Review of LHC results on the SM Higgs Boson and top quark

Paolo Azzurri – INFN Pisa

on behalf of ATLAS and CMS

International Conference on the Physics of the Two Infinities

Kyoto – 29 March 2023

Outlook

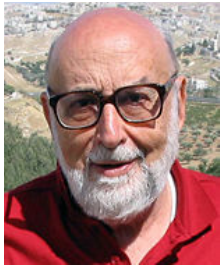
- the Higgs Boson, searches and discovery at the LHC
- status of Higgs boson measurements 10 year later
  - mass, width, decays to fermions (3rd & 2nd generation)
  - combined results on couplings, double-Higgs production and couplings
  - a couple of new results
- top quark measurements at the LHC
  - total and differential cross sections, properties
  - mass
  - a couple of new results

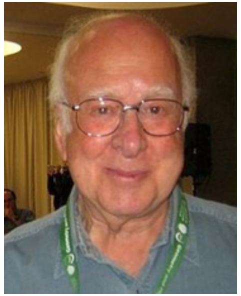
the Higgs boson

from 1964 to the LHC

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)





The field permeates the universe giving mass to elementary particles

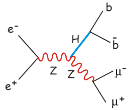
The mechanism predicts an (the only) elementary particle with zero spin : the Higgs boson

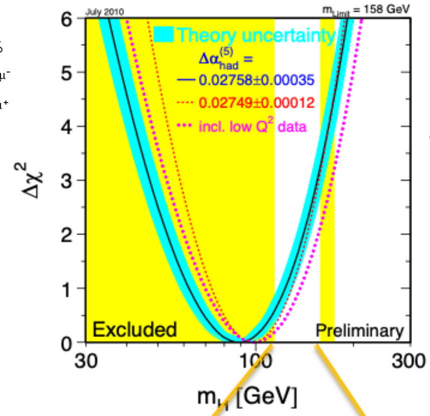
Zero charge, even parity and charge conjugation

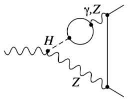
VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

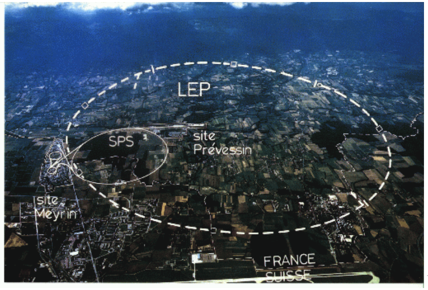
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)







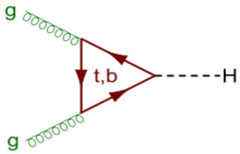
Pre-LHC Direct searches & indirect constrains



$114 < m_H < 158$ GeV

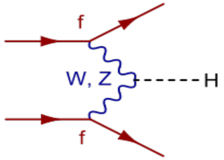
production and decay at the LHC

87%



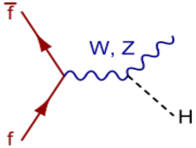
gluon fusion (ggF)

7%



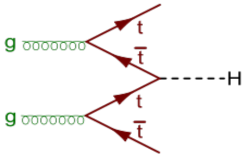
vector boson fusion (VBF)

4%

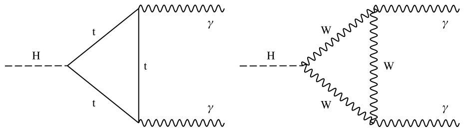


Higgs-strahlung (VH)

1%

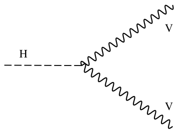


top quark fusion (ttH)



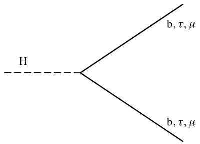
H→$\gamma\gamma$

0.23%



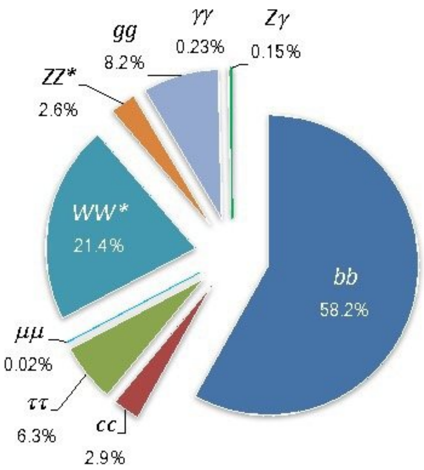
H→ZZ*, WW*

2.7%, 22%



H→ff

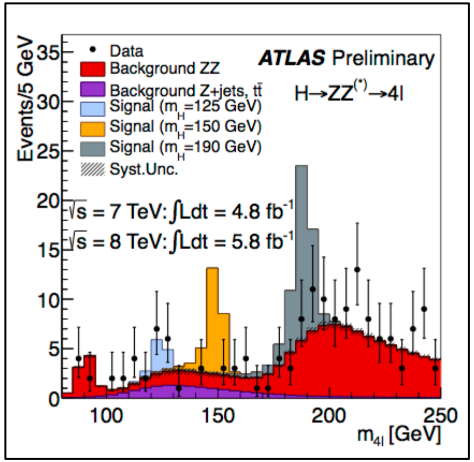
58% bb
6.2% $\tau\tau$
2.9% cc
0.02% $\mu\mu$

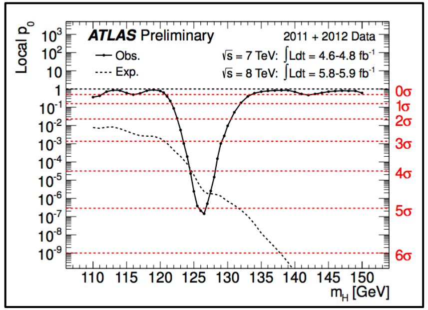


A rich variety of initial and final states !

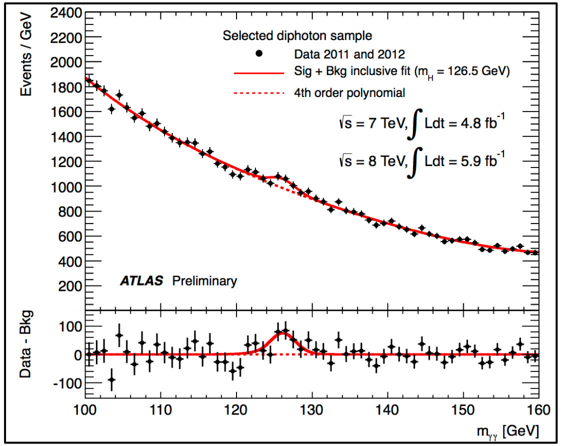
July 4th 2012

https://indico.cern.ch/event/197461/

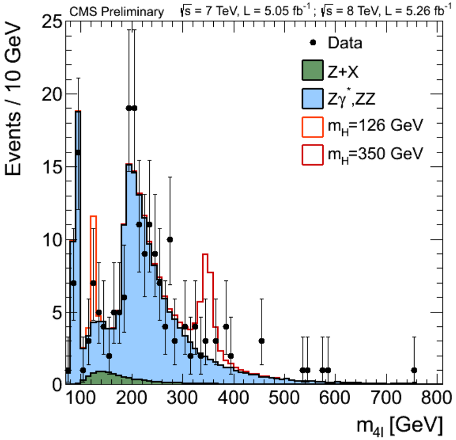


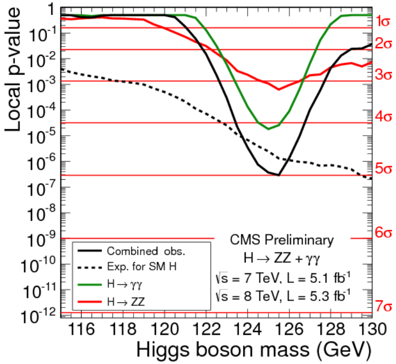


ATLAS 5.0σ @126.5 GeV



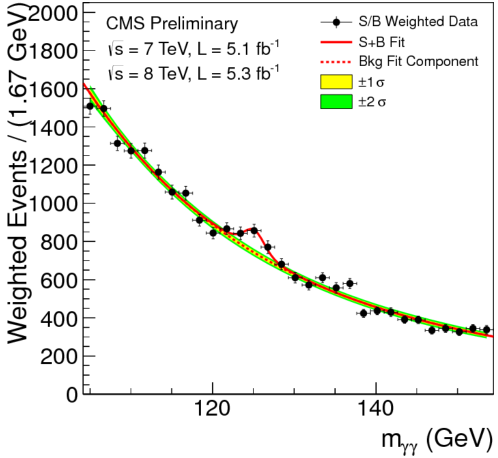
H→4ℓ



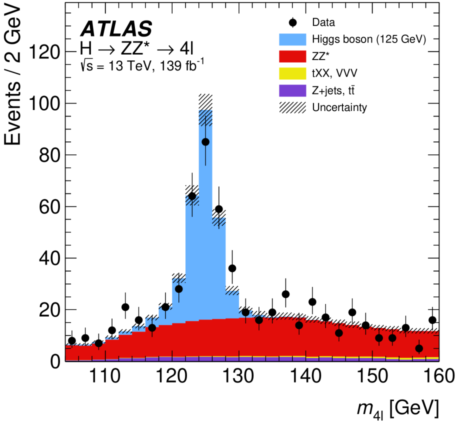


CMS 5.0σ @125.3 GeV

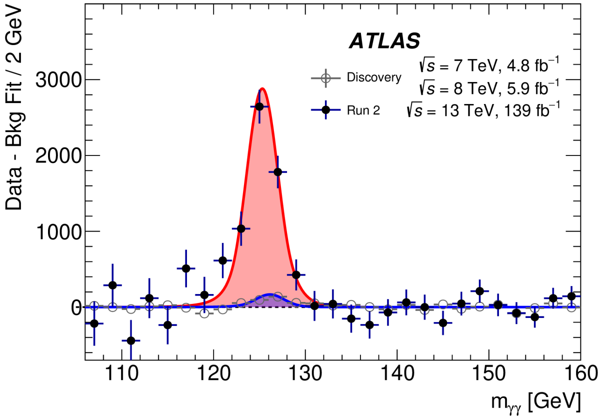
H→ $\gamma\gamma$



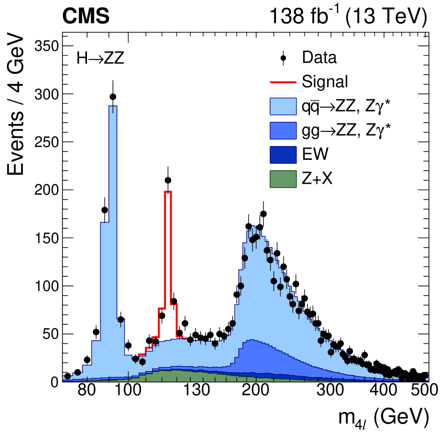
10 years later



30 times more Higgs bosons

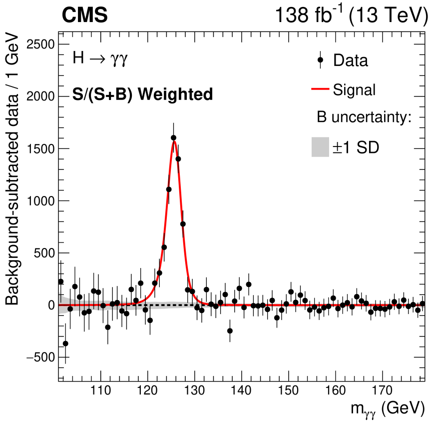


H→4ℓ



[Nature 607 (2022) 52-59]

[Nature 607 (2022) 60-68]



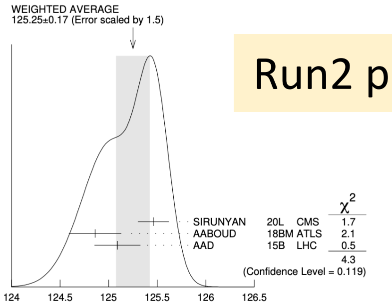
H→ $\gamma\gamma$

The Higgs Boson mass

Fits of per-event m_H, δm_H and event classifier (S/B)

Calibrations from J/ψ & $Z\to\ell\ell$ (for ℓ) - from $Z\to ee$ (for γ)

Limiting systematics for $m(\gamma\gamma)$ - $m(4\ell)$ will improve further



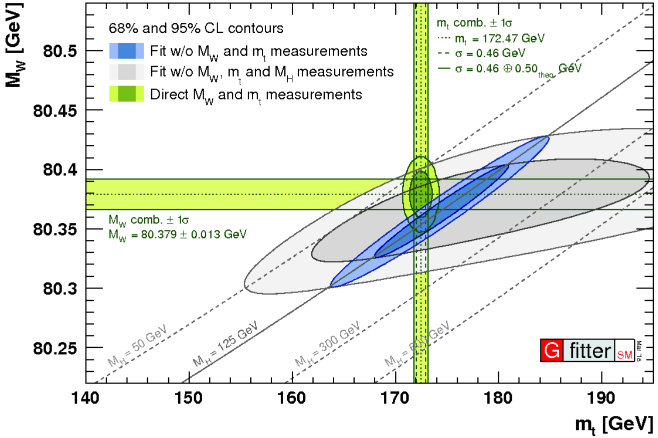
$m_{ATLAS} < m_{CMS}$

[PLB 784 (2018) 345](#)

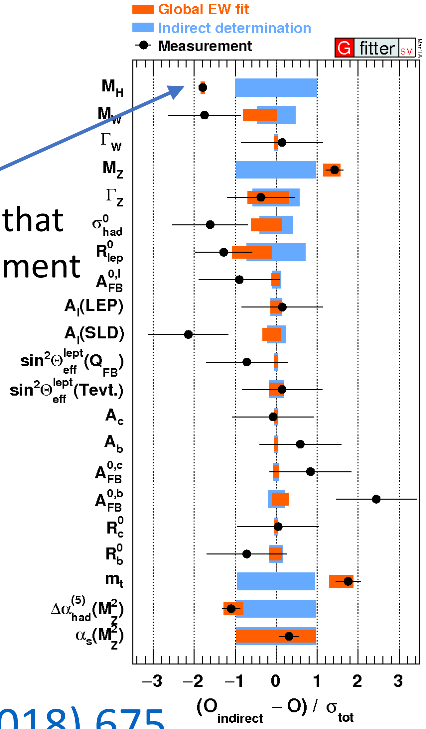
[PLB 805 (2020) 135425](#)

Run2 precision at the 0.1% level !

ultra-precise determination in the context of SM precision fits



can you see that m_H measurement error bar ?



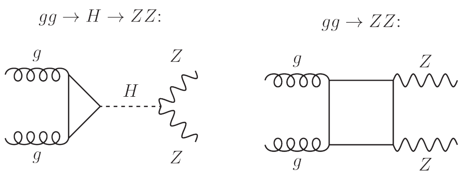
[EPJ C78 (2018) 675](#)

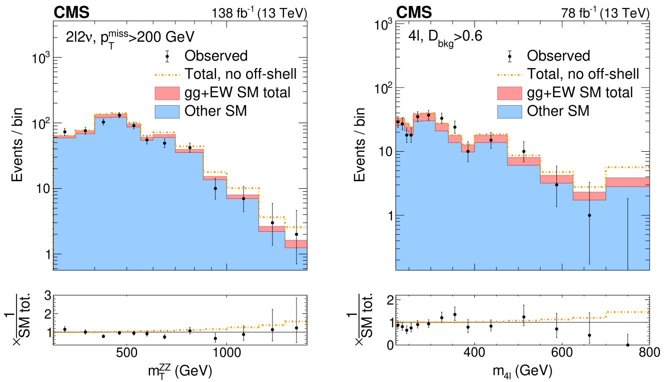
Nat. Phys. 18 (2022) 1329

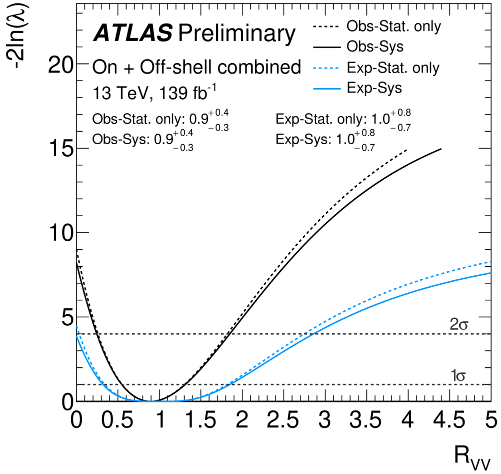
ATLAS-CONF-2022-068

The Higgs Boson width

Direct : $\begin{cases} 4\ell \text{ lineshape} \Rightarrow \Gamma_H < 1.1 \times 10^3 \text{ MeV} \\ 4\ell \text{ lifetime} \Rightarrow \Gamma_H > 3.5 \times 10^{-9} \text{ MeV} \end{cases}$







$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{(2m_Z)^2}$$

Indirect : negative interference at large $m_{4\ell}$

3.6σ / 3.2σ evidence for off-shell Higgs boson production

assuming constant couplings in the range

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

$\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV

Higgs boson couplings

Direct observation of couplings to **Z, W bosons** with or soon after discovery
Coupling to **top quarks** extracted from resolving gg production and $\gamma\gamma$ decays

Also **direct ttH** observation (2018)

H→ττ Sensitivity mostly in the **VBF** channel
Run1 observation JHEP 08 (2016) 045

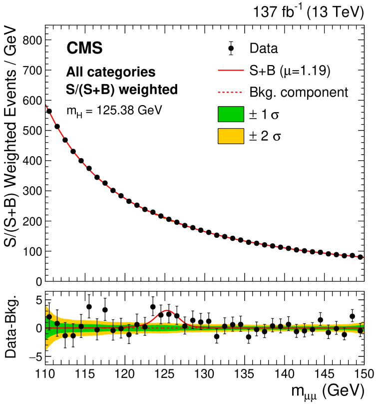
H→bb Sensitivity mostly in the **VH** channel
Separate observations with partial Run2
PLB 786 (2018) 59 PRL 121 (2018) 121801

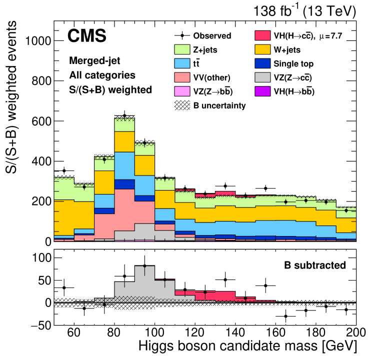
3[rd] generation Yukawa settled ! 2[nd] generation ?

H→μμ: 3.0σ Evidence !
Crucial $m_{\mu\mu}$ resolution driven by VBF channel

JHEP 01 (2021) 148

PLB 812 (2021) 135980





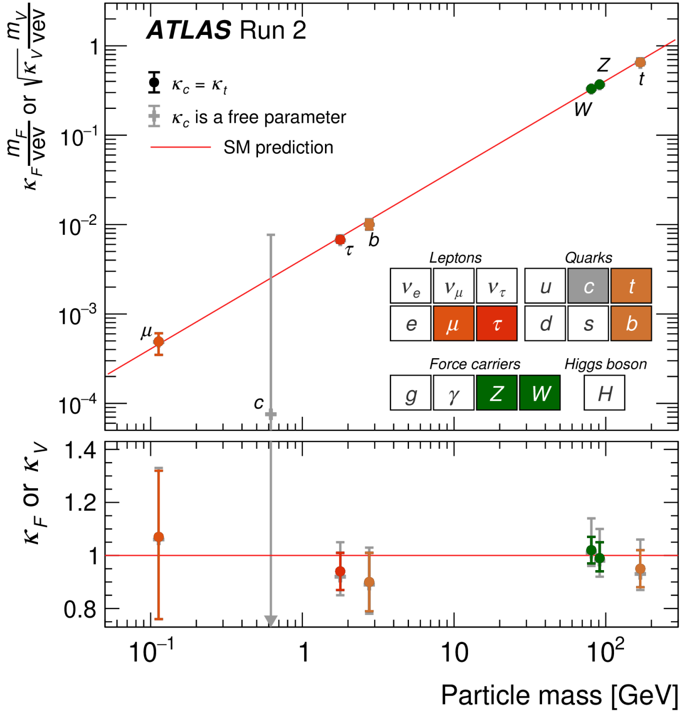
H→cc: advancing with ML

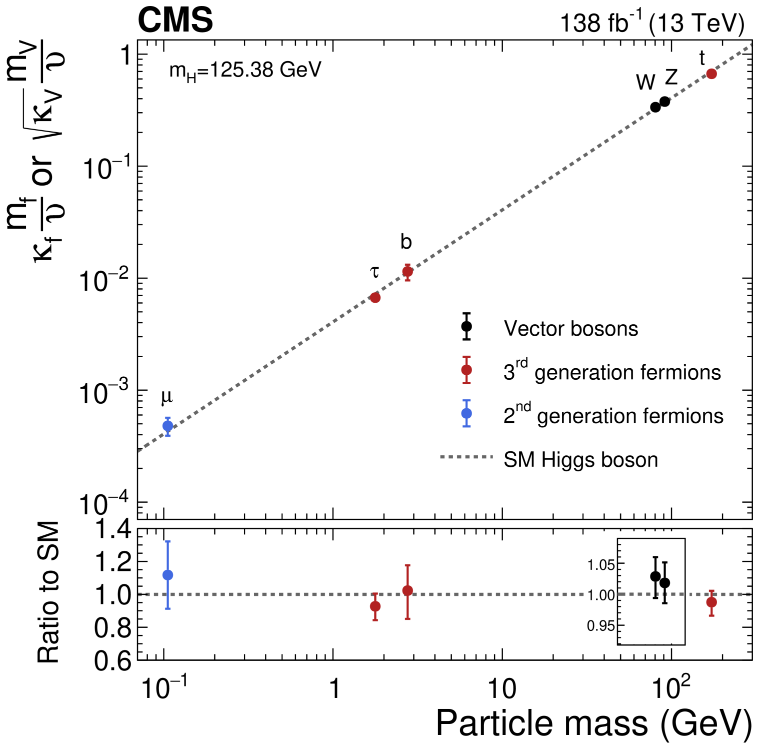
arXiv:2205.05550

VZ at 5.7σ significance
first observation of Z →cc at a hadron collider.

VH signal $7.7^{+3.8}_{-3.5}$ SM

Higgs boson couplings vs mass



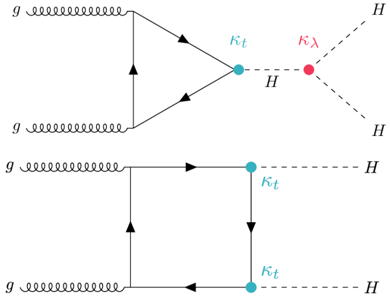


SM couplings now tested over four orders of magnitude

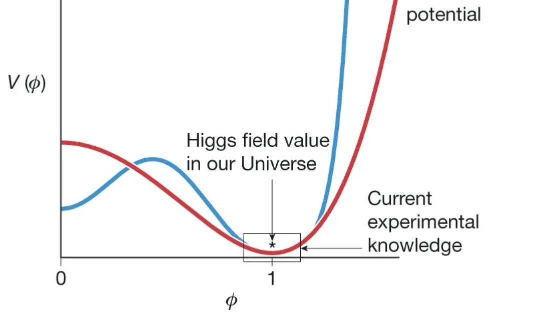
[Nature 607 (2022) 60-68](#) [arXiv:2211.01216](#)

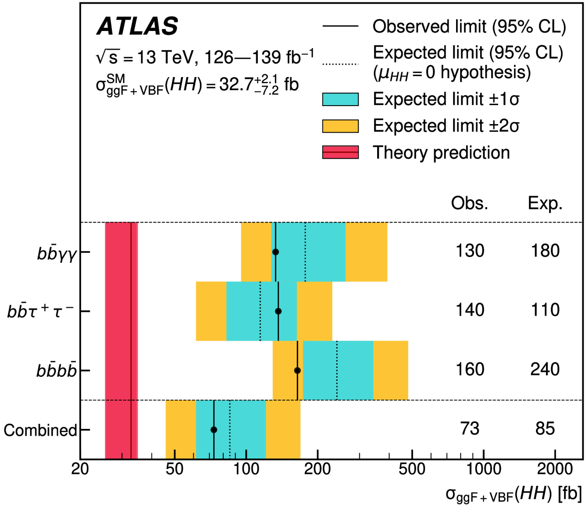
Double-Higgs production & λ

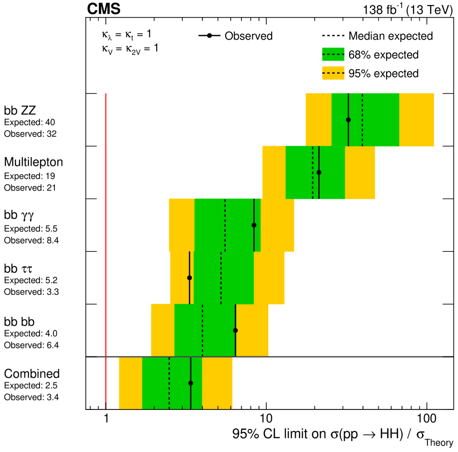
$$V(\phi) = \frac{1}{2}m_{\mathrm{H}}^2\phi^2 + \sqrt{\lambda/2}\,m_{\mathrm{H}}\phi^3 + \frac{1}{4}\lambda\phi^4$$

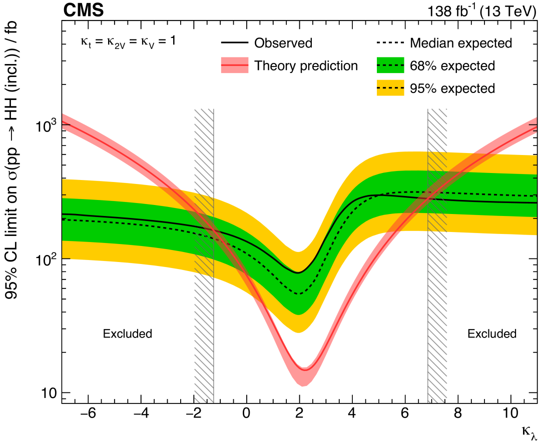


Nature 607 (2022) 41–47









CMS	ATLAS
μ_{HH} ~+1±1	μ_{HH} =−0.73±1.25
$-1.2 < \kappa_\lambda < 6.5$ (95%CL)	$-0.6 < \kappa_\lambda < 6.6$ (95%CL)

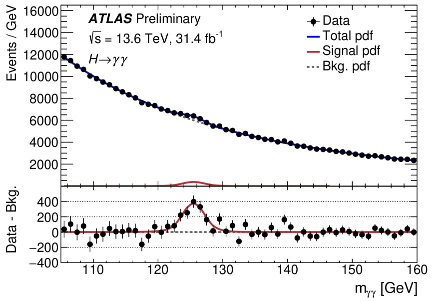
further sensitivity from higher order λ corrections to single Higgs channels

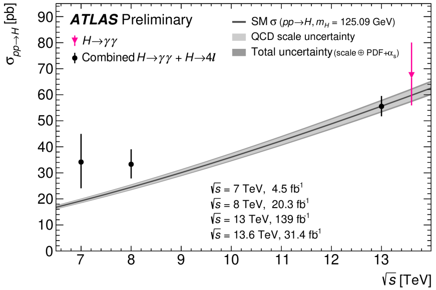
New Higgs boson results

New result from ATLAS

ATLAS-CONF-2023-003

$H \rightarrow \gamma\gamma$ cross-sections at 13.6 TeV





fiducial $\sigma(pp \rightarrow H \rightarrow \gamma\gamma)$= 76^{+14}_{-13} fb

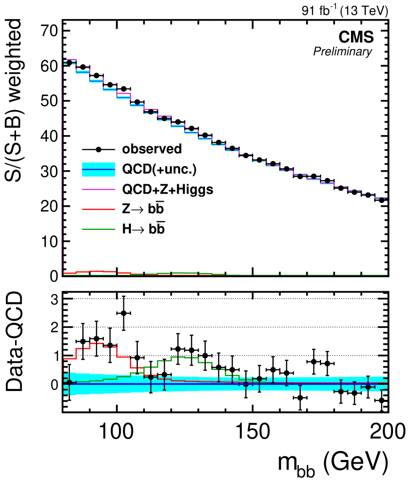
total $\sigma(pp \rightarrow H)$ = 67^{+13}_{-12} pb

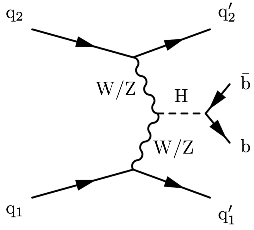
uncertainties 17% stat 11% syst

Recent result from CMS

CMS-PAS-HIG-22-009

VBF $H \rightarrow$bb





Higgs measurement in fully hadronic channel

dedicated trigger paths

2.5σ $H \rightarrow$bb signal significance

VBF signal strength μ = $0.93^{+0.53}_{-0.45}$

the top quark

The top quark

Predicted by Kobayashi and Maskawa in 1973

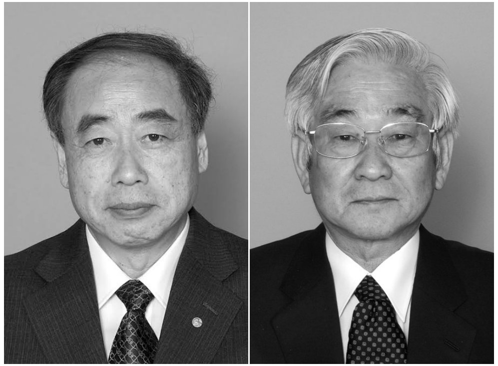
Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

***CP*-Violation in the Renormalizable Theory of Weak Interaction**

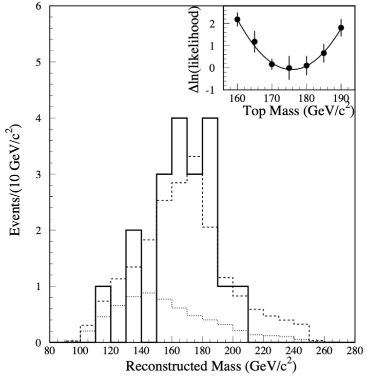
Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

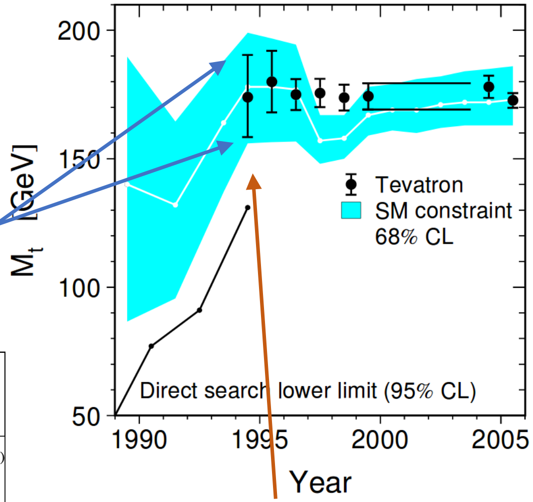
(Received September 1, 1972)



Indirect constraints from LEP EW data



[Phys.Rev.Lett. 74 (1995) 2626]



Discovered in 1995 at the Tevatron

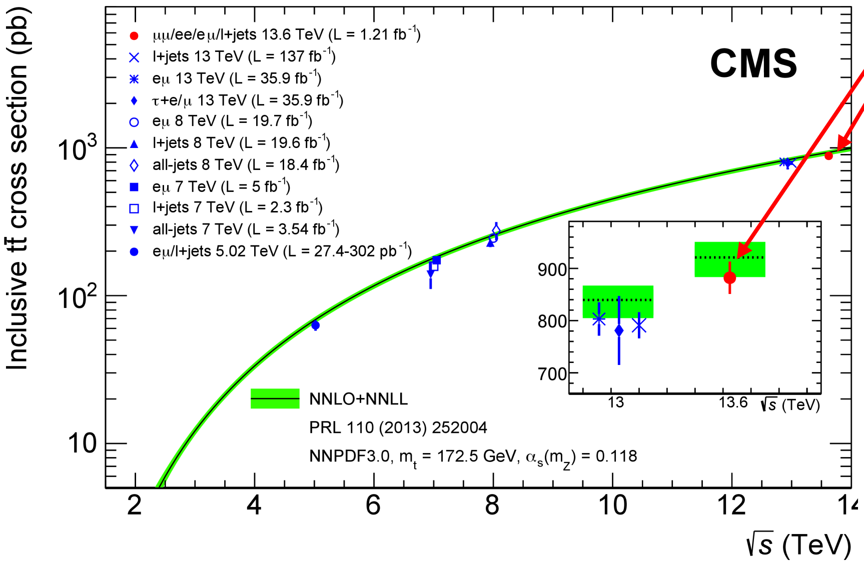
heaviest know elementary particle

LHC is a top factory

~ 100 times Tevatron cross section ⇒ **over 100 M top-pairs / exp**

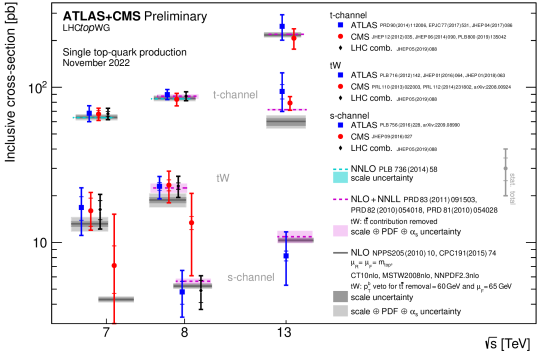
ditop production

new measurement at 13.6 TeV
arXiv:2303.10680



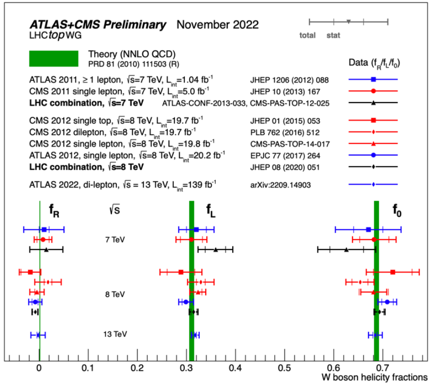
ATL-PHYS-PUB-2022-051

single-top productions



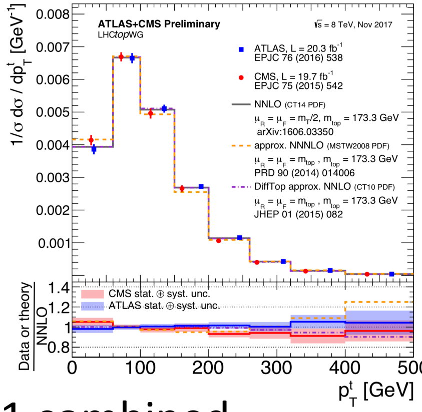
⇒ $|V_{tb}|$
LHC top WG

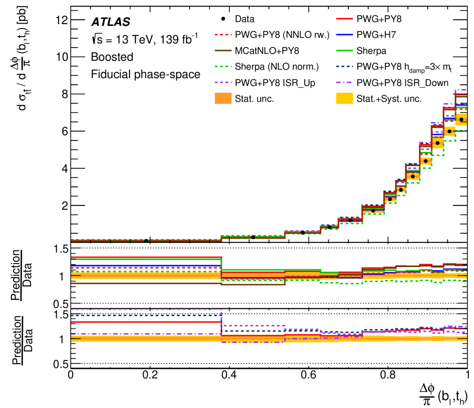
decay properties

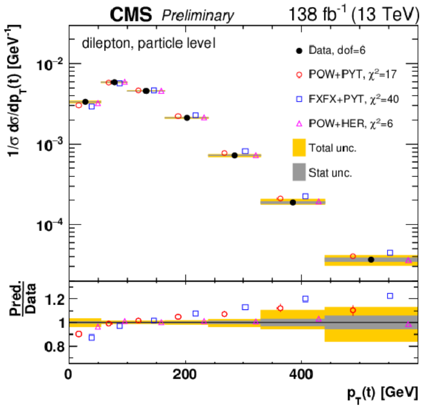


W helicity fractions
ATL-PHYS-PUB-2022-050

differential top quark measurements

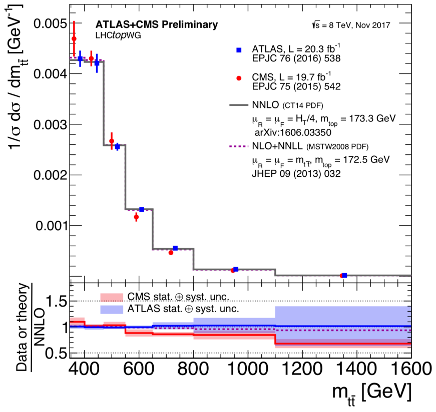




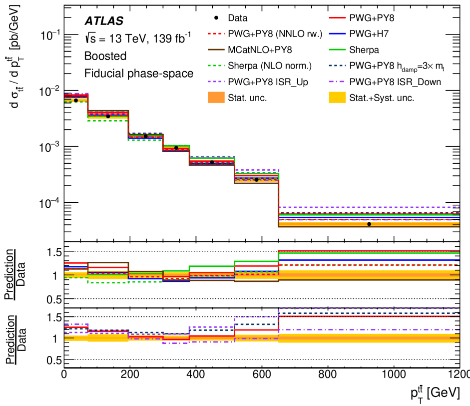


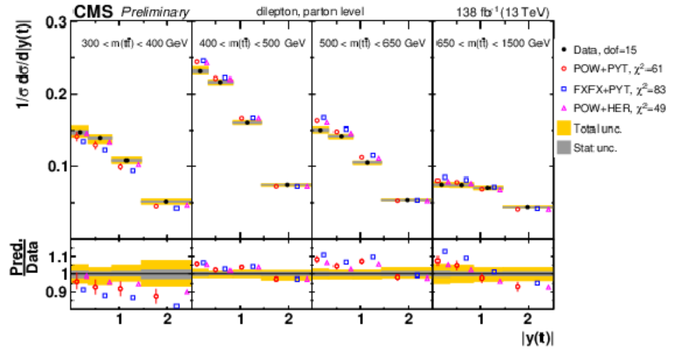
[CMS-PAS TOP-20-006]()

Run1 combined



boosted [*JHEP 06 (2022) 063*]()



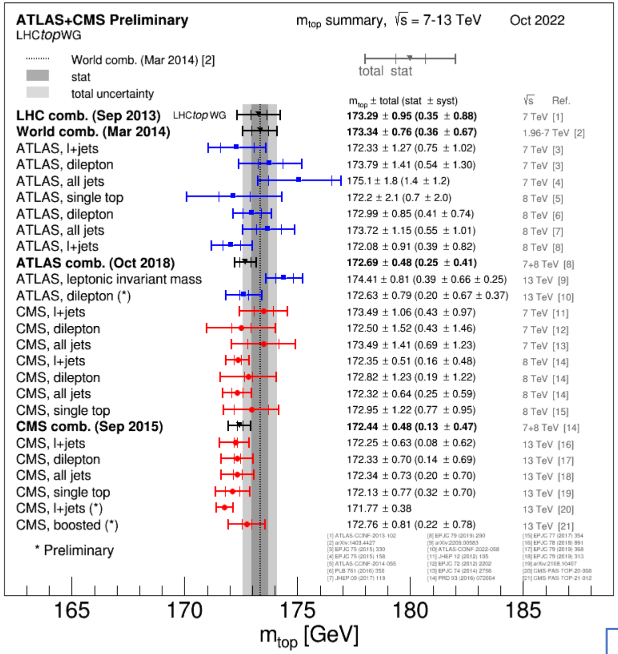


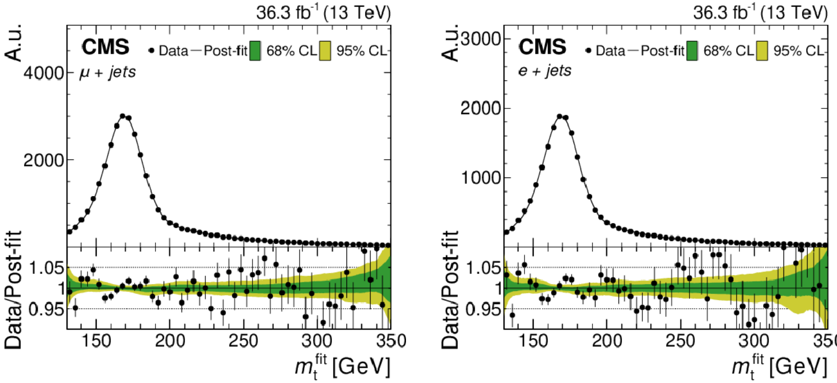
discrepancies & trends in data/models

The top quark mass

Direct reconstruction limited by systematics

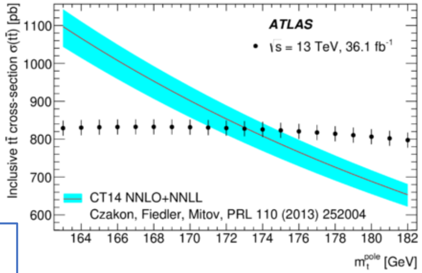
Latest: [arXiv:2302.01967]





5-D likelihood ⇒ $\mathbf{m_t}$**=171.77 ± 0.37 GeV**

Complementary extraction of pole m_t from (differential) σ_{tt}

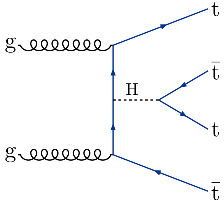


CMS : JHEP 02 (2022) 142 : m_t= 170.4±0.6 GeV

New top quark results

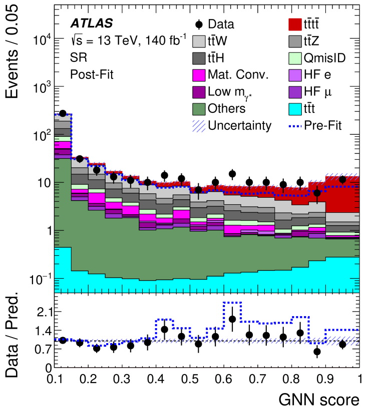
Observation of **four top** quark production

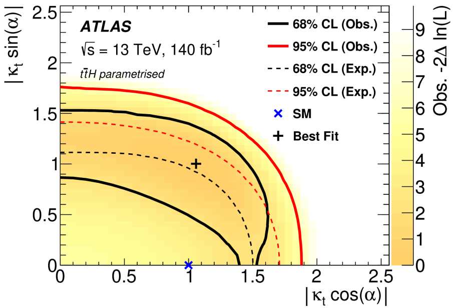
Sensitive to top–Higgs Yukawa



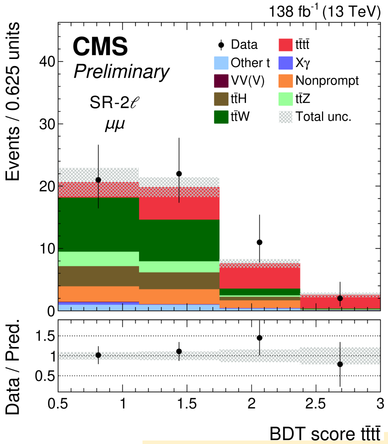
CMS-PAS-TOP-22-013

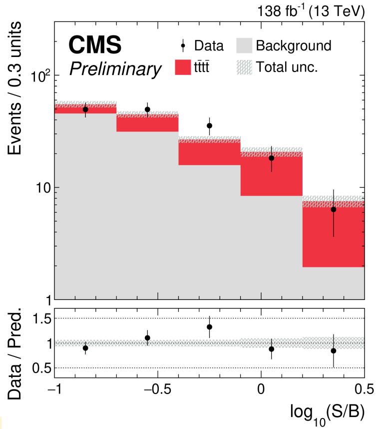
ATLAS-TOPQ-2021-08





bounds on (CP-even/odd) κ_t





$\sigma(pp \to tttt) = 22.5^{+6.6}_{-5.5}$ fb | 1.9x SM

$\sigma(pp \to tttt) = 17.9^{+3.7}_{-3.5}{}^{+2.4}_{-2.1}$ fb

$12.0^{+2.2}_{-2.5}$ fb - prediction - $13.4^{+1.0}_{-1.8}$ fb

Conclusions

- After the discovery of the Higgs boson, in the following (last) 10 years the LHC evolved **to precision Higgs physics**.
- More **advanced precision era for top quark physics** measurements : huge and pure statistics
- Experiments have done **better than predicted**, both on analysis techniques and understanding detector uncertainties.
- Theory predictions have equally improved beyond expectations, enabling stringent comparisons. Overall **agreement with minimal SM predictions is excellent**.
- The **LHC** (Run3 + HL) will remain **at the forefront of future Higgs boson and top quark measurements**. An *e+e- Higgs factory* is the next highest priority for particle physics, and should reach and scan the ditop production region.
- Higgs and top quark physics remains as a vibrant field of particle physics, in which *many interesting results and surprises may lay ahead*

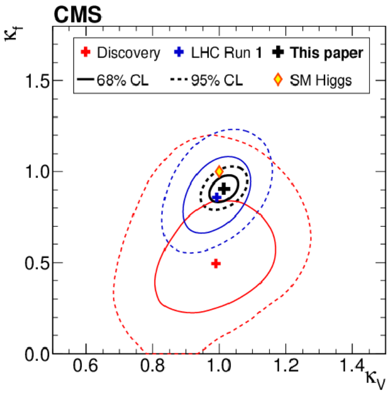
Thank you

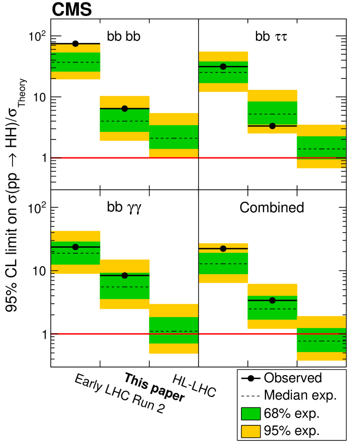
Backup

HL-LHC projections

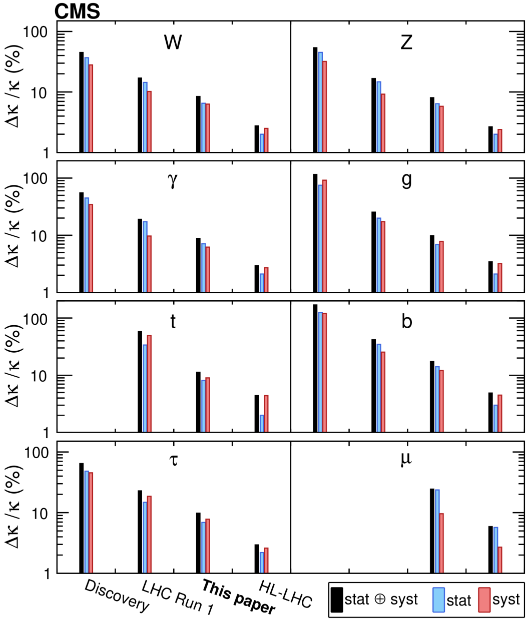
CERN-LPCC-2018-04

Snowmass White Paper
ATL-PHYS-PUB-2022-018
CMS PAS FTR-22-001

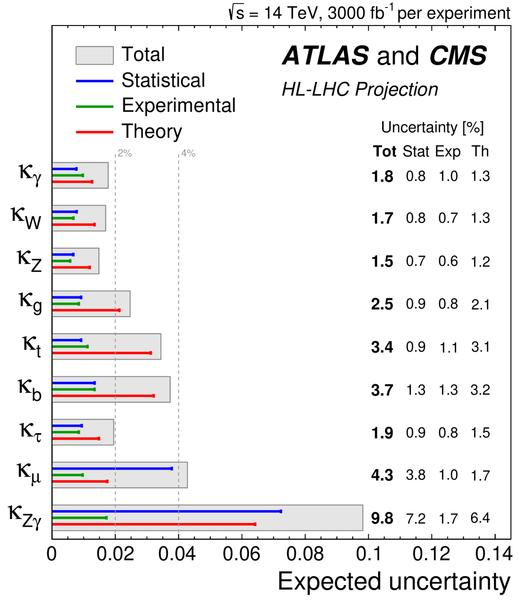




ATLAS + CMS could reach 5σ on SM λ



various scenarios are considered



dominant TH uncertainties expected