# Higgs self-coupling and HH measurements ATLAS


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on behalf of ATLAS

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Higgs Hunting 2025

15/07/2025

Paris



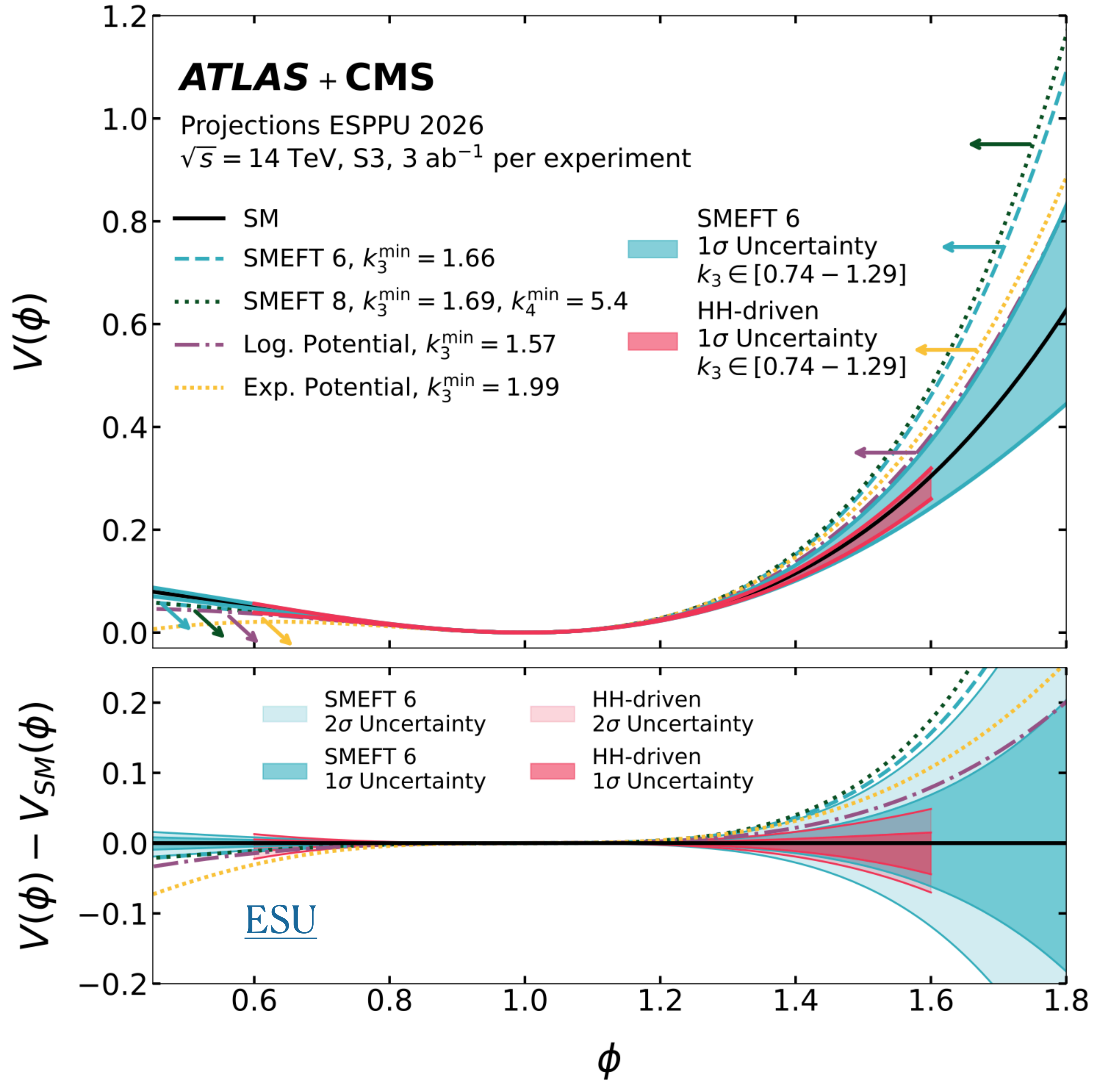
CERN

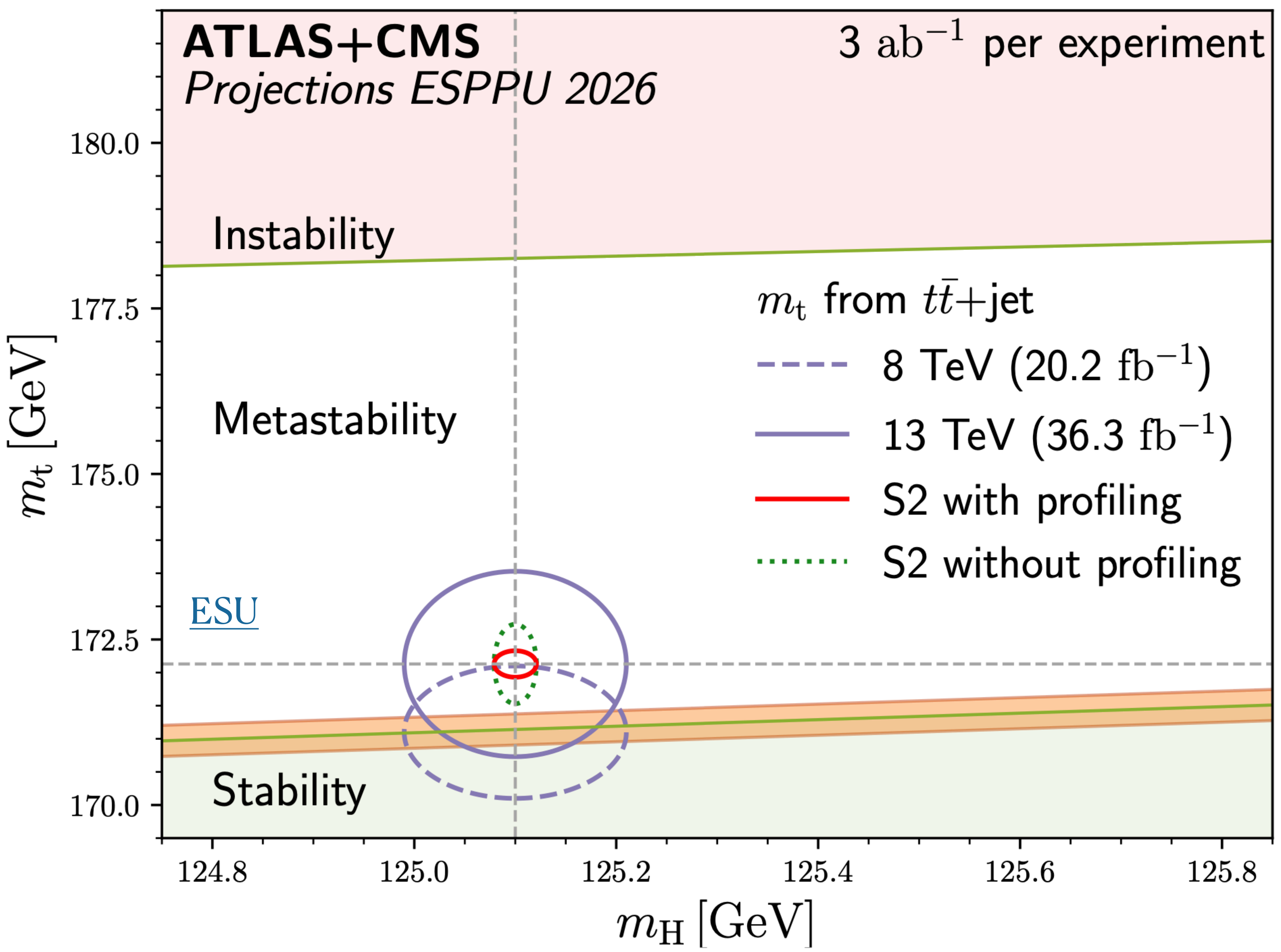
ATLAS EXPERIMENT

# Introduction

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

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




$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 \xrightarrow[\phi \to H + v]{\text{SSB}} V(H) = \frac{m_H^2}{2} H^2 + \lambda v H^3 + \frac{\lambda H^4}{4}$$

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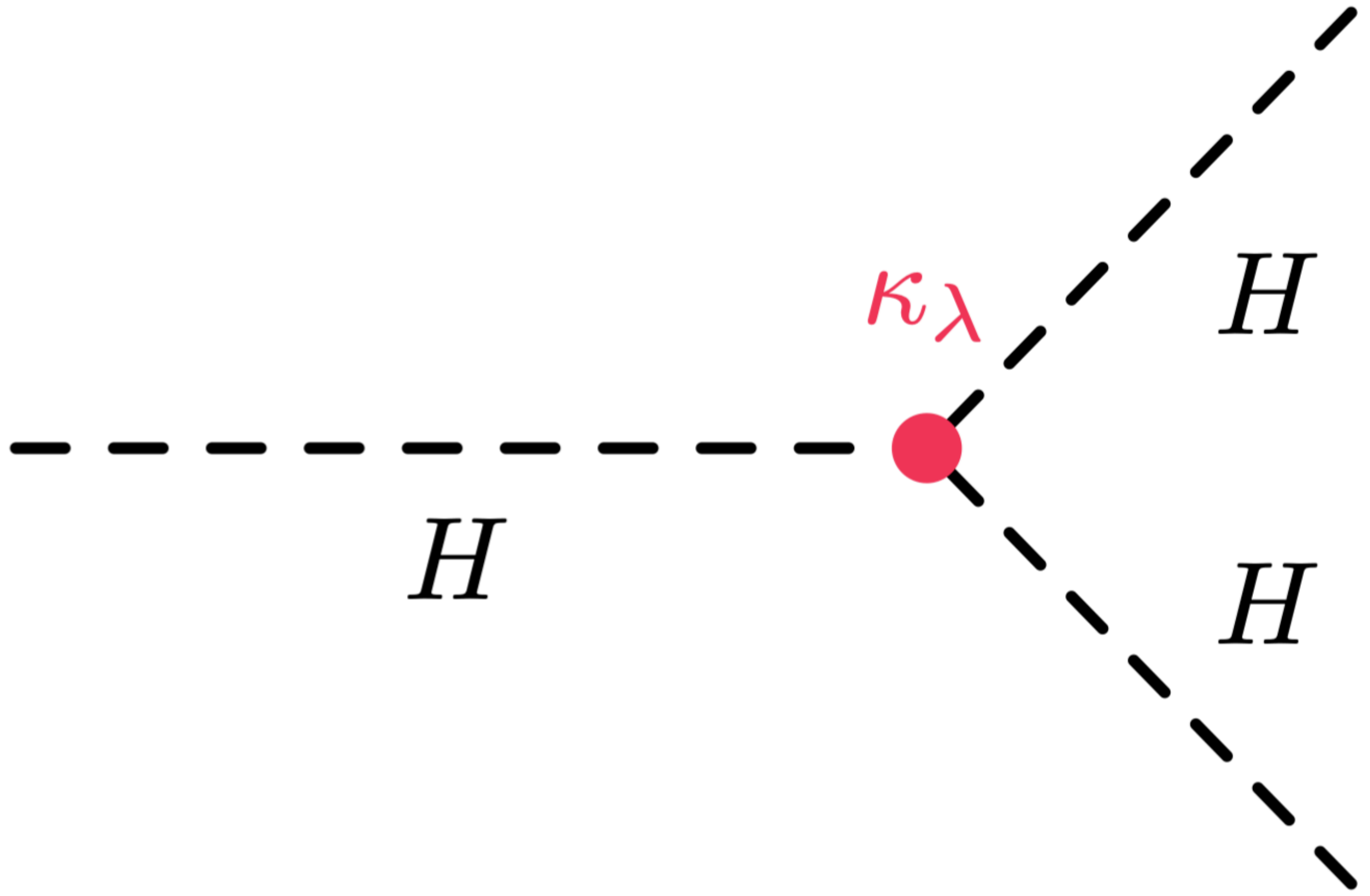
Best way to probe the self-coupling is via the Higgs-Pairs production (single-Higgs possible at NLO)

Results are provided in **upper limits on the signal-strength** $\mu_{HH}$

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



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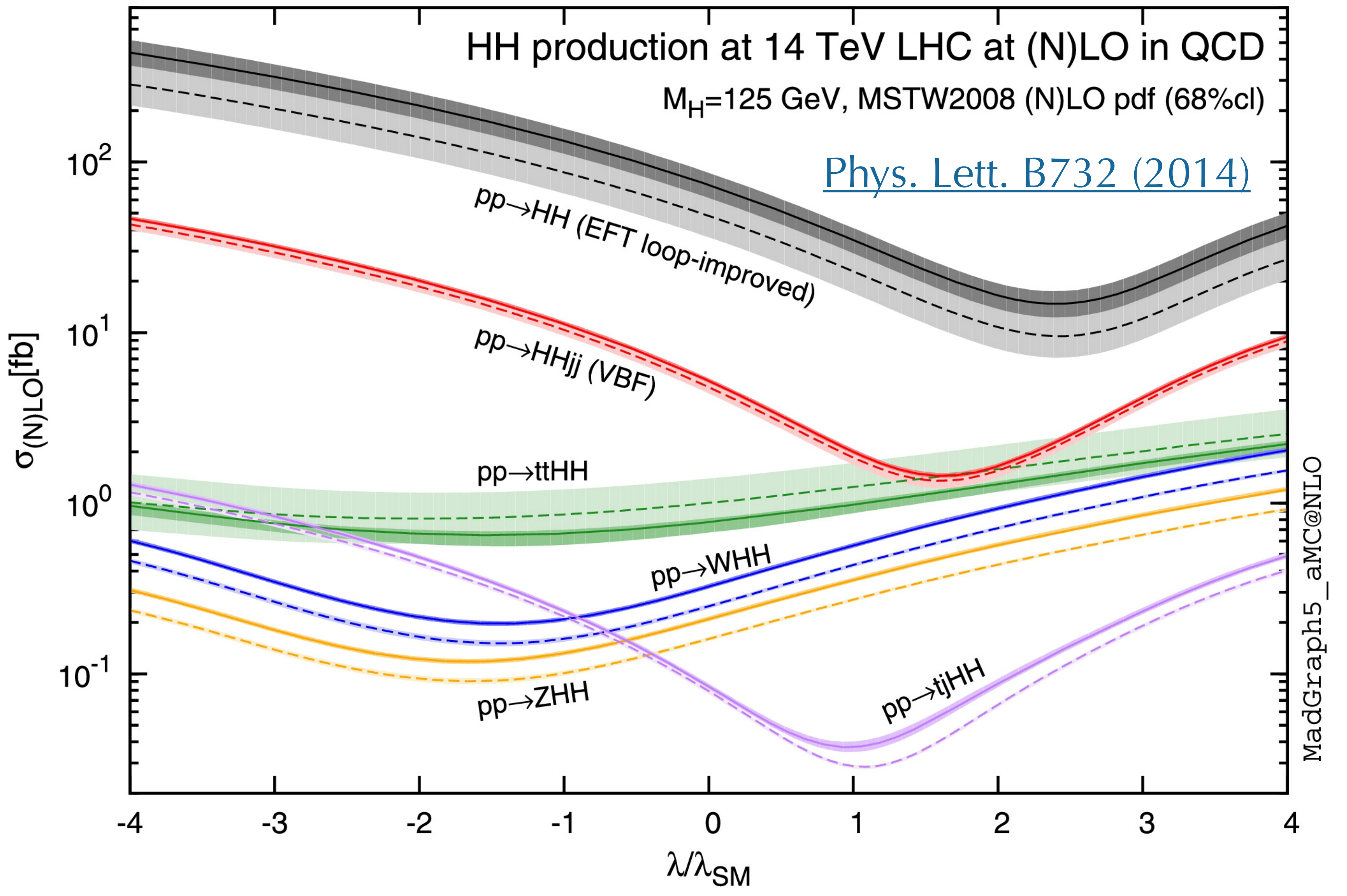
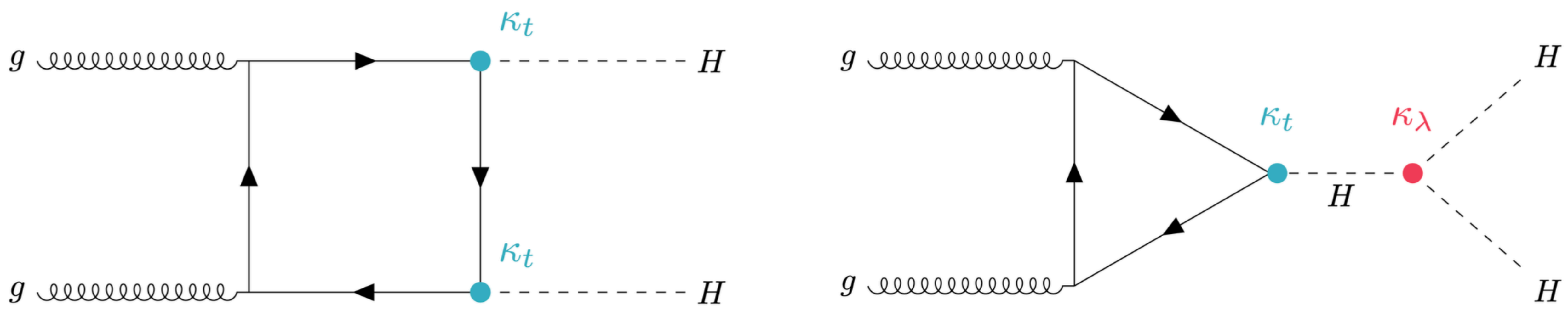



gluon-gluon Fusion (ggF) leading production mode @ LHC

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




(a) Box Diagram (b) Triangle Diagram

# Introduction

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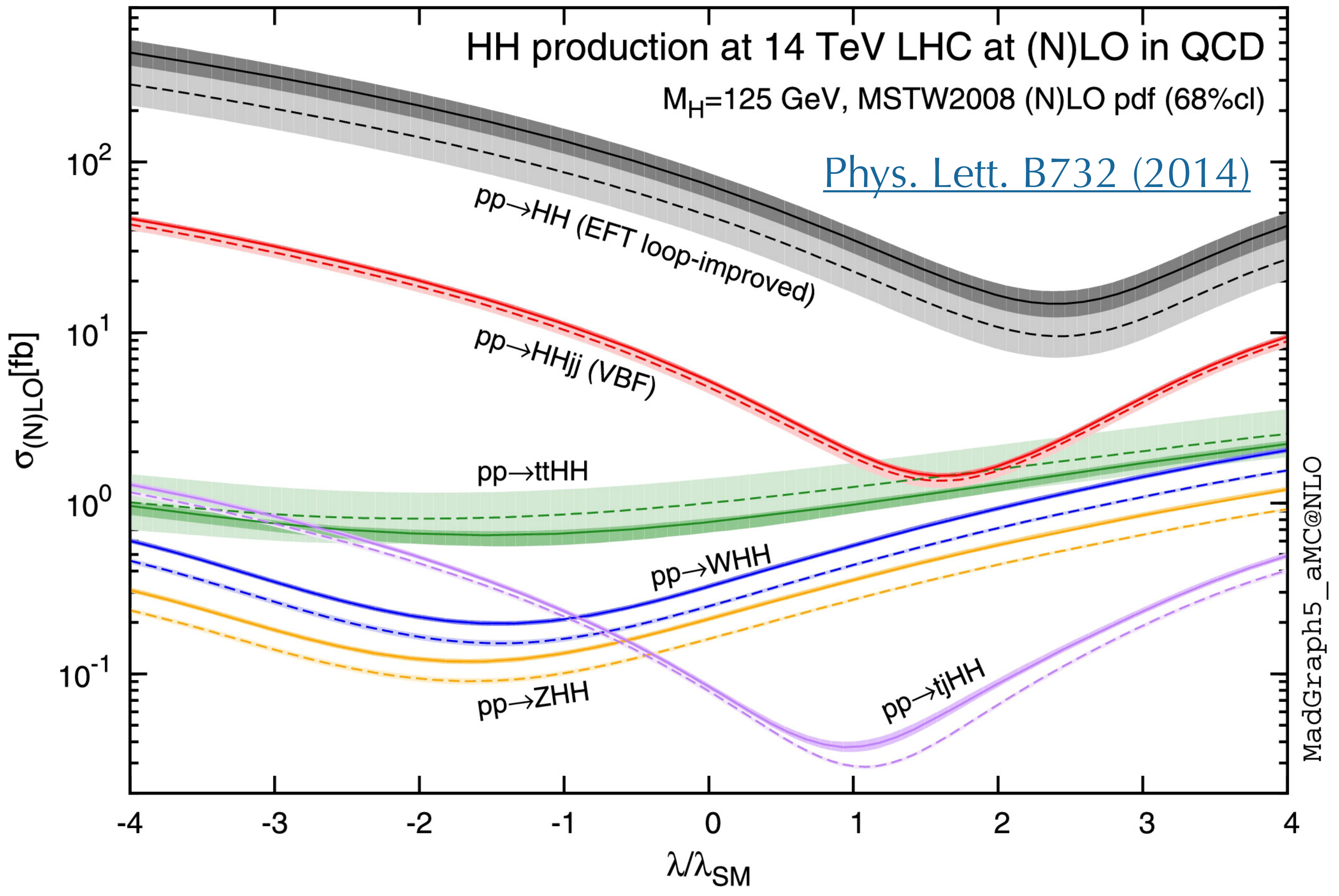
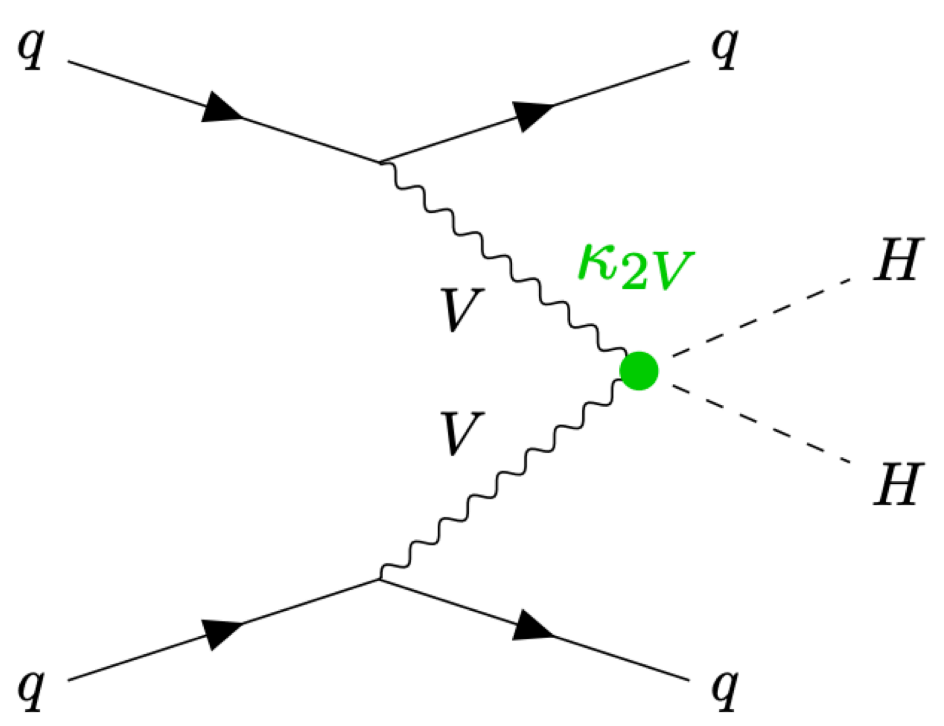



Vector Boson Fusion (VBF) second production mode @ LHC

- $\sigma_{VBF}^{SM}(SM) = 1.69 \pm 0.05\ fb$ @ 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 | ττ | ZZ | γγ |
|---|---|---|---|---|---|
| bb | 34% | | | | |
| WW | 25% | 4.6% | | | |
| ττ | 7.3% | 2.7% | 0.39% | | |
| ZZ | 3.1% | 1.1% | 0.33% | 0.069% | |
| γγ | 0.26% | 0.10% | 0.028% | 0.012% | 0.0005% |

# HH 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 | ττ | ZZ | γγ |
|---|---|---|---|---|---|
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# 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 | ττ | ZZ | γγ |
|---|---|---|---|---|---|
| bb | 34% | | | | |
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# HH Decay Channels

Several decay channels are combined together to maximize the sensitivity!

Main channels discussed today:

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

**Pros**: Very clean signature to trigger

**Cons**: Extremely small BR (0.26%)

| | bb | WW | ττ | ZZ | γγ |
|---|---|---|---|---|---|
| bb | 34% | | | | |
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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 | ττ | ZZ | γγ |
|---|---|---|---|---|---|
| bb | 34% | | | | |
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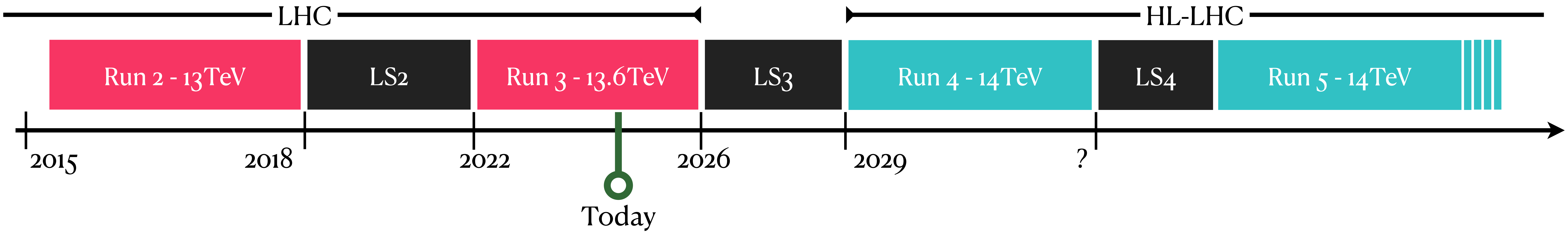
| γγ | 0.26% | 0.10% | 0.028% | 0.012% | 0.0005% |

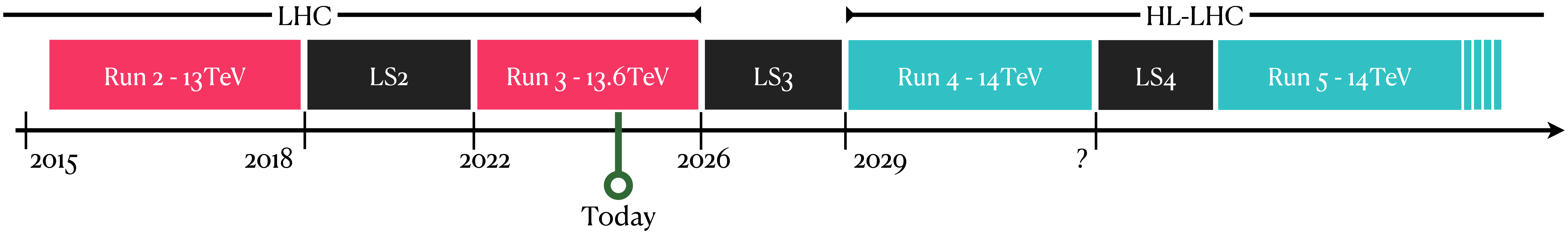
# Outline



LHC
HL-LHC
Run 2 - 13TeV
LS2
Run 3 - 13.6TeV
LS3
Run 4 - 14TeV
LS4
Run 5 - 14TeV
2015
2018
2022
2026
2029
?
Today


Higgs Hunting 2025
Results and prospects in the electroweak symmetry breaking sector
15-17
July
Orsay
Paris
www.higgshunting.fr

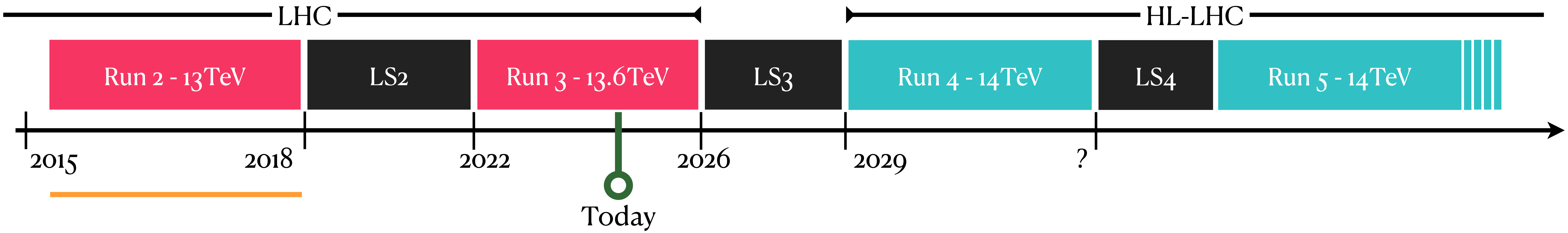
# Outline





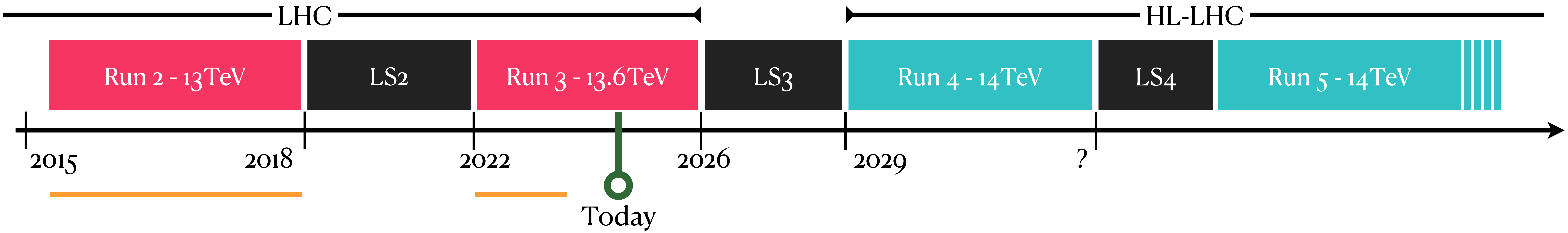
Note: I will present only a sub-set of all the results!

# ATLAS HH analyses



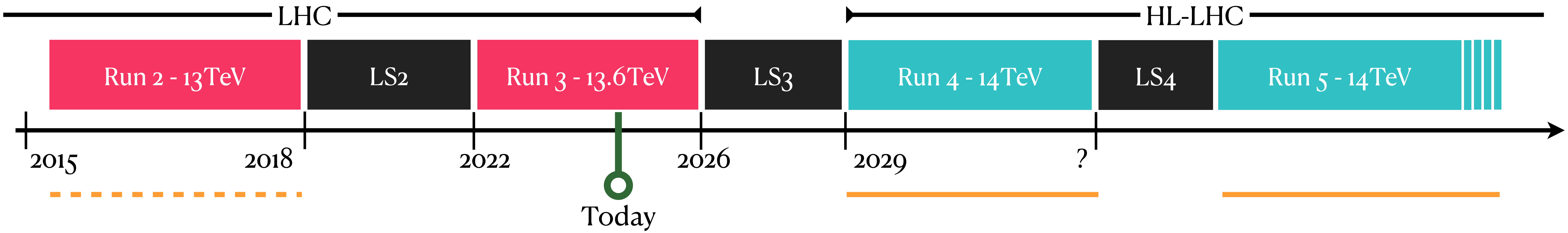

- Run 2 analyses and their combination with 140 $fb^{-1}$ collected data
  - HH Combination: Phys. Rev. Lett. 133 (2024) 101801
    - HH($b\bar{b}\tau\tau$): Phys. Rev. D 110 (2024) 032012
    - HH($b\bar{b}\gamma\gamma$): JHEP 01 (2024) 066
    - HH($b\bar{b}b\bar{b}$): Phys. Rev. D 108 (2023) 052003 (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
  - HH($b\bar{b}\gamma\gamma$) Run 2 + partial (22-24) Run 3: [Arxiv: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:
  - HH($b\bar{b}\tau\tau$): ATL-PHYS-PUB-2024-016
  - HH($b\bar{b}\gamma\gamma$): ATL-PHYS-PUB-2025-001
  - 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

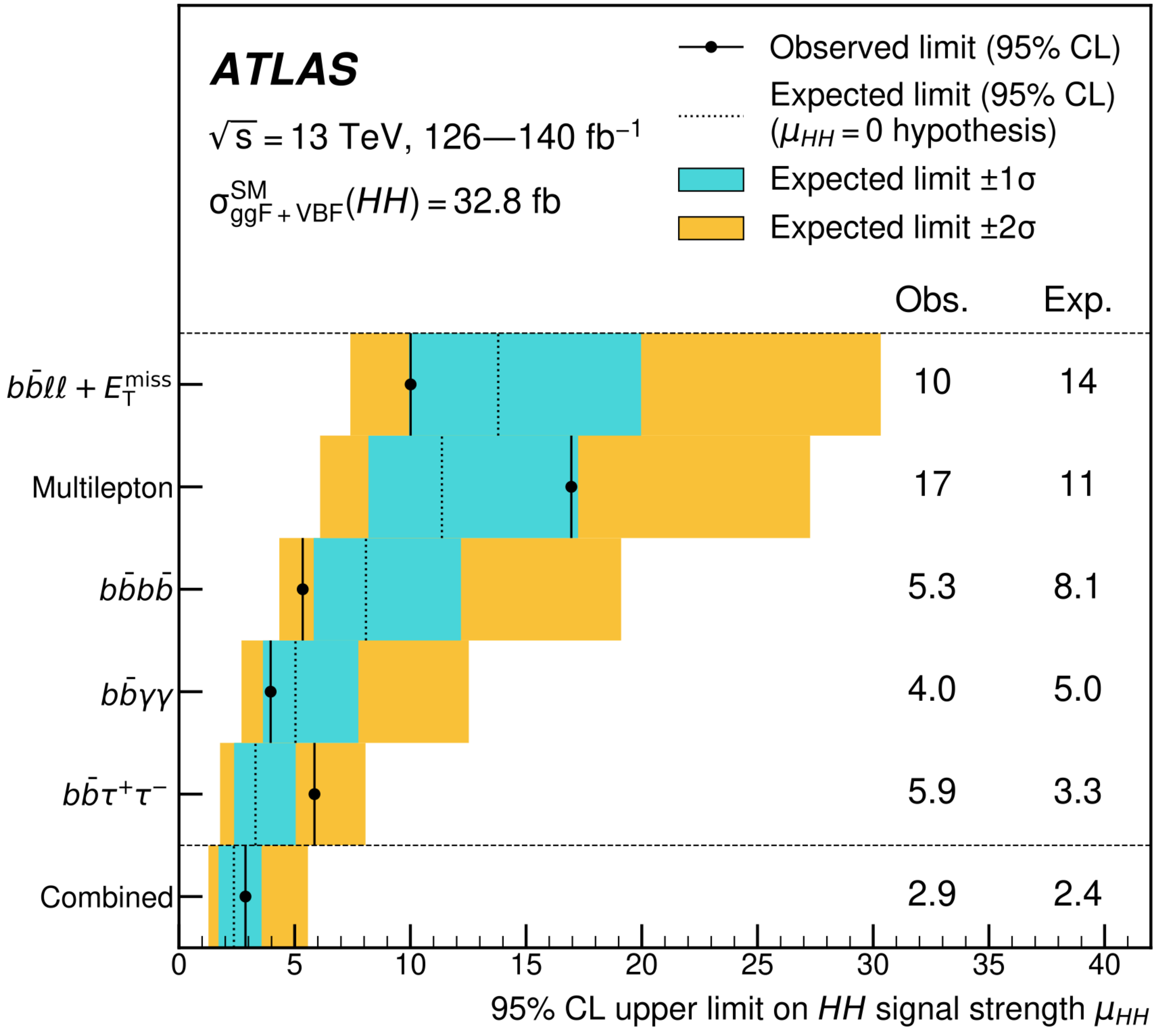
Improvements in the combination:

- 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 $\mu_{HH}$:** $2.9(2.4) \times SM$

17% improvement wrt previous result:

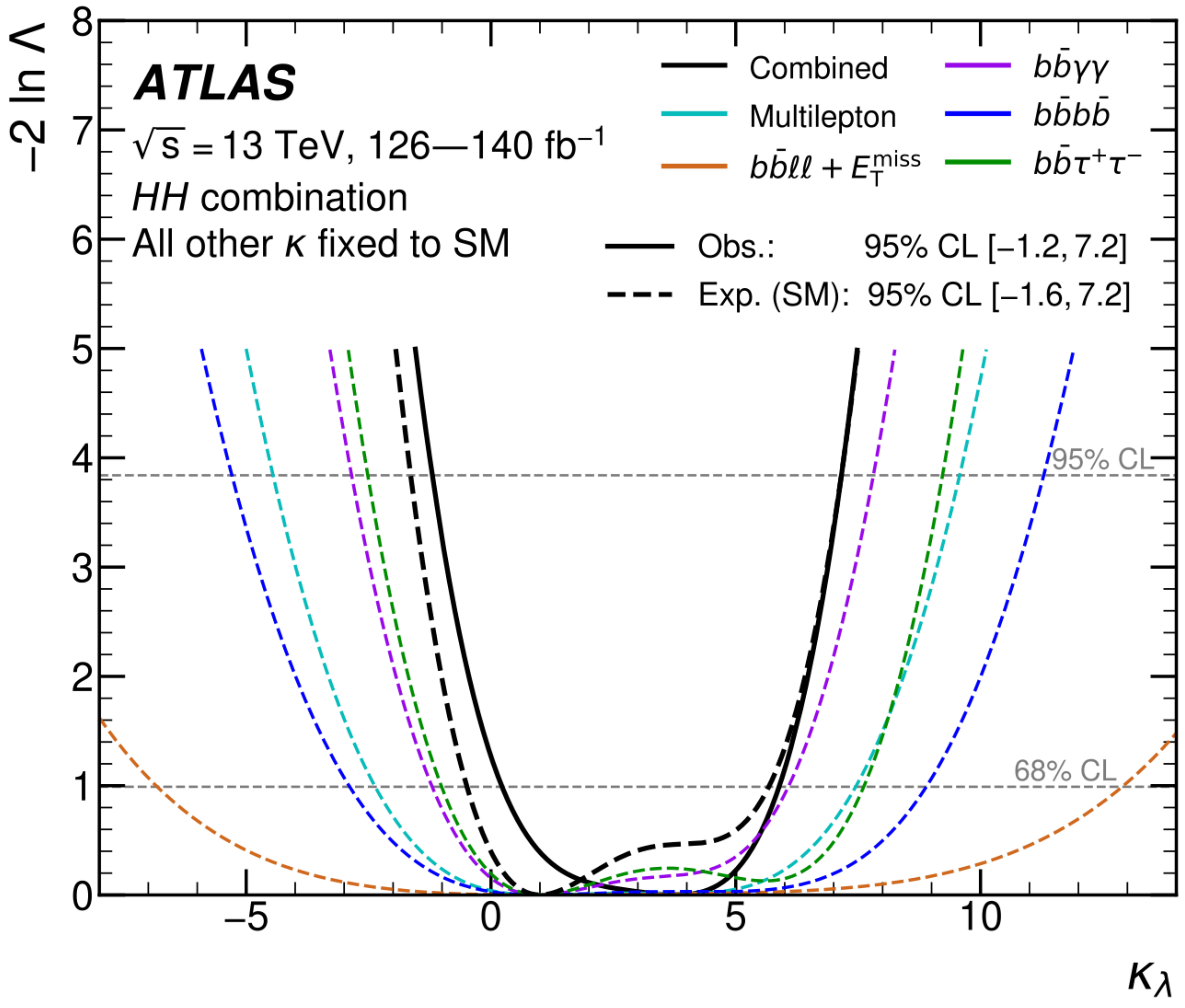
- 13% leading channels
- 4% other channels

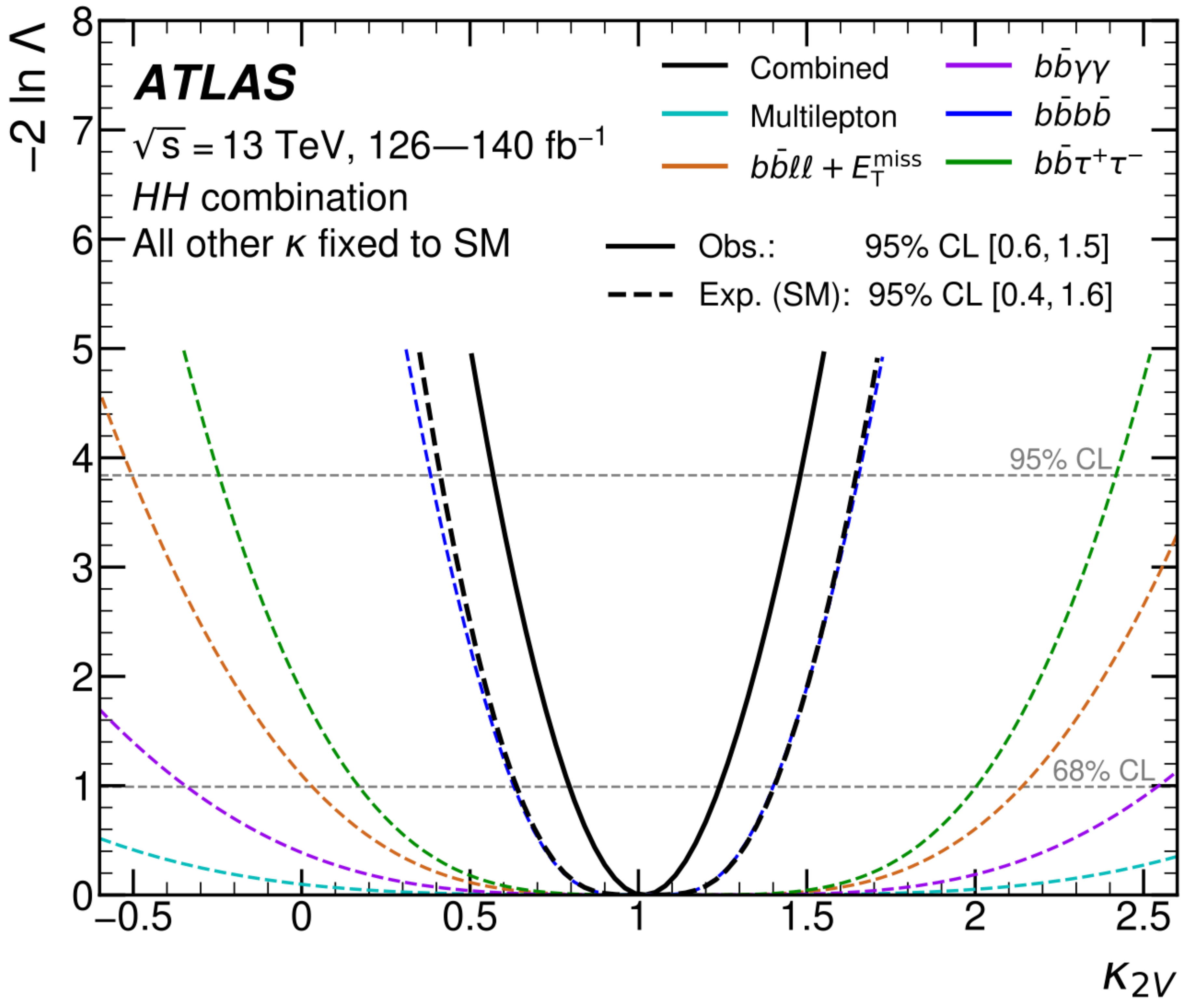



**Observed HH SM Significance: 0.4 $\sigma$**

**Expected HH SM Significance: 1.0 $\sigma$**

# Run 2 HH Combination




**Observed (Expected) limits @ 95% CL:**

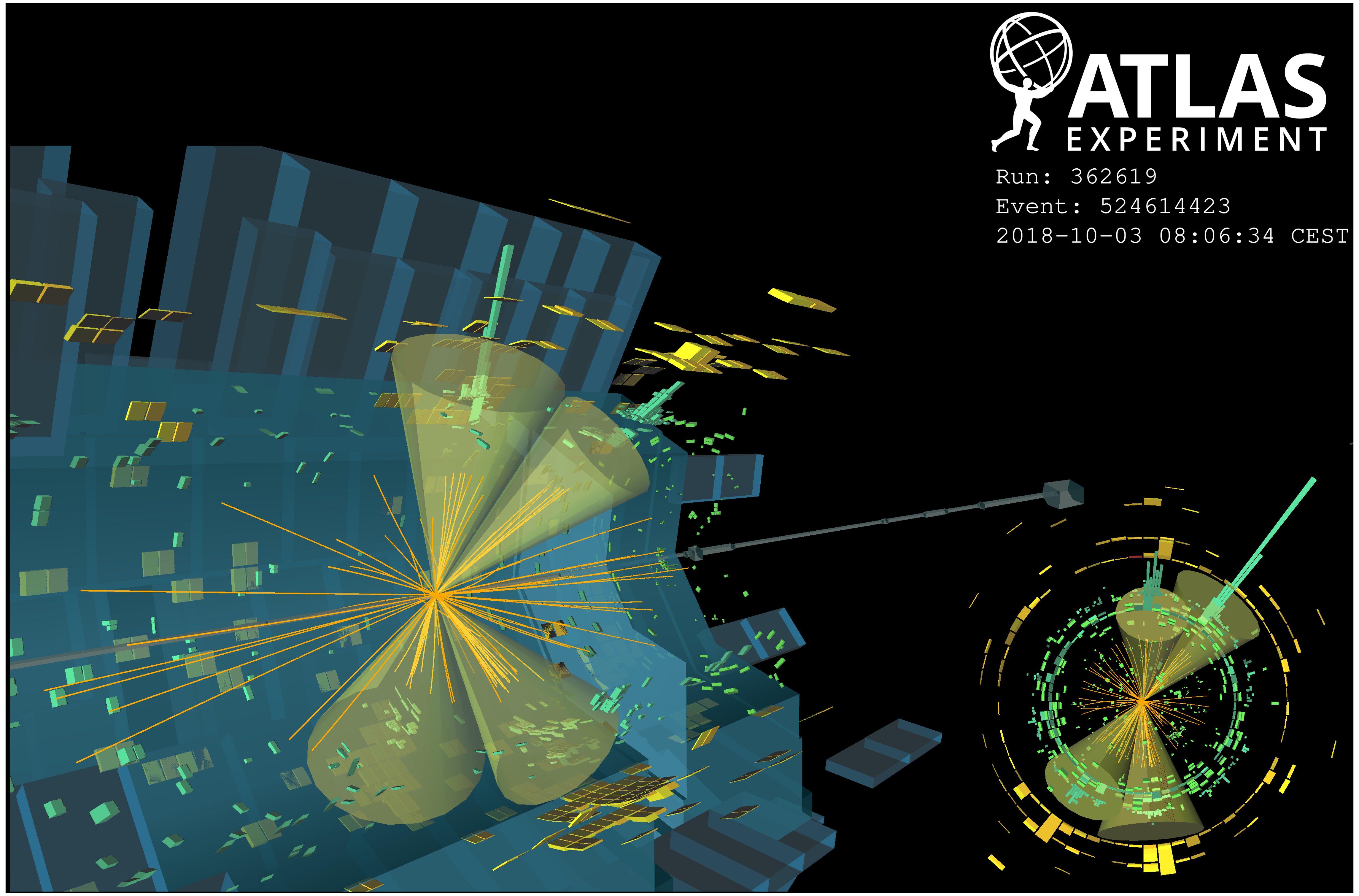
$\kappa_\lambda \in [-1.2, 7.2]([-1.6, 7.2])$

**Observed (Expected) limits @ 95% CL:**

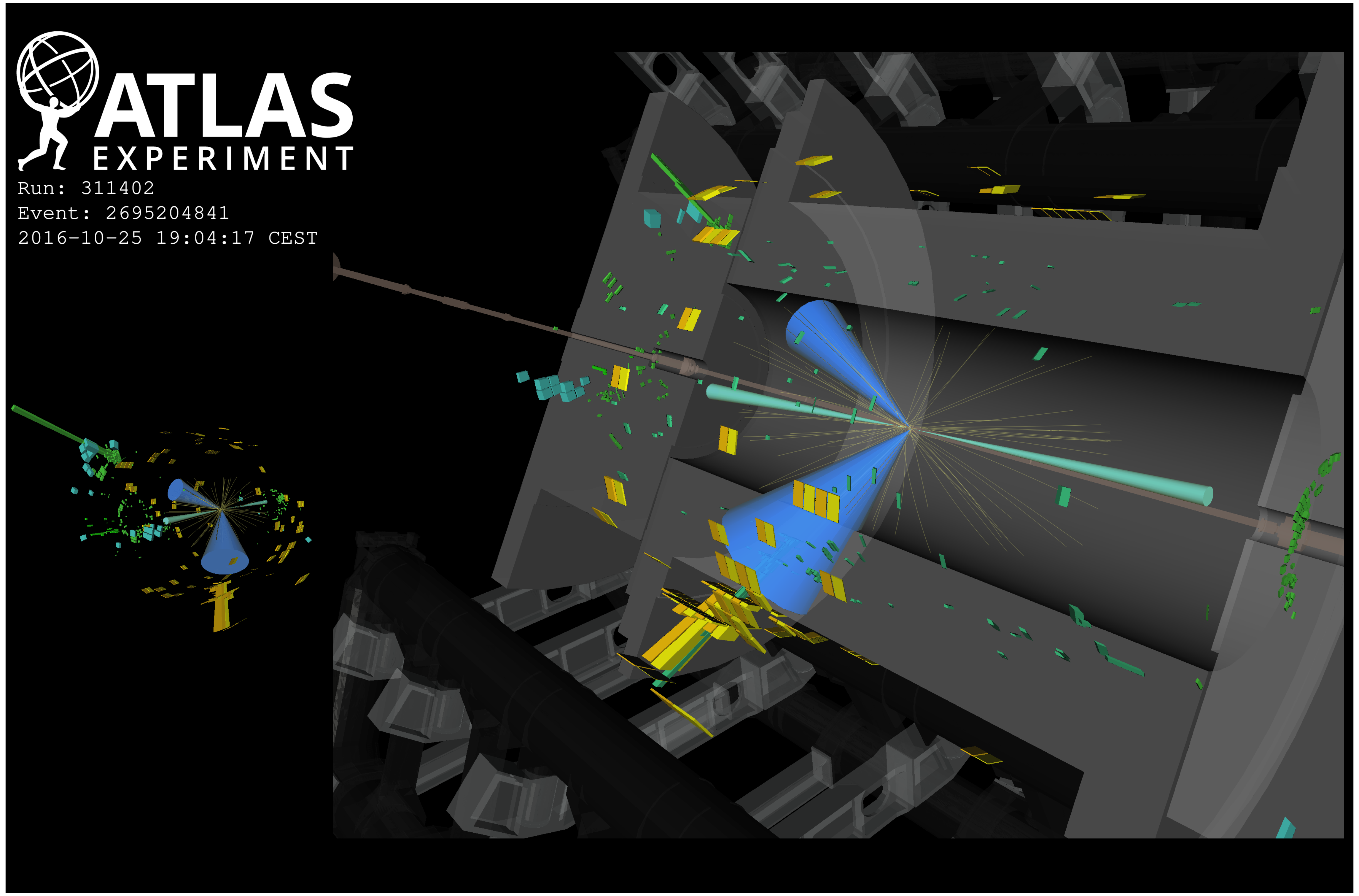
$\kappa_{2V} \in [0.6, 1.5]([0.4, 1.6])$

# Run 2 HH(bbbb)

**Resolved Topology**

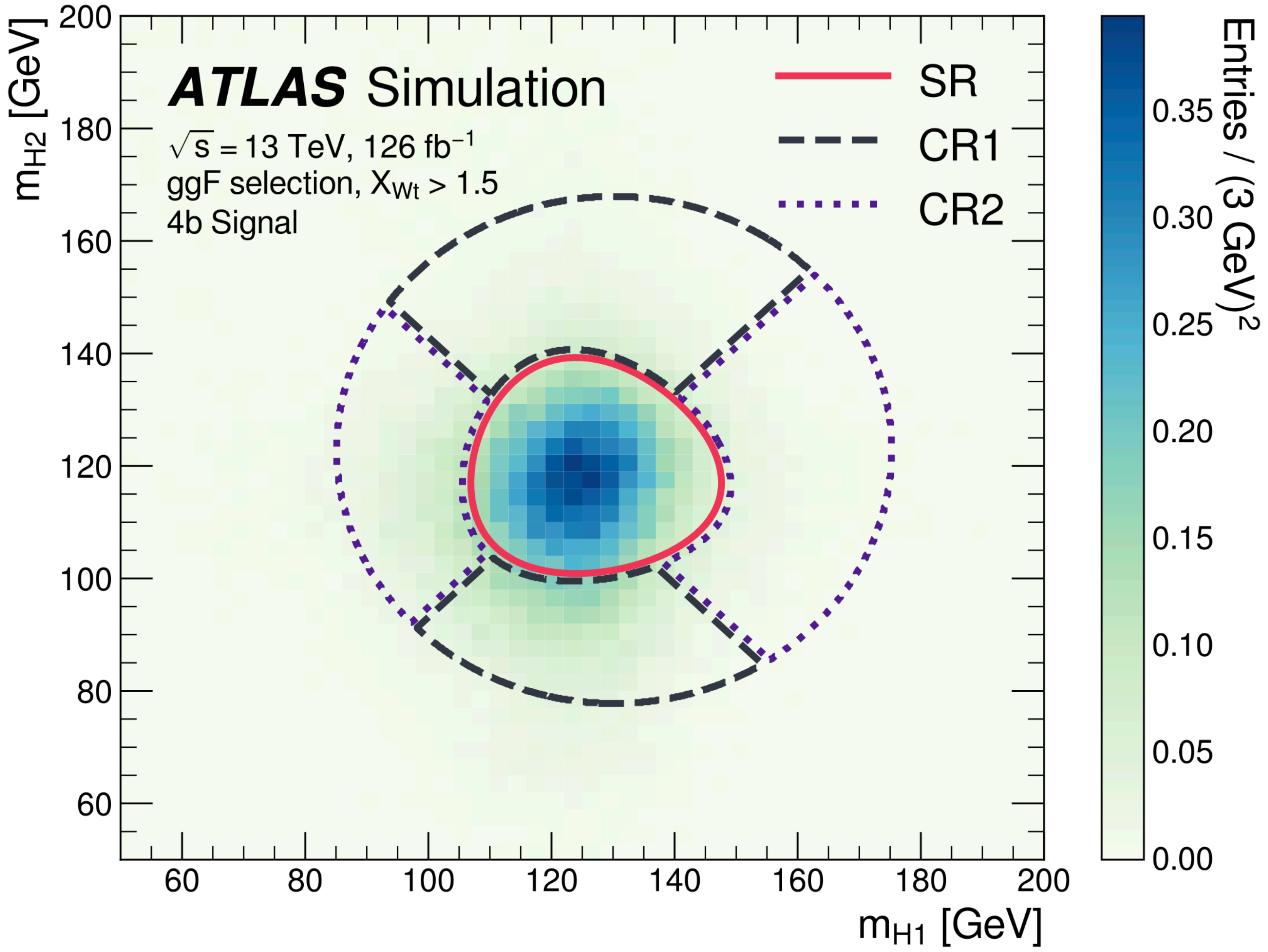



**VBF Boosted Topology**



# Run 2 HH(bbbb): Resolved

Phys. Rev. D 108 (2023) 052003

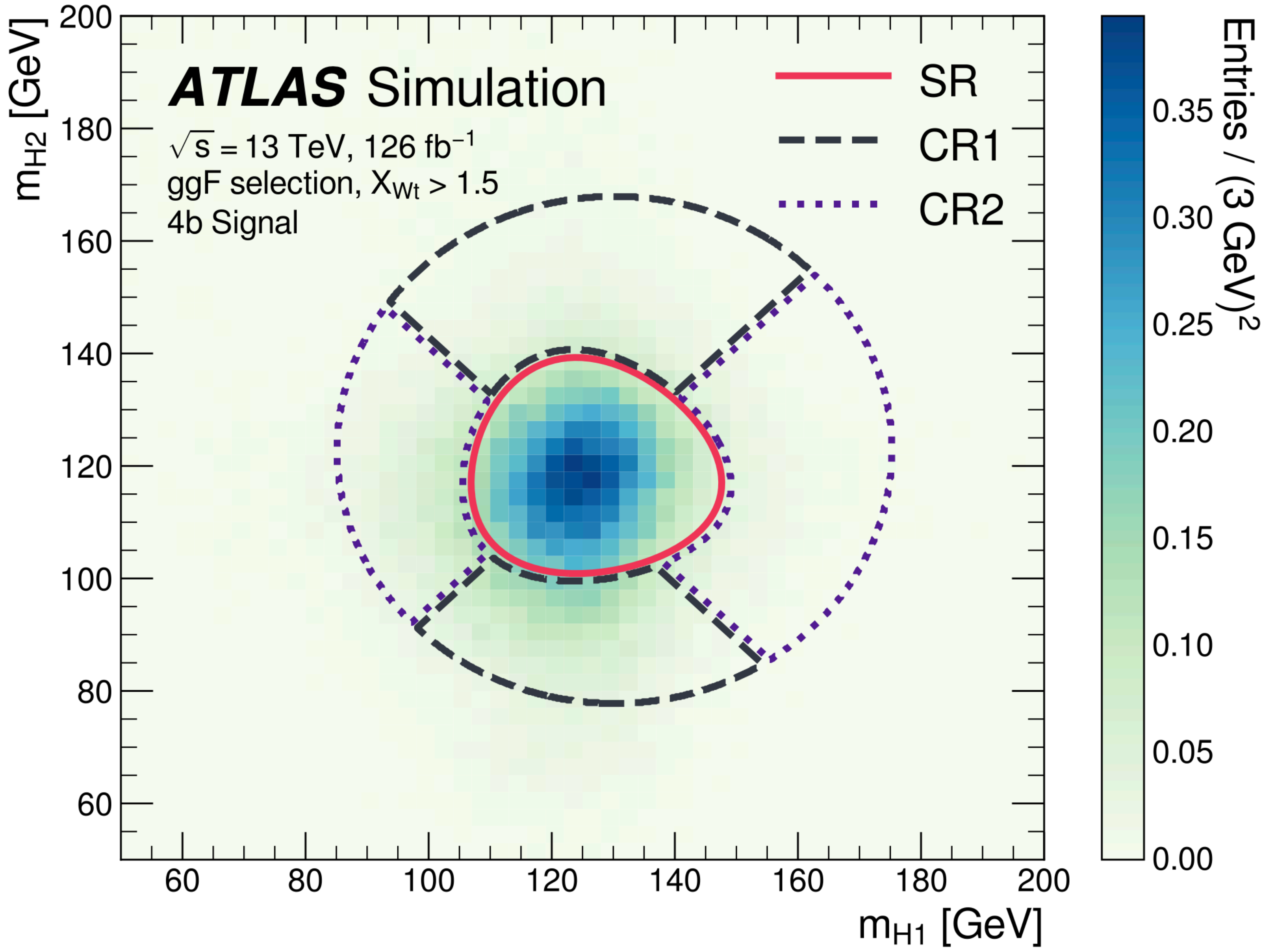


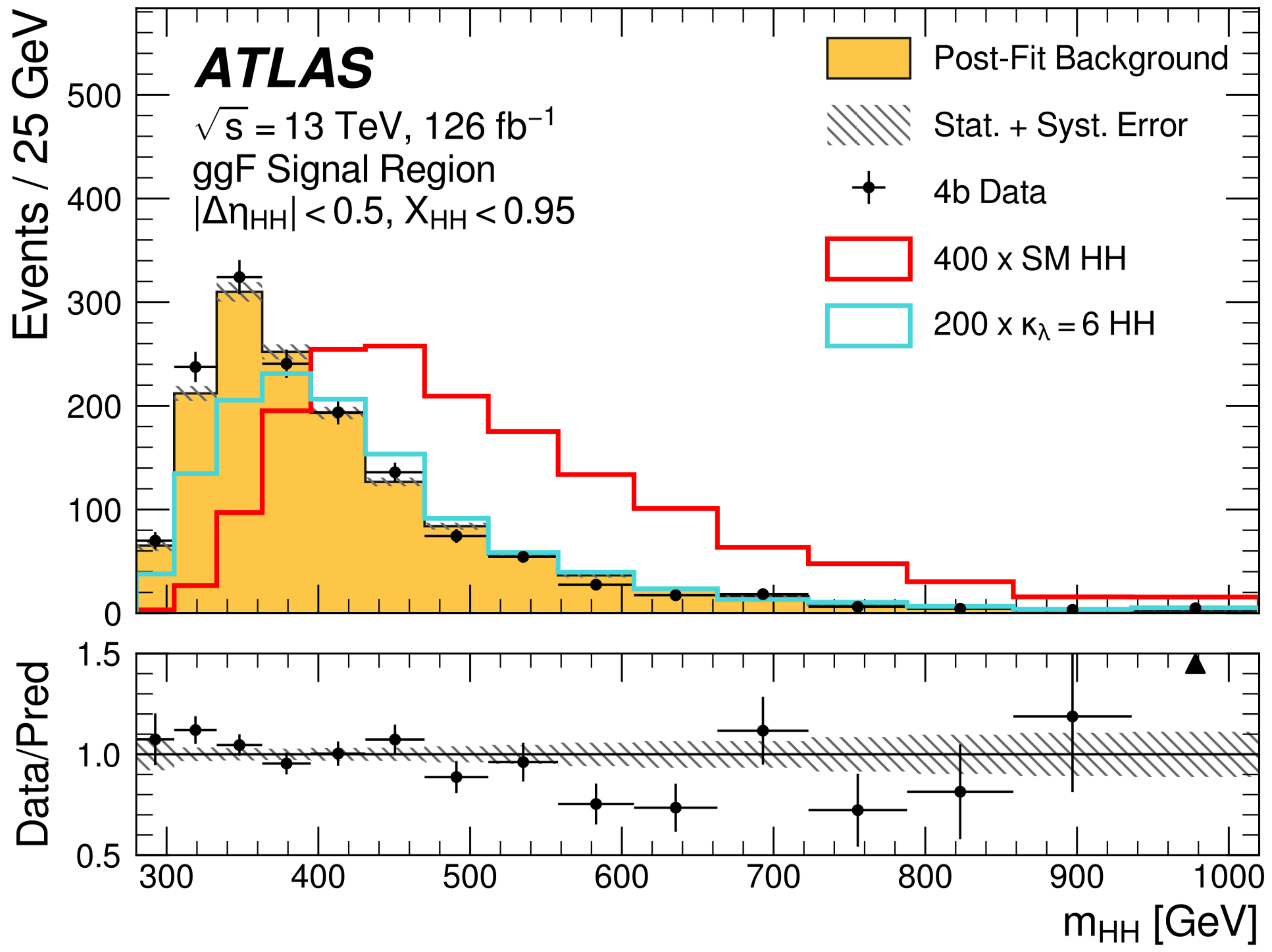

SR and CR defined based on $m_H$ of the pairs

Reweighting CR1 and Interpolation from CR2

# Run 2 HH(bbbb): Resolved

Phys. Rev. D 108 (2023) 052003




SR and CR defined based on $m_H$ of the pairs

Reweighting CR1 and Interpolation from CR2

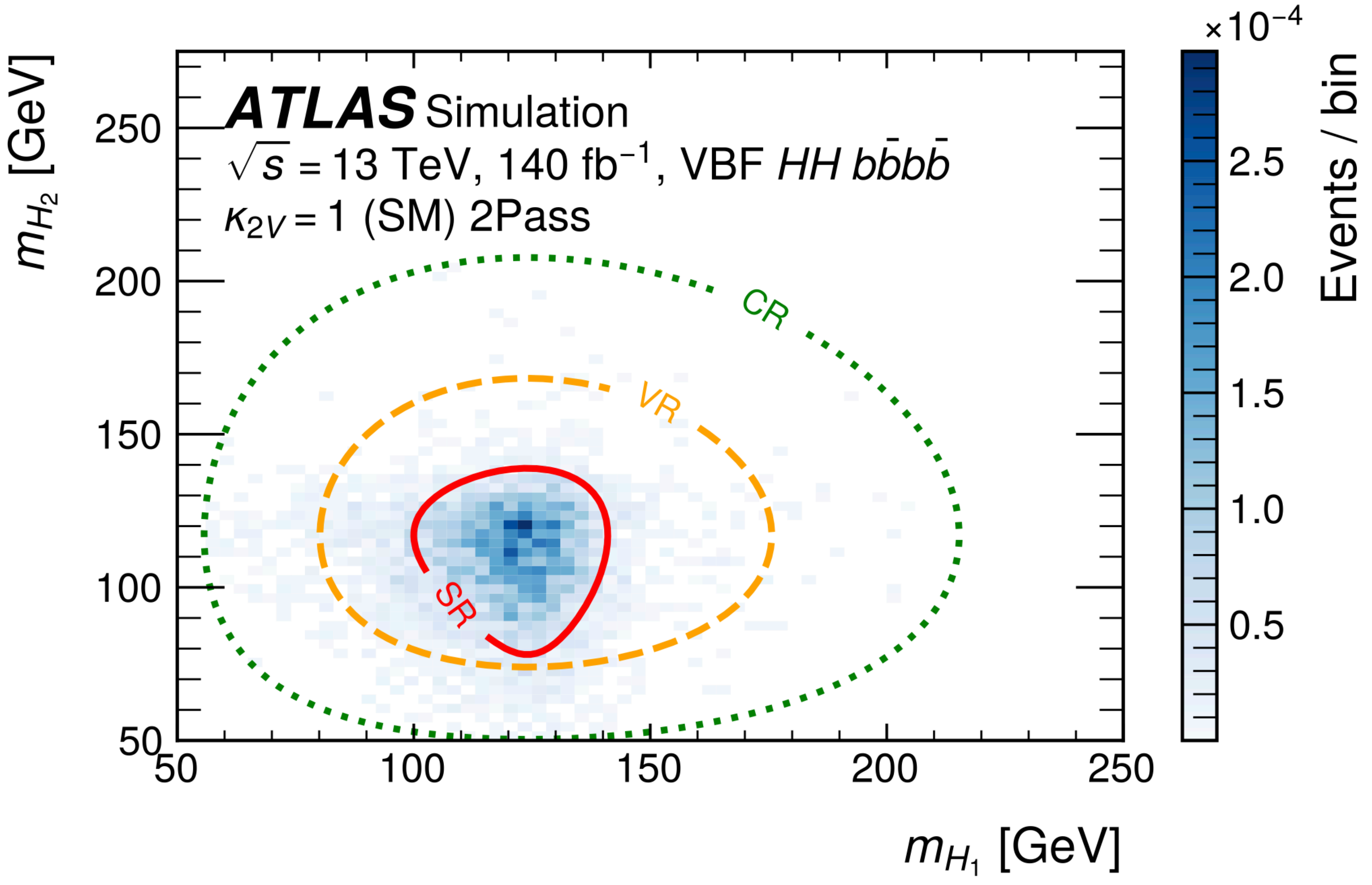
Fit performed in bins of $m_{HH}$ and $|\Delta\eta_{HH}|$

**Observed (Expected) upper limits @ 95% CL on $\mu_{HH}$:** $5.4(8.1) \times SM$

$\kappa_\lambda \in [-3.9,\ 11.1]([-4.6,\ 10.8])$

# Run 2 HH(bbbb): Boosted

Phys. Lett. B 858 (2024) 139007

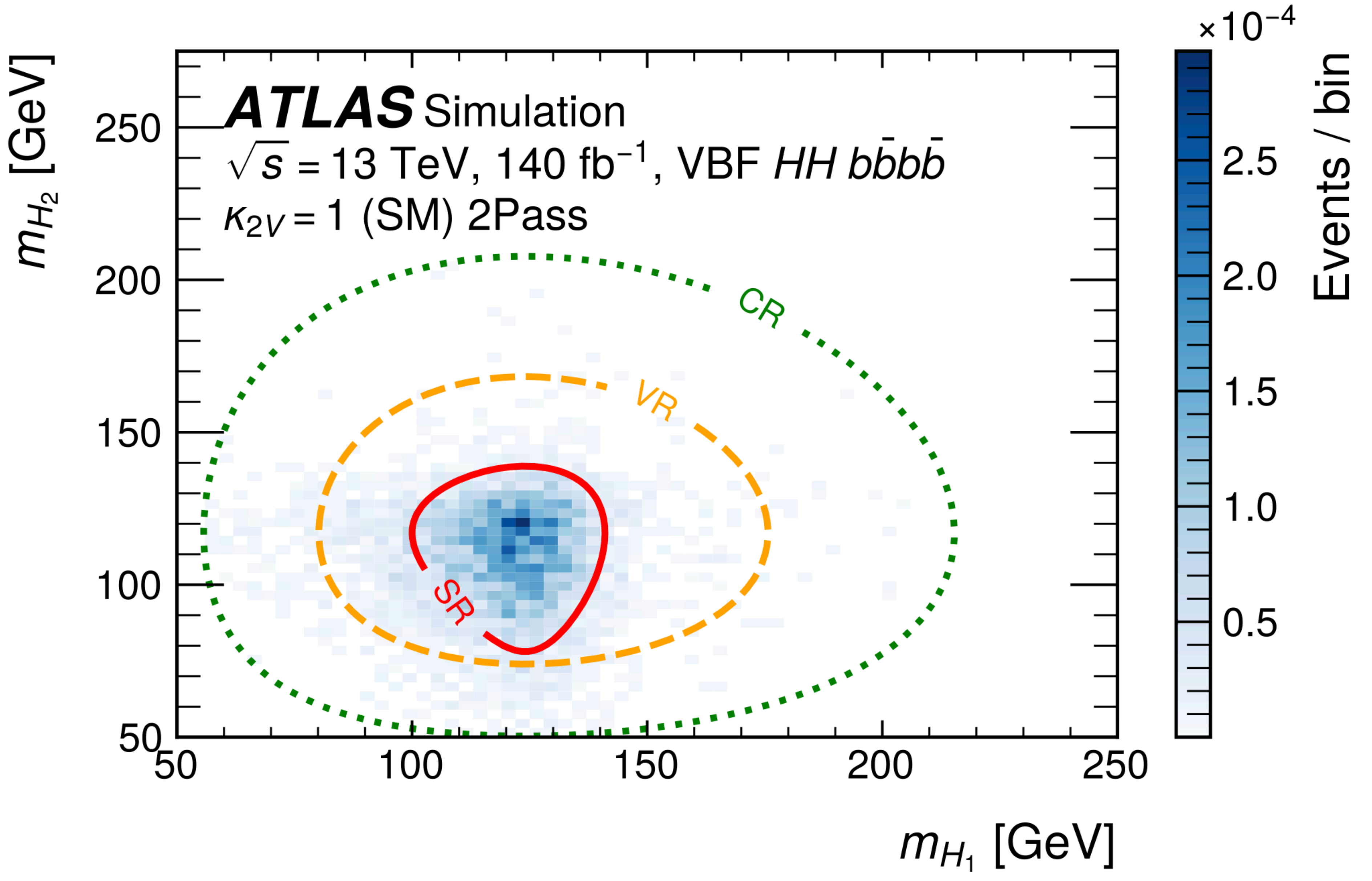


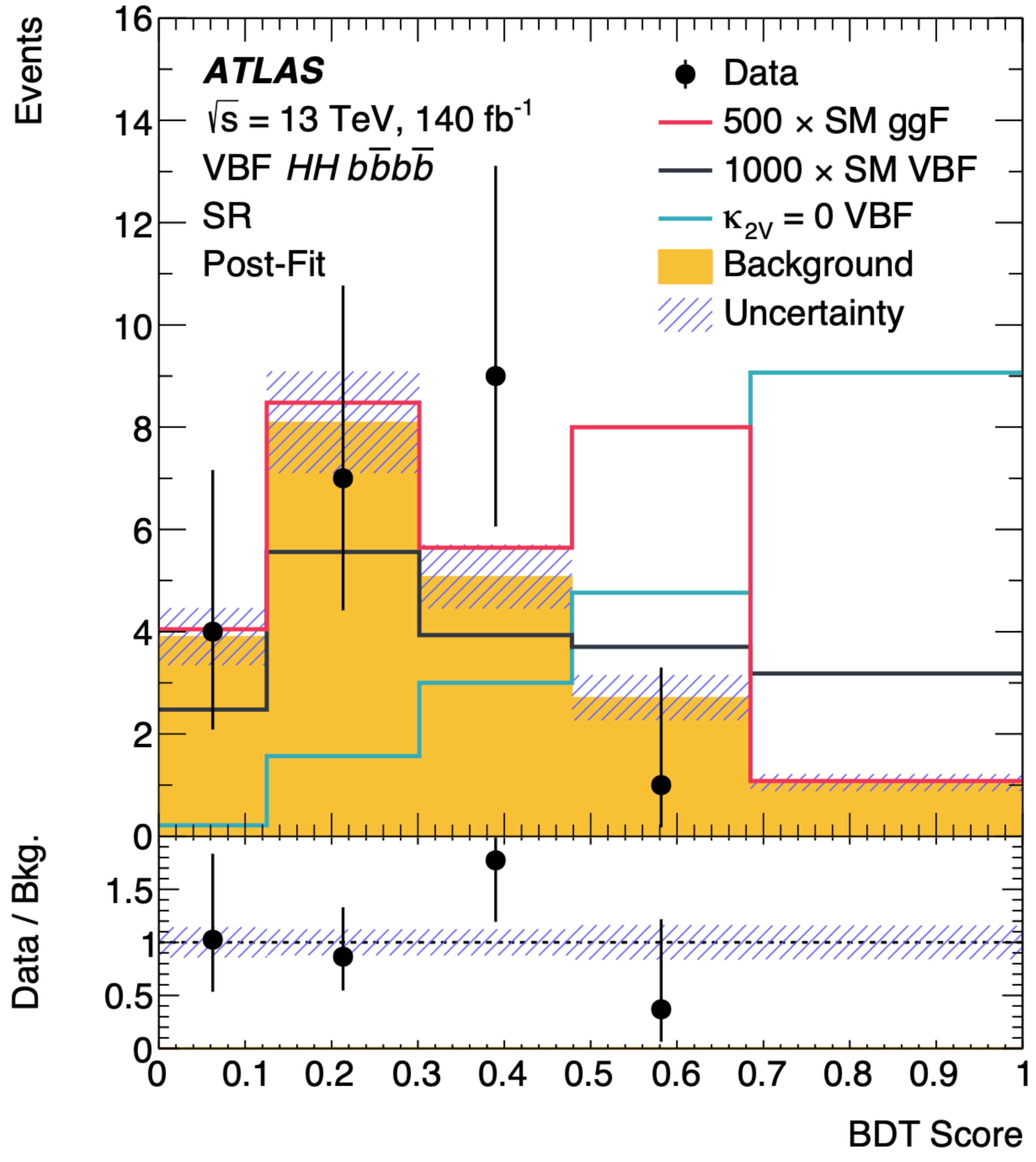

Similar procedure as Resolved

SR, VR and CR

# Run 2 HH(bbbb): Boosted

Phys. Lett. B 858 (2024) 139007




Similar procedure as Resolved

SR, VR and CR

Fit performed on BDT score

**Observed (Expected) limits @ 95% CL:**

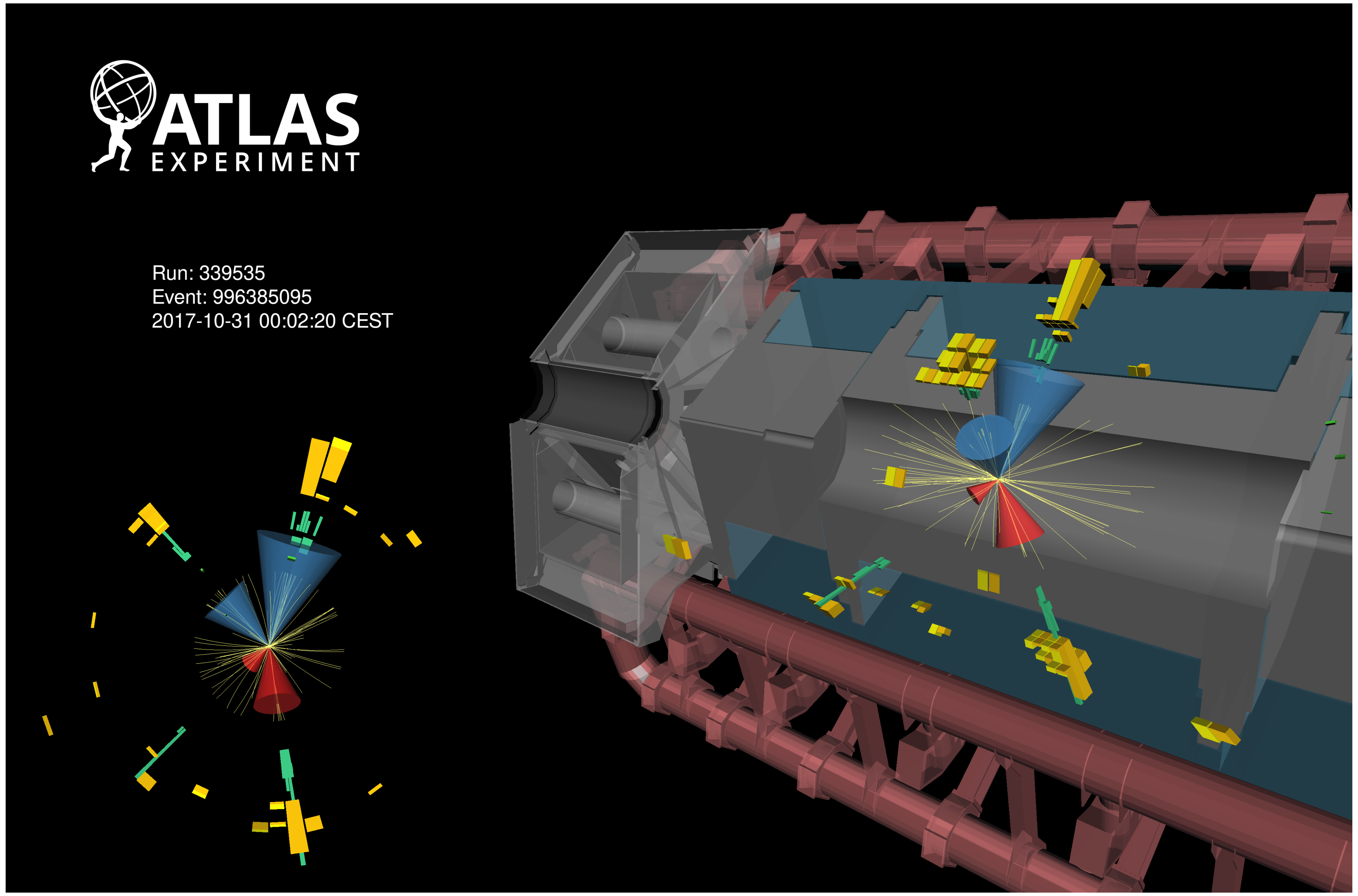
$\kappa_{2V} \in [-0.55,\ 1.49]([-0.37,\ 1.67])$ ✨

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

Phys. Rev. D 110 (2024) 032012

Target two different final state depending on the $\tau$

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



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Phys. Rev. D 110 (2024) 032012

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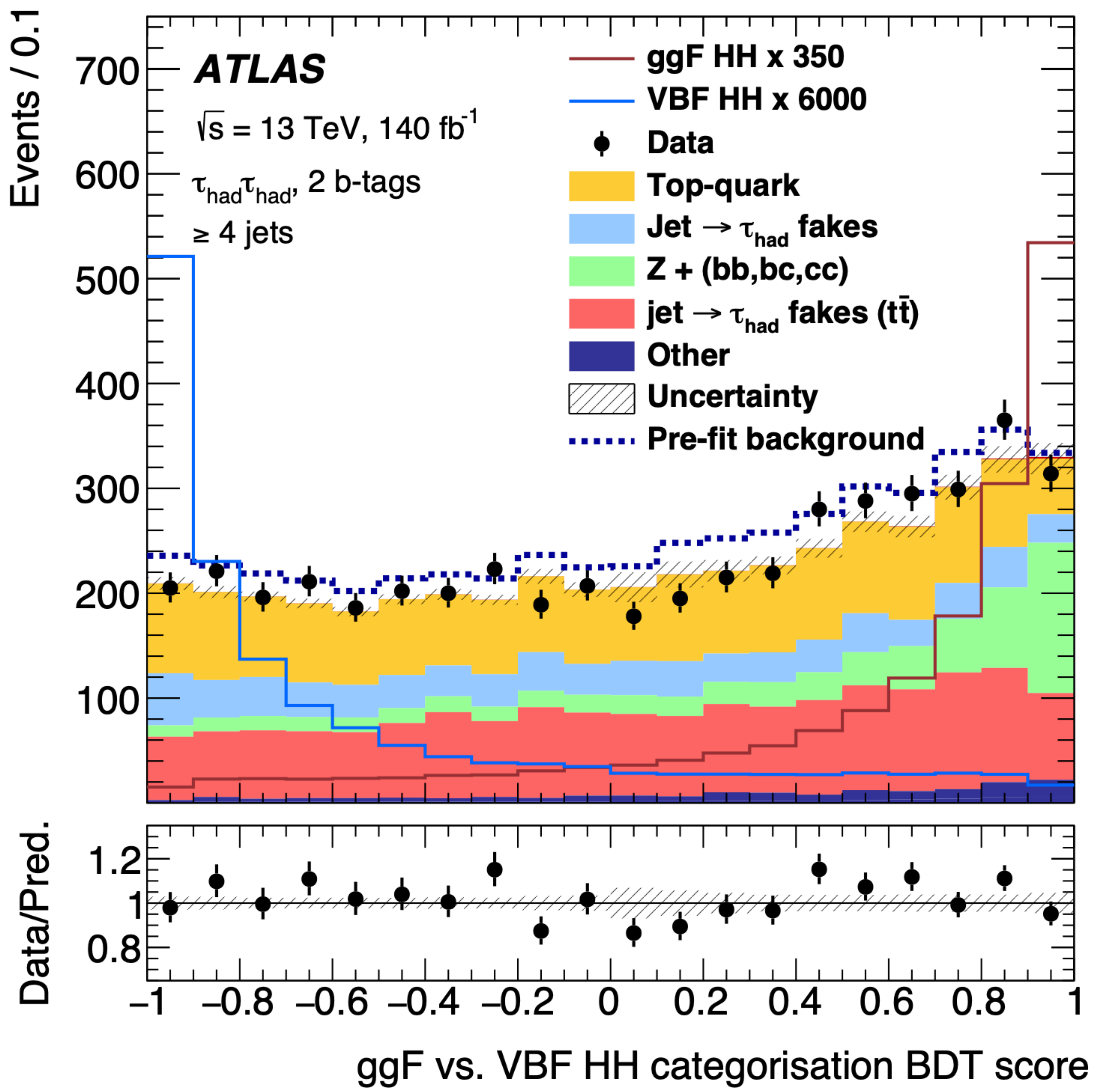
BDT score to discriminate ggF from VBF



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

[Phys. Rev. D 110 (2024) 032012](#)

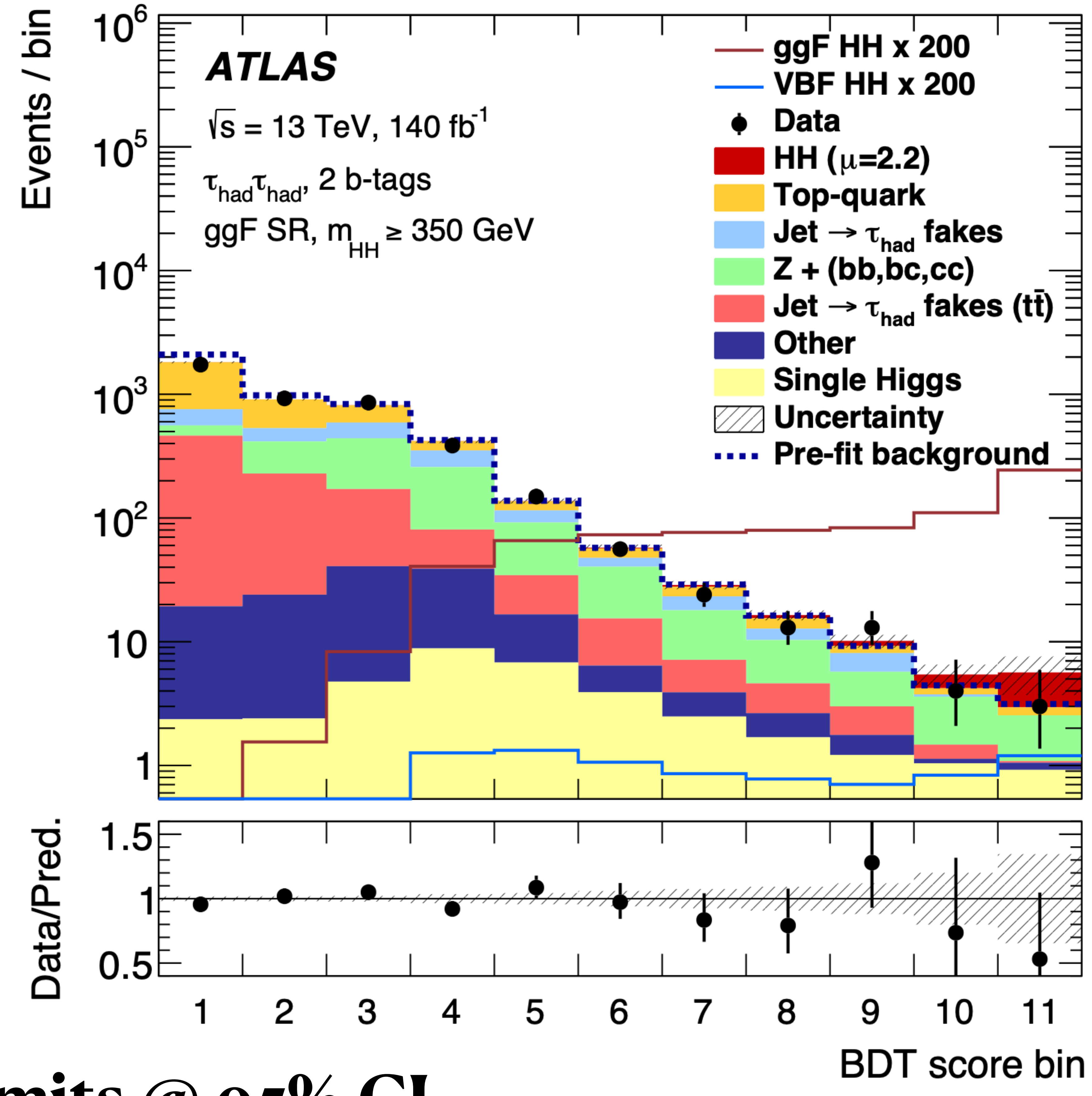
Target two different final state depending on the $\tau$

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

BDT score to discriminate ggF from VBF

Fit performed in 3 categories:

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




**Observed (Expected) upper limits @ 95% CL**

**on $\mu_{HH}$:** $5.4(3.3) \times SM$ ✨

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

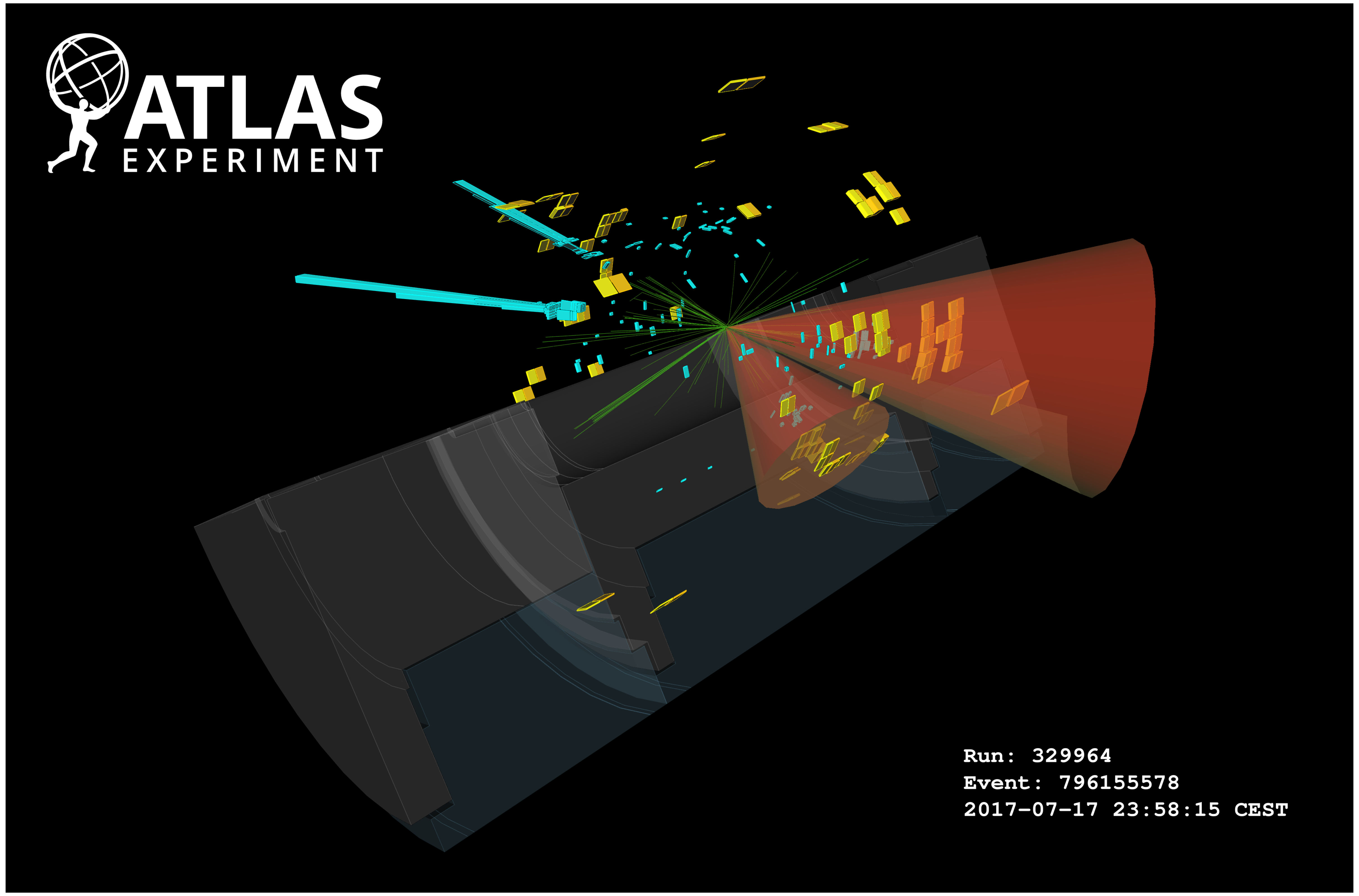
# Run 2 HH($bb\gamma\gamma$)

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-$m_{HH}$



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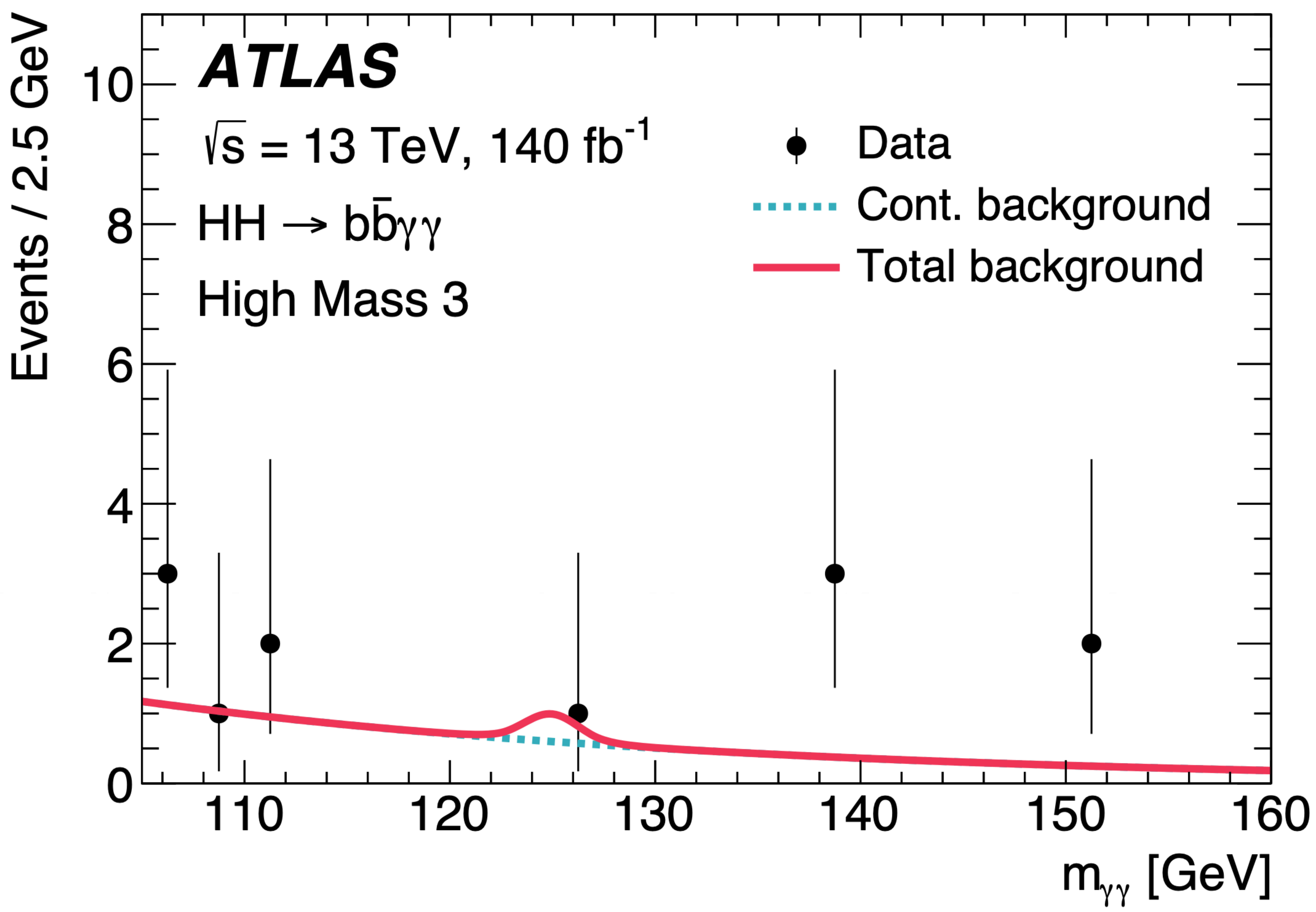
Extremely pure and stat limited channel

BDT to discriminate HH from non-resonant bkg.

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

Categorization performed to maximize the significance

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



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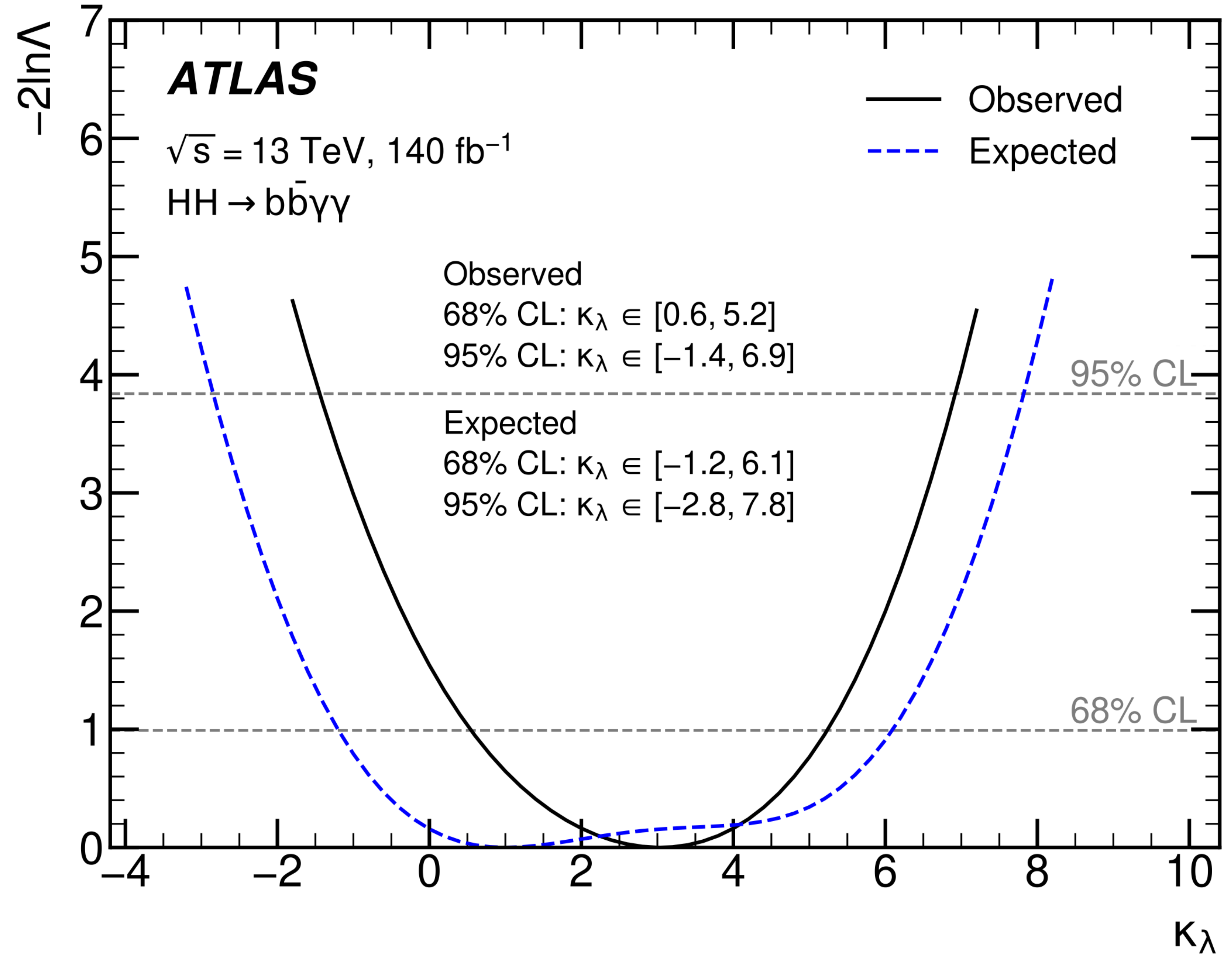
separate in low-$m_{HH}$ and high-$m_{HH}$

Categorization performed to maximize the significance

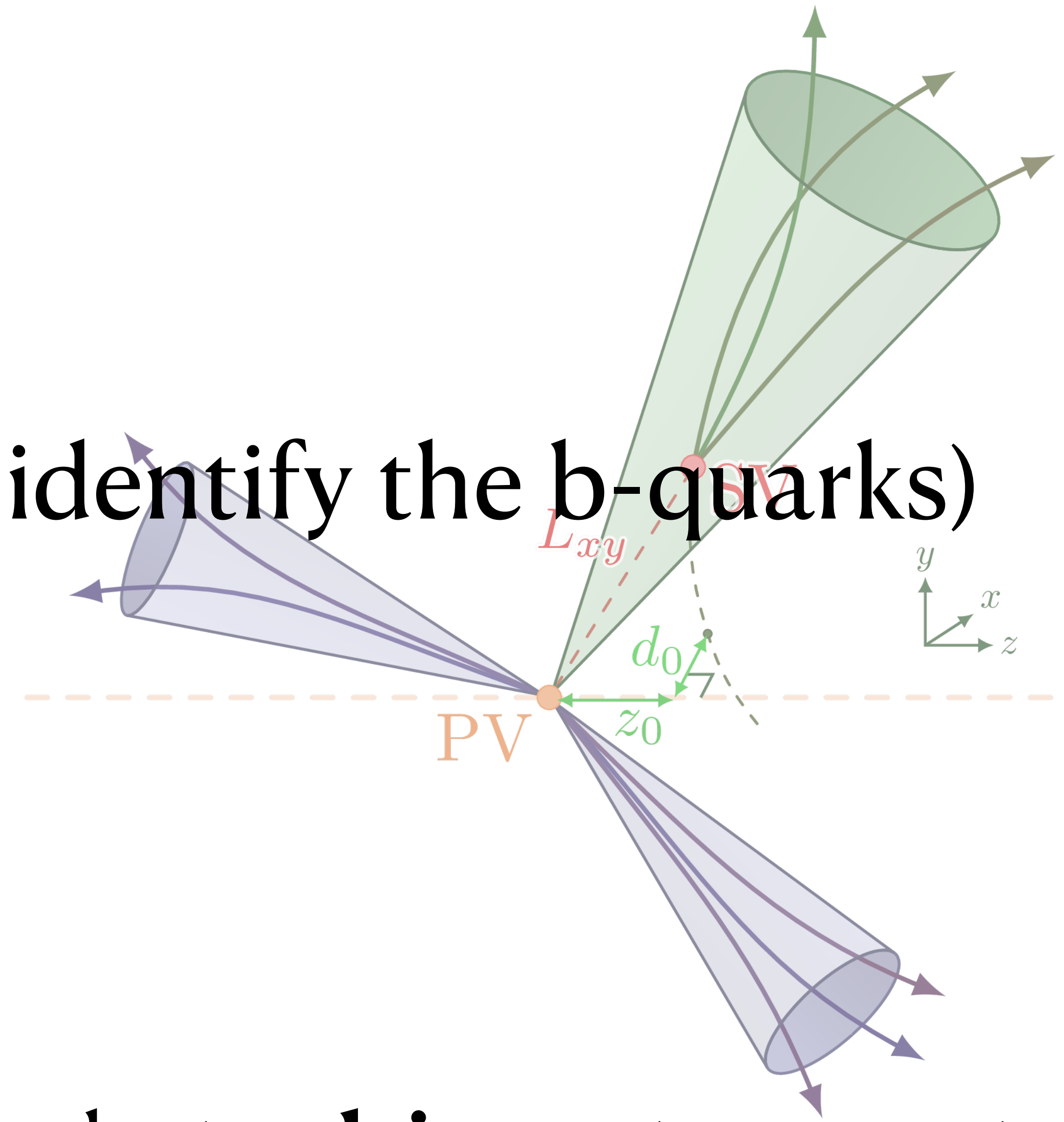
Then a simultaneous unbinned fit on $m_{\gamma\gamma}$ is performed

**Observed (Expected) upper limits @ 95% CL on $\mu_{HH}$:** $4.0(5.0) \times SM$

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

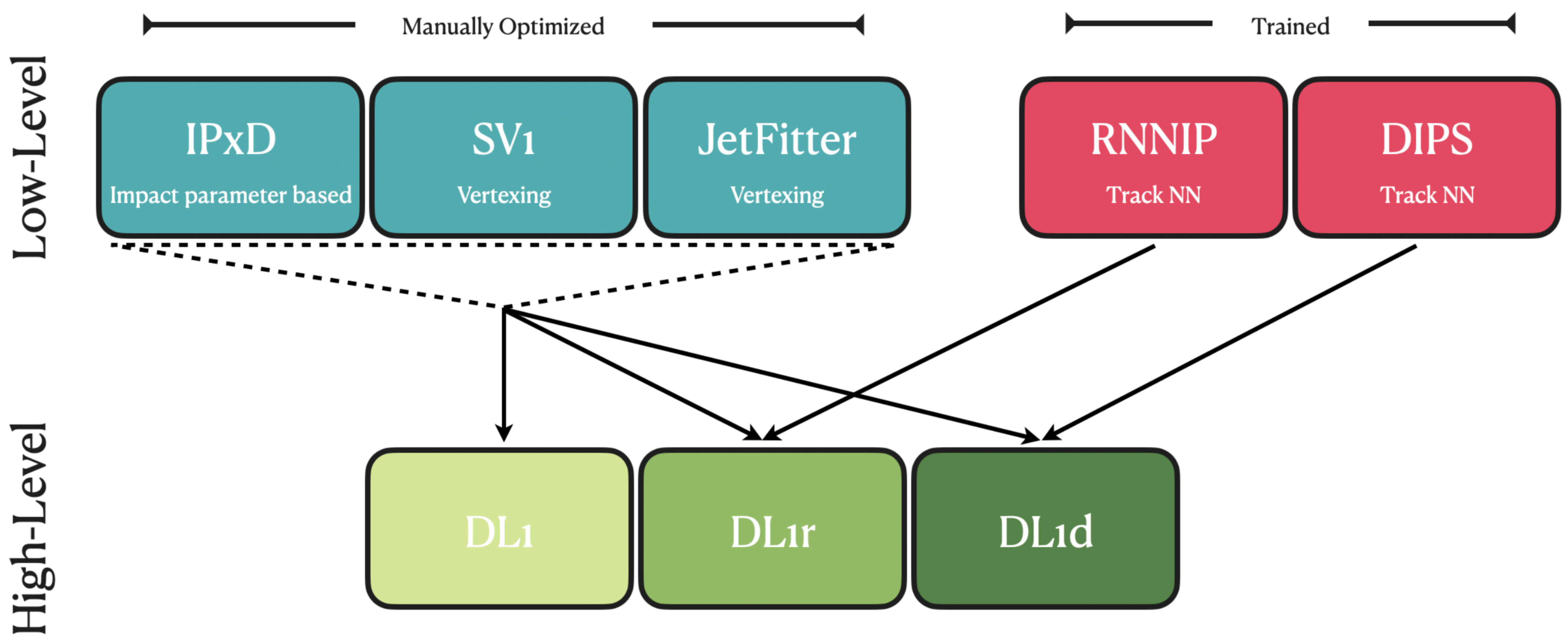


# Transforming Flavour Tagging




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

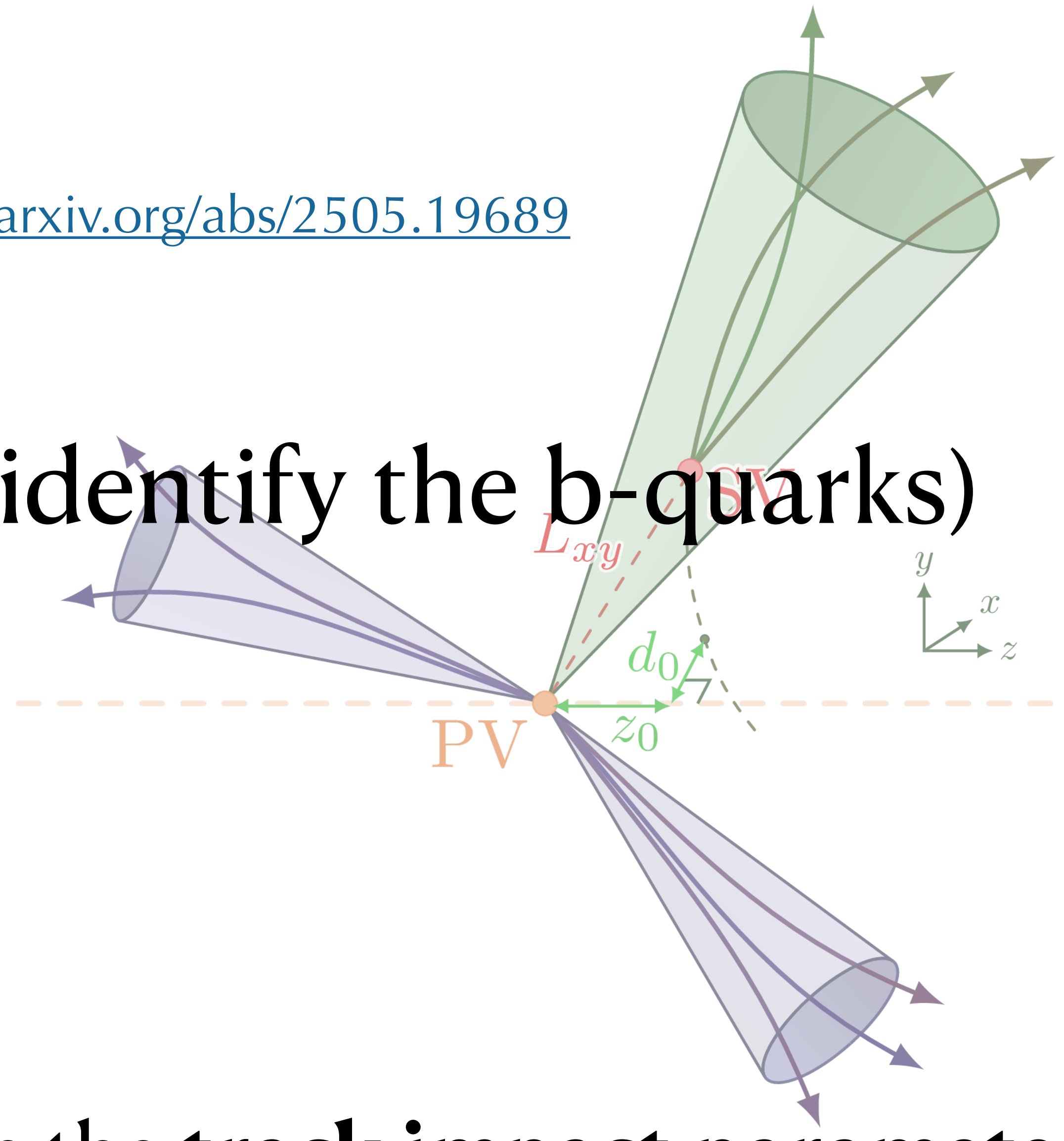



The Flavour Tagging beauty story:

- 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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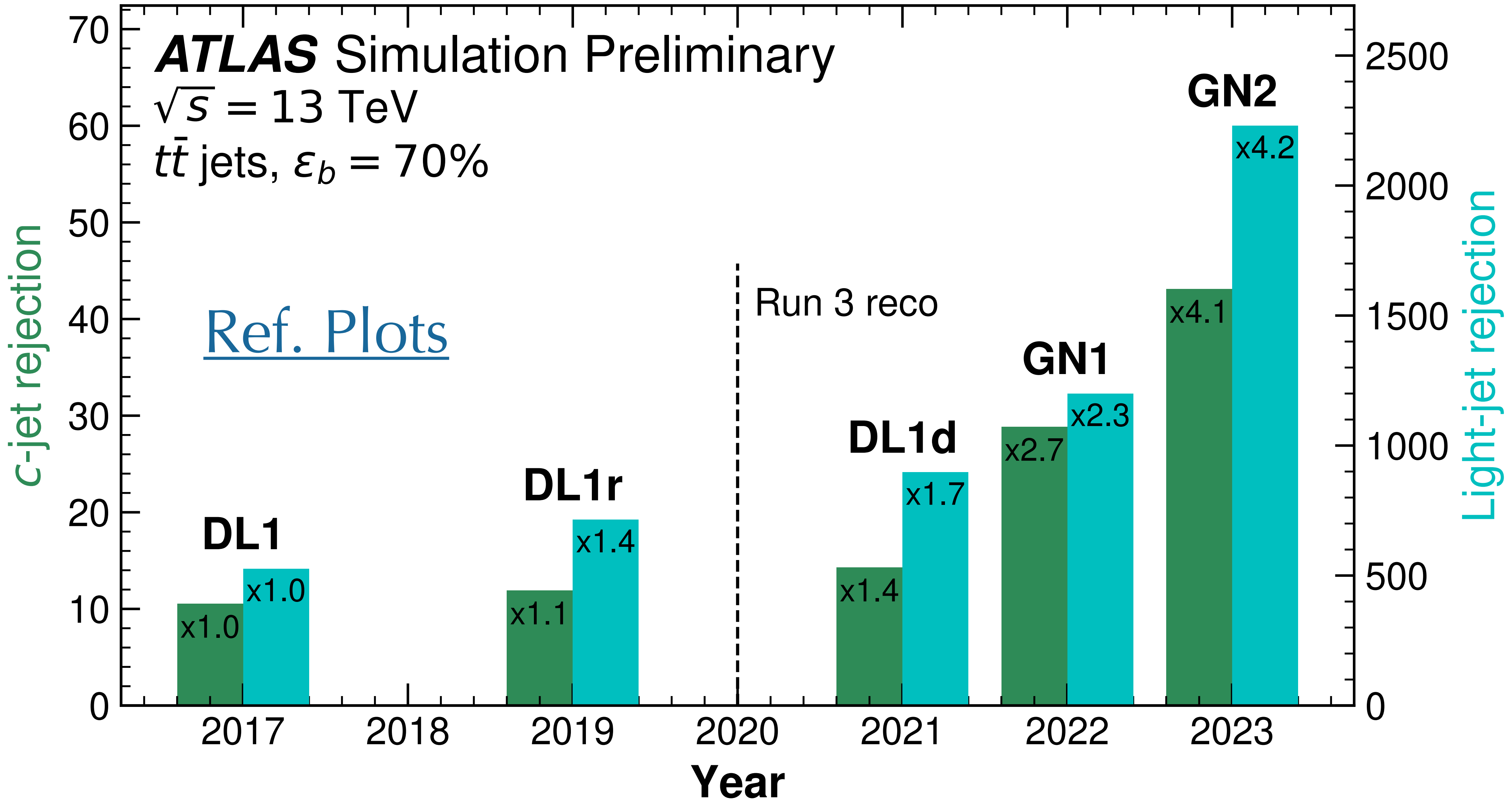
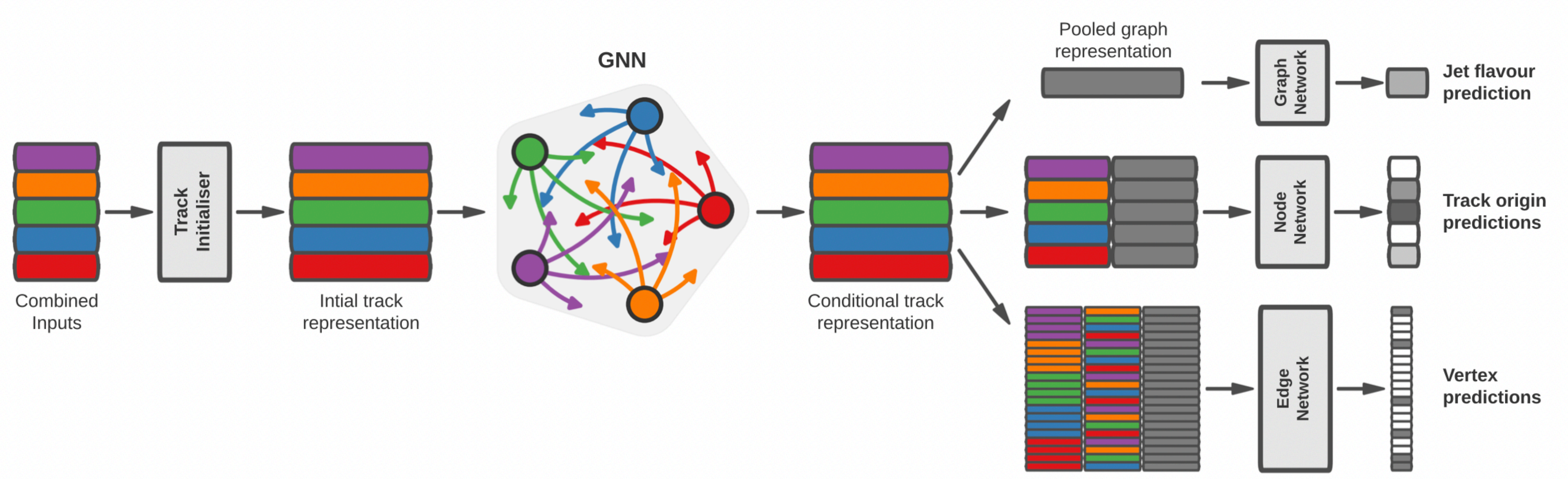



The Flavour Tagging beauty story:

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



# What’s New?

HIGP-2025-10

ATLAS EXPERIMENT

**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!

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

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

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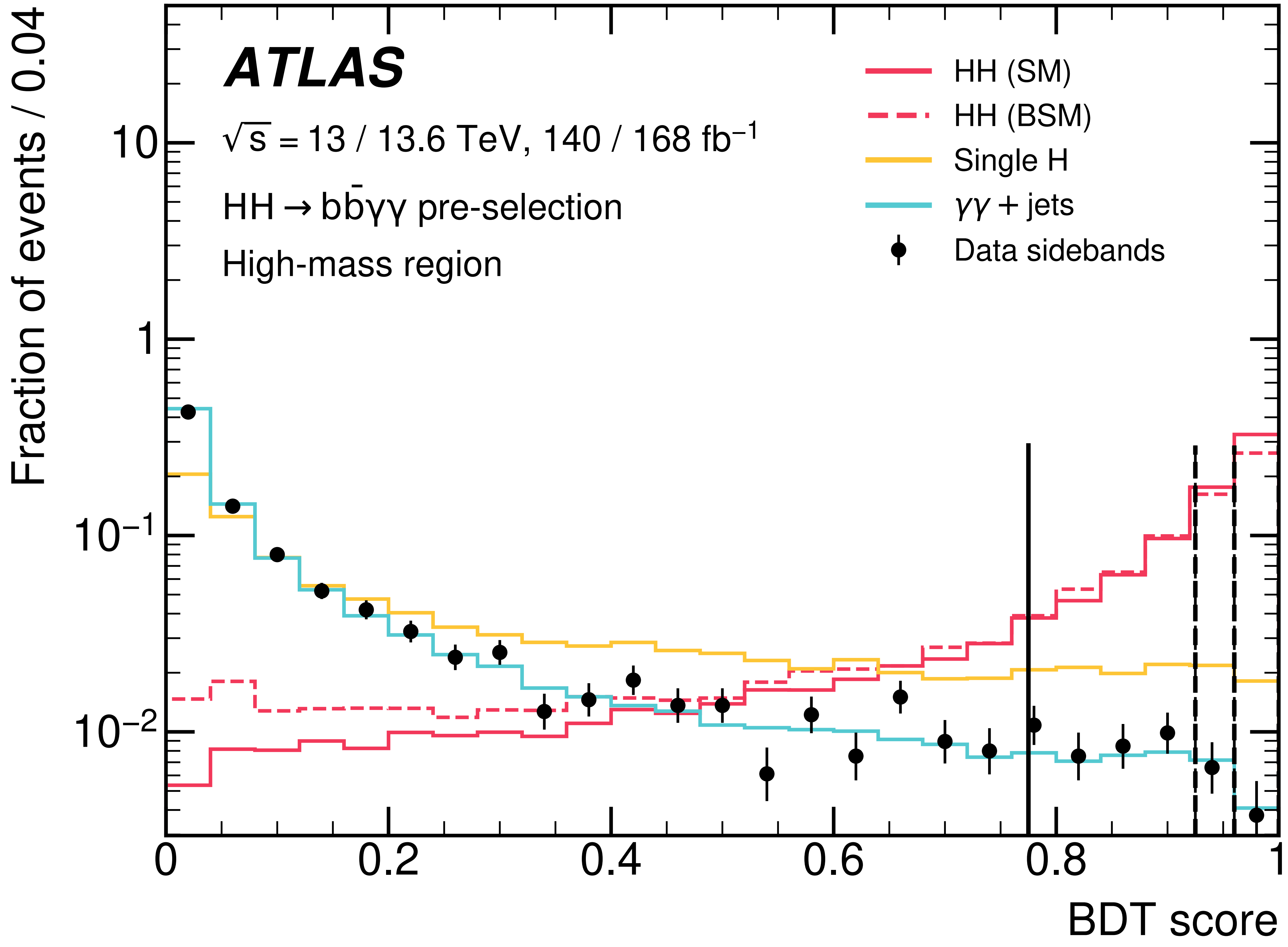
- Training simultaneous in Run 2 and Run 3 exploiting the correlation to categorize tighter



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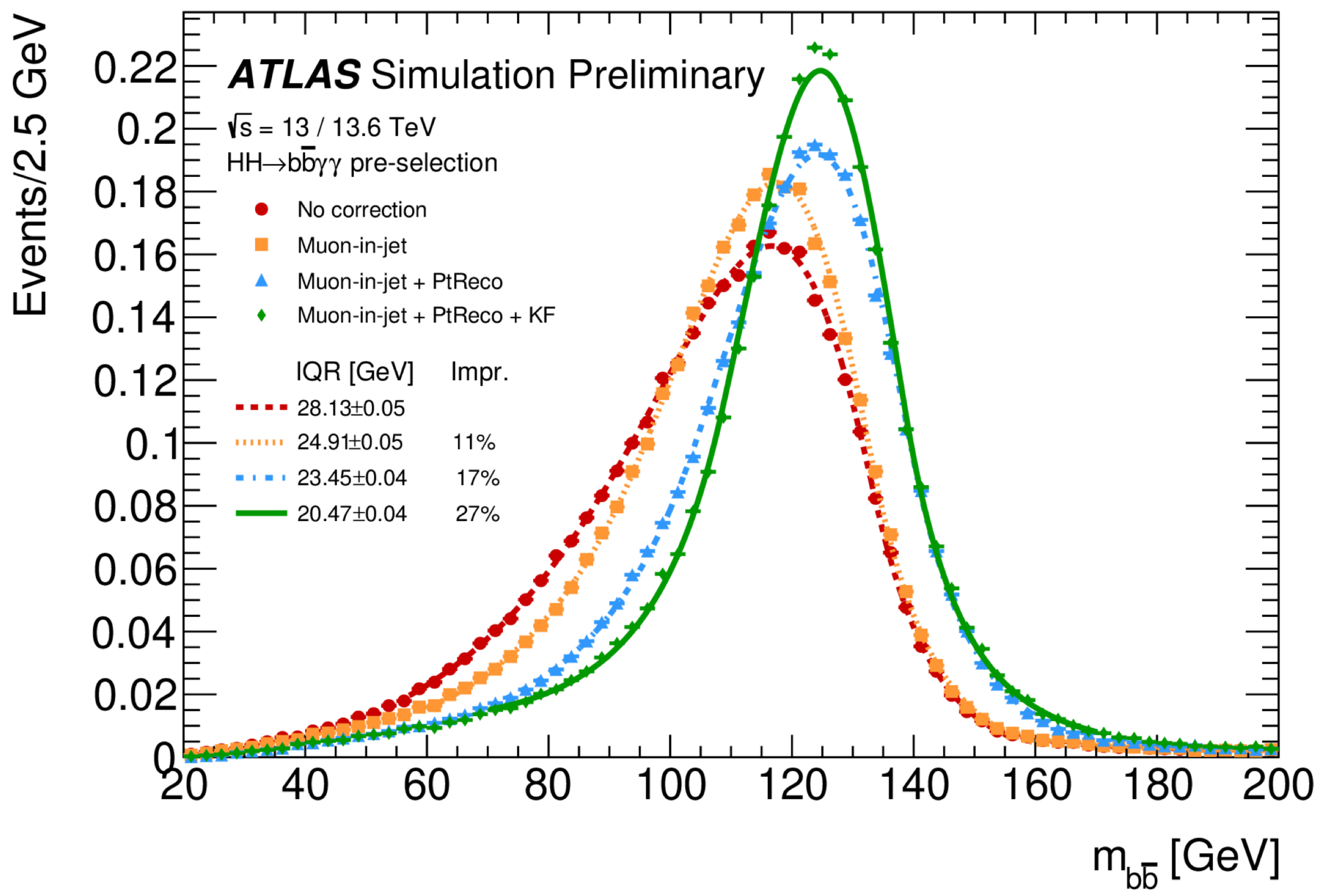
- Training simultaneous in Run 2 and Run 3 exploiting the correlation to categorize tighter
- Kinematic fit improving the $m_{bb}$ resolution



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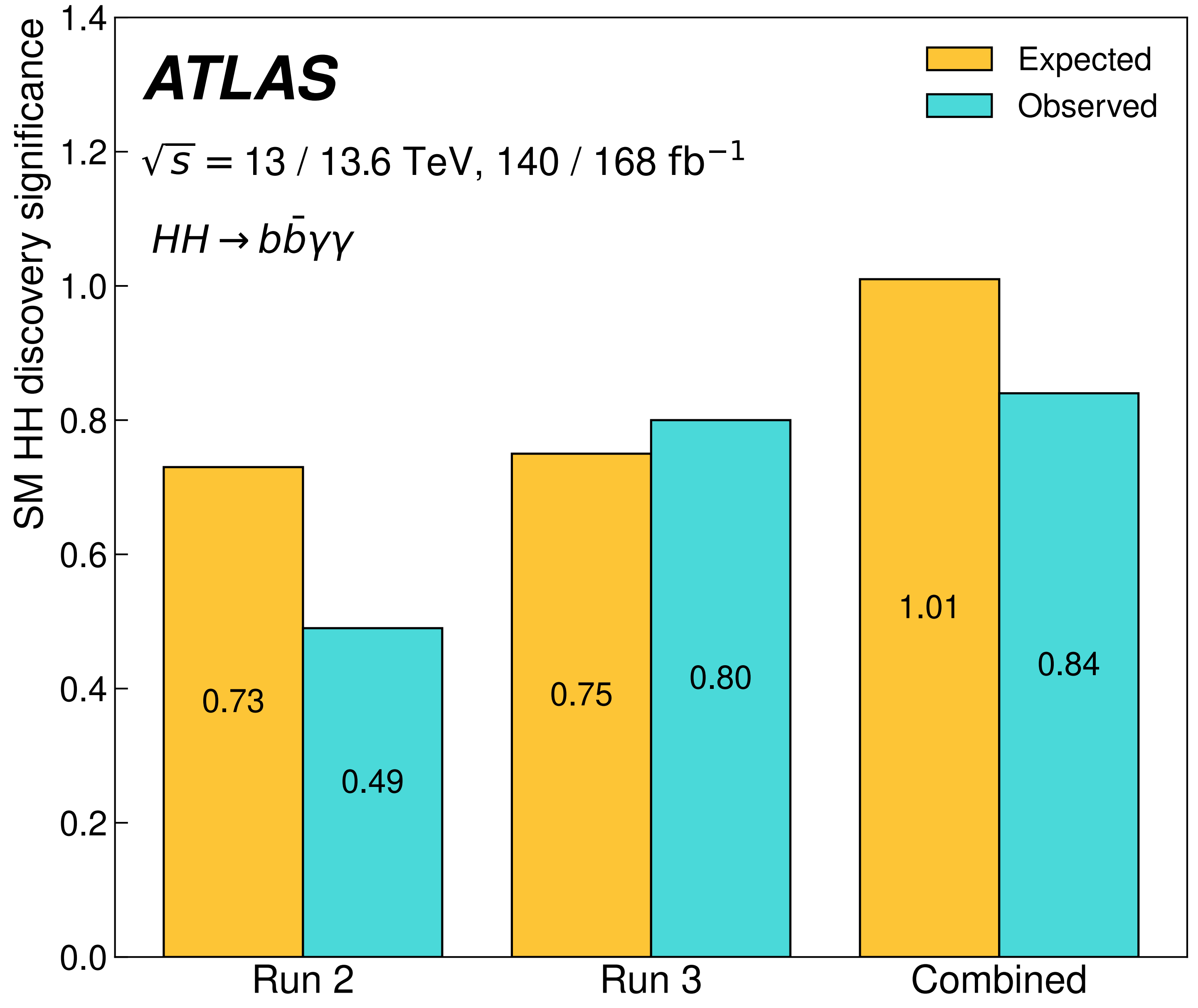
- Training simultaneous in Run 2 and Run 3
  exploiting the correlation to categorize tighter
- Kinematic fit improving the $m_{bb}$ resolution
- And of course $\times\, 2.2$ **more data !**

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

Simultaneous fit in the 14 categories

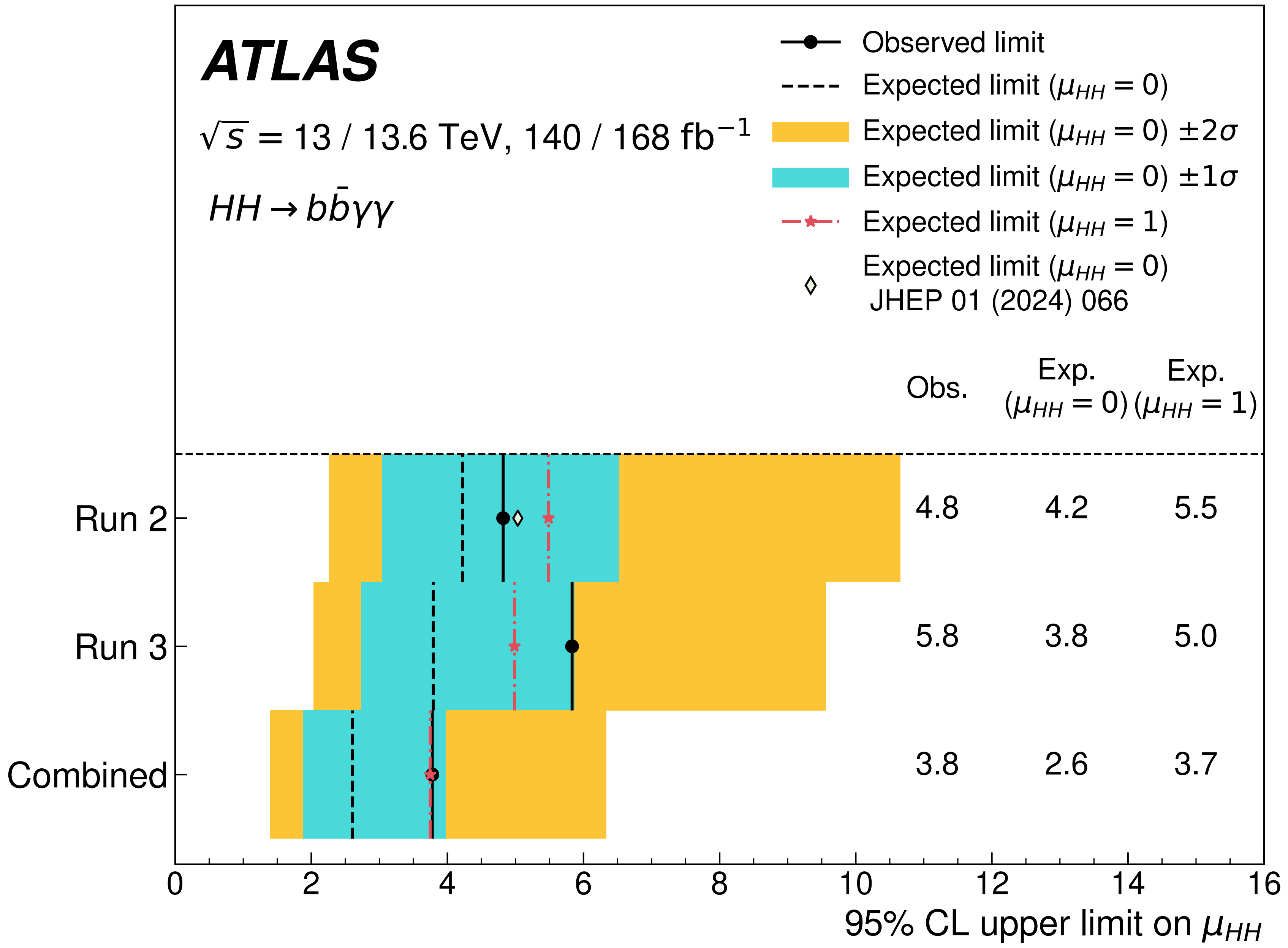
**Observed HH SM Significance: 0.8 $\sigma$**

**Expected HH SM Significance: 1.0 $\sigma$**




**Observed (Expected) upper limits @ 95% CL on $\mu_{HH}$:** $3.8(2.6) \times SM$ ✨

**! Comparable with Full Run 2 HH Combination**



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| |
|---|
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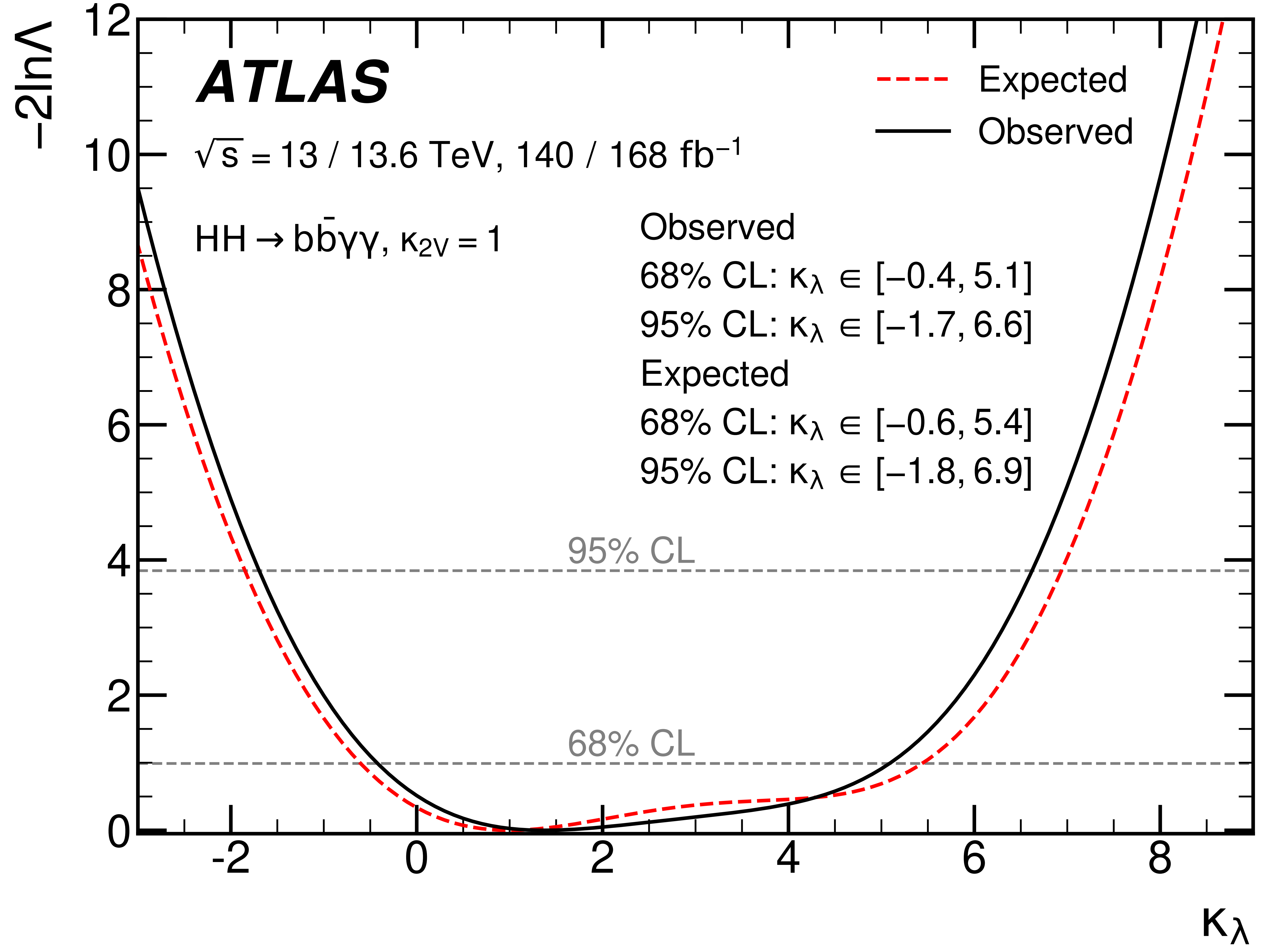


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**Observed (Expected) limits @ 68% CL:**

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

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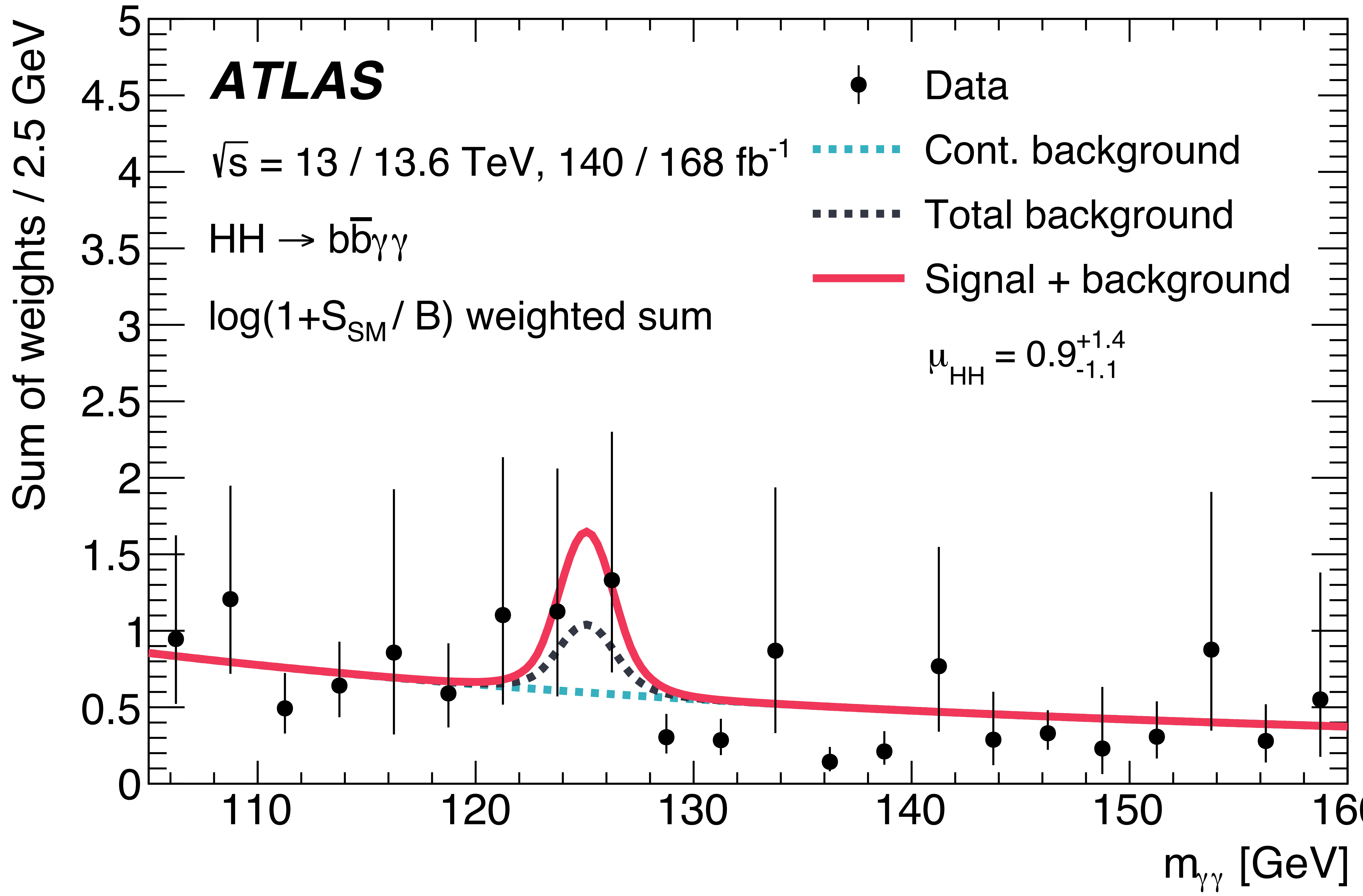


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# What’s next?

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

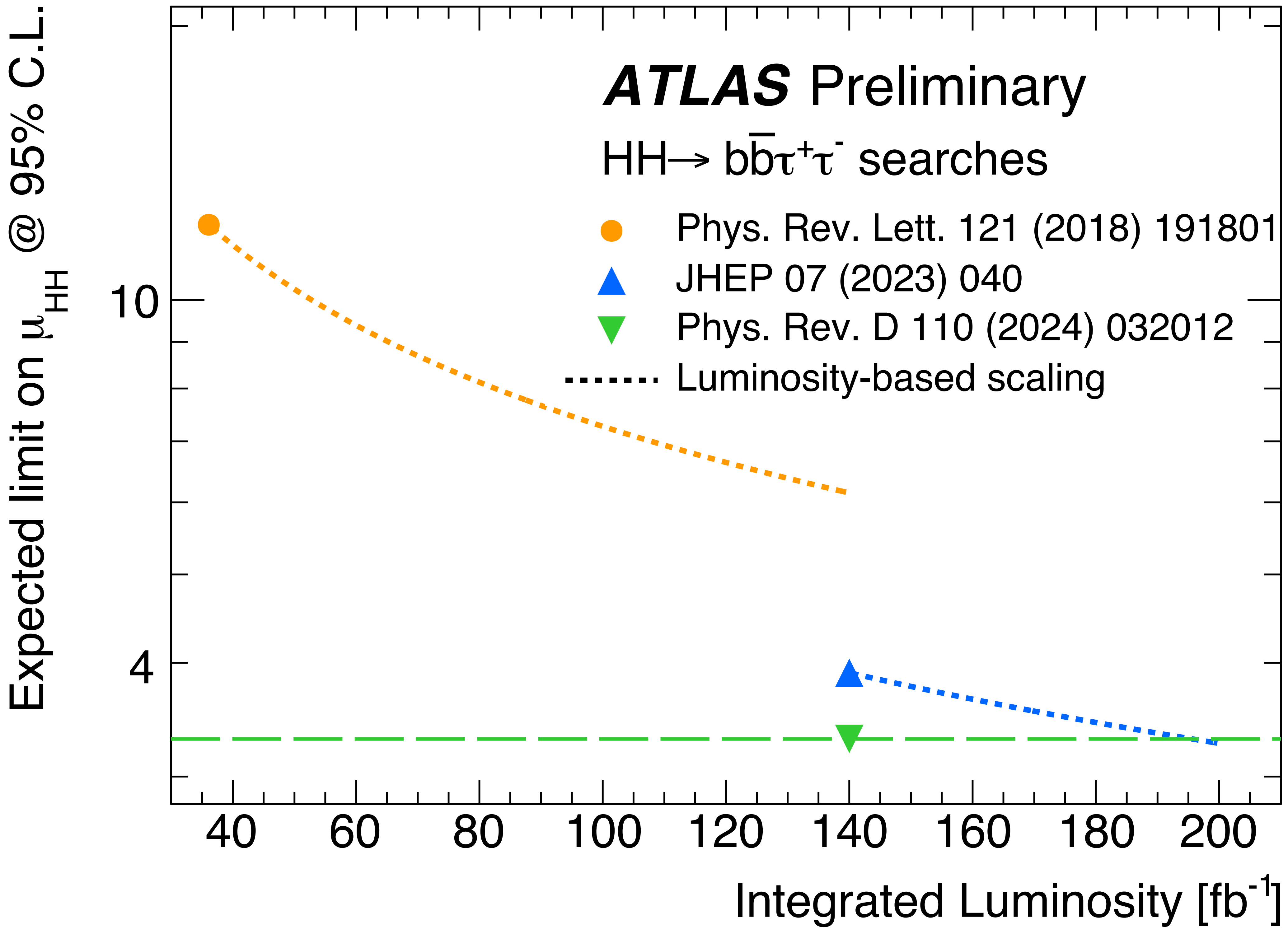
All the HH analyses have been input to the European Strategy Update:

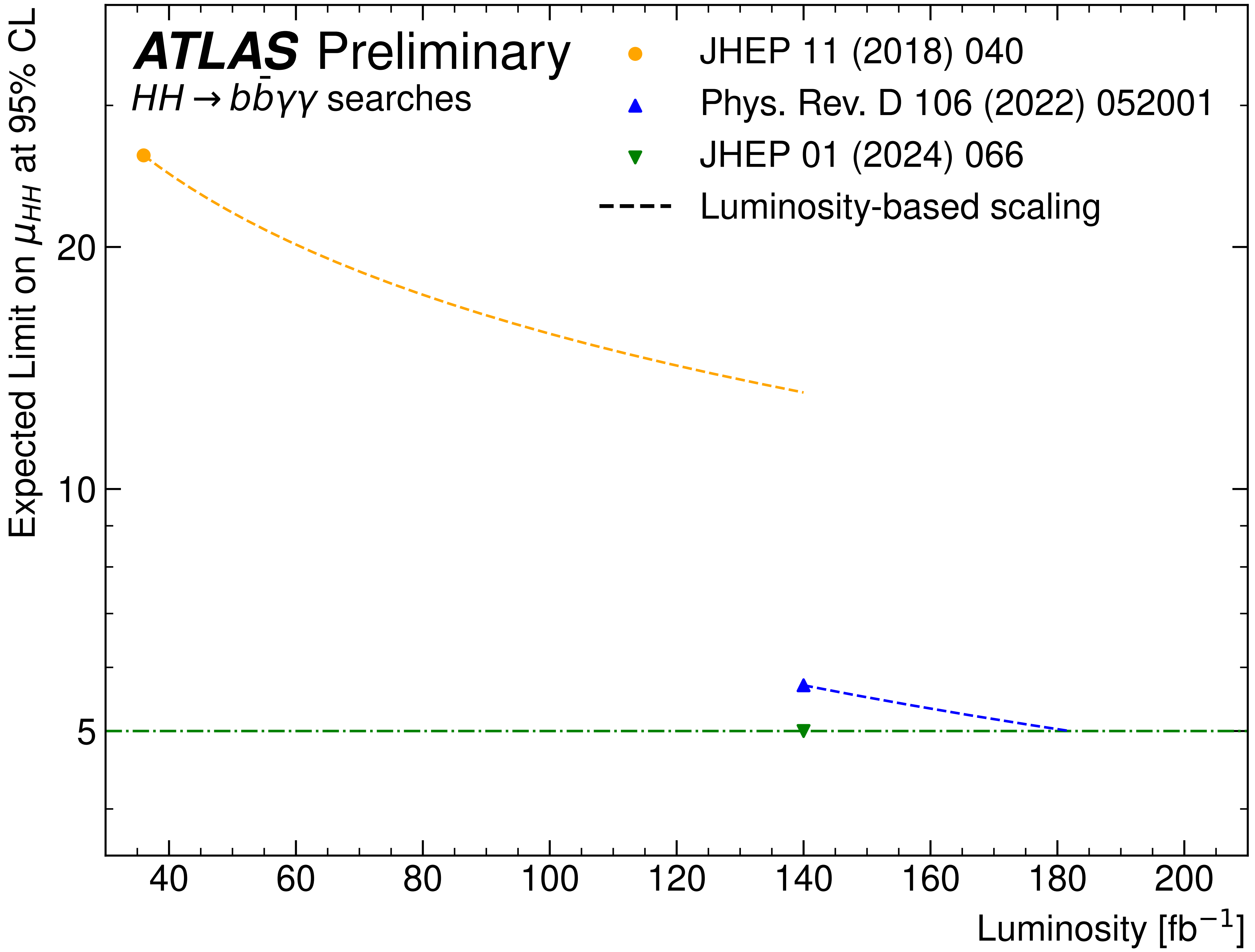
[Highlights of the HL-LHC physics projections by ATLAS and CMS]

# 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



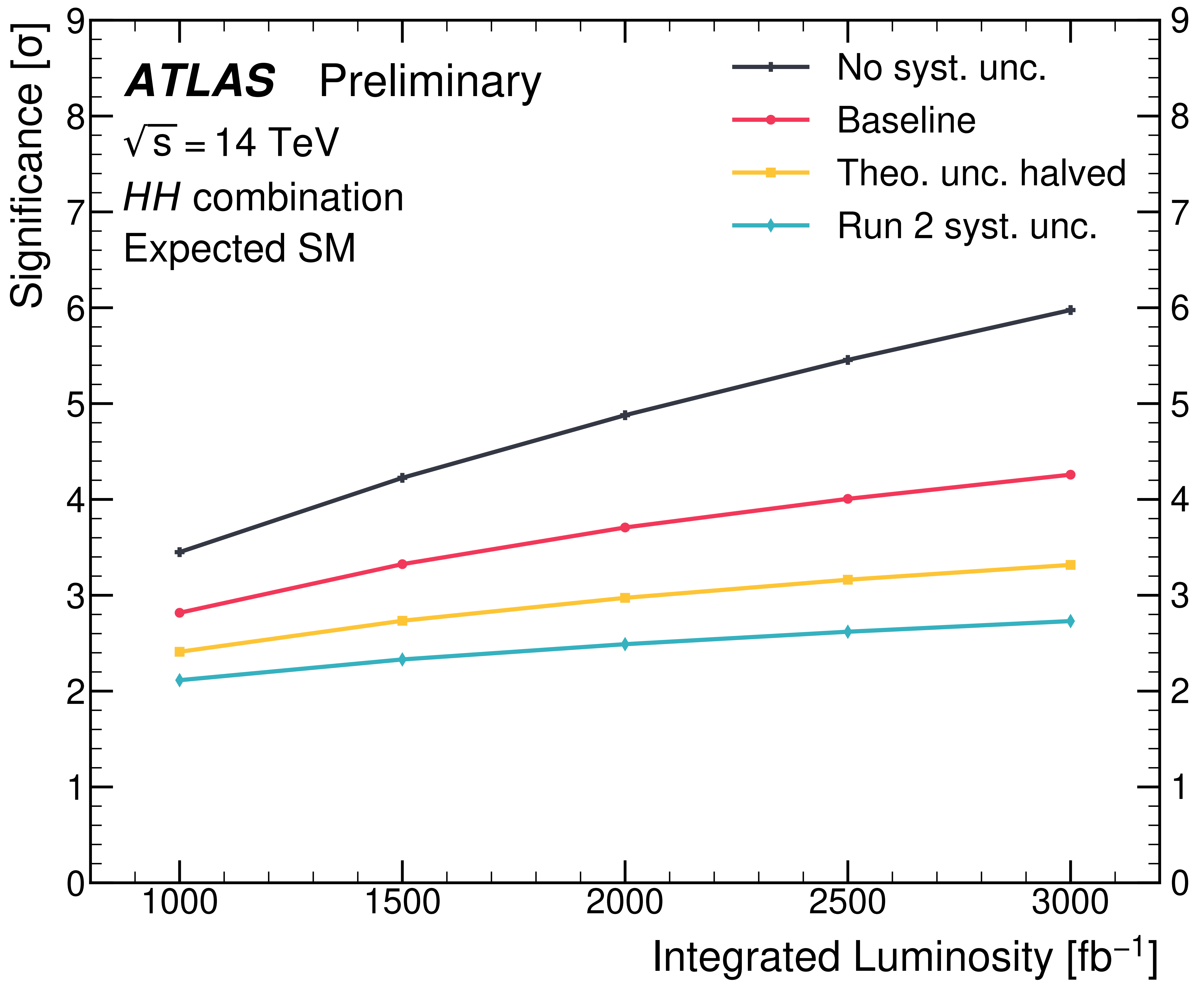
# The HL-LHC Extrapolations

Scenarios assumed:

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

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

**Expected HH SM Significance: 4.1 $\sigma$**



# The HL-LHC Extrapolations

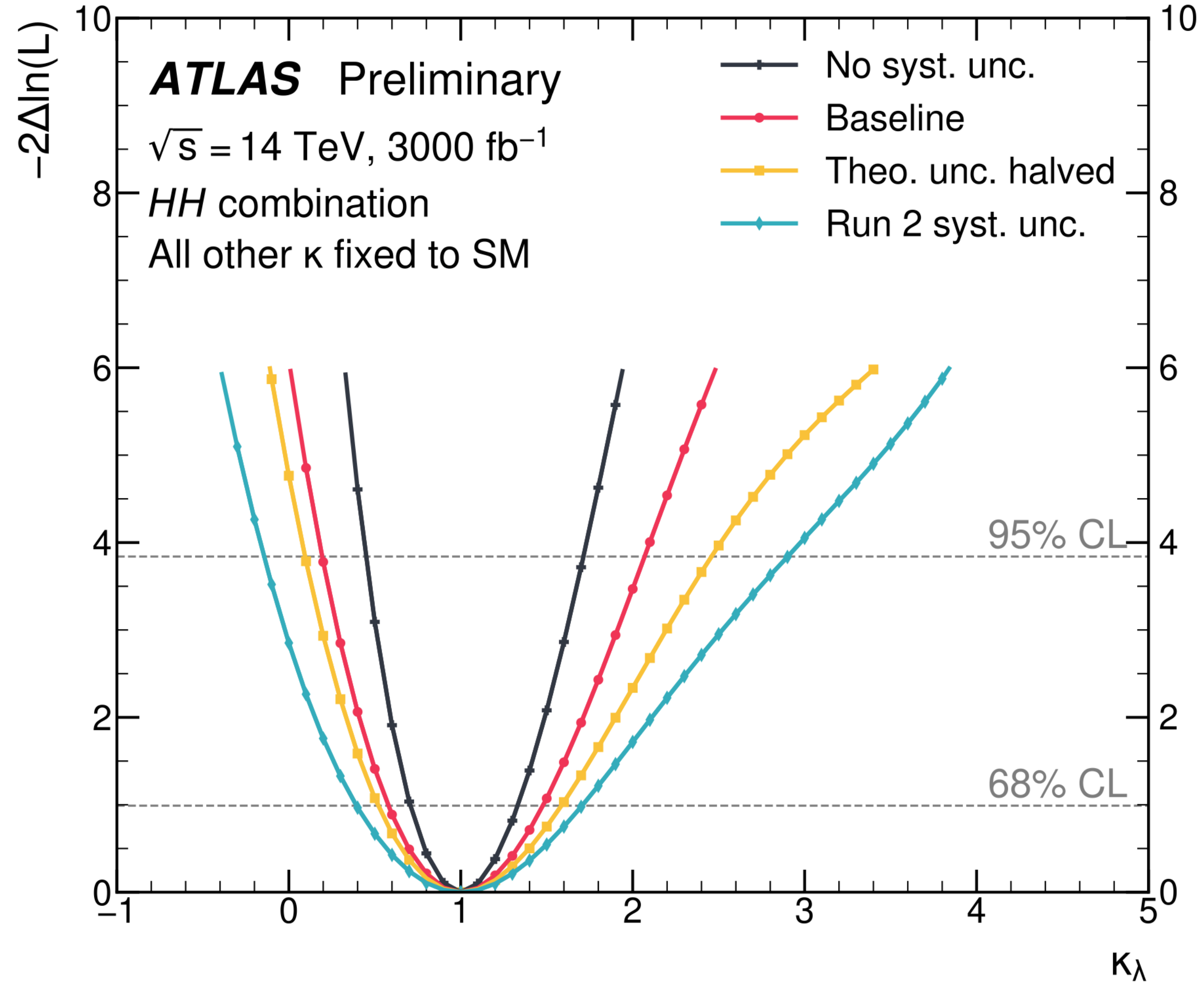
Scenarios assumed:

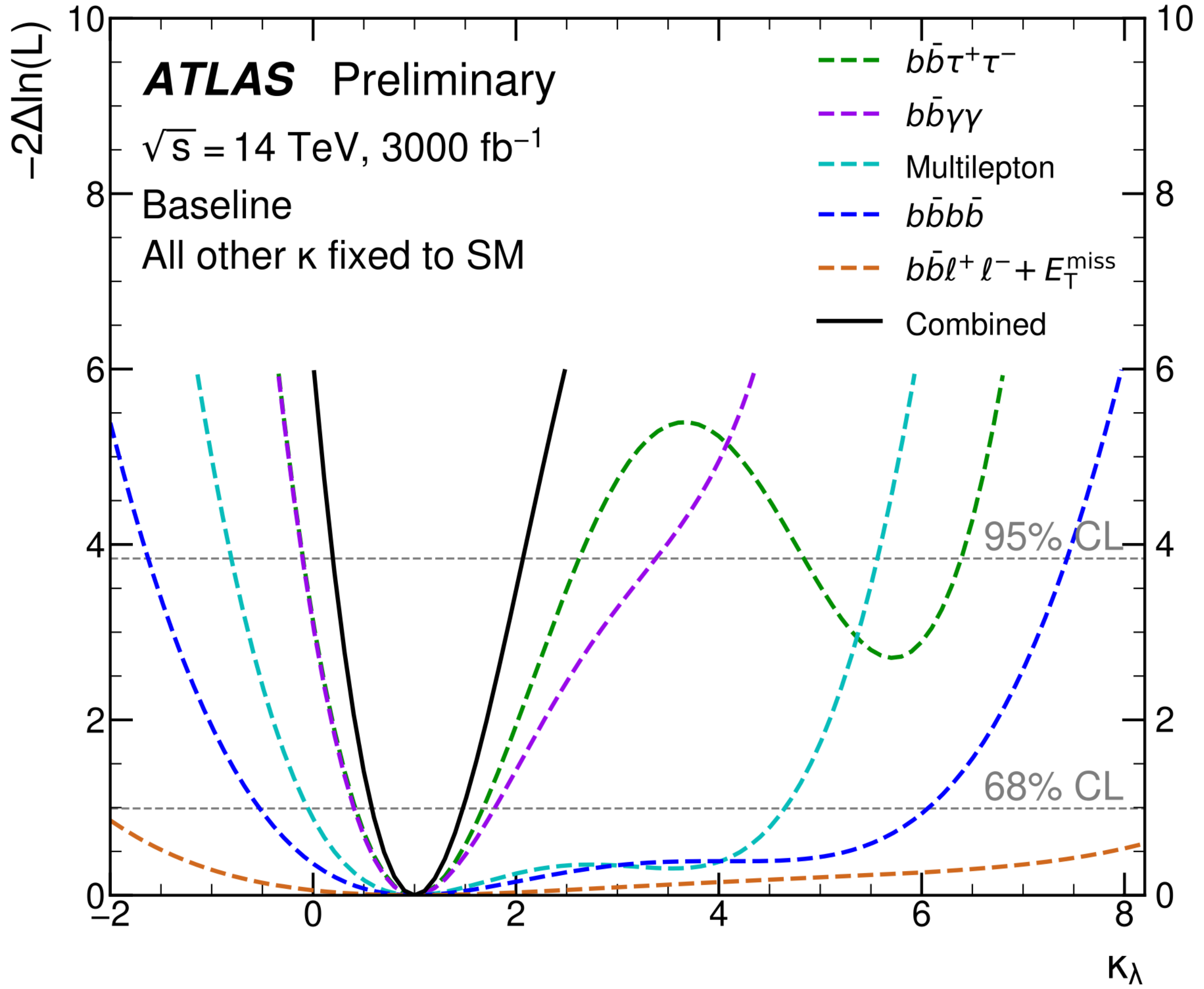
- Run 2 systematics
- Theoretical uncertainty halved
- **Baseline**
- Stat. only

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

**Expected limits @ 68% CL:**

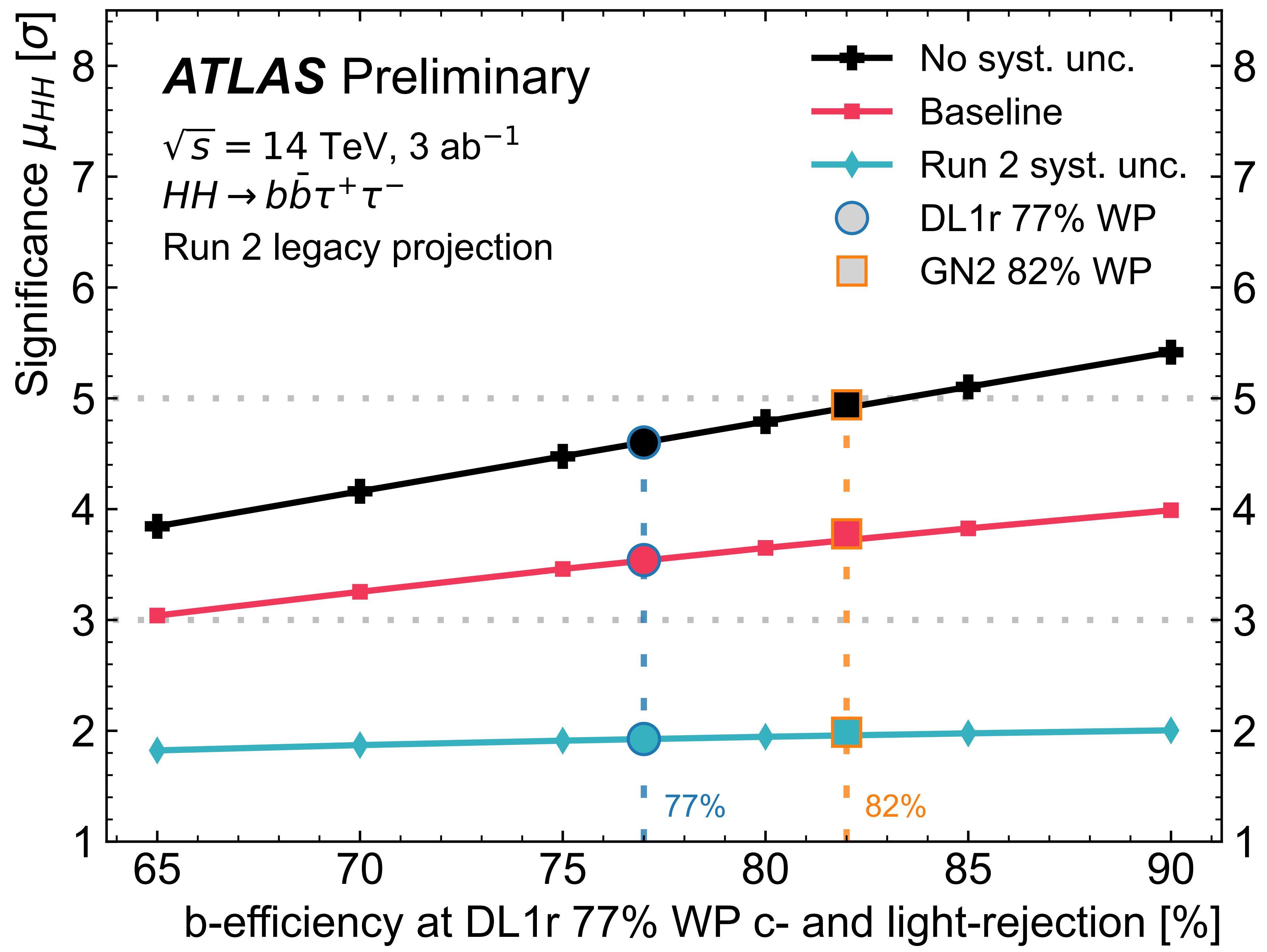
$\kappa_\lambda \in [0.71,\ 1.48]$

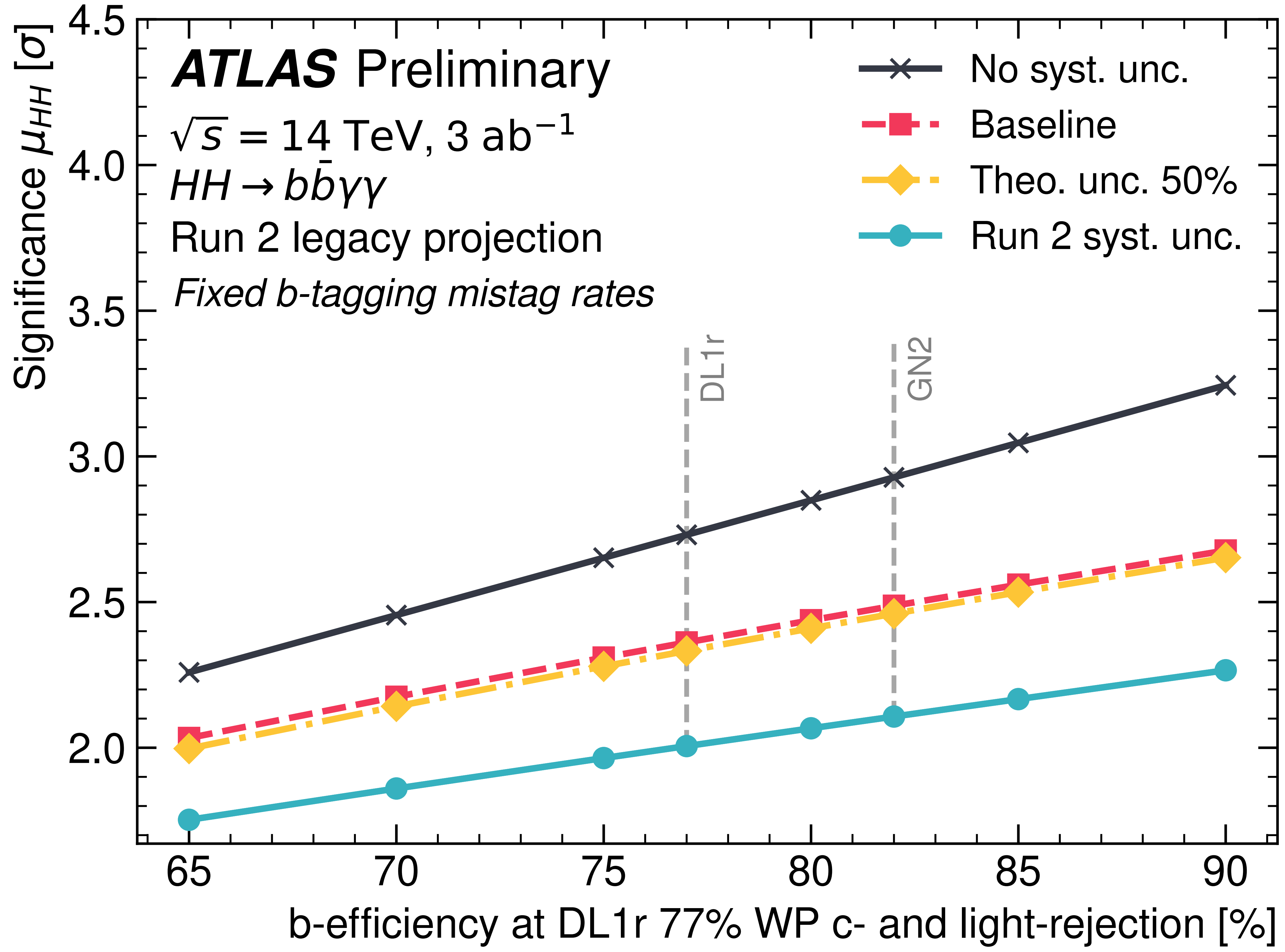


# The HL-LHC Extrapolations

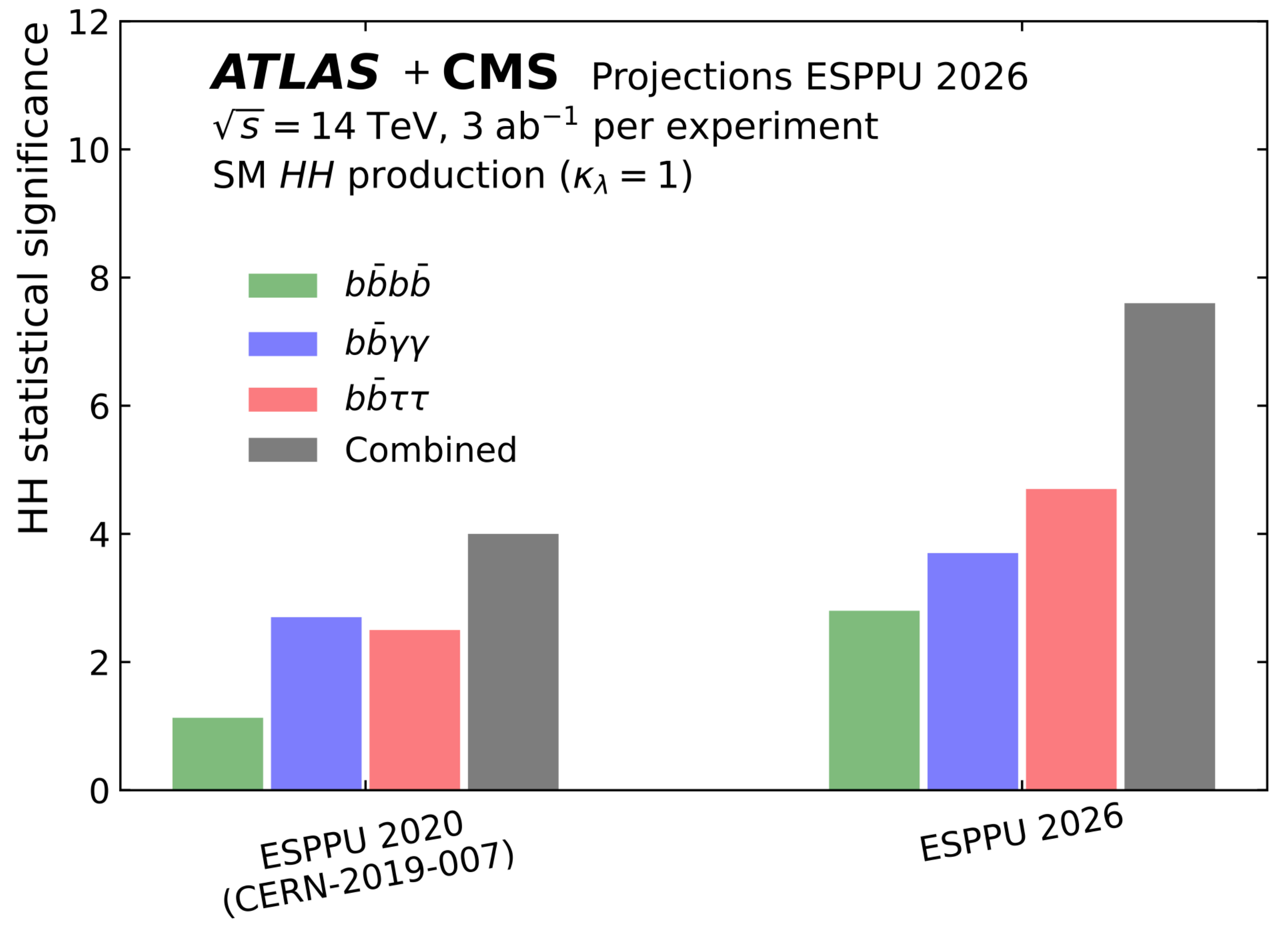
All these scenarios do not take into account possible improvements as GN2



# 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

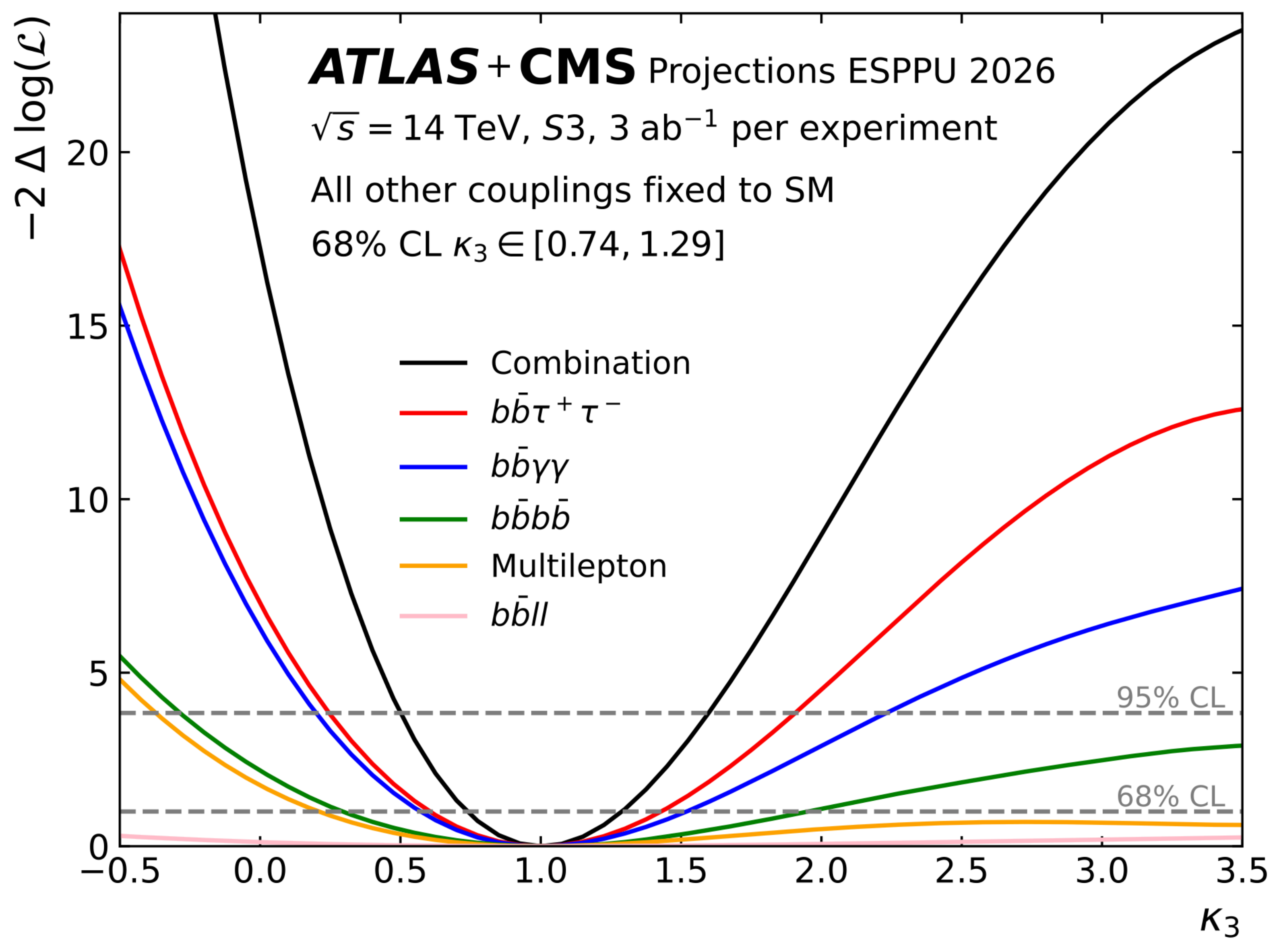



**ATLAS+CMS**

**Expected HH SM Significance: 7.2 $\sigma$**

**Expected limits @ 68% CL:**

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



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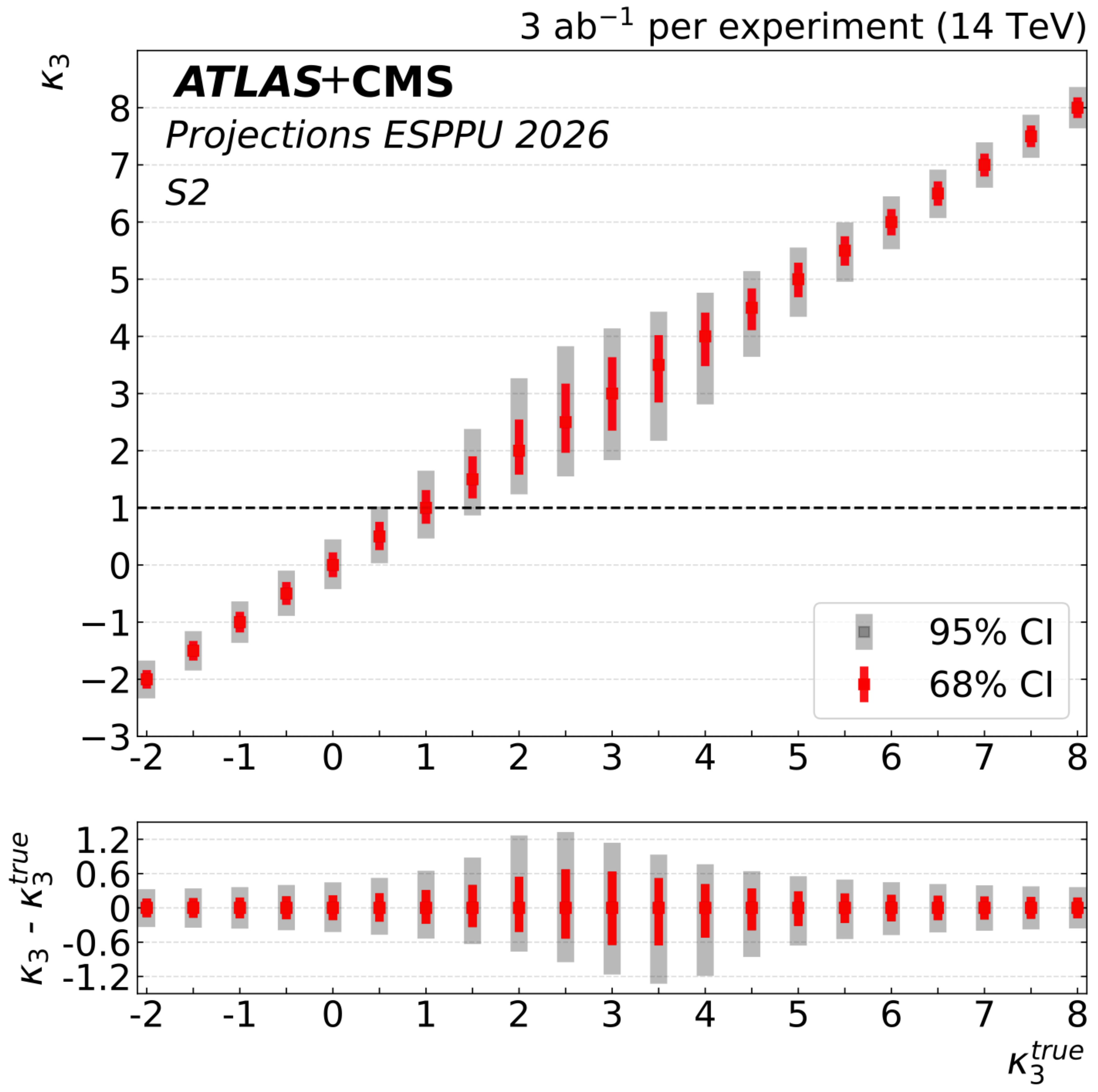


Limits provided for different $\kappa_\lambda$ scenarios

# Conclusions

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

Best way to measure directly the $\lambda$ 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