EUROPEAN PHYSICAL SOCIETY
EPS HEP2025 MARSEILLE

Recent results in Higgs physics

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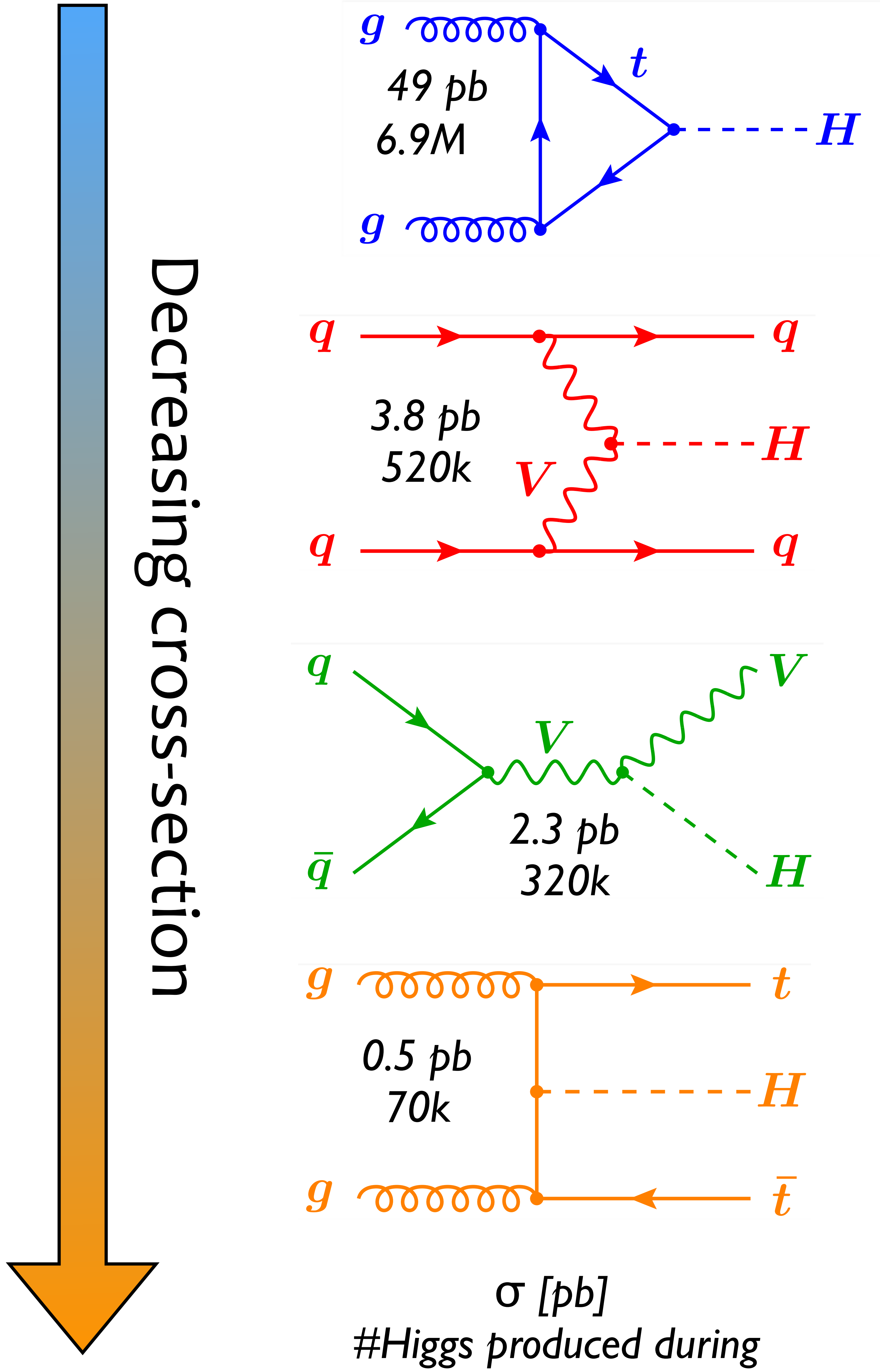
on behalf of ATLAS & CMS Collaborations

EPS HEP 2025, 8 / 7 / 2025

Higgs production at the LHC

- **LHC is a Higgs factory**
- About **8 million Higgs bosons** produced by LHC during Run-2 **per experiment**
- Since $m_H \sim 125\ \mathrm{GeV}$, a wide range of production and decay modes accessible



σ [pb]
#Higgs produced during Run-2

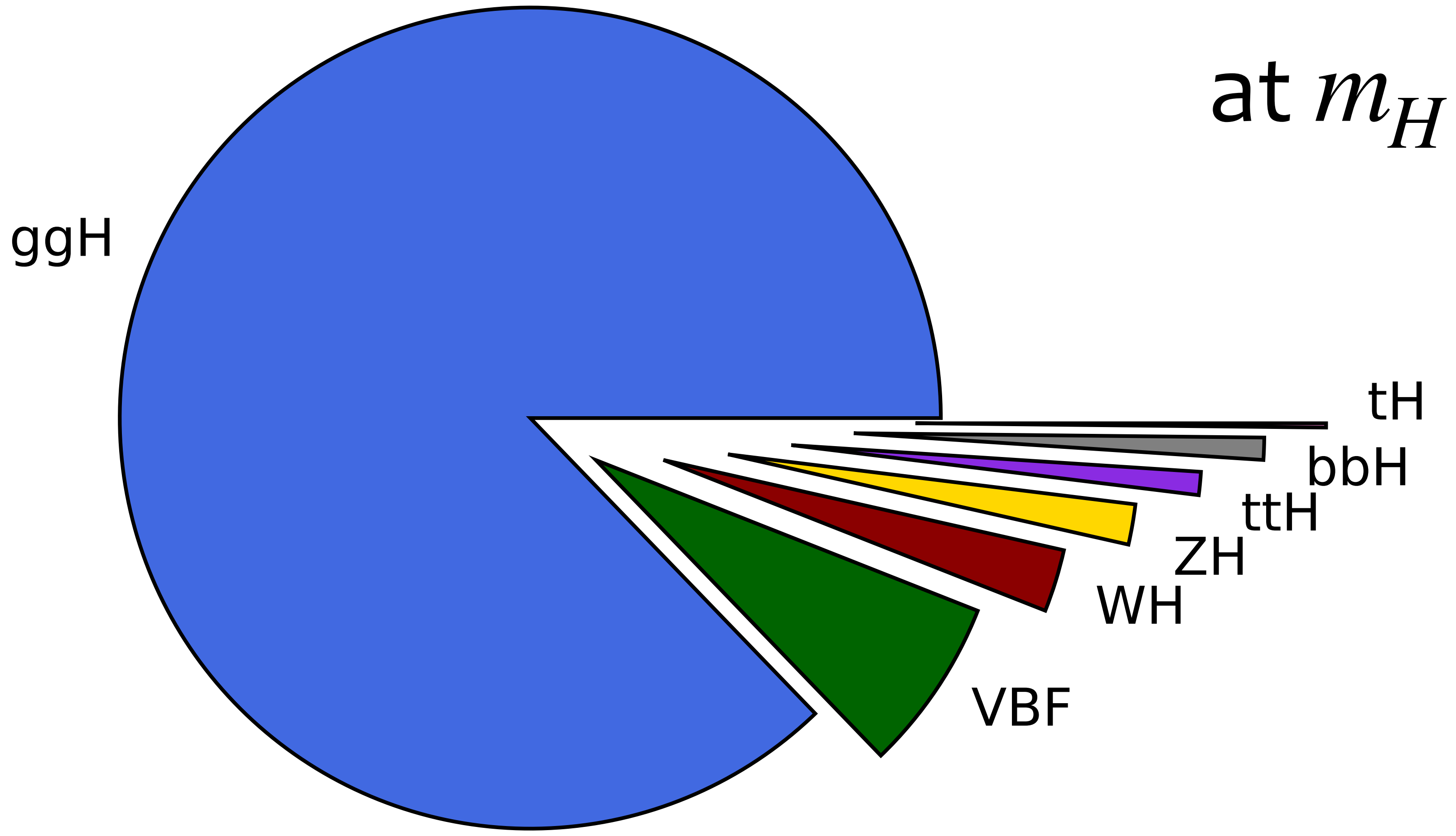
gluon fusion
ggH: 86%

vector boson fusion (**VBF**): **6.5%**

W,Z associated production
WH/ZH: 4%

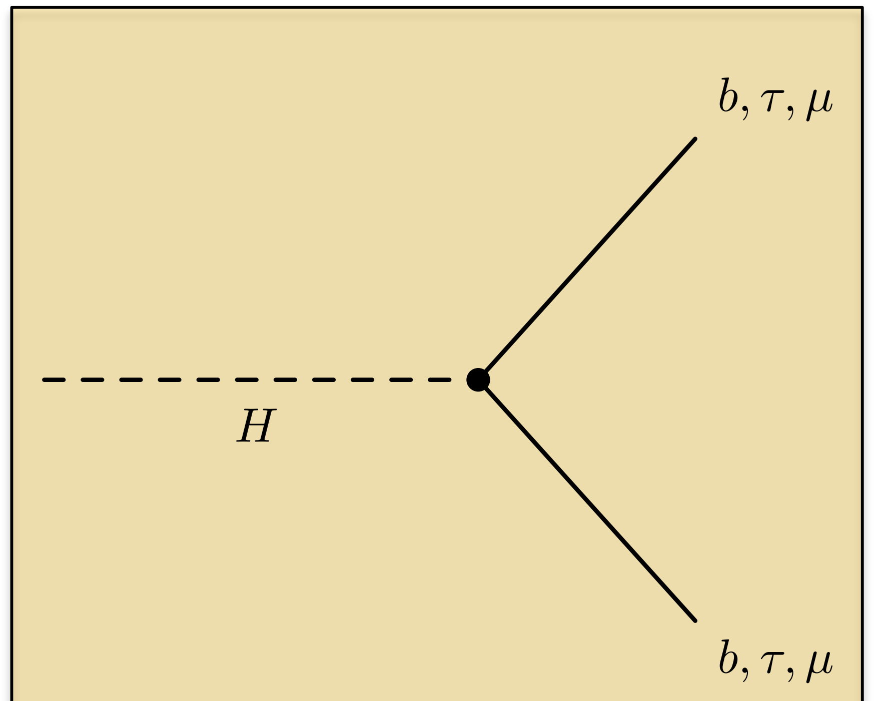
$t\bar{t}H$ associated production: 1%

Higgs production cross sections at $m_H \sim 125$ GeV

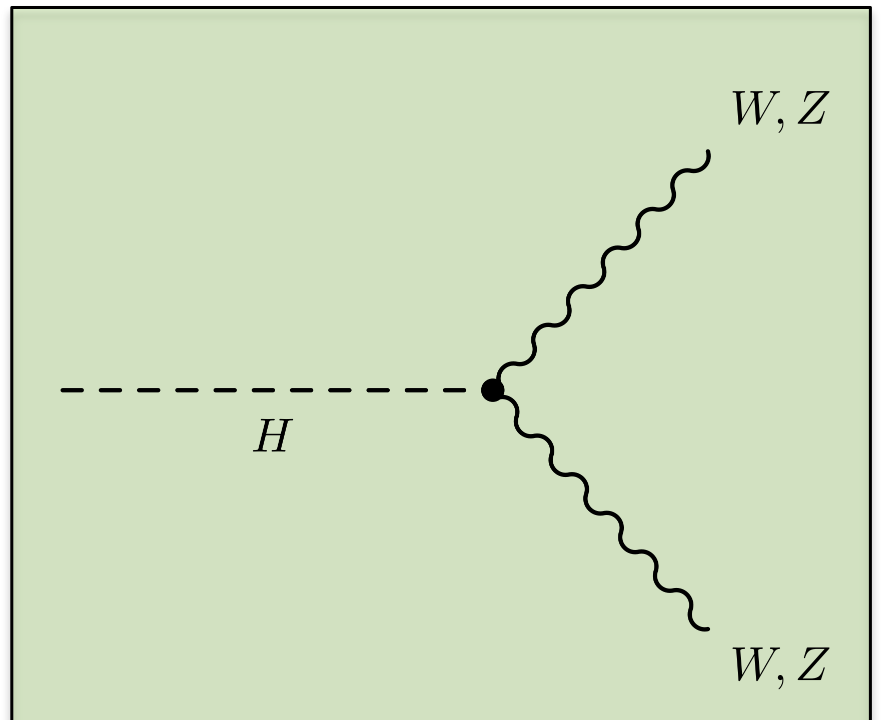


Higgs decays

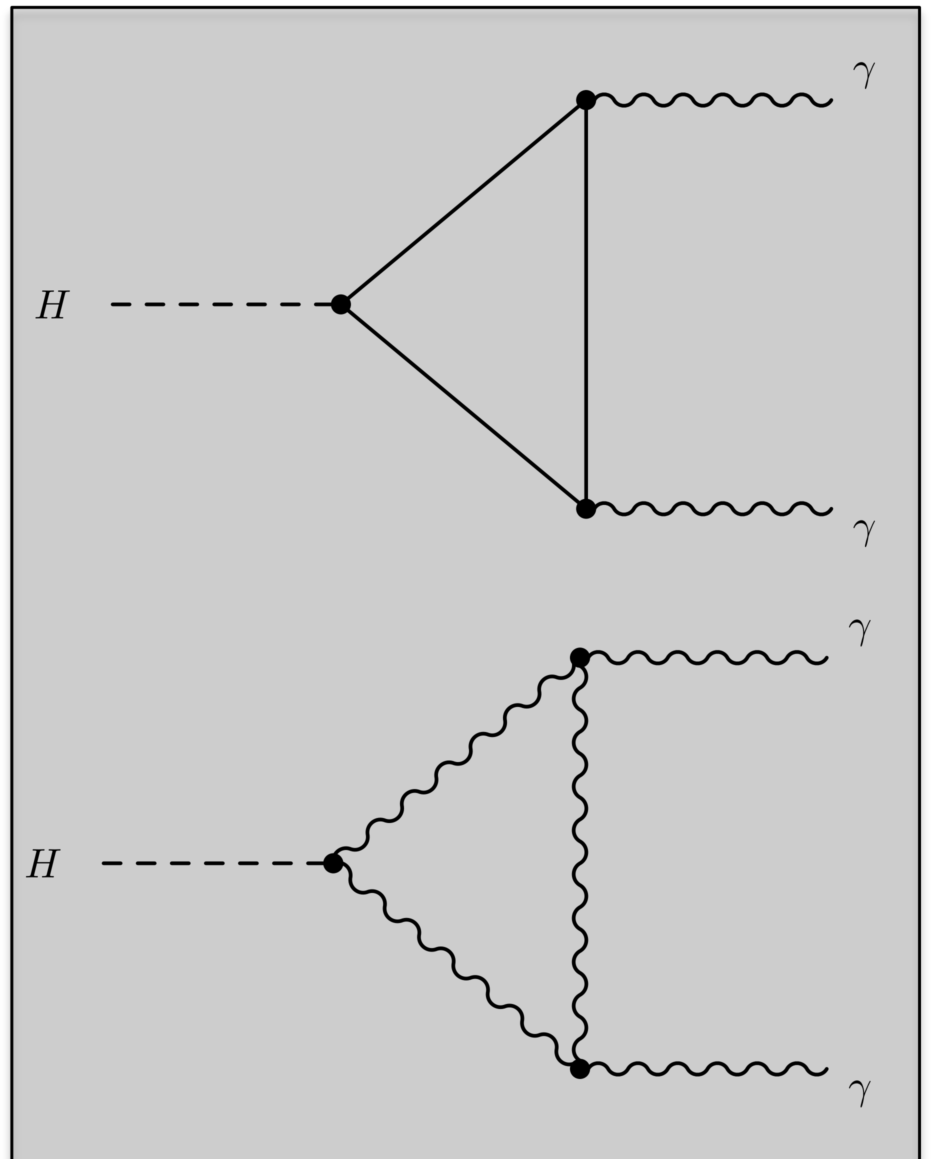
Over a decade of measurements including all productions & decay
=> Higgs boson precision probe!



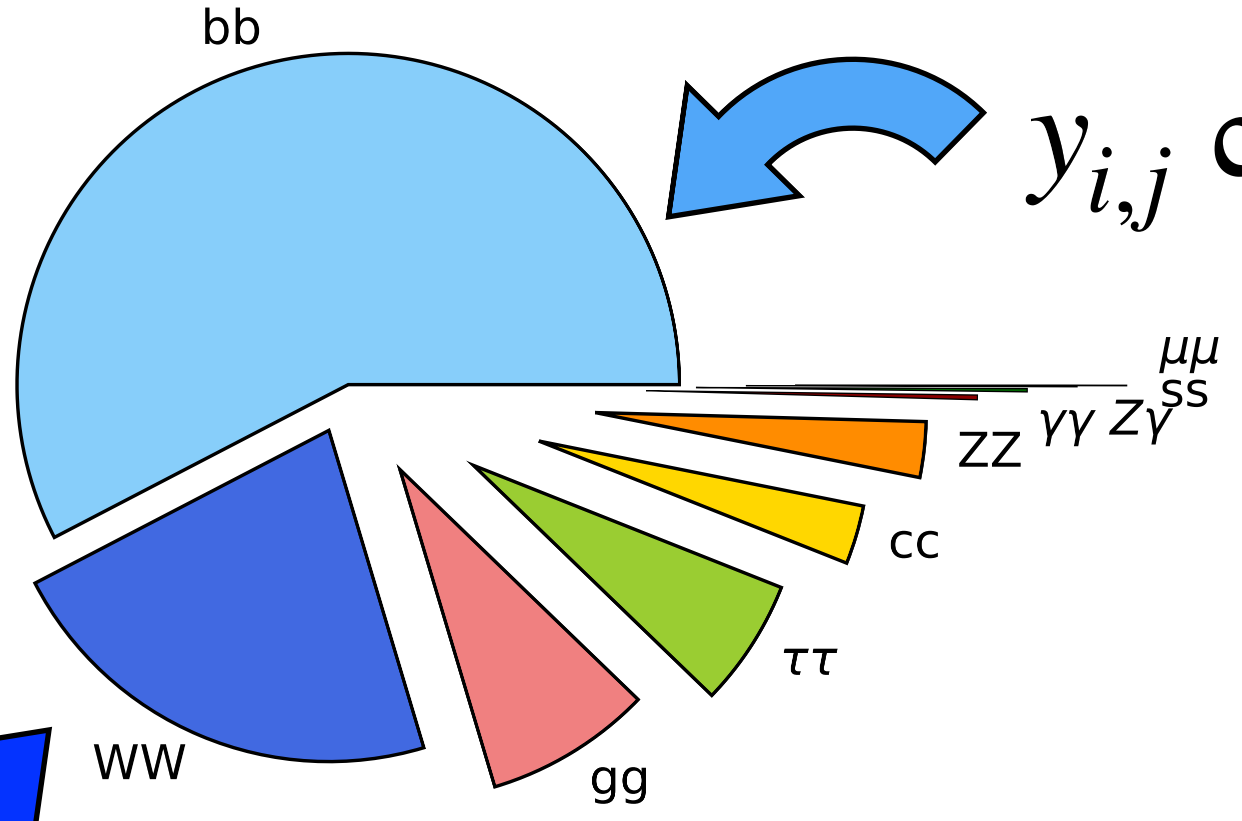
H→ff



H→VV



H→γγ



$$y_{i,j} \propto \frac{m_f}{v}\delta_{ij}$$

$$g_{HVV} \propto \frac{M_V^2}{v}$$

Run-2 → ~140 fb^{-1}

"early" Run-3 (2022-2023) → ~60 fb^{-1}

Run-3 2024 → ~100 fb^{-1}

Higgs boson cross sections and couplings

Production cross section measurements

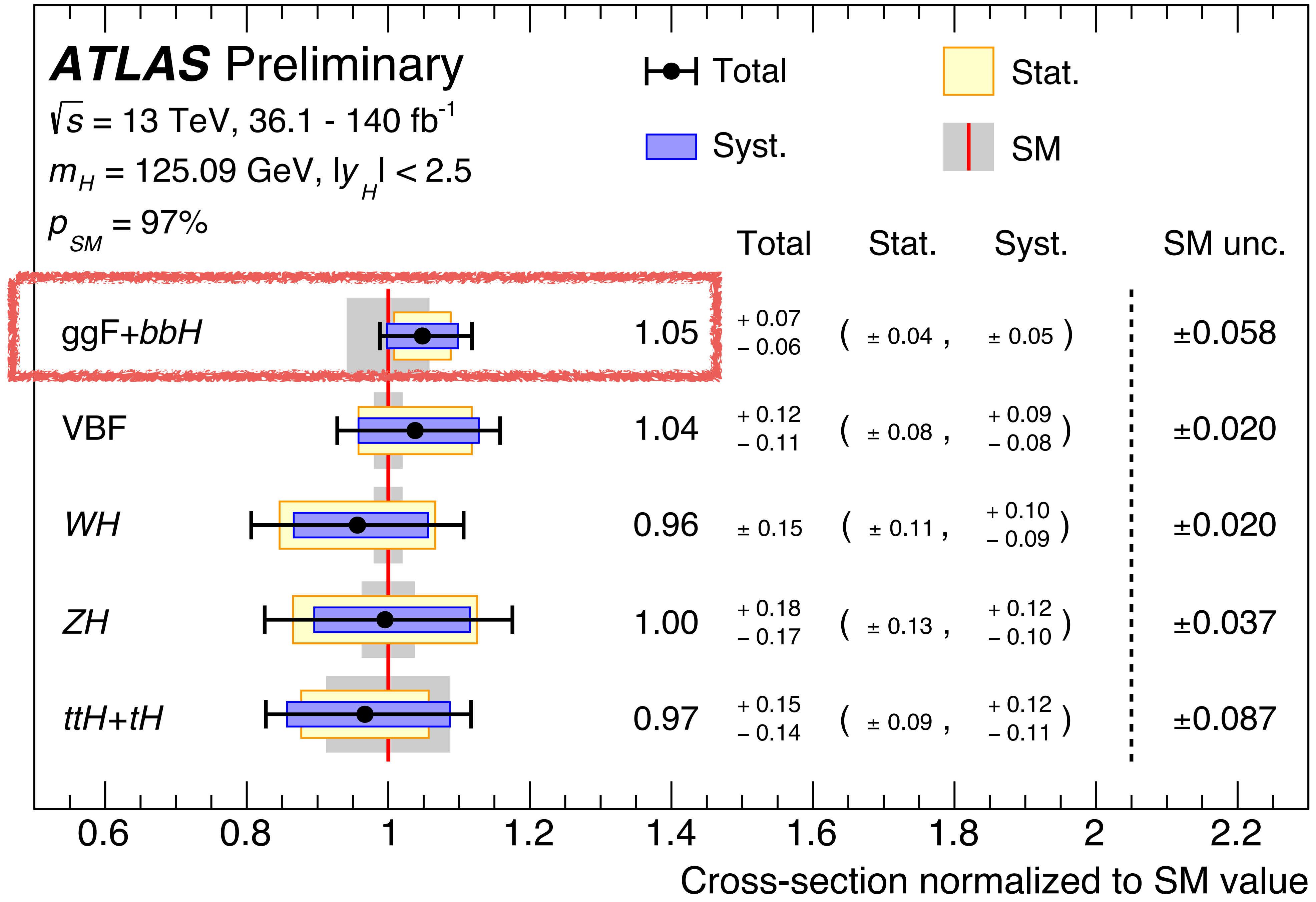
ATLAS-CONF-2025-006

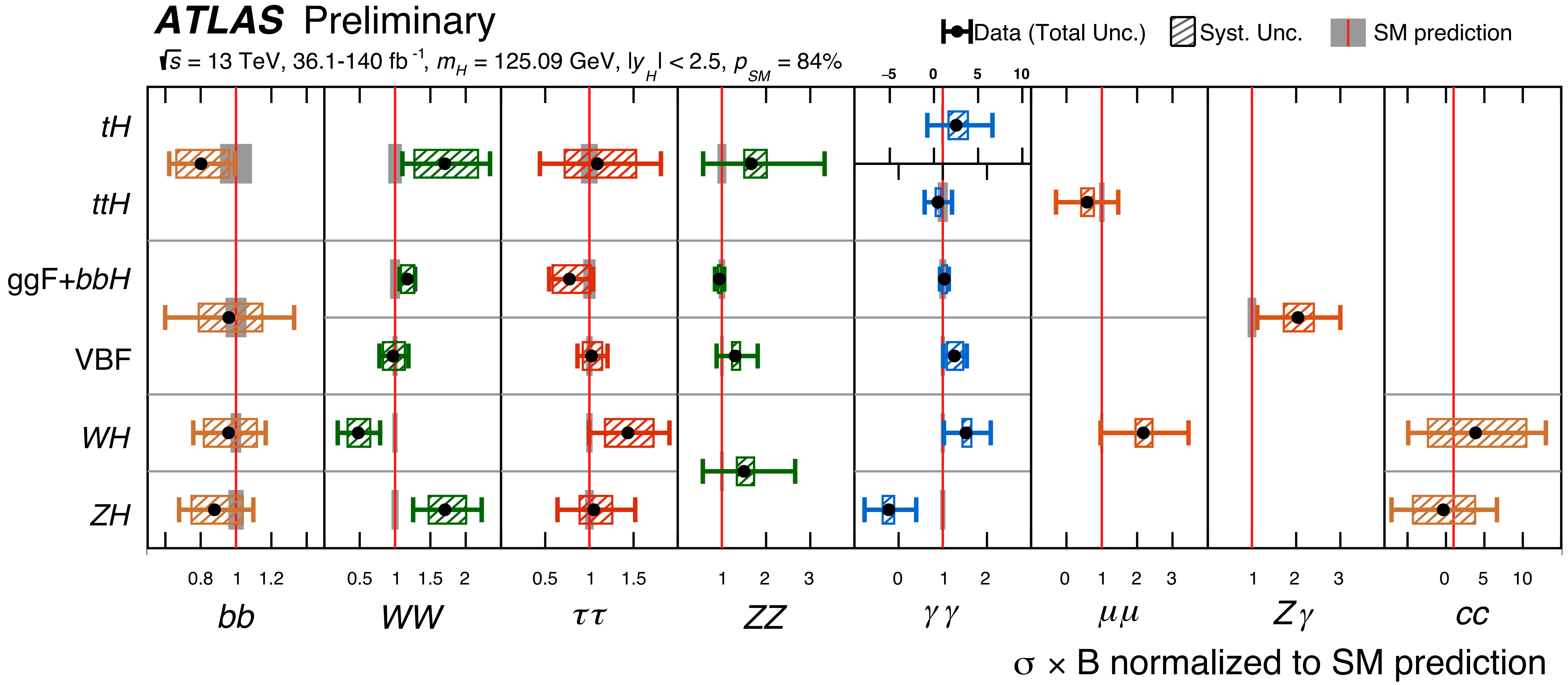
NEW

Precision era for Higgs physics:

$$\mu = 1.023 \pm 0.056 = 1.023 \pm 0.028\,(\text{stat.})^{+0.026}_{-0.25}\,(\text{exp.})^{+0.039}_{-0.036}\,(\text{sig.theo.}) \pm 0.012\,(\text{bkg.theo.})$$

New combination of inclusive / per-production / per Higgs decay σ's





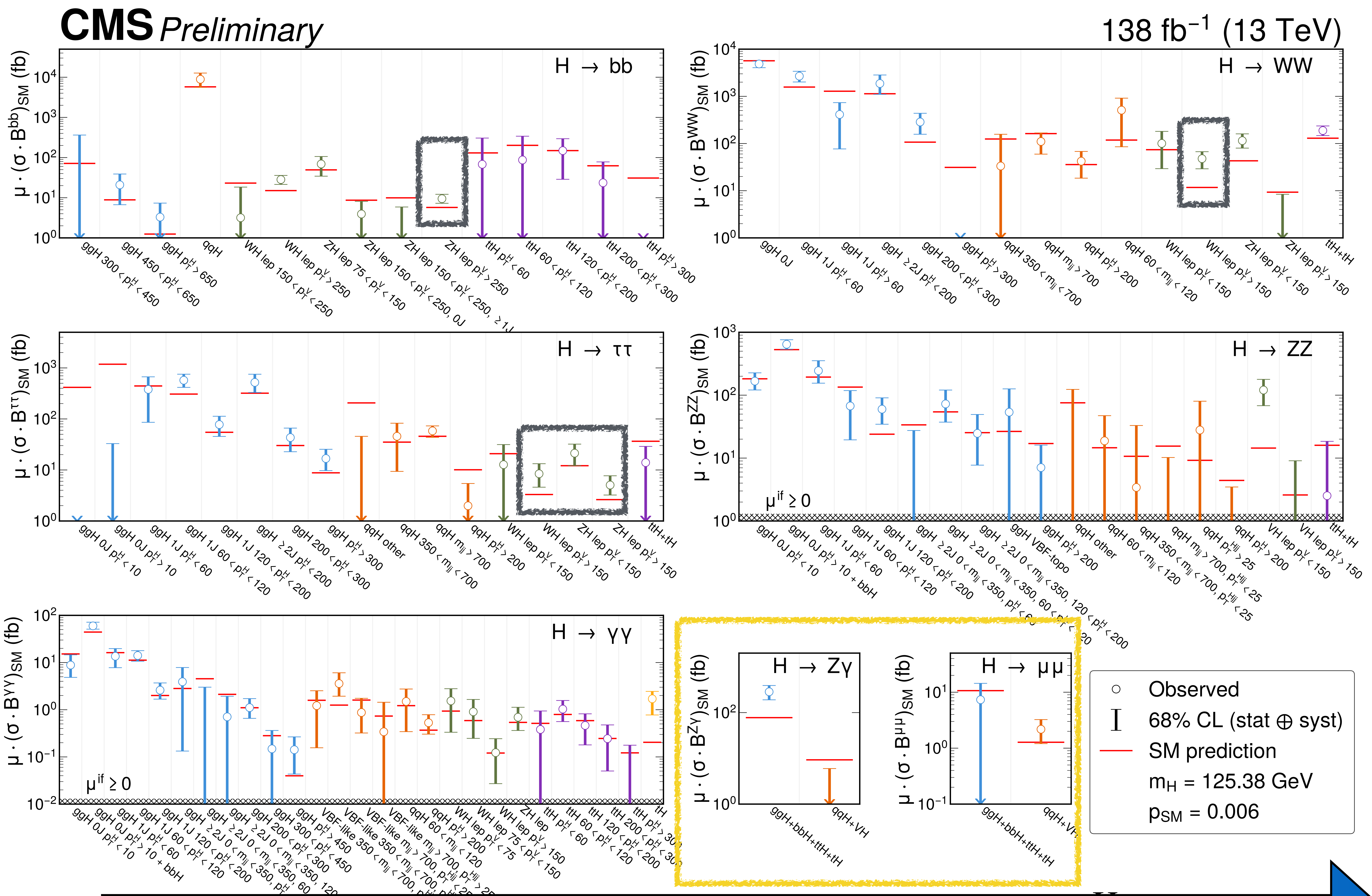
largest production / decays:

$\sigma_{stat} \sim \sigma_{syst}$: **~5% precision**

Split by production & decay

Most granular σ times BR fit

CMS-PAS-HIG-21-018



Measured **97** $\sigma^i \times BR^f$:

$$\mu^{if} = \frac{[\sigma^i \times BR^f]_{\text{obs}}}{[\sigma^i \times BR^f]_{\text{SM}}}$$

Higgs cross sections measured **over 4 orders of magnitude**

Evidence for **rare decays:** $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$

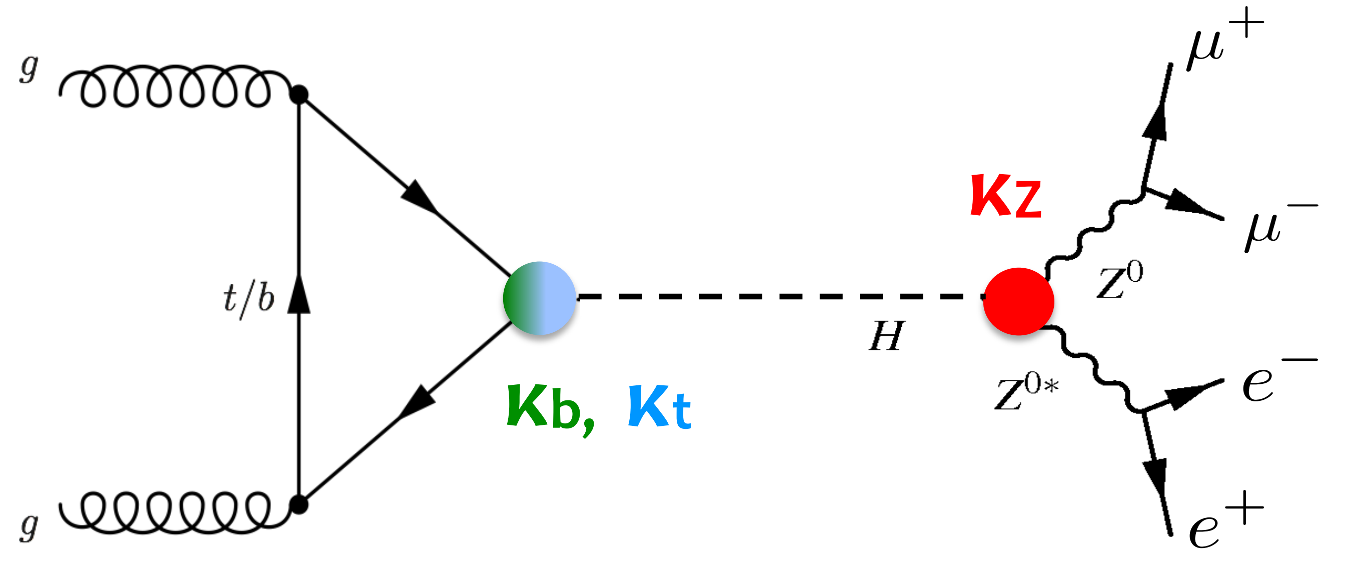
Production mode X increasing p_T^H bin

Interpreting the rates as Higgs couplings

The likelihood can be explicitly written in terms of "coupling modifiers": ***κ*-framework**

$$\mu_i = \frac{\sigma^i}{\sigma^i_{SM}} \quad \text{and} \quad \mu_f = \frac{BR^f}{BR^f_{SM}} \qquad \mu \rightarrow \mu(\kappa)\text{: } \mu^{if}(\kappa) = \sigma^i(\kappa) BR^f(\kappa) = \frac{\sigma^i(\kappa)\Gamma^f(\kappa)}{\Gamma_H(\kappa)}$$

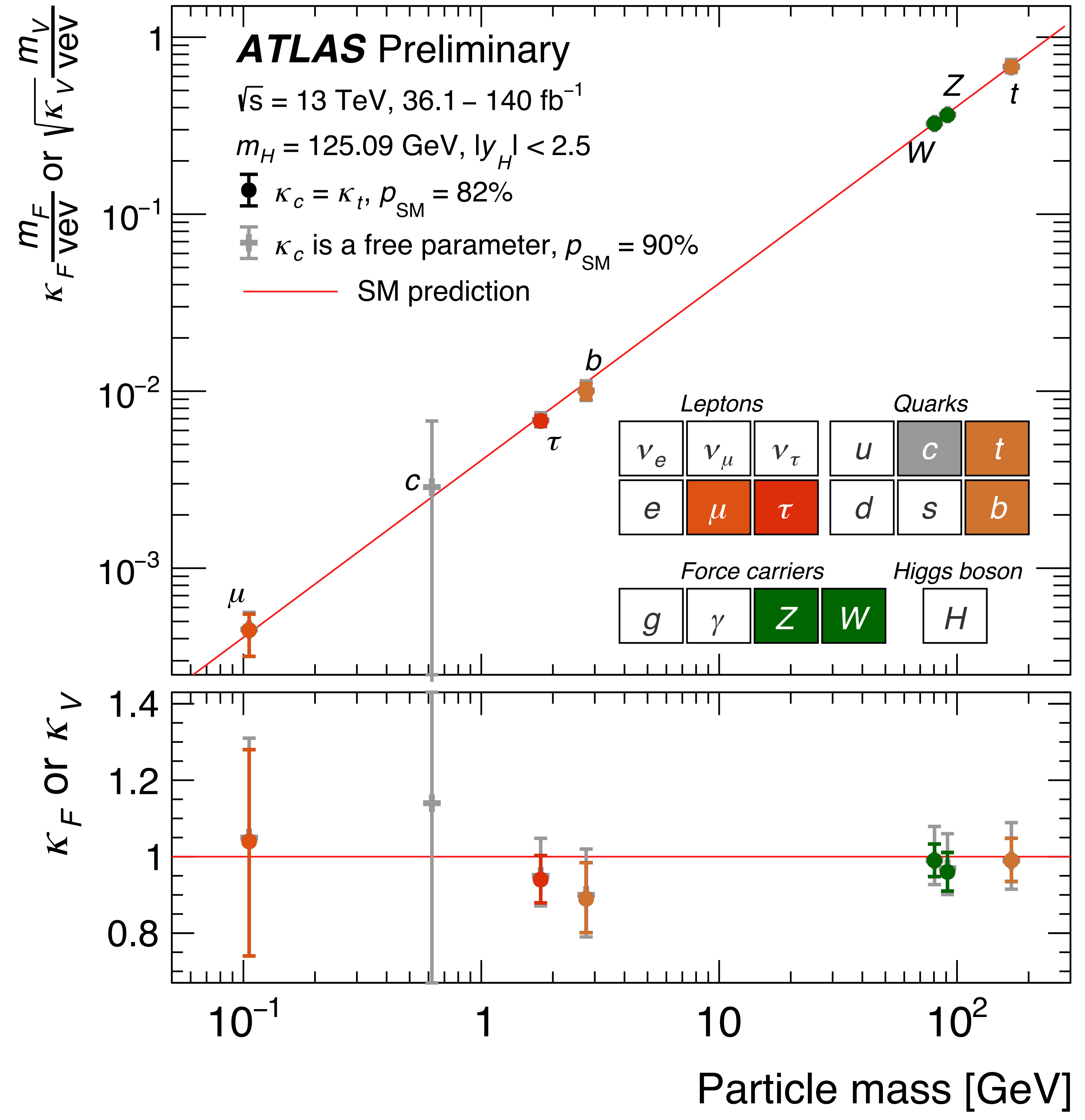
NEW



Example diagram:
ggH production,
$H \rightarrow ZZ$ decay

$$\mu_{ggH} \cdot \mu^{ZZ} \propto \frac{(1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b) \cdot \kappa_Z^2}{\kappa_H^2}$$

In the SM, Higgs couplings
proportional to particle masses => test the SM
- Couplings to **W/Z at 5-10%**
- Couplings to **3rd generation to 10-20%**



ATLAS-CONF-2025-006

Interpreting the rates as Higgs couplings

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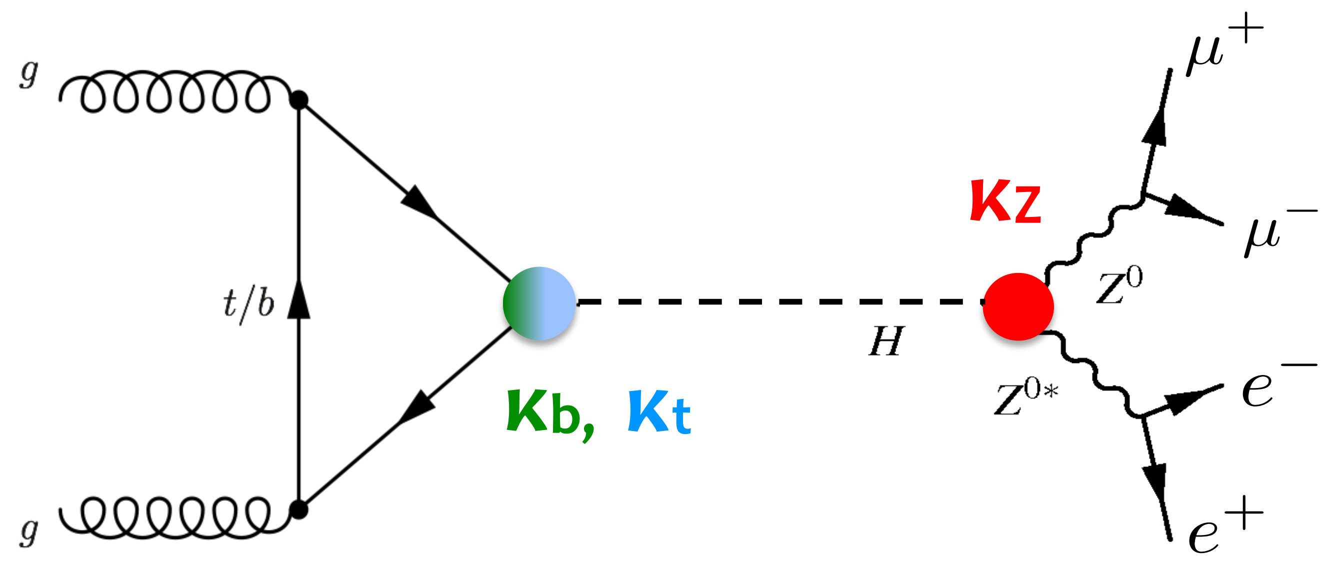
NEW



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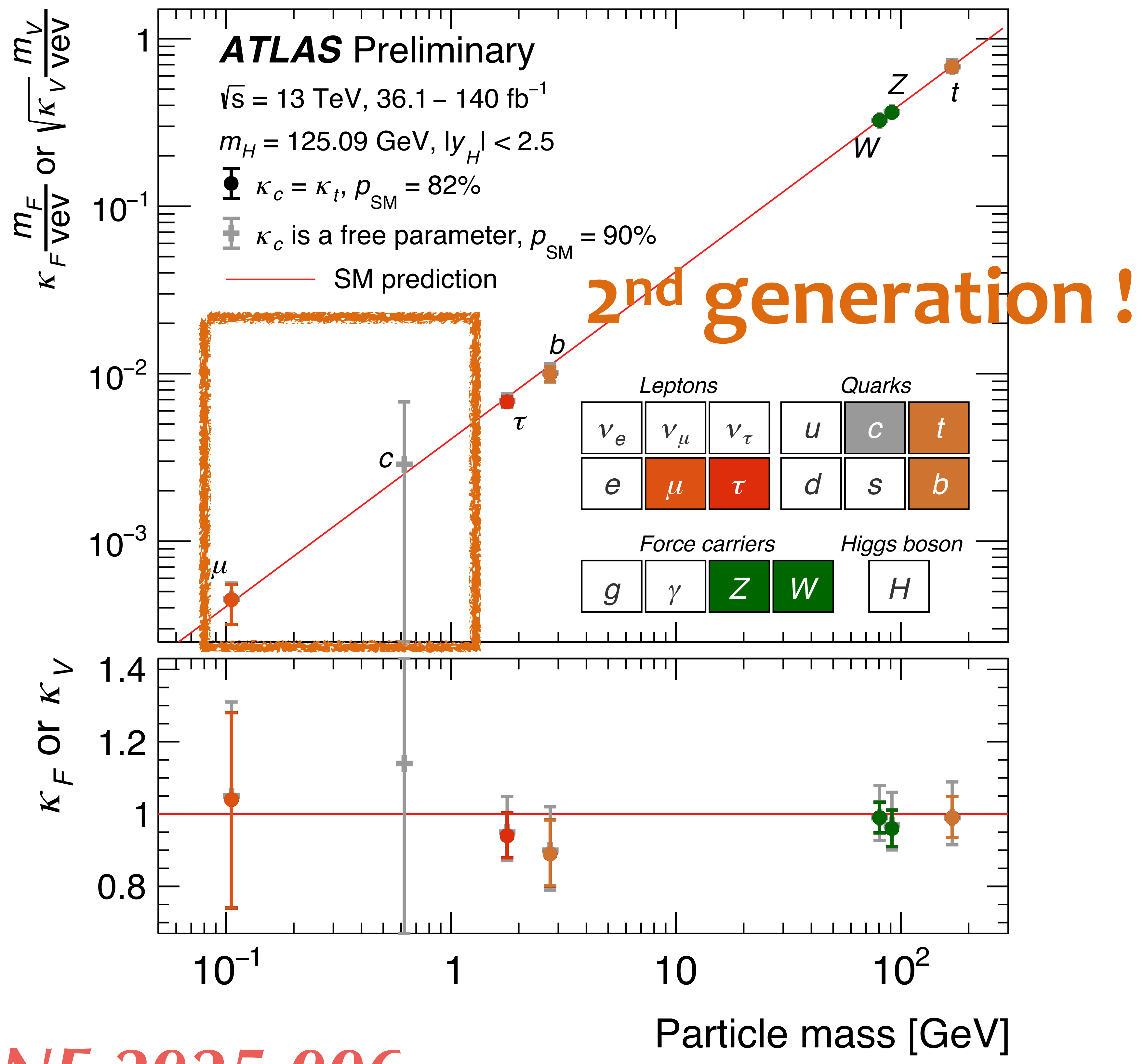
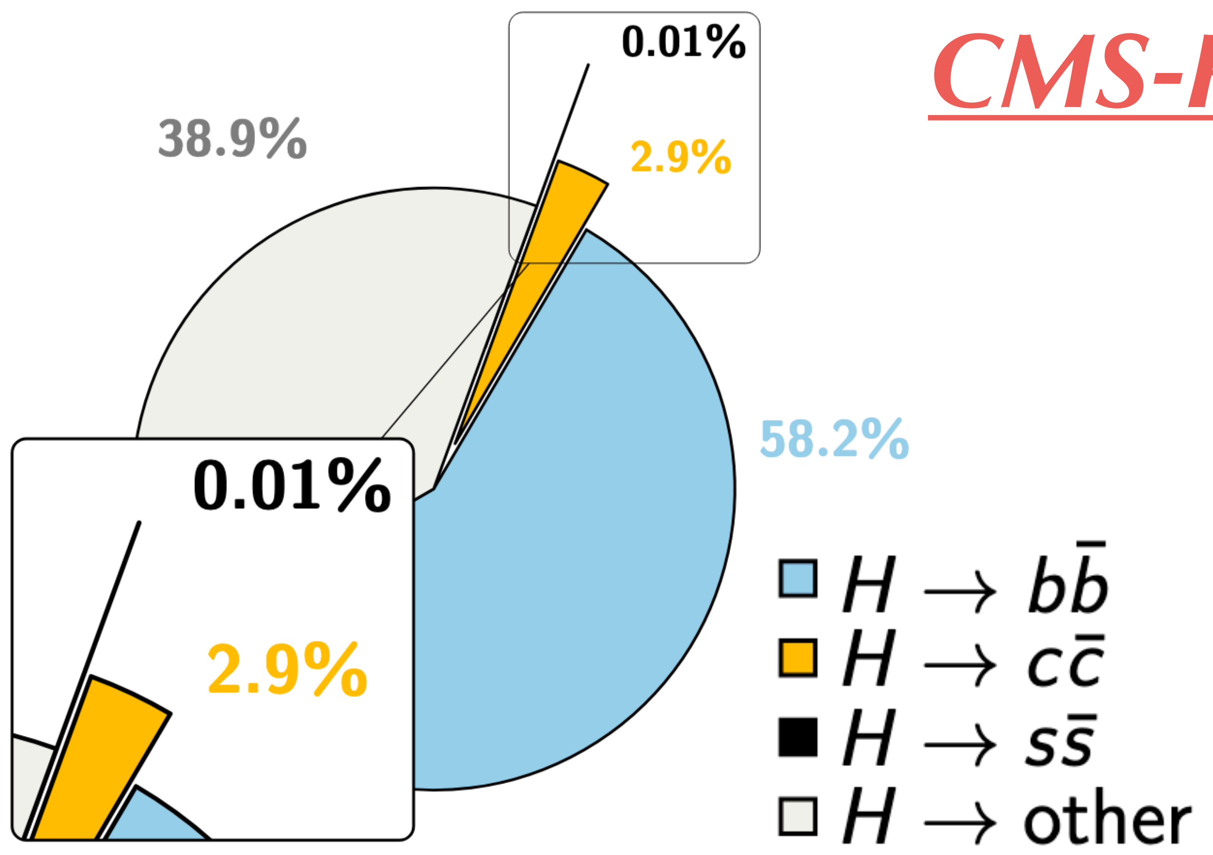


In the SM, Higgs couplings.
proportional to particle masses => test the SM
- Couplings to **W/Z at 5-10%**
- Couplings to **3rd generation to 10-20%**
- Couplings to **2nd generation 50%**

ATLAS-CONF-2025-006

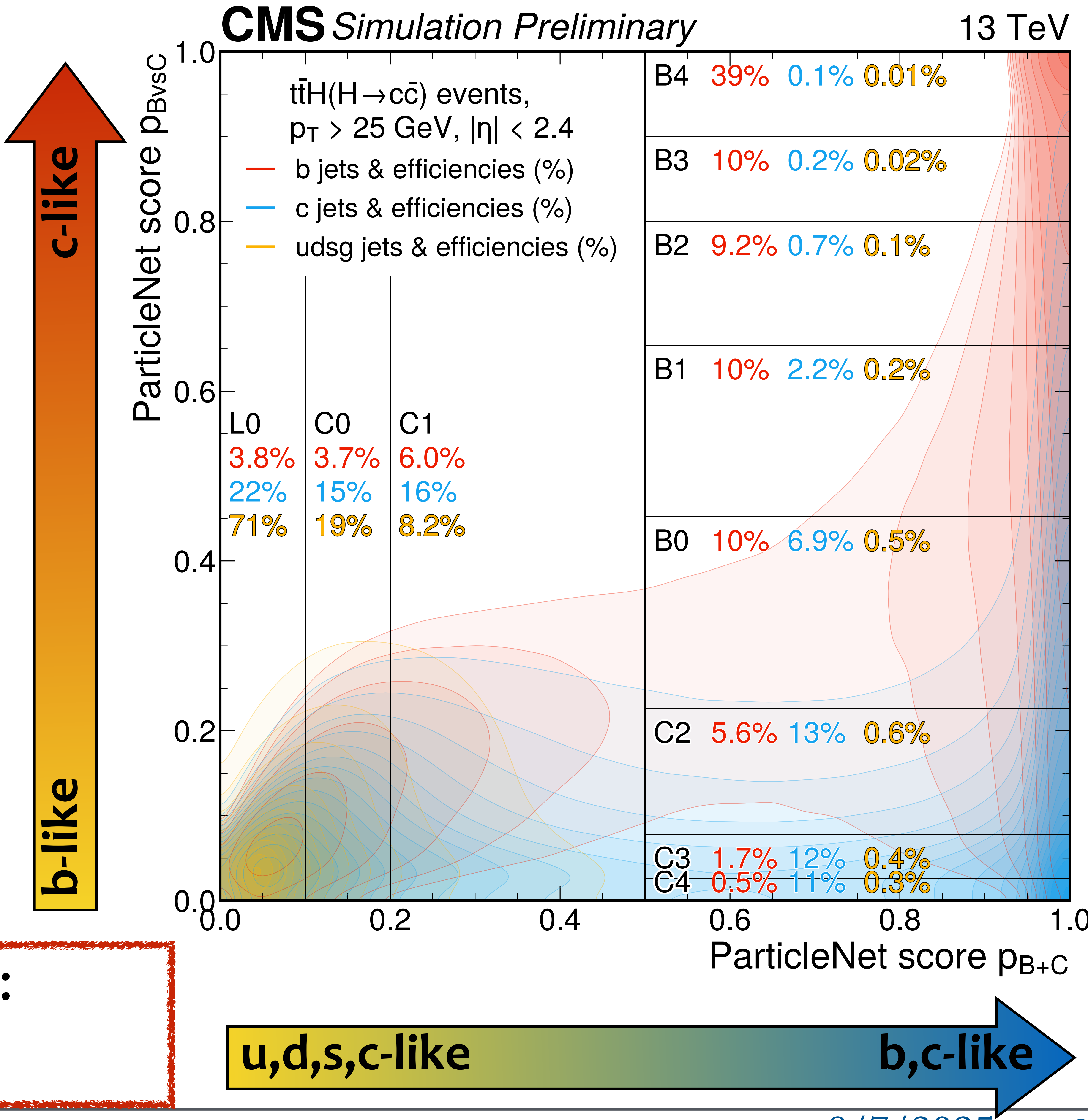
Towards 2nd generation: H-charm coupling

Next step down the line is couplings to **charm quarks:** very challenging!



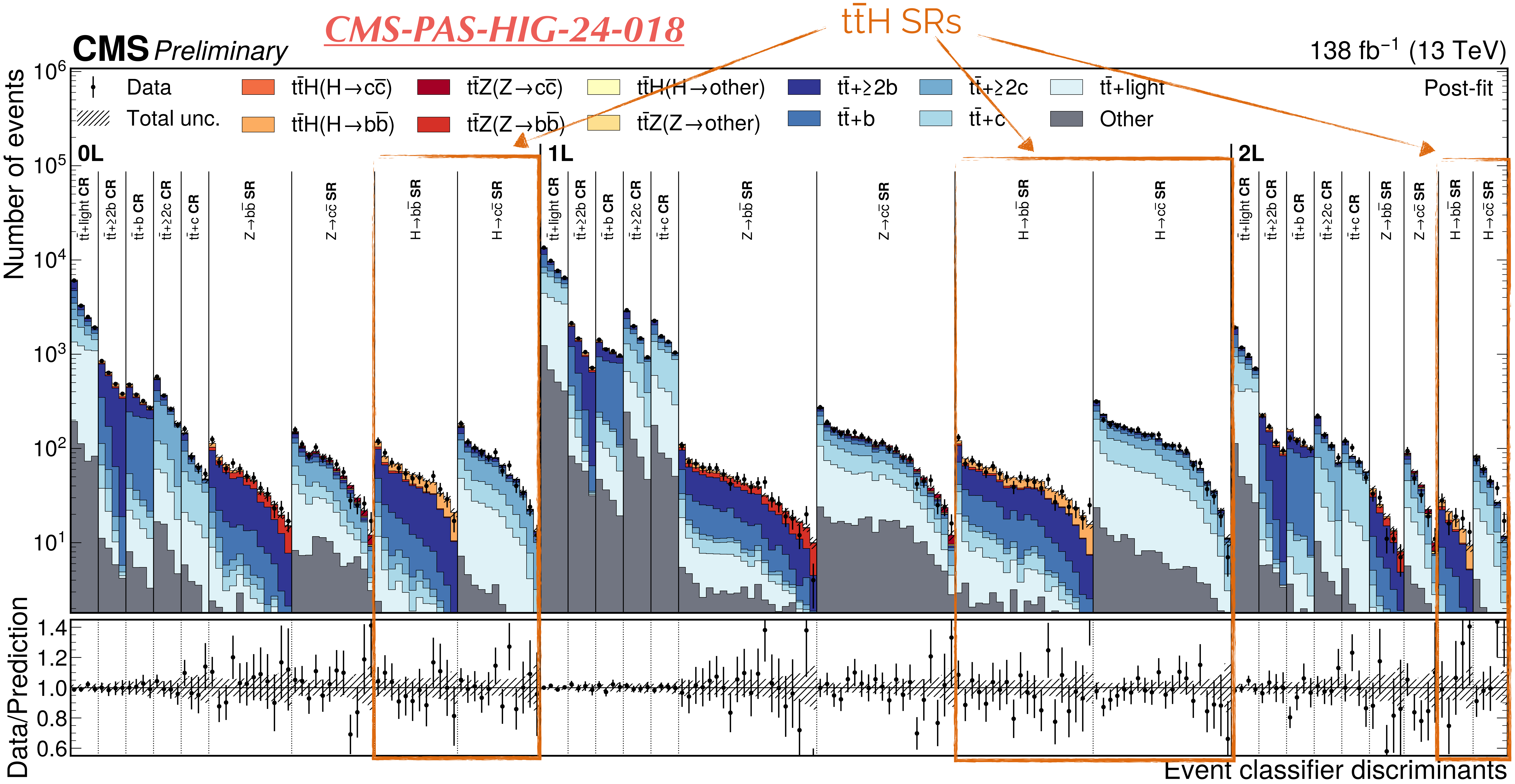
CMS-PAS-HIG-24-018

1. Separate heavy flavour (c-jets) from light flavour (u,d,s,g)-jets
2. Separate 2 kinds of heavy flavour jets: c-jets from b-jets



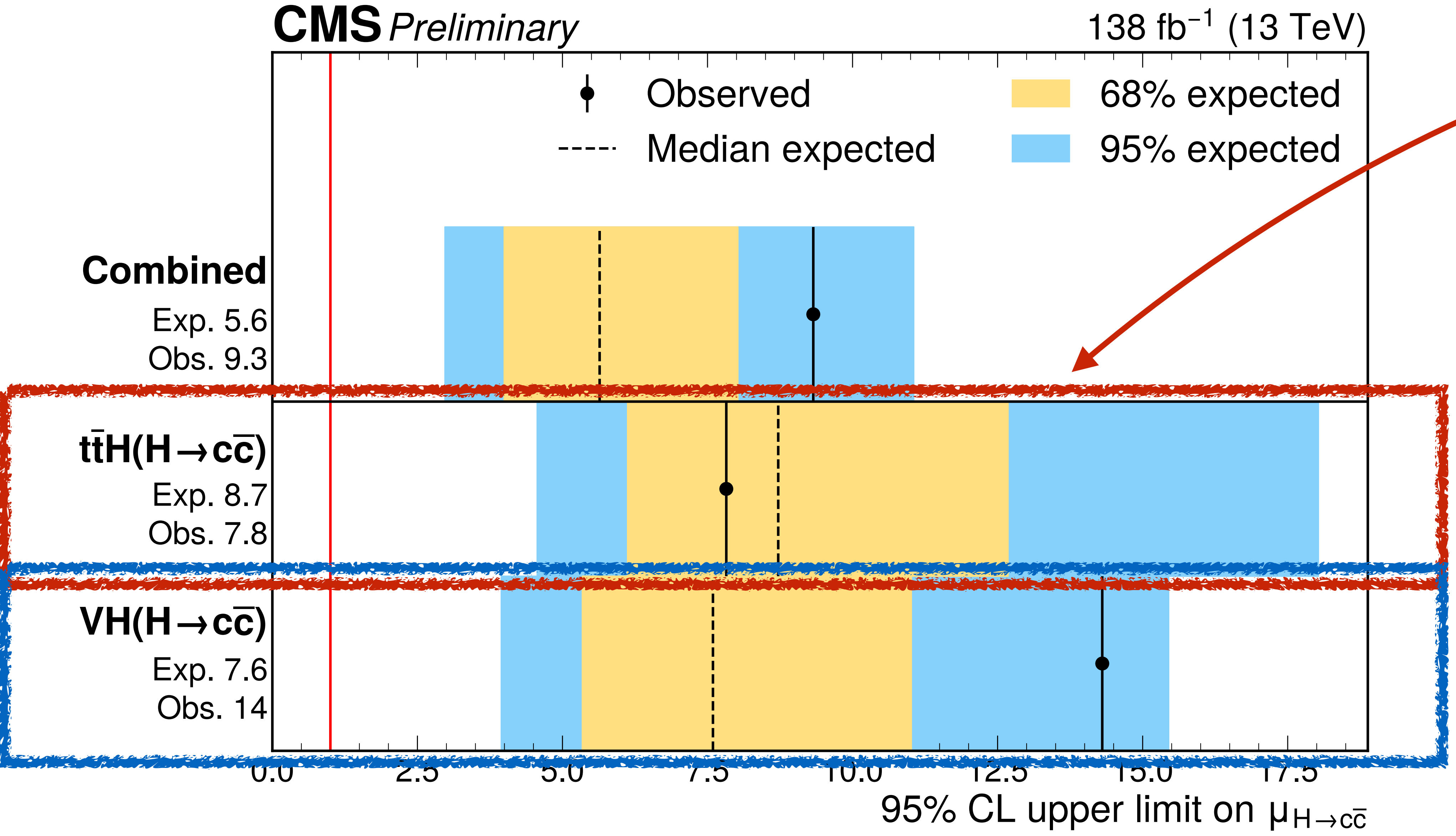
Making use of detector granularity + Graph NNs:
× **2 better with the same data**

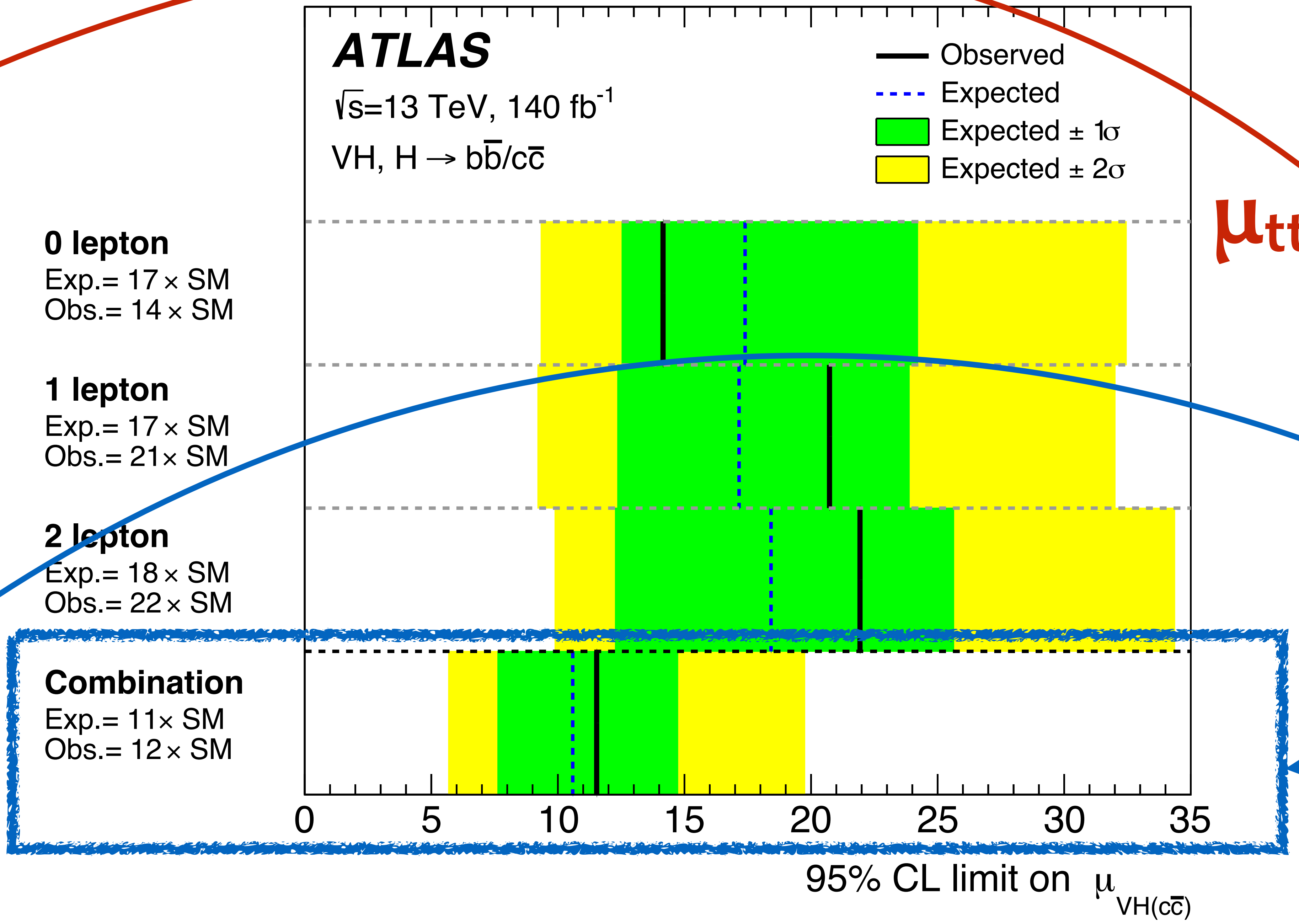
The name of the complexity: ttH(cc/bb)



Measure simultaneously ttH(H->bb) and ttH(H->cc), and SM candles ttZ(bb/cc)

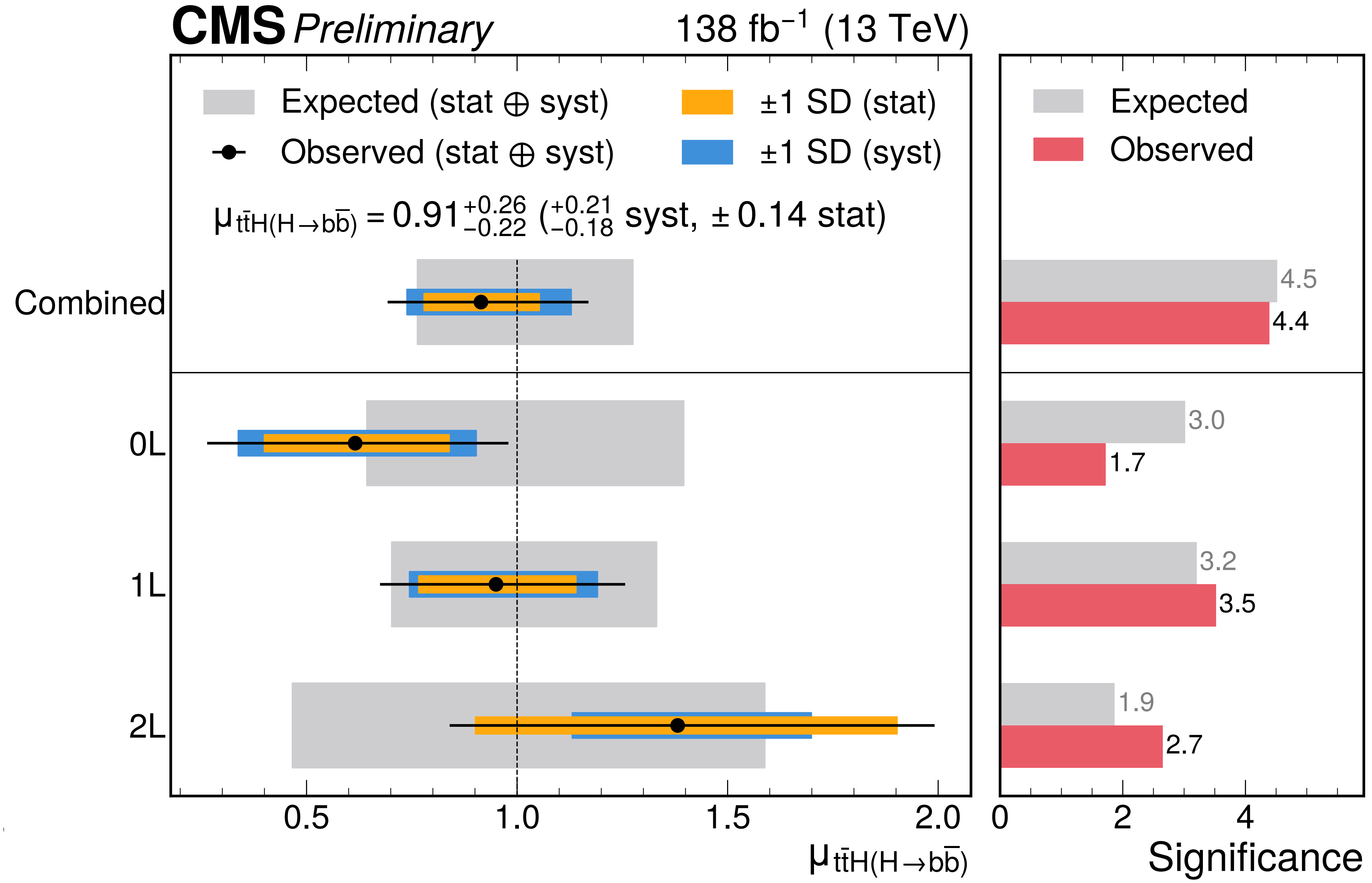
Limits on 2nd generation Higgs-Yukawa





$\mu_{ttH(H\to cc)}$: ≲ 7.8 wrt. SM

Similar sensitivity to classical channel: $VH(H \to c\bar{c})$



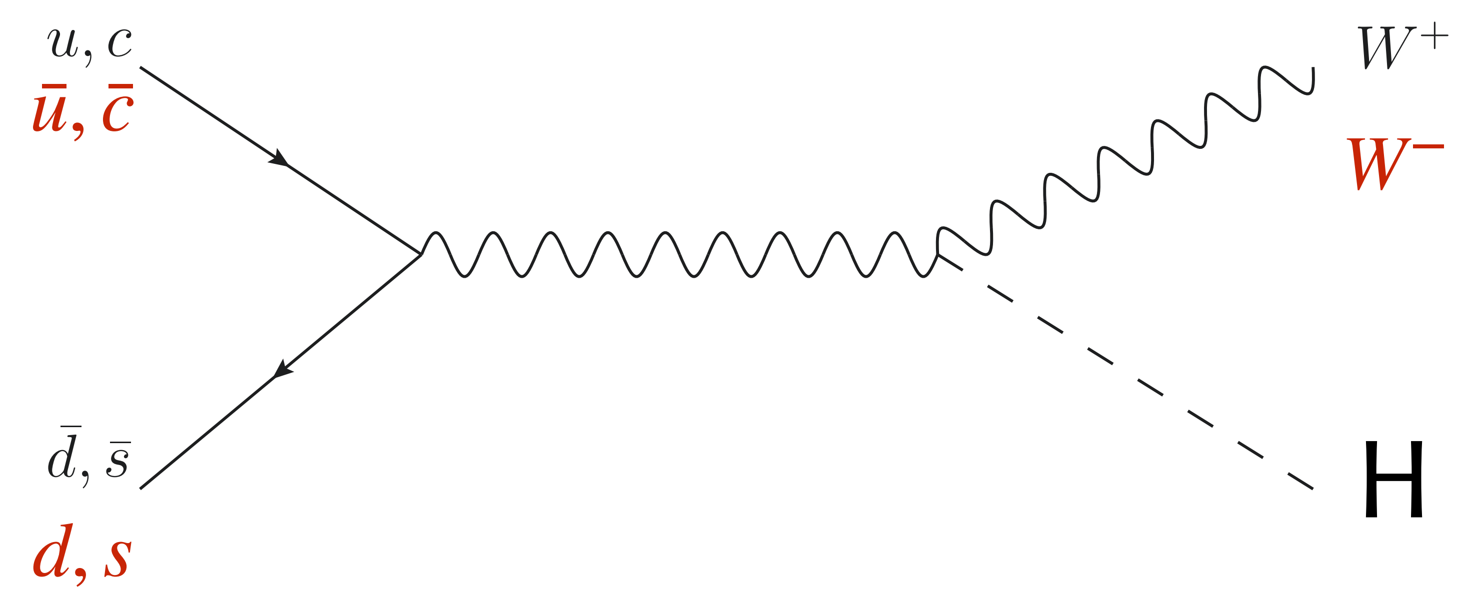
ATLAS: JHEP 04 (2025) 075

CMS-PAS-HIG-24-018

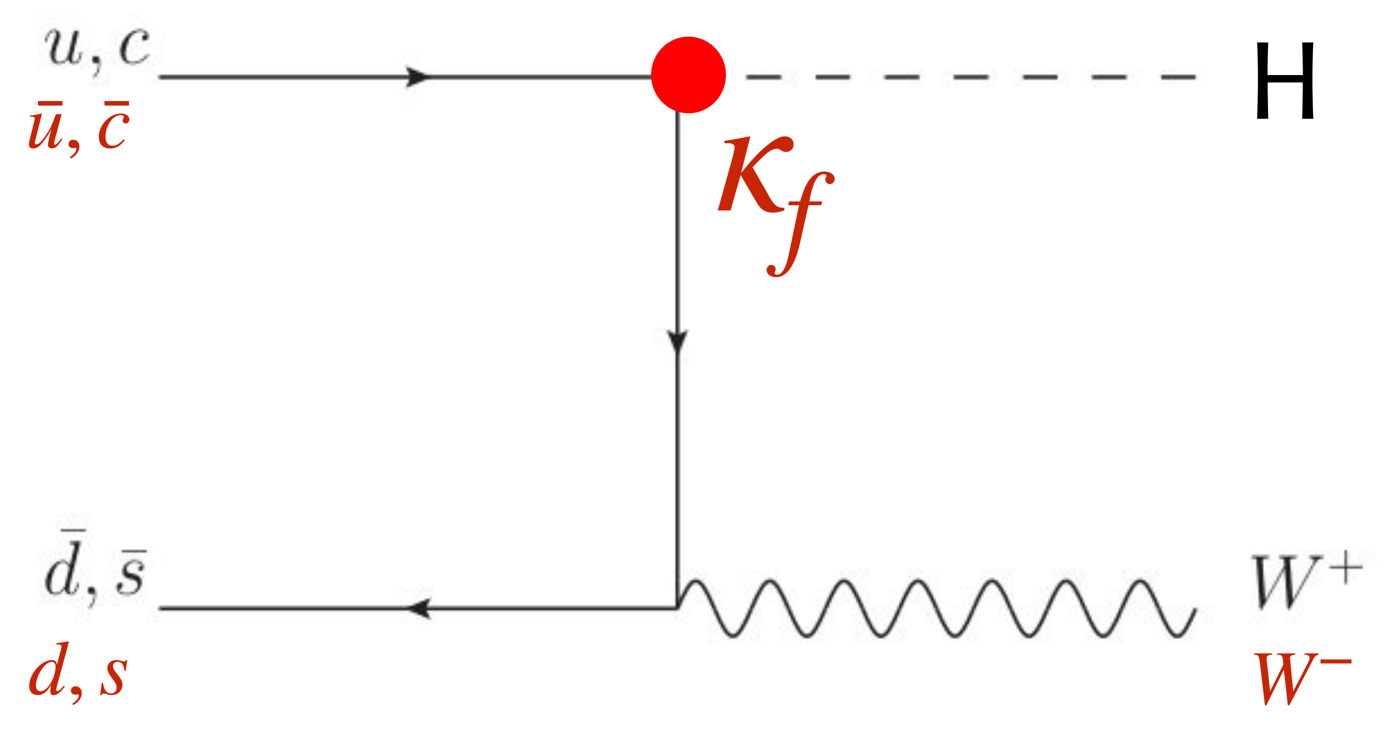
We simultaneously measure the **ttH(bb)** process:

$\mu_{ttH(H\to bb)}$ = **0.91 +0.26/-0.22 (4.4σ)**

Indirect probes of Higgs Yukawa's



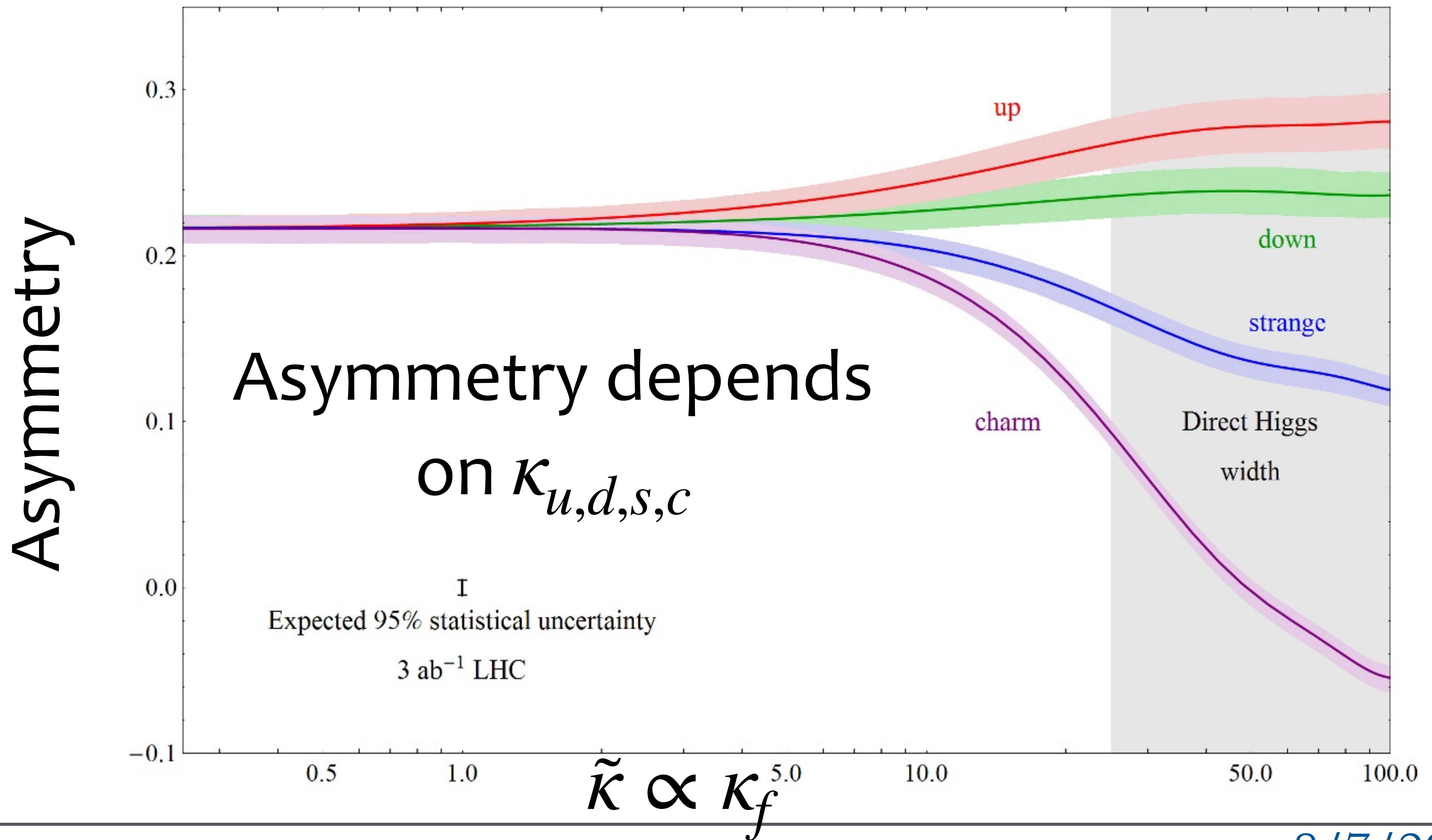
Dominant H-strahlung



Yukawa diagram

At LHC (pp collisions), $u\bar{d}(c\bar{s})$ vs $\bar{u}d(\bar{c}s)$ PDFs generate large charge asymmetry:

$$A = \frac{\sigma(W^+H) - \sigma(W^-H)}{\sigma(W^+H) + \sigma(W^-H)} \sim 0.2$$



Asymmetry depends on $\kappa_{u,d,s,c}$

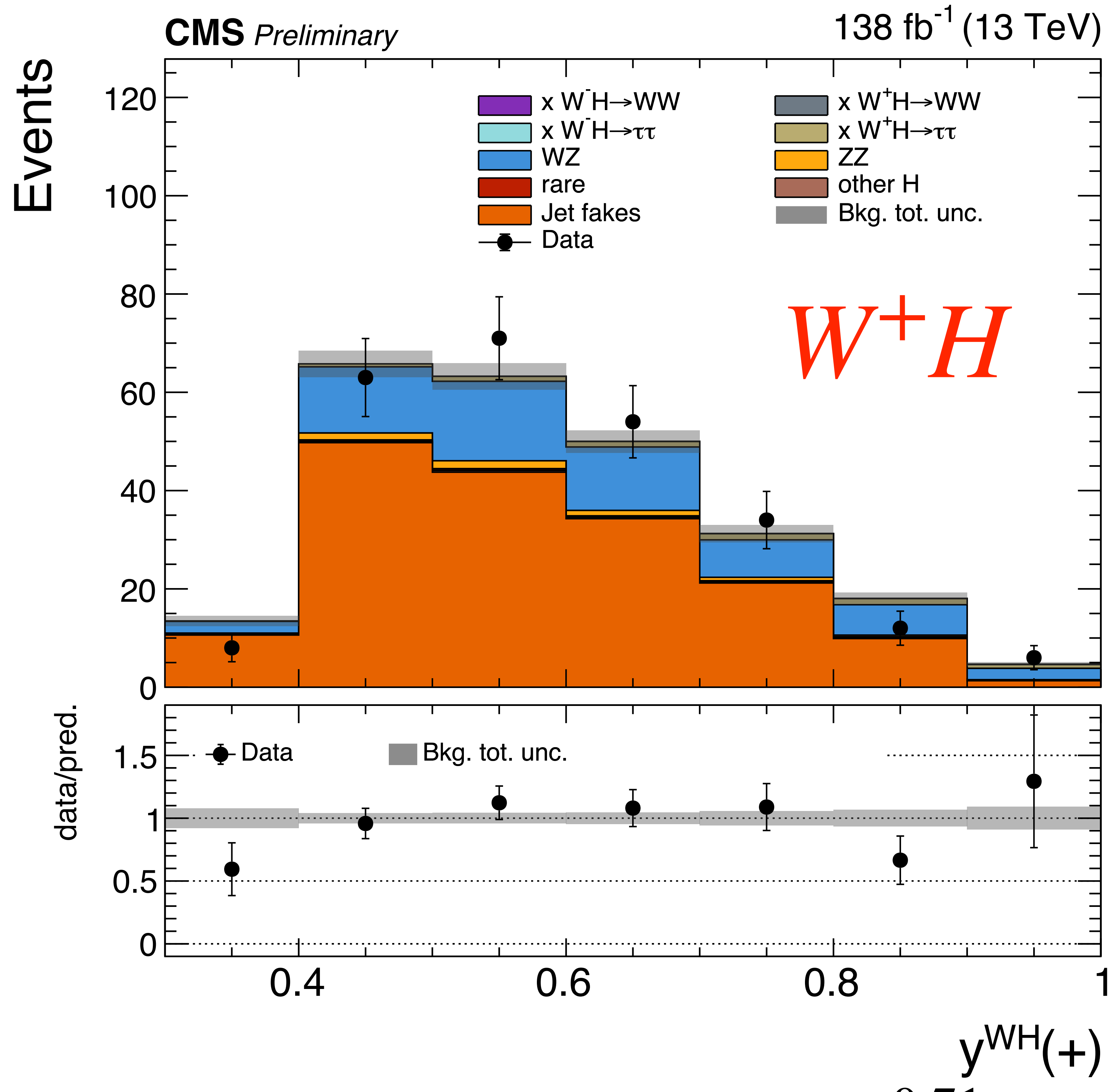
W(+/-) H(ττ) analysis

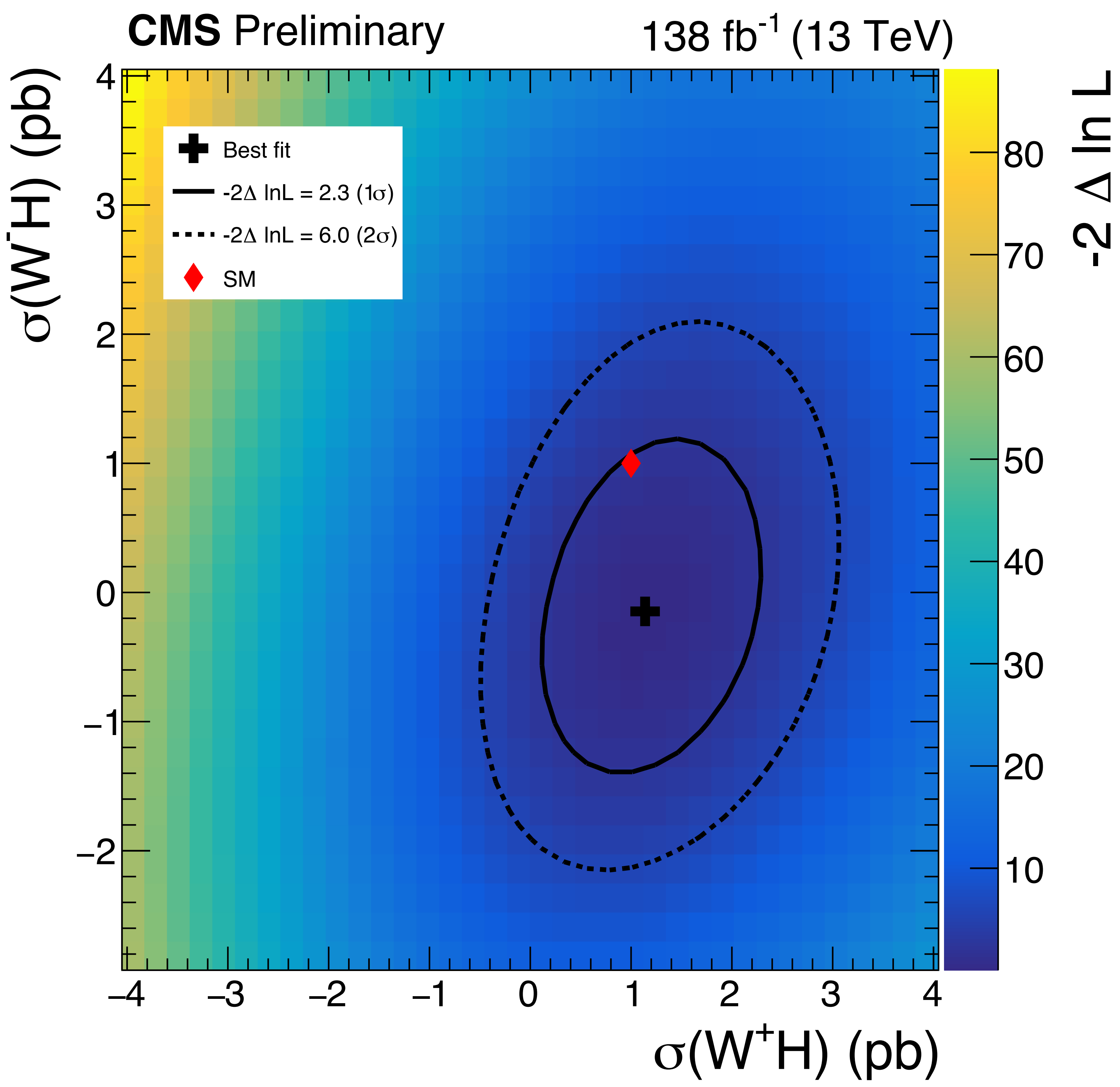
Exploit reasonably high BR and clean $H \rightarrow \tau\tau$, with:

- $W \rightarrow e/\mu\nu, H \rightarrow \tau\tau \rightarrow \mu\mu\tau_h, e\mu\tau_h, \mu/e\tau_h\tau_h$
- Irreducible backgrounds from sim: VV, ttV, ZH
- Reducible backgrounds from data: Z+jets, $t\bar{t}$ (1 jet $\rightarrow \tau_h/\mu/e$)

CMS-PAS-HIG-23-019

NEW





Charge asymmetry:

$A_{obs} = 1.18^{+0.00}_{-0.75}$

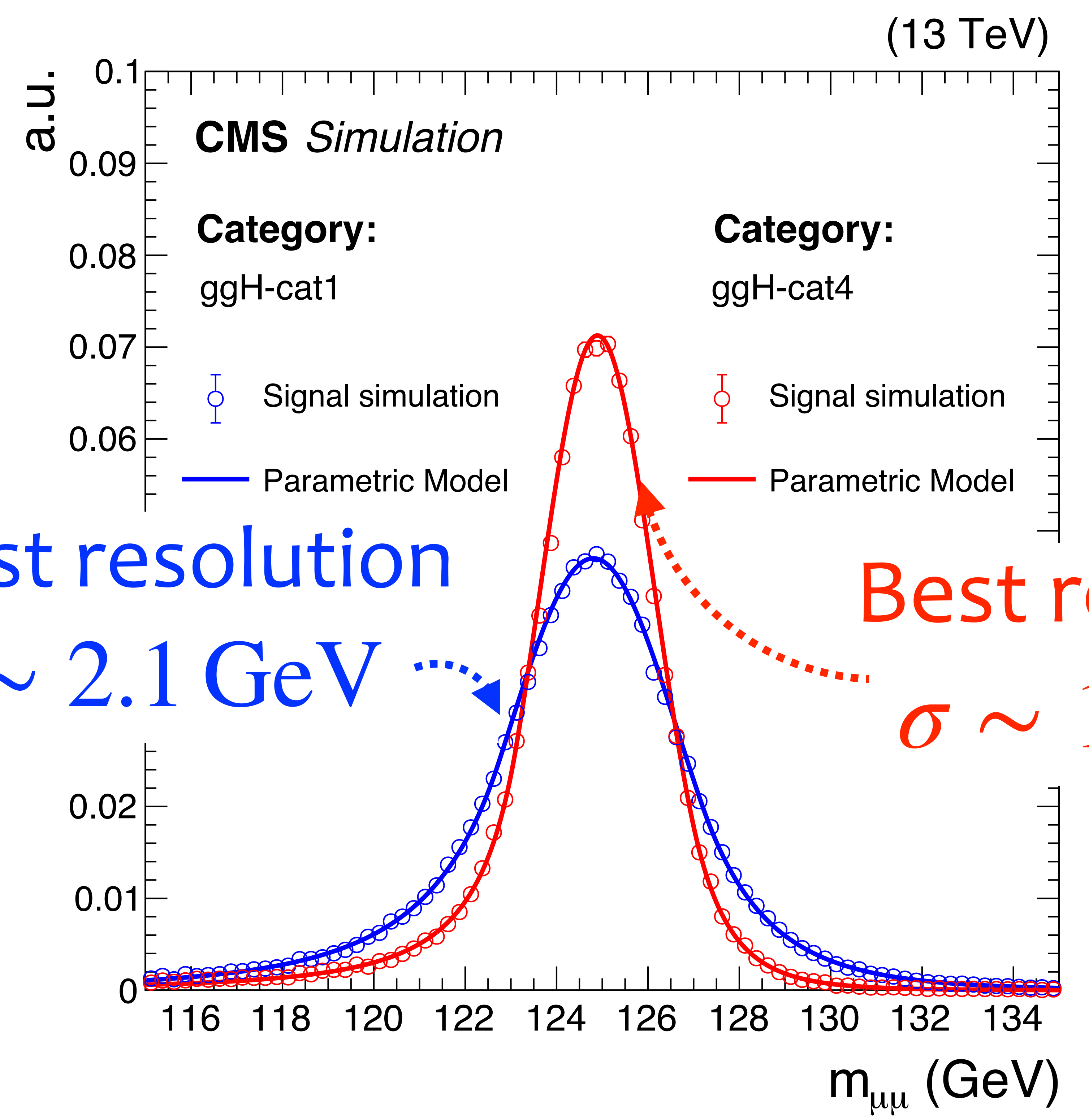
$(0.22^{+0.66}_{-0.56}$ exp.)

Consistent with SM expectation

$\mu(W^+H) = 1.16^{+0.71}_{-0.67}$; $\mu(W^-H) = -0.09^{+0.86}_{-1.03}$

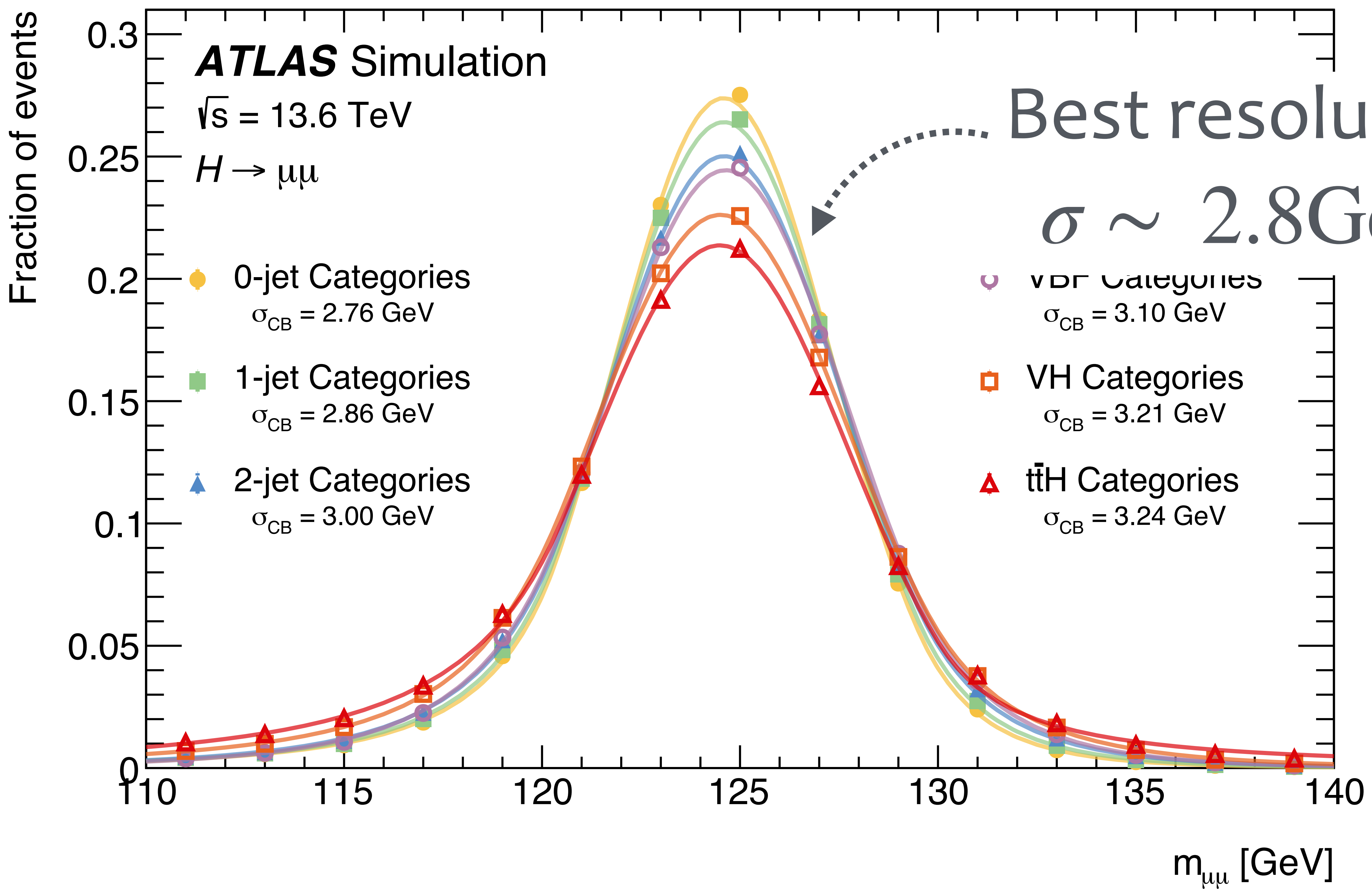
Direct 2nd generation Yukawa: H->μμ

- Rare decay: $BR(H \to \mu\mu) \approx 2 \times 10^{-4}$, with large non-resonant background from $DY \to \mu\mu$
- S/B ~ 0.1% for inclusive events at 125 GeV
- Strategies to boost the sensitivity common to ATLAS and CMS:
  - **use all production modes**: ggF, VBF, VH, ttH
  - **improve σ($m_{\mu\mu}$)**: detector alignment, FSR recovery, constrain tracks to beam line, etc



Worst resolution
$\sigma \sim 2.1$ GeV

Best resolutior
$\sigma \sim 1.5$ GeV



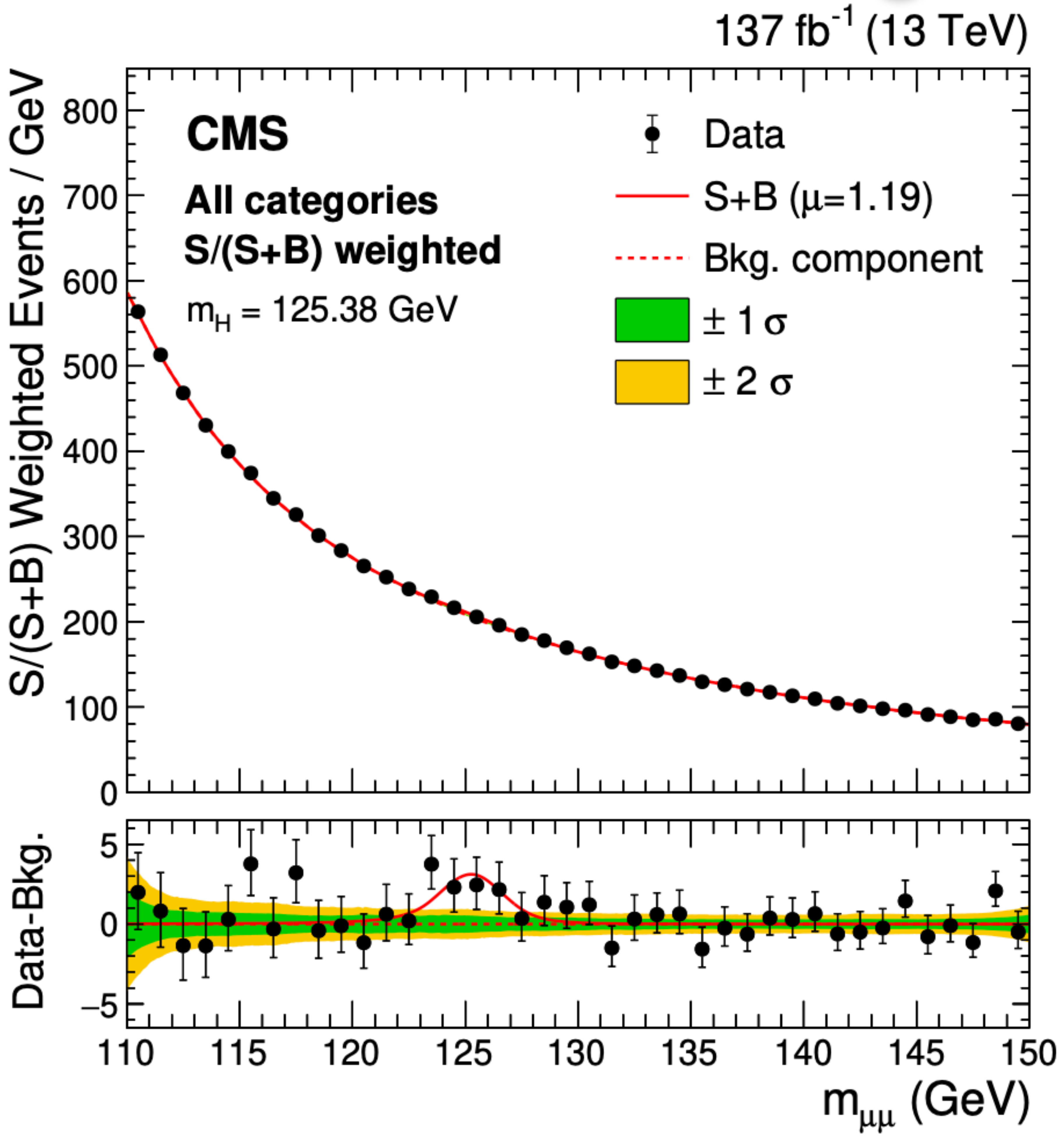
Best resolution
$\sigma \sim 2.8$GeV

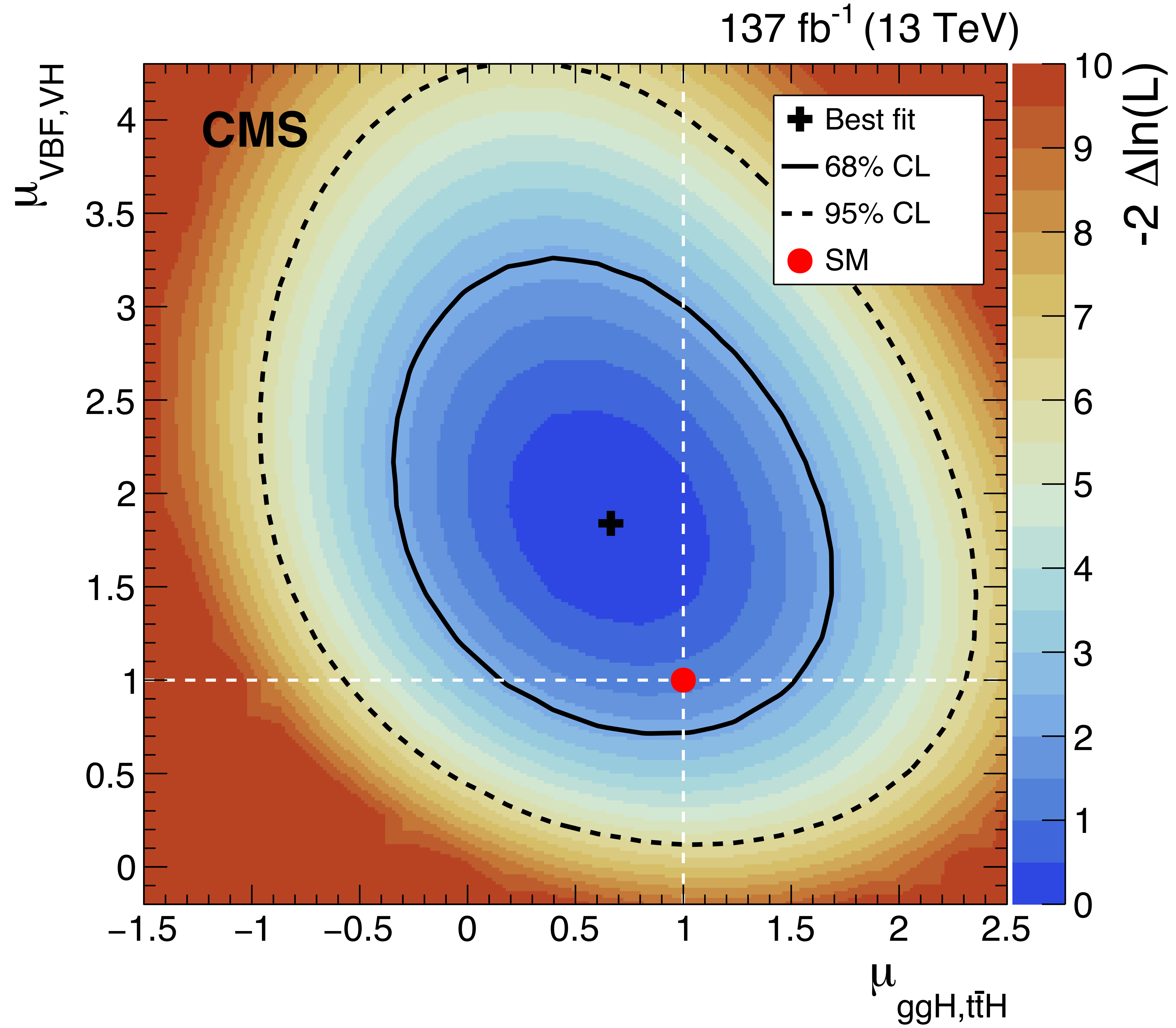
Legacy Run-2 CMS result (137 fb^{-1})

$$\mu = 1.2 \pm 0.4$$

CMS: JHEP 01 (2021) 148

significance: 3.0σ (2.5σ exp.)





gluon-fusion and VBF with similar sensitivity

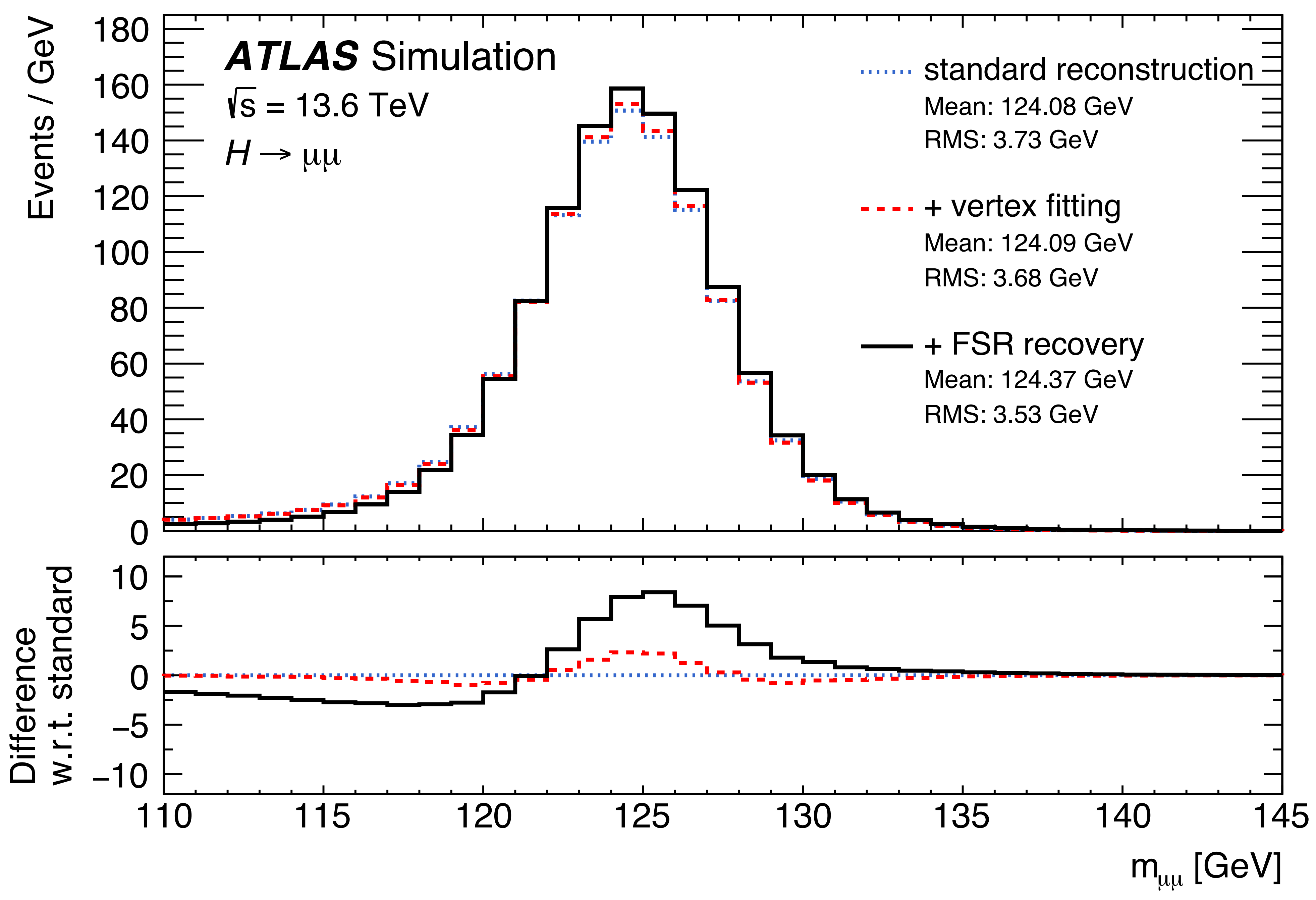
New ATLAS analysis: Run2 + Run3 (304 fb^{-1})

Analyse Run-3 dataset, 165 fb^{-1} at $\sqrt{s}$=13.6 TeV (2022-2024), and combine with Run-2 (139 fb^{-1})

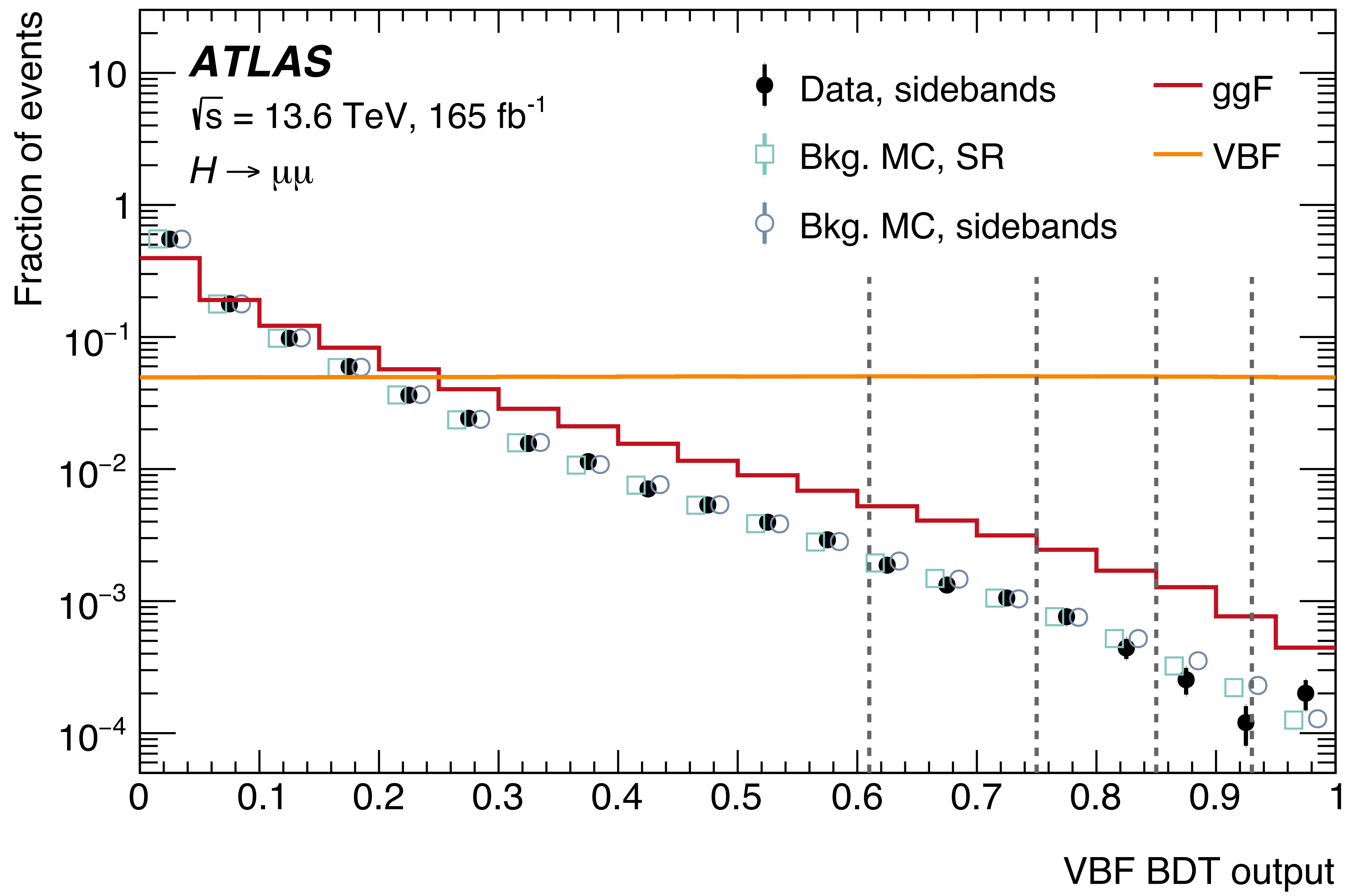
- Impressive 5×10^9 full-sim NLO DY sample
- improve the $H \rightarrow \mu\mu$ vertex fit
- Improve the categorisations, add 2leptons VH, ttH fully hadronic channels

HIGP-2024-011

NEW



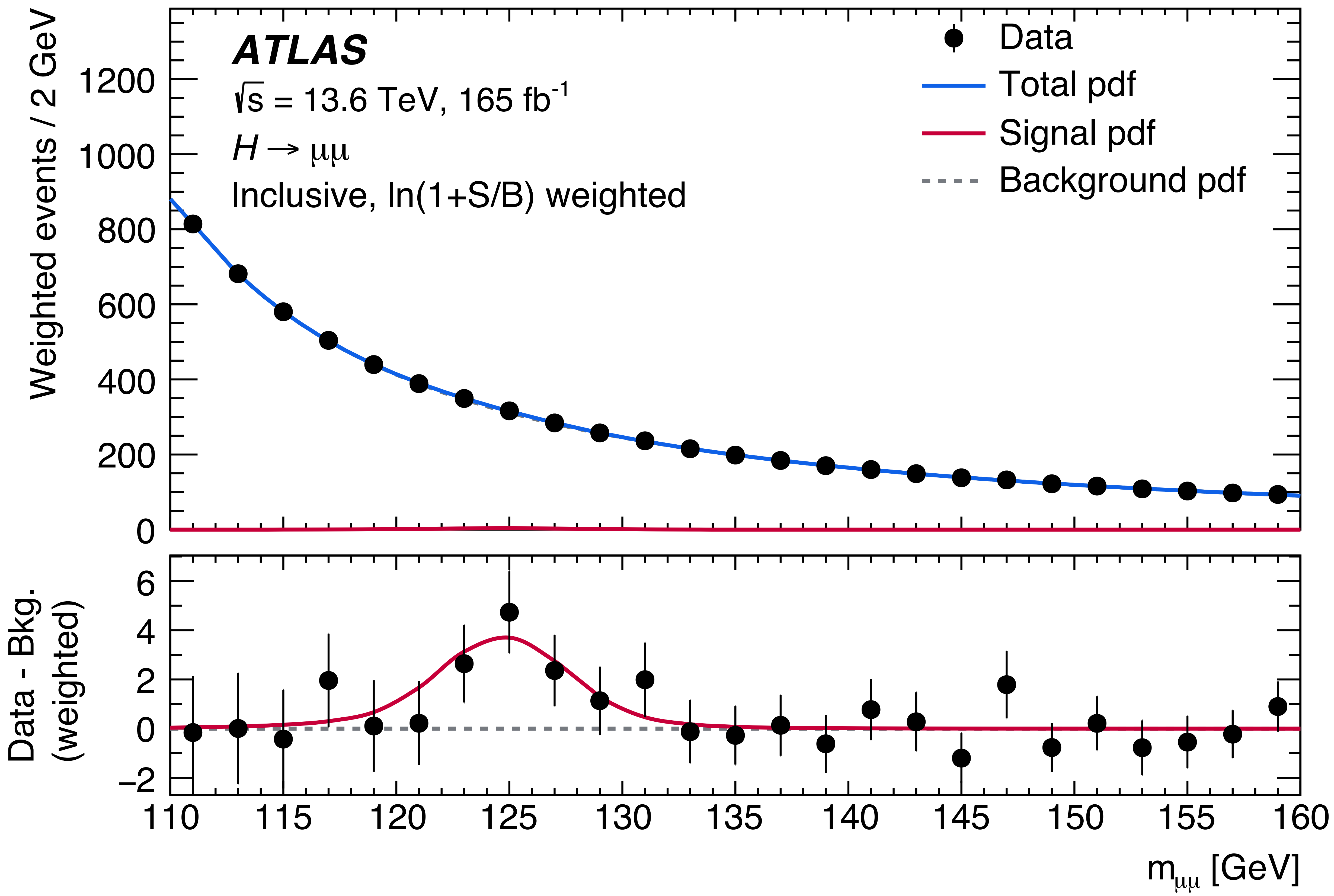
5% better resolution from detector studies



Control of analysis BDTs in Run3 data over 4 orders of magnitude

ATLAS evidence for H->μμ

Run3 (165 fb-1) only

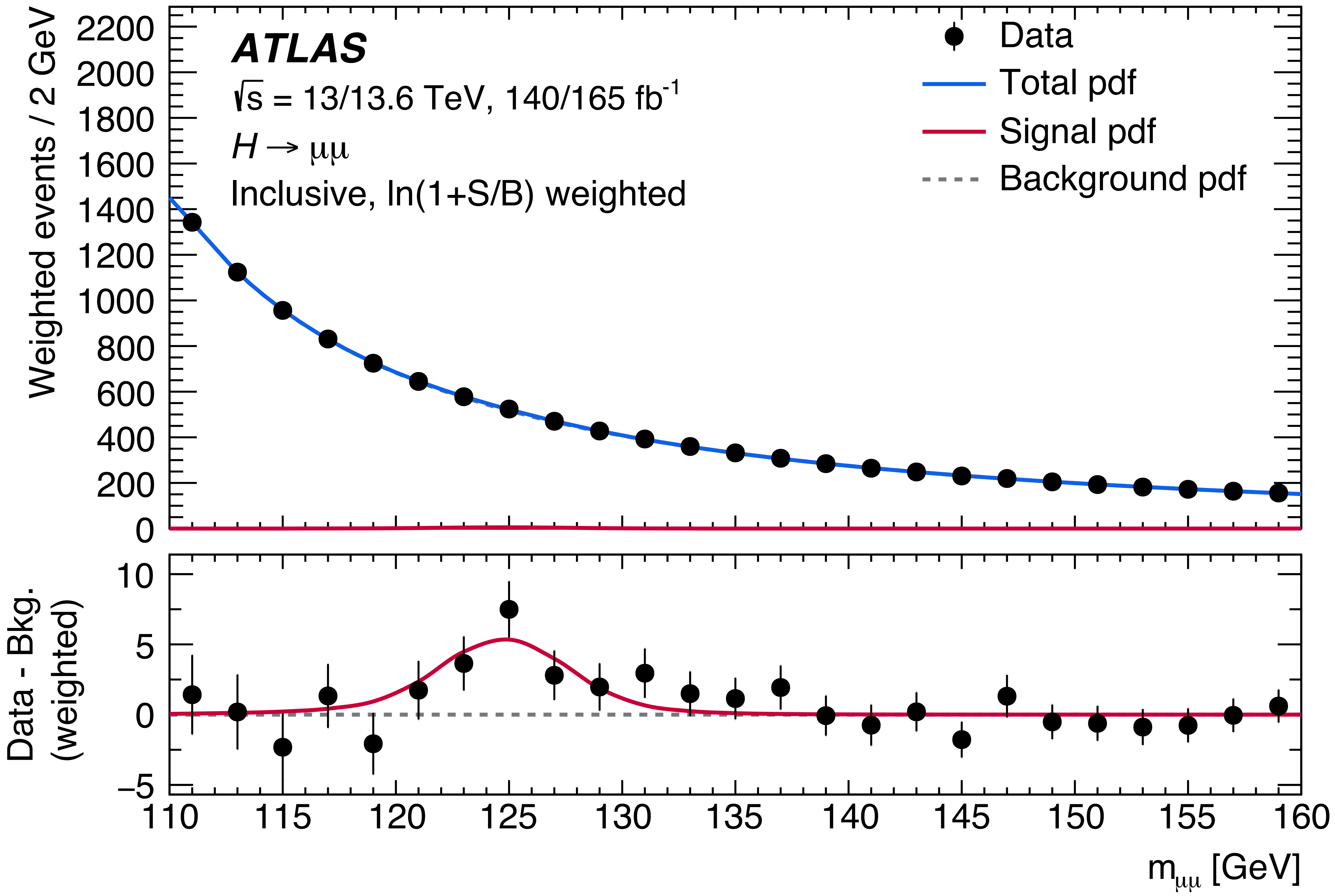


NEW

$\mu = 1.6 \pm 0.6$

HIGP-2024-011

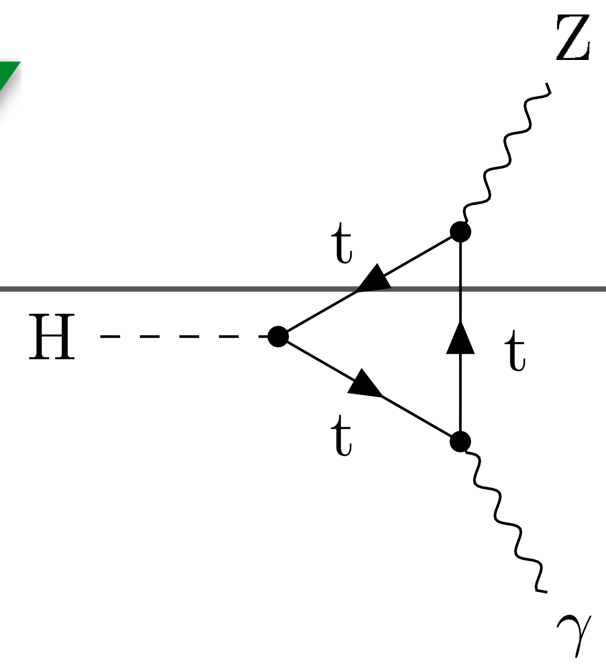
Run2 + Run3 (304 fb-1)



$\mu = 1.4 \pm 0.4$

significance: 3.4σ (2.5σ exp.)

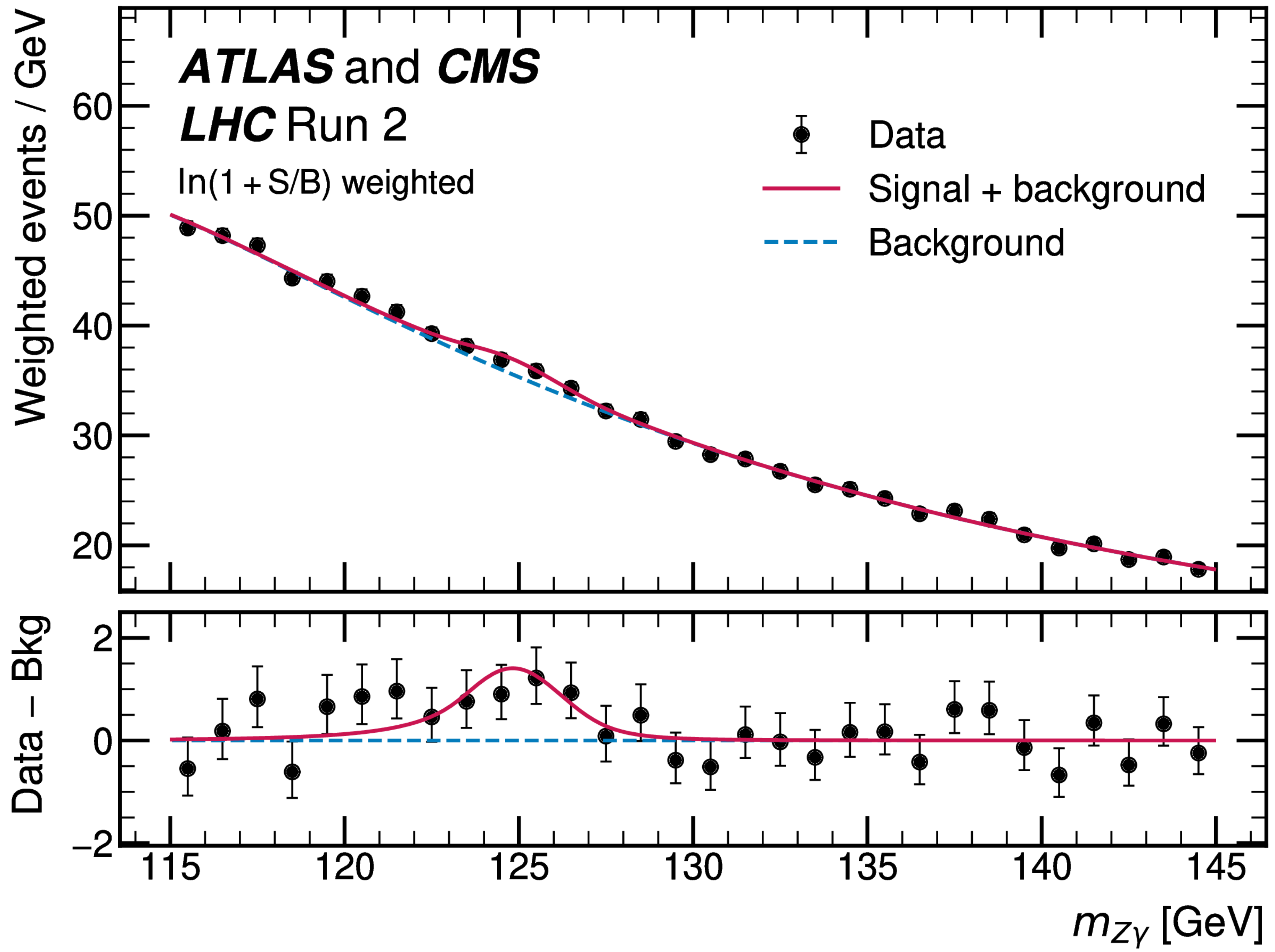
Other rare decay modes: H->Zγ

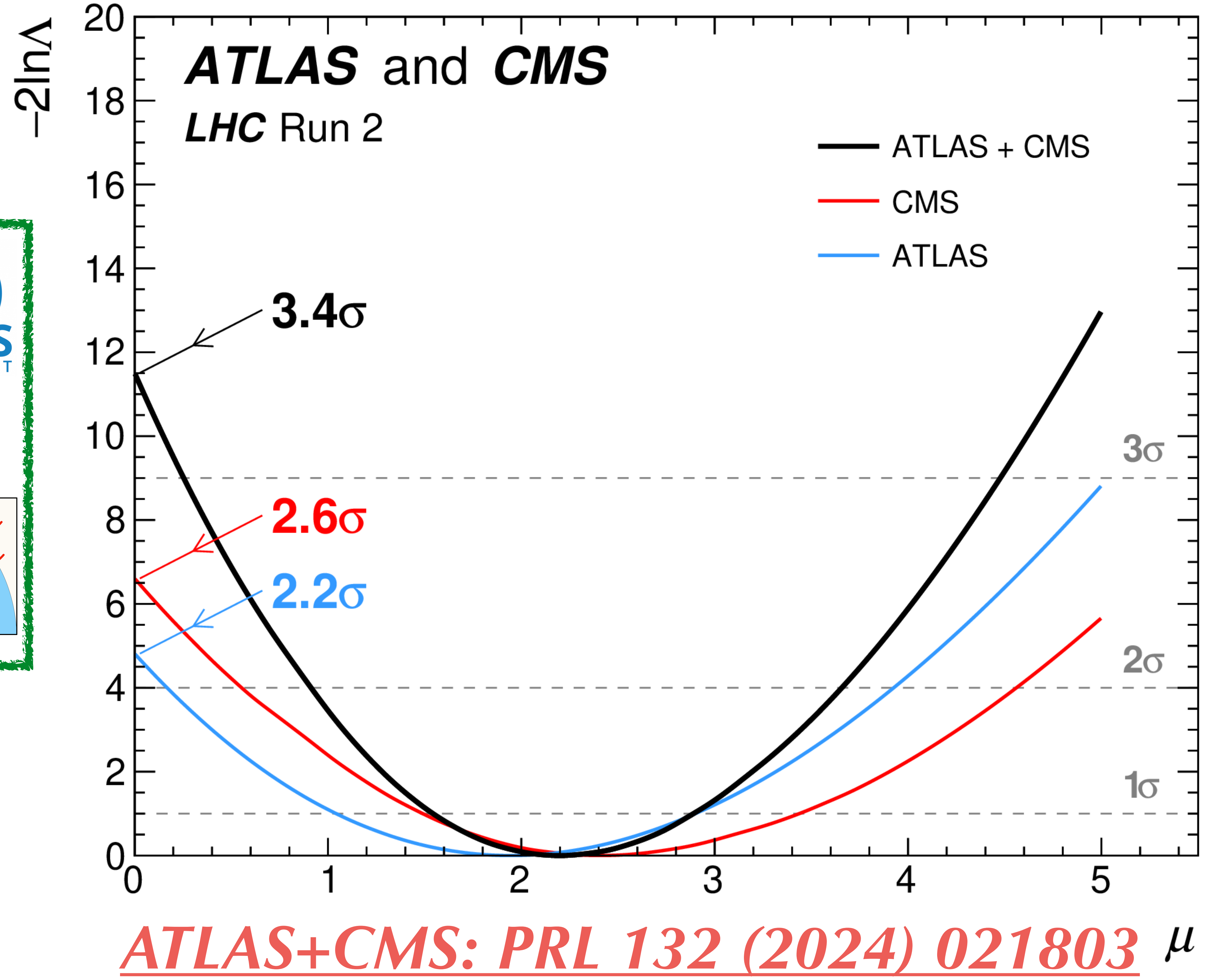


Loop-induced (BR~1.3 x 10^{-3}): sensitive to BSM

ATLAS+ CMS Run-2 combination: 1st evidence of this rare decay.

Measured (2.2 ± 0.7) **x SM** cross section
> 3σ signal





Intriguing high σ/σ_{SM}: **what's in the new data ?**

ATLAS+CMS: PRL 132 (2024) 021803

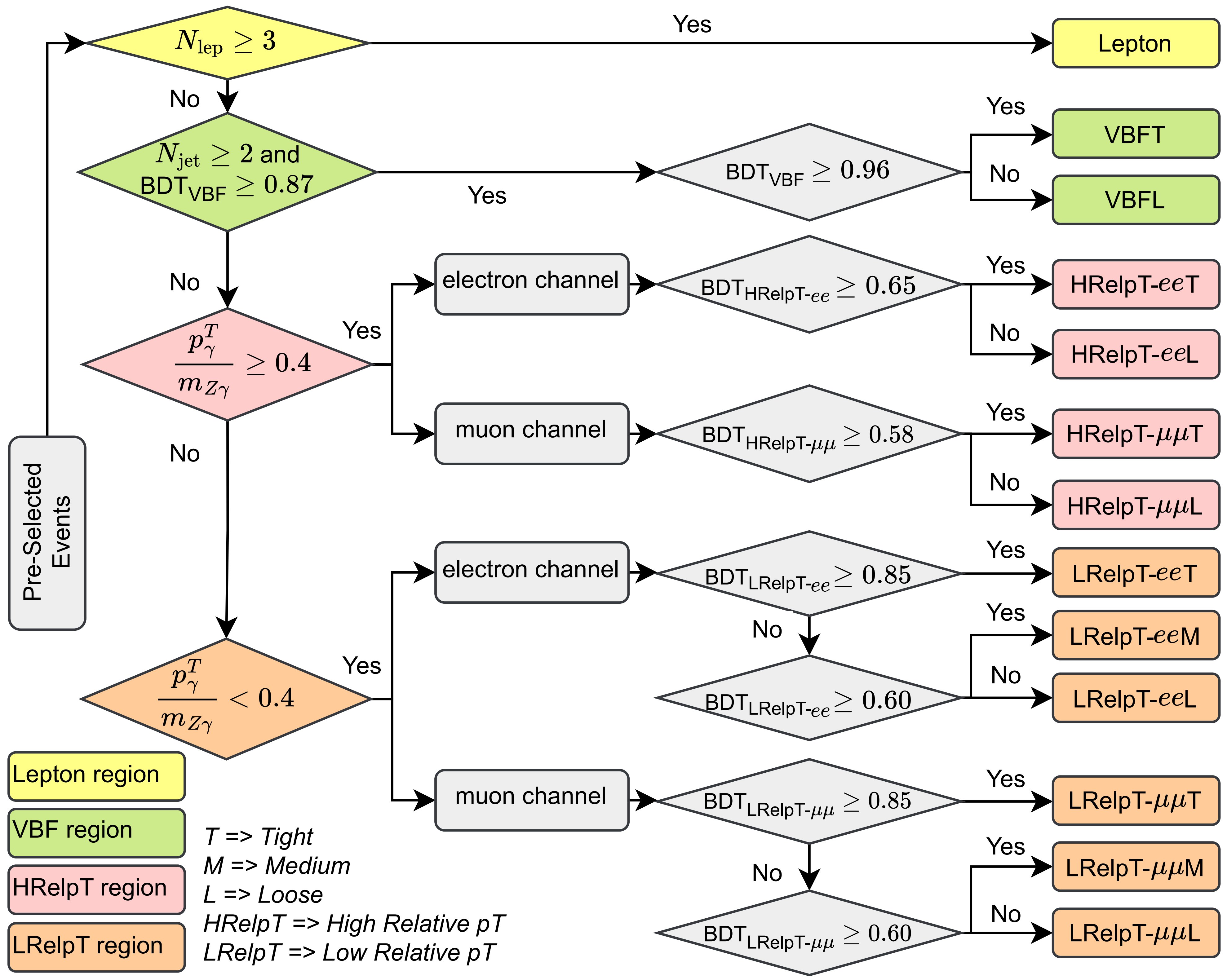
Run-3 ATLAS H->Zγ analysis

Based on 165 fb^{-1} Run-3 data (2022-2024), with strategy improvements:

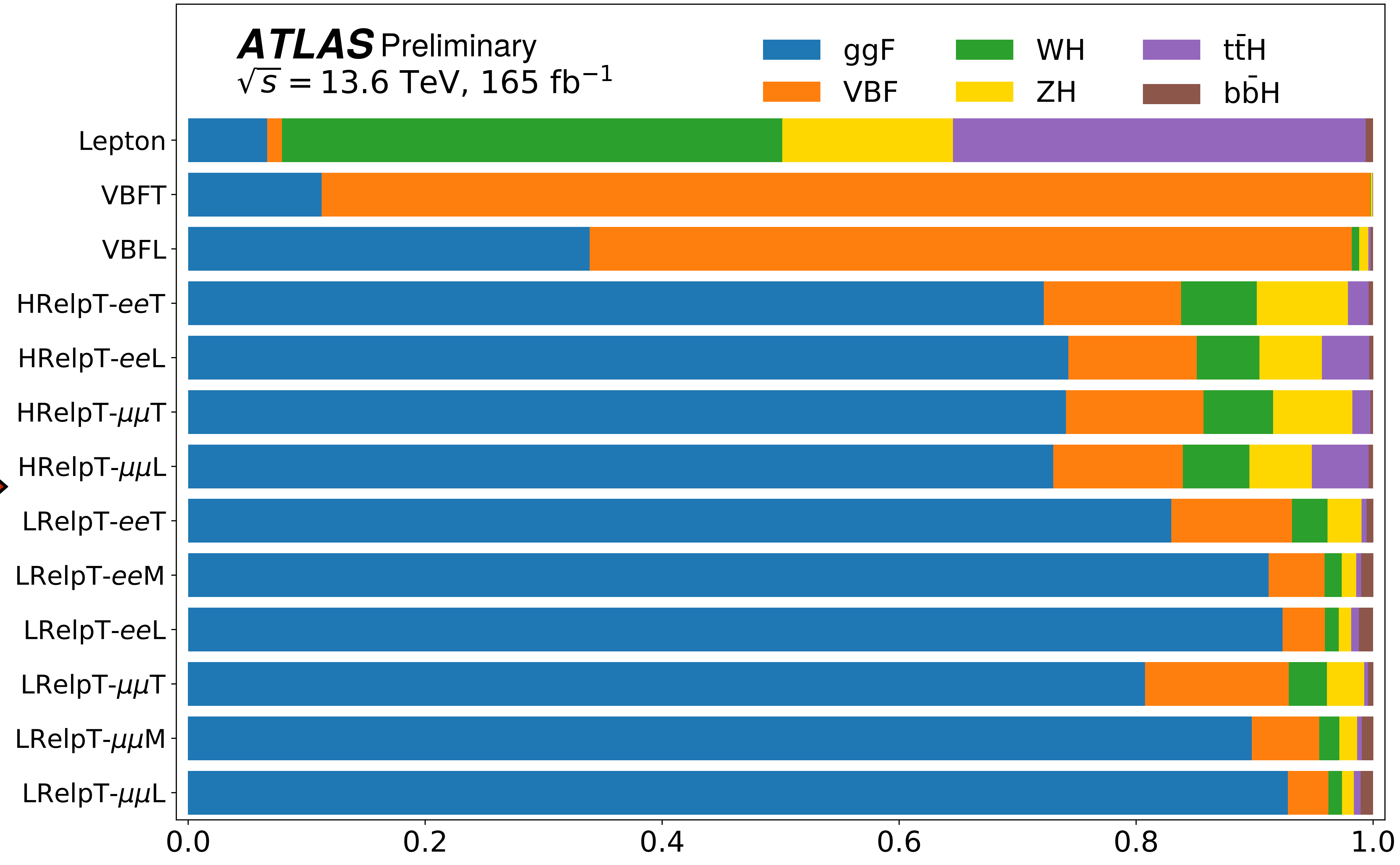
1. Relaxed e/μ pT thresholds (higher efficiency)
2. Improved categorization with MVAs
3. Added tt(multi-leptons)+H production (higher acceptance)

ATLAS-CONF-2025-007

NEW



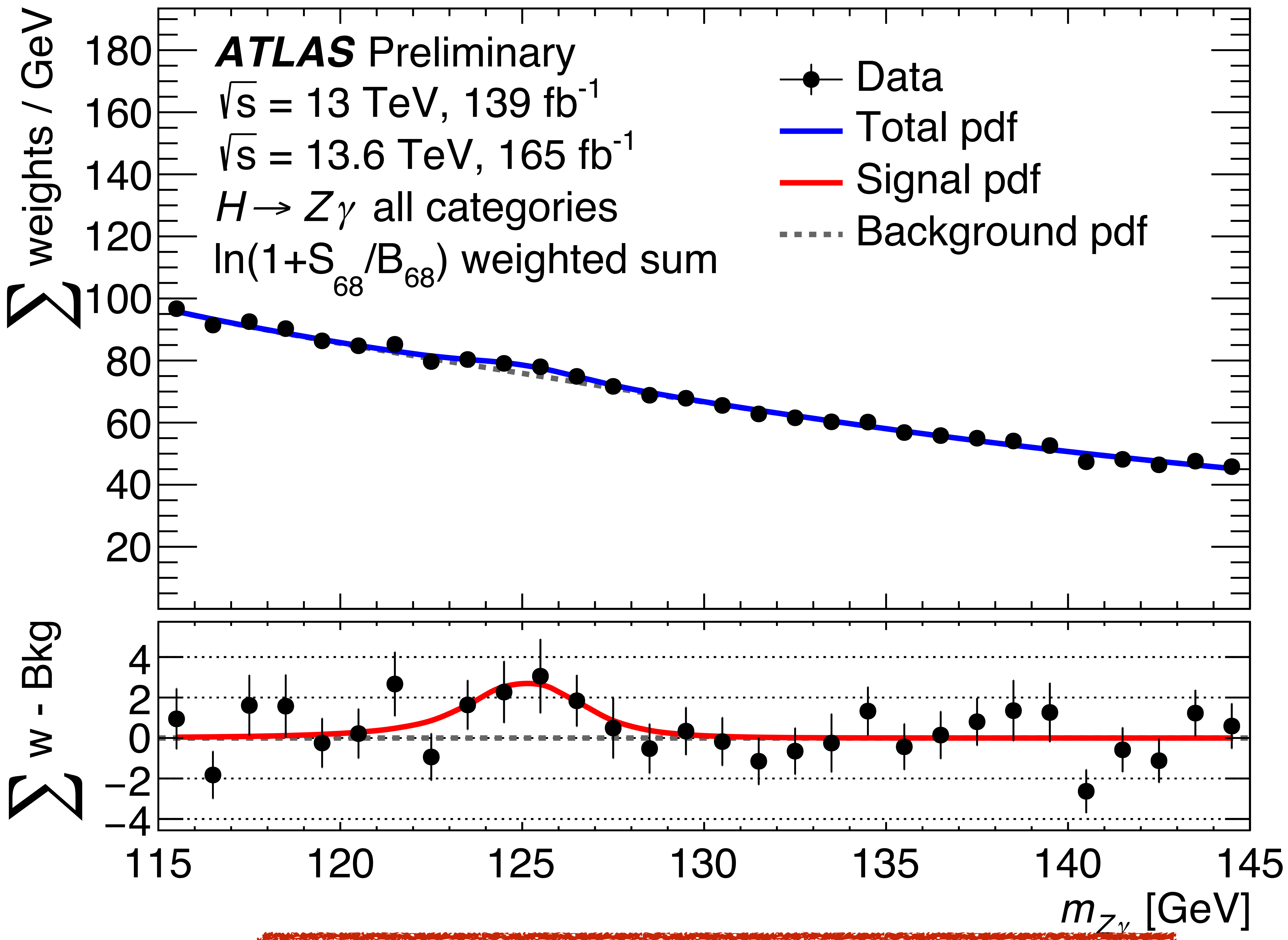
Novel Run-3 categorisation



Signal production breakdown

Run2+Run-3 ATLAS H->Zγ result

significance: 2.5σ (1.9σ exp.)

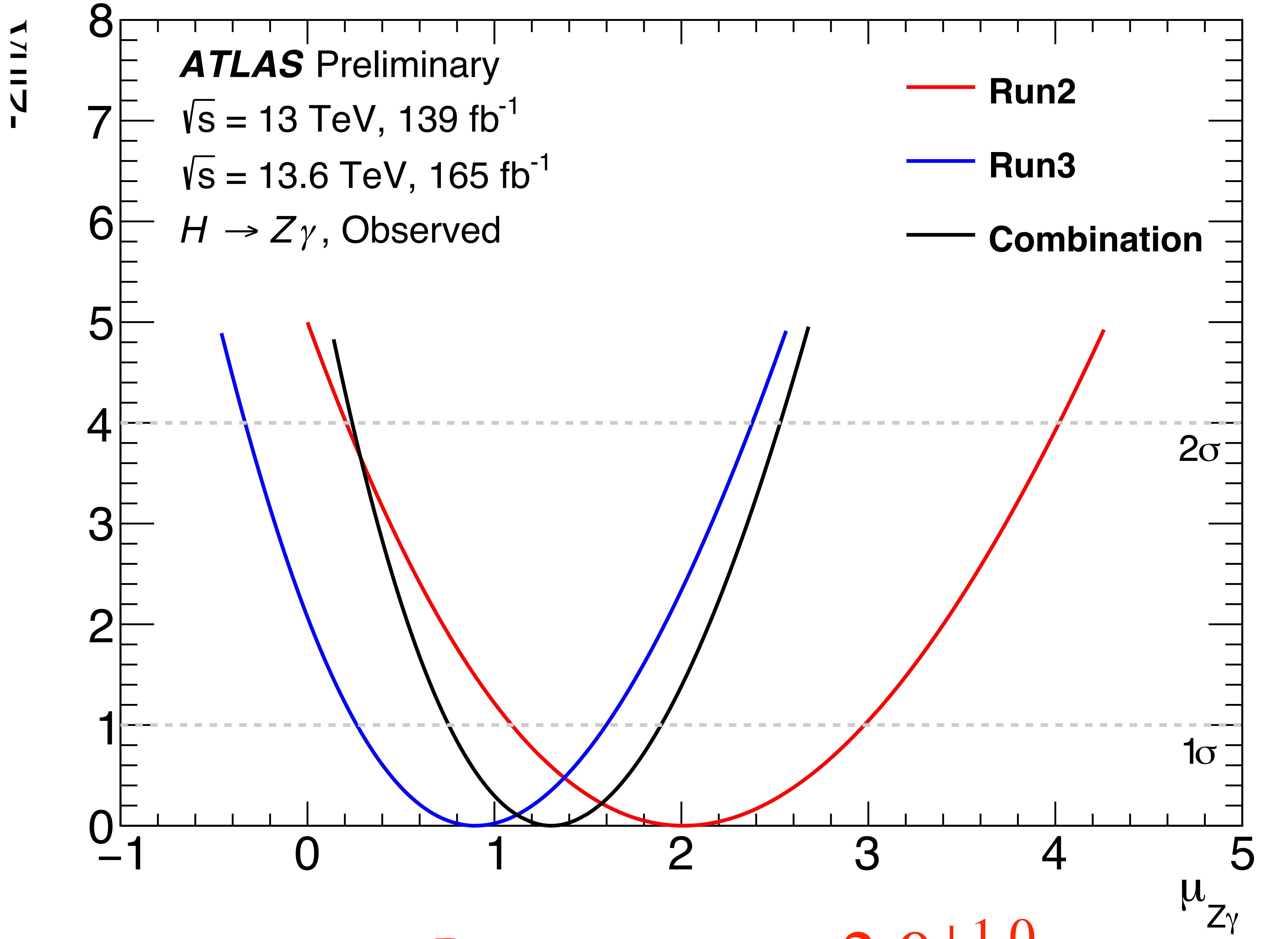


$$\mu_{\text{obs.}} = 1.3^{+0.6}_{-0.5}\,(1.0^{+0.6}_{-0.5}\,\text{exp.})$$

Most sensitive result on this rare channel to date

ATLAS-CONF-2025-007

Run-3 data more towards SM value



NEW

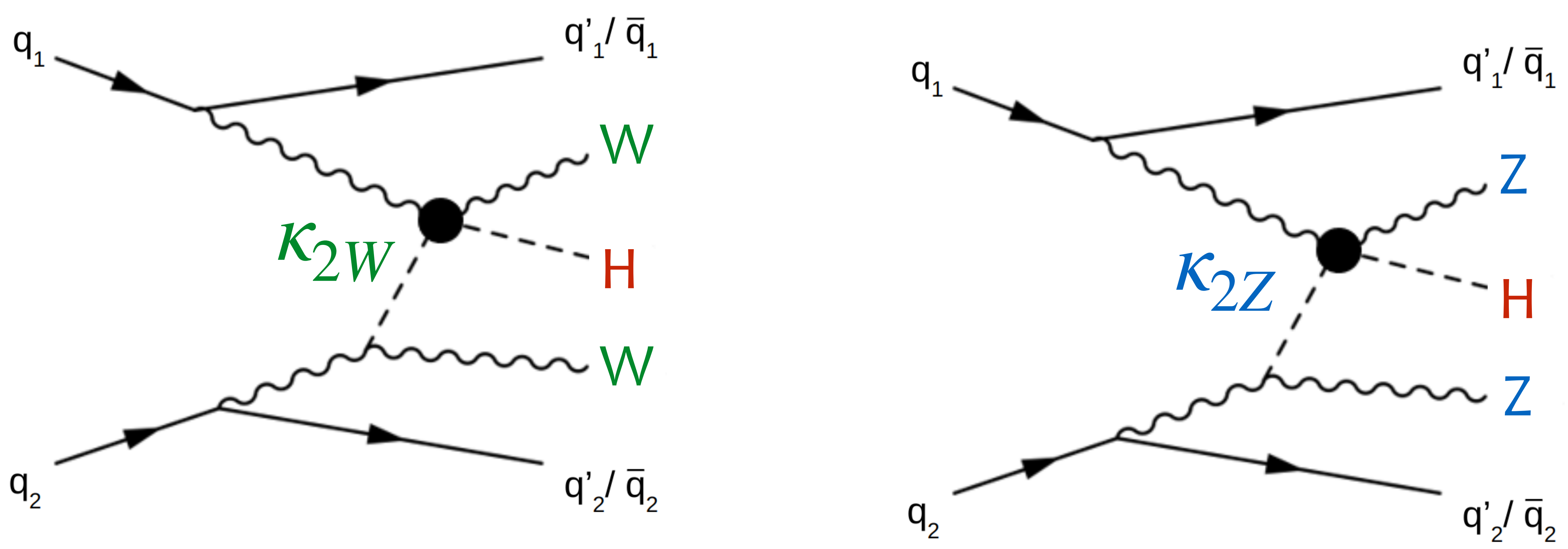
Run-2: $\mu_{\text{obs.}} = 2.0^{+1.0}_{-0.9}$

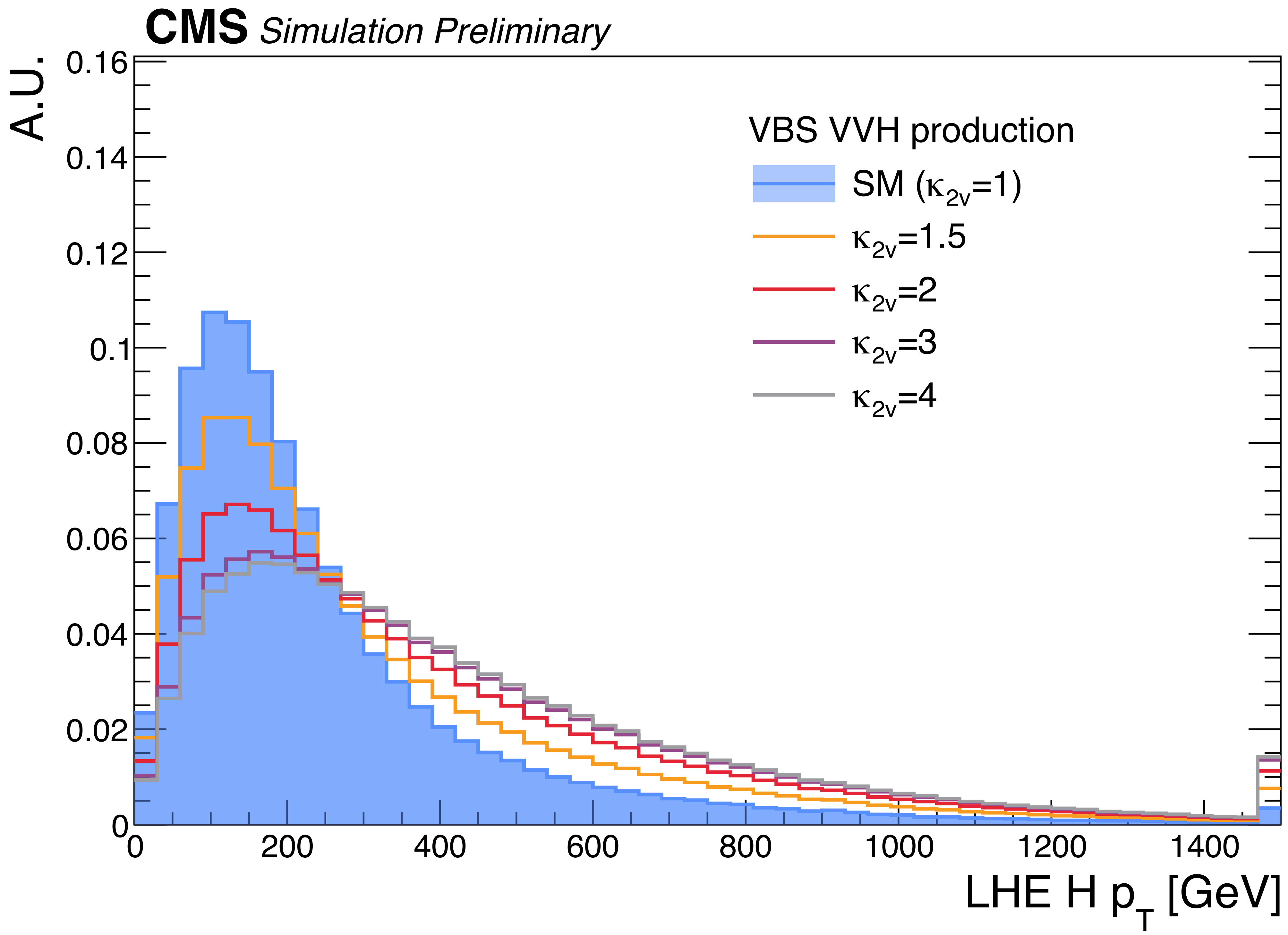
Run-3: $\mu_{\text{obs.}} = 0.9^{+0.7}_{-0.6}$

Rarer: CMS Electroweak VV H(bb)

VBS VVH production sensitive to Higgs self-coupling (κ_λ) and quartic coupling (κ_{2V})

- $\sigma(VVH) \propto (\kappa_{2V})^2$ and kinematics boosted when $\kappa_{2V} \neq 1$
- WWH and ZZH separately probe κ_{2W} and κ_{2Z}

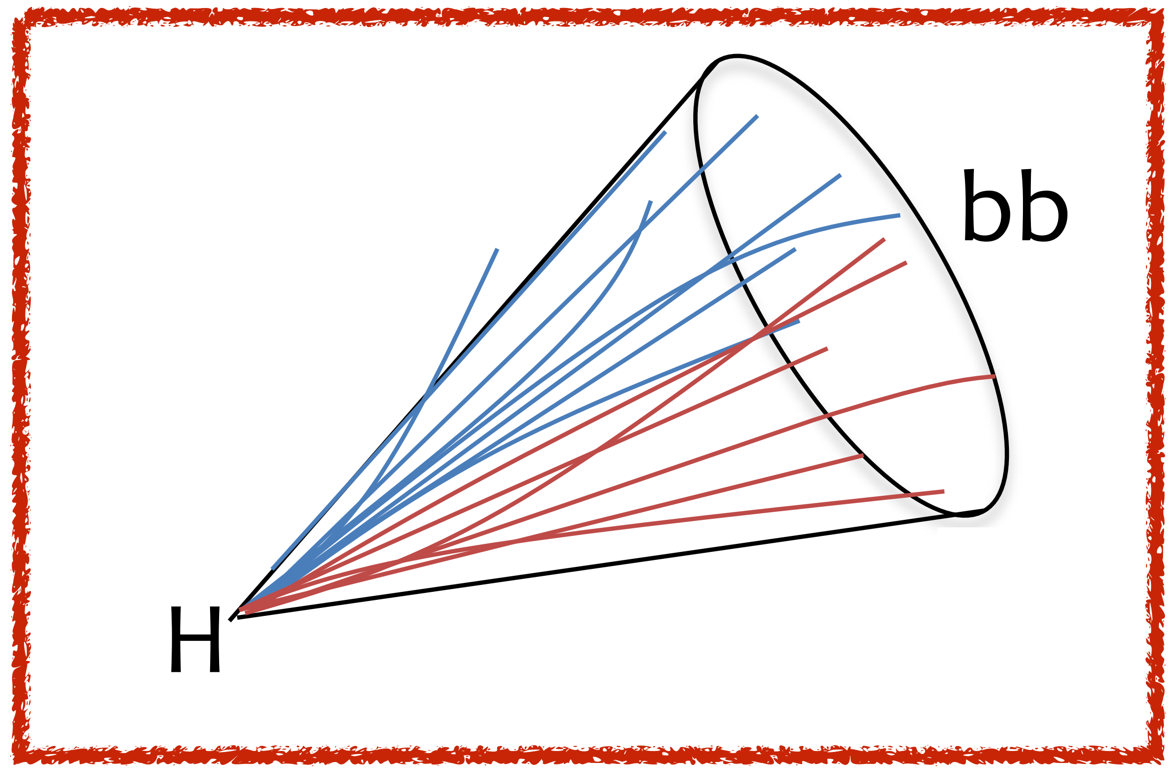




Boosted (merged jet) $H \rightarrow b\bar{b}$ +

Boosted / Resolved $V \rightarrow qq'$ or

1 lepton ($W \rightarrow \ell\nu$) or 2 leptons ($Z \rightarrow \ell\ell$)

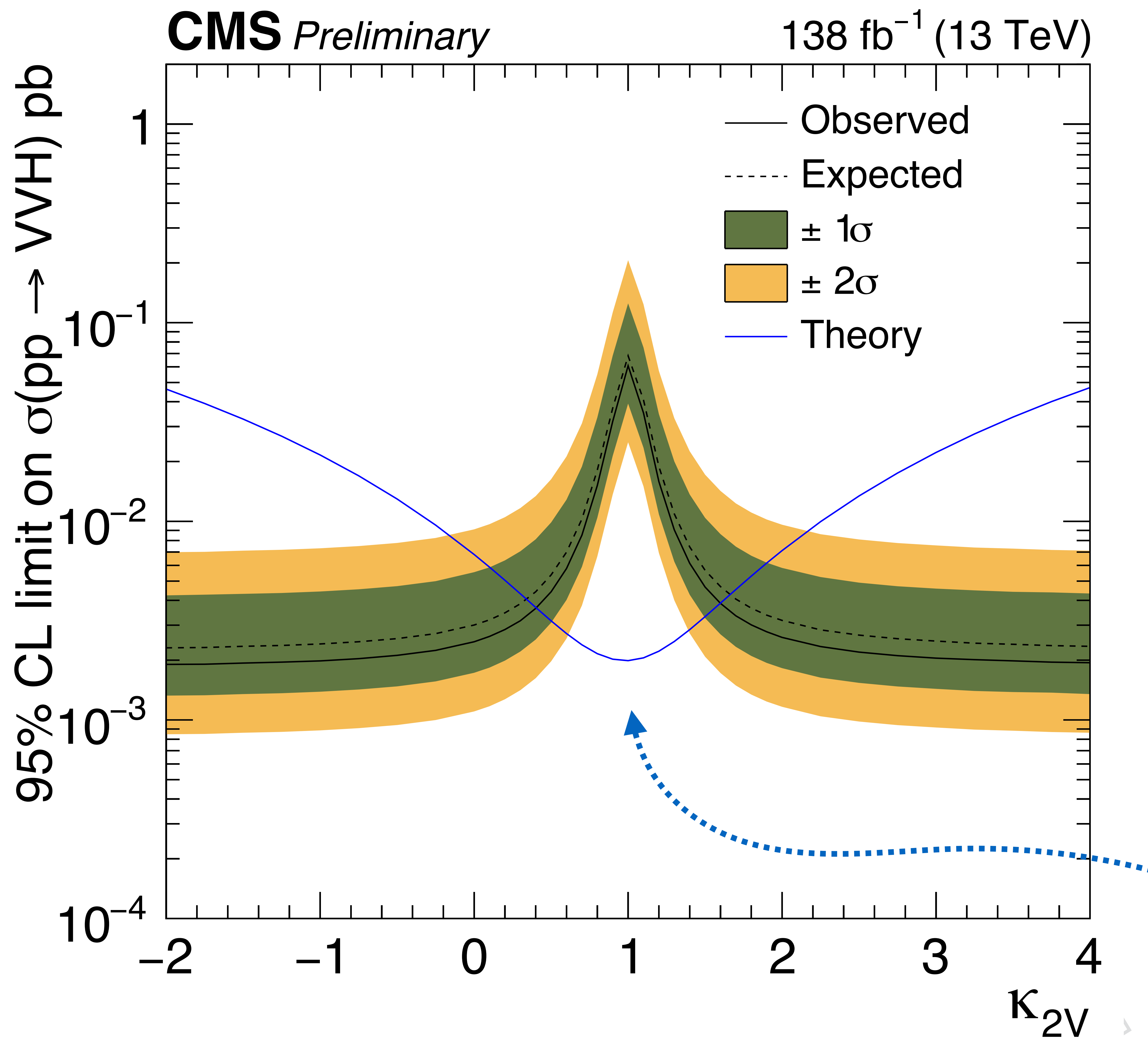


NEW

CMS-PAS-HIG-24-003

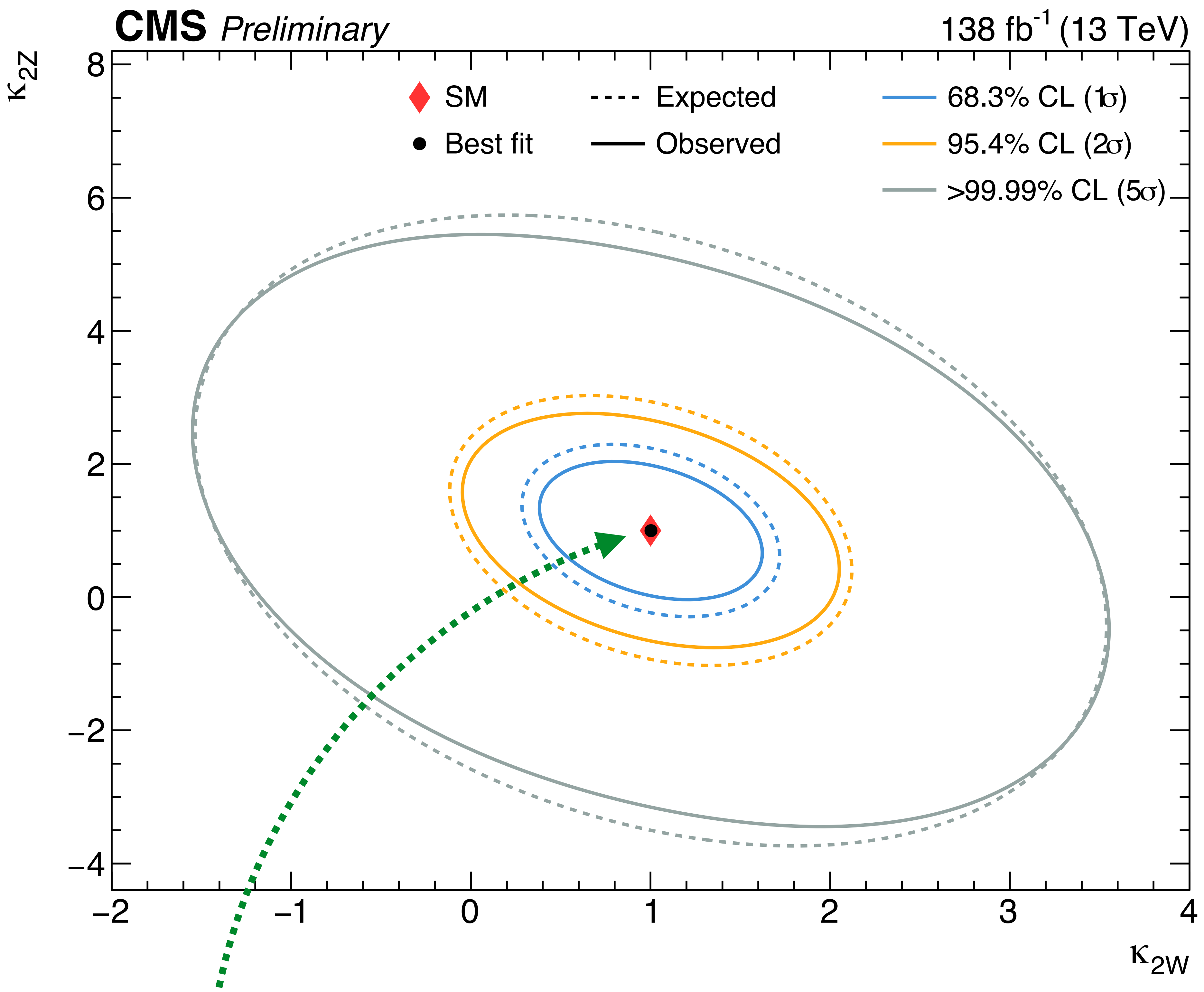
Electroweak CMS VV H(bb) results

- Low-statistics channels: cut & count
- Sensitivity mostly from semi-leptonic and fully hadronic



NEW

CMS-PAS-24-003

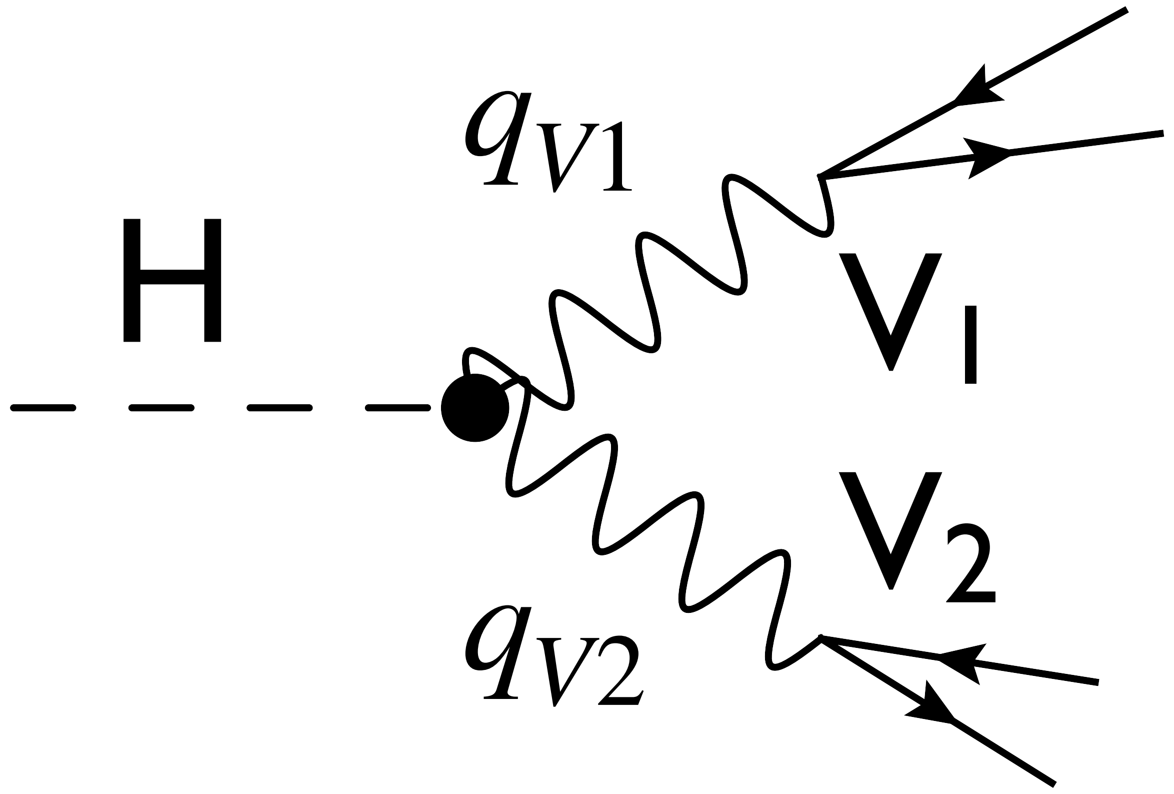


- Tightest κ_{2W} and κ_{2Z} constraints
- Assuming a single κ_{2V} : $[0.41, 1.59]$ (obs.) ([0.34,1.66] (exp.)) allowed range

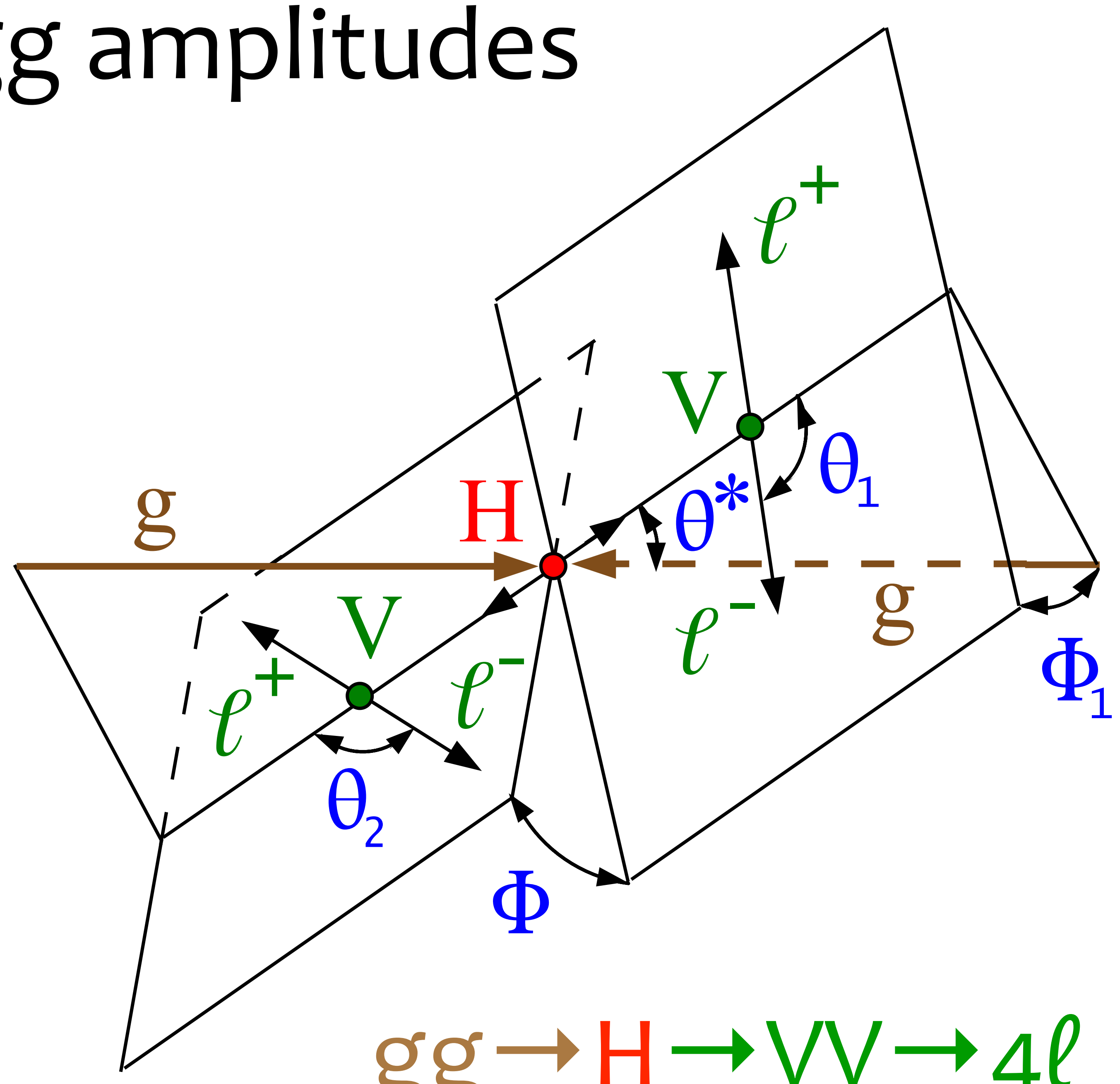
Higgs boson anomalous couplings and CP violation

Anomalous Higgs interactions

- Higgs boson confirmed to be spin-0, and consistent with CP++ since Run 1
- Pure CP-odd state excluded ≠ CP-even state
- Look for BSM contributions in the HVV, Hgg amplitudes



$V_i = W, Z, \gamma, g$



gg→H→VV→4ℓ

e.g. $H \rightarrow 4\ell$
golden channel

$$A(HV_1V_2) = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV}(q_{V1}+q_{V2})^2}{(\Lambda_Q^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

a_1: SM

Dim-6 BSM operators at a scale $\Lambda \gg \Lambda_{EWK}$

a_2: CP even BSM

a_3: CP odd BSM

Dedicated observables to CP

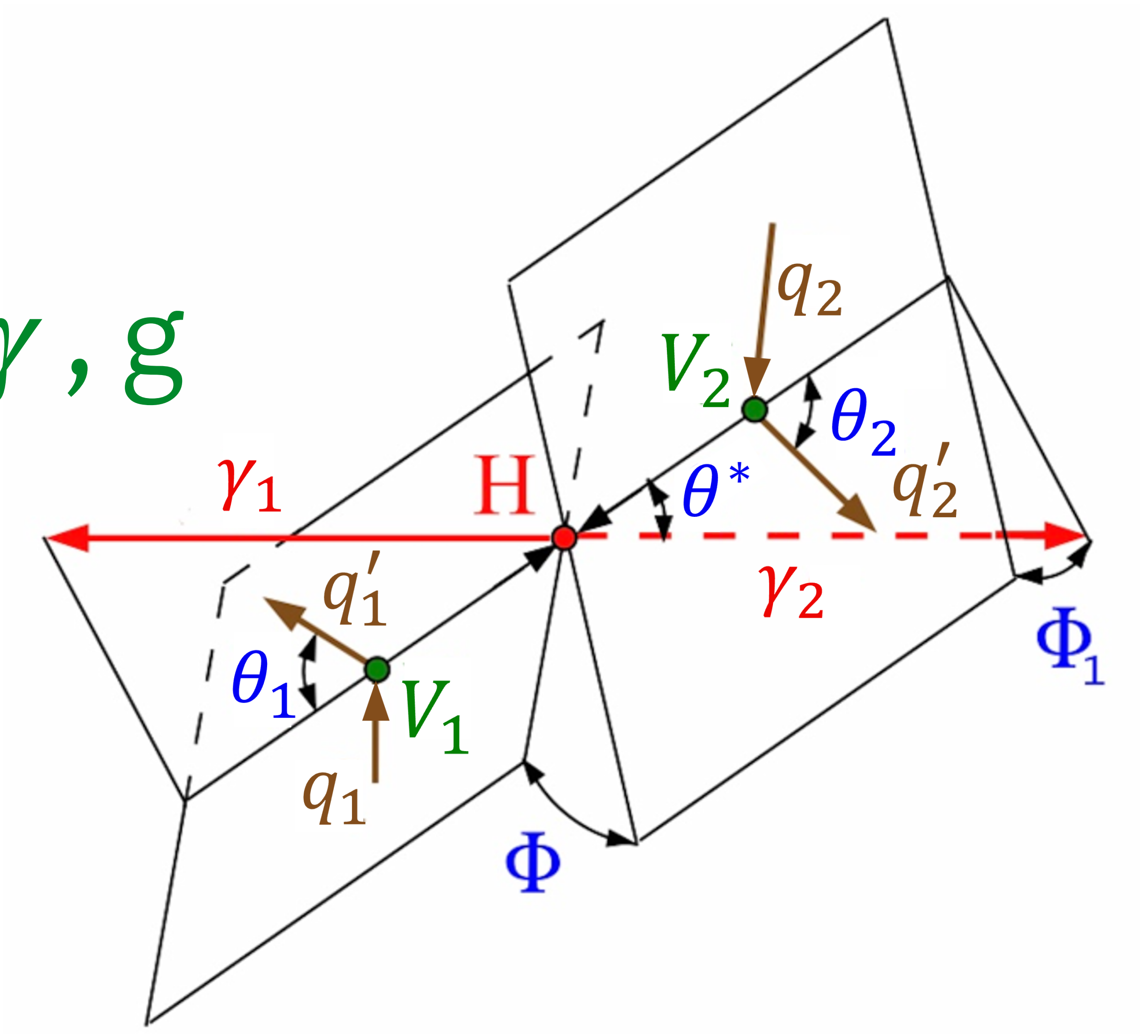
If Higgs is an admixture of CP-even ($A_{\mathrm{CP\,even}}$) and CP-odd ($A_{\mathrm{CP\,odd}}$) states, build two dedicated discriminants:

$$|A|^2 = |A_{\mathrm{CP\,even}}|^2 + 2\mathrm{Re}\left(A_{\mathrm{CP\,even}} A^*_{\mathrm{CP\,odd}}\right) + |A_{\mathrm{CP\,odd}}|^2$$

SM — **CP-sensitive** — **BSM**

V*V*→H

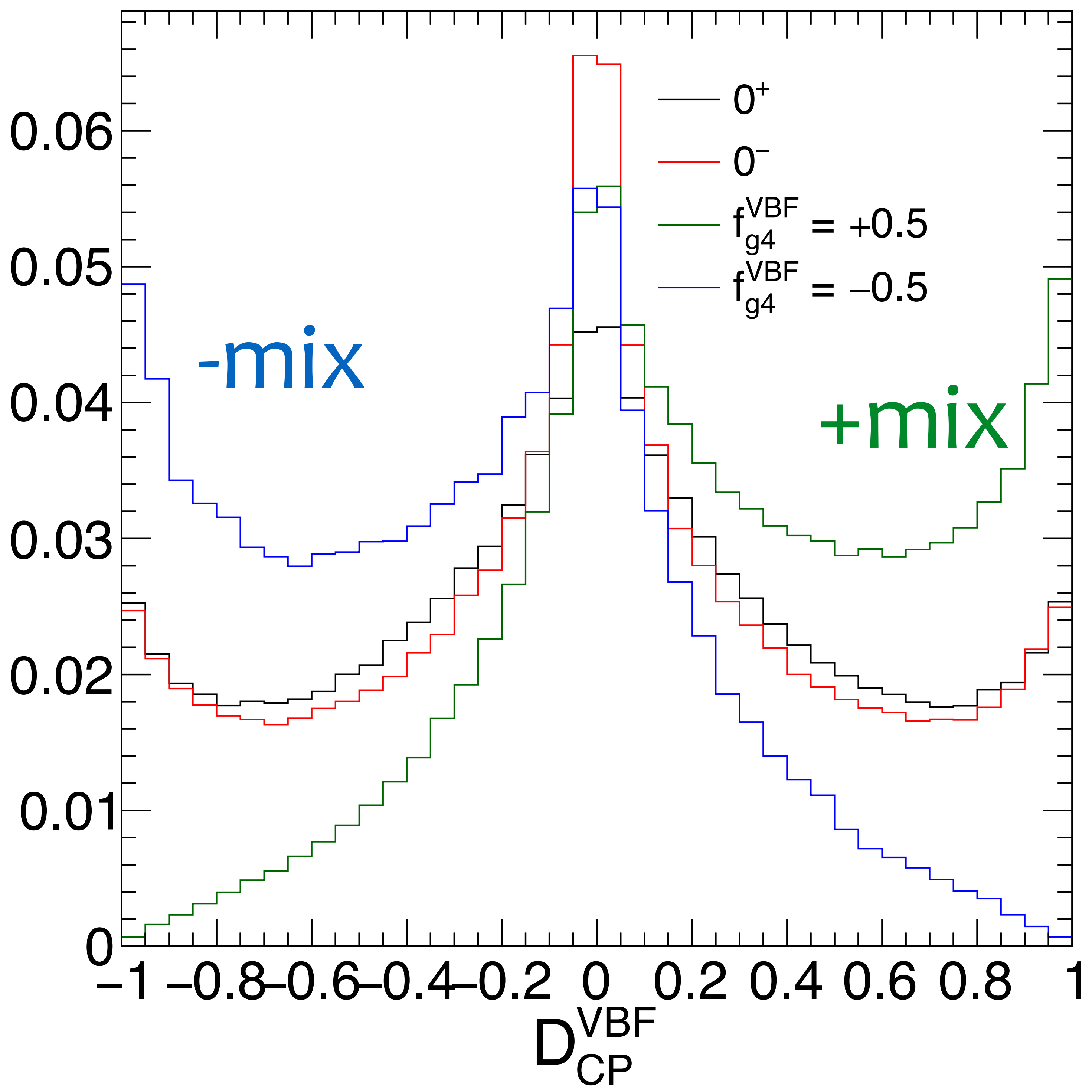
V=W , Z ,γ , g

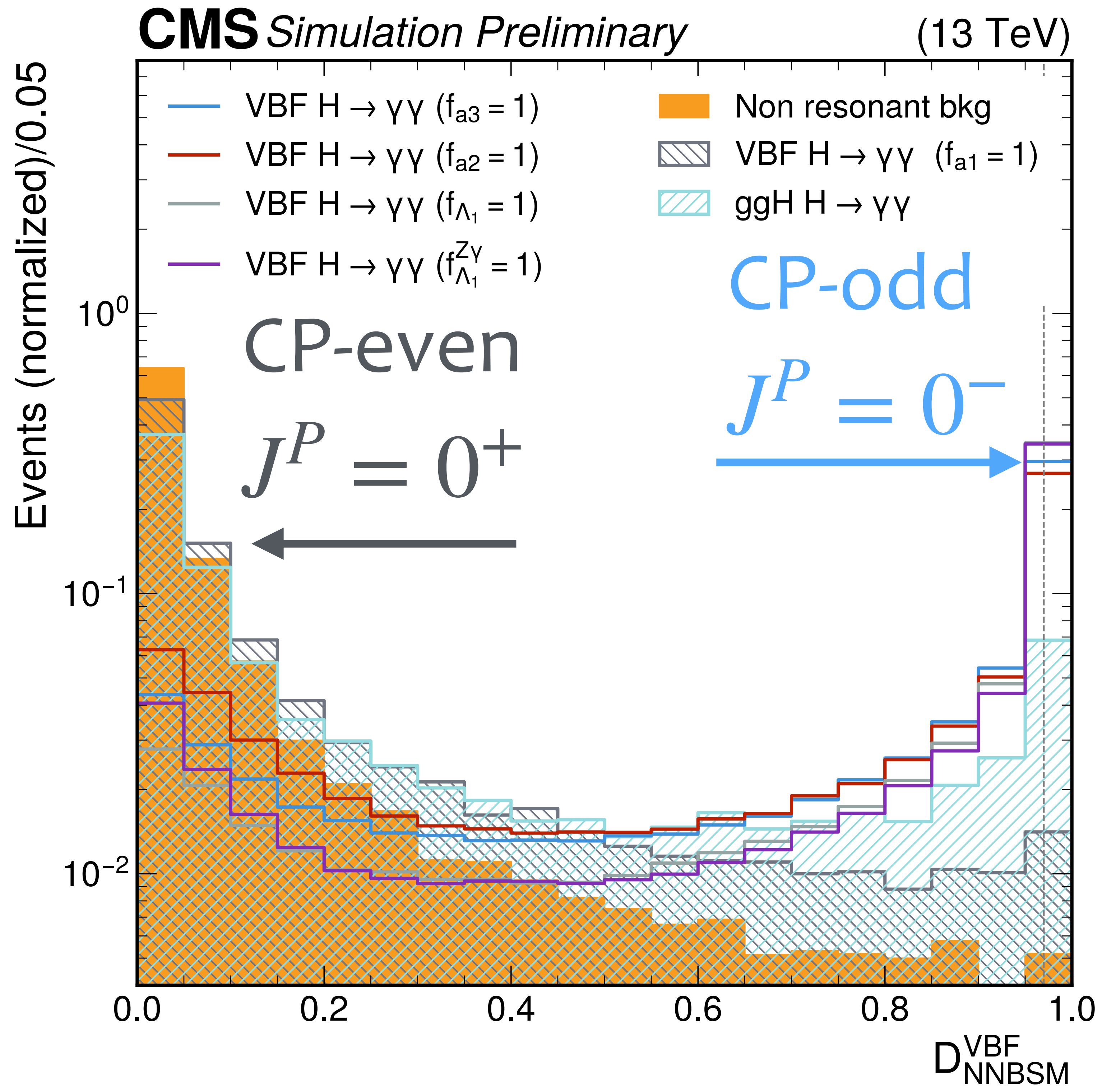


VBF production +

$H \to \gamma\gamma$ **(NEW CMS analysis)**

$H \to \tau\tau$ **(New ATLAS analysis)**



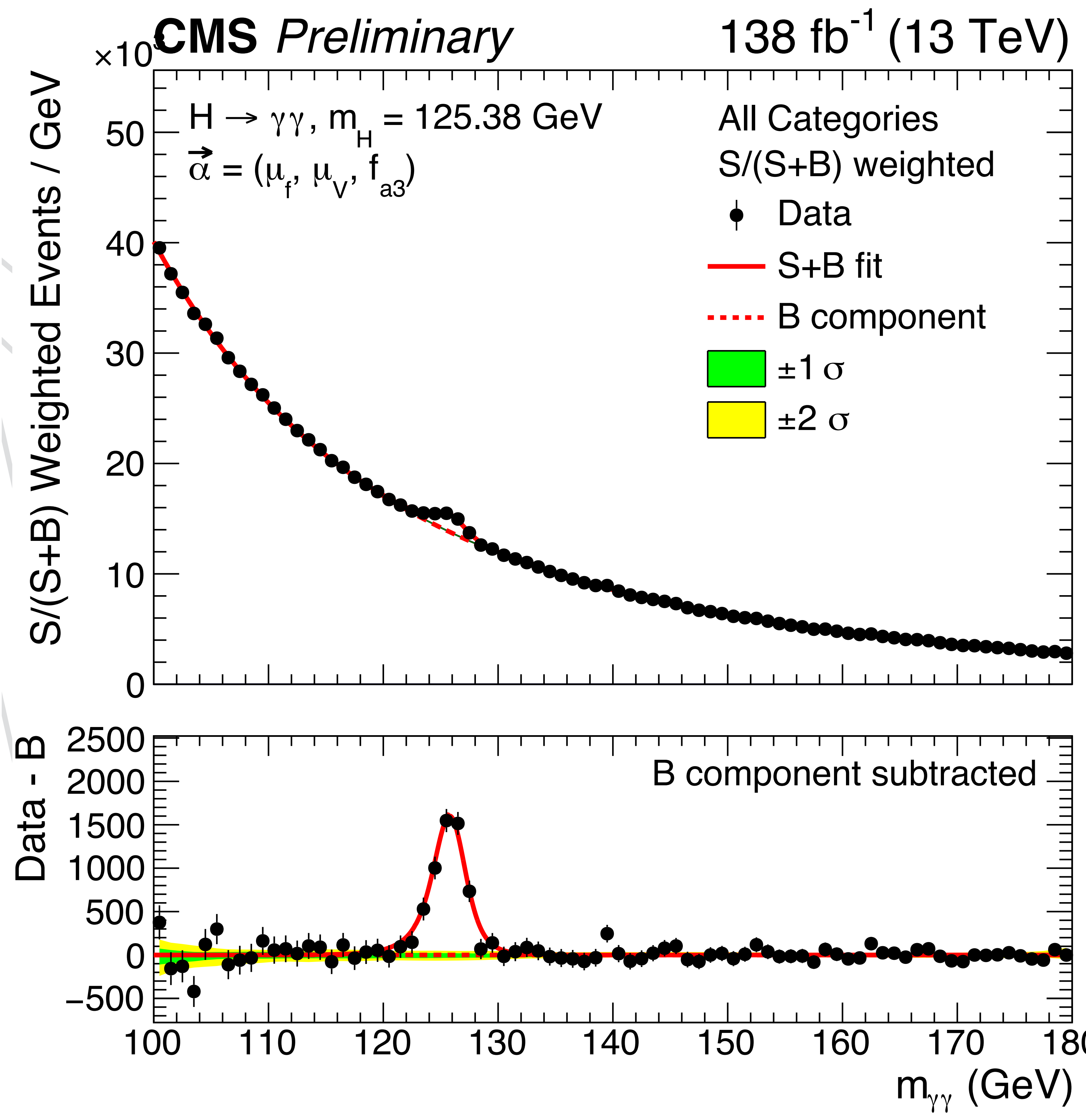


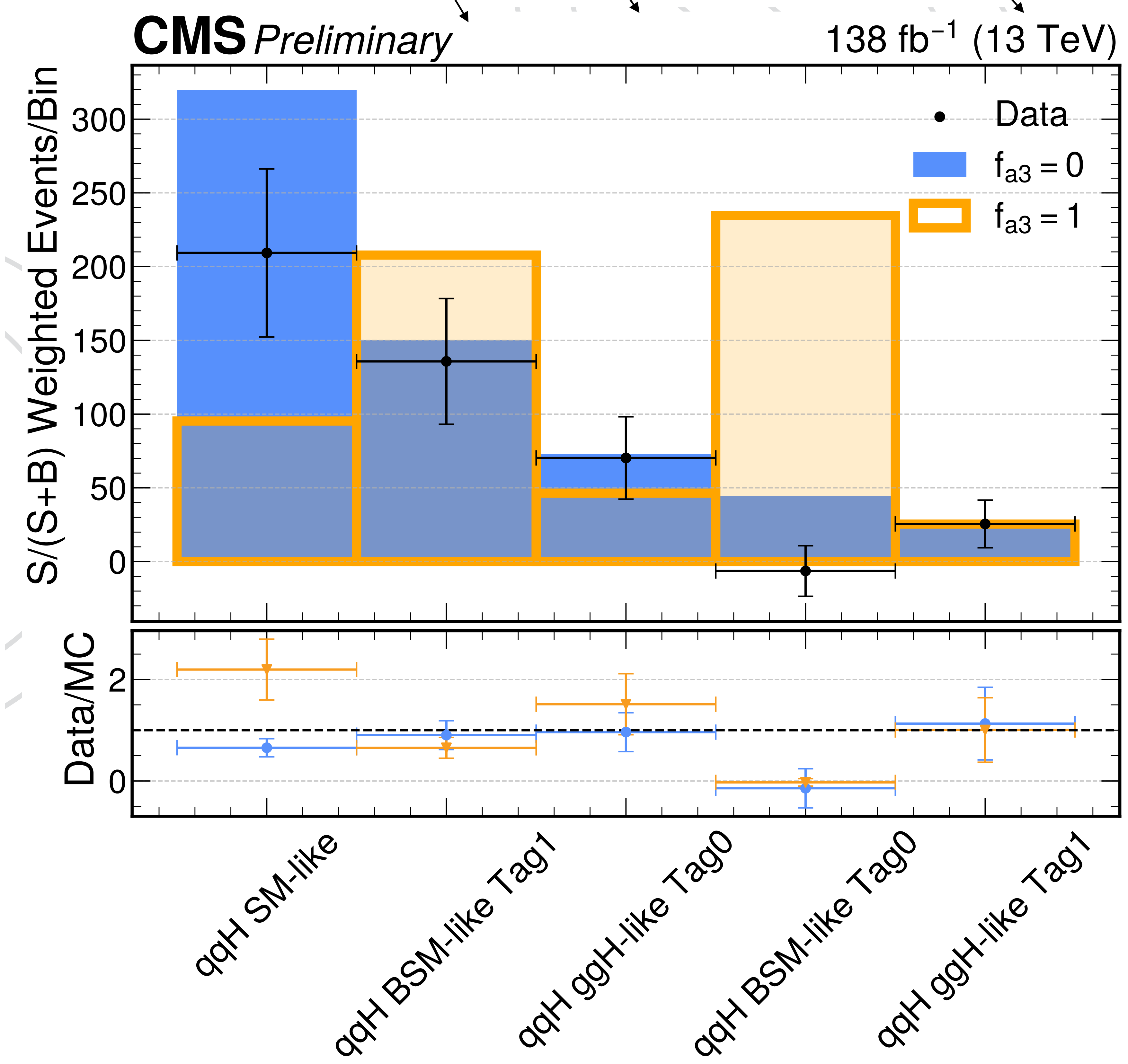
New CMS Higgs tensor structure results

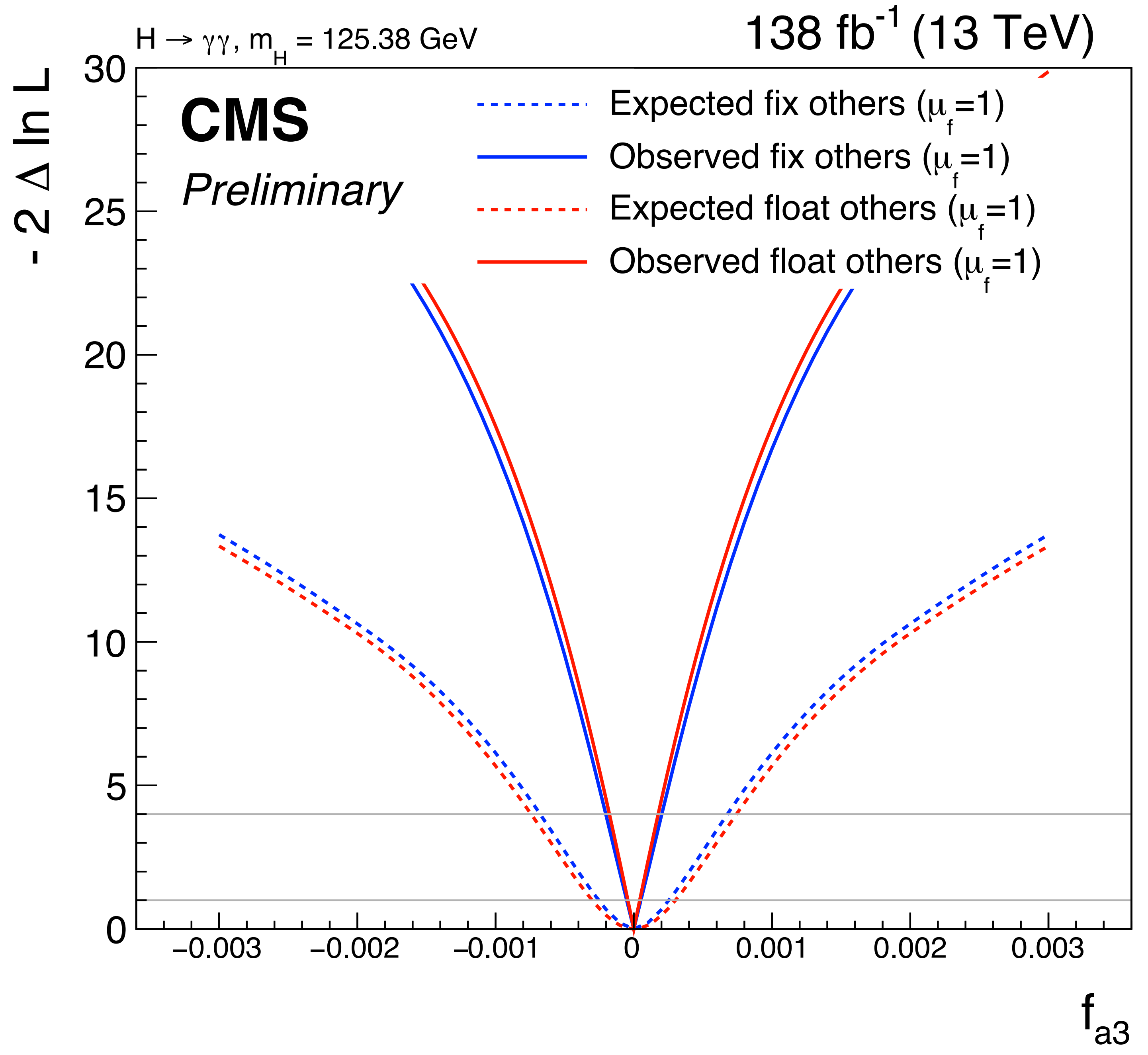
f_{ai}-sensitive categories

CMS-PAS-HIG-24-006

NEW







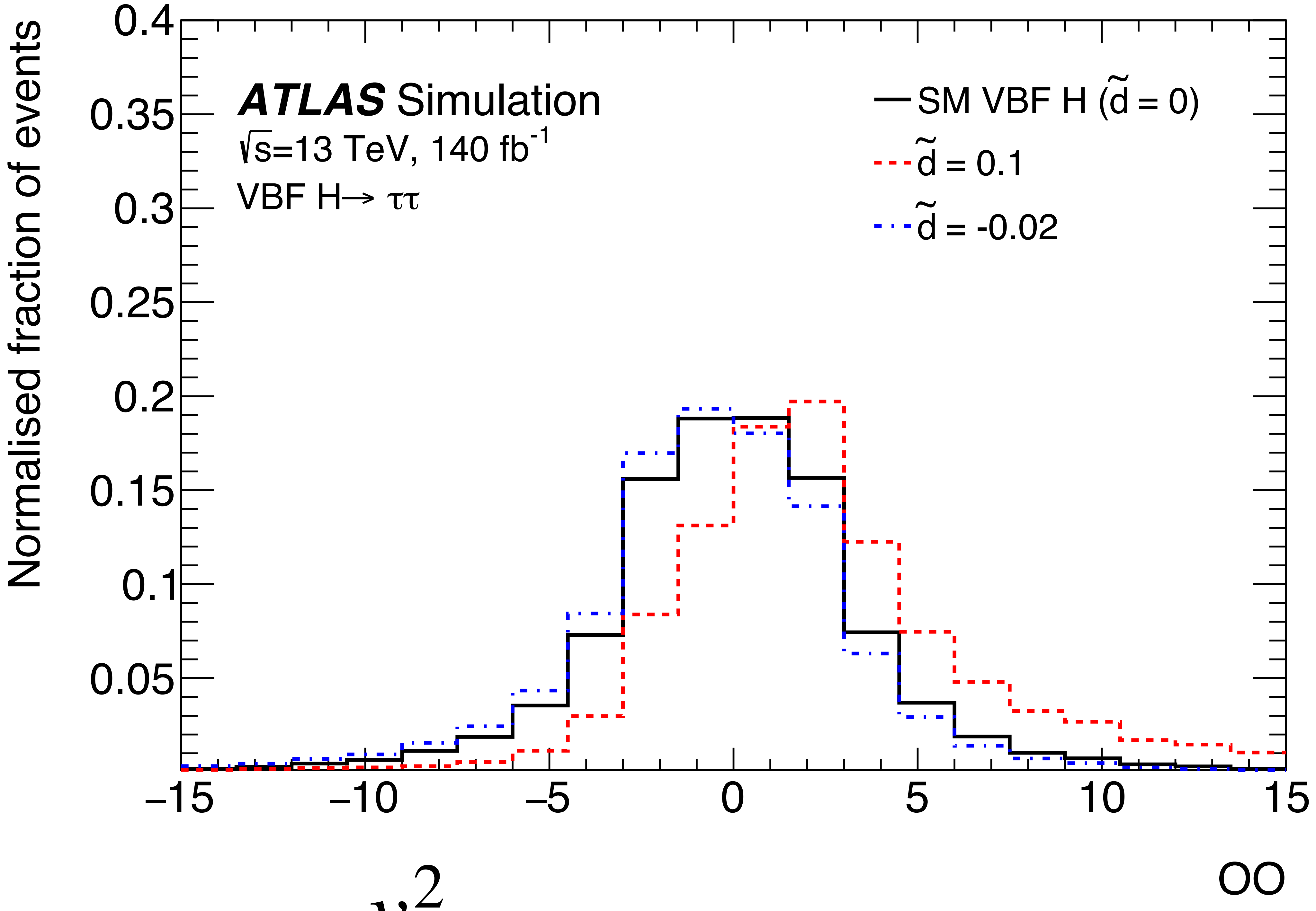
$m_{\gamma\gamma}$ fit in each category → Bkg-subtracted discriminant → xsec fraction of anomalous amplitude

ATLAS CP violation with $H \to \tau\tau$

Exploit $H \to \tau\tau$ in VBF production to test HVV interaction in production

Use the matrix element CP-sensitive "Optimal Observable" (OO) $\propto Re\left(A_{\rm CP\,even}A^*_{\rm CP\,odd}\right)$

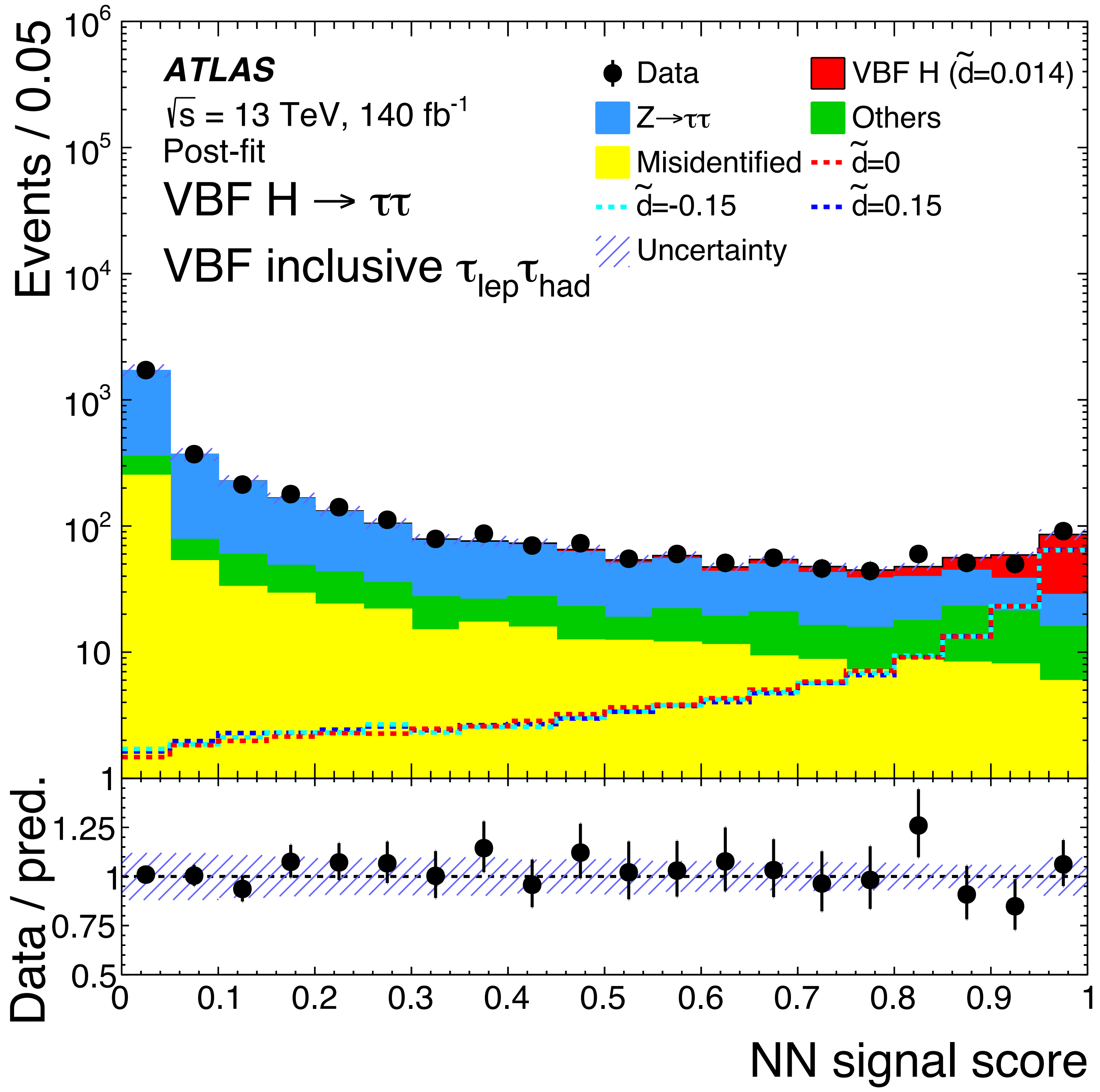
- alternative variables use the angular correlation of VBF jets $\Delta\phi_{jj}$



$$\tilde{d} = \frac{v^2}{\Lambda^2} c_{H\tilde{W}} \neq 0$$ => CP violation

Three final states: $\ell\ell, \ell\tau_h, \tau_h\tau_h$

NEW



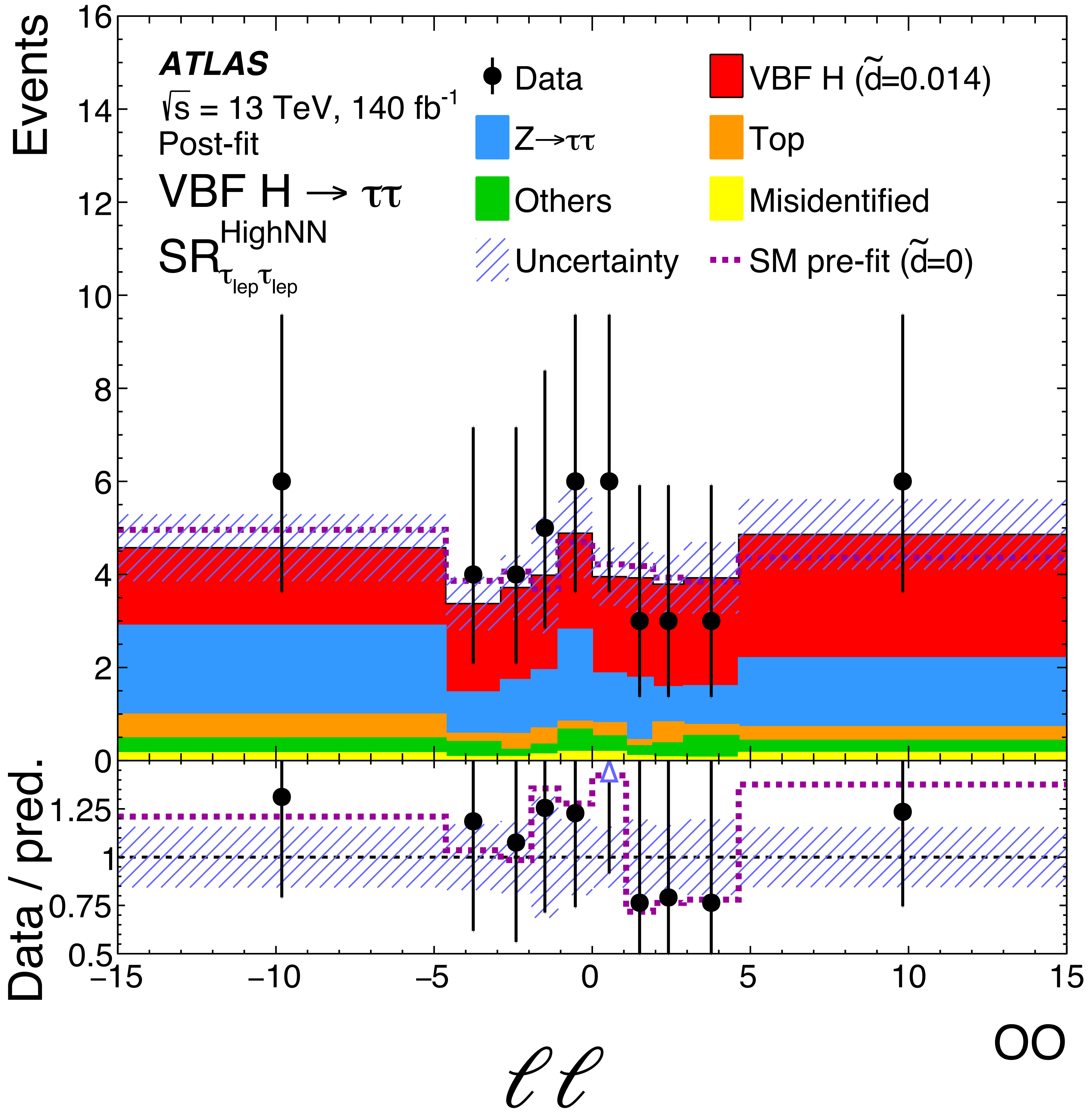
Dedicated NN to define signal and validation regions based on NN output

HIGP-2024-009

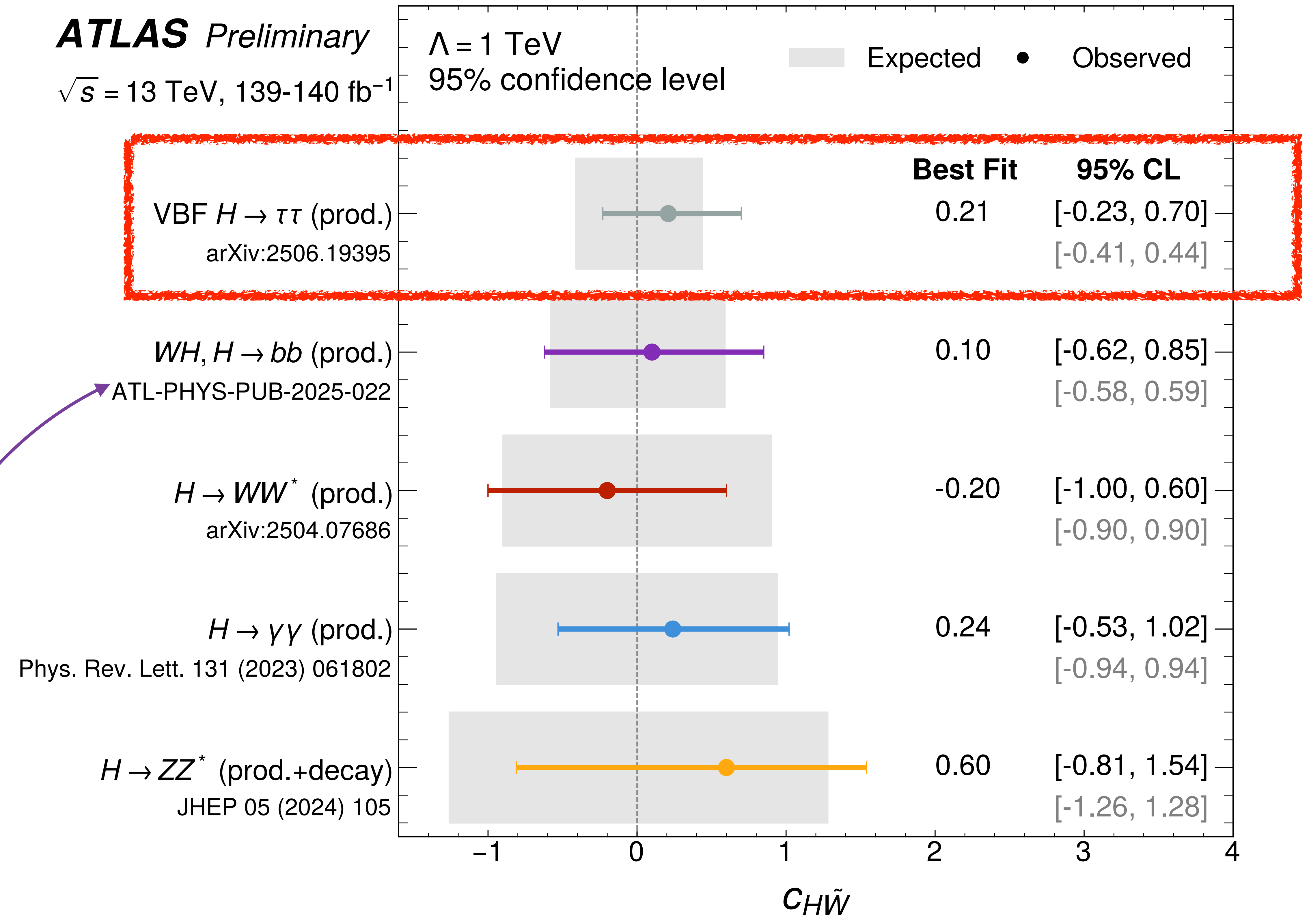
$H \rightarrow \tau\tau$ CP-sensitive distributions

Best fit OO distribution $\tilde{d} = 0.014$, [-0.012 ; 0.044] allowed range @95% CL

Well consistent with the SM $\tilde{d} = 0$



NEW



$H \rightarrow \tau\tau$ very sensitive to HVV CPV

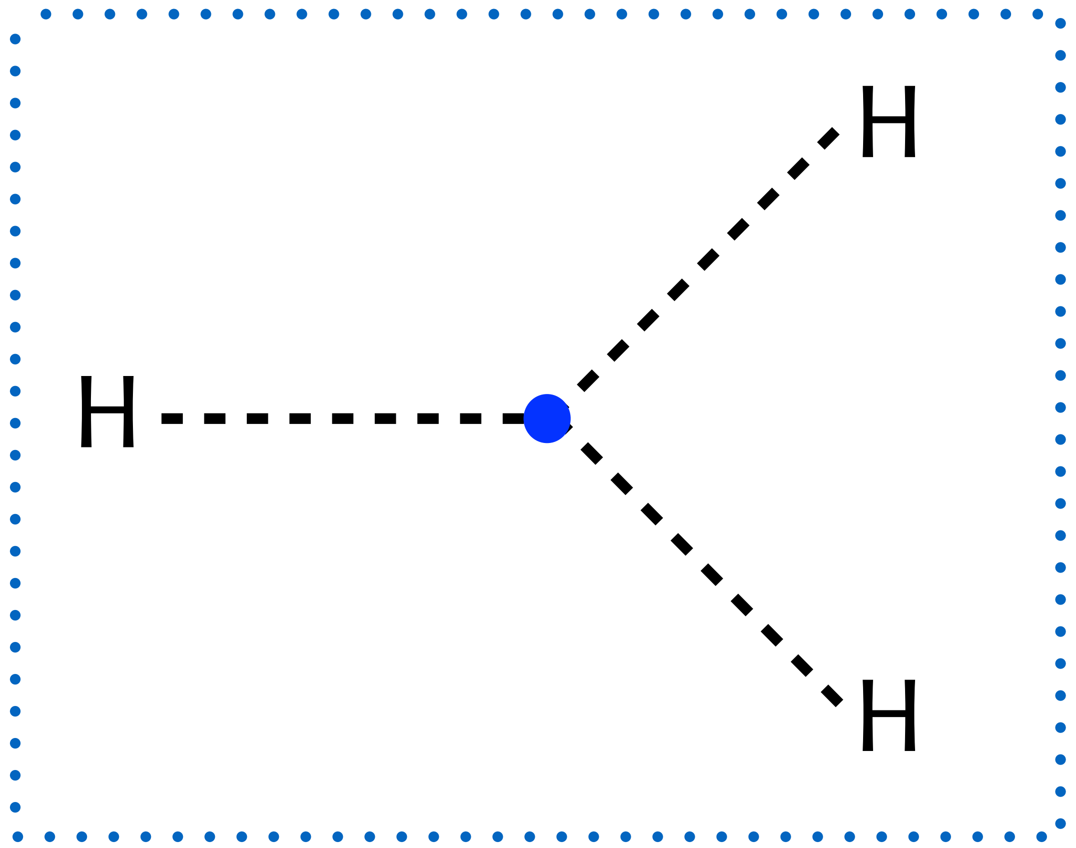
Also constrained by WH(bb): $c_{H\tilde{W}}$ in [-0.62, 0.85]

HIGP-2024-009

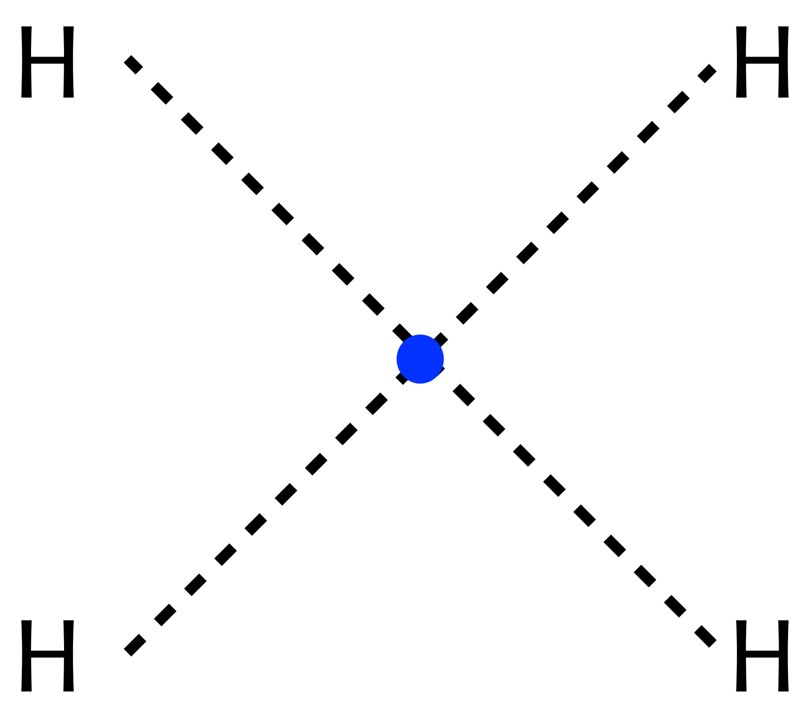
ATLAS-PHYS-PUB-2025-022

Higgs boson self coupling

H^3 ("λ_3" or simply "λ")

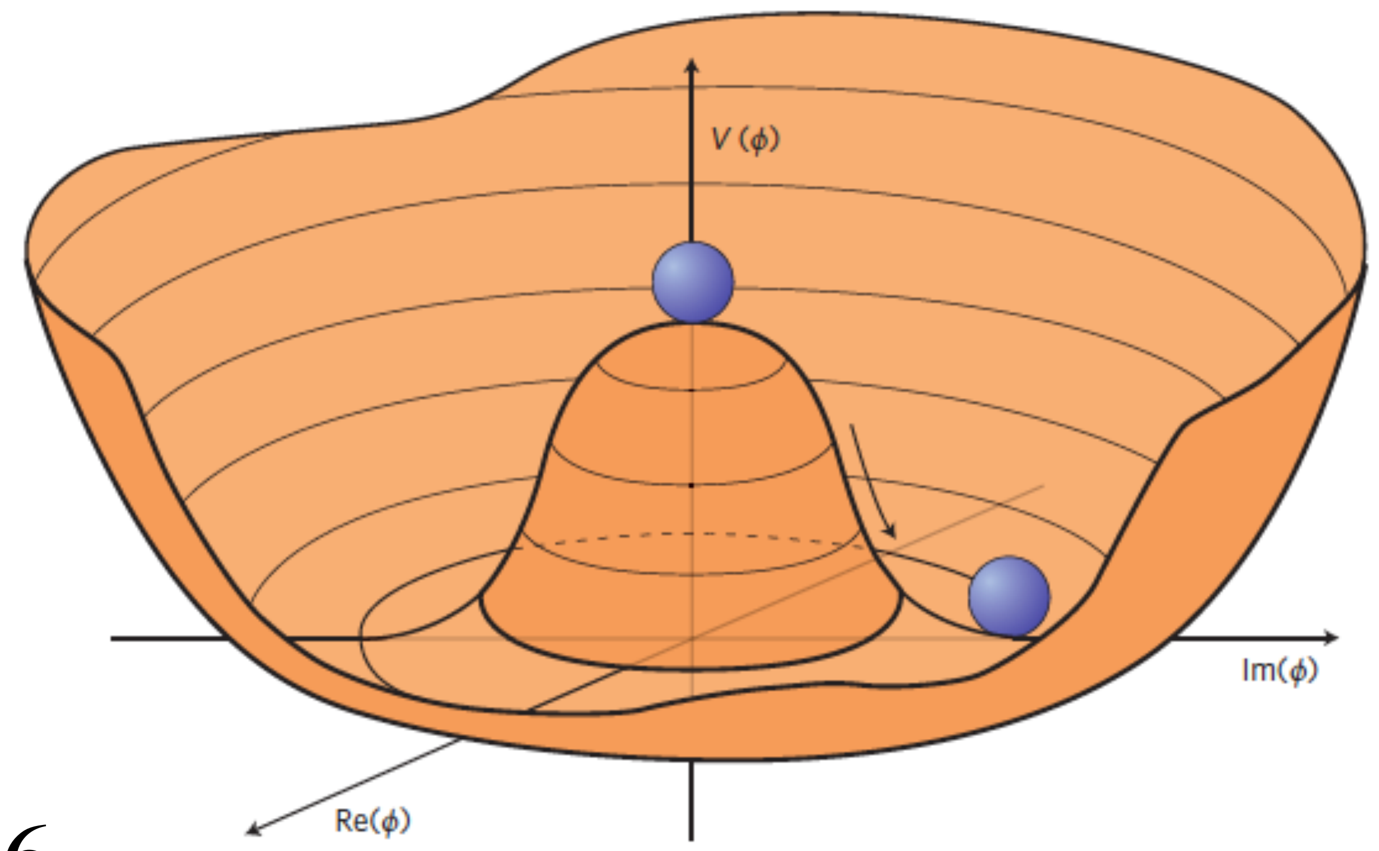


H^4 ("λ_4")



Need to measure the Higgs potential

$$V^{SM}(H) = V_0 + \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$



⇩ BSM potential at low E

$$V^{BSM}(H) = V_0 + \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + \frac{\lambda_5}{v}H^5 + \frac{\lambda_6}{v^2}H^6 + \cdots$$

In EFTs, adding dimension-6 (BSM at scale E>Λ), the λ_i are not independent:

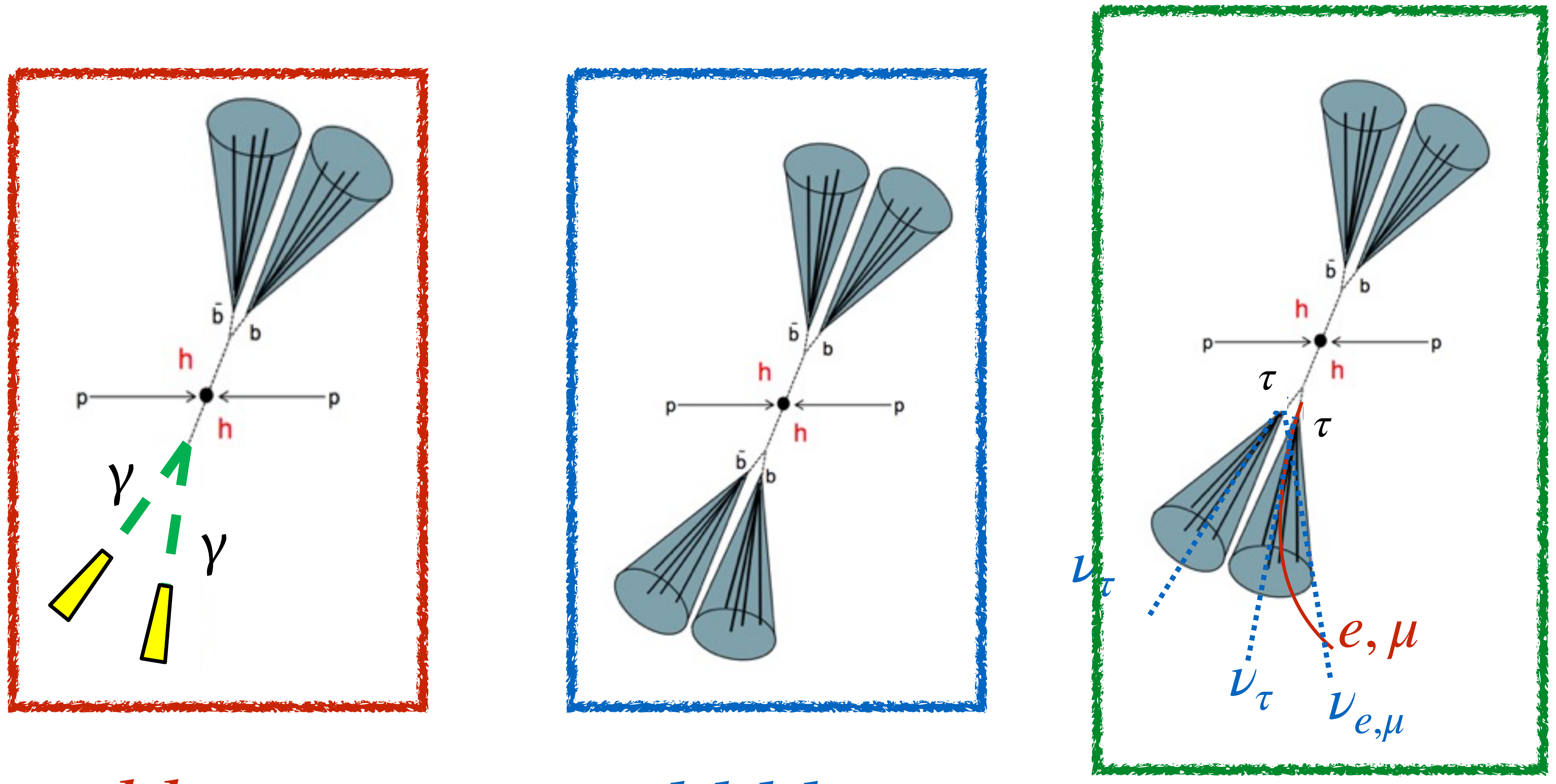
$$\lambda_3 = \lambda\left(1 + c_6\frac{2v^4}{m_H^2\Lambda^2}\right) \equiv \lambda(1 + \bar{c}_6)$$

A measure of $\bar{c}_6 \neq 0$ (e.g. **via HH rate**) **hint of 1st phase transition (Sakharov condition for $\mathrm{n_B} \gg \mathrm{n_{\bar{B}}}$)**

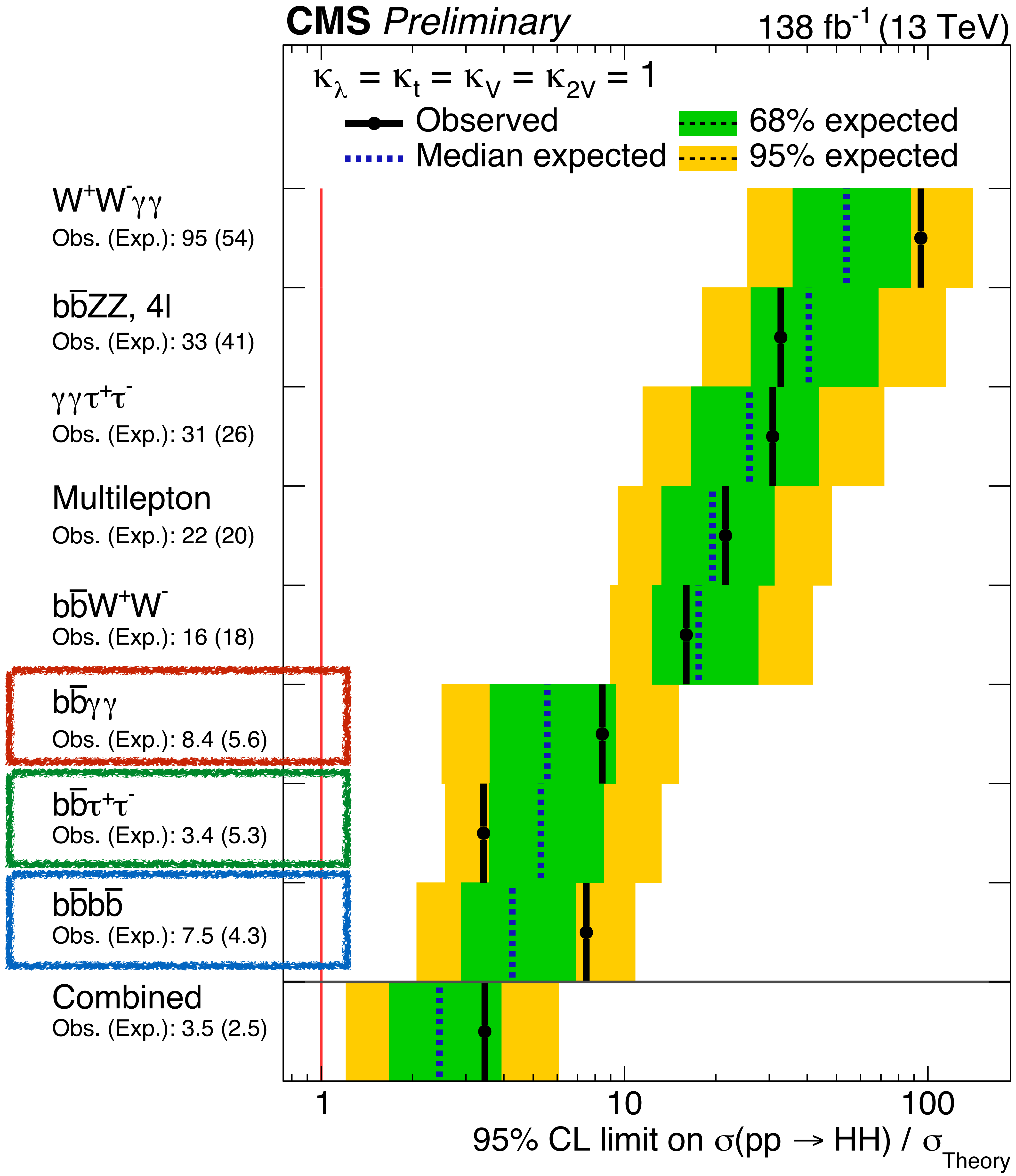
But: **HH is an extremely rare** process at LHC: $\sigma_{\mathrm{ggHH}} < \frac{\sigma_{\mathrm{ggH}}}{1000}$ (34 fb @ $\sqrt{s} = 13.6$ TeV)

HH upper limits from Run2 legacy

Three "silver" channels: $bb\gamma\gamma$, $4b$, $bb\tau\tau$



$bb\gamma\gamma$ $bbbb$ $bb\tau\tau$

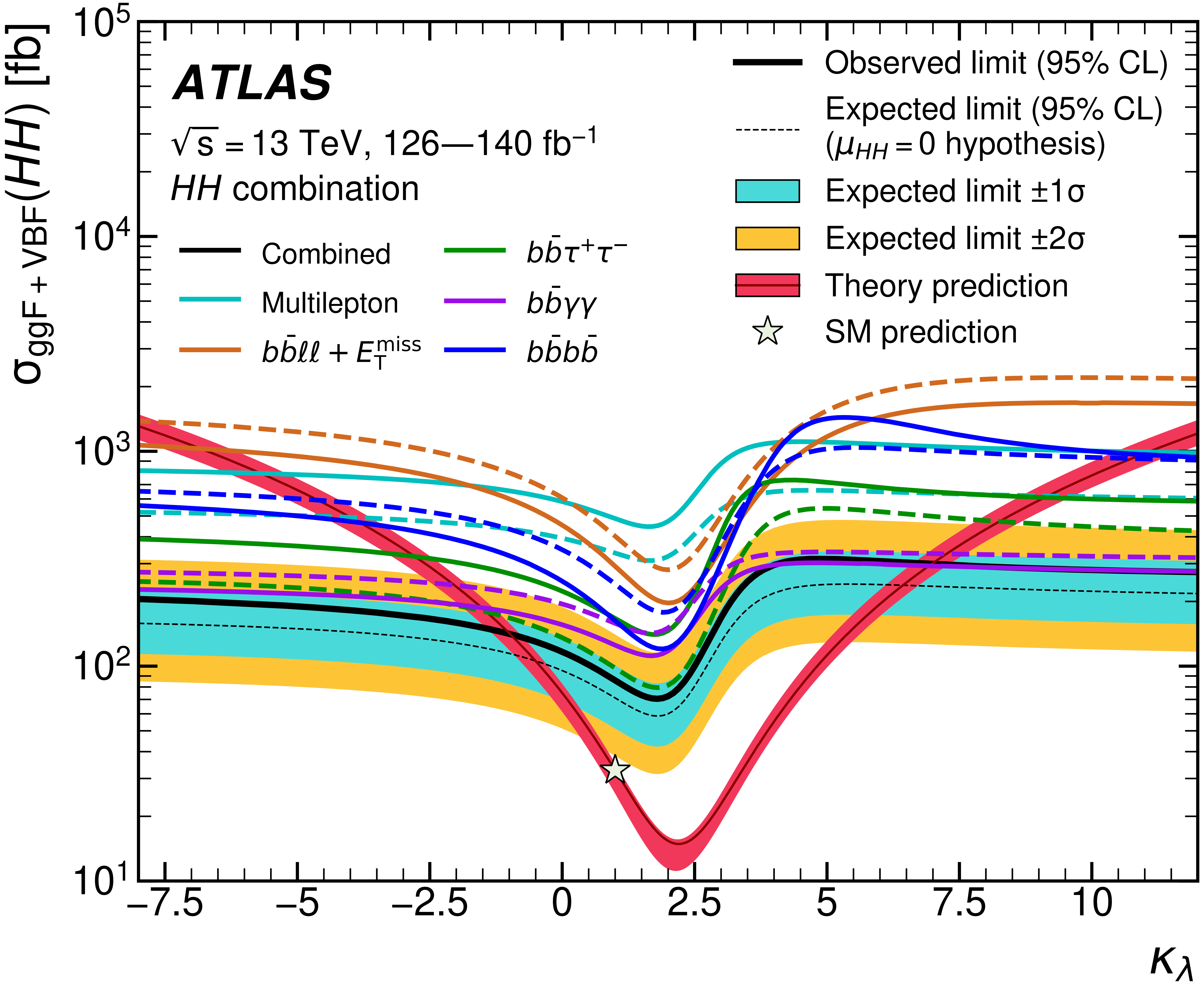


Current upper limit on $\sigma(HH)$ **~3 x SM cross section from both ATLAS and CMS**

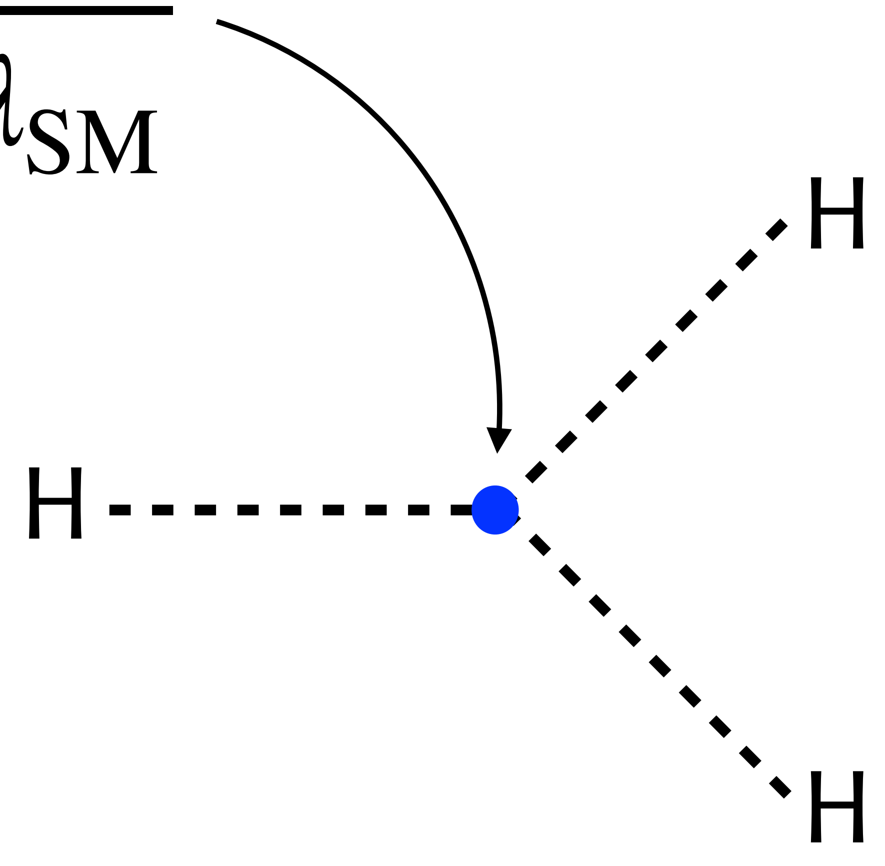
CMS-PAS-HIG-20-011

ATLAS: PRL 133 (2024) 101801

Higgs self-coupling (Run2 legacy)



$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$



most stringent 95% CLs on Higgs boson self-coupling from HH:

$$-1.2 < \kappa_\lambda < 7.2 \text{ (ATLAS)}$$

$$-1.39 < \kappa_\lambda < 7.02 \text{ (CMS)}$$

CMS-PAS-HIG-20-011

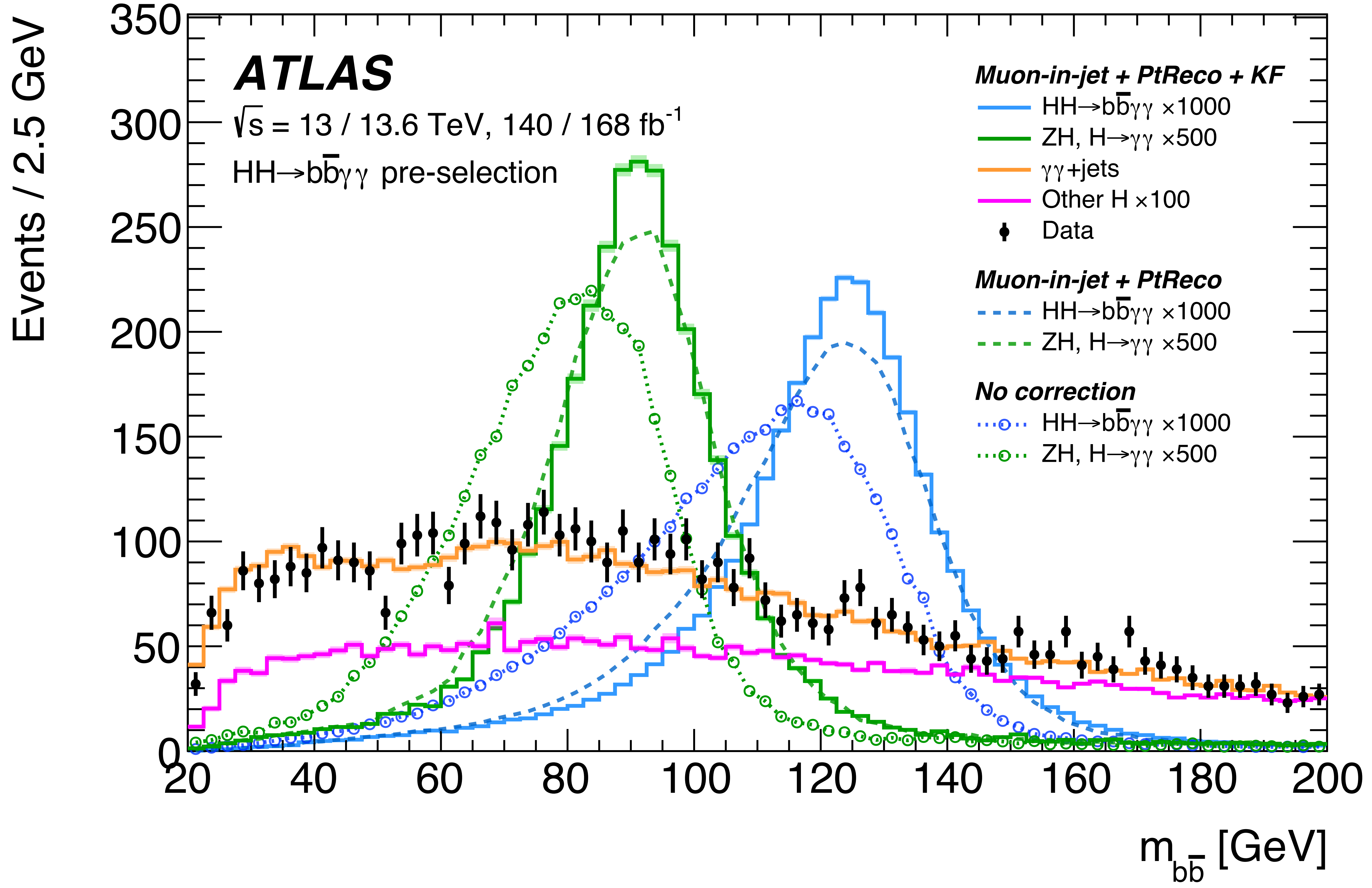
ATLAS: PRL 133 (2024) 101801

Pioneering Run3 data: ATLAS $HH \to b\bar{b}\gamma\gamma$

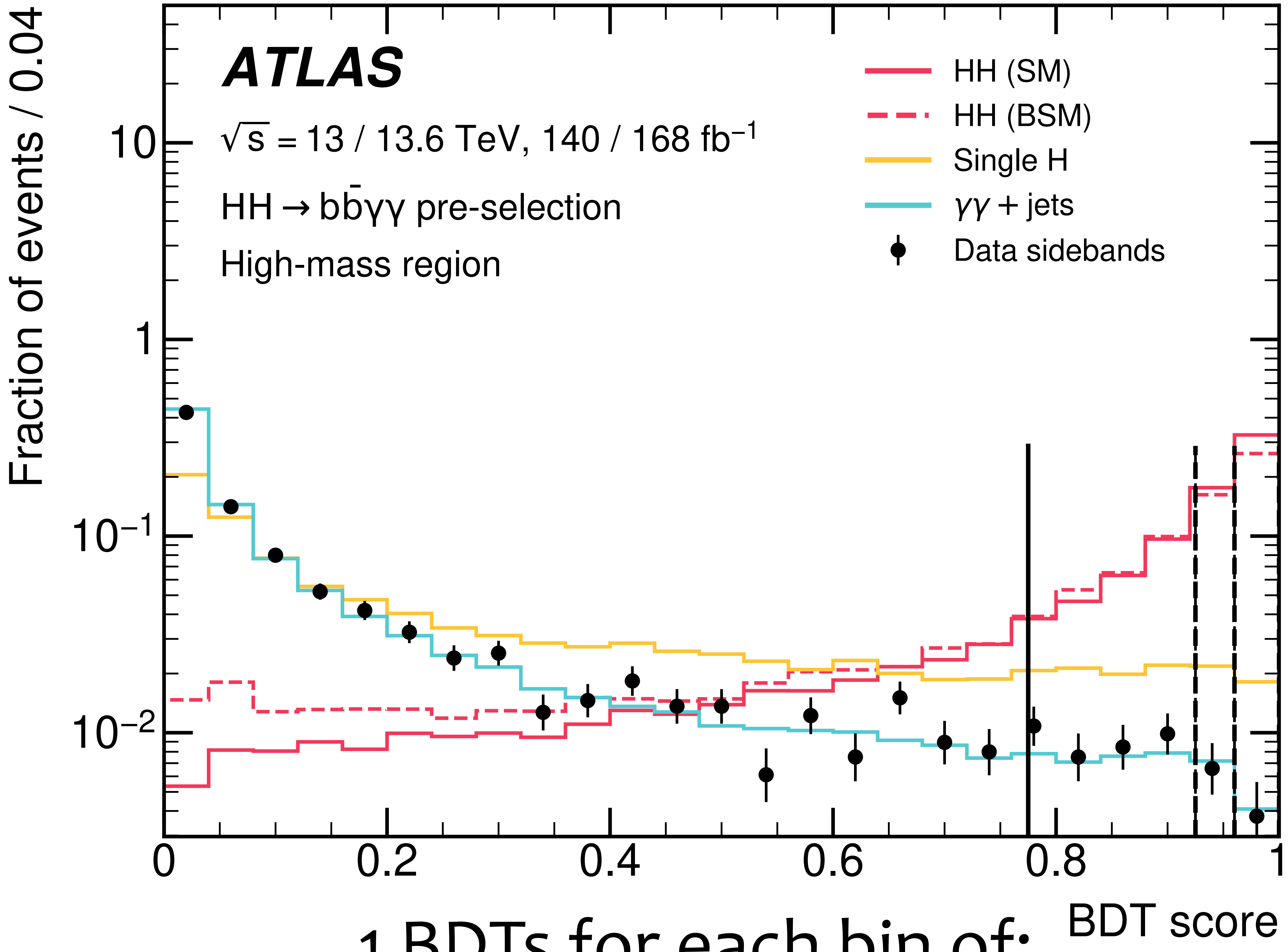
Re-analysis of Run2-[15-18] (140 fb-1) and Run3-[22-24] (168 fb-1) with several improvements:

- Use new ML (transformers) b-tagging
- Kinematic fits (KF) to improve $m(b\bar{b})$ and $m(b\bar{b}\gamma\gamma)$ resolution
- Improved categorisation m_{HH}-dependent

HIGP-2025-010



Up to 17% improvement in $m(bb)$ resolution with the KF



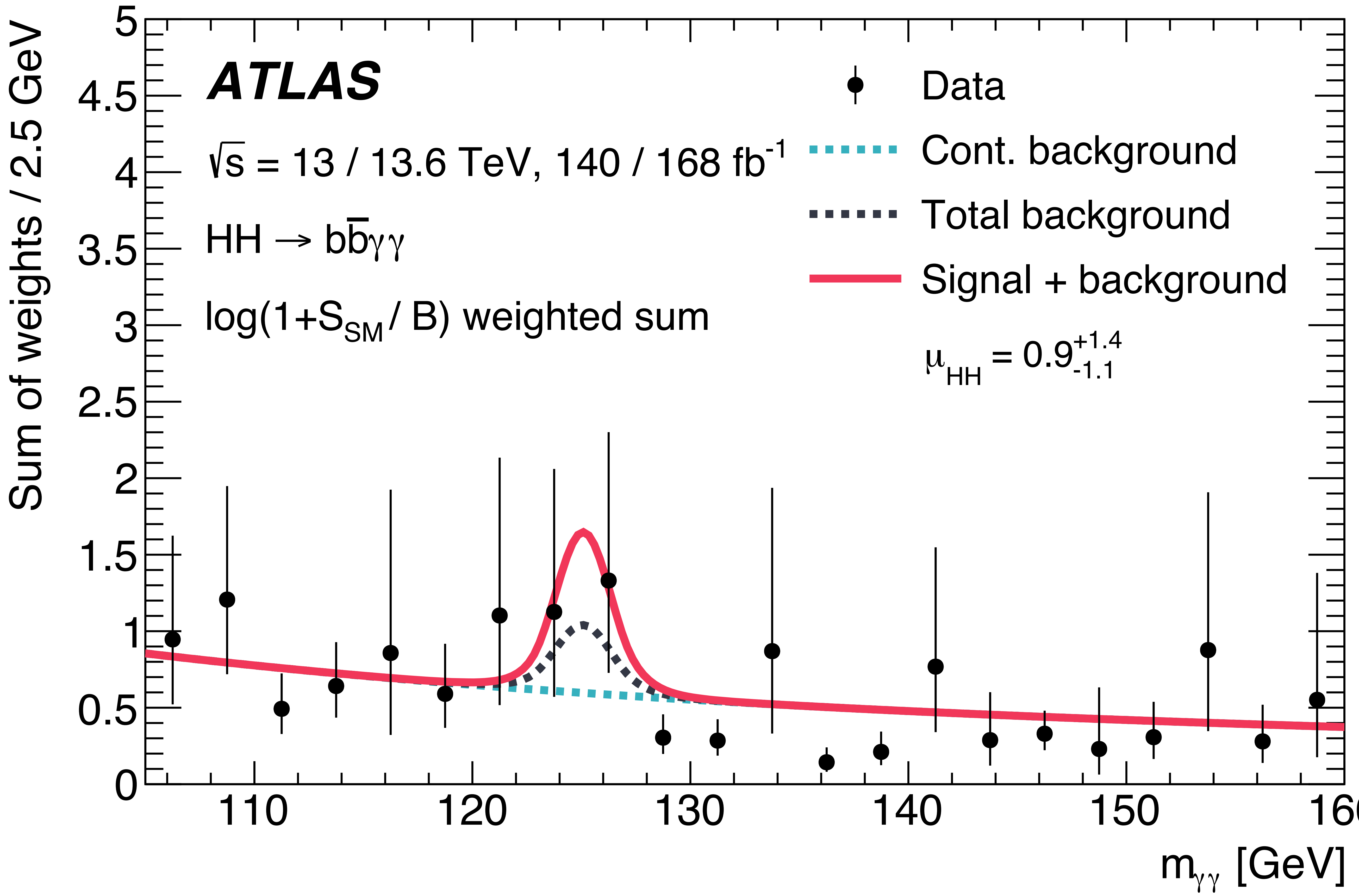
1 BDTs for each bin of:

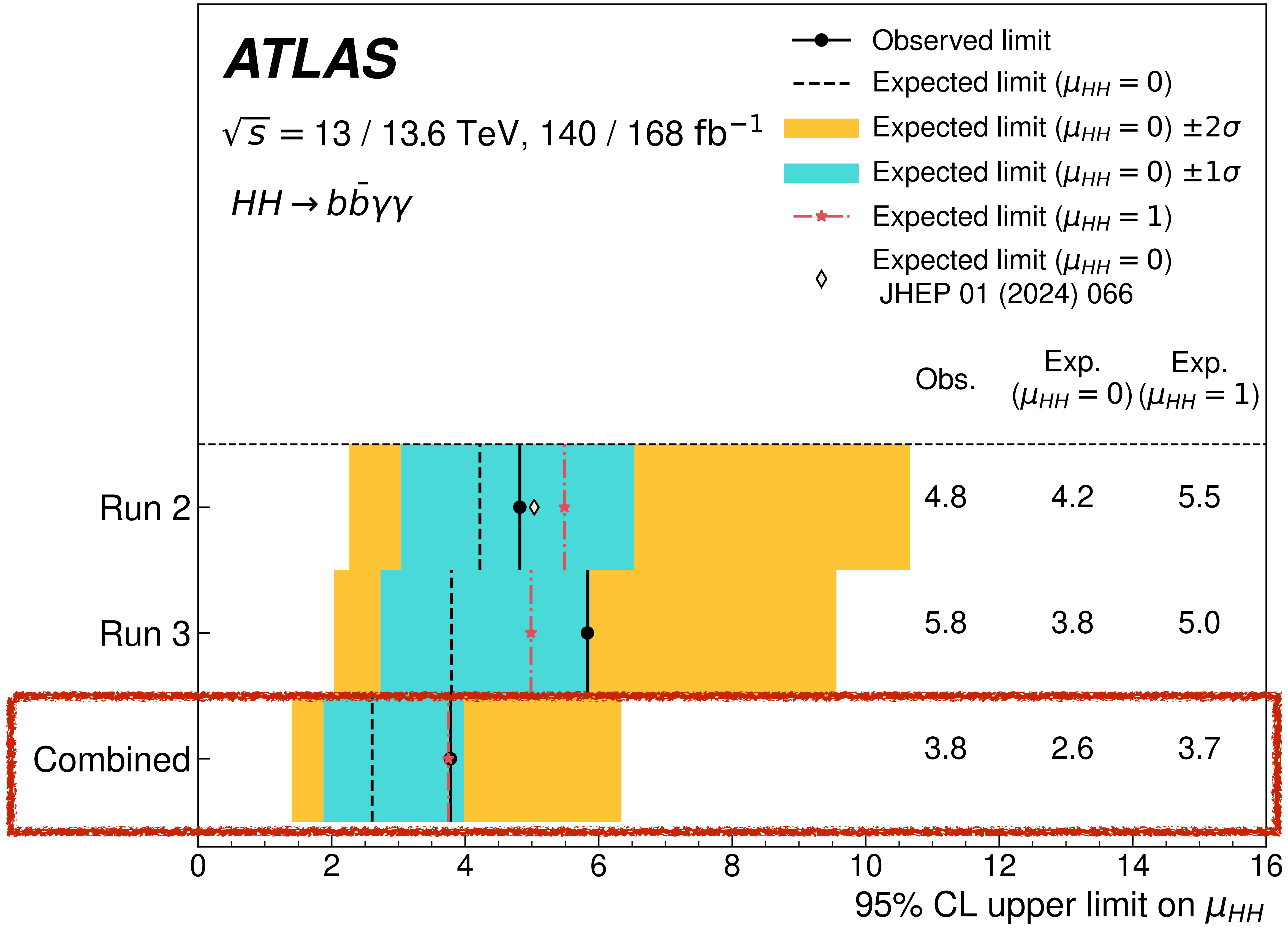
$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - m_H) - (m_{\gamma\gamma} - m_H)$$

$HH \to b\bar{b}\gamma\gamma$ results on 308 fb^{-1}

Resonant background from single-Higgs e.g. ttH($\gamma\gamma$)

HIGP-2025-010





Combined **Run2+Run3** UL is $\mu_{HH} < 3.8$, approaching the Run2 legacy combination

Limits on H self coupling: $-1.7 < \kappa_\lambda < 6.6$ @ 95% CL

Pushing further: triple-Higgs

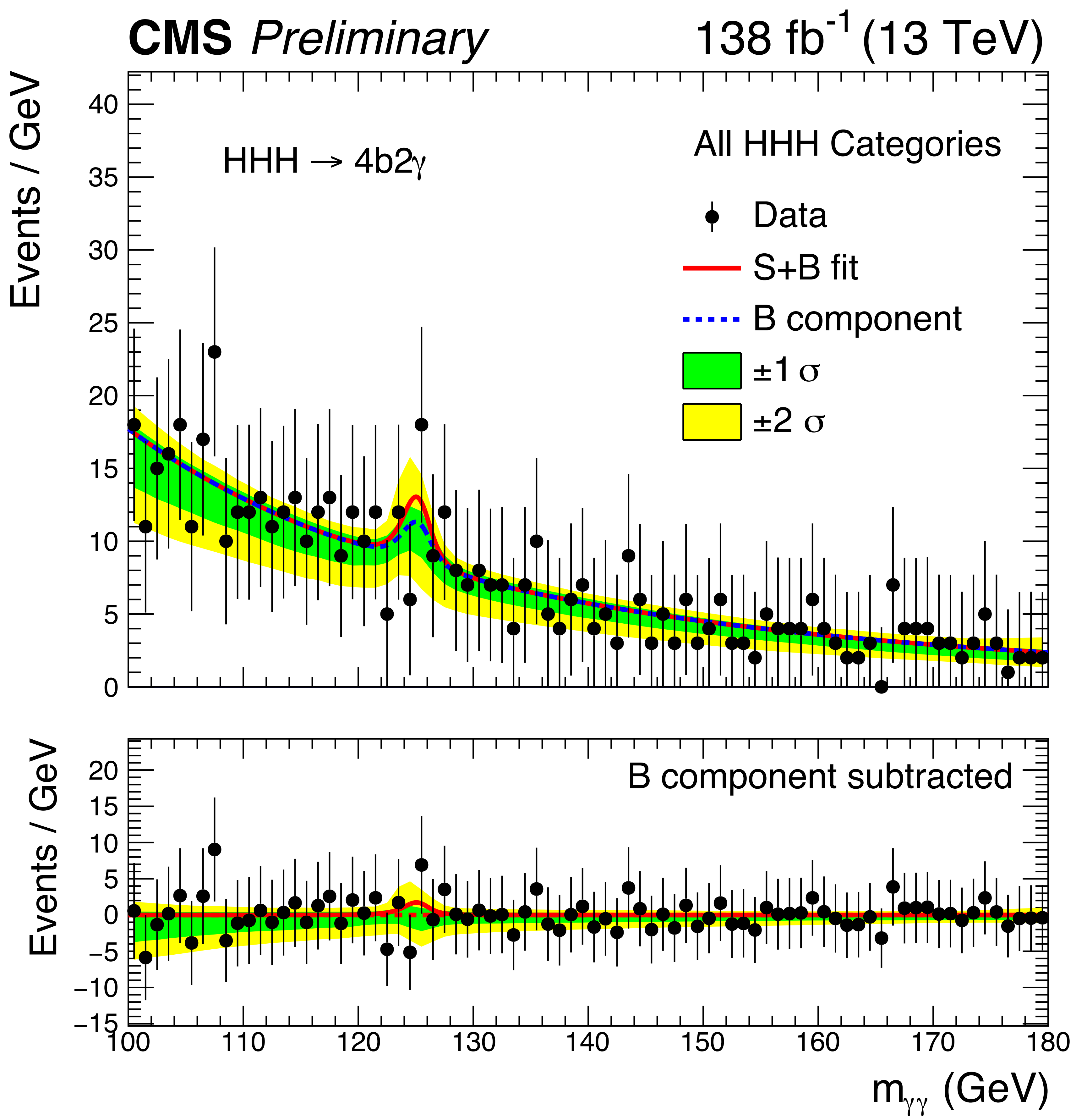
Tri-Higgs (HHH) production sensitive to both λ_3 and λ_4

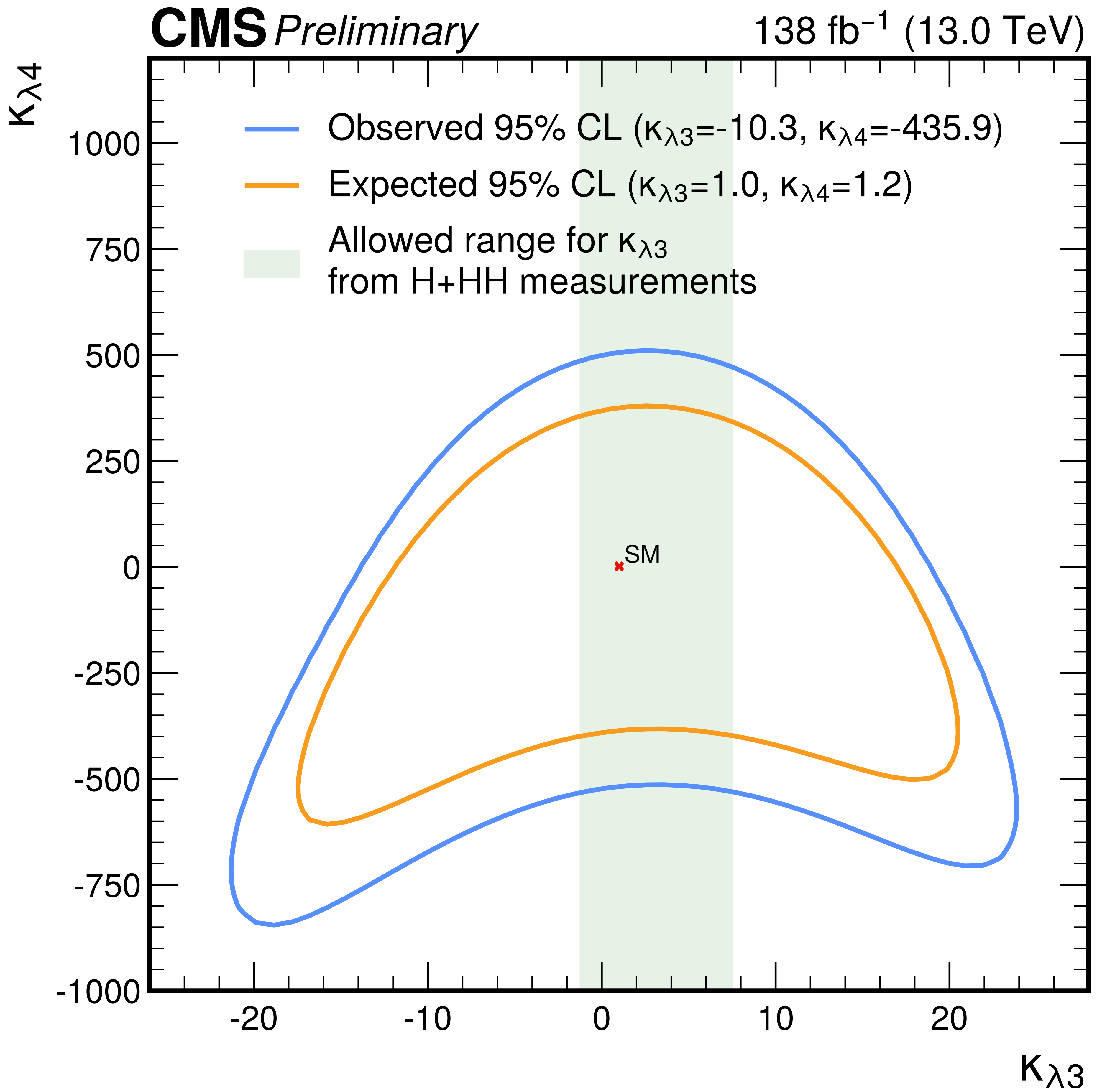
Recent ATLAS measurements: HHH → 6b (PhysRevD.111.032006)

CMS new Run-2 analysis of $HHH \to 4b2\gamma$ **ultra-rare: $\sigma \times \mathscr{B} \sim 0.2$ ab**

CMS-PAS-HIG-24-015

NEW





μ_{HHH} < 3400 (2086 exp.)

- Stronger dependence of HHH cross section from λ_3 than λ_4
- Green area: constraints from H+HH

Summary

- The **LHC Run2 and Run3** data used to fully characterize the Higgs boson
  - mass measured with **0.1% precision**, and width with **50% precision**
  - production cross sections measured differentially in many decay bins, in all production modes
  - fiducial cross sections and coupling modifiers measured at **5-10% level inclusively**
  - couplings to 2nd generation evidence with $H \to \mu^+\mu^-$, next challenge is $H \to c\bar{c}$
  - CP violation studied in many channels
  - H self-coupling constrained from direct searches for **HH production** and **single-H** and **HHH**

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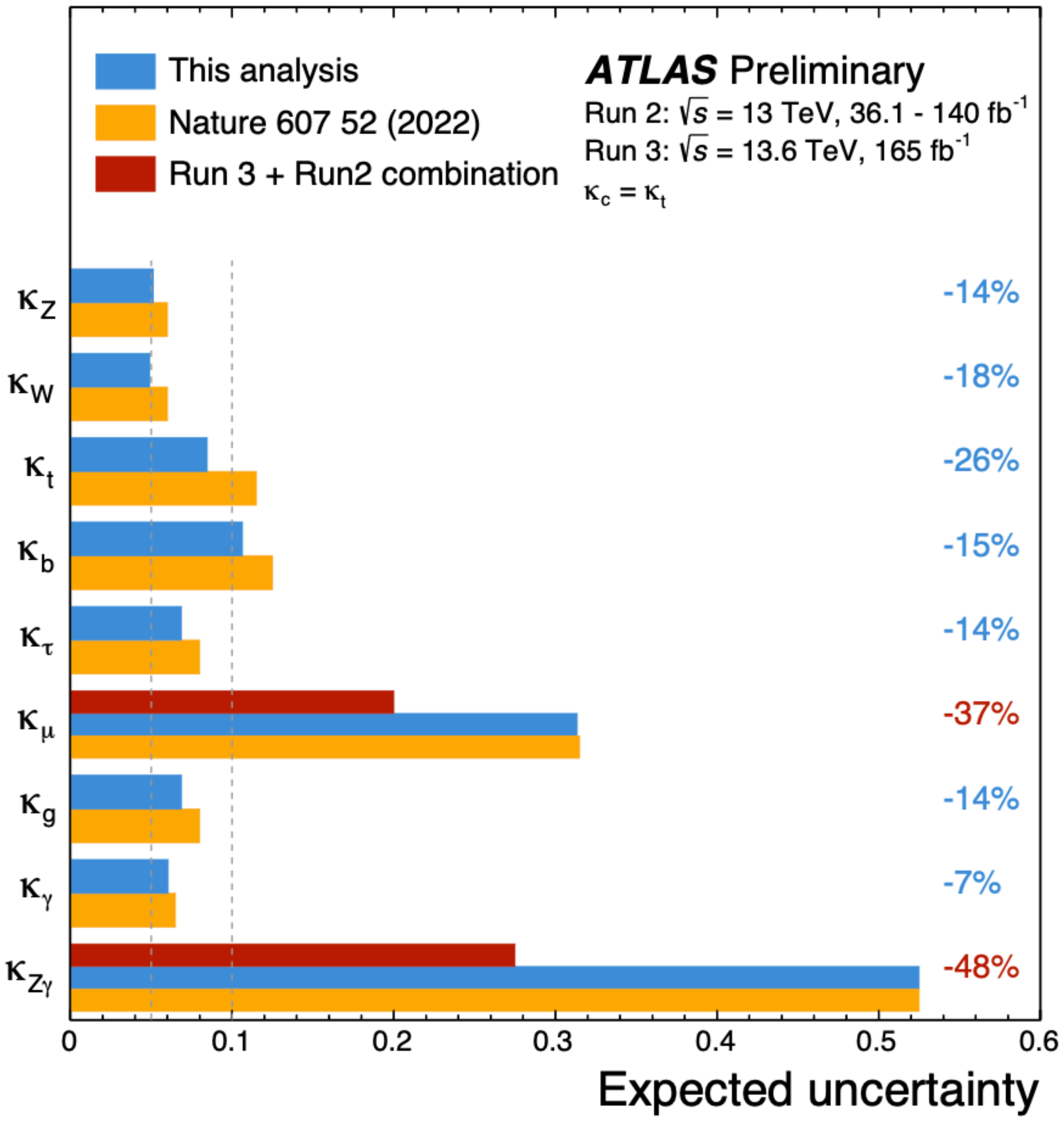
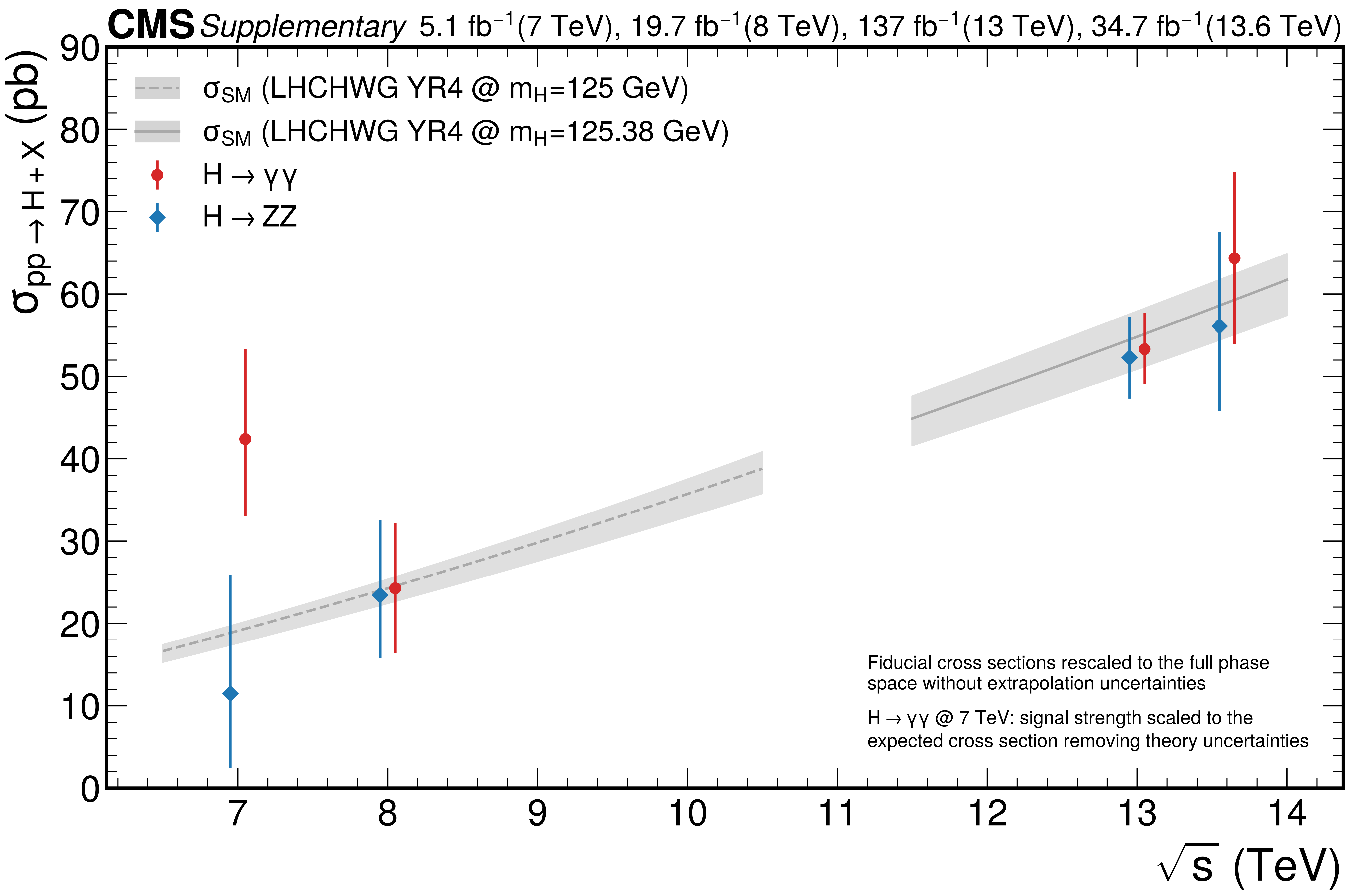
- **LHC Phase-1 dataset at the end of data taking will be ~0.5 ab^{-1} per experiment**
  - a unique opportunity to precisely characterise the Higgs potential

- **After the end of Run3**:
  - Expect **20x more data** by the end of HL-LHC
  - Expect improvements from analysis techniques to **boost new physics search in the Higgs sector**

Summary: LHC is delivering data !





LHC Run3 boosts all Higgs results!

Current run is key for precision and discovery !

THANK YOU !

Backup

Anomalous couplings in $H \to \gamma\gamma$ (CMS)

CMS-PAS-24-006

NEW

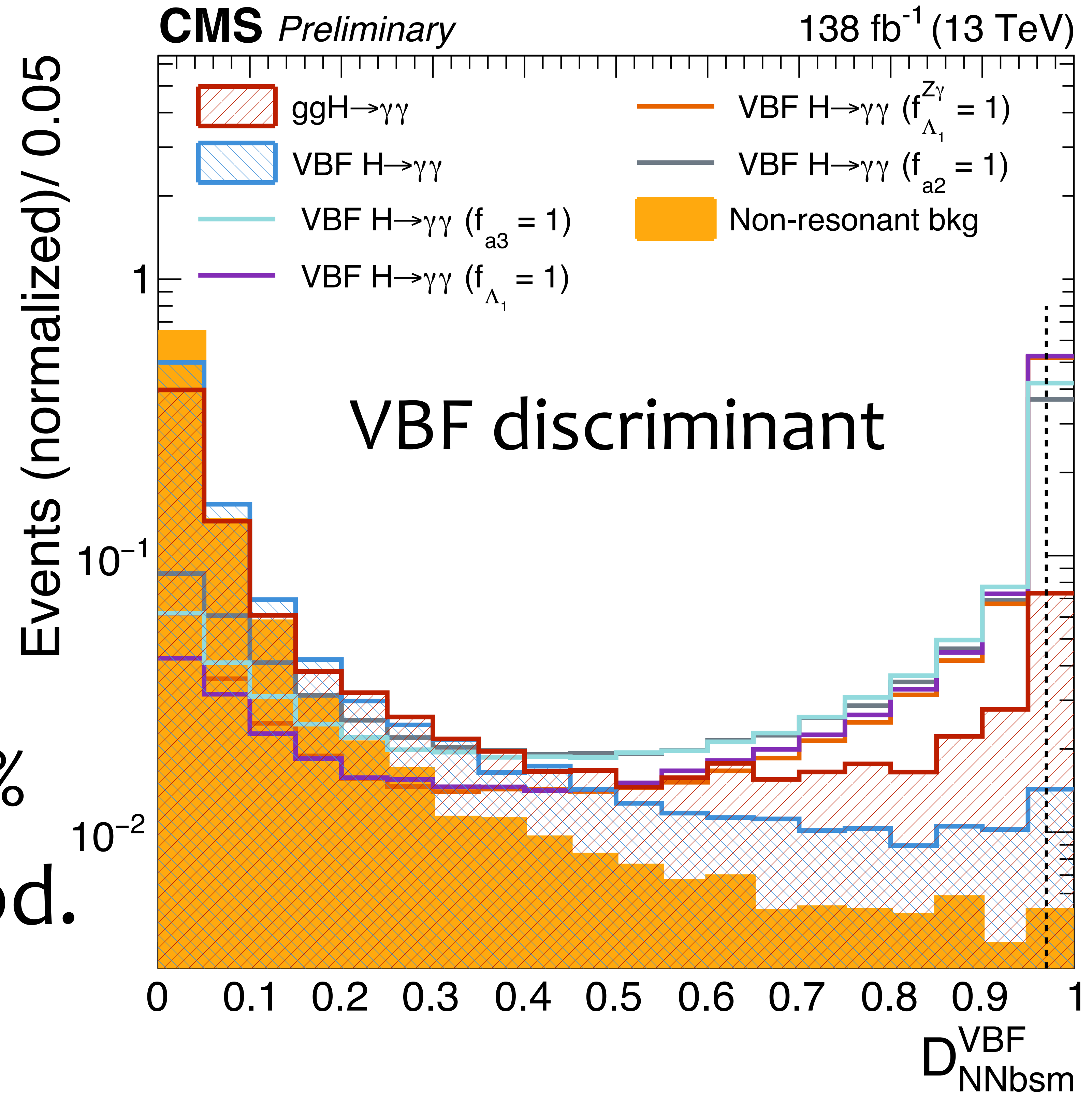
Use the clean $H \to \gamma\gamma$ final state, with all production modes

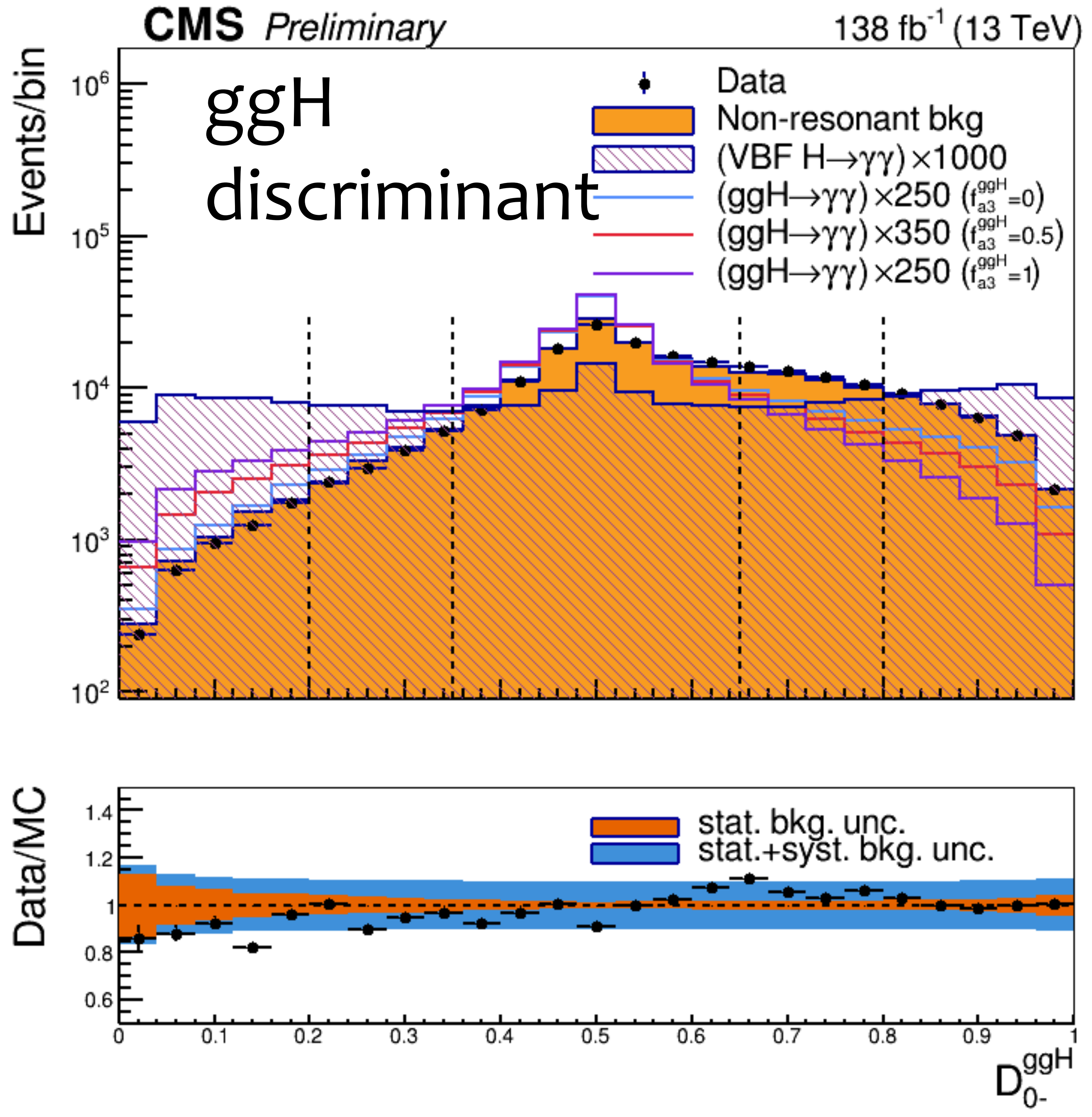
- VBF, V(qq')H, V($\ell\ell/\ell\nu$)H can probe BSM contribution up to high q^2
- ggH effective coupling: BSM particles in the loops

$f_{a3} = \pm 1$

means **fully CP-odd ($J^P = 0^-$)**

- Test BSM fractions from 0-100%
- 1 optimal discriminant / f_{ai} / prod.

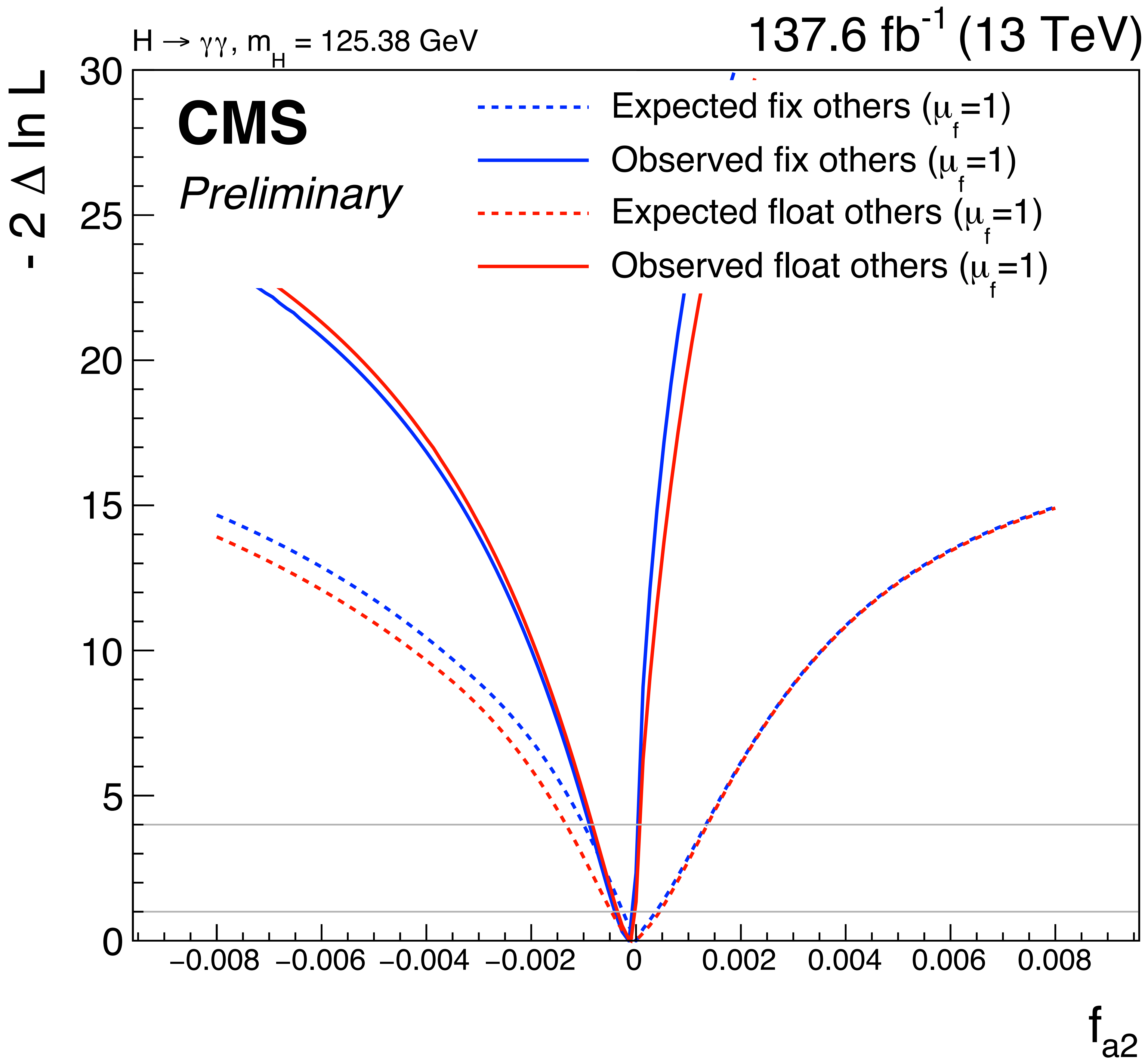




Use di-photon and associated jets kinematics in ML and MELA to discriminate SM / BSM

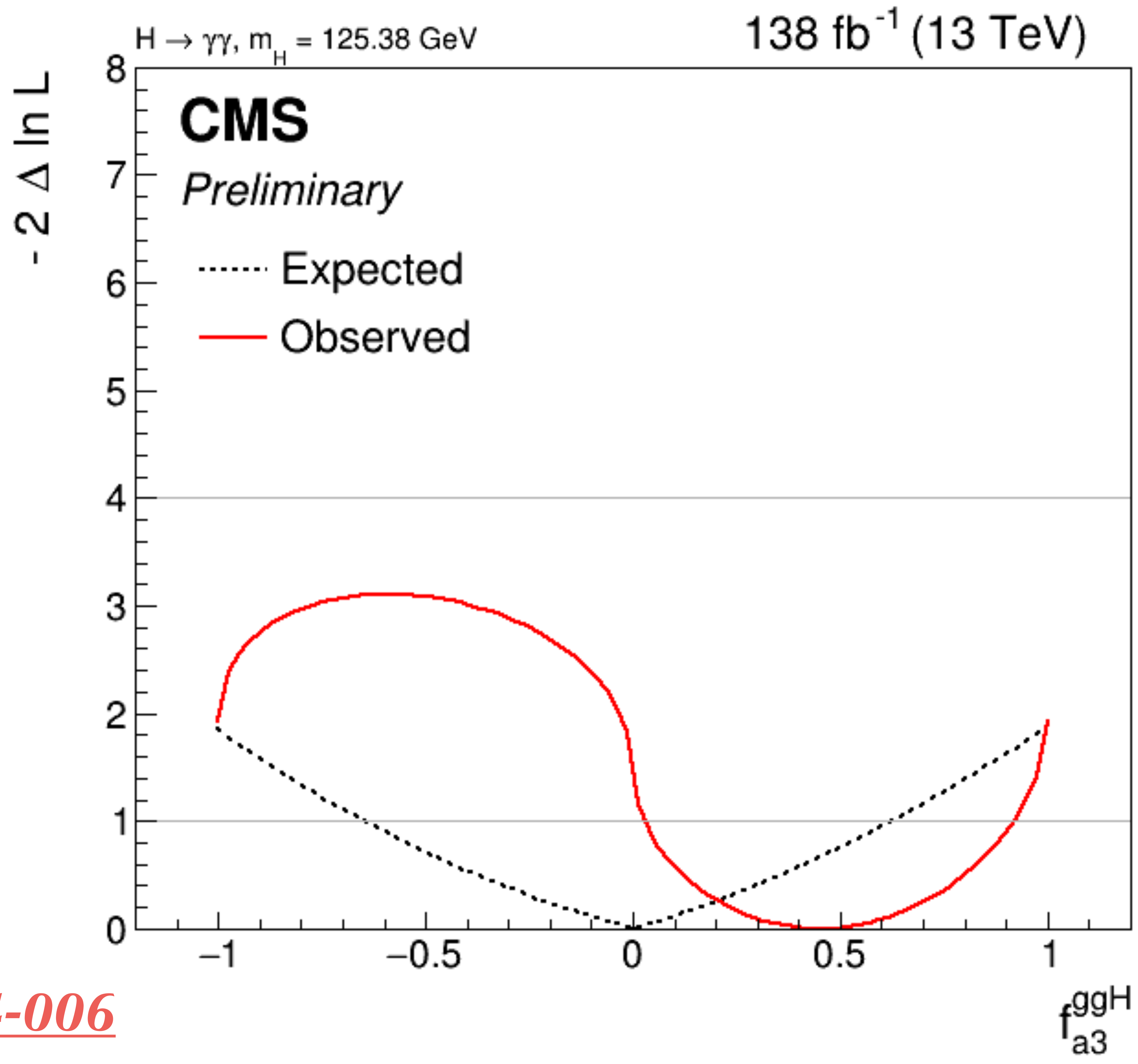
HVV and Hgg anomalous couplings

HVV CP-even BSM fraction



Hgg CP-odd BSM fraction (weaker constraint than HVV)

NEW

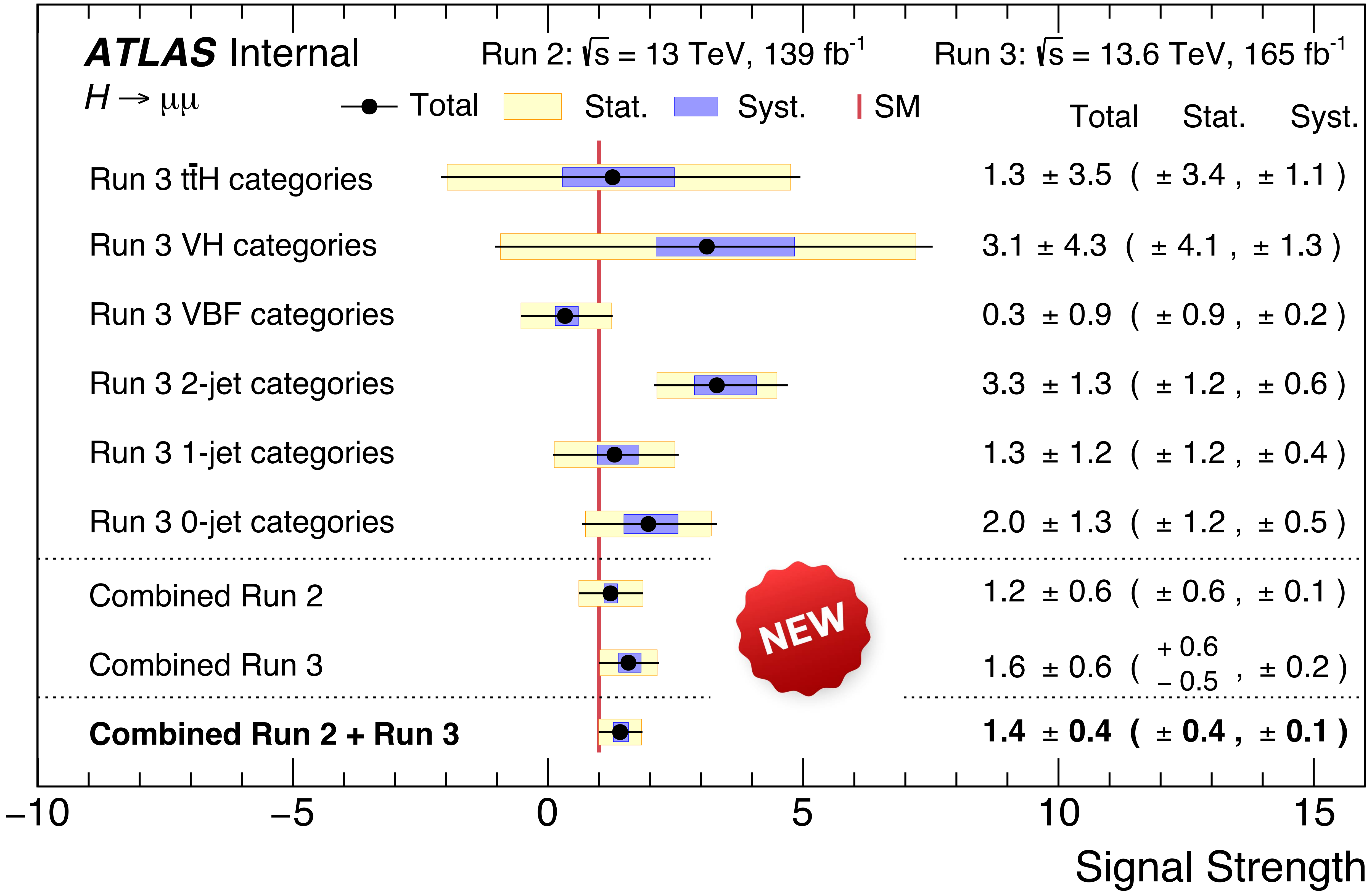


Stronger constraints when allowing 1 BSM/time

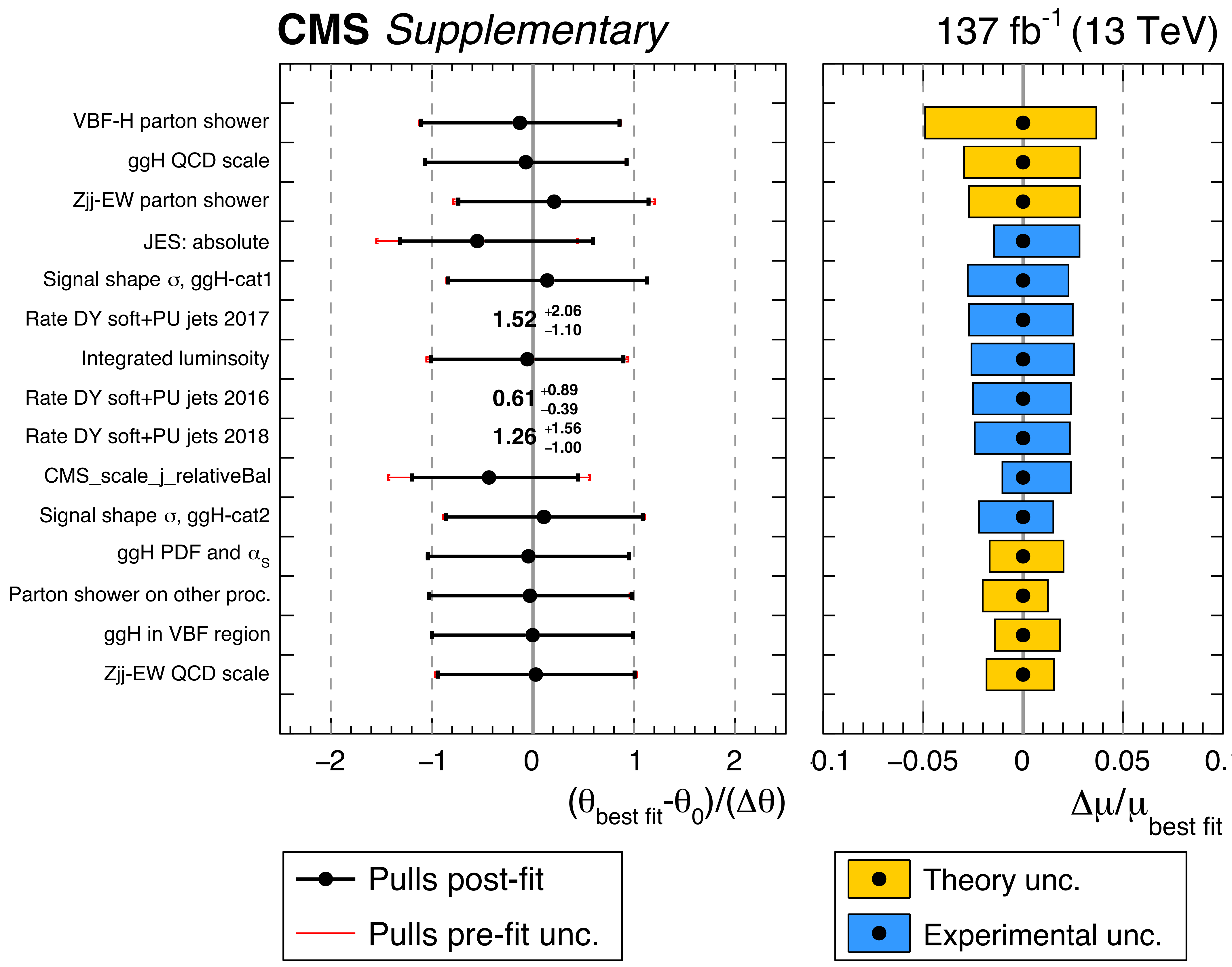
Competitive with $H \to 4\ell, H \to \tau\tau$ CMS-PAS-24-006

Impact of uncertainties on H->μμ

- All categories still statistically dominated (by far)
- VBF $H \rightarrow \mu\mu$ the most sensitive category for both experiments
- Main systematic uncertainties from theory and signal extraction biases



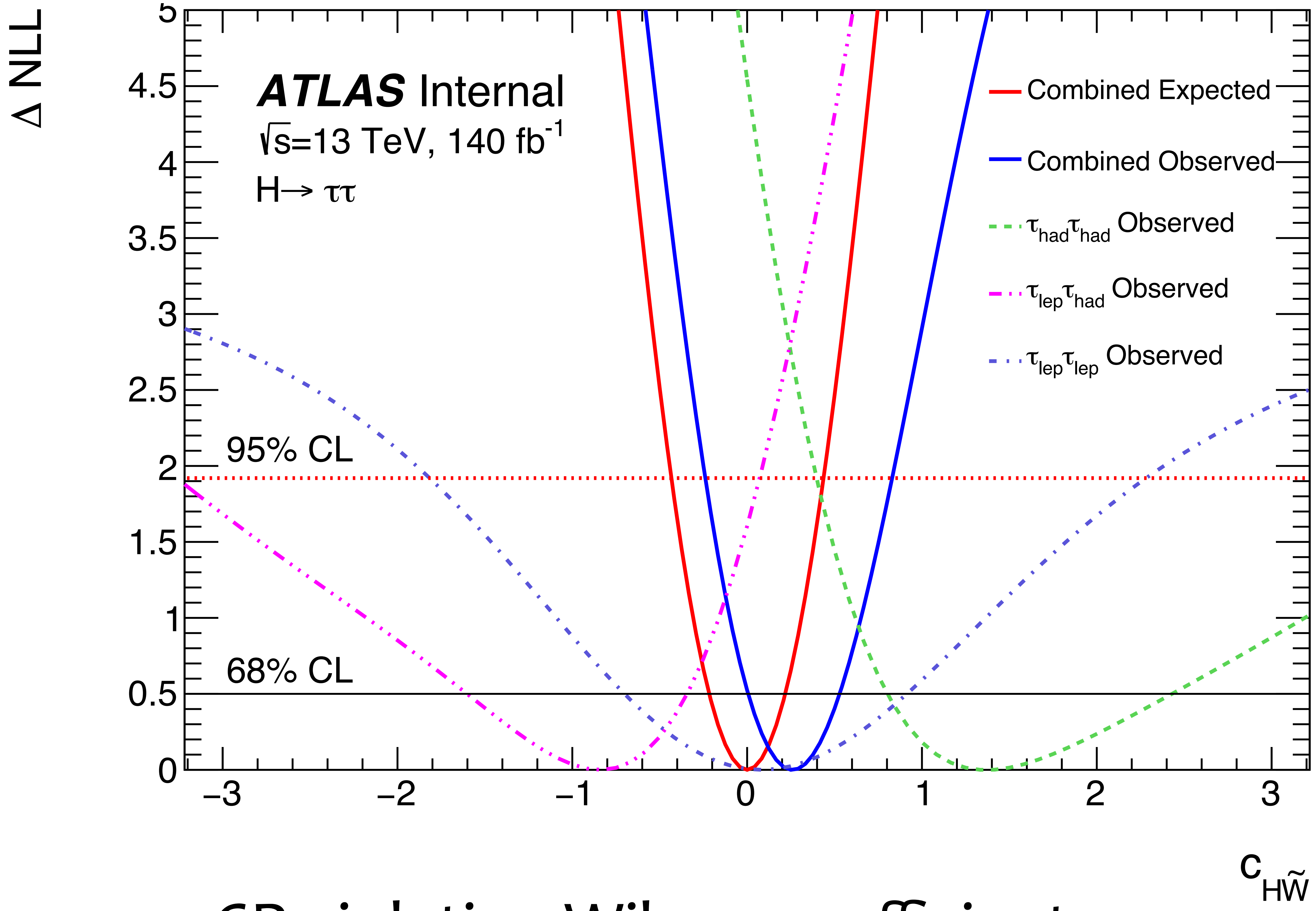
ATLAS-CONF-2024-011



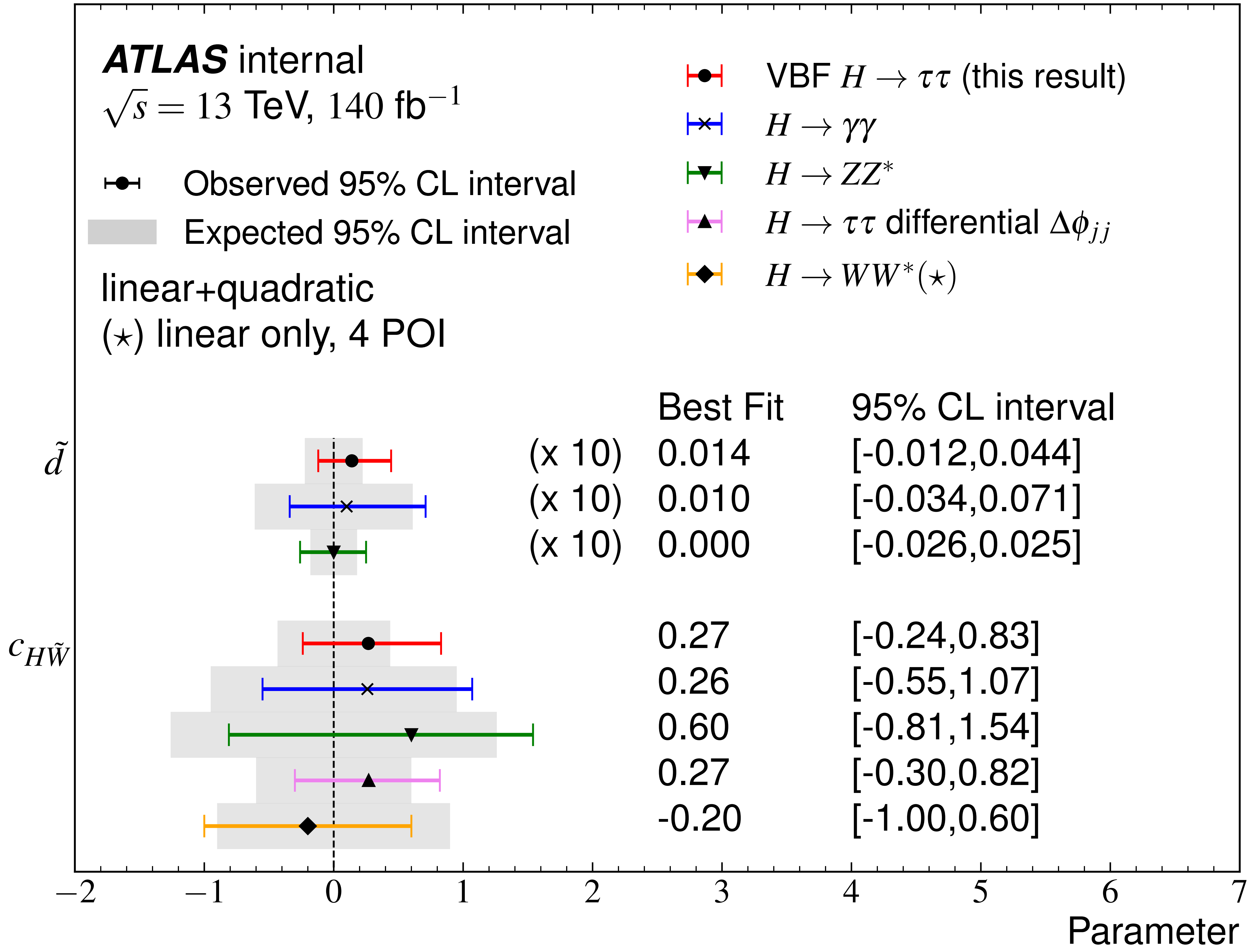
CPV in EFT interpretation

NEW

The three channels equally sensitive



CP-violating Wilson coefficient $c_{H\tilde{W}}$ consistent with 0 (SM)



$H \rightarrow \tau\tau$ one of the most sensitive to the HVV CP-odd contribution

(All others CP-odd coefficients fixed to SM)

ATLAS-CONF-2024-009

The Higgs in the Standard Model

$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi$$

Electroweak and QCD sector

$$+|D_\mu\Phi|^2$$

Gauge interactions

$$-V(\Phi)$$

Higgs potential

$$+\psi_i y_{ij}\psi_j\Phi$$

Yukawa interactions (fermion masses => proton, neutron masses), CKM matrix and CP violation

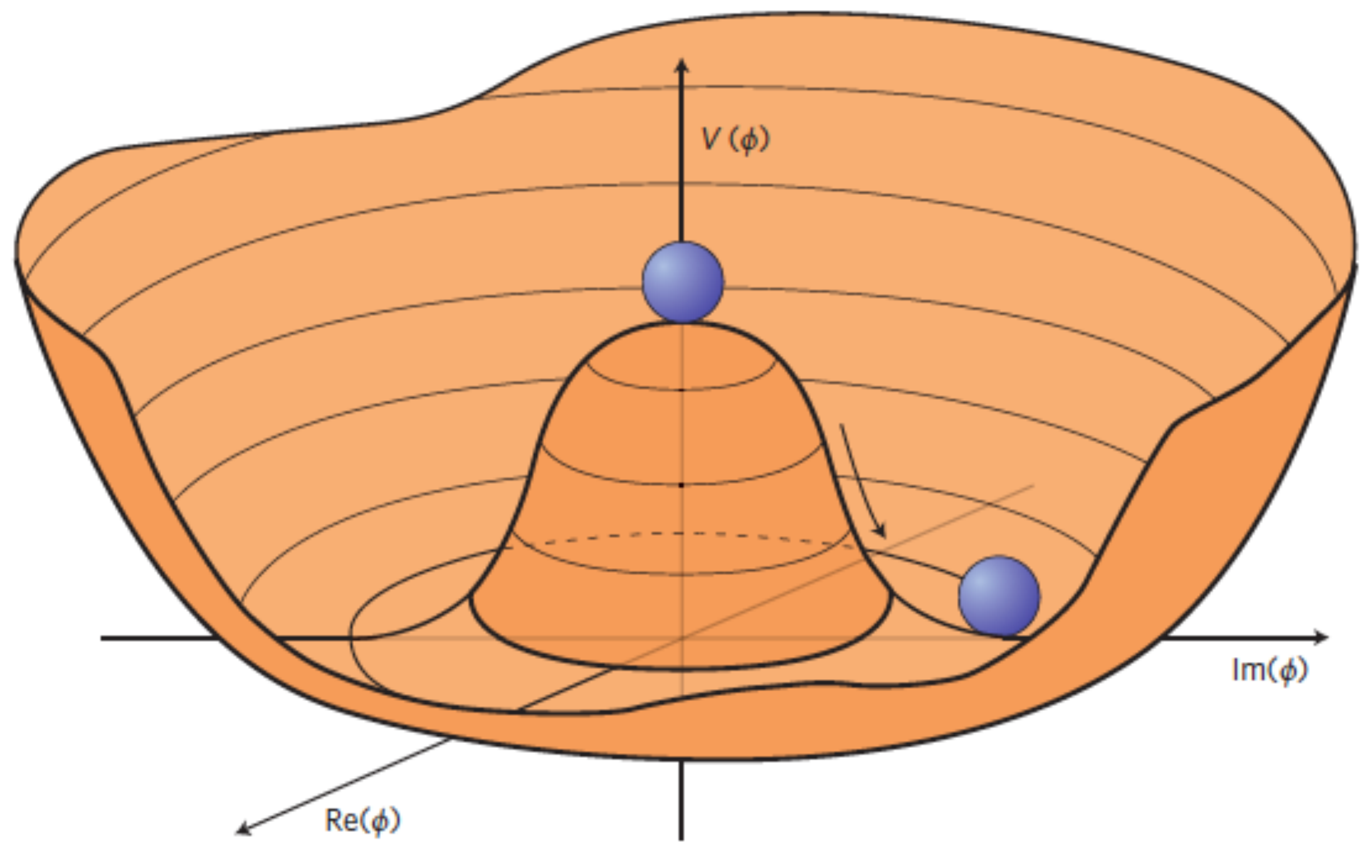
Out of 19 free parameters in the Standard Model Lagrangian, 15 are in the scalar sector

Higgs mass, Higgs self-couplings,
fermion masses, CKM parameters

1/2 of the SM Lagrangian is about Higgs!

The Higgs potential

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



Expanding around **potential minimum:**

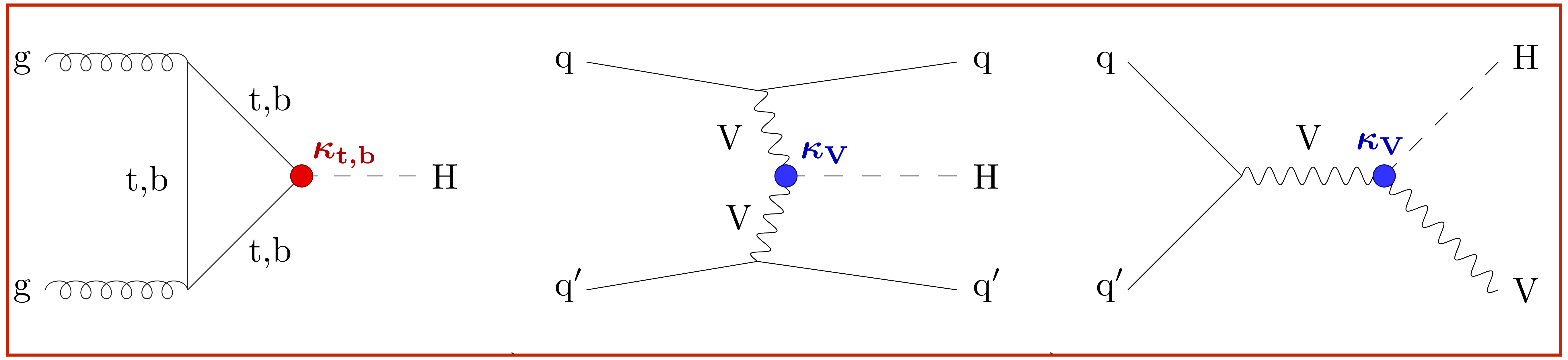
$$V(H) = V_0 + \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

- **3 parameters:** v, m_H, λ
- Relationships between them are fixed in the SM: $\lambda = \frac{m_H^2}{2v^2}$
- Characterizing the Higgs potential means measuring the H boson mass (μ) and the strength of its self coupling (λ)

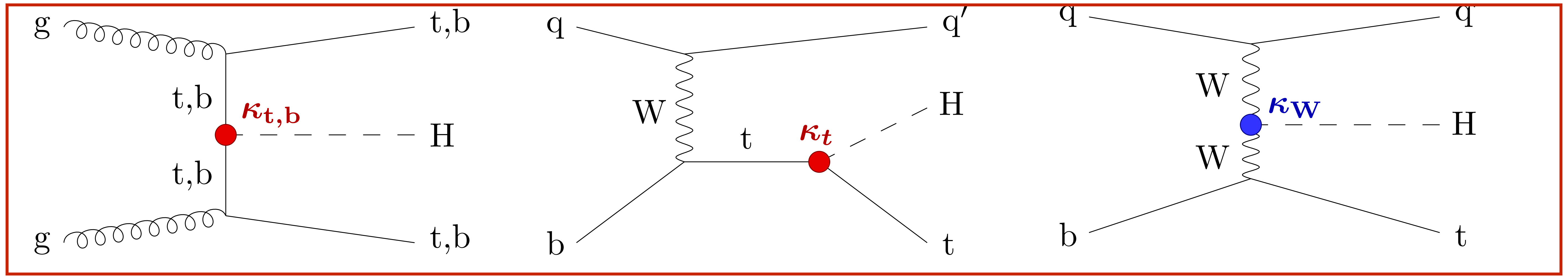
Test of the SM!

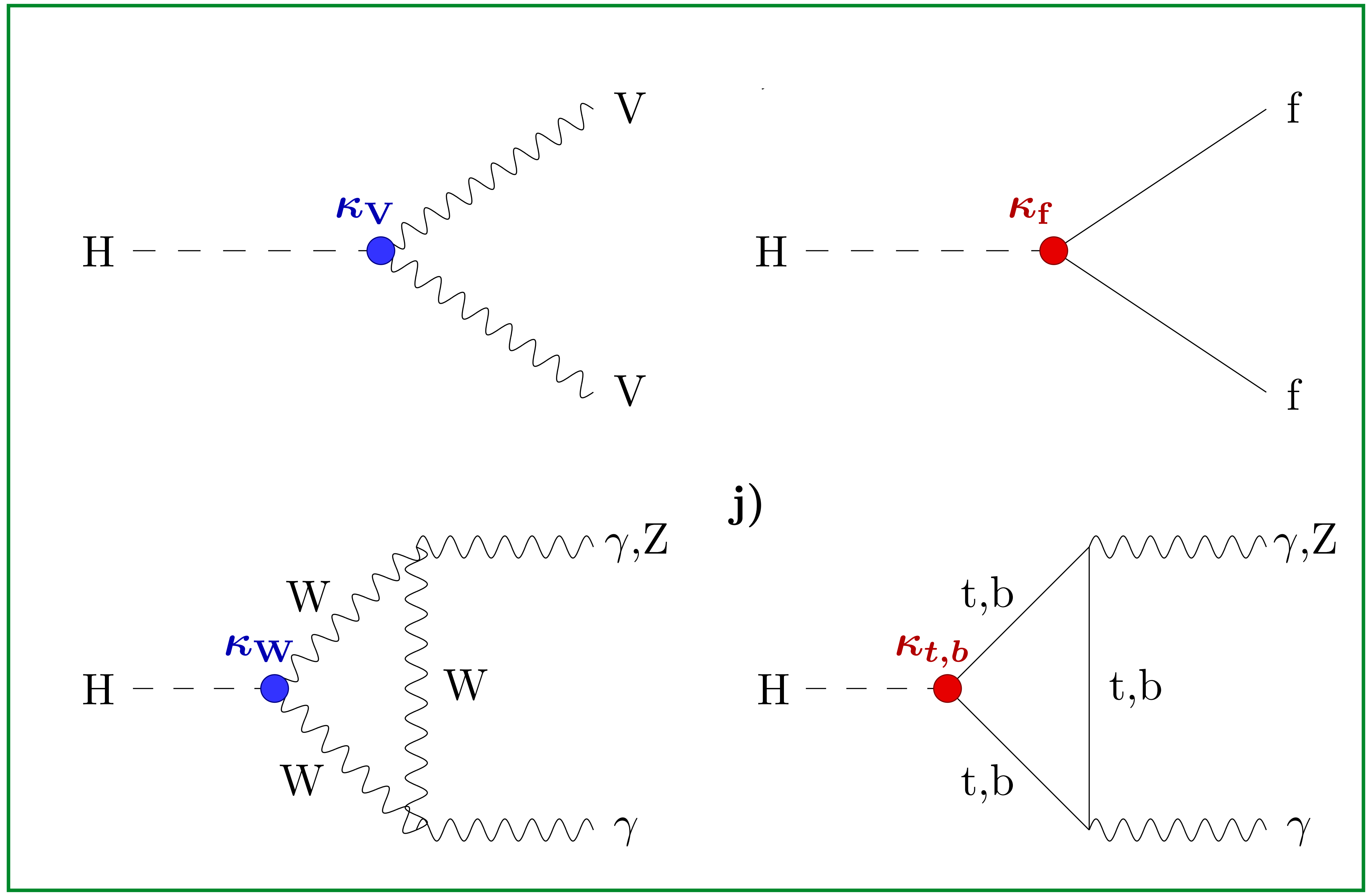
Higgs couplings in production and decay

ggH　　VBF　　WH/ZH



ttH　　tHq

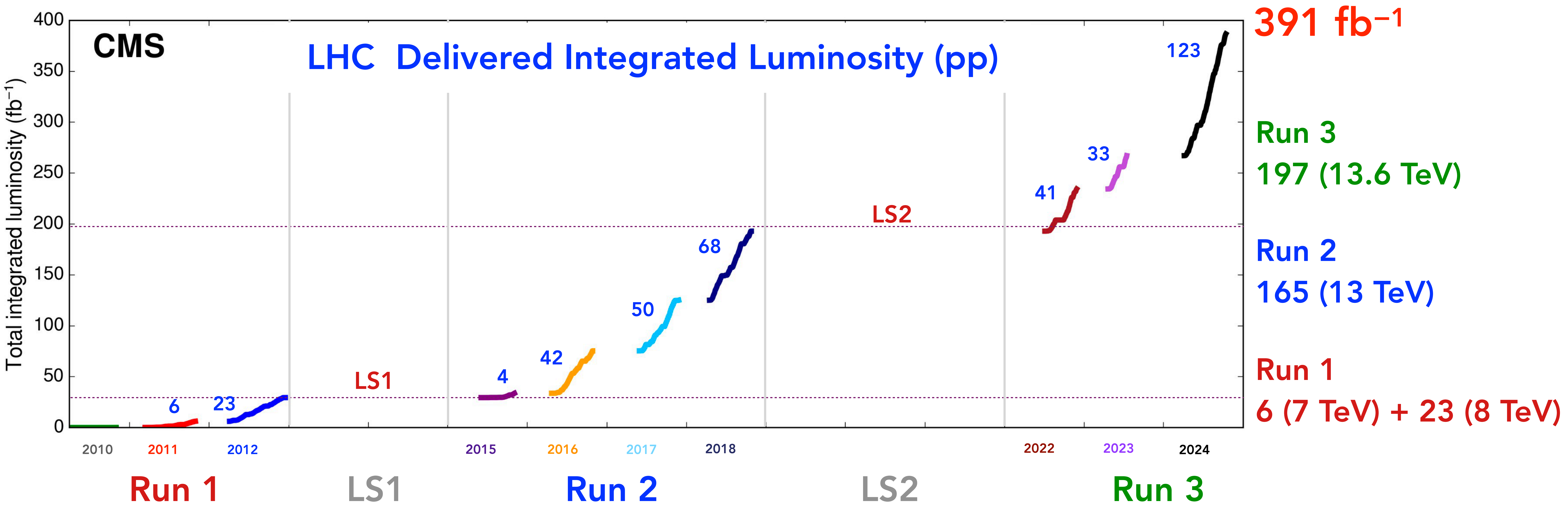




Several productions and decay modes give access to many Higgs couplings to SM particles

$\kappa_i = \frac{g_i}{g_i^{SM}}$: over-constrained test of the SM from Higgs is checking all $k_i = 1$

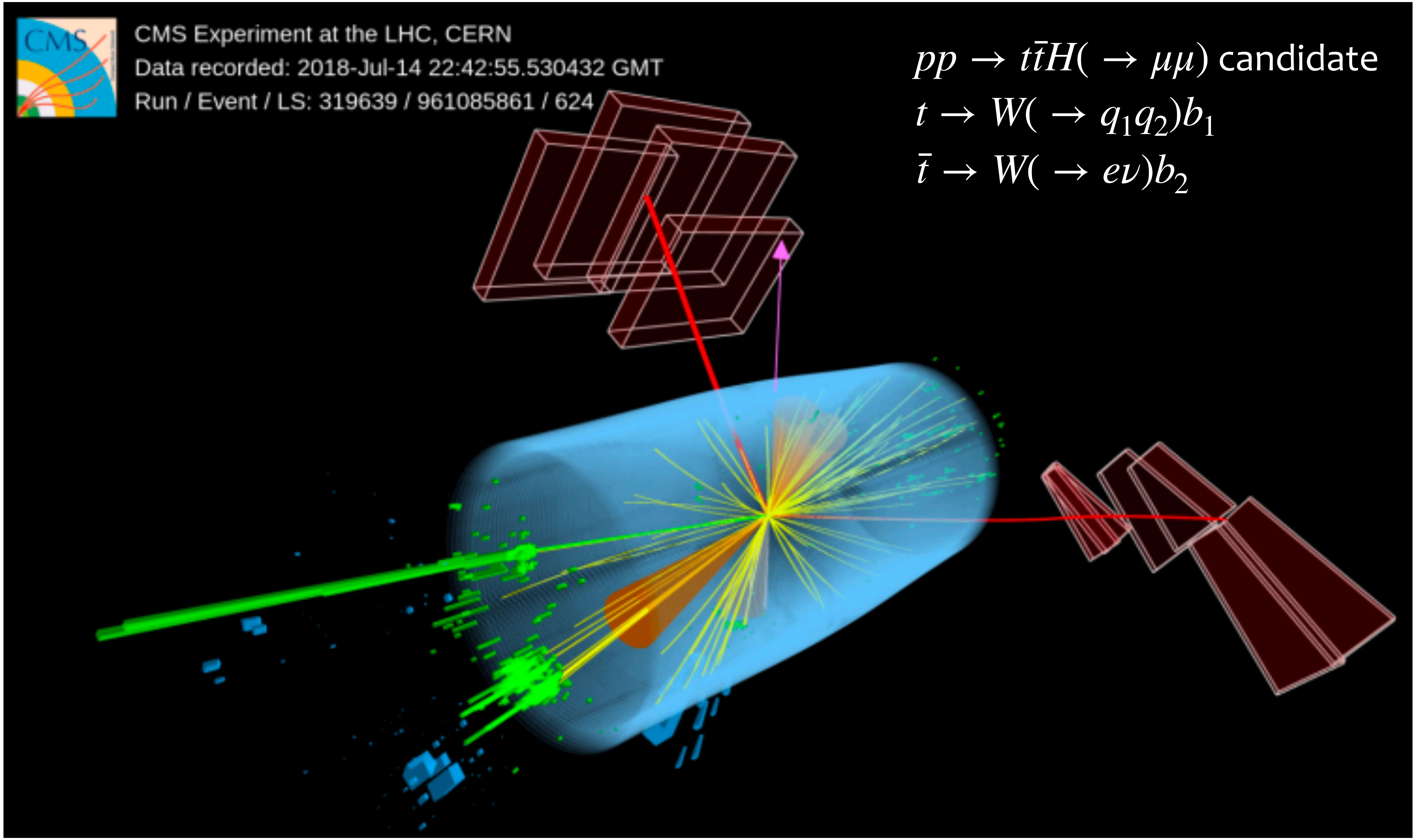
LHC from Run 1 to Run 3



Integrated luminosity of **391 fb^{-1} by now**, means **~22 millions of Higgs bosons recorded** by CMS (and the same quantity by ATLAS)

With this huge dataset, we can try to observe even rare processes !

Higgs bosons in CMS

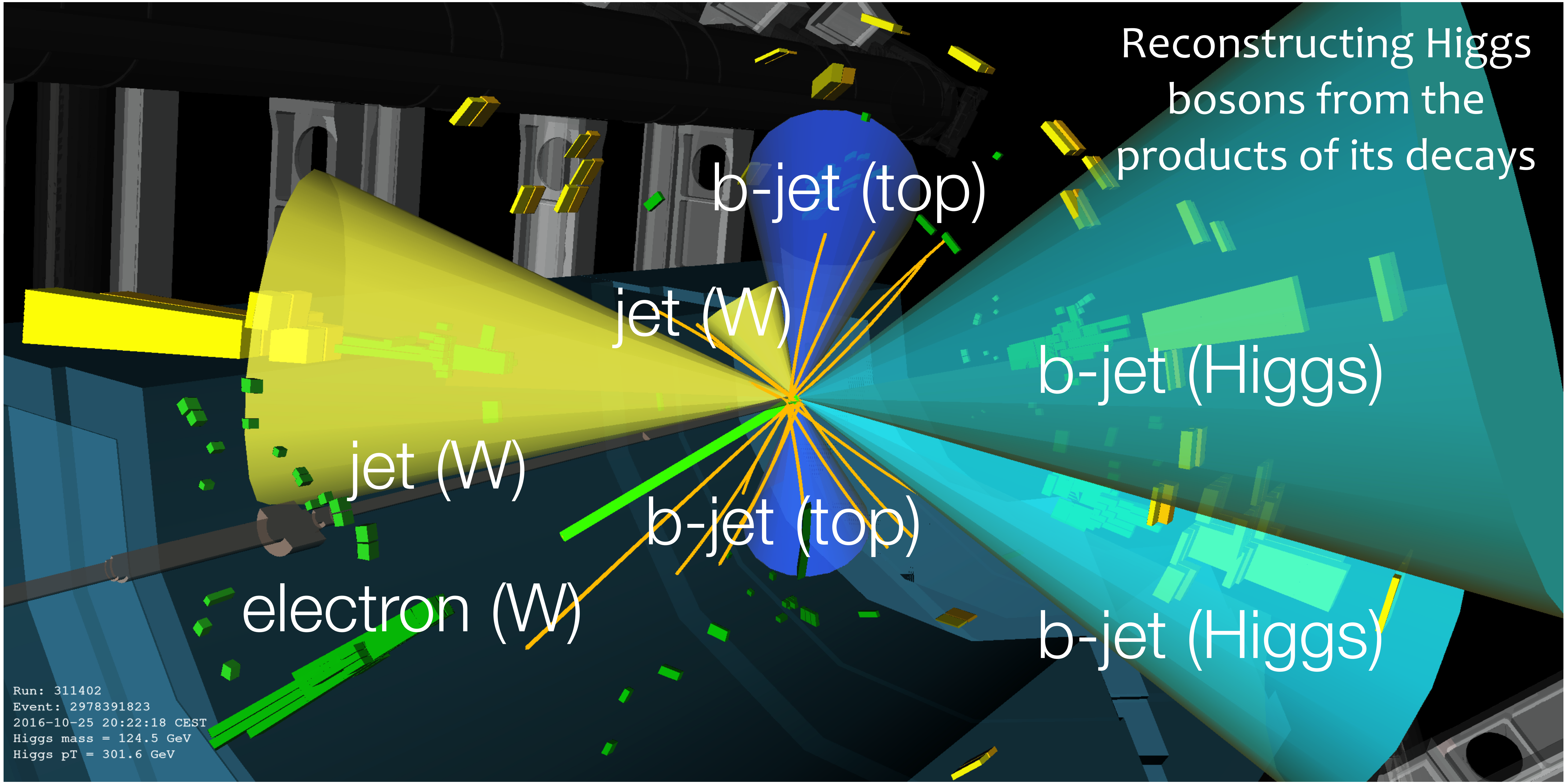


$pp \rightarrow t\bar{t}H(\rightarrow \mu\mu)$ candidate

$t \rightarrow W(\rightarrow q_1 q_2) b_1$

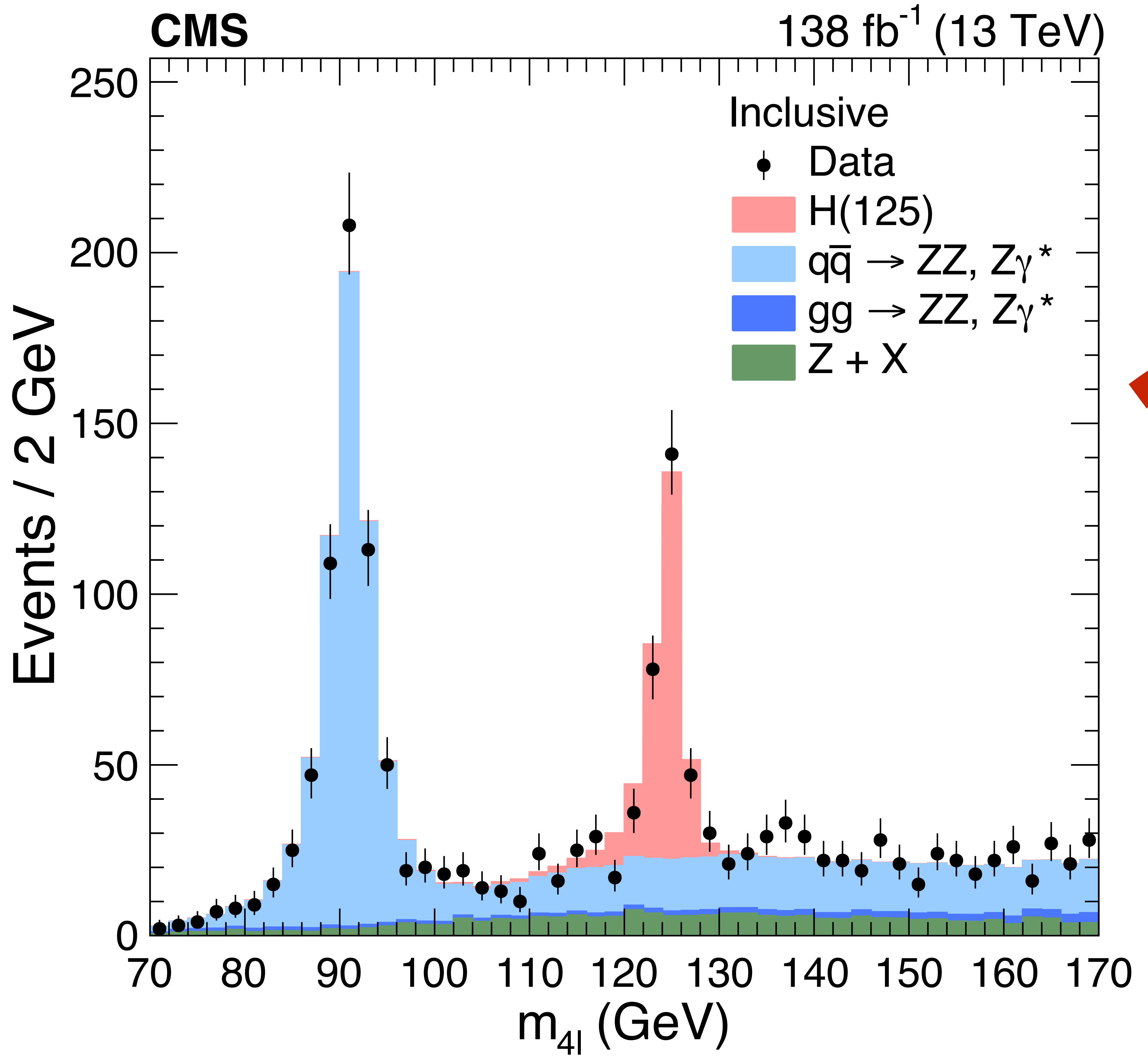
$\bar{t} \rightarrow W(\rightarrow e\nu) b_2$

Zoom inside a Higgs event in ATLAS

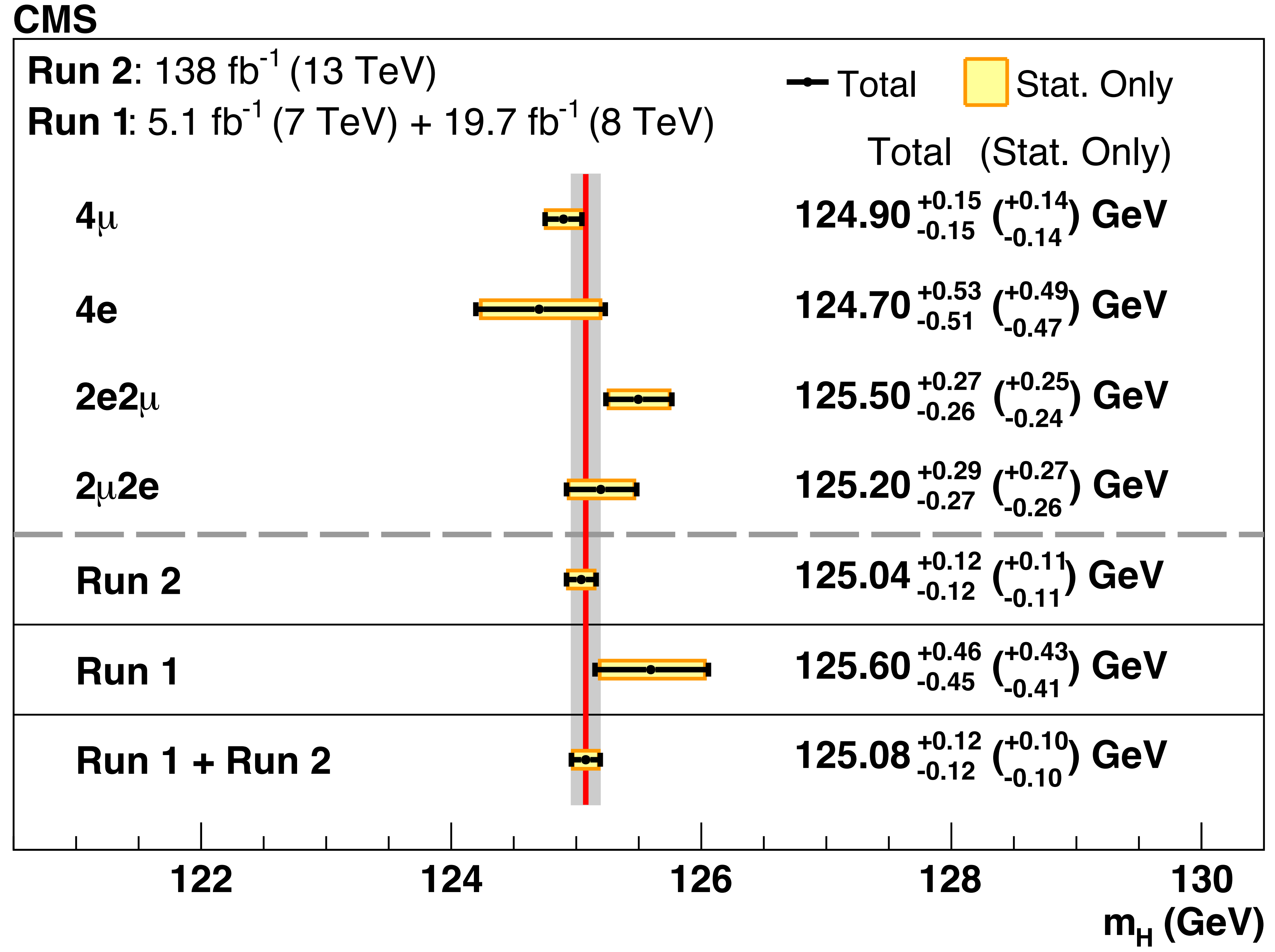


Higgs mass (e.g. from H->ZZ->4ℓ)

- Measurement done in H→4ℓ and H→γγ only
- precision dominated by statistics and experimental systematics (e.g. small non-linearities in photon energy response, muon momentum scale)



$H \to ZZ^* \to 4\ell$



$m_H = 125.08 \pm 0.12\ (\pm\ 0.10)$ GeV

precision on m_H: 120 MeV ≈ 0.1% from a single measurement

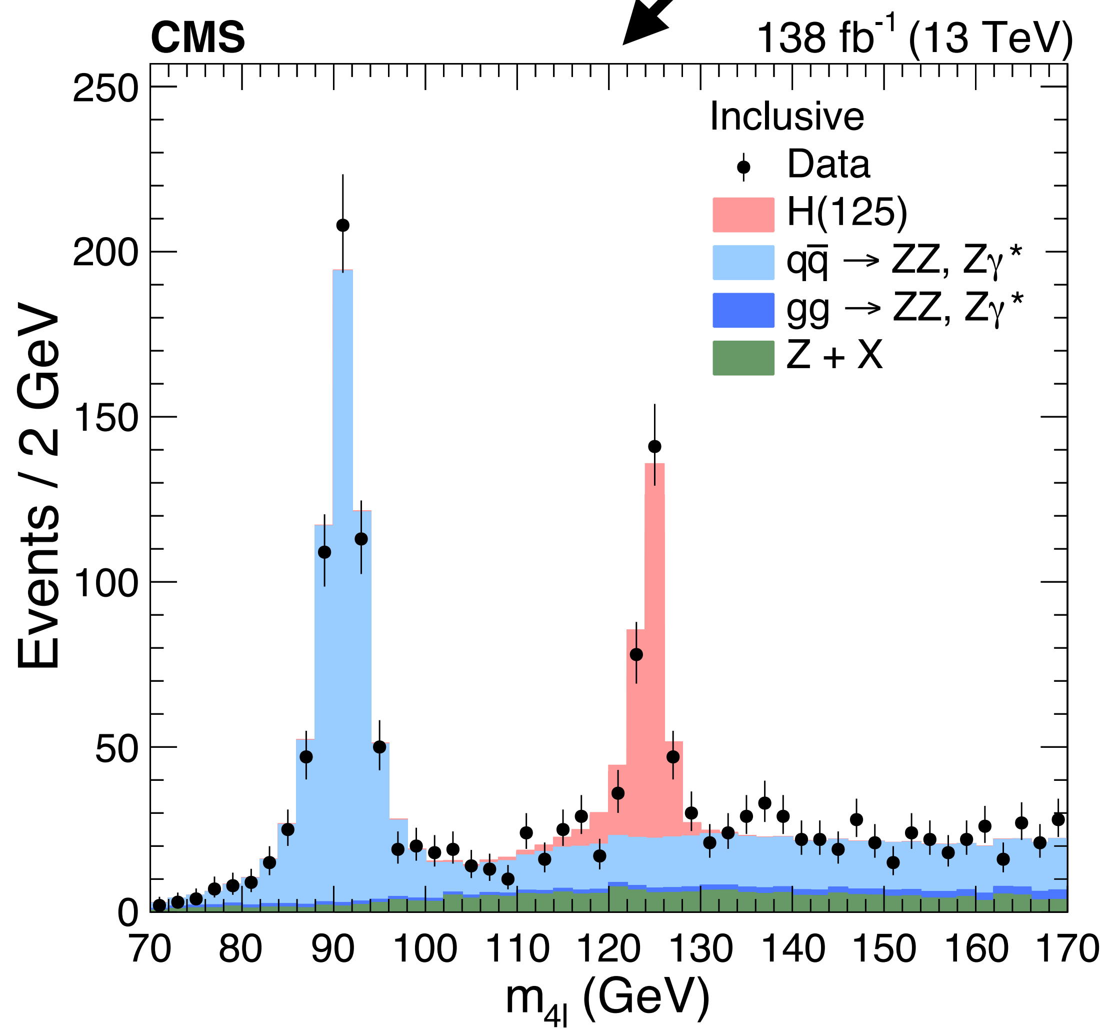
Measuring couplings from experimental data

The experimental likelihood is constructed in each channel "r" to extract the Higgs signal rate (s_r^{if}) on top of (usually) a much larger background b_r

- Simultaneously in many production modes "i" and several decays "f"

$$L_r(\vec{x};\vec{\alpha},\vec{\theta}) = \mathrm{Pois}\left(n\,;\sum_{if} s_r^{if}(\vec{\alpha},\vec{\theta}) + b_r(\vec{\theta})\right)\cdot\prod_d p(\vec{x}_d;\vec{\alpha},\vec{\theta}).$$

Data:
observed counts



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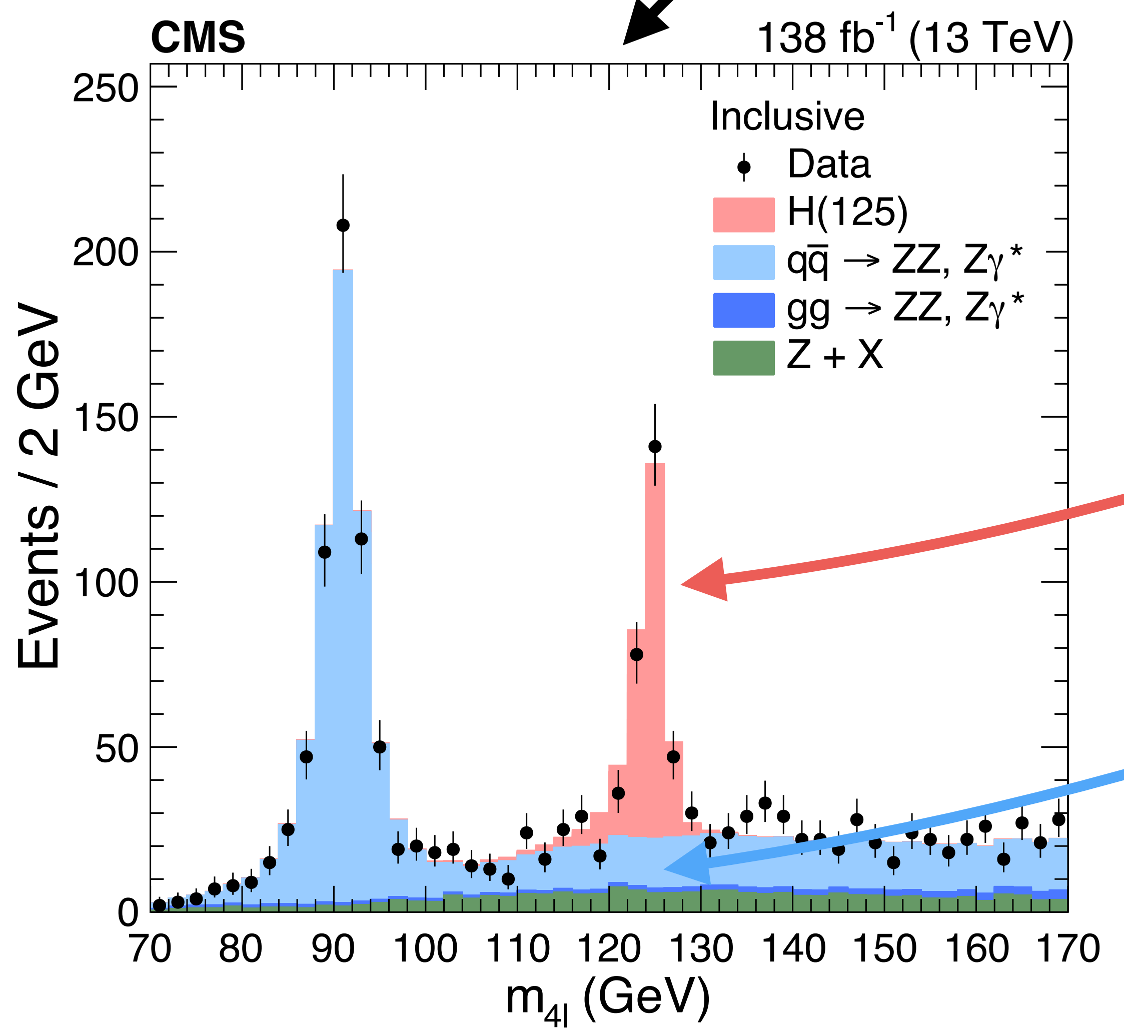
$$L_r(\vec{x};\vec{\alpha},\vec{\theta}) = \mathrm{Pois}\left(n\,;\sum_{if} s_r^{if}(\vec{\alpha},\vec{\theta}) + b_r(\vec{\theta})\right)\cdot\prod_d p(\vec{x}_d;\vec{\alpha},\vec{\theta}).$$

Data: observed counts

Inference: **Signal** yield

Inference: **Background**(s) yield



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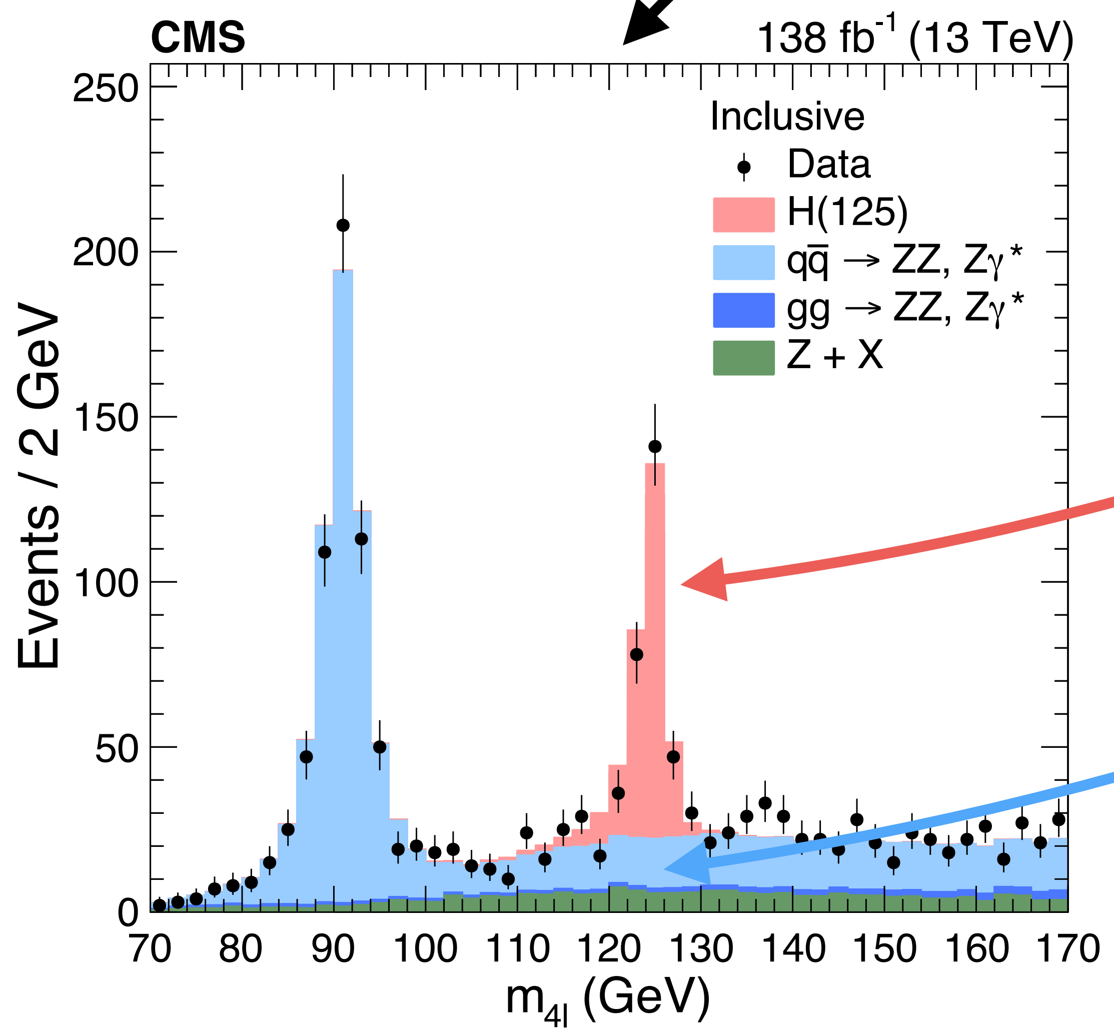
Nuisance parameters: encode the model of all experimental and theoretical **systematic uncertainties**



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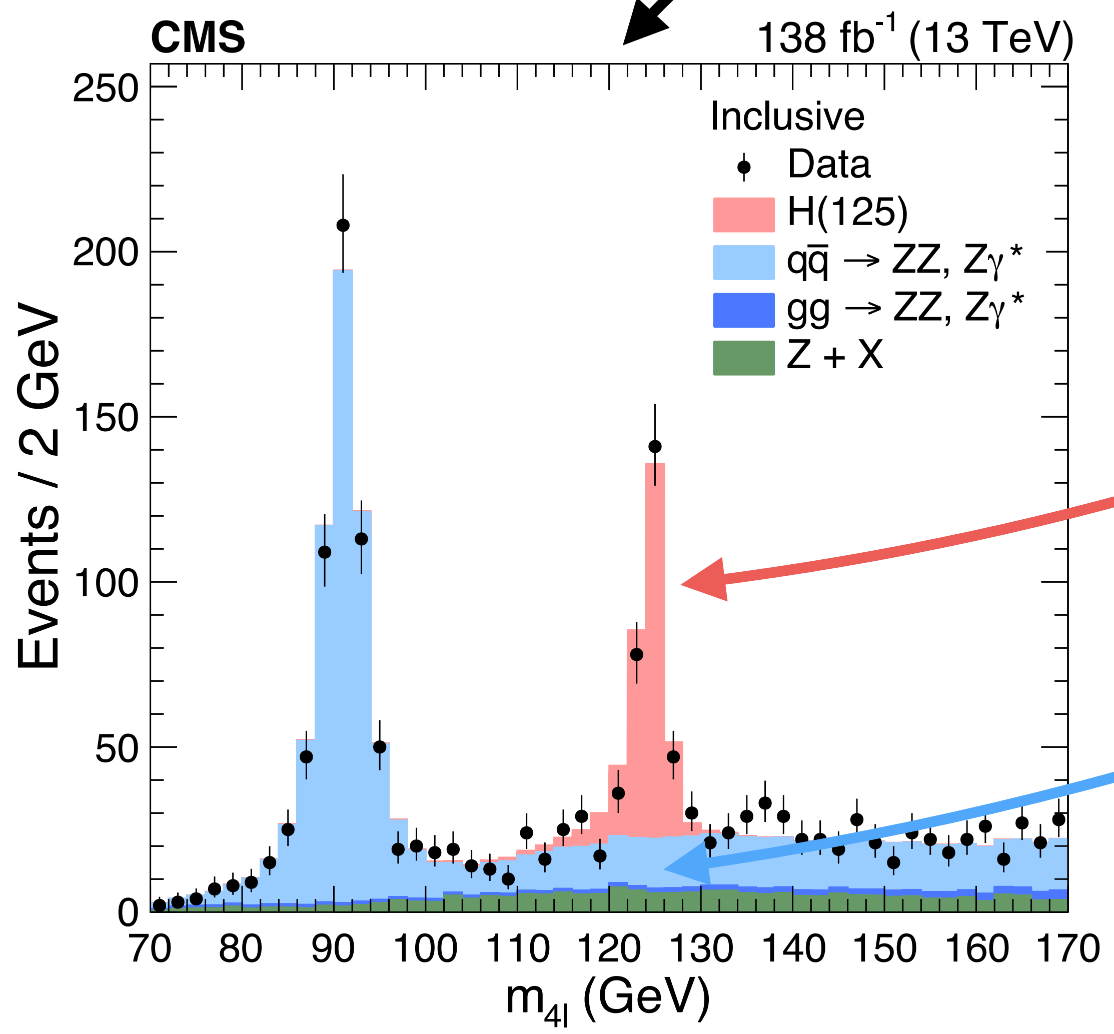


$$s_r^{if} = \mu^i \cdot \mu^f \cdot [\sigma^i \times BR^f]_{SM} \cdot \epsilon^{if} \cdot \mathscr{L}_{int}$$

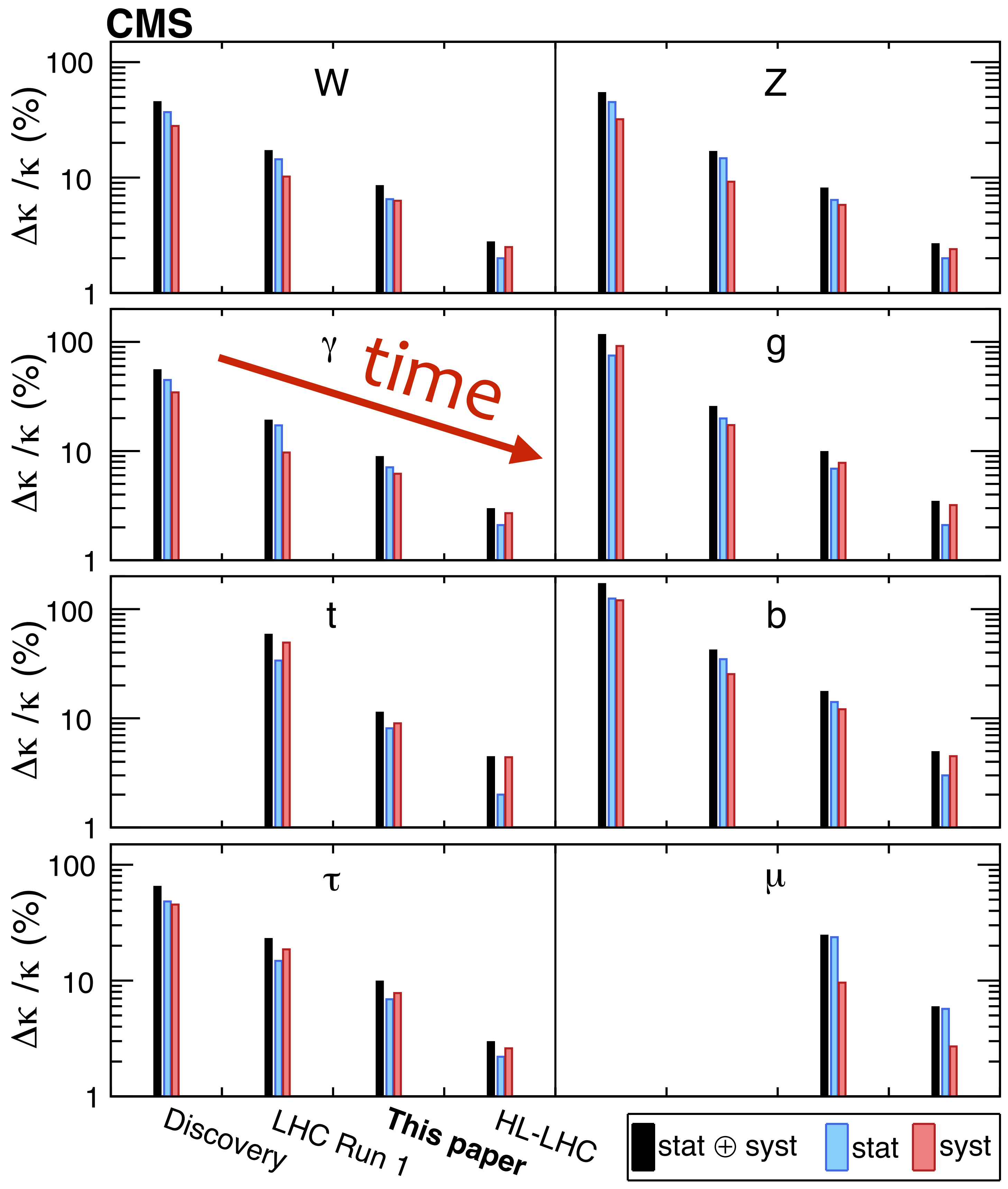
"**Signal strengths**" approach: rates relative to SM:

$$\mu_i = \frac{\sigma^i}{\sigma^i_{SM}} \quad \text{and} \quad \mu_f = \frac{BR^f}{BR^f_{SM}}$$

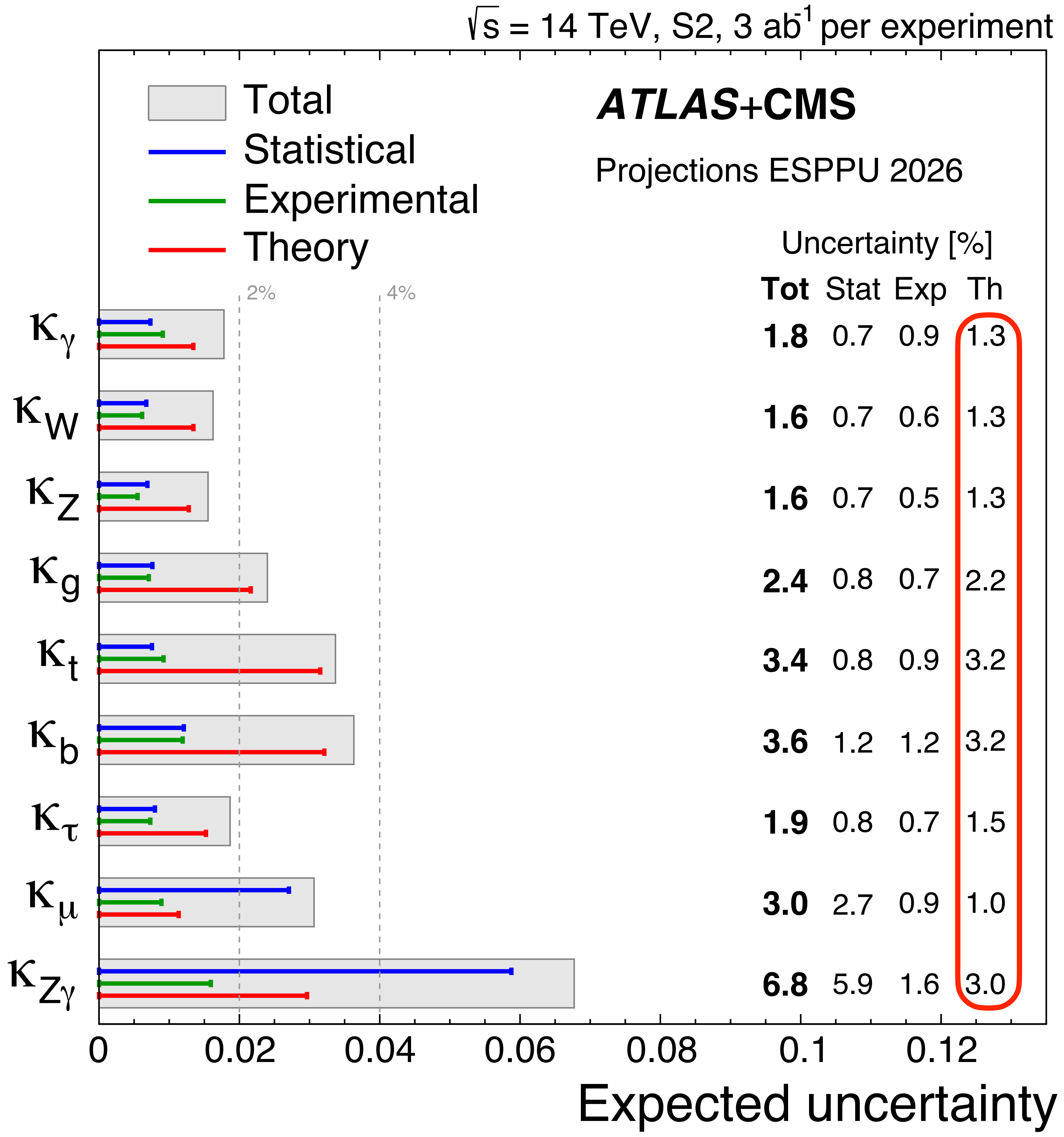
Why improving precision on κ ?

In the SM, all $\kappa_i = 1$. In BSM, $\kappa = 1 + \Delta\kappa$

$\Delta\kappa \propto v^2/\Lambda_{\mathrm{BSM}}^2$, so precision on $\Delta\kappa$ ⇔ reach in new physics scale, Λ_{BSM}, to the TeV range



CMS-only



ATLAS+CMS,
HL-LHC projections 3000 fb^{-1}

$\Delta\kappa/\kappa \sim O(v^2/\Lambda_{\mathrm{BSM}}^2)$

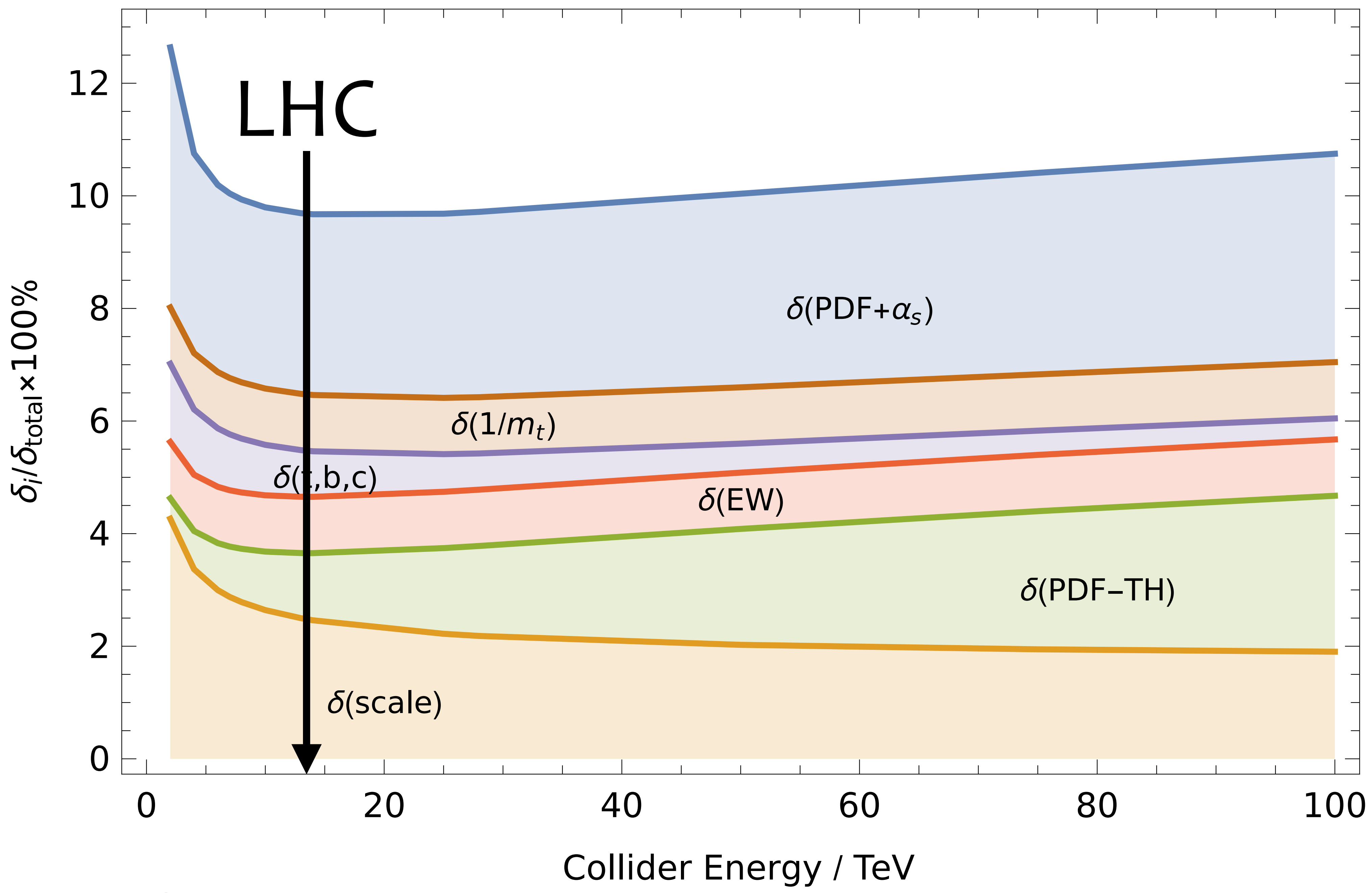
New physics at **1 TeV** =>
deviations $\Delta\kappa/\kappa \sim 6\,\%$

Theory uncertainties should improve together with experimental precision

Theory inputs towards percent accuracy

$$\delta\sigma_{PP\to H+X} = \delta(\text{PDF}+\alpha_S) + \delta(\text{theory}) = {}^{+3.63pb}_{-4.72pb} \ \left({}^{+7.46\%}_{-9.7\%}\right)$$

Largest contributions from **QCD uncertainties** and **PDFs**:



$$\begin{aligned}
\delta(\text{theory}) &= {}^{+0.13pb}_{-1.20pb} && \left({}^{+0.28\%}_{-2.50\%}\right) && \delta(\text{scale})\\
&+ \pm0.56pb && (\pm1.16\%) && \delta(\text{PDF-TH})\\
&+ \pm0.49pb && (\pm1.00\%) && \delta(\text{EWK})\\
&+ \pm0.41pb && (\pm0.85\%) && \delta(\text{t,b,c})\\
&+ \pm0.49pb && (\pm1.00\%) && \delta(1/m_t)\\
&= {}^{+2.08pb}_{-3.16pb} && \left({}^{+4.28\%}_{-6.5\%}\right), &&\\
\delta(\text{PDF}) &= \pm0.89\text{pb} && (\pm1.85\%), &&\\
\delta(\alpha_S) &= {}^{+1.25pb}_{-1.26pb} && \left({}^{+2.59\%}_{-2.62\%}\right). &&
\end{aligned}$$

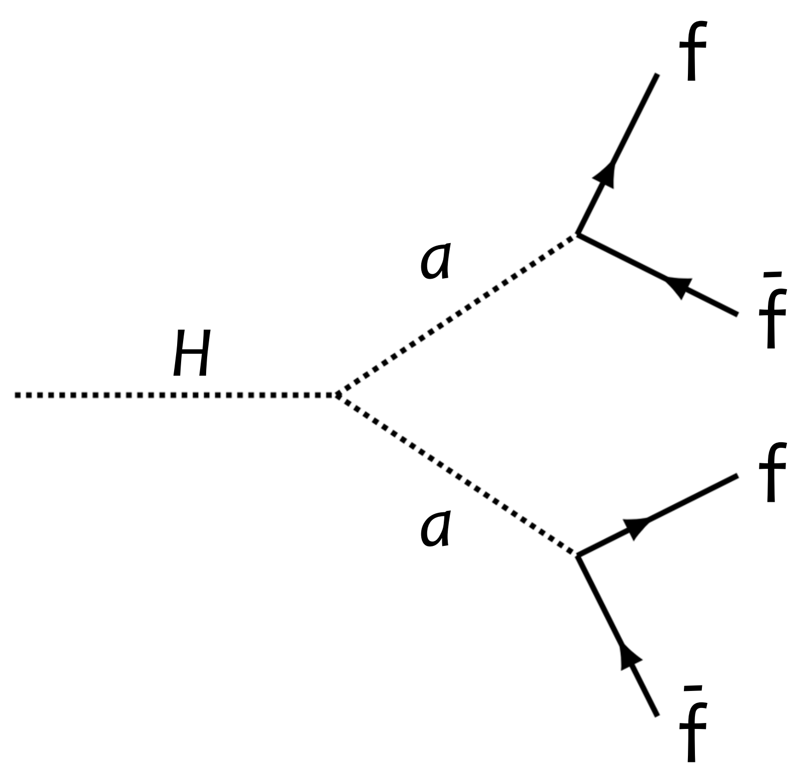
Gluon fusion: the main production mode provides crucial tests of QCD, and QCD+EW. Next challenges:

- **N3LO PDF sets** => reduce $\delta(\text{PDF} - \text{TH})$)
- More EW corrections (NLO calculations of QCD+EW)
- Large logs resummation

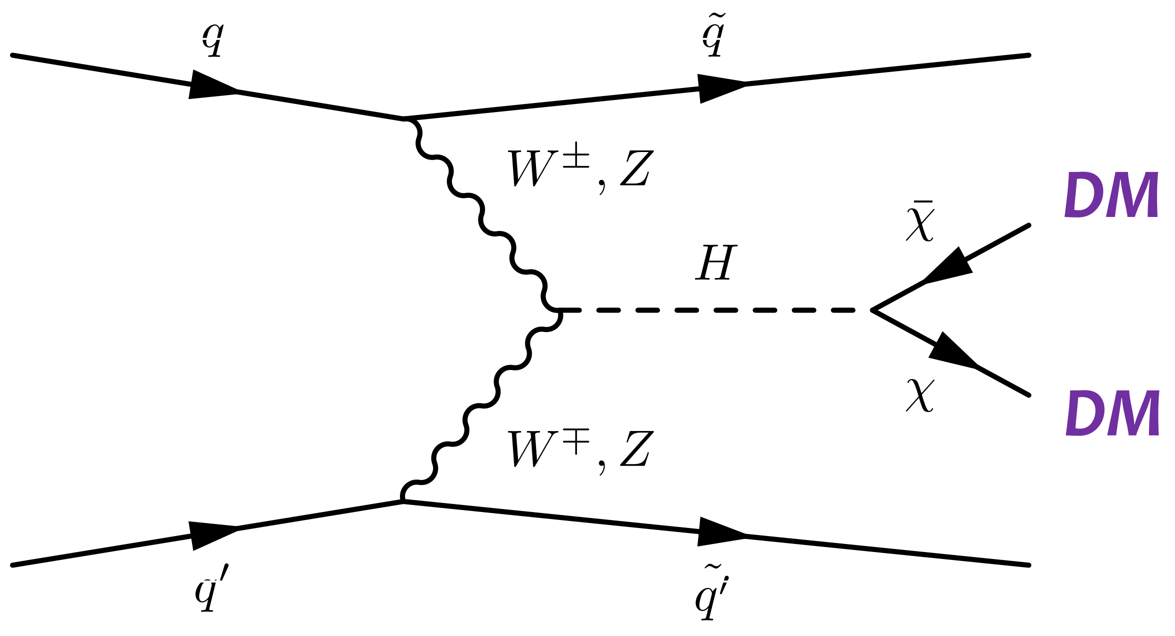
Higgs as direct BSM probe

Current measurements of Higgs couplings still allow decay modes to BSM particles:

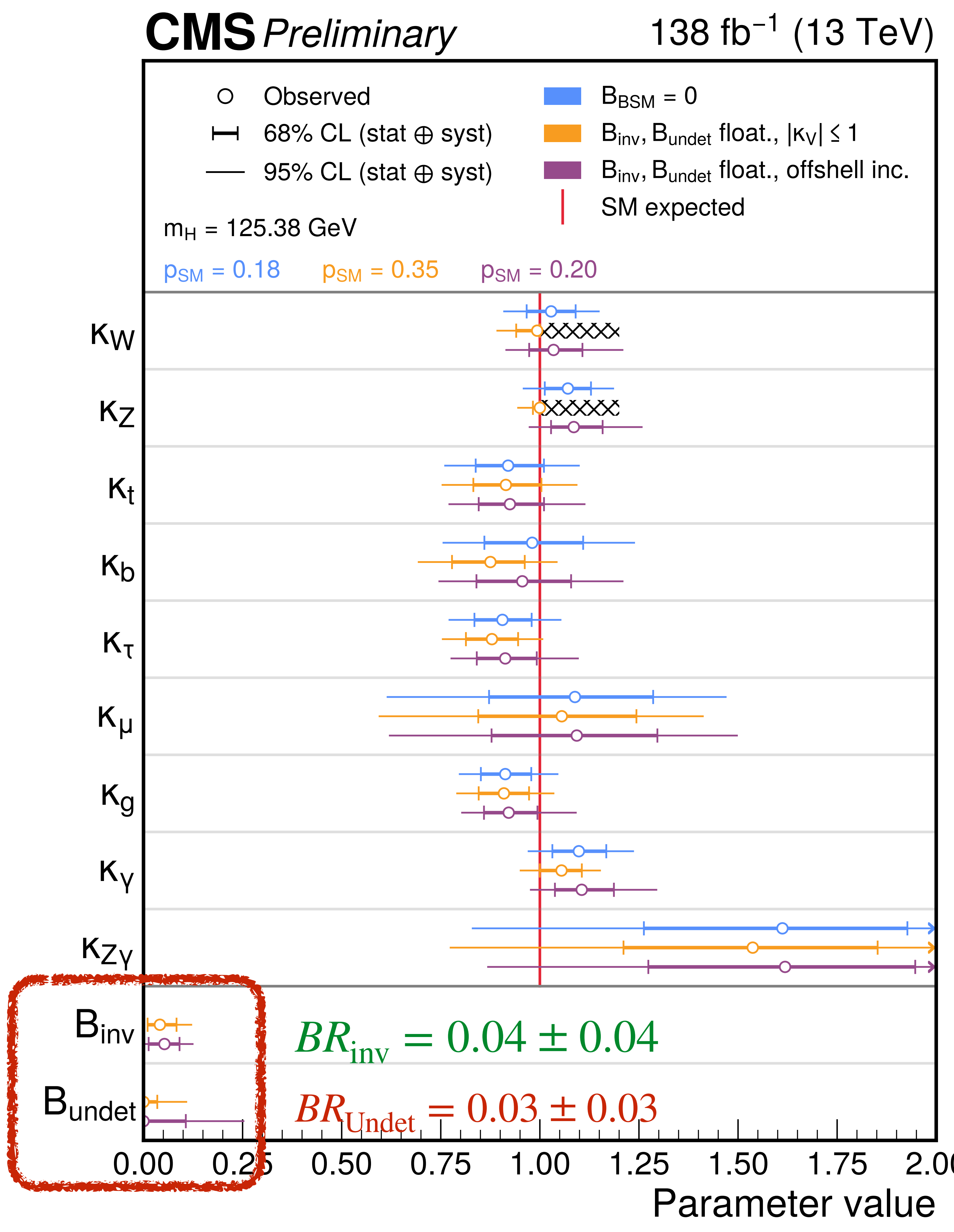
- **Undetected decay modes** (eg. 2HDM+s, nMSSM,…)
- **Invisible particles** (eg. Dark Matter)



H→2 light (pseudo-)scalars



H→2 DM particles

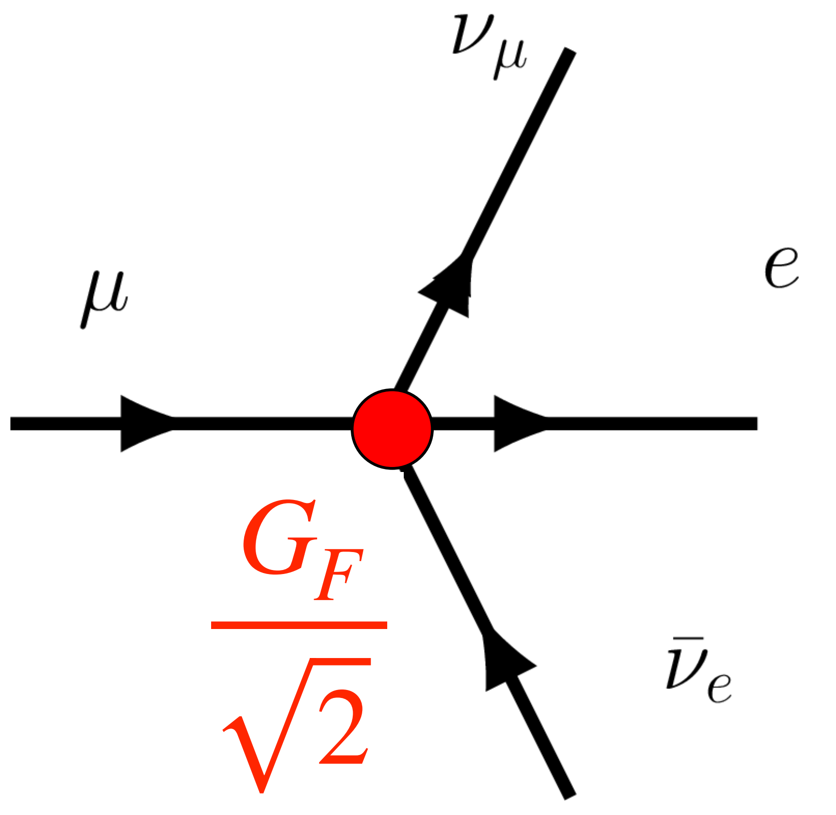


$BR_{inv} = 0.04 \pm 0.04$

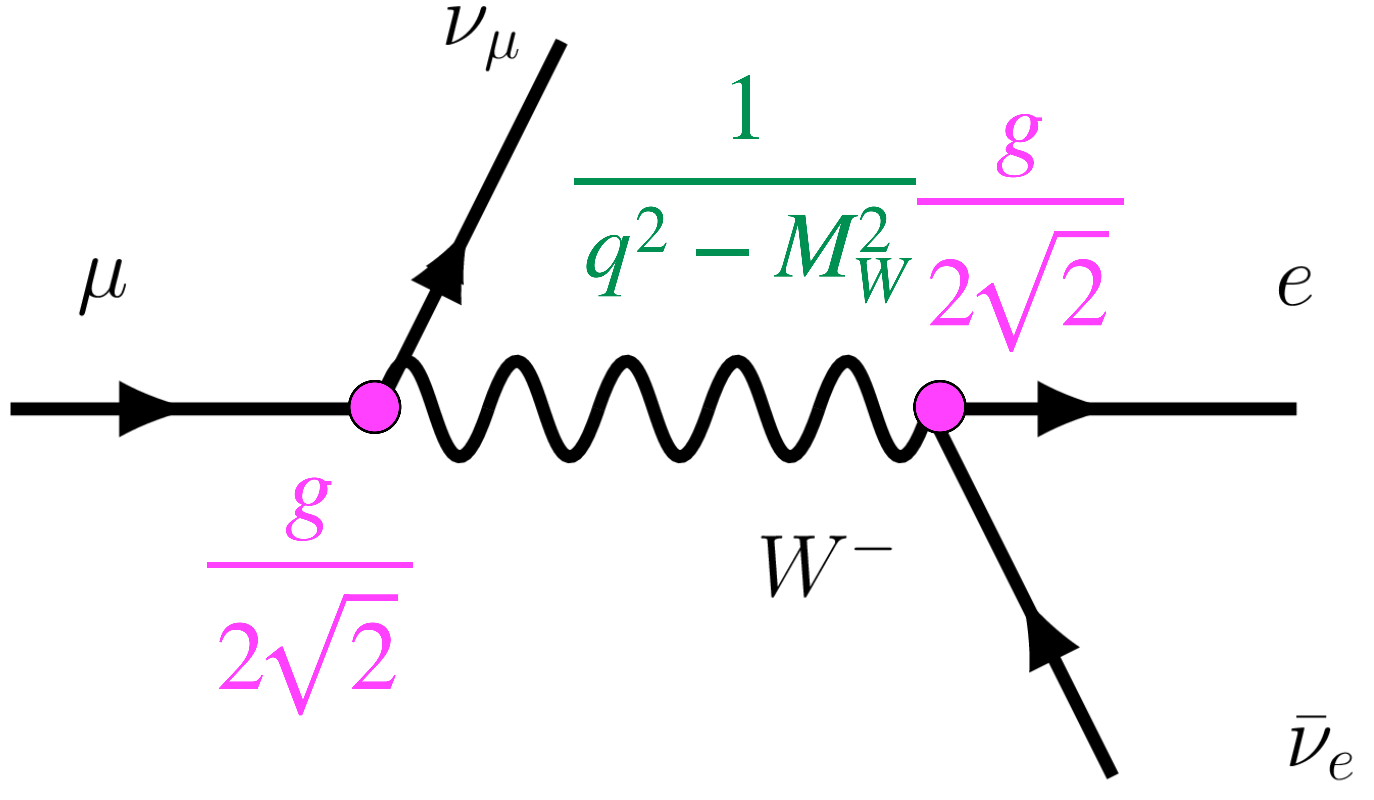
$BR_{Undet} = 0.03 \pm 0.03$

EFT framework

The point-like interaction (Fermi theory) is an **EFT of the SM**, when probed at low energy (nuclear forces E~MeV)



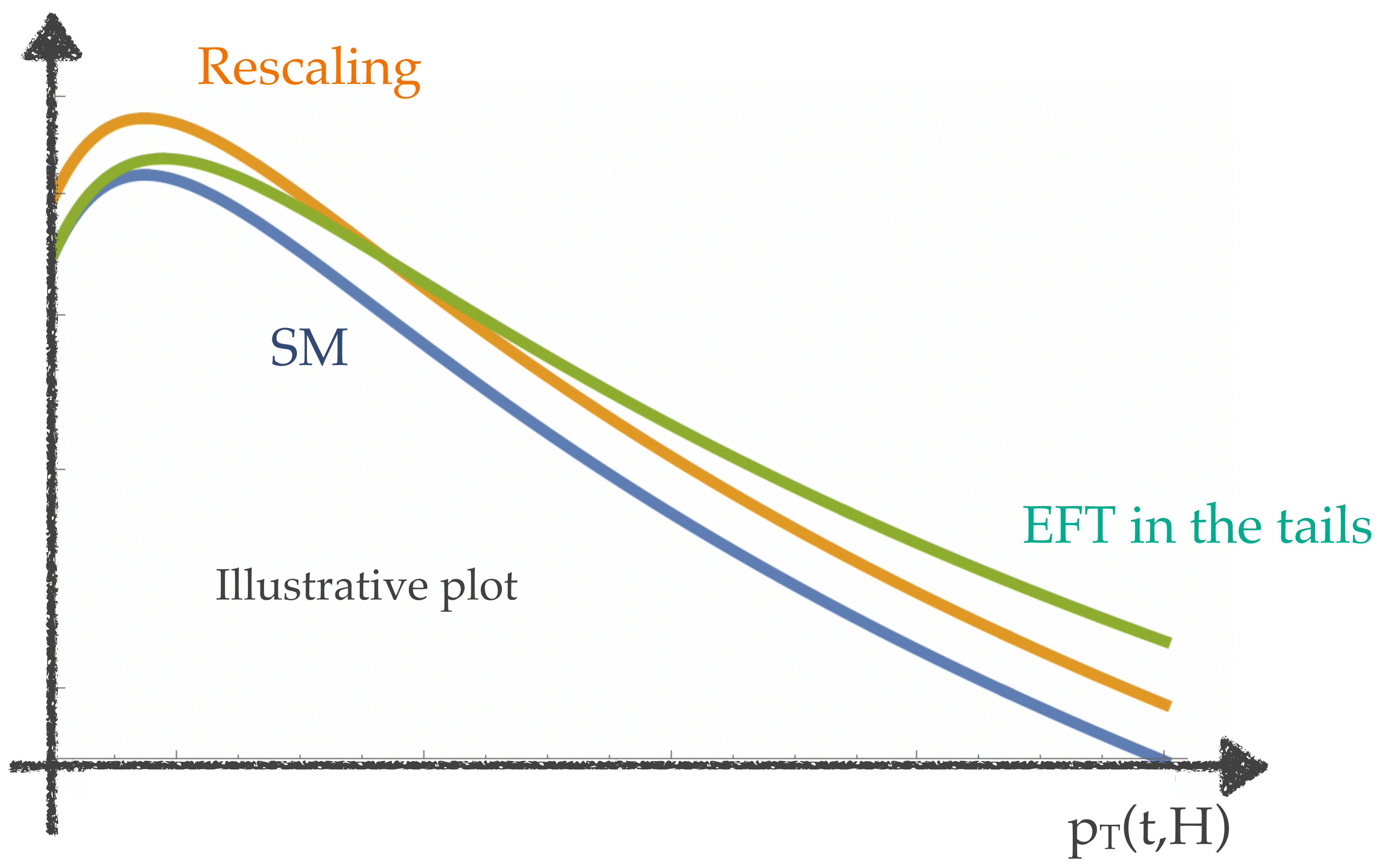
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d}^{N} \sum_{j \in \mathcal{O}^{(d)}} \frac{c_j^{(d)}}{\Lambda^{d-4}} \mathcal{O}_j^{(d)}$$



SMEFT = Effective Lagrangian built from SM fields and respecting the SM gauge symmetry

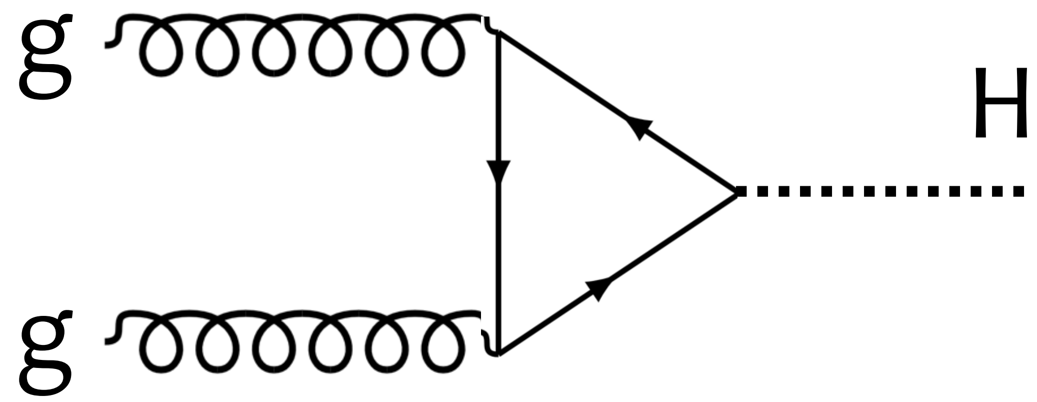
Expansion in $1/\Lambda$ affects all SM observables at both high and low energy

- **At EW scale**: change in rates (**couplings**)
- **At higher scale**, eg. Higgs p_T: change in shapes => **tails of the differential distributions**

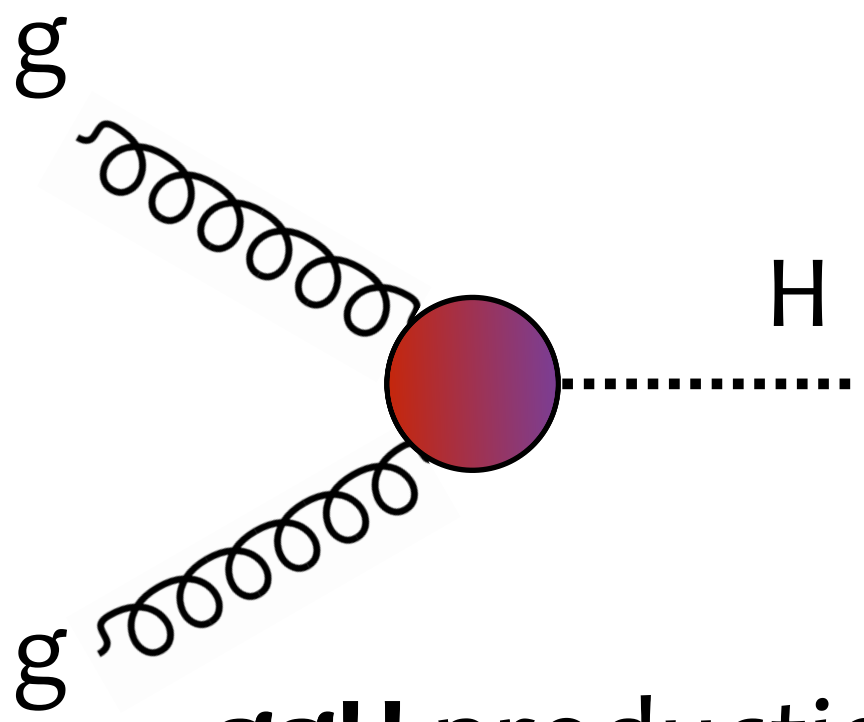


Compressing loops in Higgs couplings

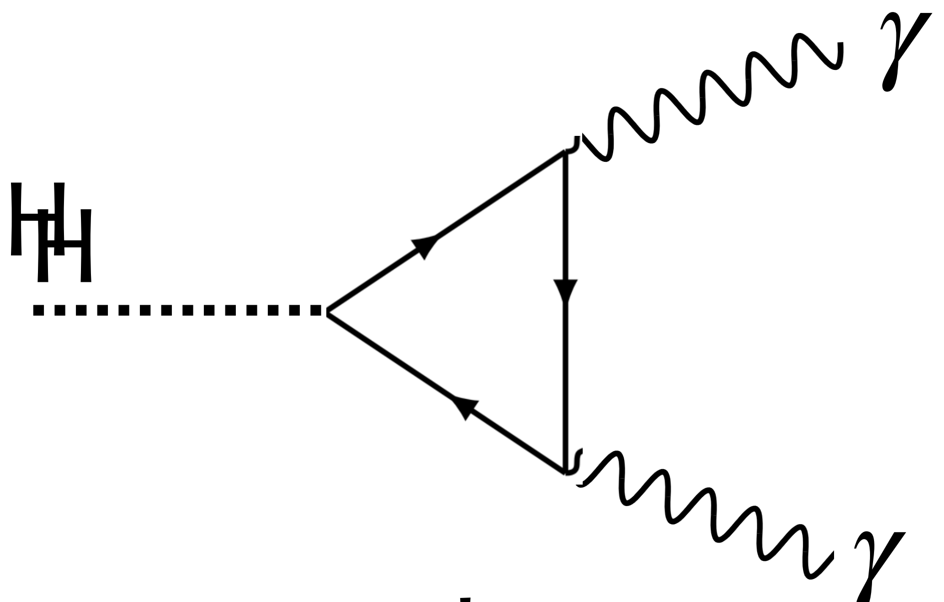
In EFTs, the Higgs diagrams involving loops can be treated as effective couplings



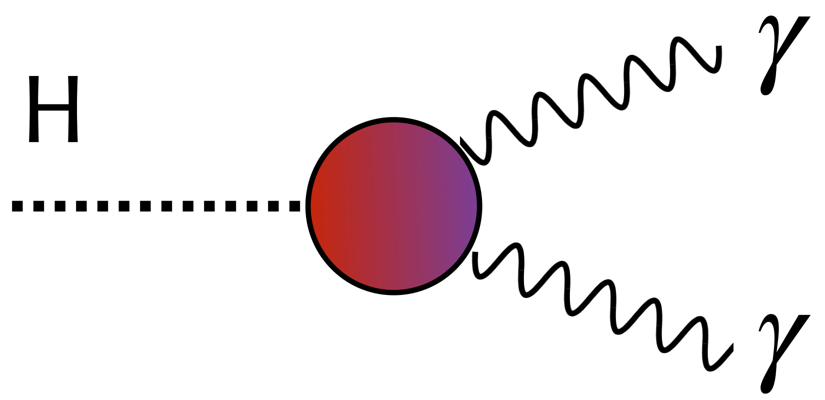
ggH production
via **quark loop**



ggH production via
effective coupling κ_g



H $\rightarrow \gamma\gamma$ decay
via **quark loop**



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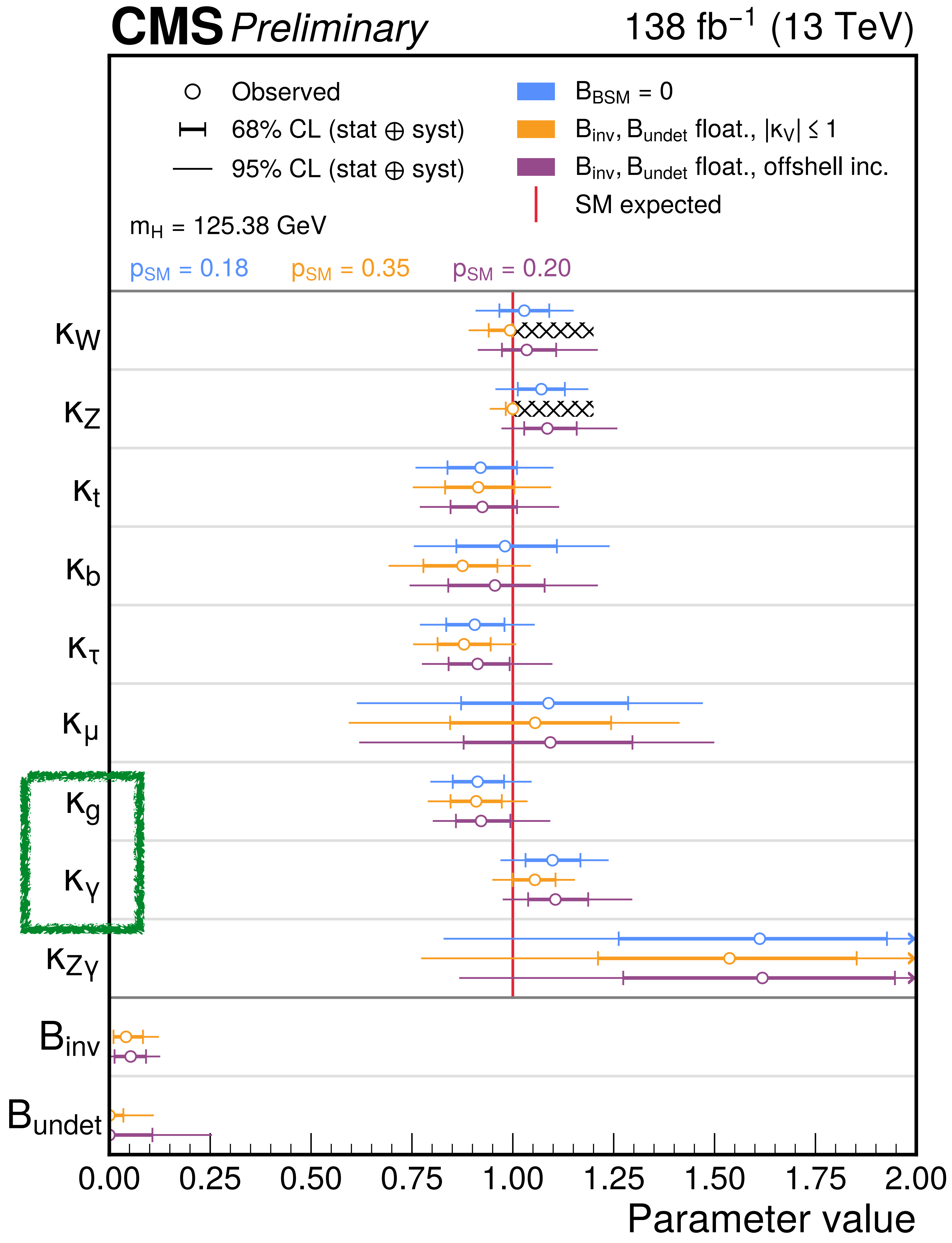
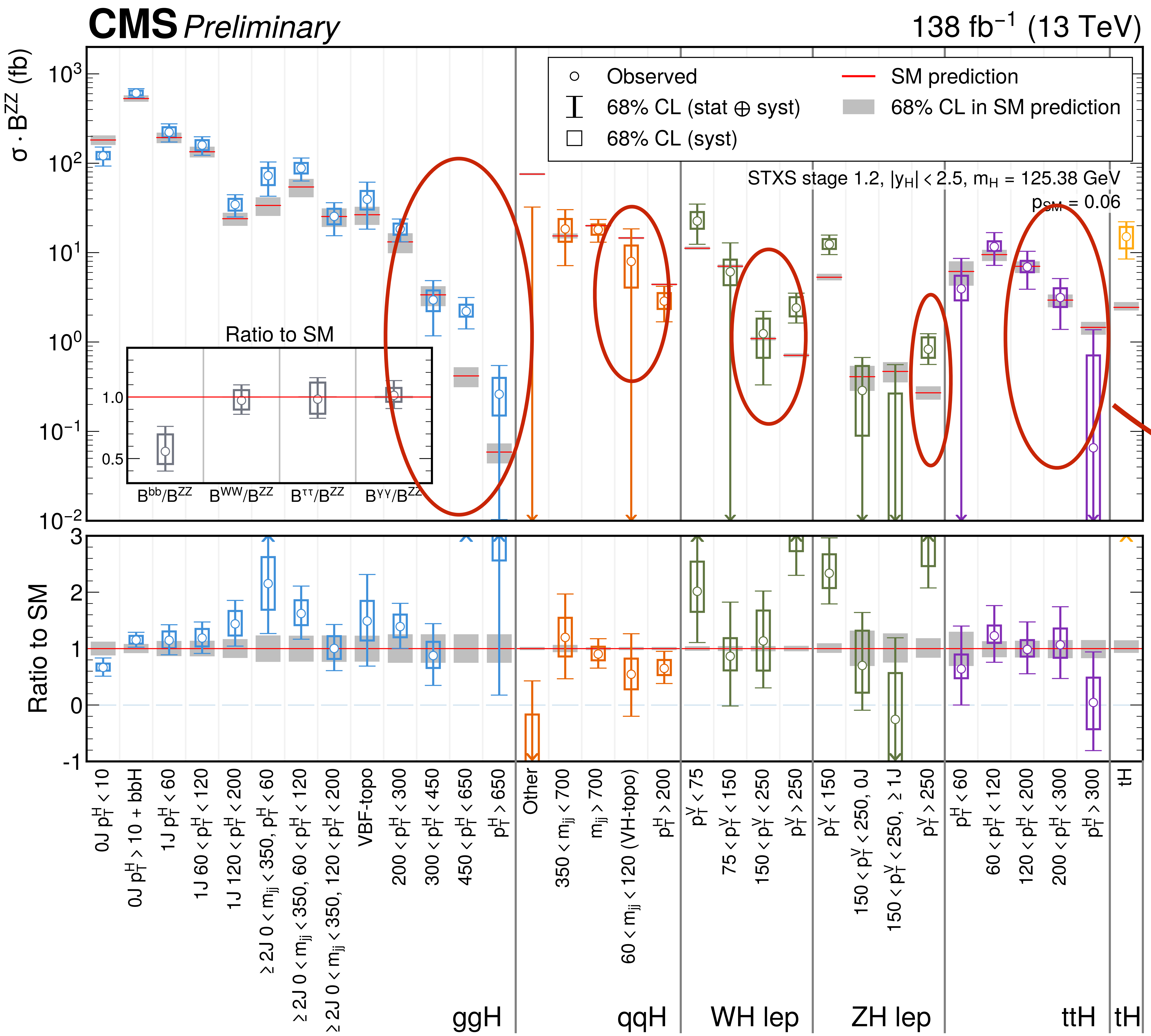
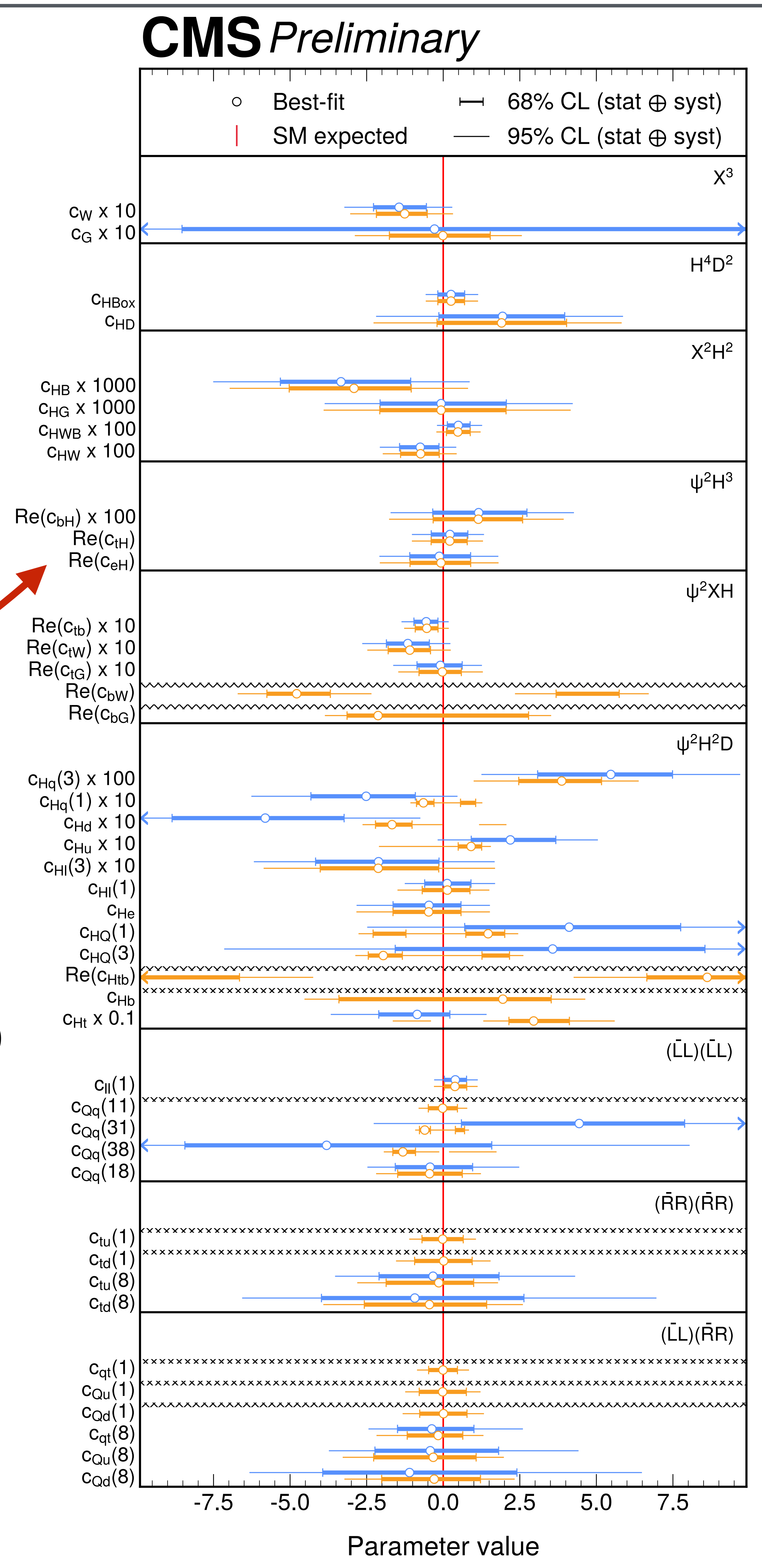


Constraints from Higgs kinematics



energy (p_T^H)

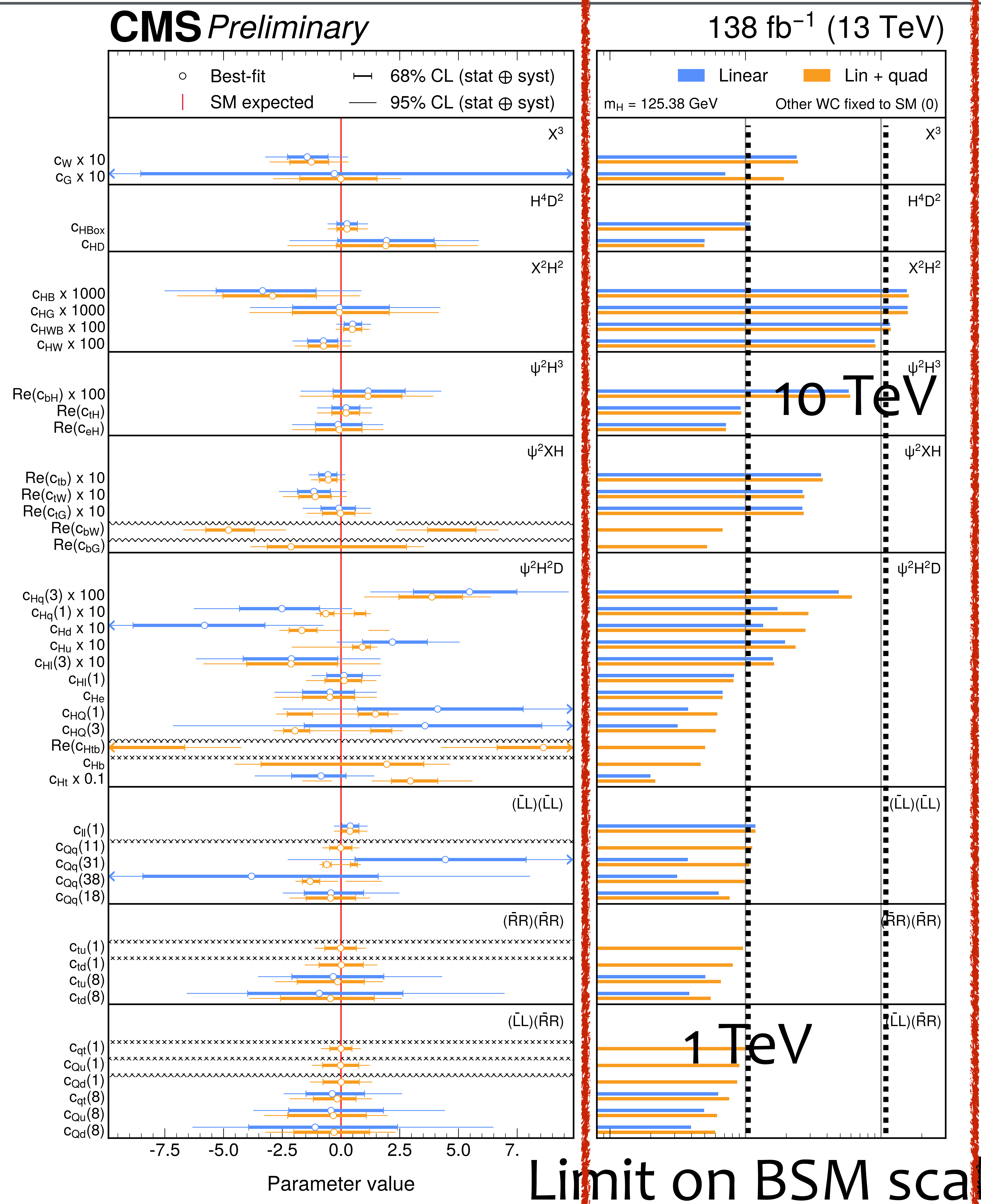


Differential cross sections per production mode parameterised in terms of Wilson Coefficients C_i

Tails in p_T^H sensitive to new physics effects

$H \rightarrow \gamma\gamma, VH(bb), ttH$ have good sensitivity

How does this map to BSM probed scale?

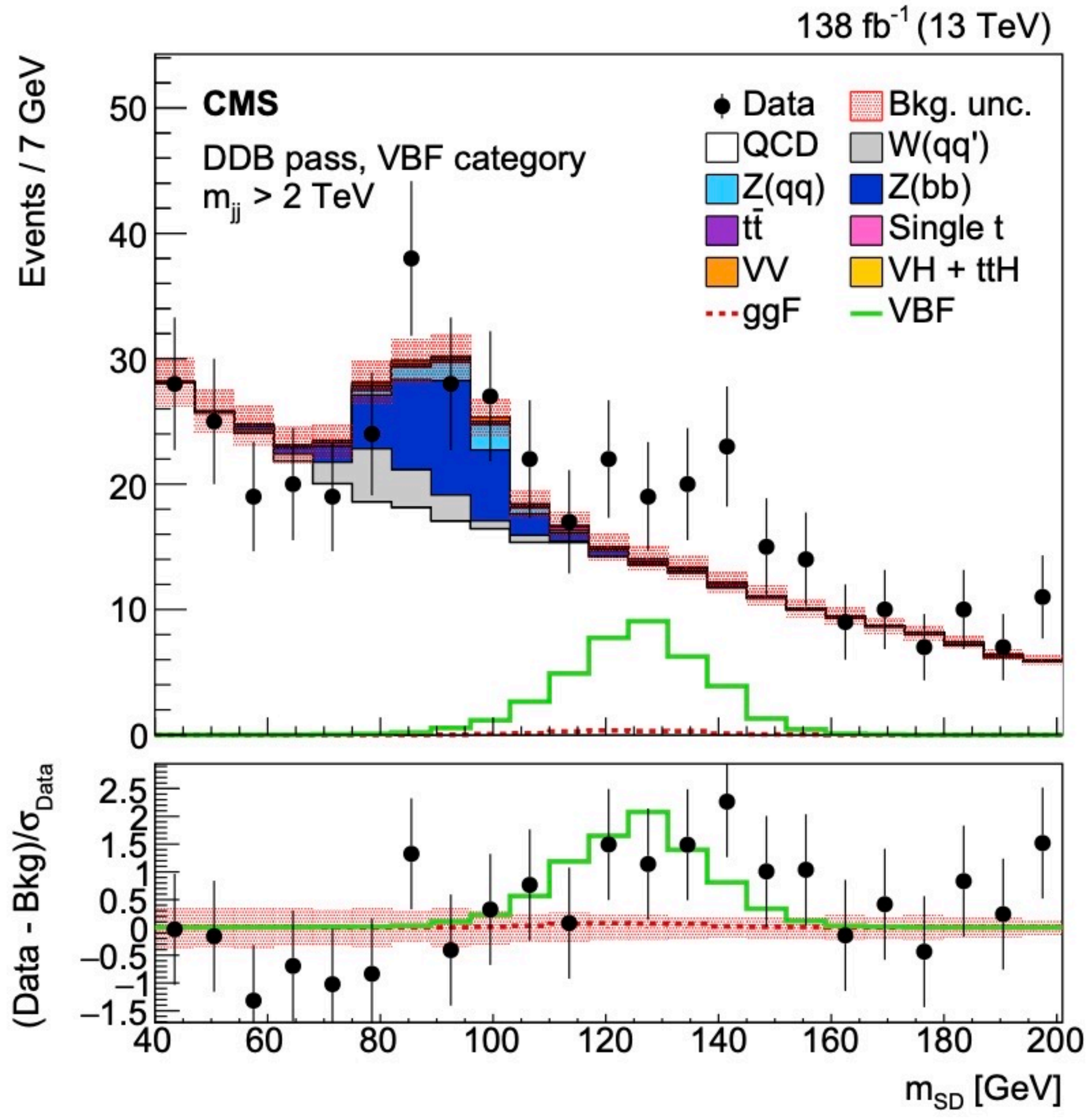


Limit on BSM scale Λ

Sensitive to 43 EFT operators

Some of them are excluded up to a scale $\Lambda \sim 10\,\mathrm{TeV}$

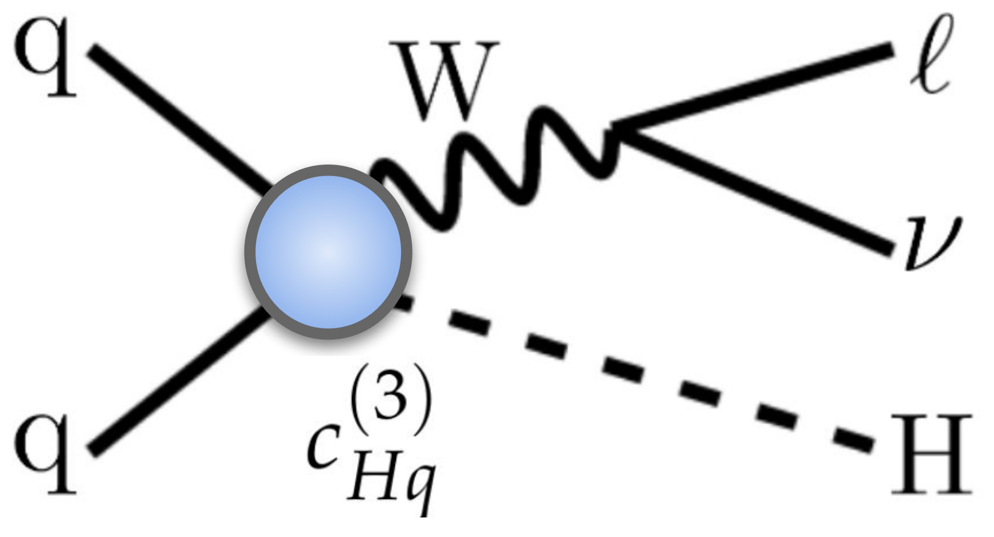
To reach very high p_T^H, make use of dedicated reconstruction tools (eg. boosted jets)



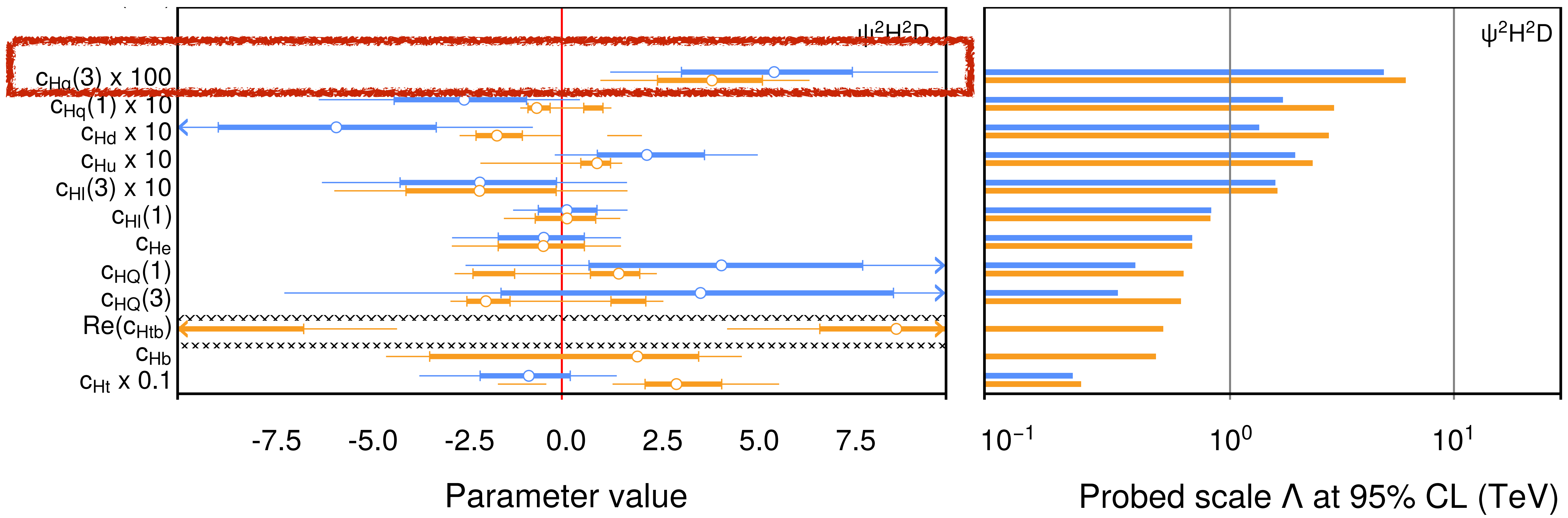
VBF, H $\rightarrow b\bar{b}$

with boosted b-jets

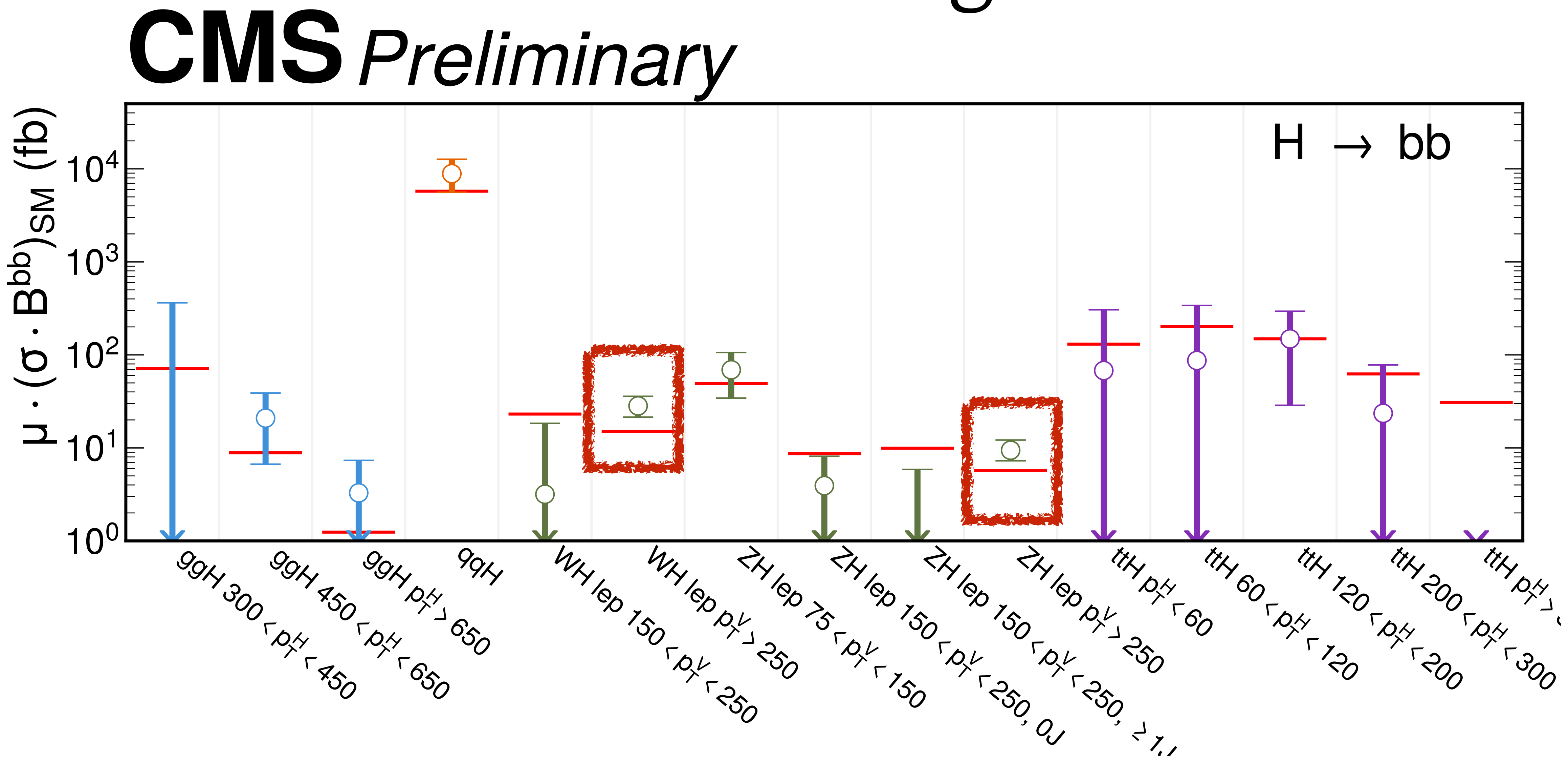
Are there anomalies?

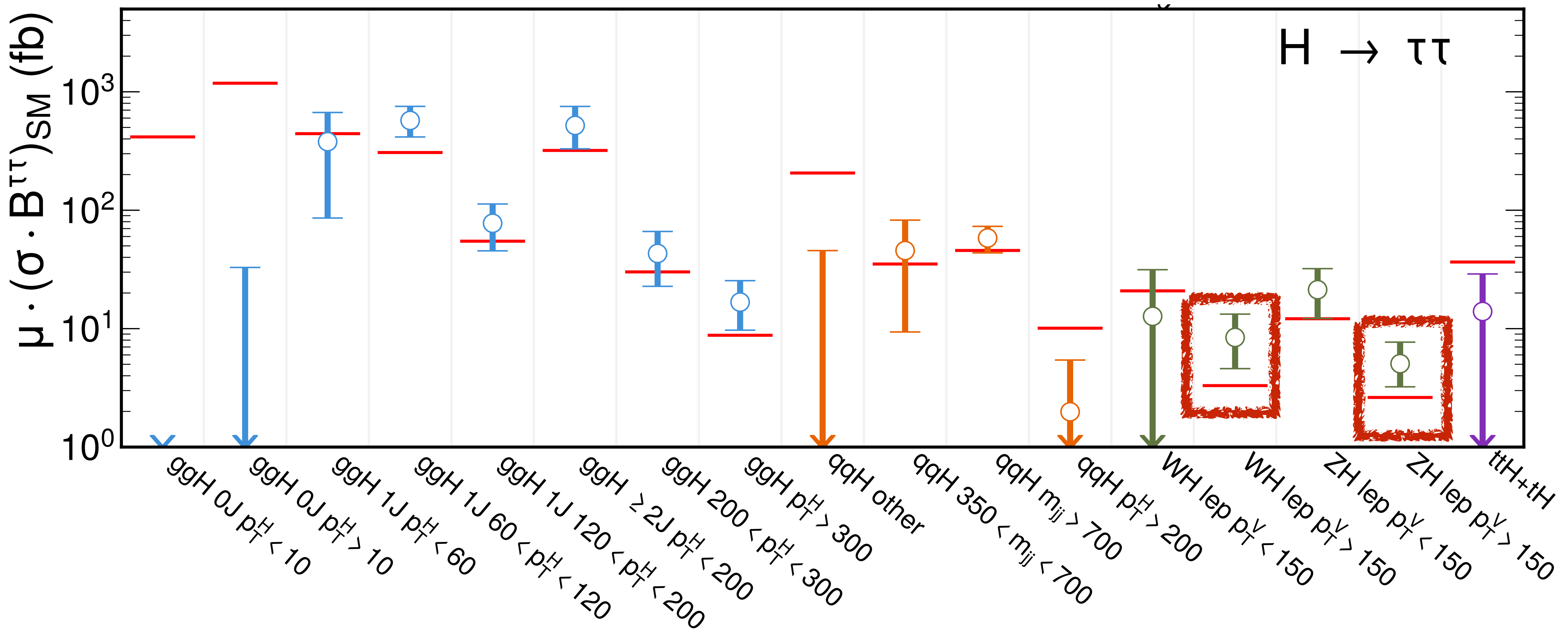


$$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$$



Coming from small deviations at **high** $p_T^{W,Z}$ **in** $H \to b\bar{b}$ **,** $H \to \tau\tau$





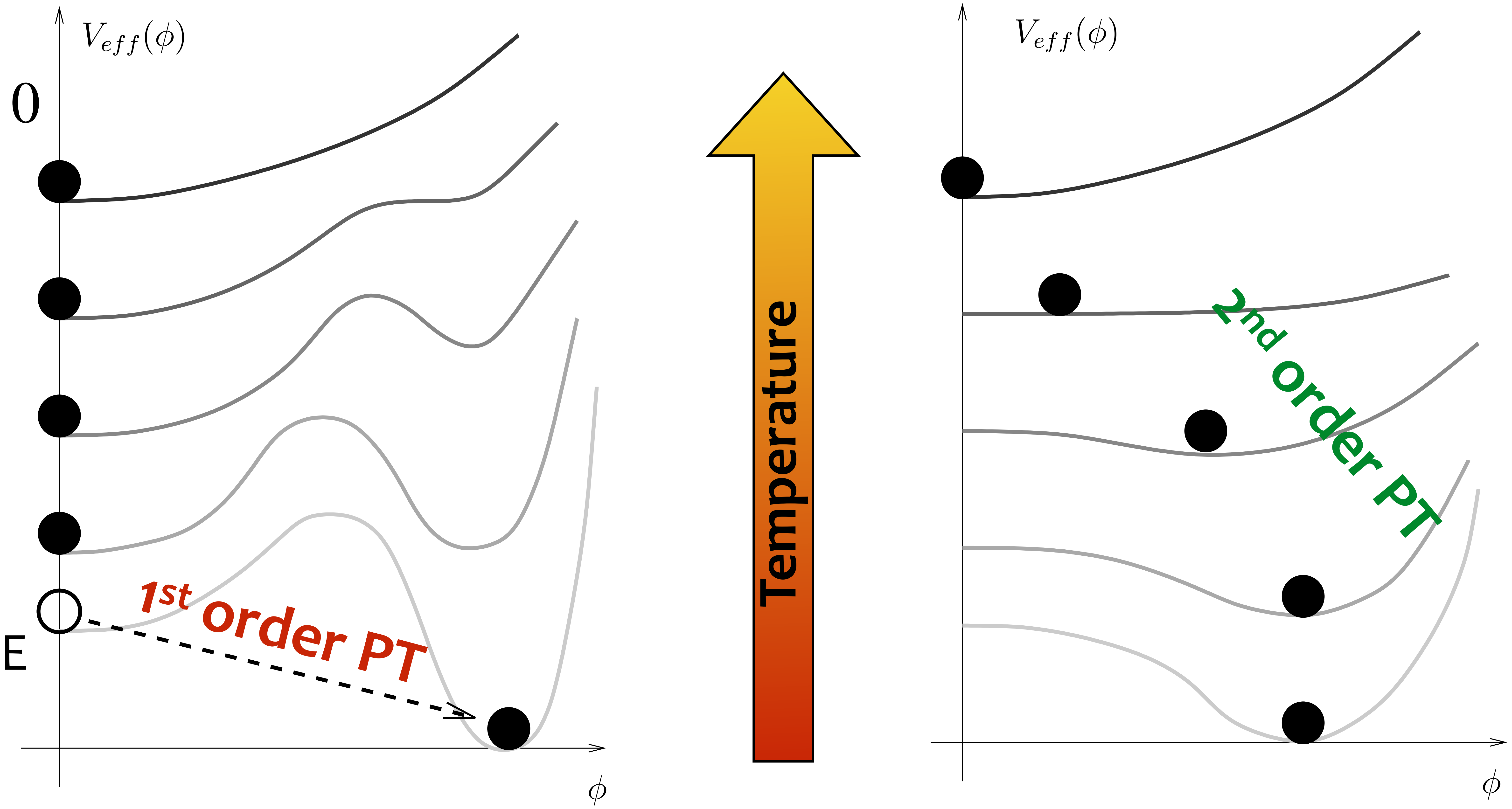
Higgs potential vs baryogenesis

Why matter >> anti-matter in the universe?

CP-violation (CKM matrix) is too weak to explain why $n_B \gg n_{\bar{B}}$

1 minimum at $\phi = 0$ (stable) at E>100 GeV

2 minima: $\phi = 0$ and $\phi \neq 0$ at low E



1 minimum at $\phi = 0$ (stable) at E>100 GeV

1 minimum at $\phi \neq 0$ at low E

Sakharov condition for $n_B \gg n_{\bar{B}}$: **1st order phase transition** (PT)

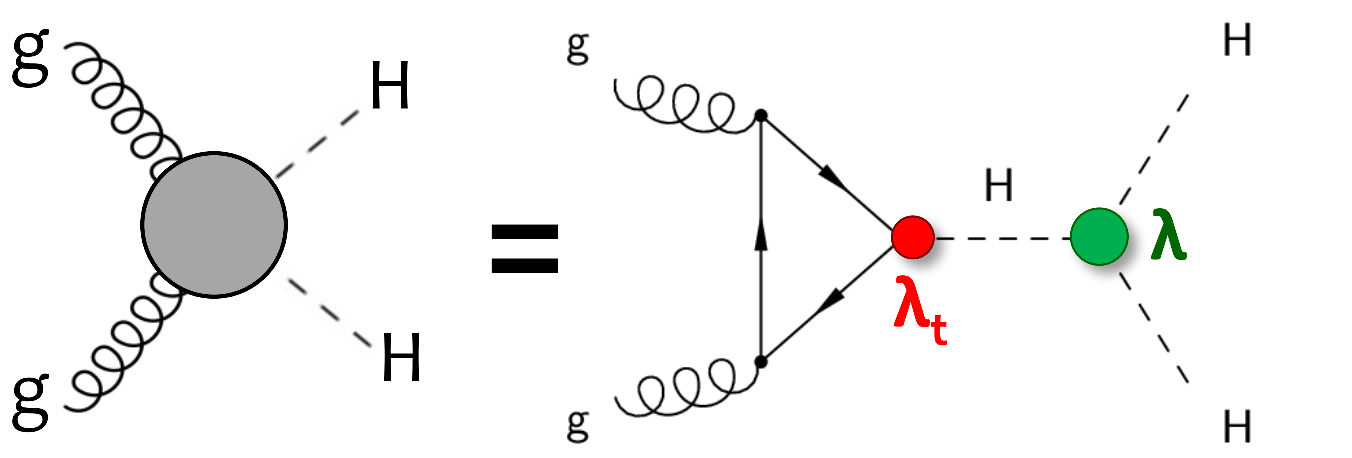
HH production at LHC

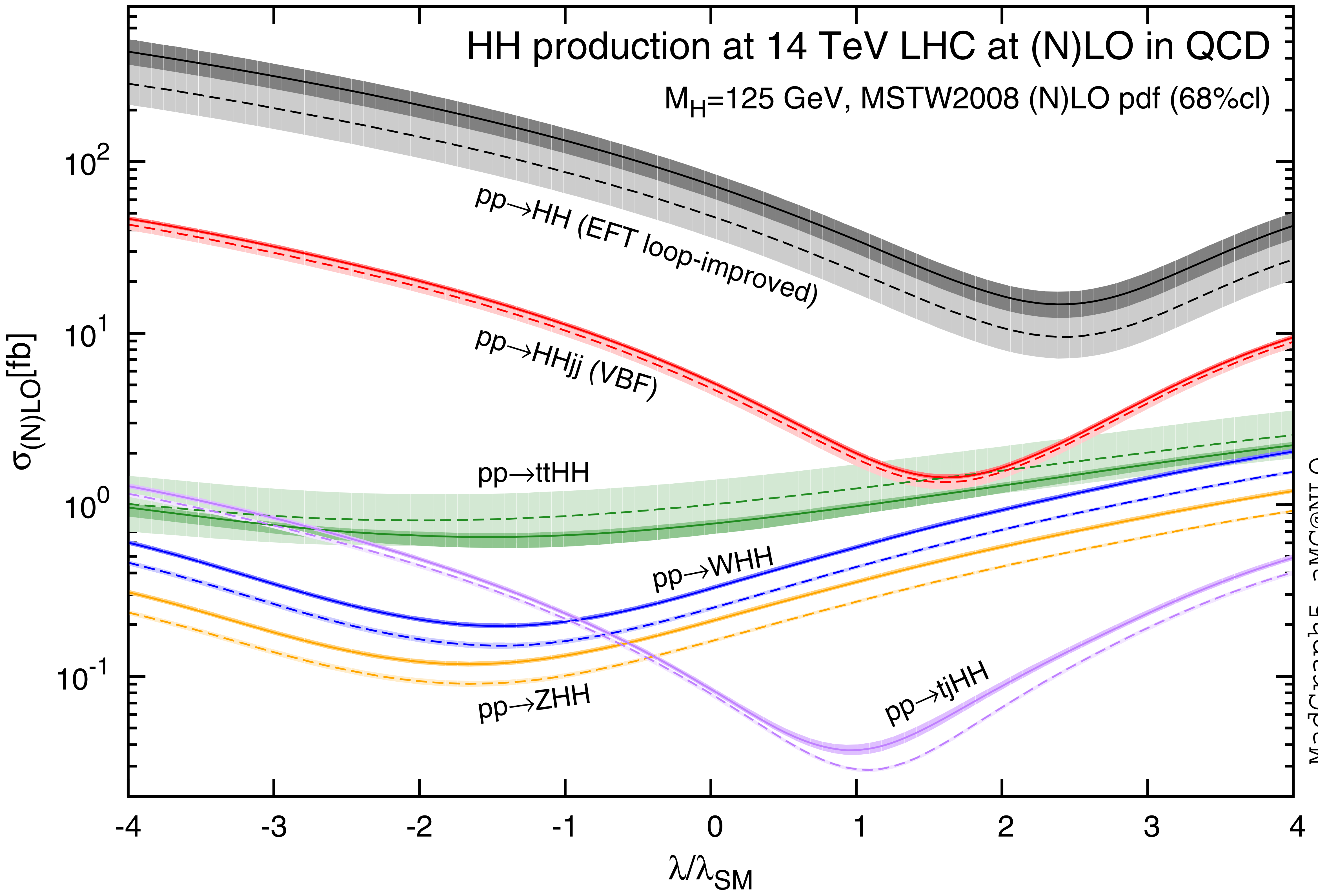
- Di-Higgs production at the LHC is dominated by the gluon-fusion process, as single-H, but **extremely smaller:**

PLB 732 (2014) 142-149

ggF: $\sigma(\mathrm{ggHH}) = 31\ \mathrm{fb} \approx 1/1500 \times \sigma(\mathrm{ggH})$

self-coupling λ





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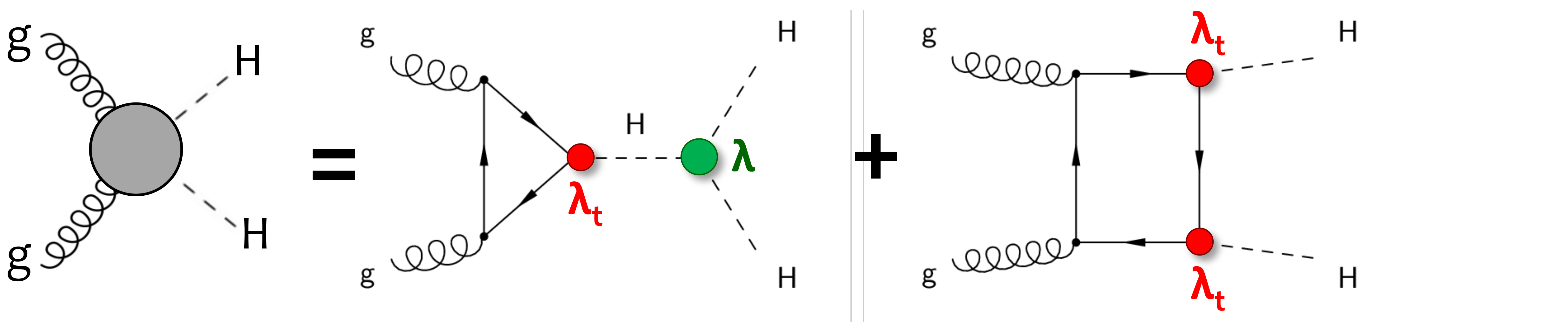
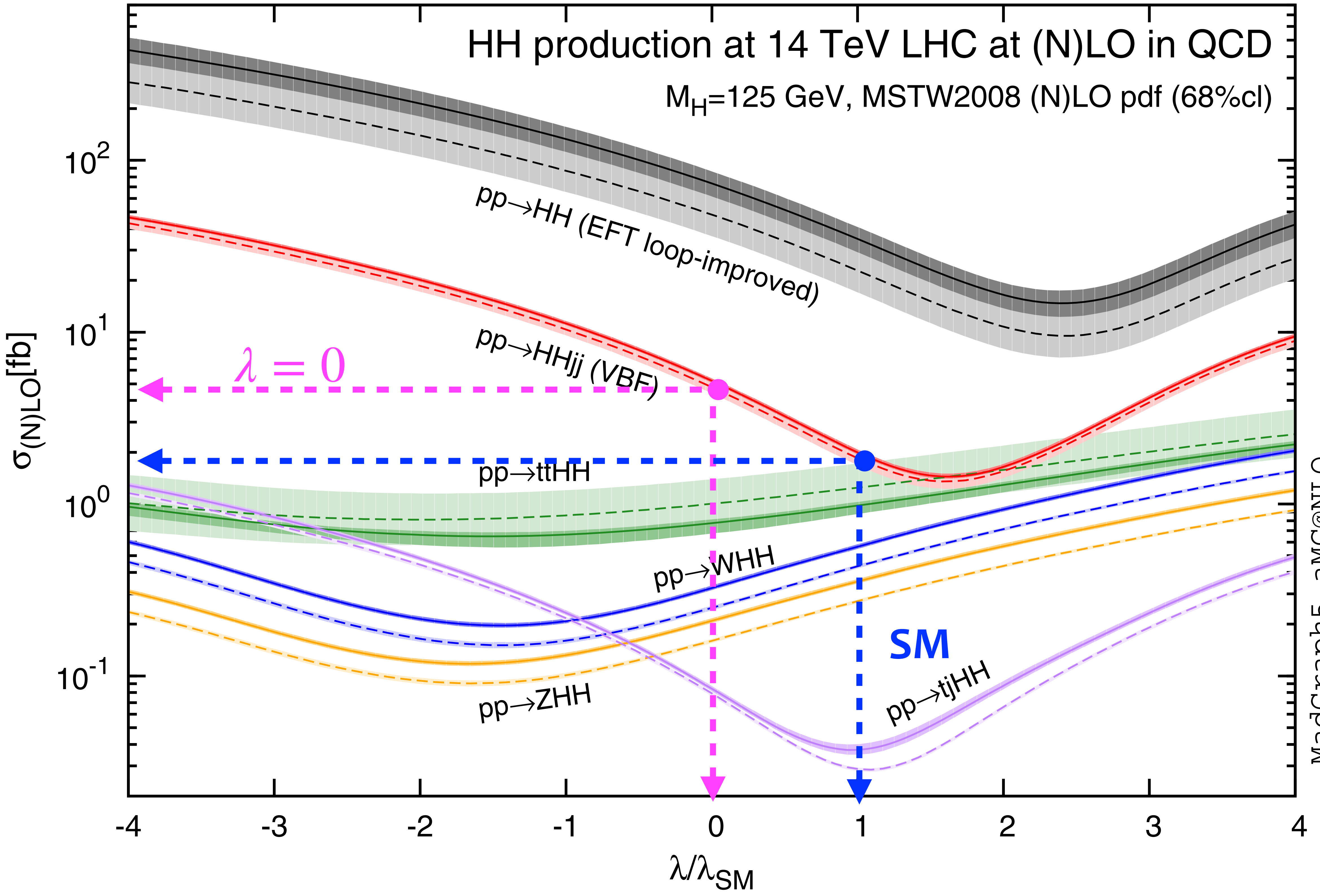
self-coupling λ **Higgs-top coupling λ_t**





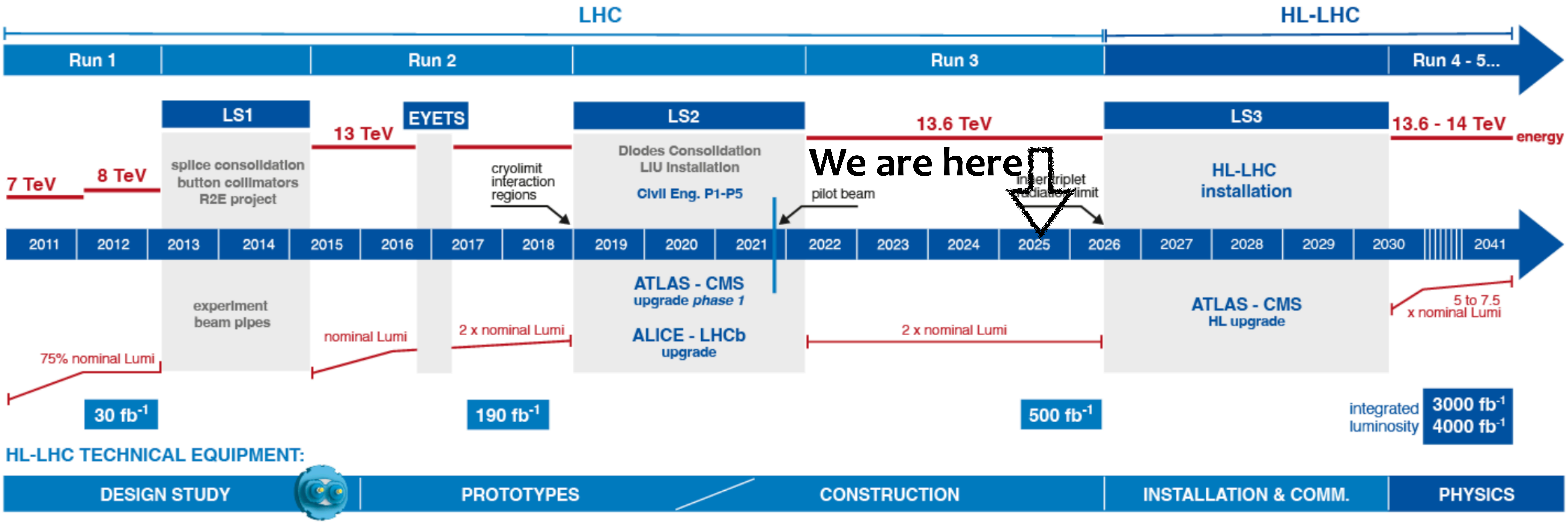
Destructive interference makes $\sigma^{\lambda=0} > \sigma^{SM}$

Difficult to observe HH production before HL-LHC,

but can test existence of self-coupling by excluding $\lambda = 0$

Beyond the running LHC

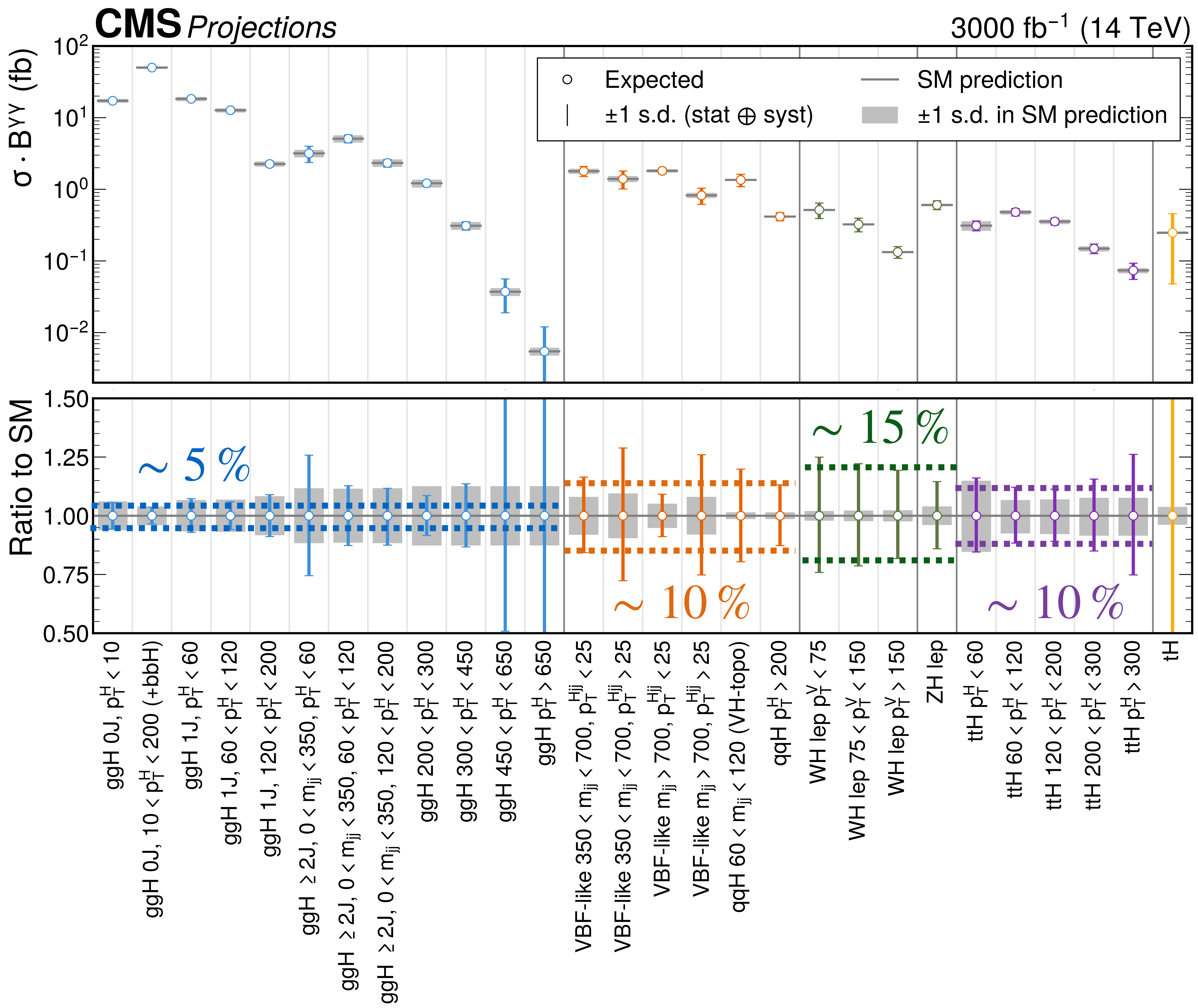
Beyond the end of Run-3, the upgrade of LHC at High-Luminosity (HL-LHC) will deliver **x20 data collected so far**



What can we do in terms of determining the Higgs potential ?

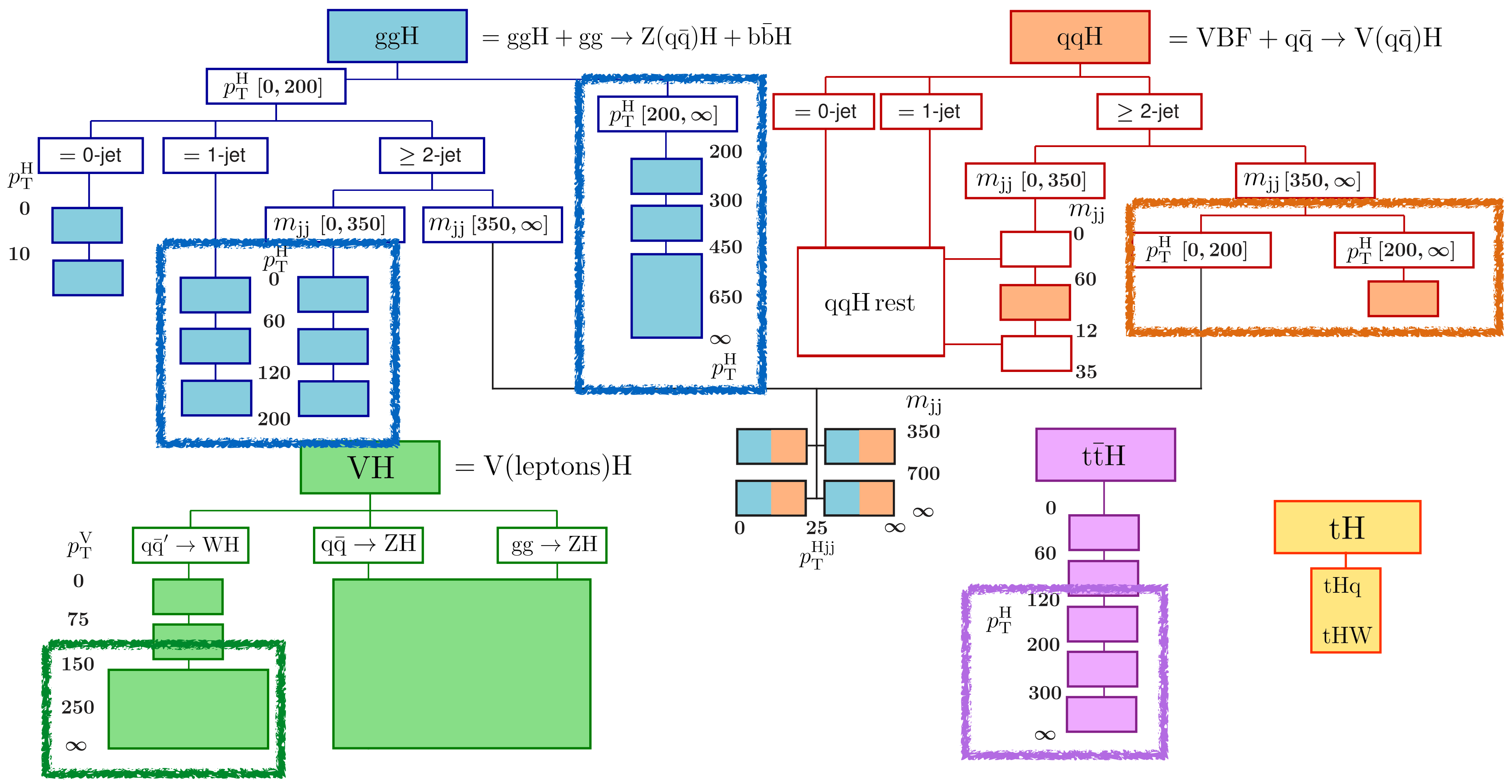
Both **single-H precision measurement** and **observation of HH** production will do

Single-H measurements at HL-LHC



ggH **VBF** **W,Z H** **ttH**

STXS bins
(production and decay categories)

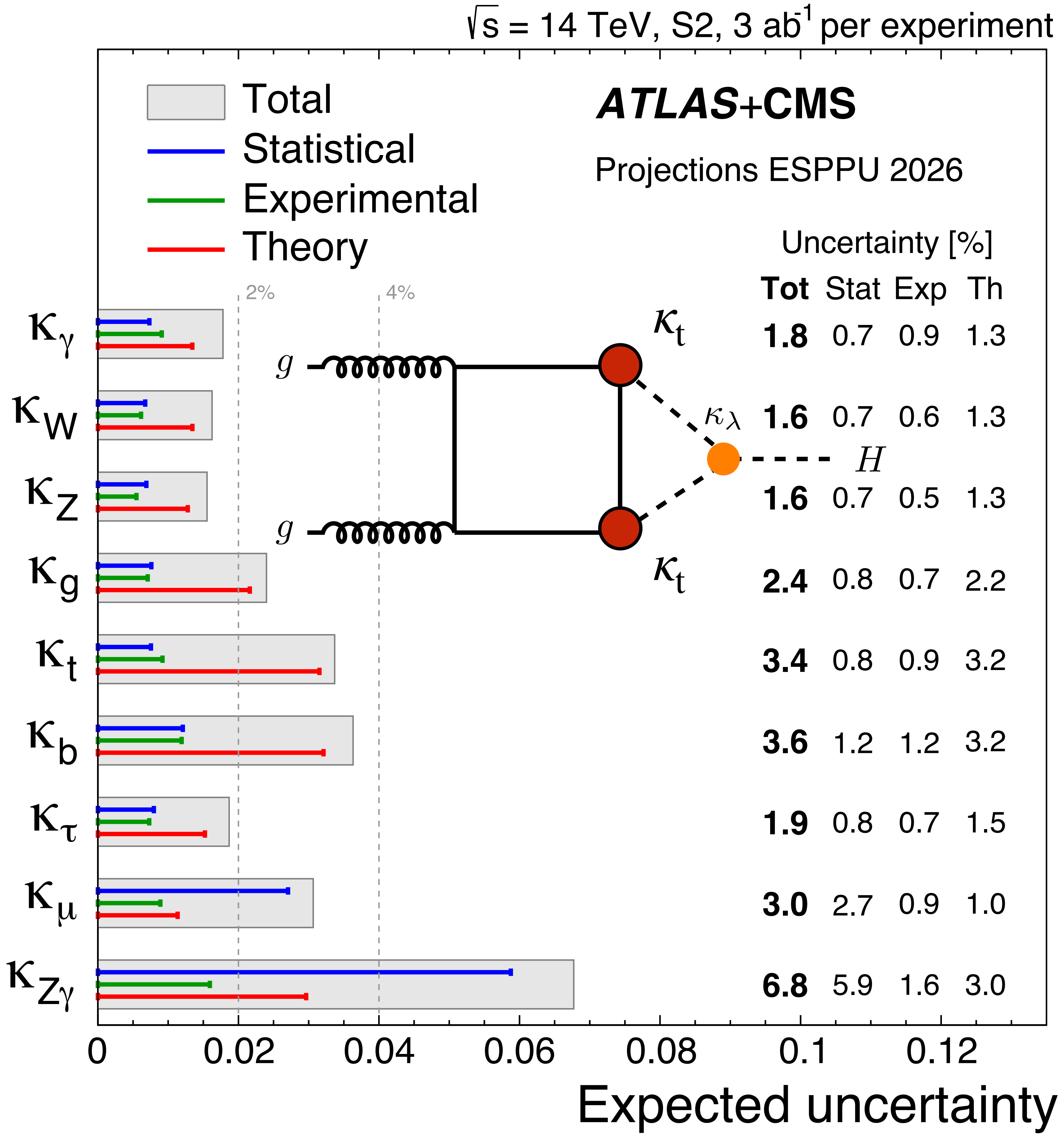


High p_T^H, high jet multiplicities, i.e. kinematic tails more sensitive to BSM.

With 20x LHC dataset, exp. precision comparable to theory: **test of the SM**

H and HH projections to HL-LHC

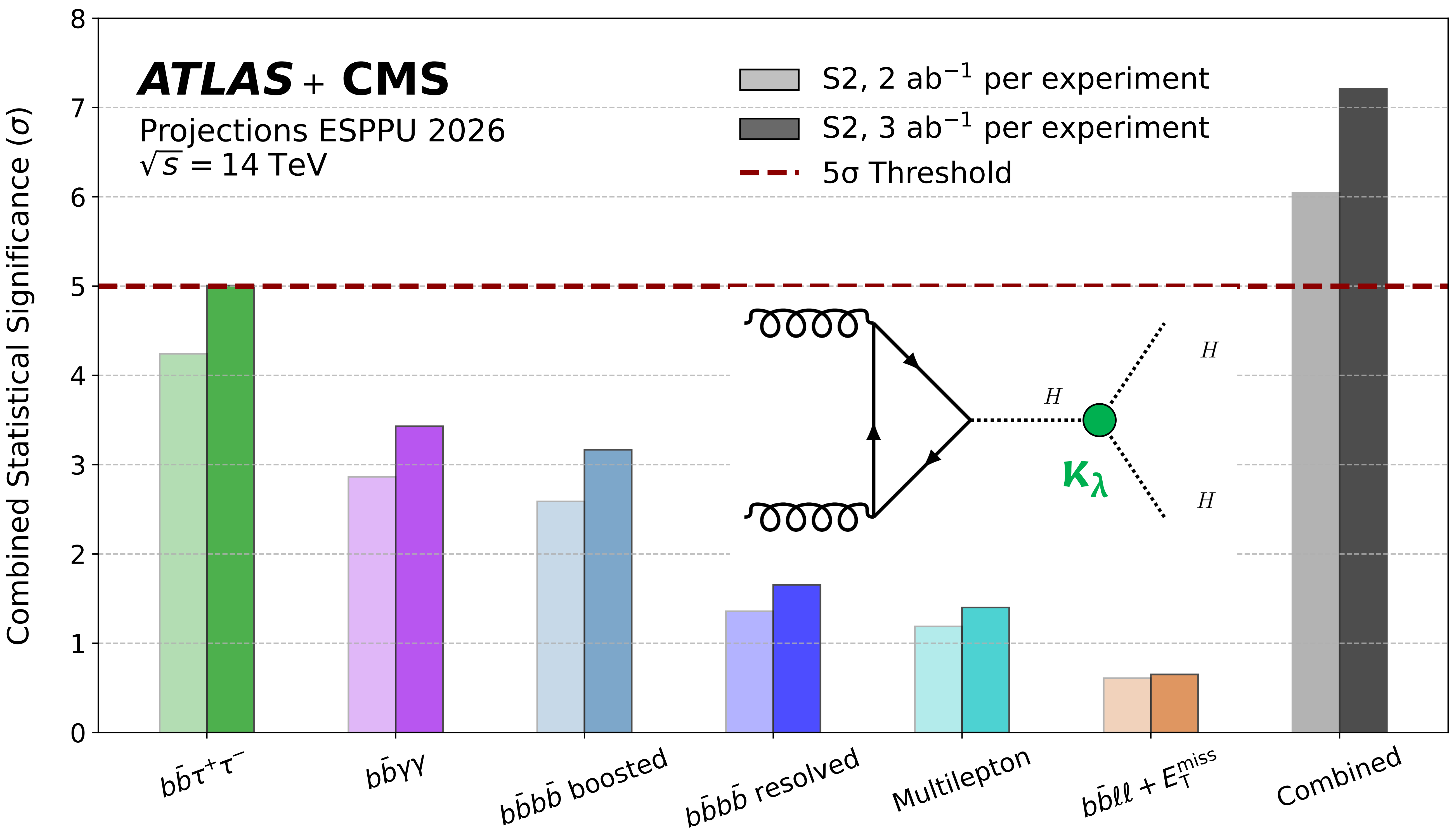
Single-H couplings



Can reach **O(1%) exp. uncertainty:** need also progress in theory

HH expected significance with

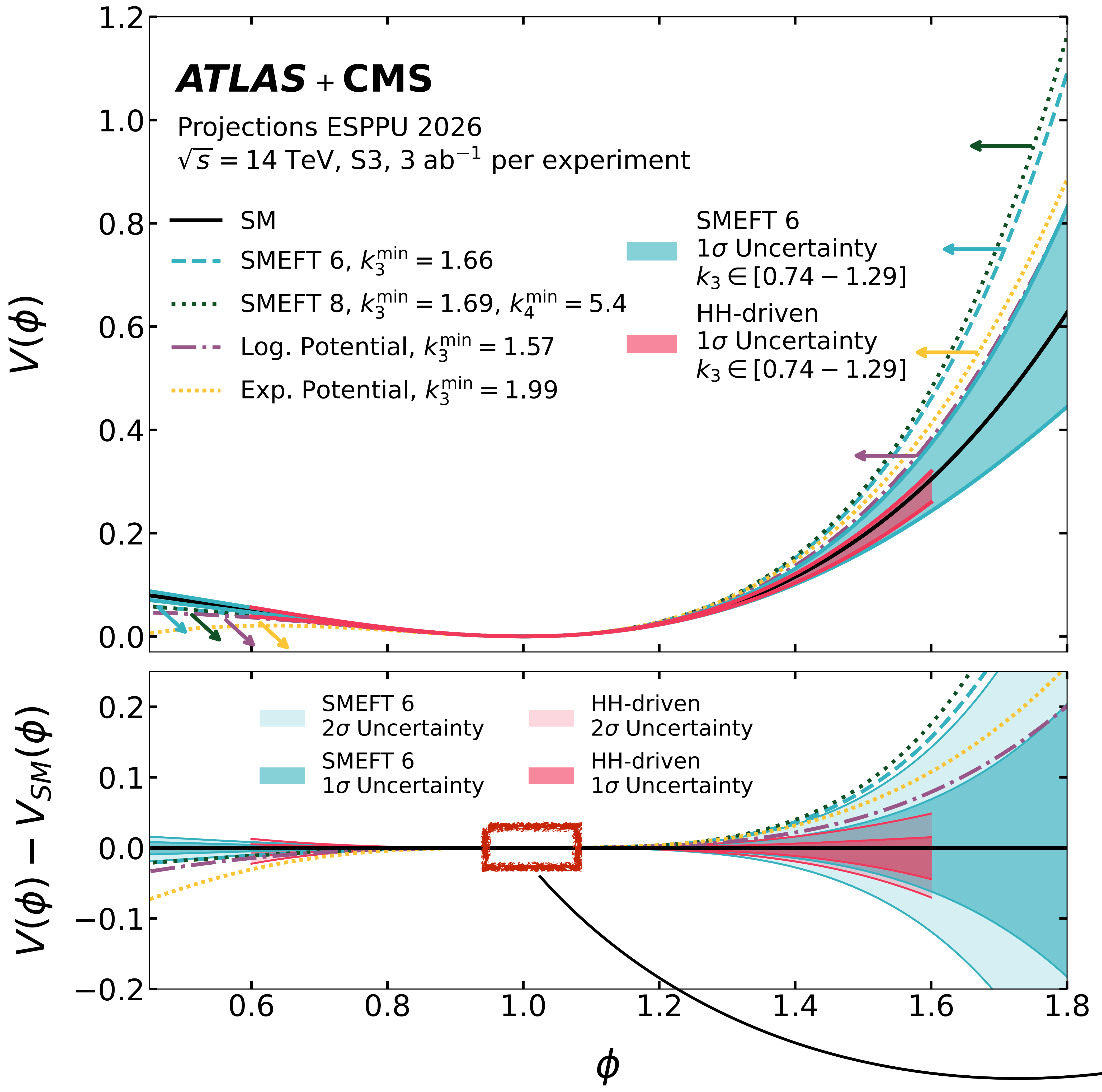
$$L = 2000\ \text{fb}^{-1} \text{ or } L = 3000\ \text{fb}^{-1}$$

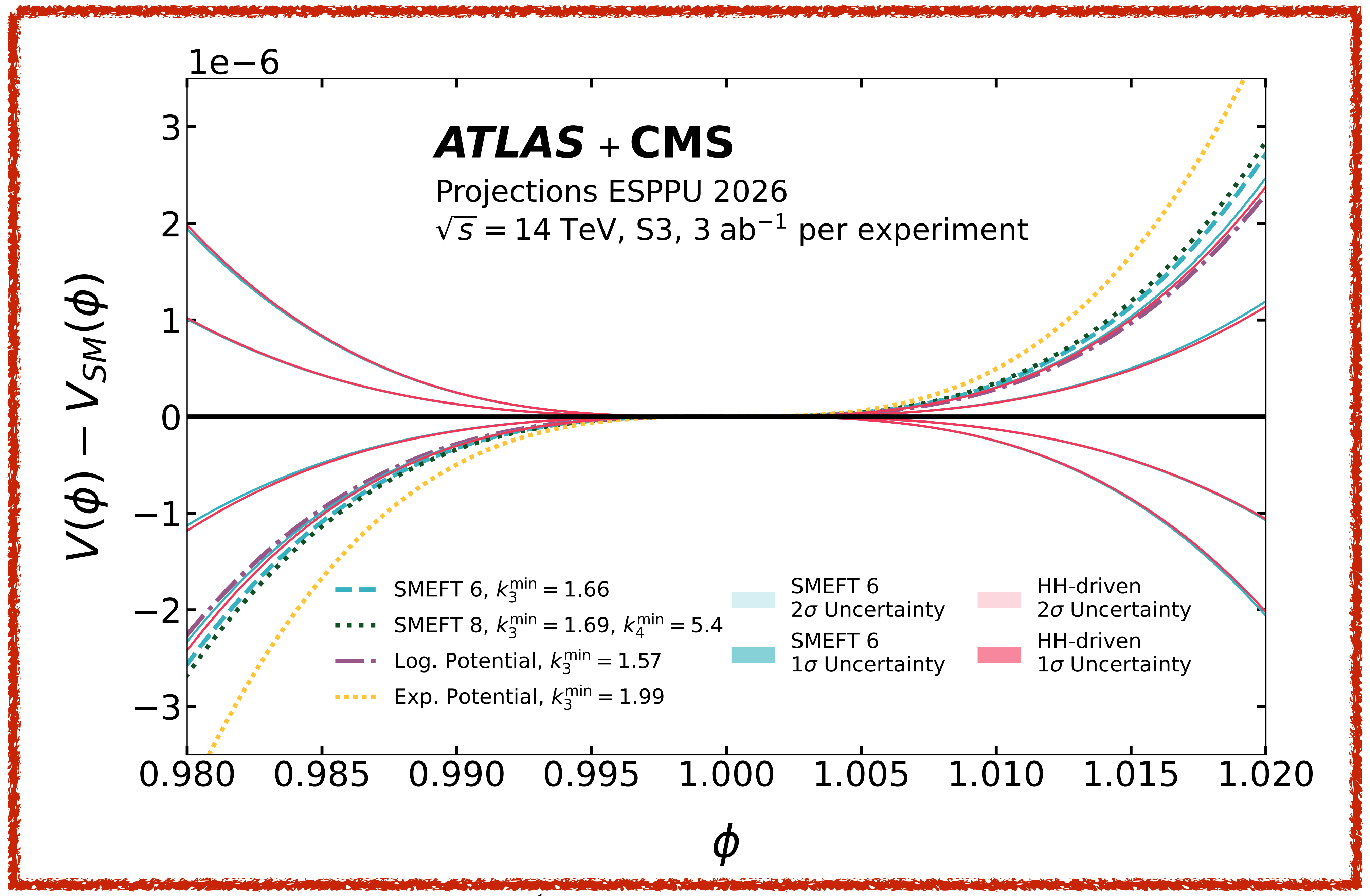


Can deliver the **HH discovery** with the **full HL-LHC** dataset

Higgs potential shape at HL-LHC

With **> 10x** of the current LHC luminosity **possible to exclude strong 1st order PT**

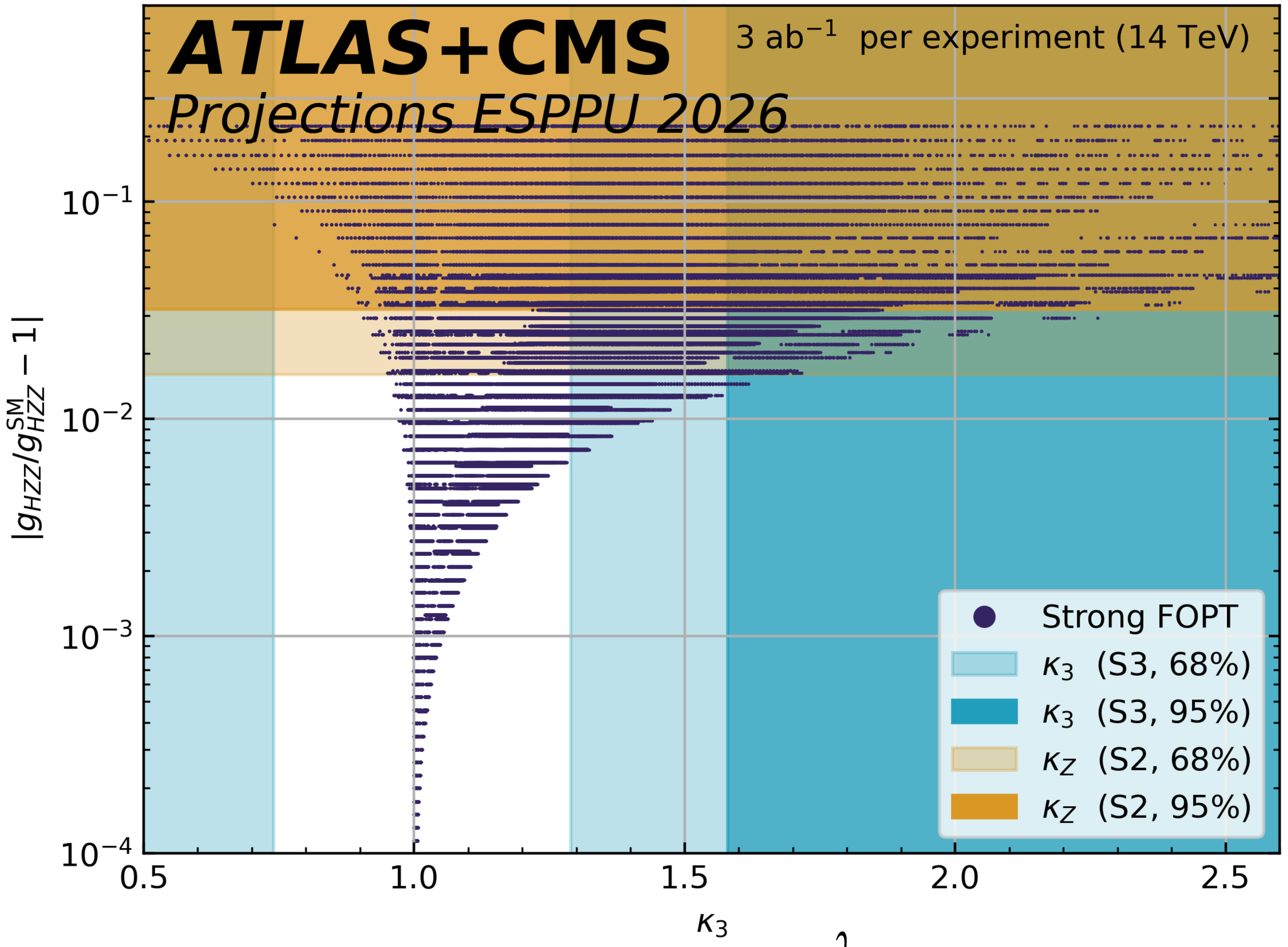




L=3000 fb^{-1}

Higgs and stability of the Universe

With 1-2% precision on H-ZZ coupling and 20-30% precision in κ_λ: **can exclude most of the region inducing 1st order PT (FOPT)**



$$\kappa_3 \equiv \kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

M_H measured with $\delta M_H \sim 20\,\mathrm{MeV}$ and $\delta m_t \sim 200\,\mathrm{MeV}$, HL-LHC can conclude on the **stability of the electroweak vacuum**