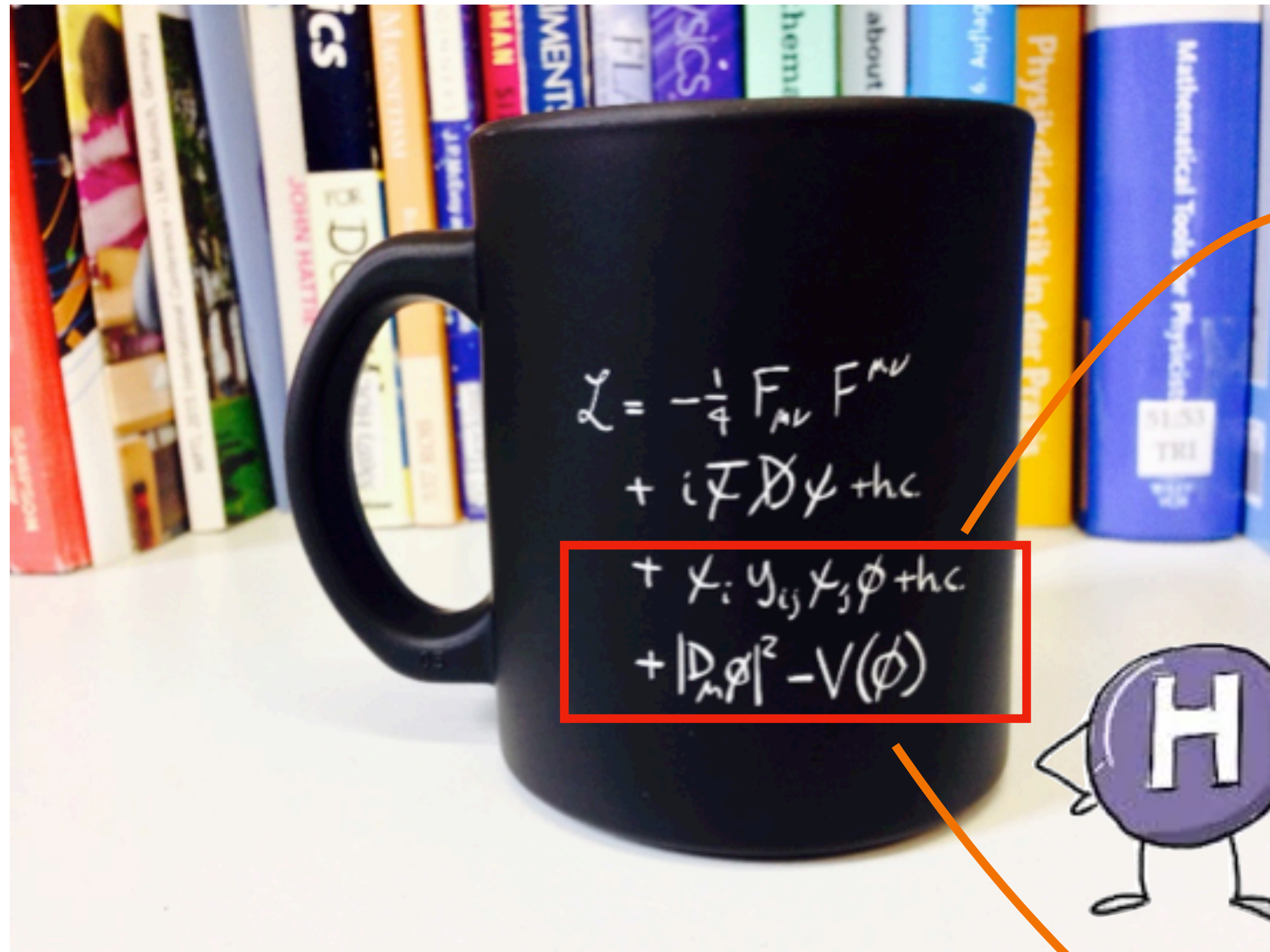


Le vide et le mécanisme de Higgs: explorations expérimentales

The Higgs boson

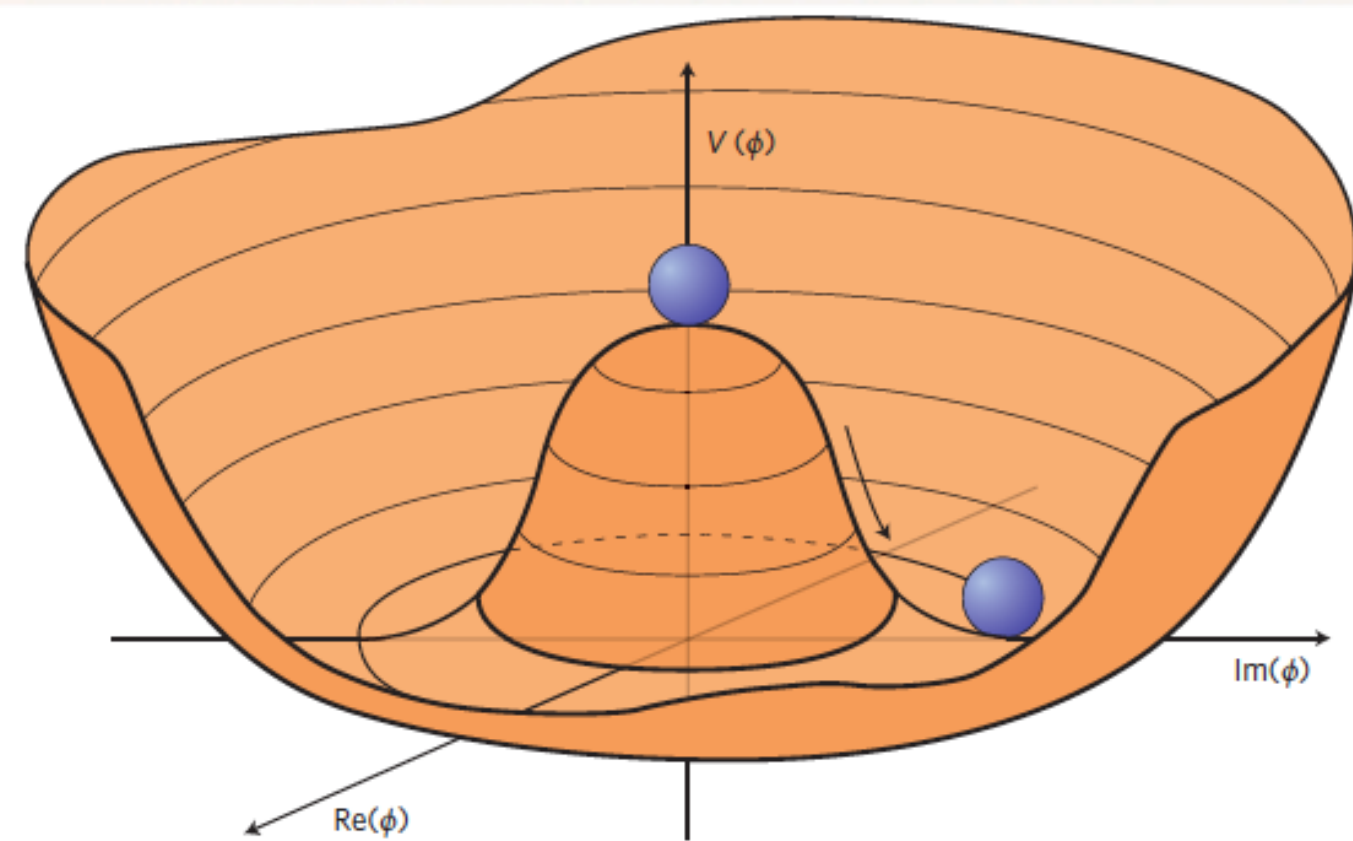


mass →	≈2.3 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

QUARKS (left side of table)

LEPTONS (left side of table)

GAUGE BOSONS (right side of table)

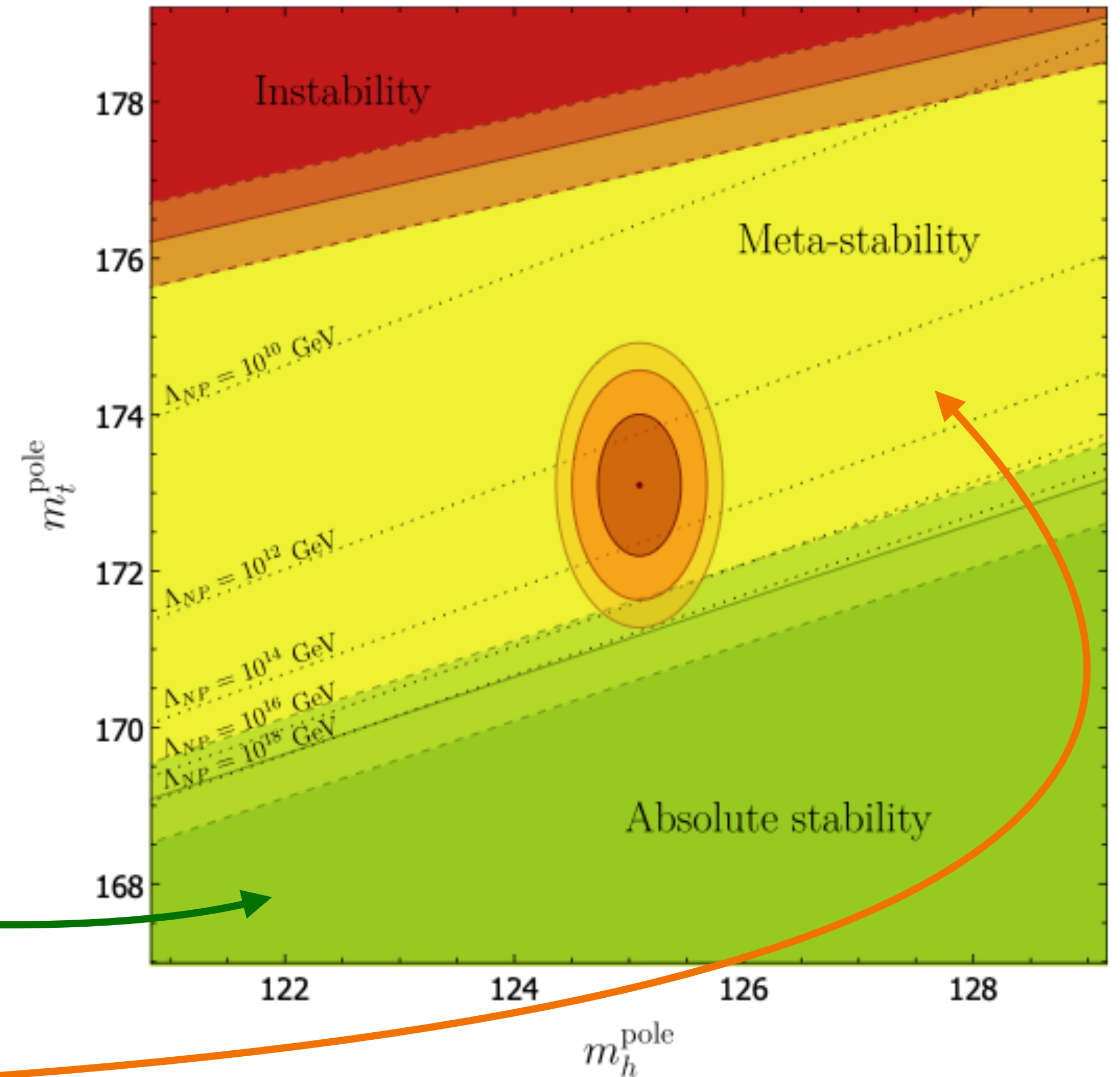
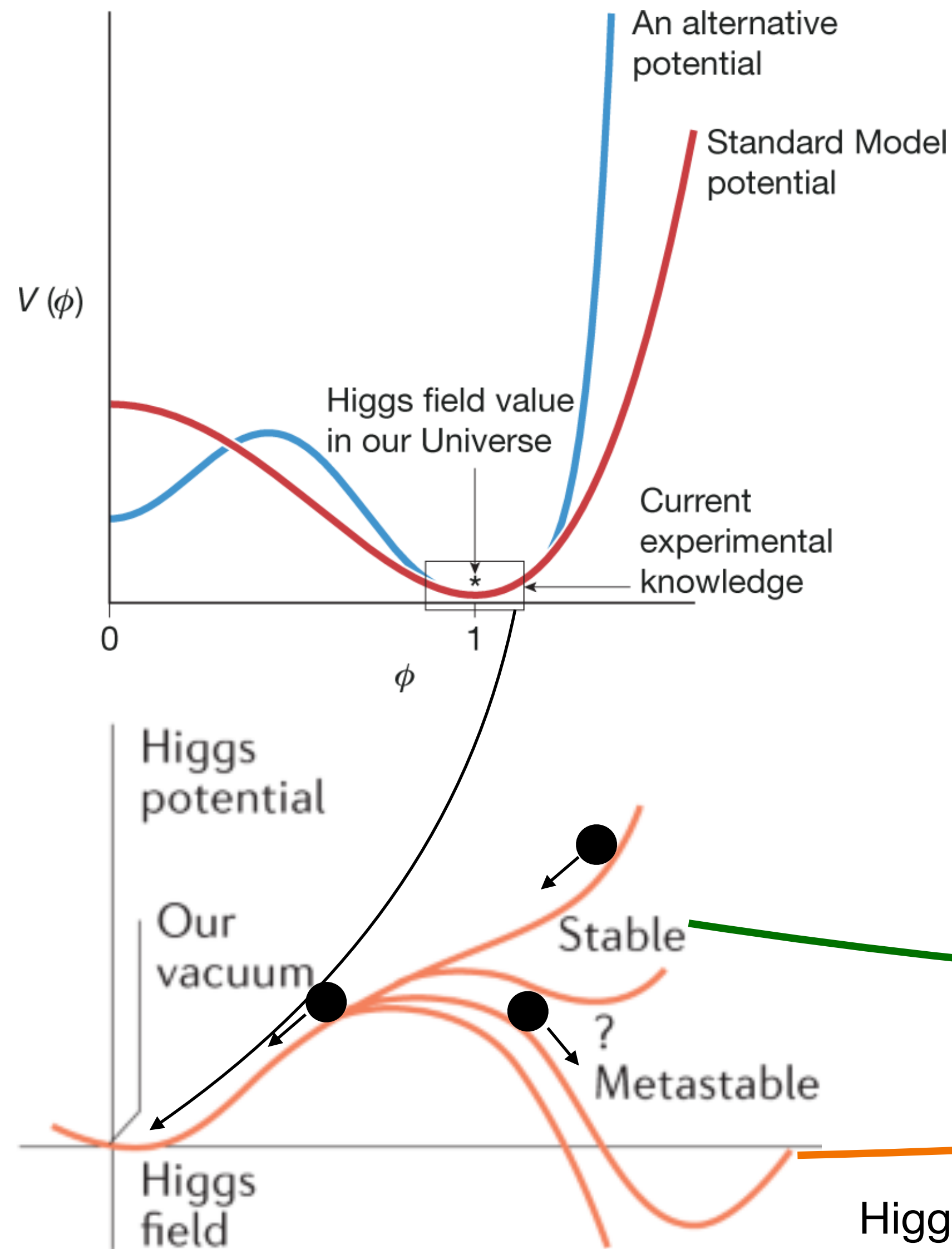


**Mass! We wouldn't be here without H
But the SM does not predict the mass of H...**

The Higgs boson and the vacuum

Nature 607 41 (2022)

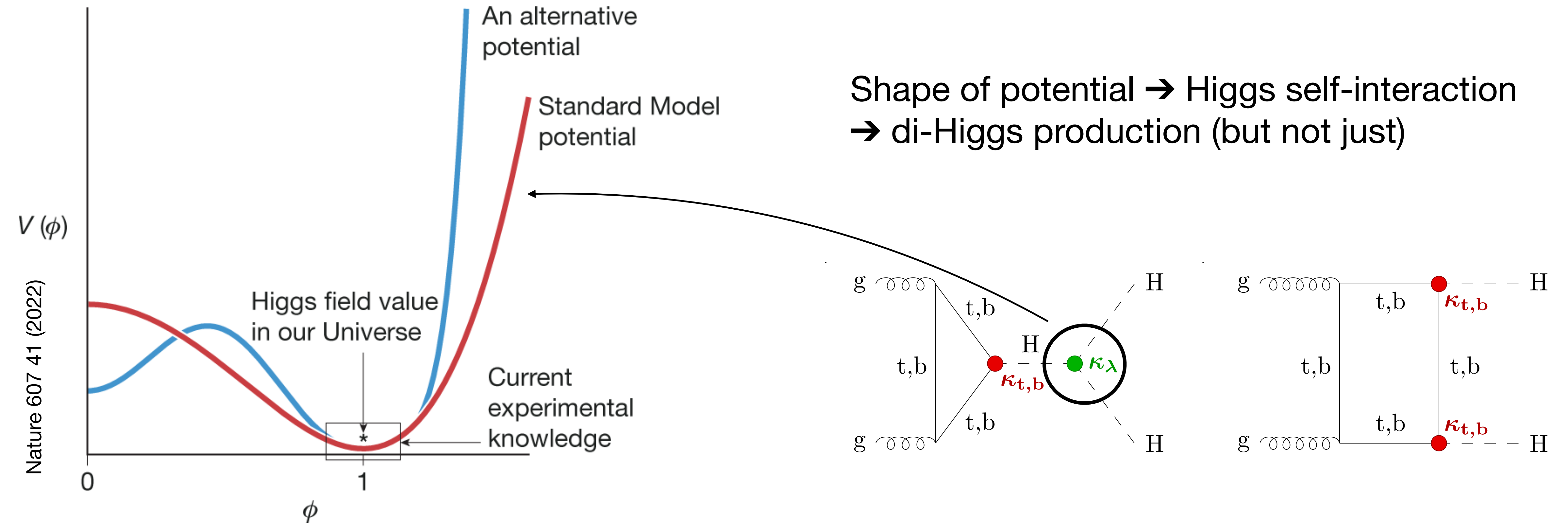
Nat. Phys. Rev. 3 608 (2021)



PRD 97 056006 (2018)

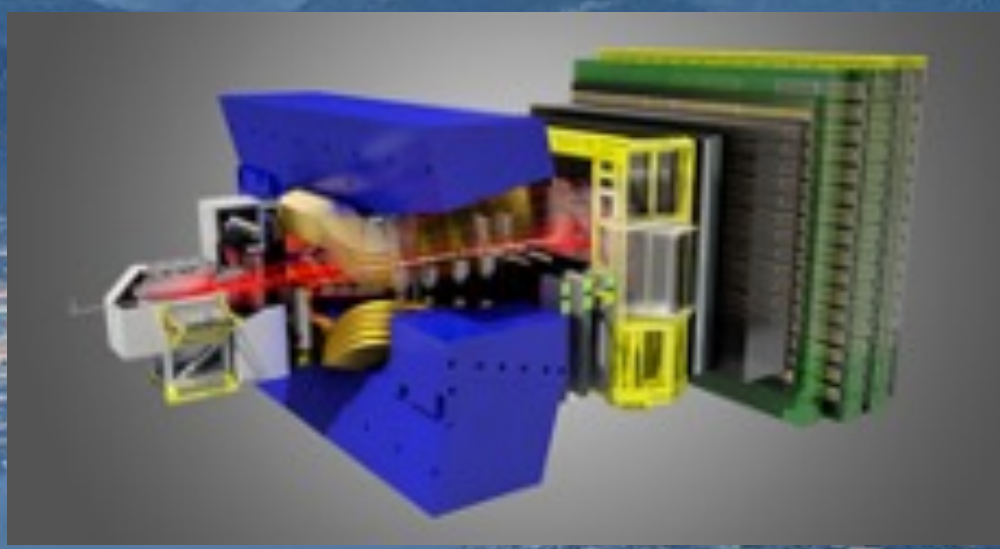
Higgs <> vacuum stability: important to measure the **mass** and its **self-interaction**₃

Attacking the Higgs boson self-coupling

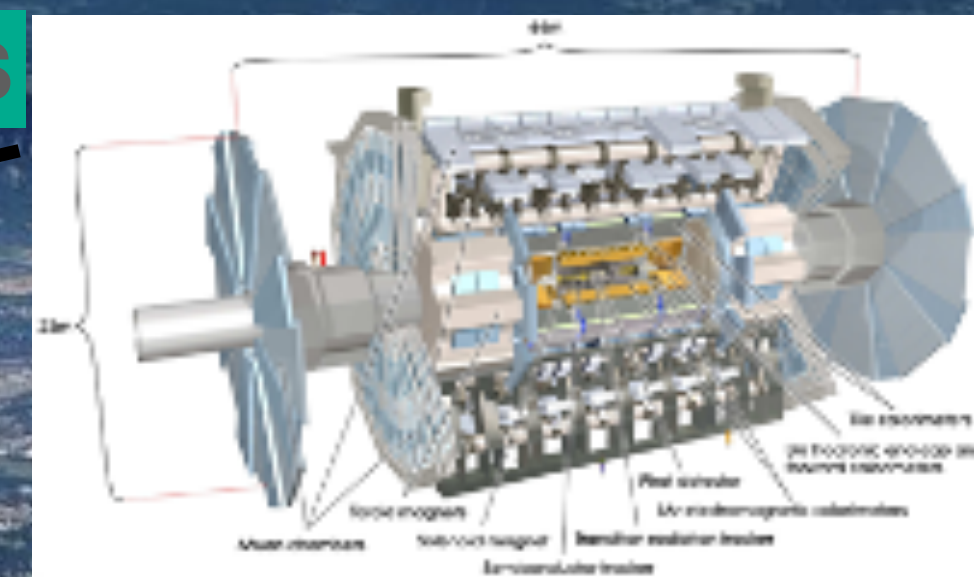


The LHC

LHCb
pp, B physics, CP violation

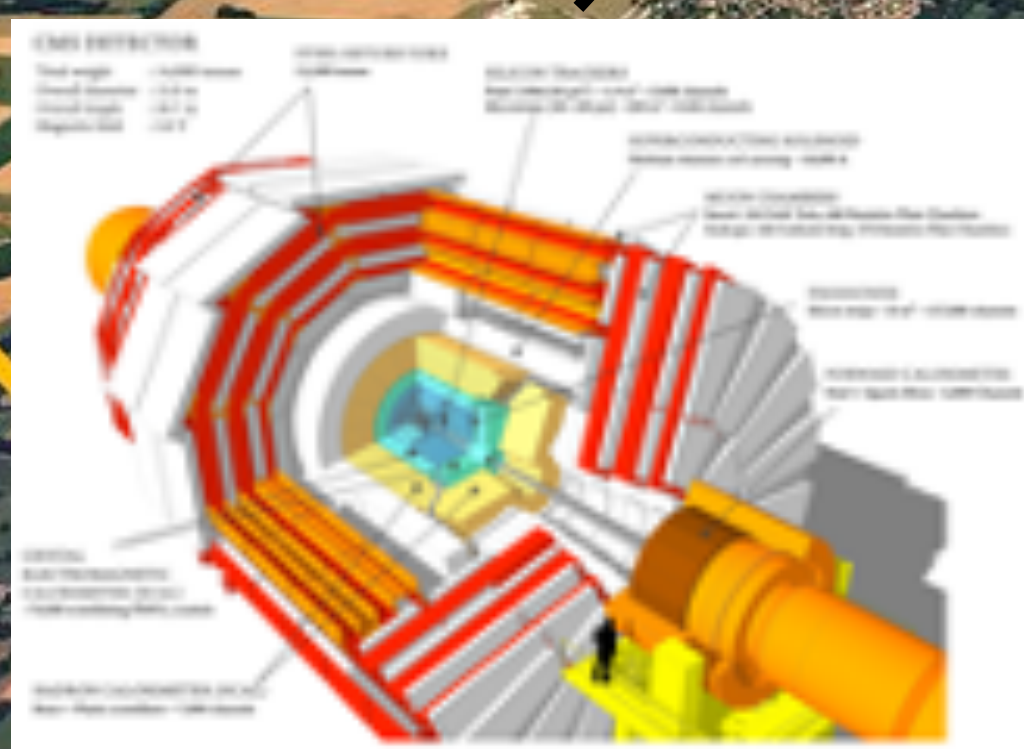


ATLAS



"General" experiments
→ study pp, heavy ion collisions
Higgs boson discovery

CMS



ALICE
Heavy ions



ALICE

LHC 27 km

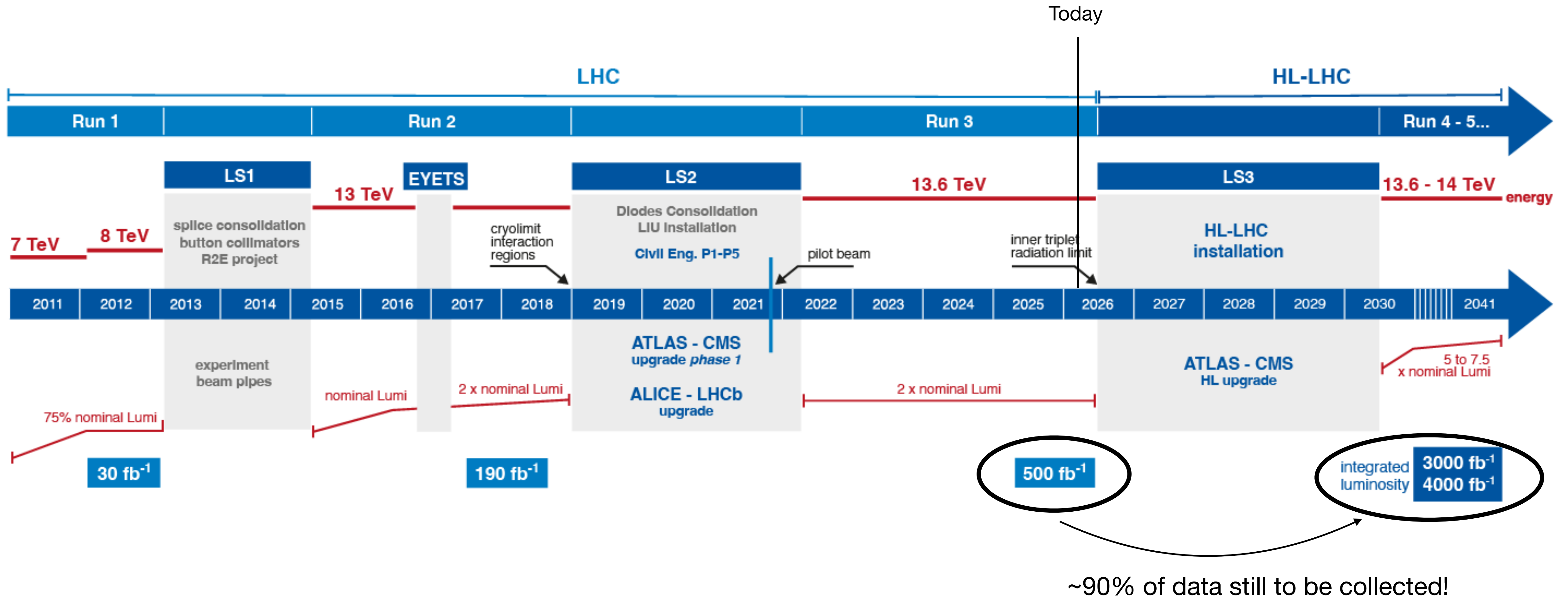
SPS 7 km

CERN Meyrin

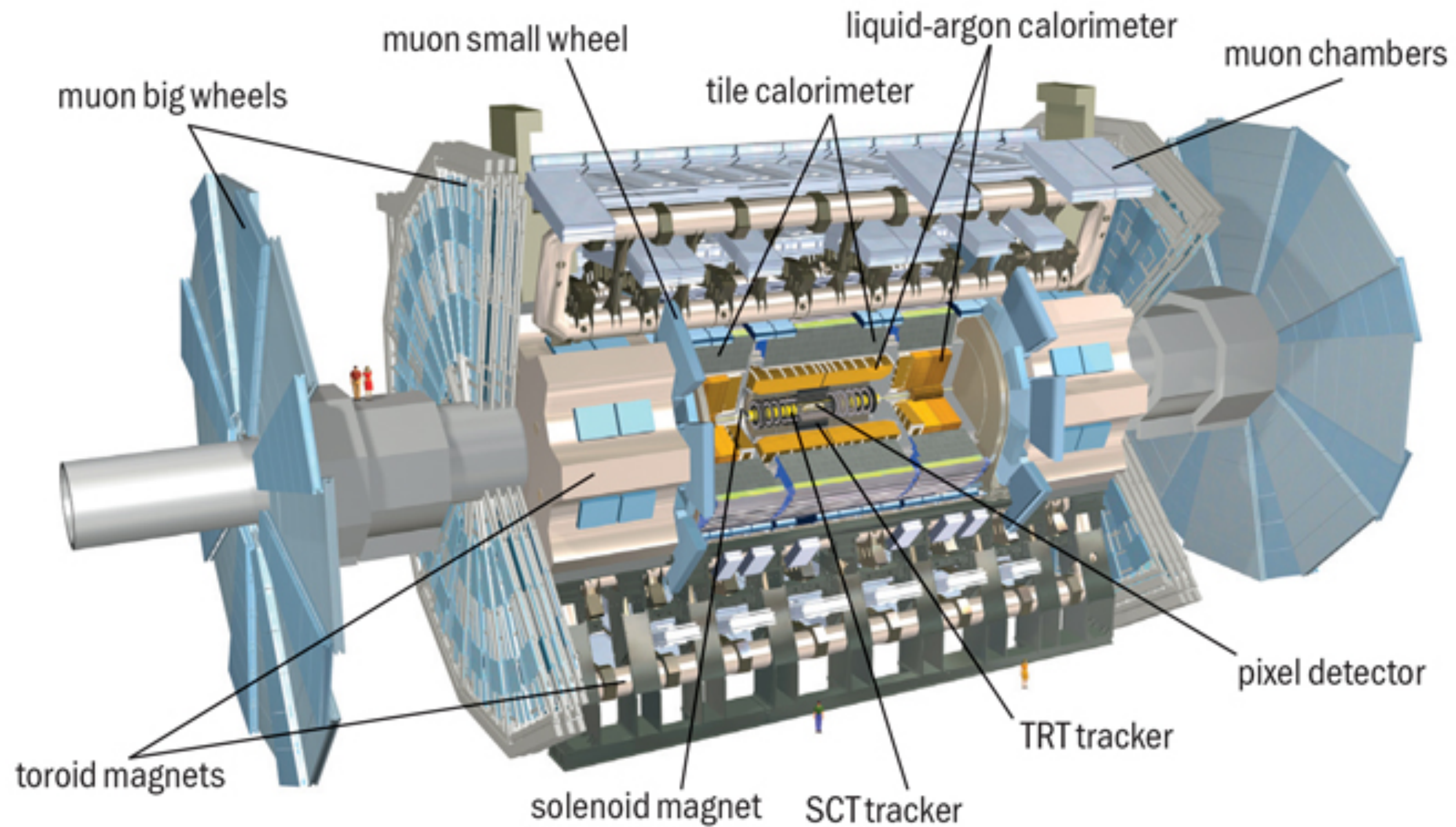
CERN Prévessin

SUISSE
FRANCE

LHC timeline



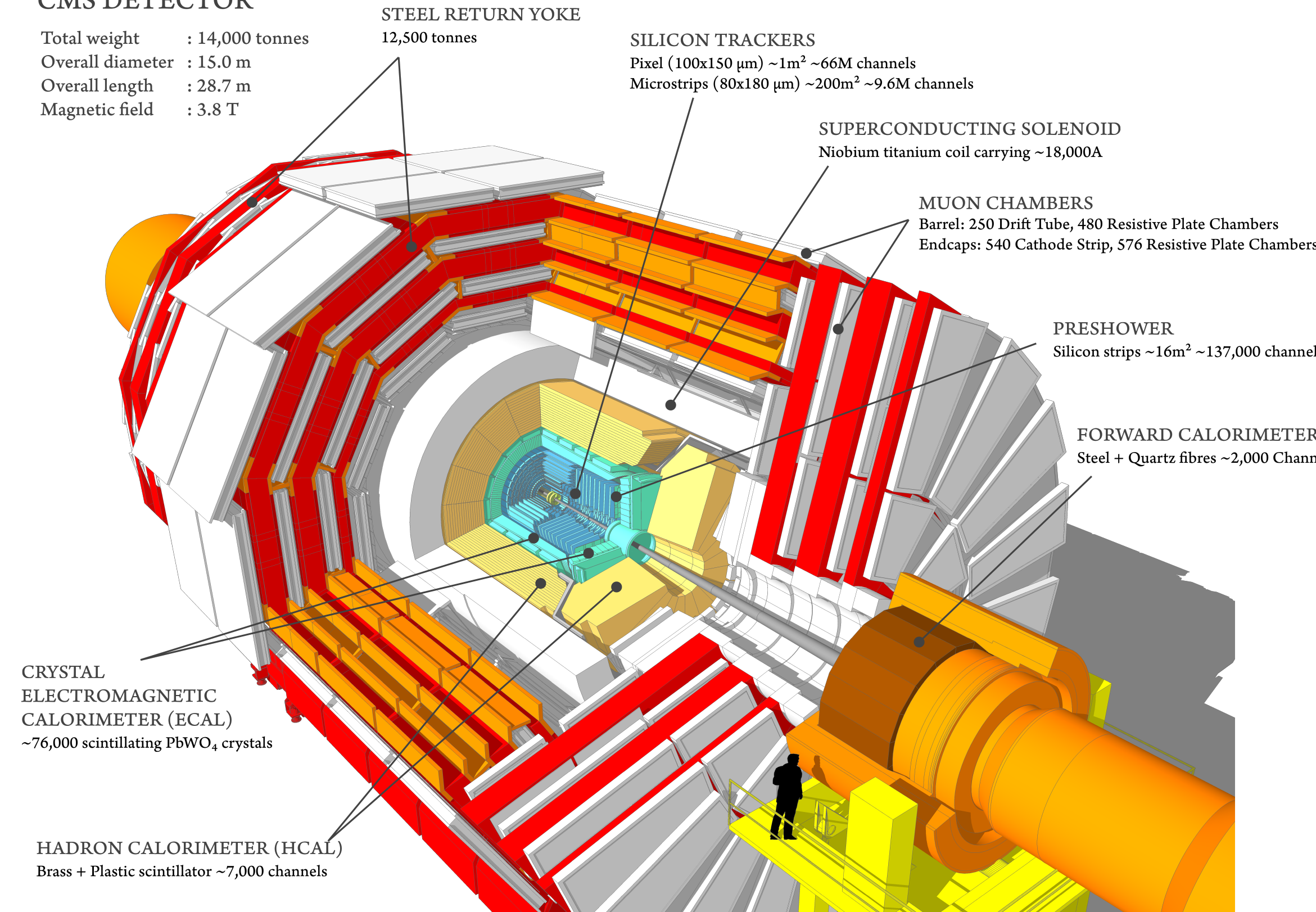
ATLAS & CMS



ATLAS

CMS DETECTOR

Total weight : 14,000 tonnes
 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T



CMS

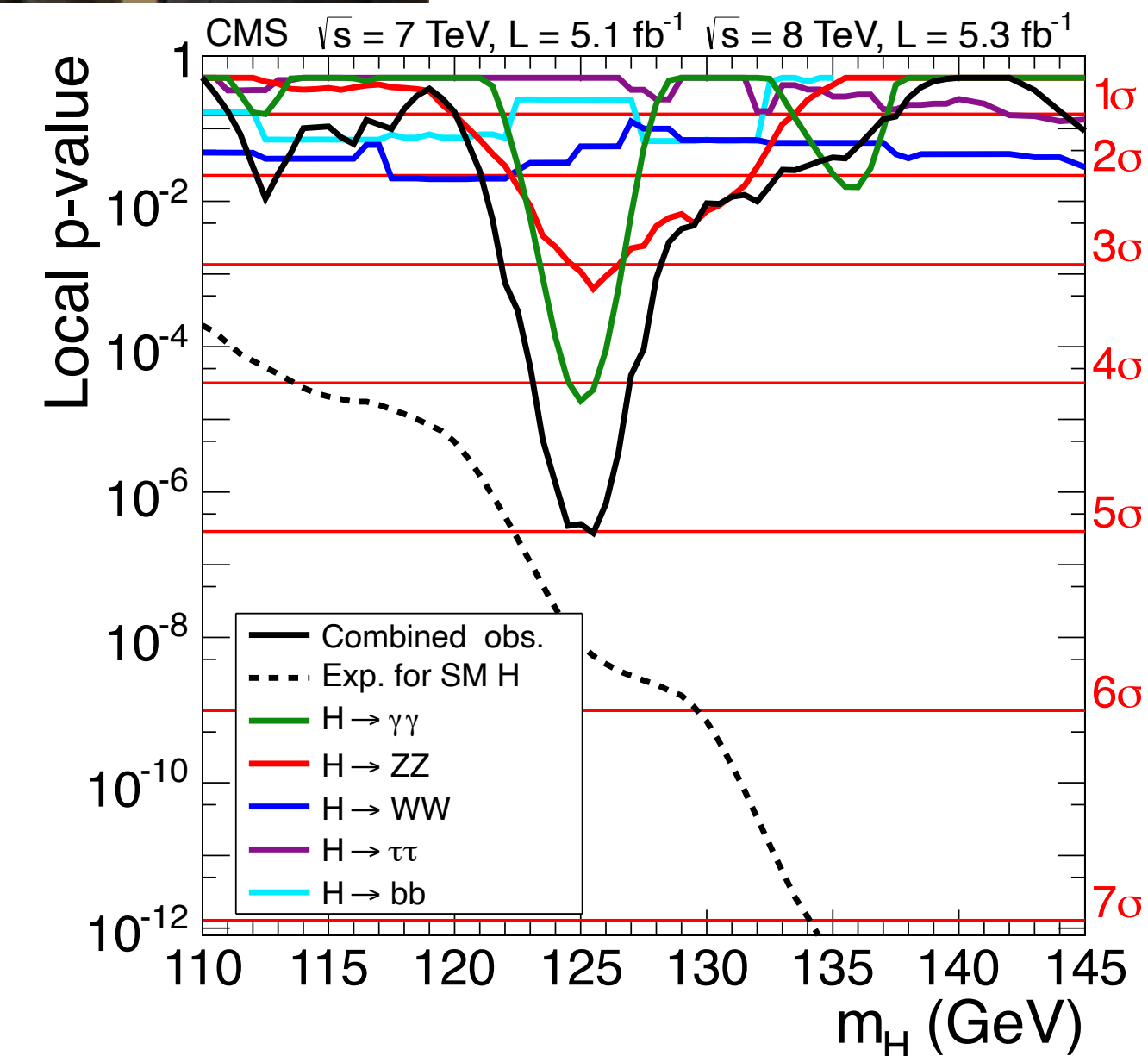
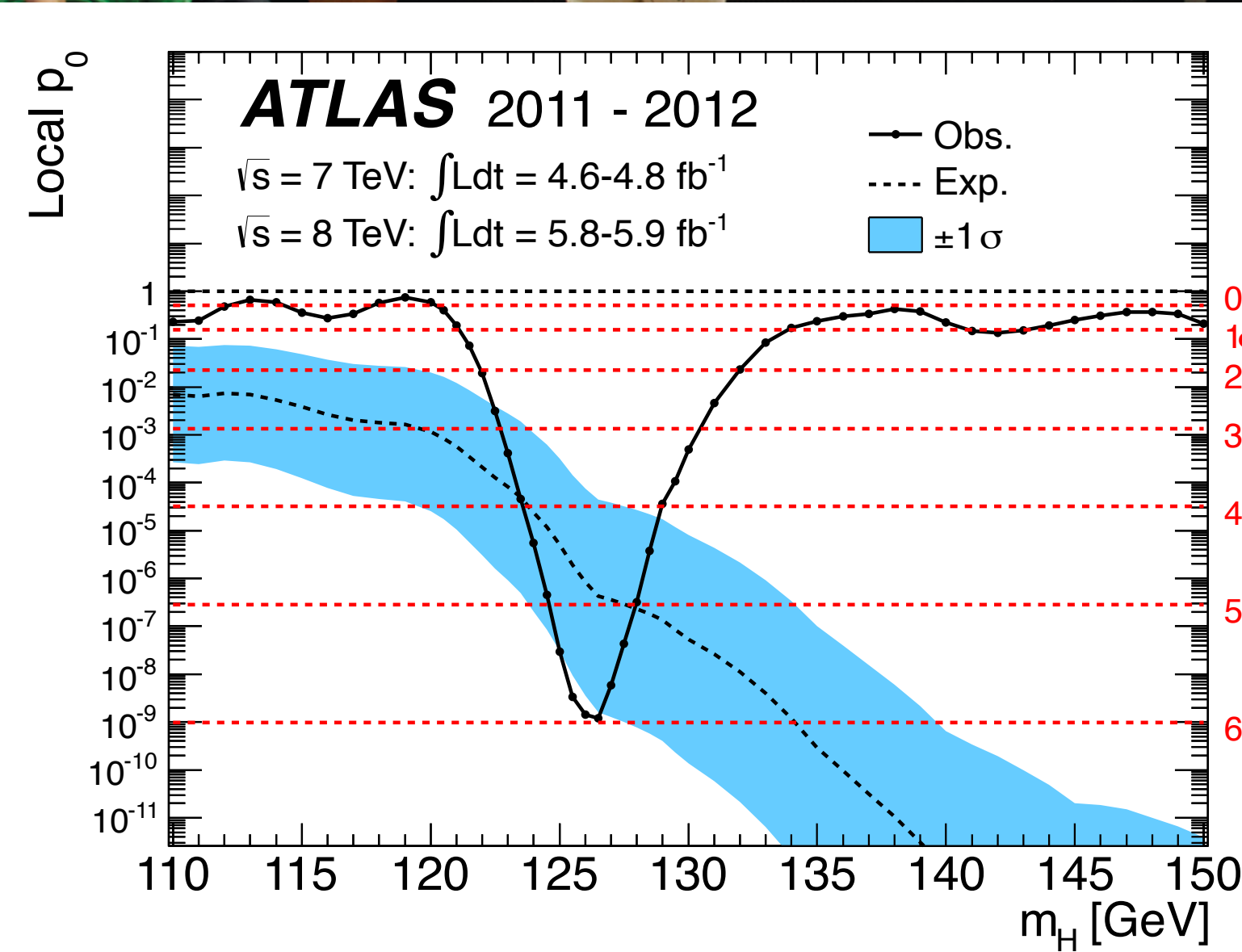
In general:

Tracker (in magnetic field): to measure trajectories (+ energies) of charged particles

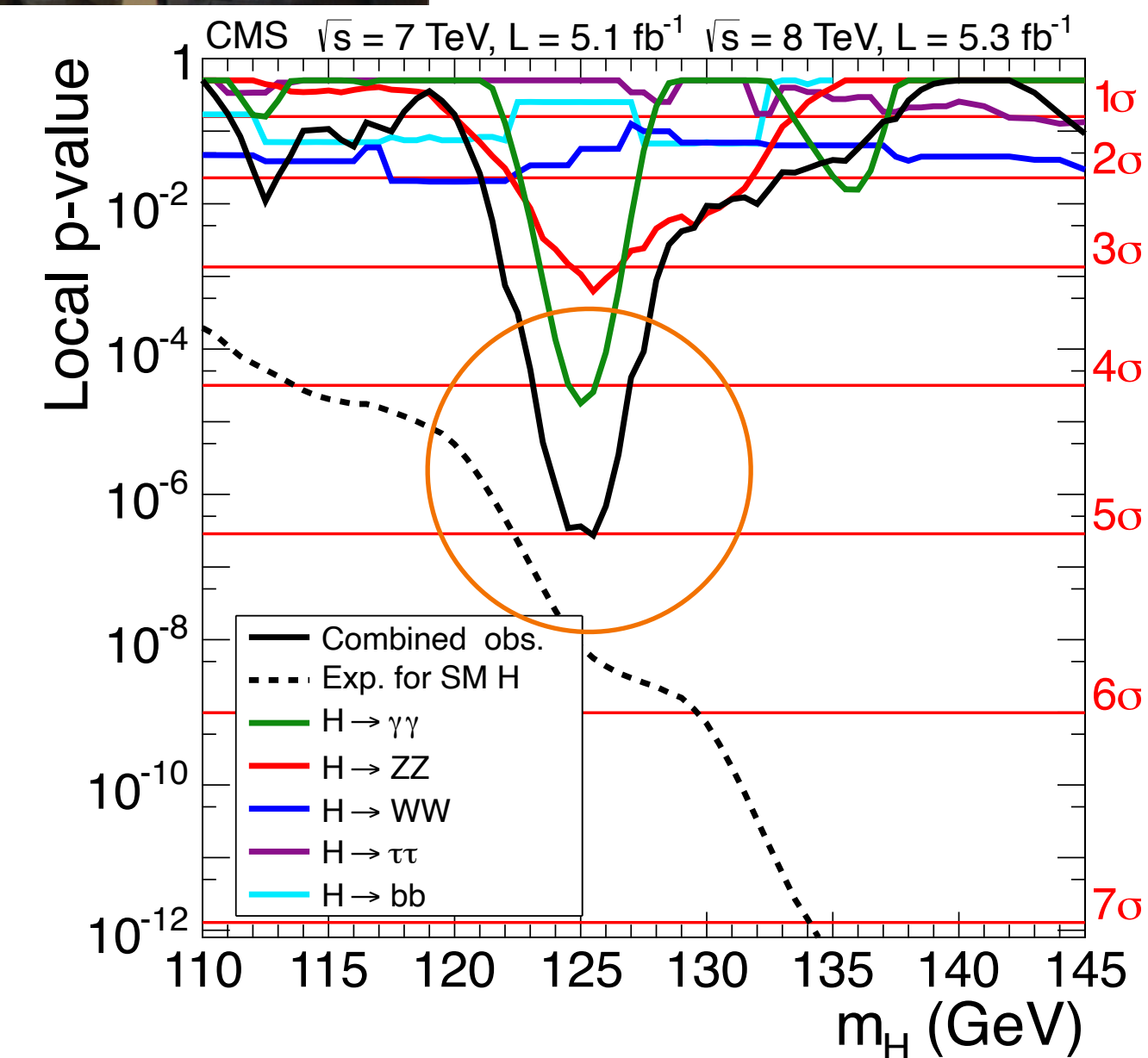
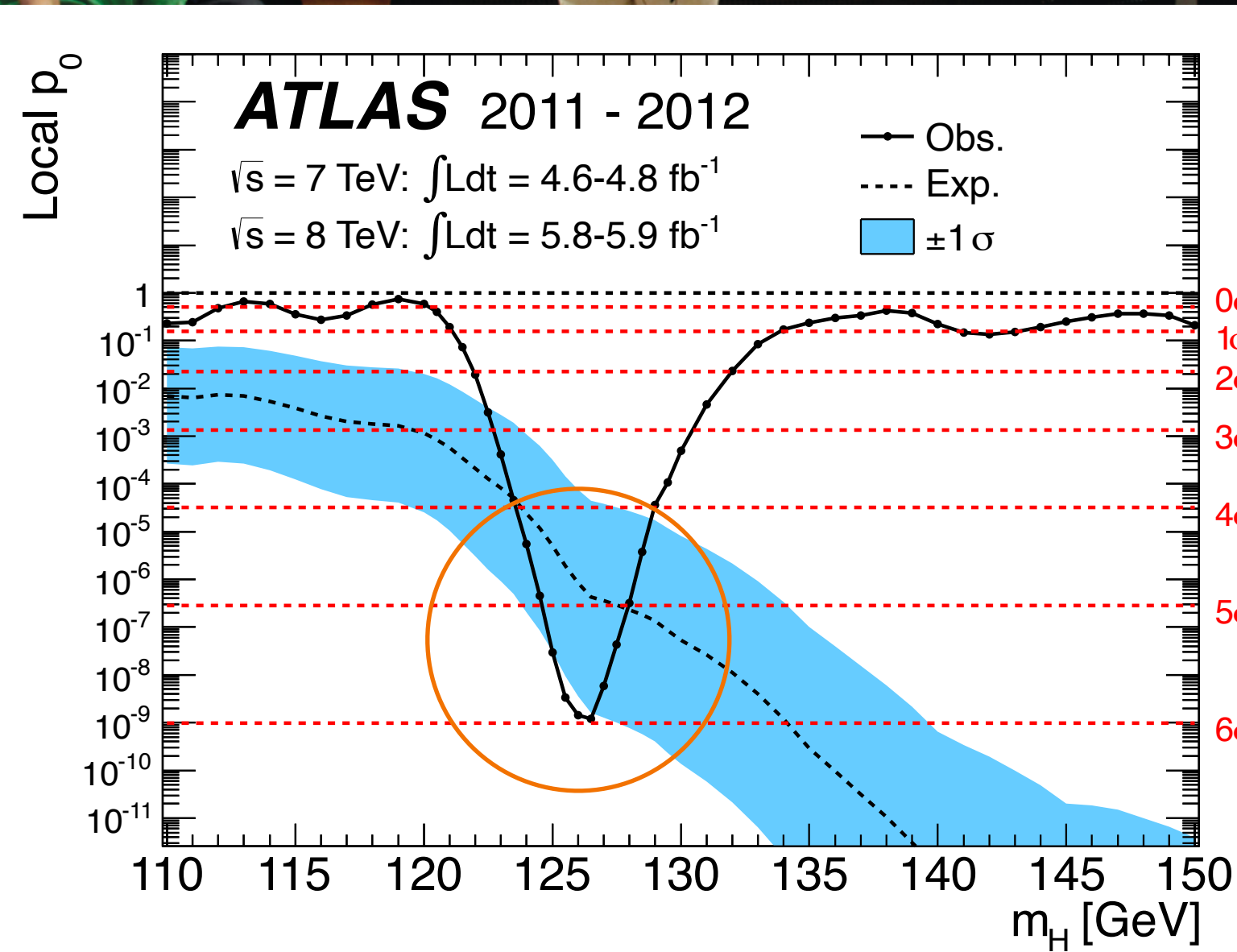
Calorimeters: to measure energy of electromagnetic and hadronic particles

Muon detectors: trajectory/energy of muons

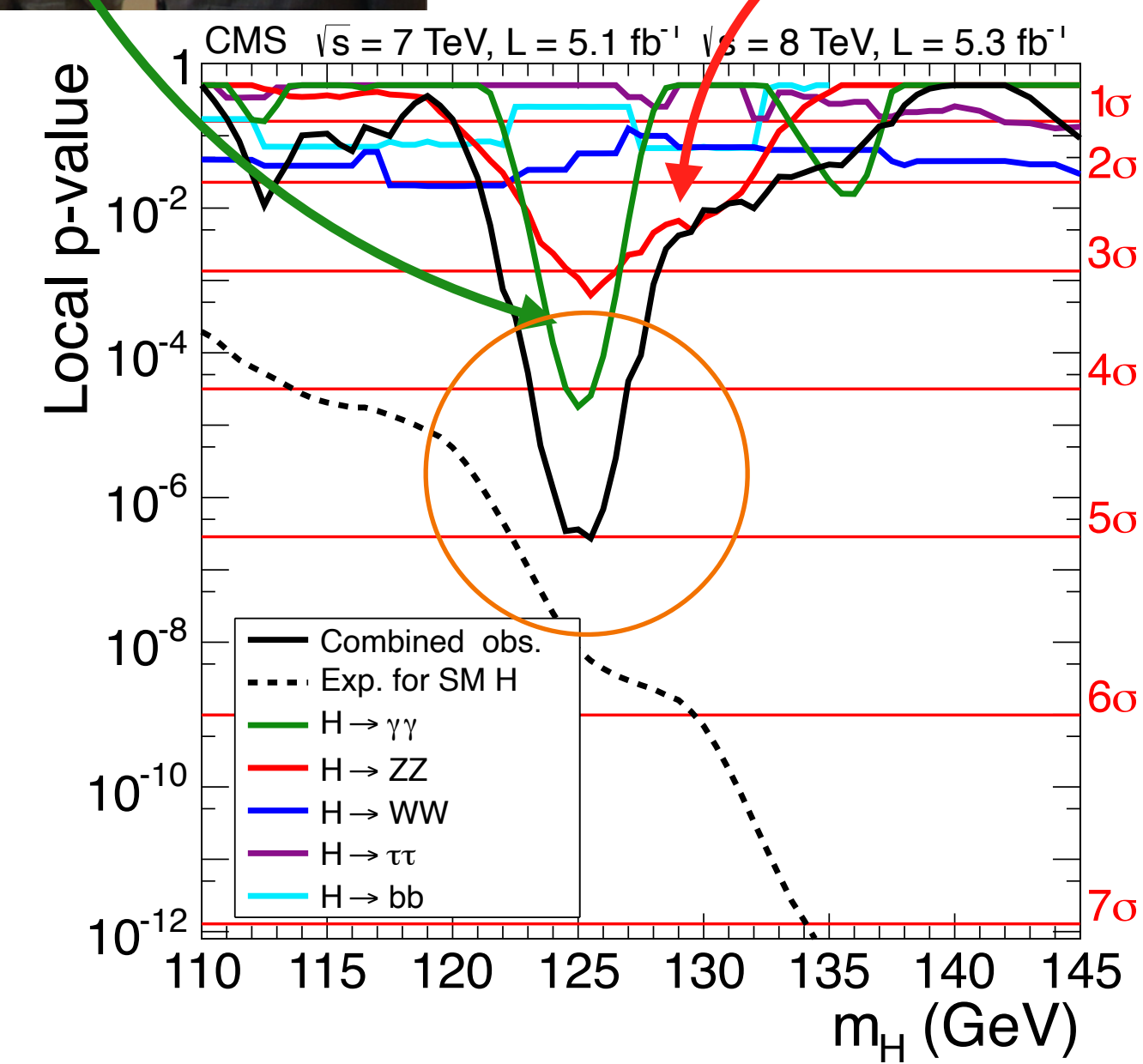
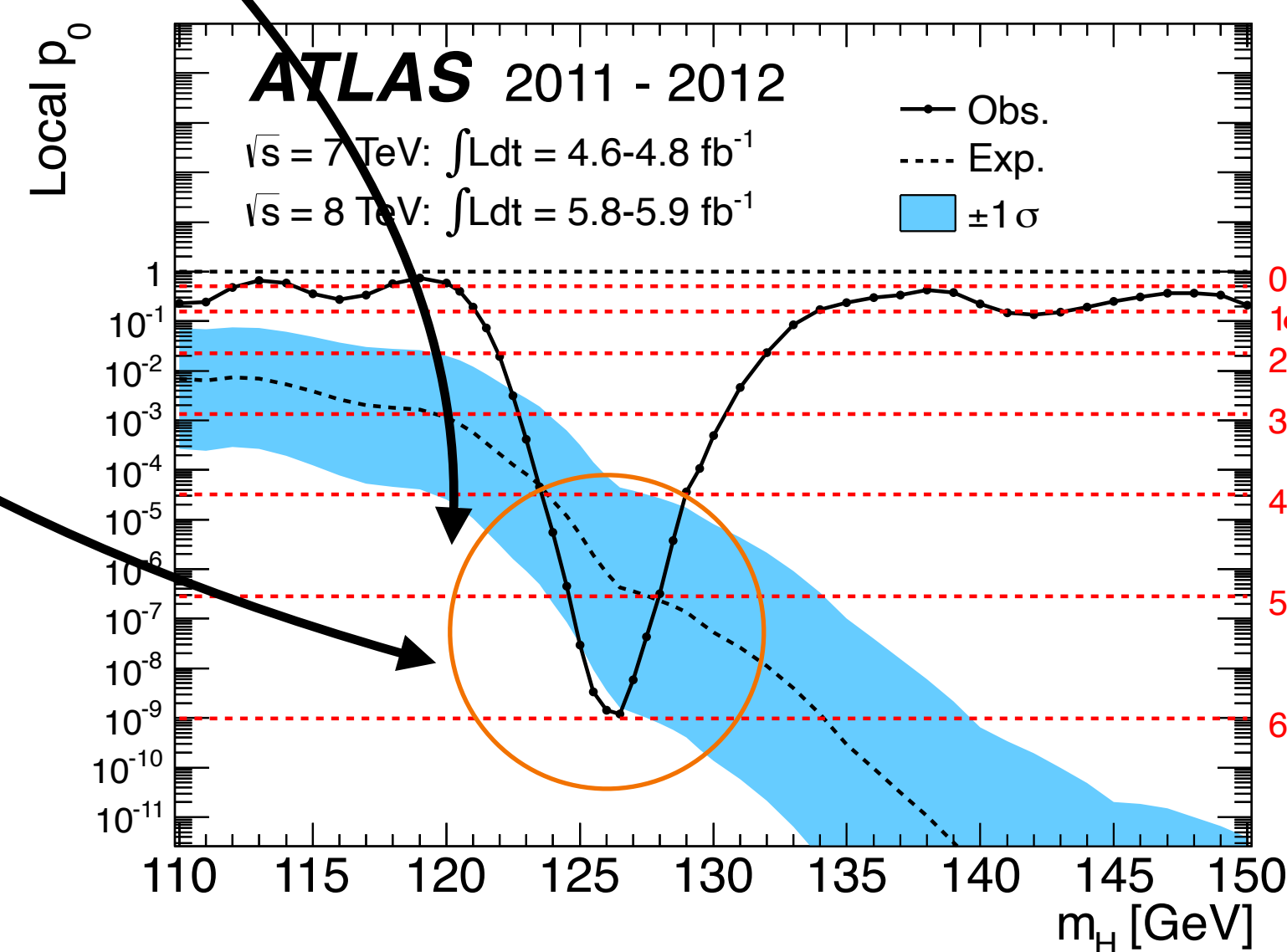
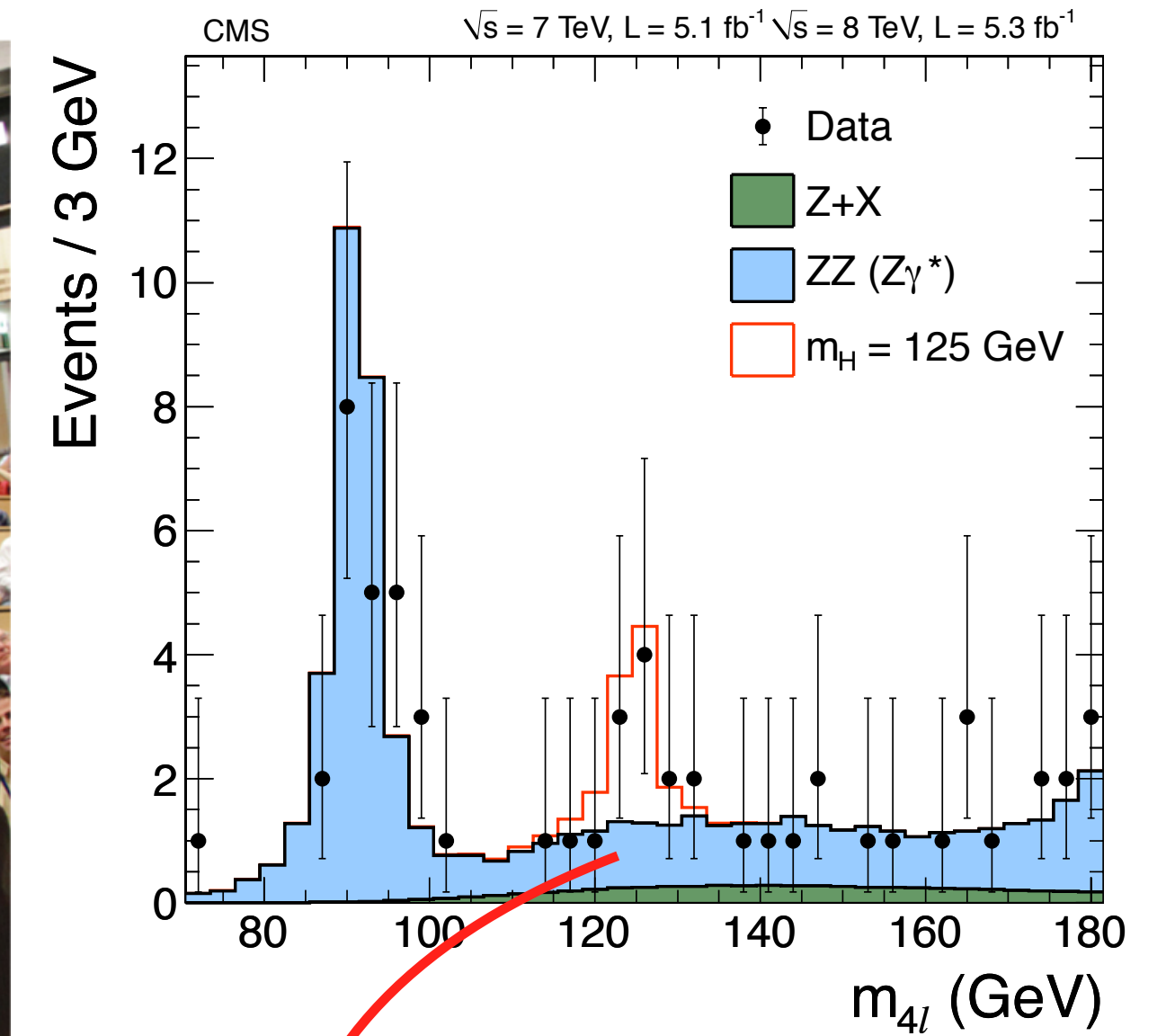
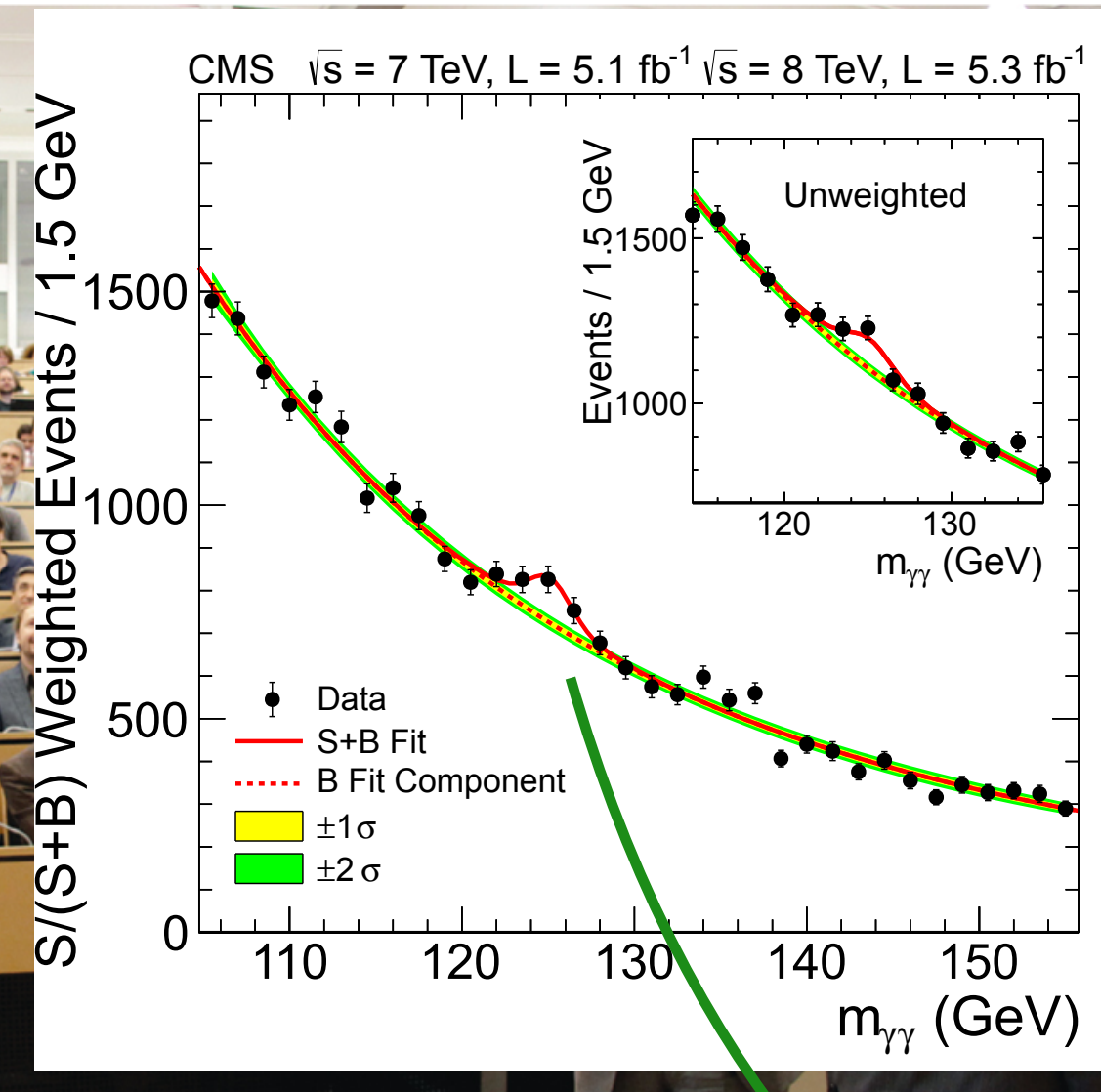
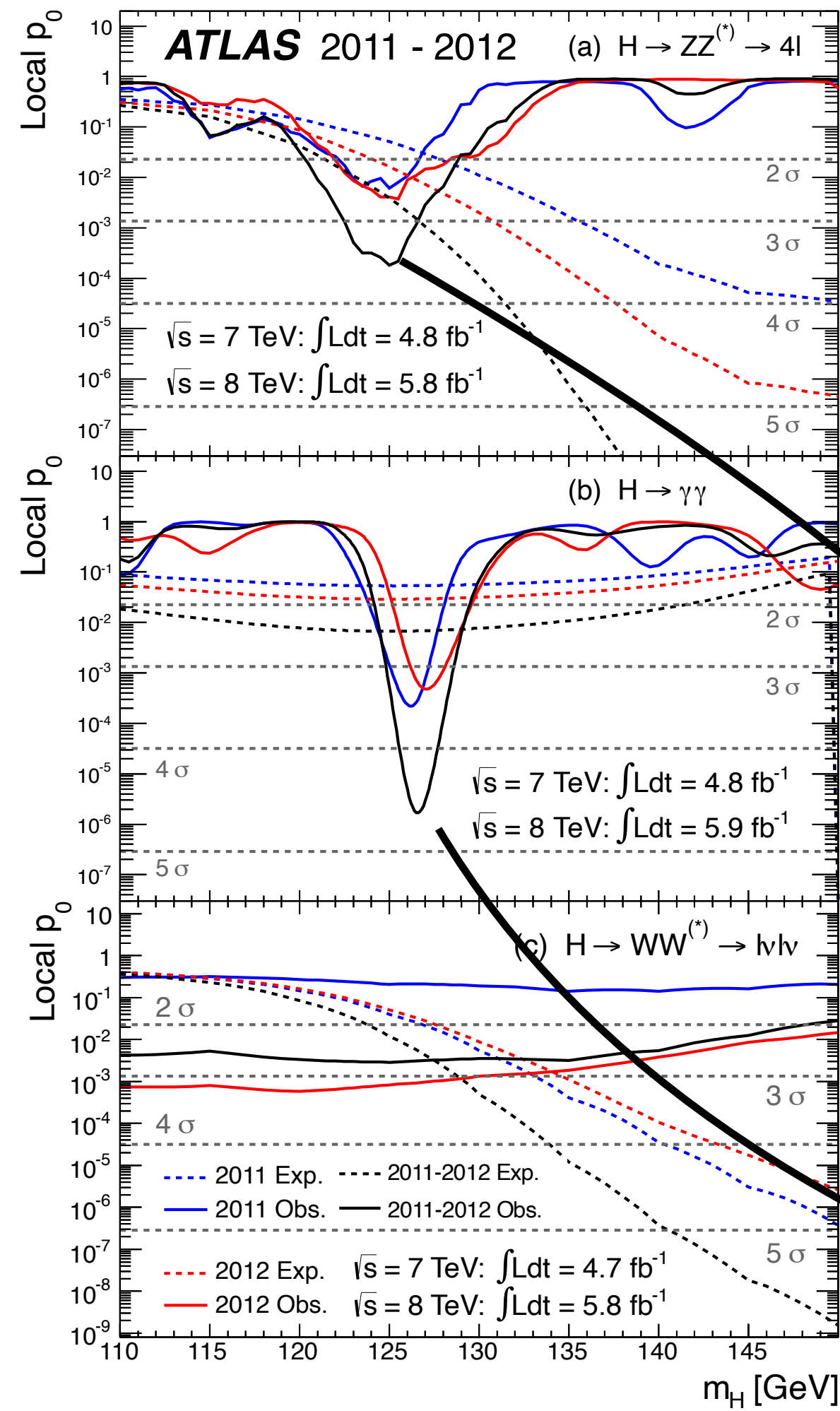
The Higgs boson discovery



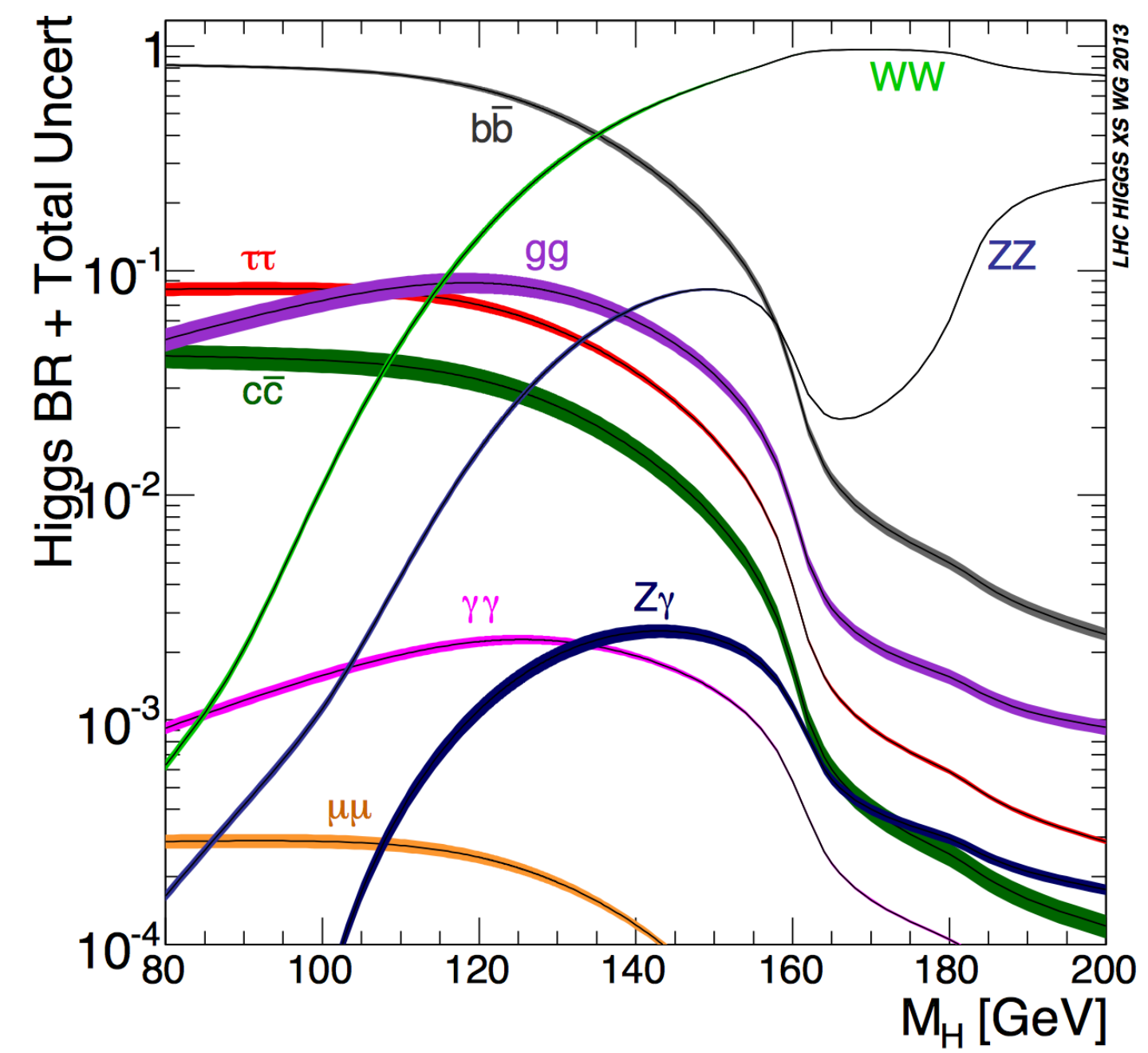
The Higgs boson discovery



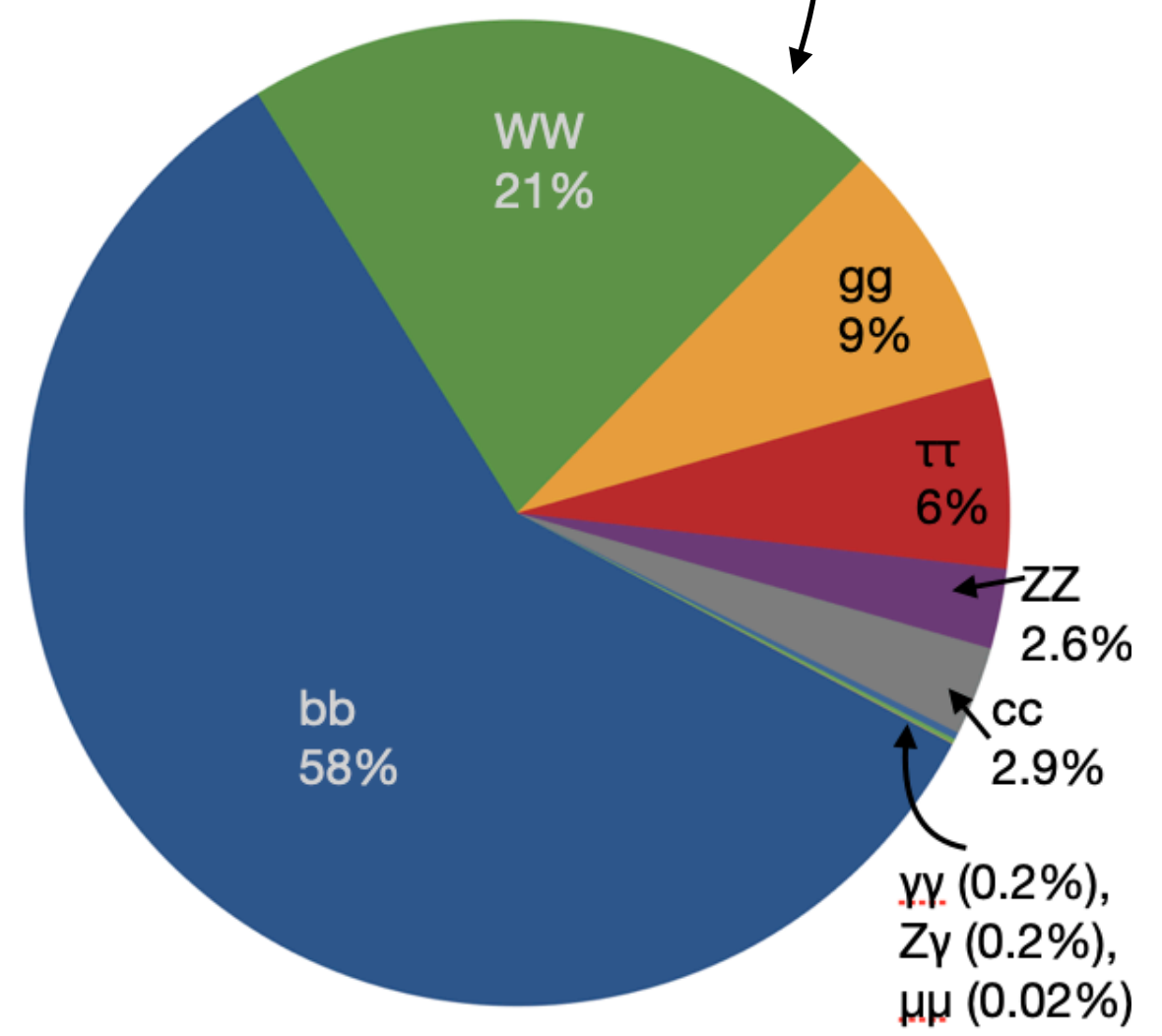
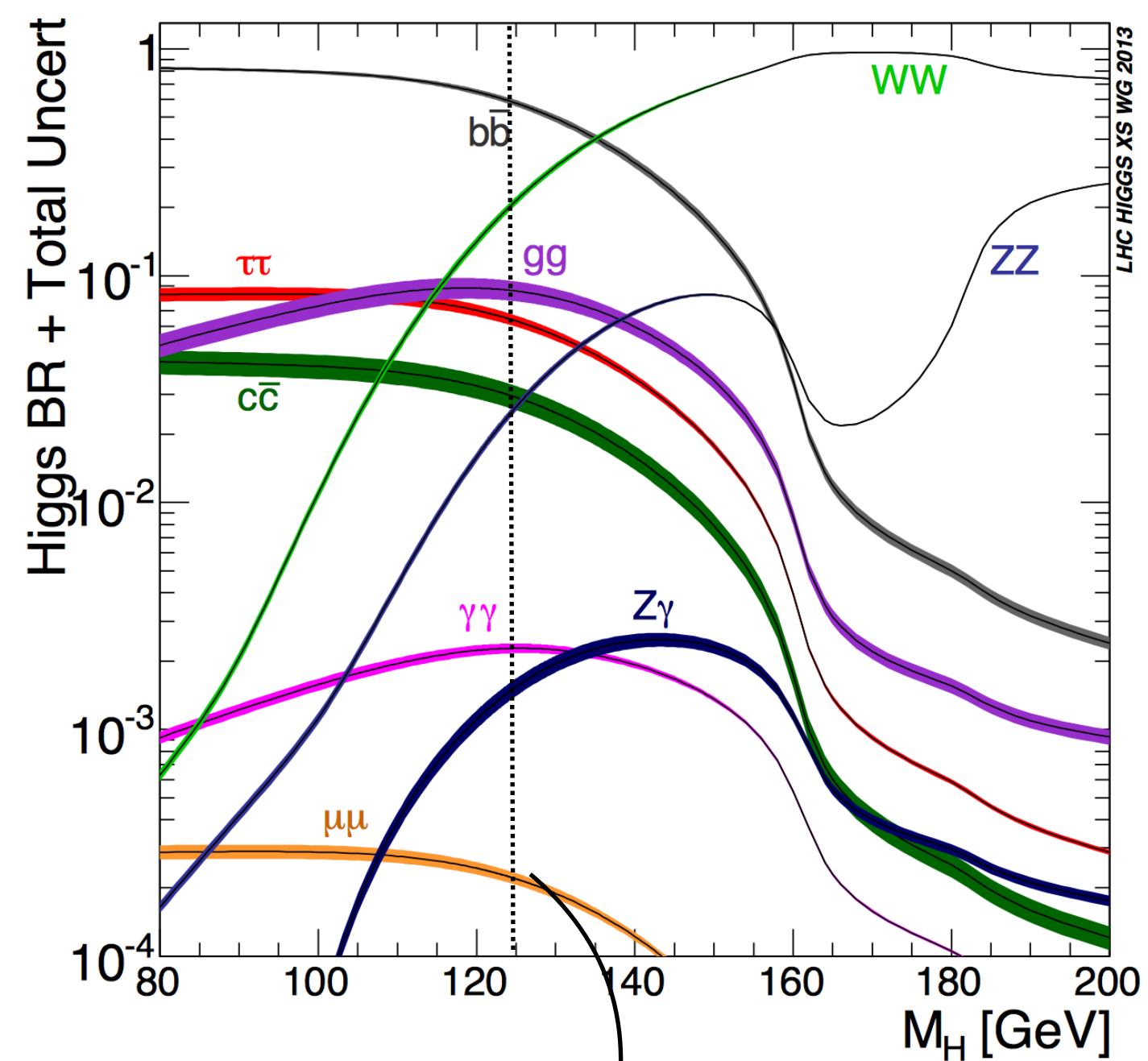
The Higgs boson discovery



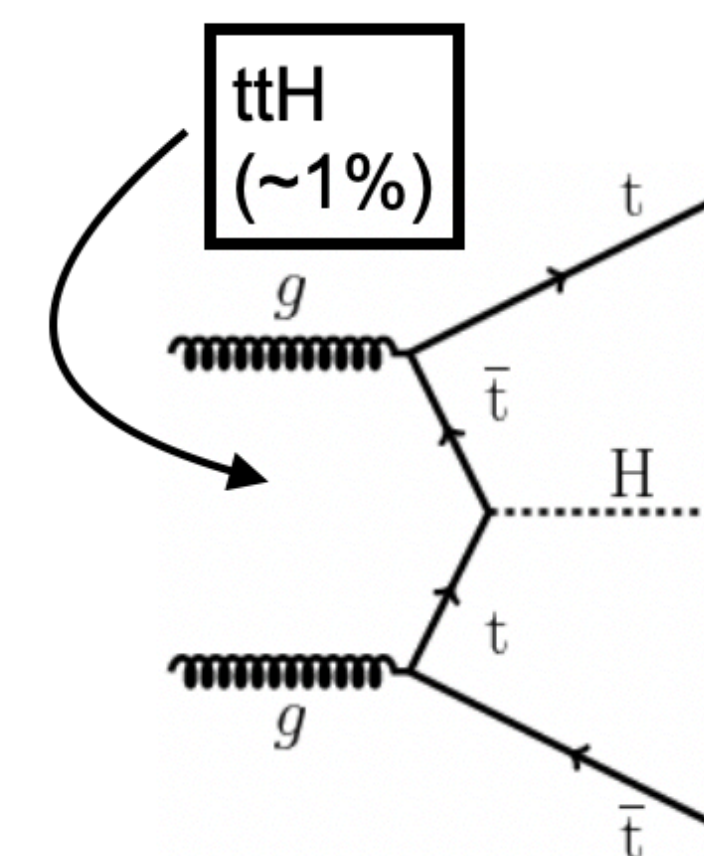
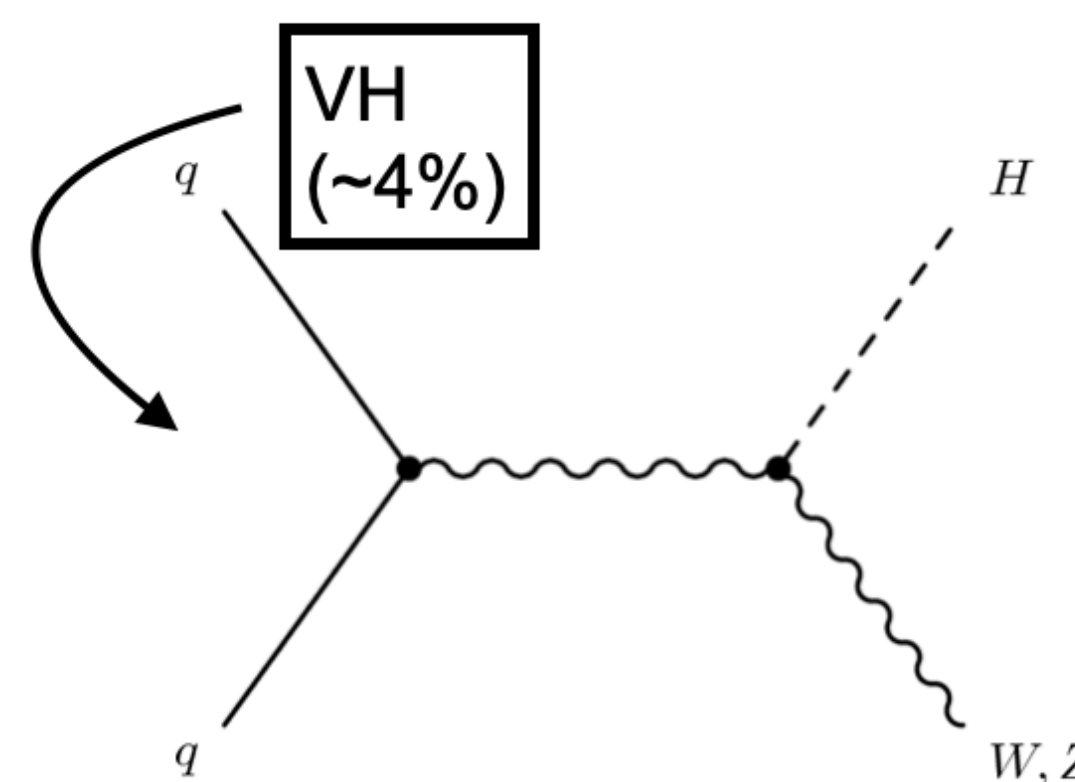
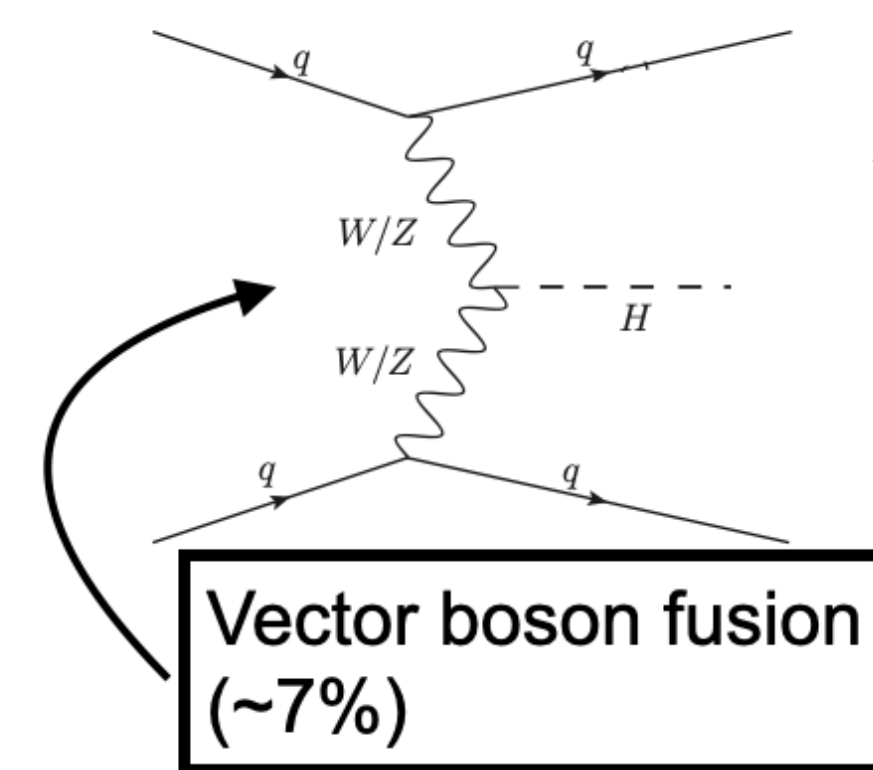
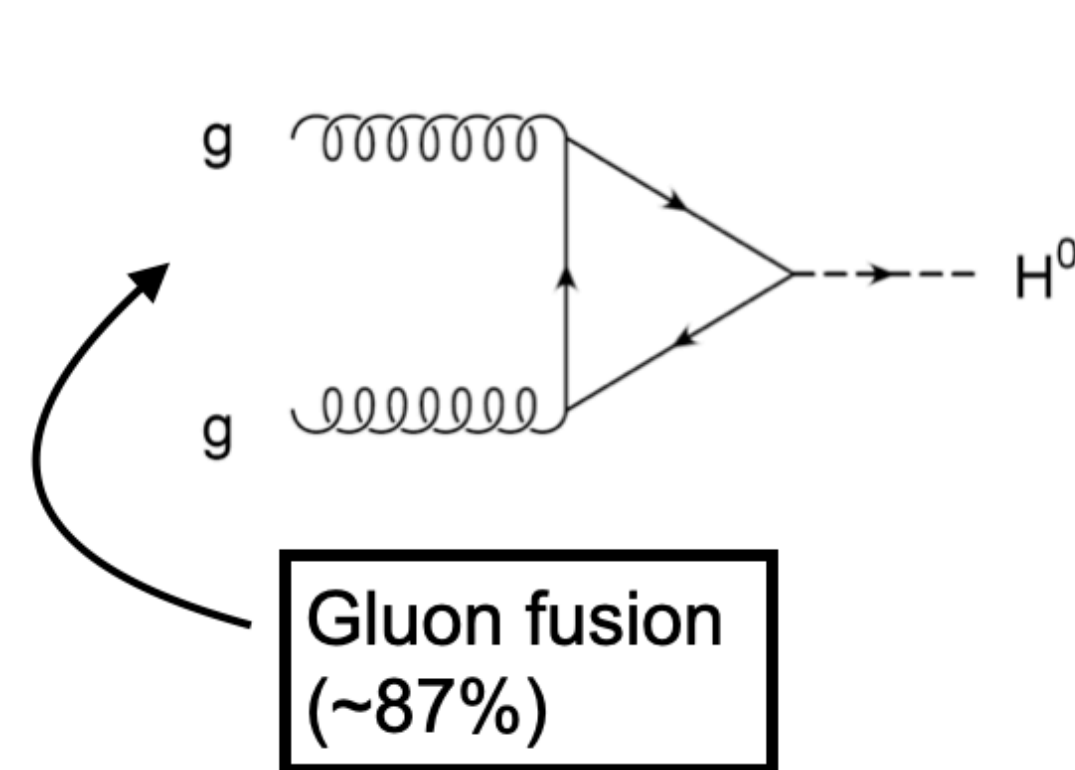
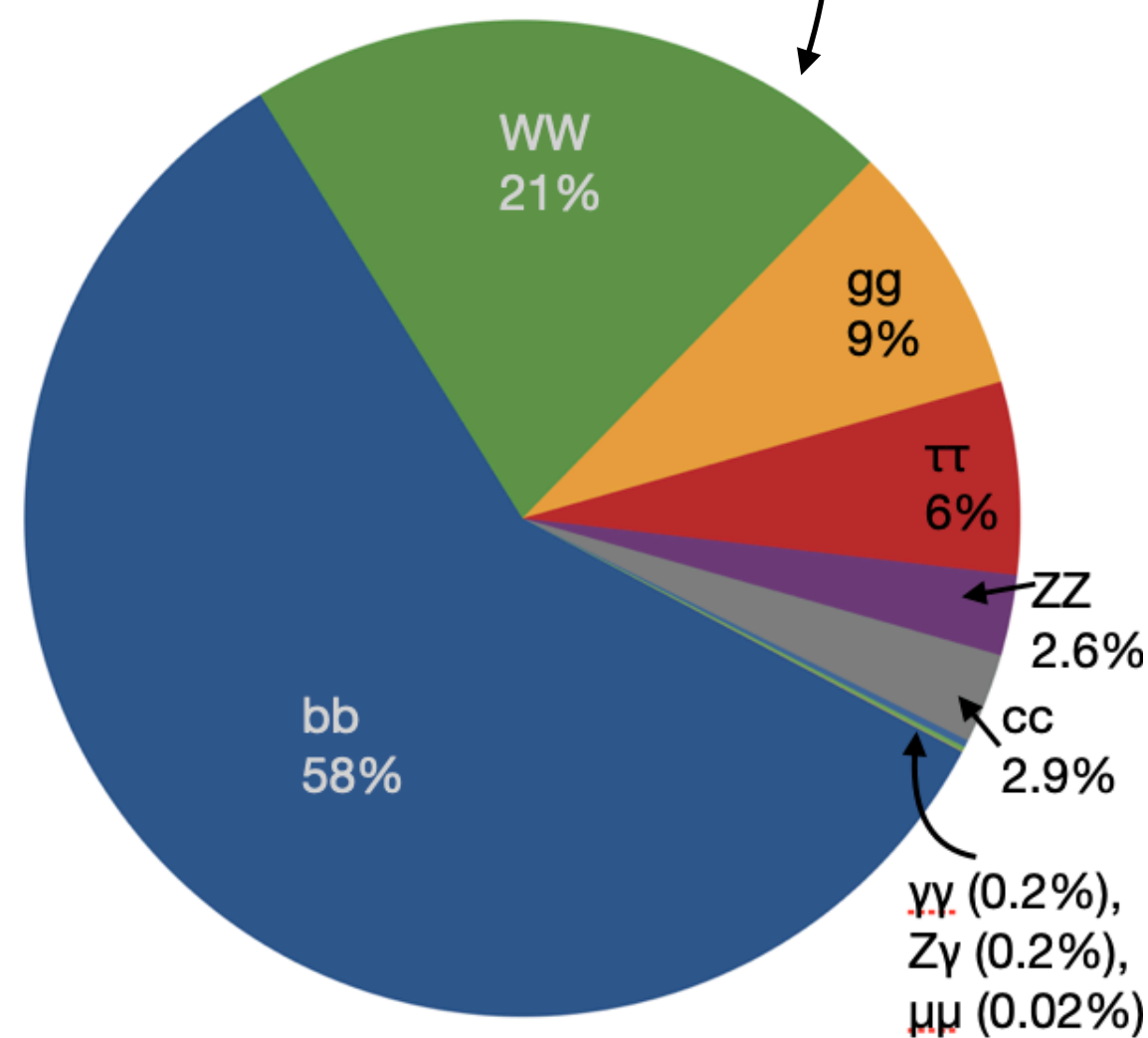
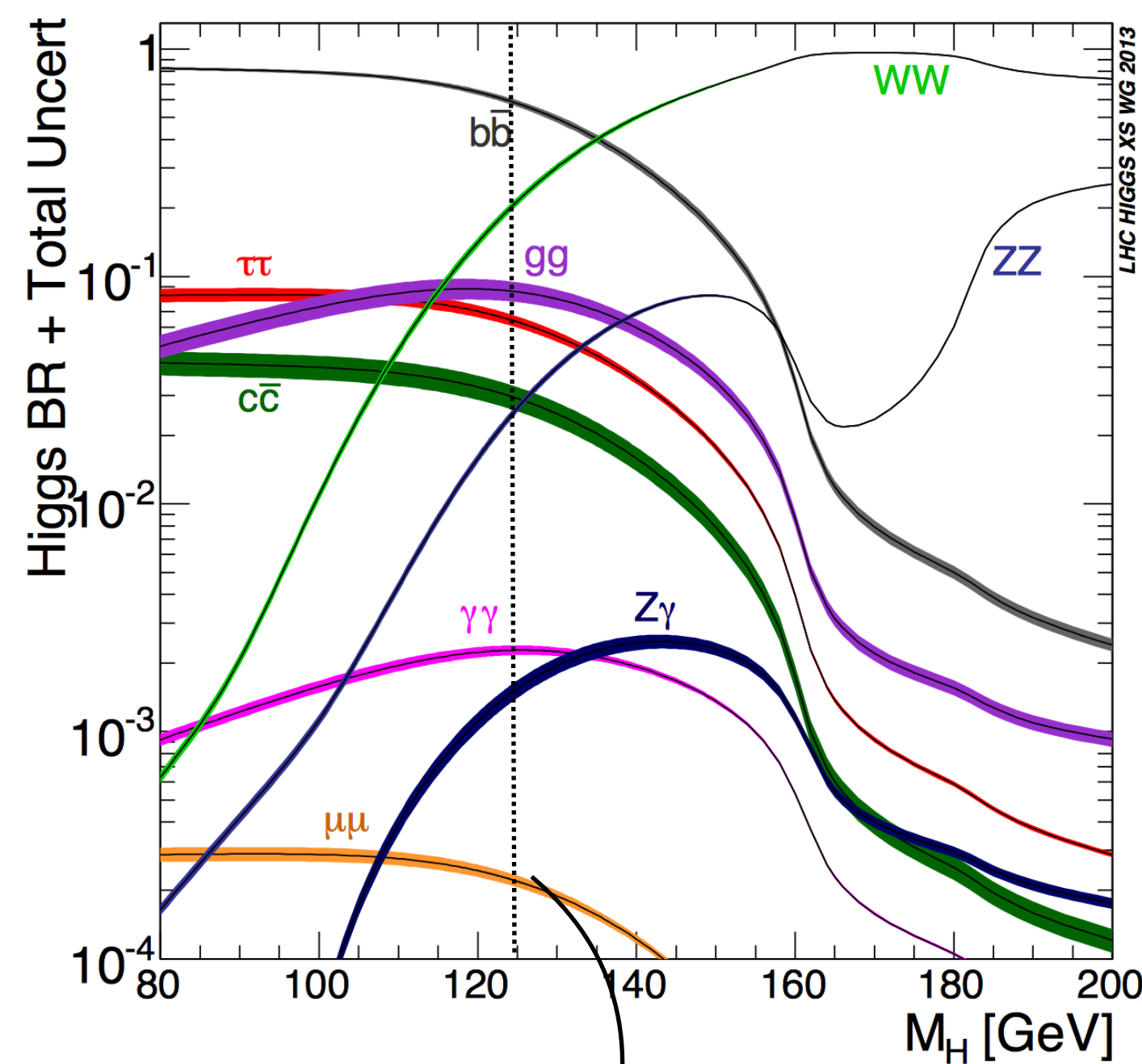
What we learnt about the Higgs boson in Run 1



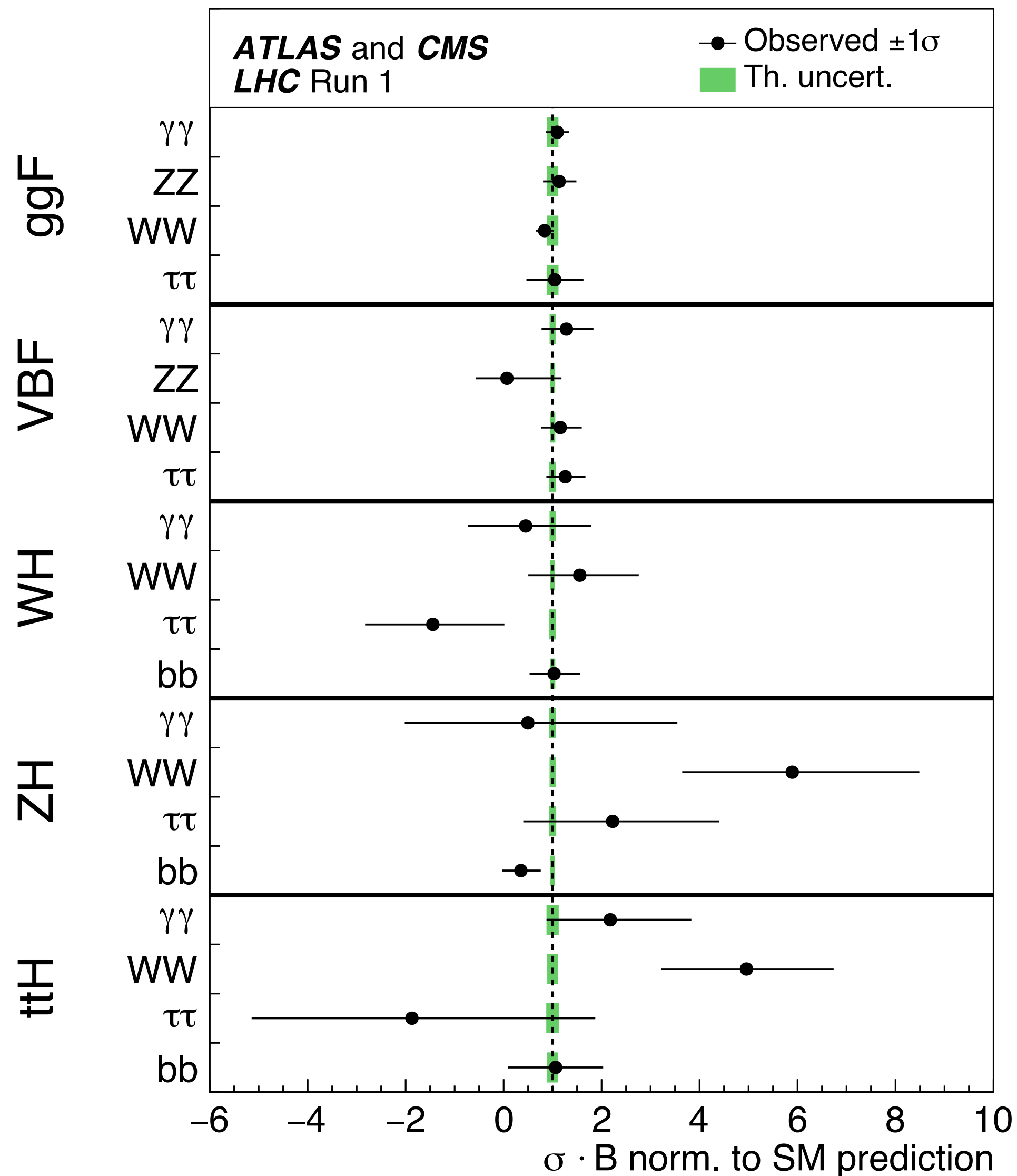
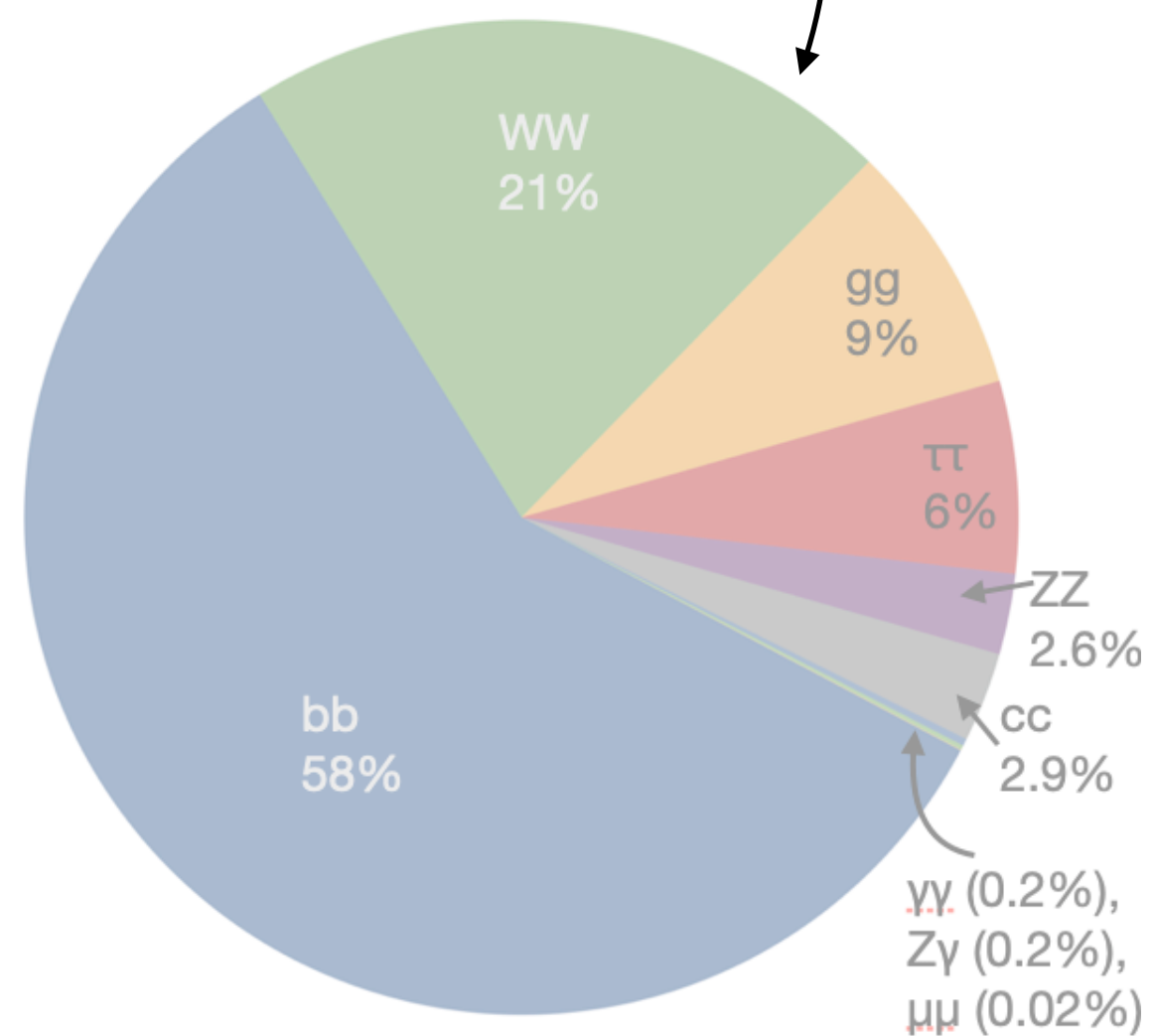
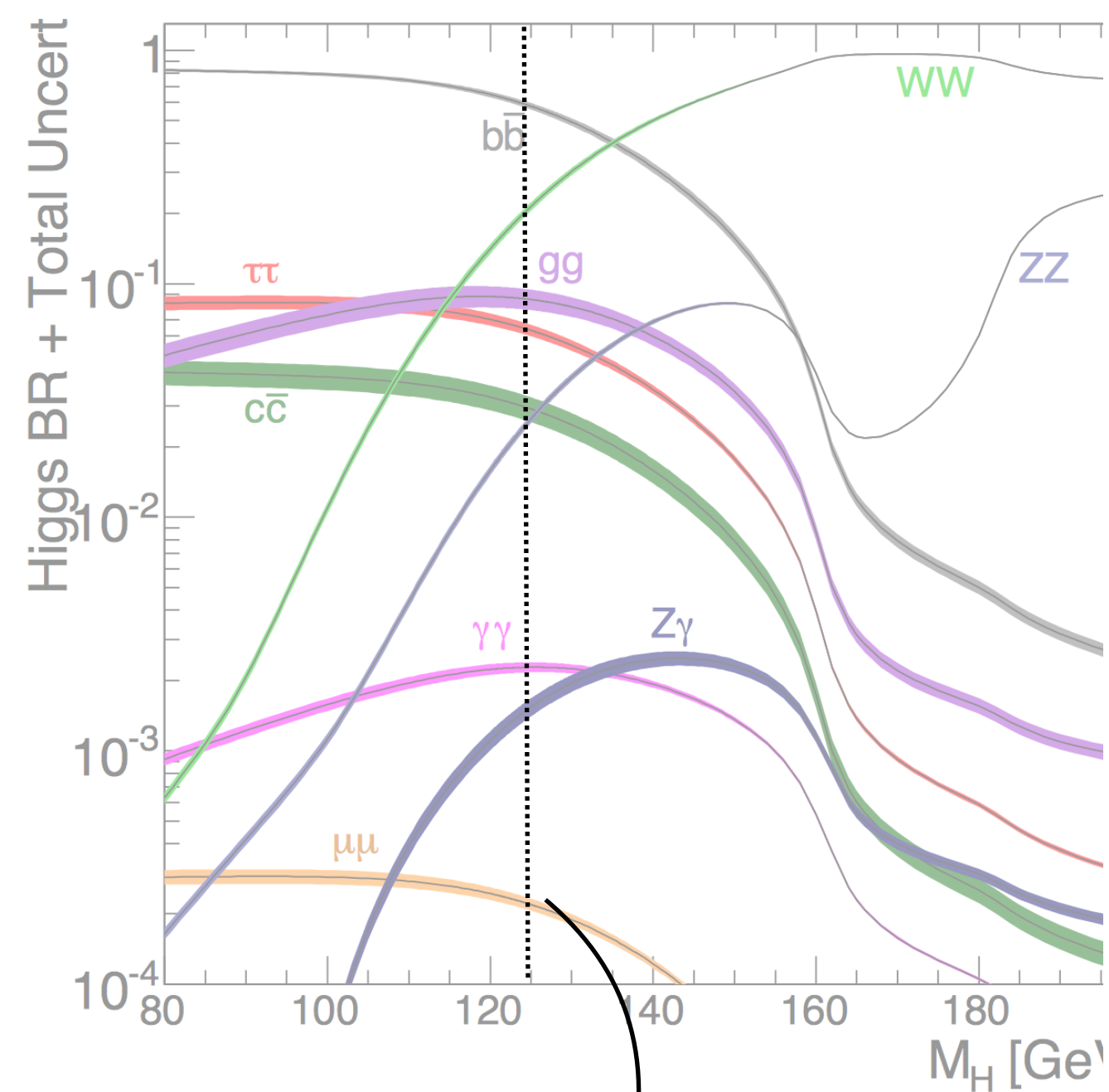
What we learnt about the Higgs boson in Run 1



What we learnt about the Higgs boson in Run 1

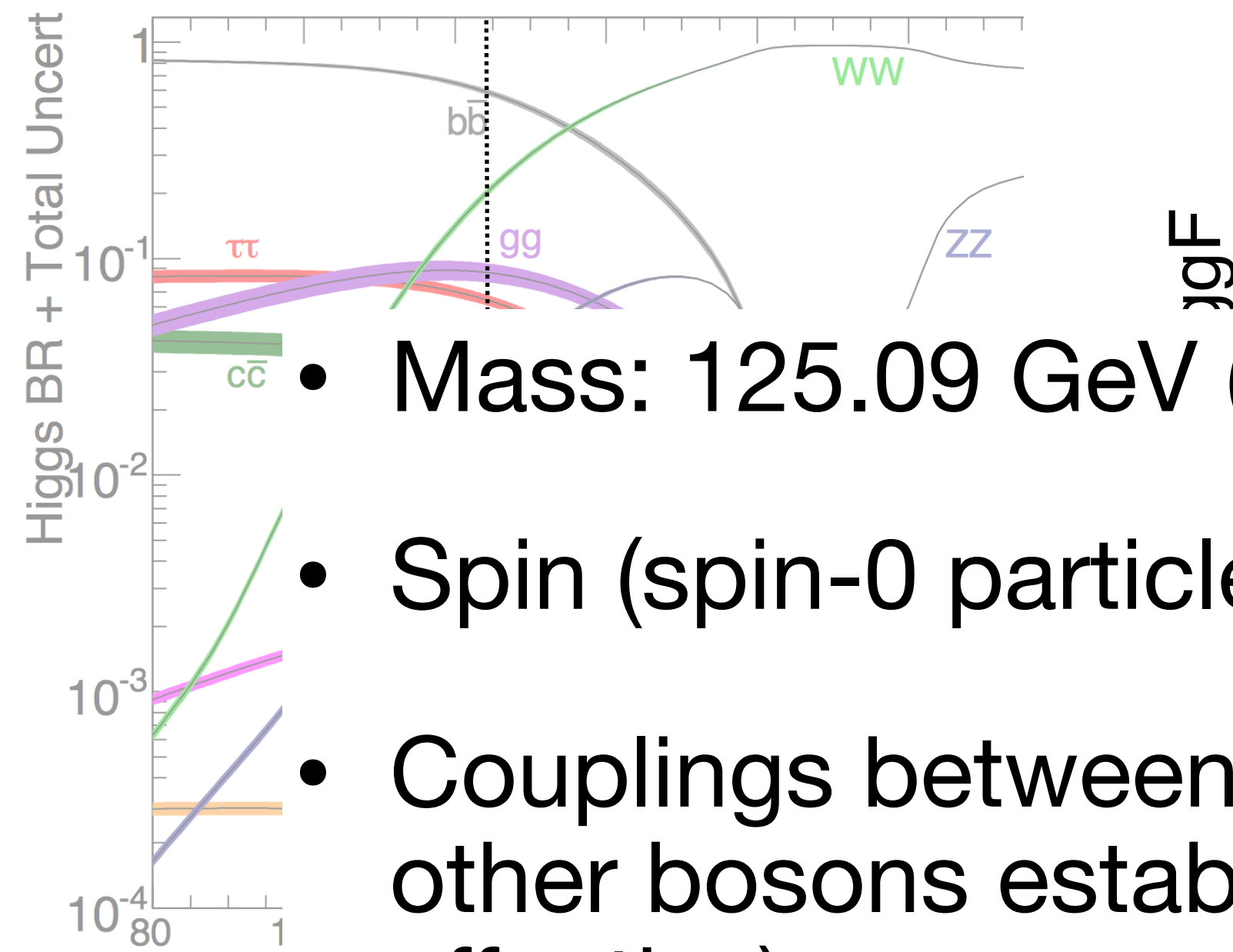


What we learnt about the Higgs boson in Run 1

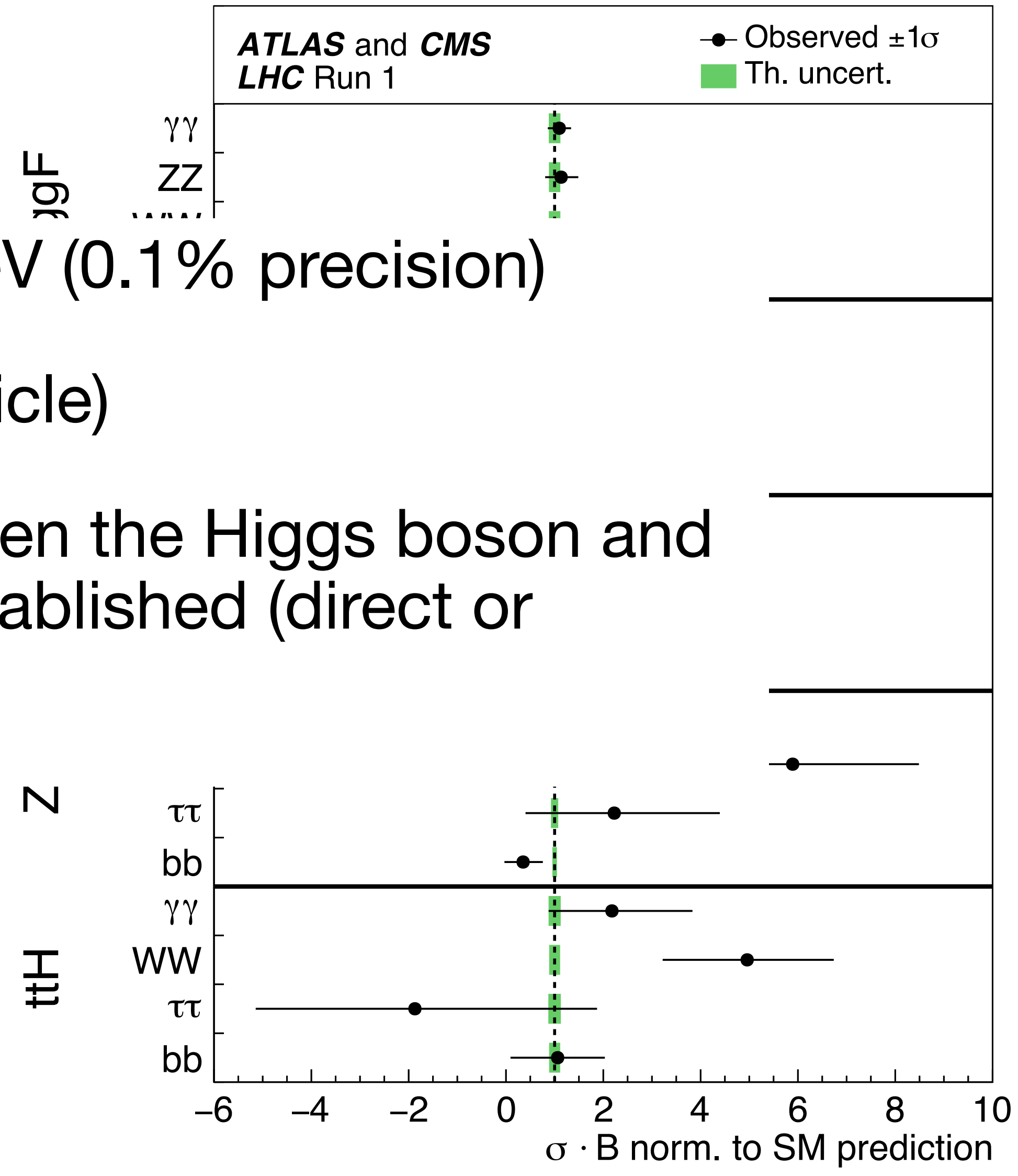
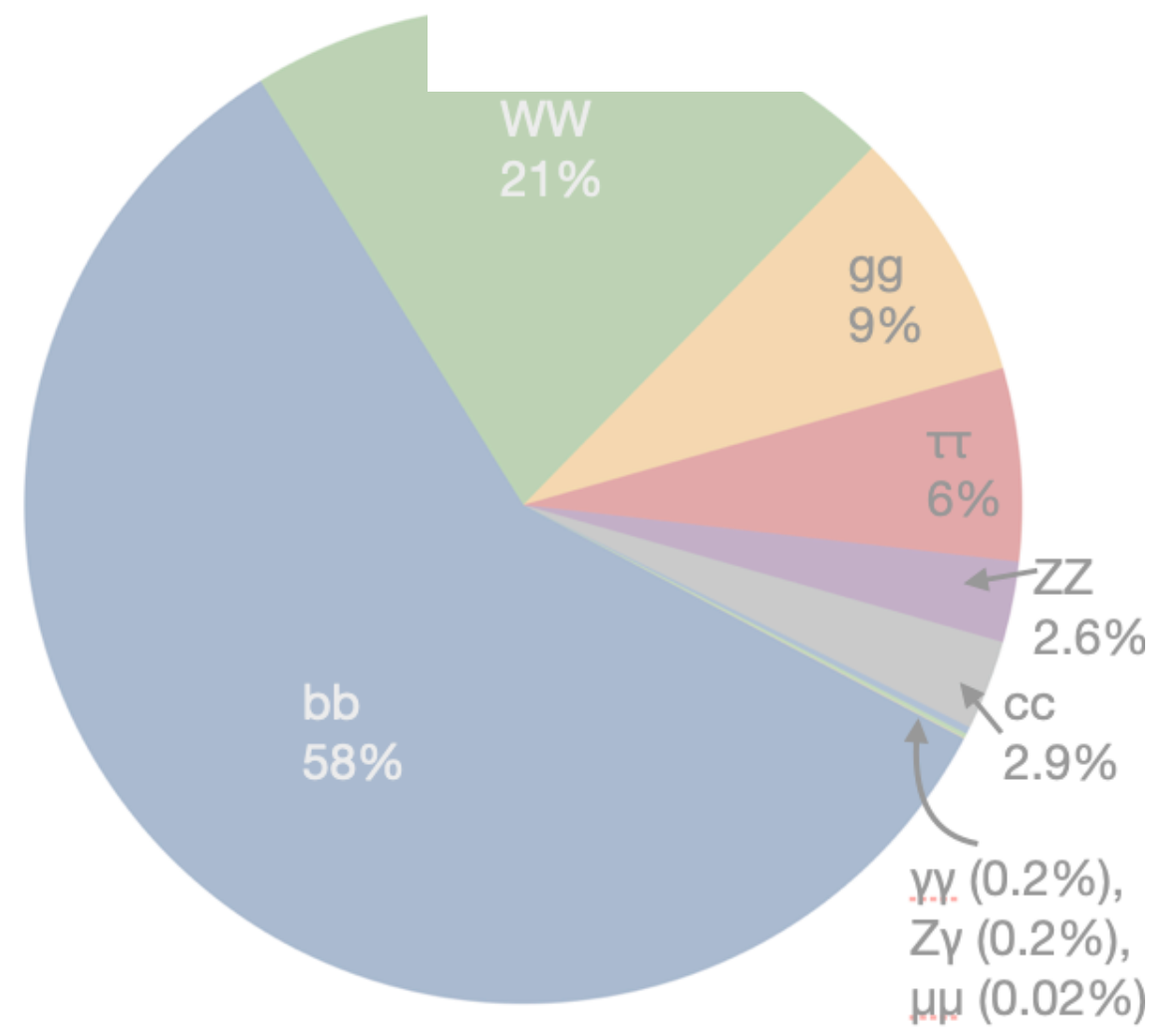


]

What we learnt about the Higgs boson in Run 1

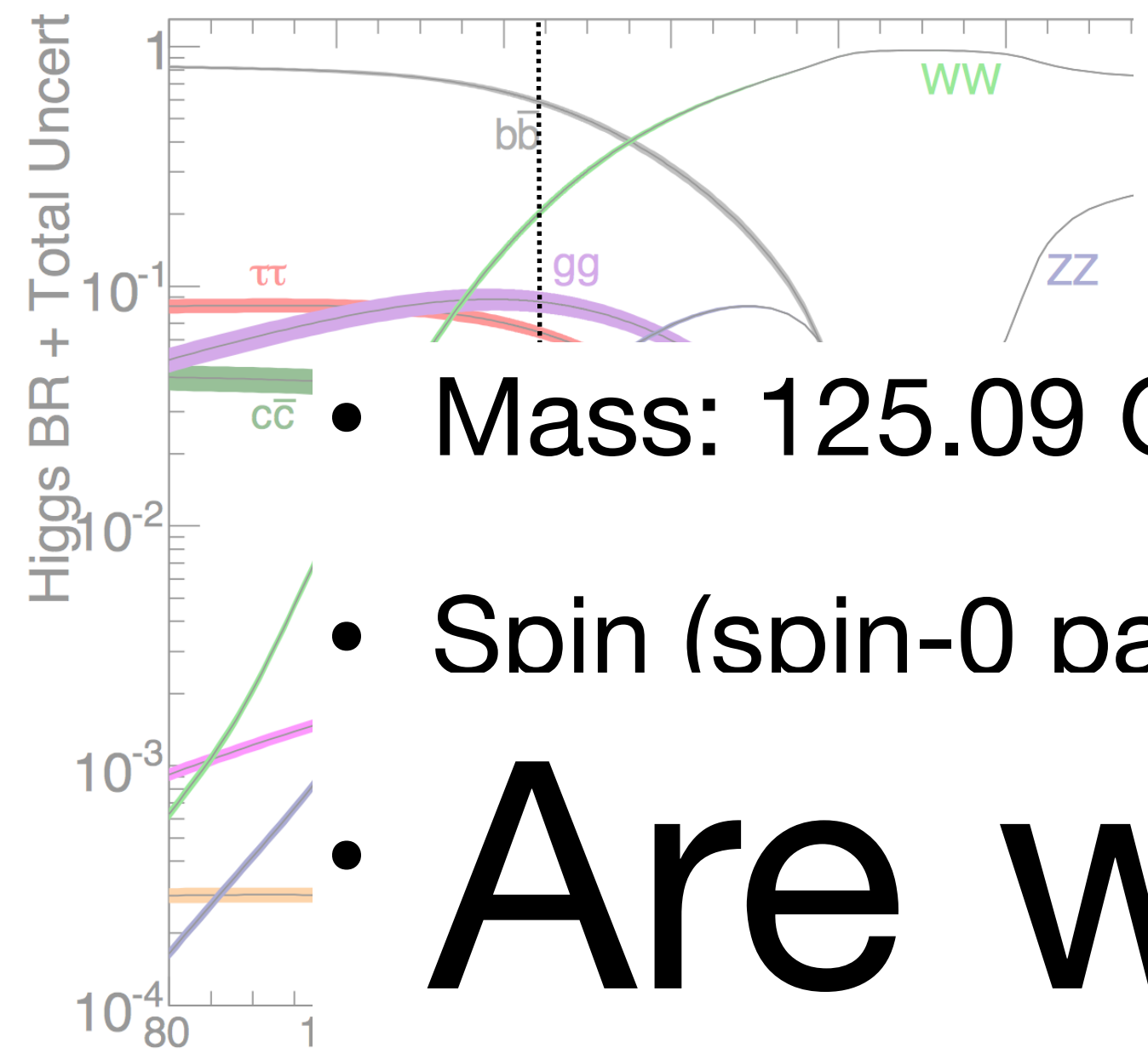


- Mass: 125.09 GeV (0.1% precision)
- Spin (spin-0 particle)
- Couplings between the Higgs boson and other bosons established (direct or effective)



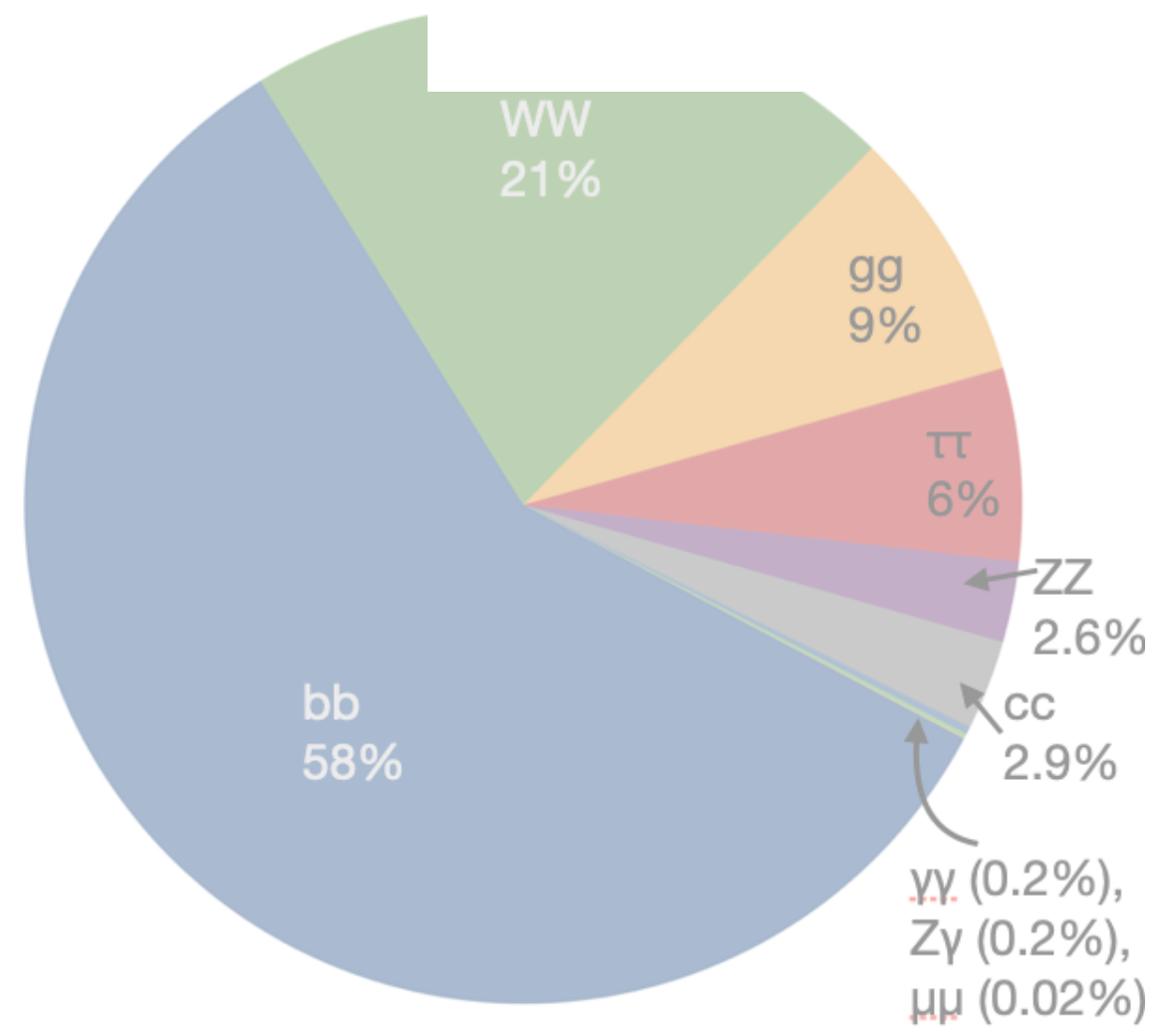
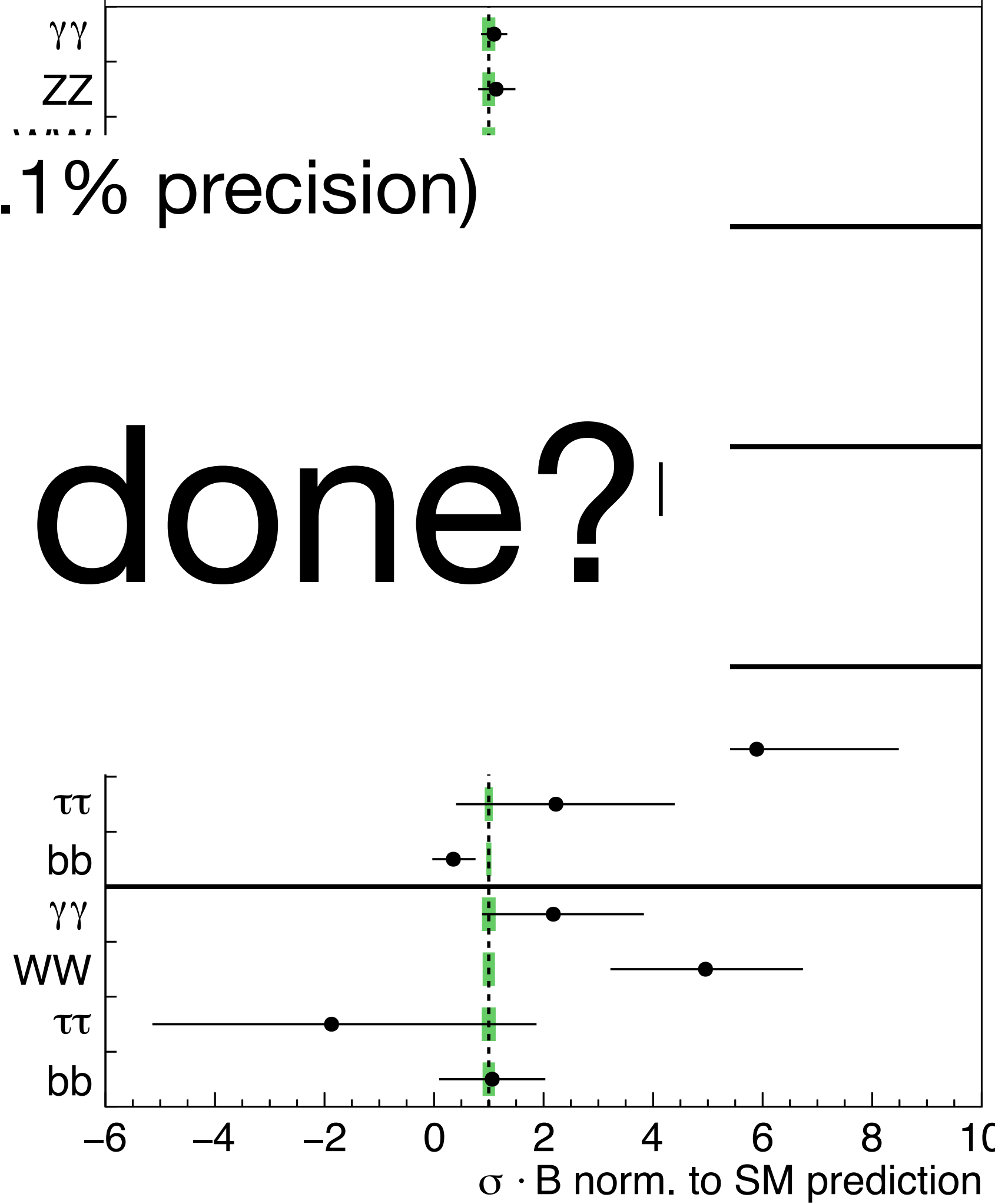
on

What we learnt about the Higgs boson in Run 1



- Mass: 125.09 GeV (0.1% precision)
- Spin (spin-0 particle)
- Are we done?

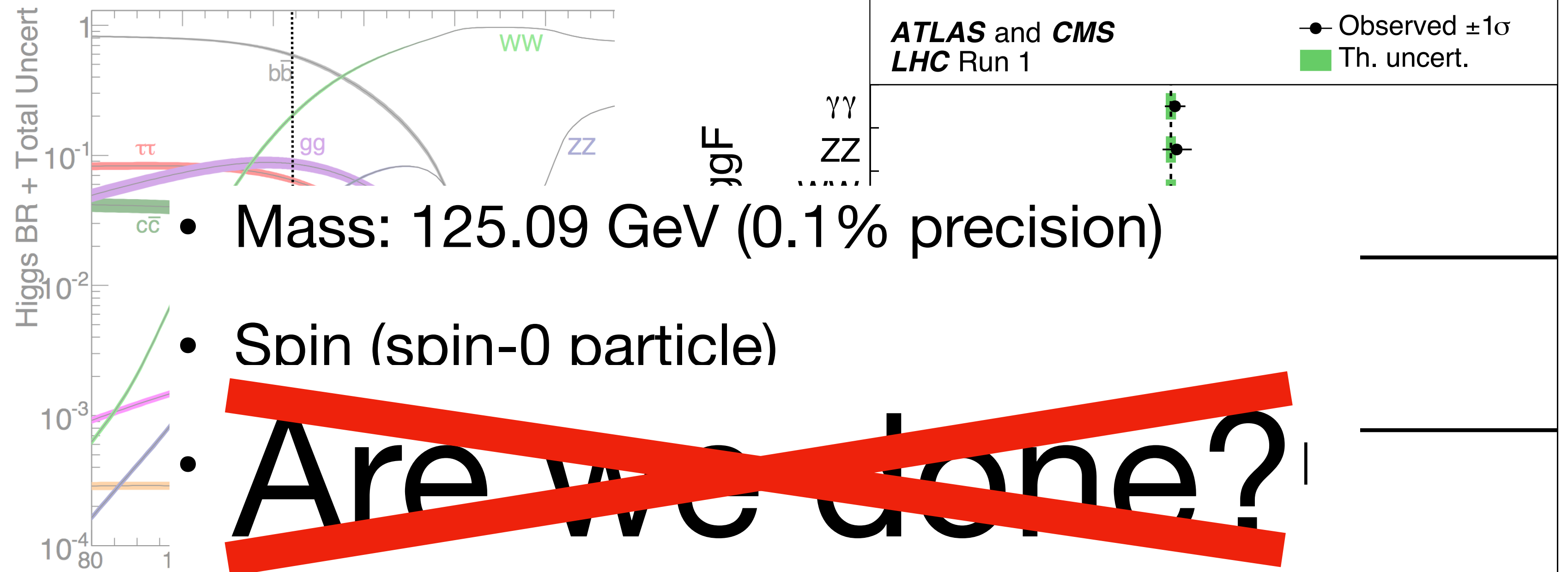
ATLAS and CMS LHC Run 1



ttH

on

What we learnt about the Higgs boson in Run 1

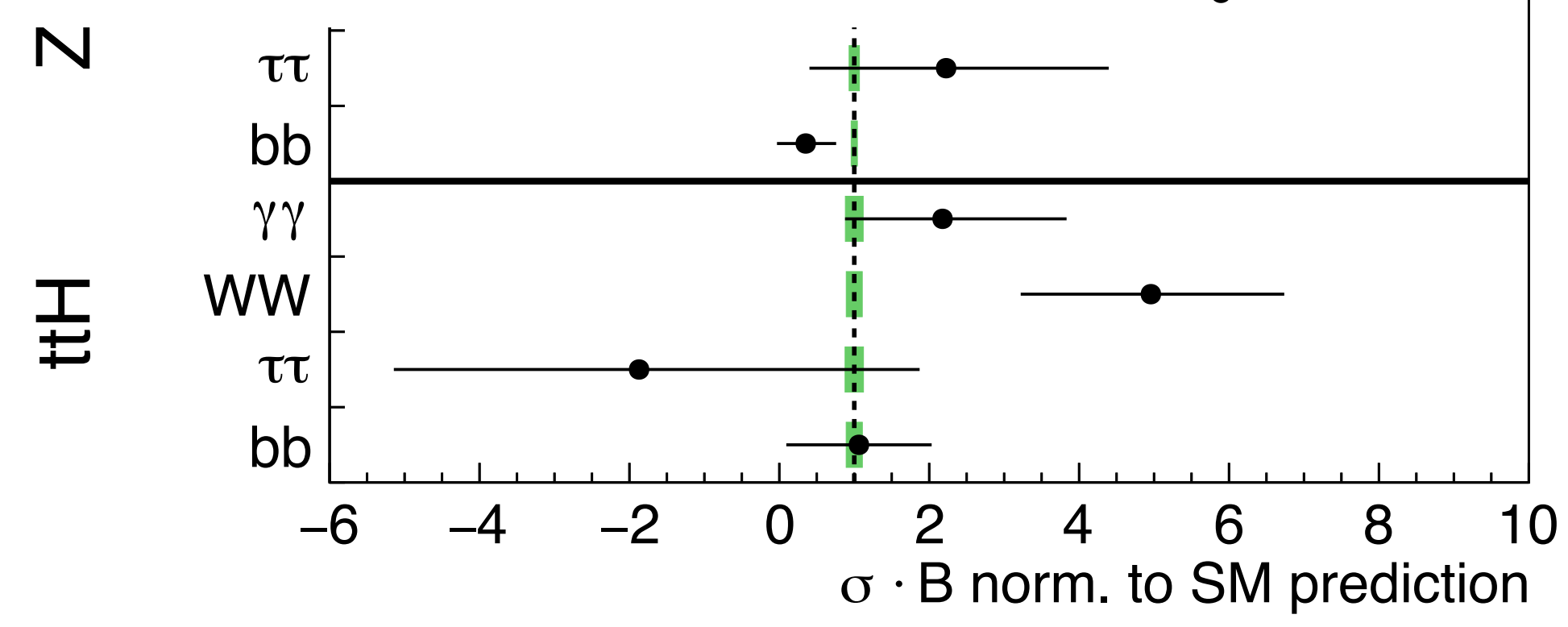
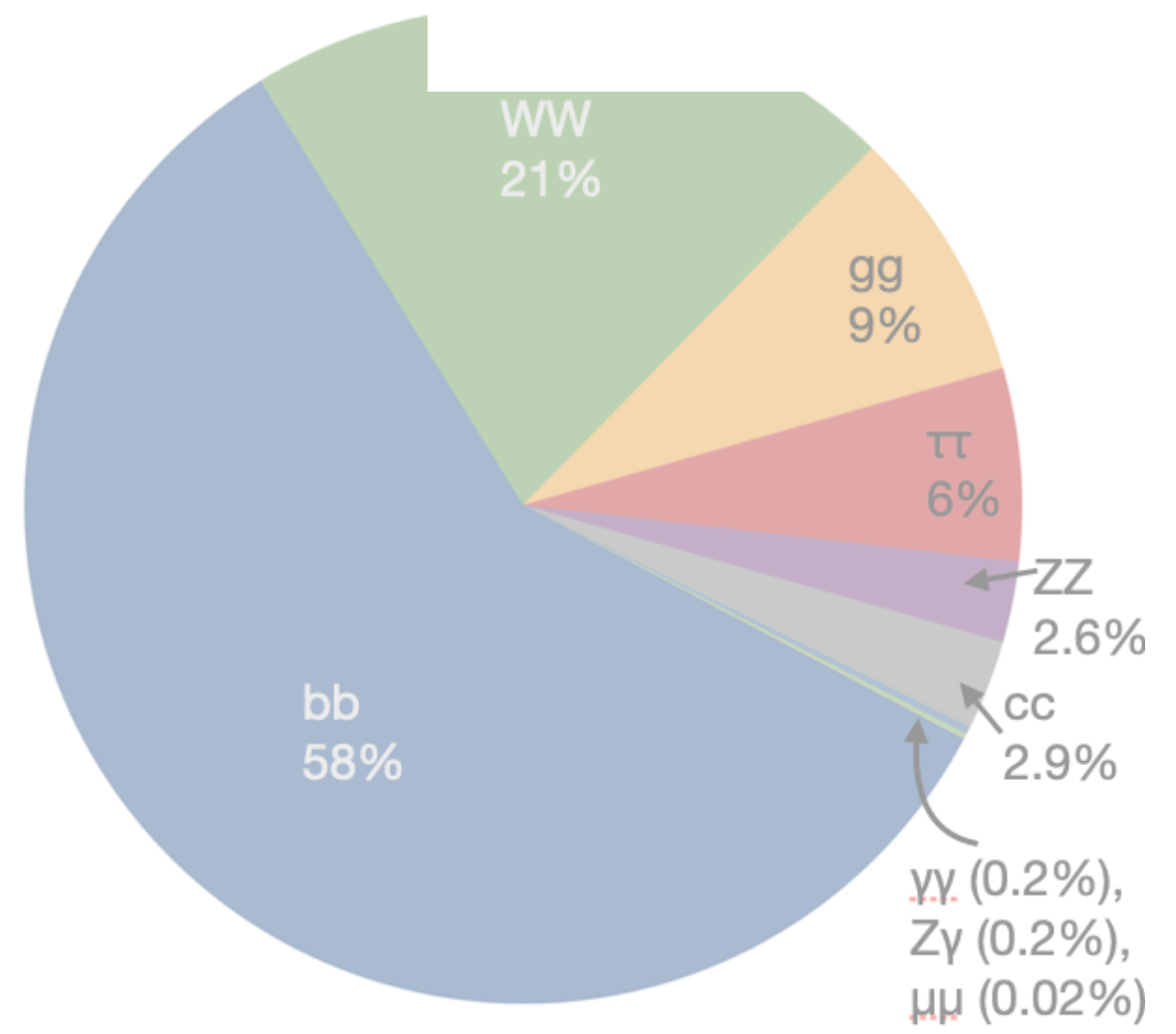


- Mass: 125.09 GeV (0.1% precision)

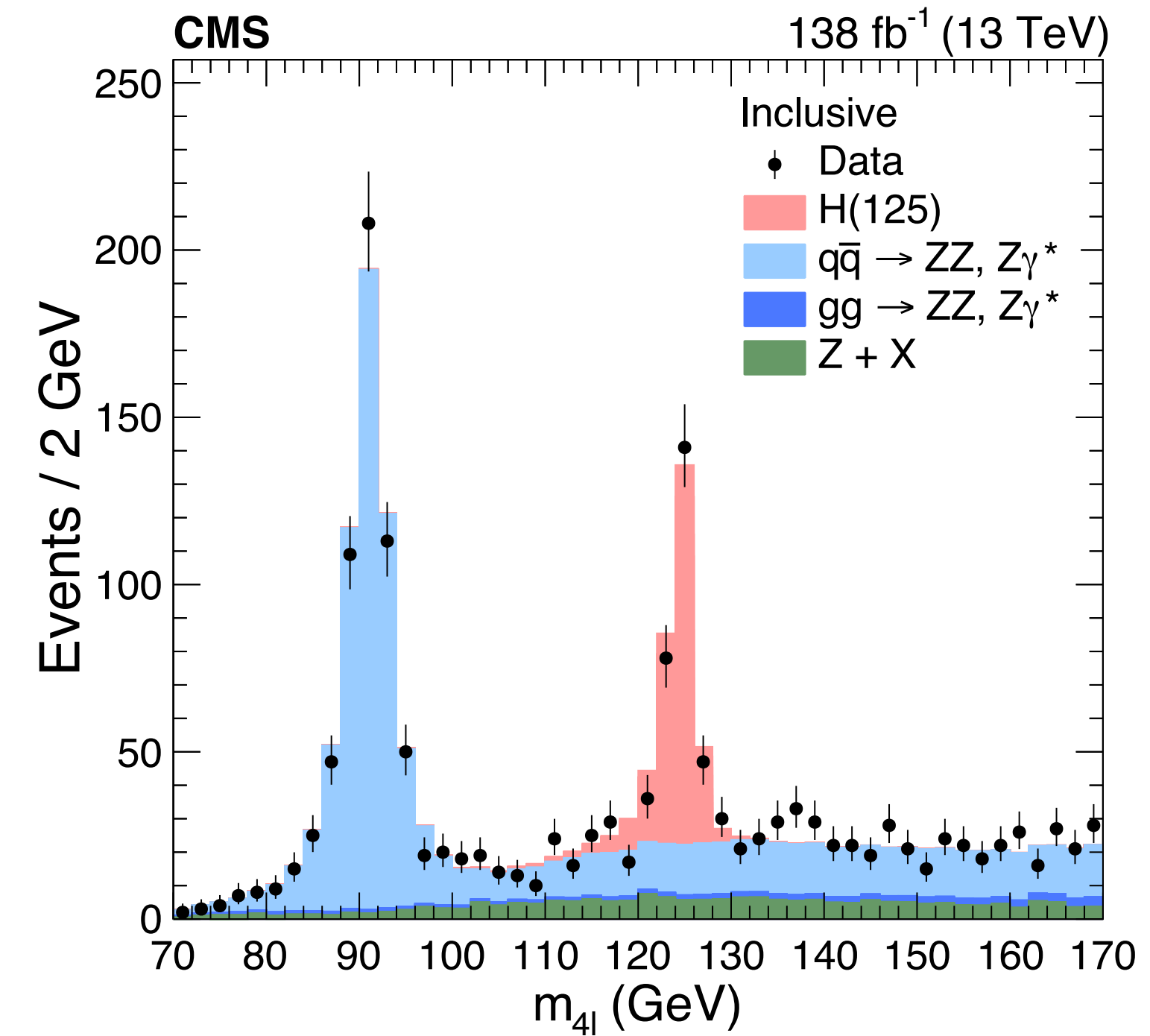
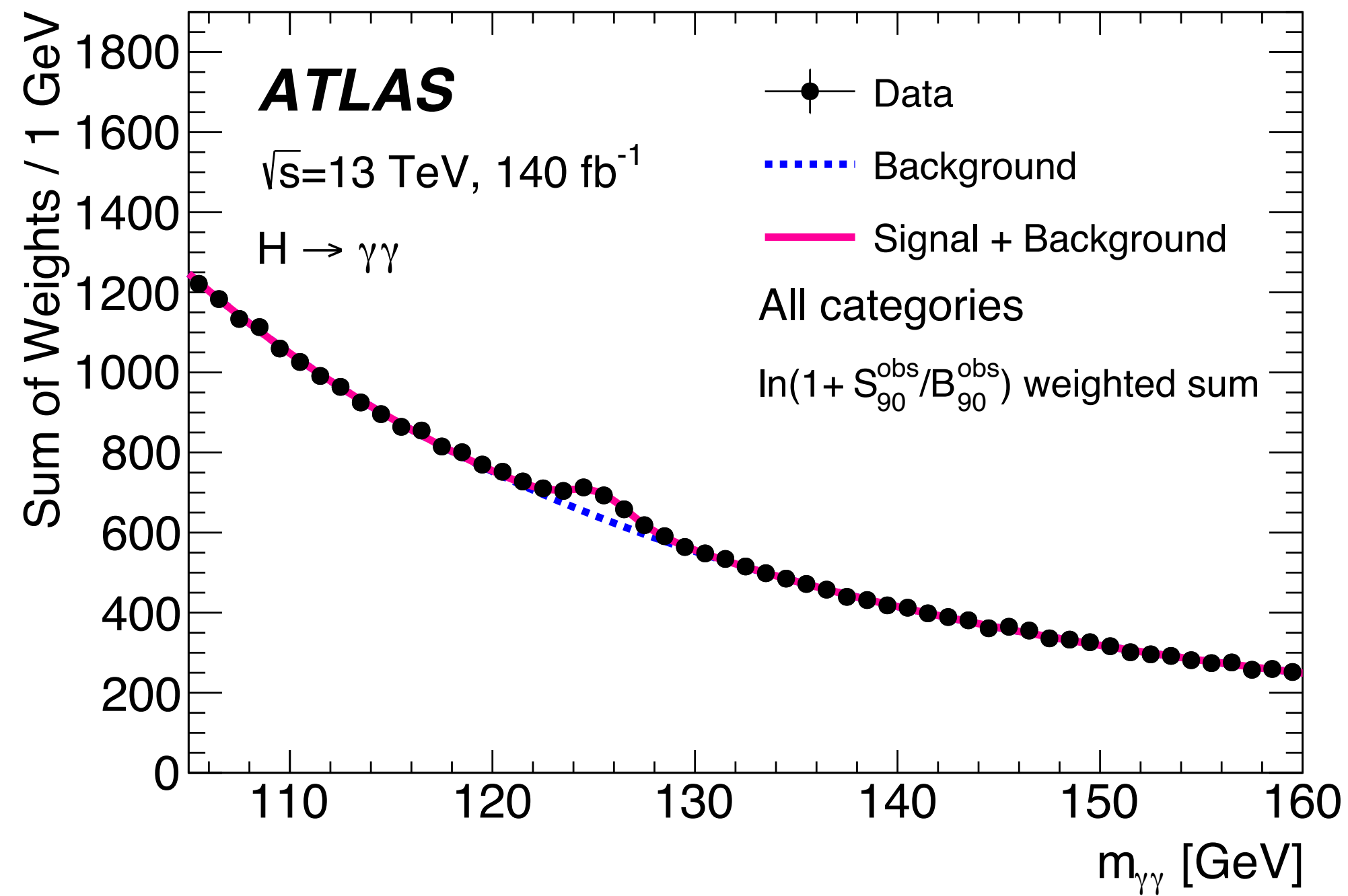
- Spin (spin-0 particle)

~~Are we done?~~

effective)



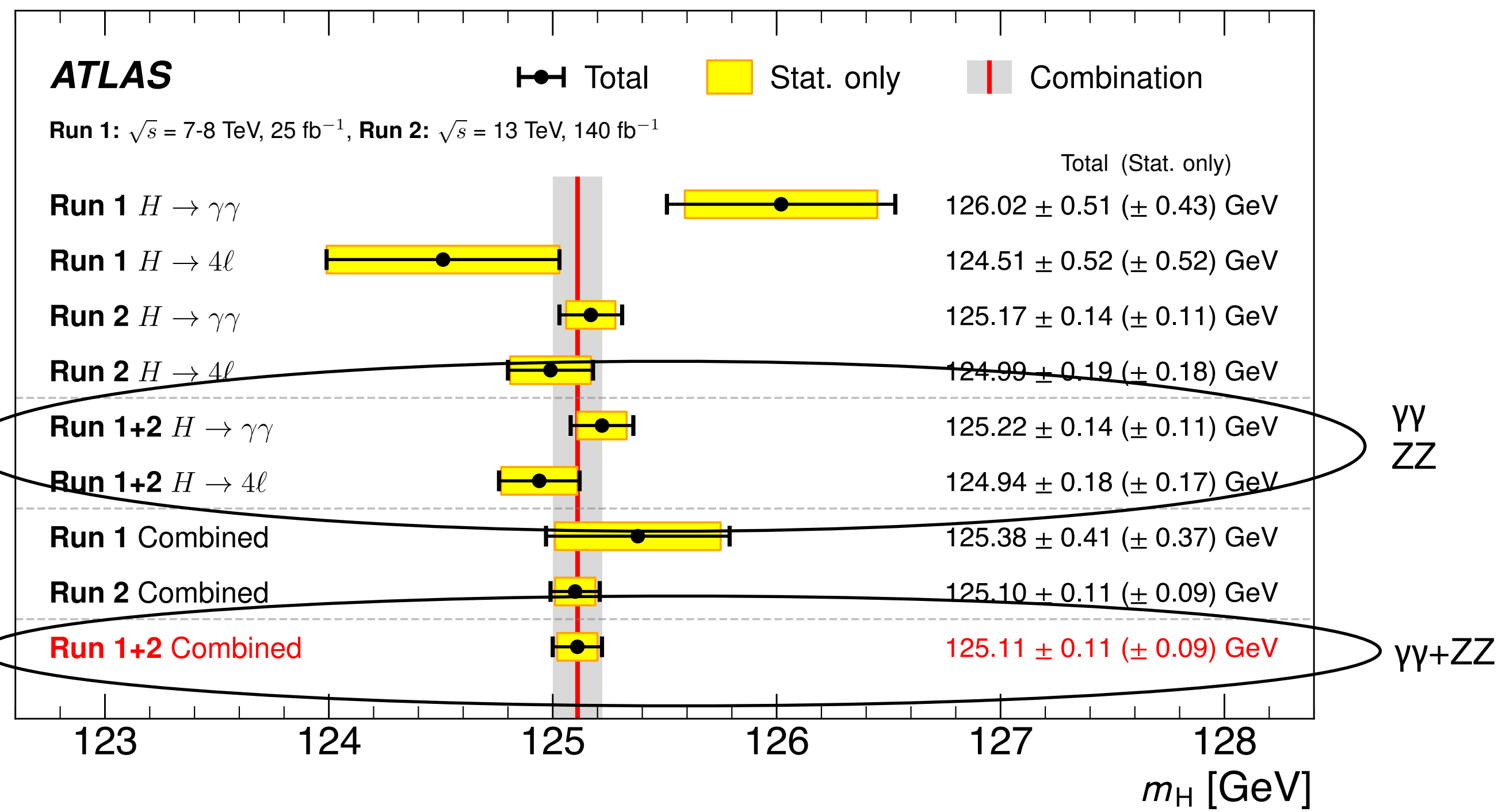
Higgs boson mass measurements



Mass measurements performed in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ channels: good experimental resolution; small backgrounds (ZZ)

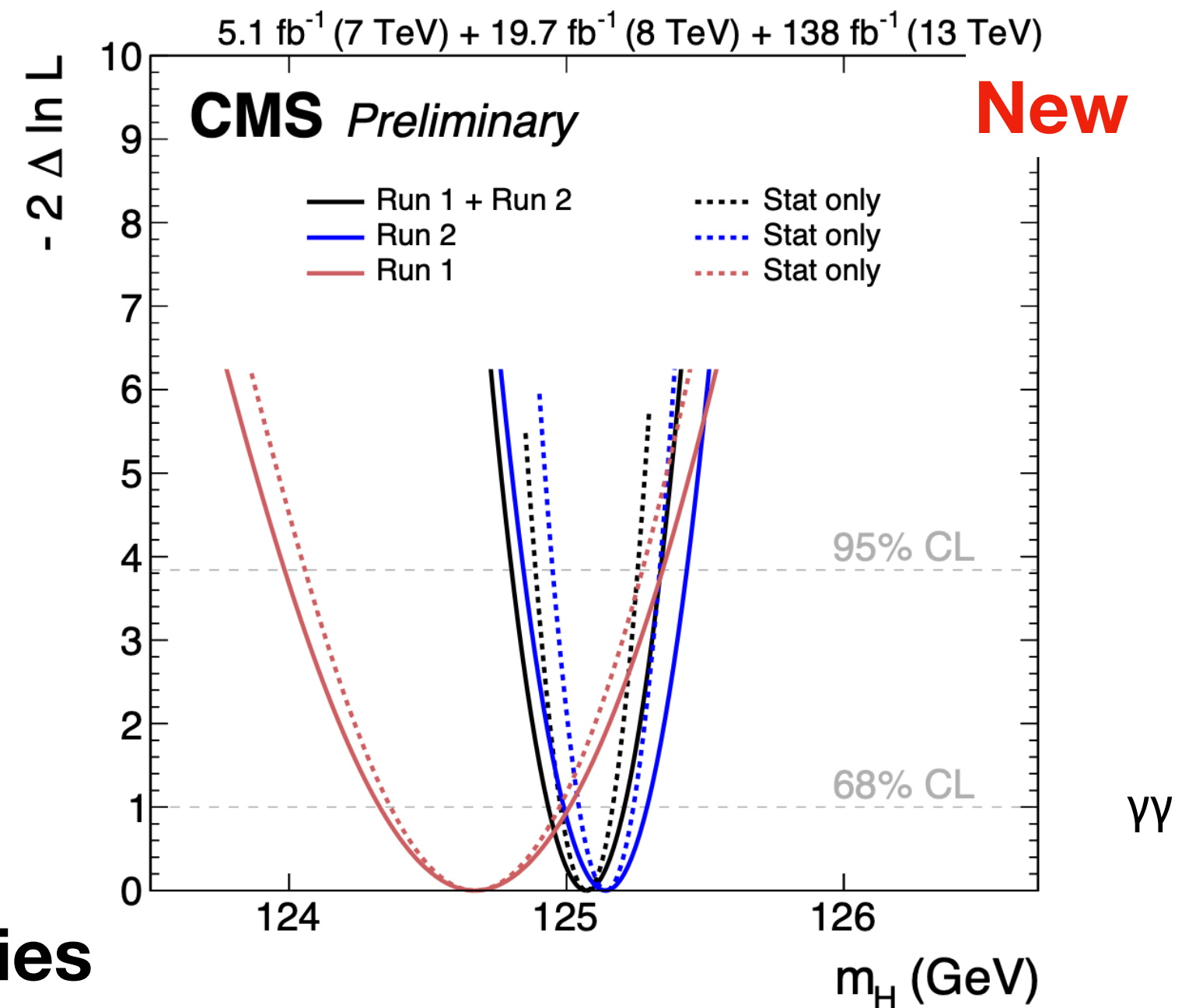
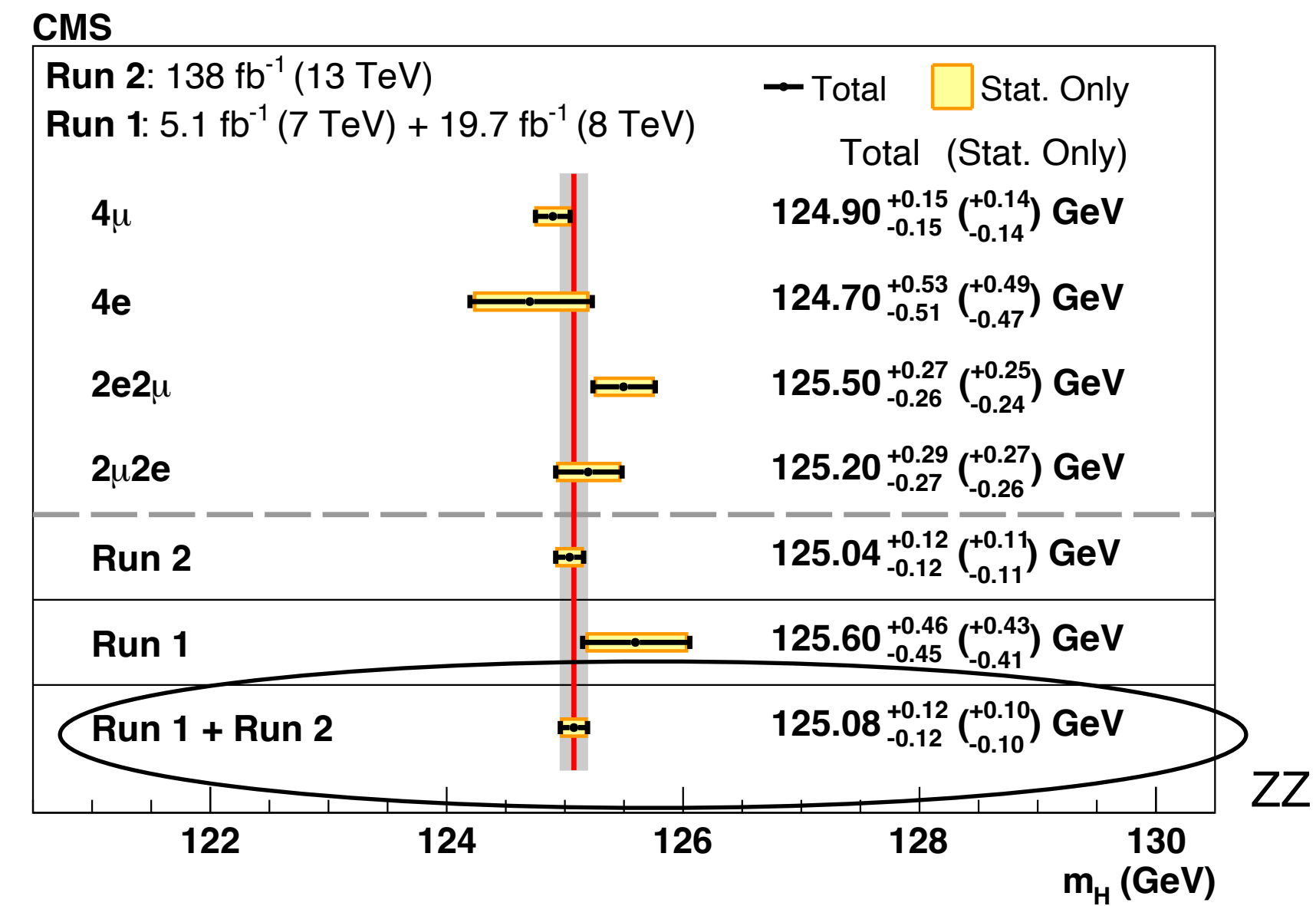
Higgs boson mass measurements

Phys. Rev. Lett. 131 (2023) 251802



ATLAS measurement of m_H combining $\gamma\gamma$, 4ℓ :
 $m_H = 125.11 \pm 0.11$ (0.09 stat; 0.06 syst)
 4x improvement in precision compared with Run 1

CMS measurement of m_H separately in $\gamma\gamma$, 4ℓ :
 ZZ: $m_H = 125.08 \pm 0.12$ (0.10 stat; 0.06 syst)
 $\gamma\gamma$: $m_H = 125.07 \pm 0.13$ (0.09 stat; 0.10 syst)

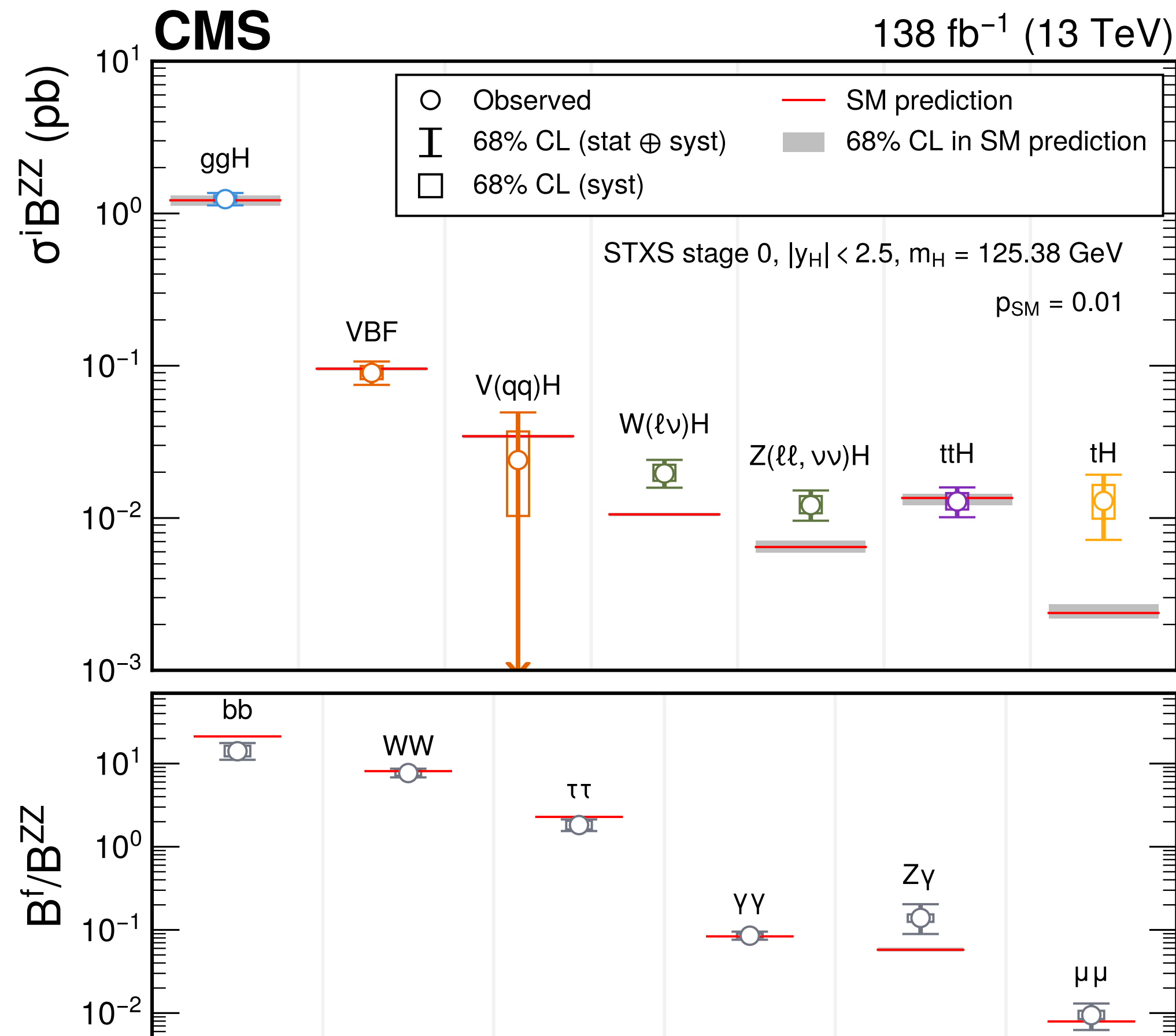


Mass measurements will soon become limited by systematic uncertainties

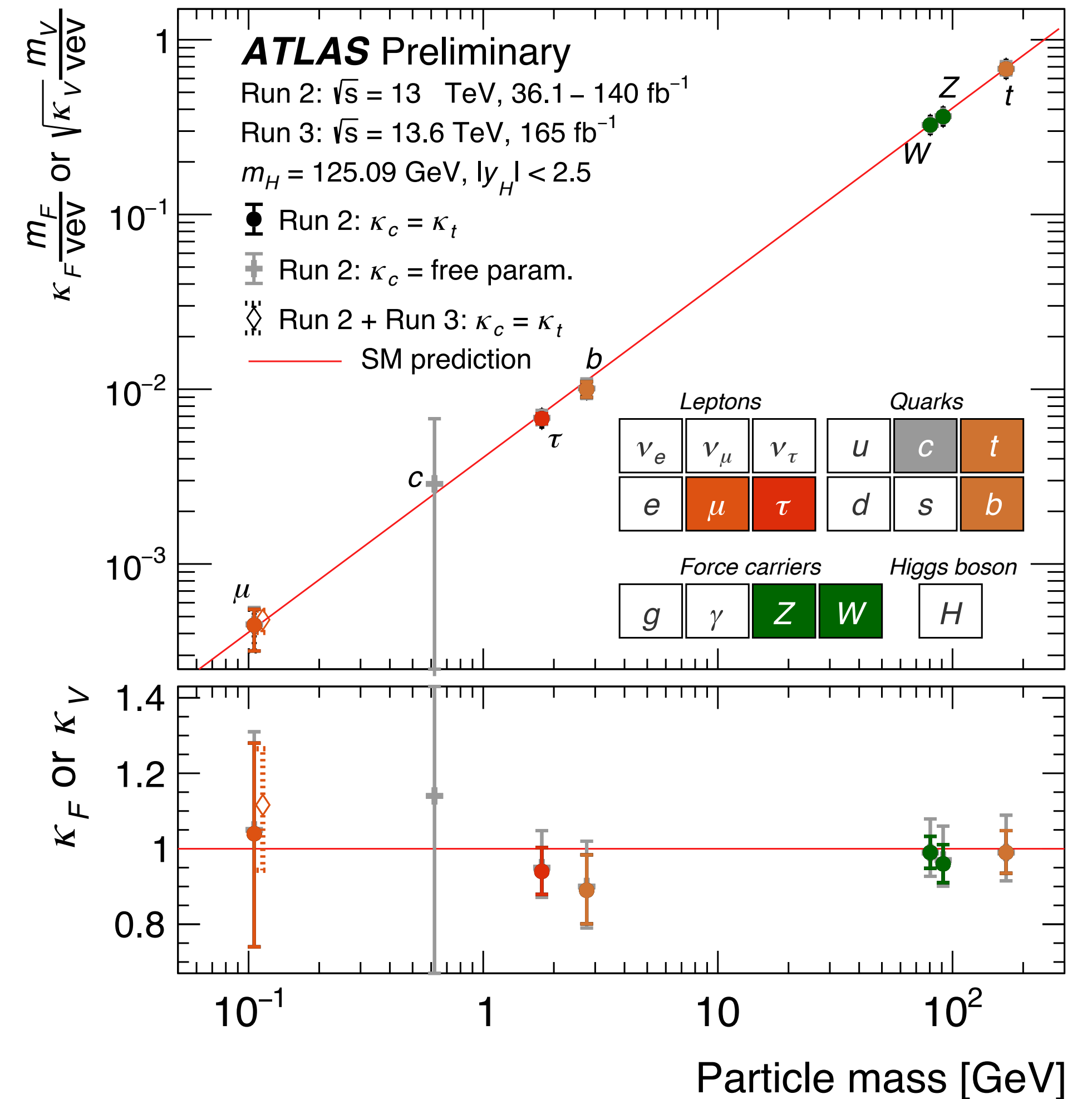
Phys. Rev. D 111 (2025) 092014

CMS-PAS-HIG-24-007

Higgs boson cross sections and couplings

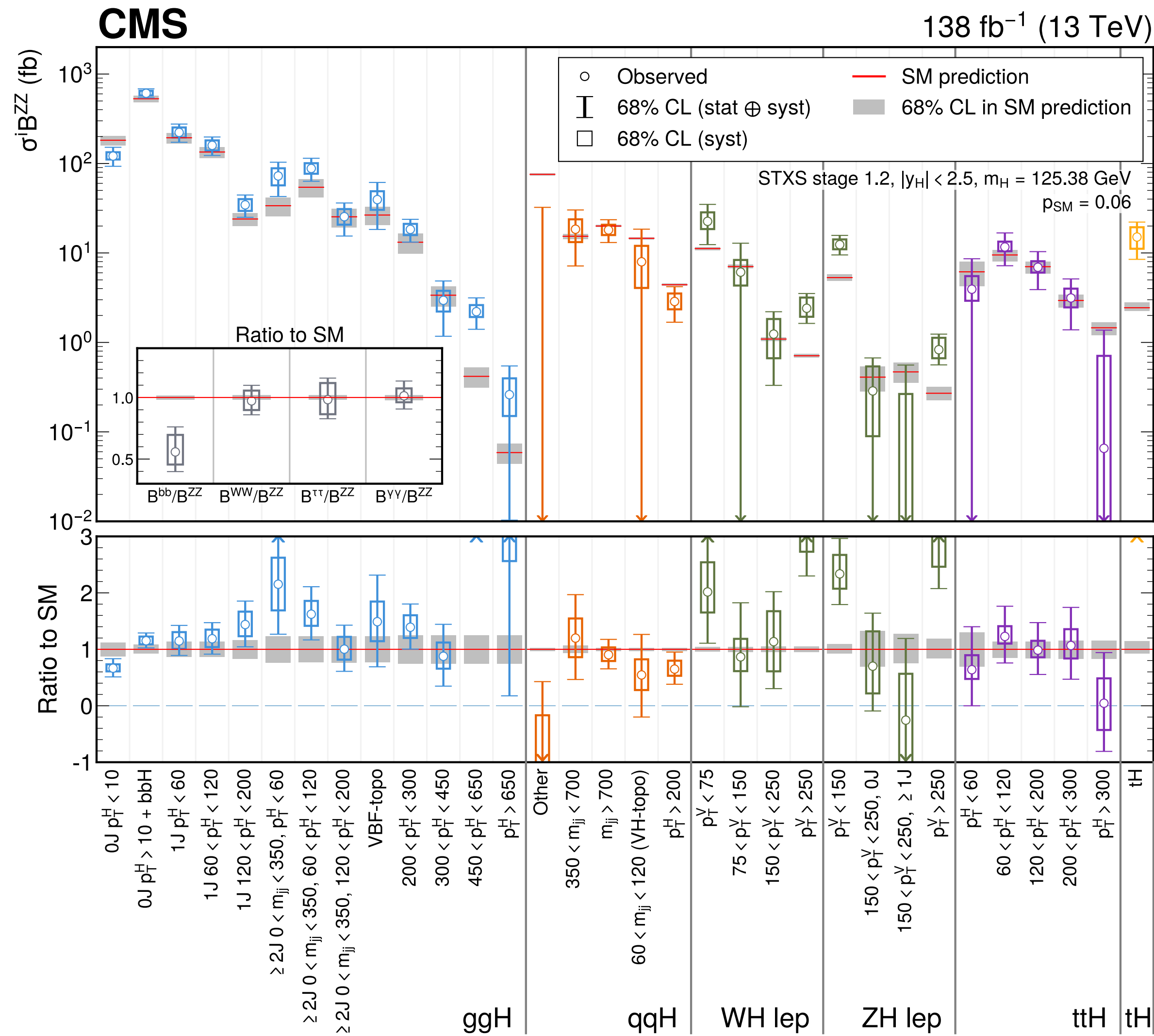


Precise measurements of inclusive cross sections and decay rates



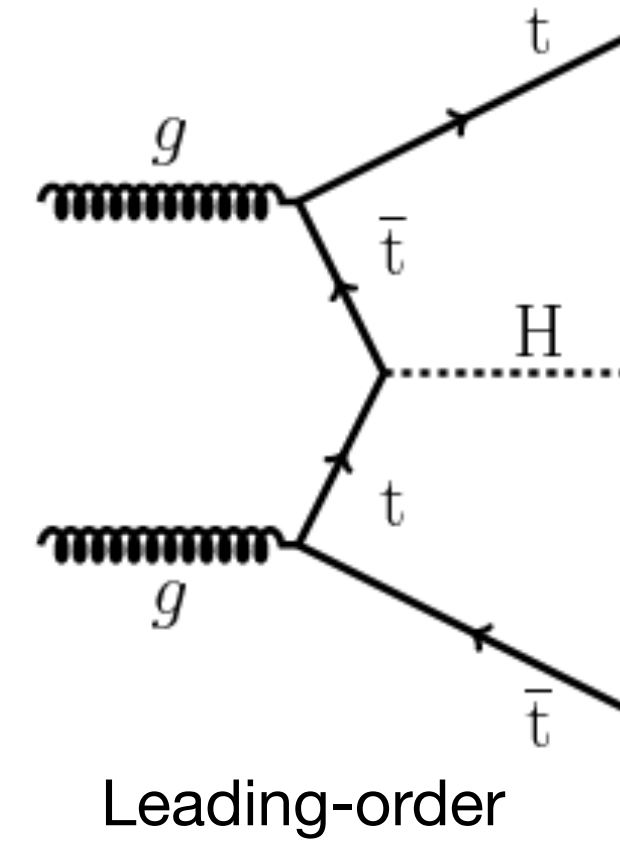
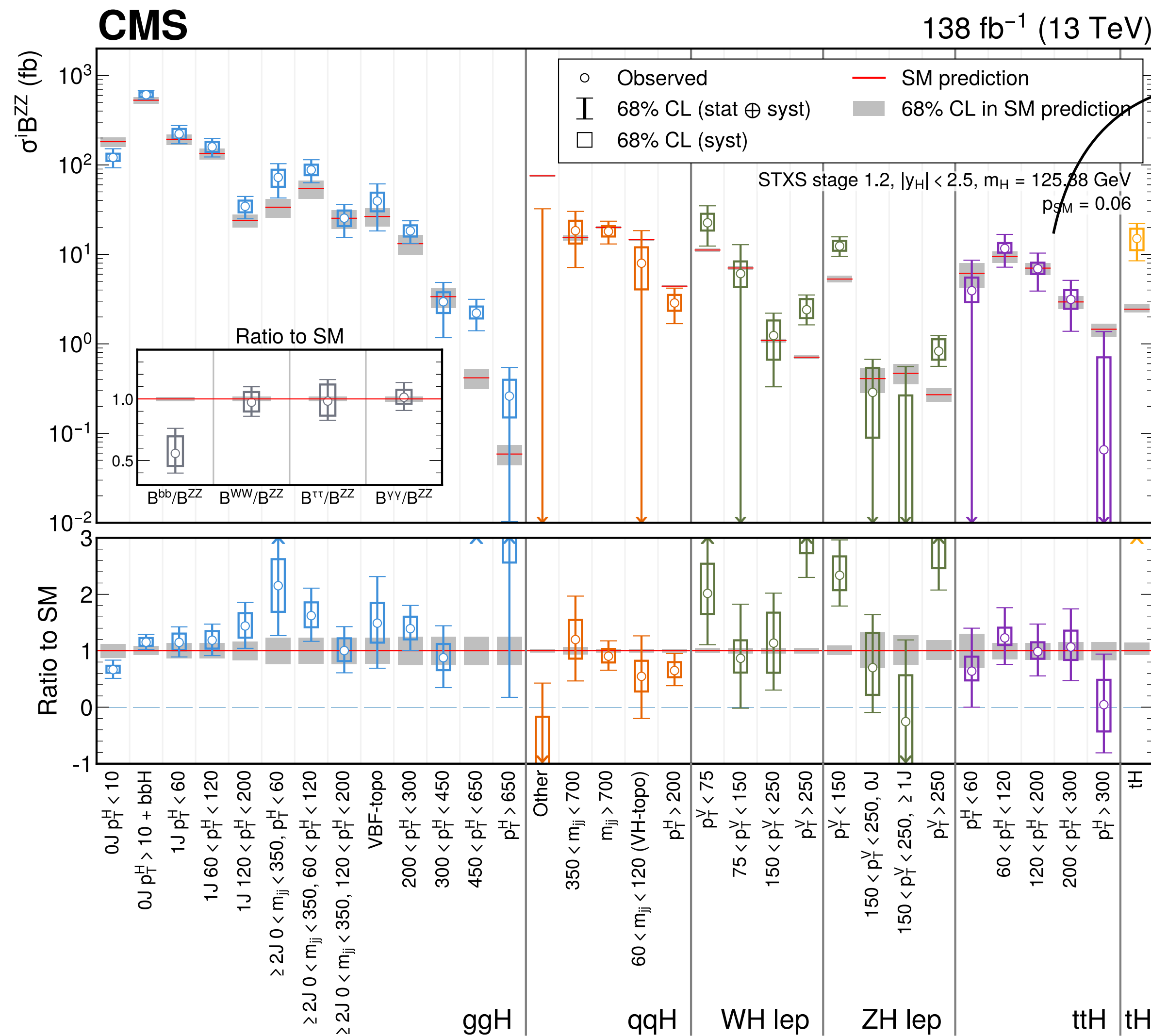
Agreement between measured couplings and predictions over 3 orders of magnitude

Beyond inclusive rates



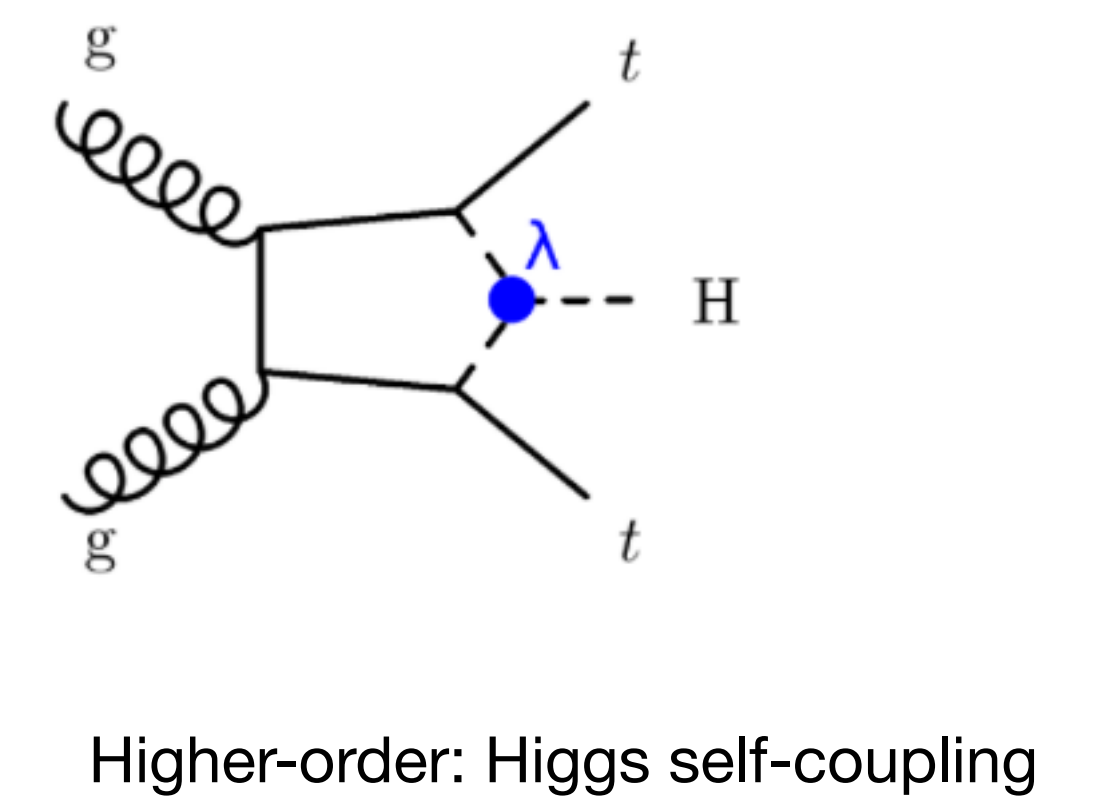
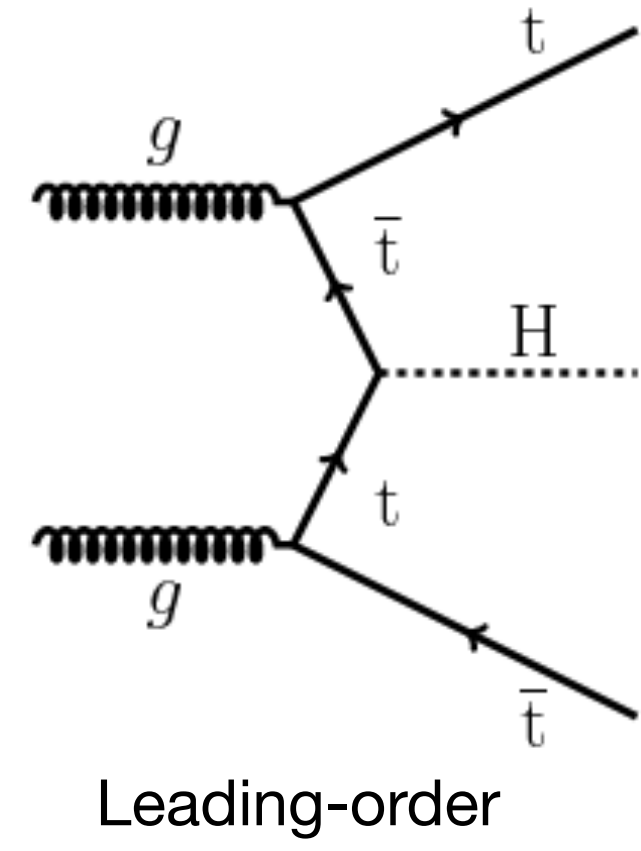
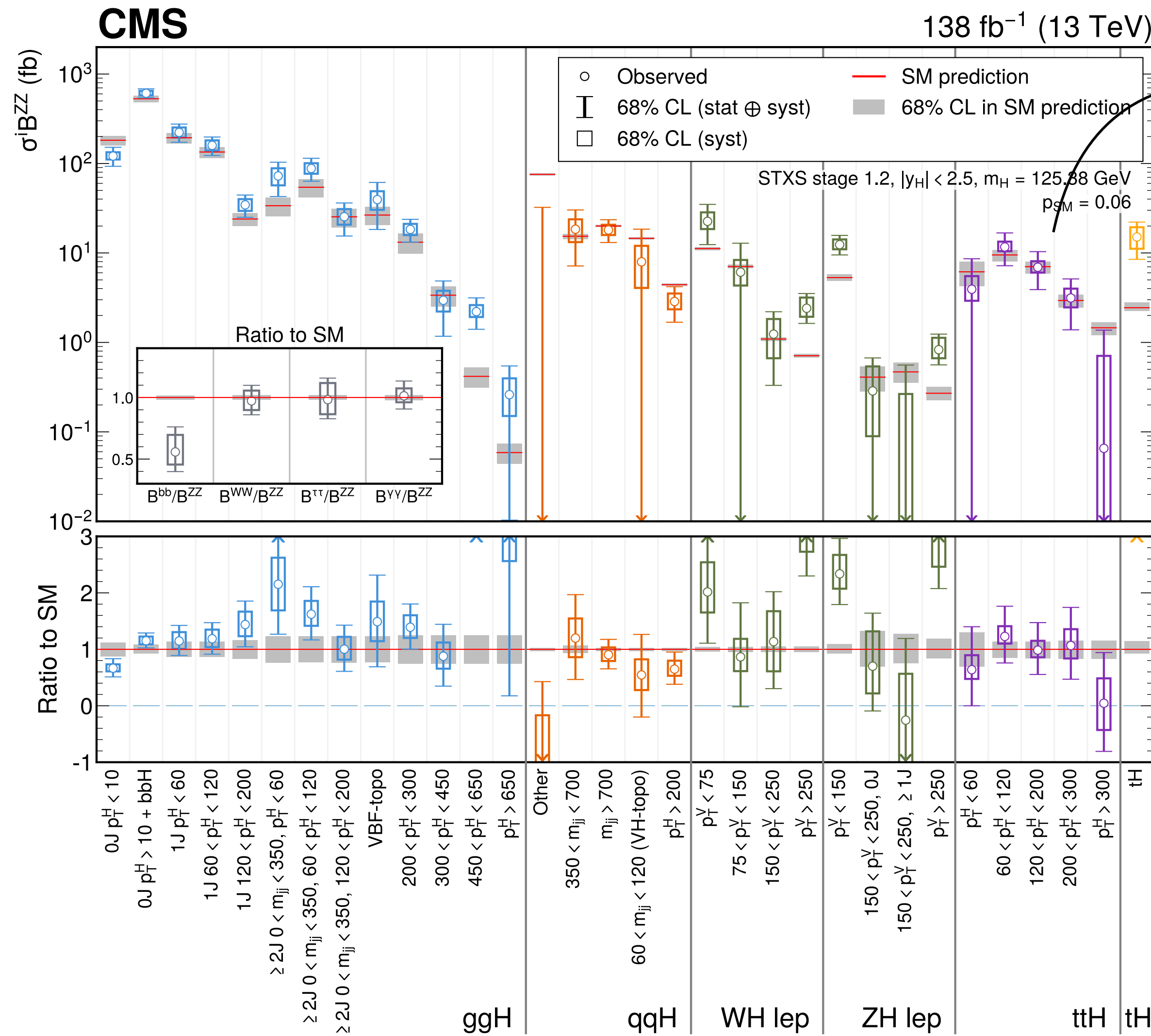
Measurements of σB relative to SM expectation in different kinematic production regions \rightarrow interpretations

Beyond inclusive rates



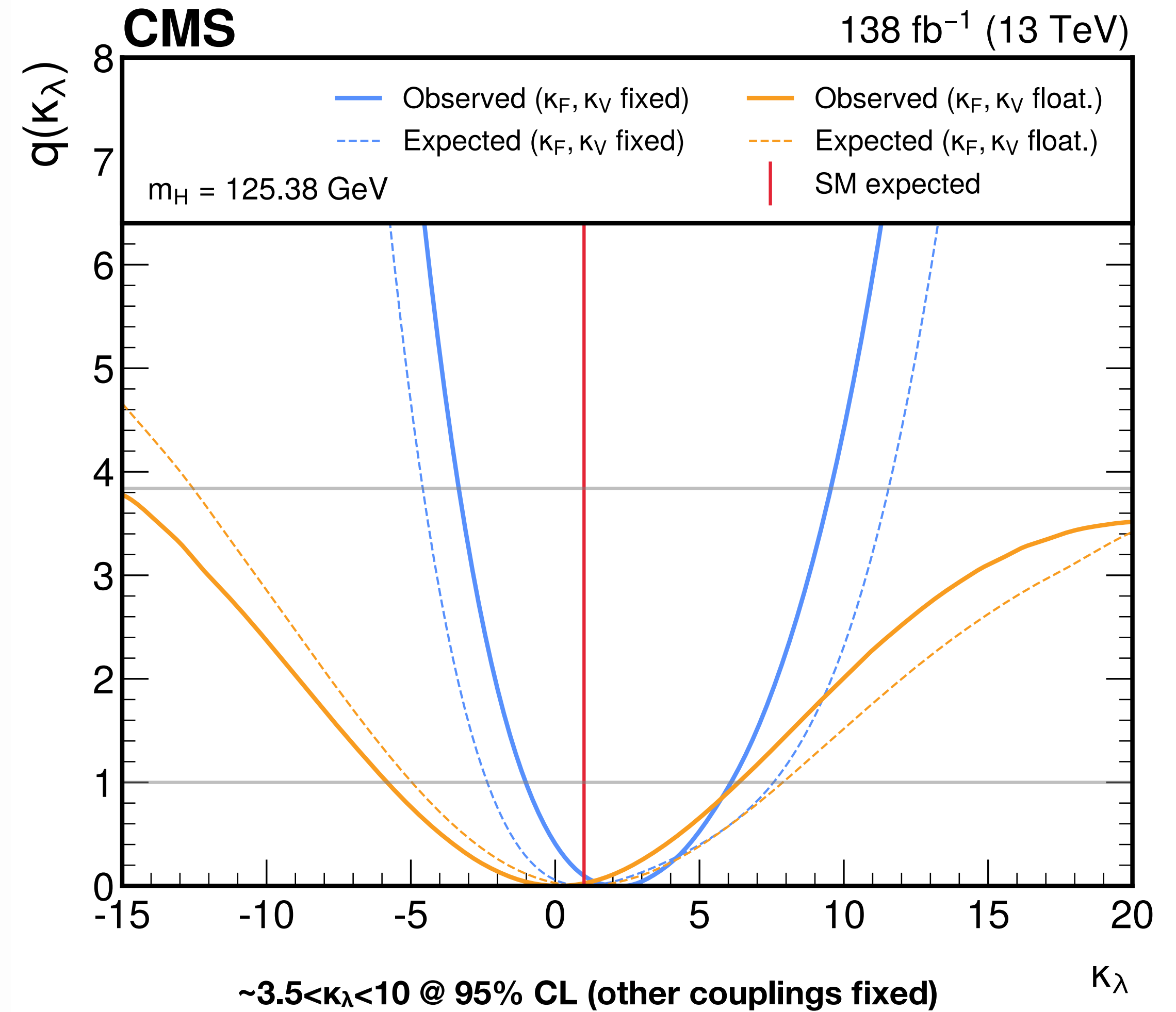
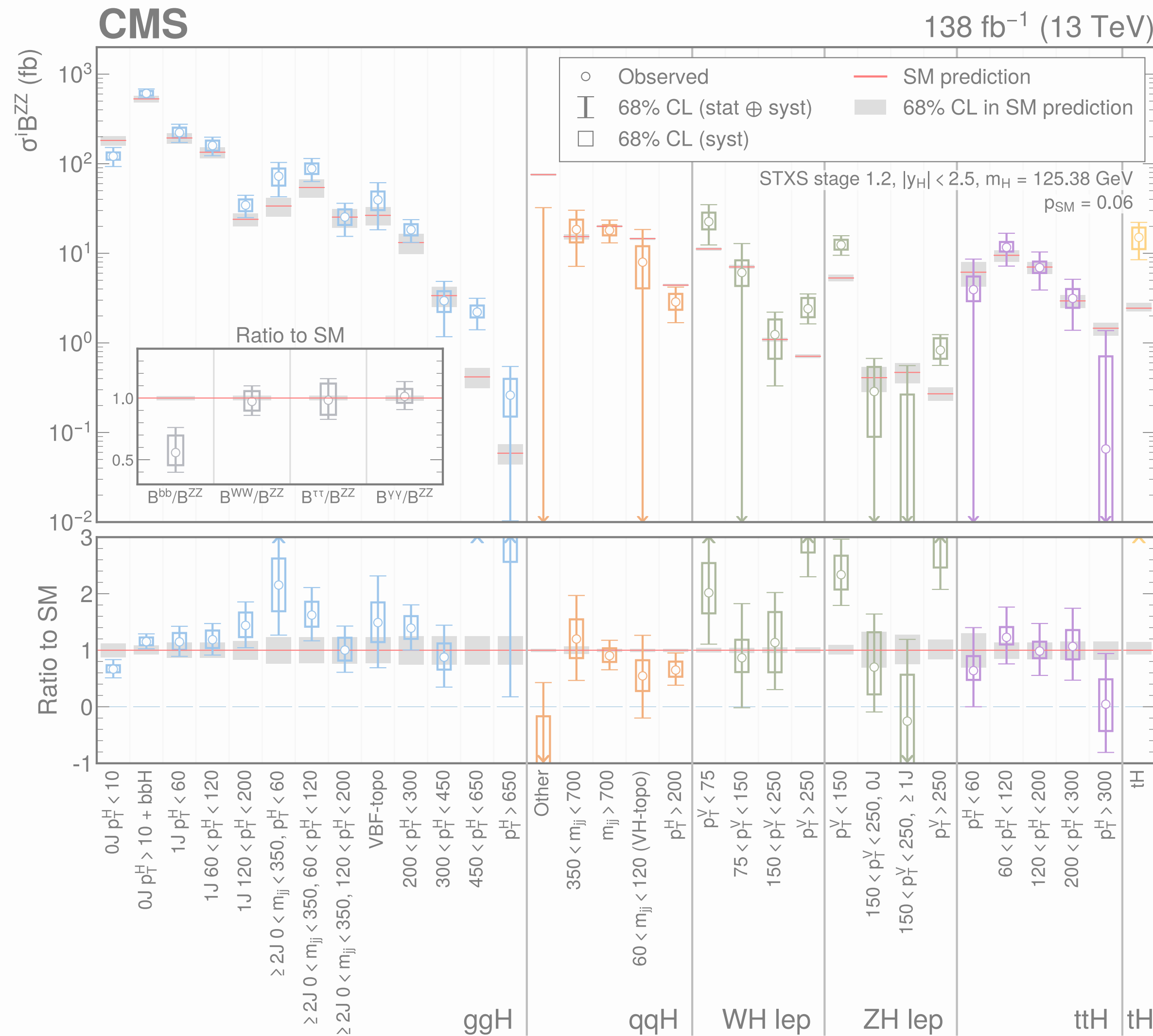
Measurements of σ^B relative to SM expectation in different kinematic production regions \rightarrow interpretations

Beyond inclusive rates



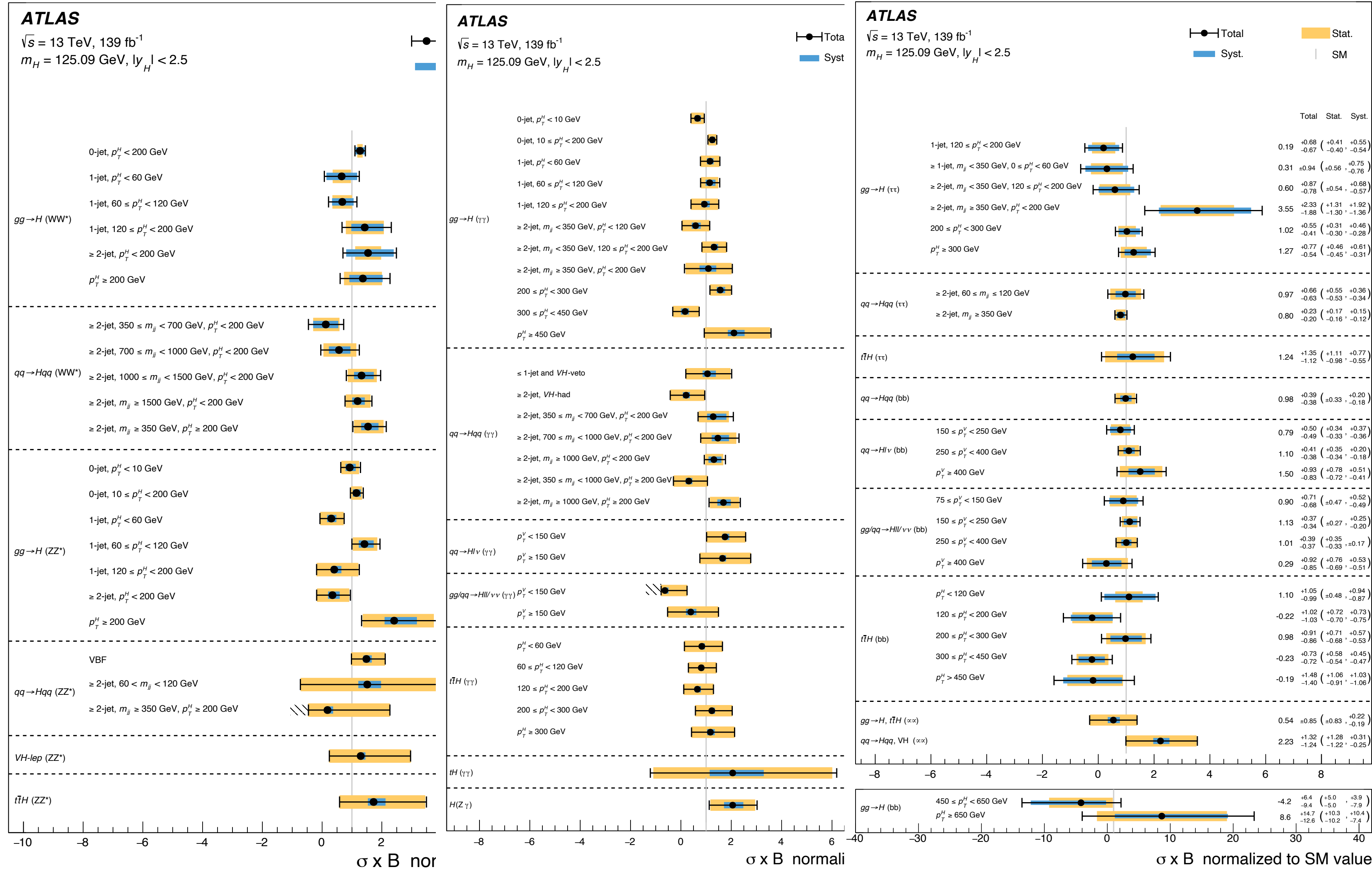
Measurements of σ_B relative to SM expectation in different kinematic production regions → interpretations

Beyond inclusive rates

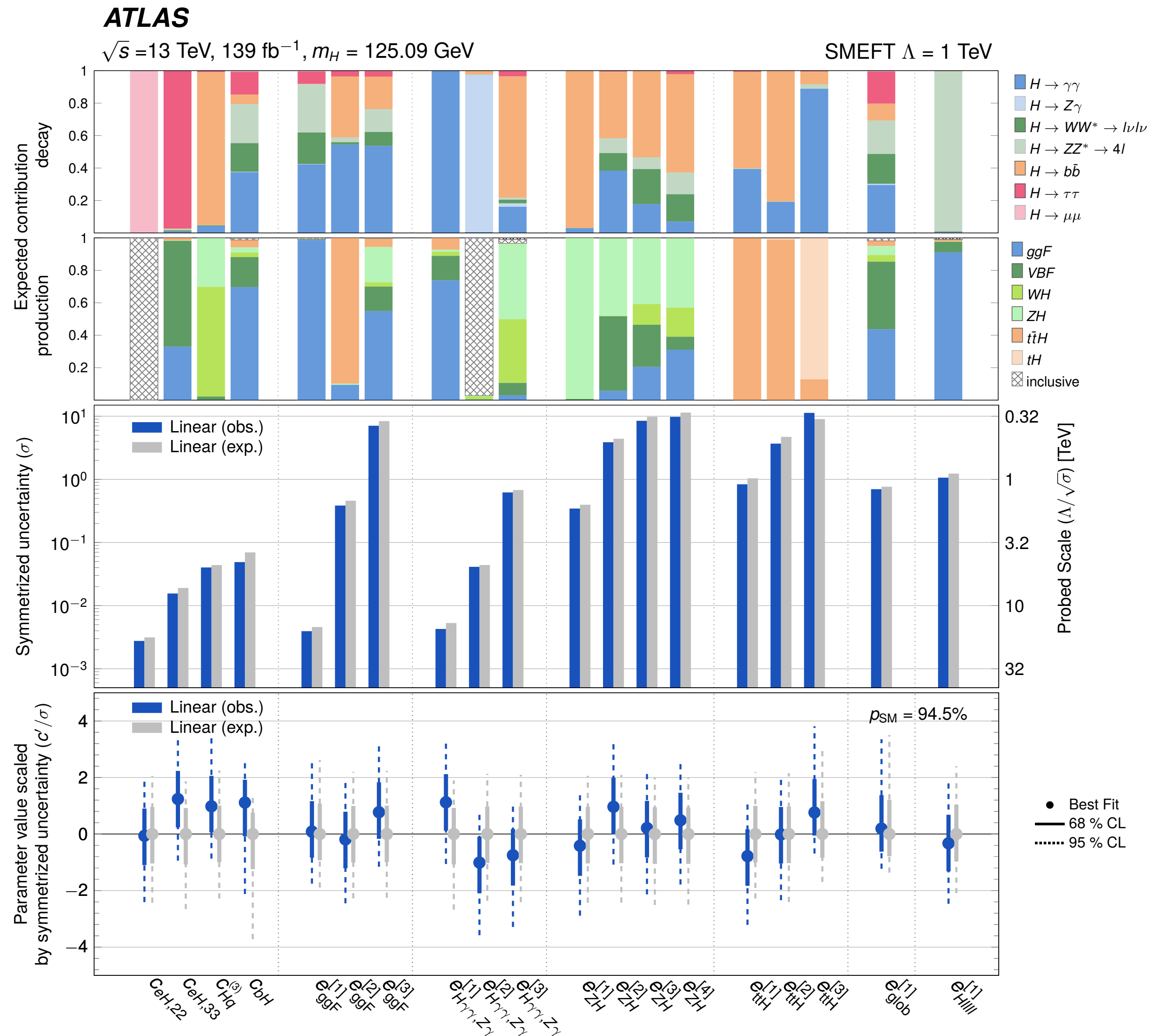
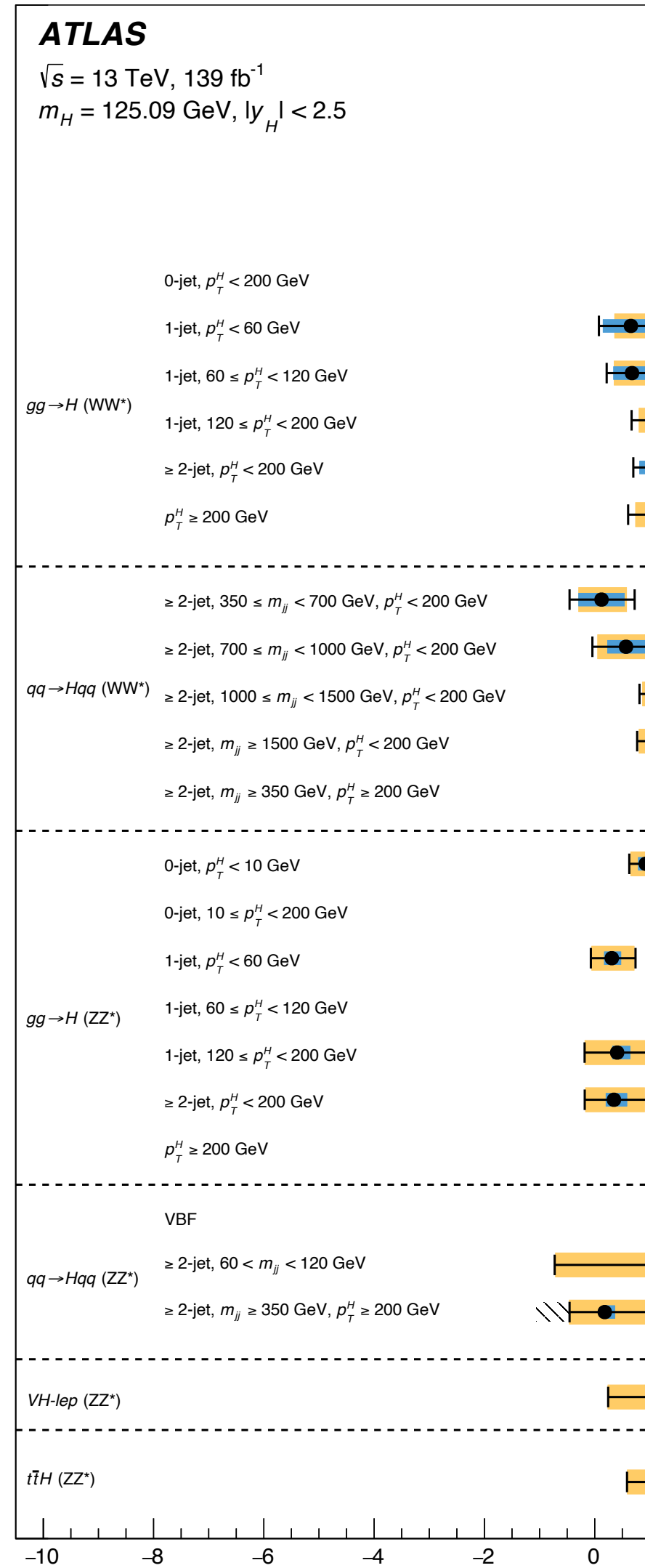


Measurements of σ_B relative to SM expectation in different kinematic production regions → interpretations

Beyond inclusive rates



Beyond inclusive rates



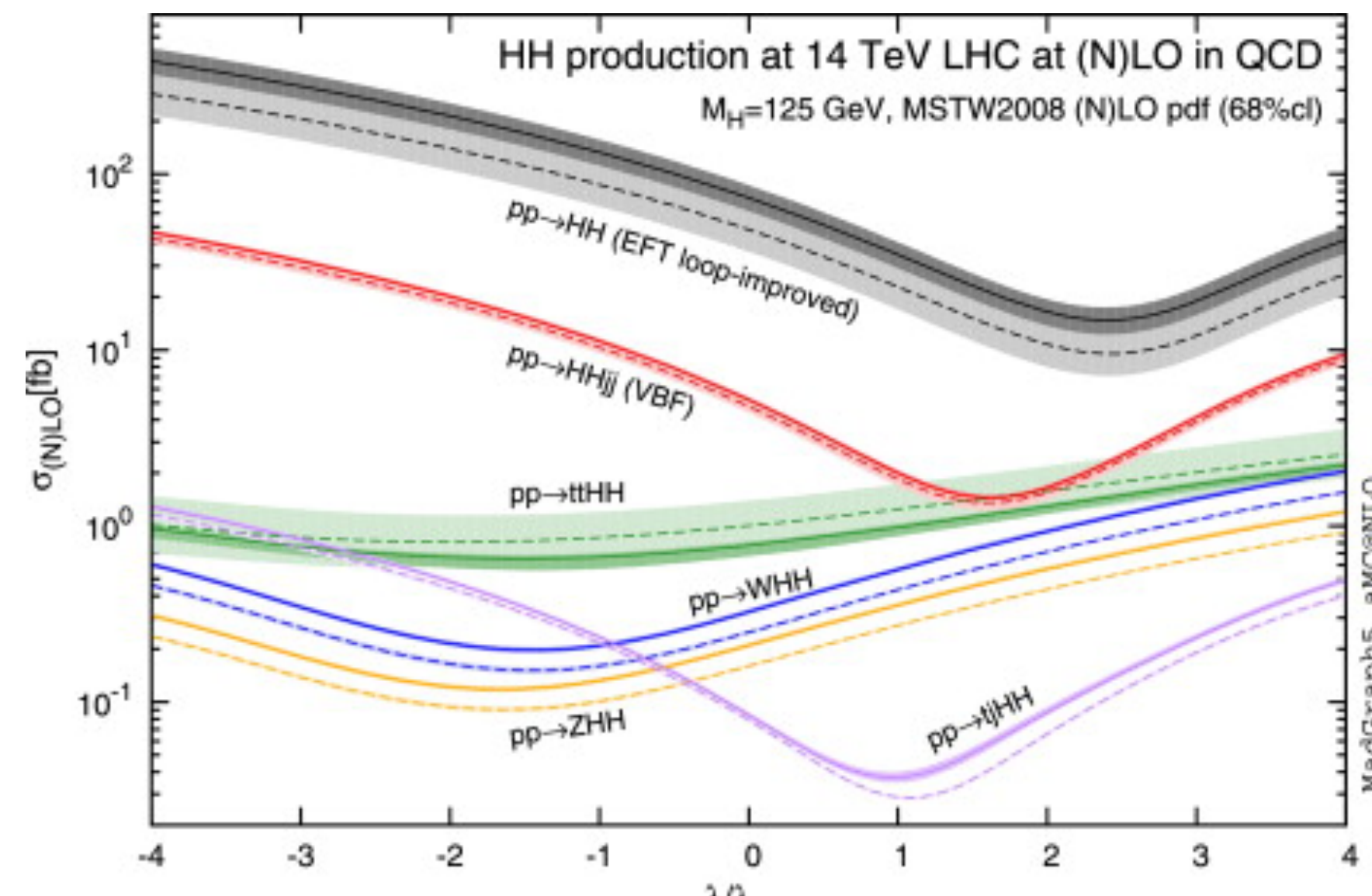
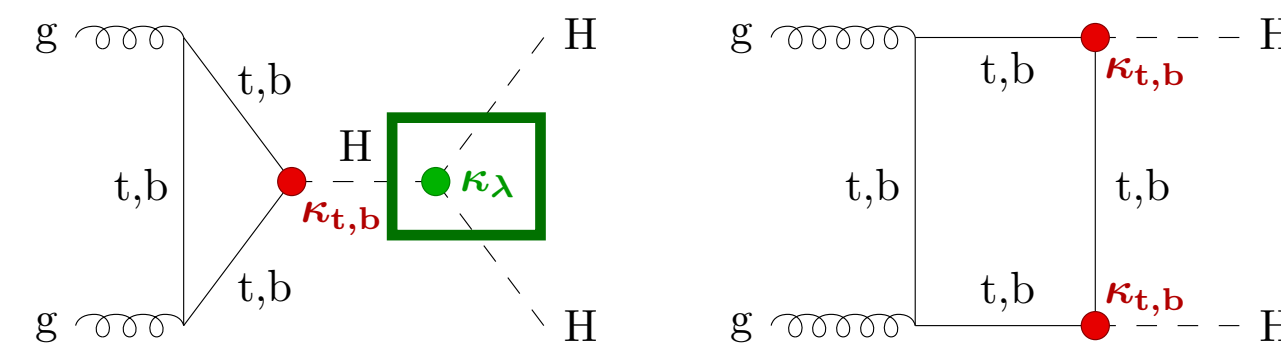
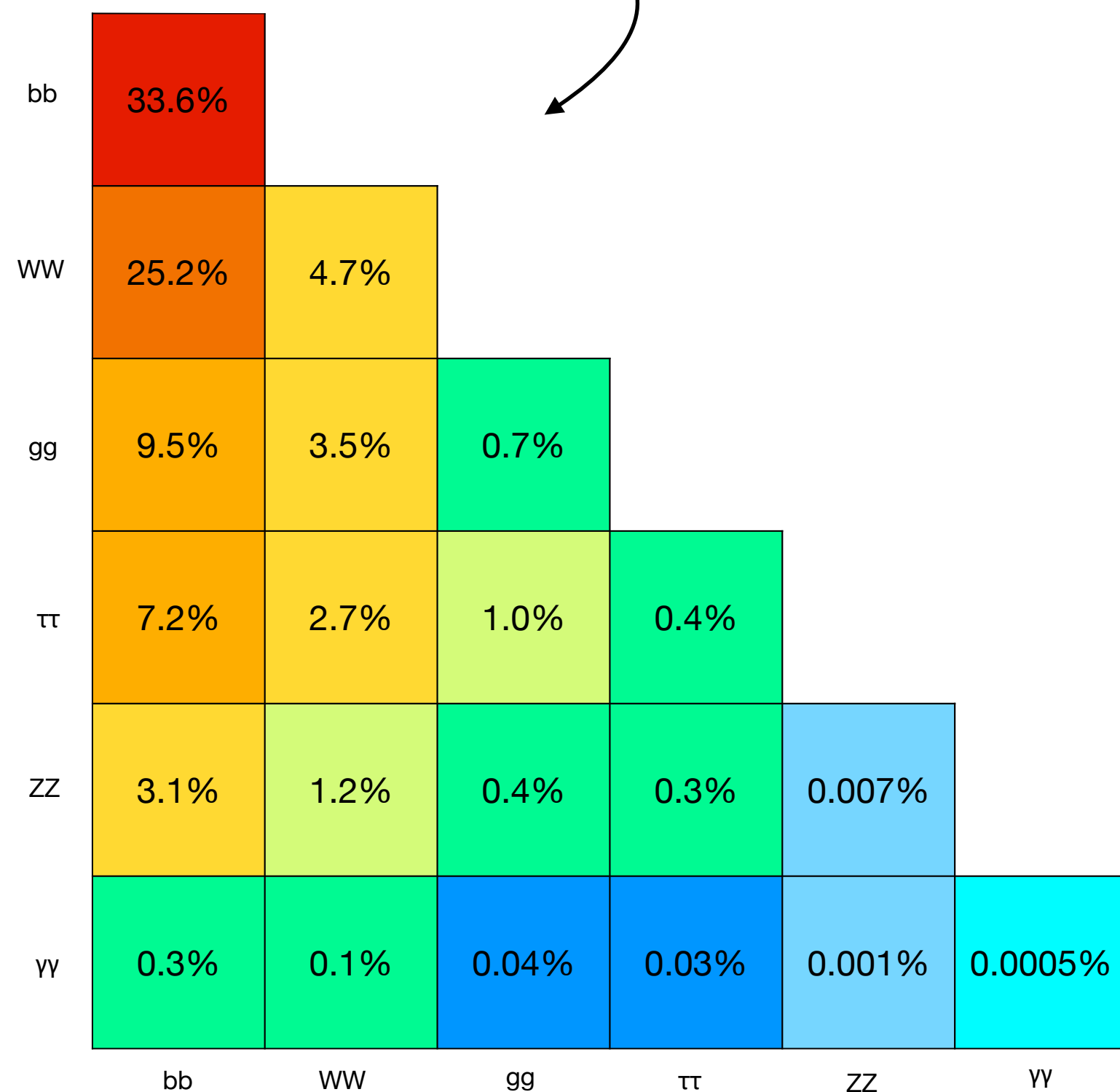
Measurements of σ_B relative to SM expectation in different kinematic production regions

80-100 measurements \rightarrow BSM interpretations

Di-Higgs production at the LHC

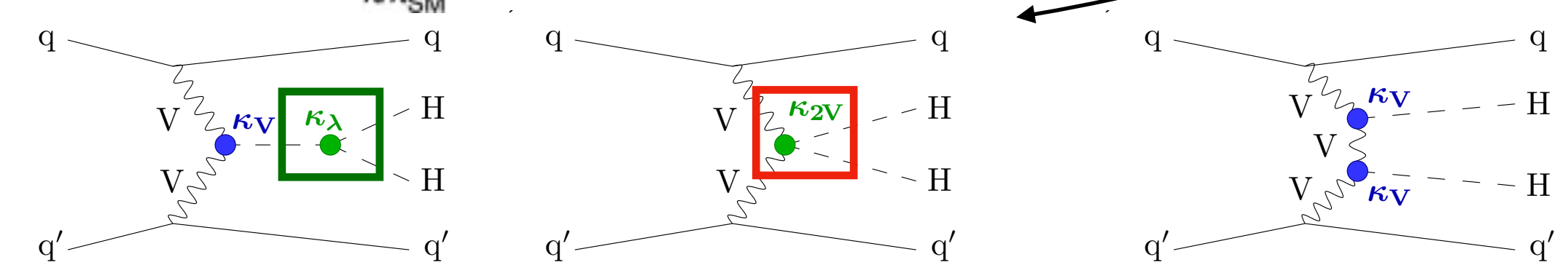
$B(HH \rightarrow XXYY)$

→ No one channel dominates



Gluon-gluon fusion: $\sigma \sim 31$ fb
(1000x less than single H)

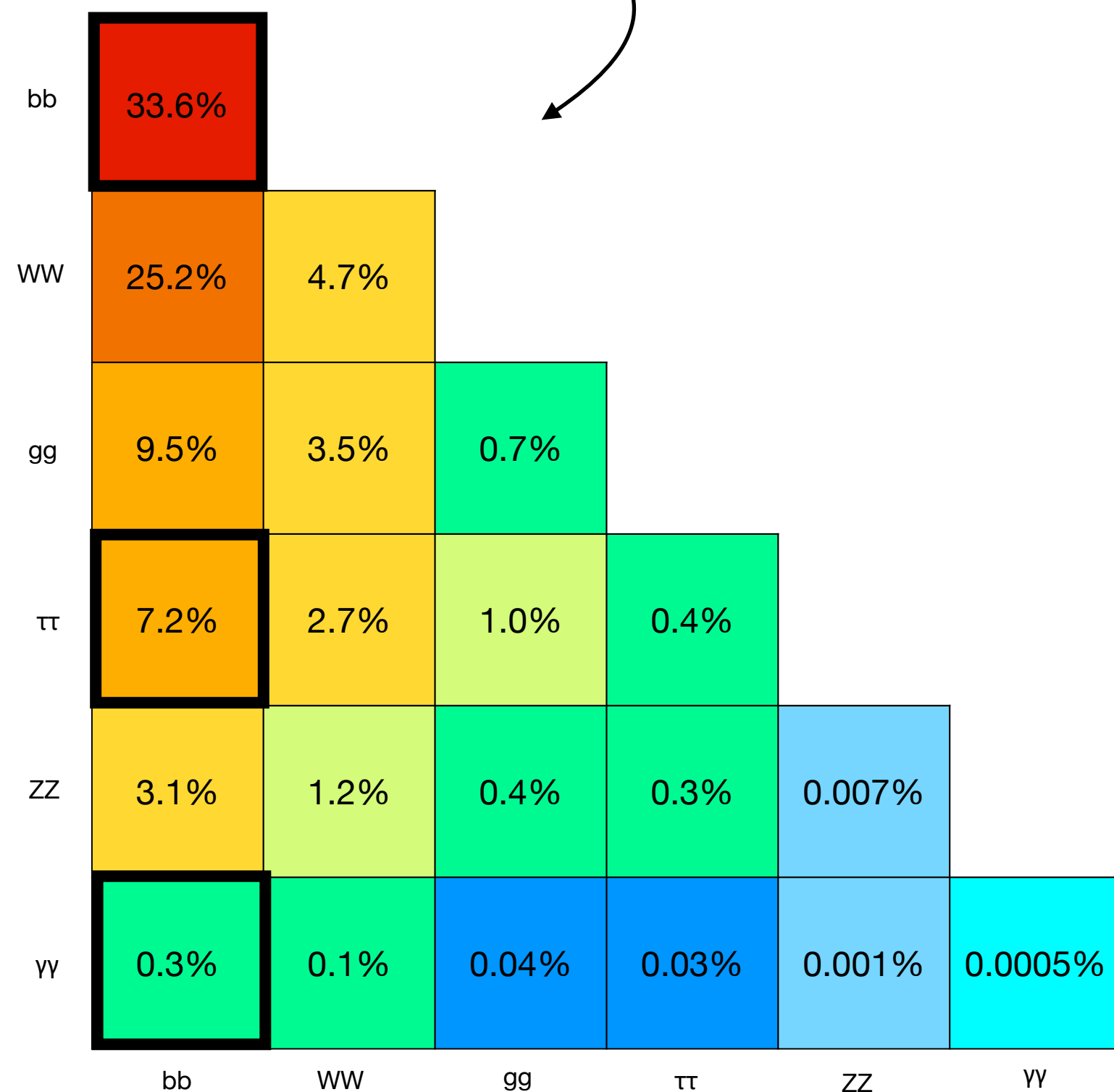
Vector boson fusion: $\sigma \sim 1.7$ fb



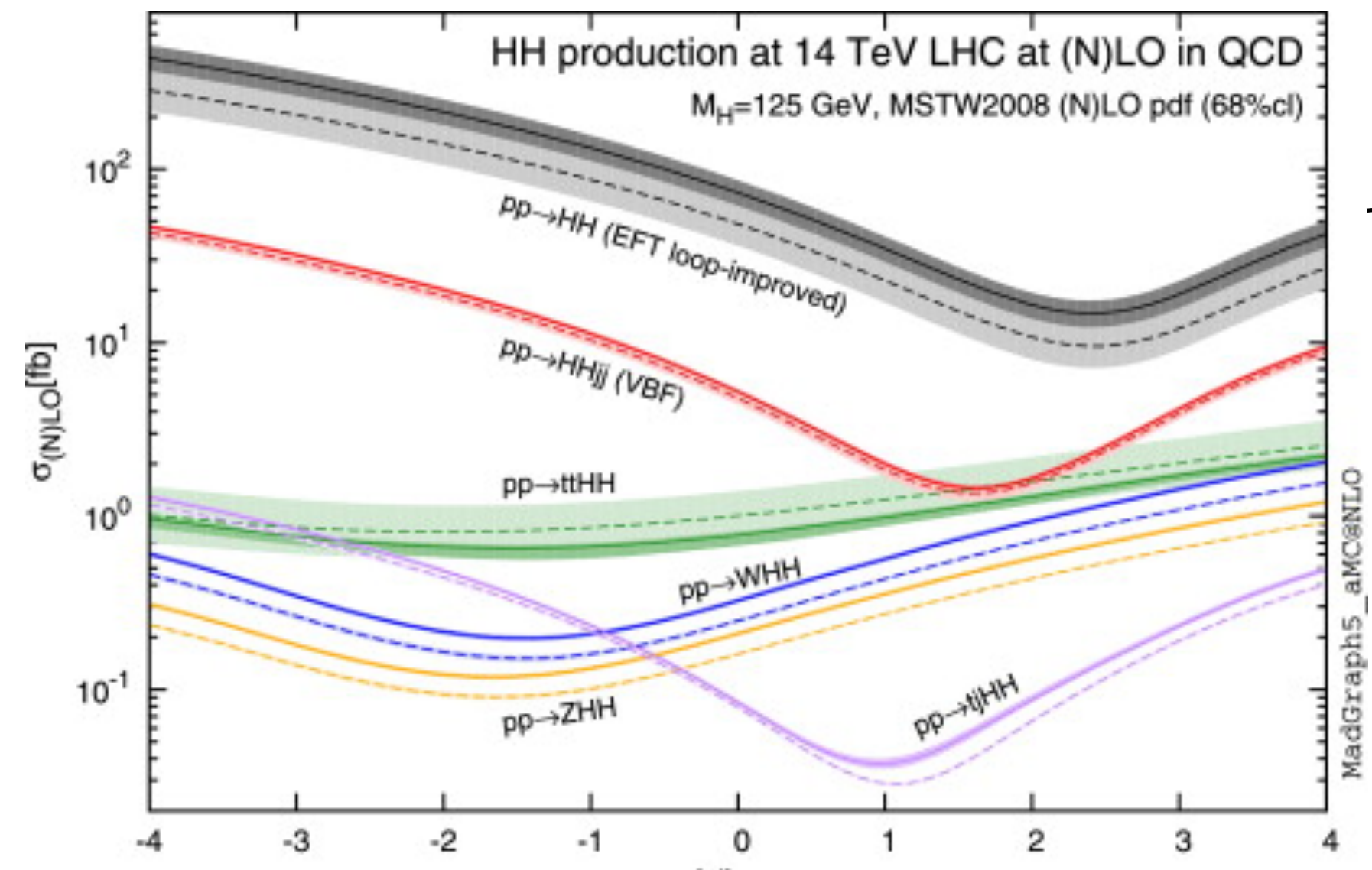
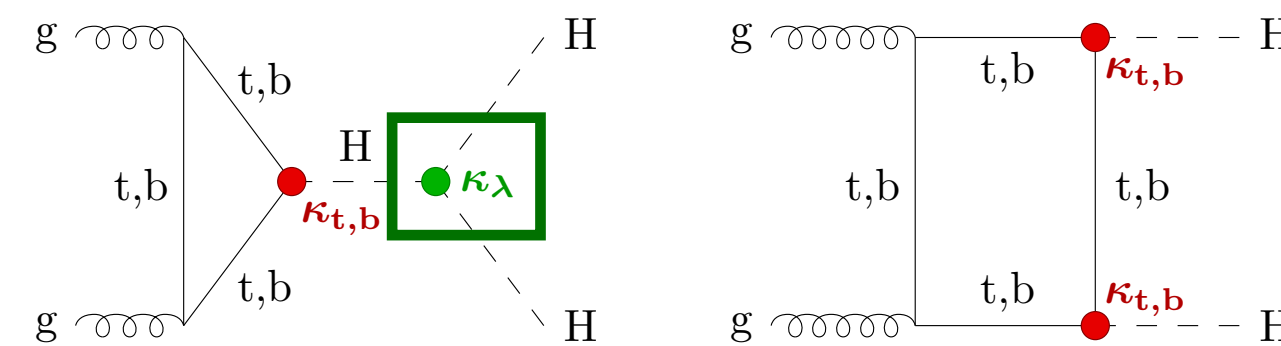
Di-Higgs production at the LHC

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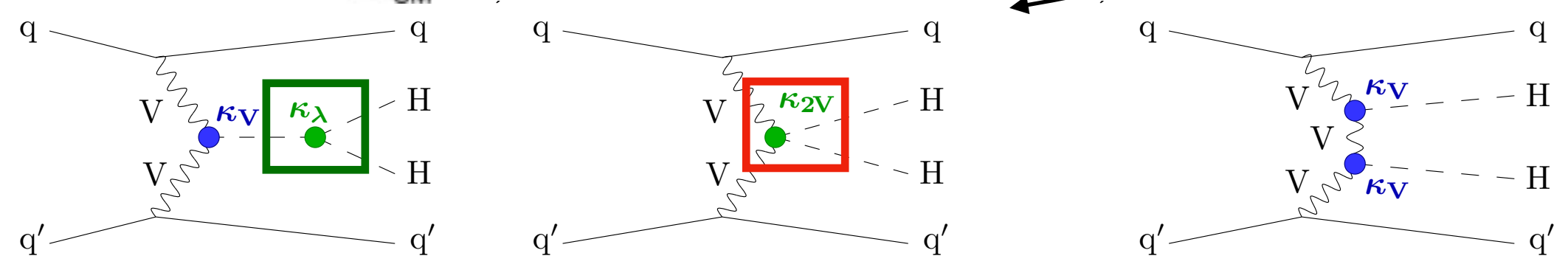


Best sensitivity

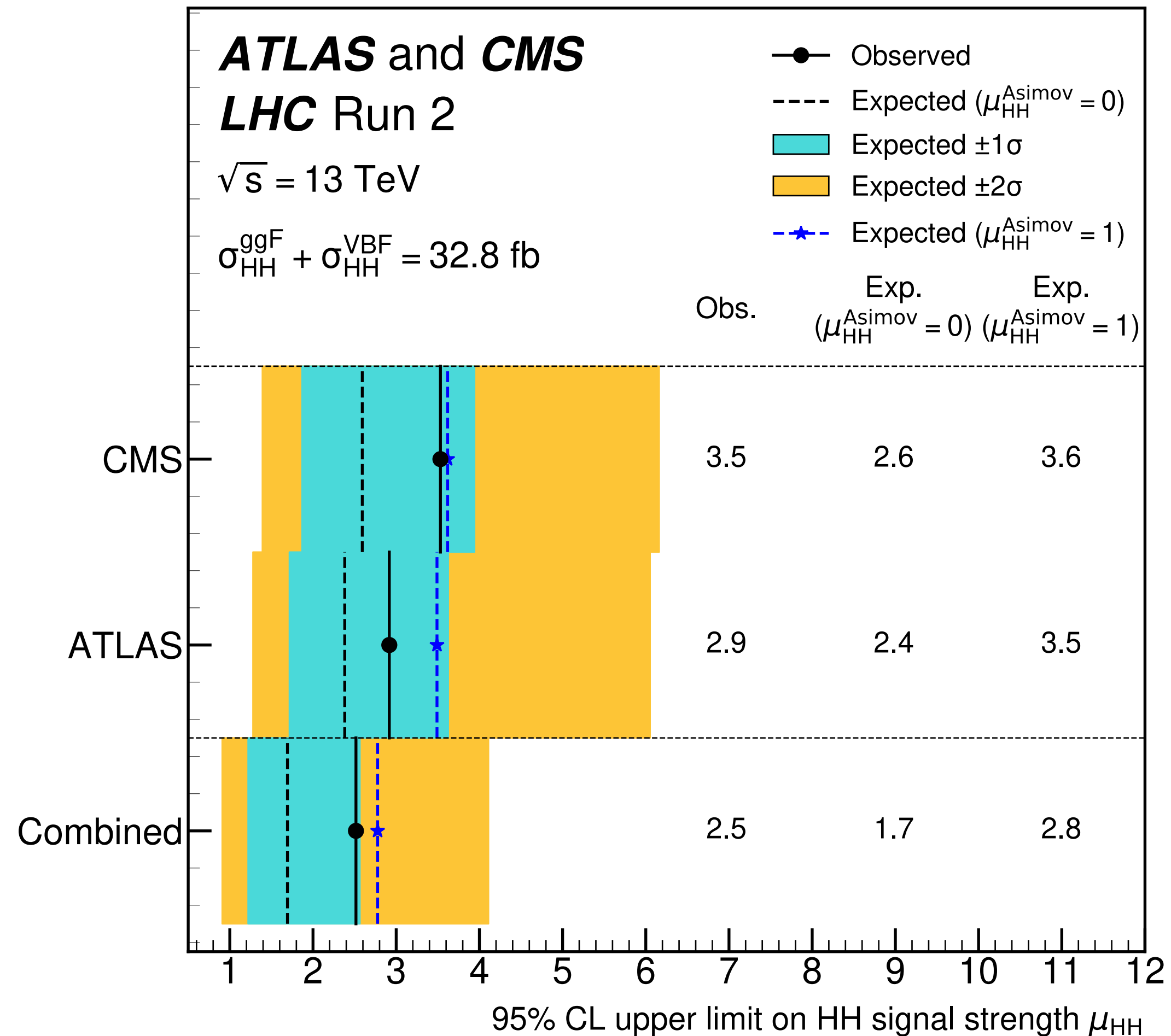


Gluon-gluon fusion: $\sigma \sim 31$ fb
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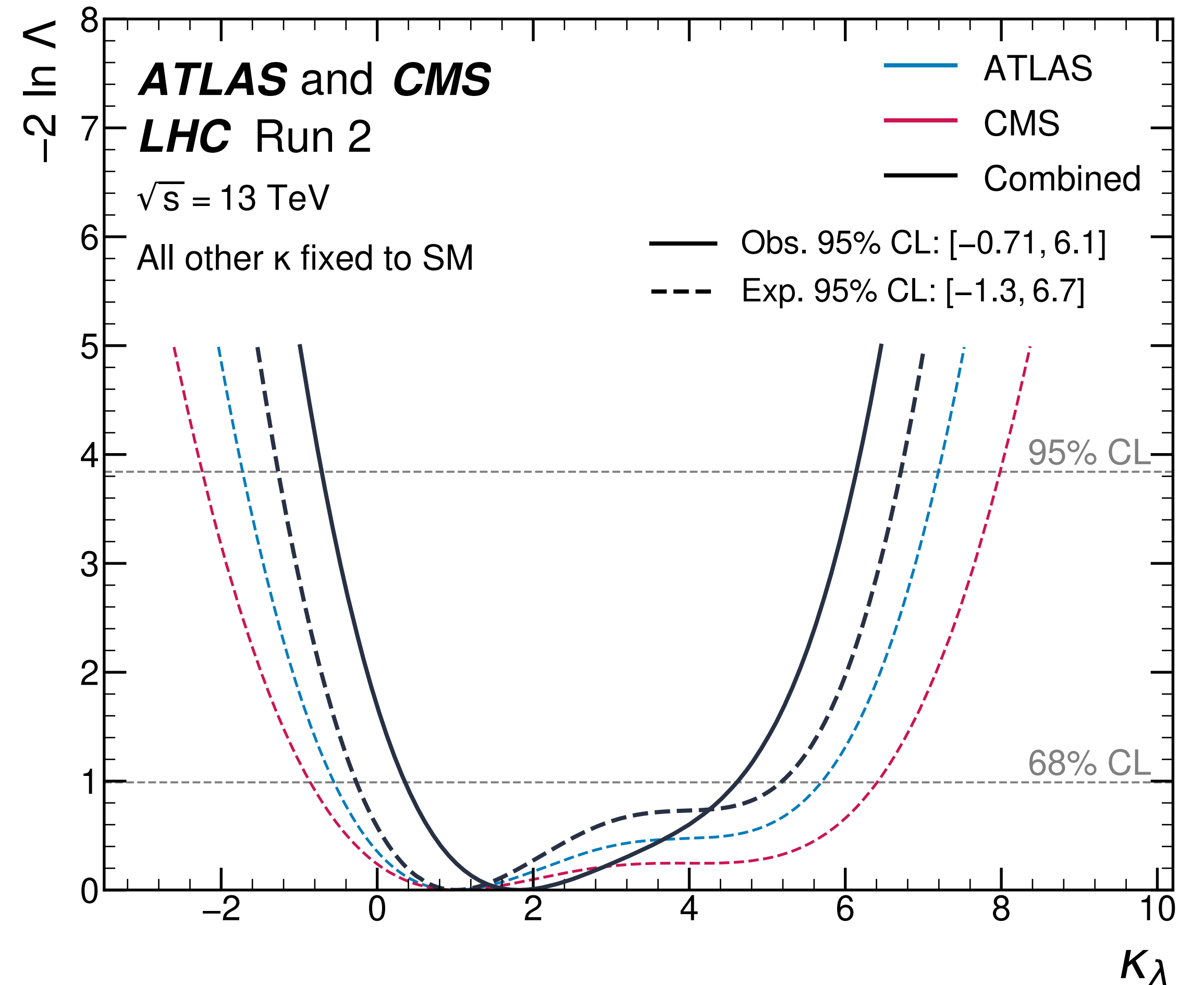
Vector boson fusion: $\sigma \sim 1.7$ fb



Di-Higgs status with data from Run 2

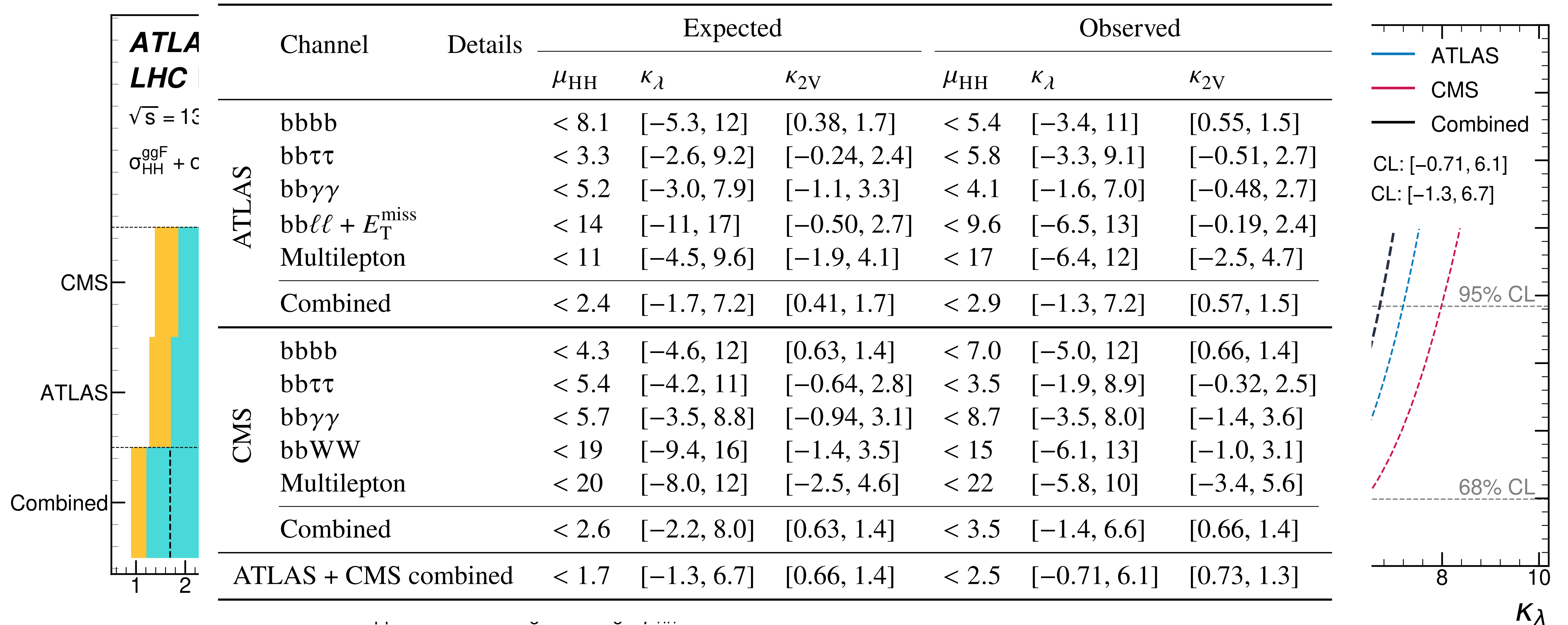


Upper limit on HH production signal strength:
2.5x SM expectation

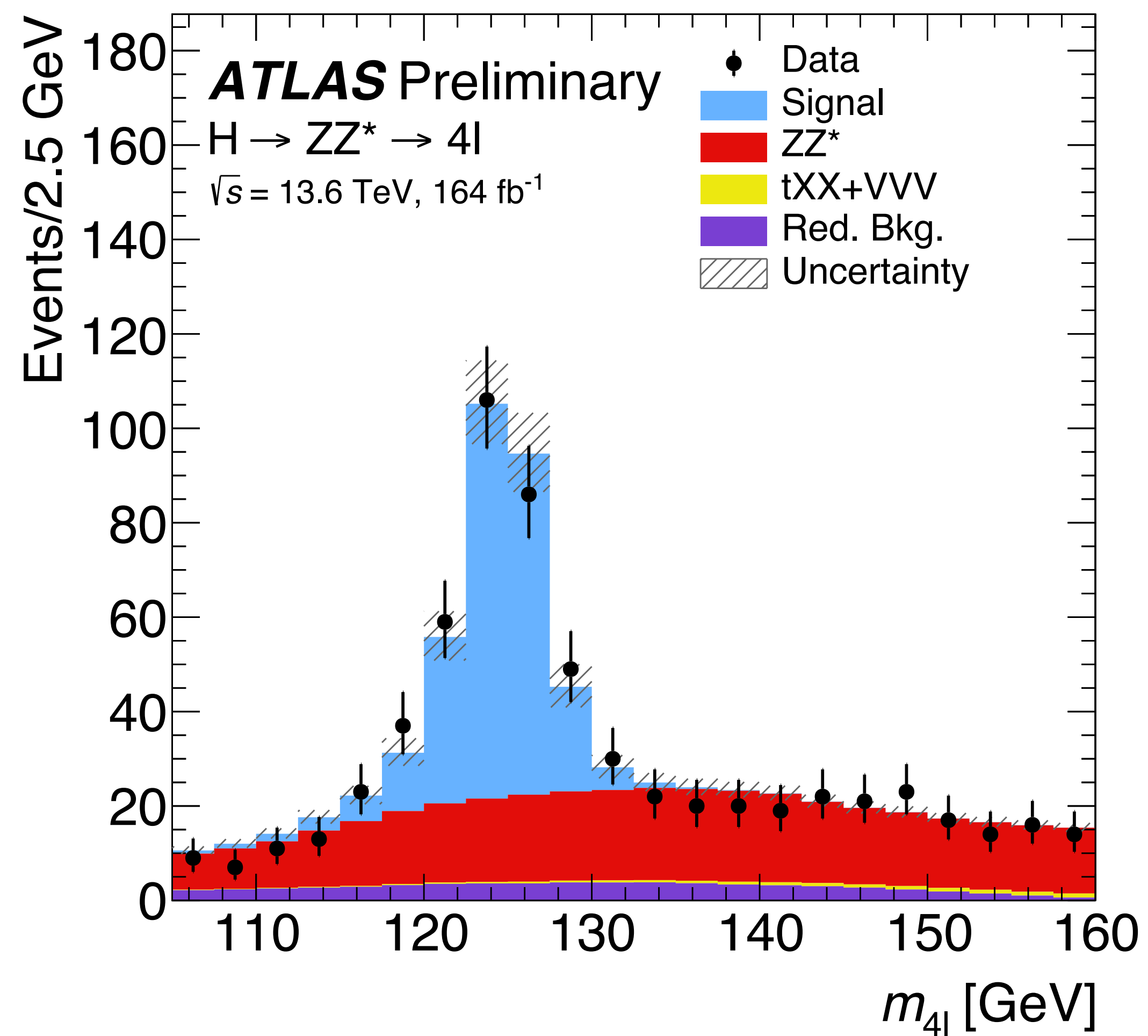


Constraint on κ_λ : **-0.71 < κ_λ < 6.1** at 95% CL

Di-Higgs status with data from Run 2

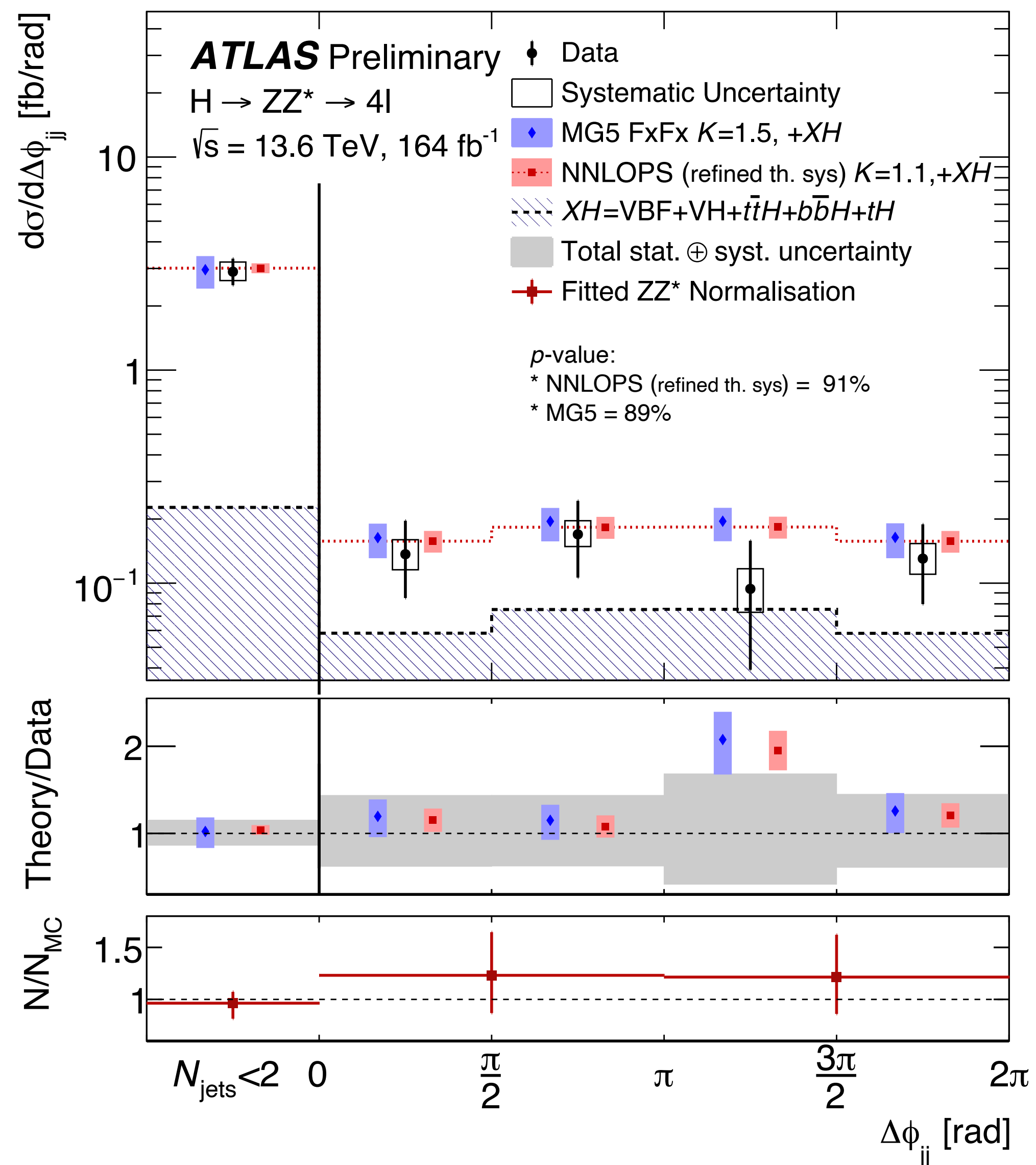


LHC Run 3: increased precision



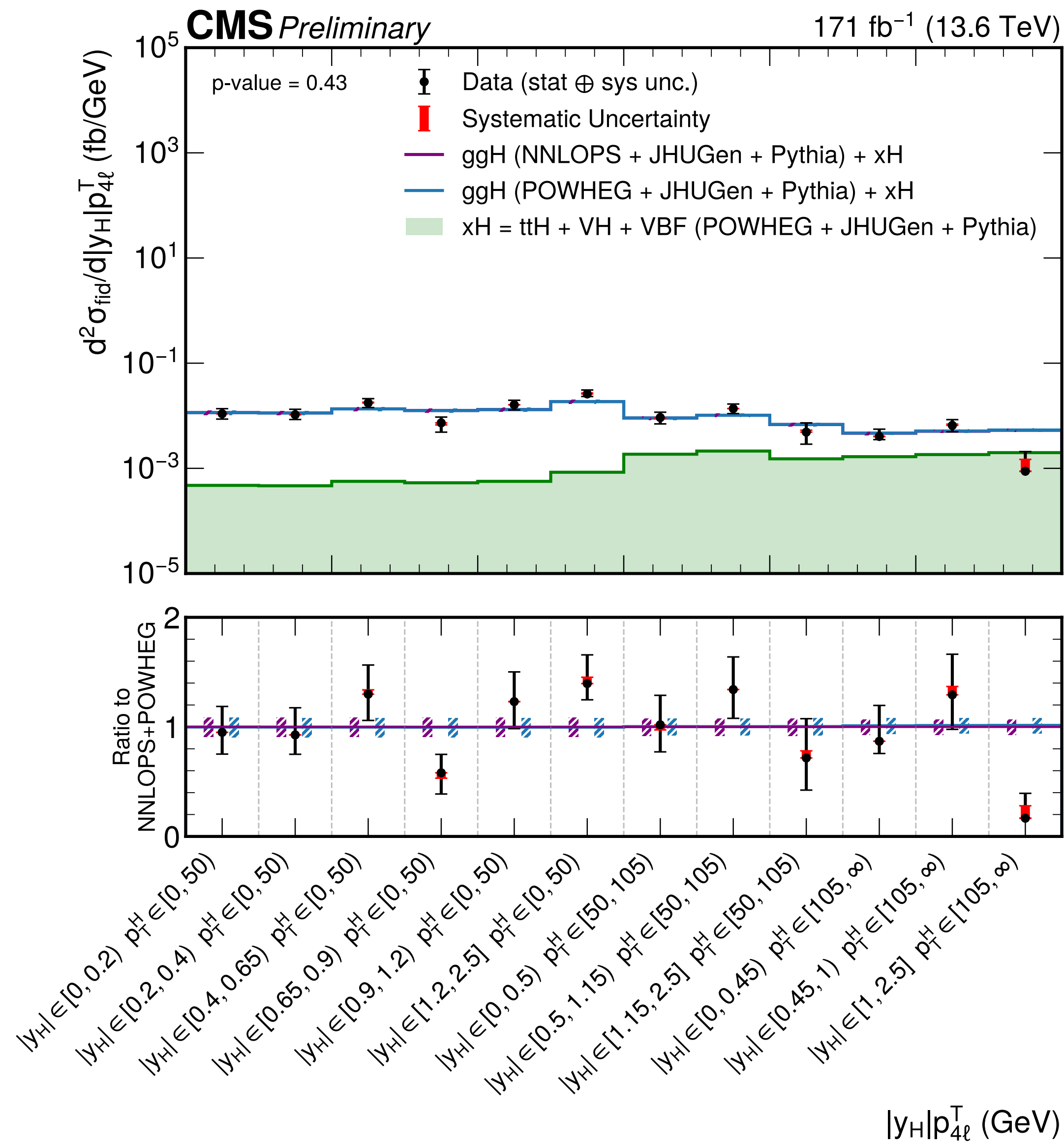
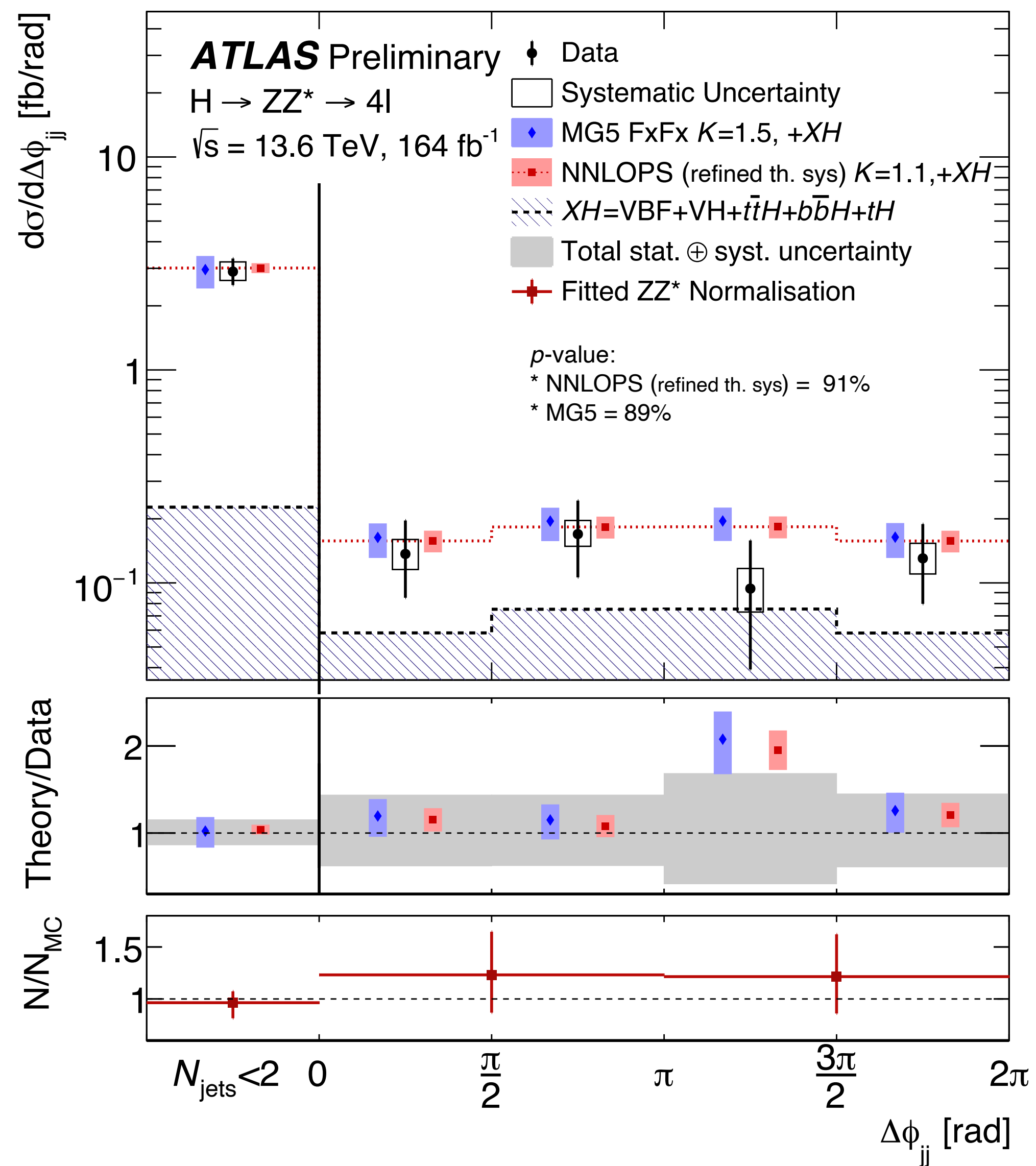
- Analysis of data collected between 2022-2024
- **Exceeding Run 2 luminosity**

LHC Run 3: increased precision



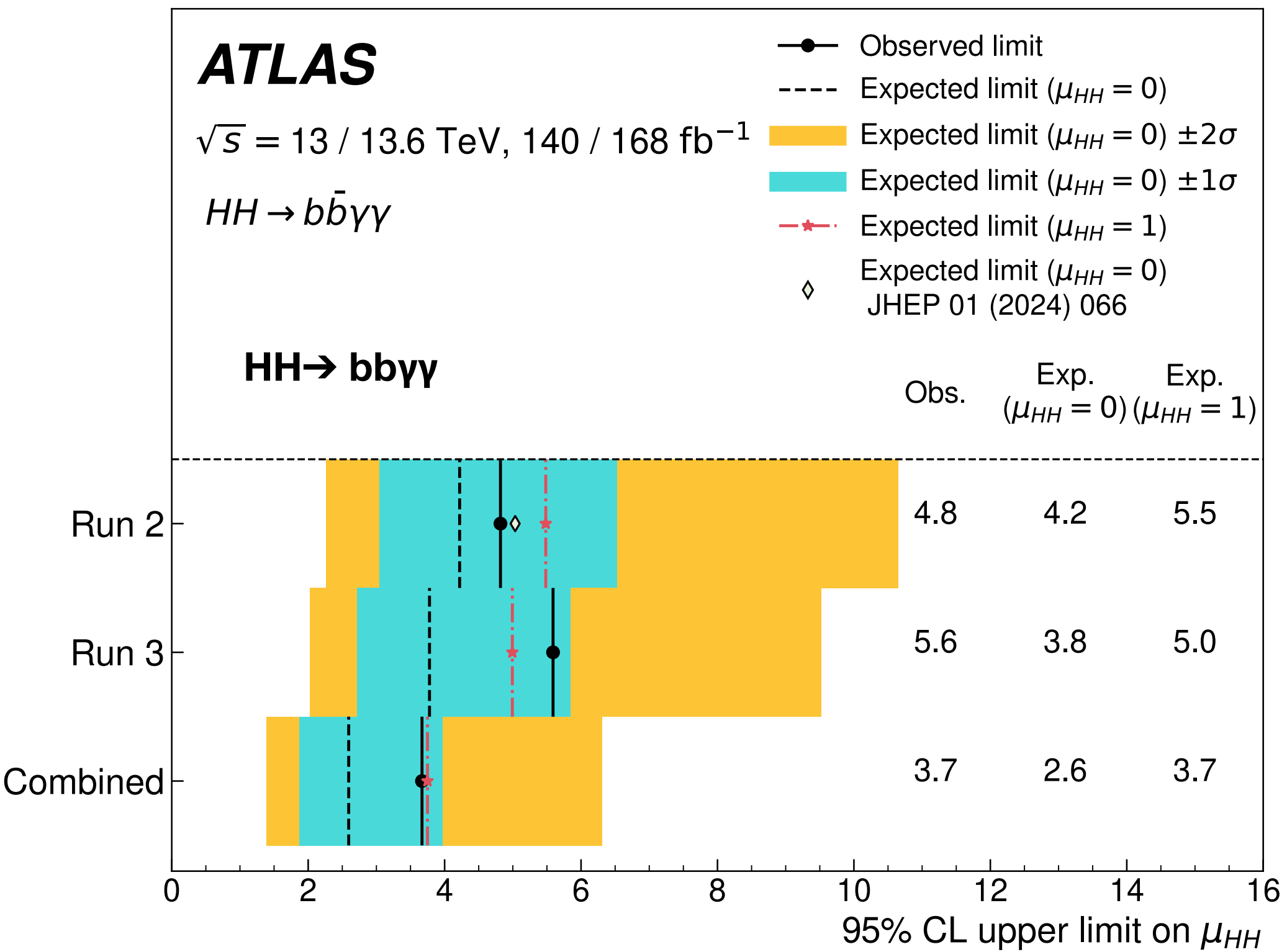
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LHC Run 3: increased precision



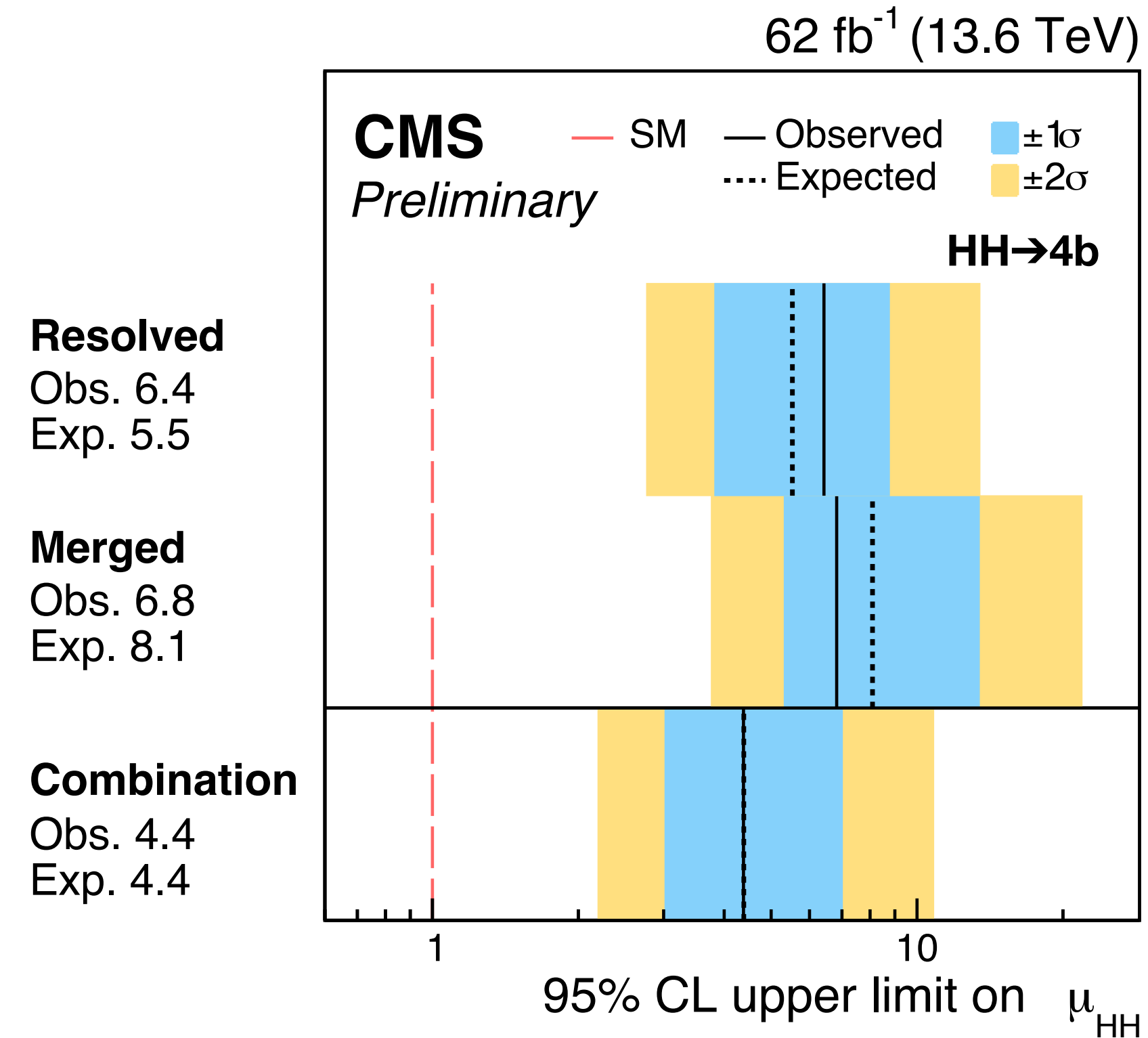
Di-Higgs in Run 3

Data from 2022-2024



Run 3 more sensitive than Run 2 (and more data to be analyzed)

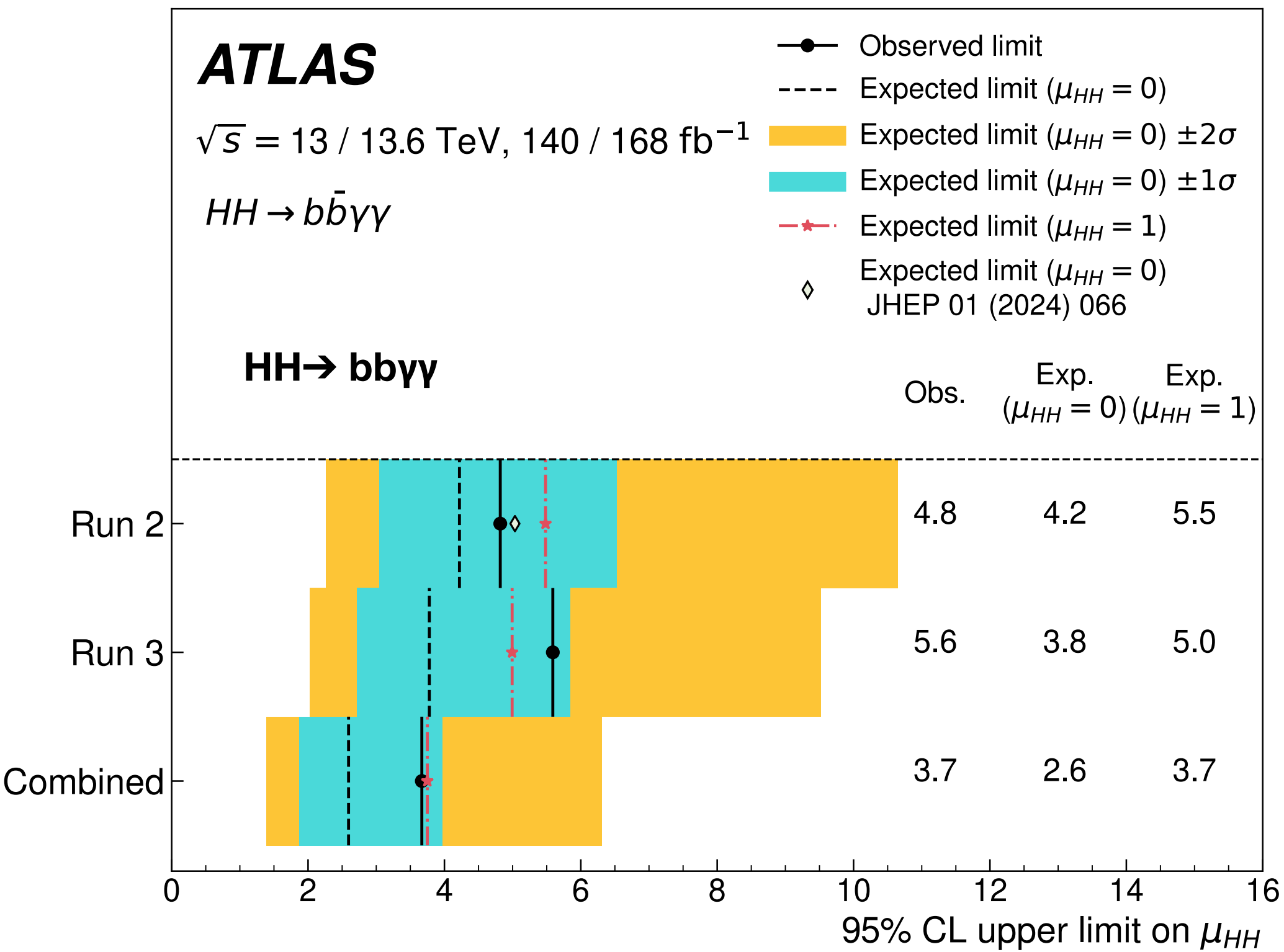
Data from 2022-2023



Similar sensitivity to Run 2, with less than half the Run 2 data set

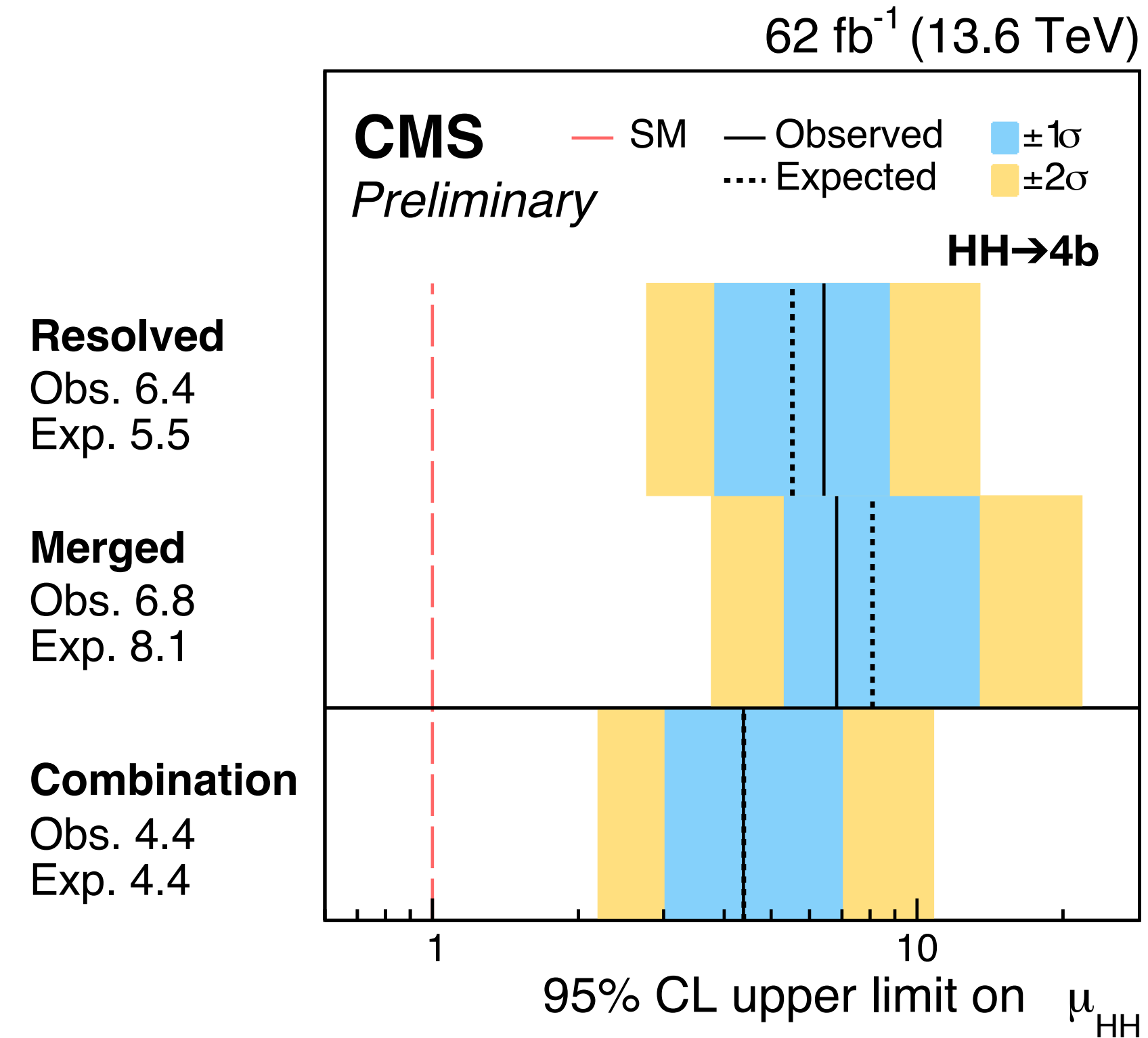
Di-Higgs in Run 3

Data from 2022-2024



Run 3 more sensitive than Run 2 (and more data to be analyzed)

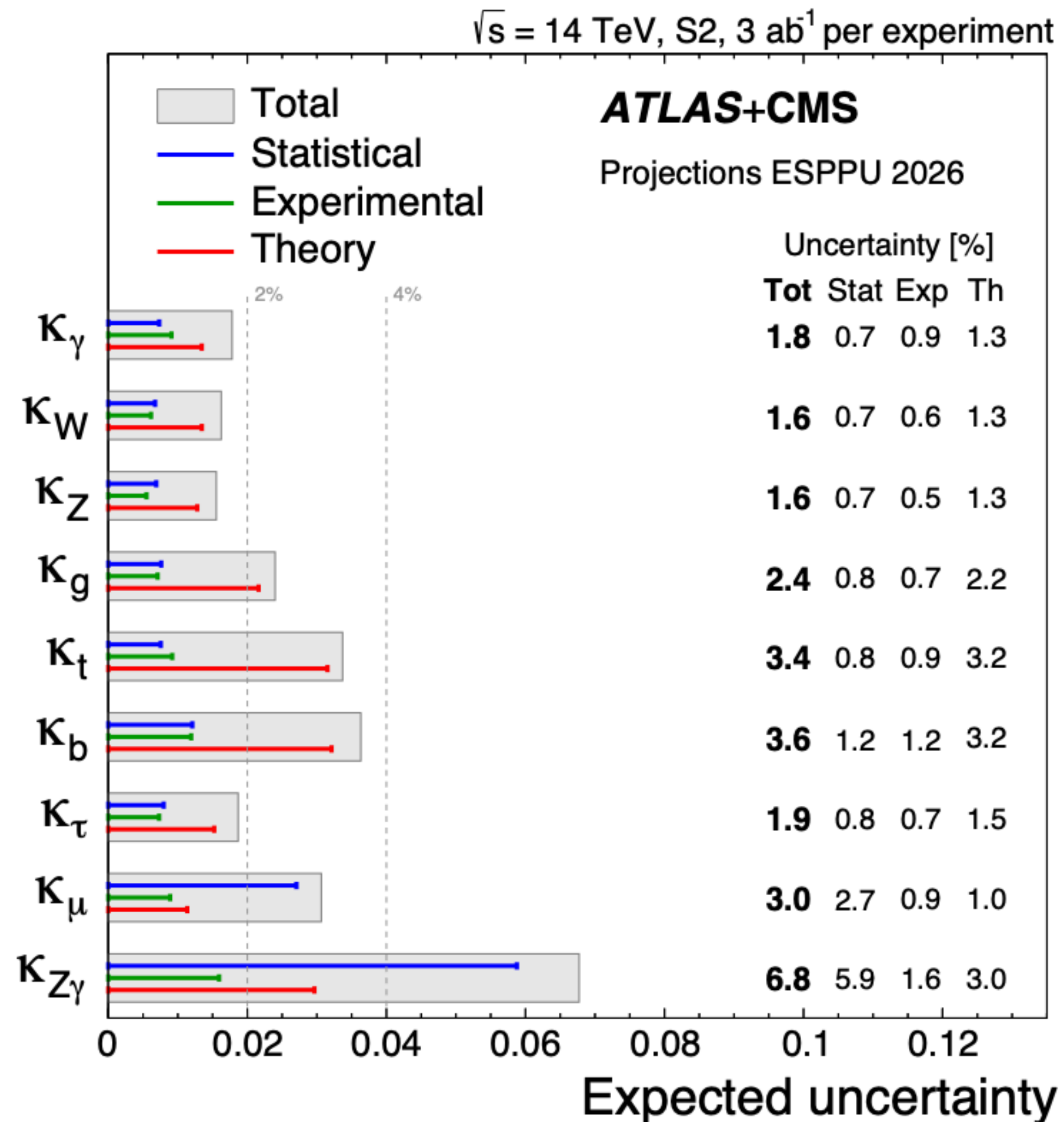
Data from 2022-2023



Similar sensitivity to Run 2, with less than half the Run 2 data set

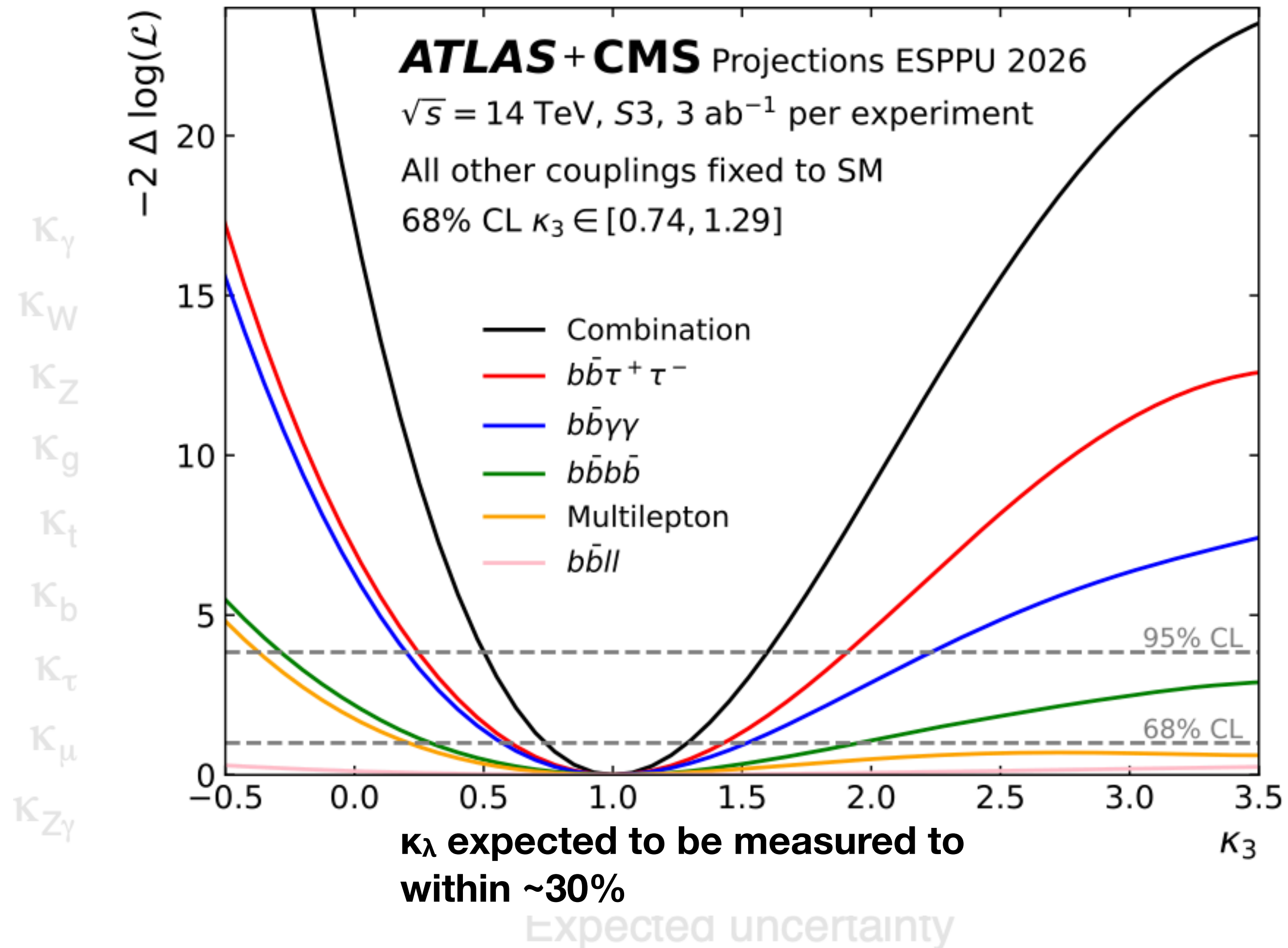
+ $HH \rightarrow b\bar{b}\gamma\gamma$ w/ 22-23:
 Not yet reaching Run 2 sensitivity

Future prospects: HL-LHC...



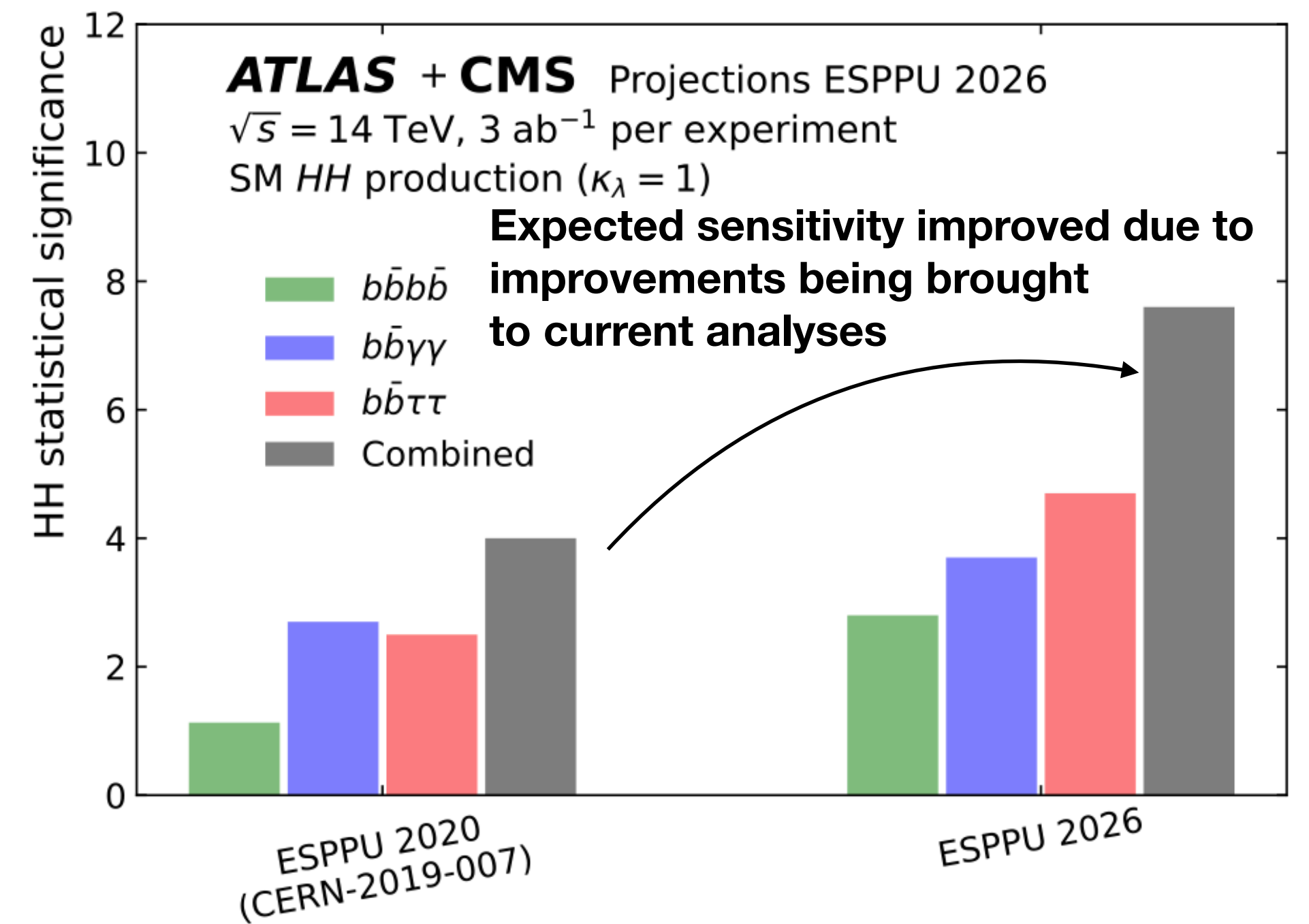
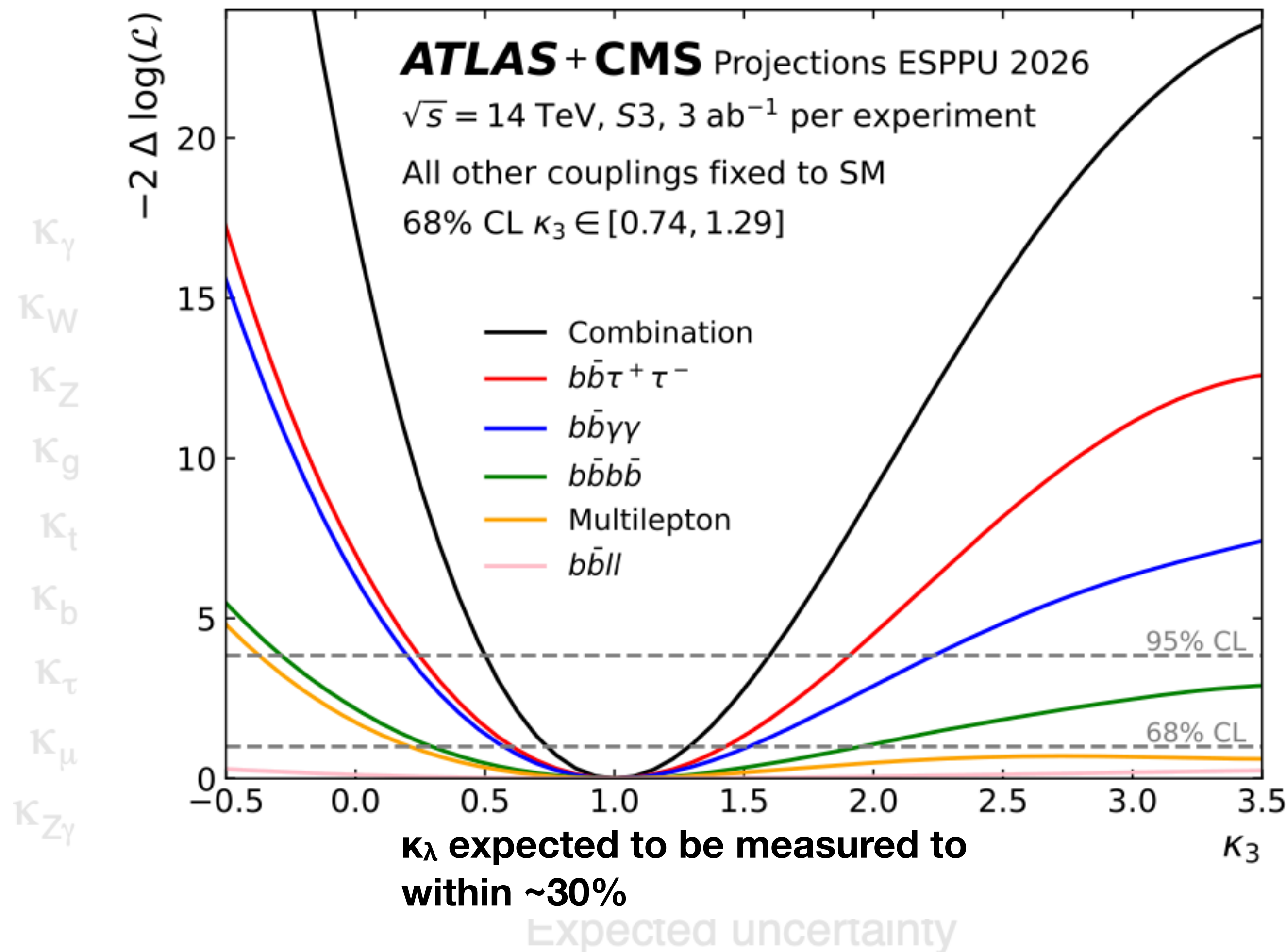
Higgs boson couplings: measurements expected to be dominated by theoretical uncertainties by the end of HL-LHC

Future prospects: HL-LHC...



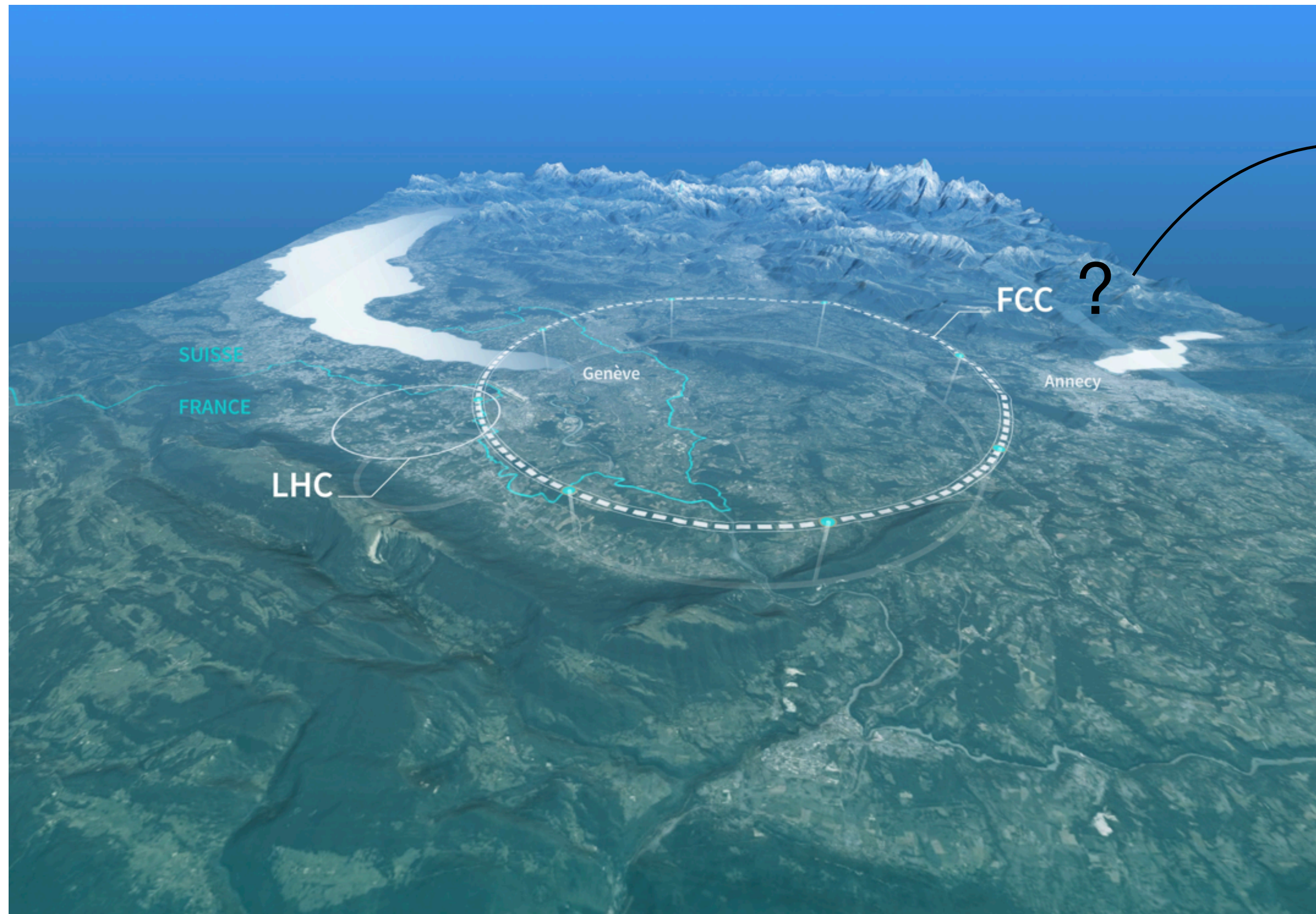
on couplings: measurements expected to be limited by theoretical uncertainties by the end of the HL-LHC

Future prospects: HL-LHC...



Or perhaps even better
 ...ed to
 ... by theoretical uncertainties by the end

... and beyond



4 MeV precision on m_H with FCC-ee

Sub per-cent level precision on many Higgs boson branching fractions

New decay modes accessible

\sqrt{s}	240 GeV		365 GeV	
channel	ZH	WW \rightarrow H	ZH	WW \rightarrow H
ZH \rightarrow any	± 0.31		± 0.52	
γ H \rightarrow any	± 150			
H \rightarrow bb	± 0.21	± 1.9	± 0.38	± 0.66
H \rightarrow cc	± 1.6	± 19	± 2.9	± 3.4
H \rightarrow ss	± 120	± 990	± 350	± 280
H \rightarrow gg	± 0.80	± 5.5	± 2.1	± 2.6
H \rightarrow $\tau\tau$	± 0.58		± 1.2	$\pm 5.6^{(*)}$
H \rightarrow $\mu\mu$	± 11		± 25	
H \rightarrow WW*	± 0.80		$\pm 1.8^{(*)}$	$\pm 2.1^{(*)}$
H \rightarrow ZZ*	± 2.5		$\pm 8.3^{(*)}$	$\pm 4.6^{(*)}$
H \rightarrow $\gamma\gamma$	± 3.6		± 13	± 15
H \rightarrow Z γ	± 11.8		± 22	± 23
H \rightarrow $\nu\nu\nu\nu$	± 25		± 77	
H \rightarrow inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H \rightarrow dd	$< 1.2 \times 10^{-3}$			
H \rightarrow uu	$< 1.2 \times 10^{-3}$			
H \rightarrow bs	$< 3.1 \times 10^{-4}$			
H \rightarrow bu	$< 2.2 \times 10^{-4}$			
H \rightarrow sd	$< 2.0 \times 10^{-4}$			
H \rightarrow cu	$< 6.5 \times 10^{-4}$			

Summary

- Much has been learned about the Higgs boson since the discovery in 2012
- Still a lot to explore with LHC Run 3, HL-LHC, and beyond

