HIGGS @ HL-LHC

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

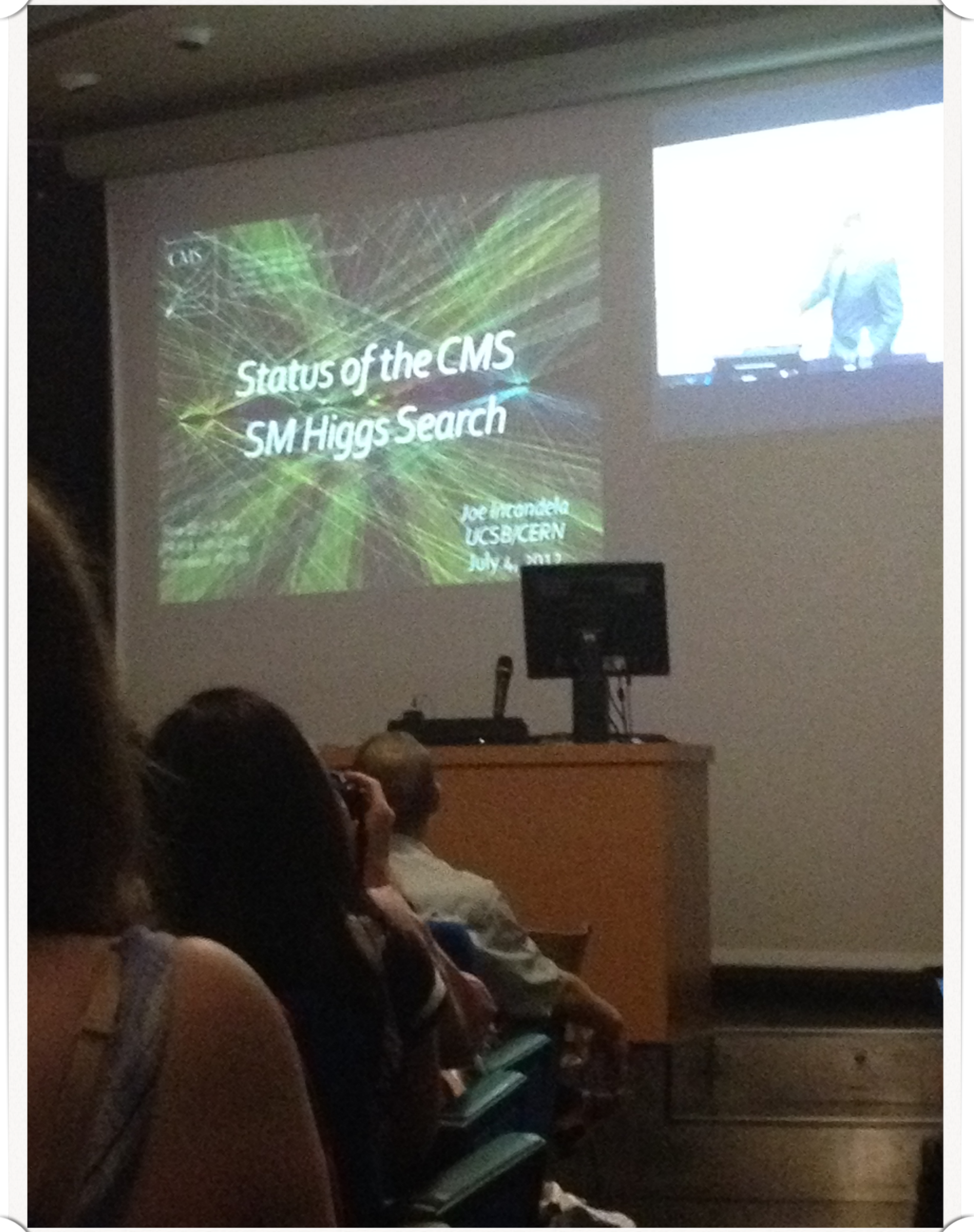
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

cfp CIEMAT física de partículas

Higgs@10 Symposium
Birmingham, 1st July 2022

ATLAS EXPERIMENT

CMS



- An impossible task: reminiscing about the future...
- And a challenge: in only 10 years, we have far surpassed the expectations: ATLAS and CMS have gone from Higgs hunters to Higgs tamers. What is our future as Higgs farmers?

RUN3 ABOUT TO START…

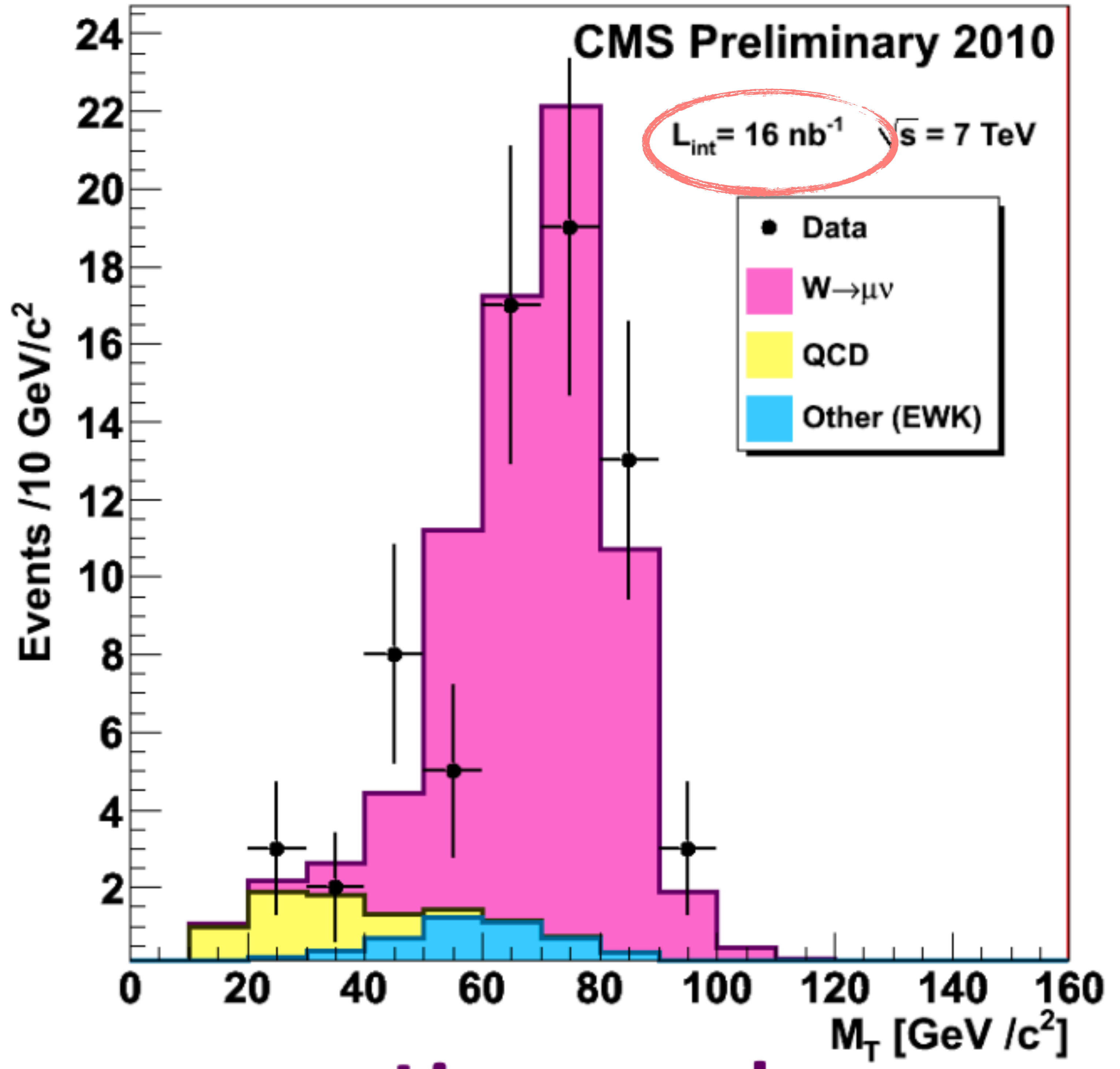
2009

CMS collaborators at CERN are invited to follow these exciting events, all together with ATLAS, on big screens in the atrium of B40.

*** Please do not go to P5 or the CMS Centre, Meyrin. ***
*** Access will be strictly restricted to people in shift and ***
*** colleagues needed for the organization of the activities. ***

We hope you will understand the complex logistics situation of the day.

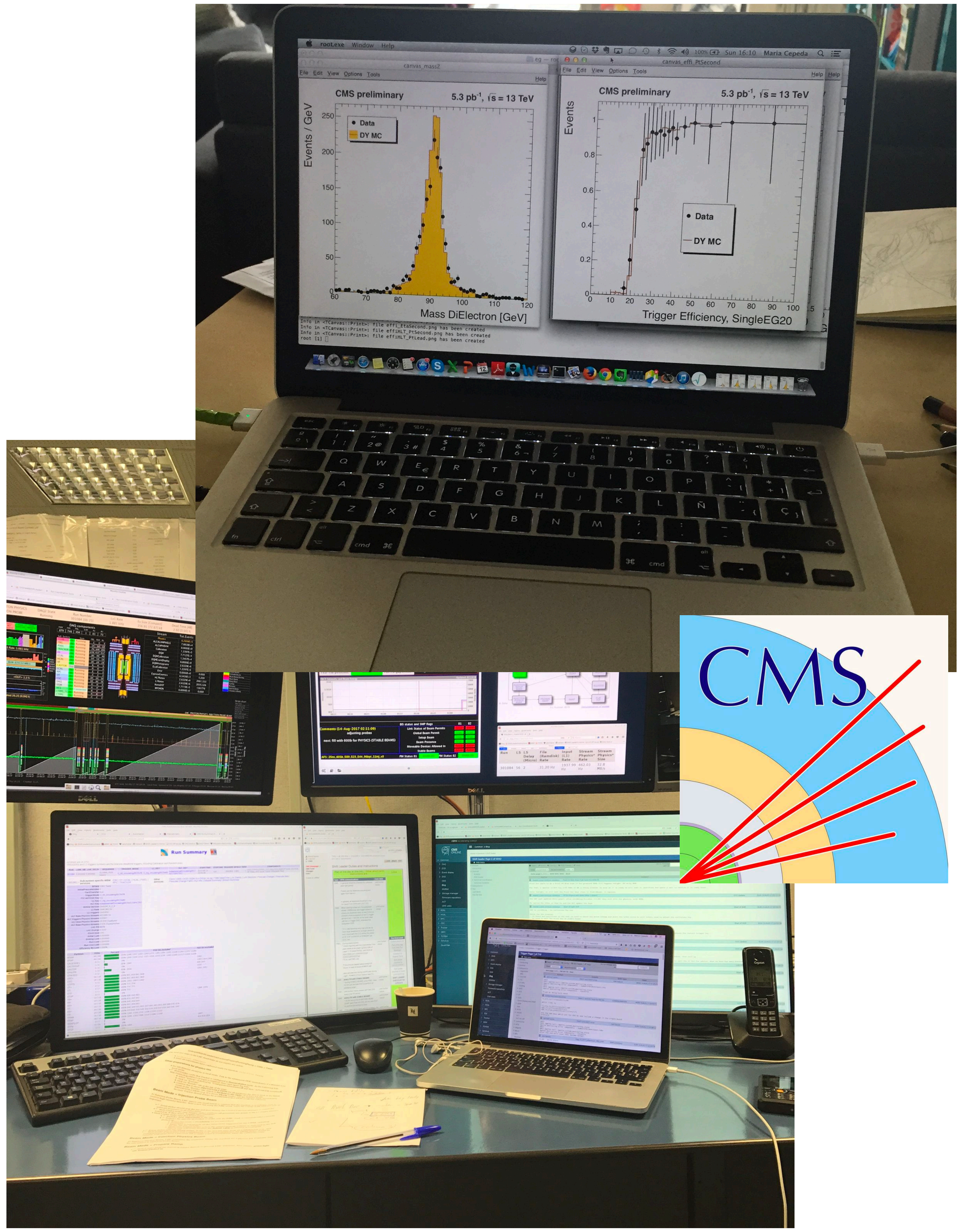
Jun 2010



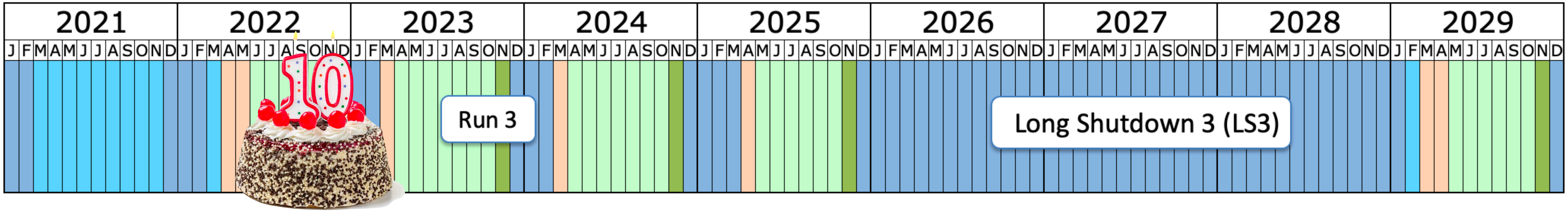
Linear scale

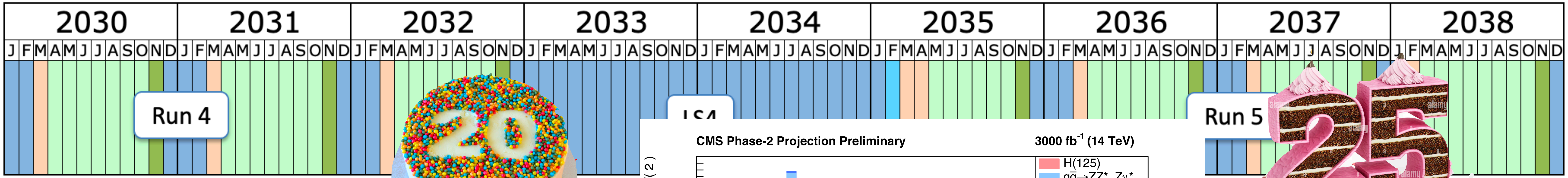
With M_T > 50 GeV: 57 events

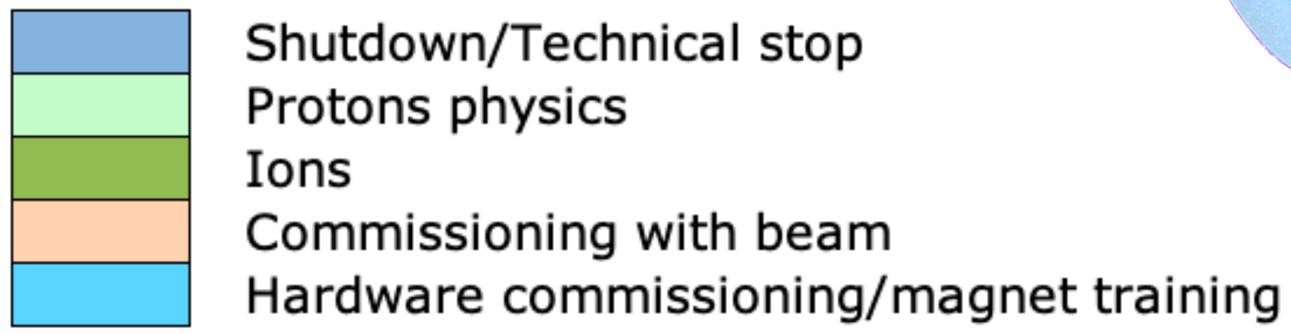
2015

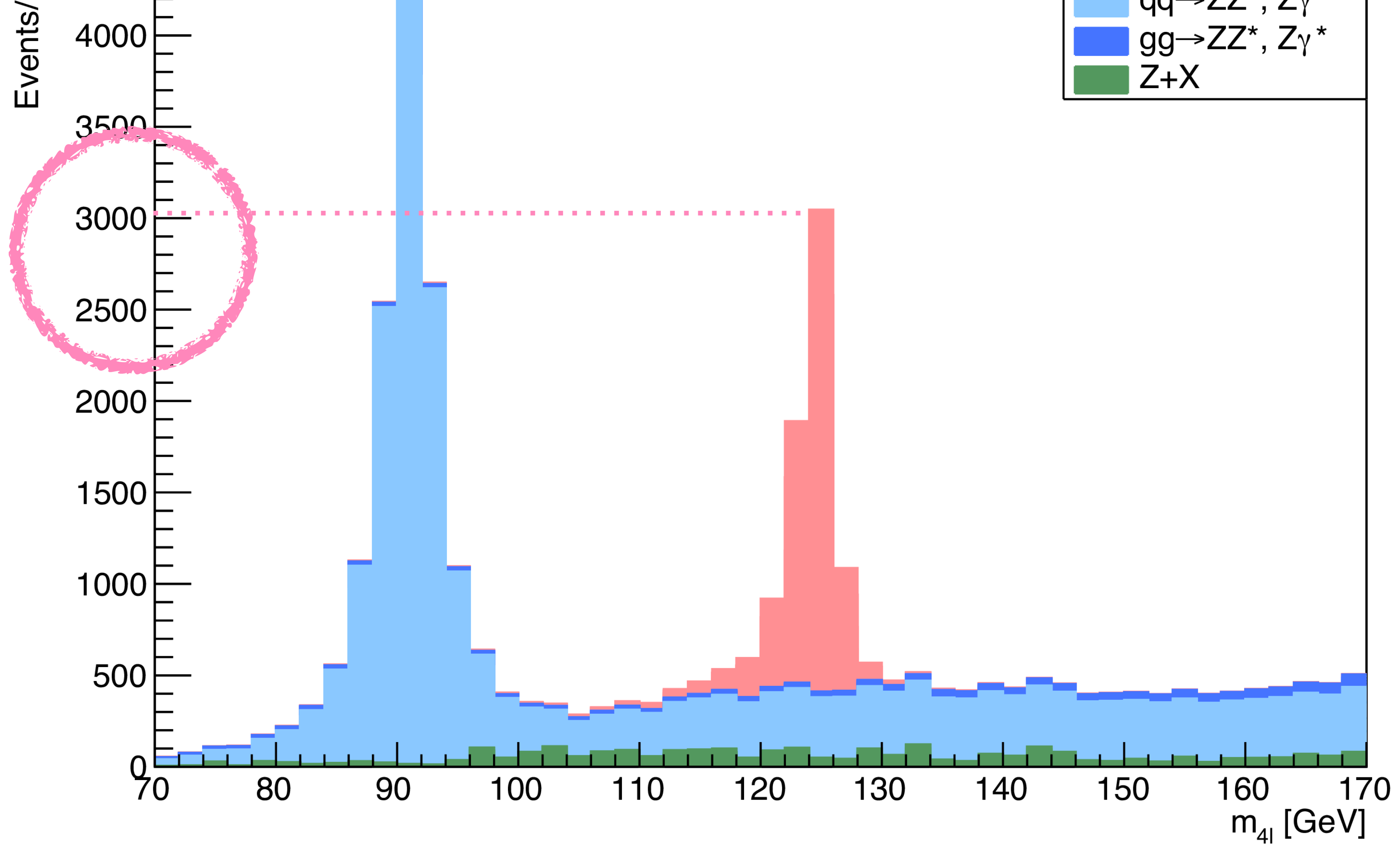


WHAT WILL WE CELEBRATE BY HIGGS@25?









250M Higgses by the end...

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 AND THE HL-LHC ERA WILL BE FUNDAMENTAL IN CHARACTERISING THE HIGGS BOSON

Higgs @ HL-LHC

What do we need to know? Where will the HL-LHC impact?

- **Precision Measurements** (Couplings to ~5%, Cross Sections, Differential Distributions, Width…)
- **Rare decays**
- **Di-Higgs production ➜** self coupling
- **BSM Higgs searches** (extra scalars, BSM Higgs resonances, exotic decays, anomalous couplings)

Higgs @ HL-LHC

What do we need to know? Where will the HL-LHC impact?

- **Precision Measurements** (Couplings to ~5%, Cross Sections, Differential Distributions, Width…)
- **Rare decays**
- **Di-Higgs production** ➜ self coupling
- **BSM Higgs searches** (extra scalars, BSM Higgs resonances, exotic decays, anomalous couplings)

4

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

30 Oct 2017, 09:00 → 1 Nov 2017, 19:00 Europe/Zurich

500/1-001 - Main Auditorium (CERN)

Aleandro Nisati (Sapienza Universita e INFN, Roma I (IT)), Andrea Dainese (INFN - Padova (IT)), Andreas Meyer (KIT and DESY (DE)), Gavin Salam (CERN), Michelangelo Mangano (CERN), Mika Anton Vesterinen (University of Oxford (UK))

Description

This is the kickoff event for a series of meetings, running throughout 2018, with plenary events and intermediate periods of working group activities.

The main goal of the Workshop is to review, extend and further refine our understanding of the physics potential of the High Luminosity LHC. The workshop aims to stimulate new ideas for measurements and observables, to extend the LHC discovery reach, to improve the modeling of LHC phenomena towards measurements at ultimate precision, and to prepare to exploit the HL-LHC data to the fullest possible extent.

The Workshop will also provide the opportunity to begin a more systematic study of physics at the HE-LHC, a new pp collider in the LHC ring with CM energy in the range of 27 TeV.

The activity of the Workshop will extend over a one year period, driven by working groups covering the following areas:

1. **QCD, EW and top quark physics**
2. **Higgs and EWSB**
3. **BSM**
4. **Flavour**
5. **Heavy Ions**

The results of the Workshop will be documented in a Yellow Report, to be completed in time (~end 2018) for submission to the next review of the European strategy for particle physics.

The deadline to reserve pre-booked rooms in the CERN Hostel has expired. To book a room, please contact directly the Hostel.

Ongoing work is being discussed on the wiki.

To join the mailing list of the Workshop, click *here*

Registration

You are registered for this event. 493 Modify registration

November 2017

Higgs @ HL-LHC

What do we need to know? Where will the HL-LHC impact?

- **Precision Measurements** (Couplings to ~5%, Cross Sections, Differential Distributions, Width…)
- **Rare decays**
- **Di-Higgs production** ➜ self coupling
- **BSM Higgs searches** (extra scalars, BSM Higgs resonances, exotic decays, anomalous couplings)

4

November 2017

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

30 Oct 2017, 09:00 → 1 Nov 2017, 19:00 Europe/Zurich

500/1-001 - Main Auditorium (CERN)

Aleandro Nisati (Sapienza Universita e INFN, Roma I (IT)), Andrea Dainese (INFN - Padova (IT)), Andreas Meyer (KIT and DESY (DE)), Gavin Salam (CERN), Michelangelo Mangano (CERN), Mika Anton Vesterinen (University of Oxford (UK))

Description: This is the kickoff event for a series of meetings, running throughout 2018, with plenary events and intermediate periods of working group activities.

The main goal of the Workshop is to review, extend and further refine our understanding of the physics potential of the High Luminosity LHC. The workshop aims to stimulate new ideas for measurements and observables, to extend the LHC discovery reach, to improve the modeling of LHC phenomena towards measurements at ultimate precision, and to prepare to exploit the HL-LHC data to the fullest possible extent.

The Workshop will also provide the opportunity to begin a more systematic study of physics at the HE-LHC, a new pp collider in the LHC ring with CM energy in the range of 27 TeV.

The activity of the Workshop will extend over a one year period, driven by working groups covering the following areas:

1. **QCD, EW and top quark physics**
2. **Higgs and EWSB**
3. **BSM**
4. **Flavour**
5. **Heavy Ions**

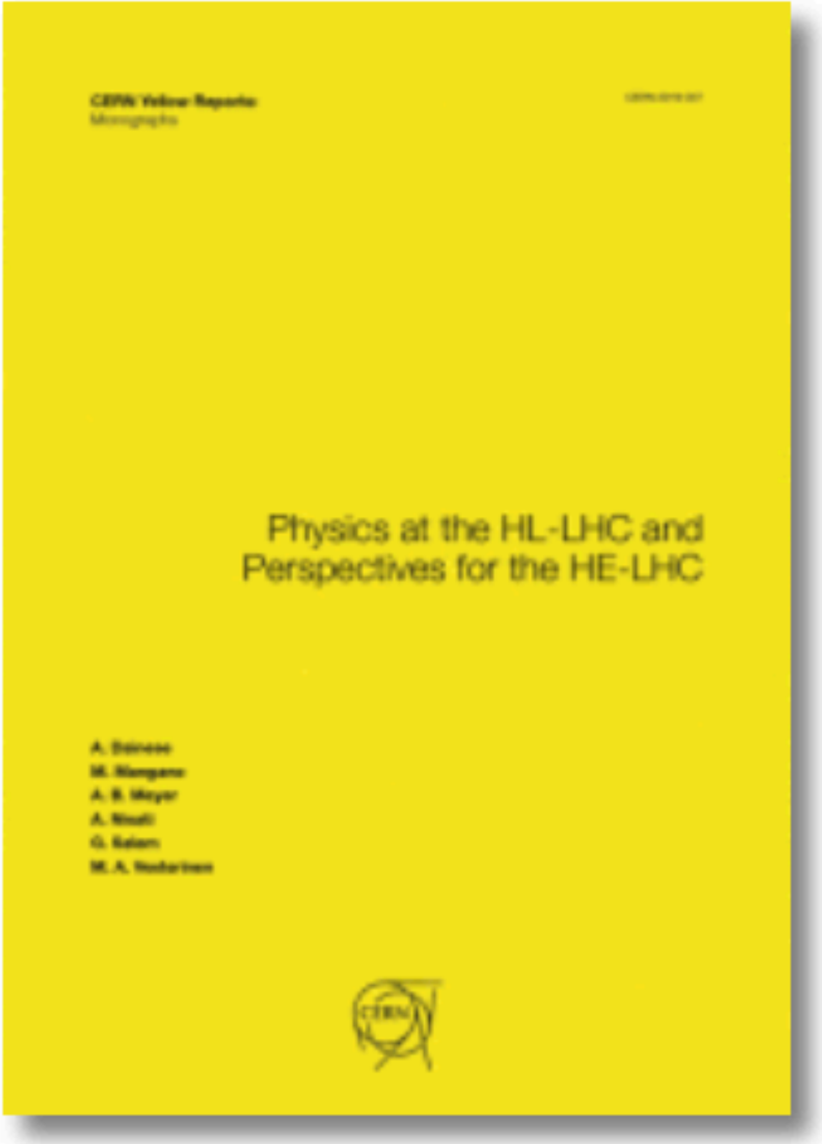
The results of the Workshop will be documented in a Yellow Report, to be completed in time (~end 2018) for submission to the next review of the European strategy for particle physics.

The deadline to reserve pre-booked rooms in the CERN Hostel has expired. To book a room, please contact directly the Hostel.

Ongoing work is being discussed on the wiki.

To join the mailing list of the Workshop, click *here*

Registration: *You are registered for this event.* 493 Modify registration



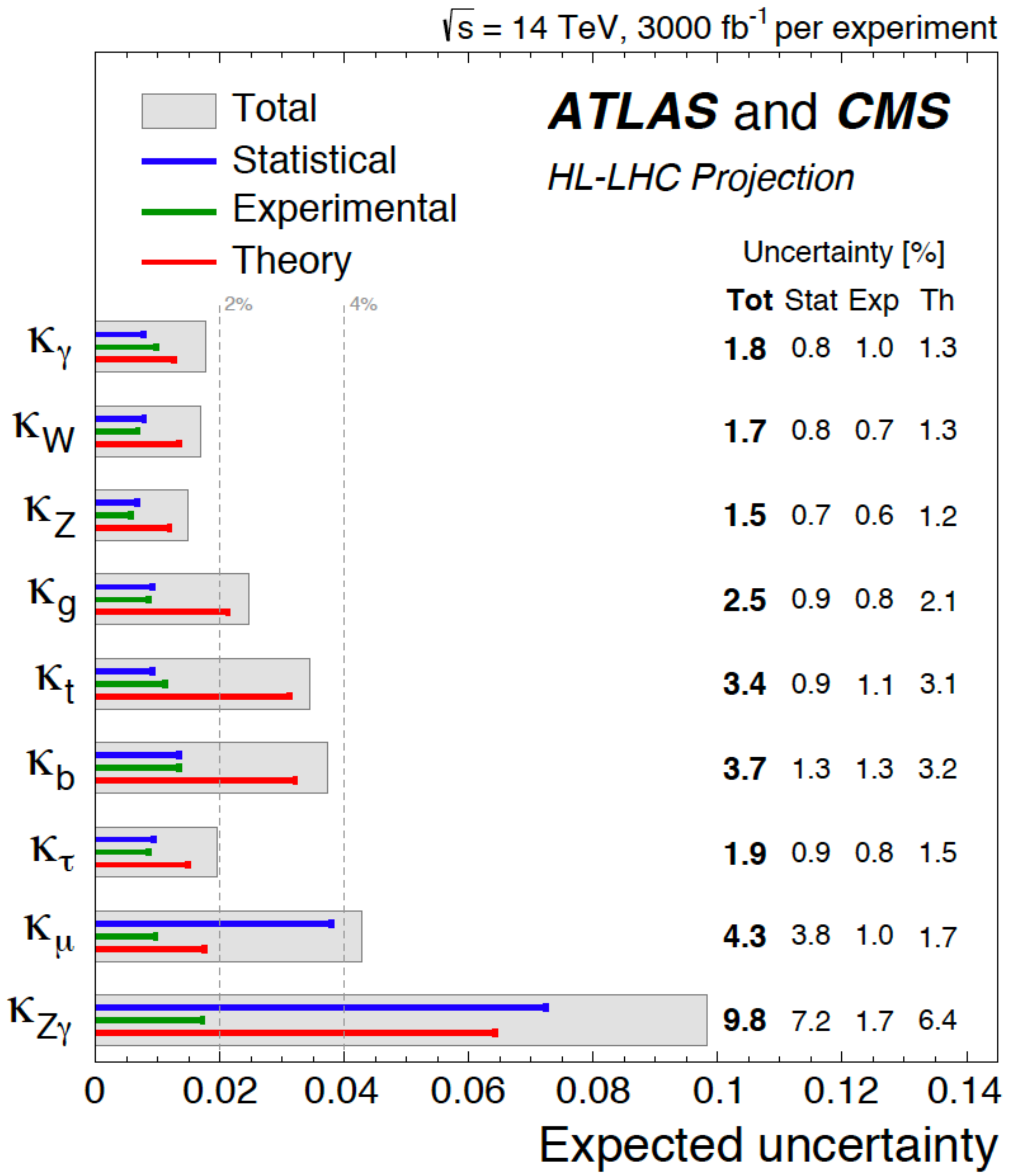
Submitted to ECFA in Dec 2018

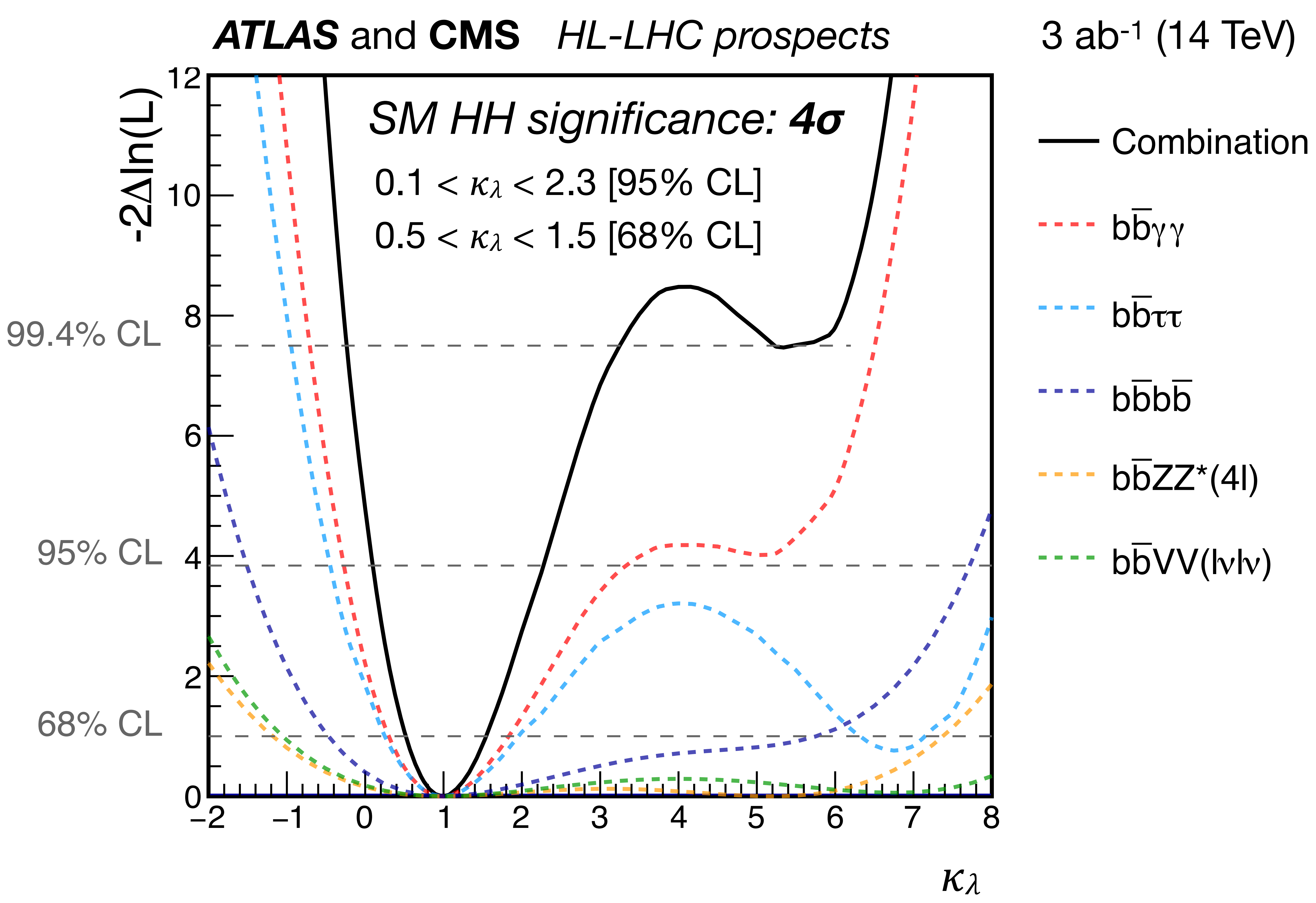
HL/HE-LHC Physics
CERN-2019-007
1418 pp.

343 pp on Higgs (+indiv exp notes). 400 authors

Summarized (including updates) to 116 pages for Snowmass —> 30 for Higgs

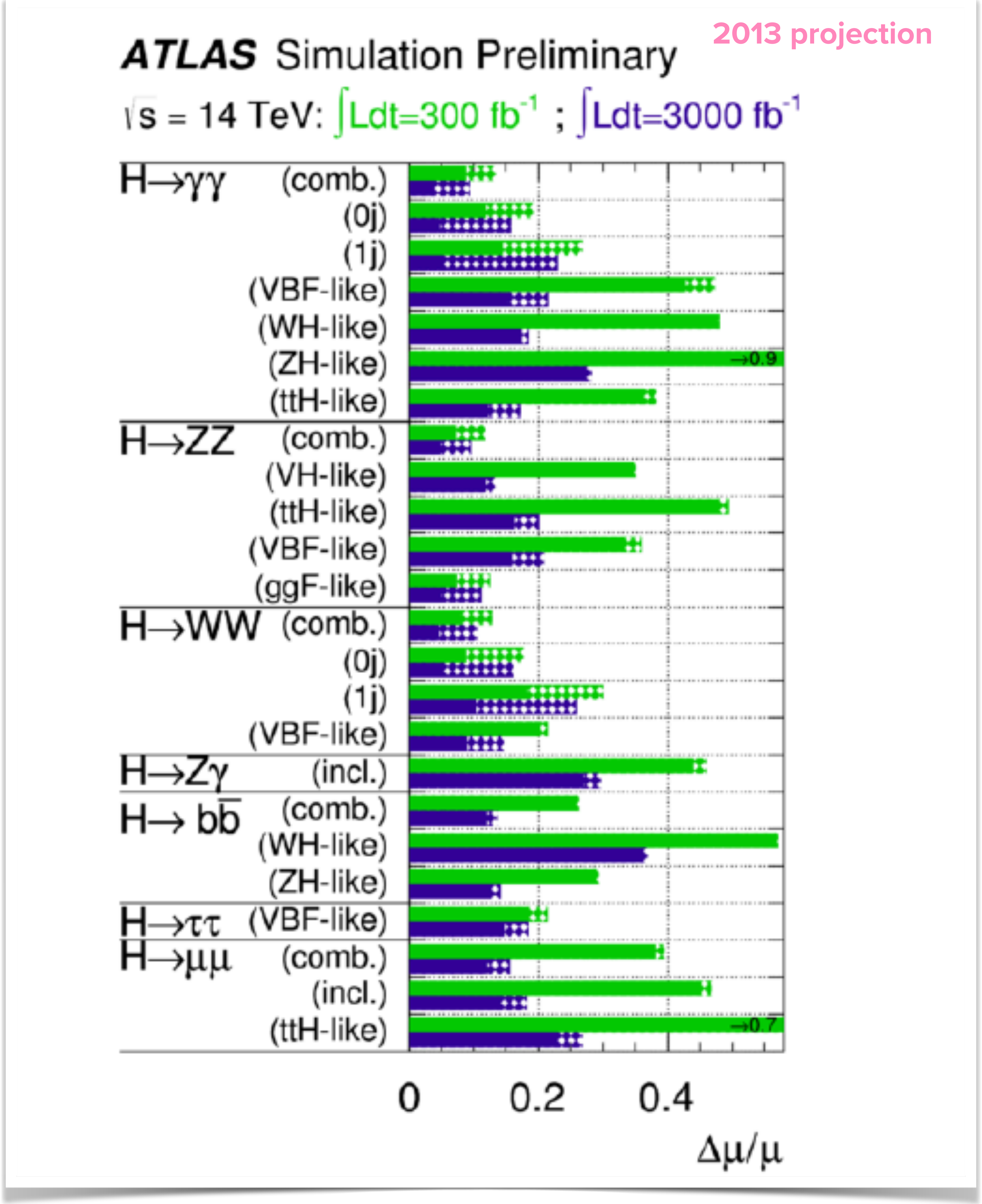
HIGGS LANDSCAPE AT THE END OF THE HL-LHC

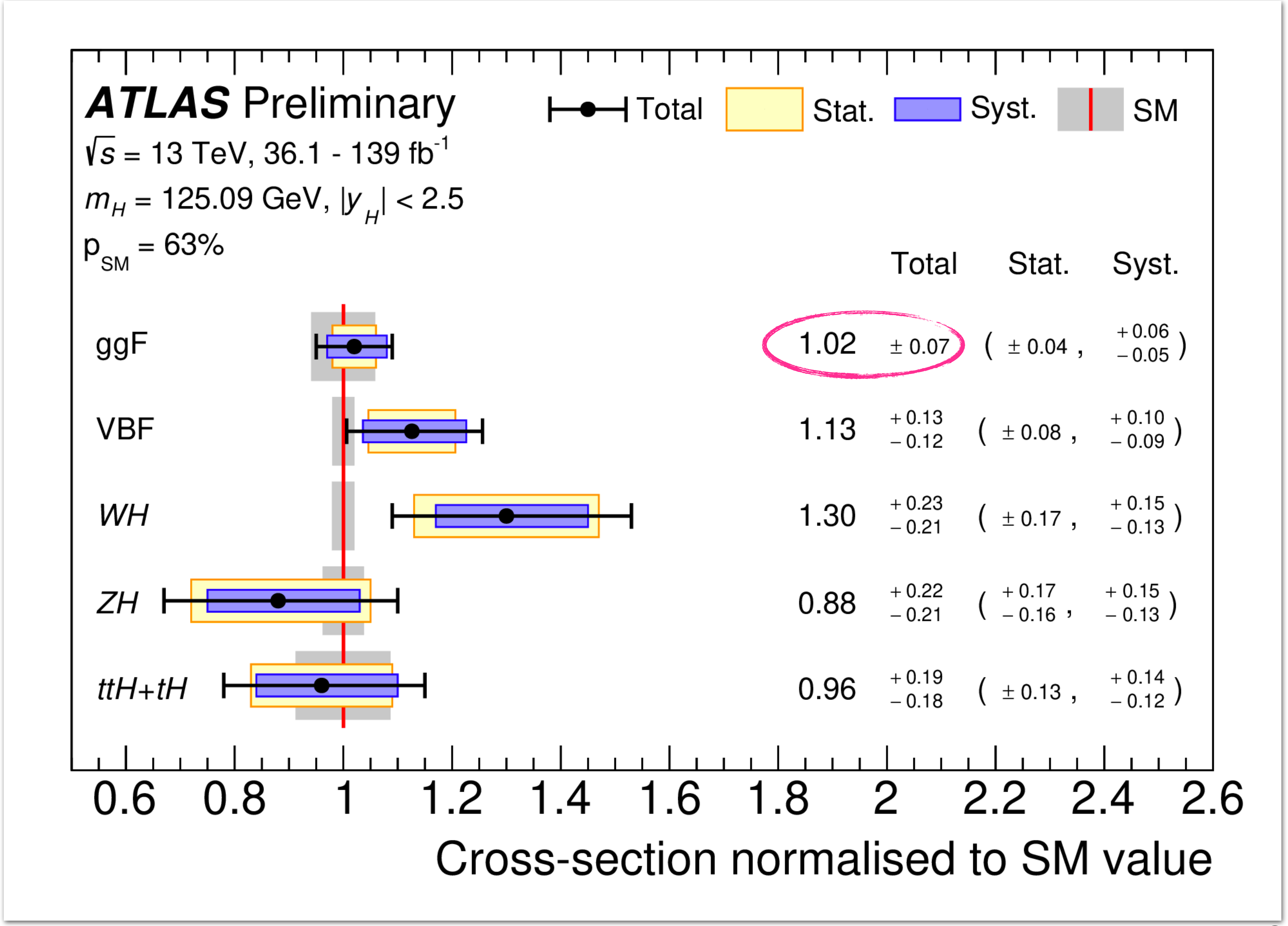




MEASURING THE HIGGS
VS
PROJECTING MEASUREMENTS

HOW WELL CAN WE PREDICT THE FUTURE?



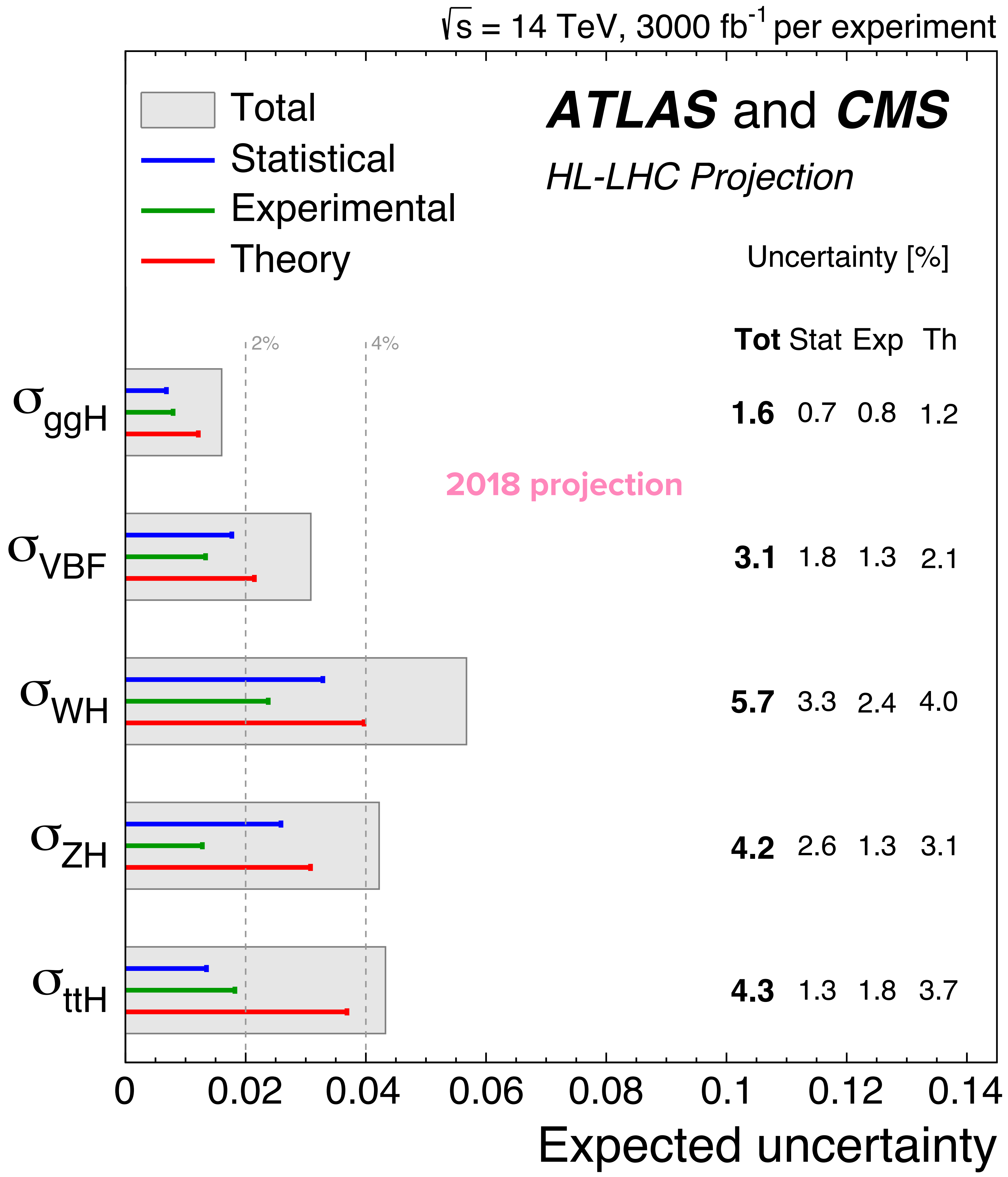


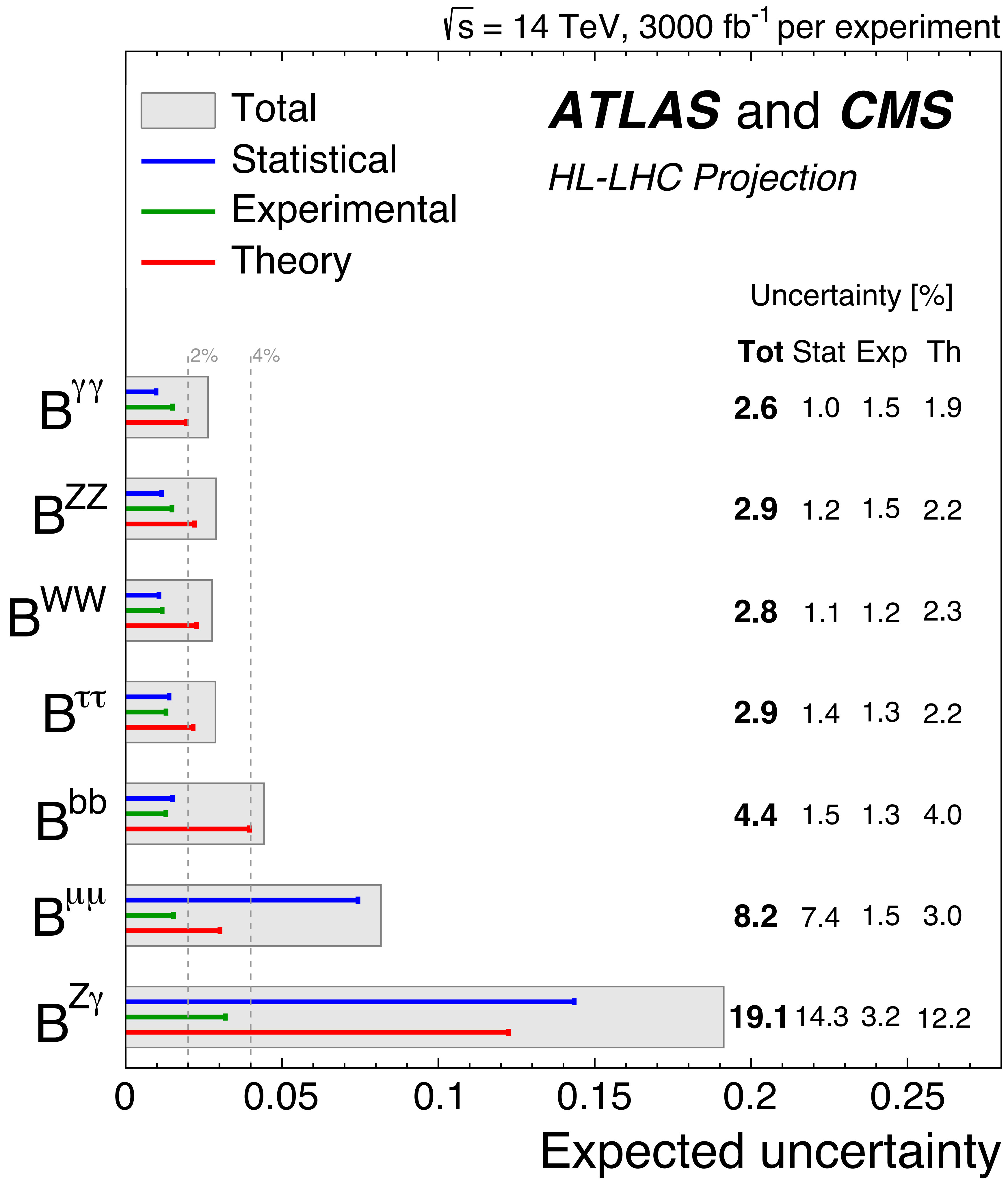
CROSS SECTIONS AND BRANCHING RATIOS @ HL-LHC

ATLAS+CMS COMBINATION

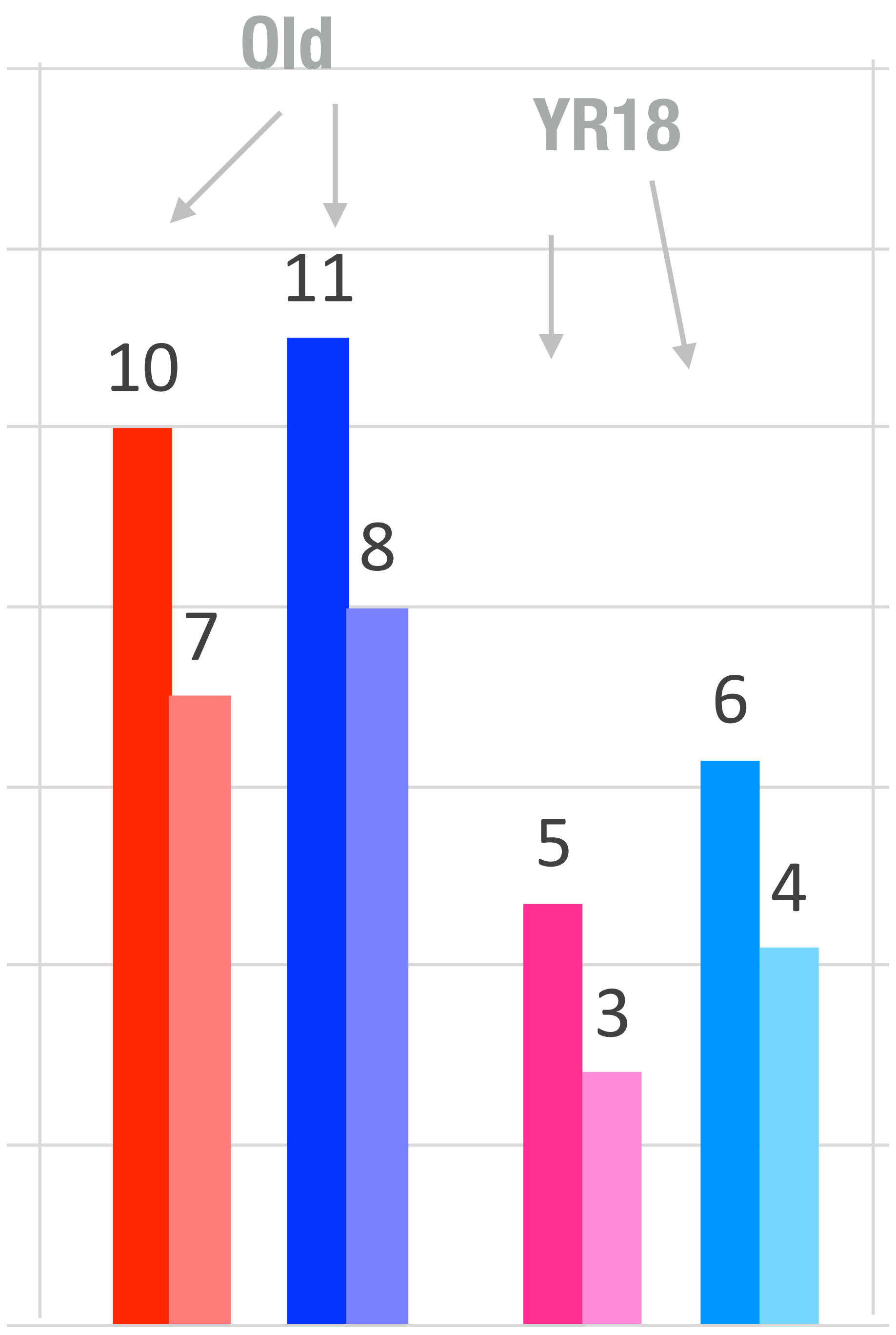
Extrapolating the 2016 analyses, and combining CMS and ATLAS, precisions of few percent can be reached for all production modes, and for all branching ratios (except for rare decays!)

Large impact of theory uncertainties (except for rare modes)





SNAPSHOTS



κt

- Projections capture a moment
- The projections of the sensitivity of the HL-LHC have improved over the years (same as Run2 analysis have)
- ‘Snowmass21’ projections outperform YR18 projections for ECFA which in turn outperform older Snowmass/ECFA prospects
- Part of the reason is easily quantifiable (eg: theoretical uncertainties improved, better understanding of HL-LHC performance, global fits)
- Others are not! Analysis improvements, or the effect of sitting ATLAS, CMS and theory together and working together
- That sentence is deceptively simple

- The prospects we have are beautiful, but we cannot take them for granted: there is a huge amount of work ahead! (eg, calibrating 3000 fb-1, probably with a reduced workforce). Do we have the tools and structures in place to deal with this?

UNCERTAINTIES AT HL-LHC?

- Main experimental uncertainties synchronised between CMS and ATLAS
- In most cases, two complementary scenarios given for each of the updated projections: S1 - Conservative, S2 - Ultimate

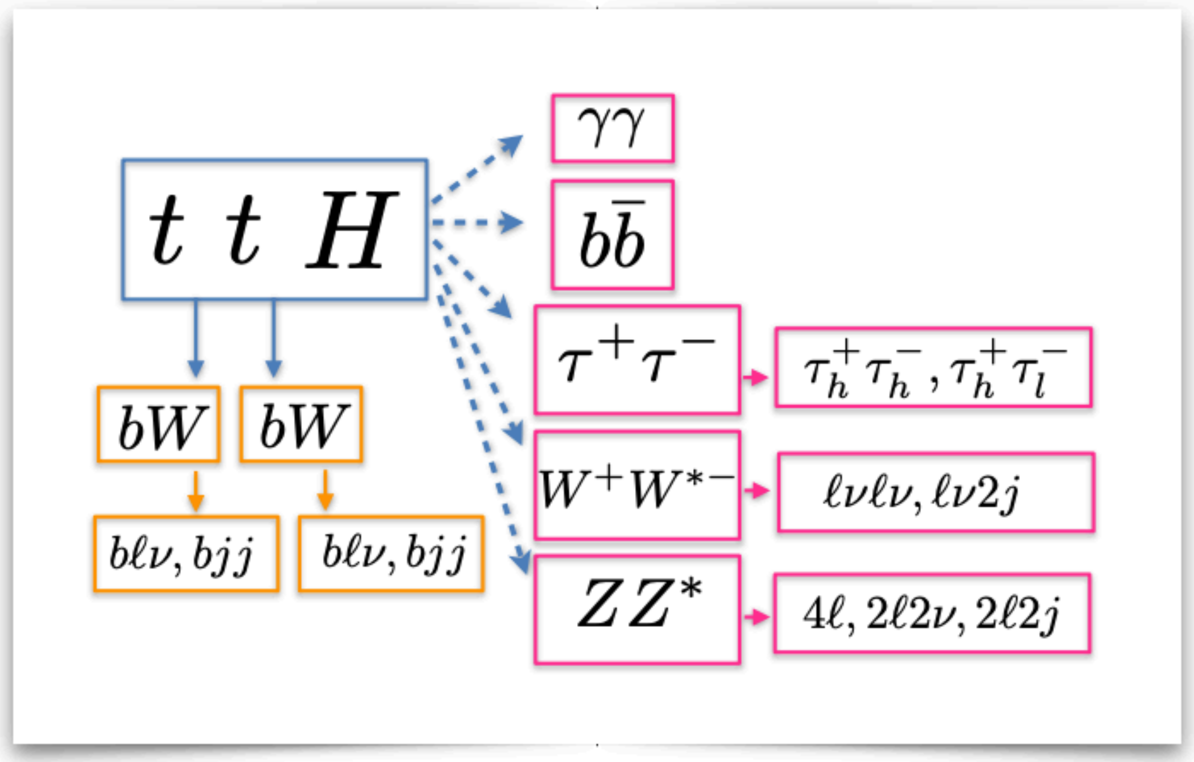
Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

- Experimental uncertainties:
  - Coordination between experiments to get to this agreement, on the basis of the up to date knowledge of the performance of the upgraded detectors
  - This was possible since we are discussing projections —> not really applicable to a combination of data measurements (oversimplified, the real data uncertainties are very comparable but not identical and logically cannot not be decided a priori)

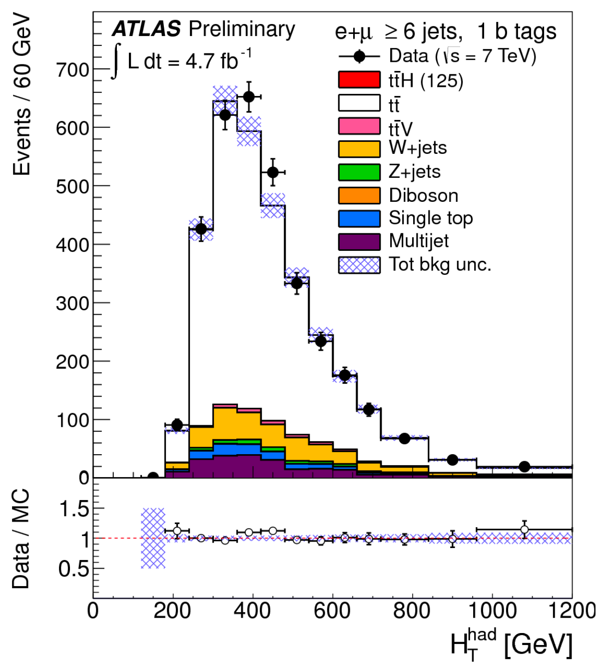
Slide From Sometime in 2018

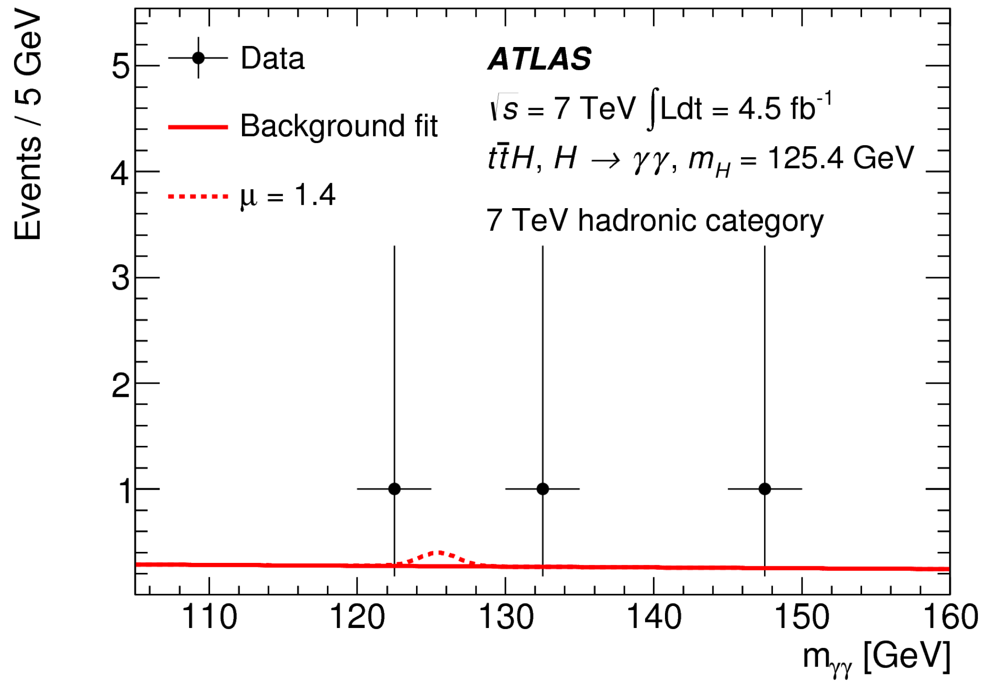
ANALYSIS EVOLVE!

ttH Analyses at LHC: Massively Complex!

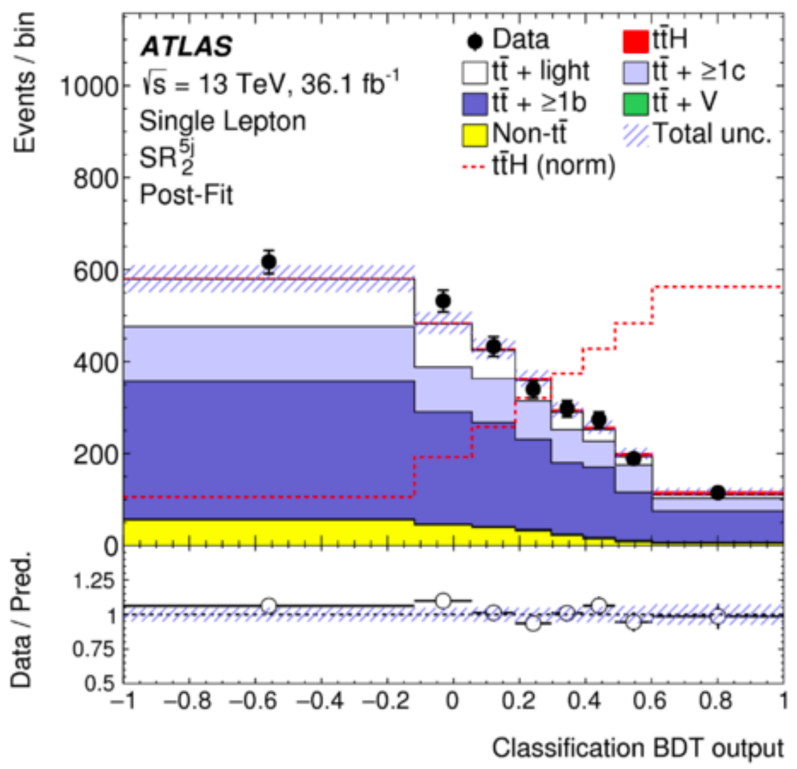


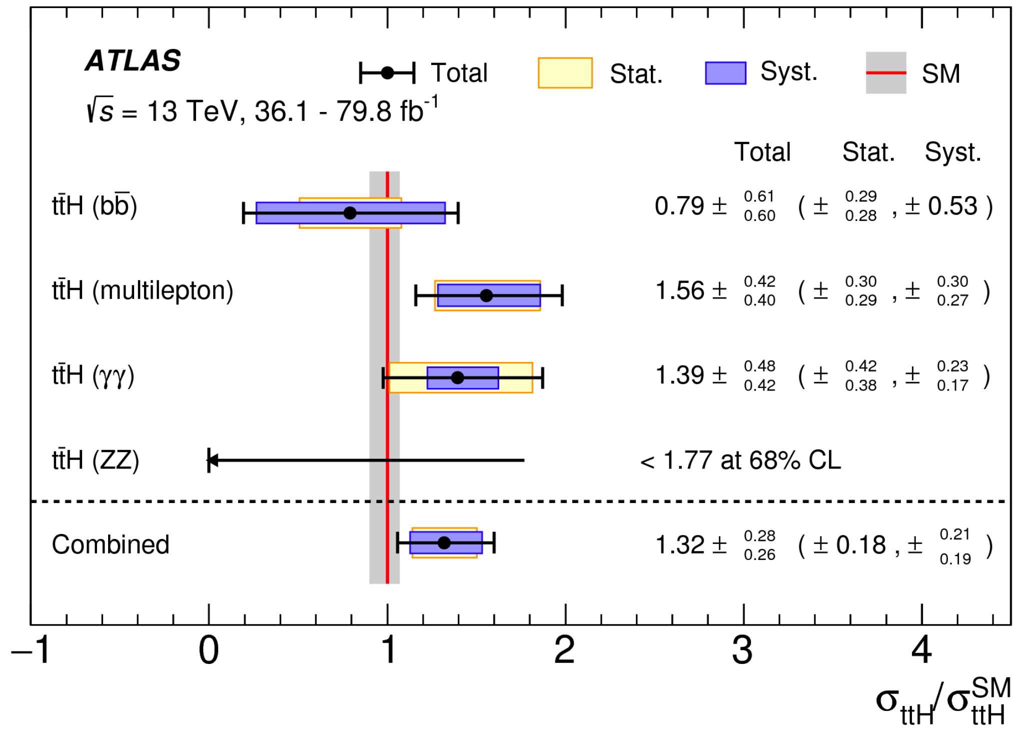
7TeV



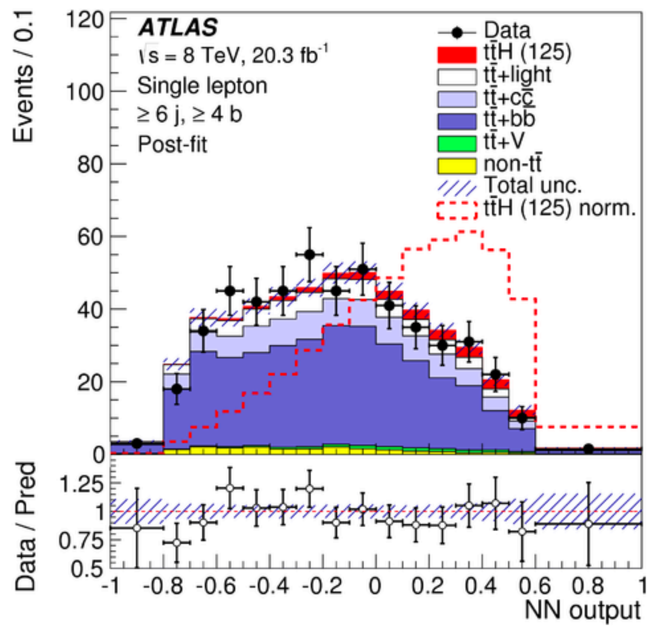


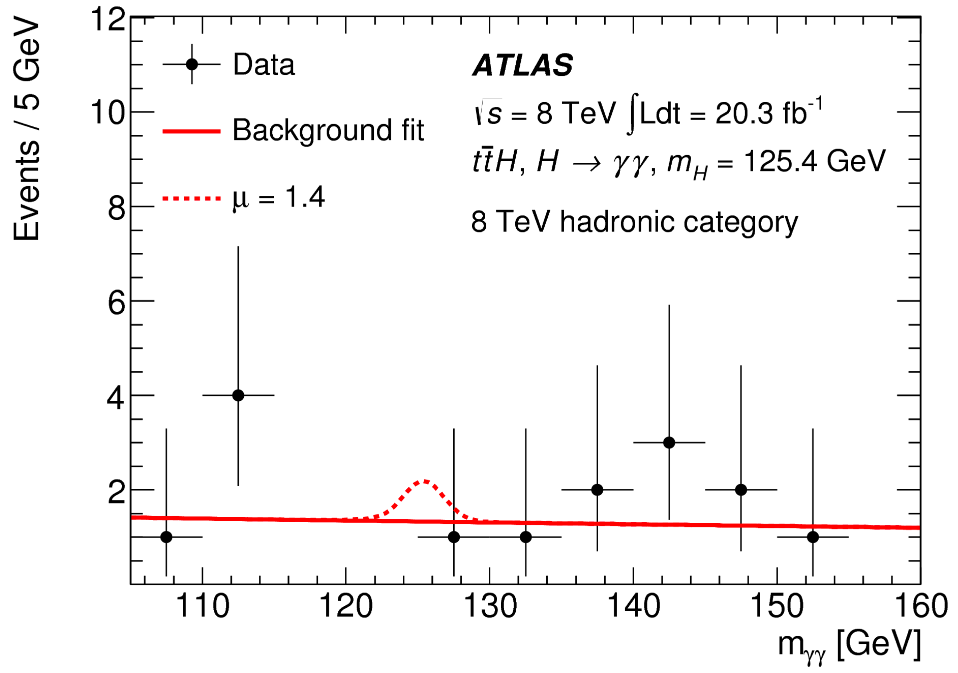
13 TeV, Partial Run II



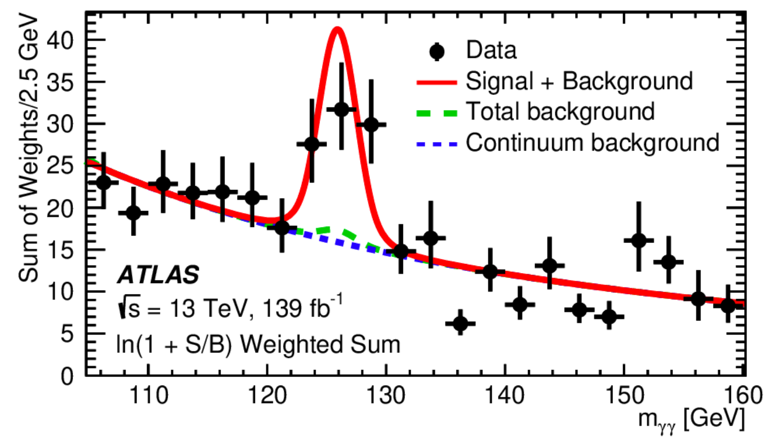


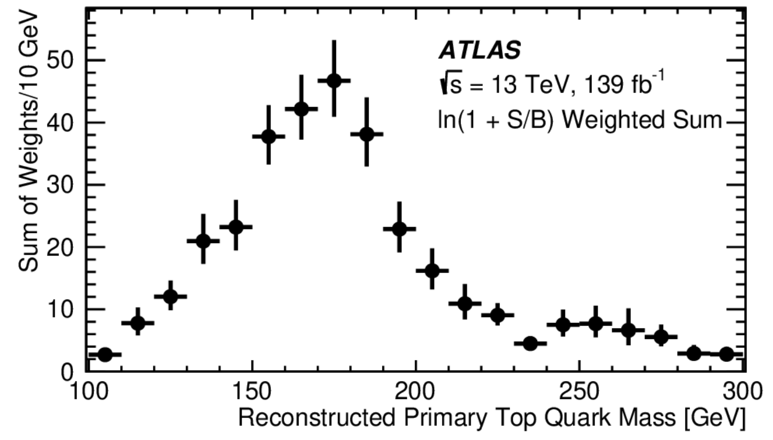
8TeV

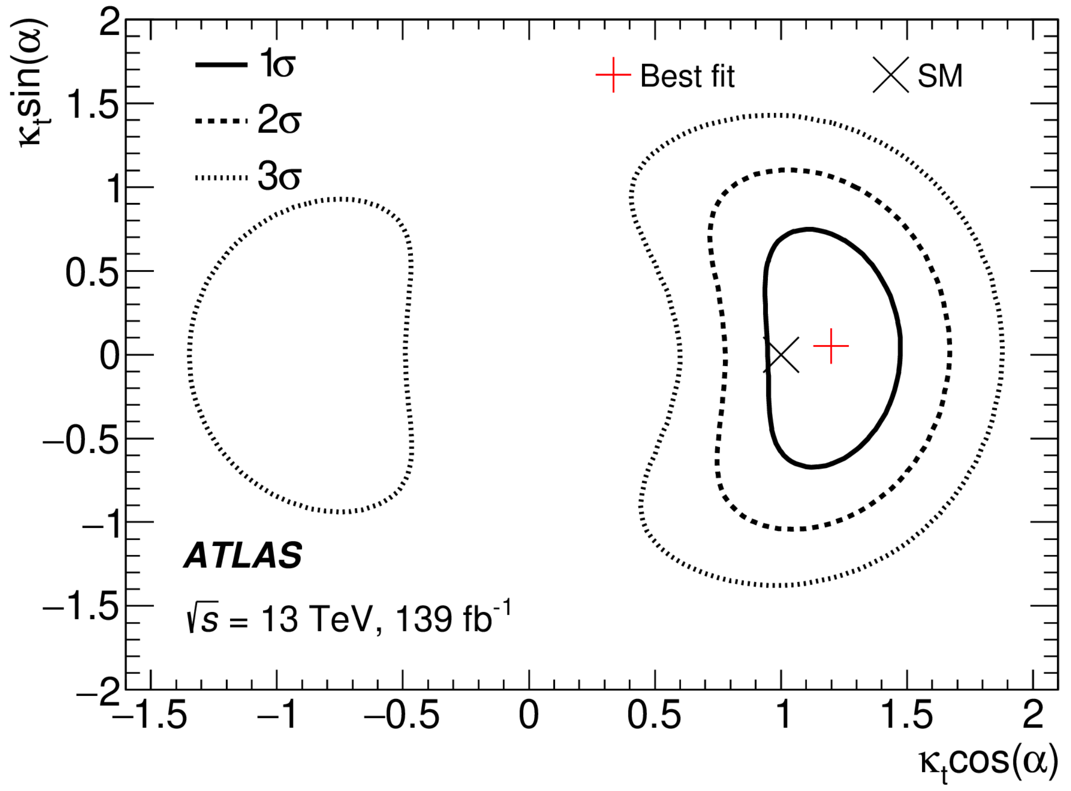




13TeV, full Run2



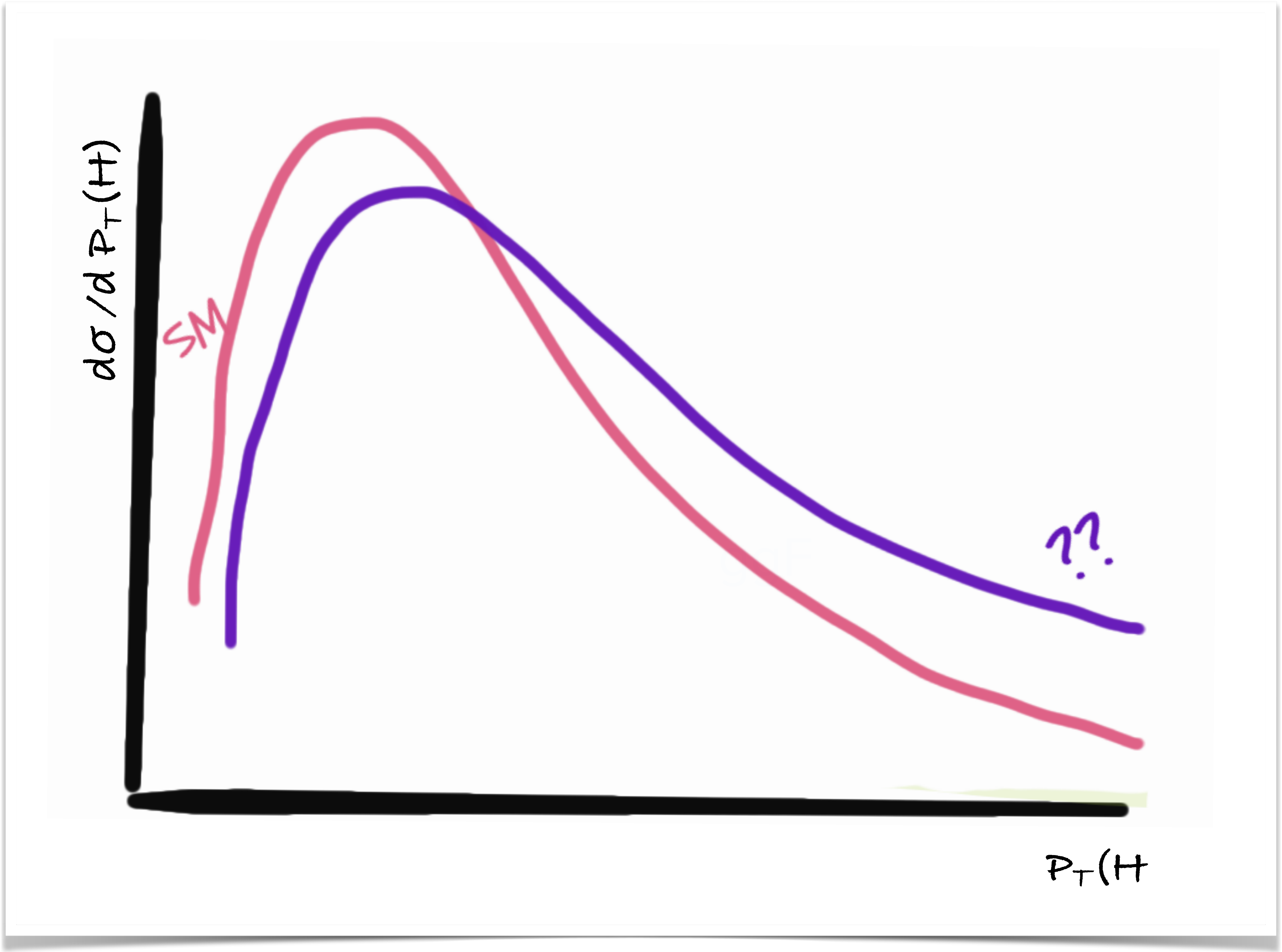




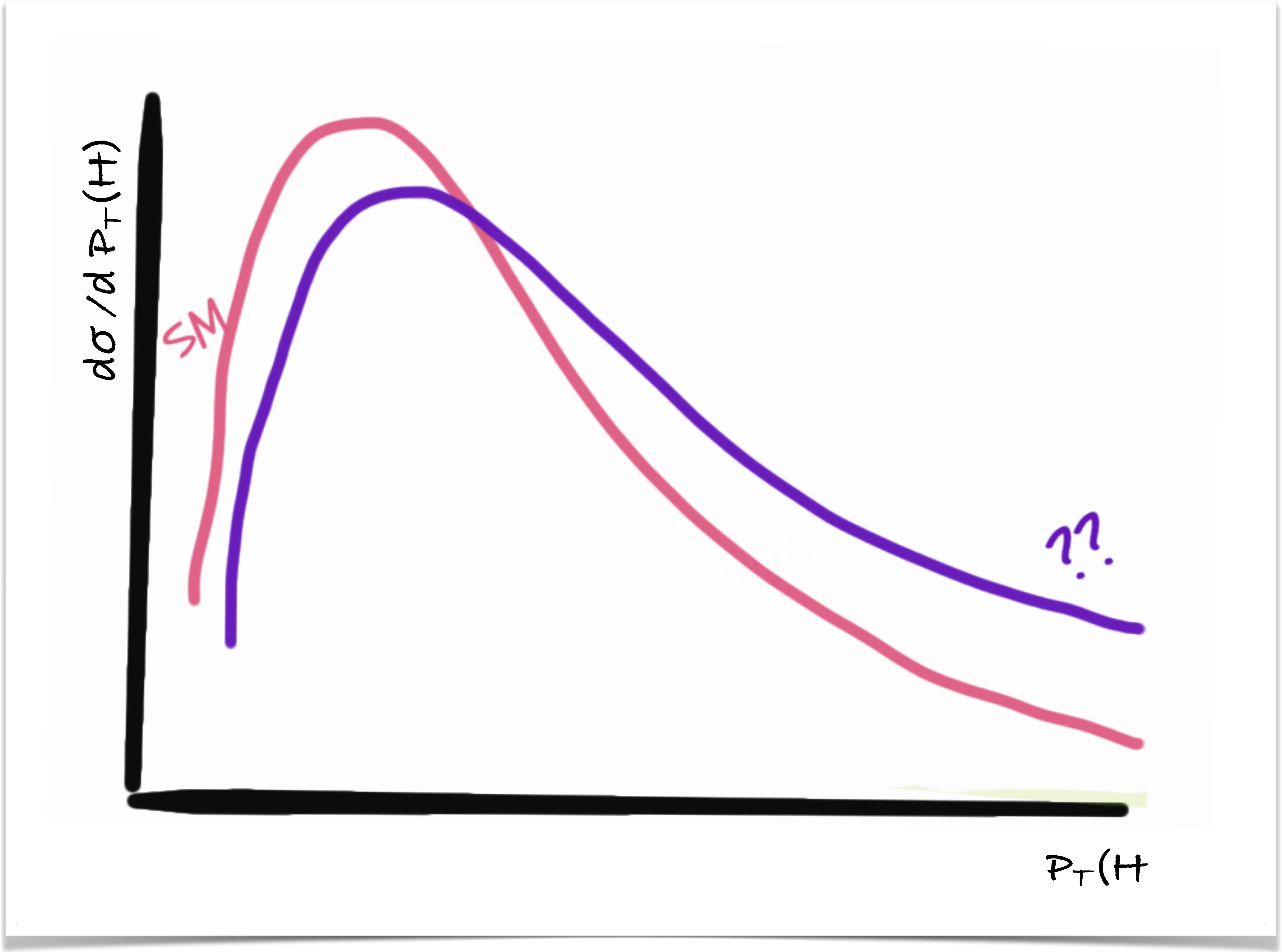
innovation cannot be projected

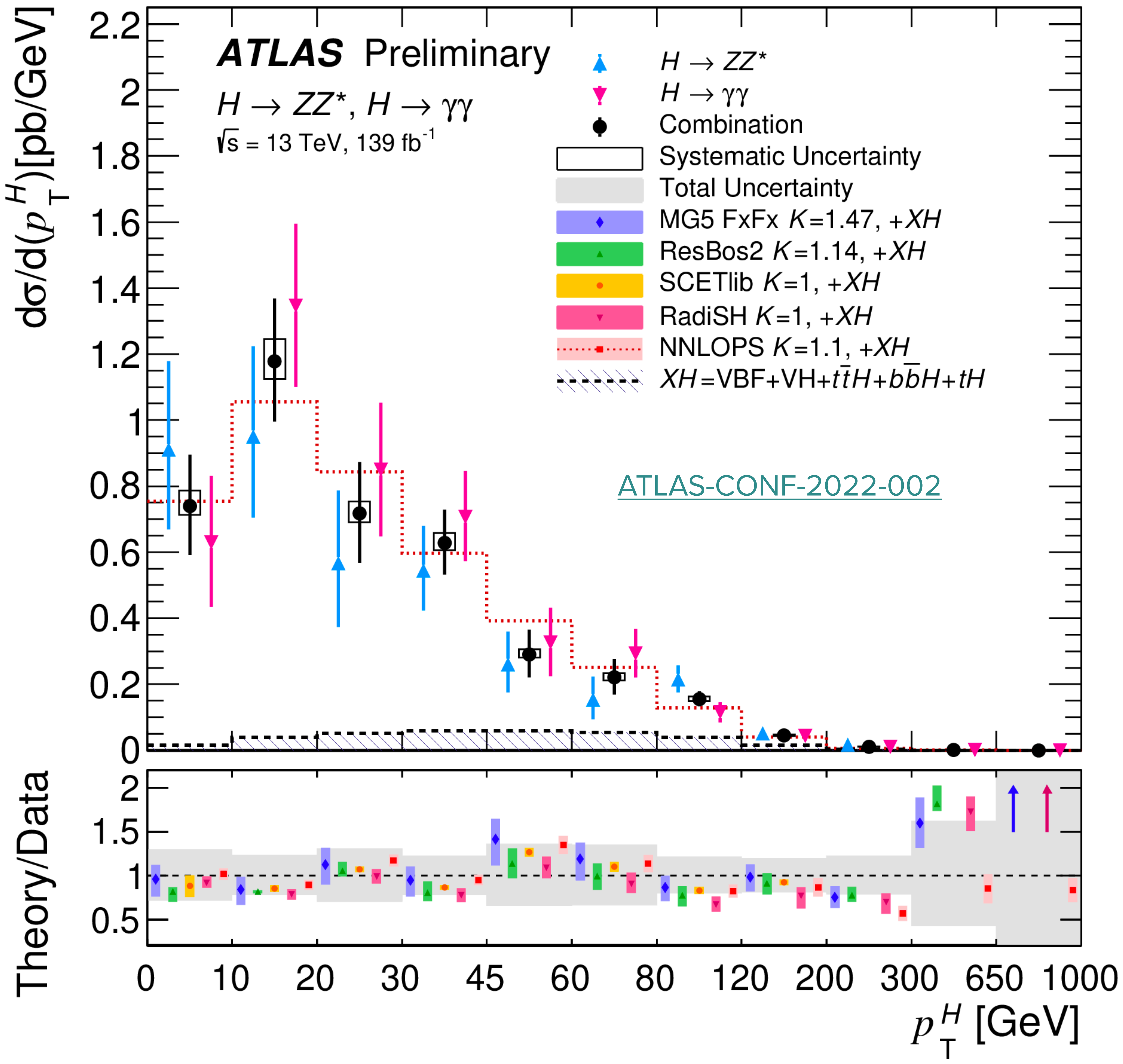
We *shouldn't* be using the techniques of today in 20 years!

OVERALL AGREEMENT IN RATE IS ONLY THE START

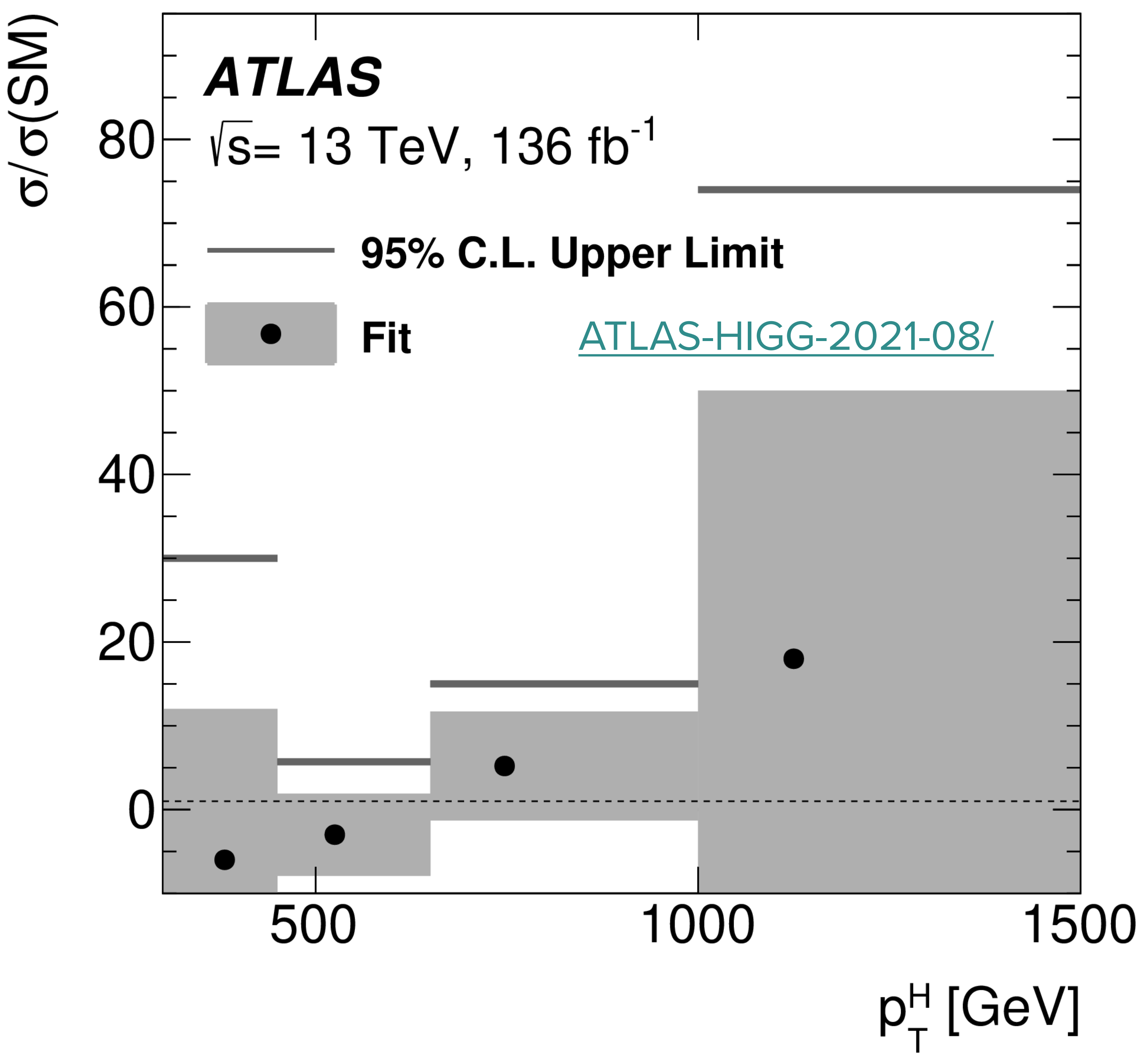


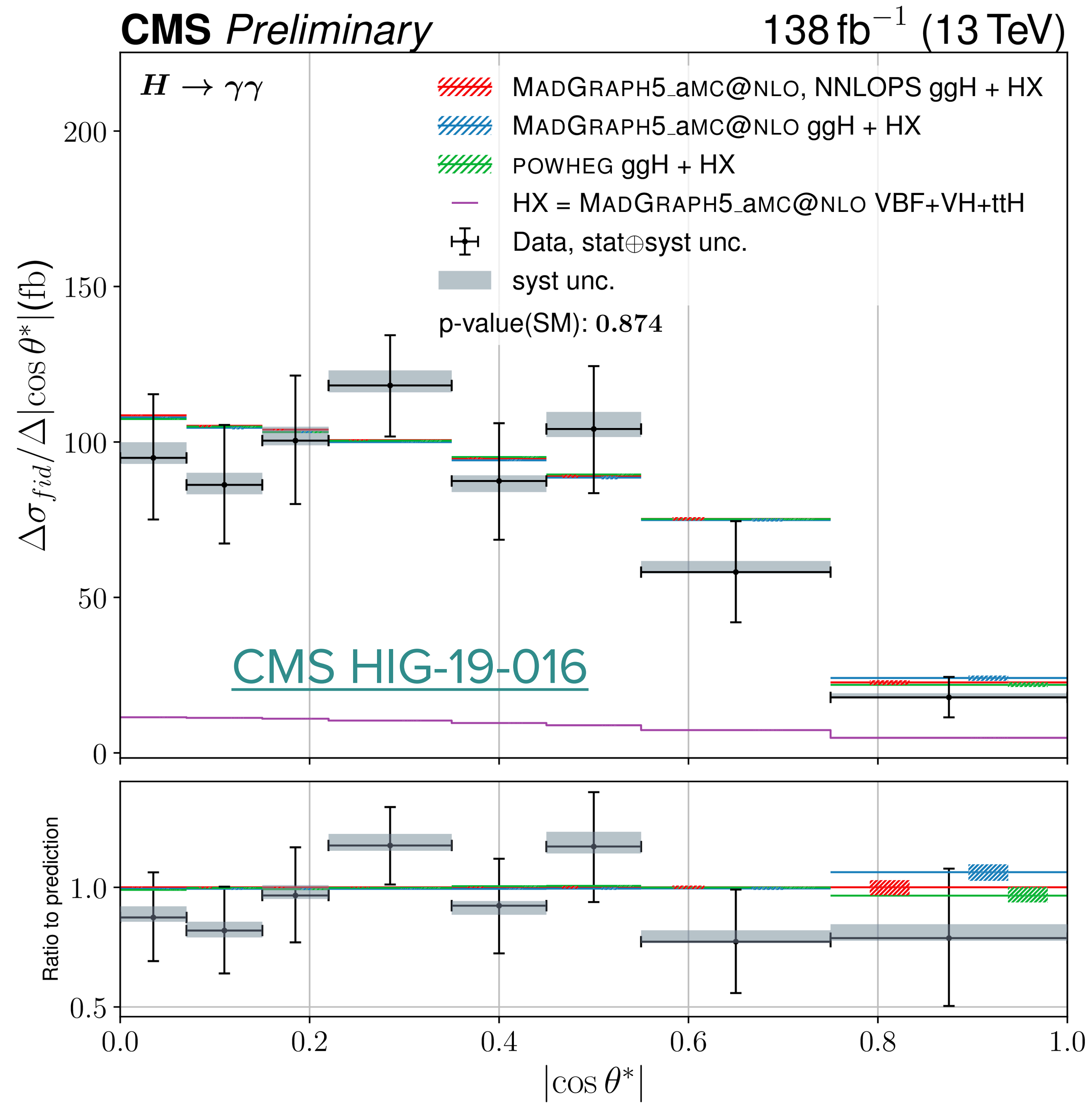
OVERALL AGREEMENT IN RATE IS ONLY THE START

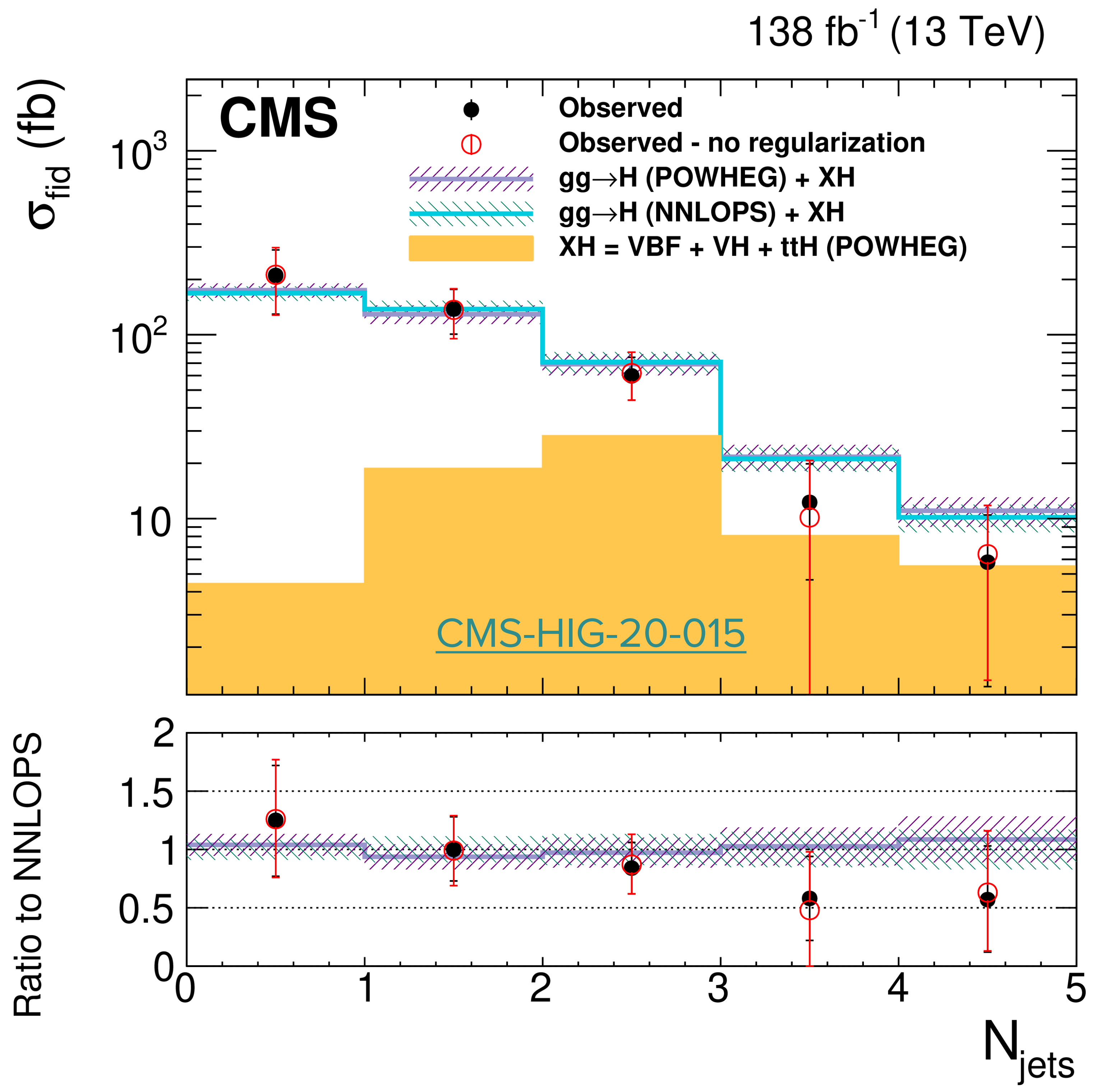




FROM SIGNAL STRENGTHS TO DIFFERENTIAL CROSS SECTIONS







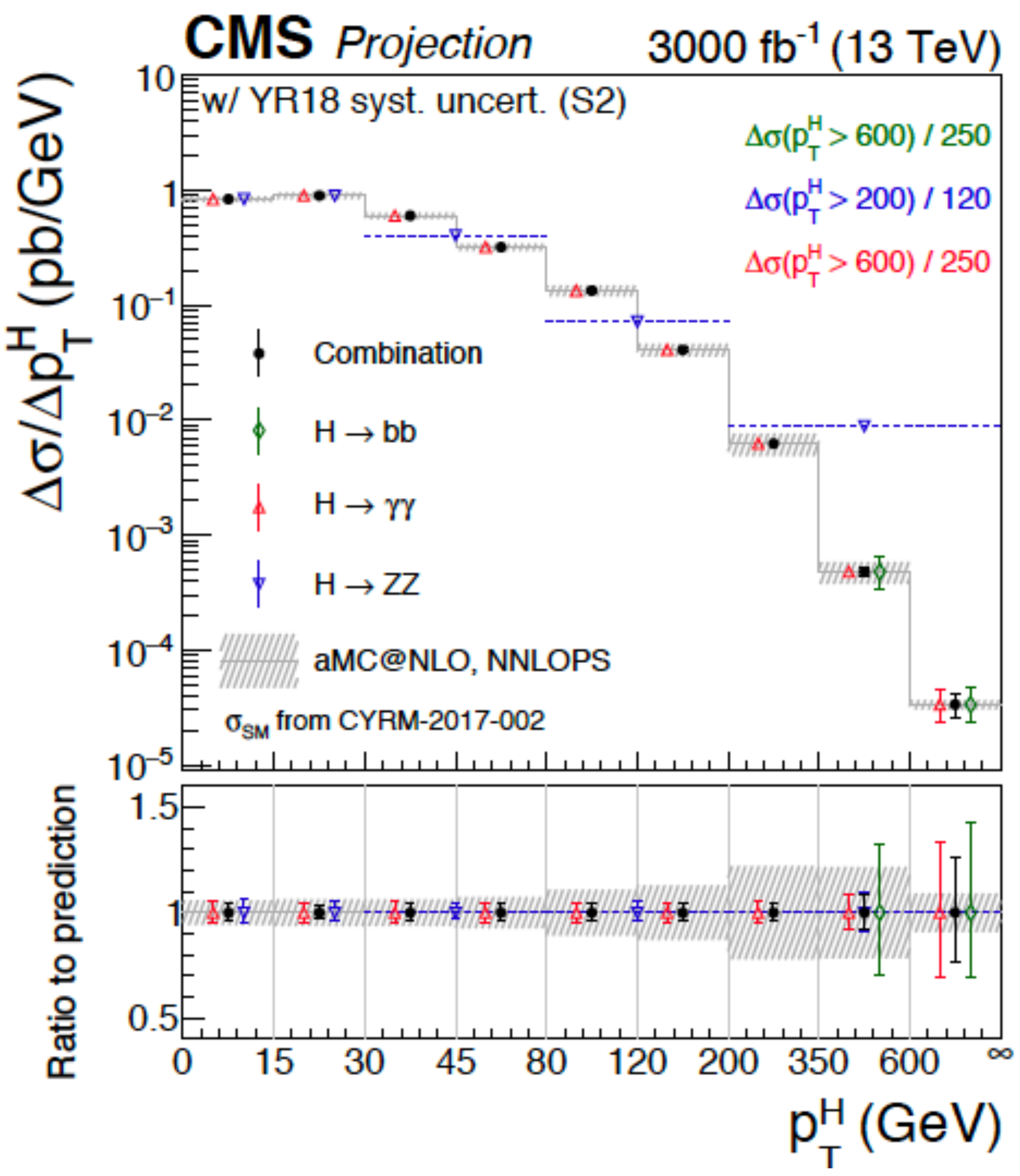
With the Run2 data we are already exploring Higgs production in depth. We need more statistics! Run3 and HL-LHC will be a game changer for many of these measurements

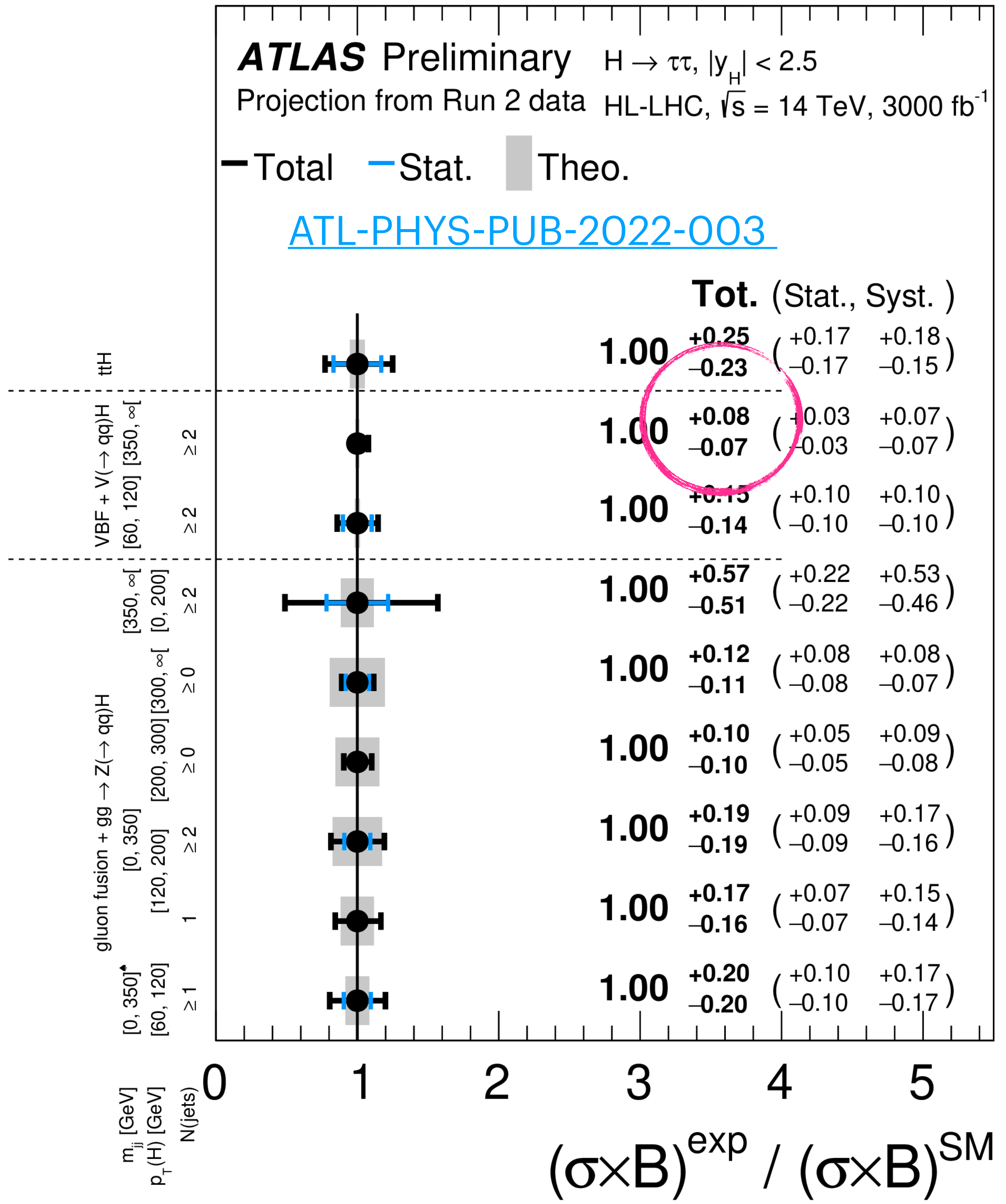
DIFFERENTIAL CROSS SECTIONS & STXS

Measurement limited by systematic uncertainties except at very high p_T.

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

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

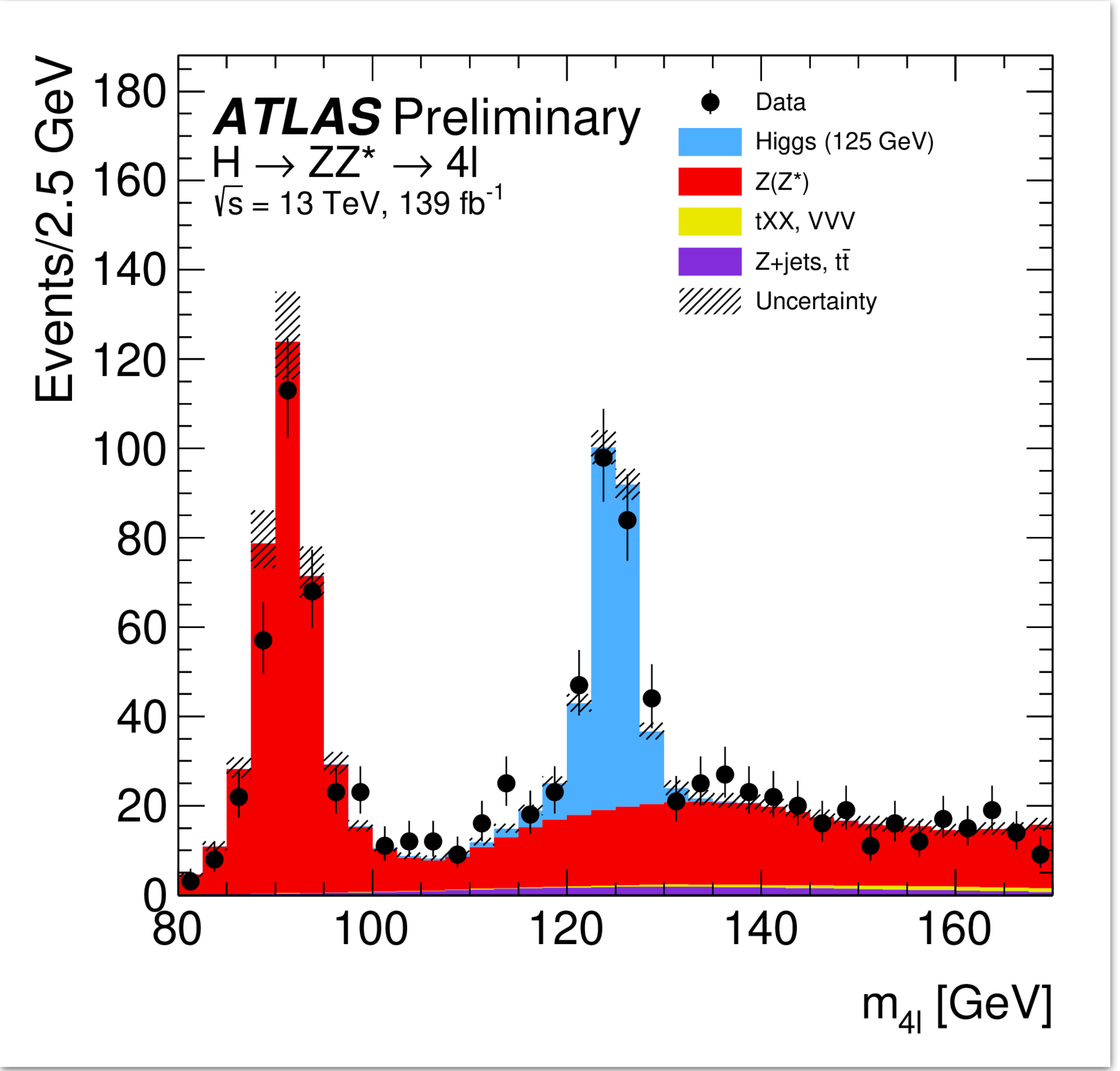




THE NATURE OF THE HIGGS

Mass

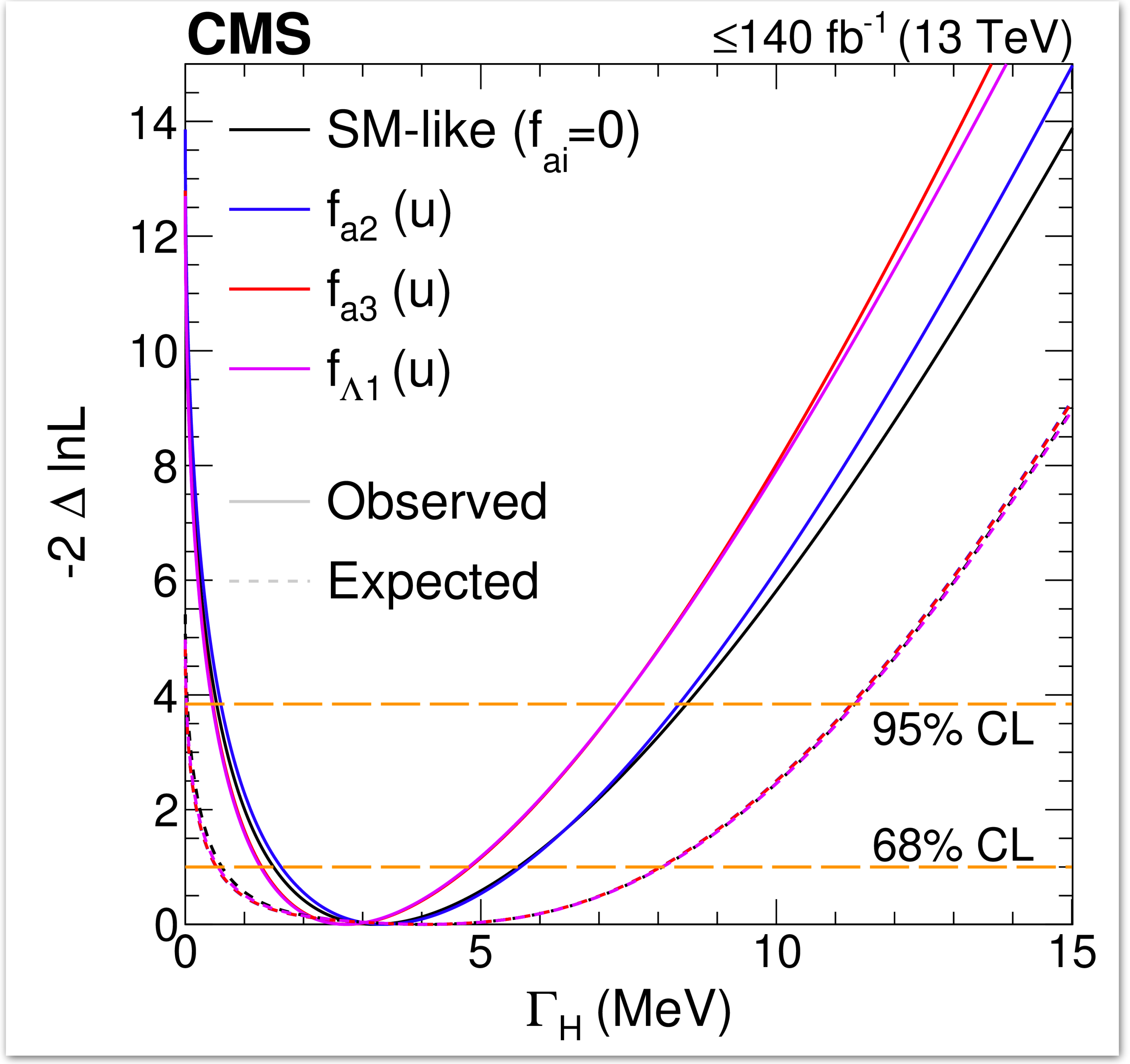
Free in the SM, now known to 0.1%
($H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow \gamma\gamma$)



$CMS: 125.38 \pm 0.14\ GeV\ (0.11\%)$
$ATLAS: 124.92 \pm 0.19(stat)^{+0.09}_{-0.06}(syst)\ GeV\ (0.17\%)$

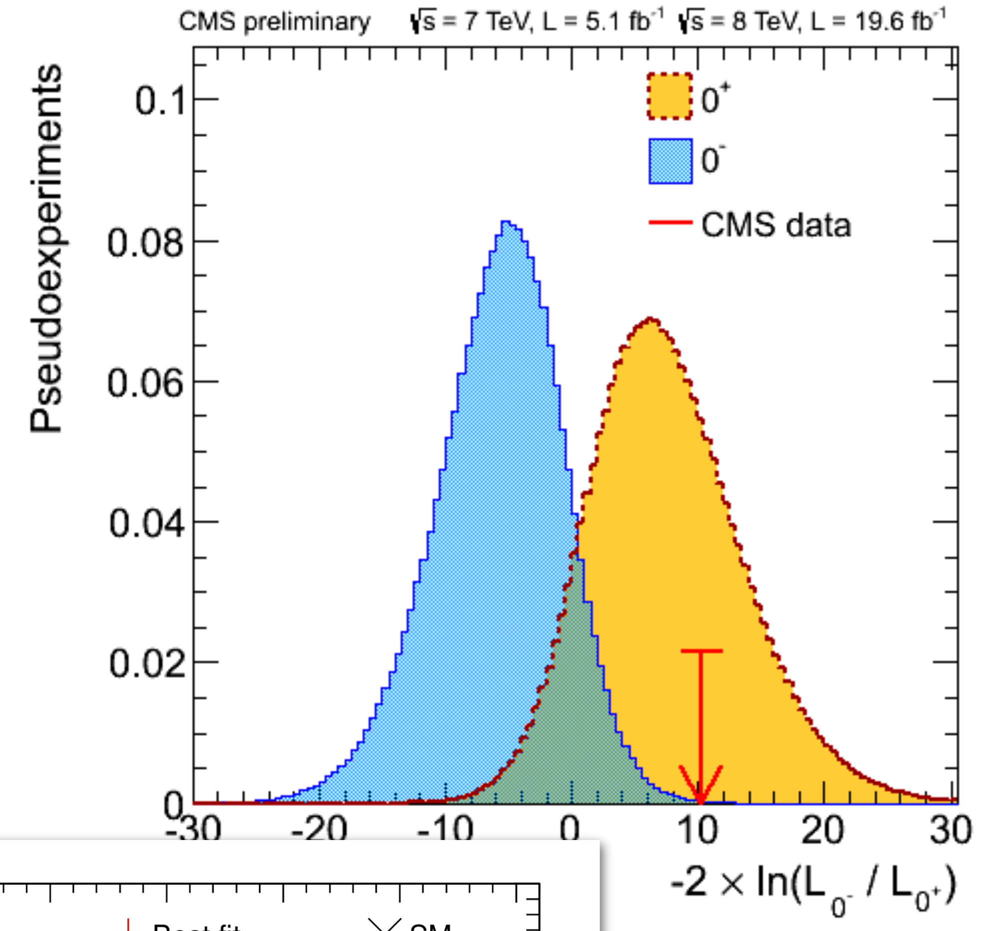
Total Width

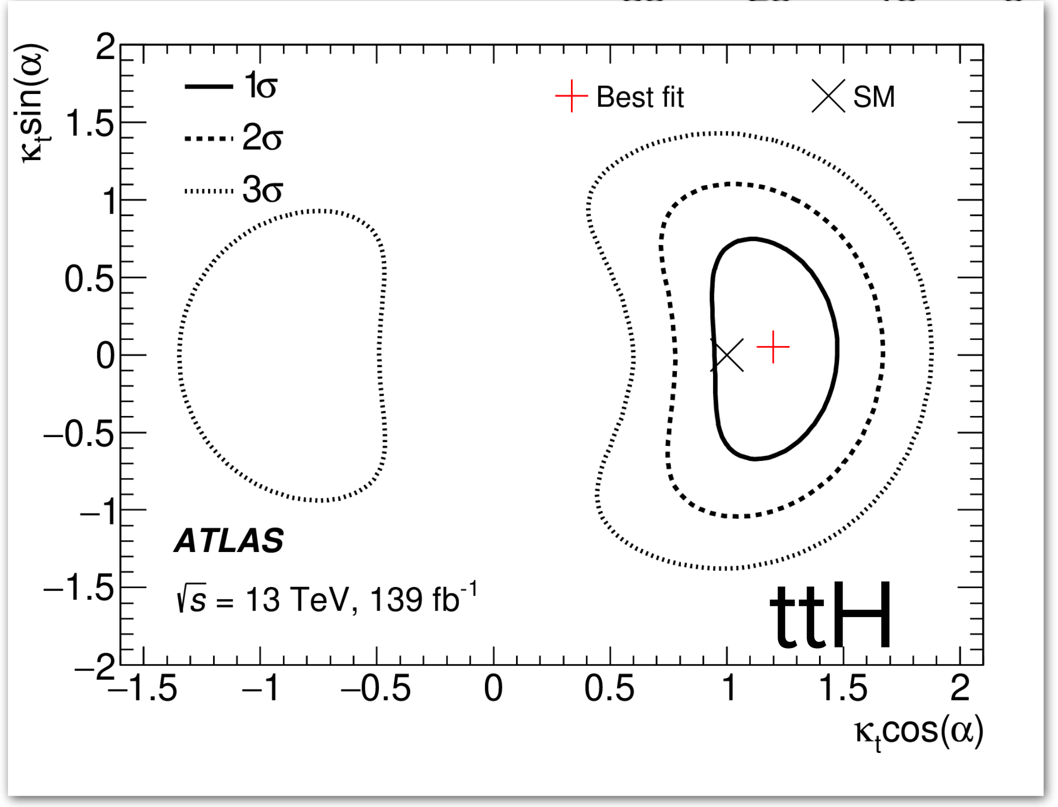
Very small in SM! (4 MeV)
Direct @ HL-LHC: <177 MeV (95%CL)
Offshell/onshell $H \rightarrow ZZ -> 4l$



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

Spin 0+ (SM-like)



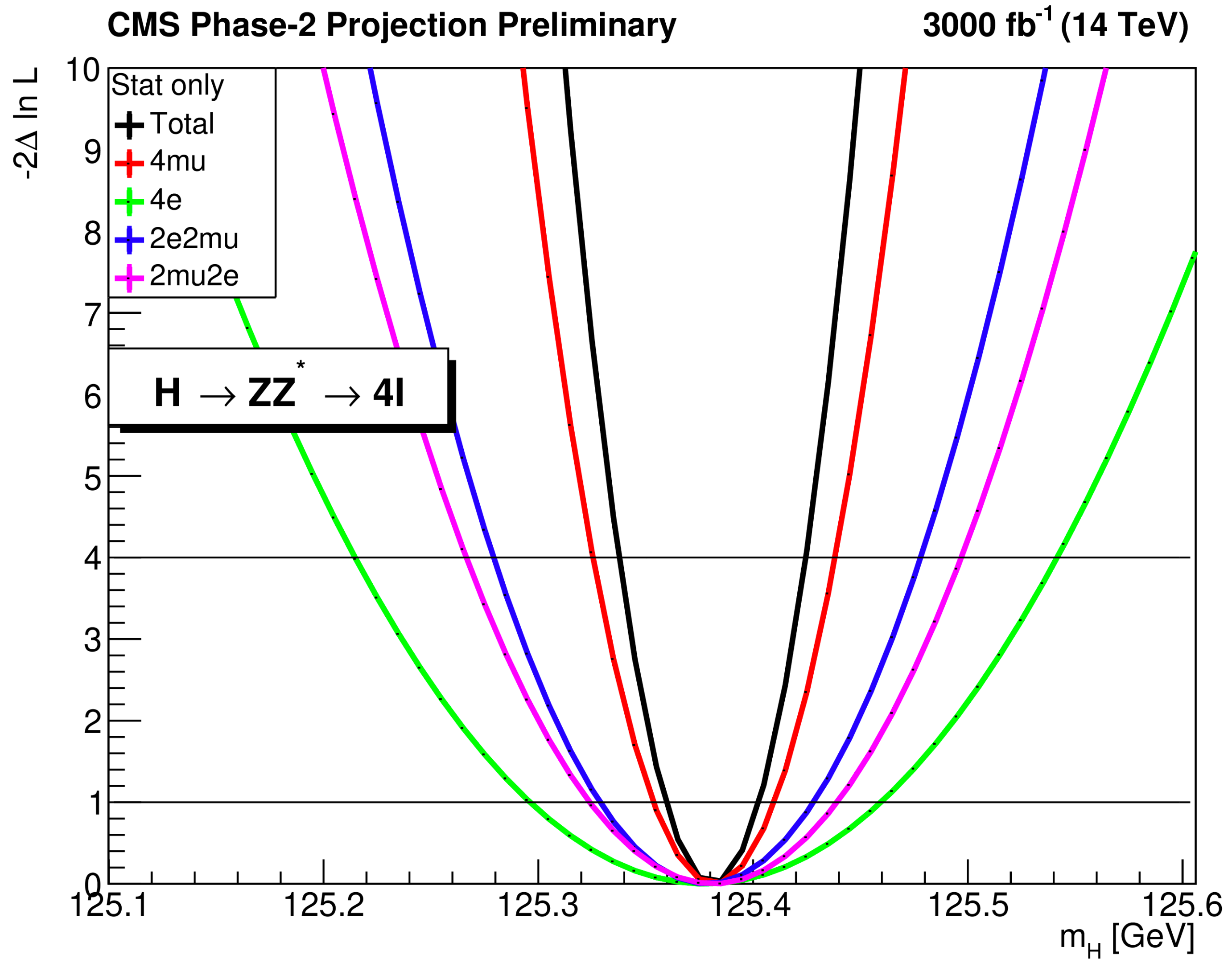


Does the Higgs sector have a new source of Charge-Parity violation?

THE NATURE OF THE HIGGS

Mass

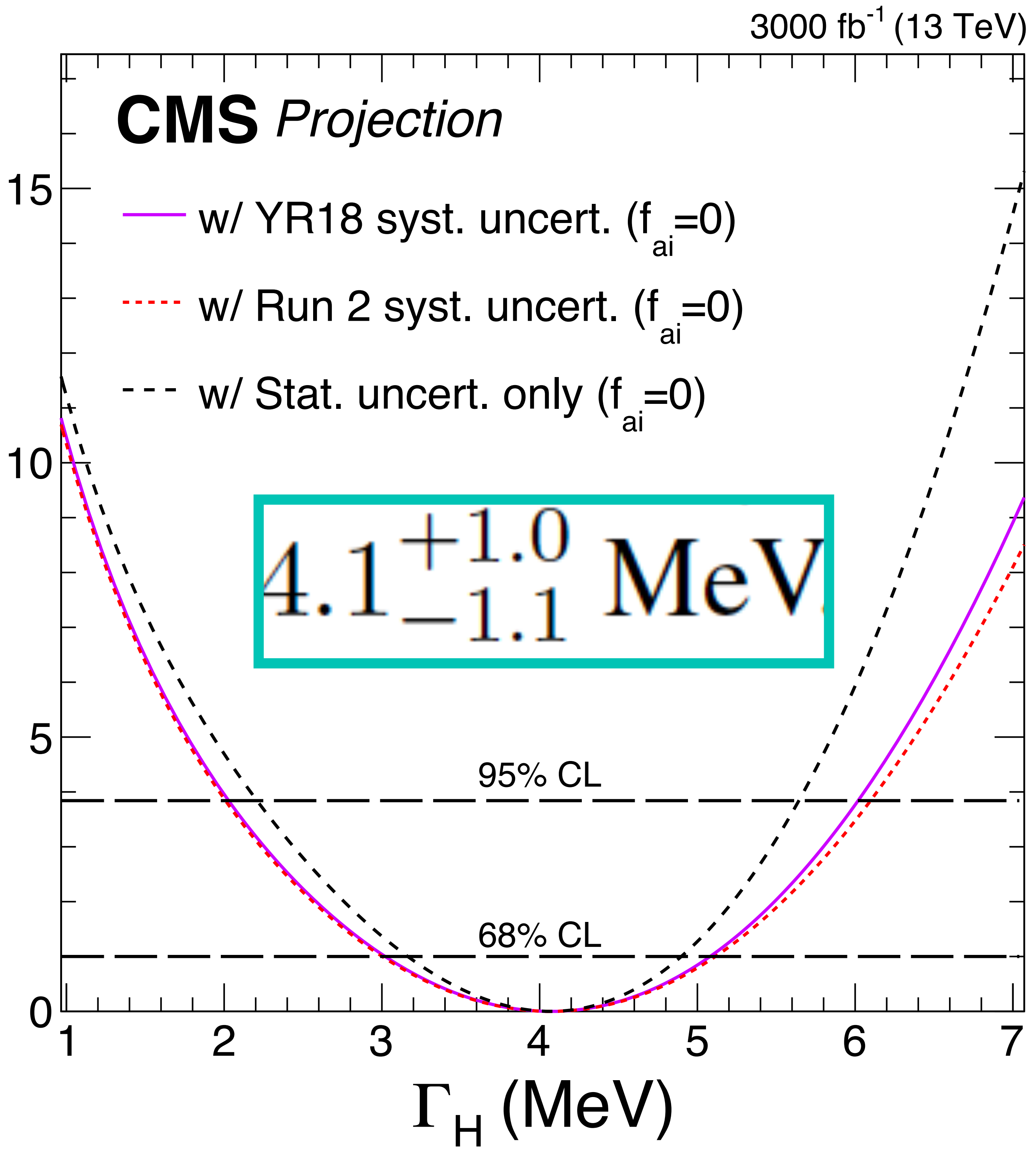
Free in the SM, now known to 0.1%
($H \to ZZ \to 4l$ and $H \to \gamma\gamma$)



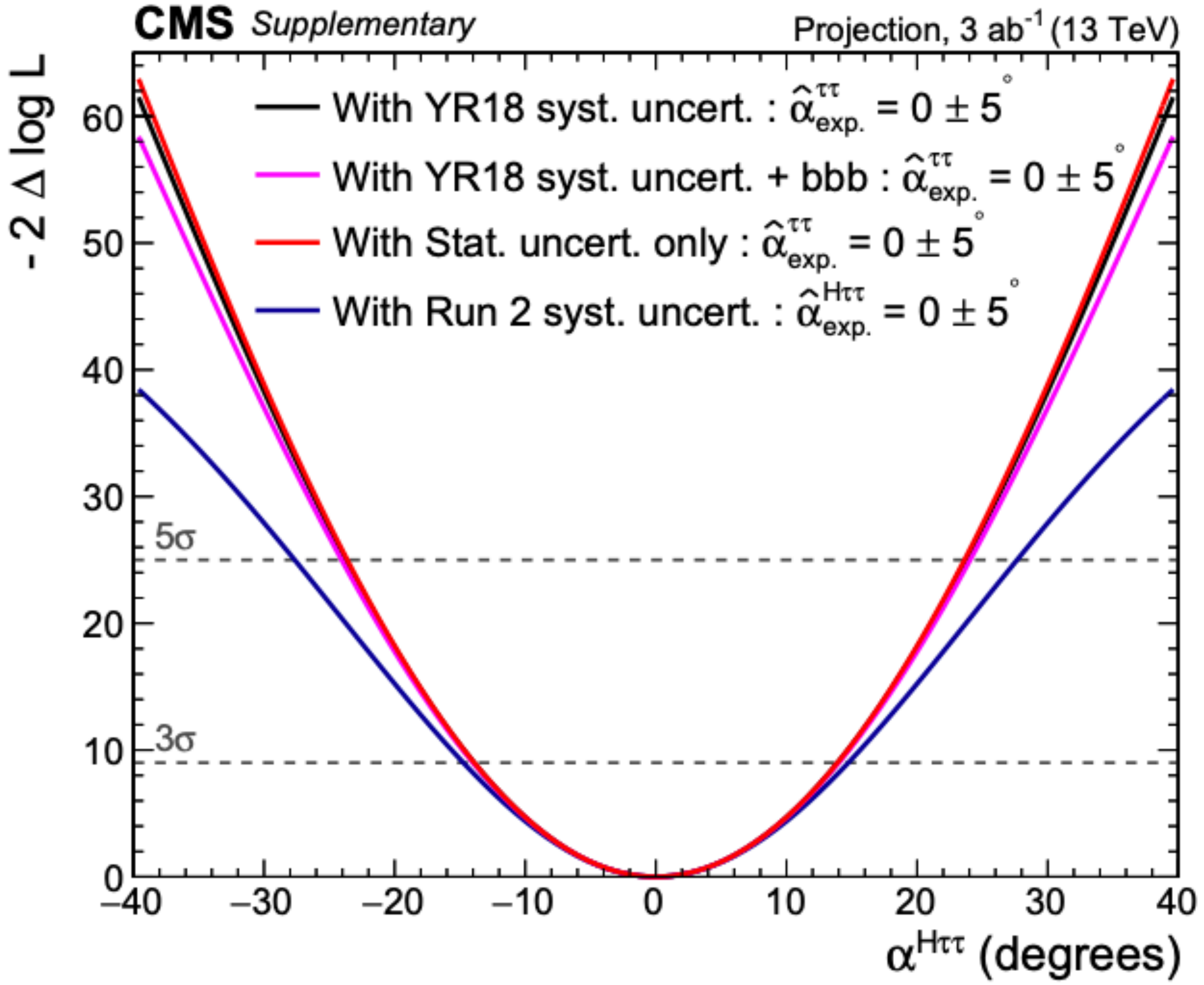
- How well can we measure mH in the future? And how well do we *need* to measure it?
- Precision better than 30 MeV reachable.

Total Width

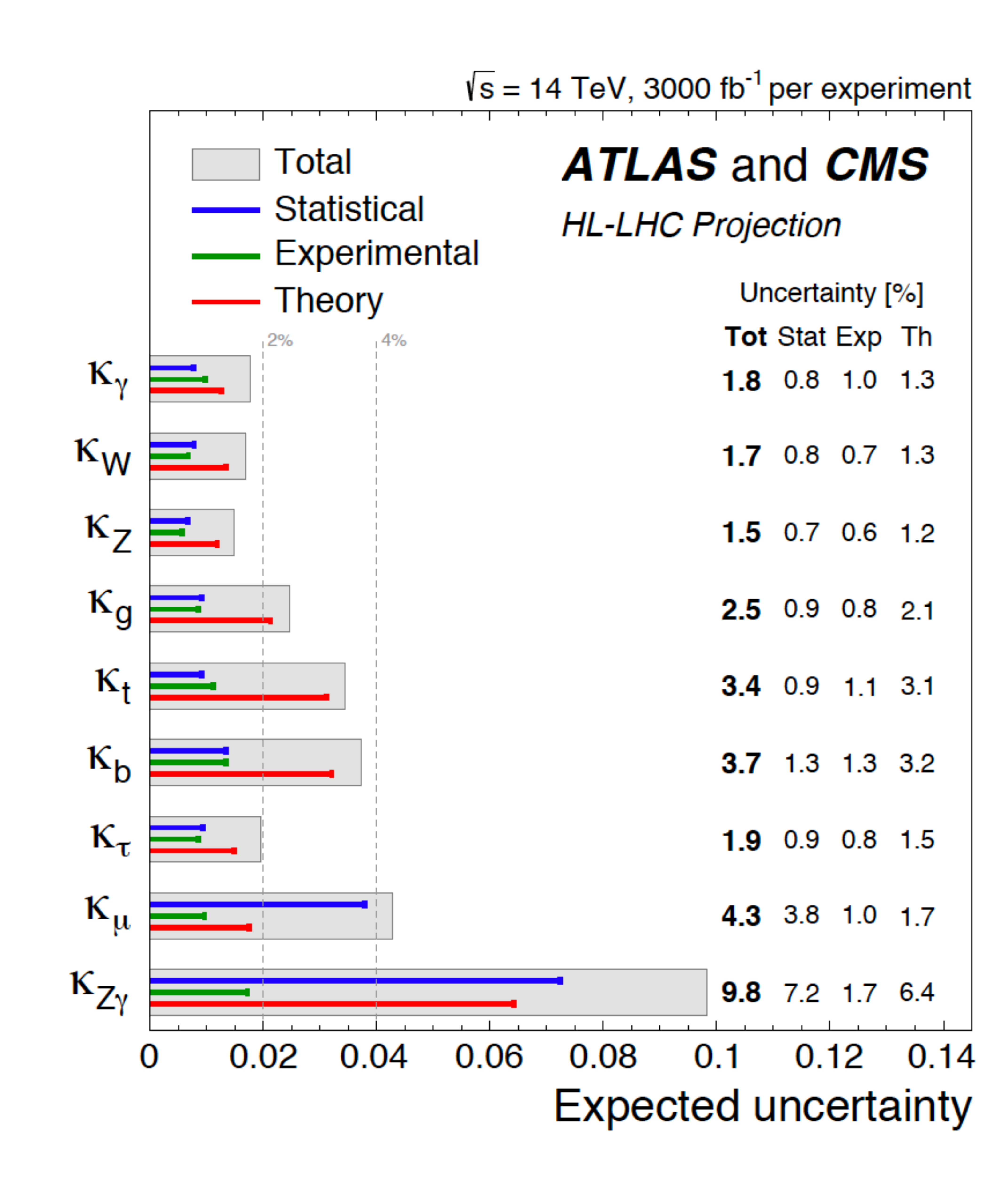
Very small in SM! (4 MeV)
Direct @ HL-LHC: <177 MeV (95%CL)
Offshell/onshell $H \to ZZ -> 4l$



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



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

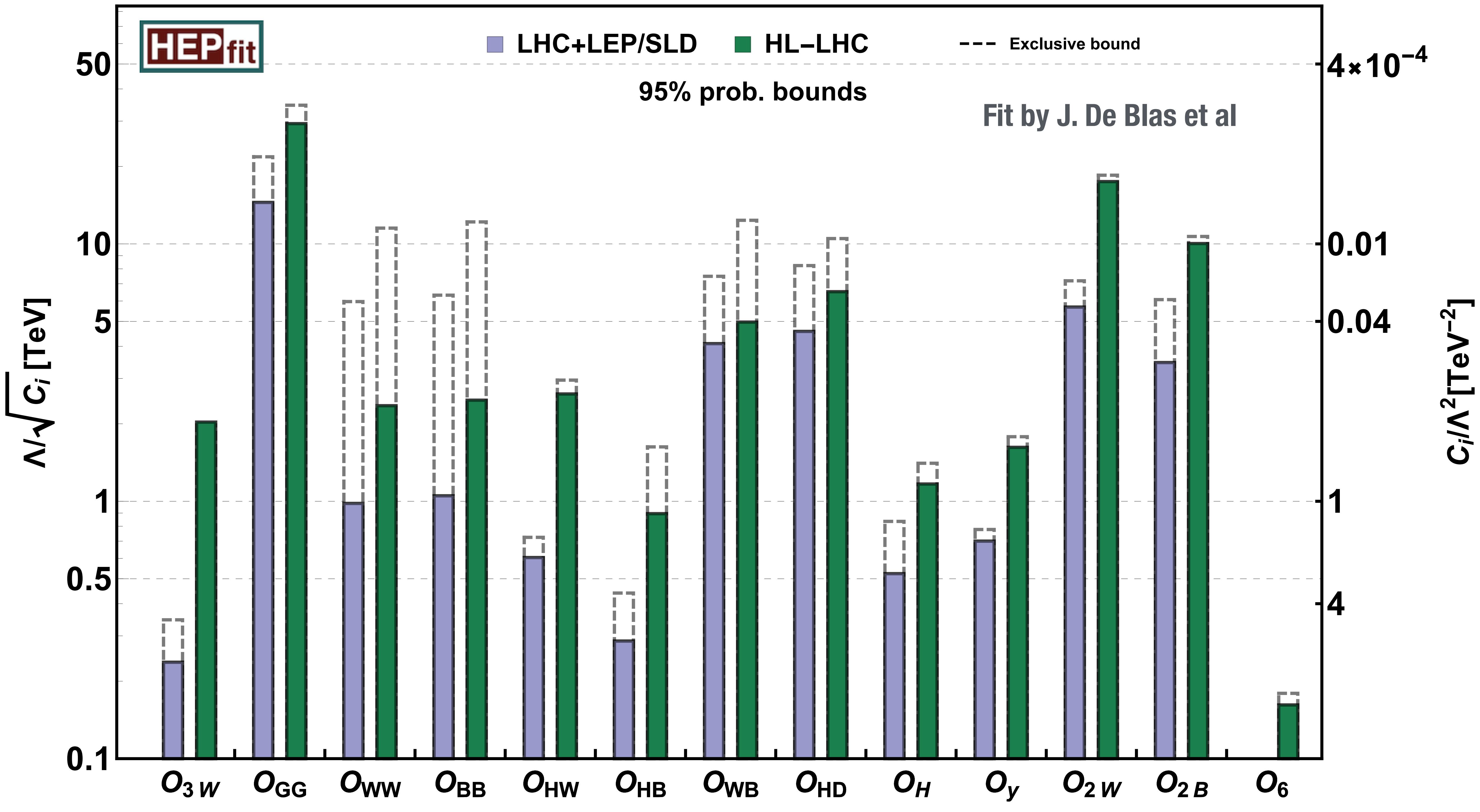
- Generically new physics effects on couplings $\sim \frac{v^2}{M^2} \sim \mathcal{O}(6\%)$ for M=1 TeV
- Only now are we approaching sensitivity where we expect deviations

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**
- **Complicated to do!: long experimental process, through Run3 to the HL-LHC**

Higgs couplings + DY + Diboson observables



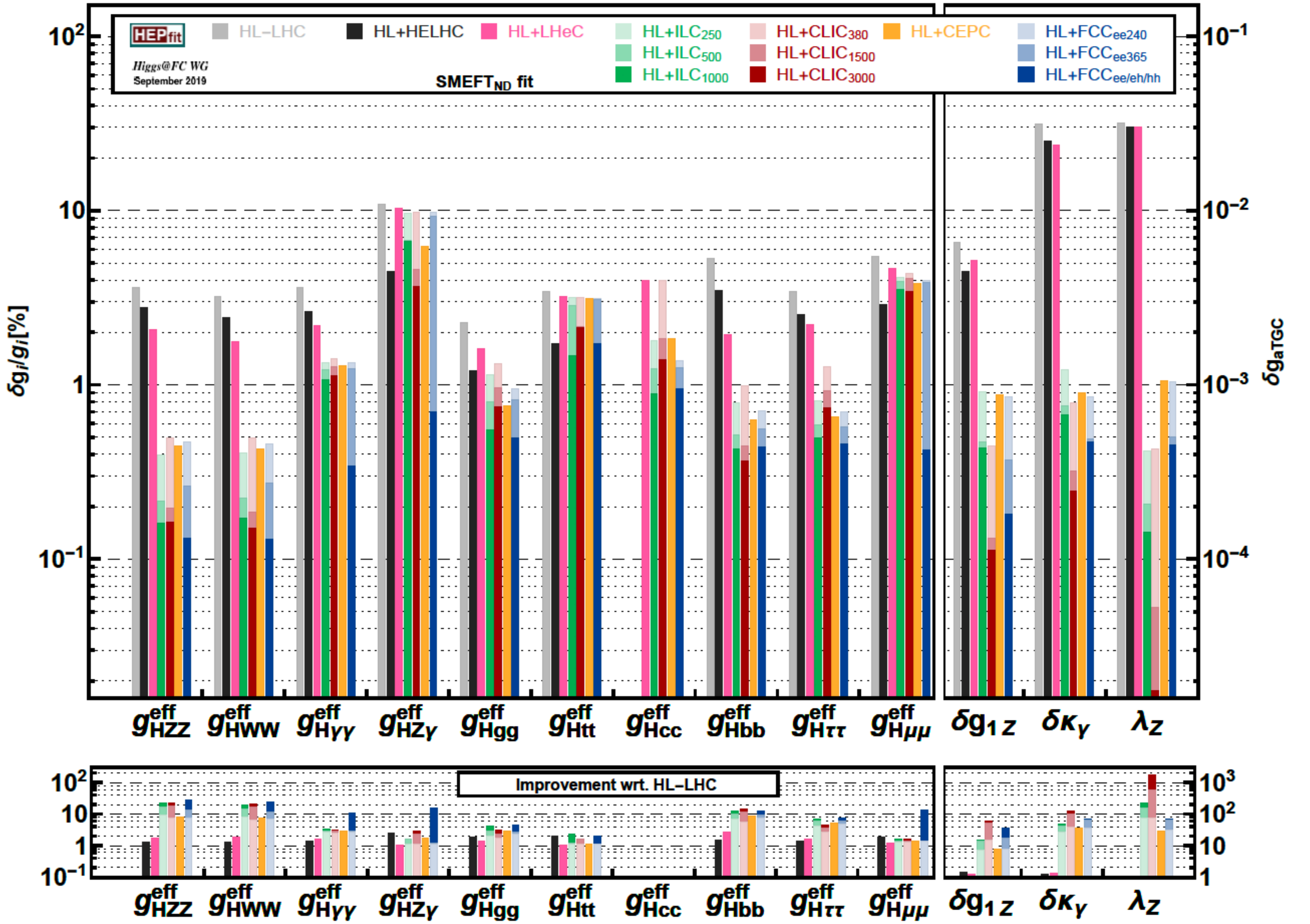
95% probability limits on the new physics interaction scale

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

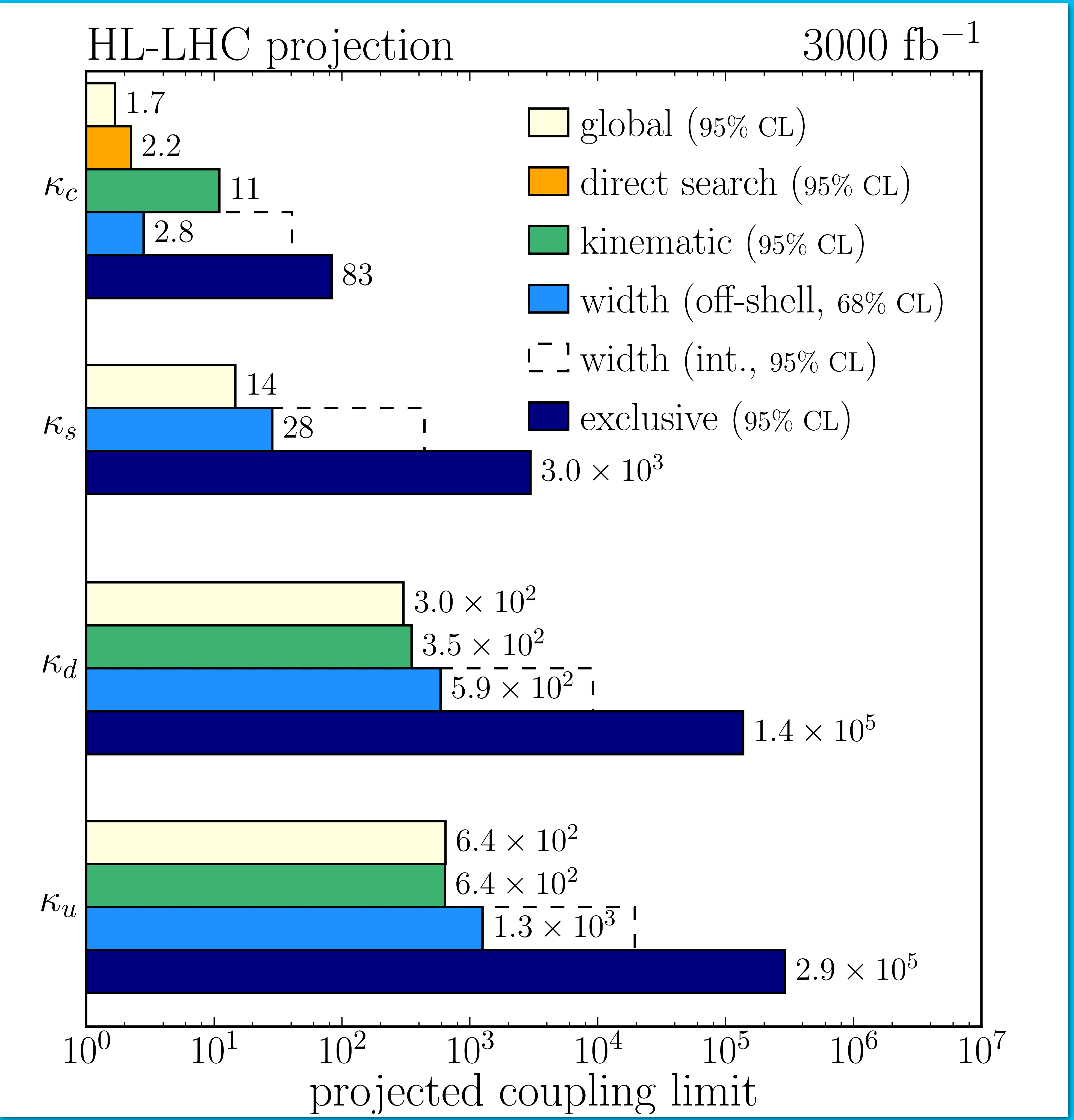
AND BEYOND HL-LHC?

	LHeC *	HE-LHC S2′ *	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
κ_W *	3.8	1.9	1.4	5.2	6.2	2.1	3.8	3.9	1.7	1.7	3.7	7.9
κ_Z *	1.9	1.9	4.5	5.9	5.7	3.0	3.2	3.3	7.2	6.5	7.6	8.1
κ_g	1.2	2.0	1.4	2.4	3.2	1.3	1.8	2.3	2.0	1.7	2.2	4.0
κ_γ	1.1	2.0	1.1	1.3	1.5	1.1	1.2	1.3	1.2	1.2	1.2	5.2
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	2.0	1.0	1.1	2.3	1.0	1.5	1.5	1.0	1.0	1.0	3.3
κ_b	2.1	1.8	2.3	4.5	5.3	2.1	4.1	4.7	2.7	2.5	3.9	5.2
κ_μ	1.0	2.9	1.0	1.1	1.2	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.1	2.1	1.5	2.5	3.0	1.1	1.6	2.0	1.8	1.7	2.4	3.5
Br_{inv}	1.7	1.3	7.3	8.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.1	1.7	2.2	2.9	2.9	1.5	1.7	1.7	3.6	3.3	4.0	4.0
Br_{unt} **		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

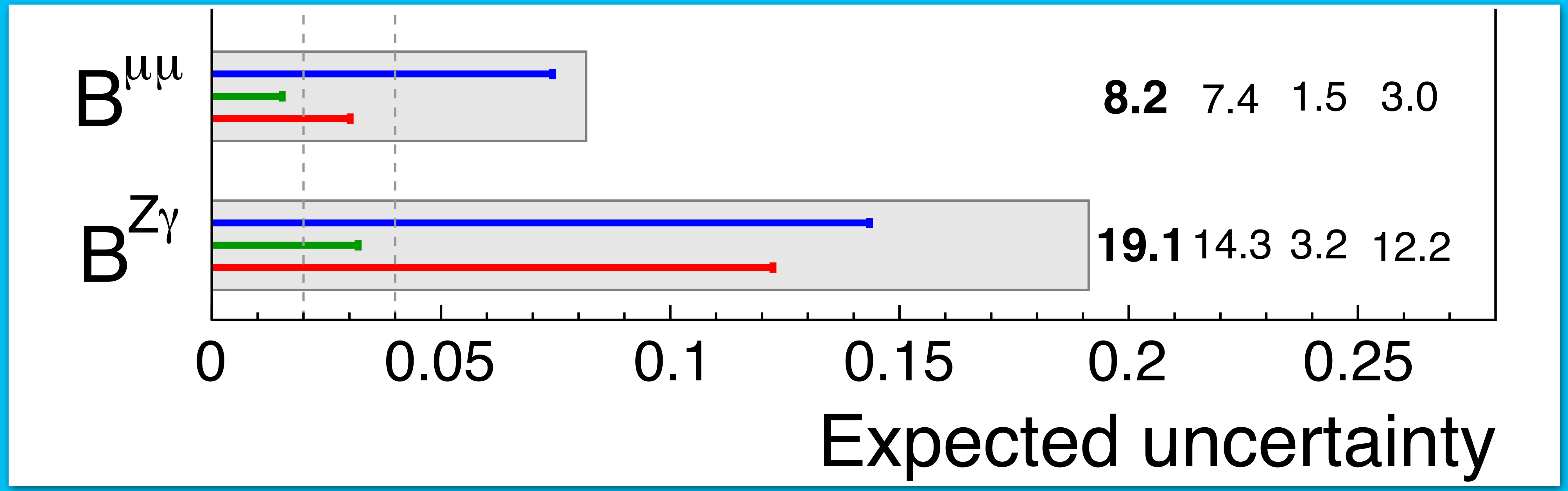
(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HLLHC



RARE DECAYS

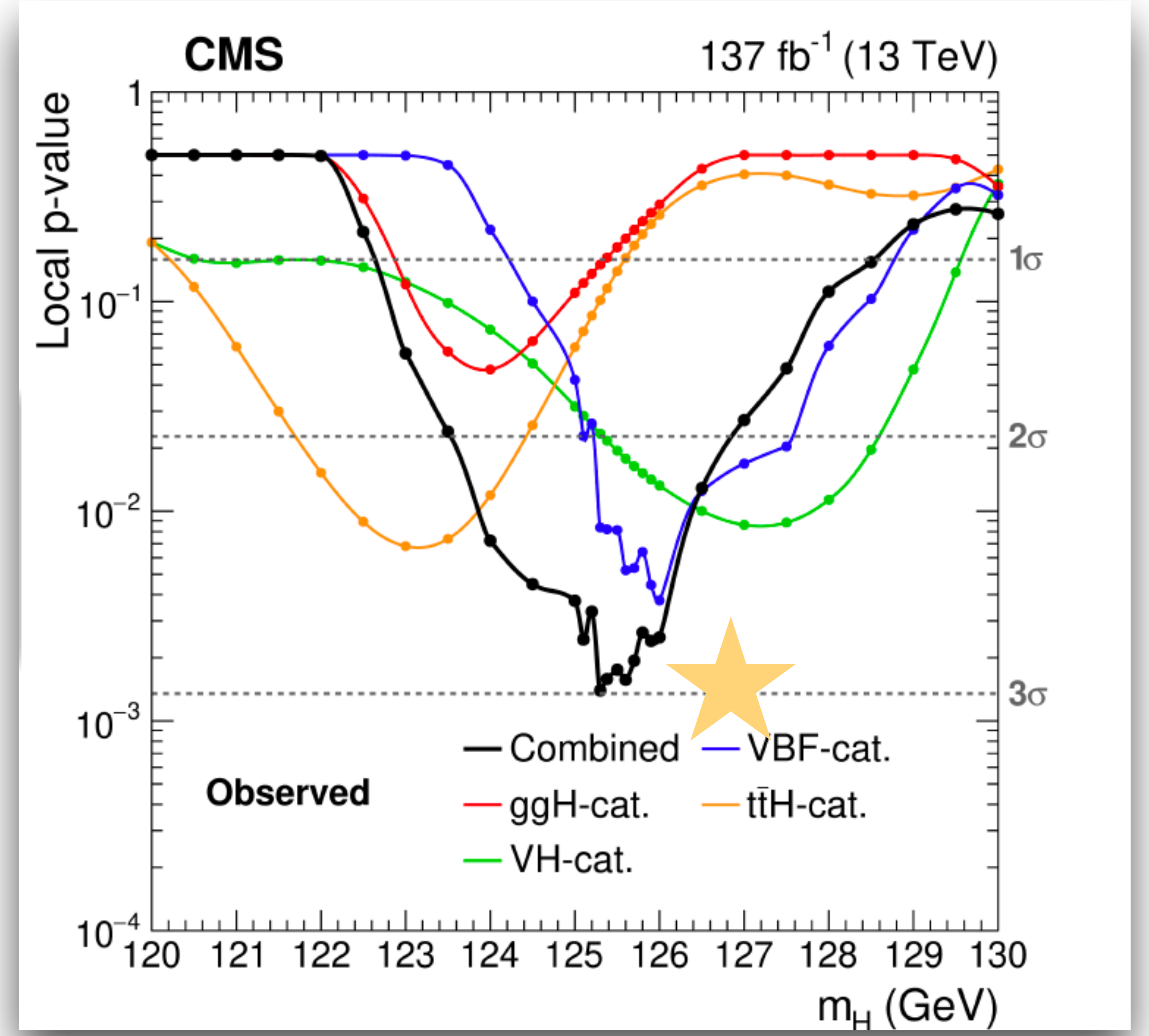


HL-LHC projection
3000 fb^{-1}
global (95% CL)
direct search (95% CL)
kinematic (95% CL)
width (off-shell, 68% CL)
width (int., 95% CL)
exclusive (95% CL)
κ_c
1.7
2.2
11
2.8
83
κ_s
14
28
3.0×10^3
κ_d
3.0×10^2
3.5×10^2
5.9×10^2
1.4×10^5
κ_u
6.4×10^2
6.4×10^2
1.3×10^3
2.9×10^5
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
projected coupling limit



$B^{\mu\mu}$
8.2 7.4 1.5 3.0
$B^{Z\gamma}$
19.1 14.3 3.2 12.2
0 0.05 0.1 0.15 0.2 0.25
Expected uncertainty

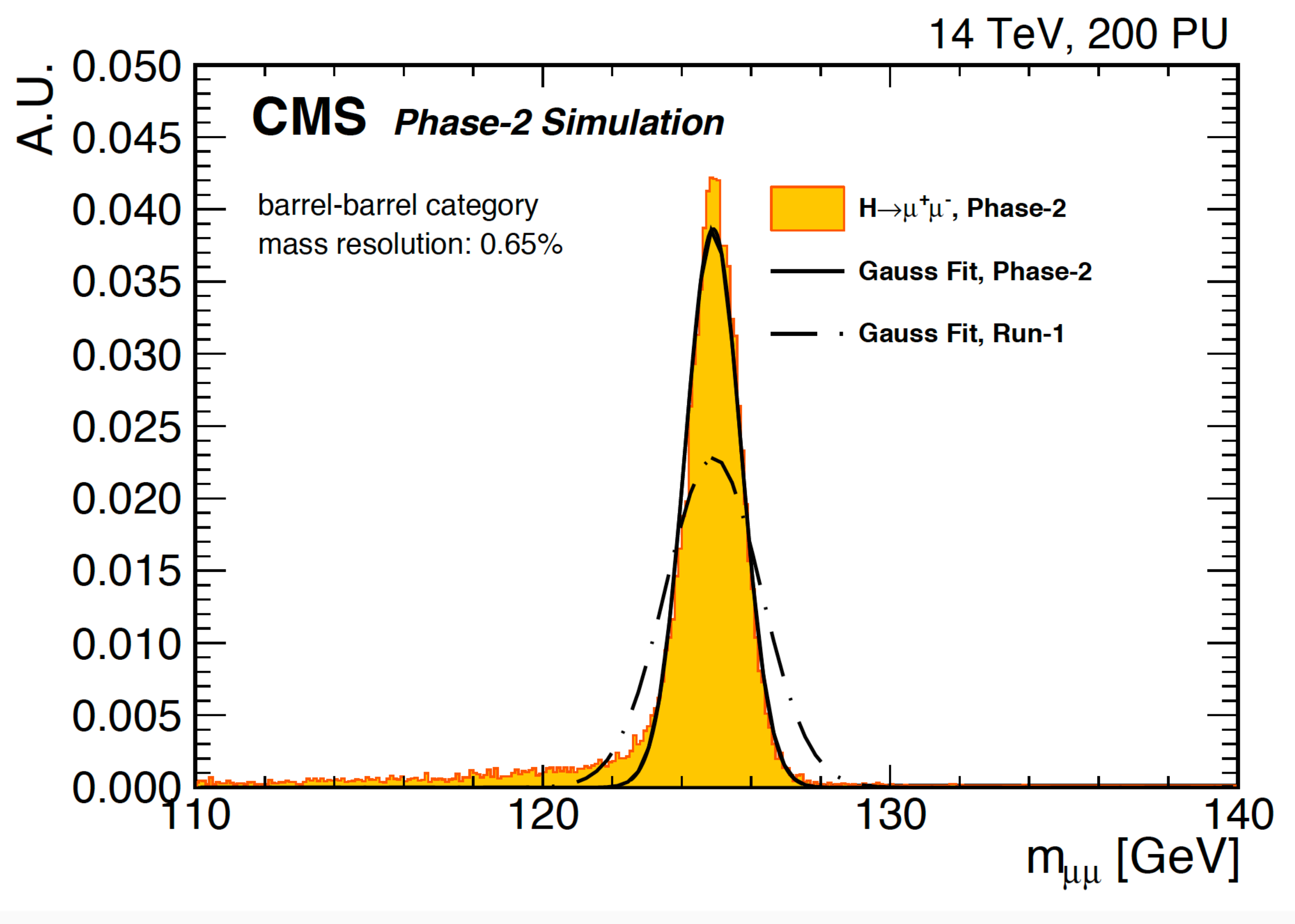
COUPLING TO THE SECOND GENERATION: H→μμ

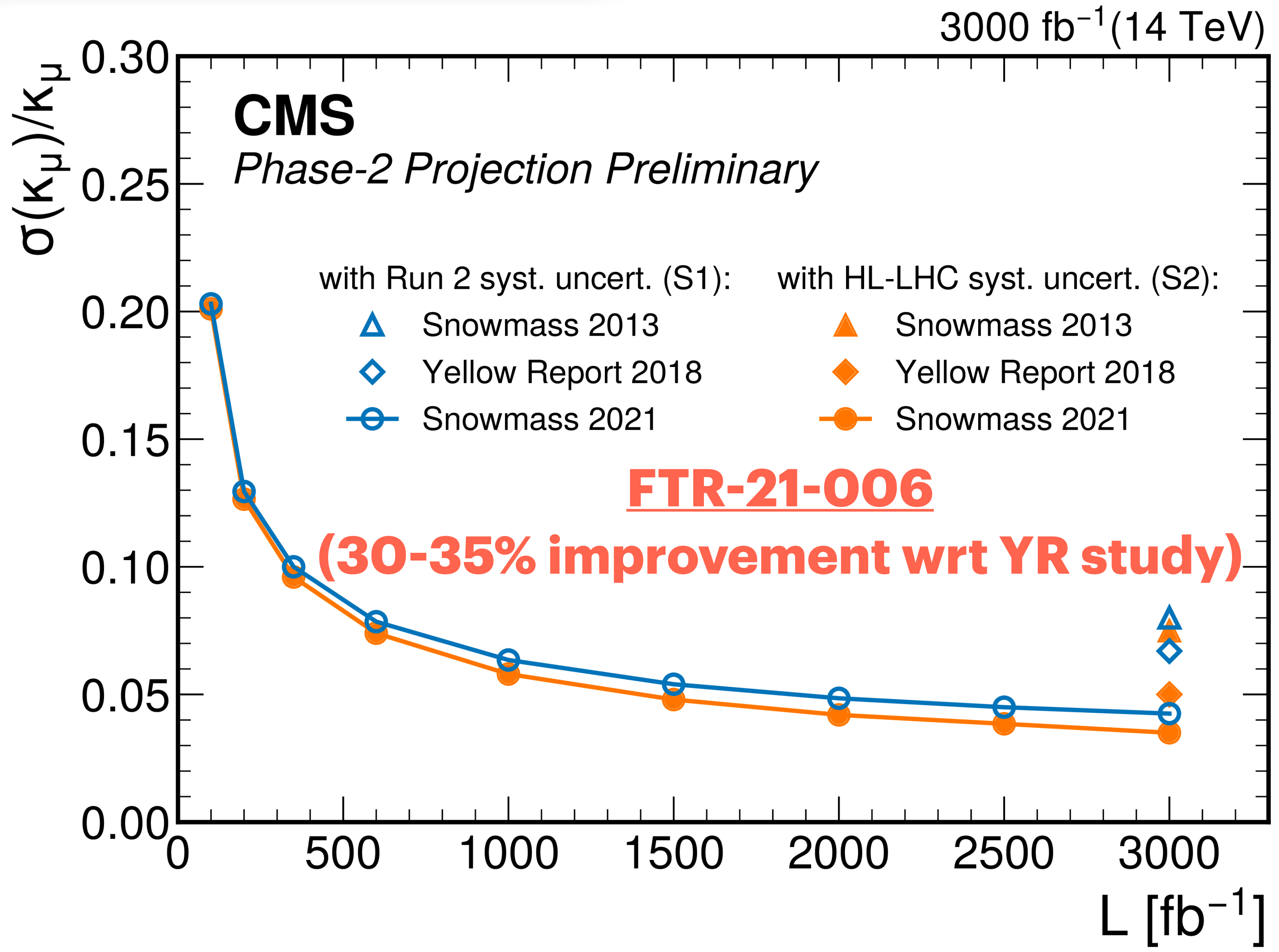


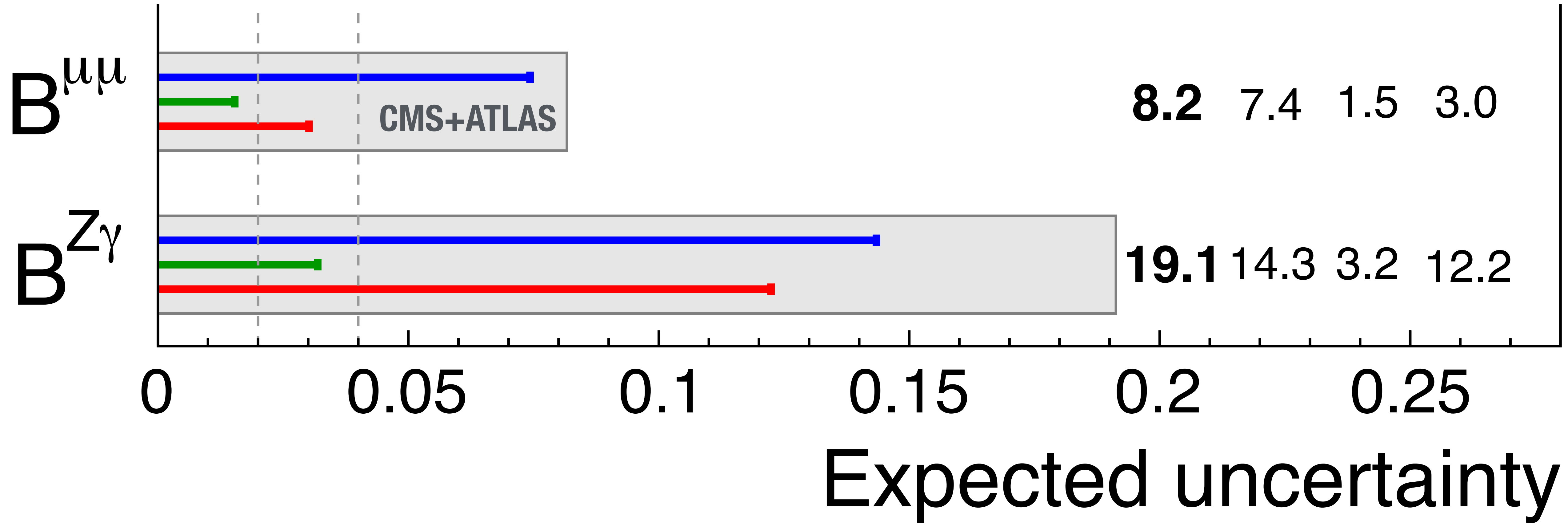
Do all SM families get their mass from the same Higgs field?

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

Observation by the end of Run3

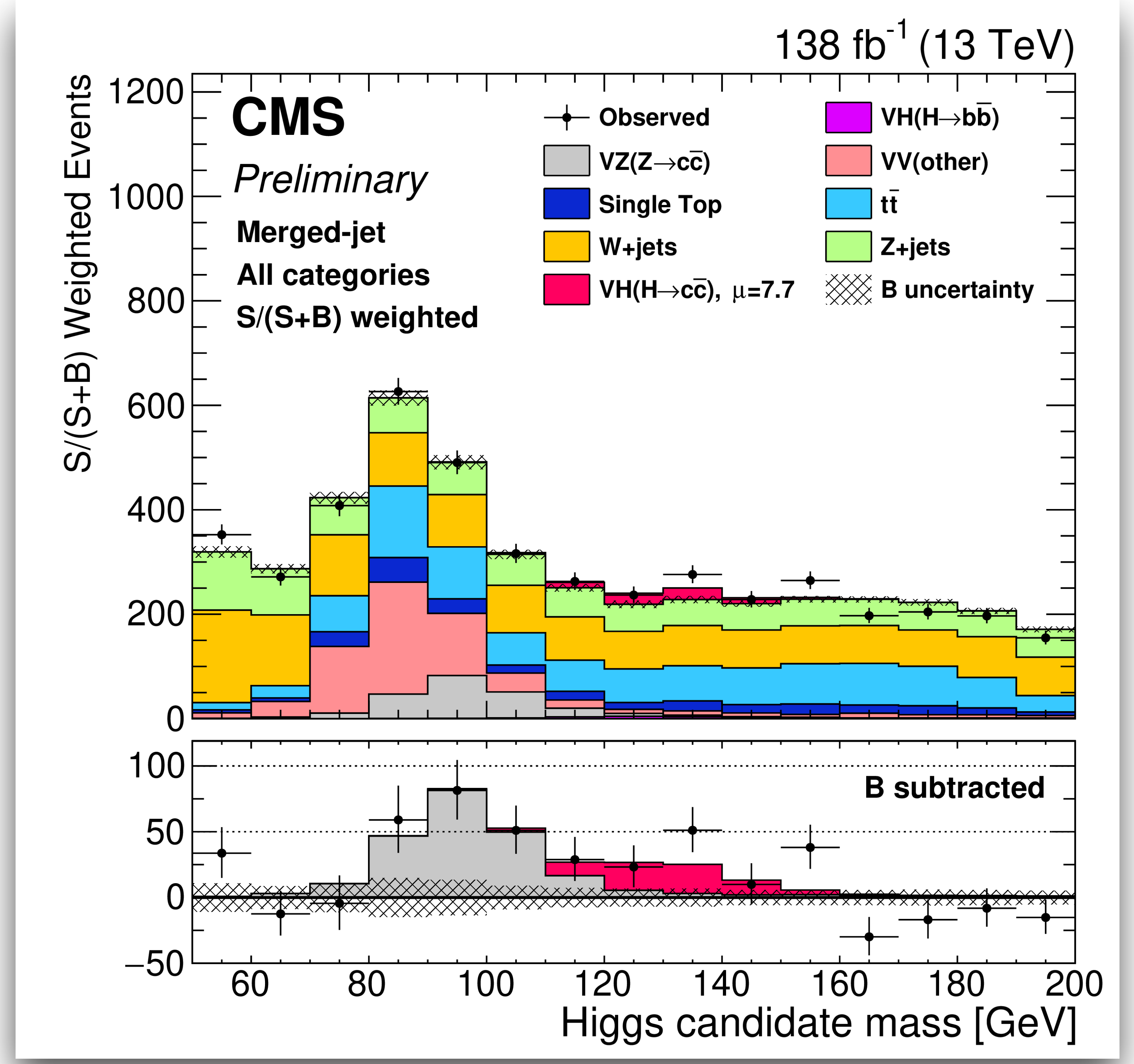


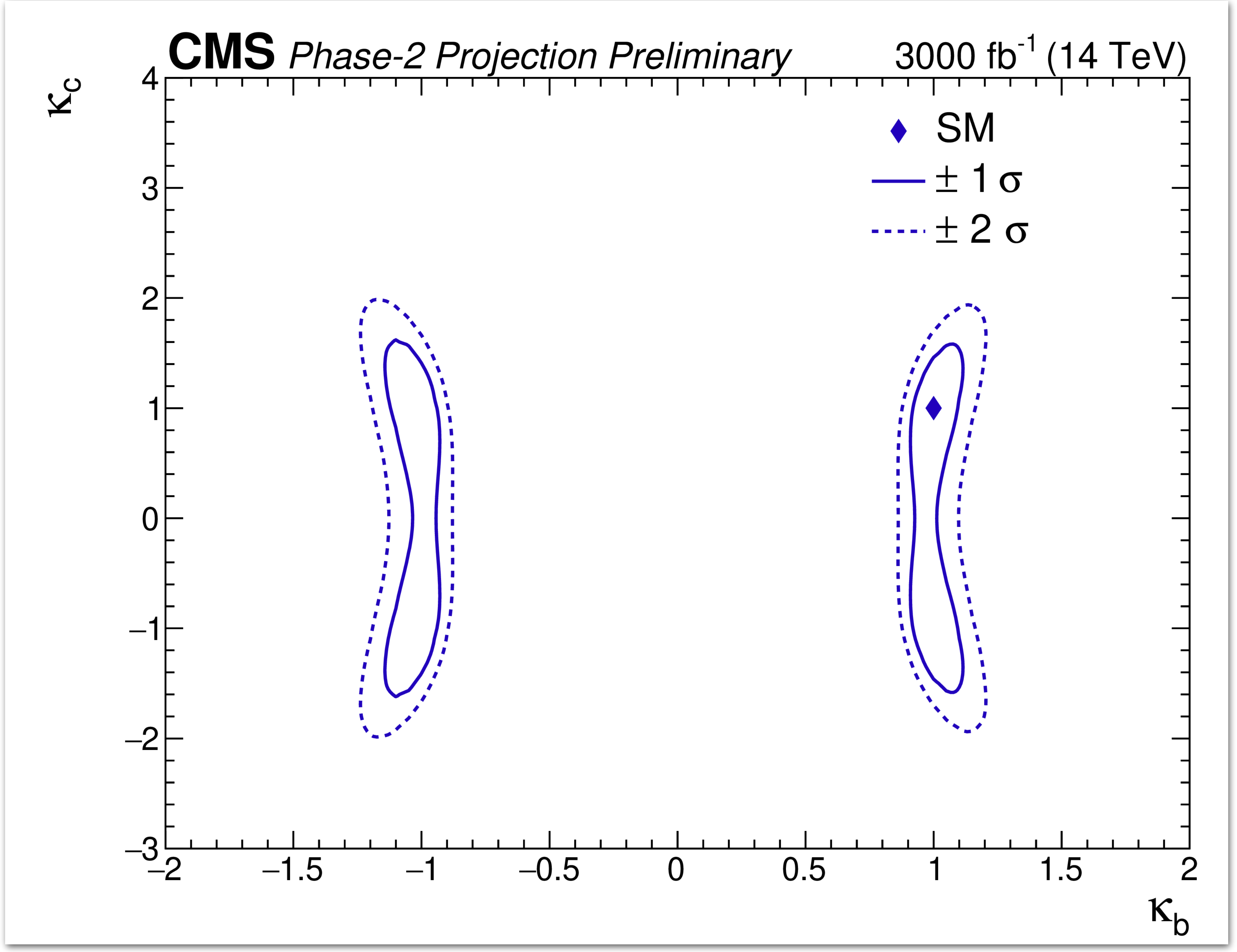




HOW CHARMING IS THE HIGGS?

- What about the coupling to second gen quarks? 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!)
- Future innovations in jet reconstruction, c-identification and analysis can have a large impact !





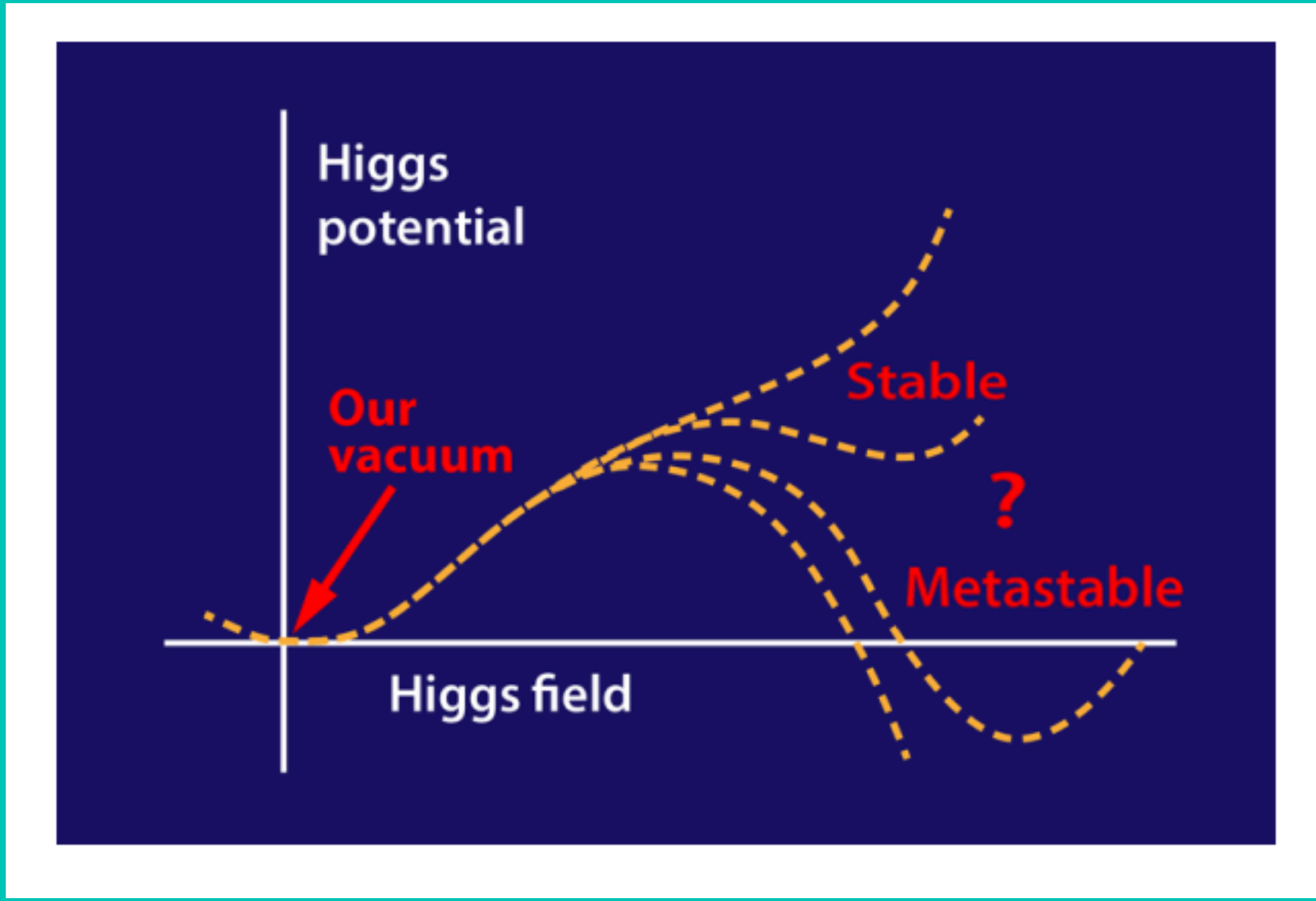
ATLAS 3000 fb^{-1}: $\mu < 6.4$

CMS 3000 fb^{-1}: $\mu < 1.6$

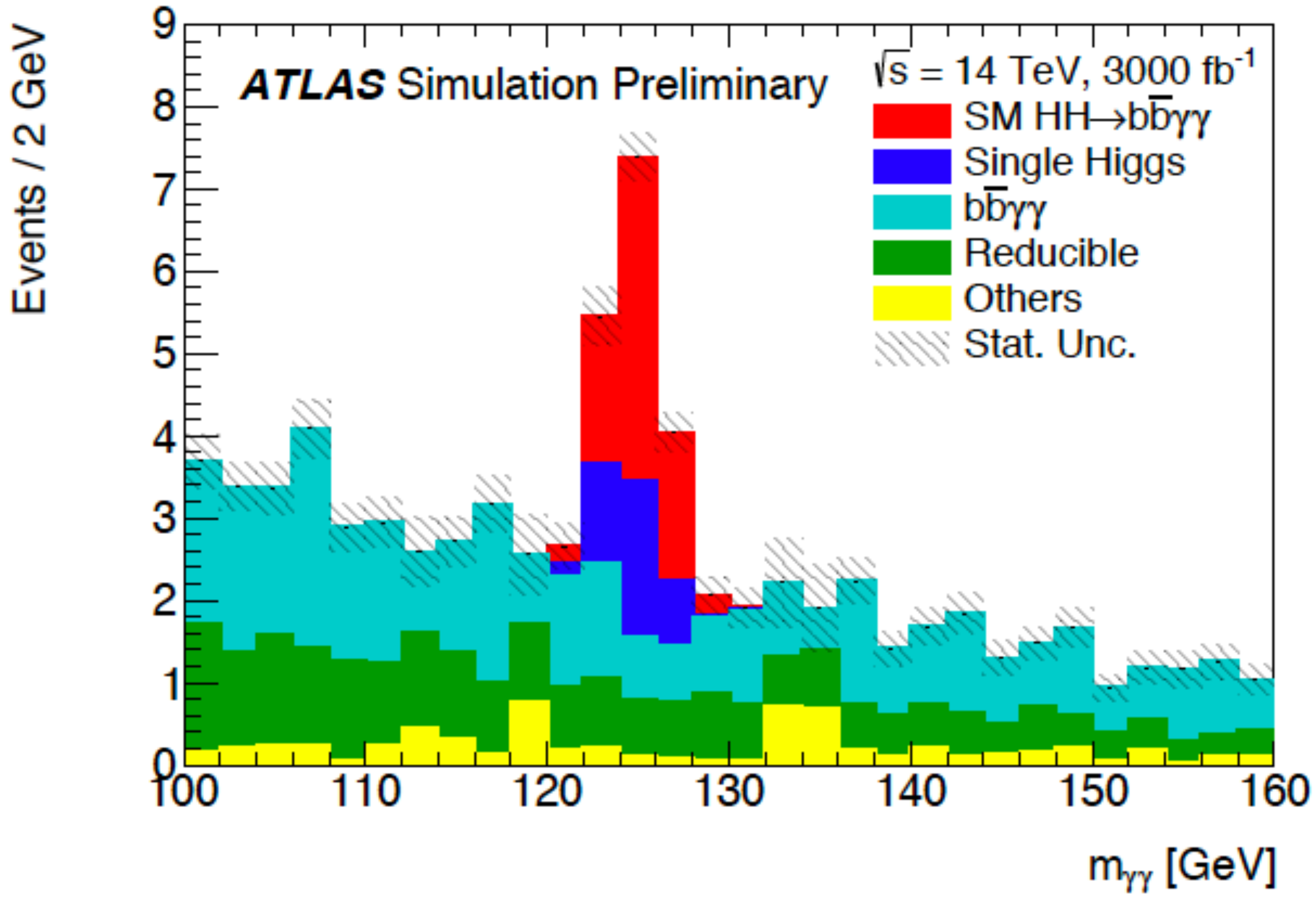
LHCb 300 fb^{-1}: $\mu < O(10)$

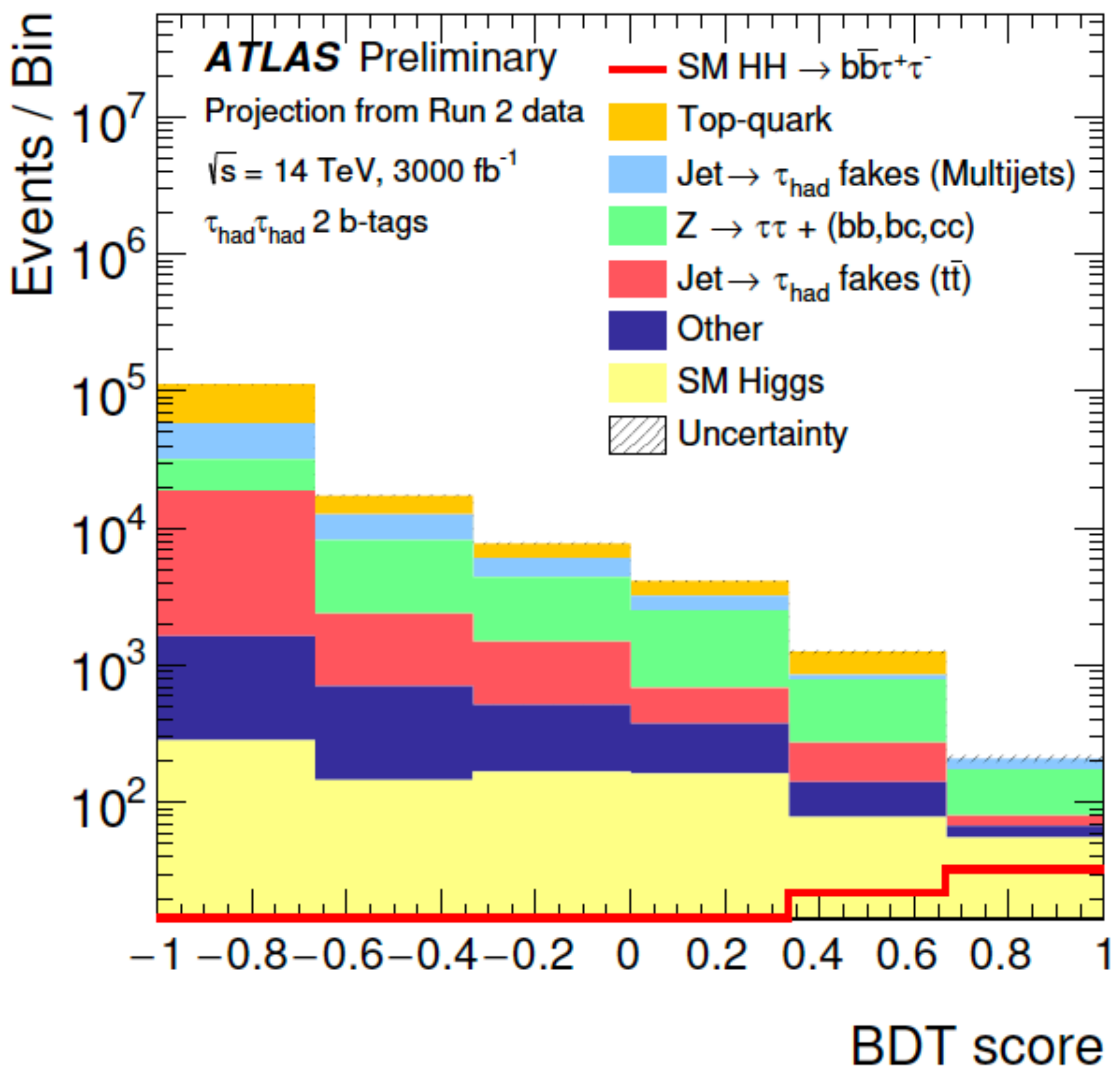
AIM FOR K_C AT $\mathcal{O}(1)$ AT HL-LHC

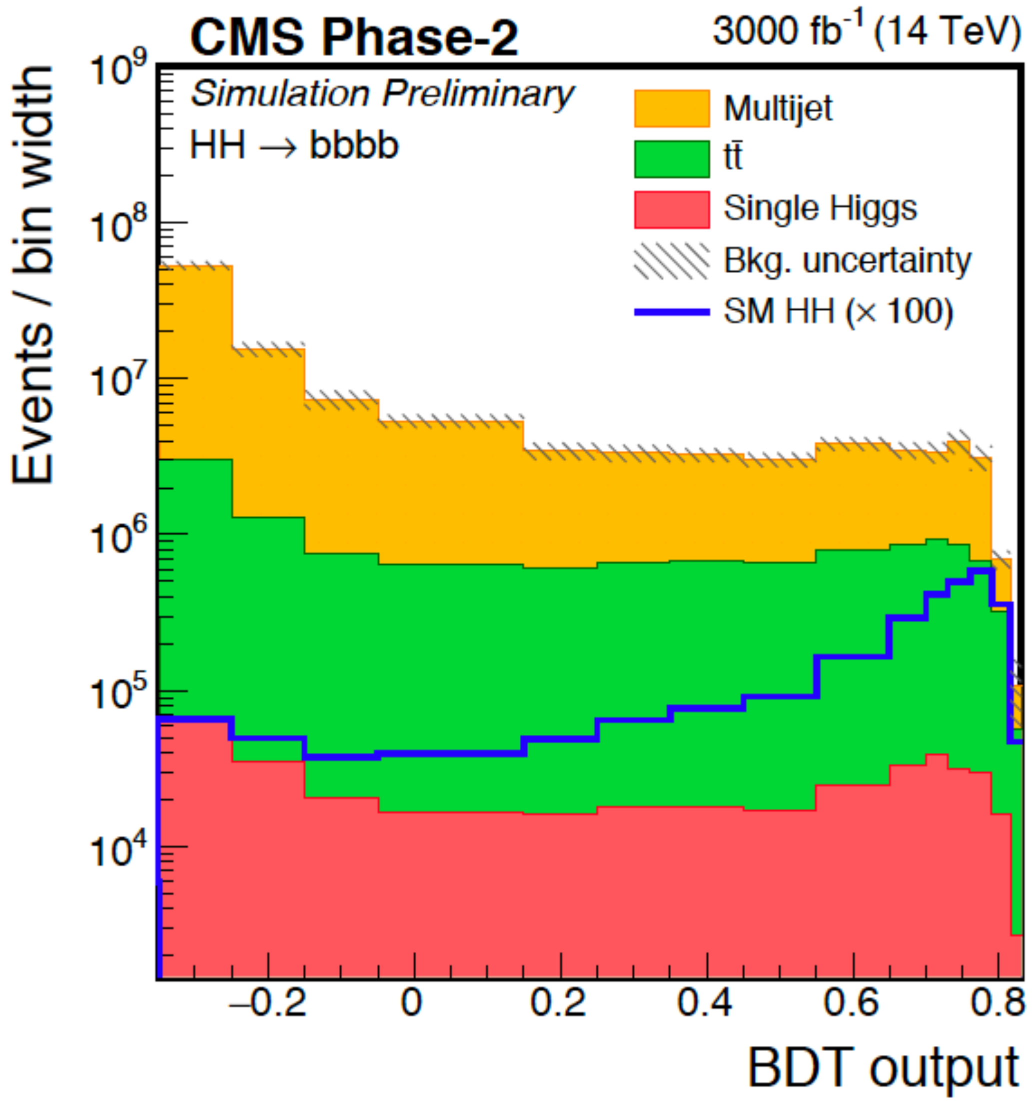
CHASING THE SELF-COUPLING

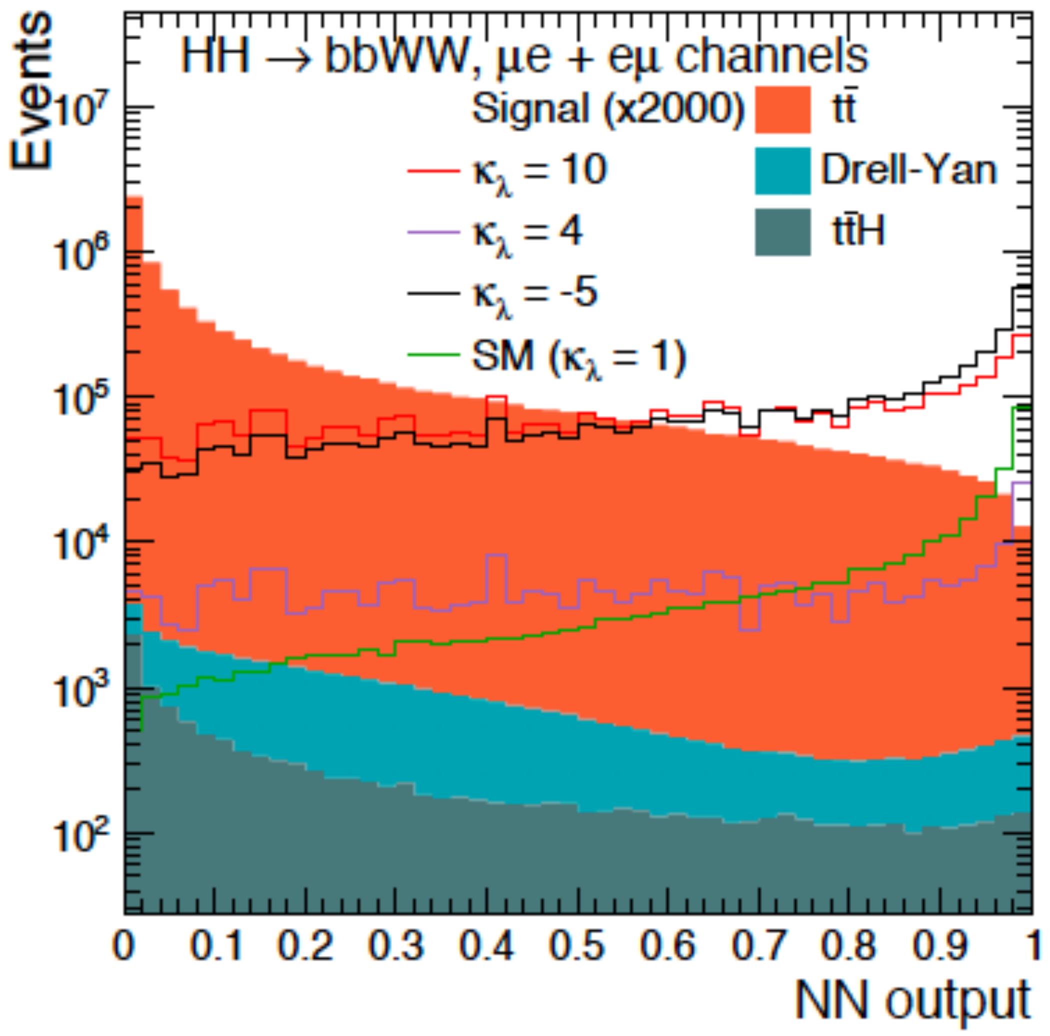


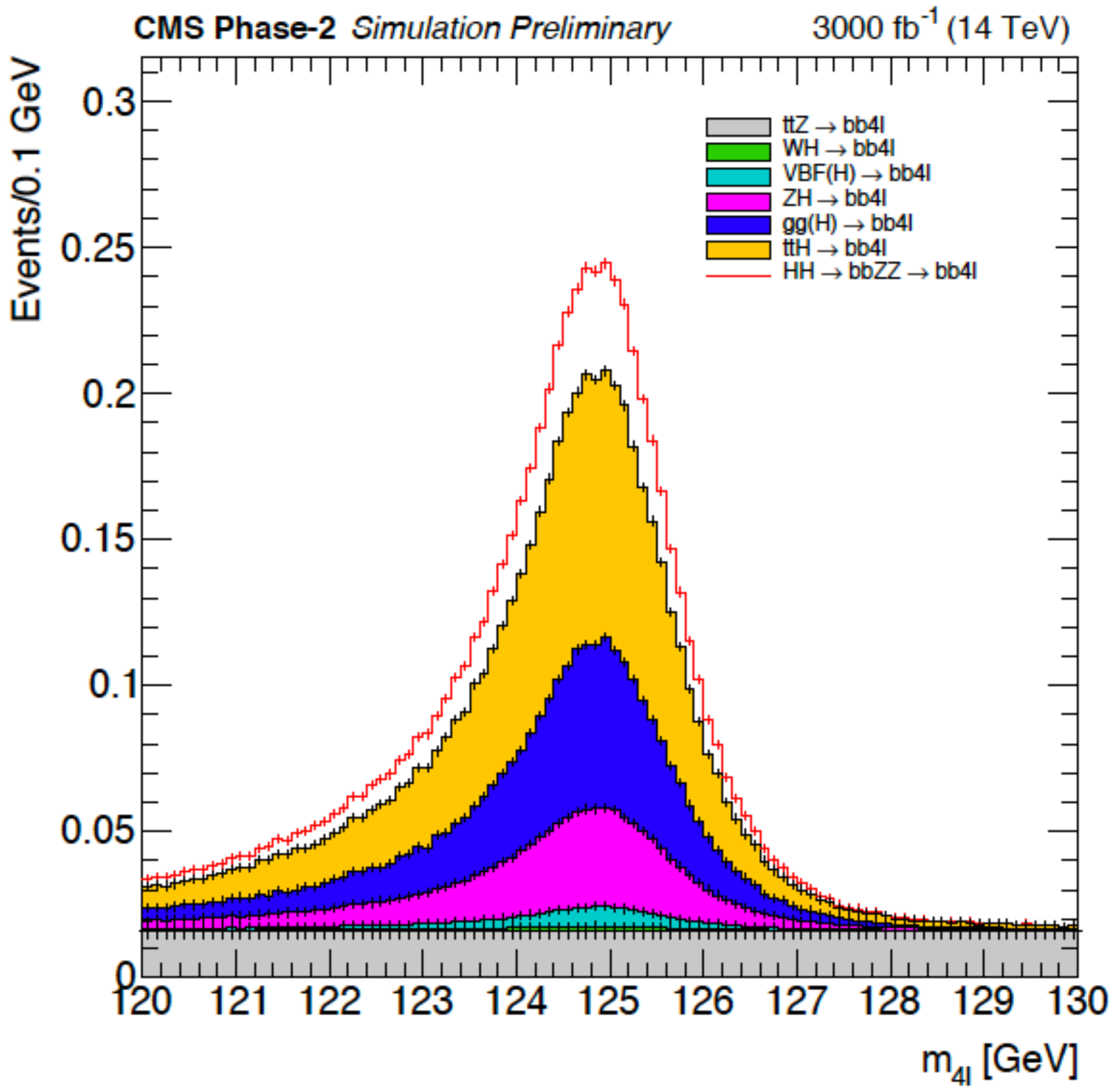
HH: BENCHMARK FOR THE HL-LHC





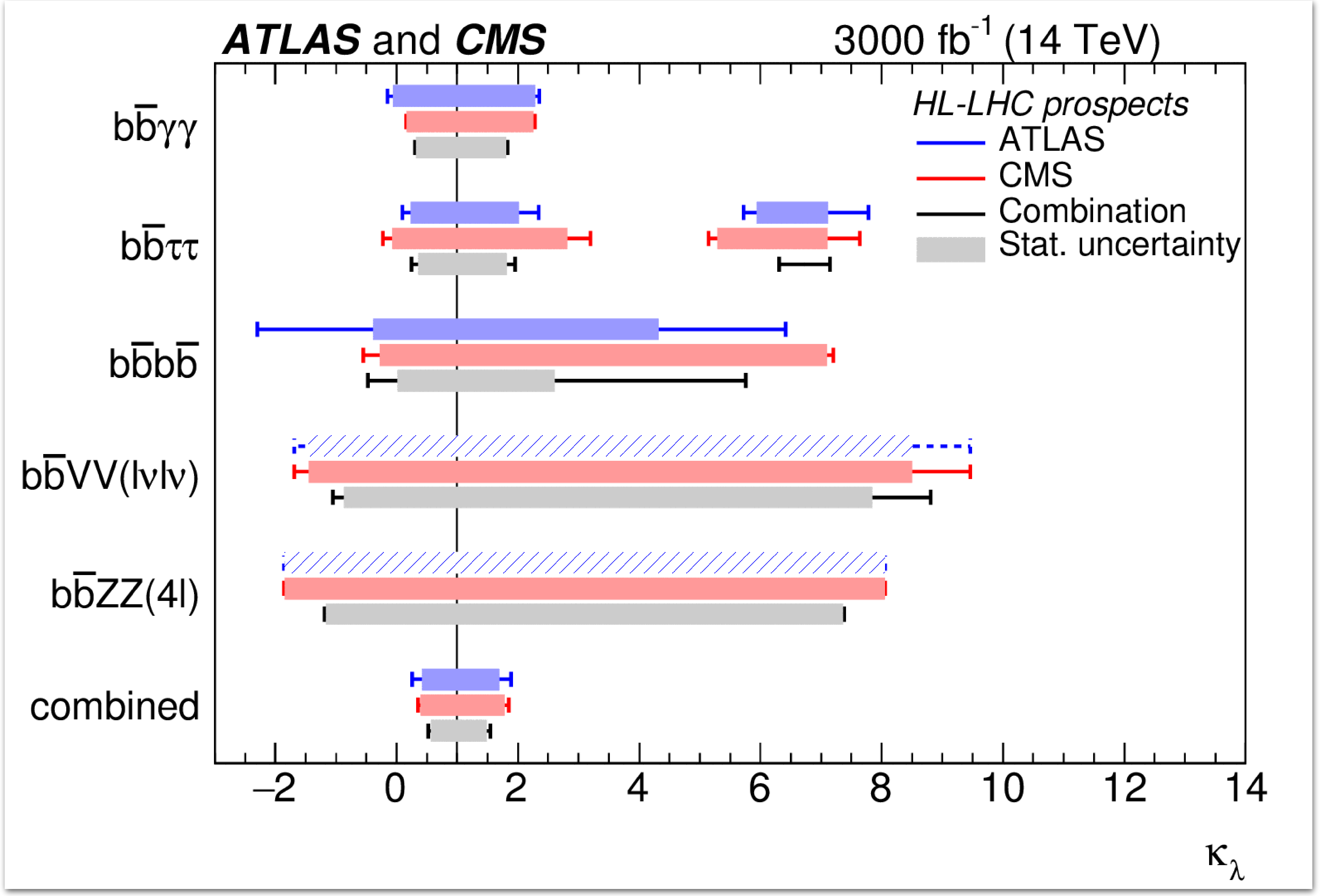


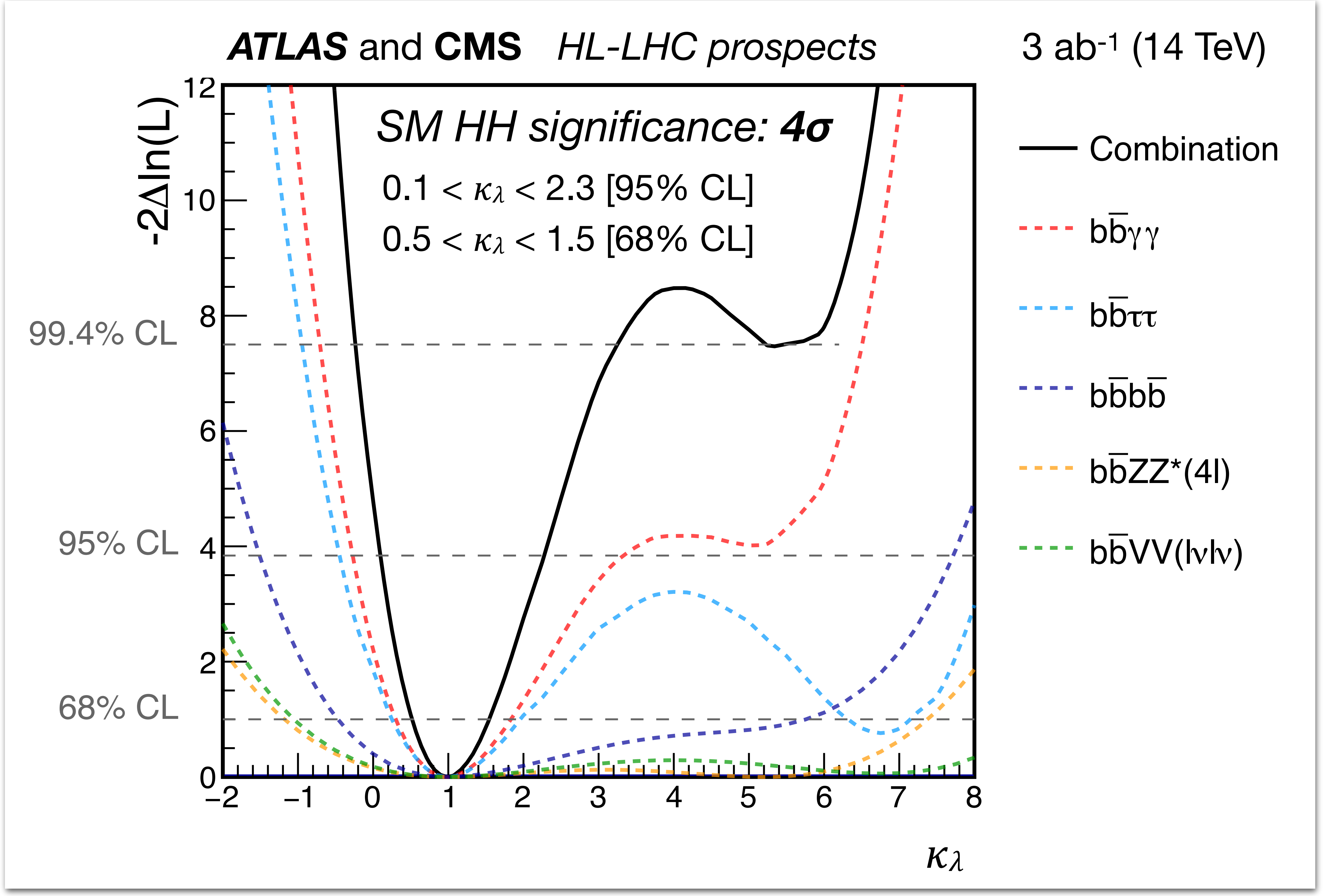




(* indirect constraints on the self coupling also possible, but HH searches dominate)

DIHIGGS @ HL-LHC

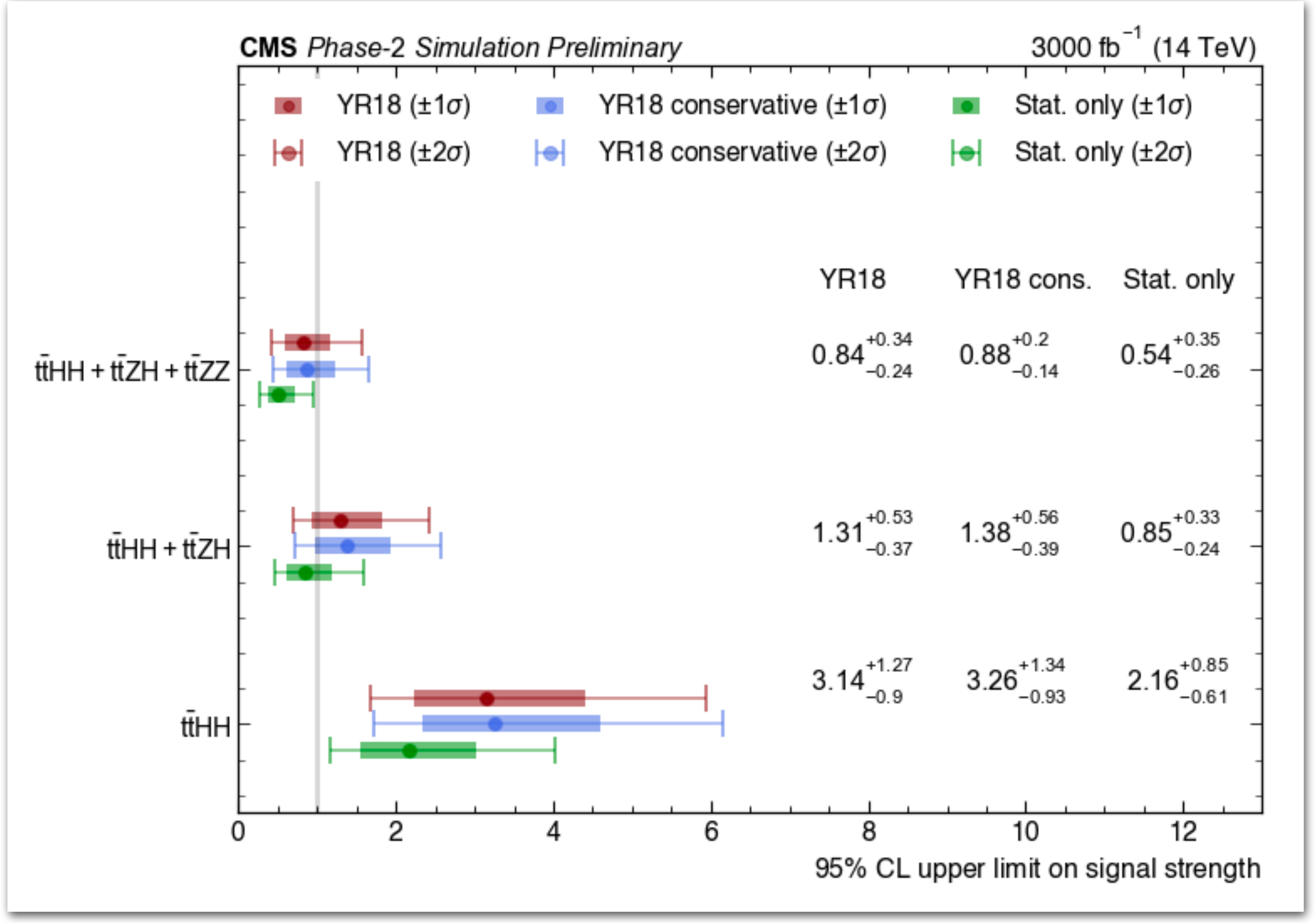




Combining CMS and ATLAS data, in 2018 we projected a significance of 4σ and a 50% uncertainty on κ_λ by the end of HL-LHC . This is likely to be outperformed, and the HL-LHC will reach 5σ

(* indirect constraints on the self coupling also possible, but HH searches dominate)

UPDATES TO THE HH PROJECTIONS

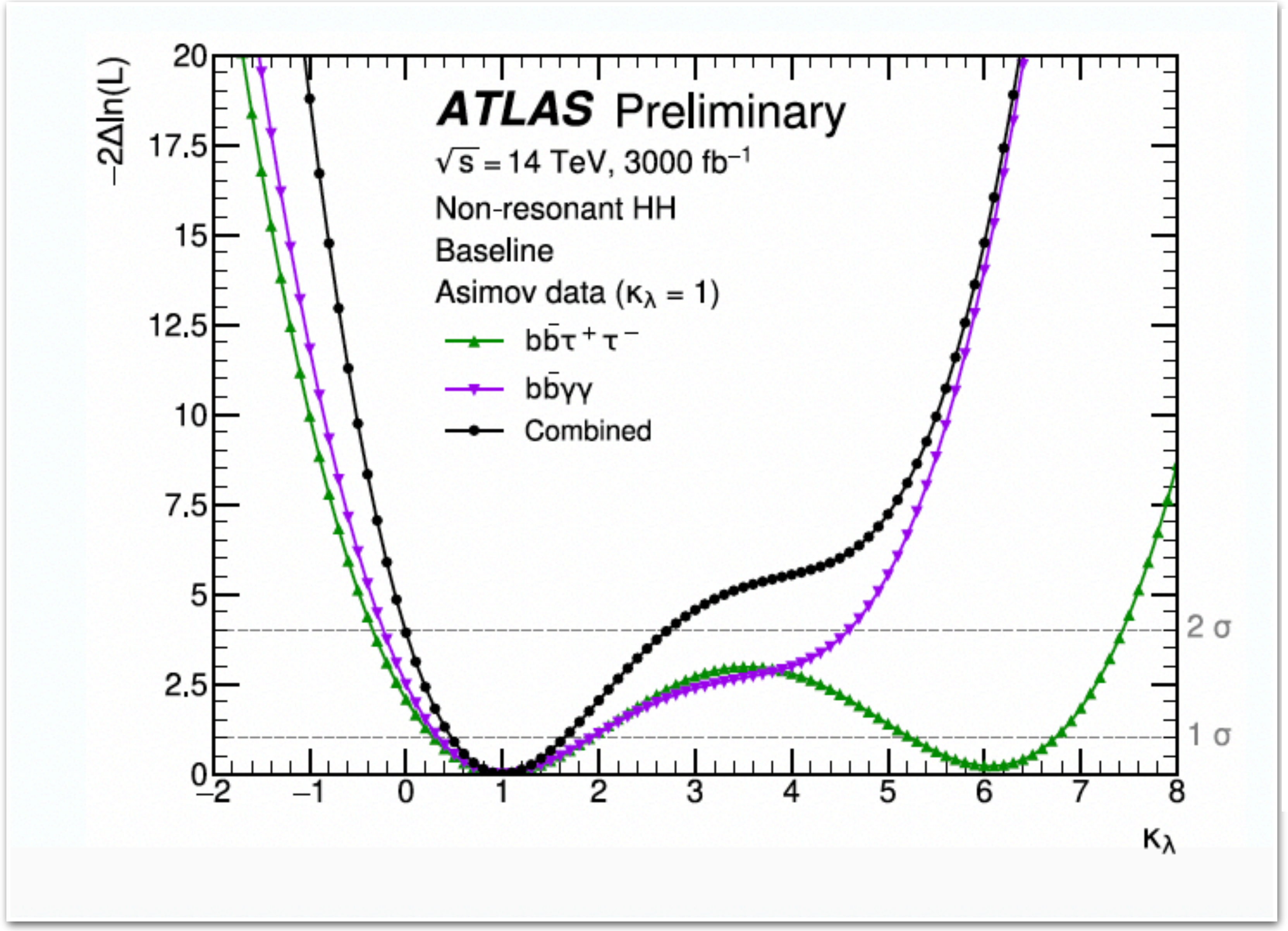


Updates to the projections done in the context of Snowmass: improvements per channel (ATLAS and CMS both improved by ~20-30%) and new channels incorporated (WWγγ ,ττγγ)

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

No VBF prospects yet!

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

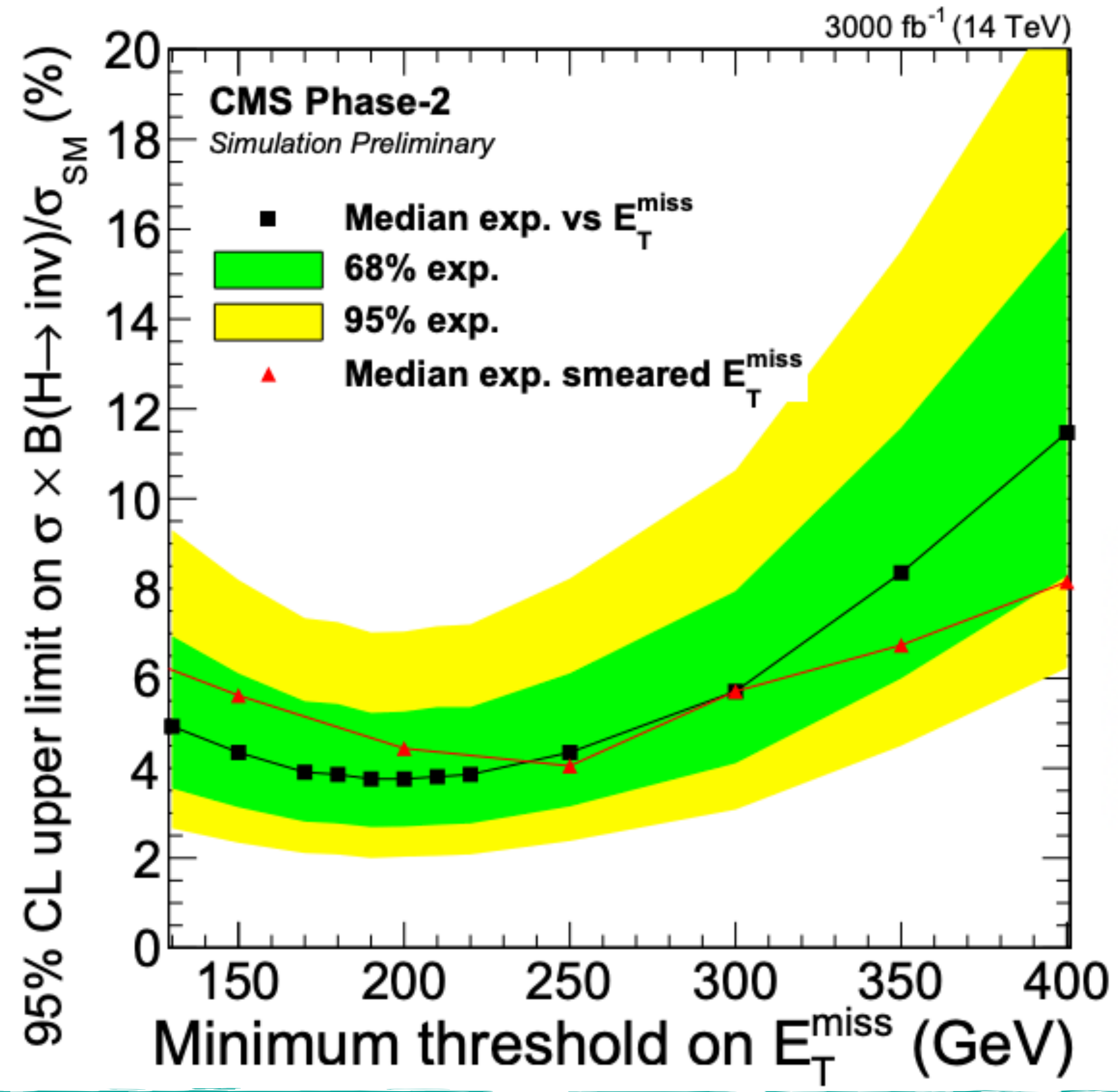


Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	Significance [σ] $b\bar{b}\tau^+\tau^-$	Significance [σ] Combination	Combined signal strength precision [%]
No syst. unc.	2.3	4.0	4.6	$-23/+23$
Baseline	2.2	2.8	3.2	$-31/+34$
Theoretical unc. halved	1.1	1.7	2.0	$-49/+51$
Run 2 syst. unc.	1.1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

WHY SHOULD WE ASSUME THE HIGGS BOSON FOLLOWS THE SM RULES?

IS THE HIGGS THE PORTAL TO NEW PHYSICS?

HIGGS→BSM



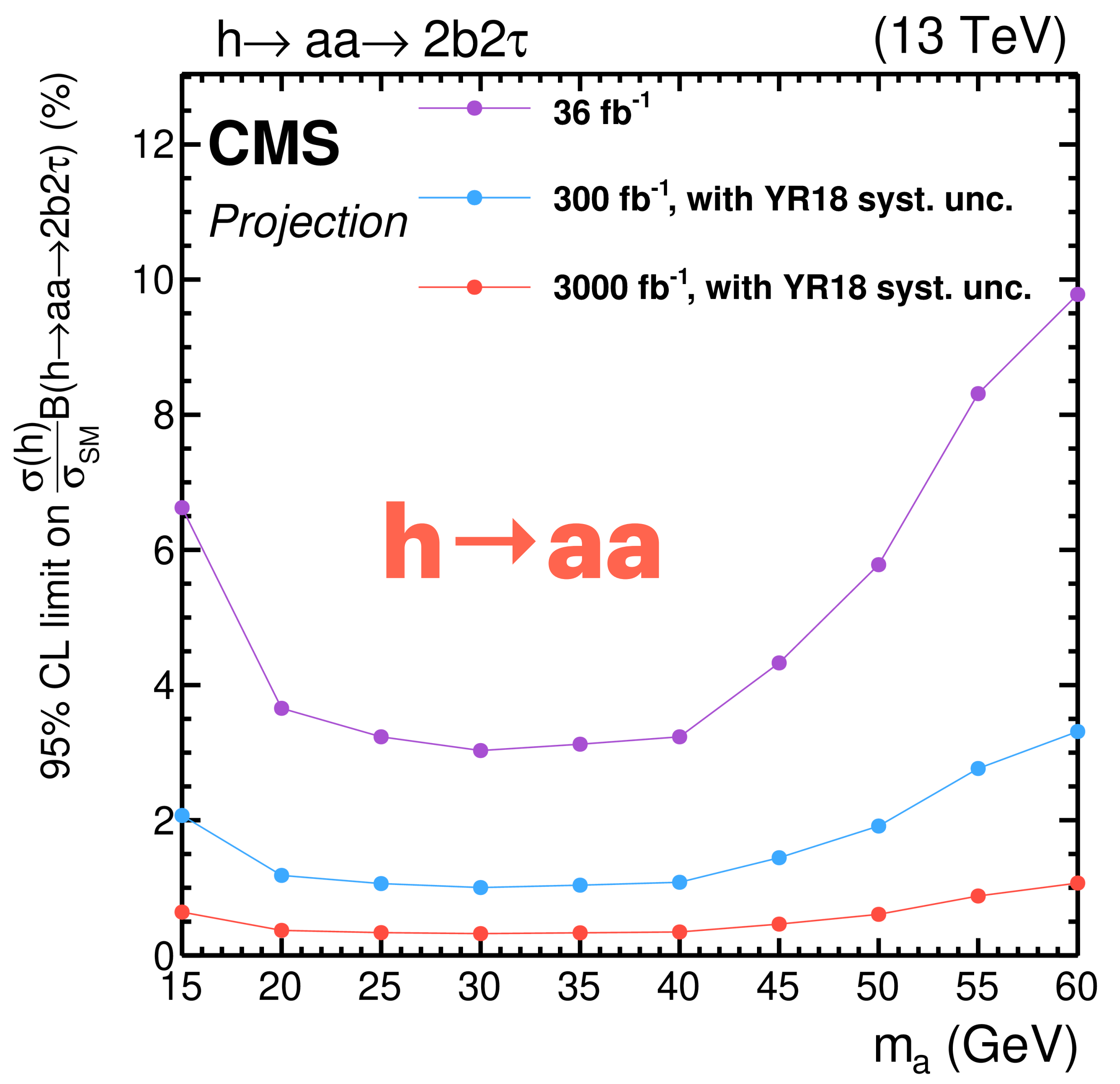
Higgs Invisible

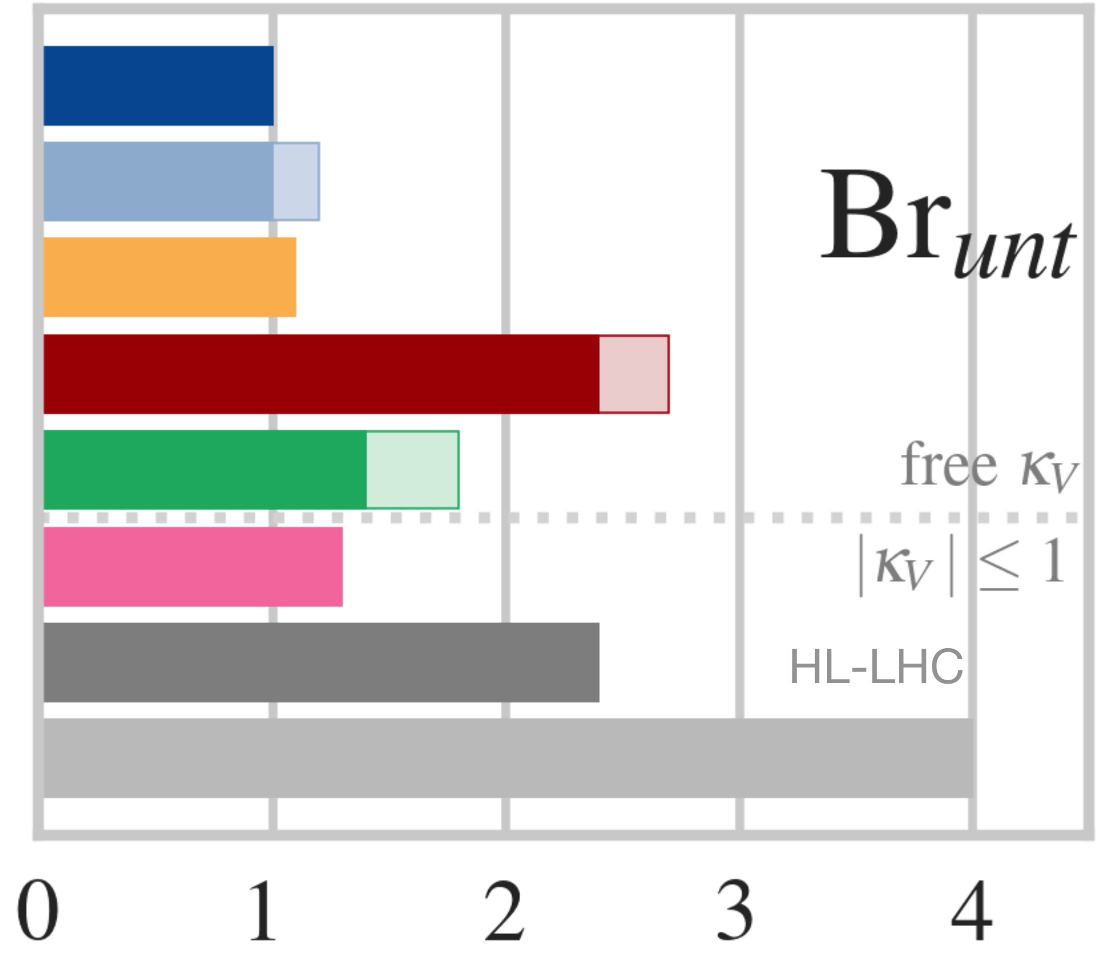
Run2 sensitivity: ~10%

HL-LHC?
- ZH: ATL-PHYS-PUB-2013-014, <8% @ 95% CL
- VBF: FTR-18-0016 , <3.8% @ 95% CL

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

From the global coupling fit, if $B_{BSM} \geq 0$ (any invisible or undetected states): $B_{BSM} < 2.5\%$ @ 95% CL





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

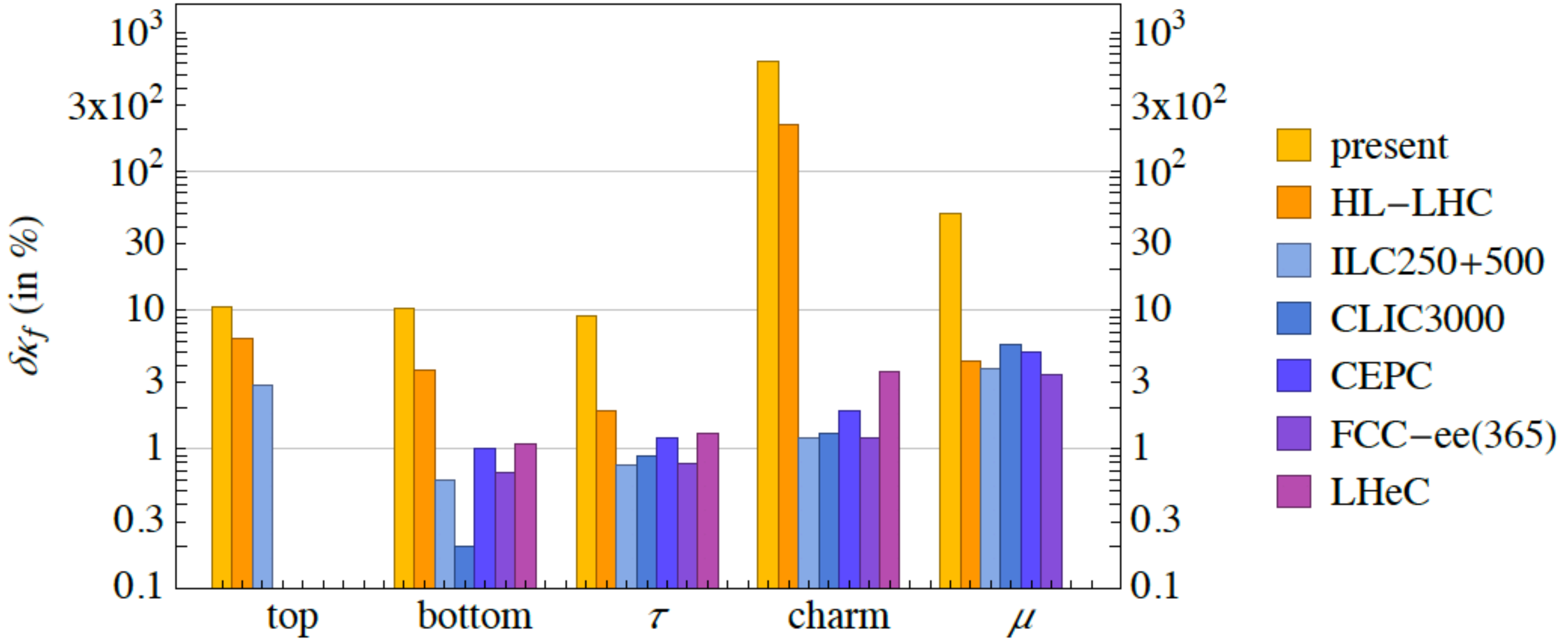
Exotic Higgs decays: invisible, LFV, new (pseudo)scalars, LLP, dark photons, ALPs,…

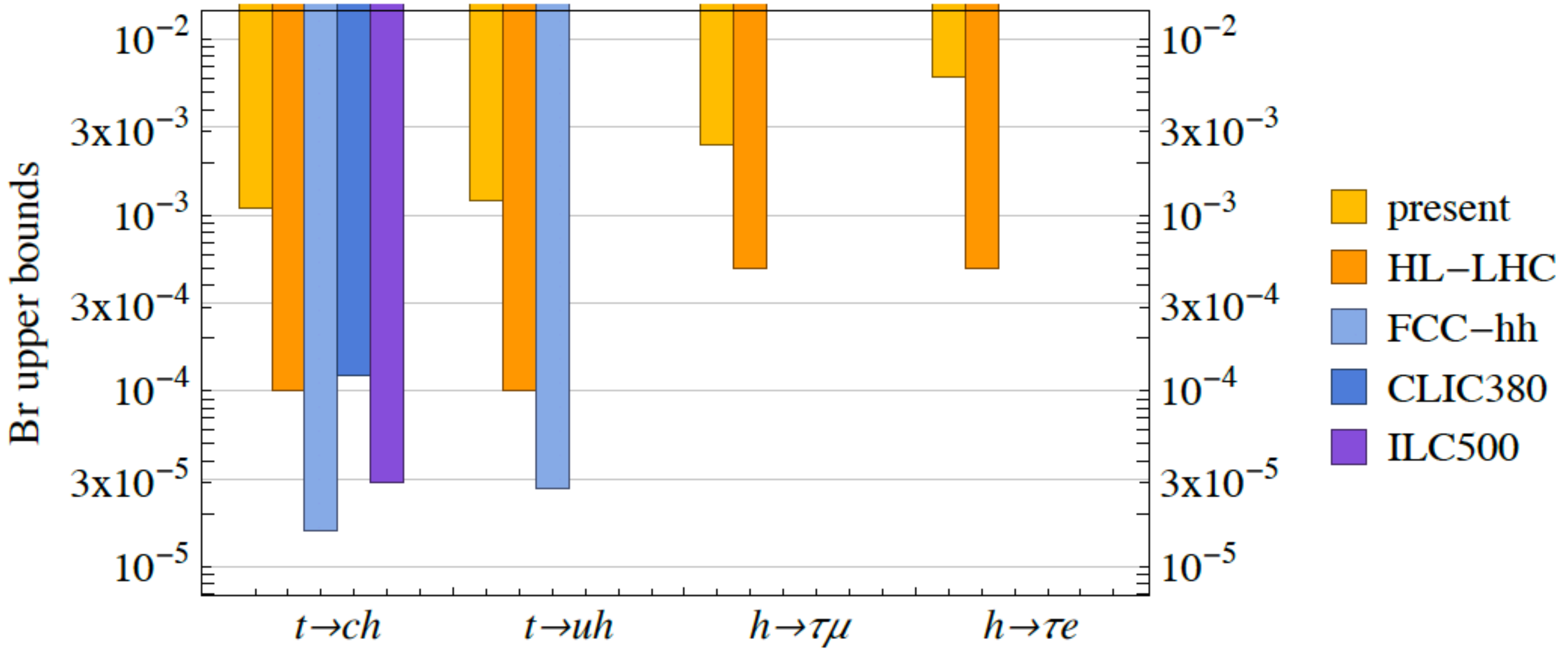
Huge phase space to probe, and very few available experimental projections

Large potential gain from detector upgrades: long lived decays

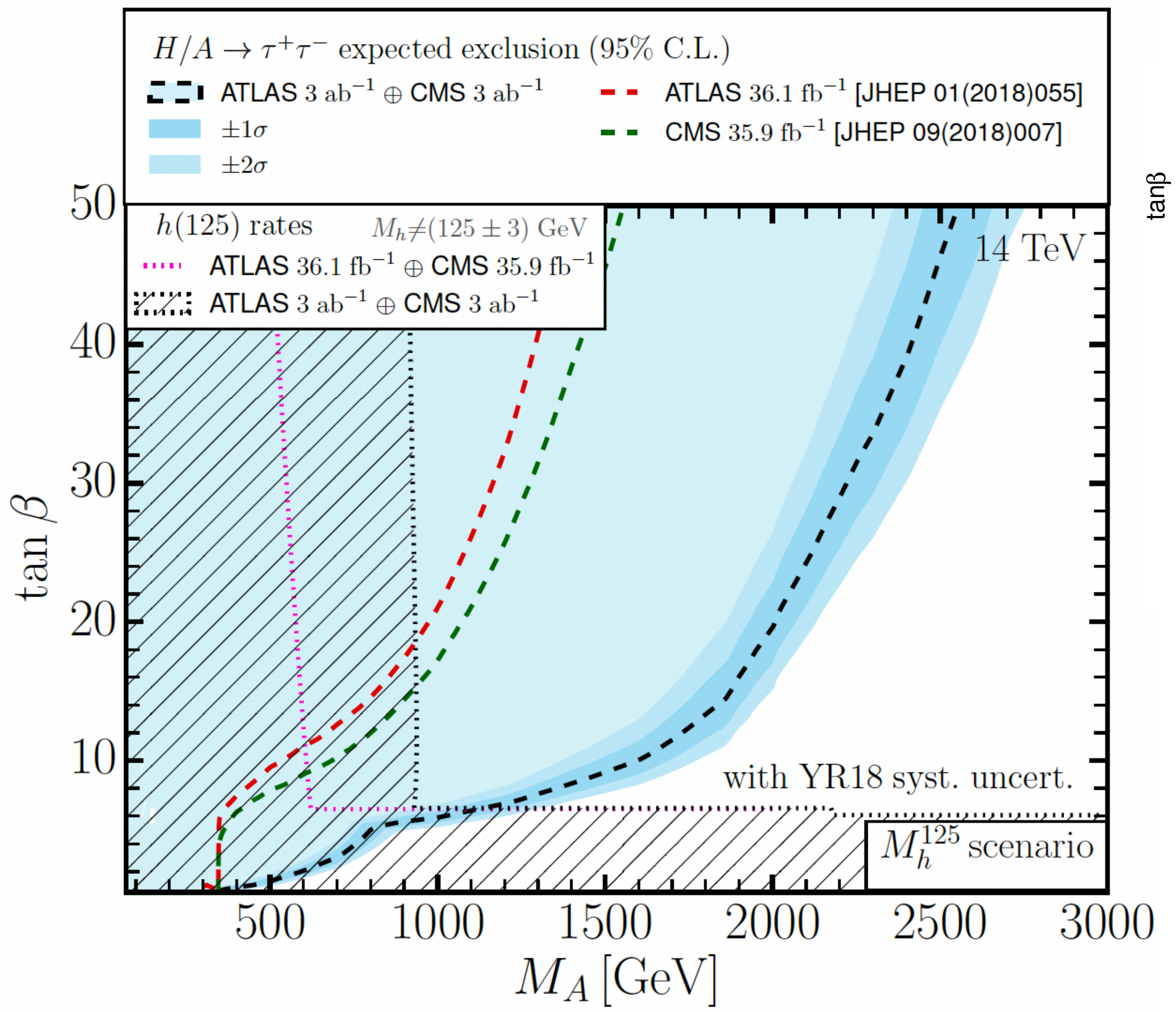
HIGGS&FLAVOUR

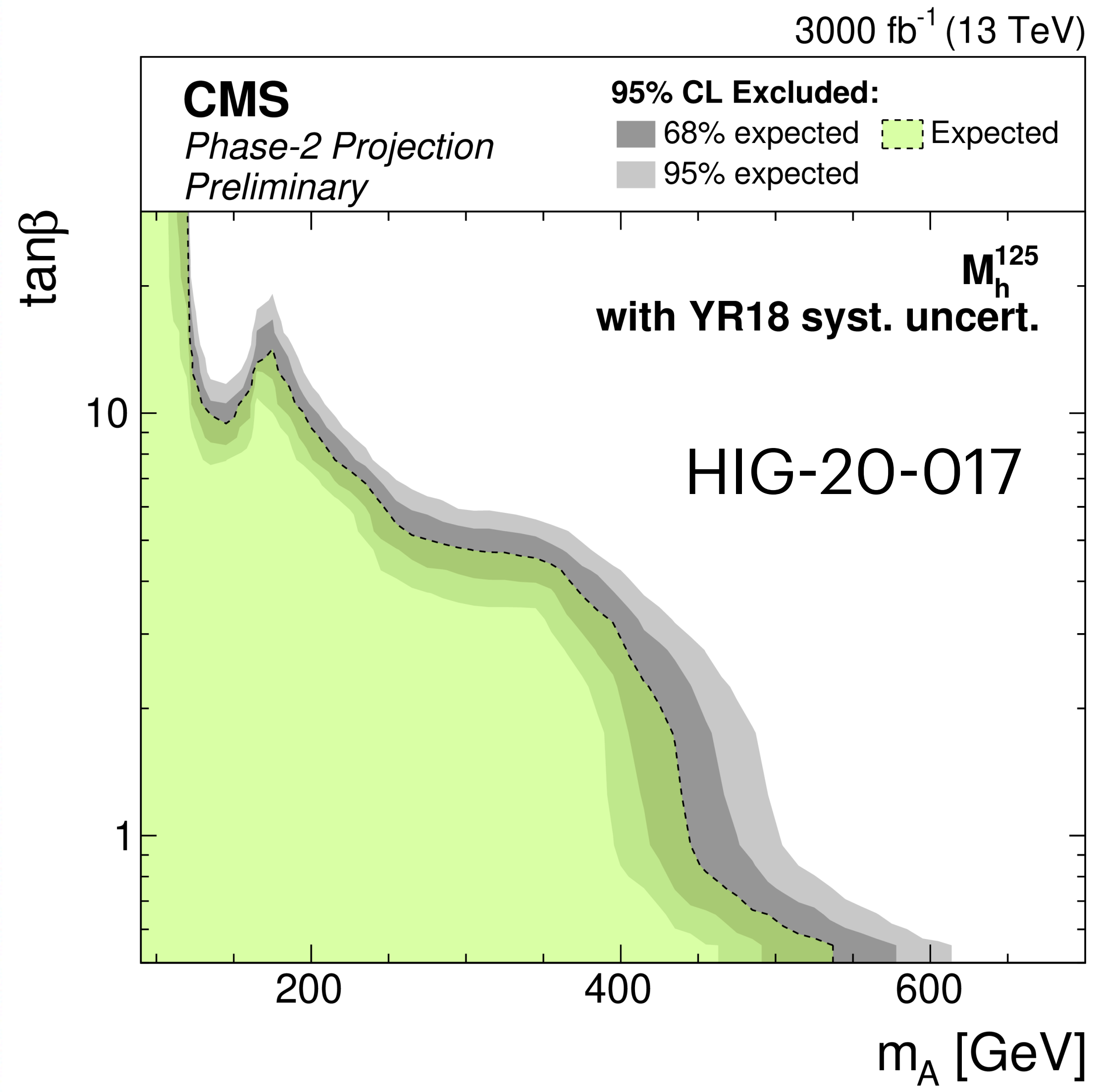
- **Are there surprises in the flavour sector?**

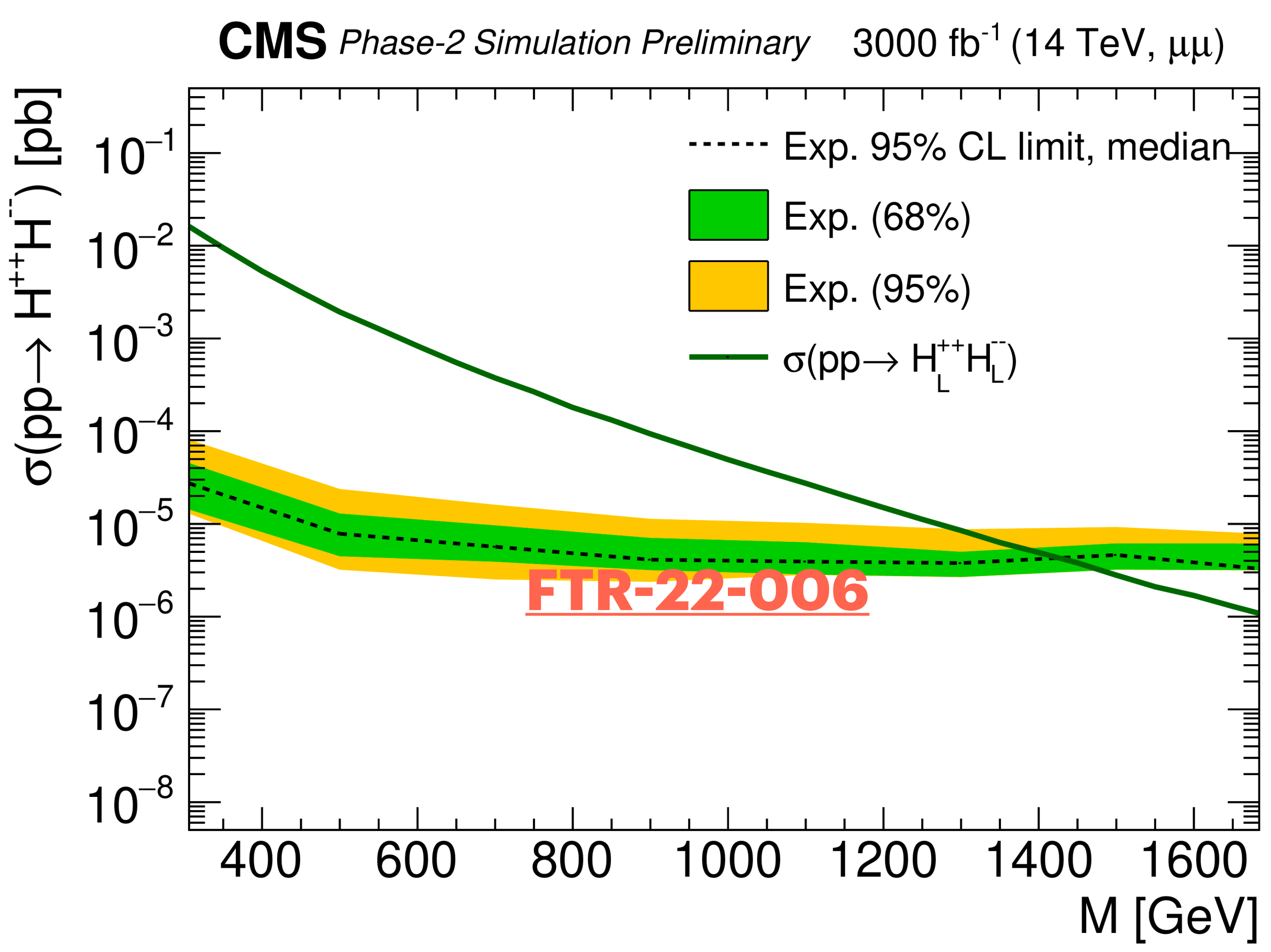




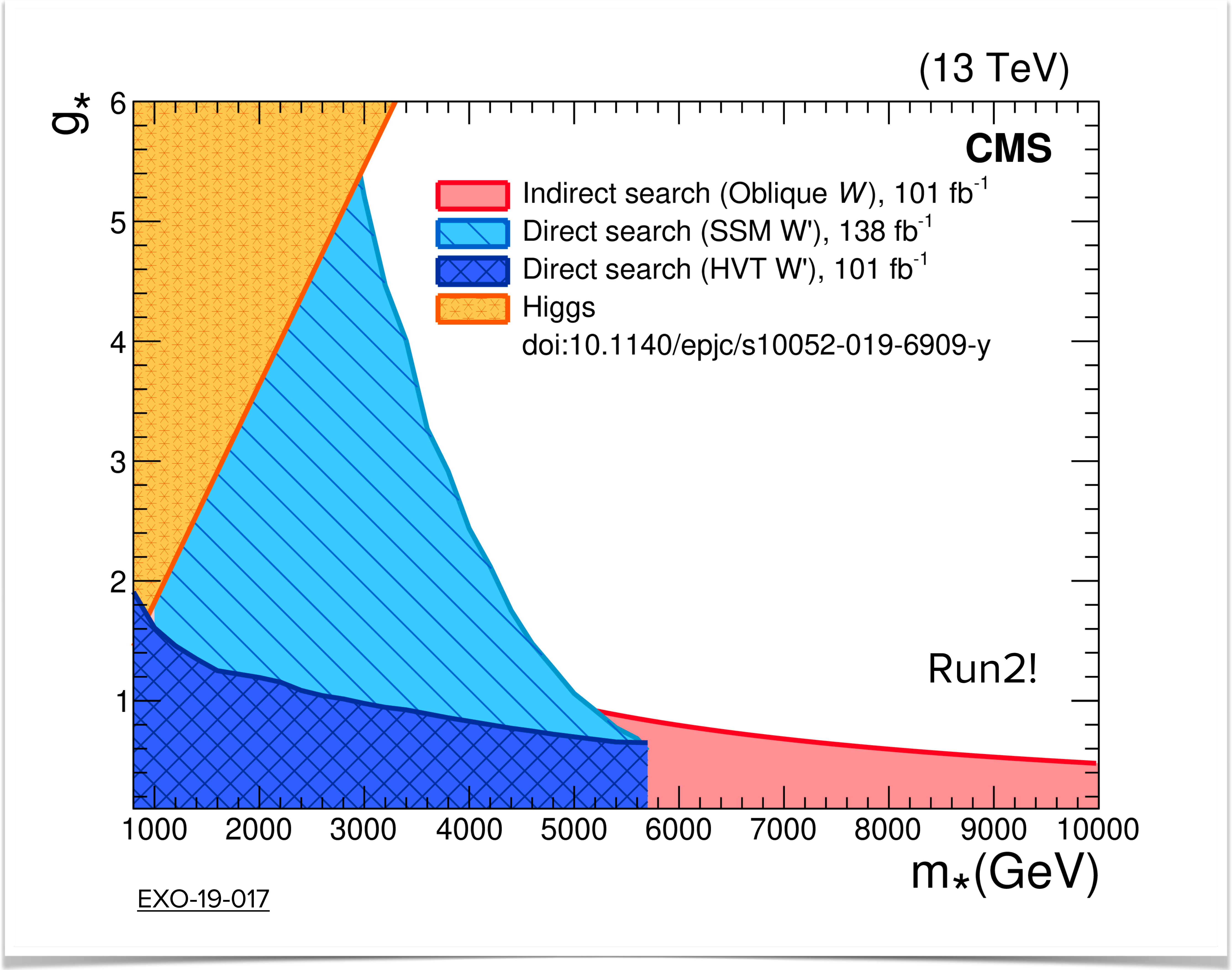
IS THE HIGGS ALONE?







IS THE HIGGS BOSON COMPOSITE?



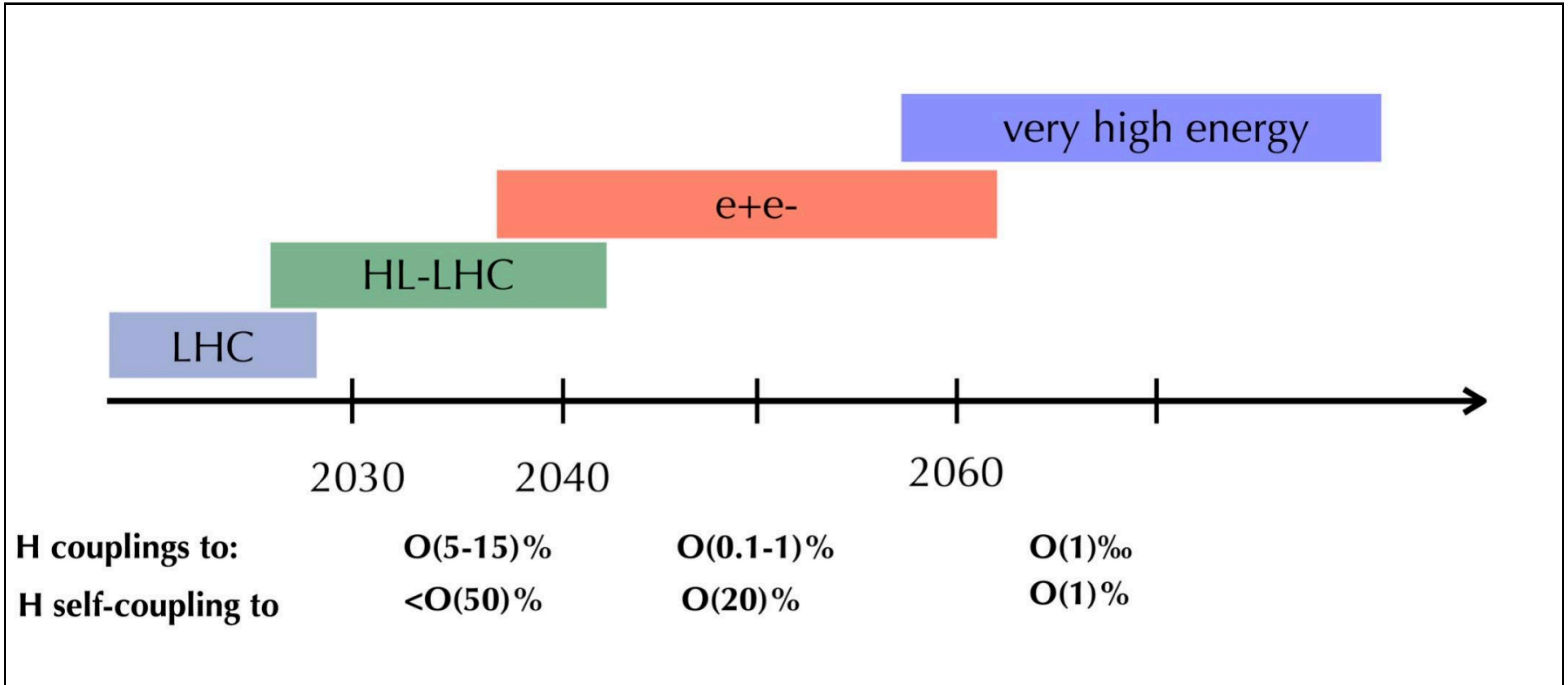
m_* - mass scale of compositeness

g_* - coupling strength of the new composite sector

Complementarity of measurements! In Yellow: Constraint coming from Higgs Couplings (CMS, 2016)

THE END?

BEYOND HL-LHC



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

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

- Vacuum energy $V_{0exp} \sim (2.10^{-3}\ eV)^4$
- Origin of quadratic divergences. Hierarchy problem
- Possible instability depending on m_H
- The flavour problem: large unexplained ratios of Y_{ij} Yukawa constants

Guido Altarelli
Lepton Photon 2009

Is it possible that the LHC finds the Higgs particle but no other new physics (pure and simple SM)?

Yes, it is technically possible but it is not natural

- 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. It is a Higgs Boson, but is it really the one and only SM Higgs boson?

- We have only explored a very small fraction of the full LHC dataset: we will celebrate the 25th anniversary of the discovery with the machine delivering data still. What will we know by then?

- We have beautiful projections of the power of ATLAS and CMS as Higgs machines. Far better than it was ever expected of the LHC. They will set the basis for Higgs physics way beyond the HL-LHC timeline.

- Warning ahead: we should not take this for granted. To make those projections go from promises to actual measurements implies years of work (from operation and calibration of the detector, to the careful analysis of 3000 fb^{-1}!). And collaboration between all the Higgs community.

THANKS!