July 18, 2022

Higgs Physics Report

Snowmass CSS

<u>Isobel Ojalvo</u>, Sally Dawson,
Patrick Meade, Caterina Vernieri

Energy Frontier Higgs SM and BSM working groups

- All reports can be found here: link
- Higgs Report: link
- Google Doc for Comments: link
- Google Doc to sign up for authorship: link

The Case for Precision Higgs Physics

Sally Dawson, Patrick Meade, Isobel Ojalvo and Caterina Vernieri

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Some motivations (more in the next talk)

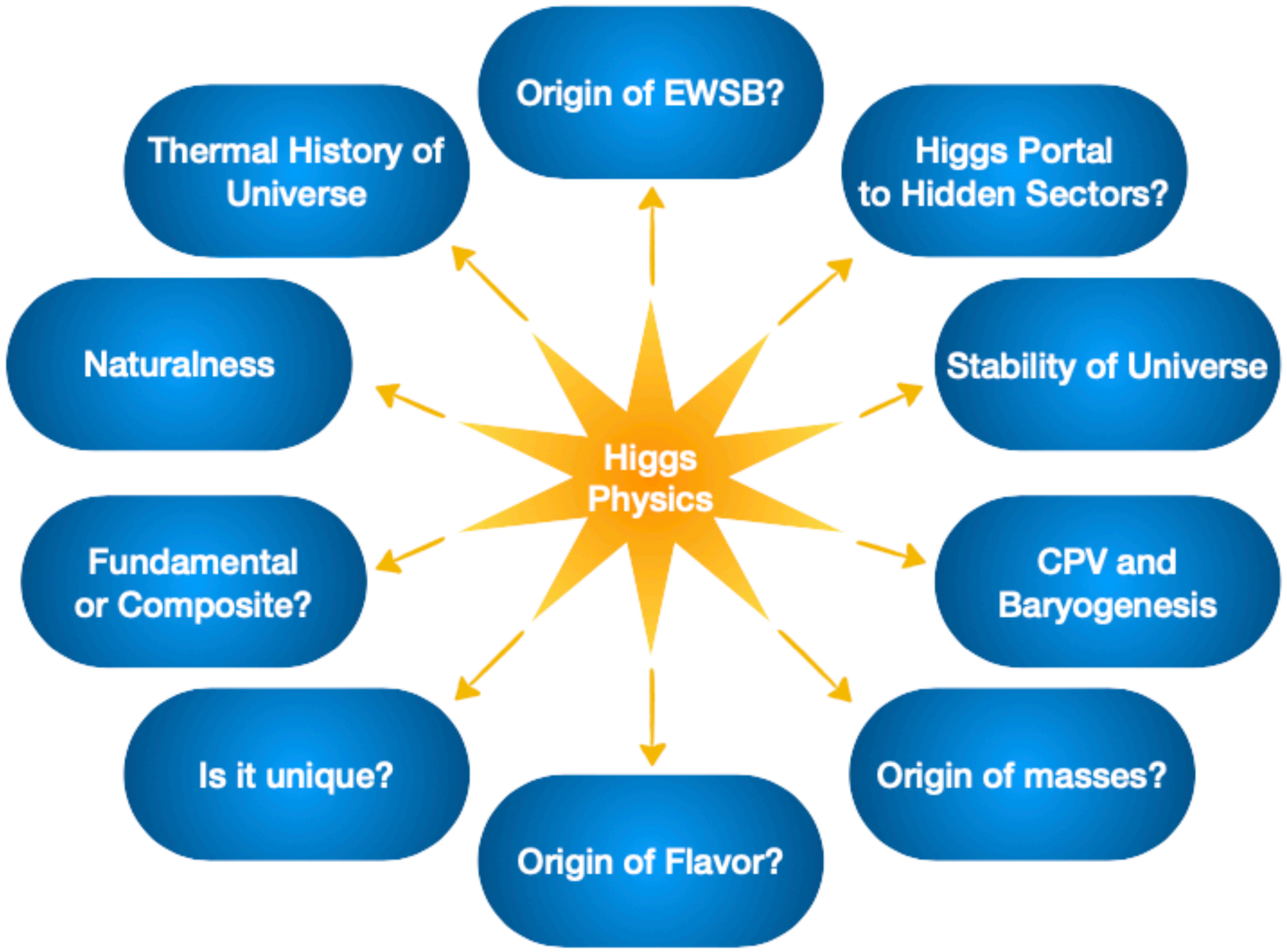

FIG. 1: The Higgs boson as the keystone of the Standard Model is connected to numerous fundamental questions that can be investigated by studying it in detail.

Some motivations (more in the next talk)

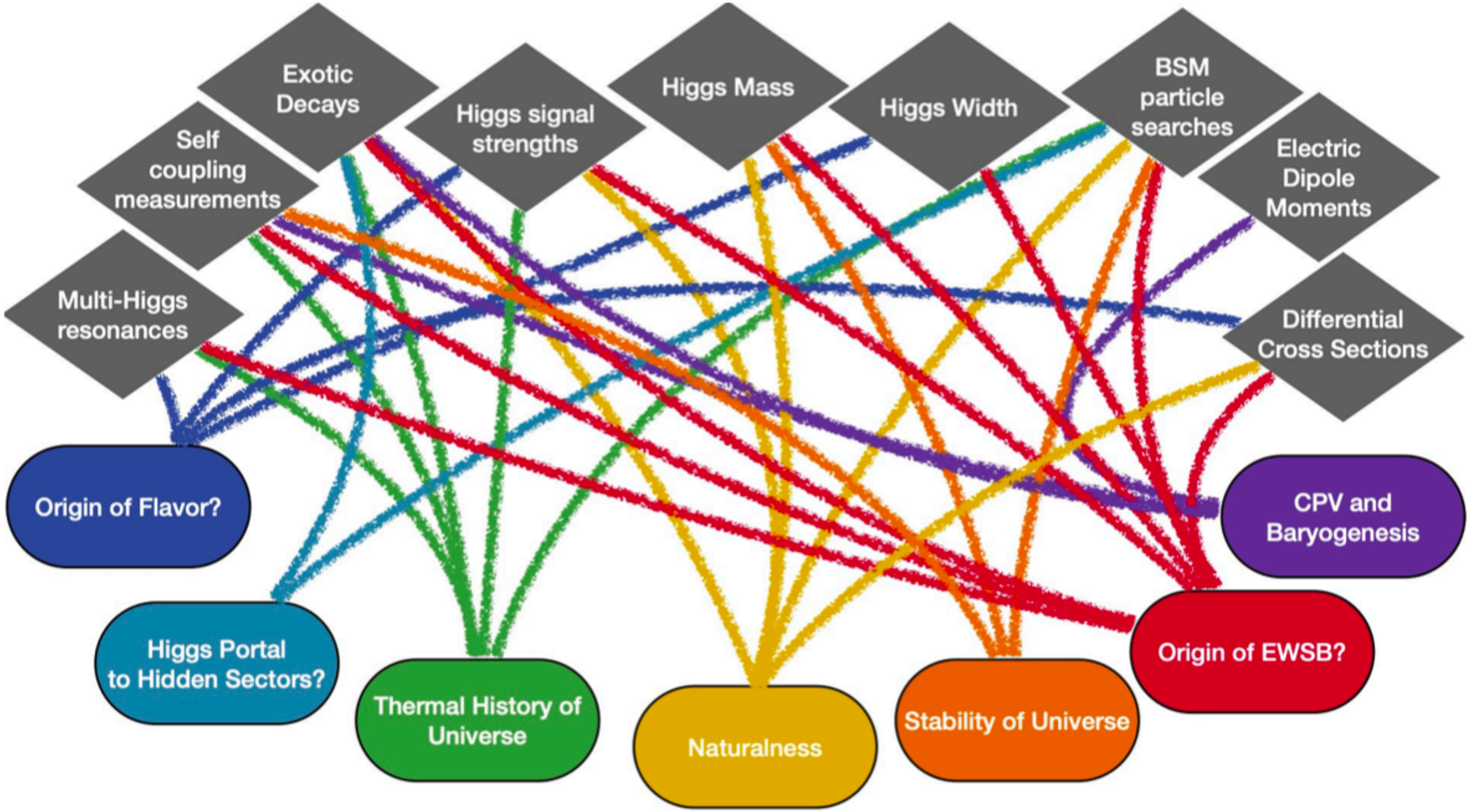

FIG. 2: Examples of the interplay between experimental observables and fundamental questions connected to the Higgs boson.

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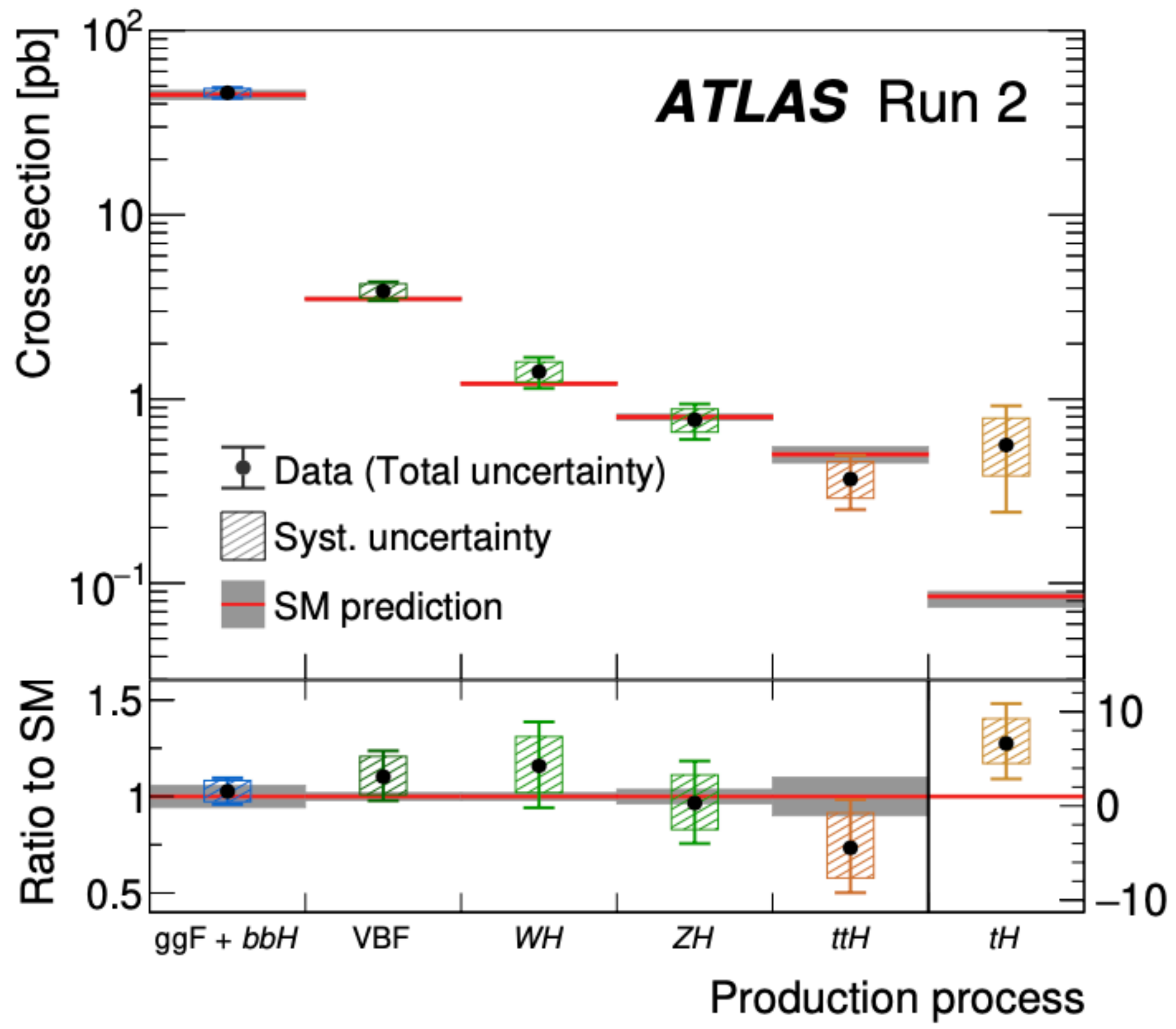
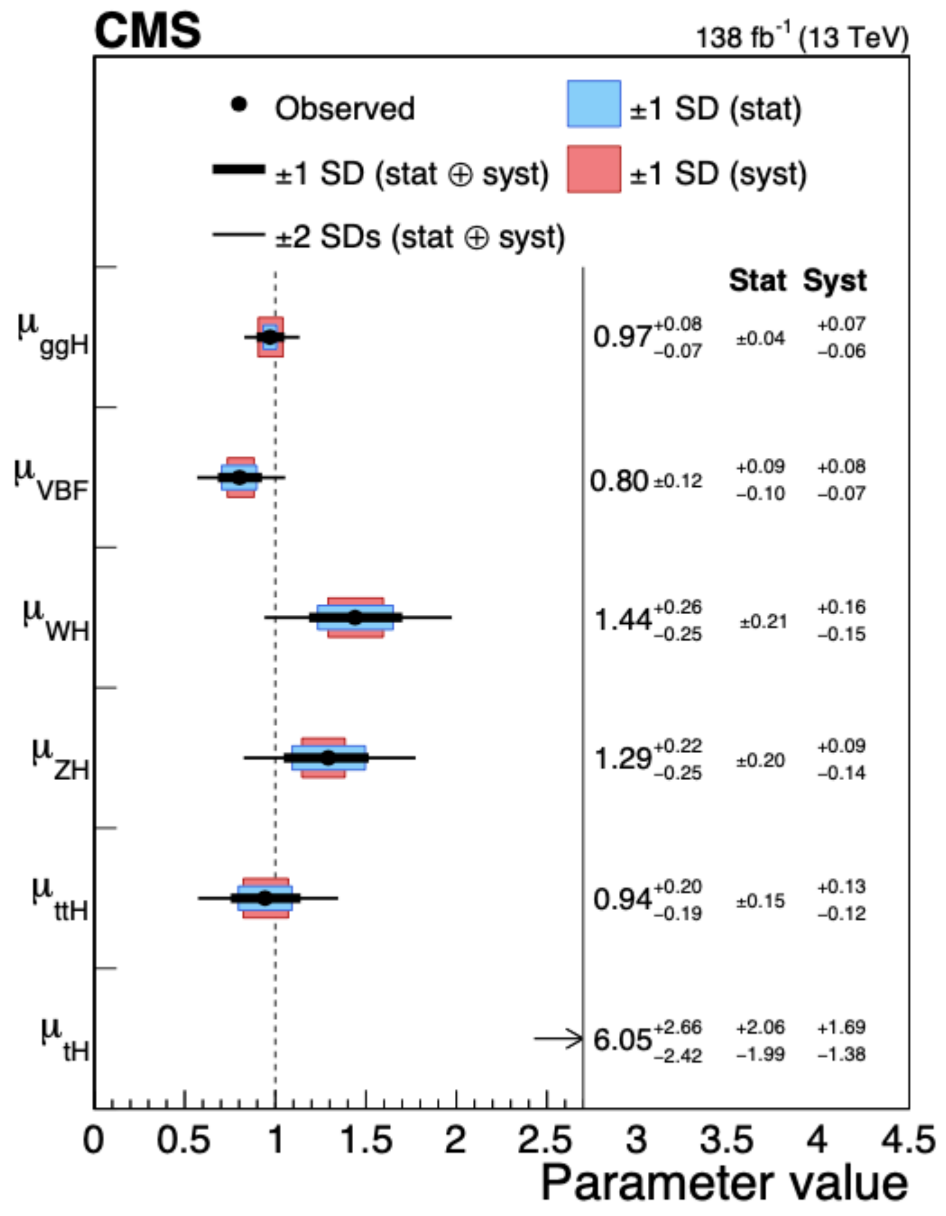
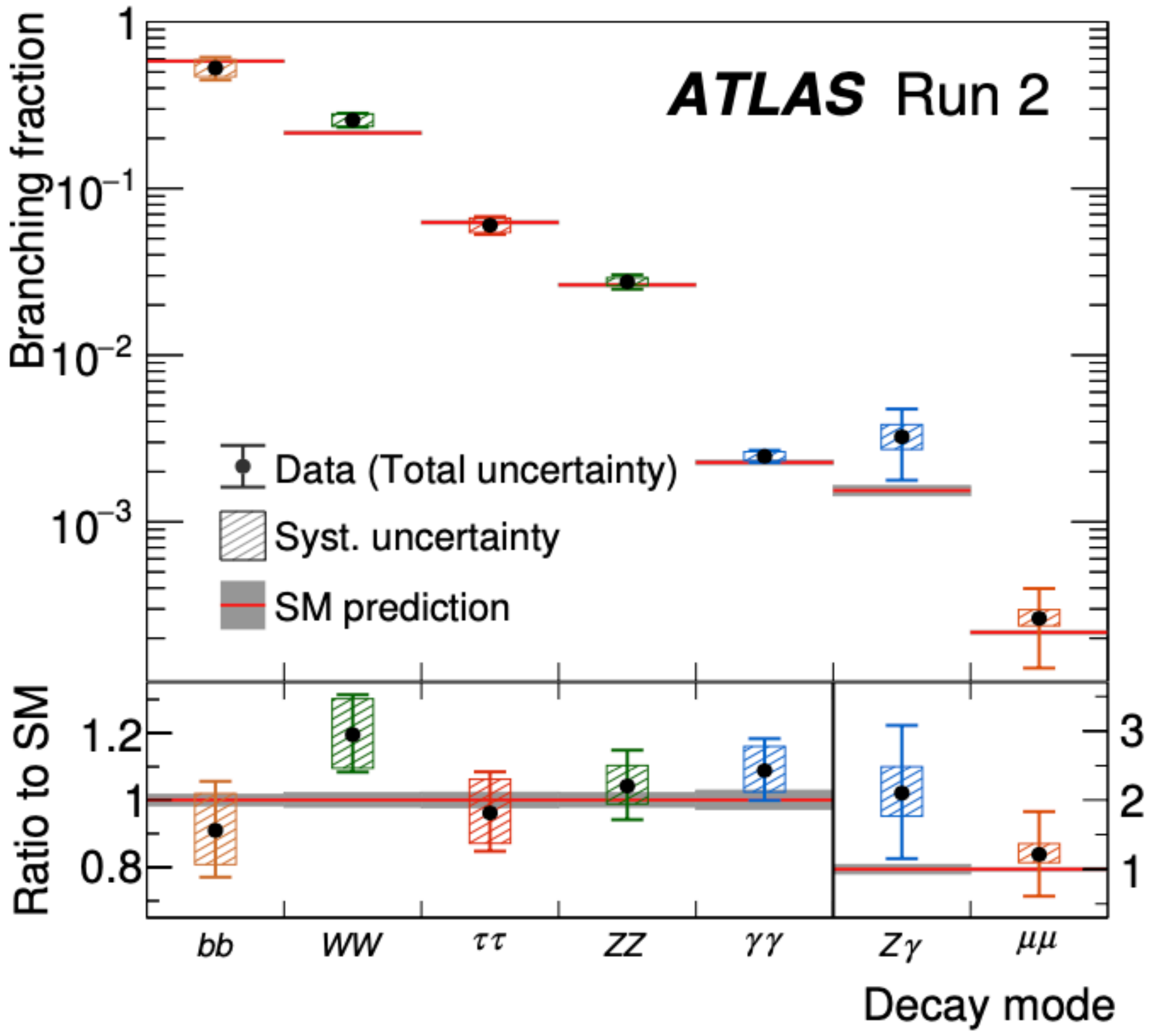
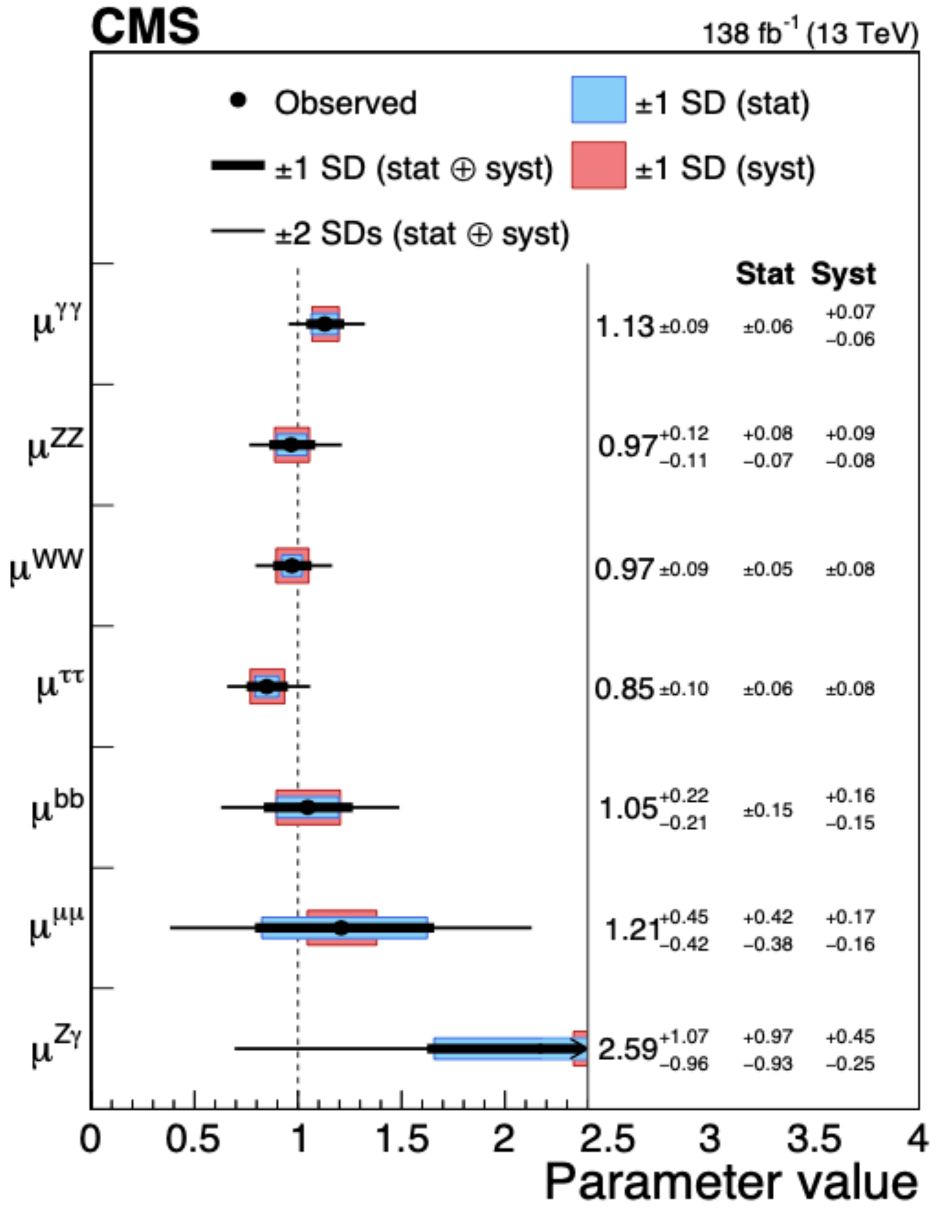
Higgs Production & Decay

- The mass is a free parameter in the SM and it is now measured to per-mille accuracy at
CMS: 125.38±0.14 GeV,
ATLAS: 124.92±0.21 GeV
- All of these channels are **precisely measured**, with the experimental sensitivity of some modes nearing the precision of state-of-the-art theory predictions









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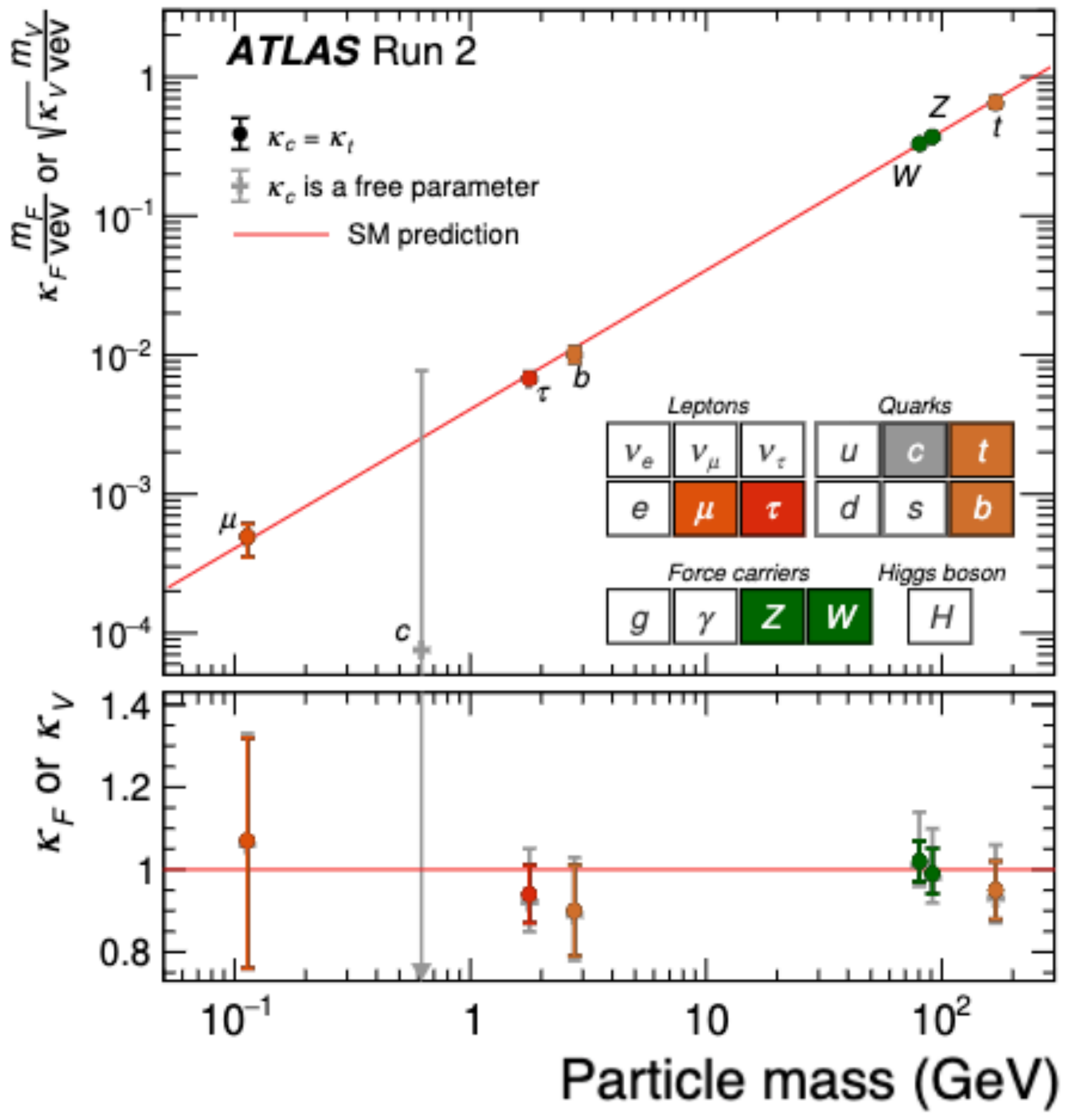
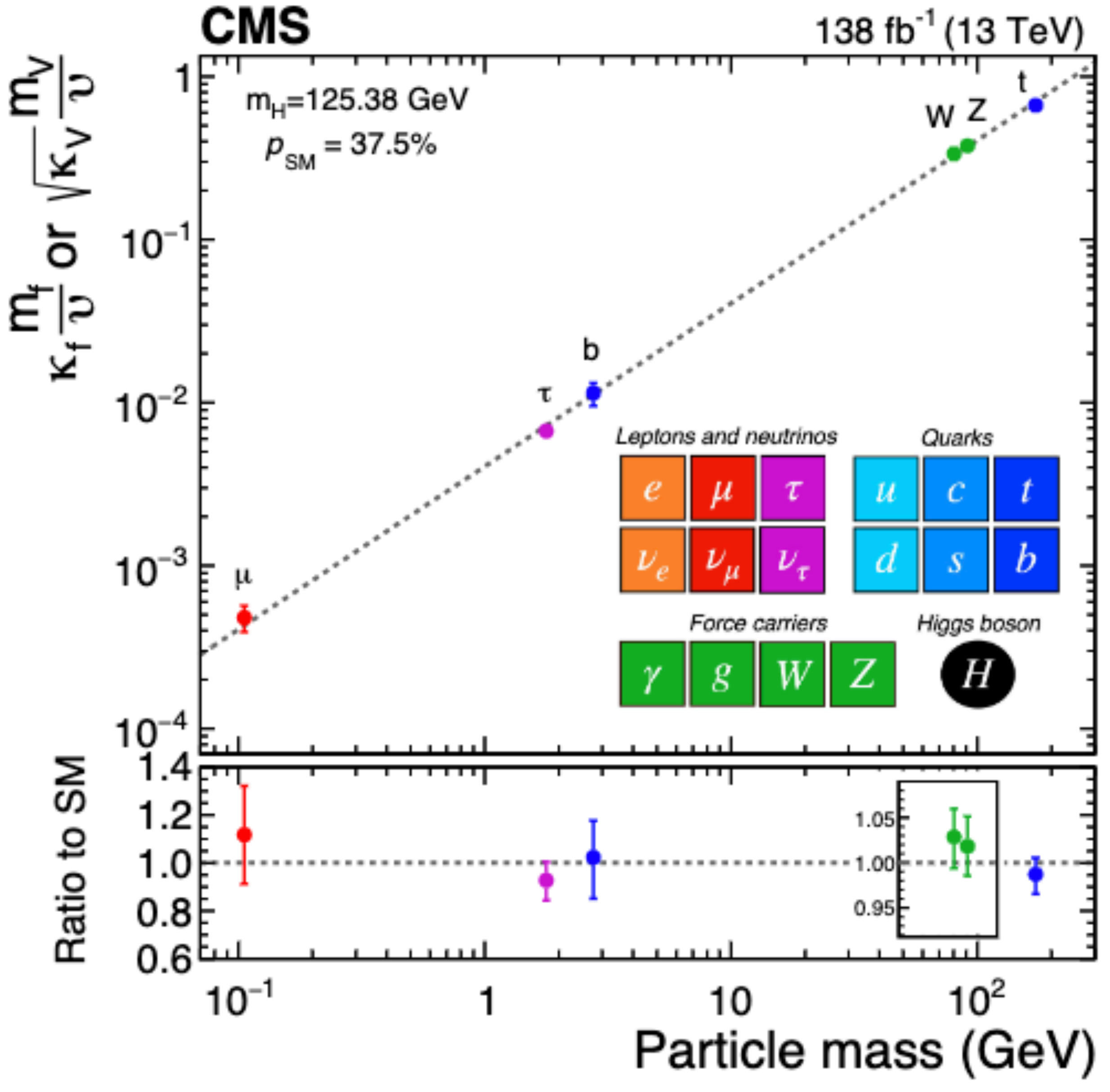
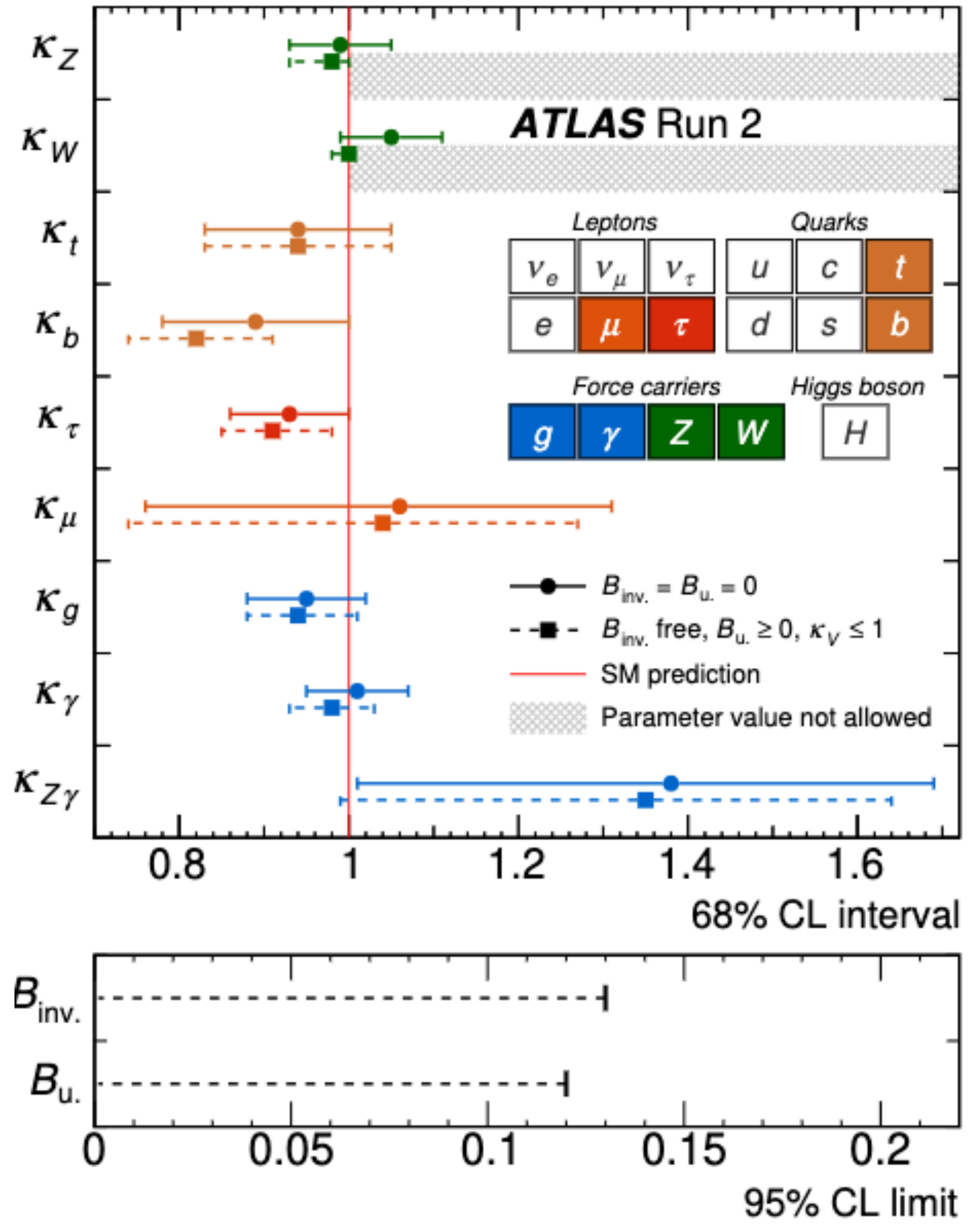
Plots featured in Higgs EF Report

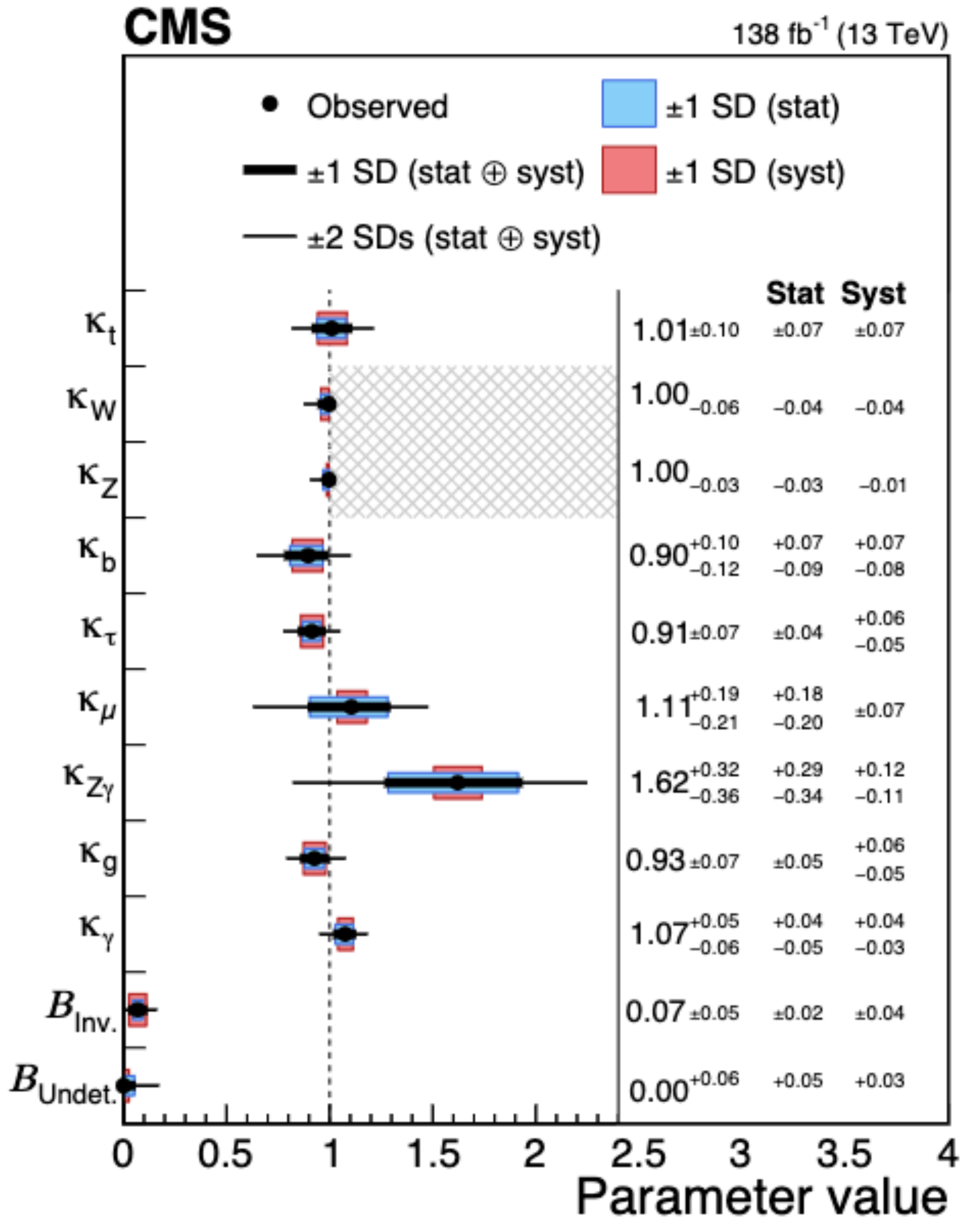
Higgs Couplings

- The strengths of the couplings increase with the masses of the elementary particles
  - So far, good agreement, within experimental uncertainties
- SM BR(h→ inv), is only about 0.1%, from the decay of the Higgs boson via ZZ*→ 4v
  - Observation of an invisible decay, would be a clear signal of BSM Physics
  - The most stringent constraint currently is set by CMS exploiting the VBF topology, with 101 fb^{-1} at 13 TeV
    - CMS 18% obs. (10% exp.)
    - ATLAS 14.5% obs. (10.3% exp.)





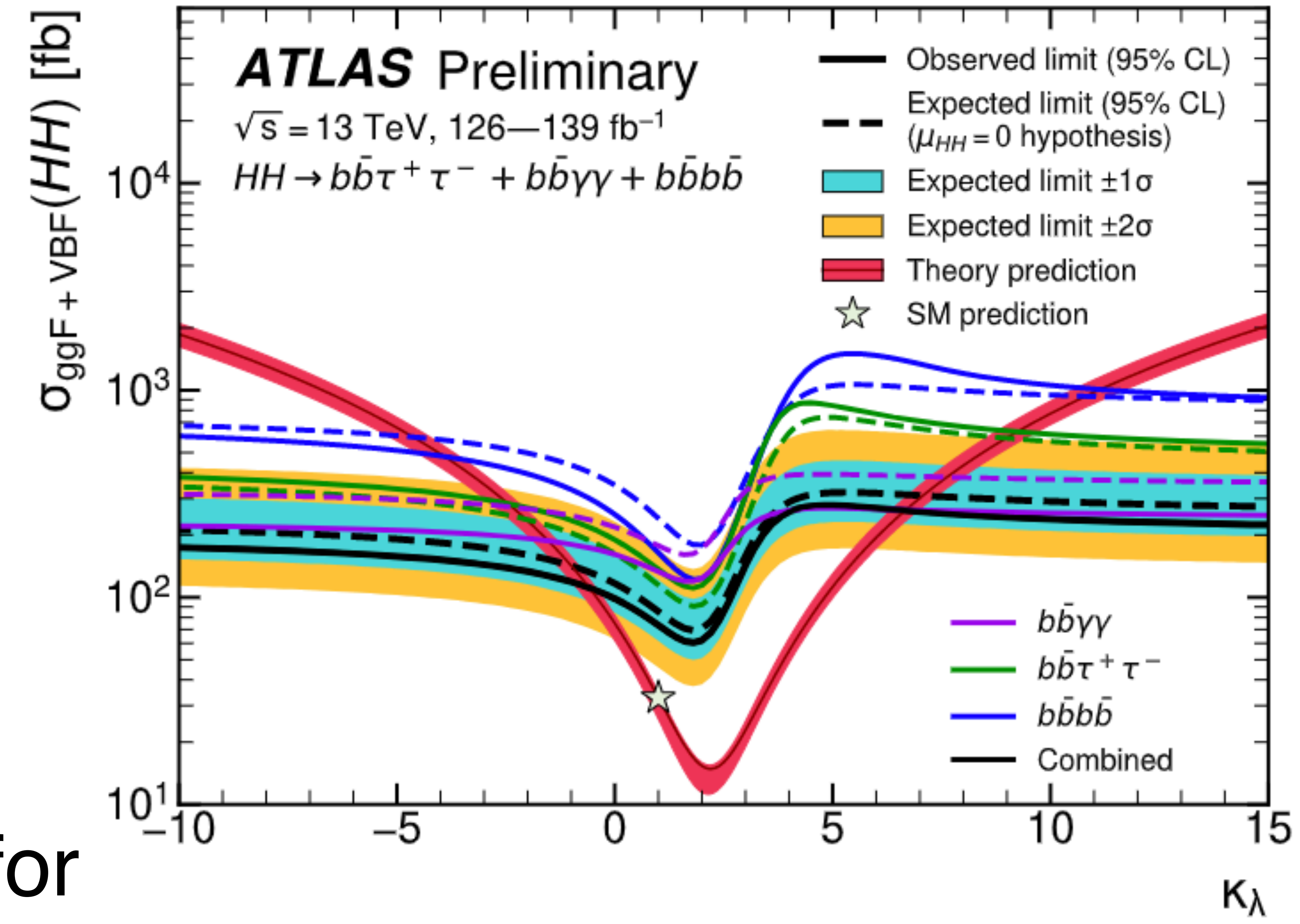


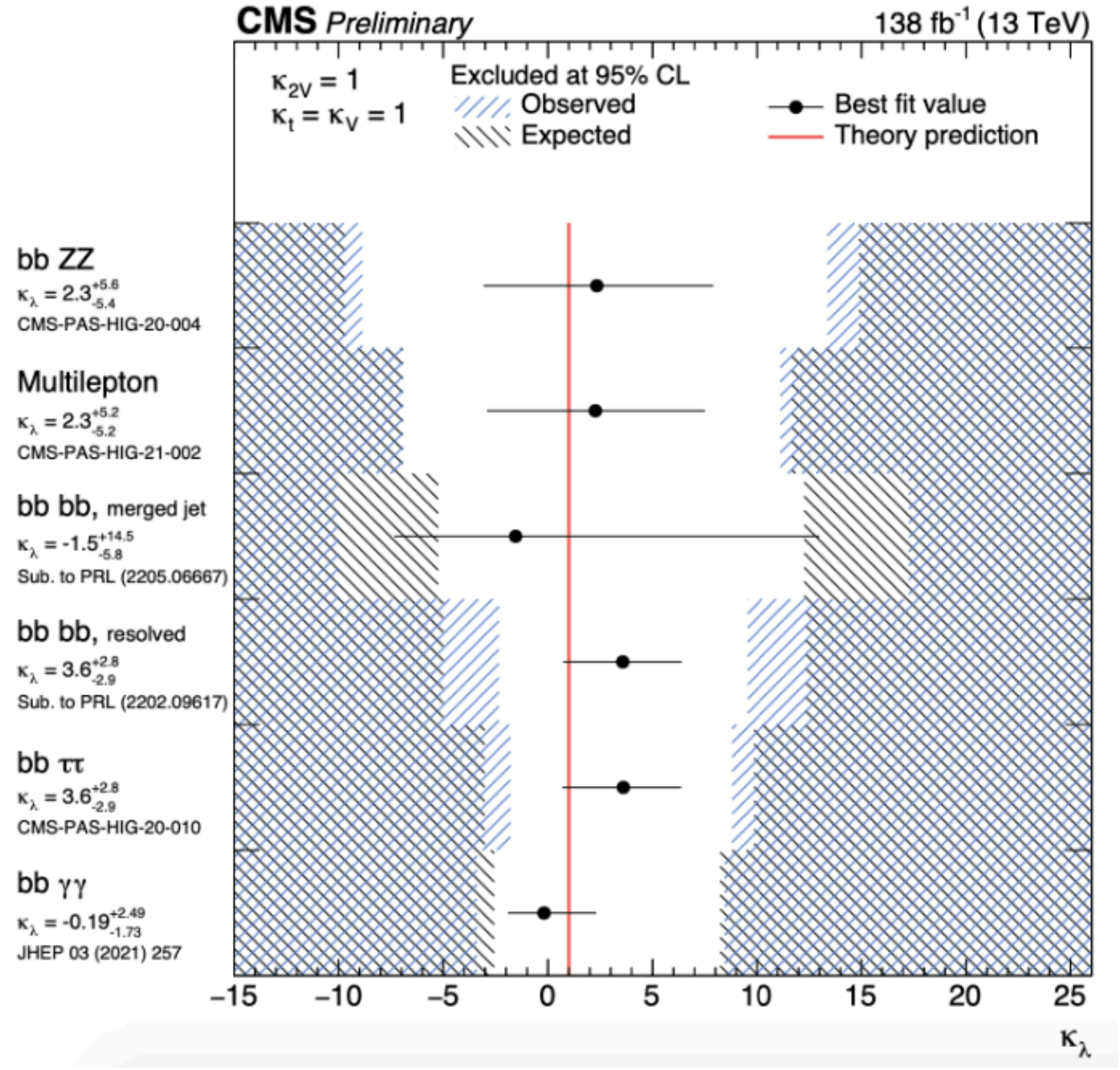


Plots featured in EF Higgs writeup

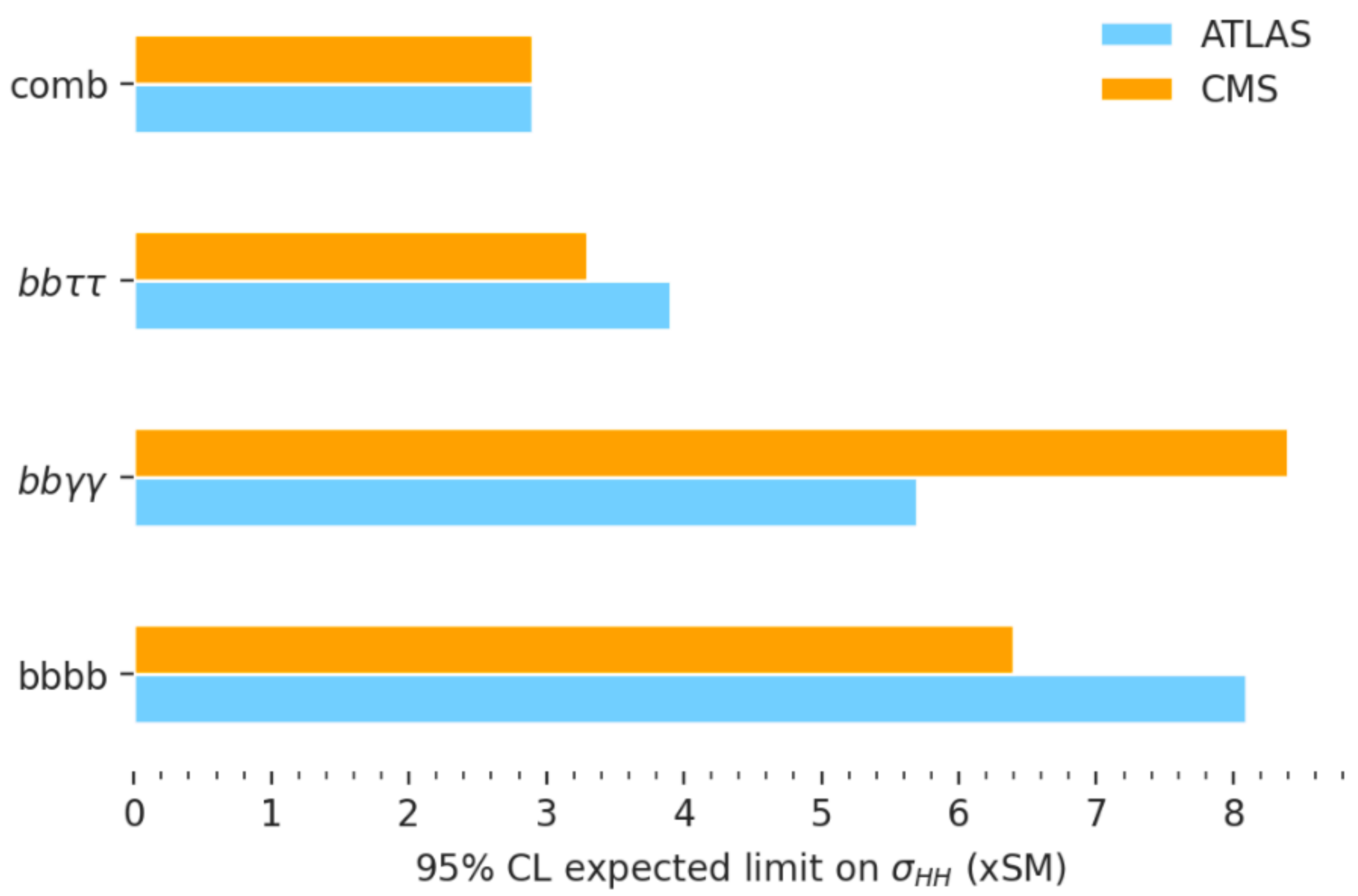
Higgs Self Coupling Status

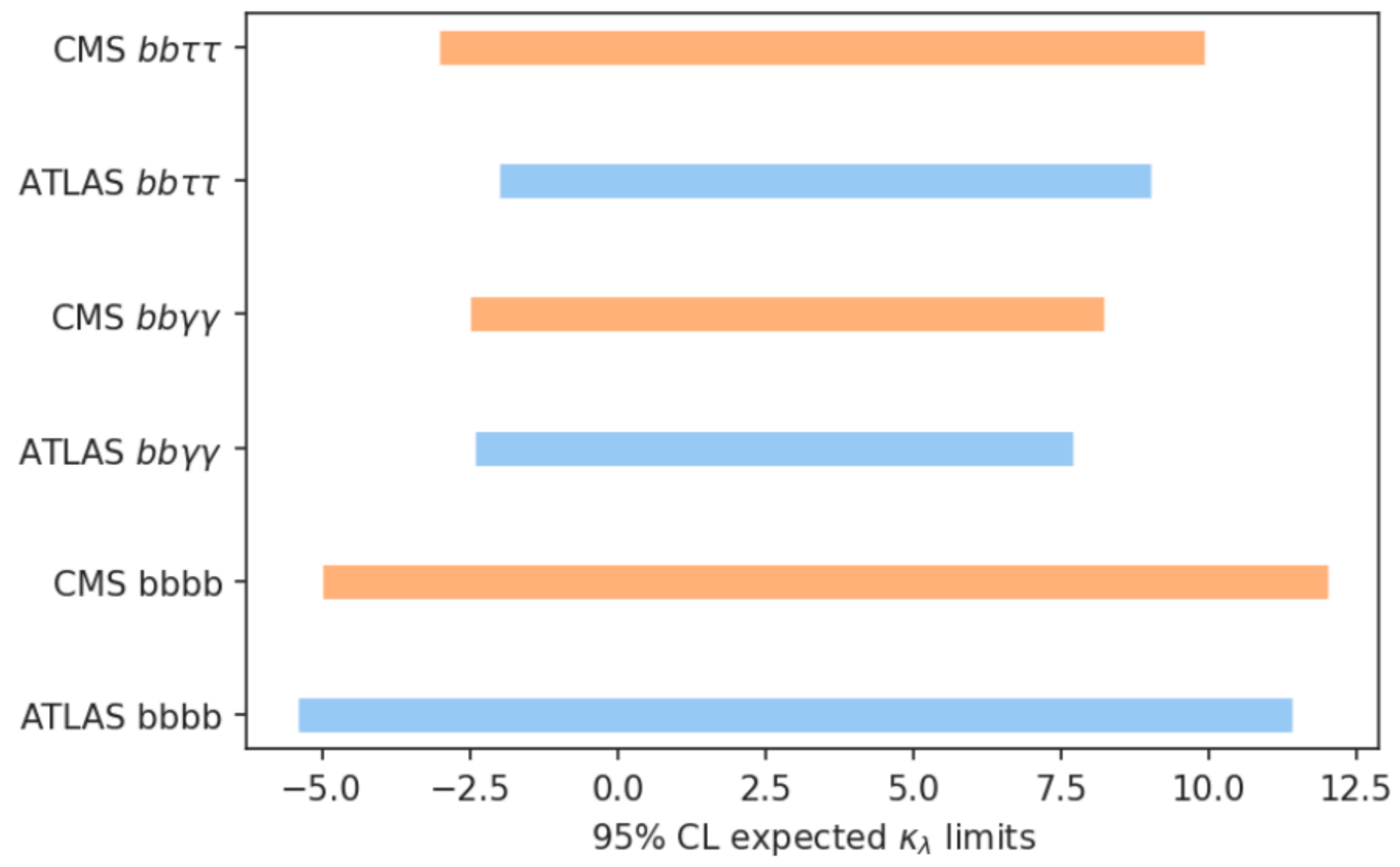
- Expected upper limit on σ(pp→hh) and κ_λ for the most significant channels analyzed by ATLAS and CMS with full Run 2 data





- Upper limit on σ(pp → hh) for a given value of κ_λ published by ATLAS and CMS
  - Combined upper limit on the cross section ~ 3 x SM





Plots featured in EF Higgs writeup

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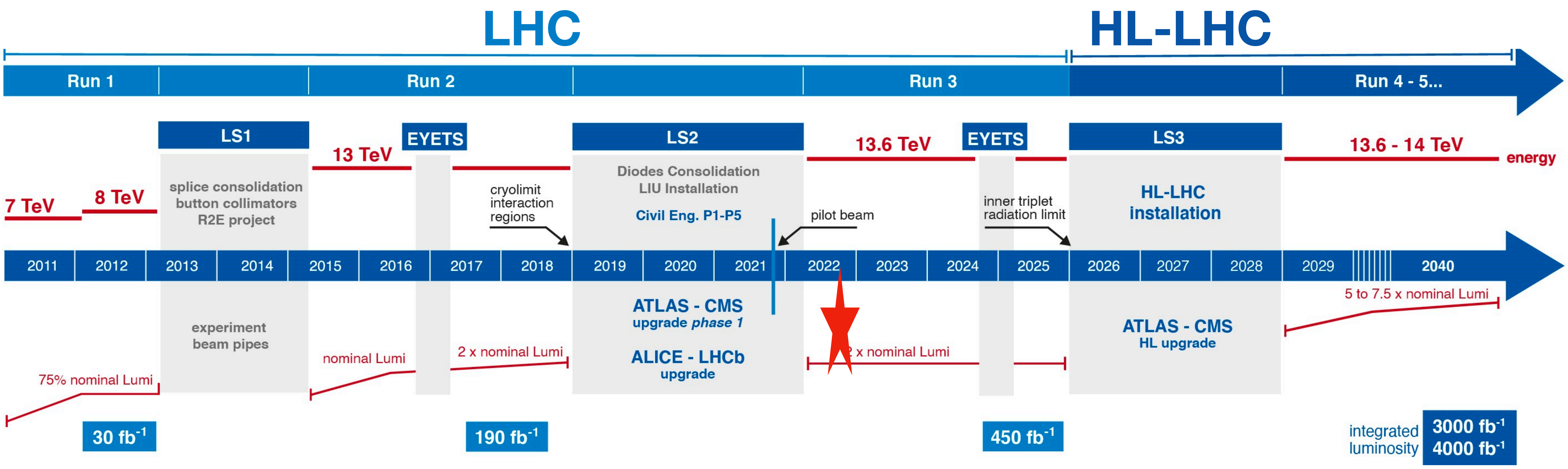
For this talk, first will discuss HL-LHC

LHC→HL-LHC



Run-2

8 Million Higgs

Run-3

16 Million Higgs

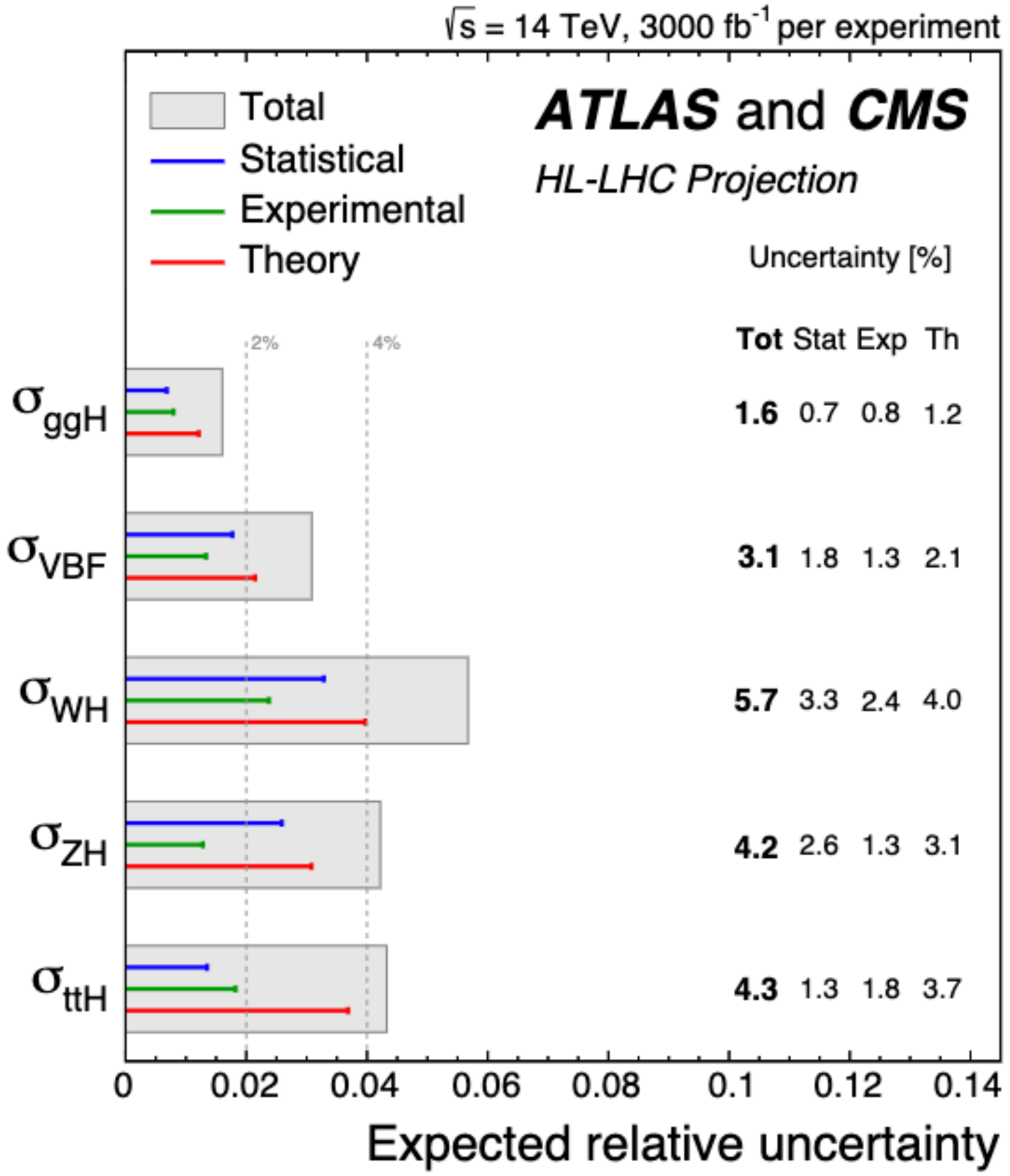
Run-4/5

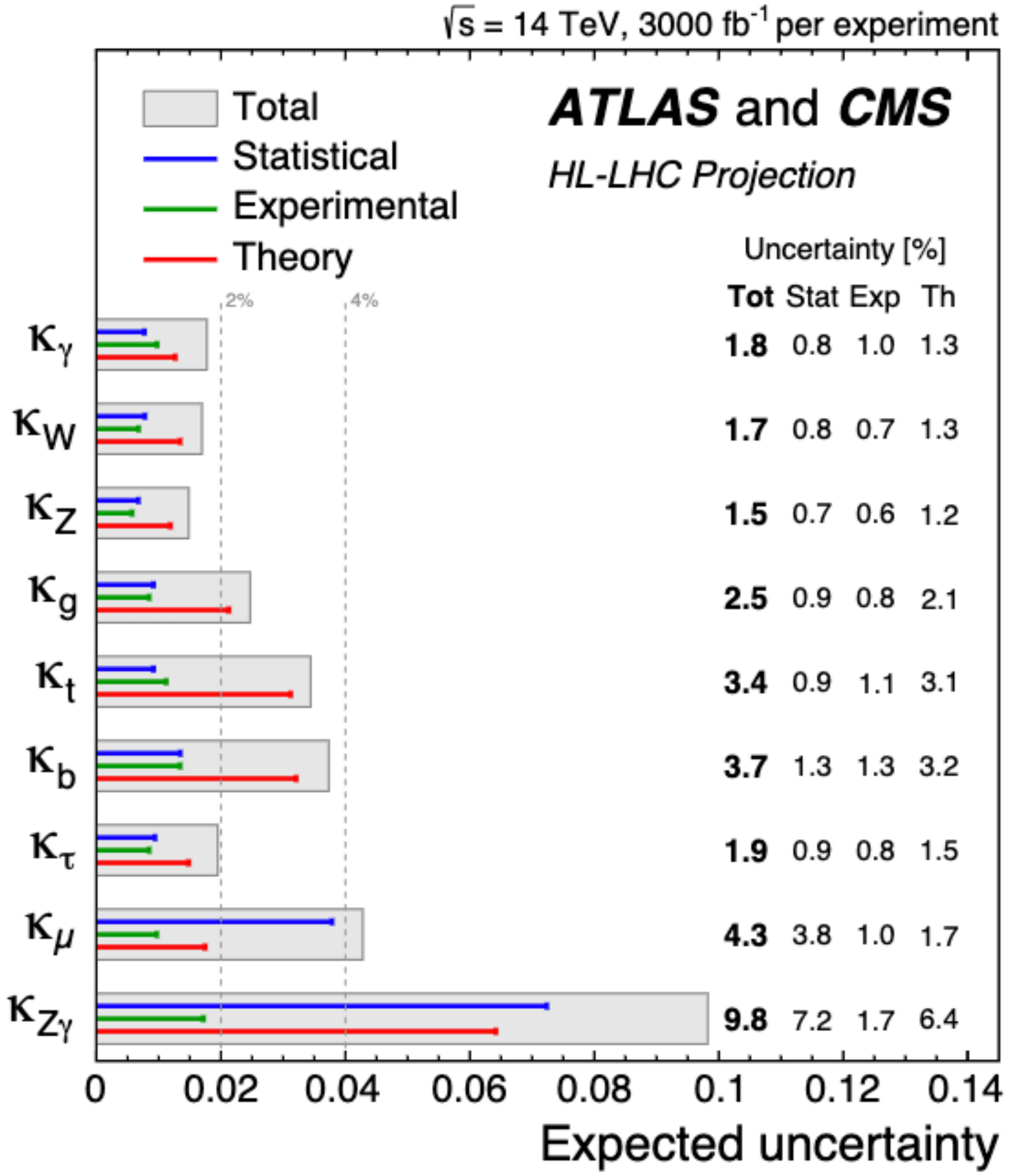
170 Million Higgs
120 Thousand Di-Higgs

Much of this already covered in Sapta's talk!

Higgs Physics at the HL-LHC

- First studies performed for the ESG with updates for Snowmass Exercise
    - YR 18 uncertainties (S2 scenario)
- H→μμ and H→Zγ measurements still limited by size of the collected dataset
- Other couplings currently dominated by **theoretical uncertainties**
- Often experiments outperform expected projections for experimental uncertainties





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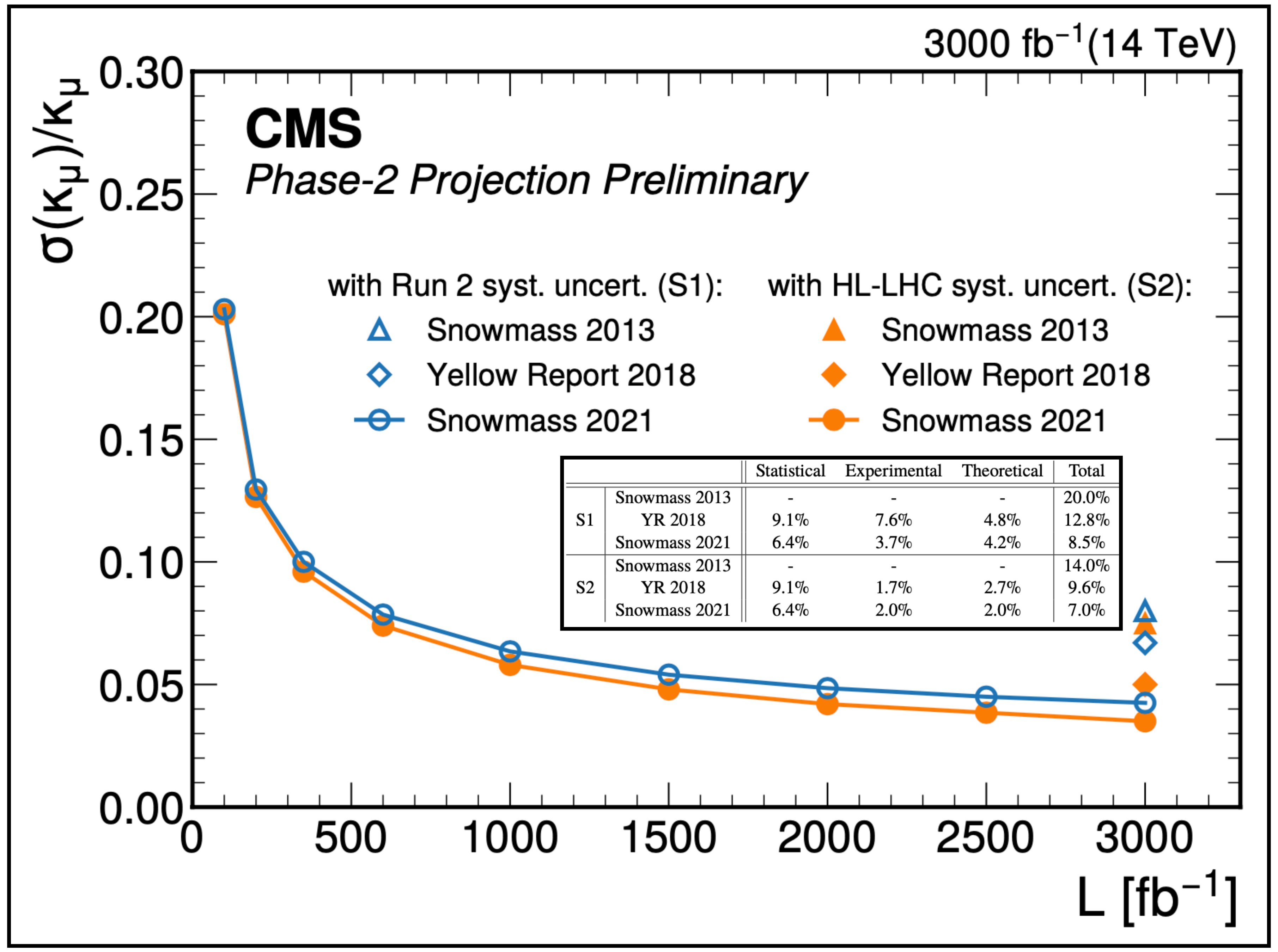
Plots featured in EF Higgs writeup

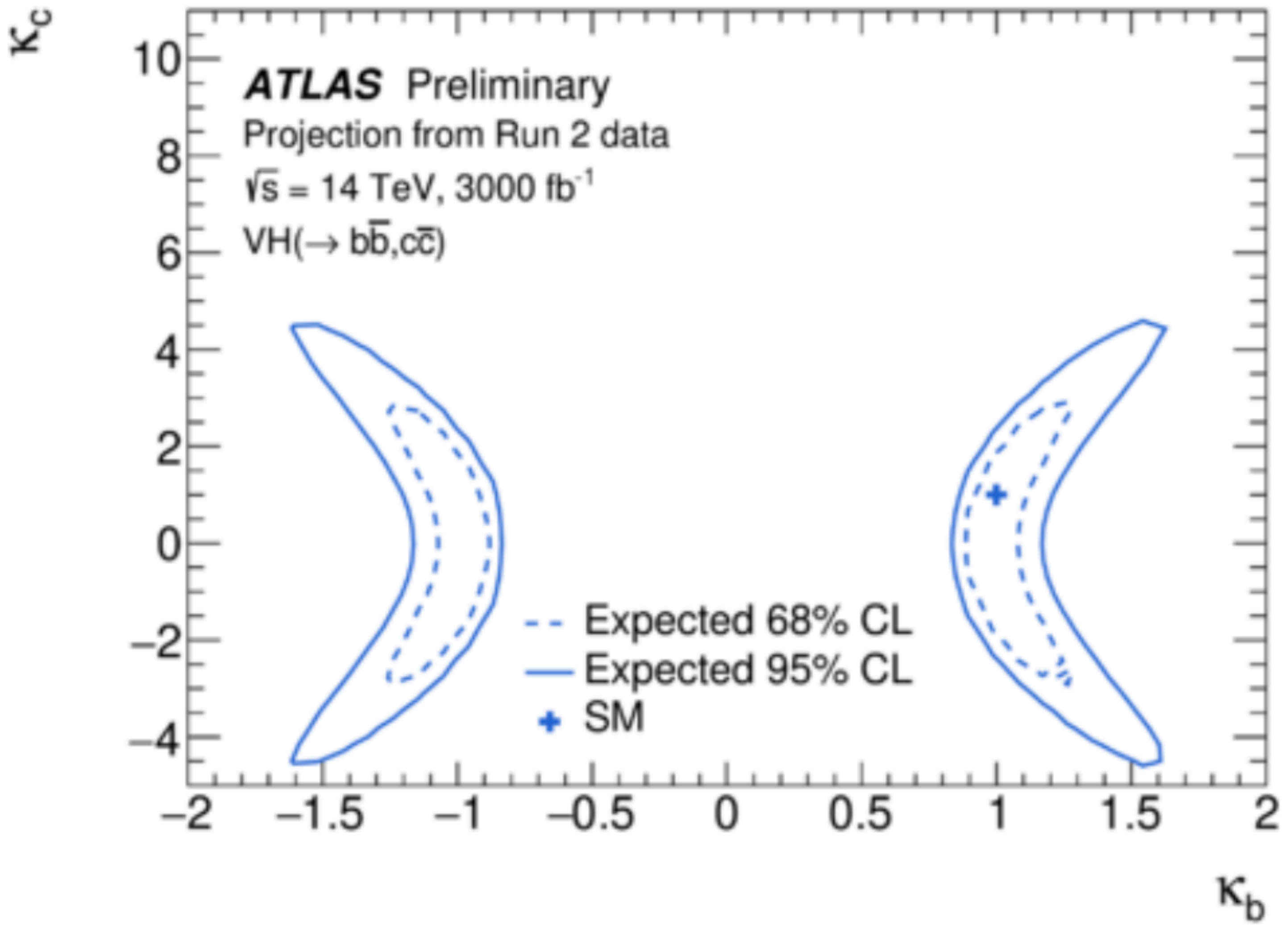
Higgs Physics at the HL-LHC

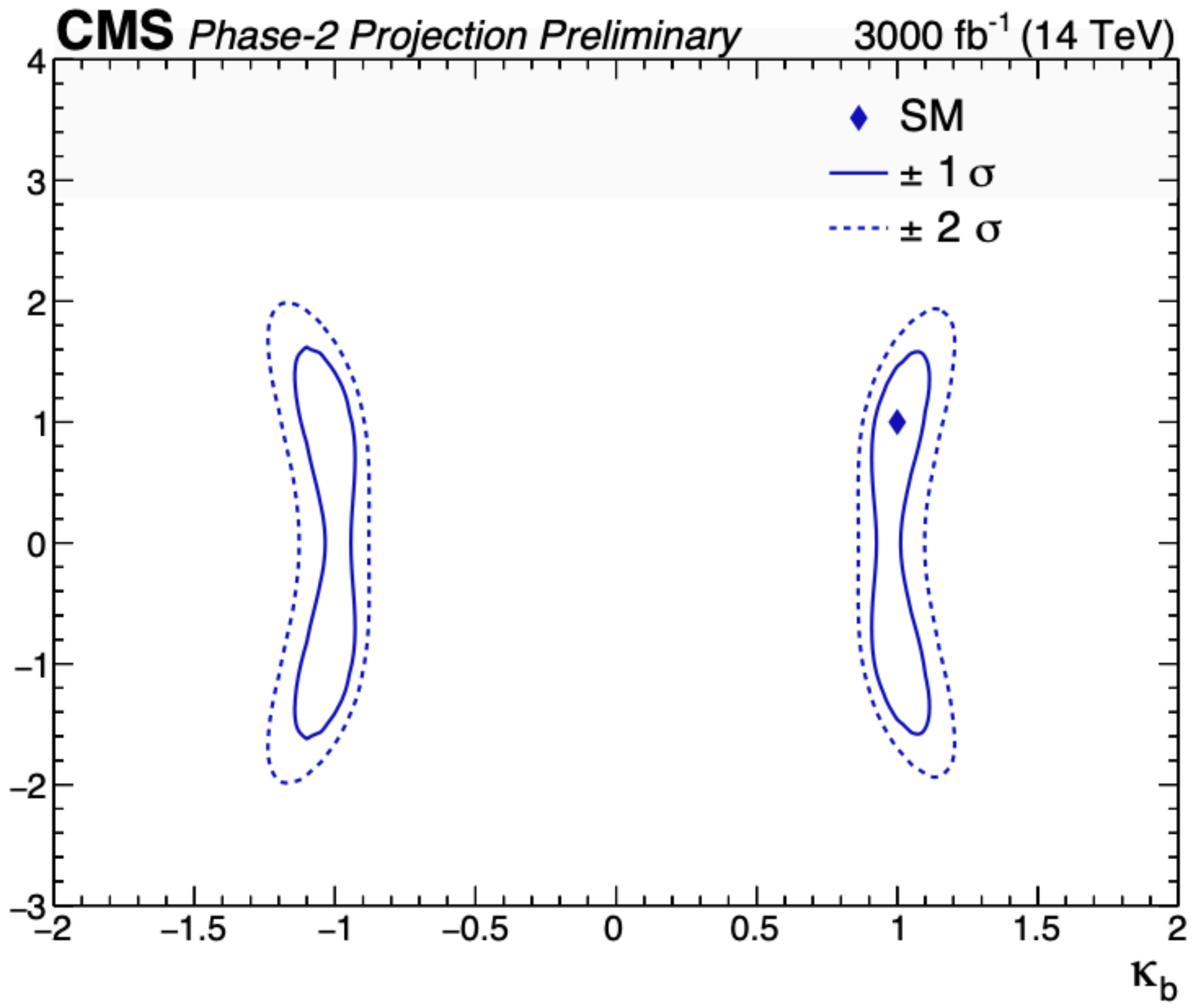
- $H \to \mu\mu$
  - YR projections performed from partial Run2 dataset analyses Full Run2 measurements have improved beyond expectations
  - i.e. $H \to \tau\tau$ or $H \to bb$ improved as $\sqrt{L}$ despite being dominated by systematic uncertainties



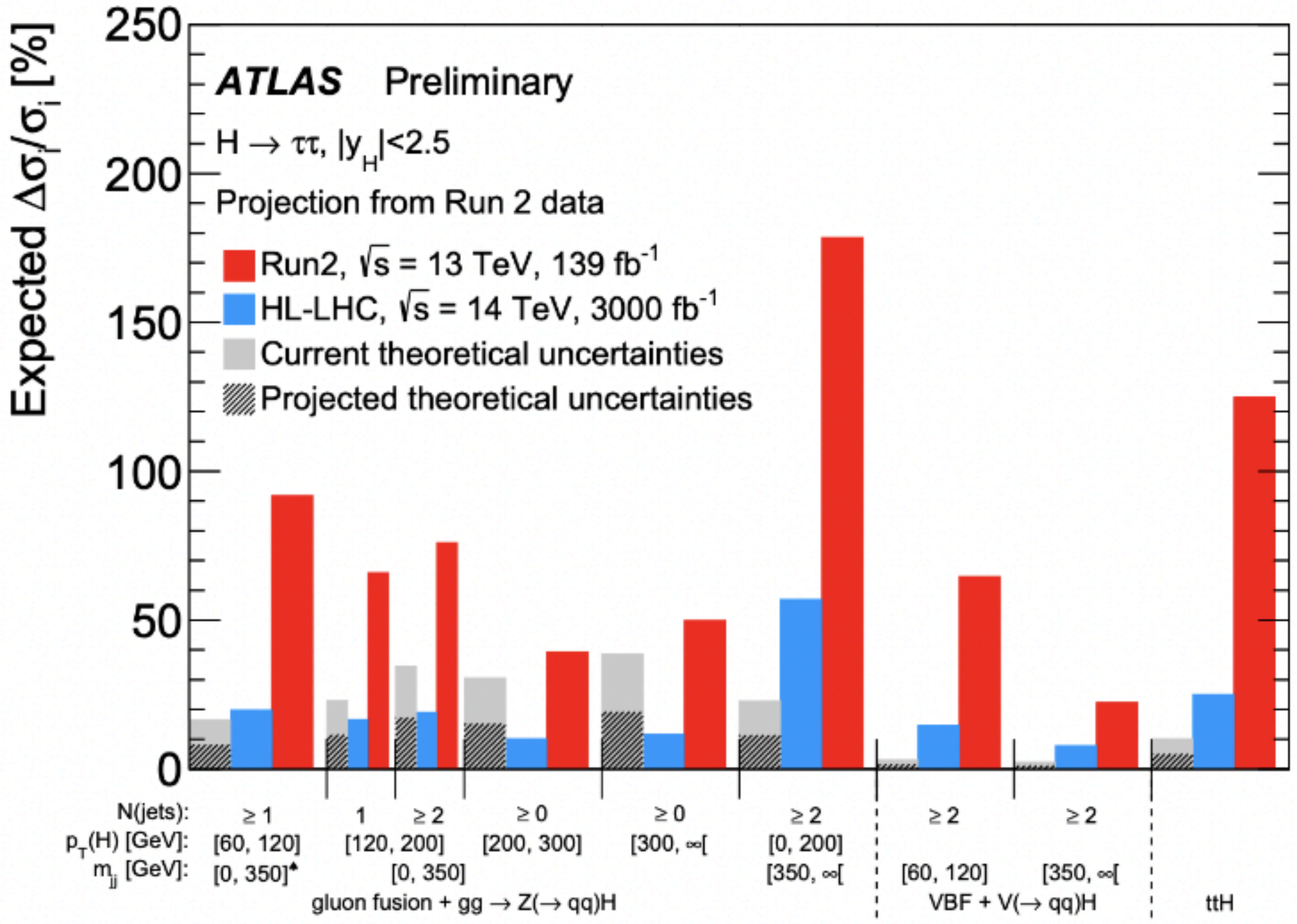
		Statistical	Experimental	Theoretical	Total
S1	Snowmass 2013	-	-	-	20.0%
	YR 2018	9.1%	7.6%	4.8%	12.8%
	Snowmass 2021	6.4%	3.7%	4.2%	8.5%
S2	Snowmass 2013	-	-	-	14.0%
	YR 2018	9.1%	1.7%	2.7%	9.6%
	Snowmass 2021	6.4%	2.0%	2.0%	7.0%

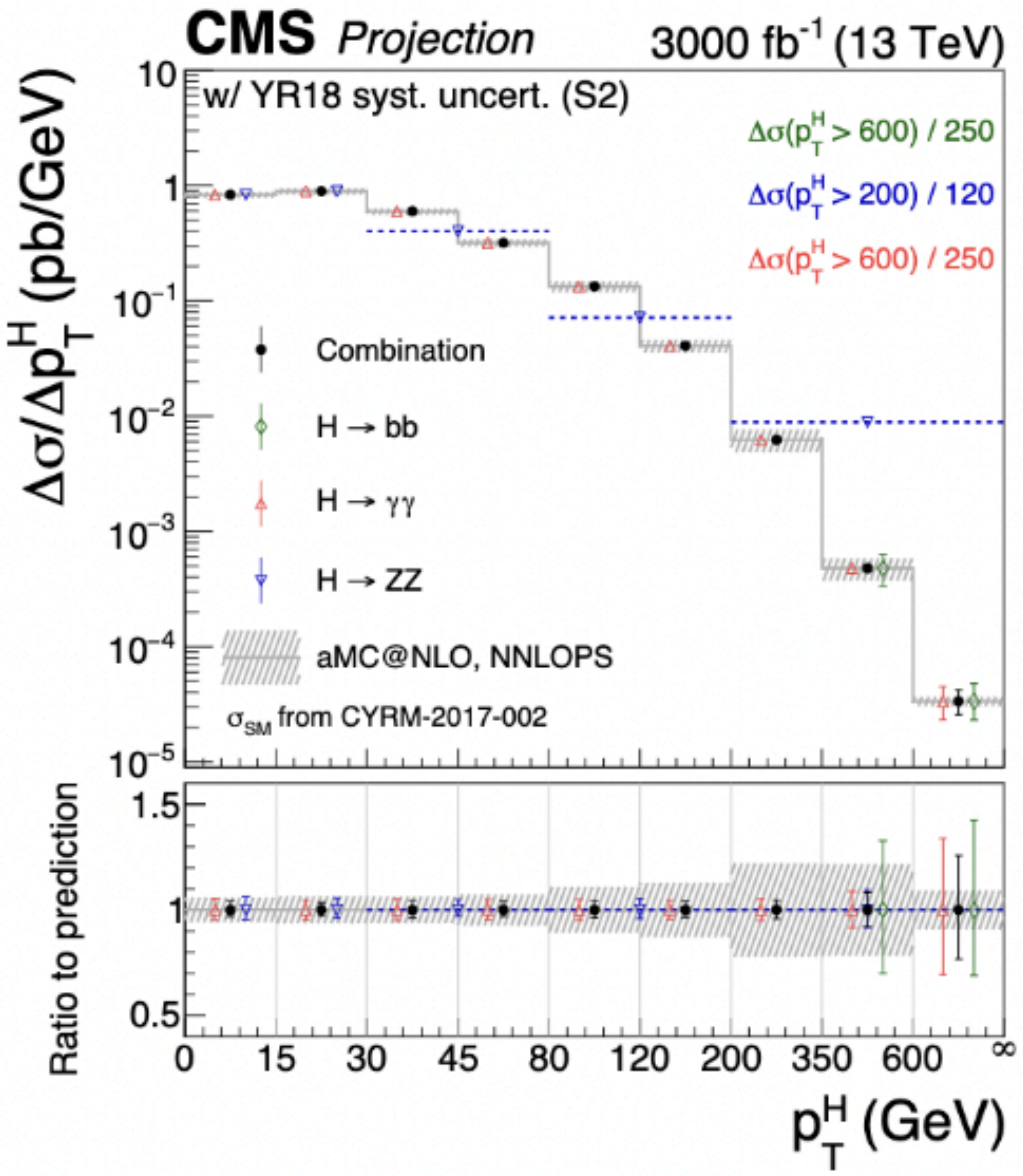
- $H \to cc$
  - Projection based on recent updates from ATLAS and CMS using Run2 dataset
  - CMS' projection makes use of the powerful boosted analysis strategy
  - Merged-jet category for events with $p_T H$ > 300 GeV
  - Direct measurement of the Higgs coupling to the charm is within reach at the HL-LHC!





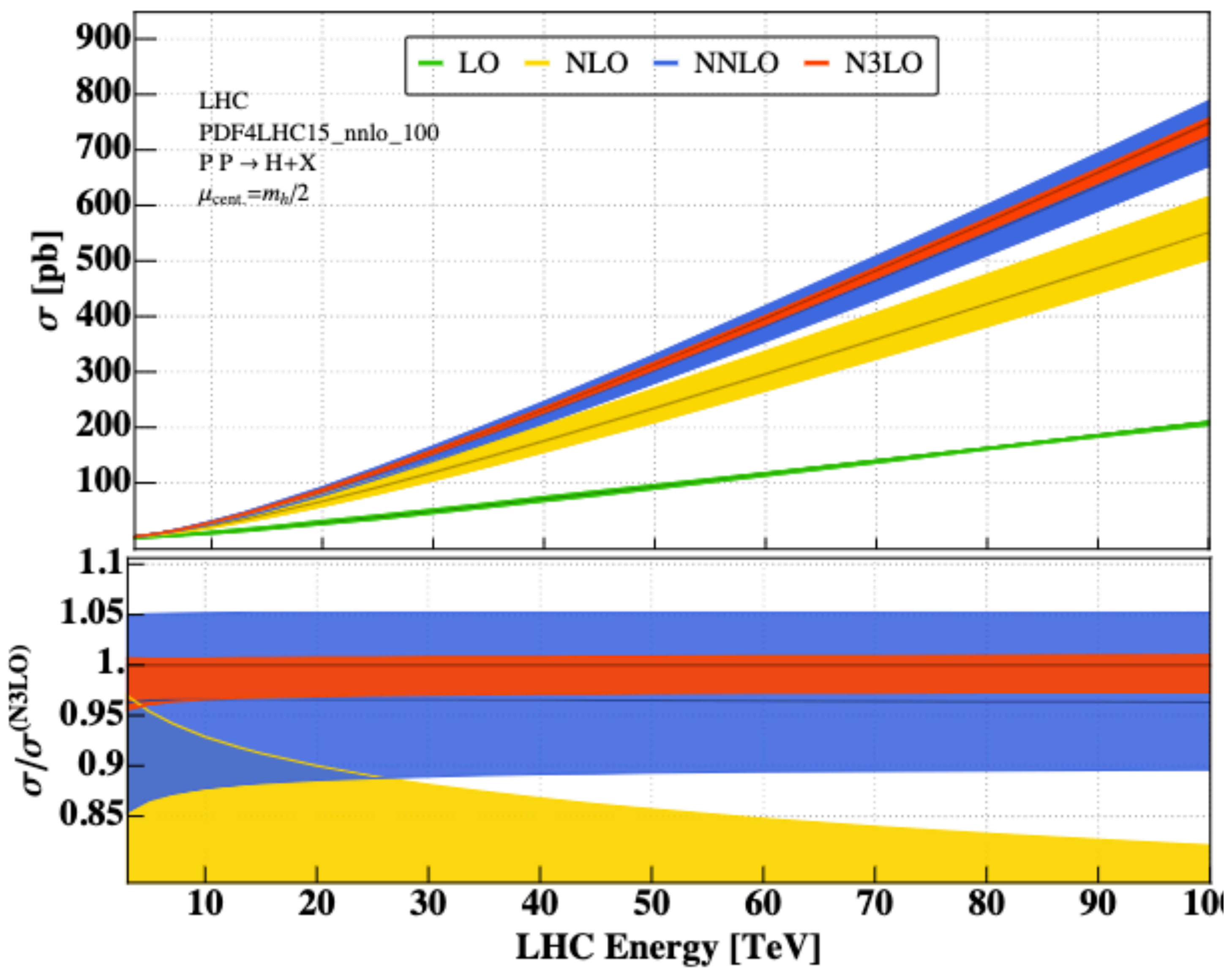
HL-LHC

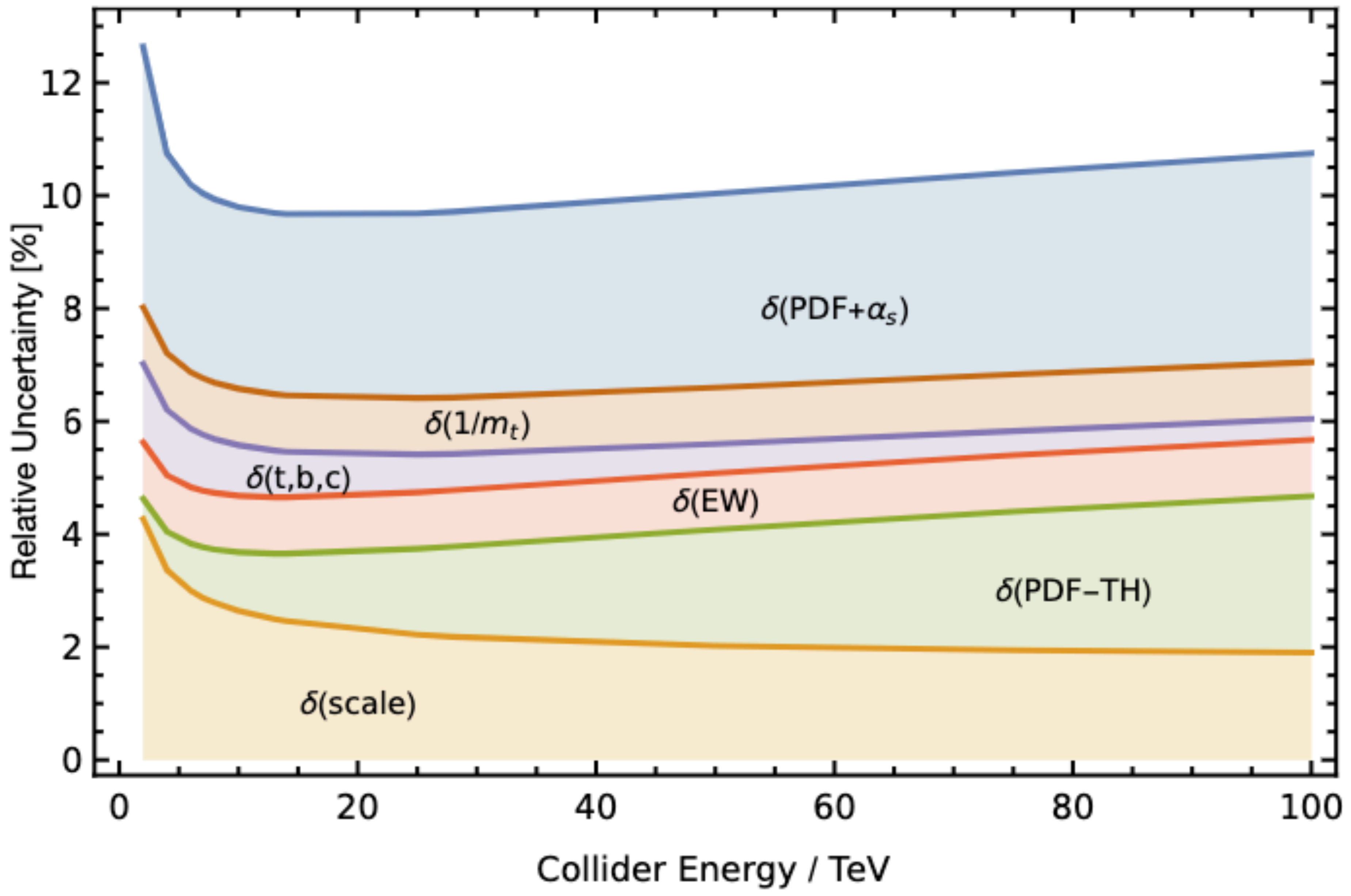


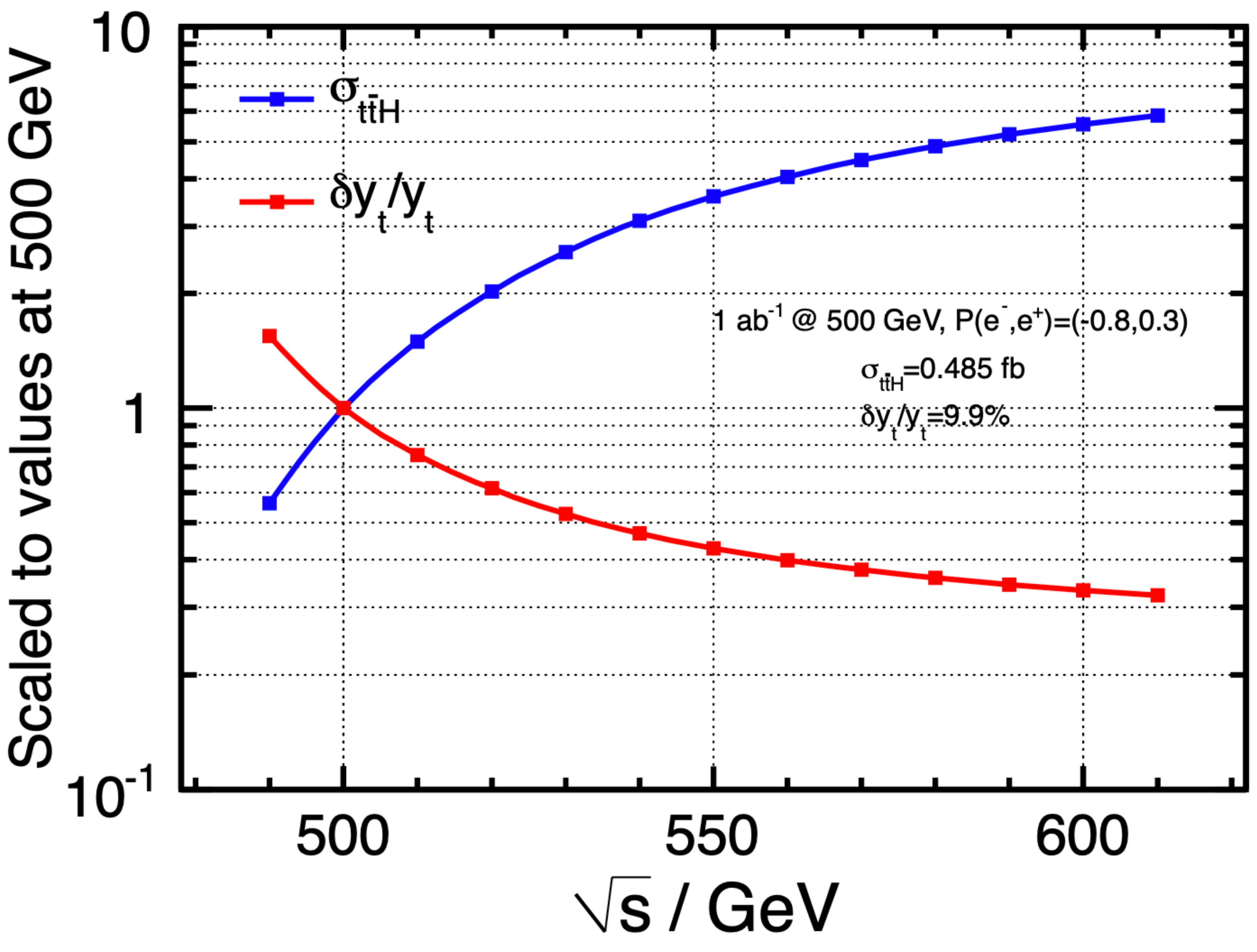


- Inclusive h → τ+τ− cross-section measurement is projected to have a precision of 5%
- Projected sensitivity for the combined ggF cross-section measurement with the h → γγ, h → ZZ* and h → b¯b decay channels, based on a preliminary Run 2 analysis with 35.9 fb^{-1}

Theory Uncertainties







- The theory uncertainty expected to be comparable to the expected statistical and systematic uncertainties of the measurements
  - Impressive theoretical progress has been, and is continuing, to be achieved, leaving theorists optimistic that the theory uncertainties can be reduced by a factor of two in the future
  - Meeting this necessary theoretical accuracy will require a dedicated effort with significant computational resources

arXiv: 2204.04200 arXiv:2203.06730

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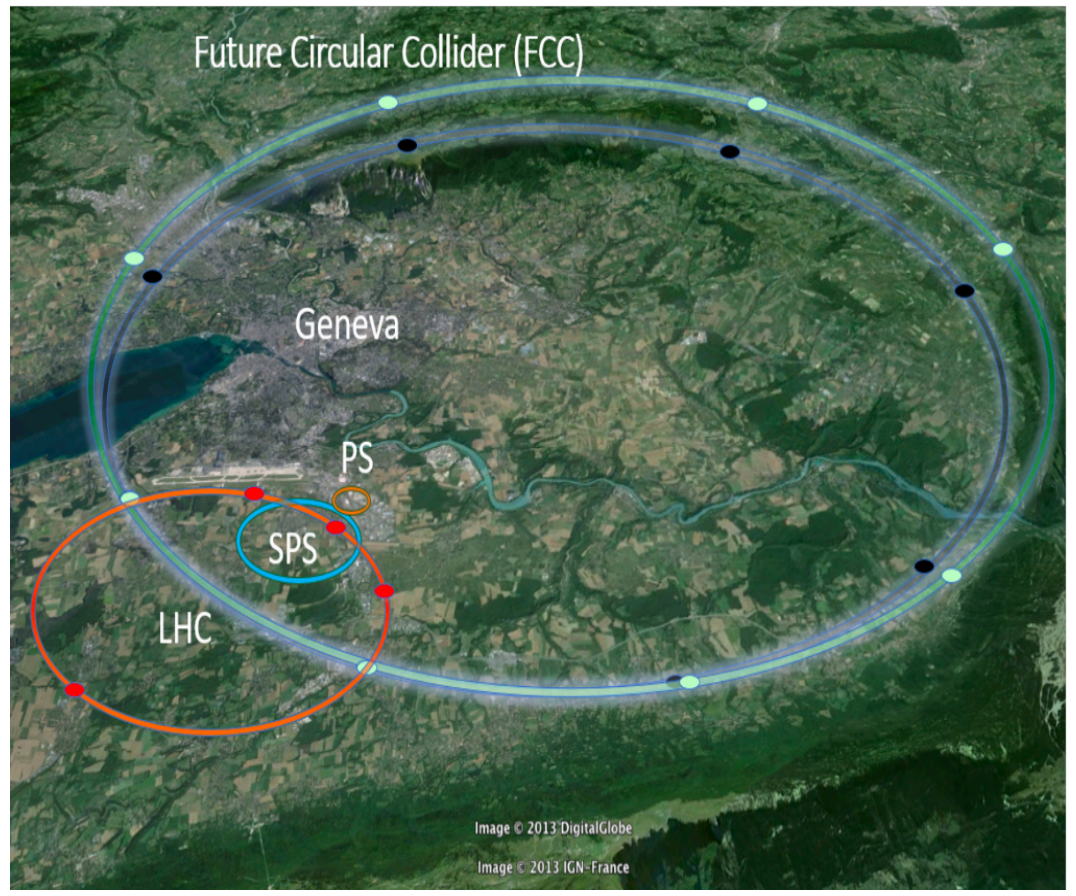
Now for some Future Collider Results

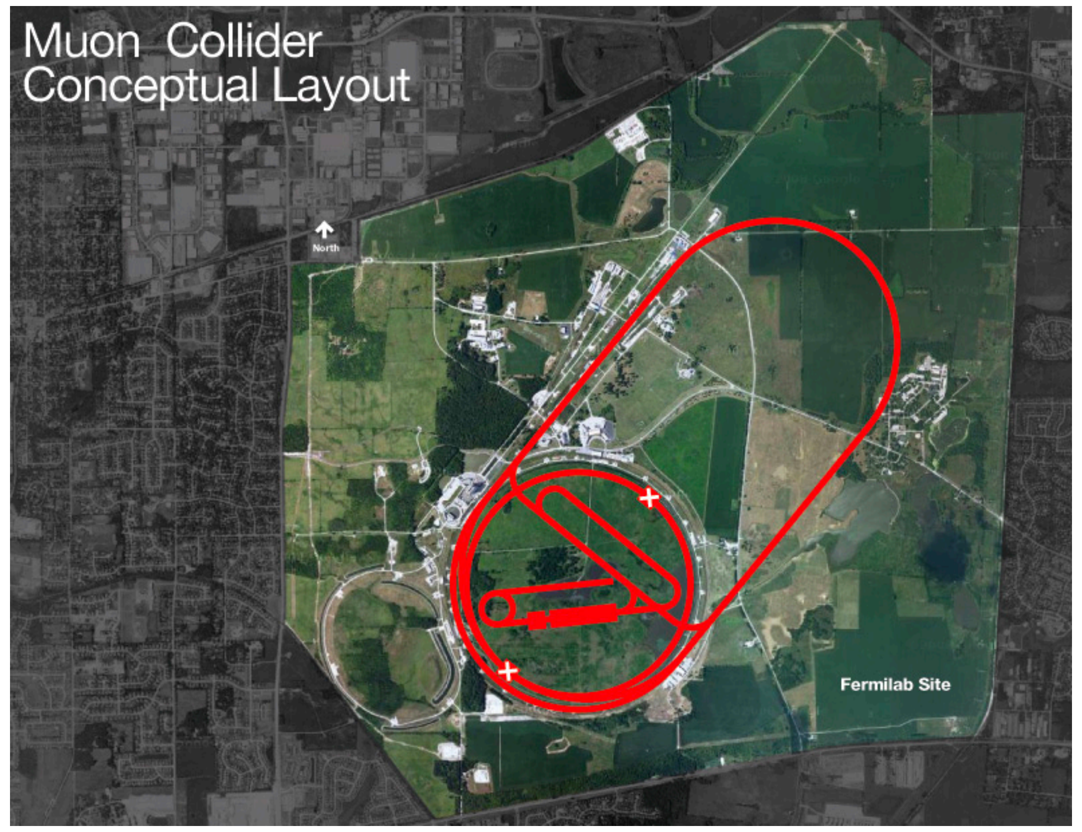
Machine Overview



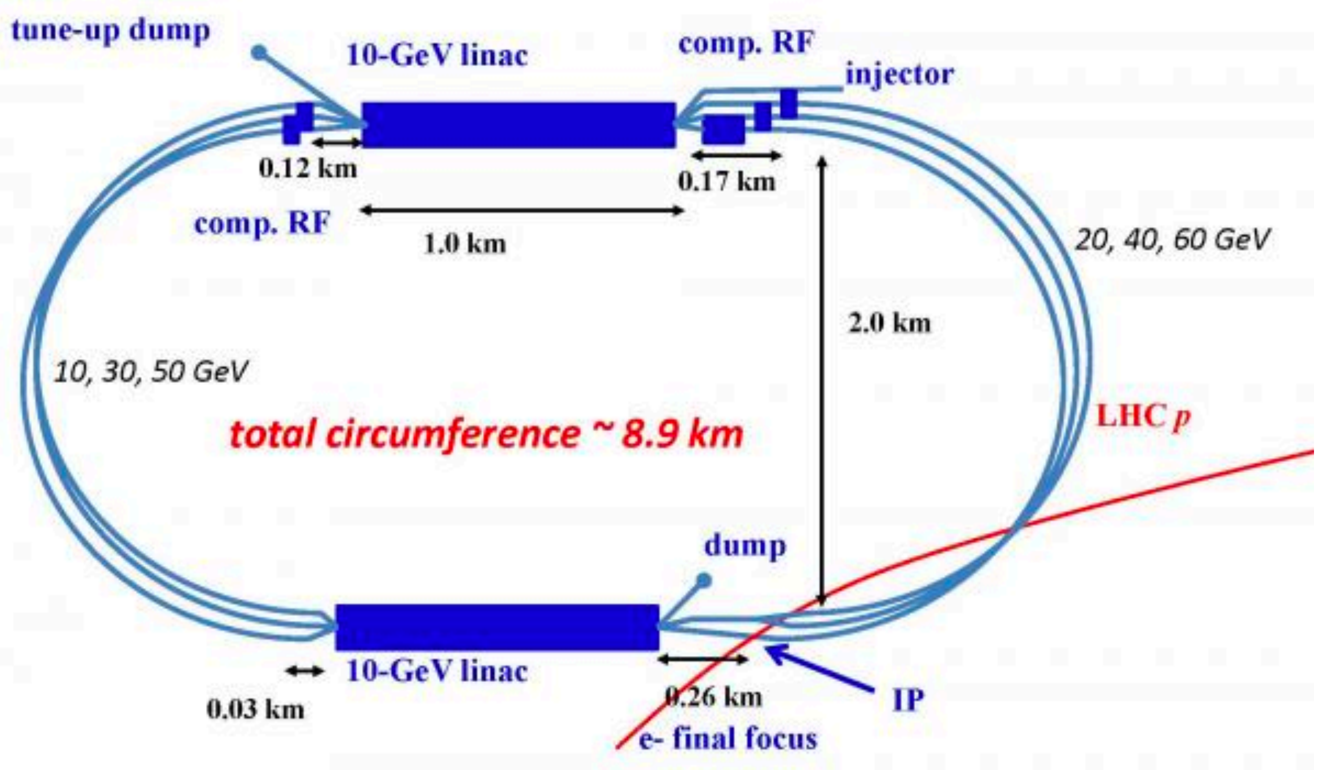
Hadrons

Discovery Machines
S/B ~10^{-10} w/o trigger
S/B ~0.1 with trigger
Divide CoM by partons
Stable particles
=> Quarks and Gluons

Leptons



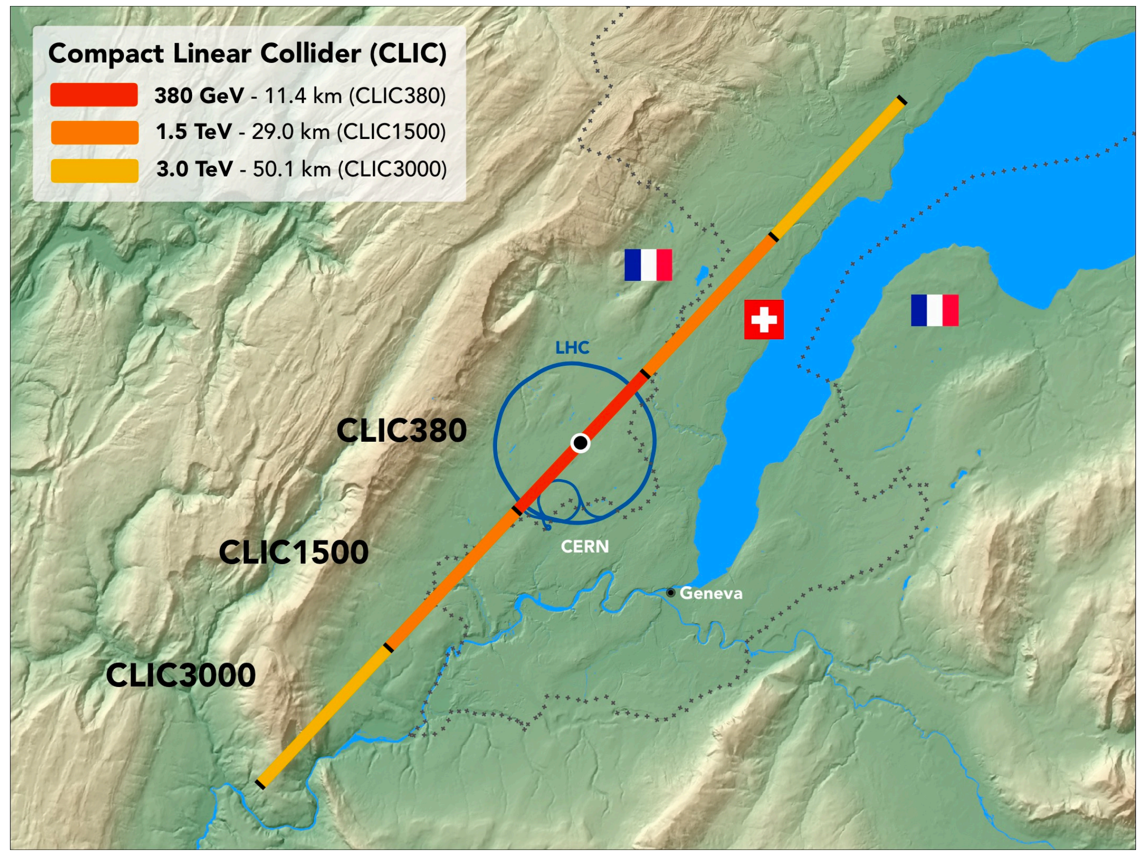
Precision and Discovery
Large S/B
Polarized beams
EW couplings



Higher luminosities
Several interaction points
Limited by Synchroton radiation

Circular

Easier to polarize beams
One IP
Large Beamstrahlung



Linear

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What Machines are under consideration after the HL-LHC?

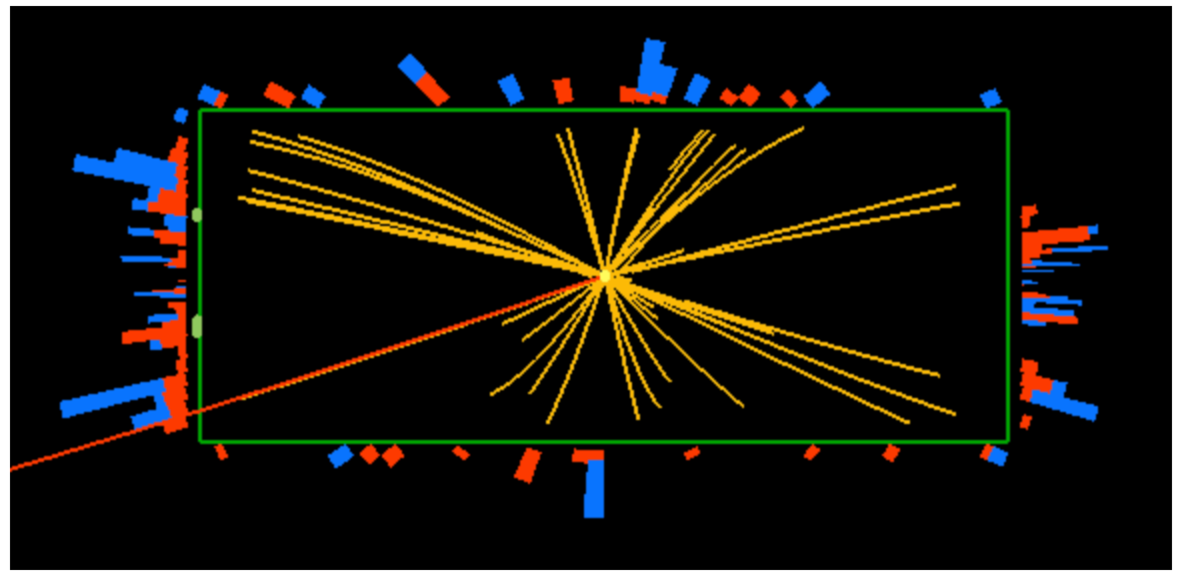
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3	ee	250 GeV	$\pm 80/\pm 30$	2
c.o.m almost		350 GeV	$\pm 80/\pm 30$	0.2
similar		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
CEPC	ee	M_Z		60
		$2M_W$		3.6
		240 GeV		20
		360 GeV		1
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2\ M_{top}$		1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HE-LHC	pp	27 TeV		15
FCC-hh	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh		3.5 TeV		2
CLIC	ee	1.5 TeV	$\pm 80/0$	2.5
		3.0 TeV	$\pm 80/0$	5
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10

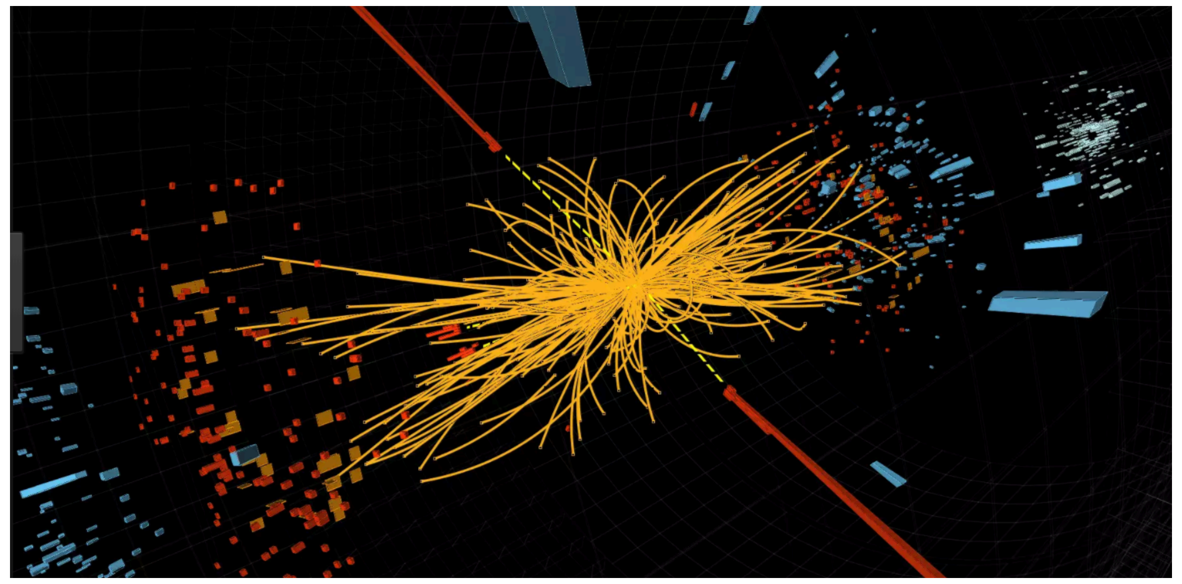
Higgs EF Report *does not review* the machines, only the Higgs-physics reach of each, given these scenarios

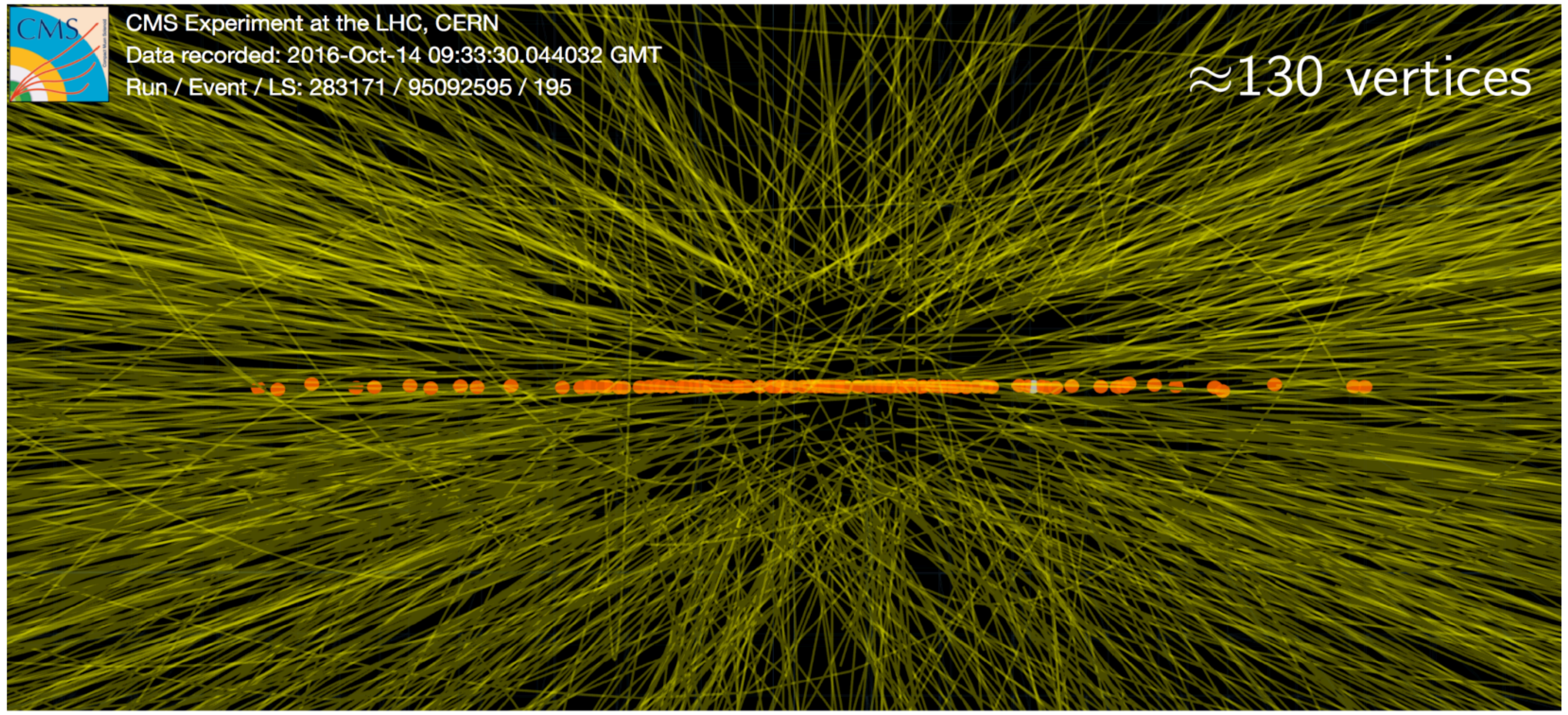
Hadron Colliders

2011 ~0.5x10^{34}cm^{-2}s^{-1}

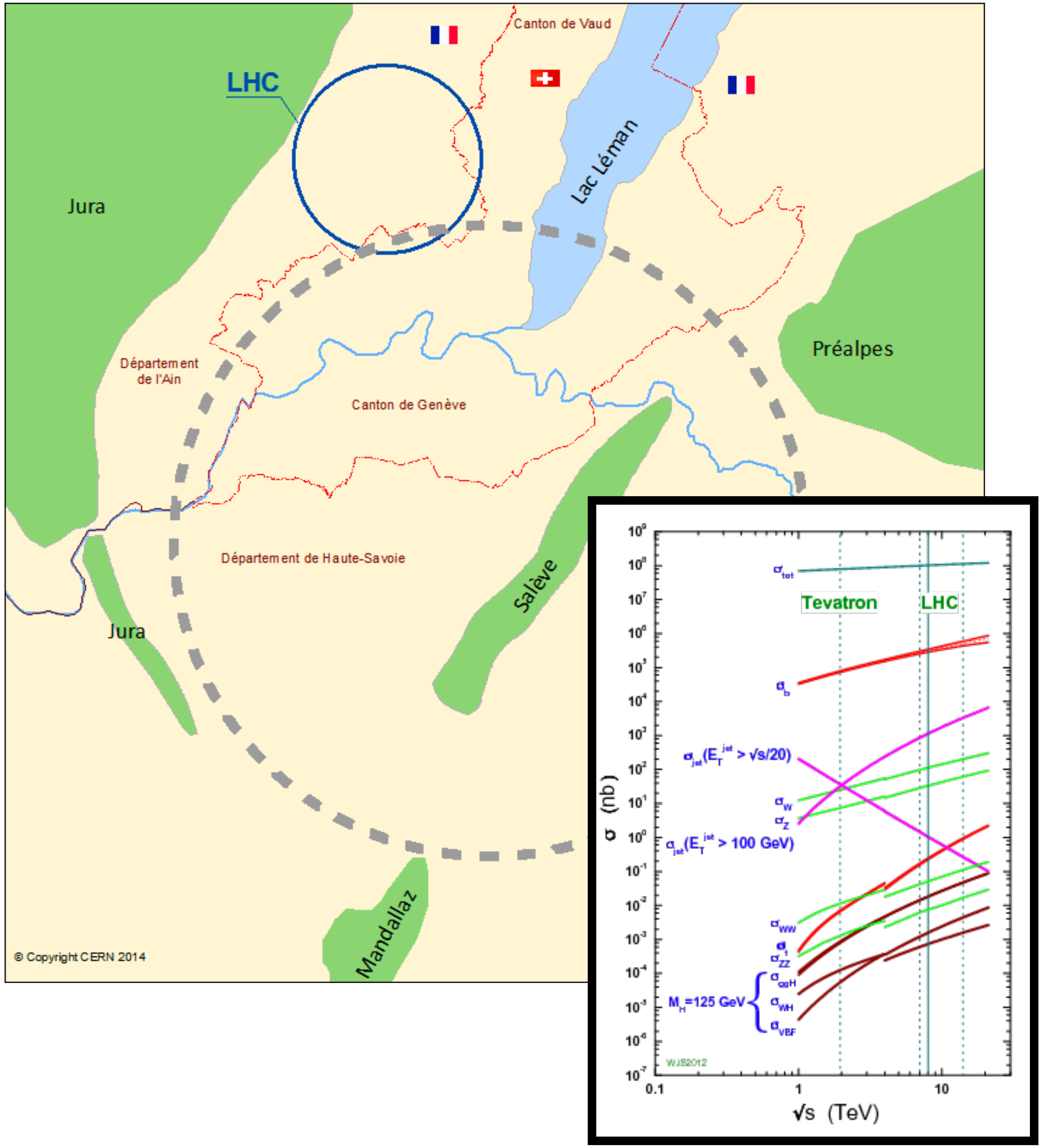


2016 2x10^{34}cm^{-2}s^{-1}



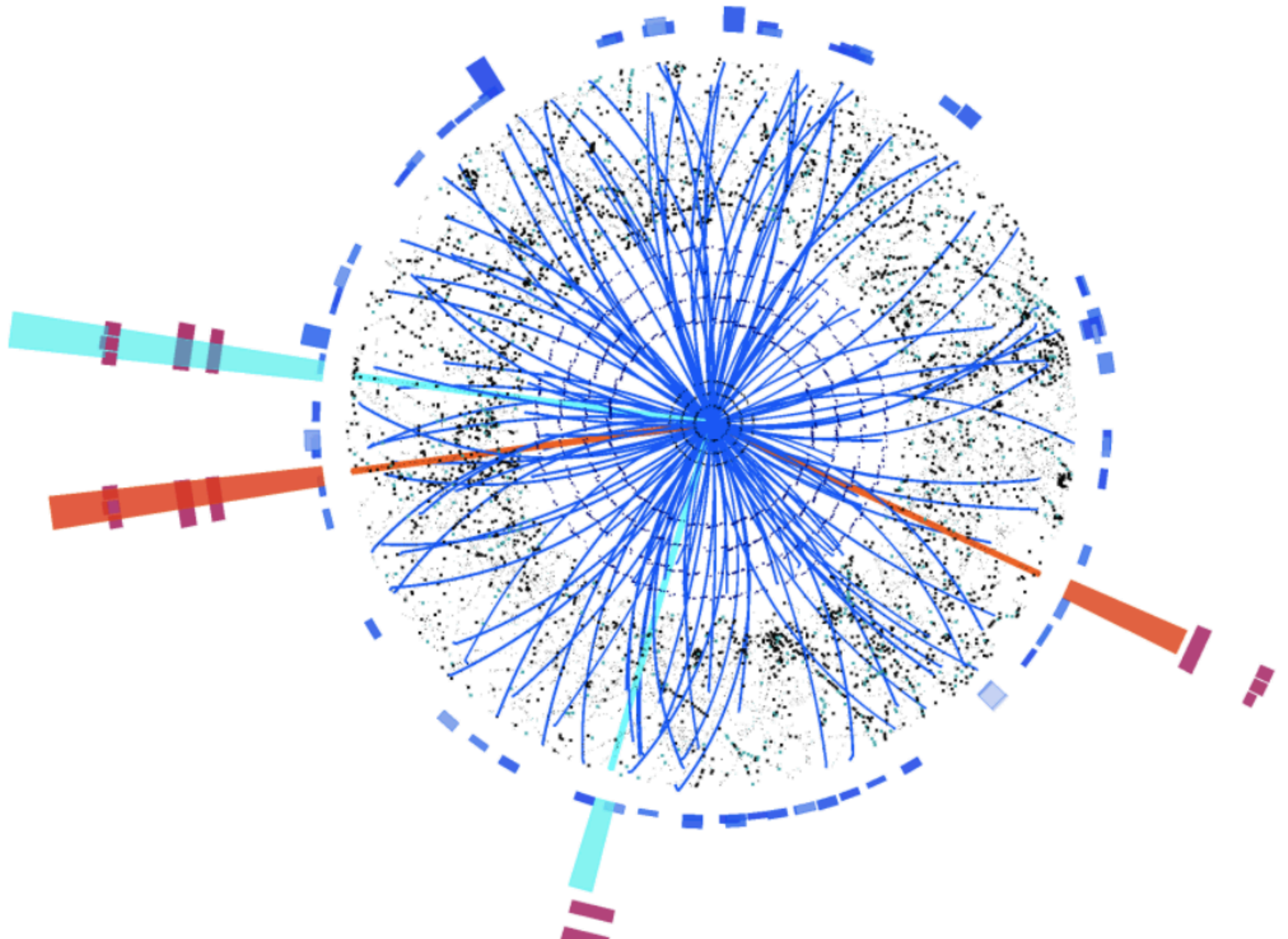


Event from Special Run in 2016, HL-LHC 150-200 vertices

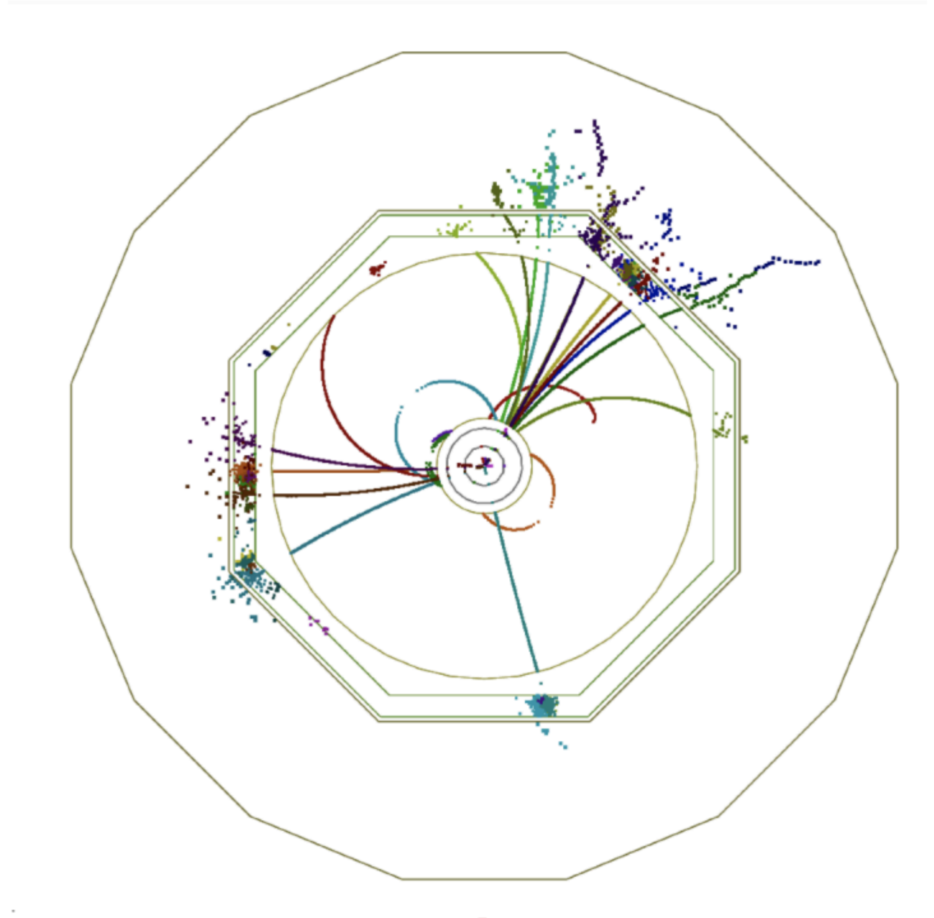


e+e- Colliders

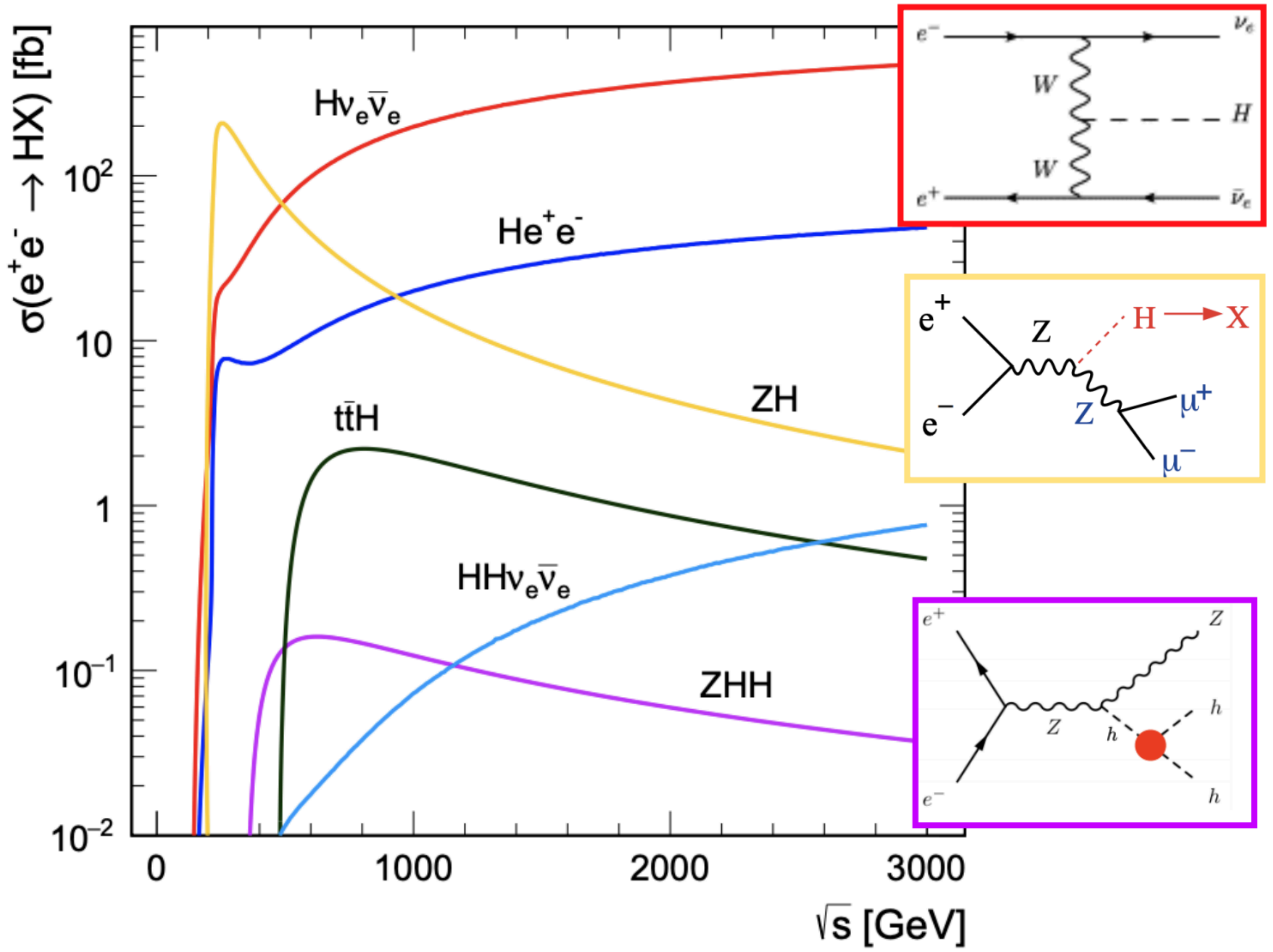
- **ZH is the dominant production mode between 250 GeV and 1 TeV**
- Measurement of the inclusive ZH cross section at 0.5-1%
- Recoil technique observes all final state, including all invisible and exotic decay modes
- **Clean environment** for excellent b- and c-tagging (and beyond?) performance: bb/cc/gg separation



pp/LHC



e^+e^-



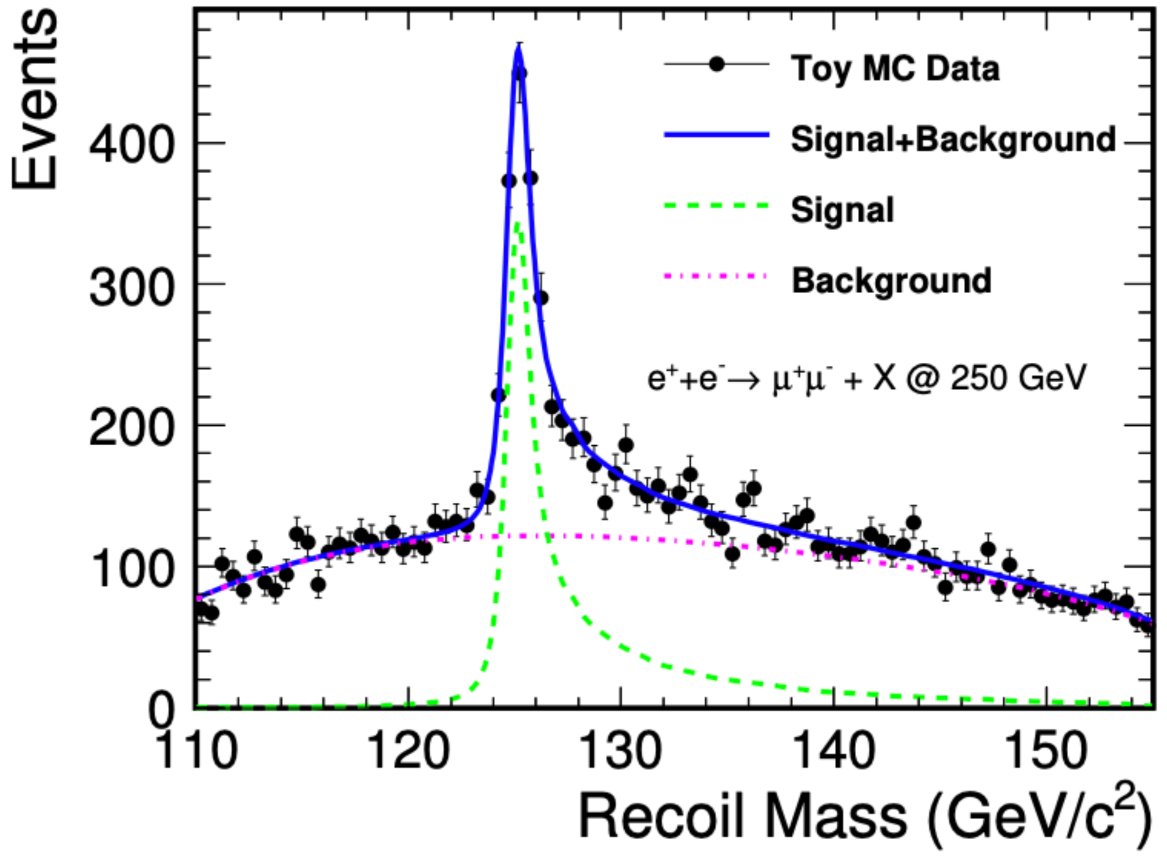


FIG. 15: Example of the recoil mass for 250 GeV e^+e^- collision energy at ILC [49].

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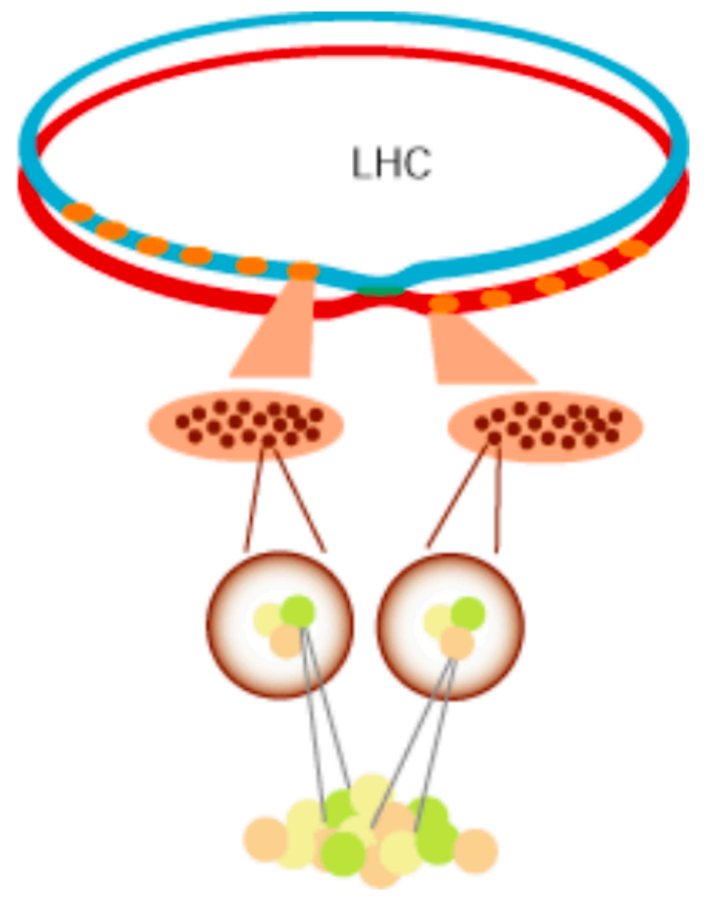
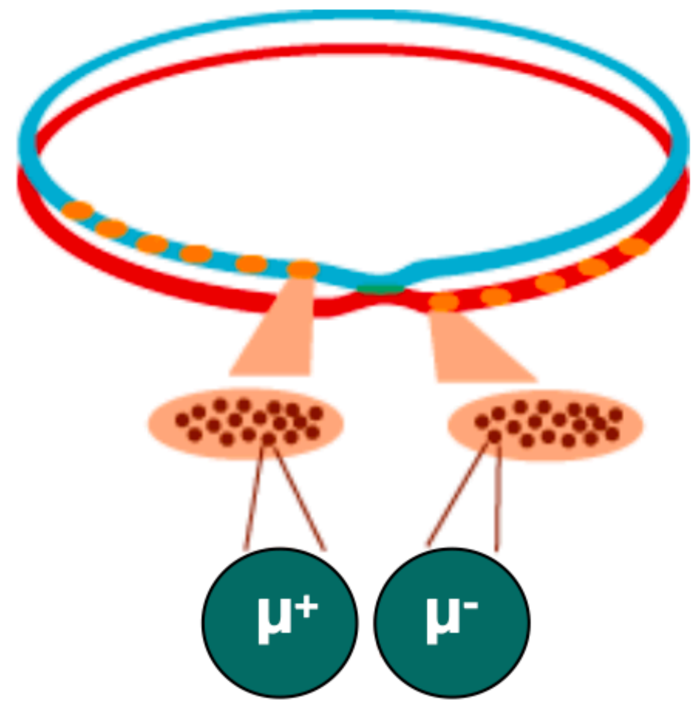
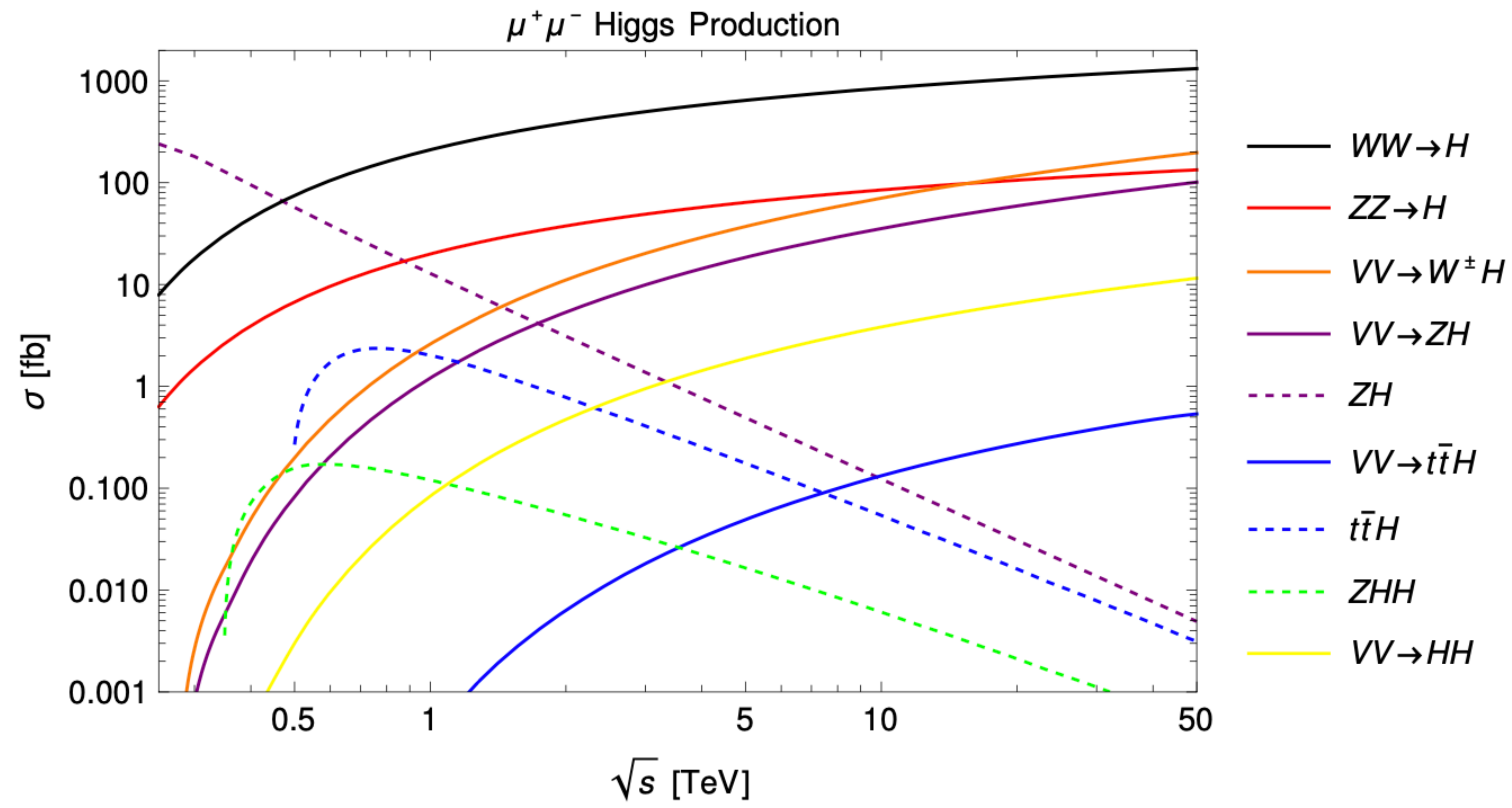
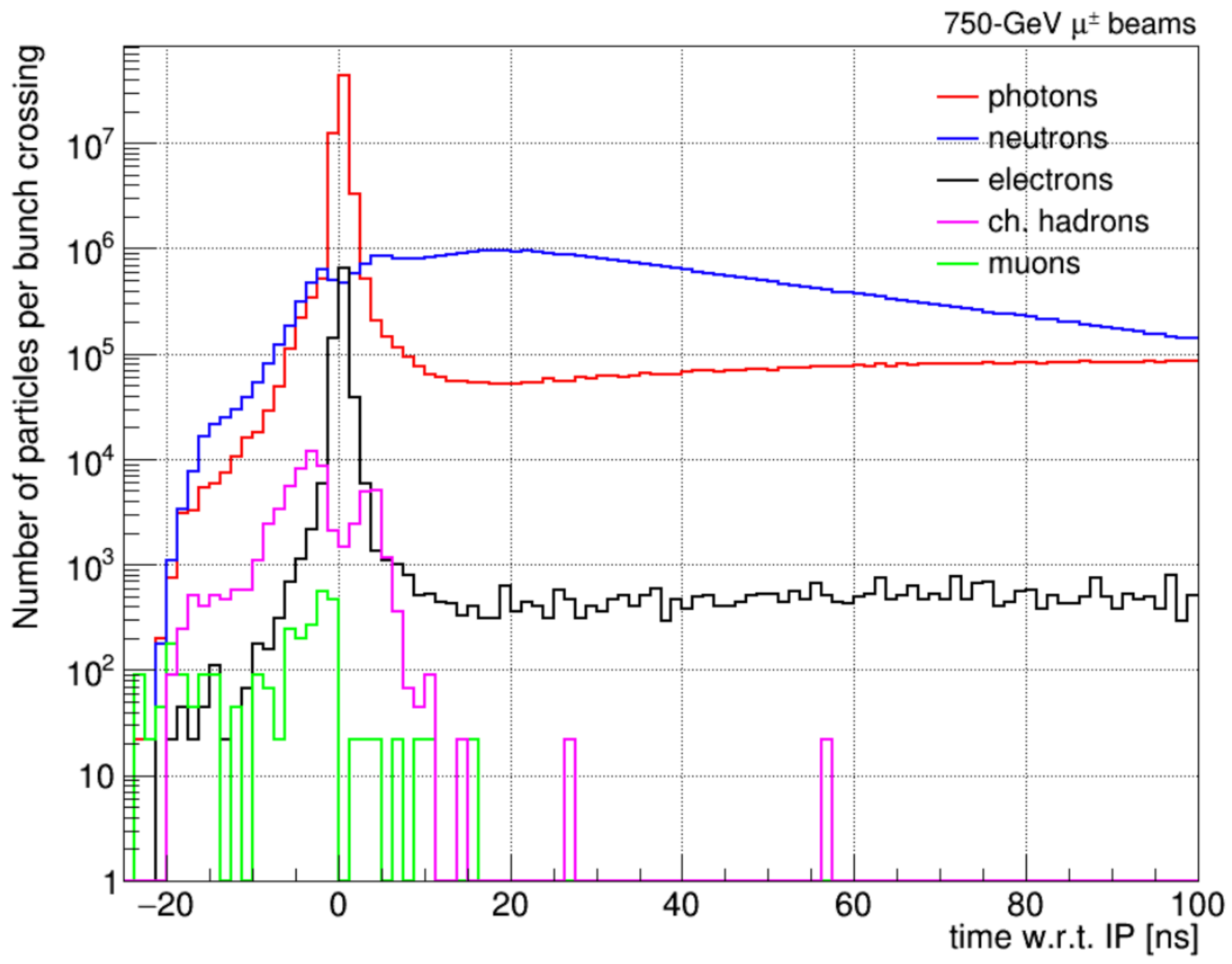
Muon Colliders

An old idea that has **new footing** due to recent technological advances





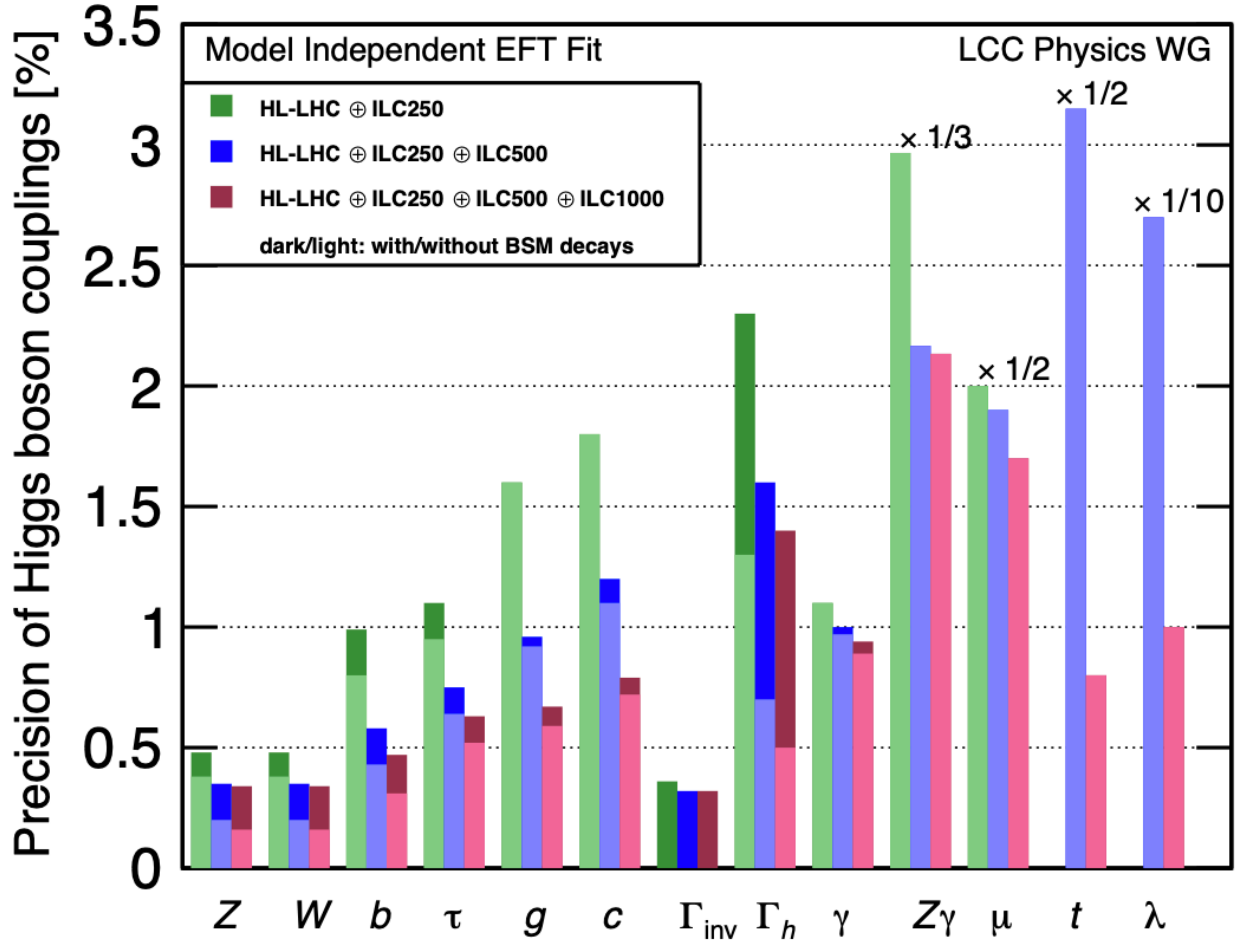


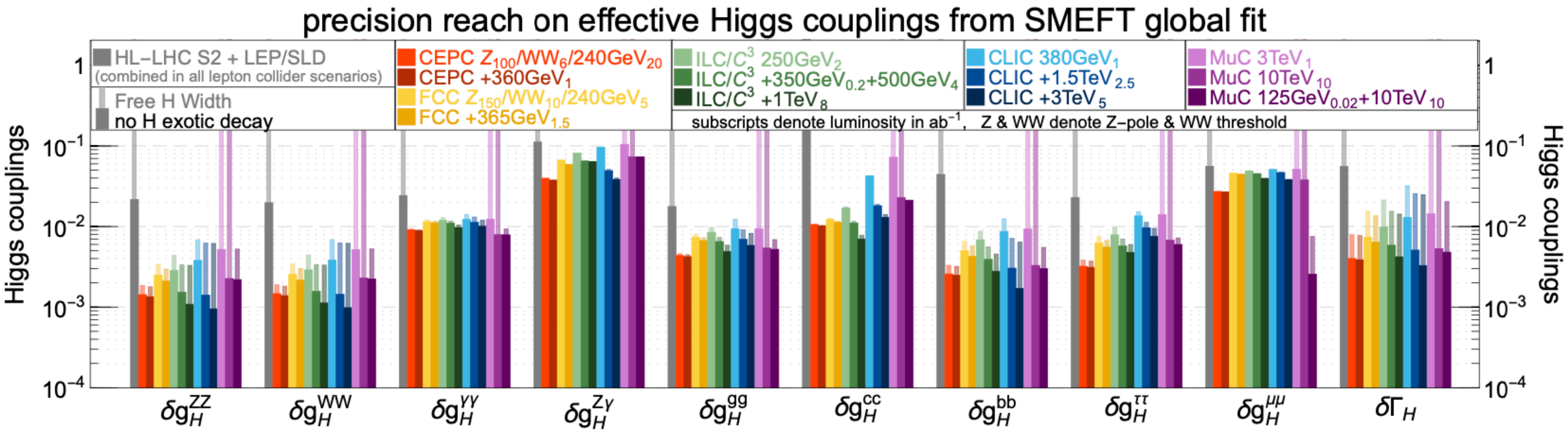


Muon Colliders are actually **EWK colliders** with a mix of initial states
→ Low Beamstrahlung, high partonic energy but large Beam Induced Background (BIB)

SMEFT

- A consistent theoretical framework requires the use of effective field theory (SMEFT) techniques
- The inclusion of the di-boson and Giga-Z data greatly improves the precision of the hWW and hZZ couplings
  - Provides a more comprehensive understanding of high scale physics





Higgs Couplings Summary

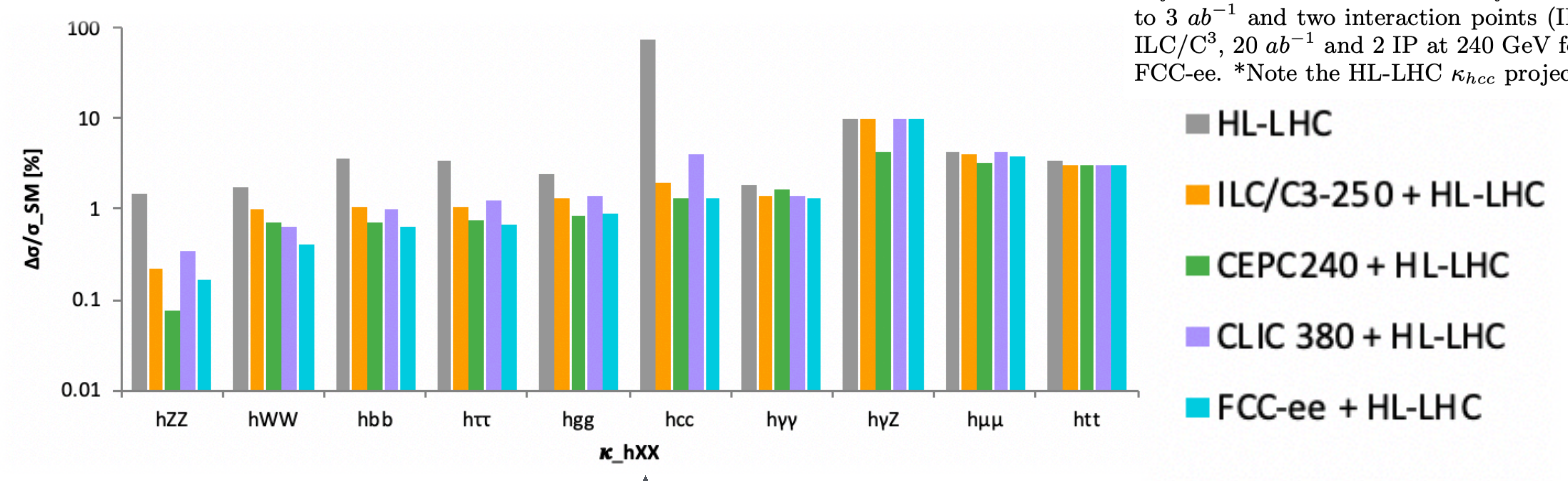
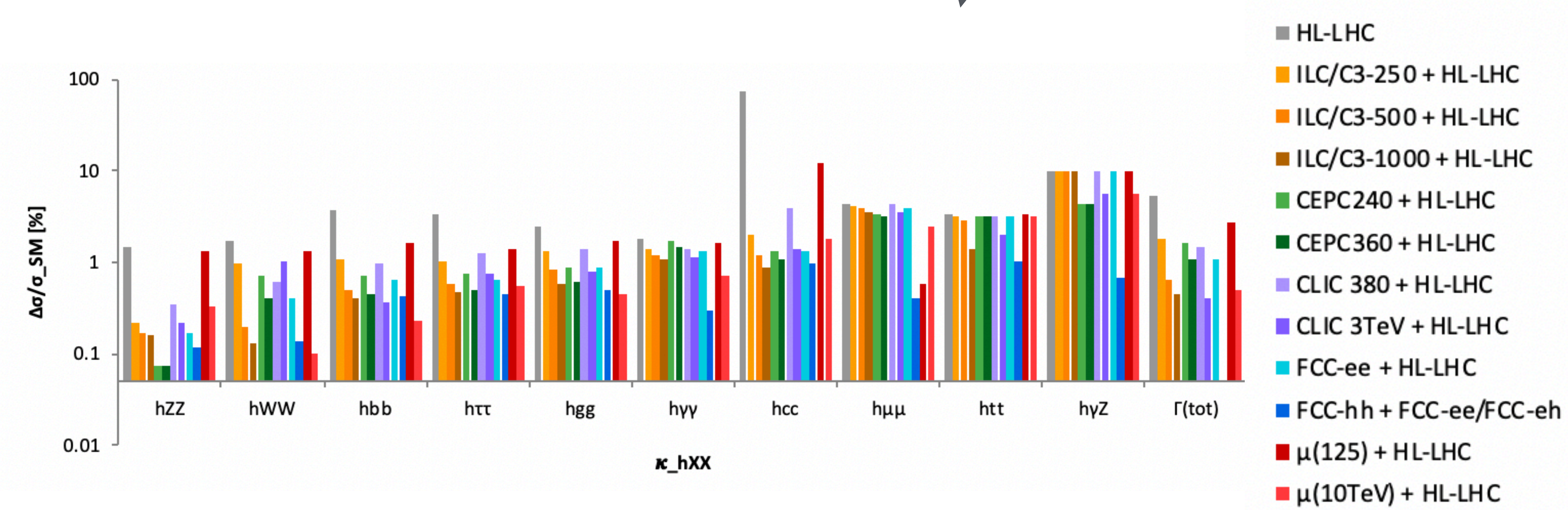


FIG. 18: Projected relative Higgs coupling measurements in % when combined with HL-LHC results. All values assume no beyond the Standard Model decay modes. In addition, only initial stages are shown for near-term colliders: This corresponds to 3 ab^{-1} and two interaction points (IPs), ATLAS and CMS, for the HL-LHC at 14 TeV, 2 ab^{-1} and 1 IP at 250 GeV for ILC/C^3, 20 ab^{-1} and 2 IP at 240 GeV for CEPC, 1 ab^{-1} and 1 IP at 380 GeV for CLIC, and 5 ab^{-1} and 4 IP at 240 GeV for FCC-ee. *Note the HL-LHC κ_{hcc} projection uses only the CMS detector and is an upper bound [56].

"Initial" Stages

"Ultimate" Stages



CP Violating Decays,

$$f_{CP}^{hX} \equiv \frac{\Gamma_{h\to X}^{CP\,\mathrm{odd}}}{\Gamma_{h\to X}^{CP\,\mathrm{odd}} + \Gamma_{h\to X}^{CP\,\mathrm{even}}}$$

- CP violation is an important research direction of future experiments in particle physics as CP violation is one of the requirements for baryogengesis
- Electron Yukawa is the smallest coupling in the SM 3 x 10^{-6}
  - Proposal to run the FCC-ee on the s-channel Higgs resonance offers the first glimmer of hope that this measurement could be accomplished
  - A possible direct-look into first generation decays

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	125	125	≥ 500	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	20,000	250	350	500	1,000	250			
HZZ/HWW	$4{\cdot}10^{-5}$	$2.5{\cdot}10^{-6}$	✓	$3.4{\cdot}10^{-4}$	$1.1{\cdot}10^{-4}$	$4{\cdot}10^{-5}$	$8{\cdot}10^{-6}$	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	$\sim$1	✓	–	–	–	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

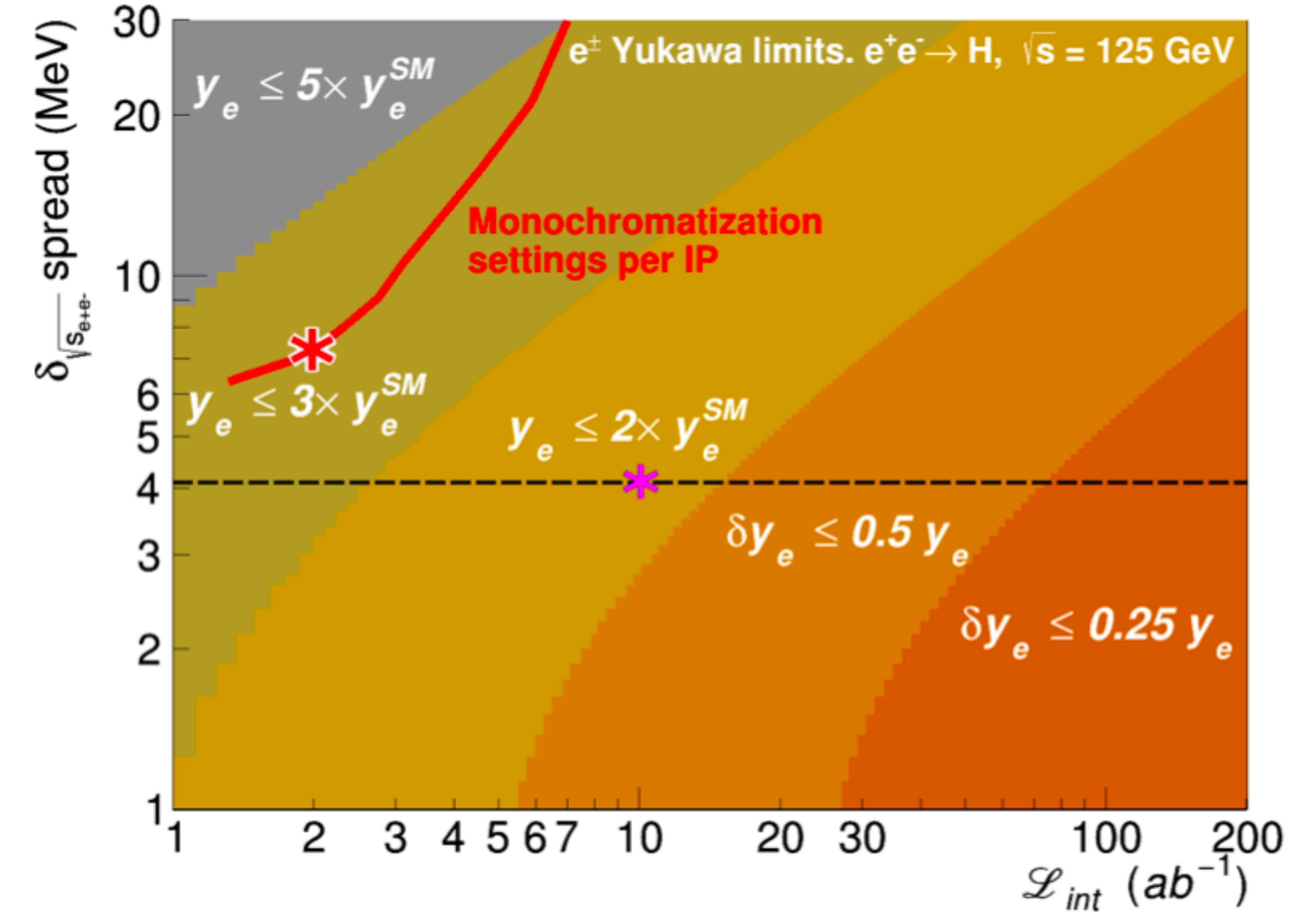


FIG. 22: Prospects for measuring the electron Yukawa in a dedicated FCC-ee run [53].

Conclusions

- Hopefully, we've given you an overview of what has gone into the first sections of the report.
  - ***The SM will not be complete until we have enough precision in all its properties to verify that all SM predicted couplings exist***
  - However, that is not the primary goal of precision Higgs physics program….
    - Please see the next talk :-)

“The only way to know the truth about our Universe is to ask it these questions. Figuring out what the laws of nature are and how particles behave is a step forward for human knowledge and the entire enterprise of science.

The only true nightmare would be if we stopped exploring, and gave up before we ever looked at all.”

Ethan Segel, Forbes

Snowmass Agora Links (slides and zoom recordings)
Snowmass Agora on Future Colliders: Linear e+e- Colliders
Snowmass Agora on Future Colliders: Circular e+e- Colliders
Snowmass Agora on Future Colliders: Muon Colliders
Snowmass Agora on Future Colliders: Circular pp and ep Colliders
Snowmass Agora on Future Colliders: Advanced Colliders