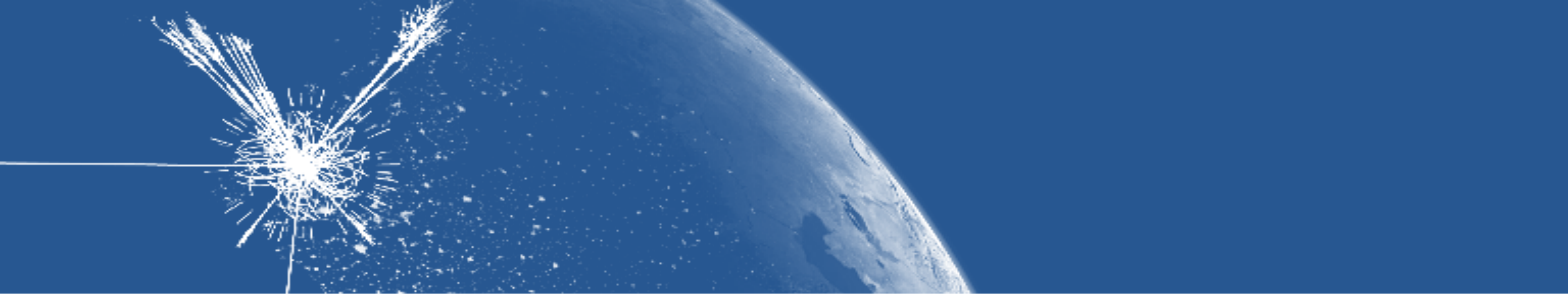
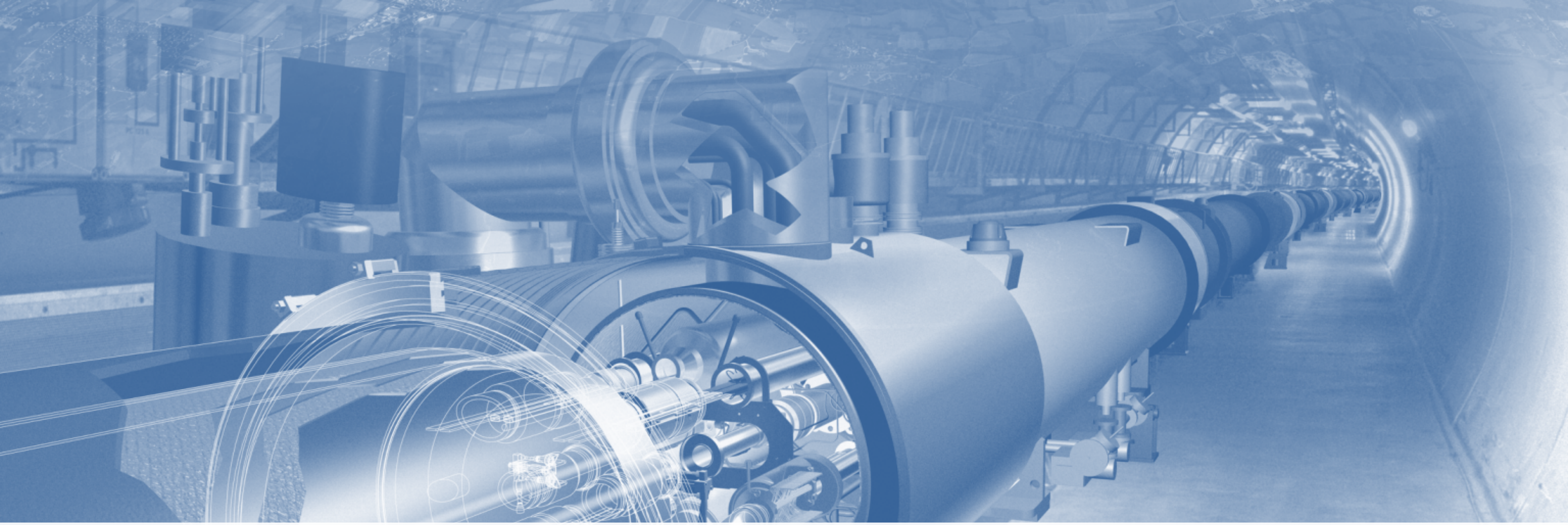


Physics at the LHC (2)

Andreas Hoecker (CERN)

Summer School on Symmetries and Fundamental Interactions
September 18–23, 2016, Abtei Frauenwörth, Germany



The LHC Run-2 at 13 TeV

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

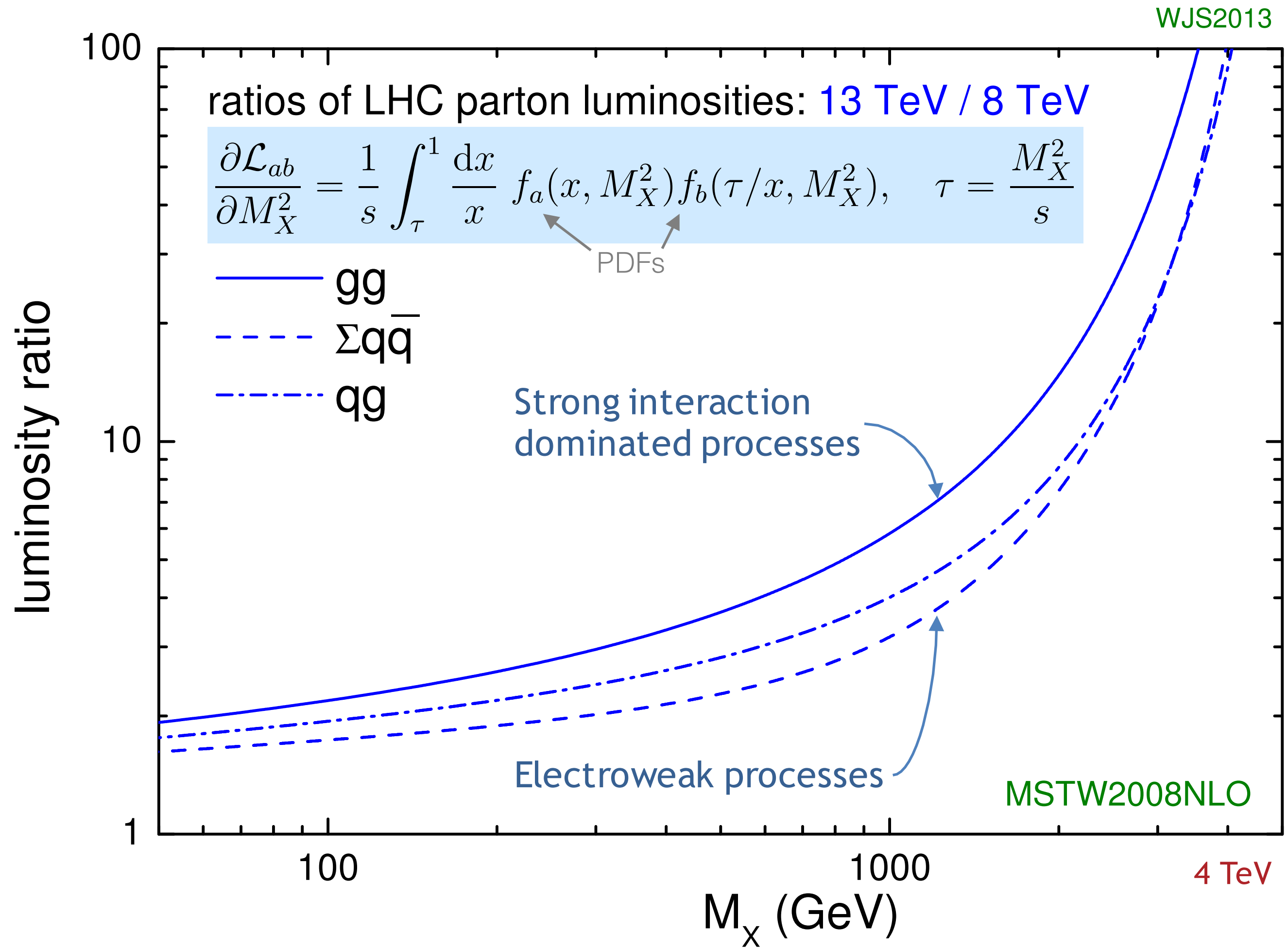
After a rocky start, the LHC delivered $L_{\mathrm{int}} = 4.2\ \mathrm{fb}^{-1}$

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

During 2016 reached peak $1.2\times10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and expect 35~40 fb^{-1} total delivered

Excellent machine efficiency!

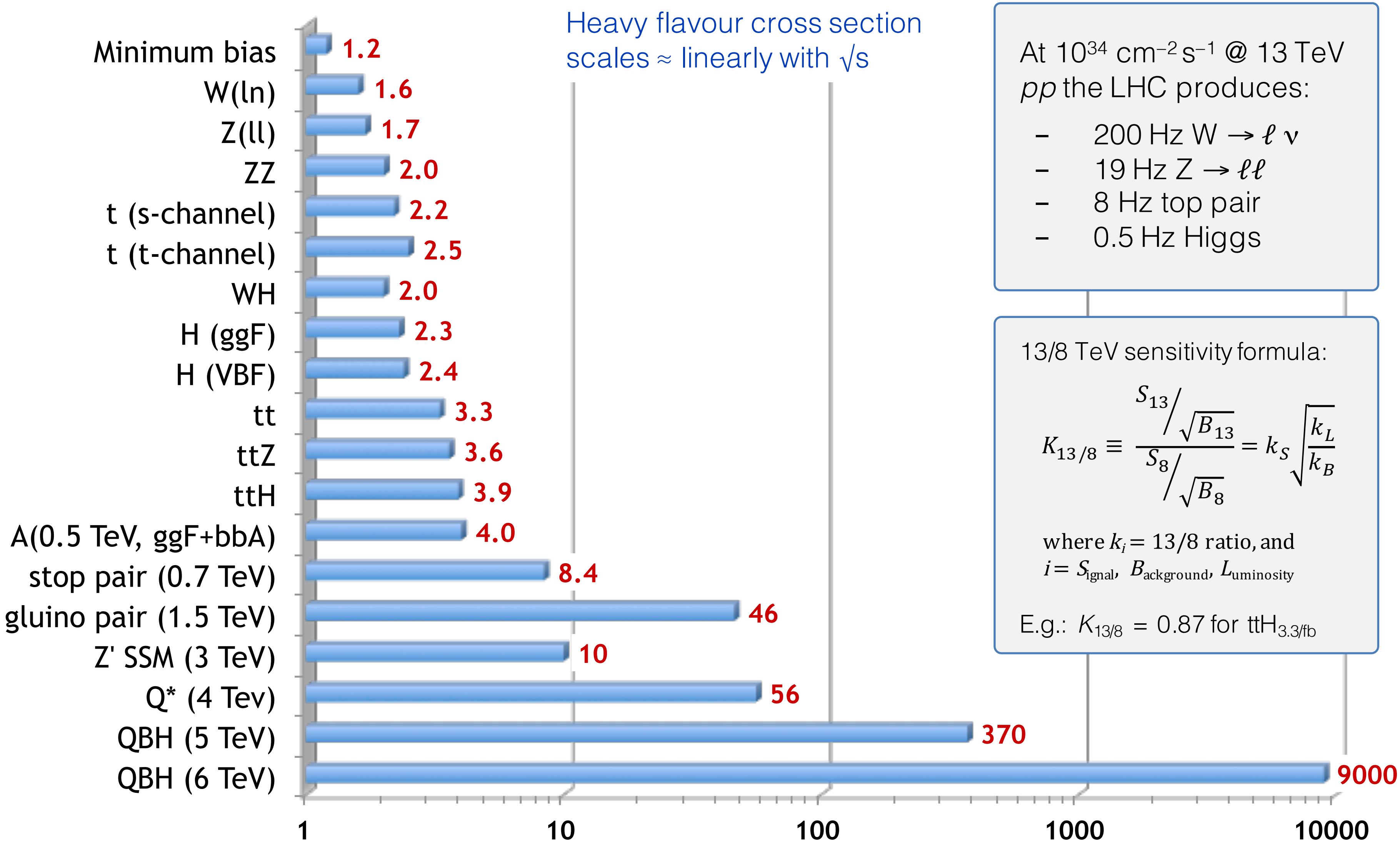
The LHC Run-2: 13 TeV / 8 TeV inclusive “parton luminosity” ratio



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 $\rightarrow \ell\,\nu$
- 19 Hz Z $\rightarrow \ell\ell$
- 8 Hz top pair
- 0.5 Hz Higgs

13/8 TeV sensitivity formula:

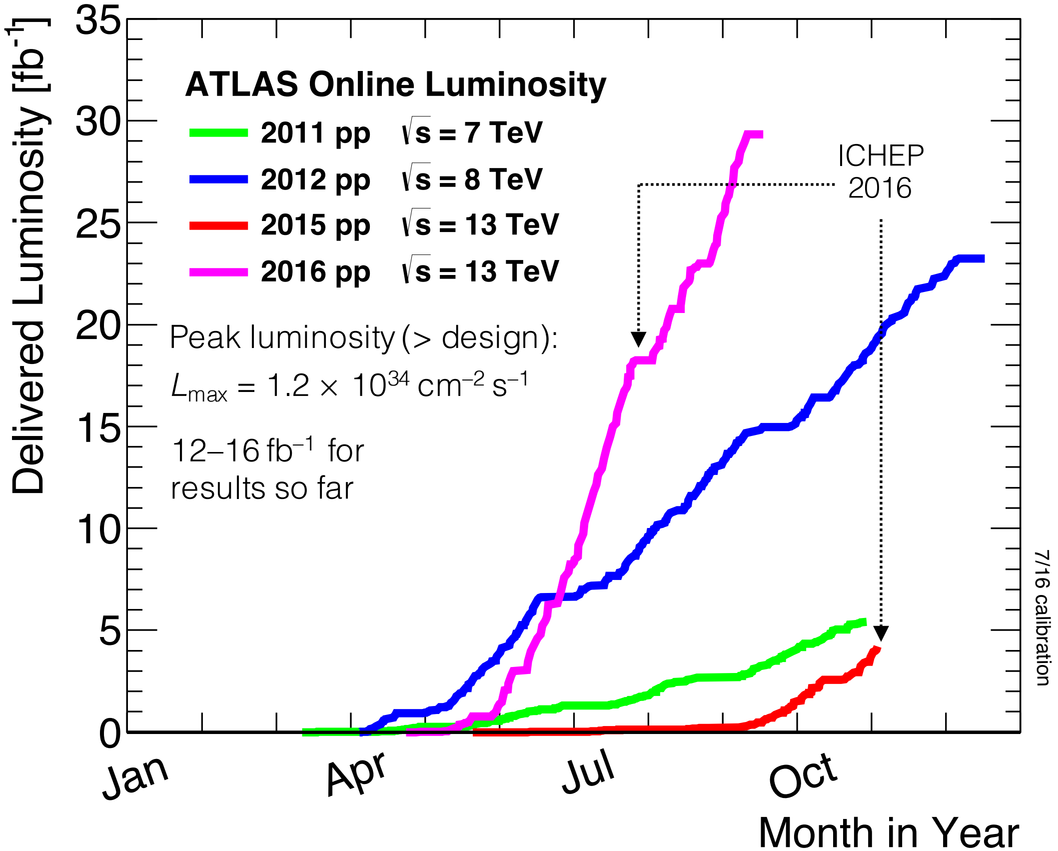
$$K_{13/8} \equiv \frac{S_{13}/\sqrt{B_{13}}}{S_8/\sqrt{B_8}} = k_S\sqrt{\frac{k_L}{k_B}}$$

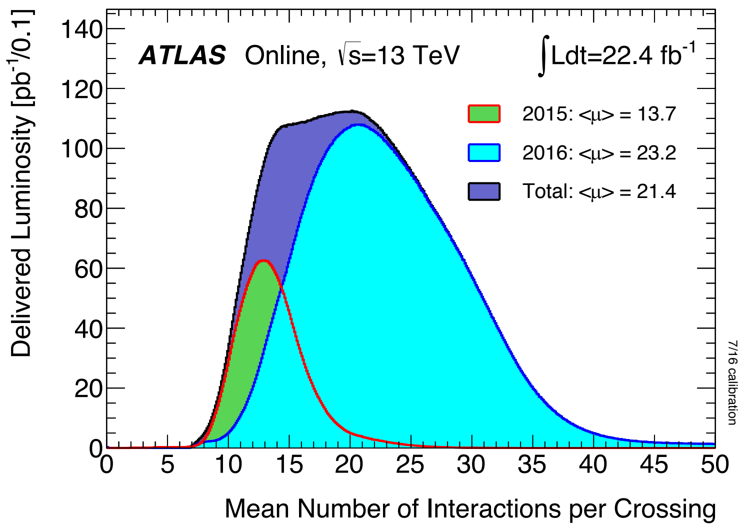
where $k_i = 13/8$ ratio, and $i = S_{\text{ignal}},\ B_{\text{ackground}},\ L_{\text{uminosity}}$

E.g.: $K_{13/8}$ = 0.87 for ttH$_{3.3/\text{fb}}$

2015 LHC proton–proton luminosities

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



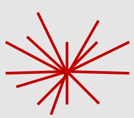


2015 and 2016 pileup profile in ATLAS & CMS
(LHCb mean pileup of ~1.7 due to levelling)

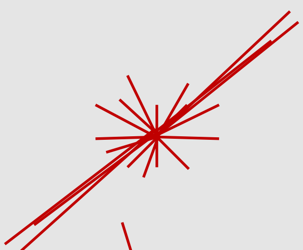
LHCb after luminosity levelling: 1.3 (1.5) fb^{-1} recorded (delivered)

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

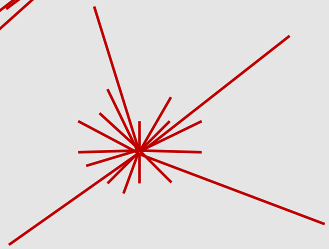
Standard Model and top physics results



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

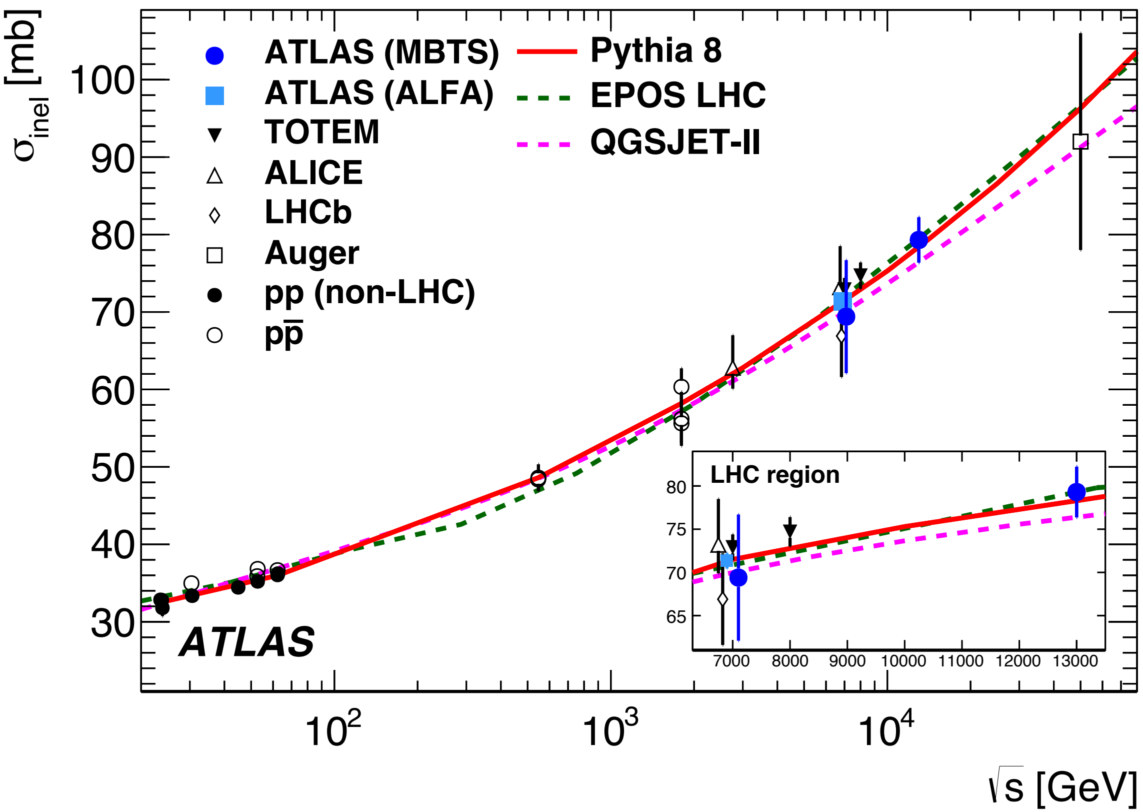
Inclusive inelastic cross-section measurement at 13 TeV

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:

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

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

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

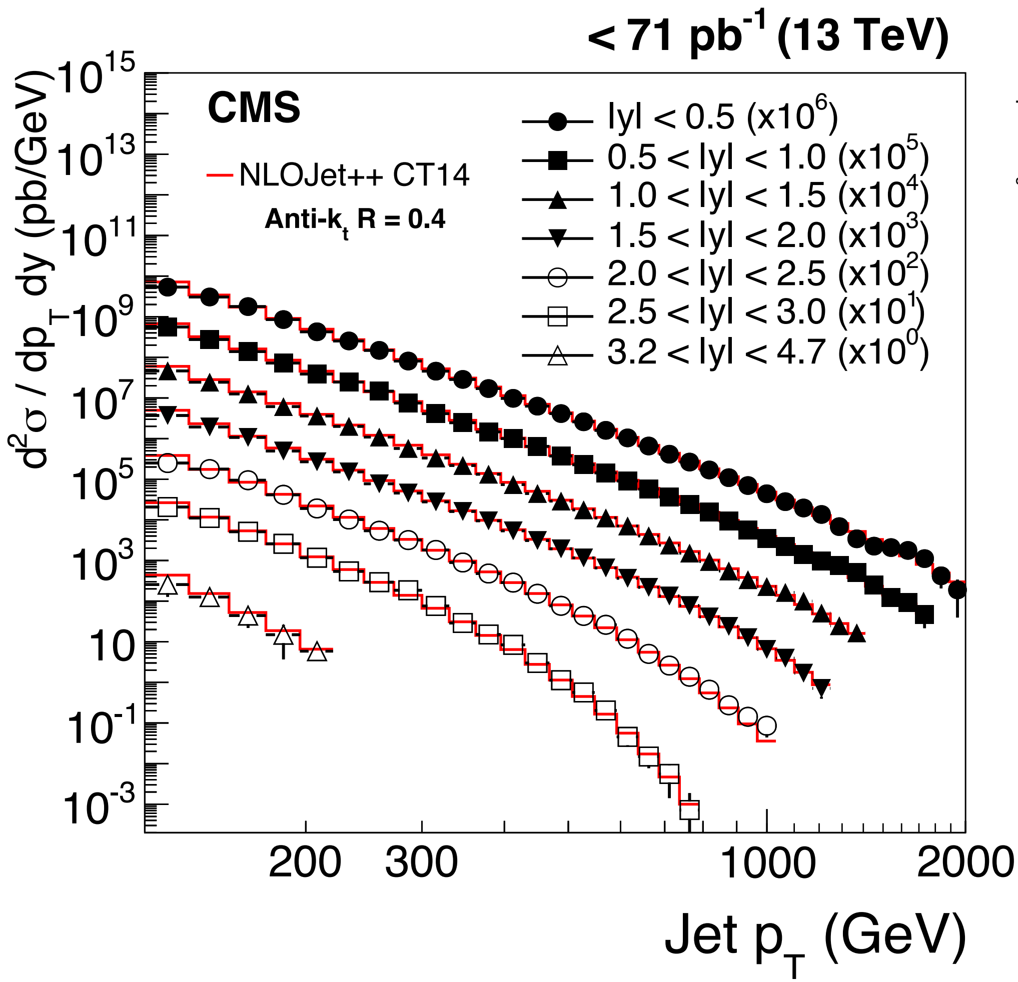
using dedicated forward devices (up to 1.4% precision in Run-1, dominated by luminosity error)

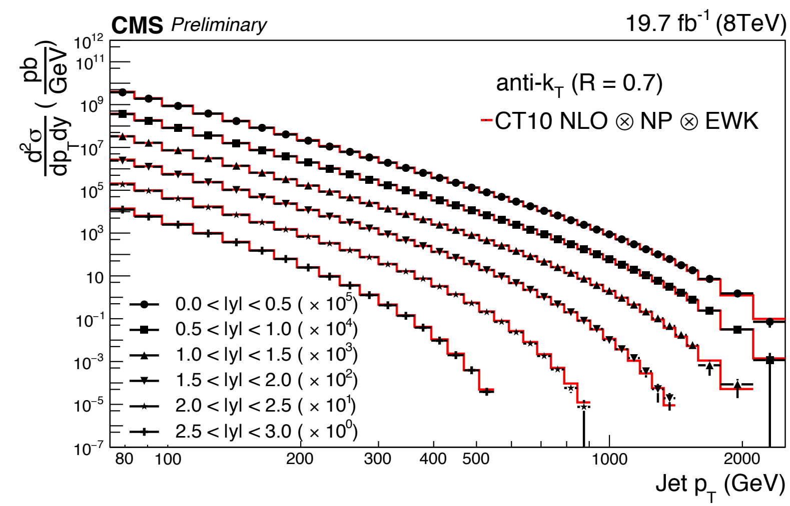
Measurement of jet cross section at 13 TeV

Primary test of QCD at highest collision energy

CMS 1605.04436

Double differential cross section measured by CMS





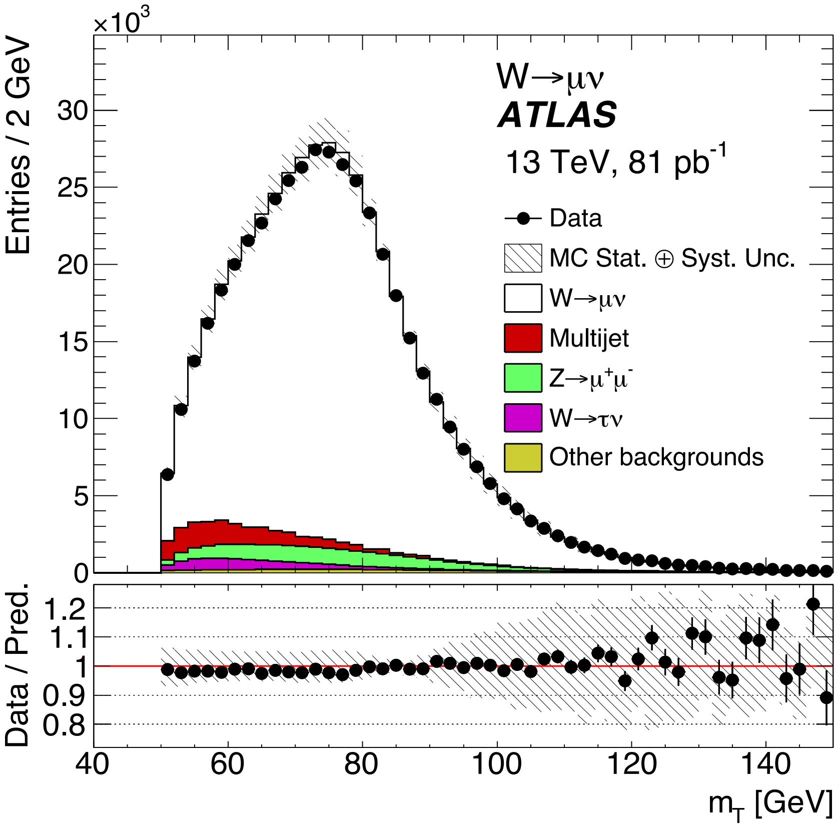
Comparison with 8 TeV plot (right) shows effect of increased parton luminosities at high jet p_T

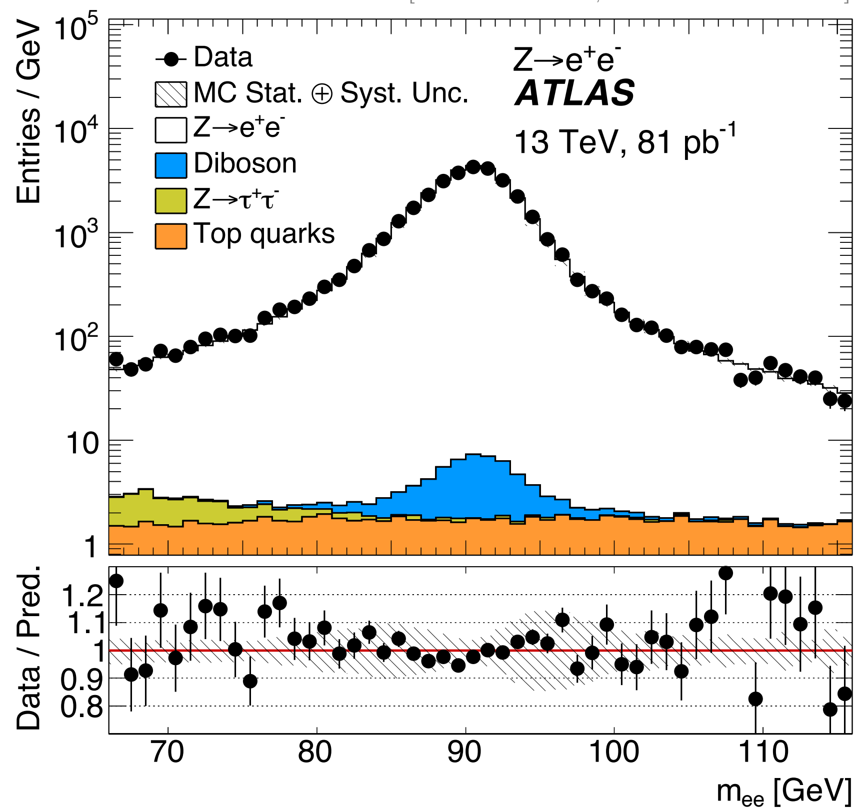
Z and W production at 13 TeV — examples: $\sigma_{Z\to\mu\mu}$ (13 TeV) ~ 1.9 nb, $\sigma_{W\pm\to\mu\nu}$ (13 TeV) ~ 19.7 nb

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]





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

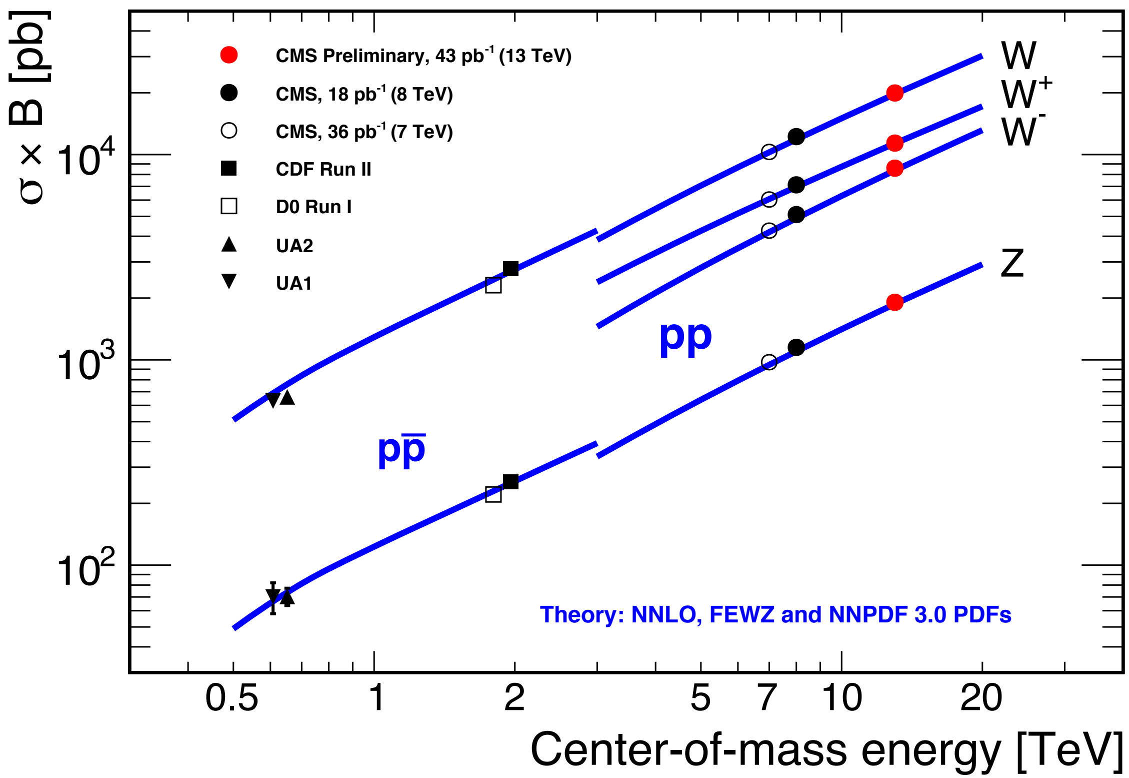
$$m_{e_1e_2} = \sqrt{2p_{T,1}p_{T,2}(\cosh\Delta\eta_{12}-\cos\Delta\phi_{12})}$$

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

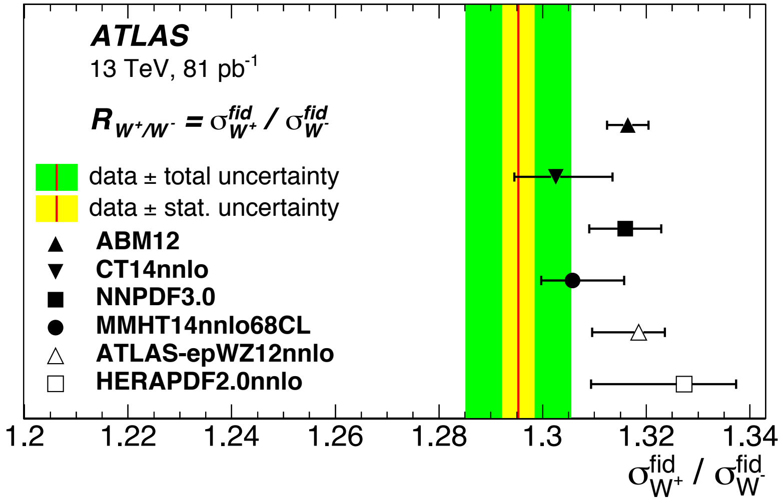
Comparison of measured cross-sections with NNLO QCD & NLO EW Drell-Yan predictions (FEWZ 3.1): good agreement found within uncertainties

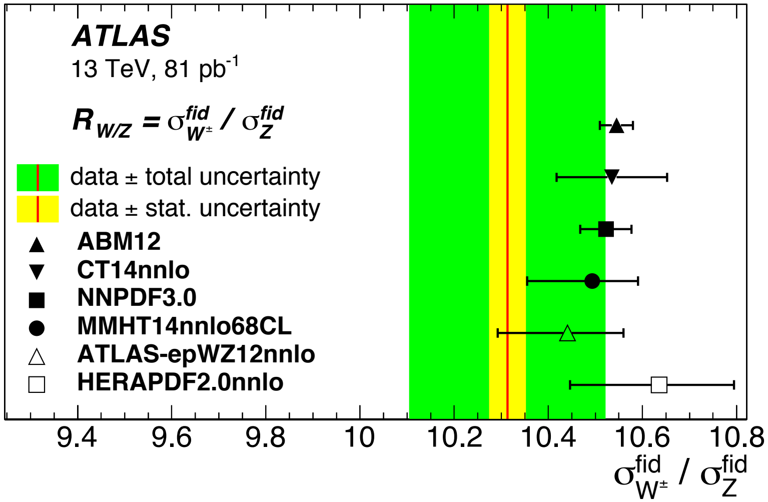


Also: LHCb σ_Z ($2.0 < \eta < 4.5$) in agreement with SM

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

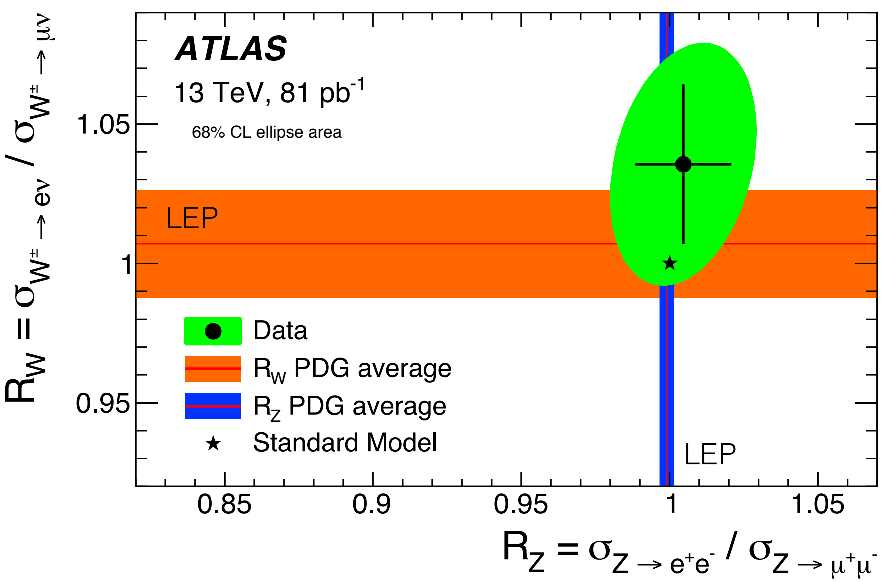
Powerful tools to constrain PDFs: W^+ / W^- sensitive to low-x u & d valence, W / Z constrains s





Lepton universality test

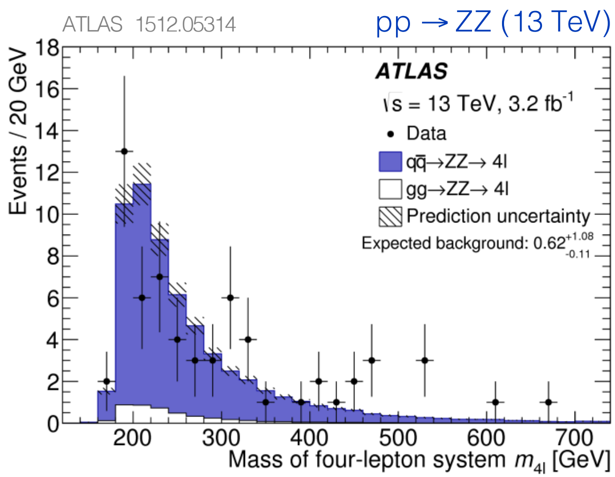
Lepton universality in charged current was measured to the 0.14% level at LEP in tau lepton decays, however at low energy (off-shell), so less sensitivity to new physics in loops

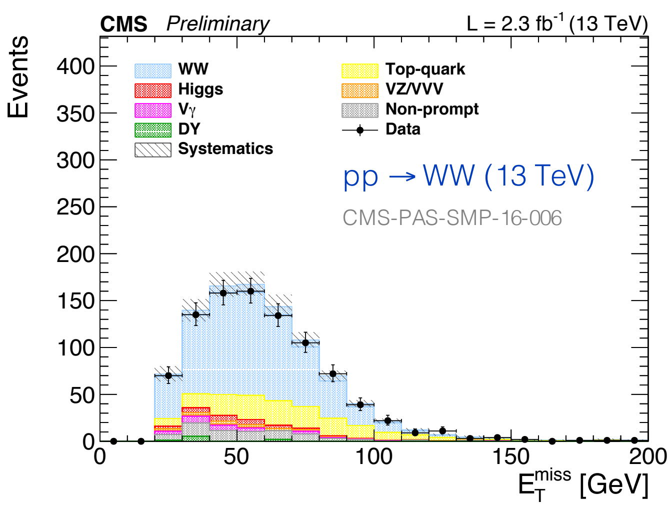


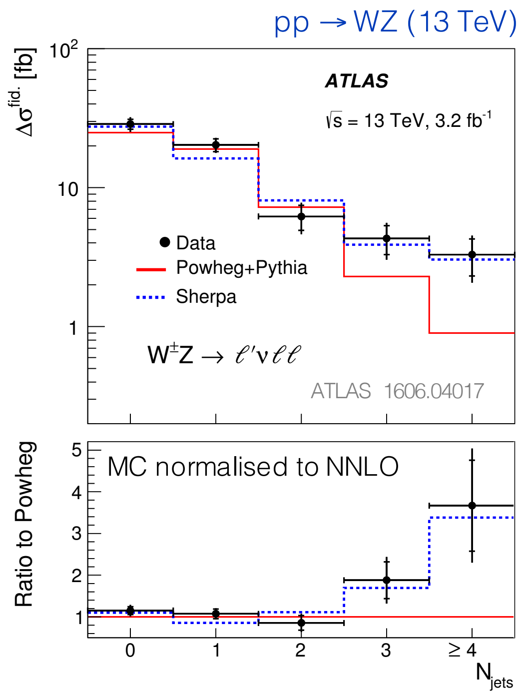
Diboson production — example: $\sigma_{WW,\text{ no Higgs}}$ (13 TeV) ~ 120 pb

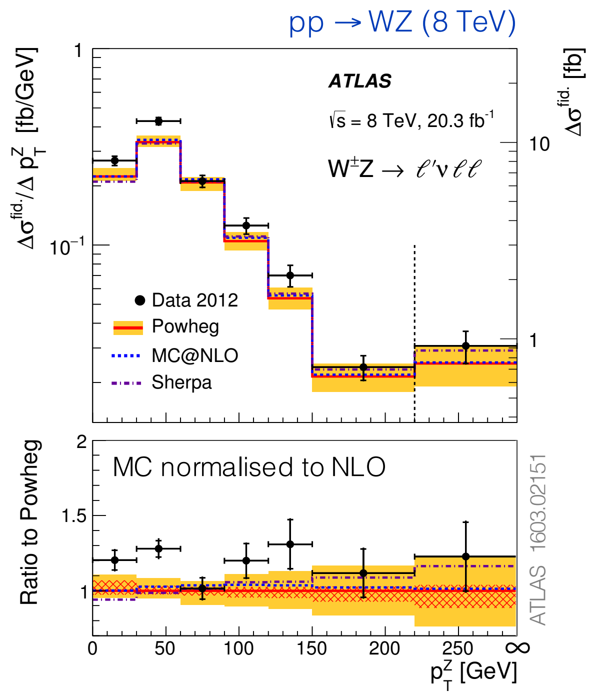
Highly important sector of LHC physics, intimately related to electroweak symmetry breaking

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)

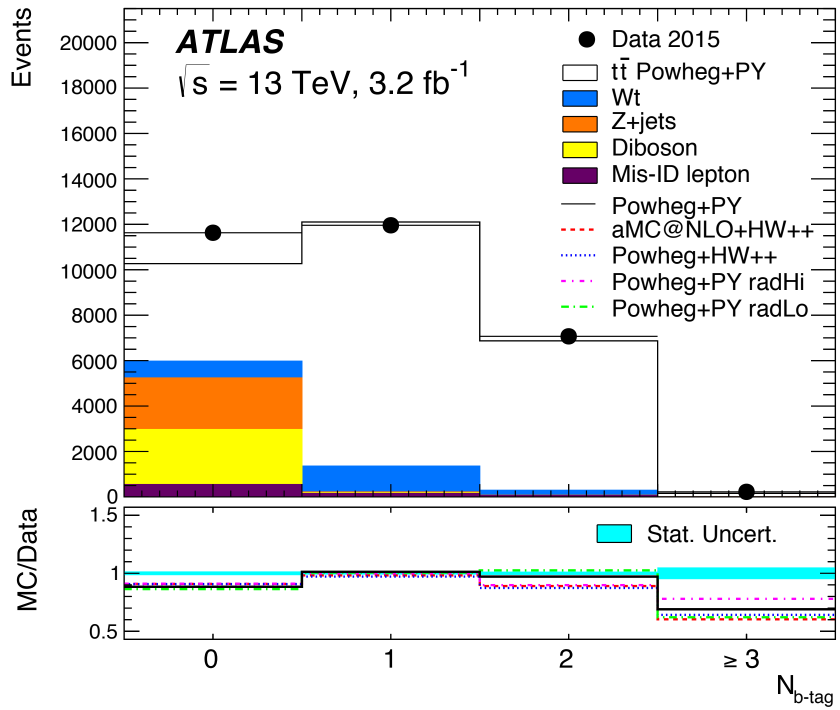
ATLAS 1606.02699, similar for CMS

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

$$N_1 = L \cdot \sigma_{t\bar{t}} \cdot \varepsilon_{e\mu} \cdot 2\varepsilon_b \cdot (1 - C_b \varepsilon_b) + N_1^{\mathrm{bkg}}$$
$$N_2 = L \cdot \sigma_{t\bar{t}} \cdot \varepsilon_{e\mu} \cdot C_b \varepsilon_b^2 + N_2^{\mathrm{bkg}}$$

MC normalised to SM expectation



Where:

- $N_{1(2)}$ – number of selected events with 1(2) b-tags
- $N_{1(2)}^{\mathrm{bkg}}$ – 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)

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

Expect: $N_1^{\mathrm{bkg}} = 1370 \pm 120$, $N_2^{\mathrm{bkg}} = 340 \pm 88$,
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

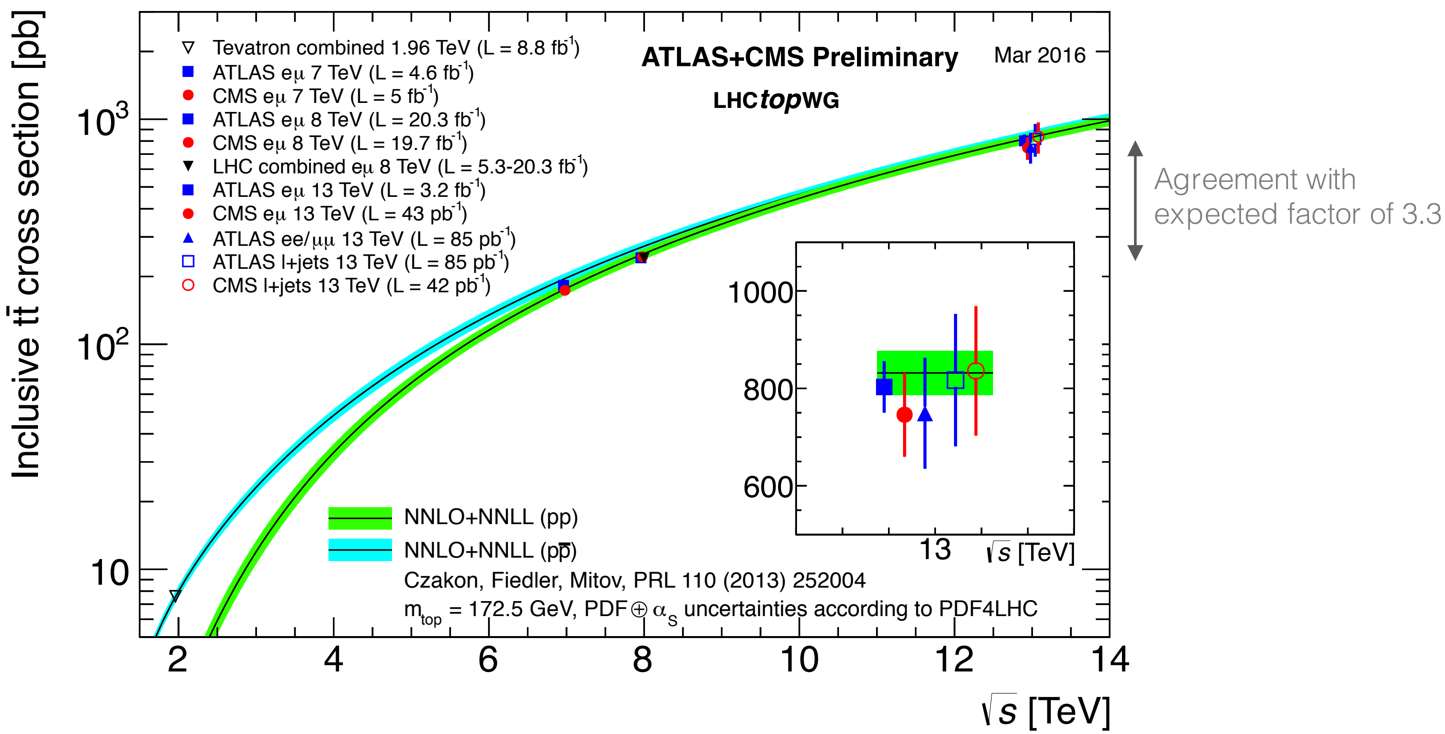
- tt parton shower & hadronisation (2.8%)
- tt NLO modelling, ISR/FSR radiation & PDF (1.1%)
- Single top modelling (0.8%)
- Electron ID + isolation (0.5%)
- Muon ID + isolation (0.5%)
- Lepton mis-identification (0.6%)

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



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

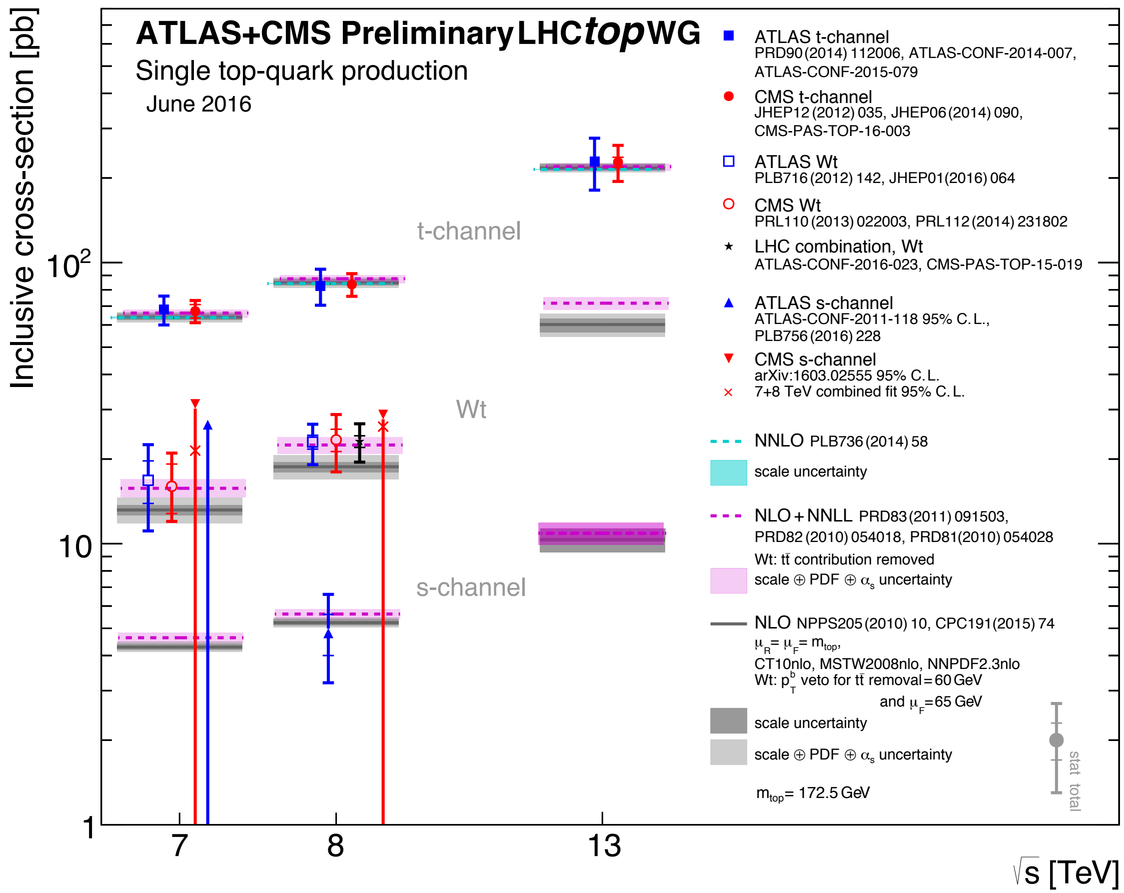
Differential cross-section measurements at 13 TeV show reasonable modelling, though some deviations at large jet multiplicity. Known modelling problems from Run-1 not all solved!

Single top quark production

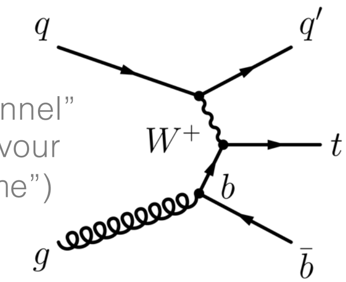
Increase of cross section by factor of 2.5 (t-channel) over 8 TeV, roughly 1/3rd of tt cross section

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

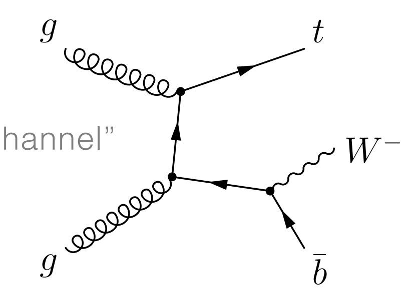
13 TeV: ATLAS-CONF-2015-079, CMS-PAS-TOP-16-003

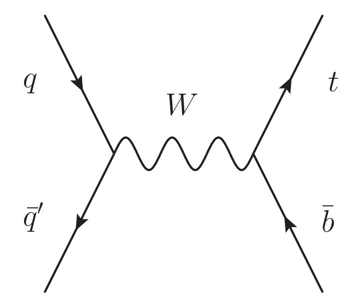


"t-channel" ("4 flavour scheme")



"Wt-channel"





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

Tevatron: 6.3σ, ATLAS Run-1: 3.2σ

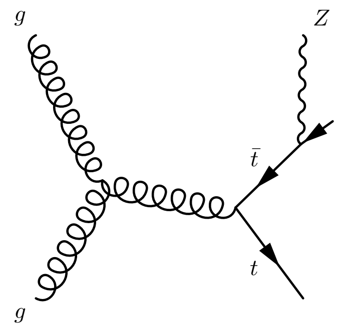
Top-antitop production and a vector boson at 13 TeV

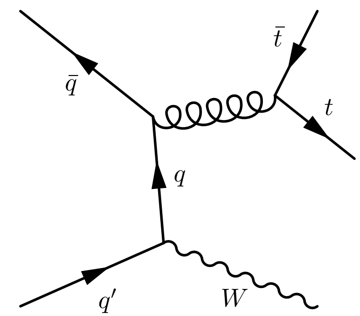
First results on important ttV process, in it's own right, and as background to ttH and searches

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)

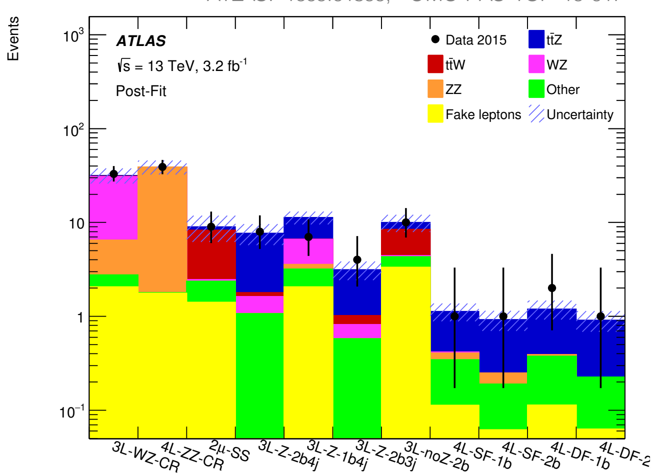


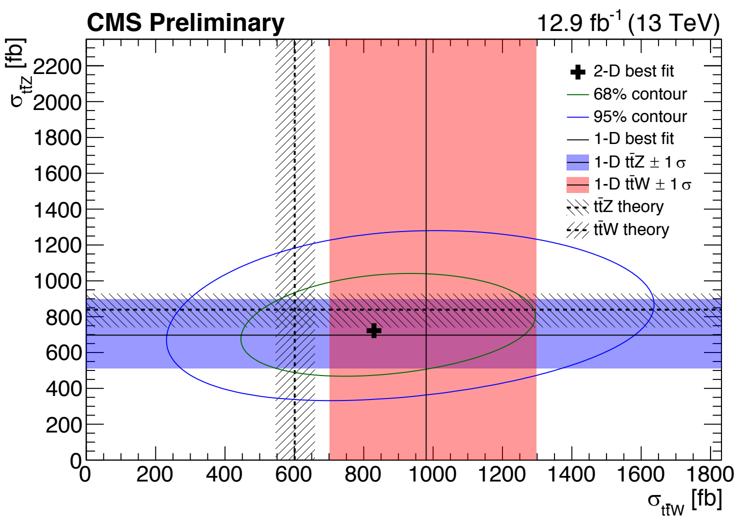


Different production processes and thus 13/8 TeV cross-section ratios for ttZ & ttW: 3.6 & 2.4

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

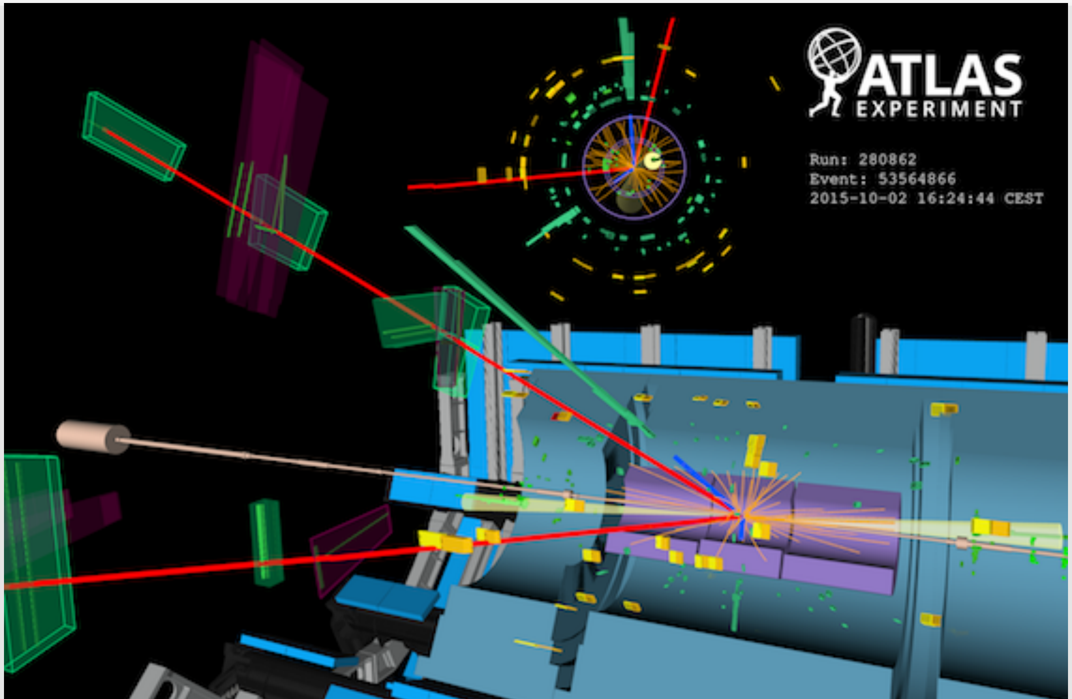
CMS (12.9 fb^{-1}, 2016):
ttW: $0.98\,^{+0.23}_{-0.22}\,^{+0.22}_{-0.18}$ pb
ttZ: $0.70\,^{+0.16}_{-0.15}\,^{+0.14}_{-0.12}$ pb

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

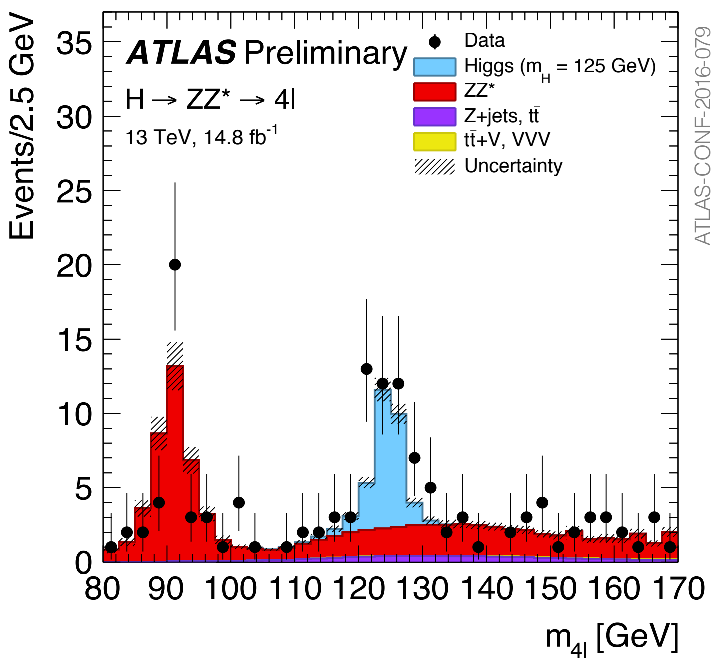


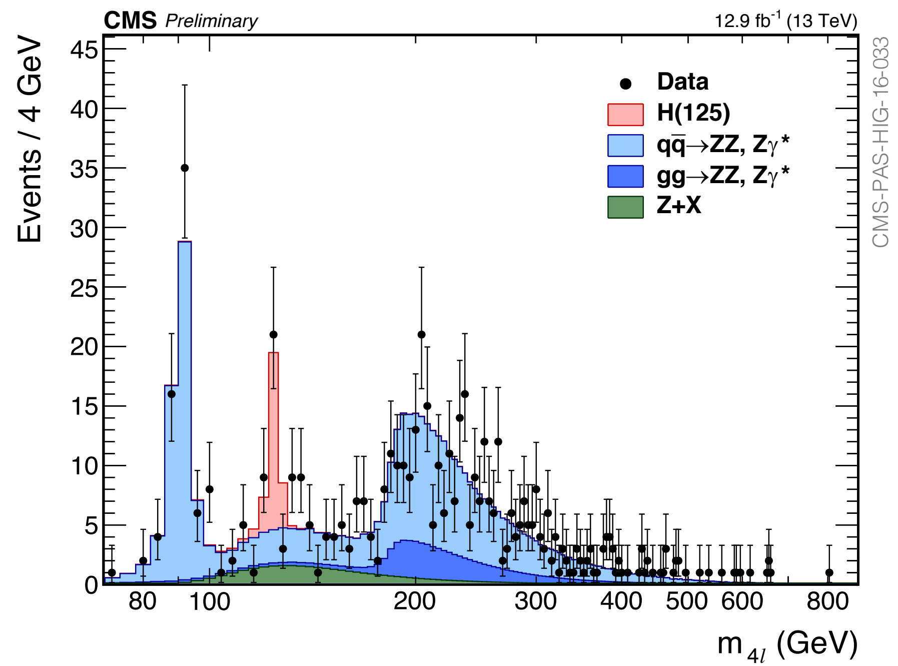
Display of H → eeμμ candidate from 13 TeV pp collisions. The electrons have a transverse momentum of 111 and 16 GeV, the muons 18 and 17 GeV, and the jets 118 and 54 GeV. The invariant mass of the four lepton system is 129 GeV, the di-electron invariant mass is 91 GeV, the di-muon invariant mass is 29 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

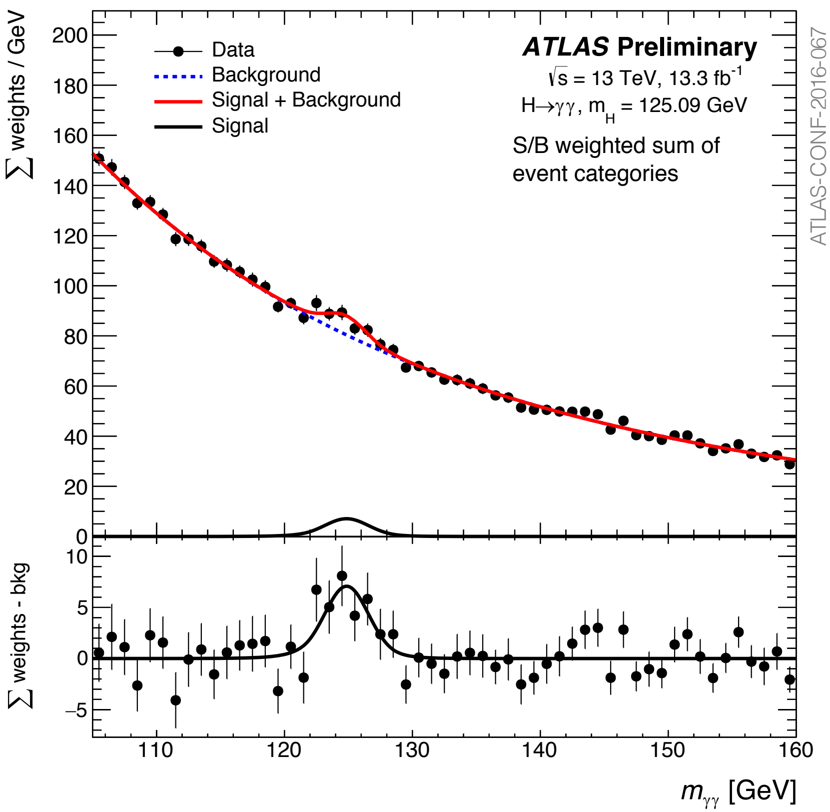
CMS also measured: $m_H = 124.50^{+0.48}_{-0.44}$ GeV

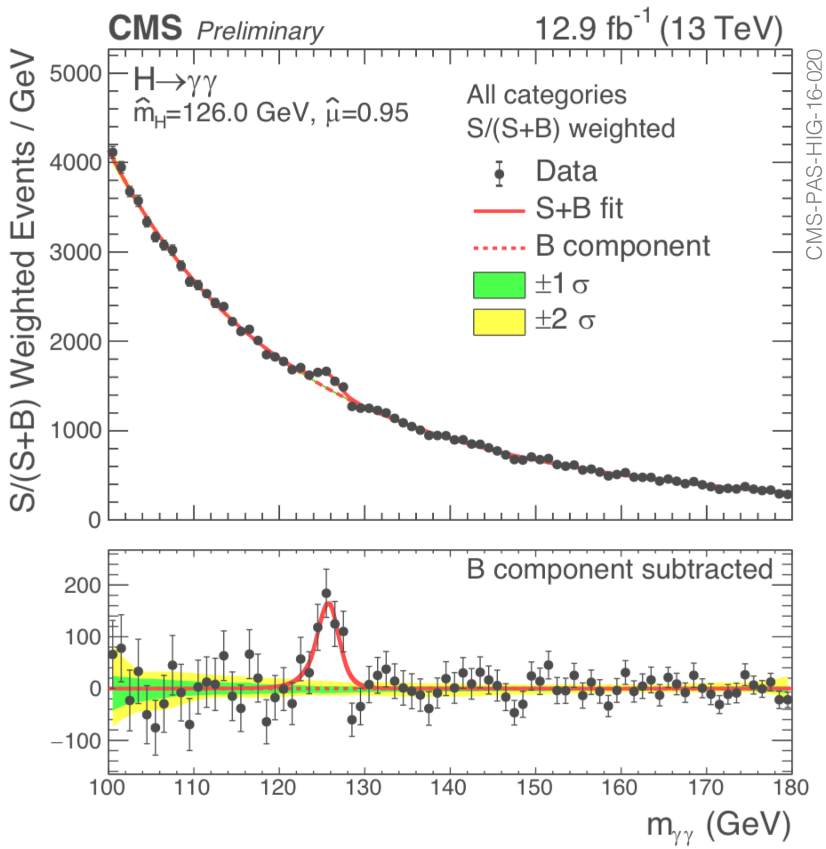
(dominated by statistical uncertainty, compare to 125.09 ± 0.24 GeV from ATLAS & CMS Run-1 combination)

ATLAS and CMS studied H_{125} in bosonic channels

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

H → γγ





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

$\mu = 0.91 \pm 0.20$

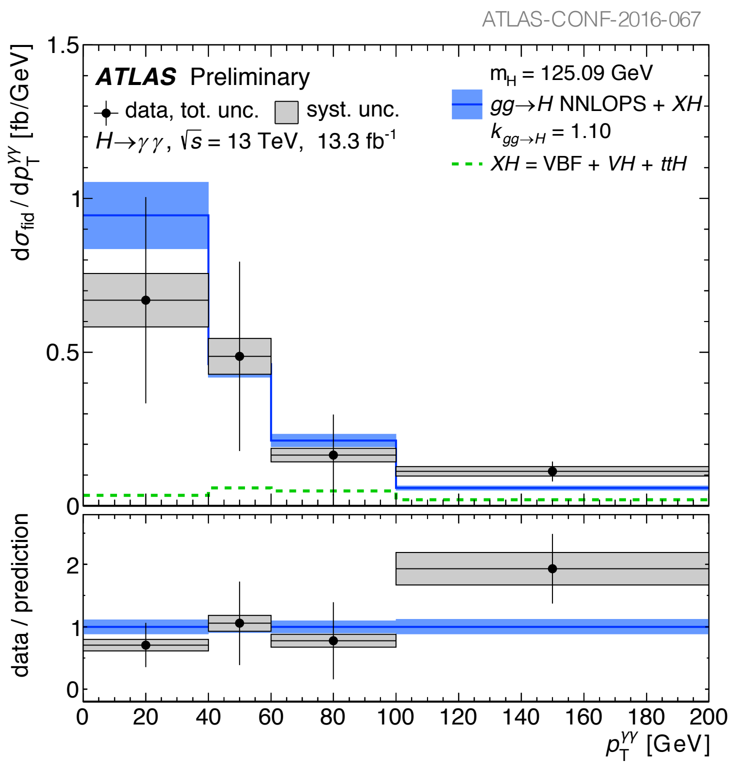
Expected significance (SM): 5.4σ

Expected significance (SM): 6.2σ

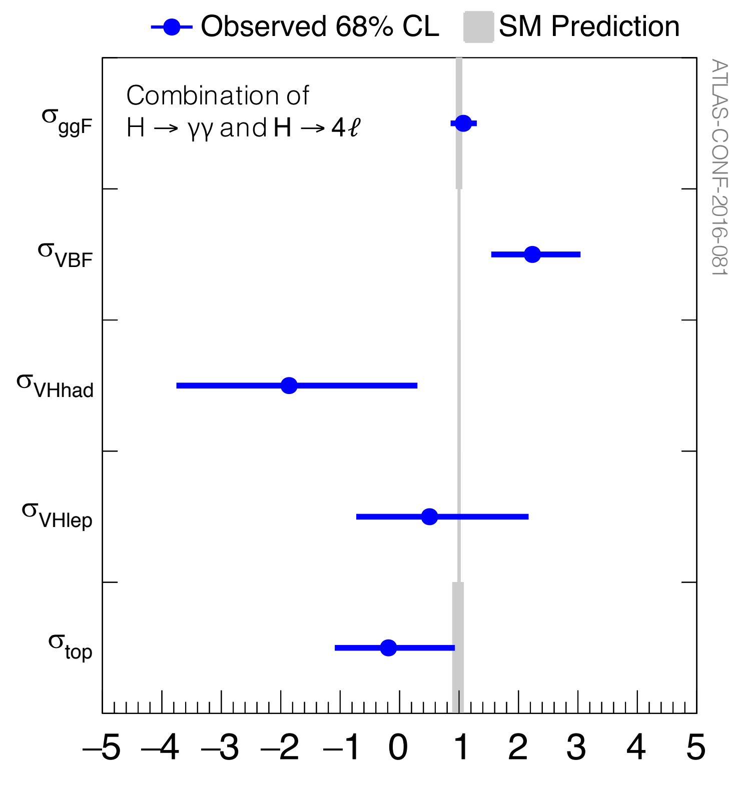
ATLAS and CMS studied H_{125} in bosonic channels

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

H → γγ and H → ZZ* → 4ℓ (right combined)



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

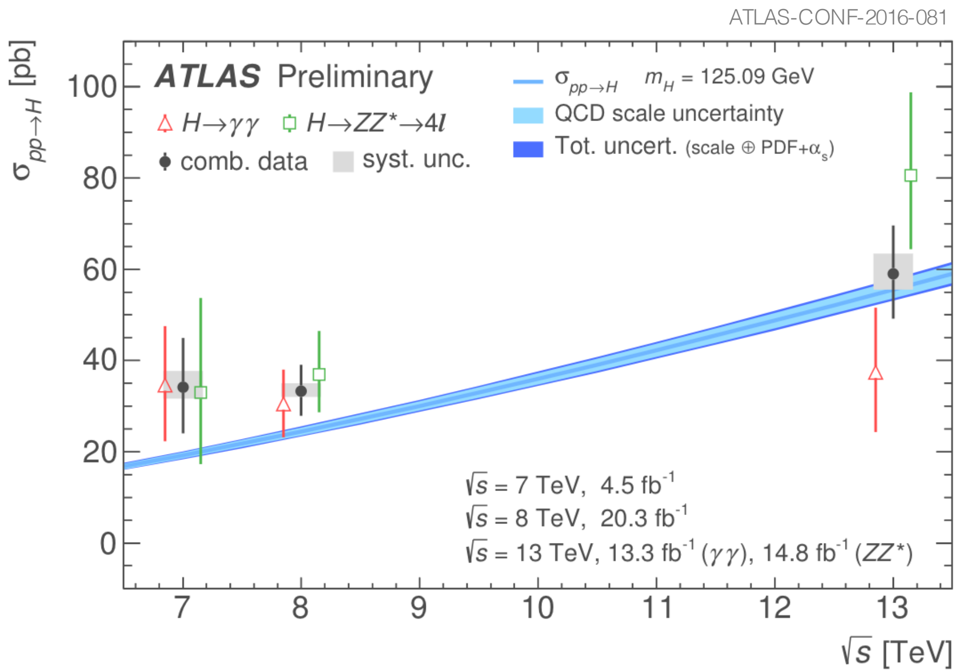


ATLAS and CMS studied H_{125} in bosonic channels

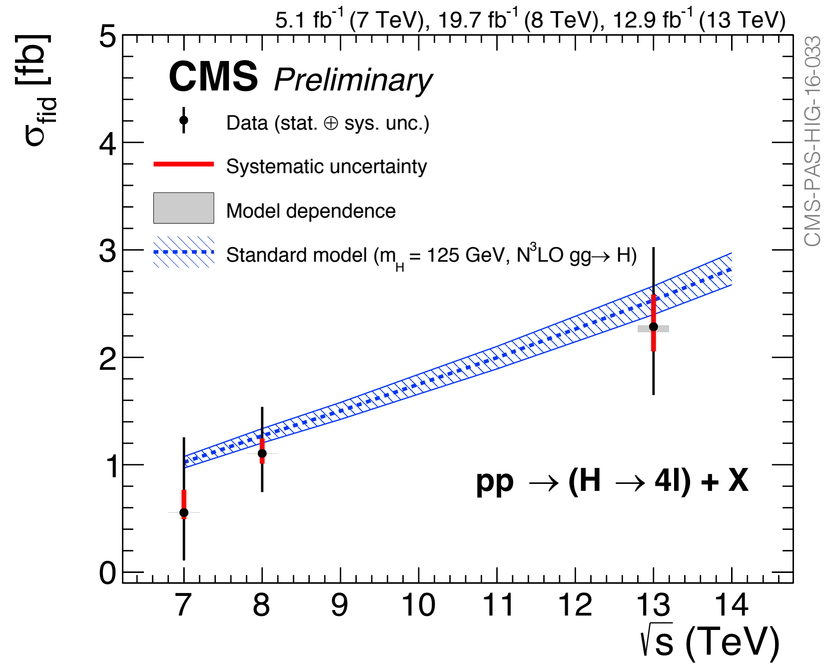
Cross section versus centre-of-mass energy

H → γγ and H → ZZ* → 4ℓ (left)

Combined H → 4ℓ, γγ



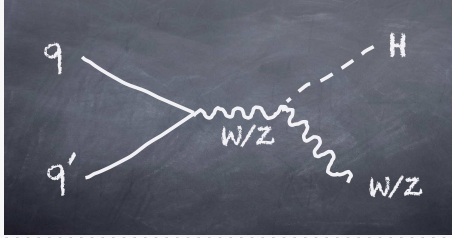
H → 4ℓ, *fiducial* cross section



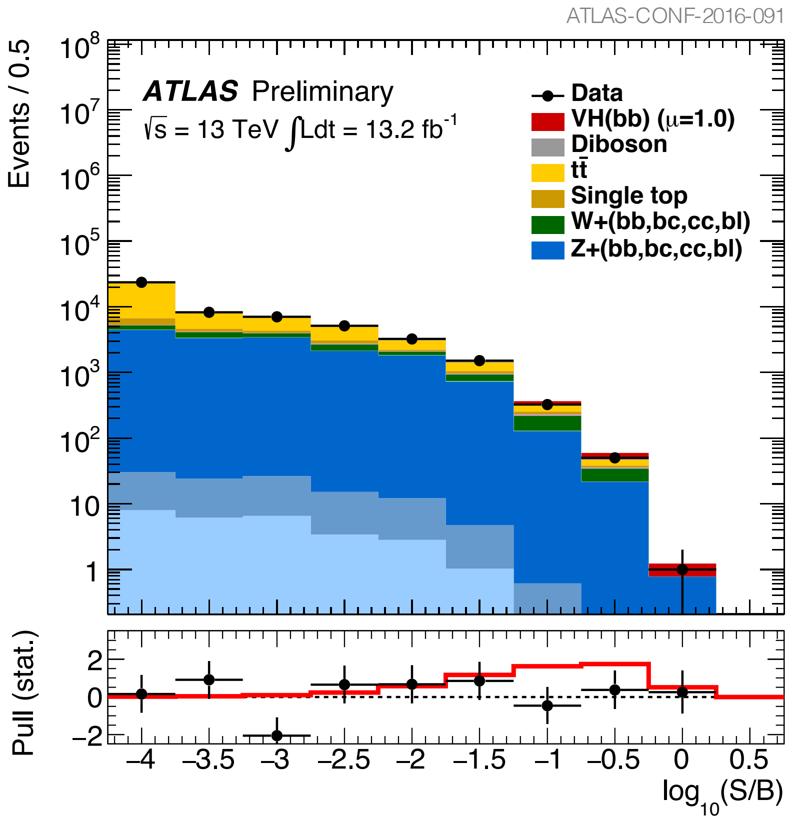
Expected rise of cross-section observed in data

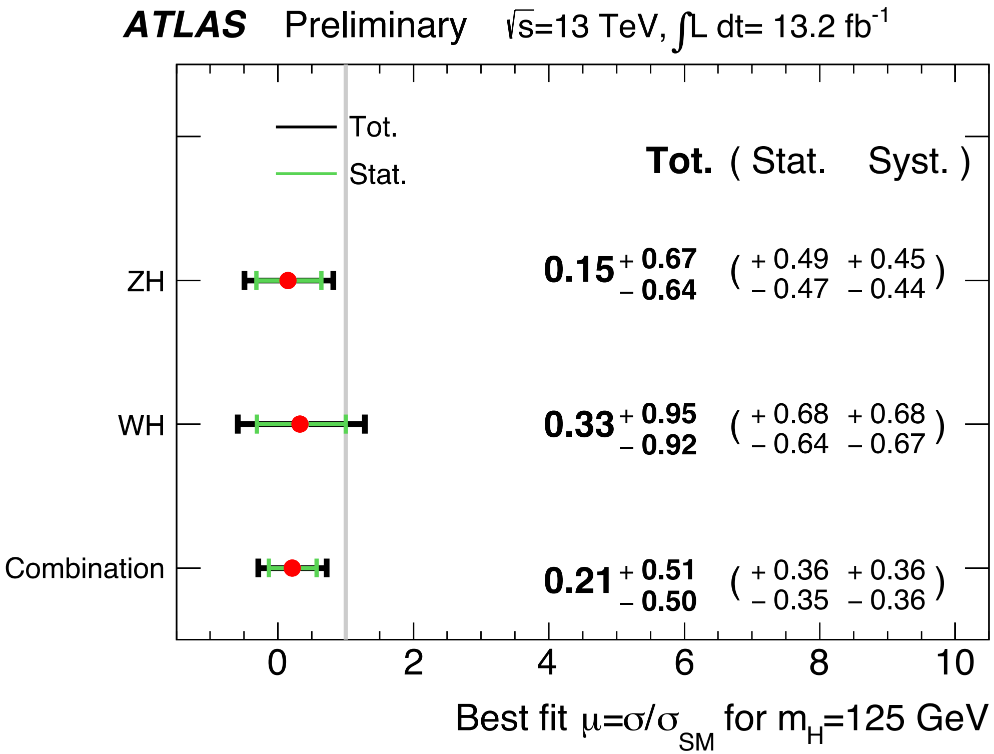
ATLAS studied H_{125} in bb decay channel

Associated production, challenging final states



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





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

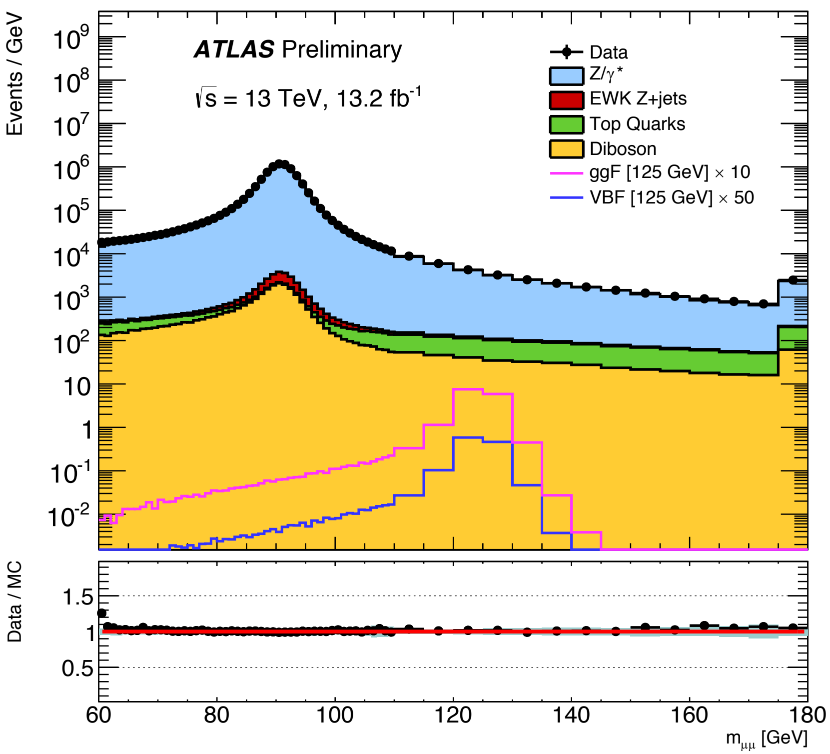
Searches for rare Higgs decays

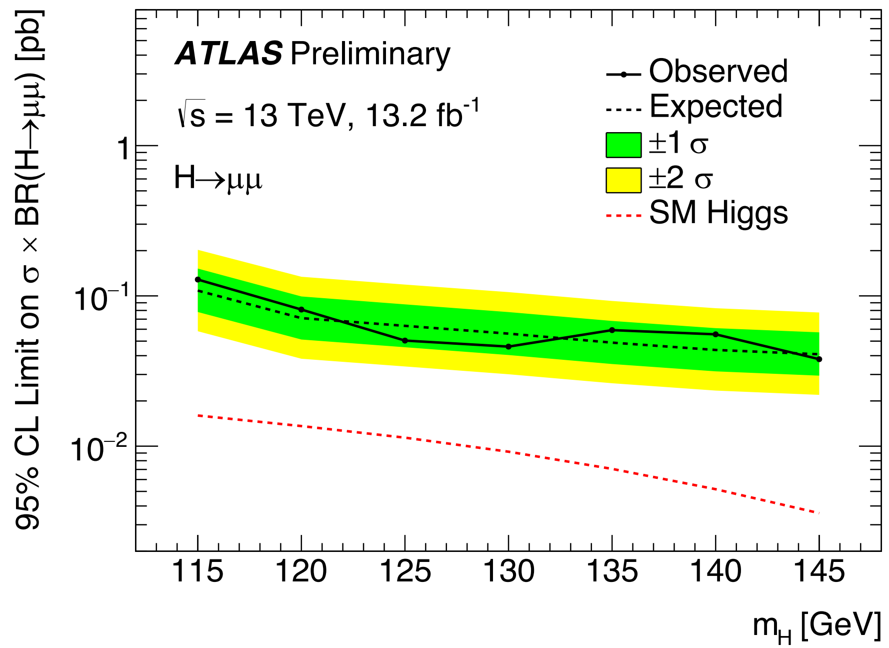
Beyond SM reach at present, but could have new physics contributions ?

H → μμ [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)

Beyond the Standard Model Higgs physics

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

Diverse search programme:

Light or heavy neutral Higgs bosons

Charged Higgs boson

Lepton flavour violating Higgs decays

BSM Higgs searches

Di-Higgs production (resonant or not)

Exotic Higgs decays

Higgs as portal to hidden sector

Higgs in BSM decay chains

BSM constraint from coupling measurements

Taken from: Thibault Guillemin @ SEARCH 2016

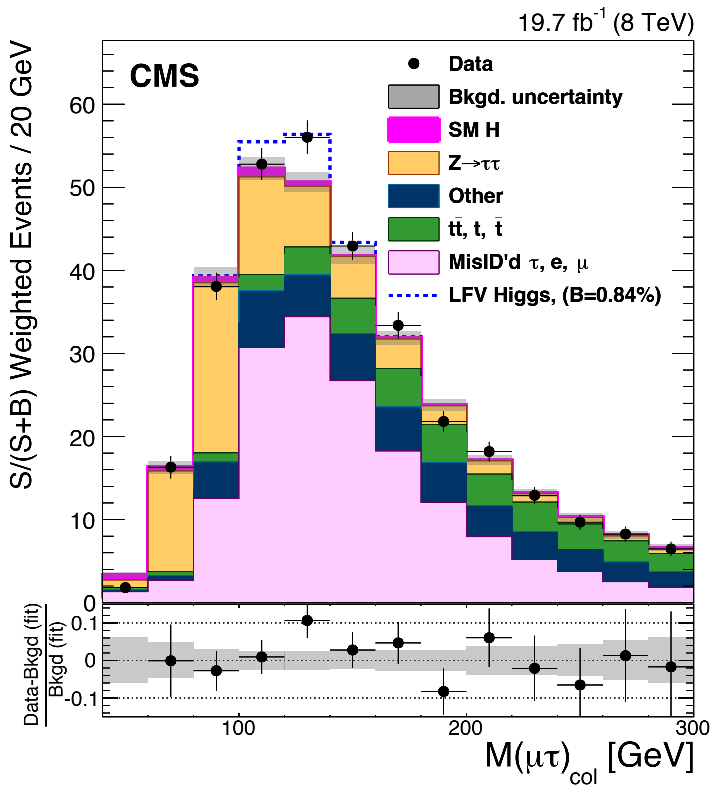
One word on lepton flavour violation in Higgs decays

Both experiments have finalised their Run-1 LFV analyses

While H → μe is severely constrained from flavour physics, H → τμ, τe are not (~10% limits)

CMS released early 2015 a H → τμ search finding a slight (2.4σ) excess

Not confirmed by ATLAS in the full Run-1 analysis



H → τμ:

ATLAS:
BR = 0.53 ± 0.51% < 1.43% (95% CL)

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

H → τe:

ATLAS:
BR = –0.3 ± 0.6% < 1.04% (95% CL)

One word on lepton flavour violation in Higgs decays

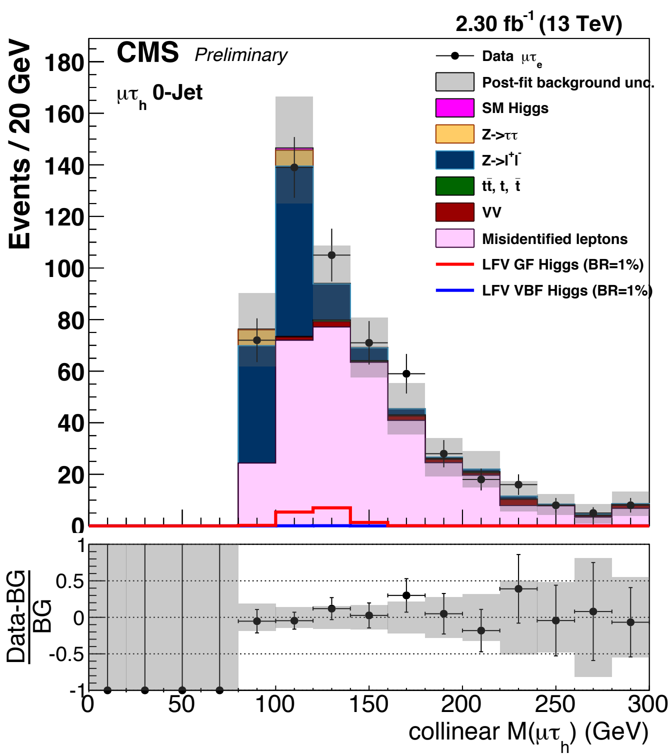
Both experiments have finalised their Run-1 LFV analyses

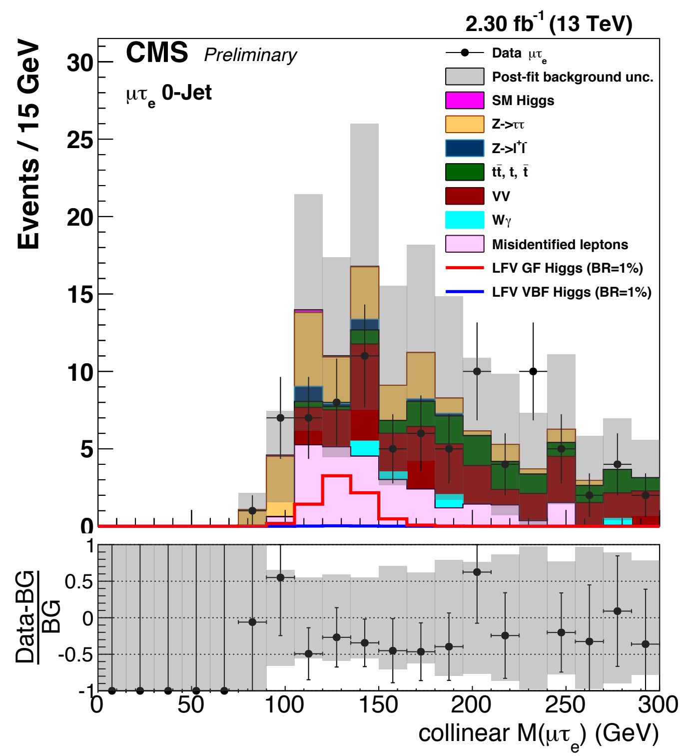
New preliminary result with 13 TeV from CMS [CMS-PAS-HIG-16-005]

Six categories considered: ($\mu\tau_h$, $\mu\tau_e$) × (0,1,2 jets)

No significant excess, combined limit: BR = –0.8 ± 0.8 % (<1.2% at 95%CL, expected: < 1.6%)

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





BSM Higgs boson searches

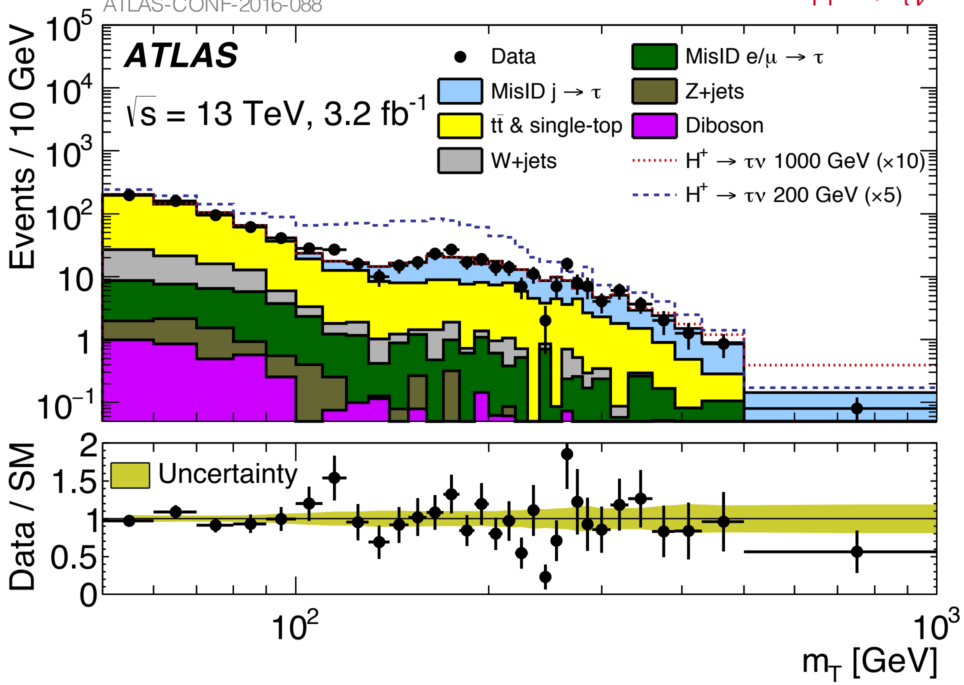
Single BEH doublet and form of potential simple but Nature may be more complex (eg, SUSY)

Beyond the SM "Higgs zoo"

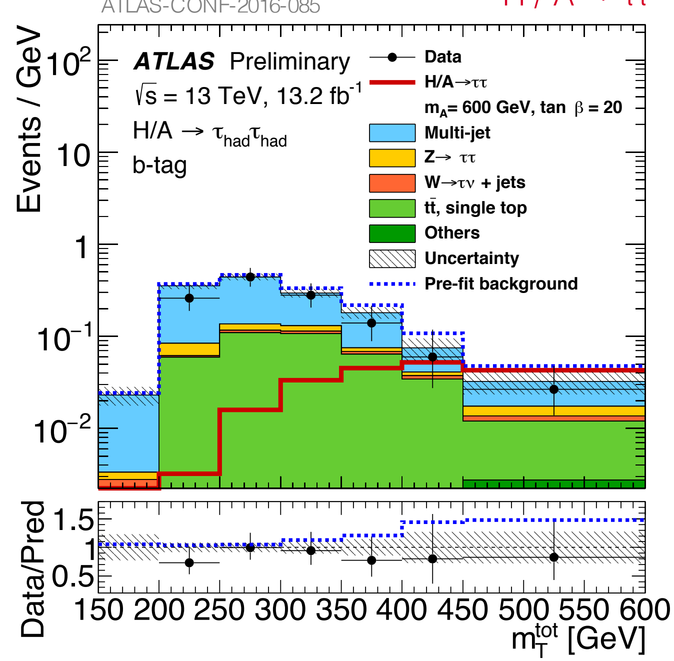
[Will Davey, LHCP 2014]

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

ATLAS-CONF-2016-088 $H^+ \to \tau\nu$



ATLAS-CONF-2016-085 $H / A \to \tau\tau$



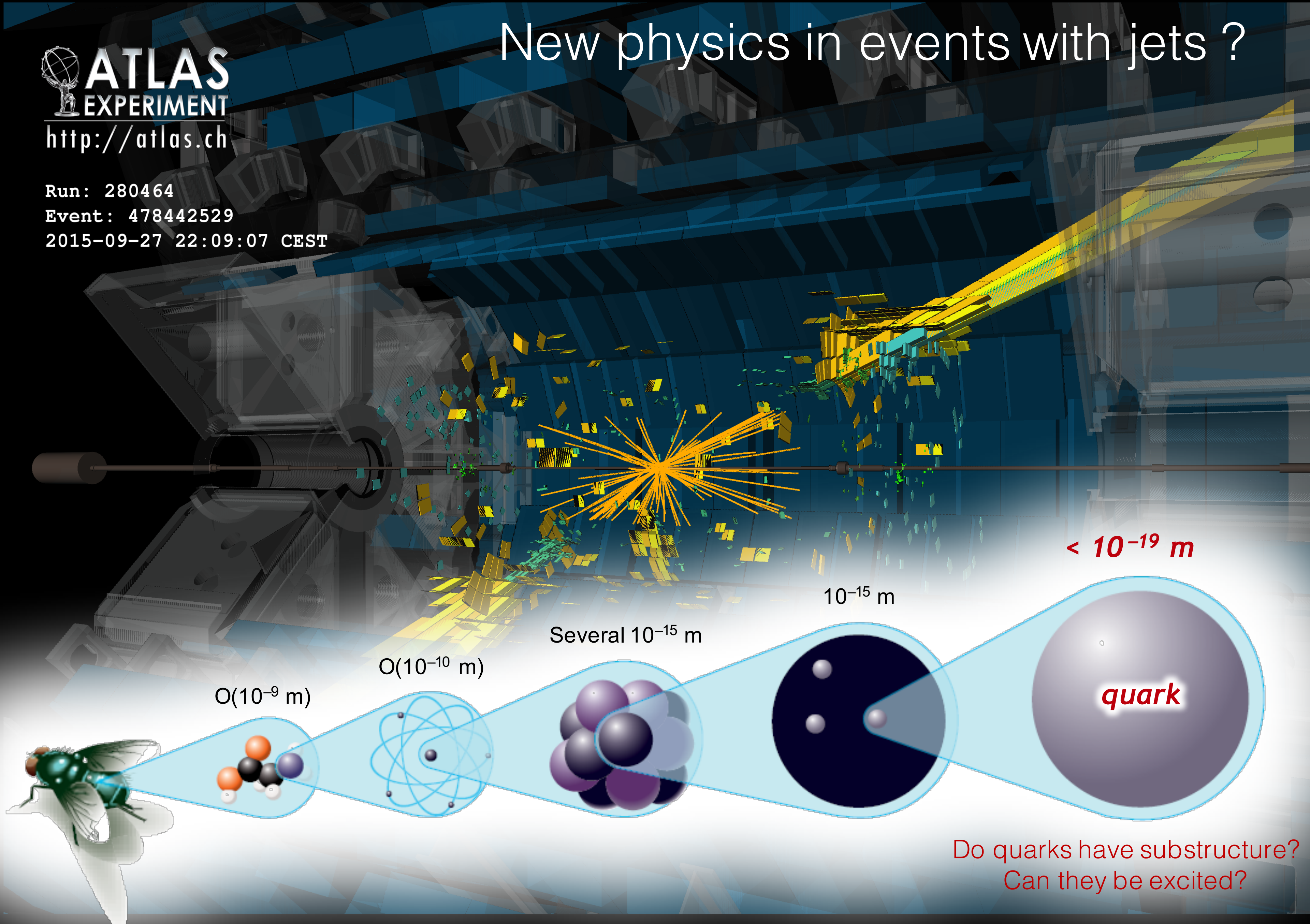
Searches — a fresh start

Will cover:

- Heavy resonances
- Supersymmetry
- Long-lived particles
- Dark matter (WIMPs)

Heavy resonance searches benefit the most and fastest from increase in centre-of-mass energy. Slow improvement with increasing luminosity

New physics in events with jets ?



Searches in high-p_T multijet final states at 13 TeV

Processes with large cross-sections, sensitivity to highest new physics scales

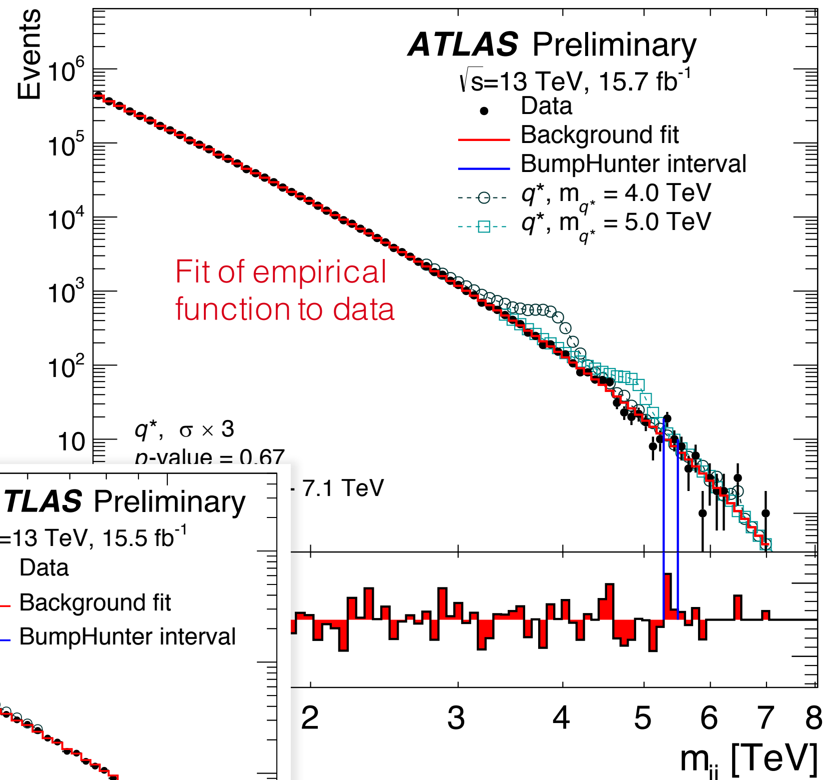
High priority early 13 TeV searches

- Dijet resonance and angular distribution (incl. lower mass via ISR)
- High-p_T multijets produced, eg, by strong gravity
- High-p_T lepton + jets (strong gravity)
- Second generation scalar lepto-quark pair production
  (μq-μq final state, excl. < 1.2 TeV)

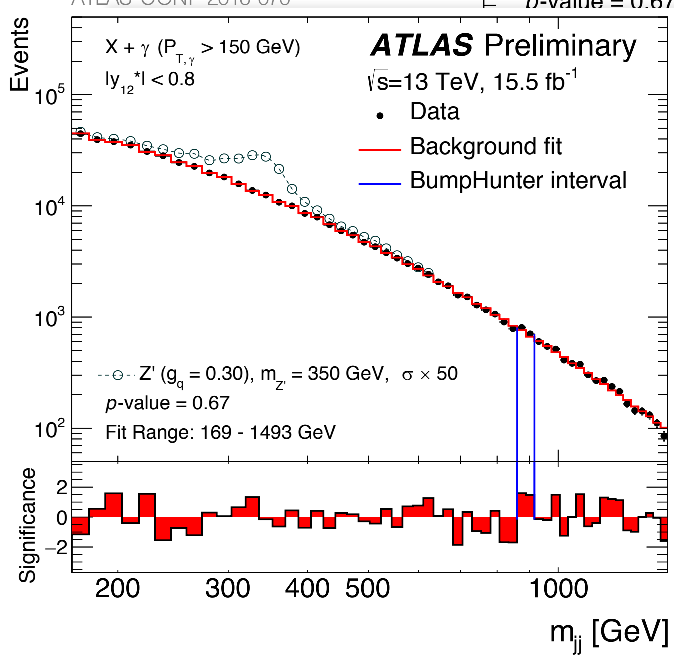
None of these searches showed an anomaly so far

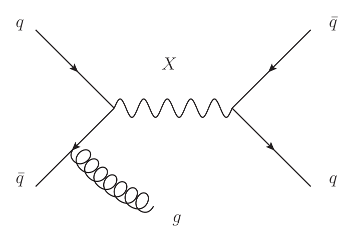
Limits on excited quarks (for example) at 5.6 TeV

ATLAS-CONF-2016-069

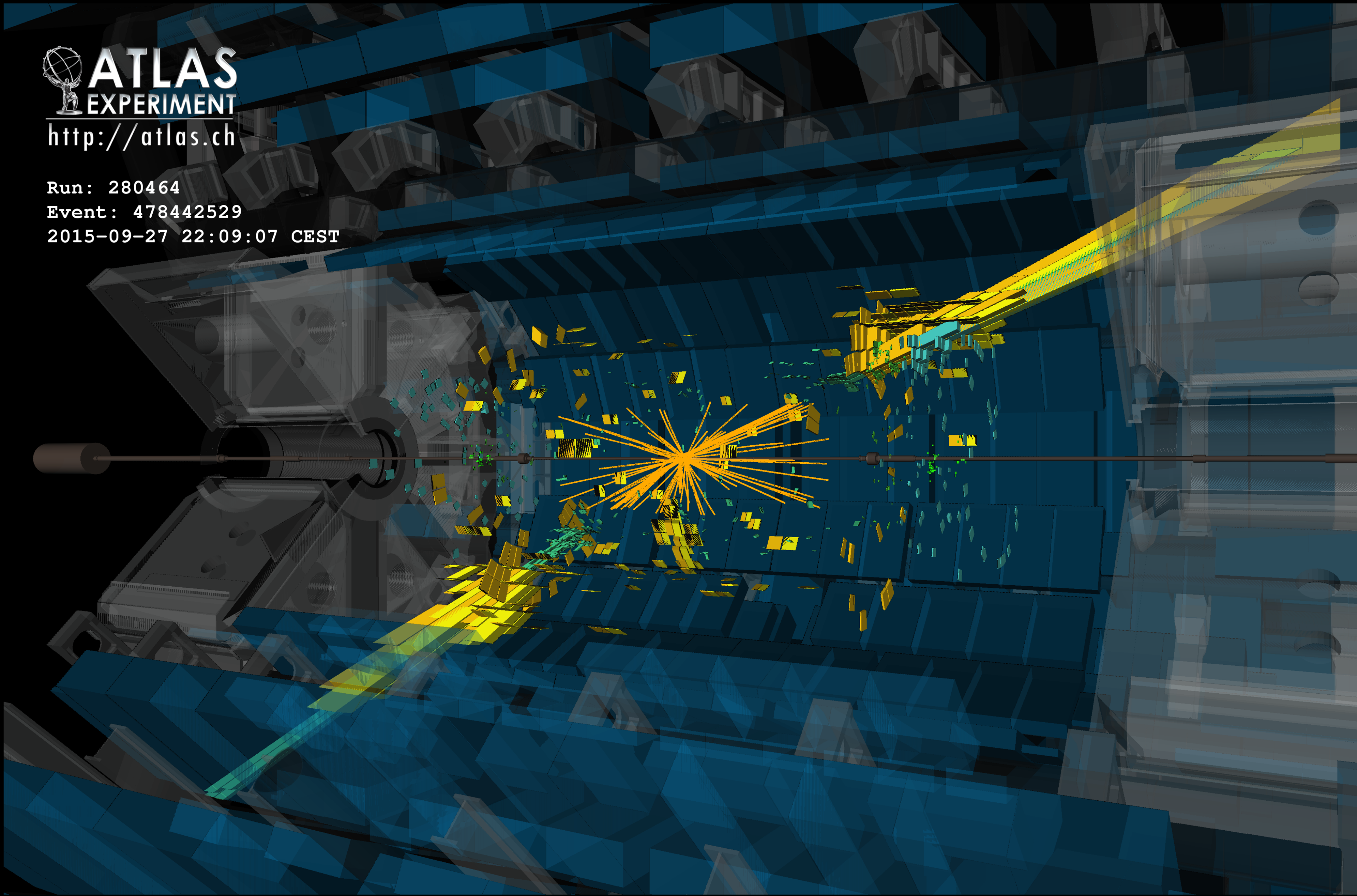


ATLAS-CONF-2016-070

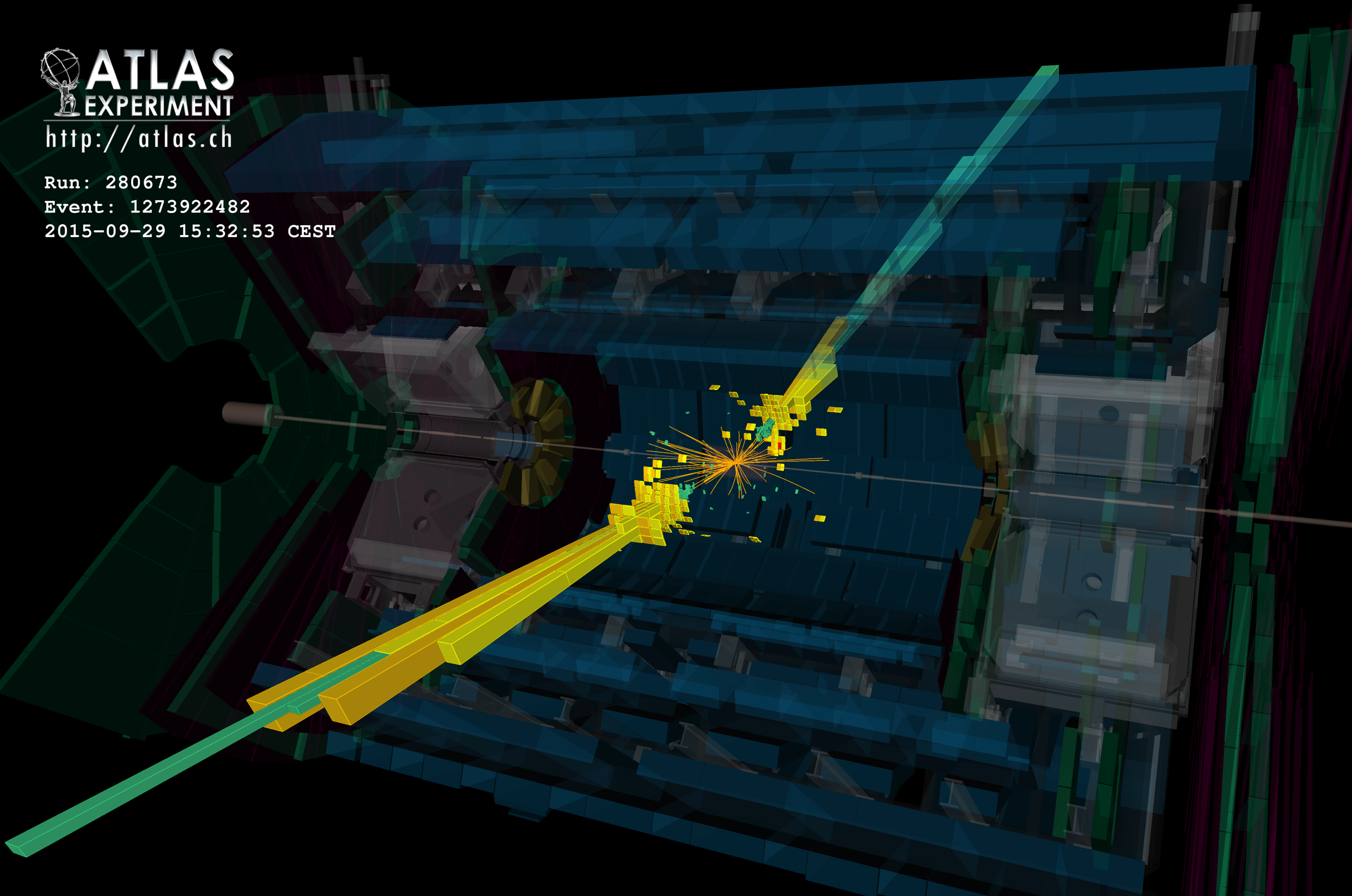




Highest mass dijet event measured by ATLAS in 2015 ($\sqrt{s}$ = 13 TeV): m_{jj} = 7.9 TeV



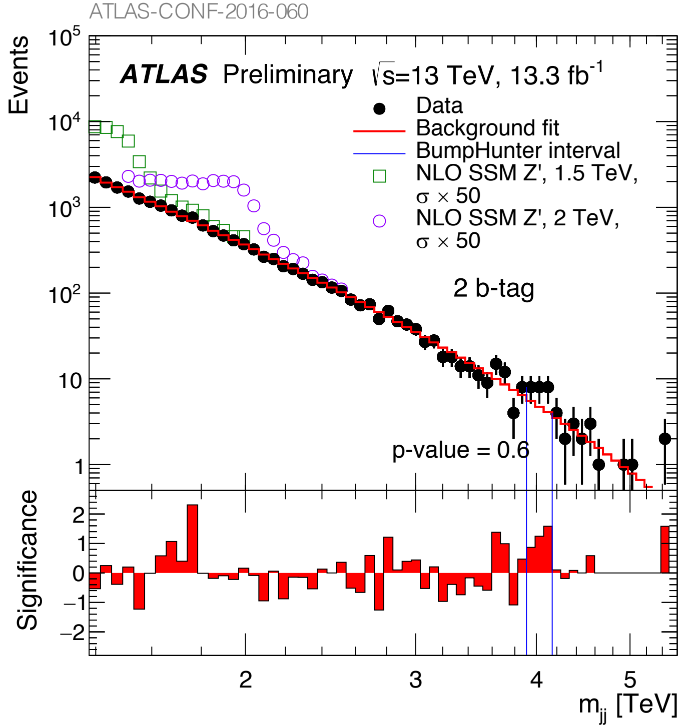
Highest mass *central* dijet event measured by ATLAS in 2015 ($\sqrt{s}$ = 13 TeV): m_{jj} = 6.9 TeV

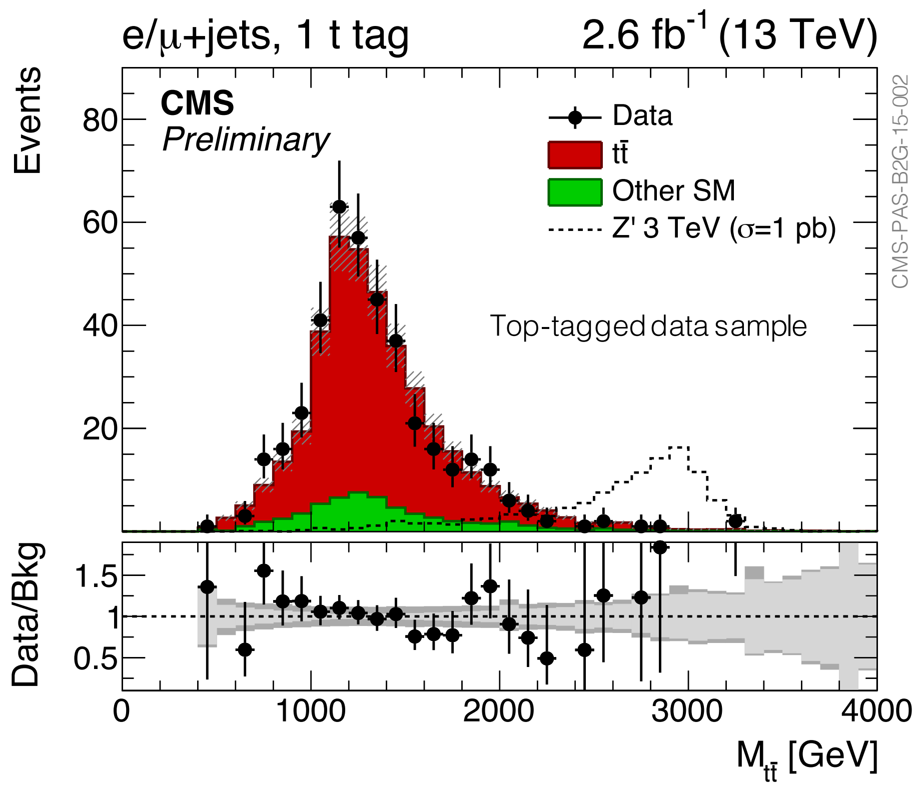


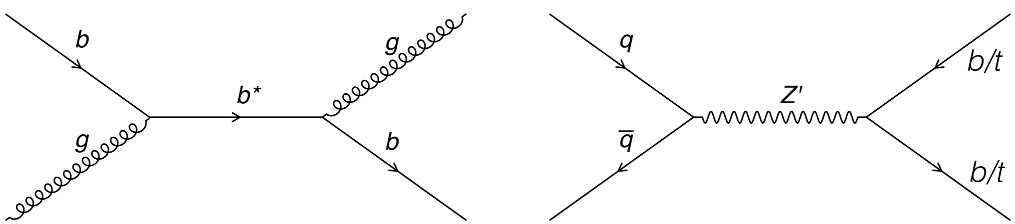
Searches in high-p_T heavy-flavour final states at 13 TeV

Processes with large cross-sections, sensitivity to highest new physics scales

Also searches for a b-anti-b and top-antitop resonance







Need to understand detector performance at highest momentum scales with practically no control samples

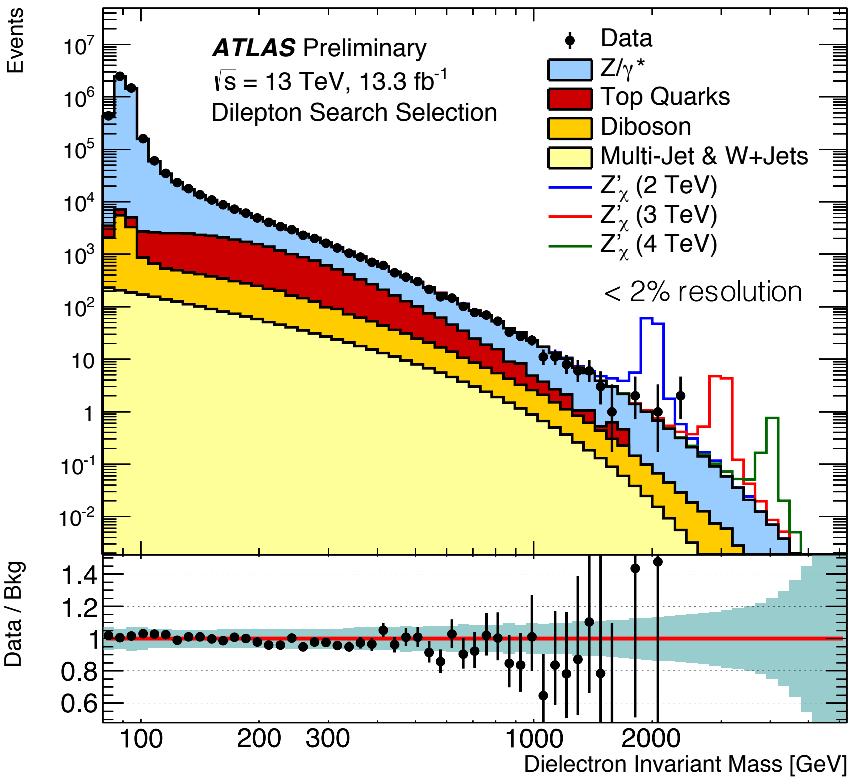
Searches in leptonic final states

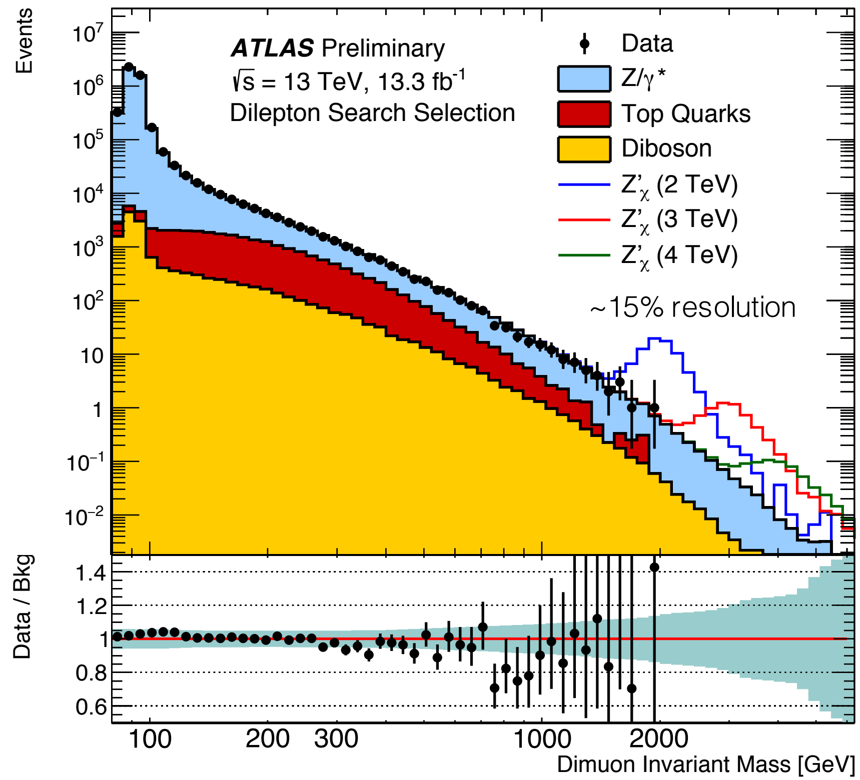
Canonical searches for new physics in high-mass Drell-Yan production ($Z' \rightarrow \ell^+\ell^-$ / $W' \rightarrow \ell\nu$)

Good Drell-Yan modelling crucial → SM diff. cross-section measurements paired with searches

High-p_T muons challenge detector alignment (30 μm in ATLAS), ~no charge information from electrons

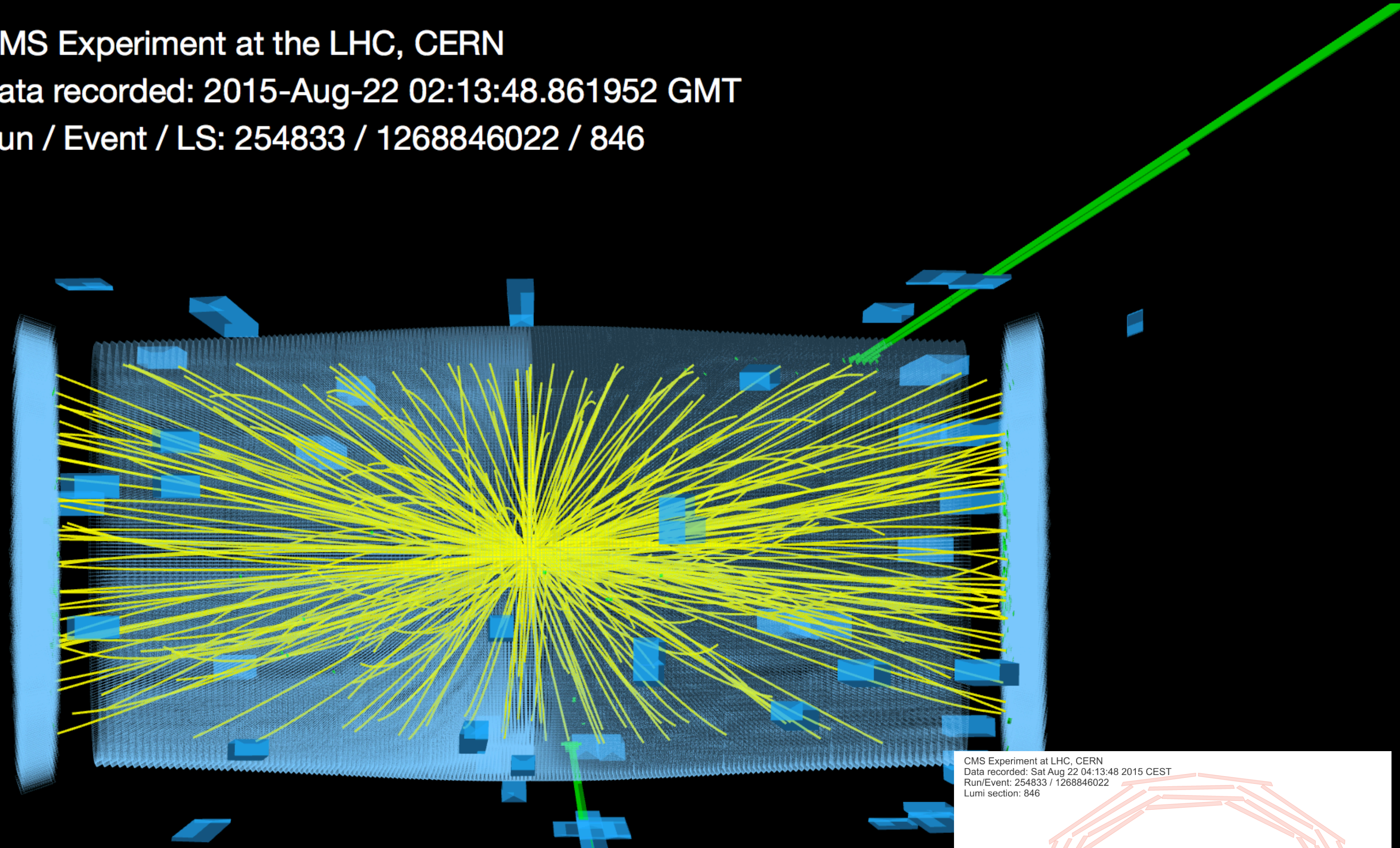
No anomaly found. SSM Z' / W' benchmark limits set at 4.0 / 4.7 TeV (2.9 / 3.3 TeV at 8 TeV)

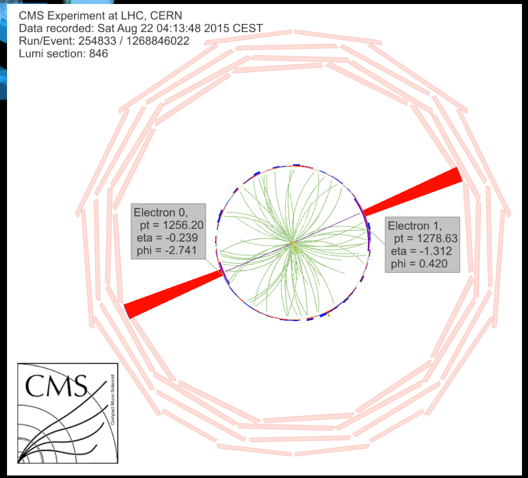




ATLAS & CMS also looked into high-mass eμ (LFV) production. Main background here: top-antitop.

CMS Experiment at the LHC, CERN
Data recorded: 2015-Aug-22 02:13:48.861952 GMT
Run / Event / LS: 254833 / 1268846022 / 846



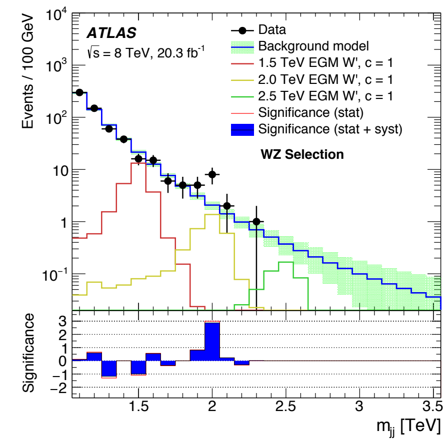


- Display of rare *colossal* e^+e^- candidate event with 2.9 TeV invariant mass
- Each electron candidate has 1.3 TeV E_T
- Back-to-back in ϕ

Highest-mass Run-1 events: 1.8 TeV (ee), 1.9 TeV ($\mu\mu$)

Searches for diboson resonances (hh, Vh, VV)

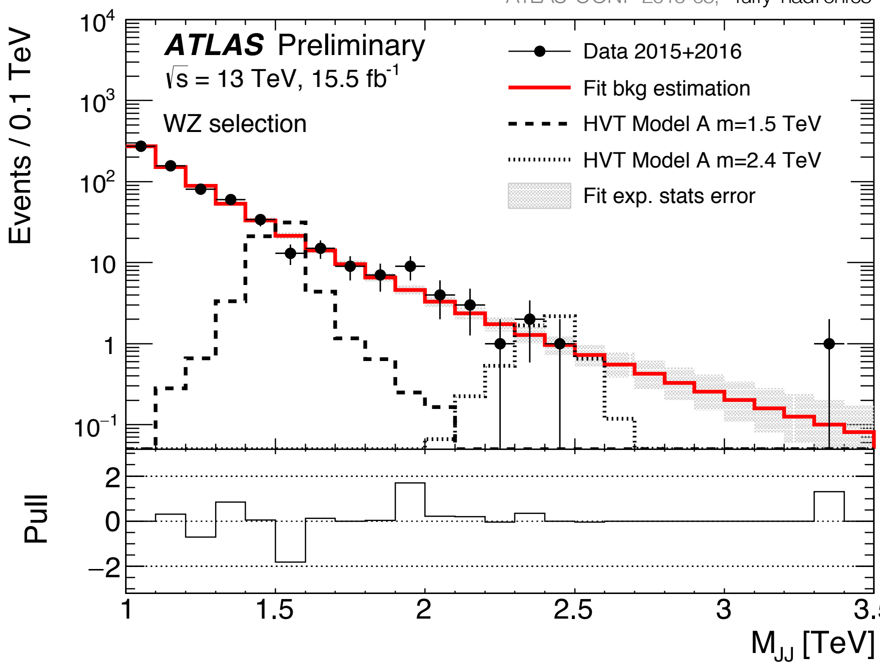
High-p_T of bosons boosts hadronic decay products into merged jets



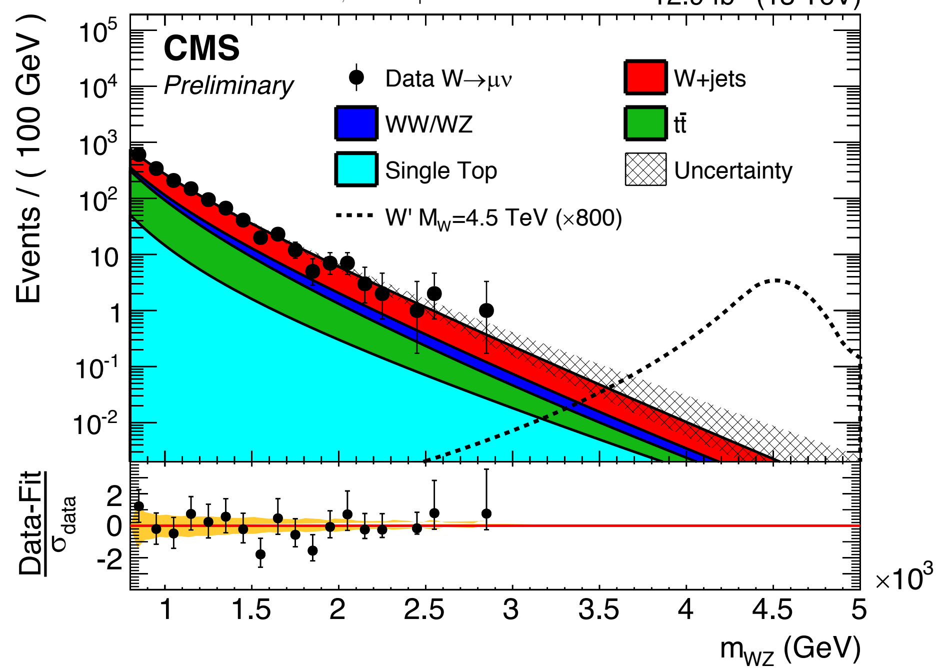
Hadronic decay modes use jet substructure analysis to reconstruct bosons. Important strong interaction backgrounds

Some excess of events around 2 TeV (globally 2.5σ for ATLAS) seen at 8 TeV in VV in fully hadronic channel, not seen in the other decay channels (eg, lνqq)

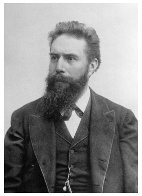
ATLAS-CONF-2016-05, fully hadronic5



CMS-PAS-B2G-16-020, semileptonic



Light quanta



First medical X-ray by Wilhelm Röntgen of his wife Anna Bertha Ludwig's hand, Nov 1895
[First Nobel price of physics, 1901]

Used since forever
as detection probe

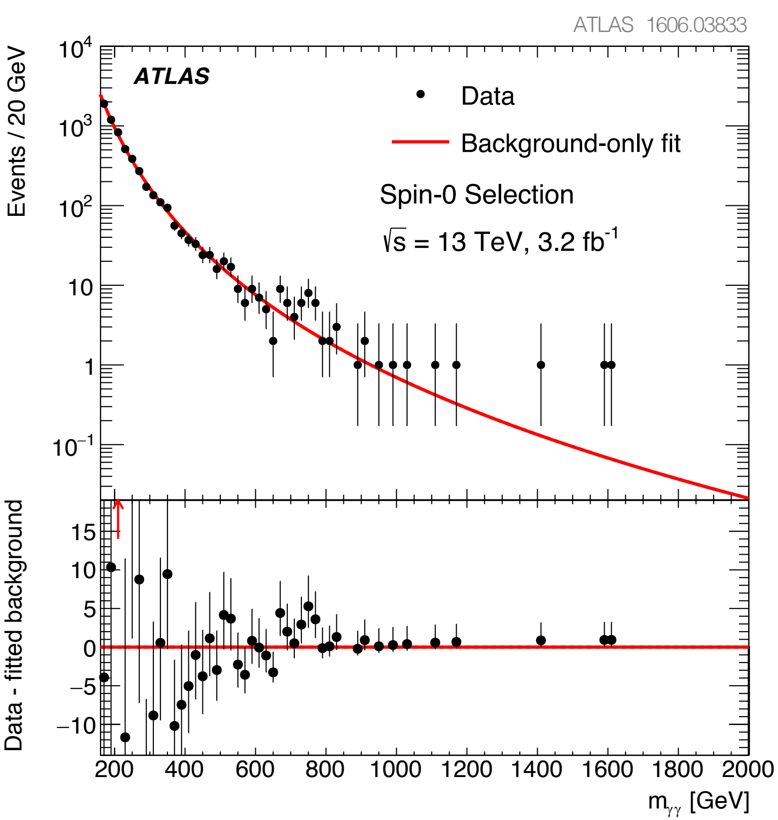
Recent example: H → yy
Other example:

Picture of a mirage

Diphoton resonance searches, the 2015 saga

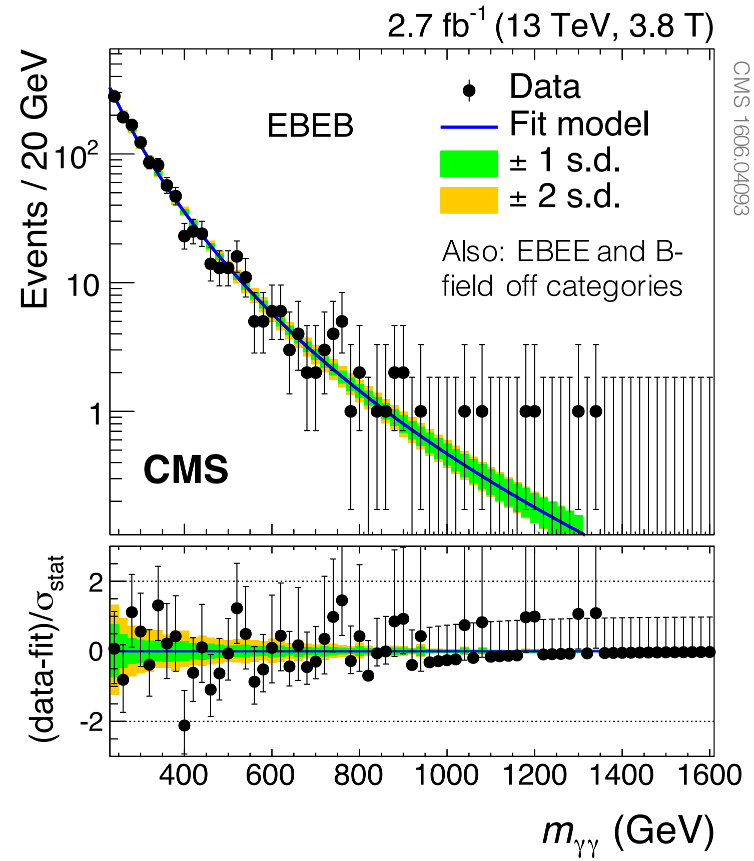
Dedicated searches for a spin-0 and a spin-2 diphoton resonance

- Photons are tightly identified and isolated. Typical purity ~94%, background modelling empirical in spin-0 (theoretical in spin-2 case for ATLAS)



Lowest p-value at ~750 GeV, Γ ~ 45 GeV (6%)

Local / **global Z** = 3.9 / **2.1σ**



Lowest p-value at ~750 GeV, narrow width

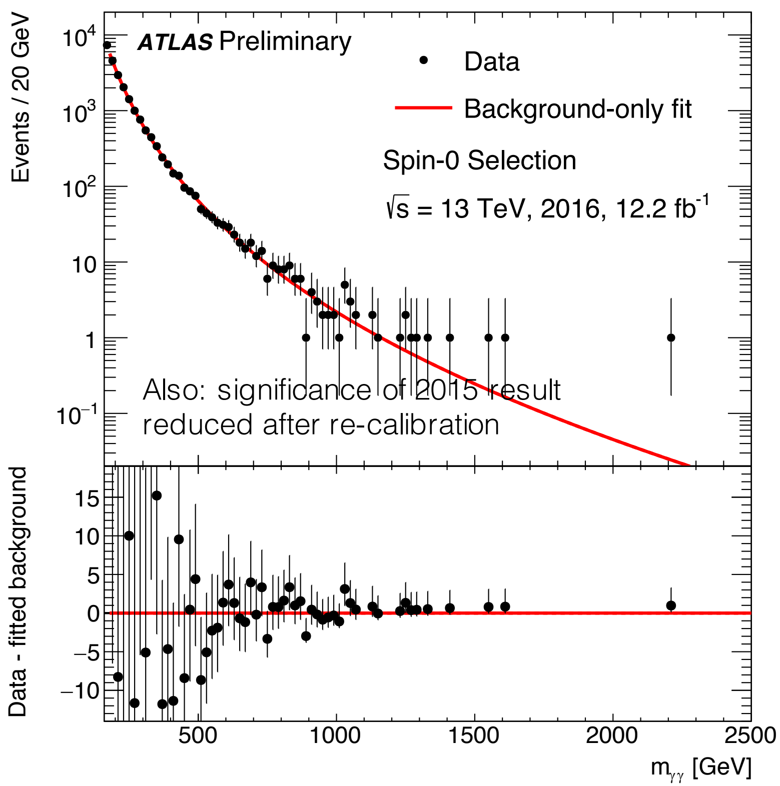
Local / **global Z** = 3.4σ / **1.6σ** (Run-1+2 combination)

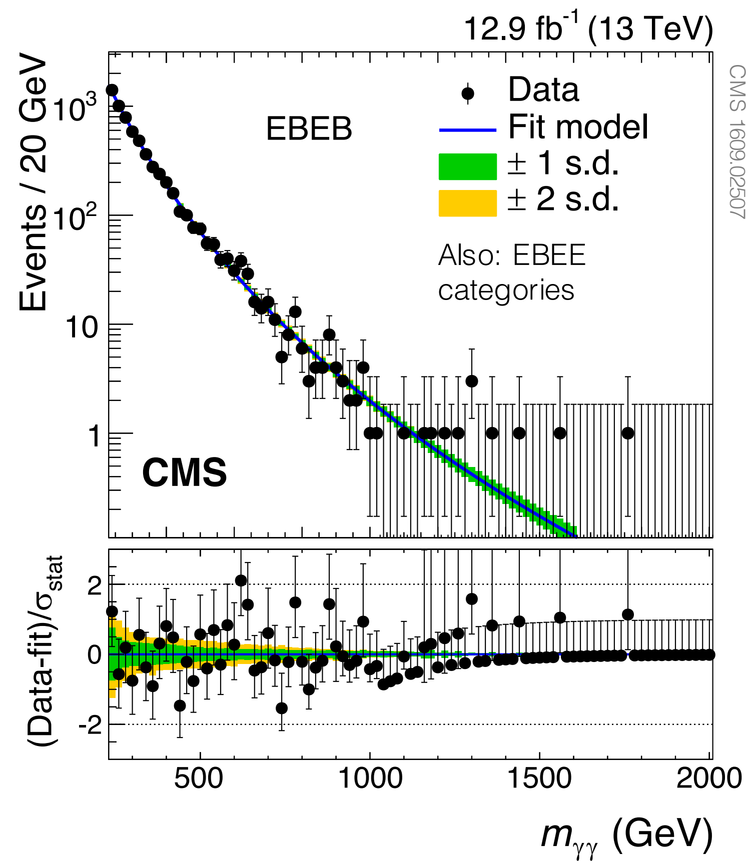
Diphoton resonance searches, the 2016 results

Repeated ~unchanged analyses with 2016 data

- Photons are tightly identified and isolated. Typical purity ~94%, background modelling empirical in spin-0 (theoretical in spin-2 case for ATLAS)

ATLAS-CONF-2016-059





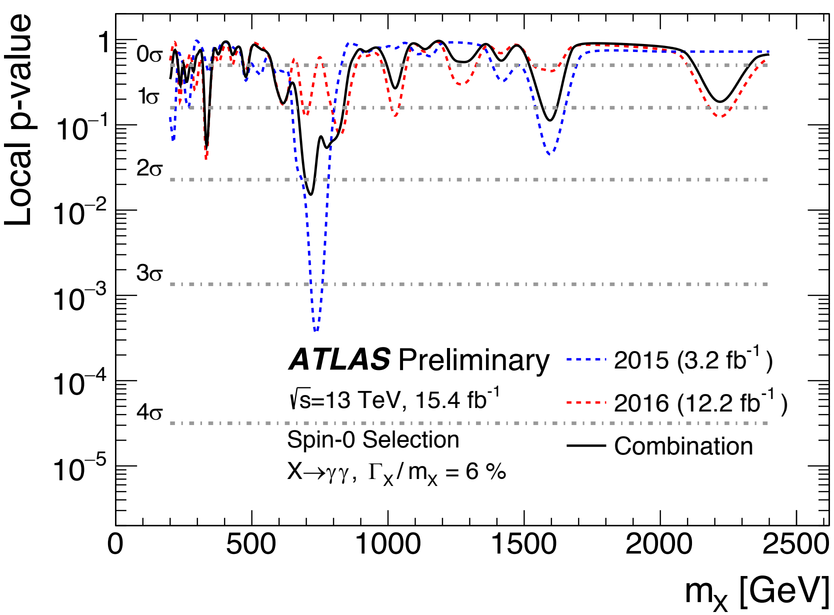
No noticeable excess in 2016 data

Diphoton resonance searches, the 2016 results

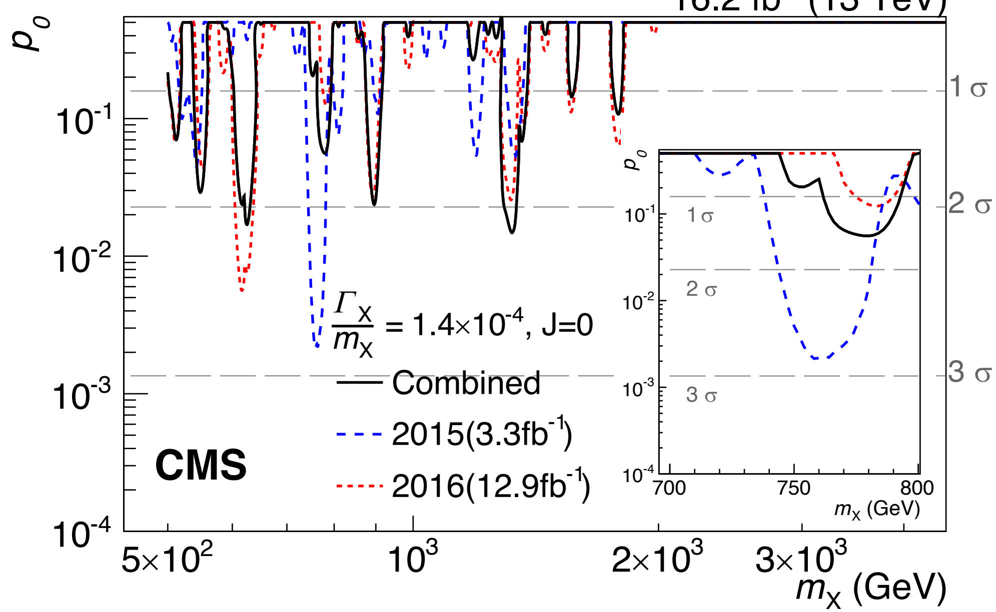
Comparison of 2015 and 2016 p-values

Resulting background-only p-values

ATLAS-CONF-2016-059



CMS 1609.02507



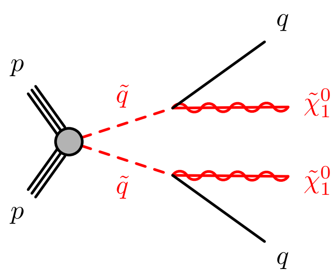
Lesson? Statistical fluctuation. Can happen, nothing wrong.

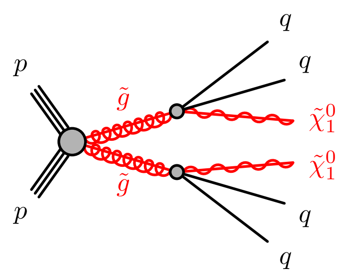
Actual trials factor larger than global factor quoted, as very many signatures probed by experiments (hard to estimate, but keep in mind!). Having a second experiment with a similar non-significant excess does not remove trials factor if you keep both. Removing 2015 data, and looking at 750 GeV in 2016 does remove trials factor.

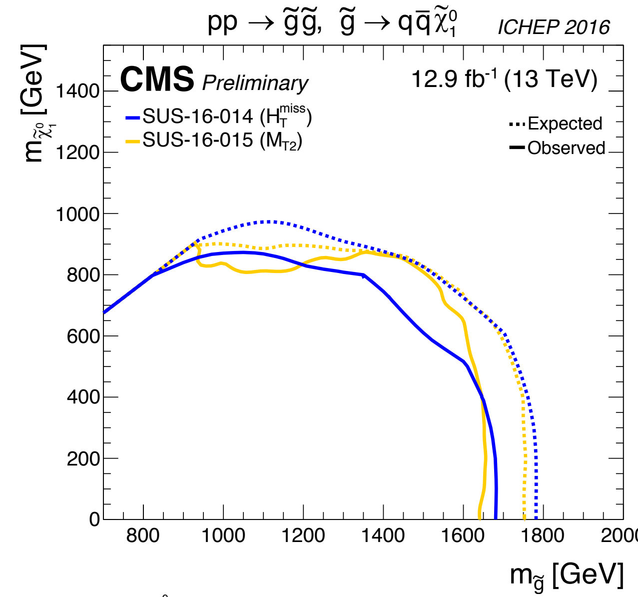
Supersymmetry

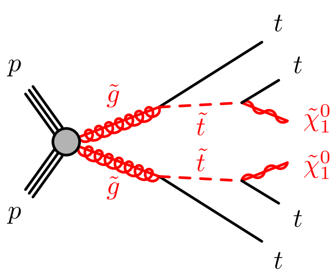
Still among the most popular SM extensions: hierarchy problem, unification, dark matter

Very diverse signatures. Highest cross-section events produce gluino / squark pairs with decays to jets and missing transverse momentum

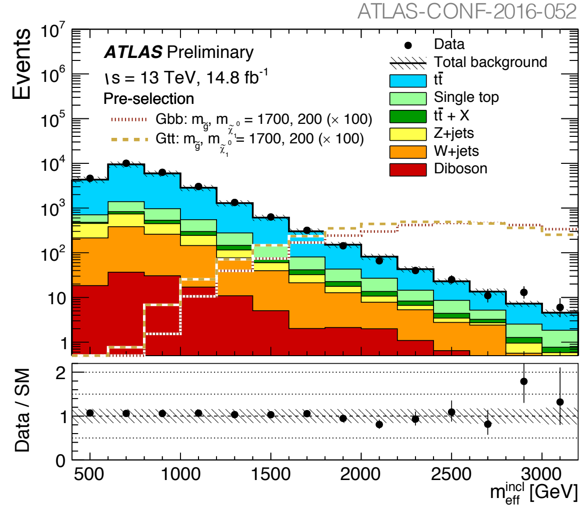


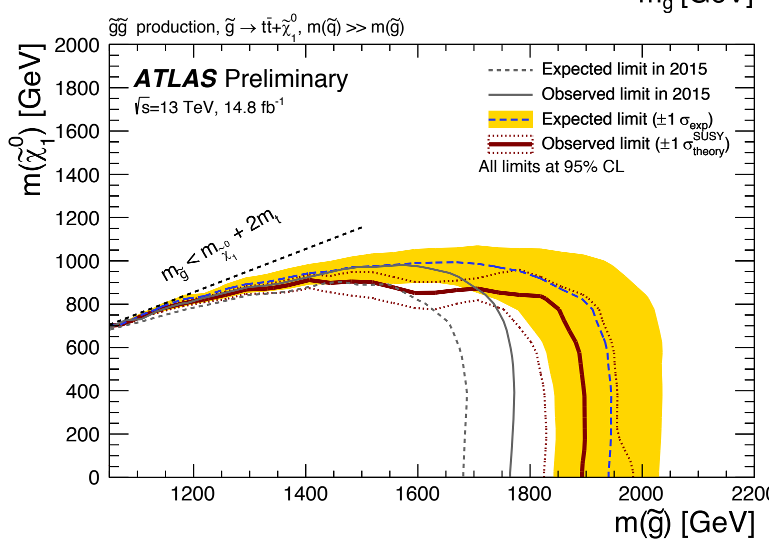






ATLAS-CONF-2016-052





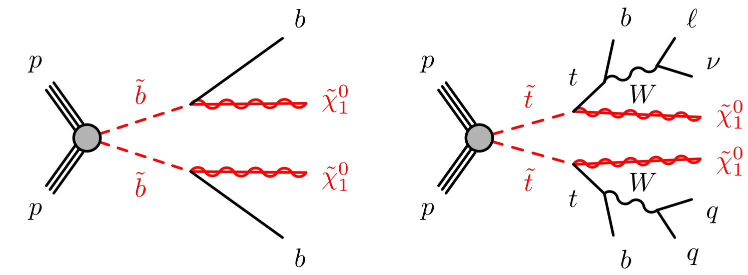
No significant anomaly seen in many different analyses

Third generation quark partners

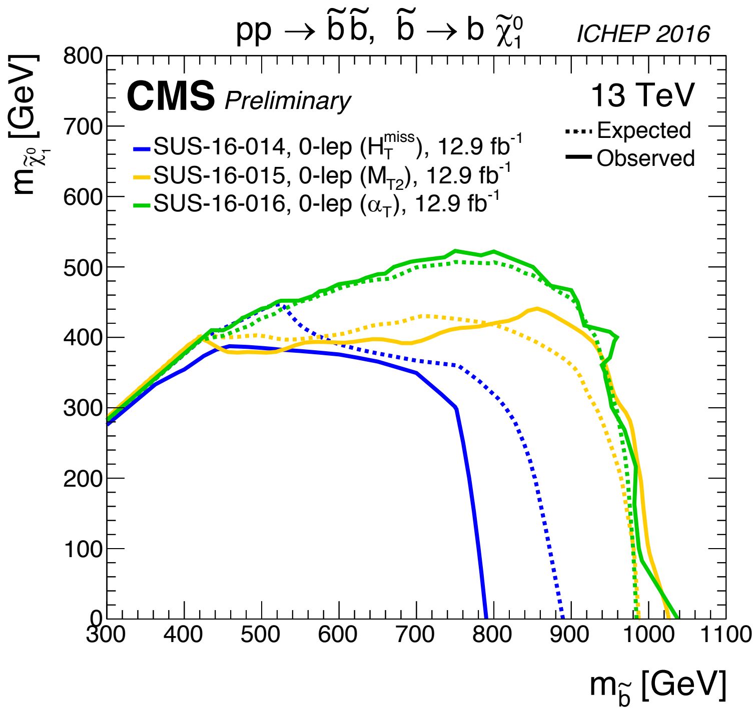
Searches for direct production

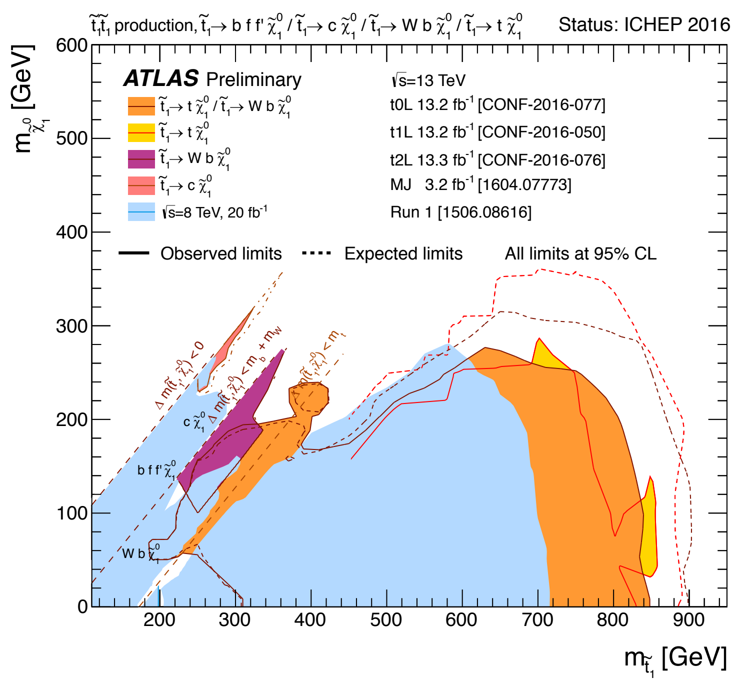
SUSY stop and sbottom may be the lightest sfermions. They have low cross-sections, so Run-2 luminosity just enough to increase sensitivity

Vector-like quarks* (VLQ) singly or pair produced decay to bW, tZ or tH. Also exotic $X_{5/3}$ → tW possible



Signatures are b-jets, jets, possibly leptons and MET





No anomaly seen

Sensitivity improved over Run-1

Similar for VLQ searches

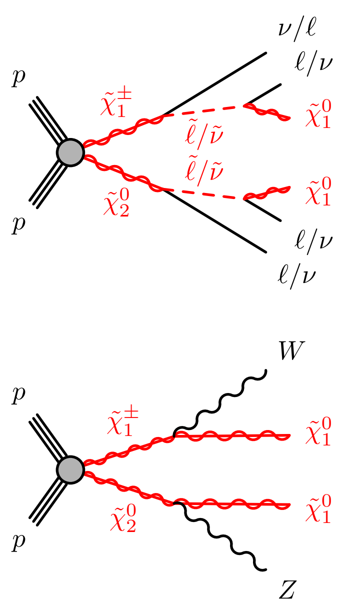
*Hypothetical fermions that transform as triplets under colour and who have left- and right-handed components with same colour and EW quantum numbers

Electroweak supersymmetry production

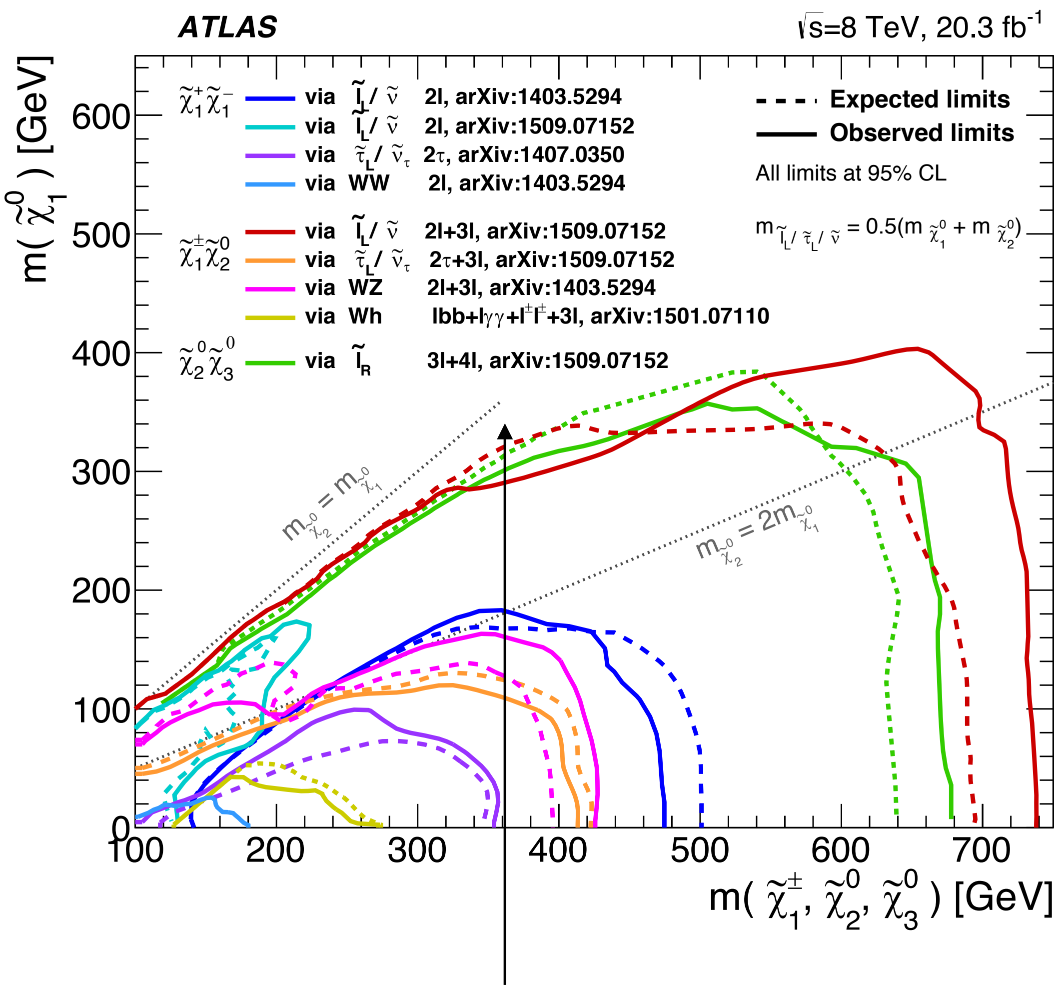
Searches for direct production

"Electroweak-inos" may be the lightest fermions. They also have low cross-sections, so Run-2 luminosity just enough to increase sensitivity

Signatures are leptons, few or no jets, MET



Example diagrams



Compressed region ("higgsino" case)

Long-lived particles predicted in many new physics models

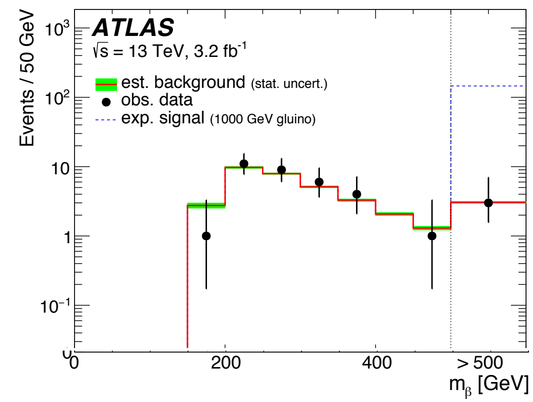
Reason: large virtuality in decay, low coupling, or mass degeneracy

Multitude of signatures depending on lifetime, charge, decay: highly ionising, slow, out-of-time decay, displaced vertex, kinked or disappearing track, lepton-jets, …

Some signatures require dedicated triggers, most requiring dedicated analysis strategies.

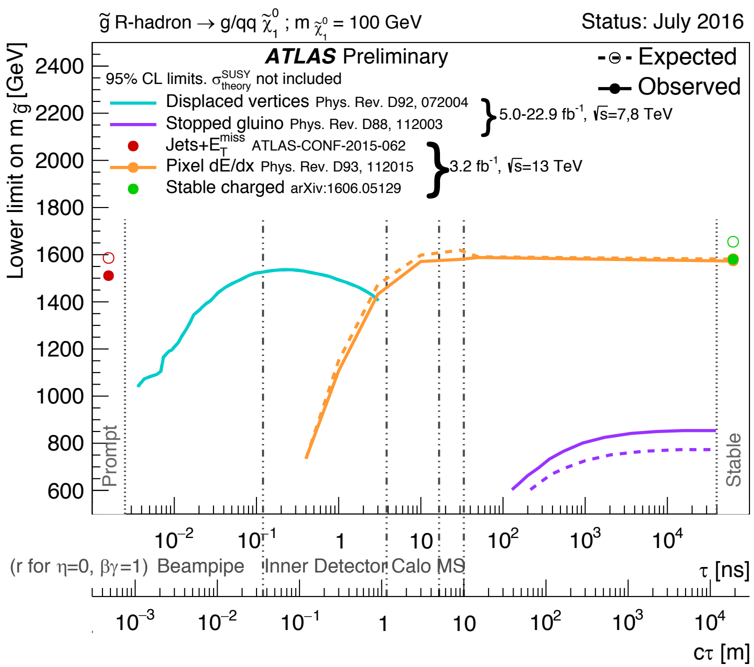
Standard searches sometimes sensitive to signatures with long-lived particles as well

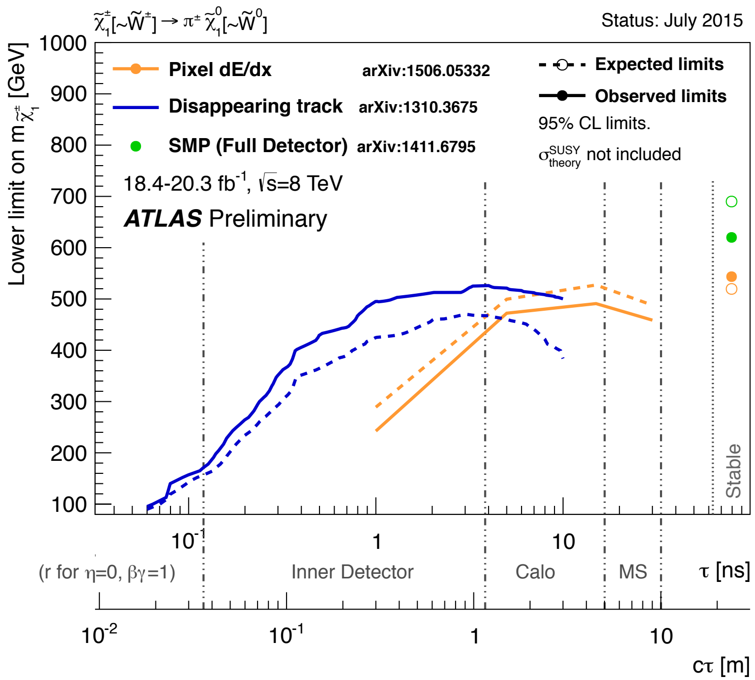
ATLAS 1606.05129



Particle mass from velocity via time-of-light measured in Tile calorimeter

Similar analysis from CMS uses tracker dE/dx and TOF from muon system





Summaries of mass limits versus lifetime of new particle

Searches for dark matter production at the LHC

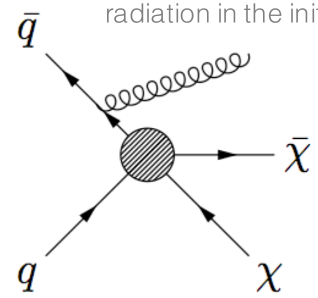
Canonical signature is 'X+MET' with large variety of 'X'

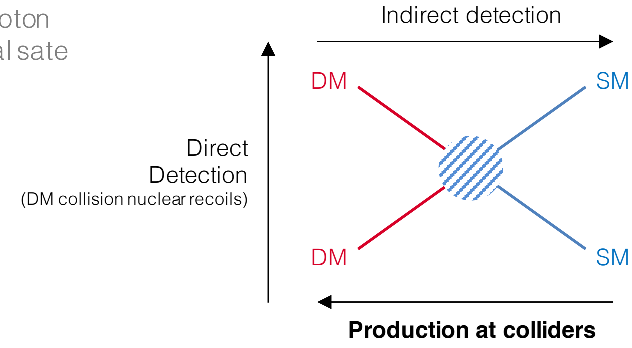
May not be able to prove at LHC that a signal is dark matter

Direct dark matter production at the LHC
Requires boost for triggering. Depending on coupling it can be made by different objects.

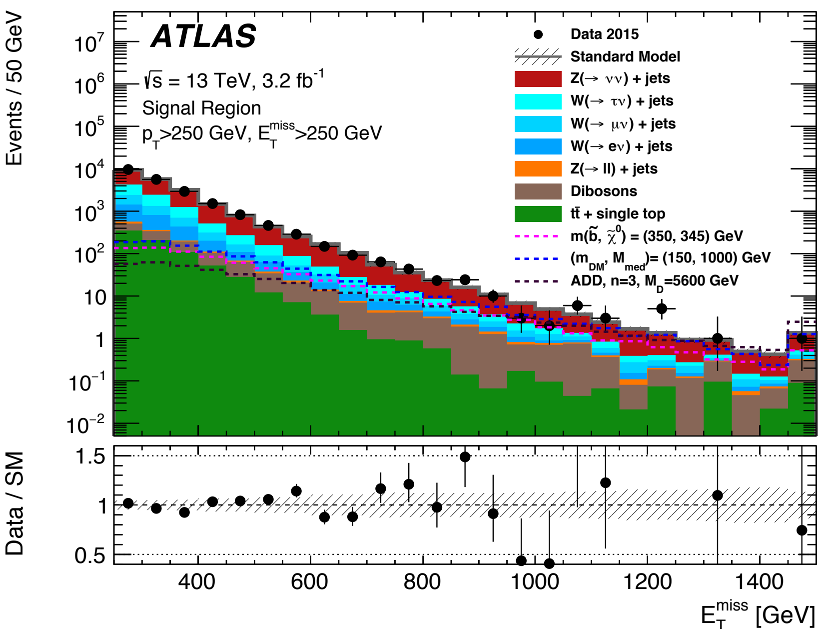
Experimentally challenging to control Z/W+jets background. Theory input needed.

Energetic gluon/photon radiation in the initial sate

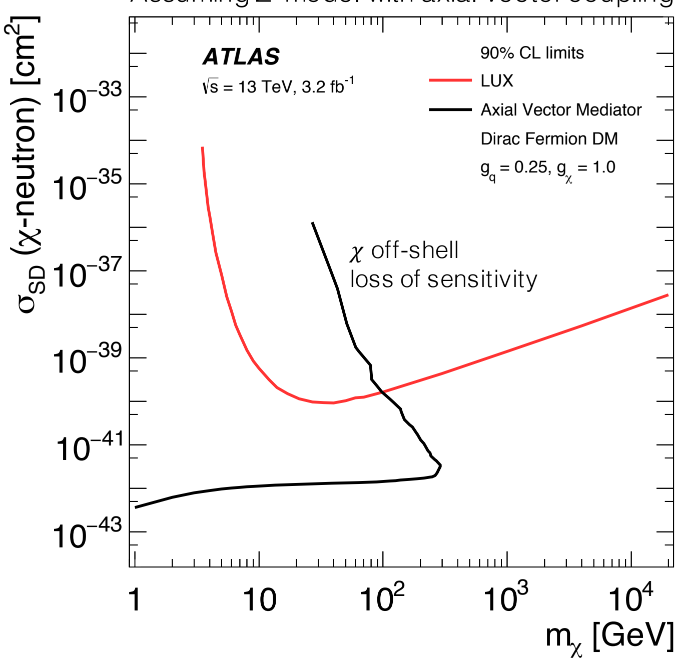




ATLAS 1604.07773



Assuming Z' model with axial-vector coupling

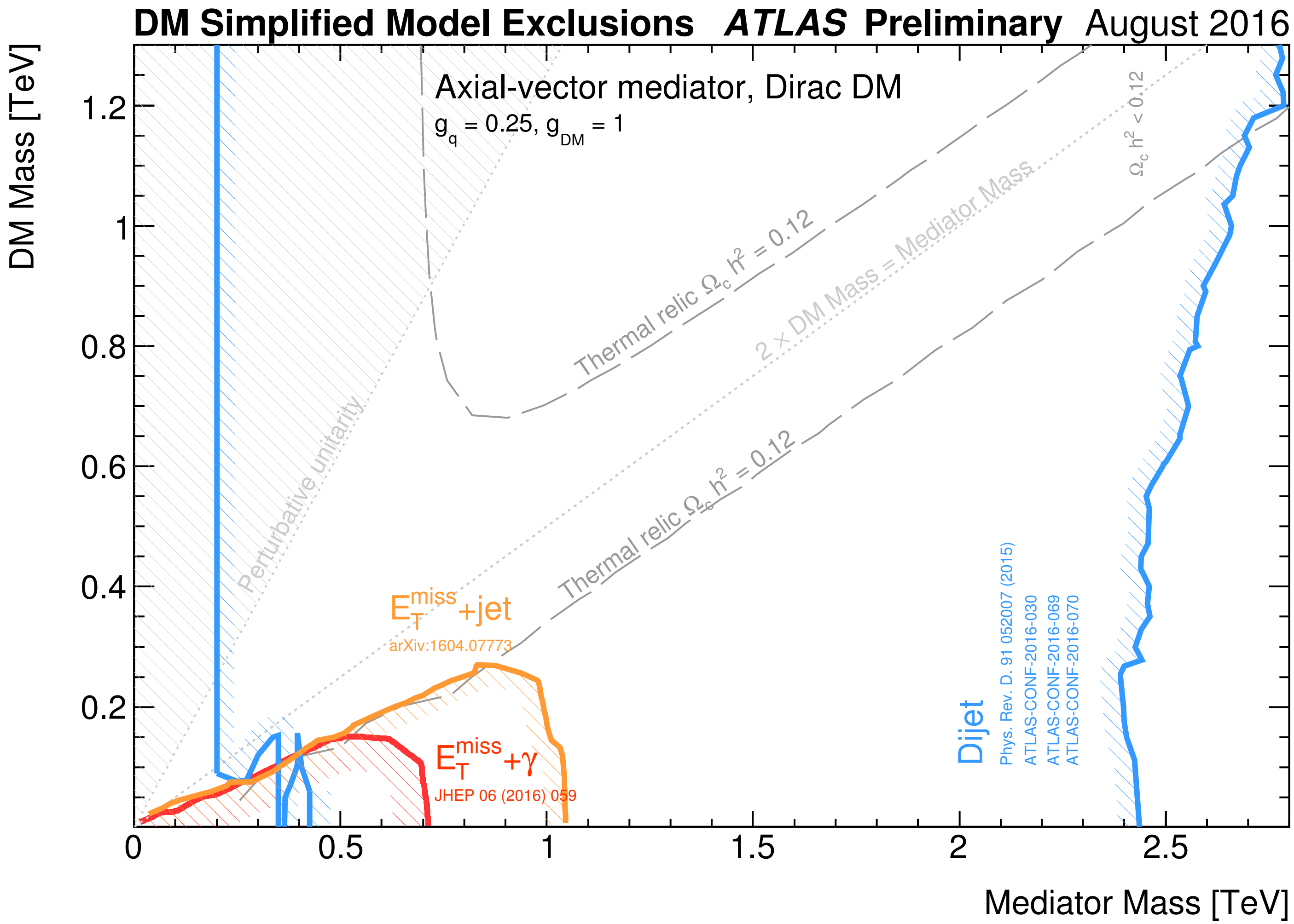


Many other 13 TeV results available:

- jets + MET
- γ + MET
- V + MET
- bb/tt + MET

No anomaly seen so far

Exclusion regions for simplified models with heavy particle mediating interaction between initial state quarks and final state WIMPs

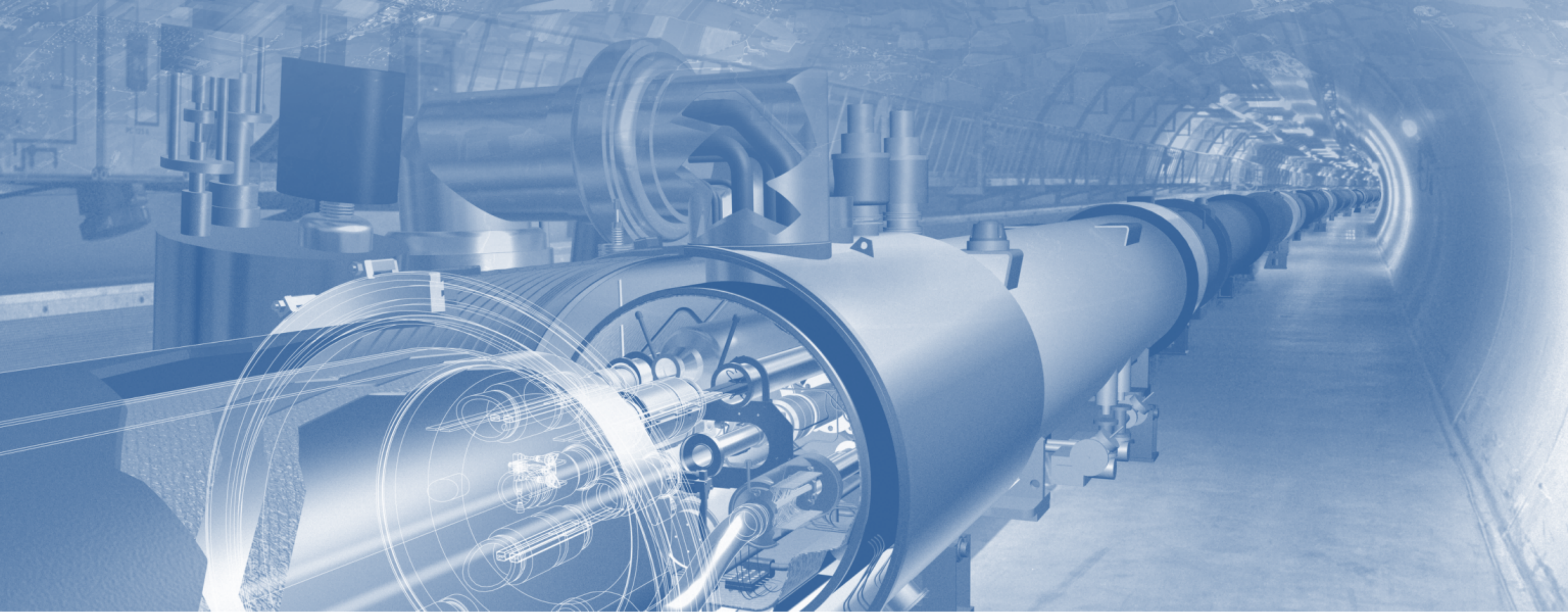


Since the mediator is produced via quark annihilation (g_q), it can also decay to quarks

For full explanation, see: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html#ATLAS_DarkMatter_Summary

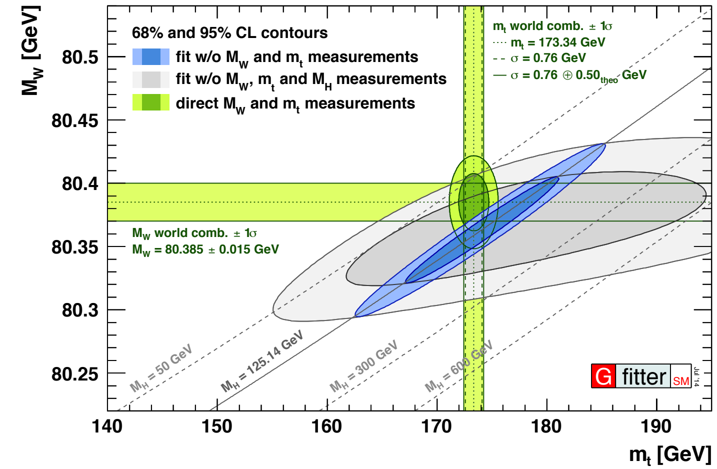
This was a very incomplete extraction of all the available 13 TeV searches only

The return of the limits …



Digression on Precision Measurements

Global electroweak fit was masterpiece of LEP/SLD era.
Discovery of Higgs over-constrains the fit and
dramatically improves predictability



Electroweak precision physics

The LHC experiments — as do D0 & CDF since long, and continuing — are investing efforts into precision measurements of EW observables: m_W, m_{top}, $\sin^2\theta_W$

All are **very** challenging

SM Predictions [1407.3792, EW fit]

$$\begin{aligned} M_W &= 80.3584 \pm 0.0046_{m_t} \pm 0.0030_{\delta_{\text{theo}} m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\text{had}}} \\ &\qquad \pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\text{theo}} M_W} \text{ GeV}, \\ &= 80.358 \pm 0.008_{\text{tot}} \text{ GeV}. \end{aligned}$$

[exp WA: σ = 15 MeV]

$$\begin{aligned} \sin^2\theta^{\ell}_{\text{eff}} &= 0.231488 \pm 0.000024_{m_t} \pm 0.000016_{\delta_{\text{theo}} m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\text{had}}} \\ &\qquad \pm 0.000010_{\alpha_S} \pm 0.000001_{M_H} \pm 0.000047_{\delta_{\text{theo}} \sin^2\theta^f_{\text{eff}}}, \\ &= 0.23149 \pm 0.00007_{\text{tot}}, \end{aligned}$$

[exp WA: σ = 0.00016]

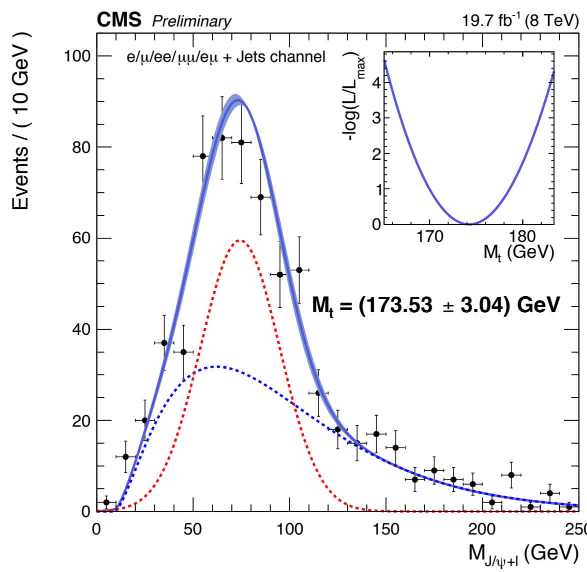
Electroweak precision measurements

Best top mass from LHC: 172.44 ± 0.13 ± 0.47 GeV (CMS), 172.84 ± 0.34 ± 0.61 GeV (ATLAS, not yet all 8 TeV)

Traditional kinematic top mass measurement method approaches systematic limit of *b*-quark hadronisation

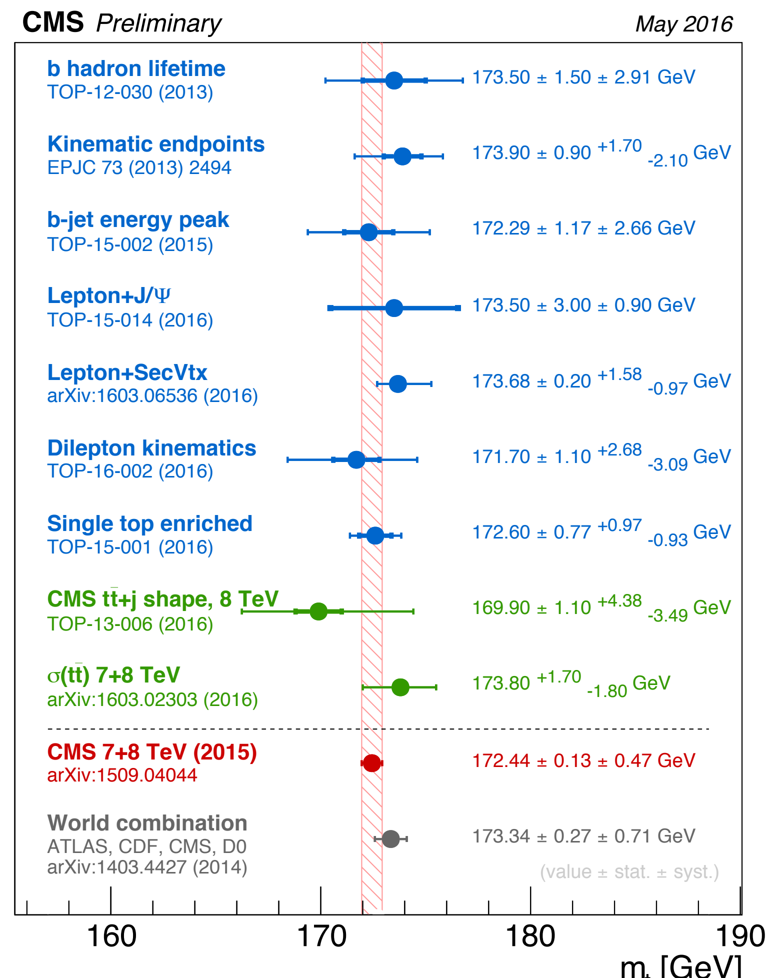
Possible ways to improve (a lot of pioneering work by CMS):

- Choose more robust observables (eg, wrt. b fragmentation)
- Select charmed mesons (rare but very clean signature)
- Use dilepton kinematic endpoint (clean but large theoretical uncertainties)
- Use cross-sections or differential variables (promising but difficult to achieve competitive precision



Currently best result (CMS): 1.7 GeV uncertainty

CMS alternative top mass measurements:



Electroweak precision measurements

$\sin^2\theta_W$ and Z asymmetries from hadron colliders

CDF, D0, and also LHC have extracted weak mixing angle from Z/γ^* asymmetry measurements

Uncertainties at Tevatron dominated by statistical uncertainties, LHCb equally, ATLAS & CMS by PDF uncertainties.

Data-driven “PDF replica rejection” method applied by CDF

Complex measurements (in particular physics modelling) that are important to pursue, but precision of hadron colliders not yet competitive with LEP/SLD

+ Newest CDF result: 0.23221 ± 0.00046

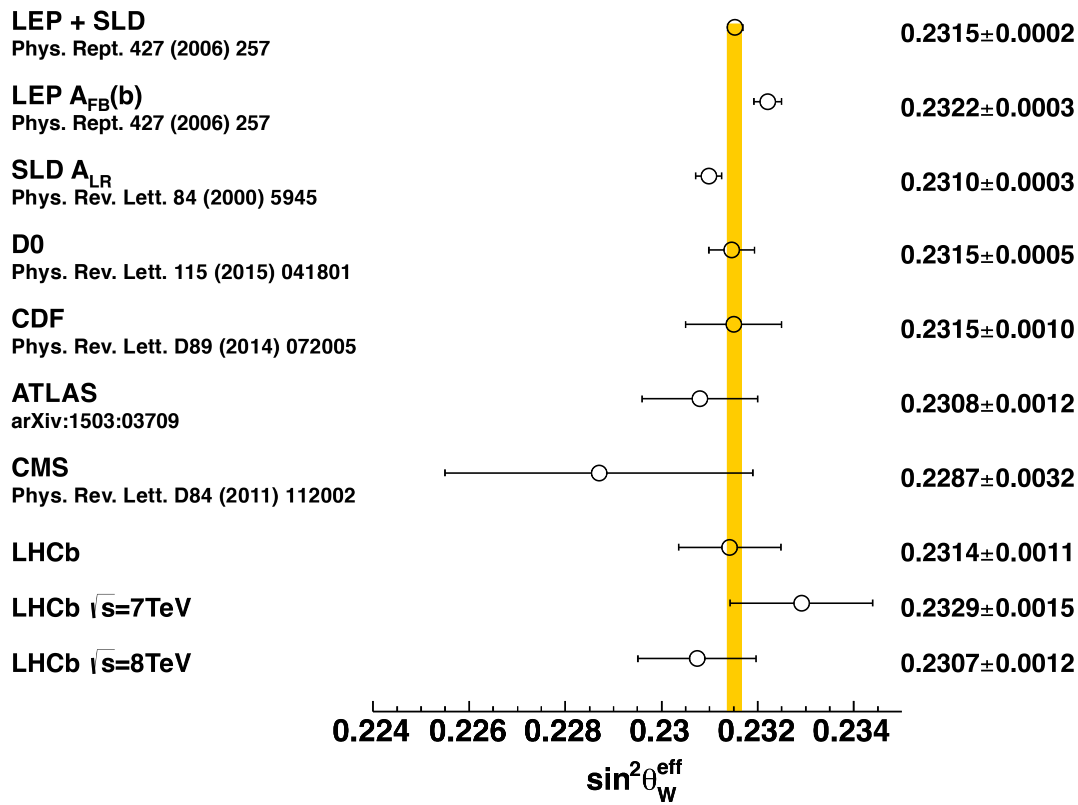


Figure from LHCb 1509.07645

Electroweak precision measurements

W mass: towards a first measurement at the LHC via decay to lepton + neutrino

ATLAS and CMS are progressing towards the (challenging) m_W measurement at the LHC

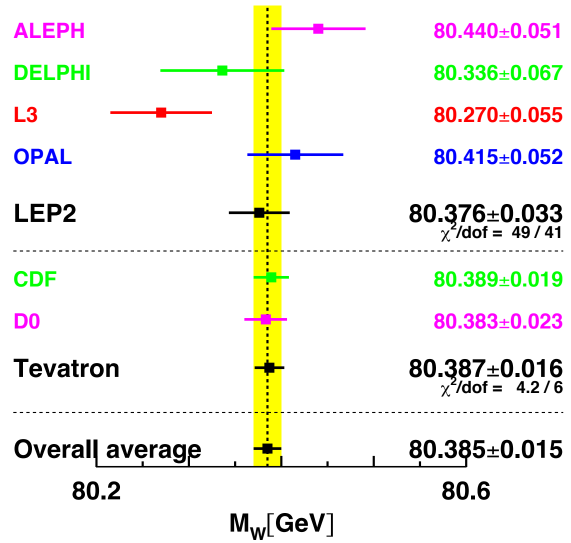
Measurement relies on excellent understanding of final state

Observables: $p_{T,\ell}$, $p_{T,\nu}$, m_T as probes of m_W

Challenges, high-precision:

- Momentum/energy scale (incl. had. recoil) calibration: Z, J/ψ, Y
- Signal efficiency and background modelling
- Physics modelling:
  - Production governed by PDF & initial state interactions (pert & non-pert): use W^+, W^-, Z, W+c data for calibration, and NNLO QCD calculations + soft gluon resummation
  - EW corrections well enough known
  - Probes very sensitive to W polarisation (and hence to PDF, including its strange density)

Current experimental picture for m_W

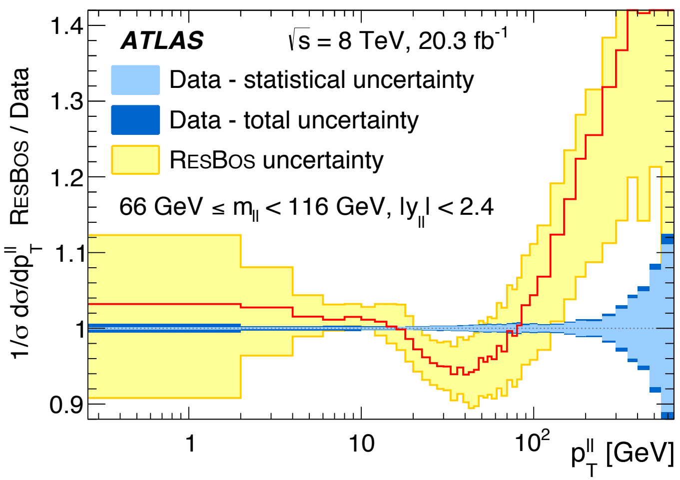


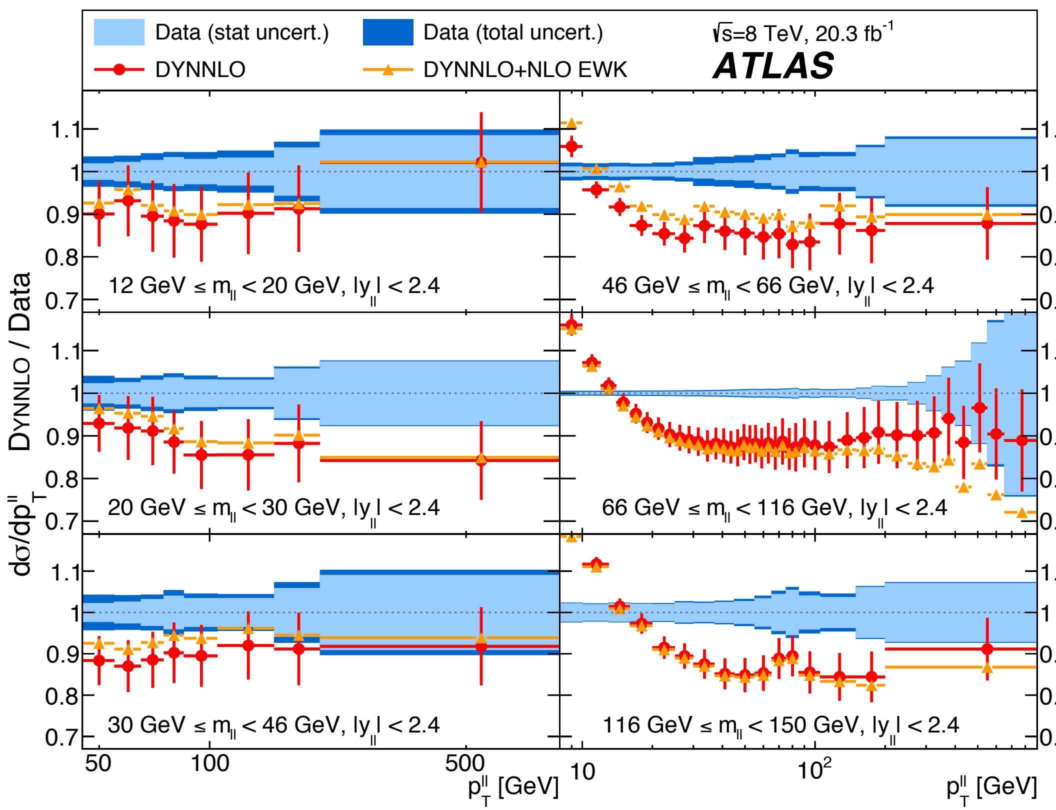
Project: Experiments are in a vigorous process of addressing the above issues. Many precision measurements (differential Z, W + X cross sections, polarisation analysis, calibration performance, …) produced on the way. Also theoretical developments mandatory. **Long-term effort.**

Electroweak precision measurements

Comprehensive Z p_T and polarisation measurements done by both CMS and ATLAS

ATLAS and CMS use precise measurements of p_T(Z) to tune p_T(W) modelling, which relies on NNLO and NNLL/resummed calculations. But: different generators predict different transfers from Z to W. Also: PDFs play different roles in Z and W production.





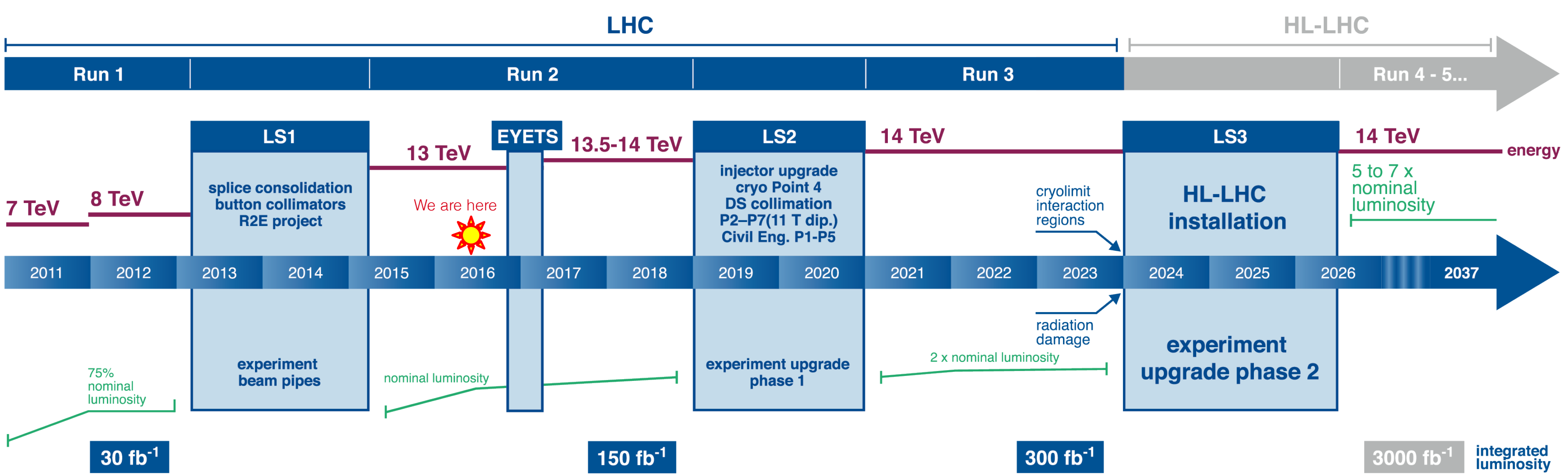
RESBOS: ISR at approximate NNLO, γ*–Z interference at NLO, NNLL soft-gluon resummation, no FSR or hadronic event activity, CT14 PDF.

DYNNLO: QCD production at NNLO, no soft-gluon resummation, CT10 PDF.

The road to the future

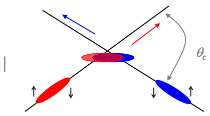
The LHC Run-2 and beyond

LHC / HL-LHC Plan



How can these LHC luminosity improvements be achieved ?

Crab crossing:
(deflects head and tail in opposite direction)



Run-1

- E_{beam} = 0.45–4 TeV
- $L_{\mathrm{max}} = 0.8 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- $\Delta t_{\mathrm{bunch}}$ = 50 ns
- $N_{\mathrm{bunches,max}}$ = 1380
- β^* = 60 cm
  [recall: $L \propto (\sigma_x\sigma_y)^{-1} = (\varepsilon_n\,\beta^*/\gamma)^{-1}$]
- Norm. emittance ε_n ~ 2.3 μm
- $N_{\mathrm{protons\ /\ bunch}} \leq 1.7 \cdot 10^{11}$
- <μ> ~ 21
  (note: μ_{peak} much larger)

Run 2 & 3 (13–14 TeV)

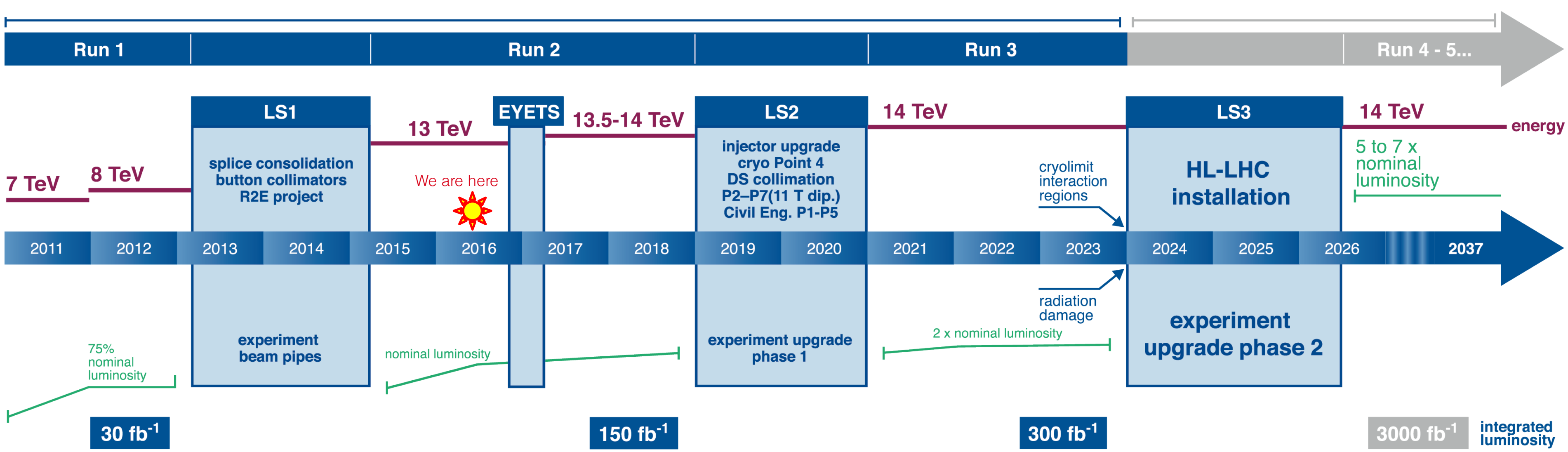
- E_{beam} = 6.5–7 TeV
- $L_{\mathrm{max}} = 0.7\text{–}2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- $\Delta t_{\mathrm{bunch}}$ = 25 ns
- $N_{\mathrm{bunches,max}}$ = 2028~2748 (?)
- β^* = 40 cm
- ε_n = 2.5–3.5 μm (2.3 μm with BCMS)
- $N_{\mathrm{protons\ /\ bunch}} \sim 1.2 \cdot 10^{11}$
- <μ> ~ 21~50

LS2: injector upgrade for increased beam brightness (batch compression in PS, new optics in SPS, collimator upgrades)

HL-LHC (14 TeV)

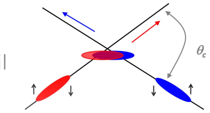
- E_{beam} = 7 TeV
- $L_{\mathrm{max}} \sim 5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- $\Delta t_{\mathrm{bunch}}$ = 25 ns
- $N_{\mathrm{bunches,max}}$ = 2748
- β^* = 15 cm
- ε_n = 2.5 μm
- $N_{\mathrm{protons\ /\ bunch}} = 2.2 \cdot 10^{11}$
- <μ> ~ 140

LS3: new triplet design (low-β^* quadrupoles, crab cavities), injector upgrades for luminosity levelling



How can these LHC luminosity improvements be achieved ?

Crab crossing:
(deflects head and tail in opposite direction)



Run-1 | **Run 2 & 3 (13–14 TeV)** | **HL-LHC (14 TeV)**

Also significant detector, in particular trigger (goal: keep current thresholds) and inner tracker, upgrades to cope with increased LHC luminosity:

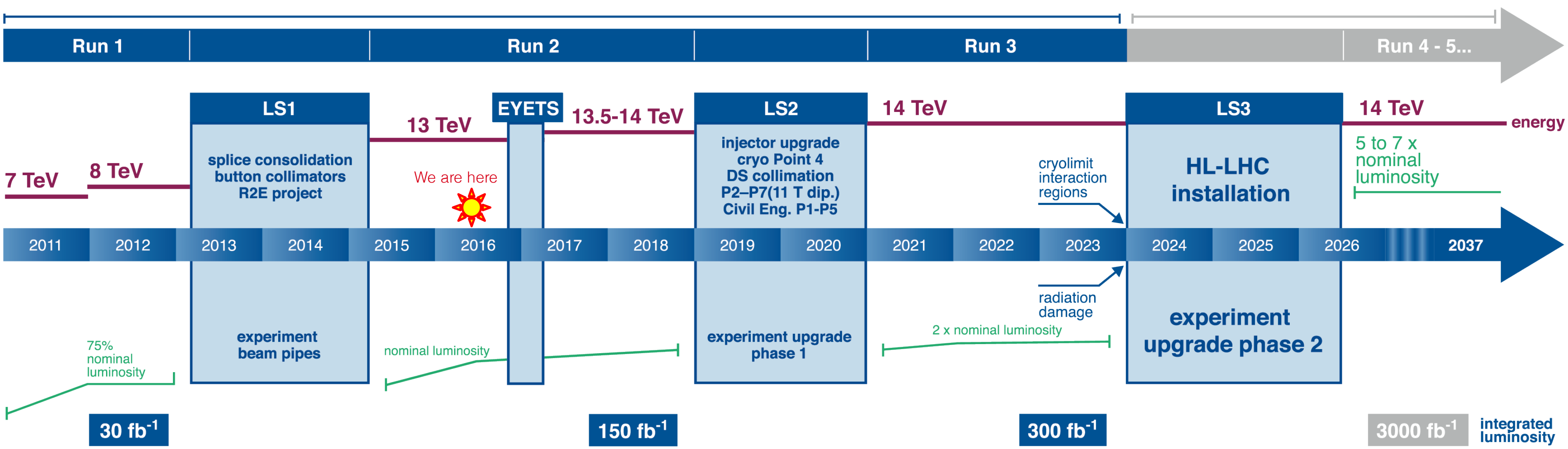
- Phase-1 during LS2 preparing for high-brightness Run-3
- Phase-2 during LS3 preparing for HL-LHC

No time for a discussion here, but happy to follow up during discussion sessions

(note: $\mathcal{L}_{peak}$ much larger)

brightness (batch compression in PS, new optics in SPS, collimator upgrades)

quadrupoles, crab cavities), injector upgrades for luminosity levelling



The main proton–proton physics goals in a nutshell

Run 1 (8 TeV)

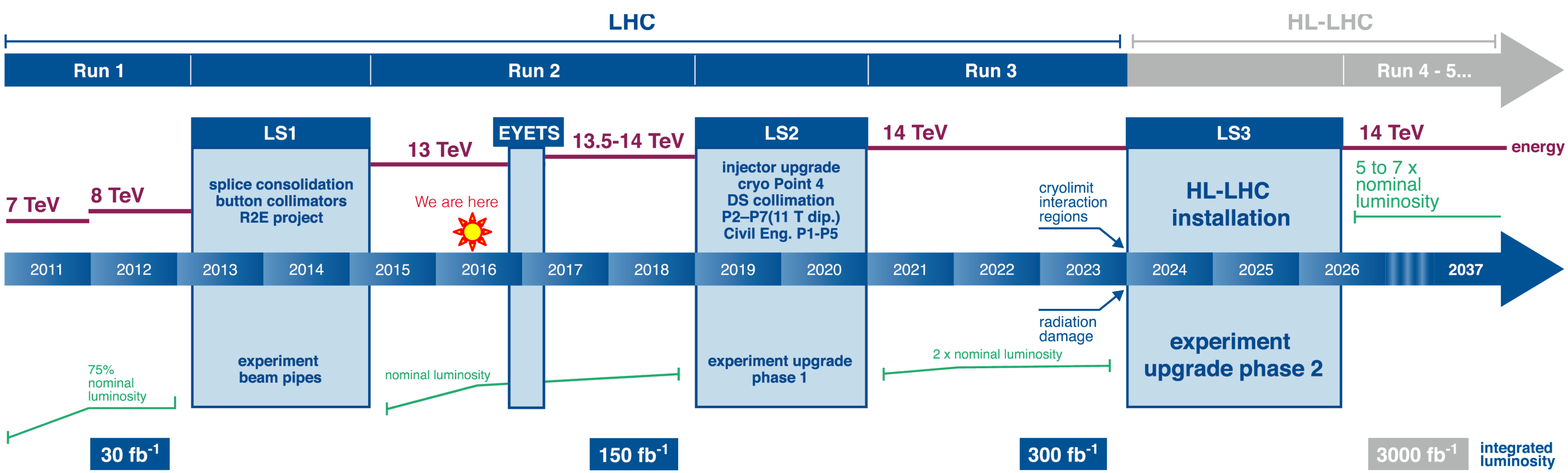
- Discovery of Higgs boson
- Searches for additional new physics (negative)
- Observation of rare processes, such as $B_s \to \mu\mu$
- Precision measurements of Standard Model processes
- Study of *CP* asymmetries in B_s sector

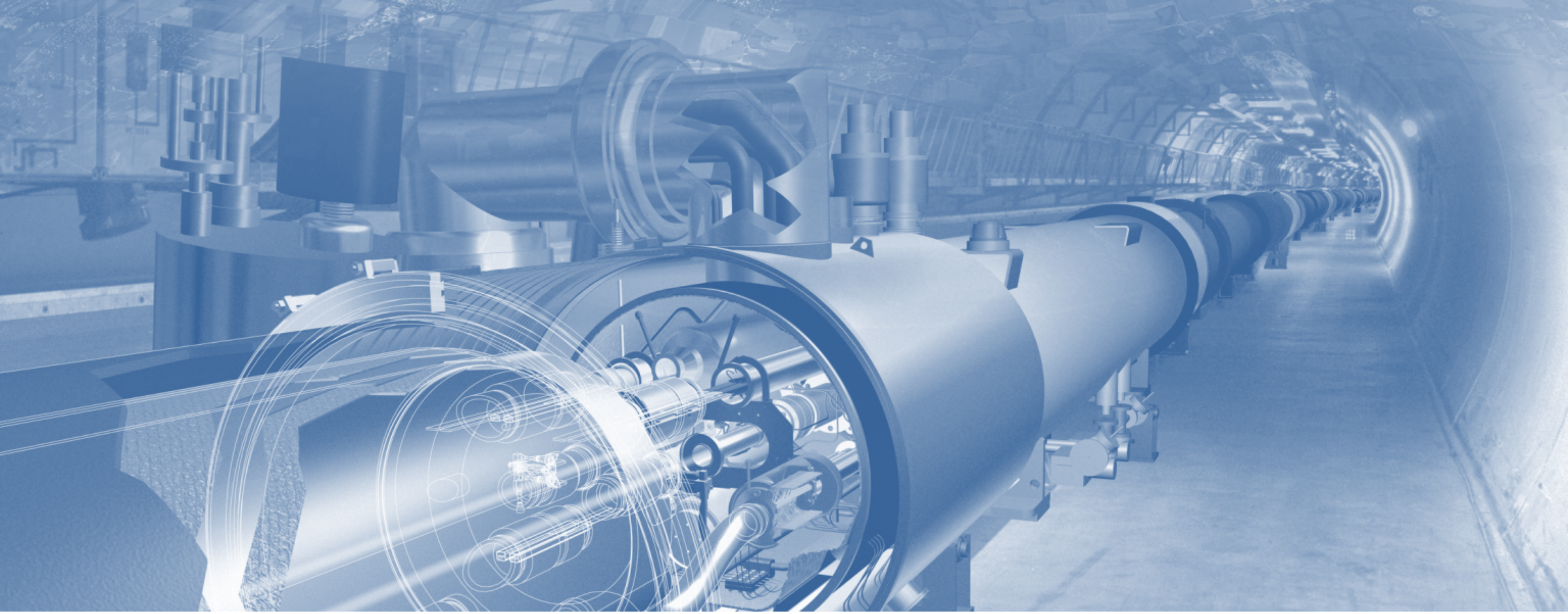
Run 2 & 3 (13–14 TeV)

- Searches for new physics
- Improved measurements of Higgs couplings in main channels
- Consolidation / observation of Higgs channels
- Measurement of rare Standard Model processes & more precision
- Improved measurements of rare *B* decays and *CP* asymmetries

HL-LHC (14 TeV)

- Precision measurements of Higgs couplings
- Observation of very rare Higgs modes
- Ultimate new physics search reach (on mass & forbidden decays, eg, FCNC)
- Ultimate SM & HF physics precision for rare processes

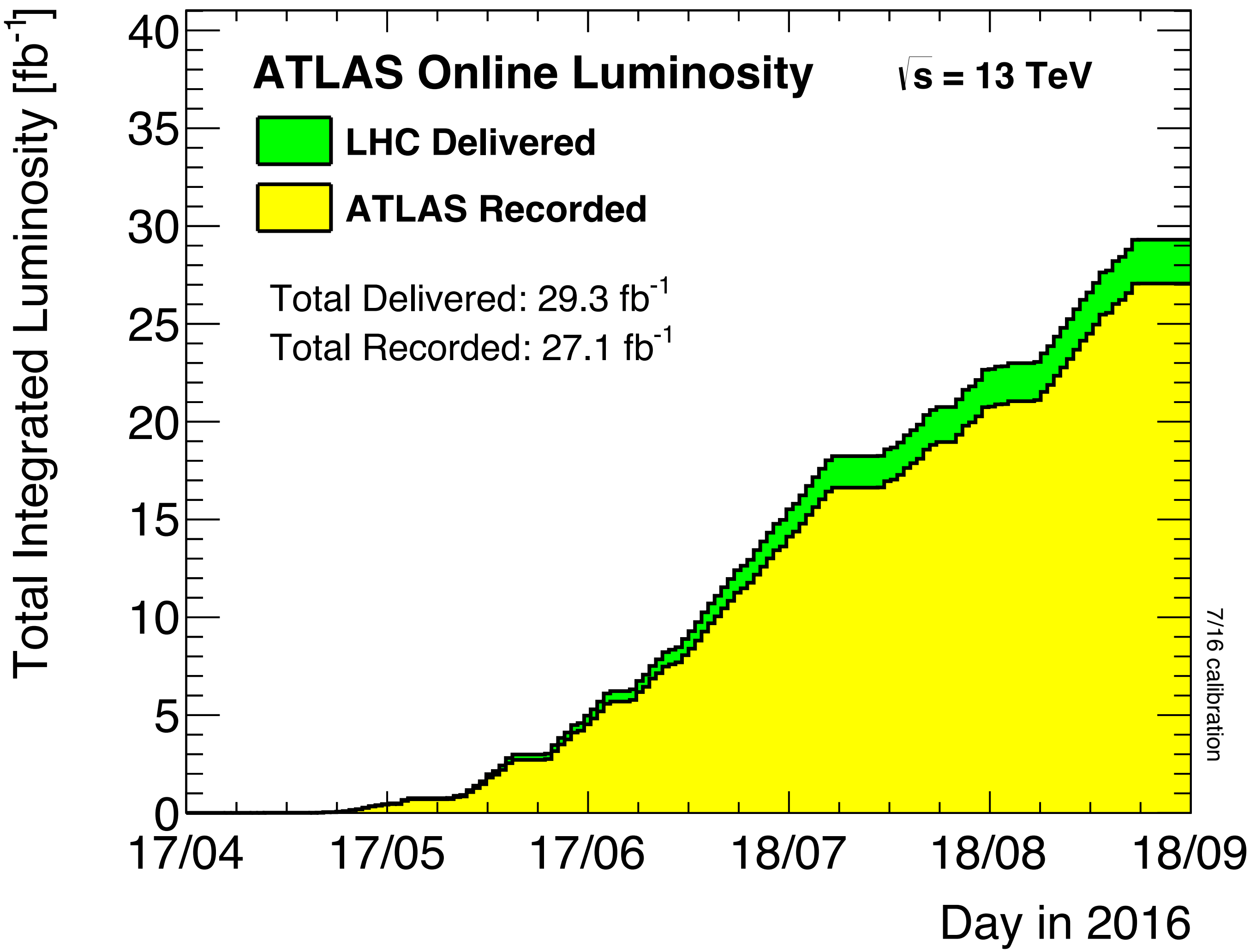




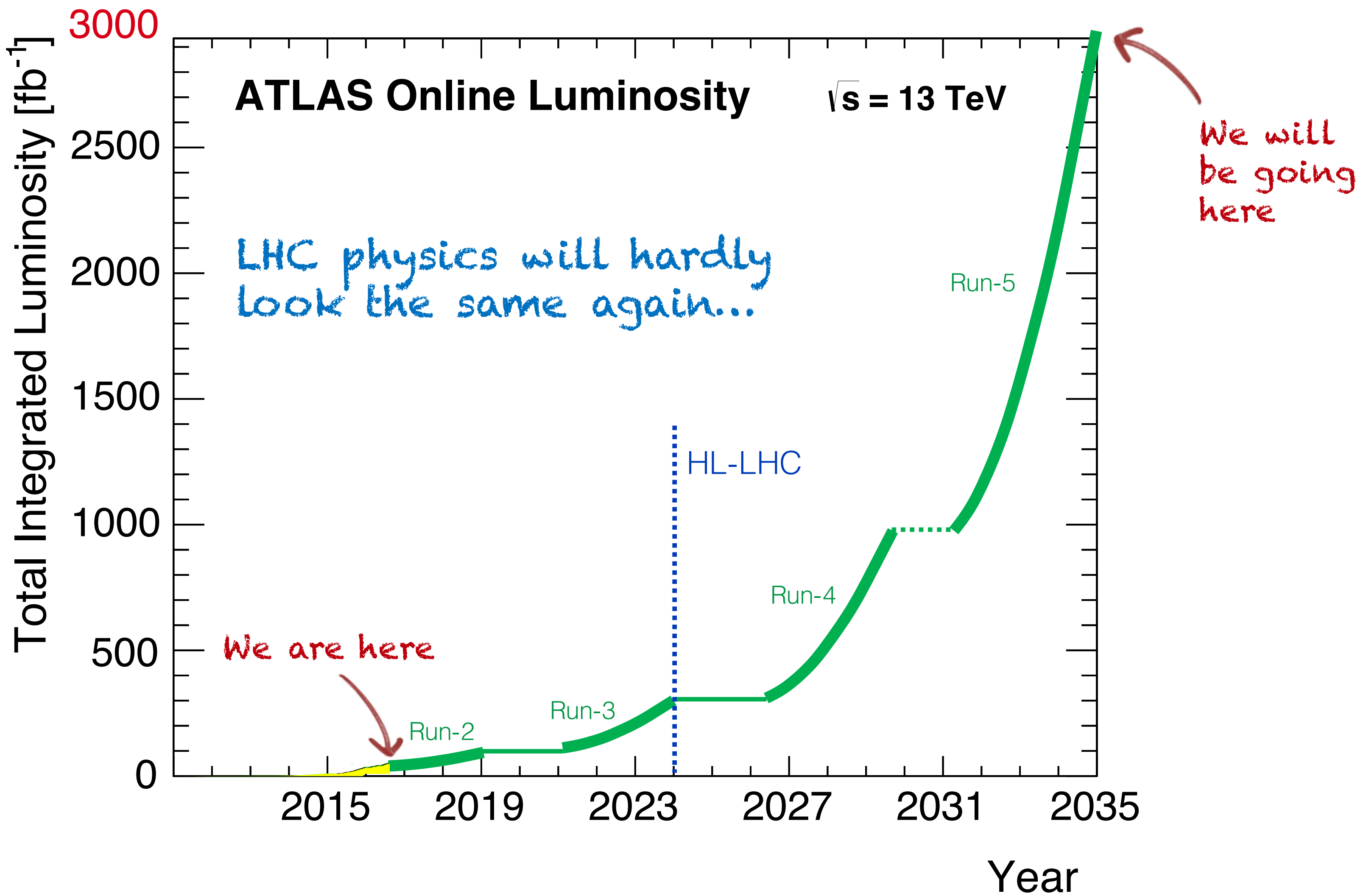
Prospects for the LHC Run-2/3 and beyond (HL-LHC)

A brief set of selected highlights, assuming no significant new physics in the current dataset

Any detection of new physics would likely be a game changer !


ATLAS Online Luminosity
$\sqrt{s}$ = 13 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 29.3 fb^{-1}
Total Recorded: 27.1 fb^{-1}
Total Integrated Luminosity [fb^{-1}]
0
5
10
15
20
25
30
35
40
17/04
17/05
17/06
18/07
18/08
18/09
Day in 2016
7/16 calibration

Expected integrated luminosity of LHC & HL-LHC

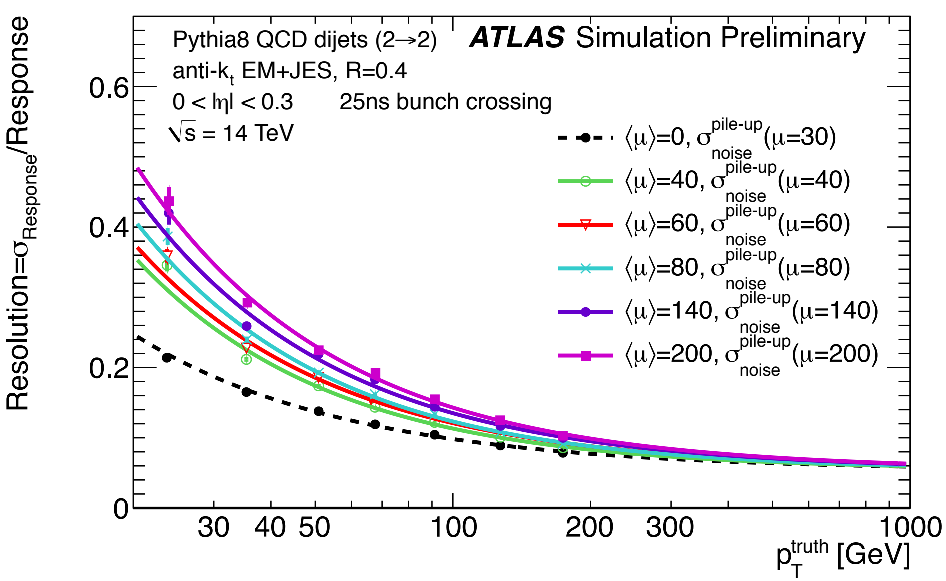


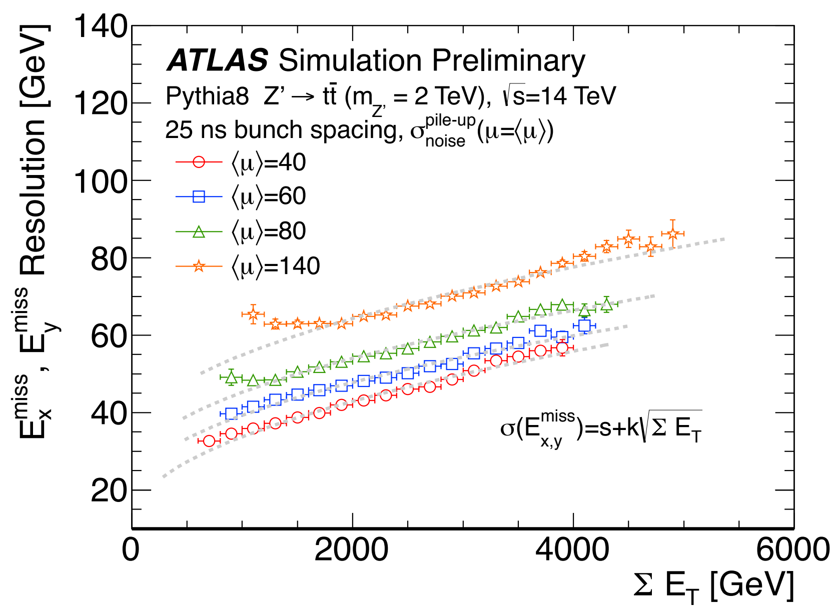
Detector performance

The performance of physics object reconstruction degrades with pileup

Pileup dependence mitigated by dedicated methods, but expect moderate decrease of electron/photon efficiency and resolution, and increase of fake rate. Muons less affected (main impact on trigger).

More difficult for tau ($H \rightarrow \tau\tau$), jets and missing transverse momentum:





The jet substructure can be resolved (eg, jet mass) with "grooming" techniques in high-pileup scenarios

Overall, no significant performance degradation expected during Run-2, some effects in Run-3

Higgs boson physics

Run-2 should increase Higgs sample by factor of ~10, ttH by factor of ~20

Higgs mass already well known (0.2%), but further improvement and – important – cross-check needed

Higgs width (SM: 4.2 MeV) cannot be directly measured; indirect constraints possible

Higgs spin & parity established as 0^+, but need to investigate possible *CP*-odd admixtures

Higgs couplings can be overconstrained from channel-wise (categorised) measurements

What is left to complete after Run-1 ?

- Complete observation of $H \to \tau\tau$
- Observe $H \to bb$
- Observe ttH and W/Z+H production
  (at large luminosity $H \to \gamma\gamma$ will be best for ttH, ATL-PHYS-PUB-2014-012)

What are long-term developments ?

- Search for $H \to \mu\mu$ (Run-1 limit: ~$7.5 \times \sigma_{SM}$)
- Search for $H \to Z\gamma$ (Run-1 limit: ~$9.5 \times \sigma_{SM}$)
- Search for di-Higgs production

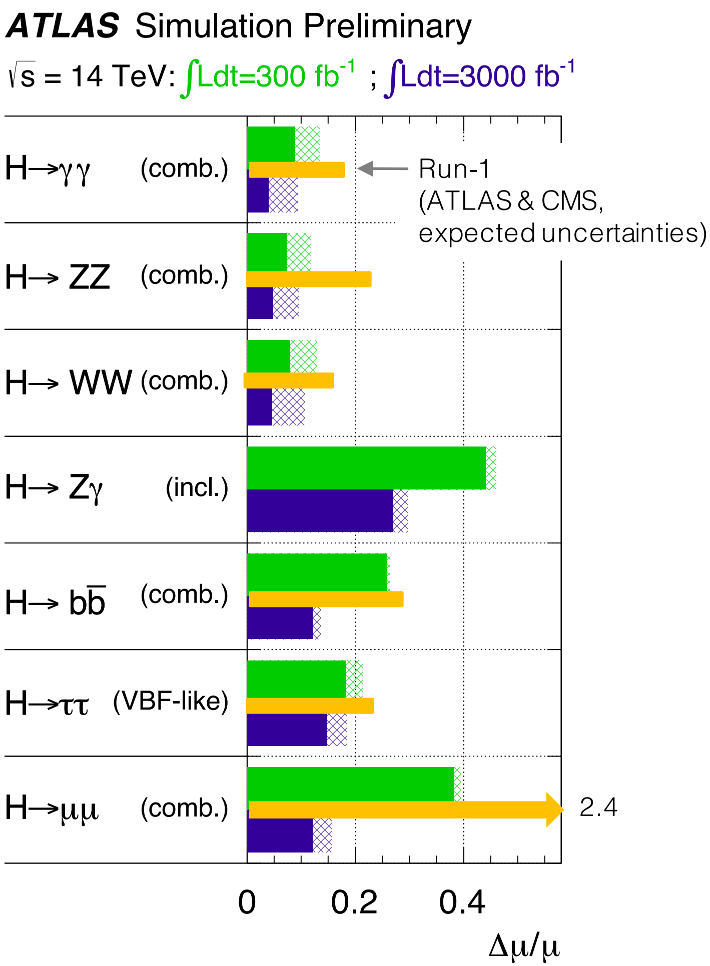
And always with high priority:

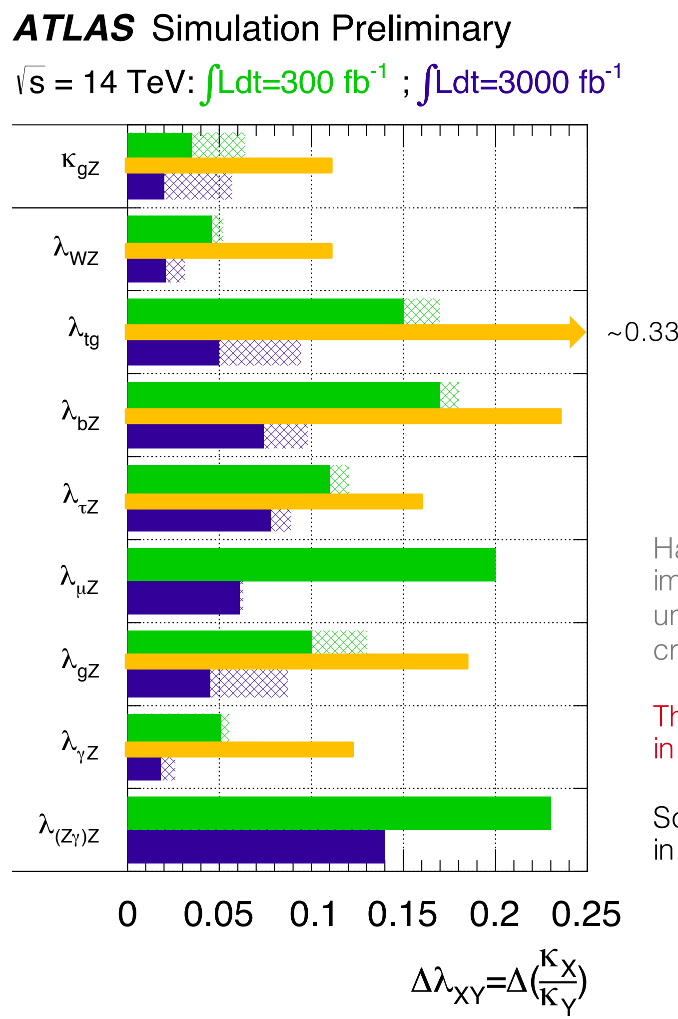
- Improve global coupling constraints
- Fiducial and differential cross-section measurements
- Searches for CPV, and for rare (eg, $H \to J/\psi\ \gamma$), forbidden (eg, $H \to \tau\mu$) and invisible decays (eg, VBF+E_T^{miss})

Higgs boson physics

(Conservative) extrapolation of Higgs coupling measurements

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





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

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

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

Theory uncertainty limiting in several cases

Some uncertainties cancel in ratios

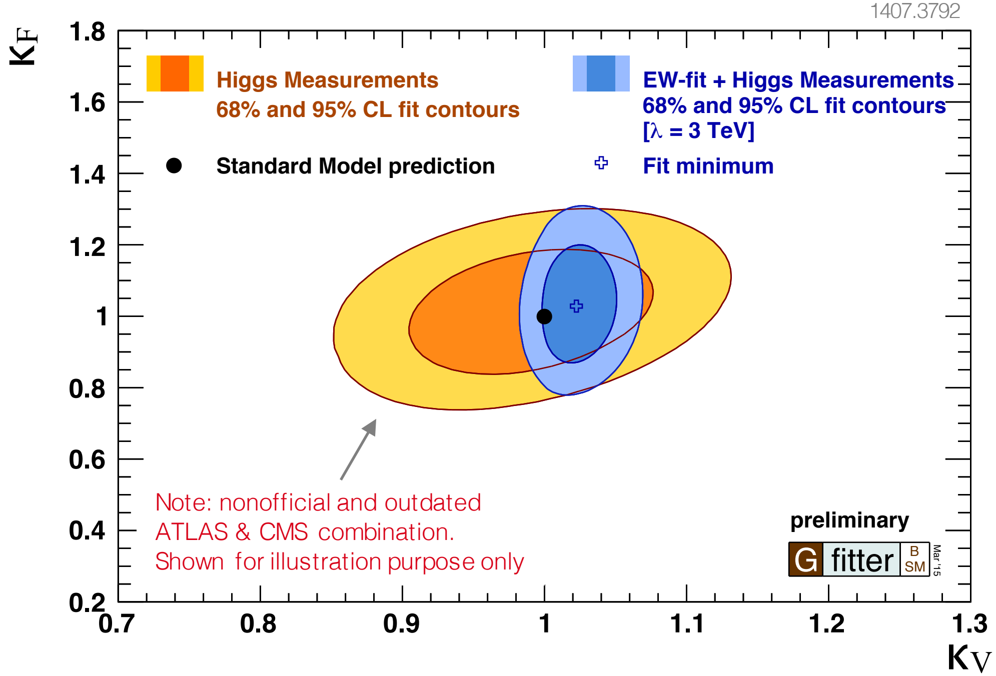
Higgs boson physics

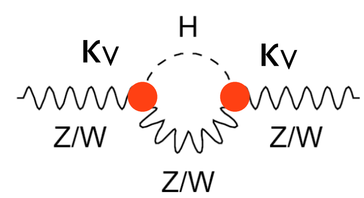
Can combine LHC measurement with constraints on κ_V from electroweak precision data

Constraints on global fermion versus vector-boson coupling modifiers

Constraints from global EW fit through “oblique parameters” S, T (SM: $S = T = 0$), parameterizing new physics contributions to electroweak observables through loop diagrams involving massive W and Z bosons

1407.3792





$$S = \frac{1}{12\pi}(1-\kappa_V^2)\ln\frac{\Lambda^2}{M_H^2}\,, \quad T = -\frac{3}{16\pi\cos^2\theta_{\rm eff}^{\ell}}(1-\kappa_V^2)\ln\frac{\Lambda^2}{M_H^2}\,, \quad \Lambda = \frac{\lambda}{\sqrt{|1-\kappa_V^2|}}$$

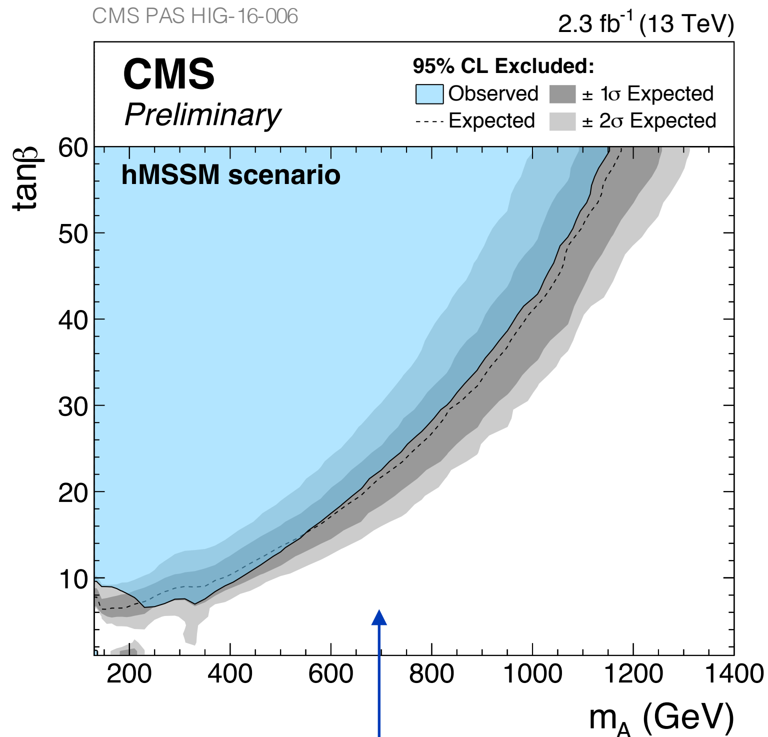
λ is cut-off parameter, set arbitrarily to 3 TeV

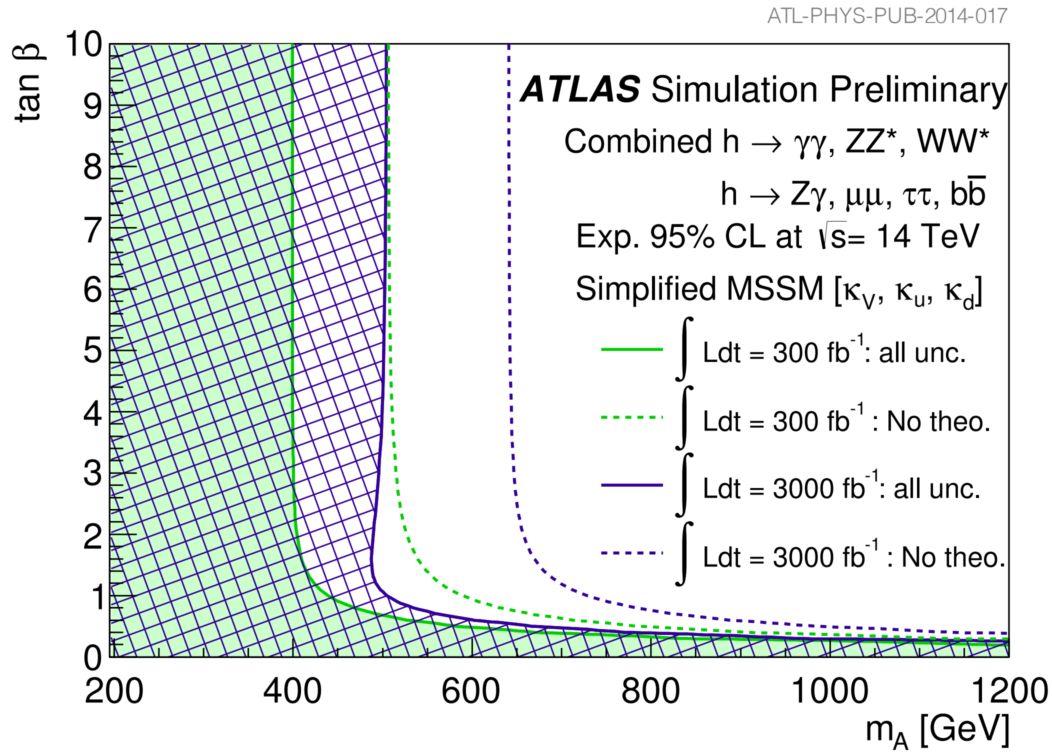
Higgs boson physics

Constraints on new physics from coupling measurements

Example application for constraint on MSSM Higgs from Higgs coupling fit

Constraints on m_A and tanβ in simplified MSSM model from direct H/A → ττ searches (left – current constraint), and from an extrapolation of global Higgs coupling measurements (right)





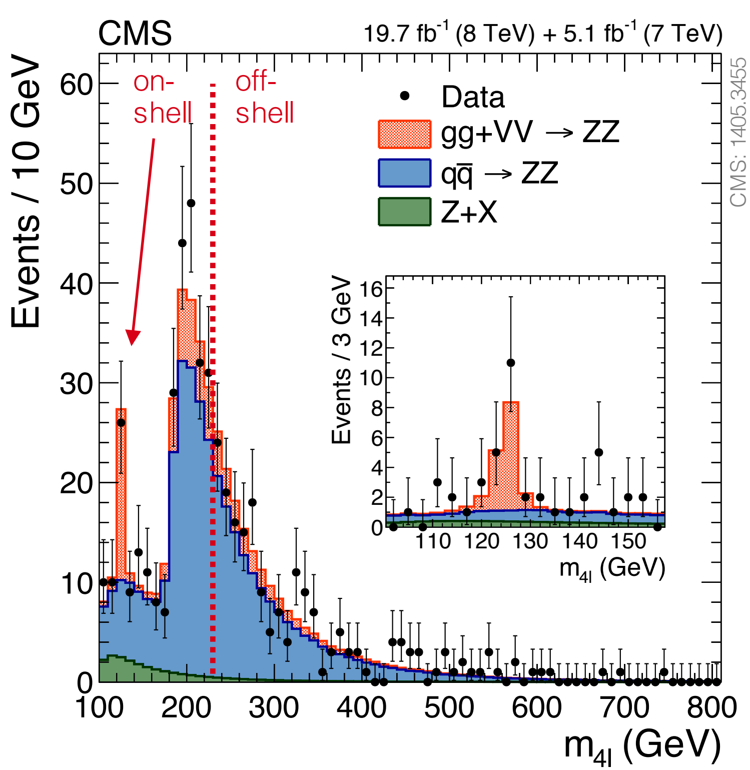
A → tt is dominant decay beyond top-pair production threshold and for low tanβ.
Very difficult channel due to interference with the continuum top pair contribution deteriorating the (broad) tt mass peak

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 $\mu_{\text{on-shell}}$



$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

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

With L_1 = 300 fb^{-1} and L_2 = 3000 fb^{-1}, one may find:

$$\mu^{(L1)}_{\text{off-shell}} = 1.00^{+0.80}_{-0.97}\ \text{(stat+sys)}$$

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

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

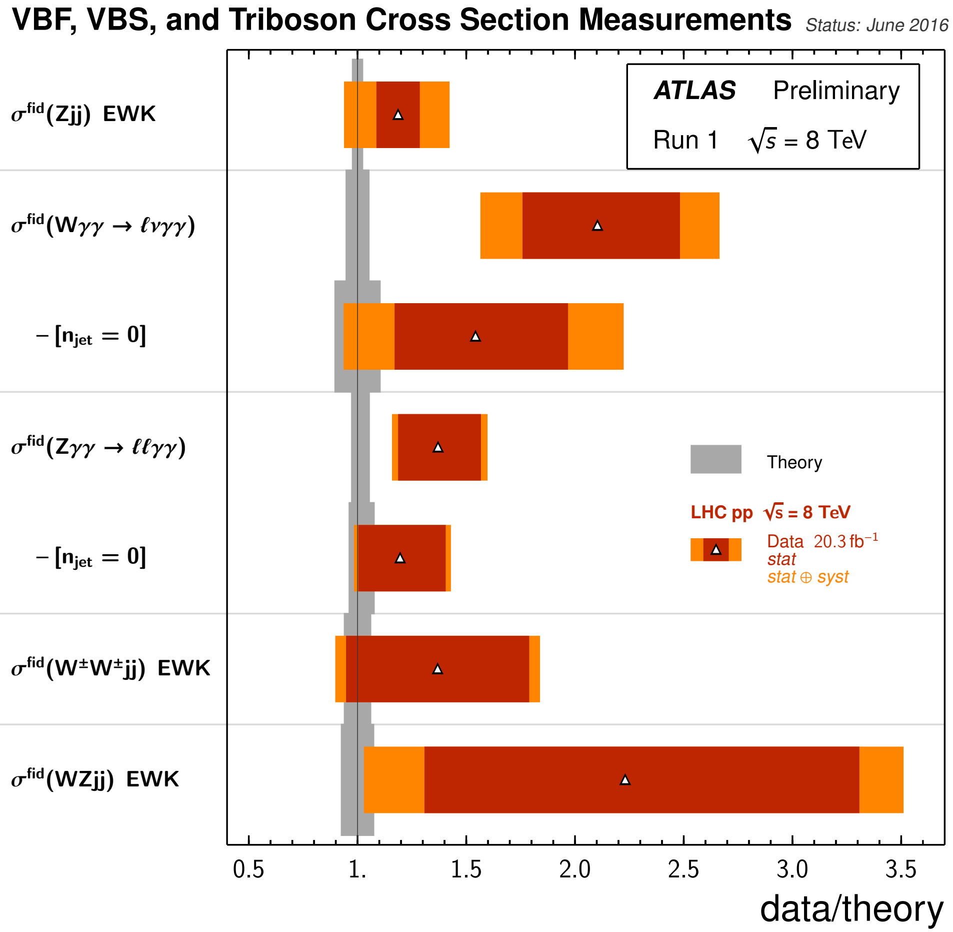
ATLAS: ATL-PHYS-PUB-2015-024

More Standard Model physics

Continuous gain in precision and reach for rare or suppressed processes

High-profile measurements:

- M_W and $\sin^2\theta_W$: *discussed before*
  (work on reduction of physics modelling uncertainties required)
- Triple (TGC) and quartic (QGC) gauge boson couplings in diboson and triboson events also via differential cross-section measurements especially at high p_T and mass. This includes VBF and **VBS diboson production**
- QCD tests with further precision differential cross-sections measurements of Z/W/γ + jets, also detailed studies of V + qq VBF production.
- PDF constraints from high-precision fiducial and differential Z/W/γ cross-section measurements



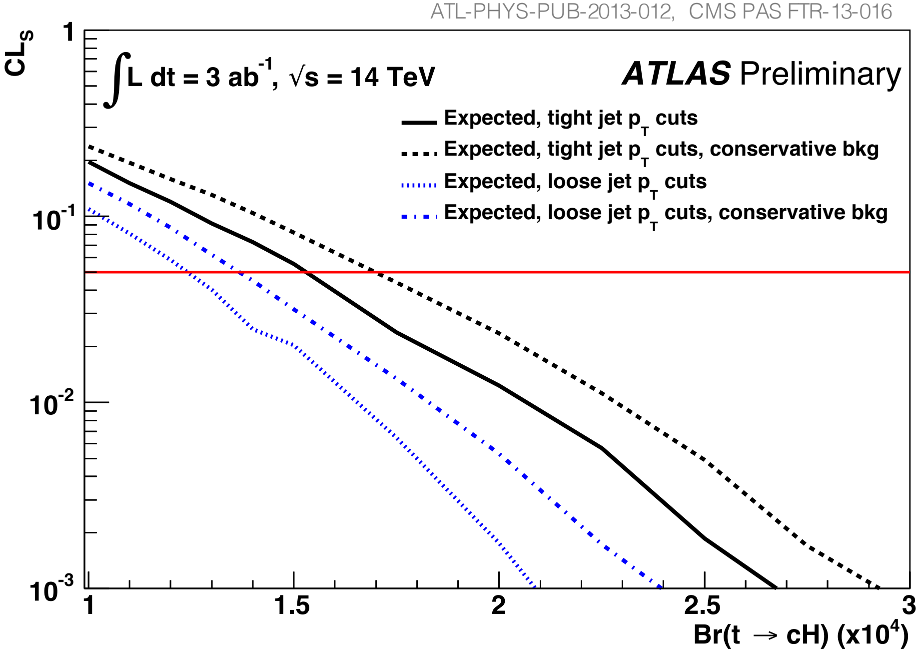
Top physics

Continuous gain in precision and reach for rare or suppressed processes

High-profile measurements:

- Mass: *discussed before*
- Differential cross-sections of top charge asymmetry, spin correlations, H_T, etc. are important theory tests
- Rare processes such as tb, ttZ, ttW, ttγ inclusively & differentially, constraints on anomalous couplings
- Forbidden processes such as the FCNC transitions t → qH, qZ, qγ, qg (q = u,c), also t → d/s+W

ATL-PHYS-PUB-2013-012, CMS PAS FTR-13-016



Numbers: at 100 fb^{-1}, LHC will have produced (13 TeV numbers, summed over charges):

→ 83M top pairs,

→ 22M t-channel top, 7M Wt, 1M s-channel top,

→ 70k tZ, 6k tH,

→ 170k ttγ, 80k ttZ, 60k ttW, …

Limit on t → cH(→ γγ) branching ratio estimated for the full HL-LHC: ~0.015% (current 8 TeV: < 0.46%)

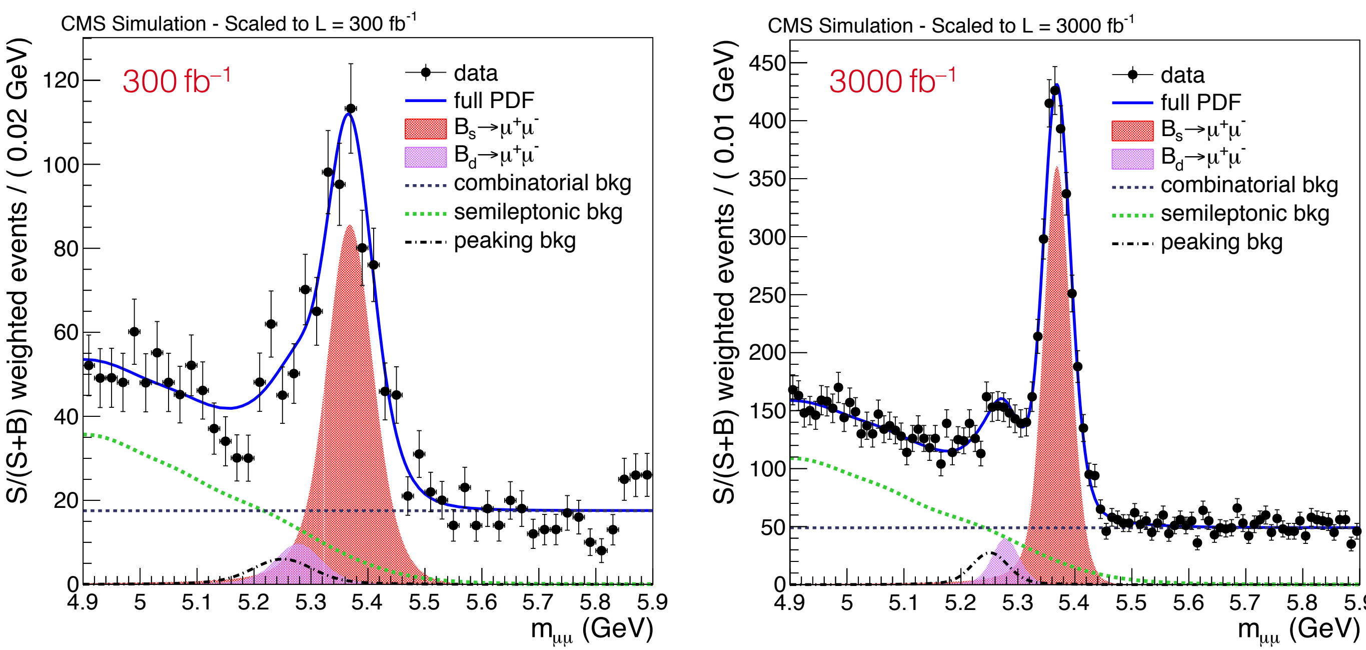
CMS for t → cZ: current/300/3000 fb^{-1} limit: < 0.10% / 0.027% / 0.010%

More Standard Model and Flavour physics

Continuous gain in precision and reach for rare or suppressed processes

High-profile flavour physics measurements (slower Run-2 luminosity rise for LHCb due to luminosity levelling, but upgrade to 40 MHz trigger readout during LS2 will increase, eg, the annual muonic B rate by factor of ten)

- Rare decays: $B_{(s)} \to \mu\mu$ and similar and $b \to s$ transitions: $B \to K^{*}\mu\mu$ and similar (LHCb, CMS, ATLAS)
- CP violation: ϕ_s (LHCb, CMS, ATLAS), γ and other CKM parameters (LHCb), also CPV in charm sector
- Lepton universality tests (LHCb)
- Spectroscopy (LHCb, CMS, ATLAS)



Prospective study by CMS for the rare $B_s \to \mu\mu$ decay

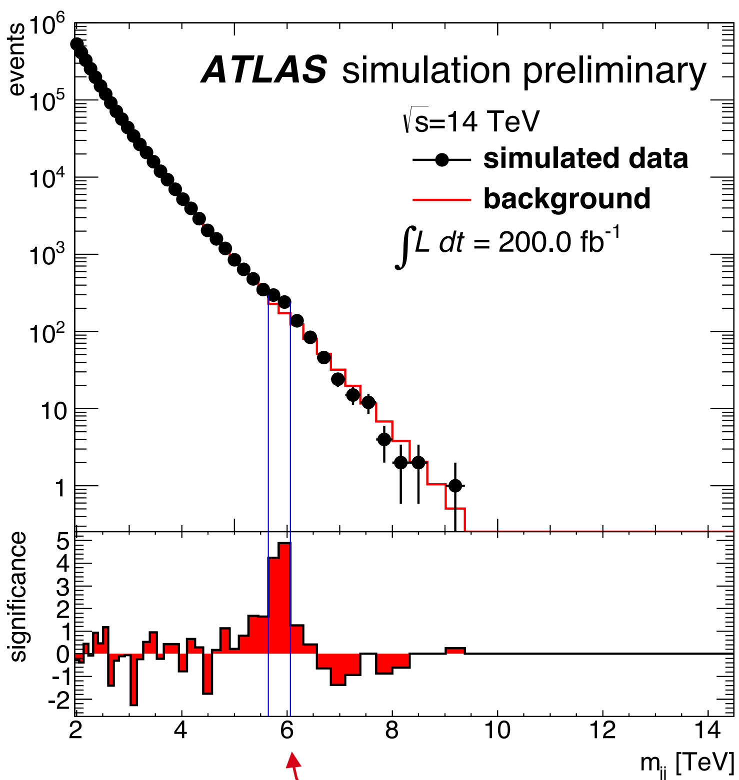
CMS-PAS-FTR-13-022

Searches

Will always stay a central piece of the LHC physics programme as a discovery machine

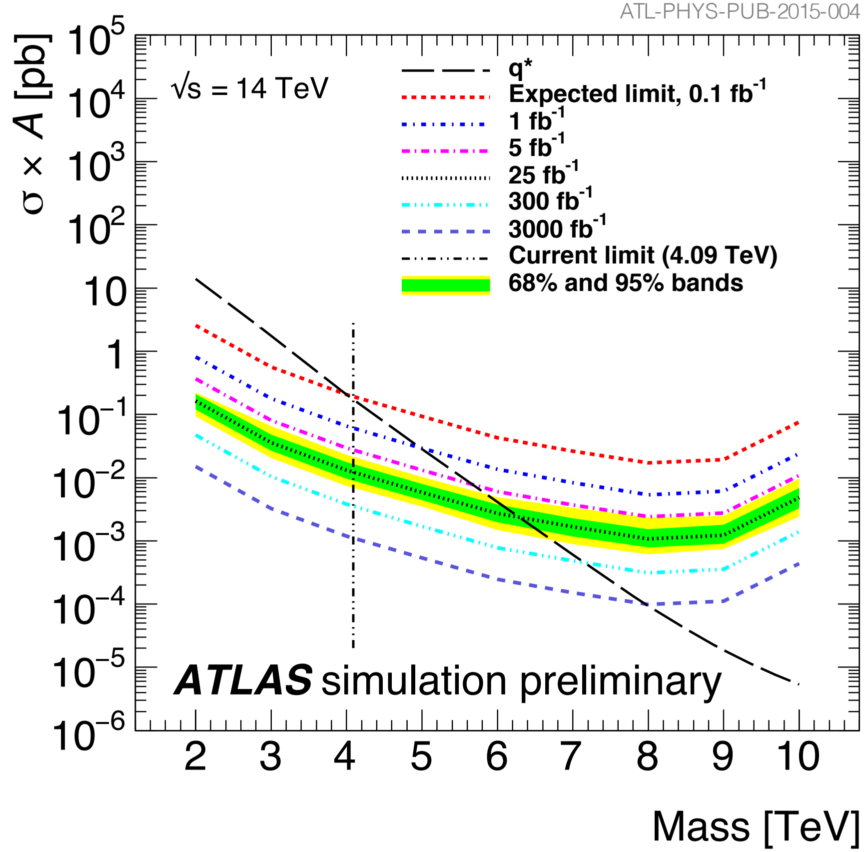
Still huge sensitivity increase this year, but will slow down with the progress of Run-2 and after.
Searches gradually move from highest masses to lower cross-sections and difficult phase space regimes

Example: dijet resonance search (interpretation with excited u & d quarks $q^* \to qg$)



6 TeV q*

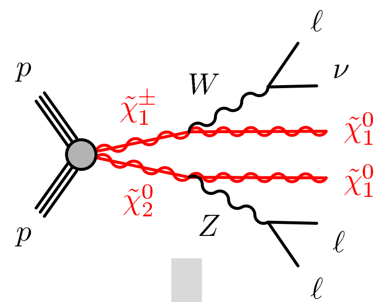
ATL-PHYS-PUB-2015-004

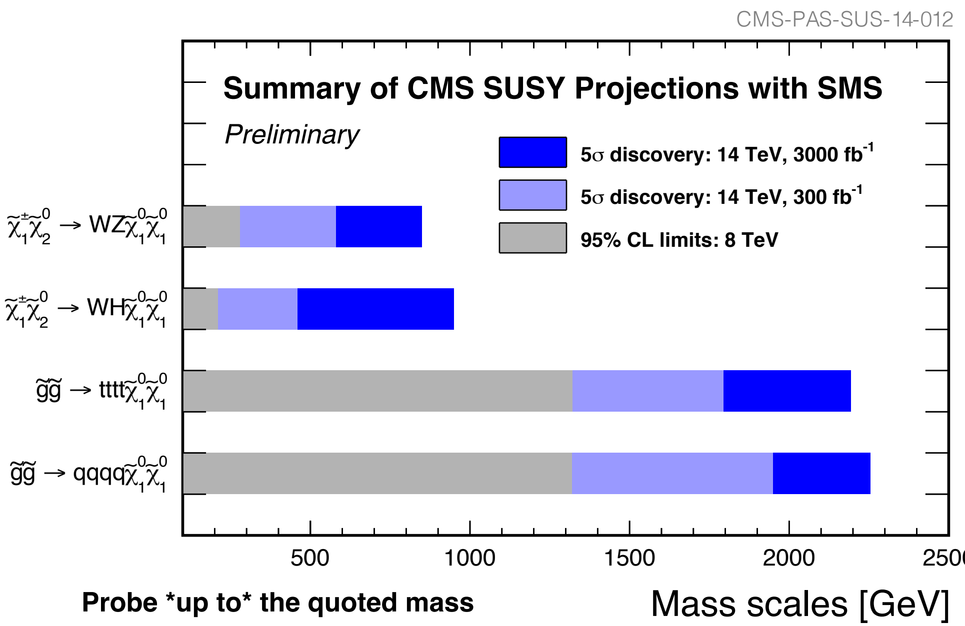


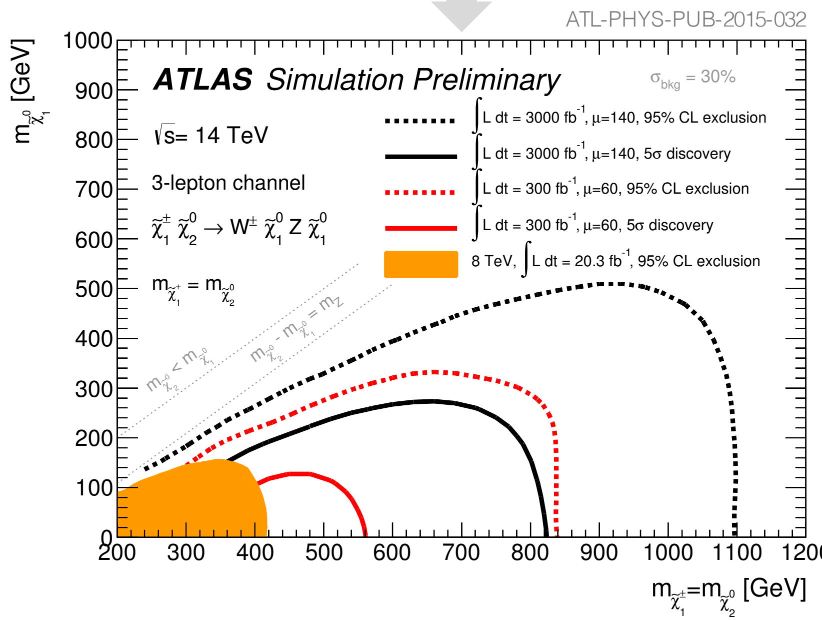
Searches

Will always stay a central piece of the LHC physics programme as a discovery machine

SUSY searches will move to low cross-section electroweak production and compressed scenarios







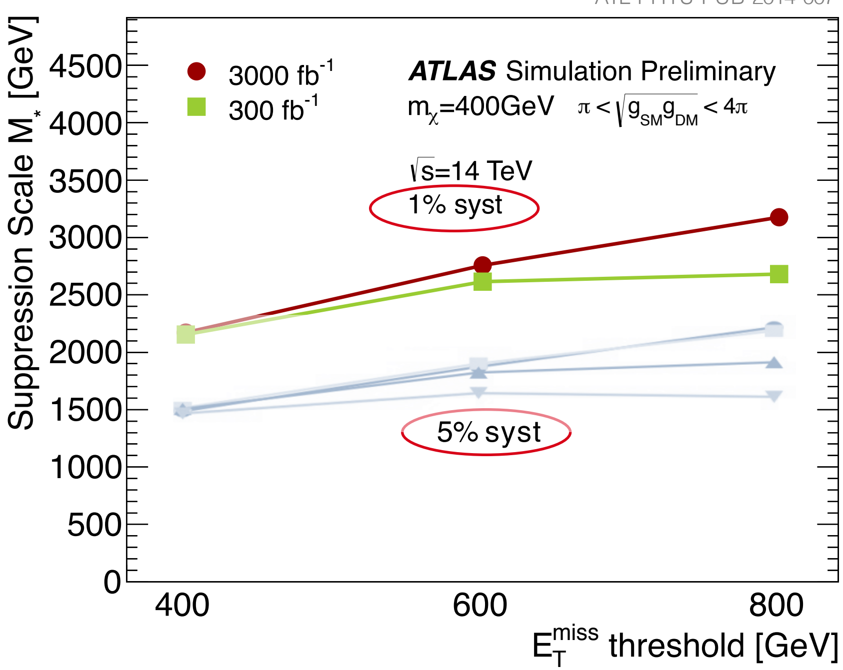
Searches

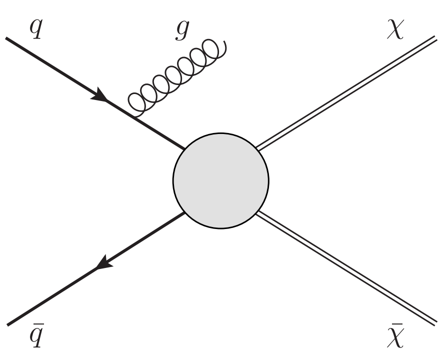
Will always stay a central piece of the LHC physics programme as a discovery machine

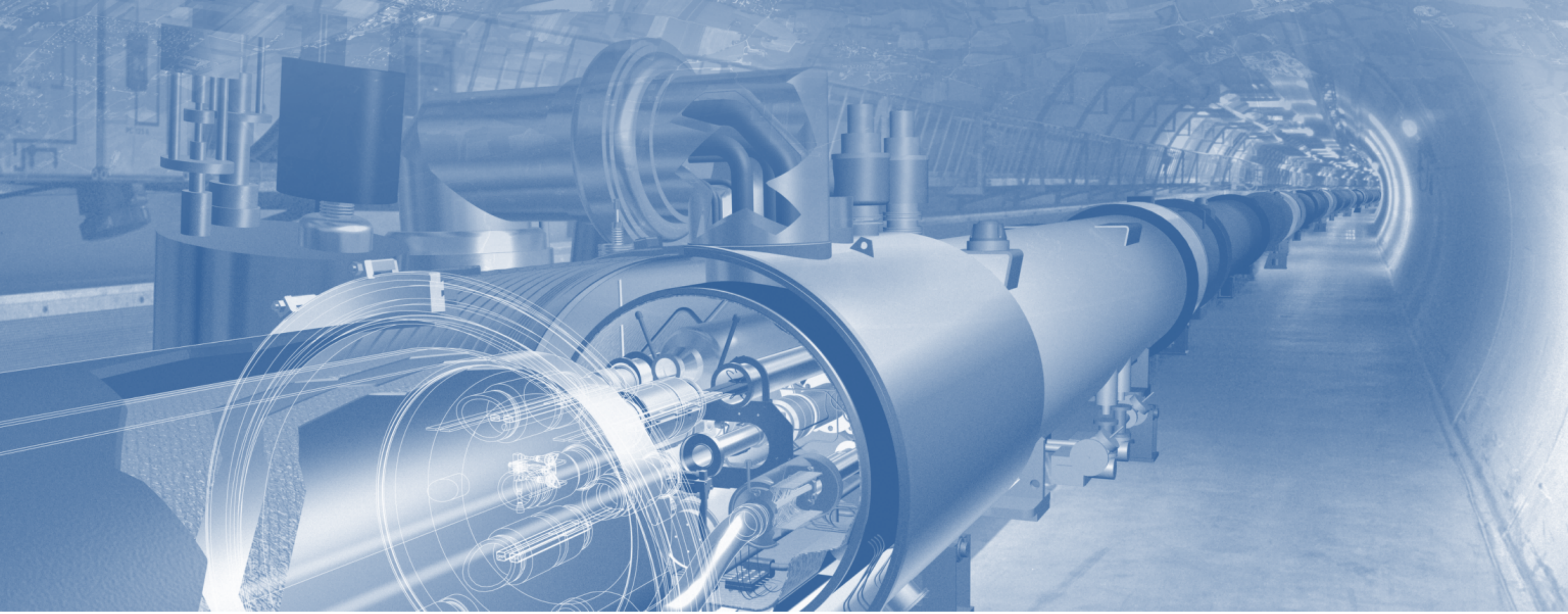
The sensitivity of dark matter searches looking for an excess in the high E_T^{miss} tail depends strongly on the systematic uncertainty achieved for the irreducible background → meets SM analysis efforts

D5 vector operator: $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$

ATL-PHYS-PUB-2014-007







Beyond the HL-LHC

Only a very brief enumeration of projects

Future hadron collider projects in a nutshell

The next discovery machine

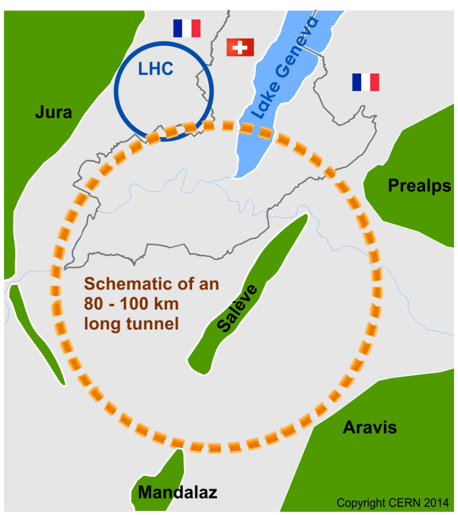
HL-LHC: E_{CM} = 14 TeV, 3 ab^{-1}, 2026~2035… (formally approved as *project* by CERN council)

Future Circular Collider FCC-hh (CERN):

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

SppC (China):

- E_{CM} ~ 71 TeV in 55 km ring, $L \sim 1 \times 10^{35}\ s^{-1}cm^{-2}$
- Requires very high gradient dipole magnets ~ 20 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/Ip [$10^{34}\ cm^{-2}s^{-1}$]	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 synchrotron radiation/beam	5 MeV 3 MW		2 MeV 5.8 MW	7 keV 5.4 kW	7 keV 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_{CM} ~ 500–1000 GeV in 31–45 km total length, L ~ 1.8×10^{34} $s^{-1}cm^{-2}$, only one interaction region
- nm beam size, possible start of physics ~ 2030

Compact Linear Collider CLIC (CERN)

*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

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

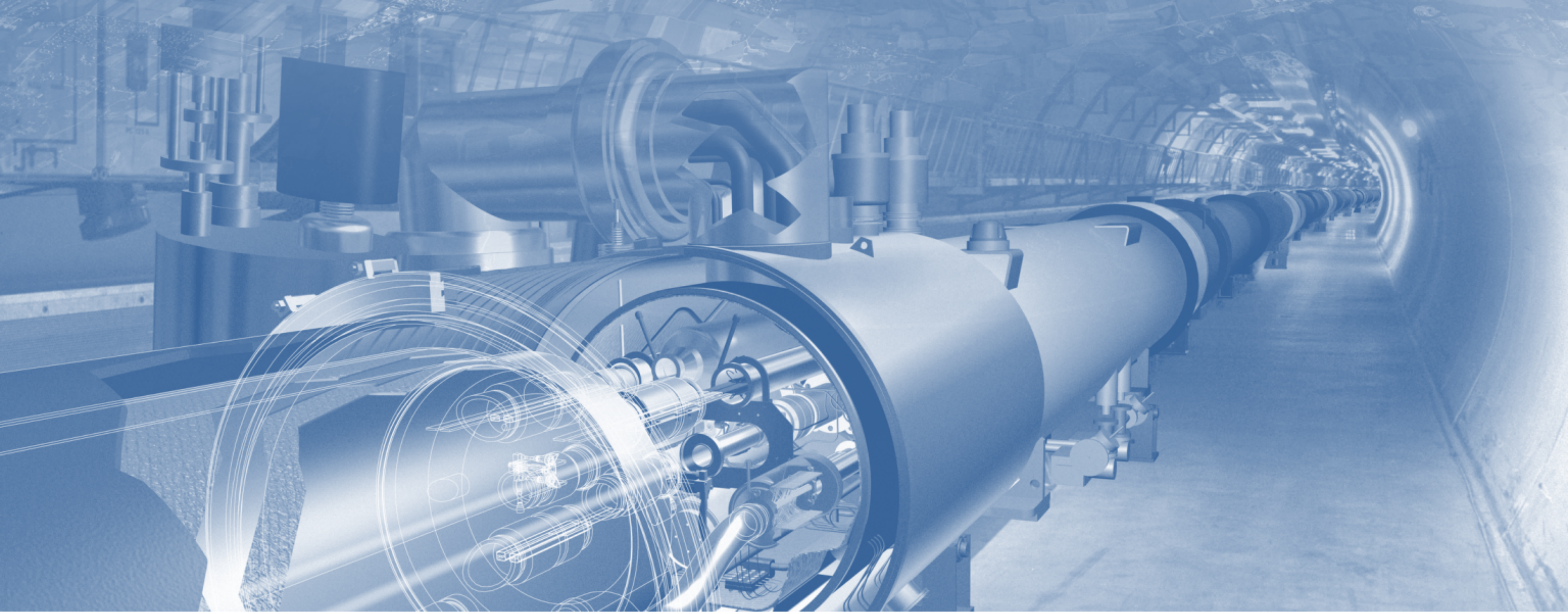
Future Circular Collider FCC-ee (CERN):

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

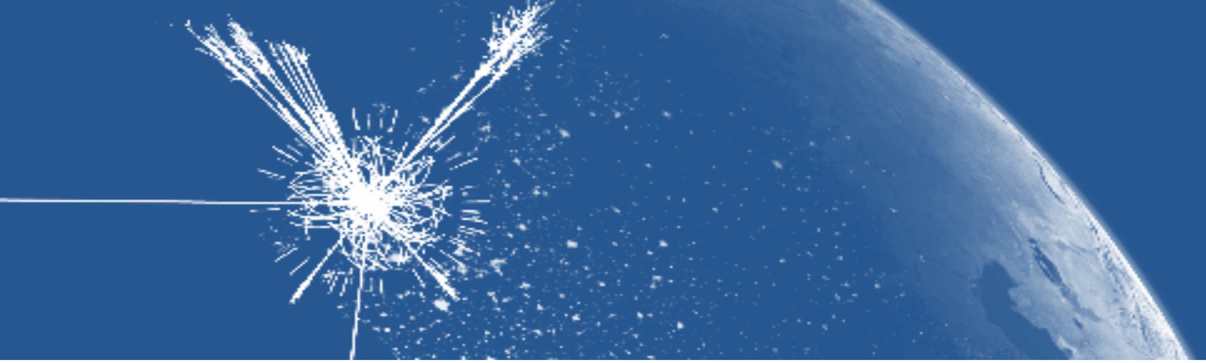
Circular EP collider CEPC (China):

- E_{CM} ~ 240 GeV, L ~ 2×10^{34} $s^{-1}cm^{-2}$
- 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 x 10^{34} $cm^{-2}s^{-1}$	**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



Conclusions



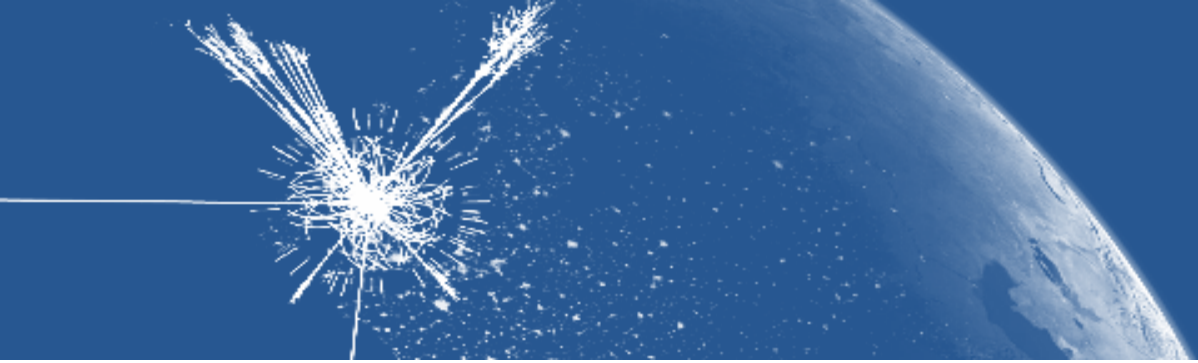
Conclusions

The LHC Run-2 is a key period for particle physics

- High CM energy and first 100 fb^{-1} are critical for searches for new physics in all signatures
- Further consolidation of Higgs sector with observation and measurement of $H \rightarrow \tau\tau$ & bb, and ttH, as well as much more precise coupling and fiducial & differential cross section measurements
- The luminosity of Run-2 will hugely increase the amount of interesting Standard Model and flavour physics measurements that can be performed

Watch out:

- New physics does not necessarily appear at high mass, need to continue to search everywhere
- Very high precision measurements are key for a better knowledge of the Standard Model
- It is thereby extremely important to measure the detector performance in data as precisely as possible
  (This can often have priority over further improving the performance, example: b-tagging.)
- Many results are dominated by theoretical uncertainties. Need to produce measurements that allow to test theory, to improve PDFs, and that motivate theorists to improve calculations and event generators



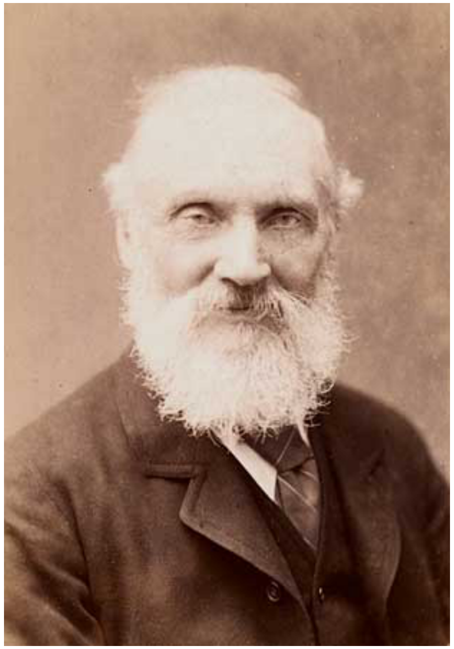
Conclusions

Accurate and minute measurement seems to the non-scientific imagination, a less lofty and dignified work than looking for something new.

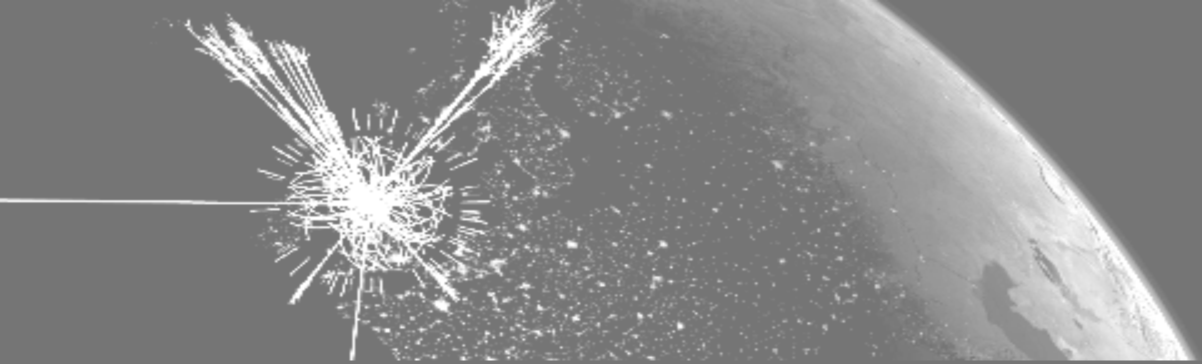
But [many of] the grandest discoveries of science have been but the rewards of accurate measurement and patient long-continued labour in the minute sifting of numerical results.

William Thomson Kelvin

2 Aug 1871 in a speech to the British Association for the Advancement of Science



Lord Kelvin



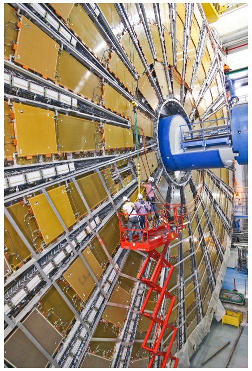
Extra slides

ATLAS improvements for Run-2

Huge consolidation & improvement programme for detector, online, offline, computing

Infrastructure upgrades: magnet & cryogenic systems, additional muon chamber shielding, new beam pipes

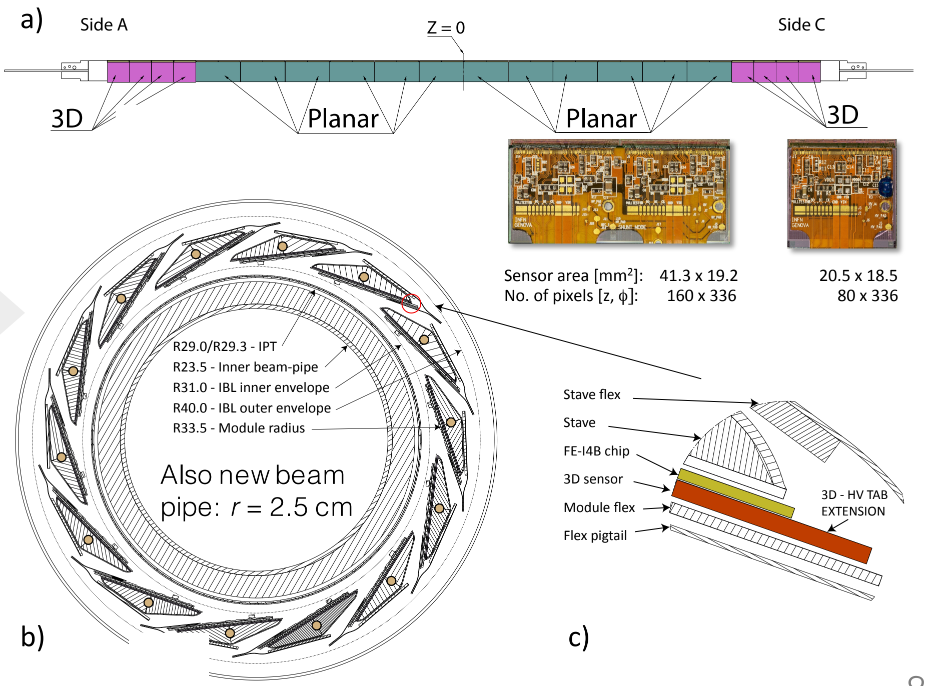
Replacement of TGC chambers



Detector consolidation: muon chamber completion ($1.0 < |\eta| < 1.3$) & replacements, calorimeter electronics repairs, improved inner detector read-out capability to cope with 100 kHz L1 trigger rate, new pixel detector services and module repairs

New topological L1 trigger and new central trigger processor, restructured high-level trigger

New *Insertable B-layer*: fourth pixel layer at 3.3 cm from beam, consisting of planar & 3D (forward) silicon sensors, smaller pixels



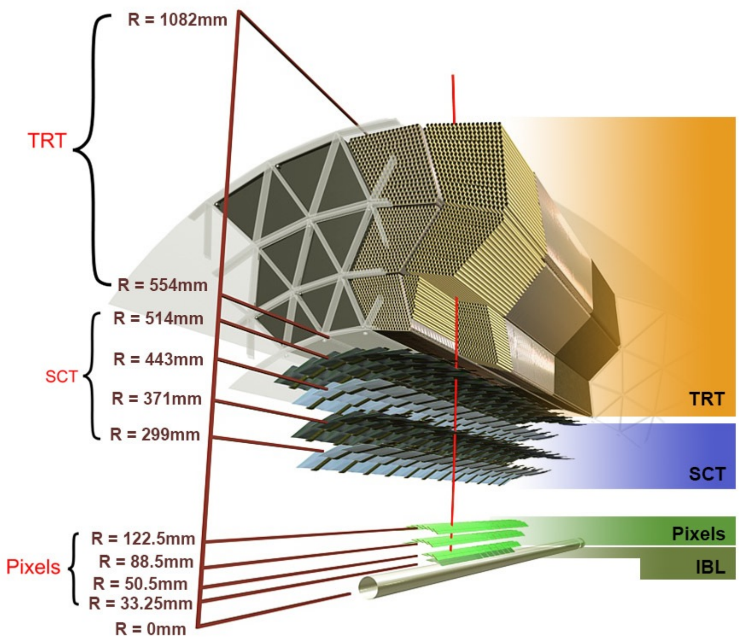
New software, new production system, new analysis model, …

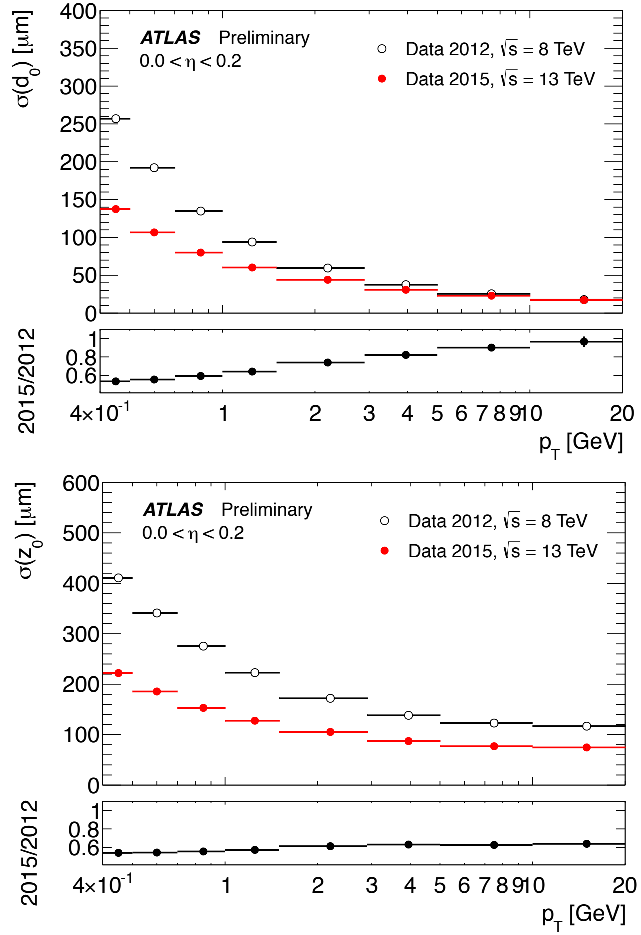
ATLAS inner tracking performance

[ATL-PHYS-PUB-2015-018]

ATLAS tracking in Run-2 features the new IBL, reduced material within acceptance, and algorithmic improvements (eg, huge speed-up, *tracking in dense environment* [ATL-PHYS-PUB-2015-006])

Sketch of ATLAS inner tracking detectors



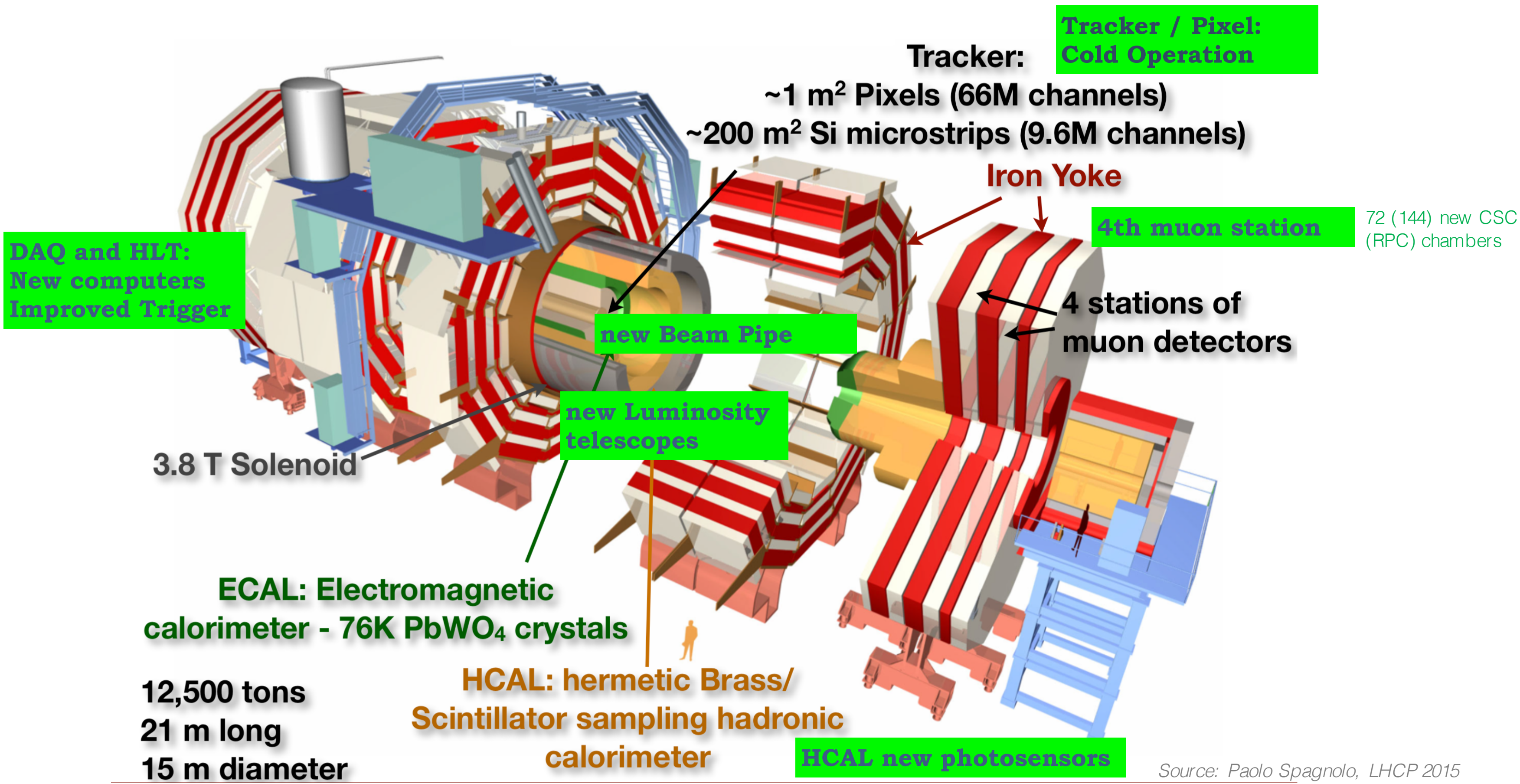


Impact parameter resolution improvement from IBL

Measured improvement of impact parameter resolution with IBL depending on track p_T

CMS improvements for Run-2

Also significant updates and improvements



Source: Paolo Spagnolo, LHCP 2015

Also:
- Multithreaded and more efficient reconstruction at CERN and Tier-1
- New compact mini-AOD format (~10% of AOD)
- Large efforts on improved (out-of-time) pileup mitigation

LHCb improvements for Run-2

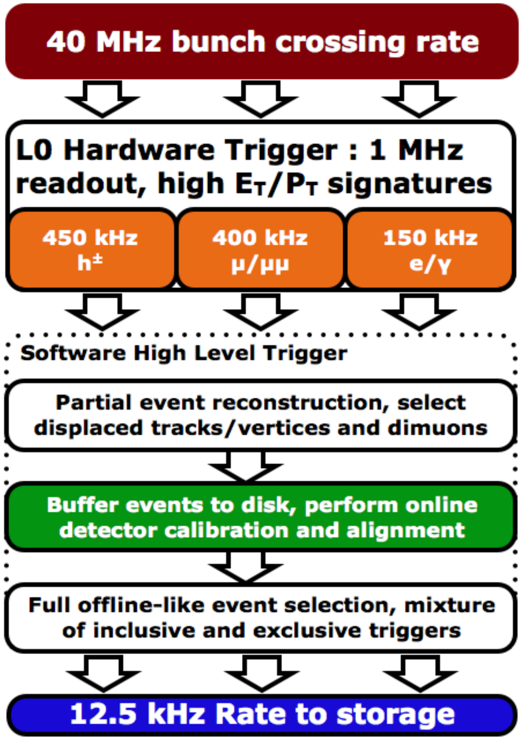
Big effort in trigger area (among others)

Detector consolidation: muon HV and grounding, 15% PMTs replace in HCAL, ECAL monitoring fibres replaced, module repairs in OT, HPD exchange in RICH, fixes in cooling, gas, power, shielding, …

HeRSCheL: new scintillating counters to extend LHCb coverage to high rapidity (CEP, diffraction, …)

Trigger upgrade — split trigger:

- All 1st stage (HLT1) output stored on disk
- Used for real-time calibration and alignment
- 2nd stage (HLT2) uses offline-quality calibration
- 5 kHz of 12 kHz to Turbo stream:
  - Objects produced by trigger are stored
  - No raw event → smaller event size
  - Used for high-yield channels (charm, J/ψ, ...)

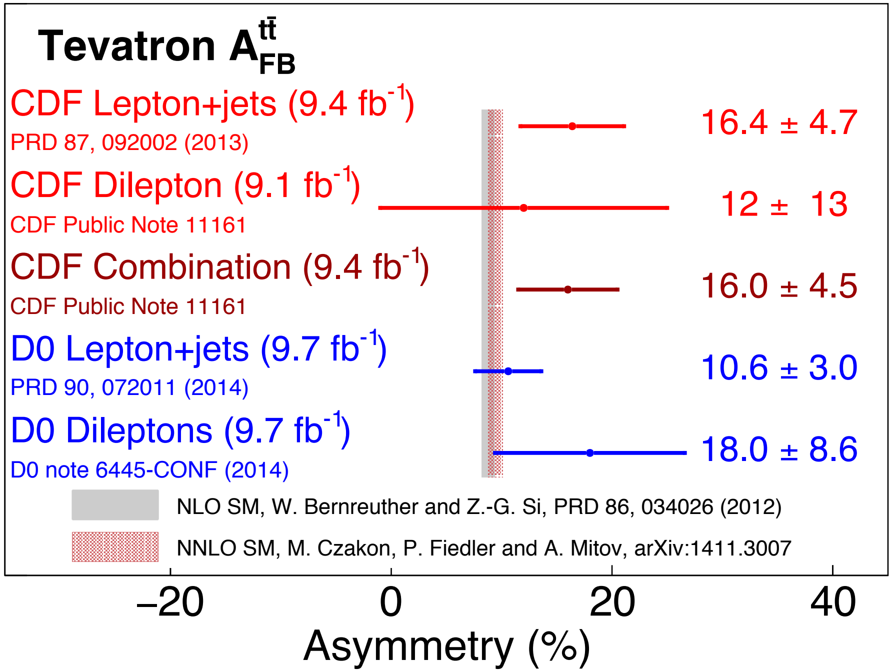


Top asymmetry at Tevatron

Historical deviation from SM

One update from the Tevatron

- Tevatron A_{FB}(tt) and NNLO SM prediction have converged towards each other
- Charge asymmetries at LHC in agreement with SM
- D0 also has beautiful new measurement of P and CP-odd observables (CP-odd one found compatible with zero)



$$A_{\text{FB}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y = y_t - y_{\bar{t}}$$

Higgs boson physics

Run-2 should increase Higgs sample by factor of ~10, ttH by factor of ~20

Higgs mass already well known (0.2%), but further improvement and – important – cross-check needed

Higgs width (SM: 4.2 MeV) cannot be directly measured; indirect constraints possible

Higgs spin & parity established as 0^+, but need to investigate possible *CP*-odd admixtures

Higgs couplings can be overconstrained from channel-wise (categorised) measurements

What is left to complete after Run-1 ?

- Complete observation of $H \to \tau\tau$
- Observe $H \to bb$
- Observe ttH and W/Z+H production

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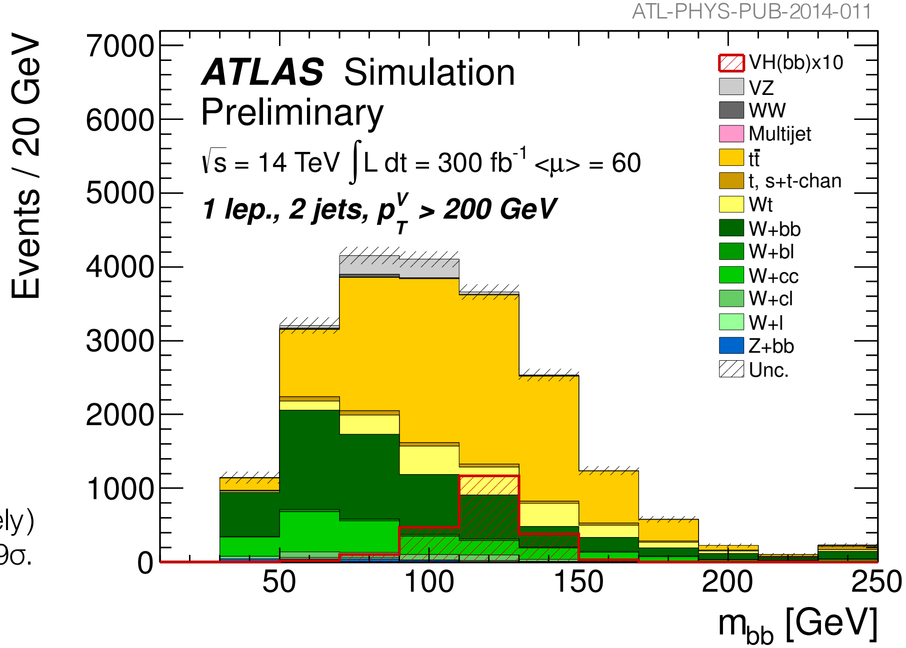


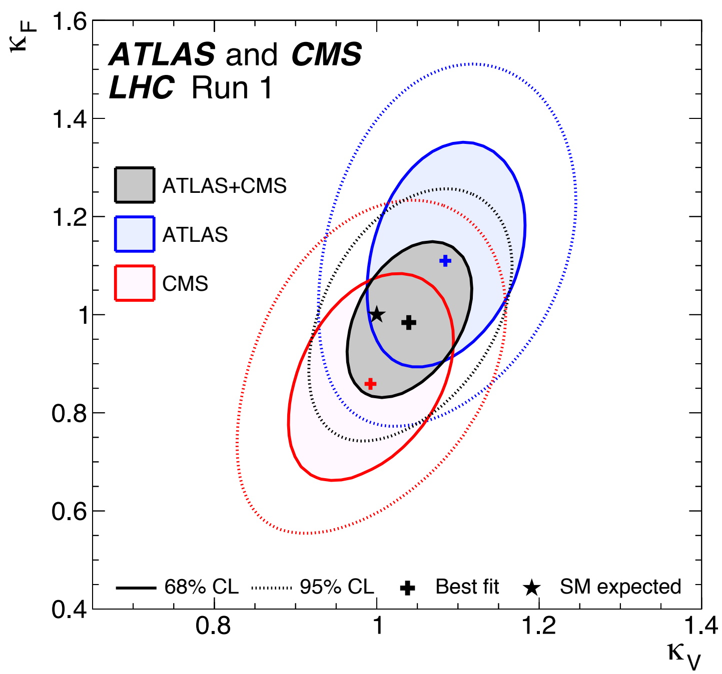
Extrapolated m_{bb} distribution in WH channel at 300 fb^{-1} and $\langle\mu\rangle = 60$. The (conservatively) estimated significance for this analysis is 3.9σ.

Higgs boson physics

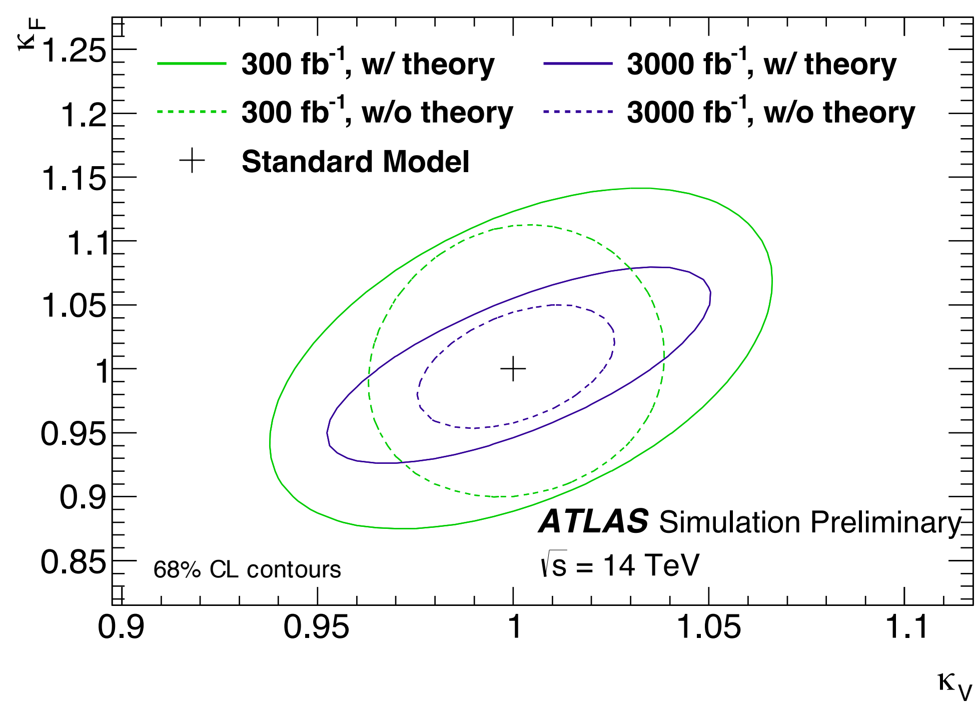
(Conservative) extrapolation of Higgs coupling measurements

Constraints on global fermion versus vector-boson coupling modifiers

Current (Run-1):



Extrapolation:



Higgs boson physics

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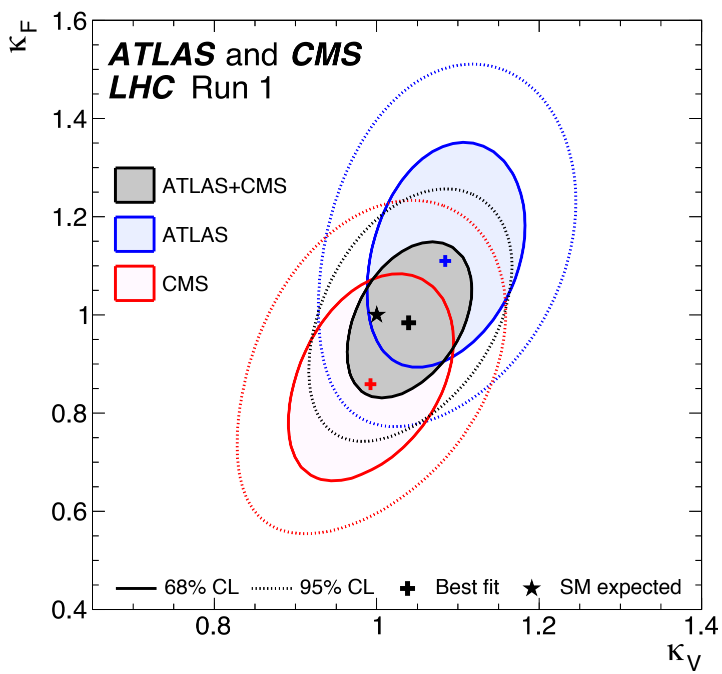
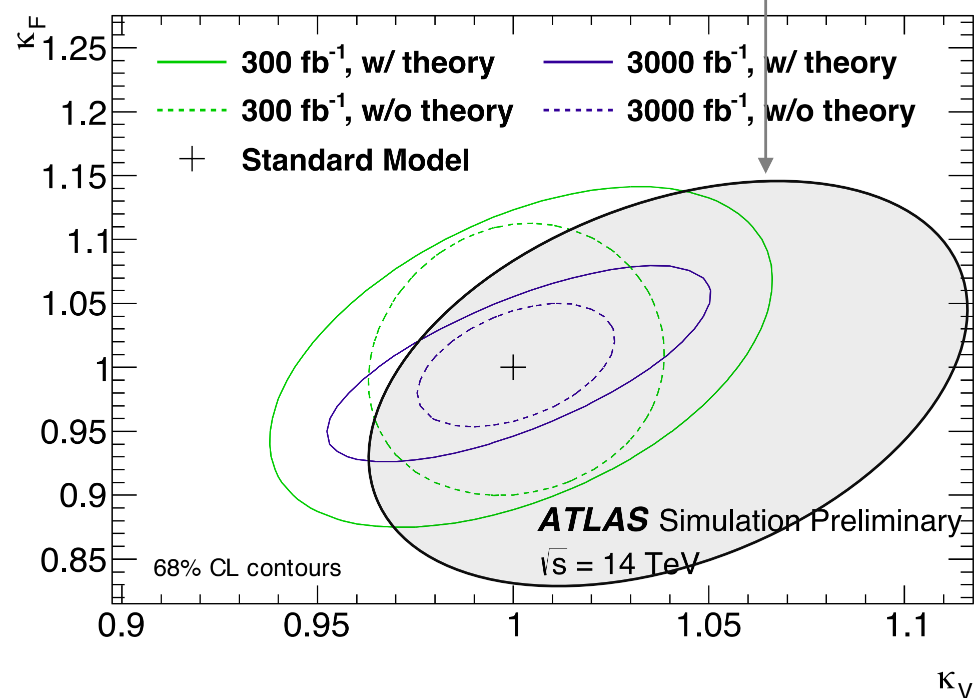


Extrapolation:

Run-1
(ATLAS & CMS,
observed 68% CL contour)

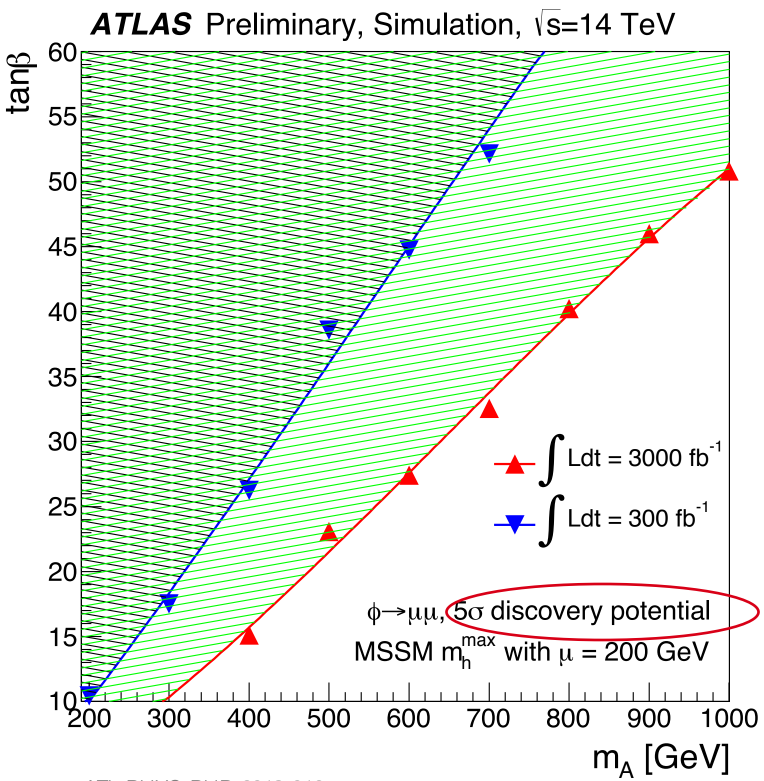


Higgs boson physics

Searches for additional Higgs bosons

The discovery potential for H/A → ττ is compromised for large m_A and low tanβ where the H/A decays predominantly to top pairs with a deteriorating interference pattern with the continuum top pair contribution

Production of gg → A → Z(→ℓℓ) h(→bb) in the 2HDM can be discovered for low tanβ and at least moderate |cos(β – α)| up to and beyond m_A = 700 GeV



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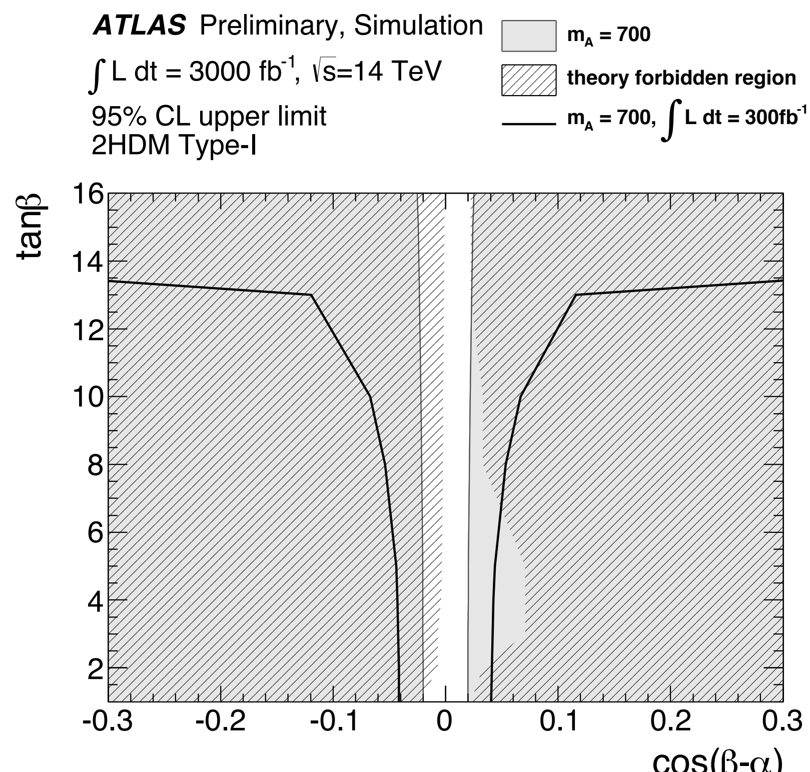

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