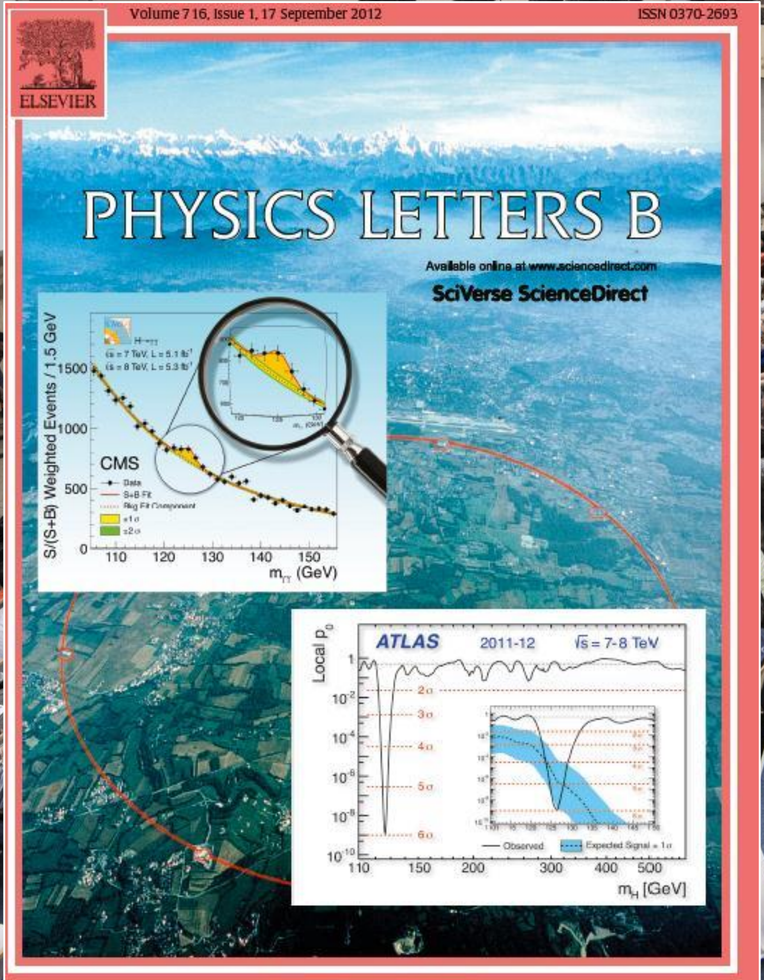
Concluding remarks and a look to the future

Fabiola Gianotti (CERN), 4 July 2022



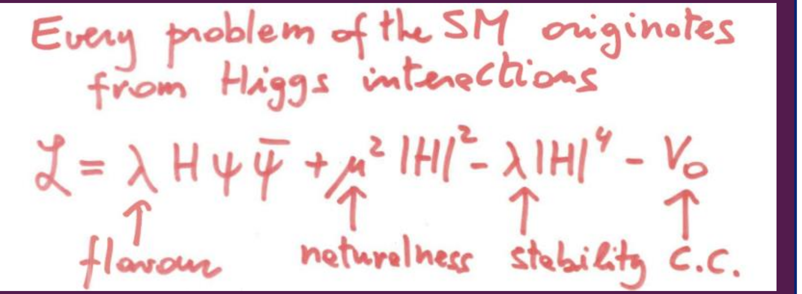
Initial remarks

1. Experimental verification of the Brout-Englert-Higgs mechanism through the discovery of the Higgs boson: monumental step forward in our understanding of fundamental physics, with wide-ranging implications for particle physics and beyond

2. Higgs boson discovery is the culmination of a long journey (completion of the Standard Model!) and the beginning of a new era:

- the Higgs boson is profoundly different from all elementary particles discovered previously (first elementary scalar?)
- brings new interactions (Yukawa, self-interaction)
- is related to the most obscure sector of the Standard Model and linked to some of the deepest structural questions (flavour, naturalness/hierarchy, vacuum, ...)

G. Giudice



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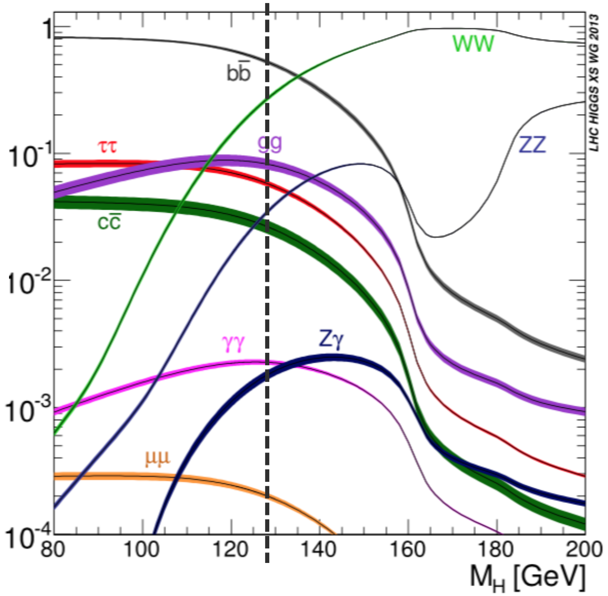
Higgs boson discovery opens new paths of exploration, provides a unique door into new physics, and calls for a compelling and broad experimental programme which will extend for decades at the LHC and beyond

Higgs boson branching ratios

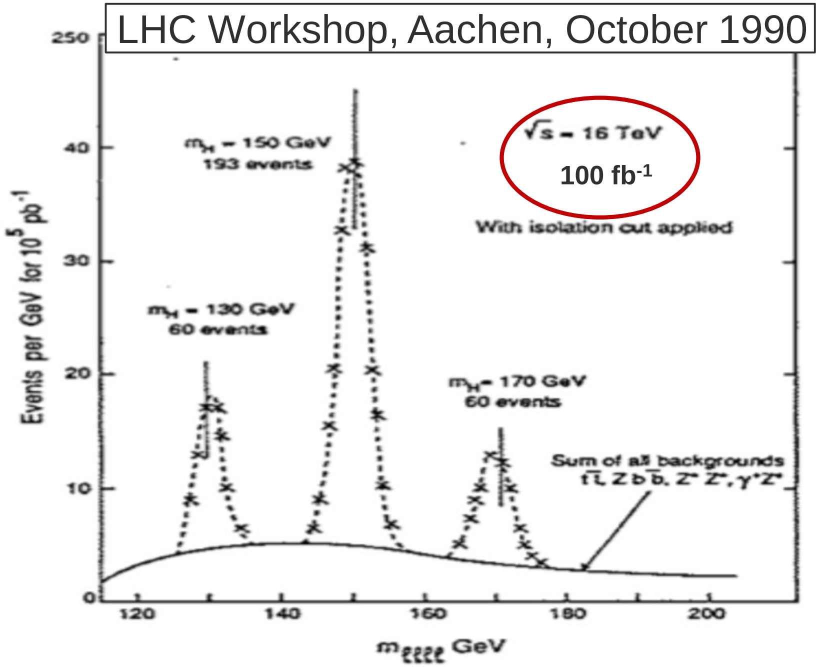


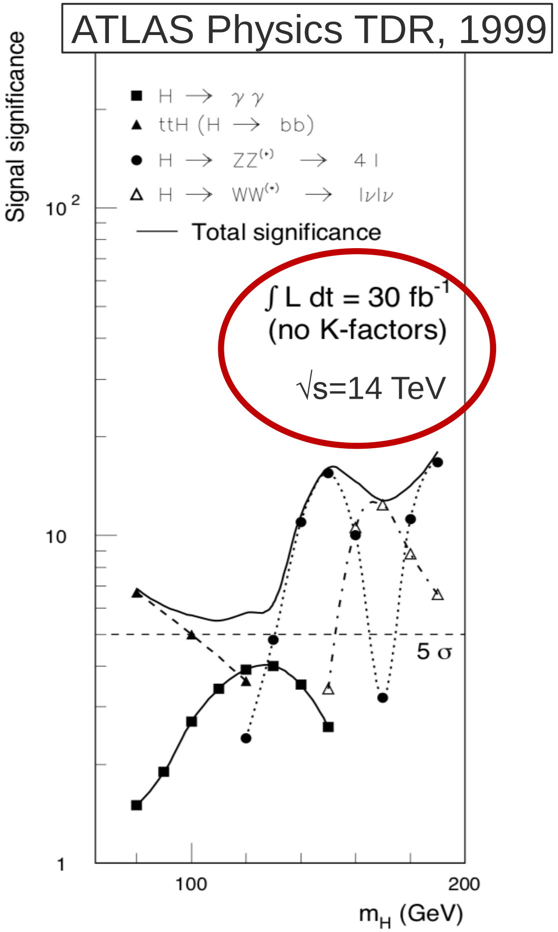
3. Nature has been kind to us: $m_H = 125$ GeV !!

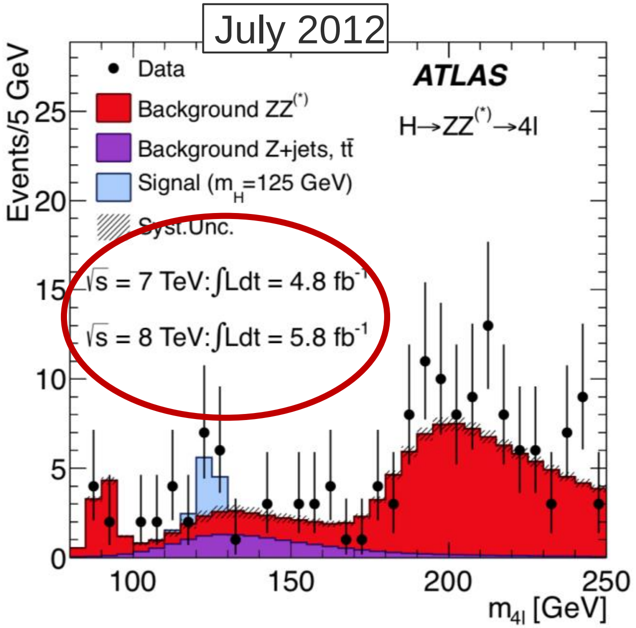
→ ~ all production and large number of decay modes accessible, allowing a vast, detailed and robust portrait of the new particle

A relatively quick discovery …

- Fast ramp up of the LHC achieving ~ 7 x 10^{33} in 2012 and excellent availability in Spring/Summer 2012
- Detector performance close to (or better than) target; fast development of methods to mitigate the impact of pile-up
- Excellent performance of the WLCG → data processed and distributed quickly to the worldwide community for analysis
- Nature: actual Higgs production cross-section (N3LO) is ~ 3 larger than predictions used in the past (LO)







2.5-3 times larger cross-sections at 14-16 TeV than at 8 TeV ~ offset by cross-section increase from LO to N3LO

In the last 10 years we have come a long way …

Immense progress on all fronts

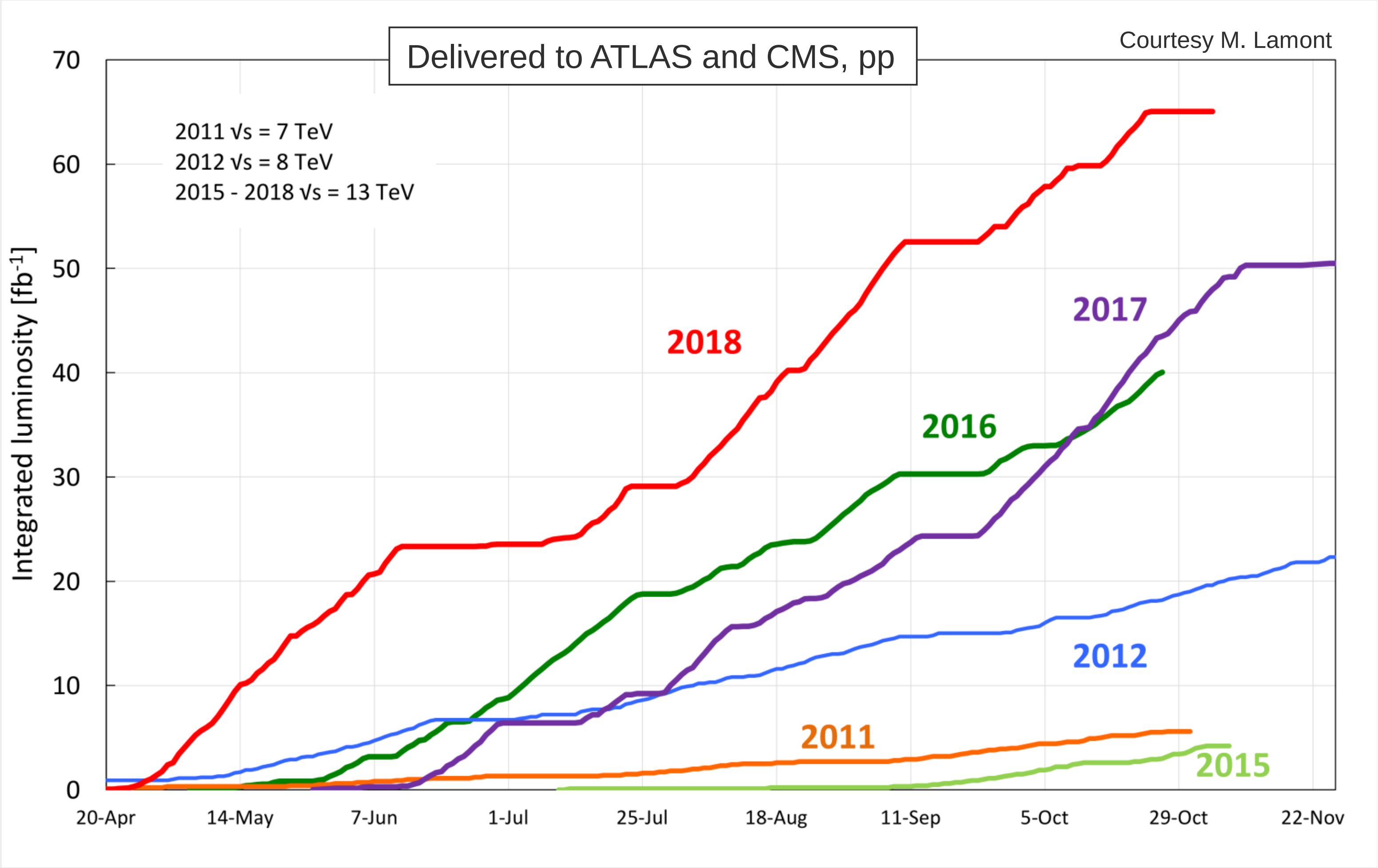
- Superb performance of the accelerator complex → > 30 times more Higgs bosons available than in 2012
- Superb (understanding of) performance of ATLAS and CMS detectors (despite aging, huge pile-up, …)
- Superb performance of WLCG in handling floods of data (storage, simulation, reconstruction, distribution, analysis, …)
- Much improved analysis methods (machine learning, statistical treatment, etc.) boosting detector performance and physics sensitivity
- Very frutiful theory-experiments collaboration (e.g. in the framework of LHC Higgs XS WG and LPCC)
- Lots of new ideas have made “impossible at hadron colliders” channels become accessible

TODAY (numbers below are per experiment):

- All main Higgs boson production modes (ggF, VBF, VH, ttH+tH) established at > 5σ
- Couplings to gauge bosons (established in Run 1) measured to 6-8%
  Couplings to 3rd generation fermions (established in Run 2) measured to 7-11%
  Couplings to 2nd generation fermions: 3σ evidence for H→ μμ; first constraints on H→ cc
- Rare decays (e.g. H→ Zγ; H→ llγ at ~ 3σ level)
  Limits on invisible and exotic decays
- HH production: sensitivity x 3 SM cross-section
- Mass measured to ~ 0.1%
- Width measurement from off-shell/on-shell production demonstrated (3.6σ evidence for H off-shell production)
- $J^{CP}=0^{++}$ (large number of alternative hypotheses excluded > 99.9% C.L.)
- Inclusive studies complemented by increasing variety of differential/exclusive measurements (useful to constrain theory; provide additional constraints on couplings; sensitive to new physics in quantum loops affecting kinematic distributions)
- Searches for additional Higgs bosons (no sign yet …)
- Etc. etc.

Note: some of the above measurements were not expected to be possible in Run 2

Accelerator complex and luminosity



~ 90% of delivered luminosity used by the experiments (high data-taking efficiency and excellent data quality)

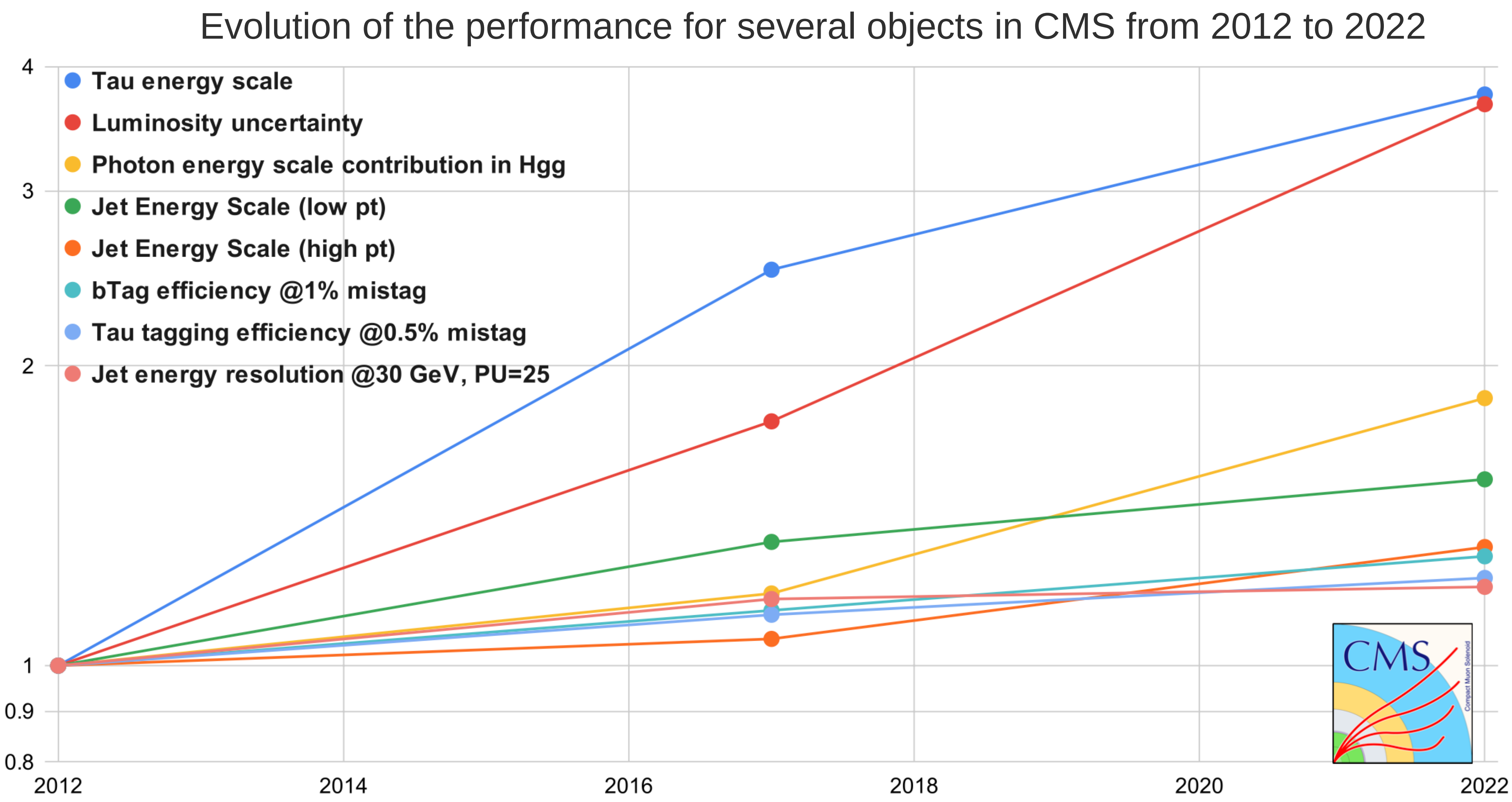
July 2012

Peak L ~ 7 x 10^{33} cm^{-2} s^{-1}
~ 12 fb^{-1} at $\sqrt{s}$ = 7-8 TeV
~ 250 000 Higgs bosons produced per experiment

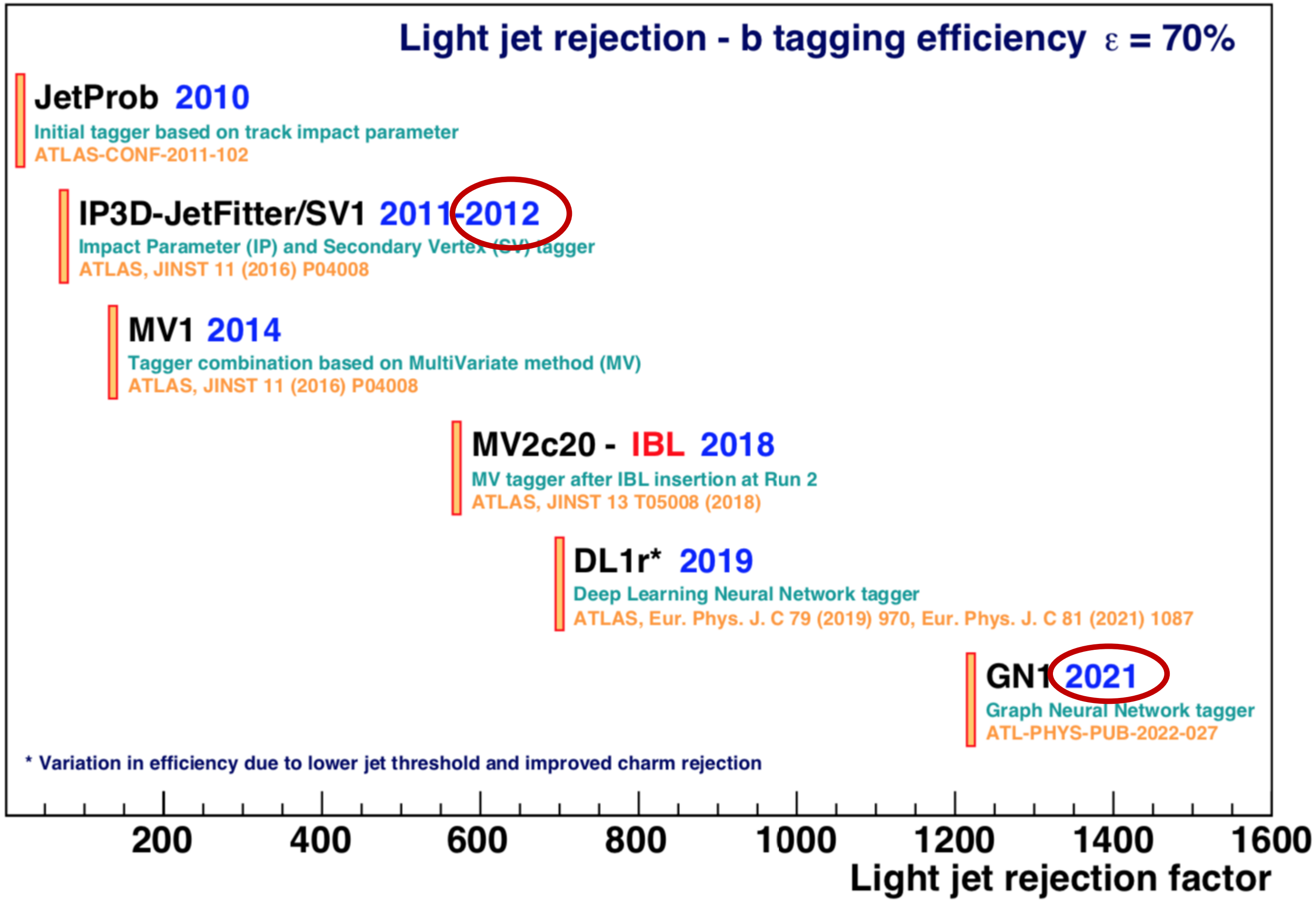
Today

Peak L ~ 2 x 10^{34} cm^{-2} s^{-1}
~ 189 fb^{-1} (~160 fb^{-1} at $\sqrt{s}$ = 13 TeV)
~ 9 M Higgs bosons produced per experiment

Detector performance

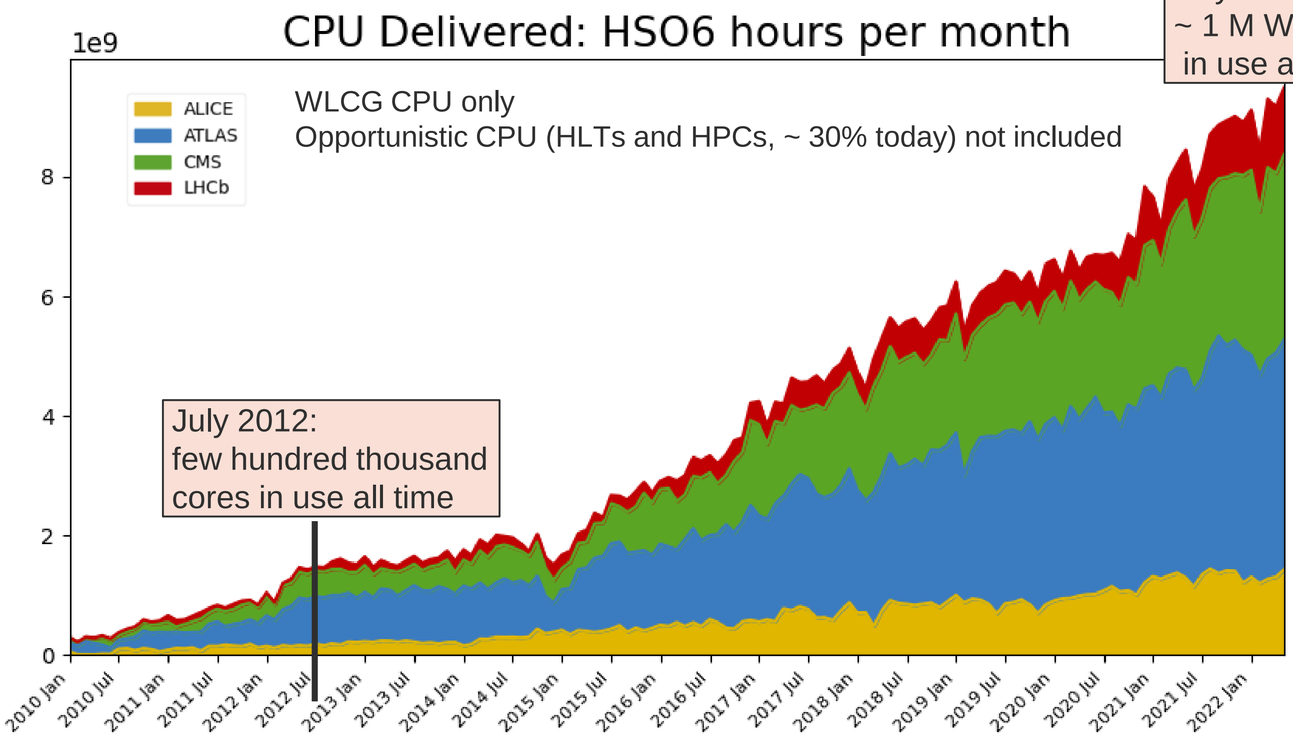


Detector performance



Computing - WLCG

	2012	2022
T0 → T1 transfer rate (GB/s, peak)	5.7	33.4
Global WLCG transfer rate (GB/s, peak)	15	80 (during data challenges)
Total processing power (HS06 hours/month)	1.6 B	9.1 B
Number of cores in use (WLCG only)	~ 250 k	~ 1 M
Total disk space (PB)	170	750
Total tape (PB)	170	1200



The big success of the **Worldwide LHC Computing Grid**: outstanding performance right from the beginning of the LHC operation, thanks also to the strong support of the Funding Agencies

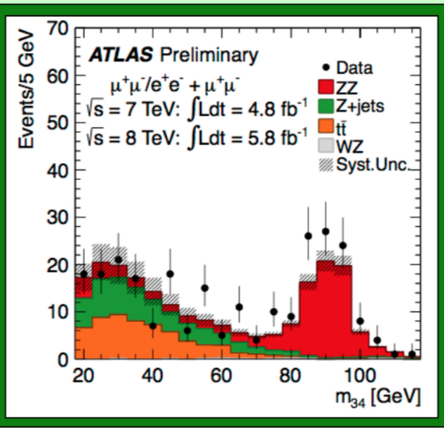
Powerpoint

4 July 2012 Comic Sans

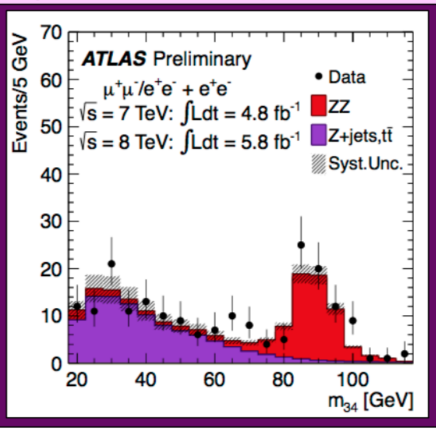
Reducible backgrounds from Z+jets, Zbb, tt giving 2 genuine + 2 fake leptons measured using background-enriched, signal-depleted control regions in data

Typical control regions:
- ❑ leading lepton pair ($l_1 l_2$) satisfies all selections
- ❑ sub-leading pair ($l_3 l_4$): no isolation nor impact parameter requirements applied

$l_3 l_4$ = μμ → background dominated by tt and Zbb in low mass region



$l_3 l_4$ = ee → background dominated by Z+jets in low mass region



- ❑ Data well described by MC within uncertainties (ZZ excess at high mass …)
- ❑ Samples of Z+"μ" and Z+"e" used to compare efficiencies of isolation and impact parameter cuts between data and MC → good agreement → MC used to estimate background contamination in signal region
- ❑ Several cross-checks made with different control regions → consistent results

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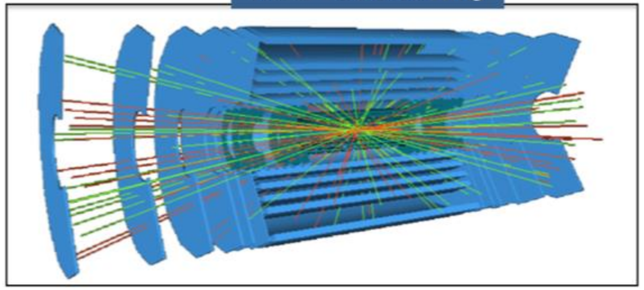
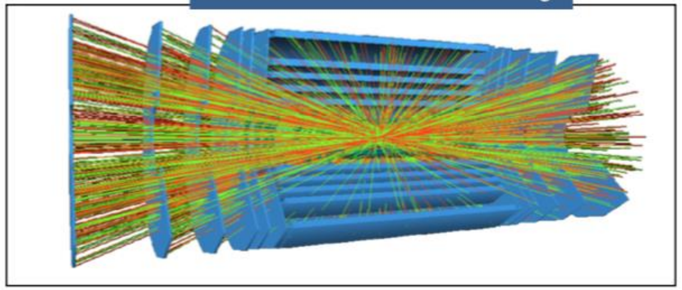
Today Arial

Higher peak luminosity and larger pile-up (from ~ 30 to 140-200 events/x-ing) require: increased radiation hardness and granularity, dedicated (timing) detectors, larger bandwith, faster and more granular readout electronics, improved triggers and higher redundancy, to provide similar or better performance than current detectors (including trigger thresholds) in much harsher HL-LHC environment

LHC: ~ 30 evts/x-ing

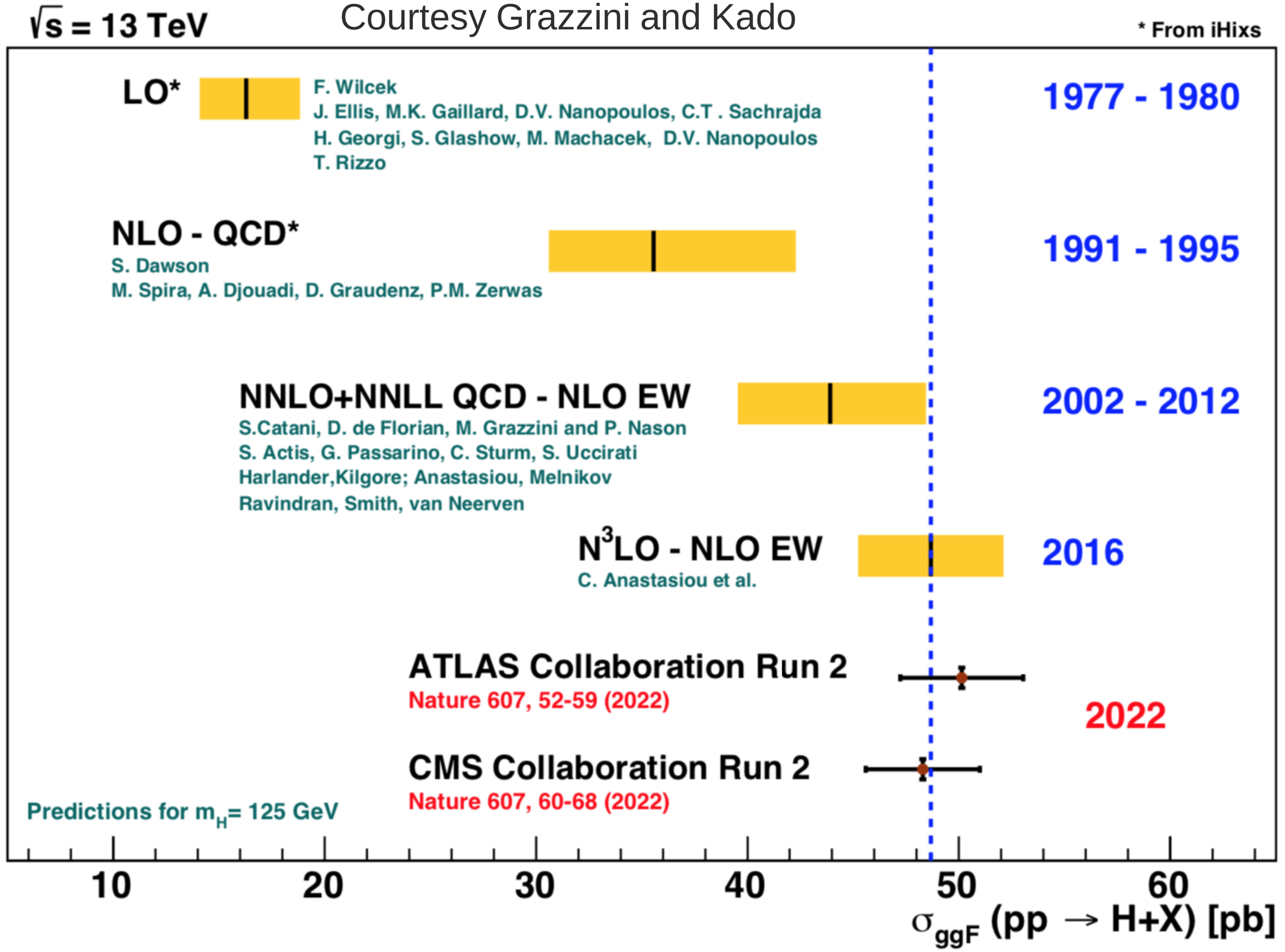


HL-LHC: ~ 140-200 evts/x-ing



Theory

Courtesy Grazzini and Kado



Huge theoretical progress (N3LO-QCD, NNLO Monte Carlos with PS matching, N3LL resummations matched to fixed order, etc.)
Challenge: theoretical uncertainties on signal and backgrounds already important today, will become dominant in many cases with increased Run 3 and HL-LHC statistics

Standard Model cross-sections

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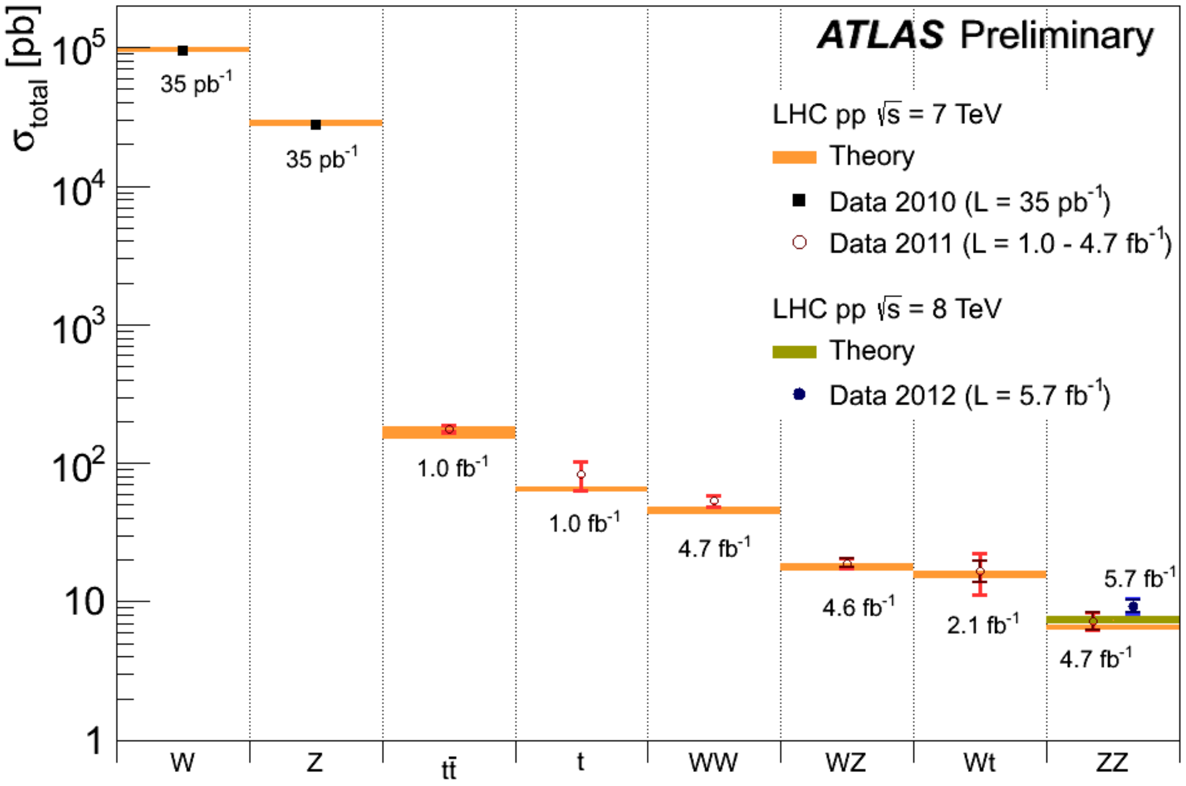
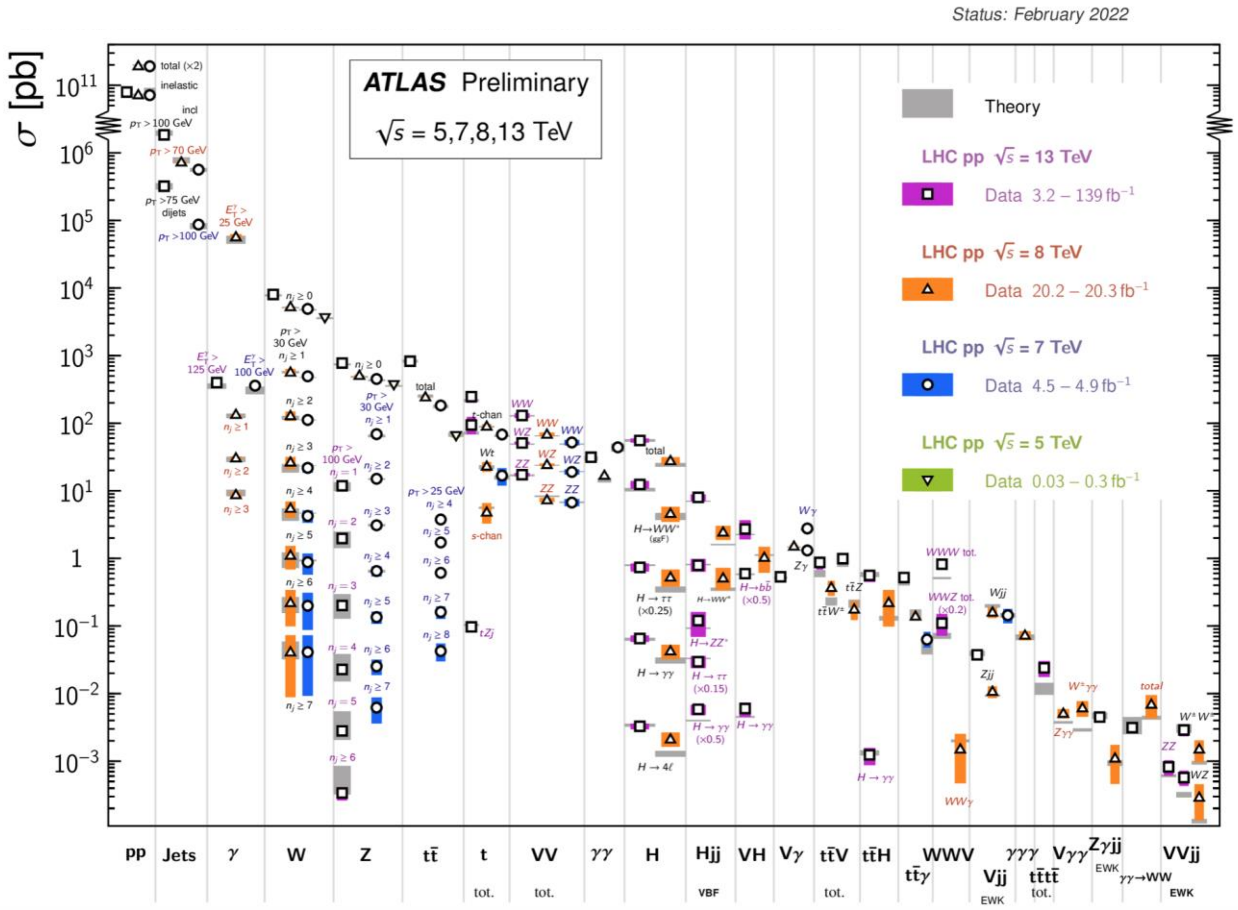


Today



Current precision on inclusive cross-sections: typically few percent over almost 14 orders of magnitude!

H → 4 leptons

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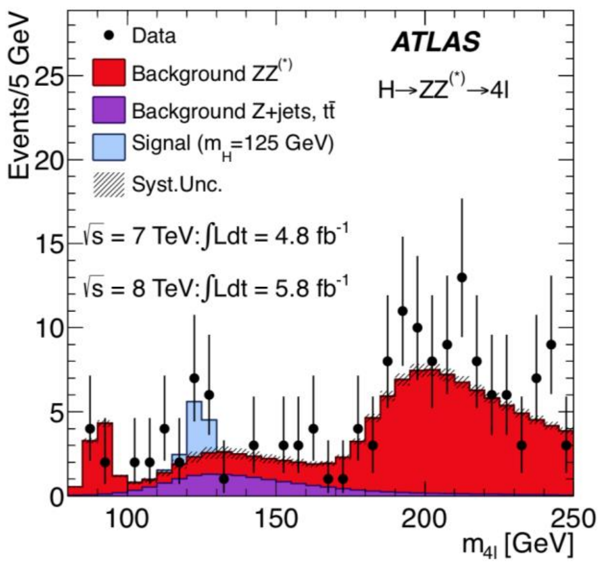
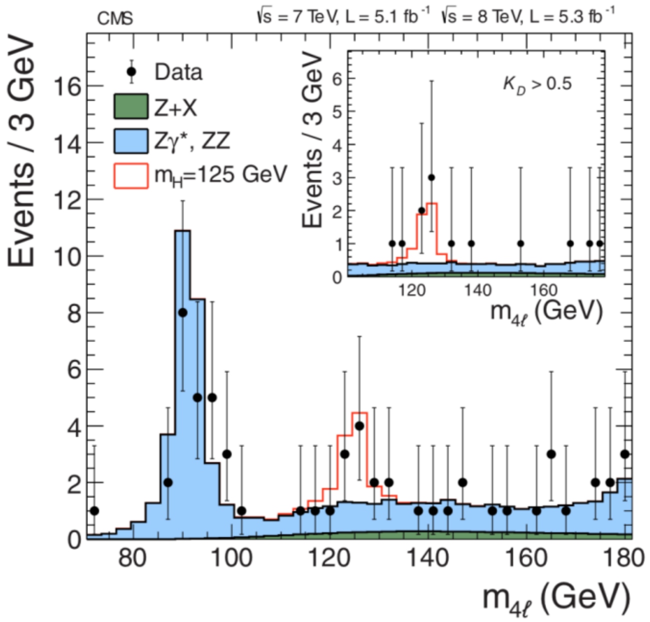
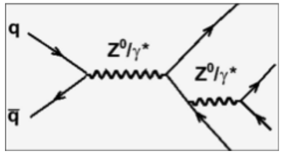
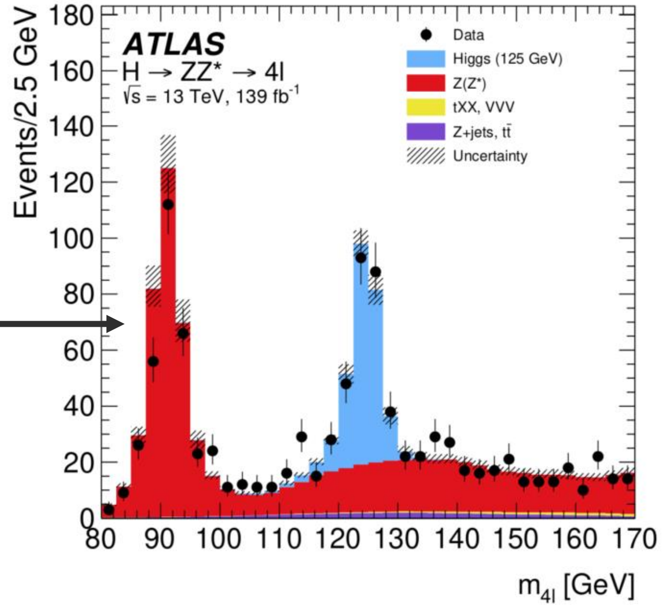


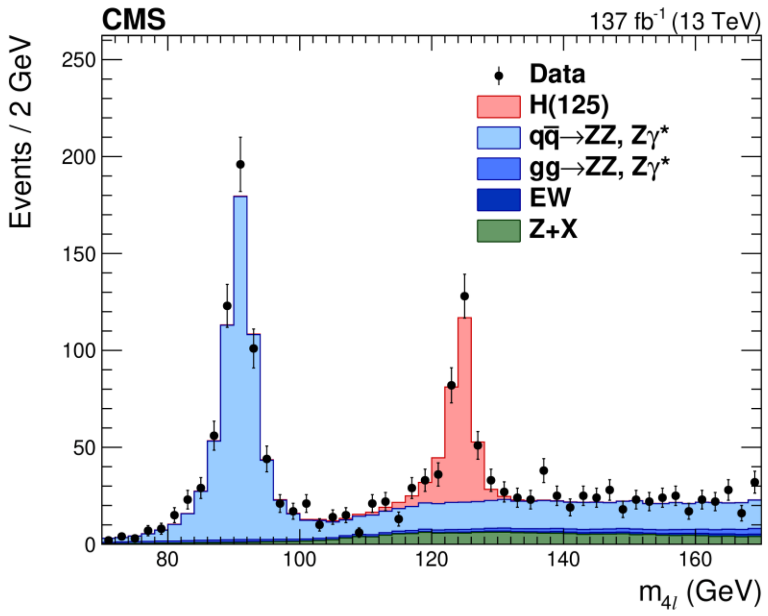


Today

Peak at m_{4l} ~ 90 GeV from Z→ 4l production







Higgs boson production and decay measurements

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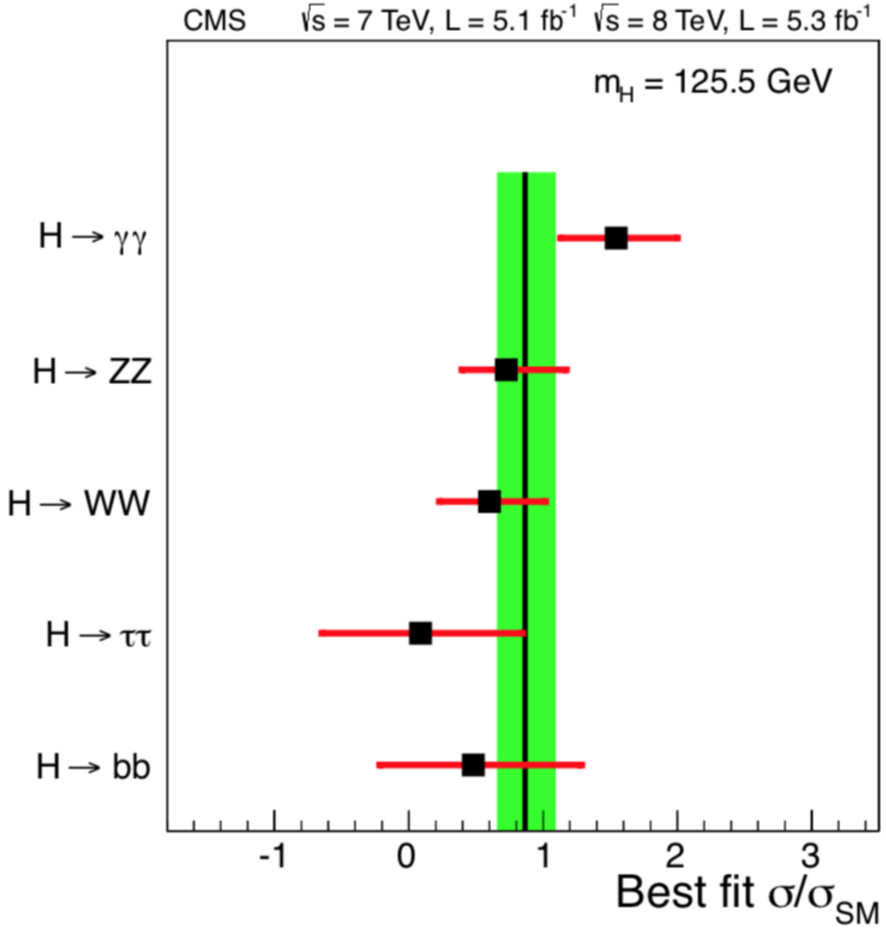
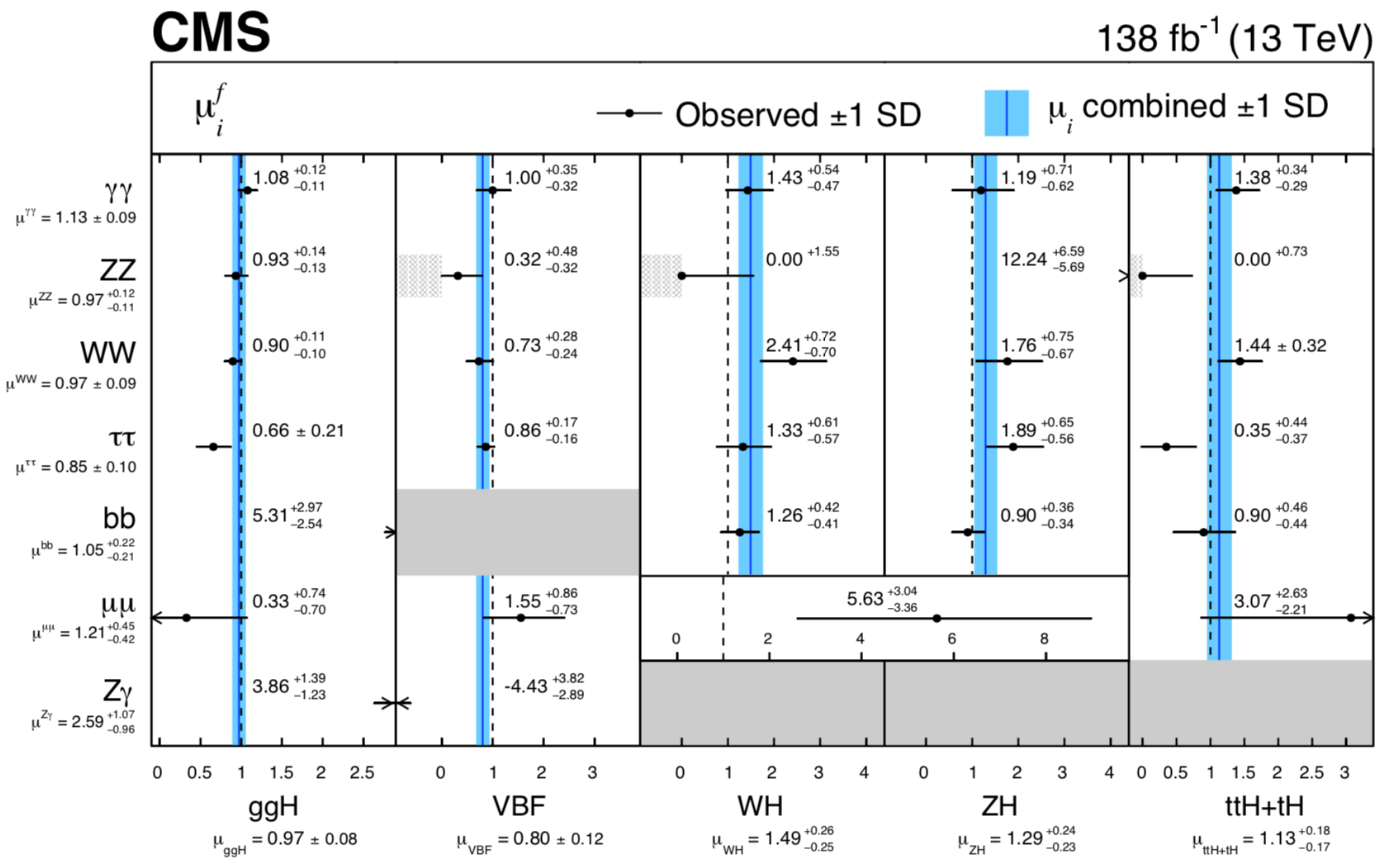


Overall signal strength normalised to SM expectation:
$\mu = 0.87 \pm 0.23$

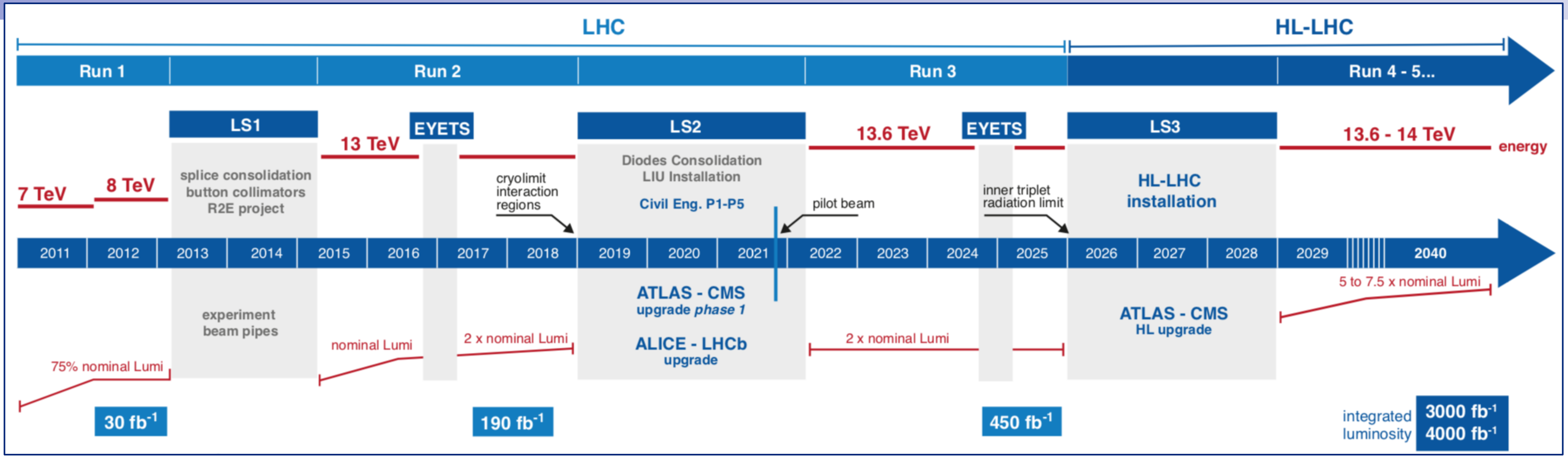
Today



Overall signal strength normalised to SM expectation:
$\mu = 1.002 \pm 0.057$

A look to the future

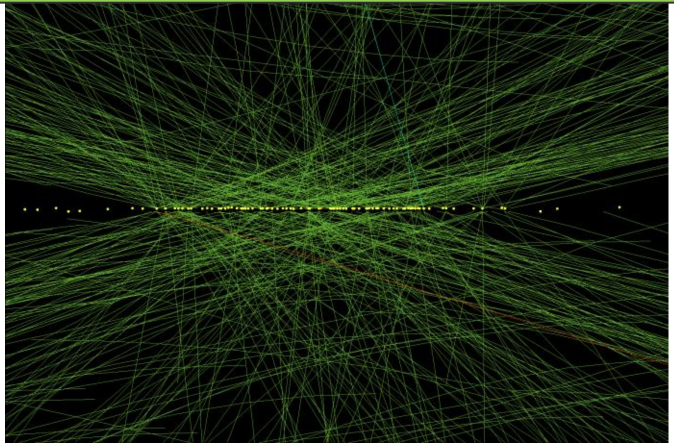
High-Luminosity LHC (HL-LHC)



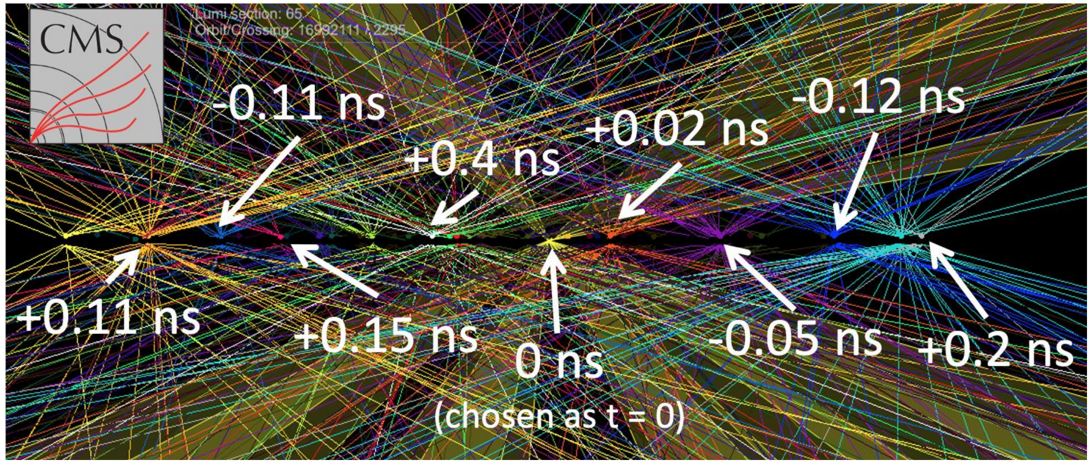
Higher peak luminosity and larger pile-up (from ~ 30-40 to 140-200 events/x-ing) require: increased radiation hardness and granularity, dedicated (timing) detectors, larger bandwith, faster and more granular readout electronics, improved triggers and higher redundancy, to provide similar or better performance than current detectors (including trigger thresholds) in much harsher HL-LHC environment.

→ Major upgrades of ATLAS and CMS

Event with 78 reconstructed vertices (CMS Run 2 data)
Note: ~ 20 expected when detectors were designed



New timing detectors with resolution ~ 30 ps in both experiments for 4-dimensional identification of primary vertex

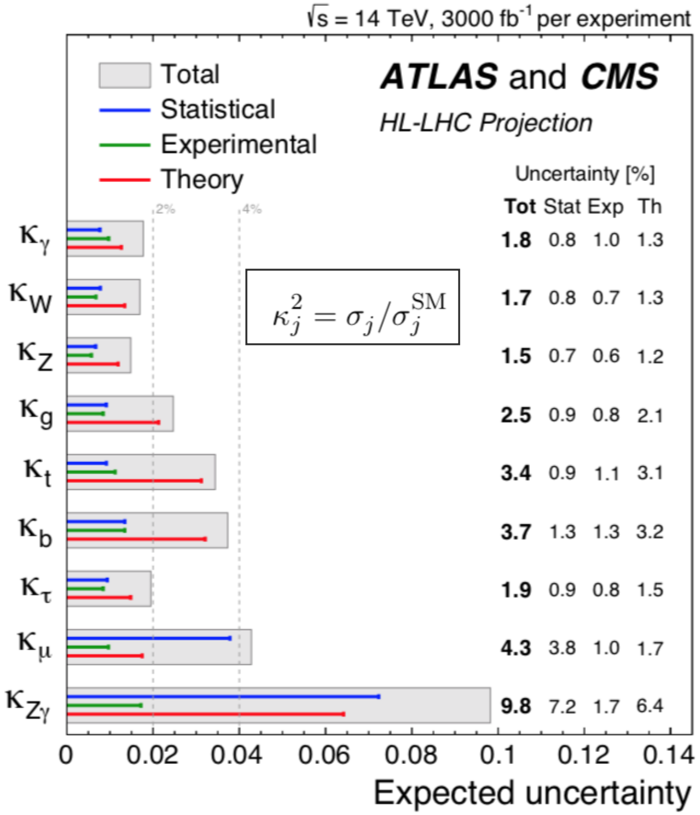


For illlustration, adapted from Chris Tully (courtesy André David).

Higgs boson at HL-LHC

Factor ~ 20 larger data sample than today (3000 fb^{-1}, ~180 M Higgs produced per experiment) and improved detectors → significant increase in sensitivity to new physics and precise measurements, e.g. rare production and decay modes, differential distributions, searches for additional H, etc.

Higgs couplings measurements

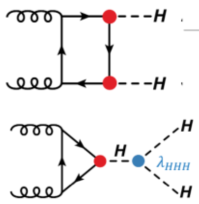


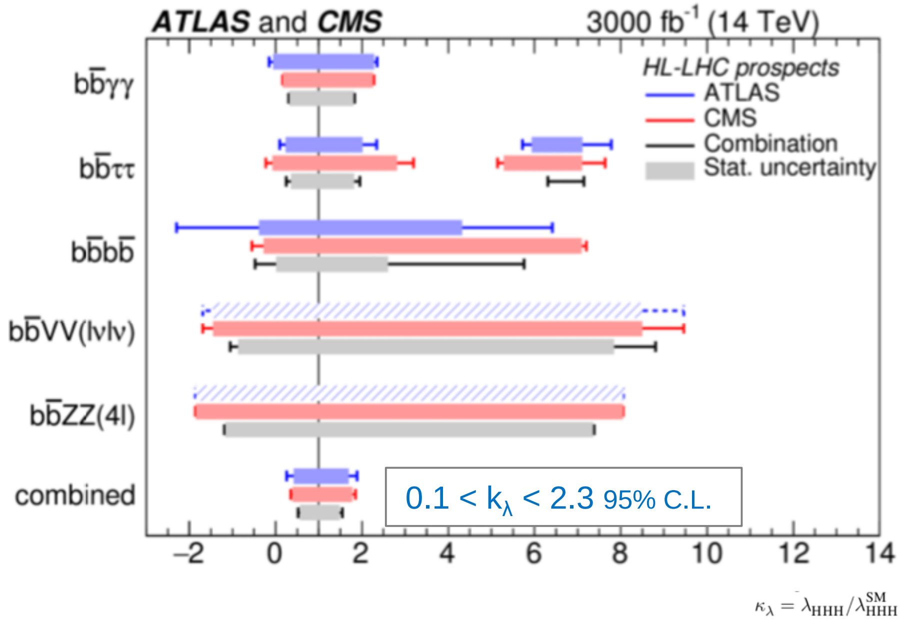
Global fit assuming no BSM contributions to Γ_H.

- 3-4 times more precise than today
- first 5σ observation of H→ Zγ (H→ μμ already in Run 3)
- experimental precision challenges theory

First observation of HH production (~ 5σ level)

$$\mathcal{L}_h = \frac{1}{2} m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$





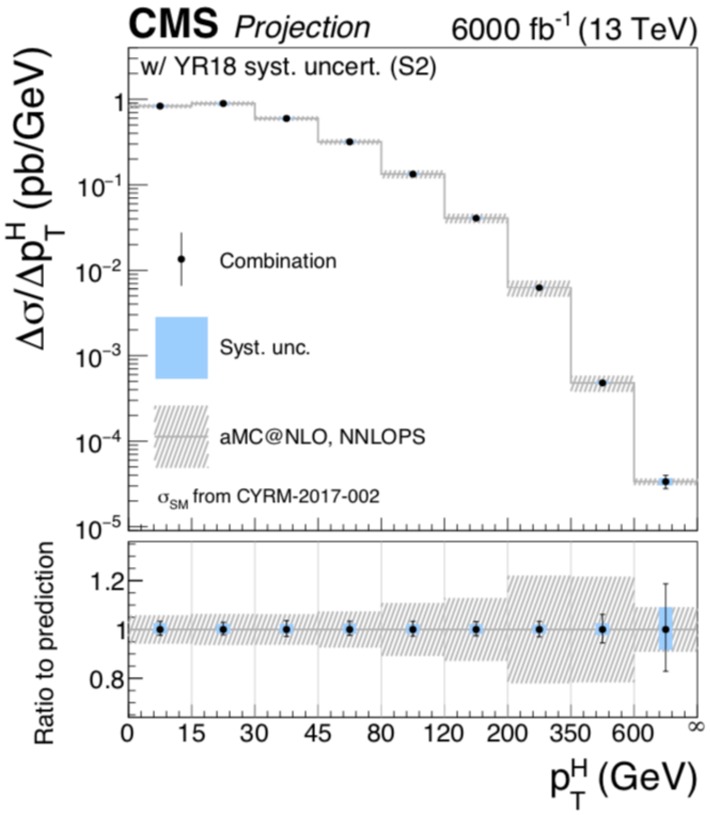
Today:

ATLAS : cross-section < 2.4 x SM (2.9 expected), - 0.6 < k_λ < 6.6 95% C.L.

CMS : cross-section < 3.4 x SM (2.5 expected), - 1.24 < k_λ < 6.49 95% C.L.

Higgs boson(s) at HL-LHC

p_T^H spectrum (sensitive to new physics) can be measured to few percent up to 600 GeV by combining ATLAS and CMS

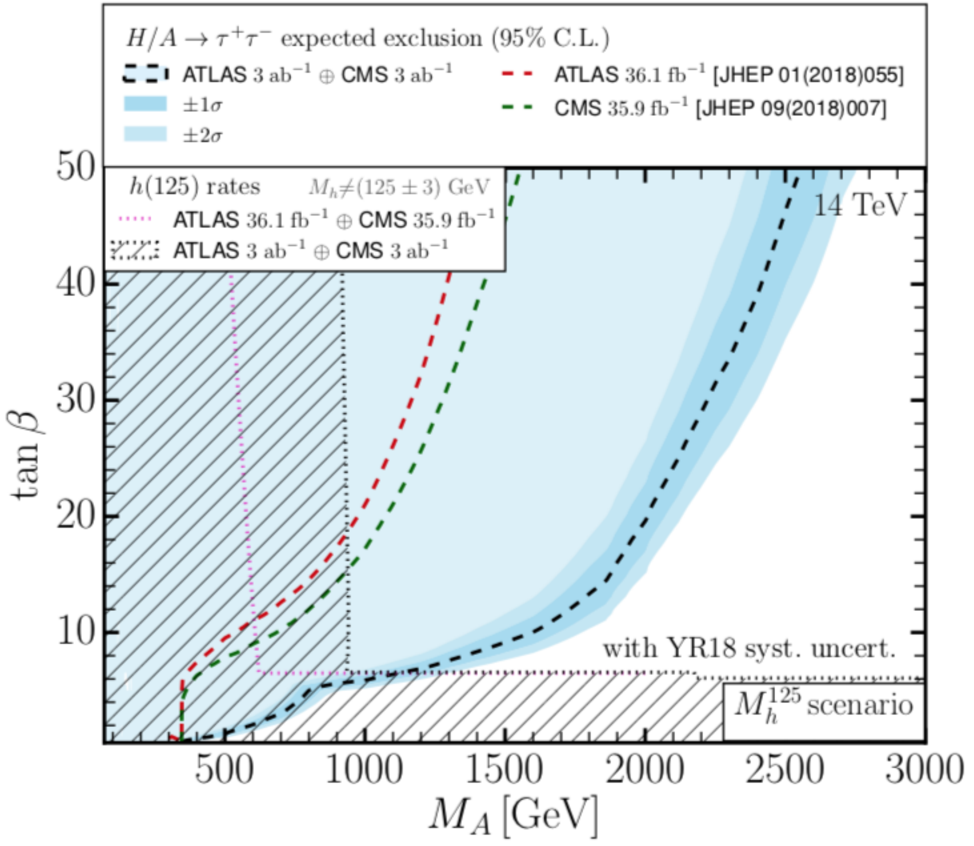


Branching ratio into invisible:
B_inv < 2.5% at 95% C.L.

Coupling to charm-quark: $|k_c|$< 1-2

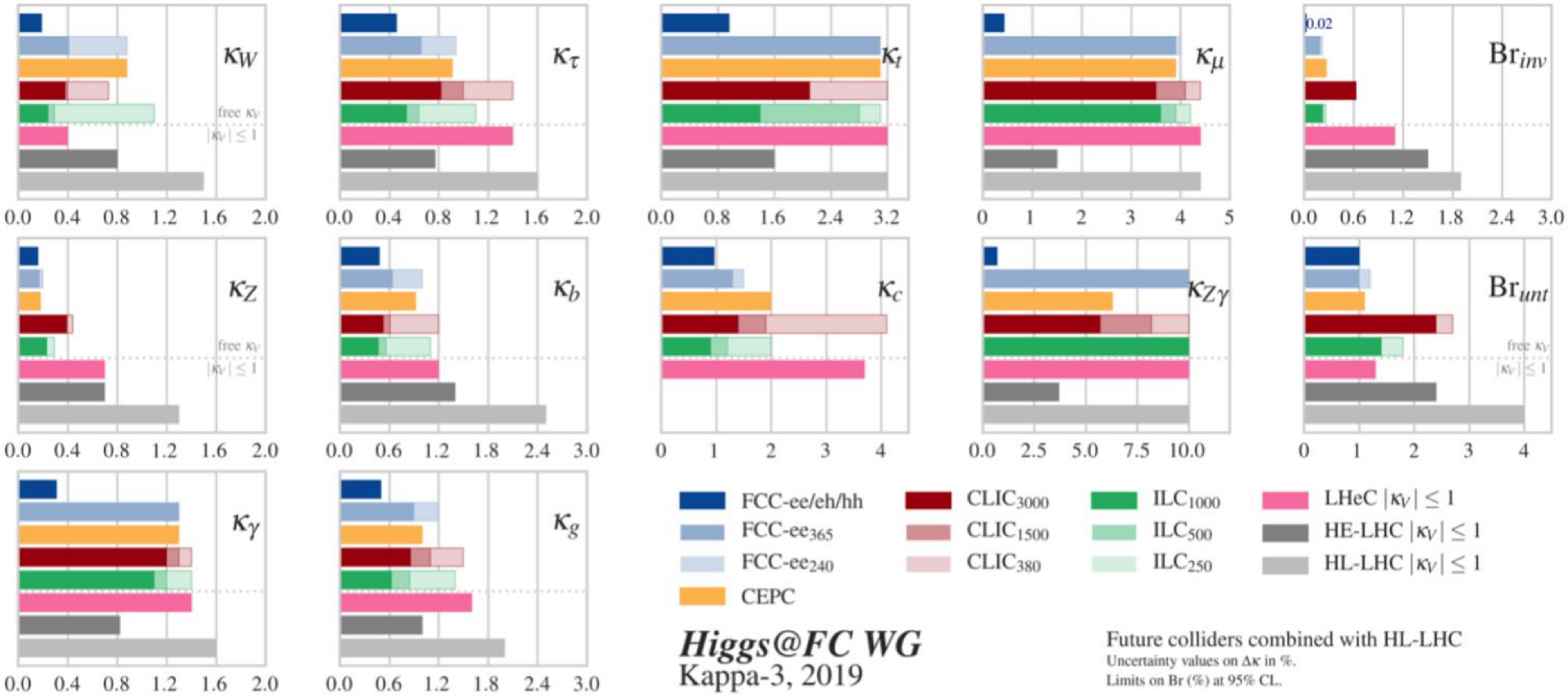
Γ_H to 20% from off-shell H→ ZZ cross-section and 5% from coupling fits (assuming |k_V|≤ 1)

Additional MSSM Higgs bosons can be excluded from direct searches or H (125) measurements well into the several TeV region

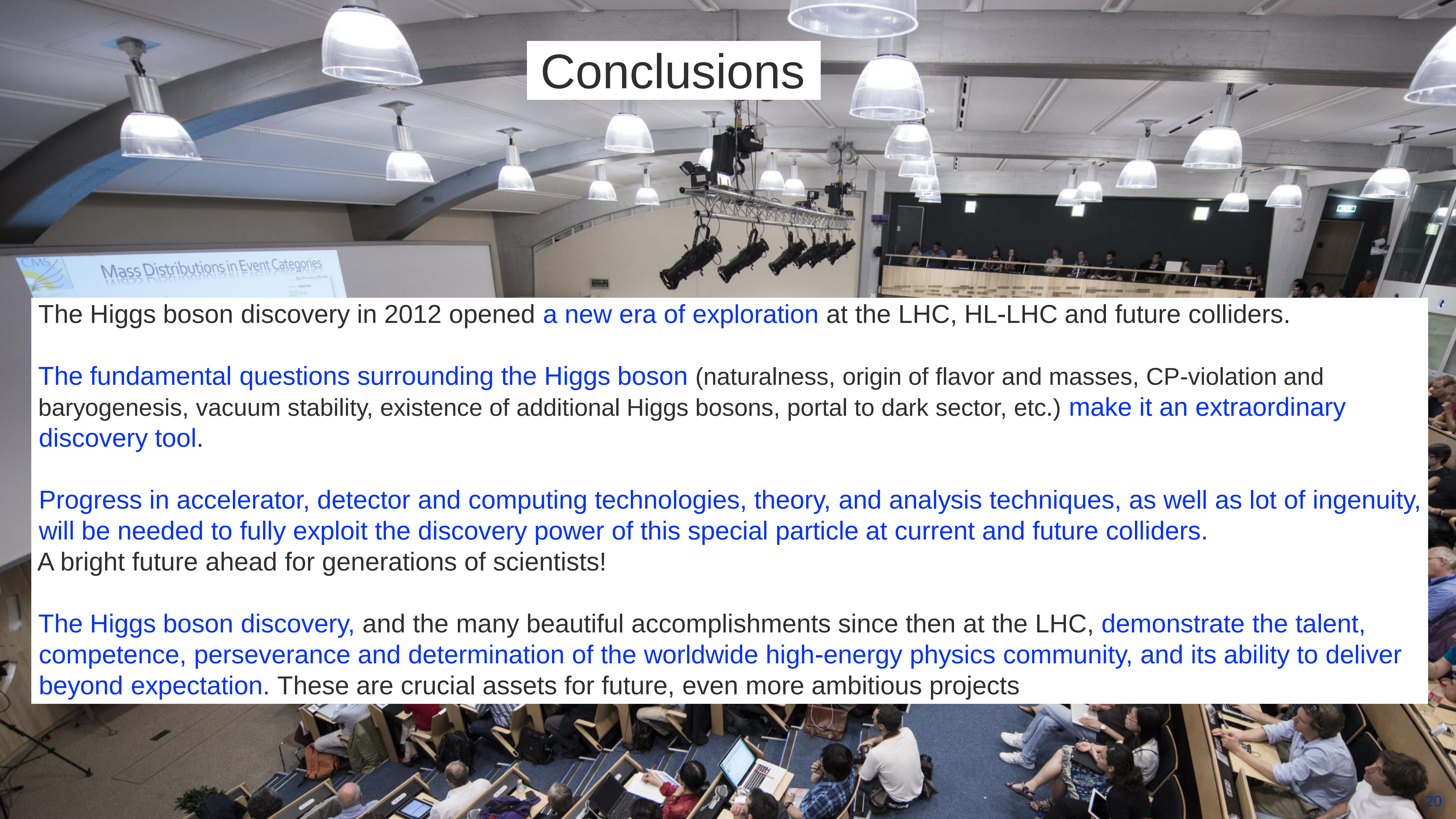


Addressing increasingly challening final states (e.g. charm tagging, E_T^{miss} at very high pile-up) requiring ingenuity and analysis improvements

Higgs boson measurements at future colliders



Future Circular Collider (FCC): input from FCC-ee (e.g. HZZ coupling and ttZ cross-section) removes model-dependence of several couplings that are best measured at FCC-hh (e.g. H→ μμ, H → $\gamma\gamma$, H → Zγ, ttH)



Conclusions

The Higgs boson discovery in 2012 opened a new era of exploration at the LHC, HL-LHC and future colliders.

The fundamental questions surrounding the Higgs boson (naturalness, origin of flavor and masses, CP-violation and baryogenesis, vacuum stability, existence of additional Higgs bosons, portal to dark sector, etc.) make it an extraordinary discovery tool.

Progress in accelerator, detector and computing technologies, theory, and analysis techniques, as well as lot of ingenuity, will be needed to fully exploit the discovery power of this special particle at current and future colliders.
A bright future ahead for generations of scientists!

The Higgs boson discovery, and the many beautiful accomplishments since then at the LHC, demonstrate the talent, competence, perseverance and determination of the worldwide high-energy physics community, and its ability to deliver beyond expectation. These are crucial assets for future, even more ambitious projects

Many thanks to

The Member States and Associate Member States for their continued, strong support over the decades and to non-Member States for their essential contributions to the LHC.

Simone Campana, María Cepeda, Valerio Dao, André David, Adinda De Wit, Marco Delmastro, Massimiliano Grazzini, Andreas Hoecker, Marumi Kado, Mike Lamont, Luca Malgeri, Chiara Mariotti, Edoardo Martelli, Panos Paparrigopoulos, Jan Steggemann, Kerstin Tackmann and Nicholas Wardle

for useful discussions and some of the material presented here.

And to the Symposium organisers

Fabio Cerutti, James Gillies, Massimo Giovannozzi, Chiara Mariotti, Matthew McCullough, Pippa Wells

CERN