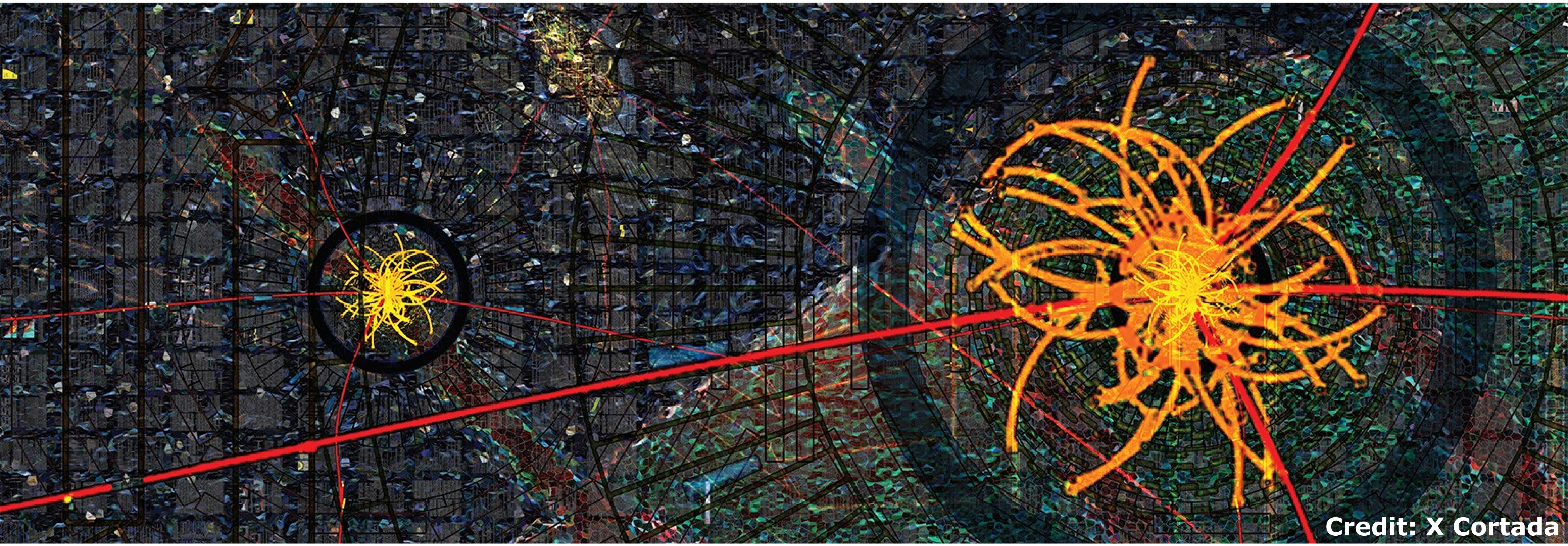
Overview of experimental results in the Higgs sector: precision, BSM and diHiggs


Credit: X Cortada

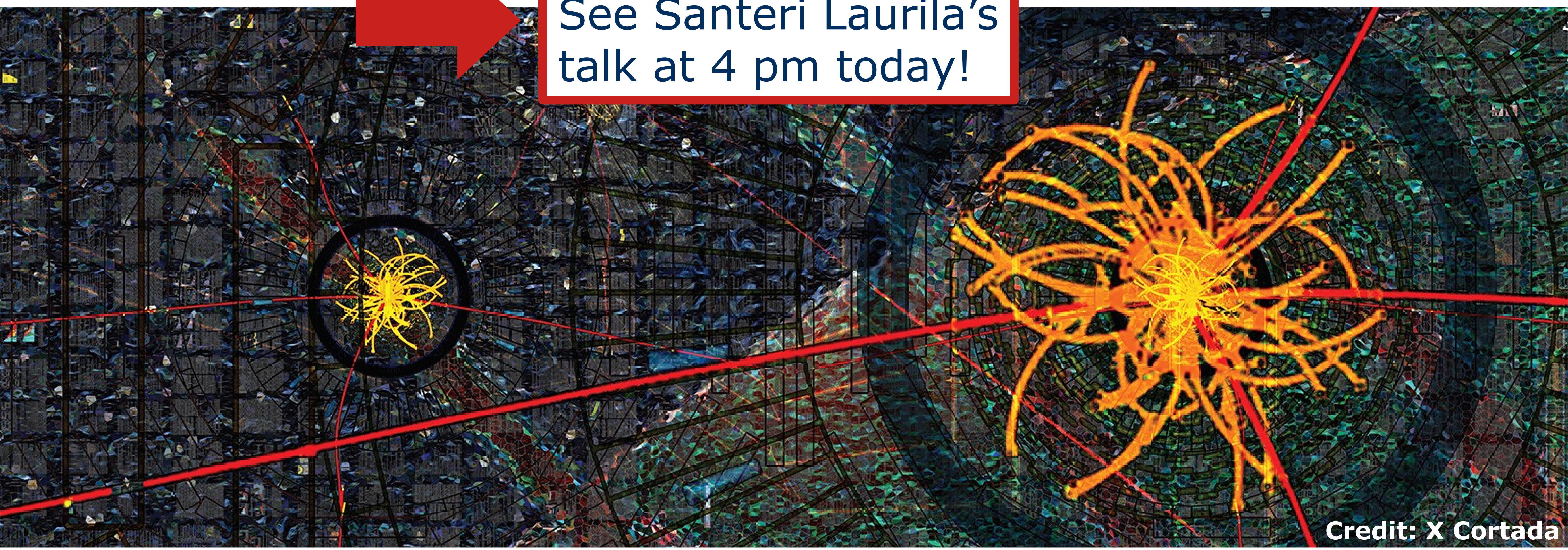
Sara Strandberg

Stockholm University

27th Nordic Particle Physics Meeting
Fefor Høyfjellshotell, 6/1 2023

Overview of experimental results in the Higgs sector: precision, ~~BSM~~ and diHiggs

See Santeri Laurila's talk at 4 pm today!



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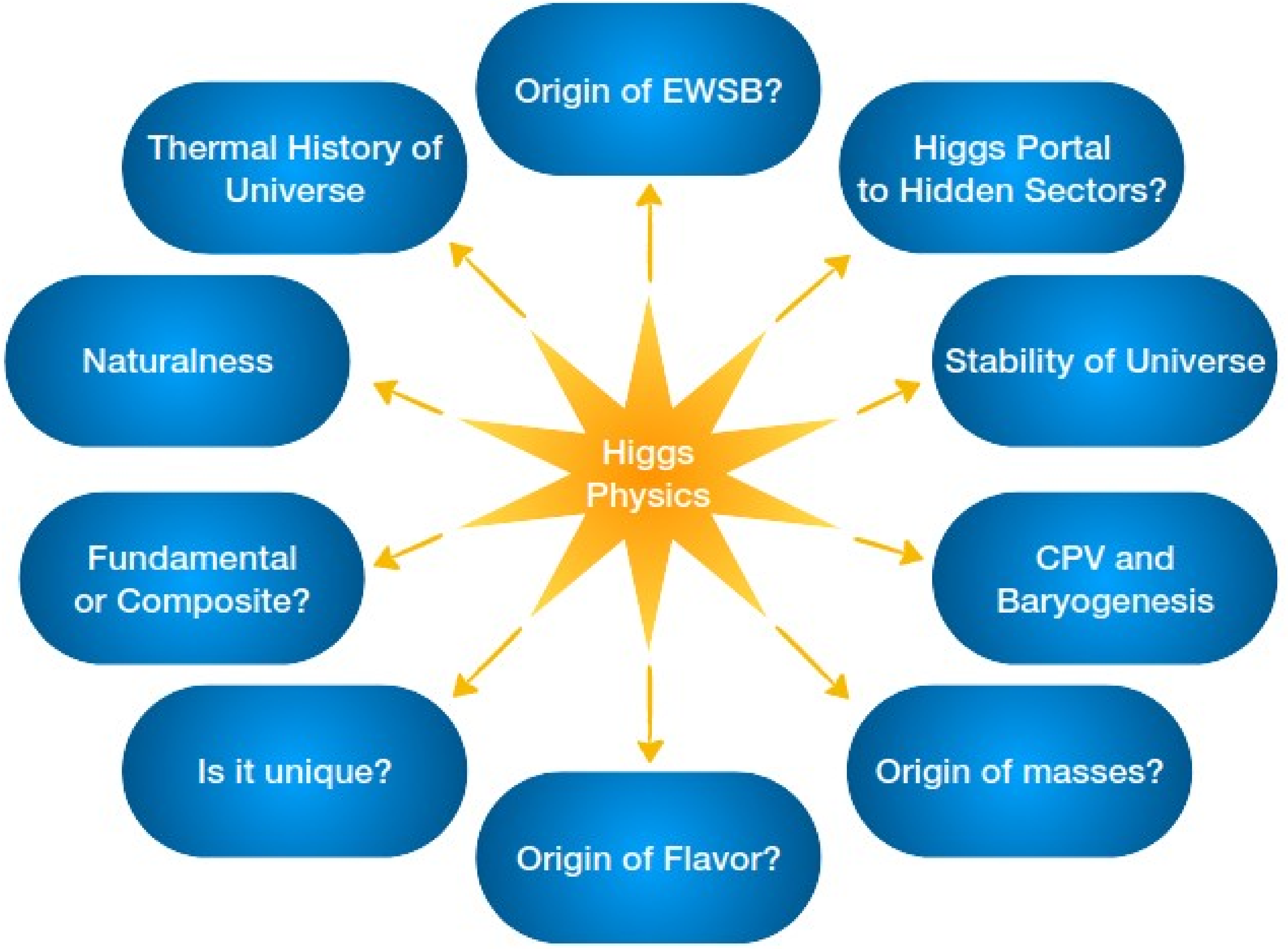
Why study the Higgs?

- The Higgs boson plays a central role in the SM and is linked to many fundamental questions.



Source: Snowmass Higgs WG report (2209.07510)

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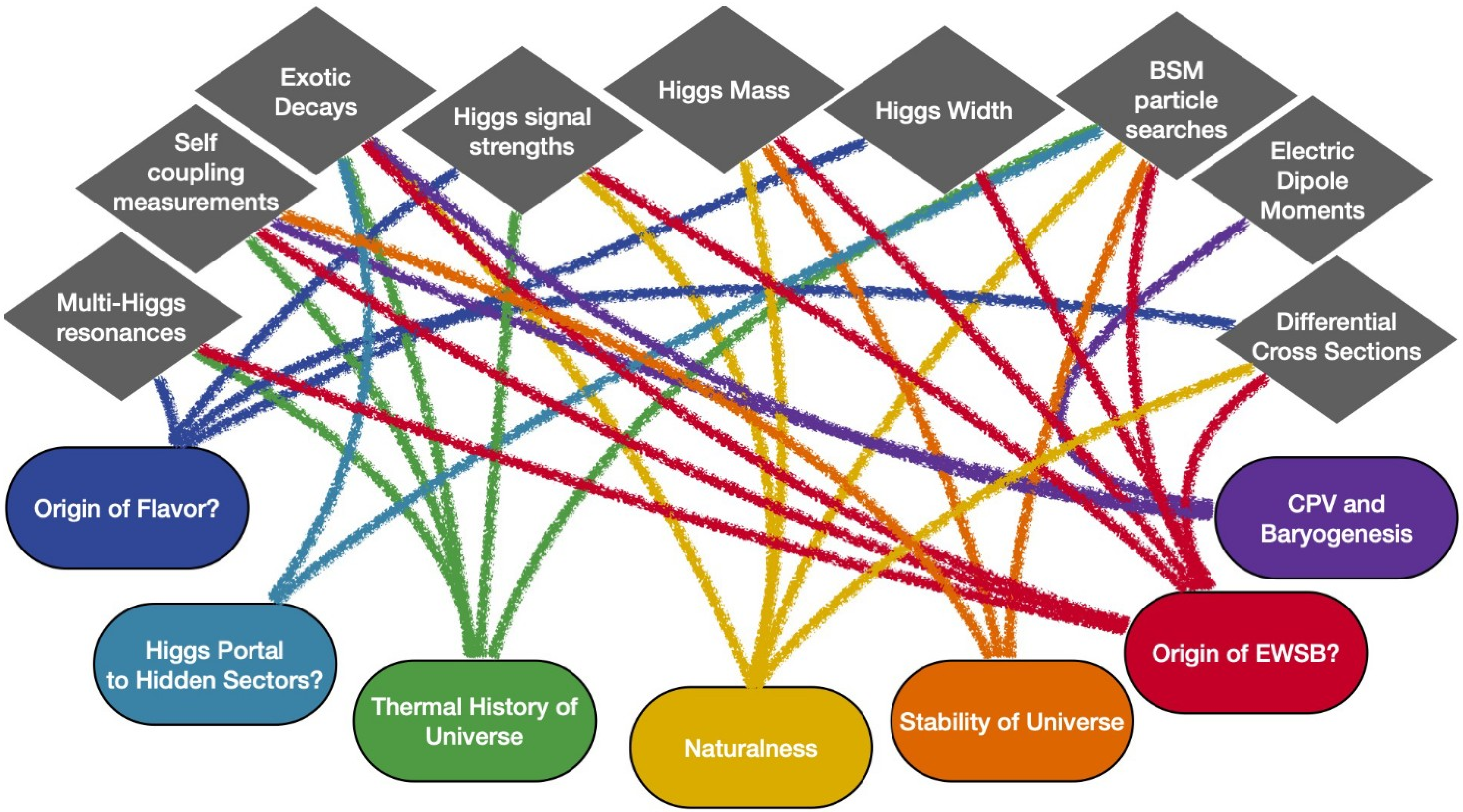

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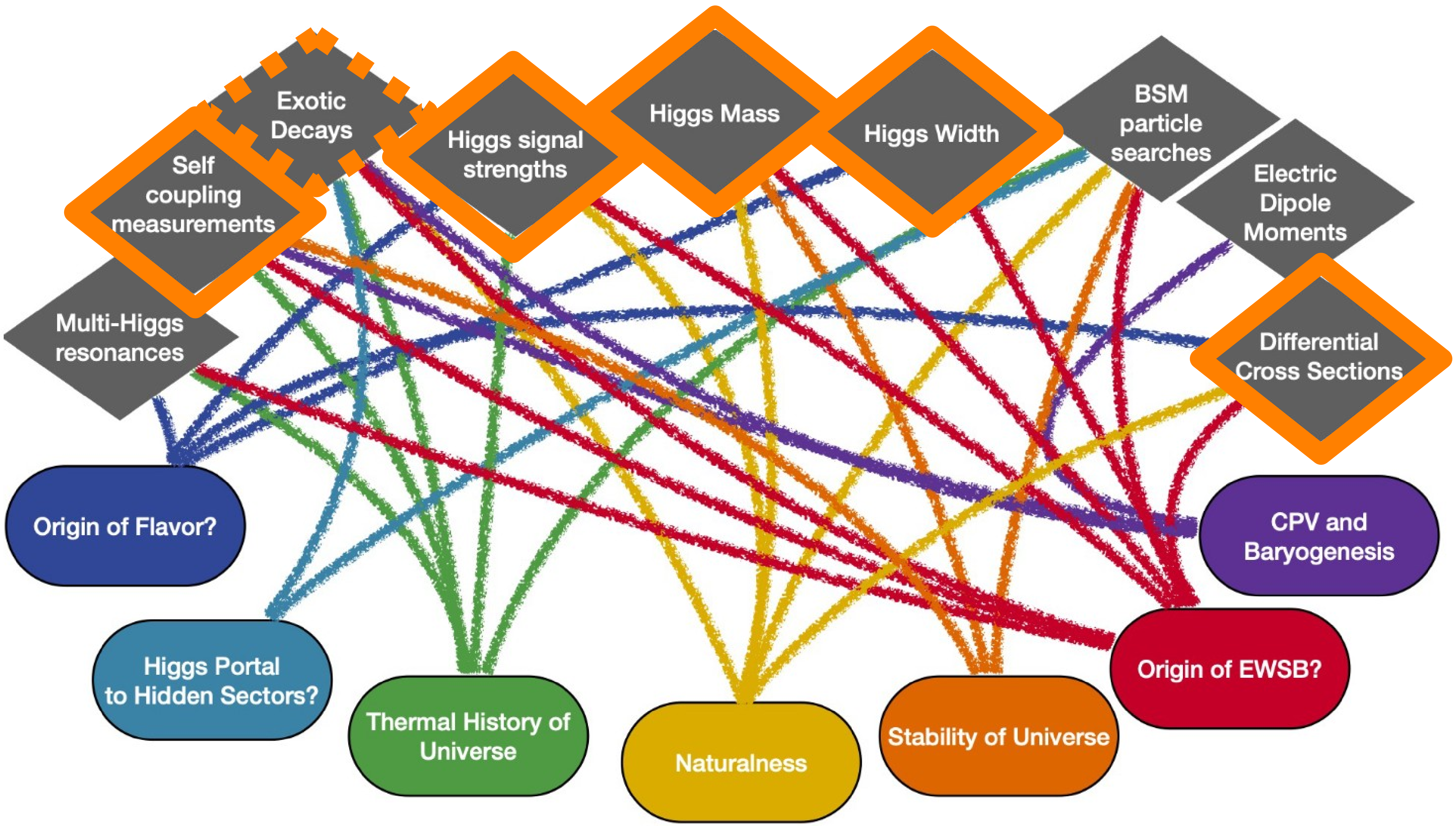

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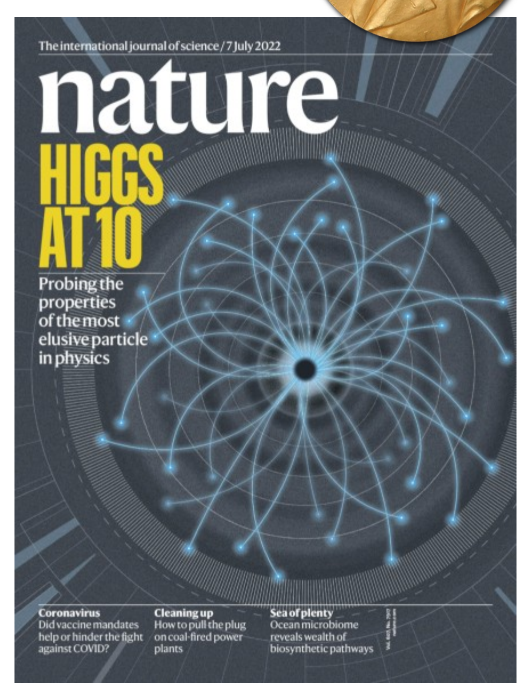
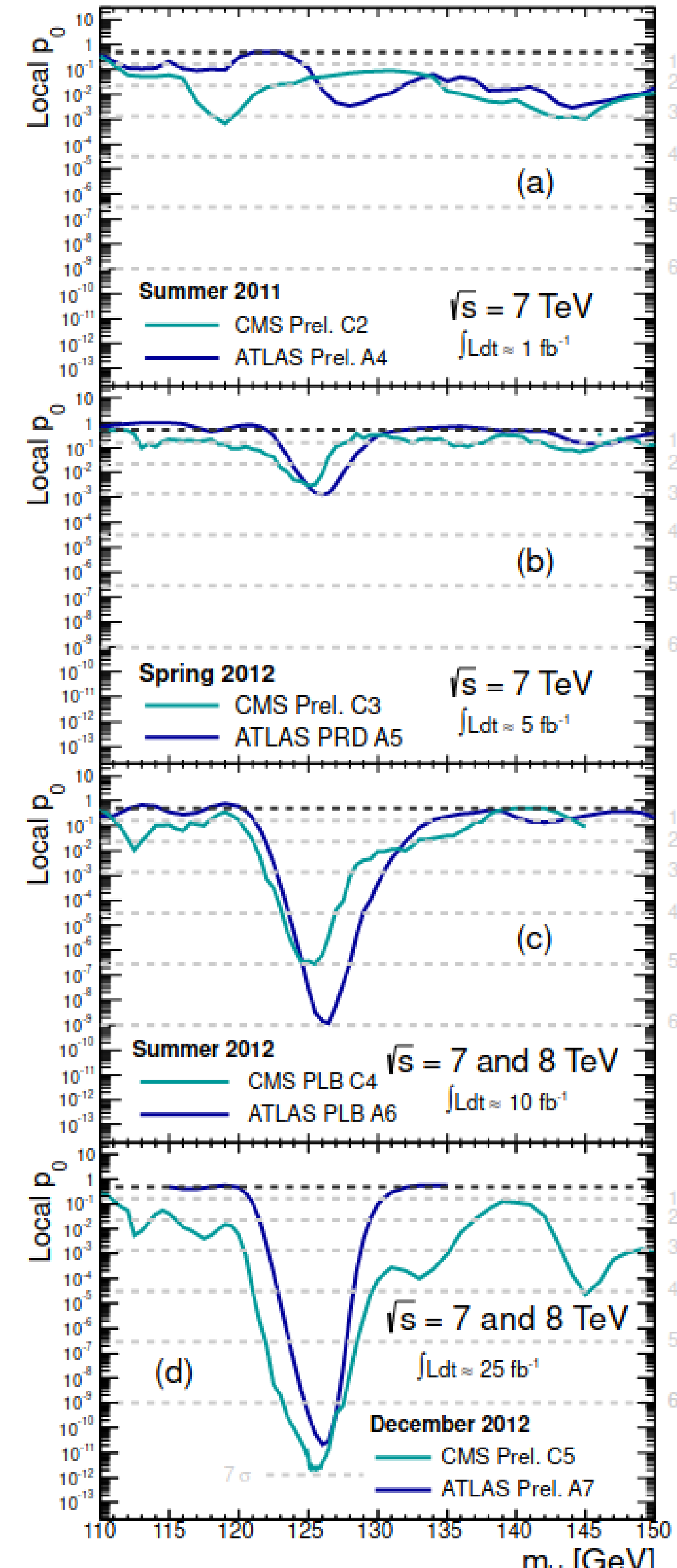
The Higgs discovery

- On July 4th 2012, ATLAS and CMS announced the discovery of the Higgs boson.
- And the 2013 Nobel prize was awarded to Peter Higgs and Francois Englert

> ”for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s LHC”

- Since then more than 10 times the data have been collected.
- These have been used to map the properties of the Higgs with increasing precision.
- Is it actually the Higgs we were searching for?





pdg 2013

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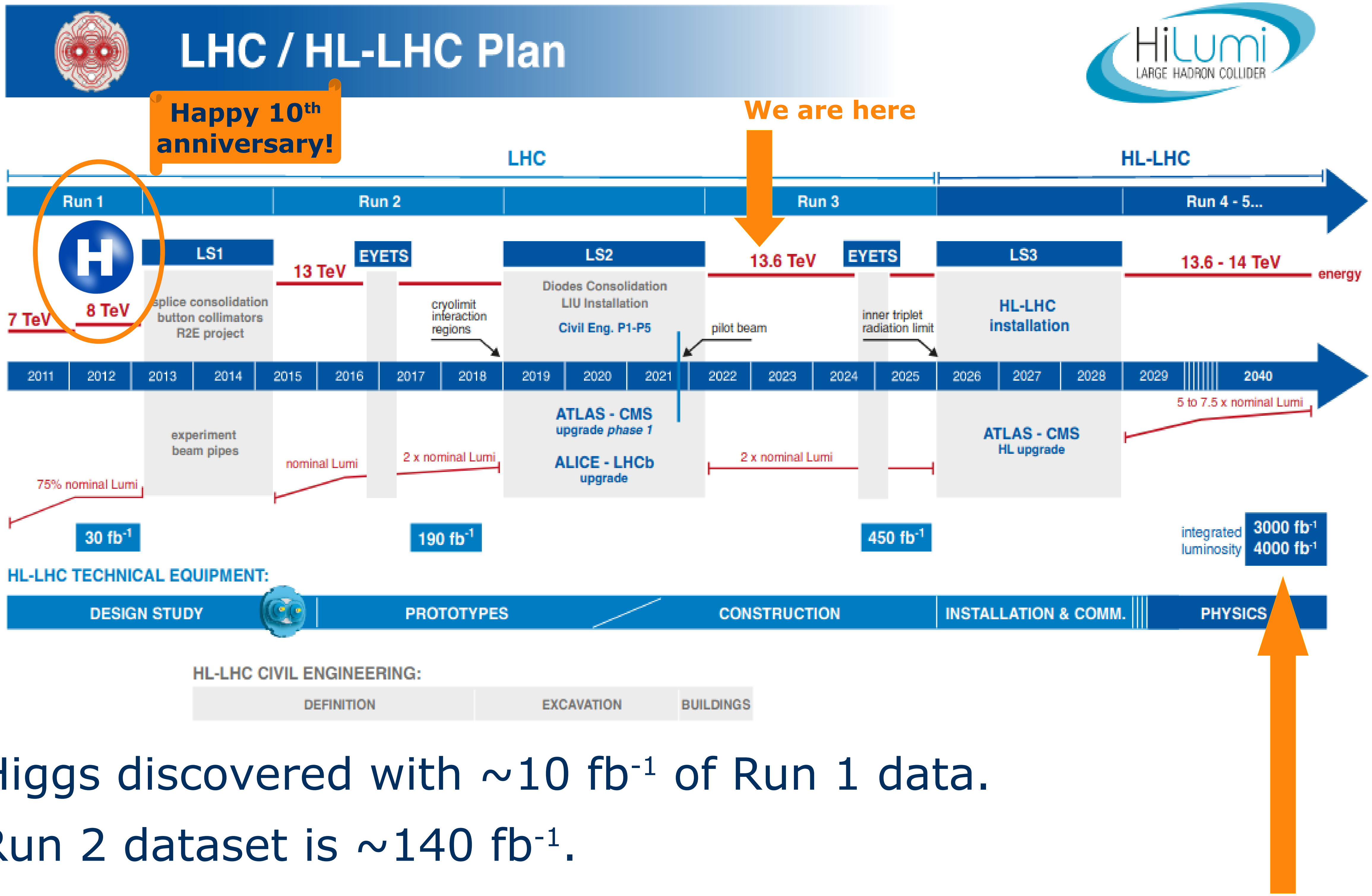
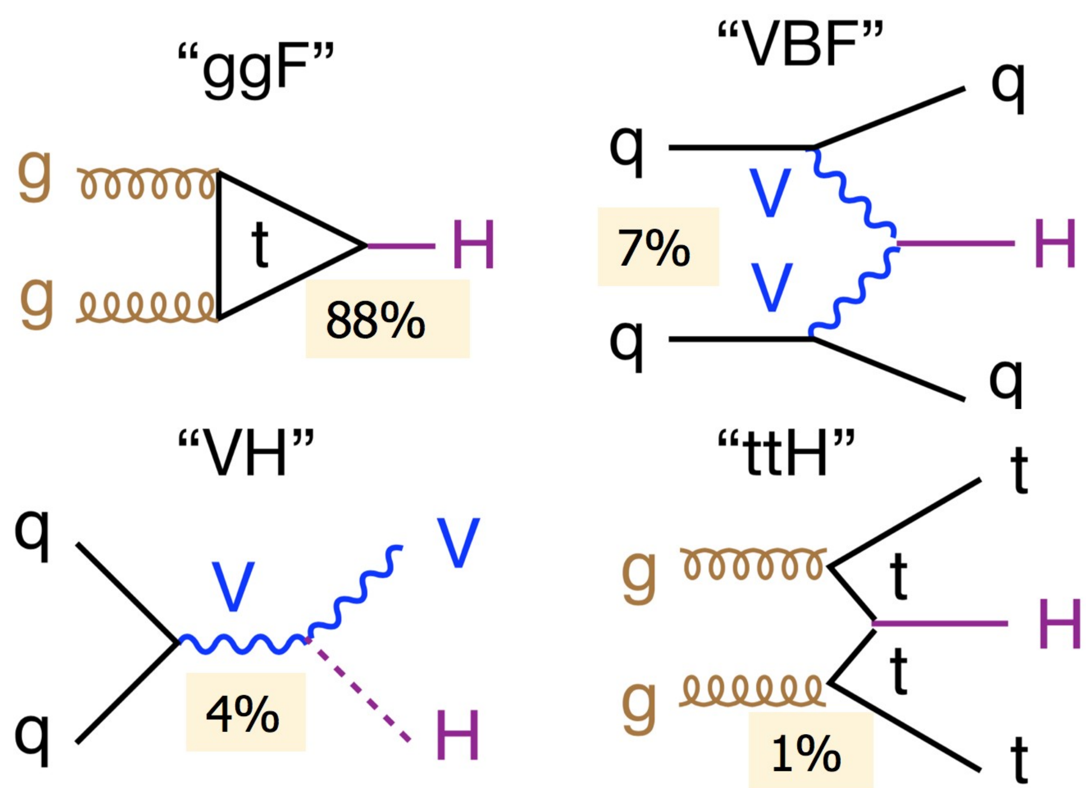
The LHC timeline

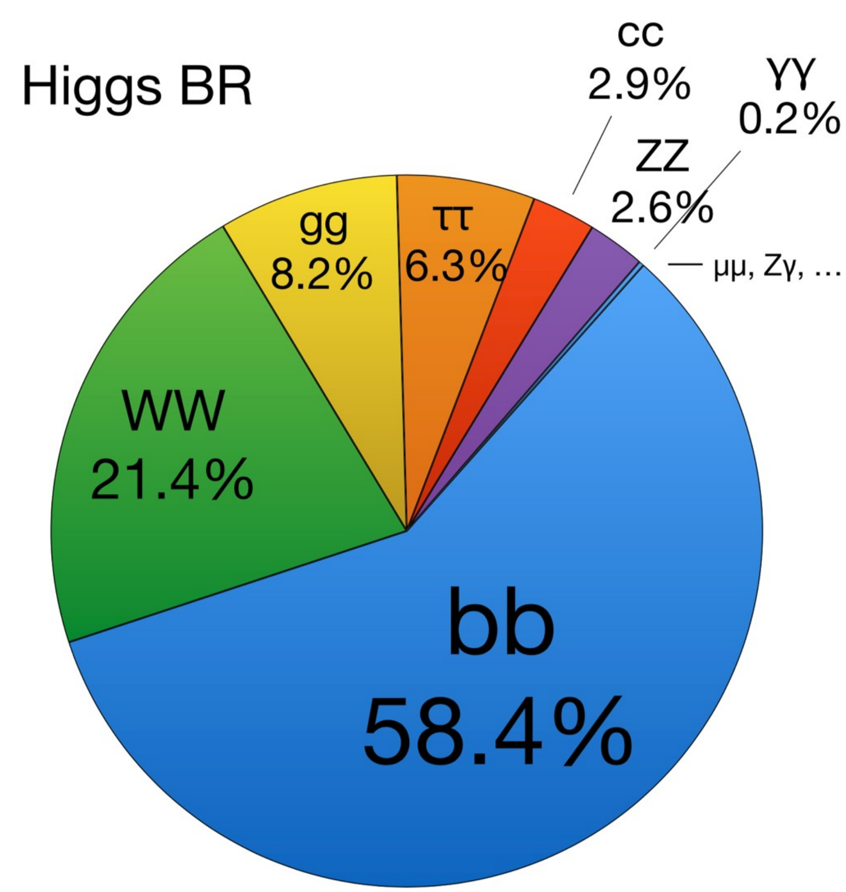


- Higgs discovered with ~10 fb^{-1} of Run 1 data.
- Run 2 dataset is ~140 fb^{-1}.
- ~3 ab^{-1} is expected by the end of HL-LHC (x20 current amount).

The SM Higgs fingerprint

- An elementary scalar particle (spin 0) with positive parity.
- Interacts with other particles with a strength that is proportion to their masses.
- Also interacts with itself.
- As soon as the mass is determined, all properties are precisely predicted by the SM.





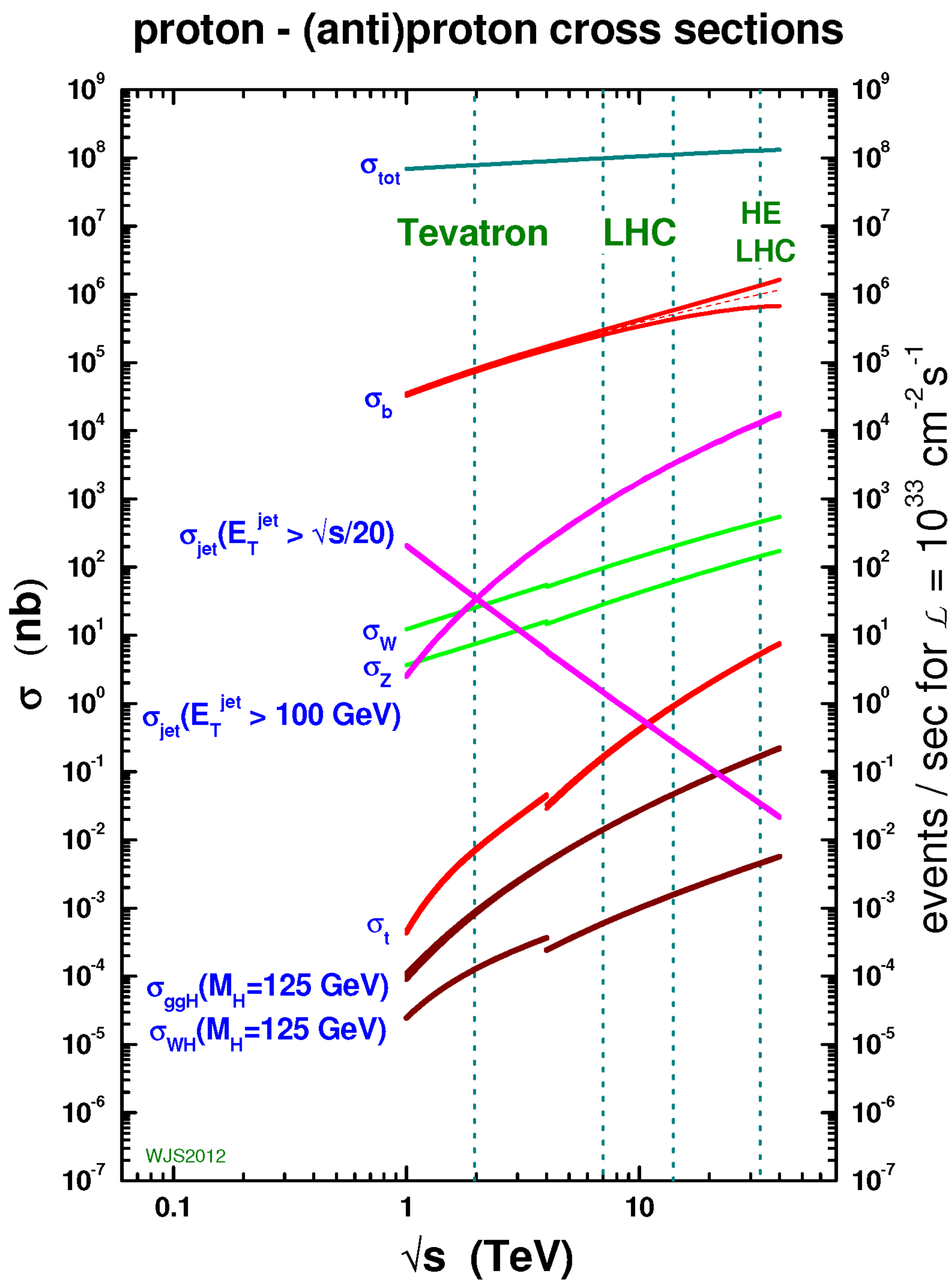
Experimentally challenging

- Production rates of Higgs bosons are several orders of magnitude smaller than for the backgrounds.
- Challenge to extract the signal and estimate the backgrounds with the required precision.

Higgs bosons per fb^{-1} (13 TeV)

	produced	selected
$H \to \gamma\gamma$	130	46
$H \to ZZ^*$	1400	1.5
$H \to WW^*$	12000	42
$H \to \tau\tau$	3500	17
$H \to b\bar{b}$	32000	66

Source: K. Tackmann Higgs symposium



How did we find the Higgs?

- The Higgs was discovered in the ggF production mode using the bosonic decay modes $\gamma\gamma$, $ZZ\rightarrow 4l$ and $WW\rightarrow l\nu l\nu$.
  [1207.7214,1207.7235]
- The $H\rightarrow\gamma\gamma$ **decay mode** is rare but the excellent mass resolution helps you.
- Background is dominated by non-resonant $\gamma\gamma$ production (after reducing the large jet and γ+jet backgrounds).
- The $H\rightarrow ZZ\rightarrow 4l$ **decay mode** is rare too because of small $Z\rightarrow ll$ branching ratio.
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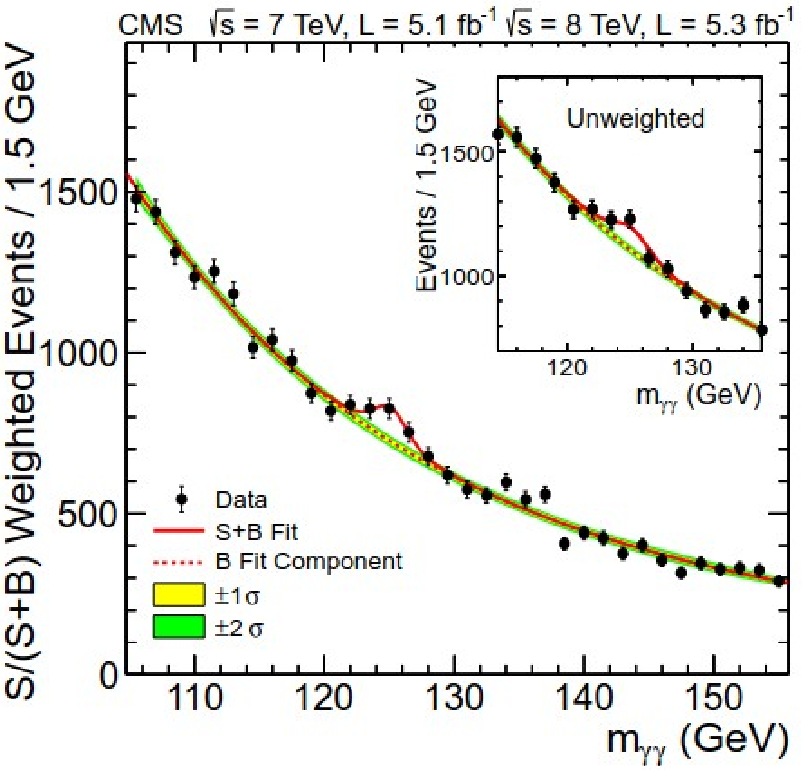

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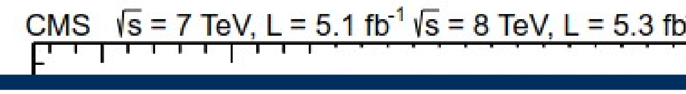

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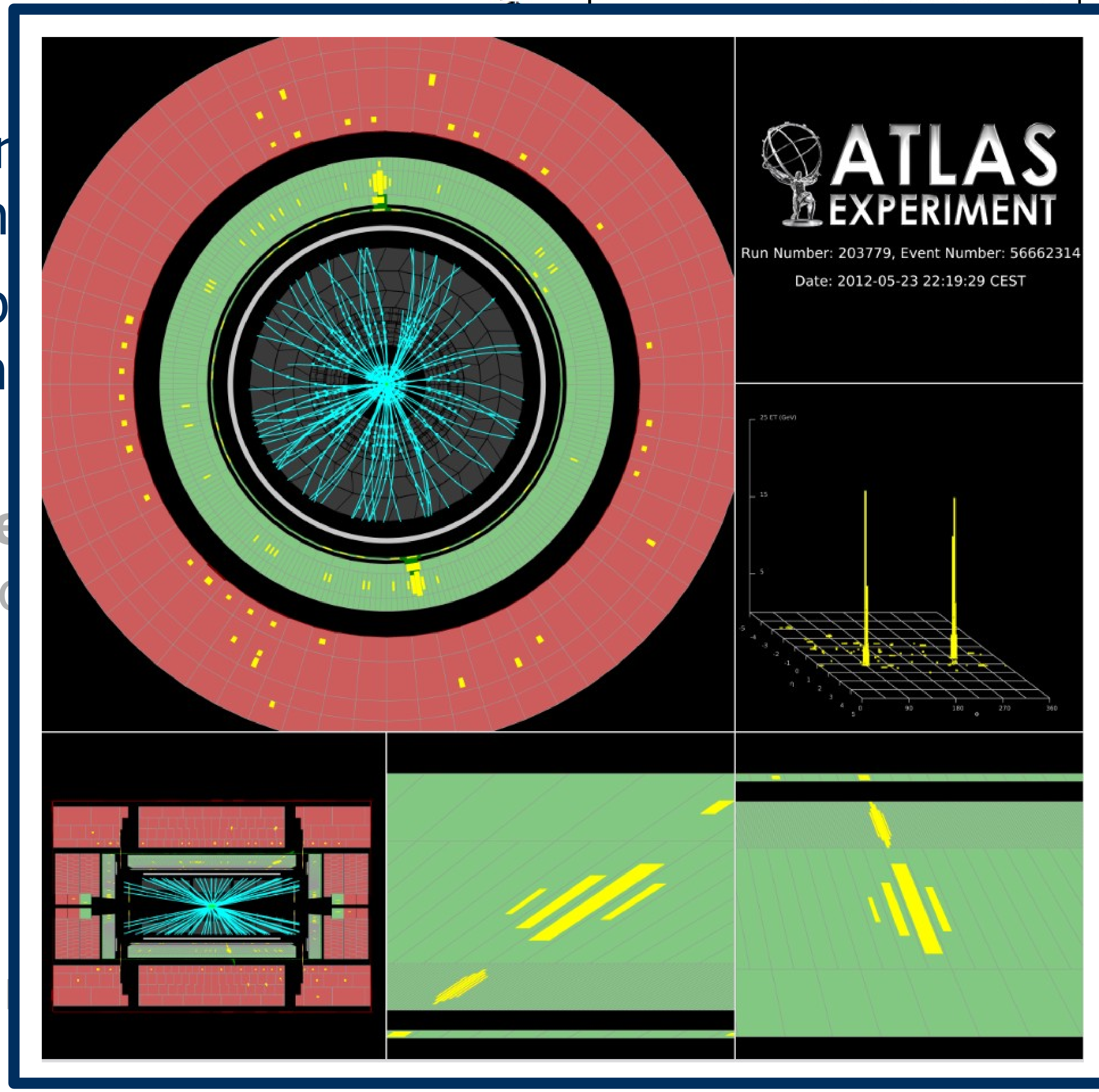

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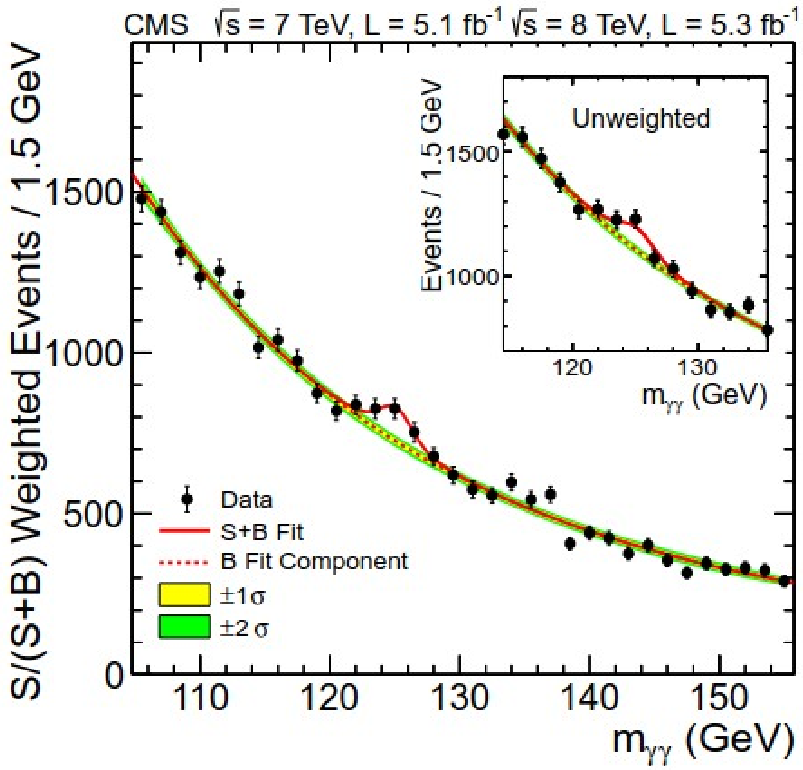

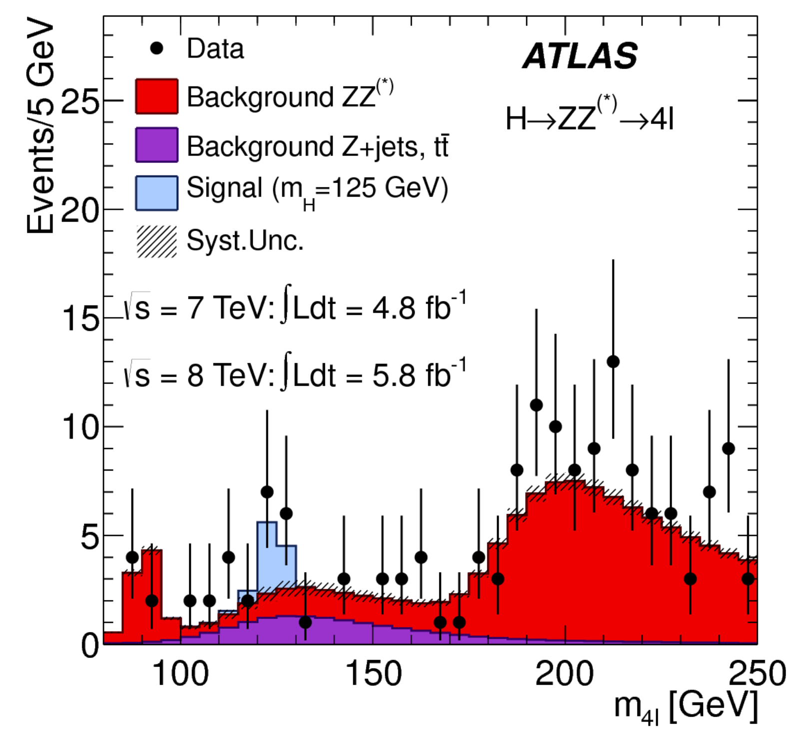

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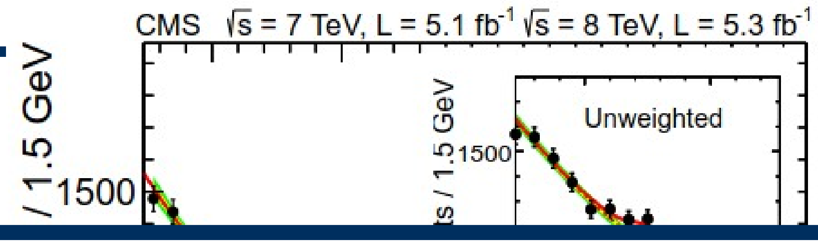

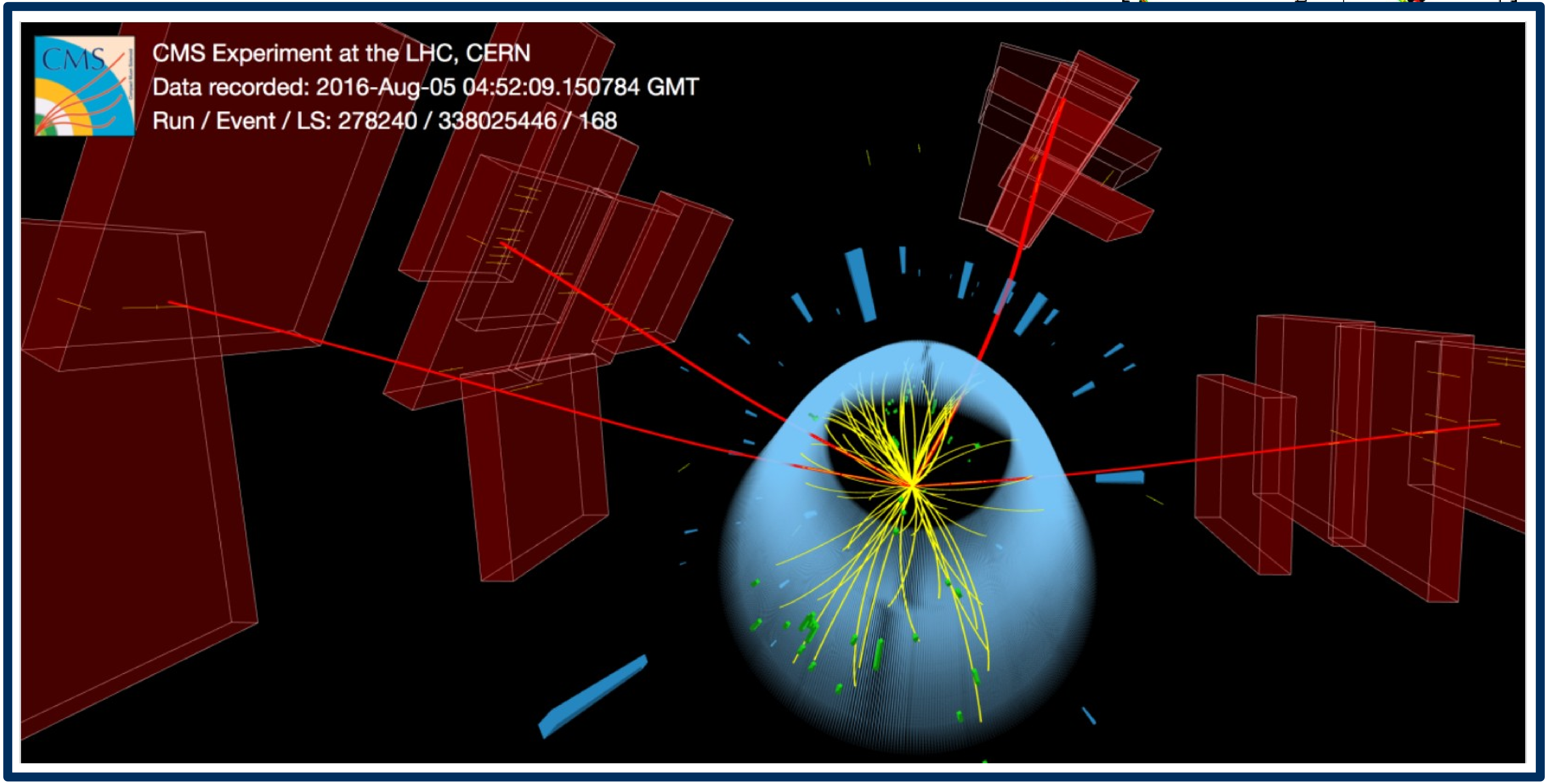

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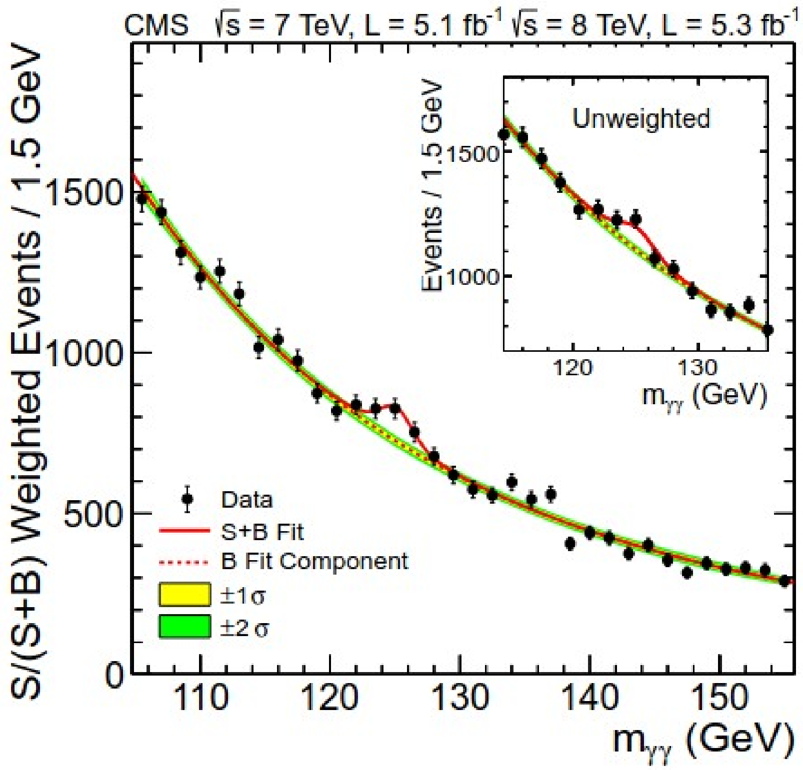

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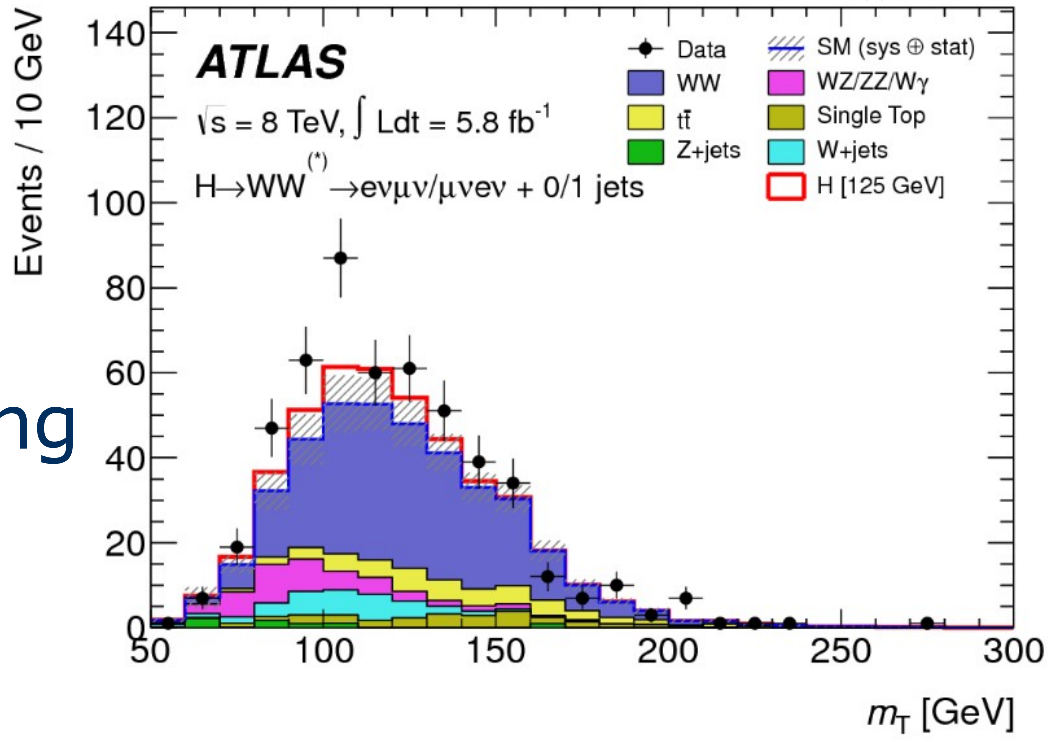

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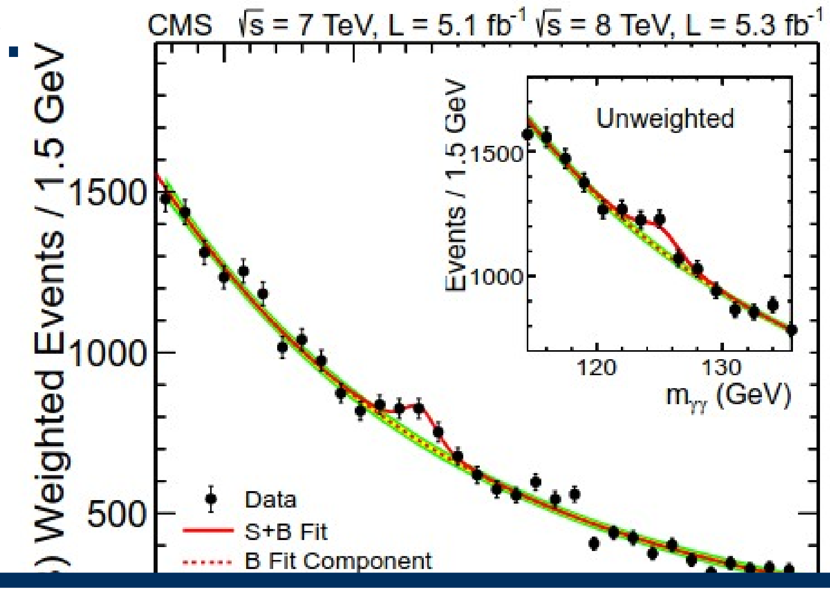
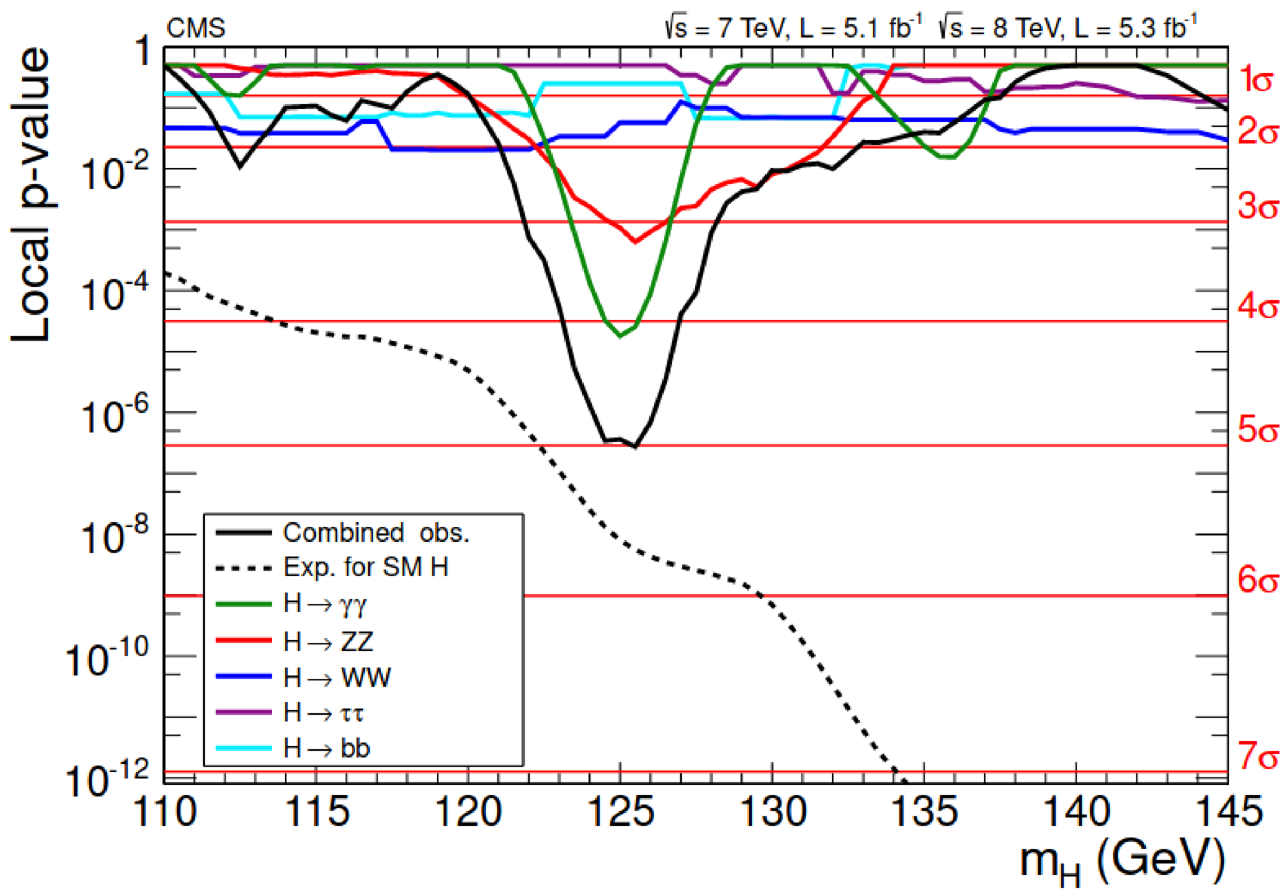
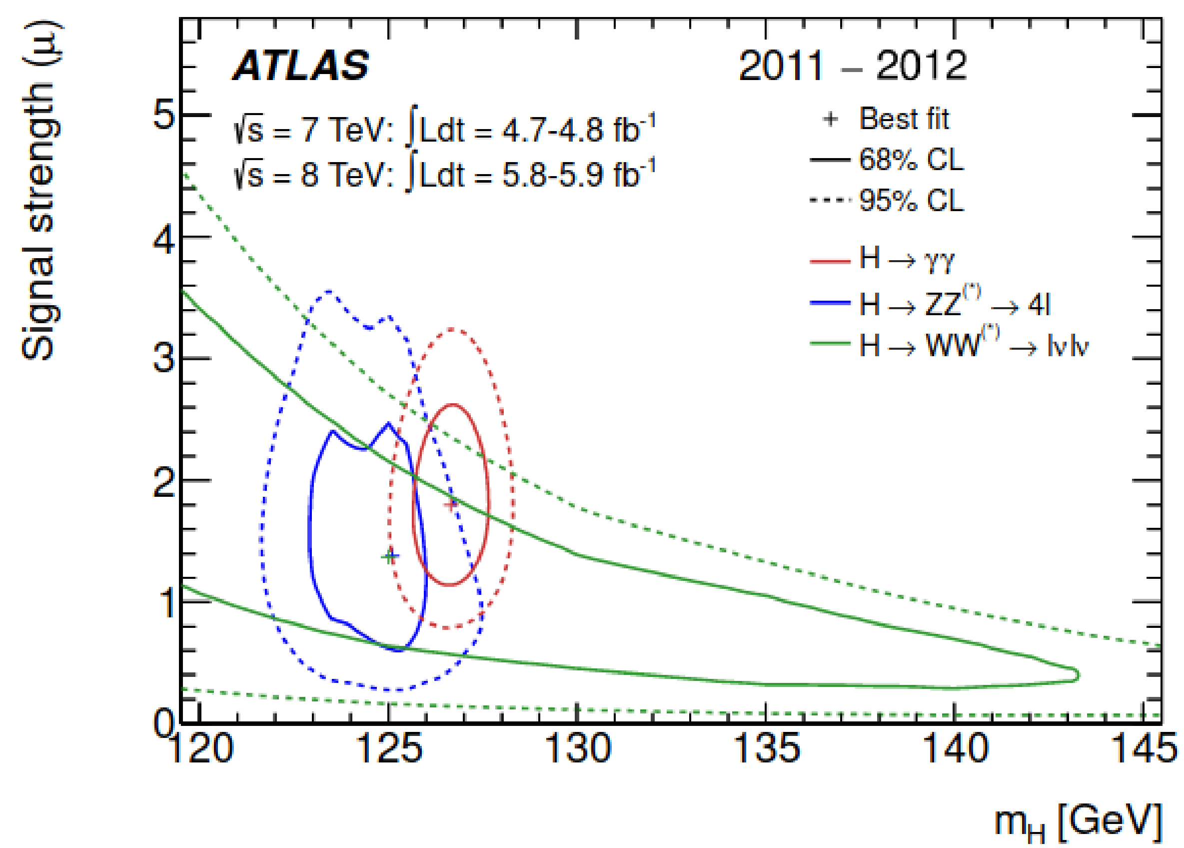
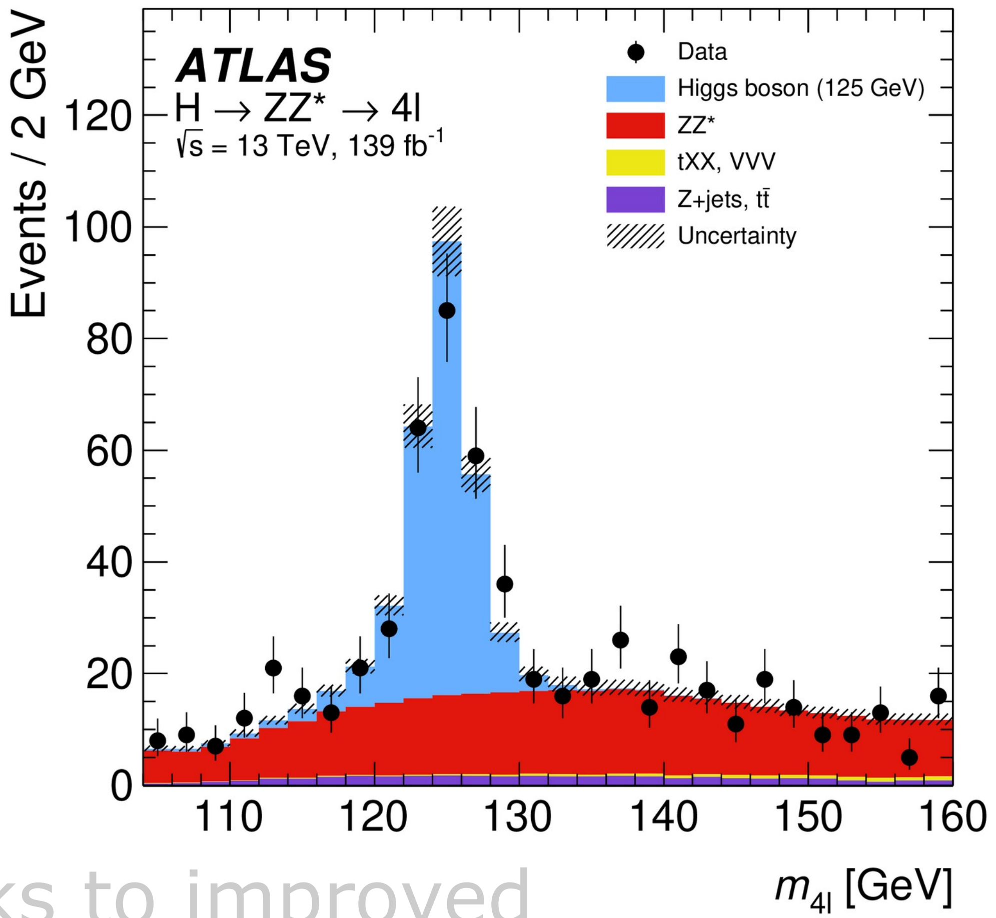






What does it weigh?

- The mass is the only Higgs property not predicted by the SM.
- Was measured with a precision of 0.5% already at discovery.
- Use decay channels with best mass resolution: $\gamma\gamma$ and $ZZ\rightarrow 4l$.
- Relies on precise energy/momentum calibration of muons, electrons and photons.
- Run 1 combination (ATLAS+CMS):
  125.09±0.21(stat.)±0.11(syst.) GeV
  → 0.19% uncertainty [1503.07589]
- $\gamma\gamma$ and $ZZ\rightarrow 4l$ Run1+2016 data (CMS):
  125.38±0.11(stat.)±0.08(syst.) GeV
  → 0.11% uncertainty [2002.06398]
- $ZZ\rightarrow 4l$ Run1+2 (ATLAS):
  124.94±0.17(stat.)±0.03(syst.) GeV
  → 0.14% uncertainty [2207.00320]
  - Reduced systematic uncertainty thanks to improved calibration of the muon momentum scale down to low pT.



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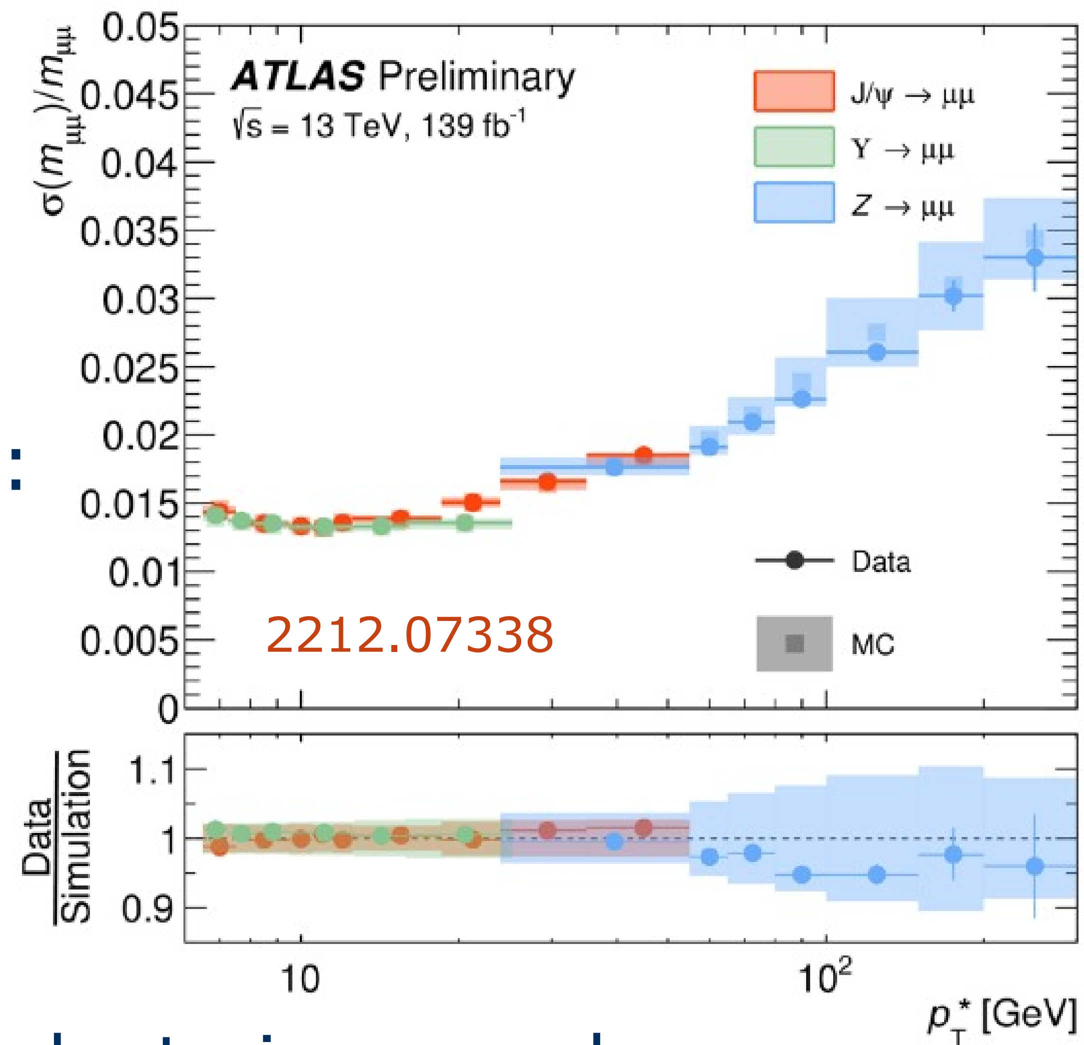
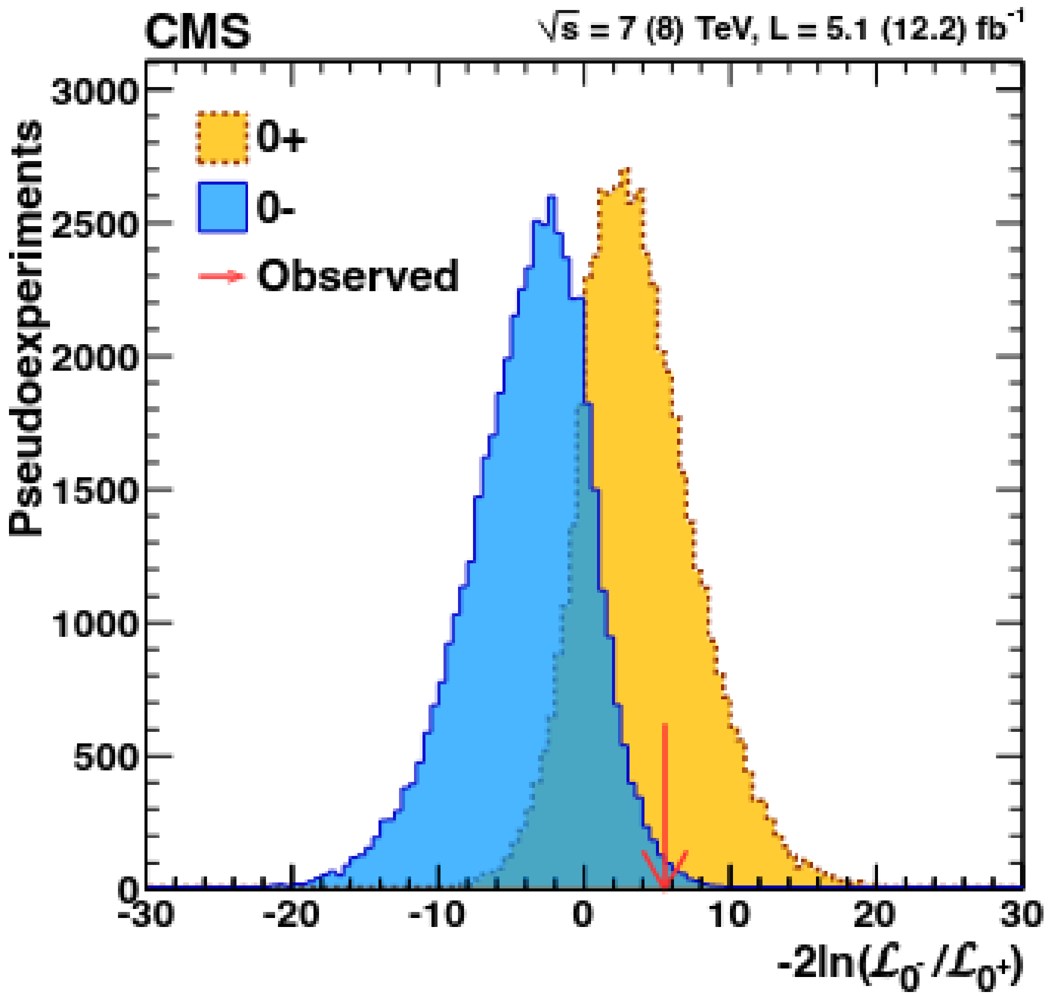
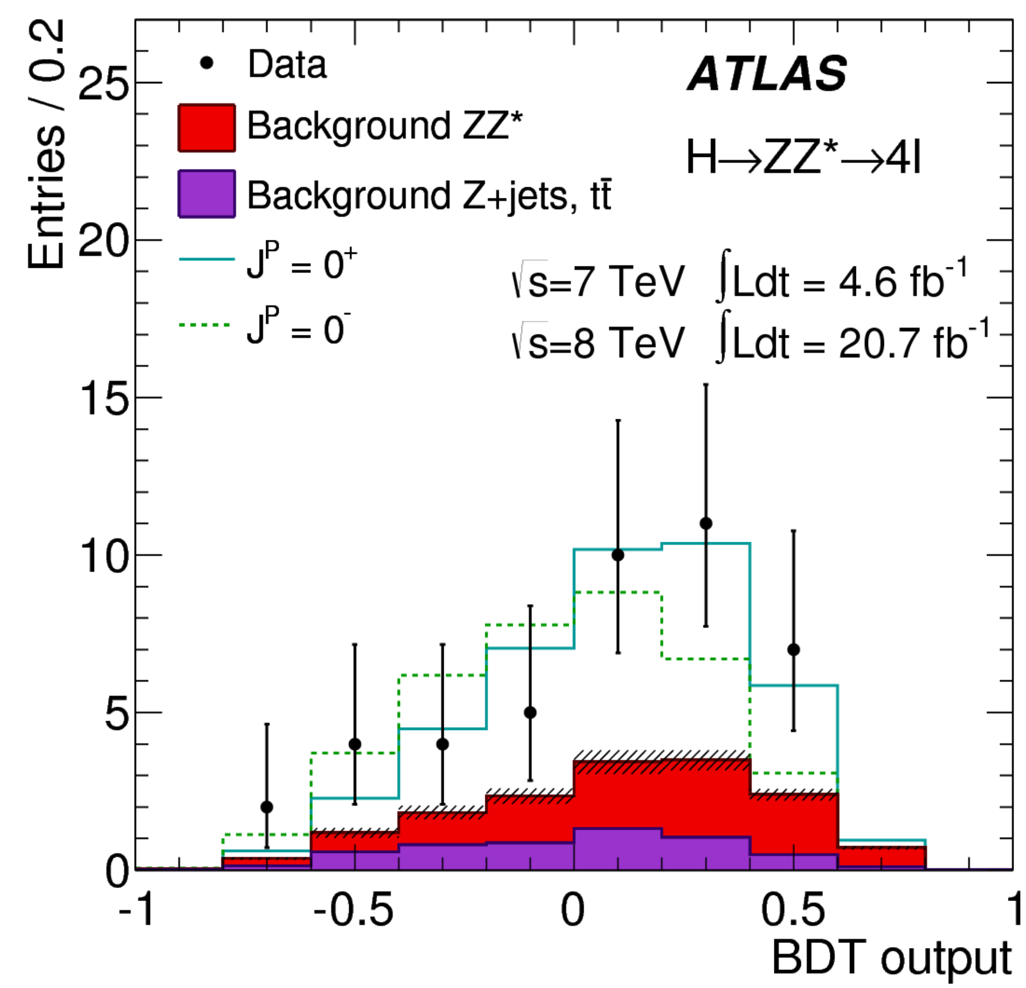


Does it spin like a Higgs?

- The spin-0 nature was already demonstrated at discovery by the fact that it decays to a pair of photons.
- The spin and parity quantum numbers were determined by CMS and ATLAS in 2013 [1212.6639] and [1307.1432].
- As predicted by the SM, the data followed $J^P=0^+$ hypothesis.

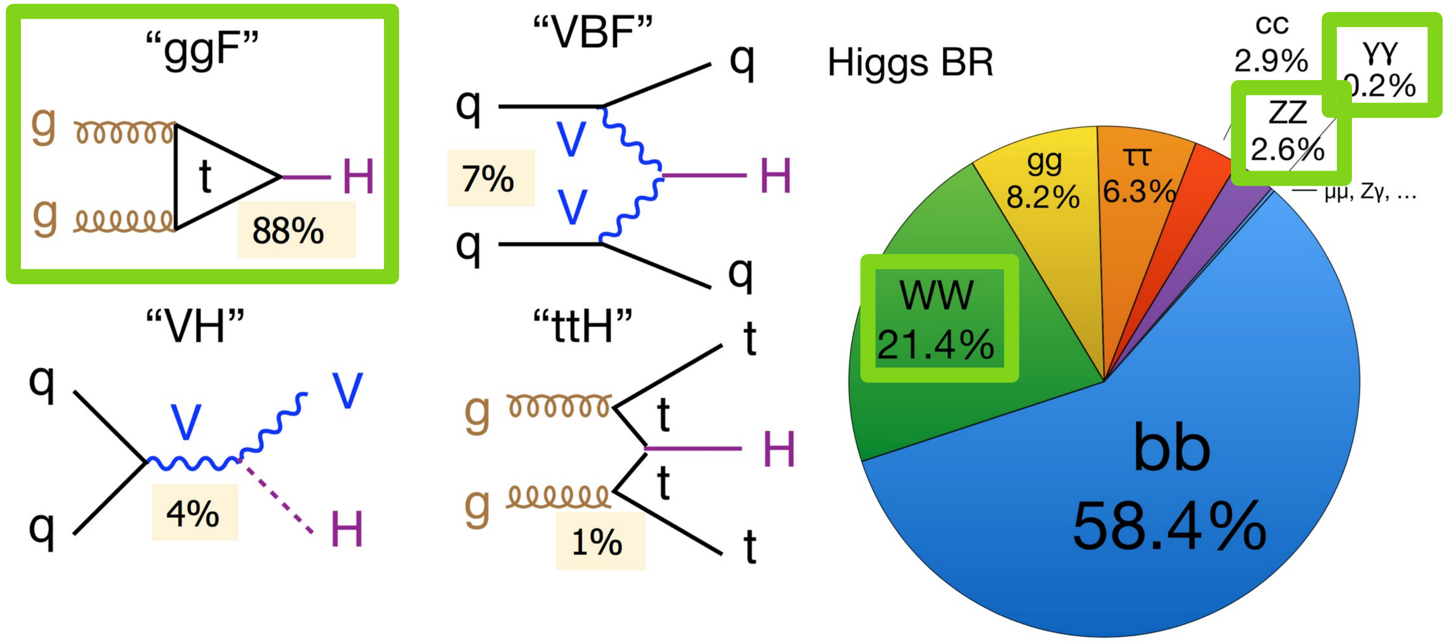




- Most recent results [1411.3441] and [1506.05669].

Does it couple like a Higgs?

- ggF production mode and $\gamma\gamma$, $ZZ\rightarrow 4l$ and $WW\rightarrow l\nu l\nu$ decay modes established from start.



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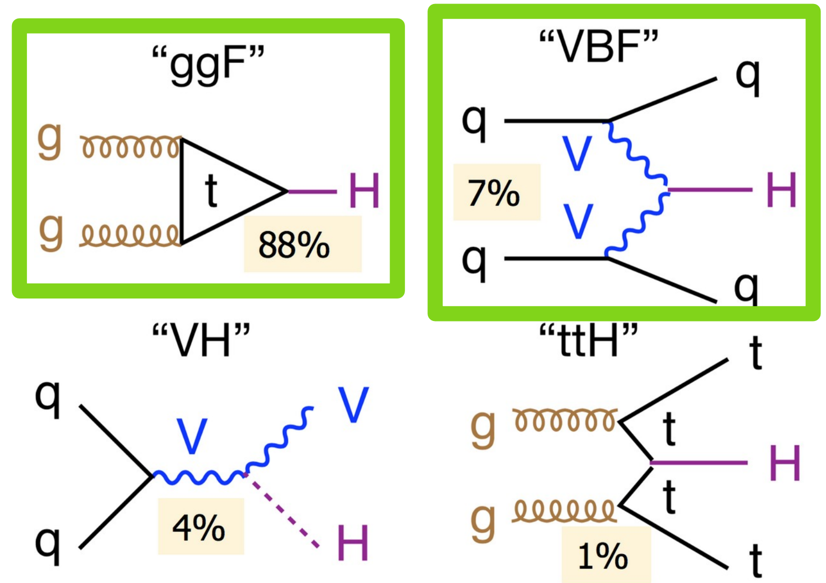
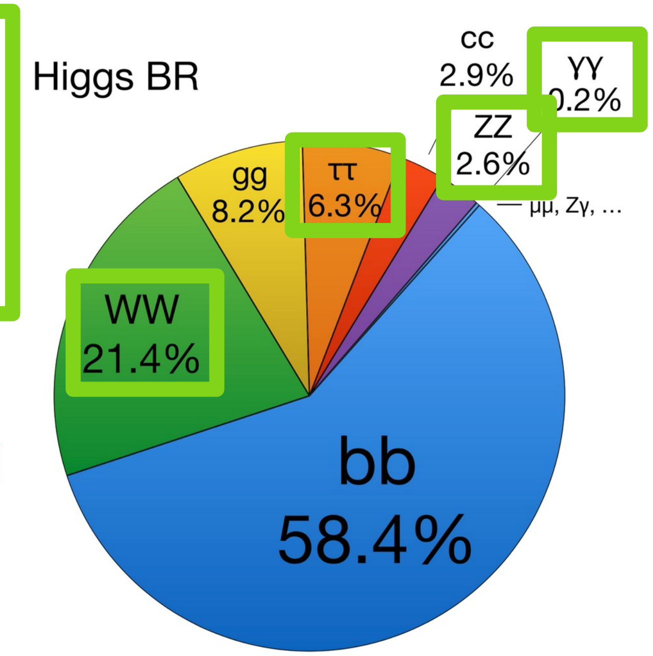
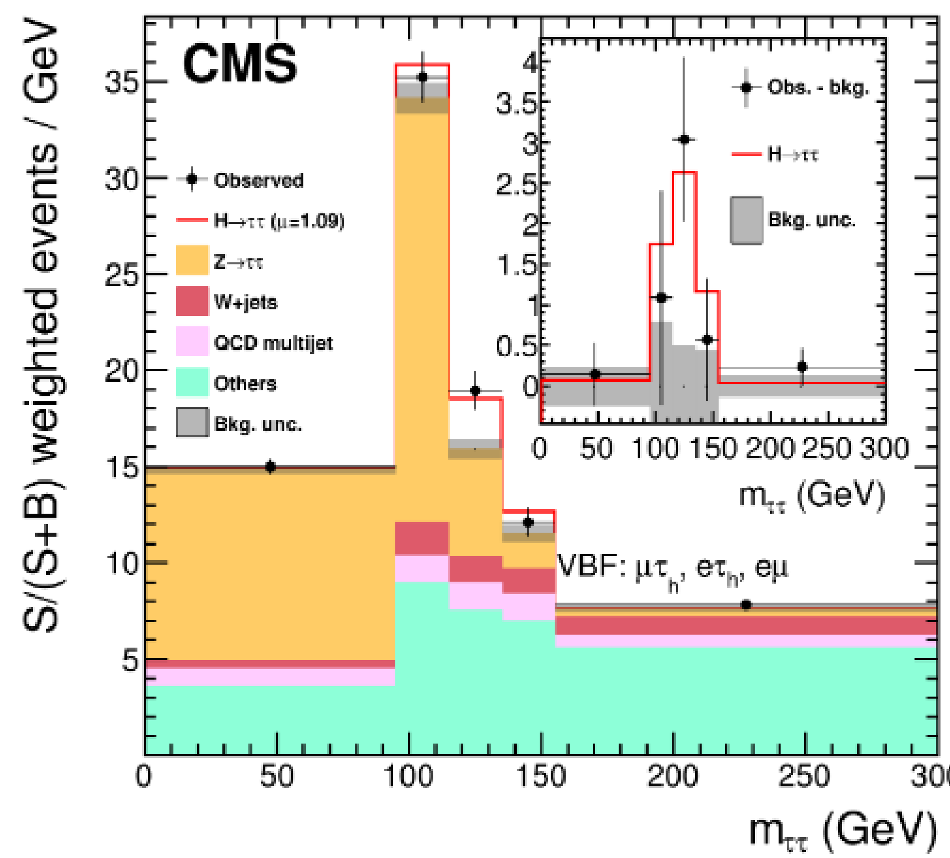
- ggF production mode and $\gamma\gamma$, $ZZ\rightarrow 4l$ and $WW\rightarrow l\nu l\nu$ decay modes established from start.
- Production via vector boson fusion and decay to fermions ($\tau\tau$) was established in ATLAS+CMS Run 1 combination in 2016 [1606.02266].
- Tau leptons can decay either hadronically (~70%) or leptonically.
- Look like narrow jets in the detector, use a BDT to identify.
- Largest irreducible background comes from $Z/\gamma^*\rightarrow\tau\tau$.







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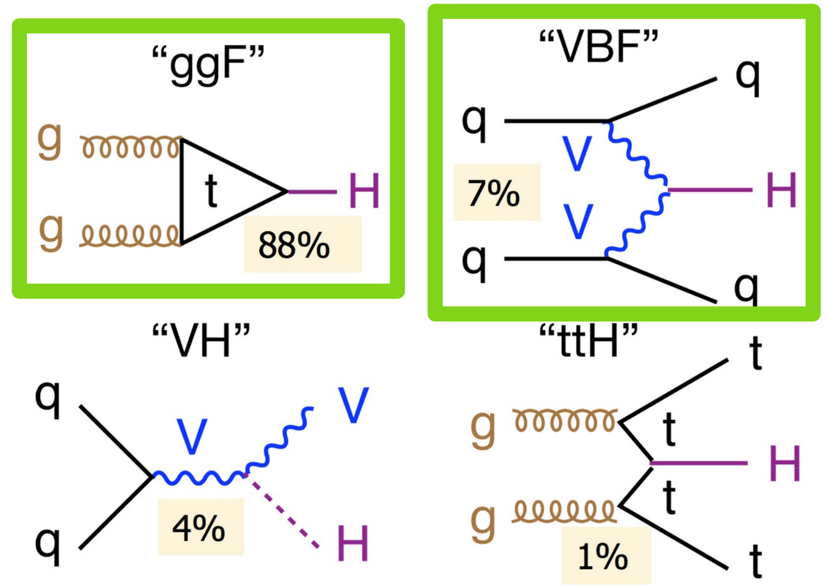
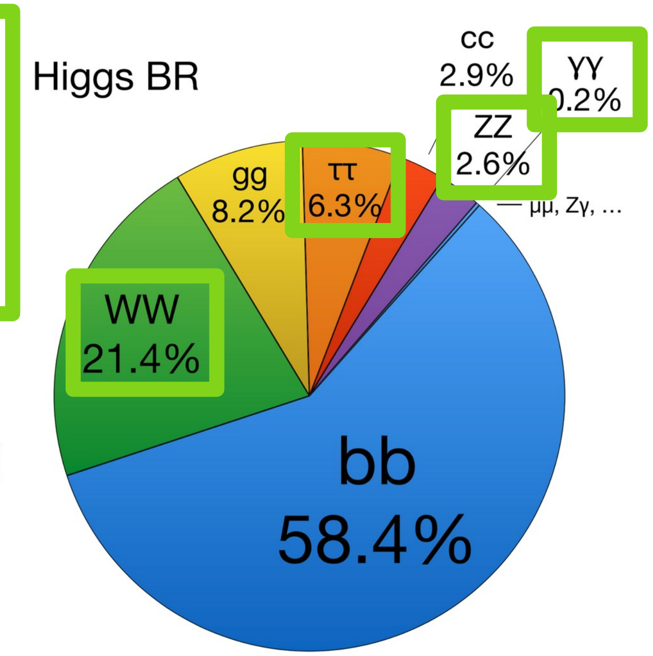
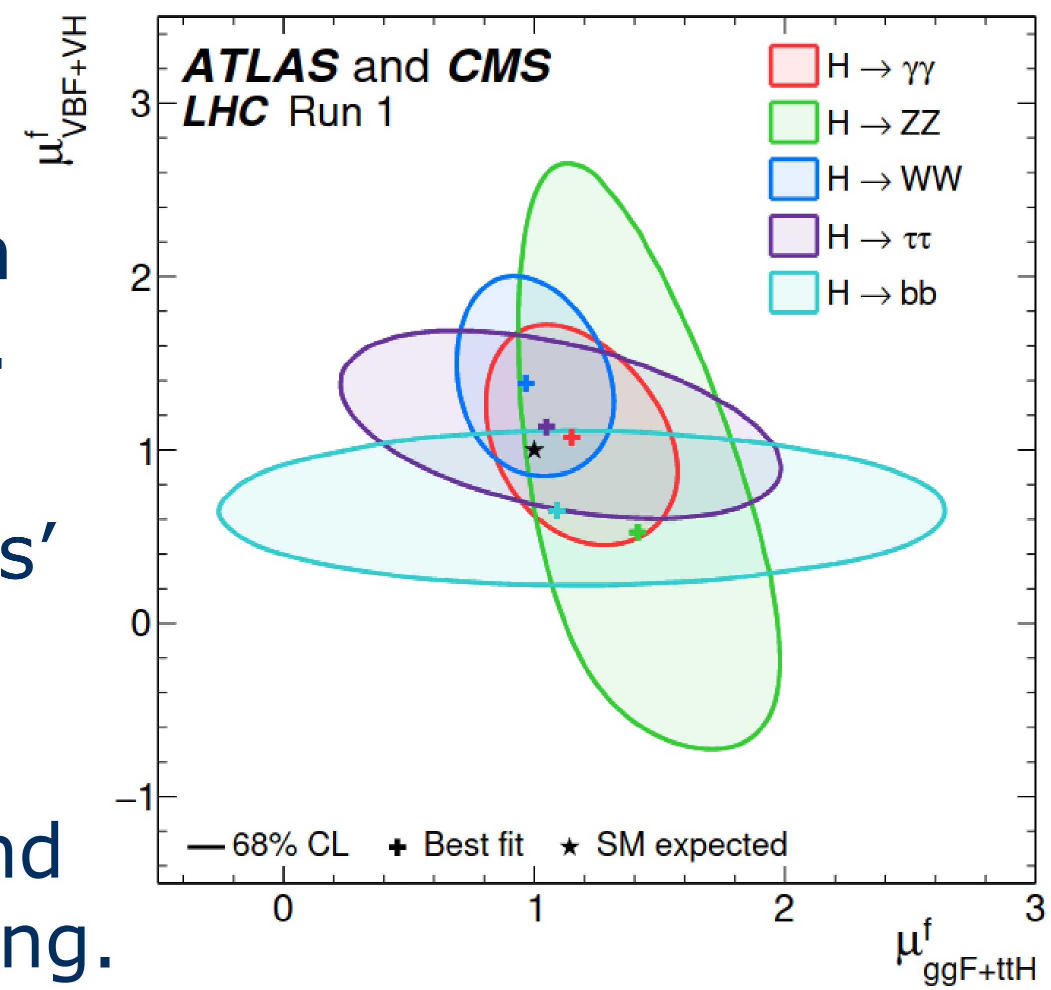
- Production via vector boson fusion and decay to fermions ($\tau\tau$) was established in ATLAS+CMS Run 1 combination in 2016 [1606.02266].
- Already then quite stringent tests on the couplings to bosons vs fermions.
- Remember that the boson couplings come from the EWSB while the Higgs' couplings to fermions are explicitly added to the SM.
- Still no measurement of bb decay and no direct measurement of top coupling.

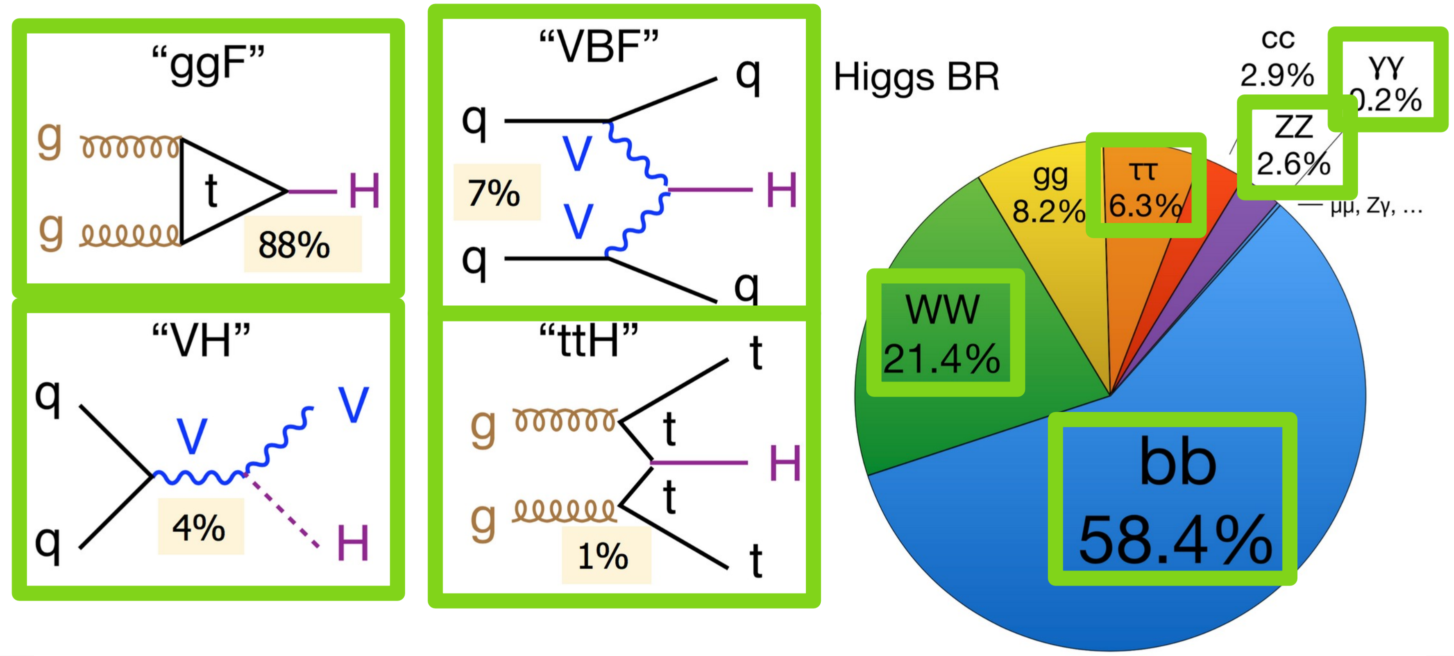






Does it couple like a Higgs?

- ttH and VH production, the latter in the bb decay mode alone, were observed in 2018 [1804.02610], [1806.00425], [1808.08238], [CMS-PAS-HIG-18-016].
- Both ttH and VH were originally considered Run3+ measurements.
- The Run 2 observations were made possible by excellent b-tagging in both experiments.



"The WH channel will be very difficult… even under the most optimistic assumptions."

— ATLAS-TDR-1999

"the discovery potential for… the WH production mode at the LHC is marginal… For $ZH \rightarrow llb\bar{b}$ a similar signal-to-background ratio is expected as for the WH channel."

— Int. J. Mod. Phys. A 20:2523-2602 (2005)

"a Higgs-boson signal could be [observed for $t\bar{t}H(b\bar{b})$]… assuming an integrated luminosity of 300 fb^{-1}"

— ATLAS-TDR-15

"[ttH and WH] are definitely high-luminosity measurements."

— CERN-PH-TH/2004-103

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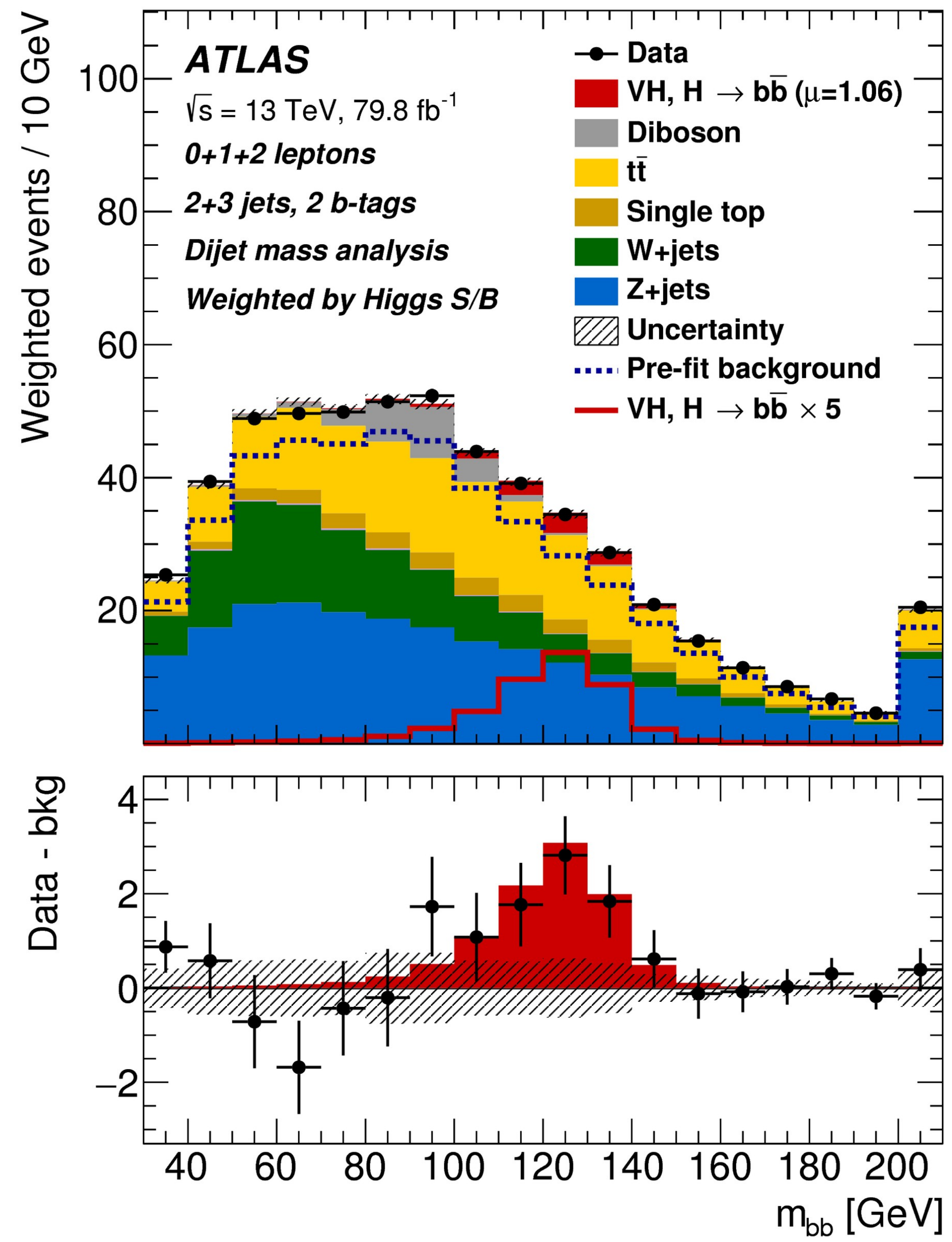
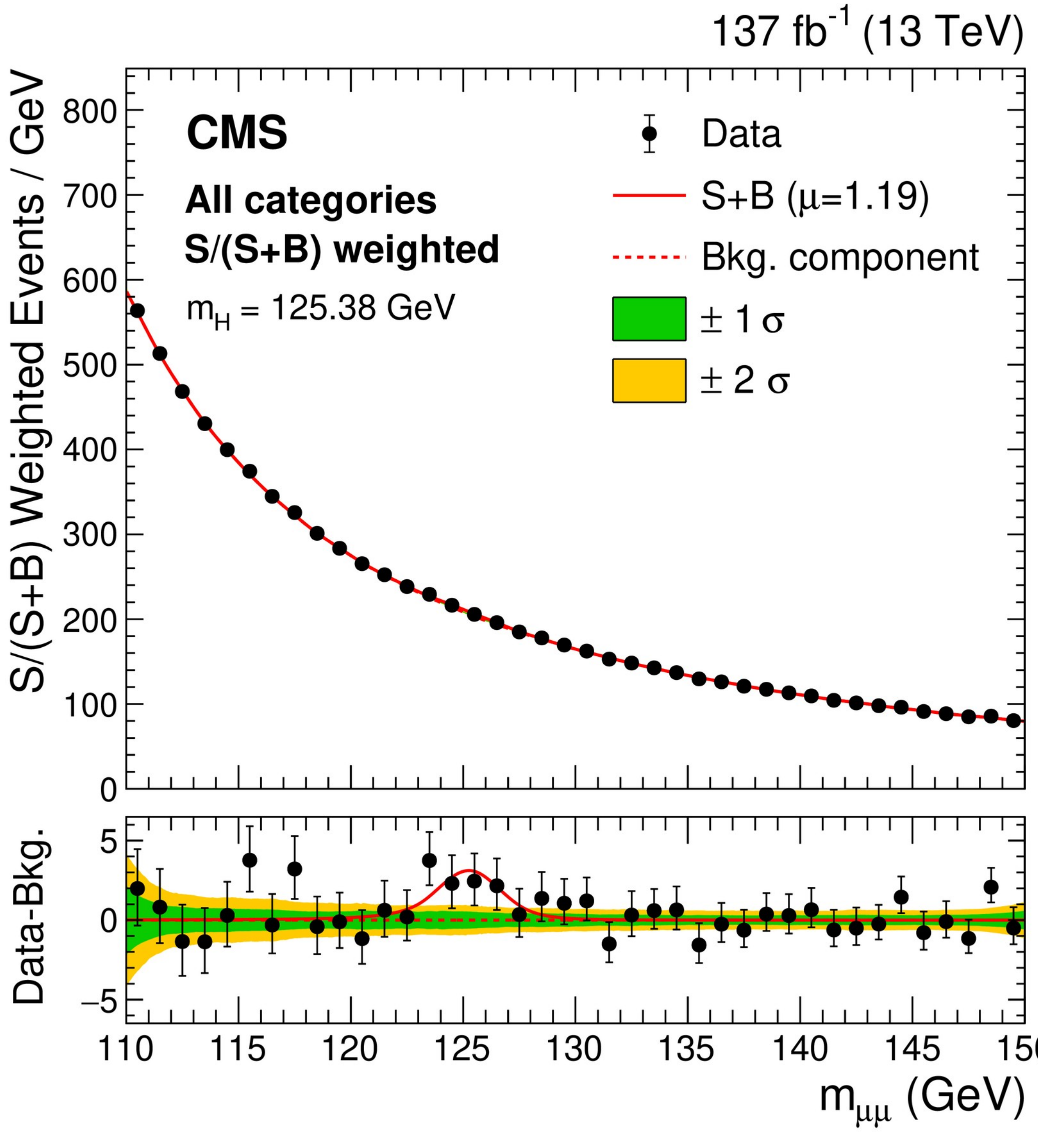


Does it couple like a Higgs?

- At present, ATLAS and CMS have established the coupling of the Higgs to all massive bosons and all* 3rd generation fermions.
- Next milestone is to establish the coupling to the 2nd generation fermions.
  - The $\mu\mu$ decay mode is on the verge of being observed.
  - Evidence by CMS in 2020 [2009.04363].
  - The *cc* decay mode is more challenging. Current limits are $\sigma<31\cdot\sigma_{SM}$ (ATLAS, 2201.11428) $\sigma<47\cdot\sigma_{SM}$ (CMS, 2211.14181)



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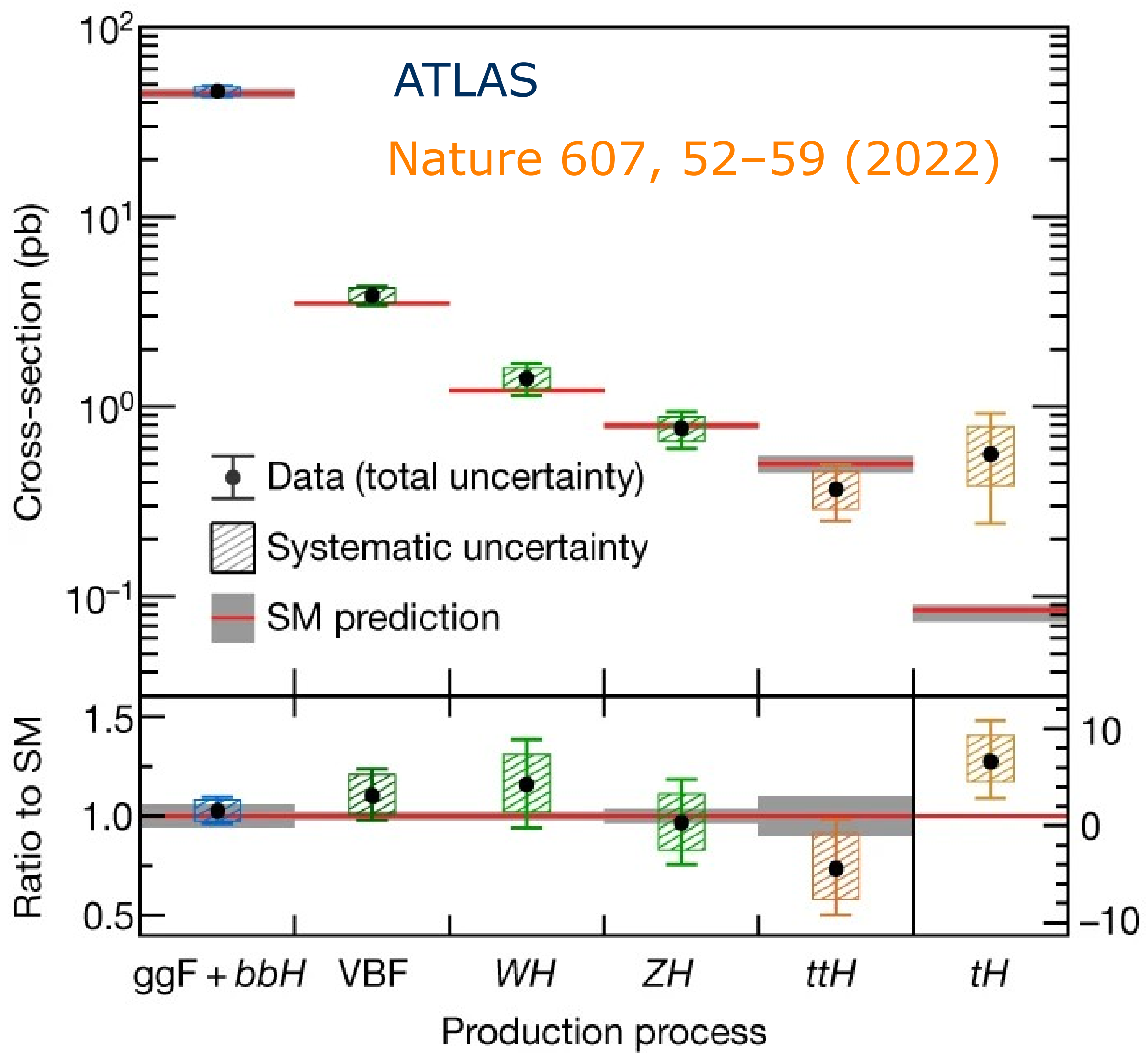

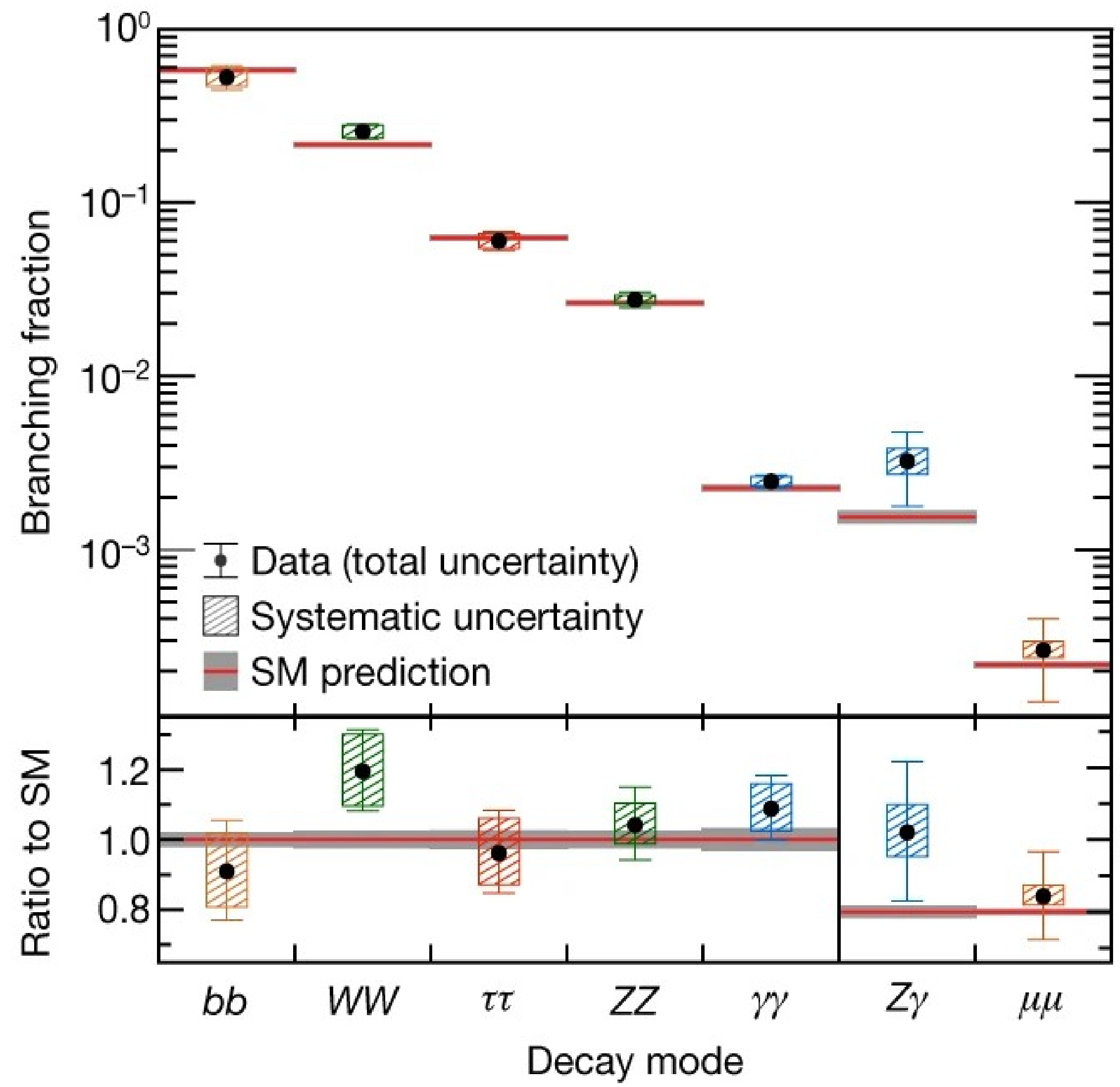

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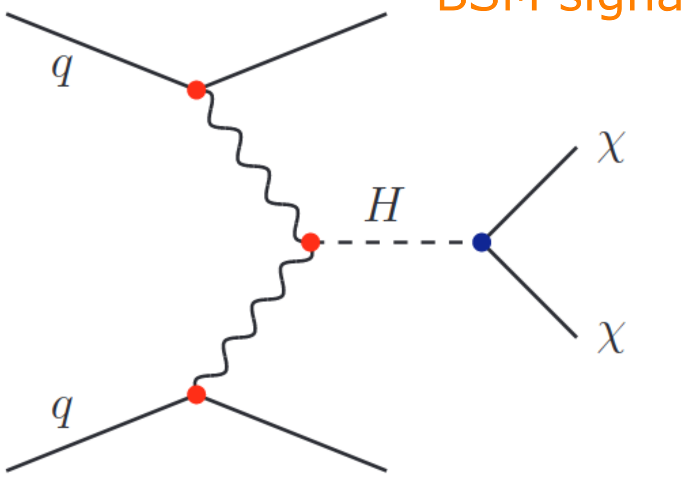
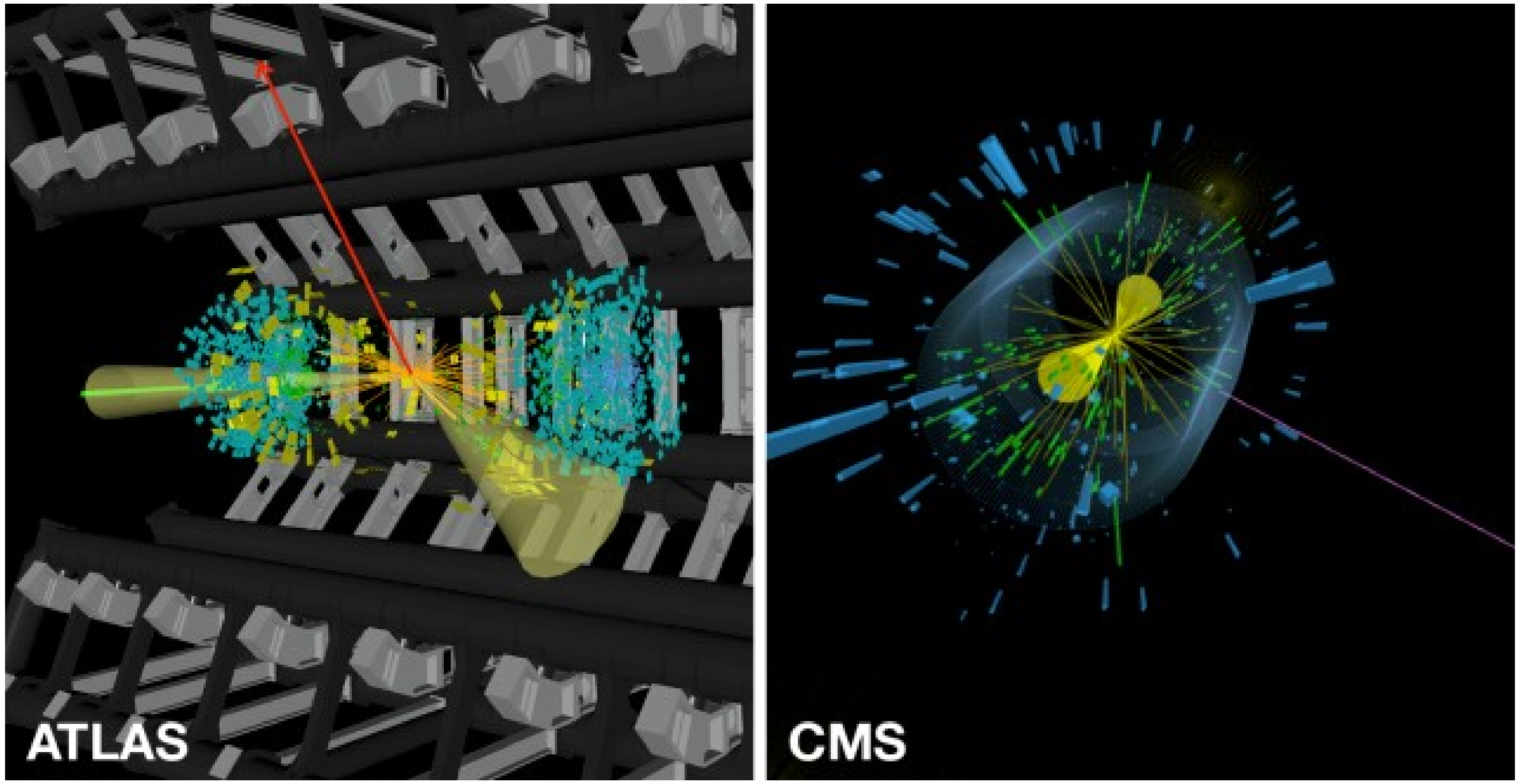
Higgs to invisible

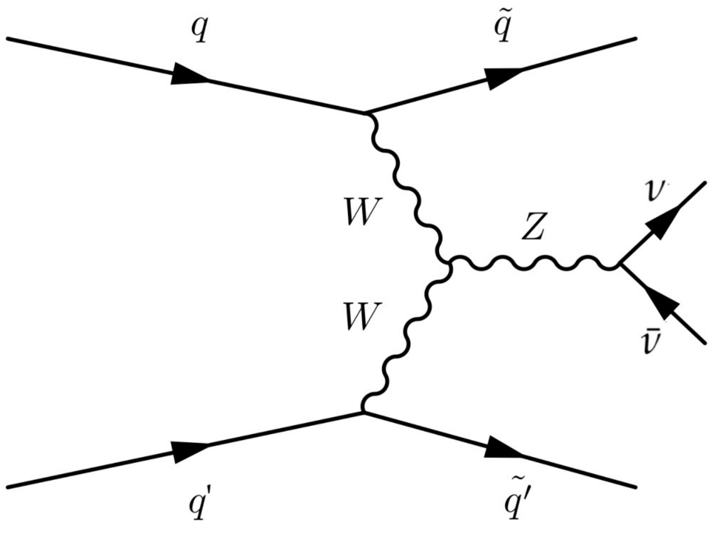
- In the SM, the Higgs is expected to decay to a fully invisible final state with a BR of 0.12%, through $H \to ZZ \to 4\nu$.
- But there are several BSM scenarios that given invisible BR of O(10%), e.g. Higgs decays to DM pairs.
- ATLAS and CMS put upper limits on BR_{inv}:
  - 0.18 (0.10 exp.) [CMS, 2201.11585]
  - 0.145 (0.103 exp.) [ATLAS, 2202.07953]

BSM signal





SM background



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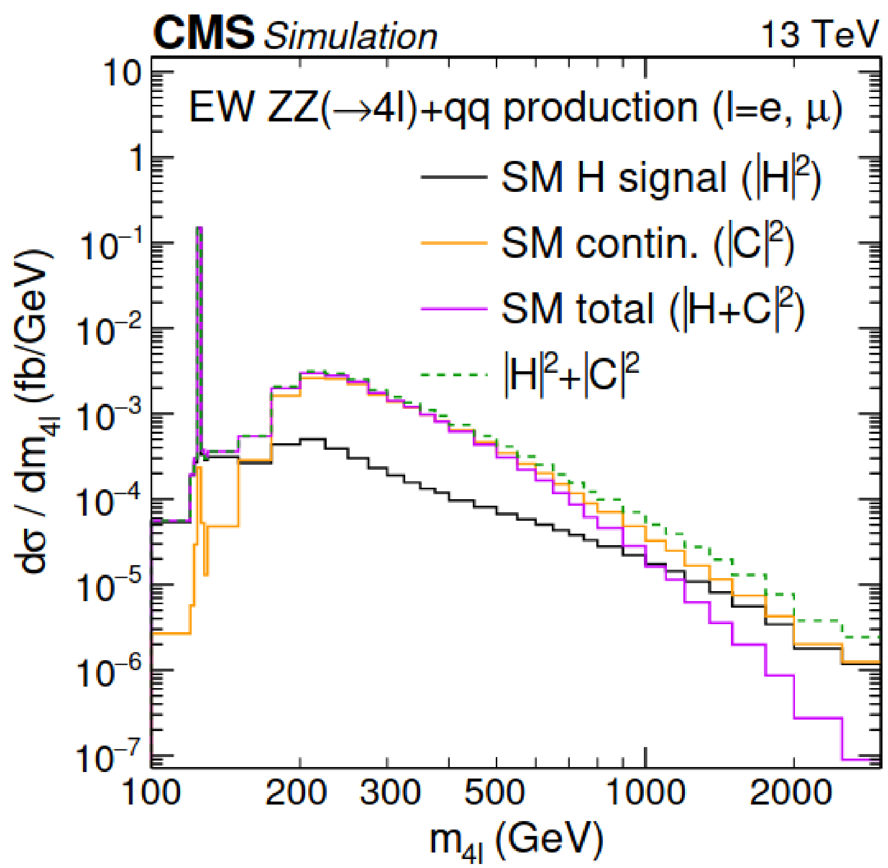
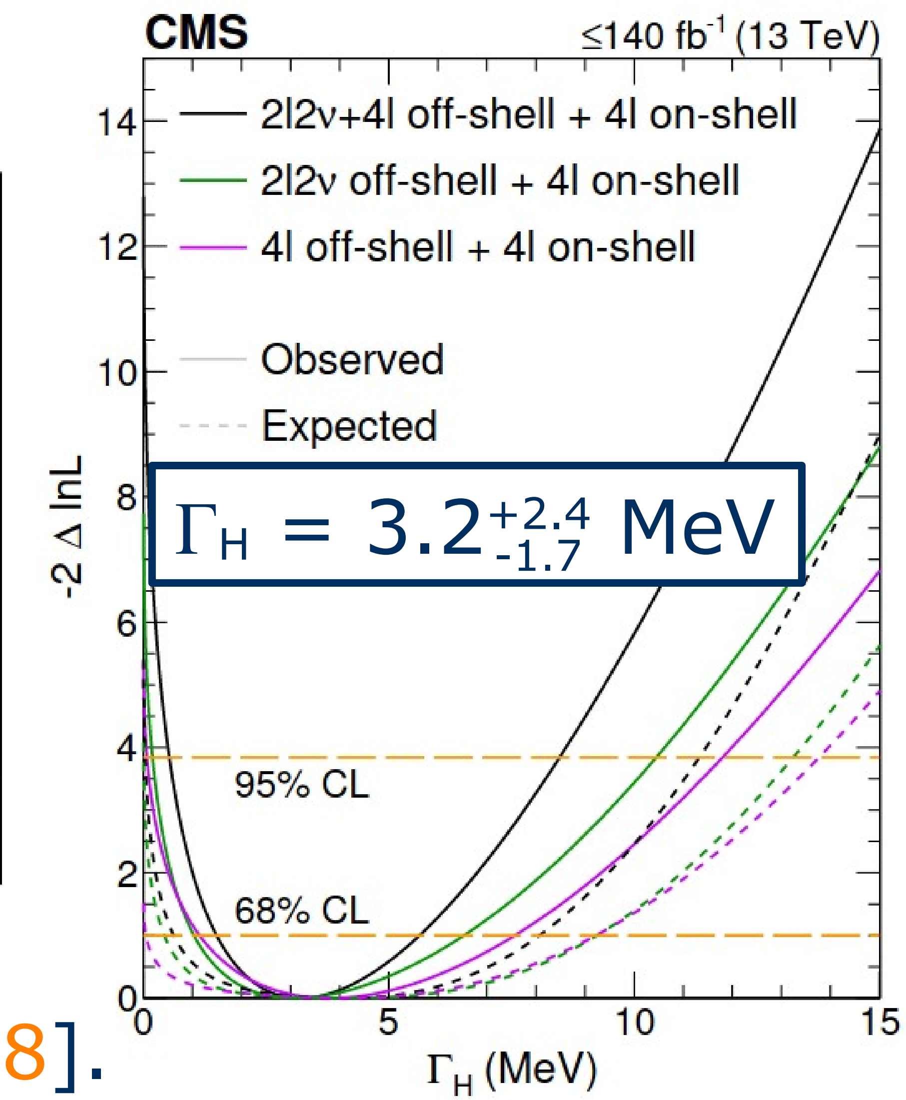
Higgs width

- Always measure $\sigma_{prod} \times BR \rightarrow$ need total width to disentangle.
- The total width of the Higgs boson is predicted to be 4.1 MeV. Impossible to measure directly (detector resolution too poor).
- First indirect measurement by CMS in 2022 [2202.06923].
- Compares on- and off-shell Higgs production; $\sigma^{\text{off-shell}} \sim \mu^{\text{on-shell}} \Gamma_H$.
- Use $ZZ \rightarrow 2l2\nu$ and $ZZ \rightarrow 4l$ decays.
- Challenging since $qq \rightarrow ZZ$ production is much larger than off-shell $H \rightarrow ZZ$.
- Binned maximum likelihood fits to >100 kinematic distributions.





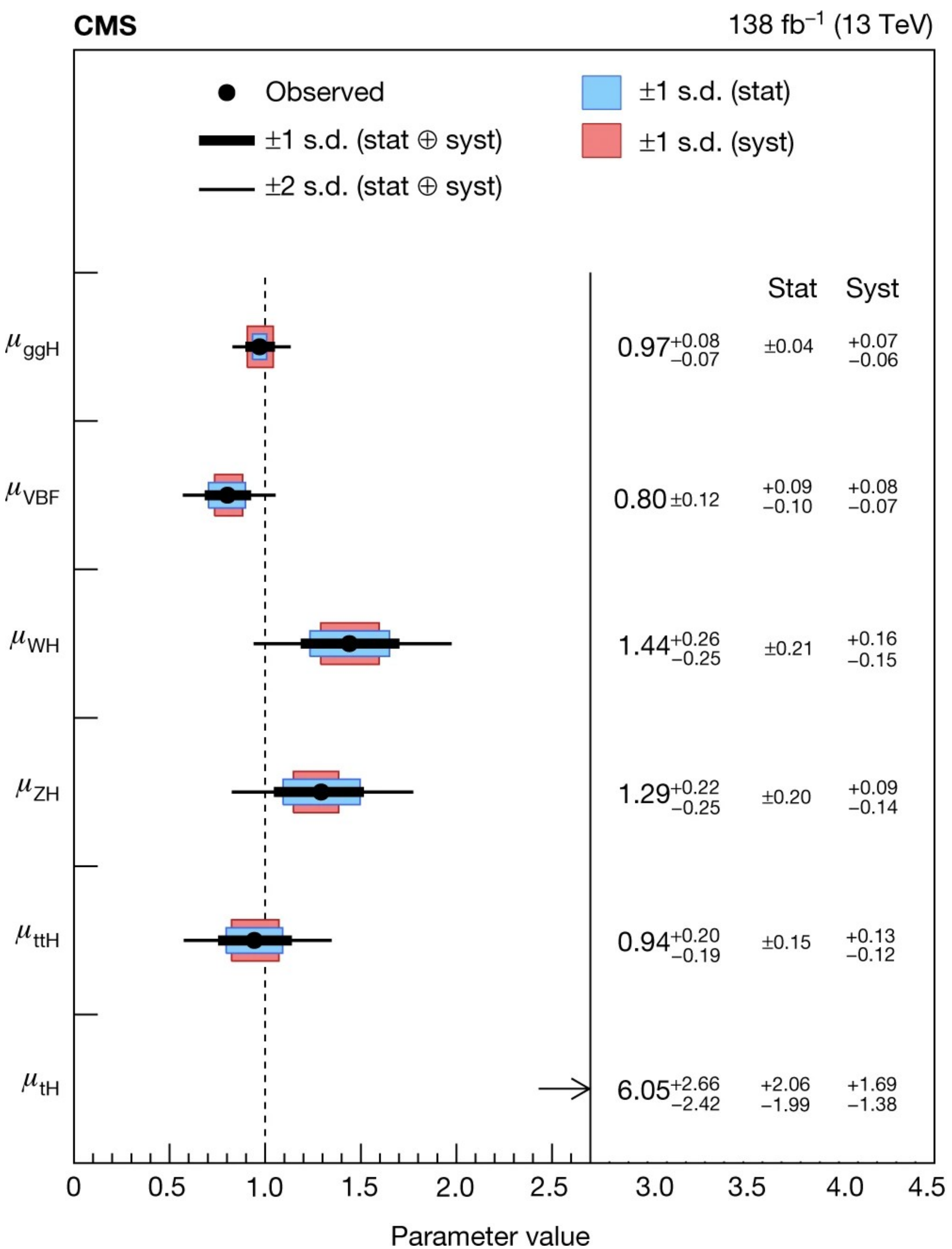
$\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

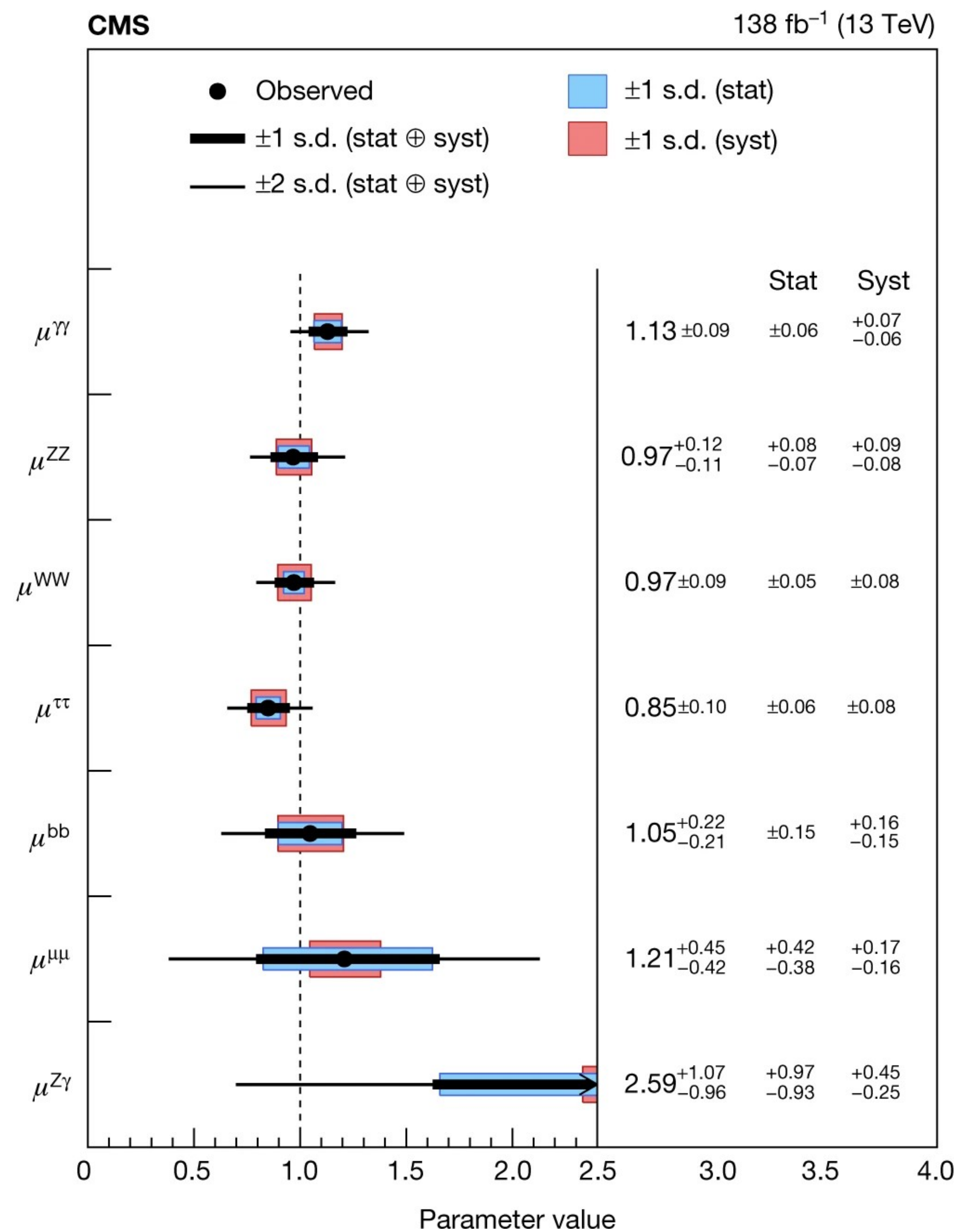
- Recent CONF note [ATLAS-CONF-2022-068].

The μ framework

- The agreement between the observed signal yields and the SM expectations can be quantified by fitting the data with a model that introduces signal strength parameters.
- These are generically labelled μ, and scale the observed yields with respect to those predicted by the SM, without altering the shape of the distributions.
- Thus $\mu = 1$ means perfect agreement with the predicted SM yield.
- Fitting the data from all production and decay modes with a single signal strength parameter yields:
  - $\mu = 0.87 \pm 0.23$ (CMS, 2012)
  - $\mu = 1.002 \pm 0.057$ (CMS, end of Run 2)
  - $\mu = 1.05 \pm 0.06$ (ATLAS, end of Run 2)
    $= 1.05 \pm 0.03\,\text{(stat.)} \pm 0.03\,\text{(exp.)} \pm 0.04\,\text{(sig. th.)} \pm 0.02\,\text{(bkg. th.)}$
- Can also derive the signal strength for individual production and decay modes.

Production and decay summary

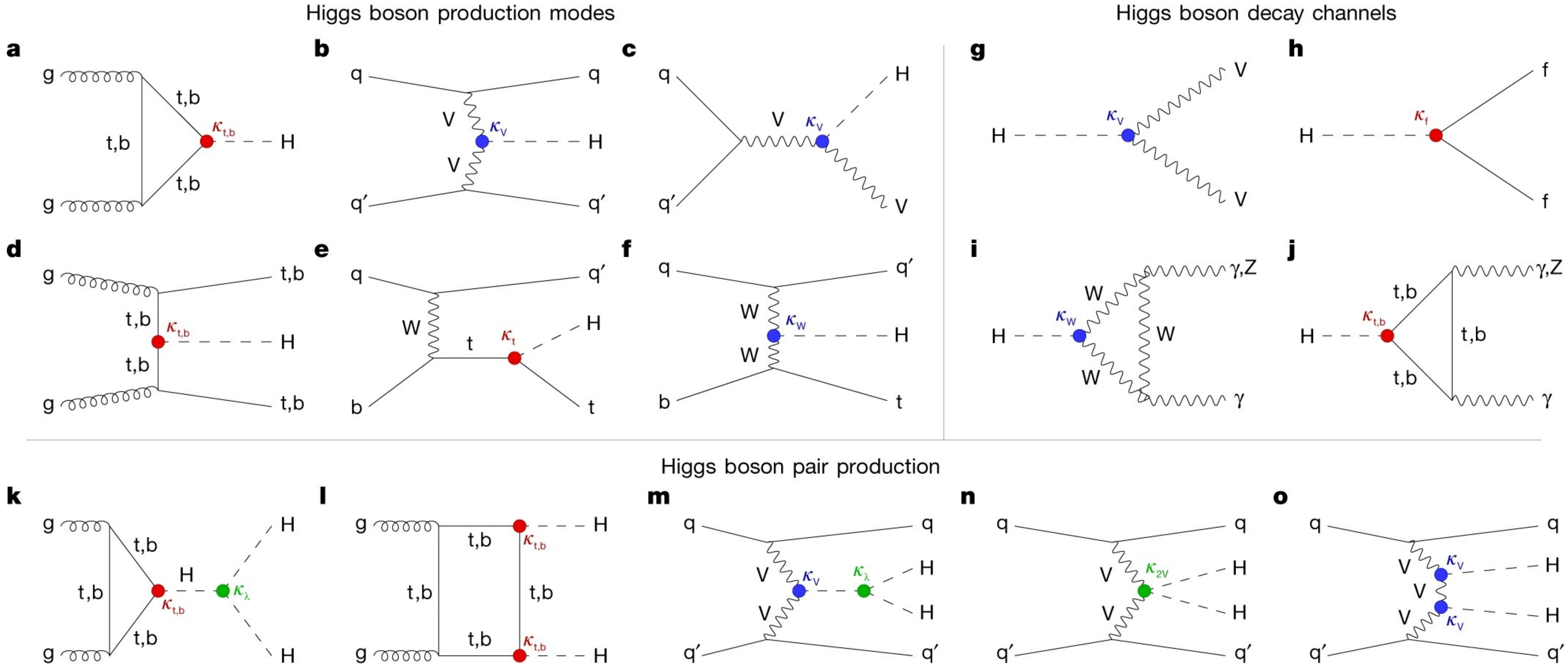




Nature 607, 60–68 (2022)

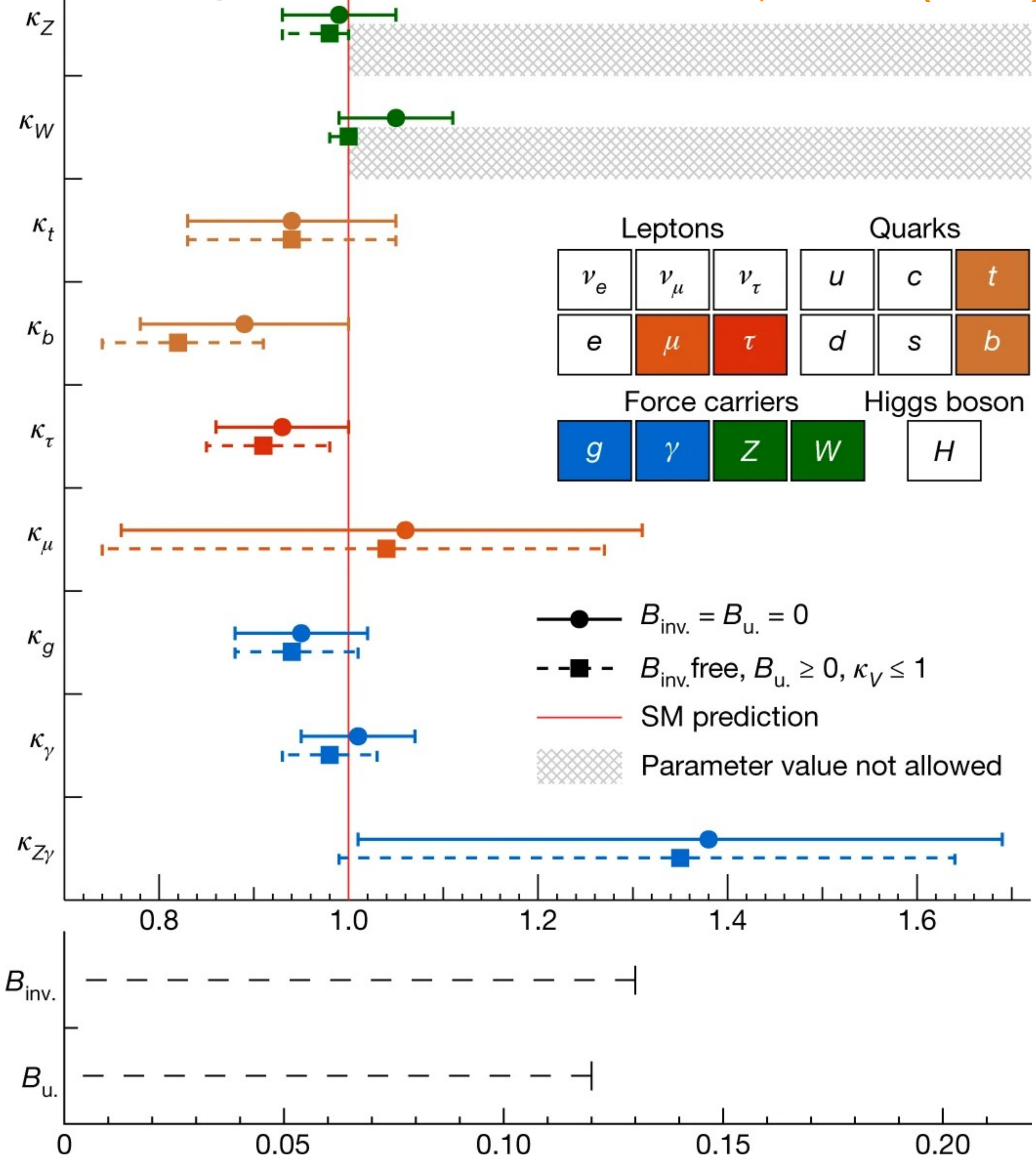
The κ framework

- A modification of the coupling strength between the Higgs and another particle can affect several processes.
  - E.g. the modification of the Higgs-top coupling strength affects both the ggF production and the $\gamma\gamma$ decay.
- This is handled by introducing coupling strength modifiers κ.
- Observables such as σ and Γ become proportional to κ^2.

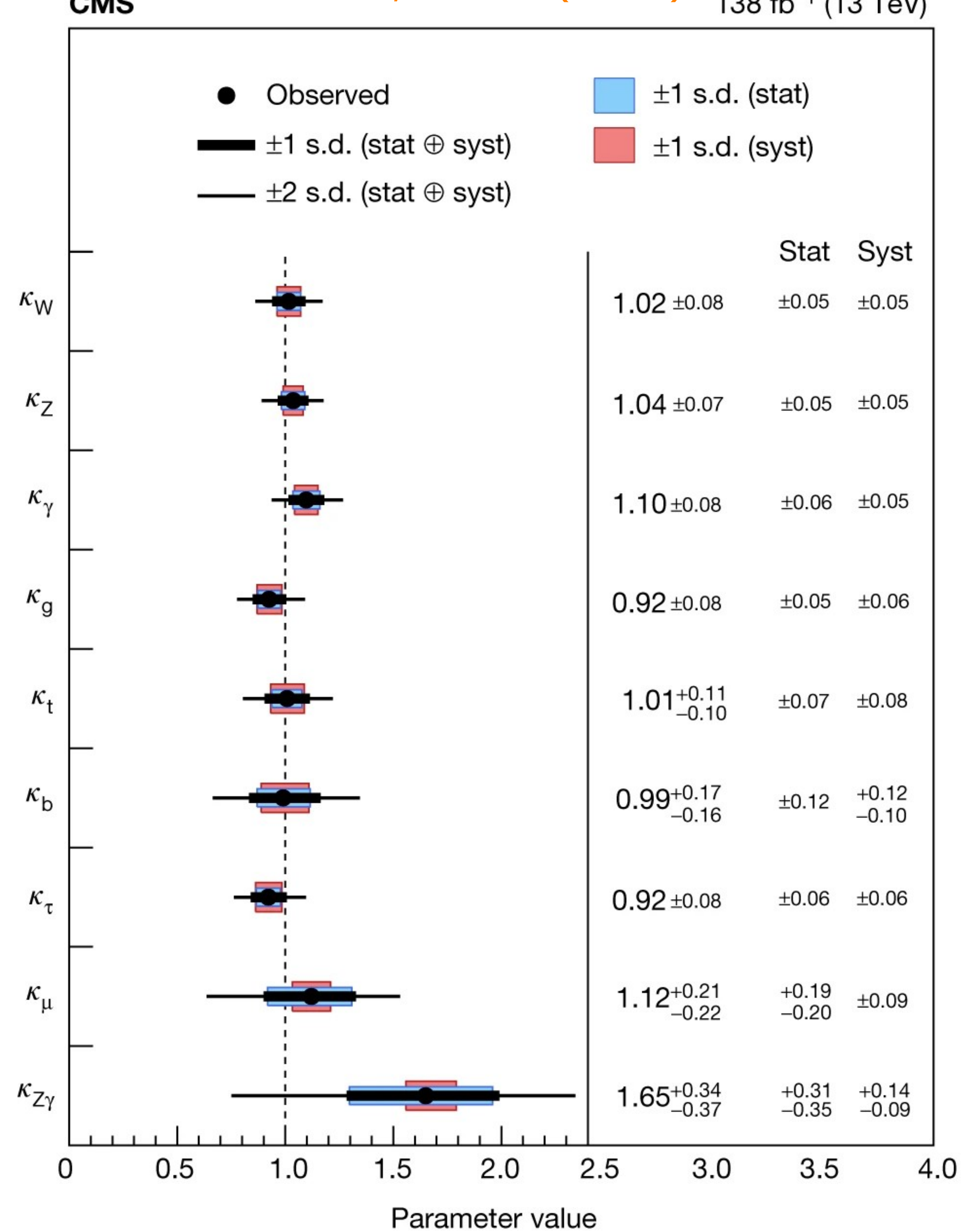


Production and decay modes

Nature 607, 52–59 (2022)

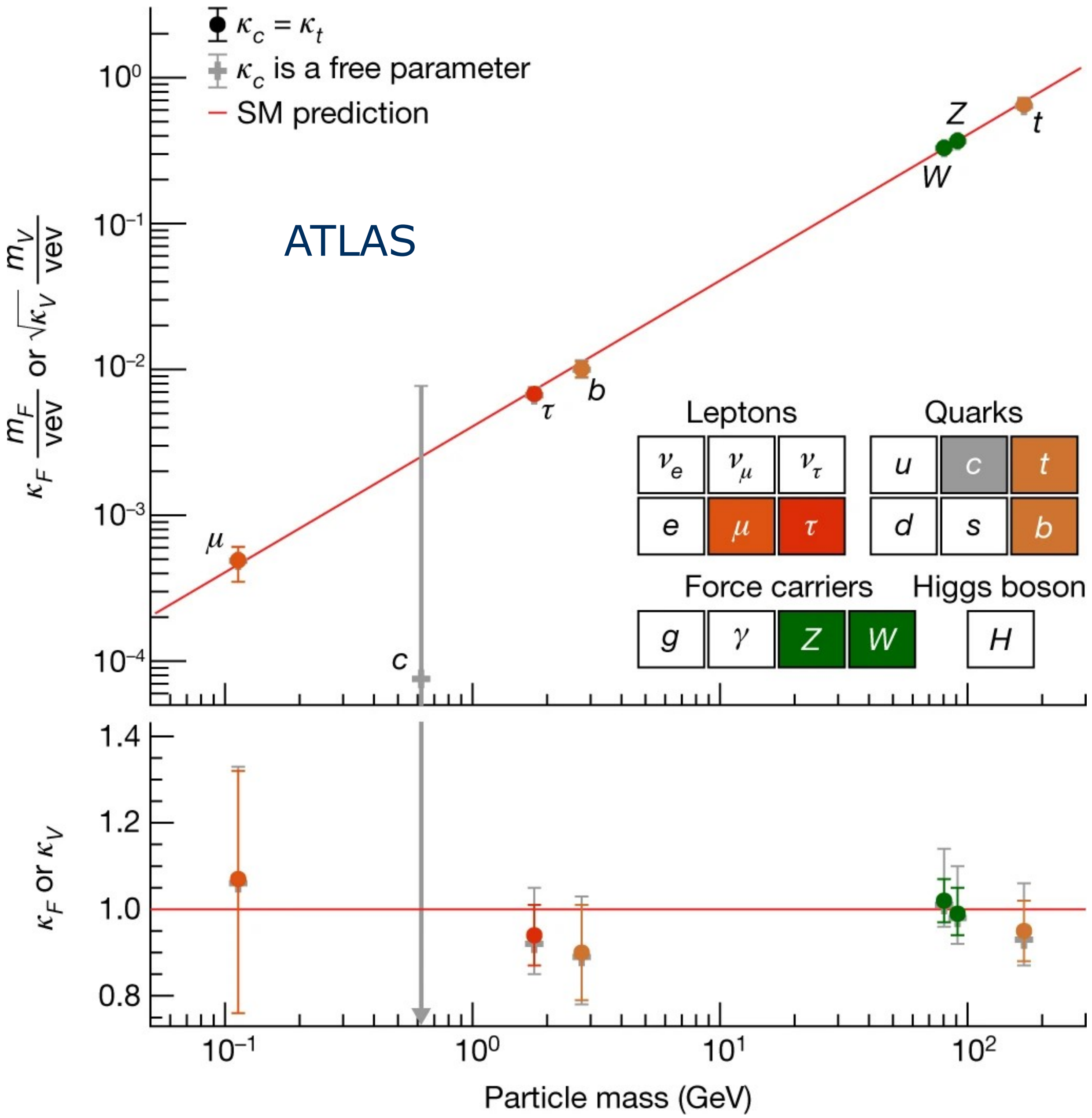


Nature 607, 60–68 (2022)

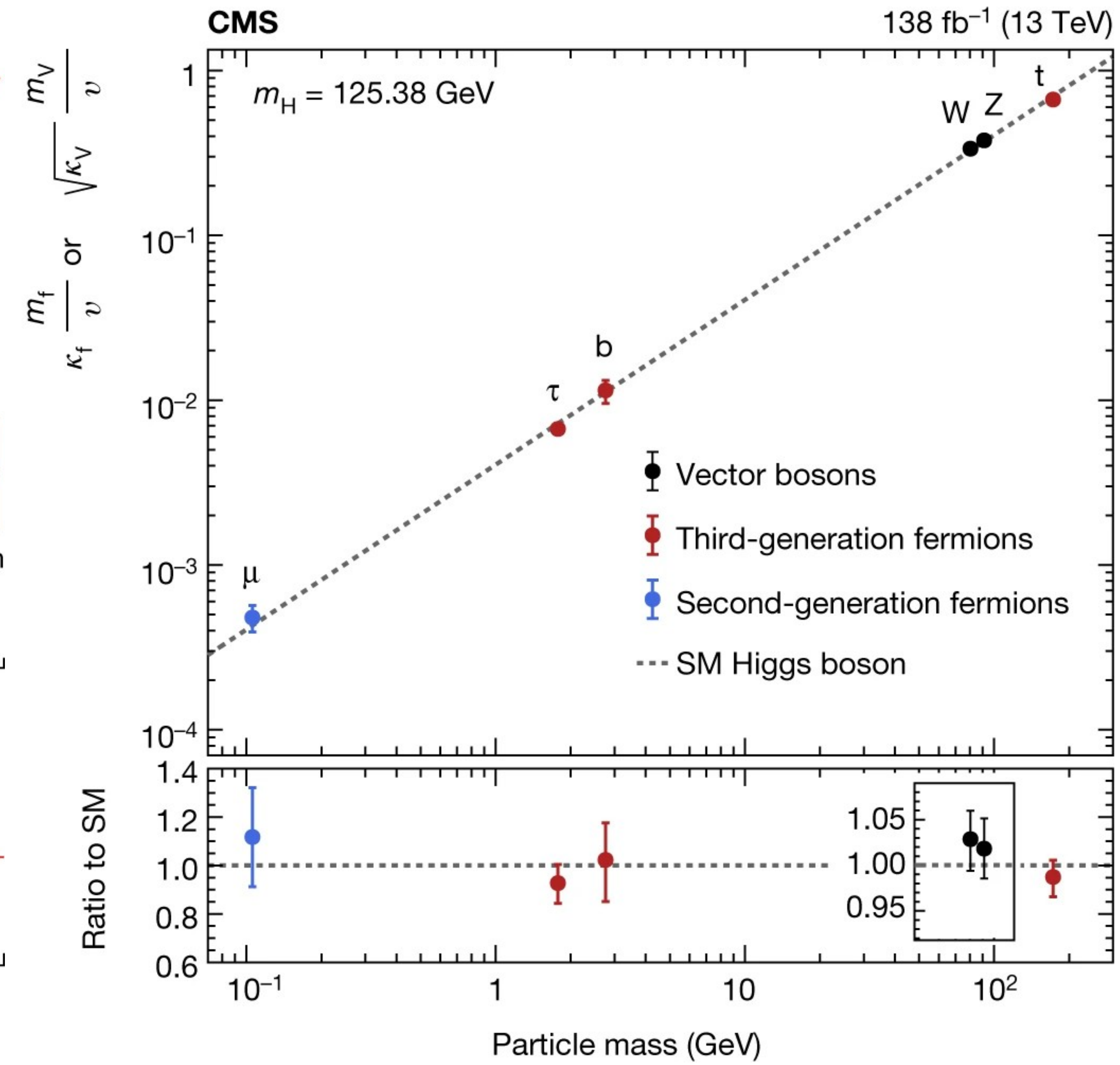


The Higgs fingerprint

- At the heart of the Higgs mechanism is the prediction that it should couple to other particles in proportion to their masses.



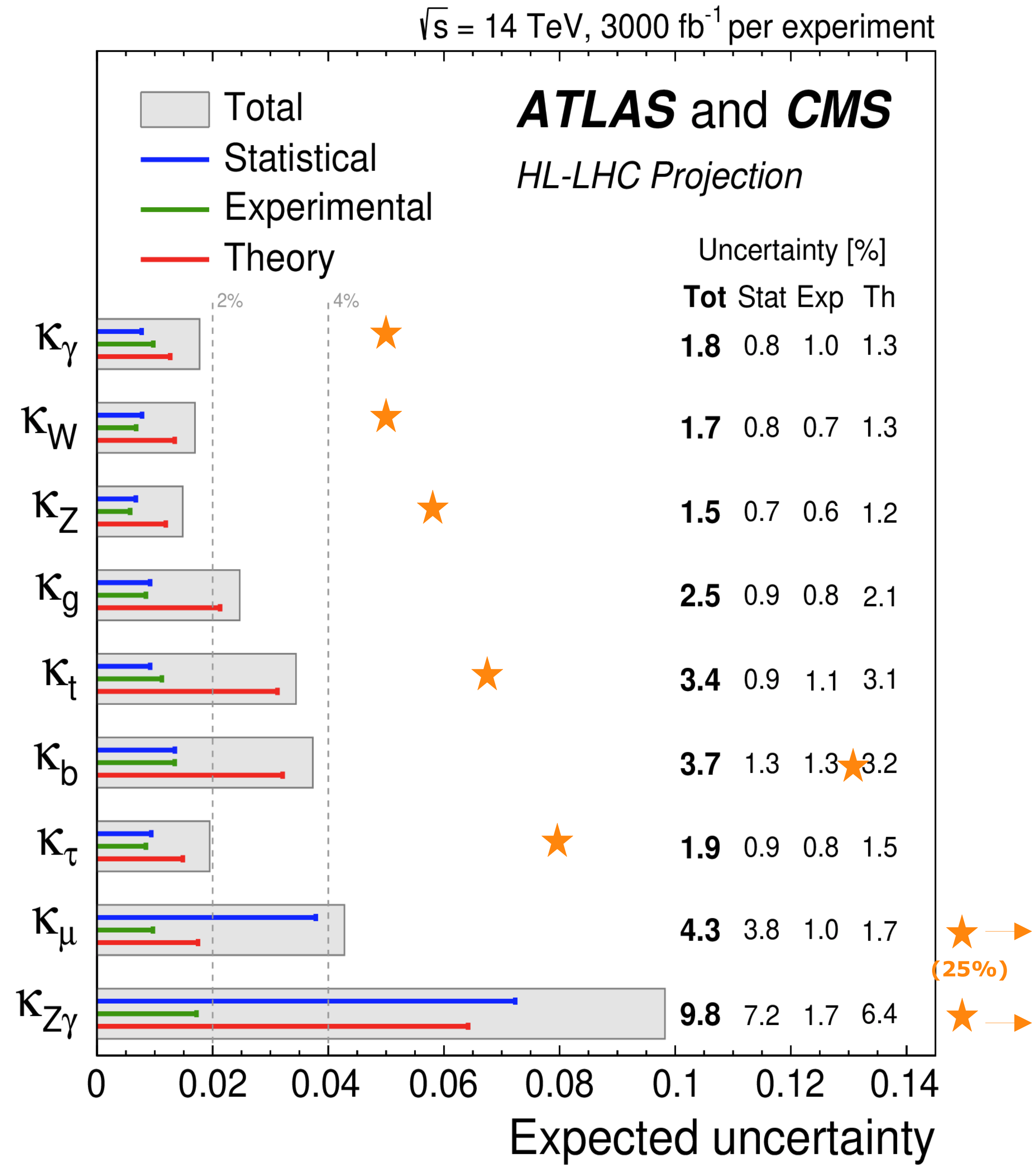
Nature 607, 52–59 (2022)



Nature 607, 60–68 (2022)

Higgs precision at HL-LHC

- Currently our precision on the measurements on the coupling strengths between the Higgs boson and the other Standard Model particles is 5-10% (some cases even as bad as 25%).
- Percent-level precision is expected on these measurements by the end of HL-LHC.
  - Will give sensitivity to BSM particles with masses in the multi-TeV regime.



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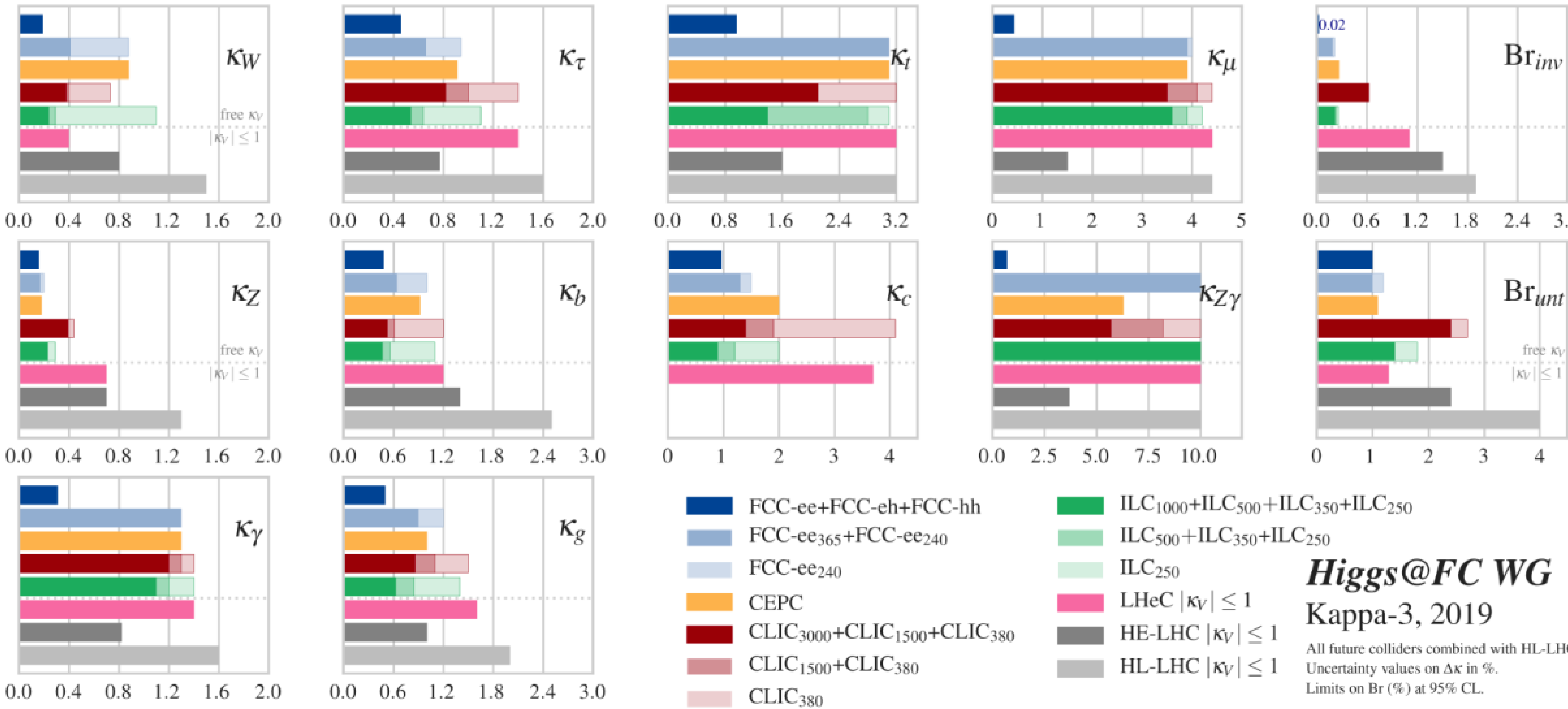
Higgs precision at future colliders



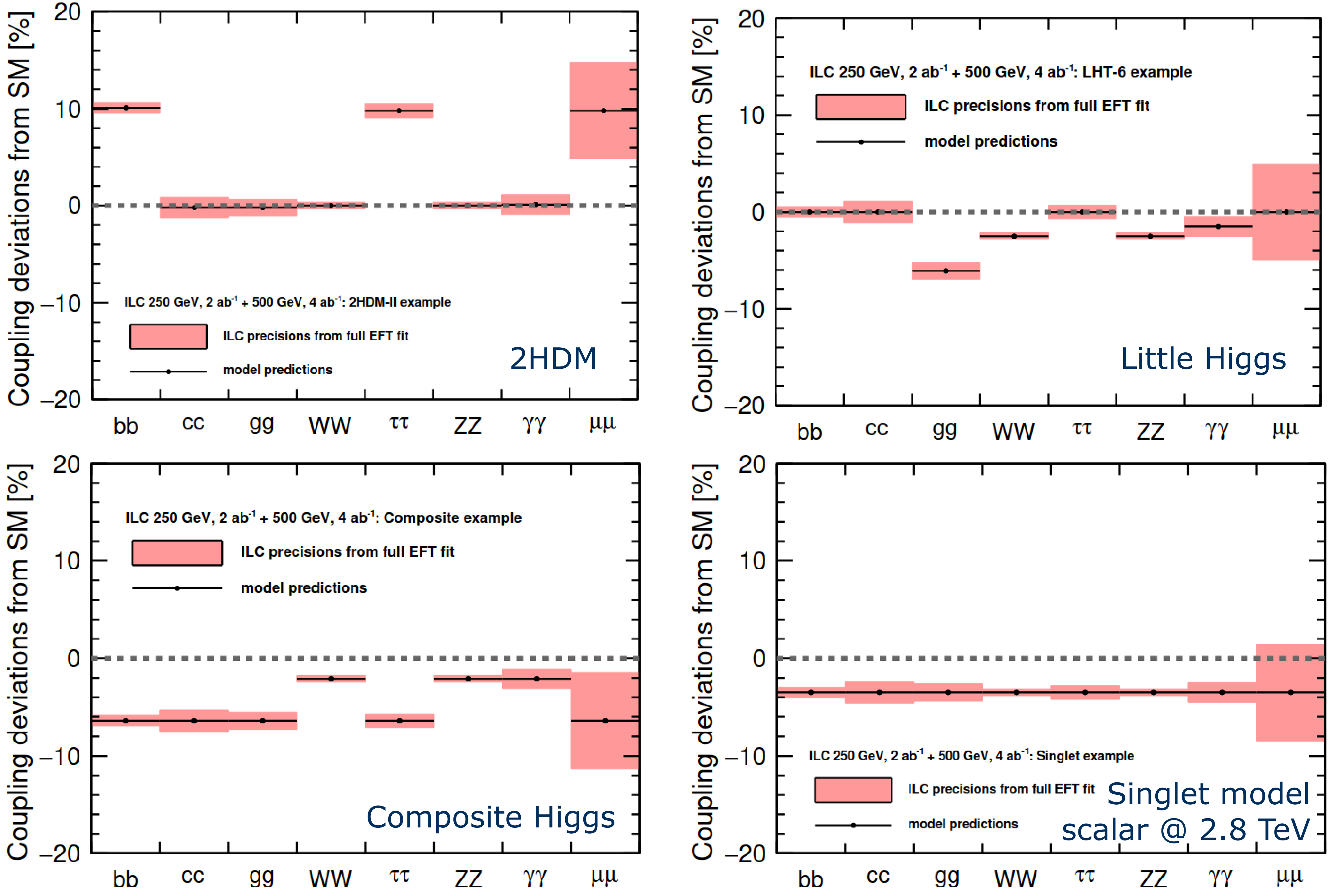
- O(1%) precision or better for many couplings with future colliders.

Physics Briefing Book

European Particle Physics Strategy Update 2019

BSM impact on couplings

- Examples of coupling modifications by different BSM models.

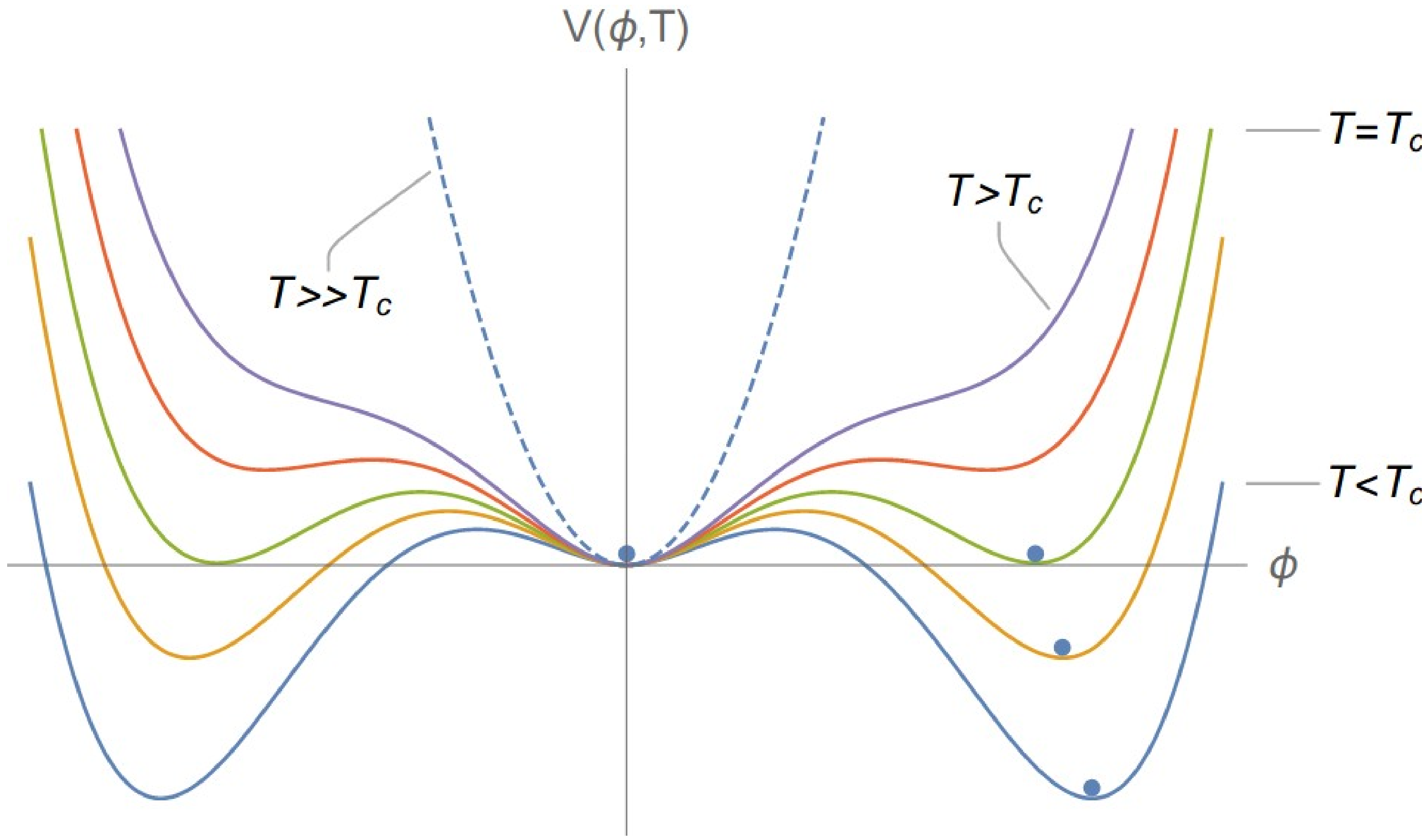


From: ILC Snowmass report

The Higgs potential

- In the early Universe, the minimum of Higgs potential was at φ=0.
- All elementary particles were massless.
- But O(ps) after the Big Bang a new minimum at φ≠0 developed.

  → EW phase transition.



Credit: Rikard Enberg

- Particles acquired mass by interacting with the ≠0 Higgs field.
- 2nd order phase transition in the SM.
- 1st order transition can generate matter-antimatter asymmetry.
- To better understand this phase transition we need to experimentally probe the shape of the Higgs potential.
- The best way to do this at the LHC is by looking for Higgs pair (a.k.a. diHiggs) production.

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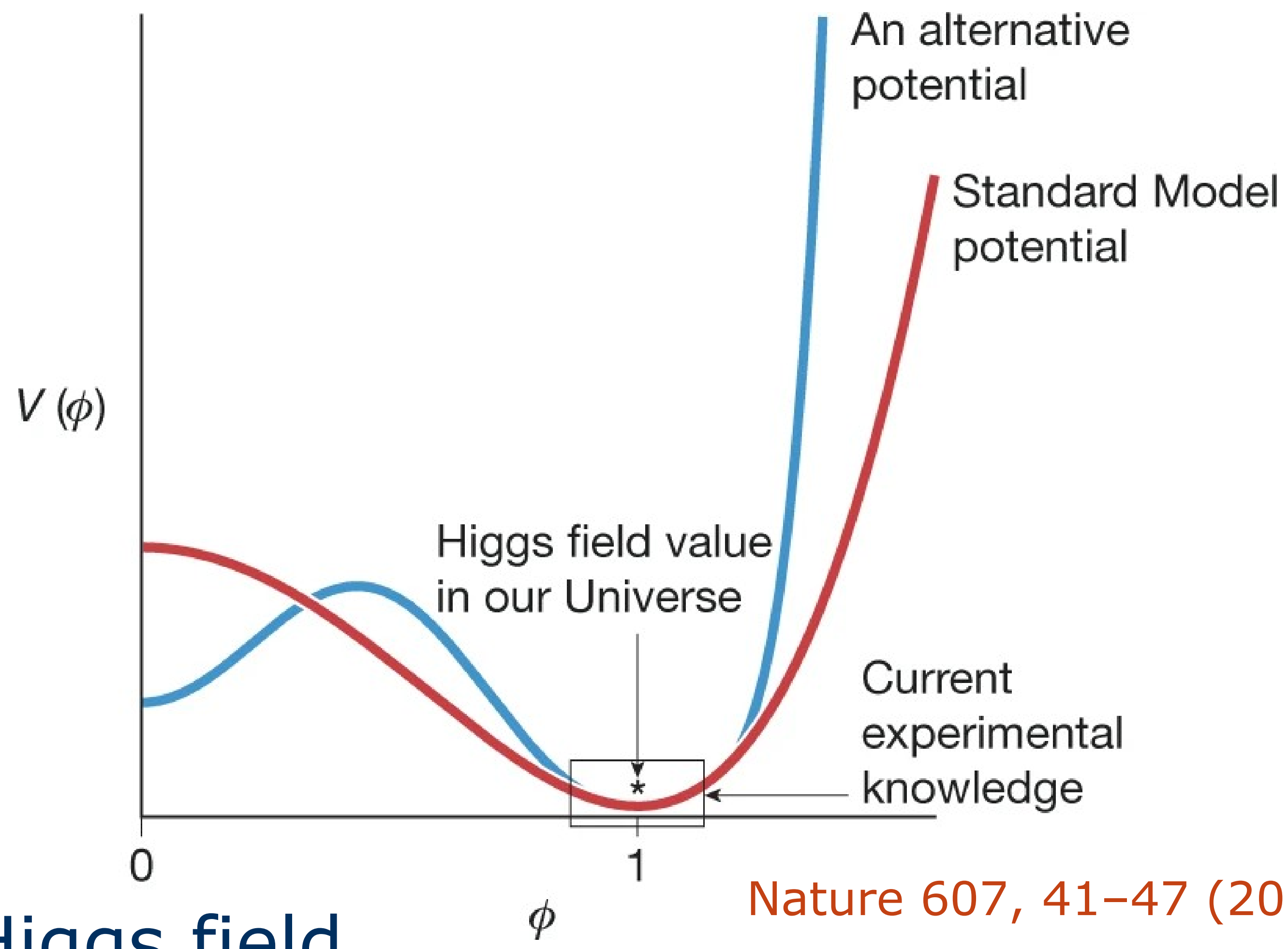

Nature 607, 41–47 (2022)

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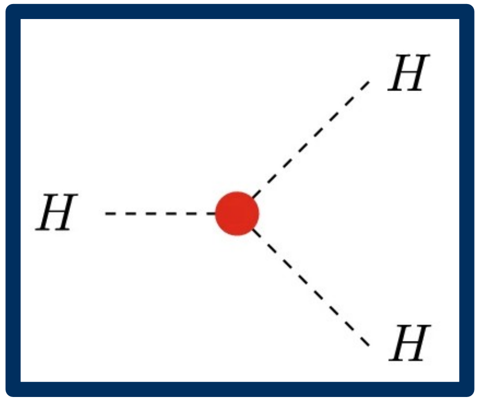
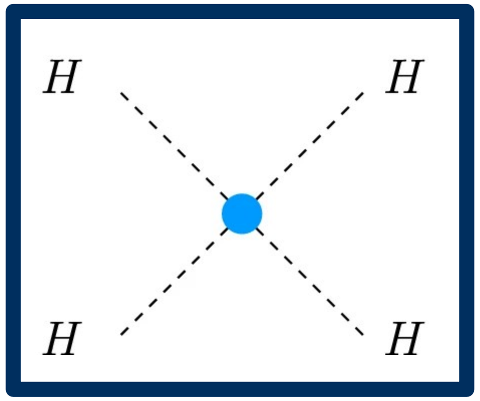
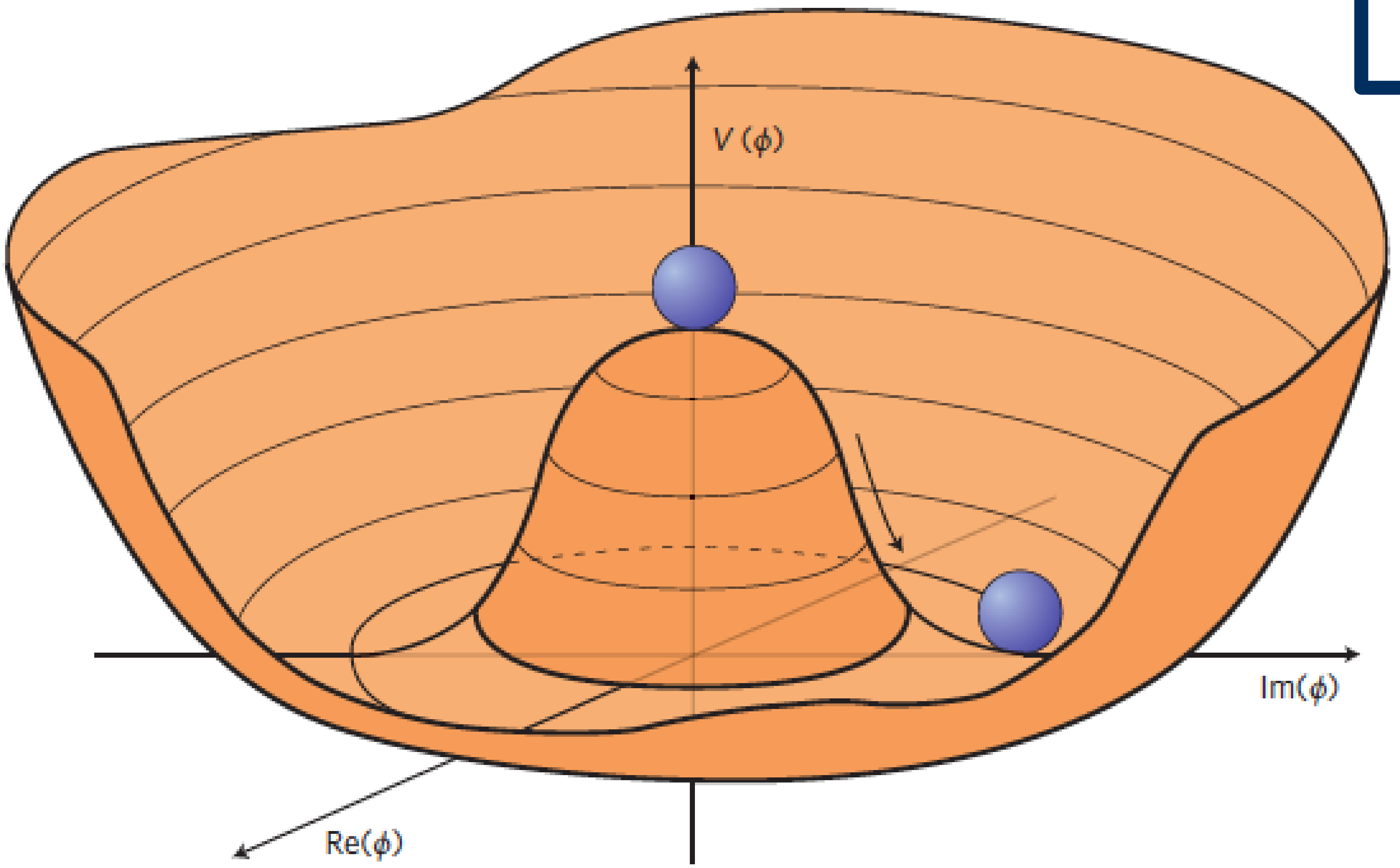
The Higgs self-coupling

- One parameter affecting the shape of the Higgs potential is the Higgs self-coupling λ:

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 + \dots$$







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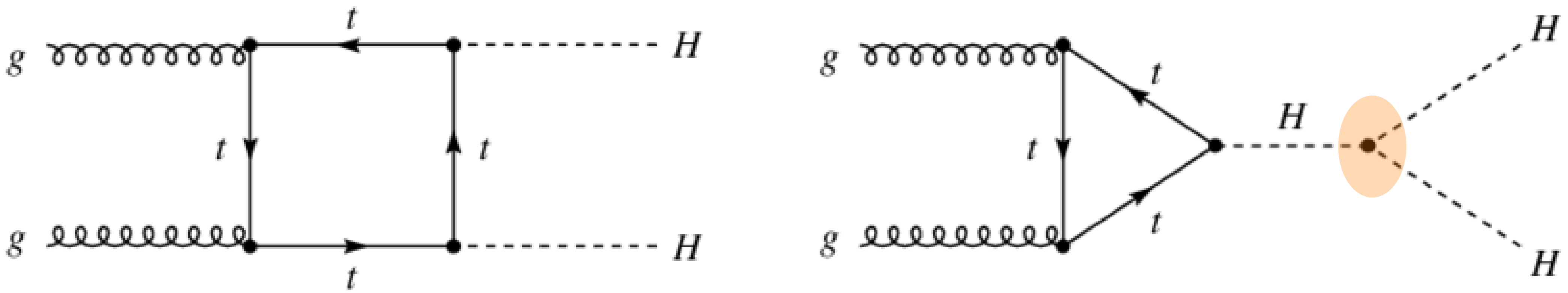
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4 + ...$$

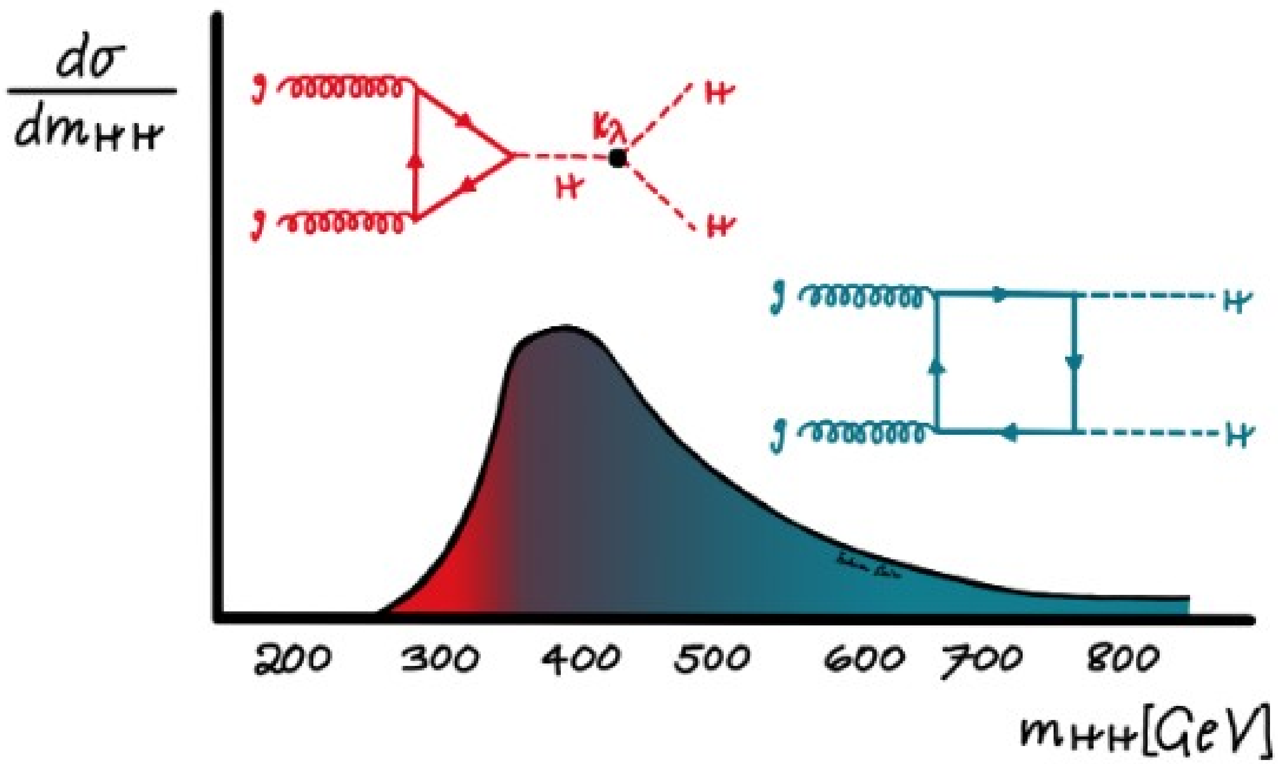
- Can be experimentally probed by measuring how often Higgs bosons are produced in pairs. → Flagship analysis at the HL-LHC.

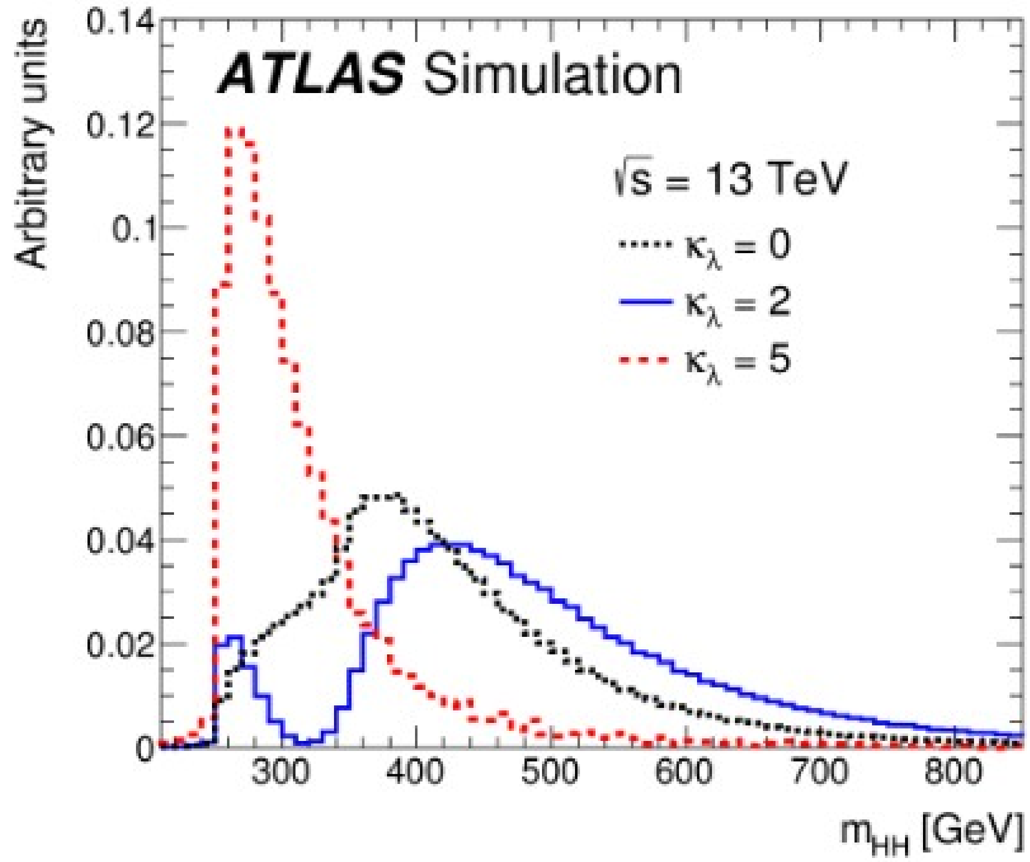


- Destructive interference of these two diagrams in the SM results in a small cross section: σ_{SM} (ggF) ≃ 31 fb [13 TeV]
- If the Higgs self-coupling has the strength predicted by the Standard Model, ATLAS and CMS combined will be able to measure HH production with the full HL-LHC data (by 2040).
- If the coupling is different from the Standard Model value, the process could be observed earlier.

The Higgs self-coupling

- The triangle and the box diagrams dominate in different parts of the HH invariant mass spectrum.
- If one moves away from the $\kappa_\lambda = \lambda/\lambda_{SM} = 1$ value in the SM, the interference changes.
- Affects both the cross section and the invariant mass spectrum.





1906.02025

The Higgs self-coupling

- The most sensitive diHiggs final states are $bbbb$, $bb\tau\tau$ and $bb\gamma\gamma$.
- $\boldsymbol{bbbb}$: highest branching ratio but large multi-jet background.
- ATLAS: ATLAS-CONF-2022-035
- CMS: 2202.09617 and 2205.06667
- $\boldsymbol{bb\tau\tau}$: Intermediate branching ratio but clean final state with moderate backgrounds.
- ATLAS: 2209.10910
- CMS: 2206.09401
- $\boldsymbol{bb\gamma\gamma}$: Tiny branching ratio but excellent $m_{\gamma\gamma}$ resolution and small backgrounds.
- Lower trigger thresholds, so better sensitivity at low m_{HH} hence to Higgs self-coupling.
- ATLAS: 2112.11876
- CMS: 2011.12373

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Credit: Katharine Leney

HH decay modes

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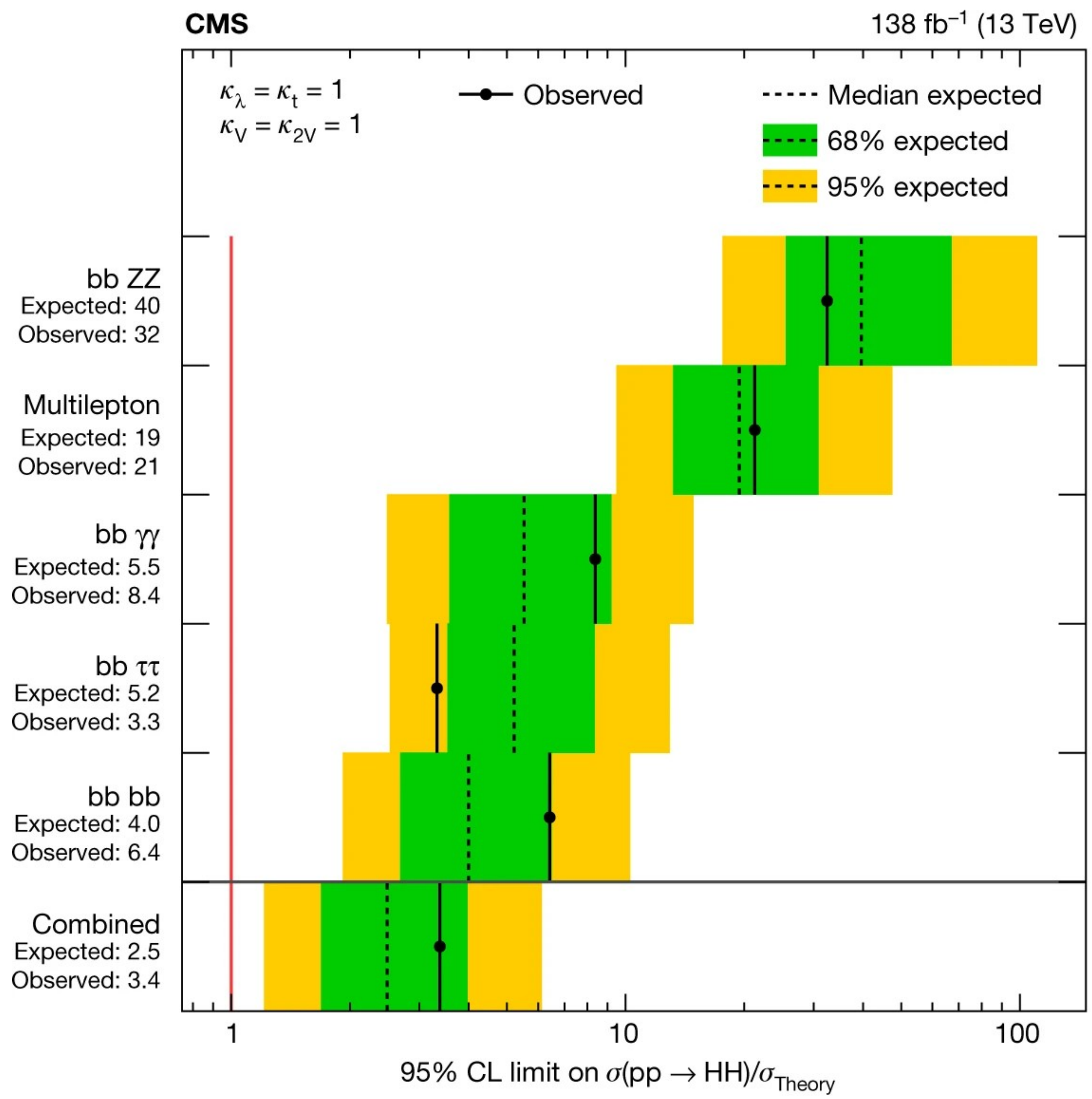

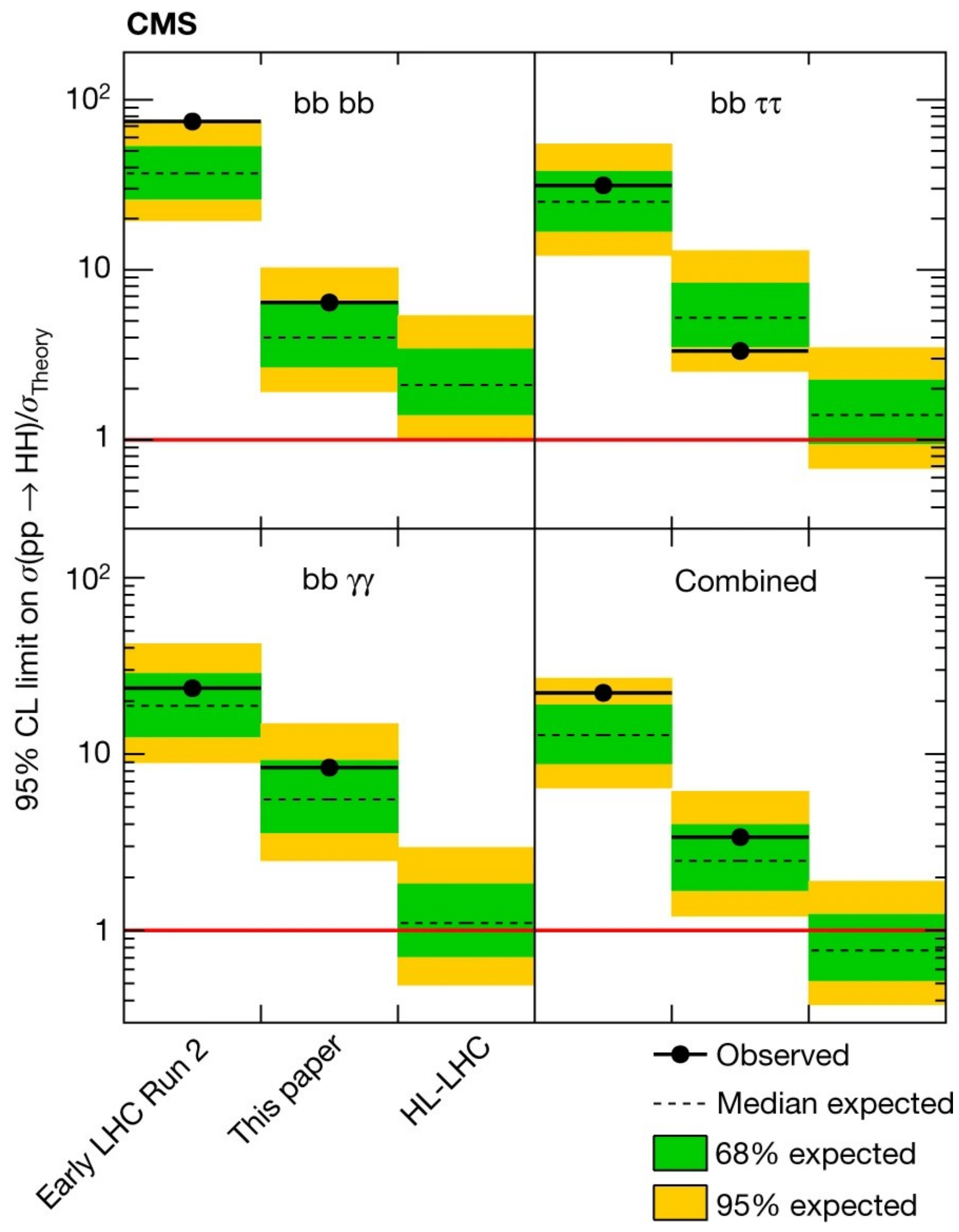

The Higgs self-coupling

- Current best limits from ATLAS and CMS:

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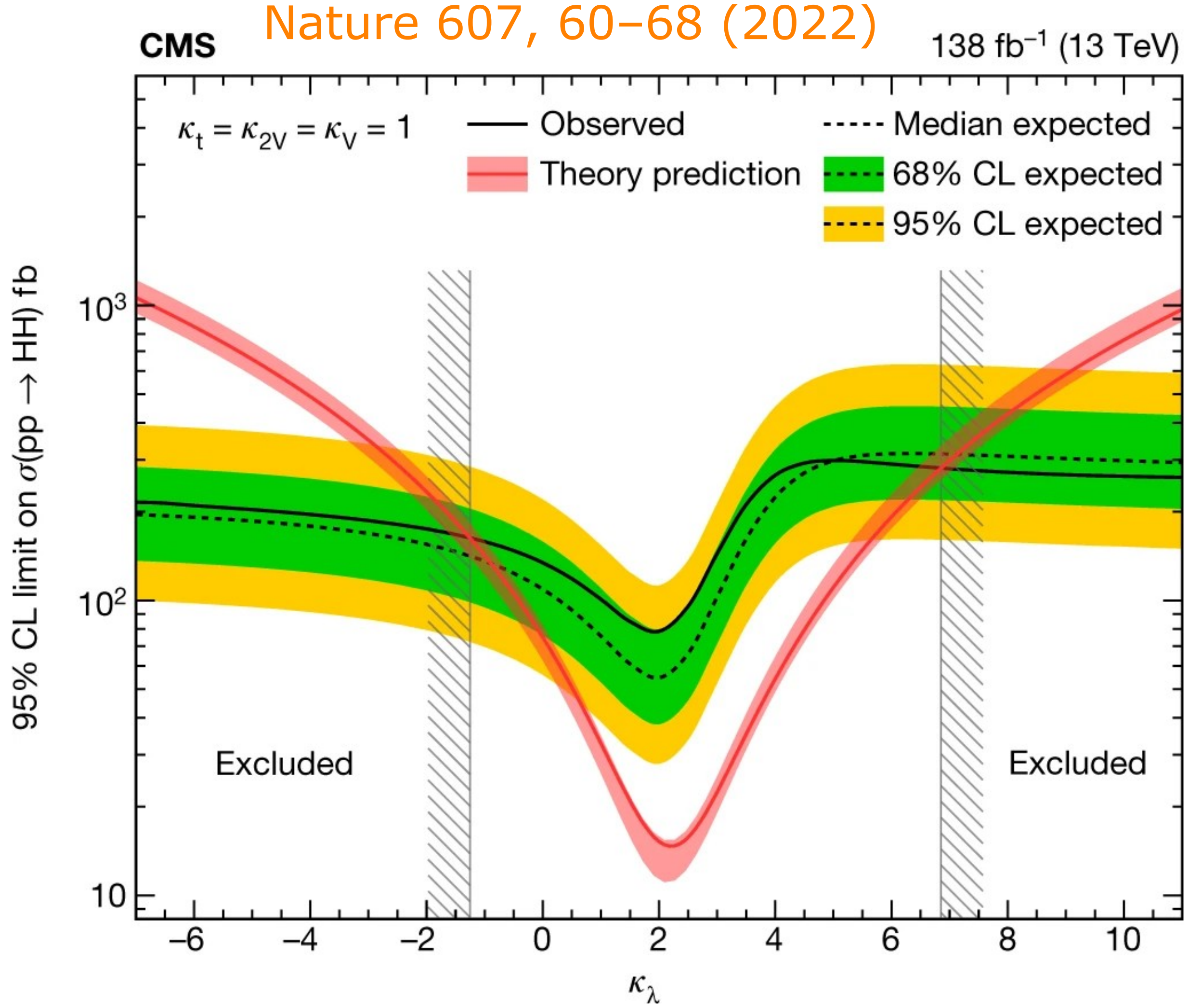

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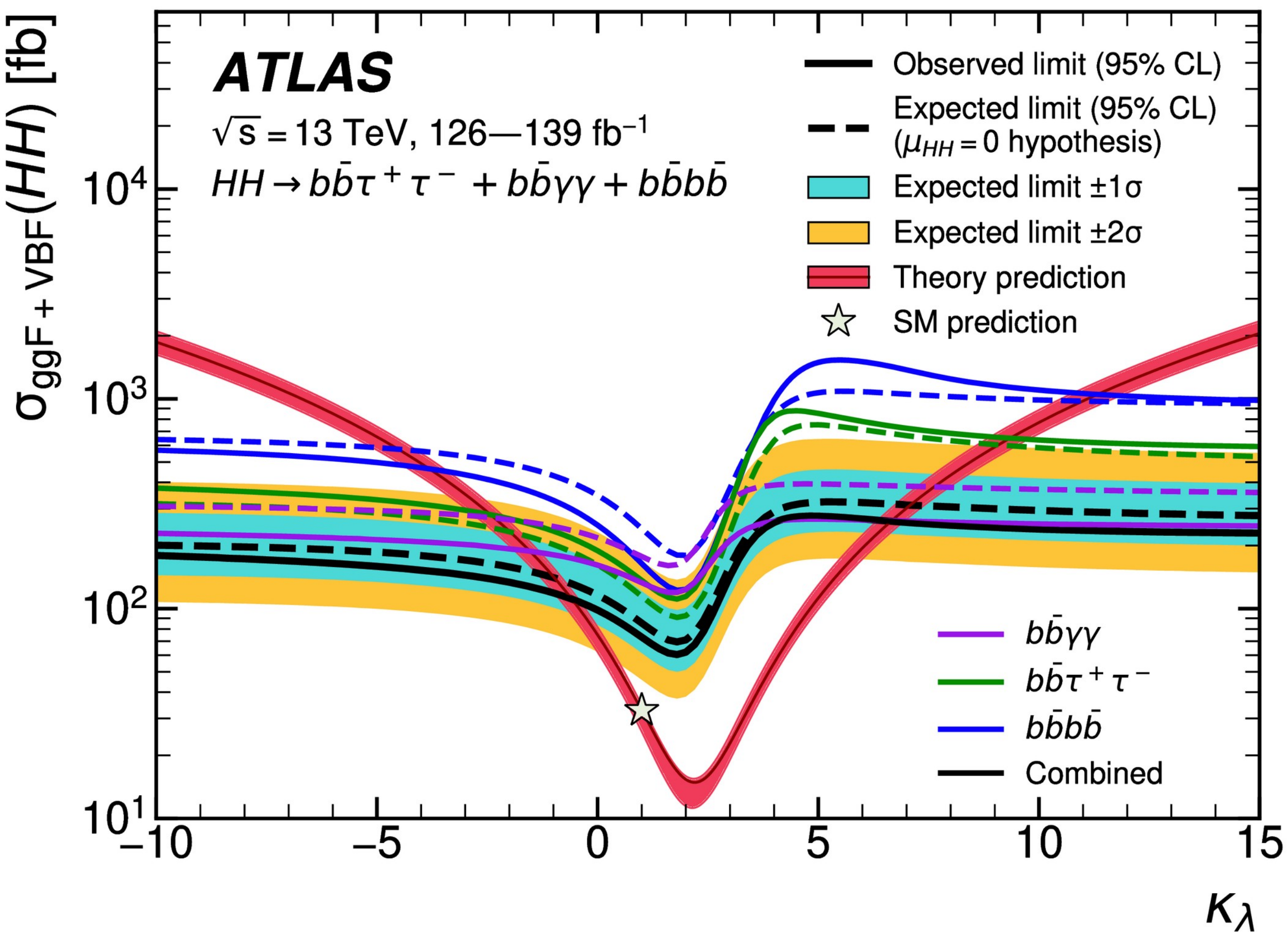
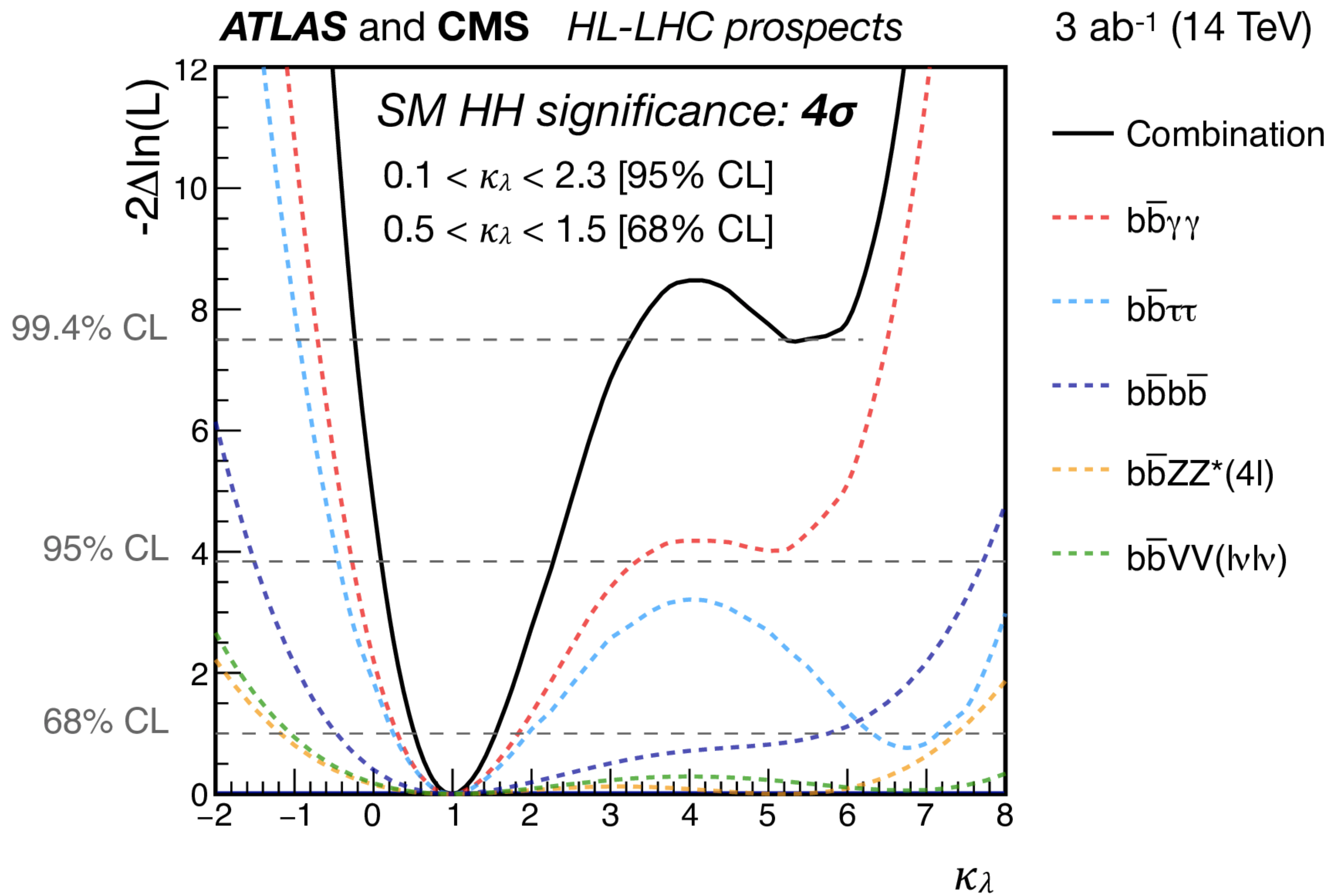


$-1.24 < \kappa_\lambda < 6.49$

$-1.1 < \kappa_\lambda < 6.6$

The Higgs self-coupling

- 4σ discovery significance for SM-like HH production by the end of HL-LHC.



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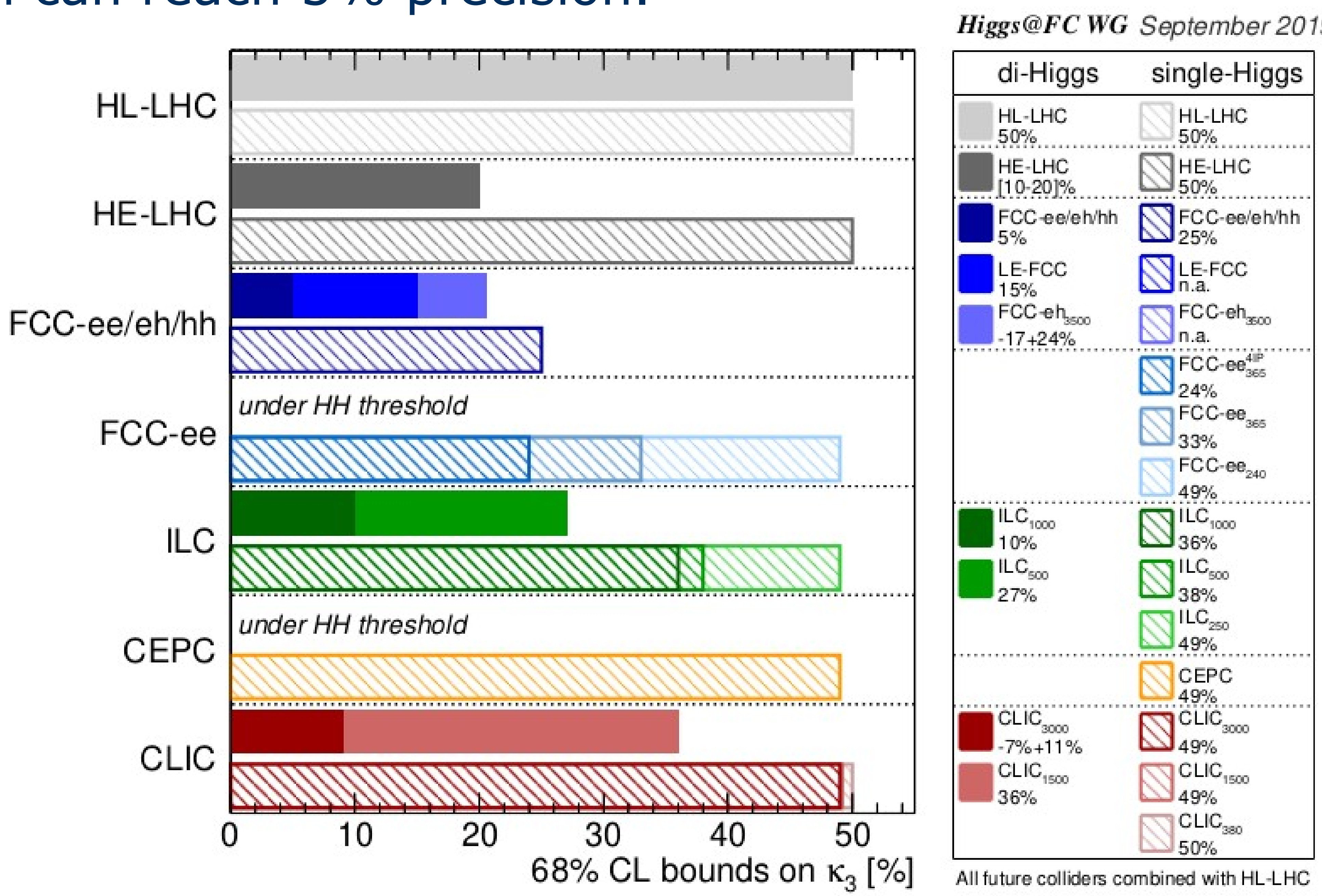
The Higgs self-coupling

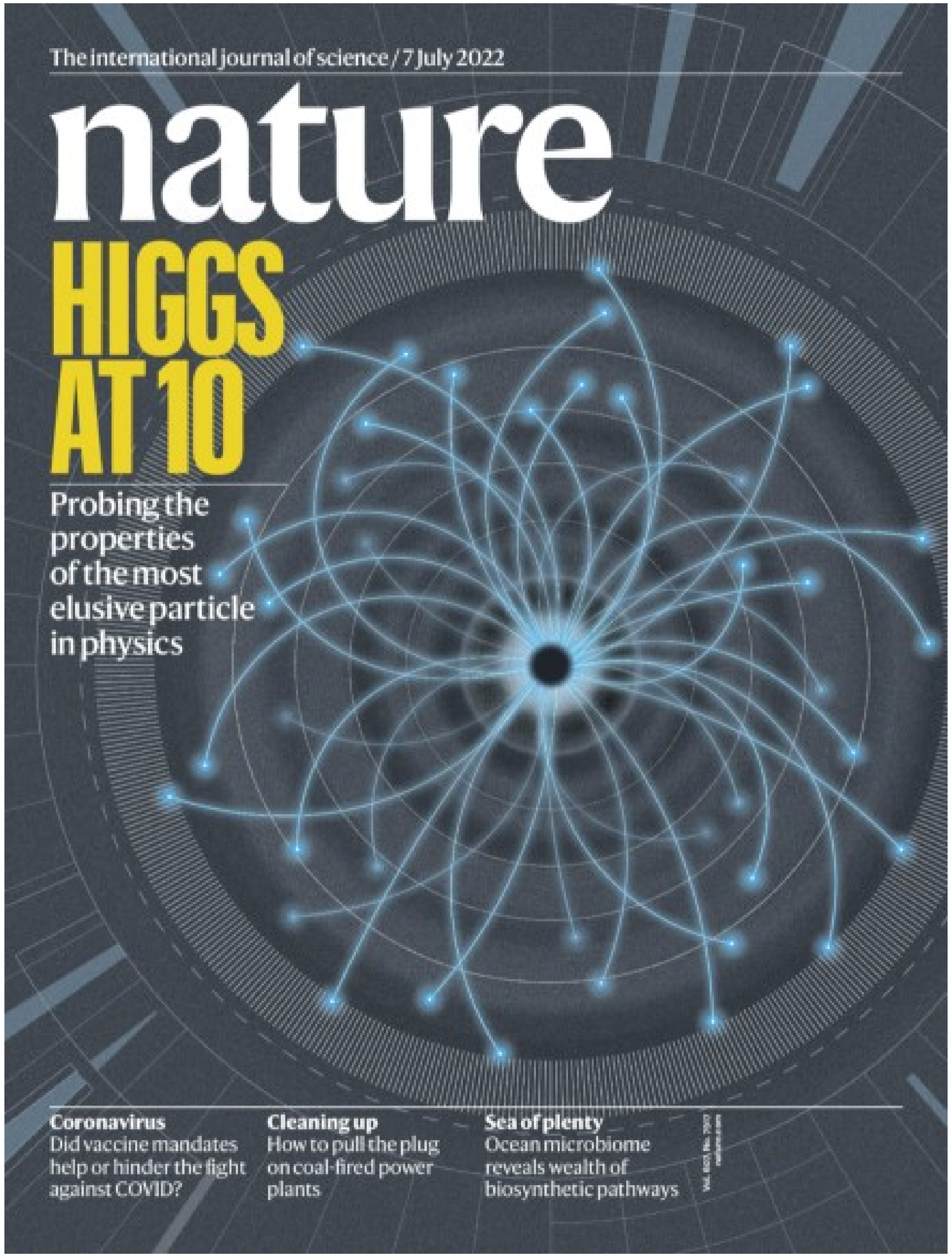
- CLIC @ 3TeV and ILC @1 TeV will reach O(10%) precision on λ.
- FCC-hh can reach 5% precision.



- 2σ sensitivity to the quartic self-coupling expected at FCC-hh.

Conclusions

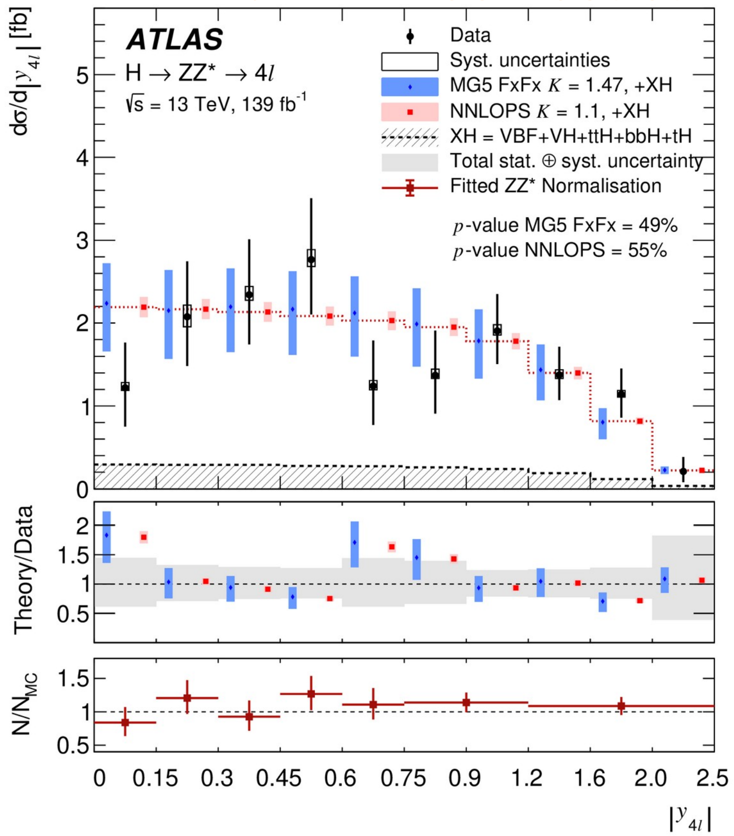
- Very productive experimental program for the past 10 years!
  - 96 CMS & 113 ATLAS papers.
  - Spanning all production and decay modes possible.
  - Targeting both SM and BSM.
- Very impressive results!
  - 0.1% precision on the mass.
  - ~5% (bosons) and ~10% (heaviest fermions) precision on couplings.
  - Much progress in searches for second generation couplings and for diHiggs production.
- HL-LHC and future colliders needed to reach the precision necessary for many BSM scenarios.



Backup

Differential measurements

arXiv: 2004.03969



Differential cross-sections

Simplified template cross-sections

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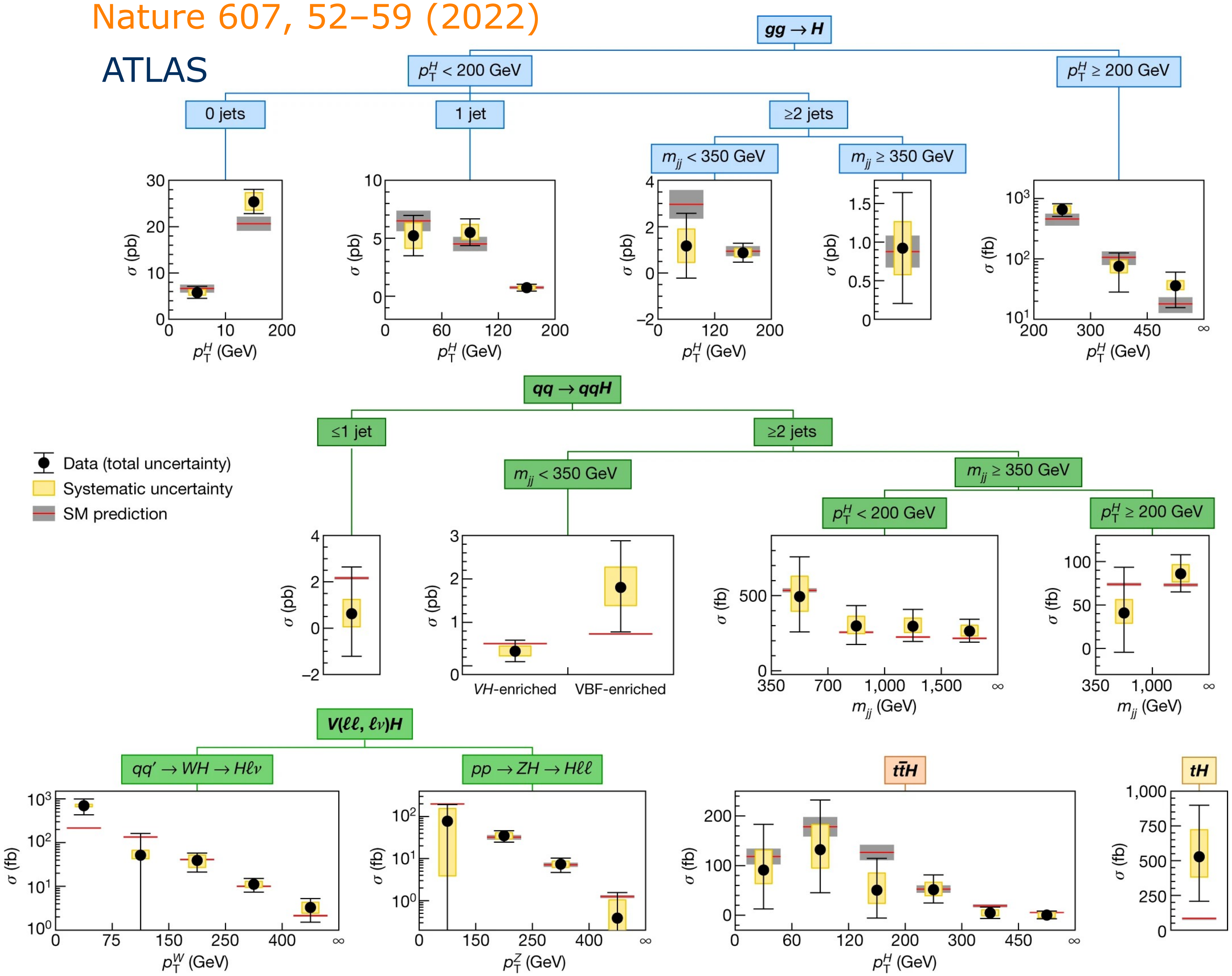

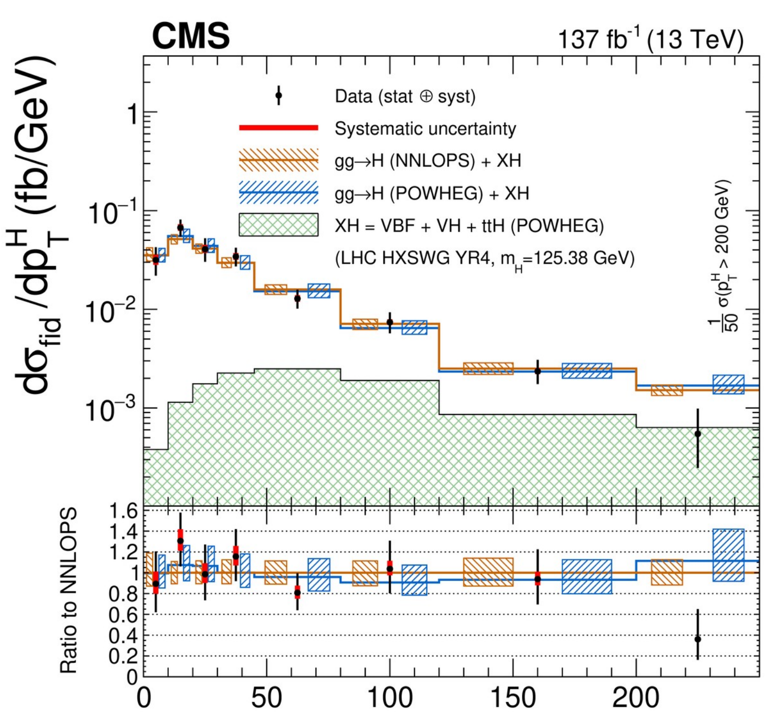

arXiv: 2103.04956

The Higgs fingerprint

- The coupling strengths to fermions and bosons are also of interest.

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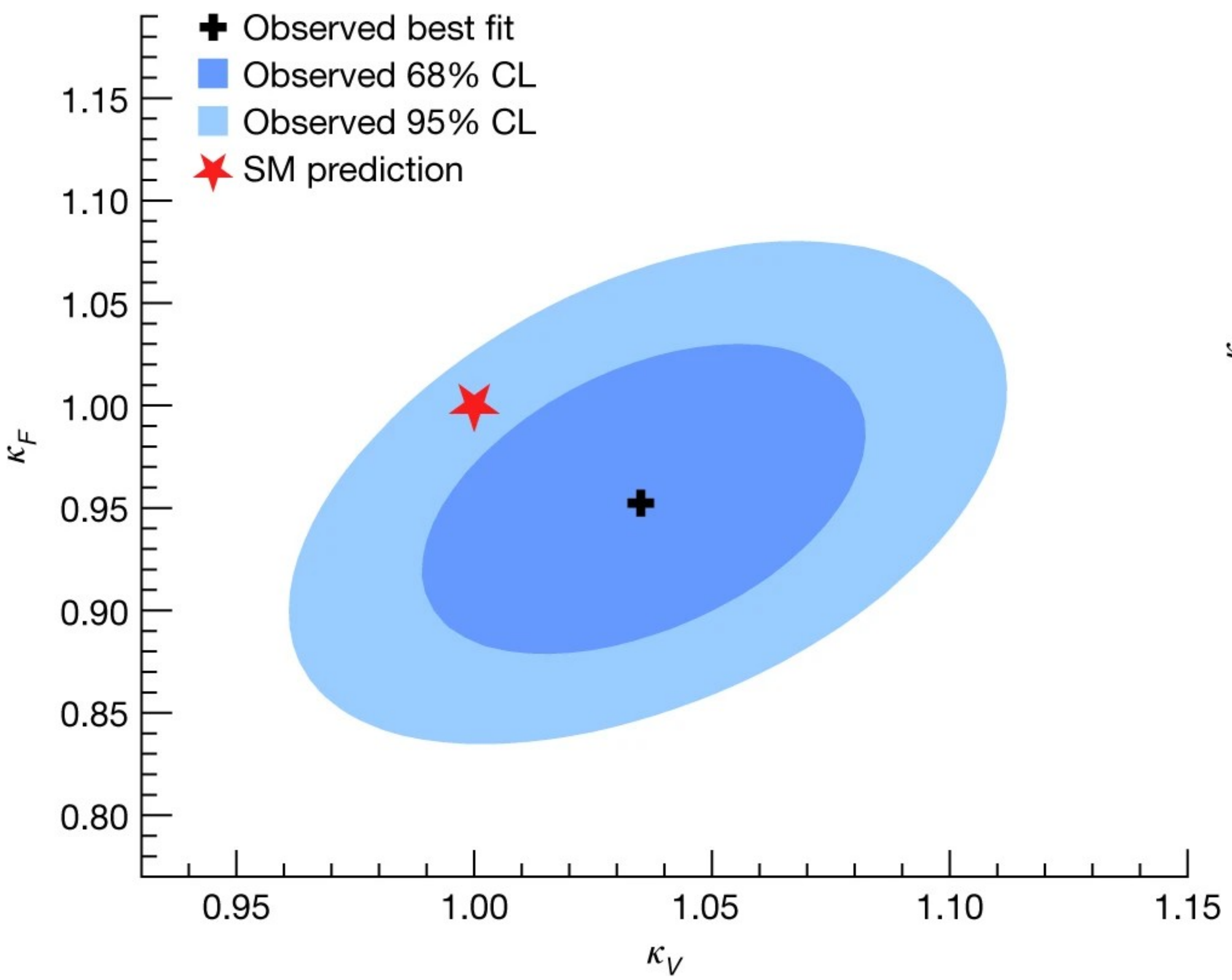
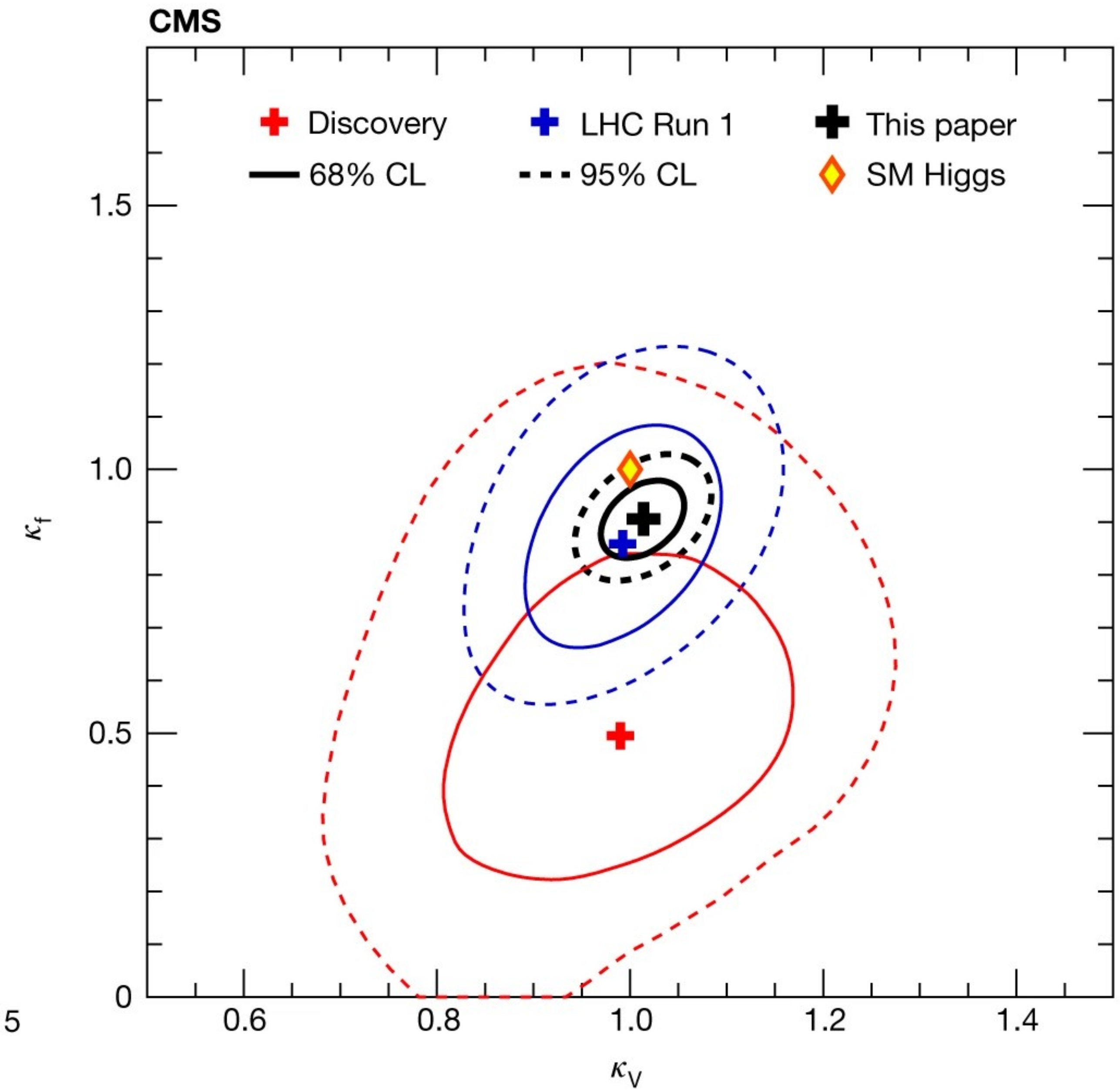
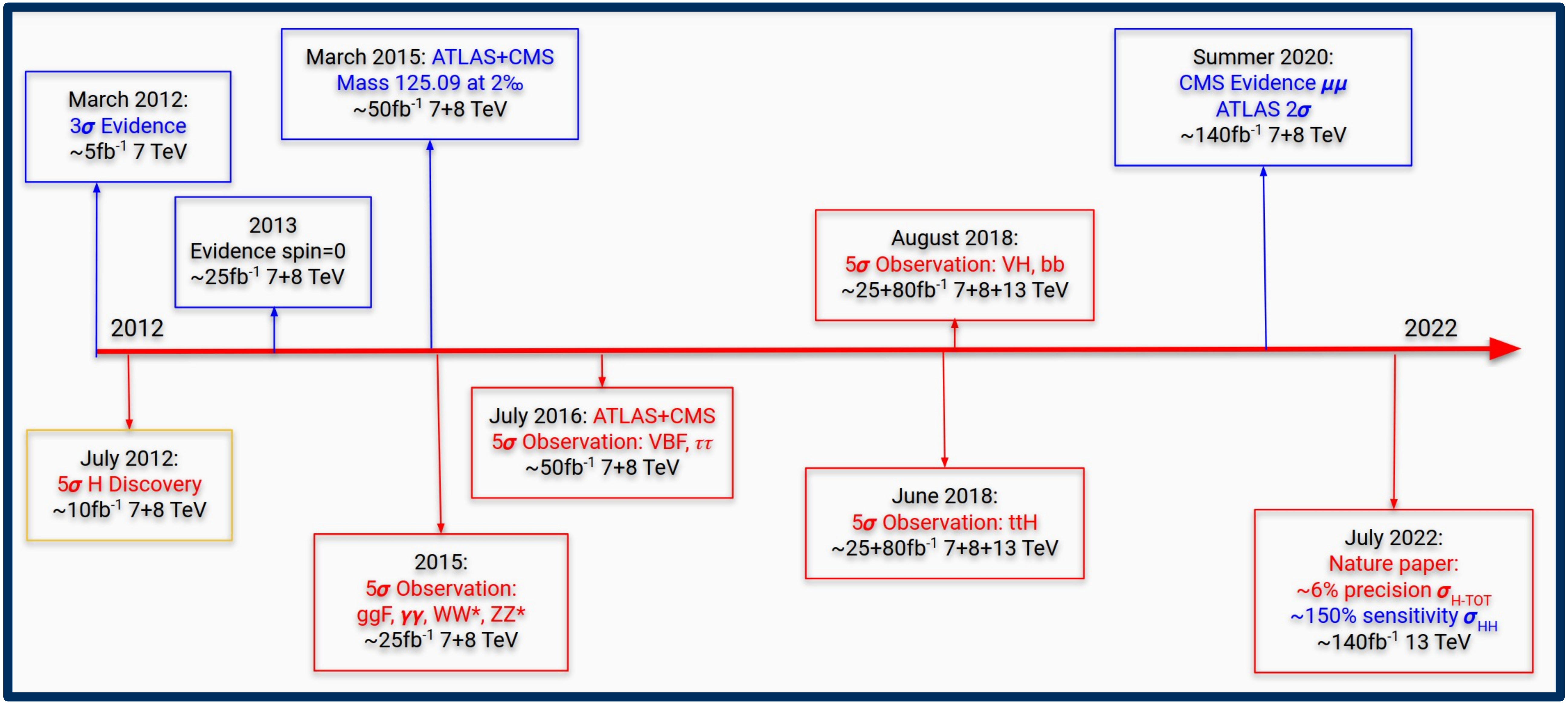
ATLAS Nature 607, 52–59 (2022)





Higgs timeline

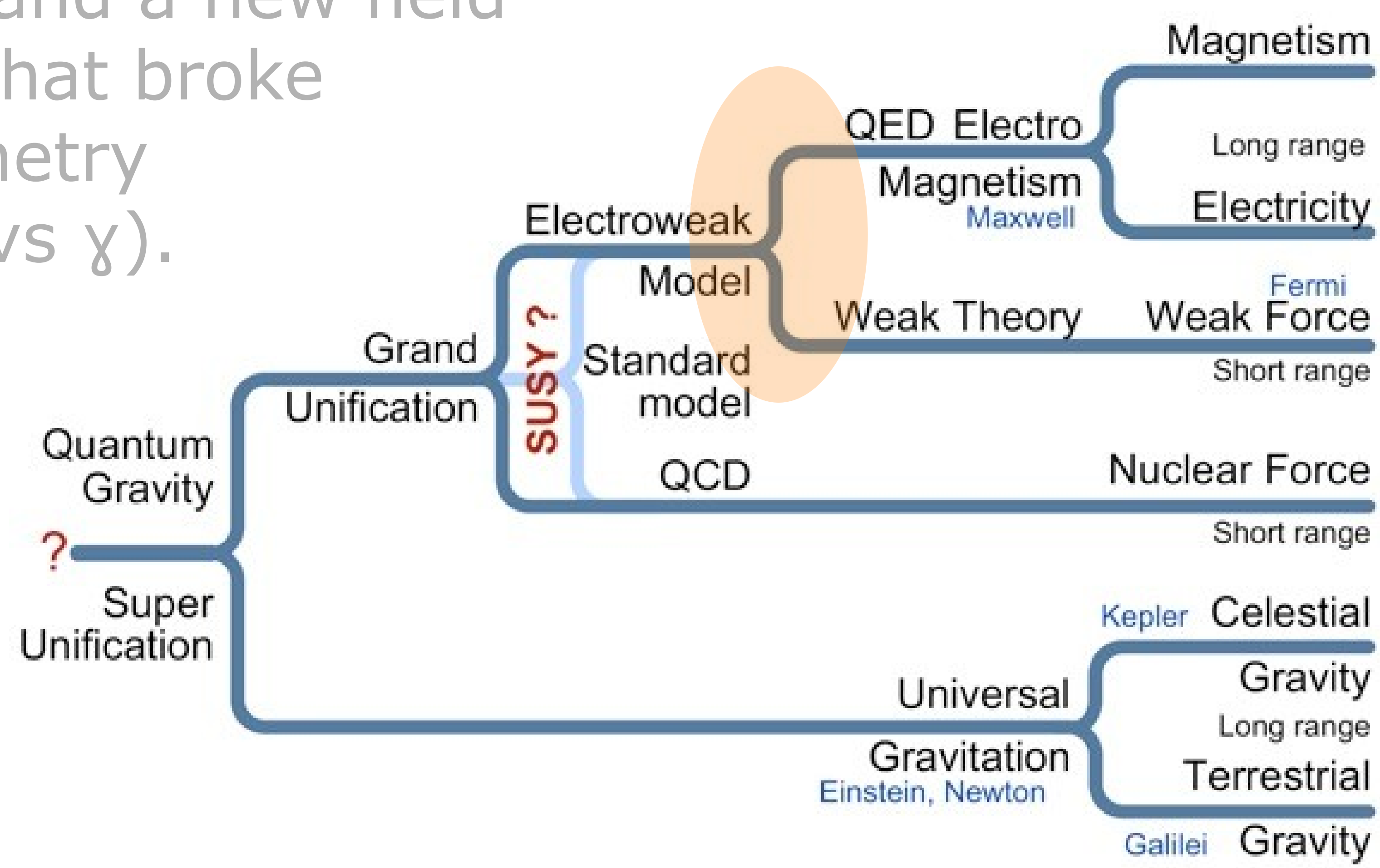
- Steady progress by the LHC experiments in the 10 years since the Higgs discovery.



Source: Nadya Chernyavskaya (CERN) and Fabio Cerutti (LBNL) (Higgs2022 talk)

Why do we need the Higgs?

- In the 60s, the Standard Model could successfully describe the observed particles, and the forces between them, with the caveat that it did not allow for massive particles.
- Solved theoretically by four independent groups of theorists (Anderson; Brout, Englert; Higgs; Guralnik, Hagen and Kibble):
  - The weak and electromagnetic forces needed to be unified, and a new field had to be introduced that broke the electroweak symmetry at low energies (W/Z vs ɣ).
  - The new field came with a new particle.
  - The missing particle became known as the Higgs boson.



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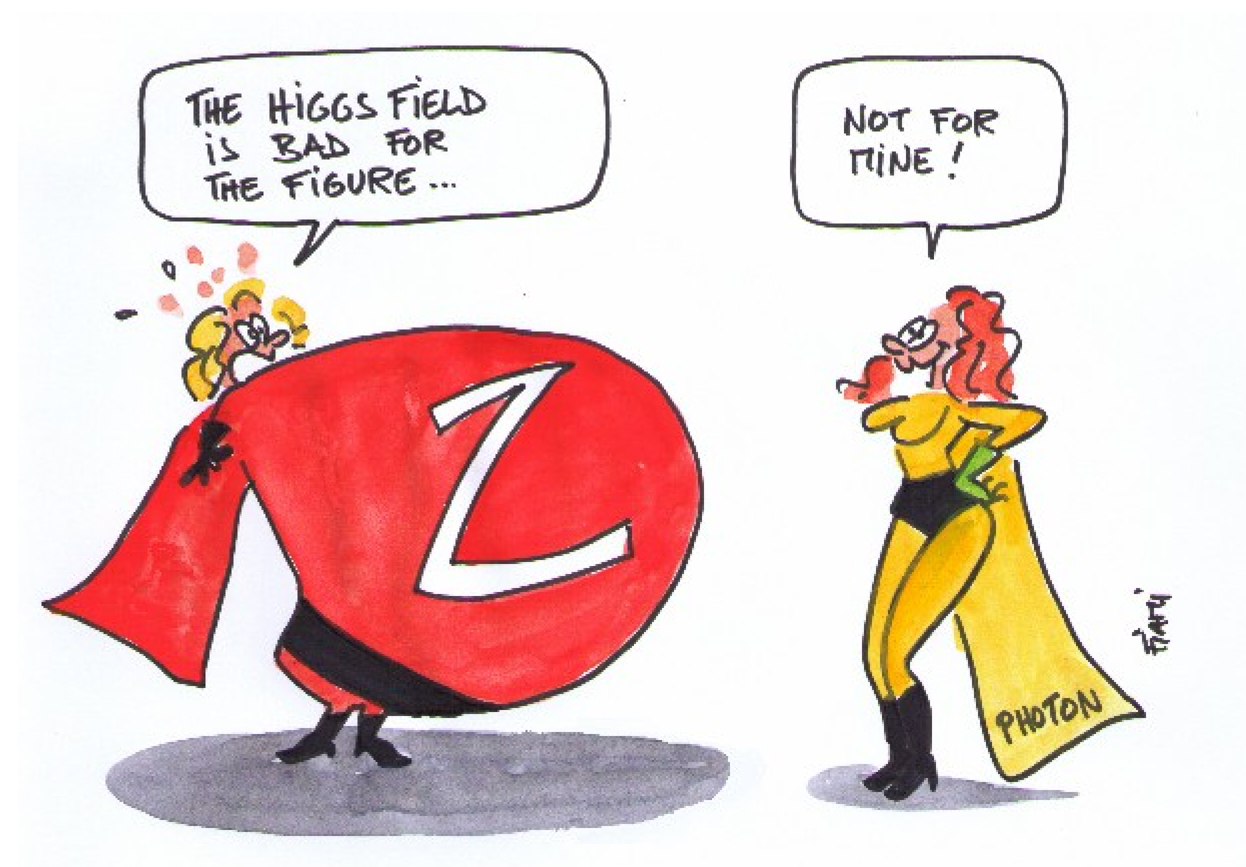
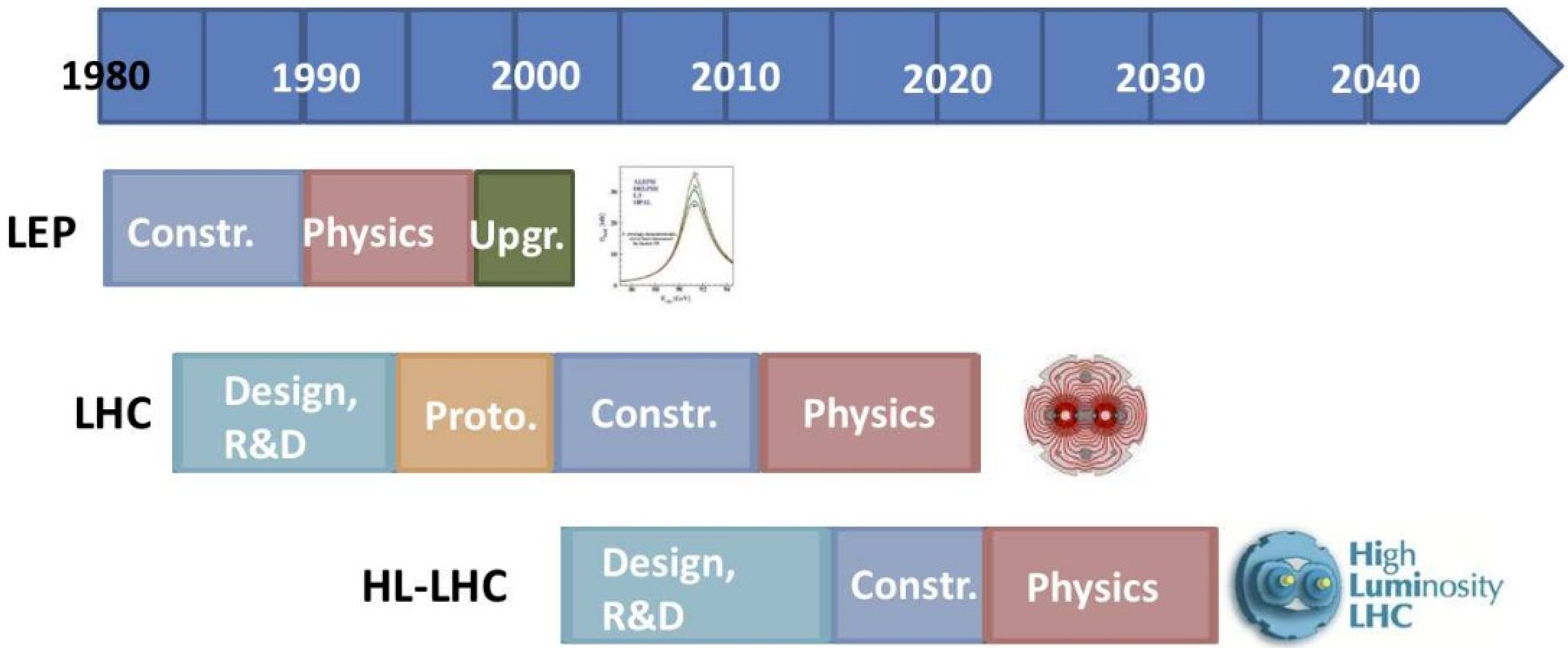
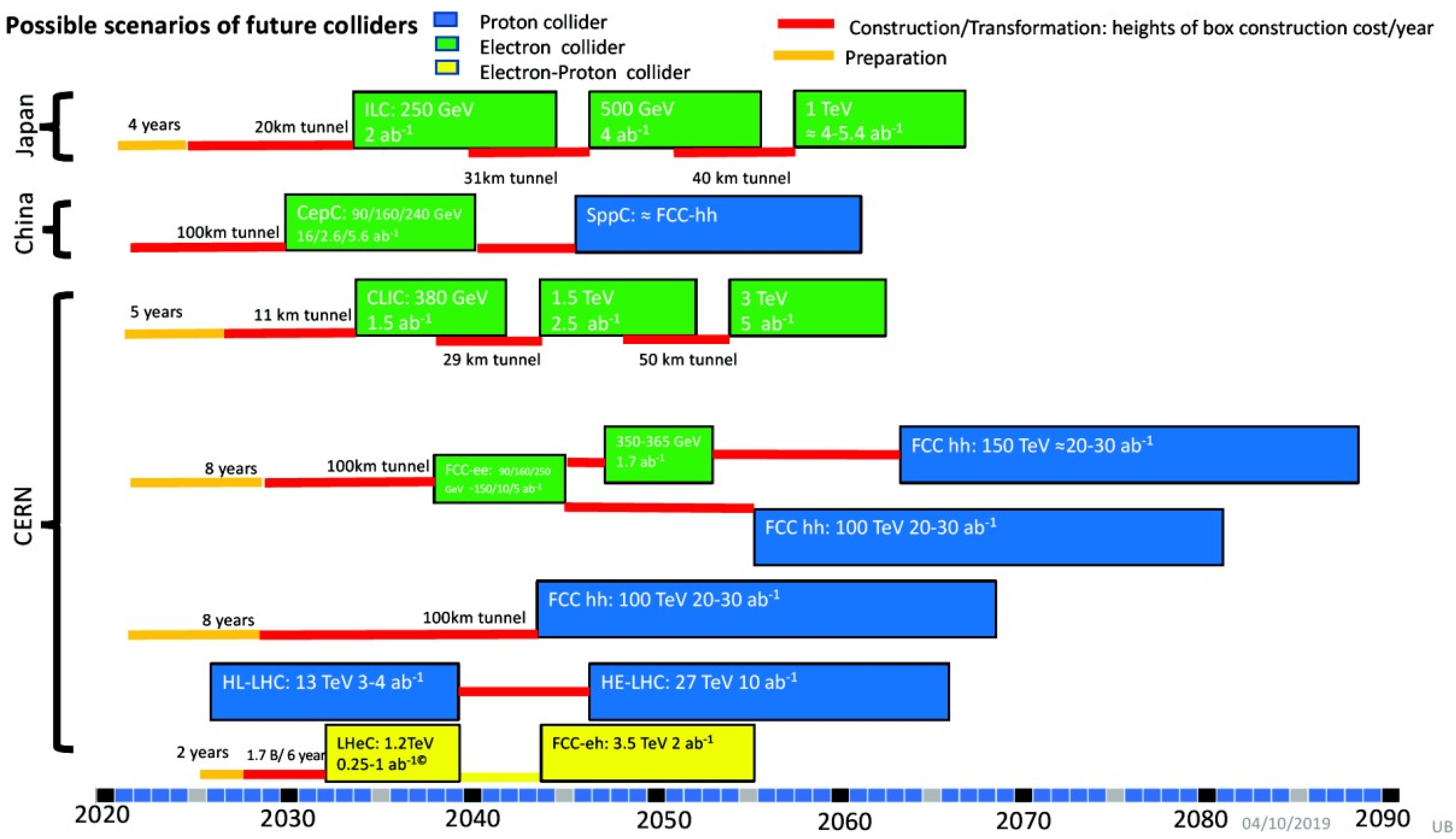


Future colliders



European Strategy Update

The starting lineup



The starting lineup

1 ILCU = 1 USD in 1/01/2012

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF
LE-FCC	pp.	37.5	15	20		14.9 GCHF. New at request of ESG.

(For reference - LHC construction cost ≈ 4 GCHF, annual CERN budget ≈ 1 GCHF.)