First results from LHC's Run-2

Andreas Hoecker (CERN)

PITT-PACC, 4 Dec 2015

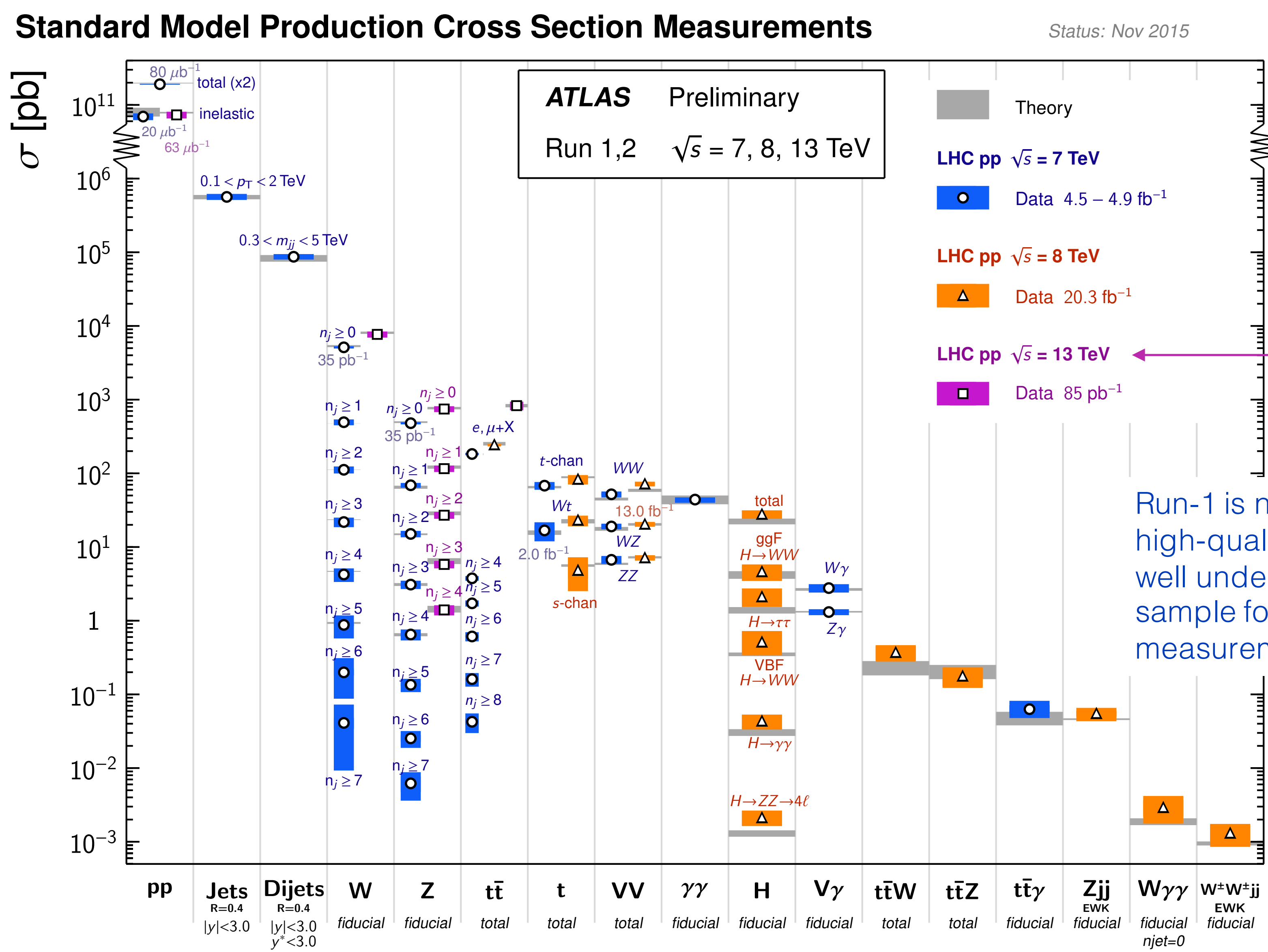
CMS
LHC ring at CERN:
27 km circumference
LHCb
So far:
0.9 / 2.8 / 5 / 7 / 8 / 13 TeV proton—proton collisions
2.8 / 5 TeV Pb—Pb collisions
5 TeV p—Pb collisions
SPS ring:
7 km circumference
ALICE
CERN (Meyrin site)
ATLAS

Run-1

7 & 8 TeV pp, 5 & 20 fb^{-1}

A few highlights, with apologies to CMS for showing a bit more ATLAS here, for convenience

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



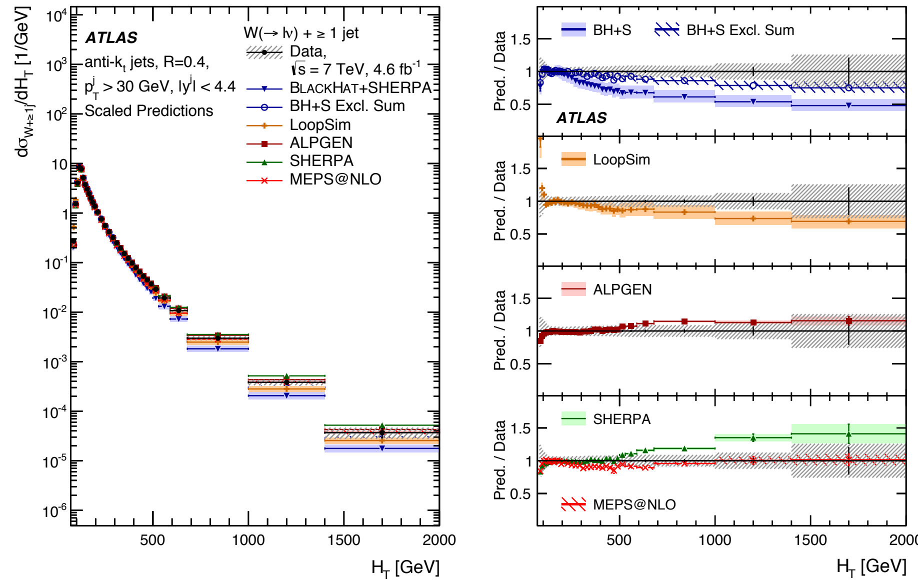
Note !

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

Numerous Standard Model measurements have driven QCD tests at hadron colliders to a new quality, accompanying new theoretical developments

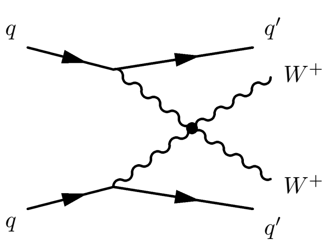
W+jets analysis [ATLAS, EPJ C 75, 82 (2015)]

Precise tests of NLO matrix element calculations matched to parton shower models

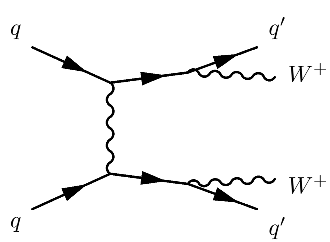


And allowed to progress on critical electroweak studies related to the scalar sector

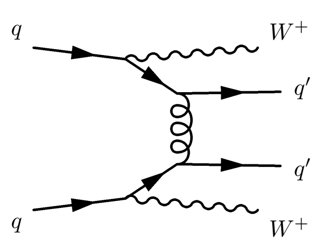
W±W± + jj production [ATLAS, PRL 113, 141803 (2014)]



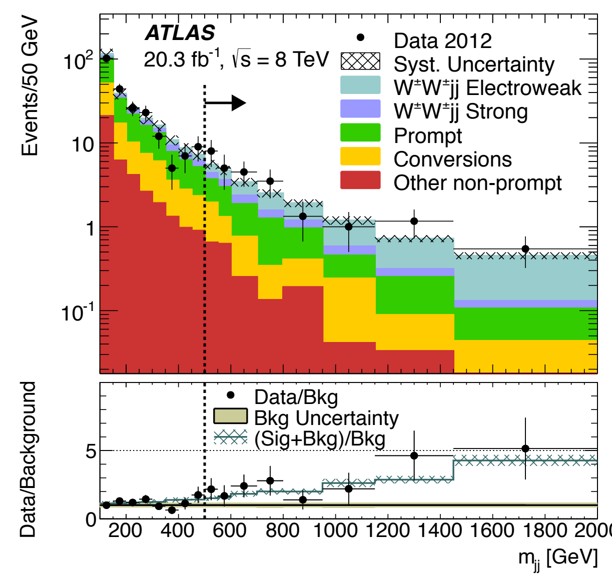
EW VBS production



Non-VBS production



Strong production

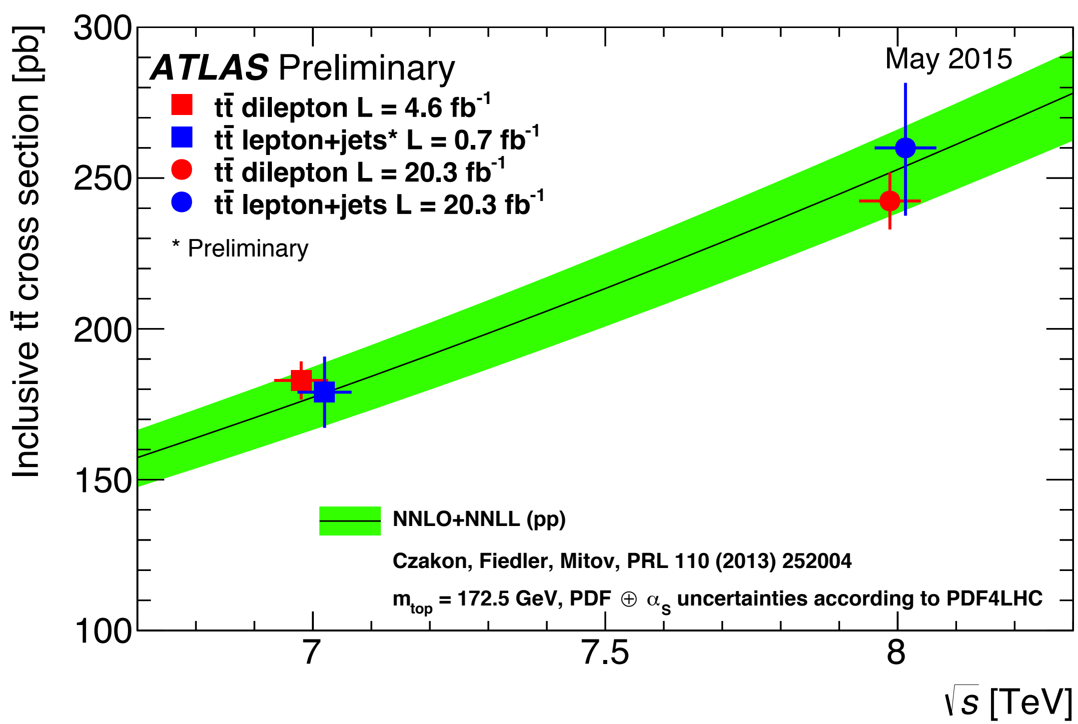


Top quark production has been studies with unprecedented experimental precision

Dilepton tt cross-section measurement

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

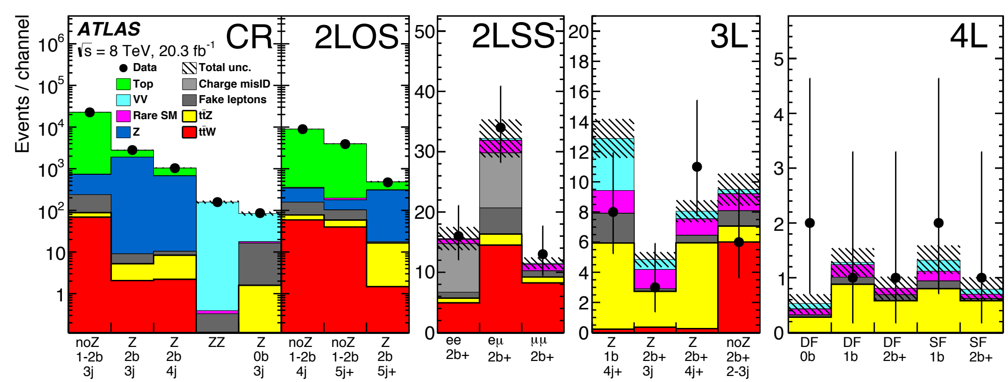
Precision test of NNLO QCD, used to derive the top mass and new physics limits



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]



Similarly for top-quark properties

Top mass measurements

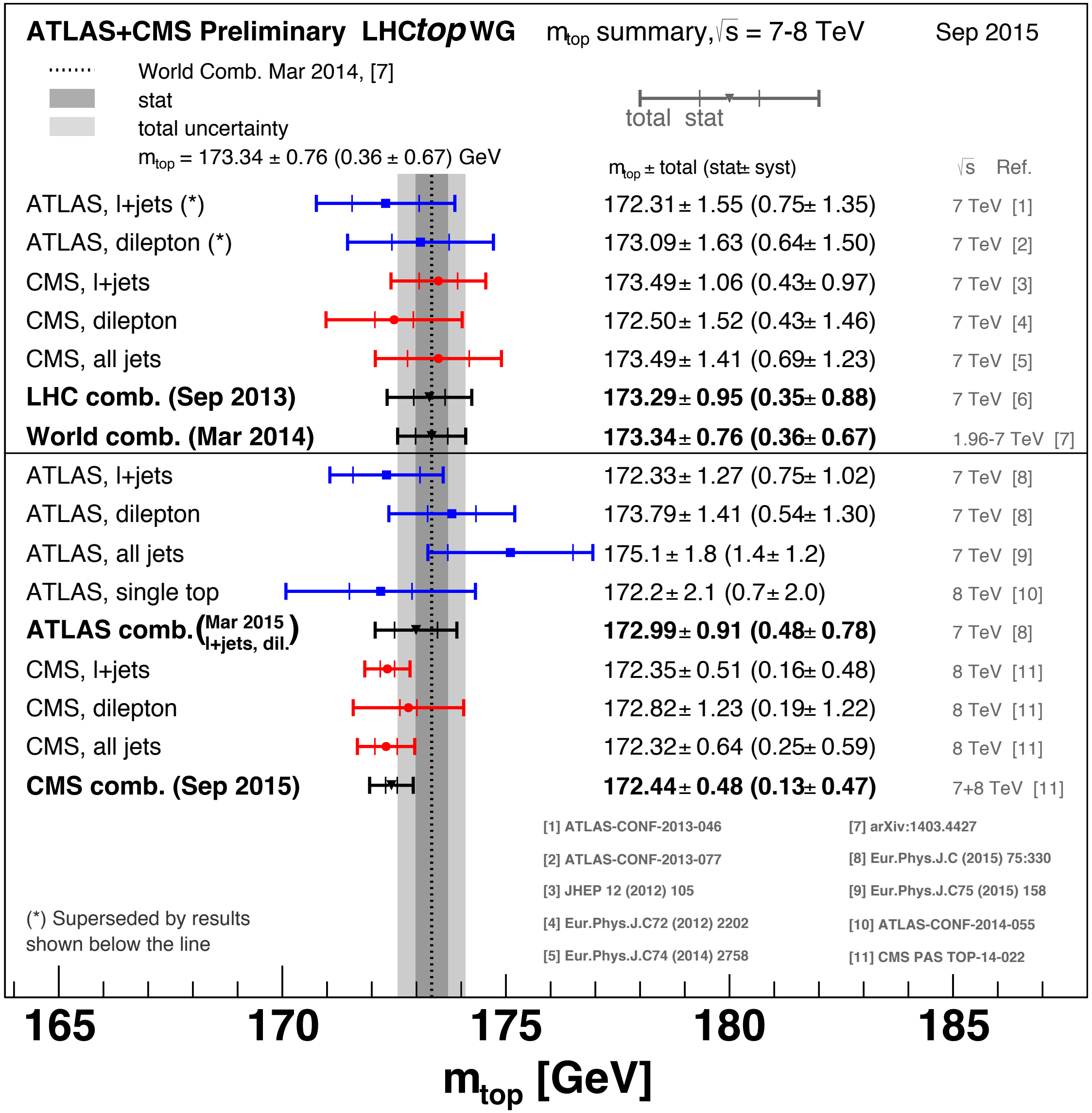
Newest top mass combination from CMS features total uncertainty of 480 MeV

[CMS, 1509.04044]

640 MeV for Tevatron combination, ATLAS has no 8 TeV result yet

Important theoretical discussion on non-perturbative uncertainties

Alternative, but less precise, m_{top} determinations via cross-section measurements



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

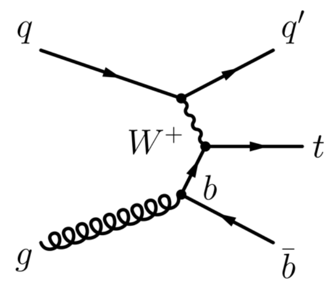
[ATLAS, 1510.03752, CMS 1401.2942]

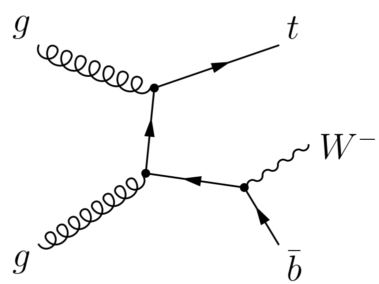
s-channel process first observed at Tevatron with 6.3σ in agreement with SM prediction

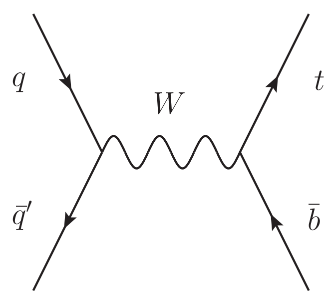
[CDF & D0, 1402.5126]

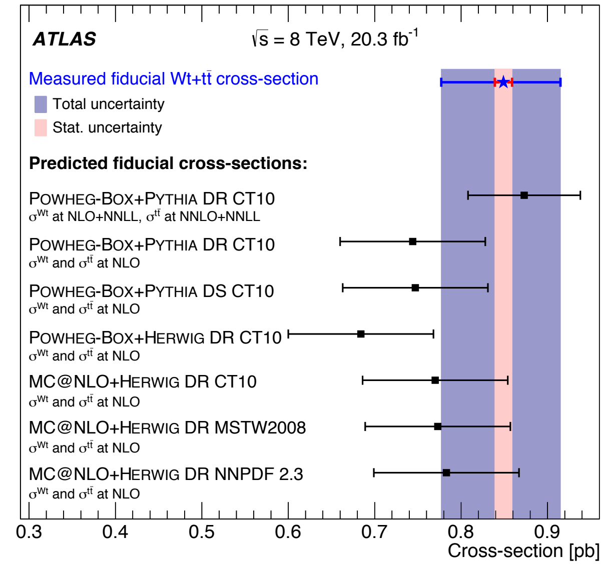
ATLAS reported 3.2σ (3.9σ exp.) evidence in agreement with SM

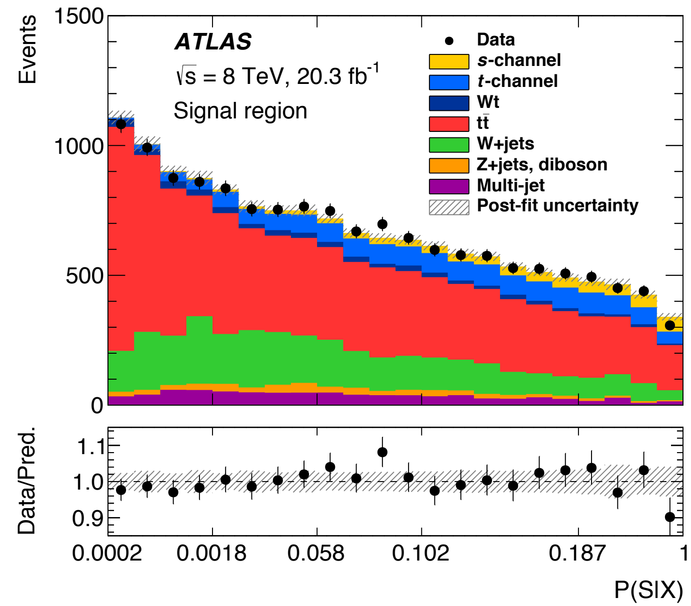
[ATLAS, 1511.05980]



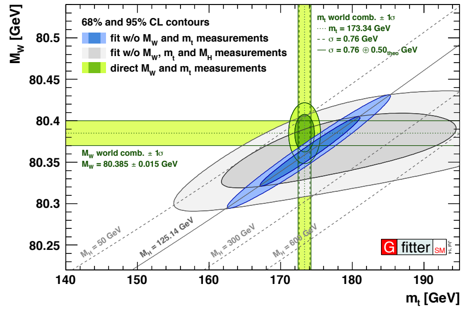








W mass



No LHC result yet

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

[CDF & D0, 1204.0042]

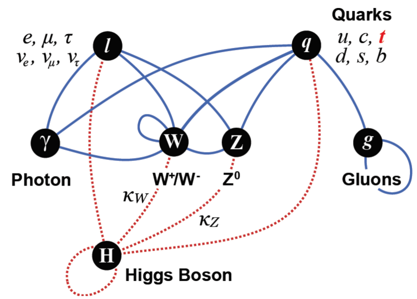
Standard Model prediction:

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

Discovery of an elementary (?) scalar boson and flurry of property measurements

ATLAS & CMS Combinations of Higgs mass and coupling measurements

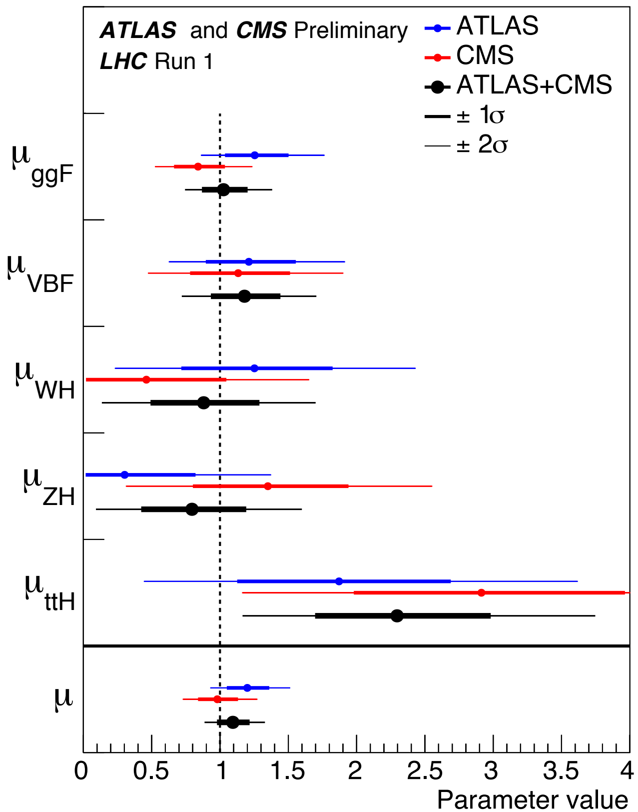
[arXiv:1503.07589, ATLAS-CONF-2015-044 & CMS-PAS-HIG-15-002]



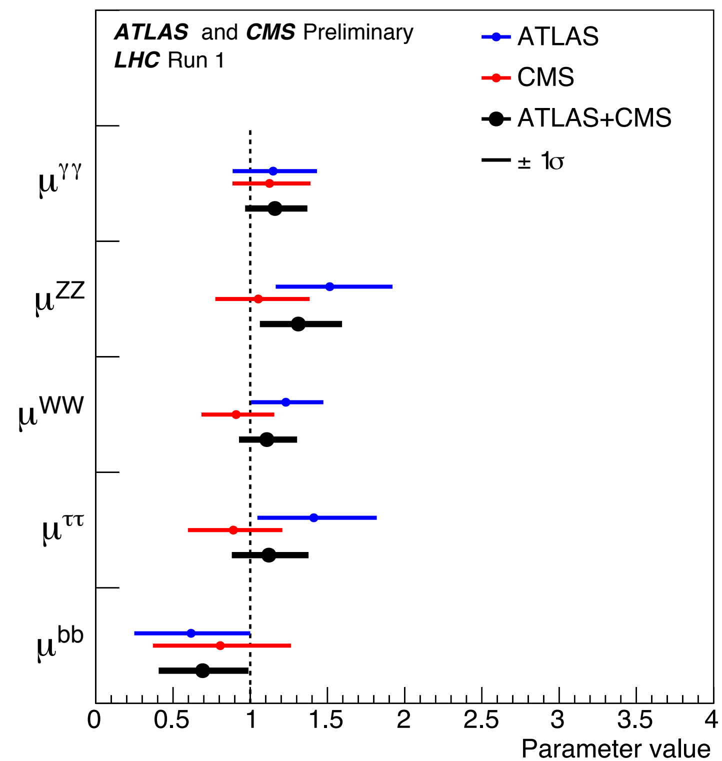
Also:

- Differential cross-section measurements
- 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



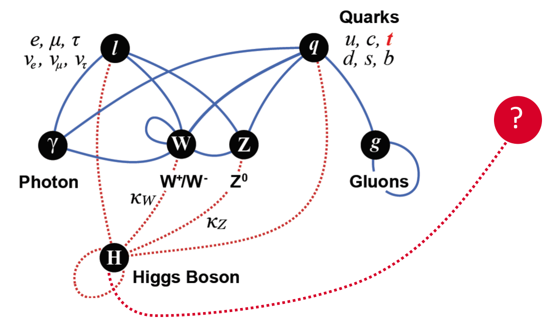
Higgs as BSM portal

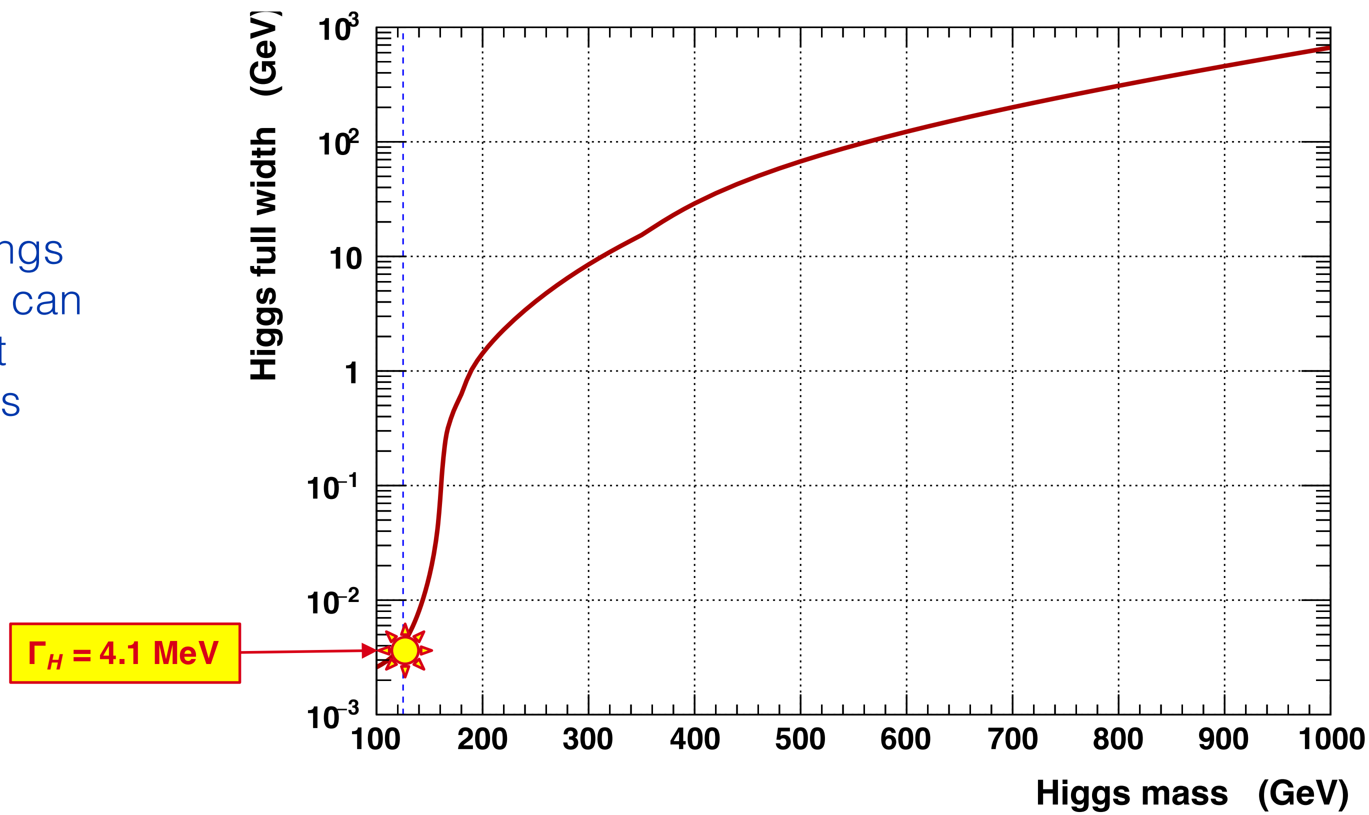
Higgs is narrow: 4.1 MeV

For comparison:

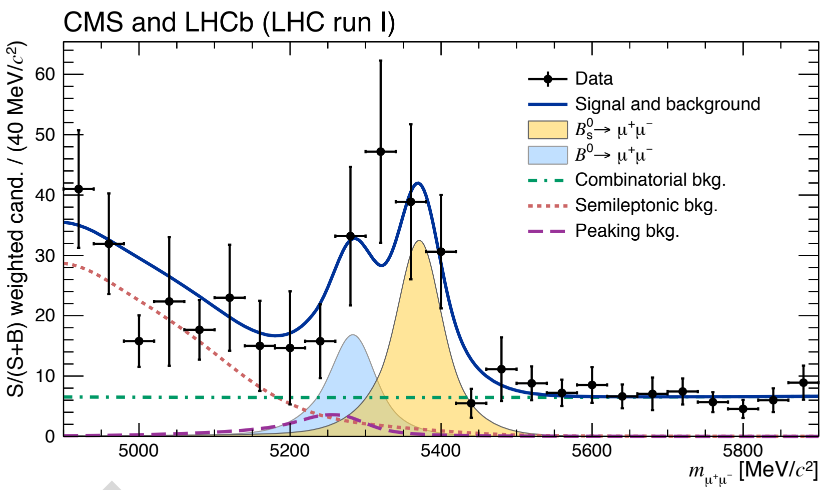
Γ_W = 2.1 GeV
Γ_Z = 2.5 GeV
Γ_{top} = 1.3 GeV

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





Flurry of beautiful results from LHCb [almost 300 papers to date]

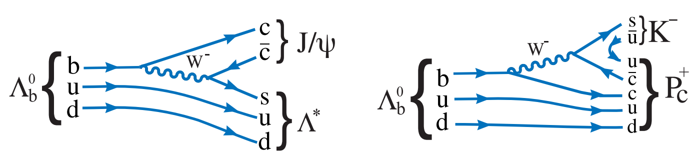


CMS & LHCb: observation of $B_s \to \mu\mu$

[Nat. 522 (2015) 68]

Observation of new states consistent with pentaquarks

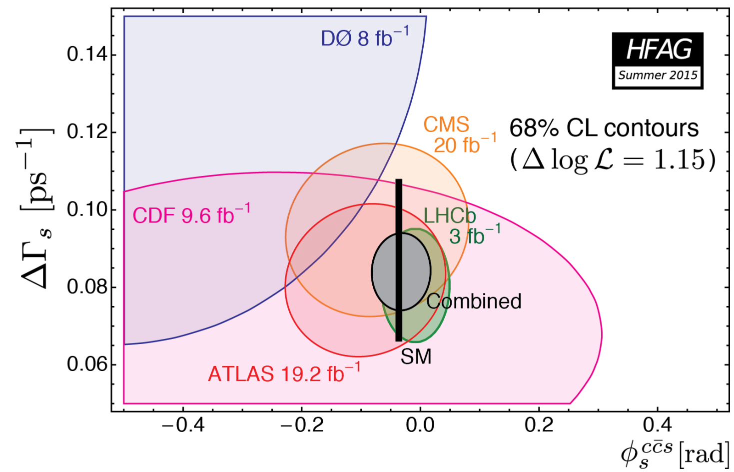
[PRL 115, 072001 (2015)]

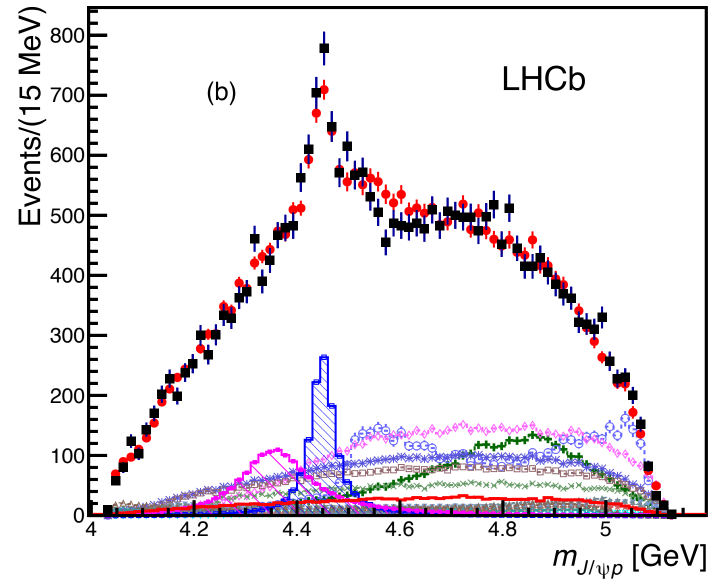


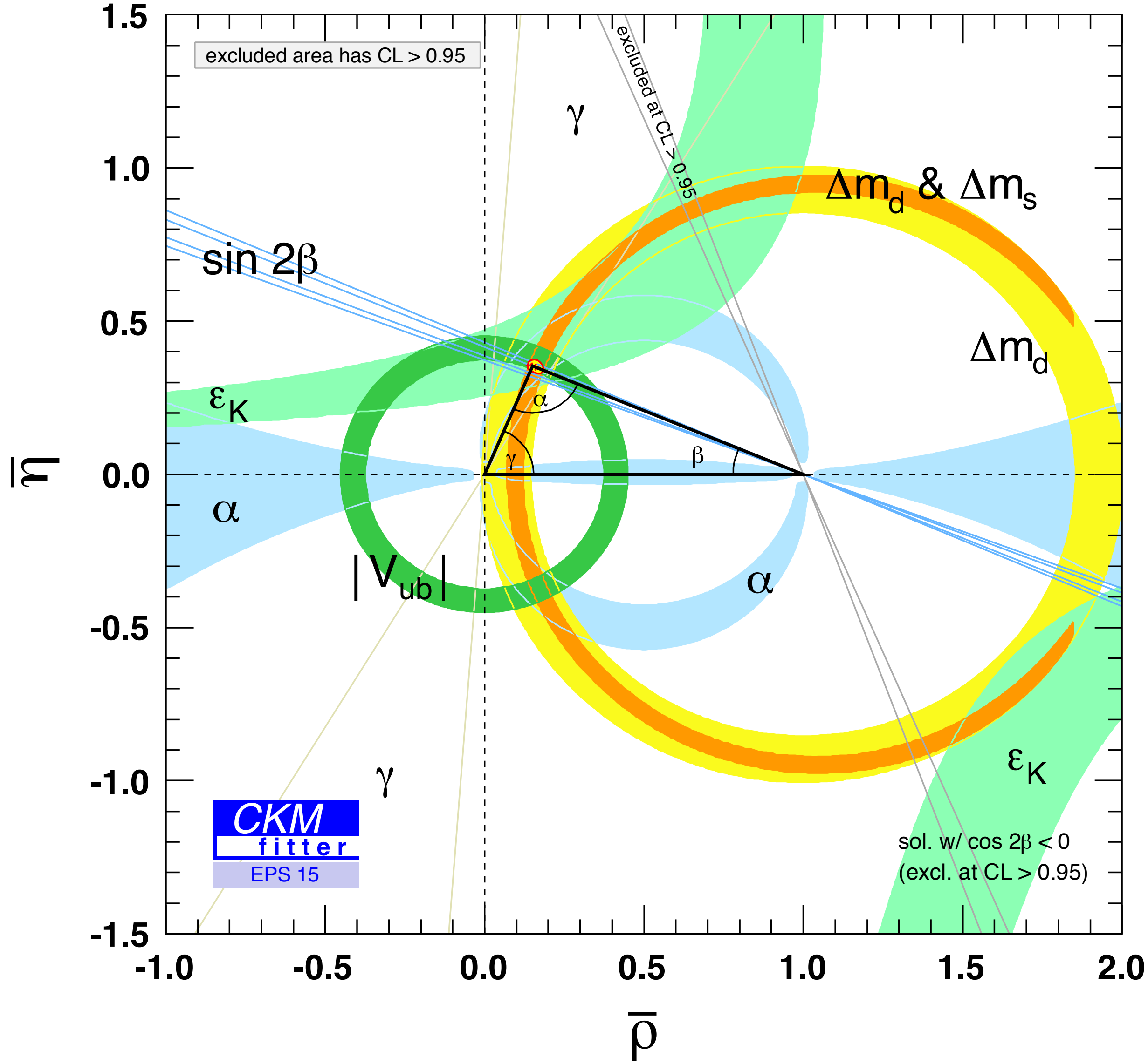
 or  or … ?

Precision measurement of ϕ_s

[PRL 114, 041801 (2015)]







The "bread-and-butter" CKM phase measurements continue to improve

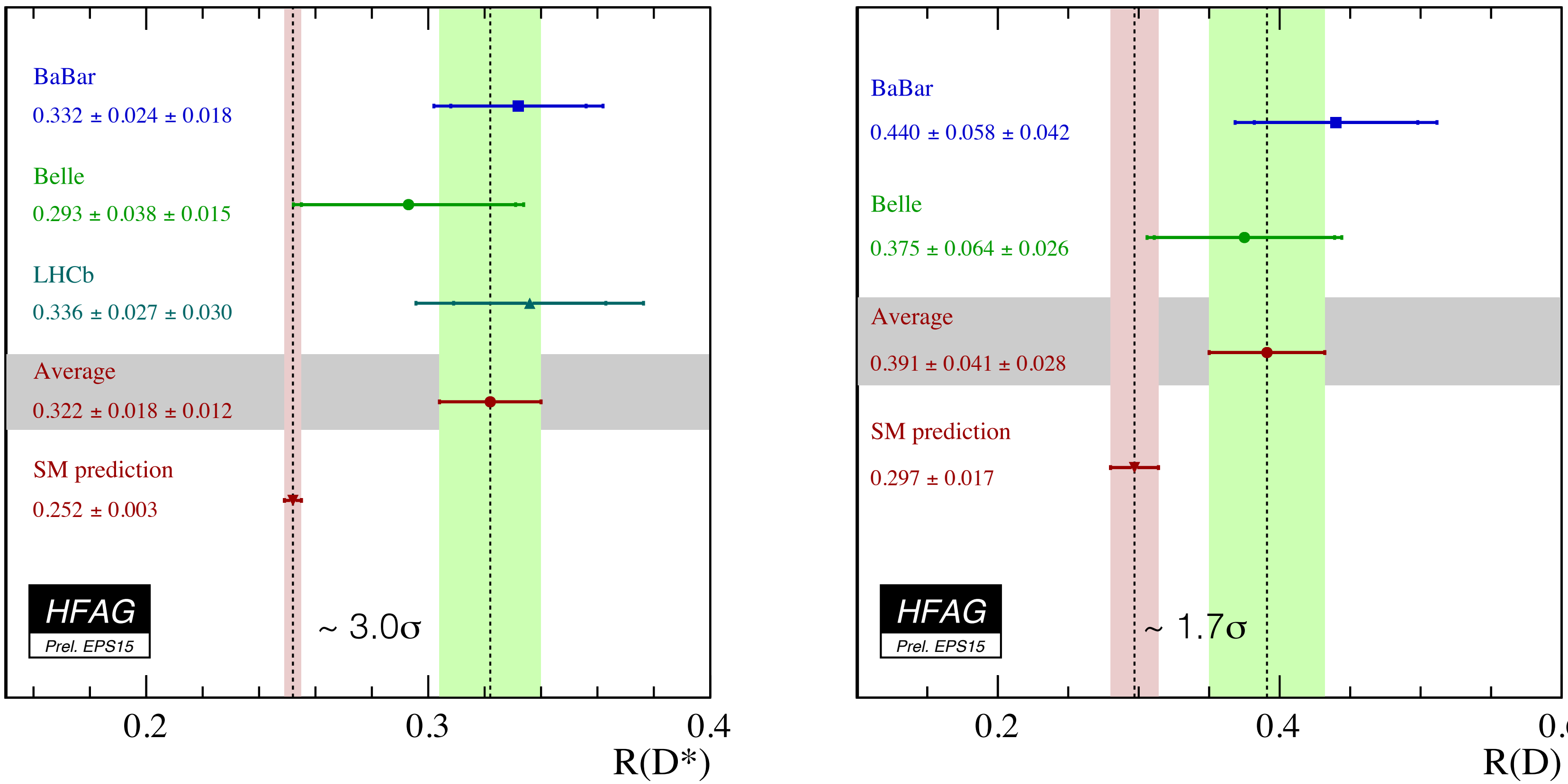
Measurements of γ, $\sin(2\beta)$, $|V_{ub}|$, $\Delta m_{s/d}$ from LHCb

Flavour anomalies ?

Test of lepton flavour universality: $R(X) = \Gamma(B \to X\,\tau\,\nu)\,/\,\Gamma(B \to X\,\ell\,\nu)$

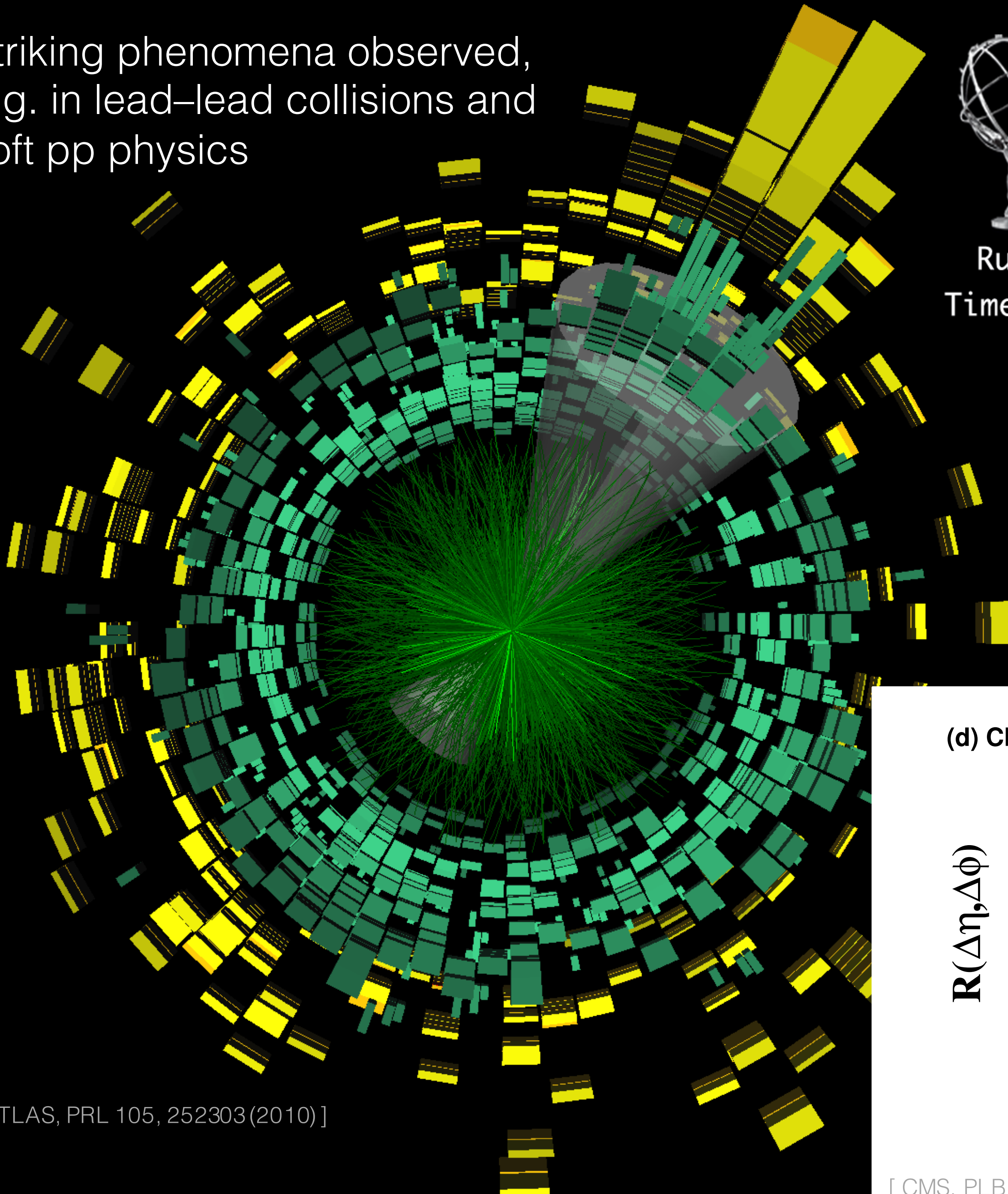
Robust theoretical prediction

HFAG, semileptonic combination for EPS-HEP 2015: http://www.slac.stanford.edu/xorg/hfag/semi/eps15/eps15_dtaunu.html

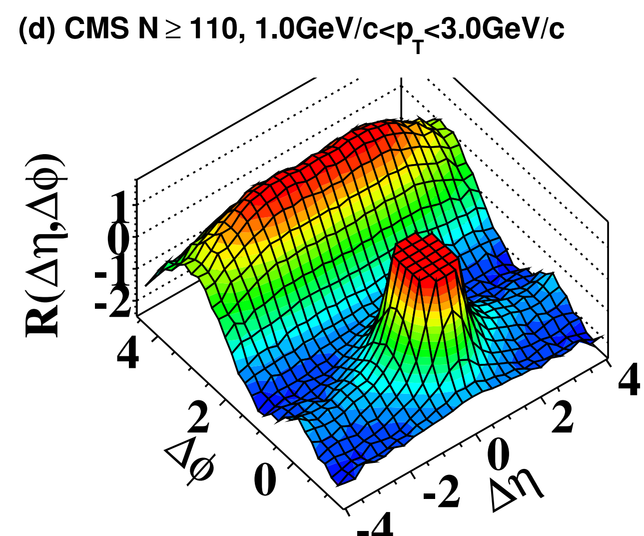


(3.9σ combined)

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



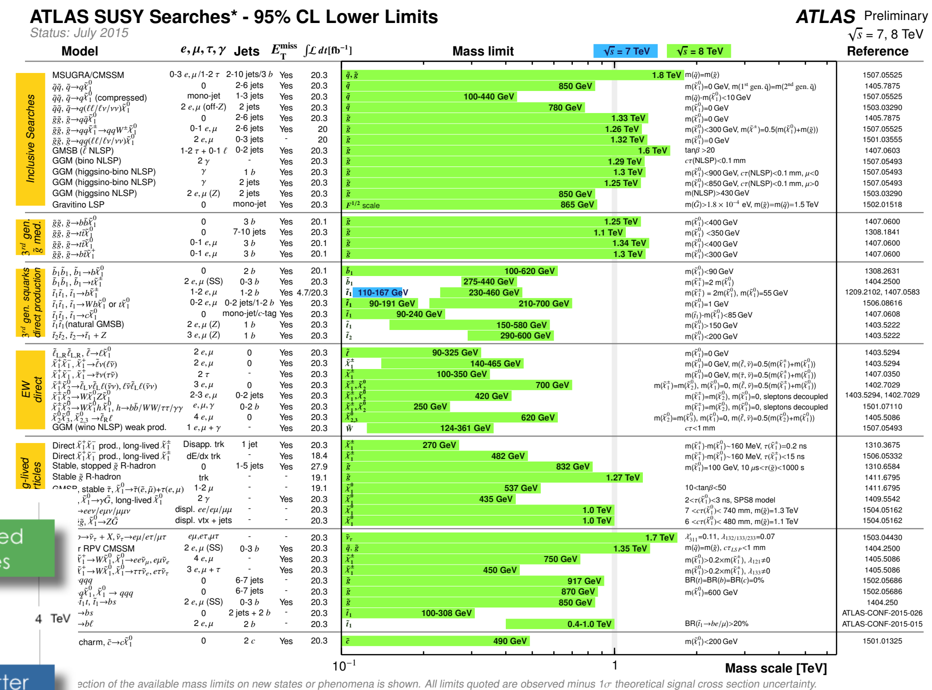
[ATLAS, PRL 105, 252303 (2010)]

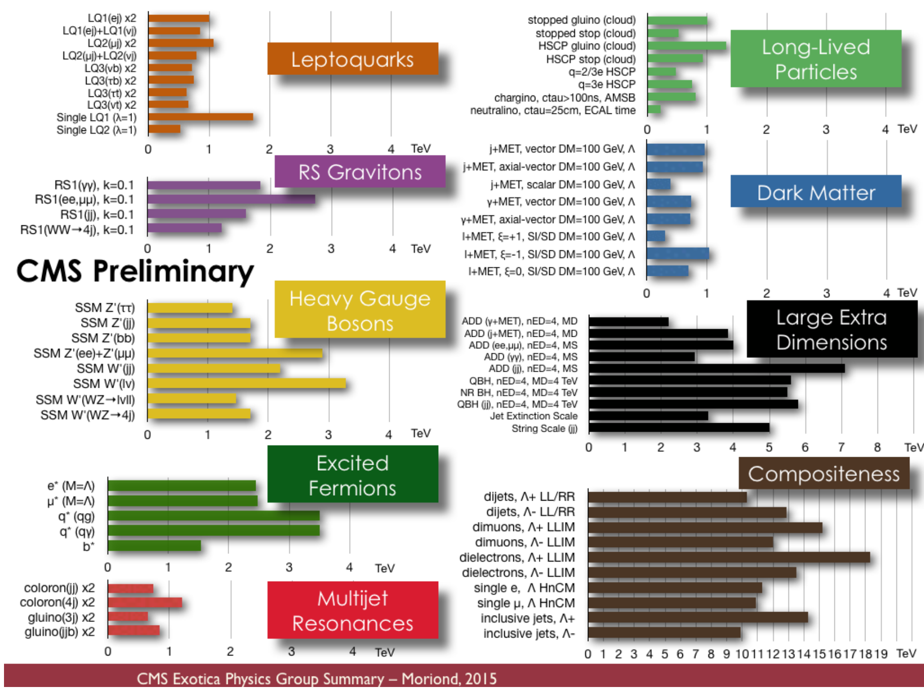


[CMS, PLB 718 (2013) 795]

Vast amount of BSM searches — with no significant anomaly seen so far

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



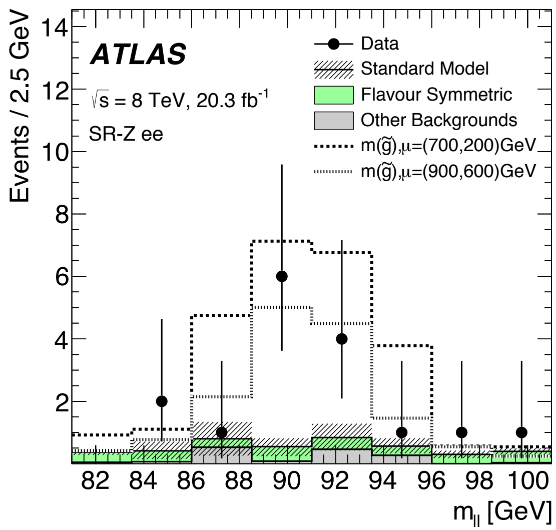


Not unexpectedly, a few of these searches ended up showing some (non-significant) anomaly, a legacy to check in Run-2

Not unexpectedly, a few of these searches ended up showing some anomaly, a legacy to check in Run-2 (shown here: ATLAS examples)

2L(Z) + MET

[ATLAS, arXiv:1503.03290]

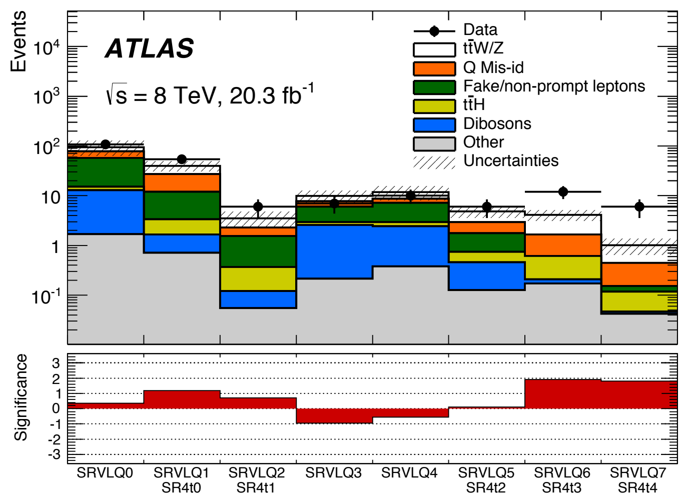


A few early papers with ideas:

http://arxiv.org/abs/1504.02244
http://arxiv.org/abs/1506.04435
http://arxiv.org/abs/1504.01768
http://arxiv.org/abs/1503.04184
…

2L(SS) + b-jets + H_T + MET

[ATLAS, arXiv:1504.04605]

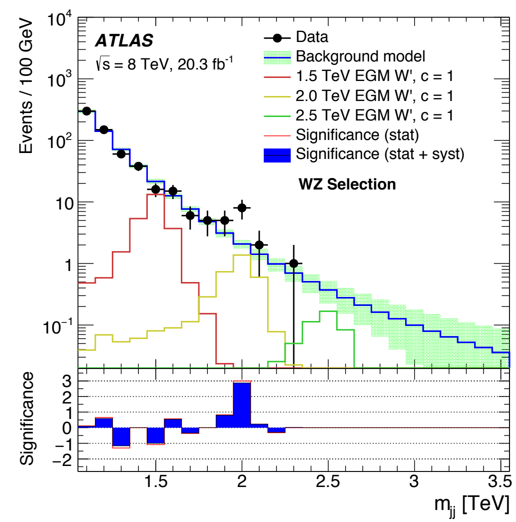


A few early papers with ideas:

http://arxiv.org/abs/1507.01601
http://arxiv.org/abs/1507.01923
…

Diboson resonance (VV' → JJ)

[ATLAS, arXiv:1506.00962]



A few early papers with ideas:

http://arxiv.org/abs/1506.04392
http://arxiv.org/abs/1506.06736
http://arxiv.org/abs/1506.03931
http://arxiv.org/abs/1506.03751
http://arxiv.org/abs/1507.06312
…

Broad search coverage — not only the standard signatures

Run-1 "tour de force" analysis of pMSSM

[ATLAS, 1508.06608]

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*

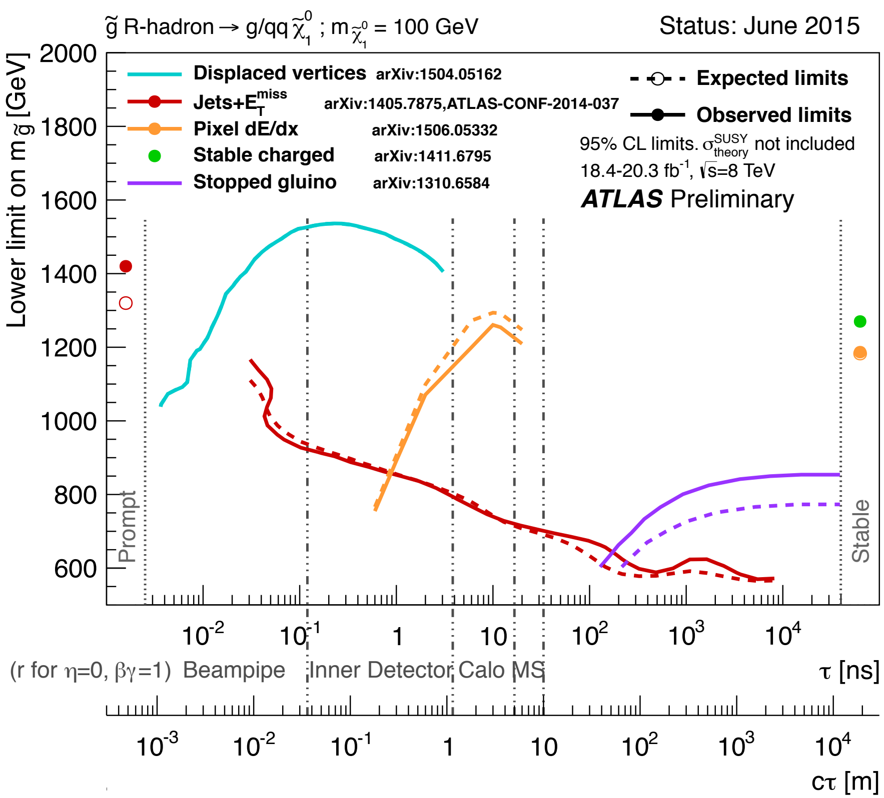
Analysis overall reproduces simplified models picture

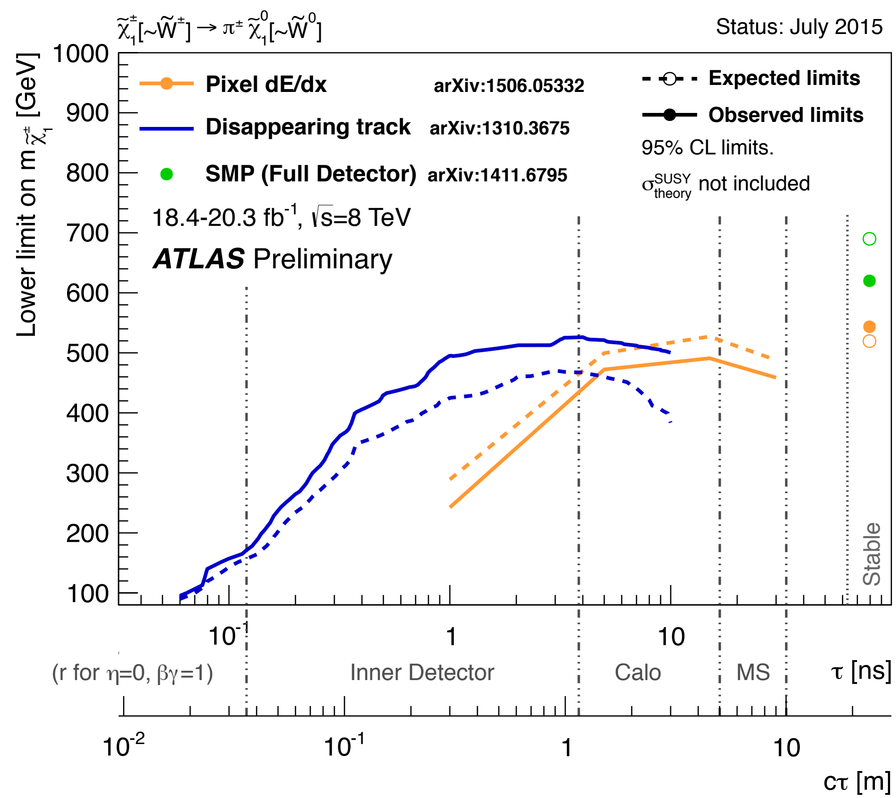
Higgsino/wino scenarios biggest challenge →

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

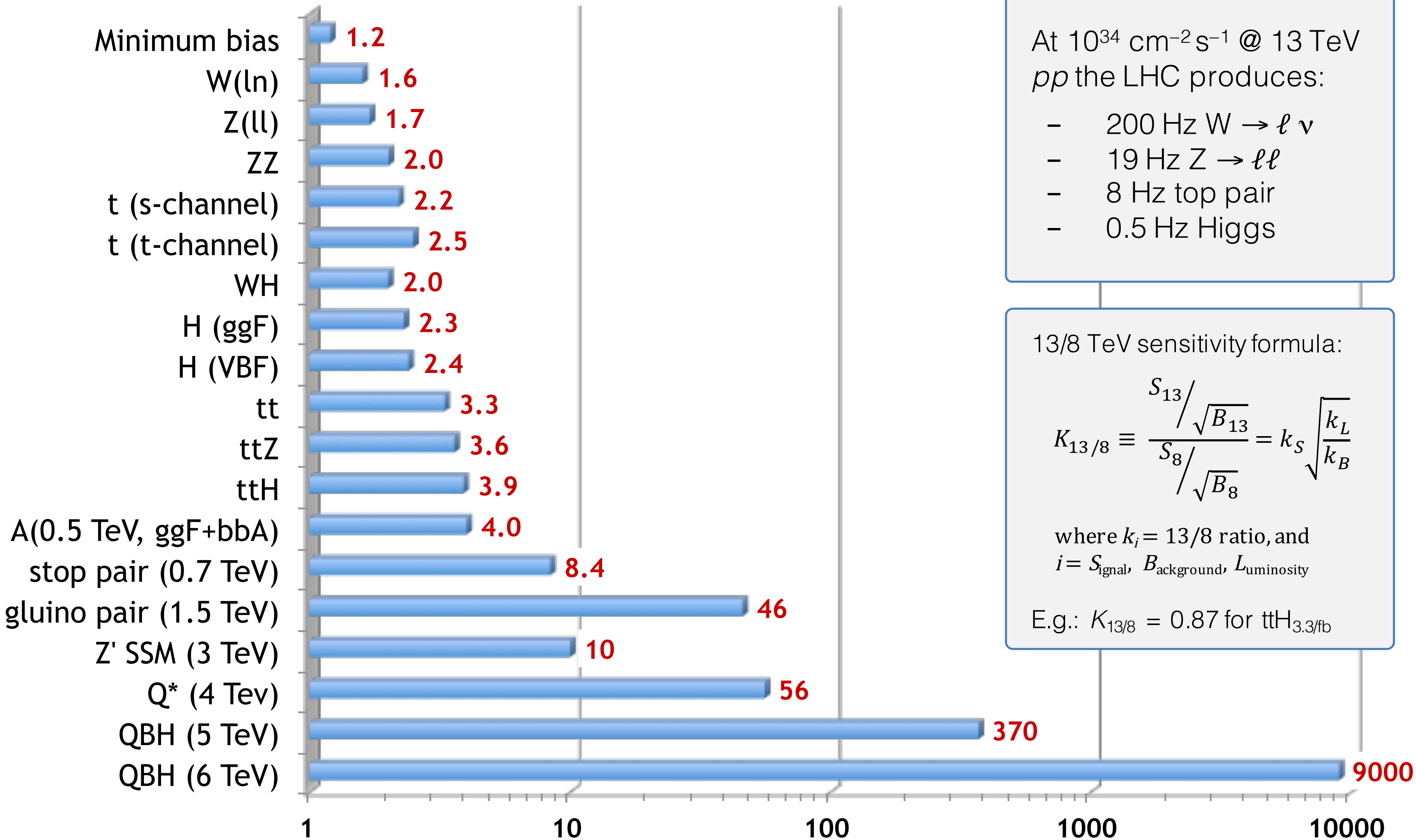




13 TeV

Complete overview of results, apologies for omitting analysis details

Life in 2015: 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

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 $i = S_{ignal},\ B_{ackground},\ L_{uminosity}$

E.g.: $K_{13/8}$ = 0.87 for $ttH_{3.3/fb}$

Shown by Mike Lamont at Lepton-Photon 2015

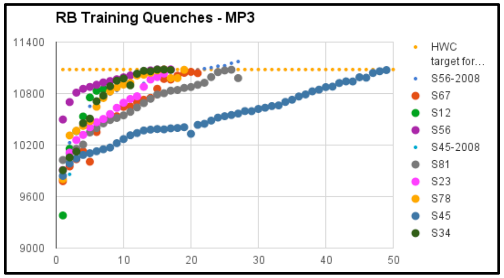
Fitzcarraldo moving a steamer over a muddy hill … (on his quest for money to build an opera house in the peruvian jungle)

Long-Shutdown 1
Preparing Run-2

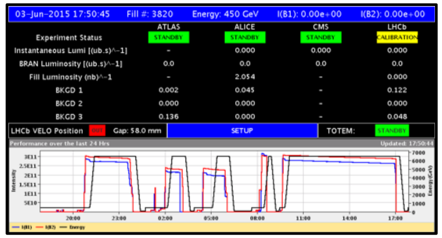
2015 LHC operation at a glance

From: Matteo Solfaroli, LHCC open session, Sep 23, 2015

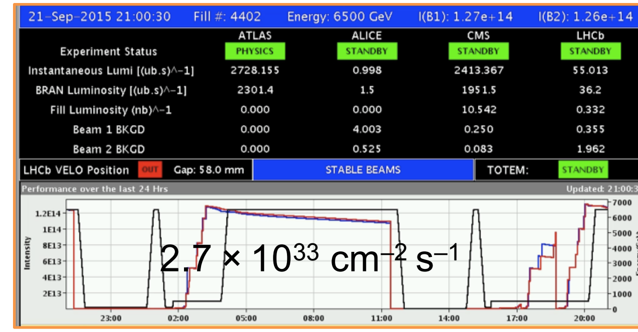
3rd Apr Completion of PT campaign



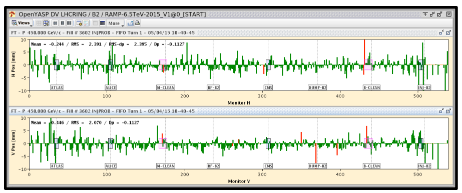
3rd June First STABLE BEAMS!



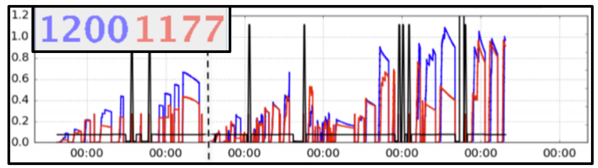
21st Sep 25 ns STABLE BEAMS with 1177 bunches/beam



5th Apr First circulating beam



30th June end of scrubbing for 50 ns

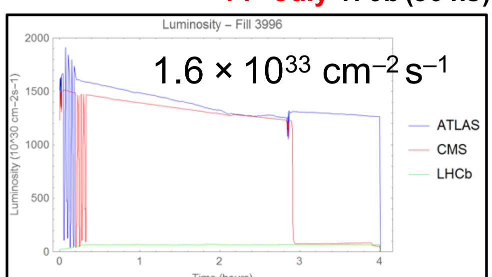


TS-1 **MD-1** **MD-2 + TS-2**

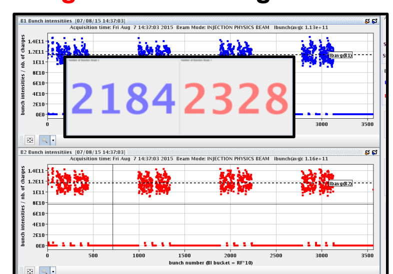
April | **Intense beam commissioning phase** | June | July | August | September

10th Apr 6.5 TeV for the first time (ever!)

14th July 476b (50 ns)

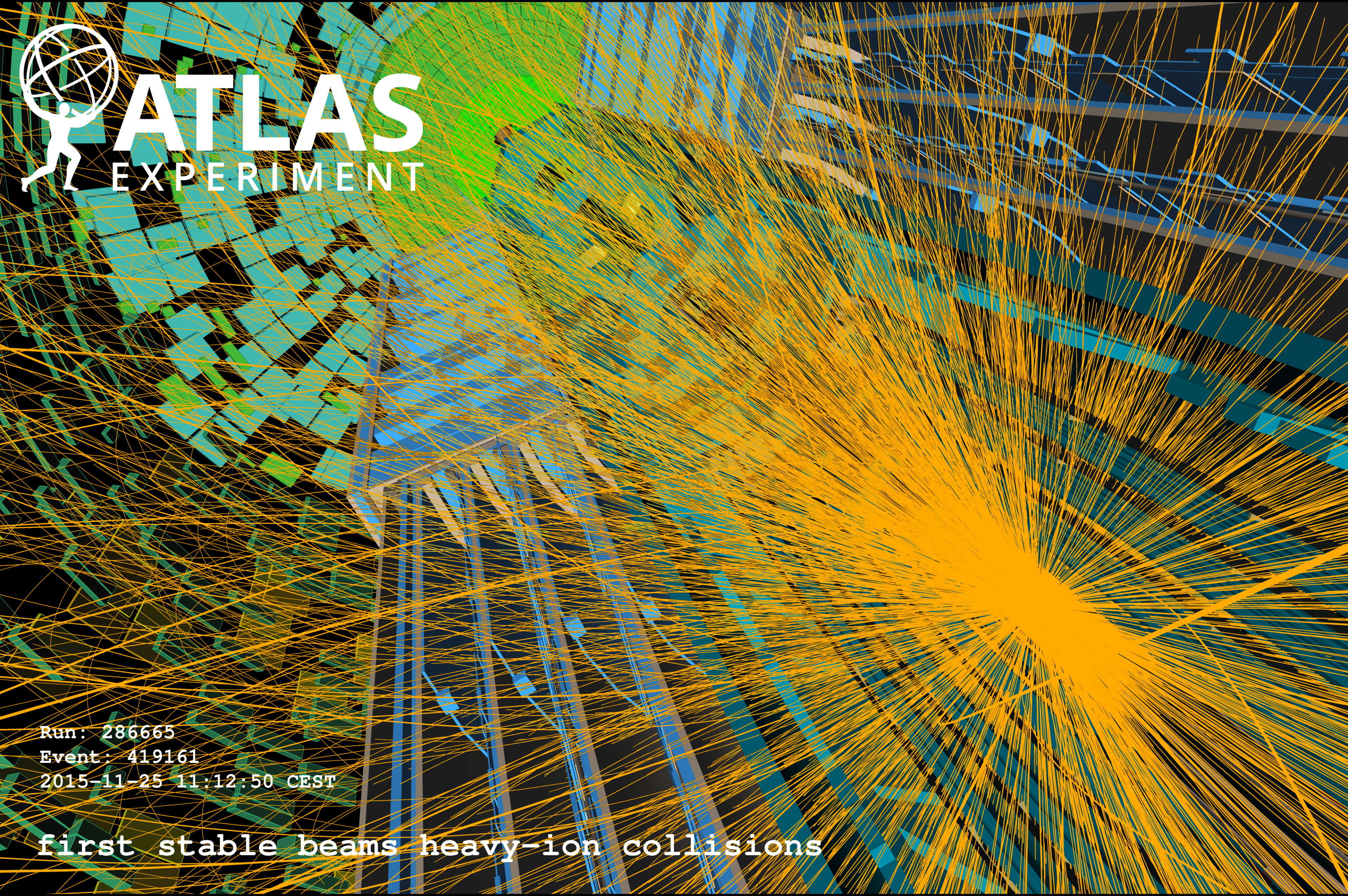


7th Aug end scrubbing for 25 ns



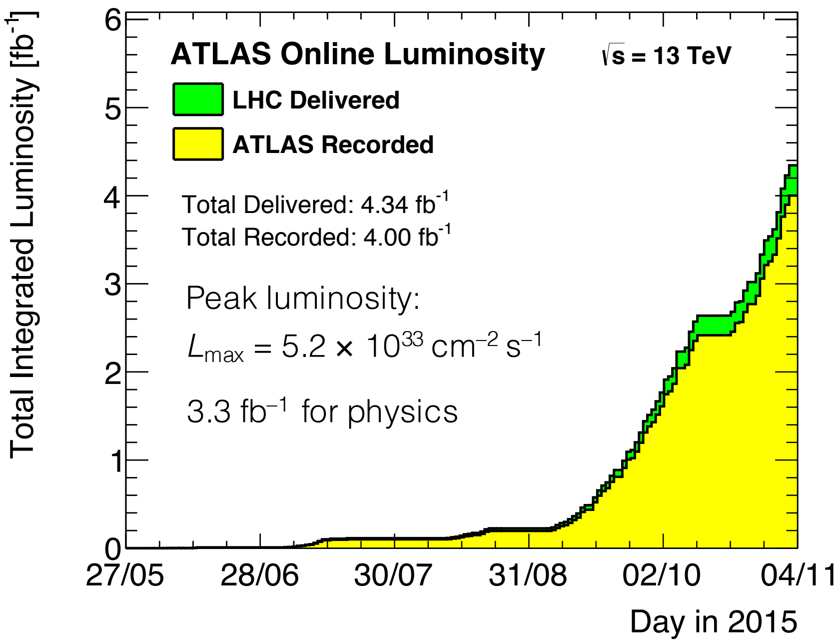
Since then, Oct/Nov:

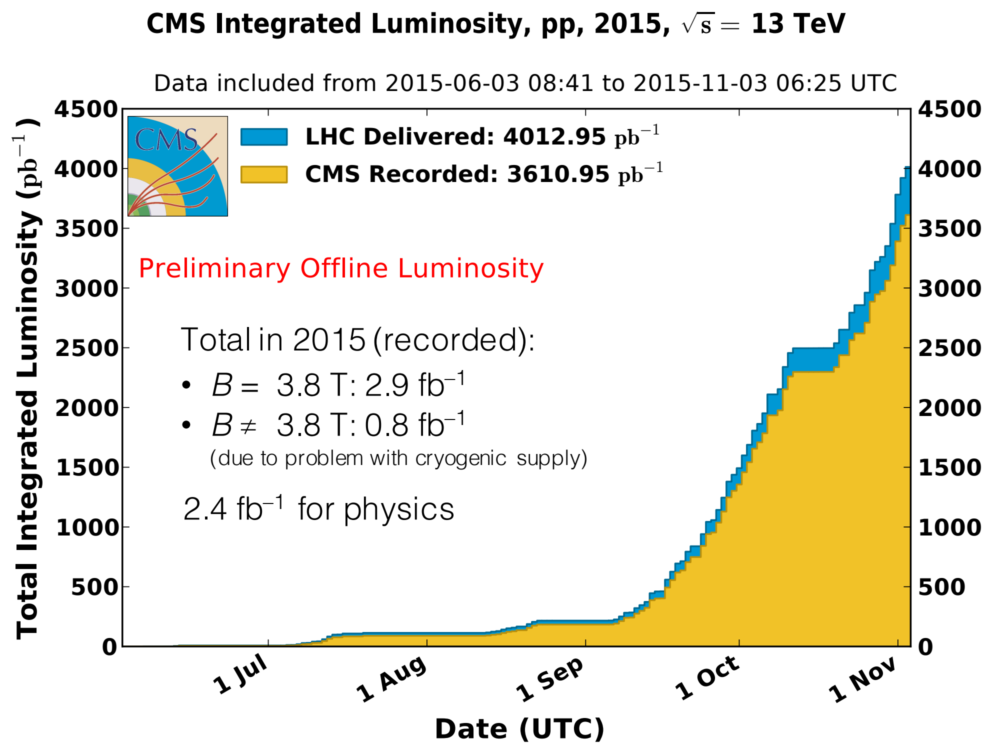
- 2232 colliding bunches in ATLAS/CMS
- L_{max} of $5.2 \cdot 10^{33}$
- Nov 4: MD/TS-3
- Nov 20: Ions


ATLAS
EXPERIMENT
Run: 286665
Event: 419161
2015-11-25 11:12:50 CEST
first stable beams heavy-ion collisions

2015 LHC proton–proton luminosities

Results reported today only use summer datasets (up to LHCP 2015, max. of 85 pb^{-1})





LHCb after luminosity levelling: 0.32 (0.36) fb^{-1} recorded (delivered)

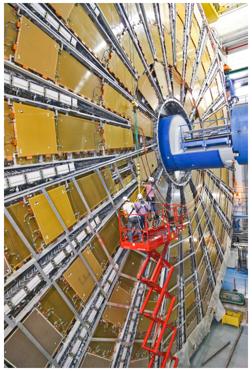
Luminosity measurements calibrated with “mini” beam-separation scans in ATLAS/CMS: σ = 9% (ATLAS), 12/4.8% (CMS), and with the beam-gas imaging method in LHCb: 3.9% (!). Differences in amount of delivered luminosity between ATLAS and CMS under scrutiny by experiments

Pileup profiles: ATLAS/CMS: $\langle\mu\rangle_{50\ ns} = 20$, $\langle\mu\rangle_{25\ ns} = 13$ ($\langle\mu\rangle_{8TeV} = 21$), LHCb: $\langle\mu\rangle \sim 1.7$

ATLAS improvements for Run-2

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

Replacement of TGC chambers

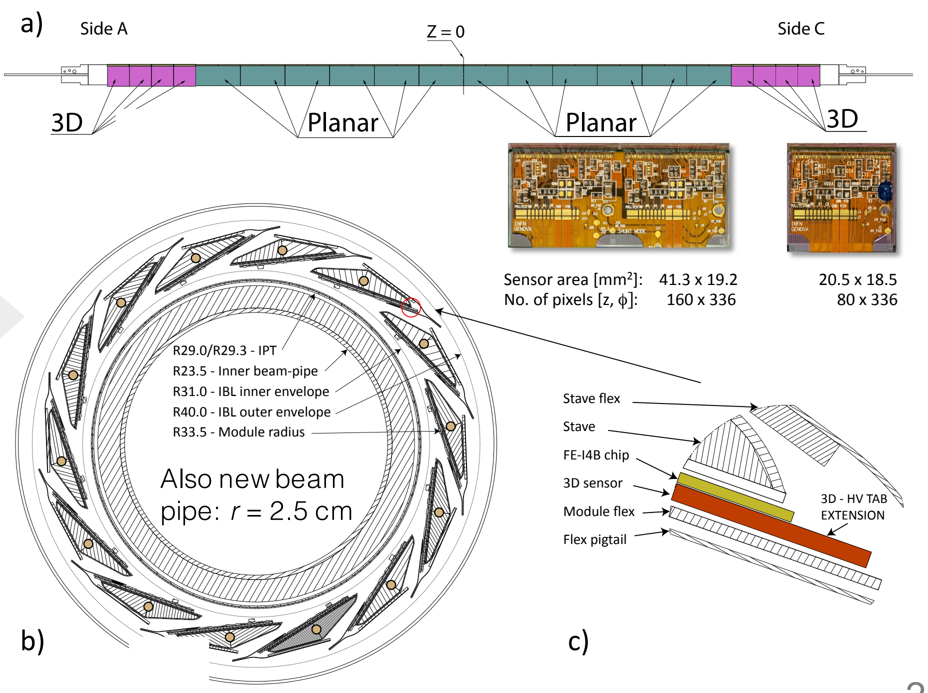


Infrastructure upgrades: magnet & cryogenic systems, additional muon chamber shielding, new beam pipes

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

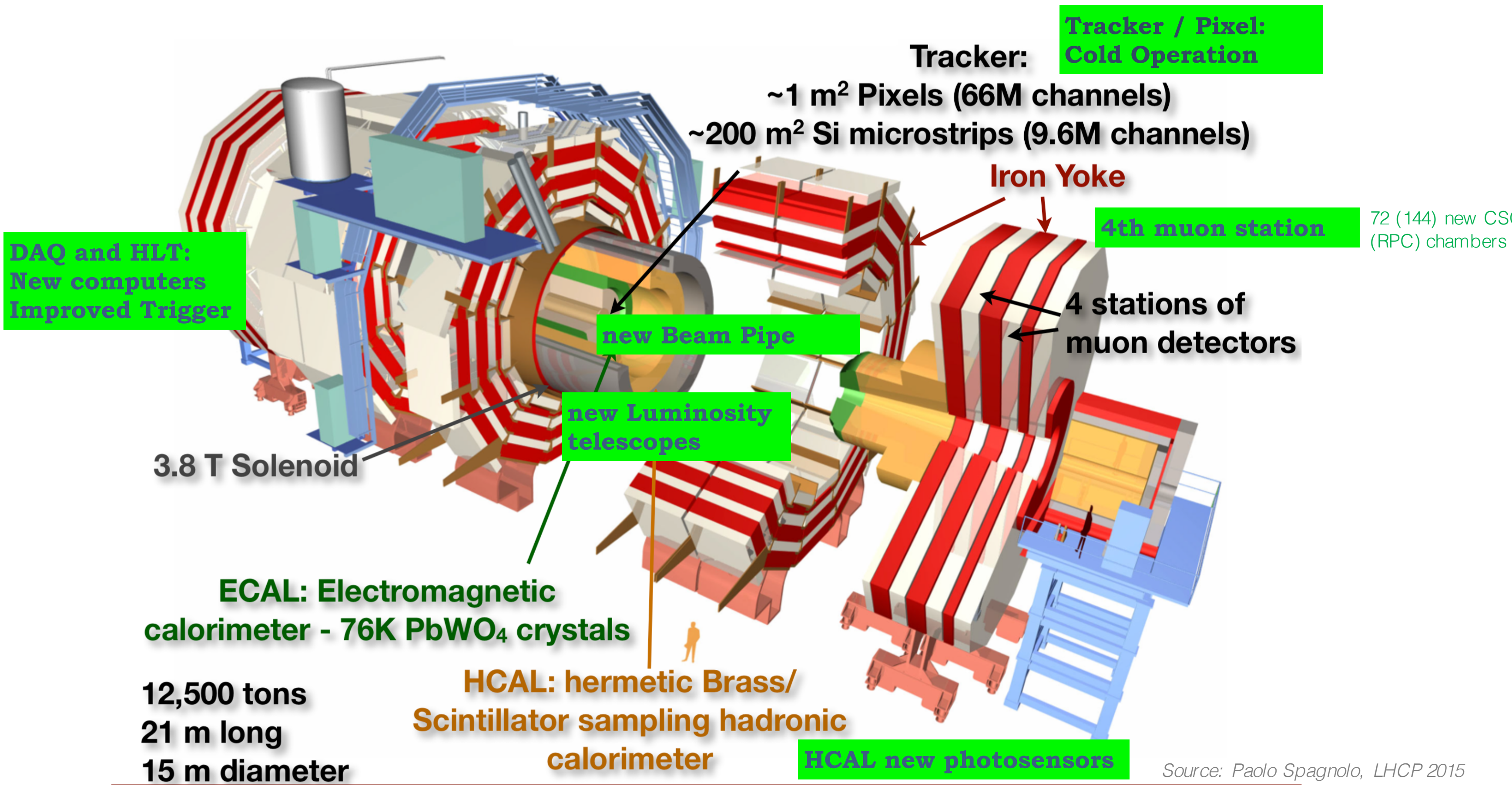
New *Insertable B-layer*: fourth pixel layer at 3.3 cm from beam, consisting of planar & 3D (forward) silicon sensors, smaller pixels



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

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

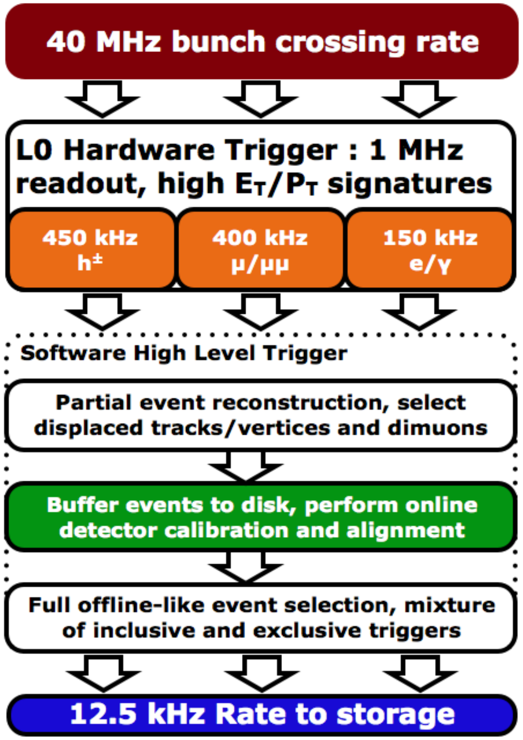
Big effort in trigger area (among others)

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, …

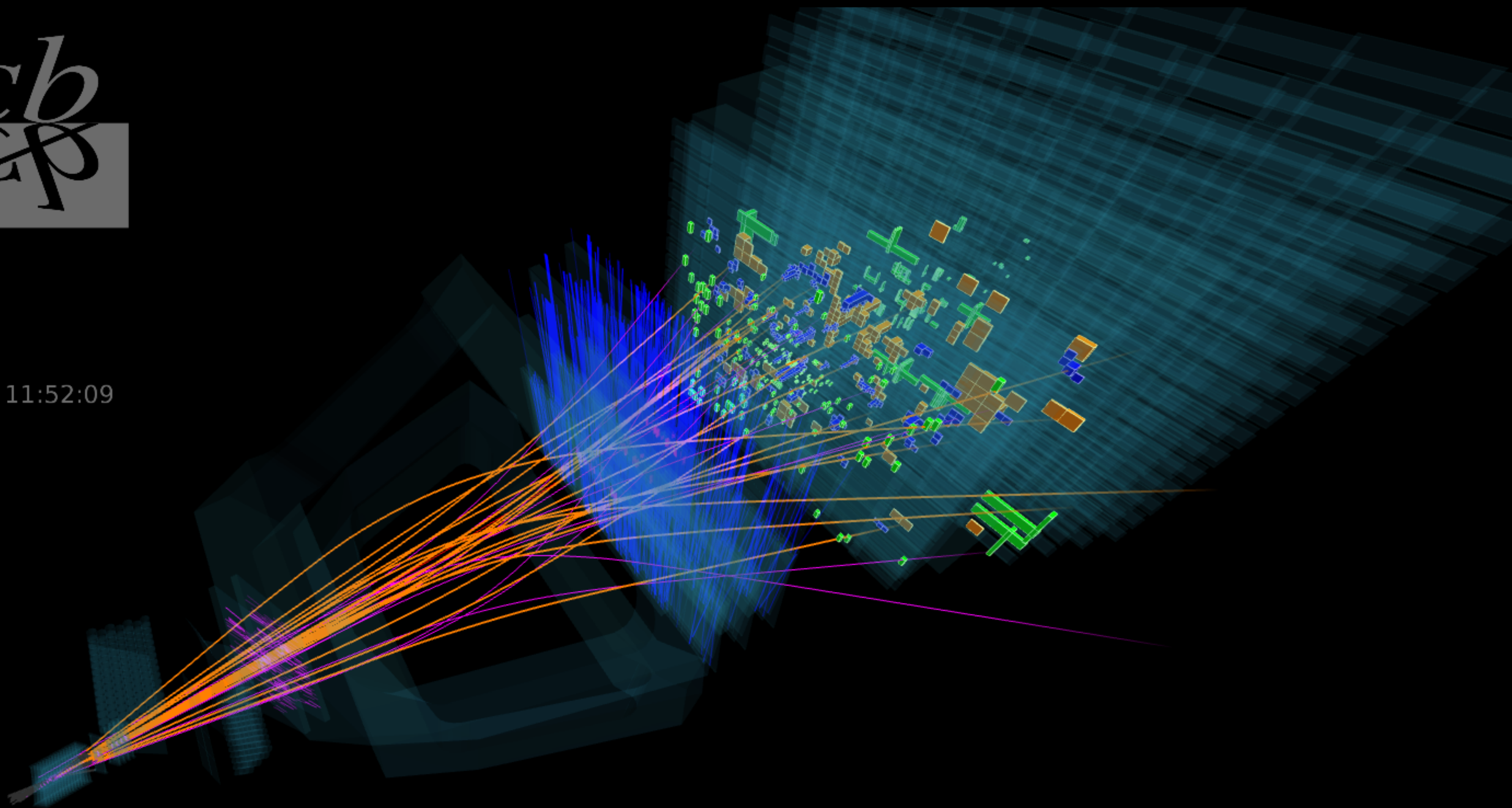
HeRSCheL: new scintillating counters to extend LHCb coverage to high rapidity (CEP, diffraction, …)

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, ...)



Event 41383468
Run 153460
Wed, 03 Jun 2015 11:52:09



Run-2 Physics & Performance

Preparation for Physics Results

A crucial ingredient for any physics result is a good understanding of the basic physics objects (tracks, e, μ, τ, jets, missing transverse momentum, flavour tagging)

For early 13 TeV physics results, ATLAS developed concept of pre-recommendations with Run-1 & MC based object calibrations and enlarged uncertainties fully available for early physics (summer conferences → results presented here)

Pre-recommendations promptly validated with first data, and then during the year replaced with fully 13 TeV data-driven recommendations (ie, calibration & uncertainties)

Early & validated MC crucial. Key role of ATLAS *Physics Modelling Group*

Soft physics with tracks at 13 TeV

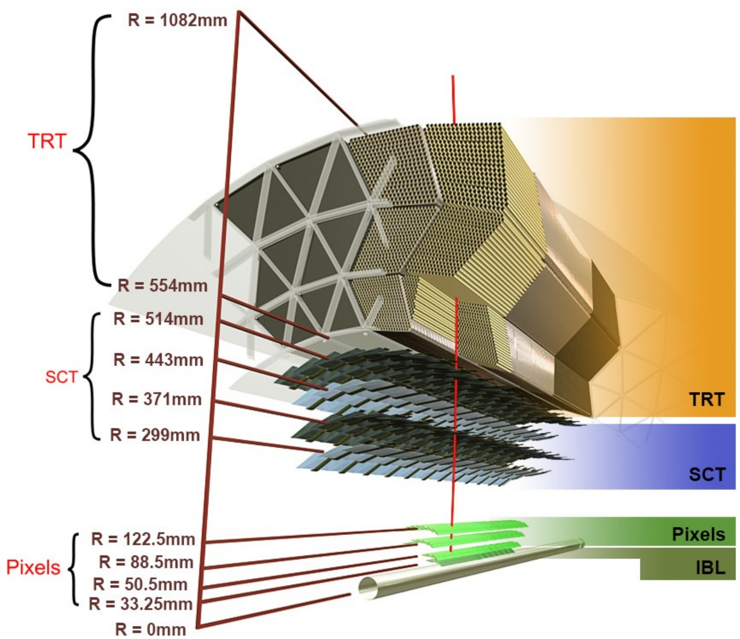
One of the very first proton–proton collisions recorded by ATLAS in “quiet beam” conditions in May 2015

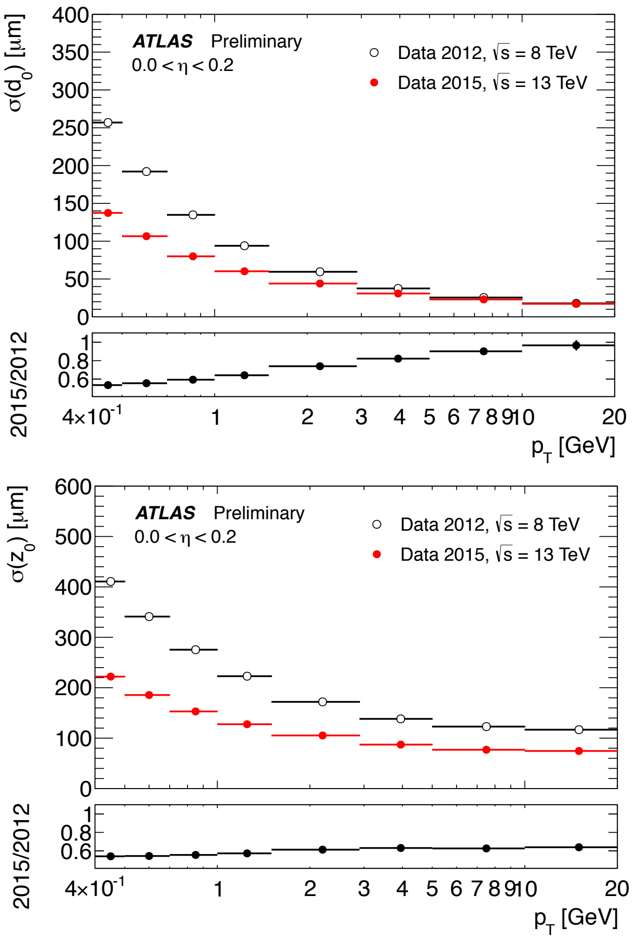
ATLAS inner tracking performance

[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

Properties of inelastic pp collisions at 13 TeV

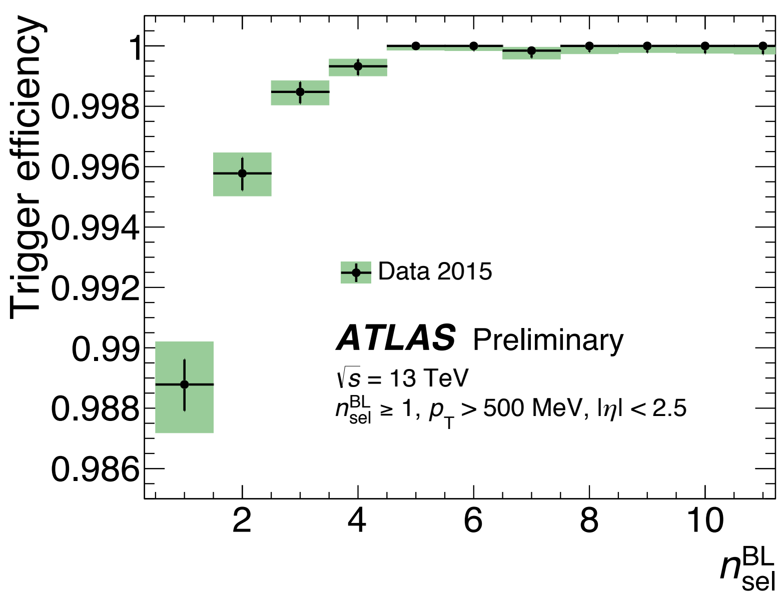
Key input to pileup and underlying event modelling, uses low-μ data

[ATLAS-CONF-2015-028]

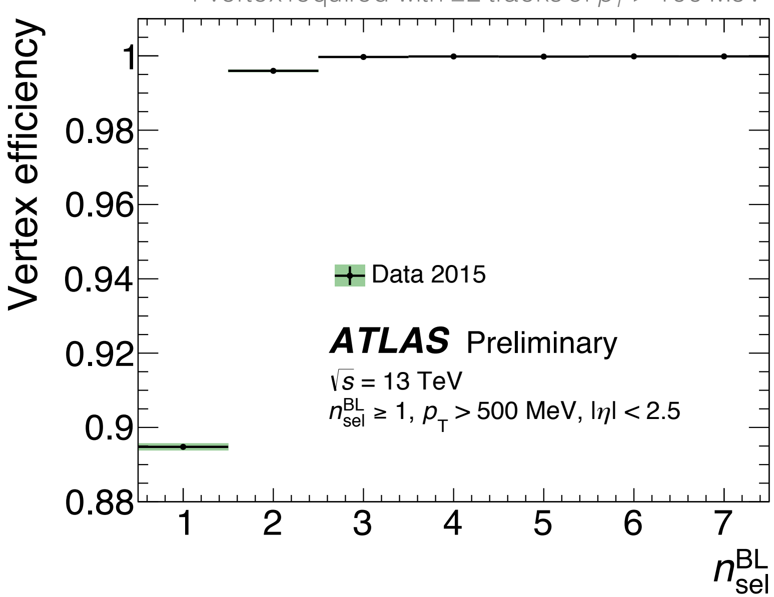
Measurement of primary charged particle production: $dN_{ch}/d\eta$, $d^2N_{ch}/d\eta dp_T$, N_{ch}, $<p_T>/N_{ch}$

Fiducial cuts: $p_T > 0.5$ GeV, $|\eta| < 2.5$, $N_{ch} \geq 1$

- Trigger events with as little "bias" as possible: ≥1 hit in forward scintillators (MBTS, $2.07 < |\eta| < 3.86$)
- Measure trigger and vertexing efficiencies from data
- Measure and subtract secondary interactions and fake tracks
- Correct for tracking inefficiency
- Unfold measured spectra from detector effects



1 vertex required with ≥2 tracks of p_T > 100 MeV



Properties of inelastic pp collisions at 13 TeV

Key input to pileup and underlying event modelling, uses low-μ data

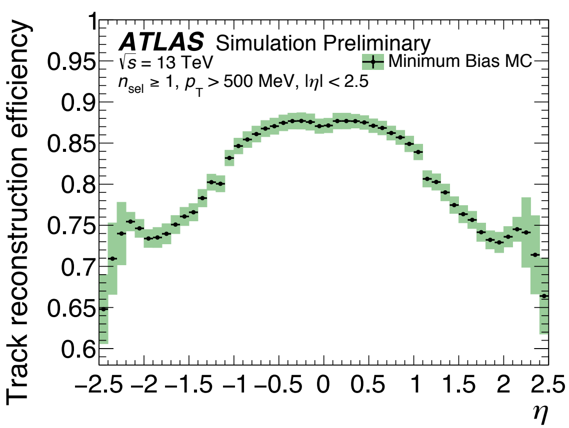
[ATLAS-CONF-2015-028]

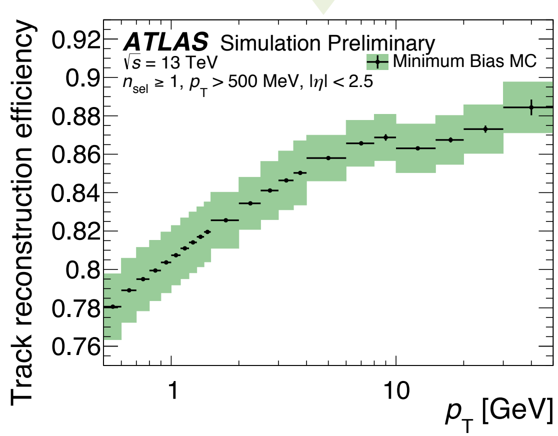
Measurement of primary charged particle production: $dN_{ch}/d\eta$, $d^2N_{ch}/d\eta dp_T$, N_{ch}, $\langle p_T\rangle/N_{ch}$

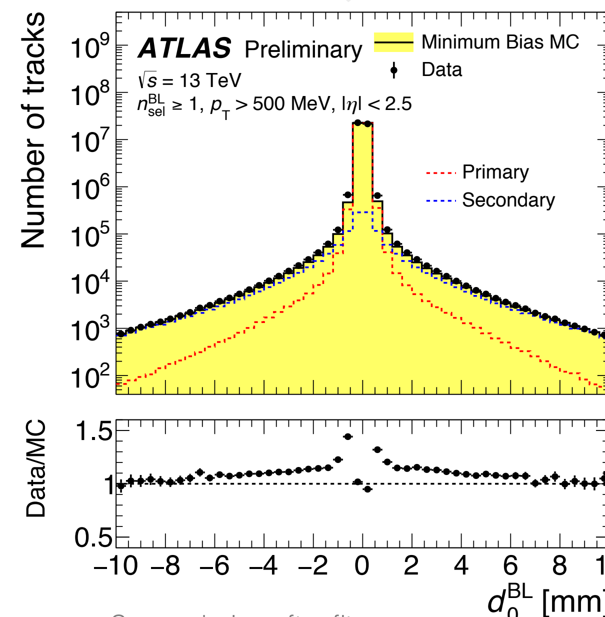
Fiducial cuts: $p_T > 0.5$ GeV, $|\eta| < 2.5$, $N_{ch} \geq 1$

- Primary particles have $\tau > 300$ ps (9 cm)
- Secondaries are produced after $\tau > 30$ ps (9 mm)
- Strange baryons with $30 < \tau < 300$ ps are excluded

- Trigger events with as little “bias” as possible
- Measure trigger and vertexing efficiencies from data
- Measure and subtract secondary interactions and fake tracks
- Correct for tracking inefficiency
- Unfold measured spectra from detector effects







Tracking efficiency dominant uncertainty: 1.1% central, 6.5% forward

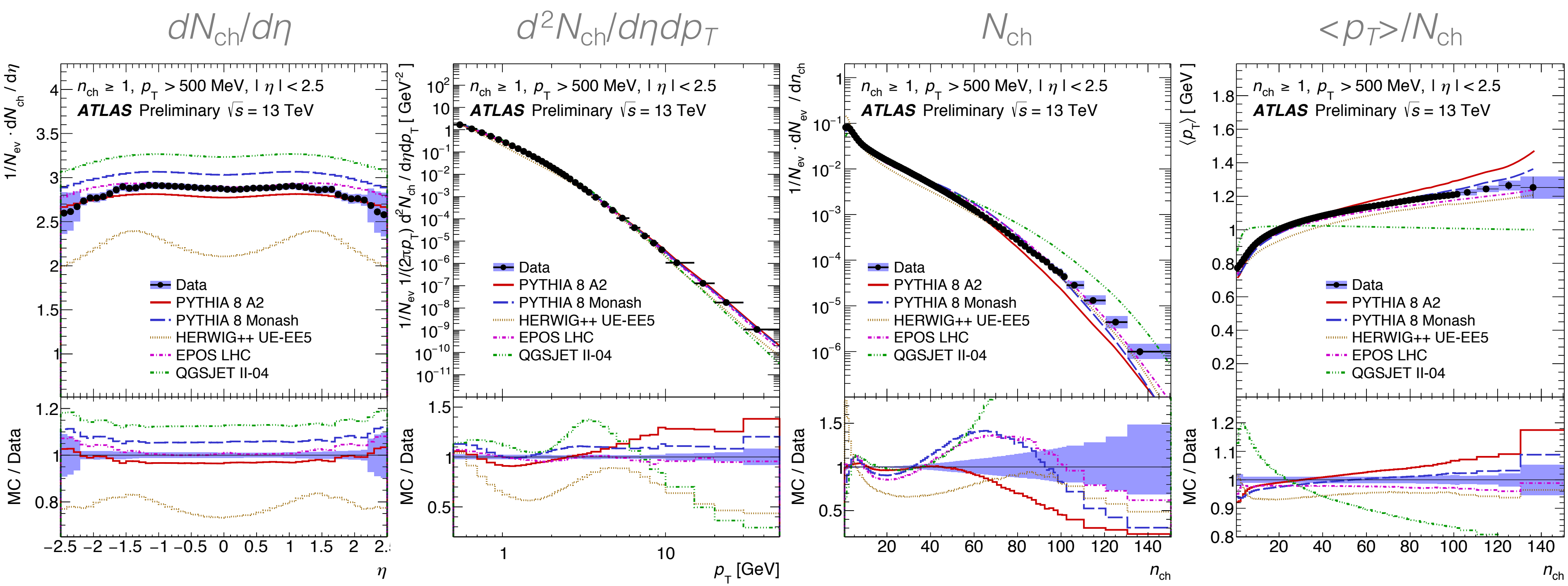
Secondaries after fit:
2.6 ± 0.6% of tracks in SR

Properties of inelastic pp collisions at 13 TeV

Key input to pileup and underlying event modelling, uses low-μ data

[ATLAS-CONF-2015-028]

Resulting spectra from 9M data events & comparison to hadronic physics models



Difficult to provide one universal tune that describe MB and UE data equally well (→ later slide)

Overall, the EPOS and PYTHIA 8 tunes describe the data most accurately

EPOS best in η, p_T, and $<p_T>$, while PYTHIA 8 (A2 – ATLAS MB default) best in N_{ch}

CMS measurement without magnetic field

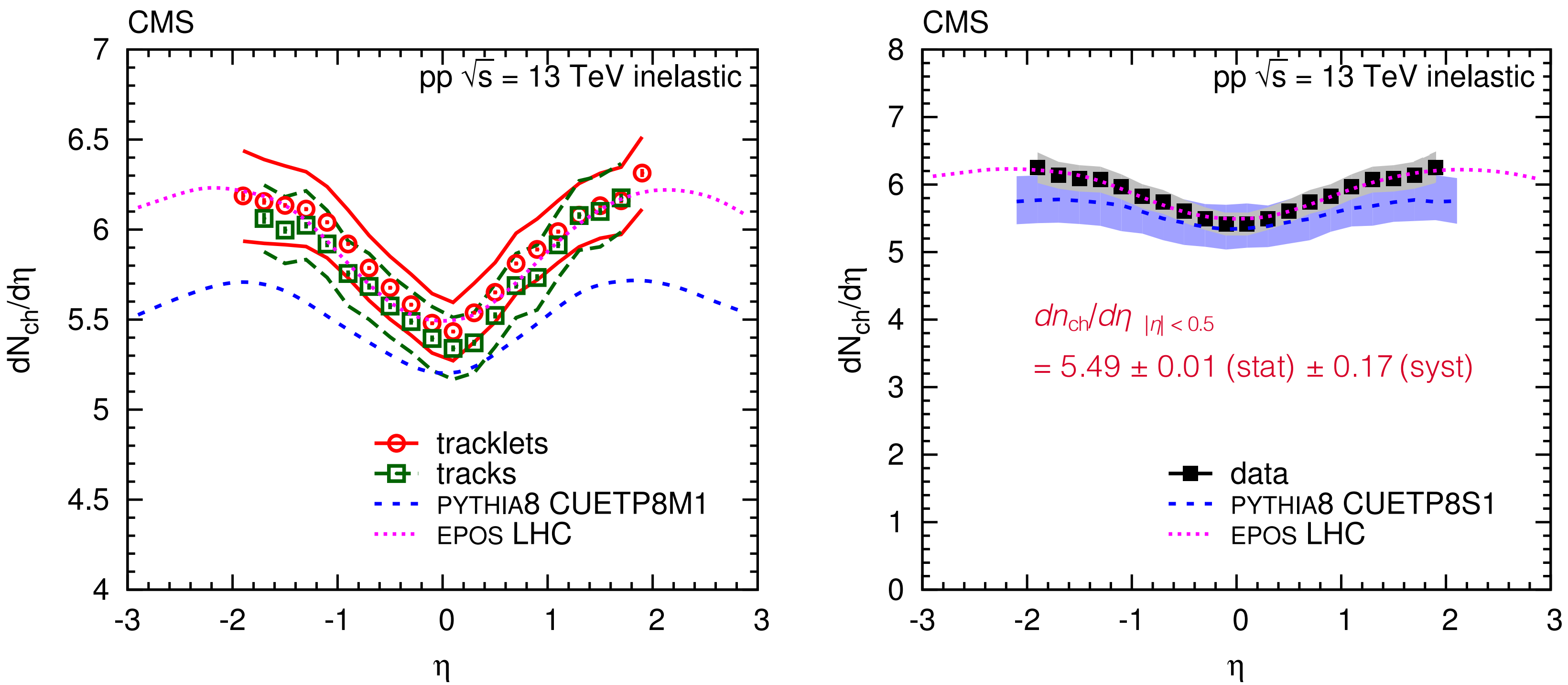
First LHC 13 TeV paper !

[CMS PLB 751, 143 (2015)]

Charged particle yield measurement for $|\eta| < 2$

Straight track (pixel, 55k events) and tracklet (pixel hit pairs, 170k) methods, good agreement

- p_T coveage down to ~50 MeV, track efficiency between 80–85%
- Secondary particle corrections, and track / tracklet acceptance & reconstruction efficiencies from MC
- Systematic uncertainties of 3–4% for both methods, dominated by vertex efficiency and MC dependence



Also preliminary ALICE result

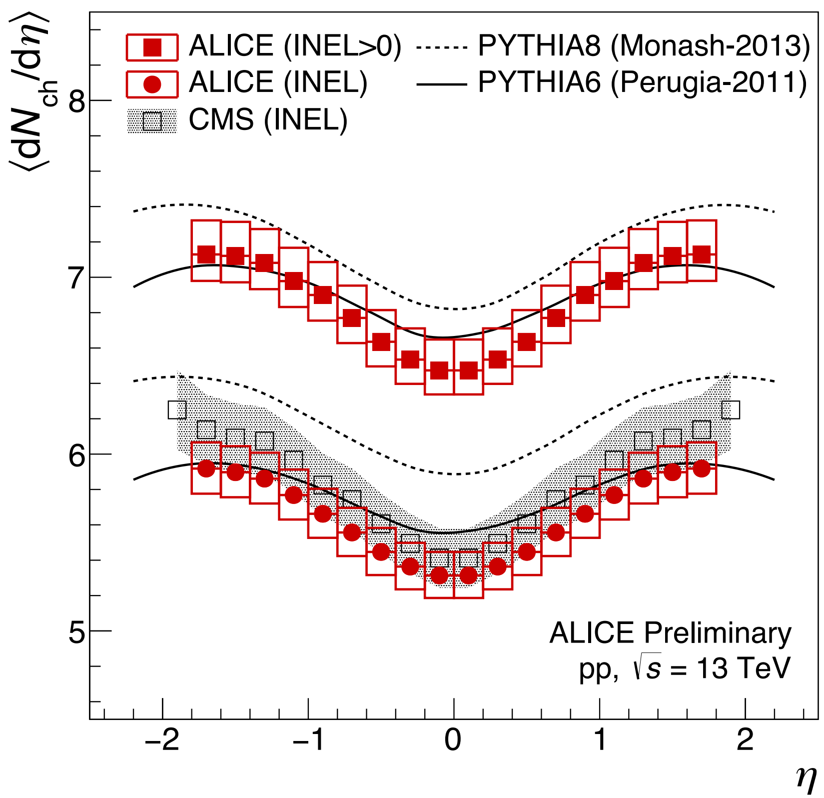
First 13 TeV result by ALICE

[CMS PLB 751, 143 (2015), ALICE-PUBLIC-2015-005]

Charged particle yield measurement for $|\eta| < 2$

Distinguish samples in inelastic (INEL) and inelastic + ≥1 track within $|\eta| < 1$ (INEL > 0)

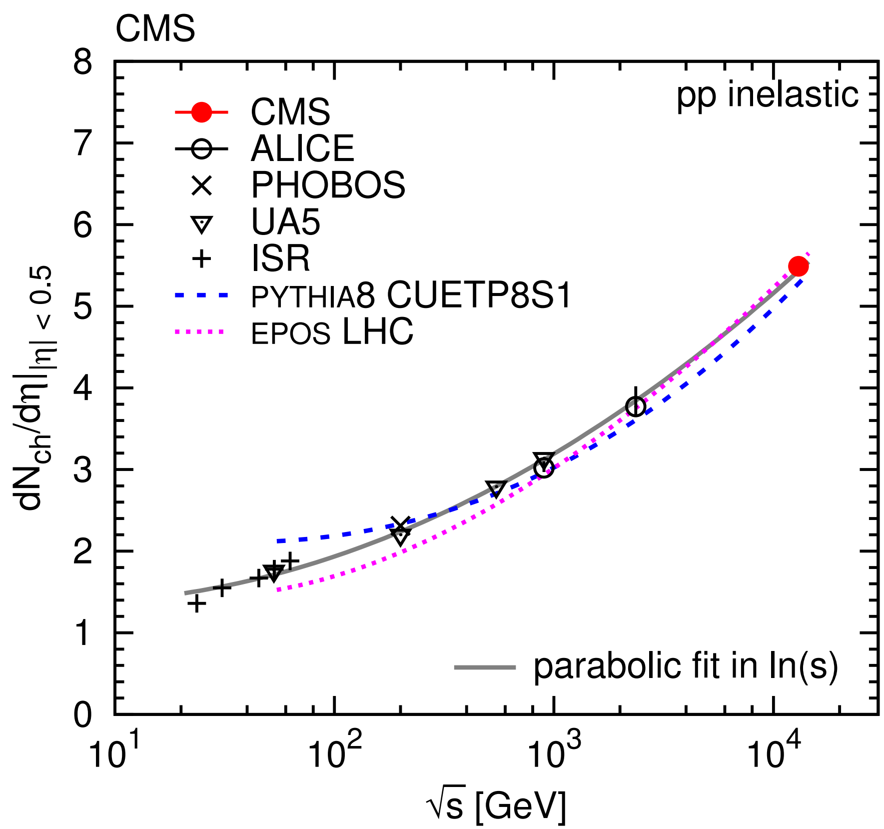
- Measure: $dn_{ch}/d\eta_{\,|\eta|<0.5} = 5.36 \pm 0.13$ in agreement with CMS

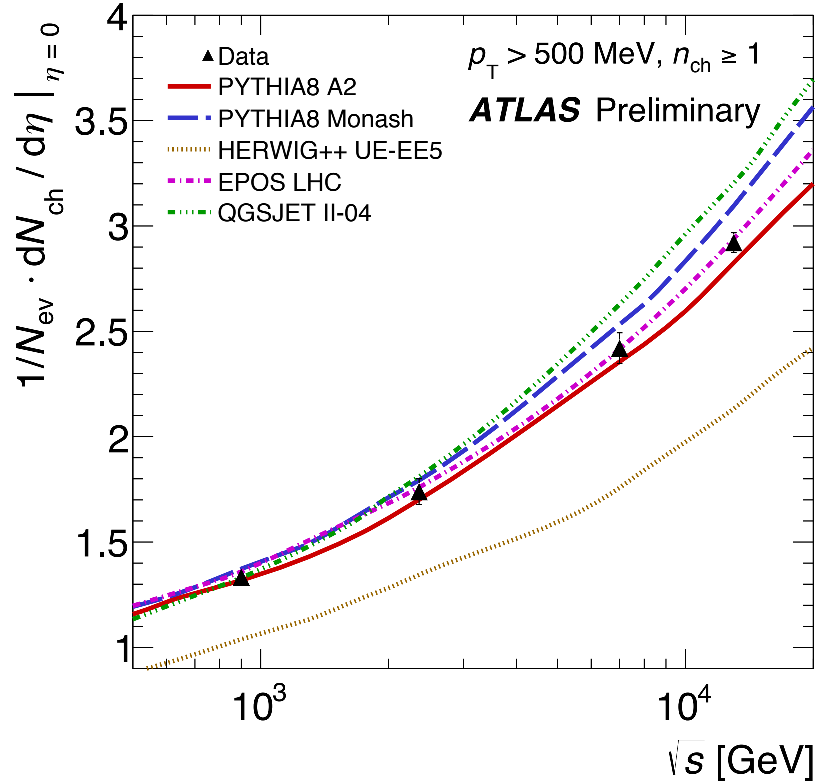


Charged particle production versus CM energy

[CMS PLB 751, 143 (2015) , ATLAS-CONF-2015-028]

Average charged-particle multiplicity per unit of rapidity for $\eta = 0$ vs $\sqrt{s}$





Fair agreement with model extrapolations

For comparison, the strange baryon contribution is included at 13 TeV in ATLAS (1.5% correction factor)

Inclusive inelastic cross-section measurement at 13 TeV

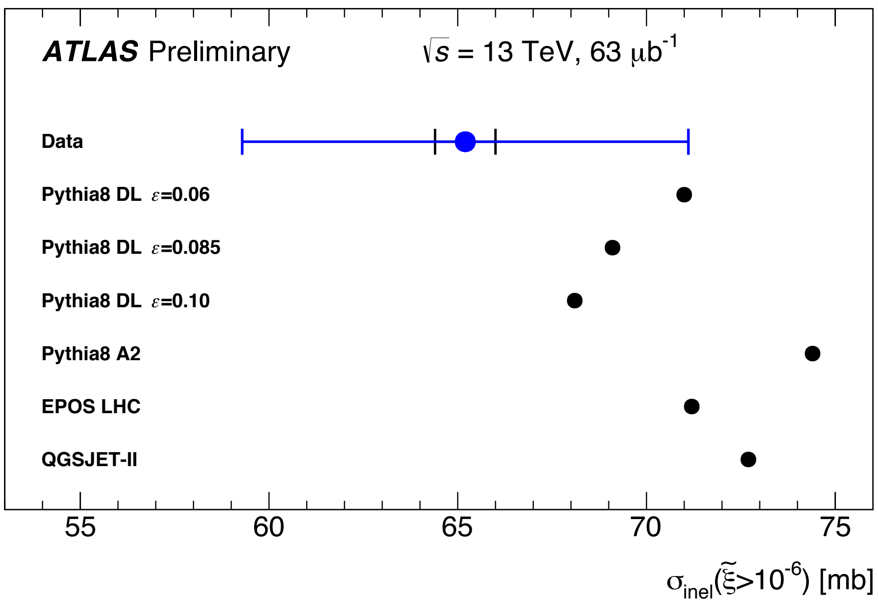
Fundamental initial measurement, based on forward scintillators

[ATLAS-CONF-2015-038]

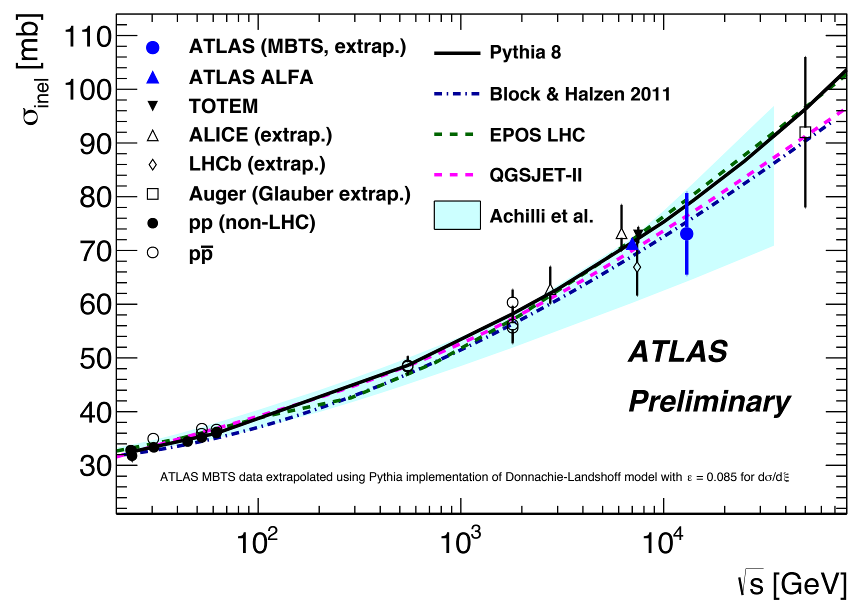
Measurement in fiducial region $\xi = M_X^2 / s > 10^{-6}$ (M_X largest mass of two proton-dissociation systems)

- Use Minimum Bias Trigger Scintillators (MBTS) with acceptance $2.07 < |\eta| < 3.86$, 4.2M selected events
- Use inclusive and single sided MBTS selections to constrain fraction of diffractive events in sample
- Systematic uncertainty fully dominated by luminosity

Fiducial cross-section compared to model predictions



Extrapolated inelastic cross-section versus CM energy



Cross-section somewhat lower than predictions. Inclusive: $\sigma_{13\ \mathrm{TeV}} = 73.1 \pm 0.9 \pm 6.6\ \text{(lumi)} \pm 3.8\ \text{(extr)}$ mb

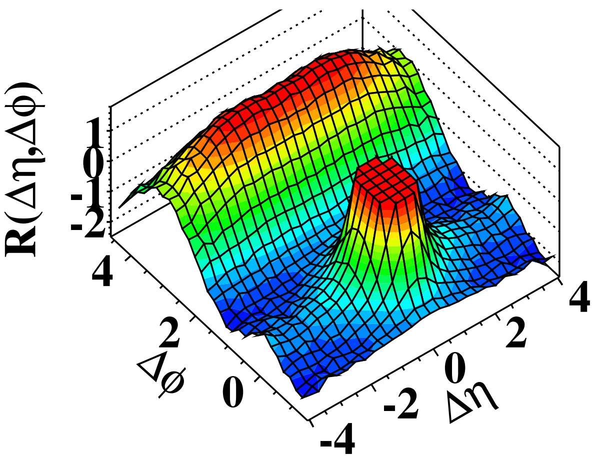
Long-range two-charged-particle angular correlations

In high-multiplicity pp collisions using low-μ data

Near-side ($\Delta\phi \sim 0$) “ridge” shape along $\Delta\eta$ seen in pp, pPb and PbPb collisions

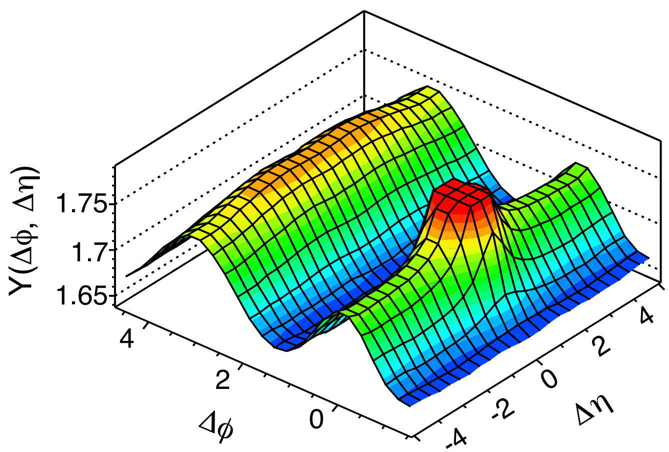
First observed in pp by CMS: effect increases with particle multiplicity and moderate p_T

CMS, pp at 7 TeV:
$N_{ch} > 110$, $1.0 < p_T < 3.0$ GeV



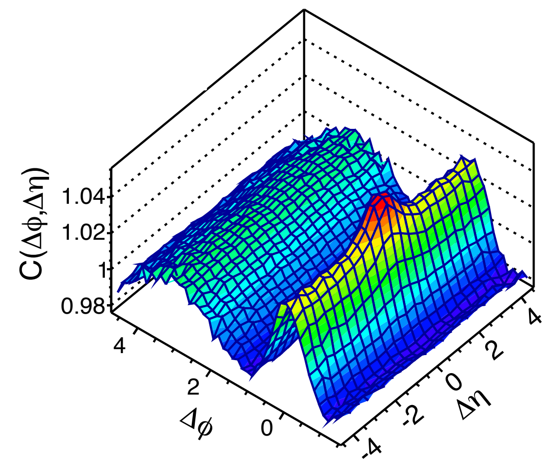
[CMS 1009.4122]

ATLAS, pPb at 5.02 TeV:
$N_{ch} > 220$, $1.0 < p_T < 3.0$ GeV



[ALICE 1212.2001,
ATLAS 1212.5198,
CMS 1409.3392,
LHCb-CONF-2015-004 (!)]

ATLAS, PbPb at 2.76 TeV:
Centrality 0–5%



[ALICE 1105.3865,
ATLAS 1504.01289
CMS 1409.3392]

[Enhancement found to be also present at $\Delta\phi \sim \pi$, when subtracting hard scattering contributions]

Two-charged-particle angular correlations at 13 TeV

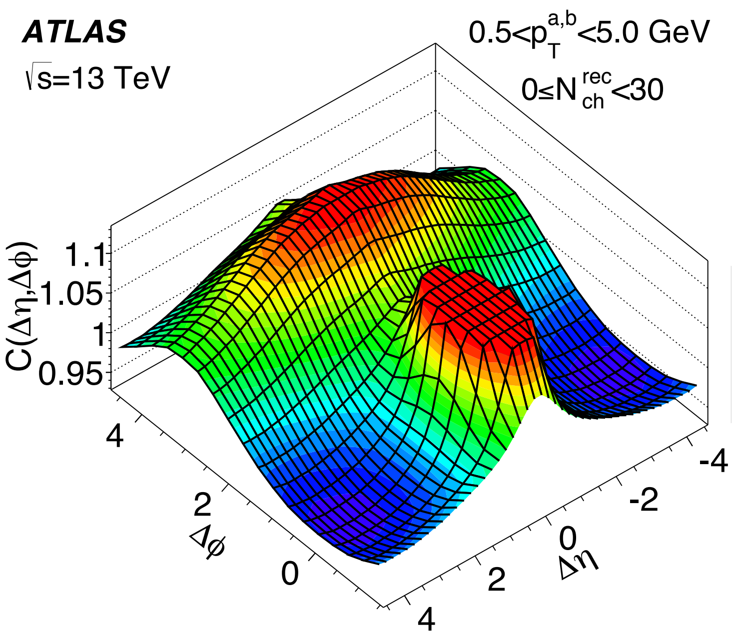
In high-multiplicity pp collisions using low-μ data

[ATLAS 1509.04776, CMS 1510.03068]

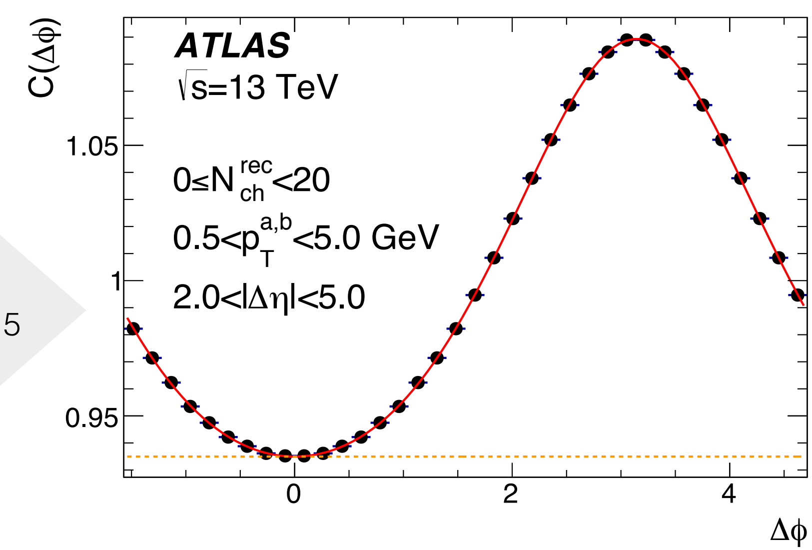
How does the pp ridge evolve with CM energy ?

- ATLAS: trigger on MBTS (97M events) & high charged multiplicity (9.5M)
- Exploit work on tracking corrections from minimum bias analysis
- Extract two-particle correlation function (background from mixed events) → $C(\Delta\eta, \Delta\phi) = \dfrac{S(\Delta\phi, \Delta\eta)}{B(\Delta\phi, \Delta\eta)}$
- Determine "ridge yield"

Low charged multiplicity



Integrate:
$2 < |\Delta\eta| < 5$



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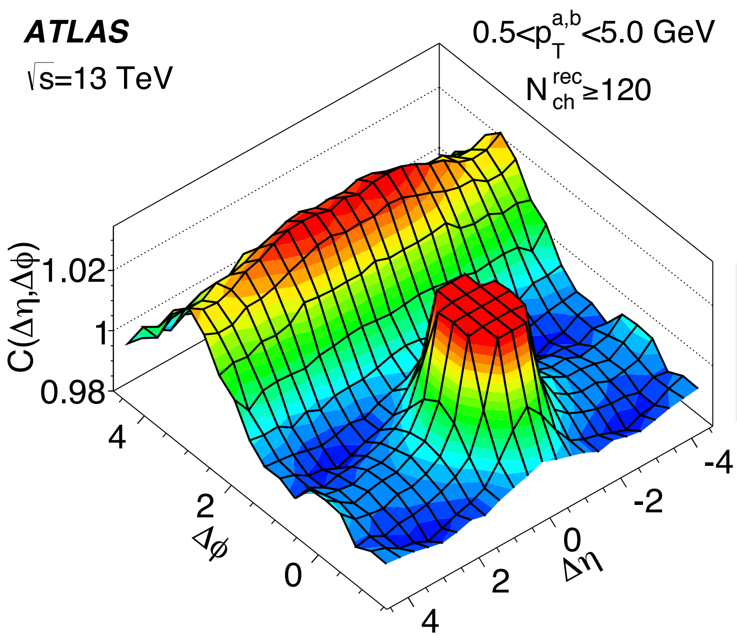

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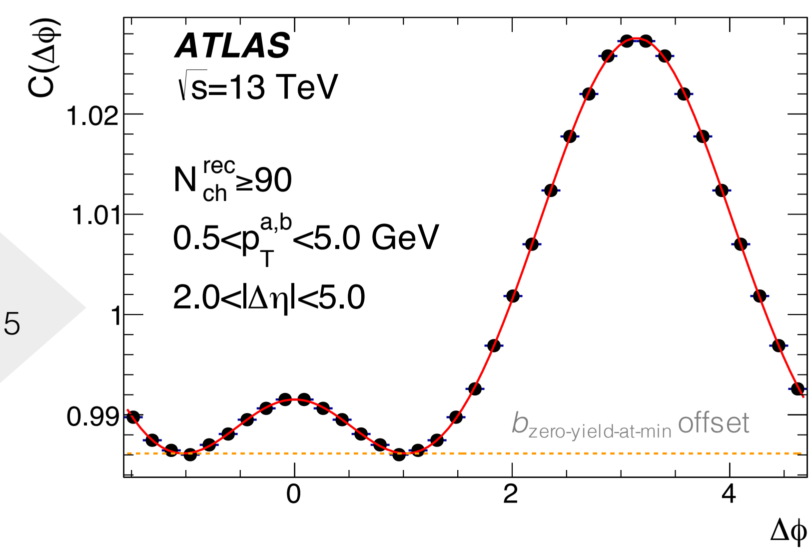

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In high-multiplicity pp collisions using low-μ data

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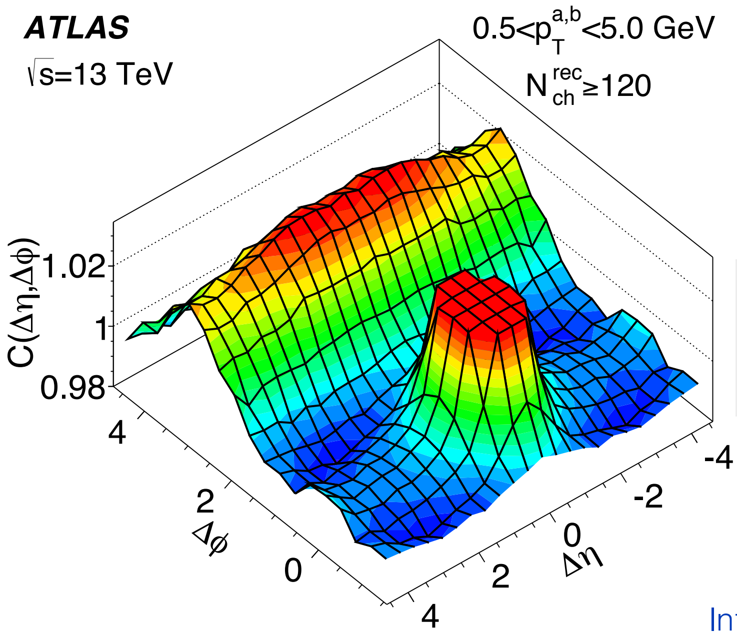
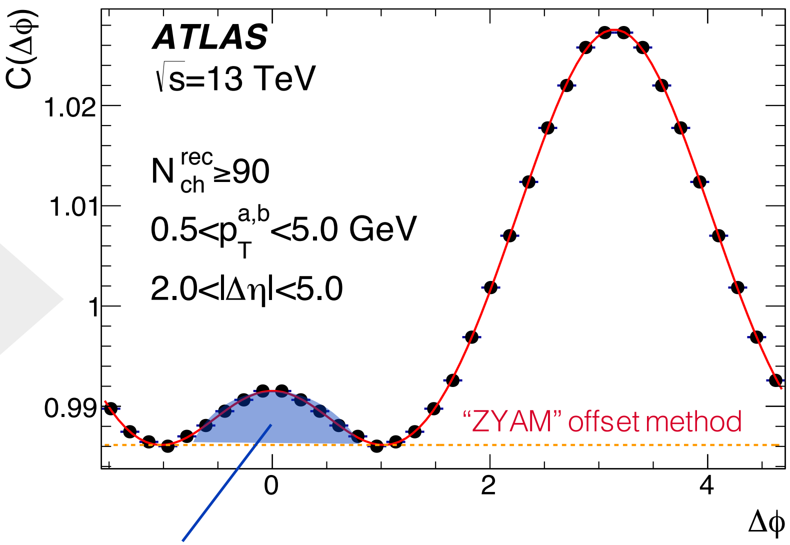


Integrate:
$2 < |\Delta\eta| < 5$



Integrated "ridge yield": Y_{int} (illustration only, integral is over appropriately normalised "per-trigger yields": $Y(\Delta\phi)$)

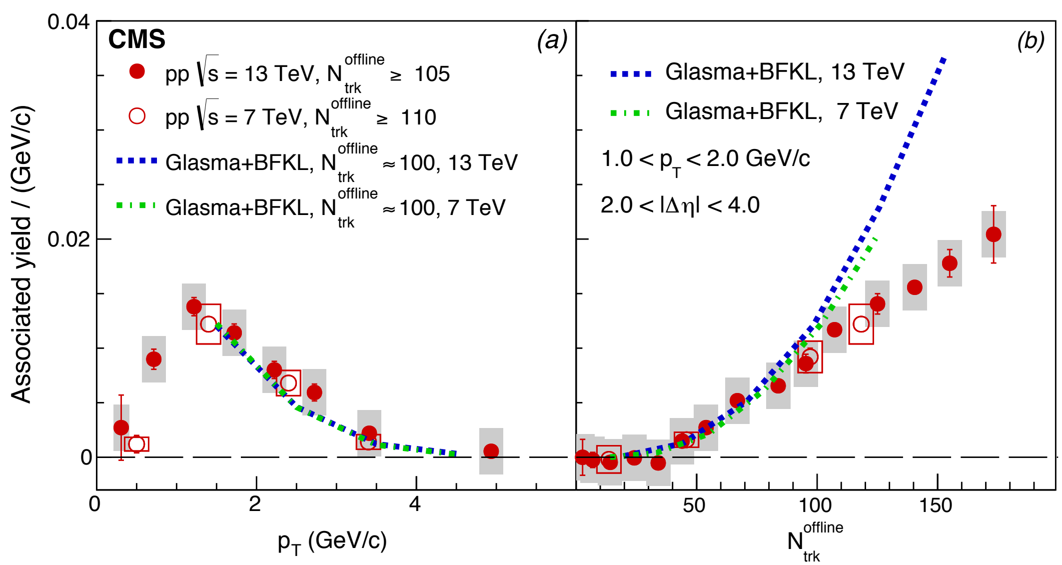
Two-charged-particle angular correlations at 13 TeV

In high-multiplicity pp collisions using low-μ data

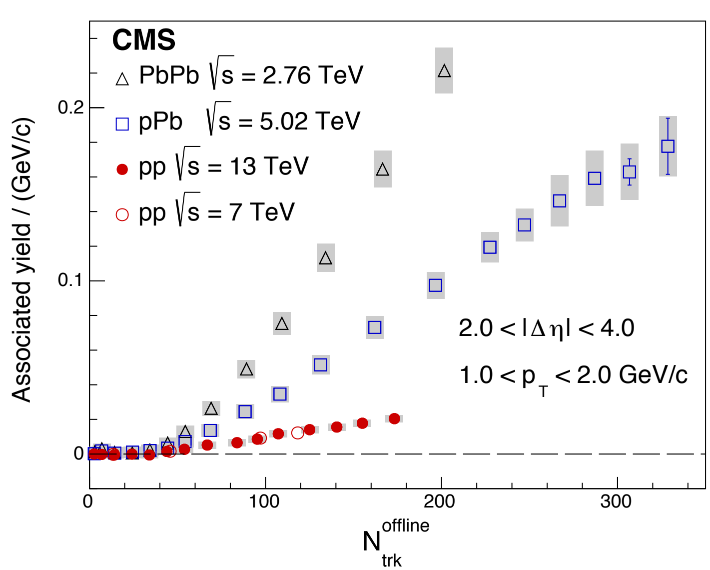
[CMS 1510.03068]

Resulting yield dependence (CMS)

- Left: versus p_T and N_{trk} and compared between CM energies for $2 < |\Delta\eta| < 4$
- Right: versus N_{trk} and compared between processes for $2 < |\Delta\eta| < 4$ and $1 < p_T < 2$ GeV
- No visible CM energy dependence of yield for pp colisions (also found by ATLAS)



The curves are predictions from gluon saturation (colour glass condensate) model: Dusling-Venugopalan, 1302.7018.



No apparent dependence on CM energy, but on size of colliding system

Two-charged-particle angular correlations at 13 TeV

In high-multiplicity pp collisions using low-μ data

[ATLAS 1509.04776]

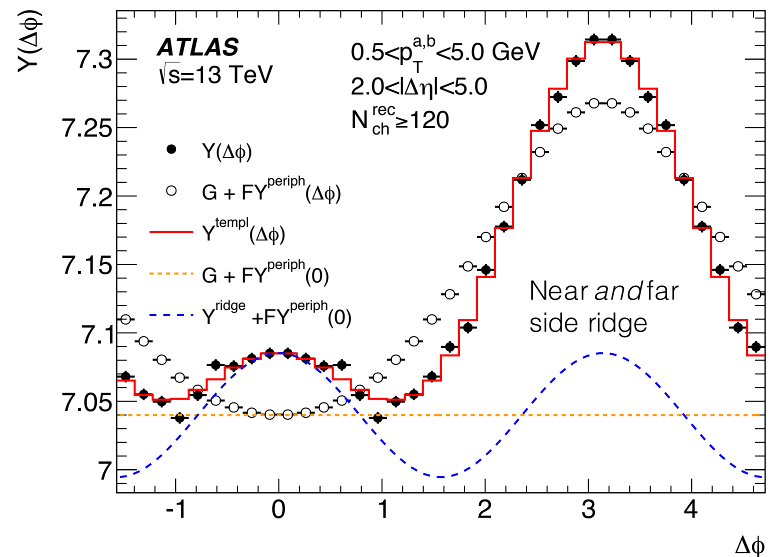
ATLAS replaced ZYAM method by template fit and measured ridge at 13 TeV and 2.76 TeV

- Ridge modulation in $Y(\Delta\phi)$ yield fitted by:

$$Y^{\rm templ}(\Delta\phi) = F\,Y^{\rm periph}(\Delta\phi) + Y^{\rm ridge}(\Delta\phi)\,,$$

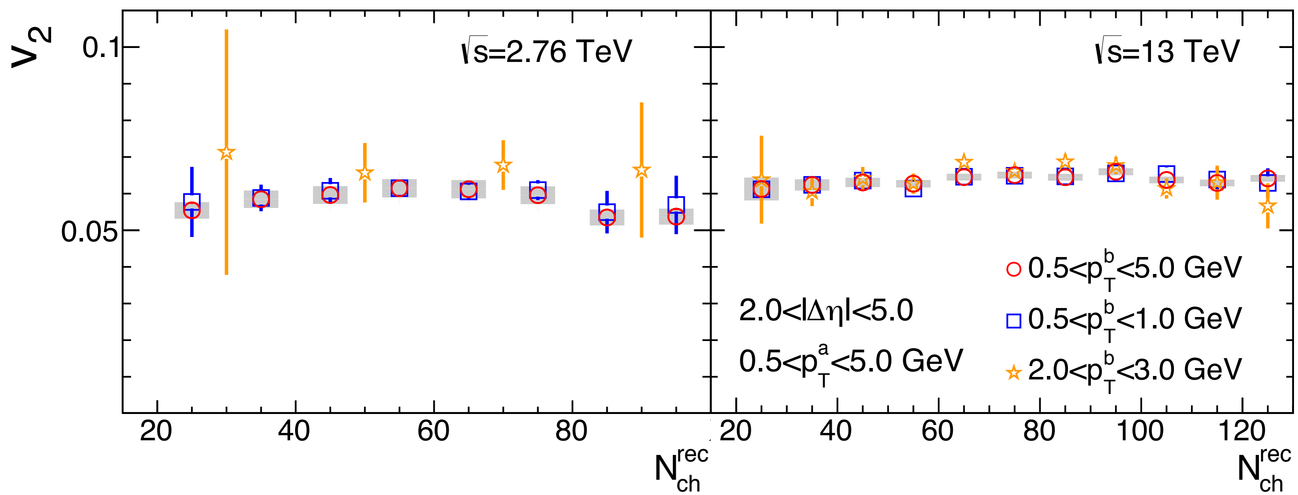
$$Y^{\rm ridge}(\Delta\phi) = G\,(1 + 2v_{2,2}\cos(2\Delta\phi))$$

- Factorisation: $v_{2,2}(p_T^{a},p_T^{b}) = v_2(p_T^{a})\,v_2(p_T^{b})$



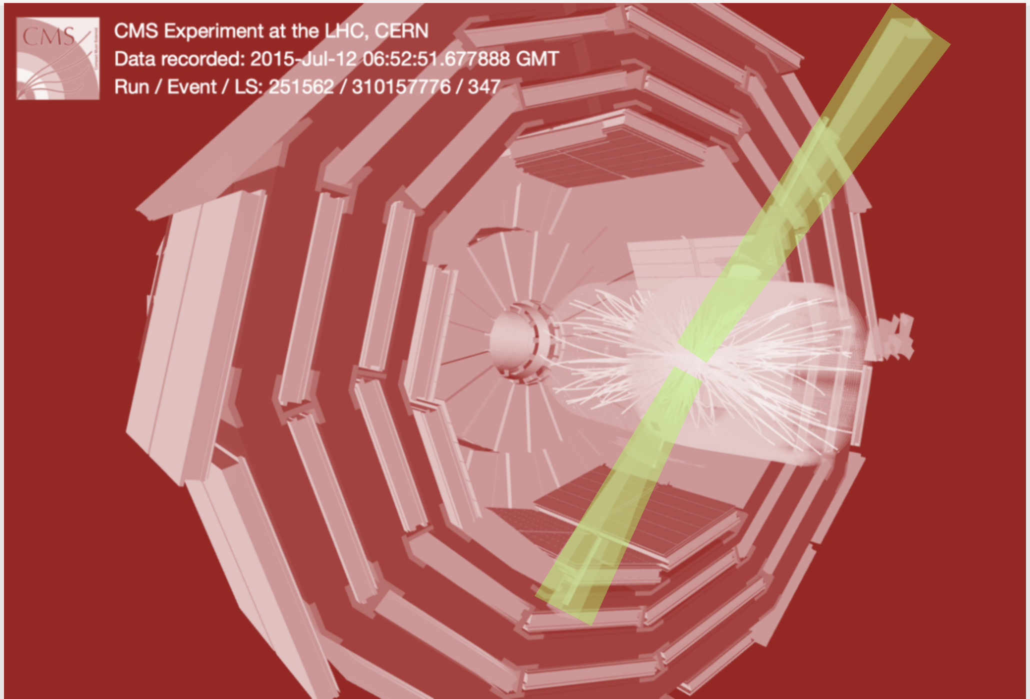
- Ridge results from per-event $\cos(2\Delta\phi)$ modulation of single-particle distribution with Fourier coefficient v_2

- v_2 ~independent of multiplicity and CM energy, p_T dependence similar to pPb and PbPb



Moving to higher luminosity and p_T

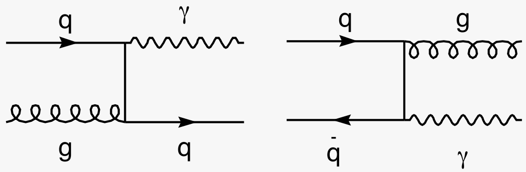
Physics with photons and jets at 13 TeV



Early 13 TeV event recorded by CMS showing two high-energy particle jets with invariant mass of 5 TeV

Photon production at 13 TeV

Test perturbative QCD in cleaner environment than jets

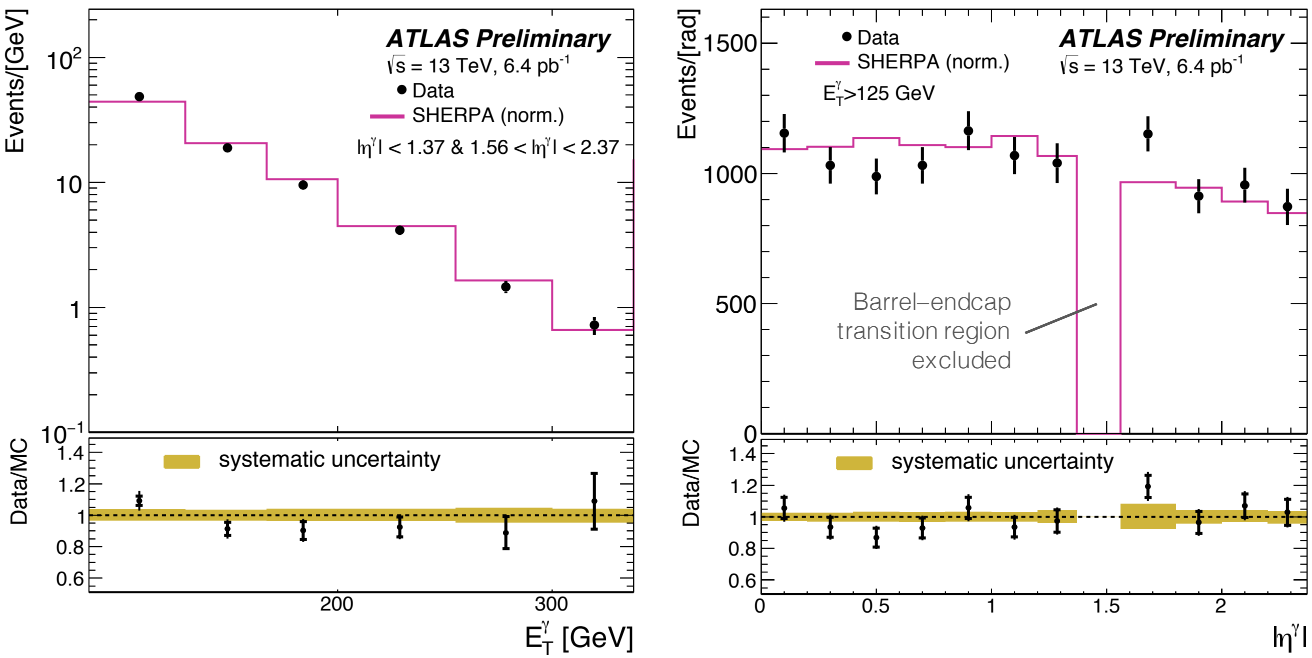


[ATL-PHYS-PUB-2015-016]

Measurement of isolated photon yield

Subtract mis-identification background from data using isolation distribution

Photon production vs. $E_{T,\gamma}$ and $|\eta_\gamma|$ (detector level, MC normalised to data)



Systematics dominated by photon energy scale, resolution and efficiency

Good agreement of shape with SHERPA 2.1 (LO + ≤3 partons)

Systematic uncertainties dominated by: photon energy scale, photon ID, background subtraction

Jet production at 13 TeV

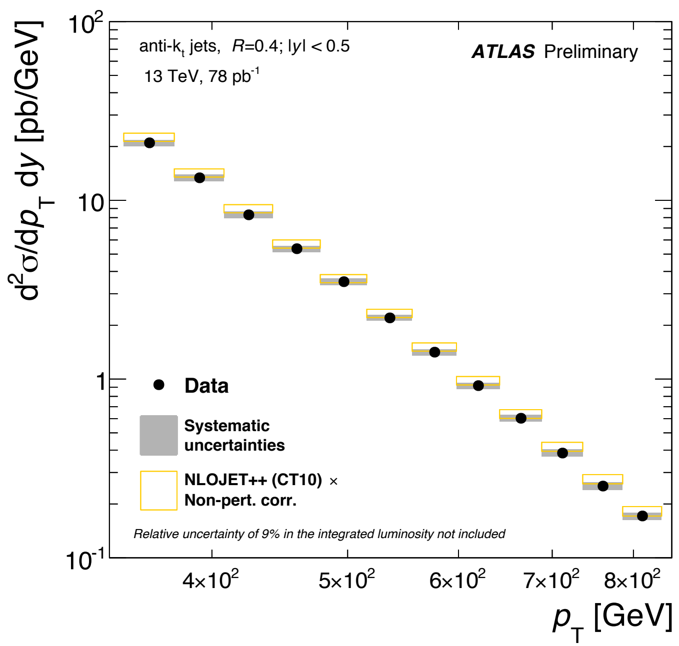
Early central-jet cross-section measurement at 13 TeV

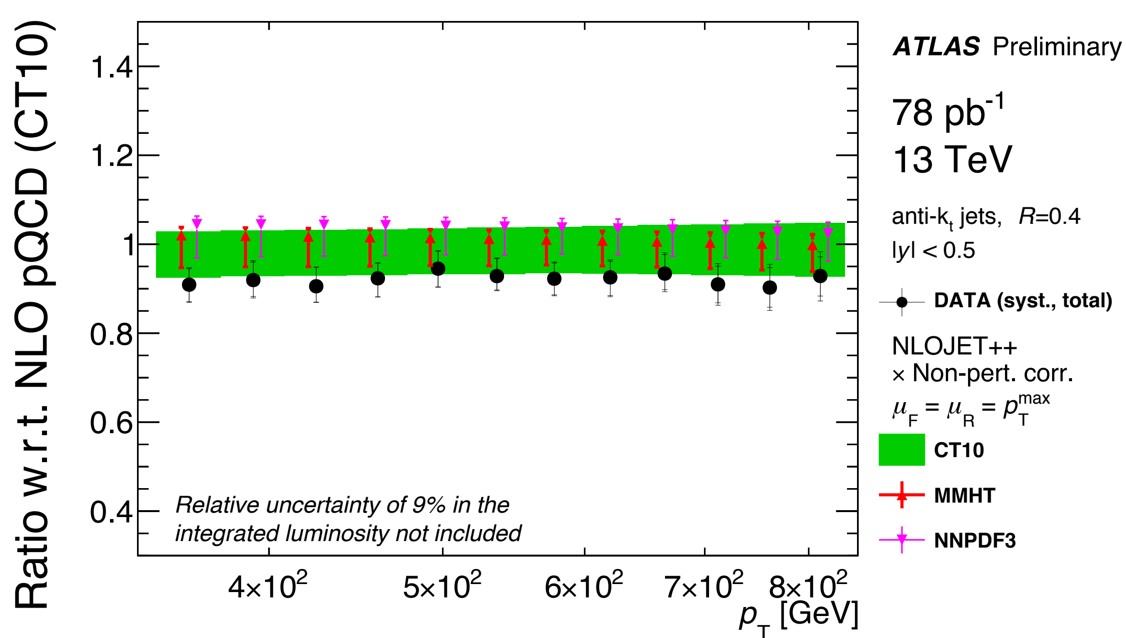
[ATLAS-CONF-2015-034]

Measurement performed within fiducial region 350 < p_T < 840 GeV and $|y_{jet}|$ < 0.5:

- Single jet trigger, fully efficient above 300 GeV jet p_T
- Reconstruct anti-k_t R = 0.4 jets, calibrated using MC and Run-1 data, validated in Run-2 data
- Unfold to particle level
- Dominant systematic uncertainty: jet energy scale and resolution

Compare with NLO theory (incl. PS+UE corrections) of measured diff. cross sections vs. p_T





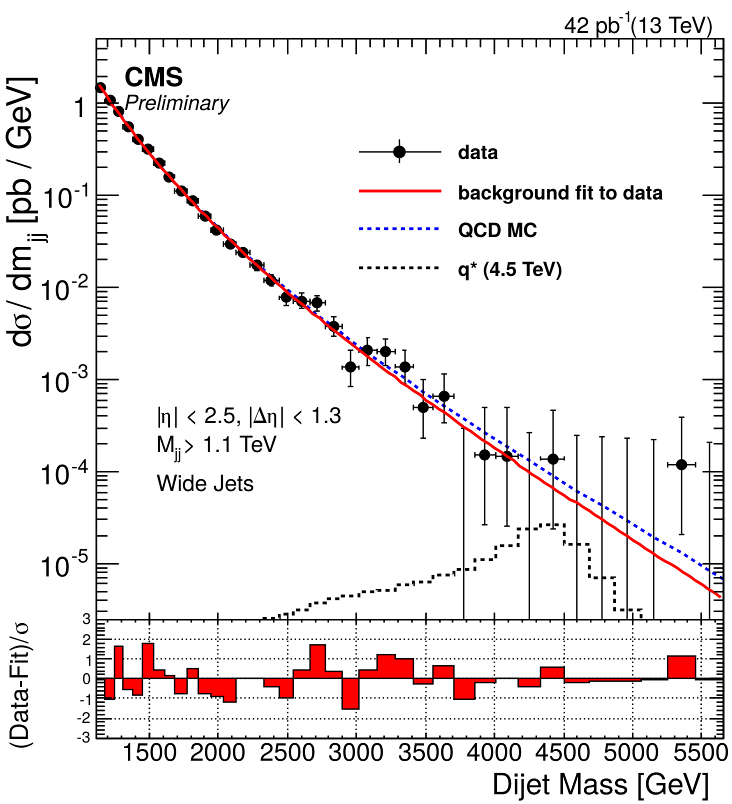
[ATLAS-CONF-2015-034, CMS-PAS-EXO-15-001]

New physics searches with dijets

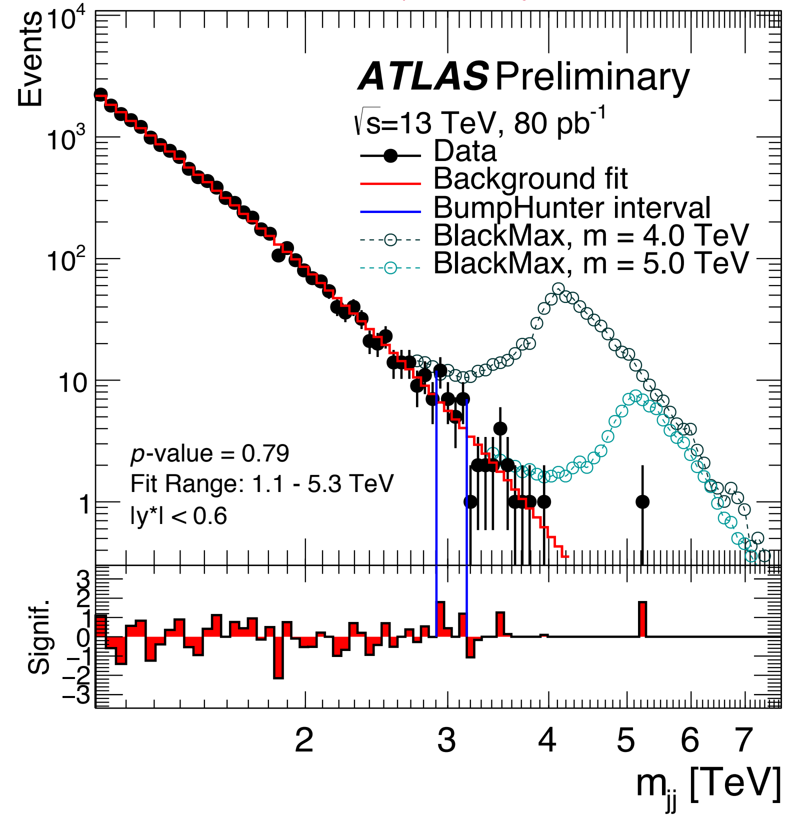
Early 13 TeV data already sensitive to very high-mass & cross section physics (eg, QBH)

Analysis strategy (dijet *resonance*):

- Look for deviation in dijet invariant mass spectrum from smooth function
- Alternative functions / more parameters used following predefined rule (independent of data outcome)



QBH limits improved by ~1 TeV over Run-1



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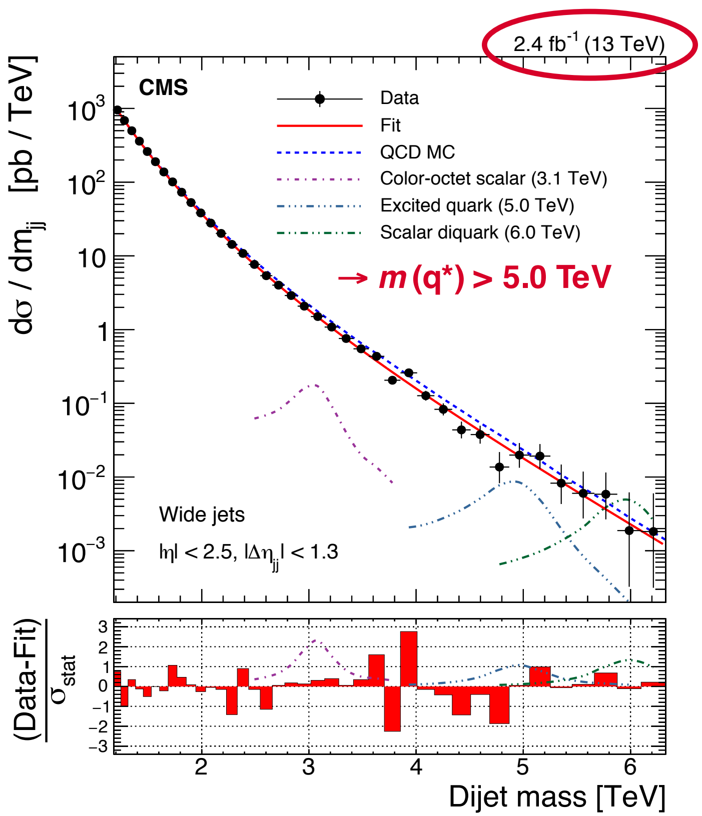
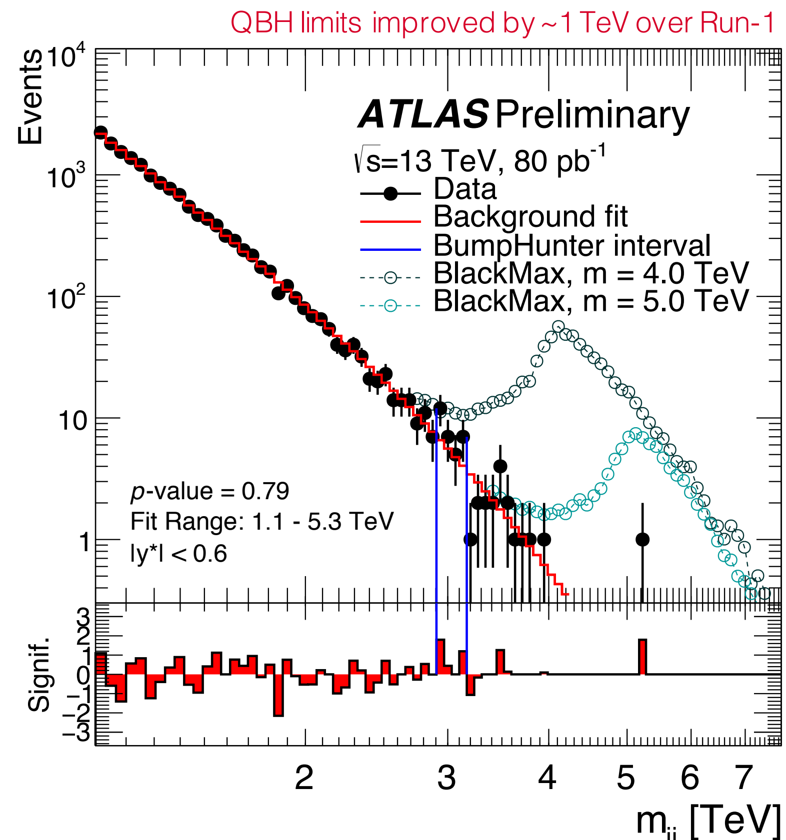


QBH limits improved by ~1 TeV over Run-1



New physics searches with dijets

Early 13 TeV data already sensitive to very high-mass & cross section physics (eg, QBH)

Analysis strategy (dijet *angular*):

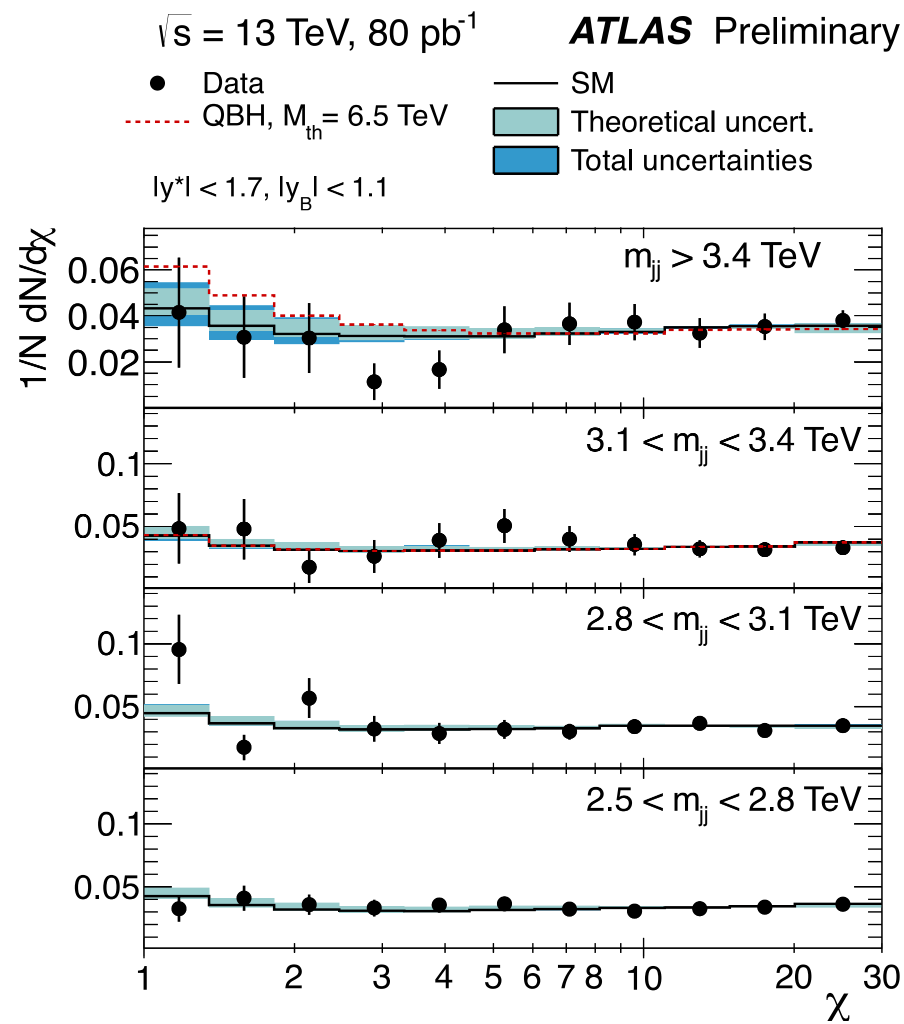
- Search for non-resonant high-mass anomalies using angular distribution
- Define for jets 1 & 2:

  $\chi = \exp|y_1 - y_2|$

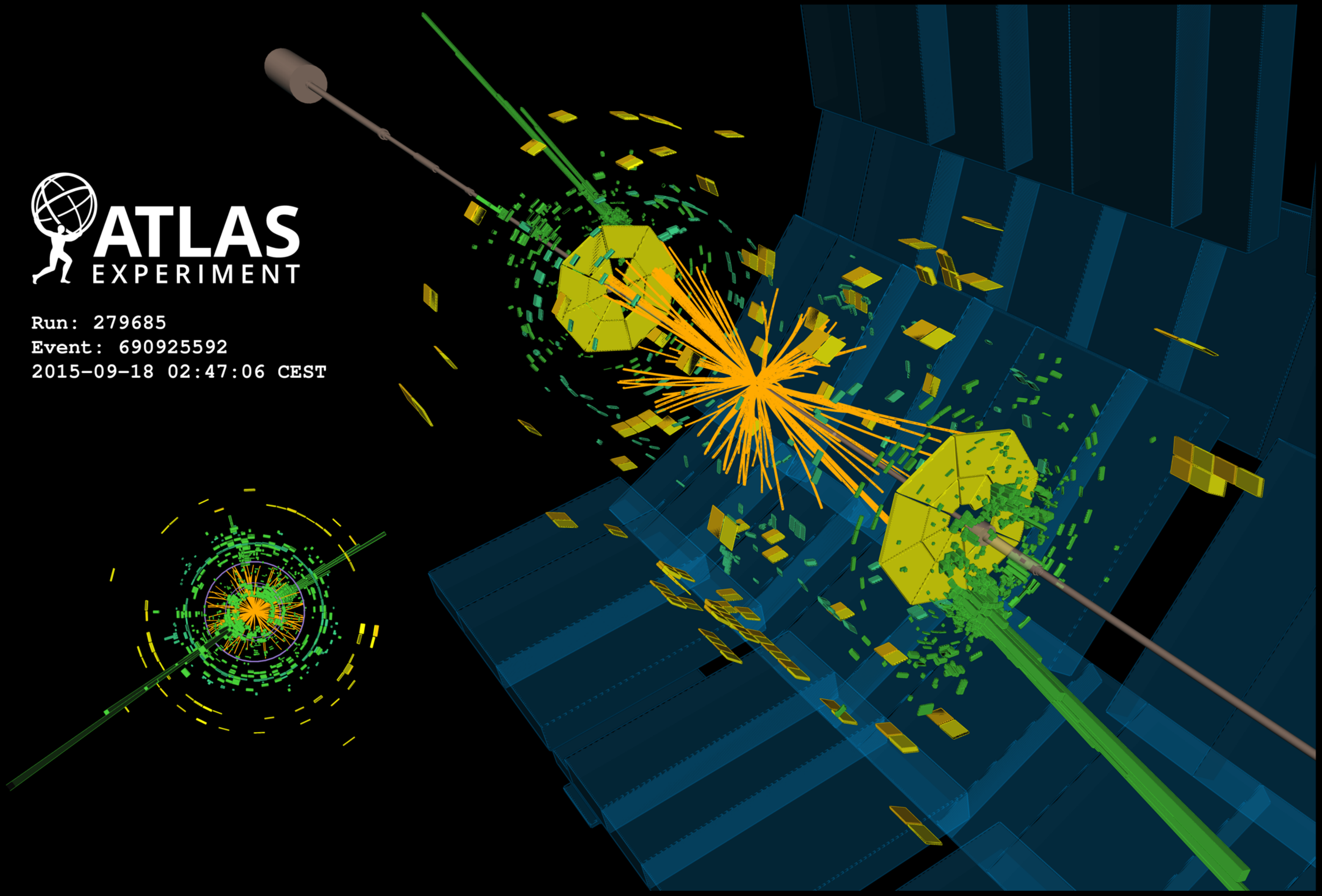
  which is ~independent of m_{12} for *t*-channel LO QCD at parton level

  Restrict analysis to $|y_1 + y_2| < 2.2$, and to $m_{12} > 2.5$ TeV

- Prediction from NLOJET++ and including electroweak effects
- Systematic uncertainty dominated by QCD prediction and jet energy scale



8.8 TeV mass dijet event collected by ATLAS in September 2015

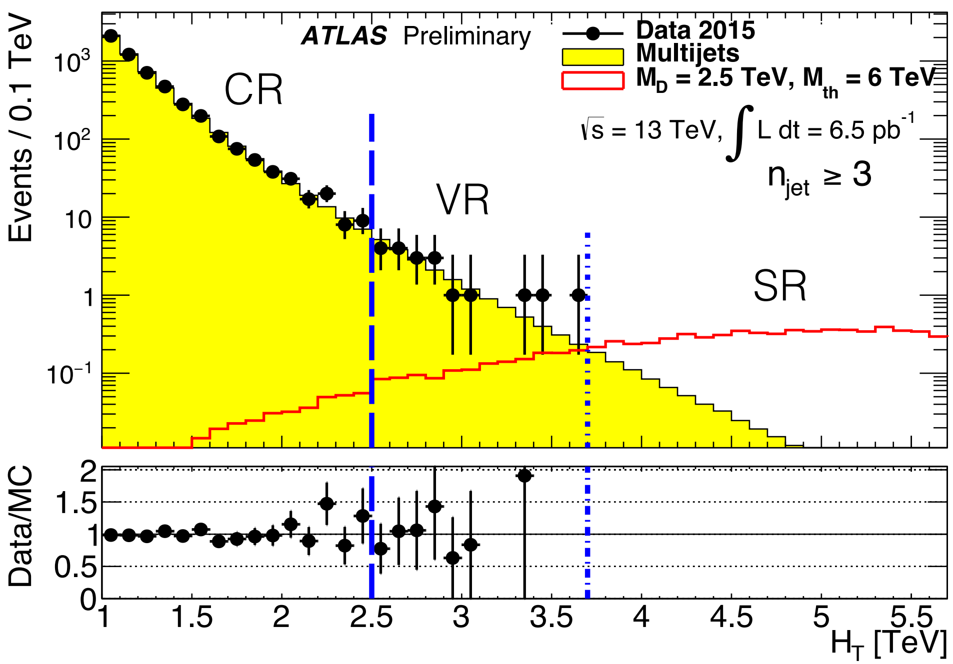


New physics searches with multiple jets

Similar analysis to dijets, but looking for deviation in inclusive jet production

Analysis strategy:

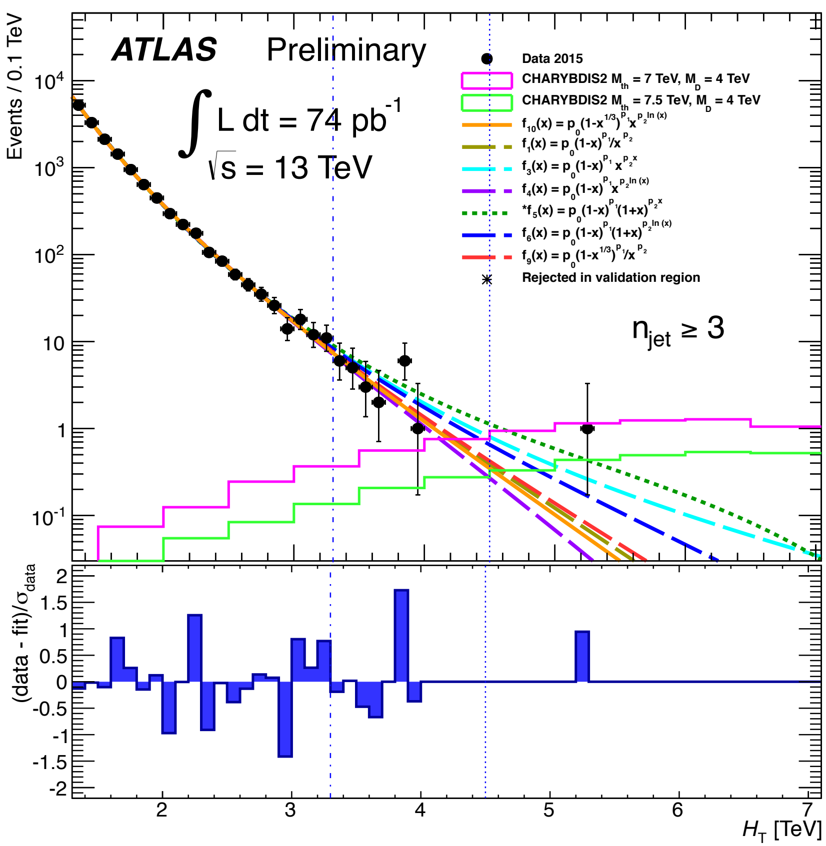
- Search for deviation in $H_T = \Sigma_{jets}\, p_T$ in events with at ≥ 3–8 jets with p_T > 50 GeV
- High-H_T trigger ~fully efficient above 1 TeV
- Data driven background fit as in dijet case, but more tricky as fit over full spectrum could "eat" signal
- Define control (CR), validation (VR), signal regions (SR) depending on low, medium, high H_T
- On lower luminosity bootstrap sample fit data in CR, use VR to validate functional form
- Use function to fit full spectrum and derive background prediction in SR
- Vary functions to assess extrapolation uncertainty

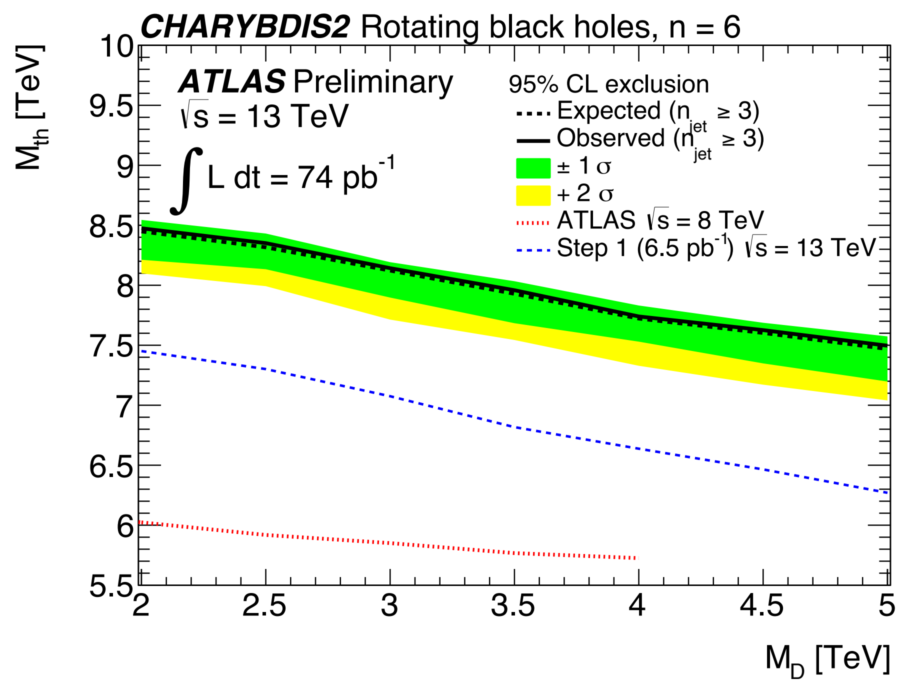


New physics searches with multiple jets

Similar analysis to dijets, but looking for deviation in inclusive jet production

Sensitivity to TeV-scale gravity models beyond that of Run-1





Limit increased over Run-1 by more than 2 TeV in threshold mass for $M_D < 4$ TeV

[ATLAS-CONF-2015-046]

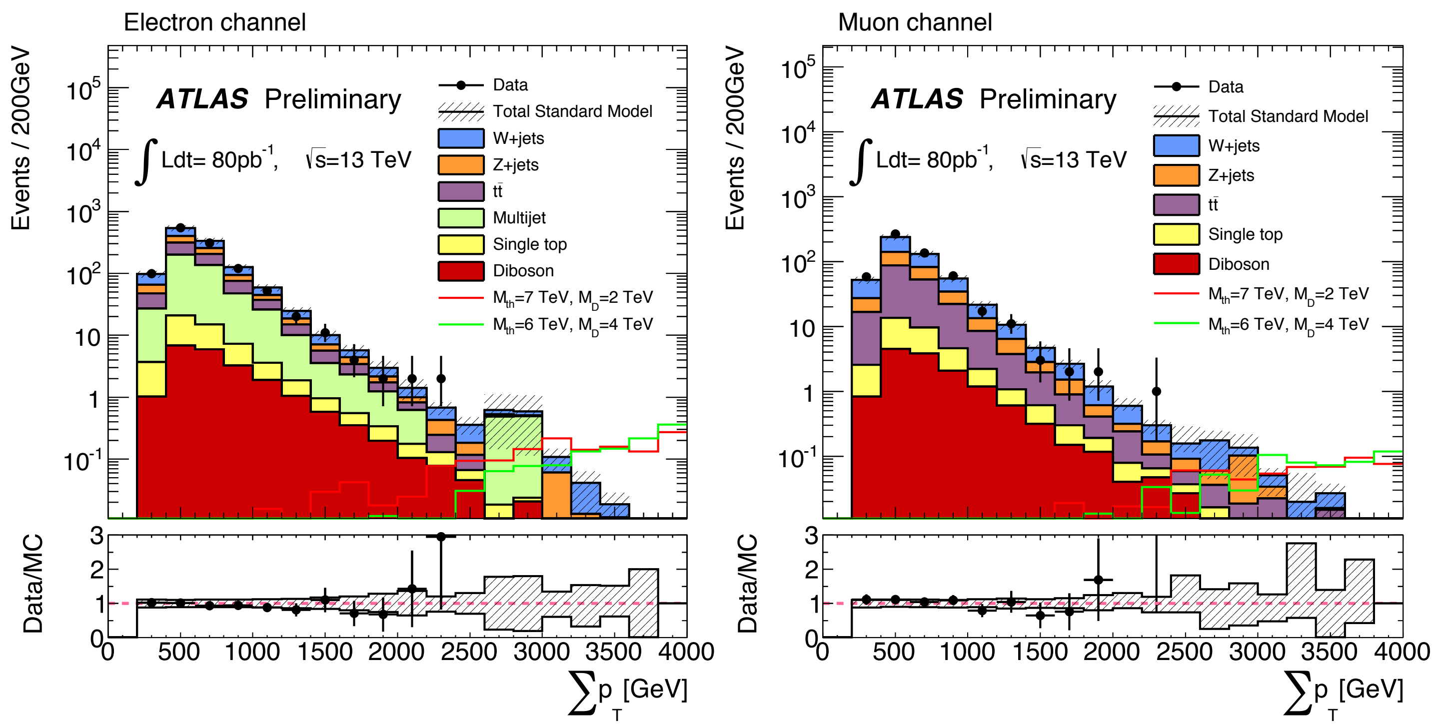
New physics searches with lepton & jets

Similar analysis to dijets, but looking for deviation in inclusive jet production

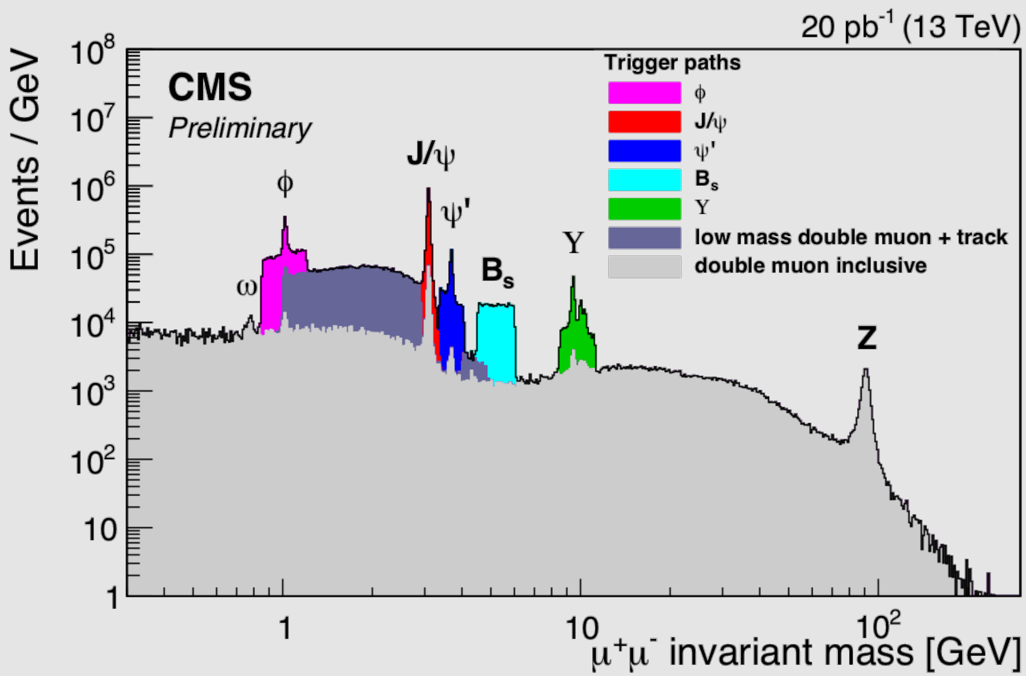
Analysis strategy:

- Search for non-resonance deviation in $\Sigma_{e/\mu\text{+jets}}\ p_T$ in events with at least 3 high-p_T objects ($\geq$ 1 lepton)
- Single lepton trigger, 2 signal regions with $\Sigma_{e/\mu\text{+jets} > 60\text{ GeV}}\ p_T > 2$ (3) TeV
- Dominant backgrounds (W/Z+jets, ttbar) from MC normalised to data in control regions, others from MC
- Propagation of exp. and theoretical uncertainties
- Validation region for $1.5 < \Sigma\, p_T < 2$ TeV

BH sensitivity improves over Run-1, but not over multijet search



Physics with leptons at 13 TeV



Dimuon mass distribution collected with various dimuon triggers

[CMS DP-2015/015]

J/Ψ production at 13 TeV

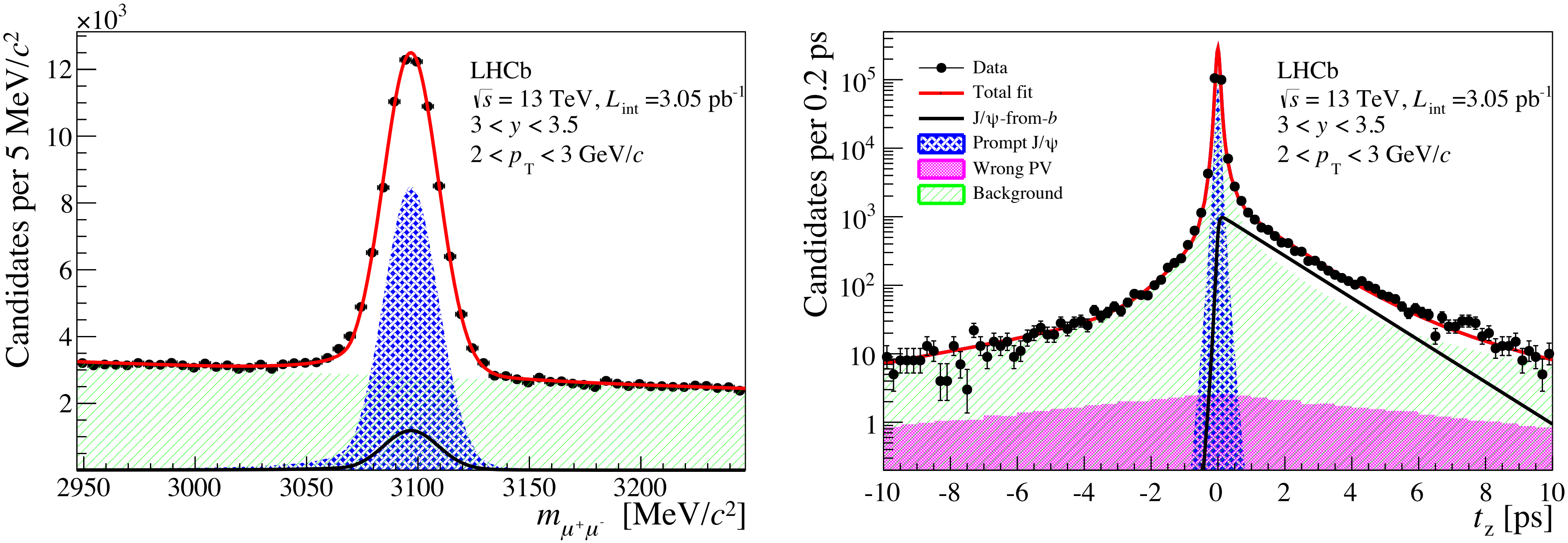
Good environment in early data with low trigger thresholds

[LHCb 1509.00771]

J/Ψ are produced promptly and via weak decays of b-hadrons

LHCb used initial 3 pb^{-1} for first prompt & non-prompt J/Ψ cross-section measurement in forward rapidity

Systematic uncertainty mostly dominated by luminosity (3.9%)



Analysis performed almost promptly thanks to the "Turbo stream" trigger line

J/Ψ production at 13 TeV

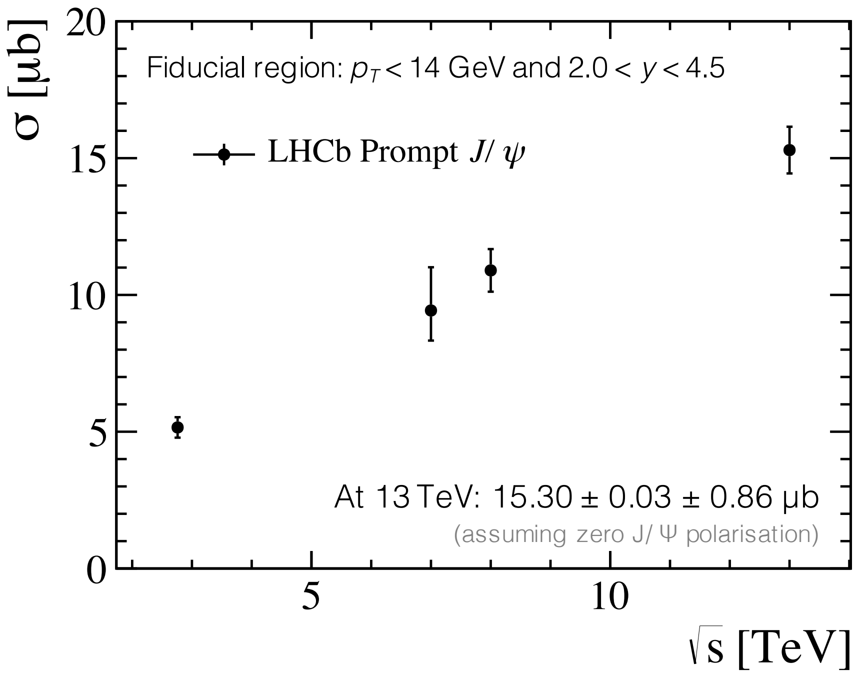
Good environment in early data with low trigger thresholds

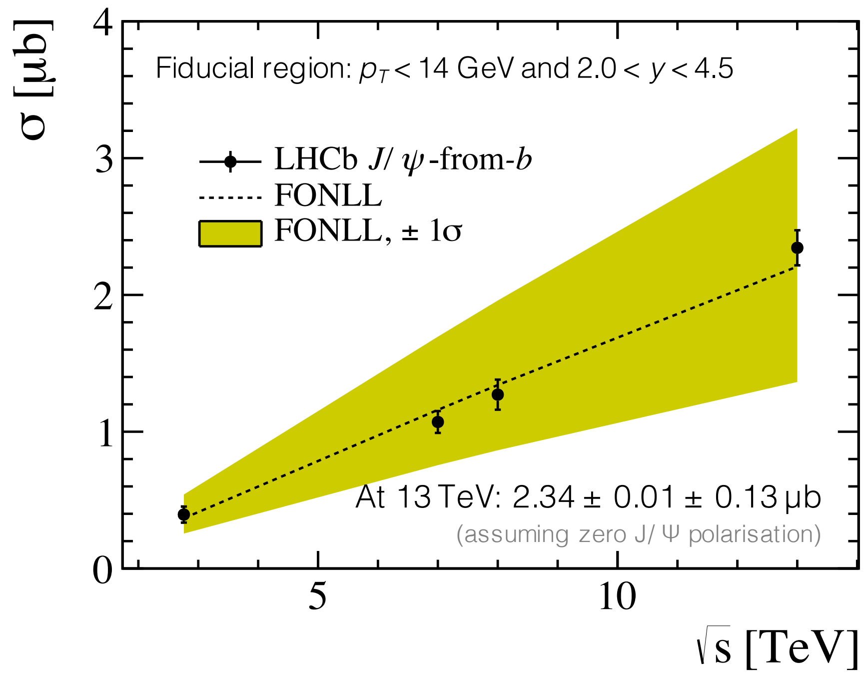
[LHCb 1509.00771]

J/Ψ are produced promptly and via weak decays of b-hadrons

LHCb used initial 3 pb^{-1} for first prompt & non-prompt J/Ψ cross-section measurement in forward rapidity

Differential absolute cross-sections and ratios to 8 TeV obtained, show total fiducial cross-sections here





Cross-sections rise mostly due to CM energy; harder p_T spectrum at 13 TeV than at 8 TeV

Total σ(pp → bb+X) = 515 ± 2 ± 53 μb (using BR(b → J/ψ X) = 1.16 ± 0.10%).

J/Ψ production at 13 TeV

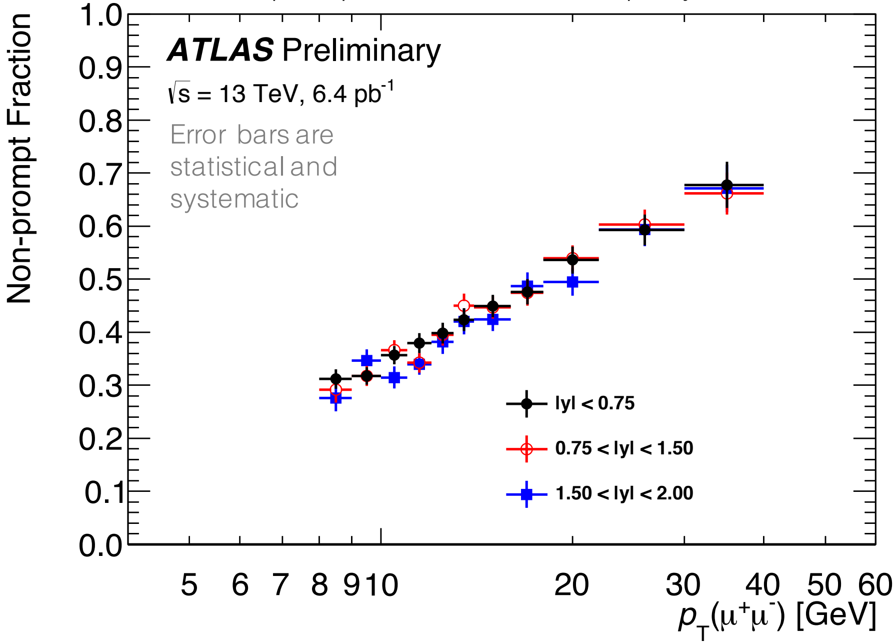
Good environment in early data with low trigger thresholds

[ATLAS-CONF-2015-030]

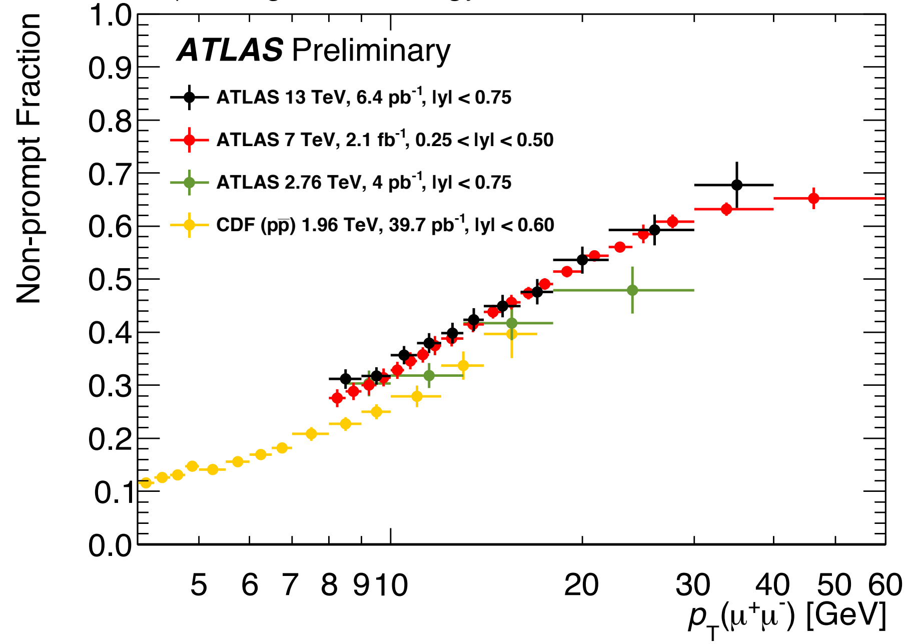
ATLAS measured the J/Ψ non-promdpt fraction at 13 TeV in early 6.4 pb^{-1} dataset

Cuts: $p_{T,\mu} > 4$ GeV, $|\eta_\mu| < 2.3$, $p_{T,\mu\mu} > 8$ GeV, $|y_{\mu\mu}| < 2$, 2D fit to $m_{\mu\mu}$ and proper decay time $\tau = L_{xy}\, m_{J/\Psi} / p_{T,\mu\mu}$

Fitted non-prompt fraction for 3 J/Ψ rapidity bins



Depending on CM energy



Non-prompt contribution to total rate rises rise from approximately 25% at $p_{T,\mu\mu}$ of 8 GeV to 65% at 40 GeV

Prompt charm production at 13 TeV

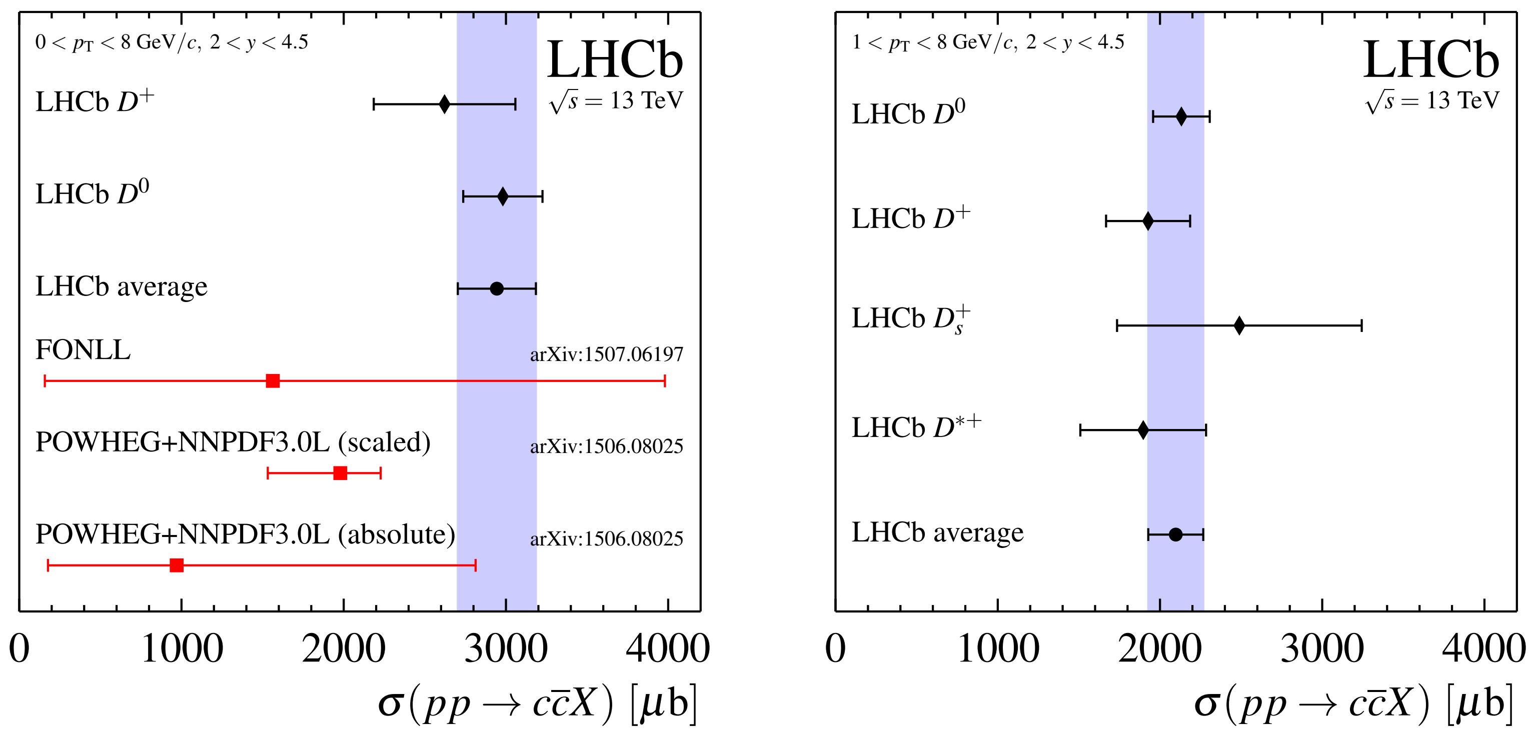
Second LHCb paper on 13 TeV

[LHCb 1510.01707]

Measurements of prompt D^0, D^+, D_s^+, D^{*+} forward cross-sections with 5 pb^{-1}

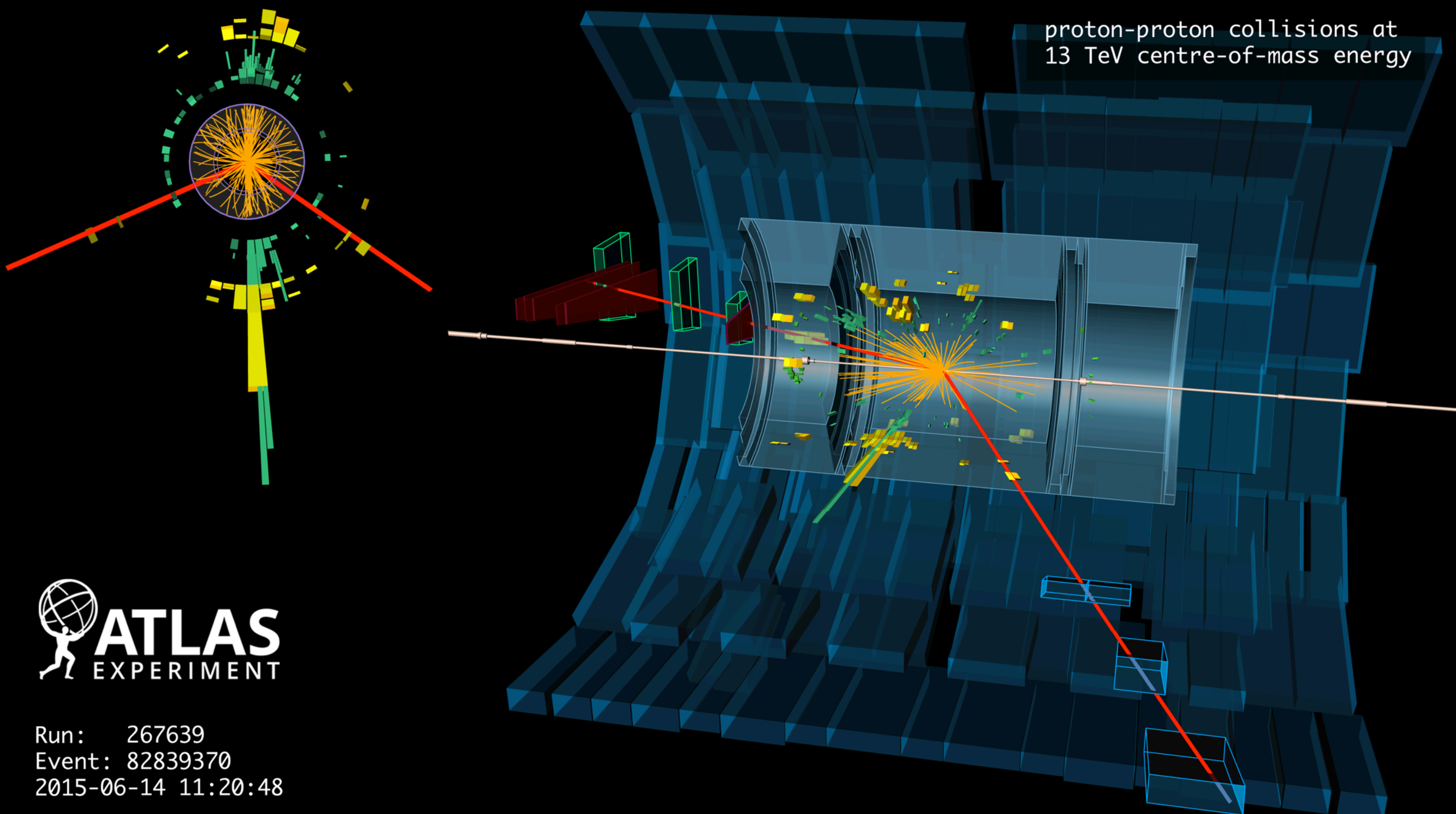
Measure differentially in bins of meson p_T and rapidity, and integrated fiducial cross-sections

Total charm (cc) cross-sections by correcting for $cc \to D$ fragmentation fractions measured at B-factories



Averaged integrated cross-section: $\sigma(pp \to cc+X)$ = 2940 ± 3 (stat) ± 180 (syst) ± 160 (frag) μb

W and Z boson production at 13 TeV



Displays of one Z(→ μμ) + jets candidate event

Z and W production at 13 TeV (ATLAS)

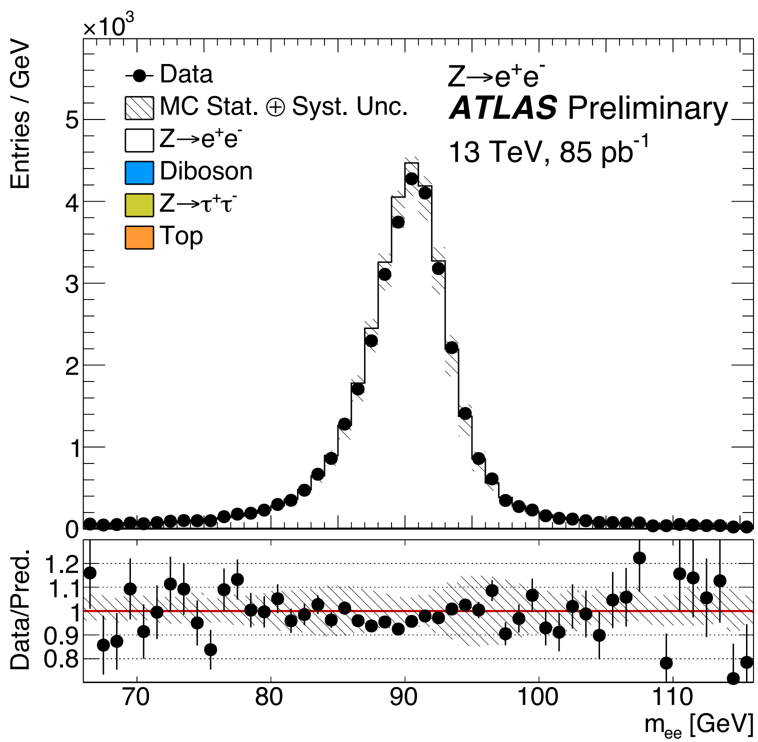
Expect increase of cross section by **factors of 1.7 and 1.6**, respectively

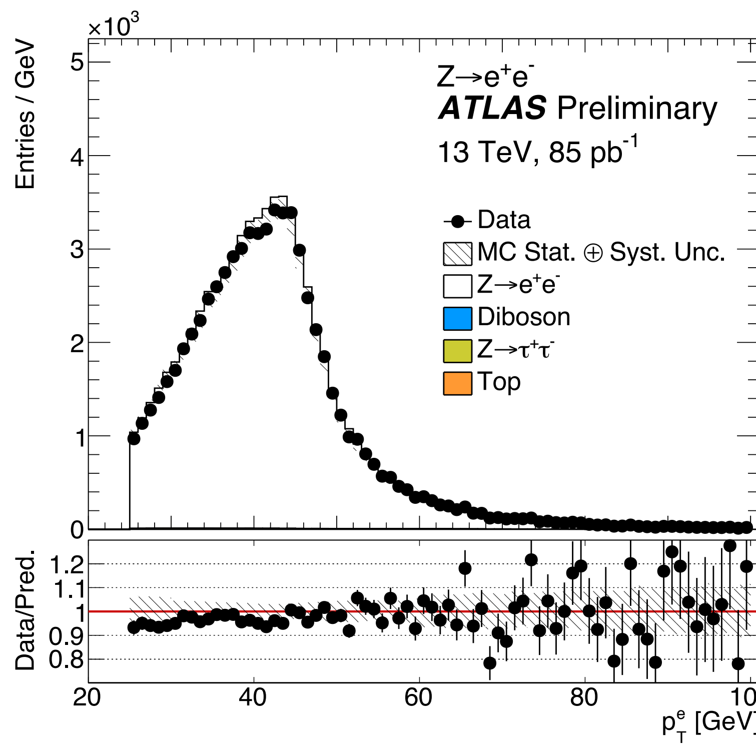
[ATLAS-CONF-2015-039]

Leptonic decays are important standard candles to verify and calibrate e/μ performance

Following plots are normalised to NNLO QCD and to luminosity. Error bands in plots do not include 9% luminosity uncertainty (leading uncertainty, other systematics dominated by lepton ID)

Electron efficiency scale factors (both trigger and offline) from data tag & probe, 8 TeV and MC extrapolation





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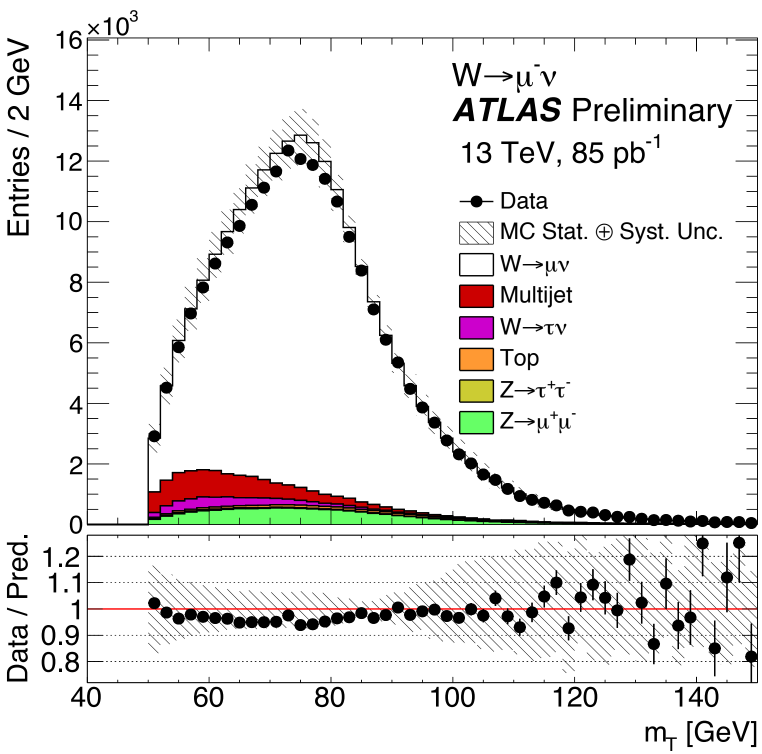
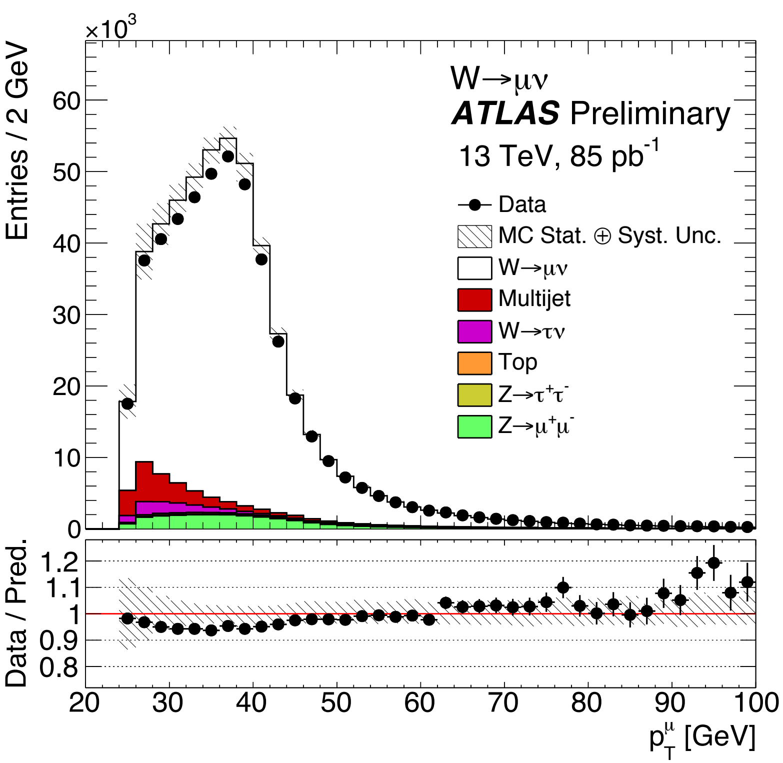
[ATLAS-CONF-2015-039]

Leptonic decays are important standard candles to verify and calibrate e/μ performance

Following plots are normalised to NNLO QCD and to luminosity. Error bands in plots do not include 9% luminosity uncertainty (leading uncertainty, other systematics dominated by lepton ID)

Muon efficiency scale factors (both trigger and offline) from data tag & probe





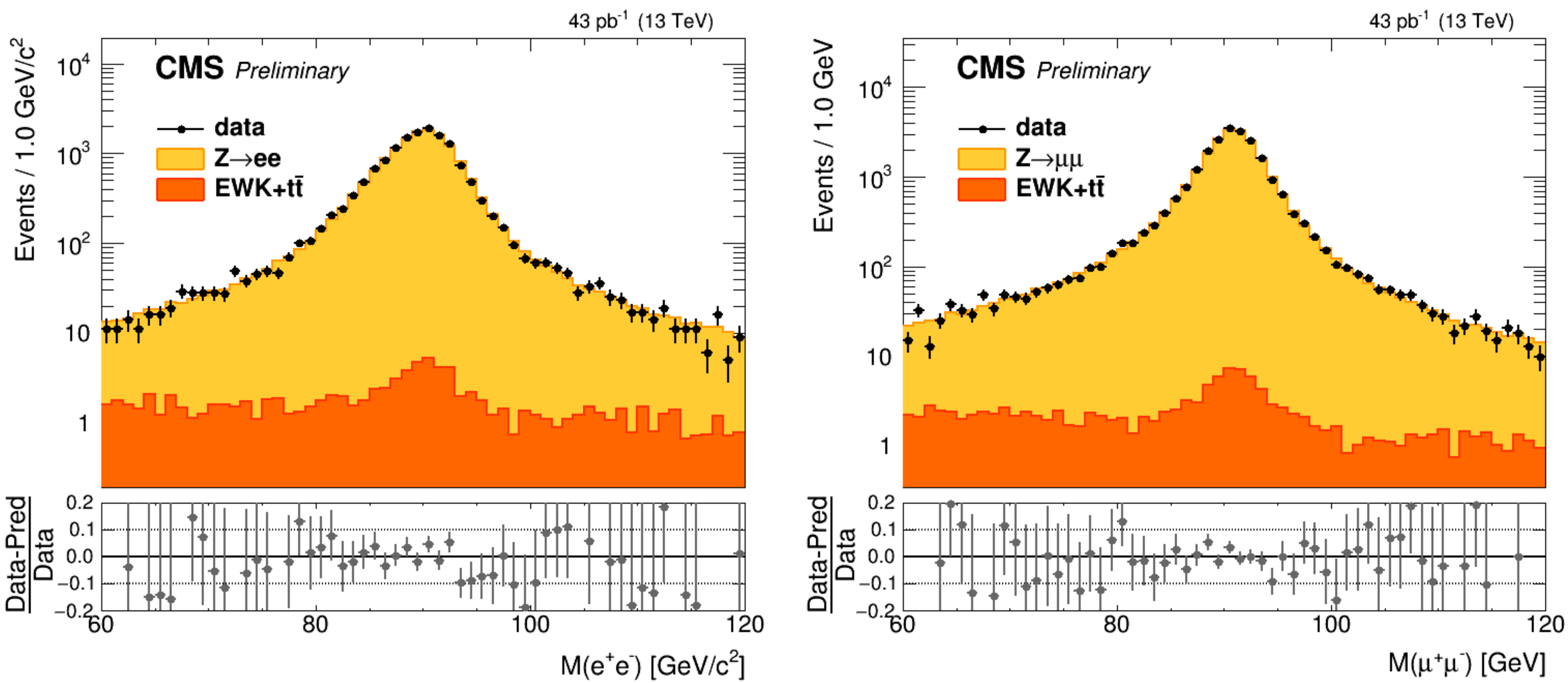
Z and W production at 13 TeV (CMS — new!)

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

[CMS-PAS-SMP-15-004]

W and Z inclusive cross section measurements

For Z: count events in $m(Z)$ region. Measurement benefits from a reduced luminosity uncertainty of 4.8%!
Leading systematic uncertainty from lepton identification (~2%)



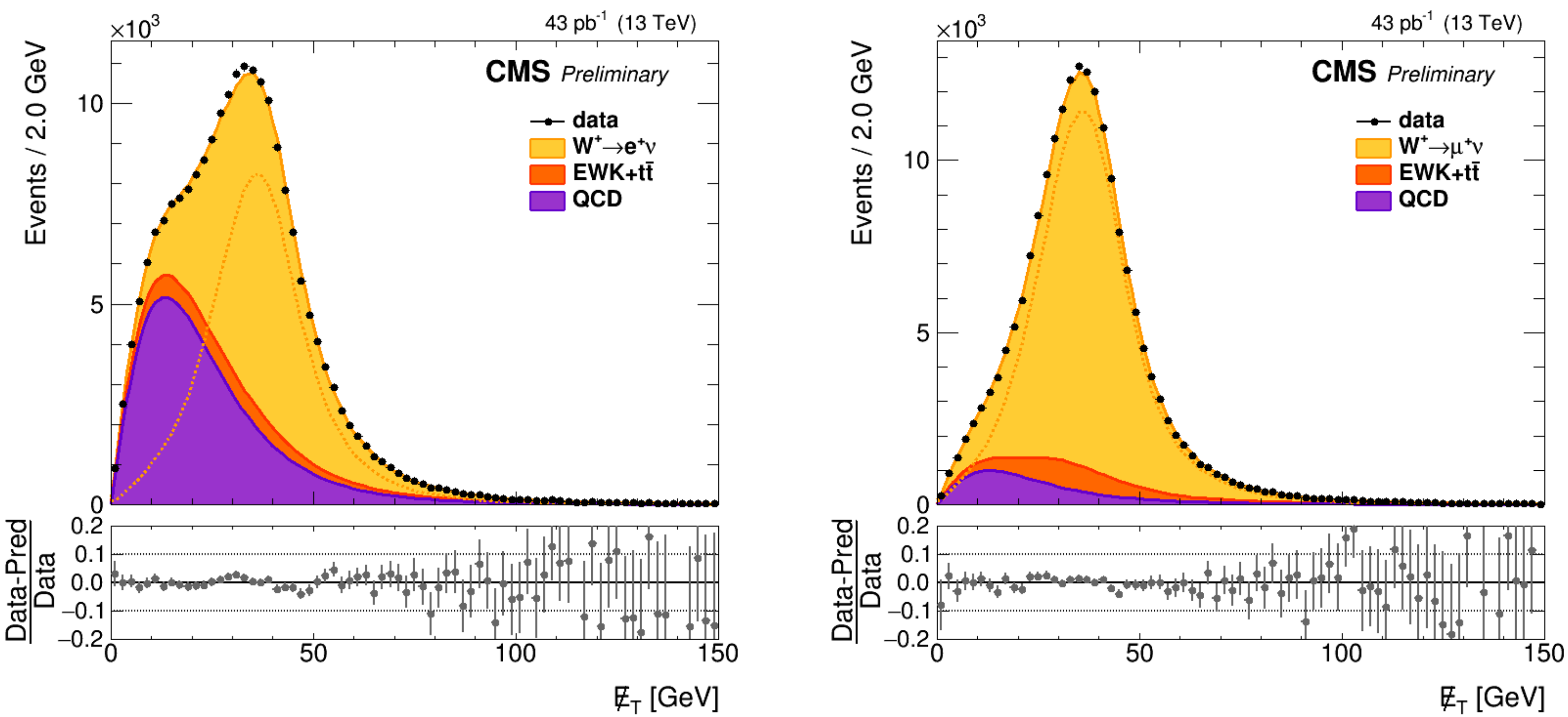
Z and W production at 13 TeV (CMS — new!)

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

[CMS-PAS-SMP-15-004]

W and Z inclusive cross section measurements

For W: fit of $E_{T,\mathrm{miss}}$ spectrum. Measurement benefits from a reduced luminosity uncertainty of 4.8%!
Leading systematic uncertainty from lepton identification (~2%)



[ATLAS-CONF-2015-039, CMS-PAS-SMP-15-004]

Z and W production at 13 TeV

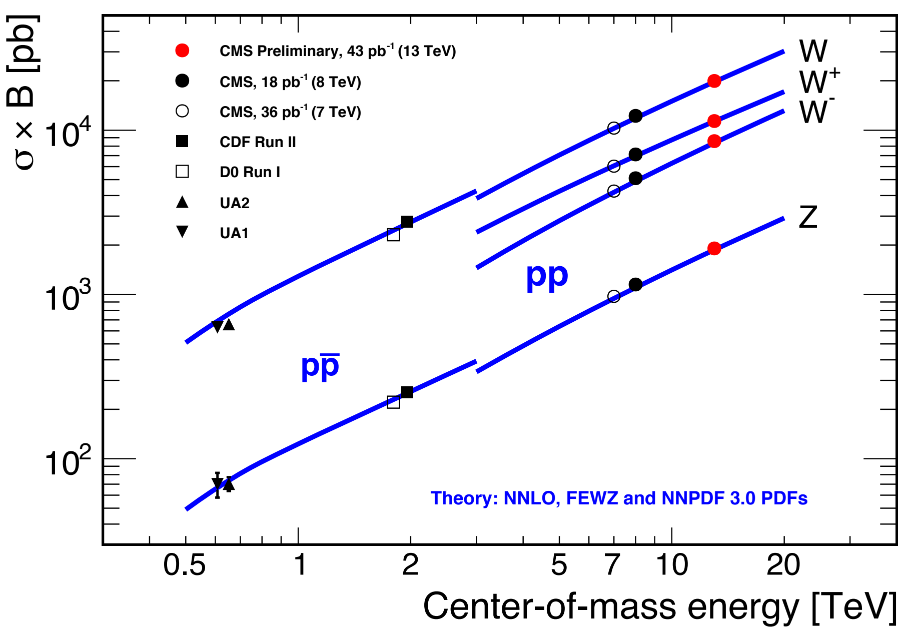
Expect increase of cross section by **factors of 1.7 and 1.6**, respectively

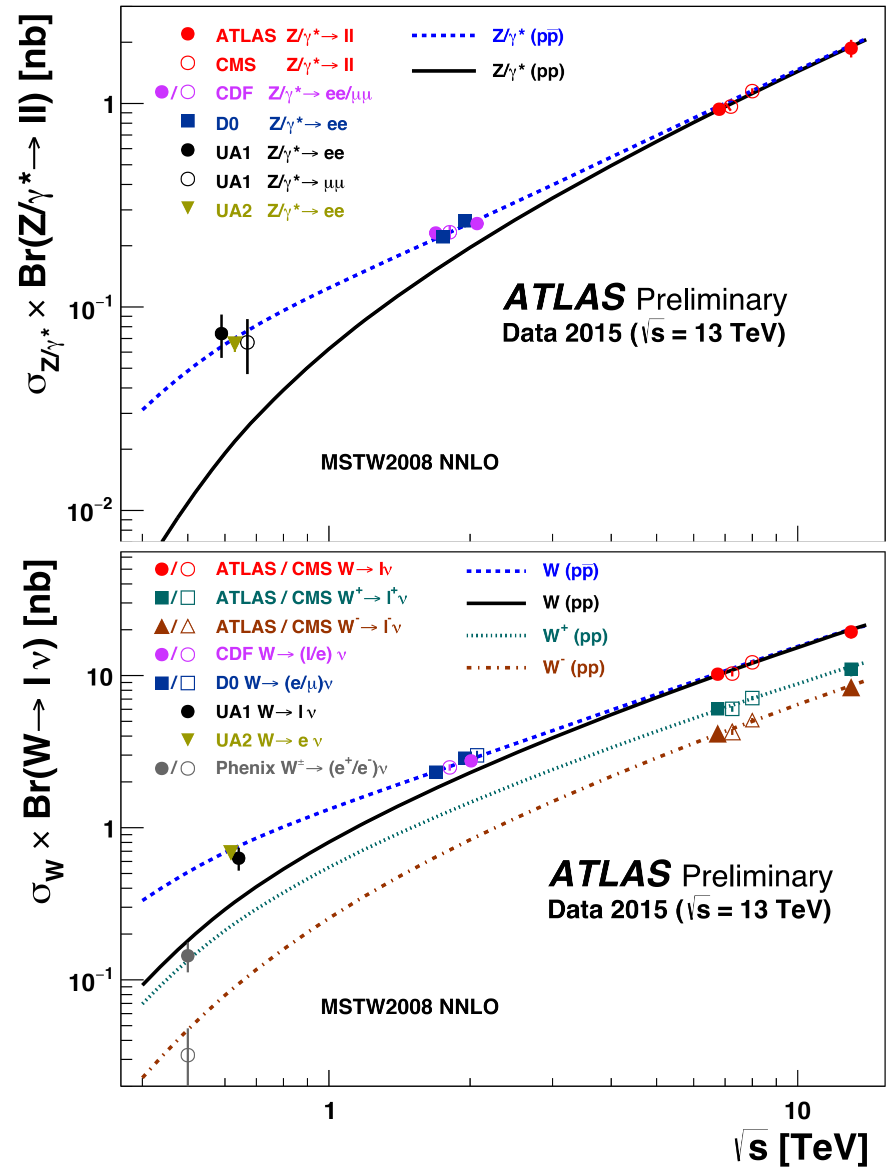
Resulting inclusive cross sections

Comparison of measured cross-sections with NNLO QCD & NLO EW predictions (FEWZ 3.1)

Good agreement found within uncertainties, also with lepton universality

Measured also fiducial cross sections



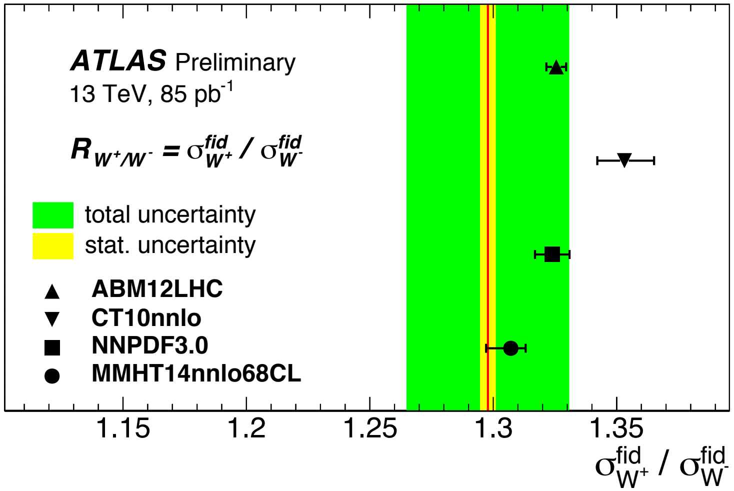


[ATLAS-CONF-2015-039, CMS-PAS-SMP-15-004]

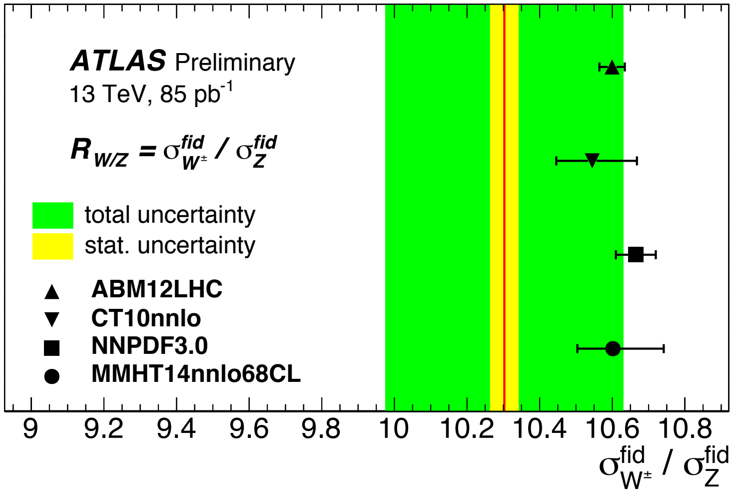
Cross-section ratios quite precise (< 3%)

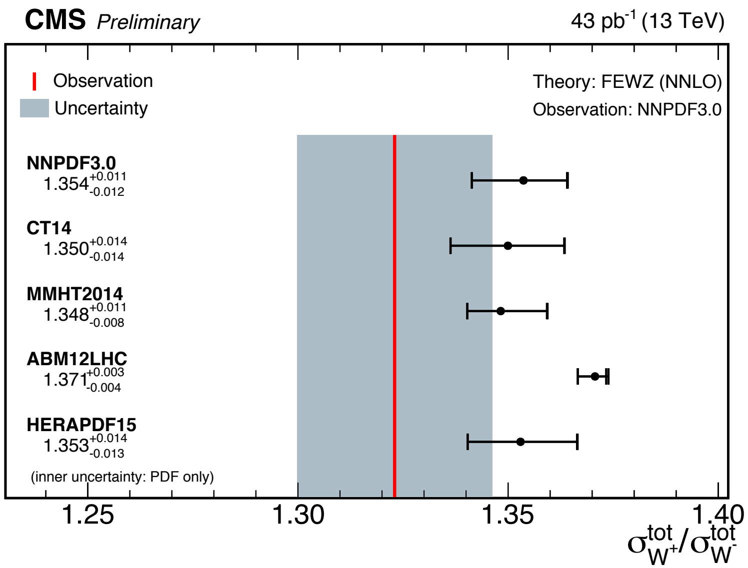
Powerful tools to constrain PDFs: W^+ / W^- sensitive to low-x u & d valence, W / Z constrains s

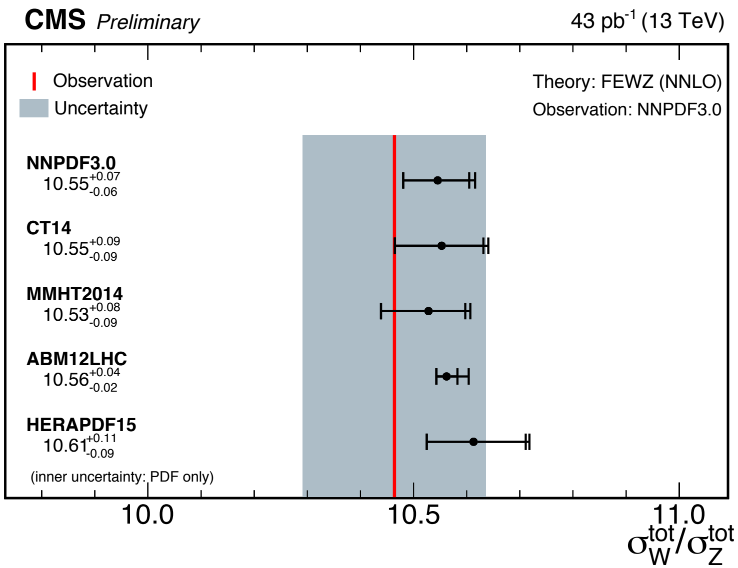
Note: fiducial cross-section ratios



Note: fiducial cross-section ratios







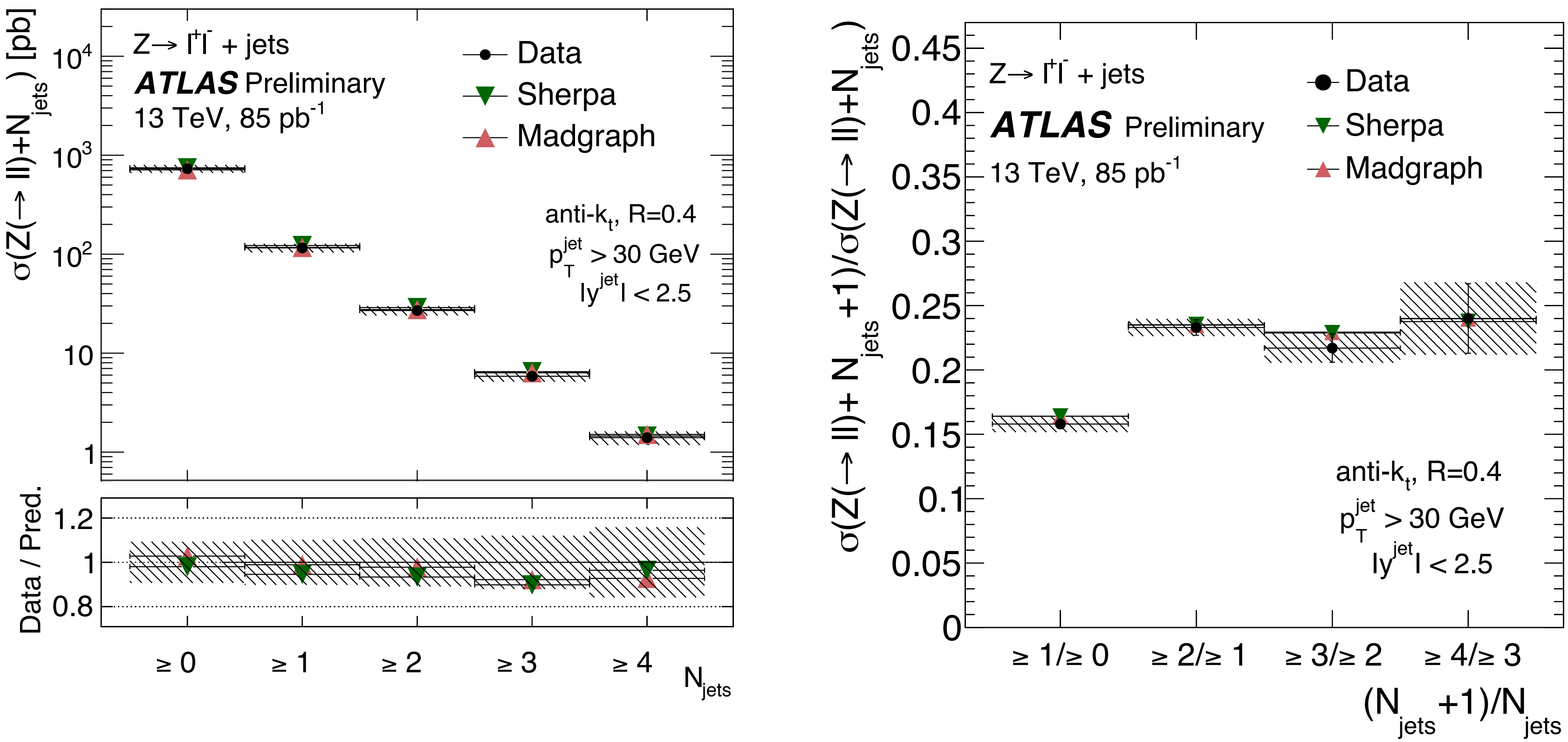
ATLAS also looked into production of Z associated with jets

Benchmark process to understanding QCD and EW physics at 13 TeV

[ATLAS-CONF-2015-041]

Measurement in its own right and validation of important background to new physics searches

Good description by SHERPA 2.1.1 (ME+PS@NLO prescription, up to 2 partons at NLO, up to 4 partons at LO ME) and Madgraph (LO)



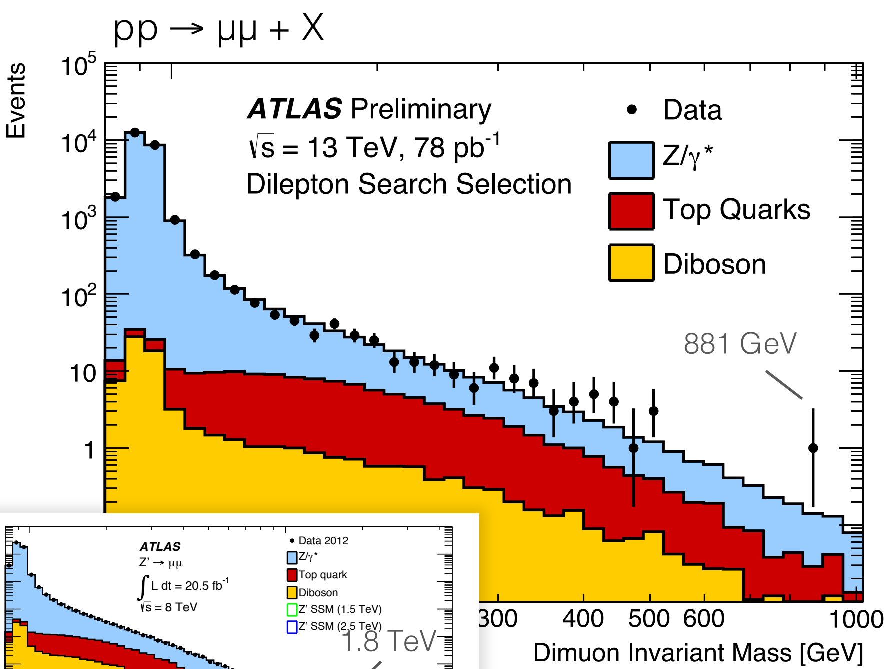
High-mass dilepton production

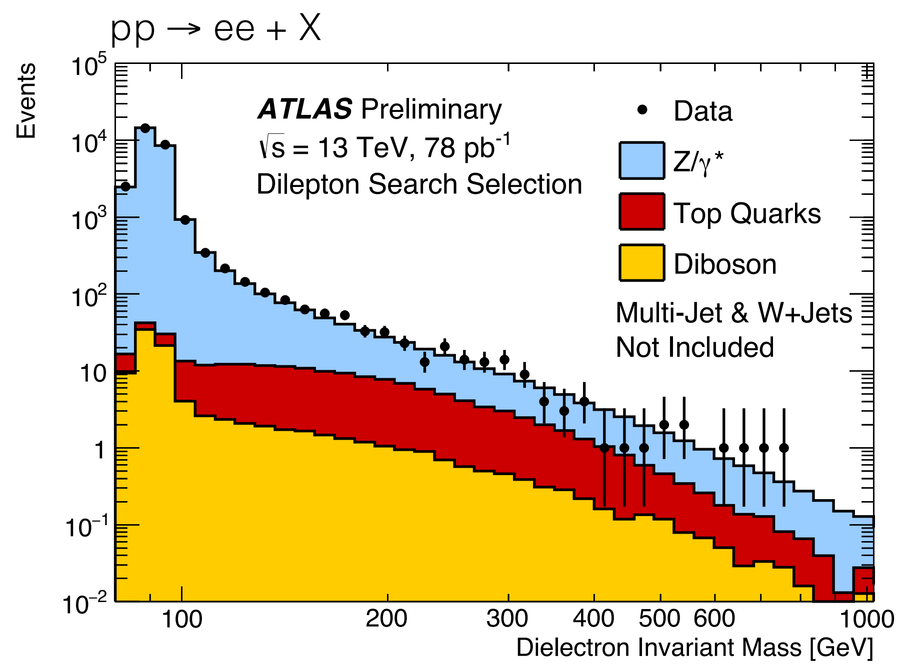
Insufficient luminosity yet to challenge Run-1 sensitivity to new physics

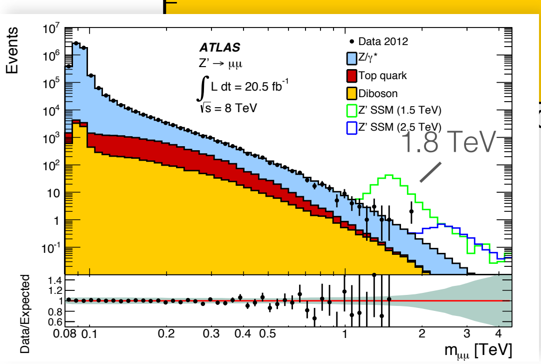
[ATLAS EXOT-2015-001,
EXOT-2015-004]

Drell-Yan production at high q^2

Dominant irreducible backgrounds taken from MC simulation, DY normalised to Z peak

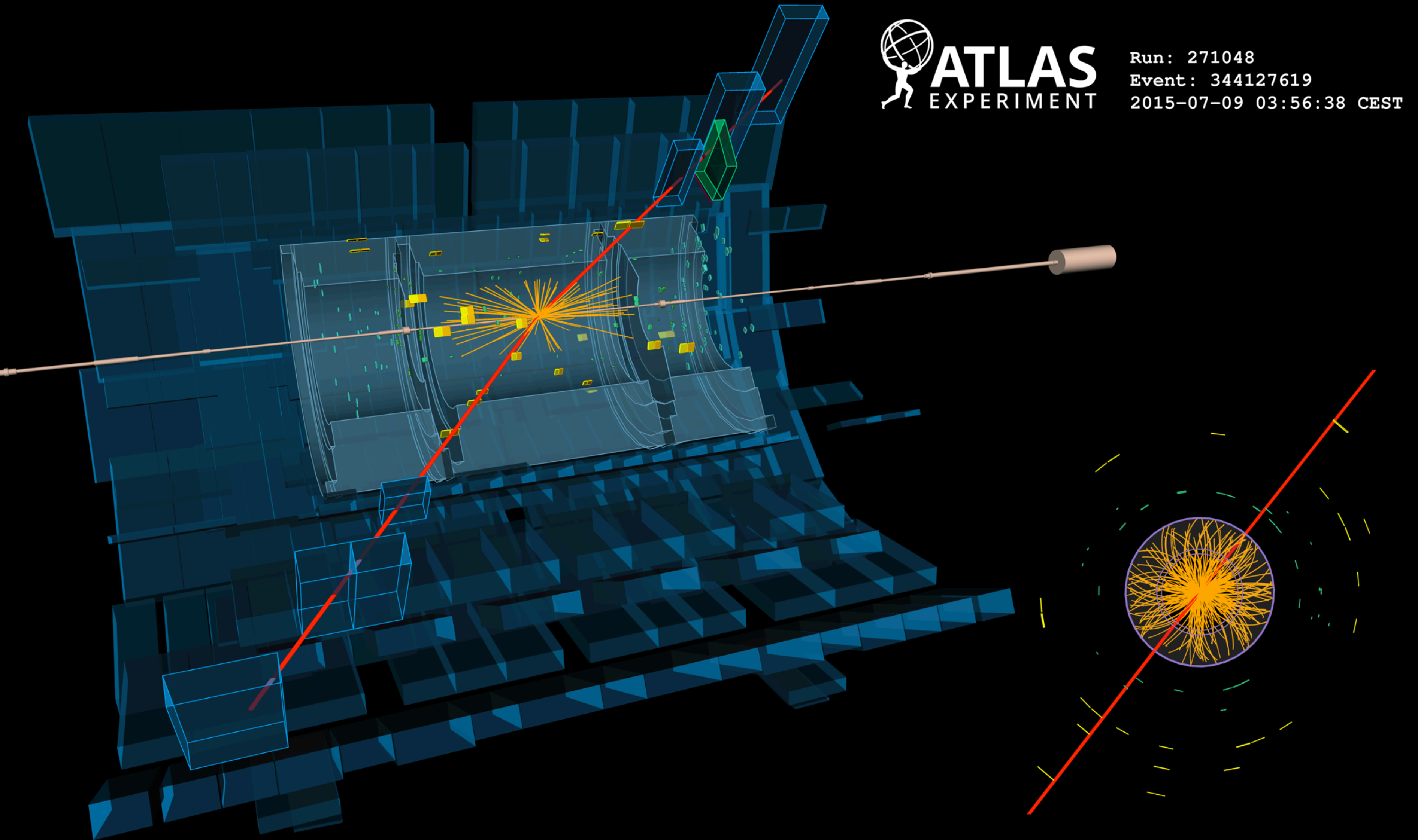




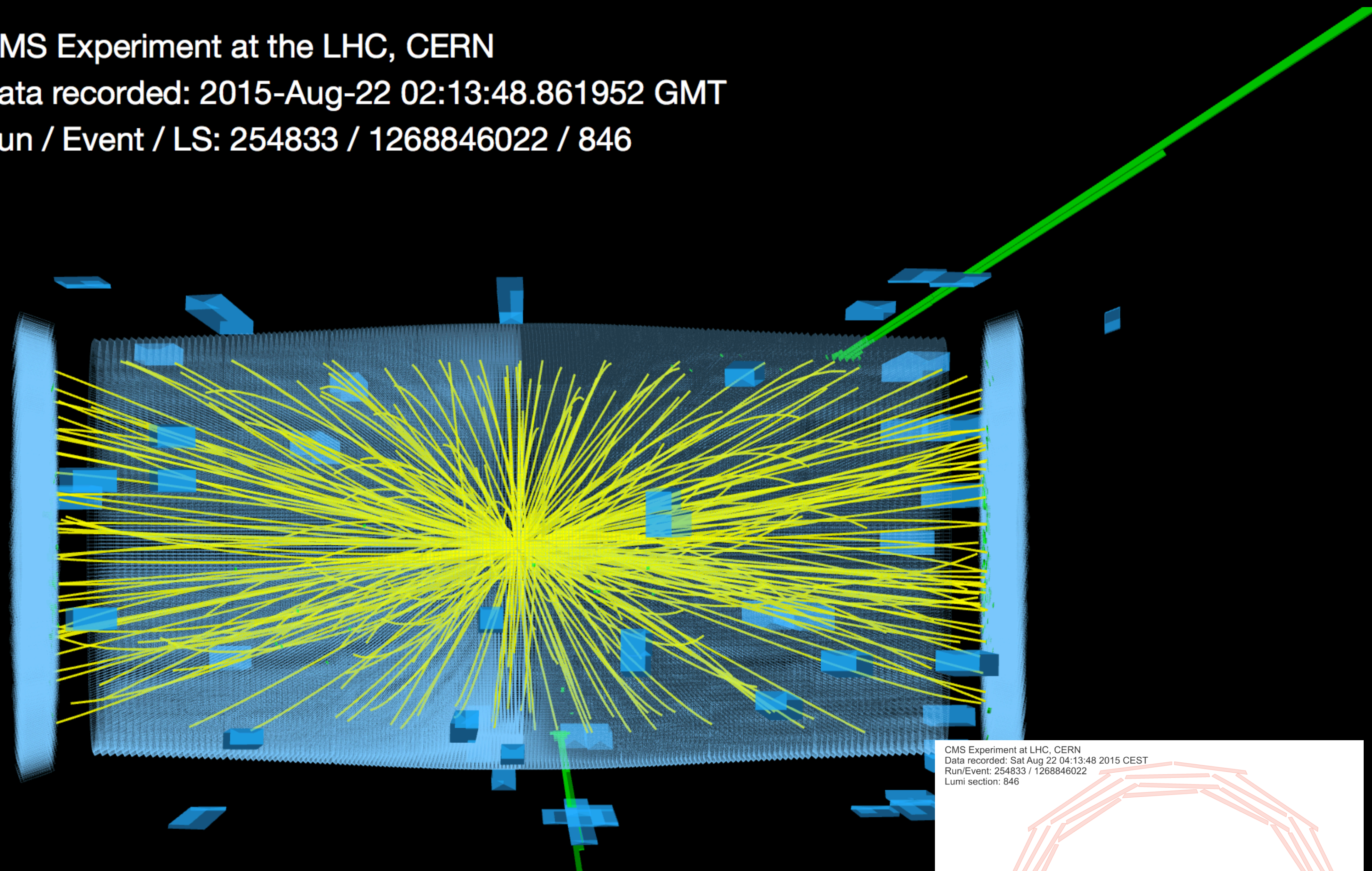


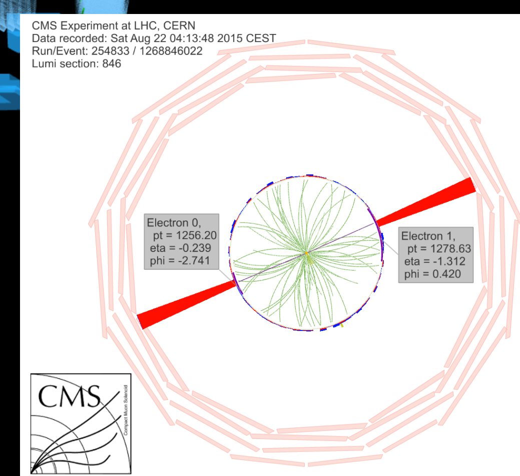
[20.3 fb^{-1}, 8 TeV, arXiv:1405.4123]

Display of μ⁺μ⁻ event with 881 GeV invariant mass



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

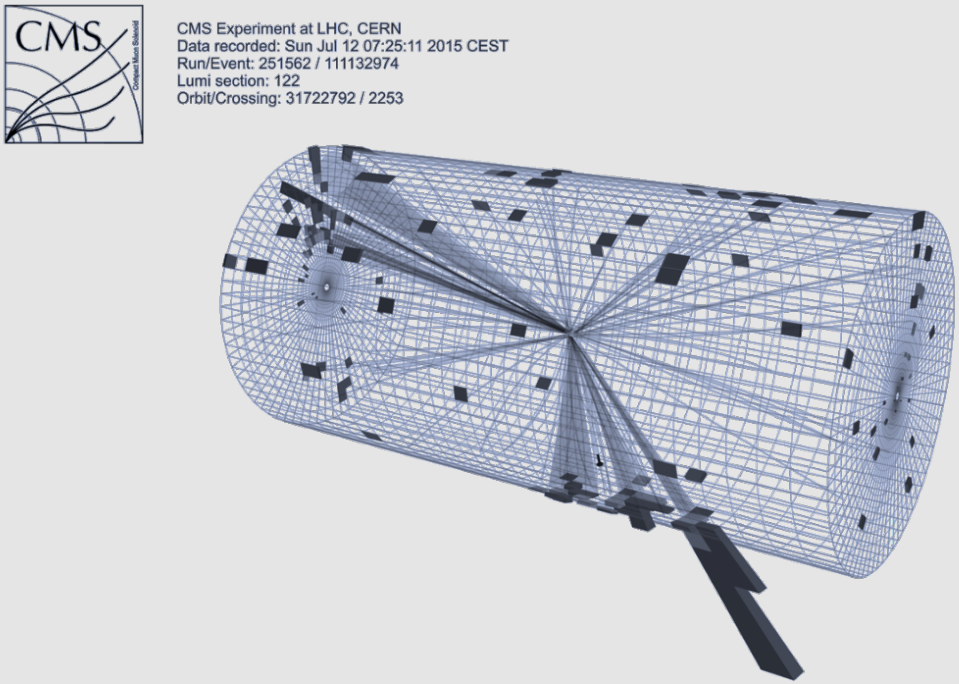




- Display of rare *colossal* e^+e^- candidate event with 2.9 TeV invariant mass
- Each electron candidate has 1.3 TeV E_T
- Back-to-back in ϕ

Highest-mass Run-1 events: 1.8 TeV (ee), 1.9 TeV (μμ)

Top quark production at 13 TeV



Boosted hadronic ttbar event
measured by CMS

Top-antitop production at 13 TeV

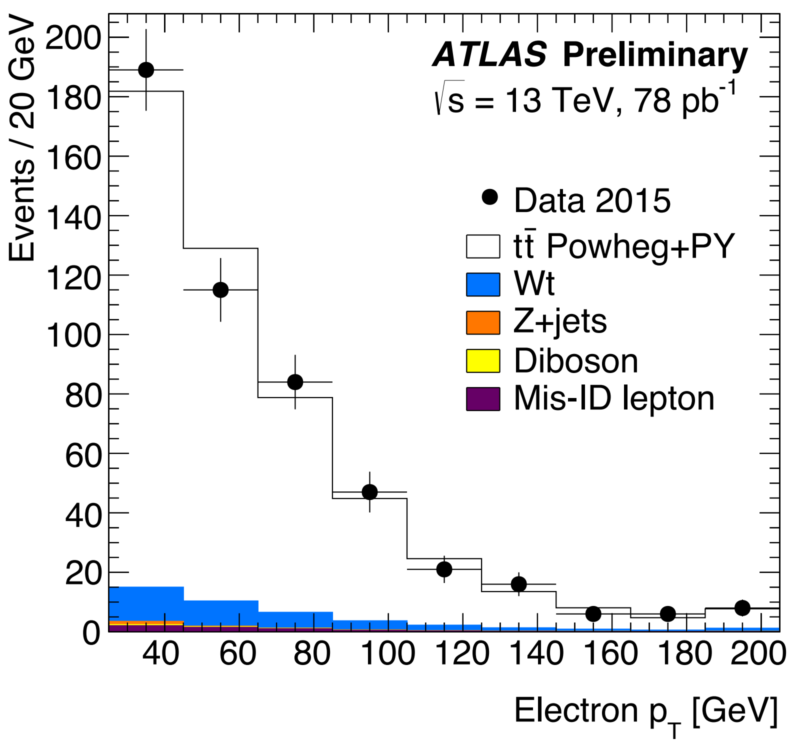
Expect increase of 8 TeV cross section by a **factor of 3.3**

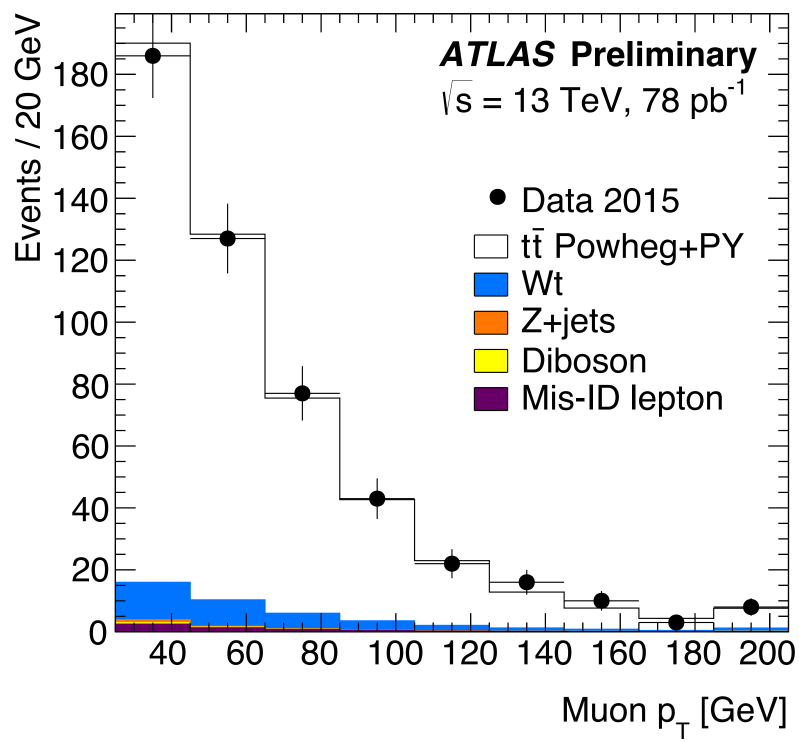
[ATLAS-CONF-2015-033, ATLAS-CONF-2015-049]

Cleanest channel: tt → (e + ν + b-jet) + (μ + ν + b-jet) = eμ + 2 b-jets + $E_{T,\text{miss}}$

Select: OS electrons & muons with p_T > 25 GeV, at least one b-tagged jet with p_T > 25 GeV
(clean channel, no $E_{T,\text{miss}}$ requirement needed → reduce systematics)

Shape comparison only. MC normalised to data





Top-antitop production at 13 TeV

Extraction of top-pair cross section

[ATLAS-CONF-2015-033, ATLAS-CONF-2015-049]

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

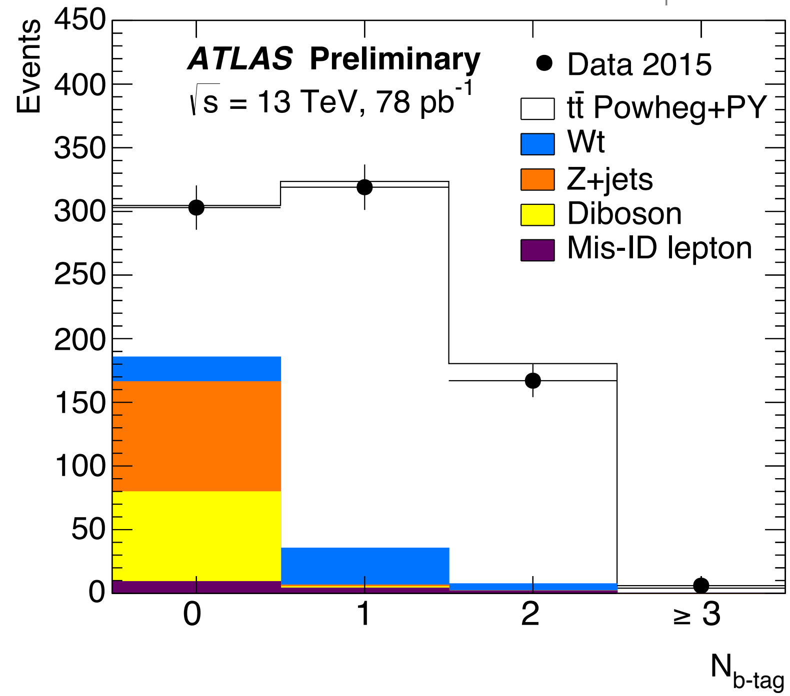
$$N_1 = L \cdot \sigma_{t\bar{t}} \cdot \varepsilon_{e\mu} \cdot 2\varepsilon_b \cdot (1 - C_b \varepsilon_b) + N_1^{bkg}$$
$$N_2 = L \cdot \sigma_{t\bar{t}} \cdot \varepsilon_{e\mu} \cdot C_b \varepsilon_b^2 + N_2^{bkg}$$

Where:

- $N_{1(2)}$ – number of selected events with 1(2) b-tags
- $N_{1(2)}^{bkg}$ – 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 (1.005 ± 0.006 from MC)

MC normalised to SM expectation



Observe: $N_1 = 319$, $N_2 = 167$

Expect: $N_1^{bkg} = 37.3 \pm 5.5$, $N_2^{bkg} = 8.5 \pm 3.5$,
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

[ATLAS-CONF-2015-033, ATLAS-CONF-2015-049]

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

σ_{tt} (13 TeV) = 829 ± 50 (stat) ± 56 (syst) ± 83 (lumi) pb

Total relative uncertainty of 14% (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 (7.3%) dominated by

- tt hadronisation (4.5%) → large Pythia8 / Herwig++ parton shower effect, to be further studied
- tt NLO modelling, ISR/FSR radiation & PDF (2.8%)
- Electron ID + isolation (3.4%)
- Muon ID + isolation (1.2%)
- Lepton mis-identification (1.4%)
- Lepton triggers (0.8%)

(Electron ID + isolation, Muon ID + isolation, Lepton mis-identification, Lepton triggers) → will improve with more data

Overall uncertainty dominated by luminosity (9%) → will improve with full van-der-Meer luminosity scan

We also measure: ε_b = 0.527 ± 0.026 ± 0.006, in good agreement with simulation: 0.543

Top-antitop production at 13 TeV

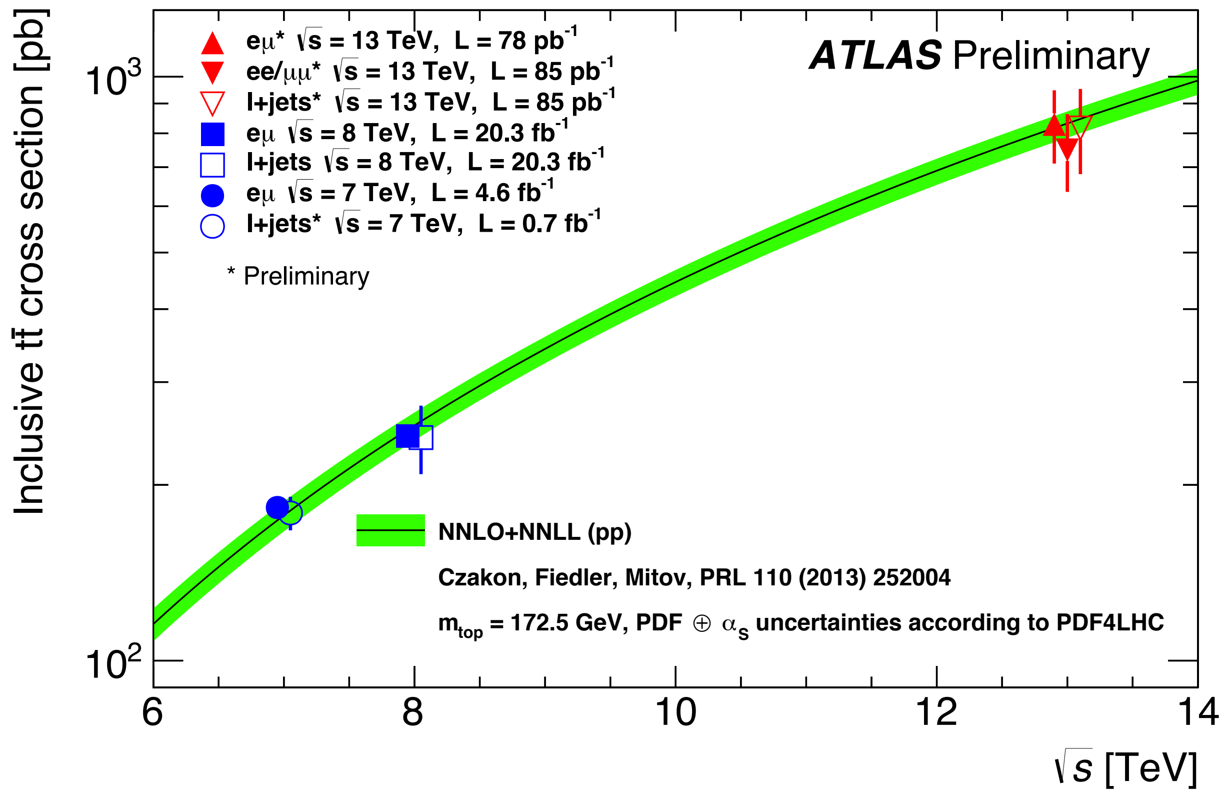
Extraction of top-pair cross section

[ATLAS-CONF-2015-033, ATLAS-CONF-2015-049]

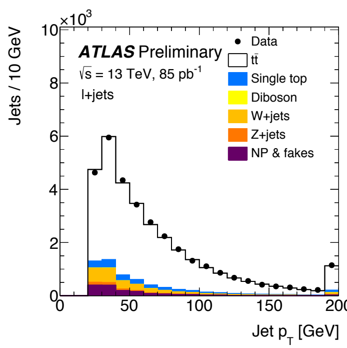
Solving the equation gives the following 13 TeV pp → tt + X cross section

σ_{tt} (13 TeV) = 829 ± 50 (stat) ± 56 (syst) ± 83 (lumi) pb

SM: 832 $^{+40}_{-46}$ pb



Also: same-flavour and lepton+jets fiducial and inclusive cross-section measurements



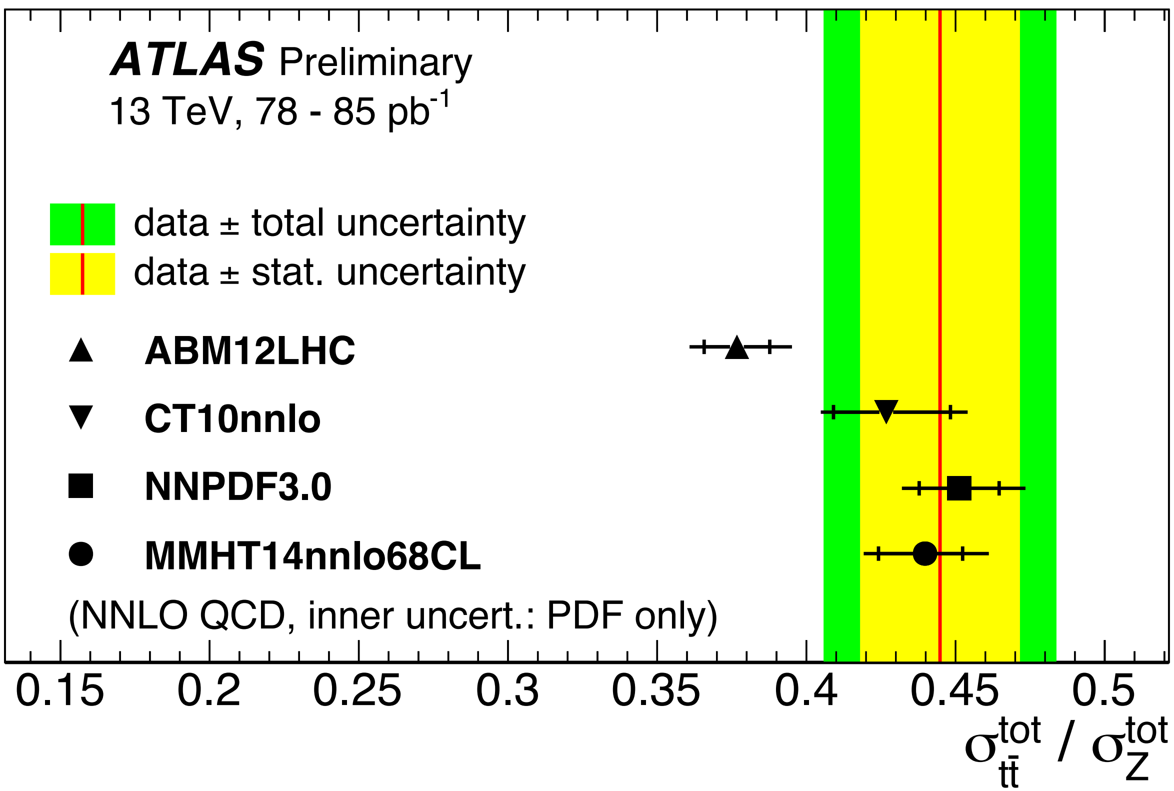
Top-antitop production at 13 TeV

Extraction of top-pair cross section

[ATLAS-CONF-2015-049]

Ratio to Z cross section reduces systematic uncertainty

$R(\text{tt} / \text{Z}) = 0.445 \pm 0.027\ (\text{stat}) \pm 0.028\ (\text{syst})$ [9%]



Ratio of ttbar(e–μ) to Z cross-section measurement

(sensitive to ratio of gluon to sea-quark PDFs)

Total and differential cross-section measurements

Test 13 TeV modelling (verify known problems during Run-1)

[CMS 1510.05302, CMS PAS TOP-15-010]

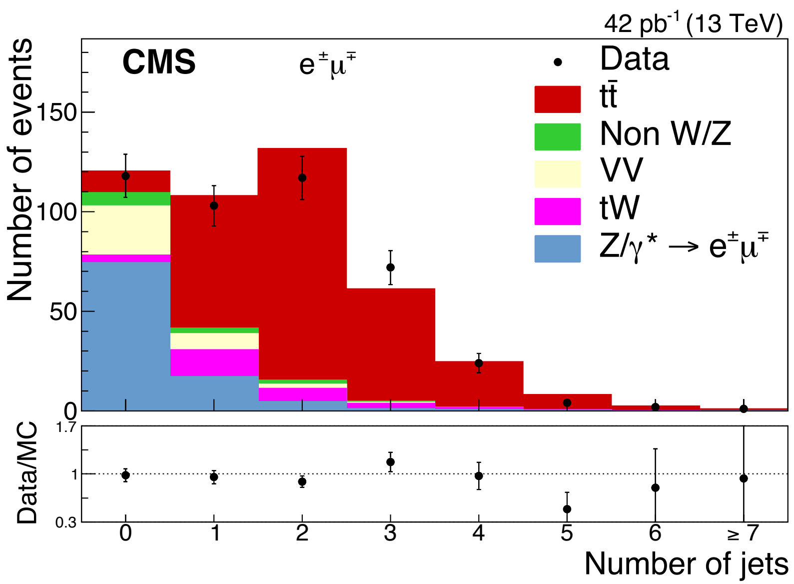
Total cross-section measurement in dilepton e–μ channel

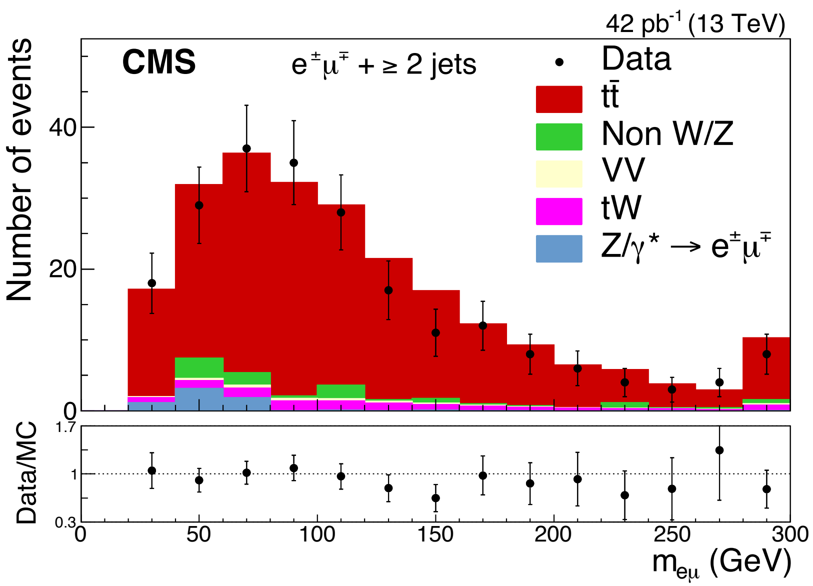
Select: OS electrons & muons with $p_T >$ 20 GeV, ≥ 2 jets with $p_T >$ 30 GeV, $|\eta_{e,\,\mu,\,jets}| <$ 2.4, no b-tagging (alternative analysis uses 0,1,2 b-tagging categories)

Trigger and lepton efficiencies largest systemtics after luminosity

σ_{tt} (13 TeV) = 769 ± 60 (stat) ± 55 (syst) ± 92 (lumi) pb

Total relative uncertainty of 16%





Total and differential cross-section measurements

Test 13 TeV modelling (verify known problems during Run-1)

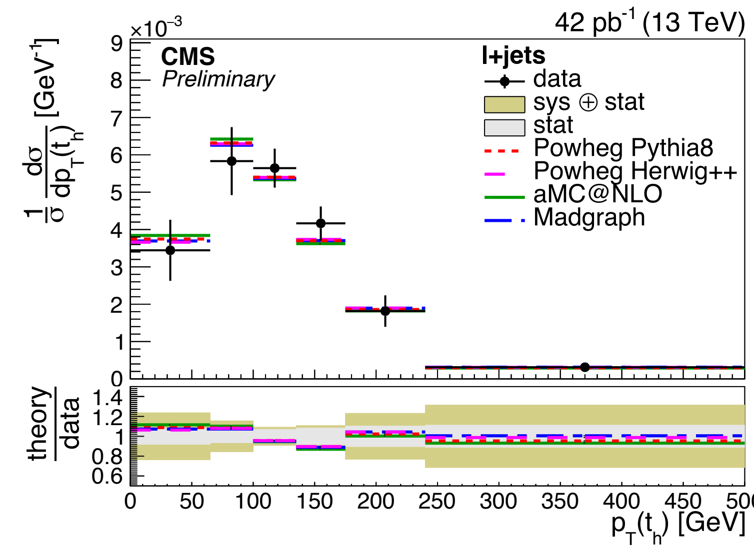
[CMS-PAS-TOP-15-005]

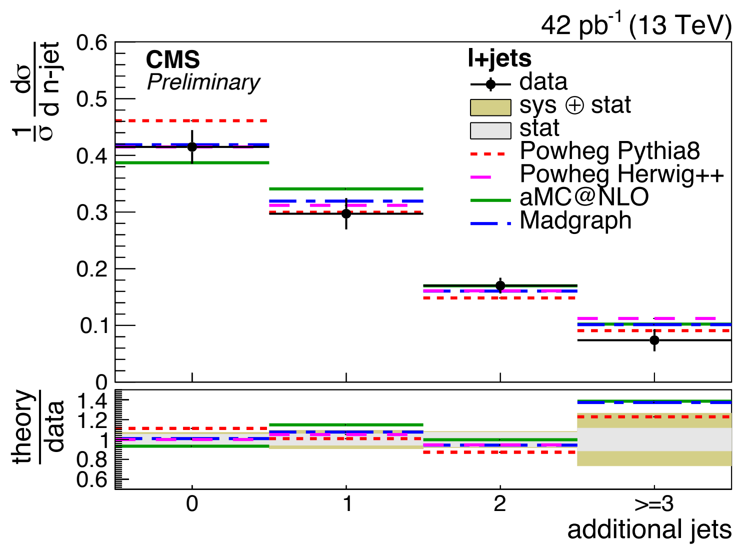
Total and differential cross-section measurements in lepton+jets channel

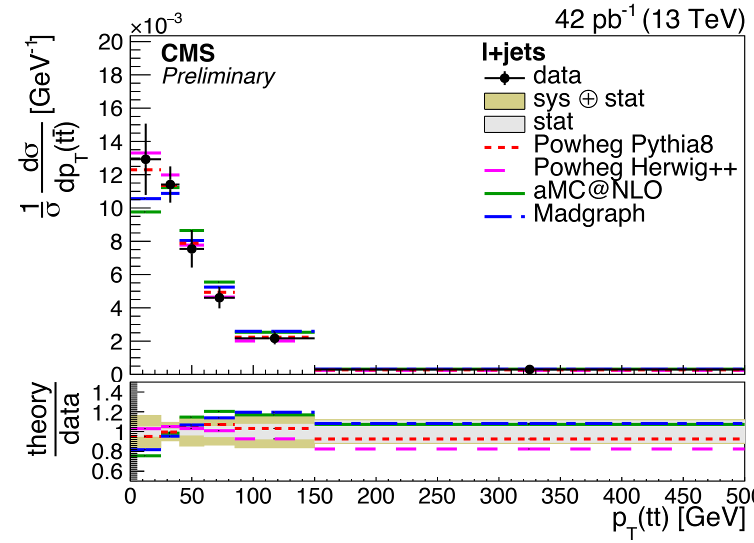
Select: 1 electron or muon with $p_T > 30$ GeV, $|\eta_{e,\mu}| < 2.1$, ≥ 4 jets with $p_T > 25$ GeV, $|\eta_{jets}| < 2.4$, ≥ 1 b-tag

Dominant systematics: luminosity, b-tagging, JES/JER, PDF, PS

Also total inclusive cross-section measurement





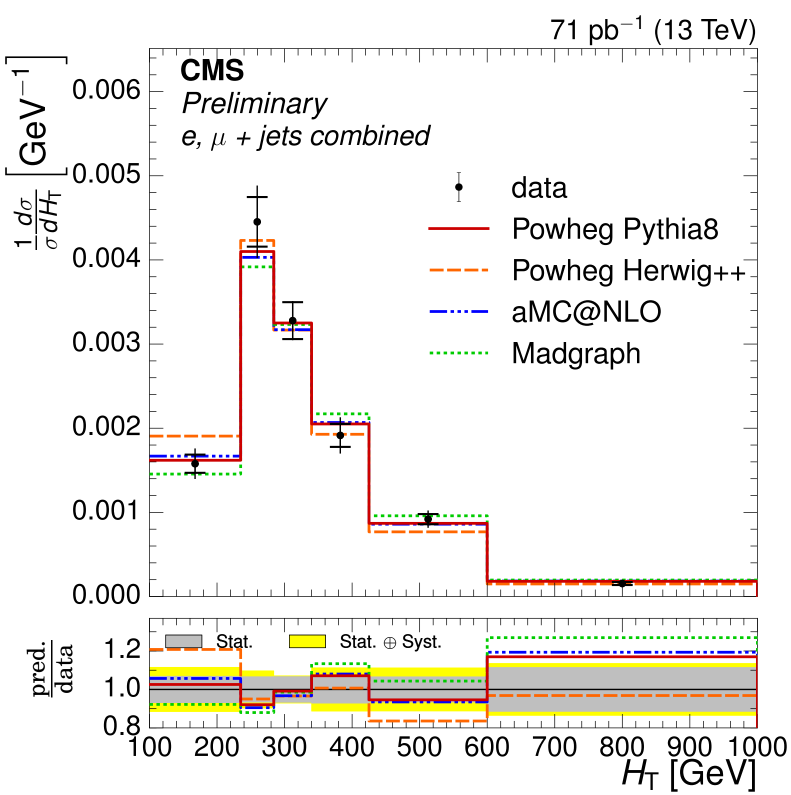


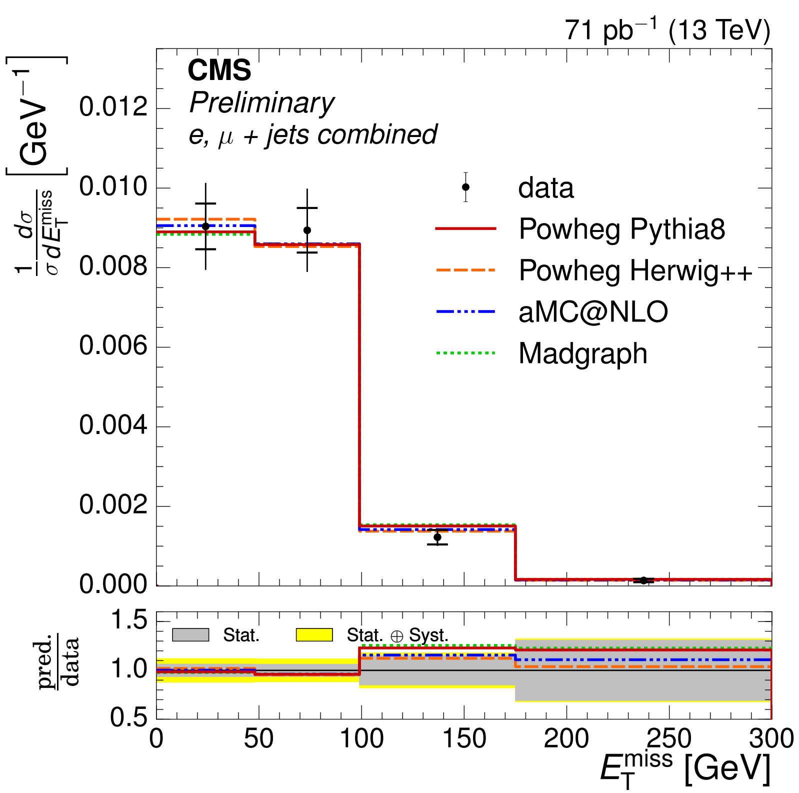
Test 13 TeV modelling (verify known problems during Run-1)

[CMS-PAS-TOP-15-013]

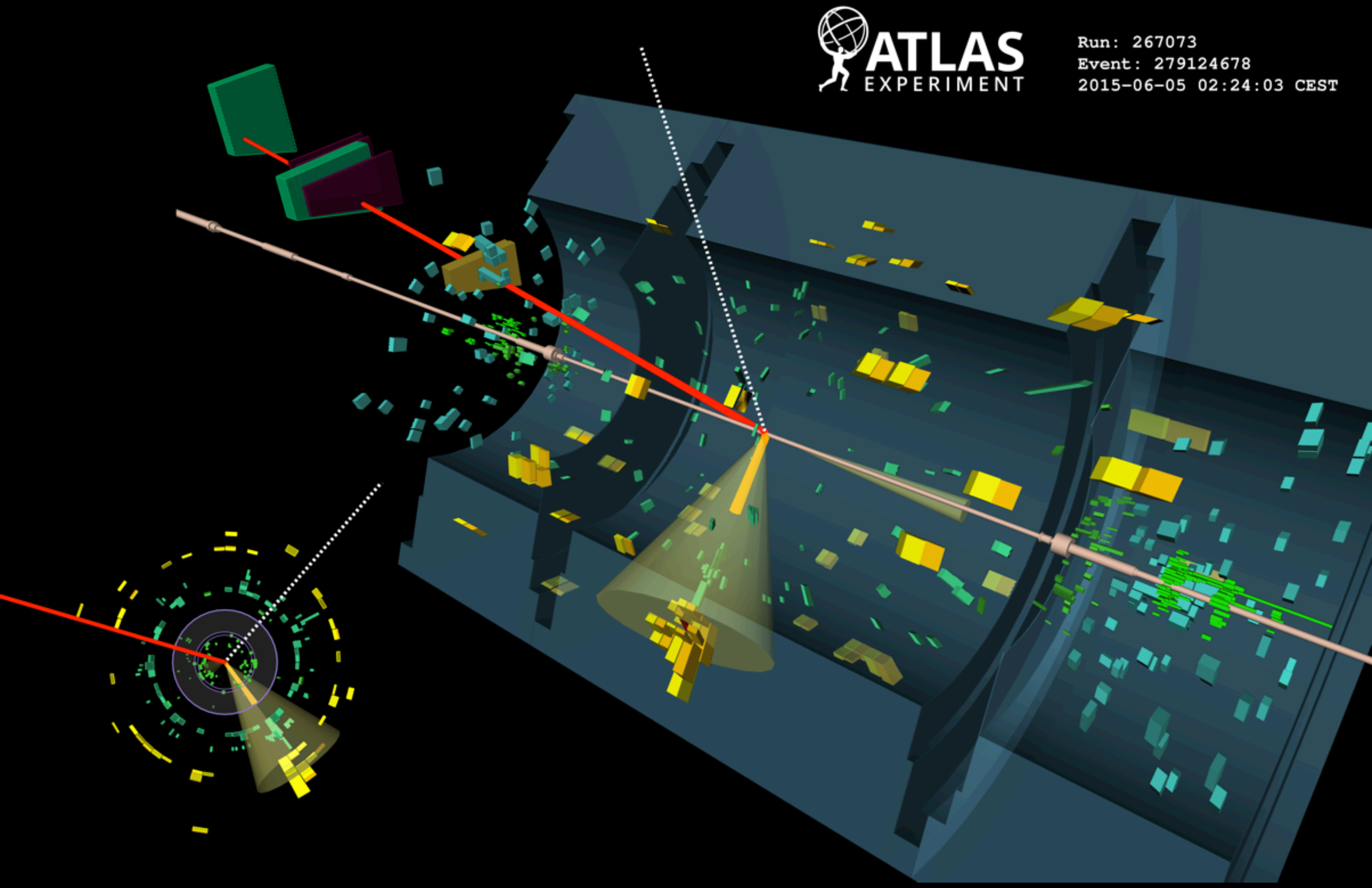
Additional recent differential cross-section measurements in lepton+jets channel

Larger luminosity of 71 pb^{-1}, different variables





Display of t-channel single-top candidate event: muon with p_T of 30 GeV, central b-tagged jet of 50 GeV, forward jet 30 GeV, $E_{T,\text{miss}}$ of 40 GeV



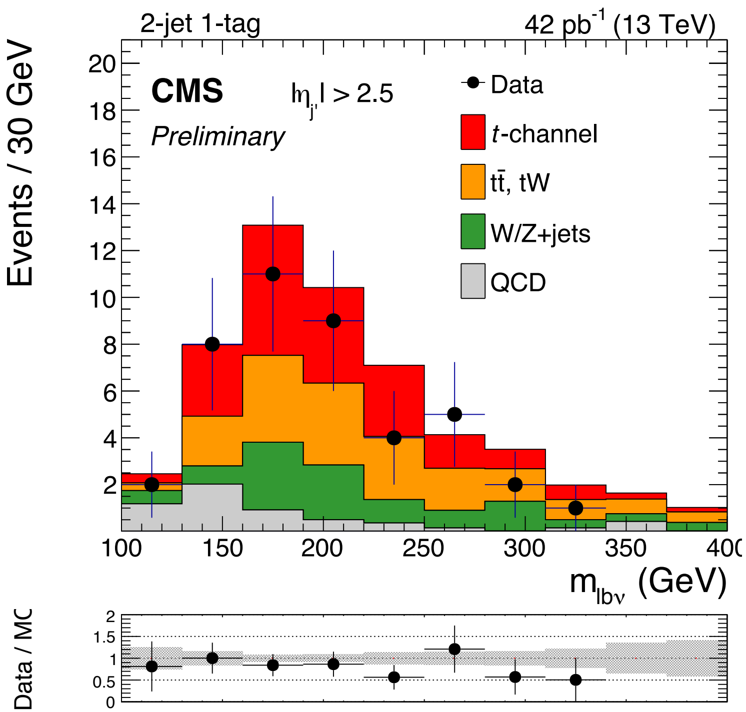
Finally: t-channel single top production

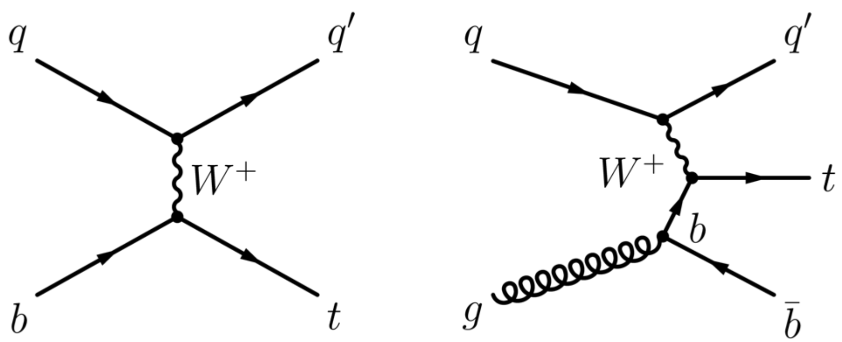
Expect factor 2.5 larger cross-section at 13 TeV compared to 8 TeV

[CMS-PAS-TOP-15-004]

Early measurement by CMS using 42 pb^{-1} of data in muon channel

Select: =1 isolated muon with $p_T > 22$ GeV, $|\eta_\mu| < 2.1$, jets > 40 GeV, $|\eta_{jet}| < 4.7$; t-channel enriched events have 2 jets, 1 b-tag and $m_{\mu\nu b} \sim m_{top}$. Signal extracted from fit to $|\eta_{light\text{-}jet}|$ distribution in $m_{\mu\nu b}$ signal region, top backgrounds from 2 b-tag control region. Systematics: JES (17%), luminosity (12%), b-tagging (6%), …





2→2 and 2→3 single-top t-channel processes

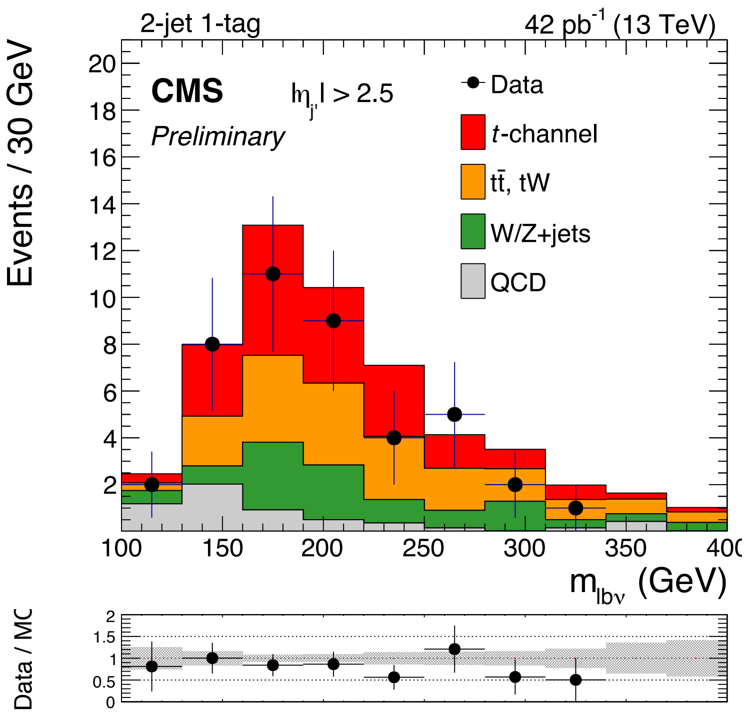
Finally: t-channel single top production

Expect factor 2.5 larger cross-section at 13 TeV compared to 8 TeV

[CMS-PAS-TOP-15-004]

Early measurement by CMS using 42 pb^{-1} of data in muon channel

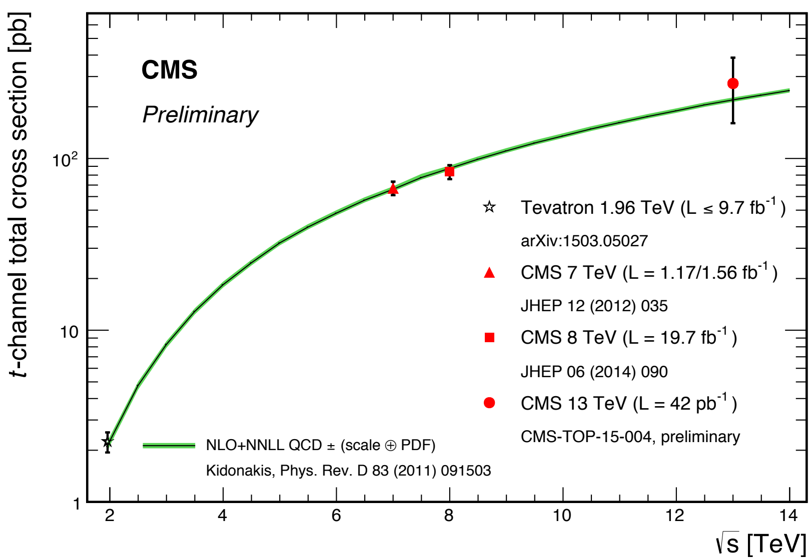
Select: =1 isolated muon with $p_T > 22$ GeV, $|\eta_\mu| < 2.1$, jets > 40 GeV, $|\eta_{jet}| < 4.7$; t-channel enriched events have 2 jets, 1 b-tag and $m_{\mu\nu b} \sim m_{top}$. Signal extracted from fit to $|\eta_{light\text{-}jet}|$ distribution in $m_{\mu\nu b}$ signal region, top backgrounds from 2 b-tag control region. Systematics: JES (17%), luminosity (12%), b-tagging (6%), …



3.5σ (2.7σ) observed (expected) significance

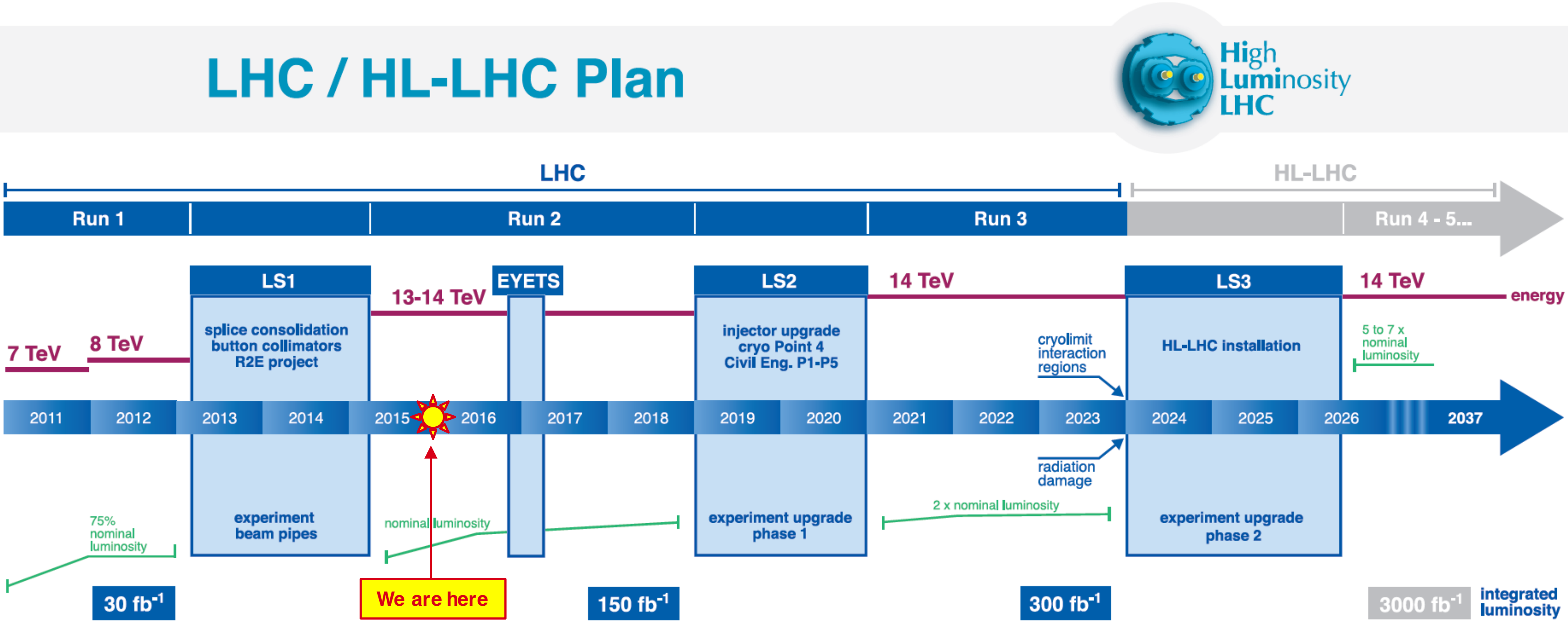
$$\sigma_{tt} = 274 \pm 98\ (\text{stat}) \pm 52\ (\text{syst}) \pm 33\ (\text{lumi})\ \text{pb}$$

$\sigma_{t\text{-channel}}$[SM] (13 TeV) = 217 $^{+7}_{-6}$ (scale) ± 6 (PDF) pb (NLO)



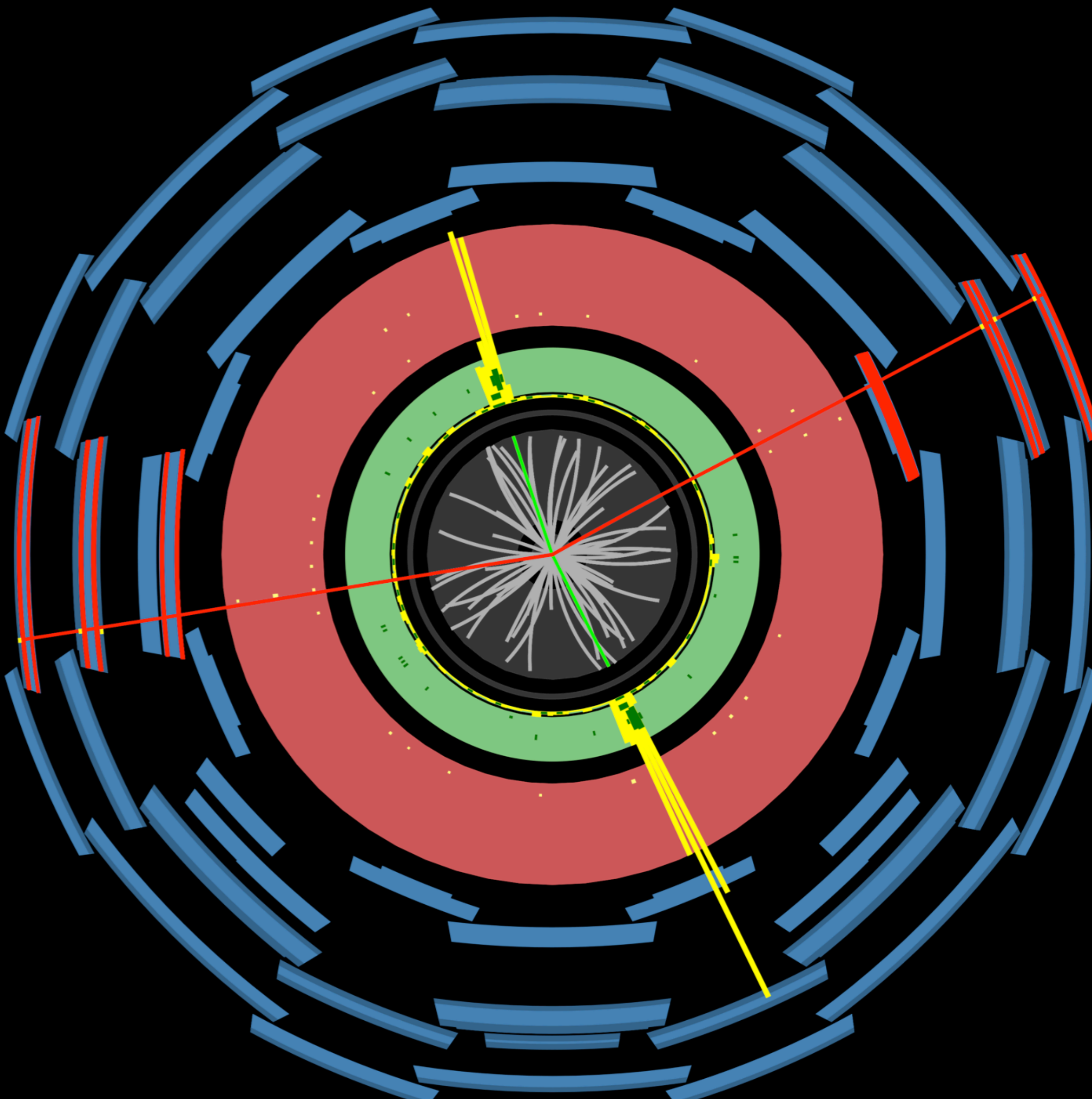
Conclusions

Successful restart by LHC and detectors after LS1
Experiments were well prepared — lots of interesting physics results already
Much more to come



Next updates: watch the archive and the end-of-year seminars, 15 Dec 2015
[http://indico.cern.ch/event/442432]

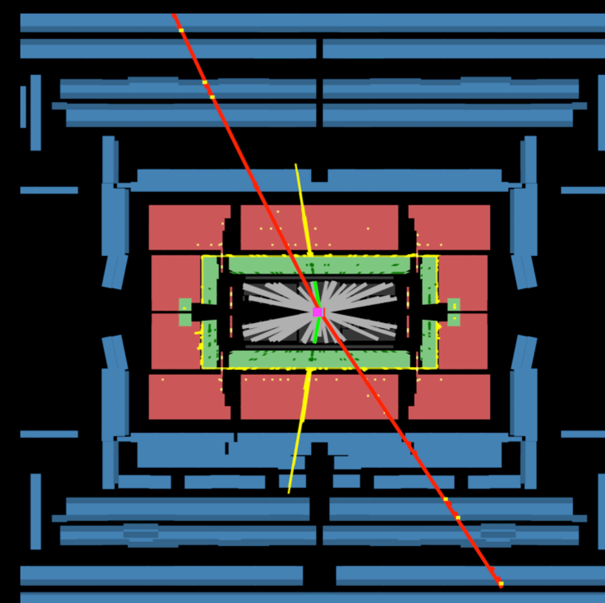
Display of ZZ → $\mu^+\mu^-$ + e^+e^- candidate event ($m_{\mu\mu\,/\,ee}$ = 94 / 86 GeV, $m_{\mu\mu ee}$ = 191 GeV)



ATLAS EXPERIMENT

Run Number: 271298, Event Number: 78224729

Date: 2015-07-10 20:50:34 CEST



Display of $H \rightarrow 2\mu 2e$ candidate from 13 TeV pp collisions. The measured momenta are: $p_T(\mu) = 55, 33$ GeV, $p_T(e) = 14, 11$ GeV The measured masses are: $m(2\mu 2e) = 123$ GeV, $m(\mu\mu) = 91$ GeV, $m(ee) = 27$ GeV.