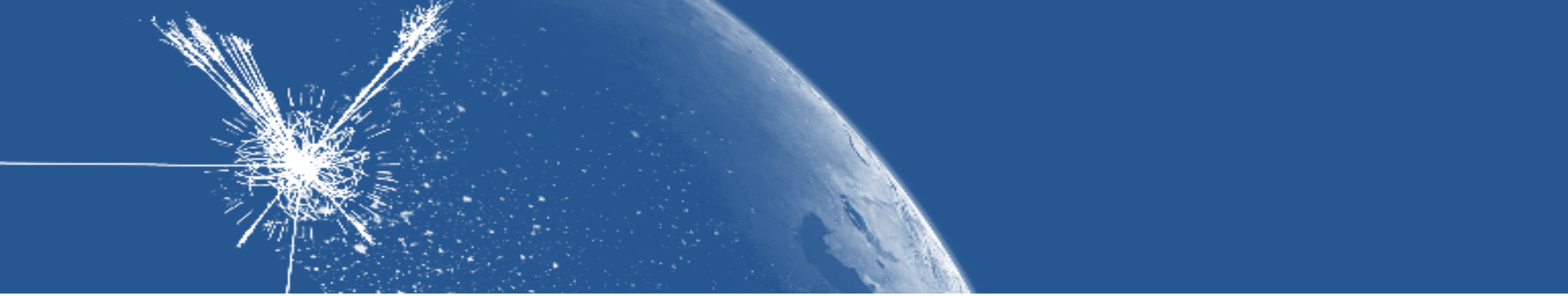


New Results from the LHC (2)

Andreas Hoecker (CERN)

September 26–28, 2016 in Freudenstadt, Germany

Outline

[3 × 1h lectures]

Yesterday:

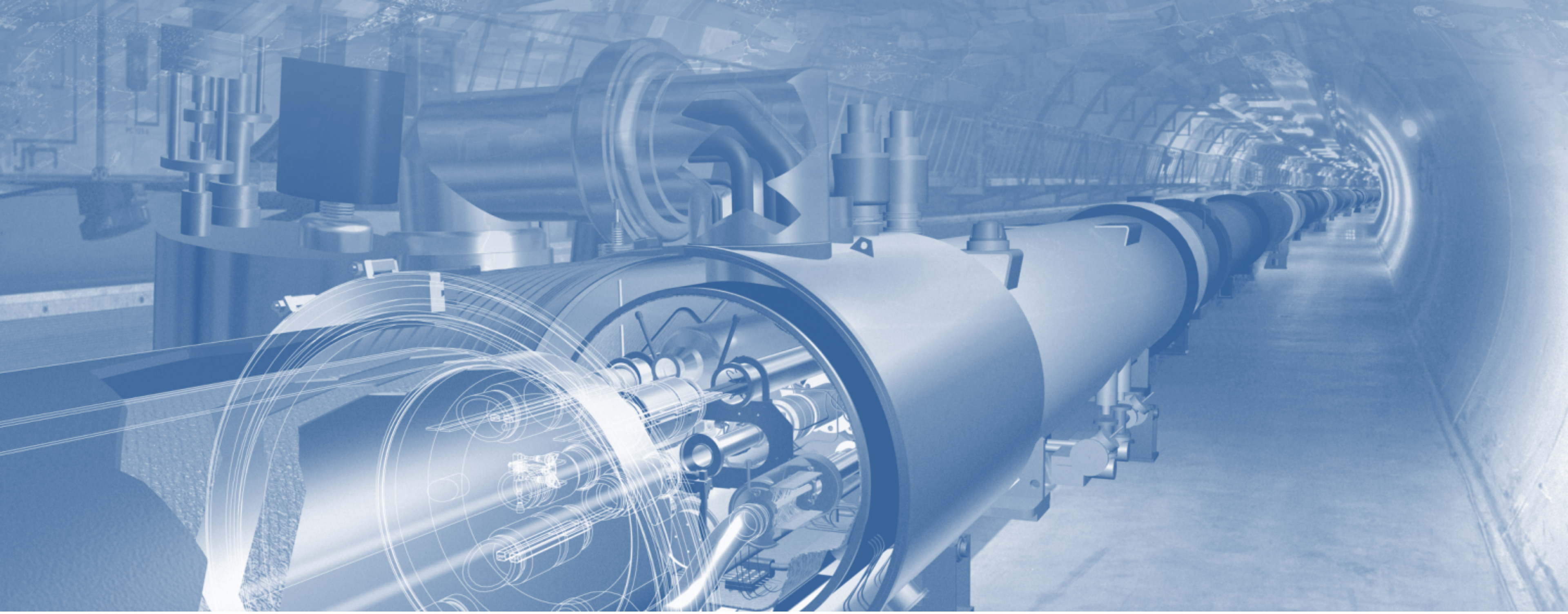
- Basic introduction
- Overview of the LHC experimental programme and methods

Today:

- A review of Run-1 physics highlights
- SM results from the LHC Run-2

Tomorrow

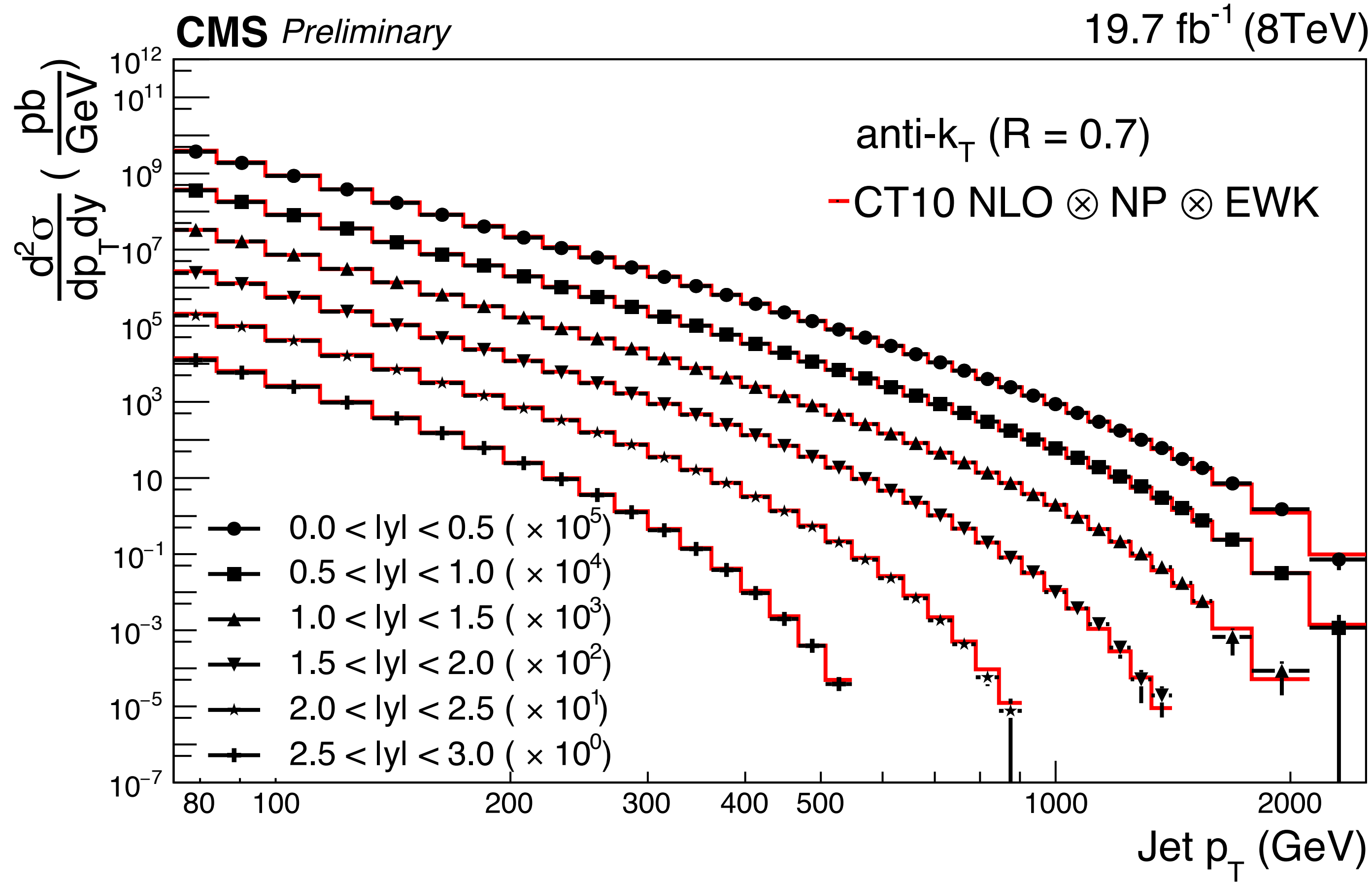
- BSM searches from the LHC Run-2
- Outlook to future projects



The LHC Run-1: 7 & 8 TeV pp, 5 & 20 fb^{-1}

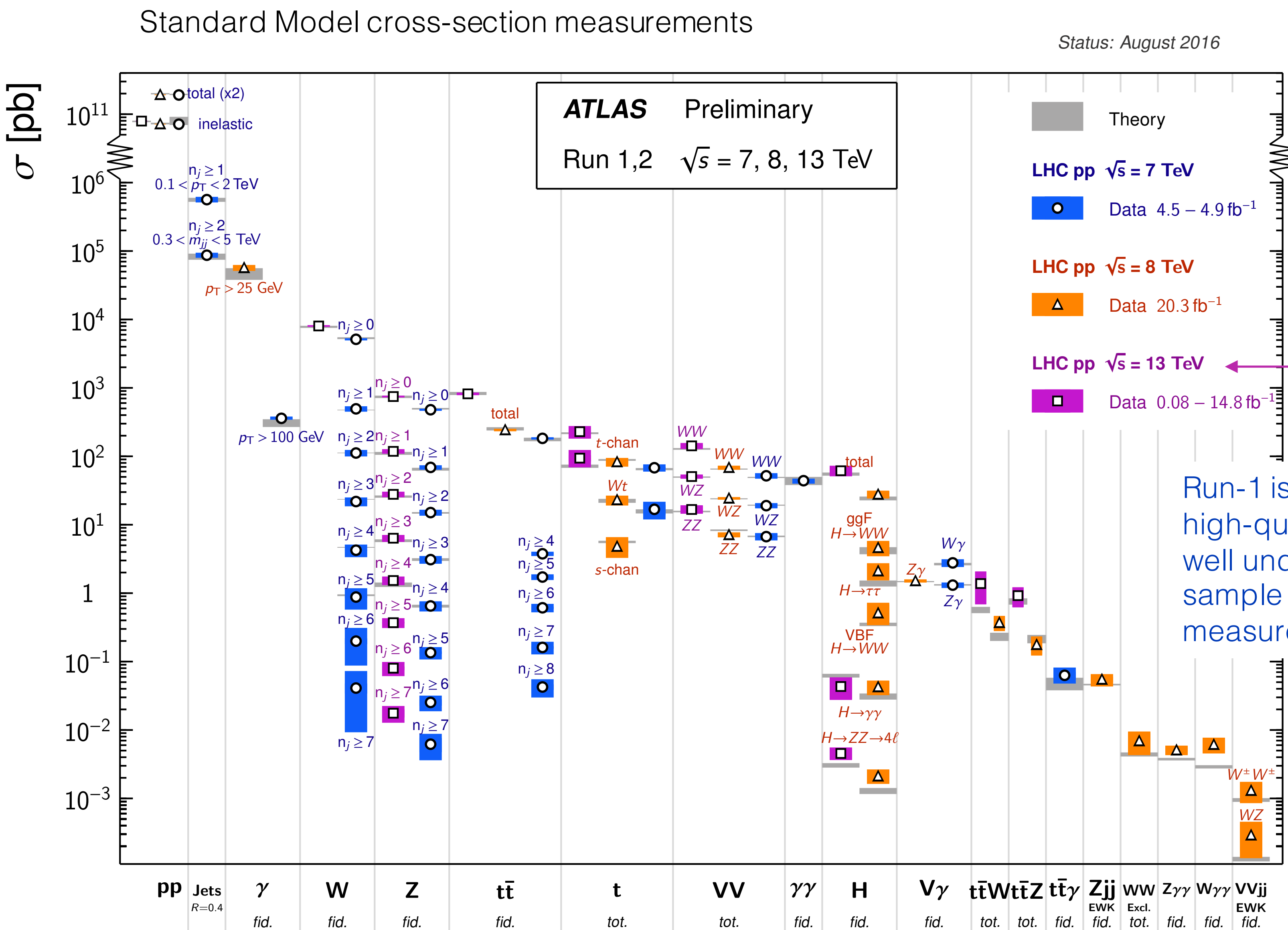
A brief history of selected highlights

Jet production [CMS-PAS-SMP-14-001]



Precision measurements & theory developments (includes nonperturbative and electroweak corrections) → new quality of QCD tests at hadron colliders

Harvest of Run-1 results (> 500 papers / exp) confirming predictive power of SM



Note !

Run-1 is not over yet: high-quality, extremely well understood data sample for precision measurements

Run-1 allowed critical first electroweak studies

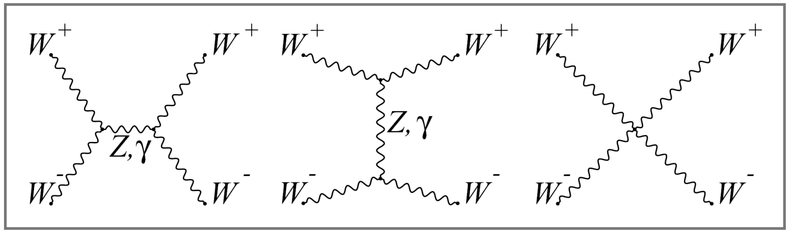
Higgs boson acts as "moderator" to unitarise high-energy longitudinal vector boson scattering

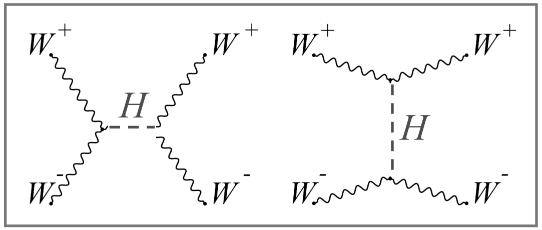
If only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering **violates unitarity**

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

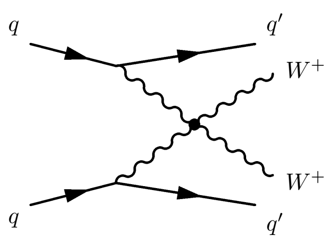
Higgs boson restores unitarity of total amplitude:

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

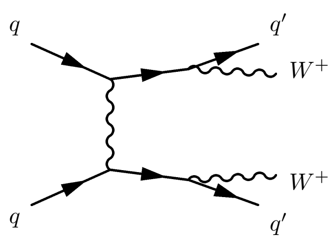




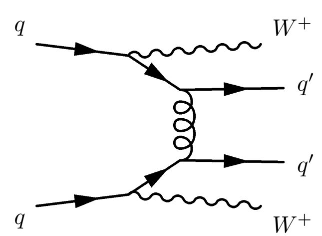
m_H must not be too large (which is fulfilled)



EW VBS production



Non-VBS production



Strong production

Look for VBS scattering in high dijet invariant mass distributions

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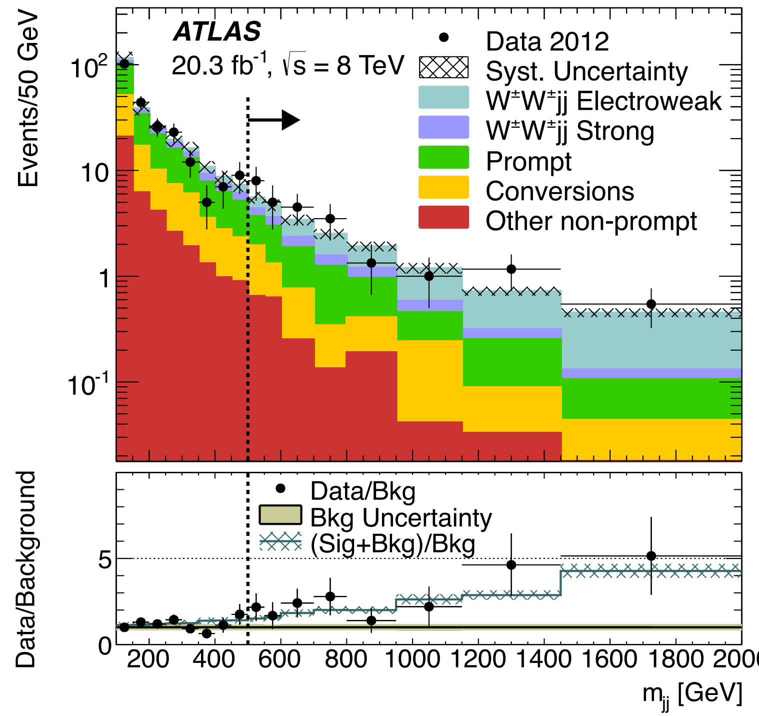
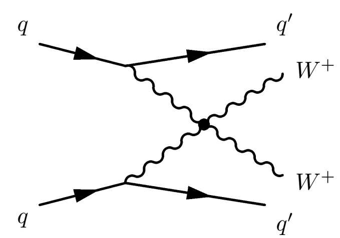
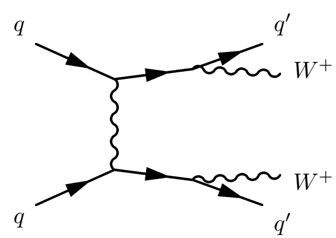
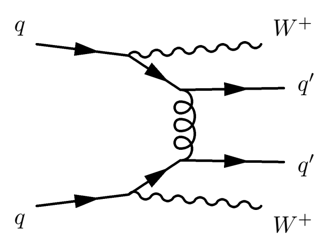




EW VBS production



Non-VBS production



Strong production

Look for VBS scattering in high dijet invariant mass distributions

Top quark production has been studies with unprecedented experimental precision

tt cross-section measurement

[ATLAS, EPJ C 74, 3109 (2014)]

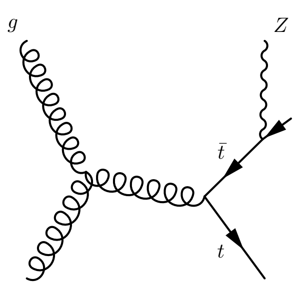
Precision test of NNLO QCD, used to derive the top mass and new physics limits

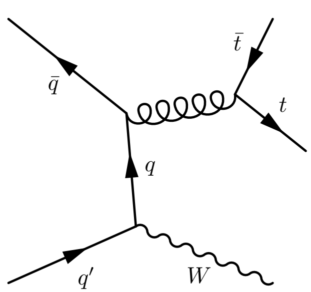
Many top properties measured

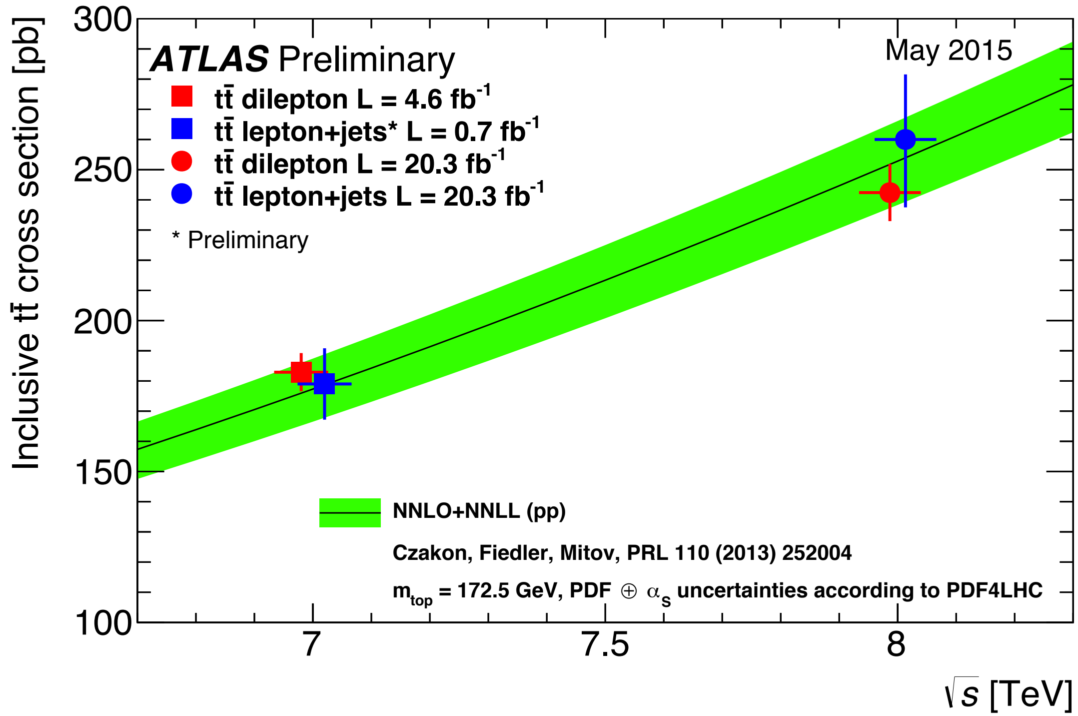
Luminosity and centre-of-mass energy open phase space to observe rare *tt* + vector-boson production

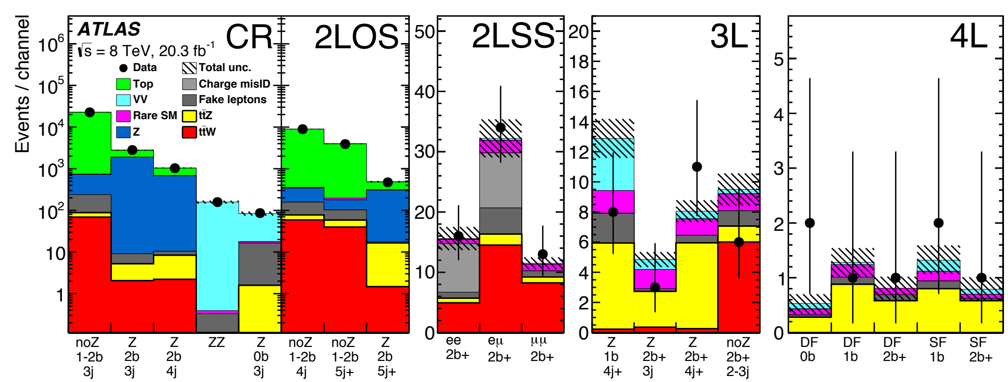
tt+W/Z: 7.1σ combined significance

[ATLAS 1509.05276]









Electroweak single top production

Top cross-sections significantly enhanced at LHC wrt Tevatron: at 8 TeV, factors of 42 (t-channel), 31 ($t\bar{t}$), but only 5 for s-channel (ie, worse S/B at LHC)

t-channel already measured differentially

[ATLAS, 1406.7844, CMS 1511.02138]

Wt channel observed with 7.7σ

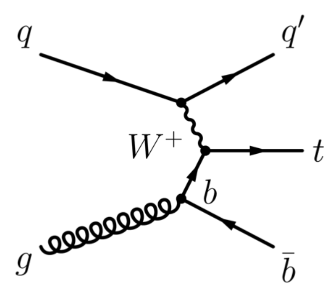
[ATLAS, 1510.03752, CMS 1401.2942]

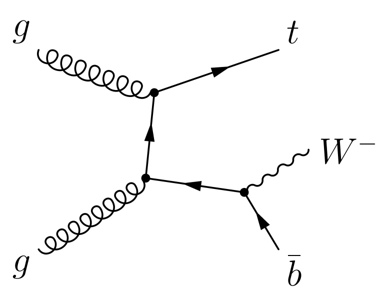
s-channel process first observed at Tevatron with 6.3σ in agreement with SM prediction

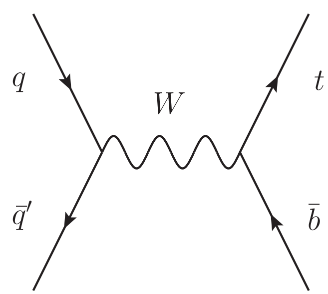
[CDF & D0, 1402.5126]

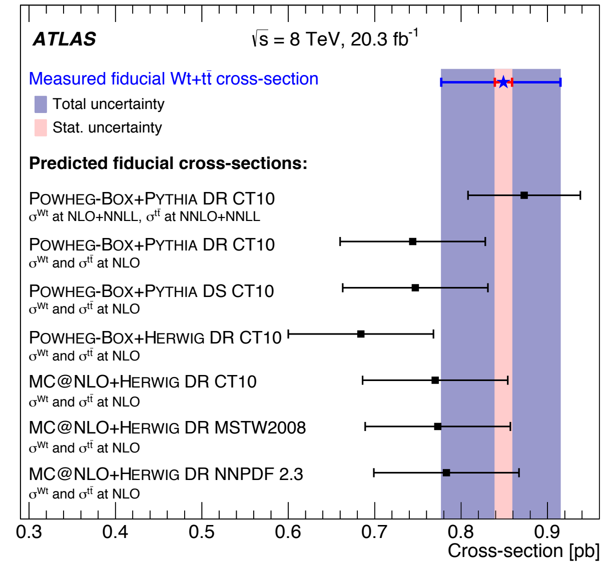
ATLAS reported 3.2σ (3.9σ exp.) evidence in agreement with SM

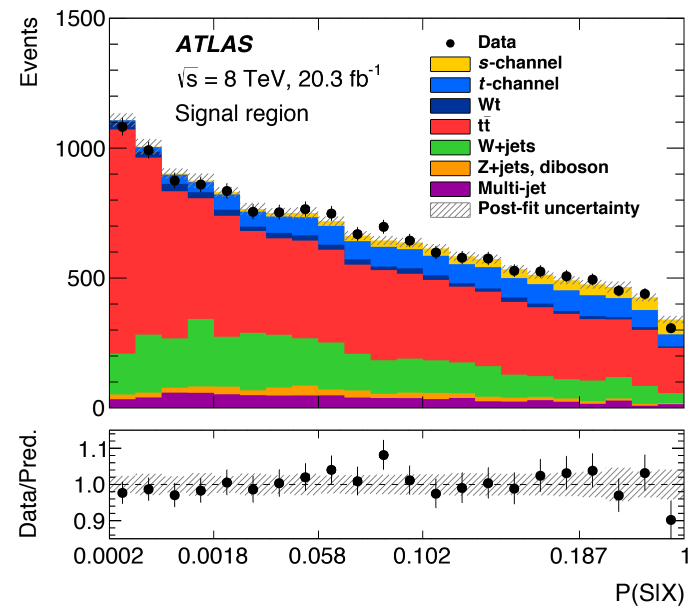
[ATLAS, 1511.05980]







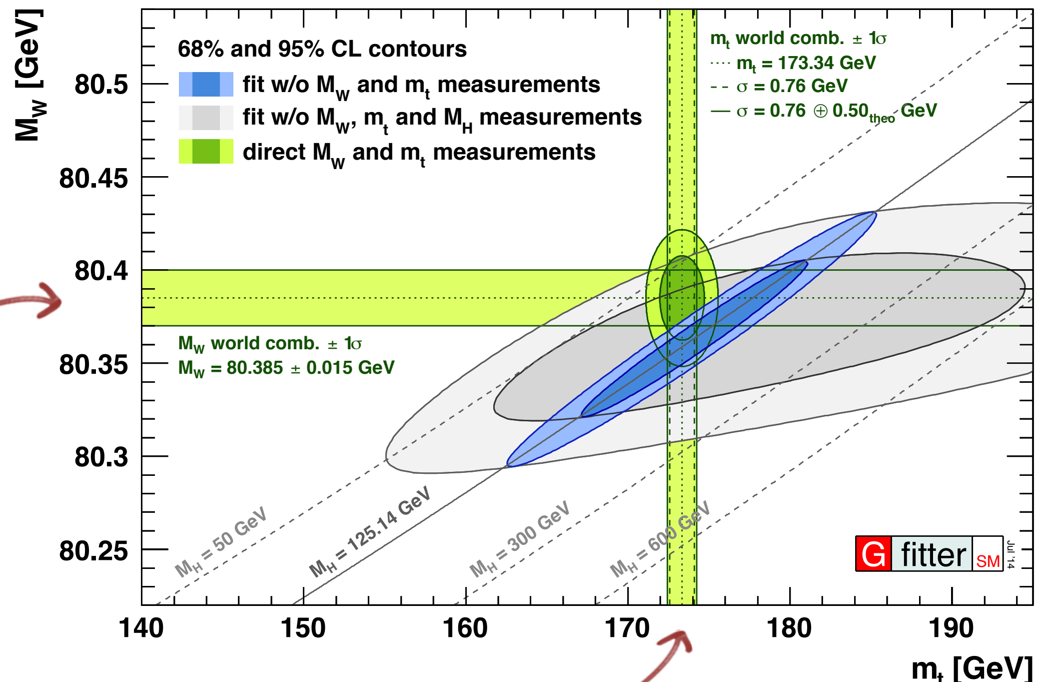




No LHC result yet

World average value dominated by Tevatron measurements : 80.387 ± 0.016 GeV

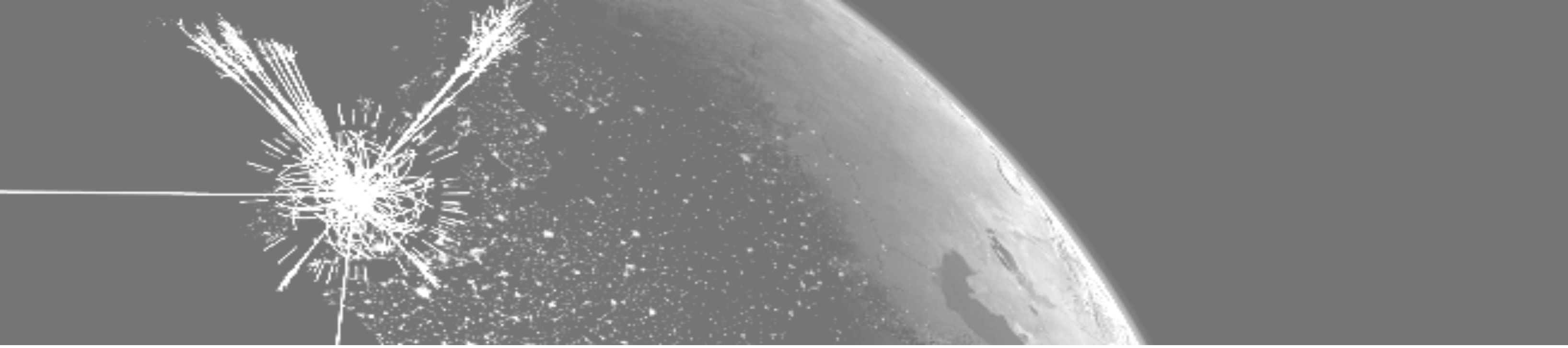
[CDF & D0, 1204.0042]

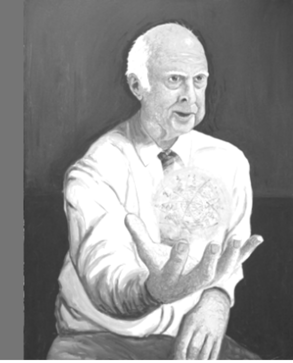


Global electroweak fit

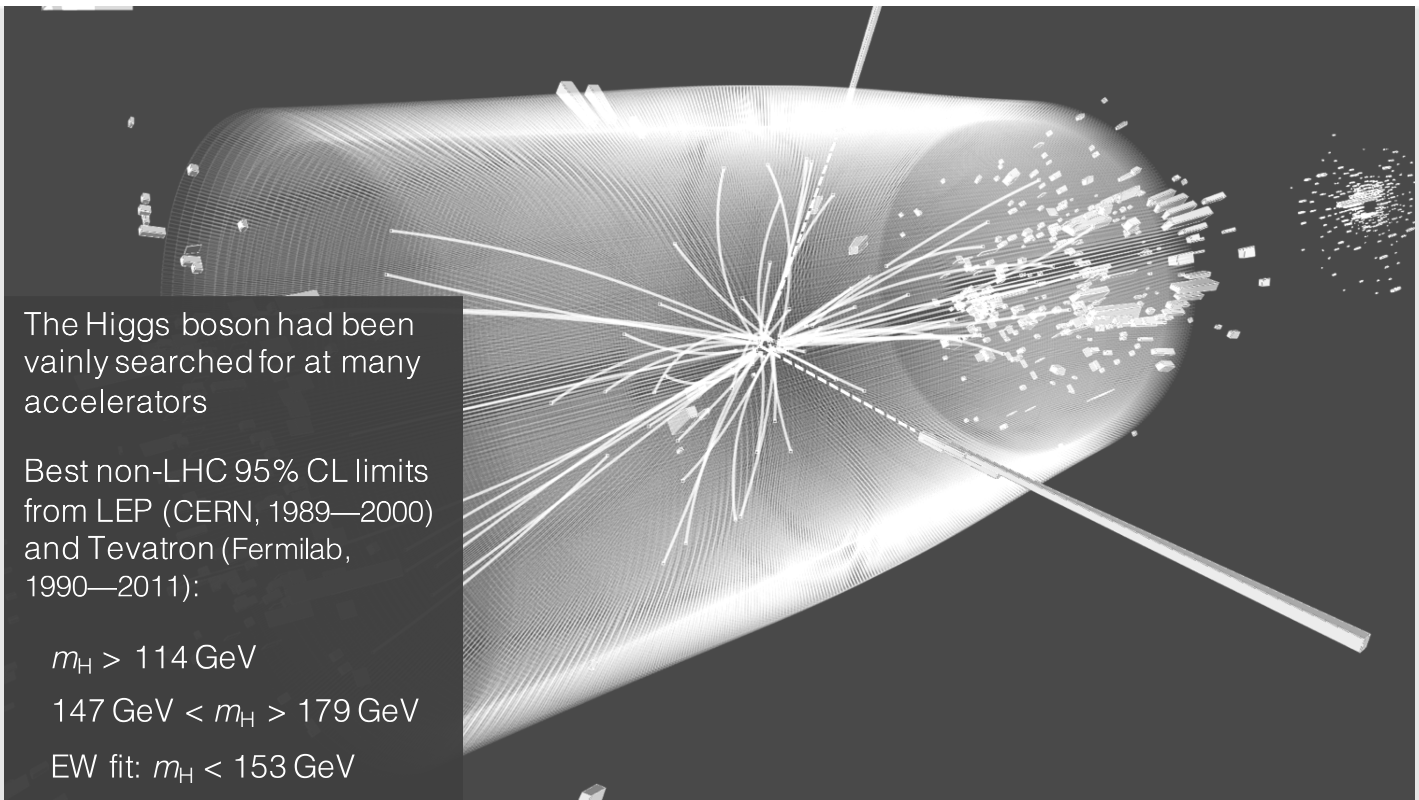
No W mass measurement from LHC yet

Competitive top mass results from the LHC





Higgs Boson — Run-1 Masterpiece



The Higgs boson had been vainly searched for at many accelerators

Best non-LHC 95% CL limits from LEP (CERN, 1989—2000) and Tevatron (Fermilab, 1990—2011):

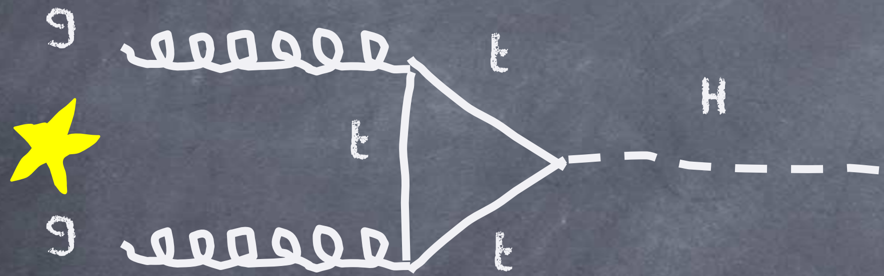
$m_H > 114$ GeV

147 GeV $< m_H >$ 179 GeV

EW fit: $m_H < 153$ GeV

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

Cross section steeply falling with Higgs mass



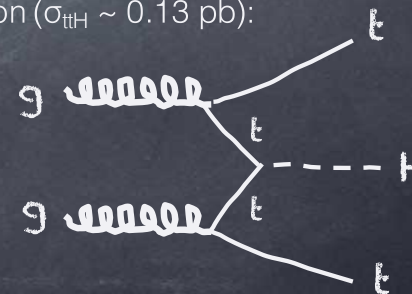
$\sigma_{H,ggF}$ ~ 19 pb

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

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

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

“ttH” production (σ_{ttH} ~ 0.13 pb):

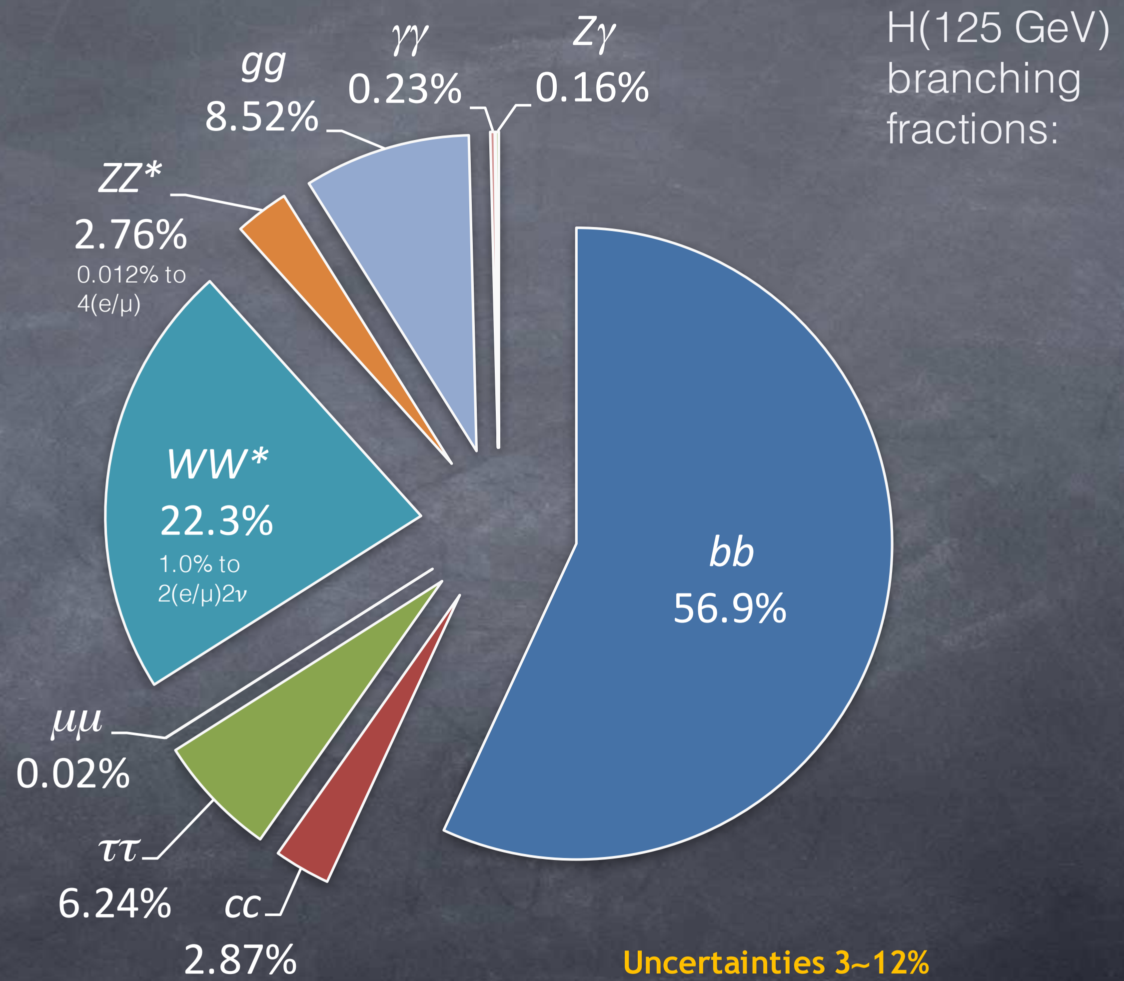


Higgs boson decay

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*)



Higgs boson decay

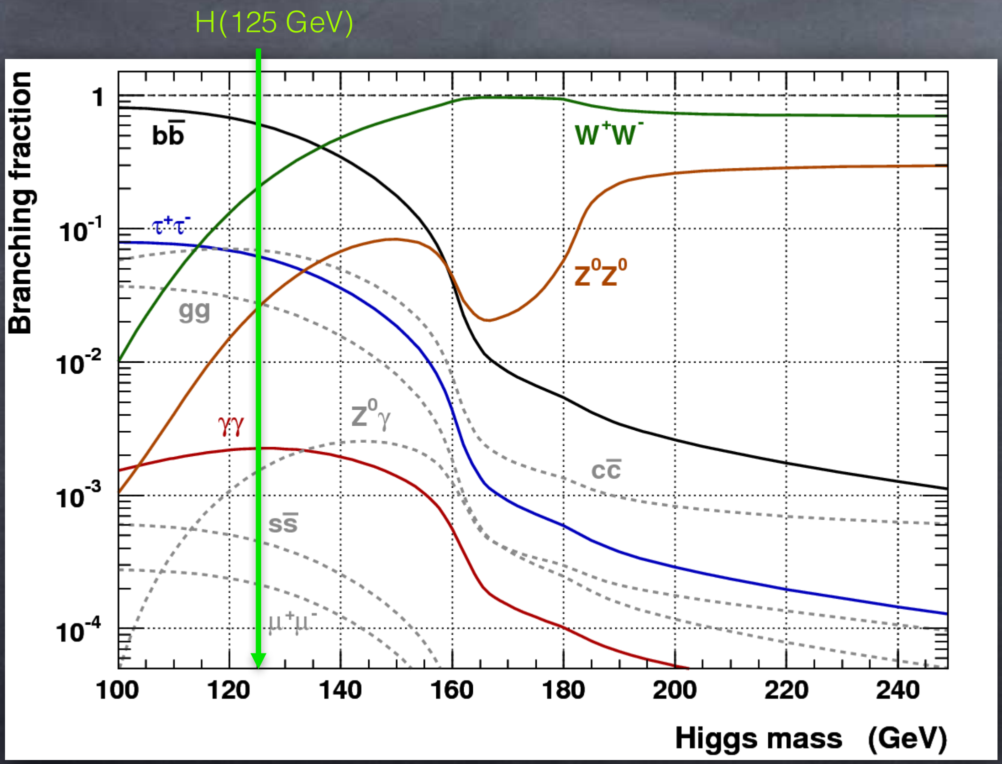
Leptonic (e/μ) and photonic final states provide best discovery significance

- $H \to \gamma\gamma$ / $ZZ^*(\to 4\ell)$ have best mass resoluton
- $H \to WW^* \to 2\ell 2\nu$ good trigger, sustainable background level, and large branching fraction

H(125 GeV)

Decay channel	Mass resolution
$H \to \gamma\gamma$	1–2%
$H \to ZZ^* \to 4\ell$	1–2%
$H \to WW^* \to 2\ell 2\nu$	20%
$H \to bb$	10%
$H \to \tau\tau$	15%

Higgs boson production at the LHC



At m_H = 125 GeV, many decays experimentally accessible!

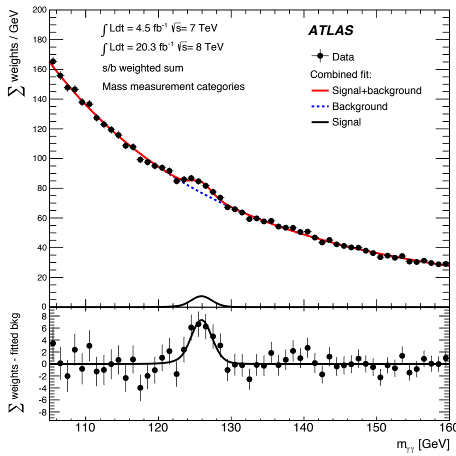
The phenomenological aspects of that mass might seem less appealing

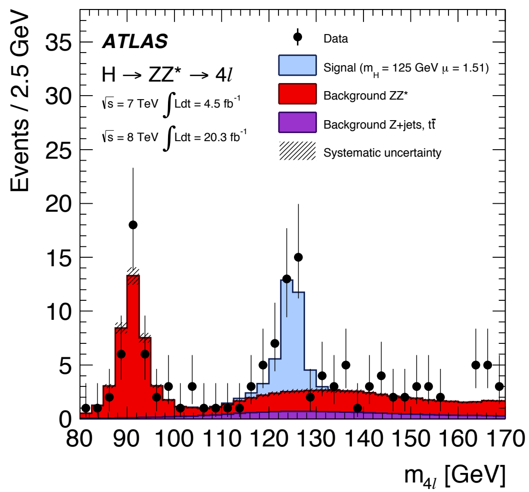
The dominant $H \rightarrow bb$ mode is only exploitable in association with *W/Z* or *tt*, also with strong Higgs boost

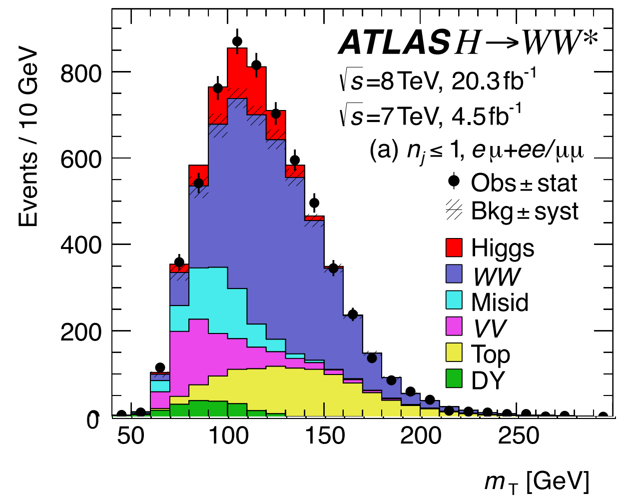
Associated leptons provide trigger signal as they help to reduce huge QCD background, $\sigma(bb)$ ~ O(100 μb)

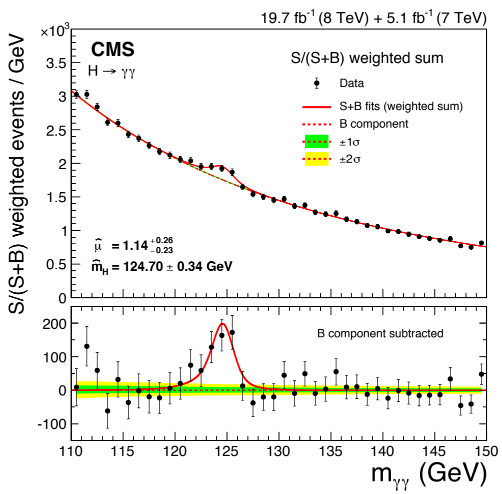
No doubt on H_{125} discovery in the bosonic channels

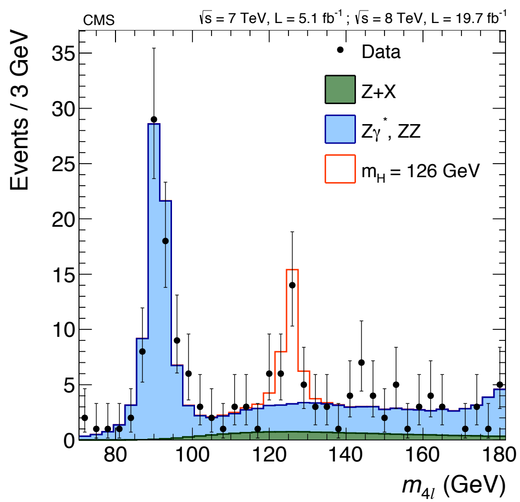
$H \to \gamma\gamma$	$H \to ZZ^{(*)} \to 4\ell$	$H \to WW^{(*)} \to 2\ell 2\nu$

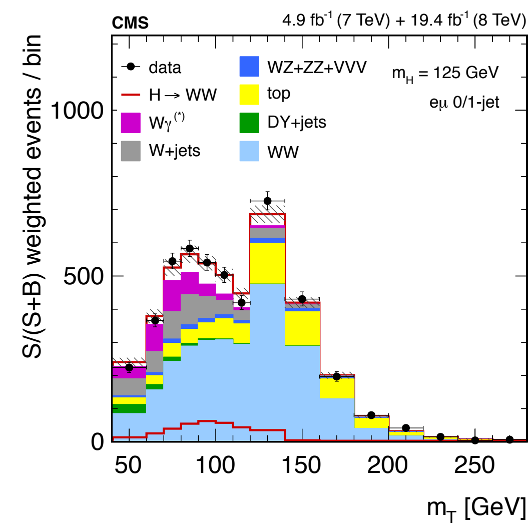












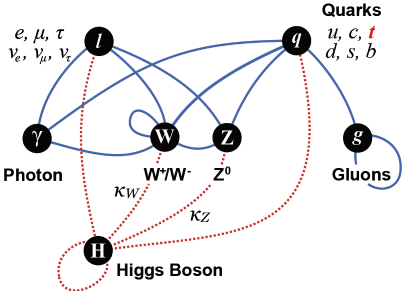
Very different experimental challenges in each of these discovery channels.
All analyses significantly improved since July 2012

Combined Higgs analysis and a flurry of property measurements

ATLAS & CMS Combinations of Higgs mass and coupling measurements

[1503.07589, 1606.02266]

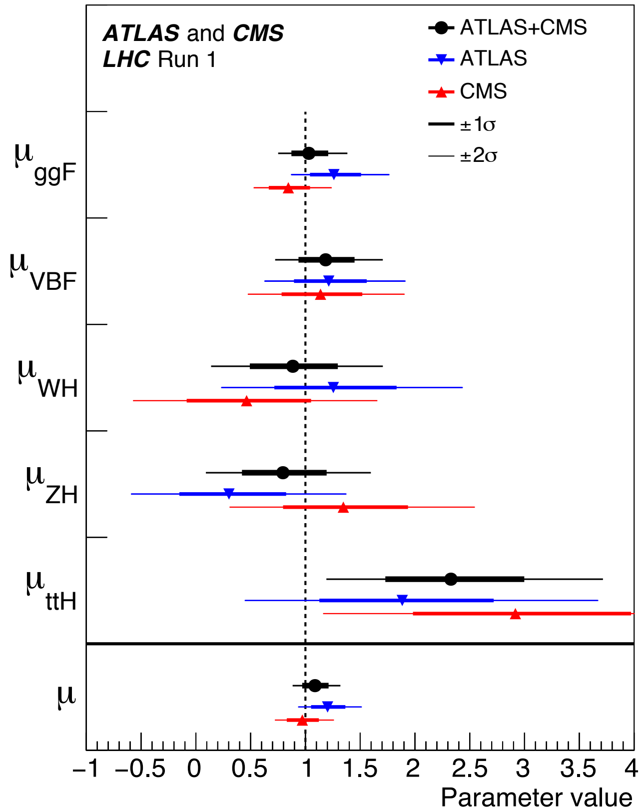
$m_H = 125.09 \pm 0.21_{stat} \pm 0.11_{syst}$ **GeV**



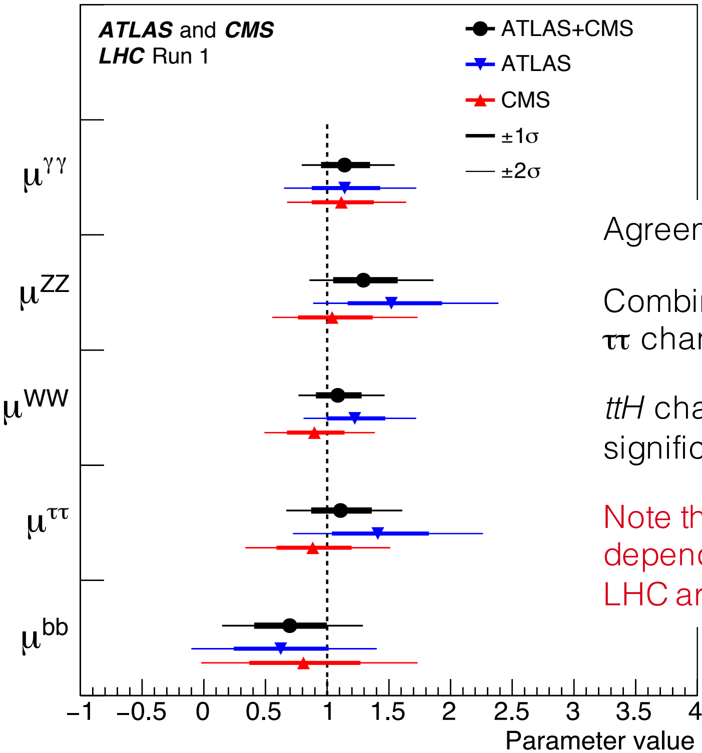
Also:

- Differential cross-section measurements
- Limit on Γ_H from off-shell to on-shell coupling ratio
- Limit on invisible Higgs branching ratio of < 25% [1509.00672, 1404.1344]
- Constraints on anomalous off-shell coupling or spin/CP, forbidden decays (FCNC) and other scalar particles (BSM Higgs)

Higgs production processes



Higgs decay processes



Agreement among experiments

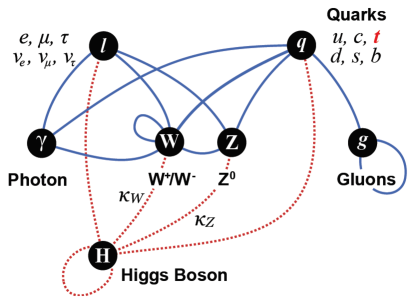
Combined observation of $H \to \tau\tau$ channel and VBF production

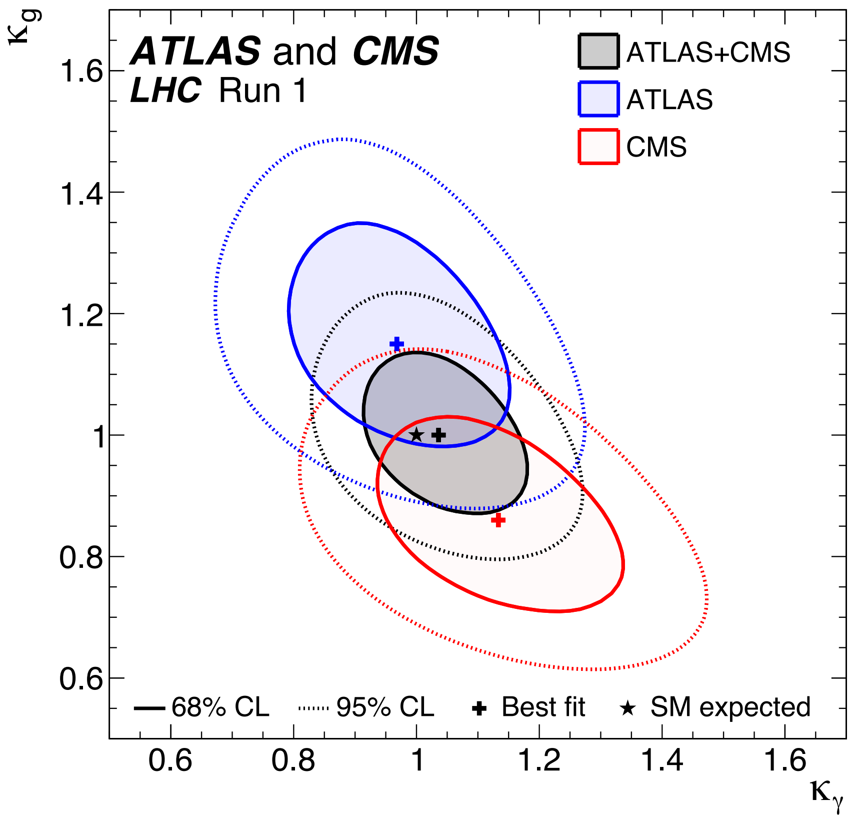
ttH channel a bit large: 4.4σ significance (2.0 exp), μ = 2.3

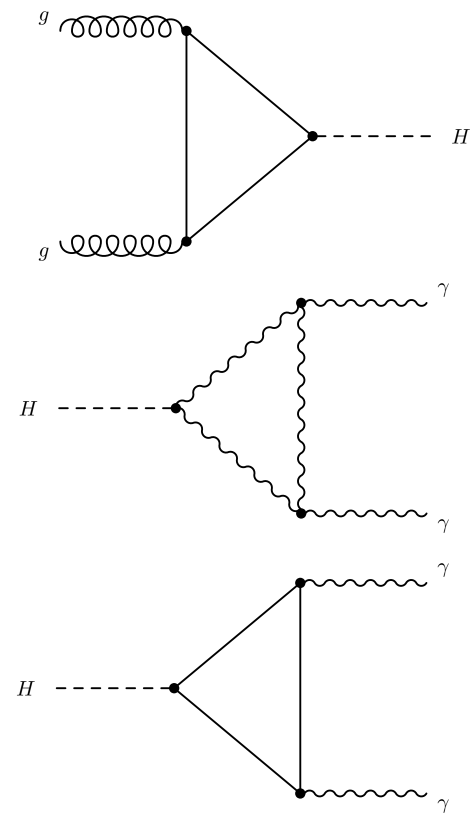
Note that the least model-dependent observables at the LHC are **ratios of couplings**

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)

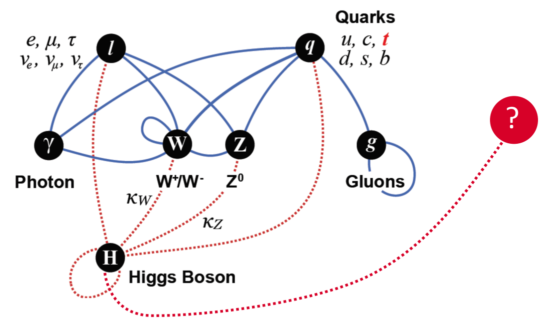
Higgs as BSM portal

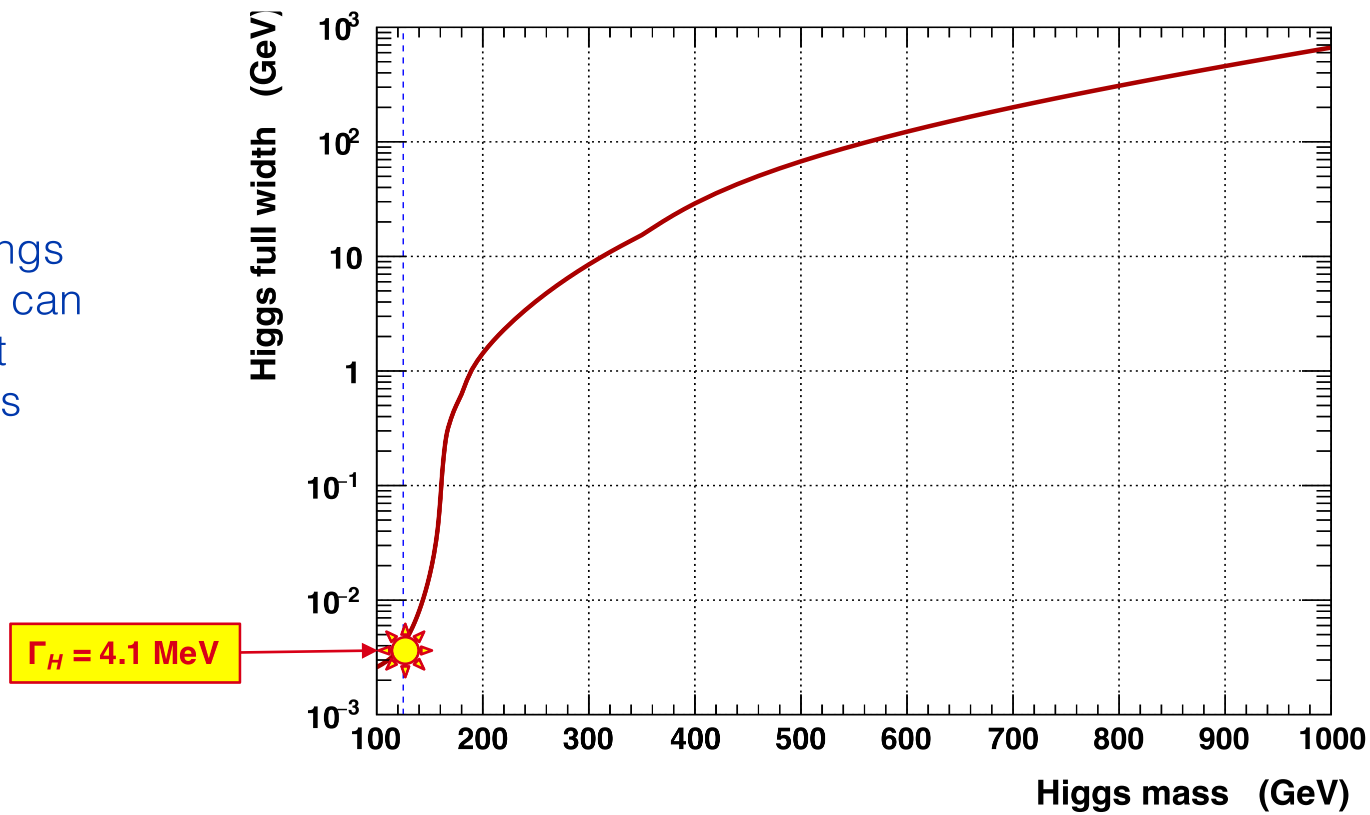
Higgs is narrow: 4.1 MeV

For comparison:

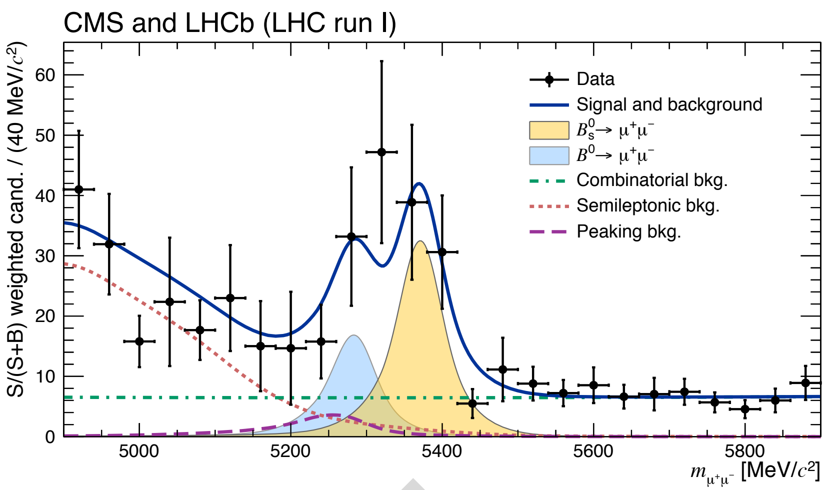
Γ_W = 2.1 GeV
Γ_Z = 2.5 GeV
Γ_{top} = 1.3 GeV

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





Flurry of results from LHCb [~300 papers to date]



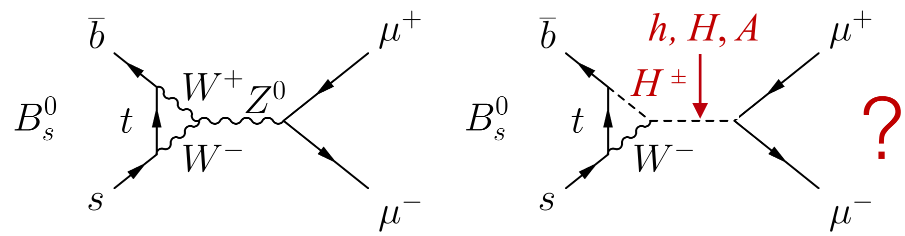
CMS & LHCb: observation of $B_s \to \mu\mu$

[Nat. 522 (2015) 68]

ATLAS Run-1 result ~2σ below SM

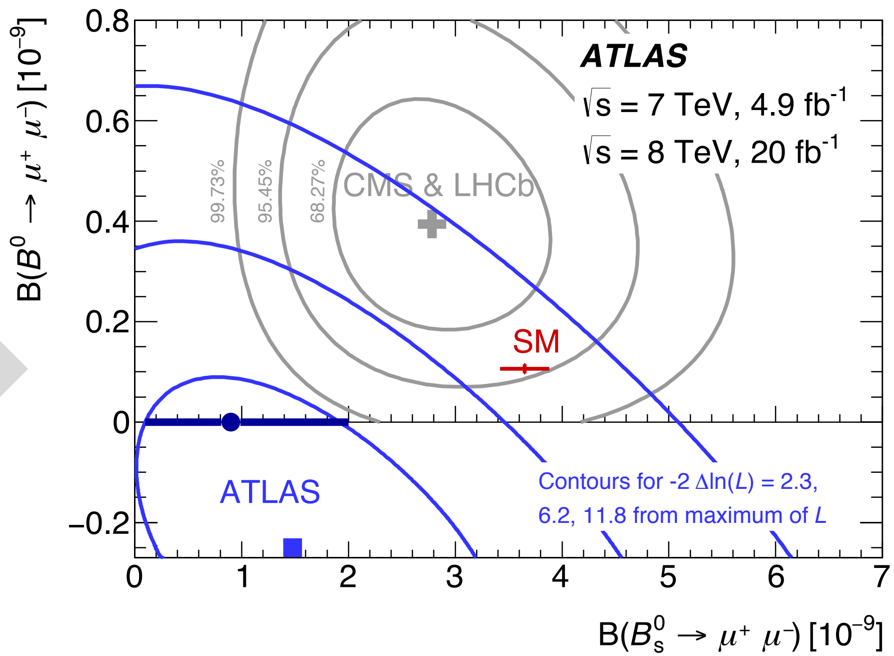
[1604.04263]

Does the Higgs boson has brothers and sisters?



$B_s \to \mu\mu$ is loop process (no tree-level FCNC) that is in addition CKM & helicity suppressed

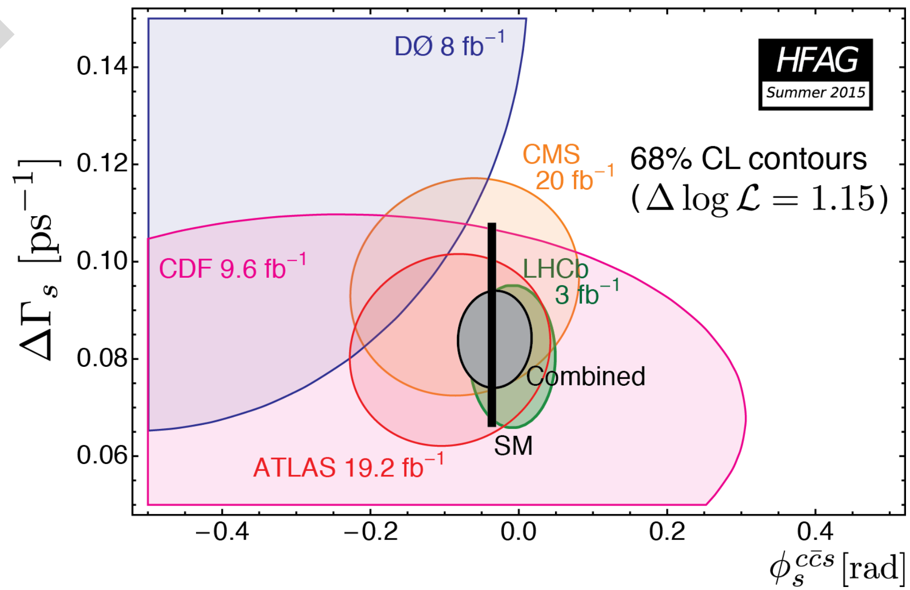
SM: $3.7 \pm 0.2 \times 10^{-9}$



Flurry of results from LHCb [~300 papers to date]

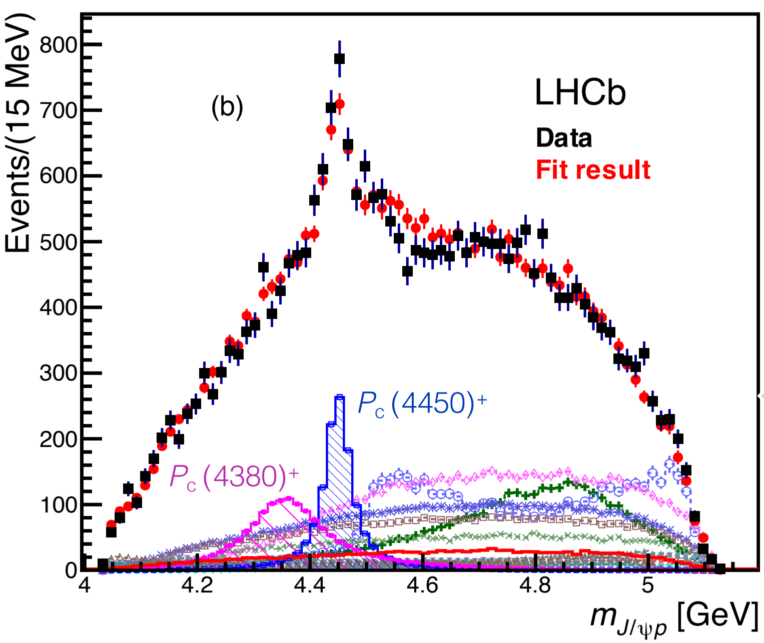
Precision measurement of ϕ_s

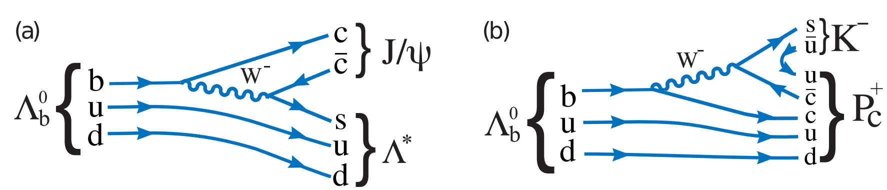
[PRL 114, 041801 (2015): $\phi_s = -0.010 \pm 0.039$]

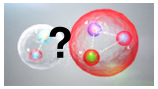


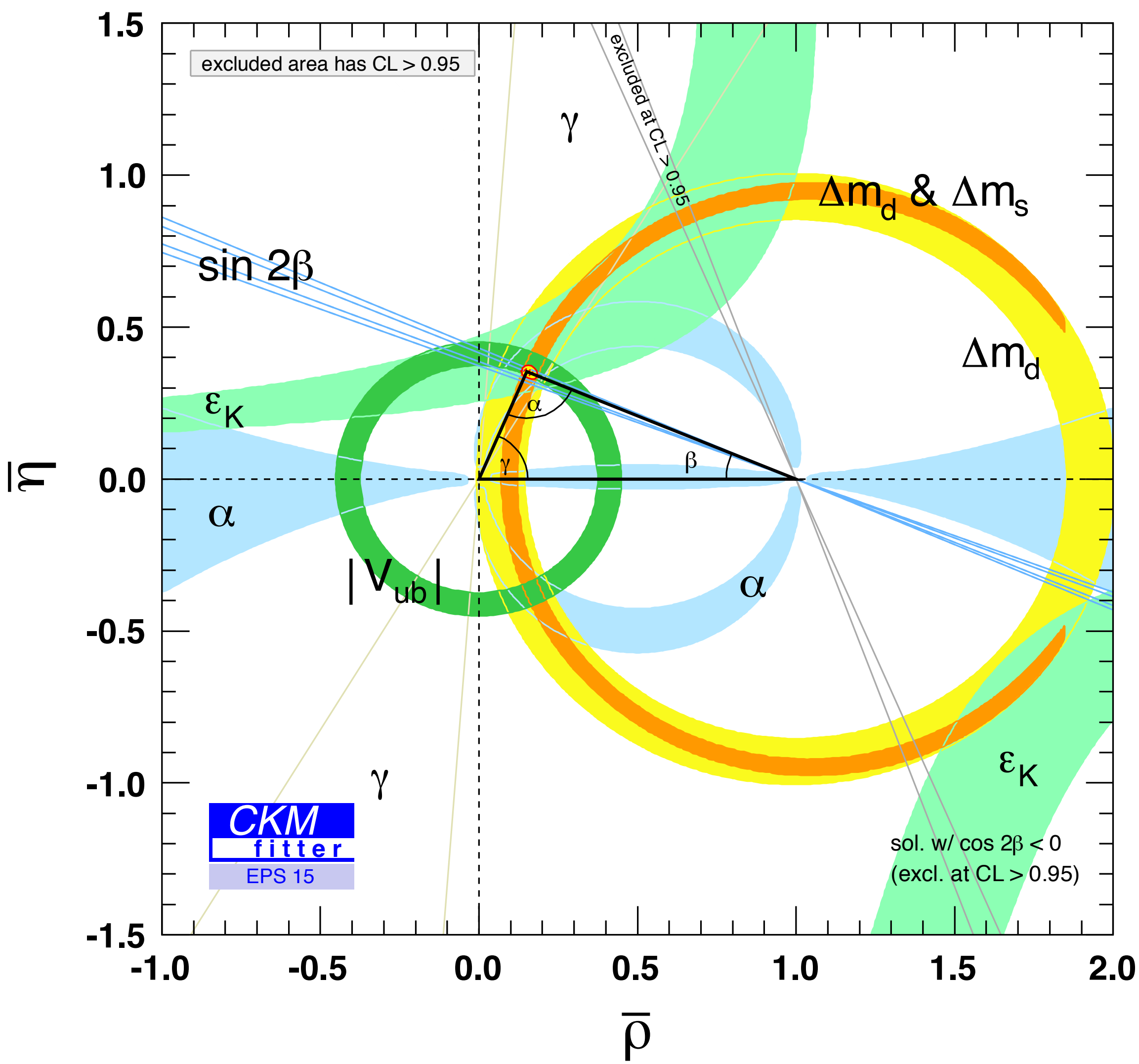
Observation of new states consistent with pentaquarks

[PRL 115, 072001 (2015)]





 or  or … ?



Long-term effort to *overconstrain* CKM matrix continues (phase value itself "accident" of nature?).

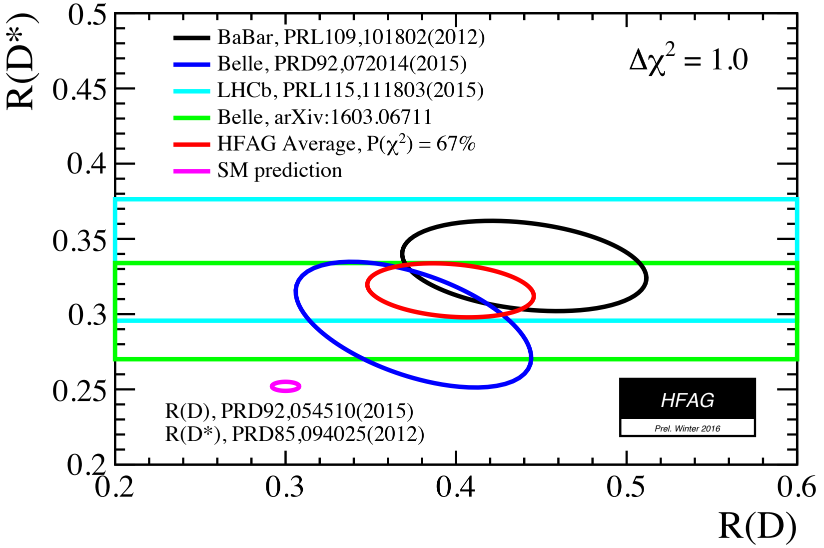
Huge contributions from LHCb:

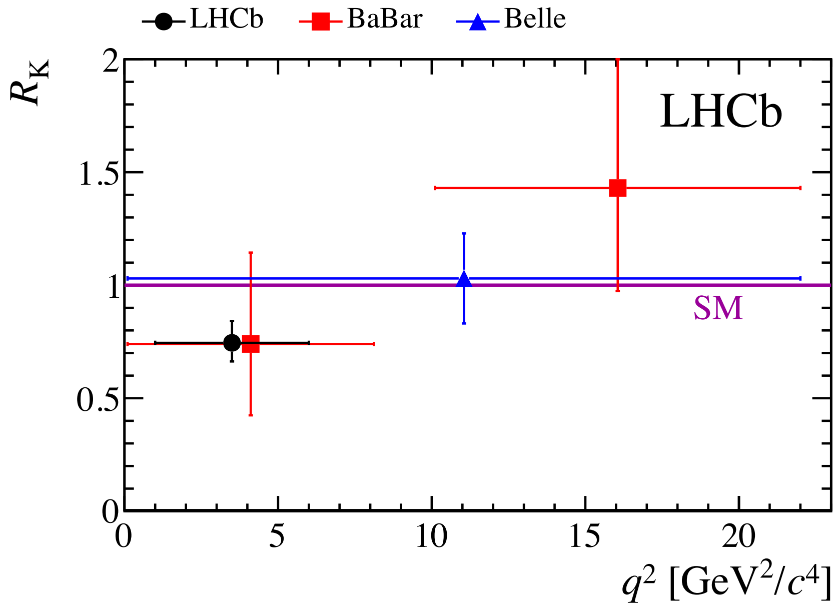
- Measurements of γ, sin(2β), $|V_{ub}|$, $\Delta m_{s/d}$ from LHCb
- World's best constraints on CP violation in $B^0_{(s)}$ mixing (a_{sl}^s, a_{sl}^d) in agreement with SM (D0 sees 3.6σ deviation)

Is the CKM phase an "accident of nature"?

B-factories and LHCb measure ratios of semileptonic B decays. Robust SM predictions

$$R_{D^{(*)}} = \frac{\mathrm{BR}(B^0 \to D^{(*)}\tau\nu)}{\mathrm{BR}(B^0 \to D^{(*)}\ell\nu)} \qquad R_K = \frac{\mathrm{BR}(B^+ \to K^+\mu\mu)}{\mathrm{BR}(B^+ \to K^+ee)}$$



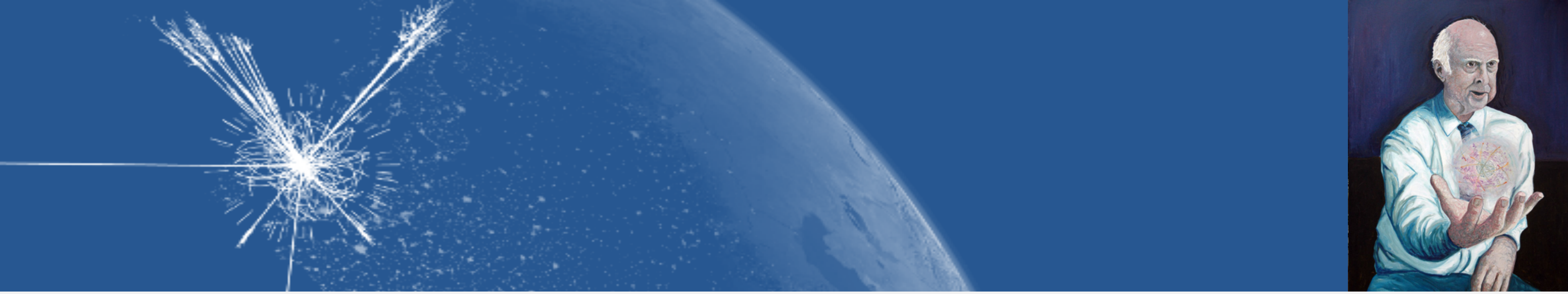


Latest measurement by Belle using semileptonic tagging of recoil B (Moriond EW):

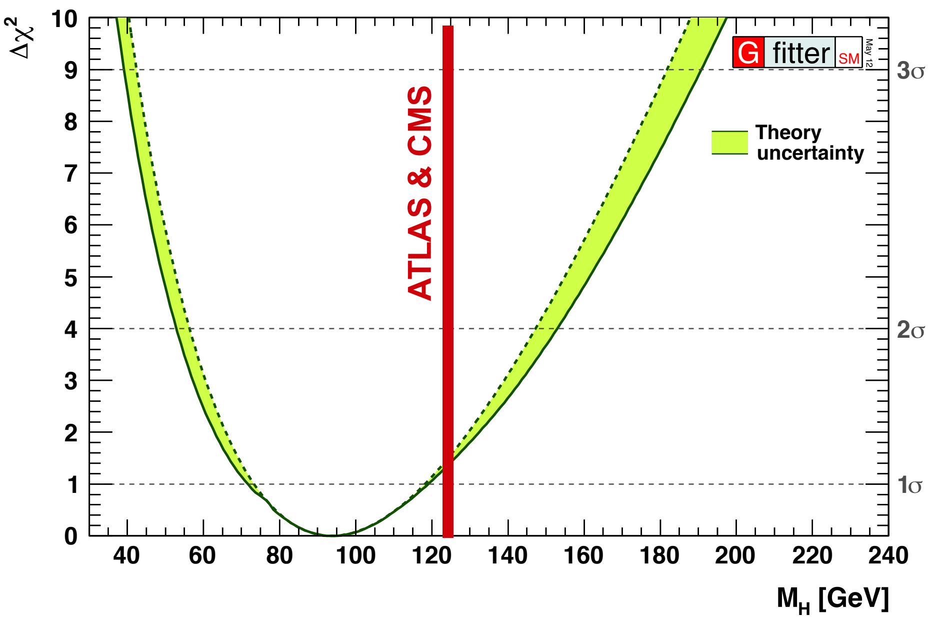
$\boldsymbol{R_{D^*} = 0.302 \pm 0.030_{stat} \pm 0.011_{syst}}$ [SM: 0.252 ± 0.003, 1.6σ]

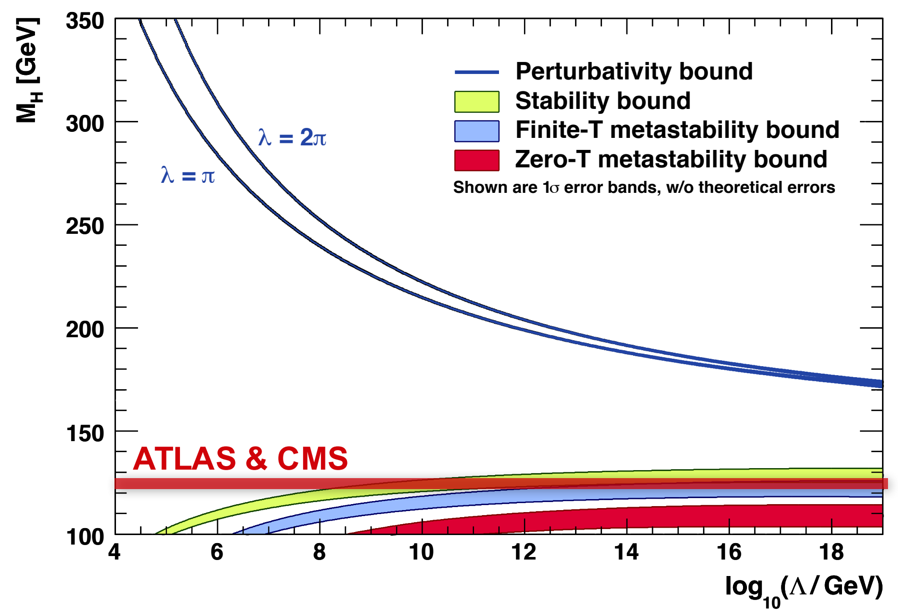
World average by HFAG: R_{D^*} = 0.316 ± 0.016 ± 0.010 (3.3σ from SM, combined R_{D^*} & R_D is 4.0σ)

http://www.slac.stanford.edu/xorg/hfag/semi/winter16/winter16_dtaunu.html



Since the LHC Run-1 the Standard Model is complete





Since the LHC Run-1 the Standard Model is complete

It is a triumph for the imagination and rigour of the scientific endeavour

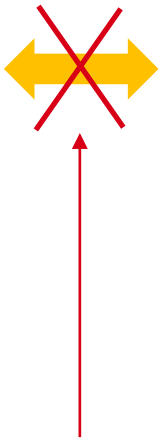
It is a triumph for the greatest experimental undertaking ever:

- Frontier of accelerator & detector technologies
- Global data sharing, analysis & collaboration

Two beautiful, extremely precise theories

The Standard Model of EW and strong interactions

Predicting the anomalous magnetic moment of the electron to a relative precision of 10^{-10} in agreement with experiment



General relativity — theory of gravitation

Tested up to an accuracy of order 10^{-5} (Cassini probe)

Unfortunately, the SM and general relativity don't work in regimes when both are important (ie, at very small scales)

Many open questions remain…

Scalar sector

- Single doublet or more
- Elementary or composite
- Form of potential
- Origin of Yukawa couplings

Quarks and leptons

- Origin of families, mass, mixing, CPV
- Matter–antimatter asymmetry
- Baryon and lepton number conservation (proton decay)

Dark matter

- Composition: WIMP, axions, sterile neutrinos, hidden sector particles, gravitational effect only
- Single or multiple sources

Neutrinos

- Origin and values of neutrino masses
- Nature: Majorana or Dirac
- CP violation
- Sterile neutrinos

Expansion of Universe

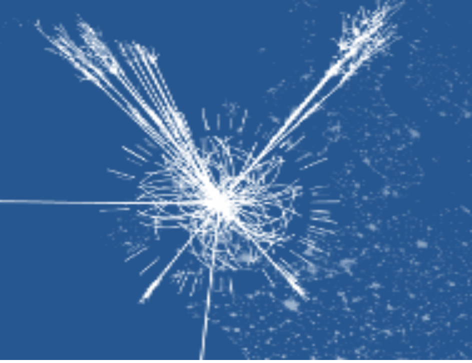
- Primordial expansion via inflation; which fields, role of quantum gravity?
- Accelerated expansion today: cosmological constant problem

High-scale physics

- Hierarchy problem and new physics at TeV scale
- Grand unification of forces
- Unification with gravity
- Quantum gravity, string theory

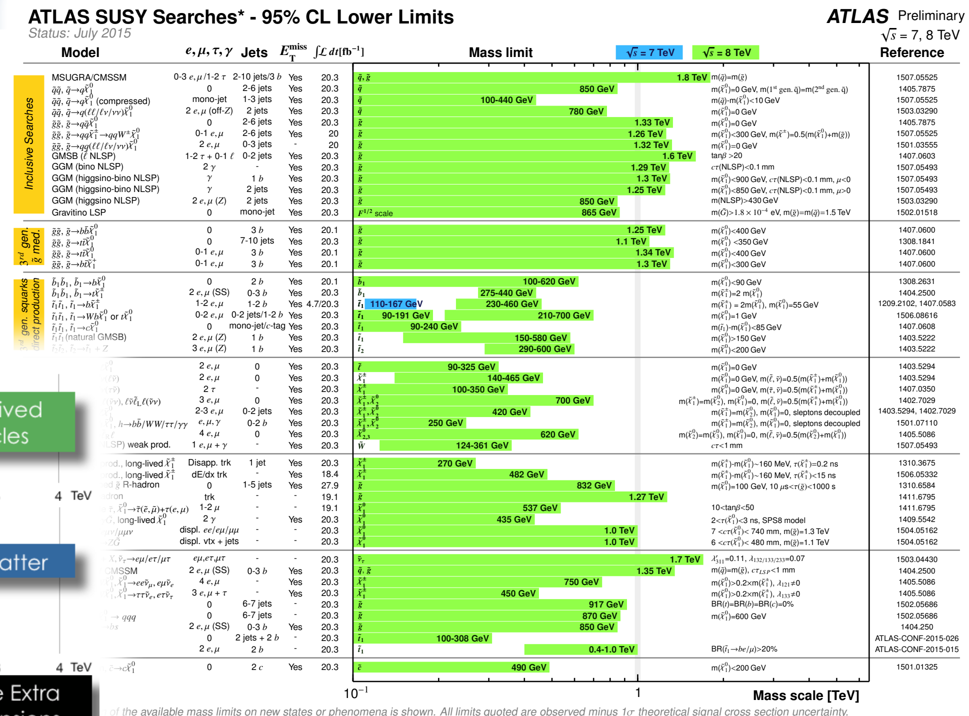
Strong CP problem

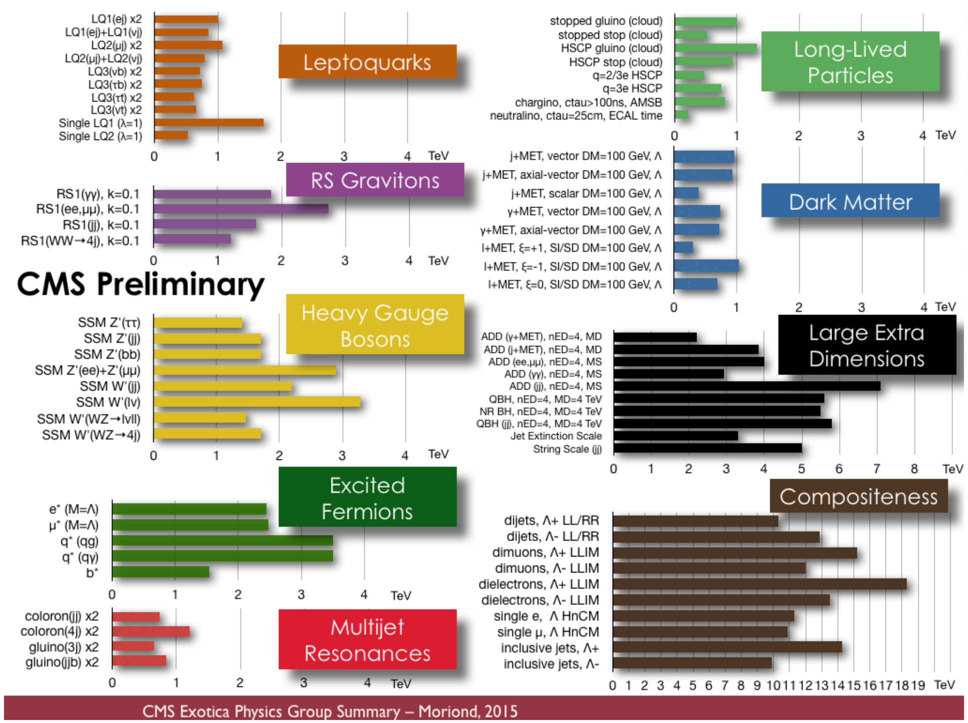
It therefore seems that the SM isn't all there is



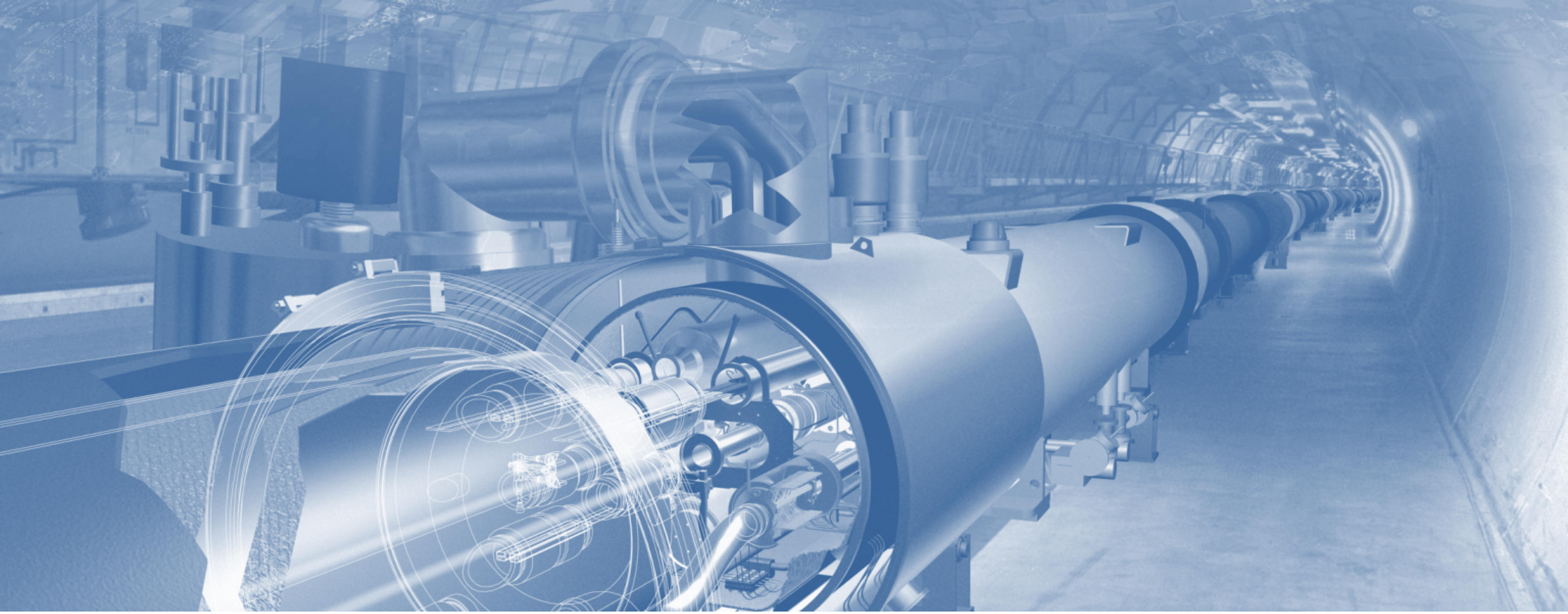
Vast amount of BSM searches

Theory-agnostic, signature based searches, as well as highly targeted model-dependent ones

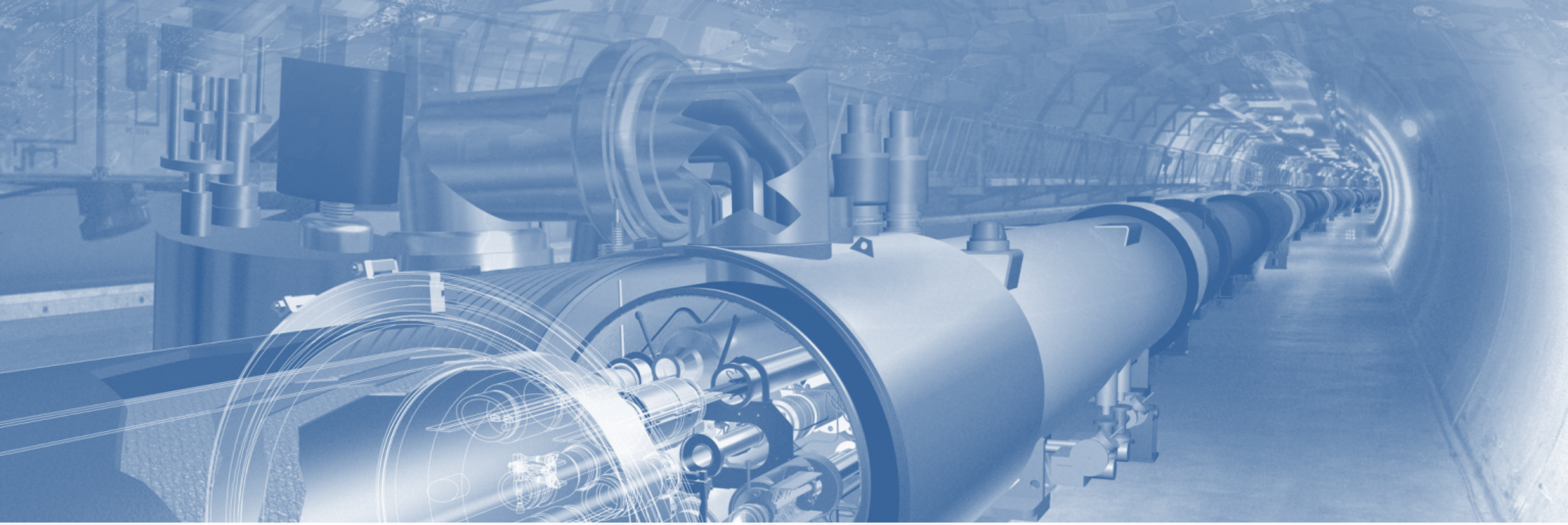




No significant anomaly seen so far



The LHC Run-2 at 13 TeV and beyond



The LHC Run-2 at 13 TeV

Huge milestone achieved in 2015 with record proton–proton collision energy of 13 TeV

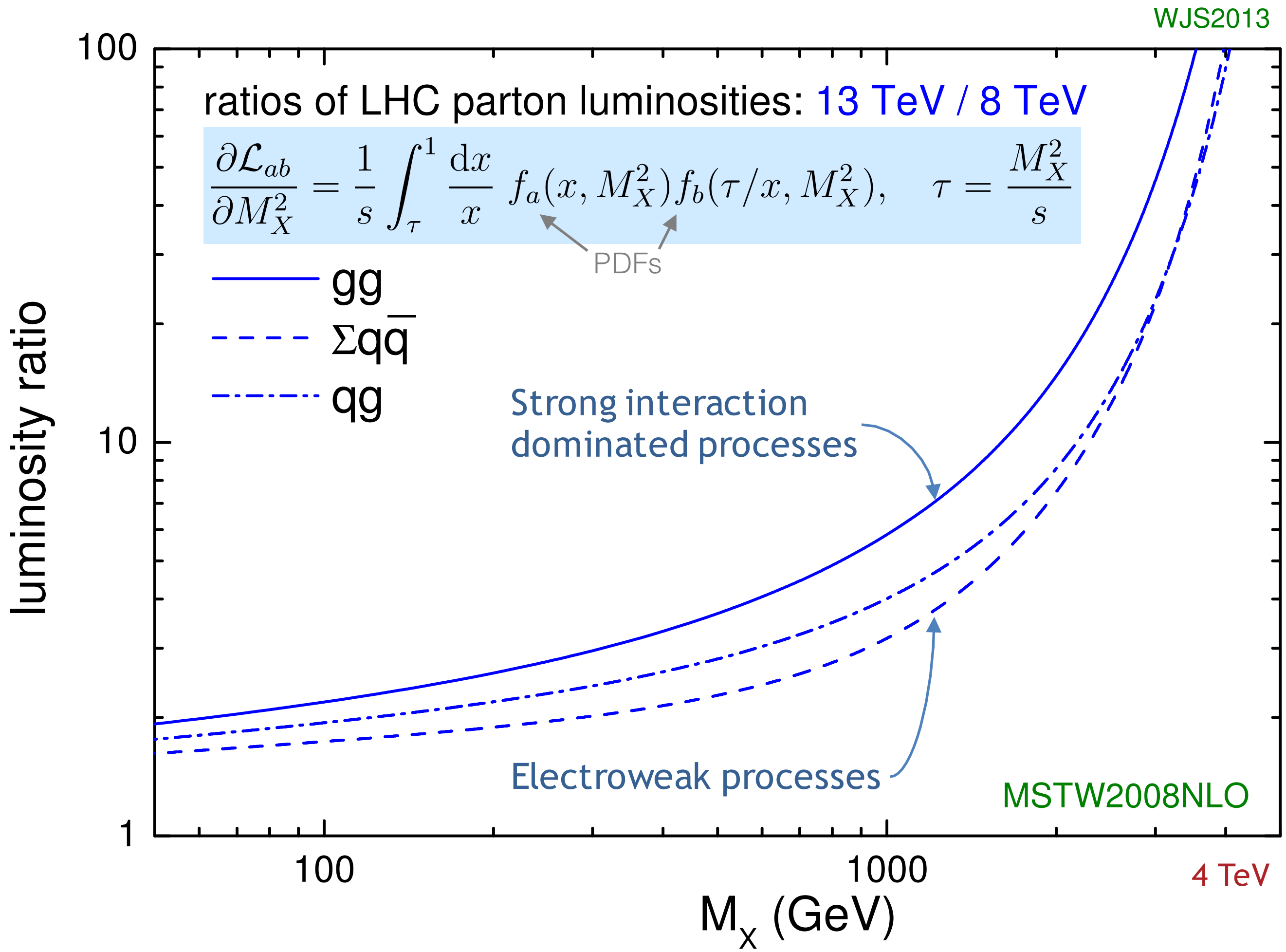
After a rocky start, the LHC delivered $L_{\mathrm{int}} = 4.2\ \mathrm{fb}^{-1}$

That luminosity already surpassed the Run-1 new physics sensitivity of many searches

During 2016 reached peak $1.2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and expect 35~40 fb^{-1} total delivered

Excellent machine efficiency!

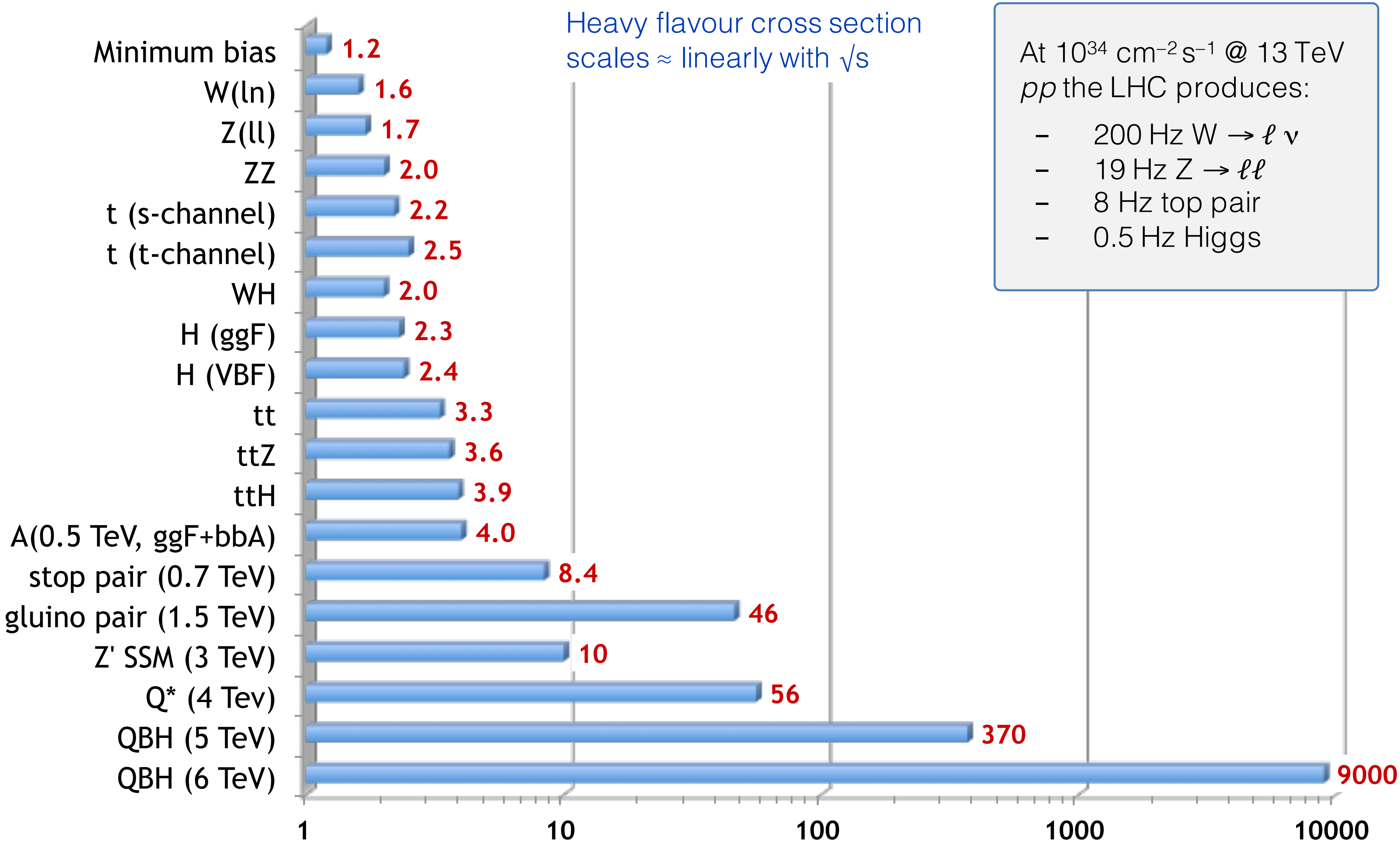
The LHC Run-2: 13 TeV / 8 TeV inclusive "parton luminosity" ratio



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

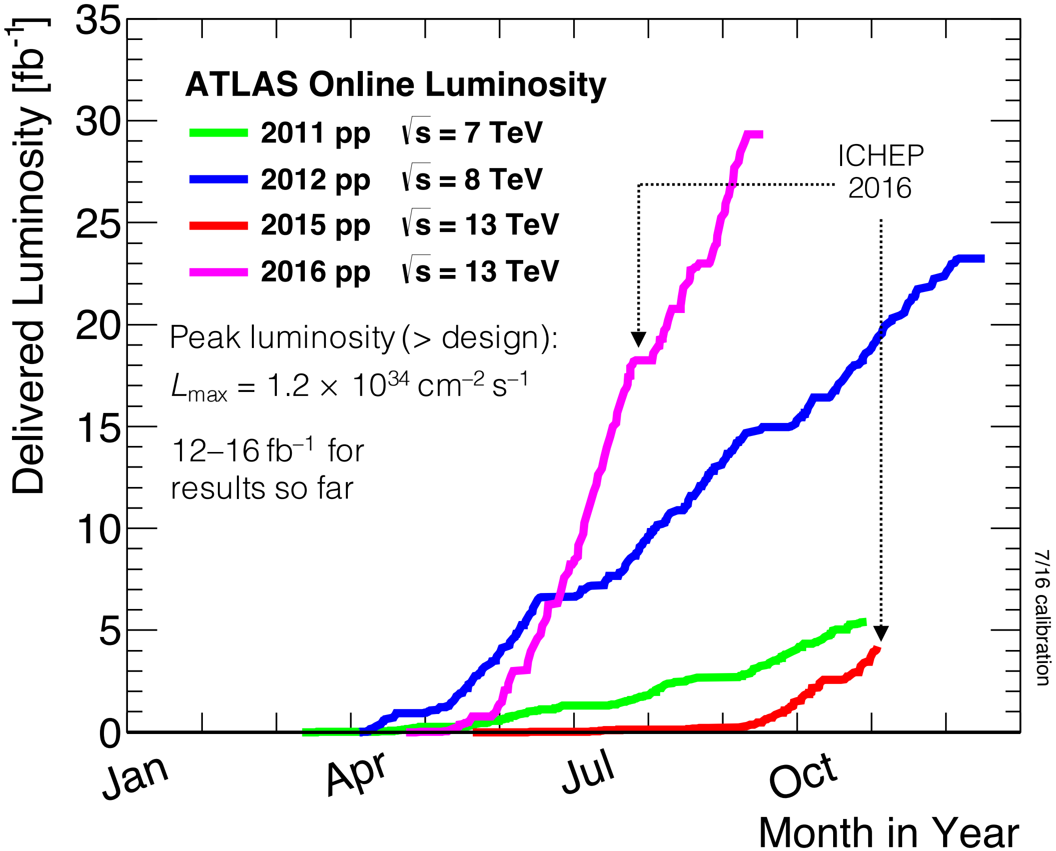


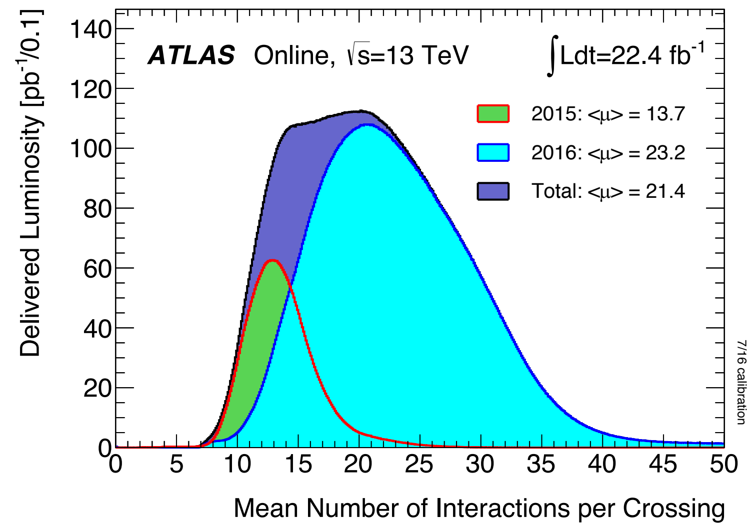
At 10^{34} $cm^{-2}s^{-1}$ @ 13 TeV *pp* the LHC produces:

- 200 Hz W → $\ell\, \nu$
- 19 Hz Z → $\ell\ell$
- 8 Hz top pair
- 0.5 Hz Higgs

2015 LHC proton–proton luminosities

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



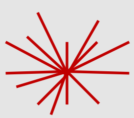


2015 and 2016 pileup profile in ATLAS & CMS
(LHCb mean pileup of ~1.7 due to levelling)

LHCb after luminosity levelling: 1.3 (1.5) fb^{-1} recorded (delivered)

Current luminosity precision from van-der Meer scans: 2.9% (ATLAS), 2.3% (CMS), 3.8% (LHCb)

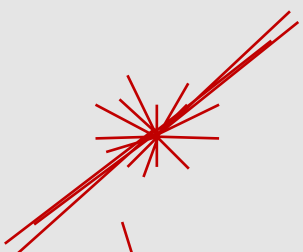
Standard Model and top physics results



Soft QCD: particle spectra

p_T < few GeV, > 99.999% of collisions

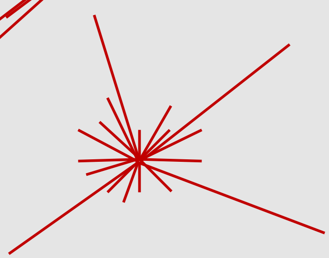
Probe LO matrix, parton shower models, generator tunings, pileup modelling



Hard QCD: jets

p_T > tens of GeV up to TeV, ~10^{-5} of collisions

Probe NLO QCD, running α_s, PDF, parton showers



Hard QCD & electroweak: W, Z, H, top → identified particles

p_T > tens of GeV, 10^{-6} ~ 10^{-8} of collisions

Probe NLO, NN(N)LO QCD, soft gluon resummation, PDF, electroweak physics

Standard Model and Higgs precision measurements

Key to the LHC programme up to the High-Luminosity LHC (HL-LHC)

Scientific perspective. No matter what BSM the LHC will unveil in the next years, improving the knowledge of Higgs properties is a must, which by itself requires and justifies the largest possible LHC statistics → stopping after 300 fb^{-1} will not be satisfying!

Pragmatic perspective. Higgs and SM physics are the only guaranteed deliverables of the LHC programme. Need to exploit this part of the programme to its maximum extent!

Utilitarian perspective. Elements of the SM, besides the Higgs, require further consolidation, control and improved precision, both in the EW and QCD sectors

- They hold a fundamental value (e.g. the precise determination of fundamental parameters), or are critical to fully exploit the BSM search potential (e.g. the knowledge of backgrounds, production rates and production dynamics)

Spinoffs. The study of SM processes at colliders is typically much more complex than that of BSM signatures (requires higher precision, larger final state multiplicities, etc), and in the years it has been the main driver of fundamental theoretical innovation

Taken from: Michelangelo Mangano @ SEARCH 2016

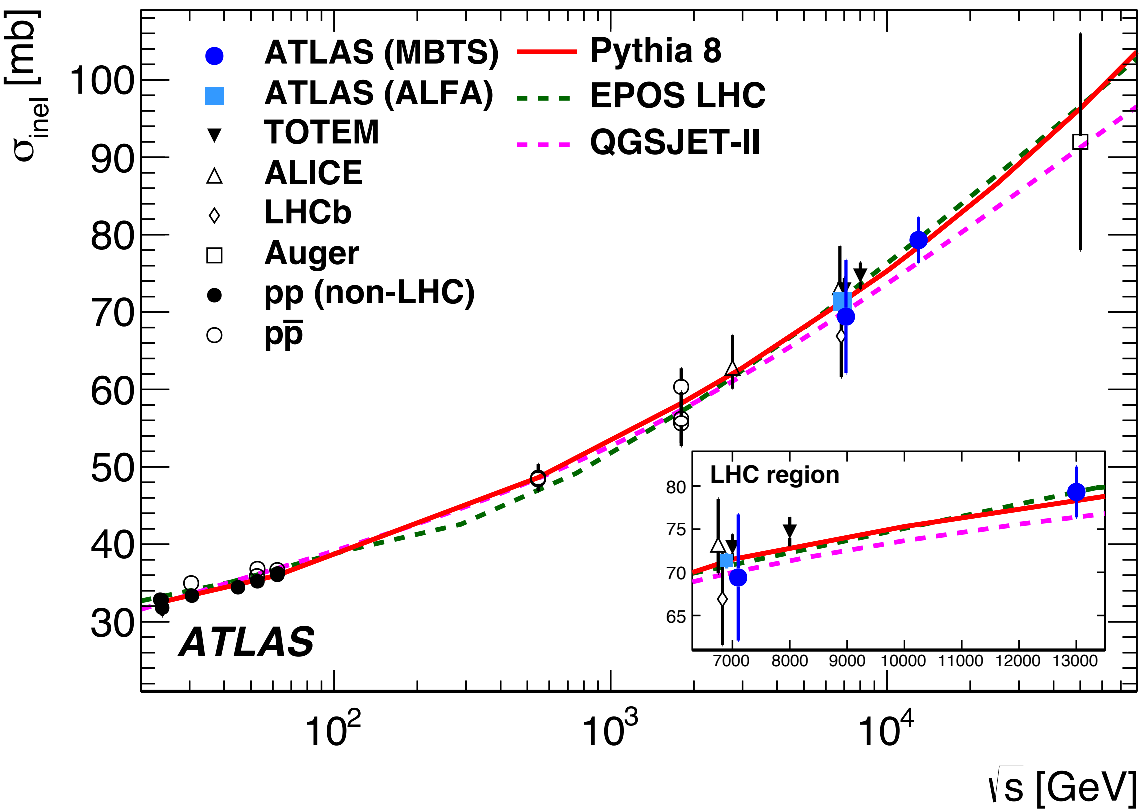
Inclusive inelastic cross-section measurement at 13 TeV

Fundamental initial measurement, based on forward scintillators

Measurement in fiducial region $\xi = M_X^2 / s > 10^{-6}$ (M_X largest mass of two proton-dissociation systems)

- Use Minimum Bias Trigger Scintillators (MBTS) with acceptance $2.07 < |\eta| < 3.86$, 4.2M selected events
- Systematic uncertainty fully dominated by luminosity

ATLAS: 1606.02625



Measured inclusive inelastic cross section:

$\sigma_{13\ \mathrm{TeV}} = 79.3 \pm 0.8 \pm 1.3\ (\mathrm{lumi}) \pm 2.5\ (\mathrm{extr})$ mb

Best measurement of total cross section via elastic scattering and optical theorem:

$\sigma_{tot} \propto \mathrm{Im}\ f_{elastic}(t \to 0)$

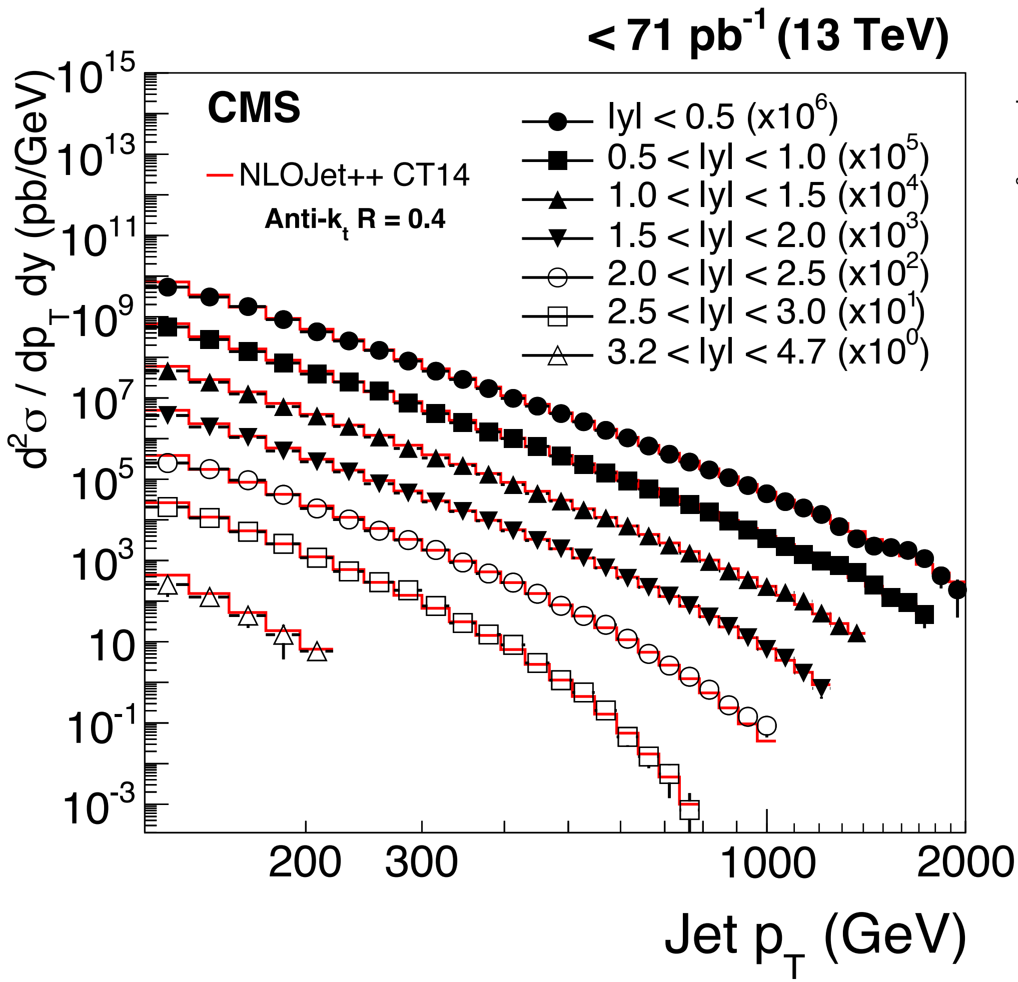
using dedicated forward devices (up to 1.4% precision in Run-1, dominated by luminosity error)

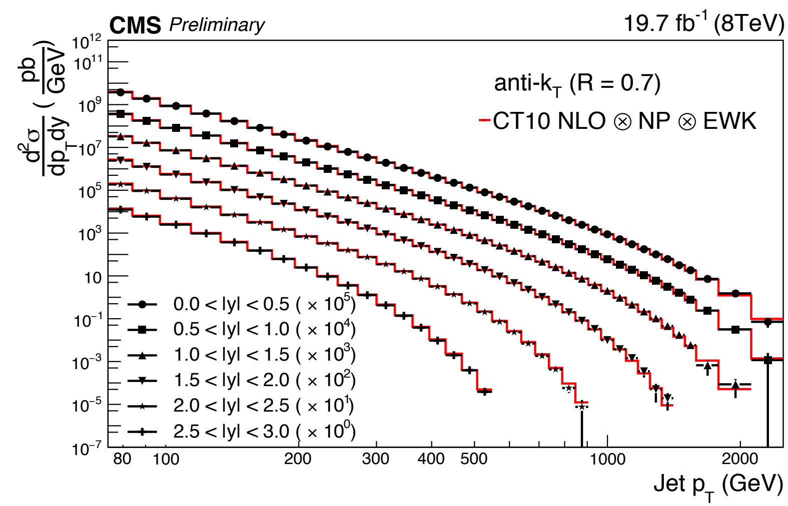
Measurement of jet cross section at 13 TeV

Primary test of QCD at highest collision energy

CMS 1605.04436

Double differential cross section measured by CMS





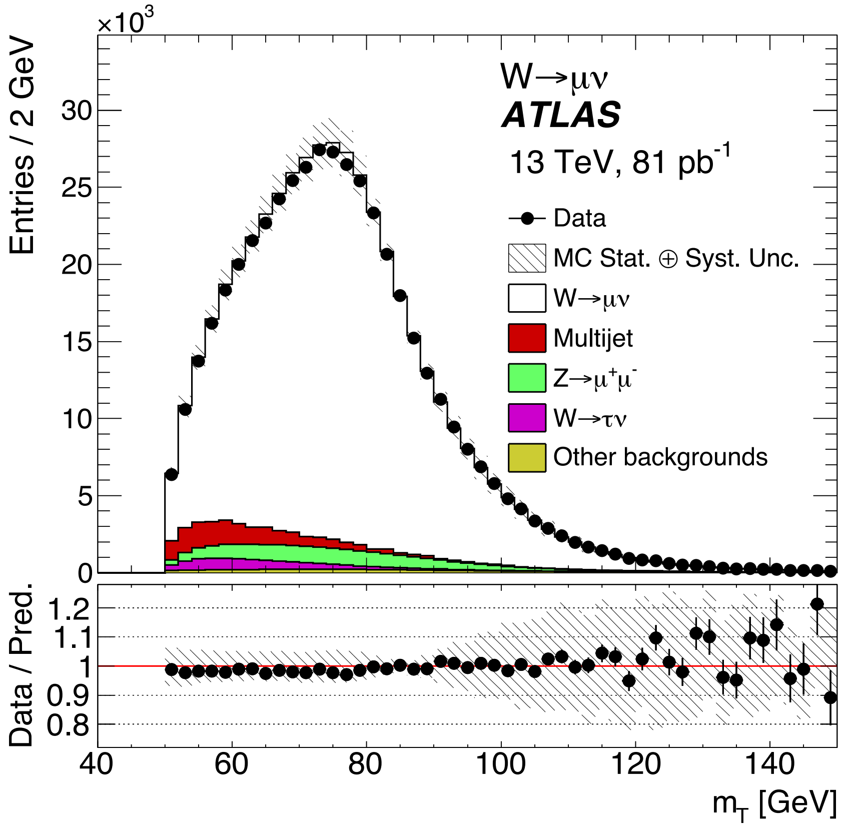
Comparison with 8 TeV plot (right) shows effect of increased parton luminosities at high jet p_T

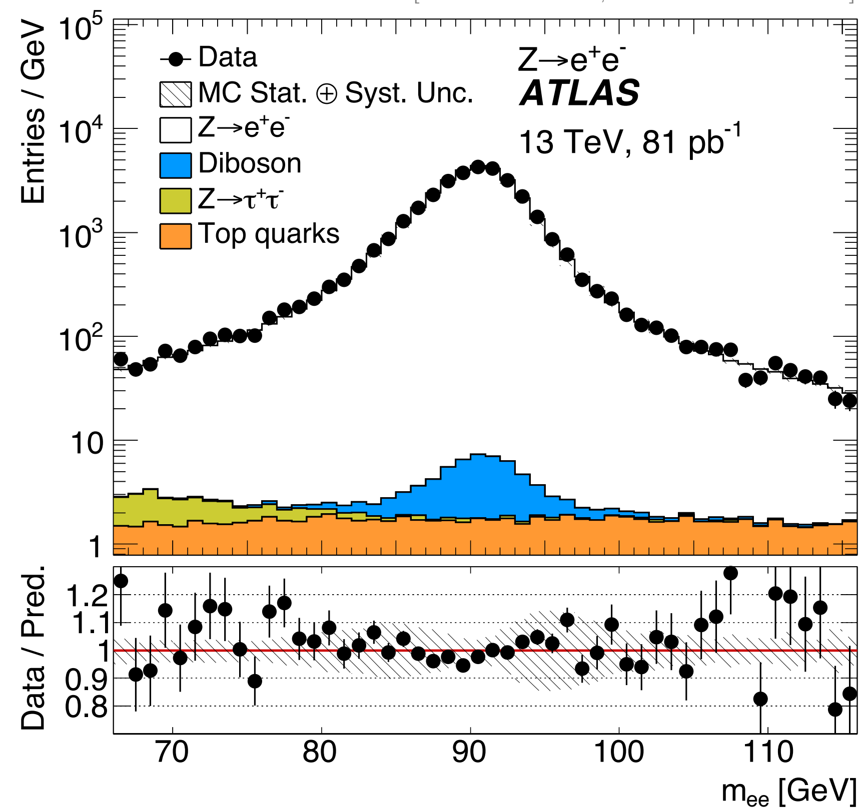
Z and W production at 13 TeV — examples: $\sigma_{Z\to\mu\mu}$ (13 TeV) ~ 1.9 nb, $\sigma_{W\pm\to\mu\nu}$ (13 TeV) ~ 19.7 nb

Expect increase of cross section by **factors of 1.7 and 1.6**, respectively

Pure channels. Leptonic decays of Z & W are also standard candles to calibrate e/μ performance

[ATLAS 1603.09222, CMS-PAS-SMP-15-004]





$$m_T = \sqrt{2p_{T,\ell}E_T^{\text{miss}}(1-\cos\Delta\phi_{\ell\nu})}$$

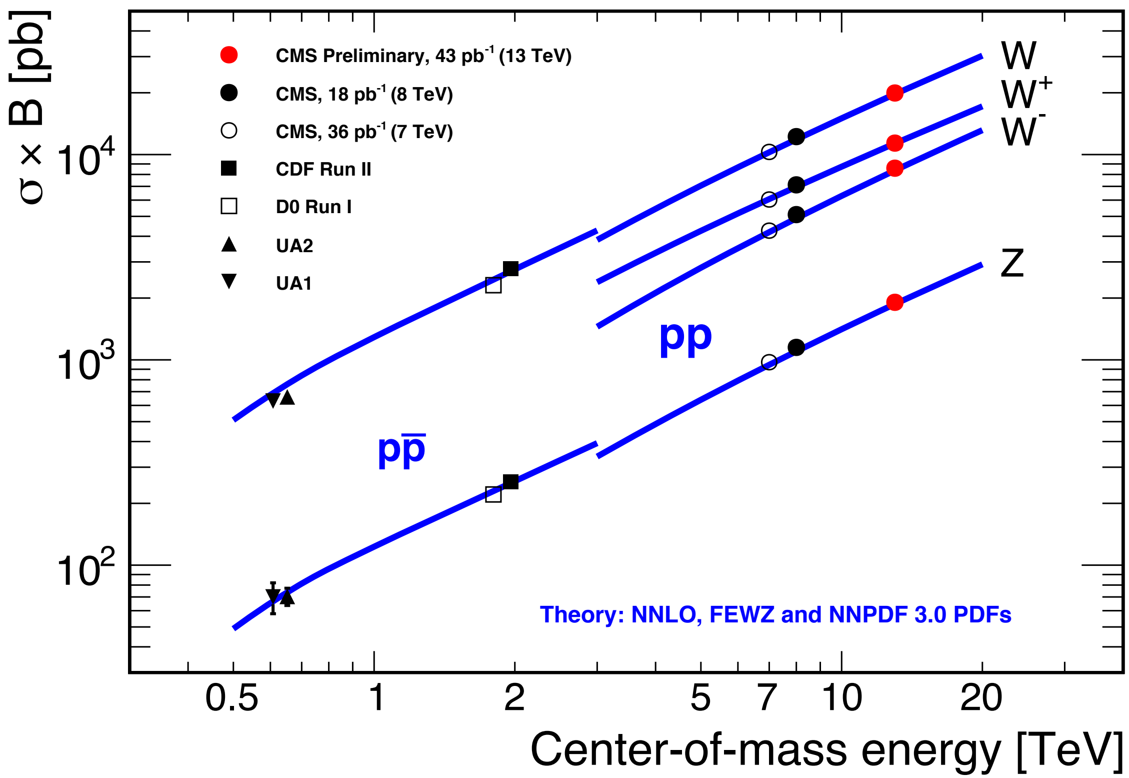
$$m_{e_1e_2} = \sqrt{2p_{T,1}p_{T,2}(\cosh\Delta\eta_{12}-\cos\Delta\phi_{12})}$$

Z and W production at 13 TeV

Expect increase of cross section by **factors of 1.7 and 1.6**, respectively

Inclusive cross sections shown, also **fiducial cross sections** measured

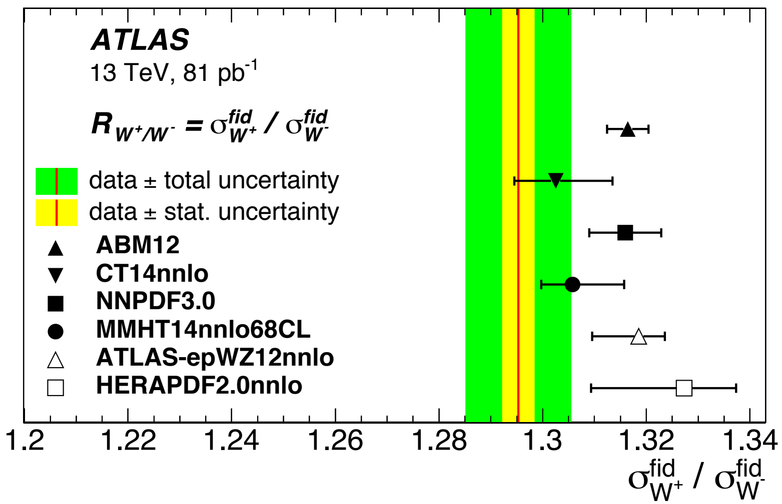
Comparison of measured cross-sections with NNLO QCD & NLO EW Drell-Yan predictions (FEWZ 3.1): good agreement found within uncertainties

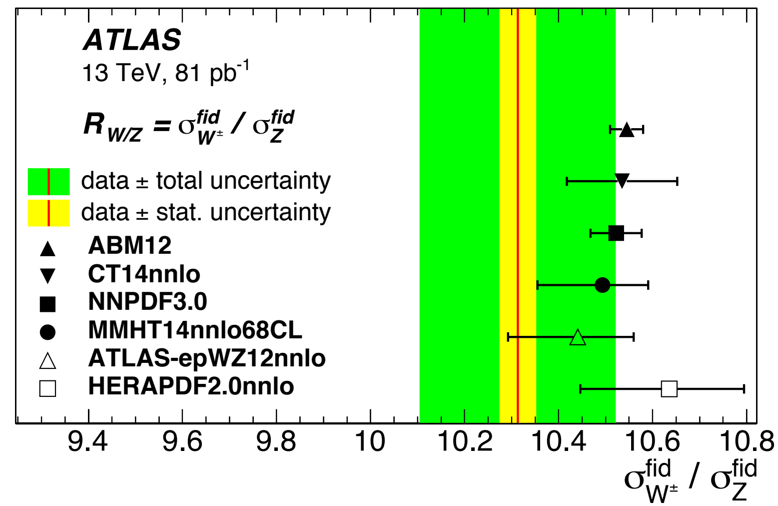


Also: LHCb σ_Z ($2.0 < \eta < 4.5$) in agreement with SM

Cross-section ratios quite precise (< 1–2%)

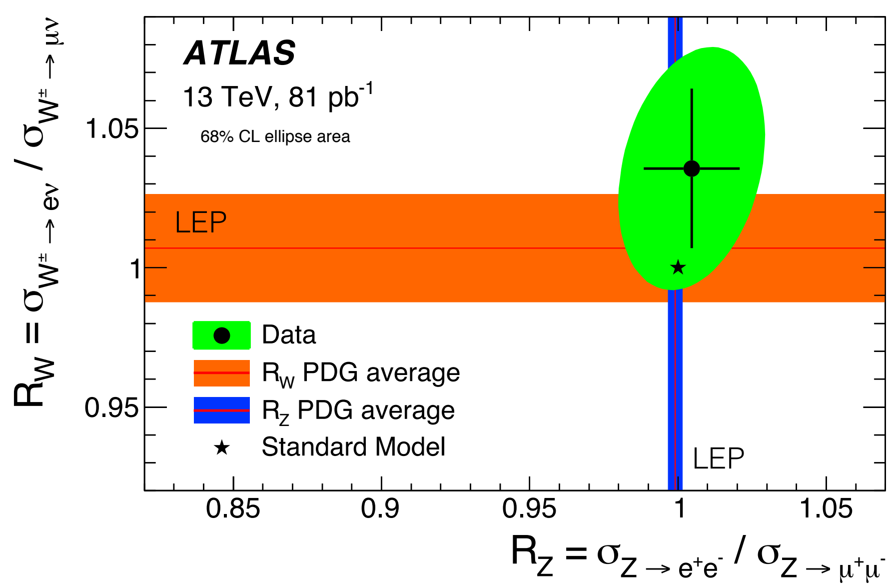
Powerful tools to constrain PDFs: W^+ / W^- sensitive to low-x u & d valence, W / Z constrains s





Lepton universality test

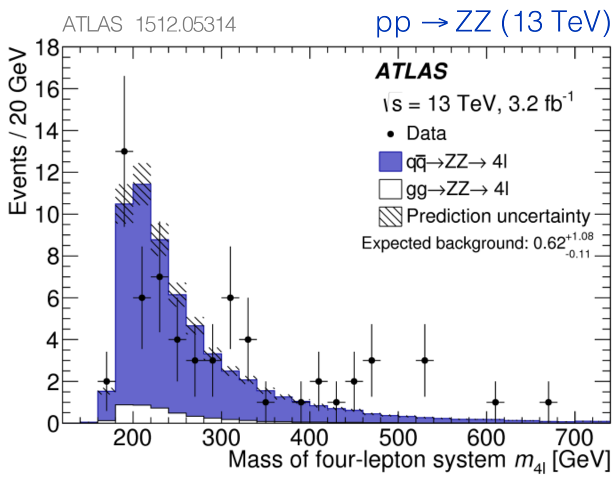
Lepton universality in charged current was measured to the 0.14% level at LEP in tau lepton decays, however at low energy (off-shell), so less sensitivity to new physics in loops

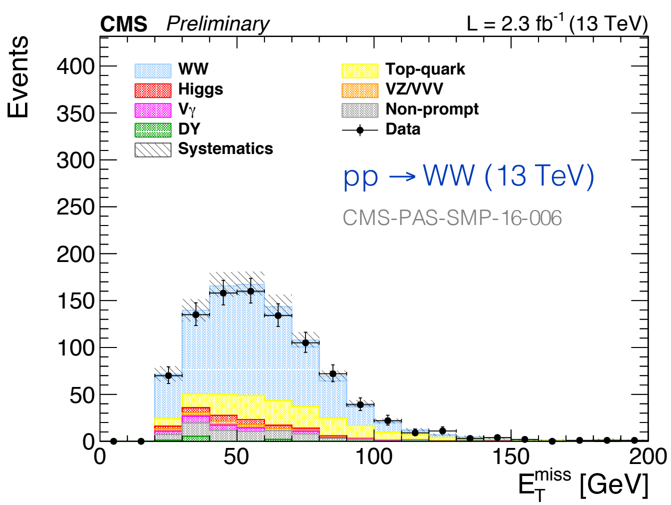


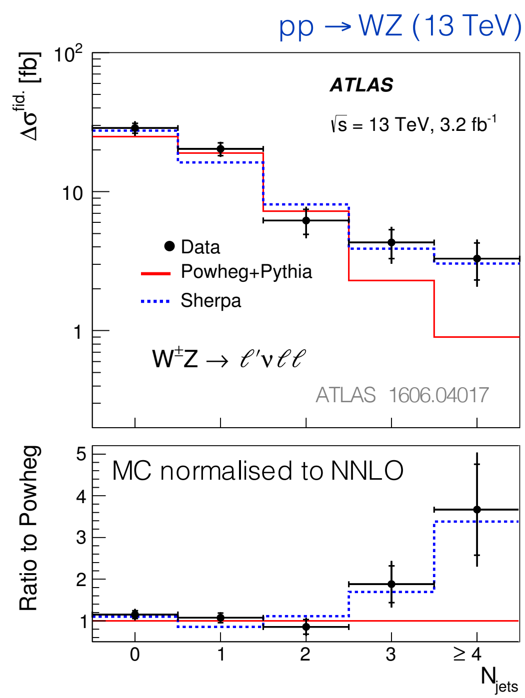
Diboson production — example: $\sigma_{WW,\text{ no Higgs}}$ (13 TeV) ~ 120 pb

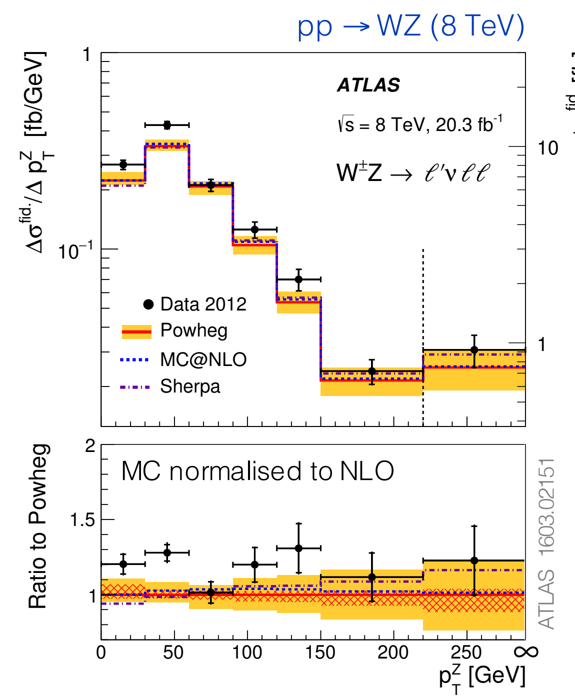
Highly important sector of LHC physics, intimately related to electroweak symmetry breaking

ATLAS & CMS performed inclusive, fiducial and differential cross-section analyses at 8 TeV.
First 13 TeV results. Theoretical predictions at NNLO needed to match data.









All measurements agree with NNLO (+ NNLL soft gluon resummation in WW case, needed because of jet veto) predictions. WZ @ 13 TeV from CMS somewhat low.

Top-antitop production at 13 TeV

Extraction of top-pair cross section (expect: 13 TeV / 8 TeV ~ 3.3)

ATLAS 1606.02699, similar for CMS

Apply robust data-driven method that provided most precise Run-1 measurements (7 & 8 TeV)

Following relation allows to simultaneously determine σ_{tt} and ε_b from data

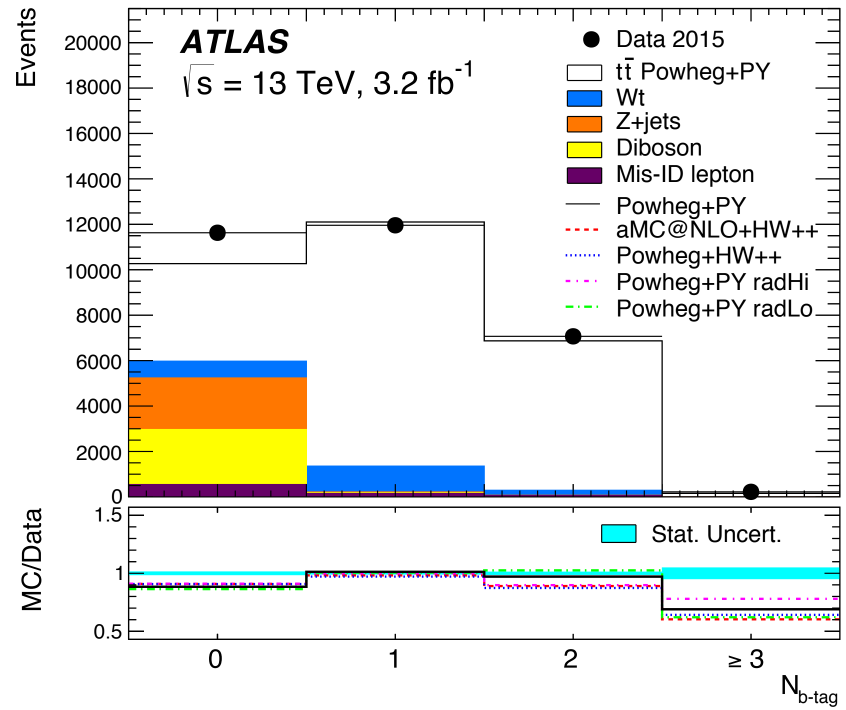
$$N_1 = L \cdot \sigma_{t\bar{t}} \cdot \varepsilon_{e\mu} \cdot 2\varepsilon_b \cdot (1 - C_b \varepsilon_b) + N_1^{\text{bkg}}$$

$$N_2 = L \cdot \sigma_{t\bar{t}} \cdot \varepsilon_{e\mu} \cdot C_b \varepsilon_b^2 + N_2^{\text{bkg}}$$

Where:

- $N_{1(2)}$ – number of selected events with 1(2) b-tags
- $N_{1(2)}^{\text{bkg}}$ – number of background events with 1(2) b-tags
- L – luminosity of data sample
- $\varepsilon_{e\mu}$ – (tt →) eμ selection eff & acc (~0.9%) incl. BR
- ε_b – probability to b-tag q from t → Wq
- $C_b = \varepsilon_{bb} / \varepsilon_b$ is non-factorisation correction (1.002 ± 0.006 from MC)

MC normalised to SM expectation



Observe: $N_1 = 11958$, $N_2 = 7069$

Expect: $N_1^{\text{bkg}} = 1370 \pm 120$, $N_2^{\text{bkg}} = 340 \pm 88$,
dominated by Wt (MC, approx. NNLO), then mis-id. e/μ (MC & data)

Top-antitop production at 13 TeV

Extraction of top-pair cross section (expect: 13 TeV / 8 TeV ~ 3.3)

ATLAS 1606.02699, similar for CMS

Solving the equation gives the following 13 TeV pp → tt + X cross section

σ_{tt} (13 TeV) = 818 ± 8 (stat) ± 27 (syst) ± 19 (lumi) ± 12 (beam-E) pb

Total relative uncertainty of 4.4% (4.3% at 8 TeV)

σ_{tt}[SM] (13 TeV) = 832^{+40}_{-46} pb (at NNLO + NNLL accuracy, m_t = 172.5 GeV, Top++ 2.0)

Systematic uncertainty (3.3%) dominated by

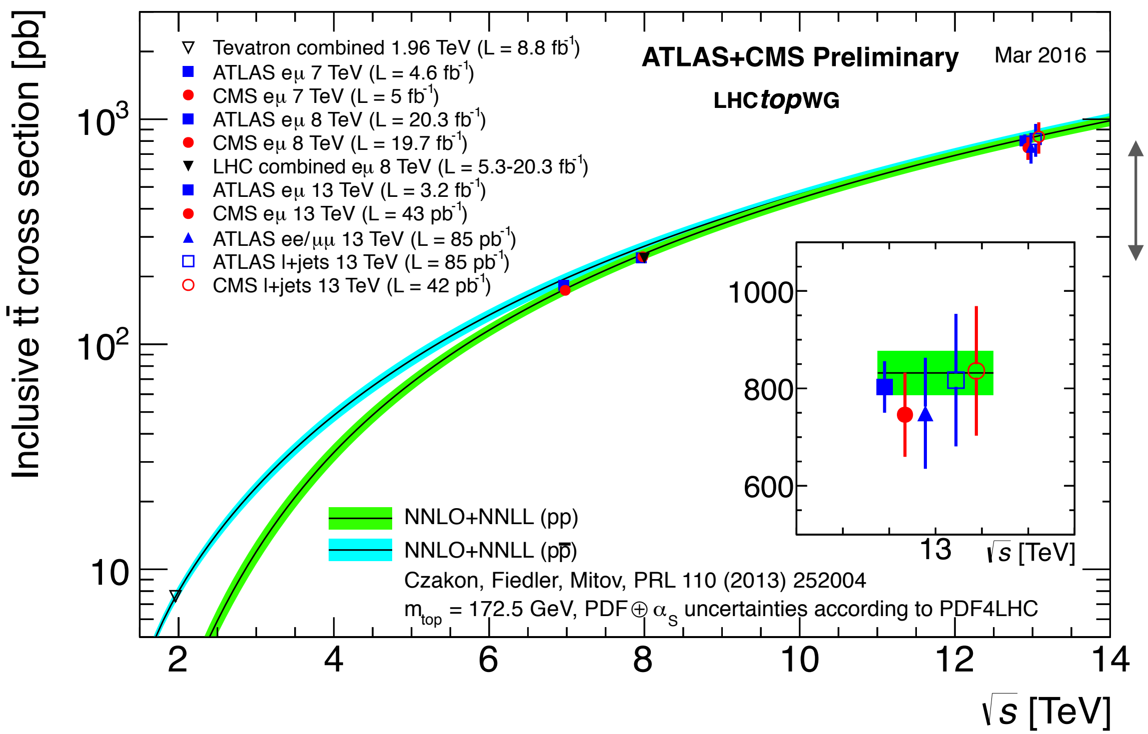
- tt parton shower & hadronisation (2.8%)
- tt NLO modelling, ISR/FSR radiation & PDF (1.1%)
- Single top modelling (0.8%)
- Electron ID + isolation (0.5%)
- Muon ID + isolation (0.5%)
- Lepton mis-identification (0.6%)

Also find: ε_b = 0.559 ± 0.004 ± 0.003, in good agreement with simulation: 0.549

Top-antitop production at 13 TeV

Extraction of top-pair cross section (expect: 13 TeV / 8 TeV ~ 3.3)

ATLAS & CMS studied top production in many ways at 13 TeV → very prompt analyses turn around



Agreement with expected factor of 3.3

Robust eμ final state gives most precise inclusive results at all CM energies

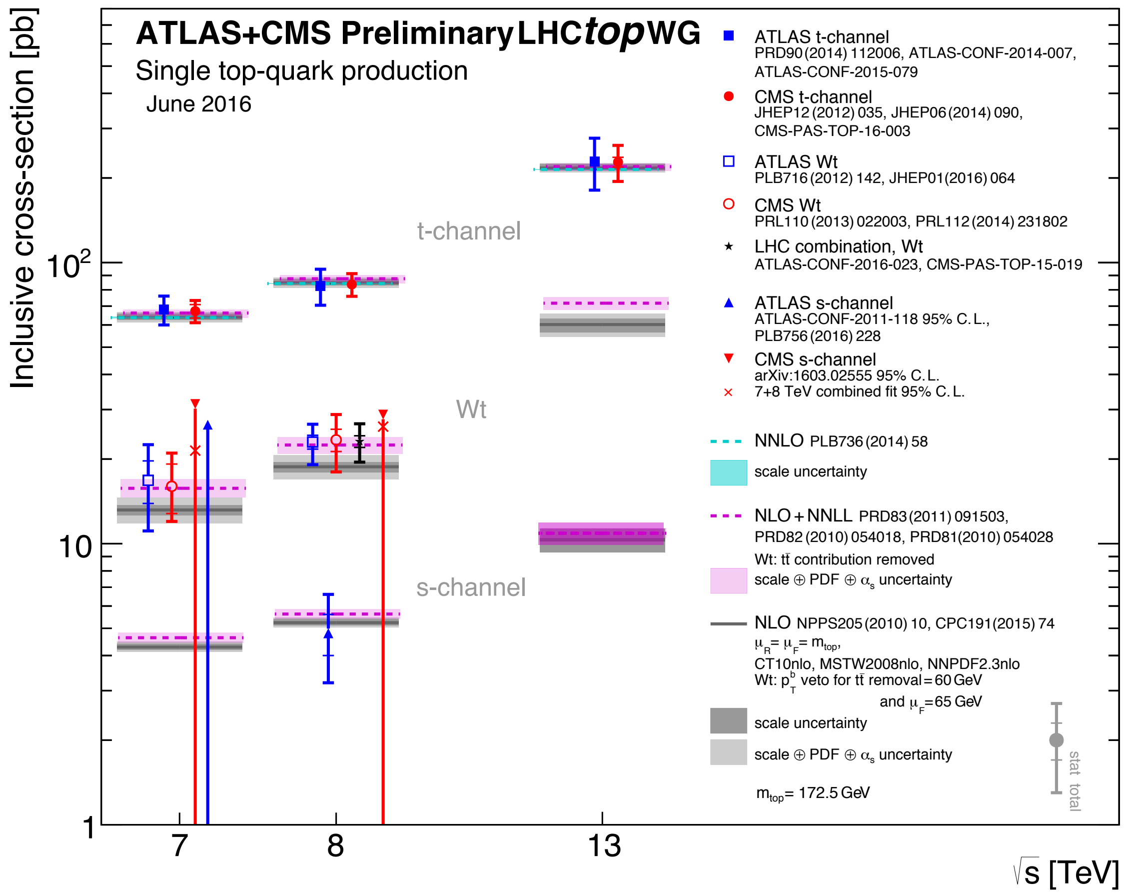
Differential cross-section measurements at 13 TeV show reasonable modelling, though some deviations at large jet multiplicity. Known modelling problems from Run-1 not all solved!

Single top quark production

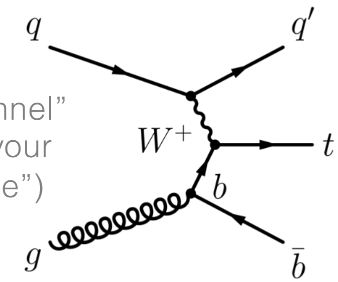
Increase of cross section by factor of 2.5 (t-channel) over 8 TeV, roughly 1/3rd of tt cross section

ATLAS & CMS have so far released preliminary t-channel measurements at 13 TeV (100 x cross-section of Tevatron)

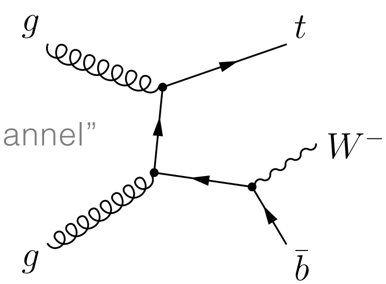
13 TeV: ATLAS-CONF-2015-079, CMS-PAS-TOP-16-003

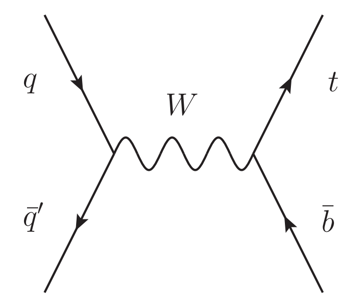


"t-channel" ("4 flavour scheme")



"Wt-channel"





"s-channel" (not easier at 13 TeV)

Tevatron: 6.3σ, ATLAS Run-1: 3.2σ

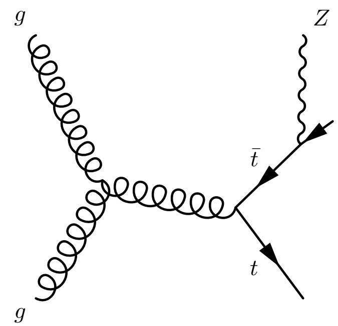
Top-antitop production and a vector boson at 13 TeV

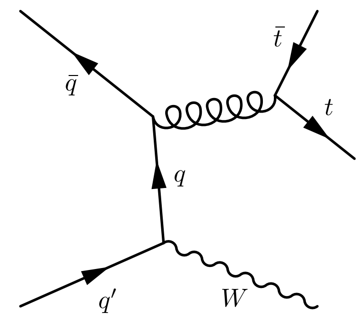
First results on important ttV process, in it's own right, and as background to ttH and searches

ATLAS & CMS have preliminary 13 TeV results

Analyses combine several multilepton final states, difficult mis-ID background

At 8 TeV, both processes observed, and found to agree with SM prediction
(ttW ~1σ up in both ATLAS & CMS)

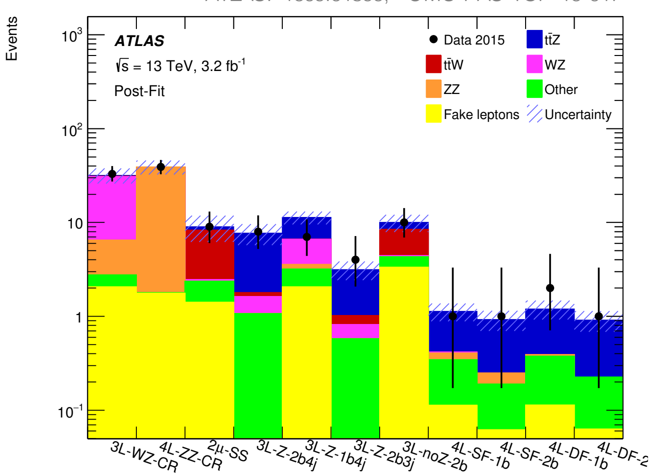


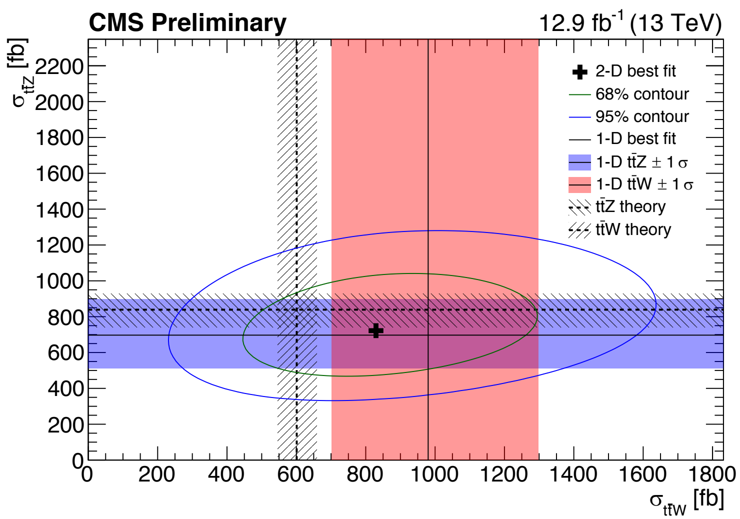


Different production processes and thus 13/8 TeV cross-section ratios for ttZ & ttW: 3.6 & 2.4

13 TeV tt+W/Z results from ATLAS and CMS in agreement with SM:

ATLAS: 1609.01599, CMS-PAS-TOP-16-017





ATLAS (3.2 fb^{-1}, 2015):
ttW: 1.5 ± 0.8 pb
ttZ: 0.9 ± 0.3 pb

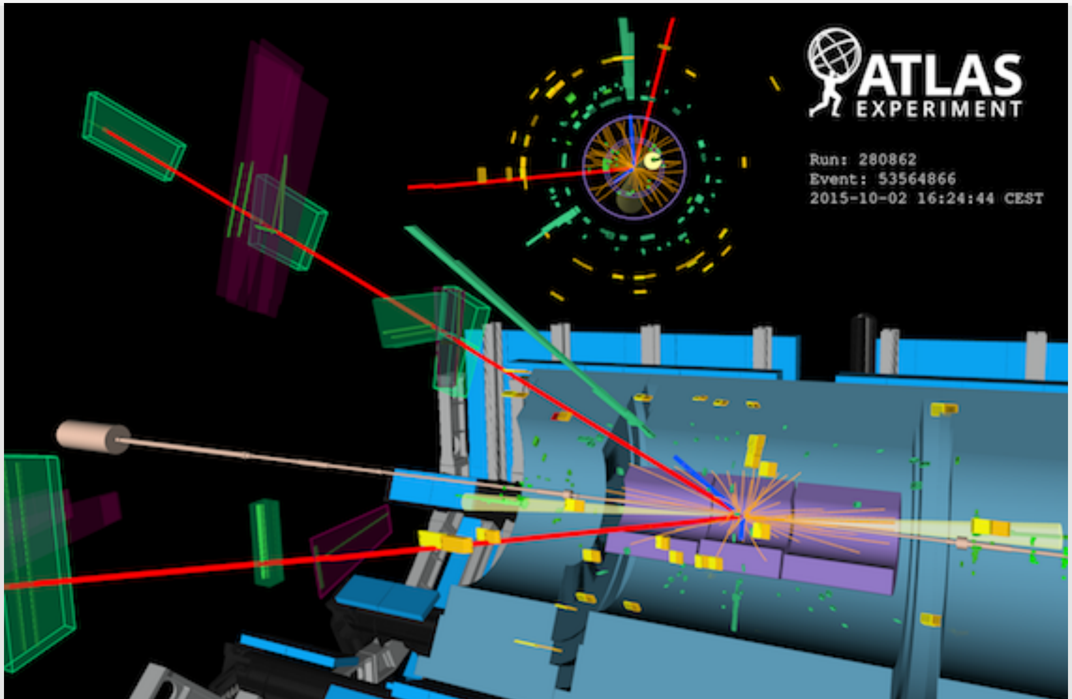
CMS (12.9 fb^{-1}, 2016):
ttW: $0.98\,^{+0.23}_{-0.22}\,^{+0.22}_{-0.18}$ pb
ttZ: $0.70\,^{+0.16}_{-0.15}\,^{+0.14}_{-0.12}$ pb

SM (NLO):
ttW: 0.60 ± 0.08 pb
ttZ: 0.84 ± 0.09 pb

Re-observation of Higgs boson at 13 TeV

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

2015 & 2016 statistics combined achieves better significance and precision than in Run-1

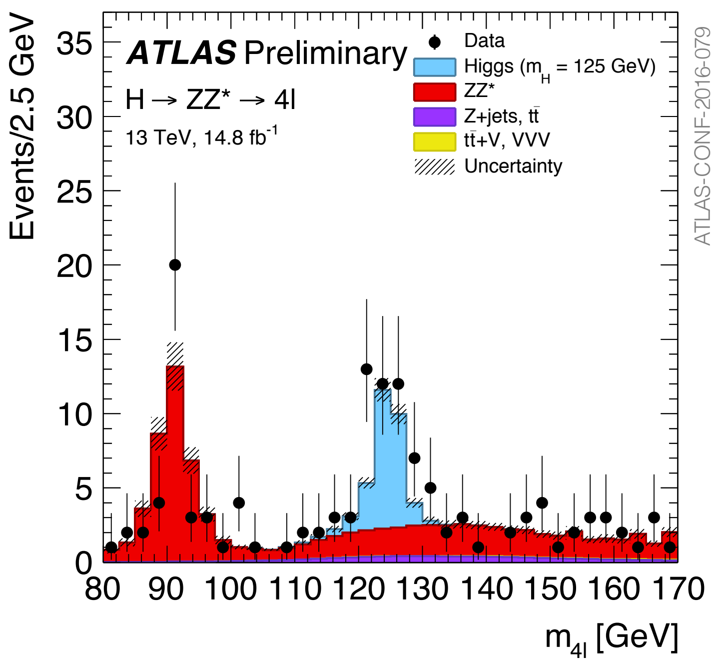


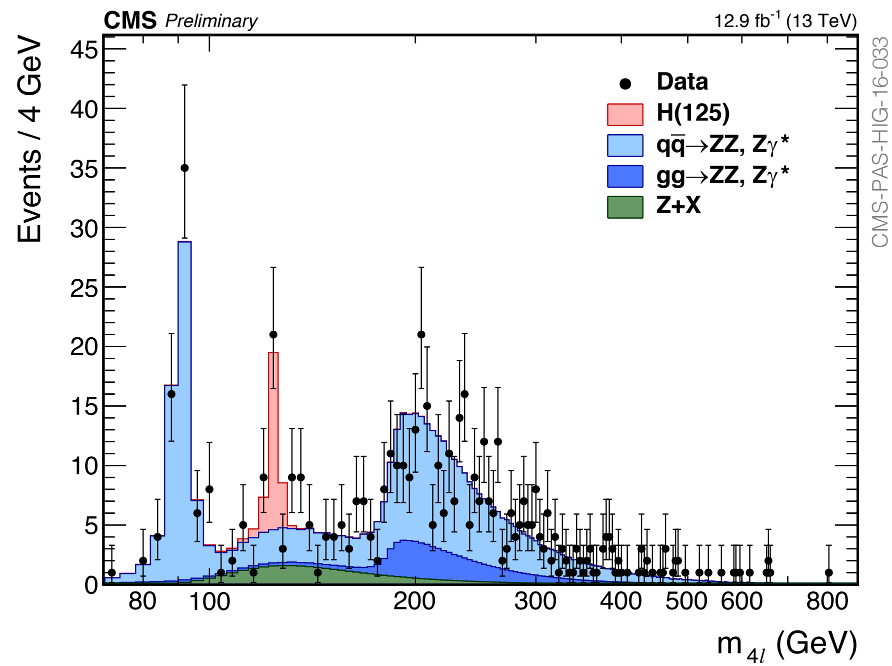
Display of H → eeμμ candidate from 13 TeV pp collisions. The electrons have a transverse momentum of 111 and 16 GeV, the muons 18 and 17 GeV, and the jets 118 and 54 GeV. The invariant mass of the four lepton system is 129 GeV, the di-electron invariant mass is 91 GeV, the di-muon invariant mass is 29 GeV, the pseudorapidity difference between the two jets is 6.4 while the di-jet invariant mass is 2 TeV. **This event is consistent with VBF production of a Higgs boson decaying to four leptons.**

ATLAS and CMS studied H_{125} in bosonic channels

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

H → ZZ* → 4ℓ





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

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

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

Expected significance (SM): 6.5σ

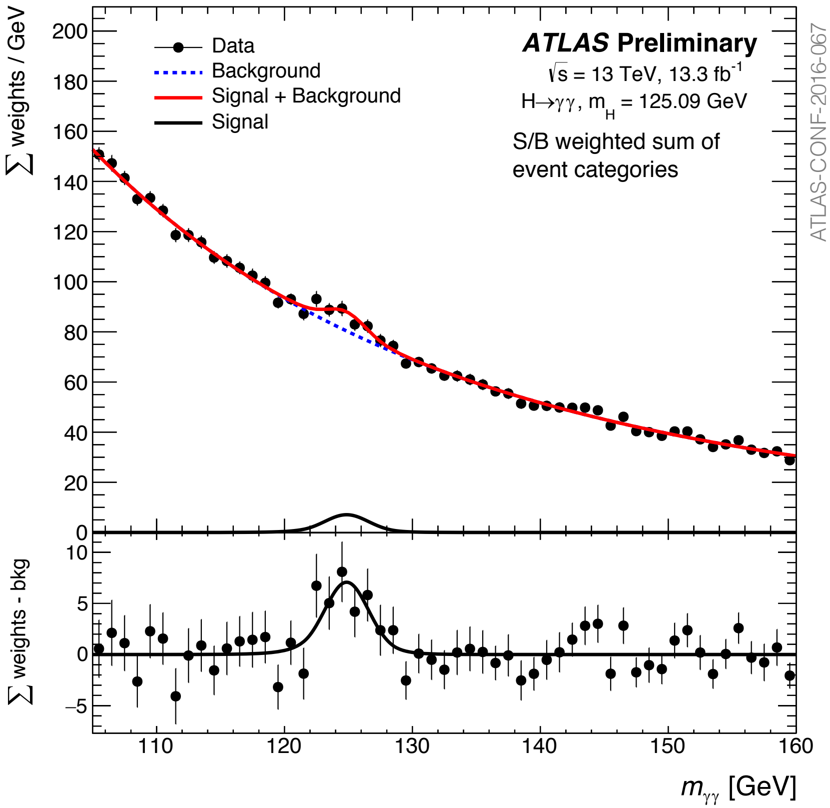
CMS also measured: $m_H = 124.50^{+0.48}_{-0.44}$ GeV

(dominated by statistical uncertainty, compare to 125.09 ± 0.24 GeV from ATLAS & CMS Run-1 combination)

ATLAS and CMS studied H_{125} in bosonic channels

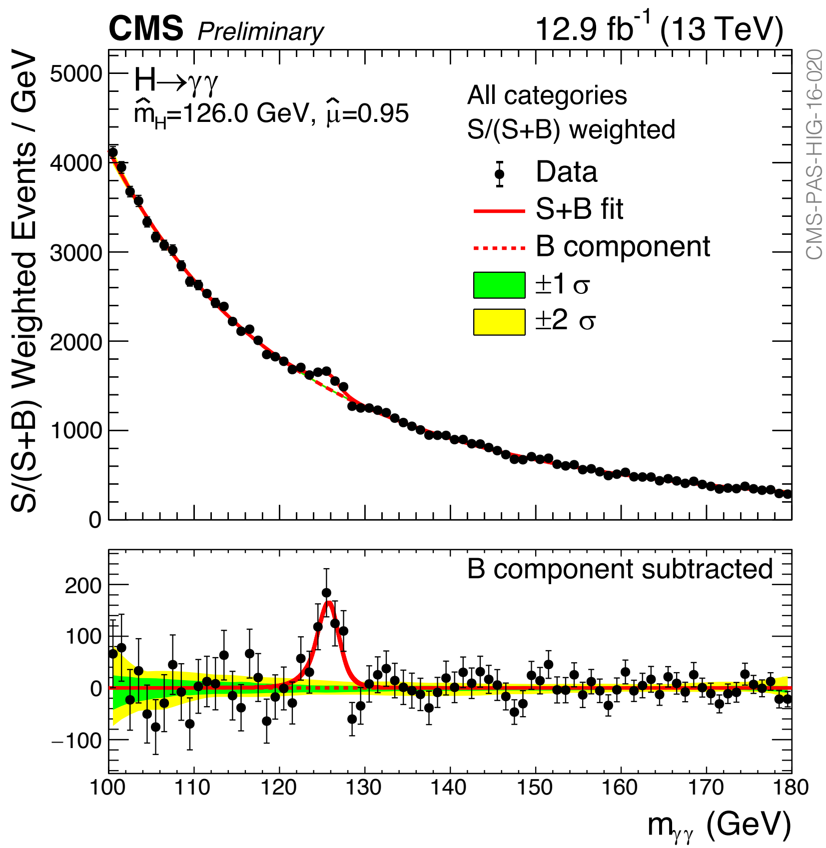
Preliminary fiducial and total cross-section and coupling measurements (ggF and VBF significant)

H → γγ



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

Expected significance (SM): 5.4σ



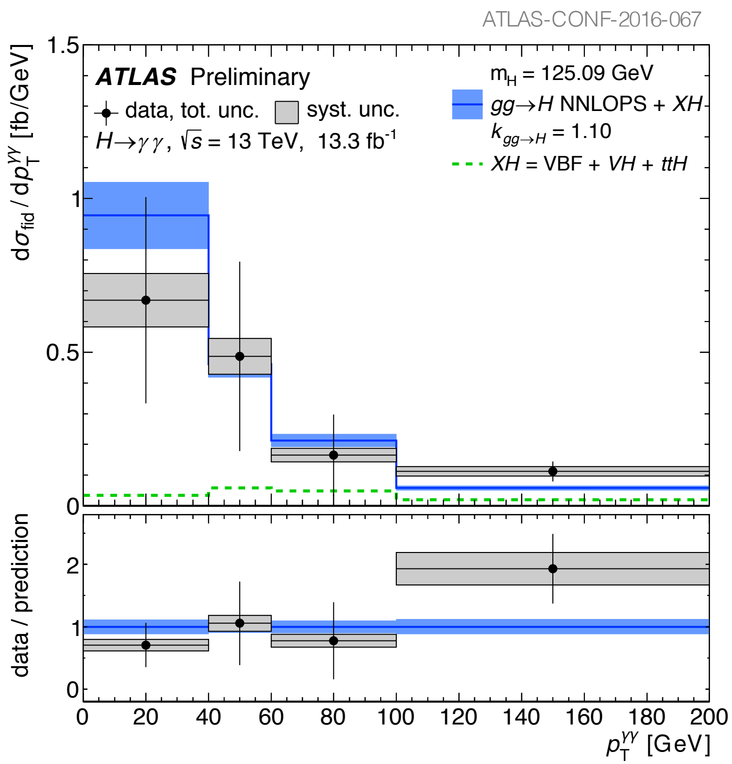
$\mu = 0.91 \pm 0.20$

Expected significance (SM): 6.2σ

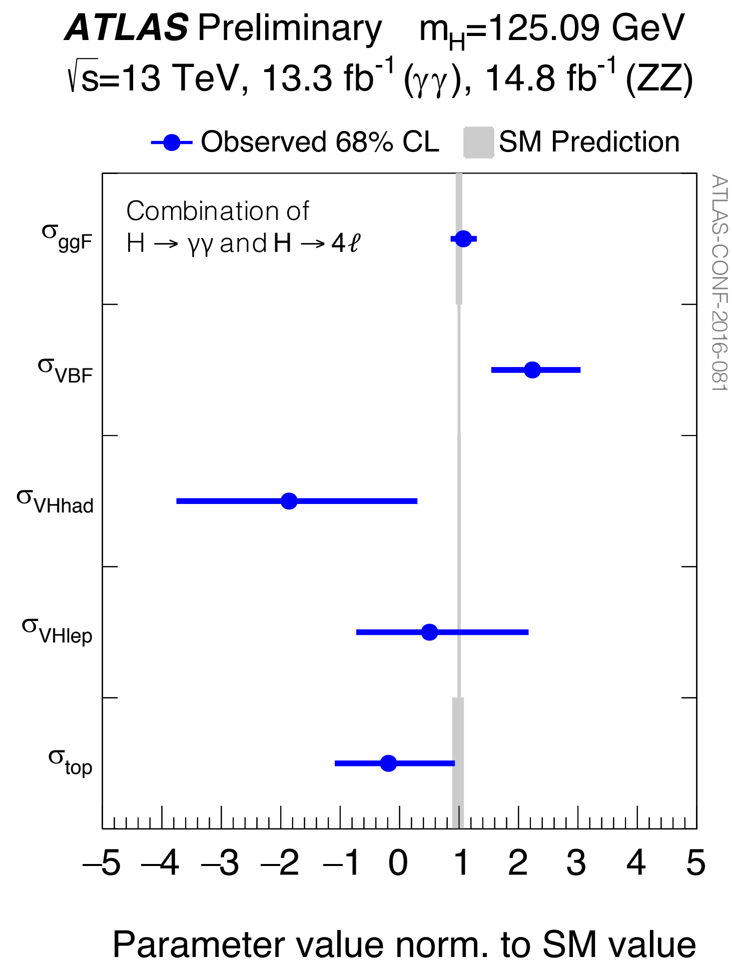
ATLAS and CMS studied H_{125} in bosonic channels

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

$H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ (right combined)



Differential fiducial cross-section measurement in $H \to 4\ell$ compared to NNLO+PS theoretical prediction

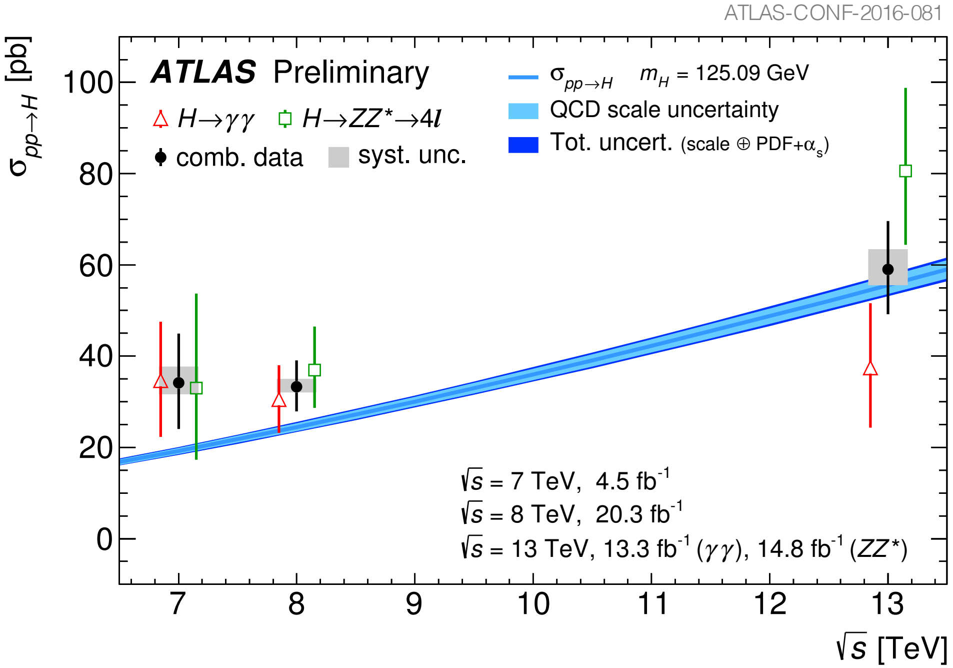


ATLAS and CMS studied H_{125} in bosonic channels

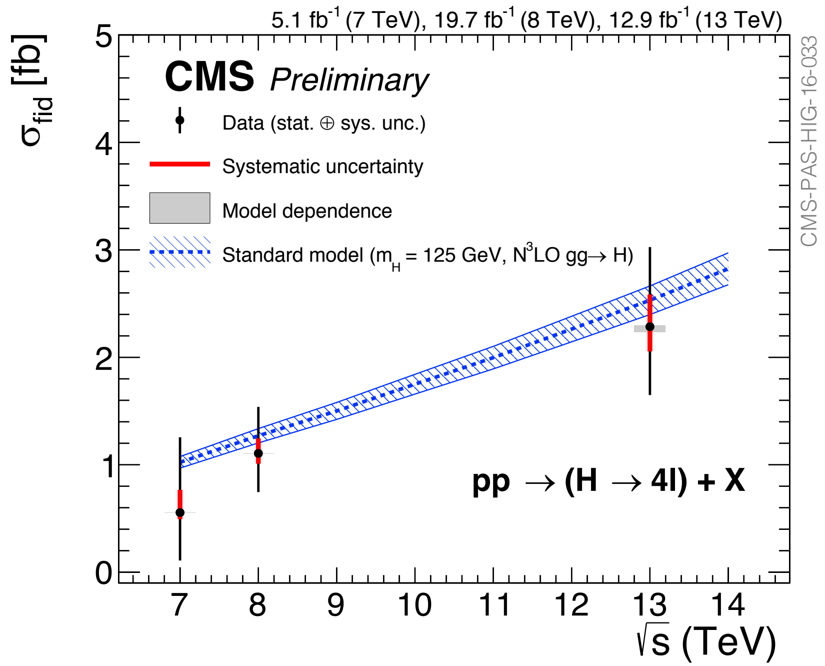
Cross section versus centre-of-mass energy

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

Combined $H \rightarrow 4\ell$, γγ



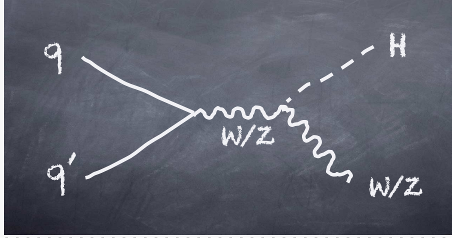
$H \rightarrow 4\ell$, *fiducial* cross section



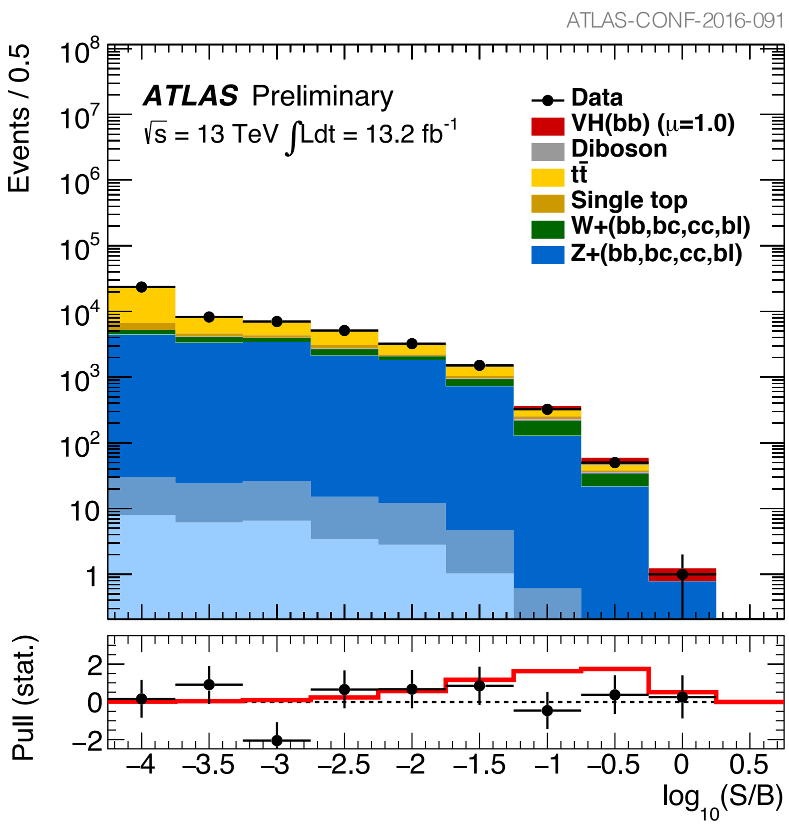
Expected rise of cross-section observed in data

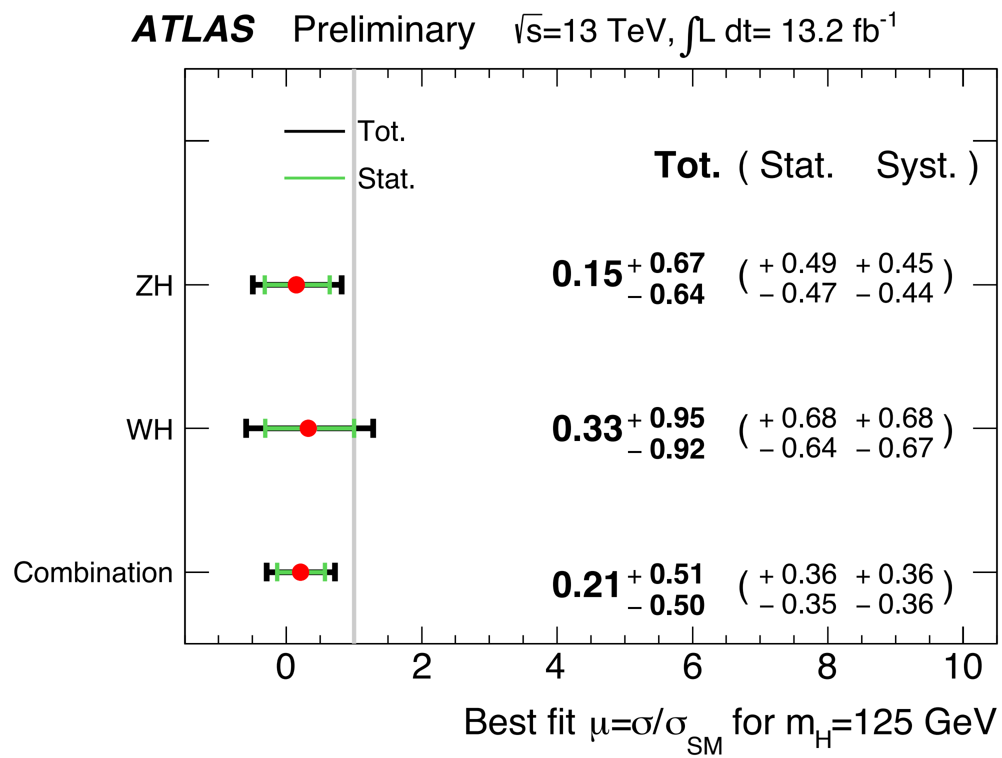
ATLAS studied H_{125} in bb decay channel

Associated production, challenging final states



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





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

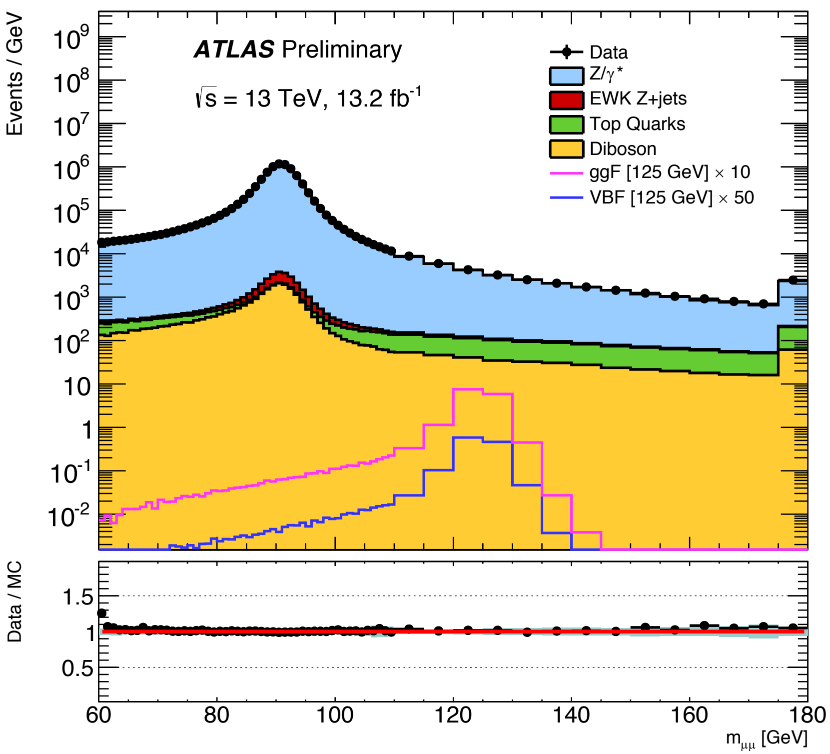
Searches for rare Higgs decays

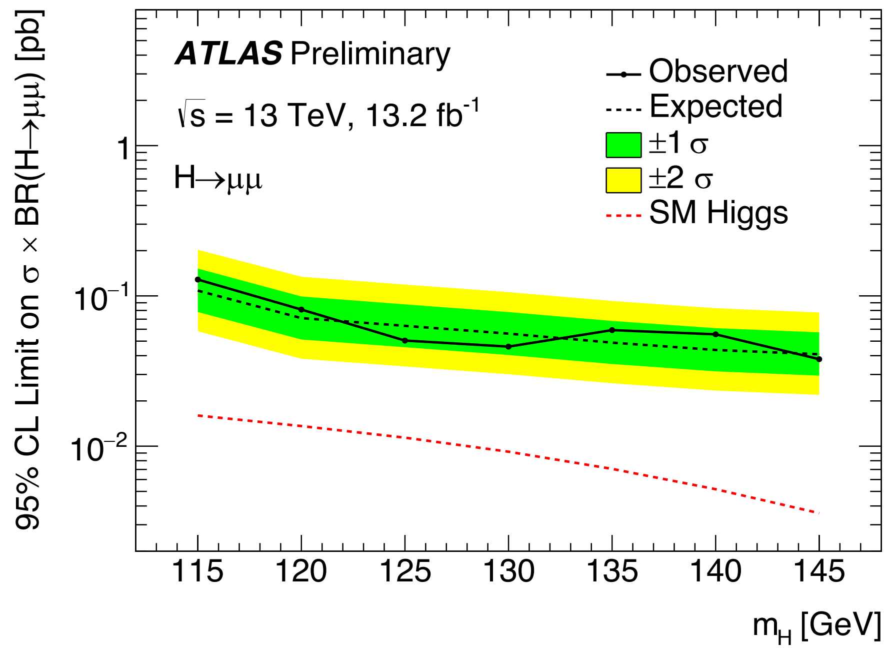
Beyond SM reach at present, but could have new physics contributions ?

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

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

ATLAS-CONF-2016-041

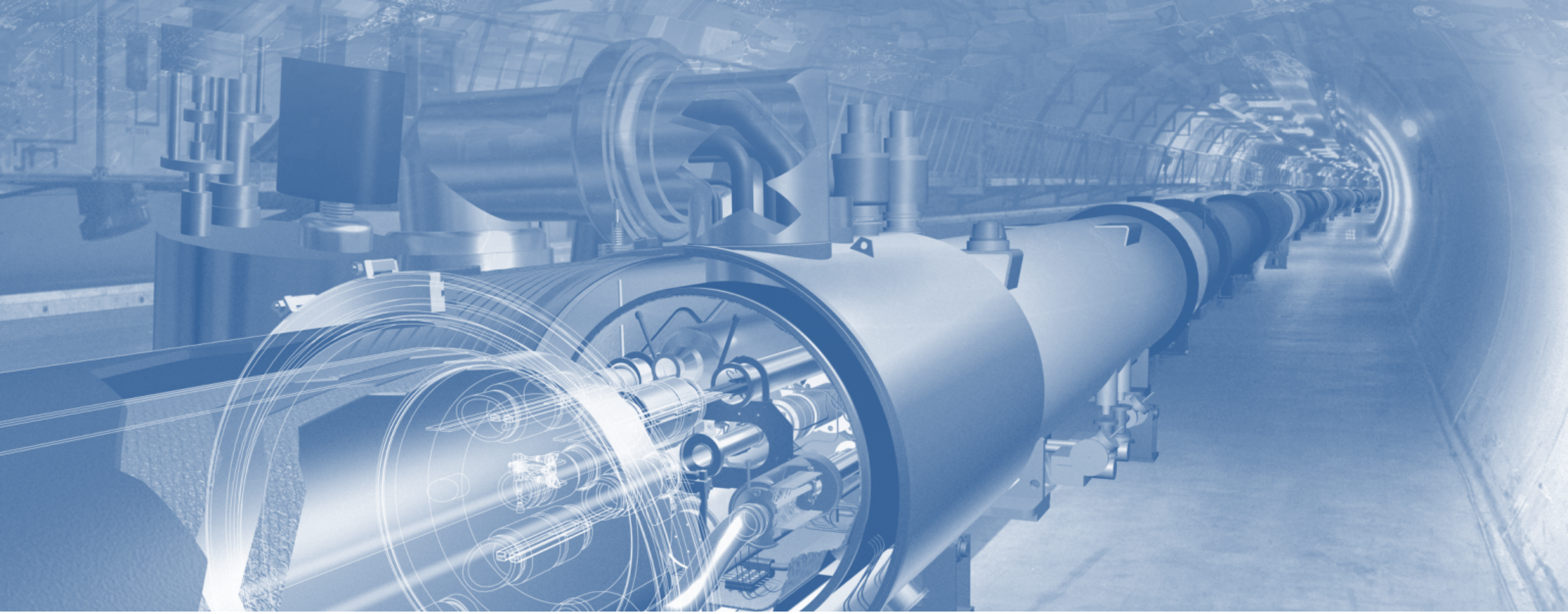




Observed limit 4.4 times SM (3.5 combined with Run-1). Need about 300 fb^{-1} of data to reach SM

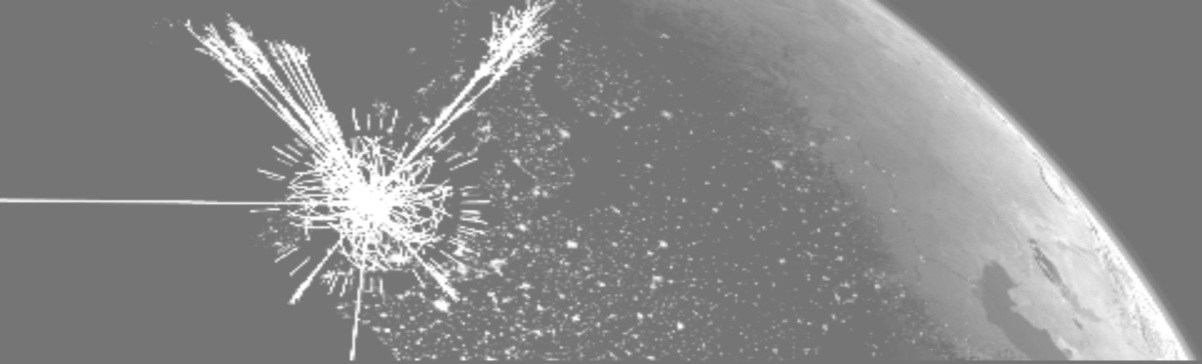
Can already exclude universal Higgs coupling to fermions !

(Would have observed H → μμ if same BR as H → ττ)



Tomorrow:

Searches — a fresh restart at 13 TeV



Extra slides

*The Standard Model is **the** legacy of 20th century particle physics*

Standard Model (36+1 particles, 3 forces)

Selected Nobel Prizes since 1957 (incomplete!)

Gauge group = $SU(3)_C \times SU(2)_L \times U(1)_Y$

EWSB

$SU(3)_C \times U(1)_{EM}$

Courtesy: Pascal Pralavorio

Broad search coverage — not only the standard signatures

Run-1 "tour de force" analysis of pMSSM

[ATLAS, 1508.06608, CMS 1606.03577]

Combined use of 22 separate ATLAS SUSY searches in addition to external constraints (m_H, EWPO, flavour, LEP searches, dark matter) to probe 19 parameter pMSSM

Distinction of LSP types: *bino*, *wino*, *higgsino*

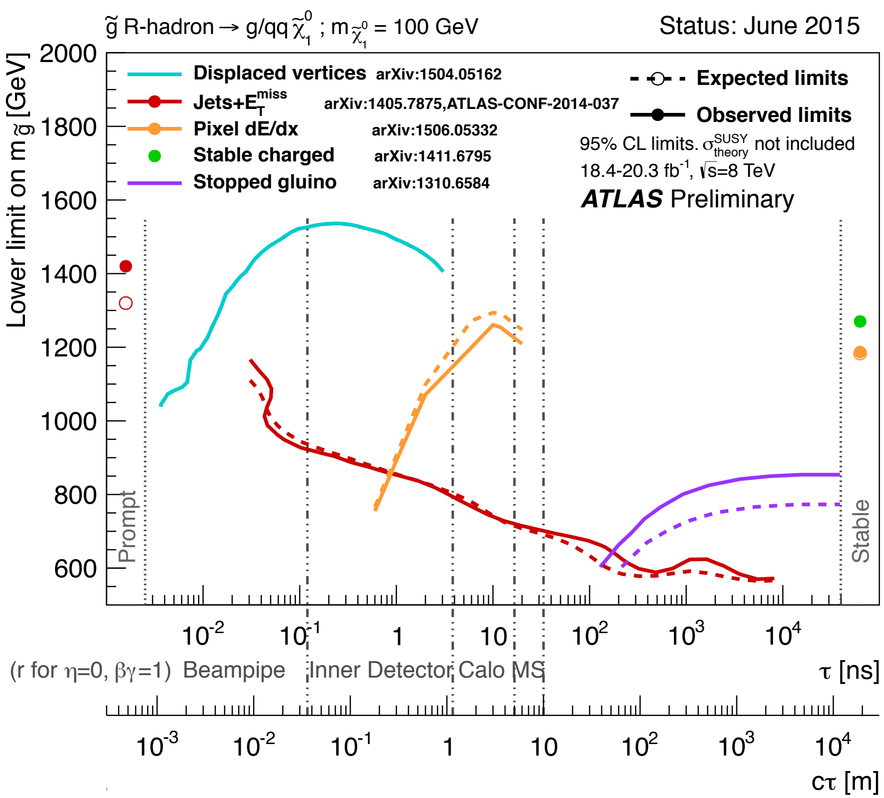
Analysis overall reproduces simplified models picture

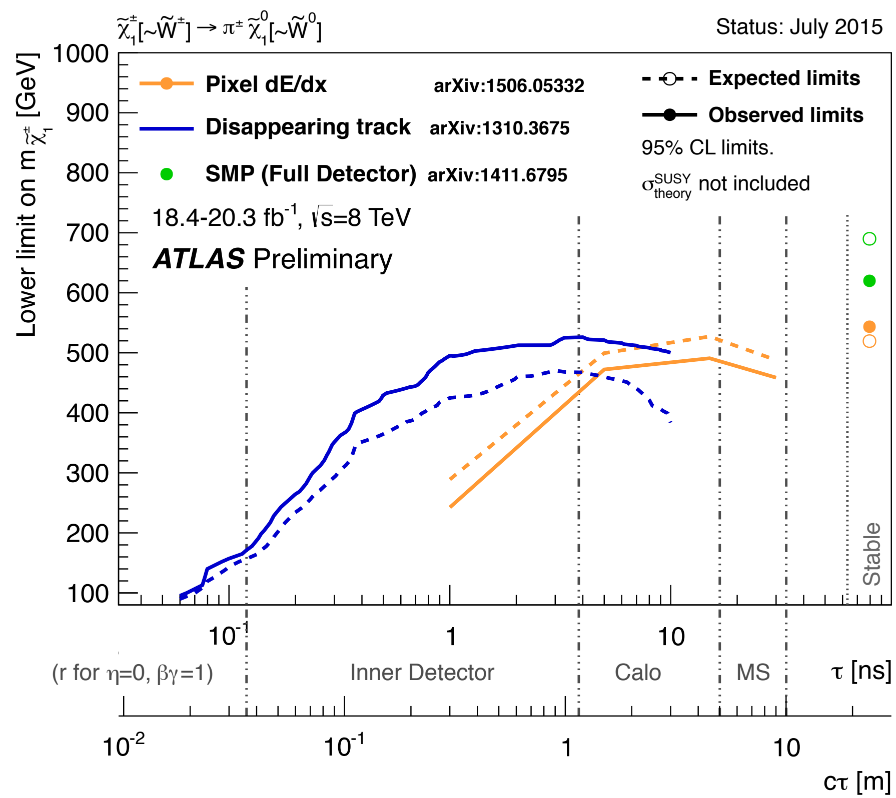
Higgsino/wino scenarios biggest challenge →

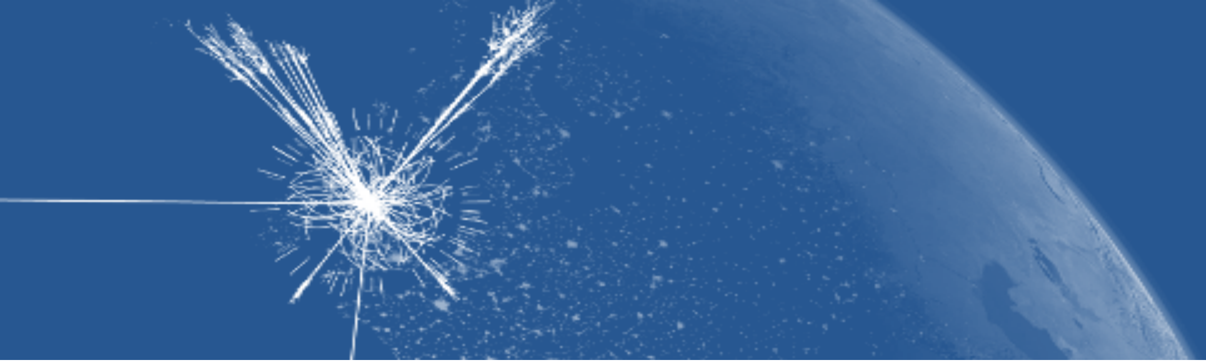
Analysis	All LSPs	Bino-like	Wino-like	Higgsino-like
0-lepton + 2–6 jets + E_T^{miss}	32.1%	35.8%	29.7%	33.5%
0-lepton + 7–10 jets + E_T^{miss}	7.8%	5.5%	7.6%	8.0%
0/1-lepton + 3b-jets + E_T^{miss}	8.8%	5.4%	7.1%	10.1%
1-lepton + jets + E_T^{miss}	8.0%	5.4%	7.5%	8.4%
Monojet	9.9%	16.7%	9.1%	10.1%
SS/3-leptons + jets + E_T^{miss}	2.4%	1.6%	2.4%	2.5%
$\tau(\tau/\ell)$ + jets + E_T^{miss}	3.0%	1.3%	2.9%	3.1%
0-lepton stop	9.4%	7.8%	8.2%	10.2%
1-lepton stop	6.2%	2.9%	5.4%	6.8%
2b-jets + E_T^{miss}	3.1%	3.3%	2.3%	3.6%
2-leptons stop	0.8%	1.1%	0.8%	0.7%
Monojet stop	3.5%	11.3%	2.8%	3.6%
Stop with Z boson	0.4%	1.0%	0.4%	0.5%
tb+E_T^{miss}, stop	4.2%	1.9%	3.1%	5.0%
ℓh, electroweak	0	0	0	0
2-leptons, electroweak	1.3%	2.2%	0.7%	1.6%
2-τ, electroweak	0.2%	0.3%	0.2%	0.2%
3-leptons, electroweak	0.8%	3.8%	1.1%	0.6%
4-leptons	0.5%	1.1%	0.6%	0.5%
Disappearing Track	11.4%	0.4%	29.9%	0.1%
Long-lived particle	0.1%	0.1%	0.0%	0.1%
$H/A \to \tau^+\tau^-$	1.8%	2.2%	0.9%	2.4%
Total	40.9%	40.2%	45.4%	38.1%

Broad search coverage — not only the standard signatures

All experiments looked for various types of long-lived massive particles







SM predictions in Monte Carlo simulations

Parton level examples (often require "hadronisation" and soft "parton shower" corrections):

- MCFM: fixed-order NLO → vector bosons etc.
- BLACKHAT+SHERPA: NLO fixed order pQCD (up to 4p) → vector bosons etc.
- Jetphox: fixed-order NLO QCD → photons
- PeTeR: resummed NNLO (NNNLL accuracy) → photons, etc.
- NLOjets++: fixed-order NLO QCD → jets
- FEWZ, DYNNLO, Njetti etc. – NNLO calculations for vector bosons

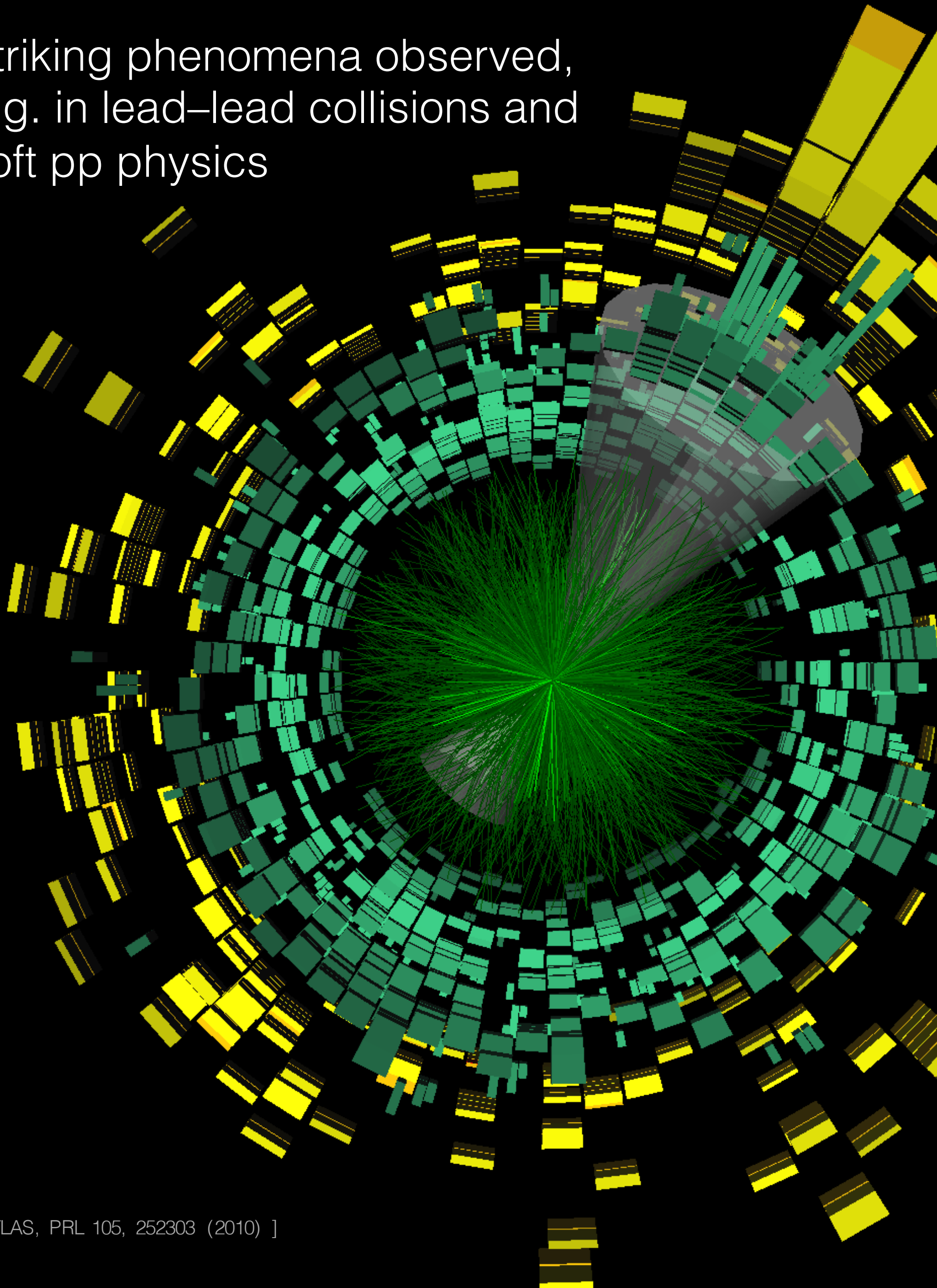
Event generators at hadron/particle level, examples:

- PYTHIA8, HERWIG++: LO ME with parton showers (PS) – general-purpose generator, hadronisation and PS tools
- ALPGEN: LO matrix element (ME) multipartons (up to 5p)
- SHERPA: LO/NLO multipartons (up to 5/2p) + PS (internal)
- MadGraph/MG5_aMC@NLO: LO/NLO MEmultiparton (5/2p)
- POWHEG, MC@NLO: NLO

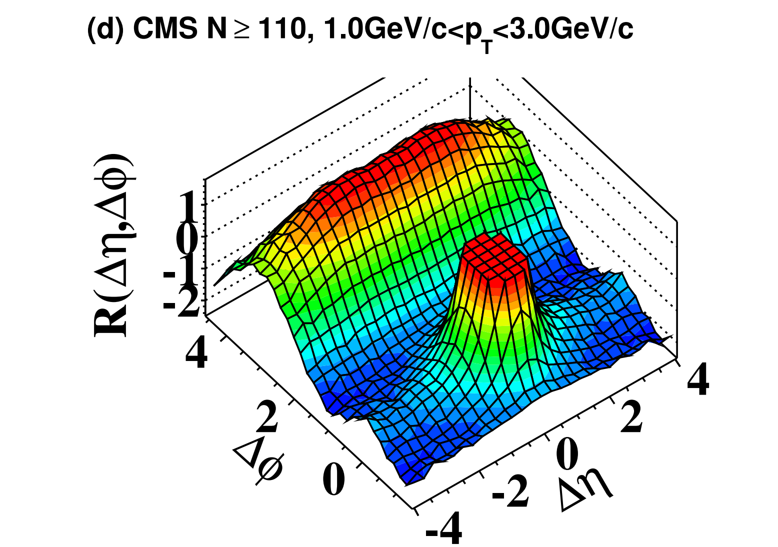
State of the art is:

- **Parton level**: NNLO with resummed logs
- **Hadron level**: NLO + PS, LO multiparton + PS

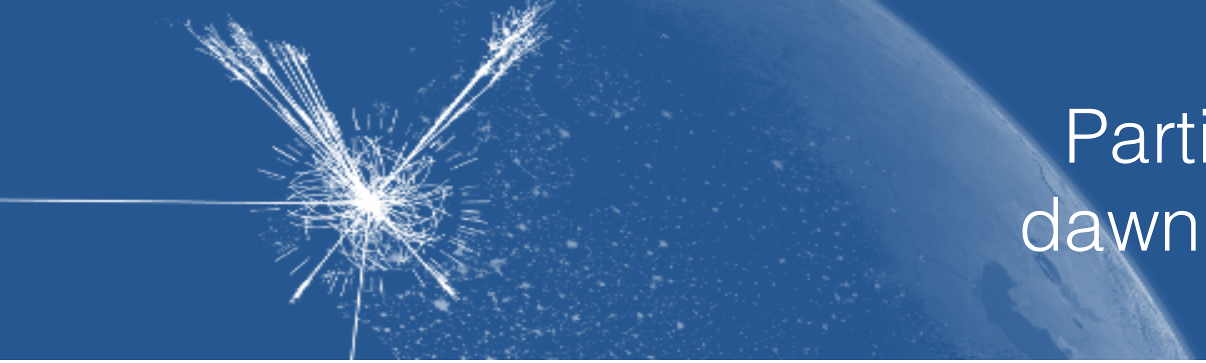
Striking phenomena observed, e.g. in lead–lead collisions and soft pp physics



[ATLAS, PRL 105, 252303 (2010)]



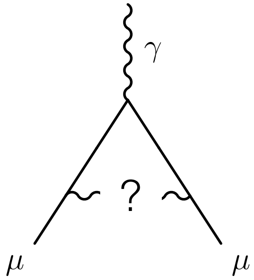
[CMS, PLB 718 (2013) 795]

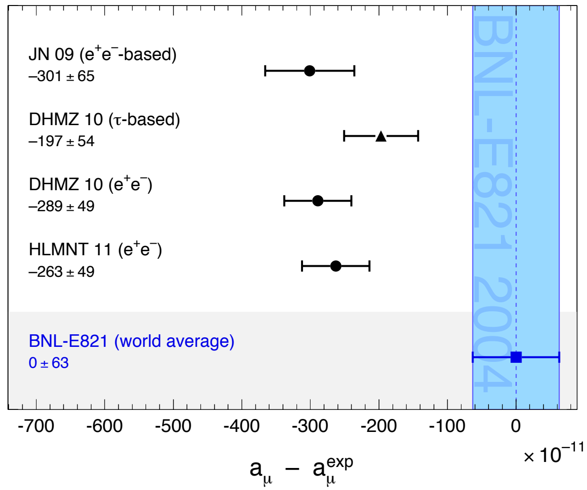


Particle physics at the dawn of the LHC Run-2

Confirmation of mass generation through spontaneous symmetry breaking in BEH potential. Scalar sector SM-like so far (but lacking precision)

QED tested to parts per million accuracy (slight anomaly in muon g–2)





Asymptotic freedom in strong interactions verified at % level

Electroweak unification tested to high precision

Quark sector: CKM picture for quark mixing & CP violation confirmed

Lepton sector: massive neutrinos, unknown masses, nature, CP violation, sterile ν's ? No flavour violation in charged lepton sector. Lepton universality tested to per-mil level

No compelling sign of new physics found at high mass scales, or anywhere else, eg: no electric dipole moments (EDM), no dark matter particles (only gravitational hints), no axions (strong CP problem), no proton decay (GUT)