Higgs and beyond at the CMS experiment

第五届粒子物理前沿研讨会 中山大学 深圳 2024年4月

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2024-04-13

北京大学
PEKING UNIVERSITY

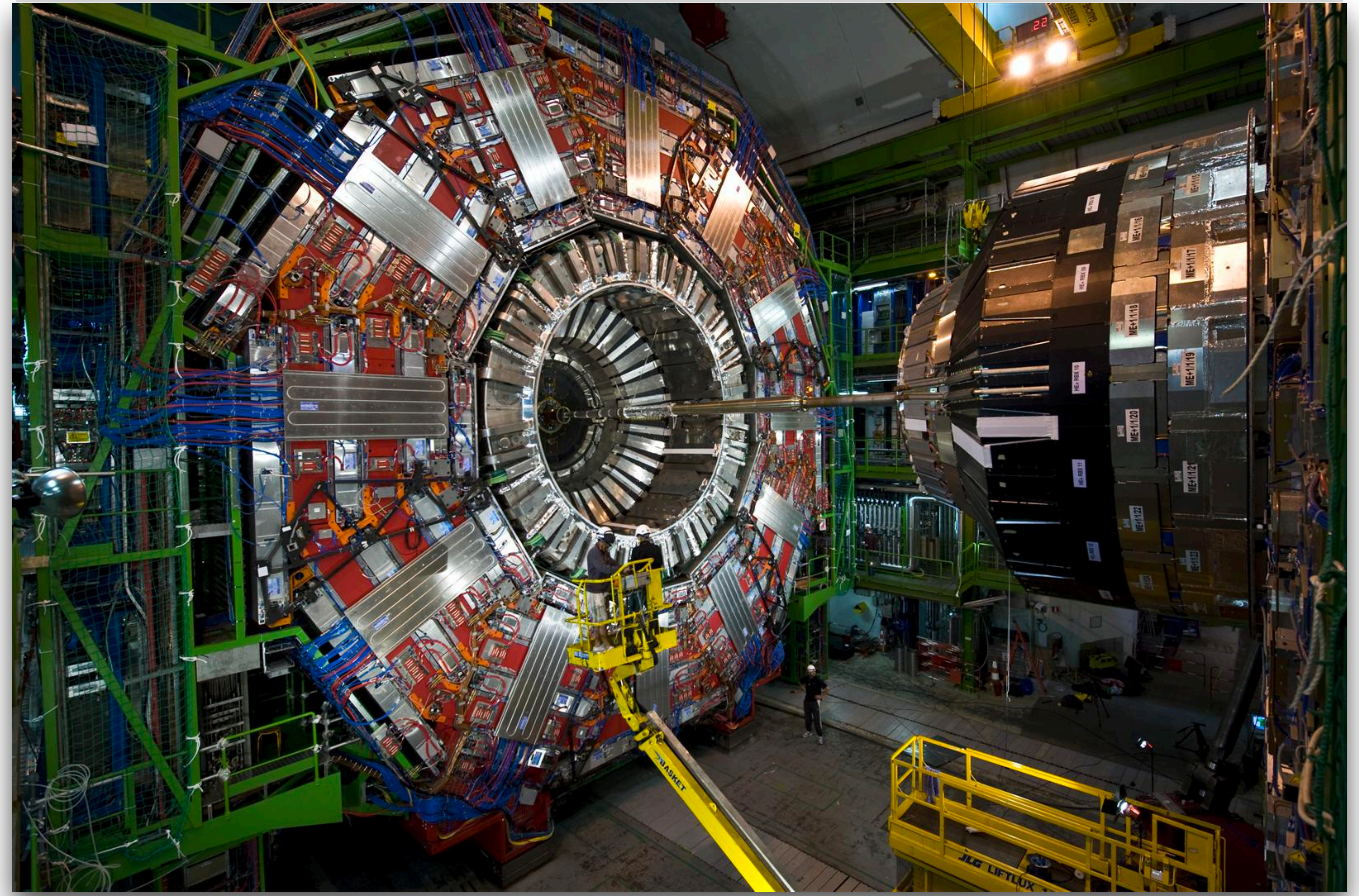
The LHC


LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
… 7, 8, 13, 13.6 TeV
LHC 27 km

General purpose detectors

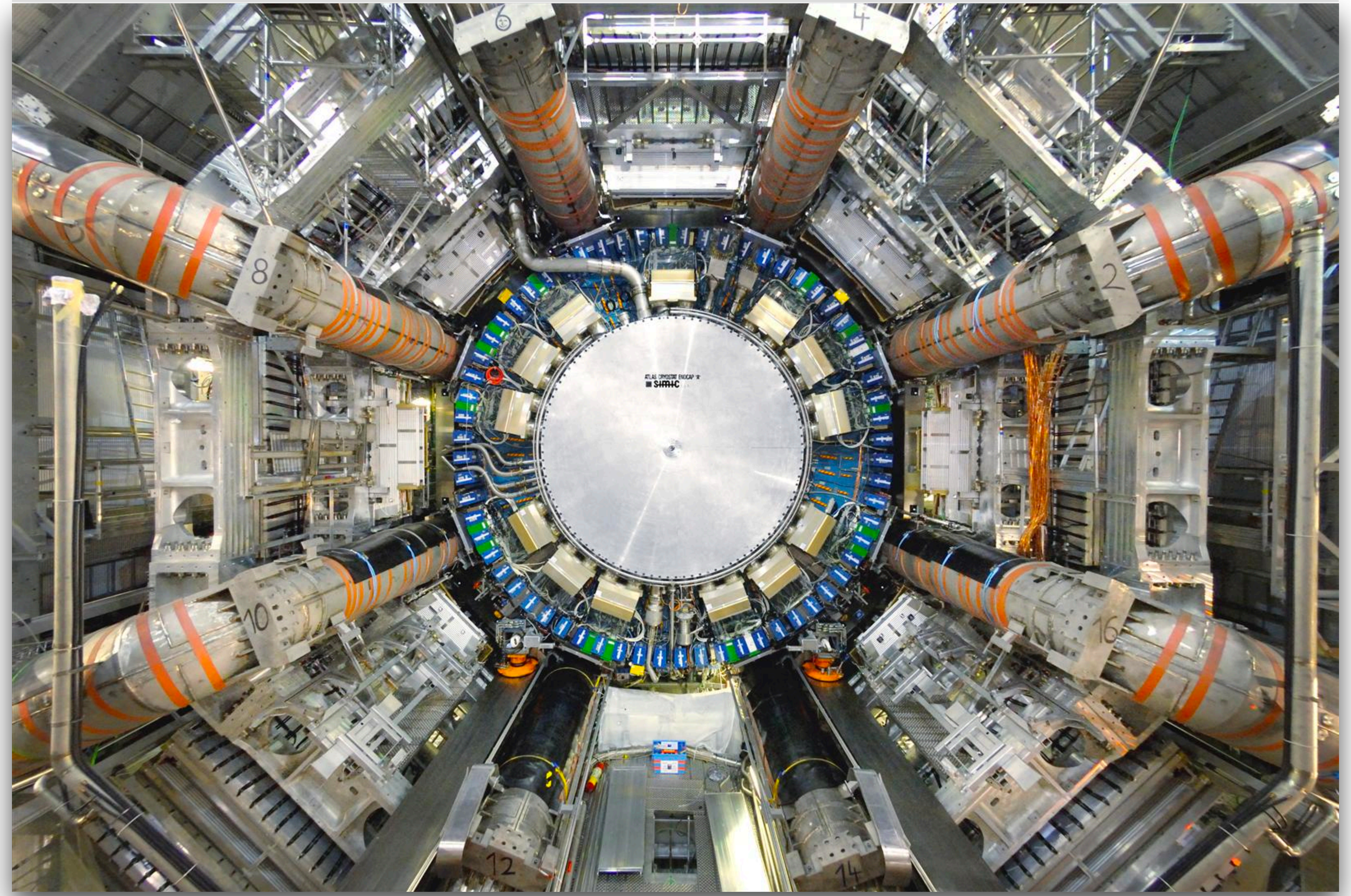
CMS

Total weight: 14000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T



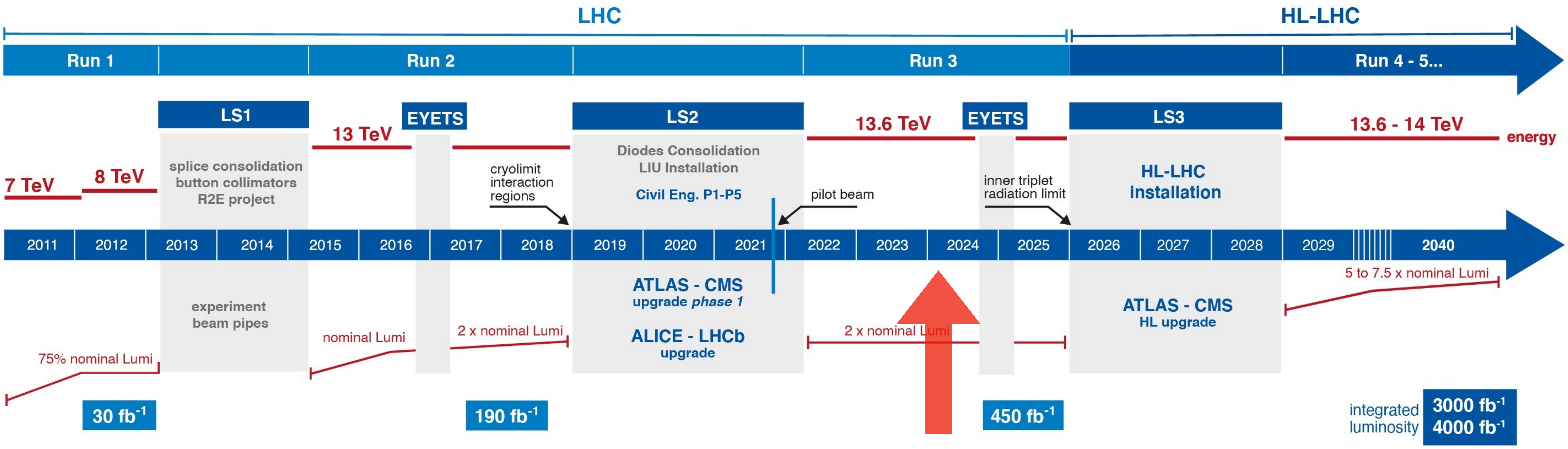
ATLAS

Total weight: 7000 tonnes
Overall diameter: 25 m
Overall length: 46 m
Magnetic field: 2 T (3.5 in toroid)

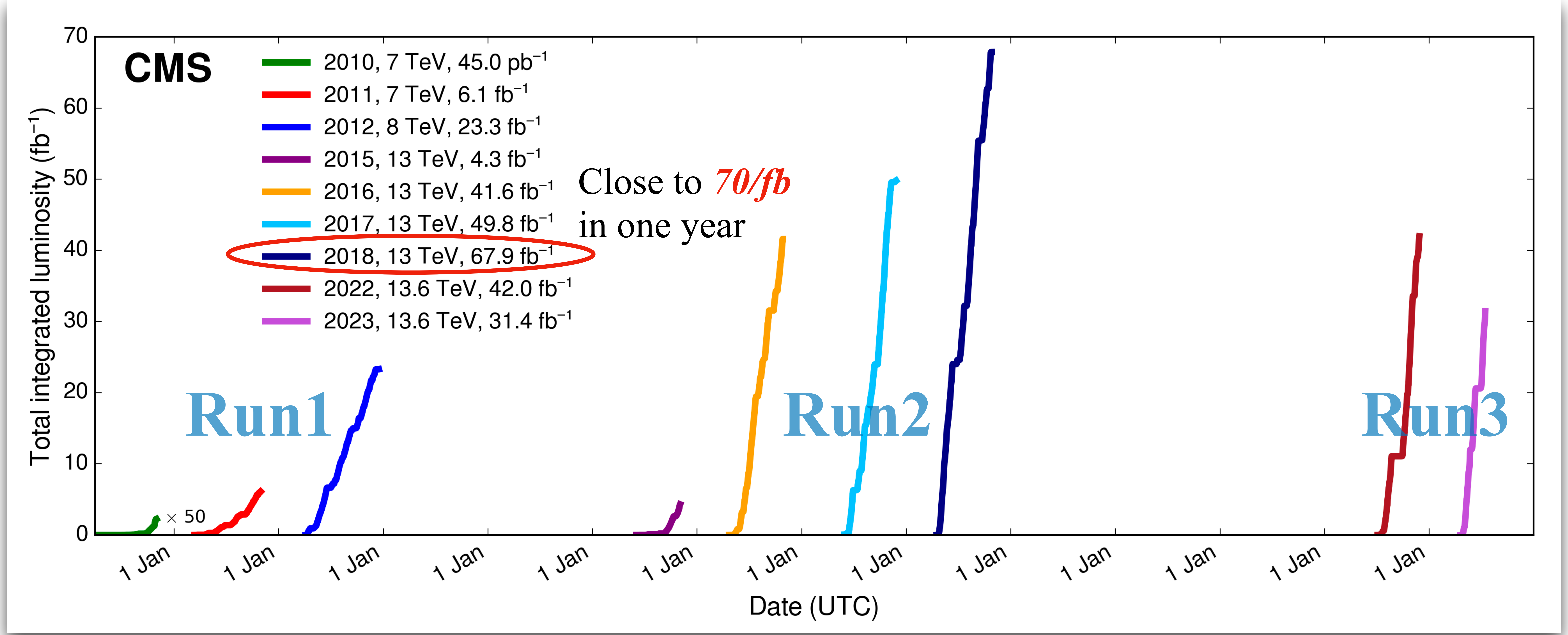


The schedule

- The whole LHC project plans multiple runs and spans over 30 years
- Now half of Run3 data taking is completed
- The analyses discussed today mostly use full Run2 data (up to ~150/fb) and a few cases of Run3 data (~40/fb in 2022)

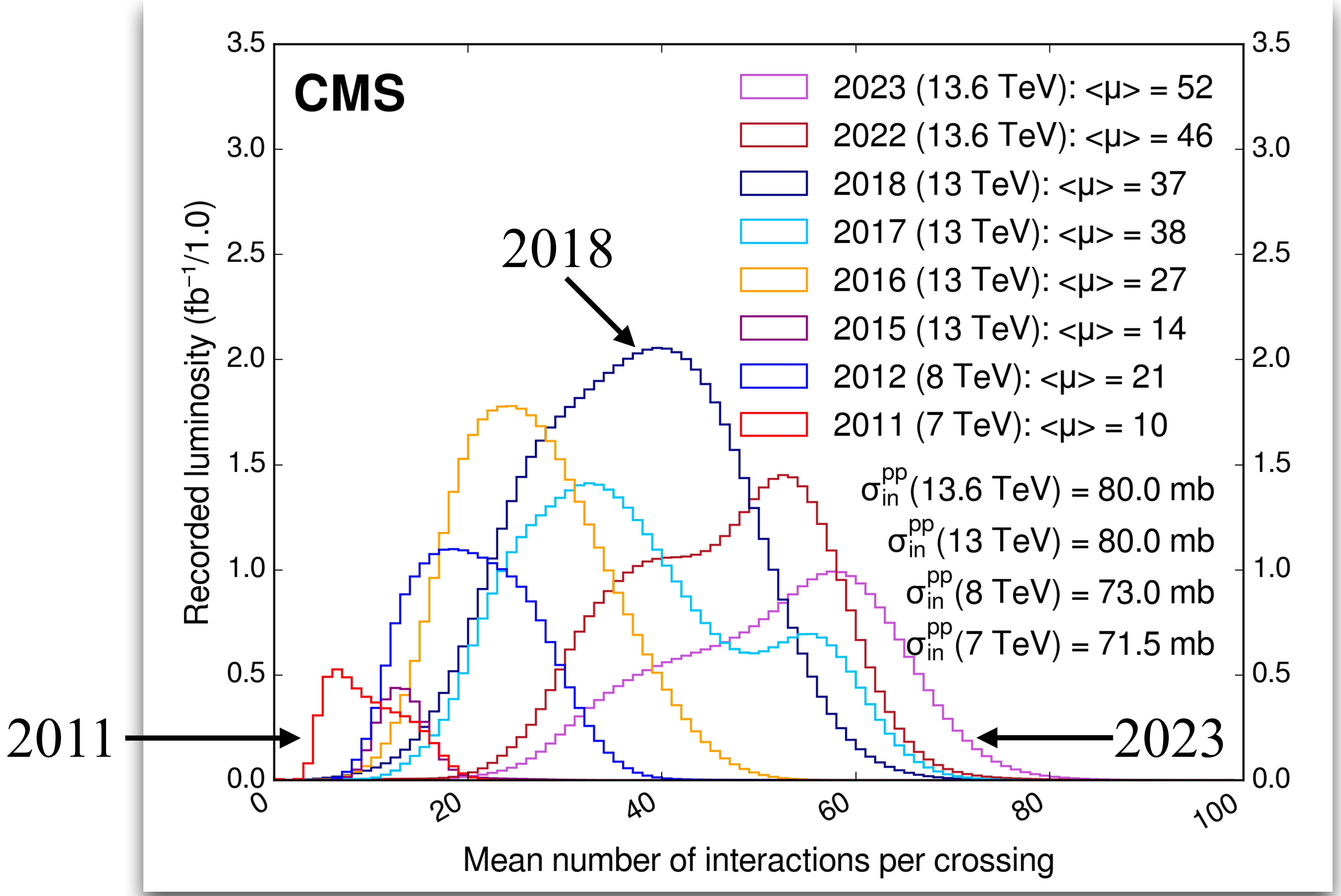


The data taking



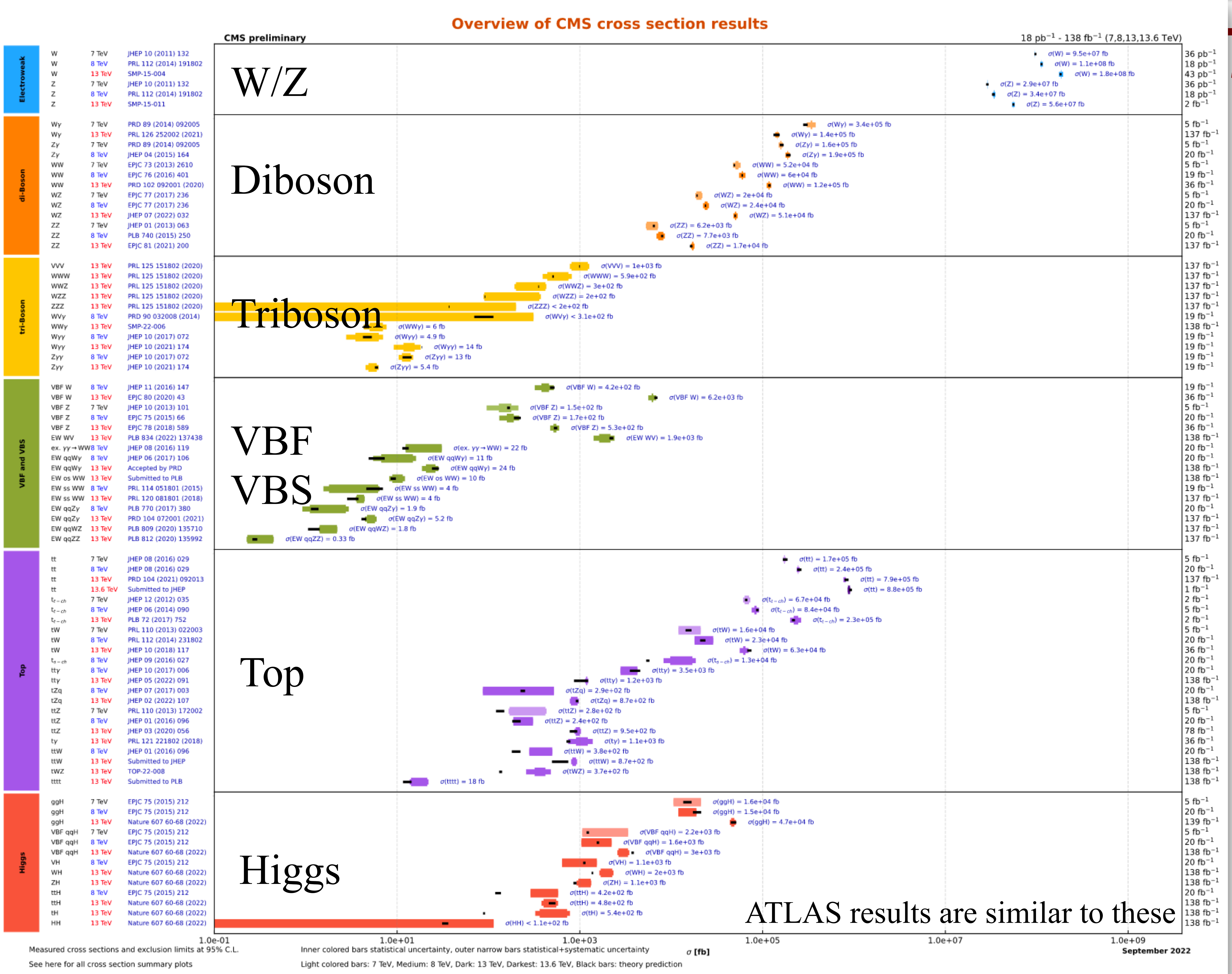
Expect to accumulate ~100/fb in 2024 and 2025 each

The pileup


CMS
2023 (13.6 TeV): <μ> = 52
2022 (13.6 TeV): <μ> = 46
2018 (13 TeV): <μ> = 37
2017 (13 TeV): <μ> = 38
2016 (13 TeV): <μ> = 27
2015 (13 TeV): <μ> = 14
2012 (8 TeV): <μ> = 21
2011 (7 TeV): <μ> = 10
σ_{in}^{pp}(13.6 TeV) = 80.0 mb
σ_{in}^{pp}(13 TeV) = 80.0 mb
σ_{in}^{pp}(8 TeV) = 73.0 mb
σ_{in}^{pp}(7 TeV) = 71.5 mb
Recorded luminosity (fb^{-1}/1.0)
Mean number of interactions per crossing
2018
2011
2023
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
20
40
60
80
100

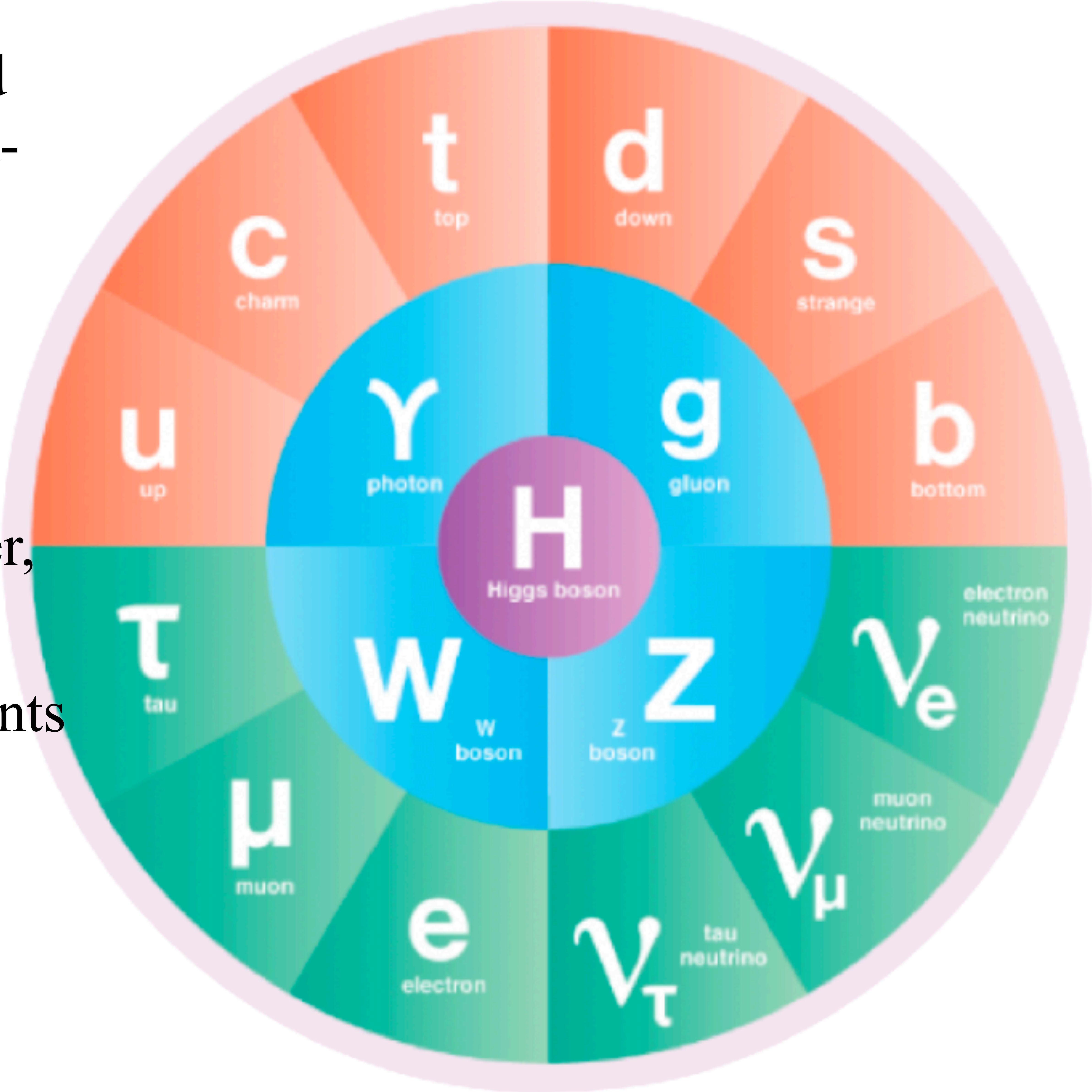
The measurements @ the LHC

- LHC is such a powerful machine, and ATLAS/CMS are high-performance detectors with excellent precisions
- The measured XS ranges over *10 orders of magnitude*
- The Standard Model survives so well so far 🤔



The Higgs boson

- The Higgs boson is at the center of the Standard Model and can also serve as a bridge to Beyond-the-Standard-Model physics
  - Stability of the universe, "portal" to dark matter, CP violation etc.
- It has been a decade after the discovery, and the profile of the Higgs boson becomes more clearer, but still not clear enough!
- This talk will cover the latest Higgs measurements by CMS on this non-exhaustive list
  - Mass and width
  - Cross-section and couplings
  - Rare and exotic decays



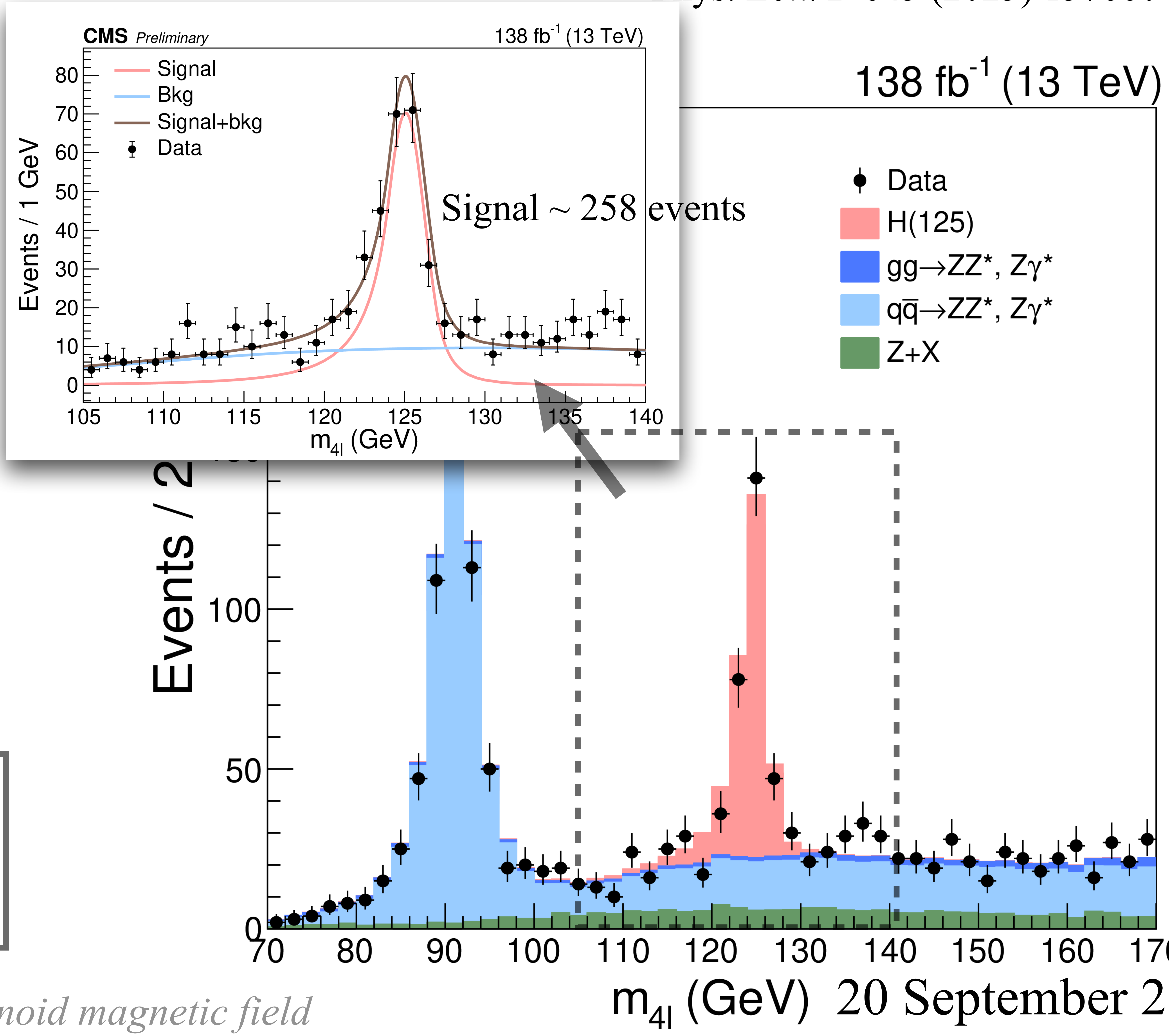
Higgs productions in SM

Higgs mass: single channel

CMS-PAS-HIG-21-019
Phys. Rev. Lett. 131, 251802
Phys. Lett. B 847 (2023) 138315
Phys. Lett. B 843 (2023) 137880

- The mass is a fundamental parameter and determines many properties (XS, BR etc.)
- Measurements largely rely on *HZZ4l* and *Hγγ* thanks to their complete reconstruction of the final state and their excellent mass resolution (1-2%)
- ***Latest*** CMS *HZZ4l* results using full Run2
  - 2D fit on m_{4l} and $\mathcal{D}^{\text{kin}}_{\text{bkg}} = \frac{\mathcal{P}_{H\to 4\ell}}{\mathcal{P}_{H\to 4\ell} + \mathcal{P}_{q\bar{q}\to 4\ell}}$ (P is calculated from matrix elements)

- **Most precise measurement via single channel!**
  $m_H = 125.04 \pm 0.12\ (0.11_{\text{stat}} \pm 0.05_{\text{syst}})$ GeV



20 September 2023

CMS stat. uncertainty ~ ATLAS / 1.6 thanks to higher solenoid magnetic field

Higgs mass: all channels

Run1 ATLAS+CMS:

$m_H = 125.09 \pm 0.24$ GeV

Phys. Rev. Lett. 114 (2015) 191803

Now CMS:

$m_H = 125.04 \pm 0.12$ GeV

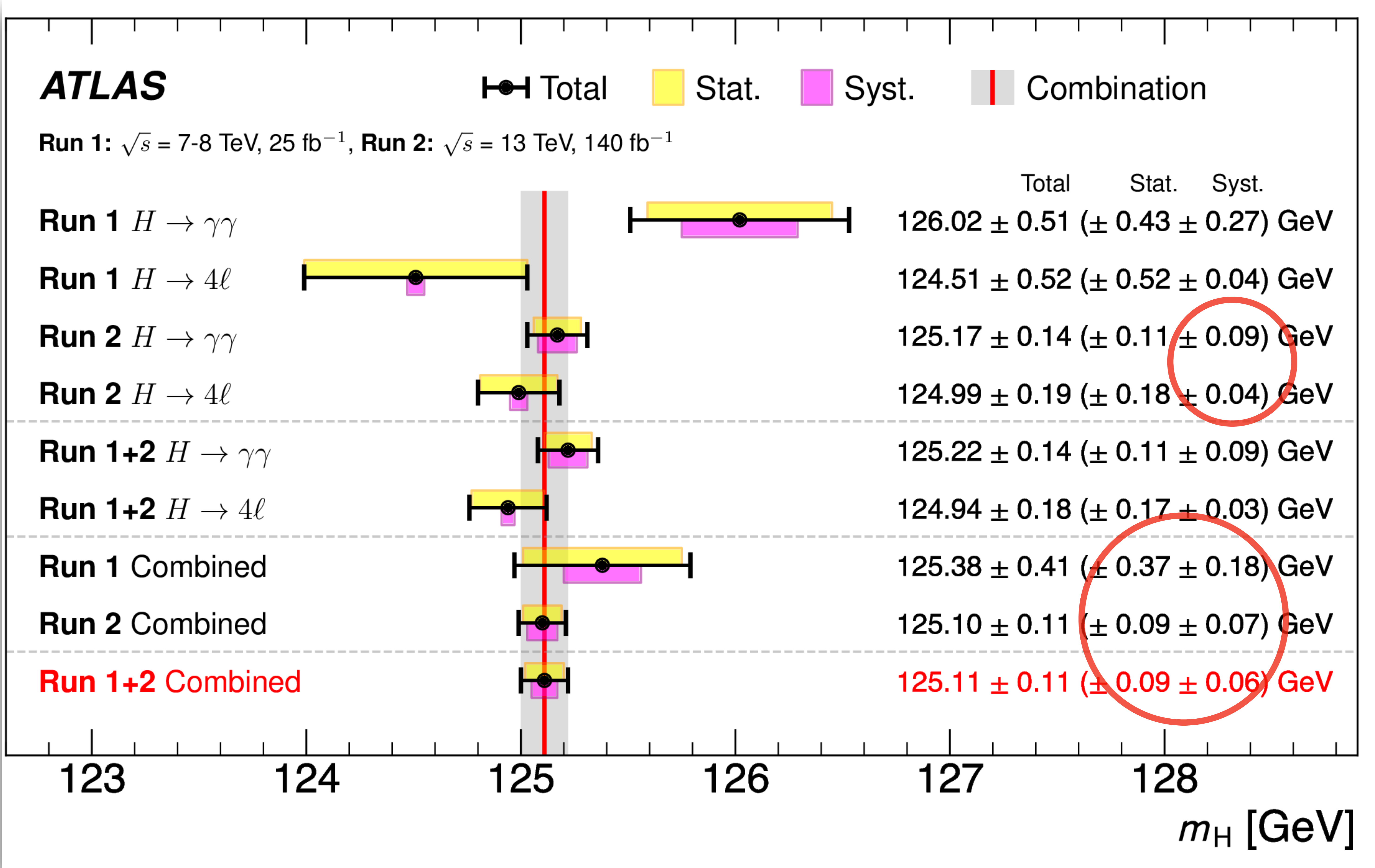
HZZ4l with Run2 ($H\gamma\gamma$ with Run2 yet to come)

Now ATLAS:

$m_H = 125.11 \pm 0.11$ GeV

$H\gamma\gamma$ & *HZZ4l* with Run1+Run2 in 2023

Source	Systematic uncertainty on m_H (MeV)
e/γ E_T-independent $Z \to ee$ calibration	44
e/γ E_T-dependent electron energy scale	28
$H \to \gamma\gamma$ interference bias	17
e/γ photon lateral shower shape	16
e/γ photon conversion reconstruction	15
e/γ energy resolution	11
$H \to \gamma\gamma$ background modelling	10
Muon momentum scale	8
All other systematic uncertainties	7



Dominant uncertainty comes from e/γ calibration

~0.1 % precision per experiment so far

Higgs width

CMS-PAS-HIG-21-019

- Not quite possible to directly measure the width that is ~4.07 MeV, given the experimental resolution at ~O(1) GeV, but can exploit the on-shell and off-shell production using *HZZ4l*
  - Observed non-zero off-shell signal at 3.6σ (CMS), 3.3σ(ATLAS)

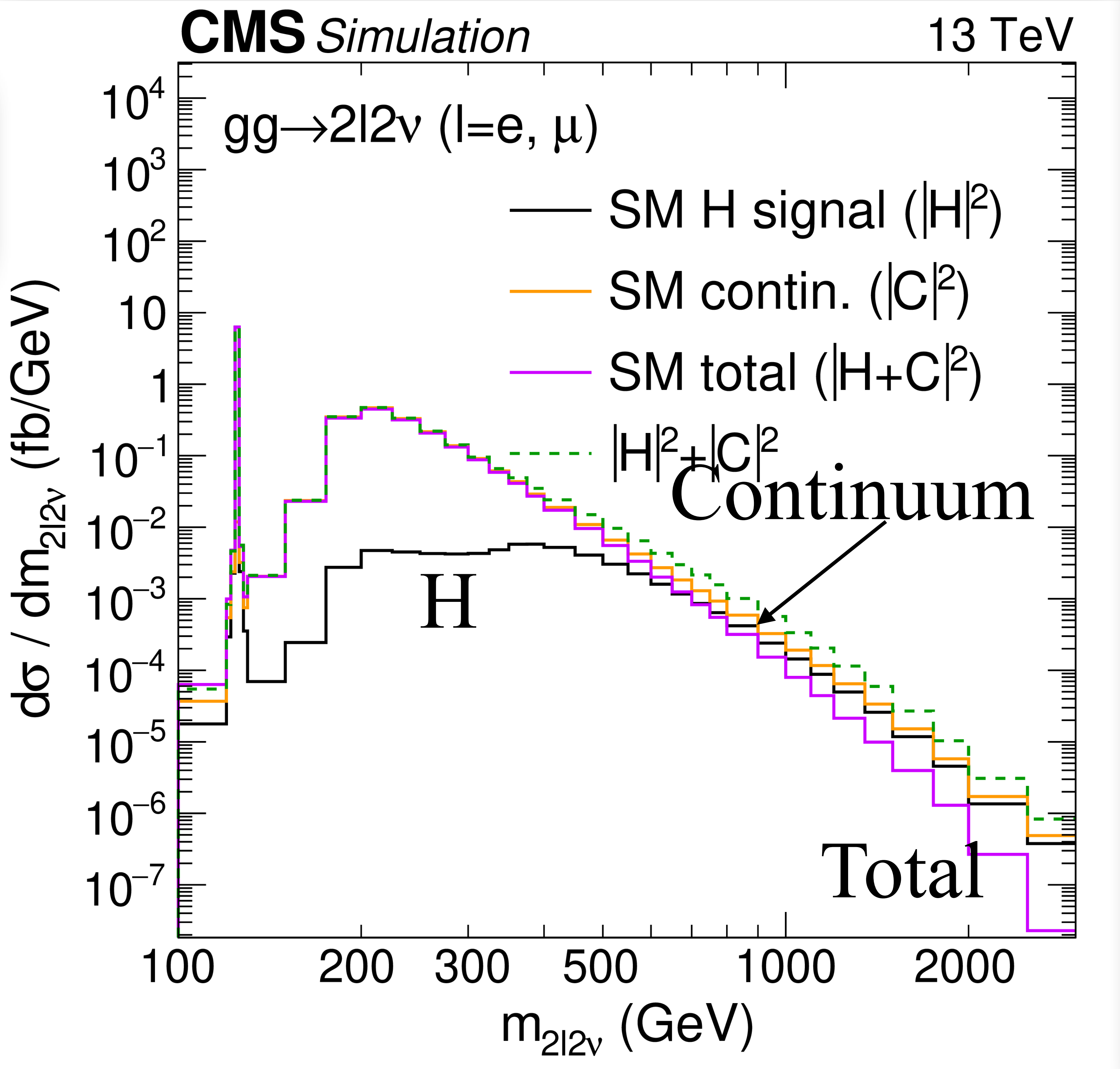
$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$

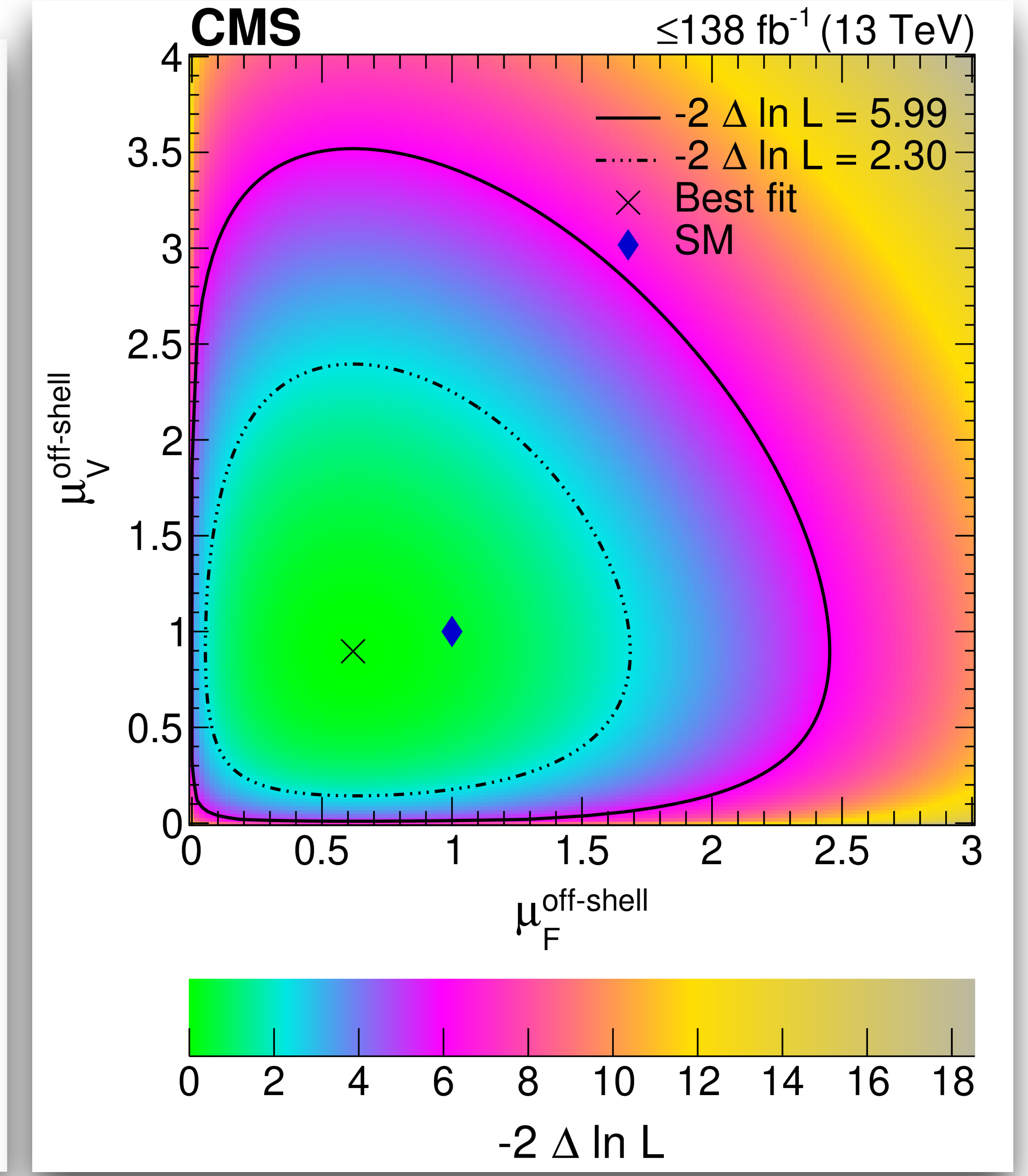
$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\mu_{off-shell}}{\mu_{on-shell}}$$

CMS $\Gamma = 3.2^{+2.4}_{-1.7}$ MeV
Nat. Phys. 18 (2022) 1329

ATLAS $\Gamma = 4.5^{+3.3}_{-2.5}$ MeV
Phys. Lett. B 846 (2023) 138223

~< 75% precision

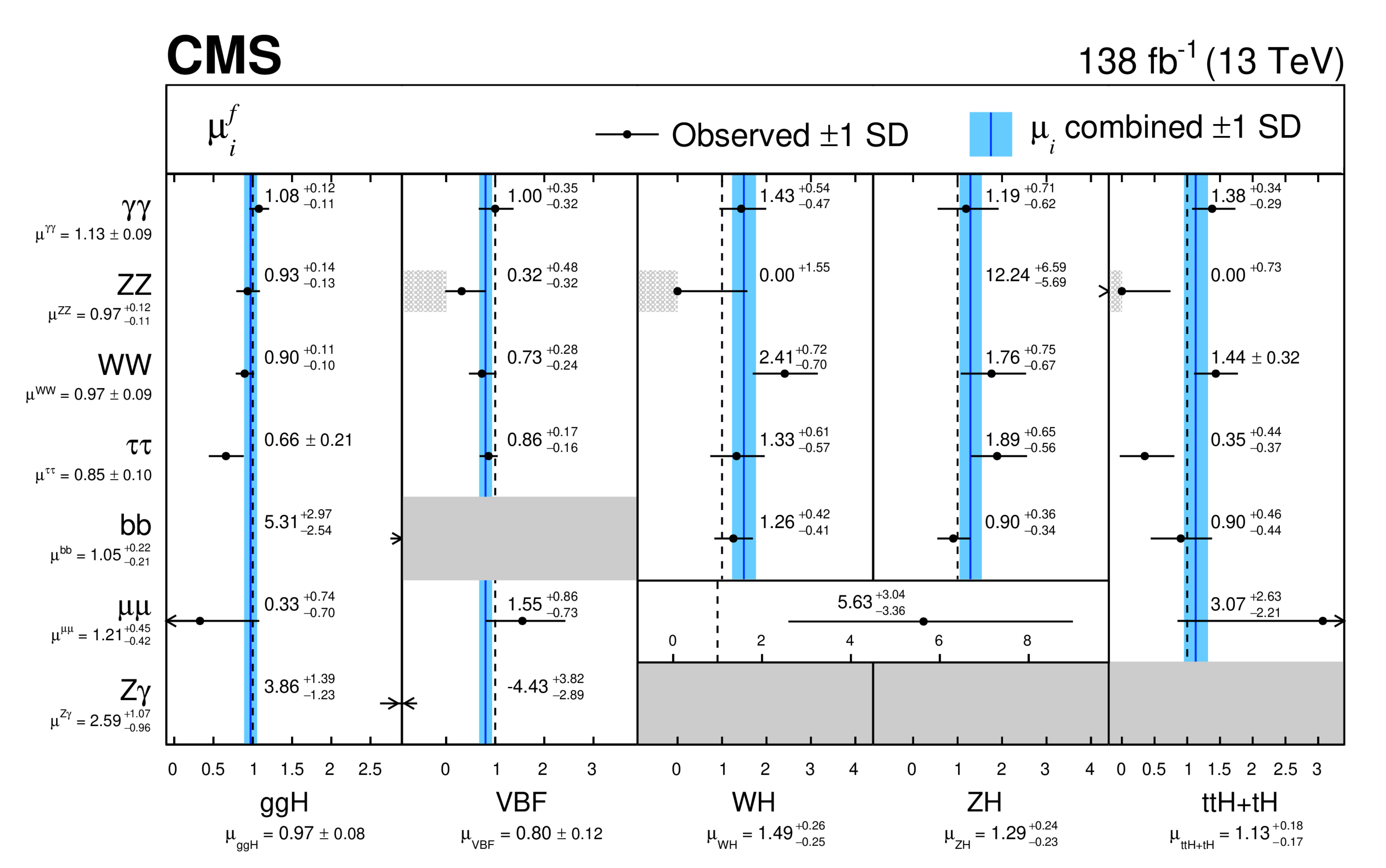




Loosely constrained by direct measurements using $m_{\gamma\gamma}$ or m_{ZZ} at CMS : Γ < 330 MeV @ 95% CL

Higgs rate - combined prod+decay

- At the 10th anniversary of the Higgs discovery, the "portrait" of the Higgs boson was published from ATLAS and CMS
  - A full combination of available experimental observables
- Results include inclusive signal strength μ, and a full breakdown from various couplings in the κ framework
- A good agreement with SM is observed at the current precision



The signal strength μ's

Nature 607 (2022) 52-59

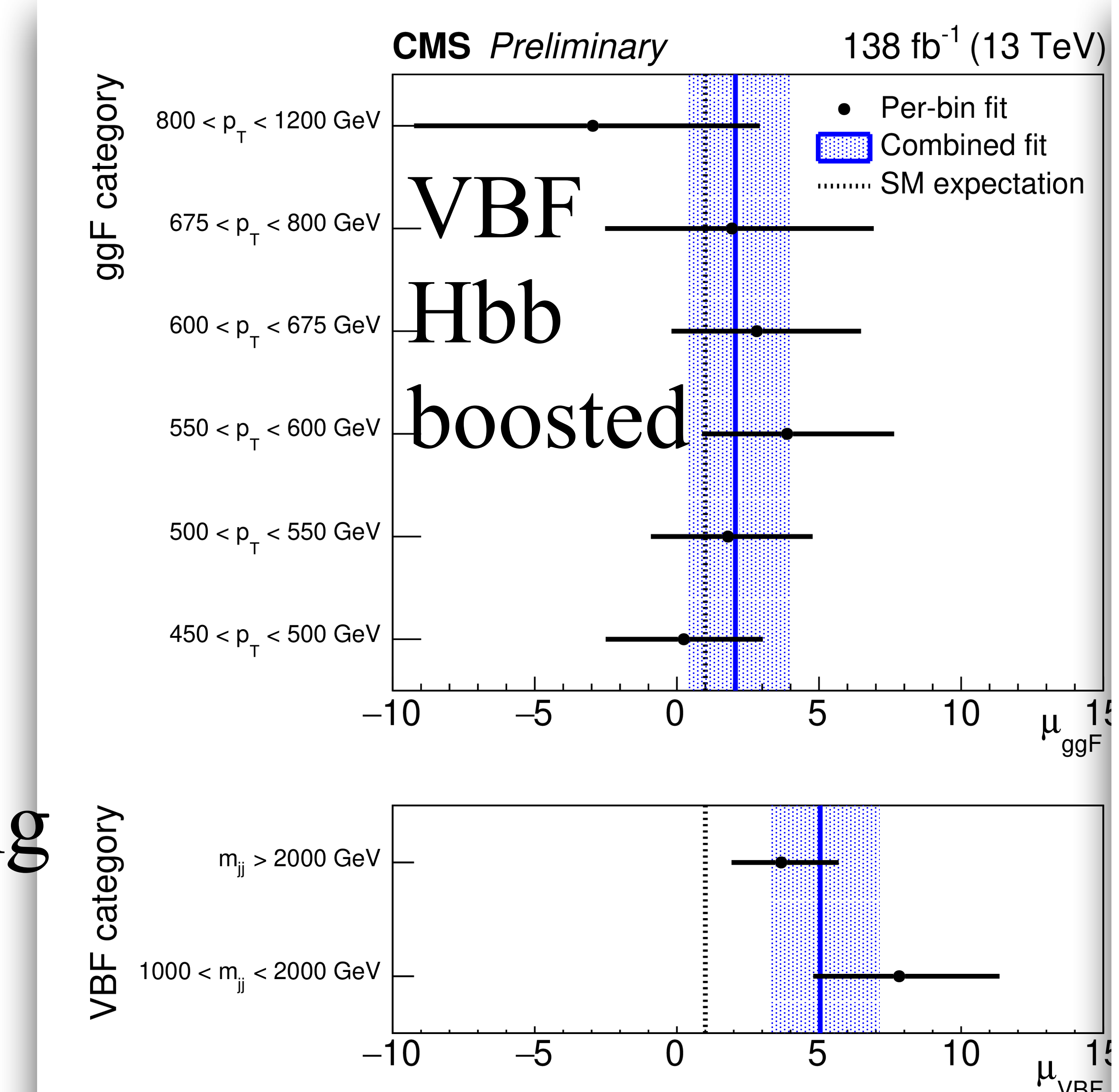
Nature 607 (2022) 60-68

Boosted Higgs

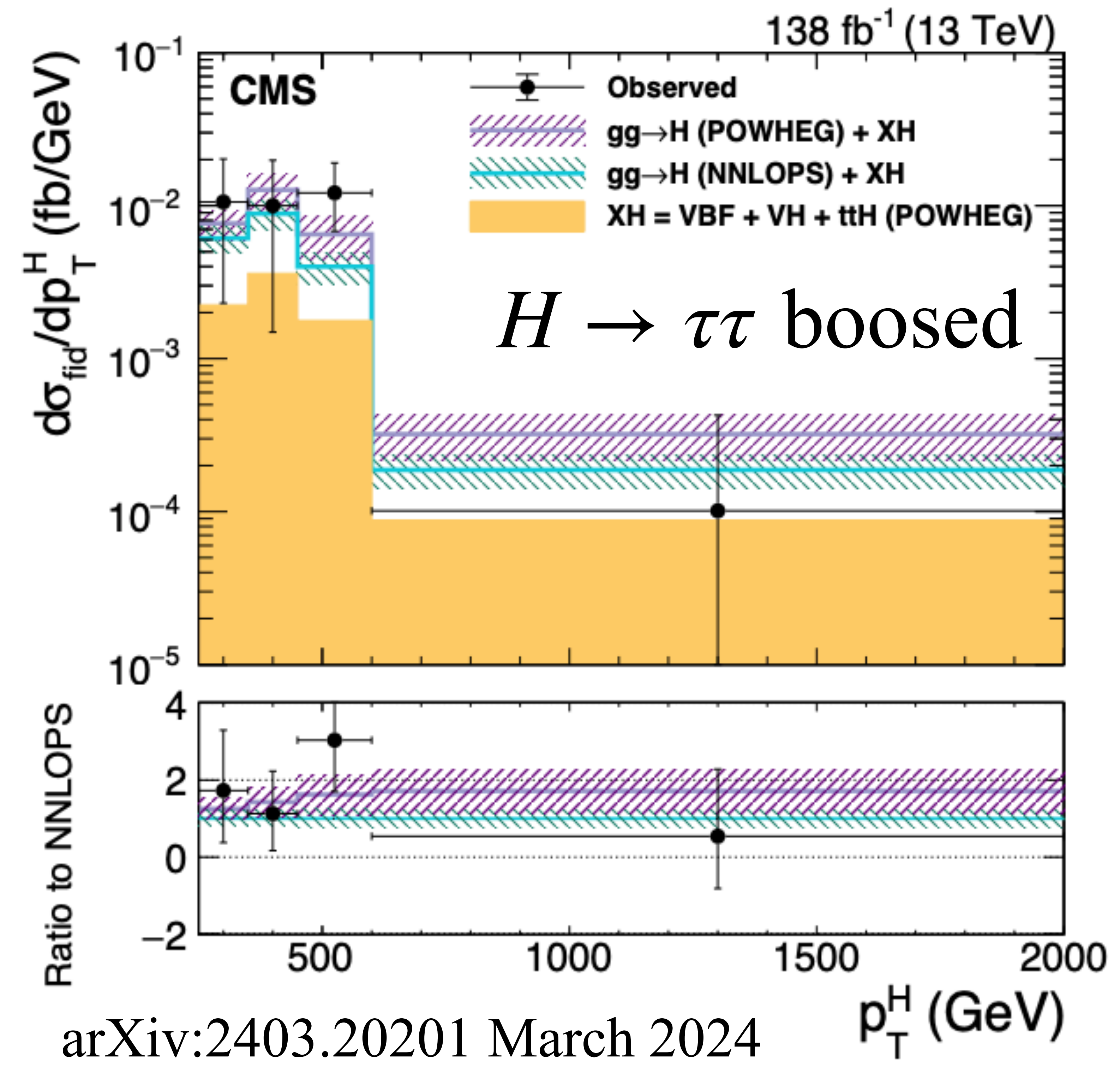
LHCHXSWG-2019-002

$p_\perp^{cut}$ [GeV]	$\Sigma_{ggF}^{NNLO^{approximate}_{quad.unc.}}(p_\perp^{cut})$ [fb]	$\Sigma_{VBF}^{NNLO}(p_\perp^{cut})$ [fb]	$\Sigma_{VH}^{NLO}(p_\perp^{cut})$ [fb]	$\Sigma_{t\bar{t}H}^{NLO}(p_\perp^{cut})$ [fb]
400	$33.30^{10.89\%}_{-12.91\%}$	$14.23^{+0.15\%}_{-0.19\%}$	$11.16^{+4.12\%}_{-3.68\%}$	$6.89^{+12.62\%}_{-12.97\%}$
450	$18.08^{10.78\%}_{-12.79\%}$	$8.06^{+0.24\%}_{-0.23\%}$	$6.87^{+4.6\%}_{-3.49\%}$	$4.24^{+12.84\%}_{-13.15\%}$
500	$10.17^{10.67\%}_{-12.74\%}$	$4.75^{+0.33\%}_{-0.29\%}$	$4.39^{+4.43\%}_{-4.04\%}$	$2.66^{+12.85\%}_{-13.22\%}$
550	$5.87^{10.54\%}_{-12.60\%}$	$2.90^{+0.34\%}_{-0.36\%}$	$2.87^{+4.44\%}_{-3.74\%}$	$1.76^{+14.23\%}_{-13.93\%}$
600	$3.48^{10.35\%}_{-12.49\%}$	$1.82^{+0.41\%}_{-0.39\%}$	$1.91^{+5.22\%}_{-4.71\%}$	$1.11^{+12.99\%}_{-13.4\%}$
650	$2.13^{10.23\%}_{-12.45\%}$	$1.17^{+0.49\%}_{-0.39\%}$	$1.30^{+4.67\%}_{-4.28\%}$	$0.72^{+12.6\%}_{-13.26\%}$
700	$1.32^{10.03\%}_{-12.32\%}$	$0.77^{+0.57\%}_{-0.45\%}$	$0.90^{+4.15\%}_{-5.4\%}$	$0.47^{+11.42\%}_{-12.74\%}$
750	$0.84^{10.05\%}_{-12.31\%}$	$0.51^{+0.69\%}_{-0.56\%}$	$0.62^{+5.15\%}_{-4.66\%}$	$0.32^{+11.53\%}_{-12.84\%}$
800	$0.54^{9.91\%}_{-12.24\%}$	$0.35^{+0.71\%}_{-0.6\%}$	$0.44^{+5.64\%}_{-4.13\%}$	$0.22^{+11.42\%}_{-13.3\%}$

- When p_T increases, ggF is not dominating any more, while other production modes start to take larger fractions
- **VBF Hbb boosted** is studied, finding that the observed (expected) significances are **3.0** (0.9) standard deviations
- ***Hττ* boosted** analysis (inclusive productions) is also performed, resulting in observed (expected) significance of **3.5** (2.2) standard deviations



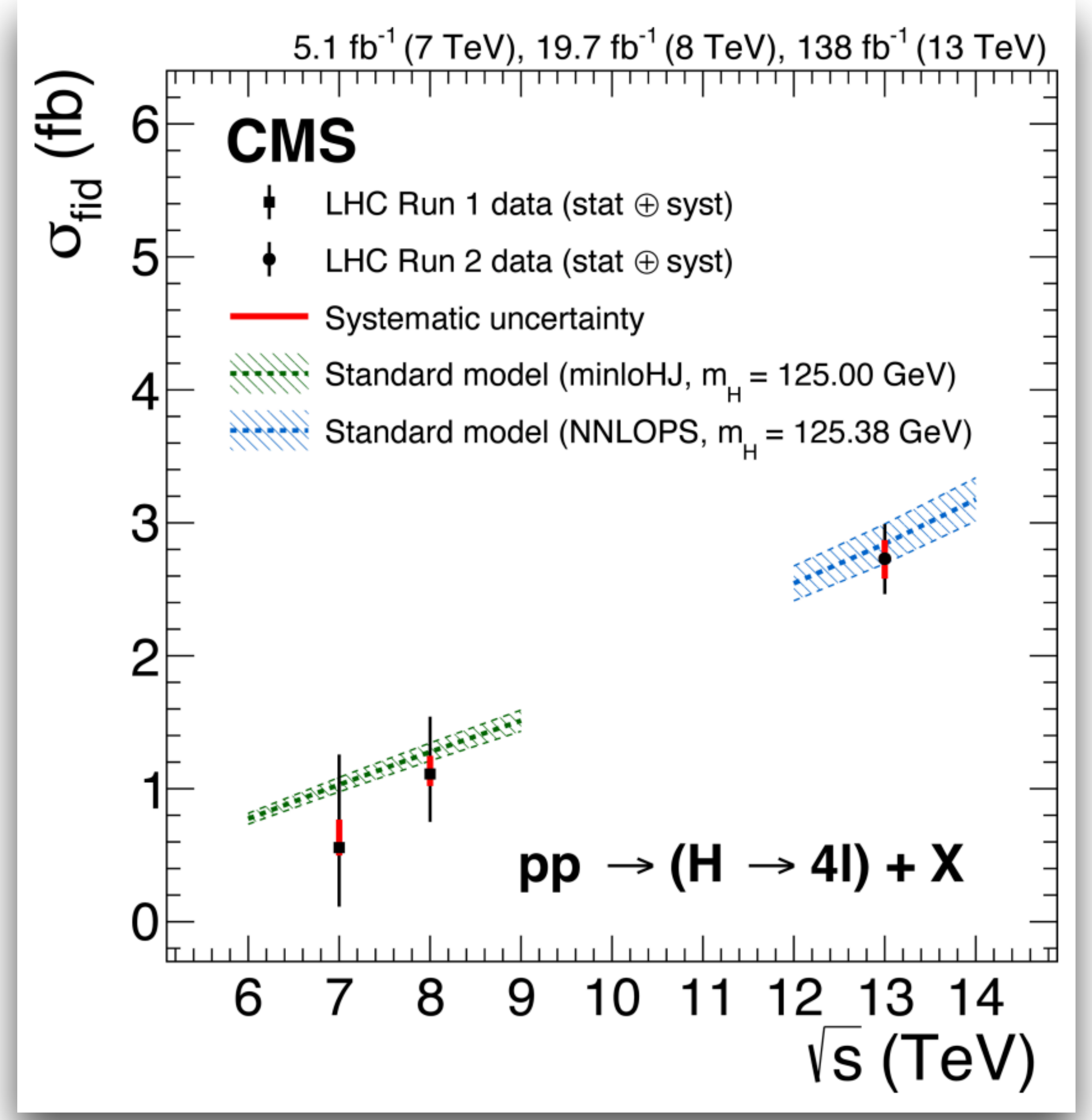
CMS-PAS-HIG-21-020 Aug 2023



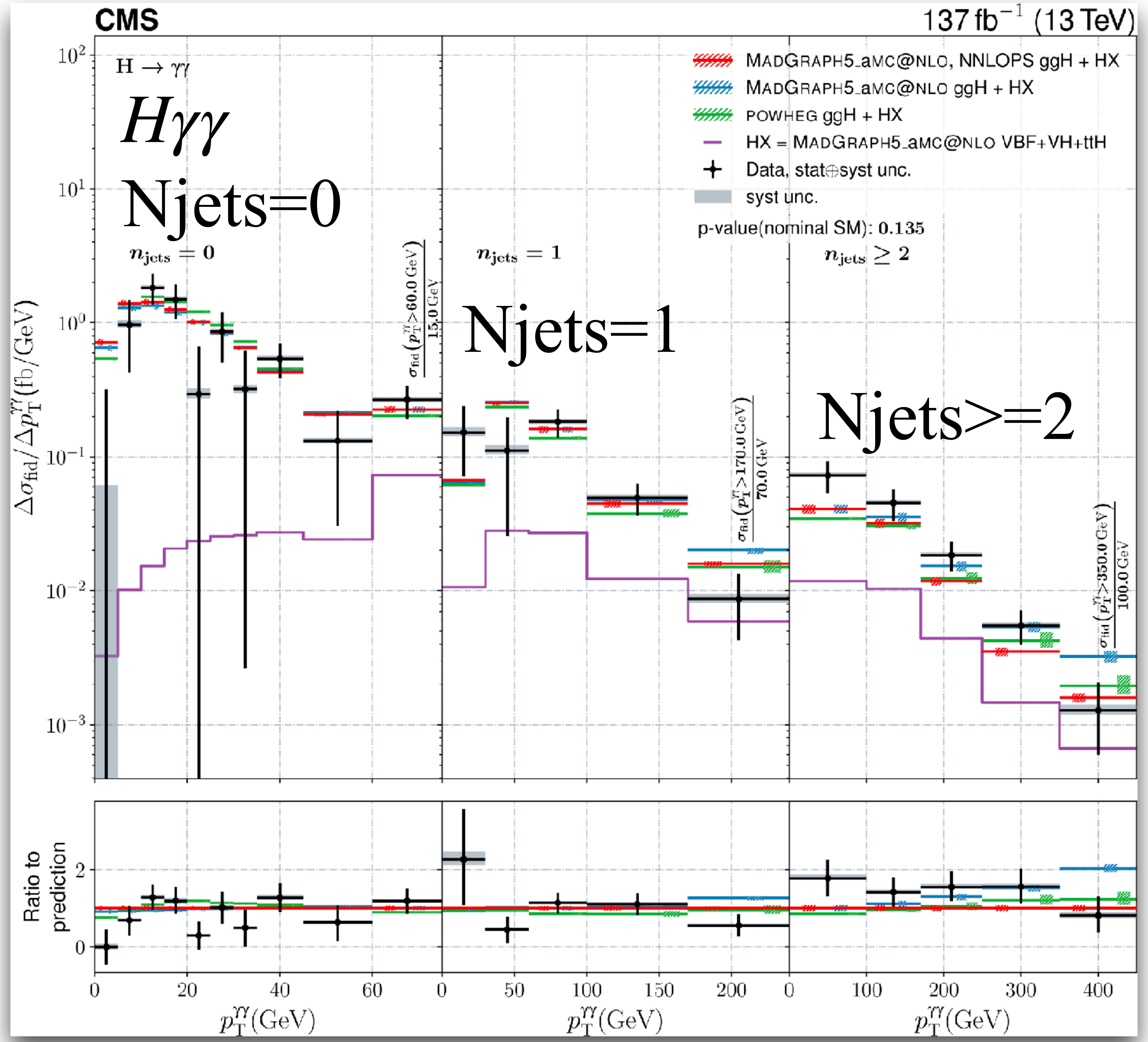
arXiv:2403.20201 March 2024

Differential XS

- Largely from *HZZ4l* and *Hγγ*
- Provide a variety of unfolded kinematics with **minimal model dependence**
  - High pT for BSM sensitivity; Njet for production decomposition and radiations



So far, the measured differential/ fiducial XS are in good agreement with the SM

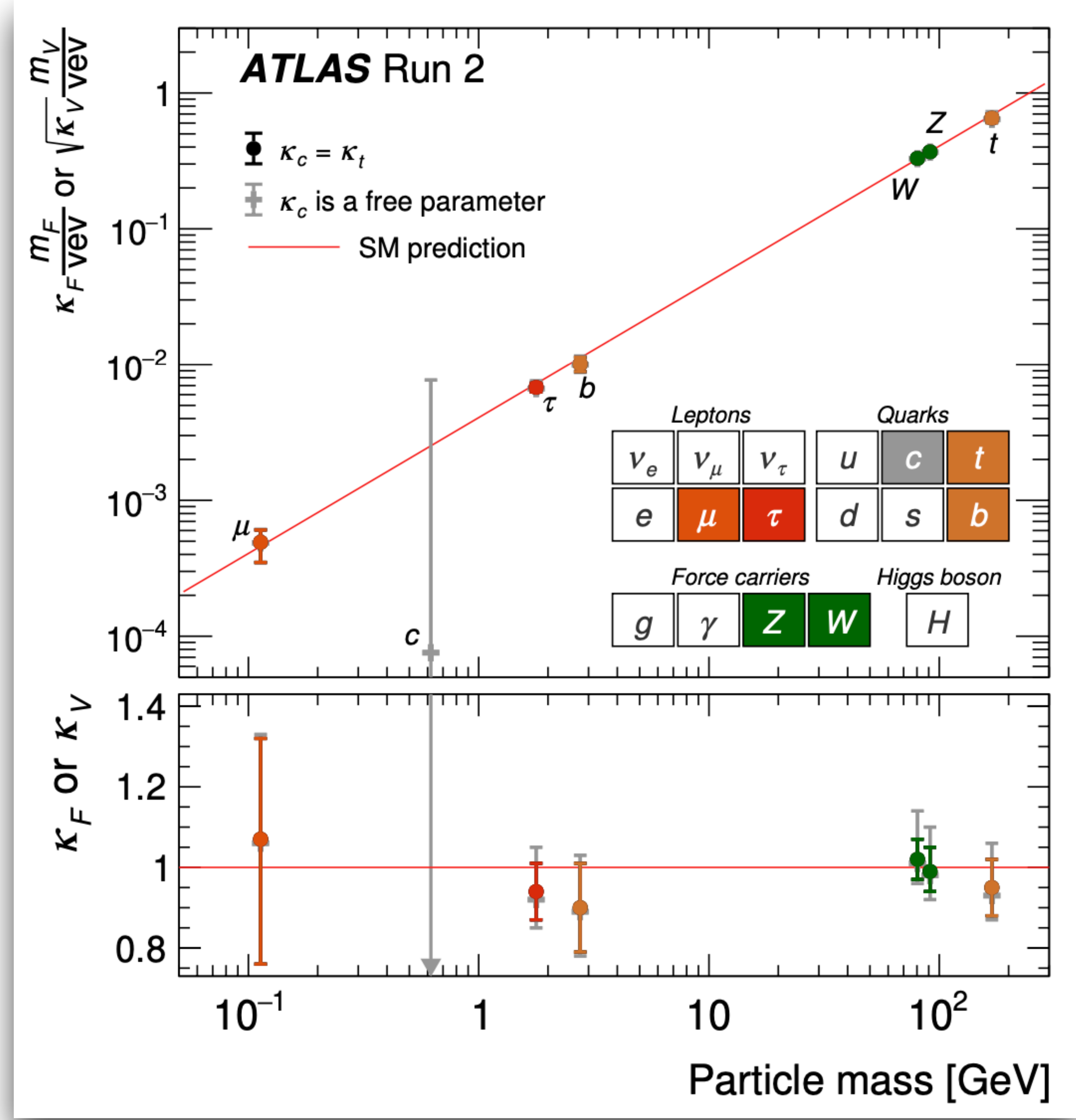


Hγγ JHEP 07 (2023) 091; HZZ4l JHEP 08 (2023) 040

Couplings

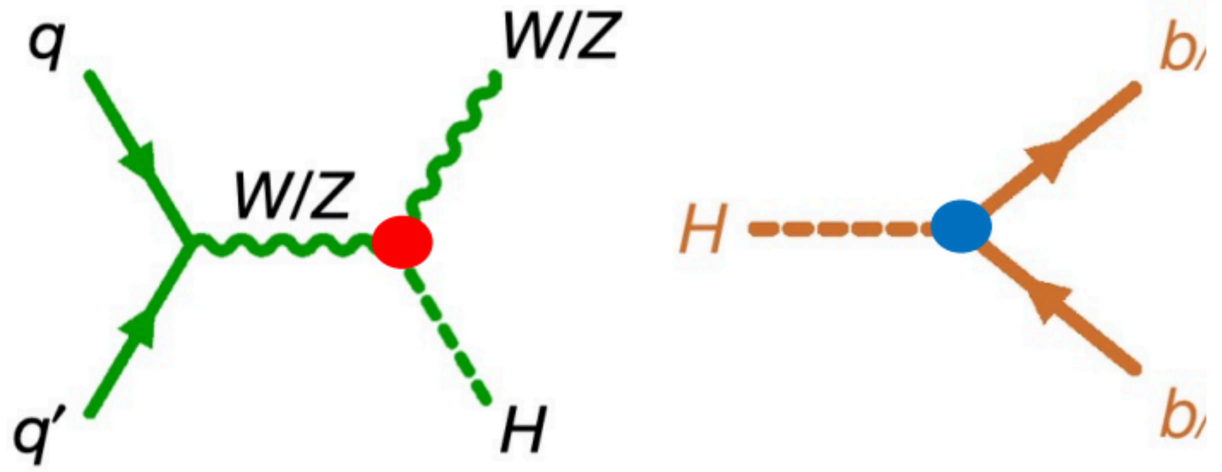
Nature 607 (2022) 52-59
Nature 607 (2022) 60-68

- The couplings measurements range over 3 orders of magnitude
- Couplings in the κ framework can be measured with a precision as good as < 10%



k-framework

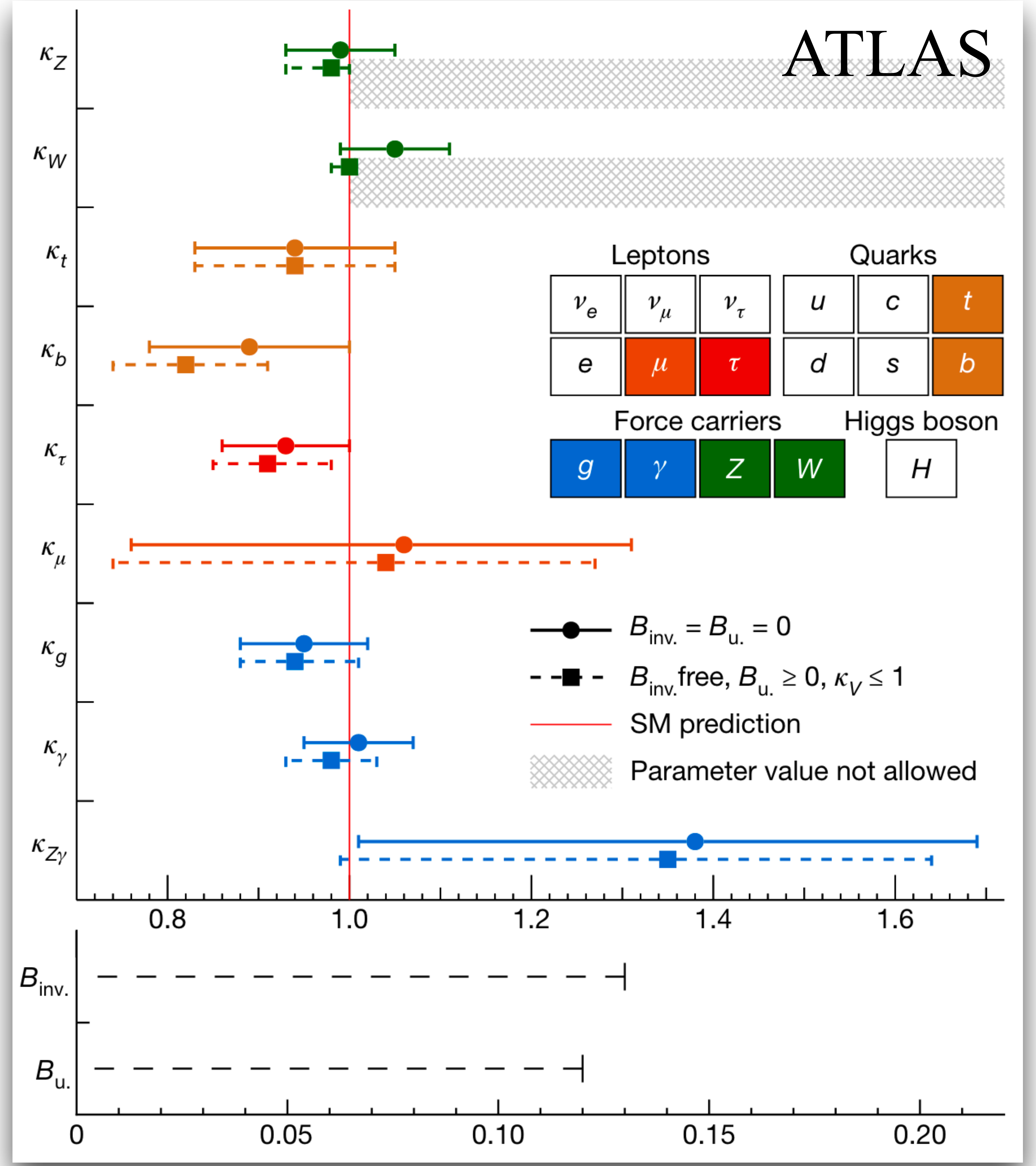
$$\kappa = g_x^{measure} / g_x^{SM}$$



$$\sigma(pp \to VH) \cdot BR(H \to bb) = k_{W/Z}^2 \cdot k_b^2 \times (\sigma_{SM} \cdot BR_{SM})$$

Tatsuya Masubuchi

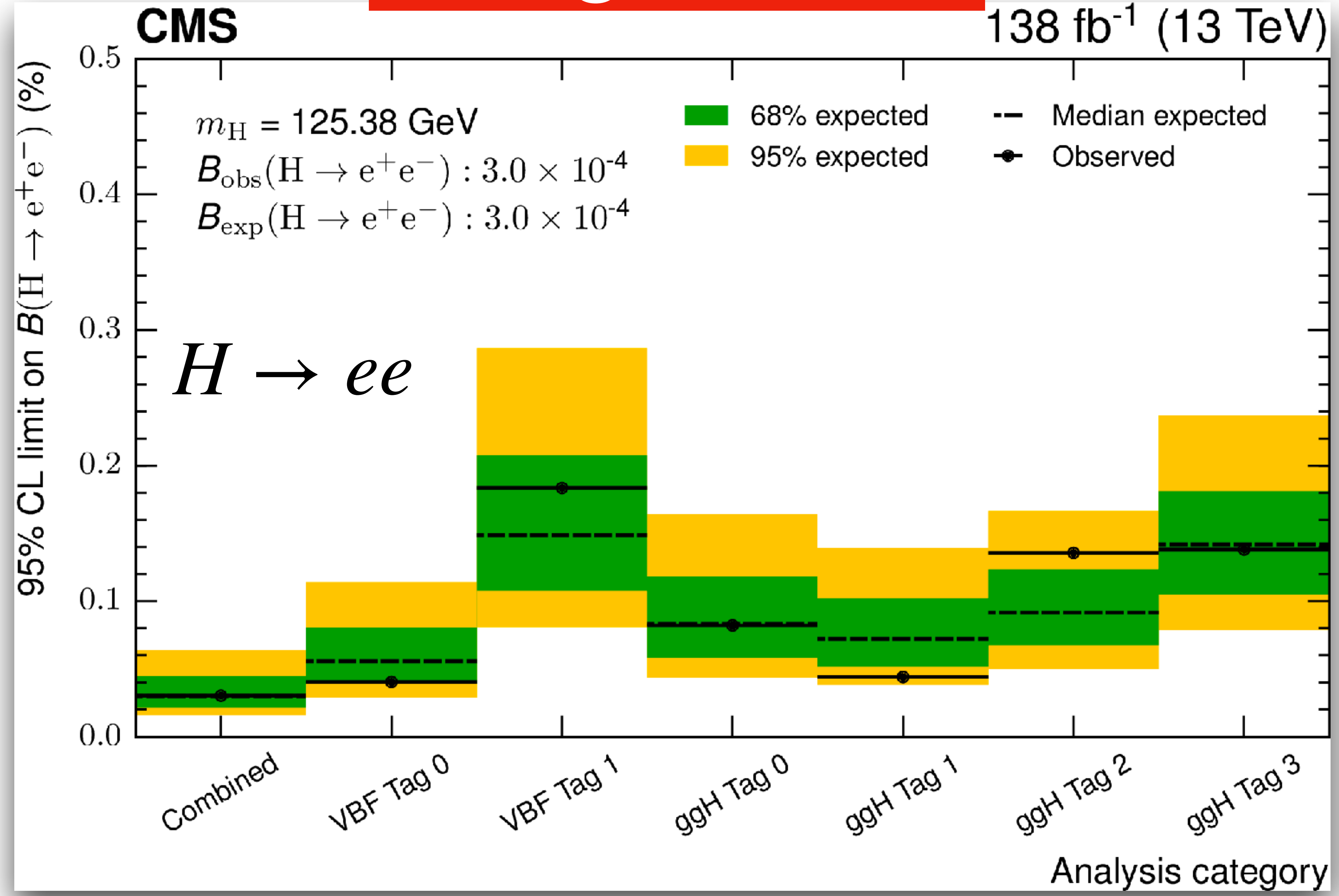
- $\kappa_{W/Z}$, κ_γ, κ_g, κ_τ ~6-8%
- κ_t, κ_b ~10%
- κ_μ ~20%
- $\kappa_{Z\gamma}$ ~40%



Couplings: lighter fermions

- Reaching out to the first and second generation fermions

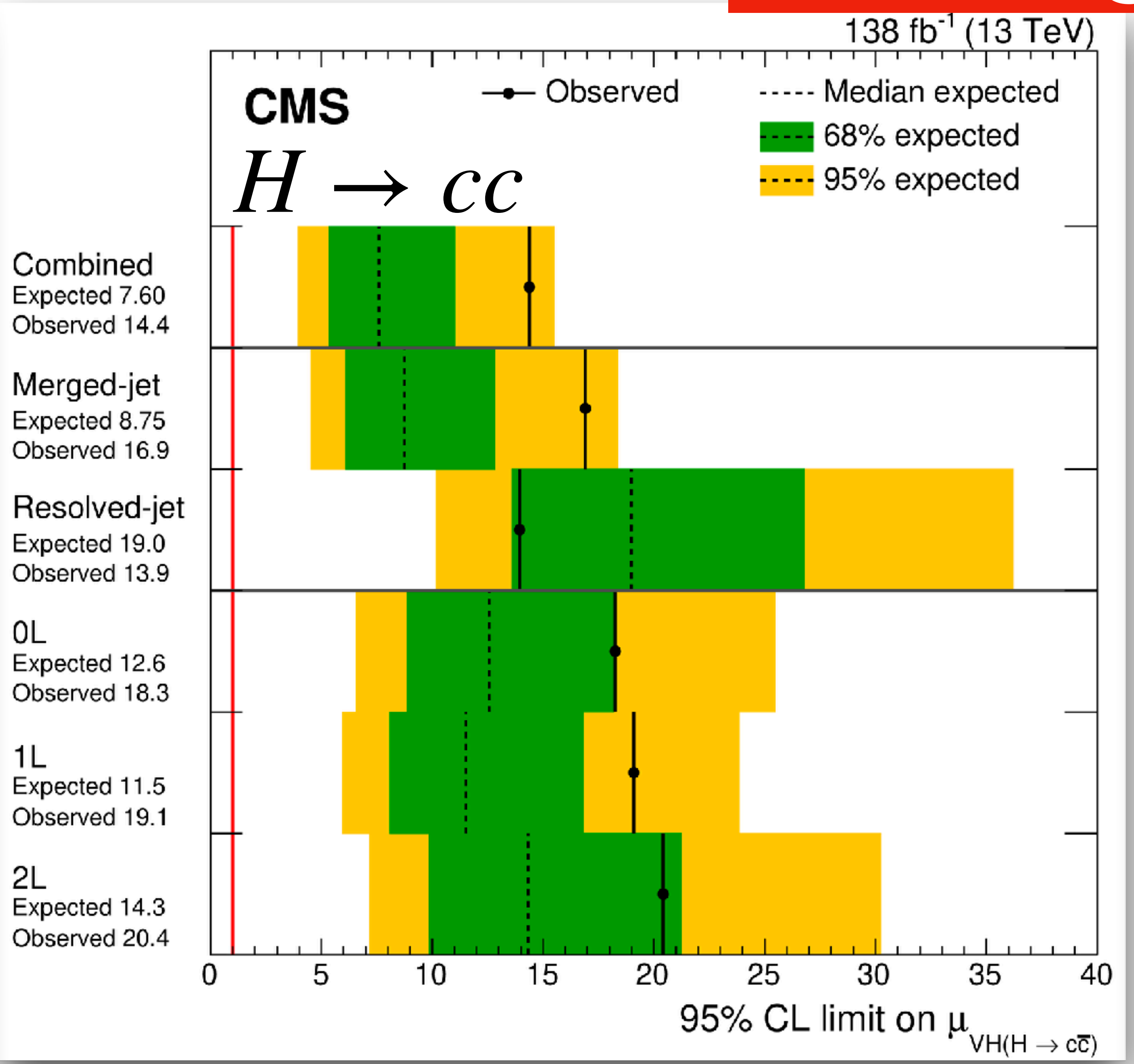
First generation



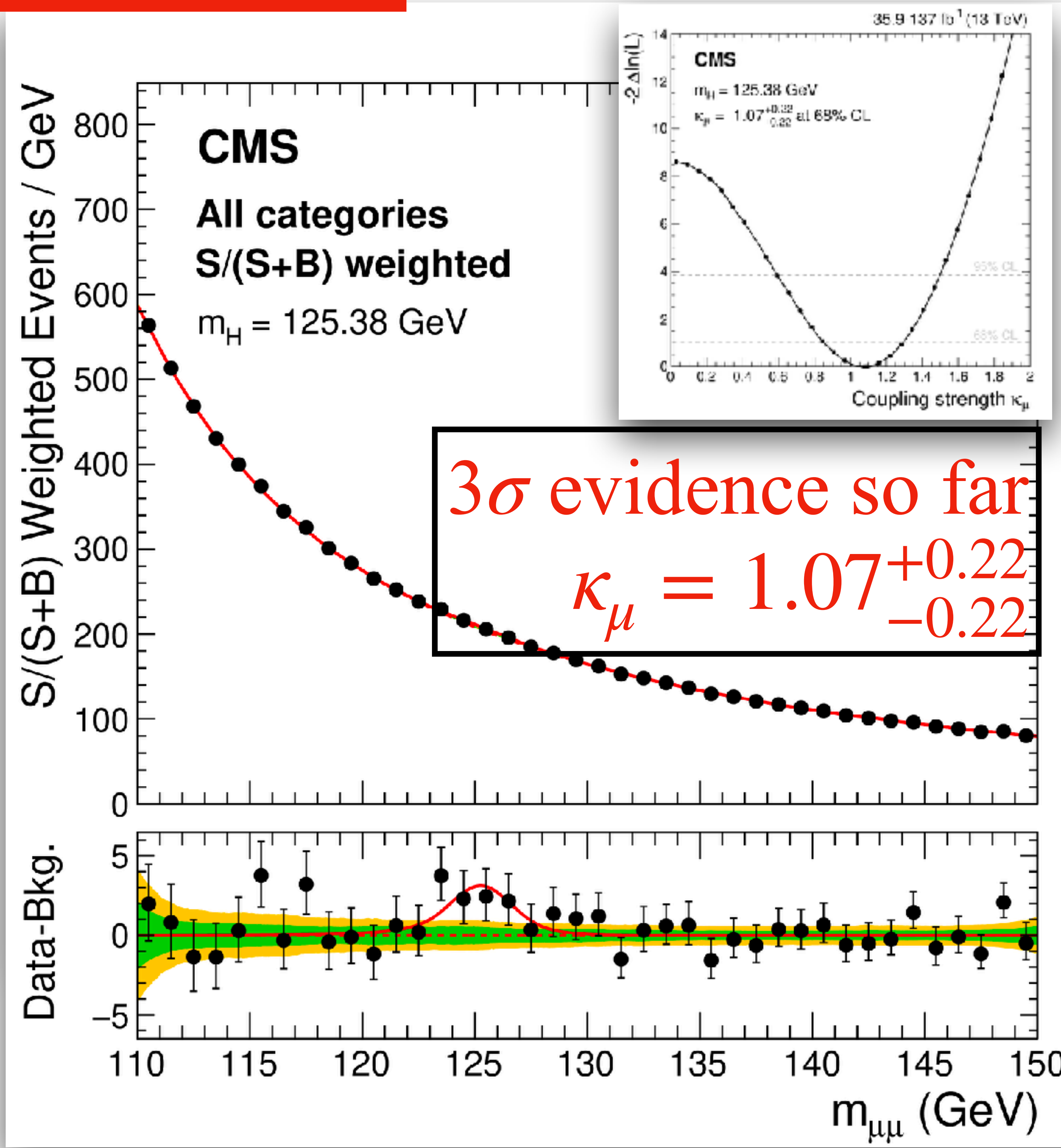
$BR(H \to ee) < 3.0 \times 10^{-4} (3.0 \times 10^{-4})$ at 95% CL. Phys. Lett. B 846 (2023) 137783

ATLAS similar results in Phys. Lett. B 801 (2020) 135148

Second generation



$1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$) at 95% CL. PRL 131 (2023) 041801
PRL 131 (2023) 061801



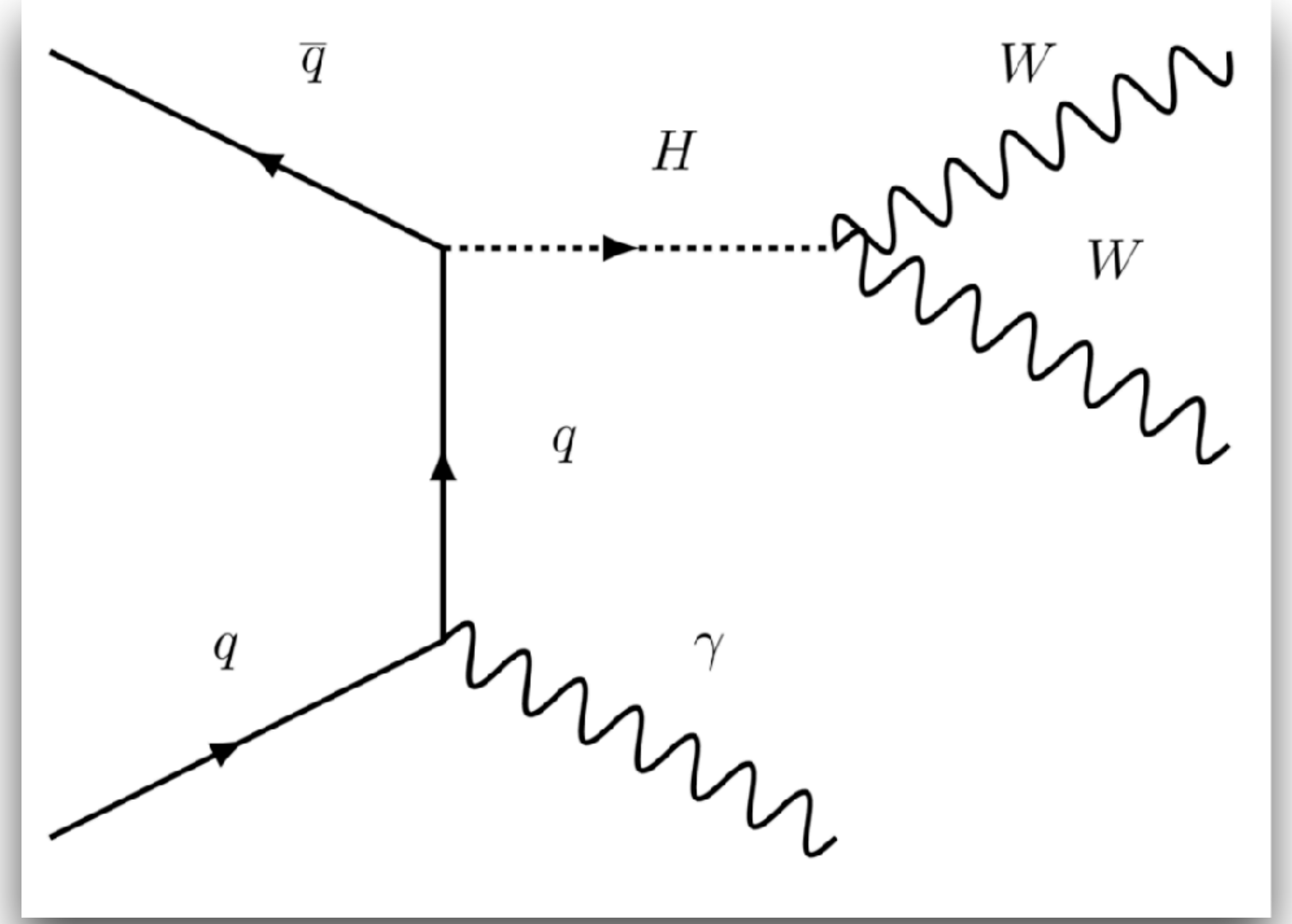
3σ evidence so far
$\kappa_\mu = 1.07^{+0.22}_{-0.22}$

$H \to \mu\mu$
JHEP 01 (2021) 148

Couplings: lighter fermions

Phys. Rev. Lett. 132 (2024) 121901

- A rare production of $pp \to \gamma H$ is probed with $H \to WW$ in the triple boson analysis of $WW\gamma$
- Particularly sensitive to u,d,c,s couplings
- Competitive constraints on u,d to date



Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL	$\bar{\kappa}_q$ limits obs. (exp.) at 95% CL
$u\bar{u} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	85 (67)	$\lvert\kappa_u\rvert \leq 16000$ (13000)	$\lvert\bar{\kappa}_u\rvert \leq 7.5$ (6.1)
$d\bar{d} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	72 (58)	$\lvert\kappa_d\rvert \leq 17000$ (14000)	$\lvert\bar{\kappa}_d\rvert \leq 16.6$ (14.7)
$s\bar{s} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	68 (49)	$\lvert\kappa_s\rvert \leq 1700$ (1300)	$\lvert\bar{\kappa}_s\rvert \leq 32.8$ (25.2)
$c\bar{c} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	87 (67)	$\lvert\kappa_c\rvert \leq 200$ (110)	$\lvert\bar{\kappa}_c\rvert \leq 45.4$ (25.0)

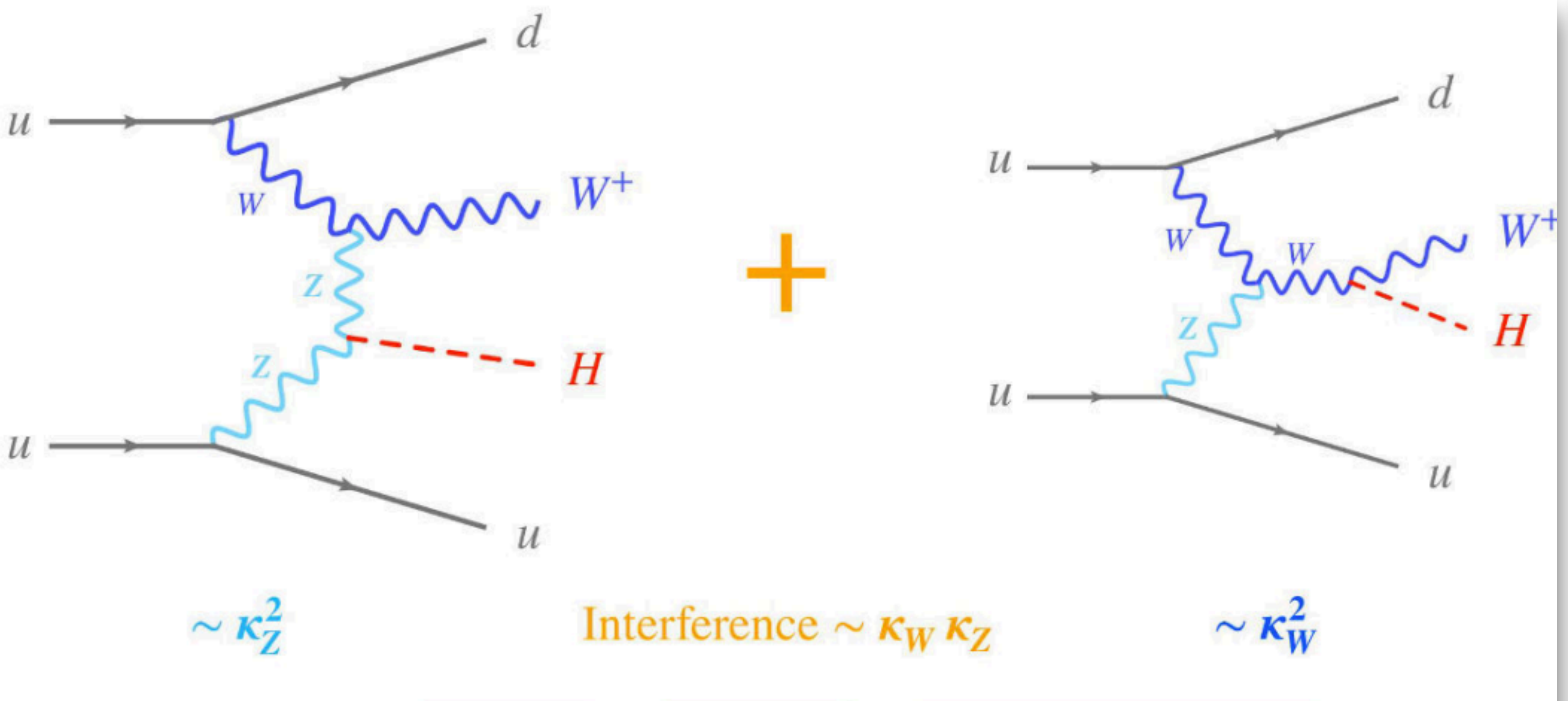
rescales κ_f into units of y_b^{SM} evaluated at $\mu = 125$ GeV

$$\bar{\kappa}_f \equiv \frac{m_f(\mu = 125\ \text{GeV})}{m_b(\mu = 125\ \text{GeV})}\kappa_f\ .$$

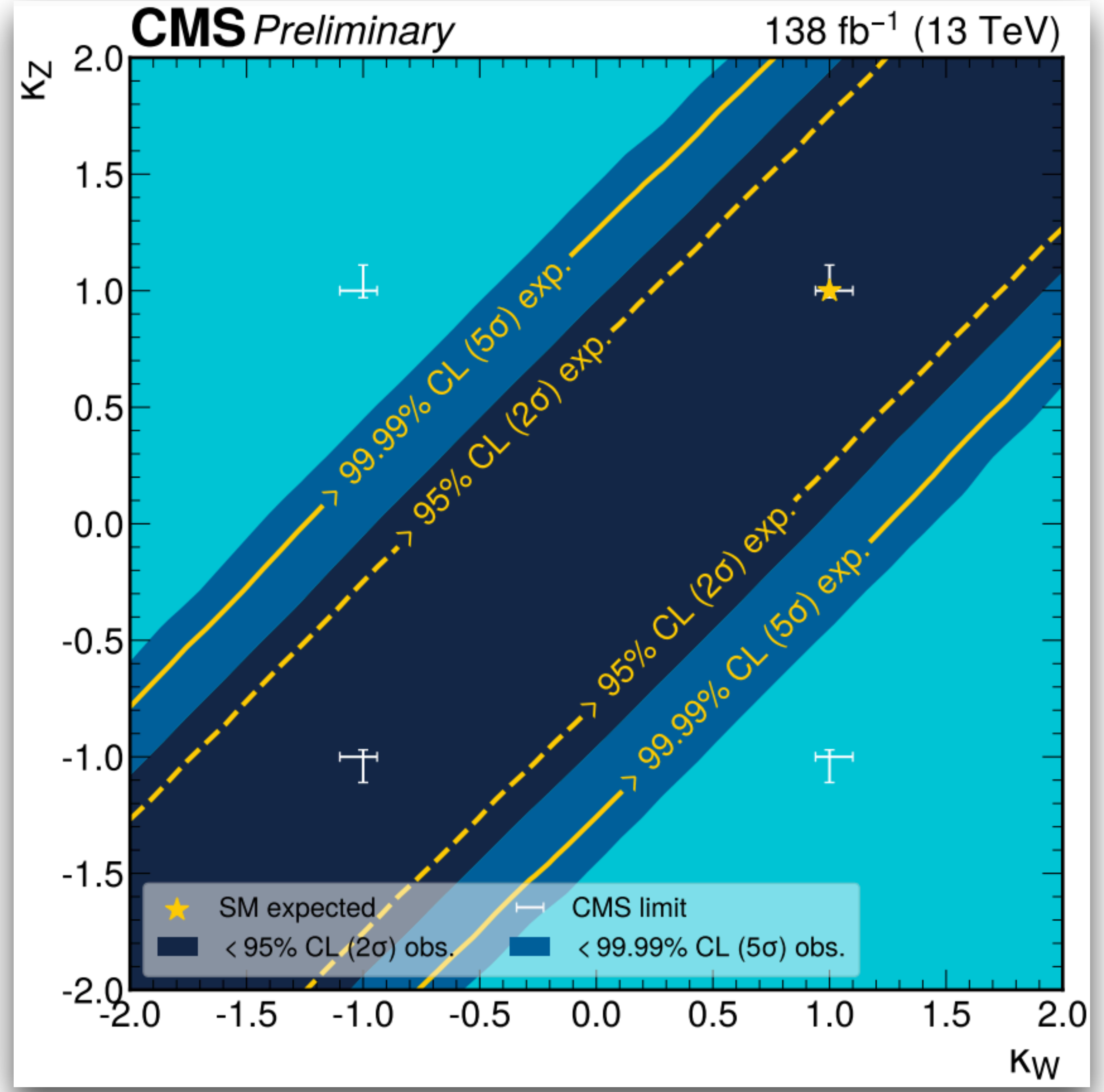
Couplings: W/Z: sign of λ_{WZ}

CMS-PAS-HIG-23-007

- Previously ATLAS & CMS have both measured $|\lambda_{WZ}| = 1$ ($\lambda_{WZ} = \kappa_W/\kappa_Z$) with a precision of ~6%, but the sign was not determined
- VBF WH is probed with merged jets ($H \to bb$), **excluding -1 with a significance of 5σ**



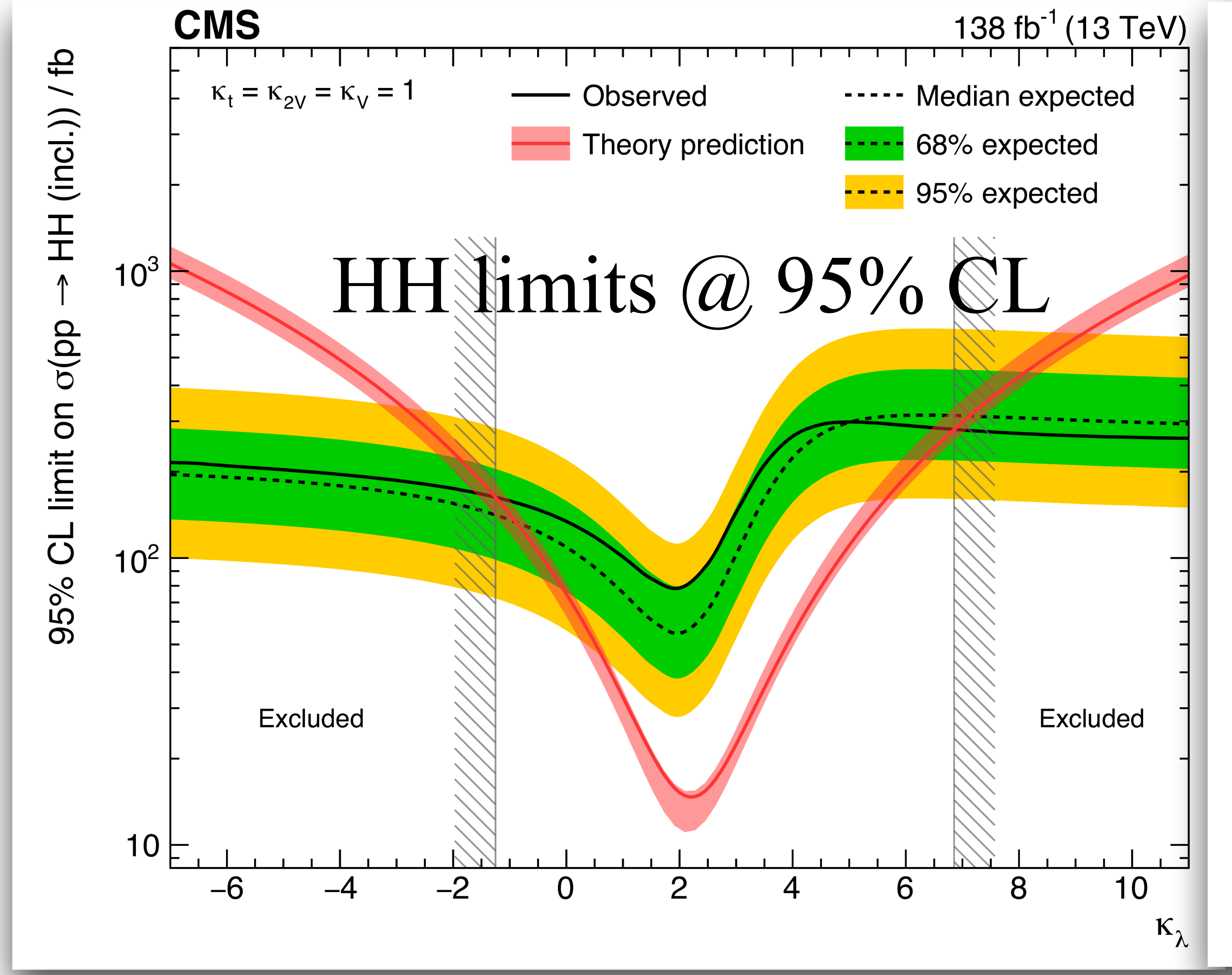
$$\sigma_{VBF,WH} \propto \kappa_Z^2|\mathcal{M}_Z|^2 + \kappa_W^2|\mathcal{M}_W|^2 - 2\kappa_Z\kappa_W \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$
$$= \kappa_Z^2|\mathcal{M}_Z|^2 + \kappa_W^2|\mathcal{M}_W|^2 - 2\kappa_Z^2 \lambda_{WZ} \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$

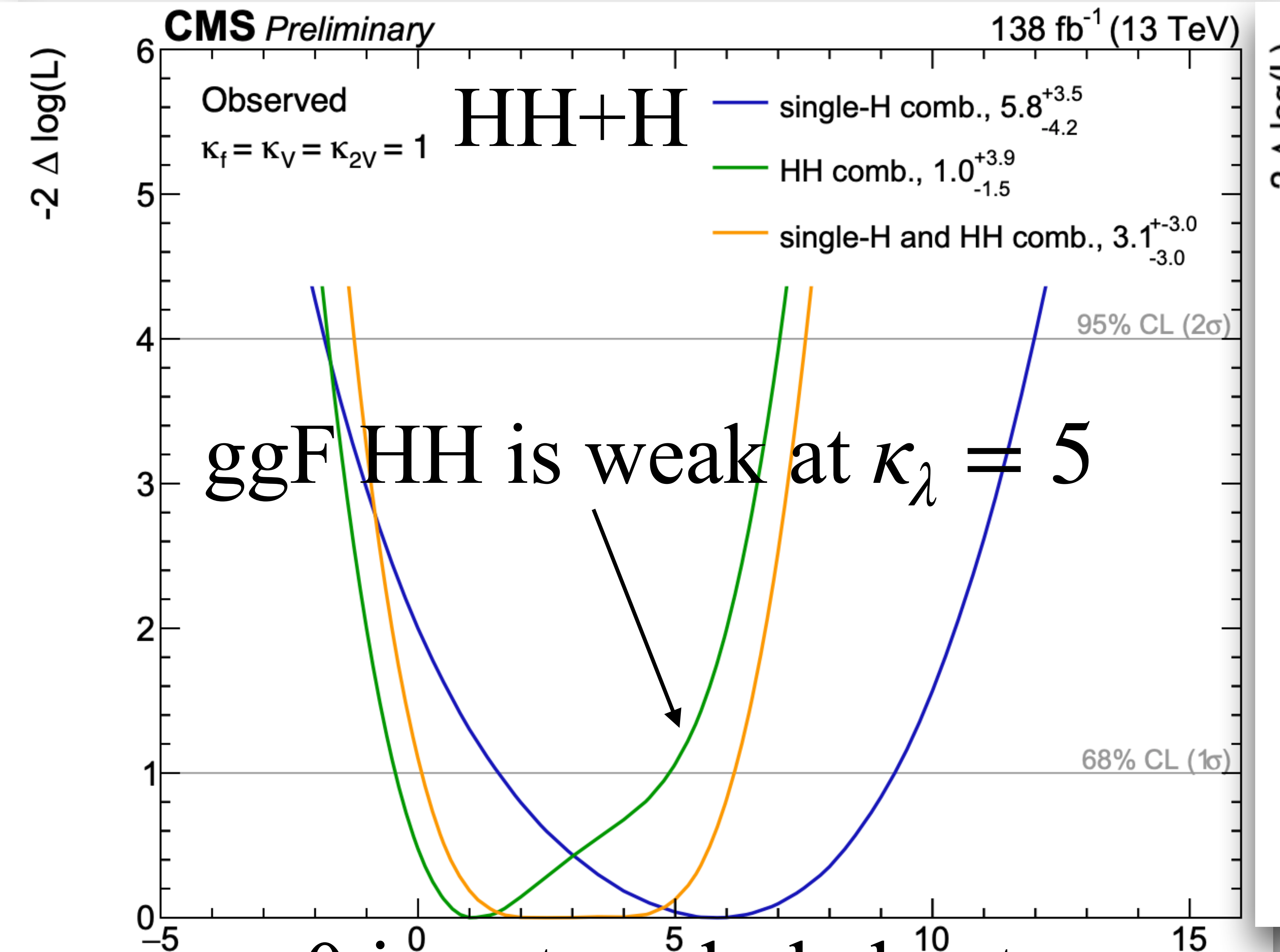


Couplings: self-interaction

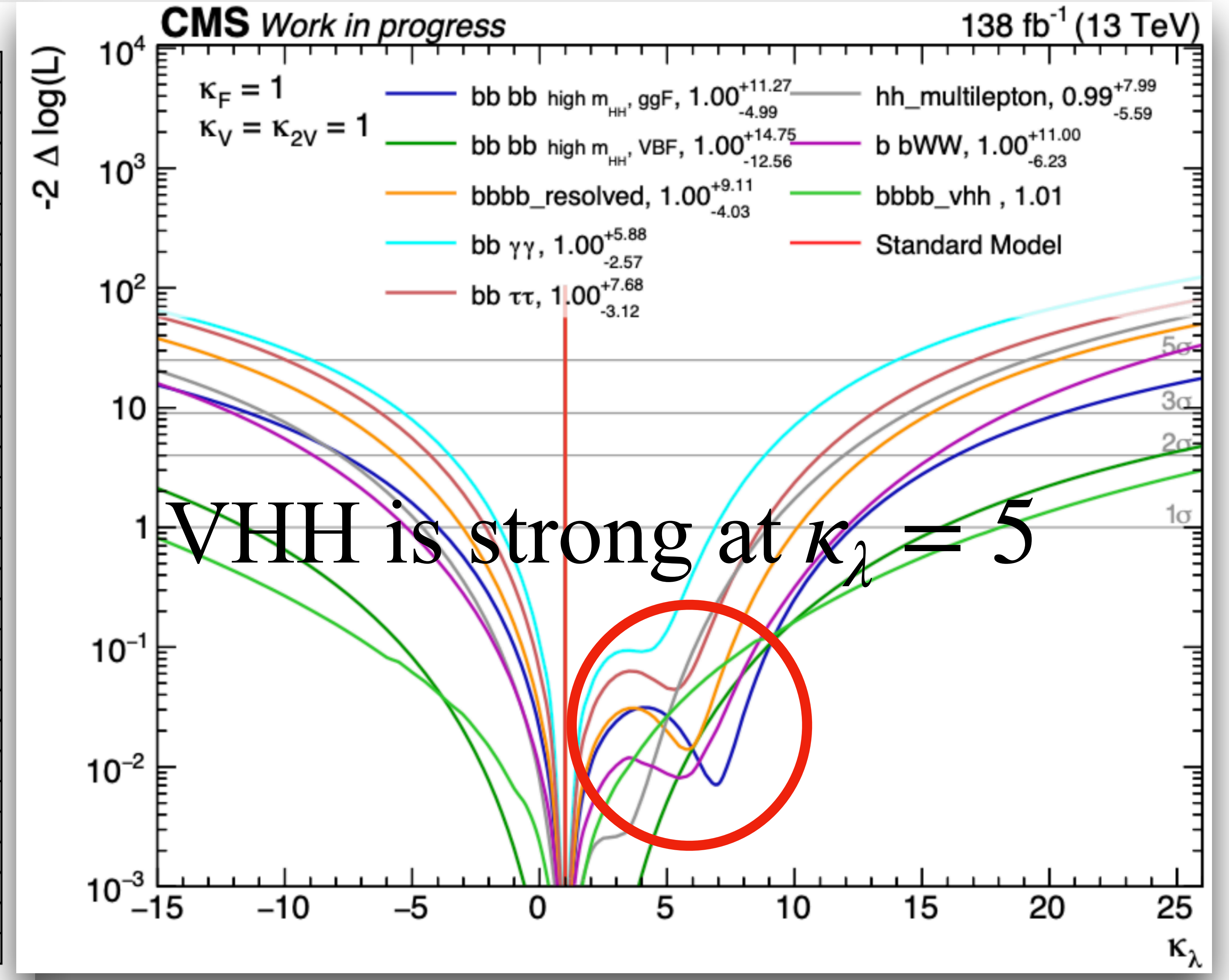
Nature 607 (2022) 60-68
CMS-PAS-HIG-23-006

- Self-coupling gives a deep insight of the Higgs potential
  - Can be probed with double Higgs (HH) directly (LO) and single Higgs indirectly (NLO EW)
- With low xsec, HH is only possible with multiple channels combined
- CMS **combines** $4b$, $bb\gamma\gamma$, $bb\tau\tau$, $bbZZ$ and multilepton





0 is not excluded yet

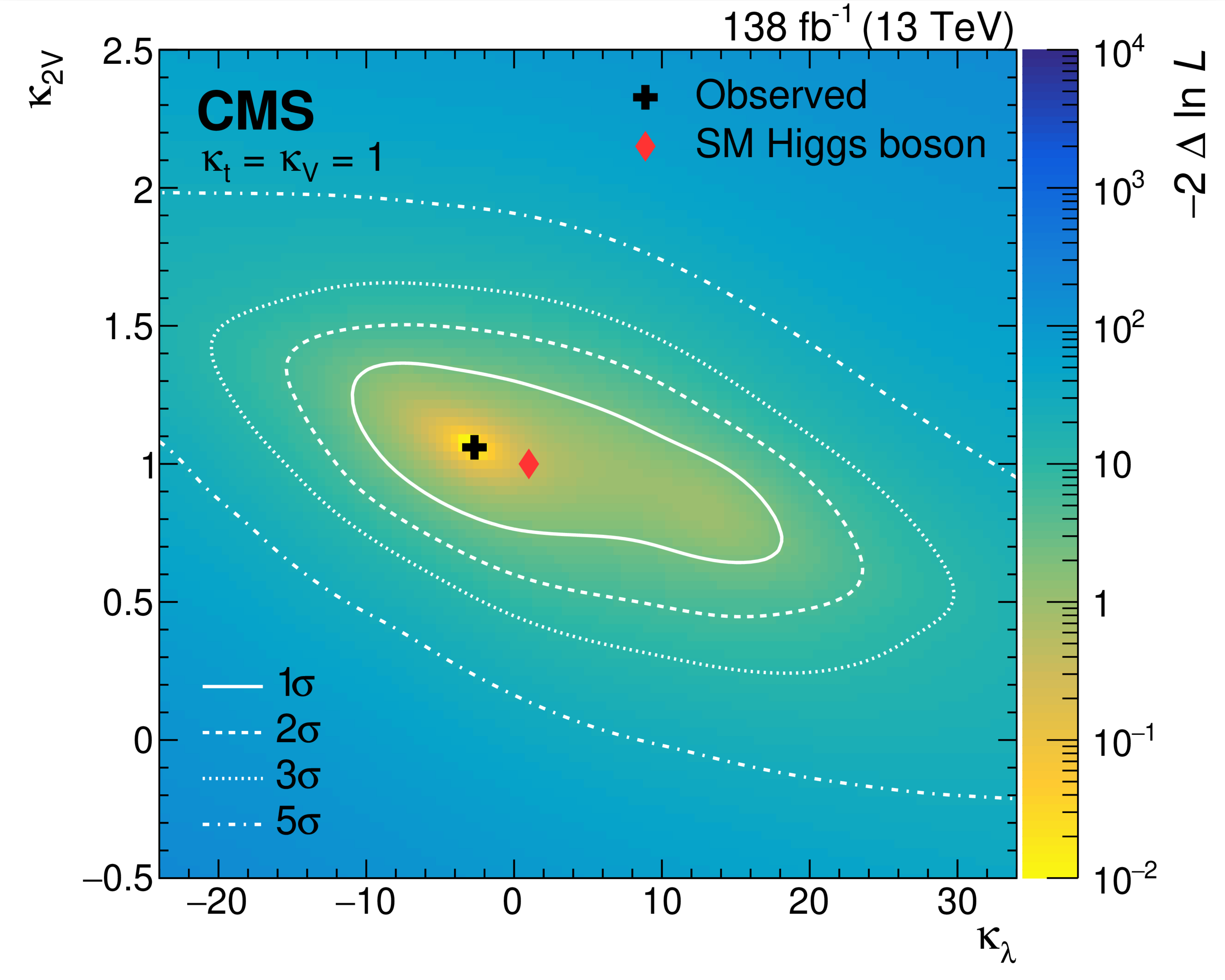


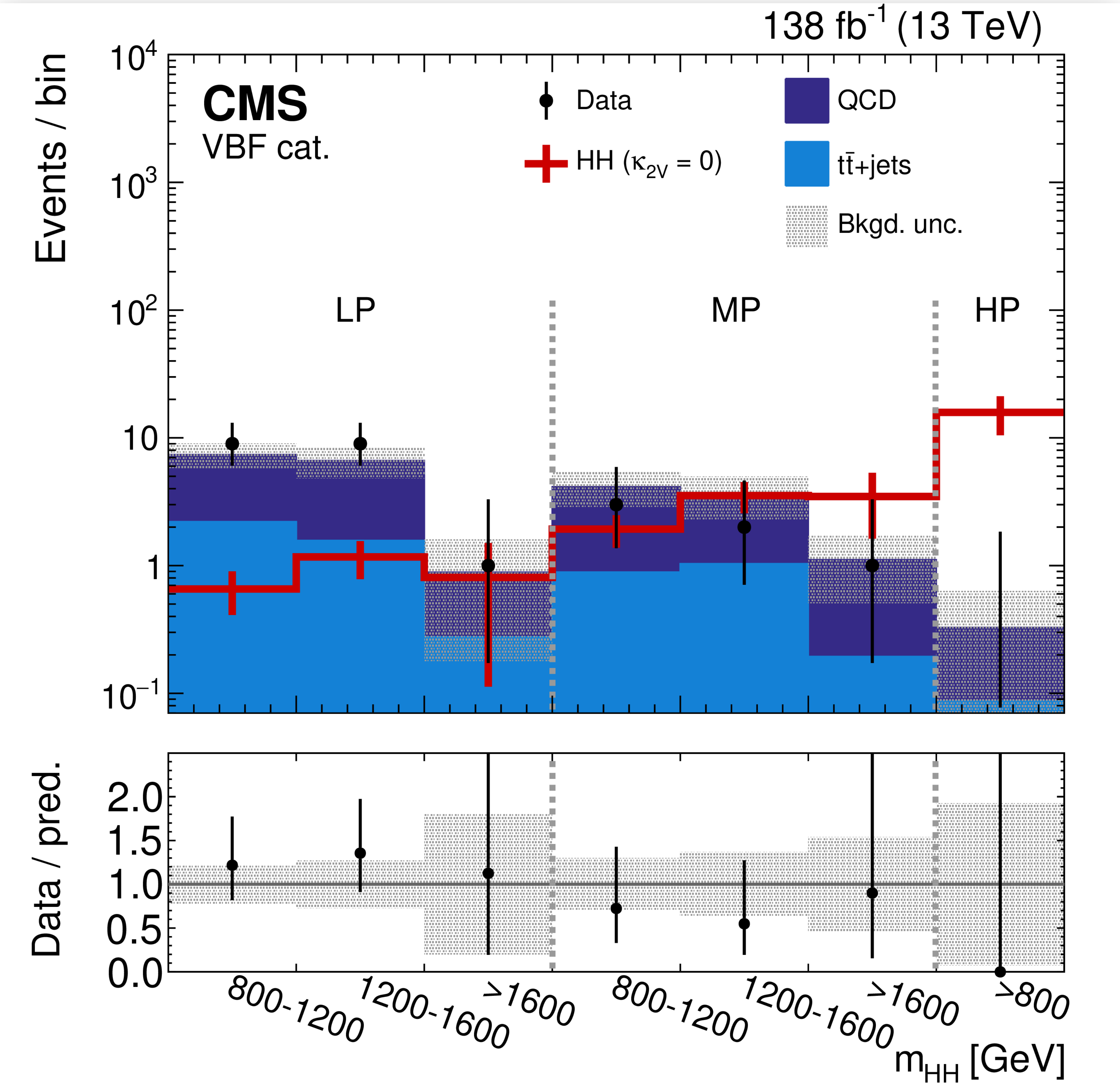
CMS-PAS-HIG-22-006
Phys.Rev.D 95 (2017) 7, 073006

Couplings: VVHH

Phys. Rev. Lett. 131 (2023) 041803

- VVHH is probed with VBF HH at CMS using advanced GNN large-R jet tagger
- VVHH $\kappa_{2V} = 0$ is excluded with more than 5σ



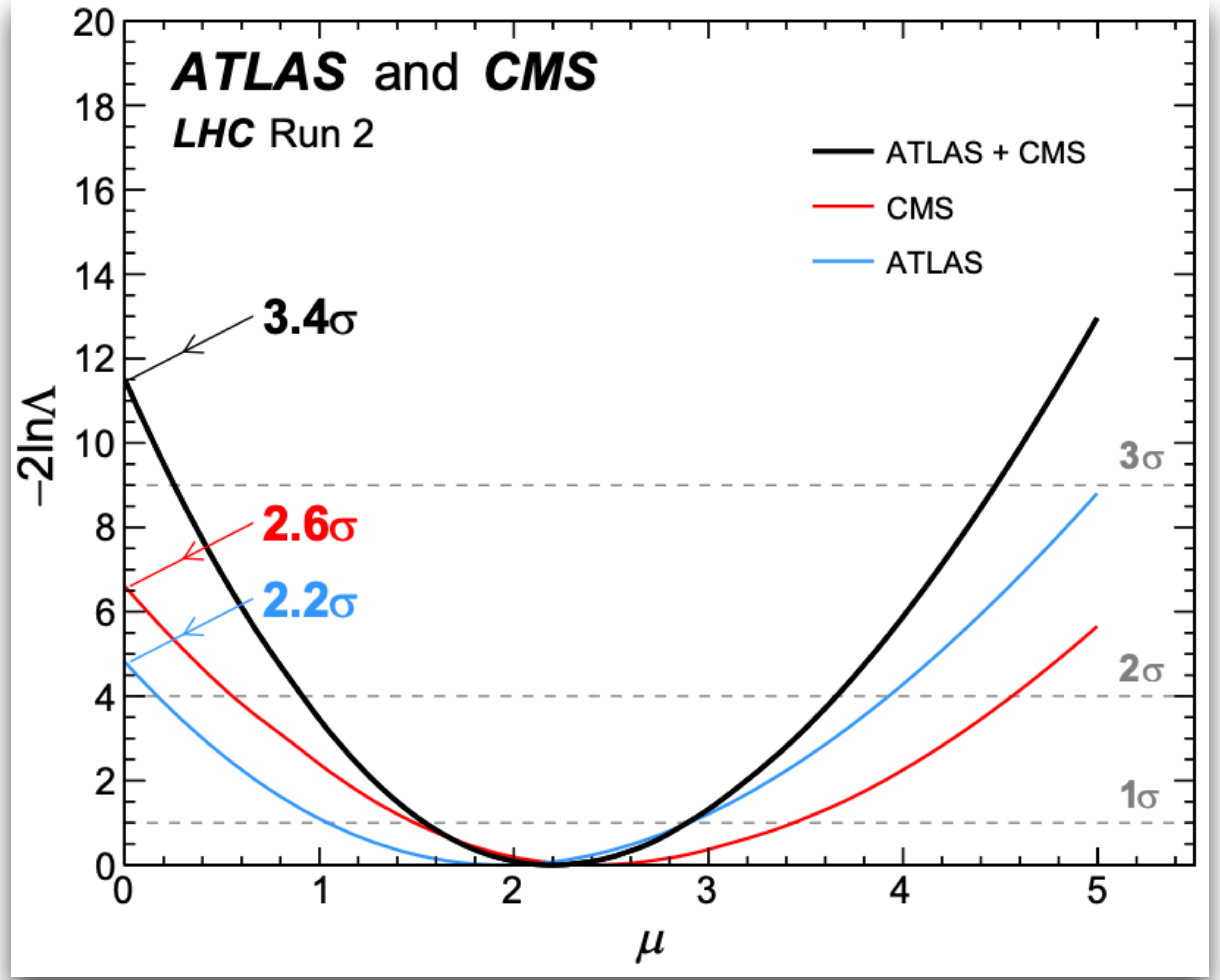


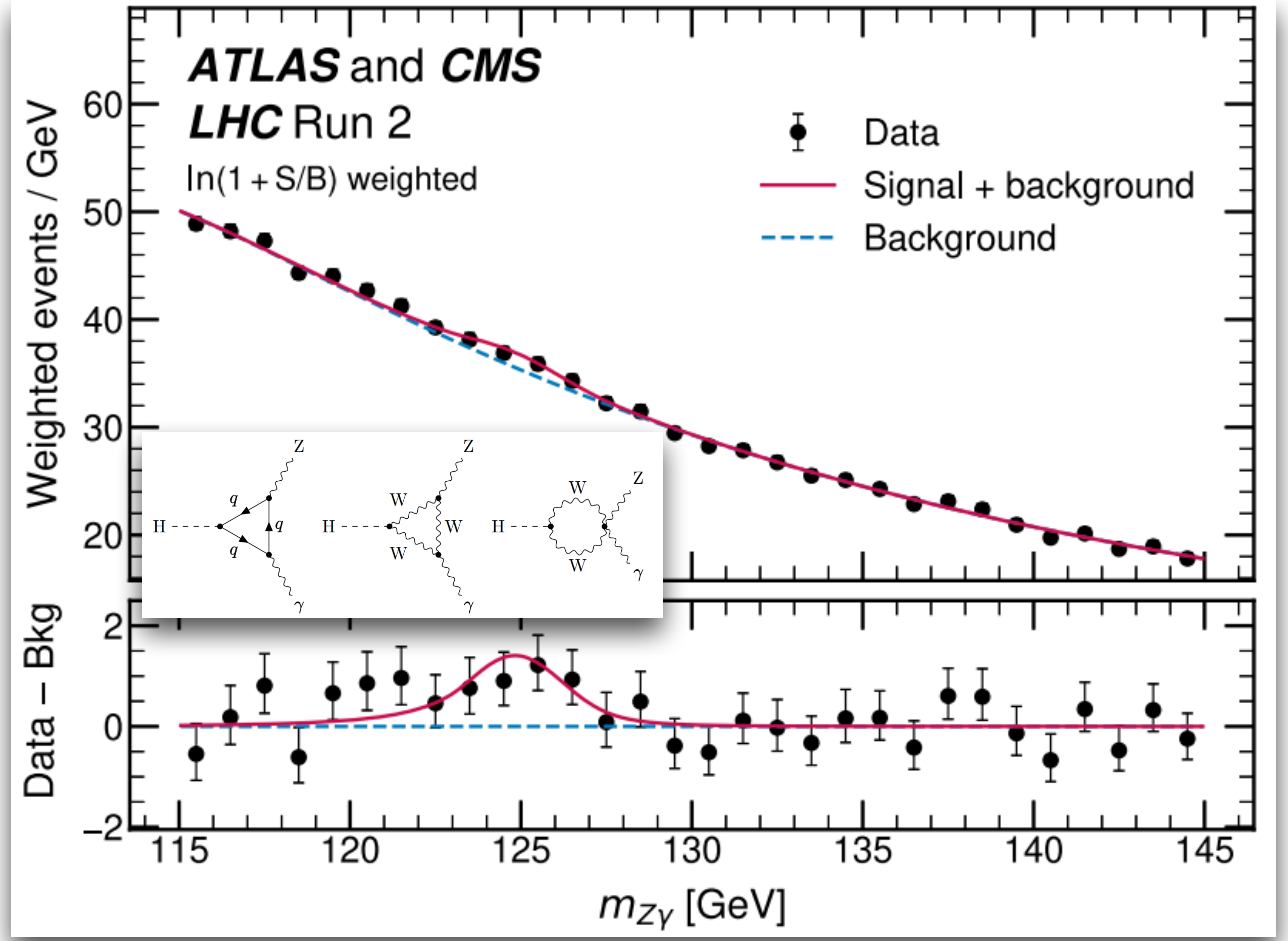
$H \to Z\gamma$ combined evidence

Phys. Rev. Lett. 132, 021803

	Observed (Expected)
ATLAS	2.2σ (1.2σ)
CMS	2.6σ (1.1σ)
Combination	3.4σ (1.6σ)

- $H \to Z\gamma$ with loop where new physics can hide
- New ATLAS and CMS results are combined for 3.4σ

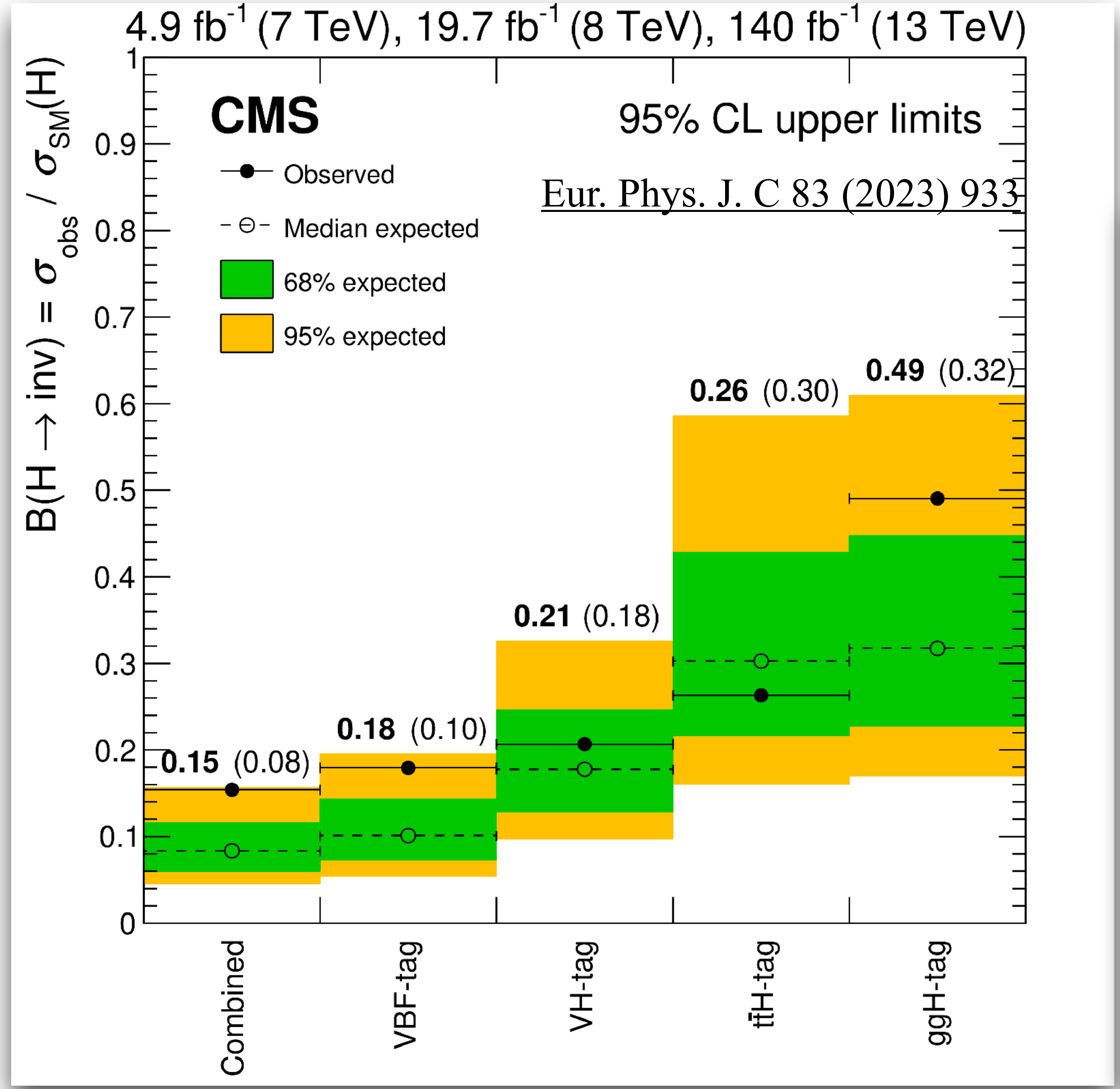


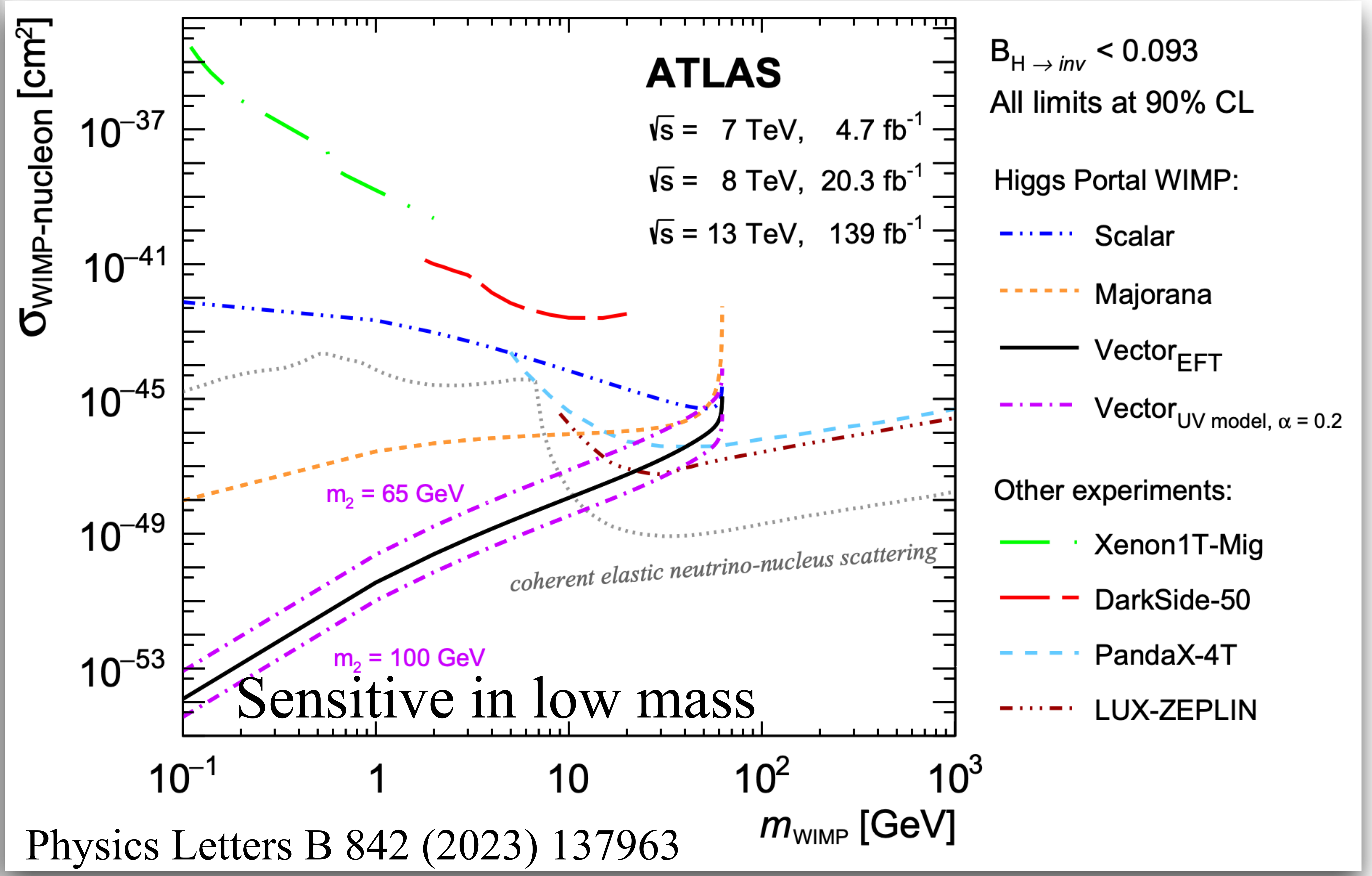


$H \to$ *invisible*

- Direct searches with MET

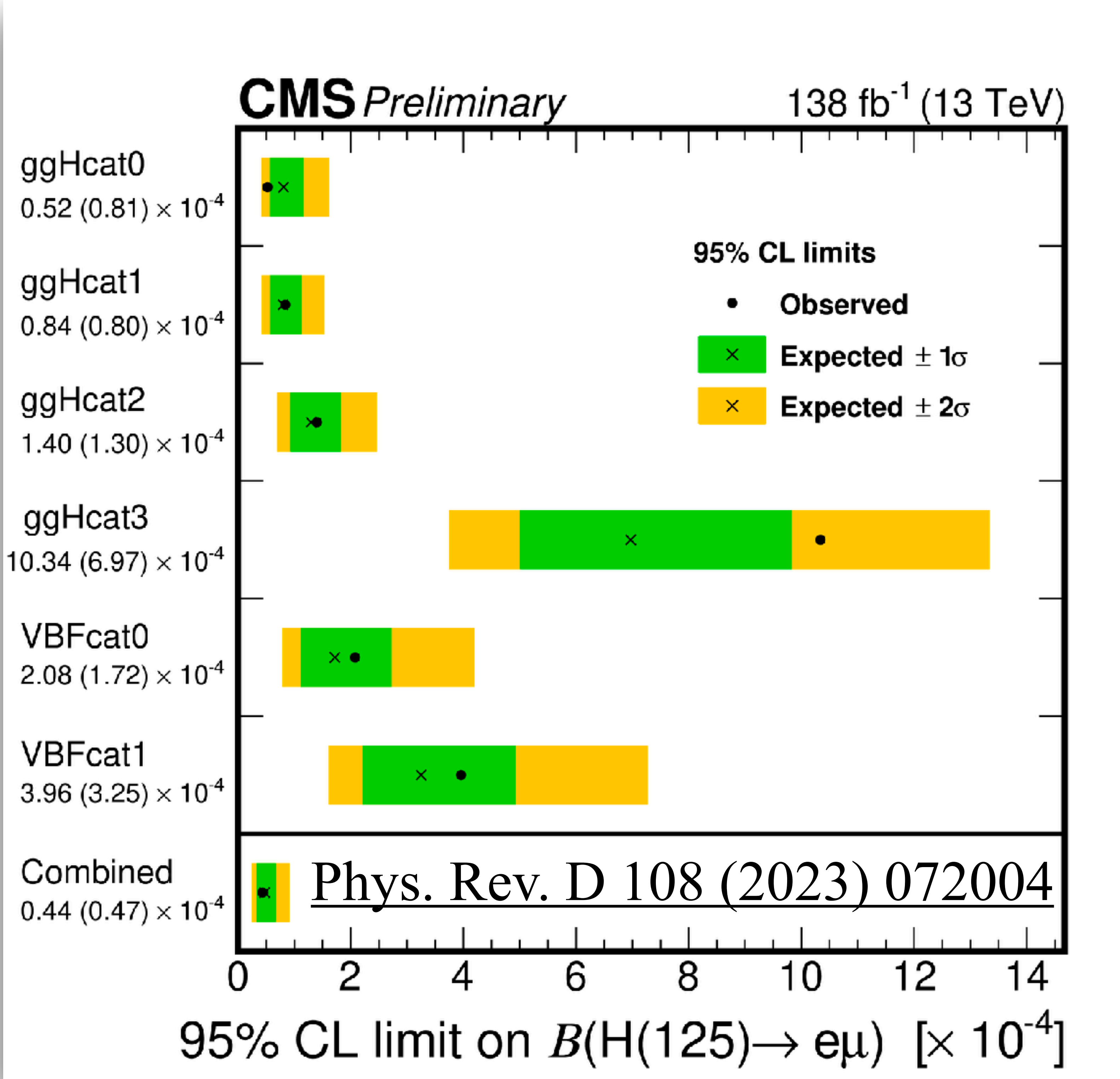
95% CL limit for H→ inv
ATLAS: 10.7% (7.7% exp.)
CMS: 15% (8% exp.)



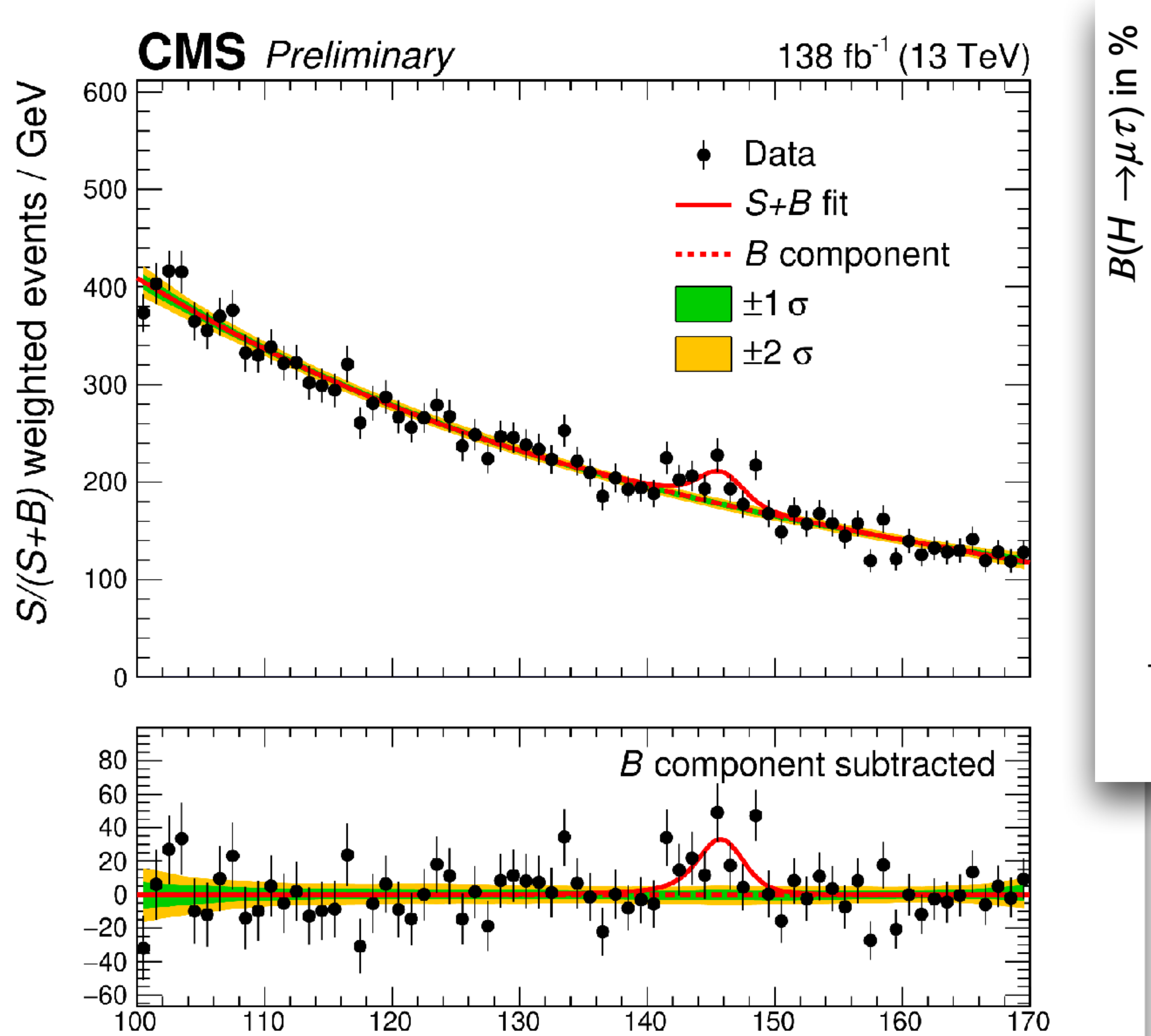


Higgs decays with lepton-flavor violation

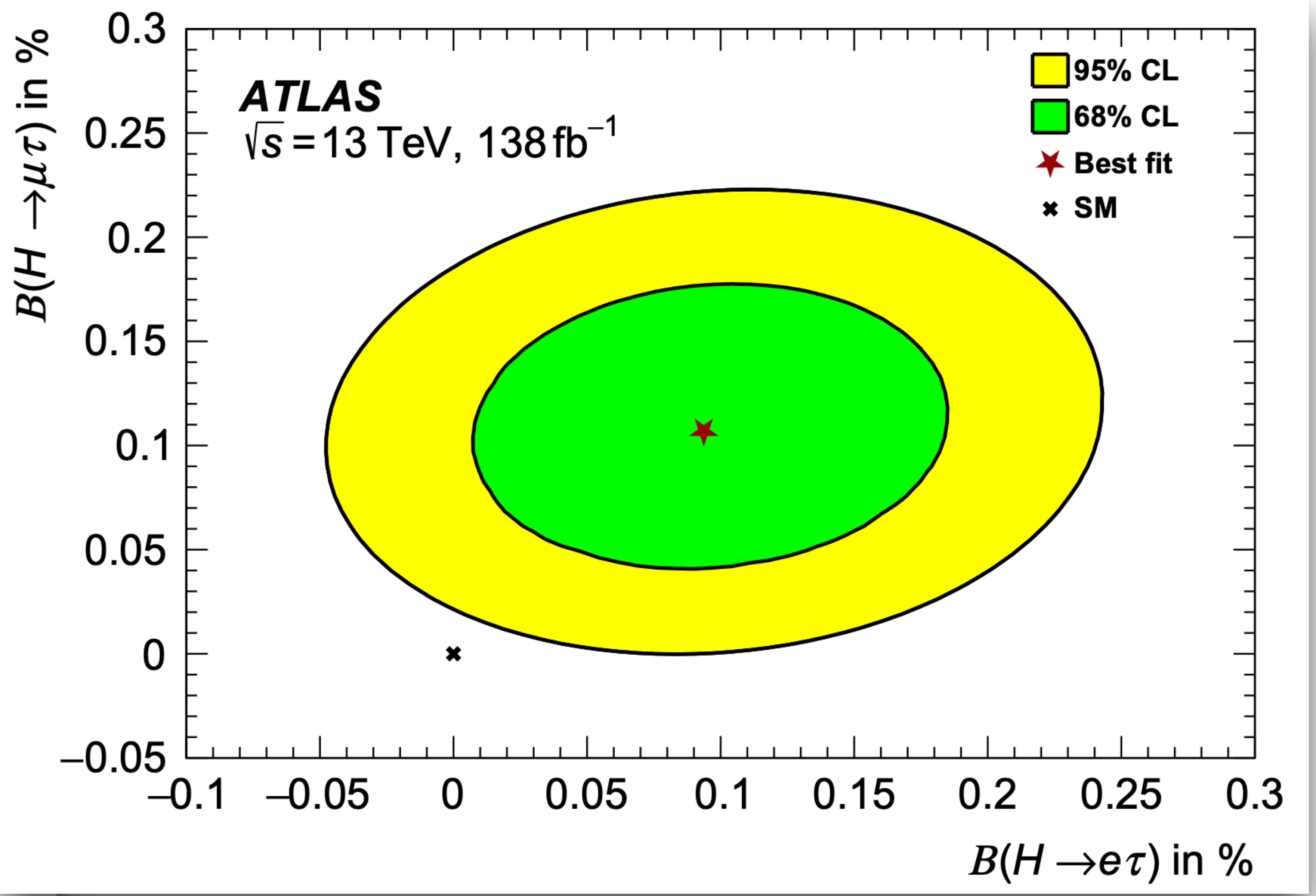
- CMS searches for $H \rightarrow e\mu$ for SM H and scans the mass from 110 to 160 GeV for BSM H
- ATLAS searches for $H \rightarrow e\tau, \mu\tau$ decays



$BR(H \rightarrow e\mu) < 4.4\ (4.7) \times 10^{-5}$ at 95% CL



Found small excess of 3.8σ (2.8σ) local (global) at 146 GeV



Simultaneous fit with 2 POIs

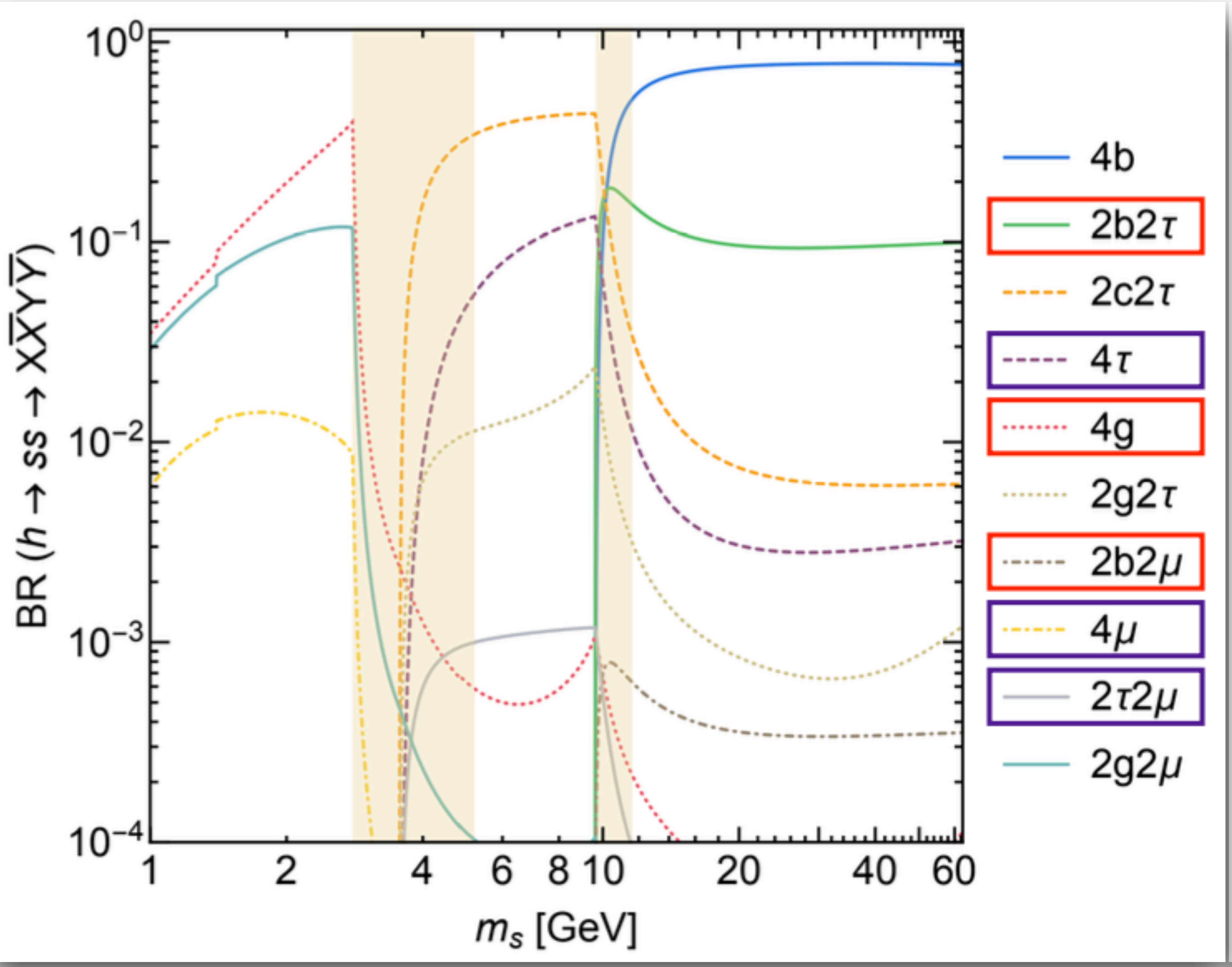
BR(H→eτ) < 0.20% (0.12% exp)

BR(H→μτ) < 0.18% (0.09% exp)

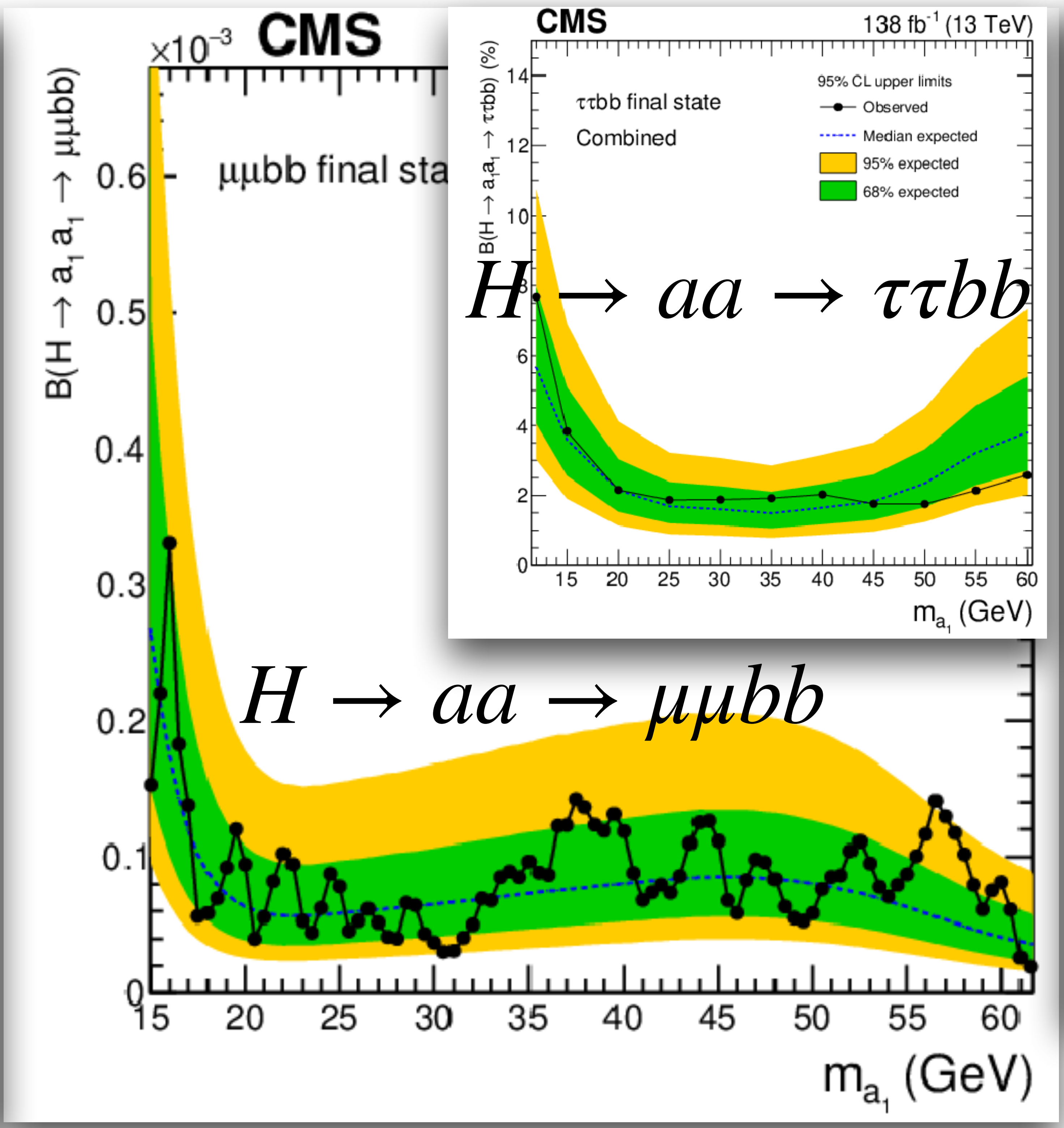
JHEP 07 (2023) 166

Higgs to pseudoscalars

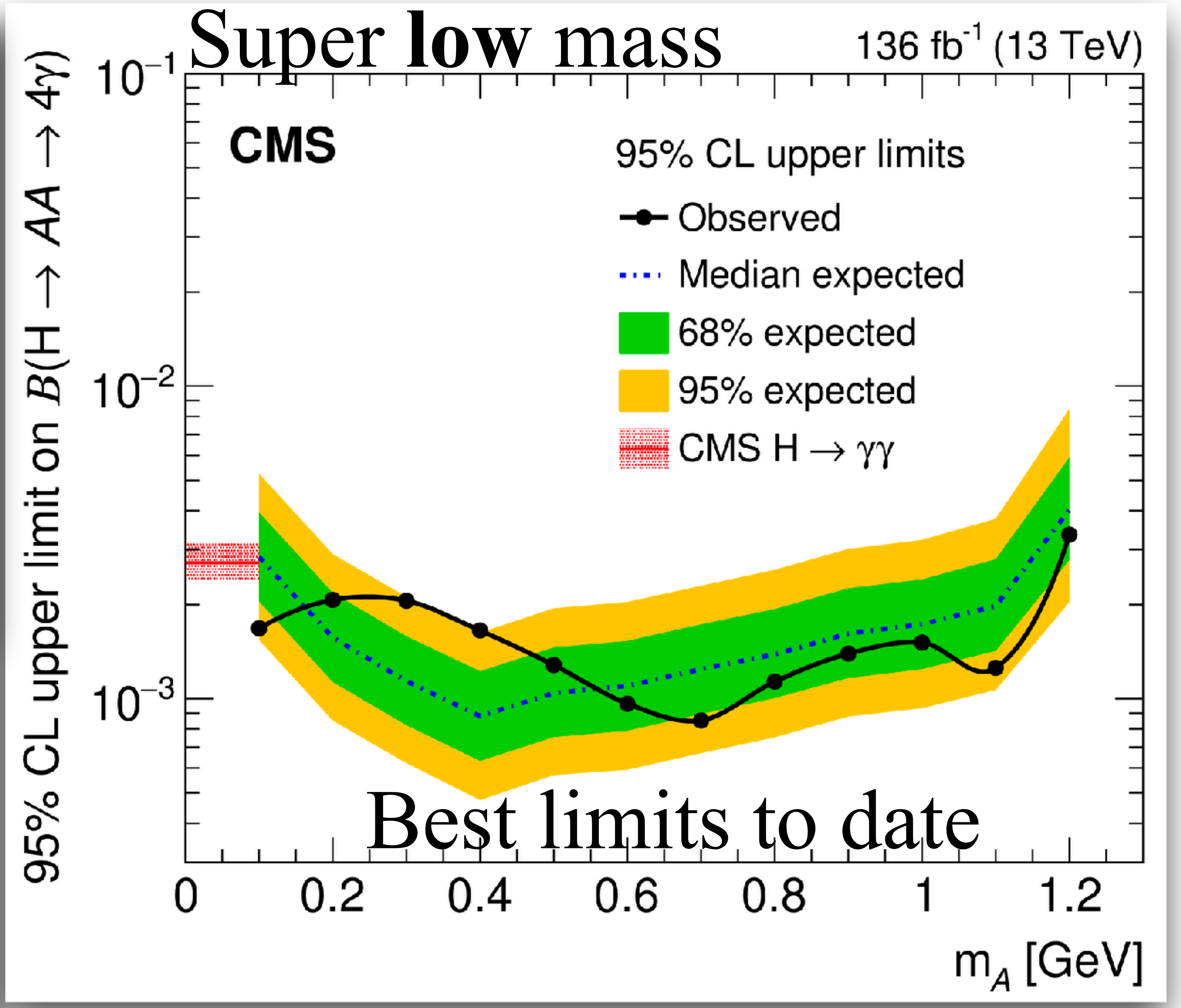
- Axion-like particles can be potential solution to strong CP problem and muon g-2 anomaly
- Copious BSM scenarios (2HDM, 2HDM+S etc.) expect Higgs to decay to a pair of pseudoscalars and these are extensively searched at CMS



Channels sensitive in different mass ranges



arXiv:2402.13358



$H \to aa \to 4\gamma$

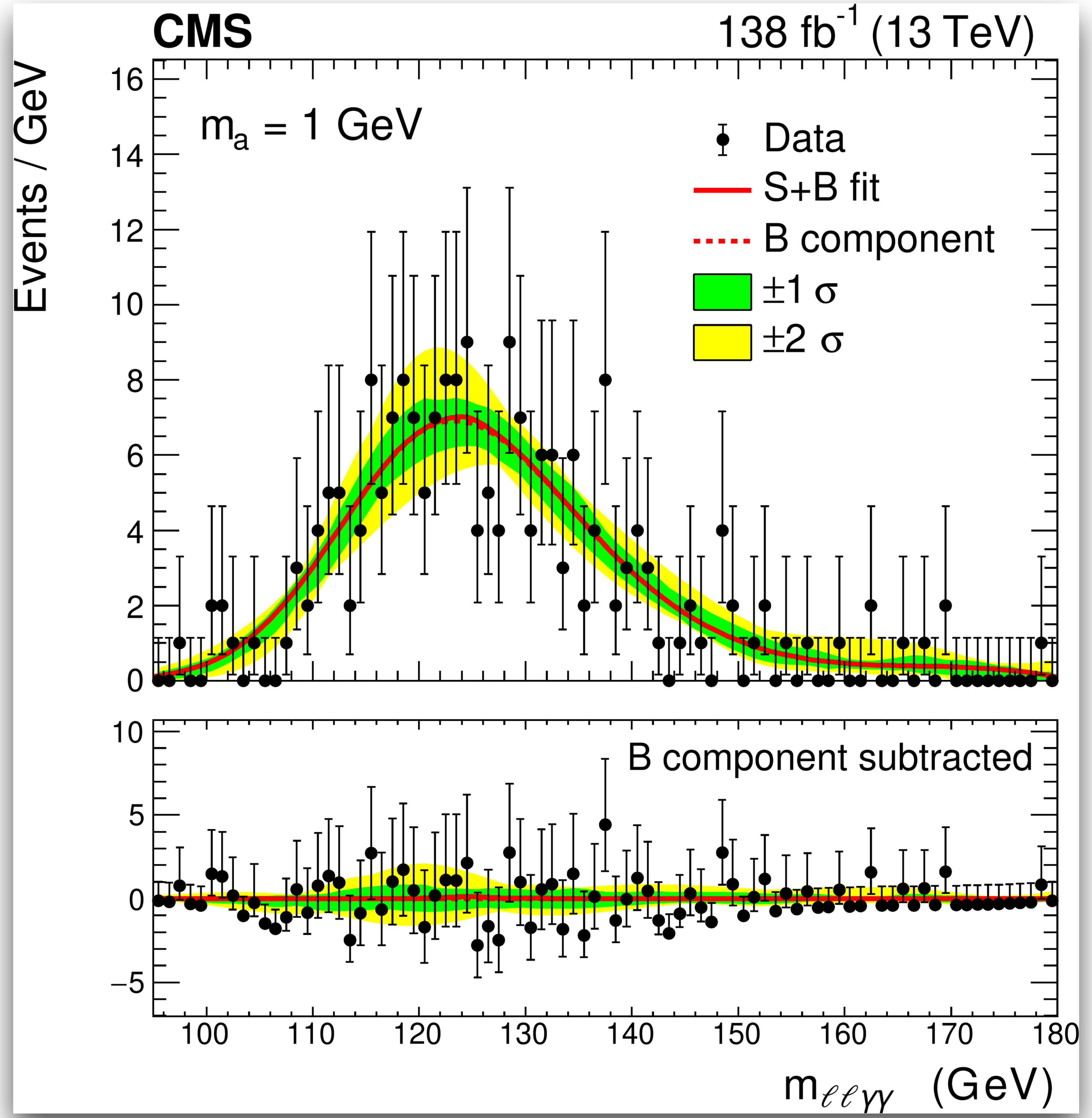
First merged diphoton topology!

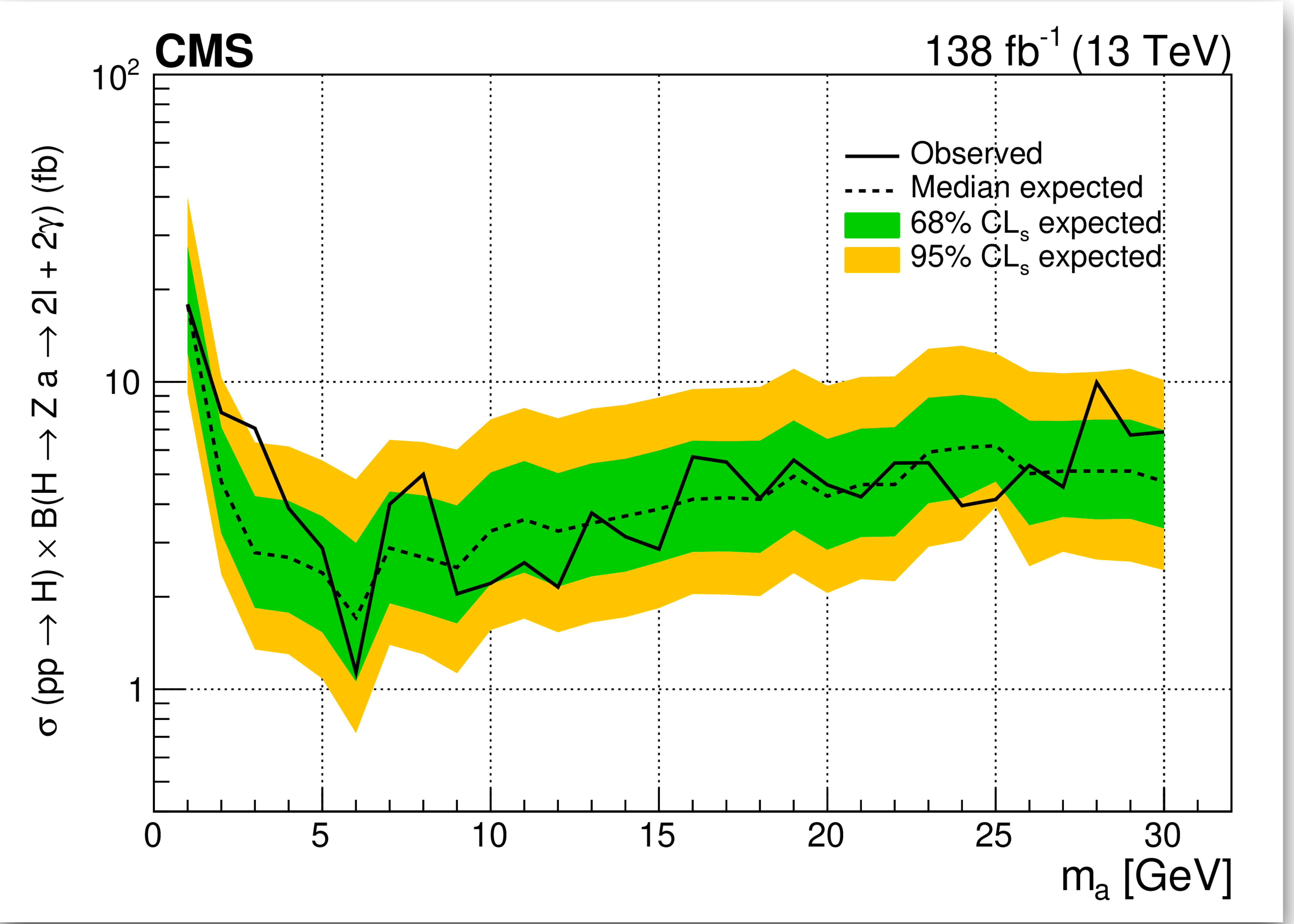
Phys. Rev. Lett. 131 (2023) 101801

Higgs to pseudoscalars

Phys.Lett.B 852 (2024) 138582

- Instead of pairs, Higgs to Z+pseudoscalar is searched as well
- Unique signature with *llγγ* classified with a BDT





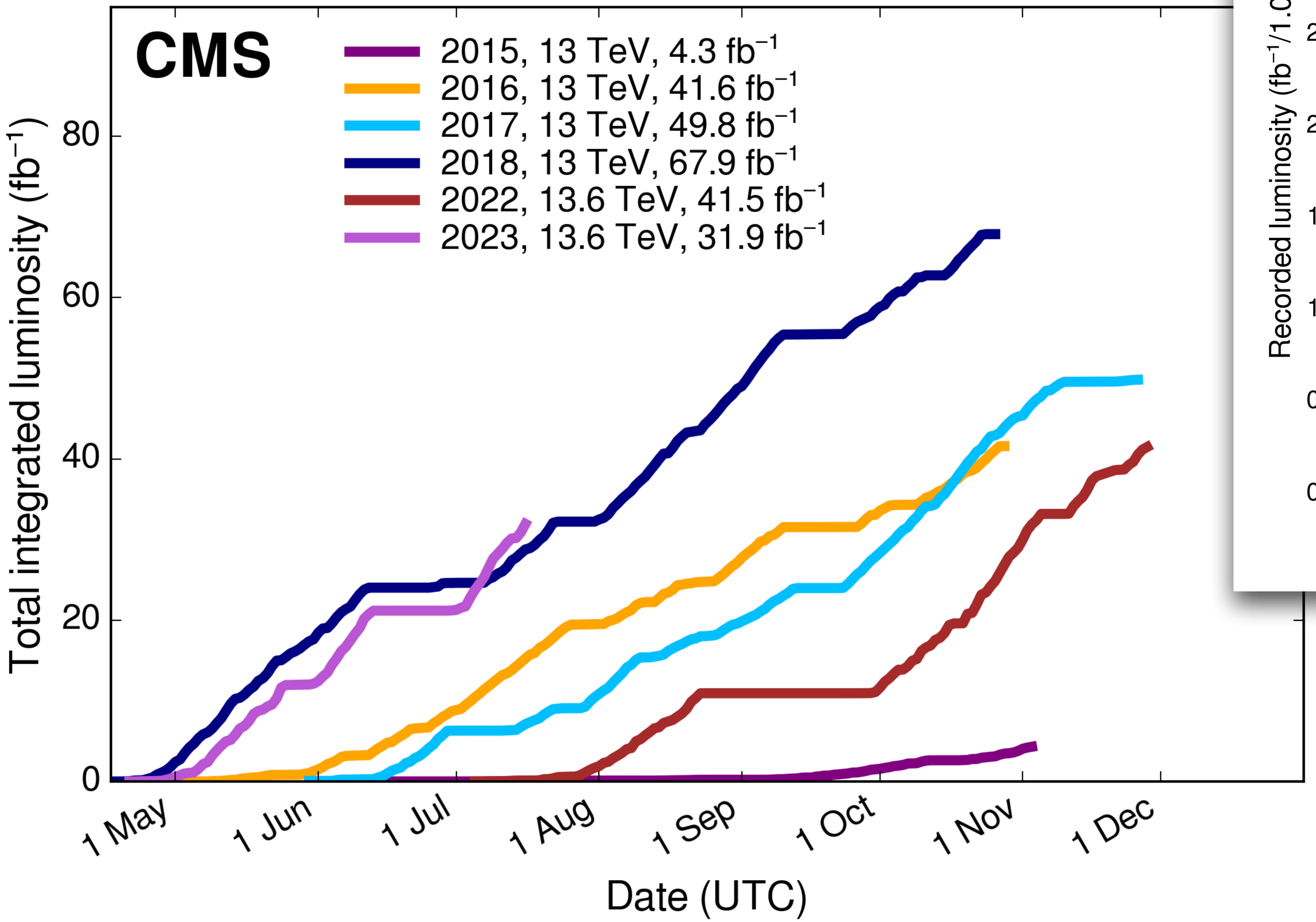
Summary

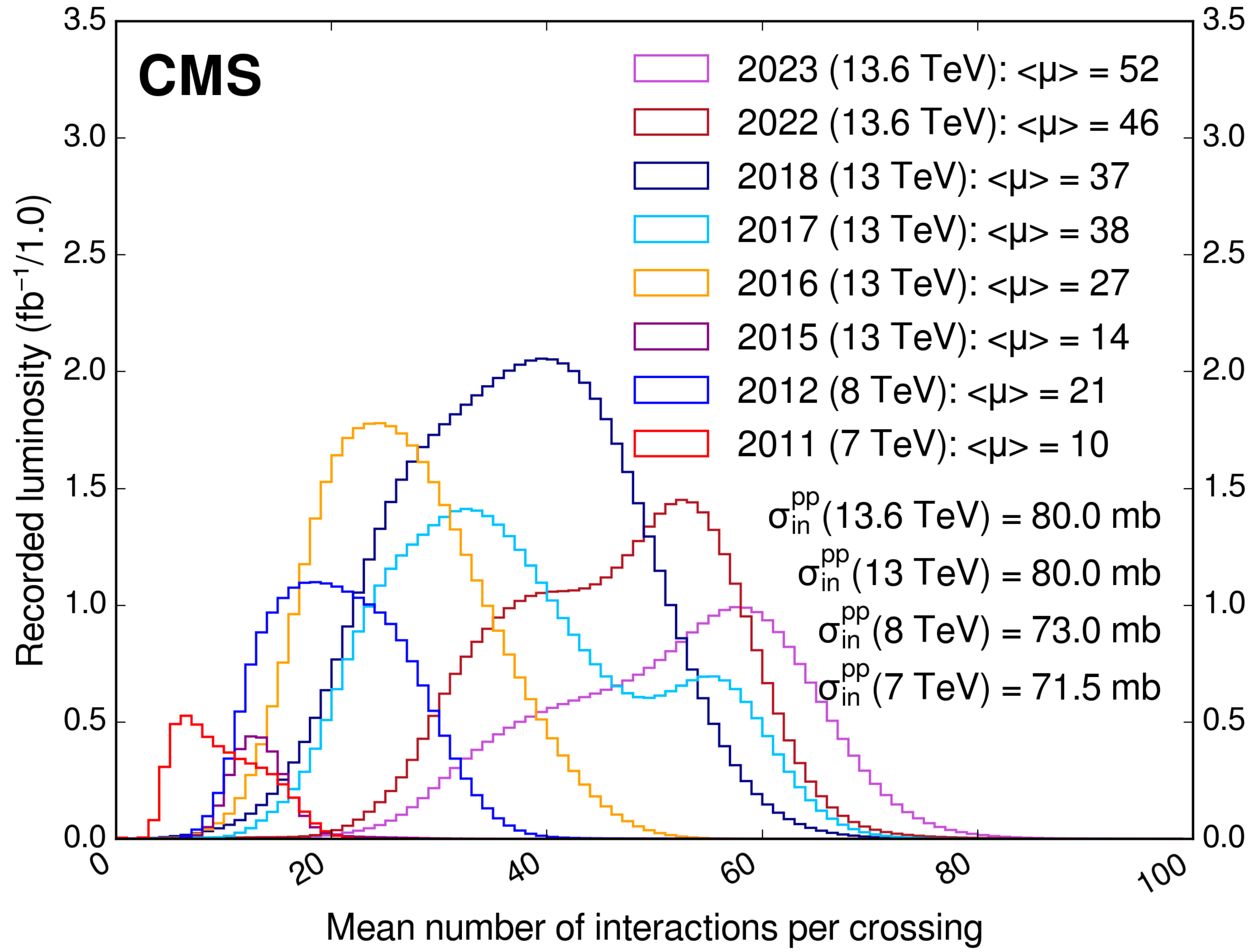
- It has been a decade after the discovery, and the profile of the Higgs boson becomes more clearer, but not clear enough!
- The Higgs mass is measured to the level 0.1%; The width is measured with the best precision ever using on/off-shell productions
- Higgs couplings are in general at 10% and reaching out to the 1st/2nd generation fermions
- No obvious sign of deviation from the SM prediction
- More Run3 analyses are on the way!

* Due to limited time, many topics are not covered, such as CP, EFT, rare/exotic decays etc.

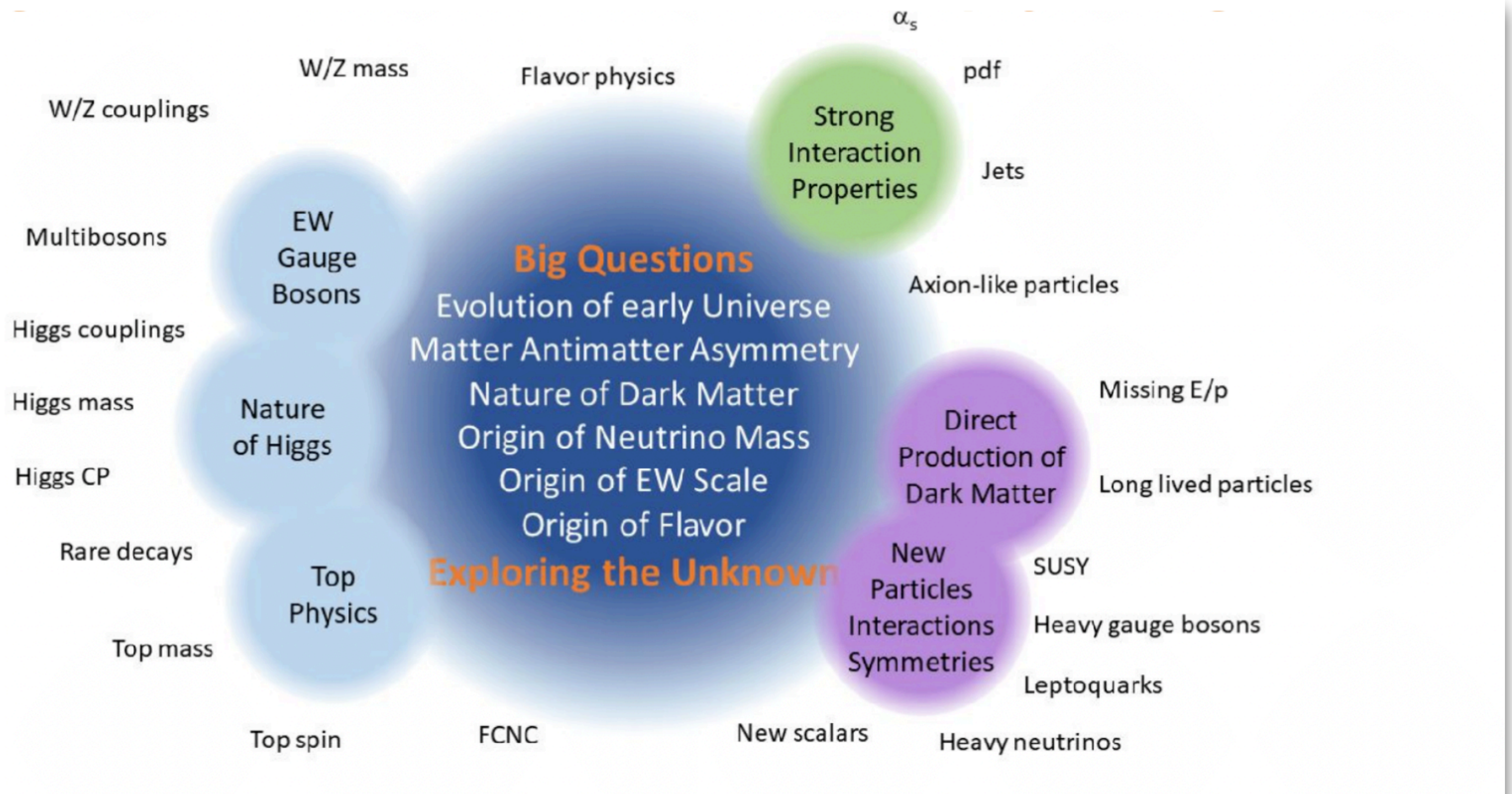
Backup

Data taking since Run2





The bigger questions

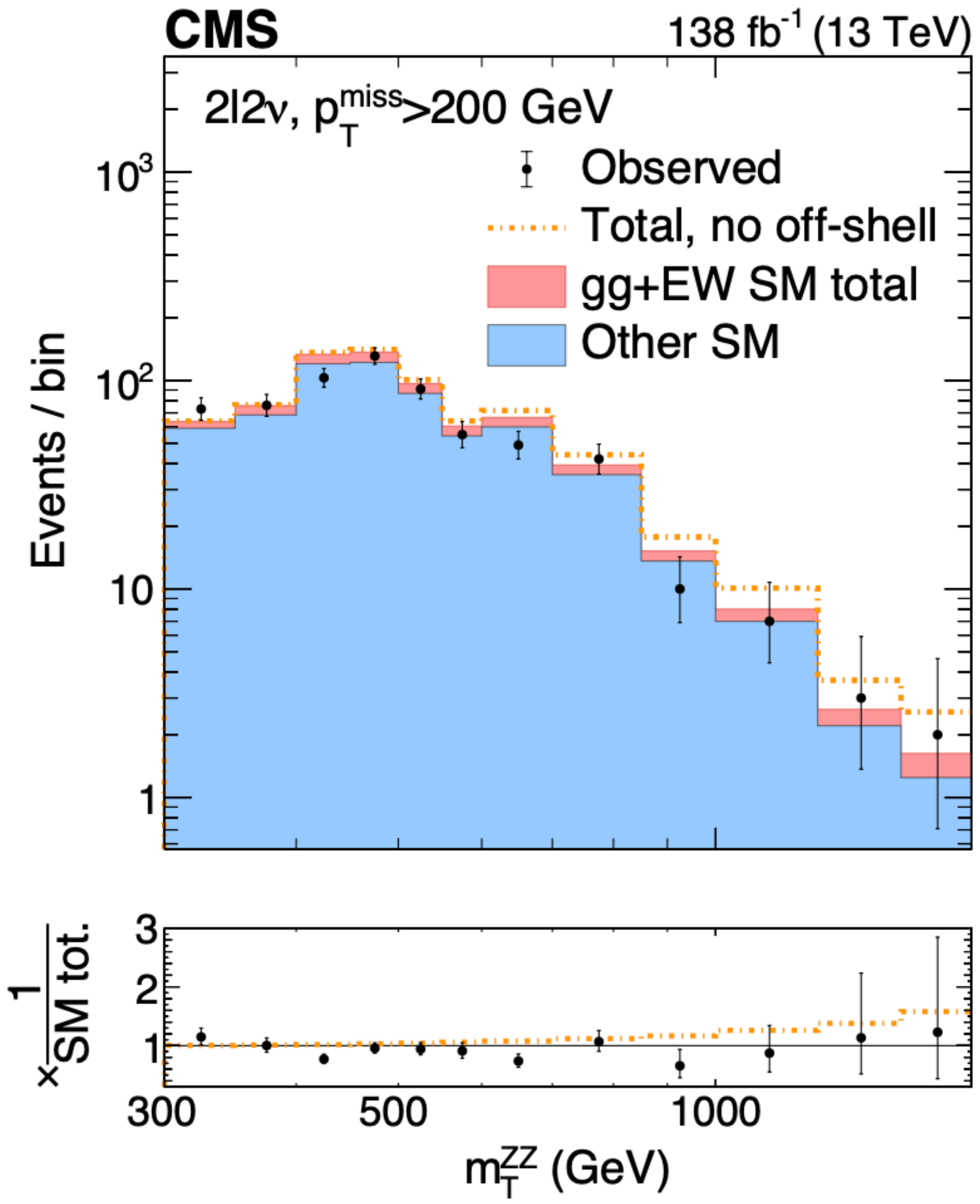


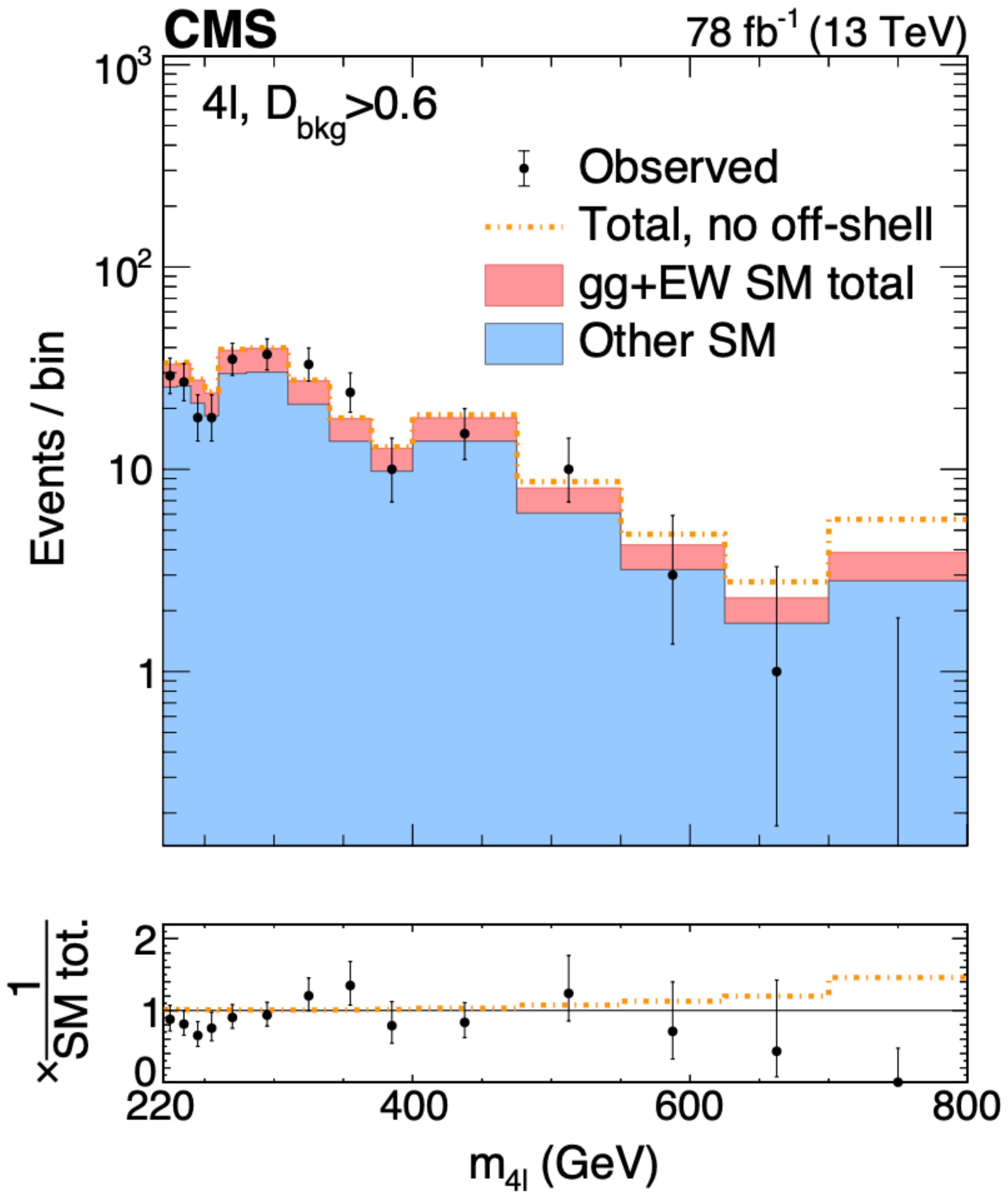
From the Snowmass Energy Frontier Report

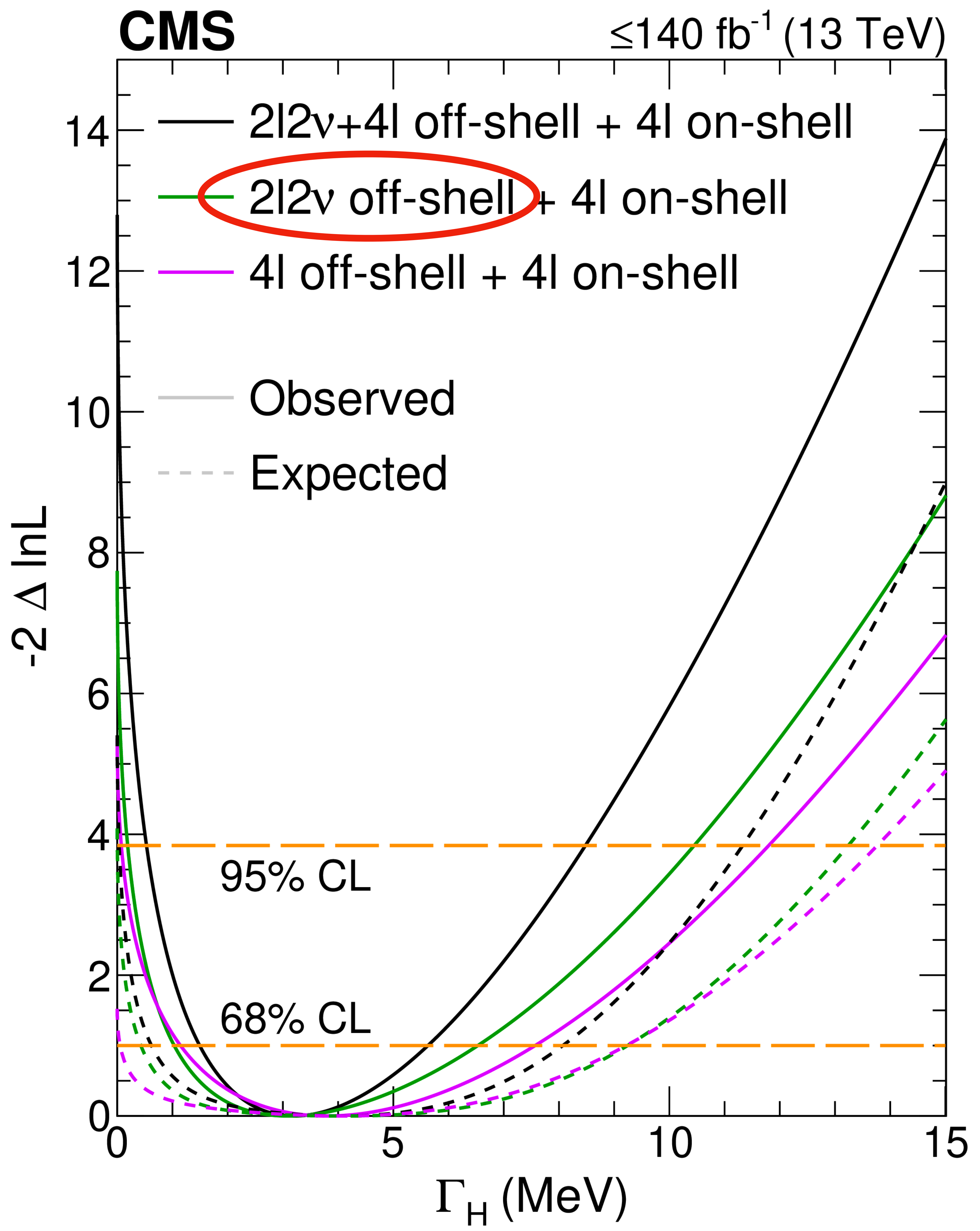
The width

4l takes its advantage in on-shell

llvv plays an important role in off-shell



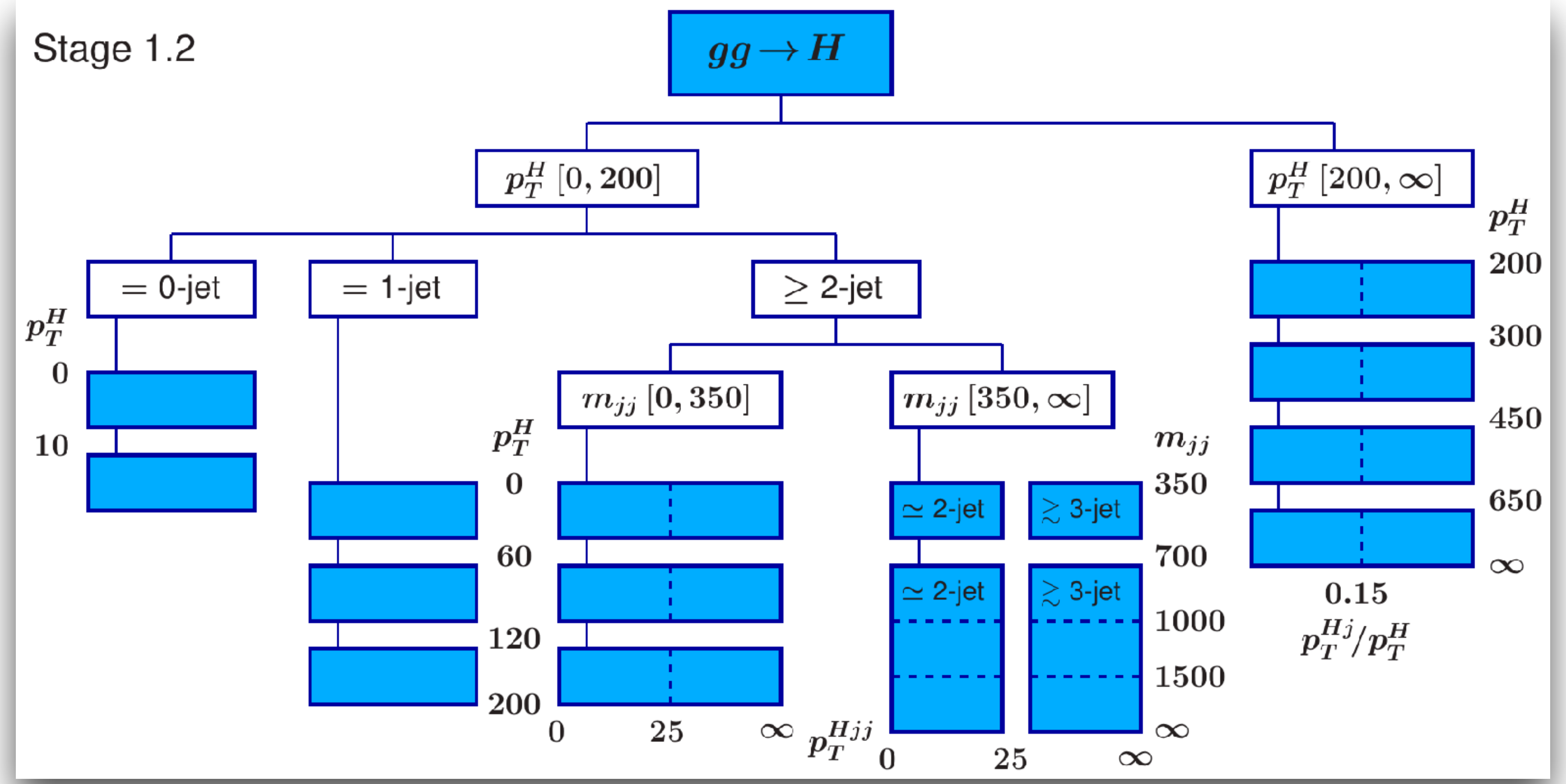


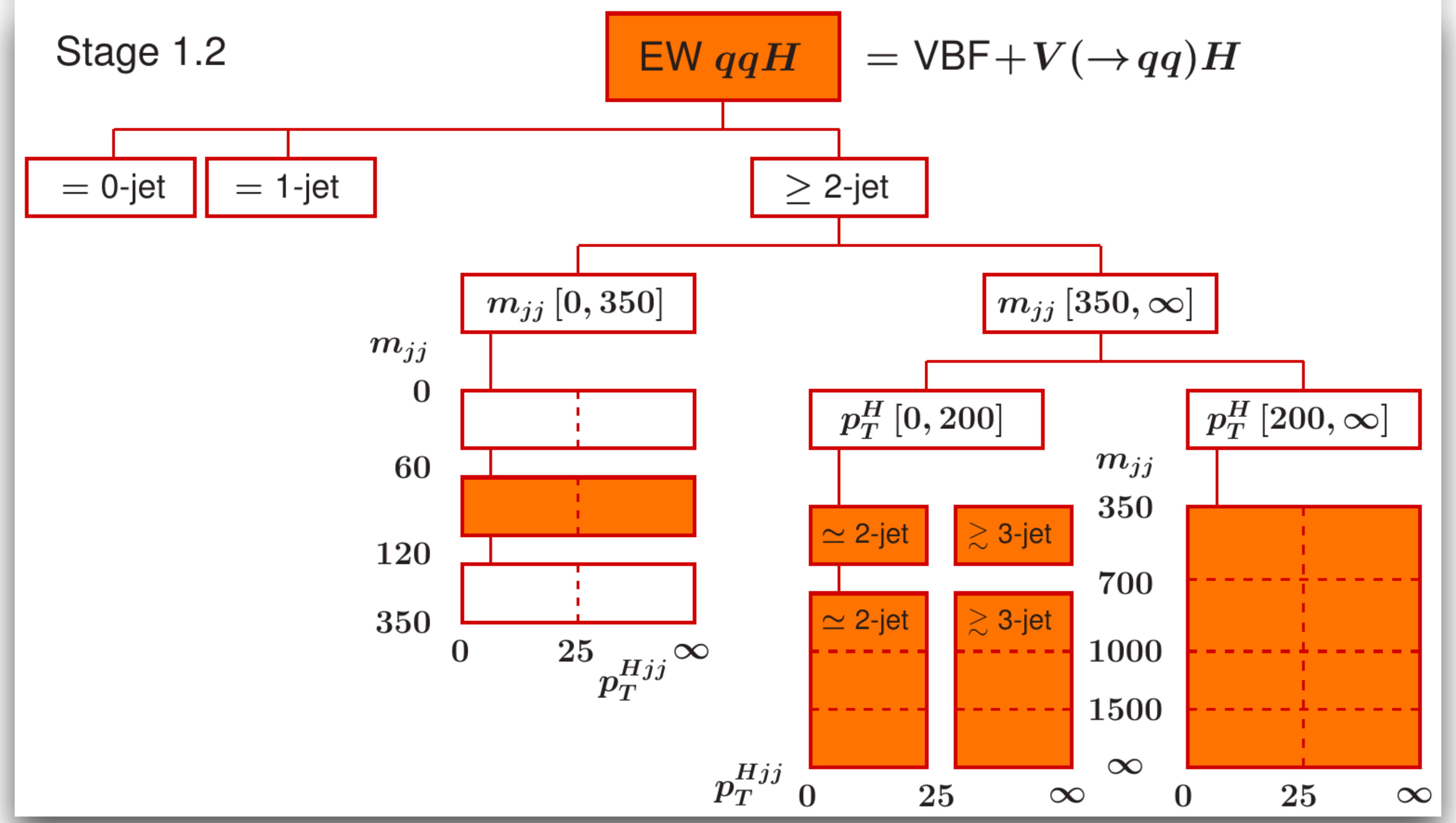


The stacked histogram displays the distribution after a fit to the data with SM couplings, with the blue filled area corresponding to the SM processes that do not include H boson interactions, and the pink filled area adding processes that include H boson and interference contributions

Rates in detail - STXS

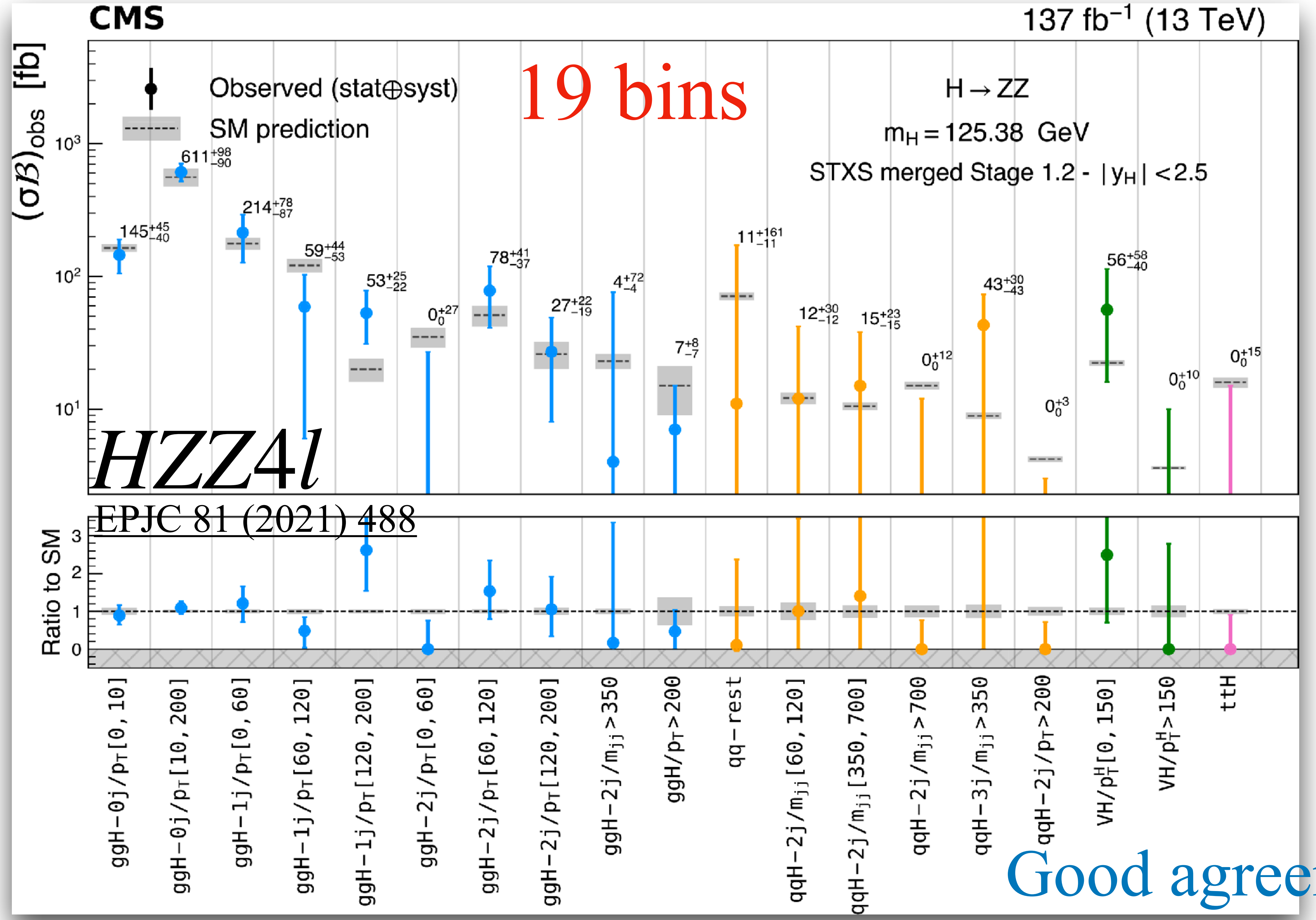
- The Simplified Template Cross Section (STXS) provides a pragmatic interface from the experimental accessibility to the theoretical handlers on SM and BSM phenomena, by using coarse kinematic bins
  - Balancing the experimental sensitivity (XS measurements with maximum sensitivities with deeply optimized cuts) and the model independence (differential XS measurements with fine kinematic bins using simple cuts)
- The experiments are reaching the precision for measuring STXS in Stage 1.2





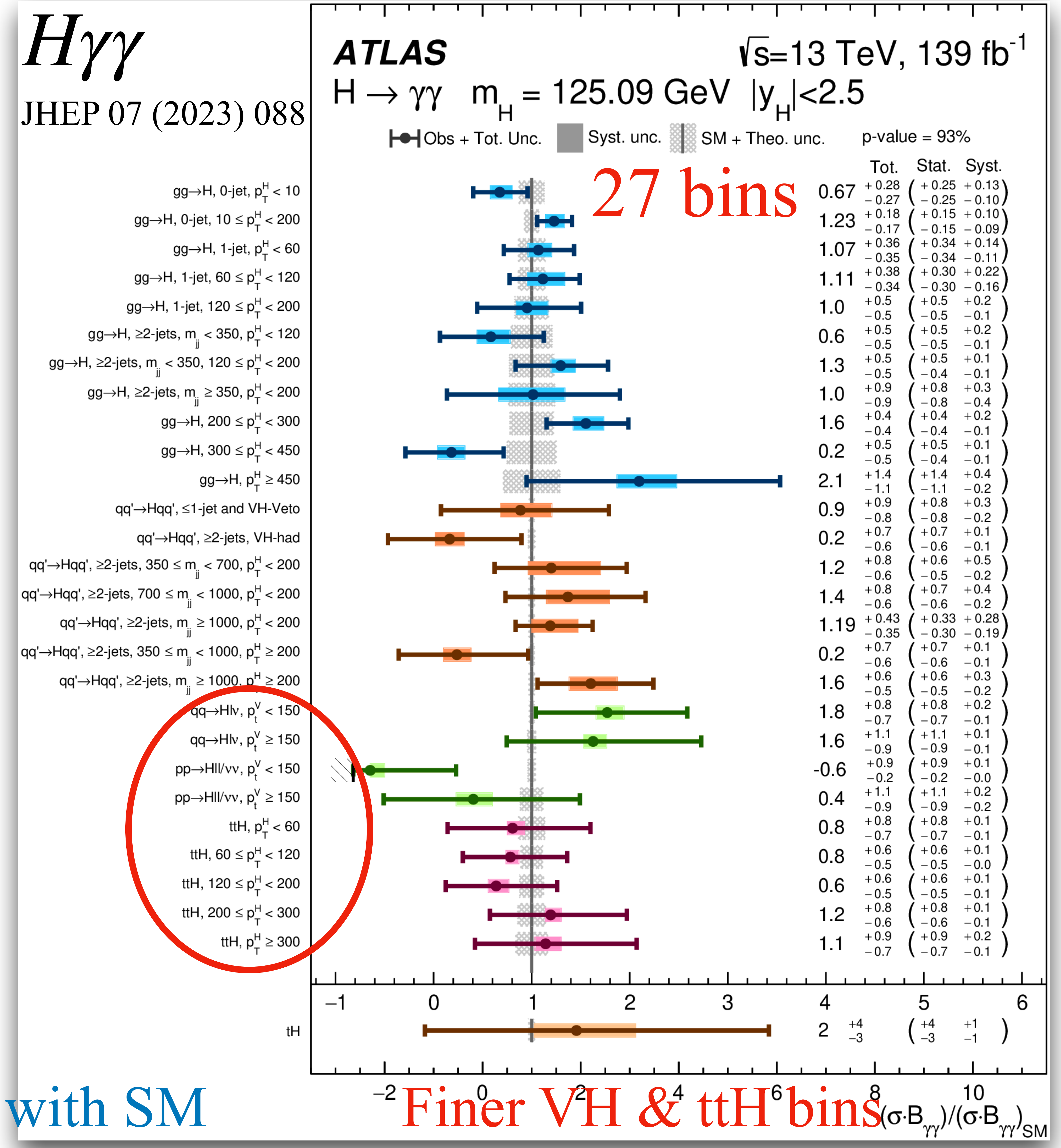
STXS in the "golden" channels

- *HZZ4l* and *Hγγ*, small BR, but high S/B, full m_H reconstruction with high resolution, providing slightly merged STXS Stage 1.2 measurements



Hγγ

JHEP 07 (2023) 088

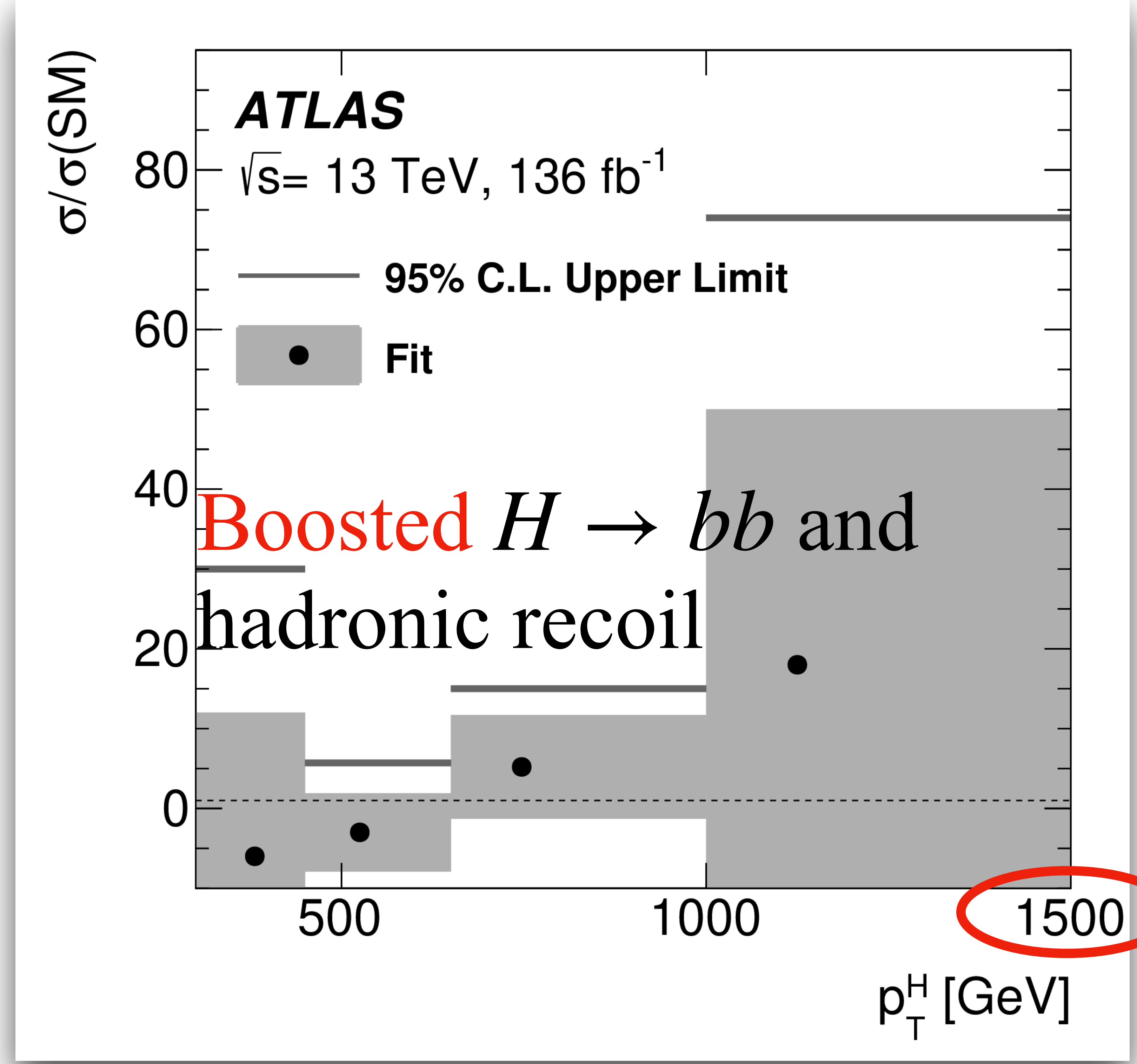


Good agreement with SM

Finer VH & ttH bins

STXS in high-stats channels

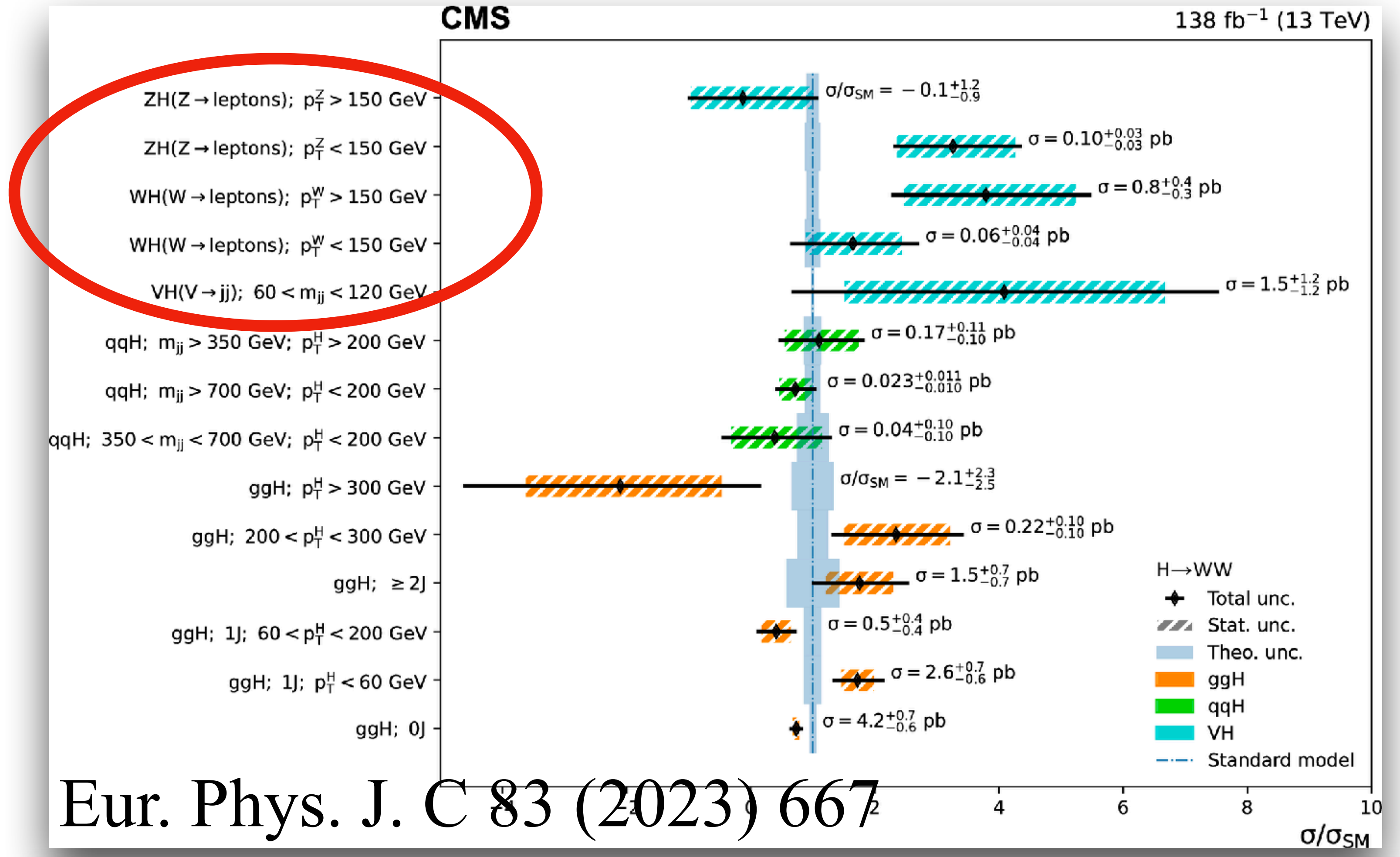
- High-stats channels including *Hbb*, *HWW* and *Hττ* provide additional sensitivities in STXS
- The focuses are mainly on ggH, qqH and V(lep)H



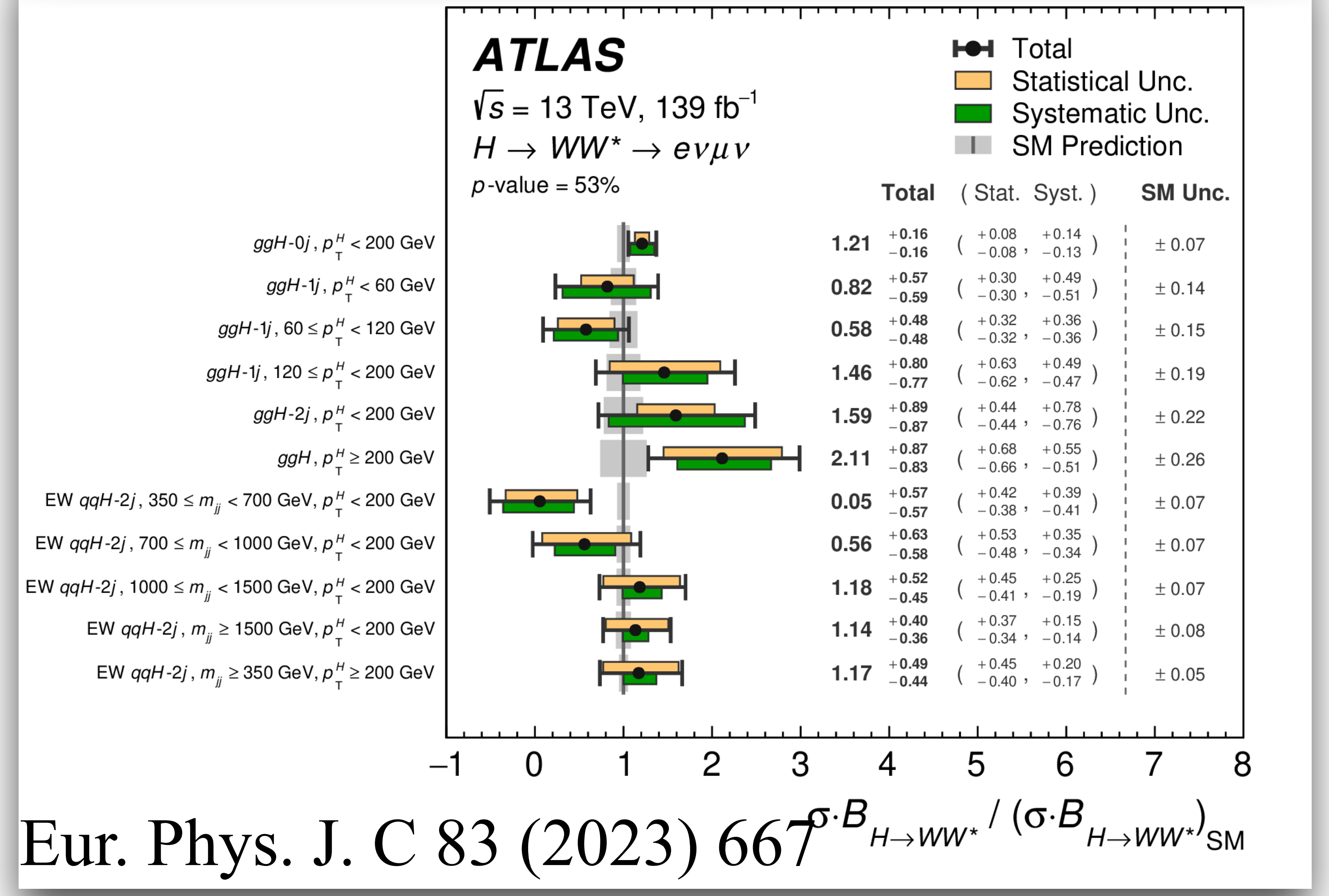
Hbb mostly focuses on V(lep)H

This ATLAS paper looked at inclusive Hbb boosted + hadronic recoil with pT>1TeV

Phys. Rev. D 105 (2022) 092003



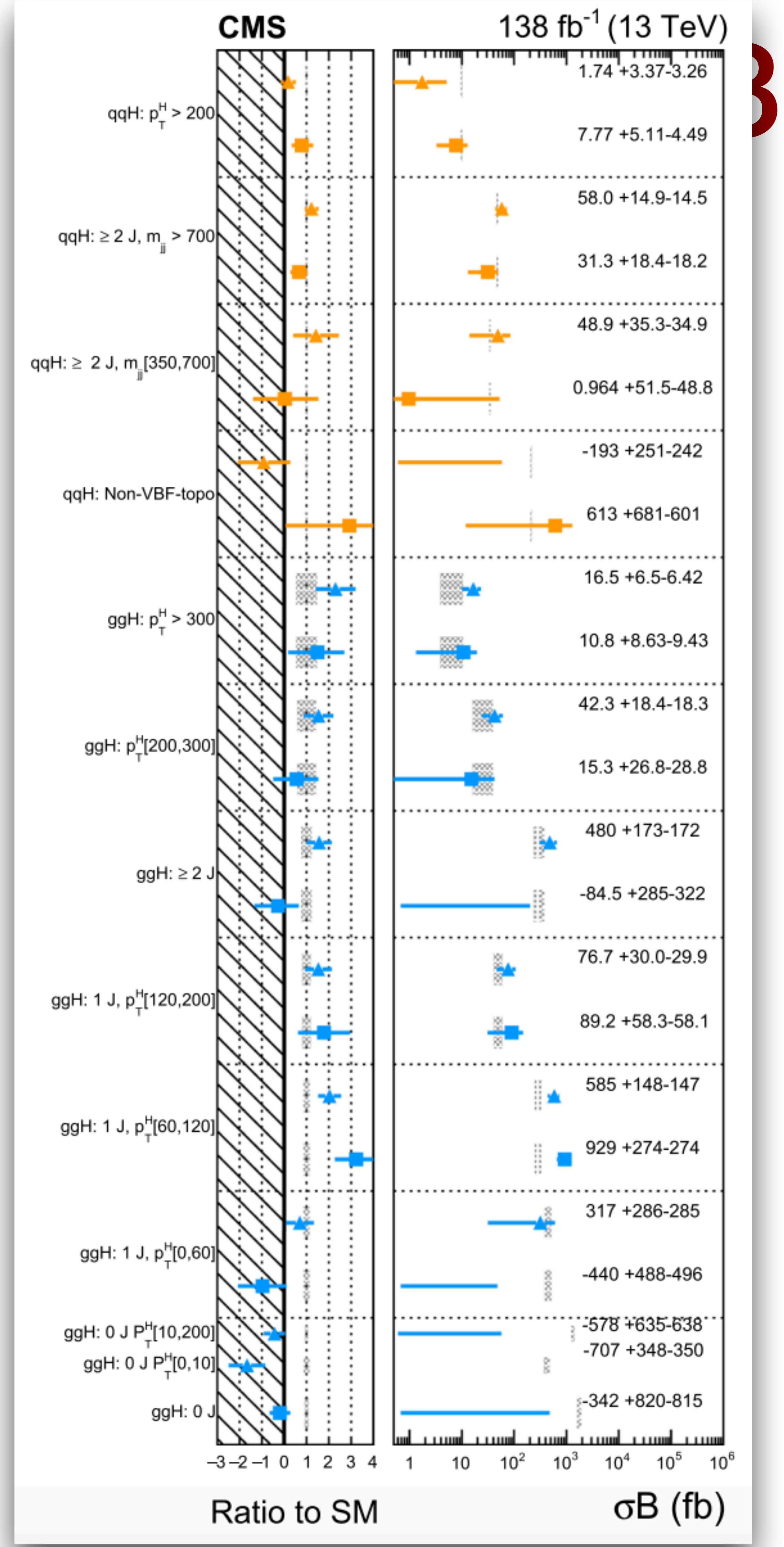
Eur. Phys. J. C 83 (2023) 667



Eur. Phys. J. C 83 (2023) 667

HWW on ggH, qqH and V(lep)H (CMS)

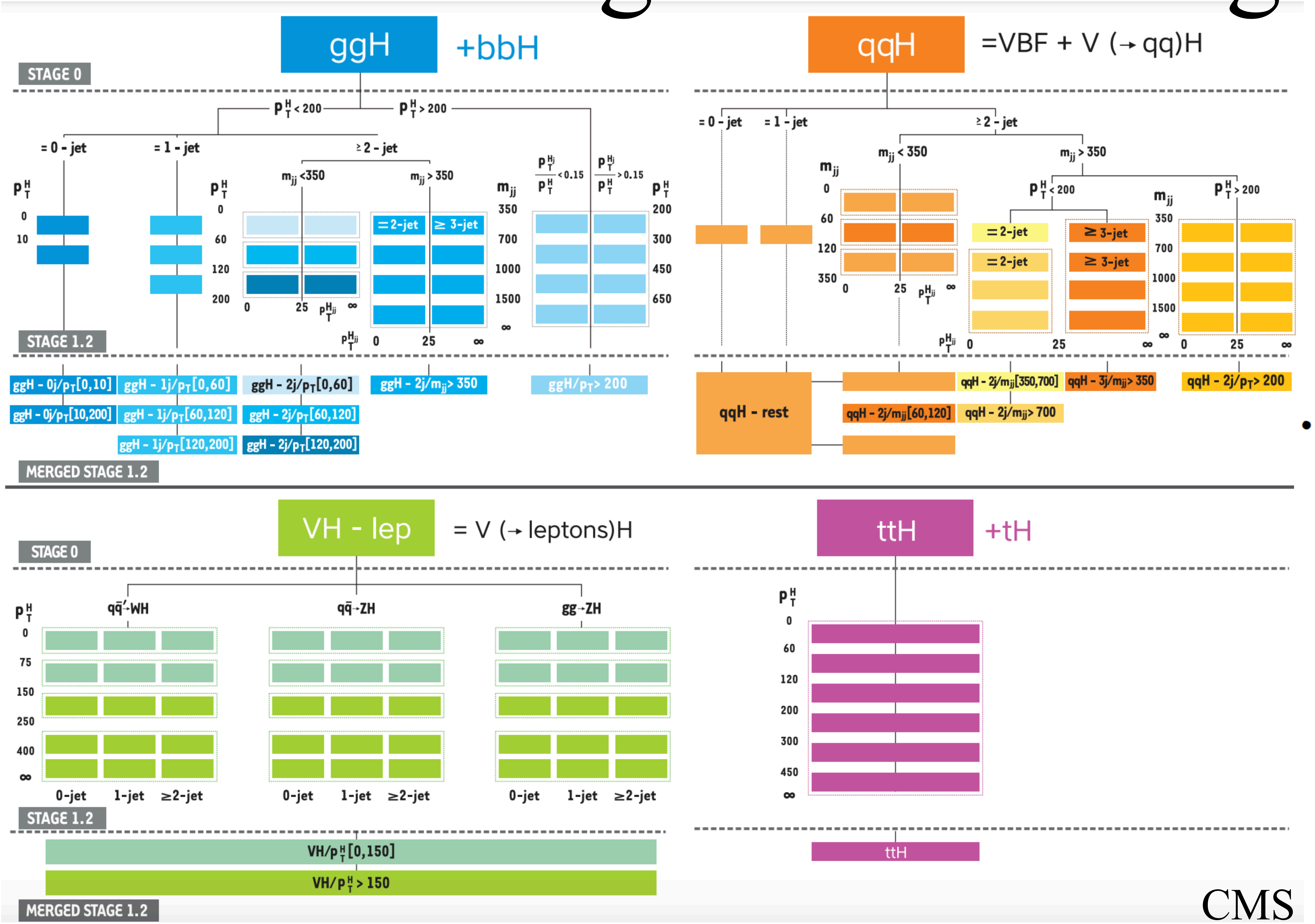
Only *eνμν* in this ATLAS paper



Hττ focuses on ggH, qqH, V(lep)H

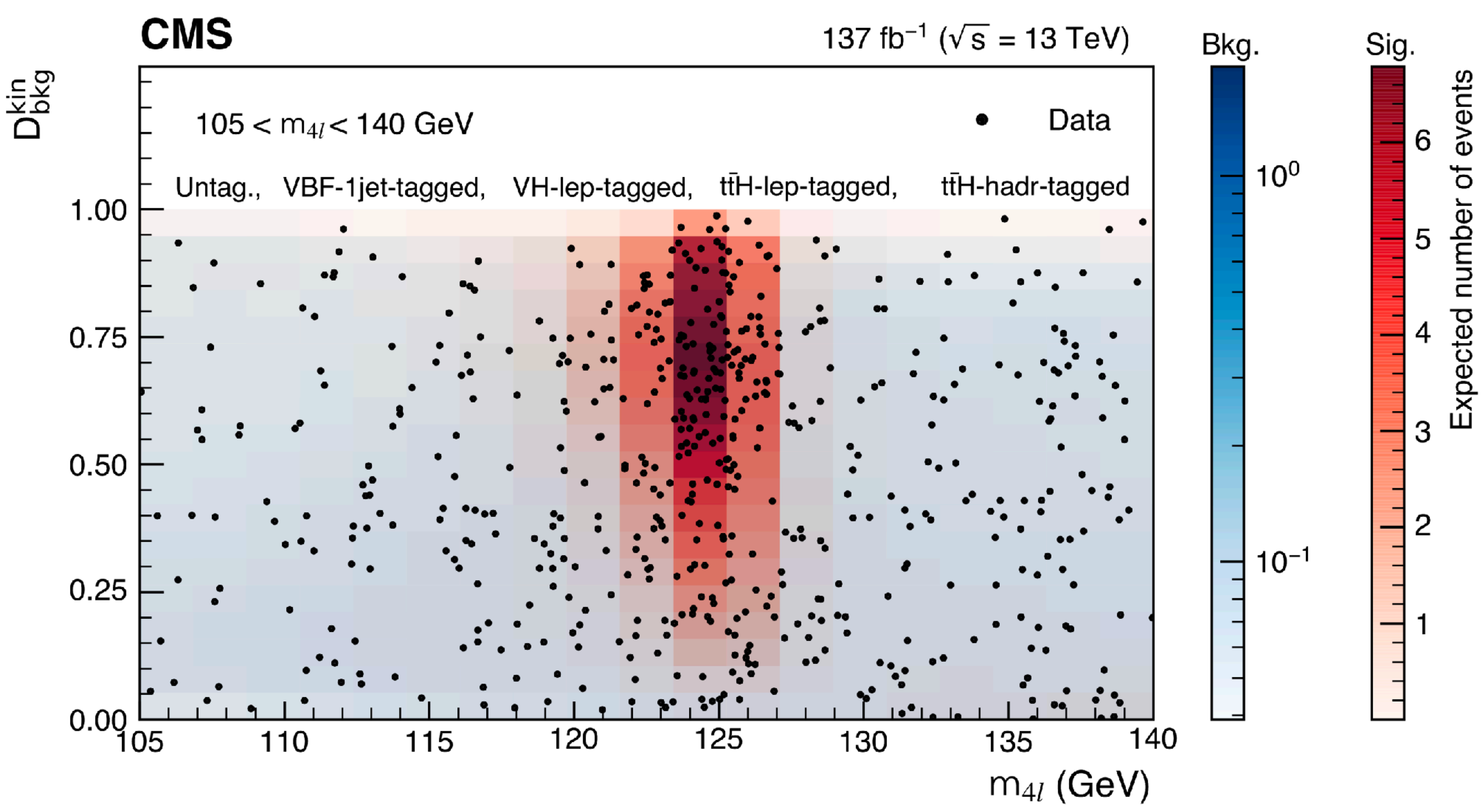
Eur. Phys. J. C (2023) 83 :562

HZZ4l merged STXS Stage 1.2

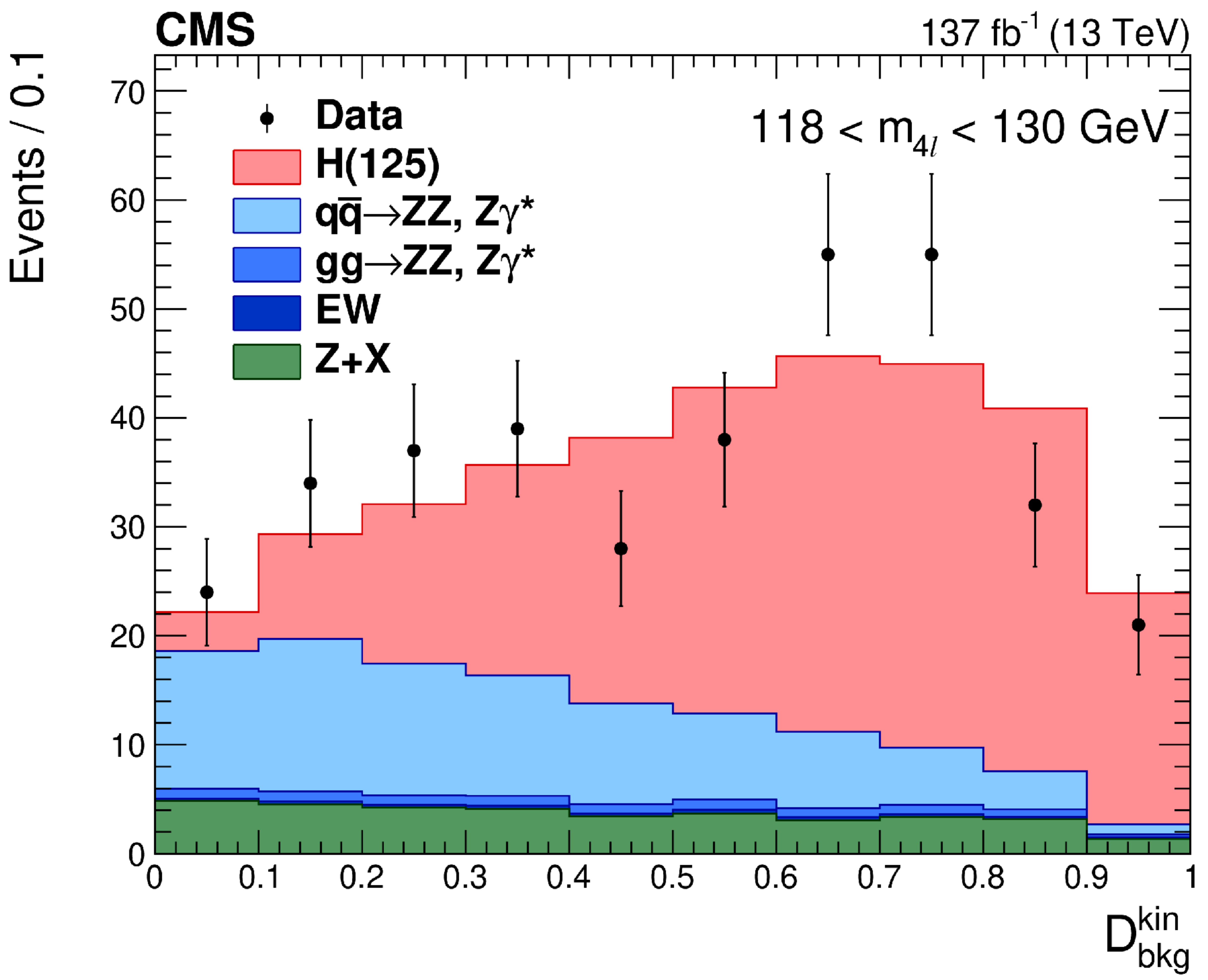


- A total of 19 STXS bins are measured
  - 10 for ggH
  - 6 for qqH
  - 2 for VH
  - 1 for ttH(+tH)

HZZ4l

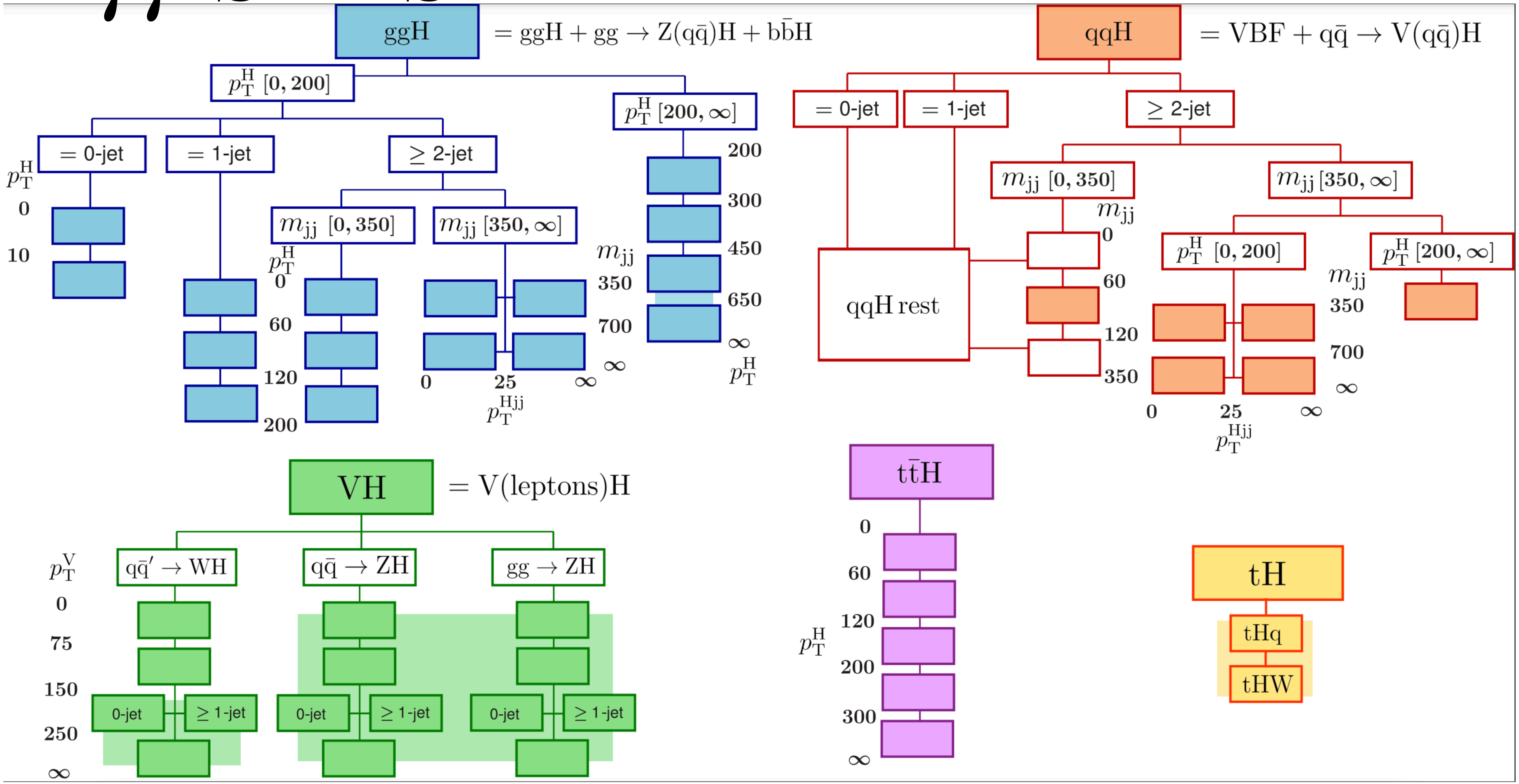


CMS
137 fb^{-1} ($\sqrt{s}$ = 13 TeV)
105 < m_{4l} < 140 GeV
Data
Untag., VBF-1jet-tagged, VH-lep-tagged, tt̄H-lep-tagged, tt̄H-hadr-tagged
D^{kin}_{bkg}
m_{4l} (GeV)
Bkg.
Sig.
Expected number of events



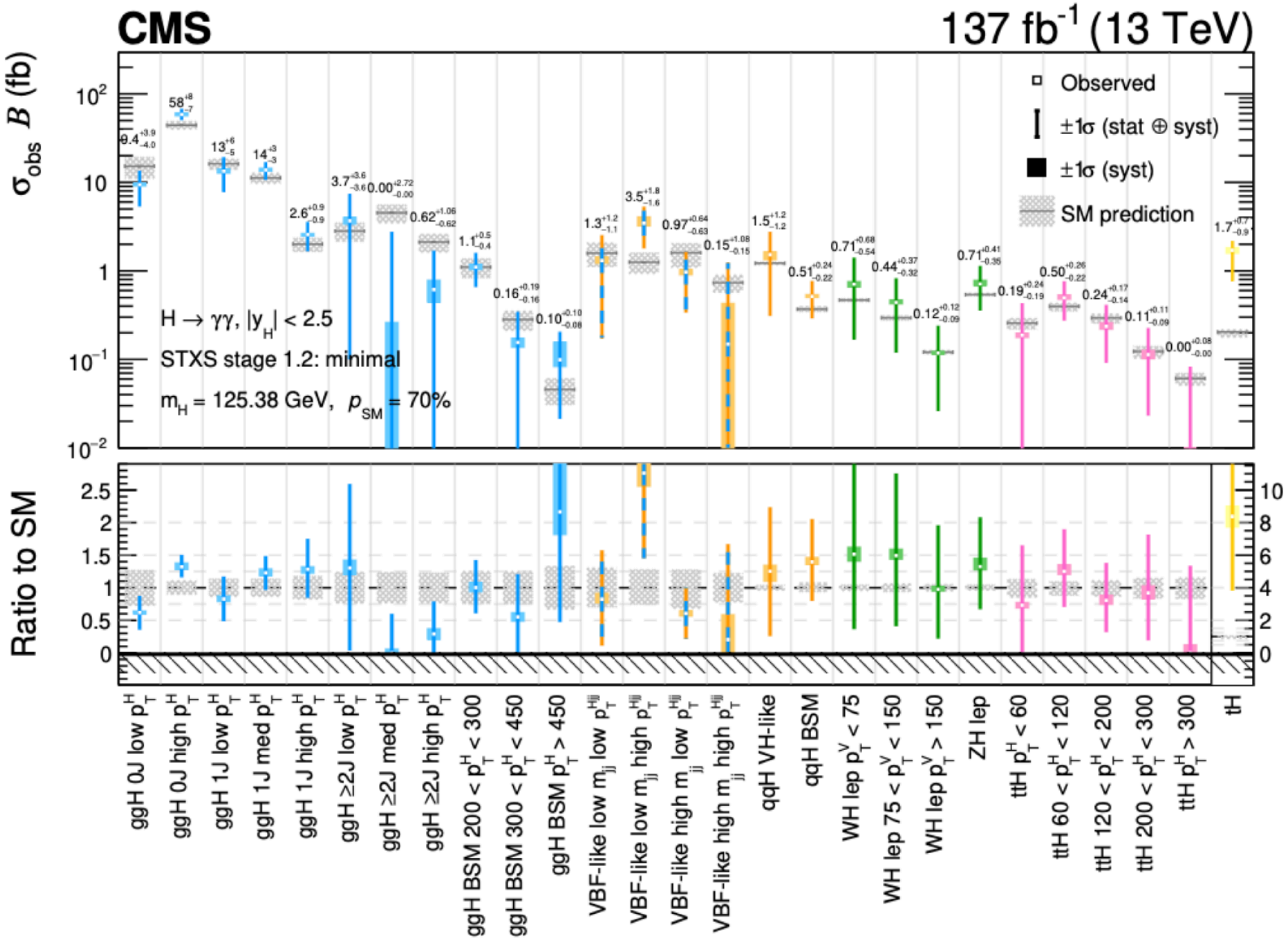
CMS
137 fb^{-1} (13 TeV)
118 < m_{4l} < 130 GeV
Data
H(125)
$q\bar{q}\to ZZ, Z\gamma^*$
$gg\to ZZ, Z\gamma^*$
EW
Z+X
Events / 0.1
D^{kin}_{bkg}

$H\gamma\gamma$ STXS



The shaded regions indicate the STXS bins that are divided at stage 1.2, but are not measured independently in this analysis.

$H\gamma\gamma$ STXS



CMS $H \to \gamma\gamma$
JHEP07(2021)027

Higgs AC and EFT

Direct analysis following the **anomalous couplings (AC)** parametrization
→ target ggH and VBS Higgs productions

Limits on AC parameters can be rotated to Warsaw basis WC limits.

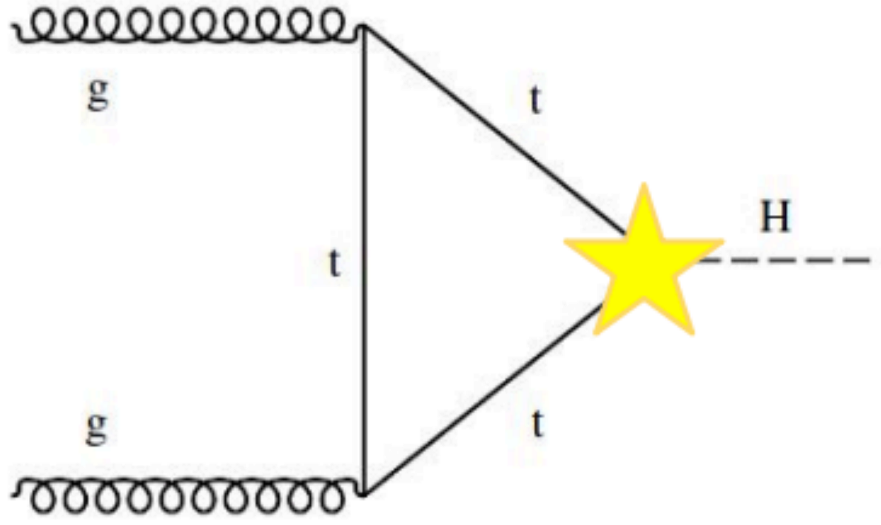
AC approach/SMEFT approach
1 Anomalous coupling:
$\tilde{\kappa}_f$: ~~CP~~

AC approach	SMEFT approach
$a_i^{ZZ}=a_i^{WW}$	SU(2) X U(1)
4 anomalous couplings:	$a_i^{ZZ} \neq a_i^{WW}$
a_2 (CP)	3 anomalous couplings:
a_3 (~~CP~~)	a_2 (CP)
$a_{\Lambda 1}$ (CP)	a_3 (~~CP~~)
$a_{\Lambda 1}^{Z\gamma}$ (CP)	$a_{\Lambda 1}$ (CP)

$$A(\mathrm{Hff}) = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + i\tilde{\kappa}_f\gamma_5\right)\psi_f ,$$

CP-even

CP-odd

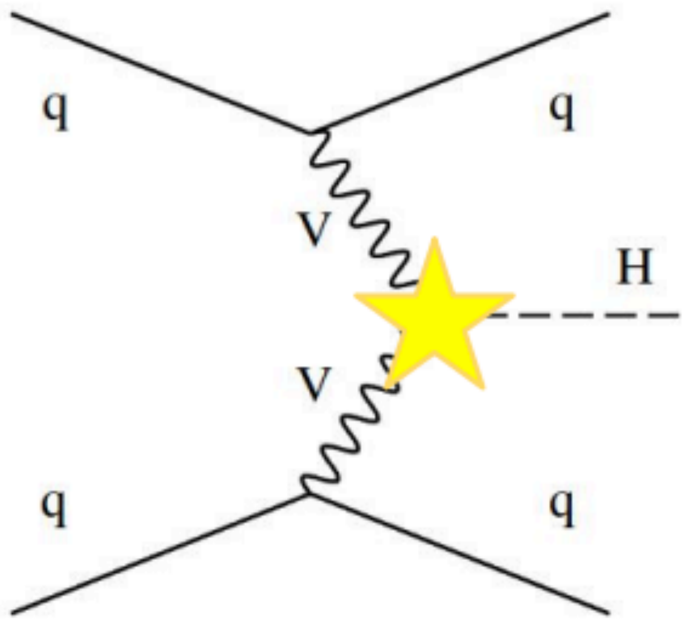


$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_{V1}+q_{V2})^2}{\left(\Lambda_Q^{VV}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}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

SM

CP-even

CP-odd



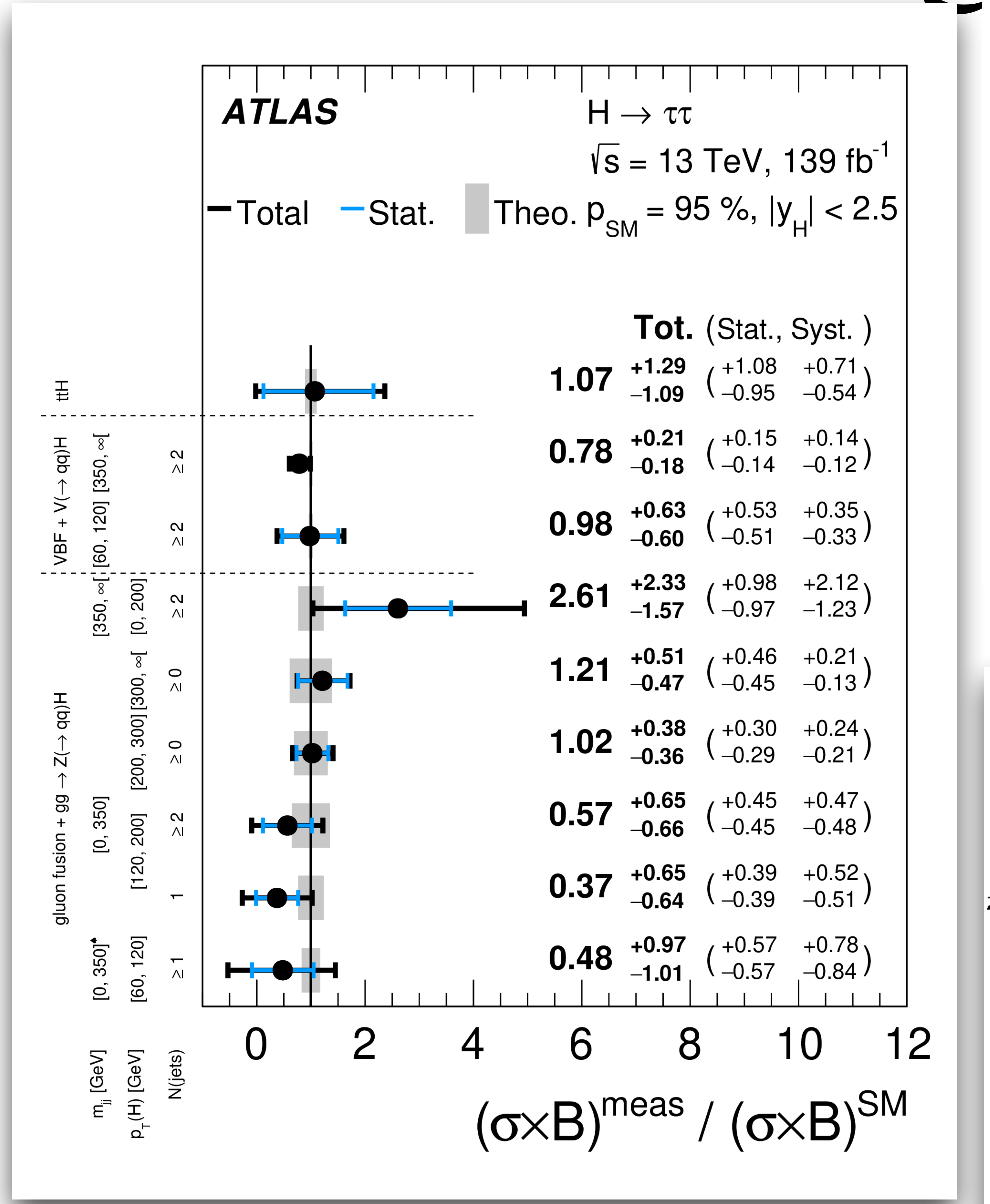
$$f_{CP}^{\mathrm{Hff}} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$

Observables:
XS fractions

$$f_{ai} = \frac{|a_i|^2\sigma_i}{\sum_{j=1,2,3...}|a_j|^2\sigma_j}\,\mathrm{sign}\left(\frac{a_i}{a_1}\right)$$

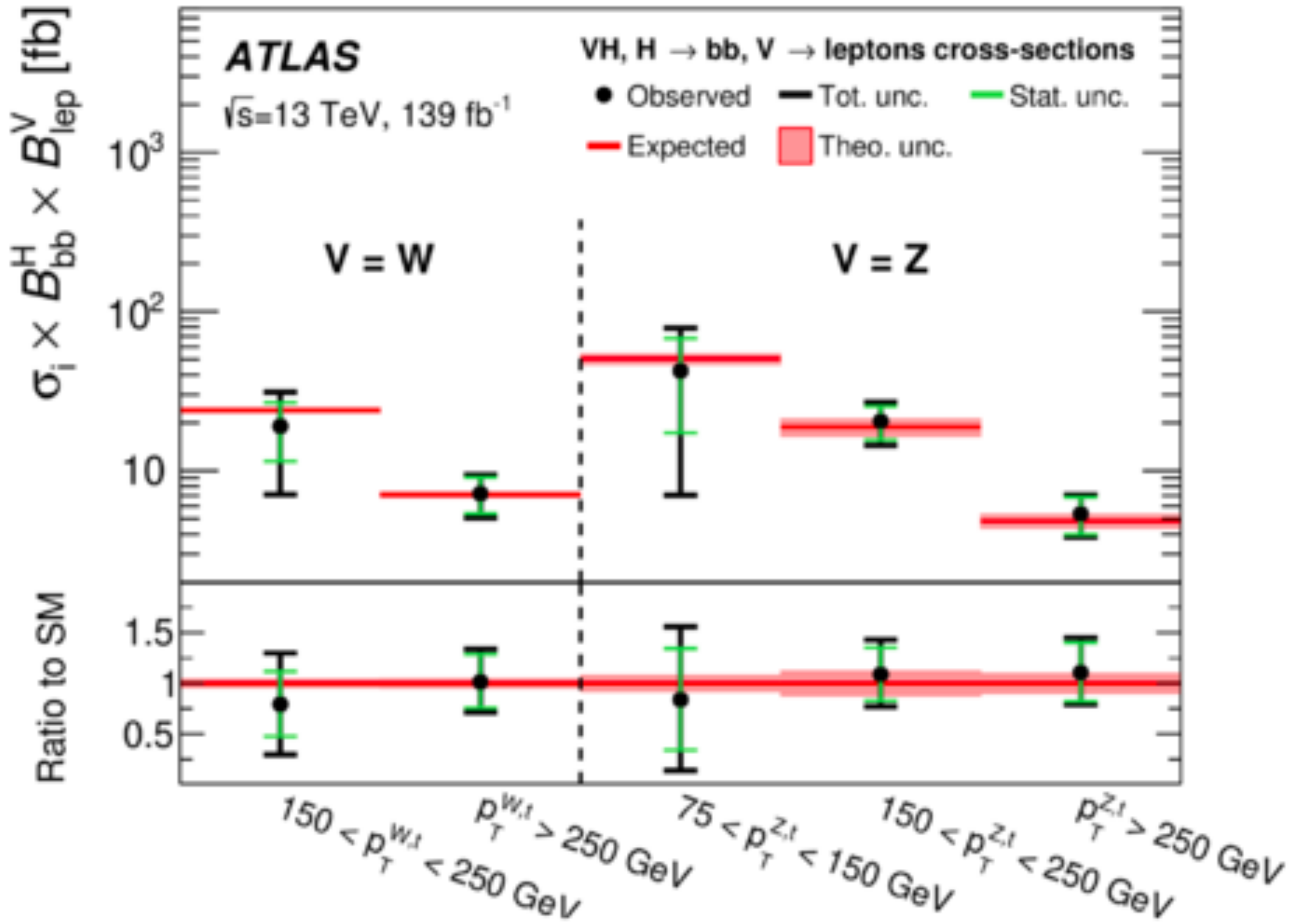
Davide Valsecchi@LHCP2023

STXS in high-stats channels



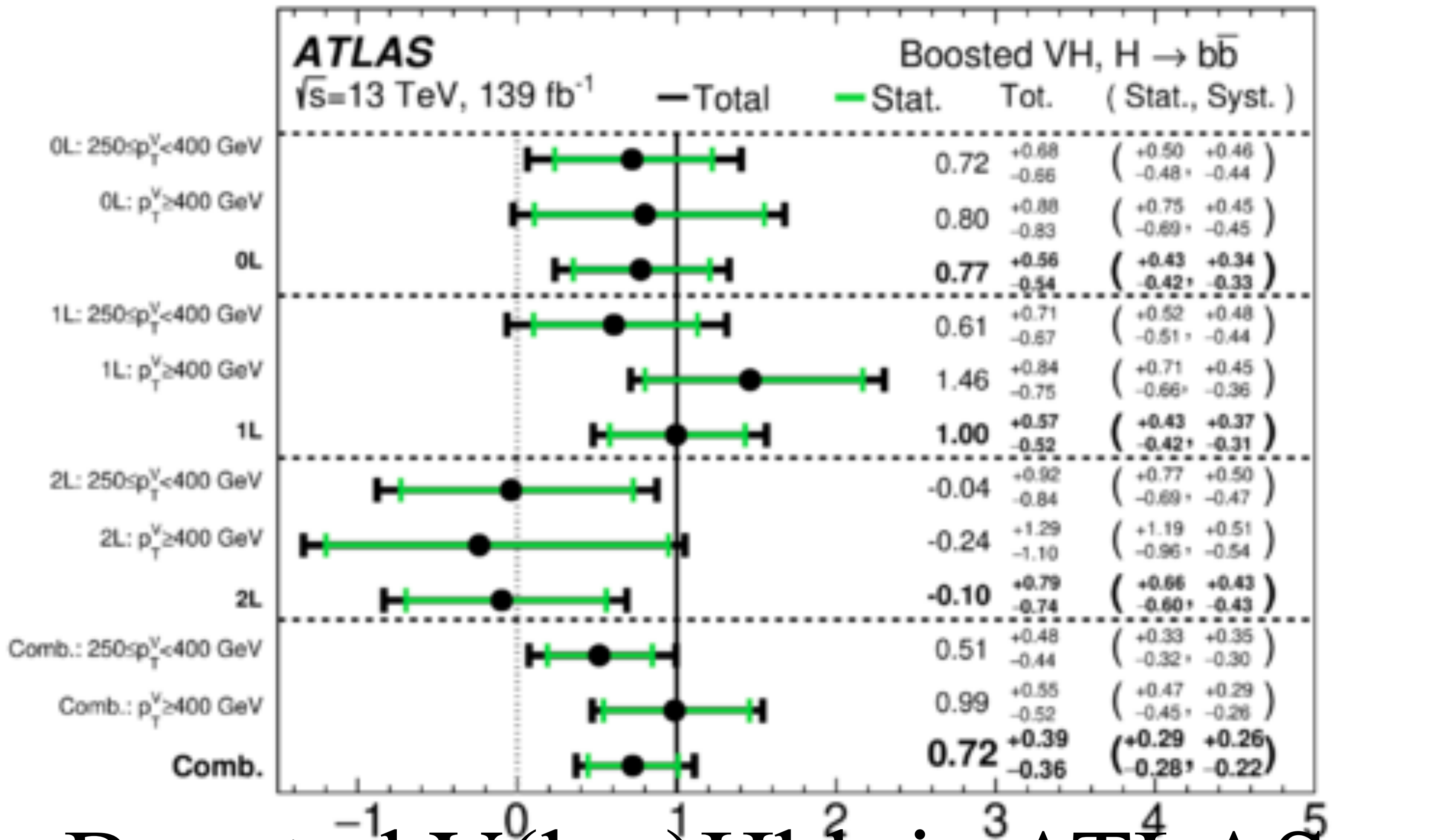
Hττ focuses on ggH and qqH

JHEP 08 (2022) 175



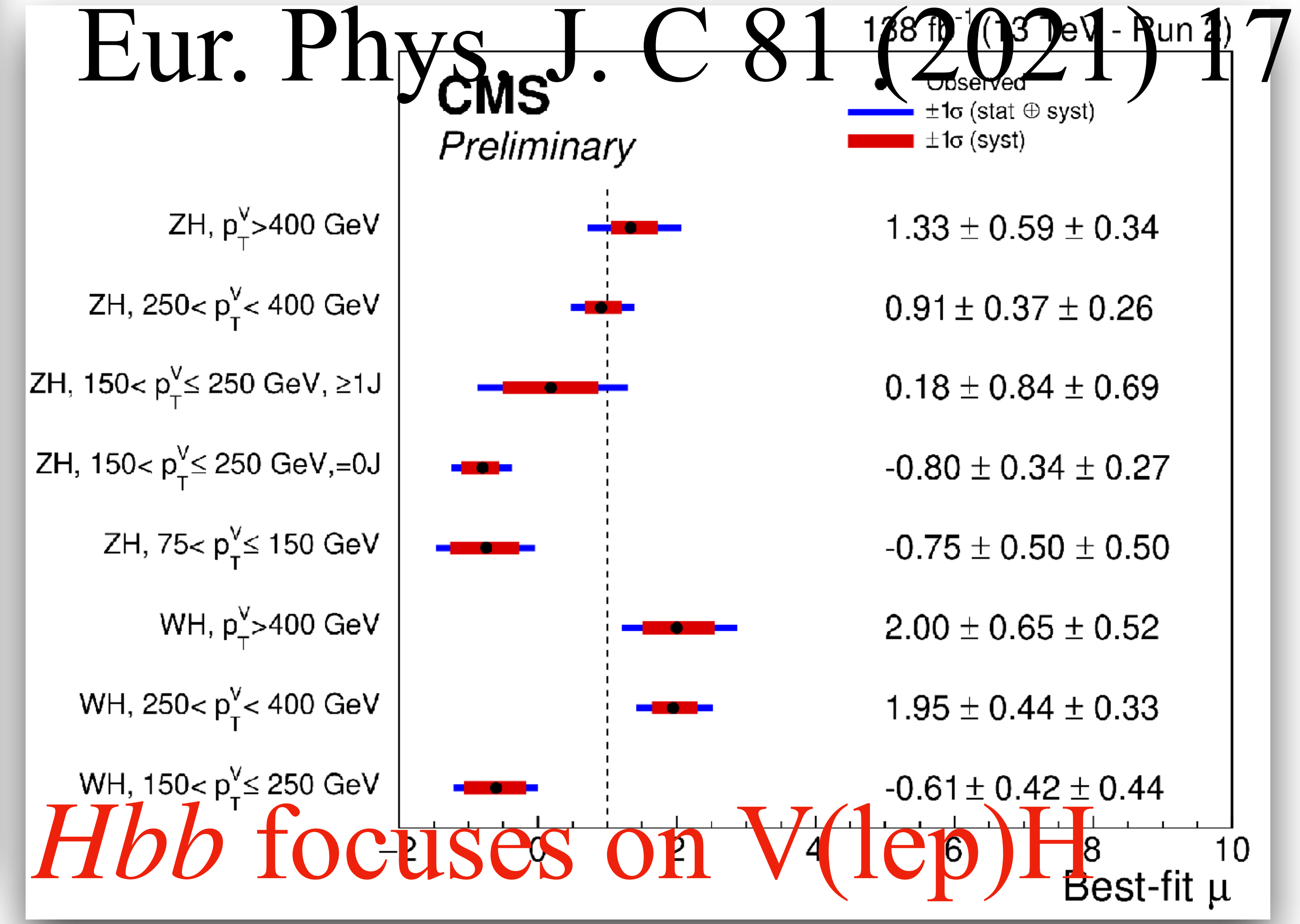
Resolved V(lep)Hbb in ATLAS

Eur. Phys. J. C 81 (2021) 178



Boosted V(lep)Hbb in ATLAS

Phys. Lett. B 816 (2021) 136204



Hbb focuses on V(lep)H (resolved+boosted)

CMS-PAS-HIG-20-001

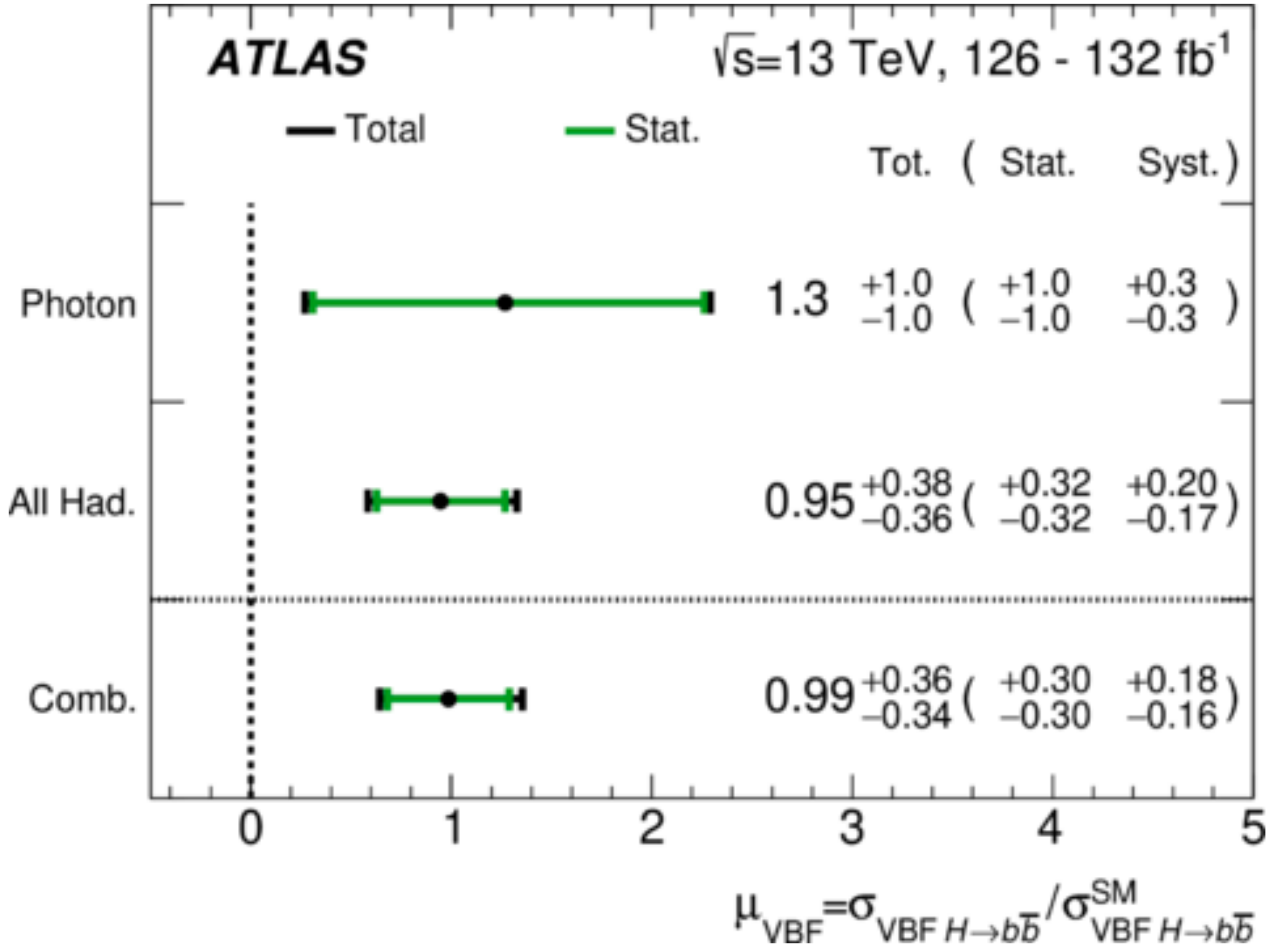
ATLAS-CONF-2021-051

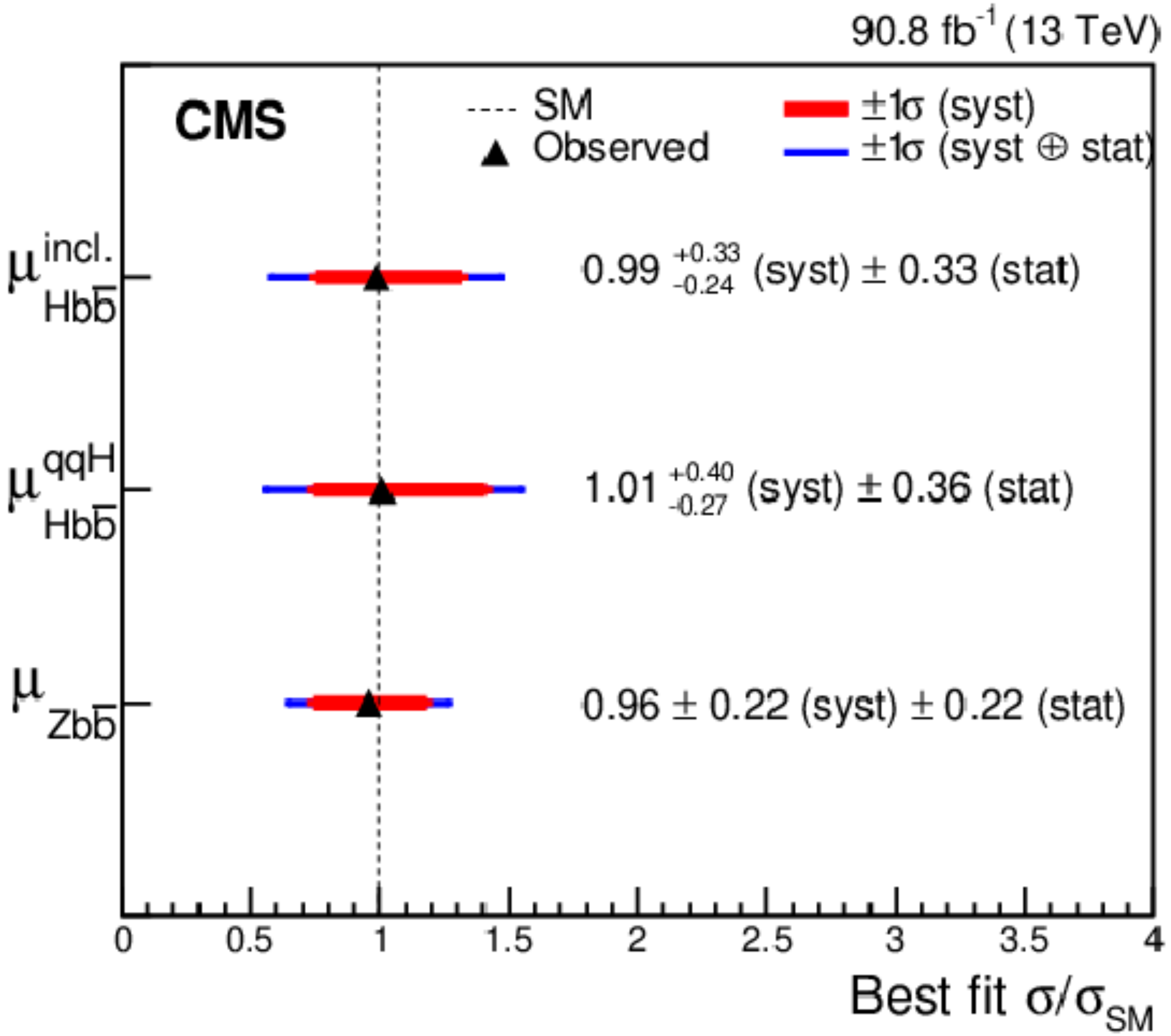
Combined V(lep)H resolved+boosted

VBF Hbb (resolved)

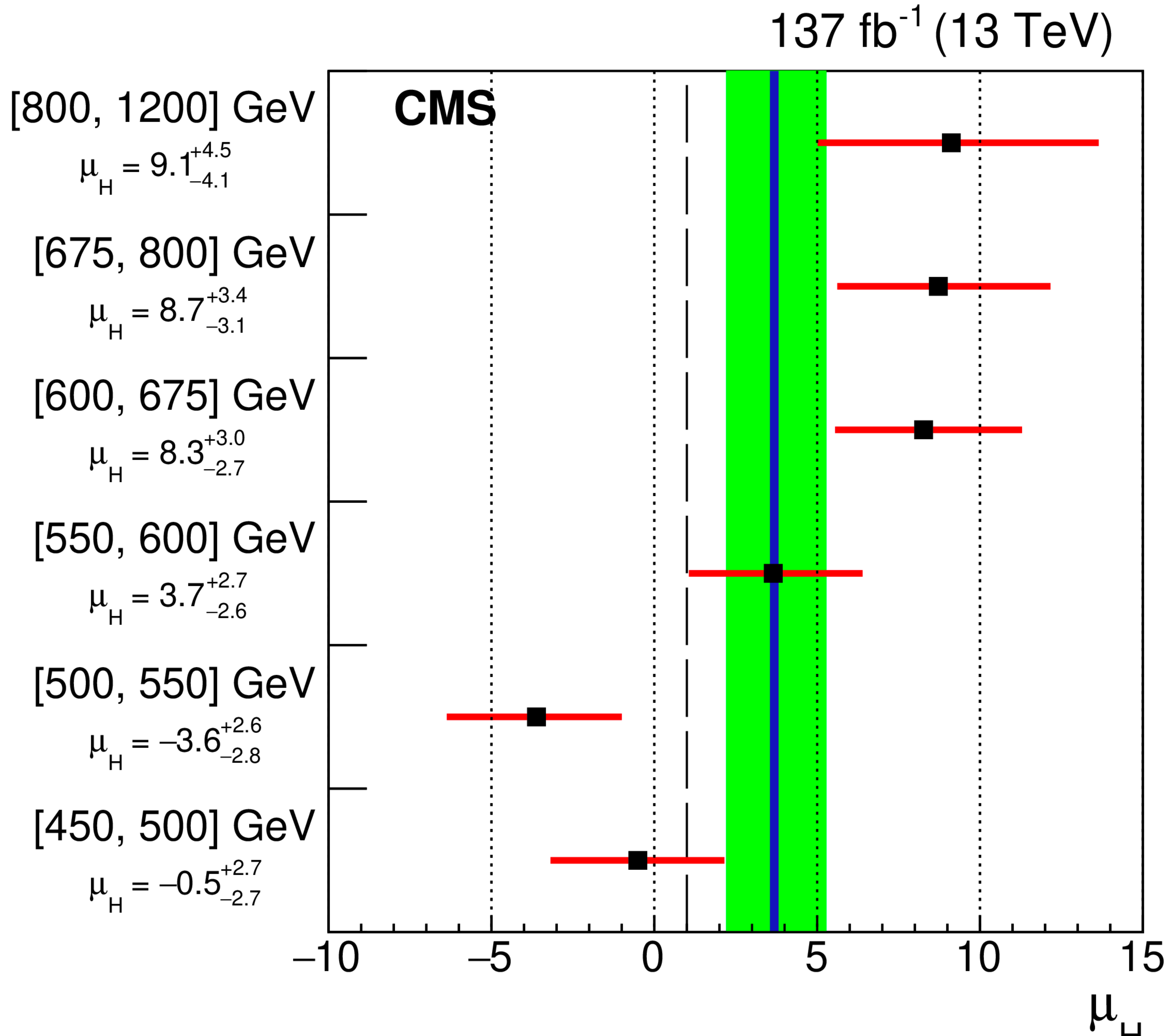
Eur. Phys. J. C. 81 (2021) 537
2308.01253

- ATLAS observed (expected) significance of 2.6 (2.8) standard deviations from the background only hypothesis
  - VBF Hbb + photon is combined
- CMS observed (expected) significance of 2.4 (2.7) standard deviations





Inclusive Hbb boosted



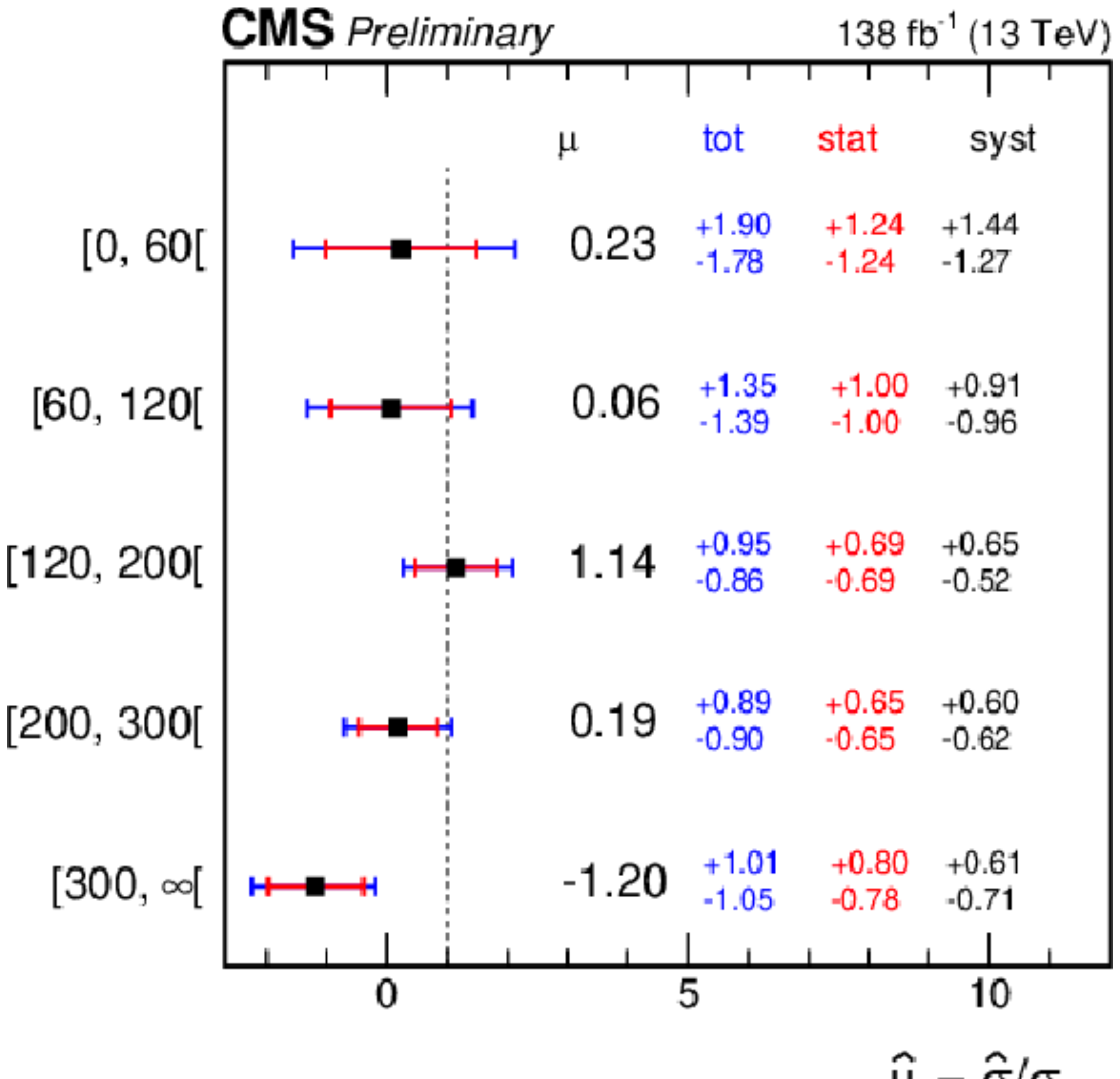
JHEP 12 (2020) 085

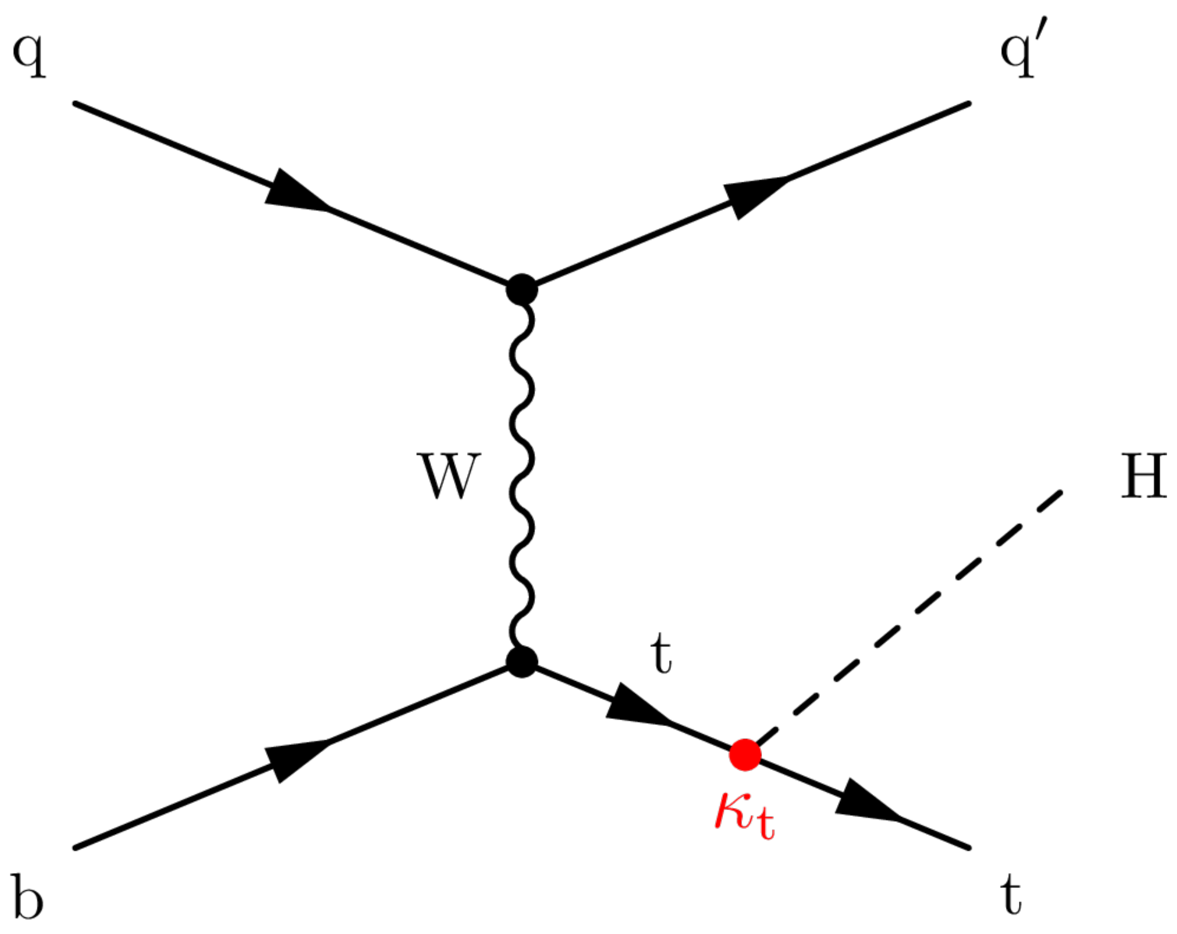
Hbb is boosted with inclusive production modes

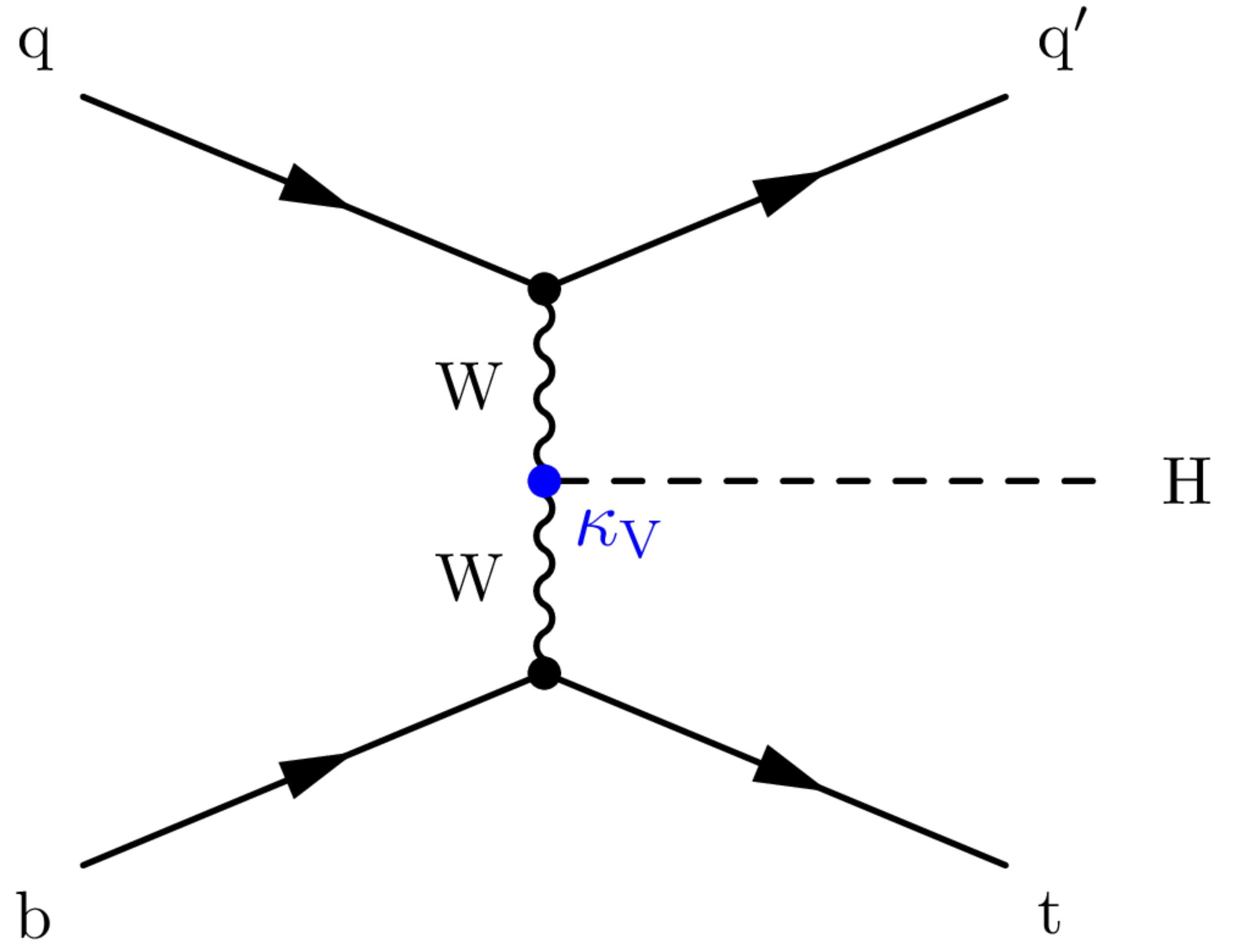
ttH/tHbb

JHEP 06 (2022) 97
CMS-PAS-HIG-19-011 Aug 2023

- CMS ttH observed signal significance 1.3σ (exp. 4.1σ)
    - tH upper limits of signal strength 14.6 (19.3)
- ATLAS ttH observed signal significance 1.0σ (exp. 2.7σ)





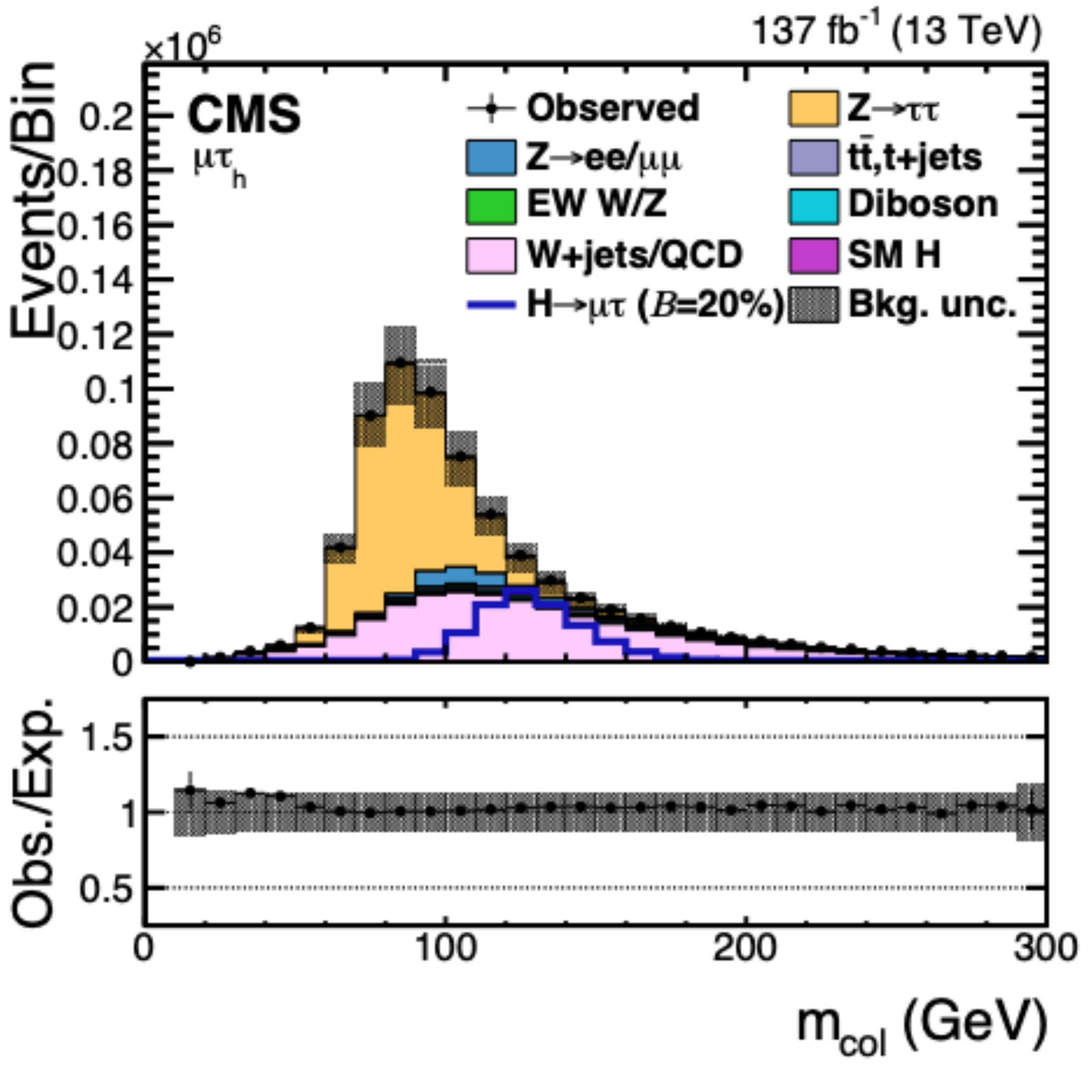


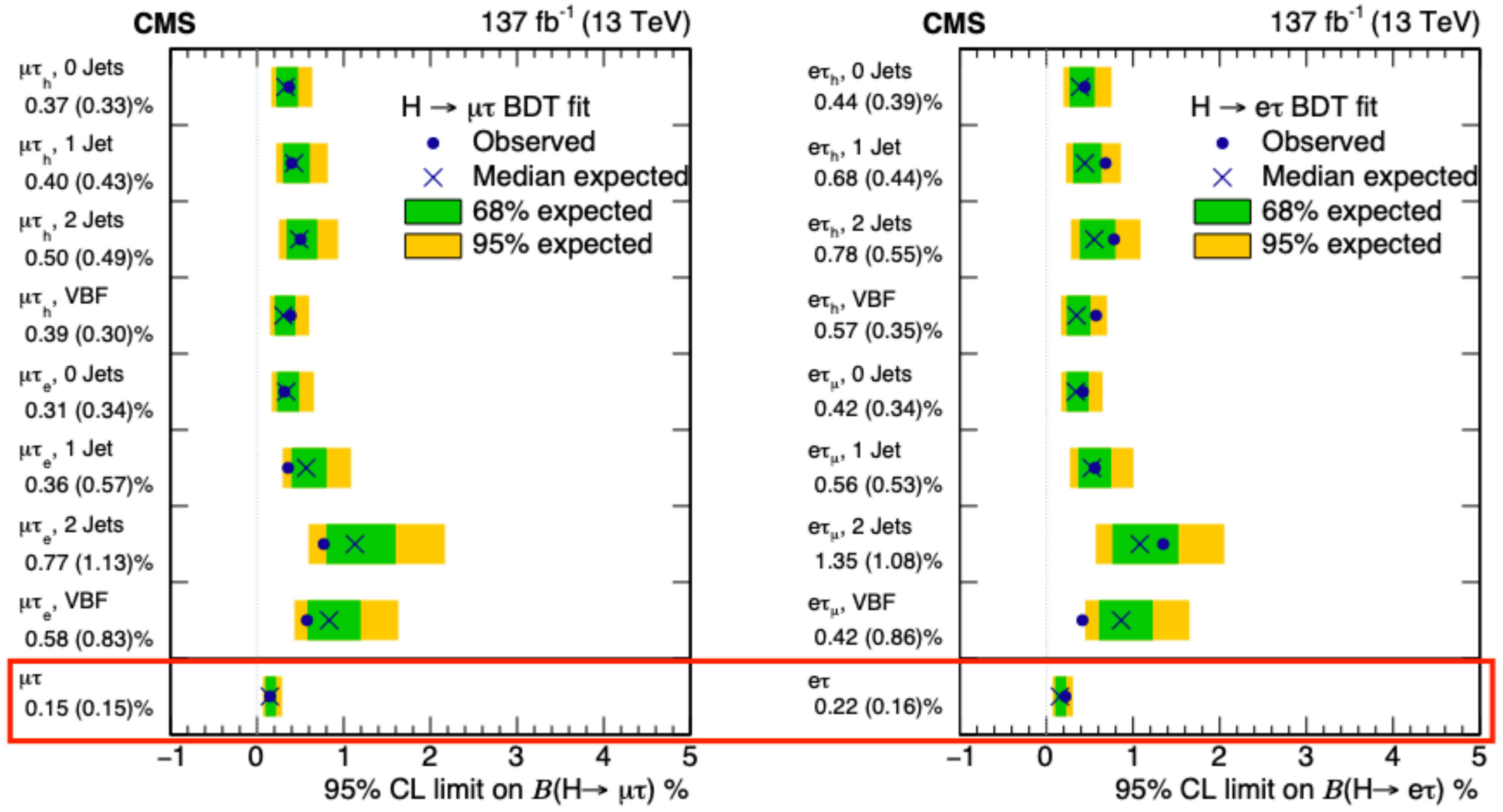
$H \to e\tau, \mu\tau$

Overview:

- Multiple signal region categories based on τ decay and jet multiplicity to enhance sensitivity
- Construct collinear mass variable $m_{col} = m_{vis}/\sqrt{x_\tau^{vis}}$ to estimate m_H

A BDT is trained in each channel and the discriminant distribution is used in a maximum likelihood fit to extract the upper limits on the Higgs BR





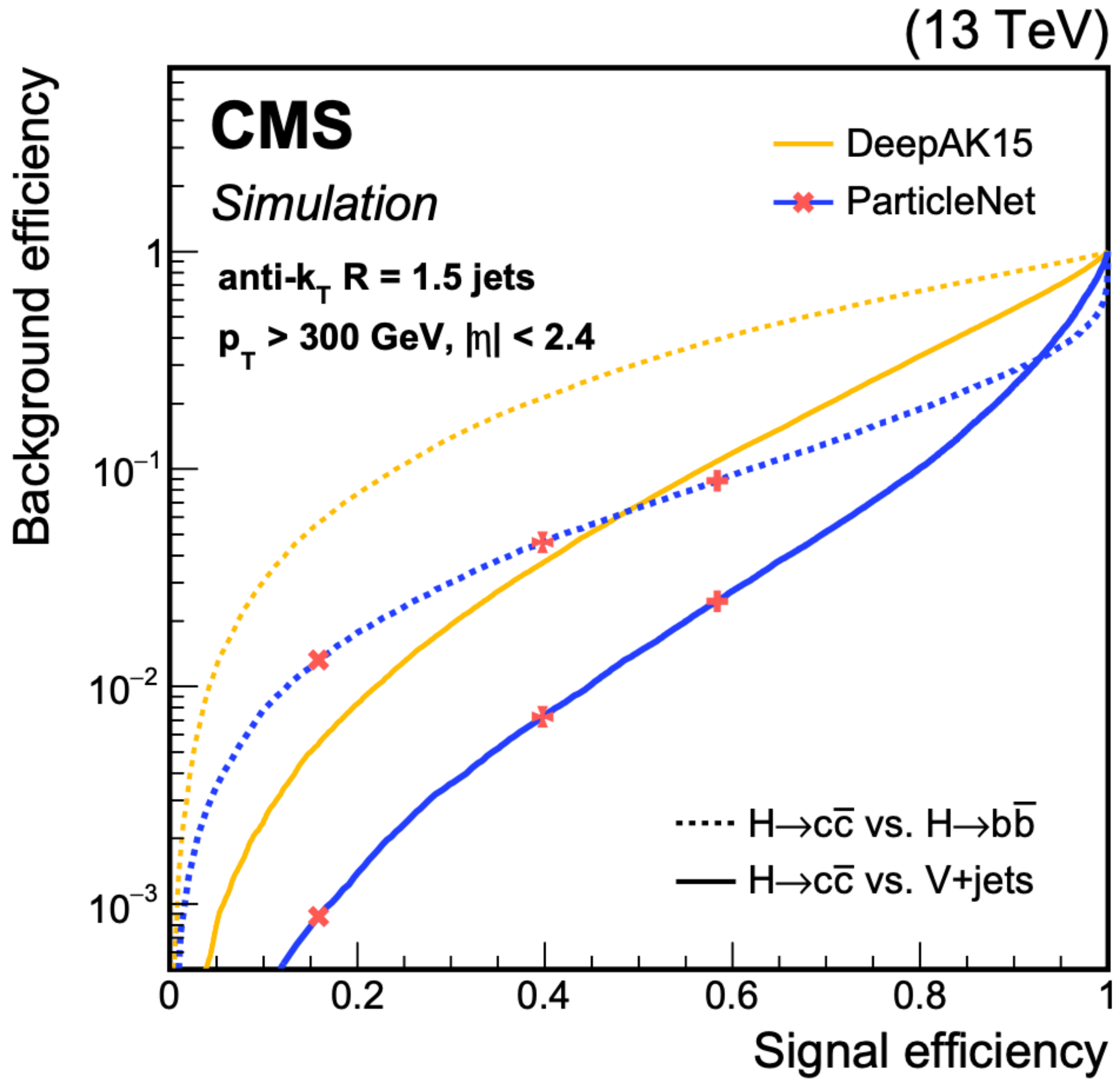
Analysis constrains BR(H→μτ) < 0.15 and BR(H→eτ) < 0.16 at 95% CL

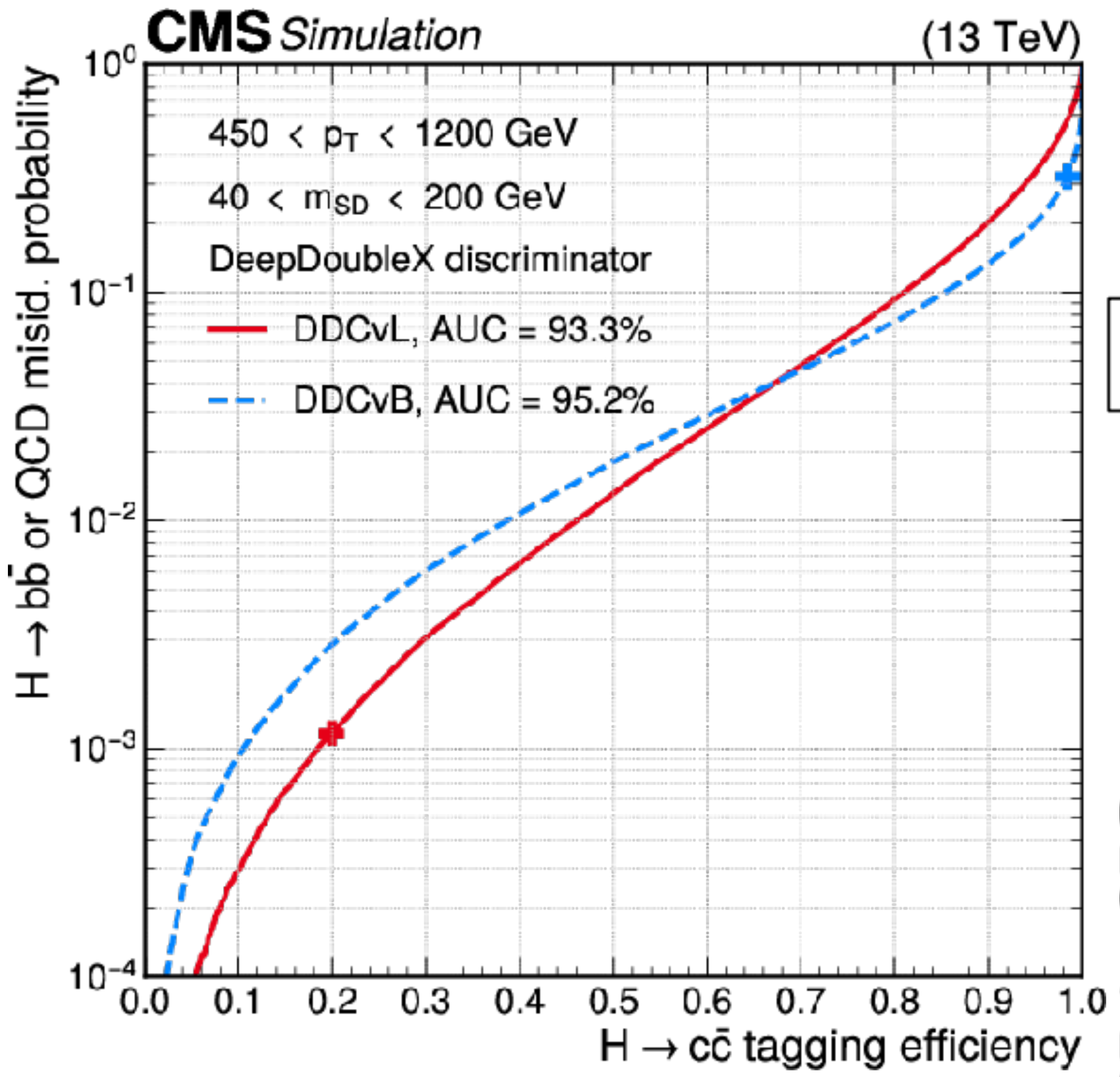
Also provides upper limits on LFV Yukawa couplings: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.11 \times 10^{-3}$ and $\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 1.35 \times 10^{-3}$

Phys. Rev. D 104 (2021) 032013

Pallabi Das@LHCP2023

Hcc



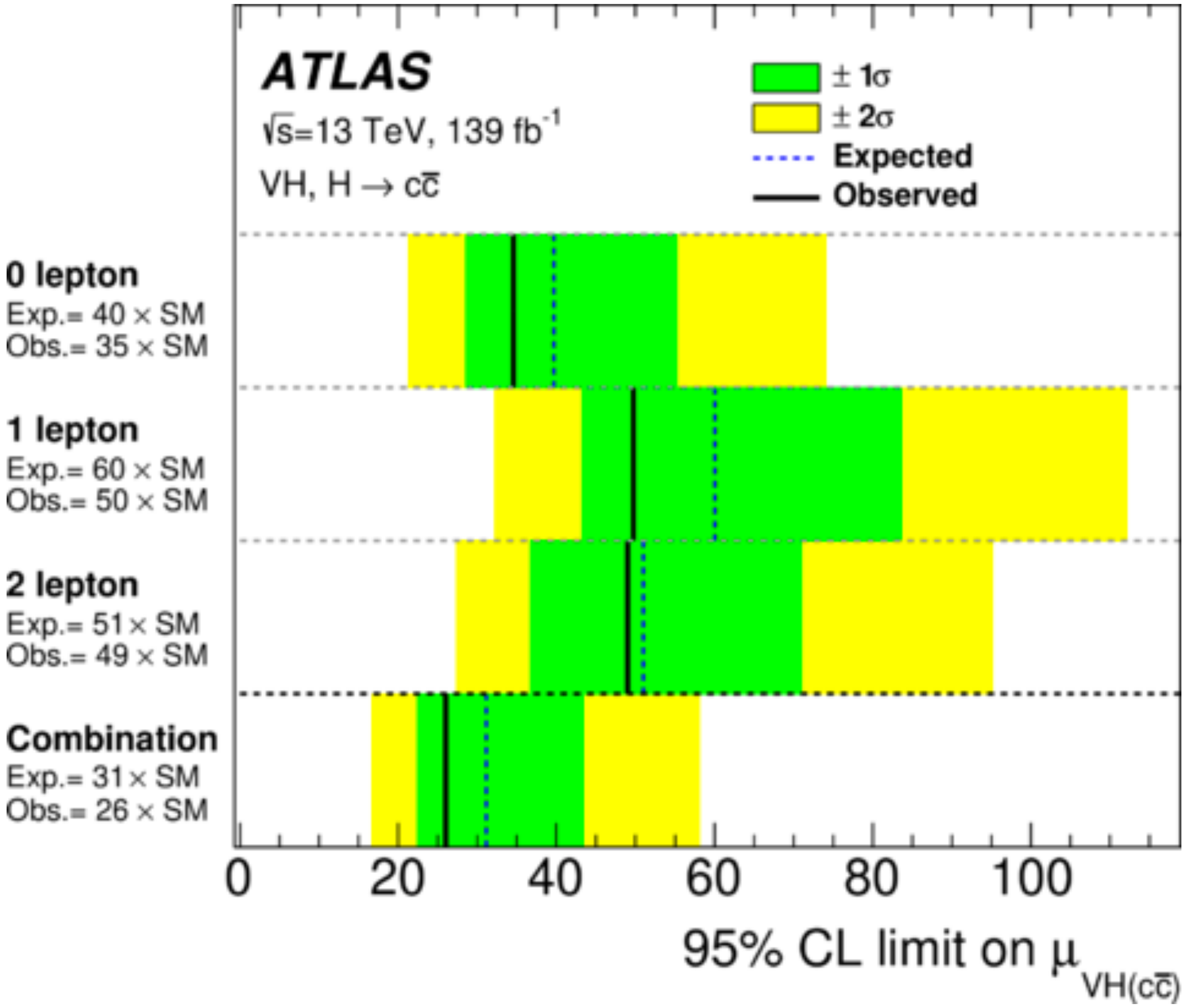


Resolved
3 working points

Boosted
2 working points

Eur. Phys. J. C 82 (2022) 717

μ(VH, H → *cc*) < 26(31) obs(exp) at 95% CL



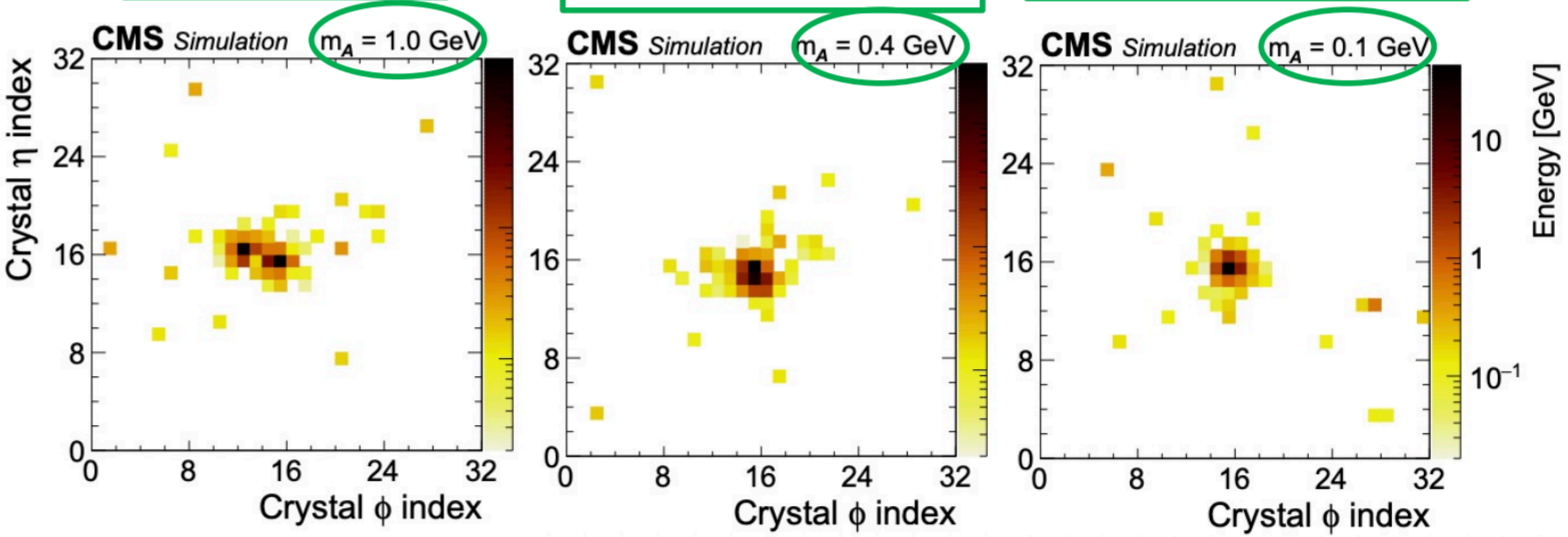
CMS VHcc limits 14.4 (7.6)

$H \to aa \to 4\gamma$ merged

Barely resolved

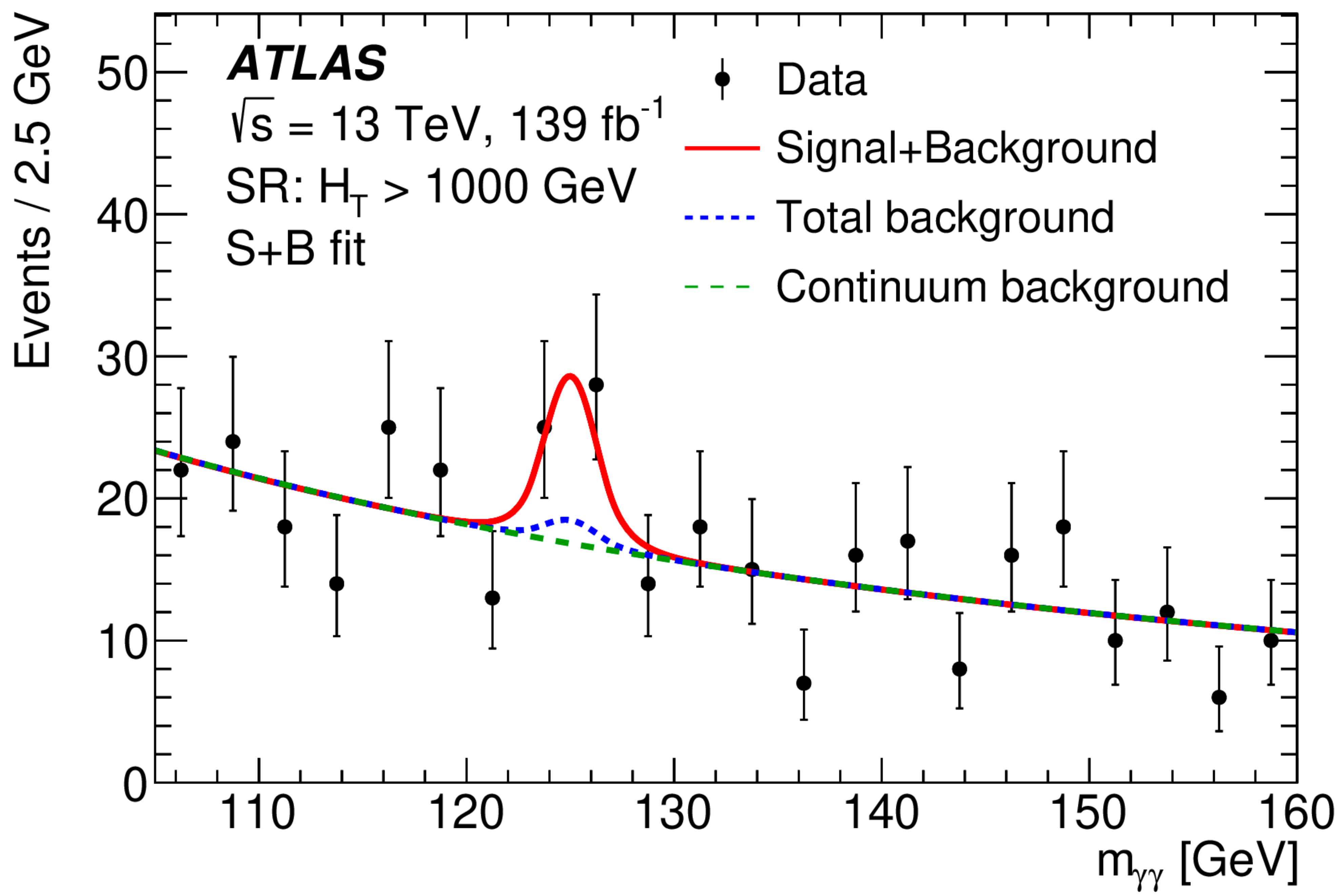
Shower merging but distinct maxima

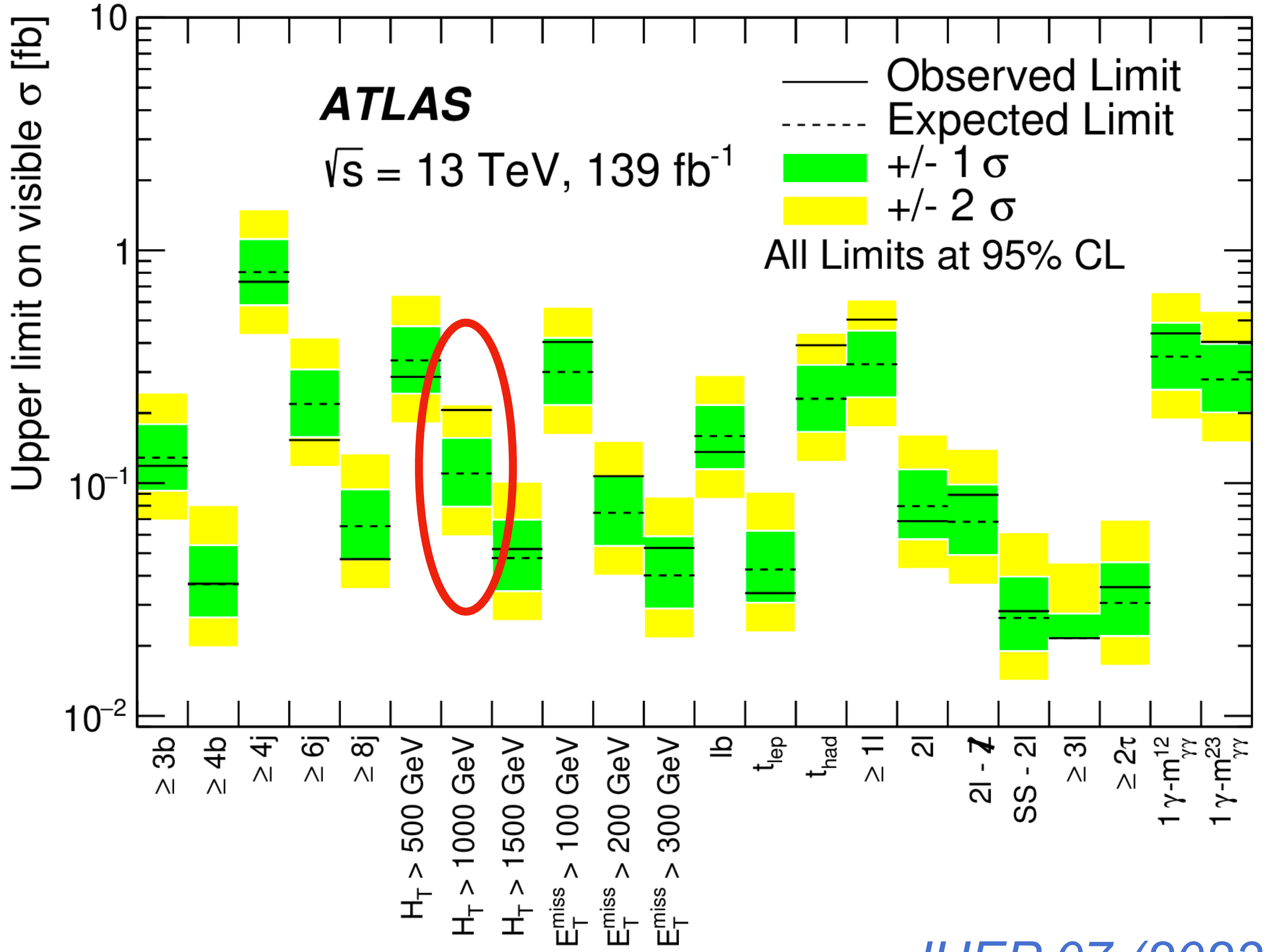
Instrumental merging



Model independence search with $H \to \gamma\gamma$

- A model independent search for new physics is performed for 22 final states categorized by objects in association with $H \to \gamma\gamma$, i.e. $H \to \gamma\gamma + X$
- No significant excess were found





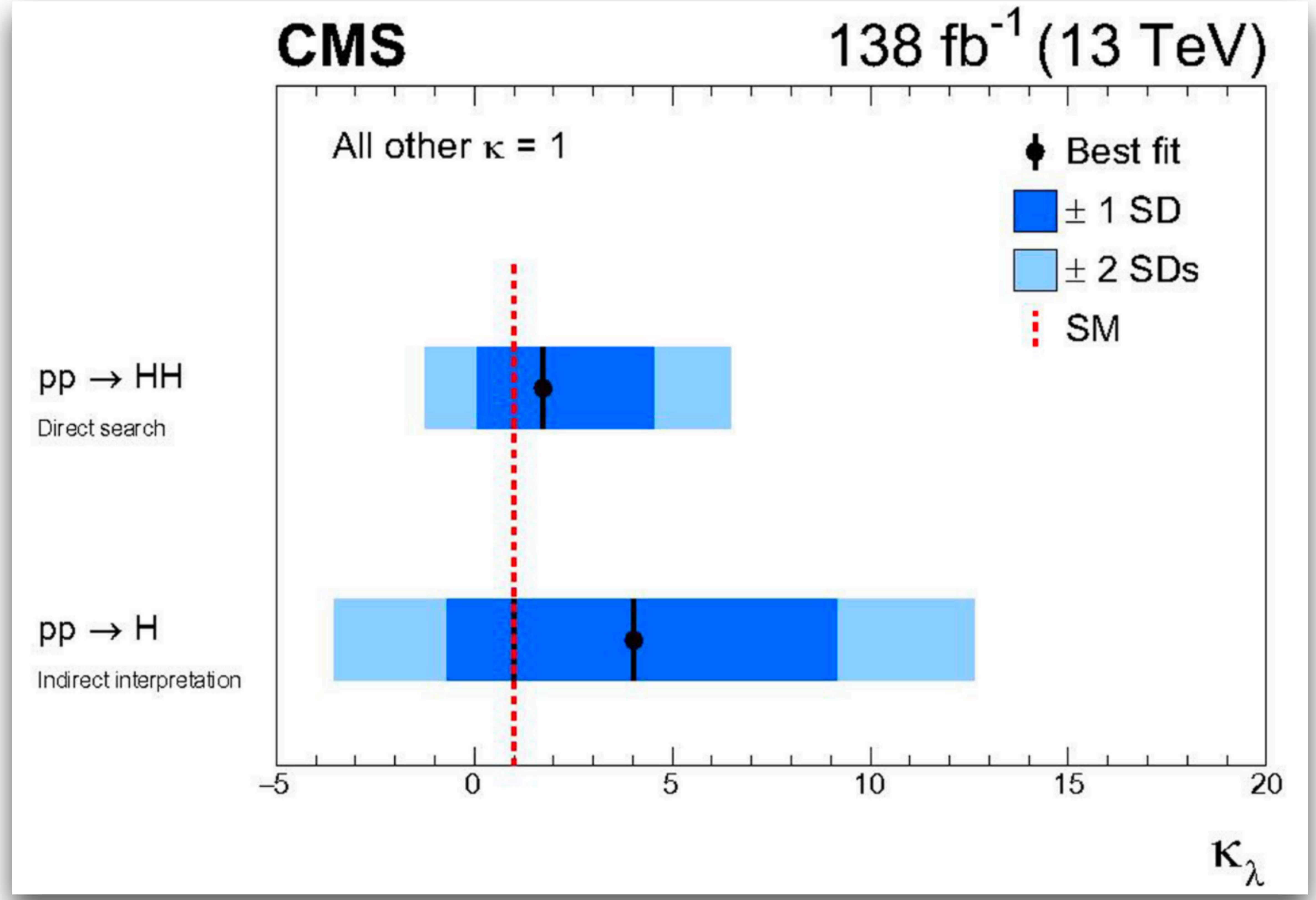
JHEP 07 (2023) 176

Detector efficiency factors are provided for theorists to easily re-interpret the results with their models

HH

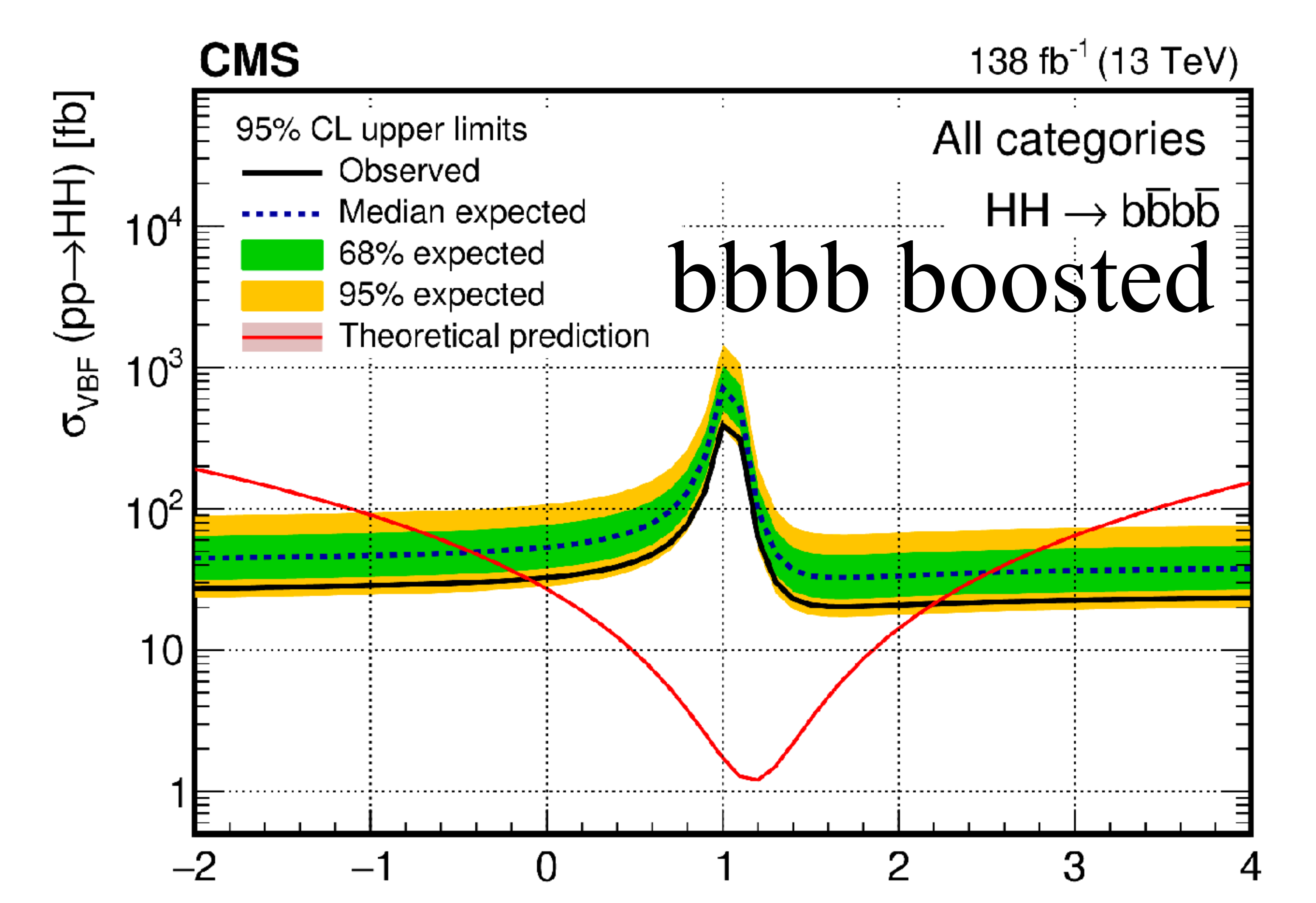
- The double Higgs processes (HH) provides a direct probe to the Higgs self-coupling and the four-boson coupling VVHH κ_{2V}, but very challenging as its XS is 3 orders of magnitude smaller than the single Higgs
- The HH sensitivity already surpassed the single Higgs in terms of Higgs self-coupling
- Both HH production and decays have been explored extensively
  - Production: ggH, VBF and VHH
  - Decays: $4b$, $bb\tau\tau$, $bb\gamma\gamma$, $bbWW$, $bbZZ$, $\tau\tau WW$, 4τ, $4W$, $WW\gamma\gamma$

Nature 607 (2022) 60-68

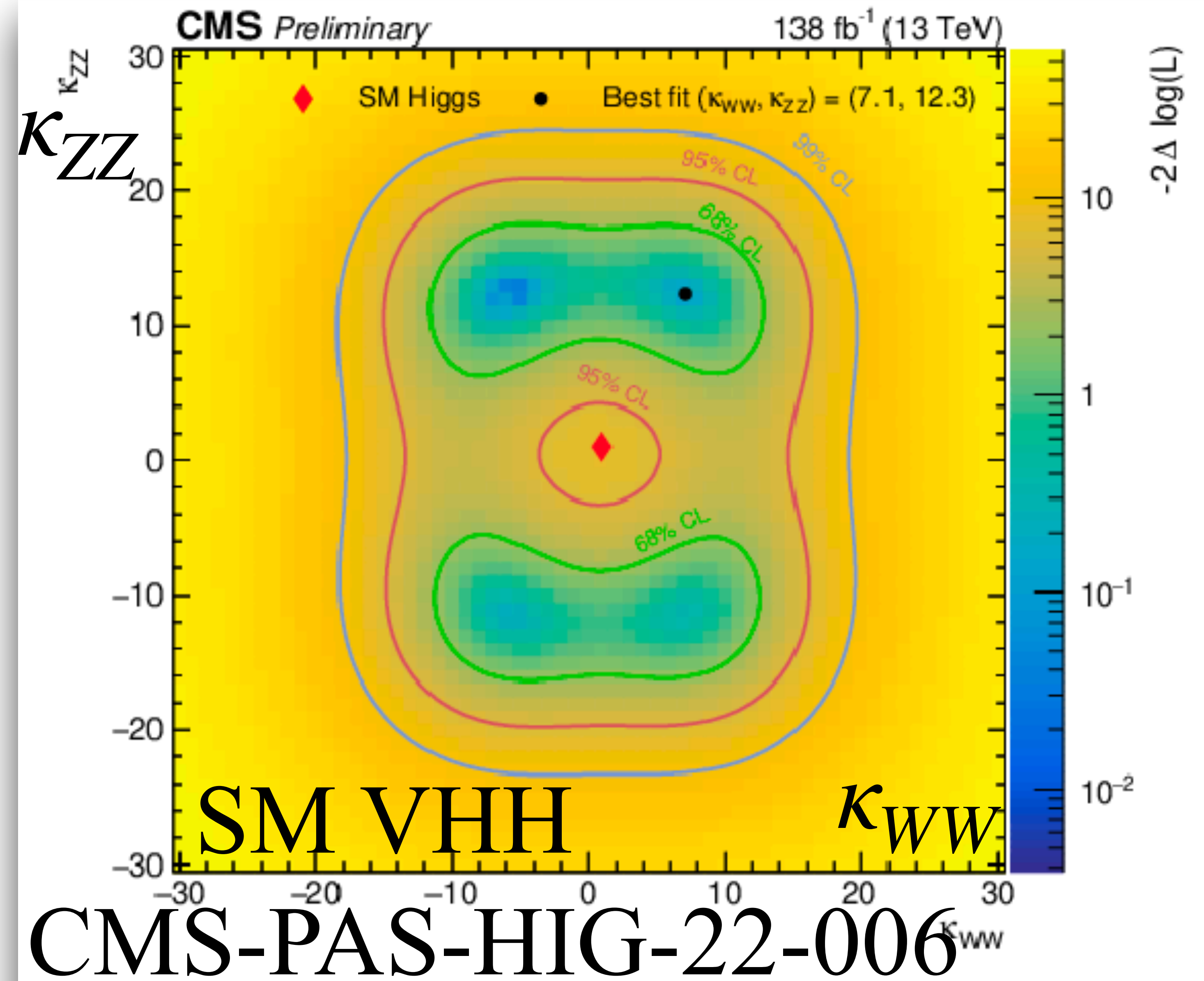


HH with 4b

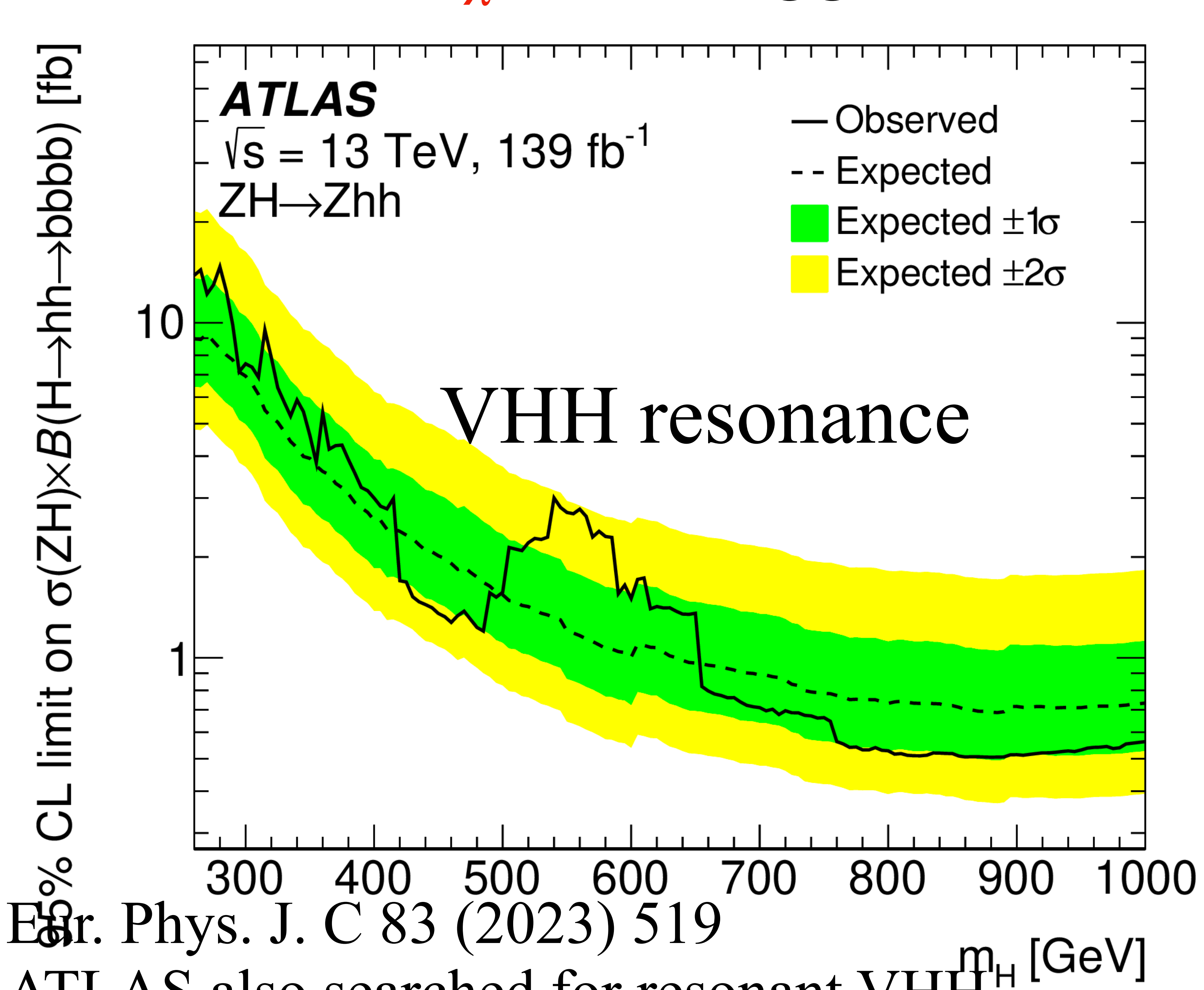
- Stats deliver in HH thanks to its largest BR among all; measure HH XS with an upper limits of 3.9 (7.8)xSM
- The boosted 4b excludes $\kappa_{2V} = 0$ for more than 5σ
- The VHH is also probed using 4b and provides unique probes to WWHH and ZZHH separately
  - Not sensitive to the κ_λ constraints in general, but way more sensitive in κ_λ~5 than ggF
  - ATLAS also uses it for resonant searches



Phys. Rev. Lett. 129 (2022) 081802



CMS-PAS-HIG-22-006

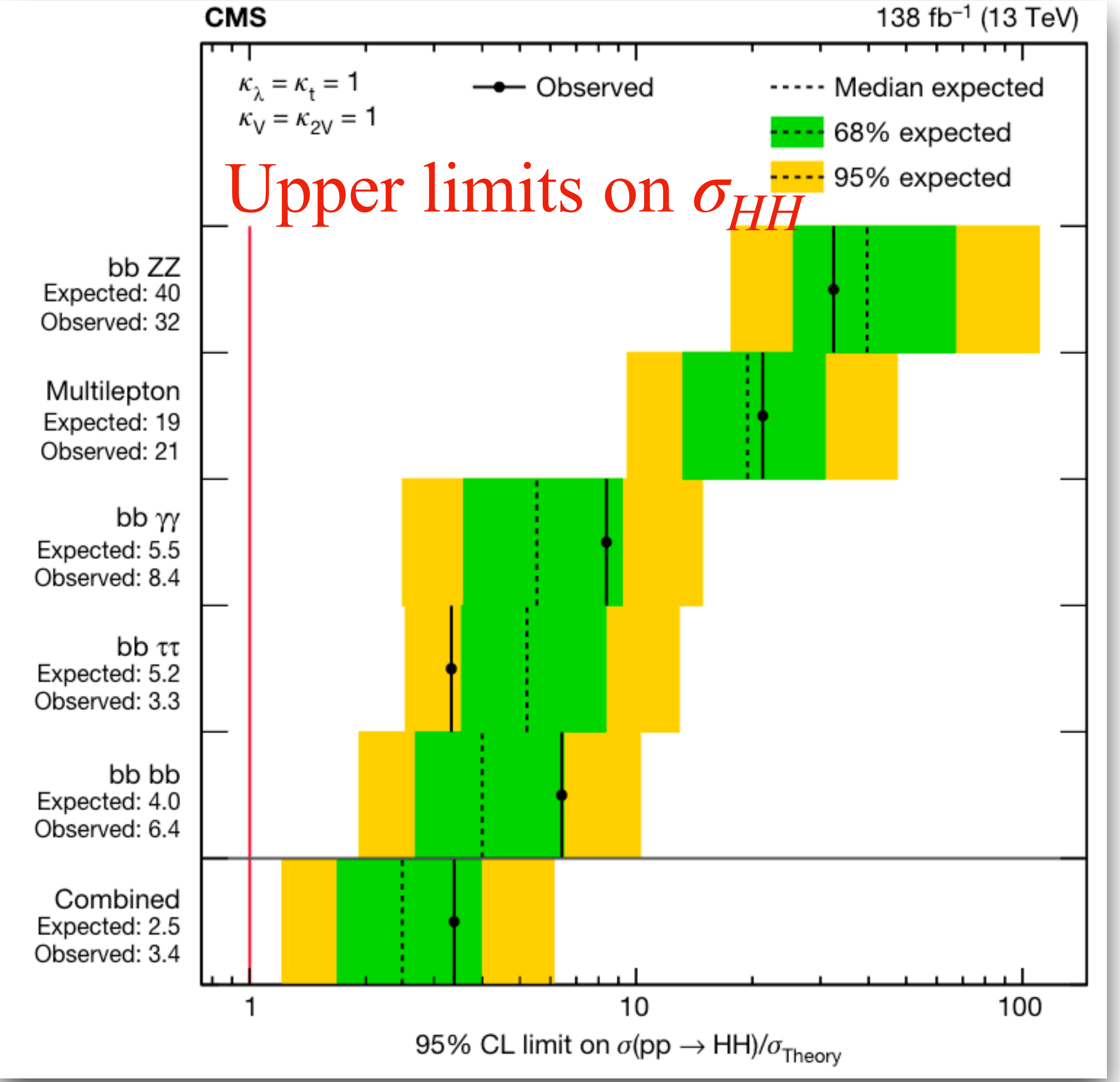


Eur. Phys. J. C 83 (2023) 519

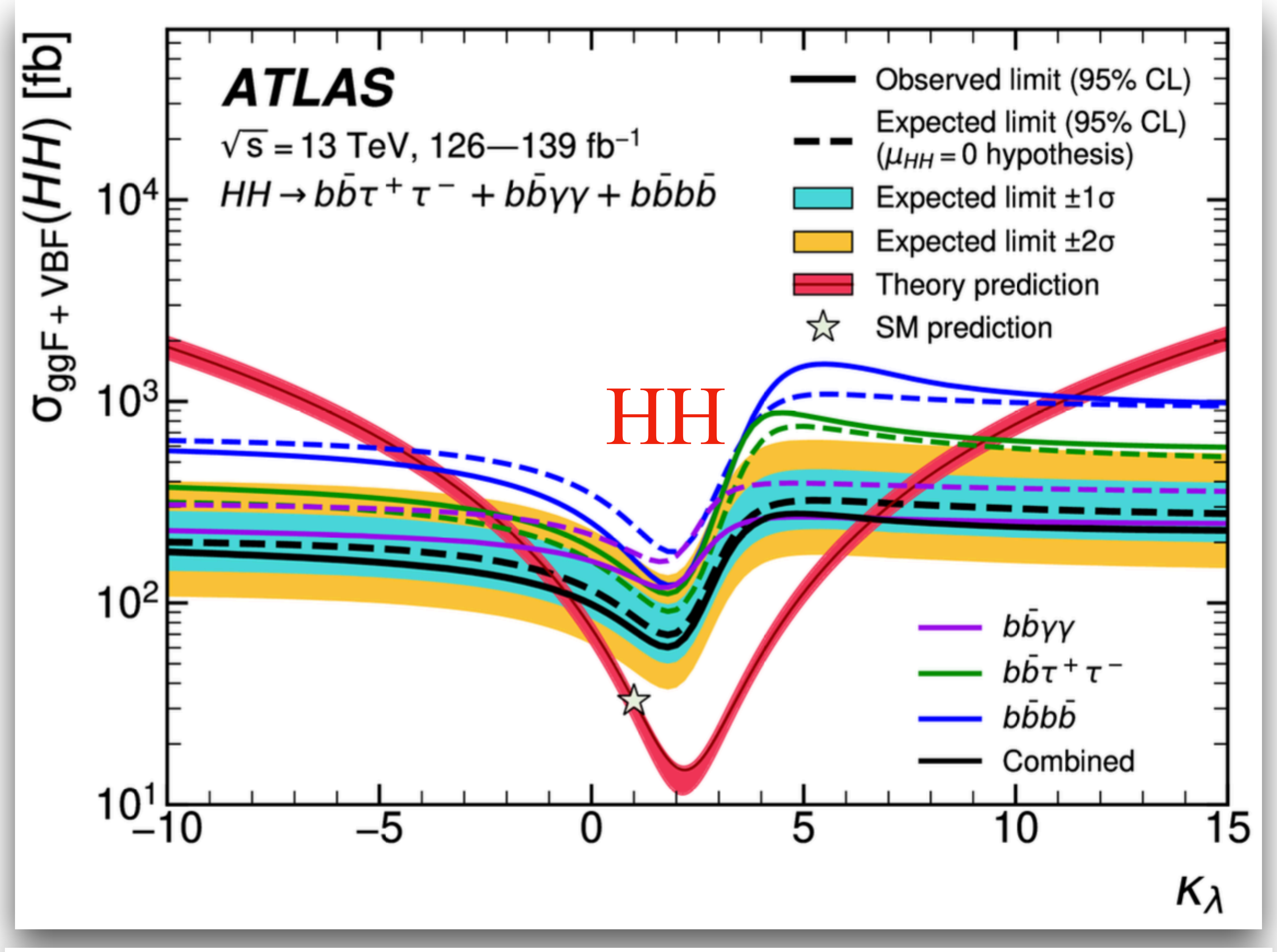
ATLAS also searched for resonant VHH

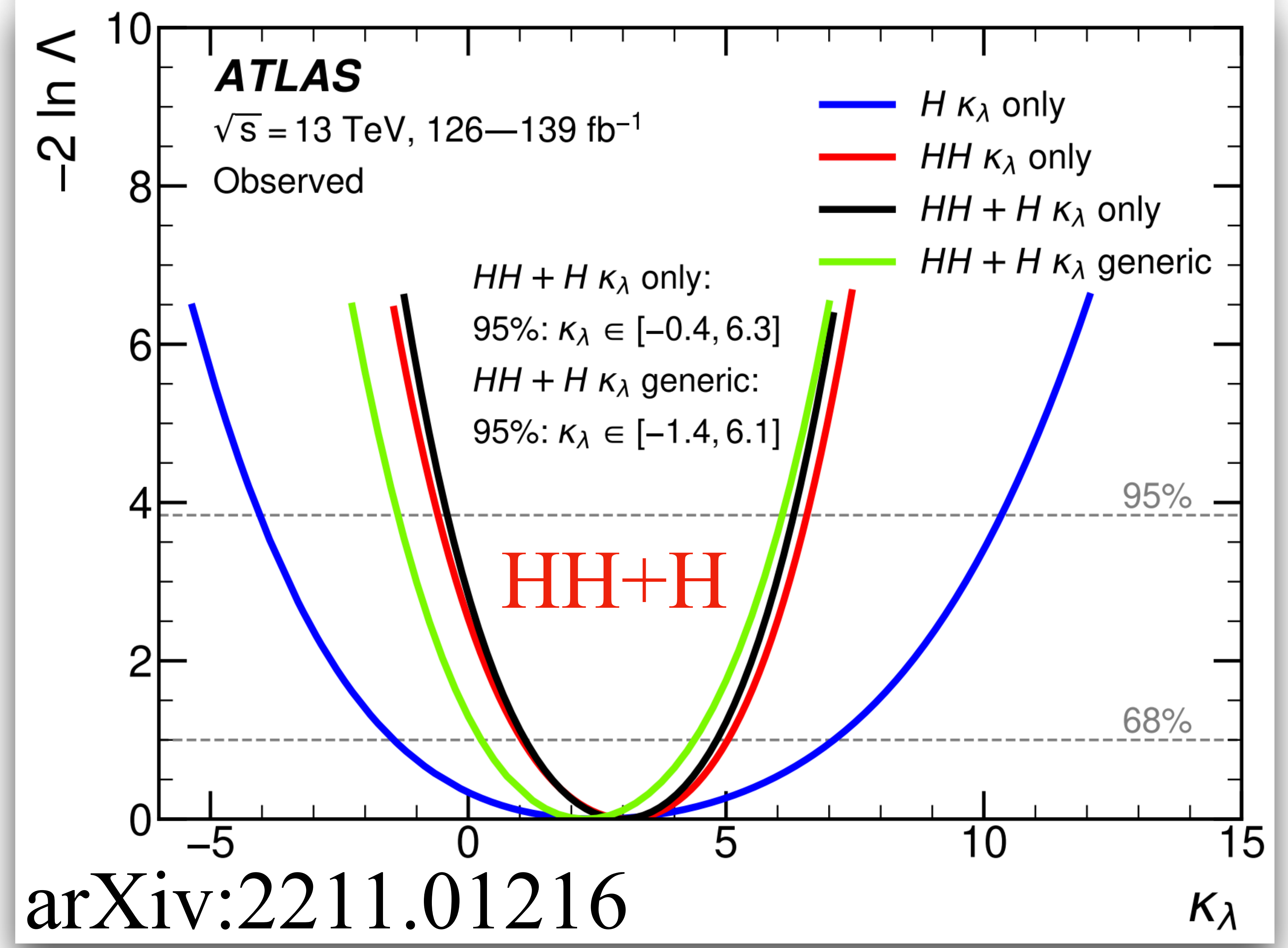
HH(+H) combined

- Still in the era of search, upper limits on HH XS get more stringent
- The combined H XS upper limit reaches 2-3 times of the SM prediction
- H is also introduced in the combination as κ_λ enters as EWK correction in H



Nature 607 (2022) 60-68





arXiv:2211.01216

A first taste of 13.6 TeV

- ATLAS release a first Higgs cross-section measurements using Run3 2022 data under 13.6 TeV
  - Inclusive and fiducial XS are measured, both of which are in good agreement with SM at new new energy!