

# Beyond the SM physics probed with Higgs boson pair production in the ATLAS experiment

FJPPN project HEP\_18

Tatsuya Masubuchi, Nicolas Berger  
The University of Osaka, LAPP



2026 Joint workshop of FKPPN and FJPPN/TYL (2025/5/18)

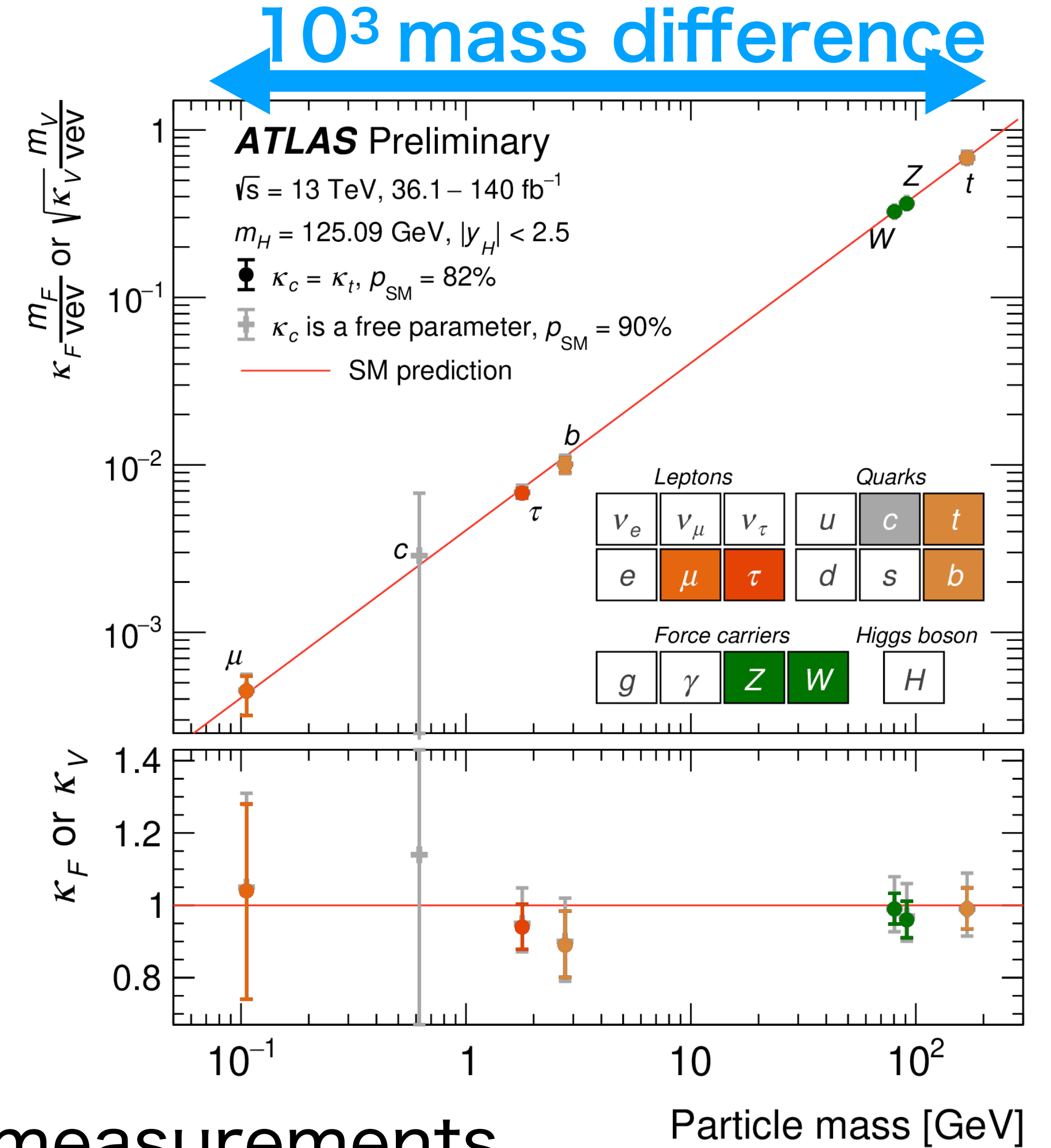
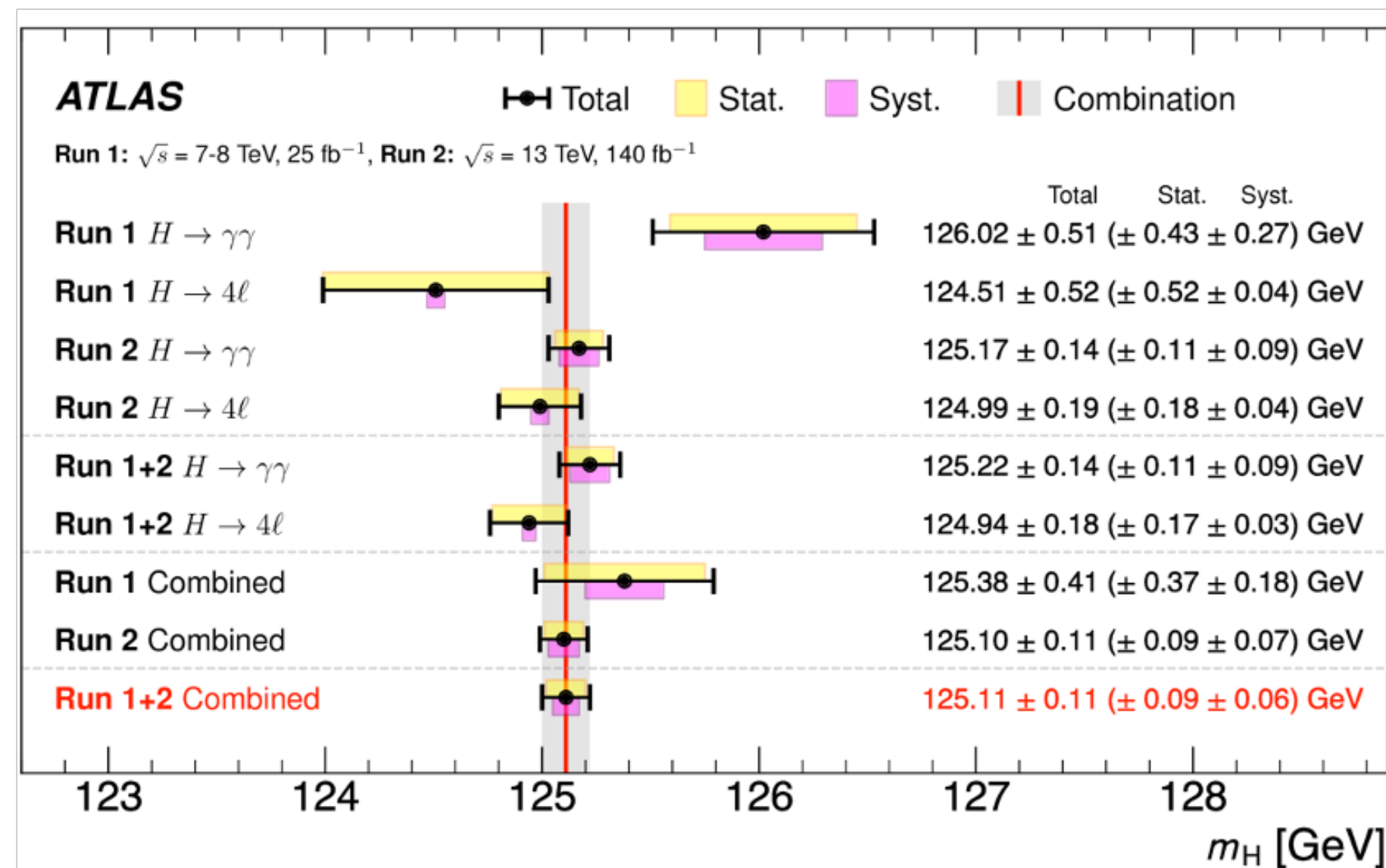
# Introduction

- Various Higgs property measurements are ongoing

- Higgs coupling

- Established coupling between Higgs and Weak boson and 3rd gen fermion (~5-10%)
- $H \rightarrow \mu\mu$  coupling (~20%) (reached  $3\sigma$ !)
- $H \rightarrow cc$  coupling (O(100%))

No strong deviation from SM

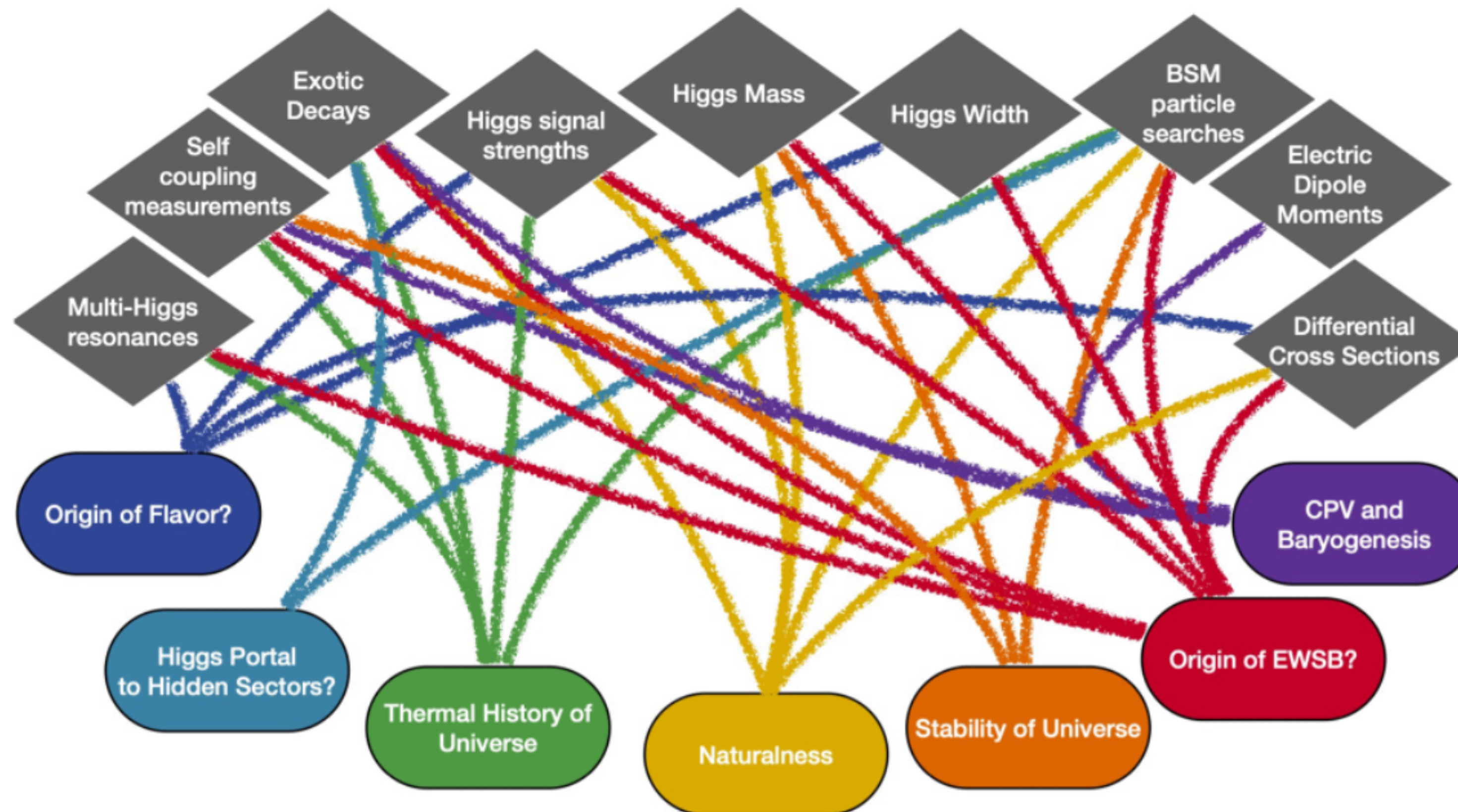


- Mass measurements

- 125.22±0.14 GeV for  $H \rightarrow \gamma\gamma$
- 124.94±0.18 GeV for  $H \rightarrow ZZ \rightarrow 4\ell$
- **125.11±0.11 GeV (Combined)**  
**0.09% precision**

# Is the SM really complete?

- Higgs measurement (Higgs sector) may connect to the fundamental unresolved mysteries of the universe

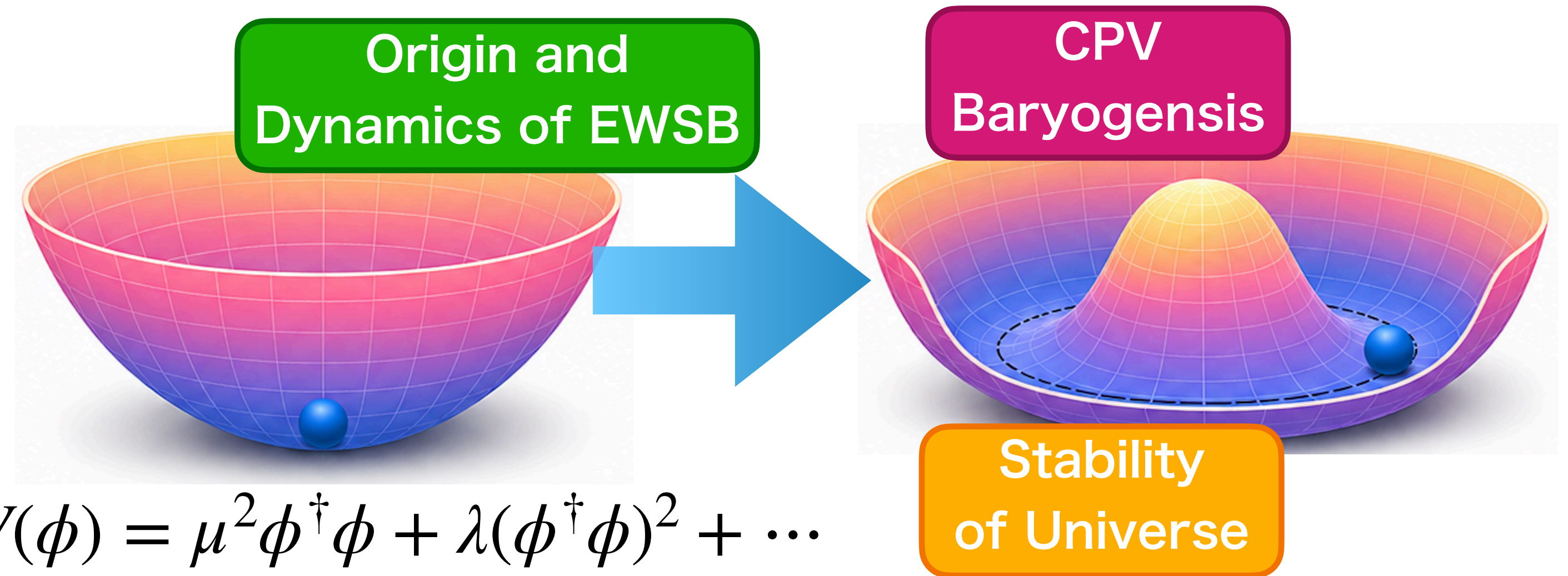


**Higgs measurements are a probe of new physics!!**

# Higgs potential and Self-coupling

Higgs potential in the SM is introduced by “hand”

➔ No first principles behind  
Key of BSM Physics?



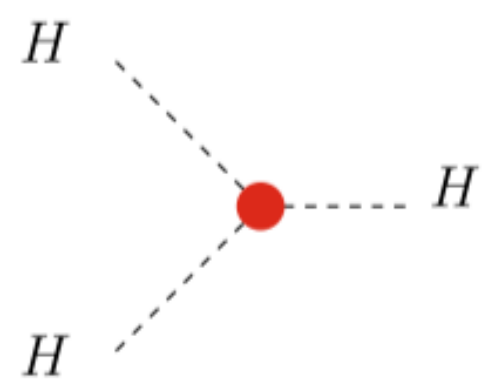
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + \dots$$

Higgs potential around vev  $V(\phi) \rightarrow V(v + h)$

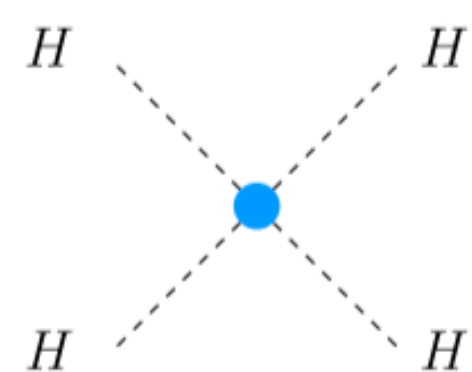
$$V(h) = \frac{1}{2} m_h^2 h^2 + \lambda_{hhh} v h^3 + \frac{1}{4} \lambda_{hhhh} h^4 + \dots$$

In the SM,  $\lambda_{hhh} \approx 0.13$

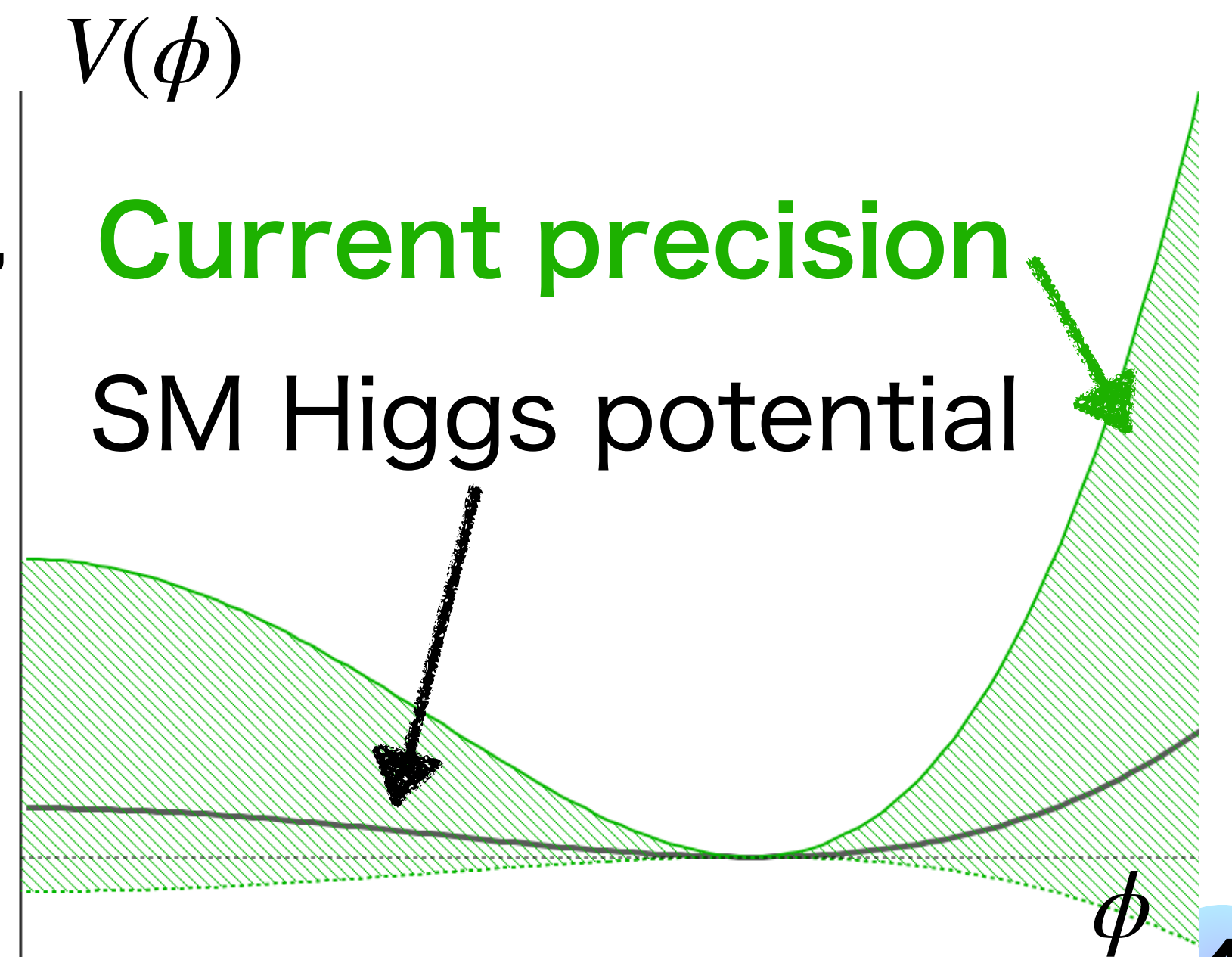
trilinear self-coupling



quartic self-coupling

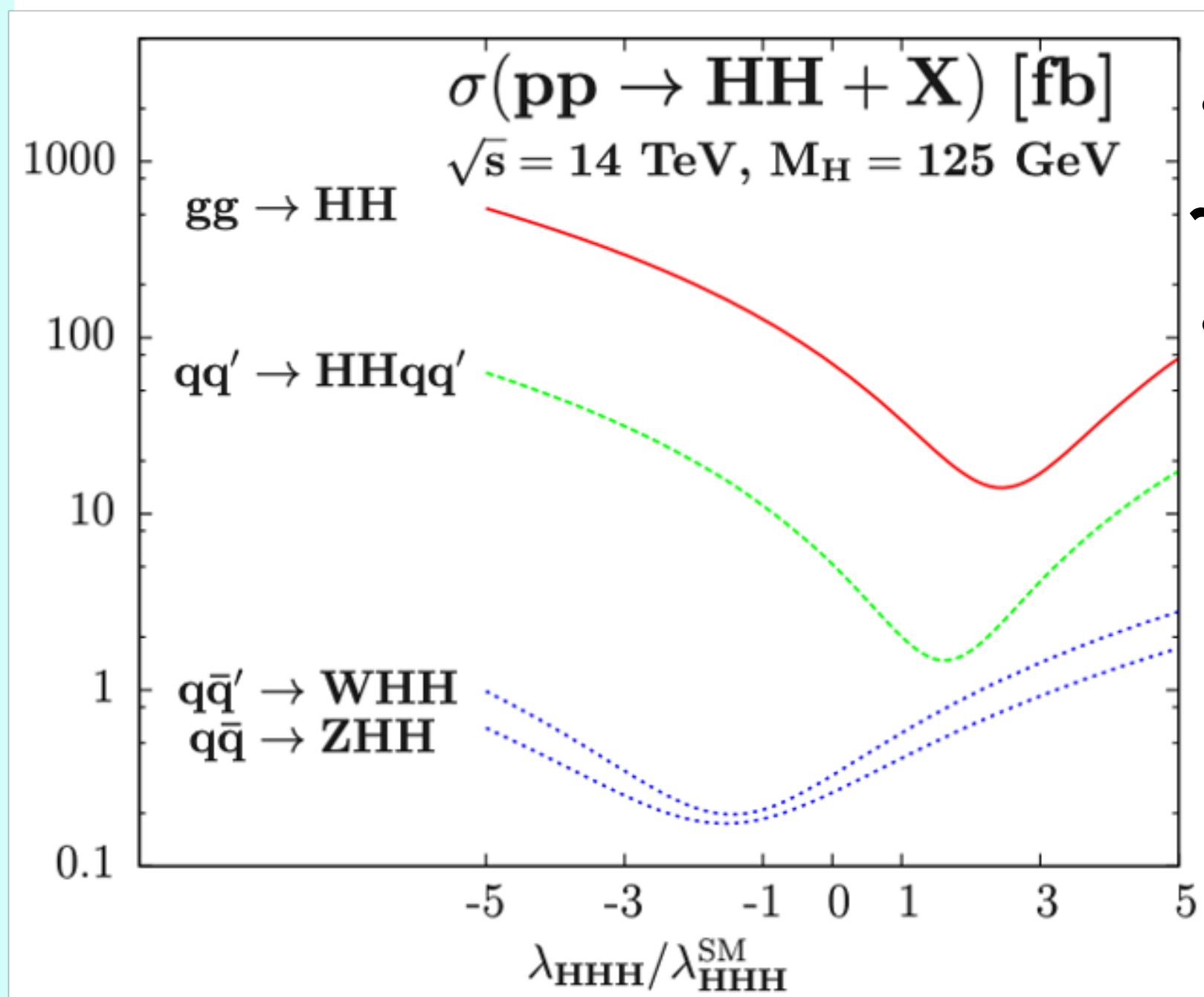
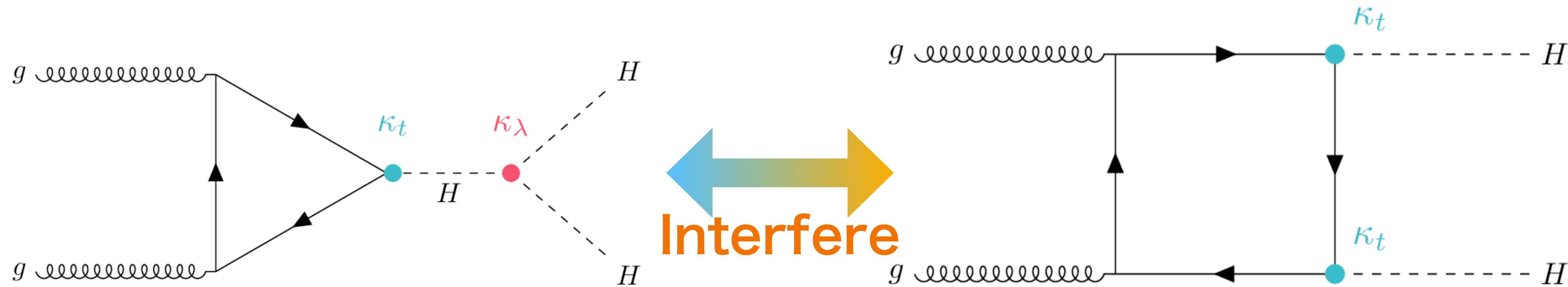


- Higgs self-coupling is not experimentally constraint yet ➔ Room of BSM physics



# Higgs Self-coupling measurement

Need to measure Higgs pair production mode



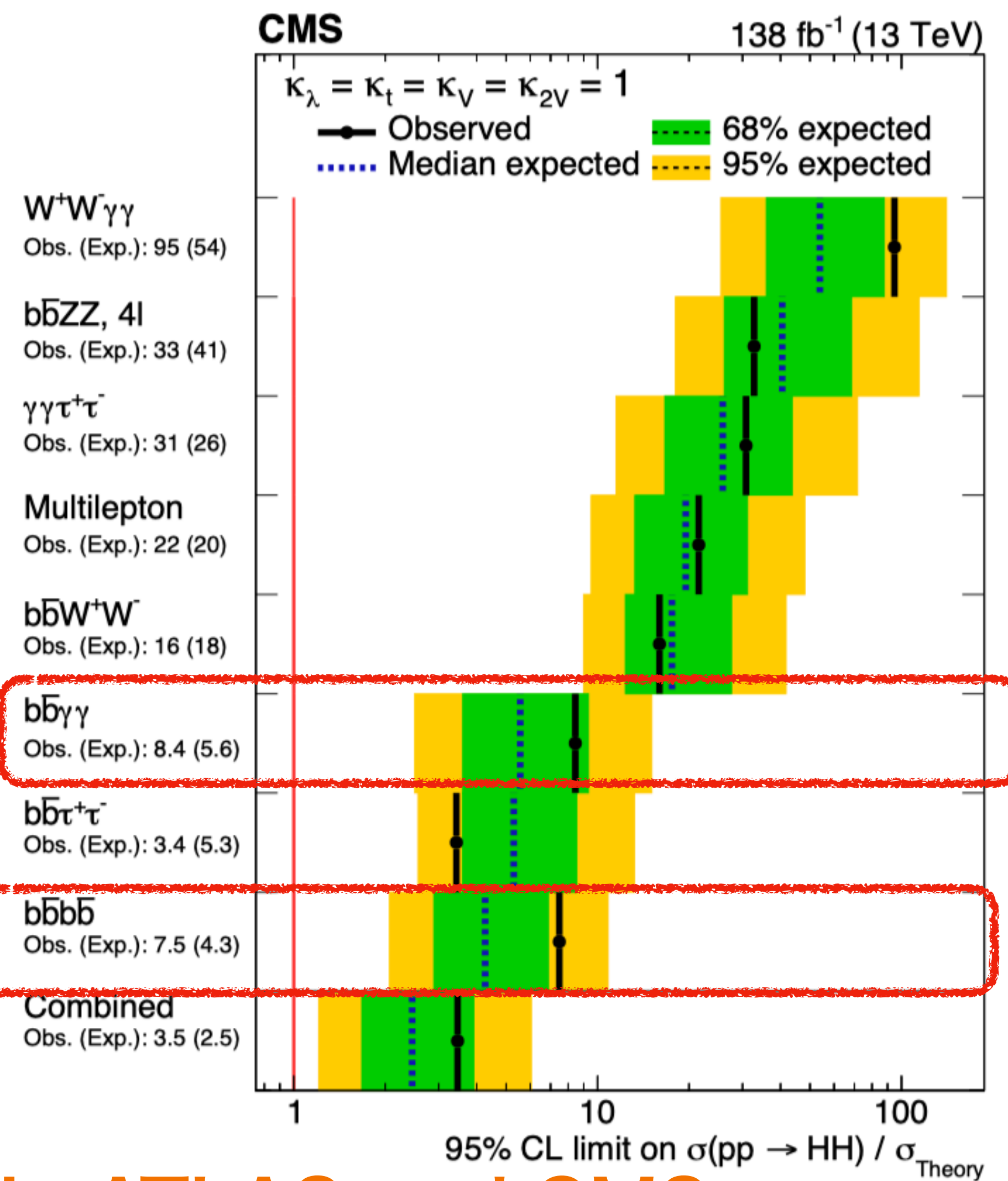
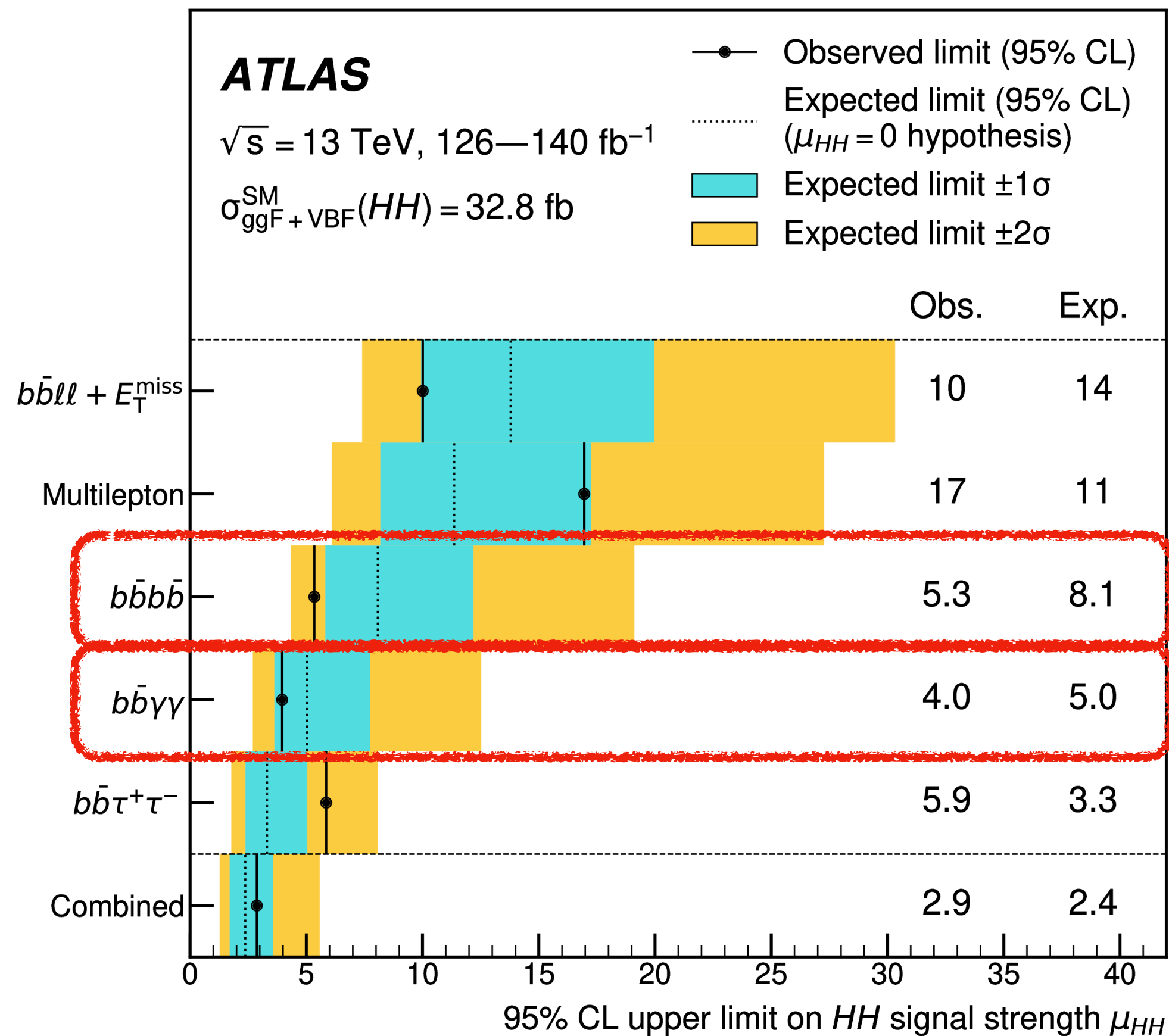
- $gg \rightarrow HH$  is dominant
- $gg \rightarrow HH$  cross-section is minimum  $\sim 2.5$

Variety of decay modes  
**4b**,  $bb \tau \tau$ ,  **$bb \gamma \gamma$**  are most powerful

|                | 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%        |

# Experimental Results

- Combined many final states analyzed in Run2

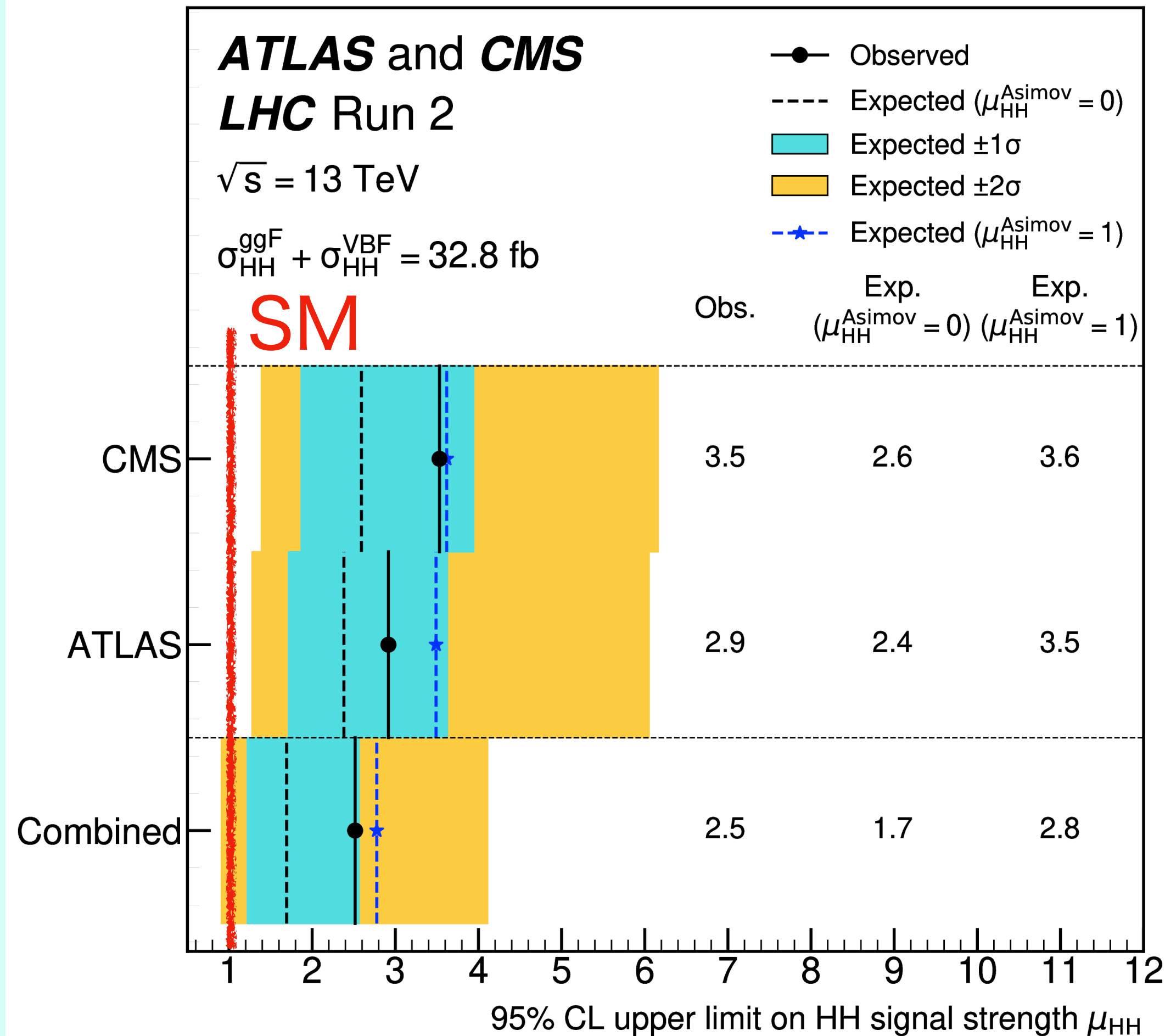


Combined sensitivity are similar in ATLAS and CMS

Observed upper limit 2.9-3.5xSM

# Run2 ATLAS+CMS Combination

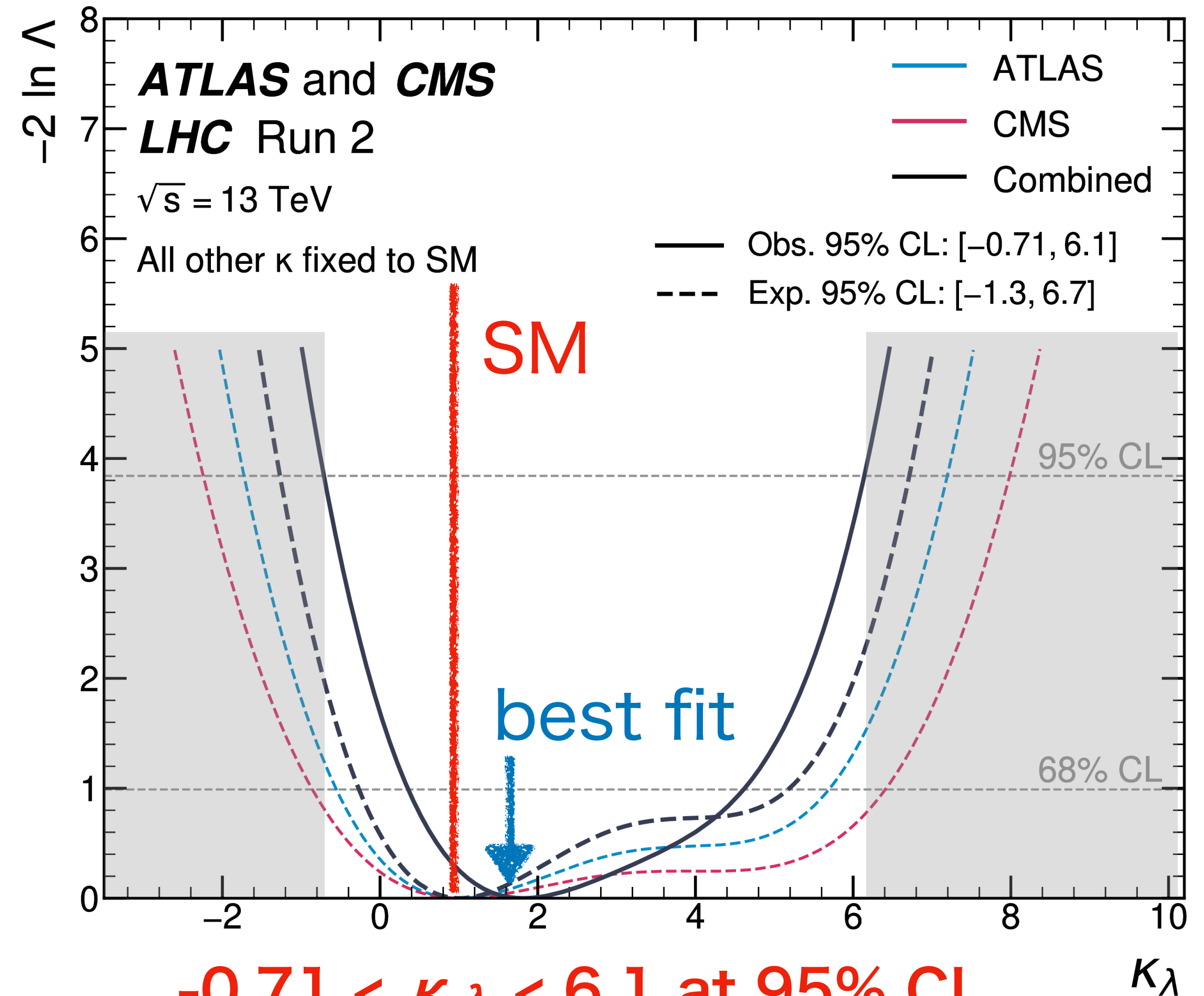
arXiv:2602.23991



**2.5 (1.7 exp. assuming  $\mu=0$ )**

**(2.8 exp. assuming  $\mu=1$ )**

**Significance  $1.1 \sigma$  ( $1.3 \sigma$  exp.)**



**$-0.71 < \kappa_\lambda < 6.1$  at 95% CL**

**(Expected:  $-1.3 < \kappa_\lambda < 6.7$ )**

# HEP\_18 Project

- Development from HEP\_17 (2024-2025) led by Marco and Yu
  - **Project Goal: Search for non-resonant HH and resonant HH, aiming for the first observation of non-resonant HH events using up to Run3 data ( $\sim 500\text{fb}^{-1}$ )**

| France  |
|---|
| Nicolas Berger(LAPP, Staff)   |
| Marco Delmastro (LAPP, Staff)   |
| Oleksii Kurdysh(LAPP, PD)   |
| Gianna Centeno(LAPP, PD)  |
| Hind Taibi(LAPP, PhD)   |

|  Japan |
|---|
| Tatsuya Masubuchi<br>(U Osaka, Staff)   |
| Yu Nakahama(KEK, Staff)   |
| Kosuke Itabashi(U Osaka, PD)  |
| Rina Kugo(U Osaka, PhD)   |

- Focus on  $\text{HH} \rightarrow \text{bb} \gamma \gamma$  and  $\text{HH} \rightarrow 4\text{b}$
- Develop state-of-the-art particle identification and boosted tagger
- Combine Run3 results
- Effective Field Theory (EFT) interpretation

# HEP\_17 Highlight

- In-person mini-workshop at LAPP (Feb 2025)

Meeting FJPPN 2024 project HEP\_17  
月曜日 2025/02/24 11:00 → 17:00 Europe/Paris  
Marco Delmastro (LAPP)

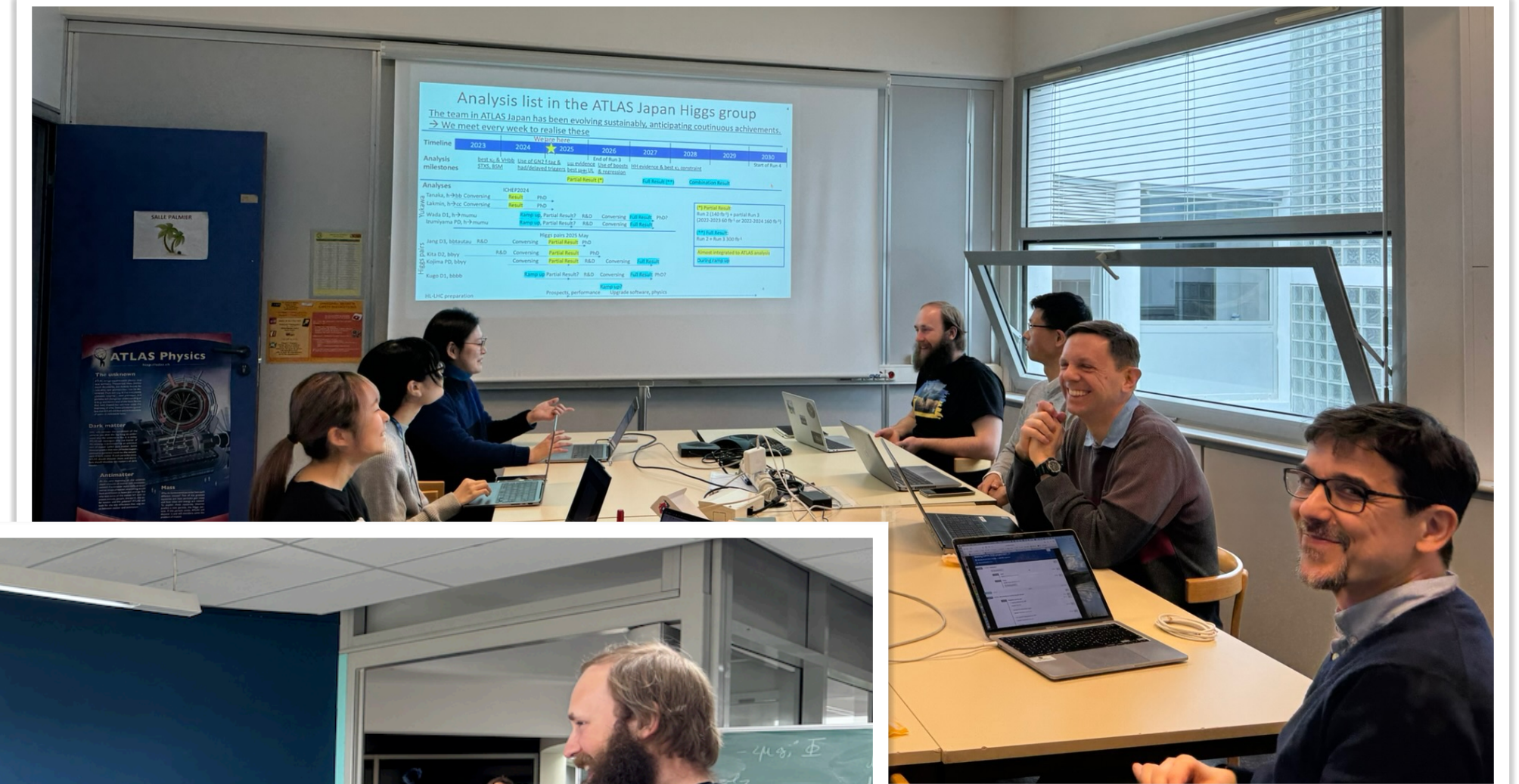
**11:00 → 12:00 Introduction**

- Application2024-...
- 11:00 Japan** (20分)  
発表者: Yu Nakahama Higuchi (KEK)  
LAPPMeeting24F...
- 11:20 France** (20分)  
発表者: Marco Delmastro (LAPP)  
Delmastro\_2025-...

**12:00 → 13:30 Lunch** (1時間 30分)

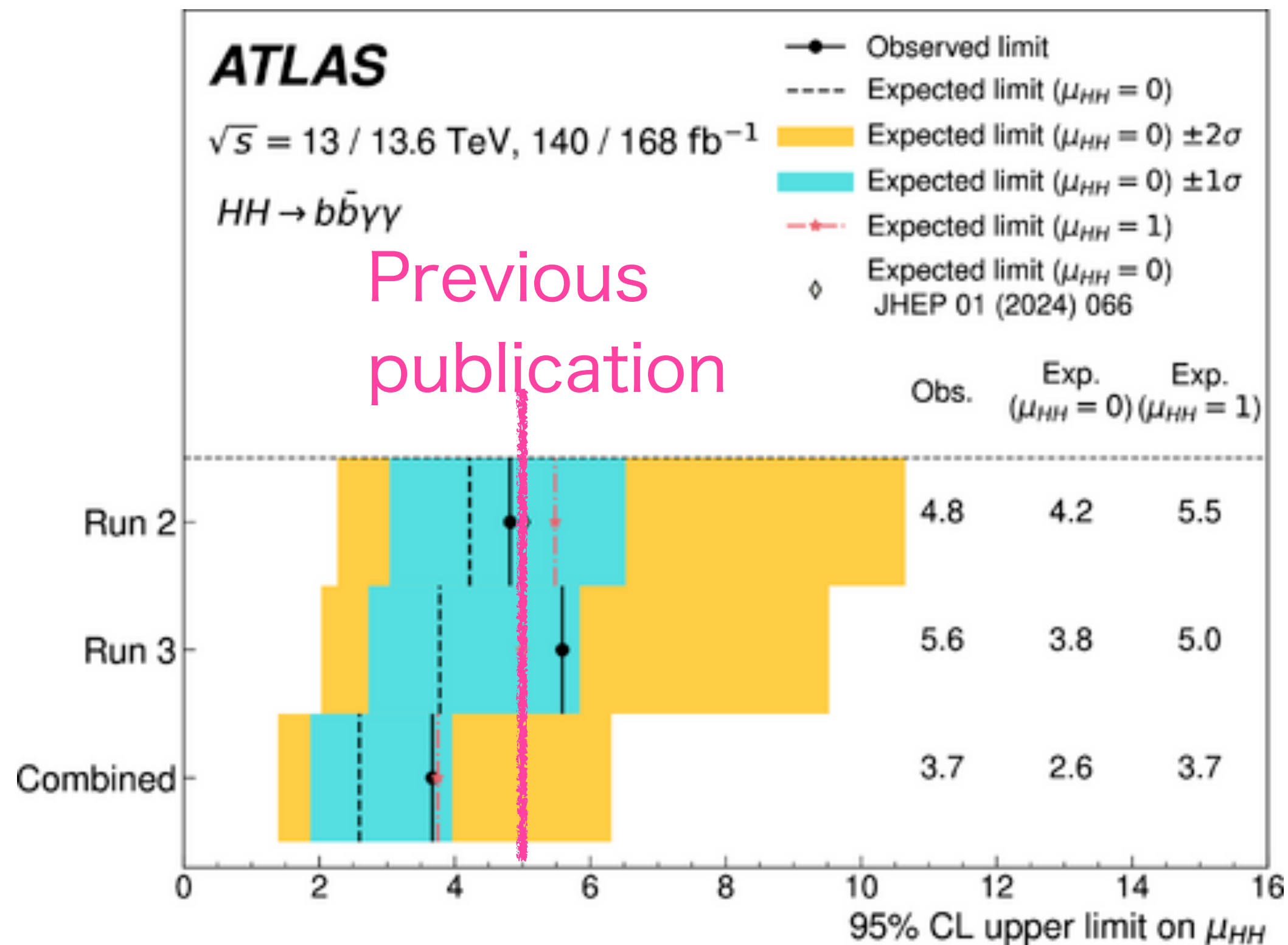
**13:30 → 16:00 Brainstorming on common interests and plan**

- 13:30 Progress in the first year** (1時間)
  - b-tagging calibration at LAPP** (15分)  
発表者: Zhibo Wu (LAPP)  
LAPPBtagCalib20...
  - Boosted HH→bbbb+GN2X tagger** (15分)  
発表者: Rina Kugo (Osaka University)  
rkugo\_20250224...
  - HH→yybb EFT interpretation at LAPP** (15分)  
発表者: Oleksii KURDYSH (LAPP)  
slide\_T4\_EFT\_sta...
  - HH→bbyy** (15分)  
発表者: Sayuka Kita (Tsukuba University)  
FJPPN\_SayukaKit...
- 14:30 Plan for next few years i.e. what to write for next-year's proposal** (20分)  
Discussion minut...
- 14:50 Future directions: HL-LHC** (20分)
- 15:10 Future directions (if enough time): future colliders** (20分)



# HEP\_17 Highlight

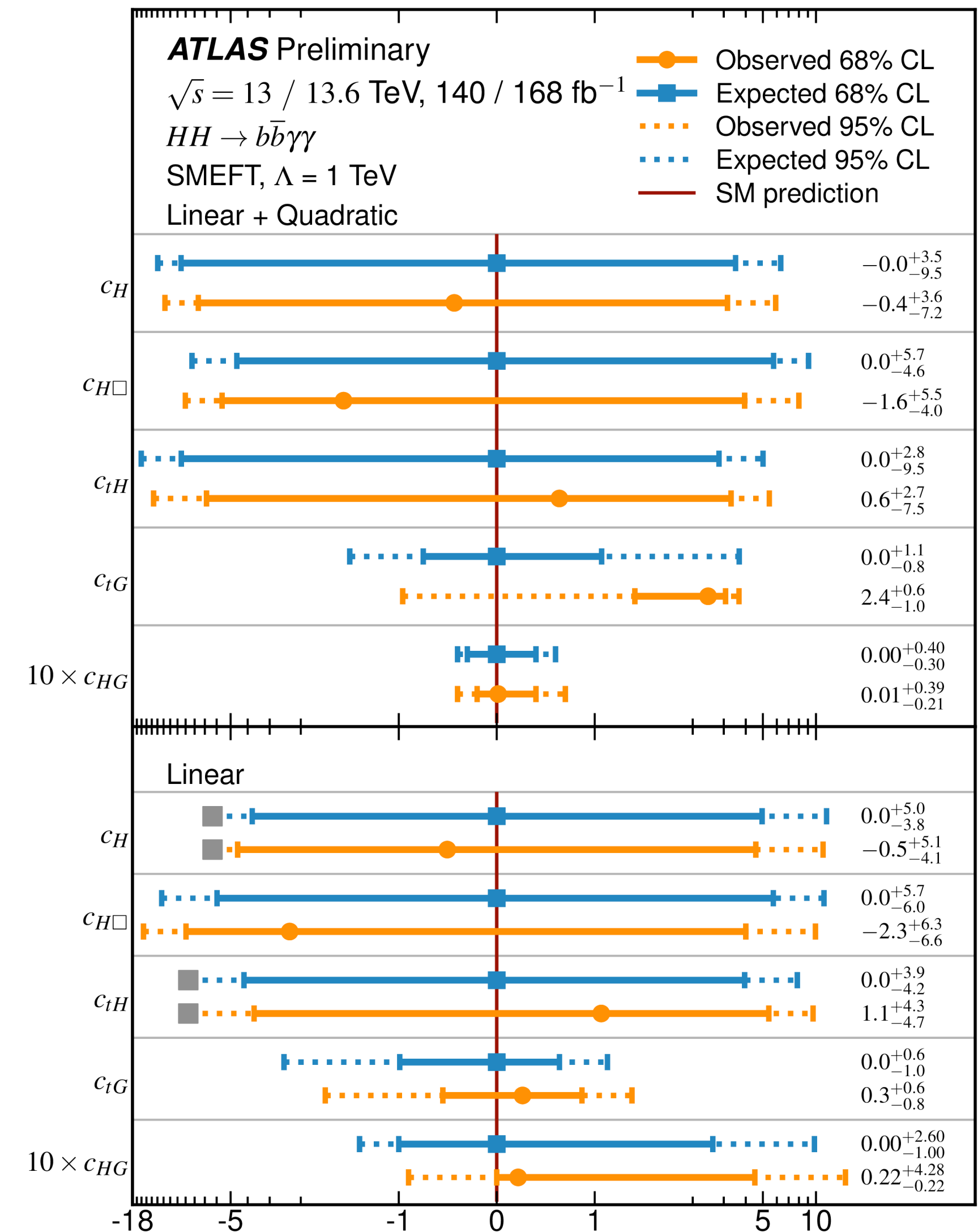
- Run2 + partial Run3 ( $\sim 300\text{fb}^{-1}$ )  $HH \rightarrow bb \gamma \gamma$  Results



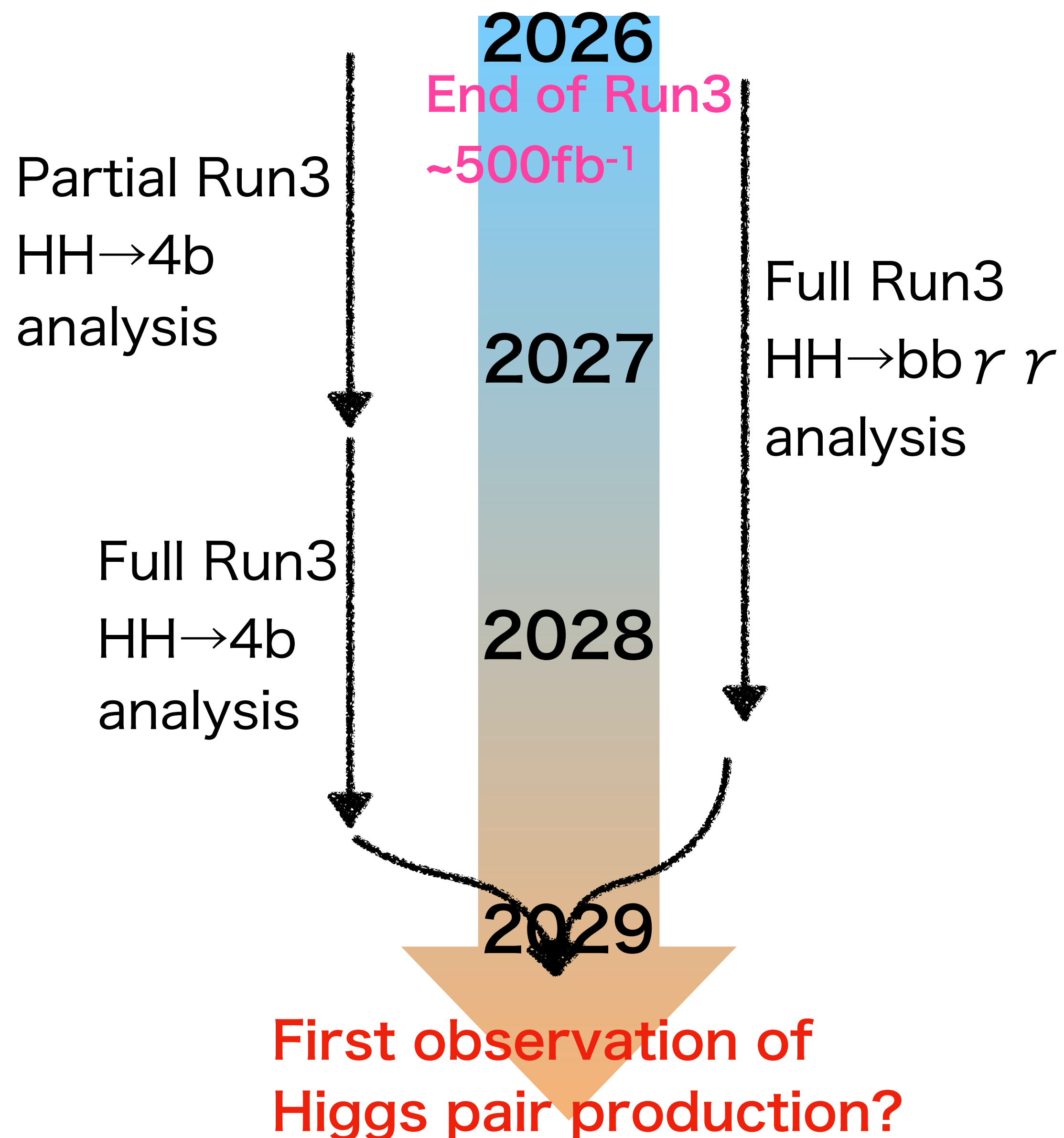
Improve upper limit by a factor of 2 from previous publications!

$-1.6 < \kappa_\lambda < 6.6$  at 95% CL

One student finished PhD in March 2026

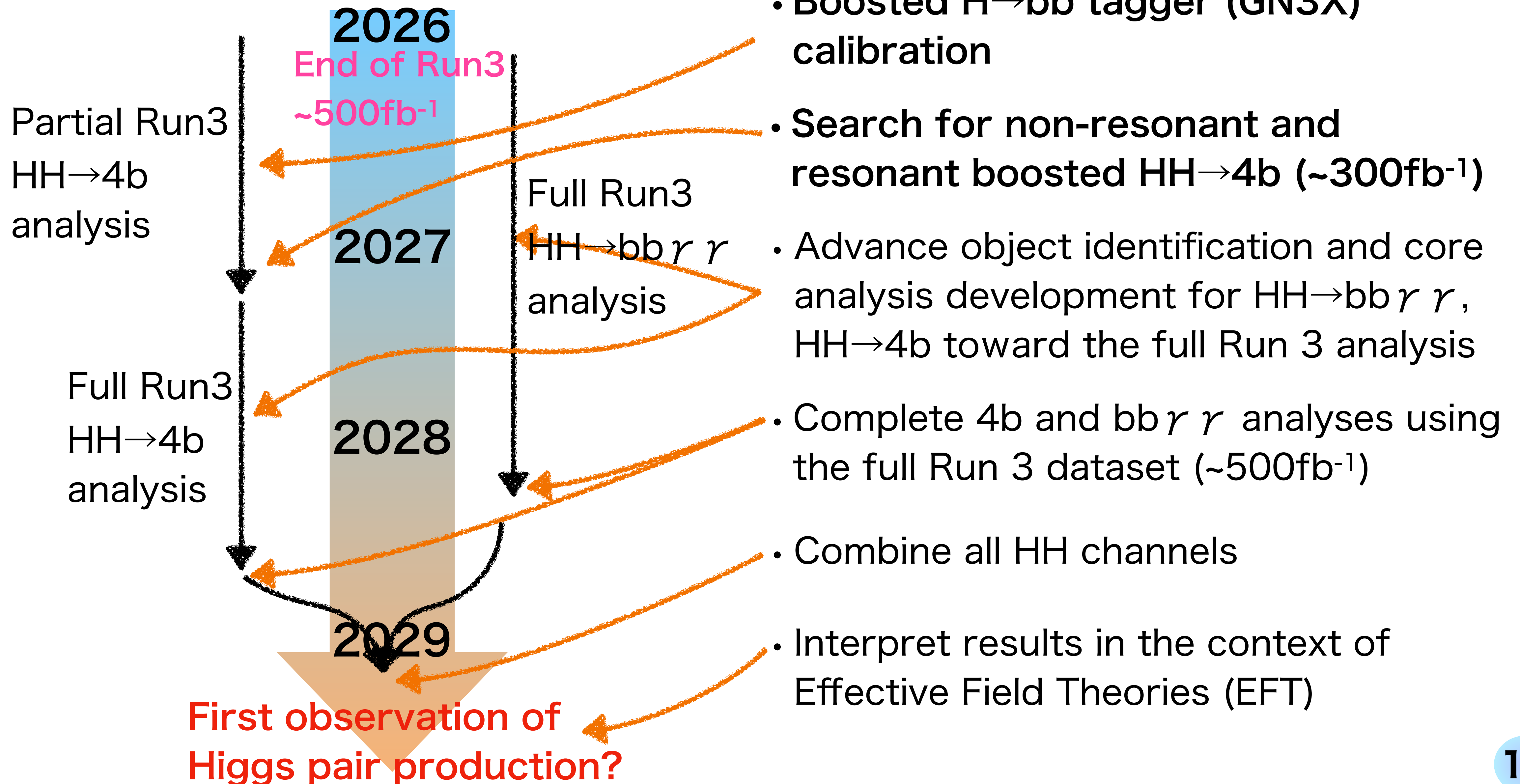


# Project Timeline and Topics



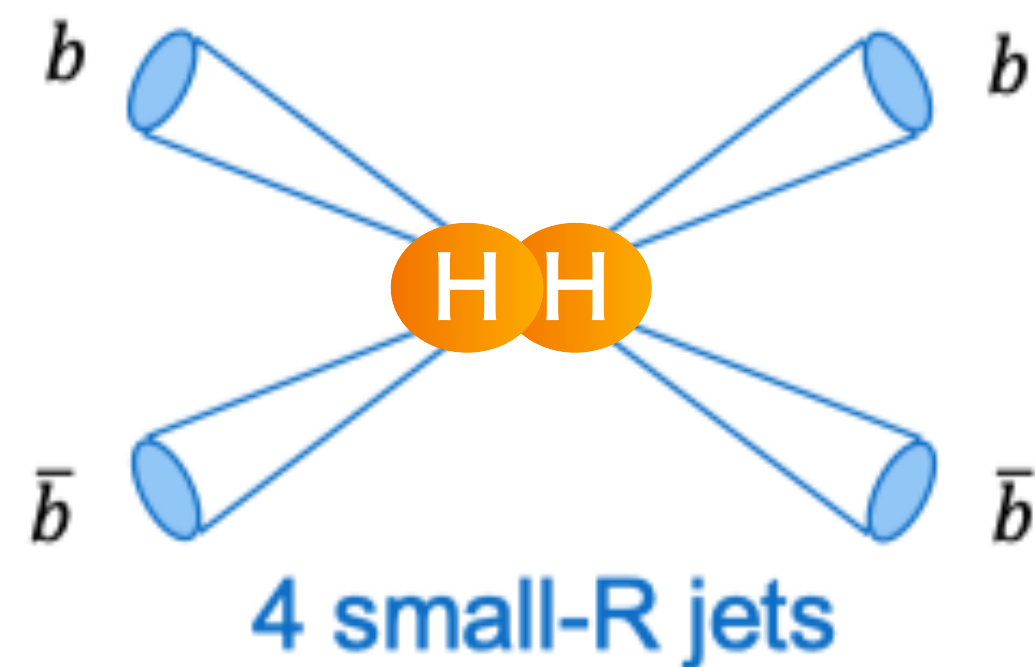
- Boosted H $\rightarrow$ bb tagger (GN3X) calibration
- Search for non-resonant and resonant boosted HH $\rightarrow$ 4b ( $\sim 300\text{fb}^{-1}$ )
- Advance object identification and core analysis development for HH $\rightarrow$ bb  $\gamma\gamma$ , HH $\rightarrow$ 4b toward the full Run 3 analysis
- Complete 4b and bb  $\gamma\gamma$  analyses using the full Run 3 dataset ( $\sim 500\text{fb}^{-1}$ )
- Combine all HH channels
- Interpret results in the context of Effective Field Theories (EFT)

# Project Timeline and Topics

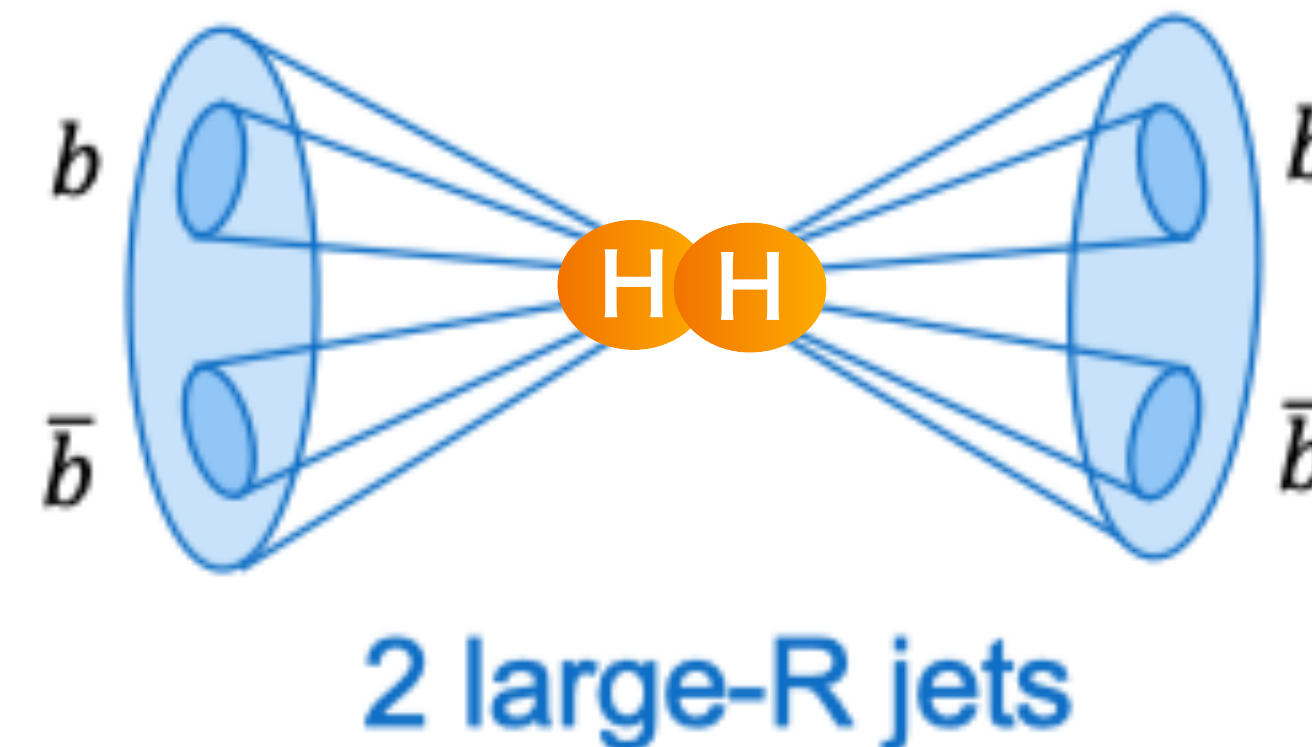


# Ongoing analysis developments

- One of the crucial developments is object identification and its calibration
  - $HH \rightarrow 4b$ ,  $HH \rightarrow 2b2\gamma$ : b-tagging and photon identification
  - Focus on boosted topology for 4b channel



Boosted Higgs  
( $p_T > 250$  GeV)

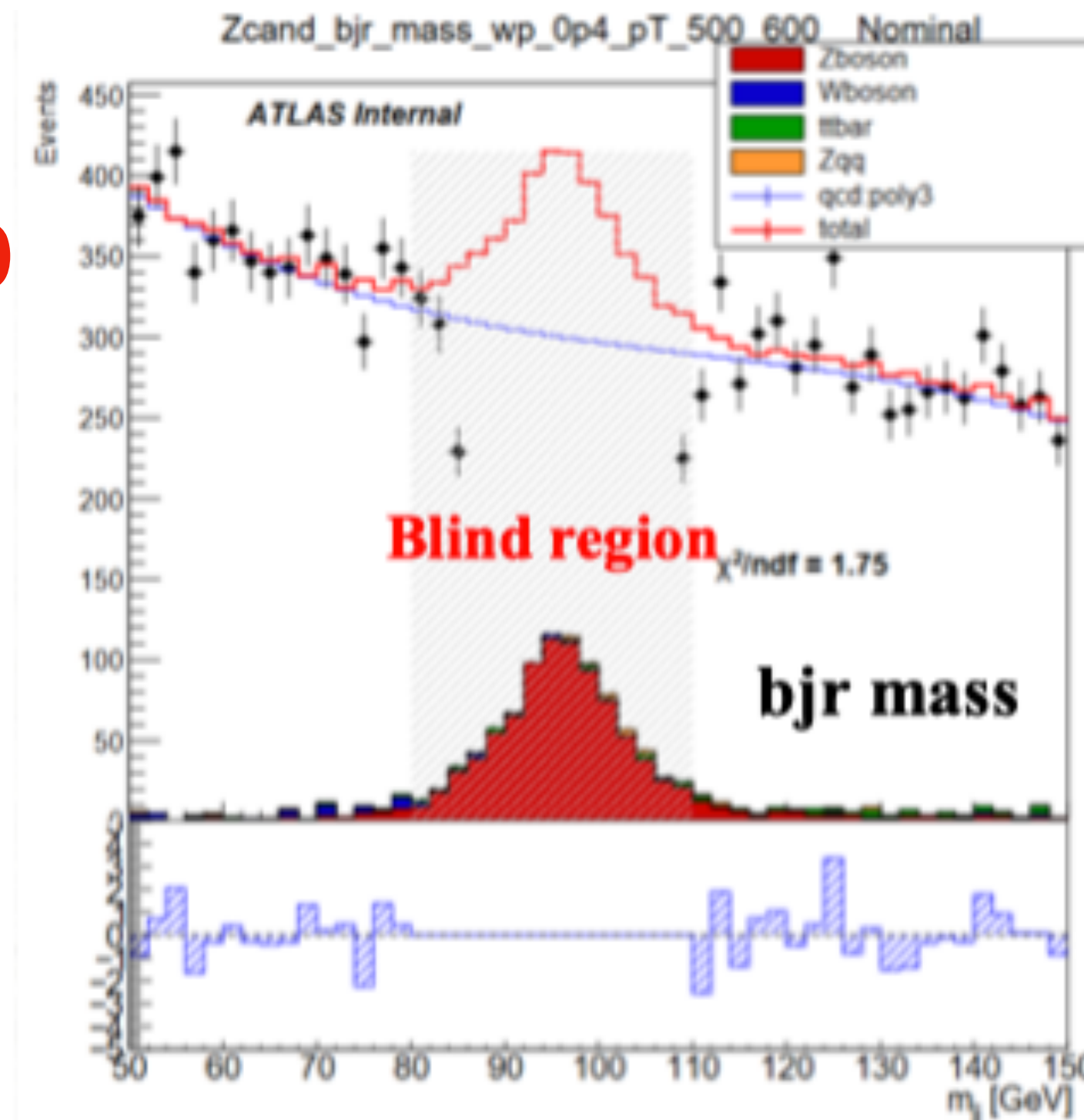
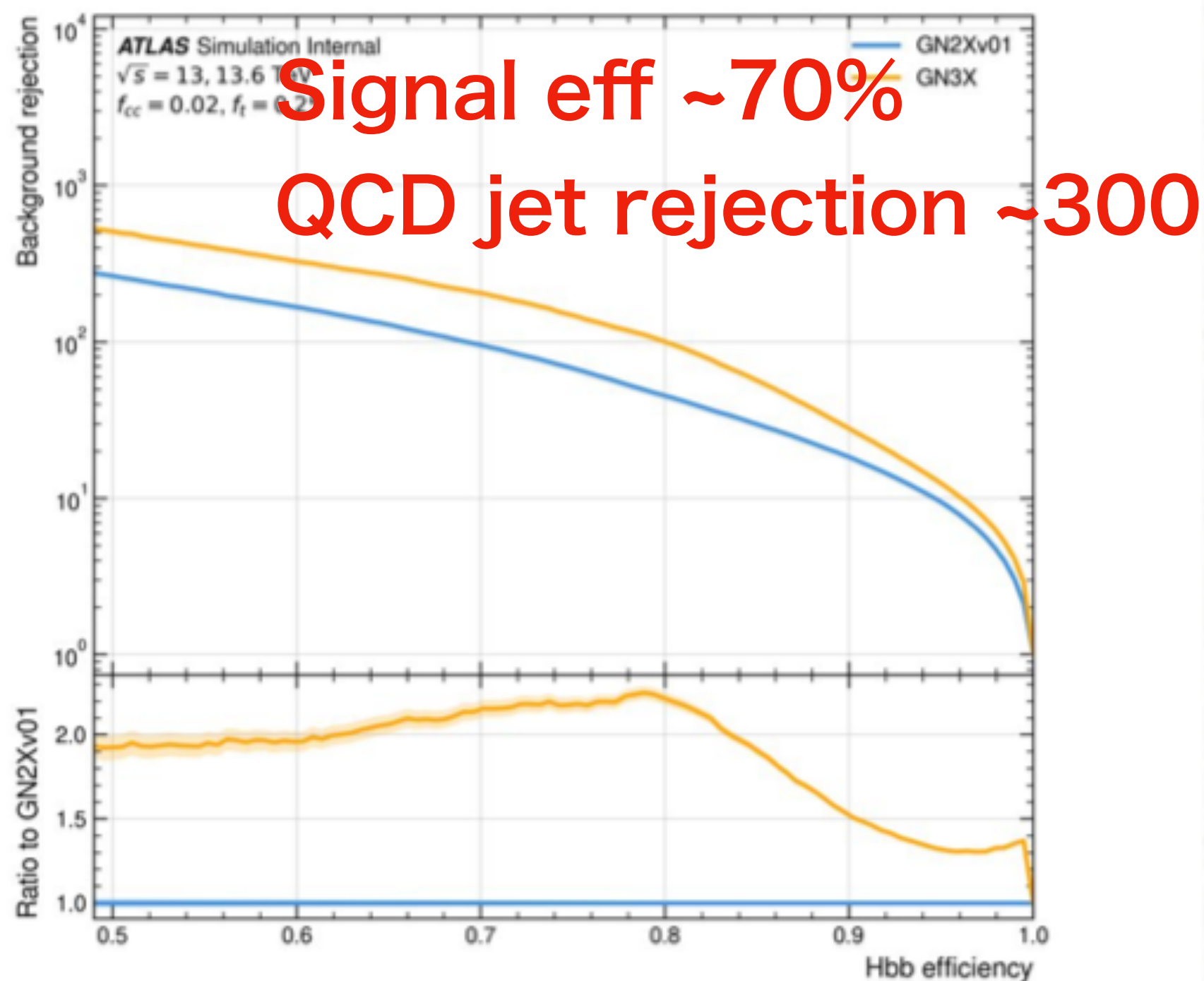
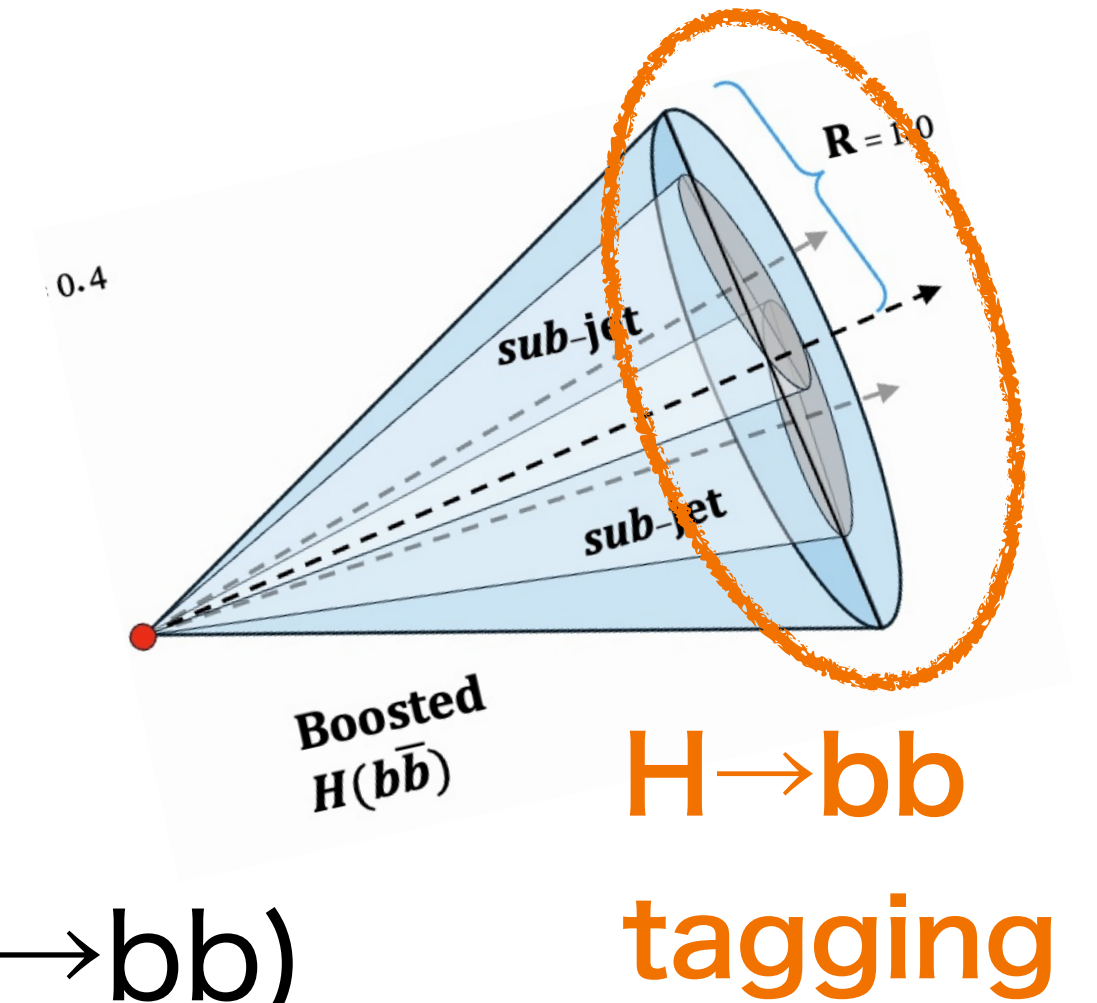


- 4b channel suffers from huge QCD multi-jet background
  - Issue with jet pairing to reconstruct Higgs
- ➔ Two Higgs(large-R) jets requirement reduces bkg significantly

**Higgs tagging and its calibration are key for 4b channel**

# Ongoing analysis developments

- Transformer-based  $H \rightarrow bb$  tagging (GN) development
  - The latest tagging (GN3X) includes calorimeter information in addition to tracking info
  - Improve Higgs mass resolution with the same GN3X model
- Crucial to calibrate of GN3X tagger using boosted  $Z(\rightarrow bb)$

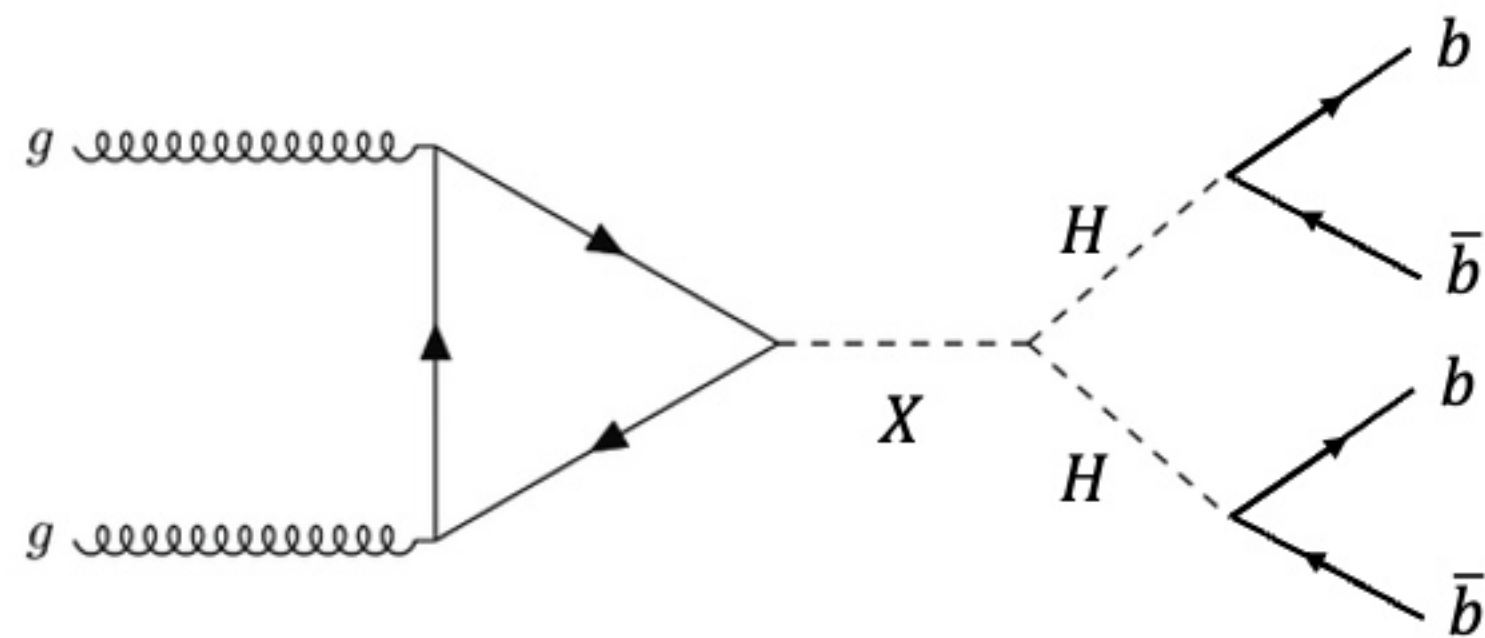


Search sensitivity of  $HH \rightarrow 4b$  improves significantly

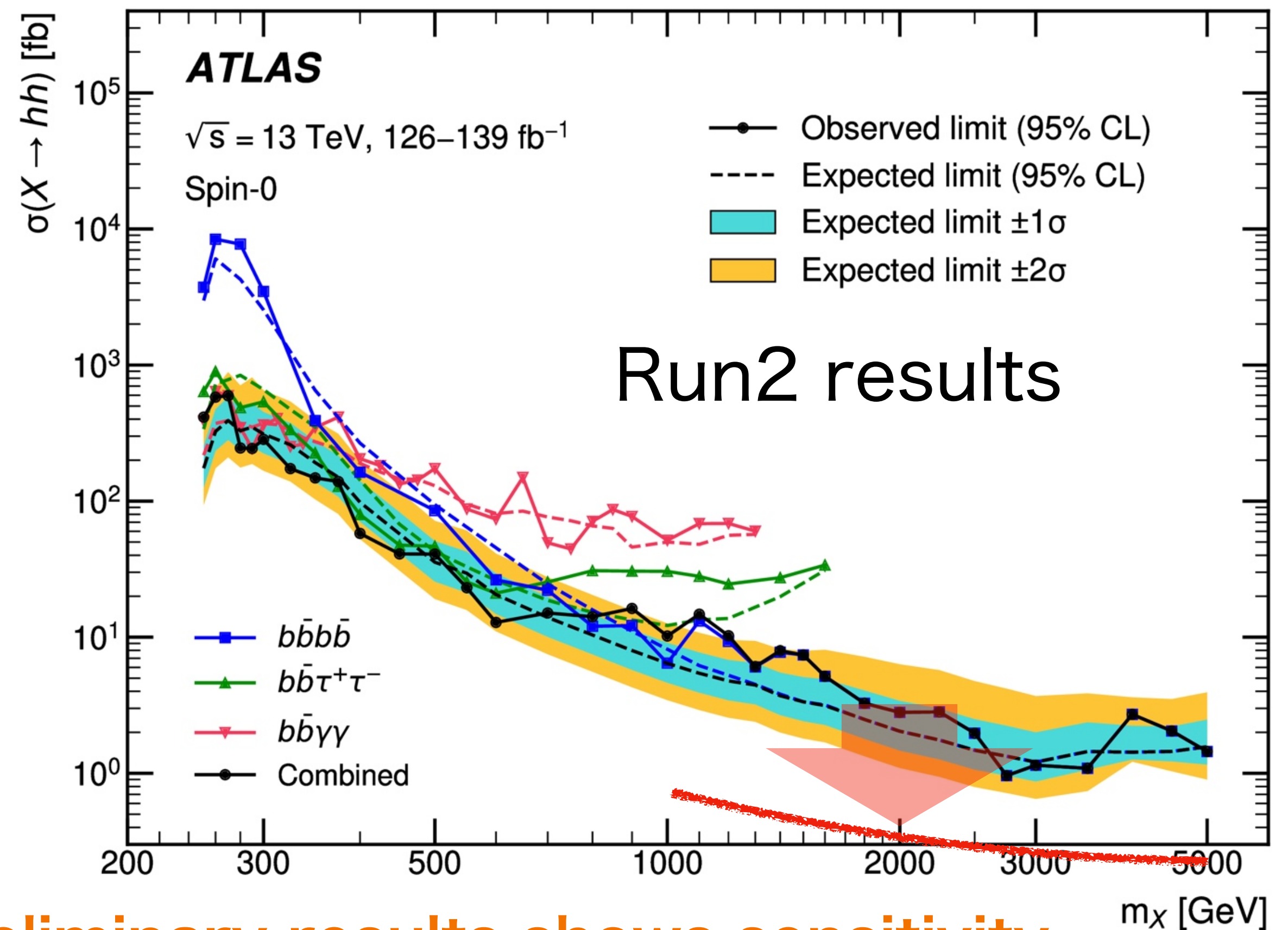
The same GNN architecture applies to Boosted  $H \rightarrow \tau \tau$

# Ongoing analysis developments

- Boosted Higgs tagging can be used for high mass resonance search
- Heavy scalars are predicted in various extended Higgs model (e.g. 2HDM)



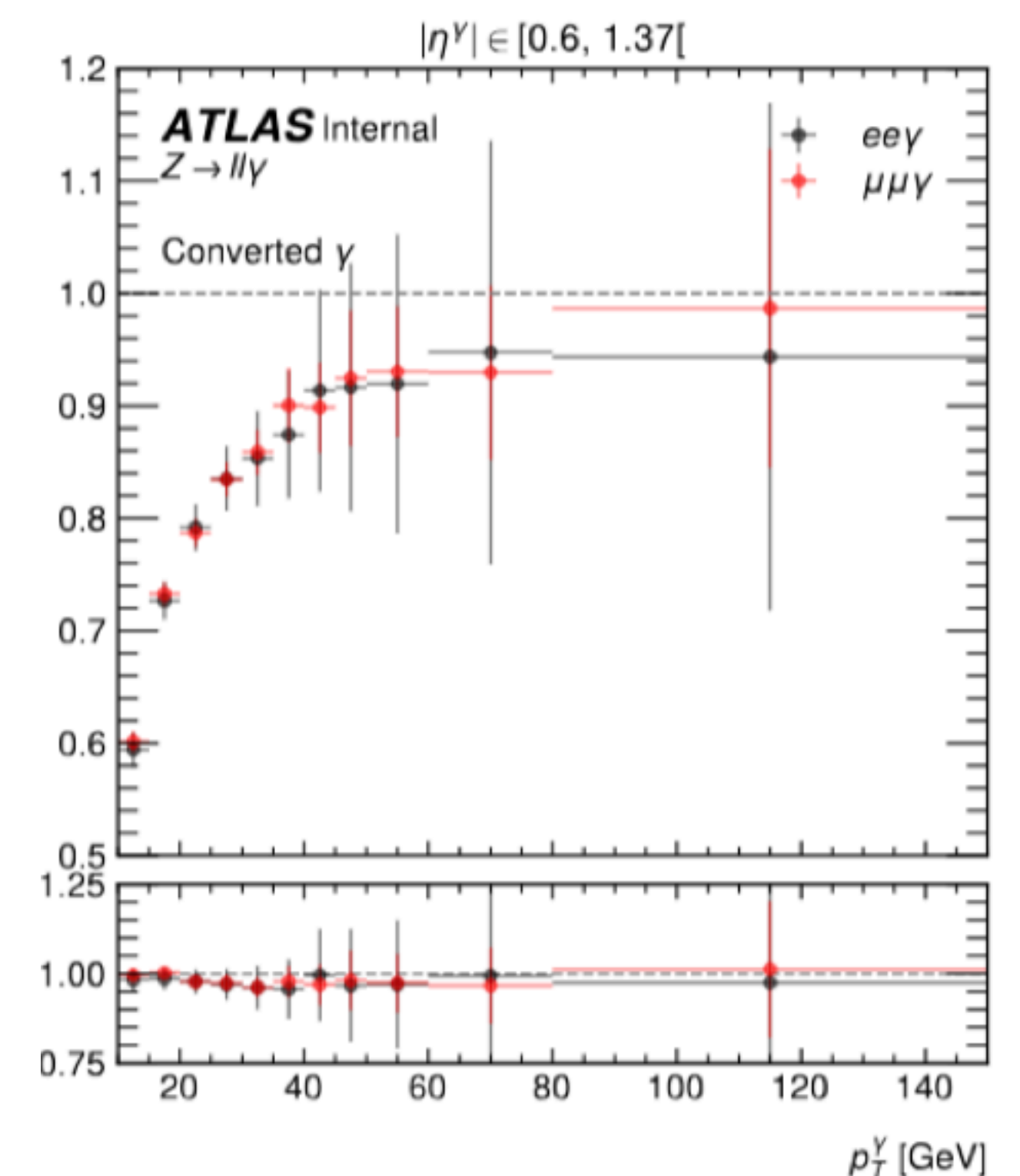
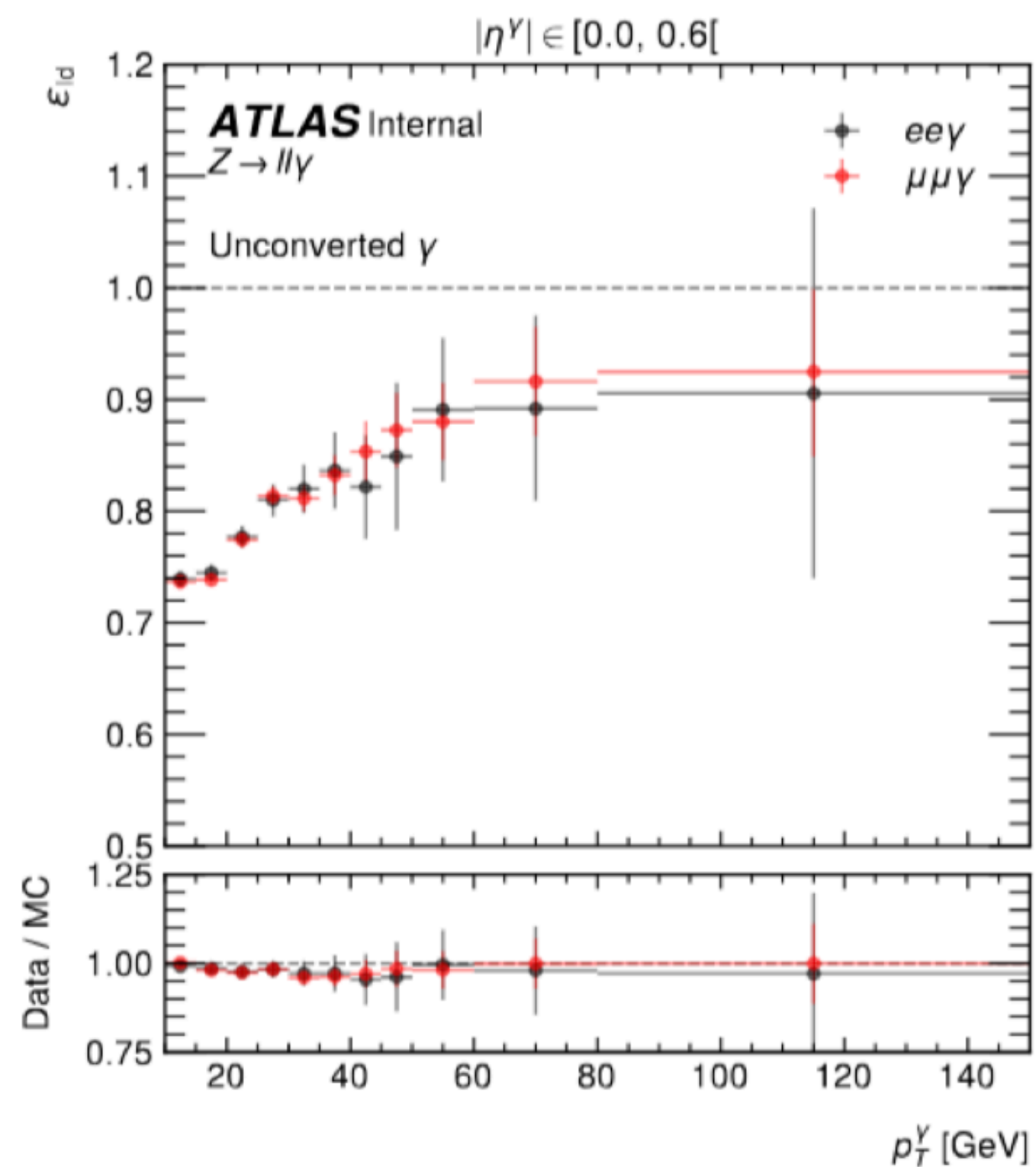
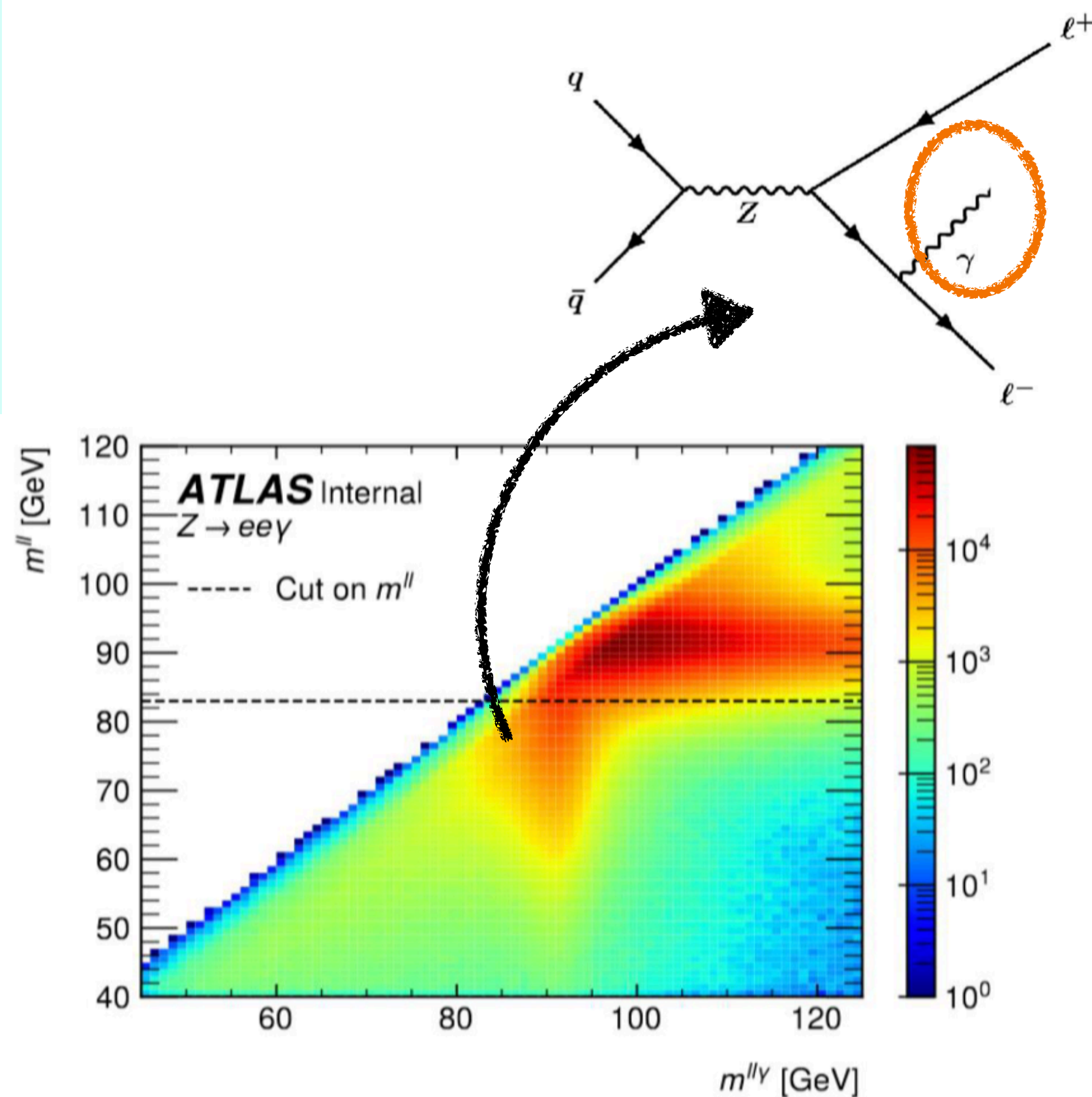
**HH → 4b is most sensitive in  $m_X > 1$  TeV**  
 → GN3X Boosted tagger provides significant sensitivity improvement!



**Preliminary results shows sensitivity improvement  $\times \sim 10$  in same data amount**

# Ongoing analysis developments

- Photon identification is key for  $HH \rightarrow bb \gamma \gamma$
- Investigating photon identification improvement using ML technique w.r.t. cut-based selection
- Photon identification is calibrated with radiative  $\gamma$  from  $Z \rightarrow ll$



# Network and synergy

The France and Japan team have good complementarities

➔ Collaboration network will maximize HH search capabilities

Japan's expertise

b-tagging (resolved jet, boosted jet) calibration

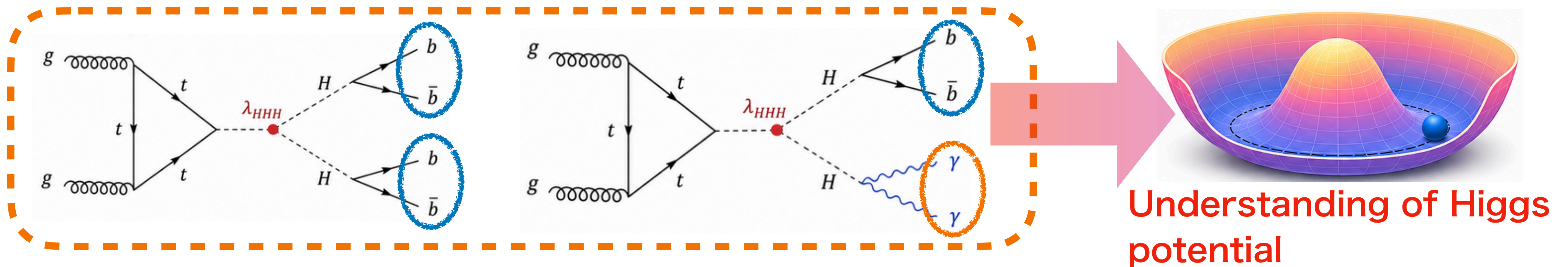
HH Resonance search

France's expertise

Photon reconstruction

Boosted  $H \rightarrow \tau \tau$  identification

Combination, EFT interpretation



Common framework/technologies can be shared in this network

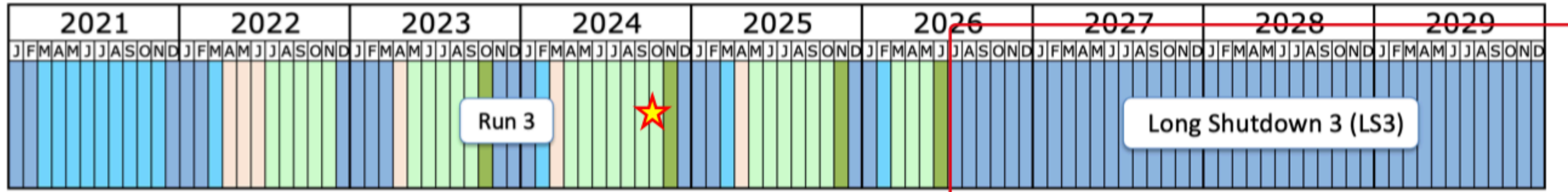
ECRs (3PD, 2 PhD) are involved in this network

➔ 2 PhDs Jointly supervised (will join more for future)

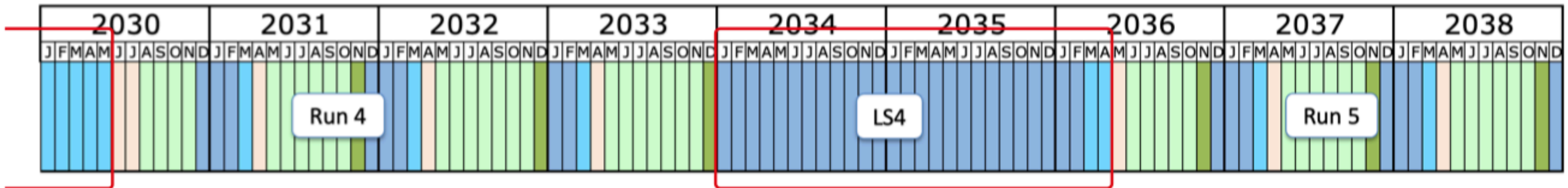
➔ More regular meetings and in-person workshops using this funding

# Backup

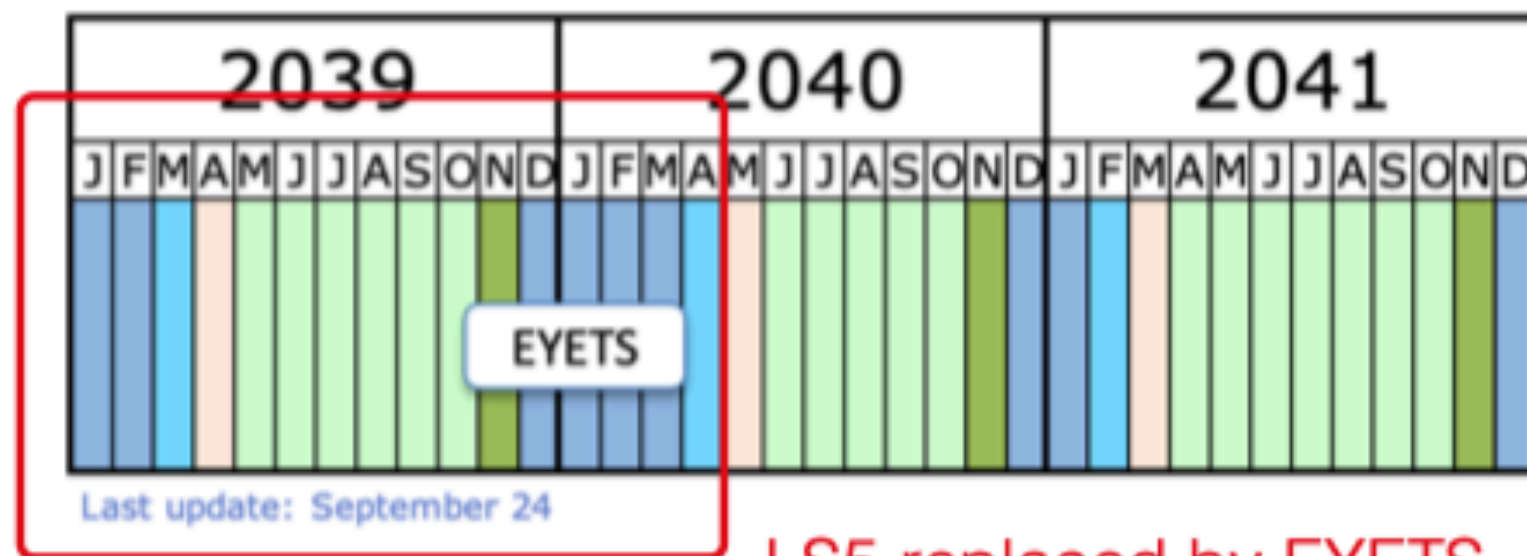
# Run3 and HL-LHC Schedule



LS3 duration: July 2026 – May 2027: 47 months



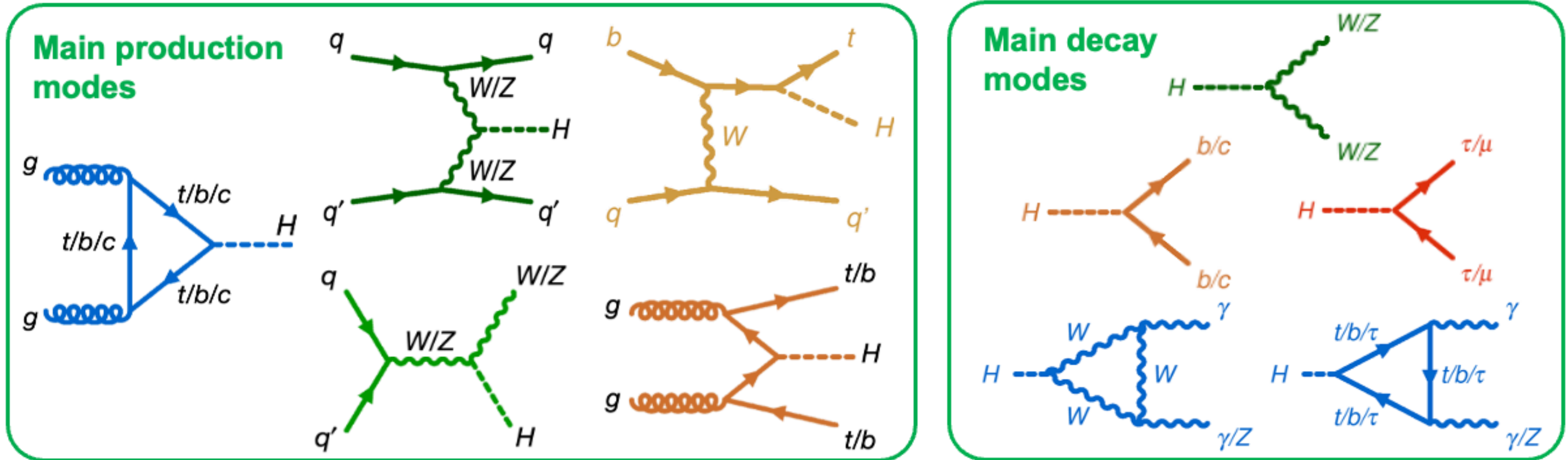
LS4 shifted by 1 year



LS5 replaced by EYETS

- Shutdown/Technical stop
- Protons physics
- Ions (tbc after LS4)
- Commissioning with beam
- Hardware commissioning

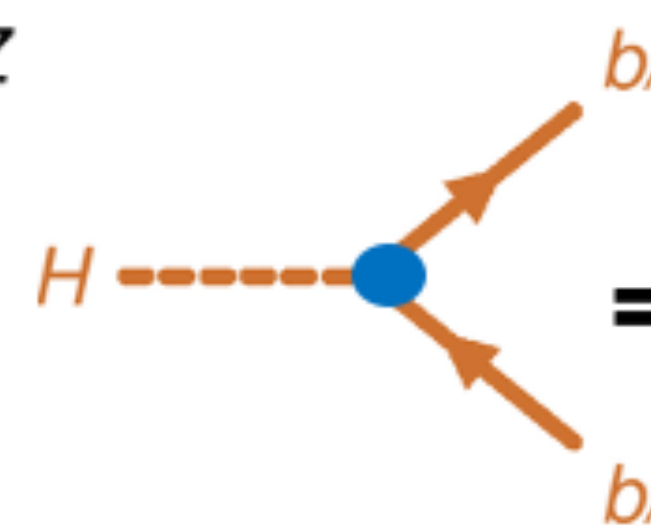
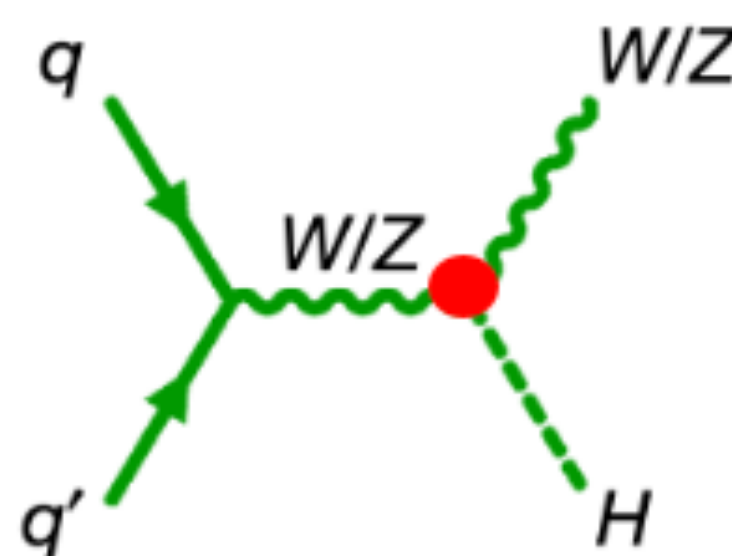
# Combined Measurements



- Combined various production and decay modes to obtain the best precisions

## k-framework

$$\kappa = g_x^{\text{measure}} / g_x^{\text{SM}}$$

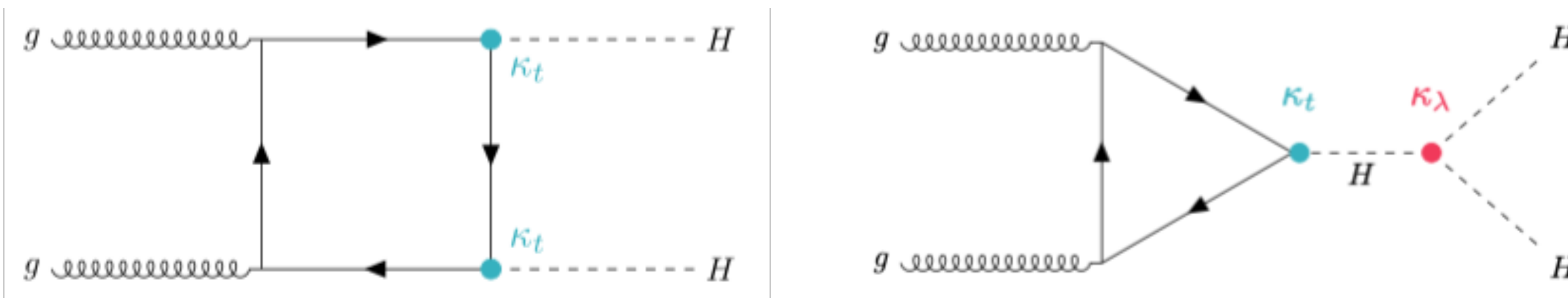


$$\begin{aligned} & \sigma(pp \rightarrow VH) \cdot BR(H \rightarrow bb) \\ &= \kappa_{W/Z}^2 \cdot \kappa_b^2 \times (\sigma_{\text{SM}} \cdot BR_{\text{SM}}) \end{aligned}$$

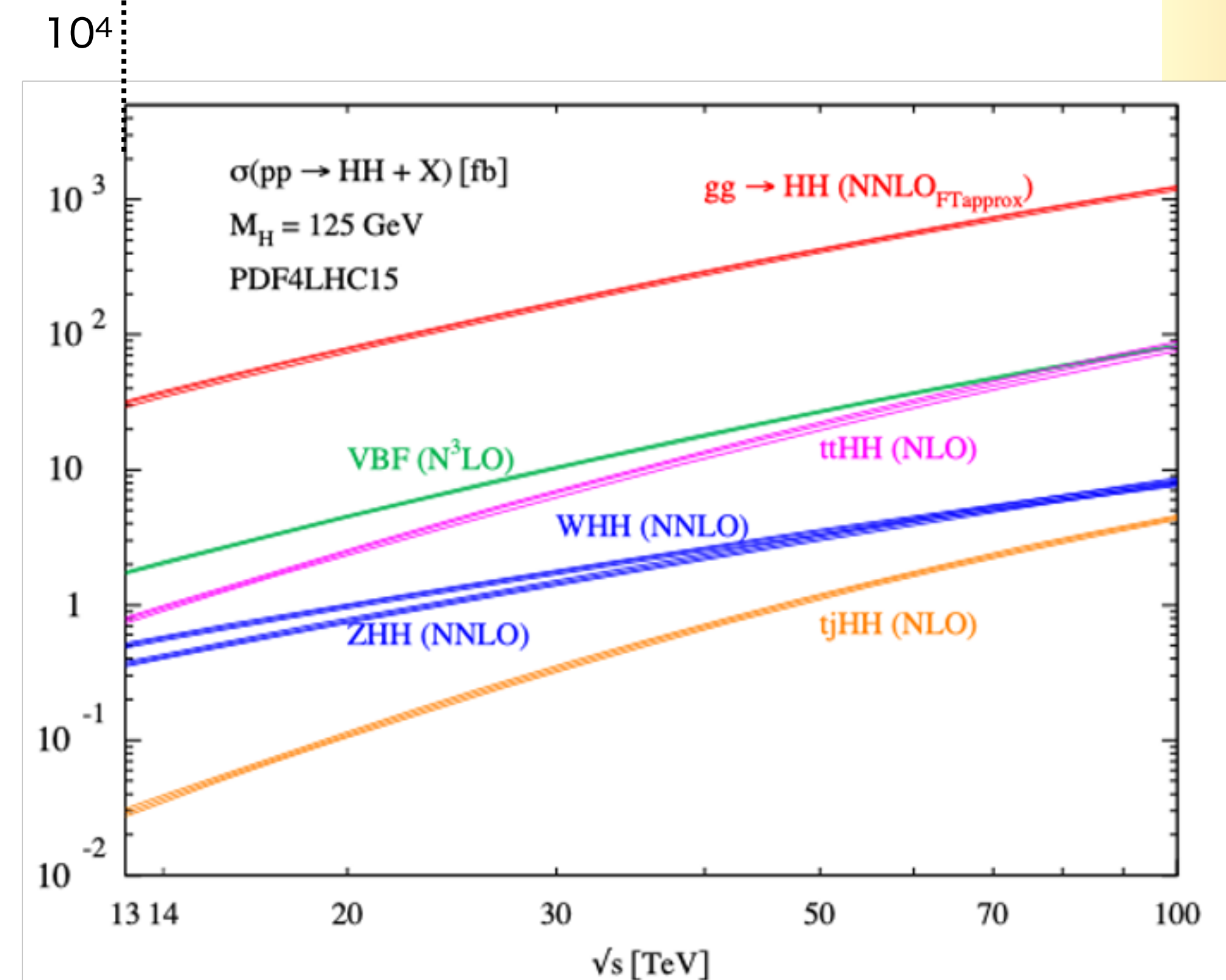
# Self-coupling and DiHiggs

- Crucial to find DiHiggs events to measure self-coupling
- Cross section is quite tiny ( $\sim 30\text{fb}$ ) at even LHC (1/1000 of  $pp \rightarrow H$ )  
 → Challenging to observe HH signal

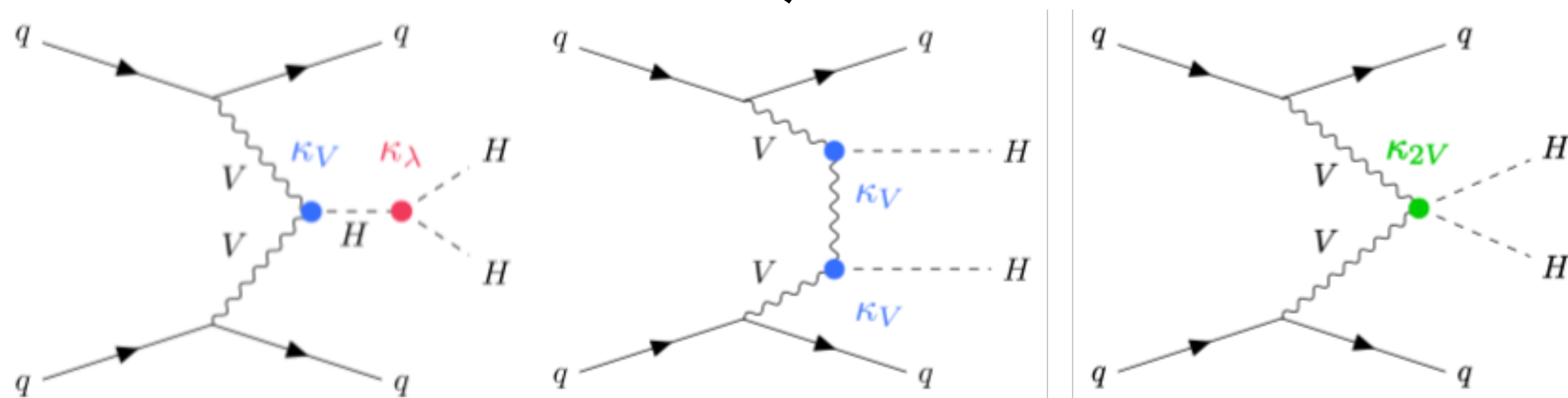
ggF( $\sim 31.05\text{fb}$  at NNLO QCD+NLO EW)



$pp \rightarrow H$  ( $\sim 60\text{pb}$ )



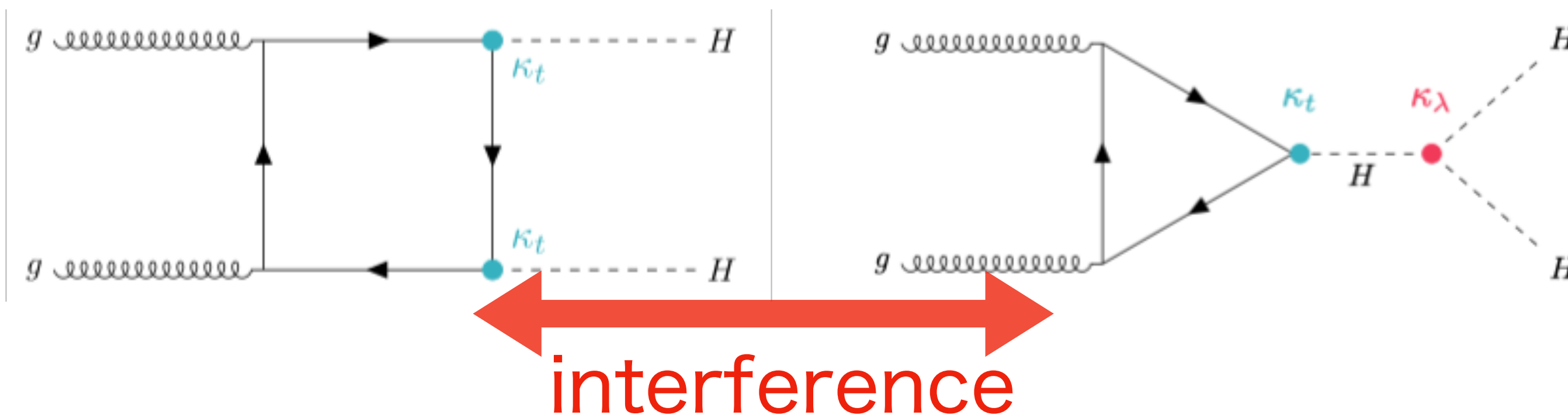
VBF( $\sim 1.73\text{fb}$  at N<sup>3</sup>LO QCD)



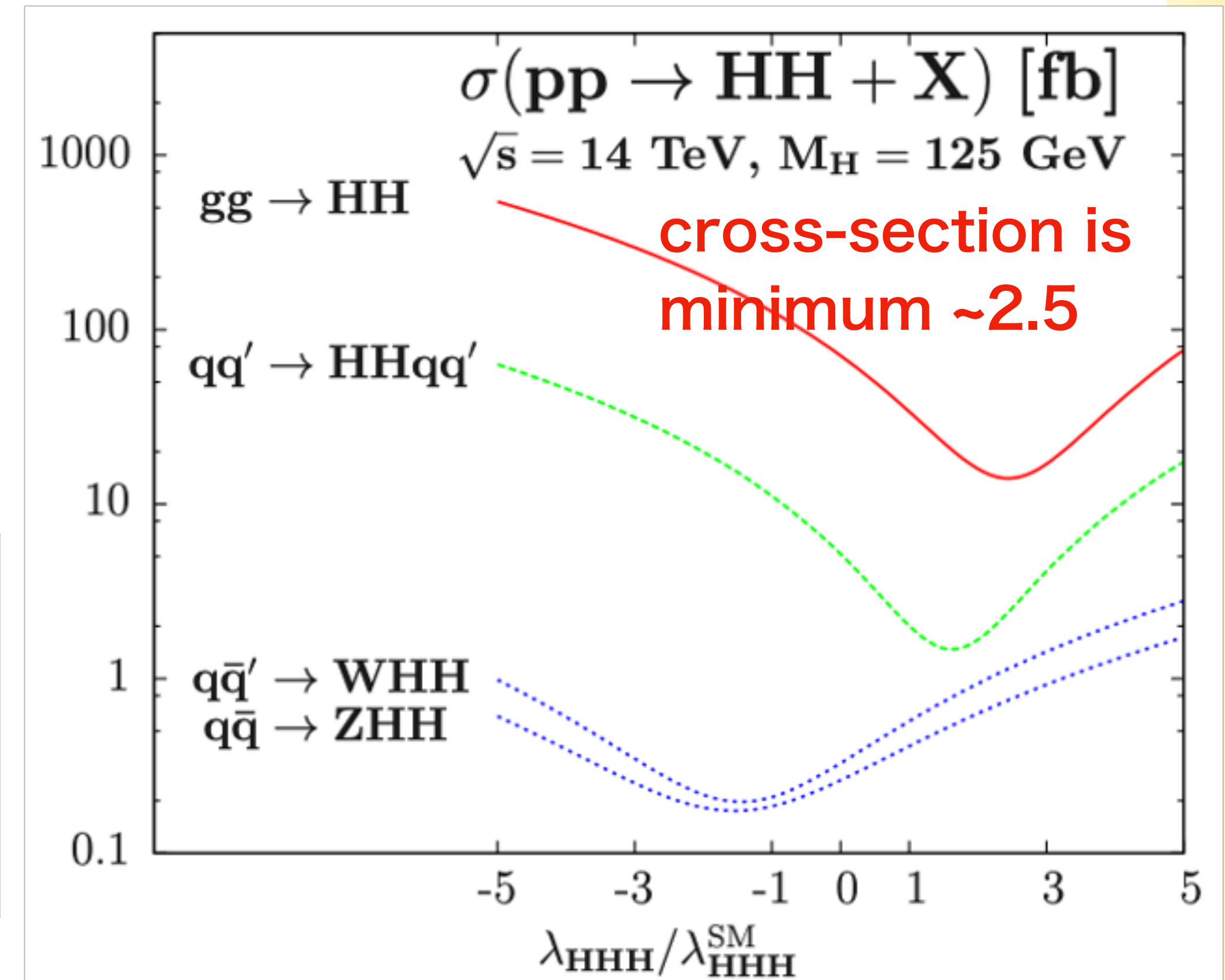
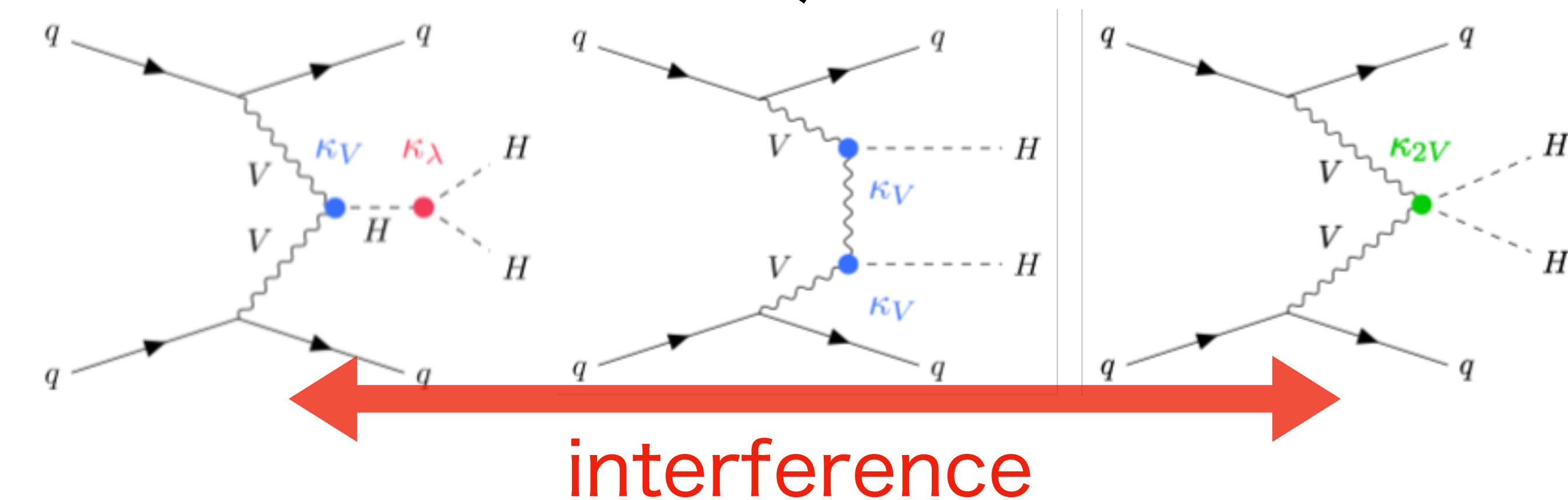
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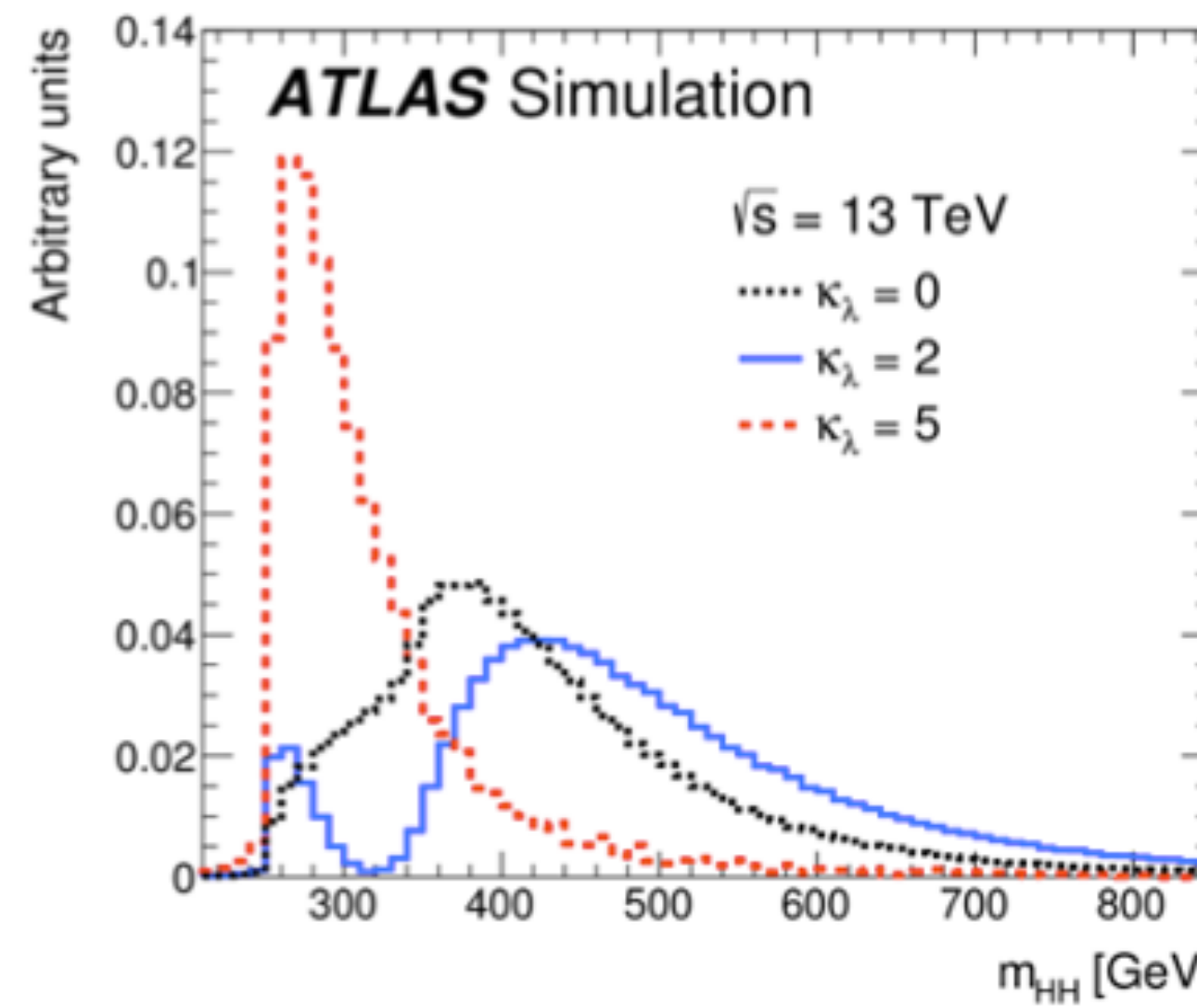
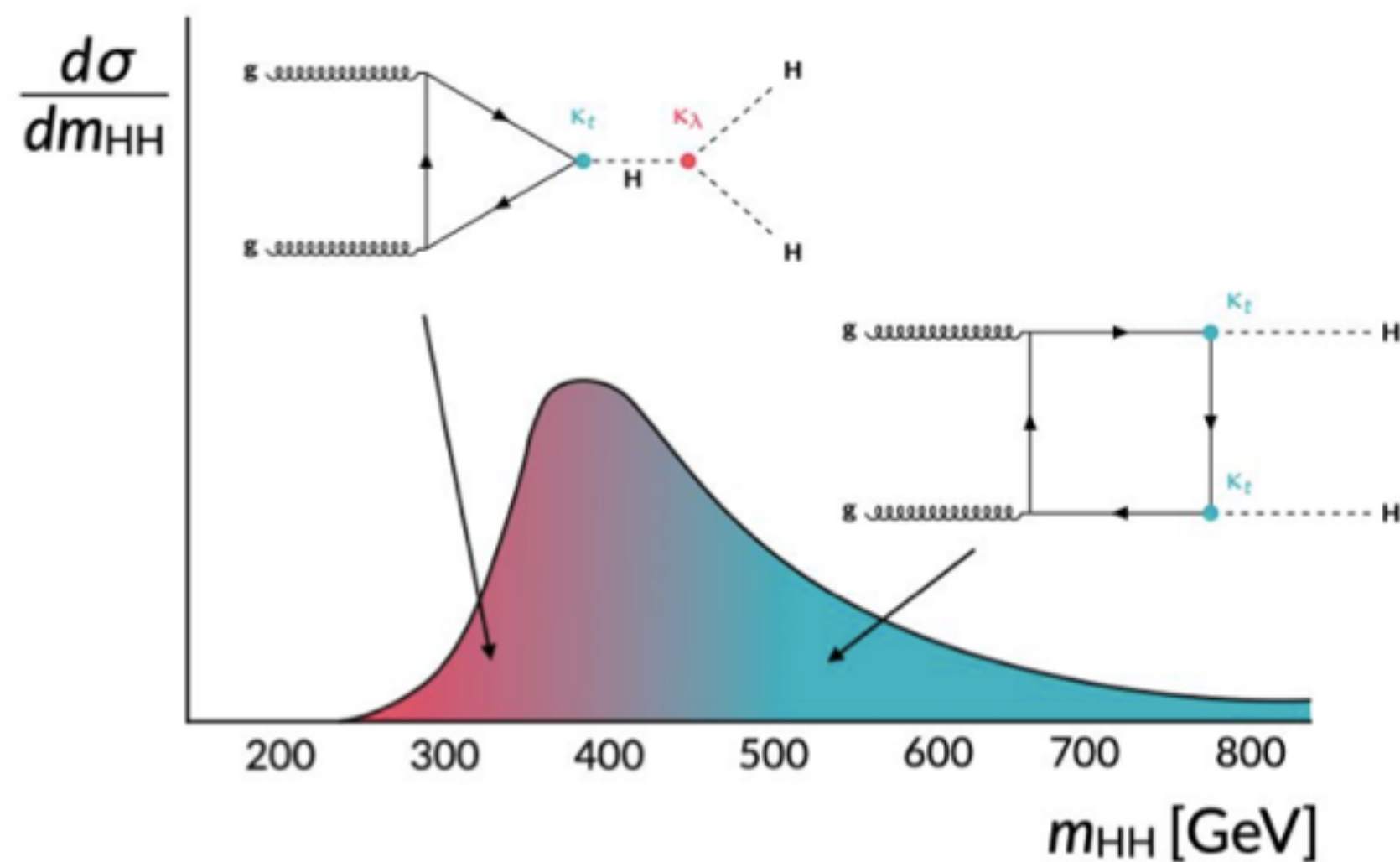
VBF( $\sim 1.73\text{fb}$  at N<sup>3</sup>LO QCD)



# Decay Mode and Search Strategy

- $HH \rightarrow bb + X$  channels are most sensitive
  - $HH \rightarrow 4b$ : Highest branching fraction
  - $HH \rightarrow bb \tau \tau$ : Relatively clean due to  $\tau$  signature
  - $HH \rightarrow bb \gamma \gamma$ : Very clean channel, but low yield

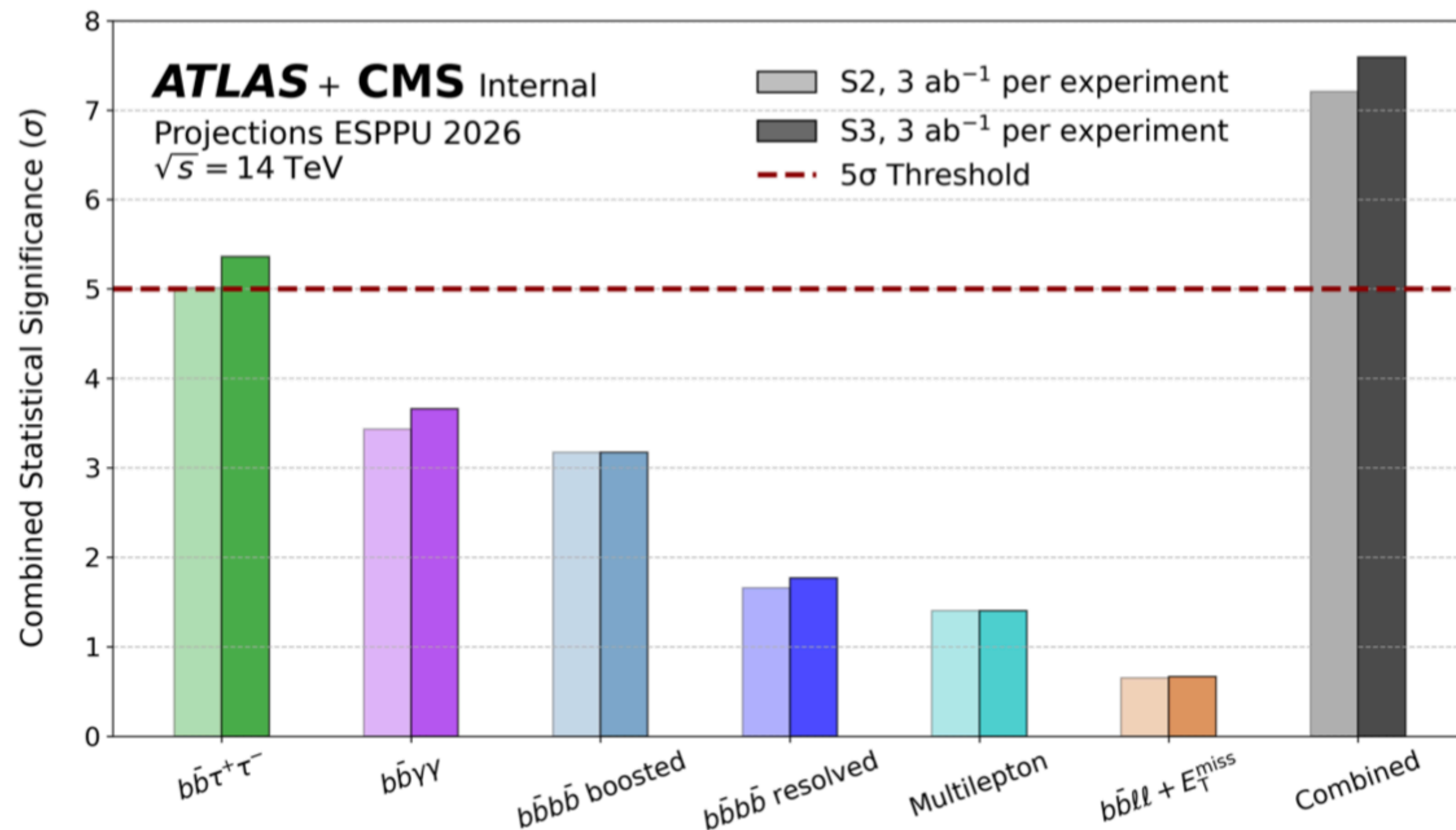
|                | bb    | WW    | $\tau\tau$ | ZZ     | $\gamma\gamma$ |
|----------------|-------|-------|------------|--------|----------------|
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| $\tau\tau$     | 7.3%  | 2.7%  | 0.39%      |        |                |
| ZZ             | 3.1%  | 1.1%  | 0.33%      | 0.069% |                |
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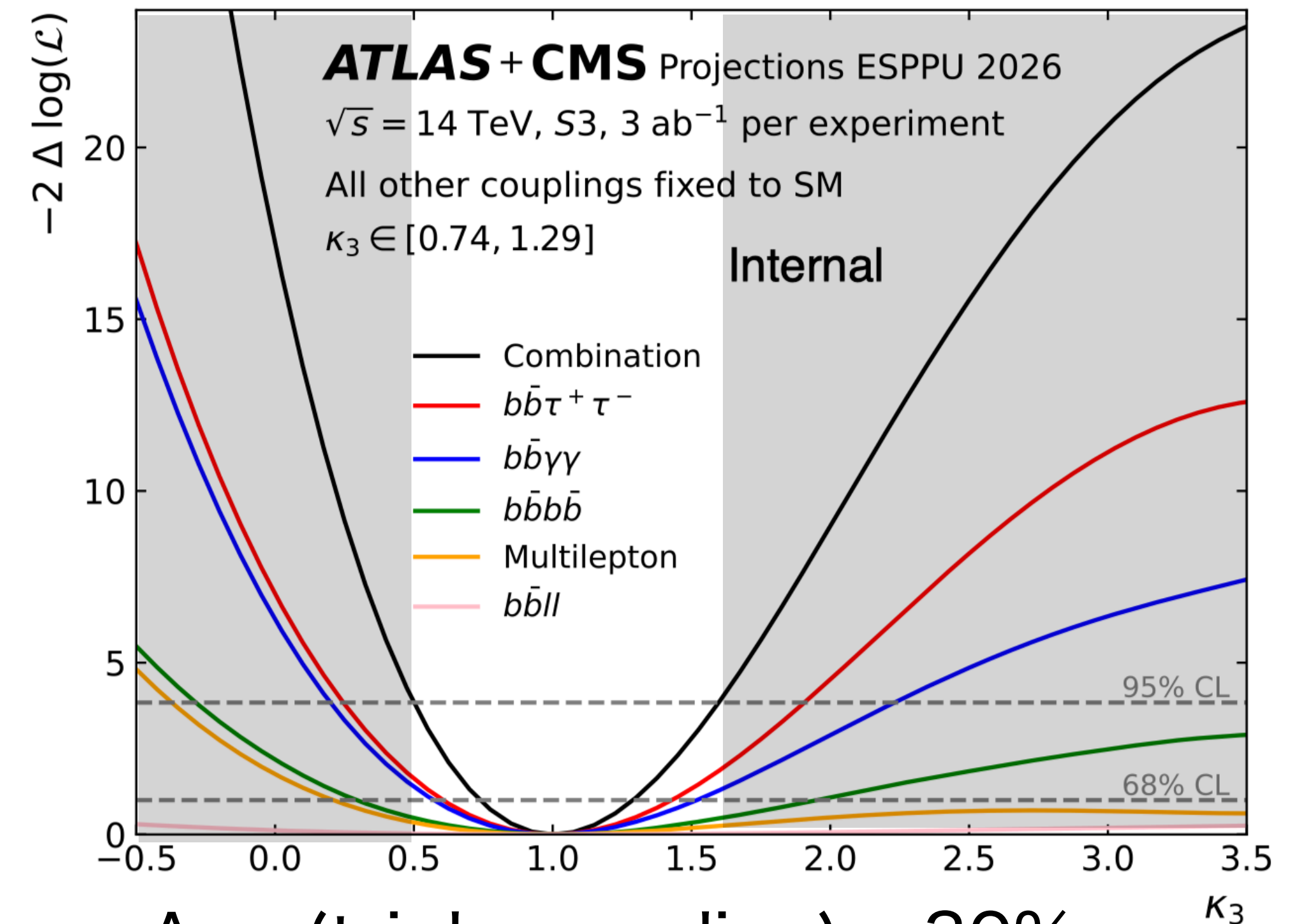
Depending on  $\kappa_\lambda$ ,  
 DiHiggs kinematics  
 change significantly  
 → Optimized by  $m_{HH}$

# HH HL-LHC prospect

- HH sensitivity and  $\kappa_\lambda$  measurement at HL-LHC
- Extrapolation from Run2 analysis to HL-LHC (No analysis improvement at HL-LHC is taken into account)
- ATLAS+CMS combined results ( $3\text{ab}^{-1} \times 2$ )



Significance over  $7\sigma$  at SM case ( $\lambda=1$ )



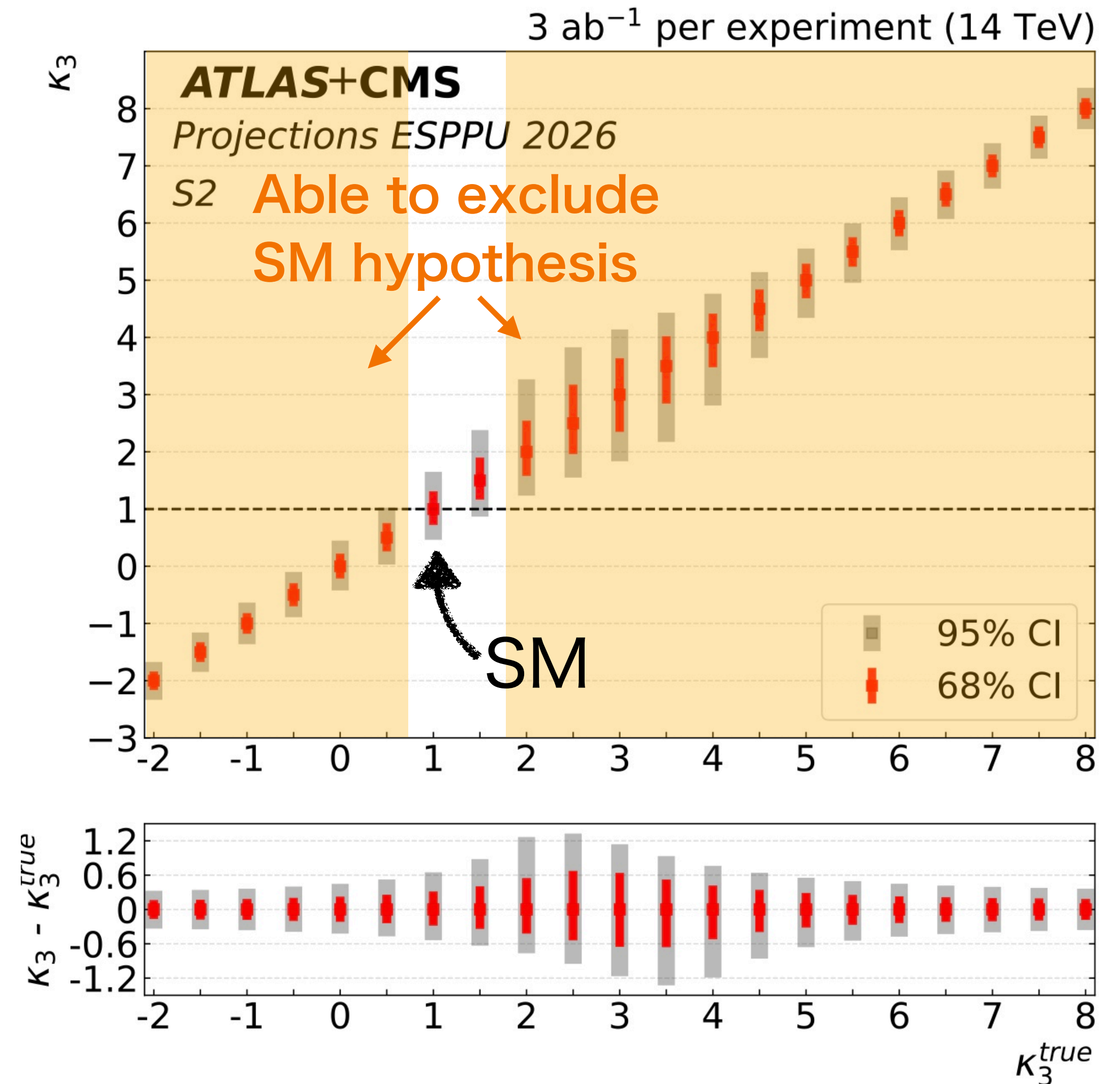
$\Delta \kappa_3$  (triple coupling)  $< 30\%$

Exclude  $\kappa_3 > 1.7$ ,  $\kappa_3 < 0.5$

# HL-LHC prospect update

- BSM ( $\lambda \neq 1$ ) scenarios:
  - if  $\kappa_3 > 2$  or  $\kappa_3 < 0.5$ , separate from SM  $> 95\%$  CL
  - It might not to be conclusive around  $\kappa_3 \sim 1.5$  (favorite region for first order phase transition, EW Baryogenesis?)

I “believe” somehow pessimistic prospects (still lots of room of improvements at HL-LHC)



# Constraint on Higgs potential

- Considering cut-off scale  $\Lambda$  beyond LHC energy

$$V_8(\phi) = \underbrace{\frac{1}{8}(\phi^2 - 1)^2}_{\text{SM}} + \underbrace{\frac{\kappa_3 - 1}{16}(\phi^3 - 1)^3}_{\text{Dim6}} + \underbrace{\frac{\kappa_4 - 6\kappa_3 + 5}{128}(\phi^2 - 1)^4}_{\text{Dim8}}$$

top mass unit:  $m_t = y_t v / \sqrt{2}, y_t \sim 1, v = \sqrt{2}, m_H = \frac{1}{\sqrt{2}}$

Investigate scenario which will alter Higgs potential shape

- ✓ EFT: dim6, dim6+dim8
- ✓ SM + logarithmic term (Coleman-Weinberg)
- ✓ SM + exponential (Instanton)

Predict strong first-order phase transition in  $\kappa_3 > 1.4 - 1.9$

HL-LHC results are sensitive to some strong FOPT scenarios

