

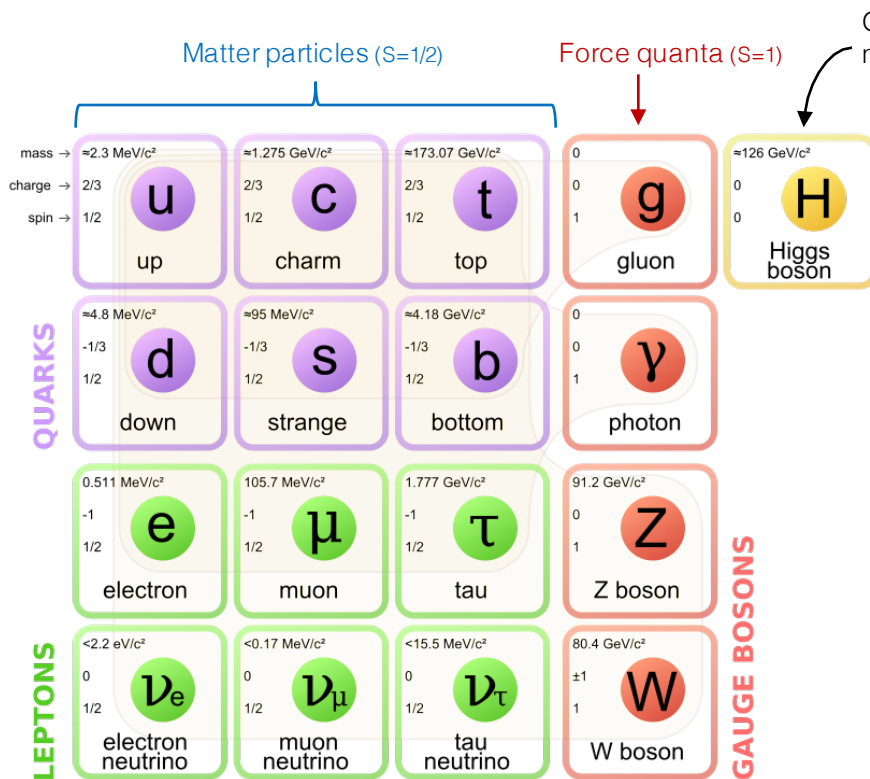
The $H(125)$ boson at the LHC

Andreas Hoecker (CERN)

Pierre Fayet Fest, December 8–9, 2016, ENS, Paris



The Standard Model

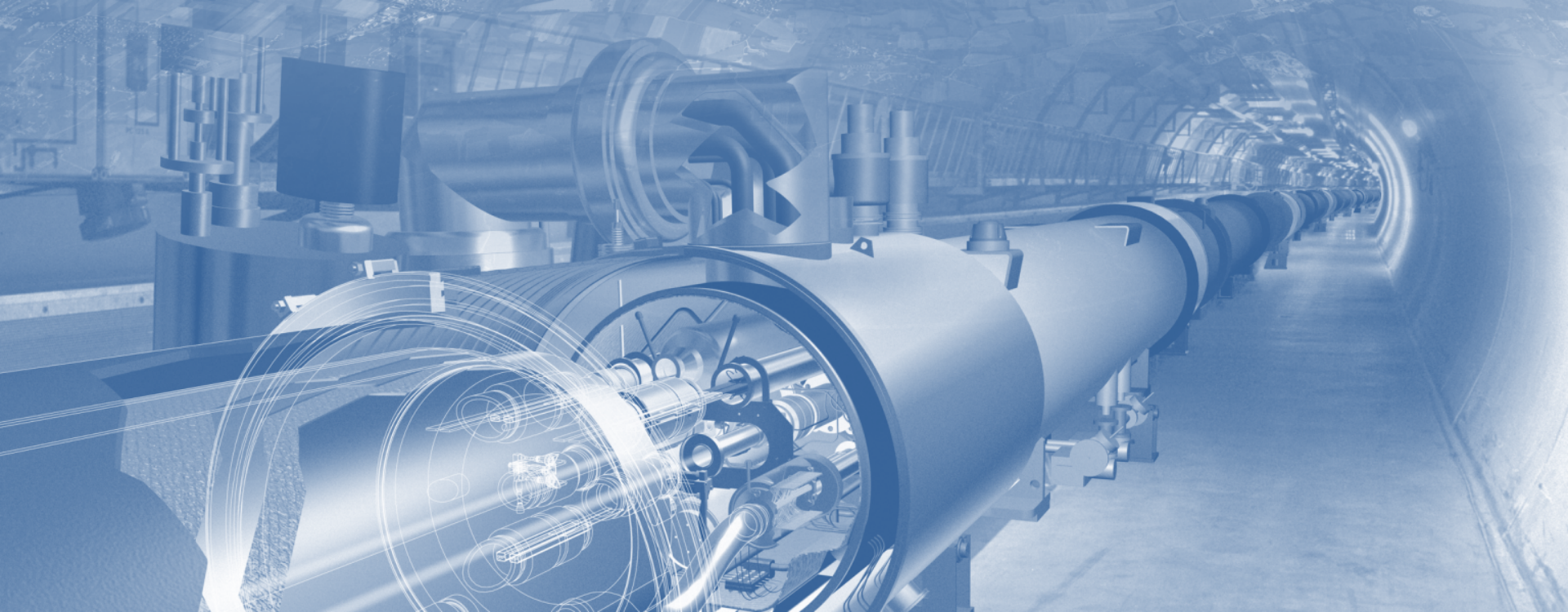


Quite special — only known elementary scalar particle. Product of BEH mechanism required by gauge symmetry and massive bosons and fermions

Tree-level BEH potential at zero temperature:

$$V(\phi) = \mu_{<0}^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

(μ , λ determined once Higgs mass known)



Producing the Higgs boson and searching for new physics
at the TeV scale requires a huge machine

The LHC is a superconducting proton/ion accelerator and collider installed in a 27 km circumference underground tunnel

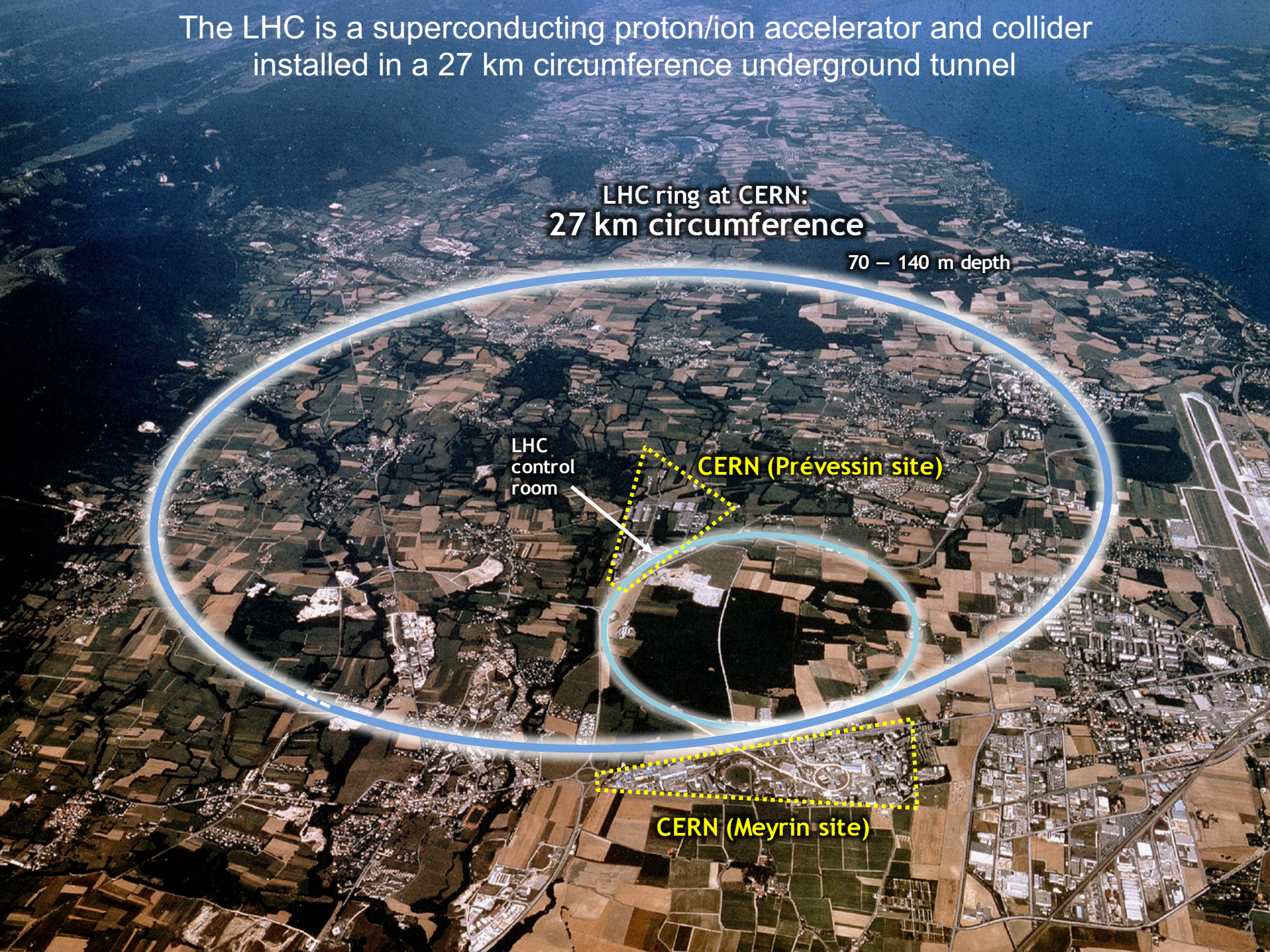
LHC ring at CERN:
27 km circumference

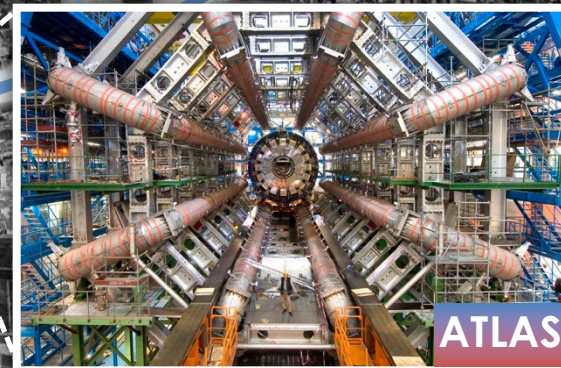
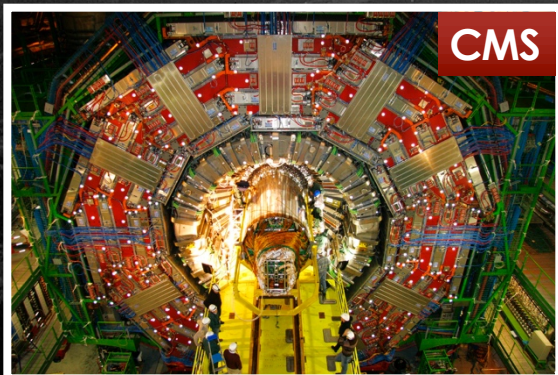
70 – 140 m depth

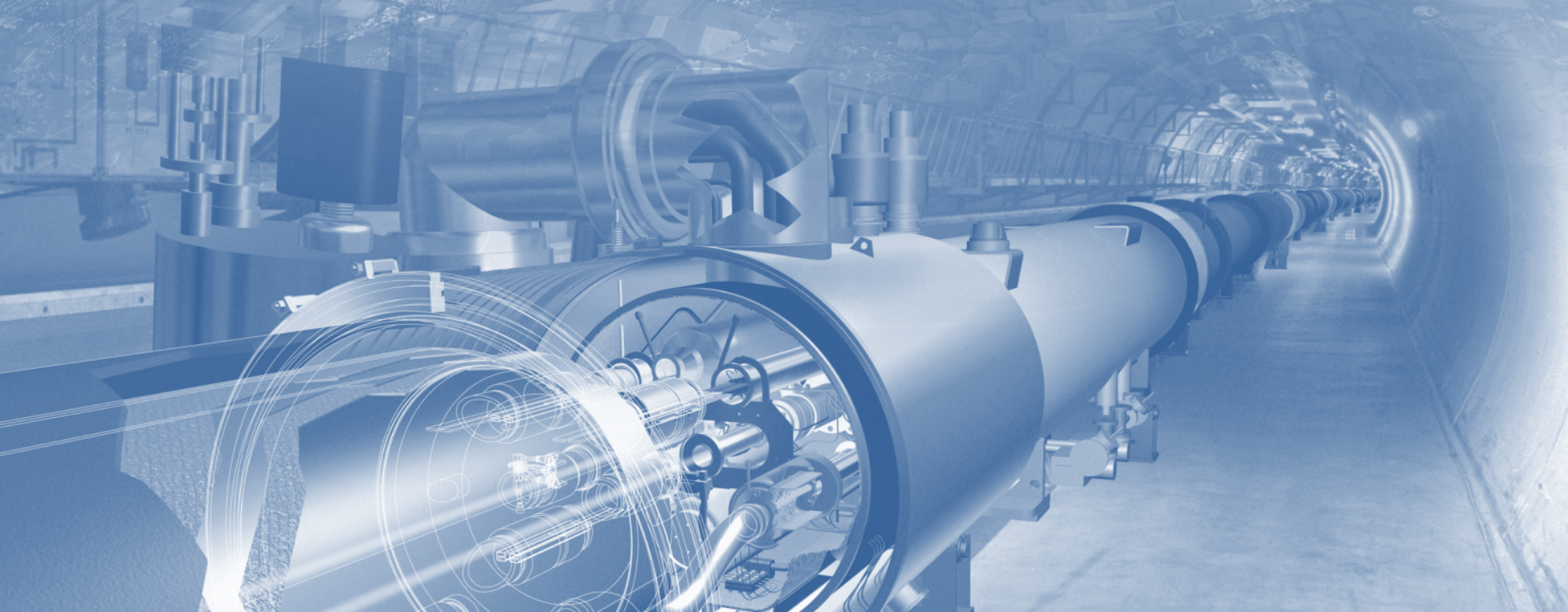
LHC
control
room

CERN (Prévessin site)

CERN (Meyrin site)





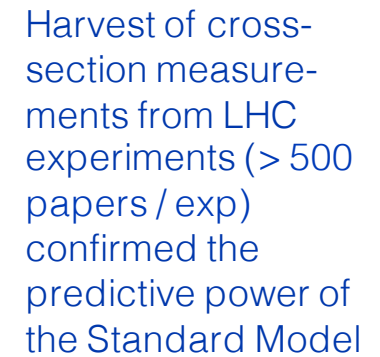


The LHC Run-1: 7 & 8 TeV pp, 5 & 20 fb⁻¹

Higgs boson discovery and first property measurements

Proton-Proton
Collisions

Status: August 2016



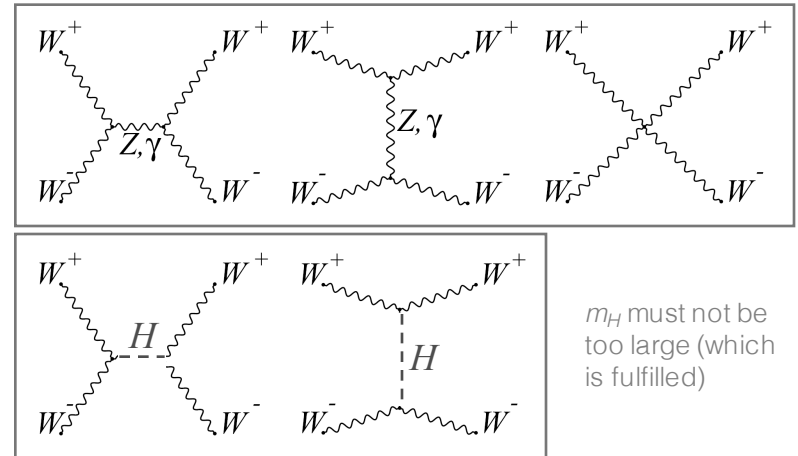
The Higgs boson as moderator

Unitarity: if only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

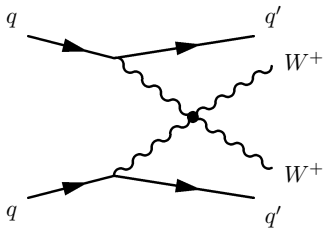
$$A_{Z,\gamma}(W^+ W^- \rightarrow W^+ W^-) \propto \frac{1}{v^2}(s+t)$$

Higgs boson restores unitarity of total amplitude:

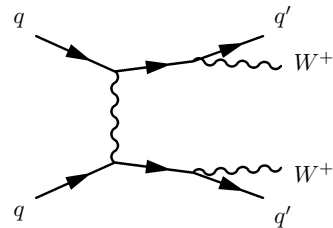
$$A_H(W^+ W^- \rightarrow W^+ W^-) \propto -\frac{m_H^2}{v^2} \left(\frac{s}{s-m_H^2} + \frac{t}{t-m_H^2} \right)$$



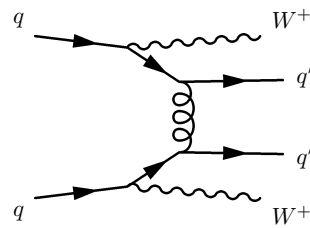
Same-sign WW selection greatly reduces strong production.
Removes s-channel Higgs process:



EW VBS production



Non-VBS production



Strong production

Look for VBS scattering in high dijet invariant mass distributions

The Higgs boson as moderator

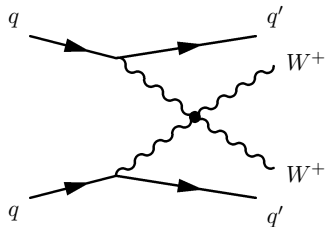
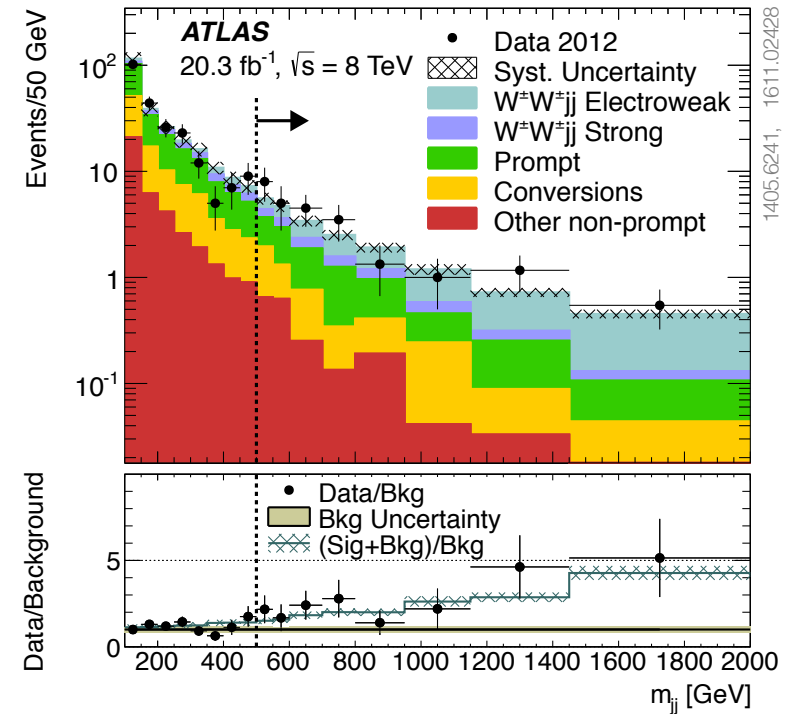
Unitarity: if only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

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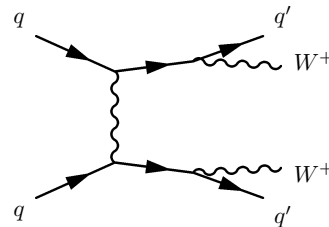
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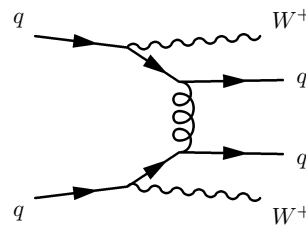
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Removes s-channel Higgs process:



EW VBS production



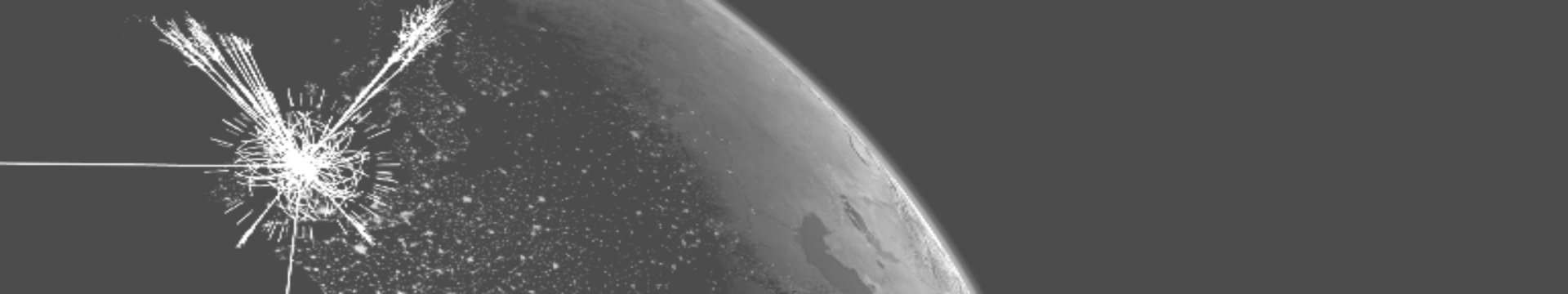
Non-VBS production



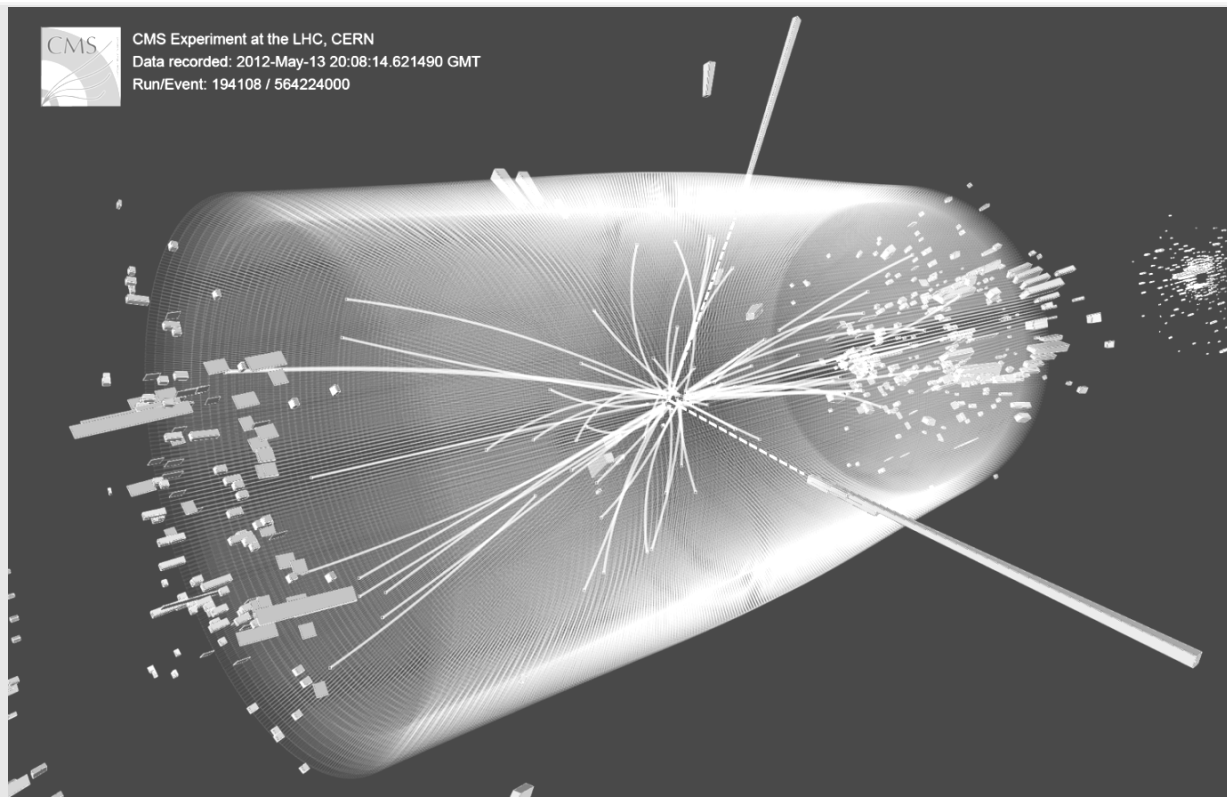
Strong production

Look for VBS scattering in high dijet invariant mass distributions

ATLAS finds 3.6σ evidence for EW production (2.3σ expected)



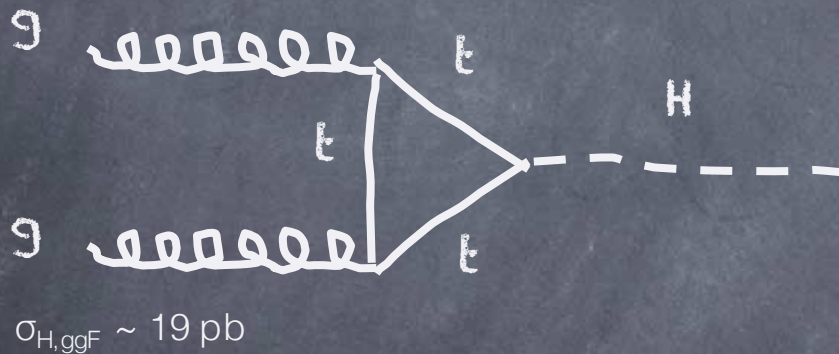
Higgs Boson discovery — Run-1 magnum opus



Higgs boson production at the LHC

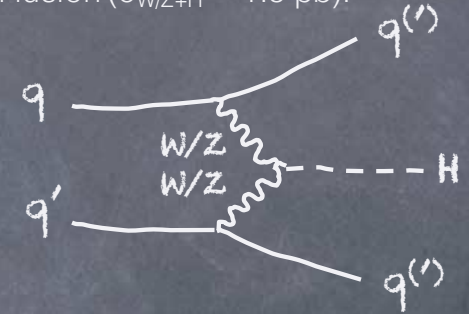
At the LHC, the Higgs boson is dominantly produced via gluon fusion for $\sigma_{H,\text{total}} \sim 22 \text{ pb}$ at 8 TeV for $m_H = 125 \text{ GeV}$

Cross section steeply falling with Higgs mass



Total production of ~470 thousand SM Higgs bosons of 125 GeV in 2012 in each ATLAS and CMS

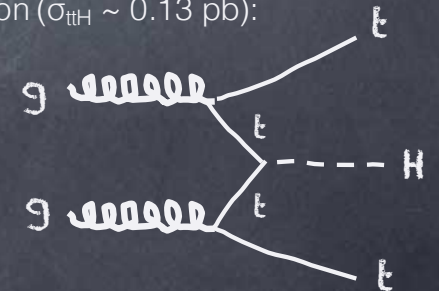
Vector boson fusion ($\sigma_{W/Z+H} \sim 1.6 \text{ pb}$):



Higgs-strahlung ($\sigma_{W/Z+H} \sim 0.7/0.4 \text{ pb}$):



"ttH" production ($\sigma_{ttH} \sim 0.13 \text{ pb}$):

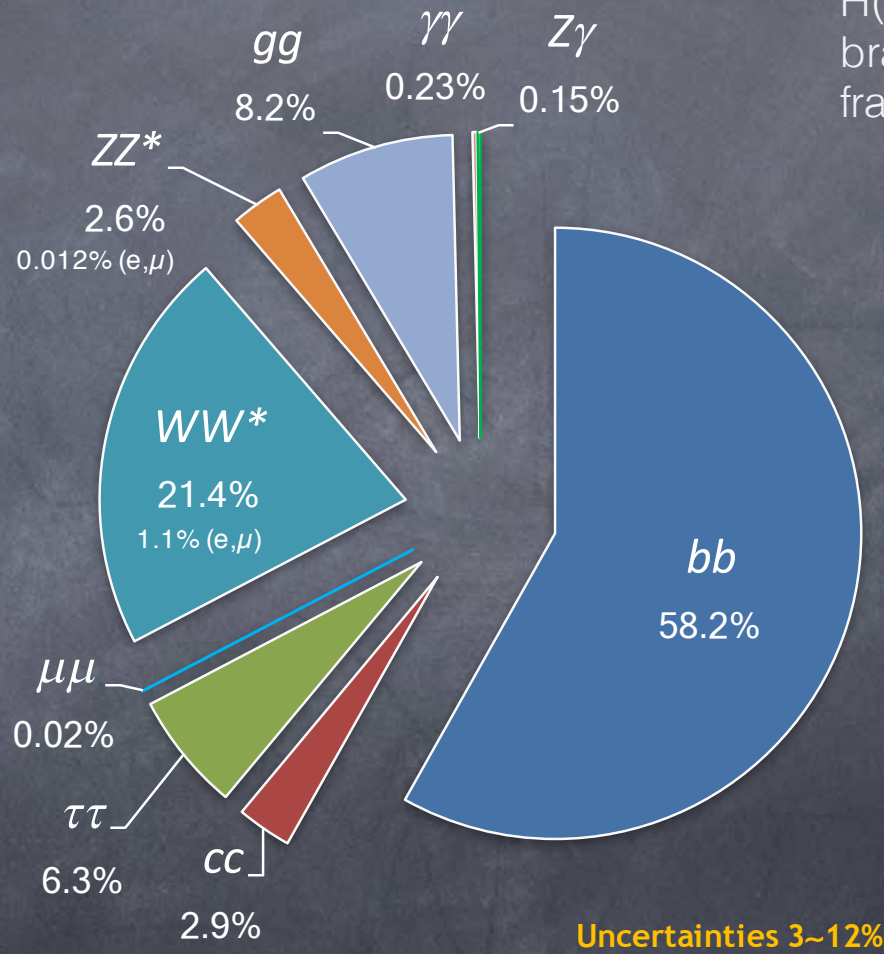


Higgs boson production at the LHC

Because of the coupling to the mass of the decay particles:

... the Higgs will decay with preference to the heaviest particles allowed

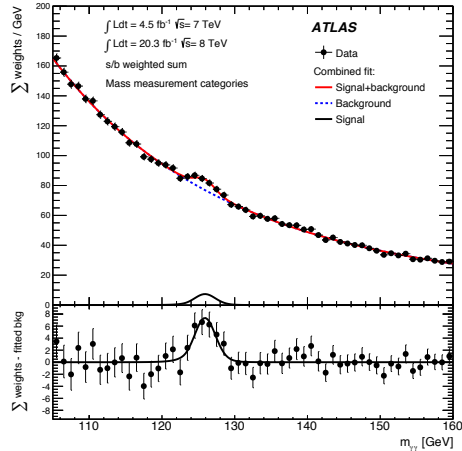
... the Higgs does not couple directly to photons and gluons, but only via “loops” involving preferentially heavy particles (e.g., top, W)



No doubt on H(125) discovery in the bosonic channels

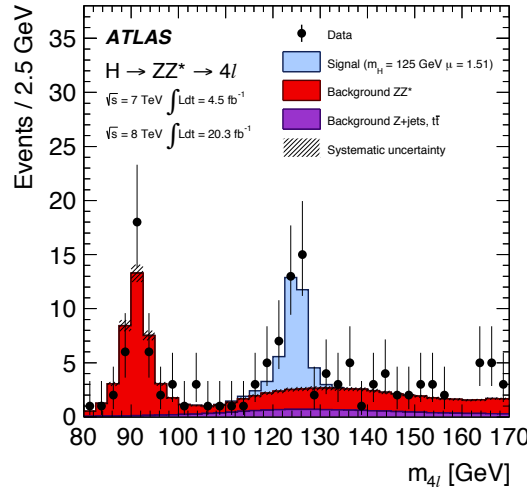
$H \rightarrow \gamma\gamma$

$\sigma(m) \sim 1-2\%$



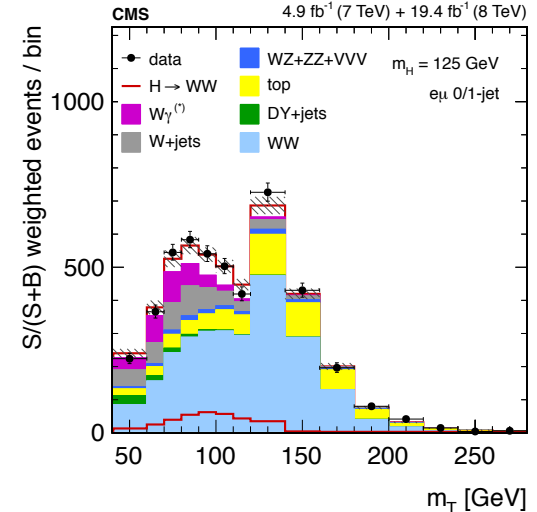
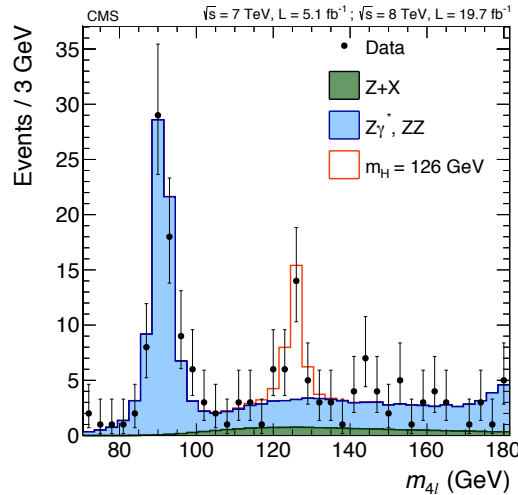
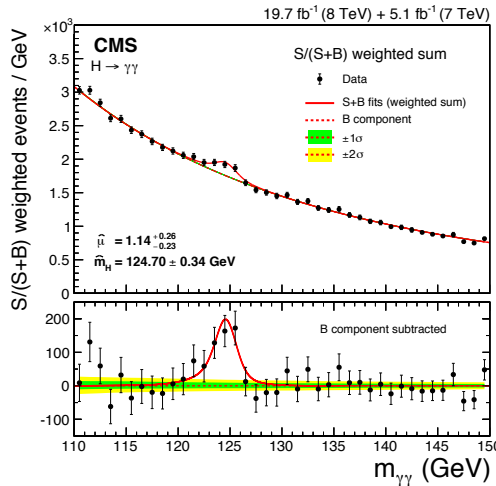
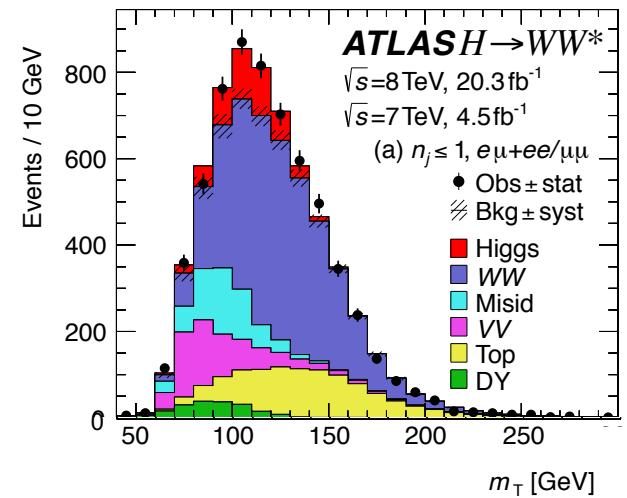
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$

$\sigma(m) \sim 1-2\%$



$H \rightarrow WW^{(*)} \rightarrow 2\ell 2\nu$

$\sigma(m) \sim 20\%$

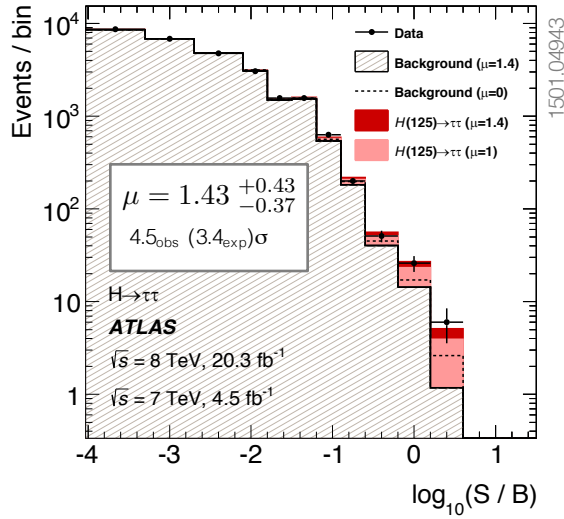


Very different experimental challenges in each of these discovery channels.
All analyses significantly improved since July 2012. Resulting yields agree with SM predictions

Fermionic modes more challenging / use of multivariate methods and complex fits

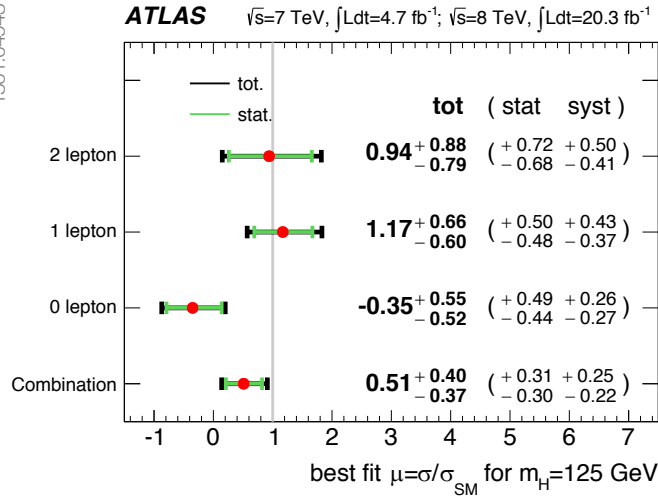
$H \rightarrow \tau\tau$

$\sigma(m) \sim 10\%$

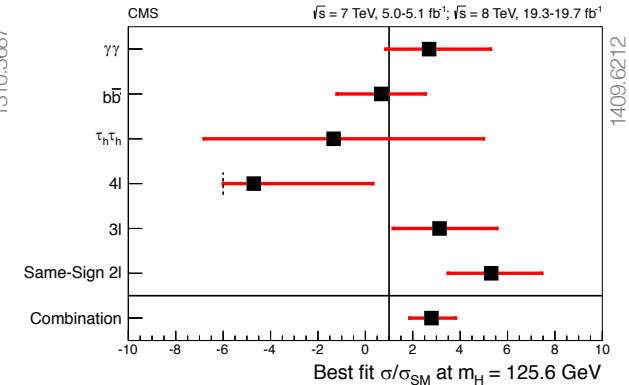
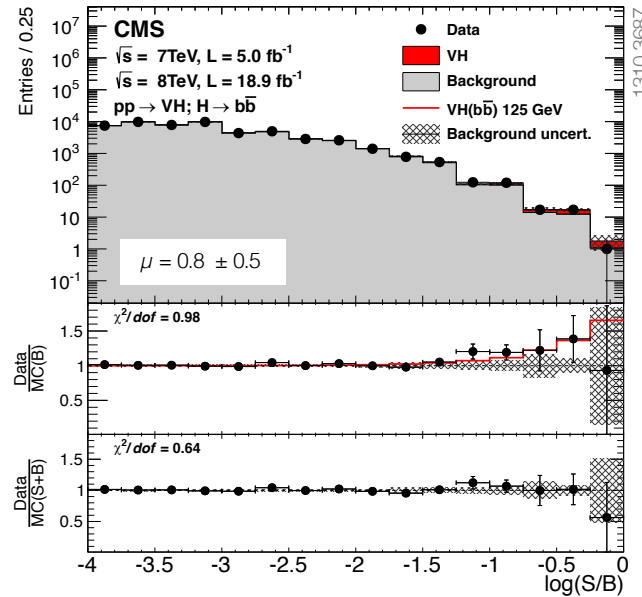
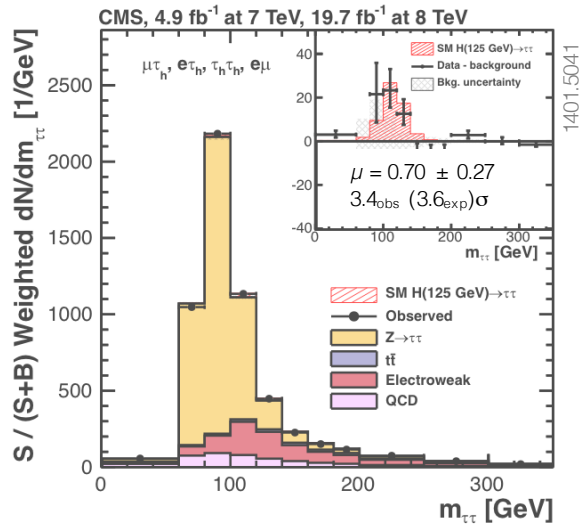
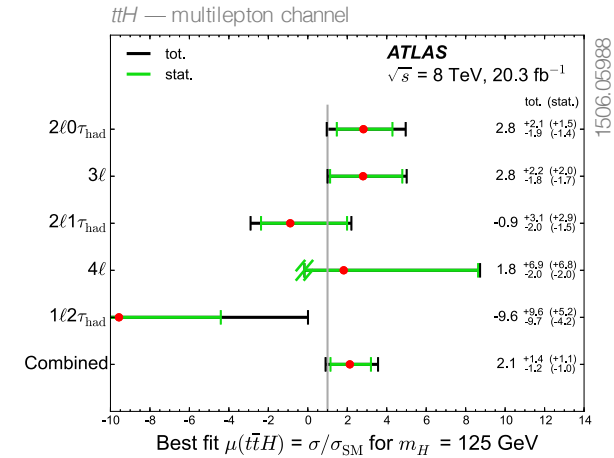


$V(ZW) + H(\rightarrow bb)$

$\sigma(m) \sim 15\%$



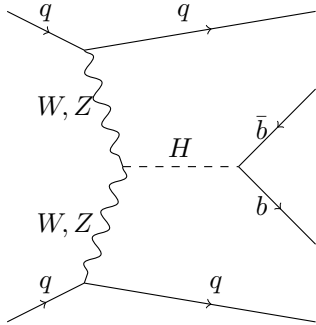
$tt + H(\rightarrow \gamma\gamma, bb, \text{leptons})$



No individual observation yet

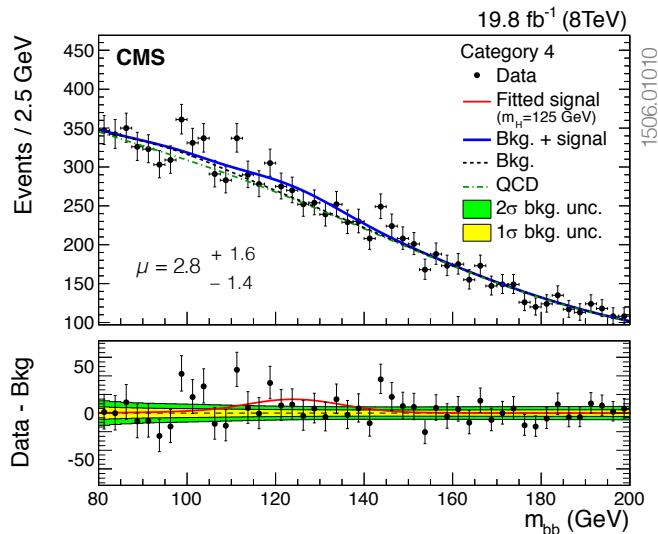
Many additional H(125) analyses and searches / examples only

VBF + H($\rightarrow$ bb)

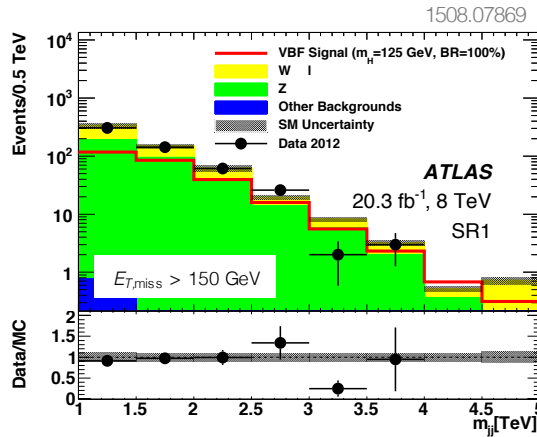


Dedicated hadronic VBF triggers
(~2% signal efficiency)

BDT + m_{bb} mass fit (bump search).
Verification with $Z \rightarrow bb$



VBF + H($\rightarrow$ invisible)



Largest background from $Z(\rightarrow \nu\nu)$
+ 2 jets (strong and EW)

Limit: $\text{BR}(H \rightarrow \text{invisible}) < 28\%$

The Higgs is narrow: 4.1 MeV

For comparison:

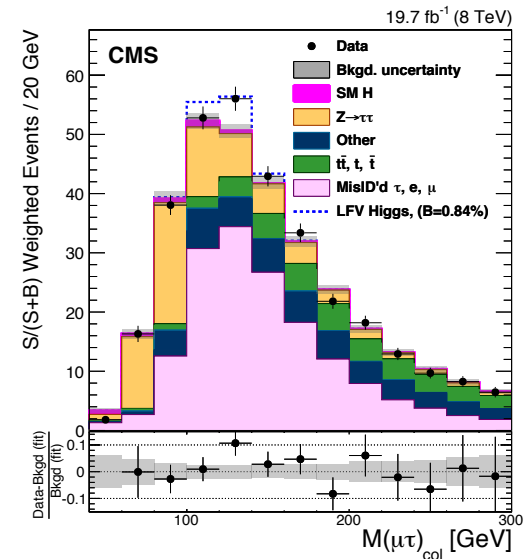
$$\begin{aligned}\Gamma_W &= 2.1 \text{ GeV} \\ \Gamma_Z &= 2.5 \text{ GeV} \\ \Gamma_{\text{top}} &= 1.3 \text{ GeV}\end{aligned}$$

Even small couplings to new light
states can measurably distort
branching fractions

$H \rightarrow \tau\mu$

While $H \rightarrow \mu e$ is severely
constrained from flavour
physics, $H \rightarrow \tau\mu$, τe are not
(~10% limits)

CMS released early 2015 a
 $H \rightarrow \tau\mu$ search finding a slight
(2.4 σ) excess:

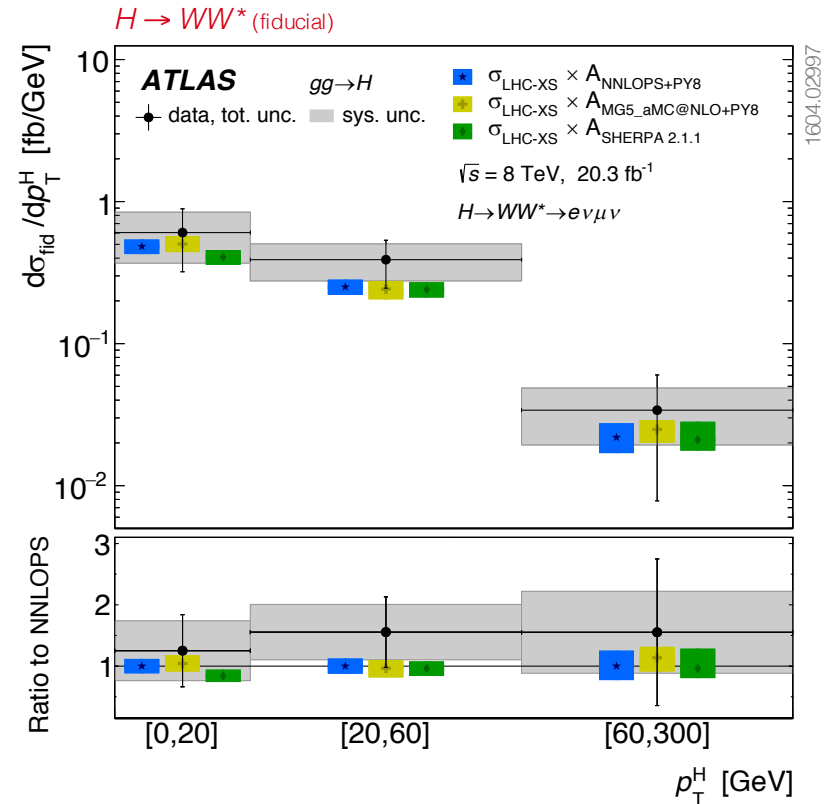
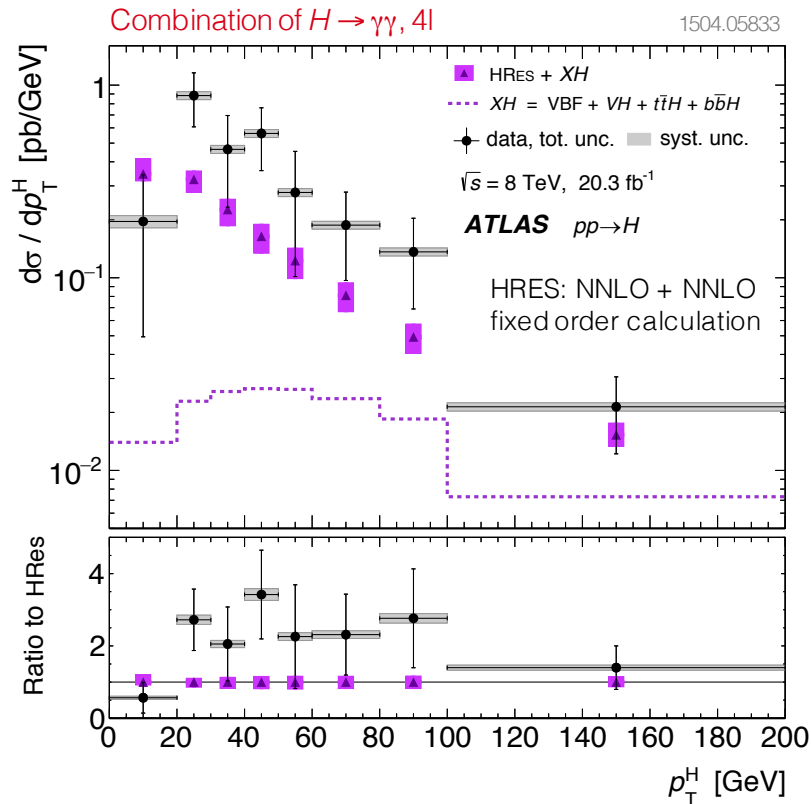


Excess **not** confirmed by
ATLAS in Run-1, neither by
CMS at 13 TeV

Properties of the new H(125)

First Higgs property measurements using Run-1 data

- Spin-parity and CP, FCNC tests
- Constraint on Γ_H via off-shell coupling measurement
- Total, fiducial and differential cross sections



Combined ATLAS & CMS Higgs analysis

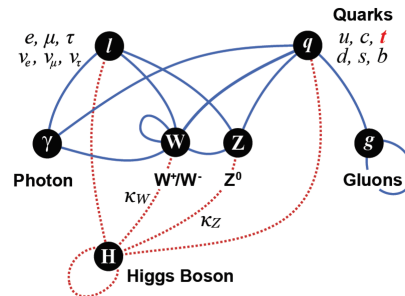
ATLAS & CMS Combinations of Higgs mass and coupling measurements

[1503.07589, 1606.02266]

Precise mass combination (0.2%):

$$m_H = 125.09 \pm 0.21_{\text{stat}} \pm 0.11_{\text{syst}} \text{ GeV}$$

Note that the least model-dependent observables at the LHC are **ratios of couplings**

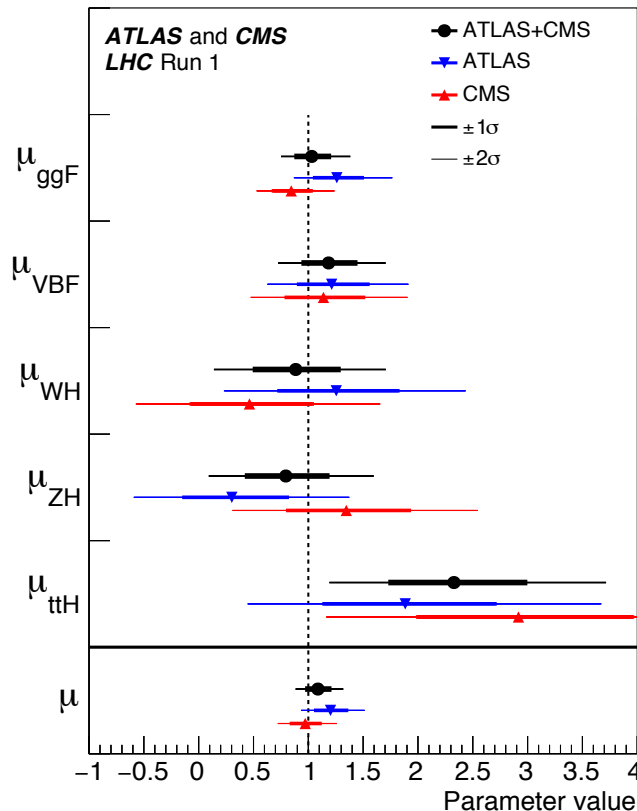


Agreement among experiments

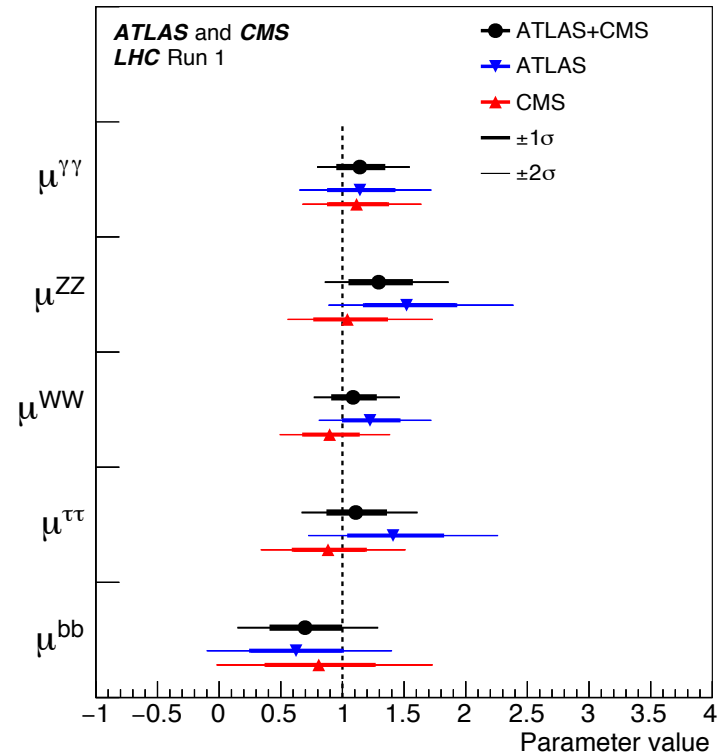
Overall comparison: $\mu = 1.09 \pm 0.11$

Combined **observation of $H \rightarrow \tau\tau$ channel & VBF production**

Higgs production processes



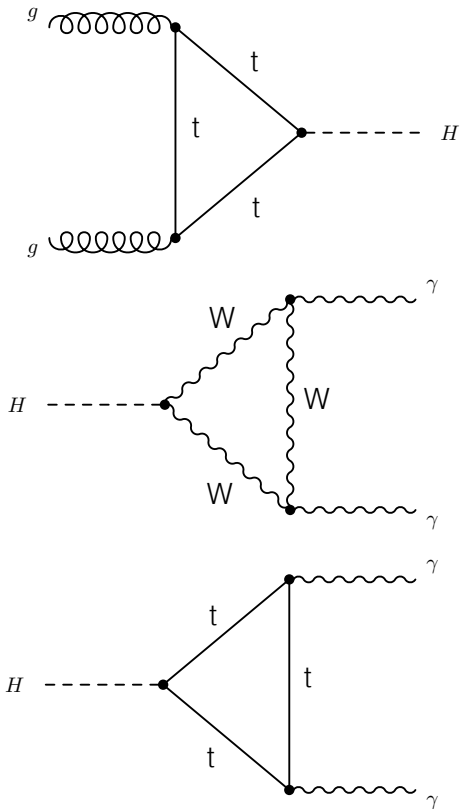
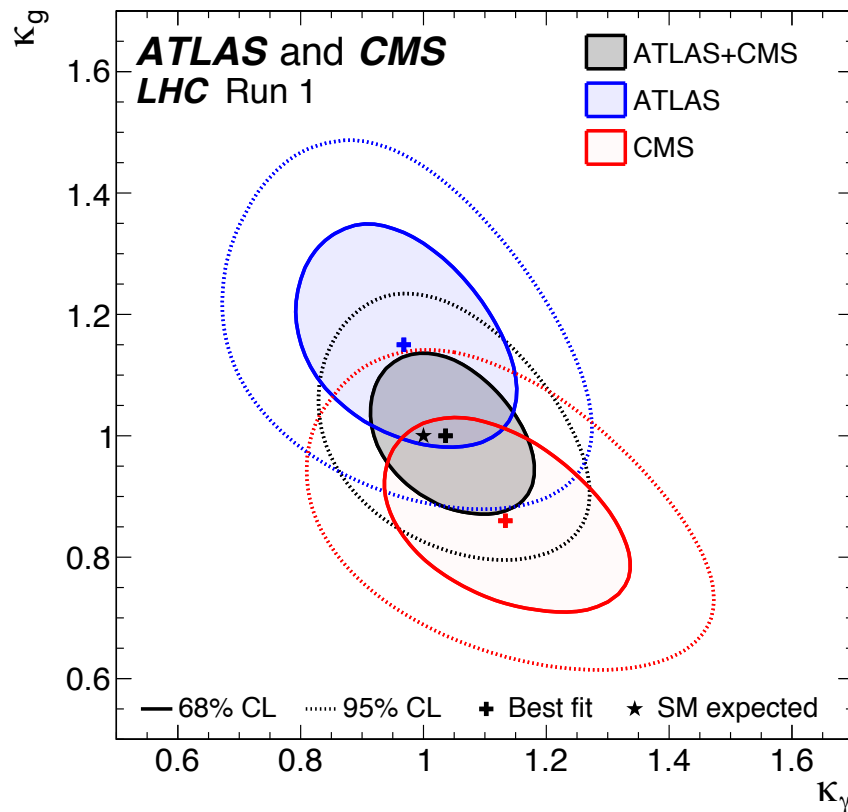
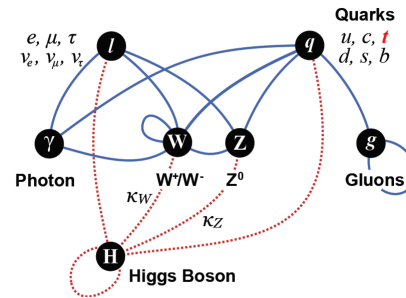
Higgs decay processes



Combined Higgs analysis and a flurry of property measurements

ATLAS & CMS Combinations of Higgs mass and coupling measurements

[1503.07589, 1606.02266]



Couplings to massless particles mediated by loops involving heavy particles

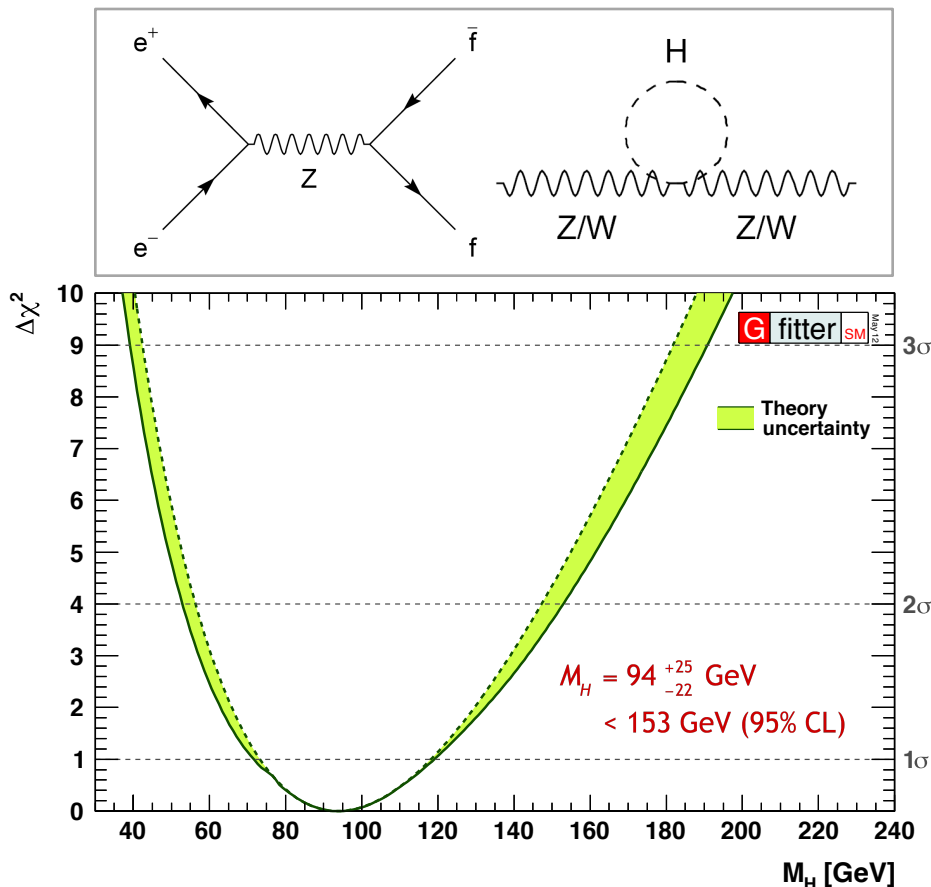
Powerful test for new physics (eg, excludes SM-like heavy 4th fermion generation)

What was known about the Higgs (mass) before the LHC ?

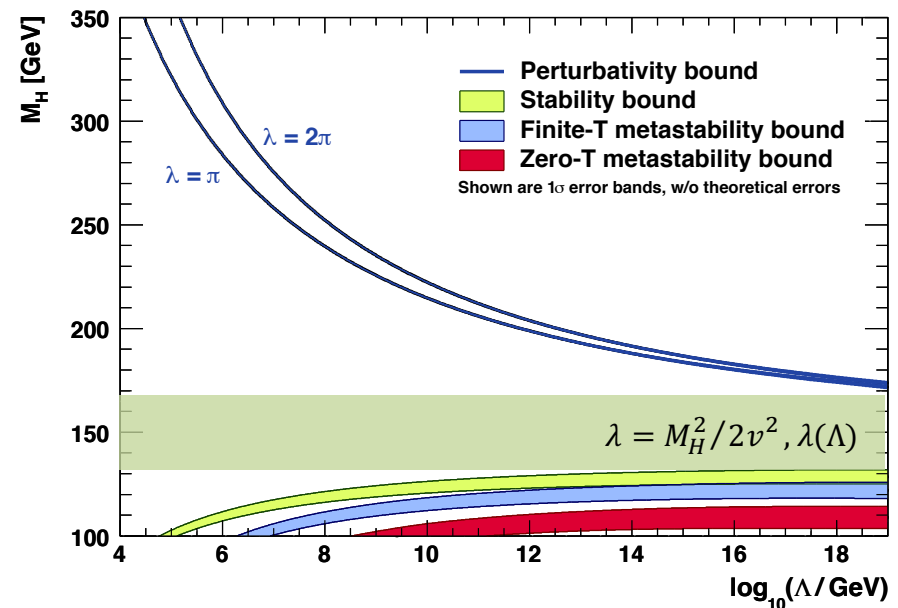
Direct searches at LEP excluded: $m_H < 114.4$ GeV | Tevatron: excluded $m_H \sim 160$ GeV

Today's Tevatron exclusion (2013): $149 < m_H < 182$ GeV

Constraint from SM fit to EW precision data:



Perturbativity and stability bounds for high SM cut-off scale Λ :

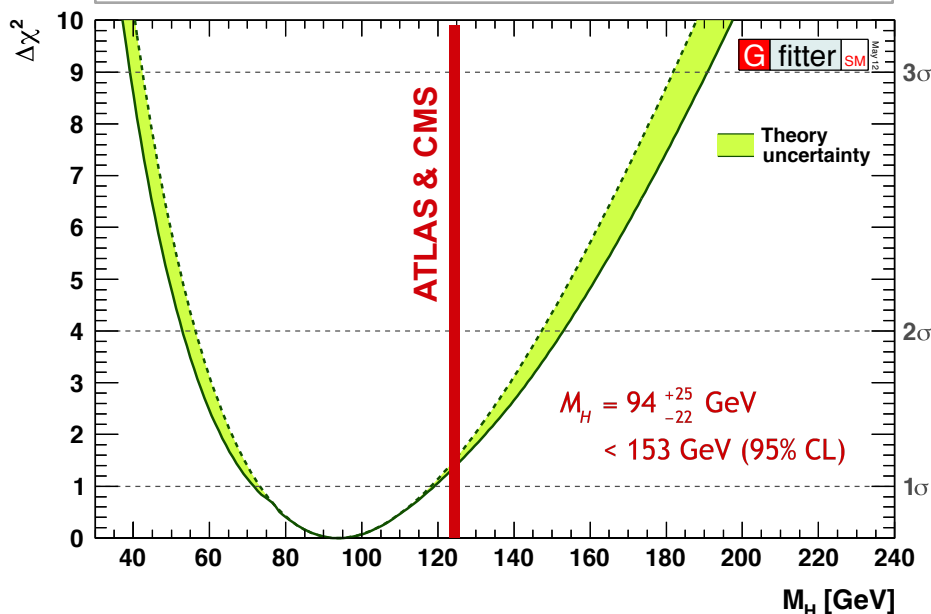
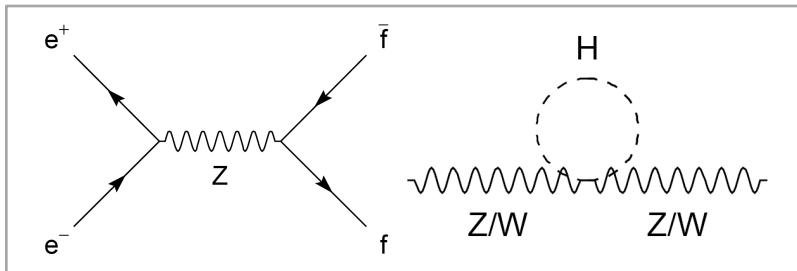


Agreement of observation with prior constraints

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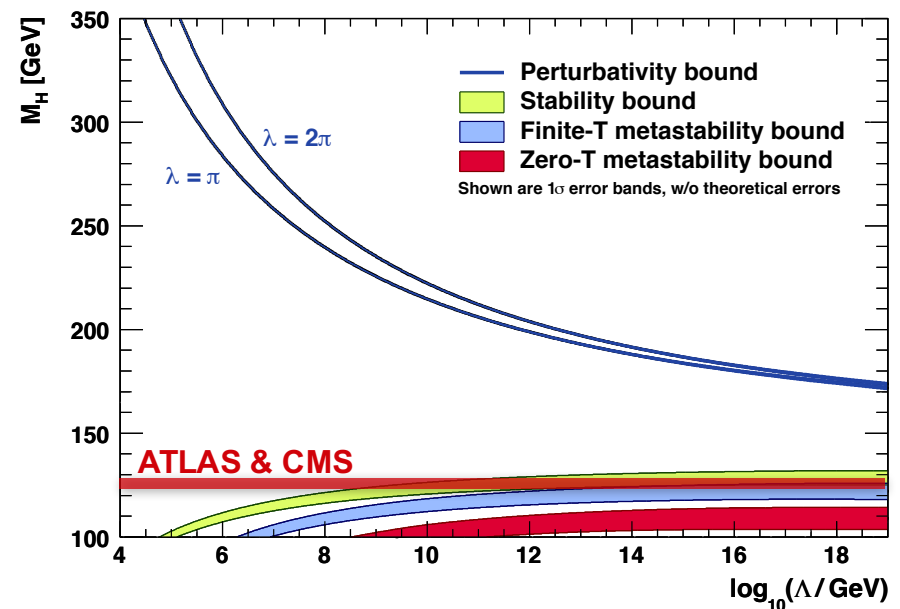
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ATLAS & CMS:

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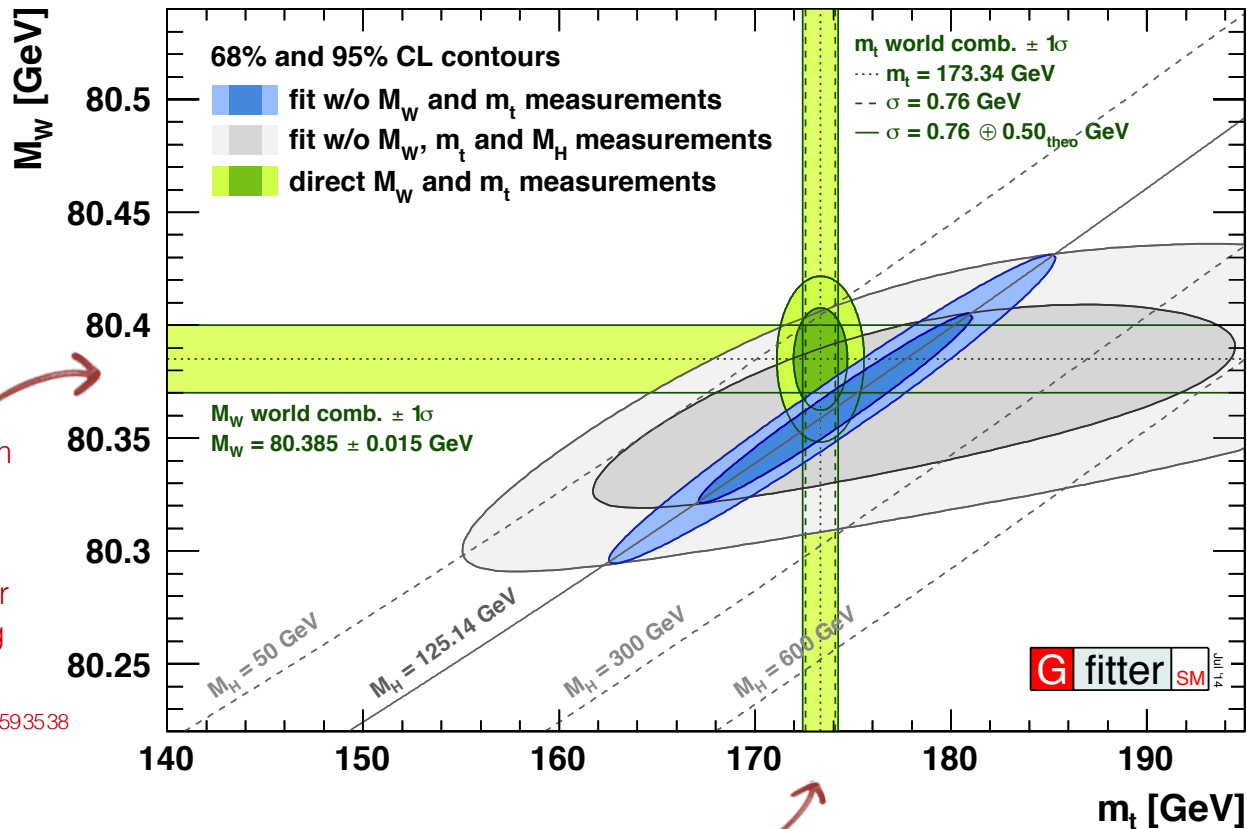
Perturbativity and stability bounds for high SM cut-off scale Λ :



Global fit to electroweak precision data

Global electroweak fit was masterpiece of LEP/SLD era.

Discovery of Higgs over-constrains the fit and dramatically improves predictability



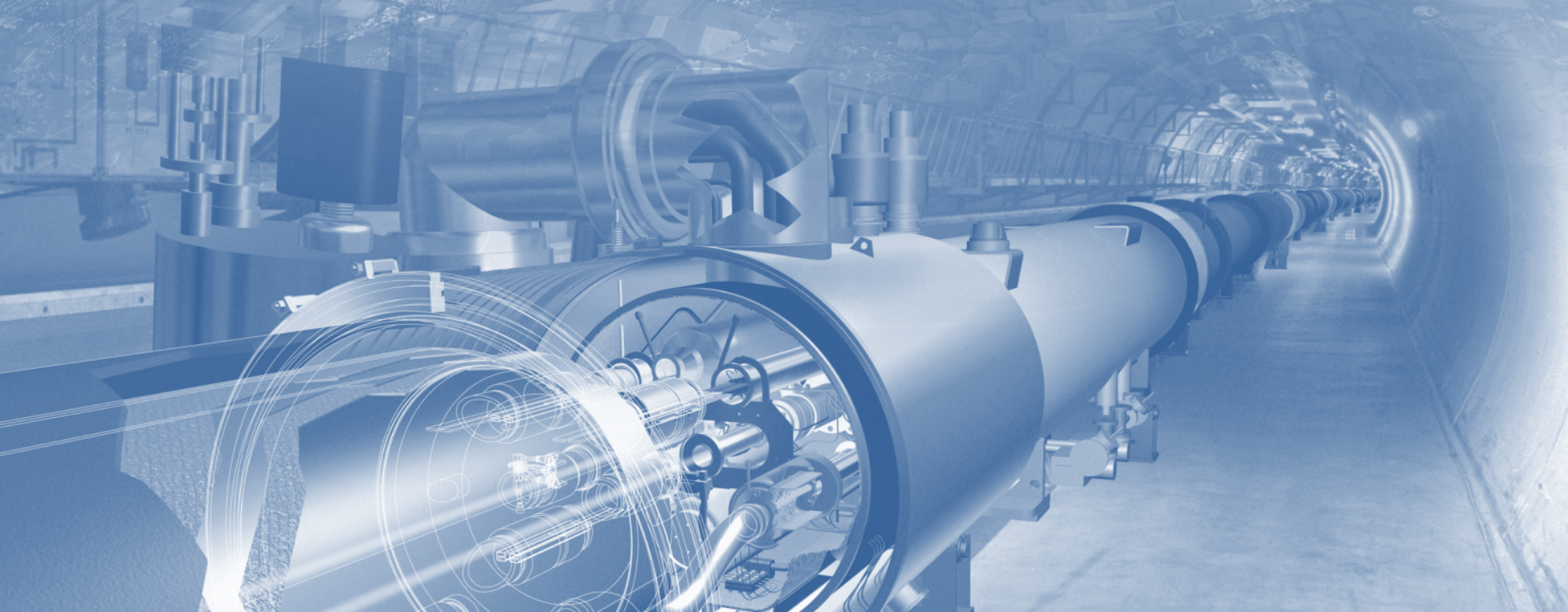
No W mass measurement from LHC just yet ...

But please follow the CERN seminar by ALTAS coming Tuesday, 11:00

<https://indico.cern.ch/event/593538>

Competitive top mass results from the LHC

Best current results: $172.44 \pm 0.13 \pm 0.47$ GeV (CMS, 1509.04044),
 $172.84 \pm 0.34 \pm 0.61$ GeV (ATLAS, 1606.02179, not yet all 8 TeV)



The LHC Run-2: 13 TeV pp collisions

Higgs boson re-observation and much more to come

Higgs re-observation at 13 TeV

13/8 TeV cross section ratios of 2~2.4 for VH, ggH, VBF, and 3.9 for ttH

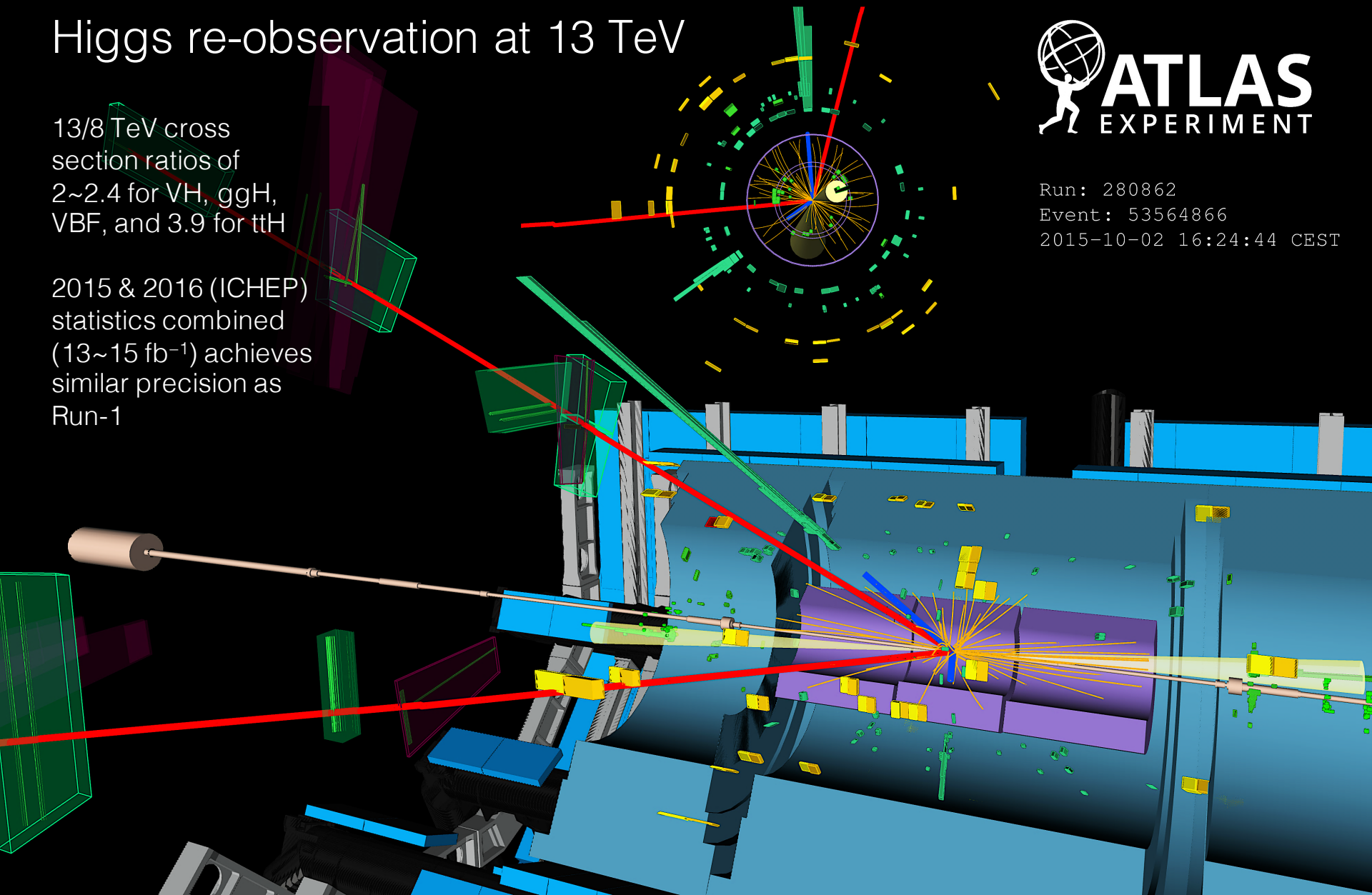
2015 & 2016 (ICHEP) statistics combined ($13\sim 15\text{ fb}^{-1}$) achieves similar precision as Run-1



Run: 280862

Event: 53564866

2015-10-02 16:24:44 CEST

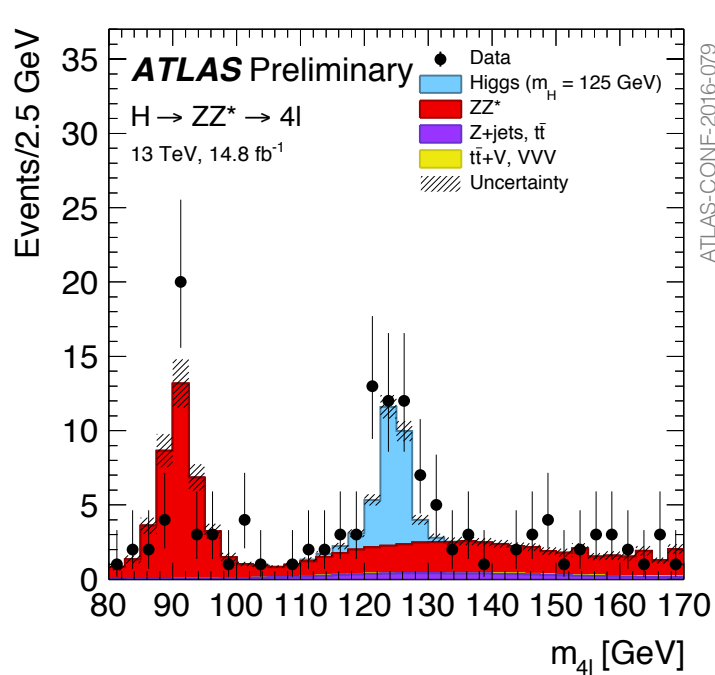


Display of VBF $H \rightarrow e\bar{e}\mu\mu + 2\text{jets}$ candidate from 13 TeV pp collisions. The electrons have a transverse momentum of 111 and 16 GeV, the muons 18 and 17 GeV, and the jets 118 and 54 GeV. The invariant mass of the four lepton system is 129 GeV, the dielectron (dimuon) invariant mass is 91 (29) GeV, the pseudorapidity difference between the two jets is 6.4 and the dijet invariant mass is 2 TeV.

Clear Higgs observation of at 13 TeV in bosonic channels

Preliminary fiducial and total cross-section and coupling measurements (ggF and VBF significant)

$H \rightarrow ZZ^* \rightarrow 4\ell$

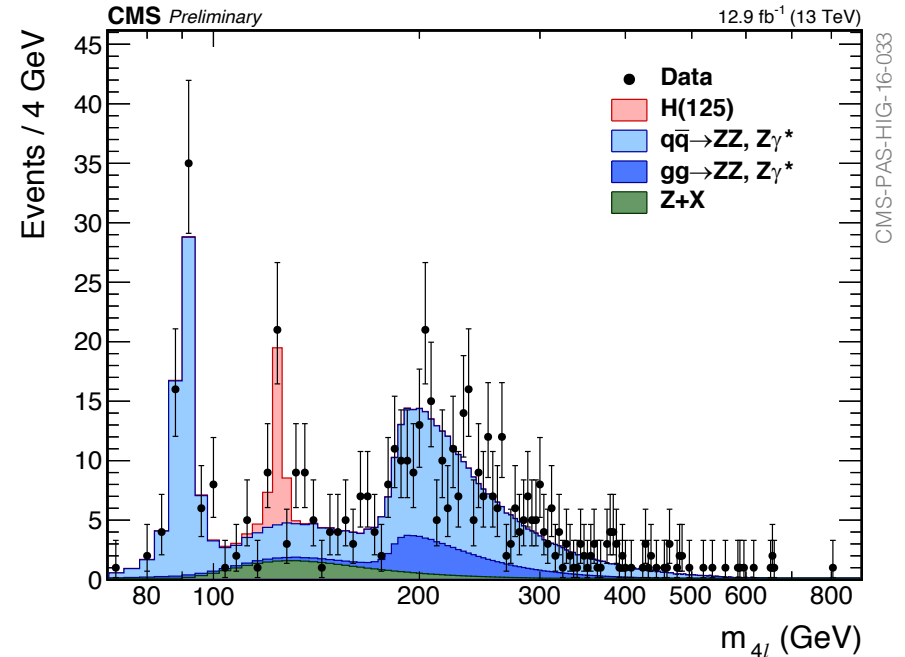


$$\sigma_{\text{tot,data}} = 81^{+18}_{-16} \text{ pb}$$

$$\sigma_{\text{tot,SM}} = 55 \pm 4 \text{ pb}$$

CMS also measured: $m_H = 124.50^{+0.48}_{-0.44} \text{ GeV}$

(dominated by statistical uncertainty, compare to $125.09 \pm 0.24 \text{ GeV}$ from ATLAS & CMS Run-1 combination)



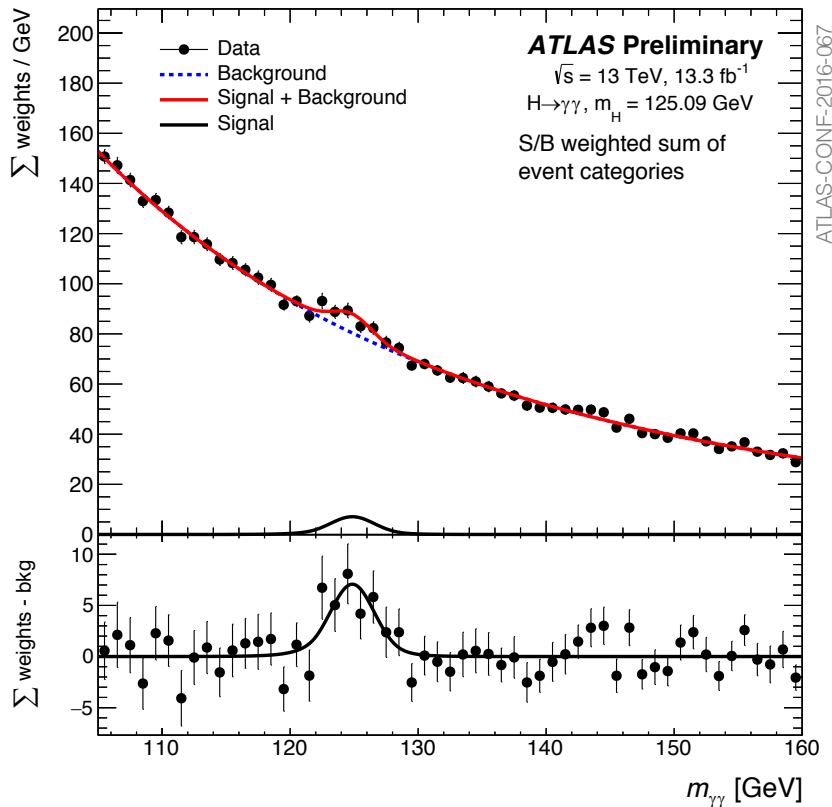
$$\mu = \sigma_{\text{data}} / \sigma_{\text{SM}} = 0.99^{+0.33}_{-0.26}$$

Expected significance (SM): 6.5σ

Clear Higgs observation of at 13 TeV in bosonic channels

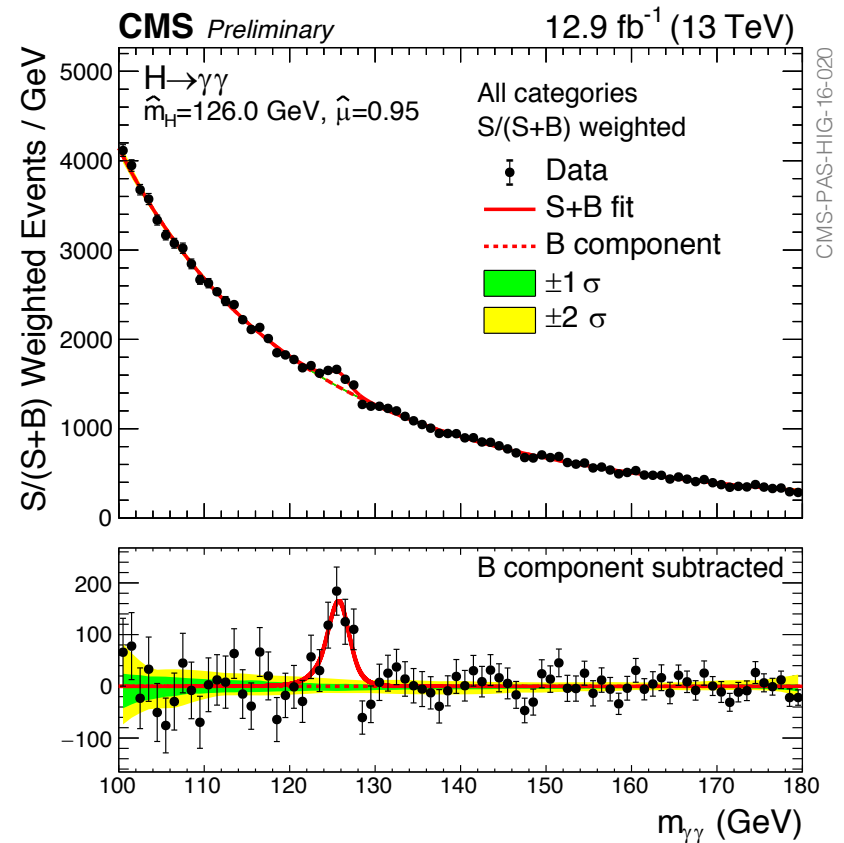
Preliminary fiducial and total cross-section and coupling measurements (ggF and VBF significant)

$H \rightarrow \gamma\gamma$



$$\mu = 0.85^{+0.22}_{-0.20}$$

Expected significance (SM): 5.4σ



$$\mu = 0.91 \pm 0.20$$

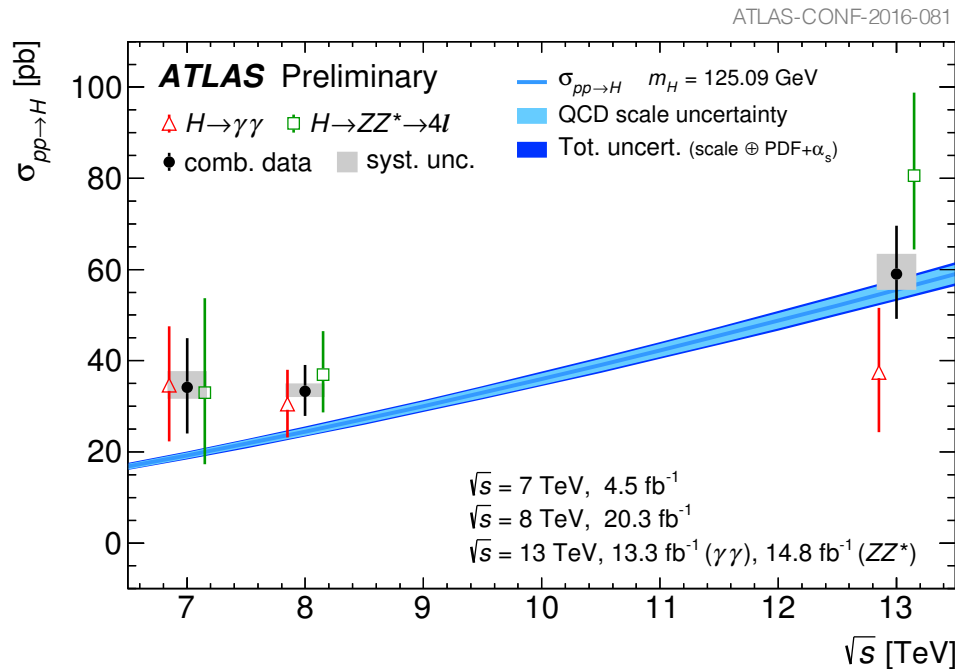
Expected significance (SM): 6.2σ

ATLAS and CMS studied H(125) in bosonic channels

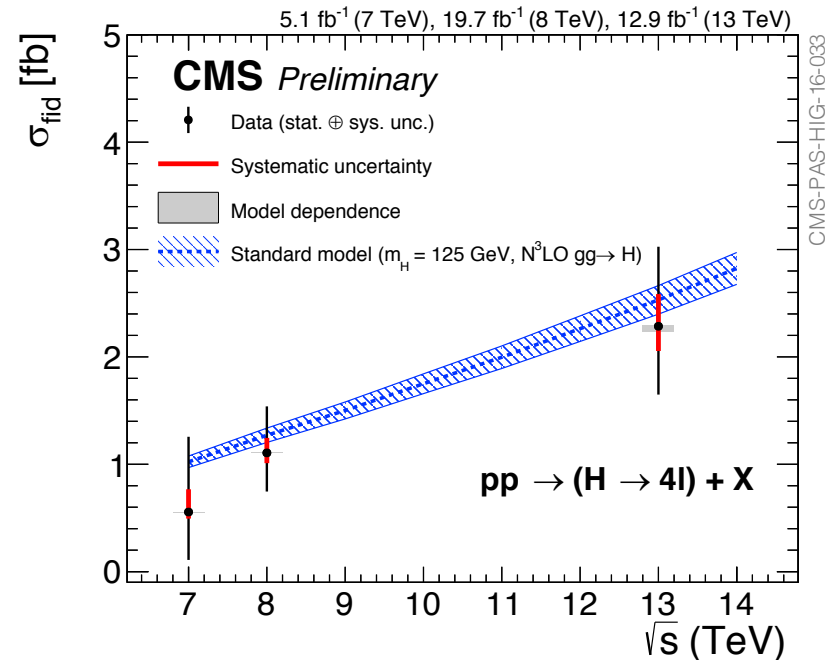
Cross section versus centre-of-mass energy

$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ (left)

Combined $H \rightarrow 4\ell, \gamma\gamma$



$H \rightarrow 4\ell$, *fiducial* cross section

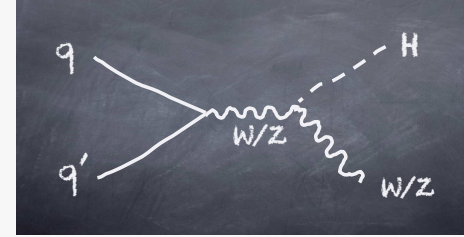


Assuming SM branching fractions and acceptance (left)

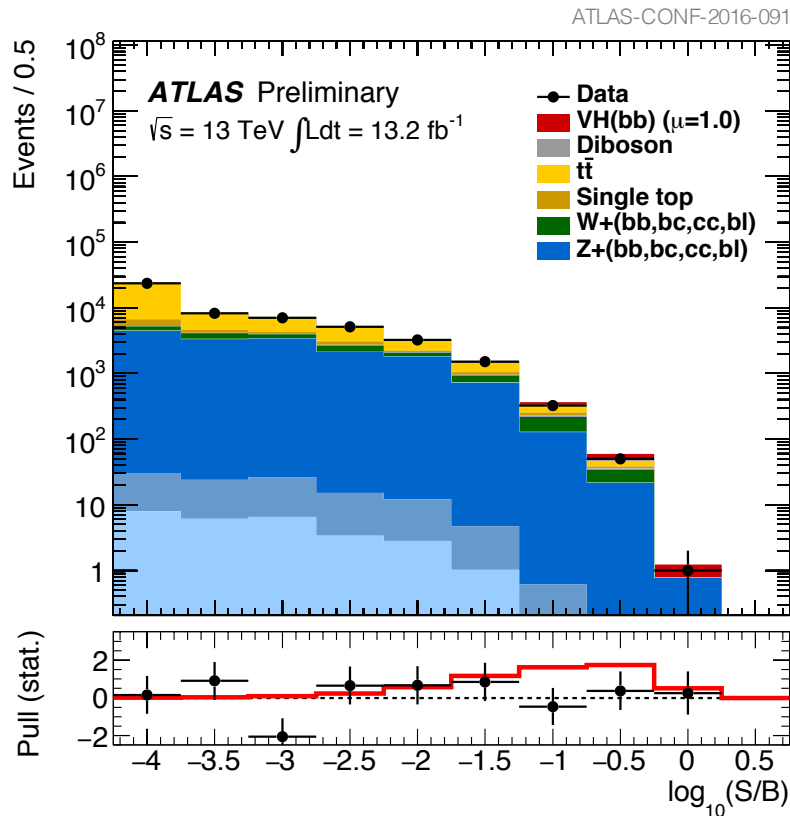
Expected rise of cross-section observed in data

ATLAS studied H(125) in bb decay channel

Associated production, challenging final states



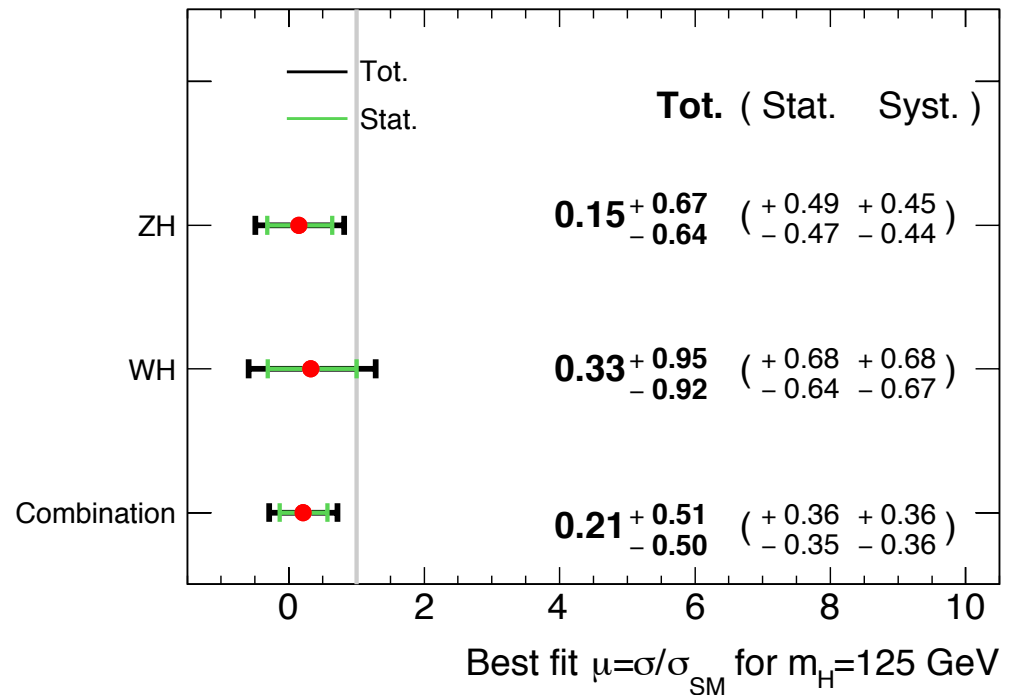
$W/Z + H \rightarrow \ell\nu / \ell^+\ell^-, \nu\nu + bb$



Powerful cross-check
 with $V+Z(\rightarrow bb)$:

$$\mu = 0.91 \pm 0.17^{+0.32}_{-0.27}$$

ATLAS Preliminary $\sqrt{s}=13 \text{ TeV}$, $\int \mathcal{L} dt = 13.2 \text{ fb}^{-1}$



Slightly lower yield than SM, similar for Run-1
 ($\mu = 0.7 \pm 0.3$ for ATLAS & CMS, $\mu = 0.5 \pm 0.4$ for ATLAS)

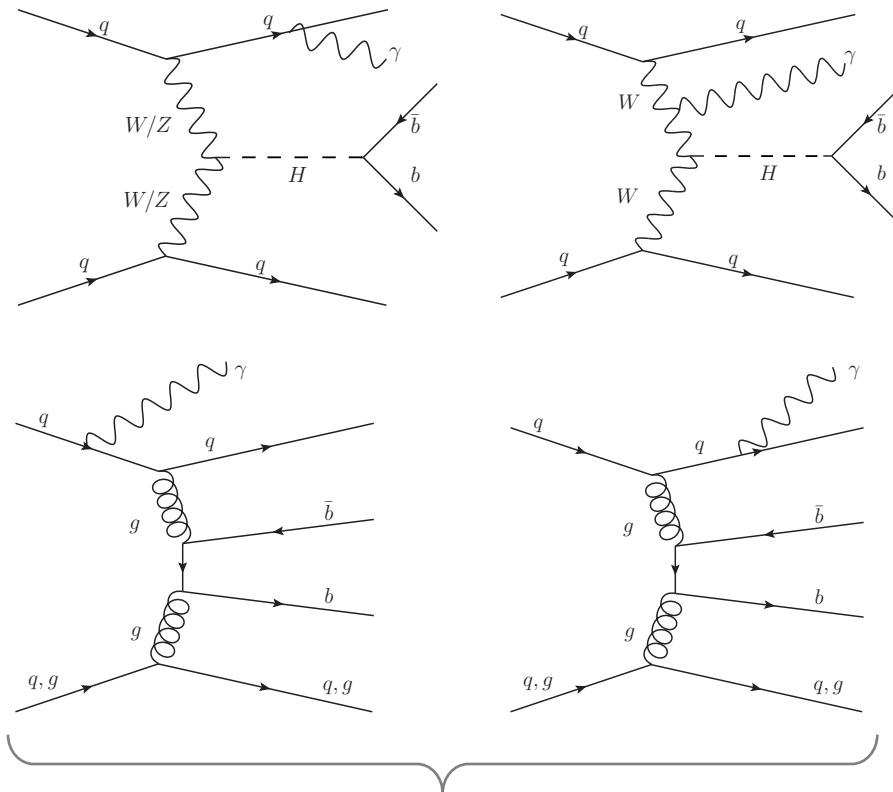
ATLAS studied H(125) in bb decay channel

Looked also for VBF + H(bb) events with high-energetic photon!

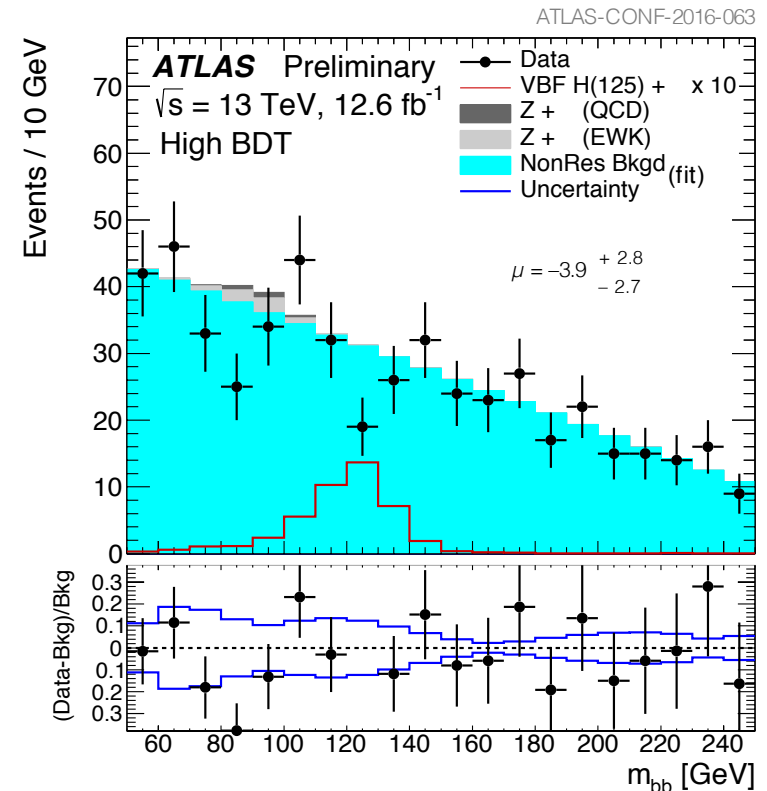
Following idea by E. Gabrielle et al., hep-ph/0702119

VBF + H ($\rightarrow$ bb) + γ ($E_T > 30$ GeV)

Uses dedicated photon+VBF trigger. Background reduction by >10 over α_{QED} owing to suppression of gluon production of $bbq\bar{q}\gamma$ and destructive interference between continuum ISR/FSR γ amplitudes



Interfere destructively



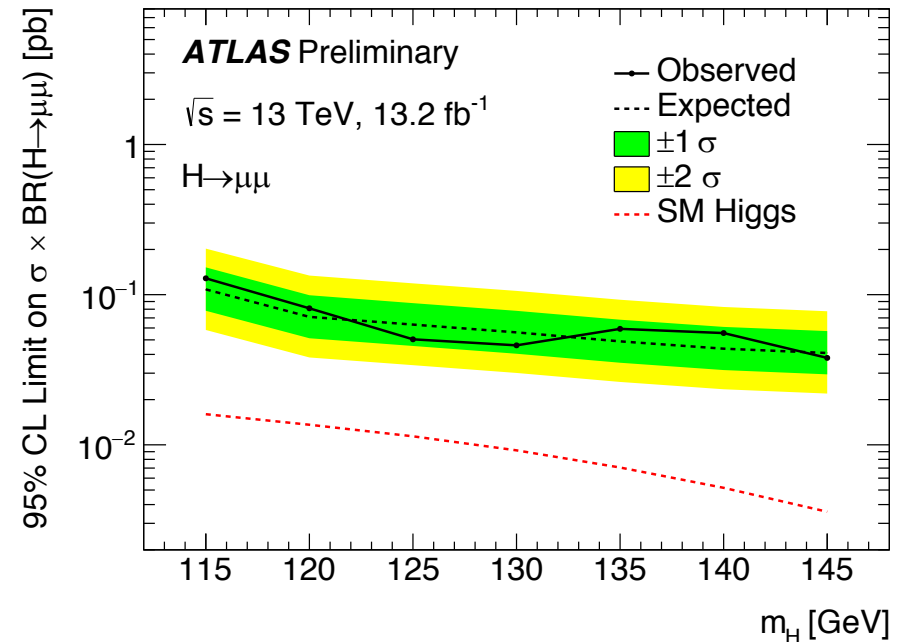
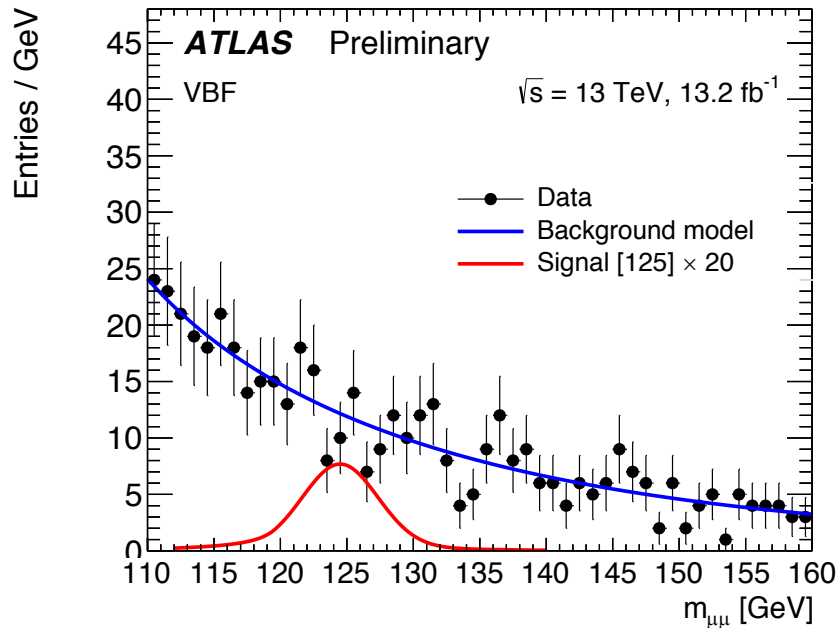
$\mu < 4.0$ (expected: < 6.3) at 95% CL

Searches for rare Higgs decays

Beyond SM reach at present, but could have new physics contributions ?

$H \rightarrow \mu\mu$ [expected branching fraction: 0.02%]

Strongly resolution dependent, improve sensitivity by categorising events (low/high p_T , central/forward, VBF)



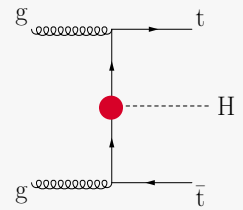
Observed limit 4.4 times SM (3.5 combined with Run-1). Need about 300 fb^{-1} of data to reach SM

Can already exclude universal Higgs coupling to fermions !

(Would have observed $H \rightarrow \mu\mu$, if same BR as $H \rightarrow \tau\tau$)

First search for ttH production at 13 TeV by CMS

Direct measurement of Higgs–top coupling



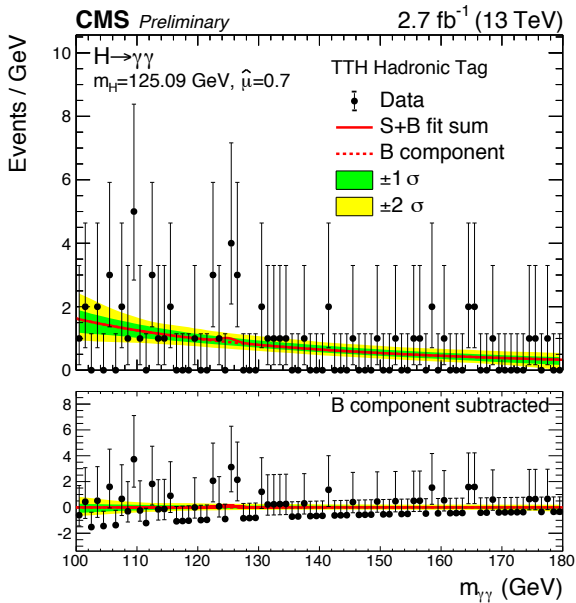
CMS showed preliminary results for ttH in all major Higgs decay channels: **H** → **γγ**, **multi-leptons**, **bb**

Highly complex analyses, huge effort to get these done so quickly after data taking (already by Moriond 2016)

H → **γγ**,
tt → 0 & 1 leptons

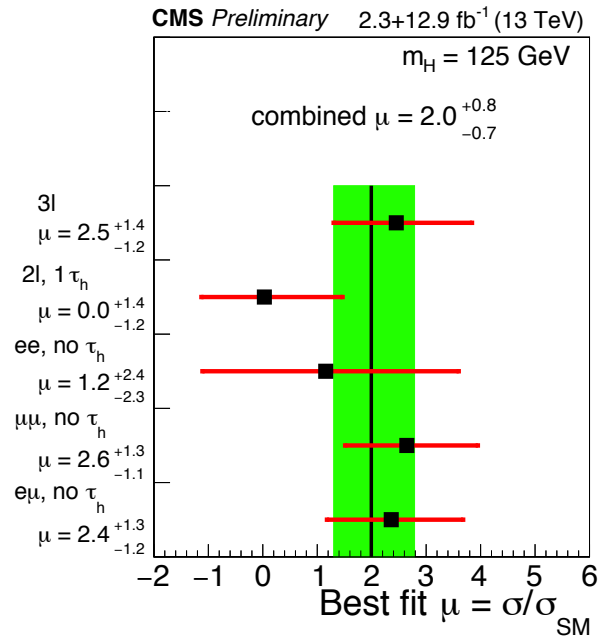
ttH → **multi-leptons**
2 same charge (+ τ) / 3 leptons

H → **bb**
tt → 1 & 2 leptons



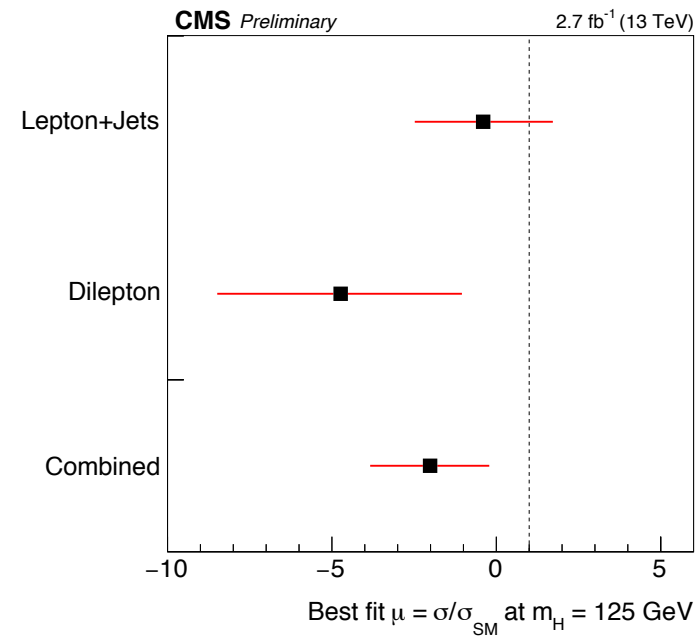
$$\mu = 3.8^{+4.5}_{-3.6}$$

CMS-PAS-HIG-15-005



$$\mu = 2.0^{+0.8}_{-0.7}$$

CMS-PAS-HIG-16-022

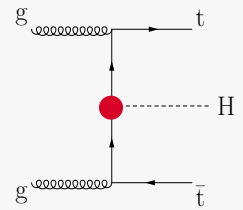


$$\mu = -2.0 \pm 1.8 < 2.6 \text{ (95\% CL)}$$

CMS-PAS-HIG-16-004

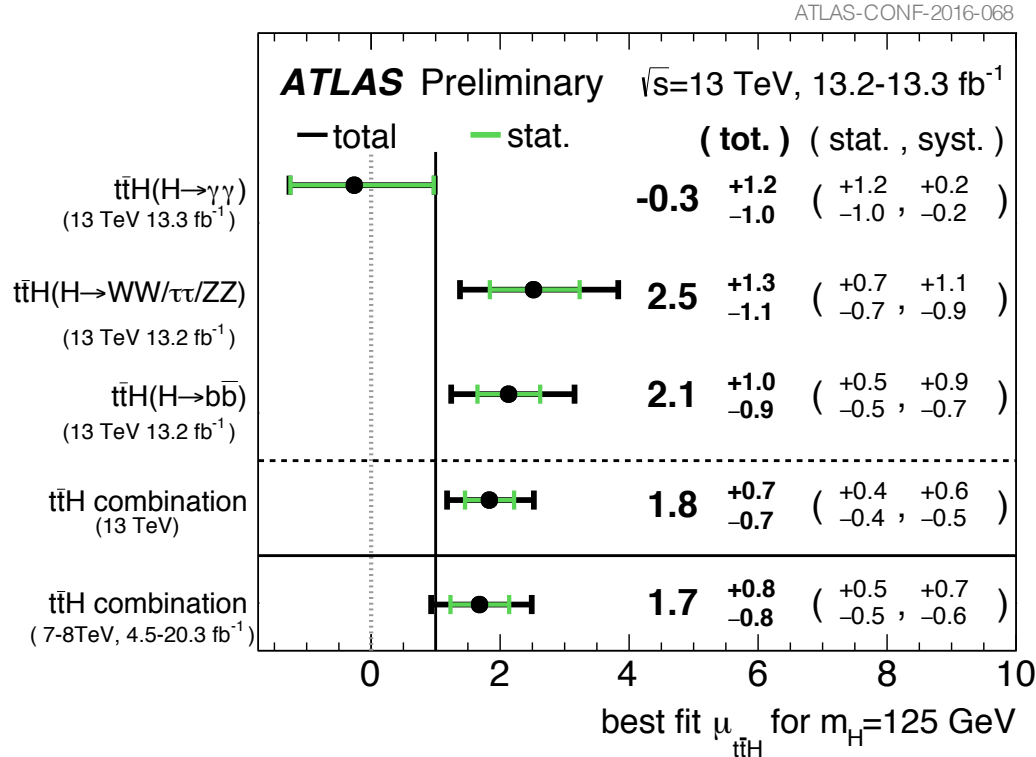
First search for ttH production at 13 TeV by ATLAS

Direct measurement of Higgs-top coupling



ATLAS showed preliminary results for ttH in **all major channels** and their combination at ICHEP 2016

Individual channels and combination



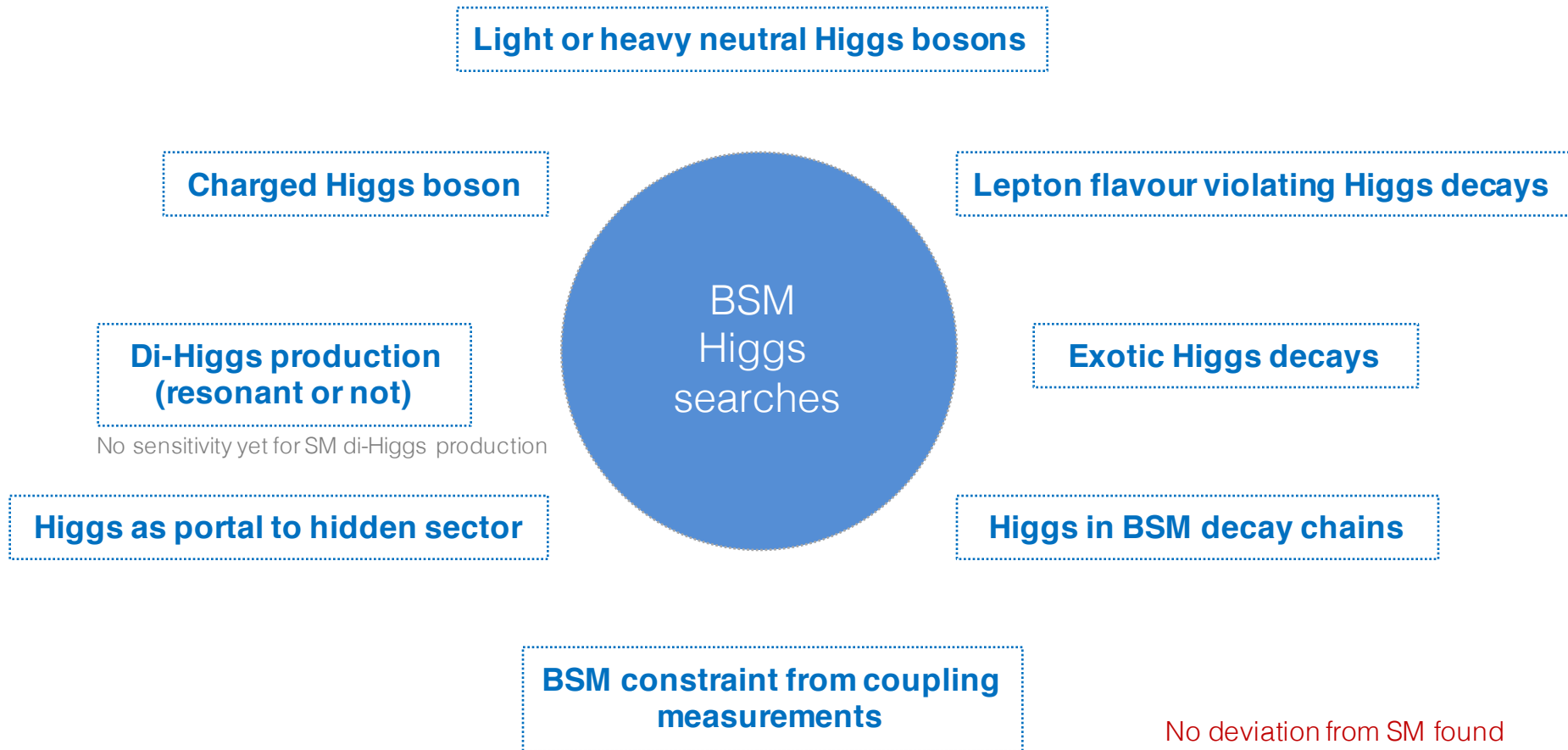
$2.8_{\text{obs}} (1.8_{\text{exp}})\sigma$

Improved sensitivity
over Run-1

Beyond the Standard Model Higgs physics

Higgs sector may be non-minimal and/or Higgs boson may couple to new physics

Diverse search programme:



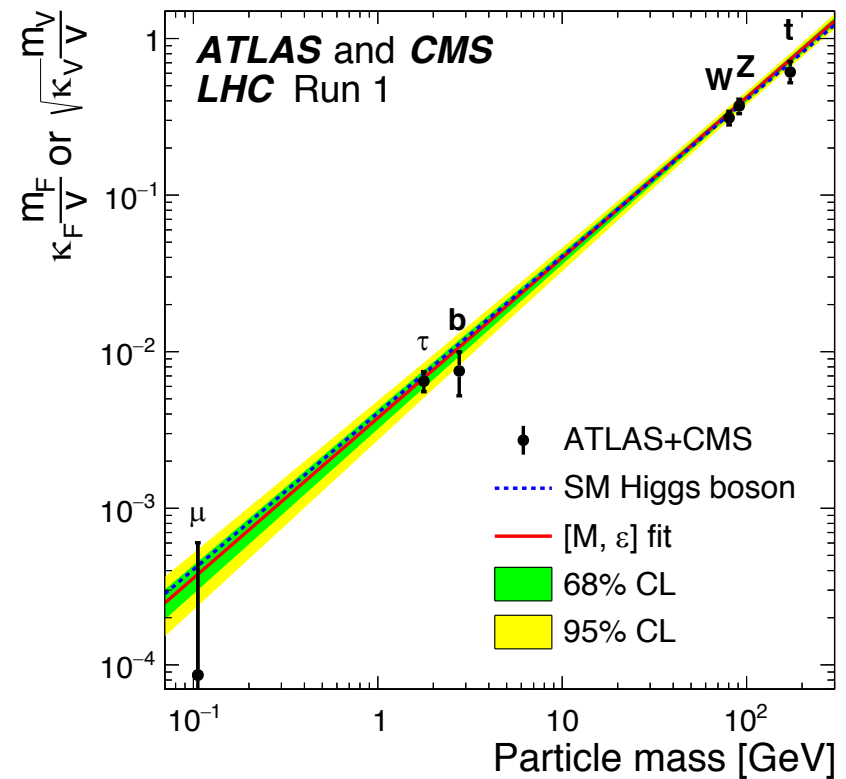
No deviation from SM found
in any of these searches

Conclusions

The Higgs-boson discovery and a flurry of property measurements proved true the BEH mechanism to break gauge symmetry

However, apart from the mass, none of these measurements are yet very precise and leave room for significant deviations. Also, important modes are still unseen (bb , ttH , $\mu\mu$, $Z\gamma$, HH)

And then, the reasons for new physics are all still valid, as is the beauty of SUSY...



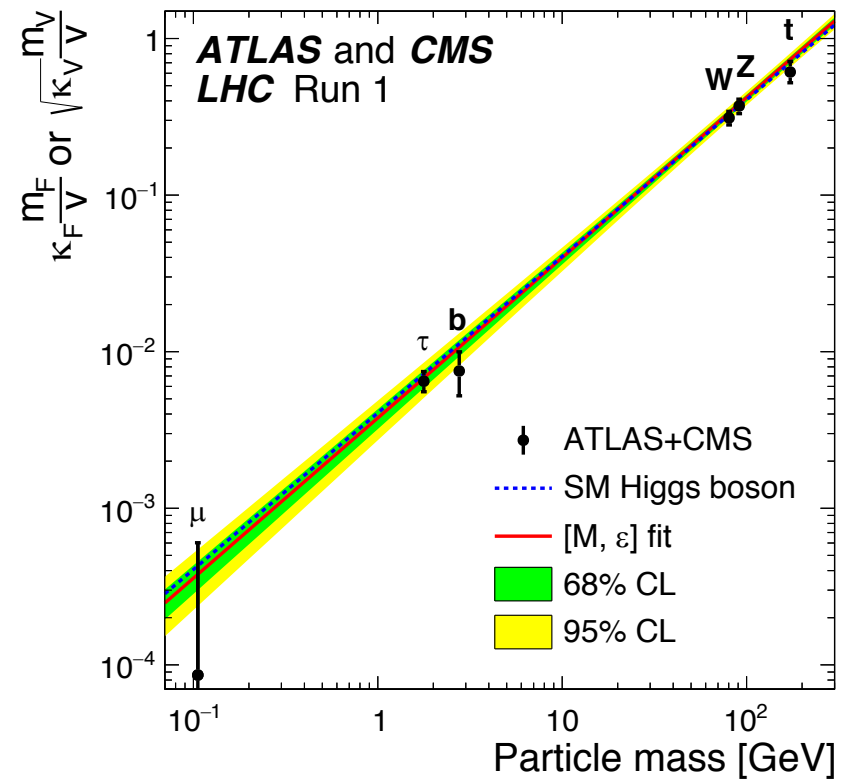
Conclusions

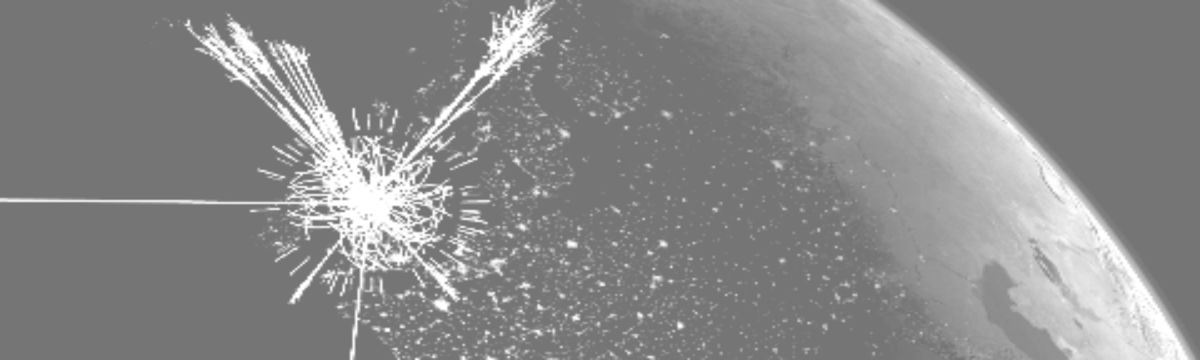
The Higgs-boson discovery and a flurry of property measurements proved true the BEH mechanism to break gauge symmetry

However, apart from the mass, none of these measurements are yet very precise and leave room for significant deviations. Also, important modes are still unseen (bb , ttH , $\mu\mu$, $Z\gamma$, HH)

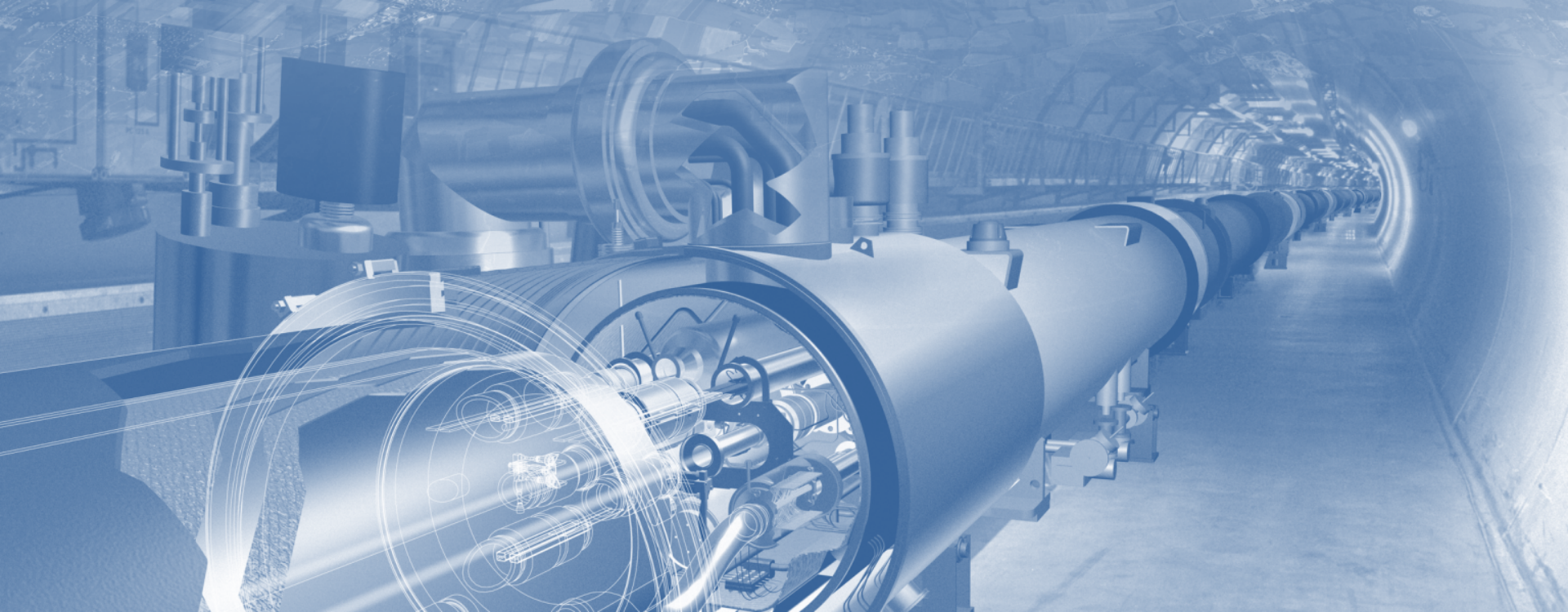
And then, the reasons for new physics are all still valid, as is the beauty of SUSY...

...so we may still hope Pierre was right !





Extra slides

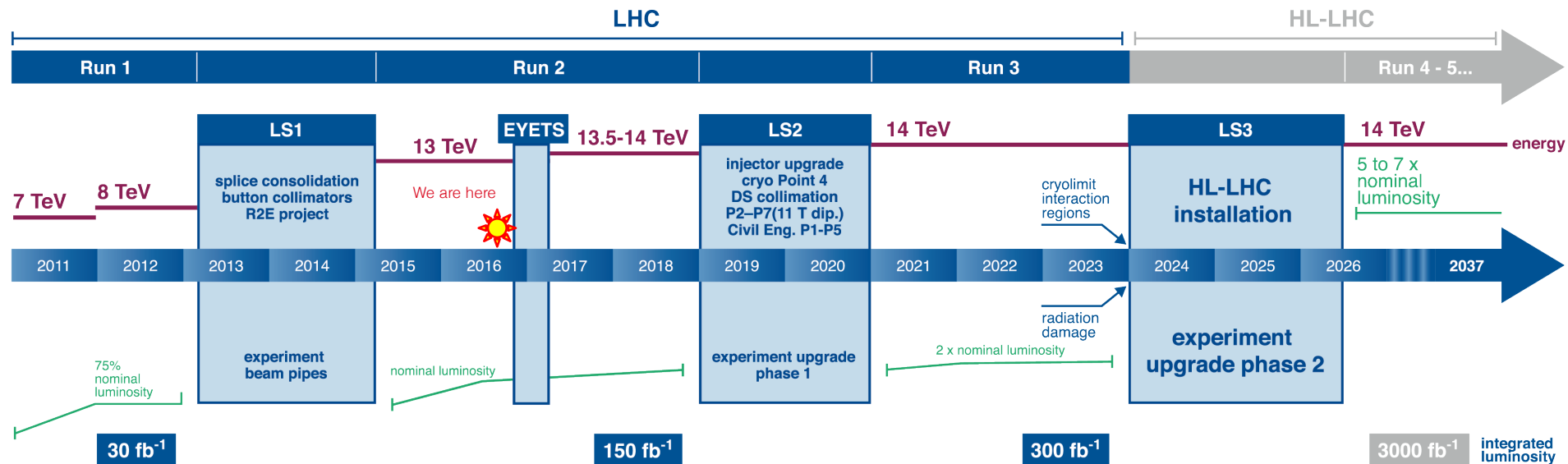


A brief look into the future

The road to the future

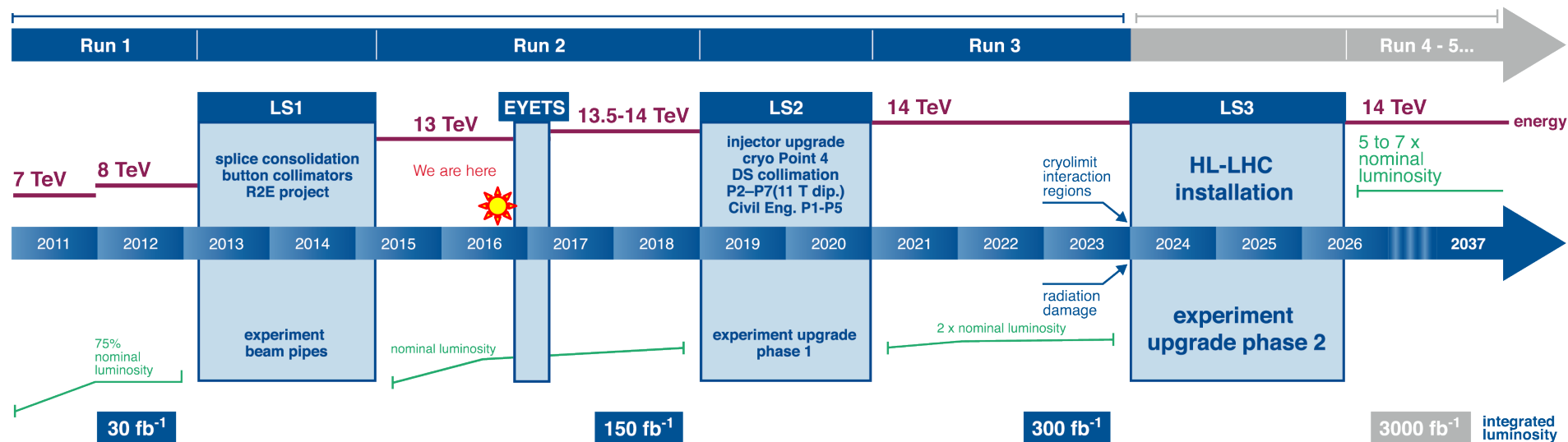
The LHC Run-2 and beyond

LHC / HL-LHC Plan



How can these LHC luminosity improvements be achieved?

Parameter	LHC Run-1	LHC Run-2 & 3	HL-LHC
Beam energy [TeV]	0.45–4	6.5–7	7
Peak inst. luminosity [$\text{cm}^{-2} \text{s}^{-1}$]	$0.8 \cdot 10^{34}$	$(0.7\text{--}2) \cdot 10^{34}$	$5 \cdot 10^{34}$ (levelled)
Bunch distance [ns]	50	25	25
Max. number of bunches	1380	2028~2748	2748
β^* [cm]	60	40	15
ε_n [μm]	2.3	2.5–3.5 (2.3 with BCMS)	2.5
Max. num. protons per bunch	$1.7 \cdot 10^{11}$	$1.2 \cdot 10^{11}$	$2.2 \cdot 10^{11}$
Average pileup $\langle\mu\rangle$	21	21~50	140



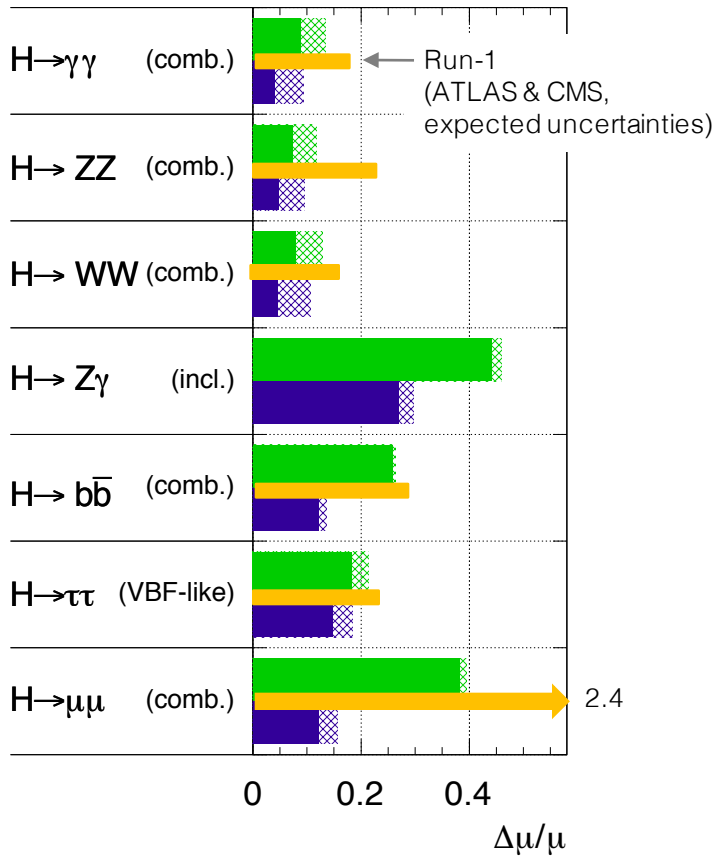
Higgs boson physics

(Conservative) extrapolation of Higgs coupling measurements

Higgs signal strengths (left) and ratios of coupling modifiers (right), compared to current precision (orange)

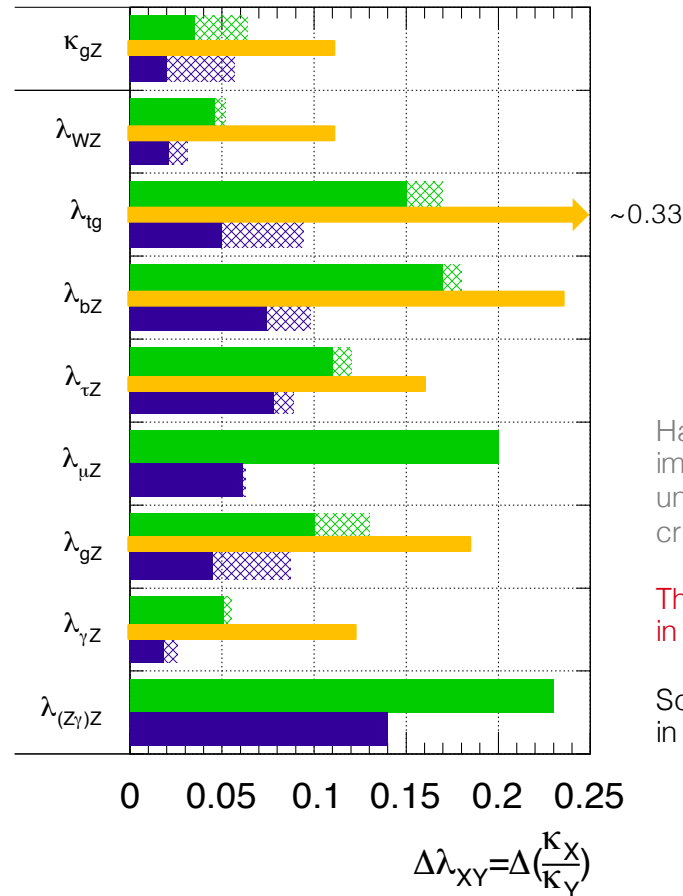
ATLAS Simulation Preliminary

$\sqrt{s} = 14$ TeV: $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$; $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$



ATLAS Simulation Preliminary

$\sqrt{s} = 14$ TeV: $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$; $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$



$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

$$\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$

Hatched areas indicate impact of theoretical uncertainties on expected cross-sections

Theory uncertainty limiting in several cases

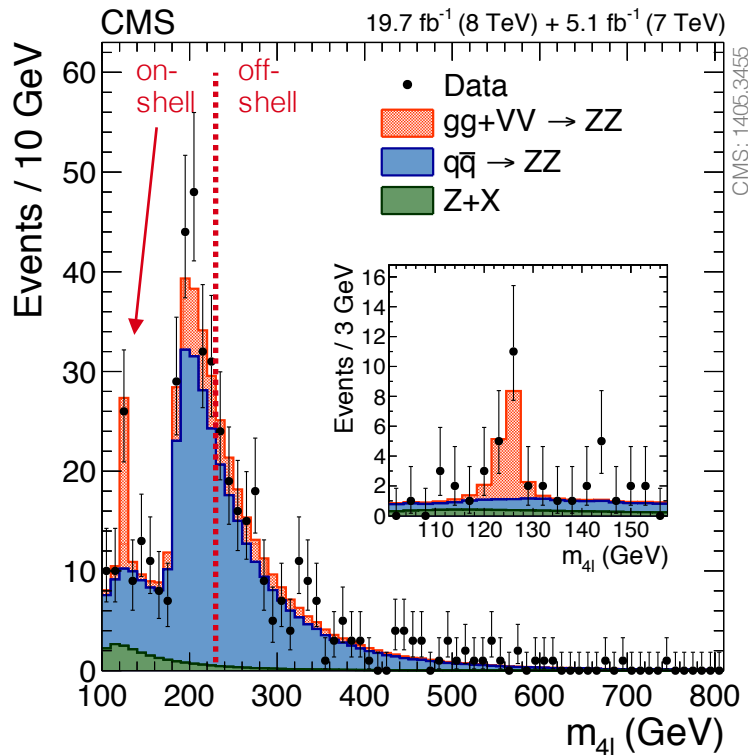
Some uncertainties cancel in ratios

Higgs boson physics

Constraining the Higgs off-shell coupling

Both CMS and ATLAS have constrained the Higgs off-shell coupling and through this obtained upper limits on the Higgs total width Γ_H

The method uses the independence of off-shell cross section on Γ_H and relies on identical on-shell and off-shell Higgs couplings. One can then determine Γ_H ($=4.2$ MeV in SM) from the measurements of $\mu_{\text{off-shell}}$ and $\mu_{\text{on-shell}}$



$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma_{\text{off-shell}}^{gg \rightarrow H^* \rightarrow VV}(\hat{s})}{\sigma_{\text{off-shell, SM}}^{gg \rightarrow H^* \rightarrow VV}(\hat{s})} = \kappa_{g, \text{off-shell}}^2(\hat{s}) \cdot \kappa_{V, \text{off-shell}}^2(\hat{s})$$

$$\mu_{\text{on-shell}} = \frac{\sigma_{\text{on-shell}}^{gg \rightarrow H \rightarrow ZZ}}{\sigma_{\text{on-shell, SM}}^{gg \rightarrow H \rightarrow ZZ}} = \frac{\kappa_{g, \text{on-shell}}^2 \cdot \kappa_{Z, \text{on-shell}}^2}{\Gamma_H / \Gamma_H^{\text{SM}}}$$

With Run-1, limits of the order of $5 \times \Gamma_H^{\text{SM}}$ obtained

With $L_2 = 3000 \text{ fb}^{-1}$ expect:

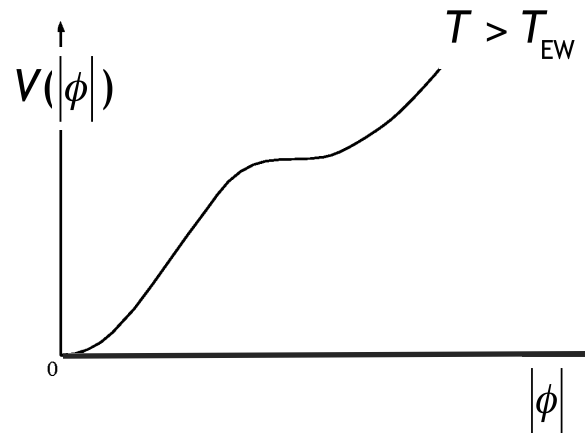
$$\mu_{\text{off-shell}}^{(L2)} = 1.00^{+0.43}_{-0.50} \text{ (stat+sys)}$$

$$\Rightarrow \Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1} \text{ MeV (stat+sys)}$$

ATLAS: ATL-PHYS-PUB-2015-024

BEH Potential

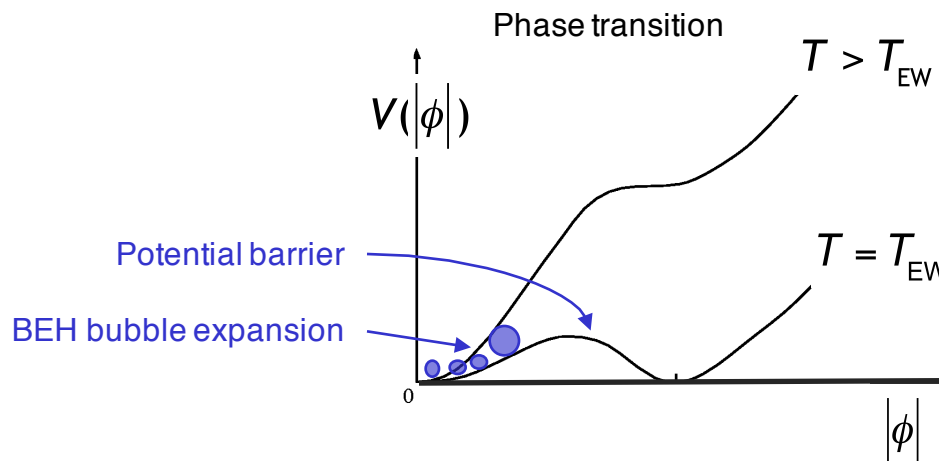
The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)



$V(T)$ dependence mainly governed by top loop, adding a cubic ϕ^3 term

BEH Potential

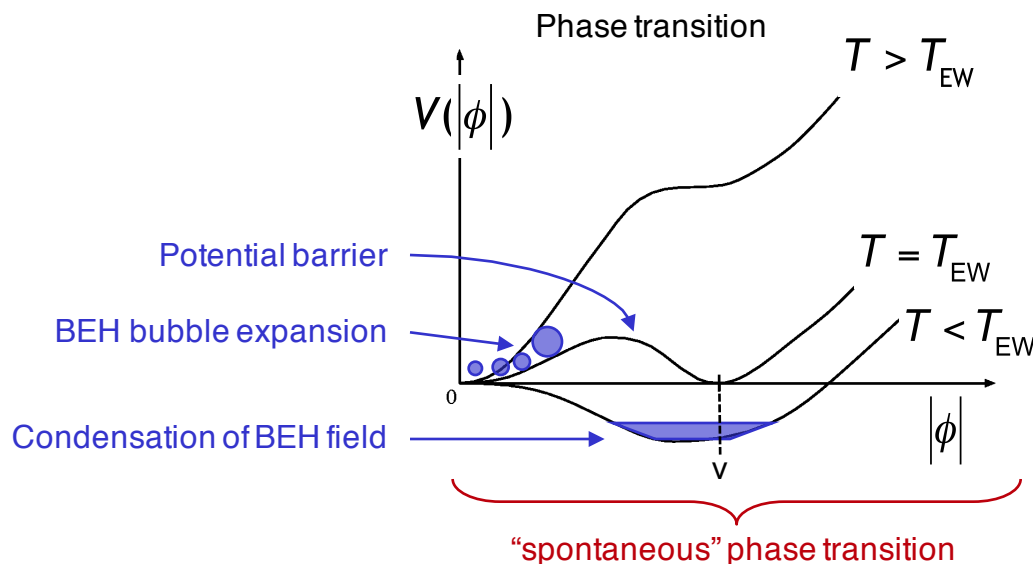
The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
A phase transition at $\sim T_{EW}$ ($\sim$ several 10^{-11} s after big bang, causal domain of few cm) led to $|\phi_{min}| > 0$



Picture describes a 1st order phase transition that would require light Higgs, or new physics $\rightarrow$ currently disfavoured

BEH Potential

The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
 A phase transition at $\sim T_{EW}$ ($\sim$ several 10^{-11} s after big bang, causal domain of few cm) led to $|\phi_{min}| > 0$



The condensed field fills all space and time but without orientation as it has no spin. (One might view it as a Lorentz-invariant ether creating a vacuum viscosity)

Tree-level BEH potential at $T=0$:

$$V(\phi) = \mu_{<0}^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

(μ, λ determined once Higgs mass known)

Simplest scalar potential that breaks ground state symmetry. Does what we need, but bears fundamental problems.

Carries the seeds of new physics ...

The Standard Model

BEH mechanism

Early universe: symmetric phase,
fundamental particles are massless
→ gauge symmetry is respected

Symmetric phase – early universe

Gravity 

Photon 

Weak boson 

Neutrinos 

Electrons 

Top quark 

The Standard Model

BEH mechanism

Early universe: symmetric phase,
fundamental particles are massless
→ gauge symmetry is respected

A Higgs field displaces ground state
breaking gauge symmetry

It fills all space time (but without
orientation as it has no spin)

Particles interact with Higgs field and
effectively reduce their velocity.
Acquired mass proportional to
interaction strength

→ Action of the Higgs field
creates “vacuum viscosity”

Higgs quantum liquid in broken phase

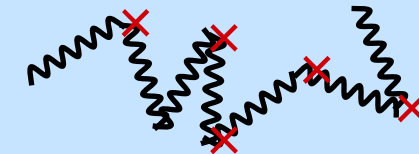
Gravity



Photon



Weak boson



Neutrinos



Electrons



Top quark



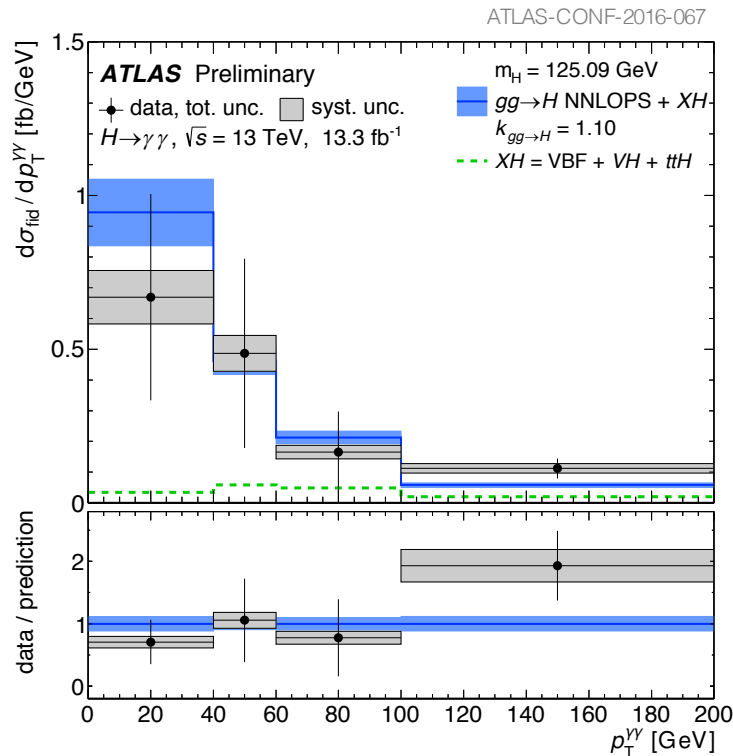
Interaction with Higgs
field alters chirality of
massive Dirac fermion

H. Murayama

ATLAS and CMS studied H(125) in bosonic channels

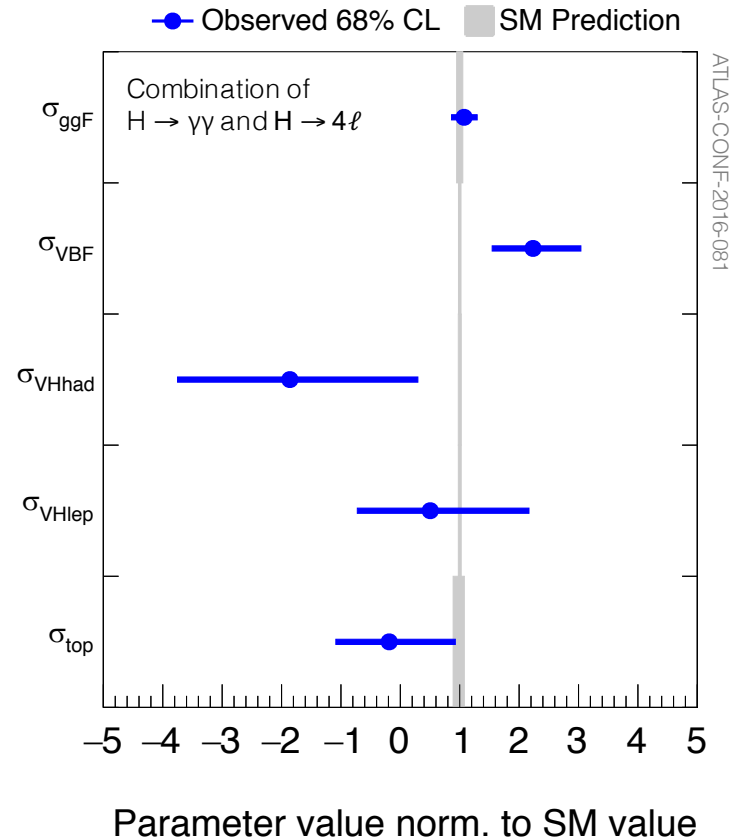
Preliminary fiducial and total cross-section and coupling measurements (ggF and VBF significant)

H → $\gamma\gamma$ and H → ZZ* → 4 ℓ (right combined)



Differential fiducial cross-section measurement in H → 4 ℓ compared to NNLO+PS theoretical prediction

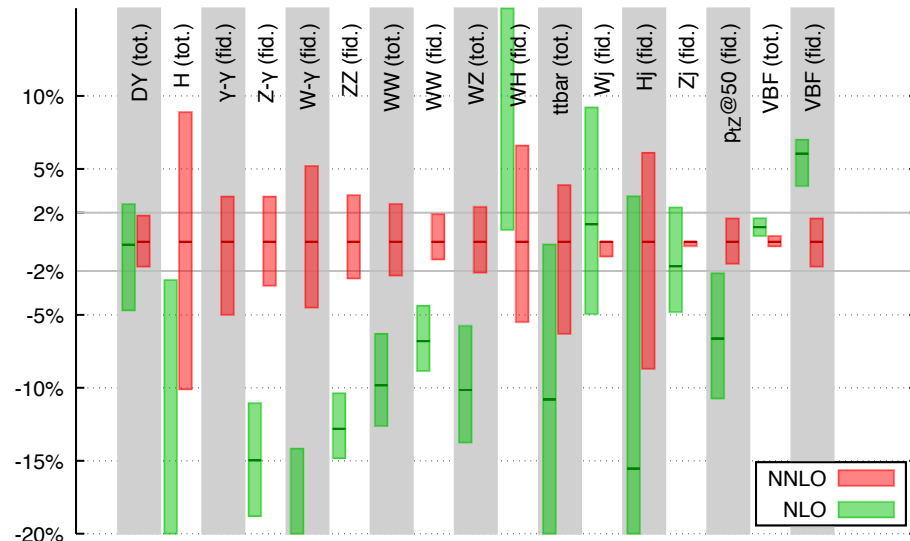
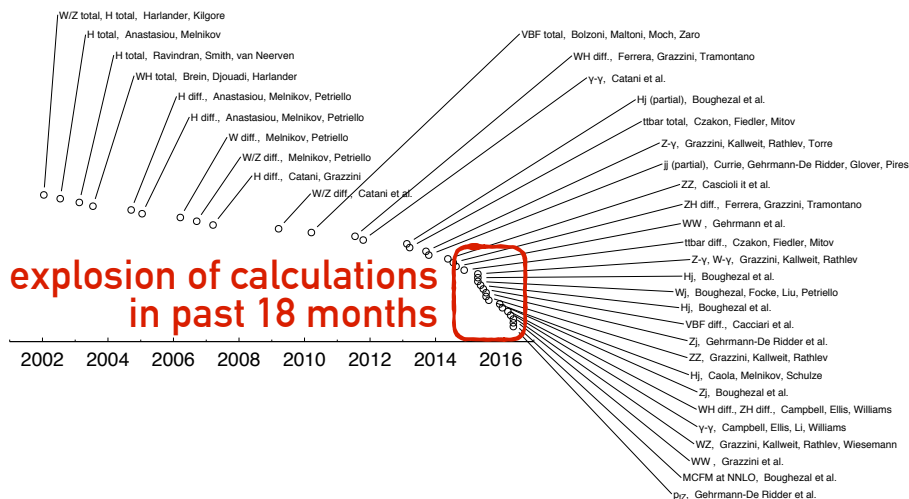
ATLAS Preliminary $m_H = 125.09$ GeV
 $\sqrt{s} = 13$ TeV, 13.3 fb $^{-1}$ ($\gamma\gamma$), 14.8 fb $^{-1}$ (ZZ)



Theoretical cross-sections and uncertainties

Progress in theoretical calculations*

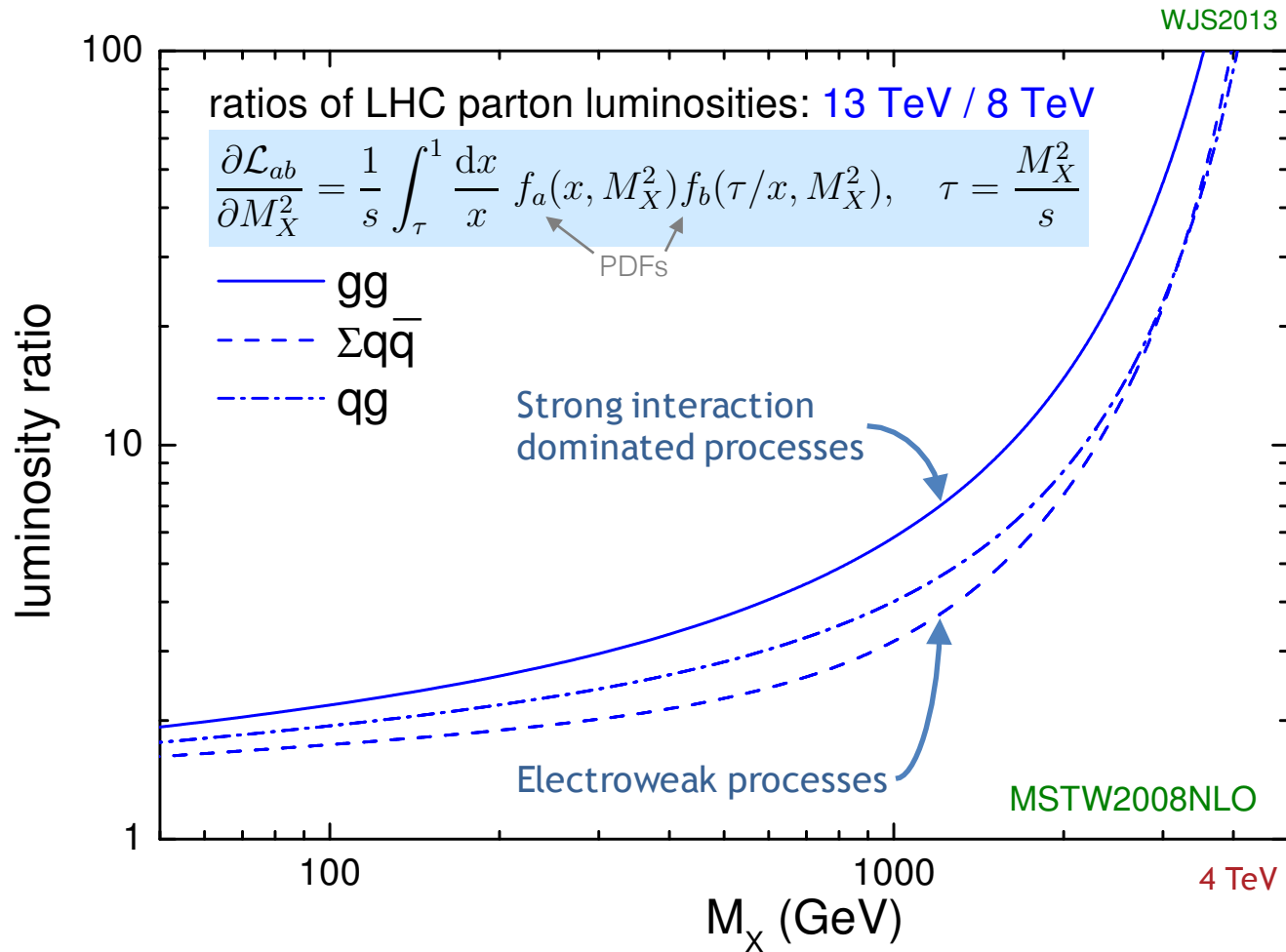
NNLO revolution



For many processes NNLO scale band is $\sim \pm 2\%$
But only in 3/17 cases is NNLO (central) within NLO scale band...

Also experimental knowledge of PDFs is limiting precision in many LHC analyses !

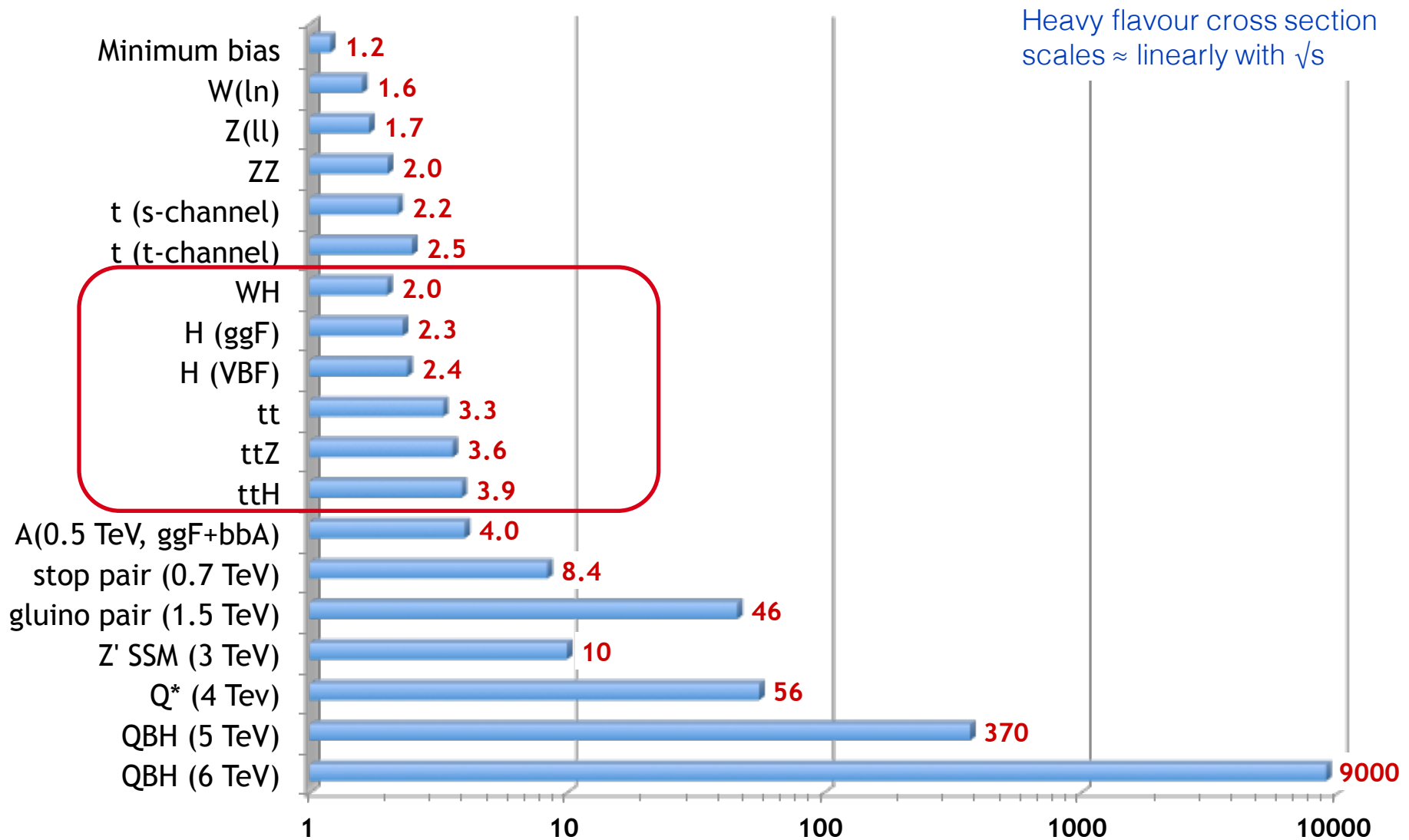
The LHC Run-2: 13 TeV / 8 TeV inclusive “parton luminosity” ratio



Larger cross section increase for gluon induced than for quark induced processes

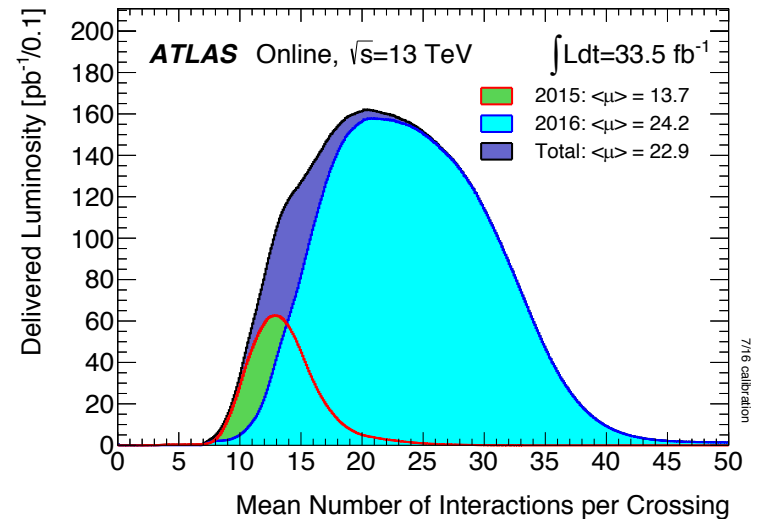
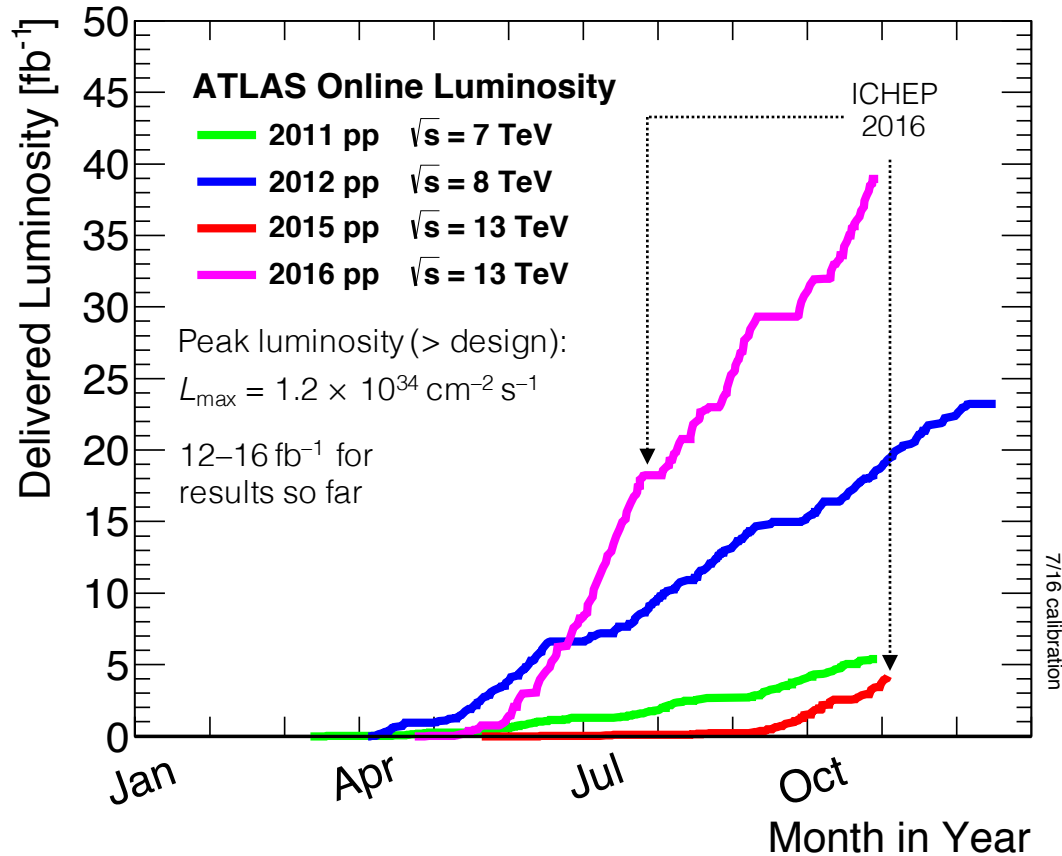
Early Run-2 puts emphasis on searches

The LHC Run-2: 13 TeV / 8 TeV inclusive pp cross-section ratio



2015 LHC proton-proton luminosities

Most results reported by ATLAS & CMS use total 2015 and summer 2016 dataset



2015 and 2016 pileup profile in ATLAS & CMS
(LHCb mean pileup of ~ 1.7 due to levelling)

LHCb after luminosity levelling: 1.7 (1.9) fb $^{-1}$ recorded (delivered)

Current luminosity precision from van-der Meer scans: 2.9% (ATLAS), 6.2% (CMS 2016), 3.8% (LHCb)

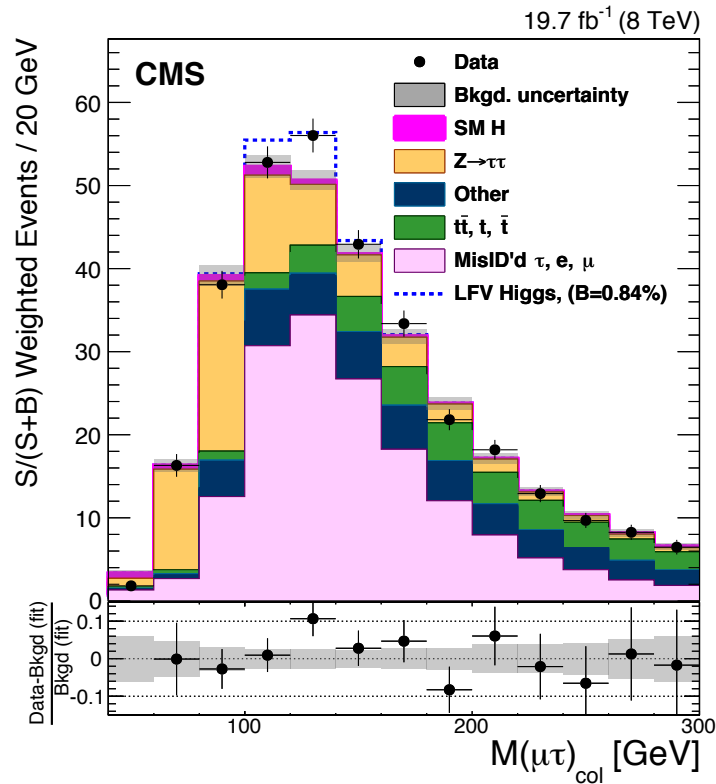
One word on lepton flavour violation in Higgs decays

Both experiments have finalised their Run-1 LFV analyses

While $H \rightarrow \mu e$ is severely constrained from flavour physics, $H \rightarrow \tau\mu$, τe are not ($\sim 10\%$ limits)

CMS released early 2015 a $H \rightarrow \tau\mu$ search finding a slight (2.4σ) excess

Not confirmed by ATLAS in the full Run-1 analysis



$H \rightarrow \tau\mu$:

ATLAS:

$$\text{BR} = 0.53 \pm 0.51\% < 1.43\% \text{ (95\% CL)}$$

CMS:

$$\text{BR} = 0.84^{+0.39}_{-0.37} \% < 1.51\% \text{ (95\% CL)}$$

$H \rightarrow \tau e$:

ATLAS:

$$\text{BR} = -0.3 \pm 0.6\% < 1.04\% \text{ (95\% CL)}$$

One word on lepton flavour violation in Higgs decays

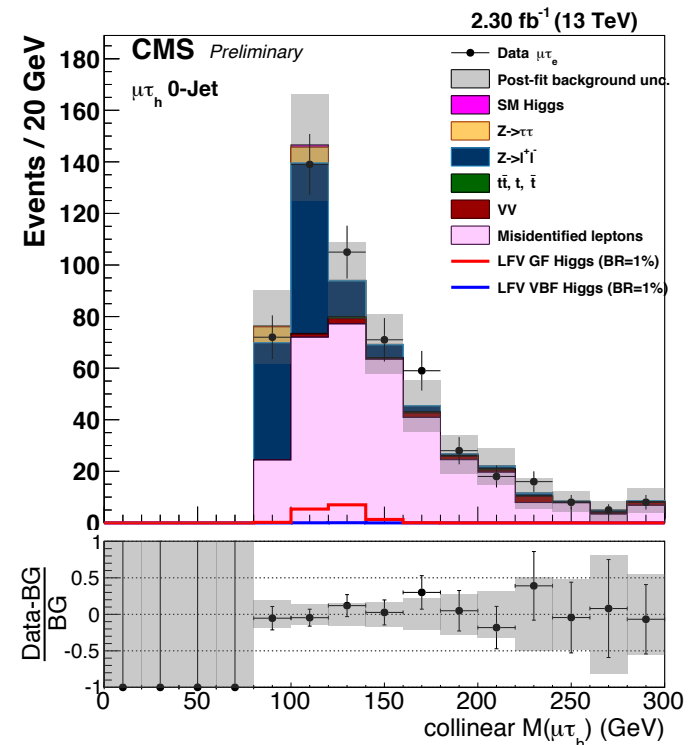
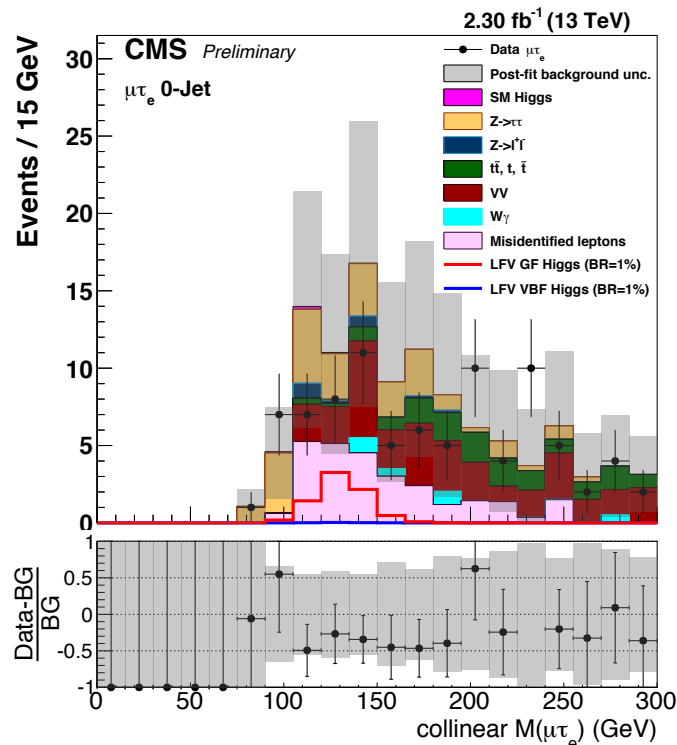
Both experiments have finalised their Run-1 LFV analyses

New preliminary result with 13 TeV from CMS [CMS-PAS-HIG-16-005]

Six categories considered: $(\mu\tau_h, \mu\tau_e) \times (0, 1, 2 \text{ jets})$

No significant excess, combined limit: $BR = -0.8 \pm 0.8 \% (<1.2\% \text{ at } 95\%CL)$

Limit on non-diagonal Yukawa couplings: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.16 \times 10^{-3}$



BSM Higgs boson searches

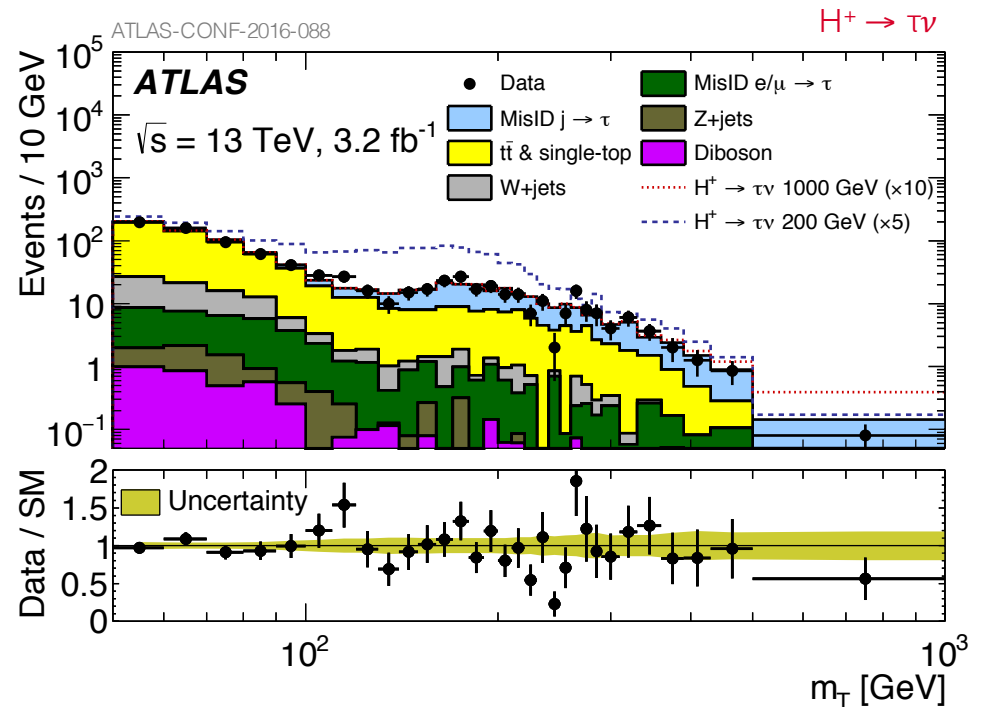
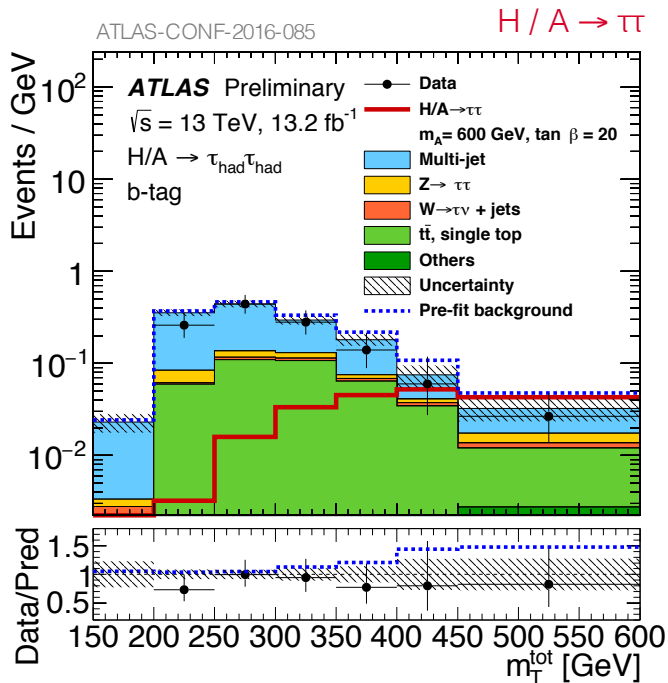
Single BEH doublet and form of potential simple but Nature may be more complex (eg, SUSY)

Beyond the SM “Higgs zoo”

[Will Davey, LHCP 2014]



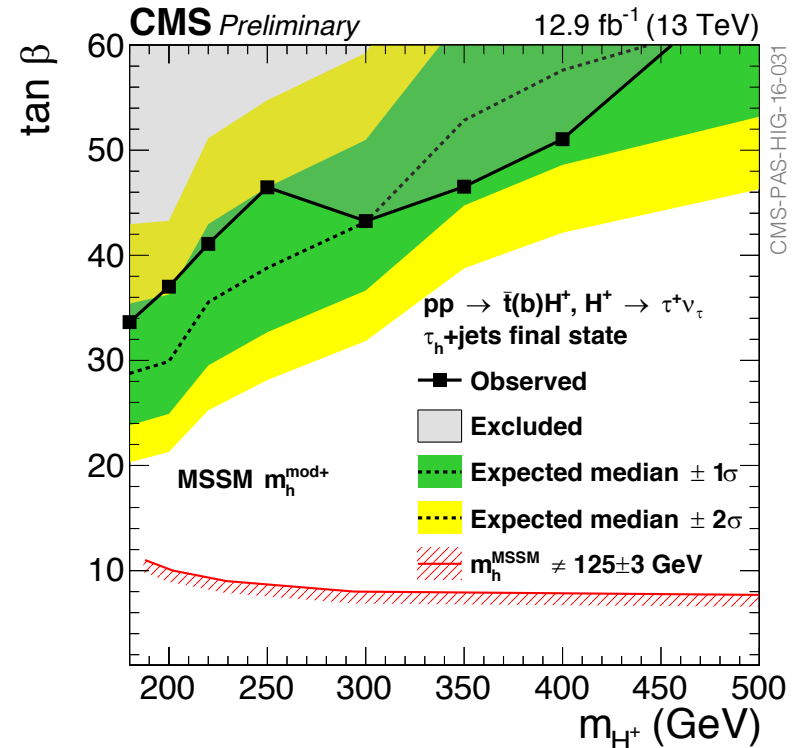
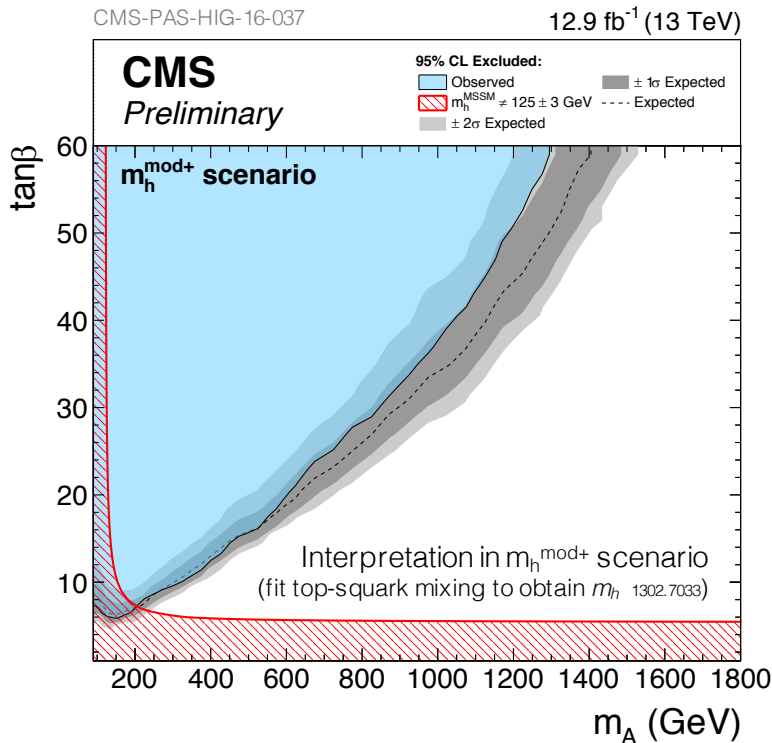
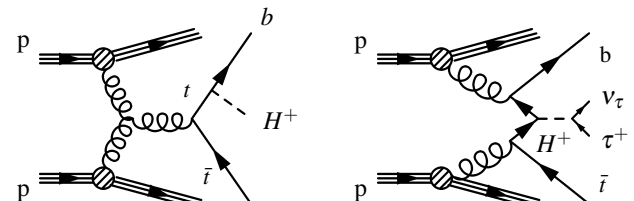
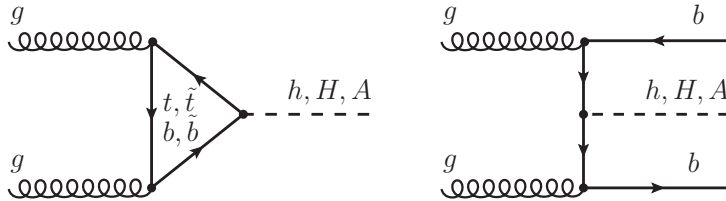
Higgs coupling to mass, look for decays to tau leptons or weak bosons, for example:

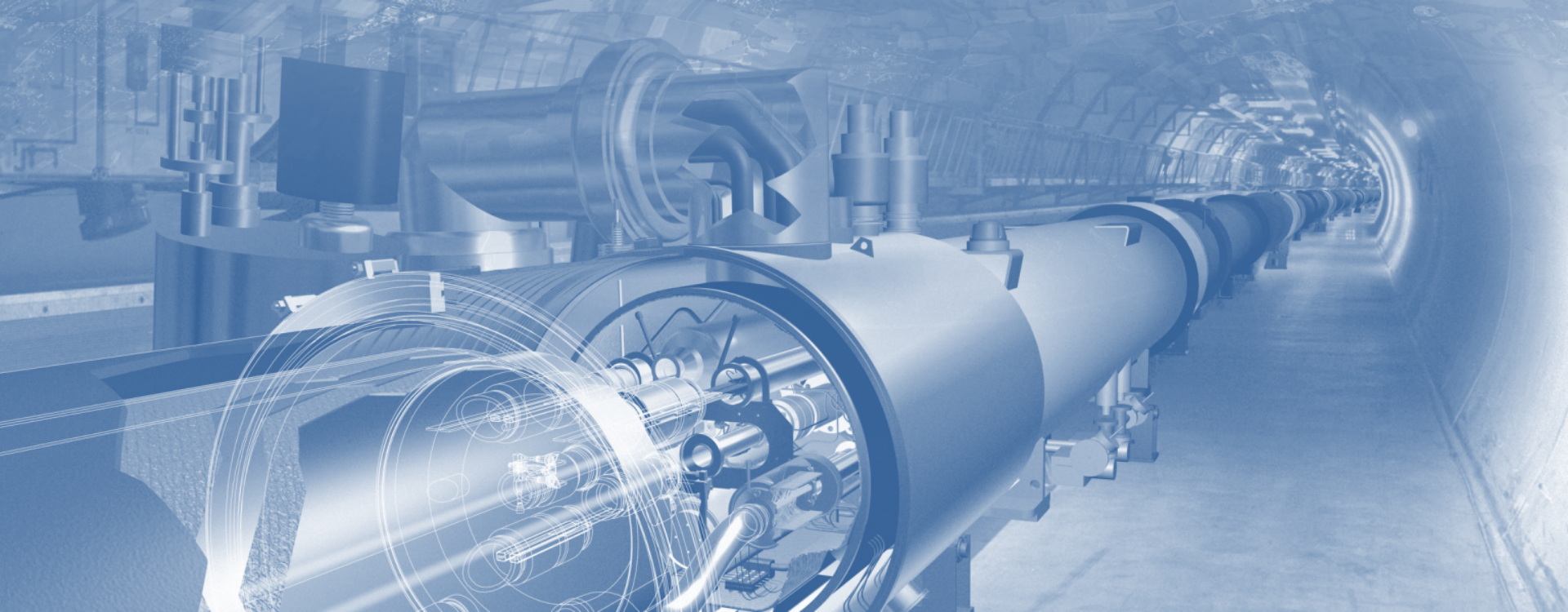


Limits on 2HDM / MSSM Higgs

Many final states studies. Here: $H/A \rightarrow \tau\tau$ (left) and $H^\pm \rightarrow \tau\nu$ (right)

Limits on production of neutral (left) and charged (right) Higgs bosons





Beyond the HL-LHC

Future hadron collider projects in a nutshell

The next discovery machine

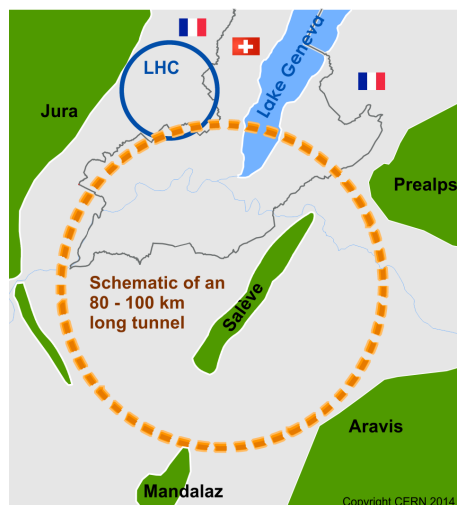
HL-LHC: $E_{\text{CM}} = 14 \text{ TeV}$, 3 ab^{-1} , 2026~2035... (formally approved as *project* by CERN council last week)

Future Circular Collider FCC-hh (CERN):

- $E_{\text{CM}} \sim 100 \text{ TeV}$ in 100 km ring, $L \sim 2 \times 10^{35} \text{ s}^{-1}\text{cm}^{-2}$
- $\sim 16 \text{ T}$ magnets, possibly HE-LHC ($E_{\text{CM}} \sim 28 \text{ TeV}$) as intermediate stage
- Huge detectors for muon p_T measurement
- Possible start of physics ~ 2035

SppC (China):

- $E_{\text{CM}} \sim 71 \text{ TeV}$ in 55 km ring, $L \sim 1 \times 10^{35} \text{ s}^{-1}\text{cm}^{-2}$
- Requires very high gradient dipole magnets $\sim 20 \text{ T}$
- Possible start of physics ~ 2042



Parameter	FCC-hh		SppC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main + 2		2	2 main + 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/lp [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	5	~ 25	12	1	5
events/bunch crossing	170	~ 850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
E-loss/turn	5 MeV		2 MeV	7 keV	7 keV
synchrotron radiation/beam	3 MW		5.8 MW	5.4 kW	9.5 kW

Future e⁻e⁺ collider projects in a nutshell

Measure EW & EWSB sector to highest precision

International Linear Collider ILC (host candidate: Japan)

- 20 years of R&D, mature technology, ~32 MV/m accelerating gradient ~ xFEL at DESY (45 MV/m for 1 TeV)
- $E_{\text{CM}} \sim 500\text{--}1000$ GeV in 31–45 km total length, $L \sim 1.8 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$, only one interaction region
- nm beam size, possible start of physics ~ 2030

Compact Linear Collider CLIC (CERN)

- High-gradient 2-beam scheme*: 100 MV/m gradient
- $E_{\text{CM}} \sim 380\text{--}3000$ GeV, 11–50 km total length, $L \sim \text{a few} \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$, only one interaction region
- 0.5 ns bunch distance, nm beam size, large beamstrahlung, physics ~ 2035

*A low energy, high current, “drive” beam is decelerated in power extraction structures and the RF power is transferred to the cavities that accelerate the main beam

Future Circular Collider FCC-ee (CERN):

- $E_{\text{CM}} \sim 90\text{--}350$ GeV in 2 rings (90k bunches), $L \sim 70\text{--}1.3 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$
- Synchrotron power (E^4/R up to 7.5 GeV/turn): 100 MW (LEP-2: 22 MW)

Circular EP collider CEPC (China):

- $E_{\text{CM}} \sim 240$ GeV, $L \sim 2 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$
- Single ring, 50 bunches
- Possible start of physics ~ 2028

parameter	FCC-ee			CepC	LEP2
energy/beam [GeV]	45	120	175	120	105
bunches/beam	90000	770	78	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP $\times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$	70	5	1.3	2.0	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.08	3.0	10	6.9	3.5