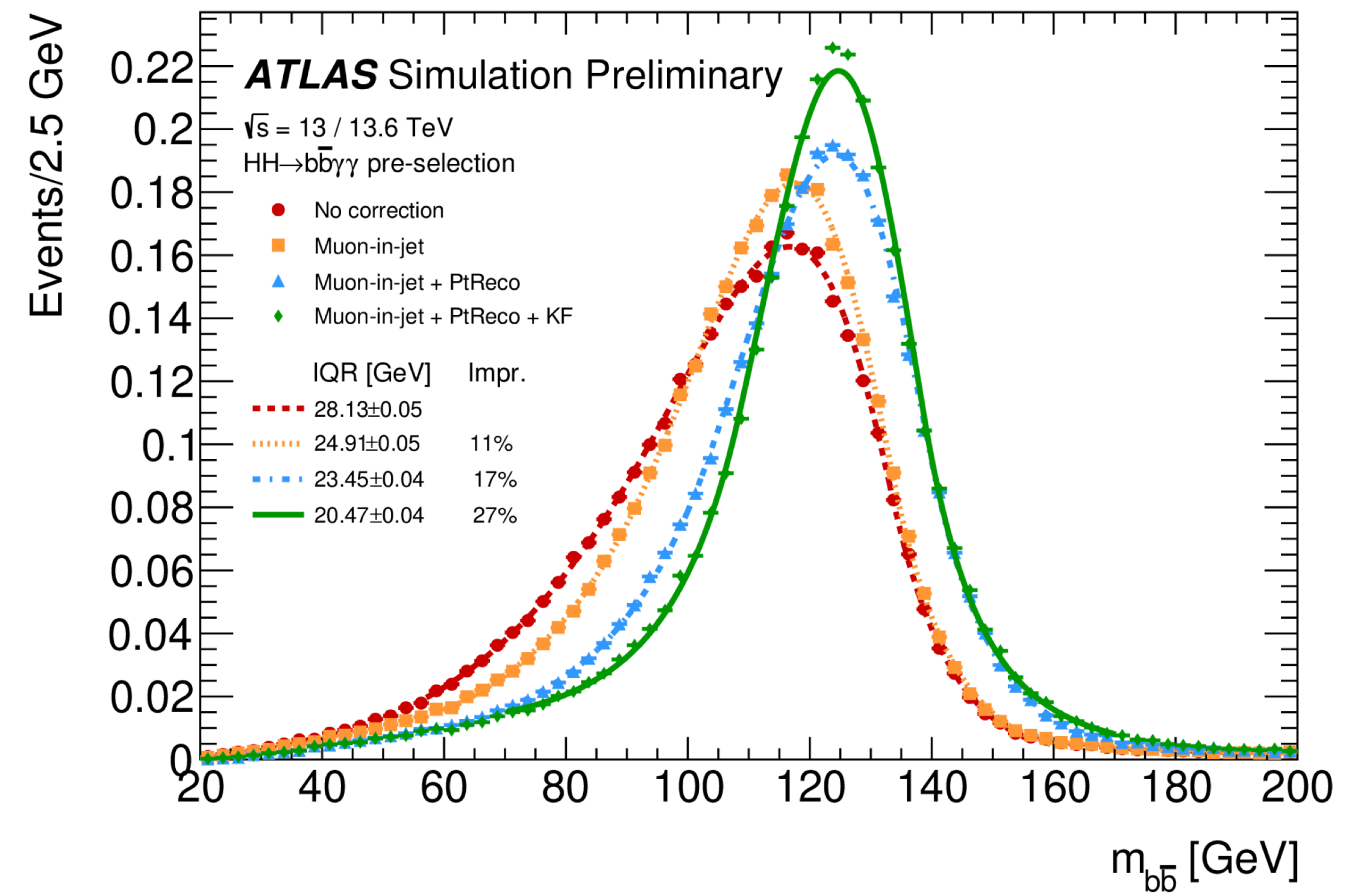


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- Selection improved requiring ≥ 2 b-jets with GN2 $\epsilon_b = 85 \%$
- Training simultaneous in Run 2 and Run 3
exploiting the correlation to categorize tighter
- Kinematic fit improving the m_{bb} resolution
- And of course $\times 2.2$ **more data** !

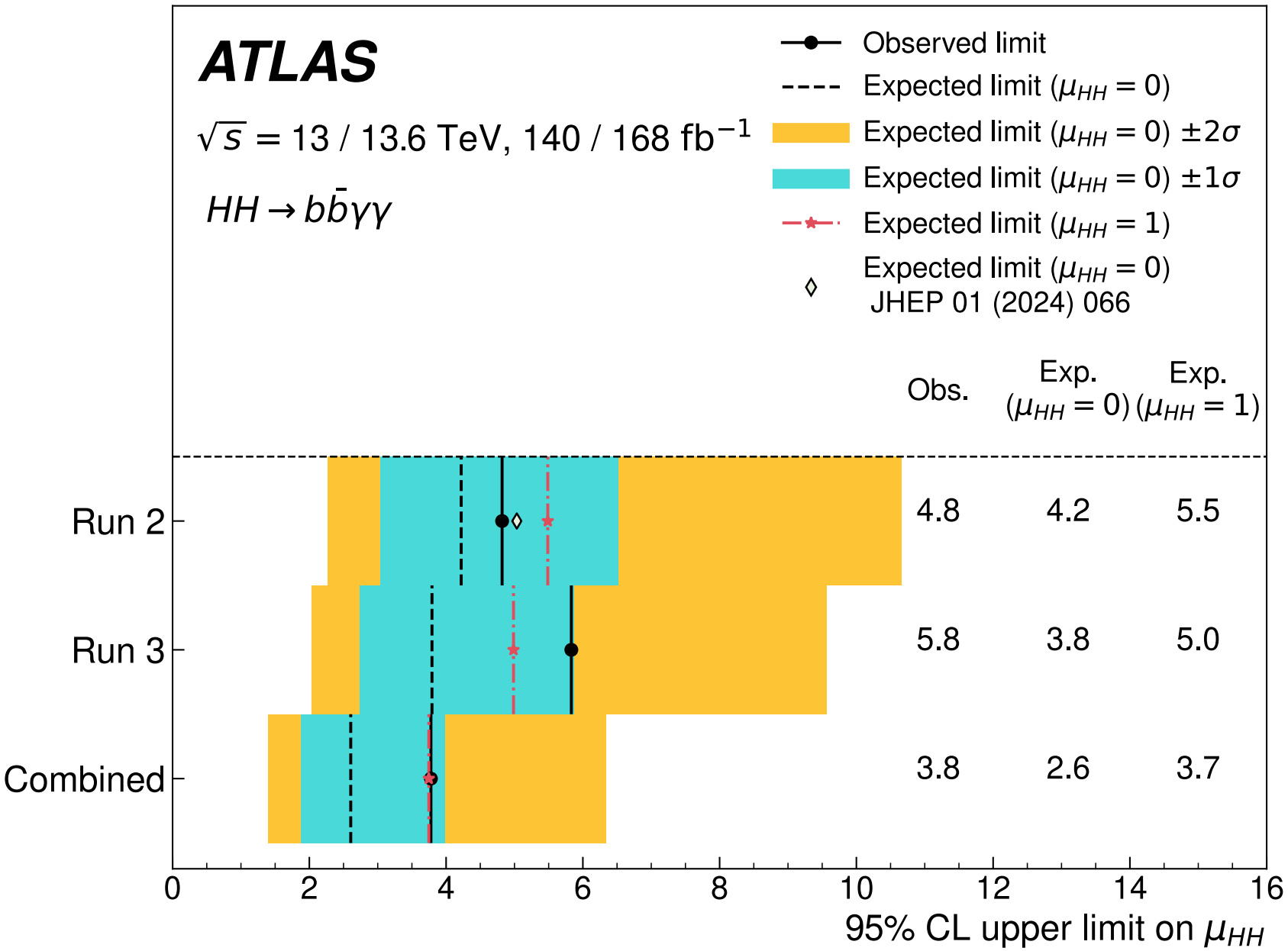
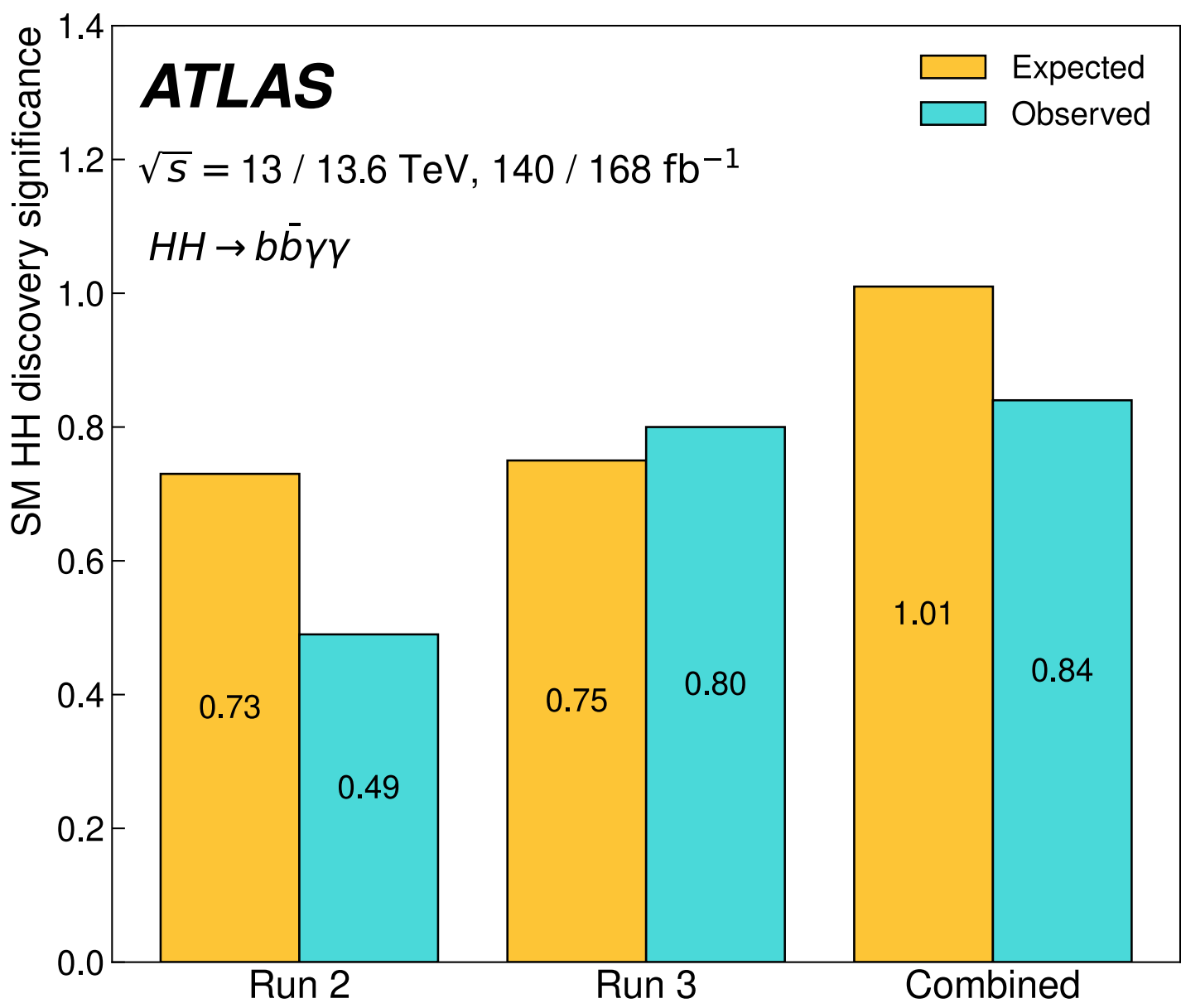


Run 2 + partial Run 3 HH($b\bar{b}\gamma\gamma$)

Simultaneous fit in the 14 categories

Observed HH SM Significance: 0.8σ
Expected HH SM Significance: 1.0σ

Observed (Expected) upper limits @ 95% CL
on μ_{HH} : $3.8(2.6) \times SM$ ✨
! Comparable with Full Run 2 HH Combination



Run 2 + partial Run 3 HH($bb\gamma\gamma$)

Simultaneous fit in the 14 categories

Observed HH SM Significance: 0.8σ

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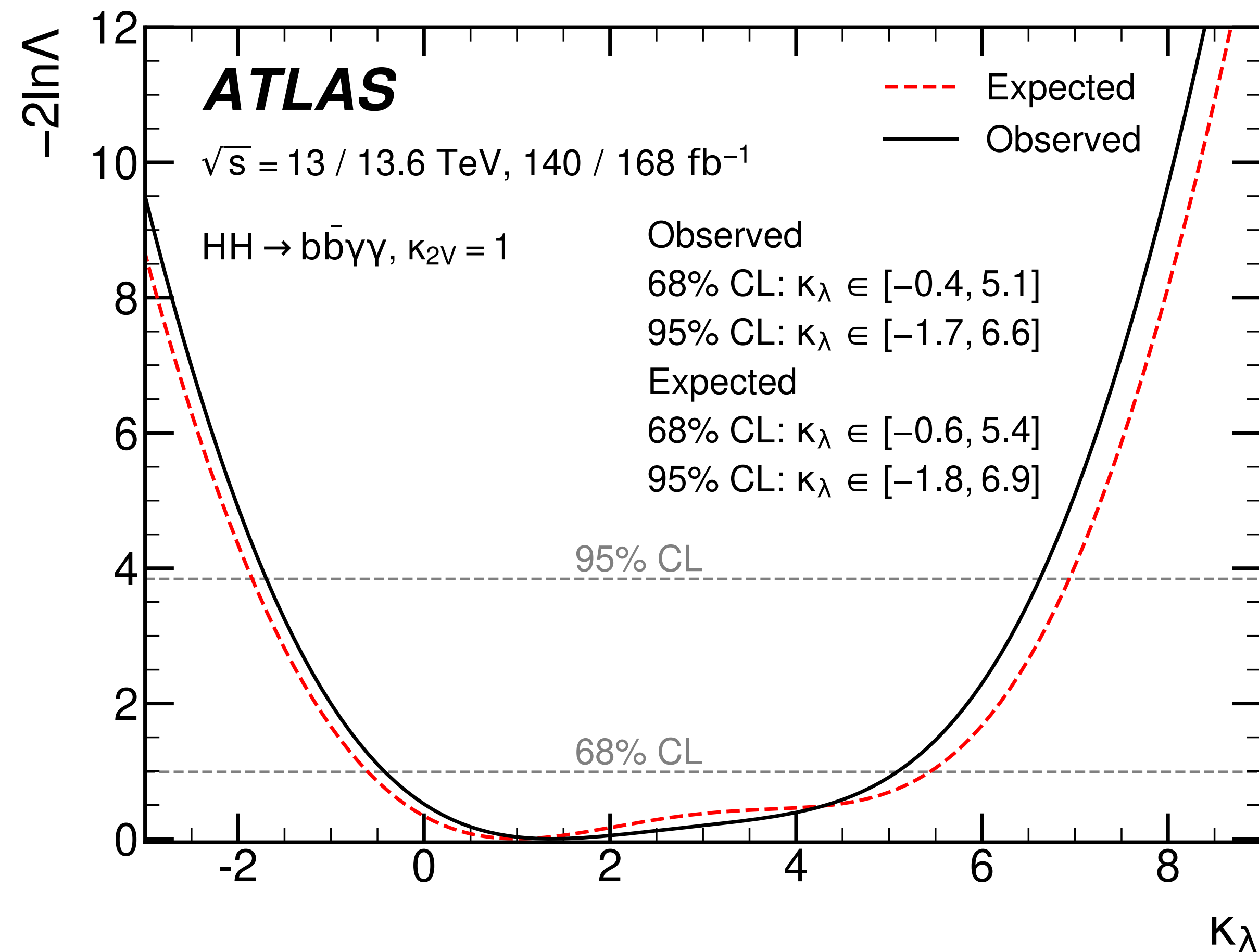
Observed (Expected) upper limits @ 95% CL

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! Comparable with Full Run 2 HH Combination

Observed (Expected) limits @ 68% CL:

$\kappa_\lambda \in [-0.4, 5.1]([-0.6, 6.9])$ ✨



Run 2 + partial Run 3 HH($b\bar{b}\gamma\gamma$)

Simultaneous fit in the 14 categories

Observed HH SM Significance: 0.8σ

Expected HH SM Significance: 1.0σ

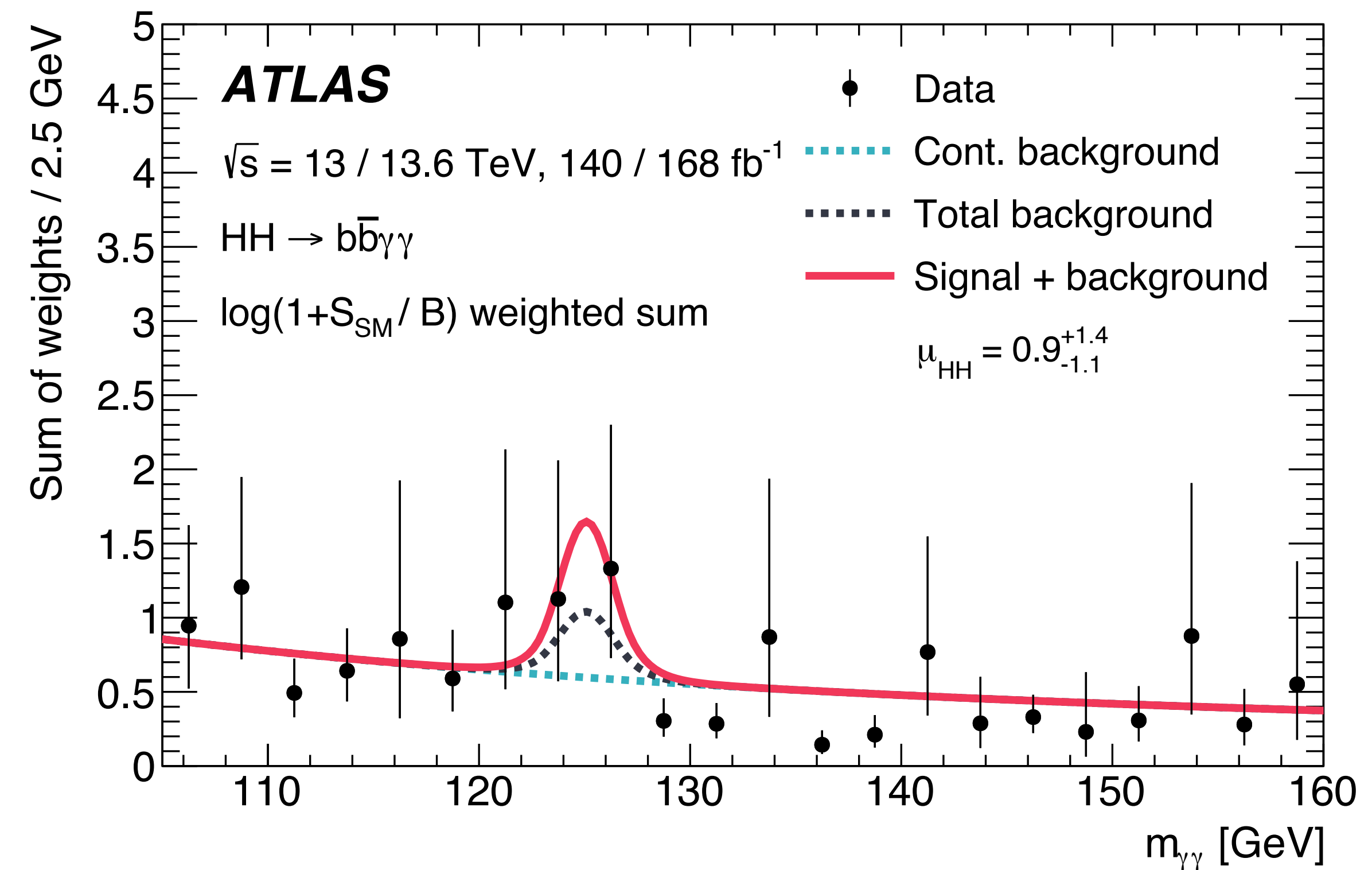
Observed (Expected) upper limits @ 95% CL

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Observed (Expected) limits @ 68% CL:

$\kappa_\lambda \in [-0.4, 5.1]([-0.6, 6.9])$ ✨



What's next?

The Higgs pairs program plays a crucial role for HL-LHC program

All the HH analyses have been input to the European Strategy Update:

[Highlights of the HL-LHC physics projections by ATLAS and CMS](#)



**23-27
JUNE
2025**

European Strategy
for Particle Physics

OPEN SYMPOSIUM

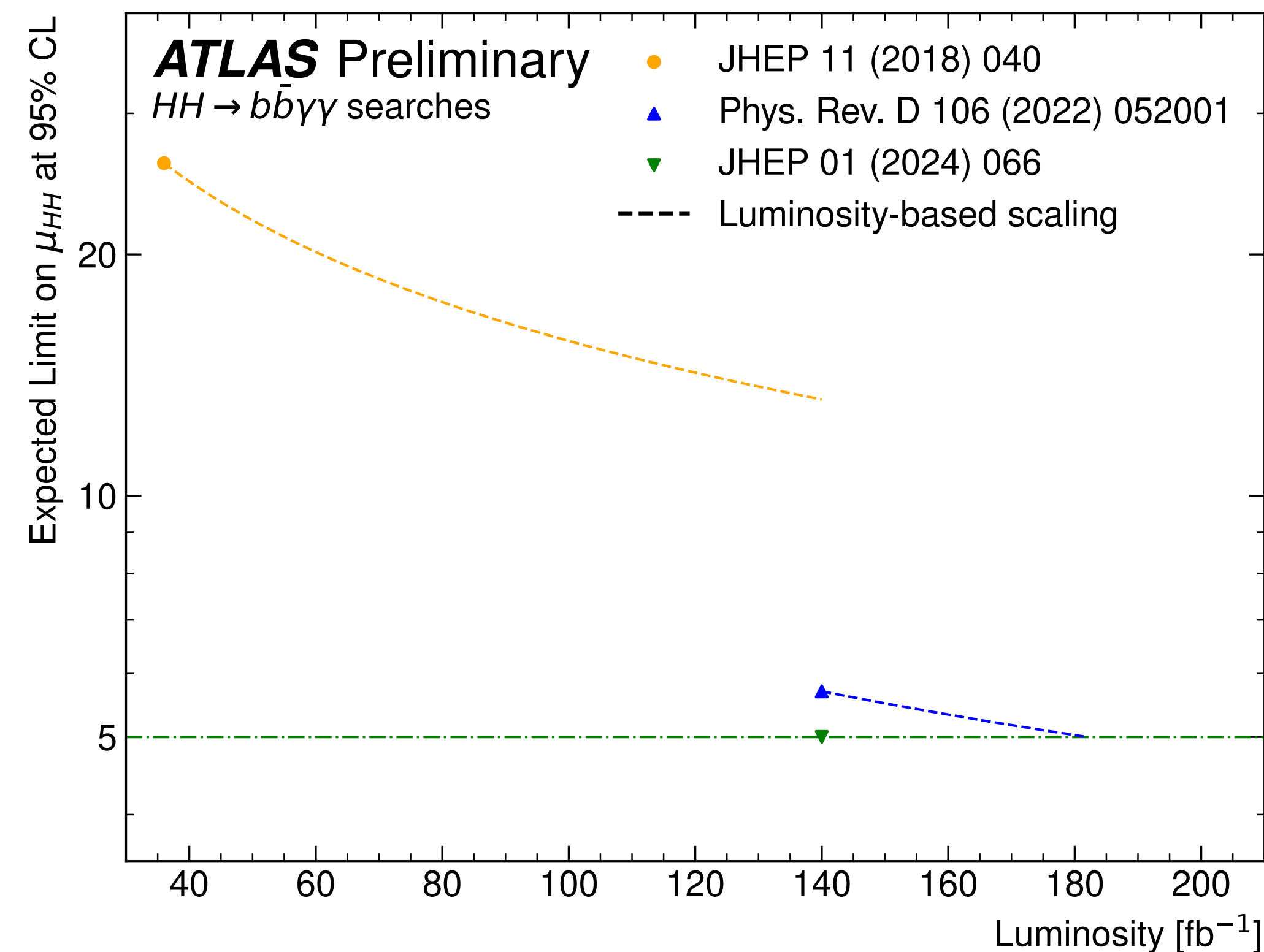
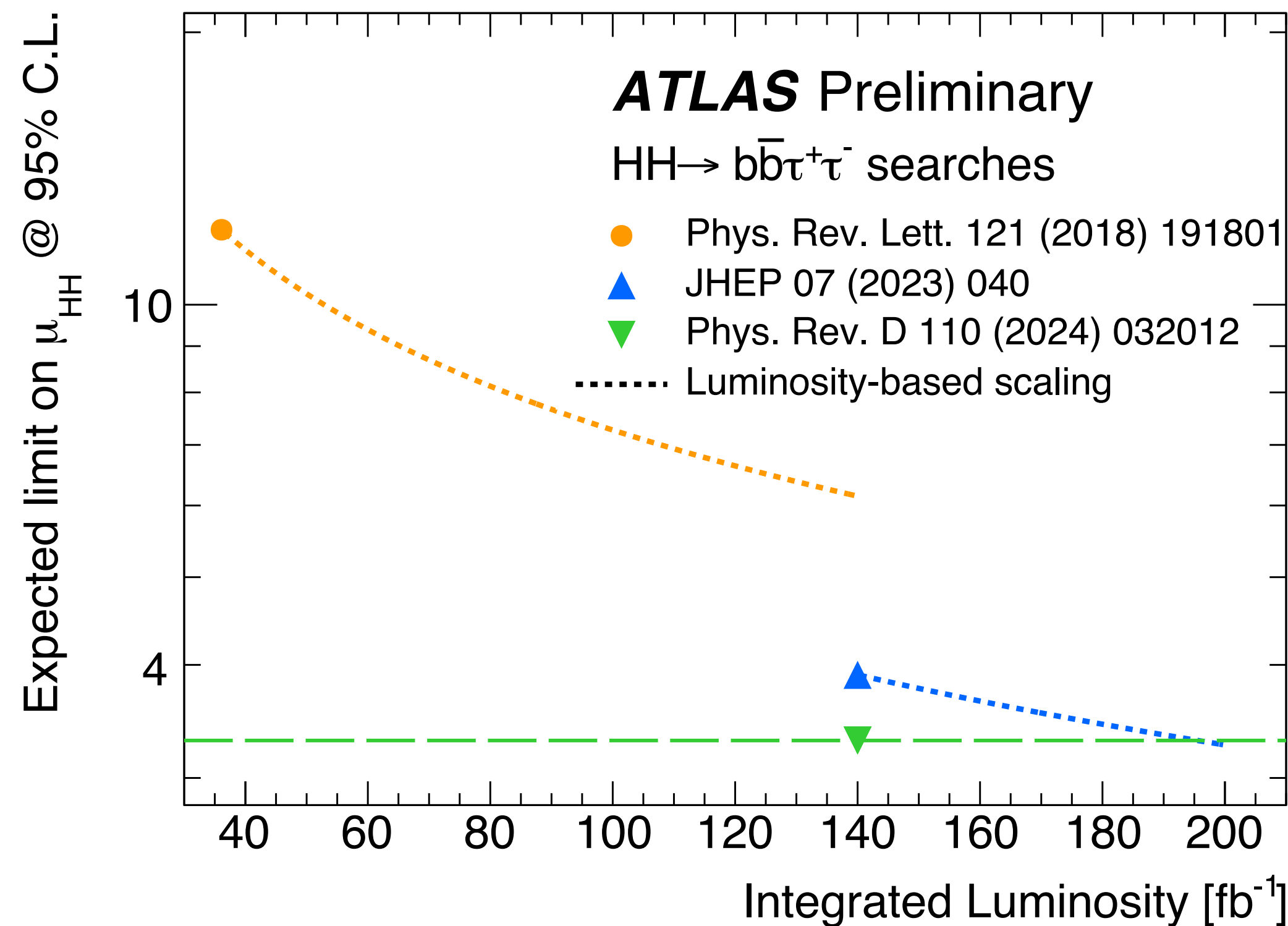
**European Strategy
for Particle Physics**

2026 UPDATE

A community-wide event
inviting participants to debate
the future orientation
of European particle physics.

The HL-LHC Extrapolations

The latest Run 2 results have been extrapolated to HL-LHC expected sensitivity in several scenarios!
Usually the extrapolations are be conservative given many improvements happens along the way



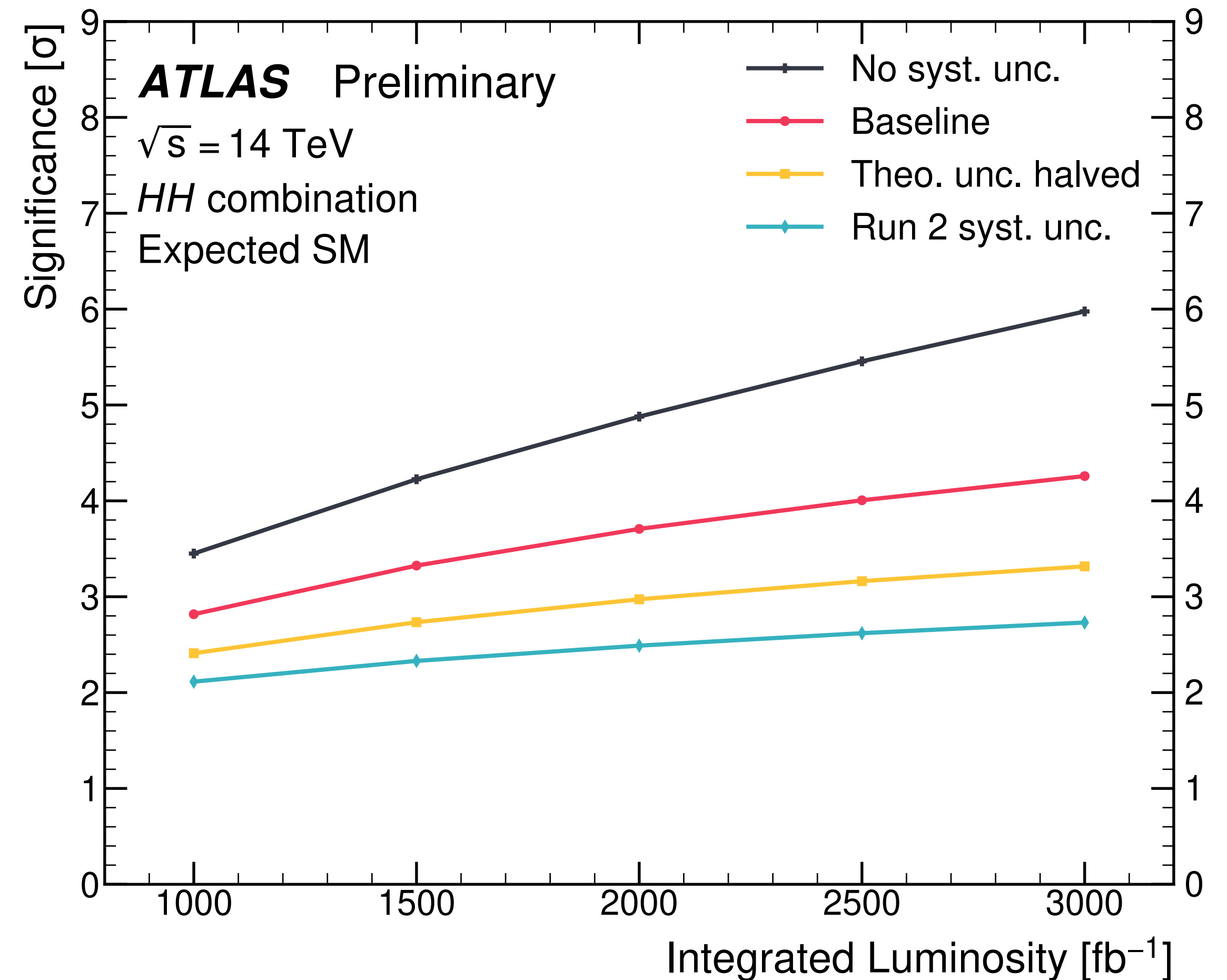
The HL-LHC Extrapolations

Scenarios assumed:

- Run 2 systematics
- Theoretical uncertainty halved
- **Baseline**
- Stat. only

Benchmark: 3000 fb^{-1} at 14 TeV

Expected HH SM Significance: 4.1σ



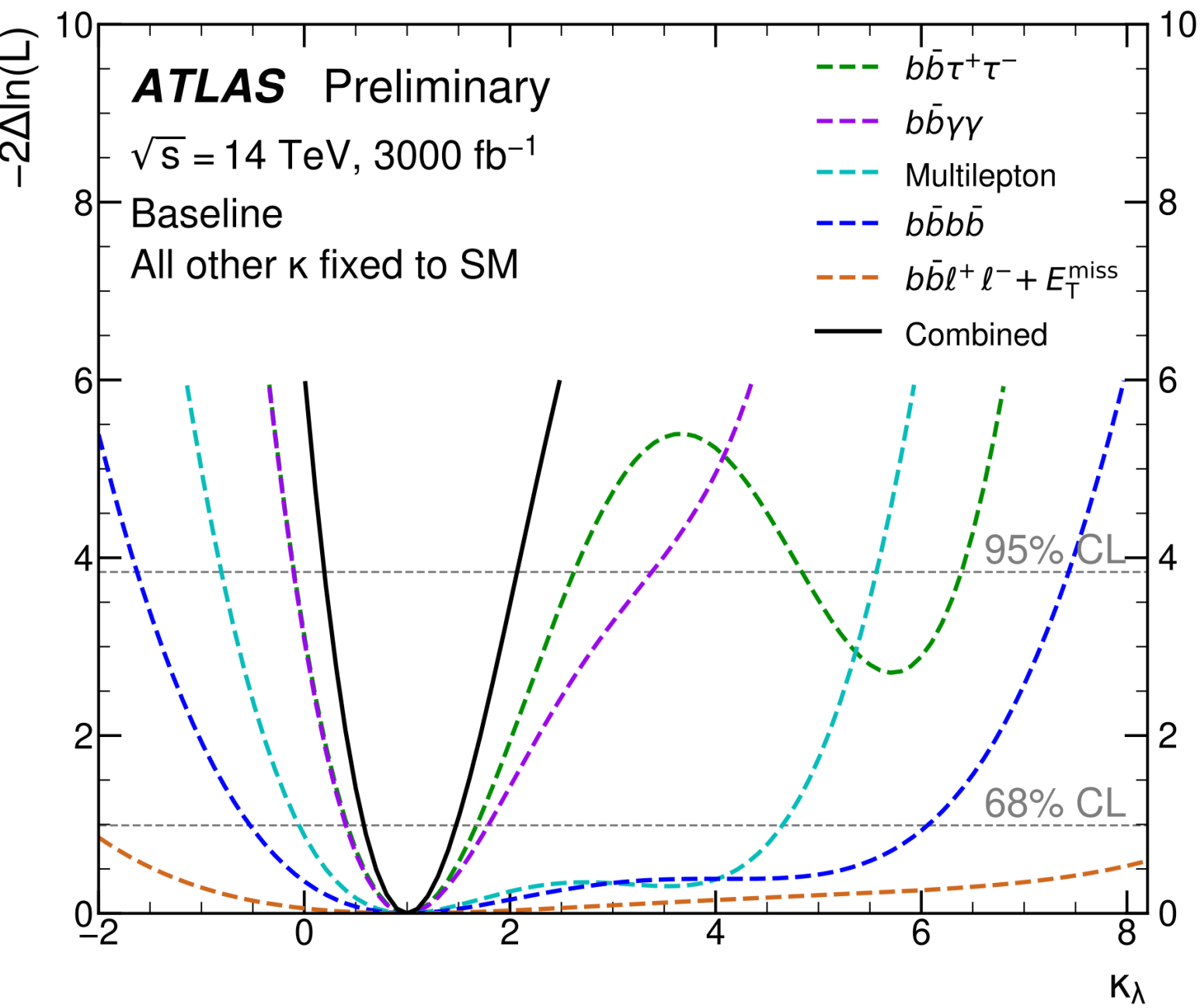
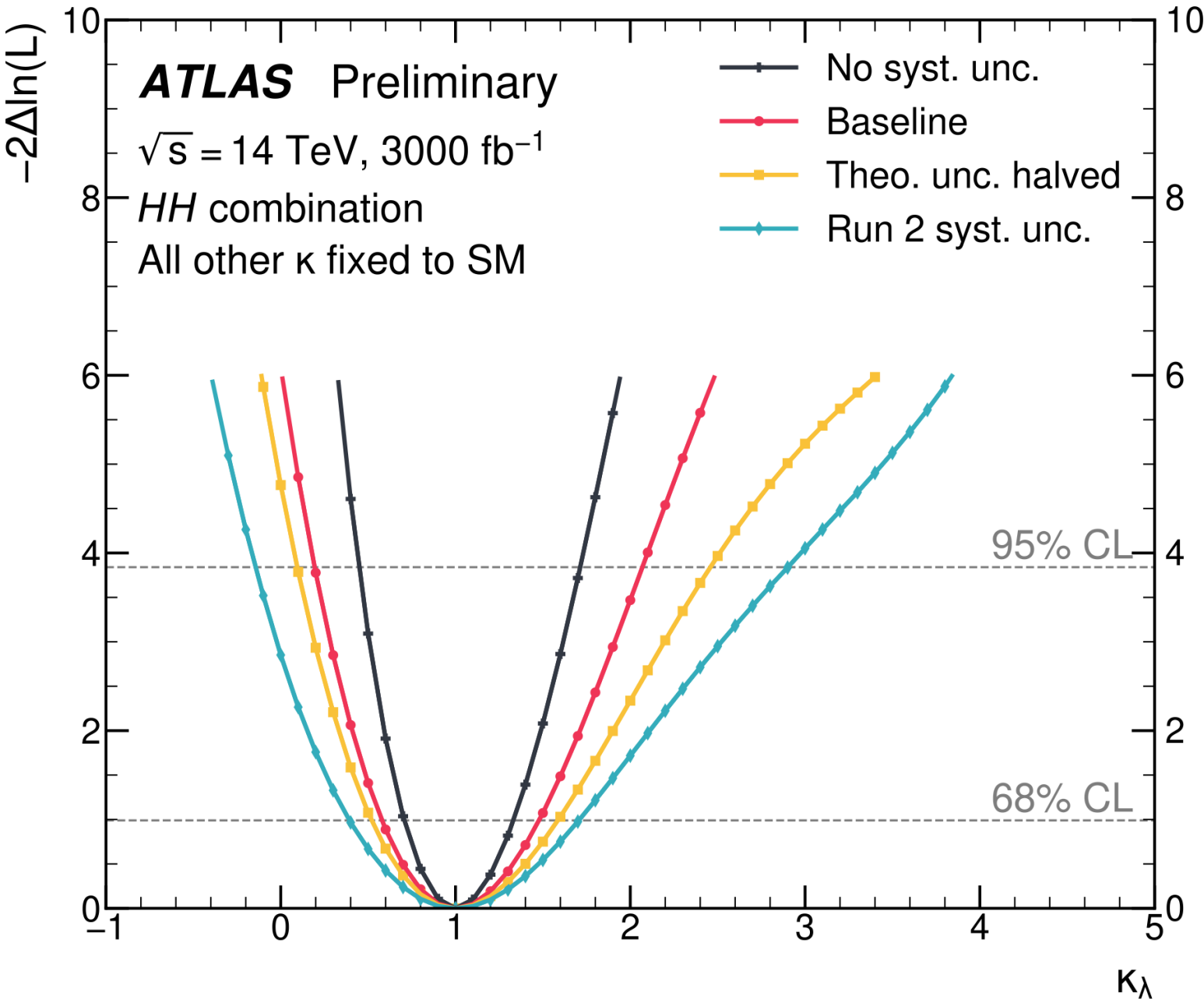
The HL-LHC Extrapolations

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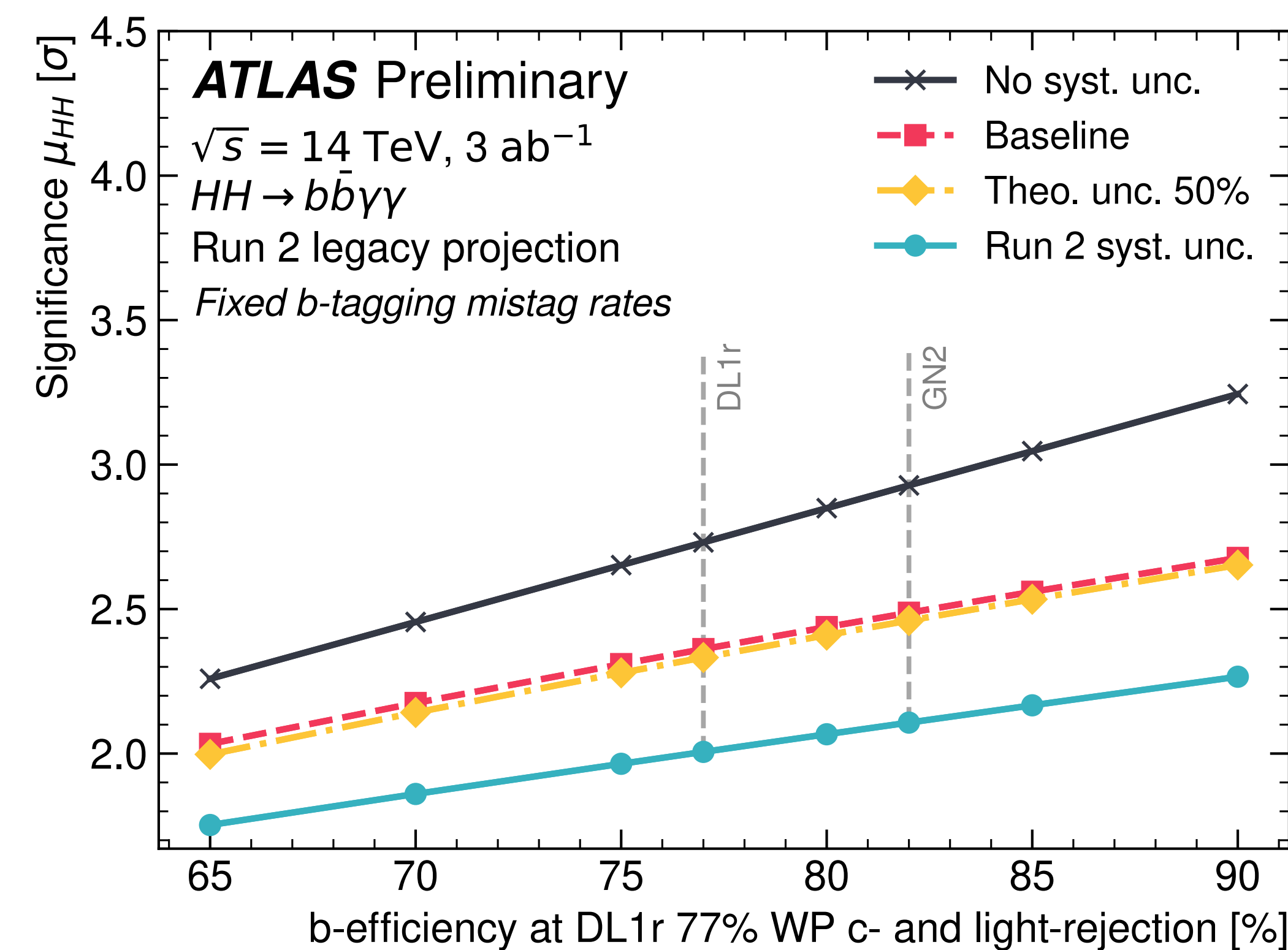
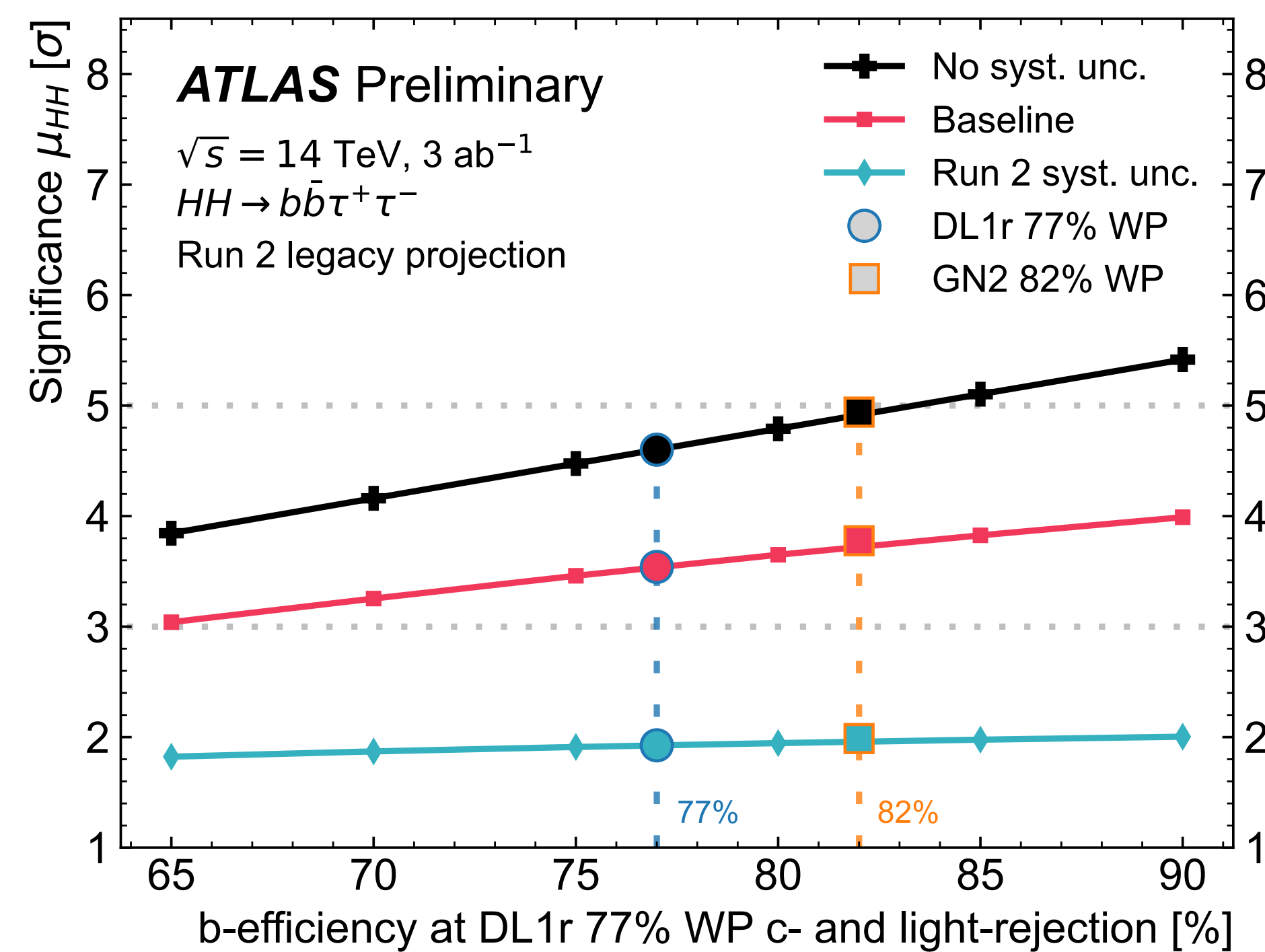
Benchmark: 3000 fb^{-1} at 14 TeV

Expected limits @ 68% CL:
 $\kappa_\lambda \in [0.71, 1.48]$



The HL-LHC Extrapolations

All these scenarios do not take into account possible improvements as GN2



The HL-LHC Extrapolations

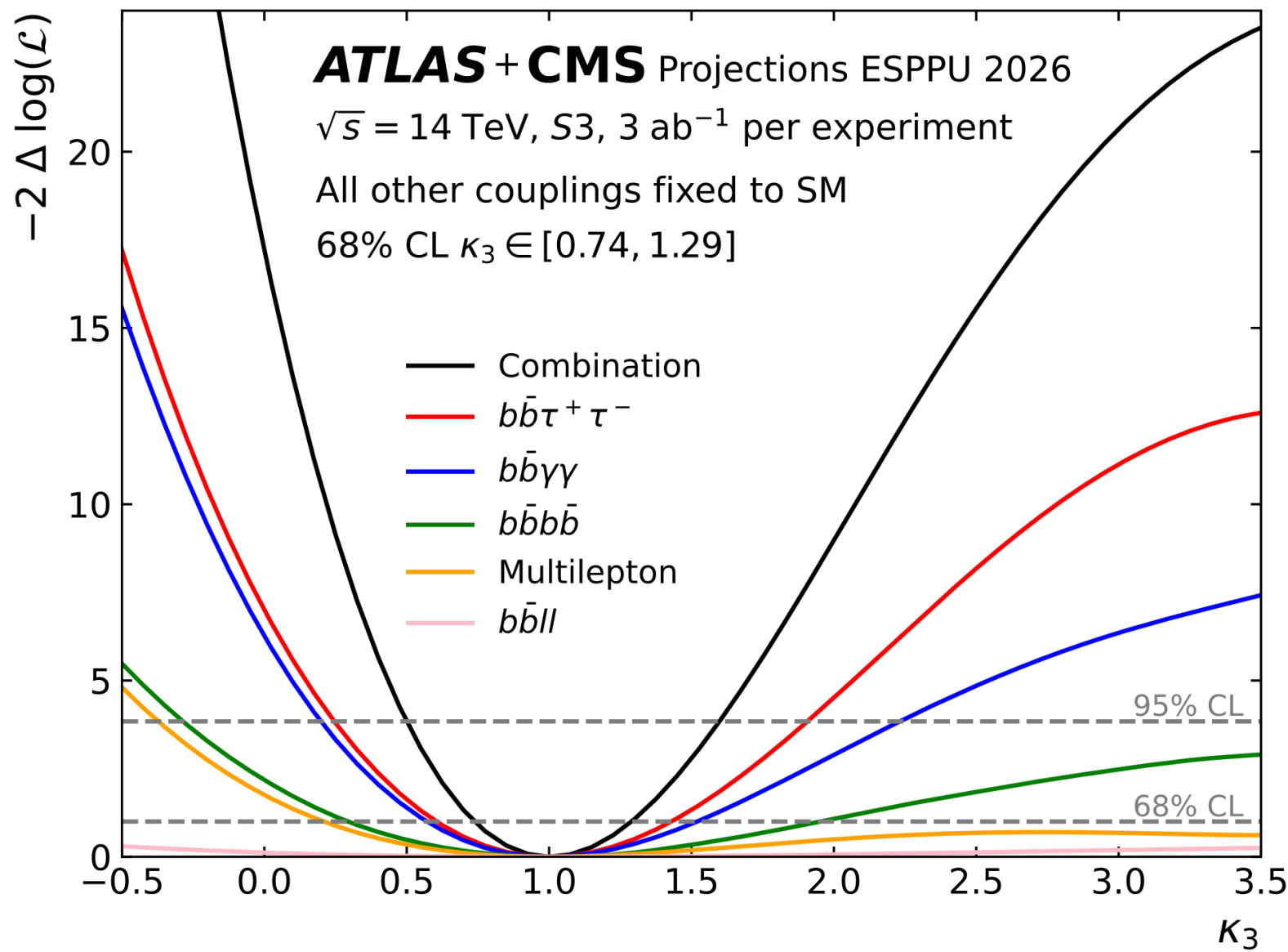
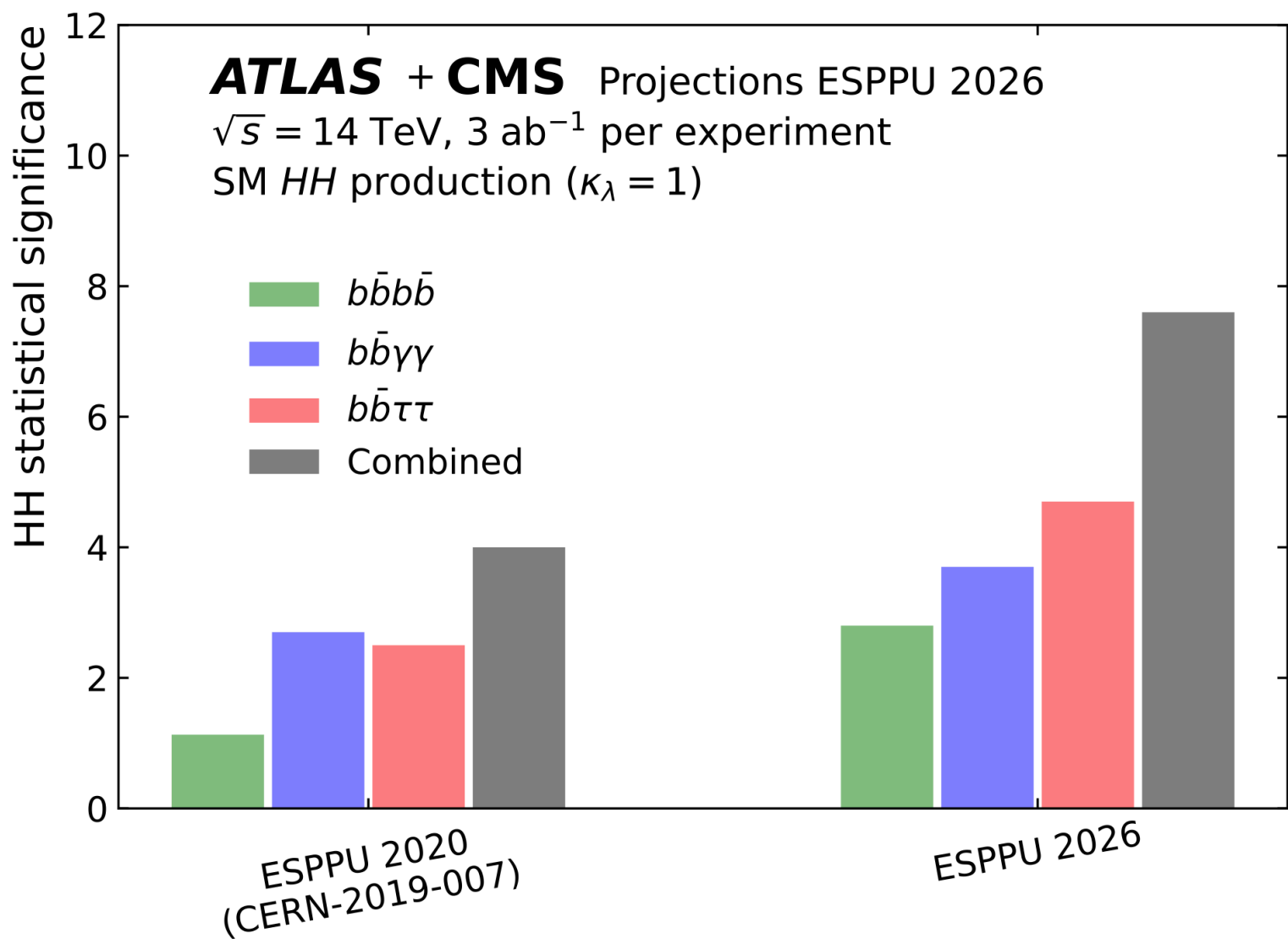
All the improvements in the analyses directly reflects to the updated combined extrapolation results where the expected sensitivity is almost doubled

ATLAS+CMS

Expected HH SM Significance: 7.2σ

Expected limits @ 68% CL:

$\kappa_\lambda \in [0.73, 1.31]$



The HL-LHC Extrapolations

All the improvements in the analyses directly reflects to the updated combined extrapolation results where the expected sensitivity is almost doubled

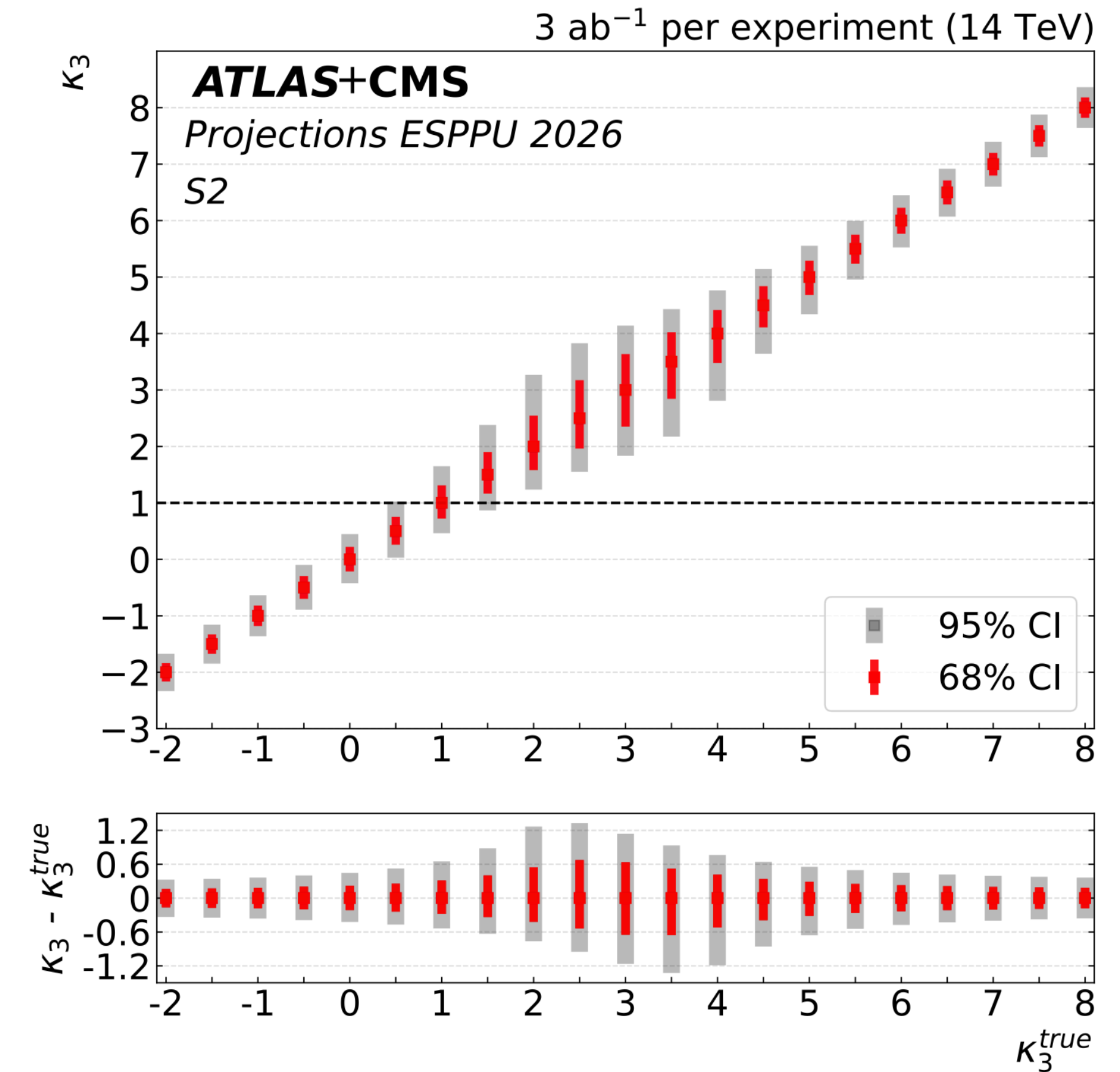
ATLAS+CMS

Expected HH SM Significance: 7.2σ

Expected limits @ 68% CL:

$$\kappa_\lambda \in [0.73, 1.31]$$

Limits provided for different κ_λ scenarios



Conclusions

The Higgs pairs production is crucial process to probe the Electroweak symmetry breaking

Best way to measure directly the λ self-coupling

Run 2 ATLAS data-taking has been fully exploited

Run 3 is ongoing and many more results have yet to come

HL-LHC is just around the corner and promising results lie ahead

Higgs Hunting 2025

Results and prospects in the electroweak symmetry breaking sector

15TH HIGGS HUNTING

15-17 July
Orsay
Paris

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