LOOKING TO FUTURE HIGGS MEASUREMENTS AT THE LHC

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CERN ACADEMIC TRAINING
10TH JUNE 2022

ATLAS EXPERIMENT

CMS

HIGGS MEASUREMENTS AT THE LHC

- Wednesday's lecture by John Ellis: Historical perspective and theoretical implications
- Thursday's lecture by Marumi Kado: CMS, ATLAS, the Higgs discovery and Run2
- Today: the future! →

Outline of today's lecture:

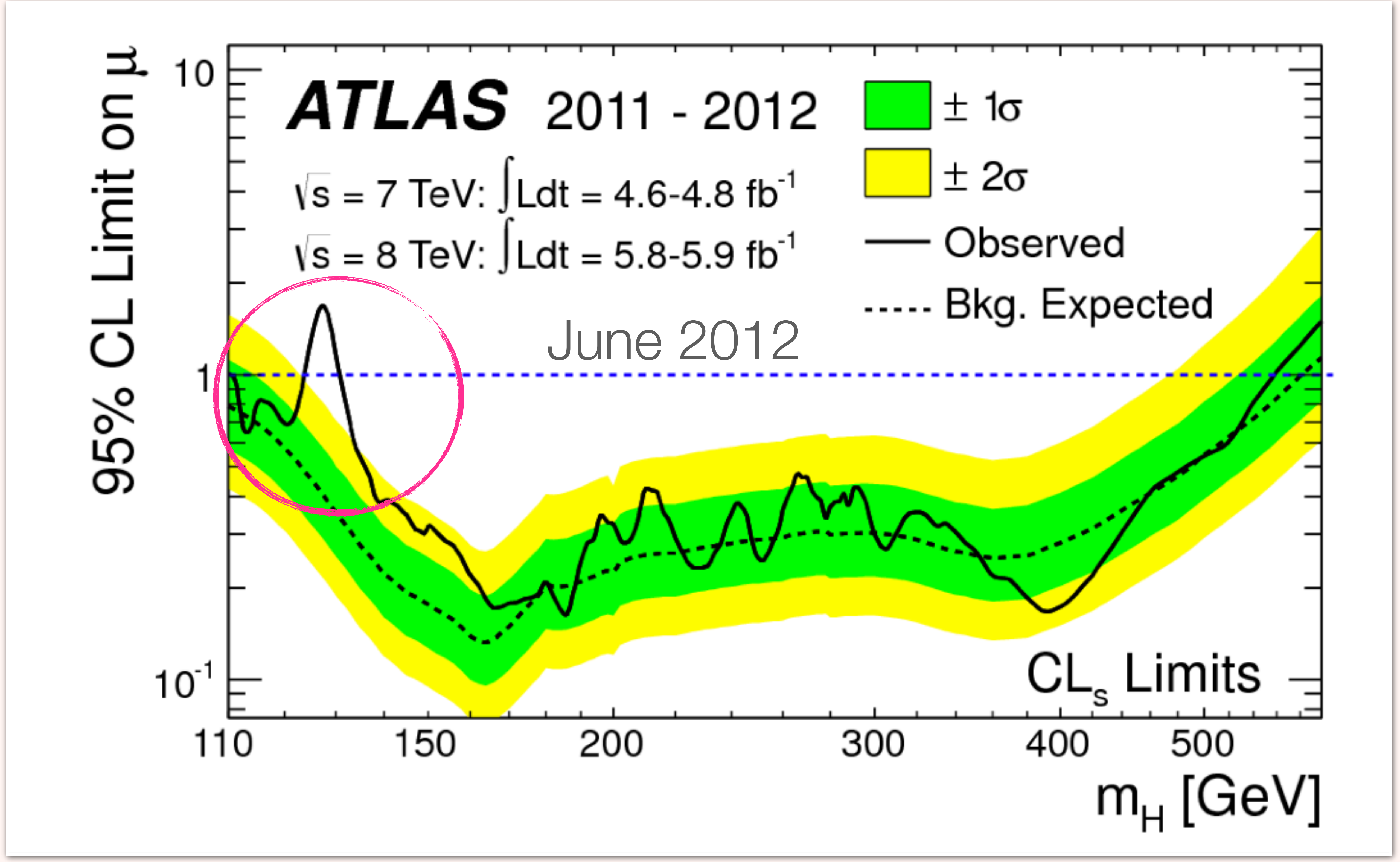
- Brief introduction
- Measuring Cross sections and Branching ratios
- Higgs properties
- Rare Decays
- Higgs Couplings
- HH
- BSM Higgs
- And beyond?

Not possible to cover all future prospects in detail: general picture

I won't have time to discuss detector upgrades!

FROM DISCOVERY TO PRECISION

ONLY? ALREADY? 10 YEARS AGO…



H^0 $J = 0$

Mass $m = 125.18 \pm 0.16$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

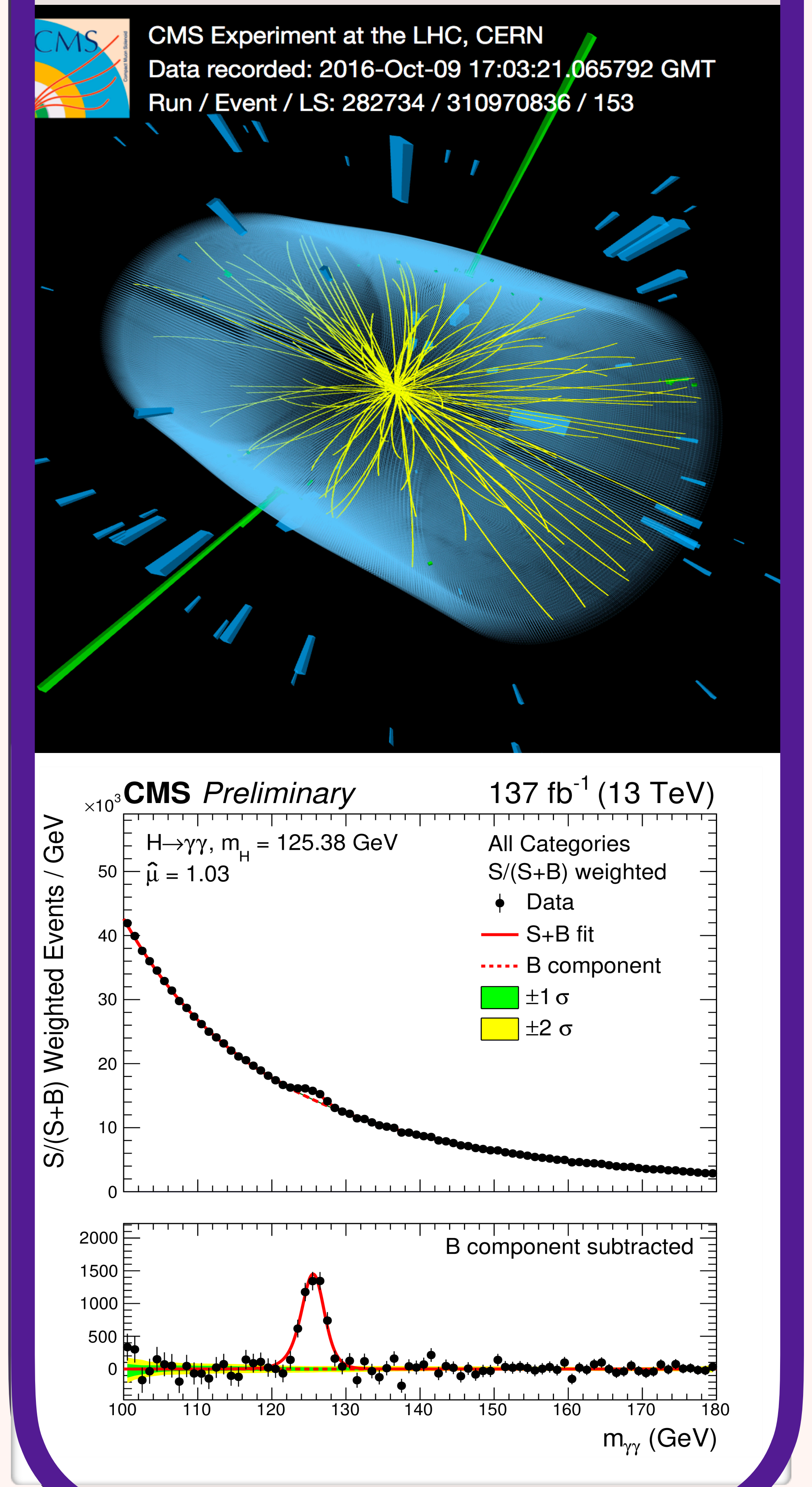
See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11
$WW^* = 1.08^{+0.18}_{-0.16}$
$ZZ^* = 1.14^{+0.15}_{-0.13}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.95 \pm 0.22$
$\mu^+\mu^- = 0.0 \pm 1.3$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 6.6$, CL = 95%
$t\bar{t}H^0$ Production $= 2.3^{+0.7}_{-0.6}$

As Marumi explained yesterday, we have really come a very long way since the discovery plots

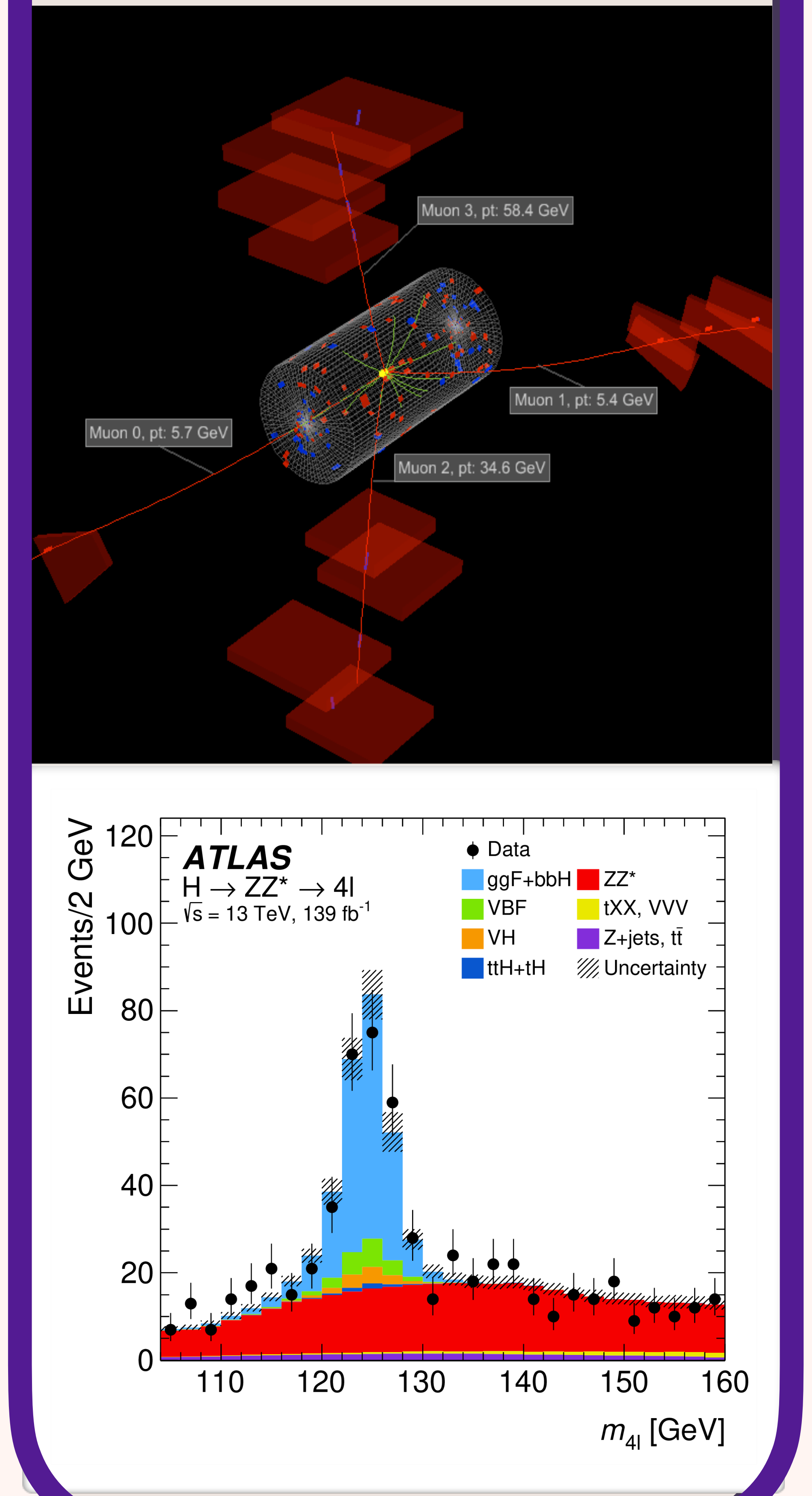
$H \to \gamma\gamma$

Br~0.2%



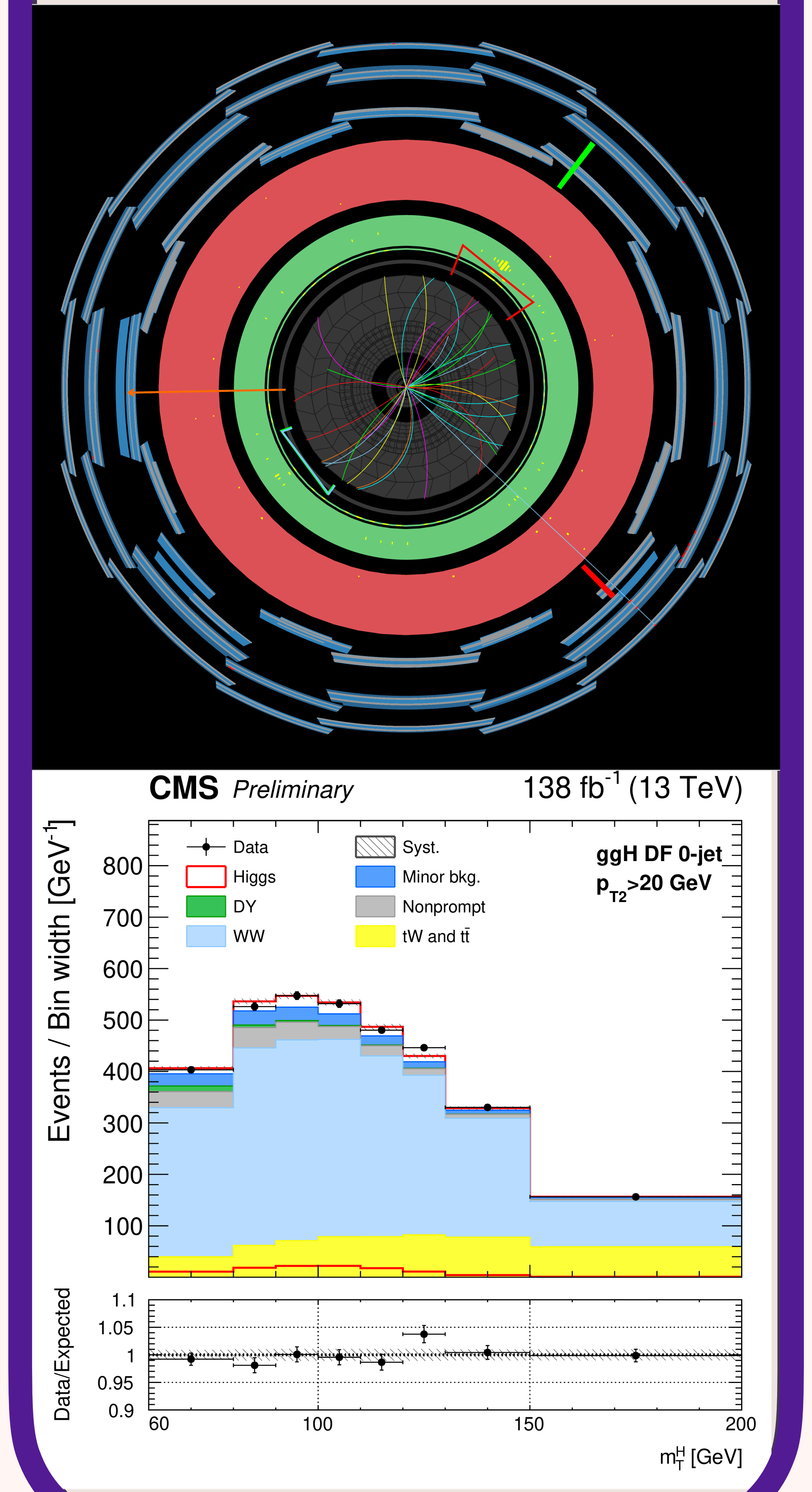
$H \to ZZ$

Br~3%



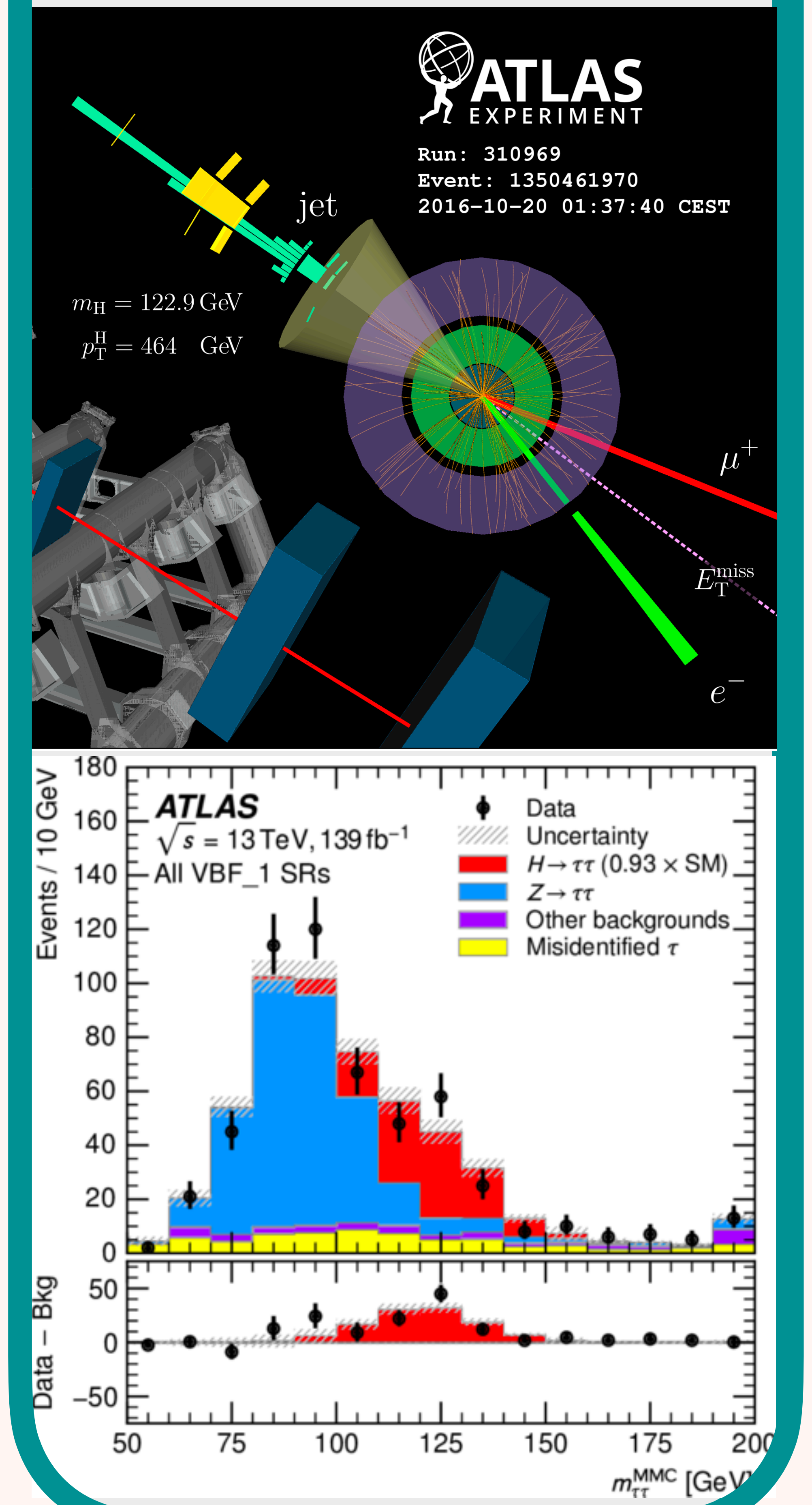
$H \to WW$

Br~21%



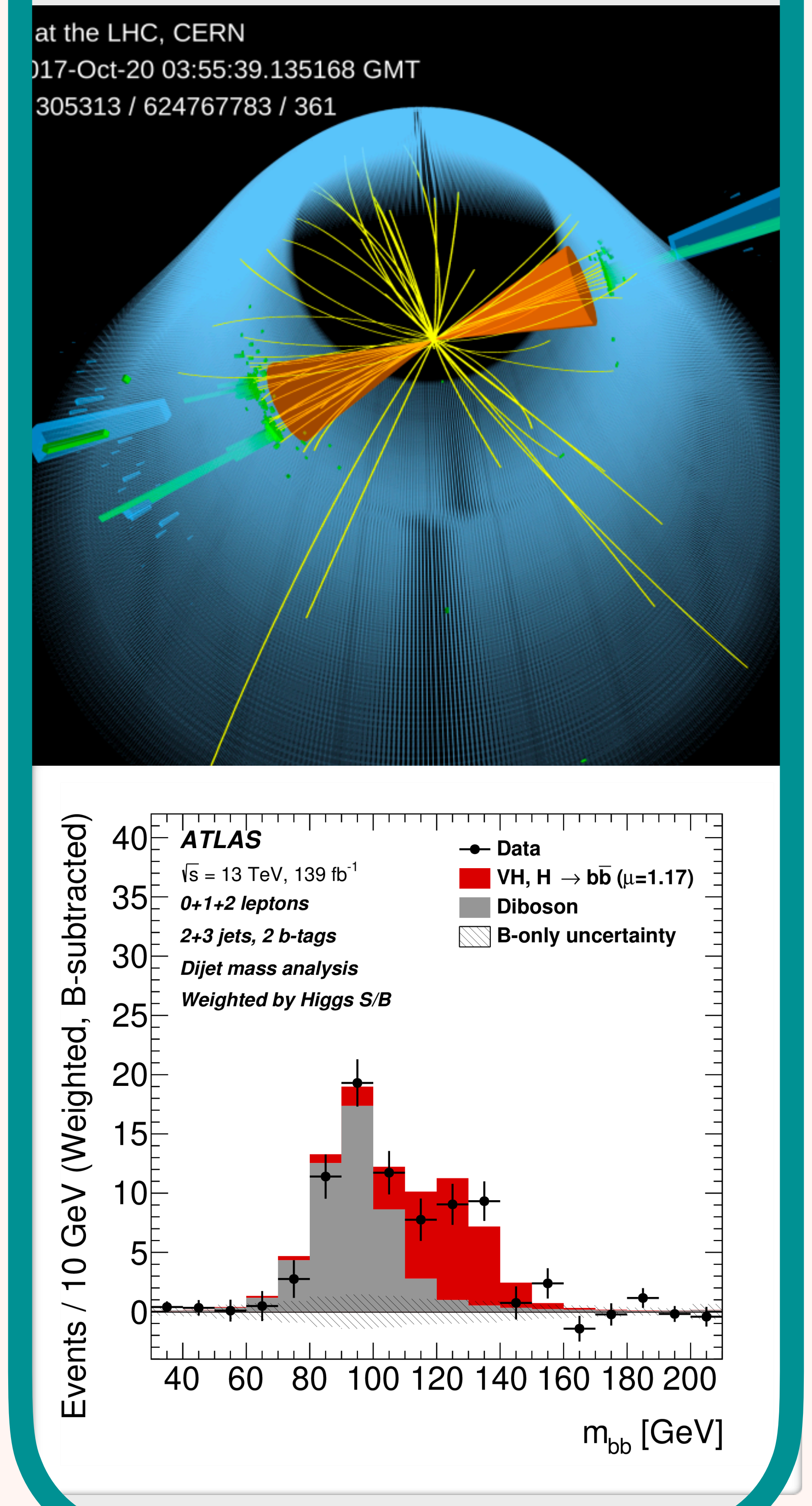
$H \to \tau\tau$

Br~6%

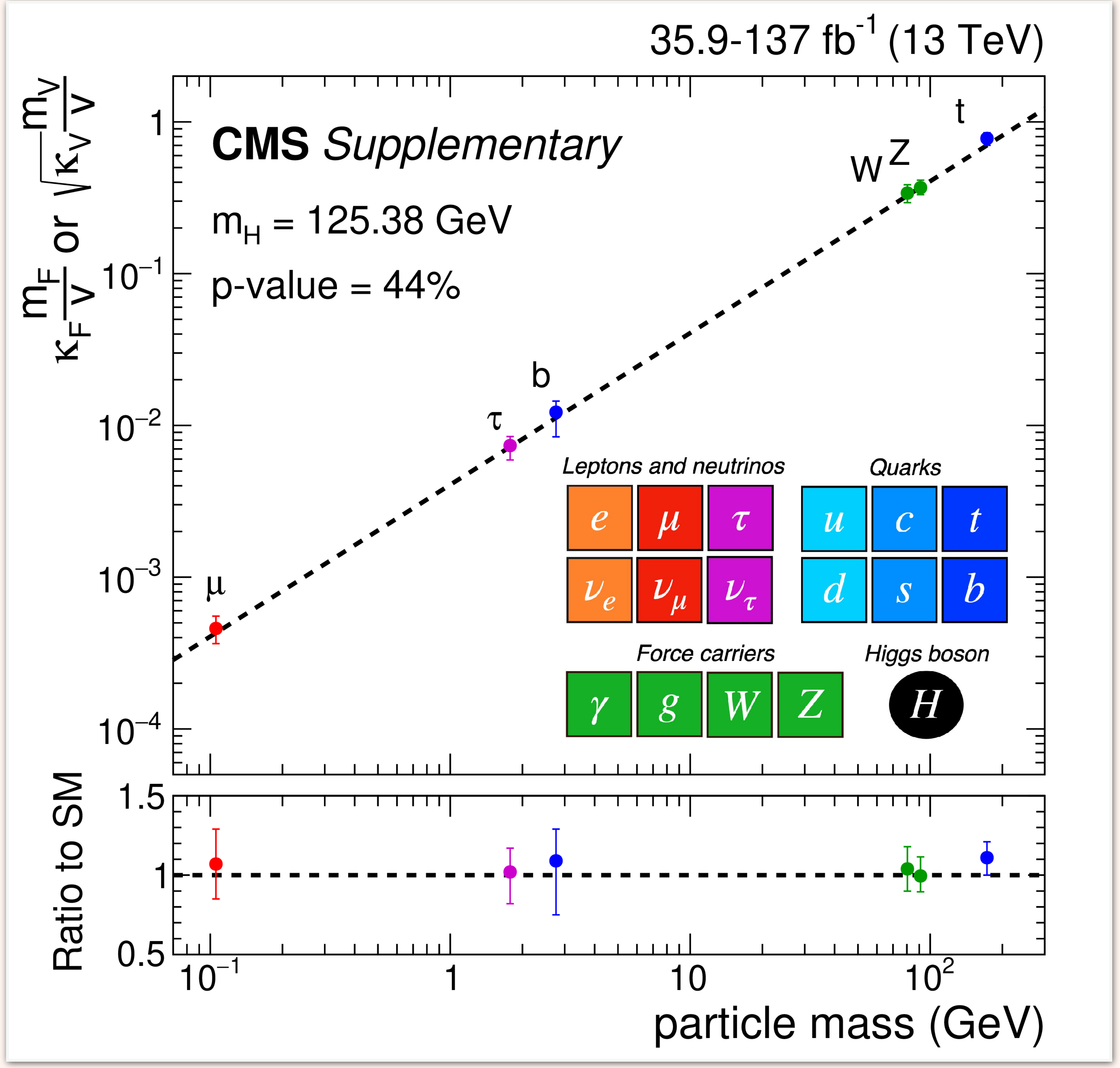


$H \to bb$

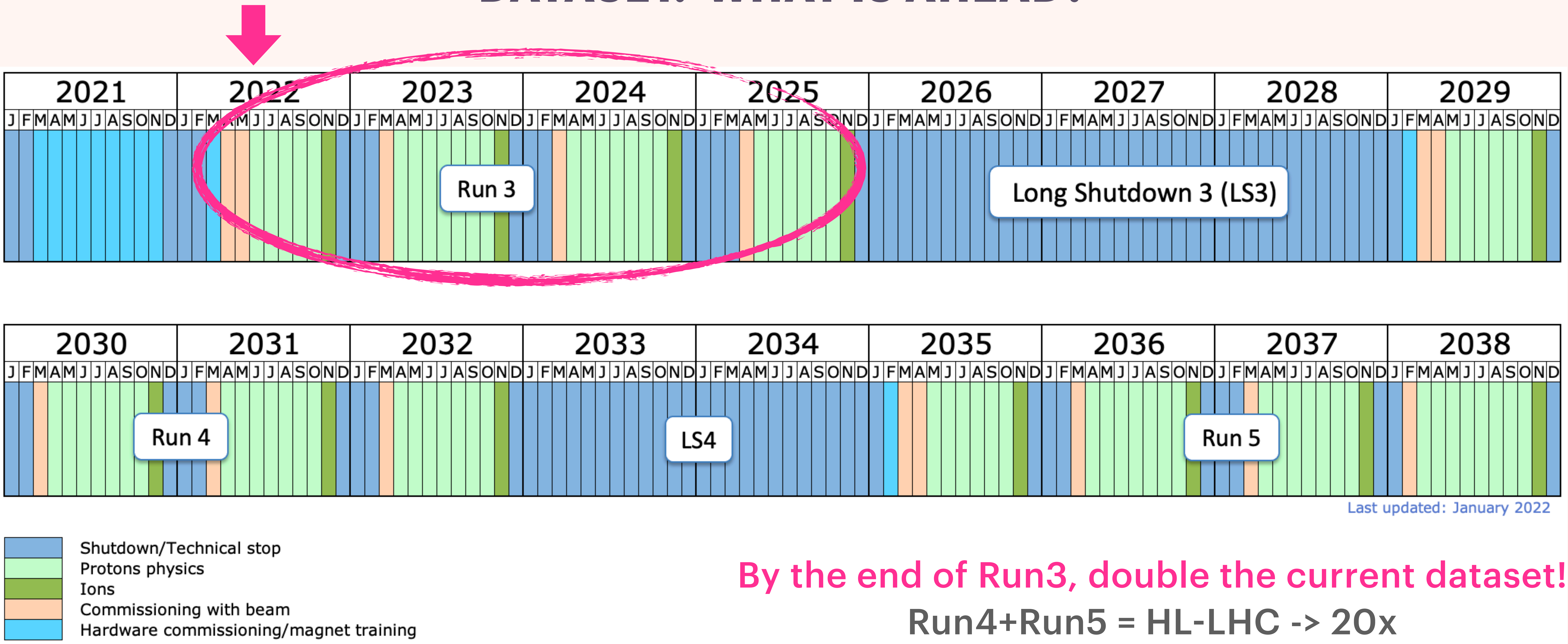
Br~58%



- Measurements of Mass (to 0.11%!), Width, CP
- The main production modes have been explored in detail, with precise measurements of the signal strength/cross section (down to 10% precision)
- The coupling to the SM particles is well established for the main decay modes, and already at evidence level for several of the statistically dominated ones
- Extensive list of searches for BSM properties, so far finding good agreement with the SM, but with ample phase-space to probe in the future



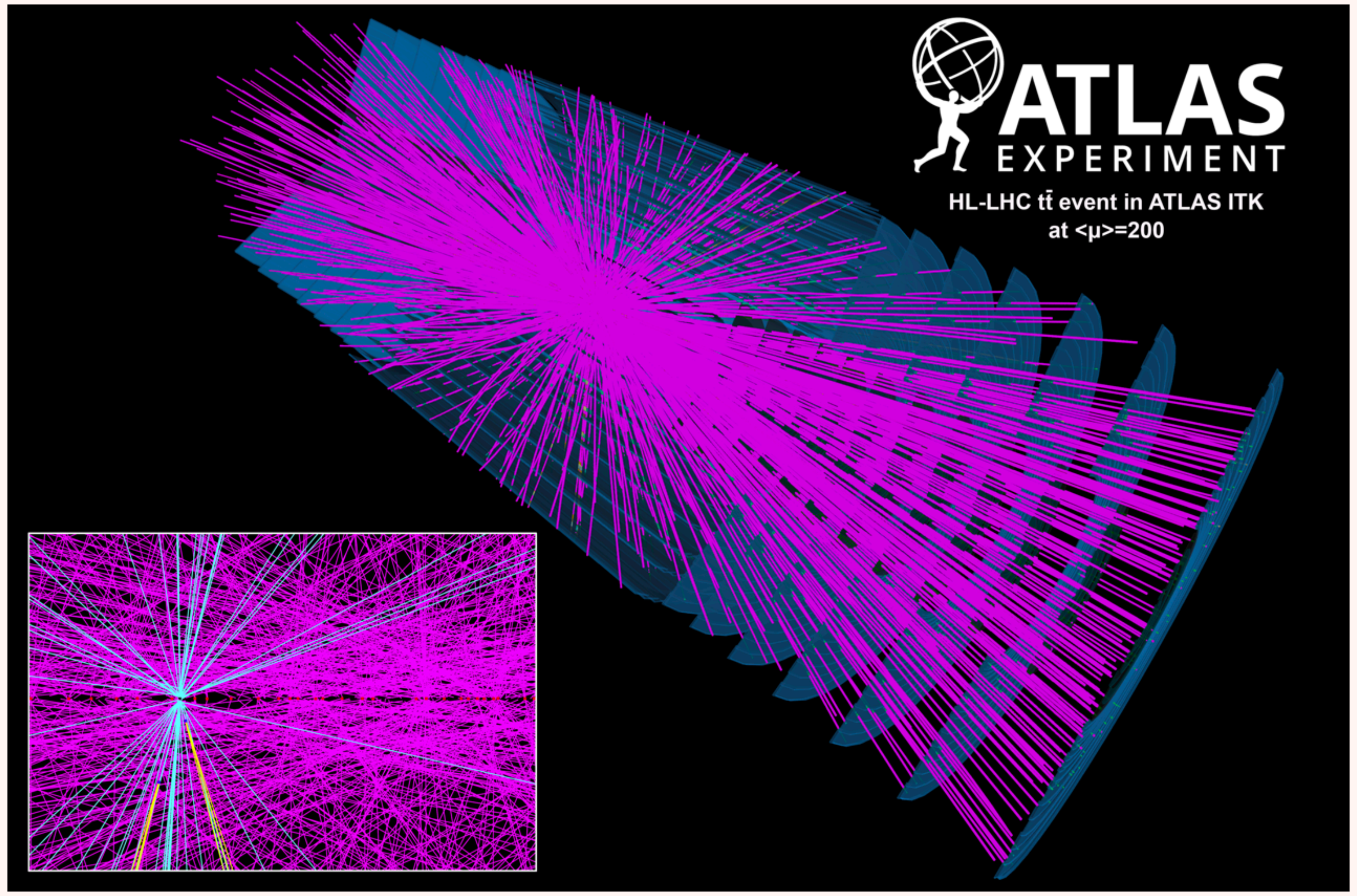
STILL, WE HAVE ONLY ACCESSED A 5% OF THE FULL LHC DATASET. WHAT IS AHEAD?

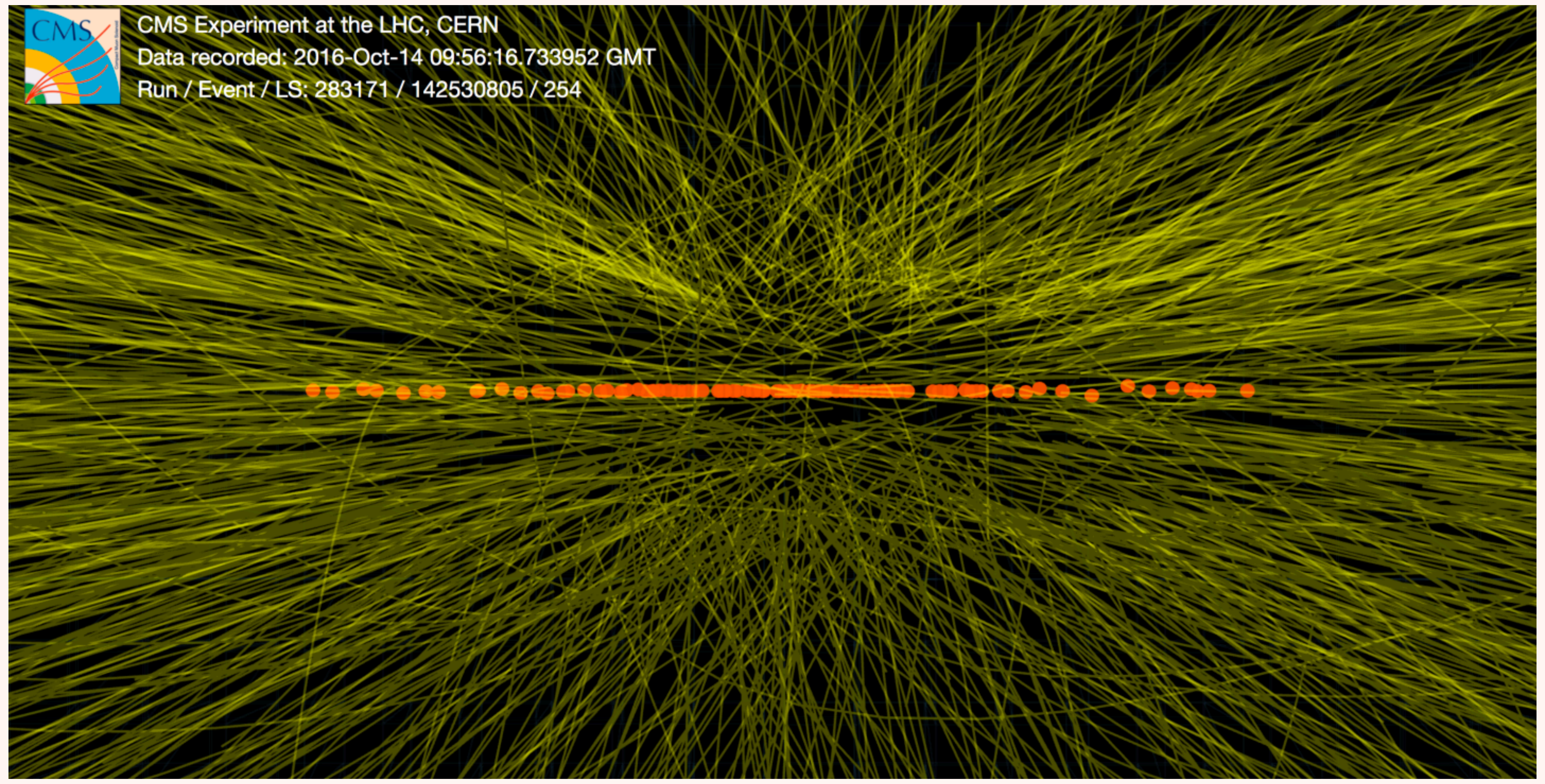


By the end of Run3, double the current dataset!

Run4+Run5 = HL-LHC -> 20x

HIGH LUMI & HIGH PILEUP



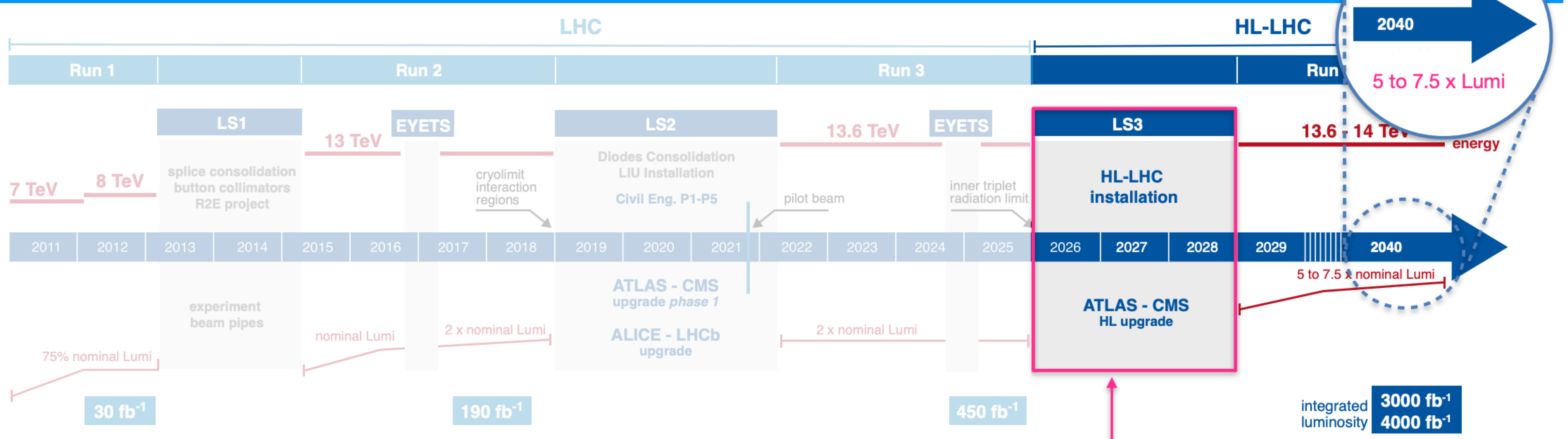


- **High statistics does not come for free: extremely challenging conditions**
  - High luminosity ➔ 200 soft pp interactions per crossing
  - Detector elements and electronics are exposed to high radiation dose

- Extensive **upgrade** program by ATLAS and CMS underway, with the goal of at least maintaining the current performance despite the hard conditions
  - Effective pileup mitigation & extended capabilities with new algorithms
  - Increased detector acceptance
  - Increased spatial granularity to resolve signals from individual particles
  - Precise timing measurements to provide an additional dimension for discrimination

REMEMBER YESTERDAY'S LECTURE!

The next 20 Years of LHC: Towards HL-LHC



Phase 2 (Major **ATLAS** and **CMS** upgrades with deployment during LS3) **2024-2026**

ATLAS

- **Full Si tracker up to 4** (with HW track trigger).
- Calorimeter electronics upgrade
- **Timing detector** with partial eta coverage (2.4 - 4) LGAD silicon: 30 ps resolution.
- Muon coverage (also possibly at LS4)

CMS

- **Strips and pixels replaced with higher granularity up to 3.8** (and HW trigger).
- New EndCap calorimeters HGCAL (High granularity) Silicon Pb/Steel 26 X0 and Scintillator/Steel 9 Int. Lengths.
- ECAL Barrel: New shaping with faster time rise to reach 30 ps timing resolution!
- **Full coverage timing** detector (up to eta 3) LGAD silicon: 30-40 ps resolution.

Longer term LS4 **2030**

Upgrades planned and under discussion

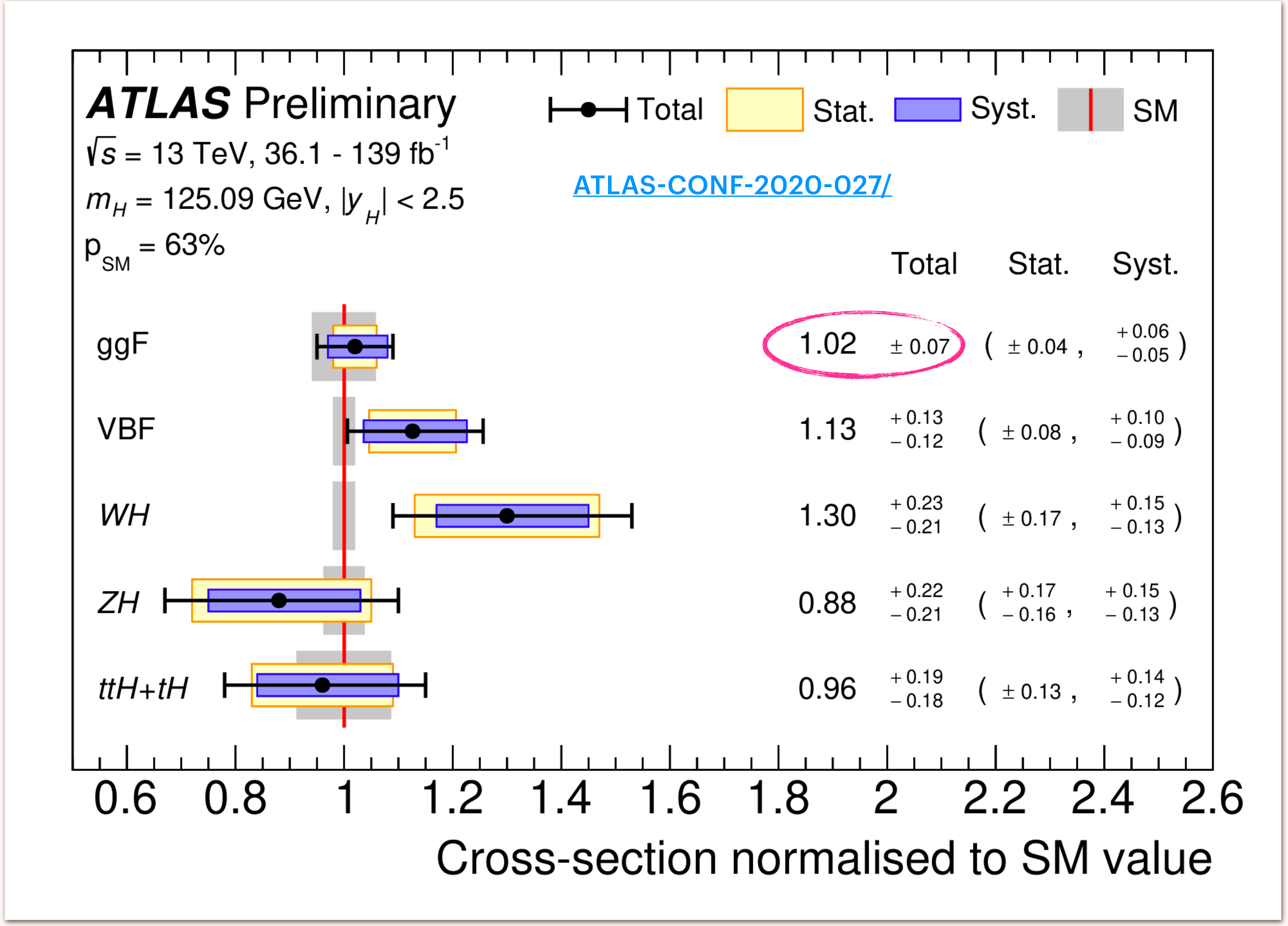
EXPLORING THE FUTURE DATA OF THE LHC

- Do we really understand how the Higgs boson is produced? And how it decays?
- What is the nature of the Higgs? (Properties: Mass, Width, Spin)
- How does it couple to Standard Model particles?
  - Does it couple to the second generation?
  - Does it couple to itself?
- Does it decay unusually? (BSM, eg: Dark Matter?)
- Is the Higgs alone?
- Is it really an elementary particle?
- Where does the Higgs mechanism come from?

The data of the Run3 of the LHC and of the HL-LHC era will be fundamental in characterising the Higgs boson

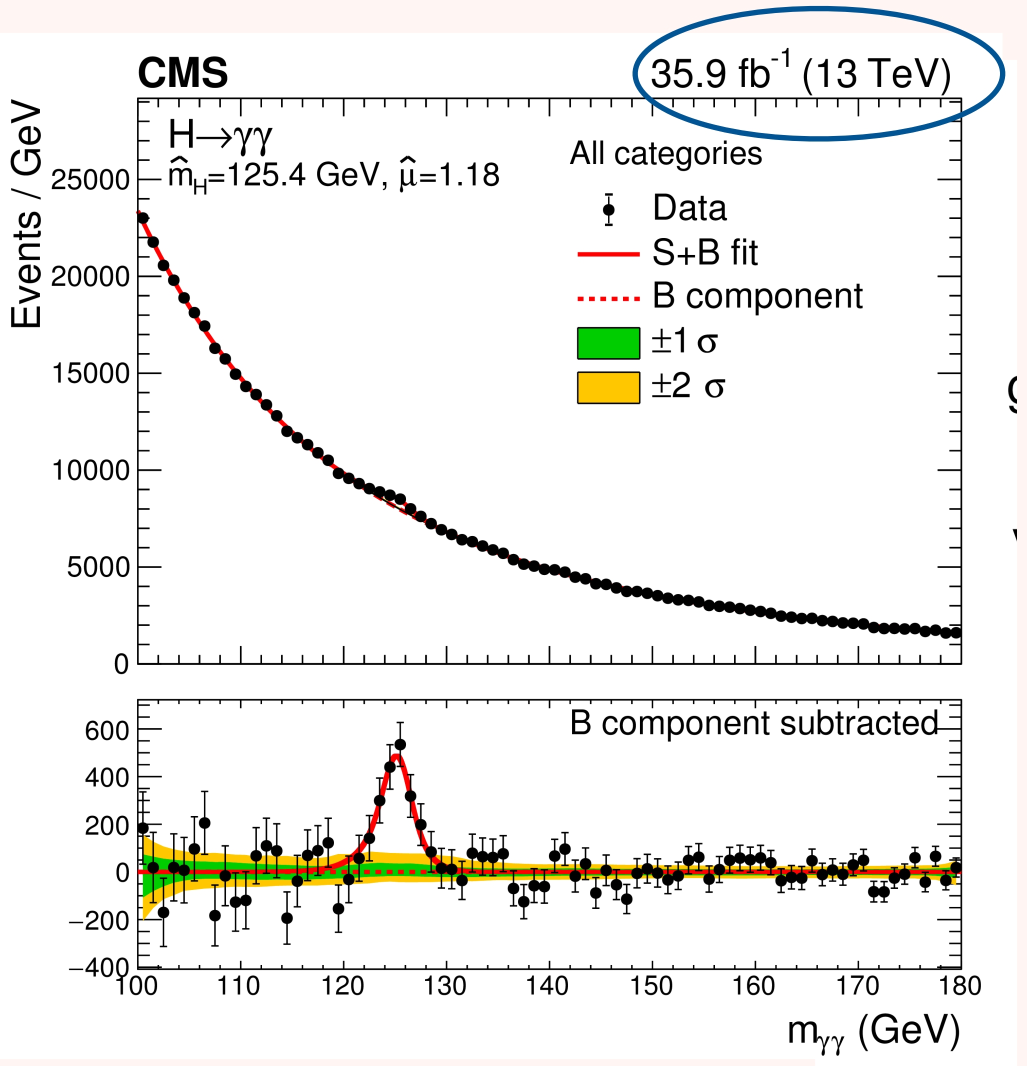
MEASURING CROSS SECTIONS AND BRANCHING RATIOS

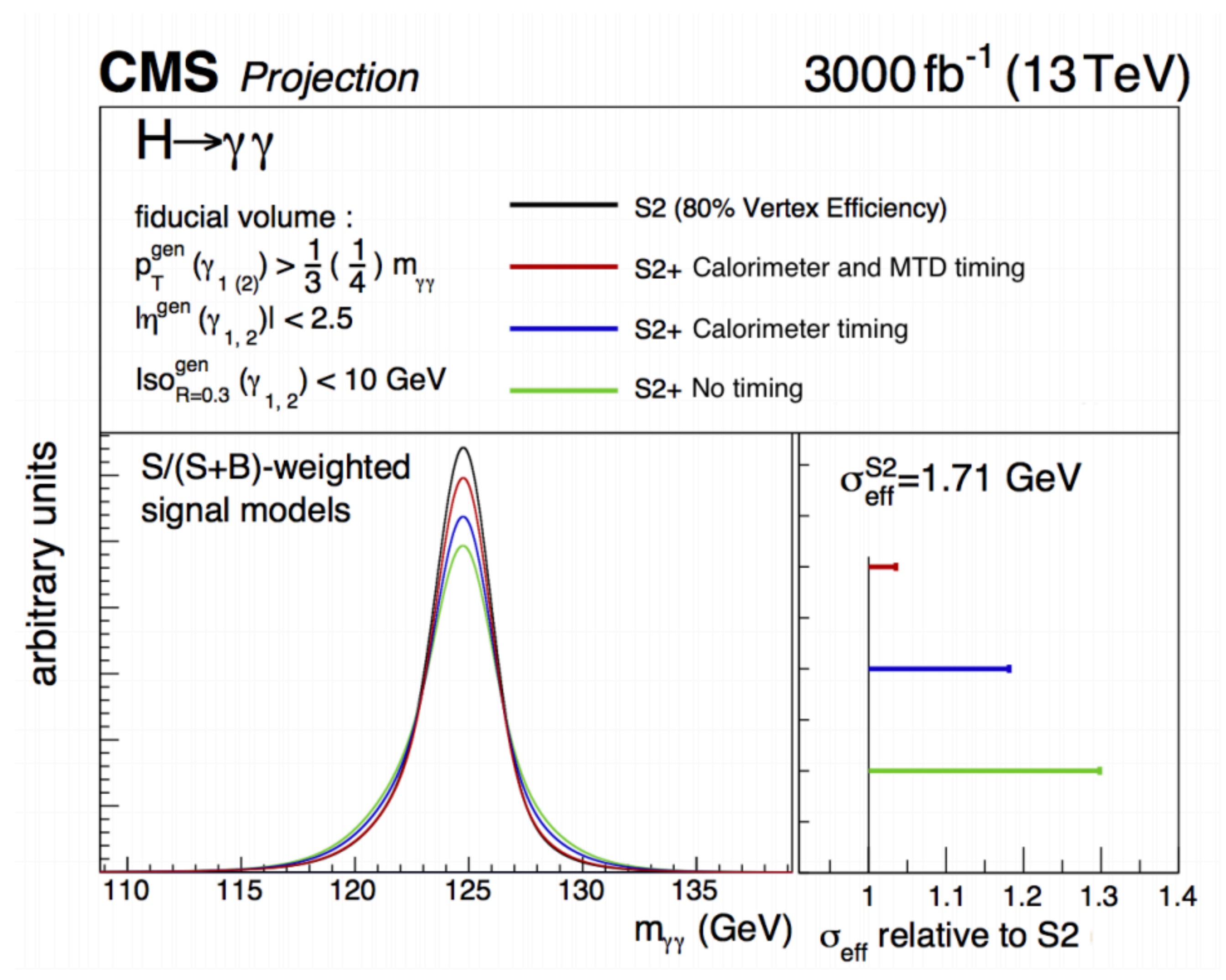
CROSS SECTIONS TODAY

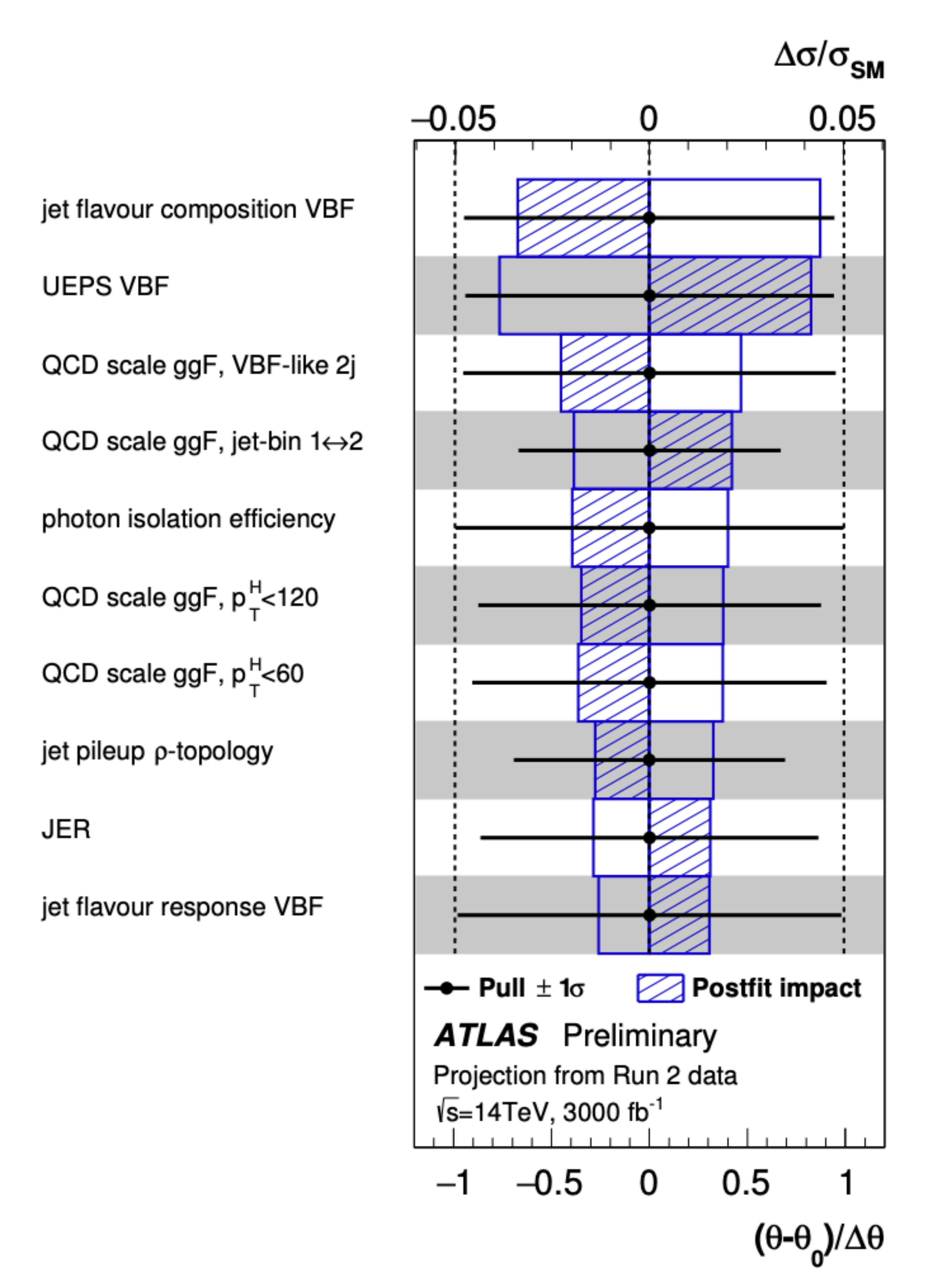


How well will we know cross sections (and branching ratios) by the end of the LHC?

INGREDIENTS OF A HL-LHC PROJECTION







- Not just a matter of replicating the current analysis with HL-LHC luminosity!:
  - Uncertainties: will they improve (larger datasets for studies, better detectors) or worsen (higher pileup)?
  - New techniques: can we learn to do better?
  - How will the upgraded detectors improve the results?
  - Extrapolations of Run2 vs Delphes/Full Phase2 Sim?
  - 13 TeV→ 14 TeV (ggF: 48.6 pb → 54.7 pb)

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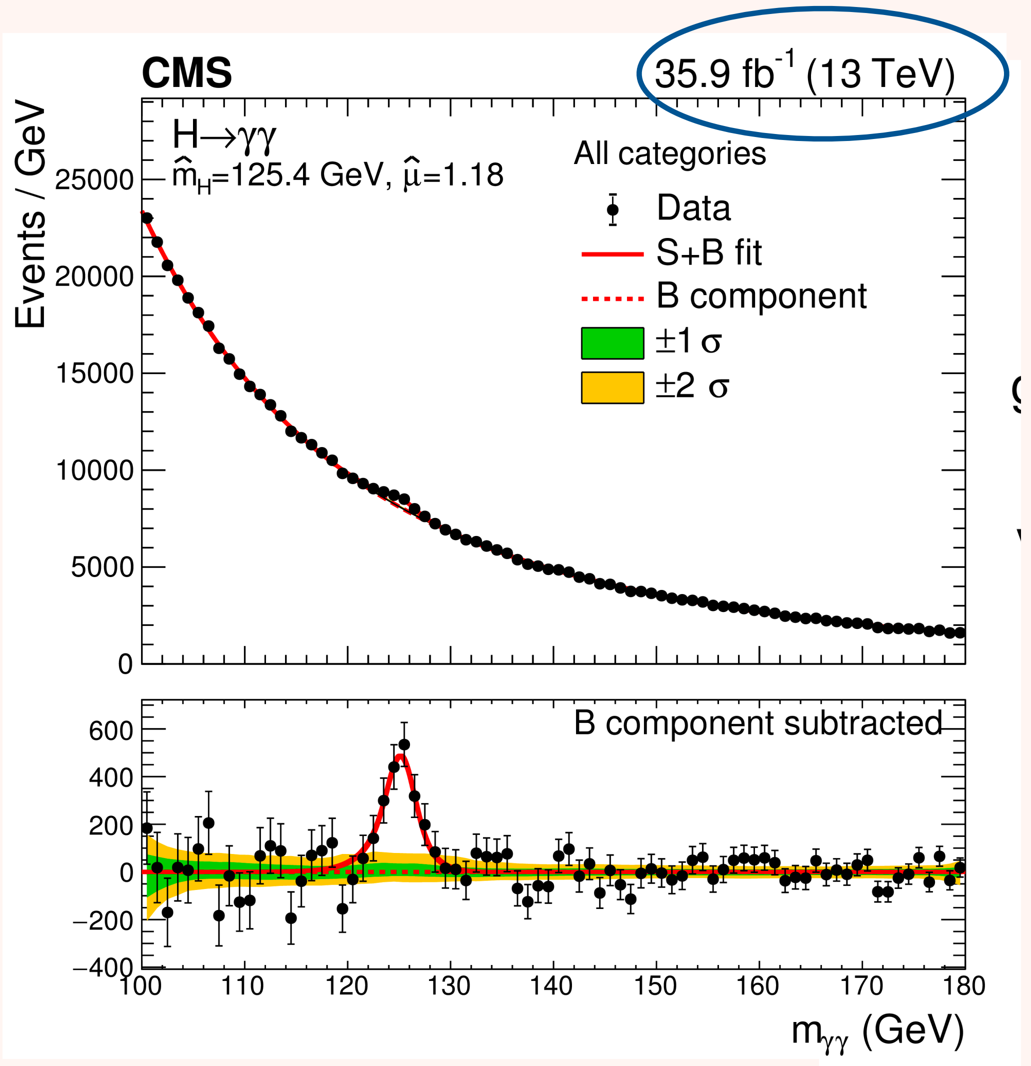
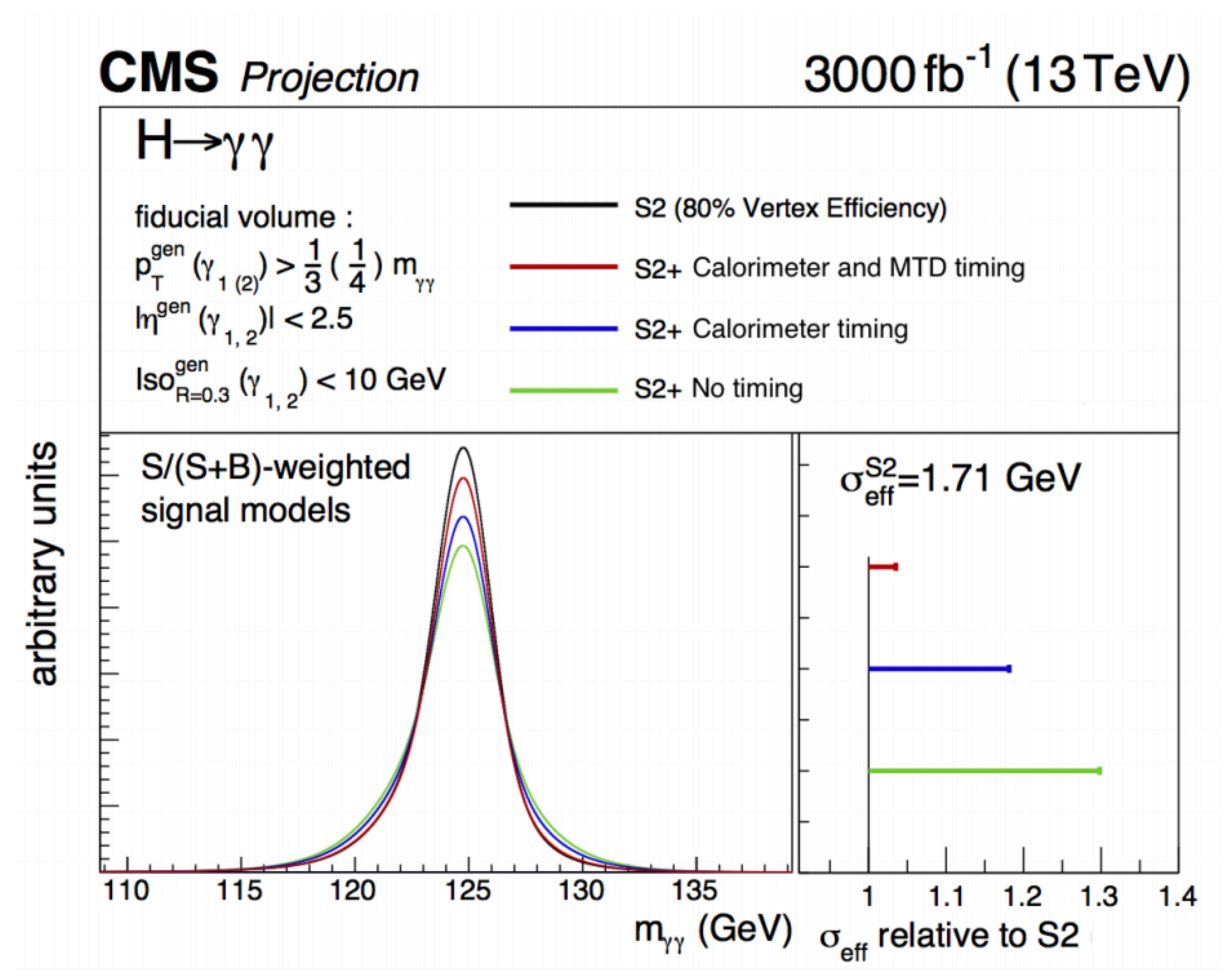
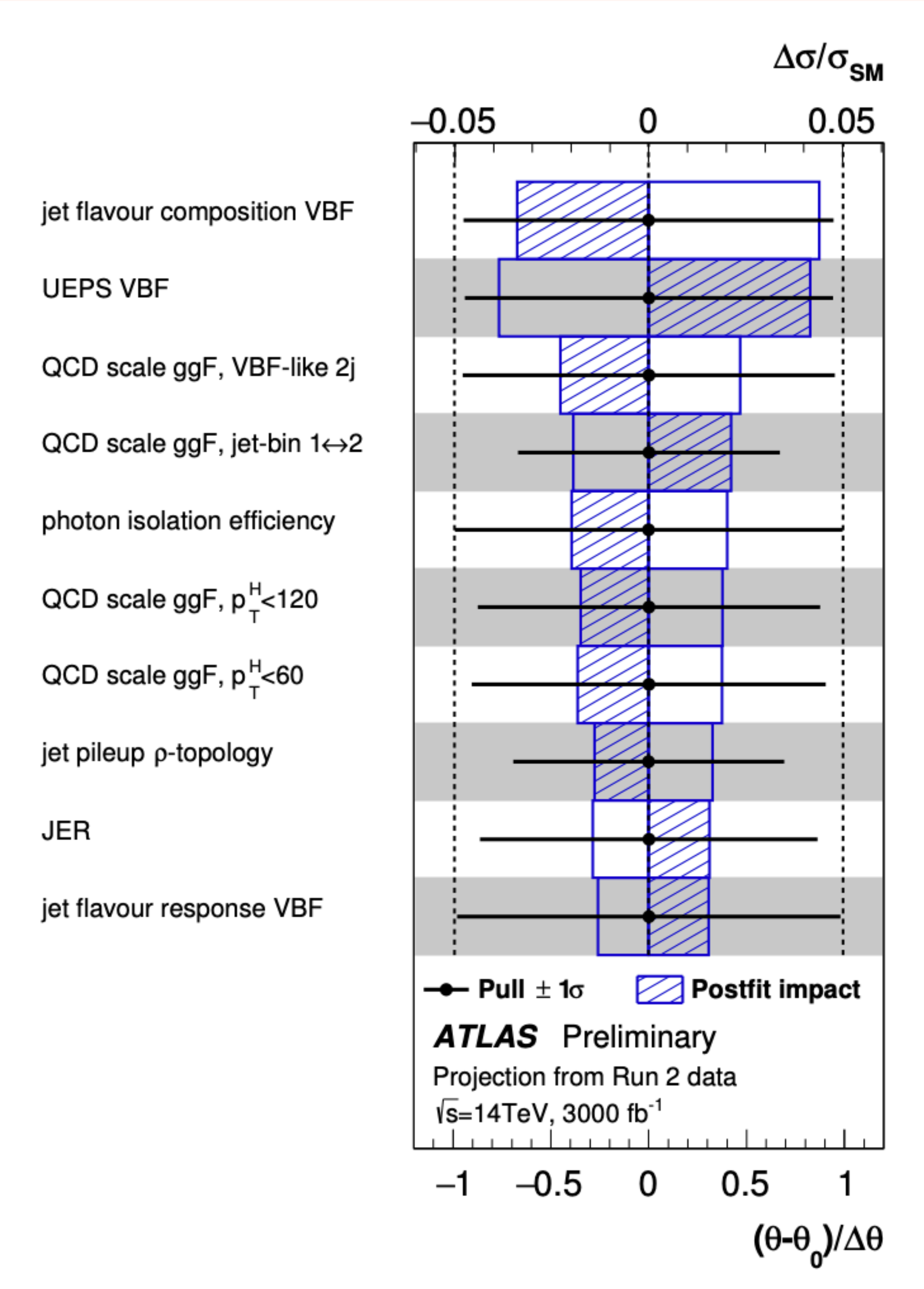
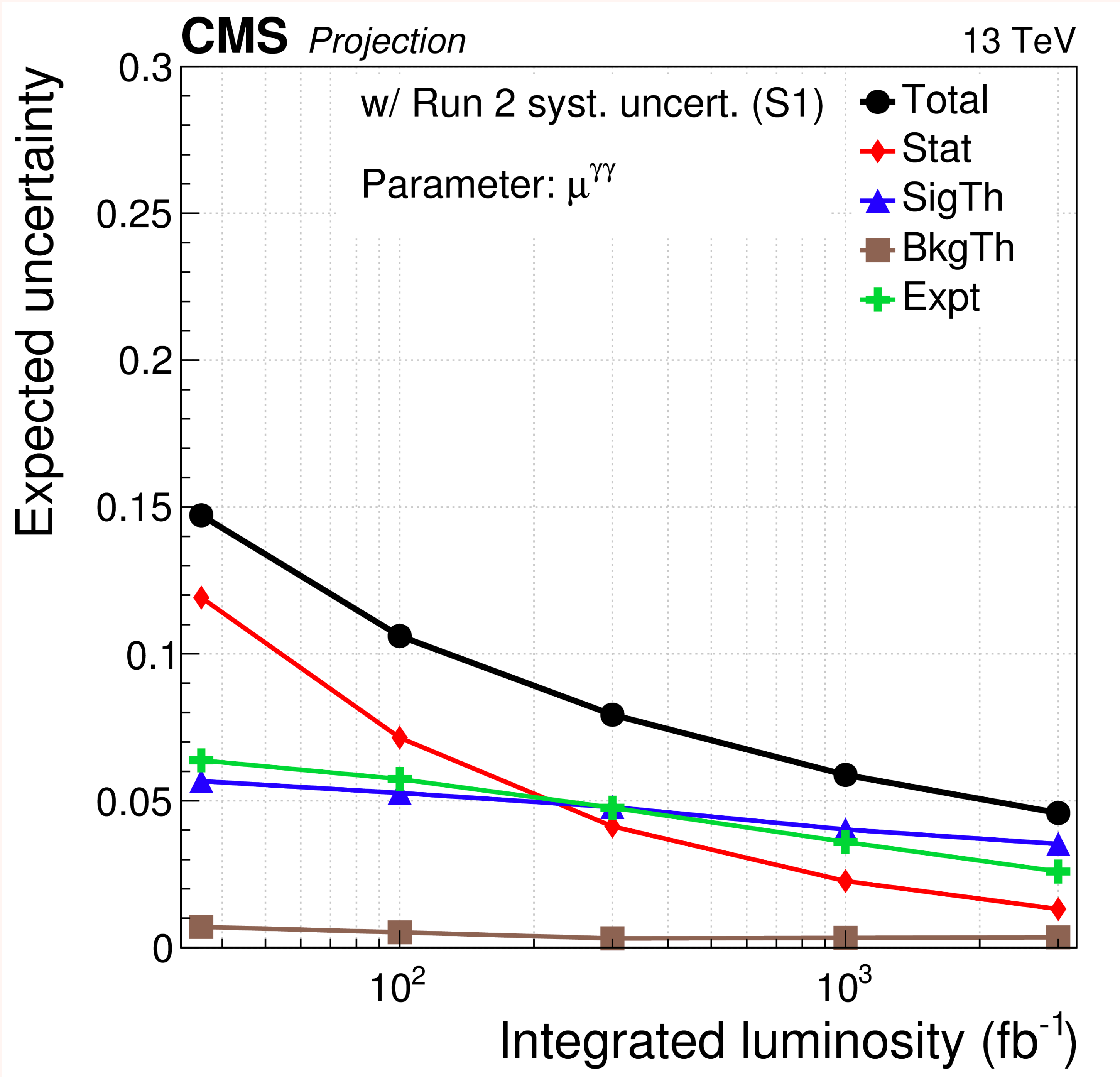


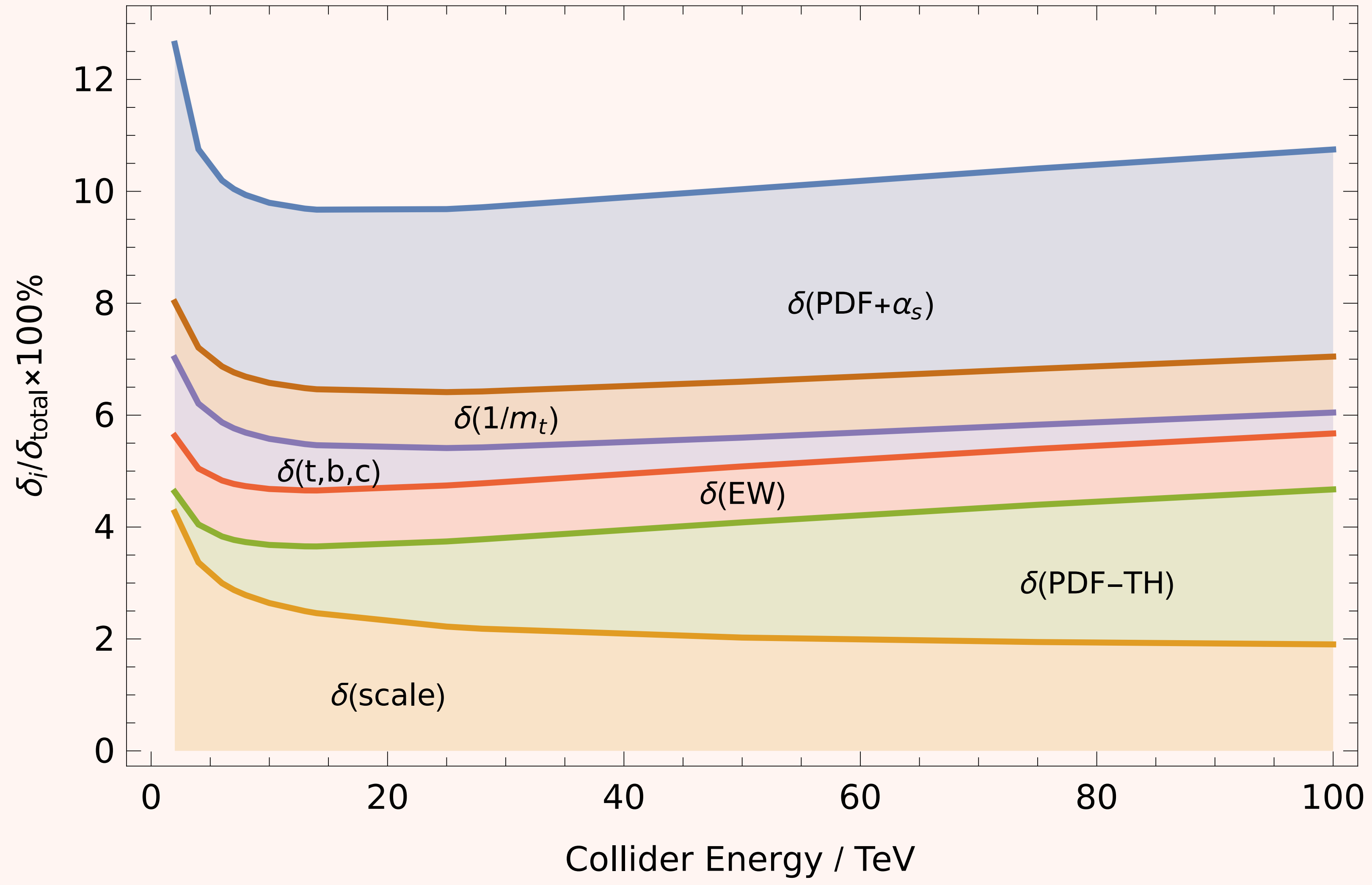


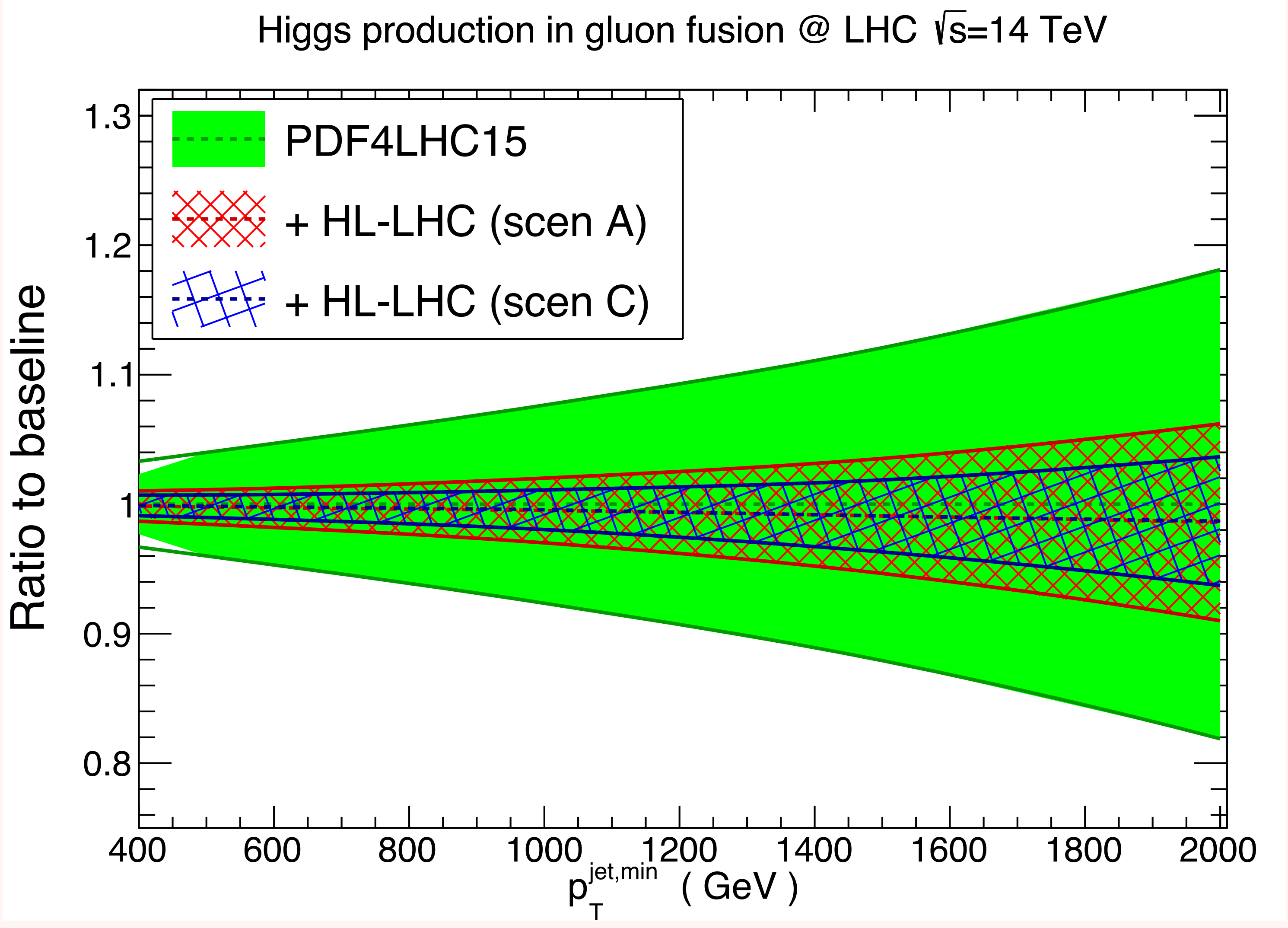




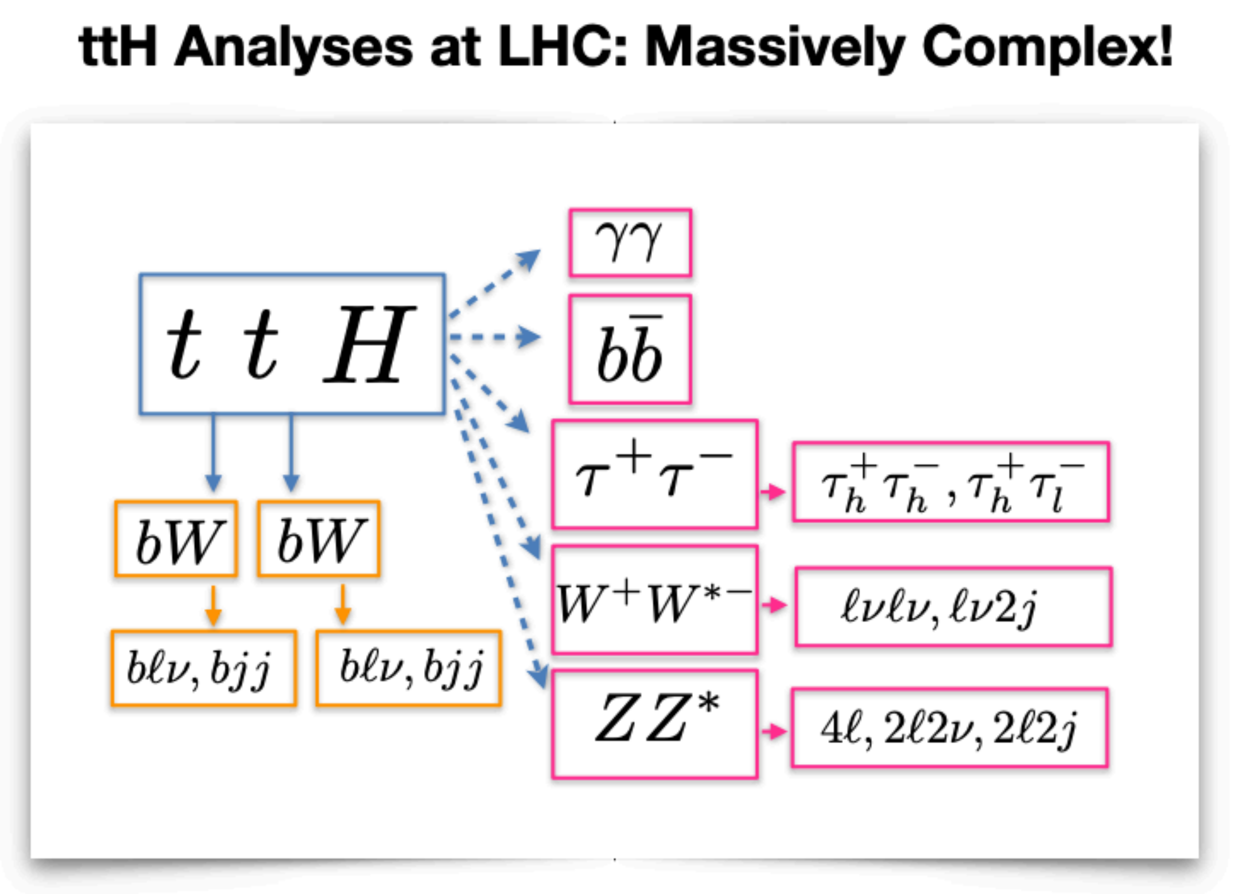
A CHALLENGE FOR THE FUTURE: THEORY UNCERTAINTIES

- Theoretical uncertainties (on signal and backgrounds) already very important in Higgs measurements. As statistics increase and our handle on experimental uncertainties gets better, they will become dominant
- The data of the LHC will feed into our understanding of some of these uncertainties: eg, PDFs
- HL-LHC projections usually assumes improvement upon current (YR4): flat factor of 1/2
    - Experimental uncertainties are also assumed to improve in the projections (taking into account the upgraded detectors future performance)
- In practice, the improvements needed depend heavily on the process under study and the phase space (eg, high pt)

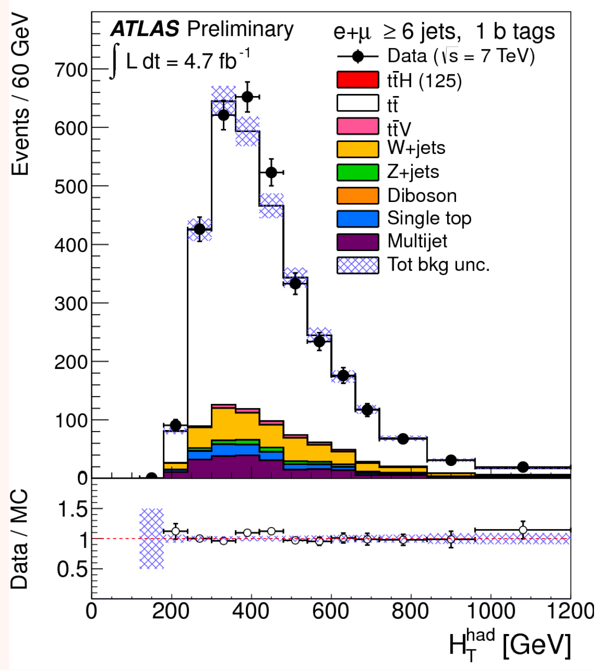


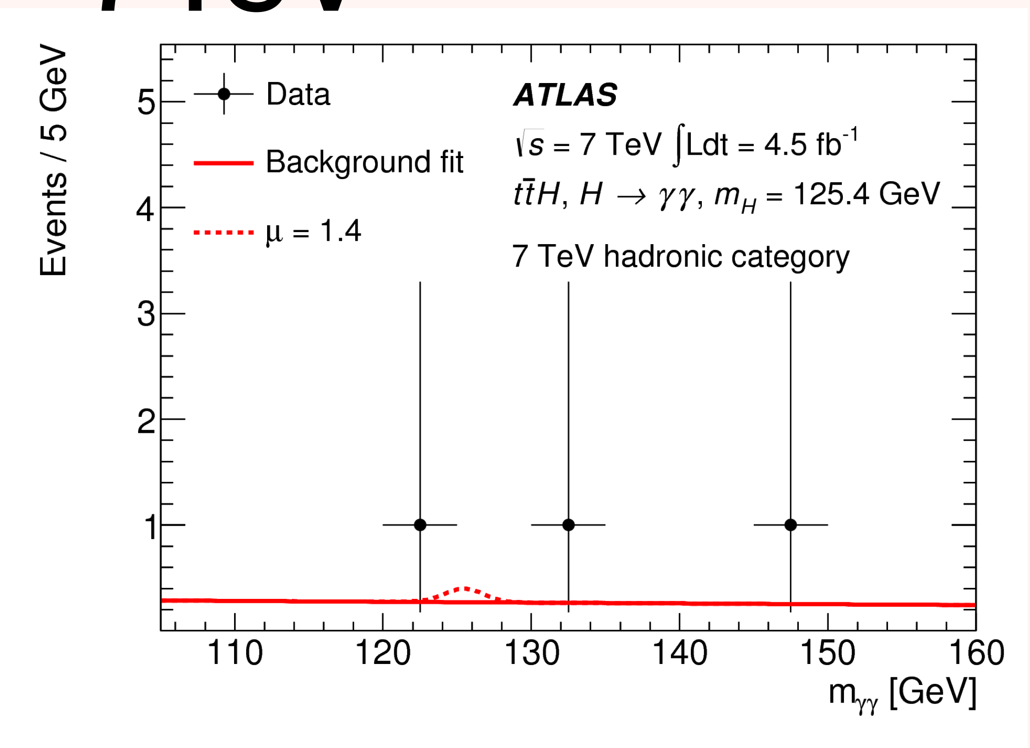


ANALYSIS EVOLVE!

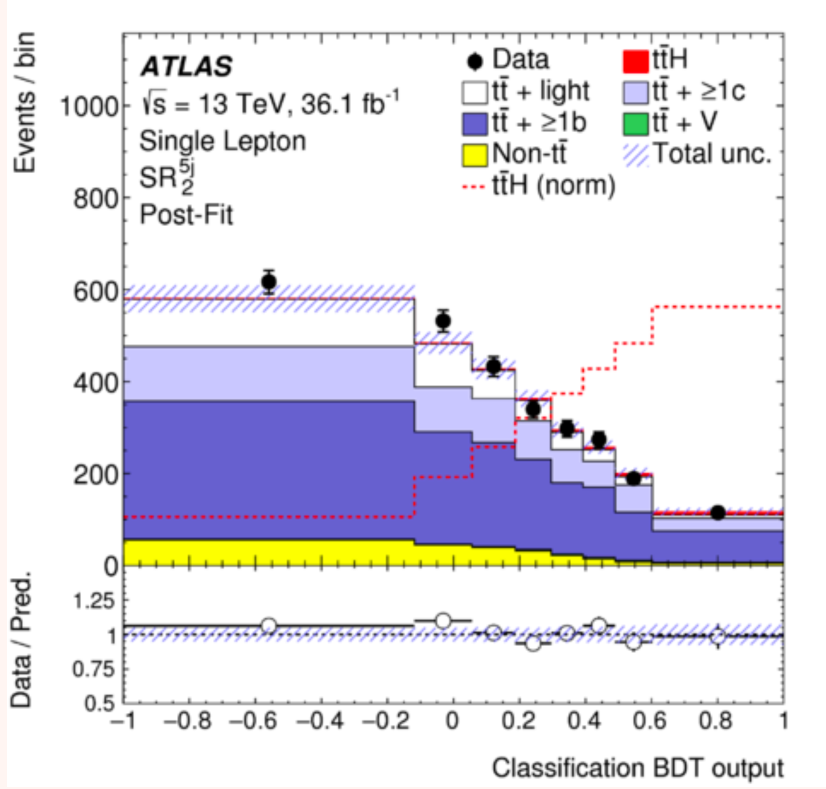


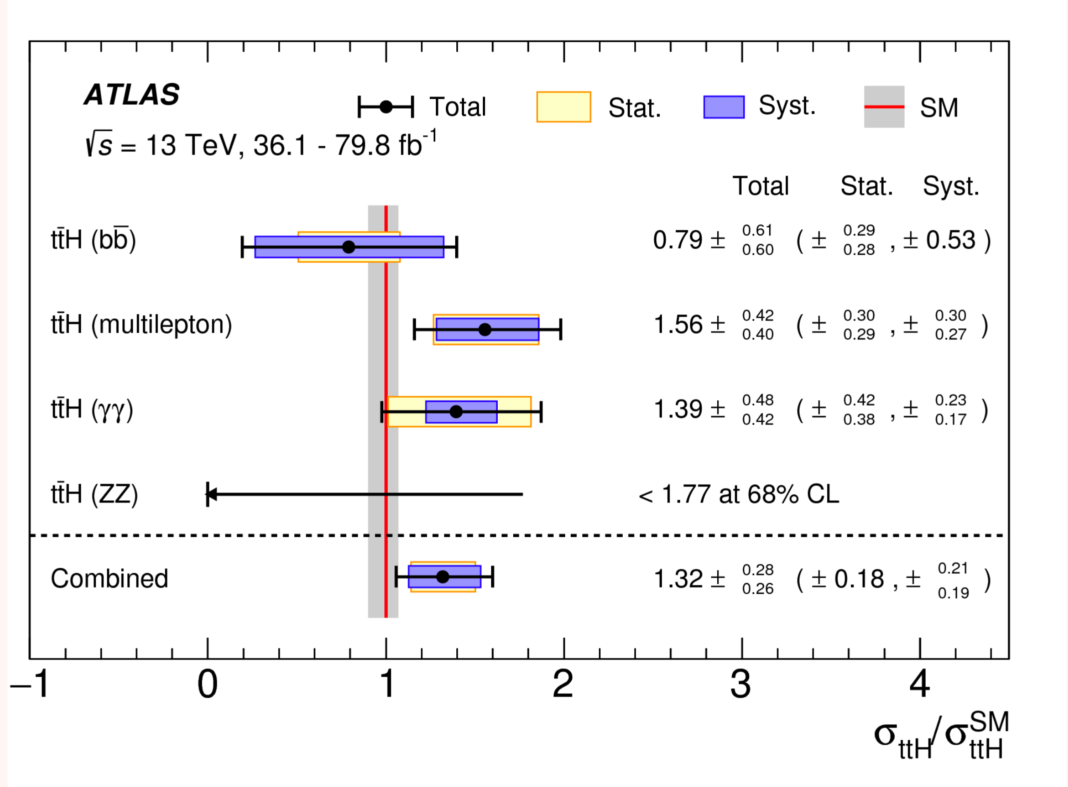
7TeV



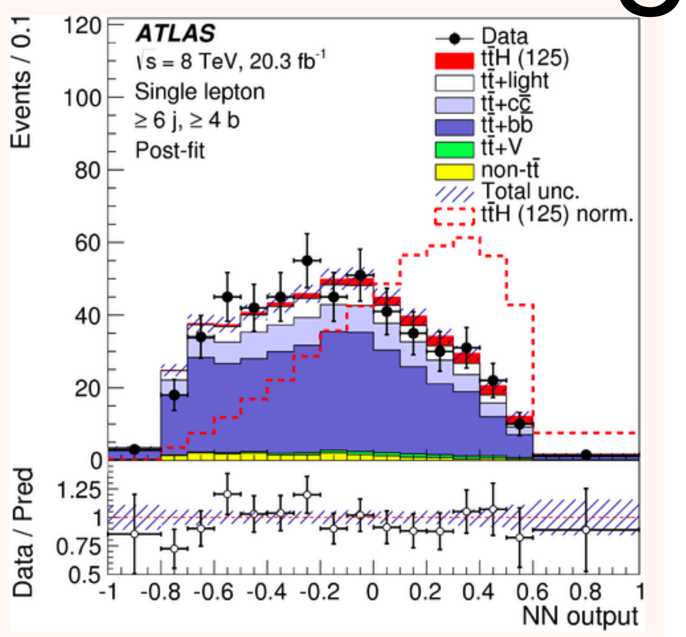


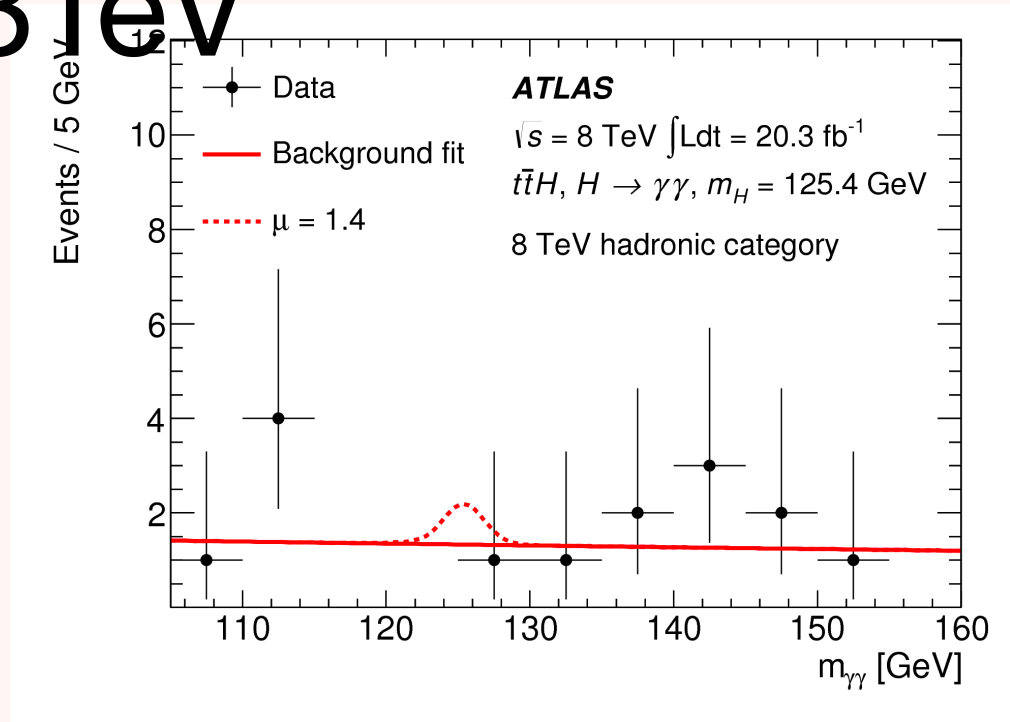
13 TeV, Partial Run II



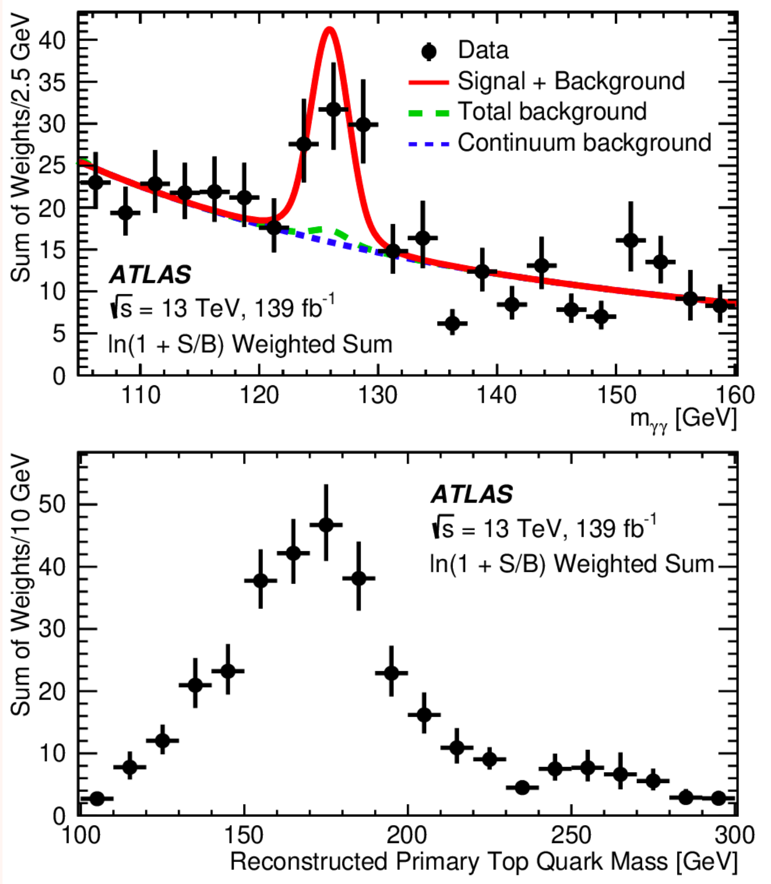


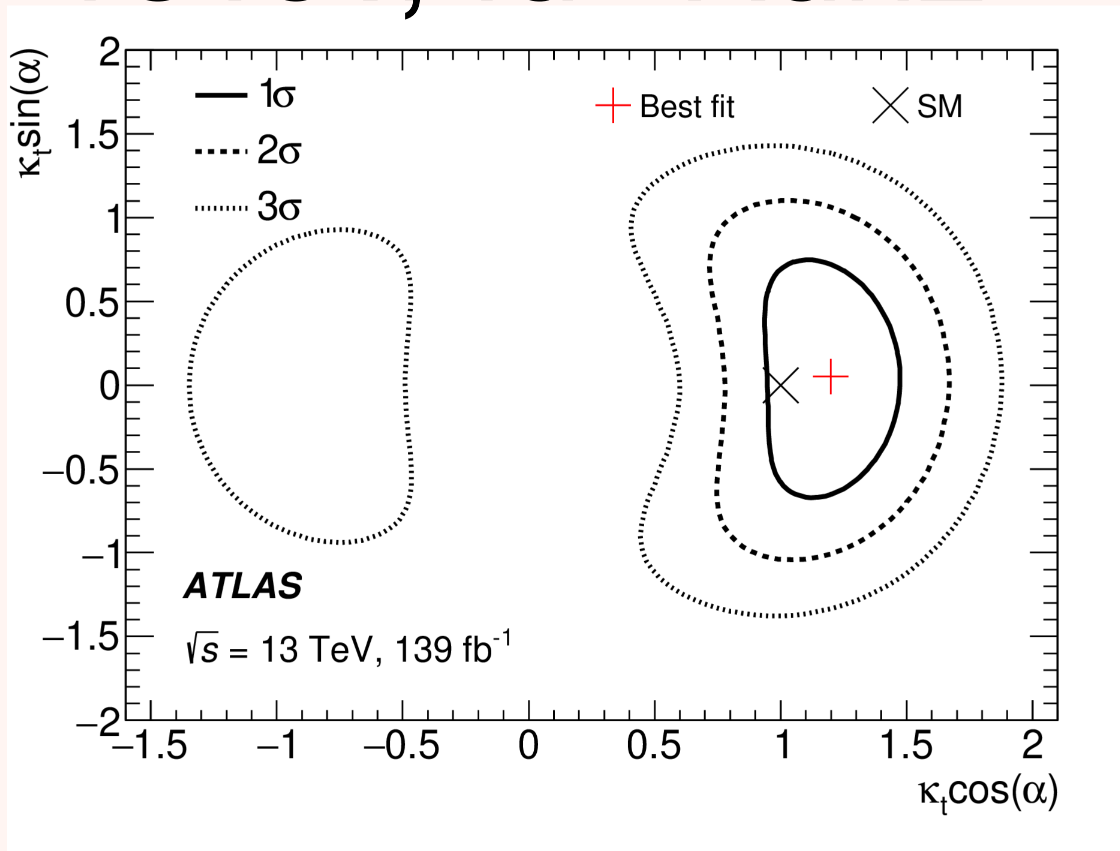
8TeV





13TeV, full Run2





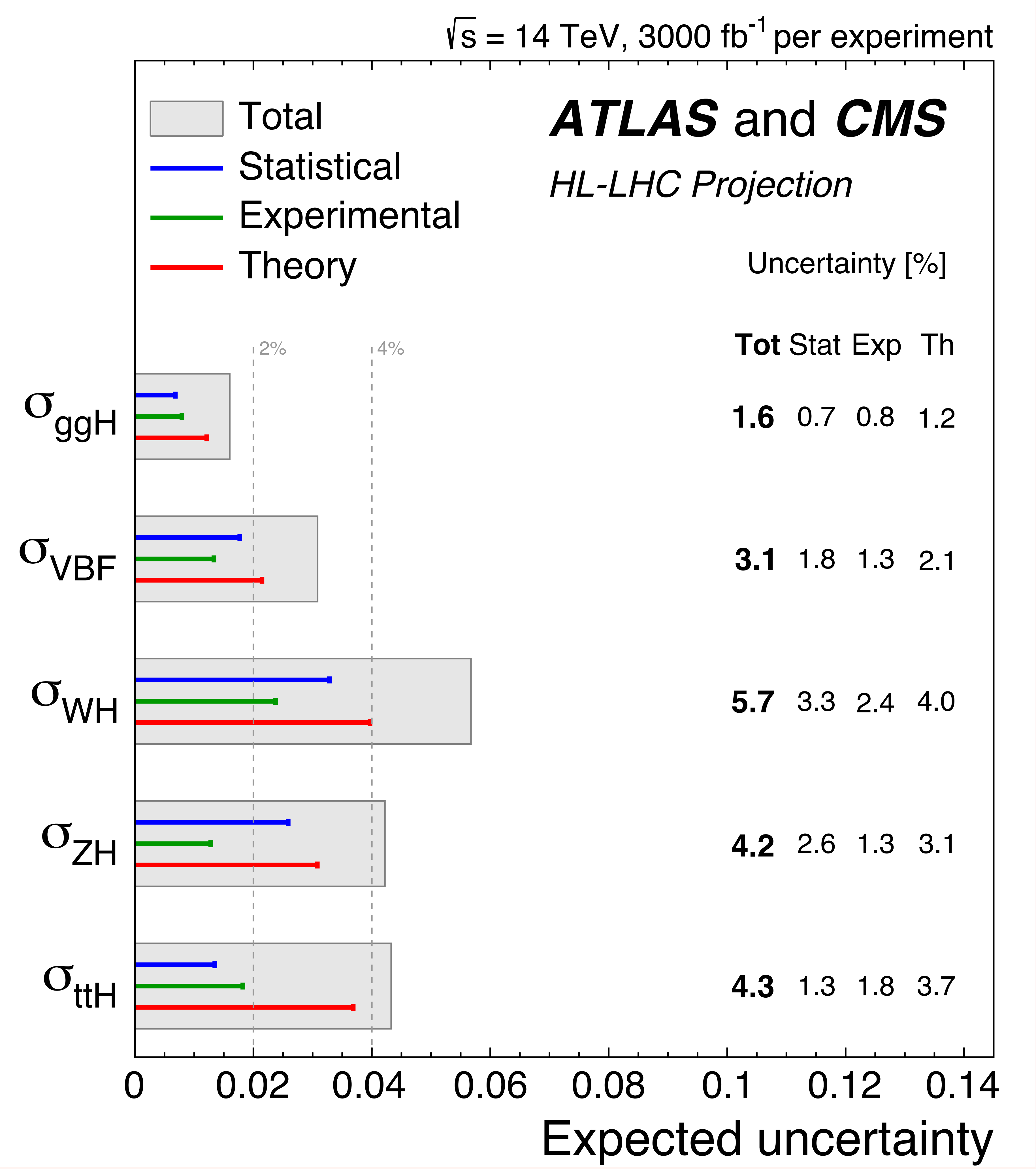
We have many years ahead to incorporate bright new ideas - innovation cannot be projected. Larger datasets come with more room to try new techniques and ideas.

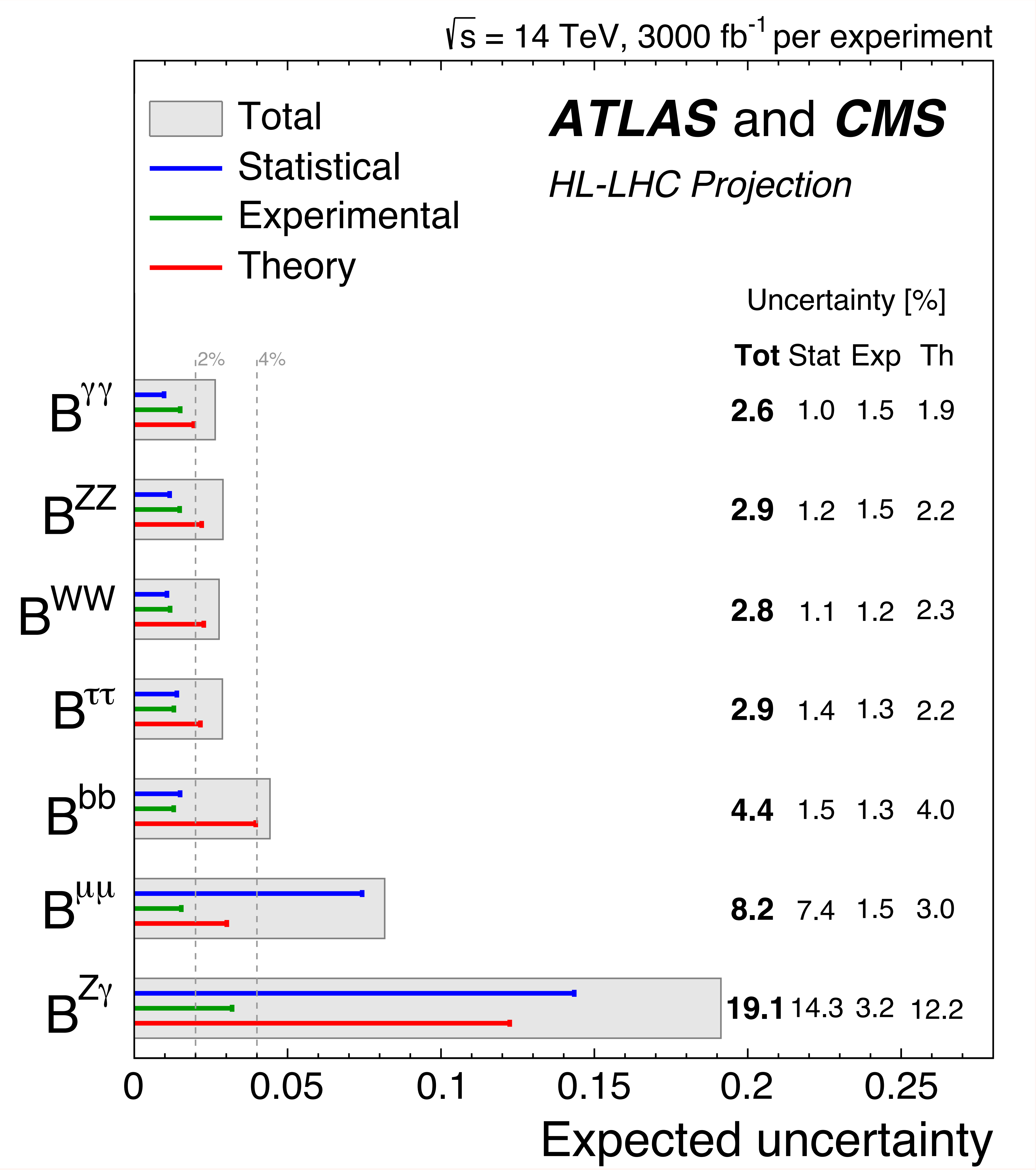
CROSS SECTIONS AND BRANCHING RATIOS @ HL-LHC

ATLAS+CMS combination

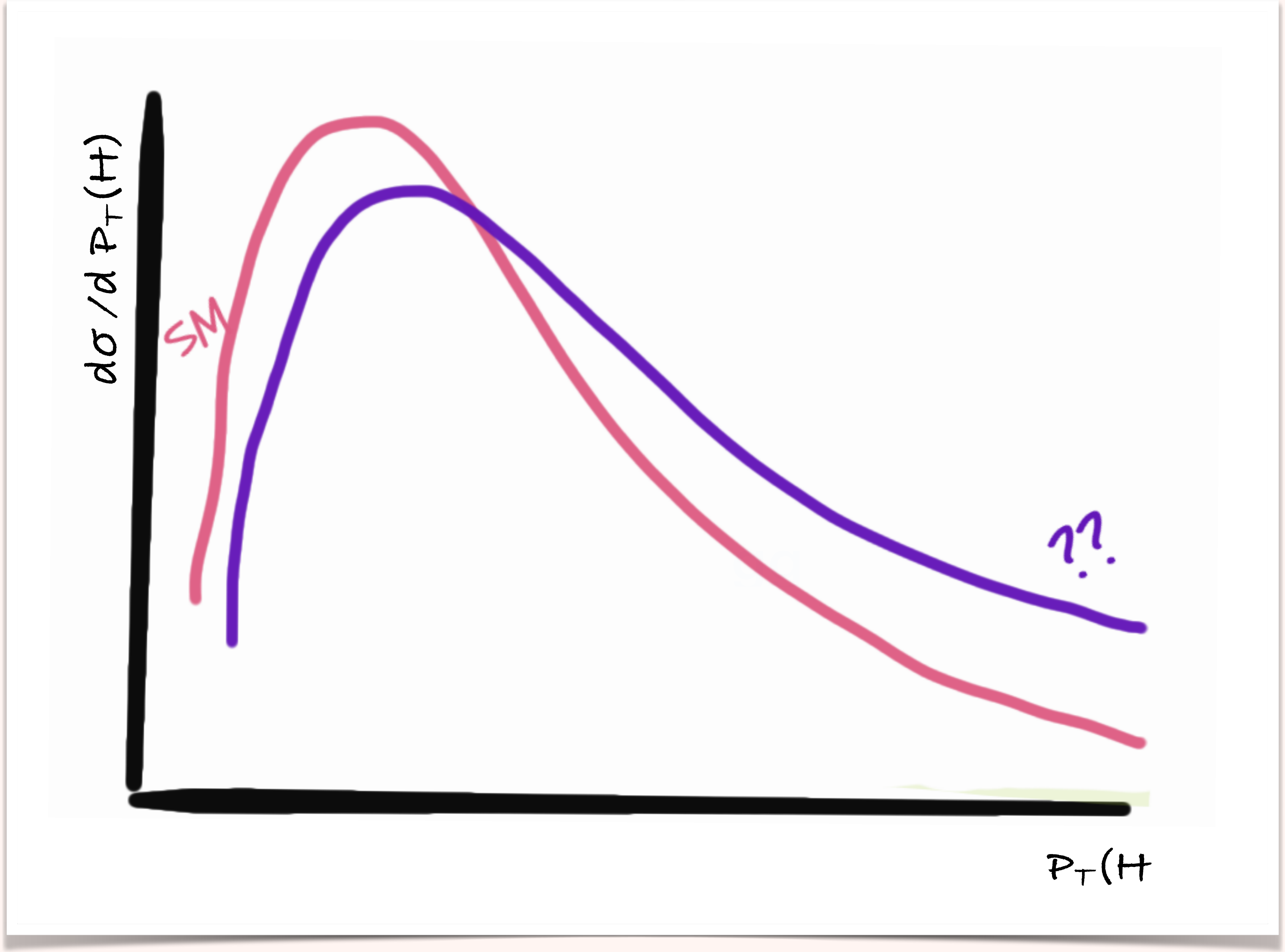
Extrapolating the current analyses, and combining CMS and ATLAS, precisions of few percent can be reached for all production modes, and for all branching ratios (except for rare decays!)

Large impact of theory uncertainties (except for rare modes)





OVERALL AGREEMENT IN RATE IS ONLY THE BEGINNING



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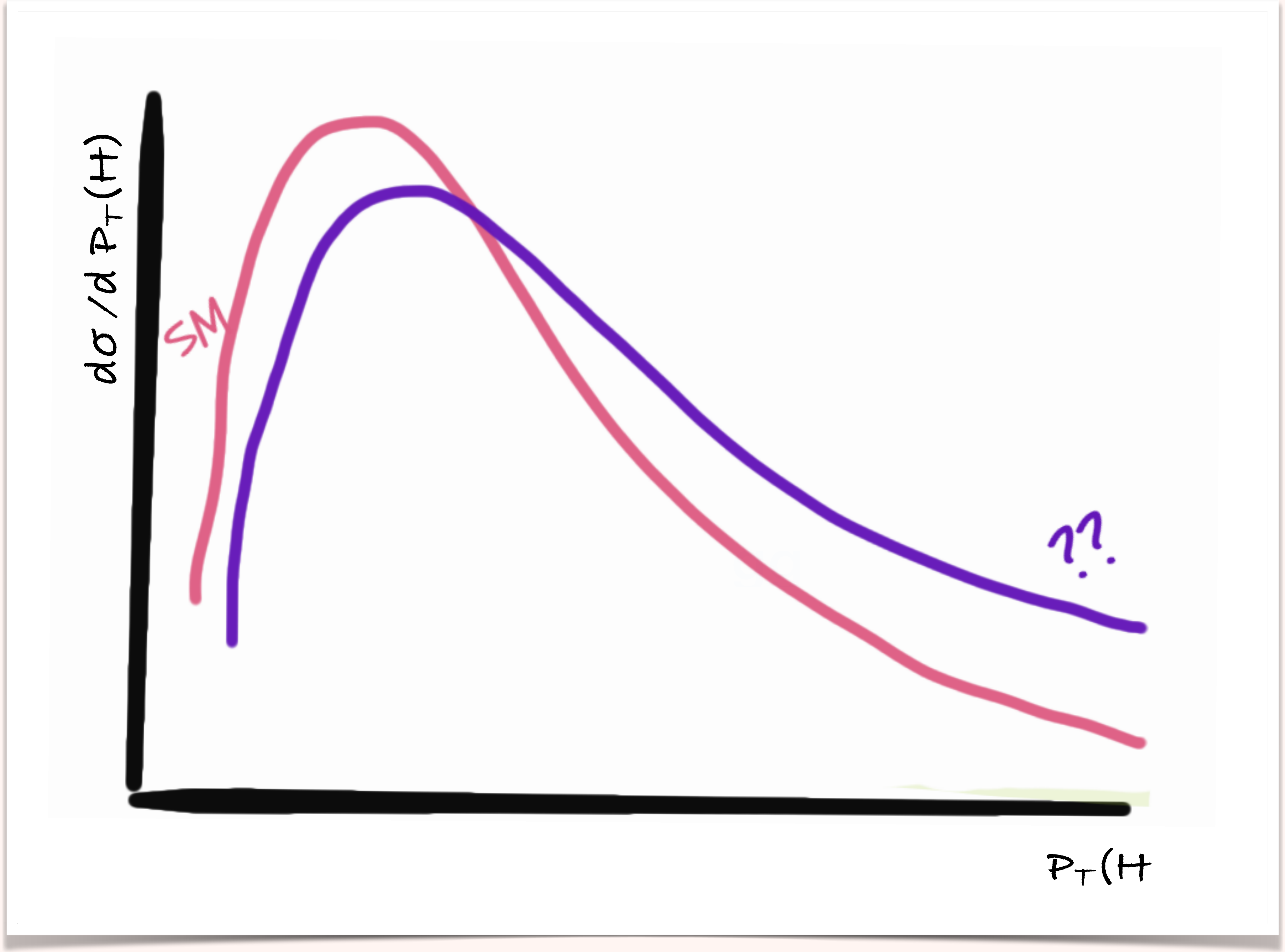
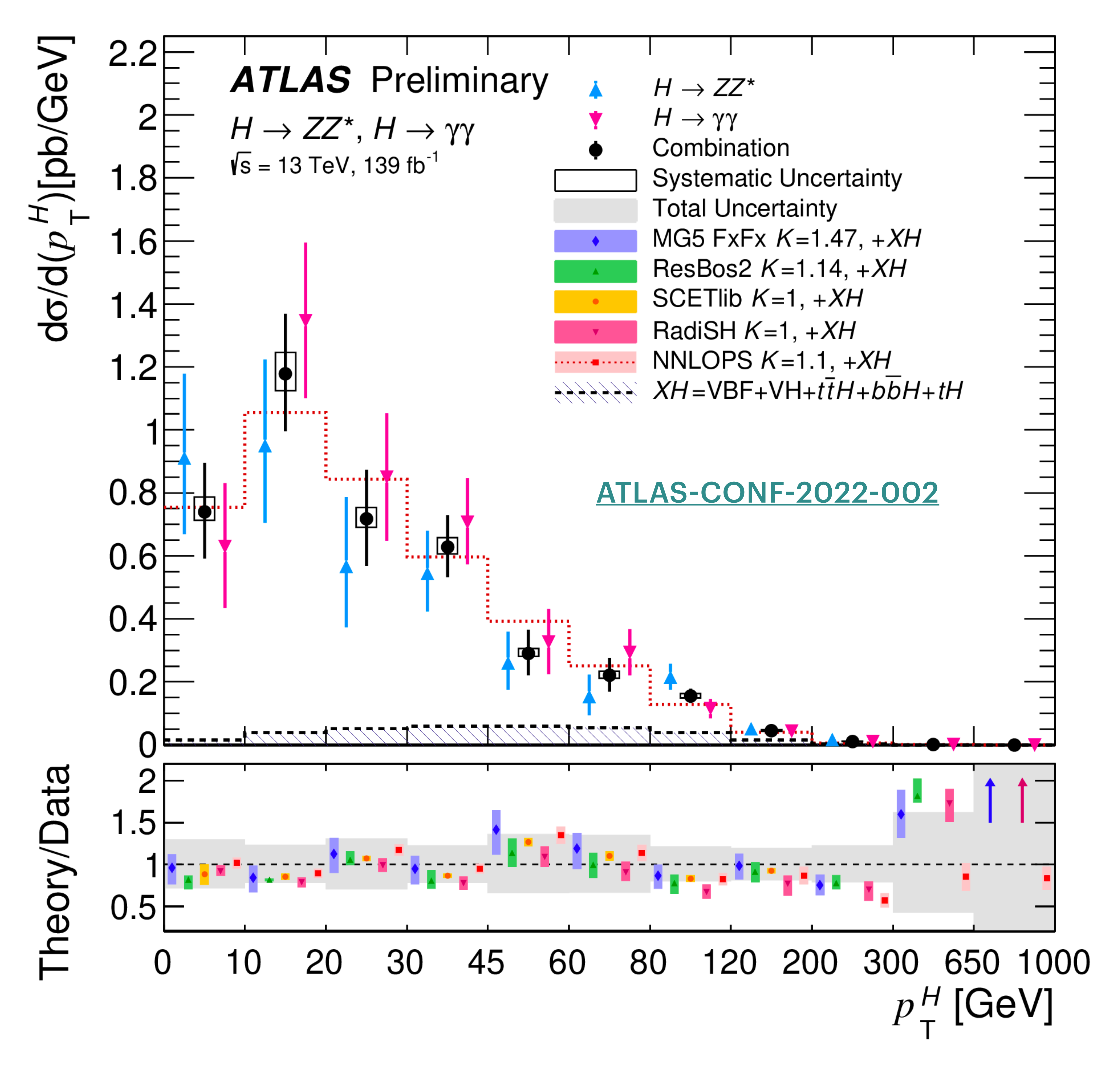
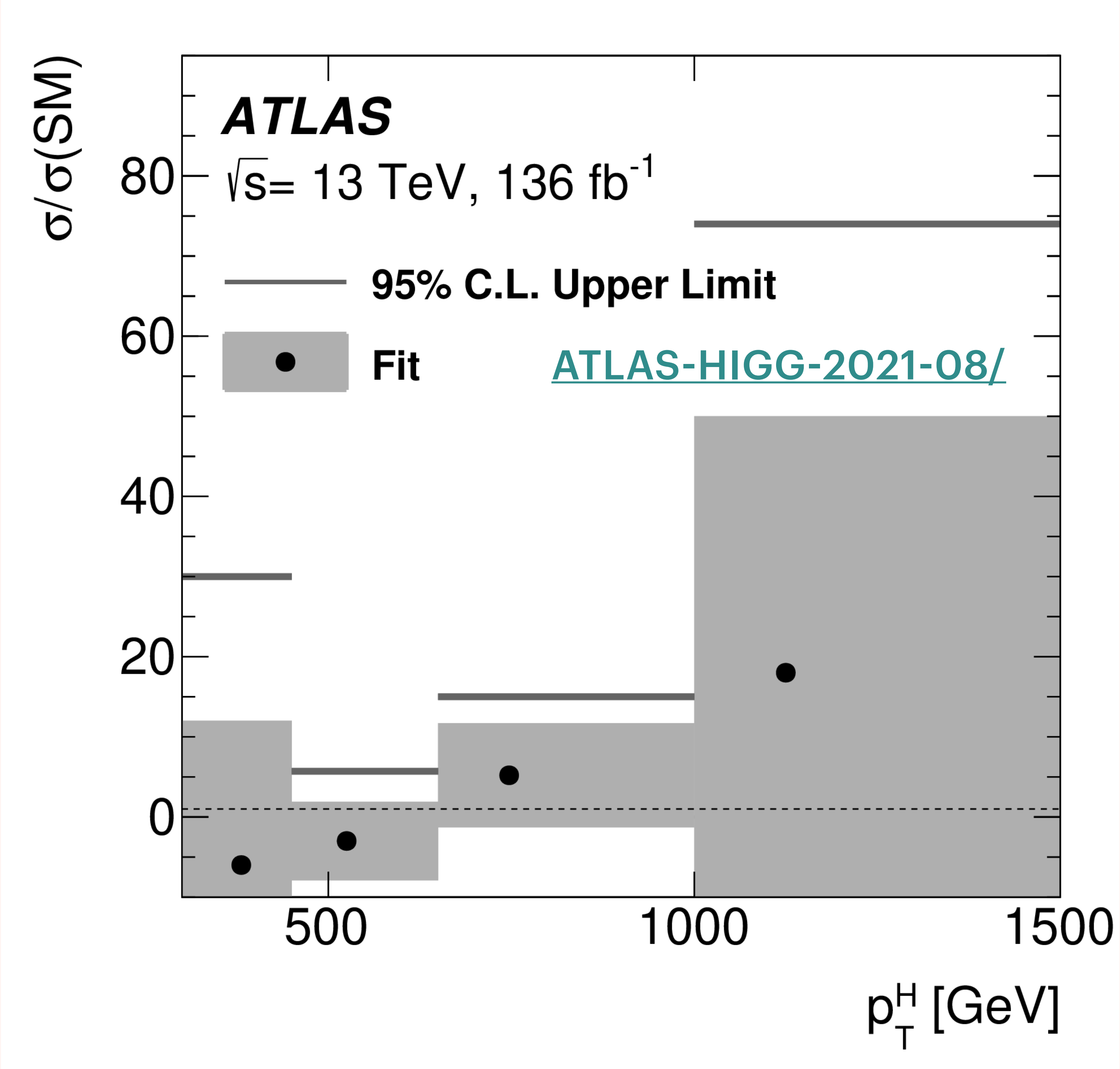
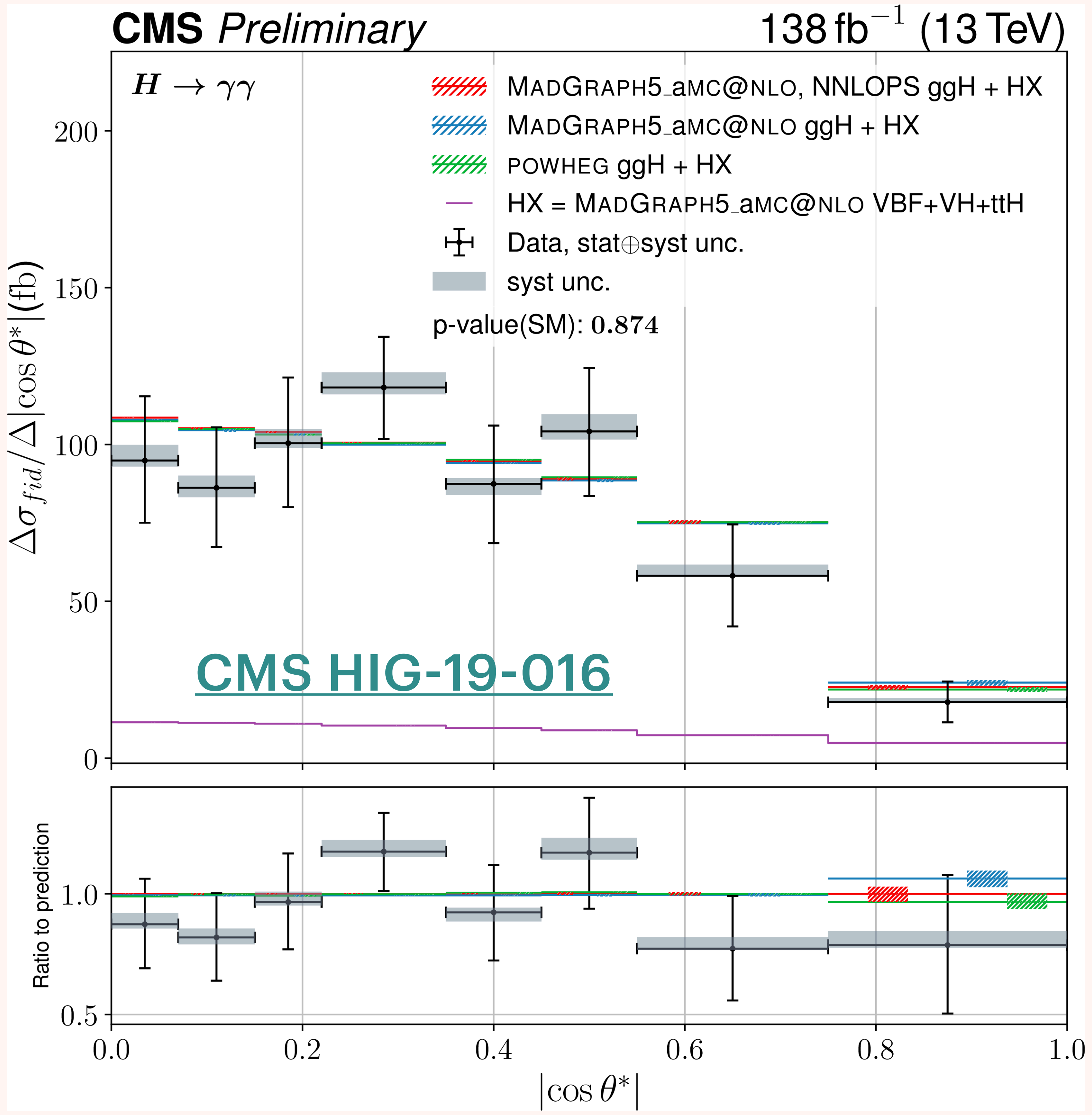
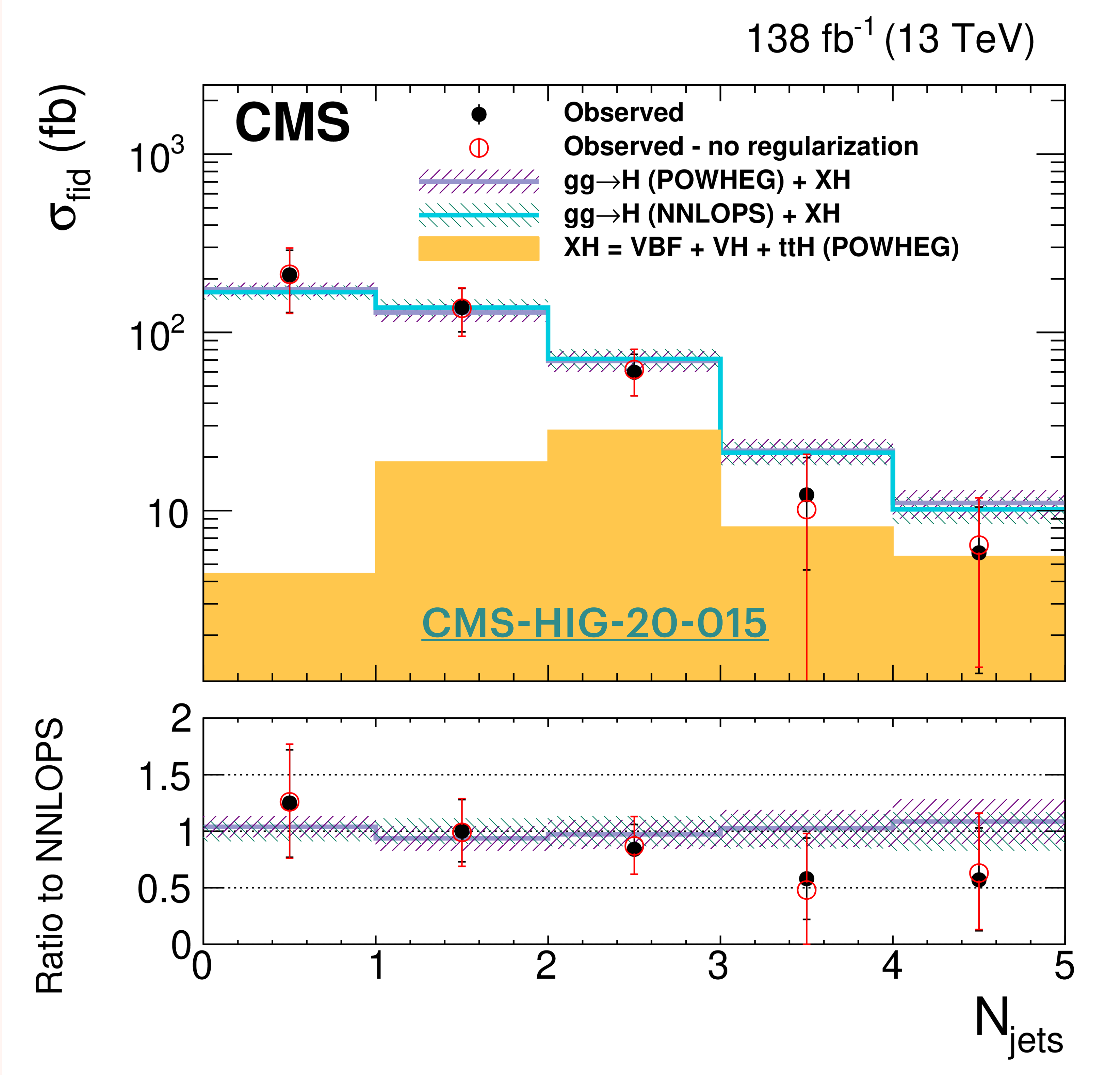




FROM SIGNAL STRENGTHS TO DIFFERENTIAL CROSS SECTIONS





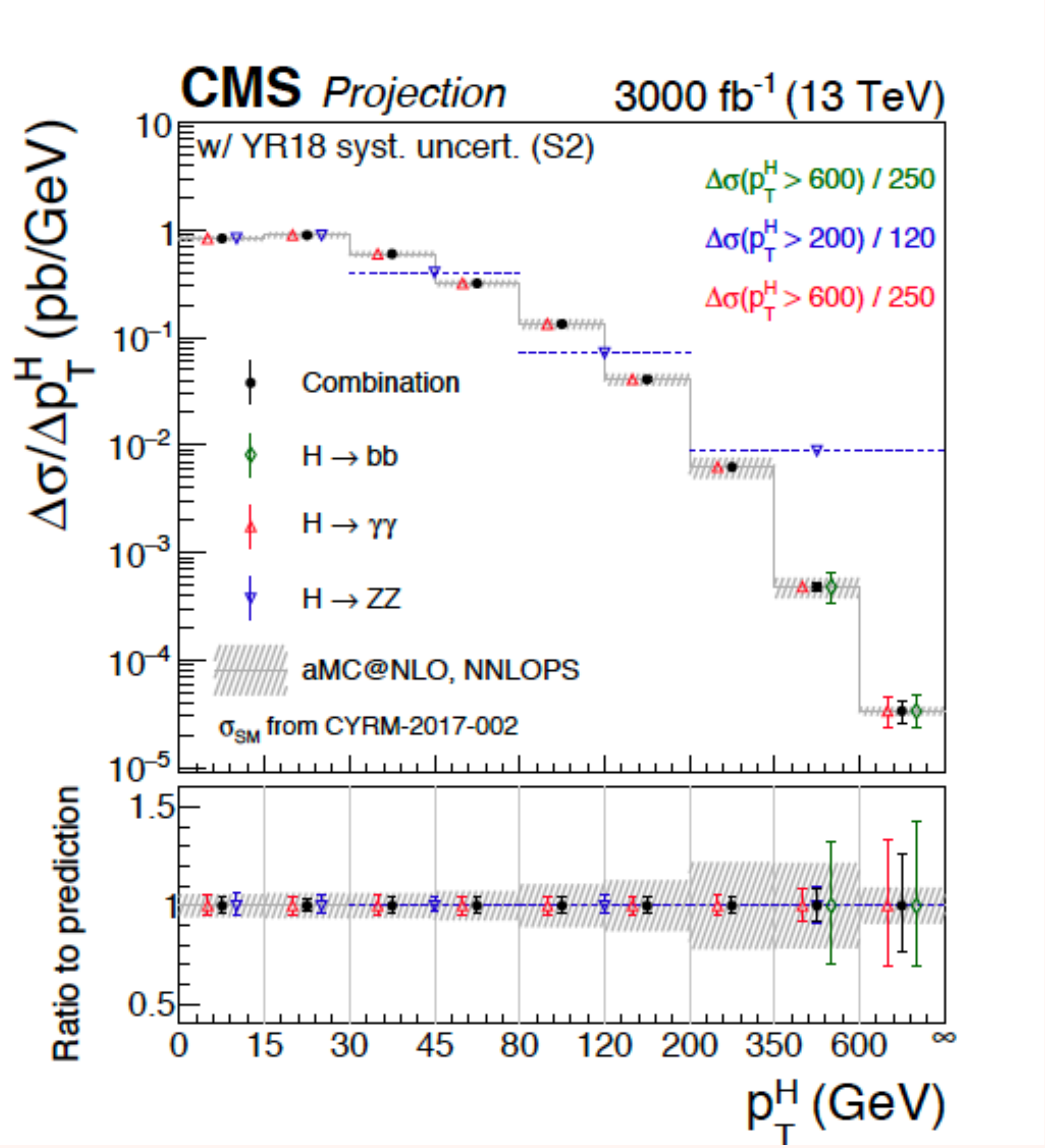


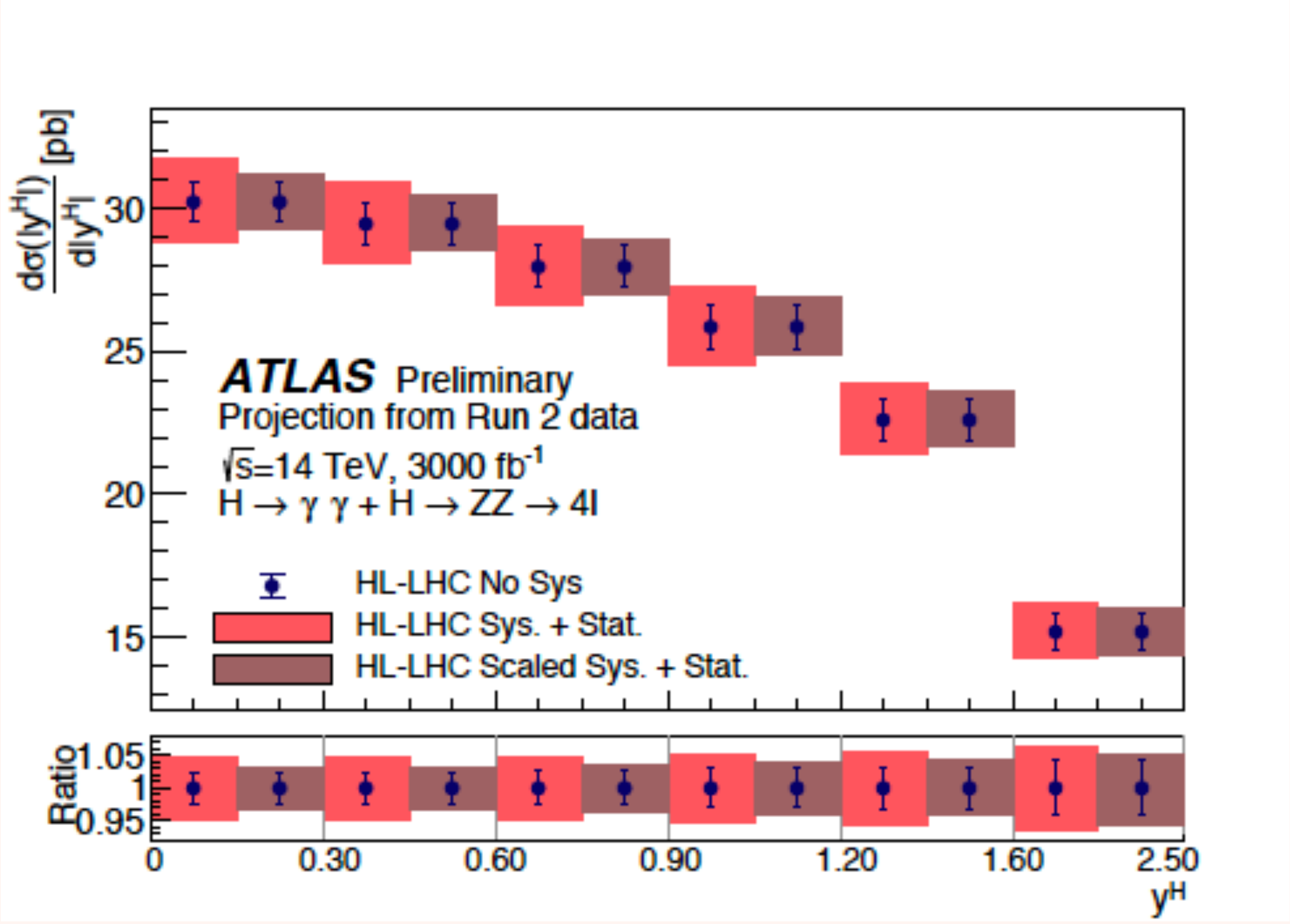
With the Run2 data we are already exploring Higgs production in depth. We need more statistics! Run3 and HL-LHC will be a game changer for many of these measurements

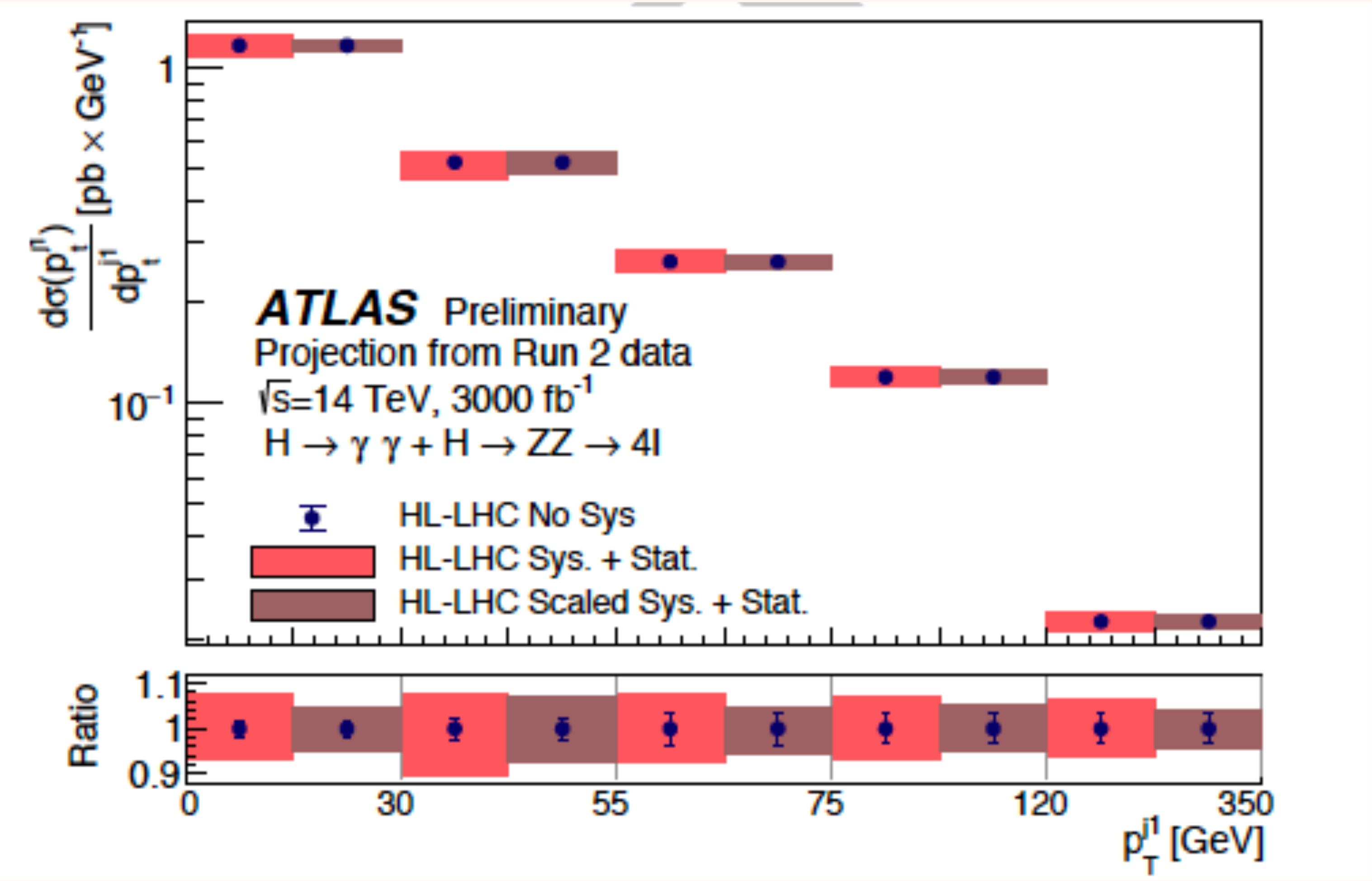
DIFFERENTIAL CROSS SECTIONS @ HL-LHC

Measurement limited by systematic uncertainties except at very high p_T.

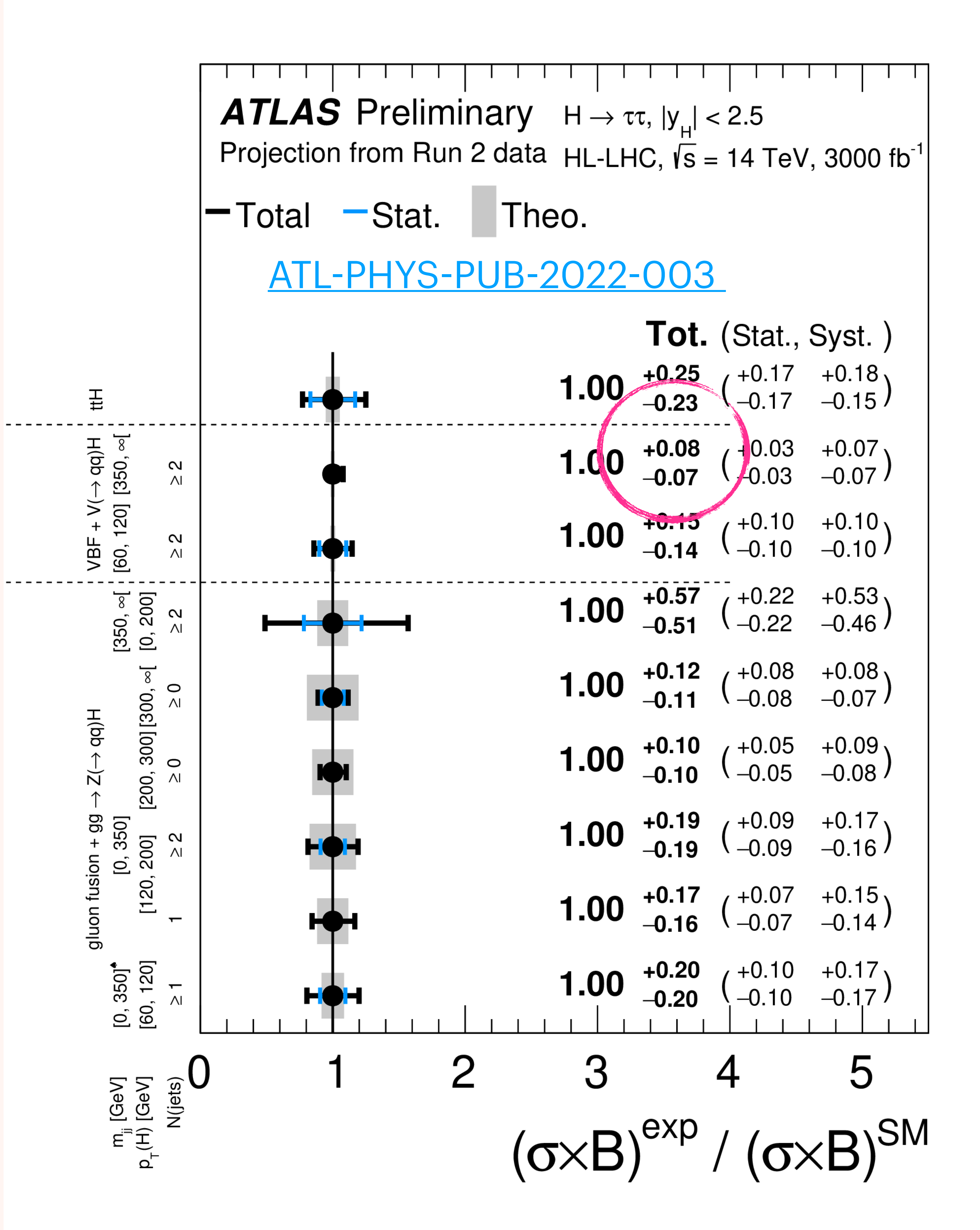
Expected precision of ~ 10% for $p_T(H)$ > 350 GeV



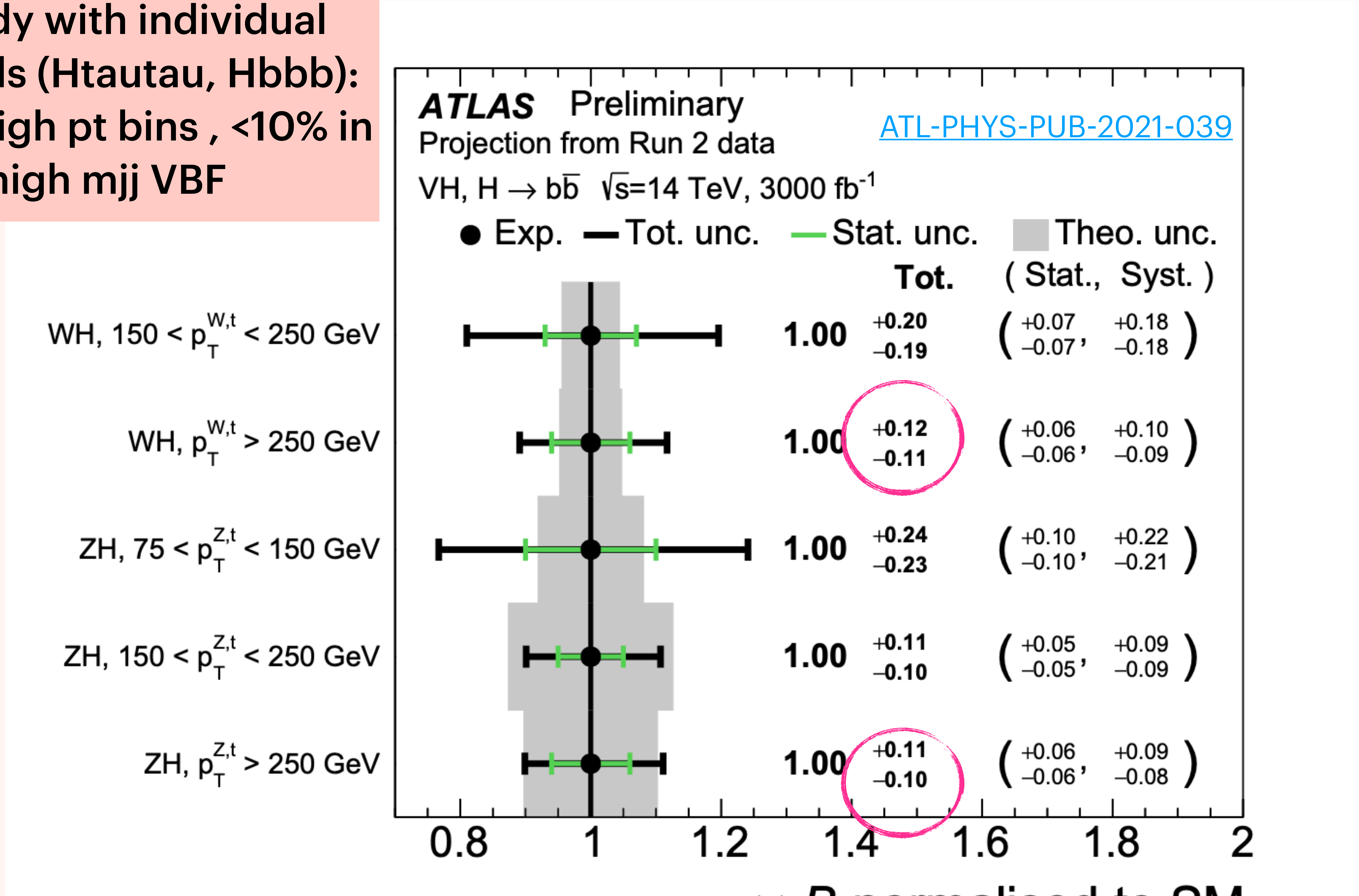




SIMPLIFIED TEMPLATE CROSS SECTIONS



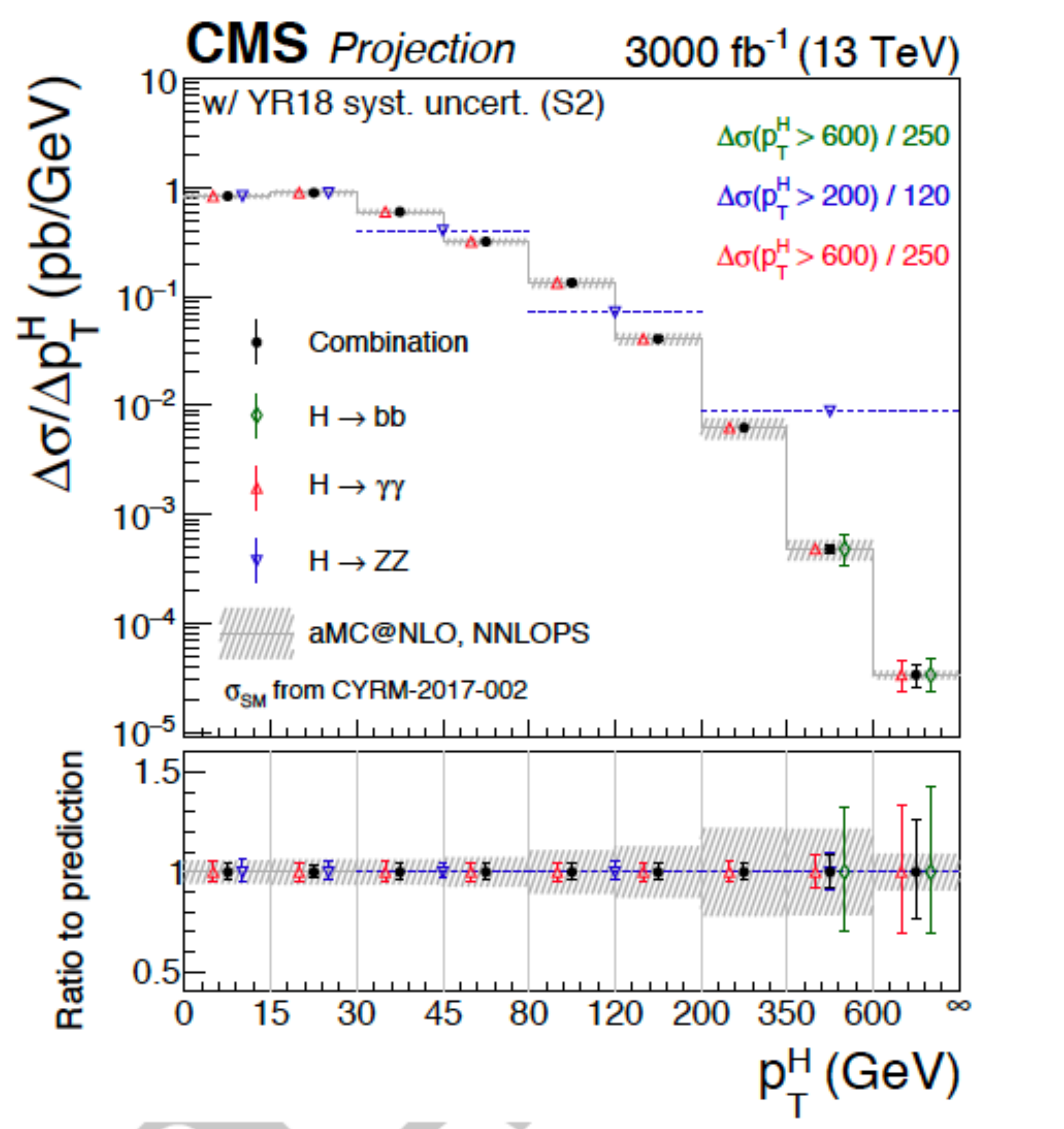
Already with individual channels (Htautau, Hbbb): 10% in high pt bins , <10% in high mjj VBF

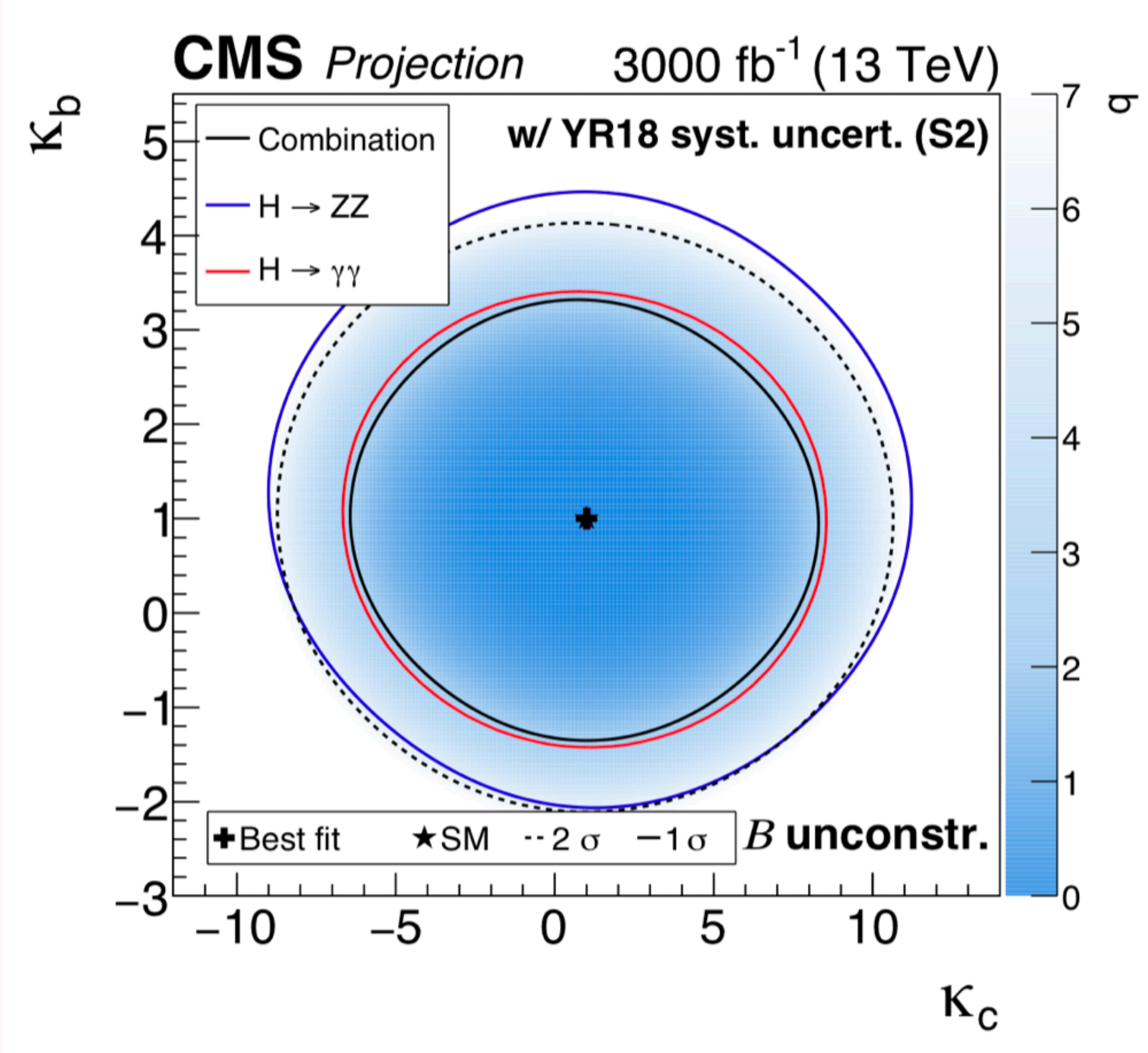


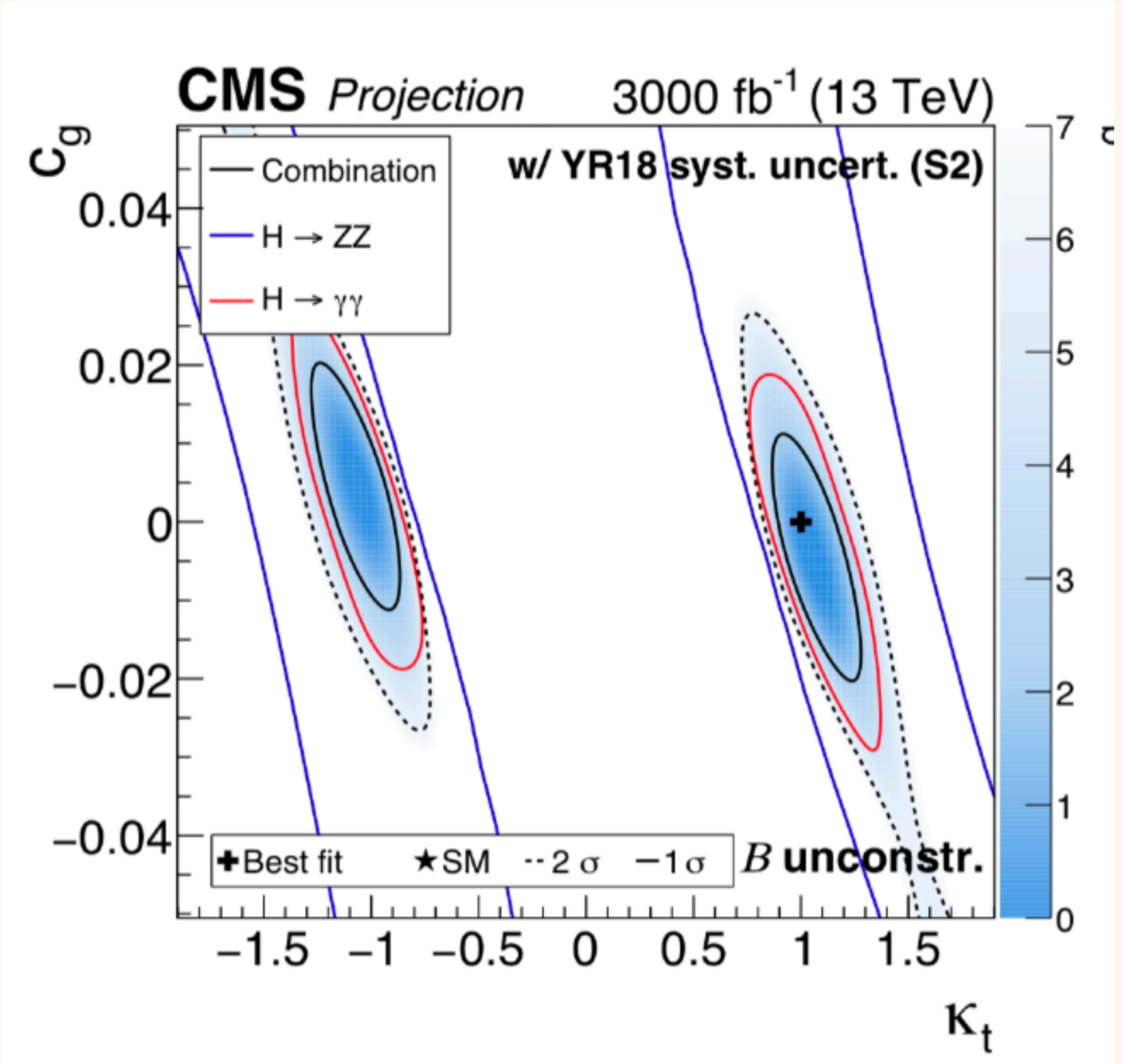
NEW FOR SNOWMASS!

INDIRECT CONSTRAINTS

New physics modifies kinematics: we can obtain constraints on new physics from the precise measurement of differential distributions







HIGGS PROPERTIES

THE NATURE OF THE HIGGS

Mass?

Total Width?

$$\Gamma \propto lifetime^{-1}$$

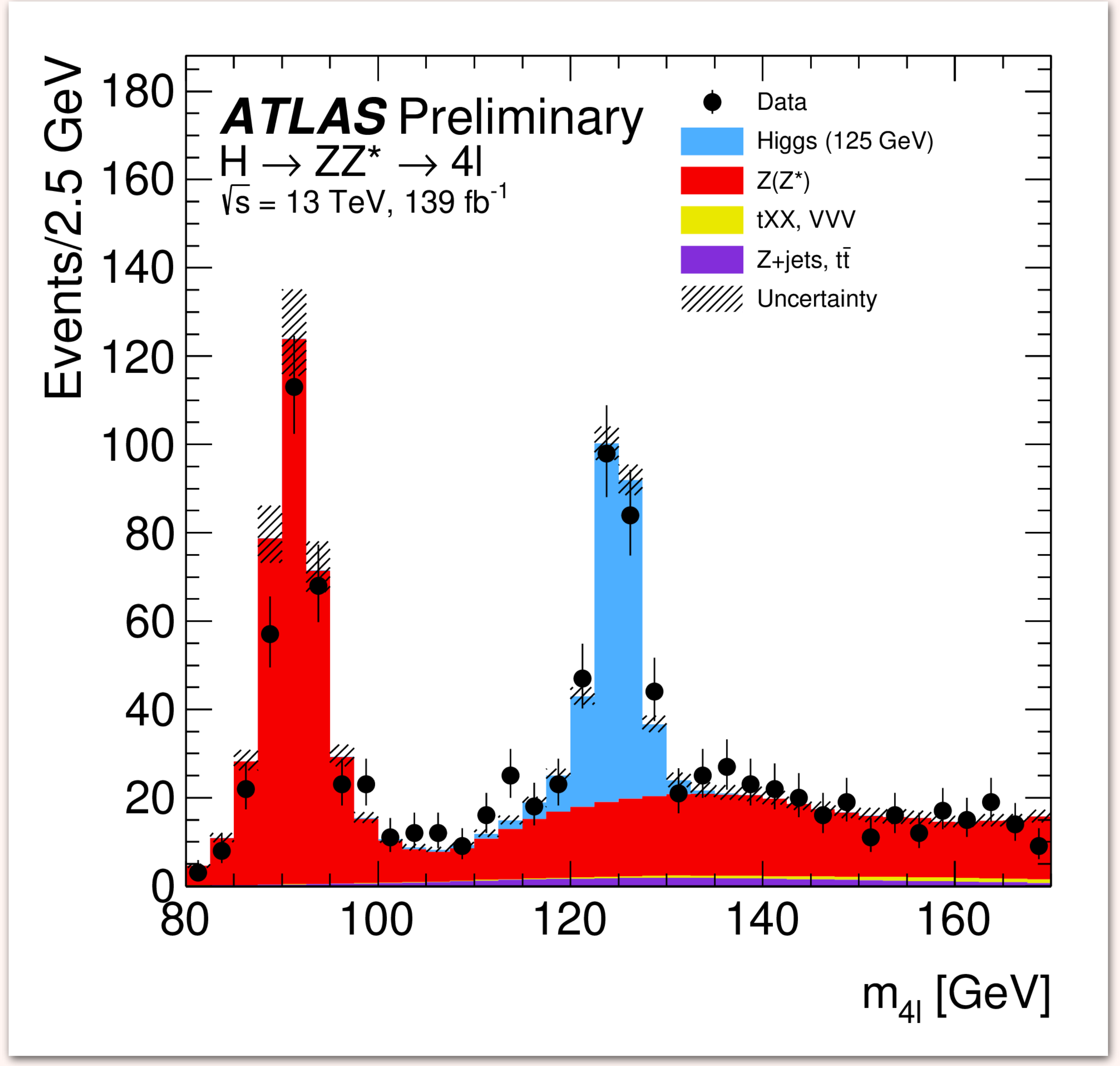
Spin?

THE NATURE OF THE HIGGS

Mass

Free in the SM, now known to 0.1%

($H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow \gamma\gamma$)



$CMS: 125.38 \pm 0.14\ GeV\ (0.11\%)$

$ATLAS: 124.92 \pm 0.19(stat)^{+0.09}_{-0.06}(syst)\ GeV\ (0.17\%)$

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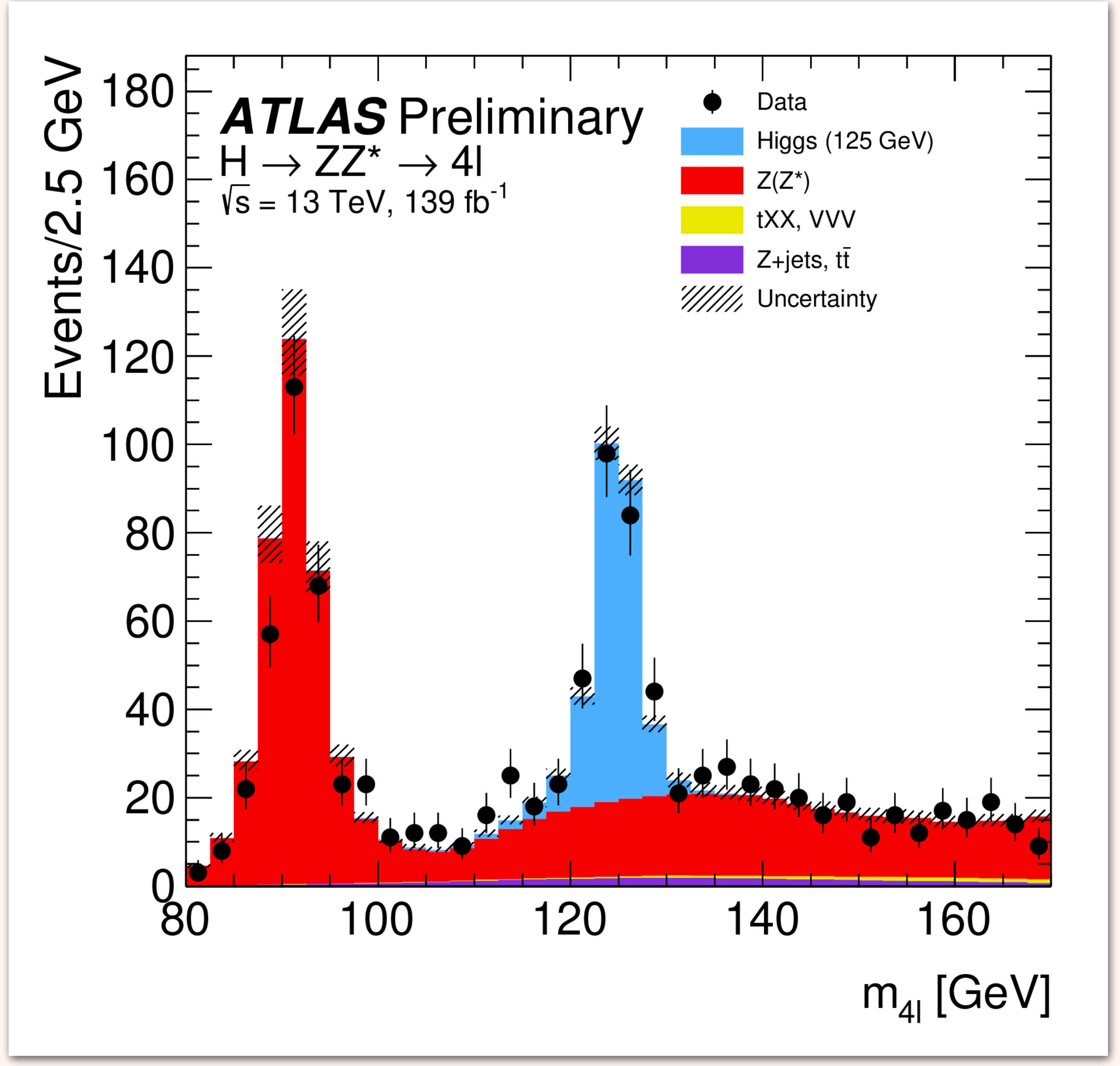

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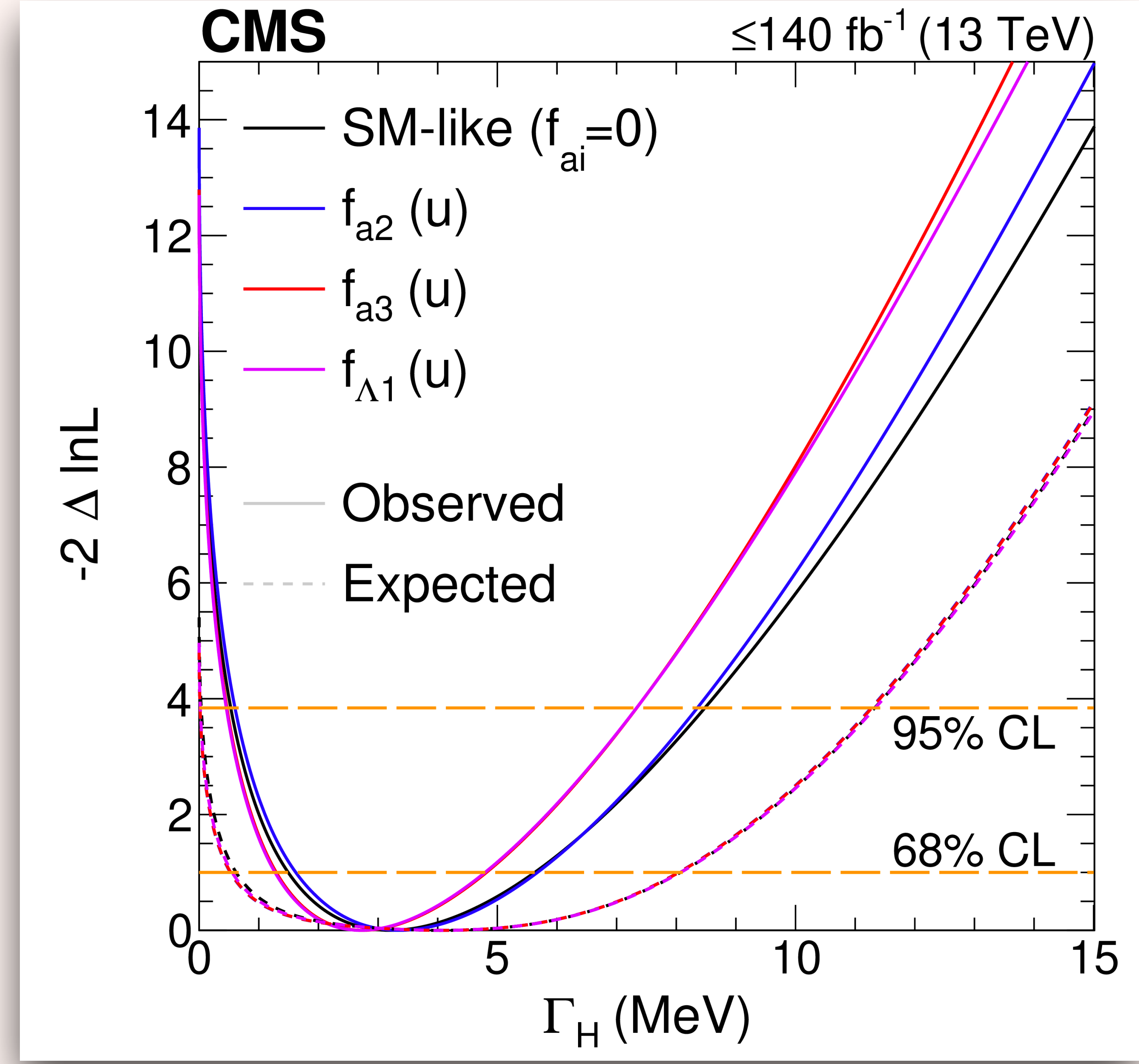
Total Width

Very small in SM! (4 MeV)

Direct measurement: <1.1 GeV (95%CL)

Offshell/onshell $H \rightarrow ZZ -> 4l$



$\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

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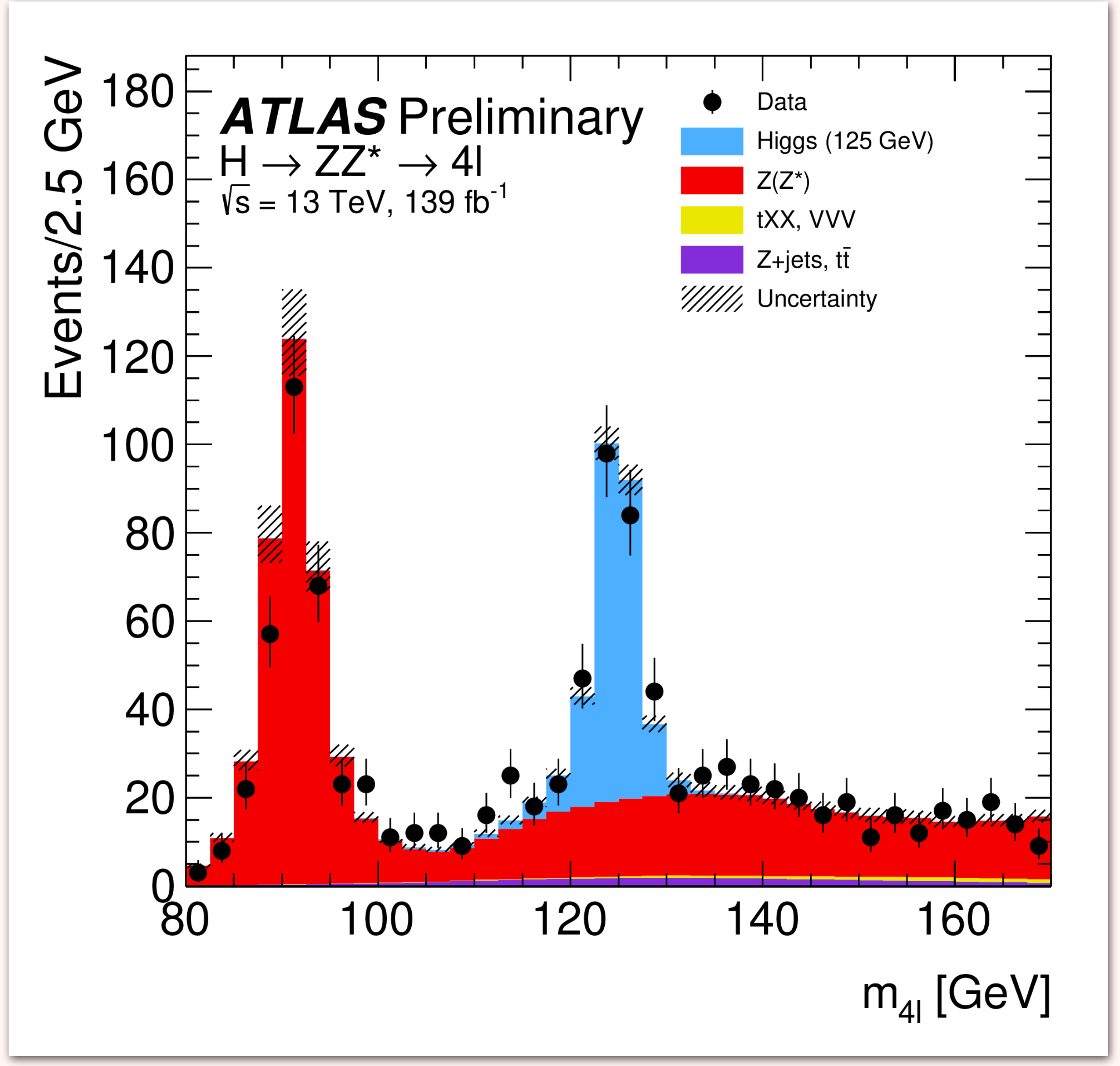

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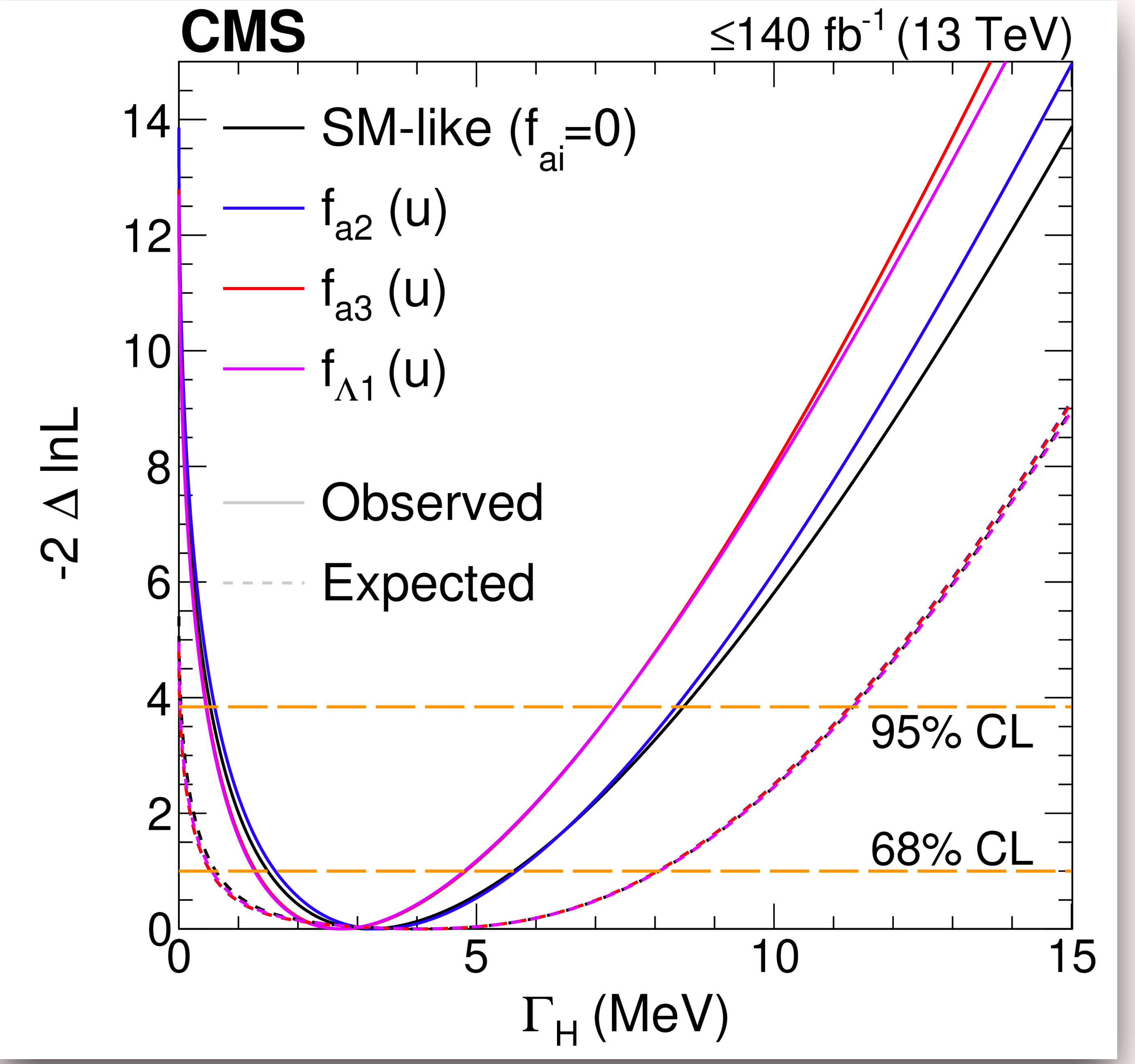
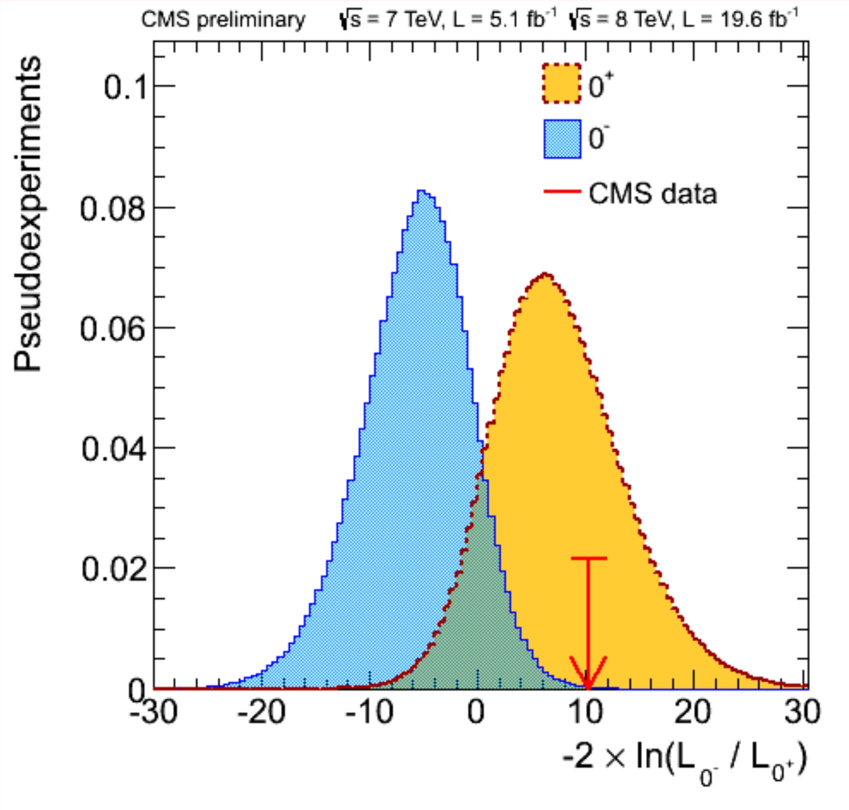
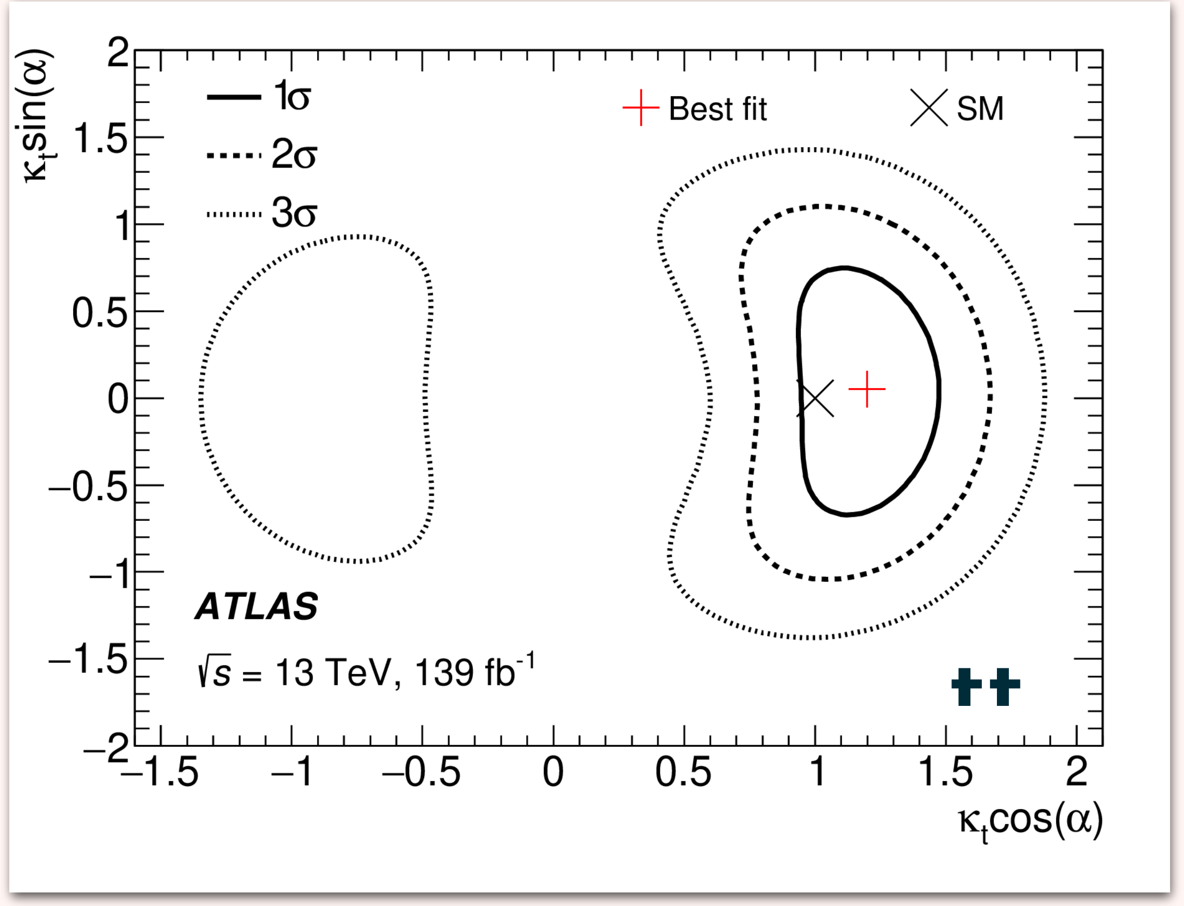


$\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

Spin: 0+ (SM-like)



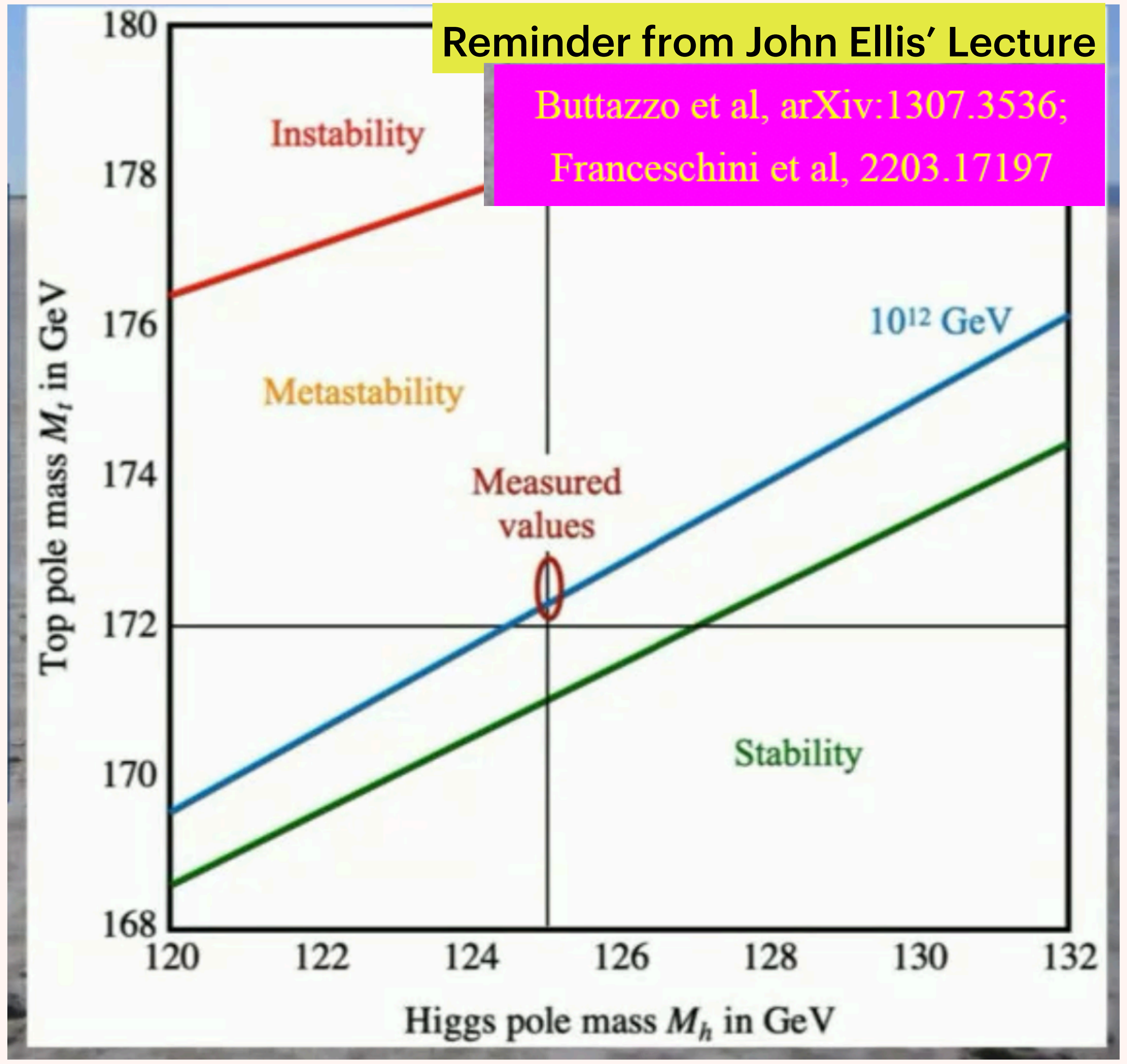


Does the Higgs sector have a new source of Charge-Parity violation?

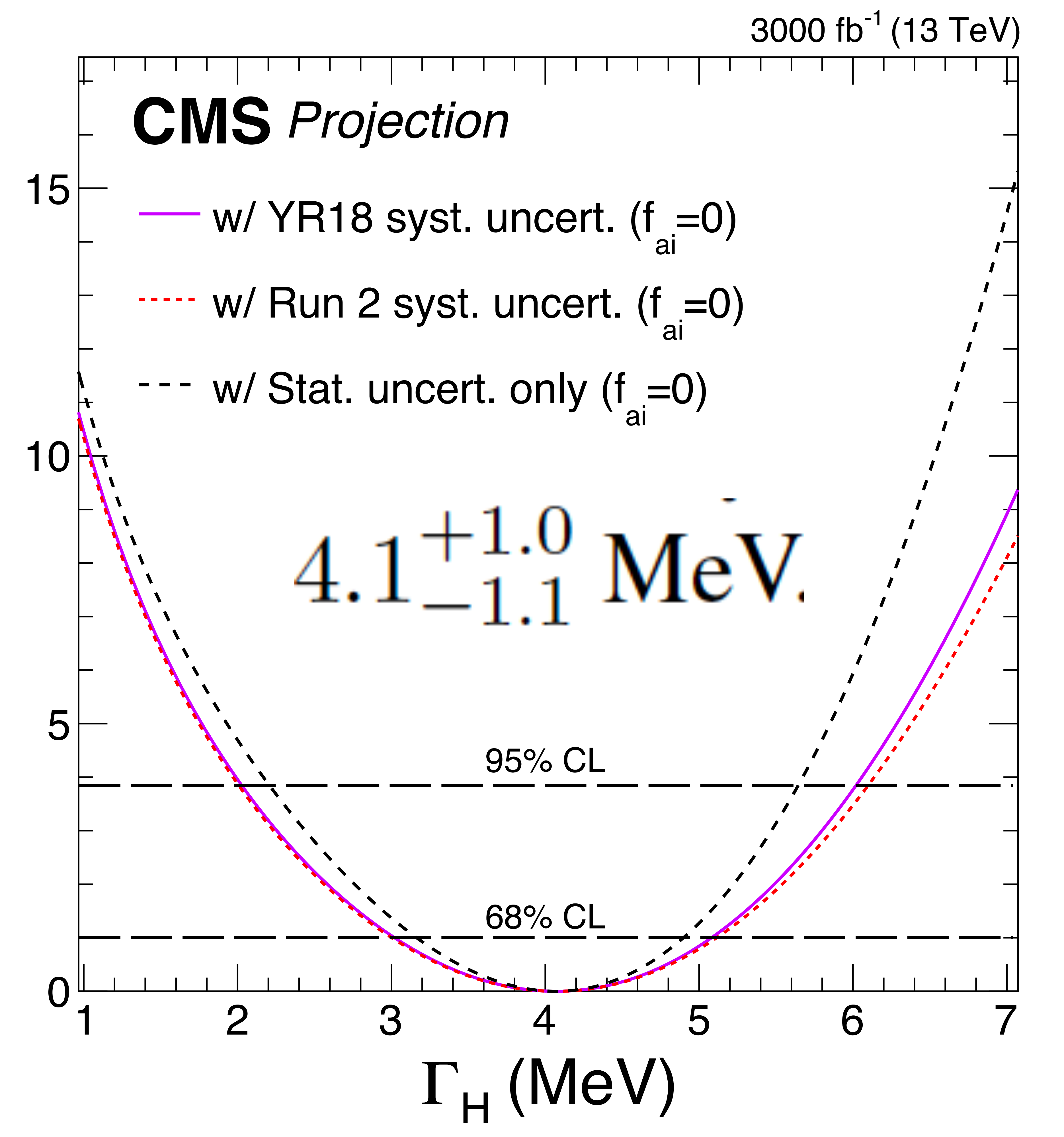
MASS MEASUREMENT @ HL-LHC

- **Relies on $H \to ZZ \to 4l$ and $H \to \gamma\gamma$: narrow peaks, good mass resolution**
- The precision with which we can measure m_H is directly linked to precision with which we can measure photons and leptons (energy scale and resolution)
- How well can we measure mH in the future? And how well do we *need* to measure it?
- **Precision of few tens of MeV reachable.** The ultimate HL-LHC will combine $H \to ZZ -> 4l$ and $H \to \gamma\gamma$ and with ATLAS. Can we get to 10-20 MeV?

H→ZZ	Mass uncertainty (MeV)					Width upper limit at 95 % CL (MeV)
	Combined	4μ	4e	$2e2\mu$	$2\mu 2e$	Combined
Stat. uncertainty	22	28	83	51	59	94
Syst. uncertainty	20	15	189	94	95	150
Total	30	32	206	107	112	177



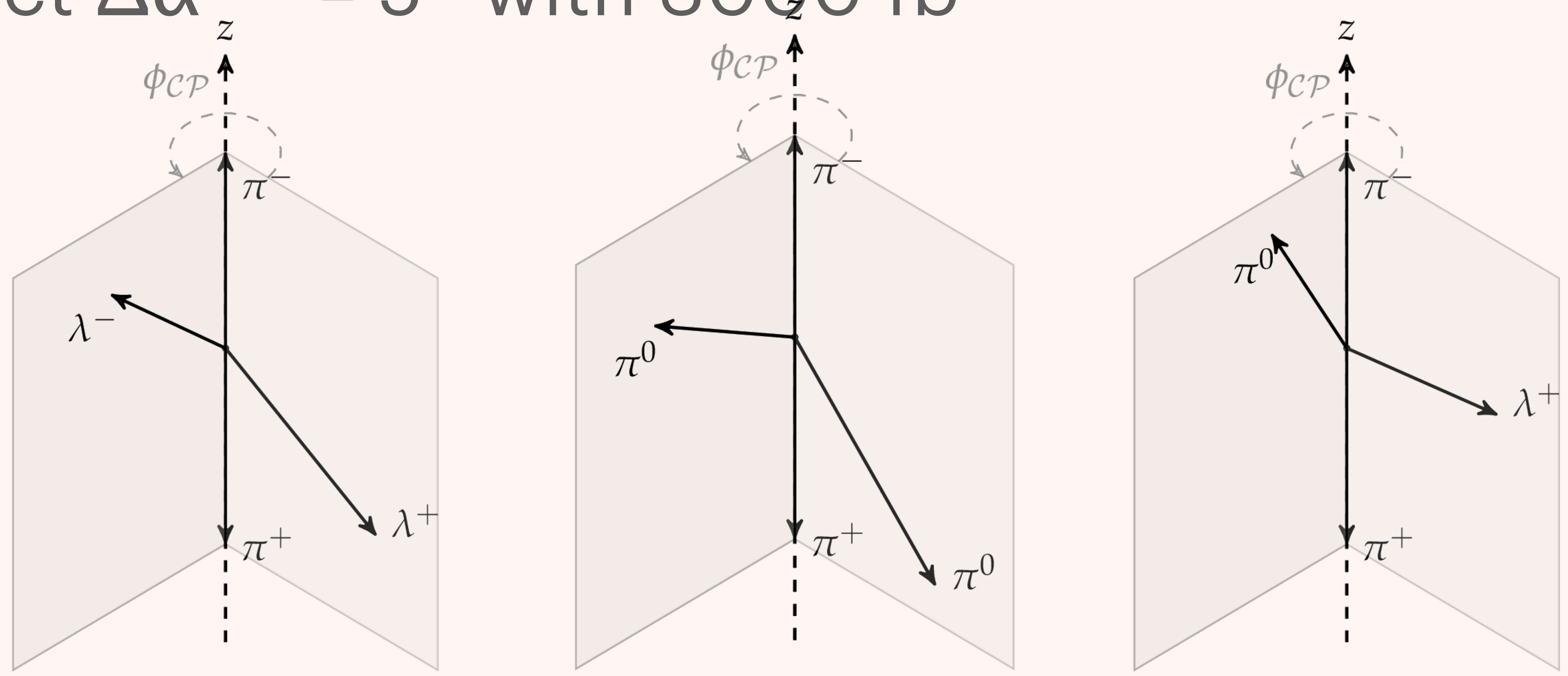
HIGGS WIDTH @ HL-LHC

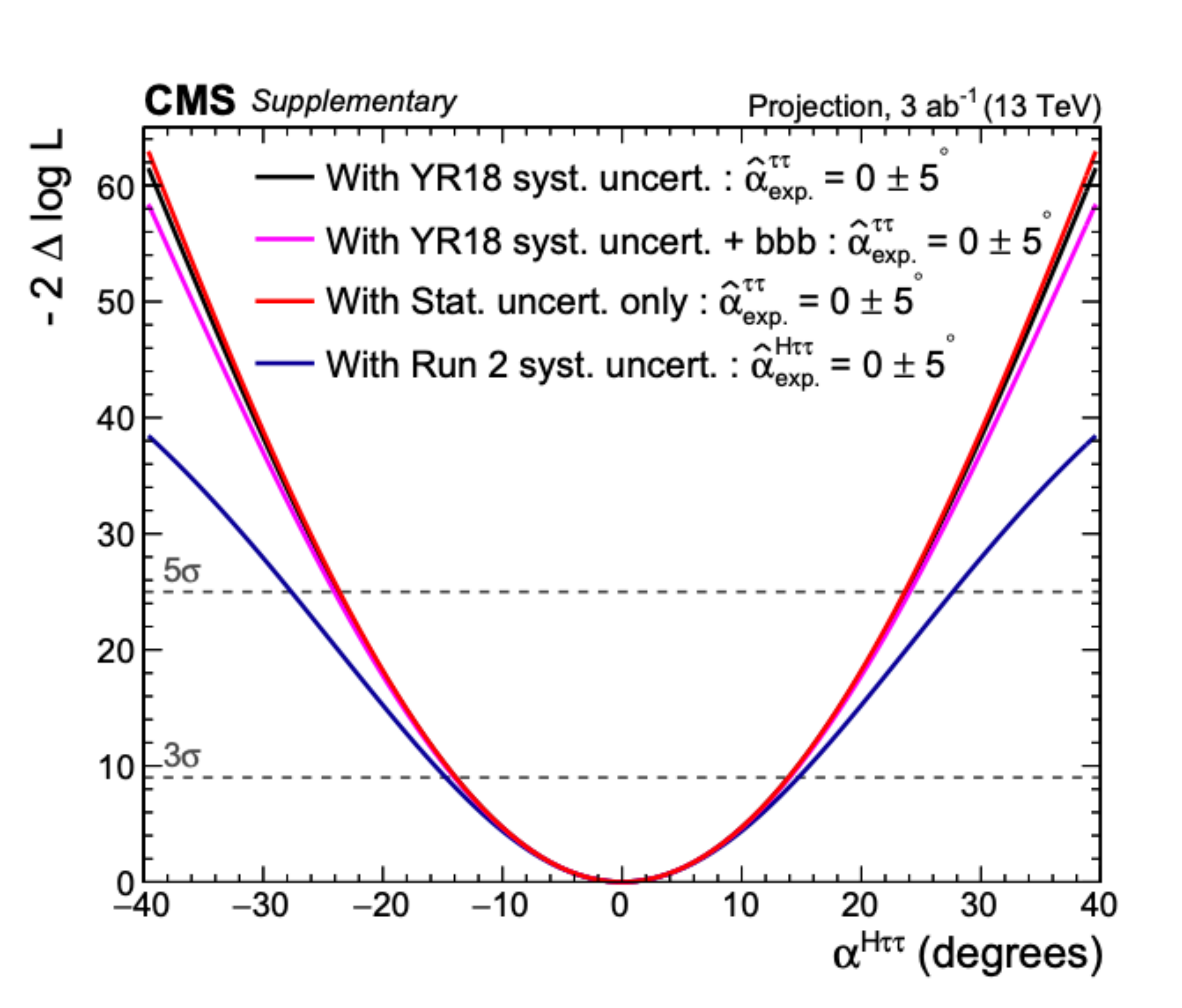


- **Remember: Very small in SM! (4 MeV)**
- **Exploit $H \to ZZ$ measurements:**
  - Direct width: 177 MeV @ 95% CL (CMS, Snowmass)
  - **4L Offshell: 25% precision at 68% CL (20% assuming CMS+ATLAS: +-0.8 MeV)**
- From couplings: Γ_H if $k_V \leq 1$ —> 5% precision at 95% CL
- $H \to \gamma\gamma$ interference study: <40-50 Γ_{SM} (old, ATLAS), reduction of the on-shell rate by 2% (Campbell, Carena, Harnik, Liu)
- Completely different picture in lepton colliders! (~1-2%)

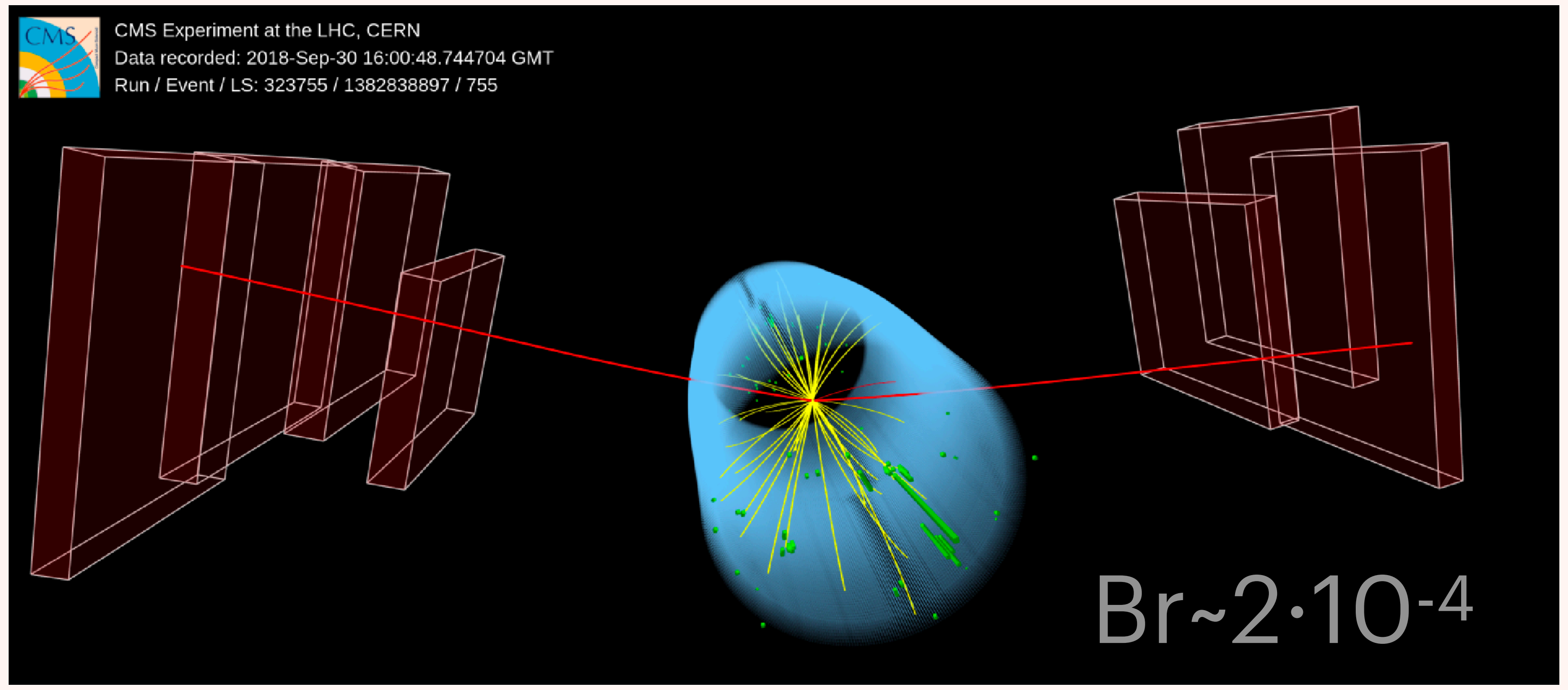
CP IN THE HIGGS SECTOR

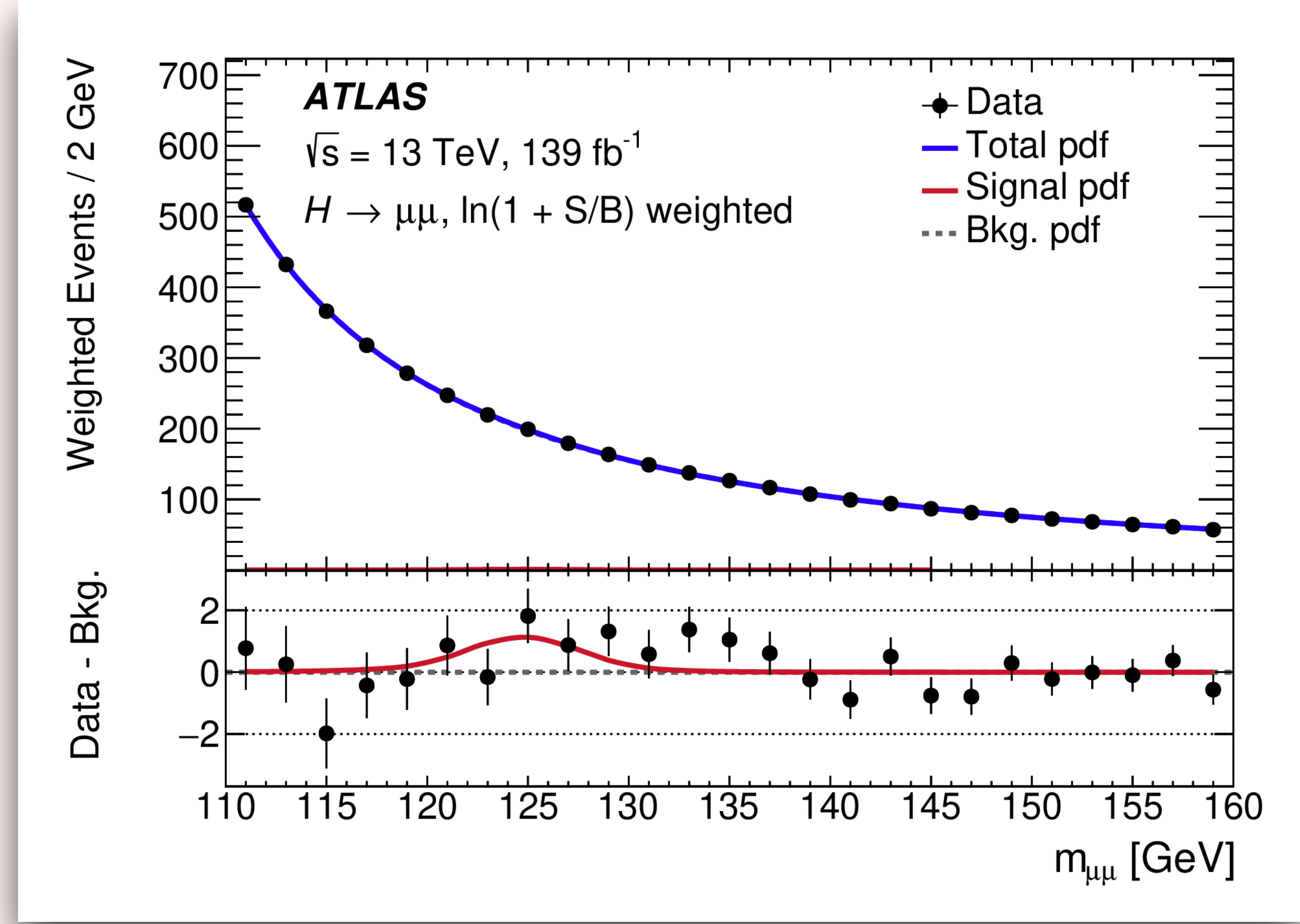
- **Does the Higgs sector have a new source of Charge-Parity violation?**
- Constraints based on HVV, ttH, Hττ
- For example, using $H \rightarrow \tau\tau$ decays: scan the mixing angle $\alpha^{H\tau\tau}$, where 0 (90)º corresponds to a pure scalar (pseudoscalar) coupling
  - Run2: $\alpha^{H\tau\tau}$ = -1±19º (0±21º exp) at 68%CL
  - Expect $\Delta\alpha^{H\tau\tau}$ = 5º with 3000 fb^{-1}





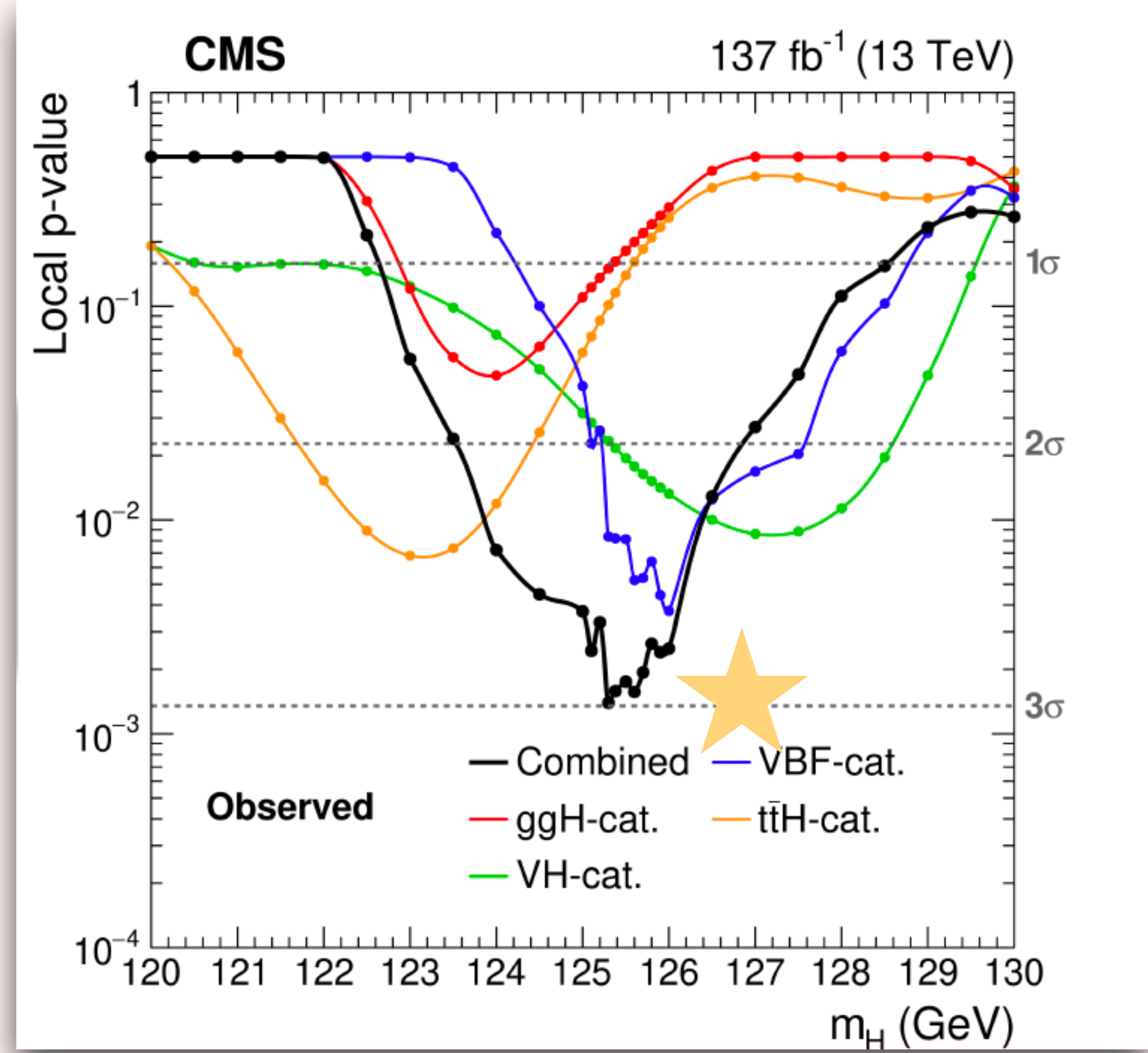
RARE DECAYS





Do all SM families get their mass from the same Higgs field?

Highlight of 2020: evidence for the coupling to the second generation!

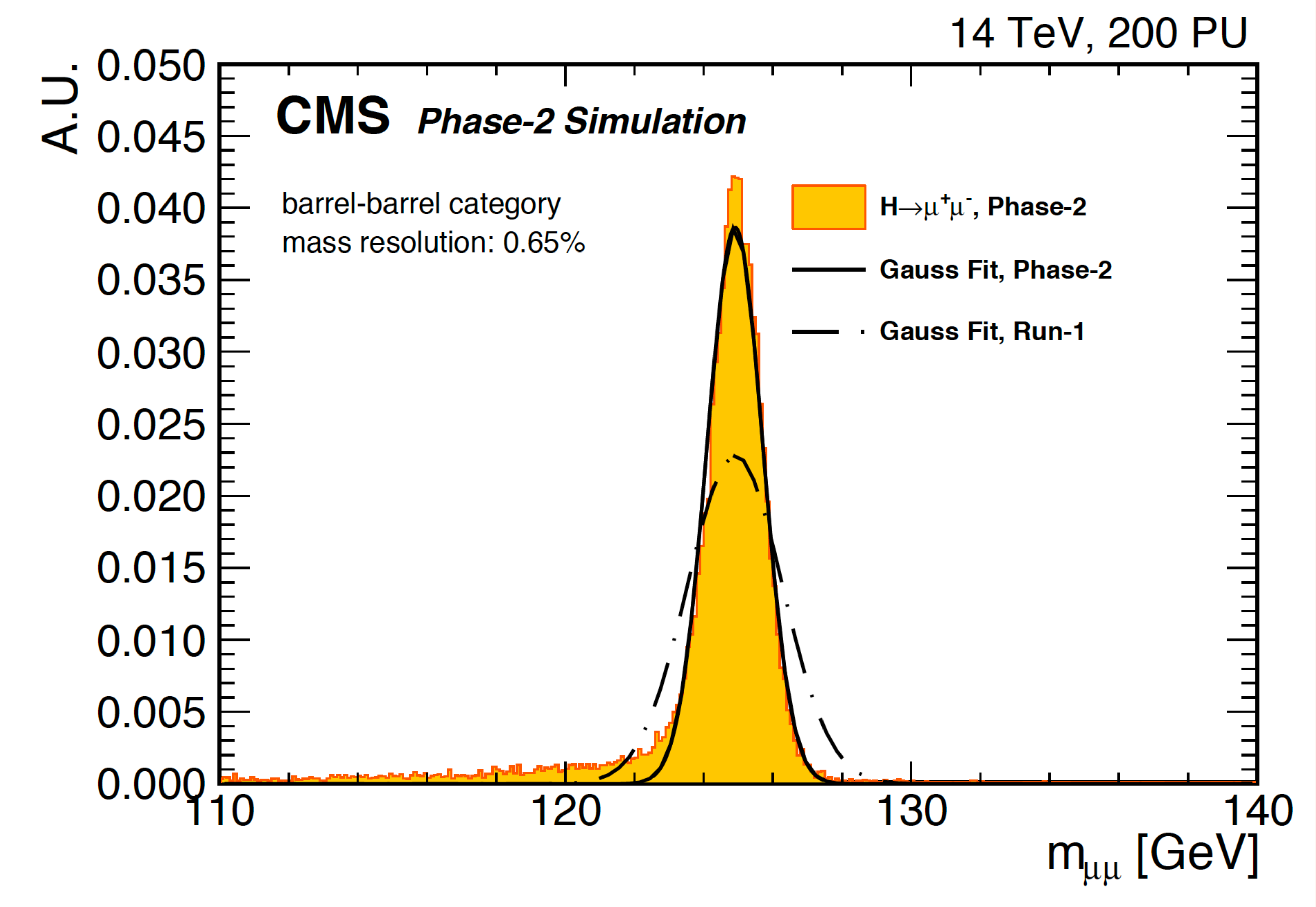


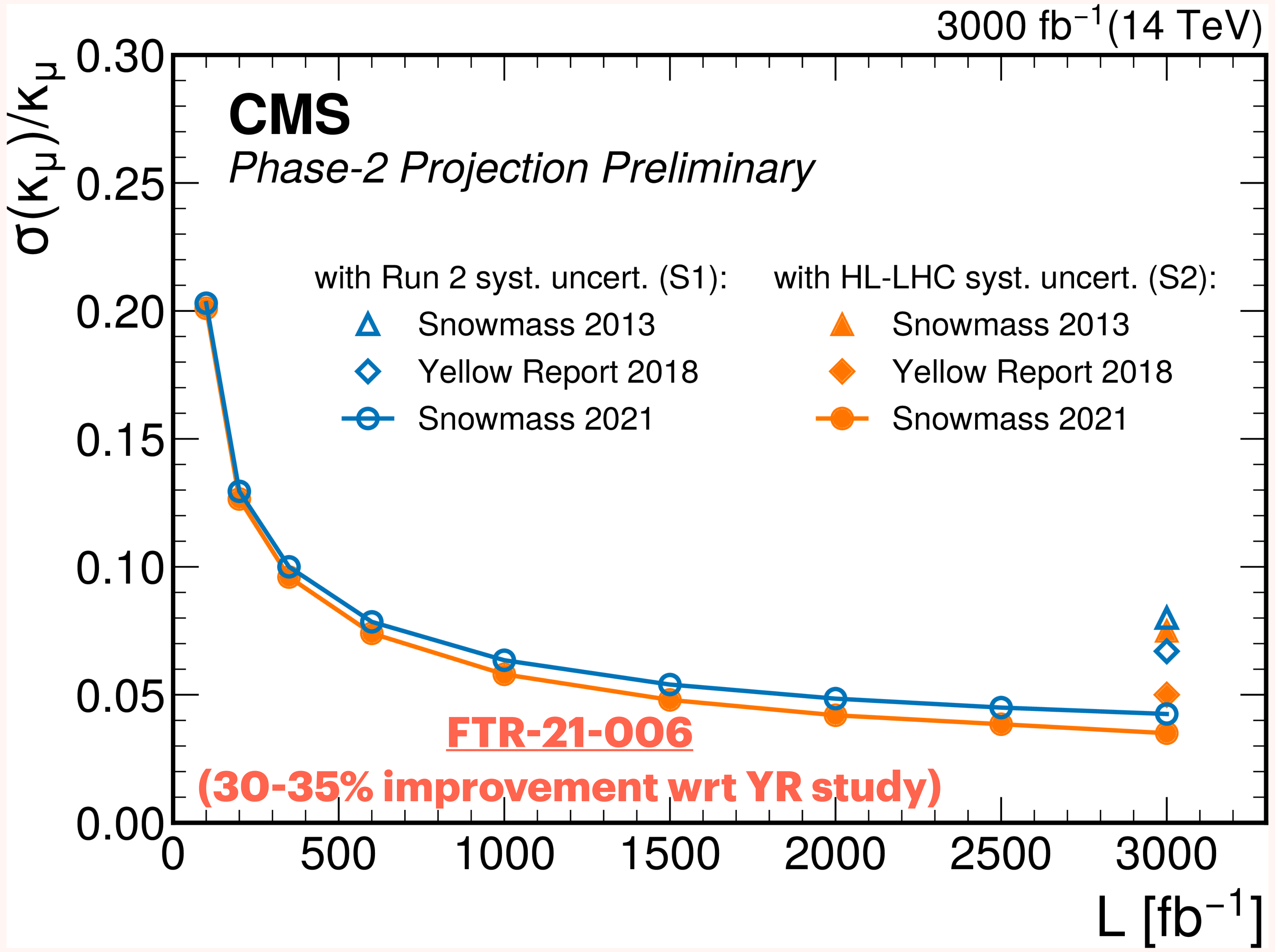
CMS: $\mu=1.19^{+0.40}_{-0.39}\,(stat)^{+0.15}_{-0.14}\,(syst) \rightarrow 3.0(2.5)\sigma$

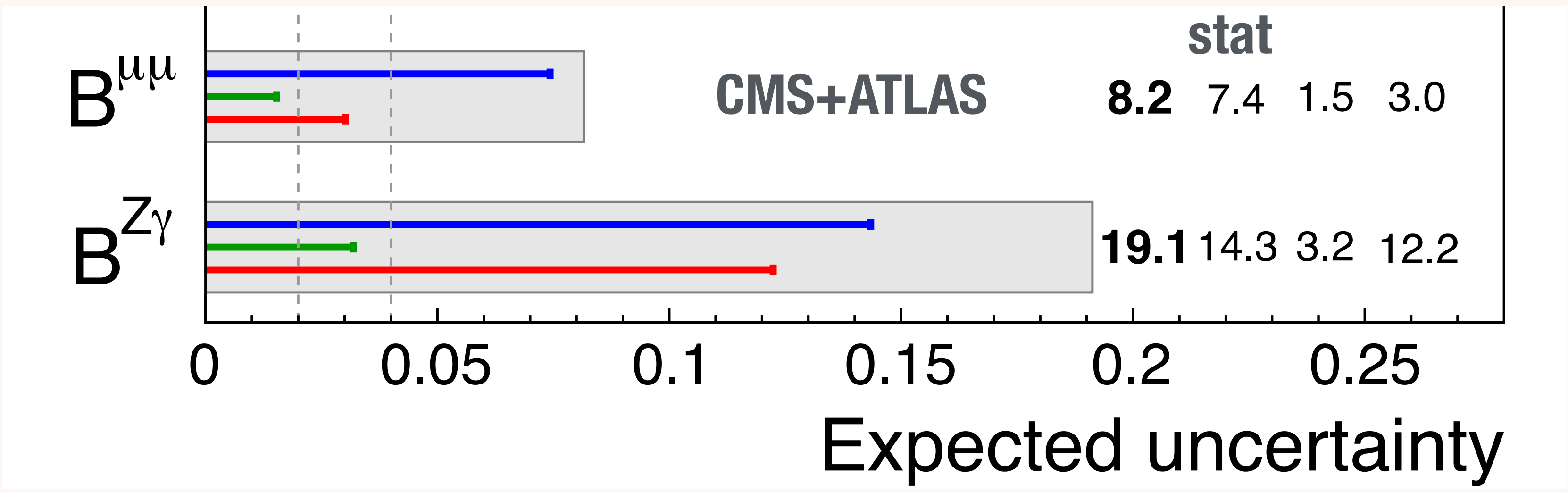
ATLAS: $\mu=1.2 \pm 0.6 \rightarrow 2.0(1.7)\sigma$

COUPLING TO THE SECOND GENERATION: H→μμ

- **Statistically limited: Run3 and HL-LHC game changers**
- Upgrades also very important: CMS example, tracker upgrade brings on resolution improvements
- **Observation by the end of Run3**







HOW CHARMING IS THE HIGGS?

- **What about the coupling to second gen quarks?**
- Charm quark: only up-type quark for which we could possibly measure the branching ratio (~3%)
  - Do up-type quarks get their mass from the same Higgs fields as down-type quarks and charged leptons?
- Difficult measurement (not only statistics, we need to be able to identify charm jets!)

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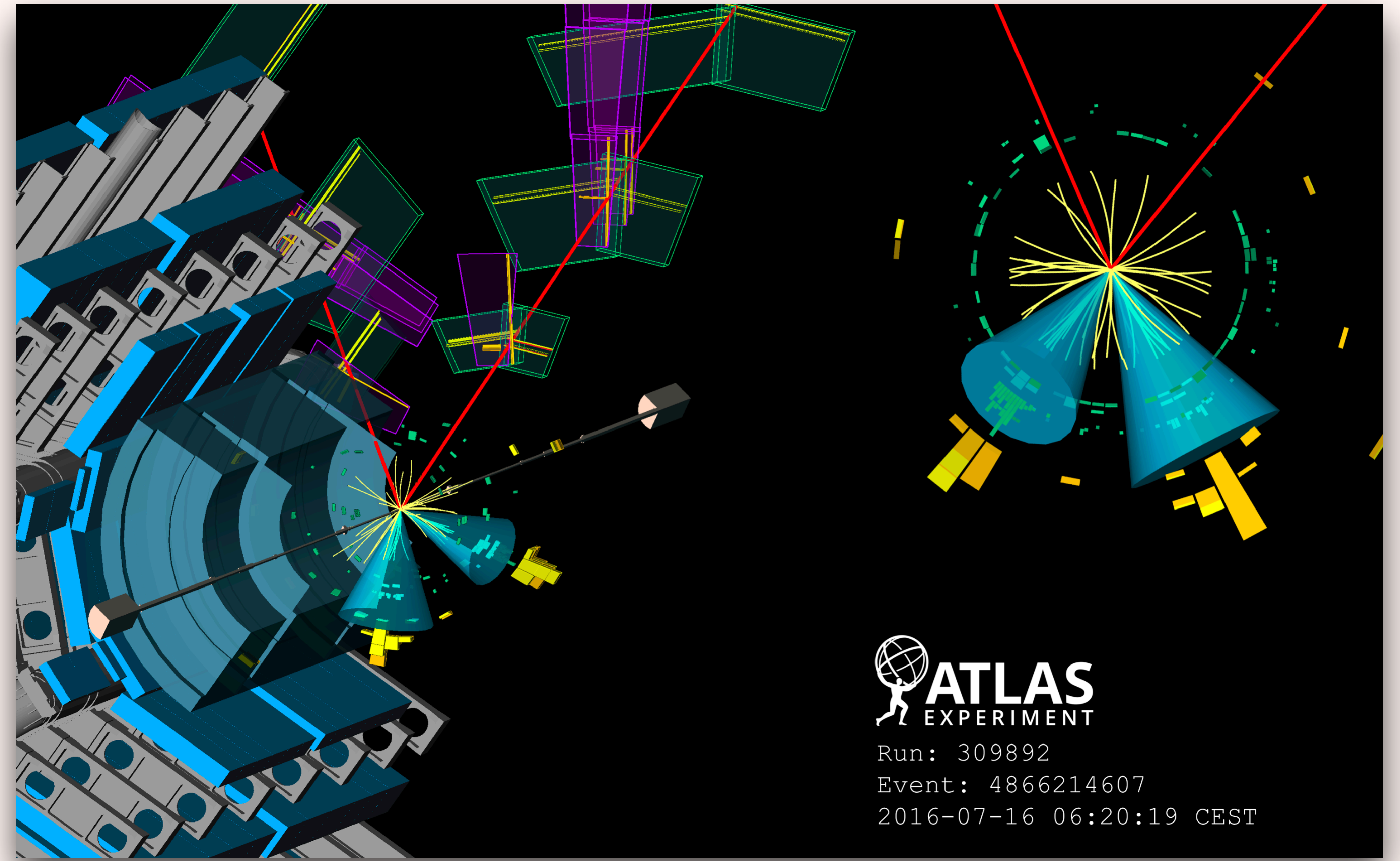
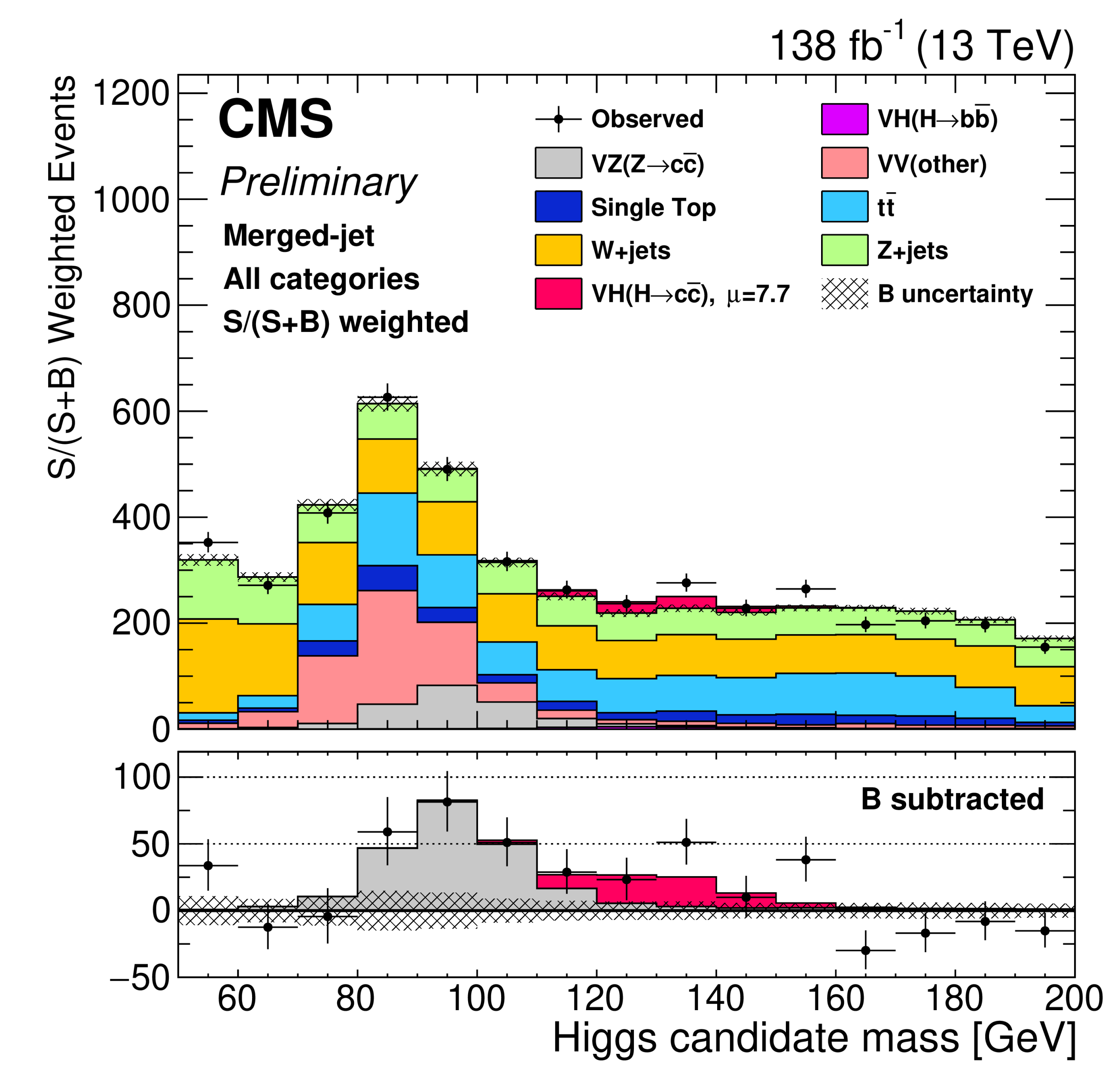




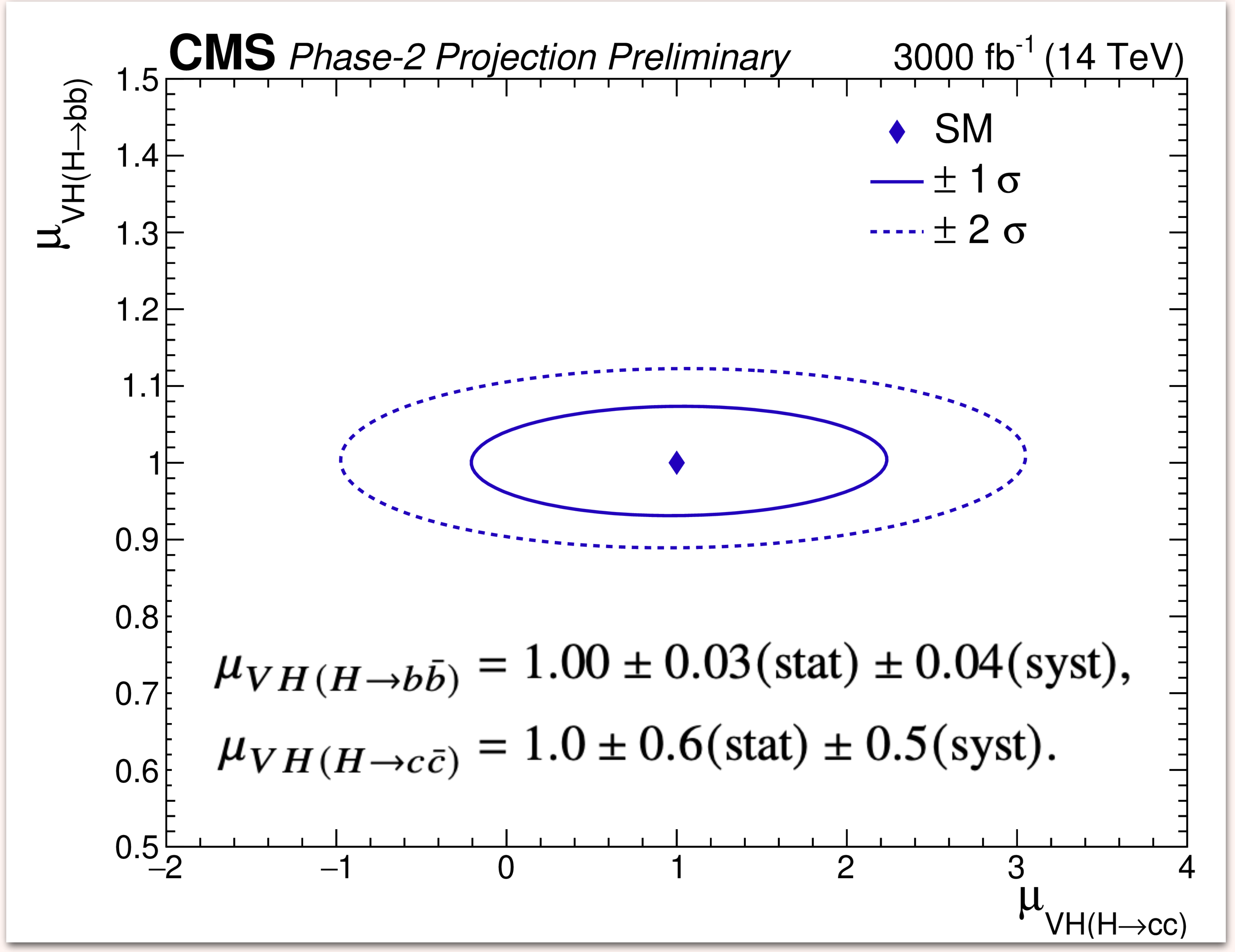
CMS:
μ(VH, Hcc) < 7.60(14.4)xSM (95%CL)

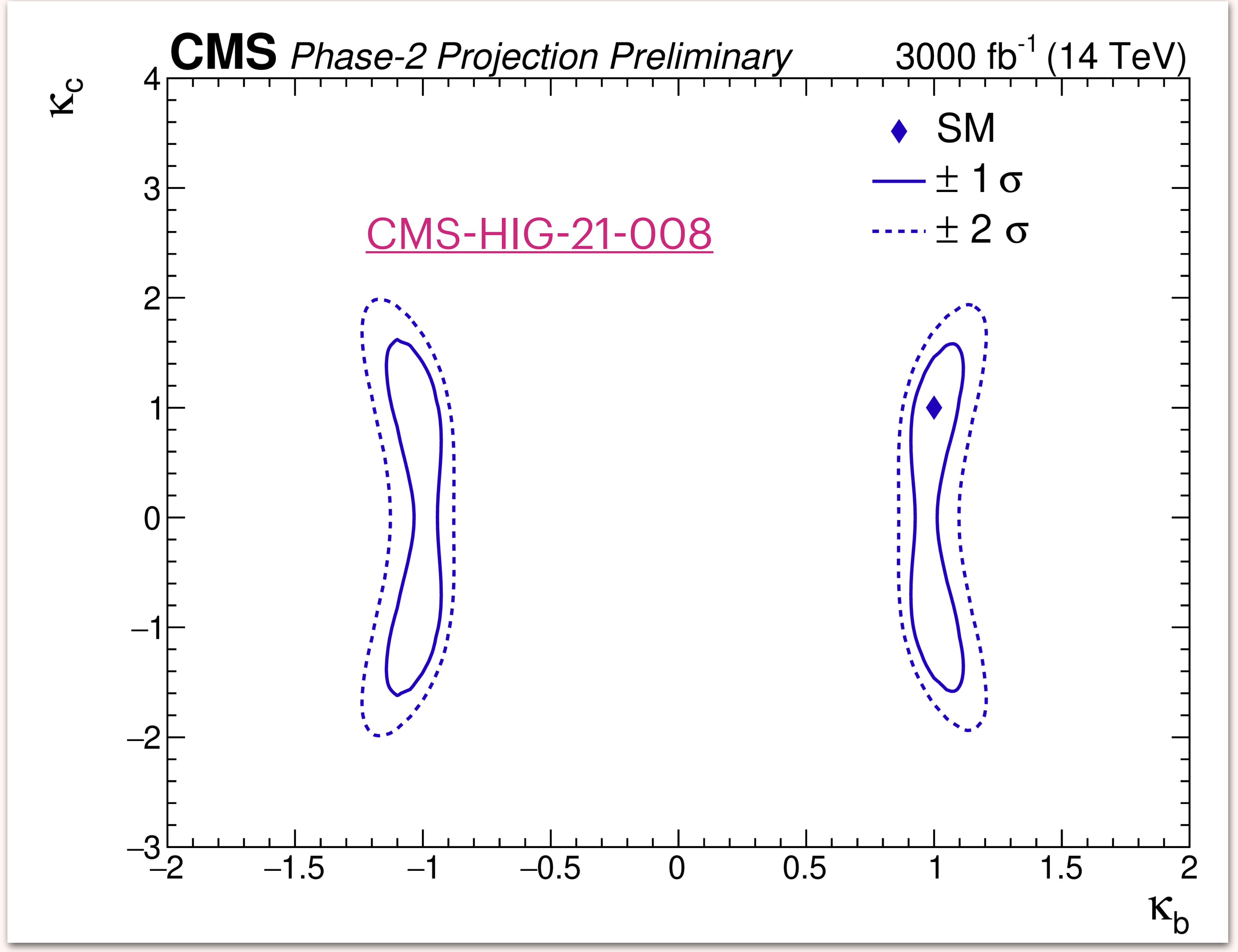
ATLAS:
μ(VH, Hcc) < 26(31)xSM (95%CL)

CAN WE MEASURE THE CHARM COUPLING AT HL-LHC?

- The projections of the latests Run2 results bring a large jump in sensitivity with respect to the previous prospects
- **Future innovations in jet reconstruction, c-identification and analysis can have a large impact here !**

ATLAS	3000 fb^{-1}:	$\mu < 6.4$
CMS	3000 fb^{-1}:	$\mu < 1.6$
LHCb	300 fb^{-1}:	$\mu < O(10)$





Aim for k_c at $\mathcal{O}(1)$ at HL-LHC

OTHER RARE DECAYS

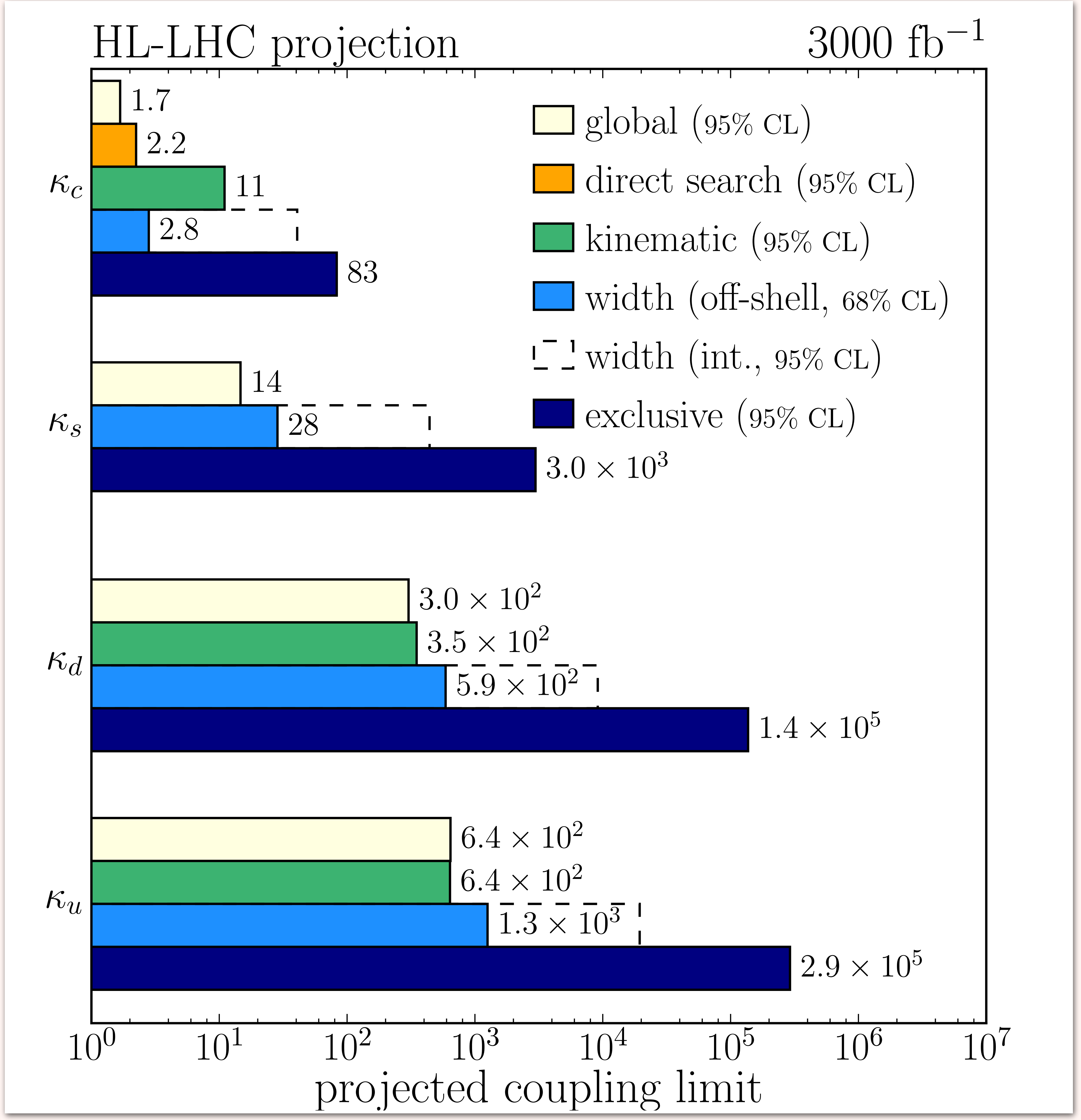
- **The large datasets collected in Run3 and HL-LHC will be fundamental to search for rarer decays of the Higgs and to probe the lighter yukawa couplings**

- H->Zγ already discussed by Marumi yesterday. A very good example of how analyses outpace projections!

- Other examples:
  - H->J/ψ γ (probe c coupling)
  - H->Φγ / ργ (probe light-quark couplings)
  - H->γQ, ZQ, or QQ (could arrive at values of several 10^{-5}, close to the SM or reducing the range for several BSM scenarios)

- Light Yukawa: Indirect constraints (eg from differential distributions, off-shell couplings, or from the global coupling fits) complement the direct searches

- What about H->ee? Very small Br~5×10^{-9} in the SM: at the LHC we can look for deviations in the yukawa. Run2 limits ~3x10-4 at 95 % CL (CMS, similar in ATLAS) and statistically limited



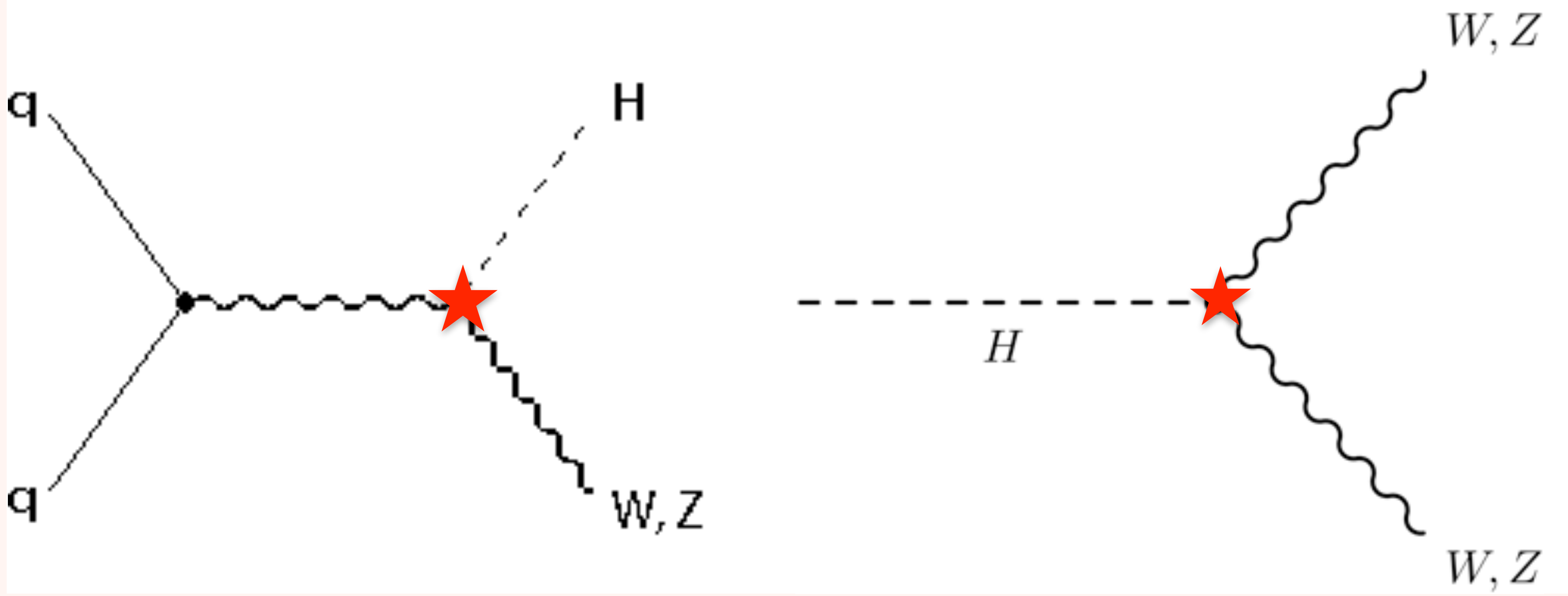
HIGGS COUPLINGS

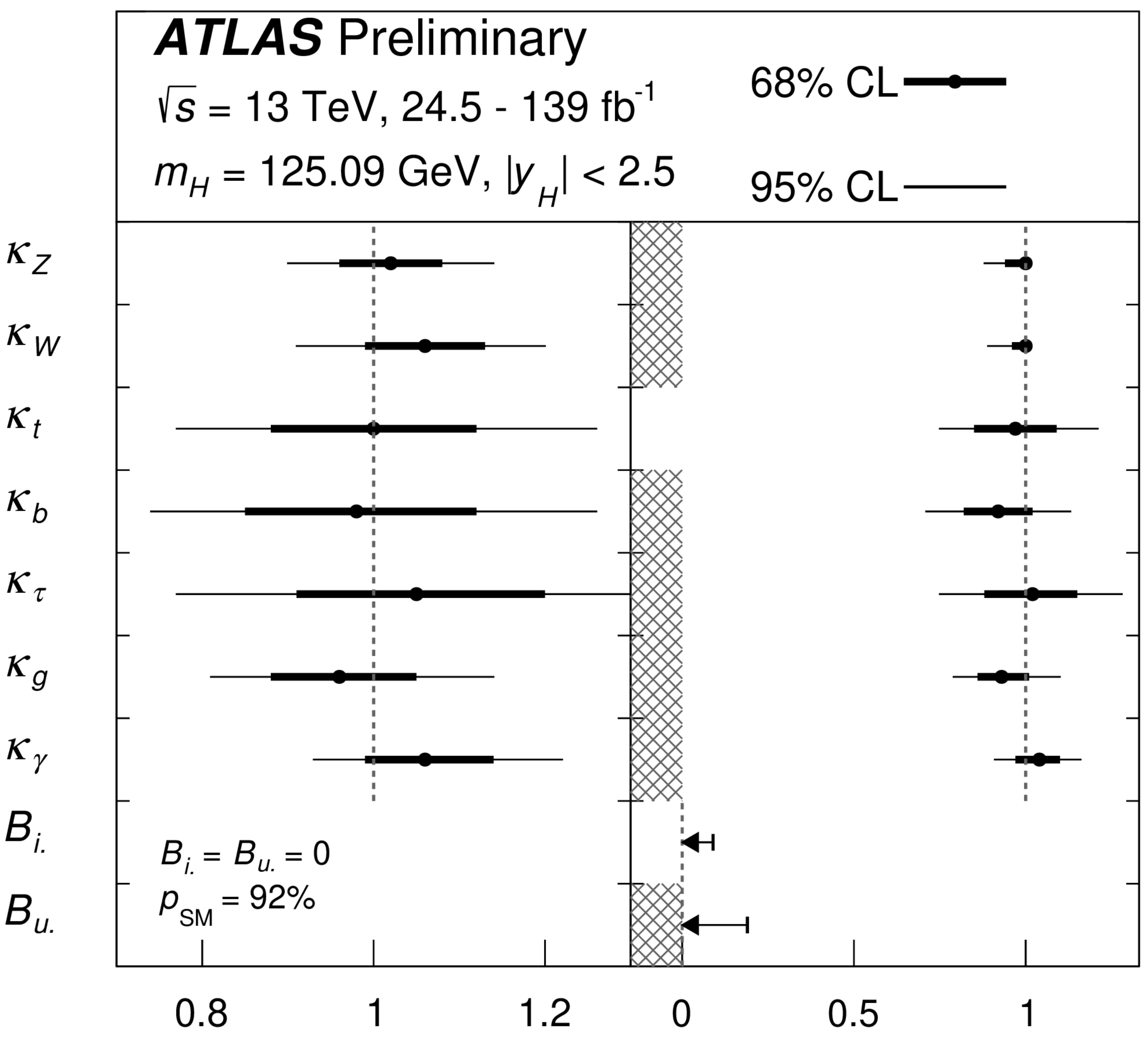
HOW WELL DO WE KNOW THE HIGGS COUPLINGS?

- In the Kappa Framework (simple parametrisation widely used by LHC experiments), already known to 6-15% (still with partial Run2 statistics)

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

$$\sigma_i = \kappa_i^2(\vec{\kappa}) \cdot \sigma_i^{SM} \qquad \Gamma^f = \kappa_f^2(\vec{\kappa}) \cdot \Gamma^{f,SM}$$

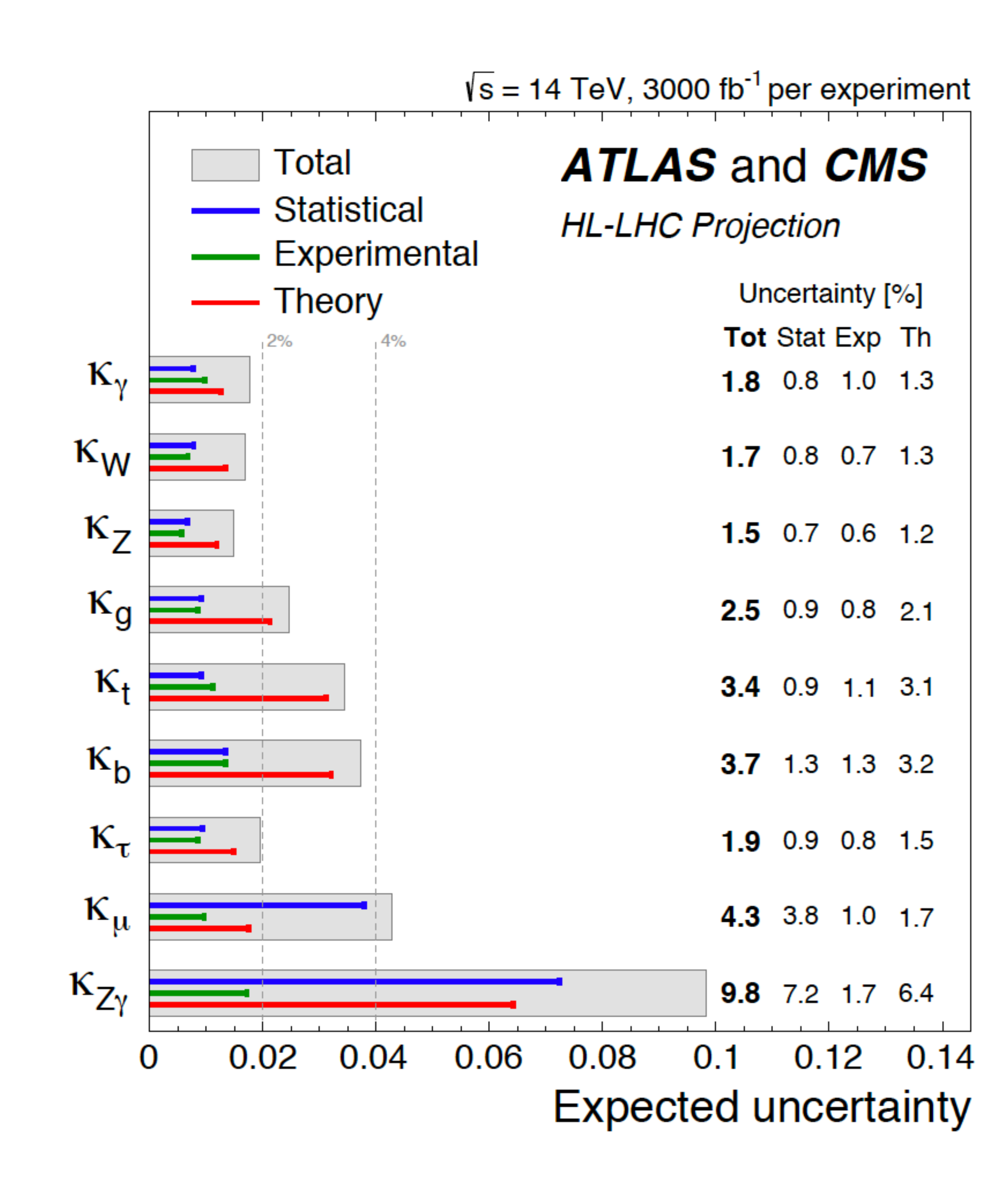




ATLAS-CONF-2020-027

HOW WELL *WILL* WE KNOW THE HIGGS COUPLINGS?

Precision of 2-4% can be reached for the non-statistically dominated modes

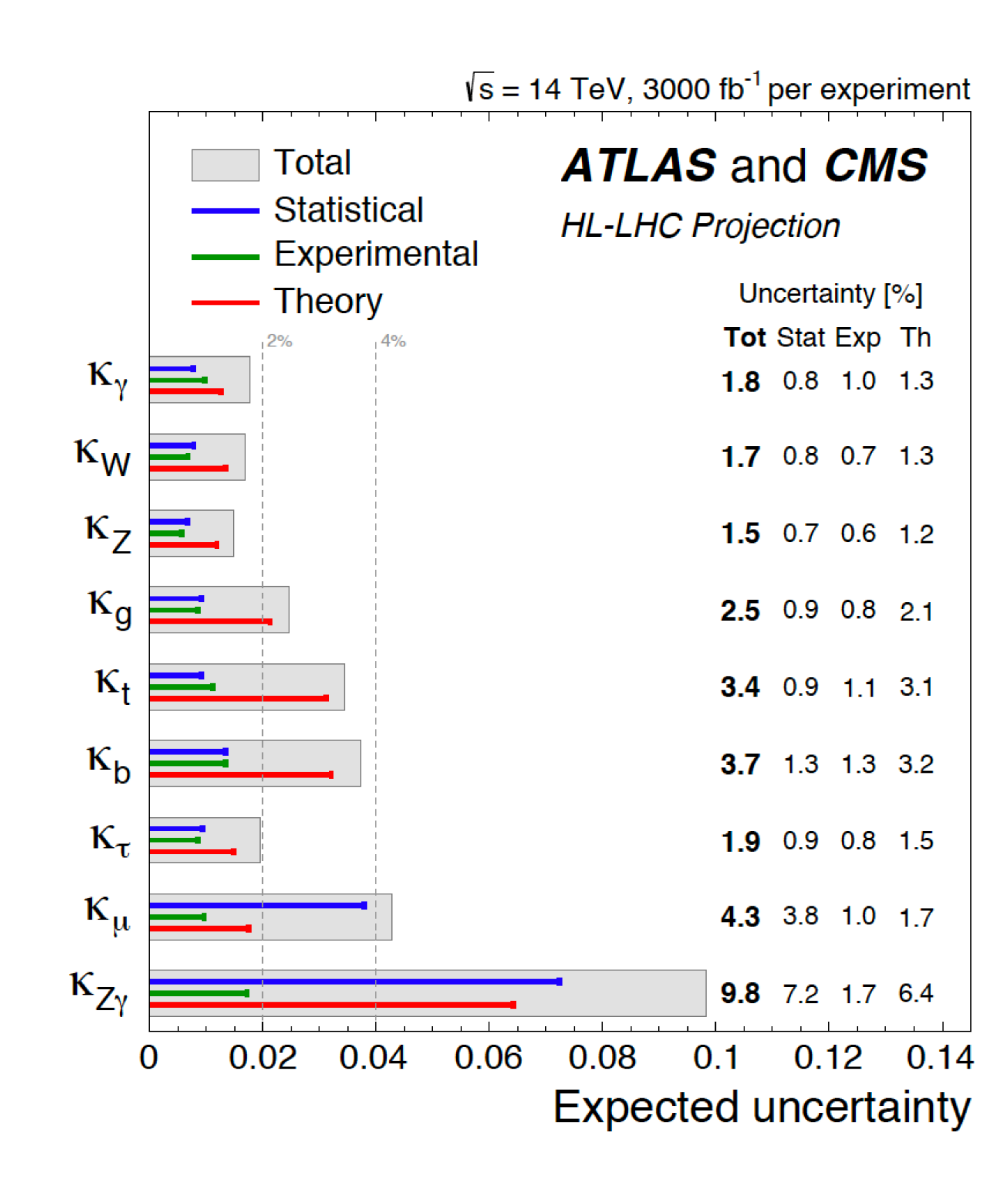


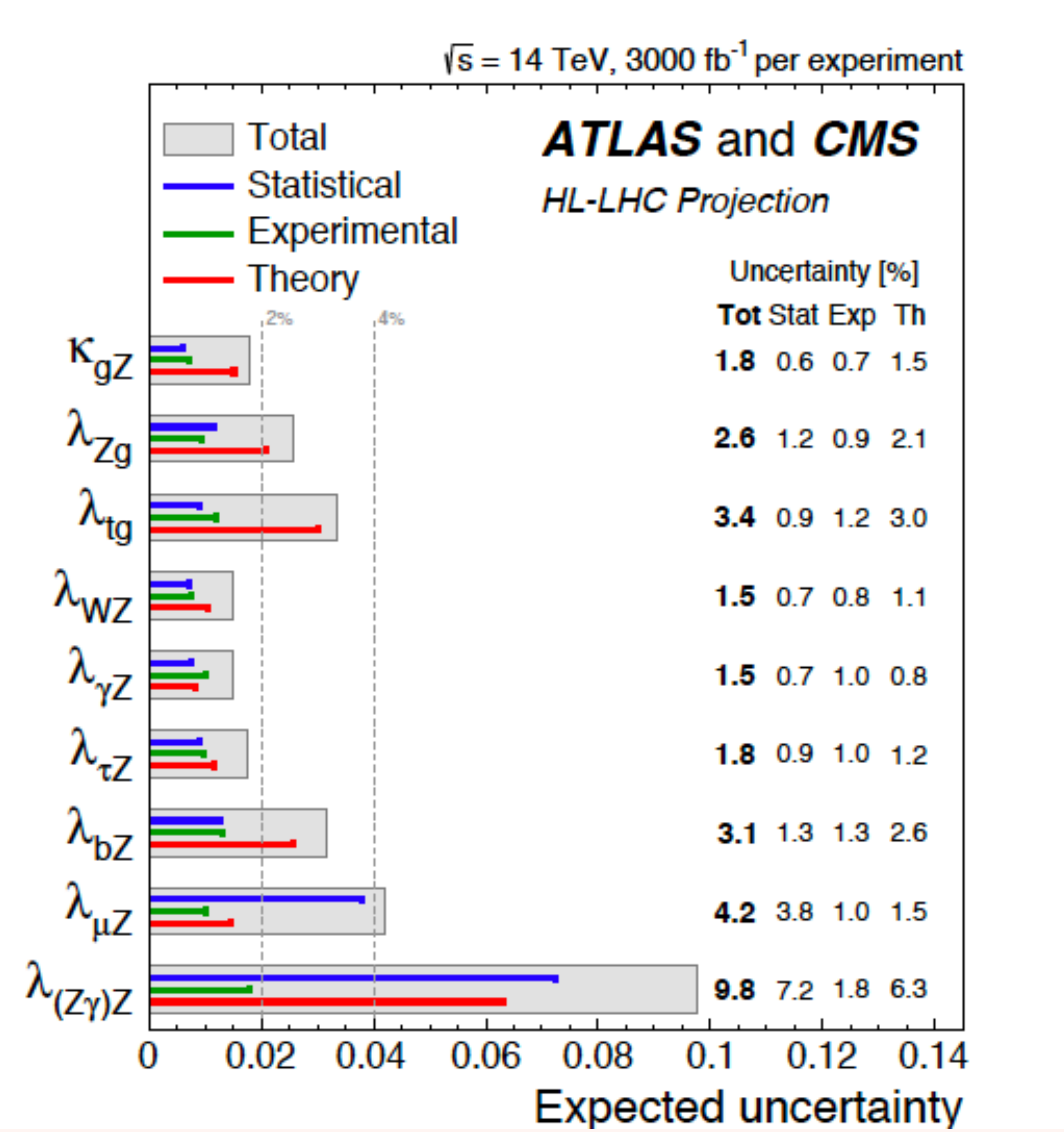
HOW WELL *WILL* WE KNOW THE HIGGS COUPLINGS?

Precision of 2-4% can be reached for the non-statistically dominated modes

If uncertainties are a bottleneck: exploit ratios.

Improved precision through cancelation of uncertainties





HOW WELL *SHOULD* WE KNOW THE HIGGS COUPLINGS?

SMALL CORRECTIONS EXPECTED IN MANY BSM MODELS

If new physics is at 1 TeV:

	$\delta\kappa_V$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet	<6%	<6%	<6%
2HDM (large t_β)	~1%	~10%	~1%
MSSM	~.001%	~1.6%	~-.4%
Composite	~-3%	~-(3-9)%	~-9%
Top Partner	~-2%	~-2%	~1%

Patterns of deviations can pinpoint specific BSM physics

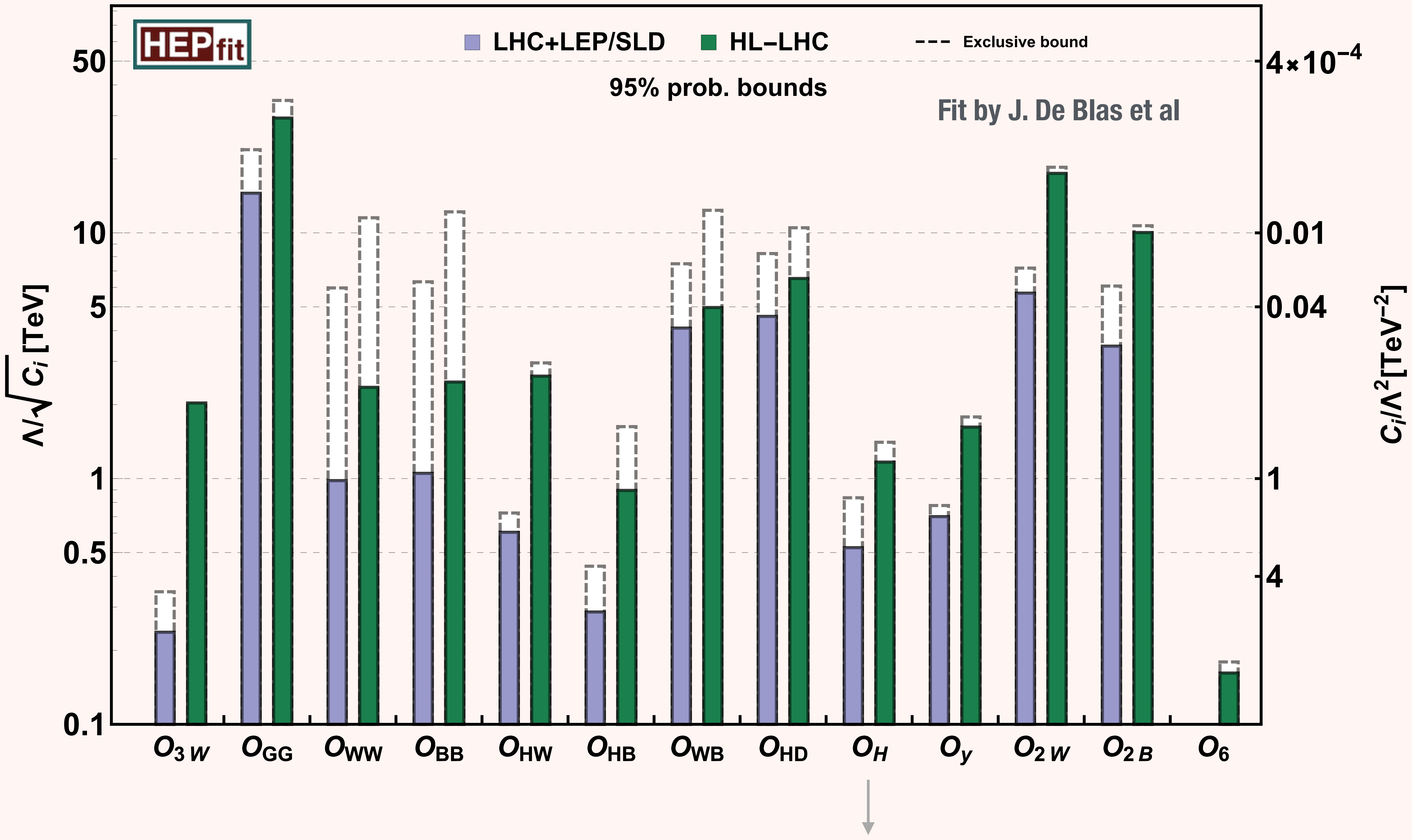
- Generically new physics effects on couplings $\sim \frac{v^2}{M^2} \sim \mathcal{O}(6\%)$ for M=1 TeV
- Only now are we approaching sensitivity where we expect deviations

Sally Dawson

GLOBAL FITS

- Higgs results tells us only part of the story: we need to think globally about all LHC measurements
- Slow move to EFT approaches that eventually will involve all precision data available
- Very complicated to do well: long experimental process, through Run3 to the HL-LHC

Higgs couplings + DY + Diboson observables

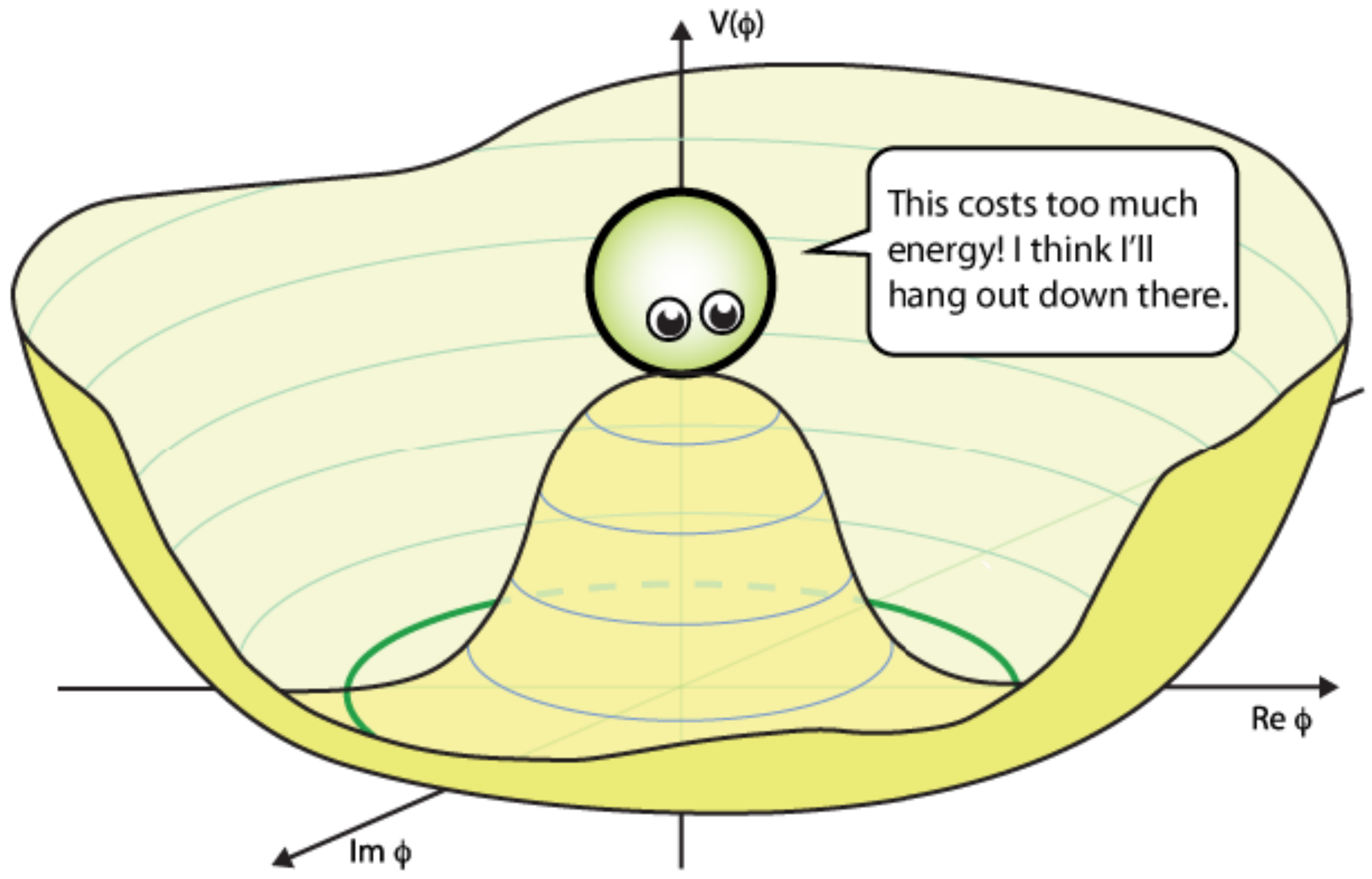


95% probability limits on the new physics interaction scale

eg: compositeness f>1.6 TeV, mass scale 20TeV

CHASING
THE SELF-COUPLING

THE HIGGS SELF-COUPLING

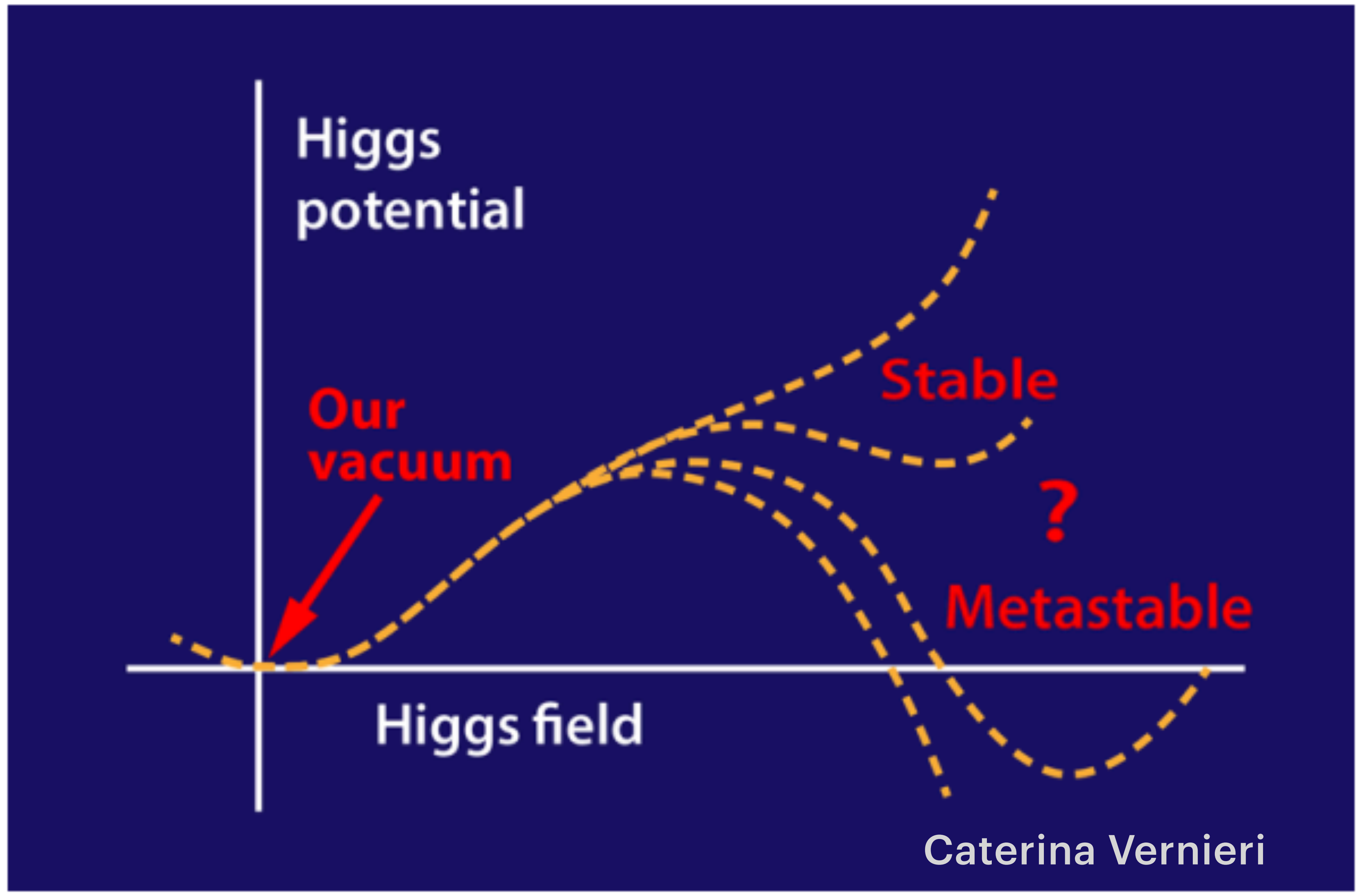


$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2\Phi^2 - \lambda\Phi^4$$

$$\text{For } \mu^2 < 0, \quad \text{minimum } v = \sqrt{-\frac{\mu^2}{2\lambda}}$$

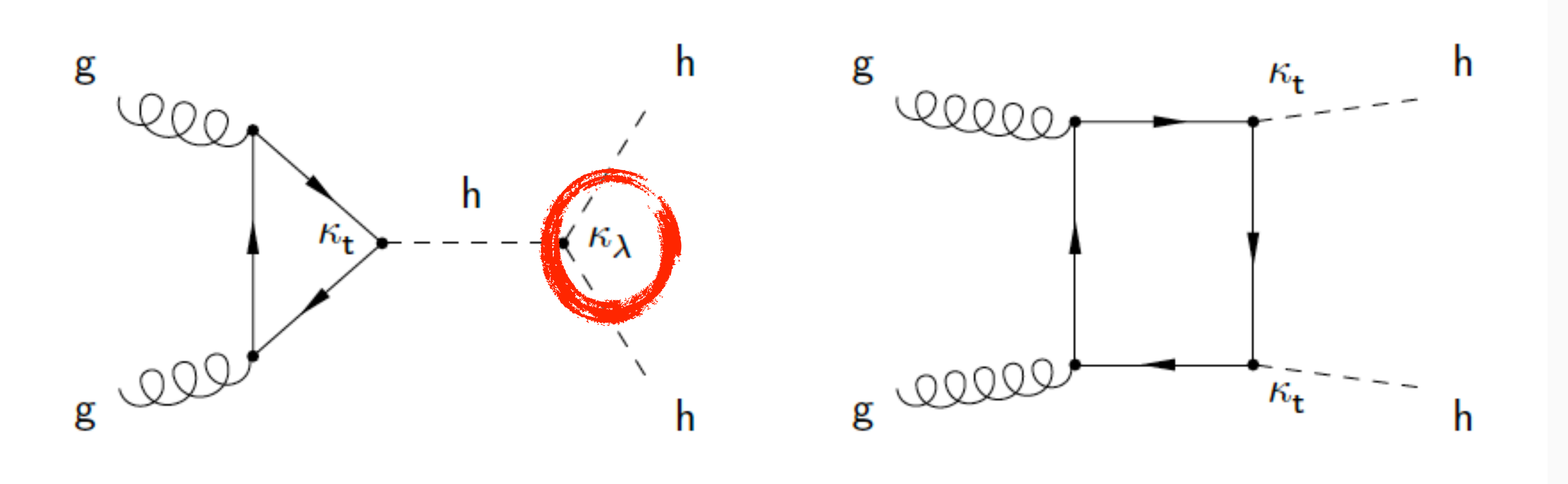
→Does the Higgs couple to itself?

→Access the shape of the Higgs potential!



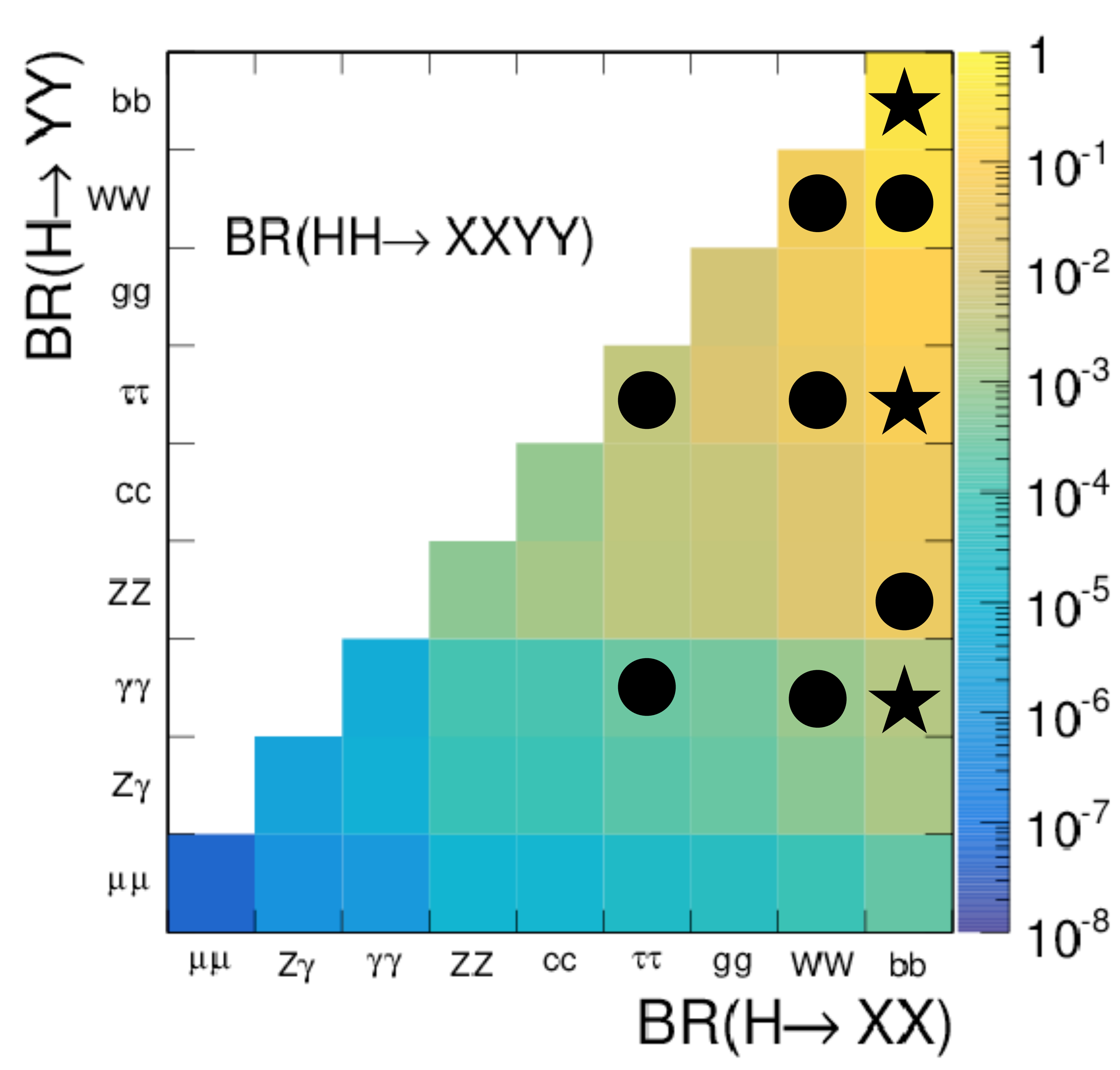
LOOKING FOR PAIRS OF HIGGS BOSONS

- **Main avenue at LHC to probe the self-coupling: HH production. Very small cross section!**
  - Deviations in the Self-coupling: $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$



- **<u>Current reach (at 95% CL):</u>**

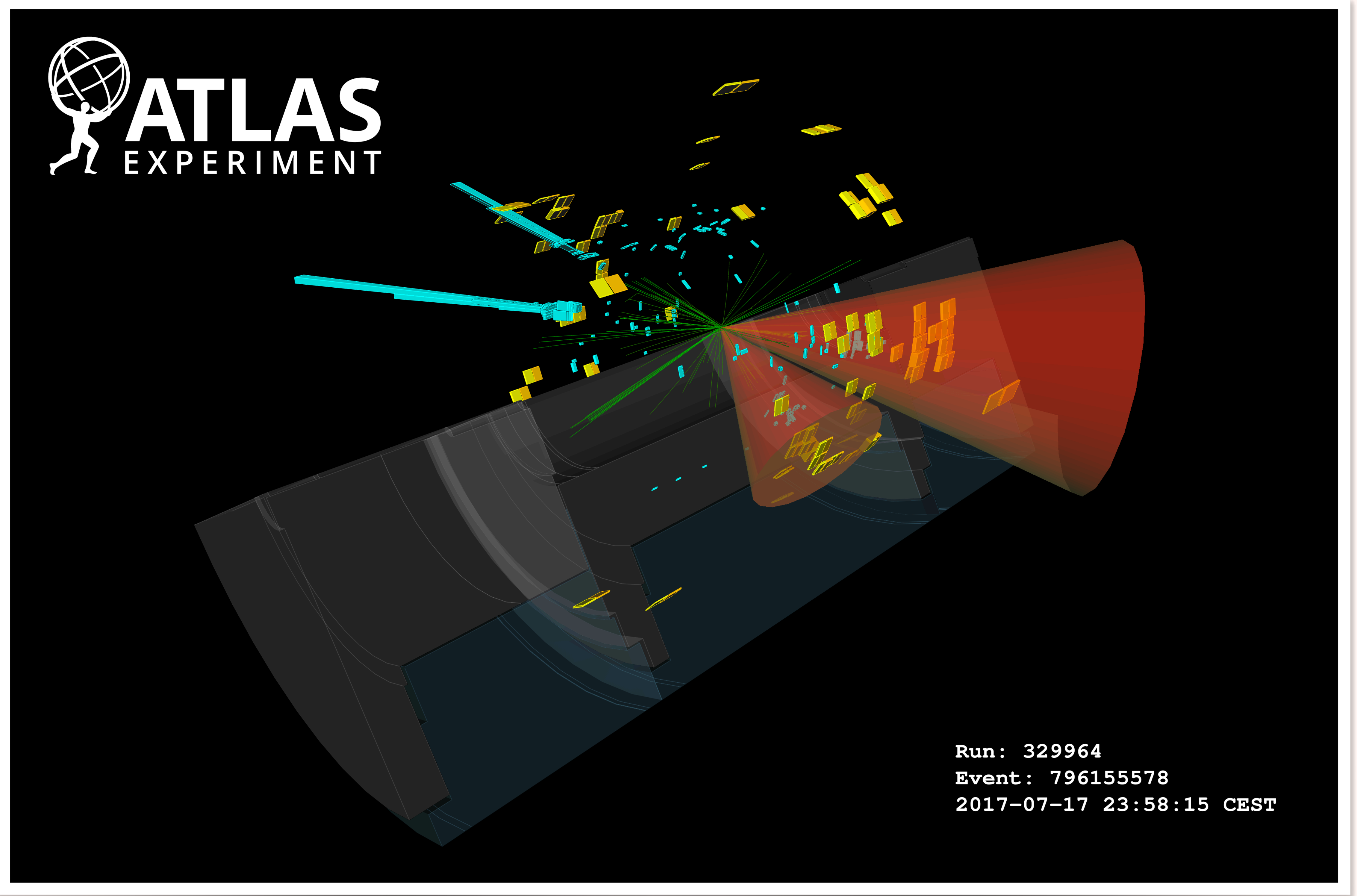
$$\frac{\sigma_{HH}}{\sigma_{HH}^{SM}} \lesssim 3 \text{ and } -1 \lesssim \kappa_\lambda \lesssim 6$$

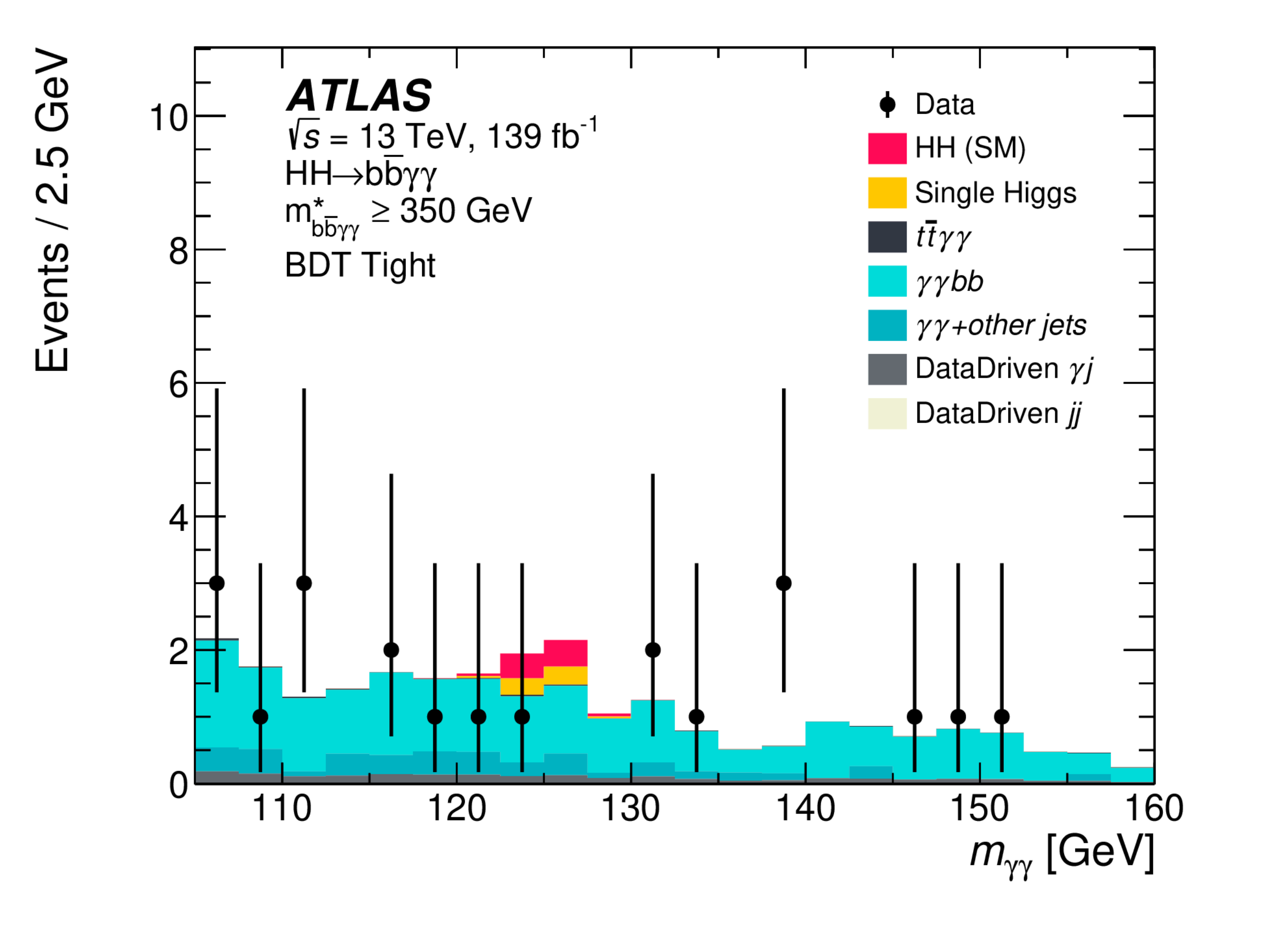


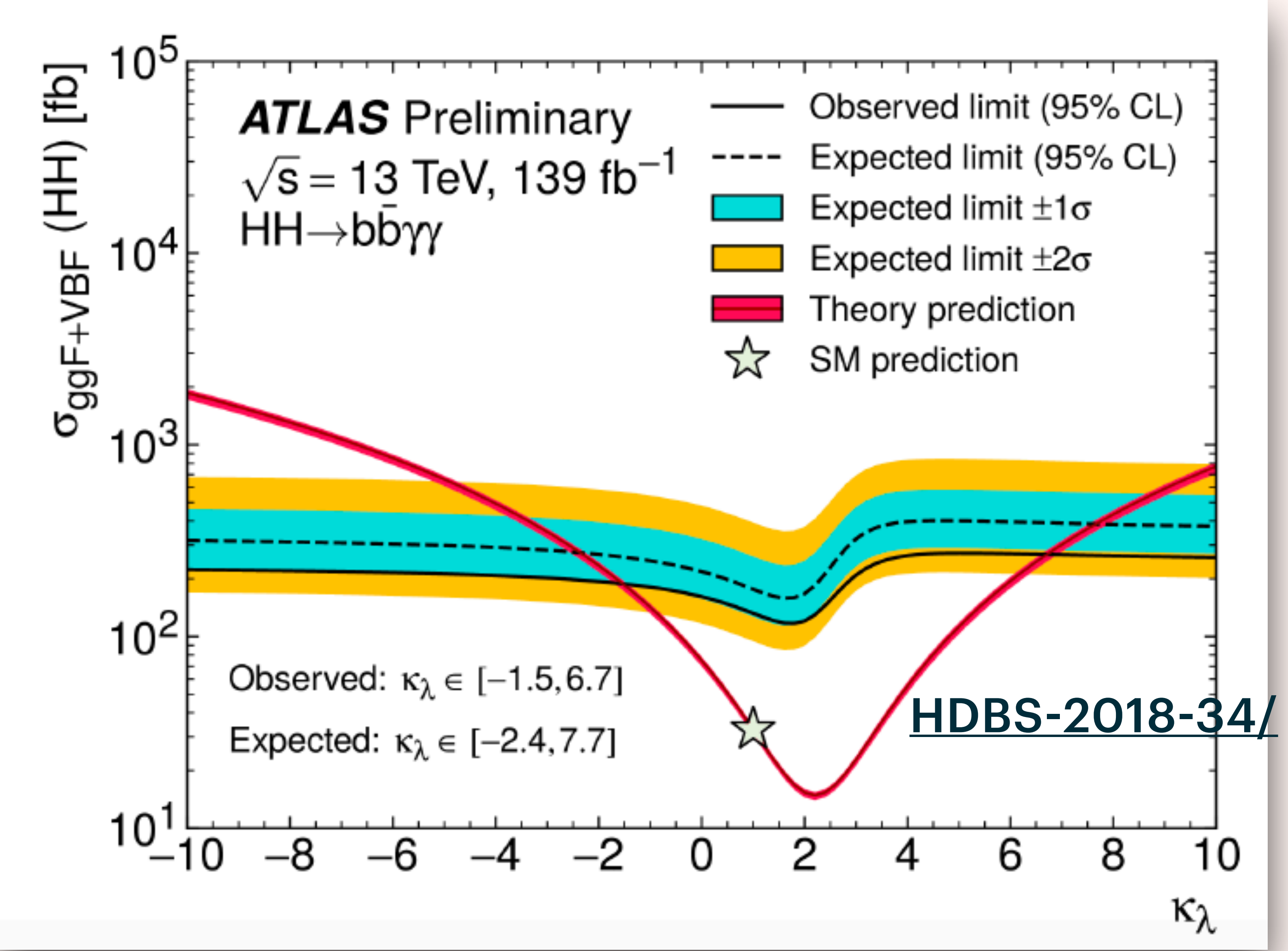
- Two Higgses: <u>many</u> possible decays
- **Golden channels: bbγγ , bbττ, bbbb**

$HH \to b\bar{b}\gamma\gamma$

- Small rate, but clean: one of the golden channels
- Exploits the excellent diphoton resolution of the detectors
- Categories designed to probe larger and smaller ranges of κ_λ, κ_{2V}



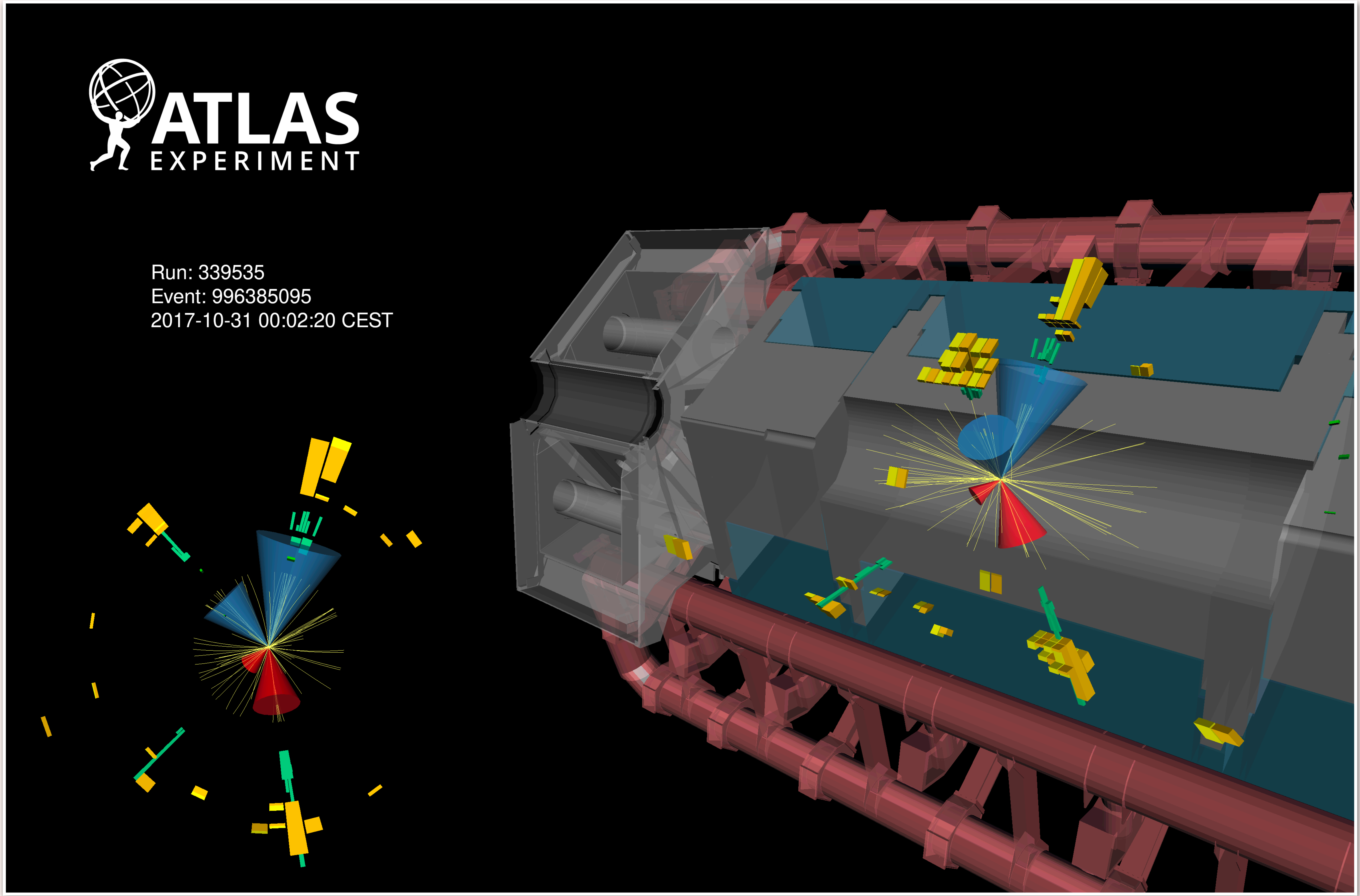


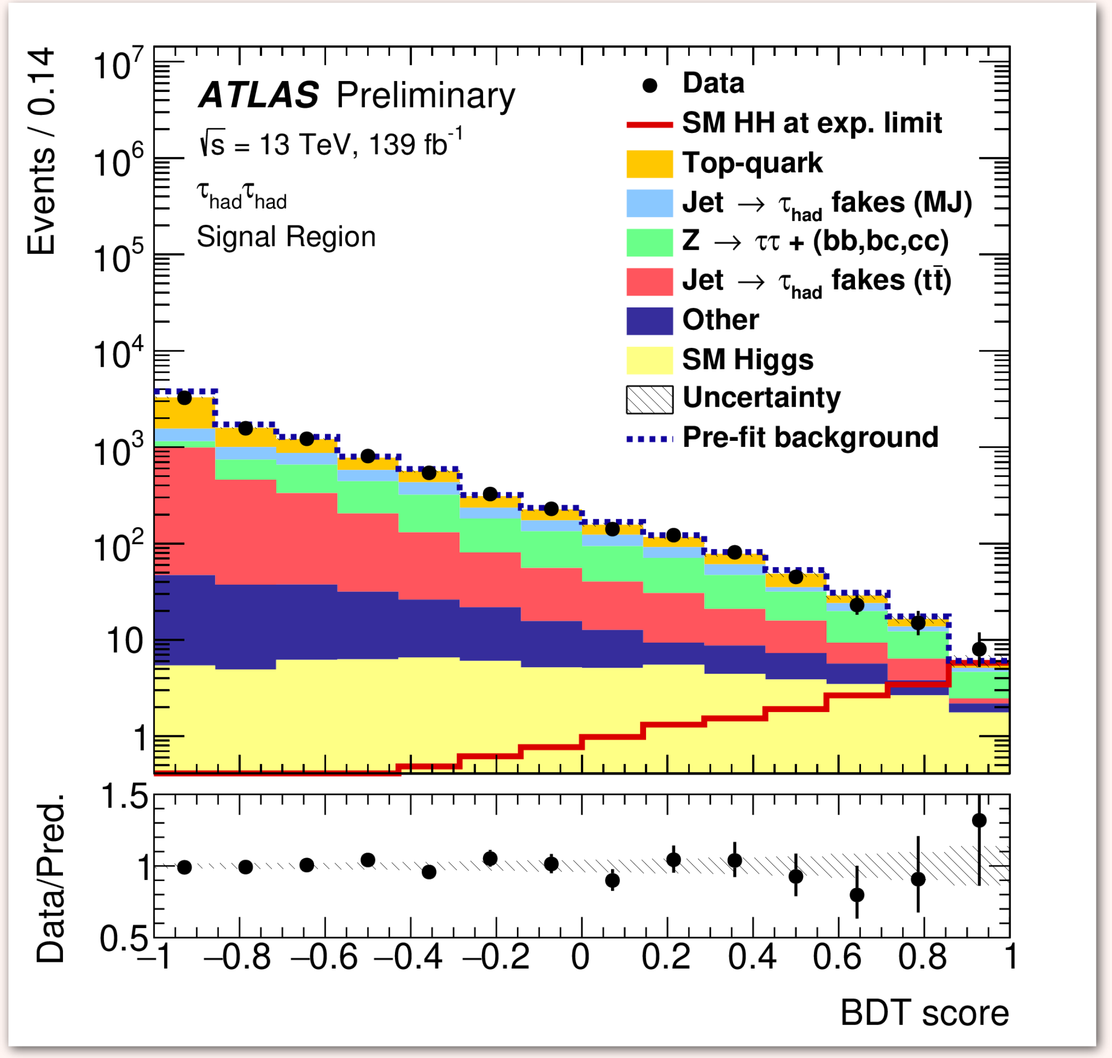


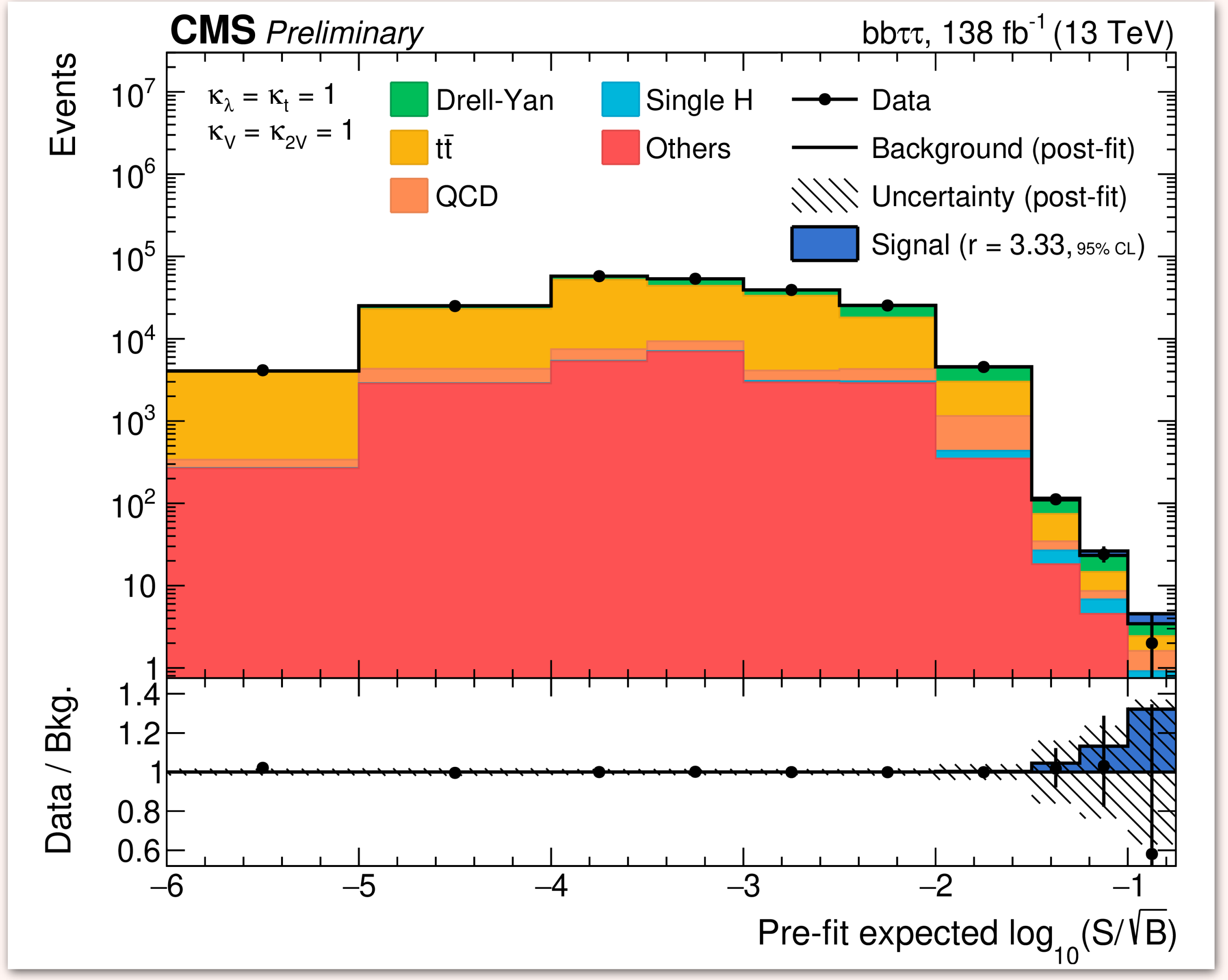
HDBS-2018-34/

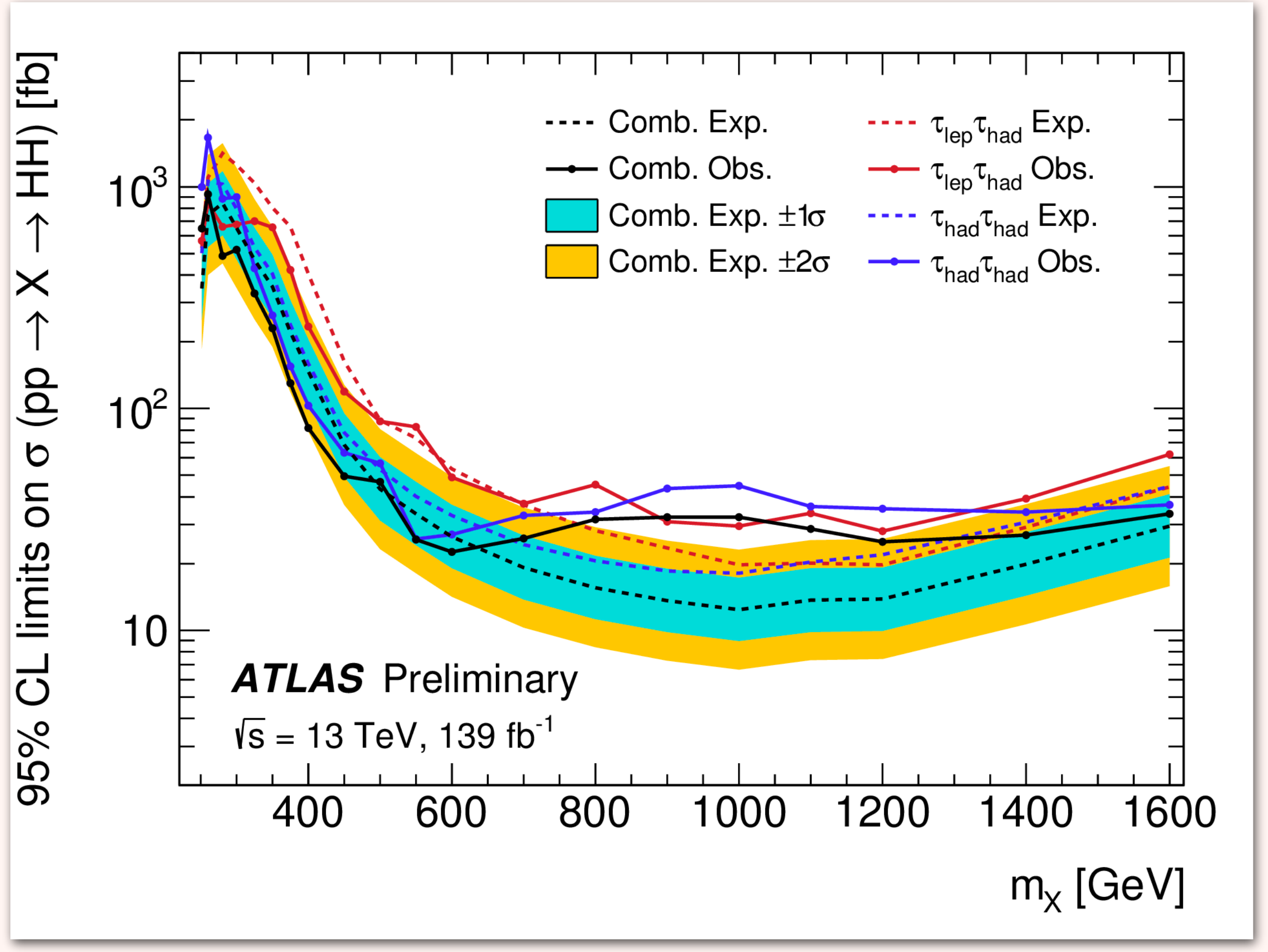
$HH \rightarrow b\bar{b}\tau\tau$

- Relies on excellent tau identification
- Backgrounds ranging from ttbar to misidentified taus







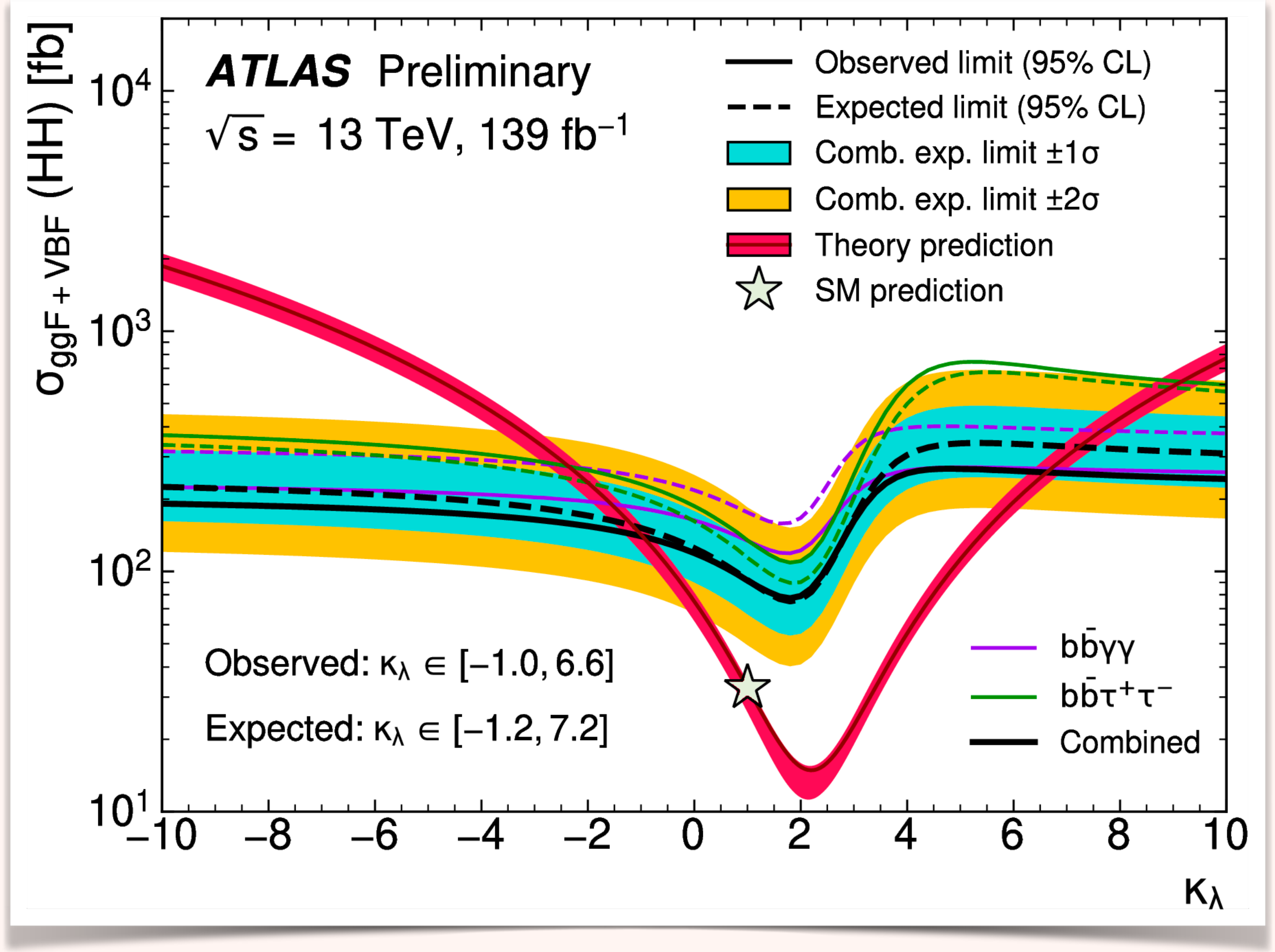


PS: also searches for X->HH!

STATUS OF FULL RUN2 SEARCHES

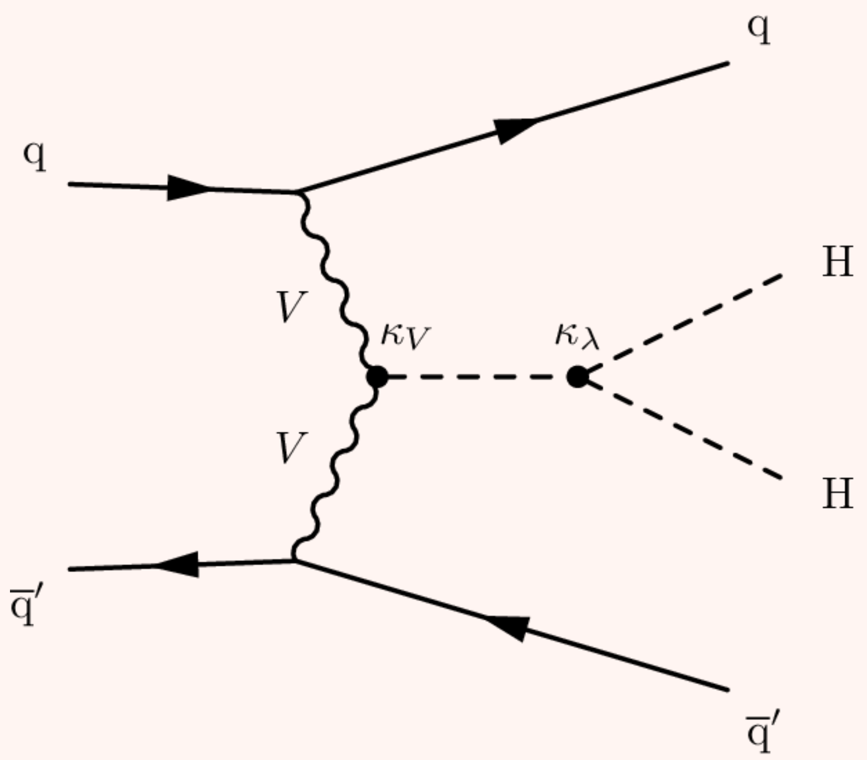
	ggF+VBF: upper limit at 95% CL on σ/σ_{SM}	95%CL limits on κ_λ observed
HH→bbγγ	4.2 (5.7) 7.7 (5.2)	[-1.5 , 6.7] [-3.3, 8.5]
HH→bbττ	4.7 (3.9) 3.3 (5.2)	[-2.4 , 9.2] [-1.8, 8.8]
HH→bbbb	— 3.9 (7.8) 9.9 (5.1) (boosted)	— [-2.3, 9.4] [-9.9, 16.9]
HH→bbZZ	30 (37)	[-9, 14]
HH→WWWW, HH→ττττ, HH→WWττ	21.8 (19.6)	[-7, 11.7]
Partial combination	**3.1 (3.1)**	**[-1.1 , 6.6]**

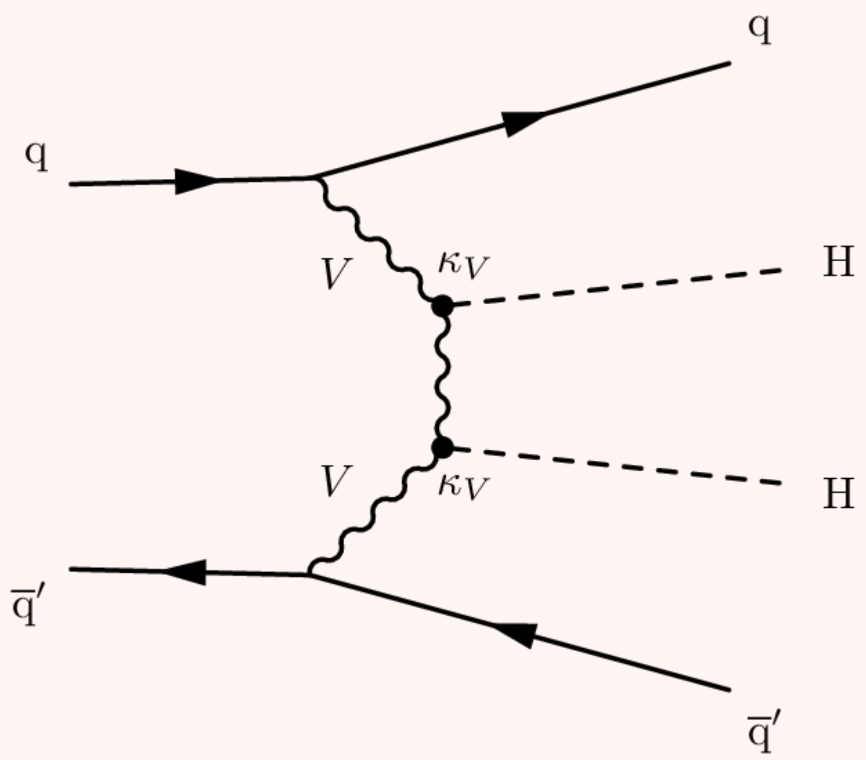
ATLAS
CMS
Obs(Exp)

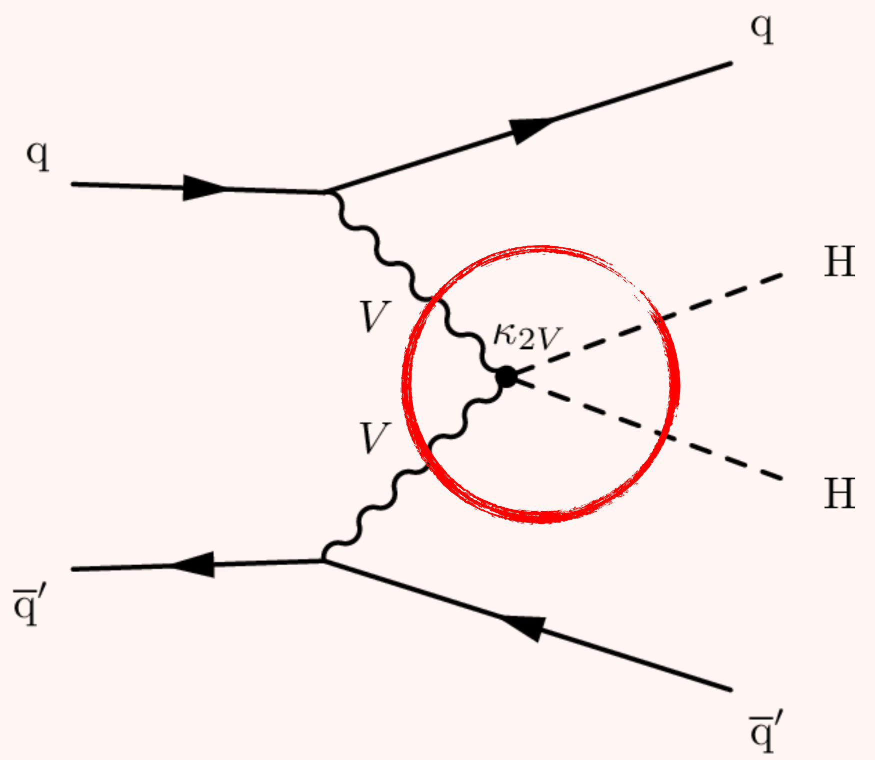


More channels (eg, bbWW) and final Run2 combination coming soon!

VBF HH AND κ_{2V}





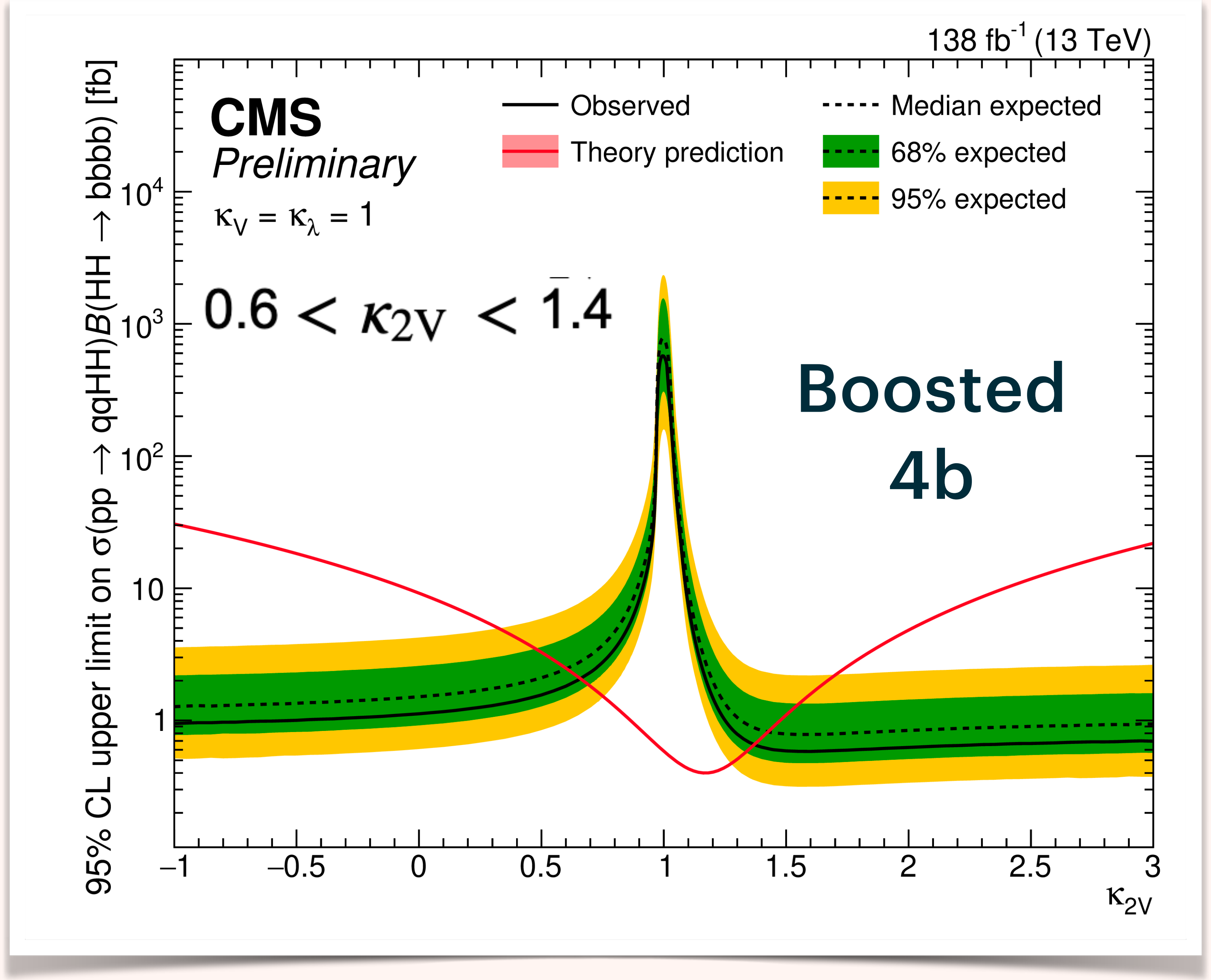


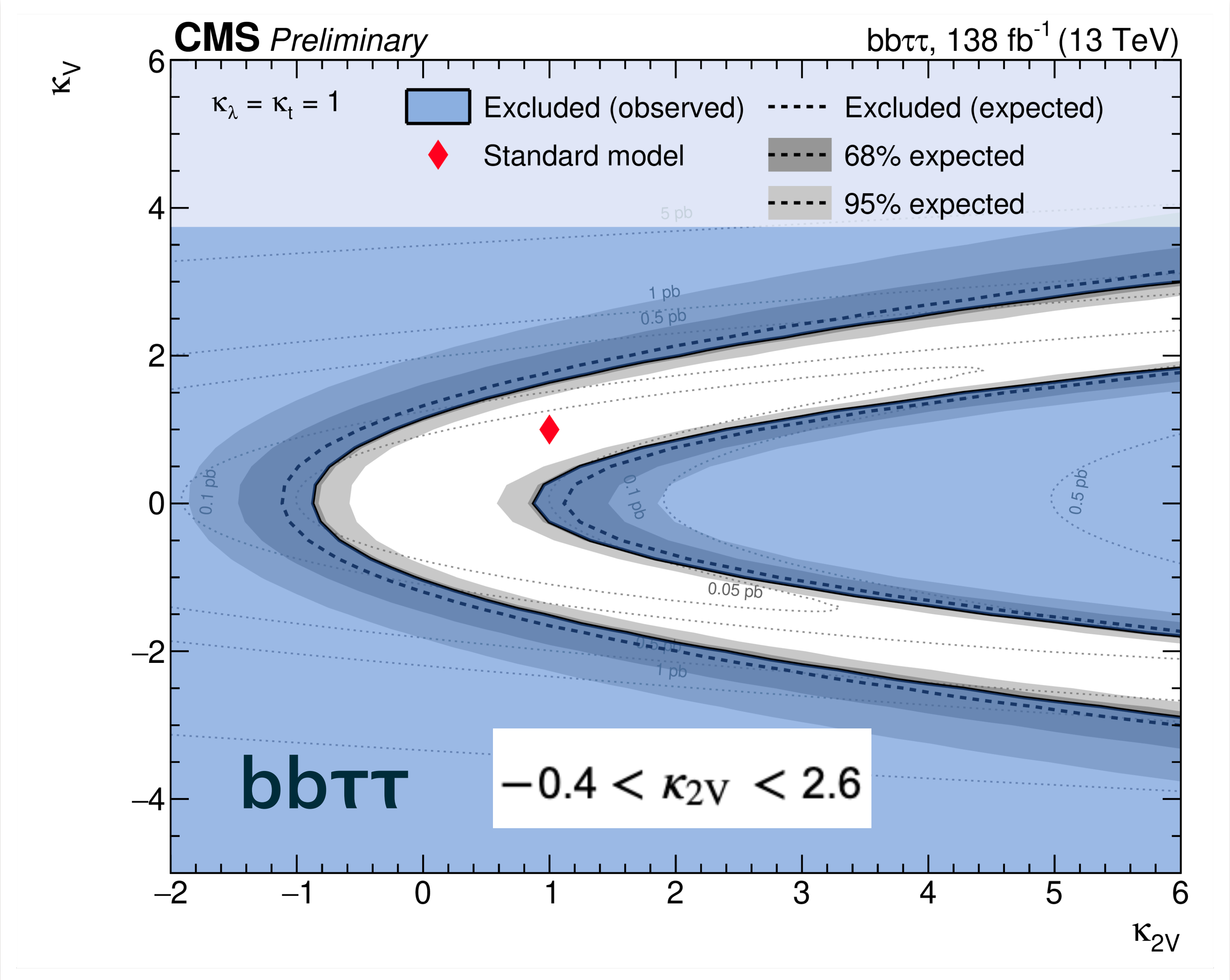
- Cross Section:very small in the SM, experimental limits still two orders of magnitude over

$$\sigma^{HH}_{VBF} = 1.726^{+0.03\%}_{-0.04\%}(\text{scale}) \pm 2.1\%(\text{PDF+}\alpha_S)\ \text{fb}$$

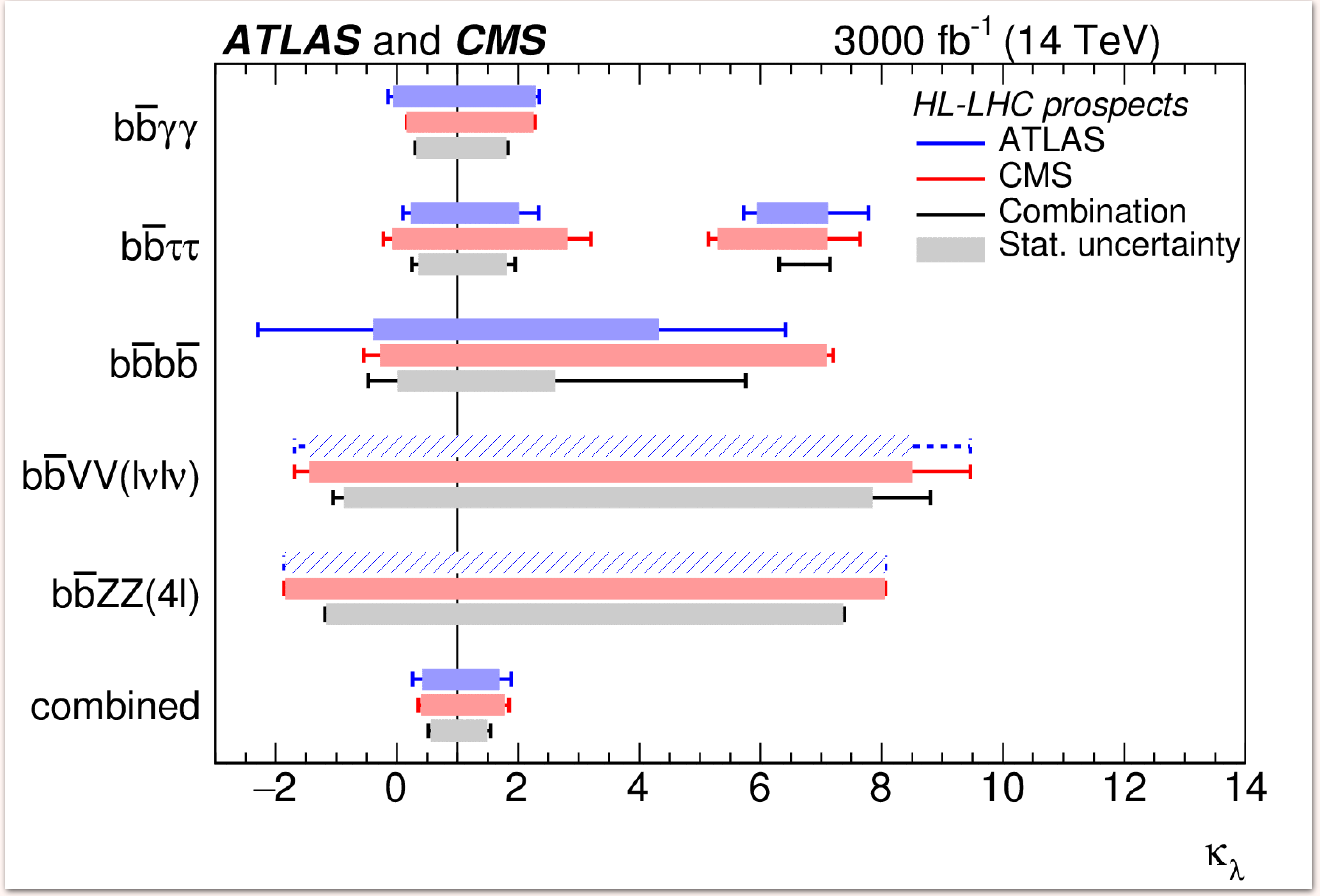
- Example CMS bbττ : upper limit at 95% of 124(154)xSM

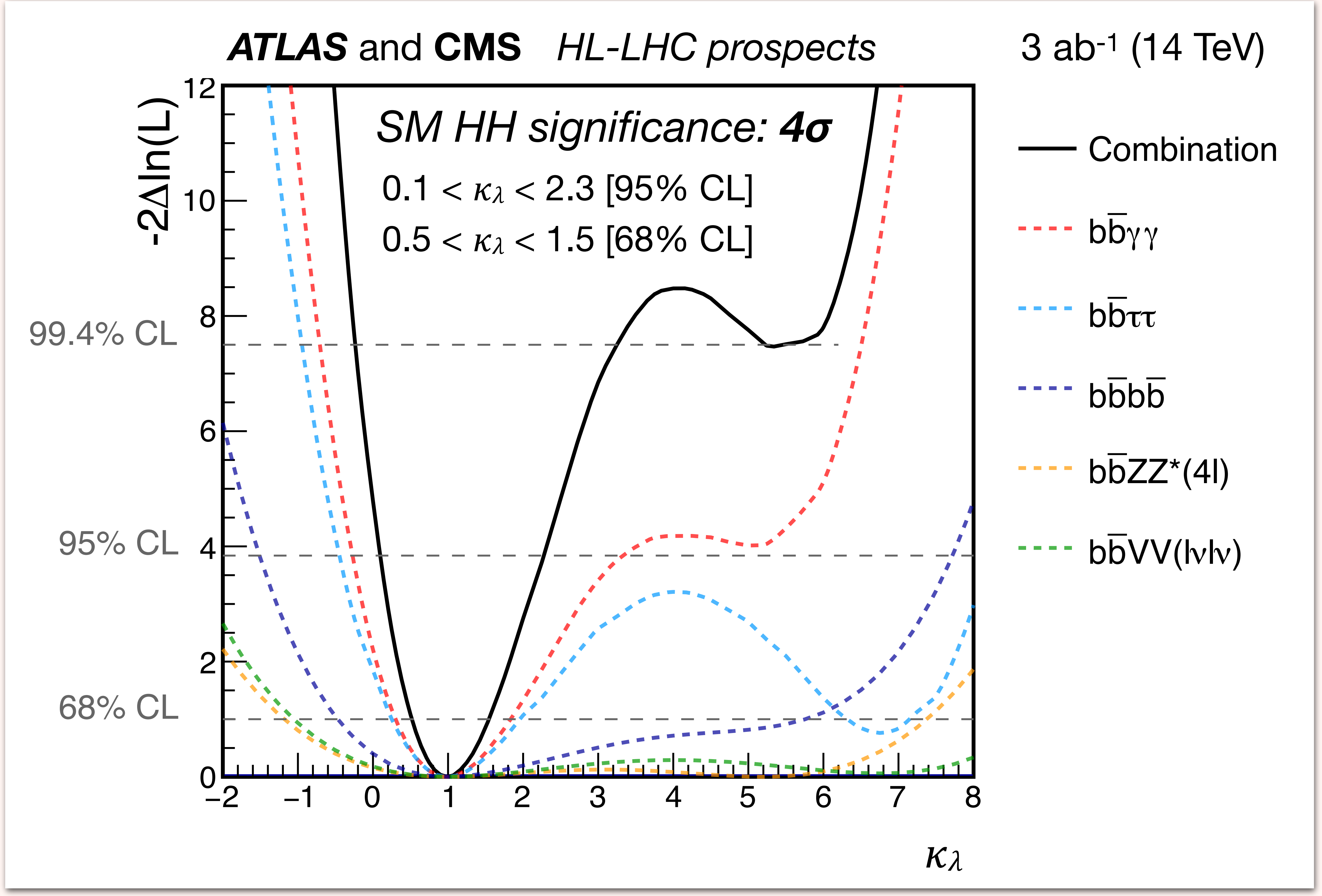
- **Constraints on κ_{2V}**





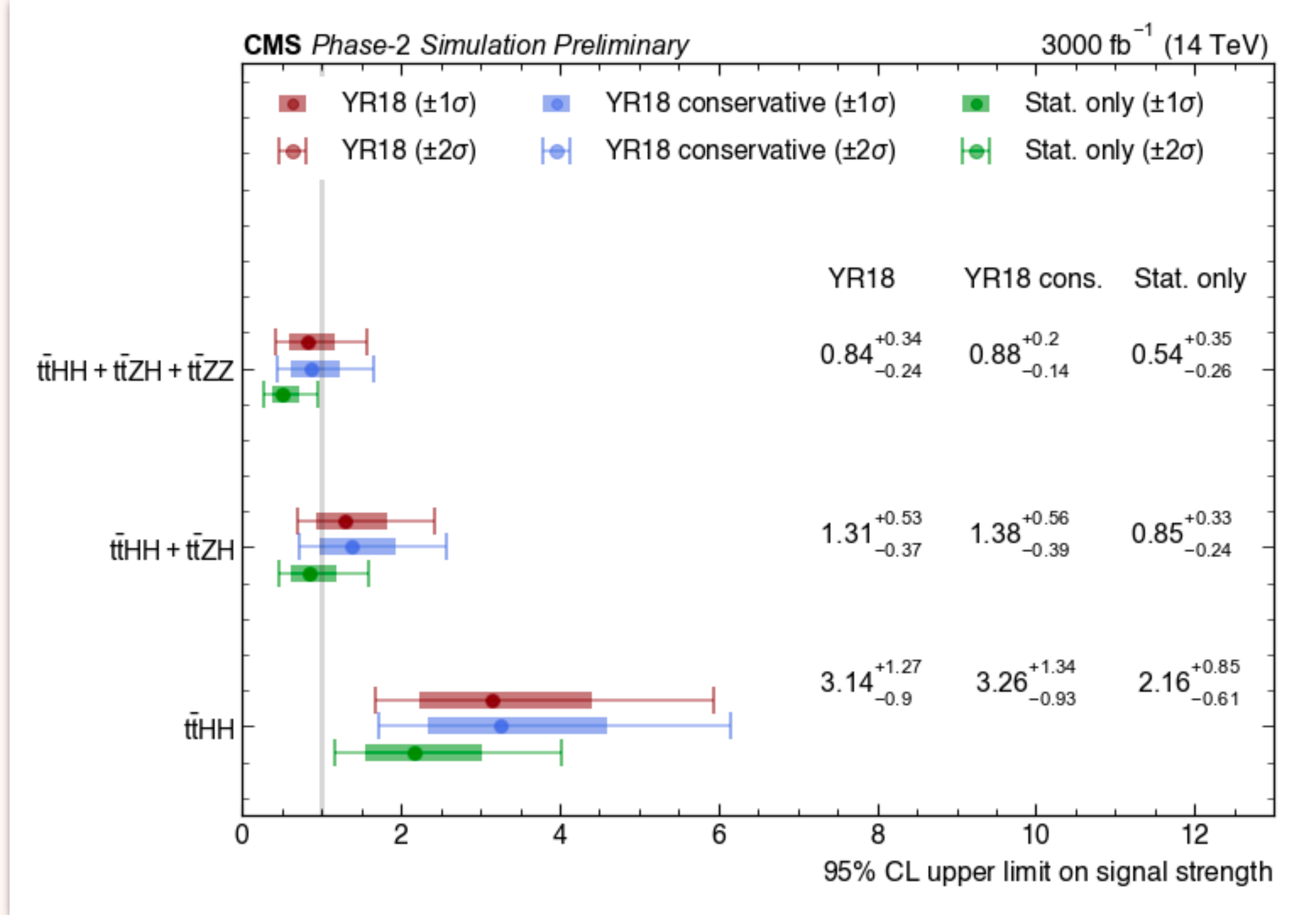
DIHIGGS @ HL-LHC





Combining CMS and ATLAS data, in 2018 we projected a significance of **4σ and a 50% uncertainty on κλ by the end of HL-LHC** . This is likely to be outperformed, and the HL-LHC will reach 5σ

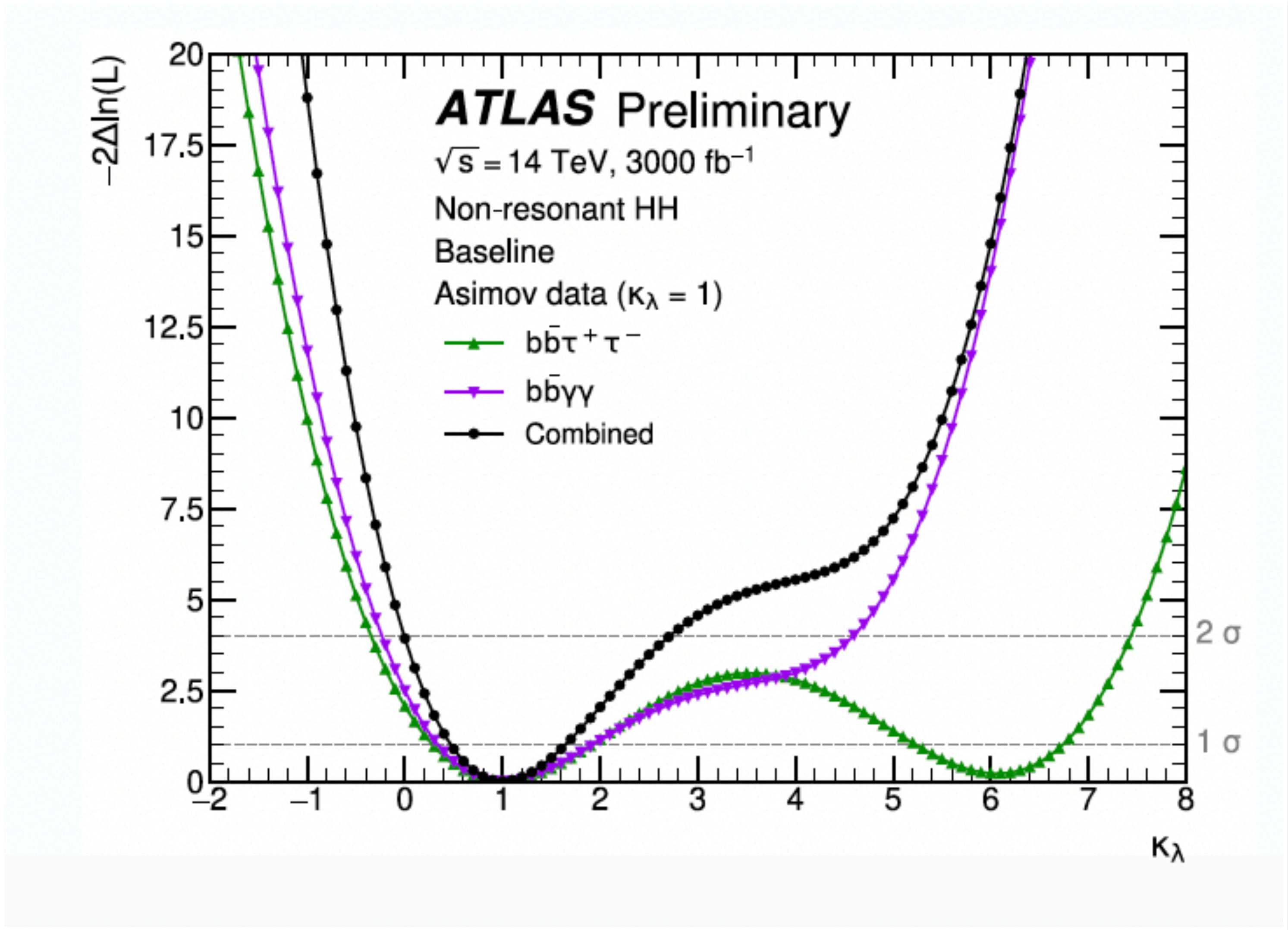
UPDATES TO THE HH PROJECTIONS



Updates to the projections done in the context of Snowmass: improvements per channel (ATLAS and CMS both improved by ~20-30%) and new channels incorporated (WWγγ ,ττγγ)

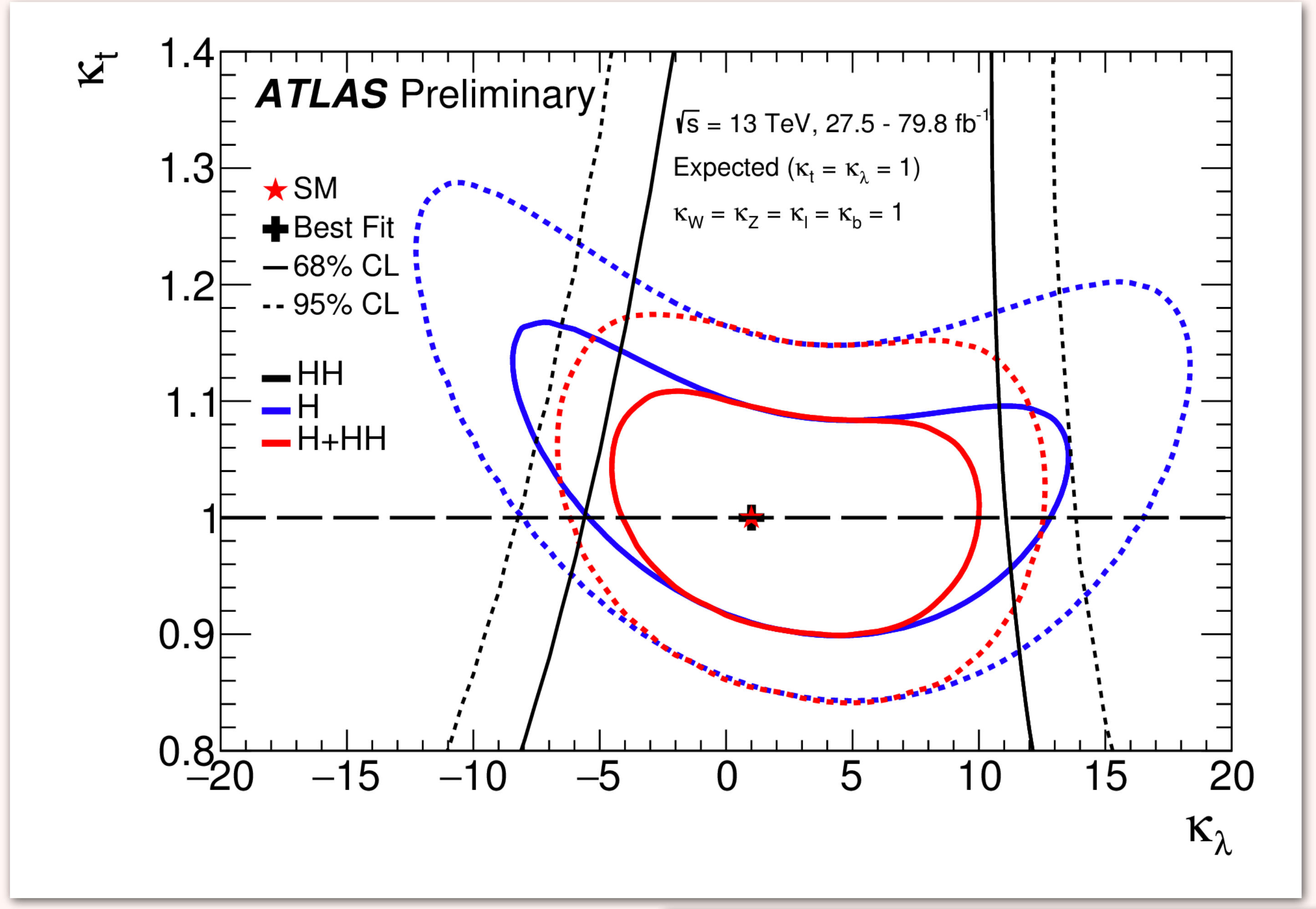
Full CMS+ATLAS combination not yet redone: on track for the 5 sigmas

First ttHH projection (Third largest cross section among the HH production models, interplay between ttH and ttHH)



Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination	Combined signal strength precision [%]
No syst. unc.	2.3	4.0	4.6	$-23/+23$
Baseline	2.2	2.8	3.2	$-31/+34$
Theoretical unc. halved	1.1	1.7	2.0	$-49/+51$
Run 2 syst. unc.	1.1	1.5	1.7	$-57/+68$

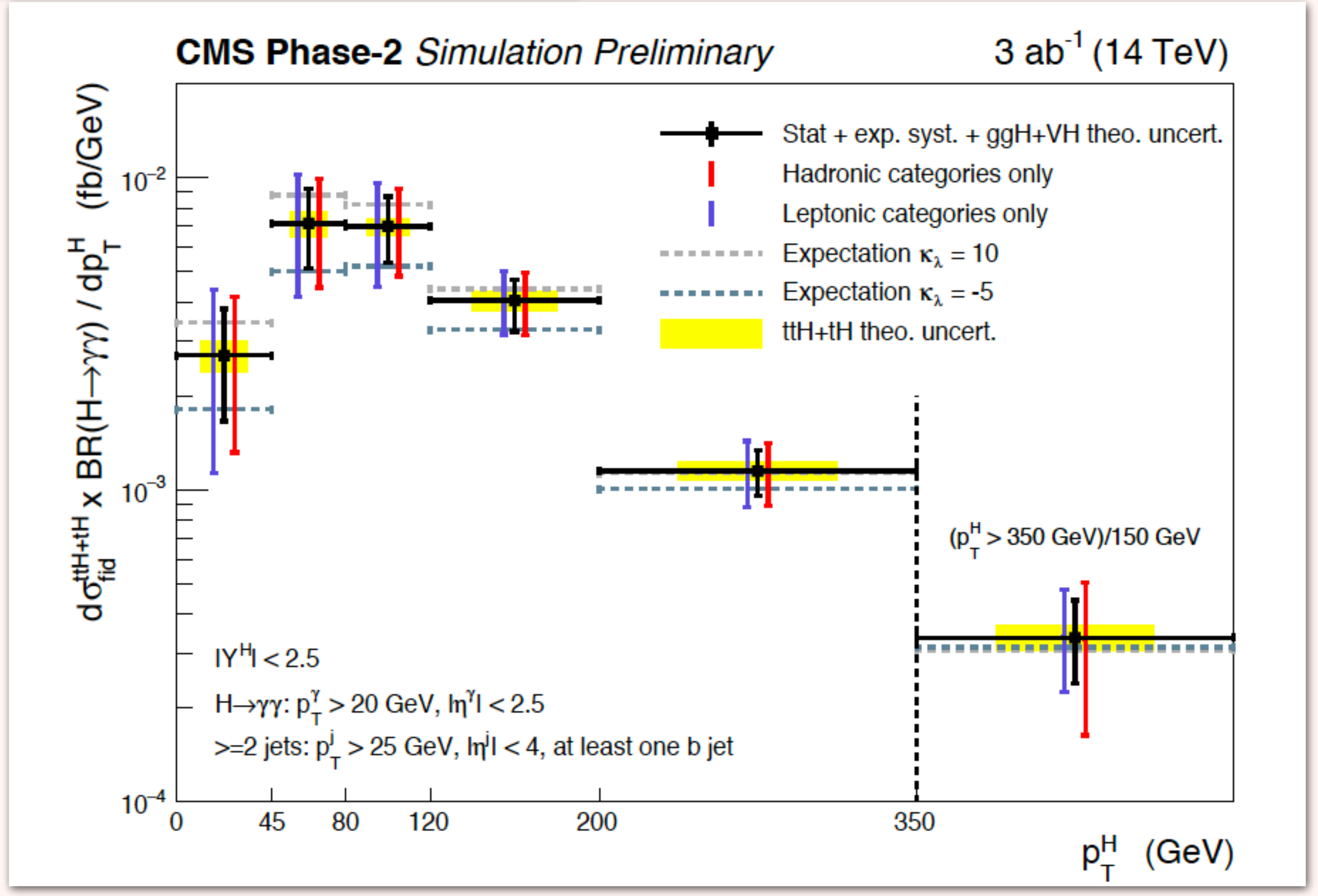
INDIRECT CONSTRAINTS

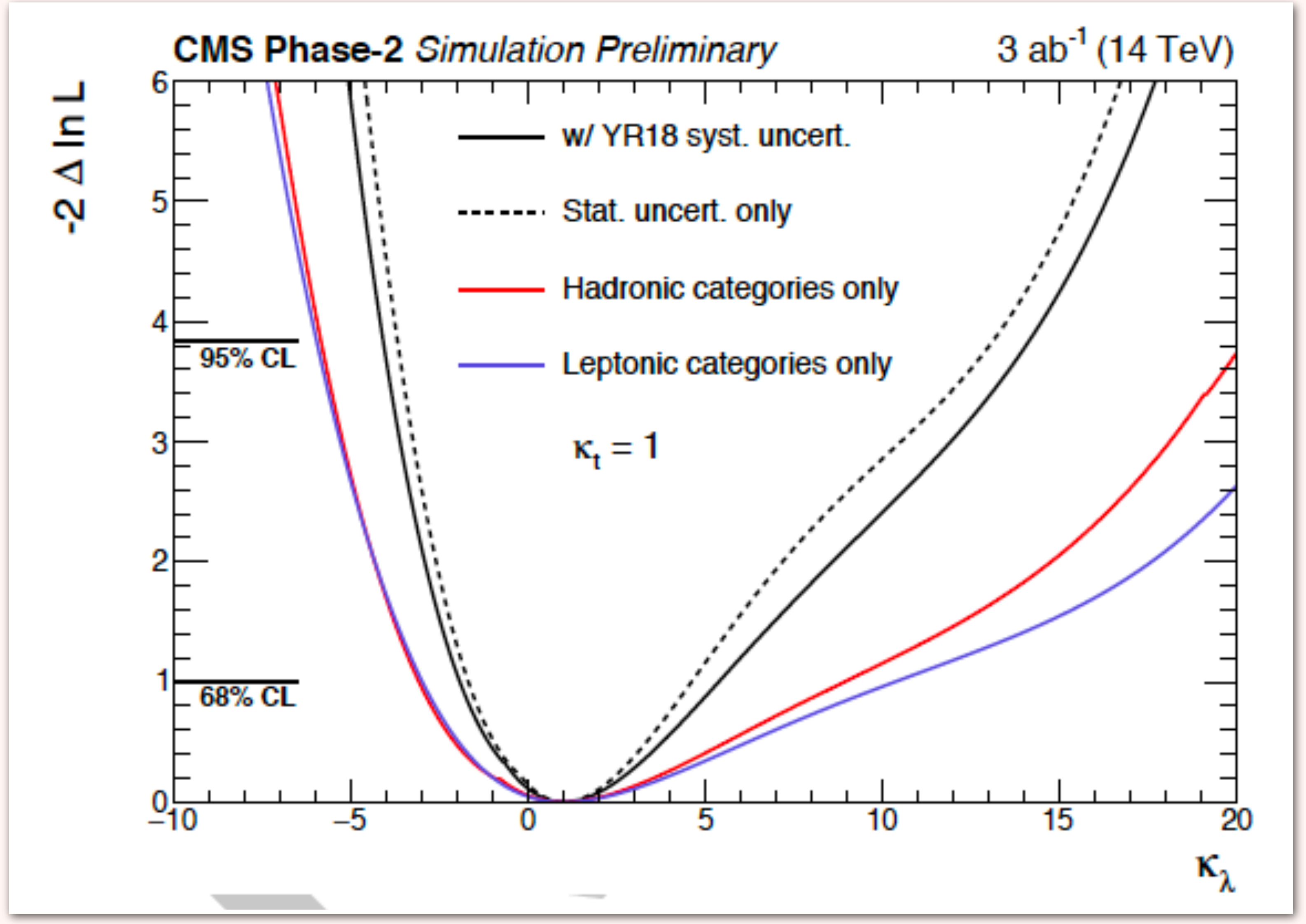


HH searches dominate the self-coupling hunt, but Single Higgs measurements can also yield interesting constraints on the self coupling, and be combined with HH production.

Run2 examples: Single Higgs constraints from STXS, combined analysis of H and HH in Hγγ modes

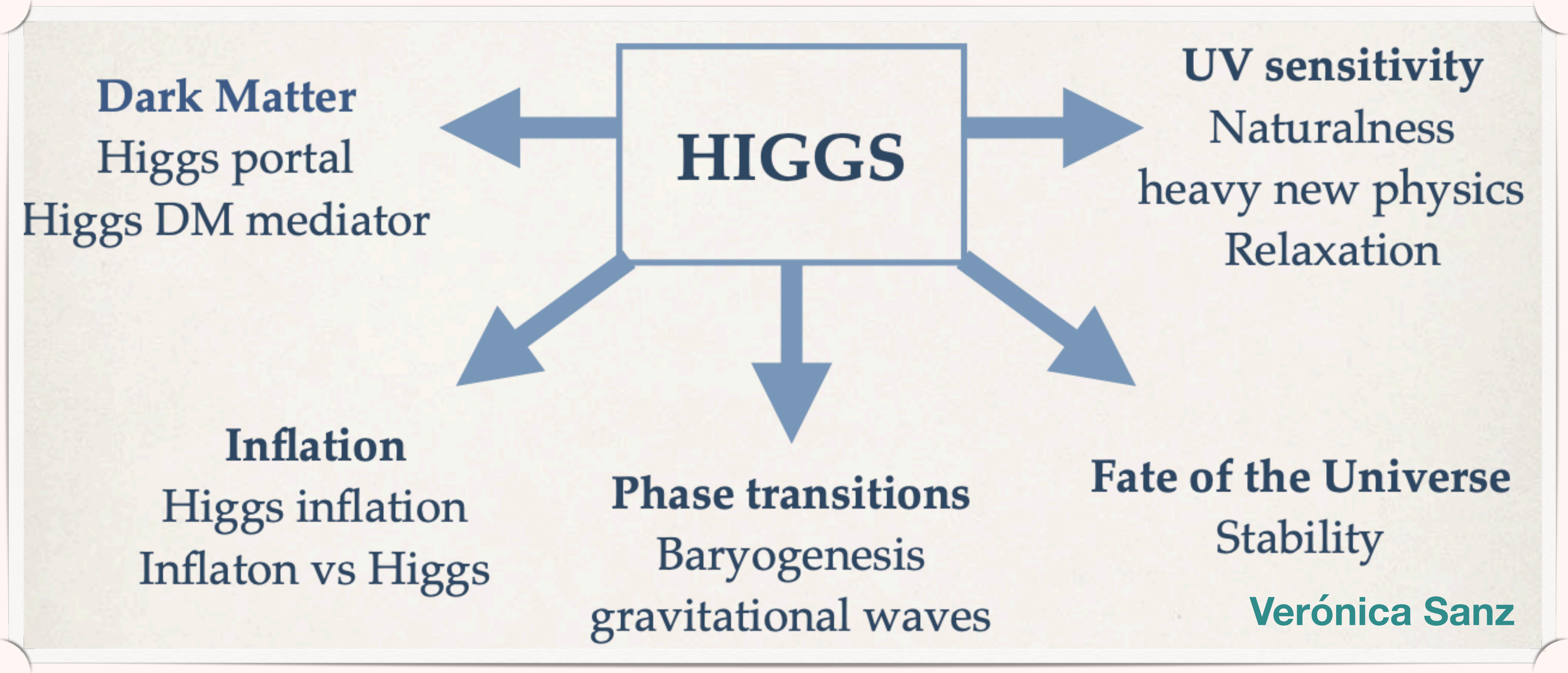
HL-LHC projection example: constraint from ttH Hγγ



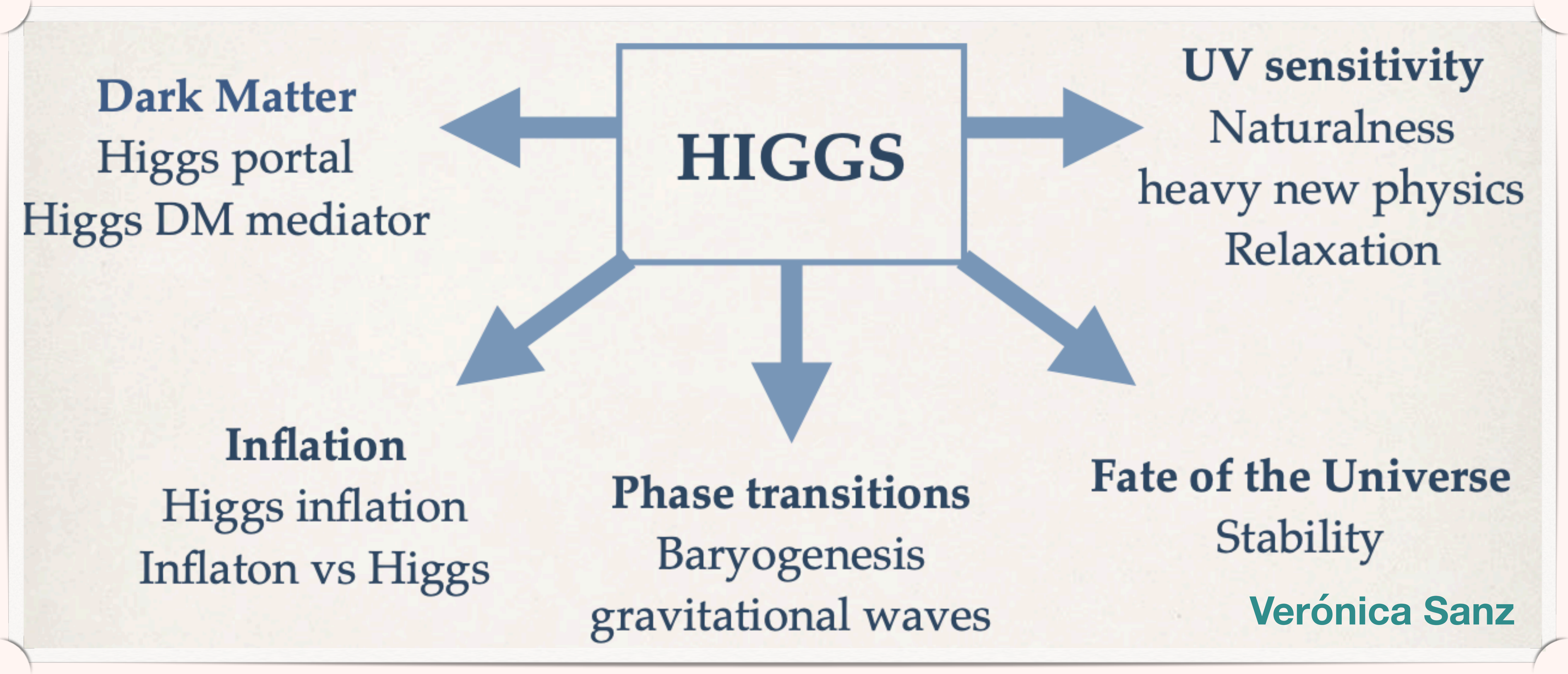


IS THE HIGGS THE PORTAL TO NEW PHYSICS?

MOVING BEYOND THE SM



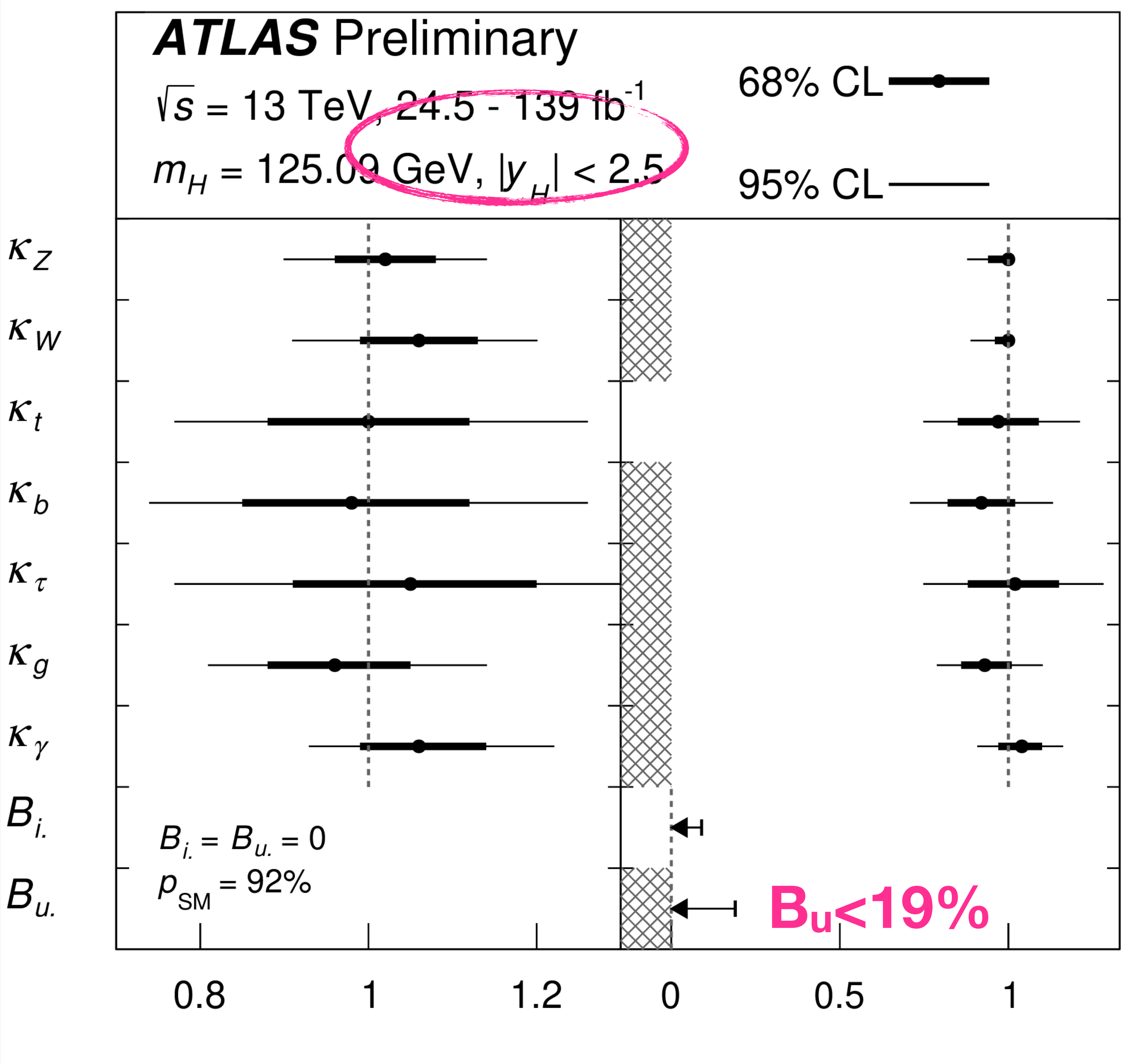
MOVING BEYOND THE SM



We have found and measured a Higgs boson with m_H=125 GeV
But do we really understand what it is, what it means, where it comes from?

CAN THE HIGGS BOSON DECAY “UNUSUALLY”?

- **Why should we assume the Higgs boson follow the SM rules strictly?**
- We can also **search for Higgs → BSM . eg: Dark Matter, LFV,light (pseudo)-scalars…**



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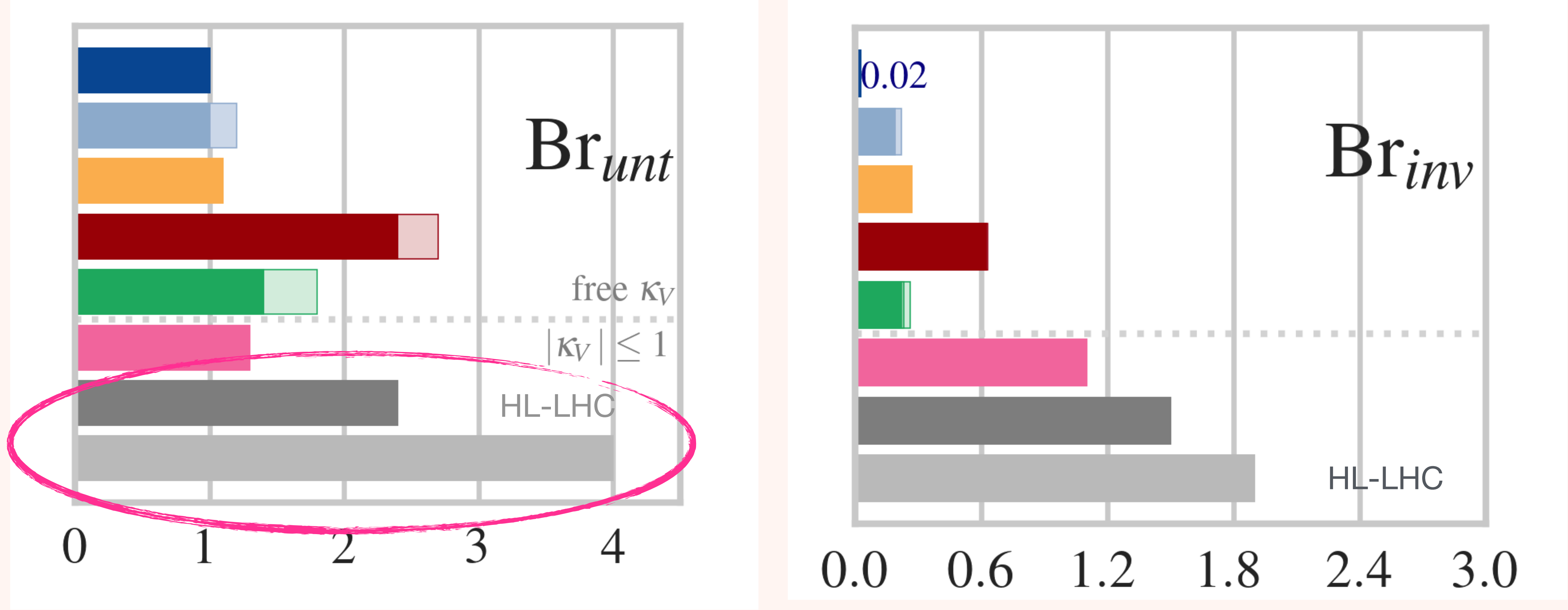
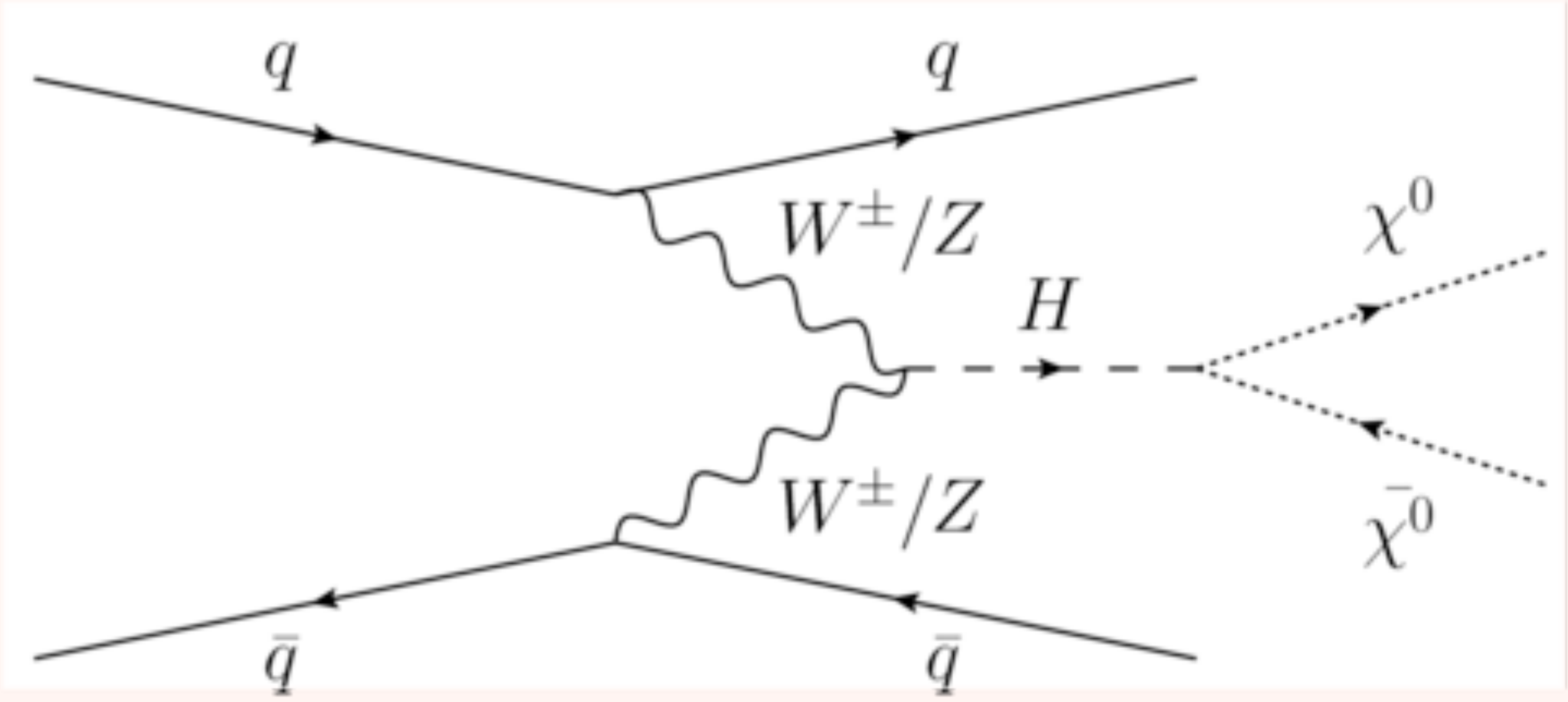


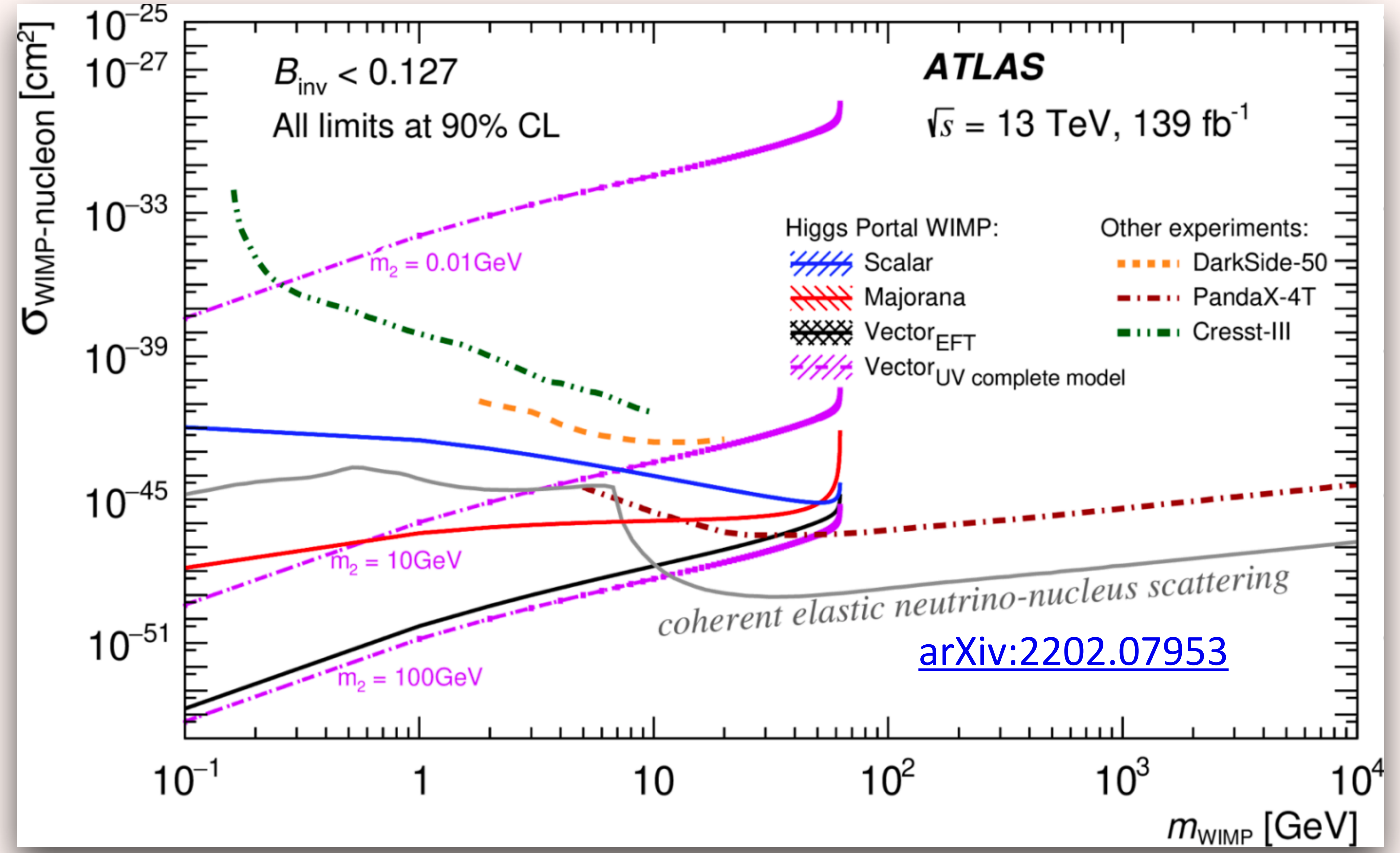
J. High Energ. Phys. 2020, 139 (2020)

$$\Gamma_H = \frac{\Gamma_H^{SM} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{undet})}$$

DOES THE HIGGS BOSON COUPLE TO DARK MATTER?



- Higgs → BSM particles?
- Direct searches for Higgs decays to **undetectable** particles ('invisible decays') → search for Dark Matter! (Higgs Portal)



Current Sensitivity:10% level (95%CL)

CMS: $Br(H_{inv}) < 0.18$ (0.10)
ATLAS: $Br(H_{inv}) < 0.145$ (0.103)

HIGGS INVISIBLE @ HL-LHC

Remember: Run2 sensitivity ~10% @ 95%CL (dominated by the VBF channel)

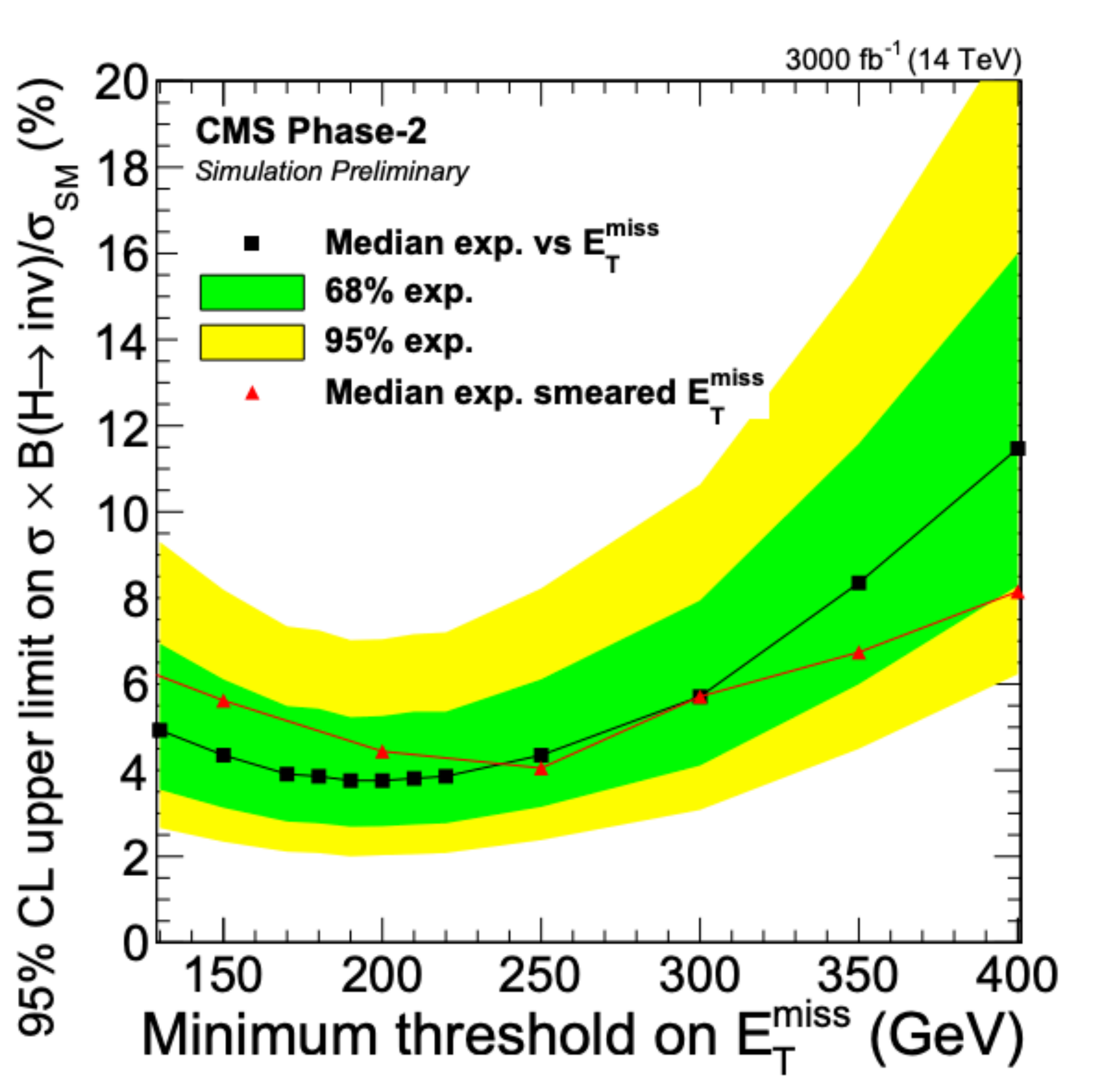
The challenge here is the high PU : the upgraded detectors will be instrumental

A Delphes analysis for the VBF analysis show that with optimisation, changing the MET thresholds, we can maintain the sensitivity

Adding H->Inv to the global coupling fit: limit better than 2% @ 95 %CL (ATLAS+CMS)

VH: ATLAS, 2013: <8% @ 95%CL
VBF: CMS, 2018: <3.8% @ 95%CL

$$(\mu_{\mathrm{VBF},VH} \cdot \mathrm{BR}_{\mathrm{inv}})^{\mathrm{HL\text{-}LHC}} \leq 2.5\%,$$

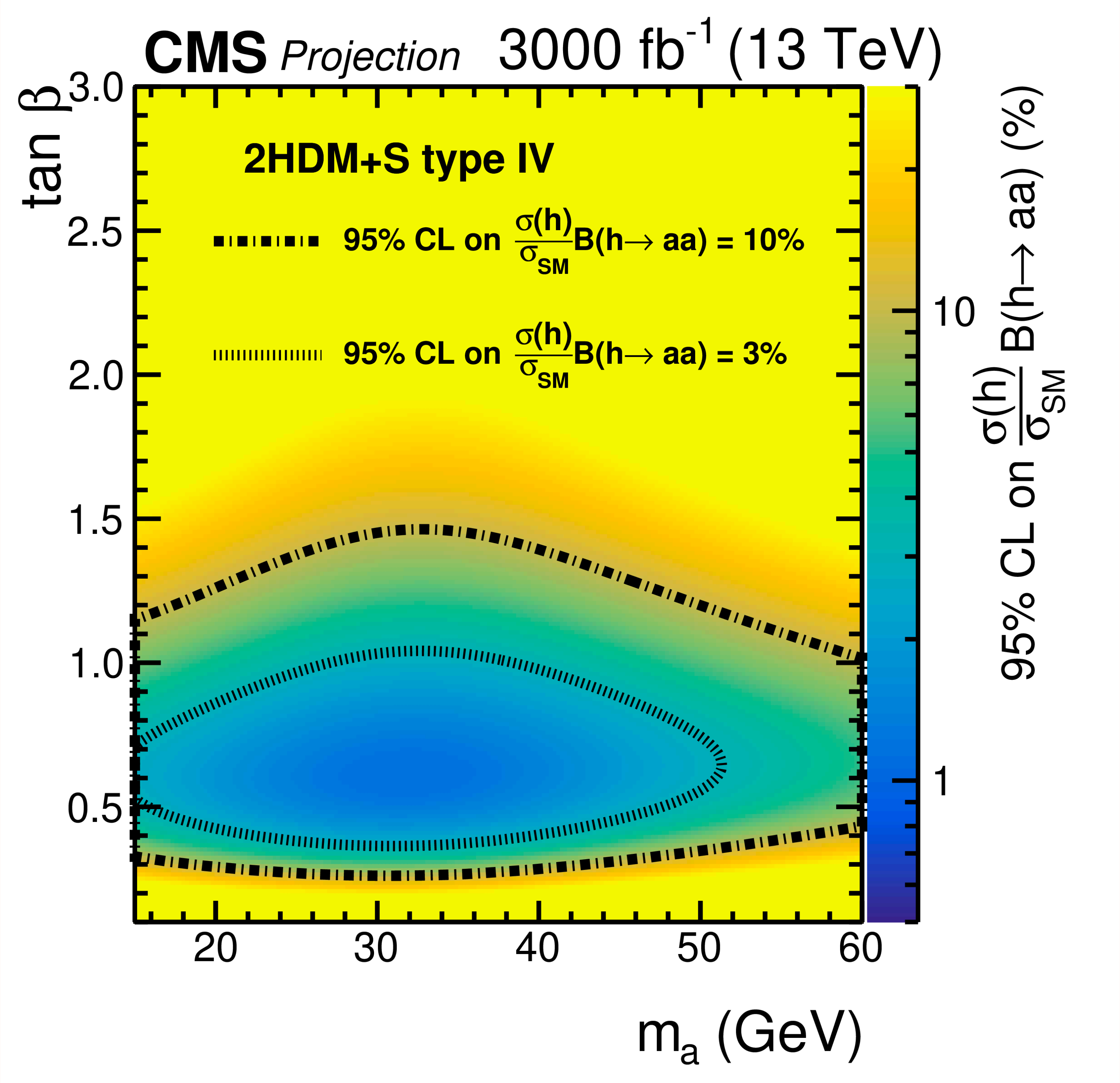


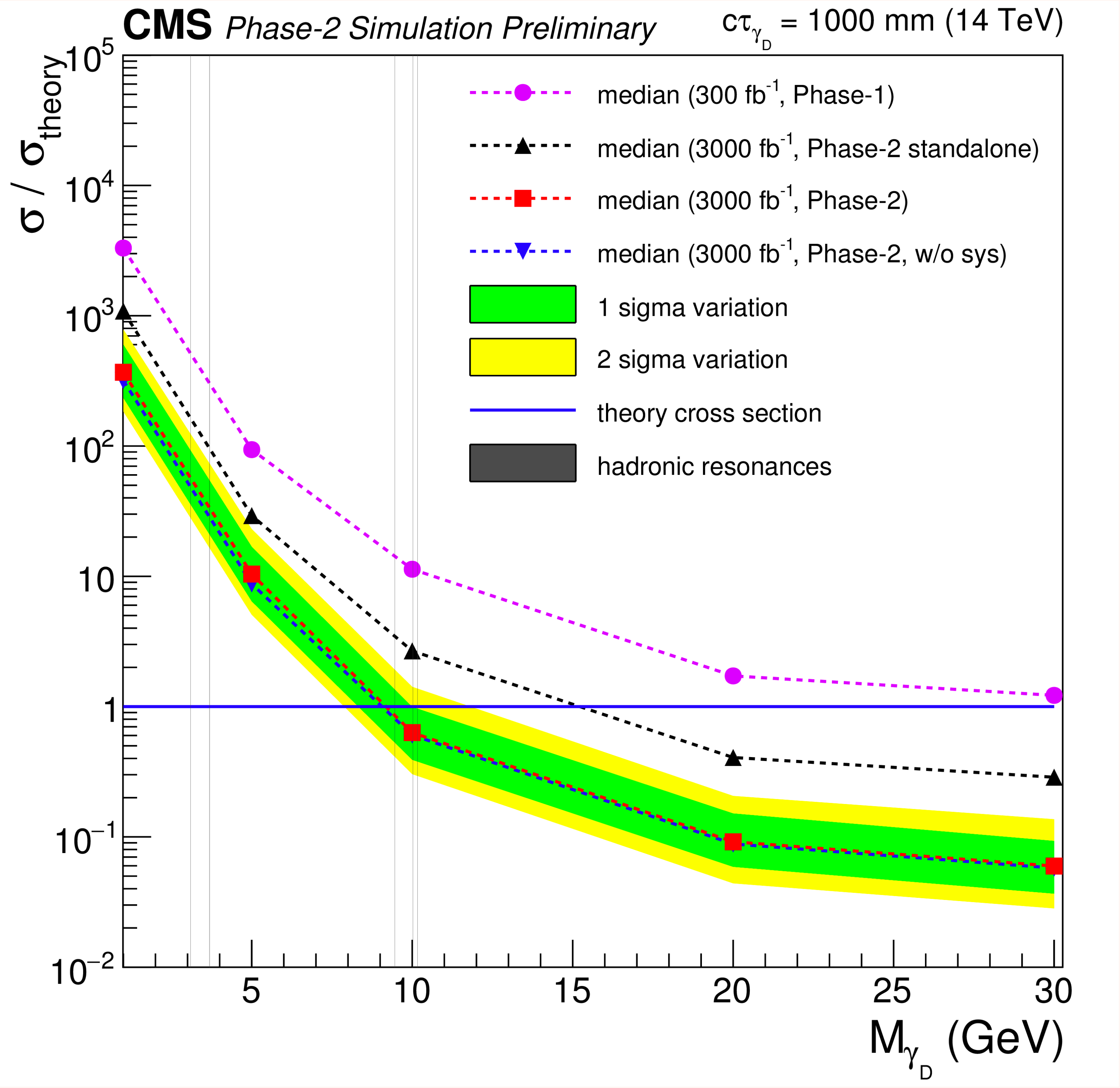
OTHER EXOTIC HIGGS DECAYS

Exotic Higgs decays beyond invisible, LFV, new (pseudo)scalars, LLP, dark photons, ALPs,…

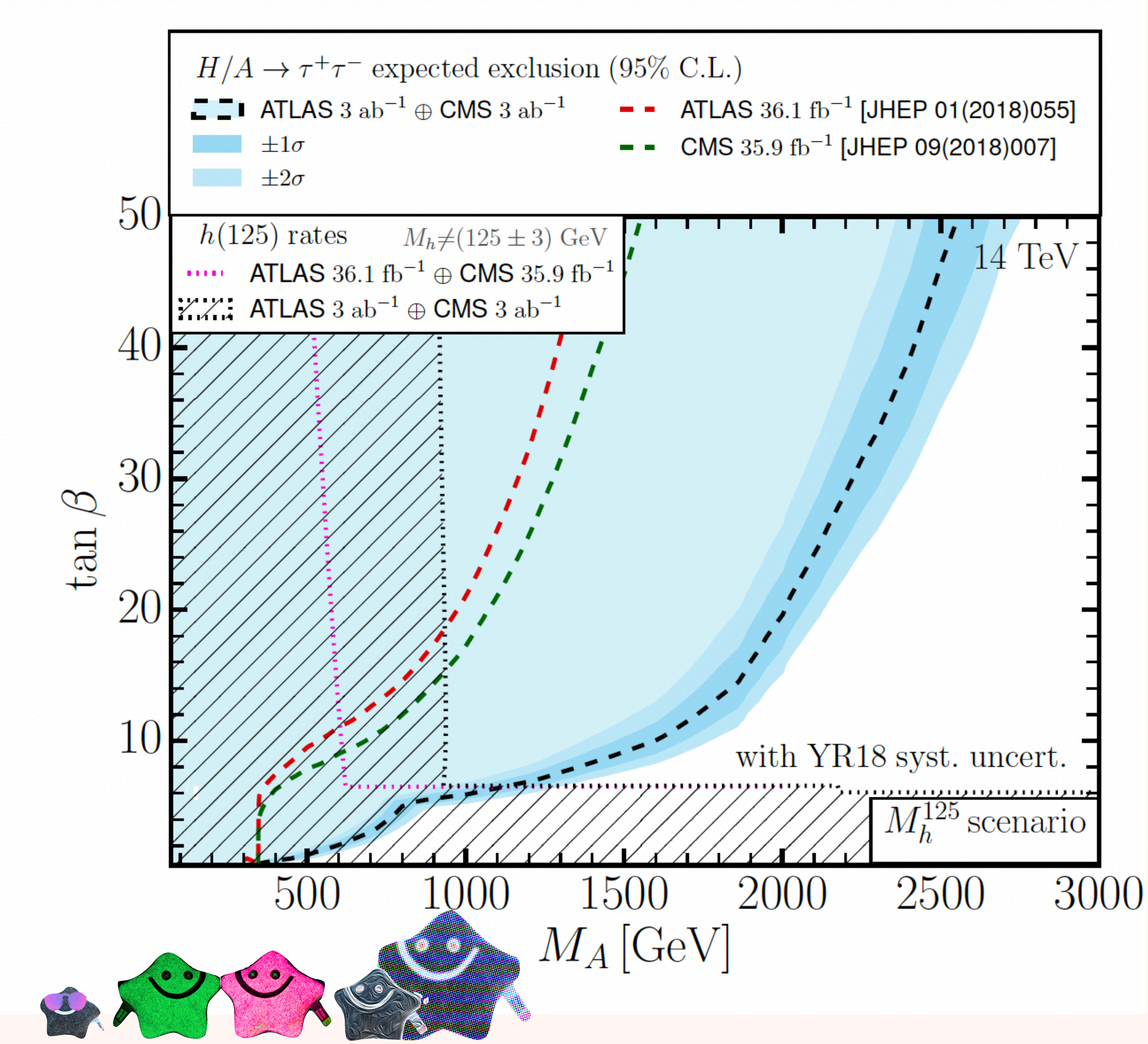
Huge phase space to probe, analysis typically limited by statistics… however very few available projections

Large potential gain from detector upgrades: track triggers, timing, long lived decays





EXTENDED HIGGS SECTORS

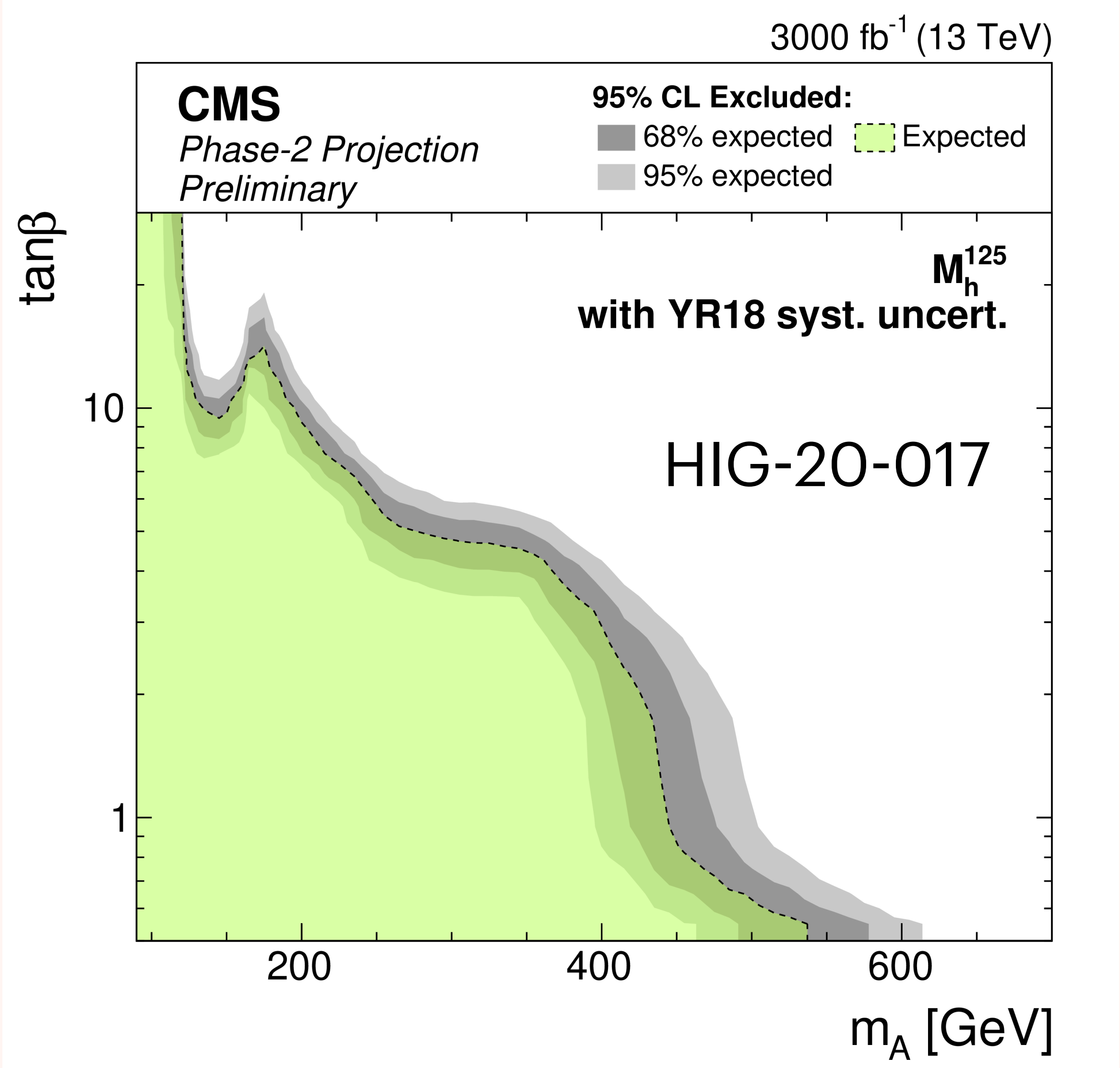


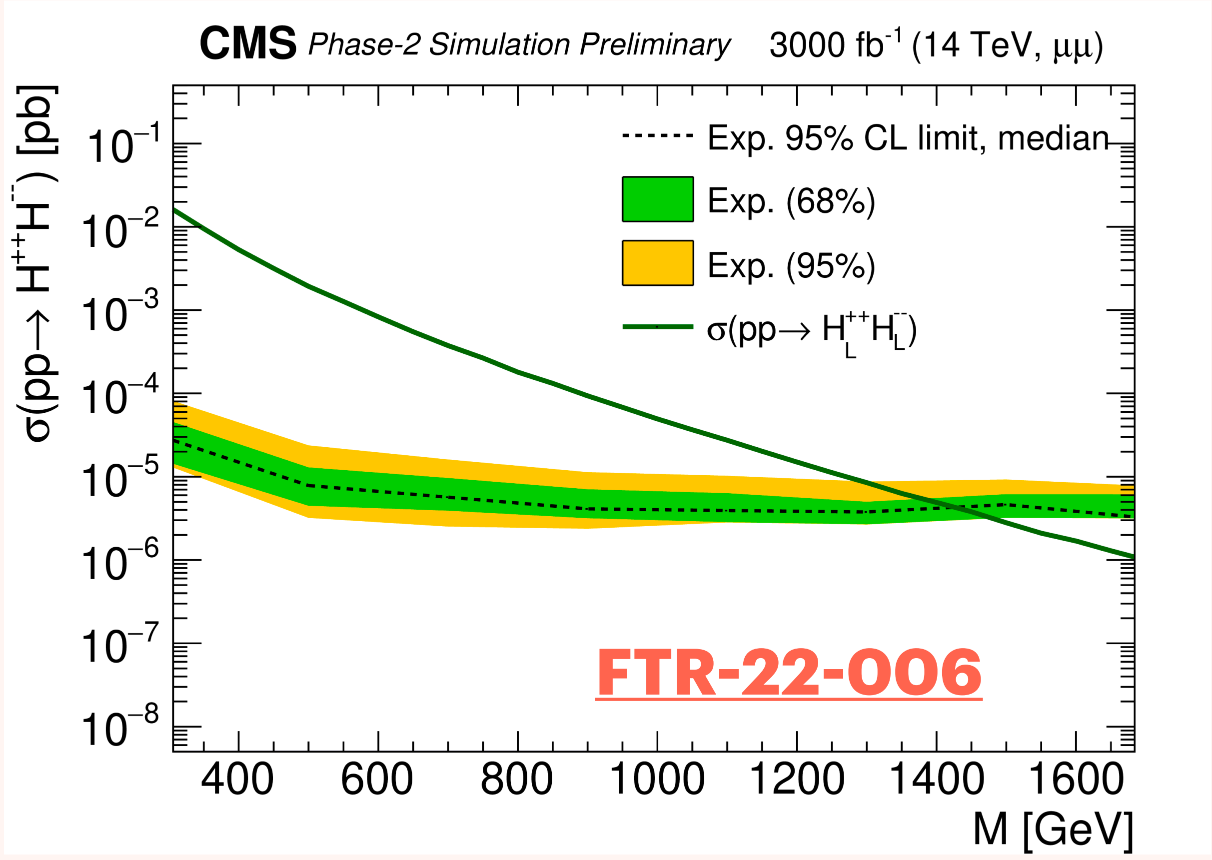
Is the Higgs alone?

Many different topologies and models to explore, from 2HDM onwards

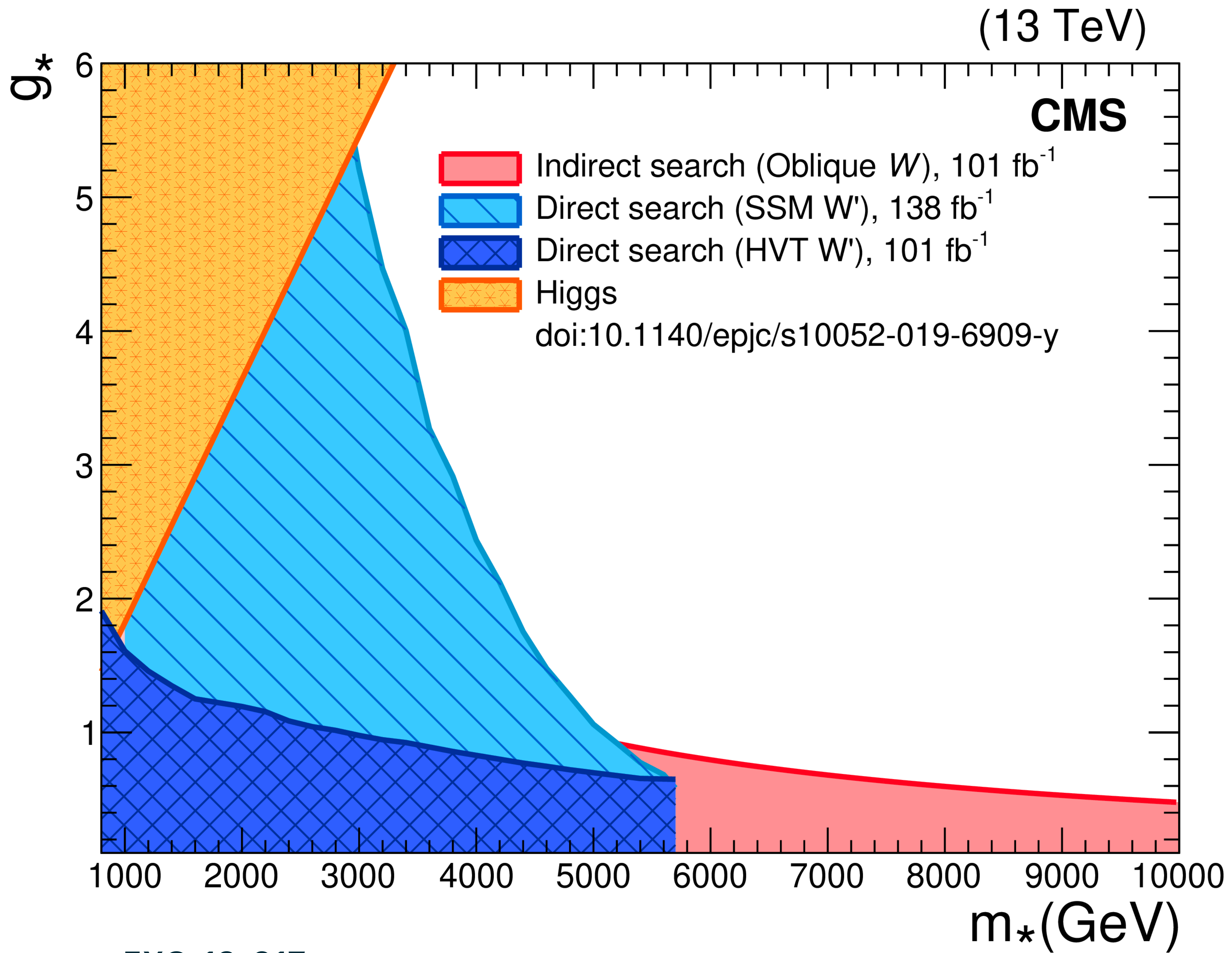
Model independent searches (for any sign of a new Higgs-like particle) combined with model dependent interpretations

Very wide landscape of searches beyond the ττ benchmark, large potential gain from the very large HL dataset : the large statistics will allow us too explore the high mass range in depth





IS THE HIGGS BOSON COMPOSITE?



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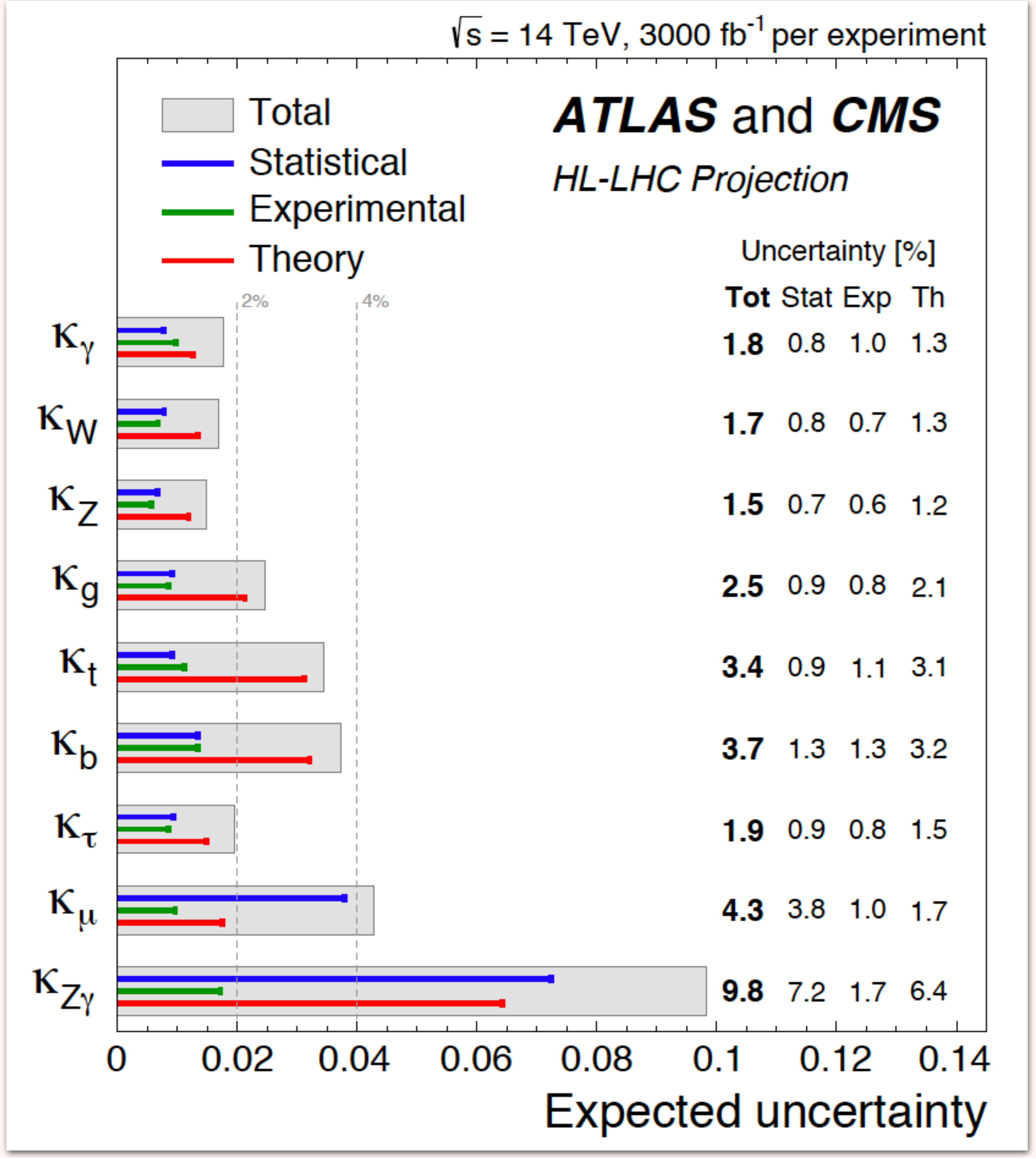
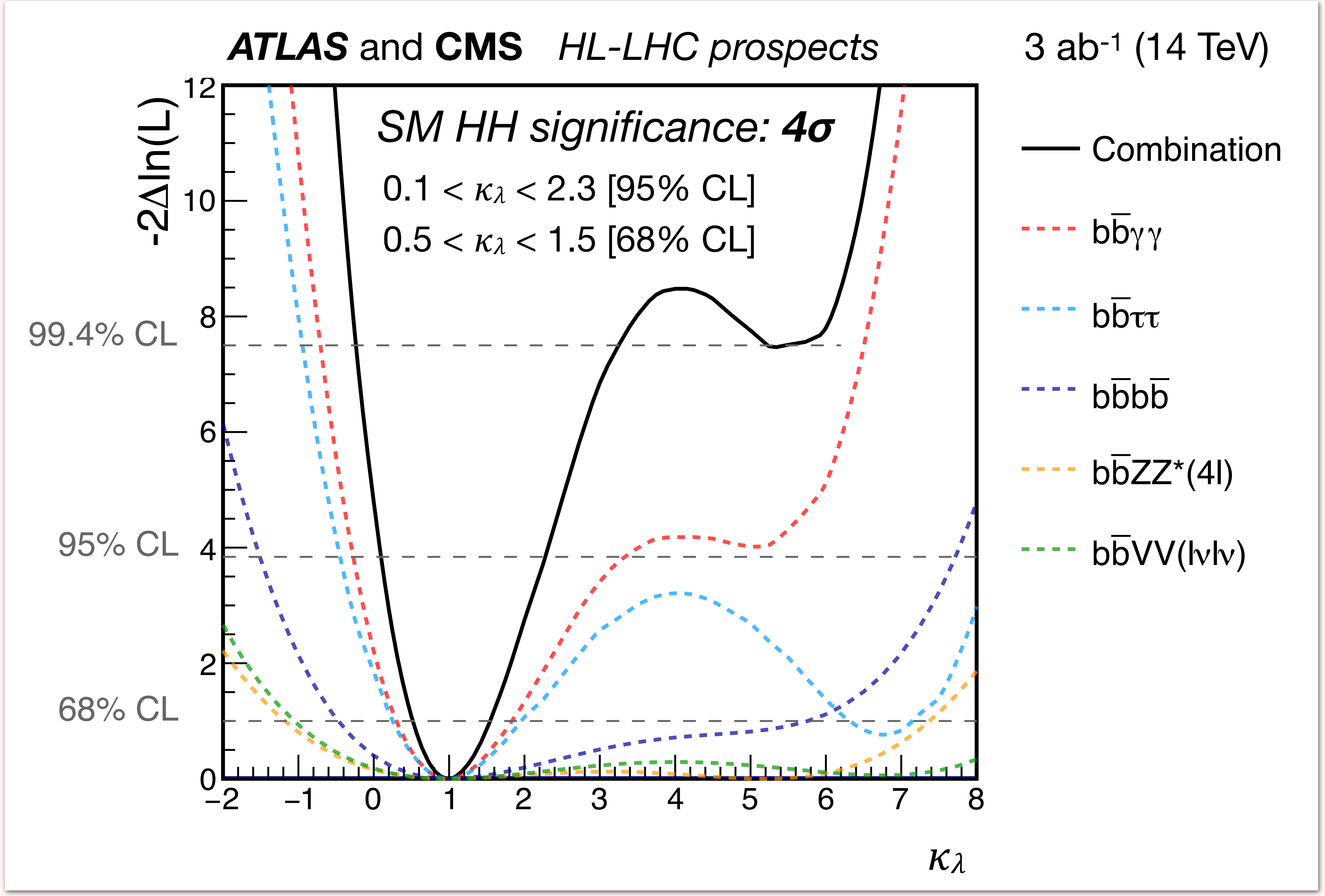
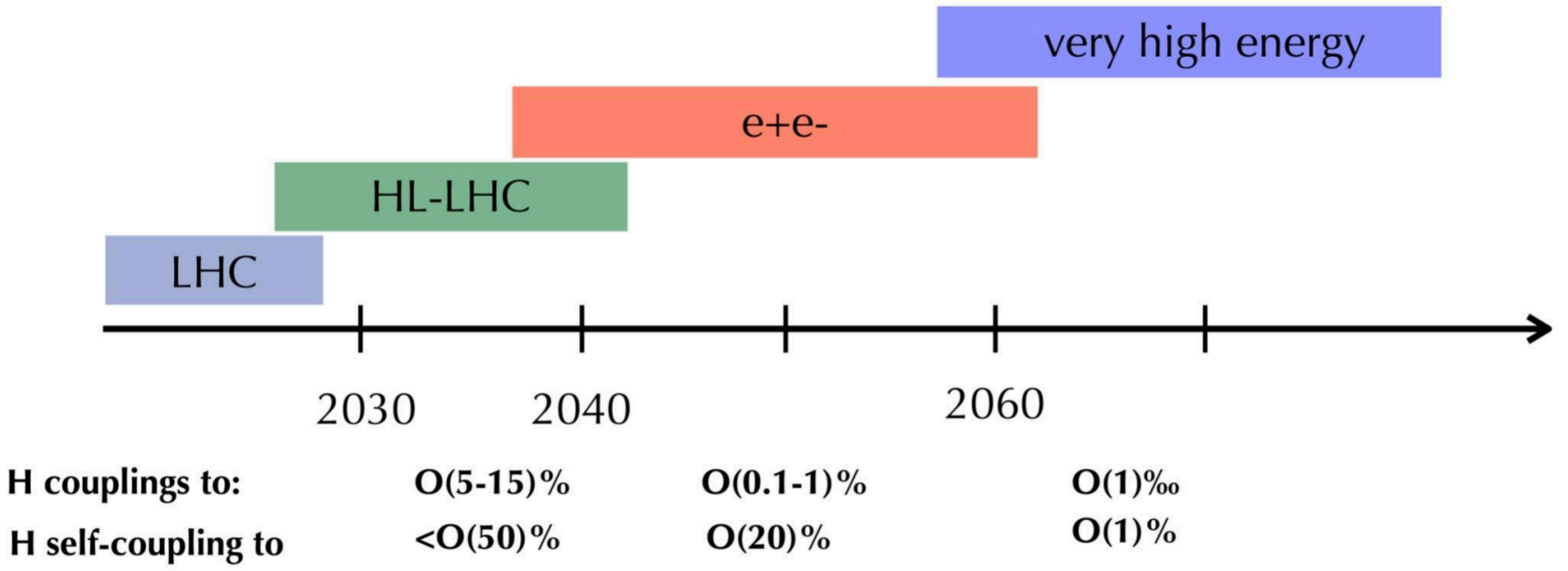
BEYOND THE LHC

HIGGS AT THE END OF THE HL-LHC



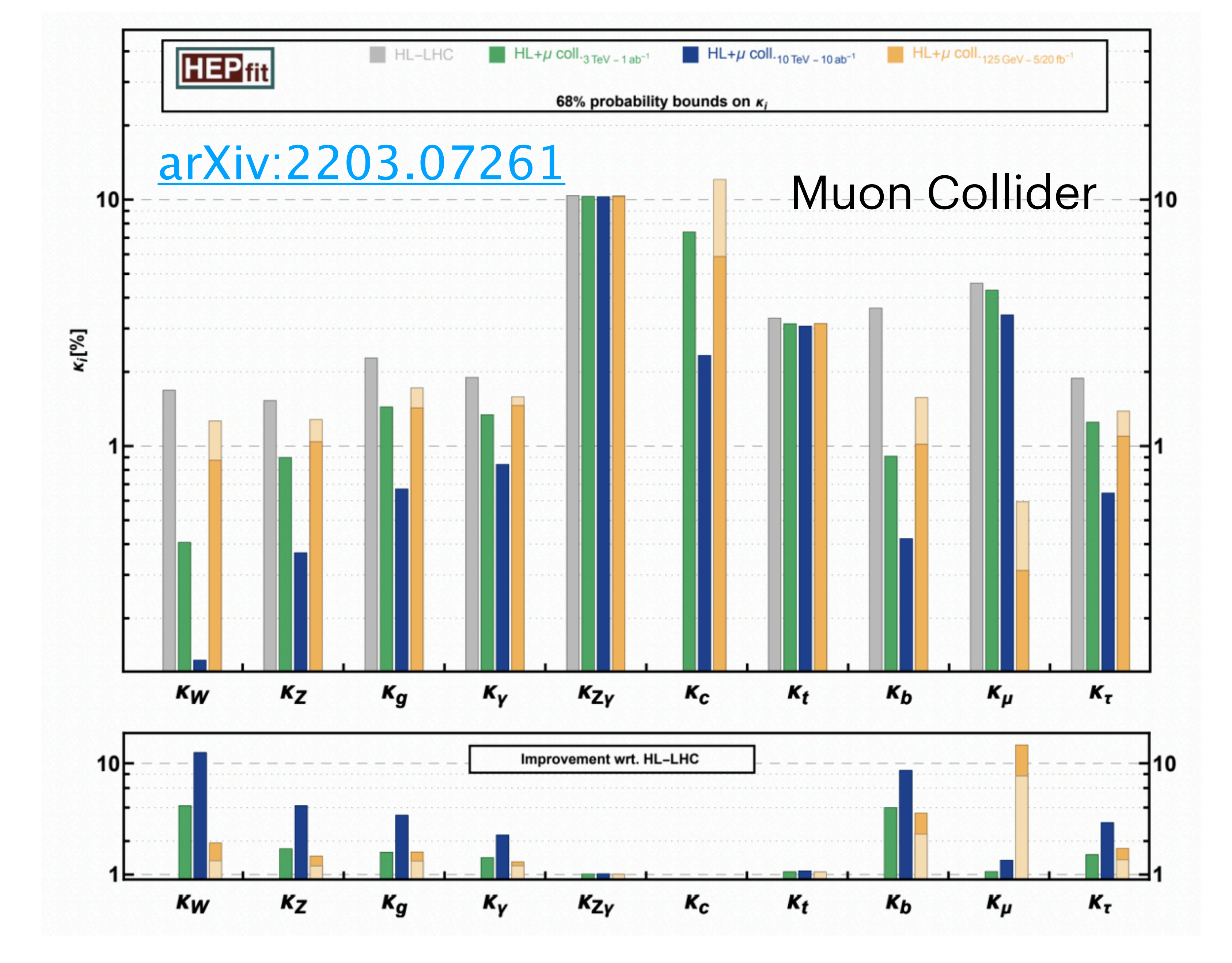


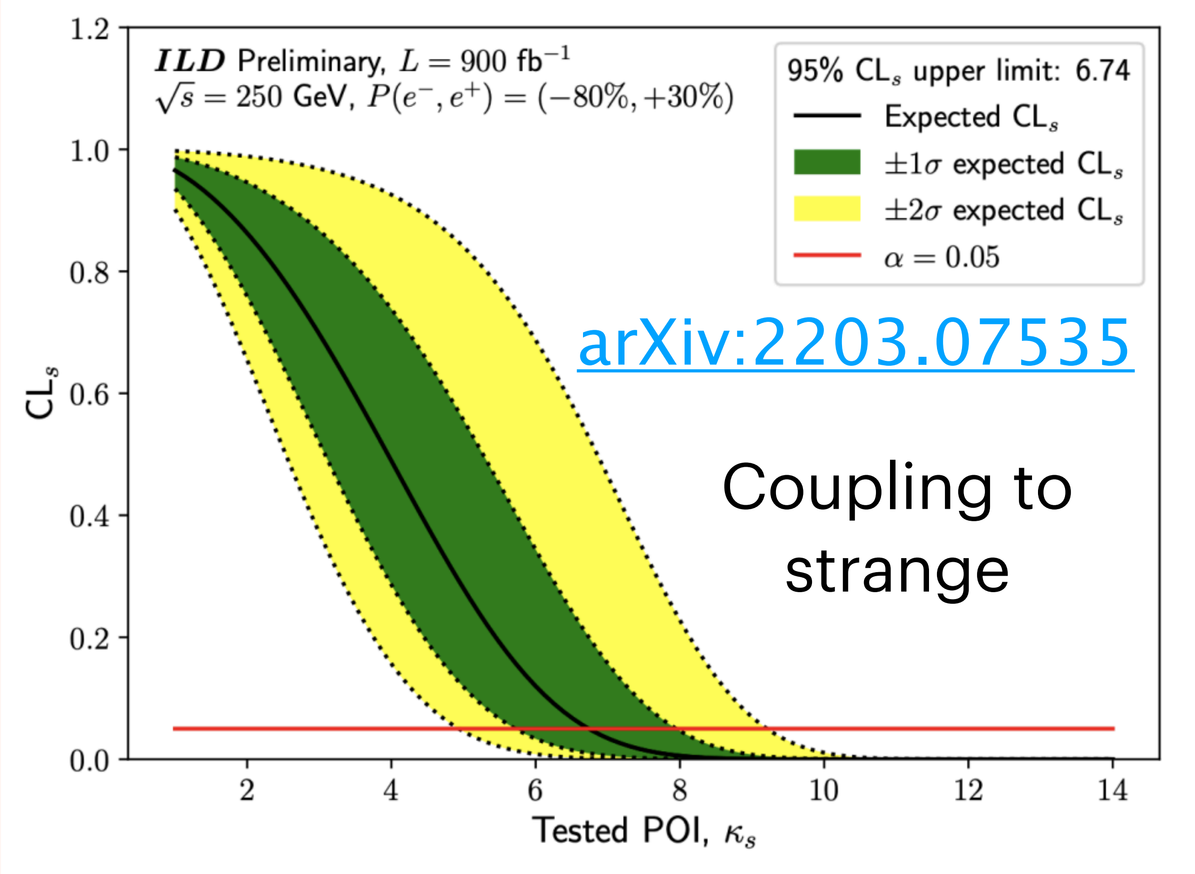
BEYOND HL-LHC

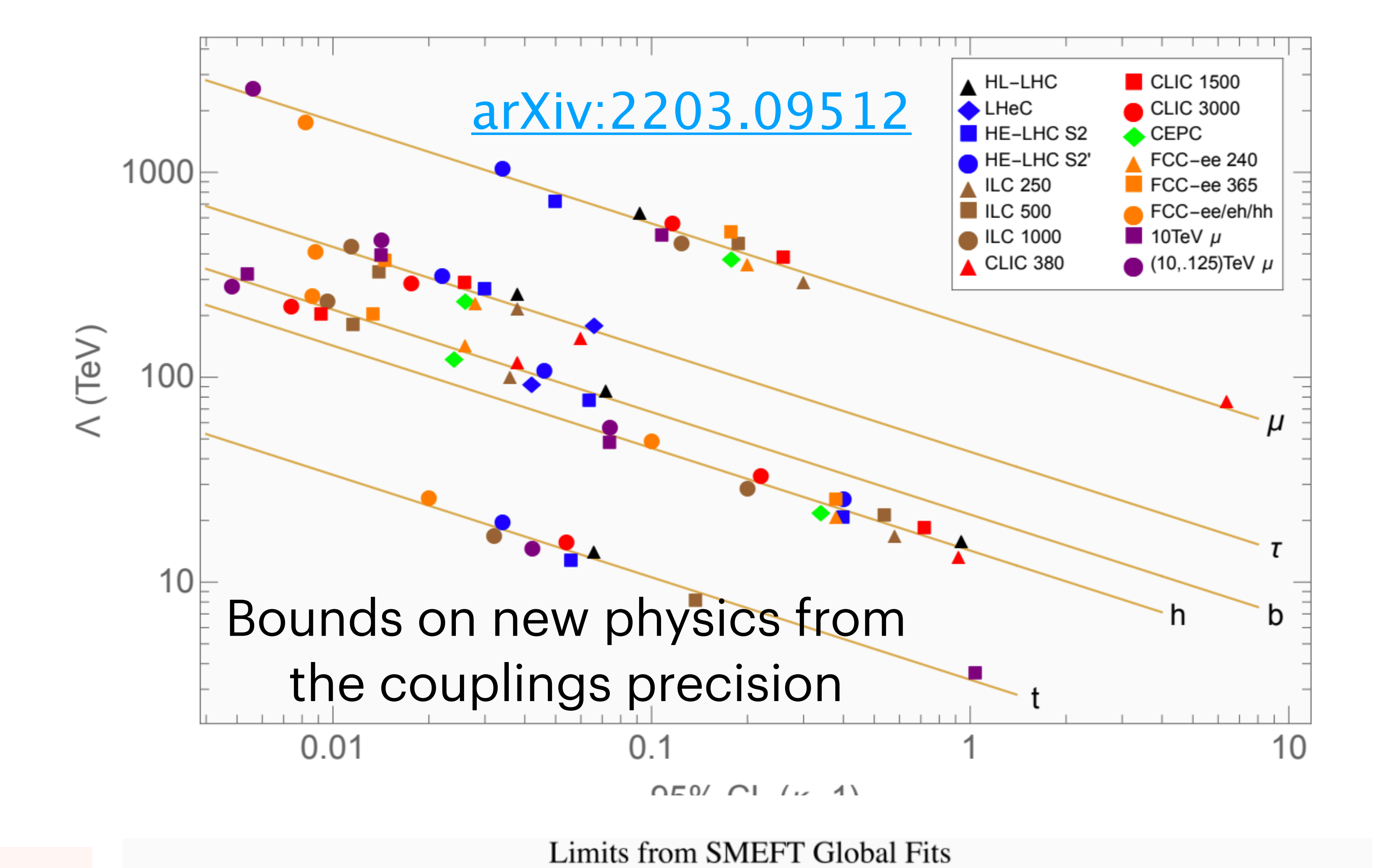


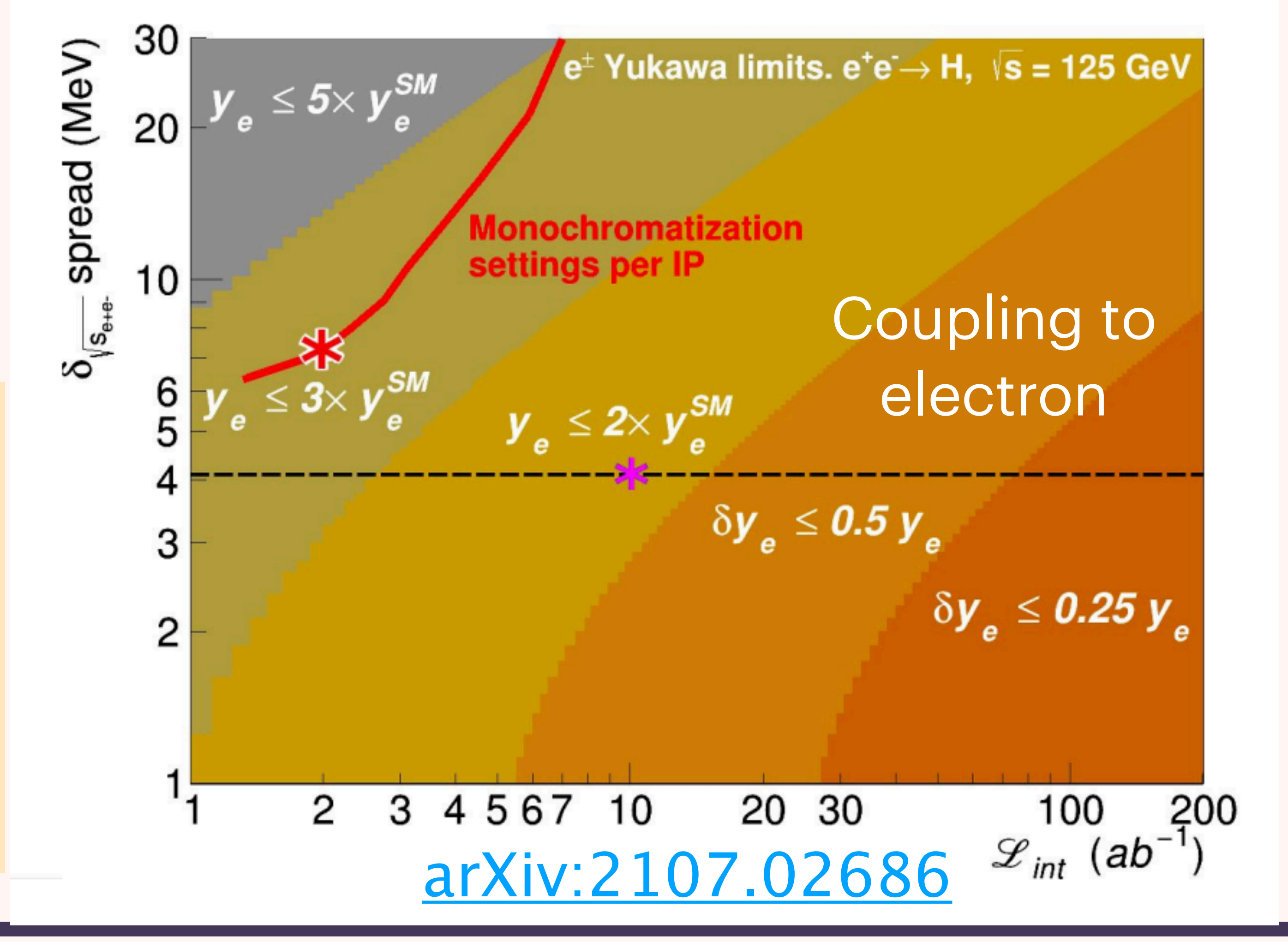
From C. Vernieri - EF Workshop - Brown U. - March 2022

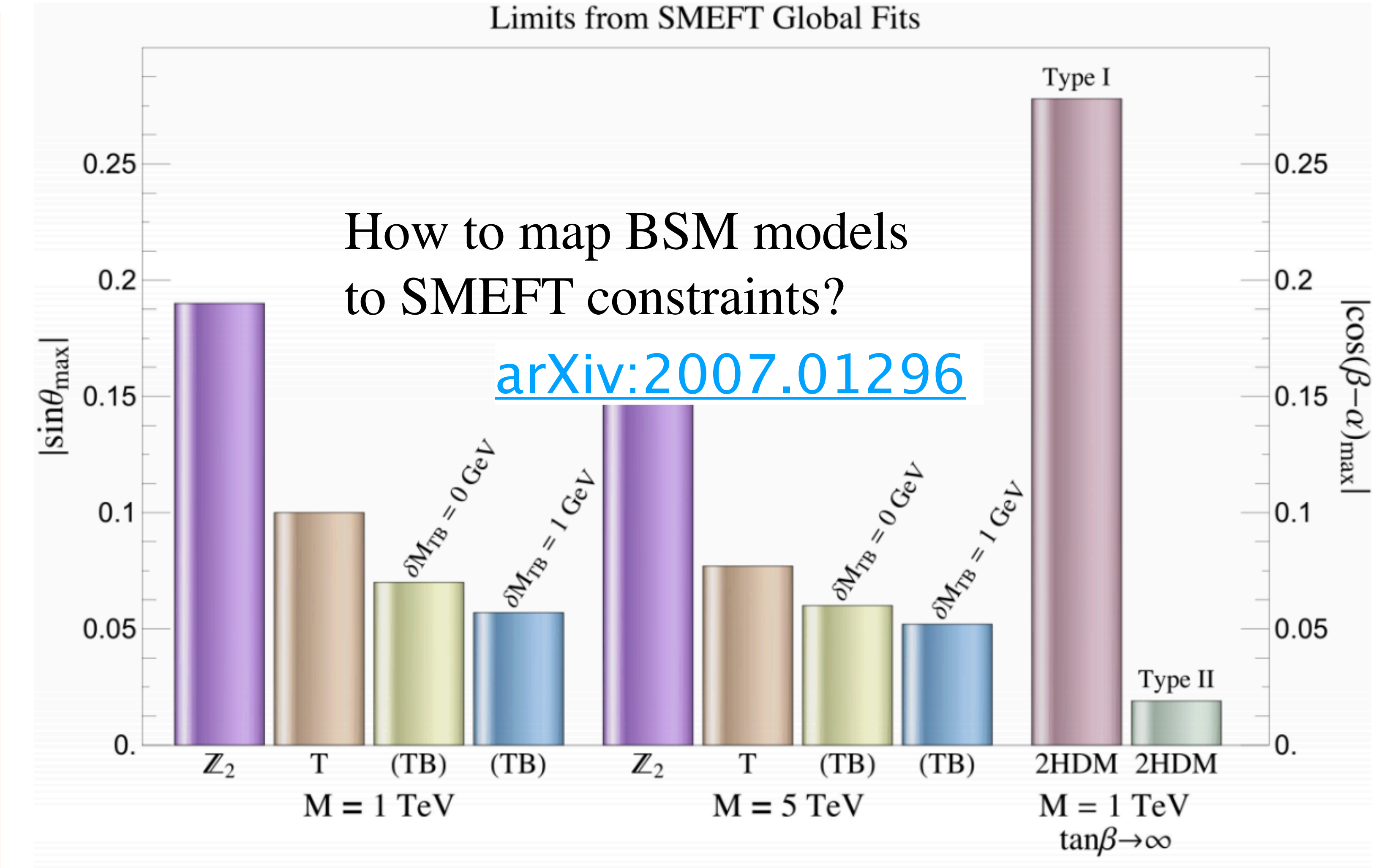
THE FUTURE IS BRIGHT











Examples taken from the summary talks at the Snowmass EF workshop: https://indico.fnal.gov/event/52465/ and Laura Reina's talk at SM@LHC

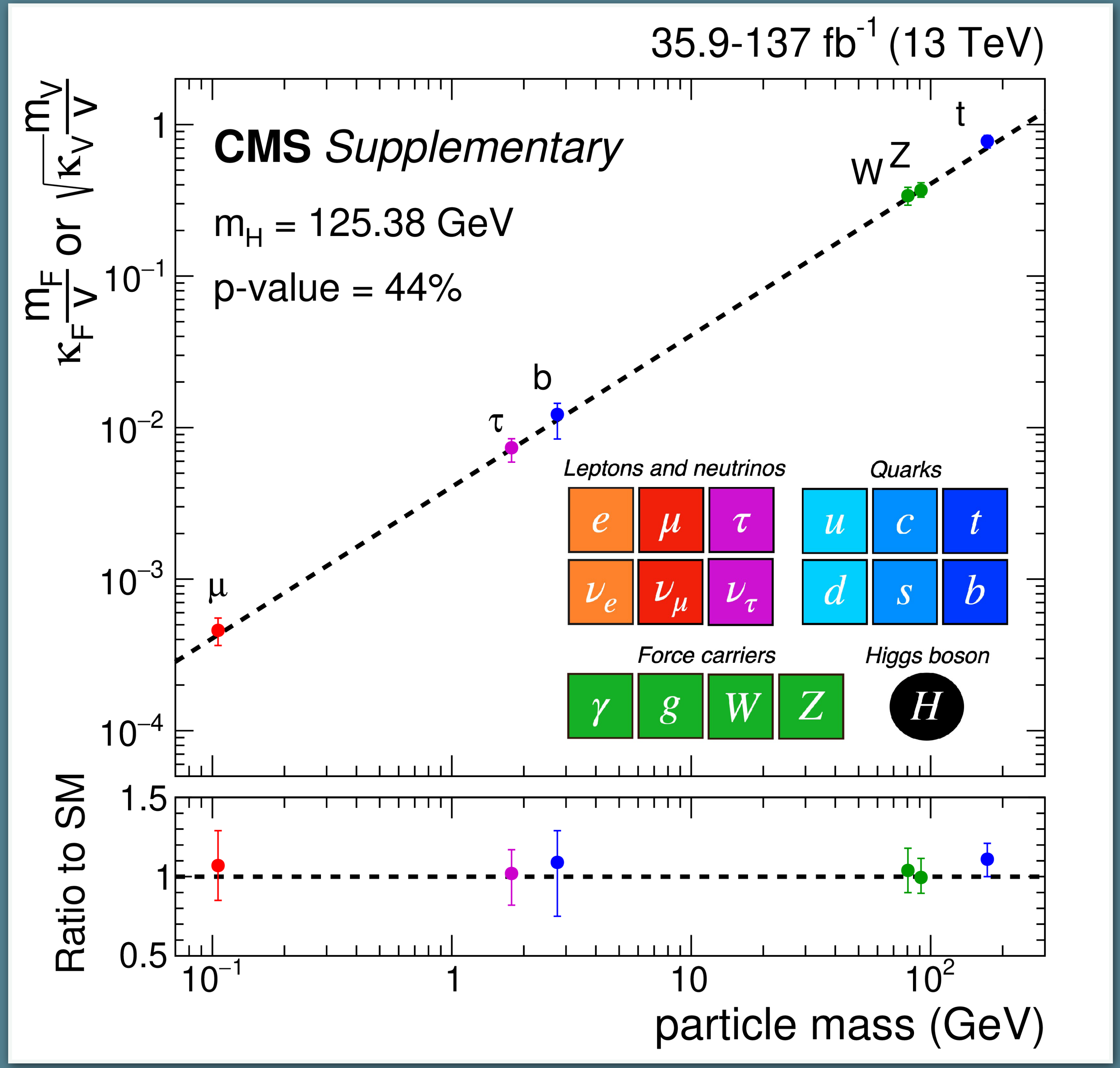
CONCLUSIONS

- In 2012 we knew we had found a new particle that looked like the Higgs boson, but we did not yet know what it was

- 10 years later, we have measured its properties, observed it couple to bosons and fermions, and studied of its kinematics with increasing precision. It is now one of our best tools to understand the standard model and go beyond. We have a lot of work ahead.

- It is a Higgs Boson, but is it really the one and only SM Higgs boson? Do we understand what it is, what it implies for the universe? Measuring precisely its properties is one of the keys to the unknown BSM realm, and one of the main goals of experimental particle physics today

- We have only explored a very small fraction of the full LHC dataset, we have a lot of work and data ahead to understand the particle properly



CMS and ATLAS Higgs results:

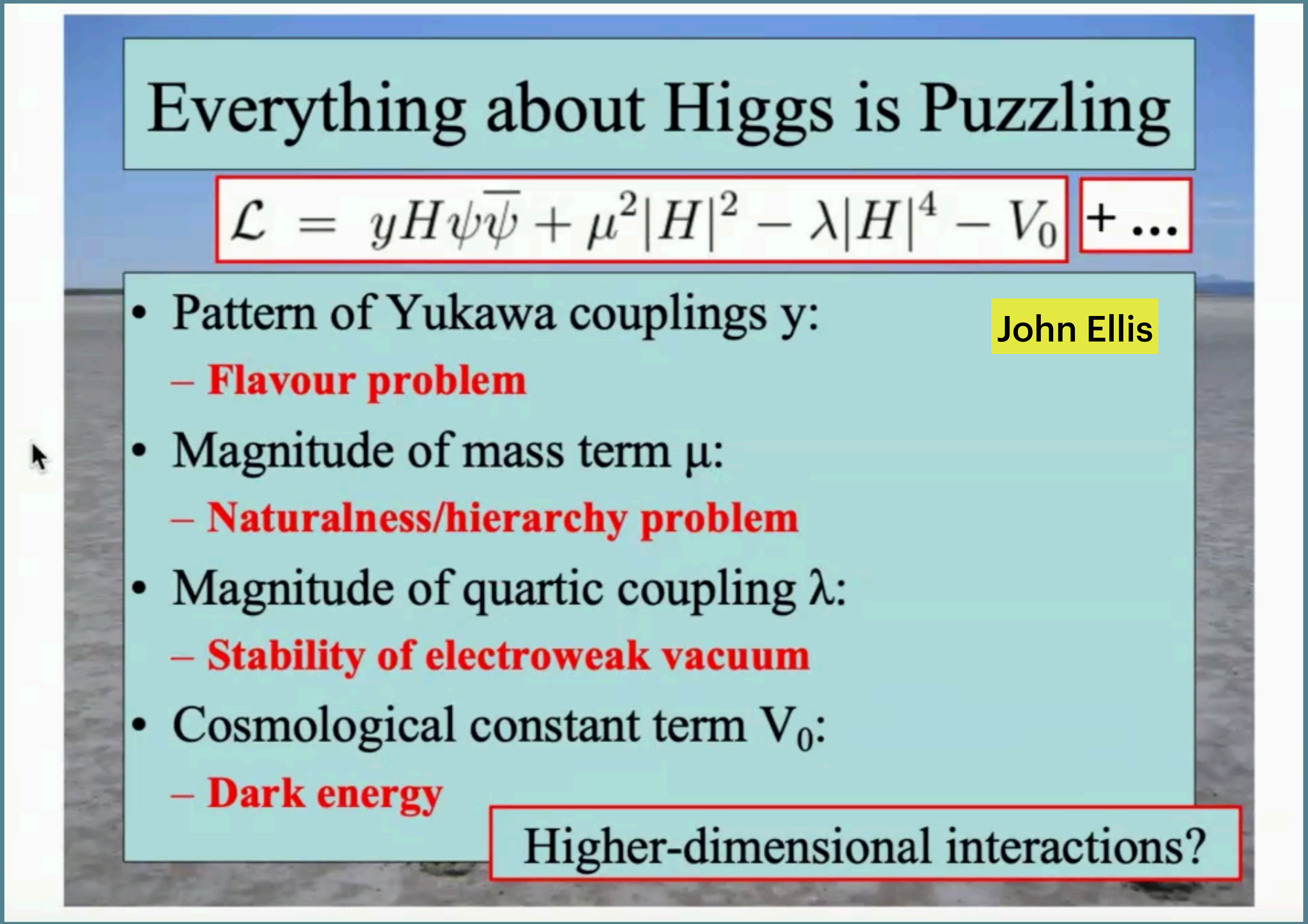
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HDBSPublicResults

European Strategy Yellow Report 2018: CERN-LPCC-2018-04

Snowmass 21 White Paper



- Many questions ahead: ATLAS and CMS will continue puzzle-solving during Run3 and the HL-LHC
- The next chapter of “Higgstory” awaits us

THANKS!