Recent QCD results at the LHC

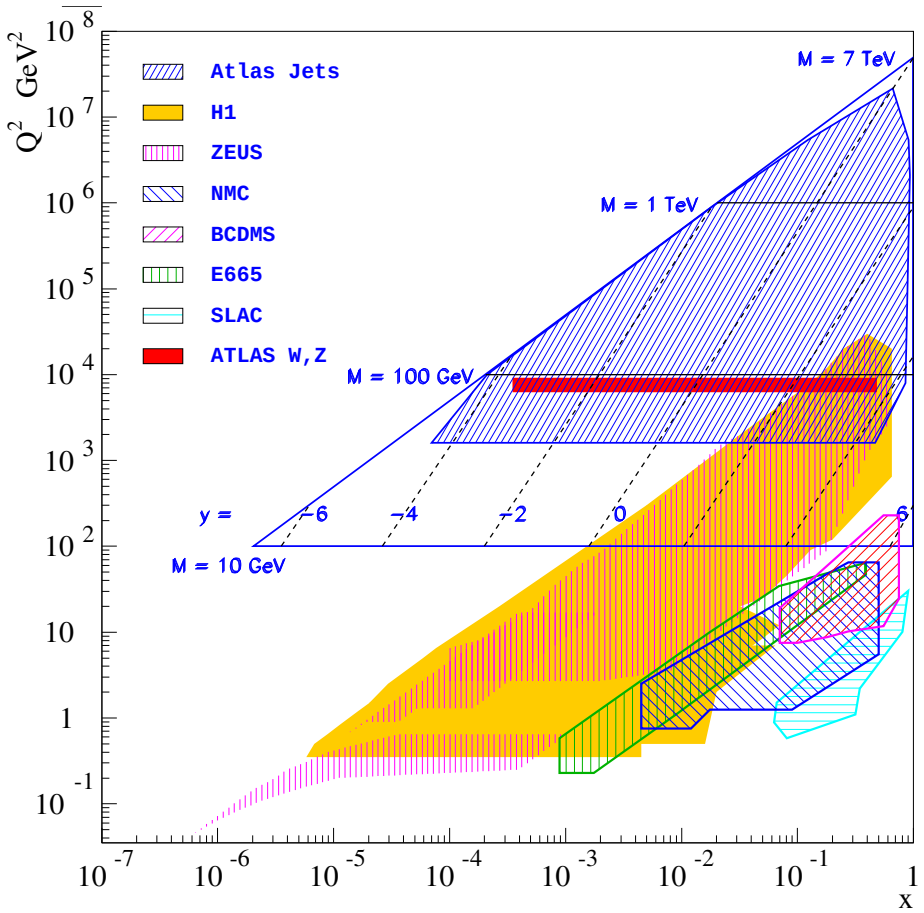
S. Glazov, Dallas, Nov 21 2016

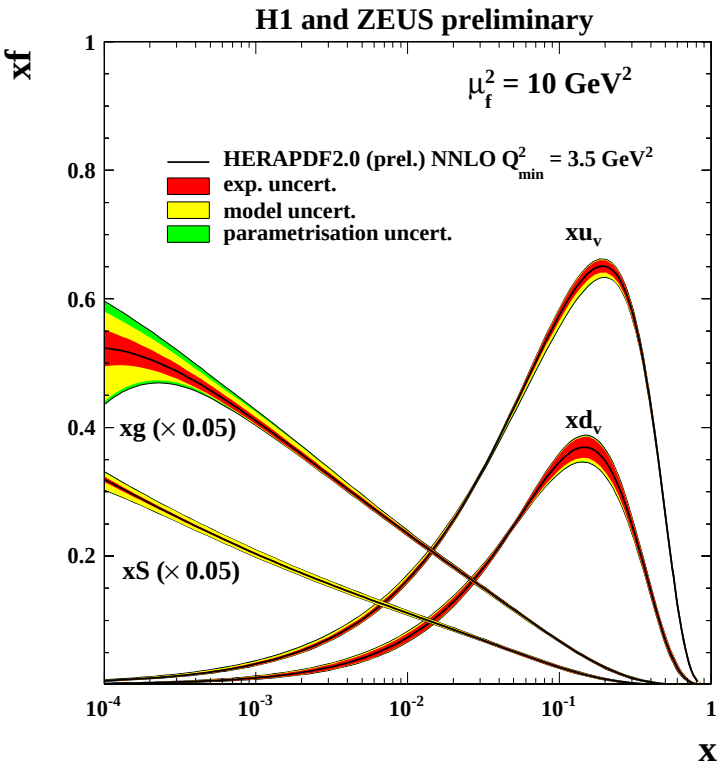
The LHC: proton-proton collider

Circumference	27 km
Beam energy	4 – (6.5) TeV
Centre of mass energy	8 (13) TeV
Run-I operation	2010-2013
Run-II start	2015

Main experiments: ATLAS, ALICE, CMS, LHCb.

The LHC: parton-parton collider

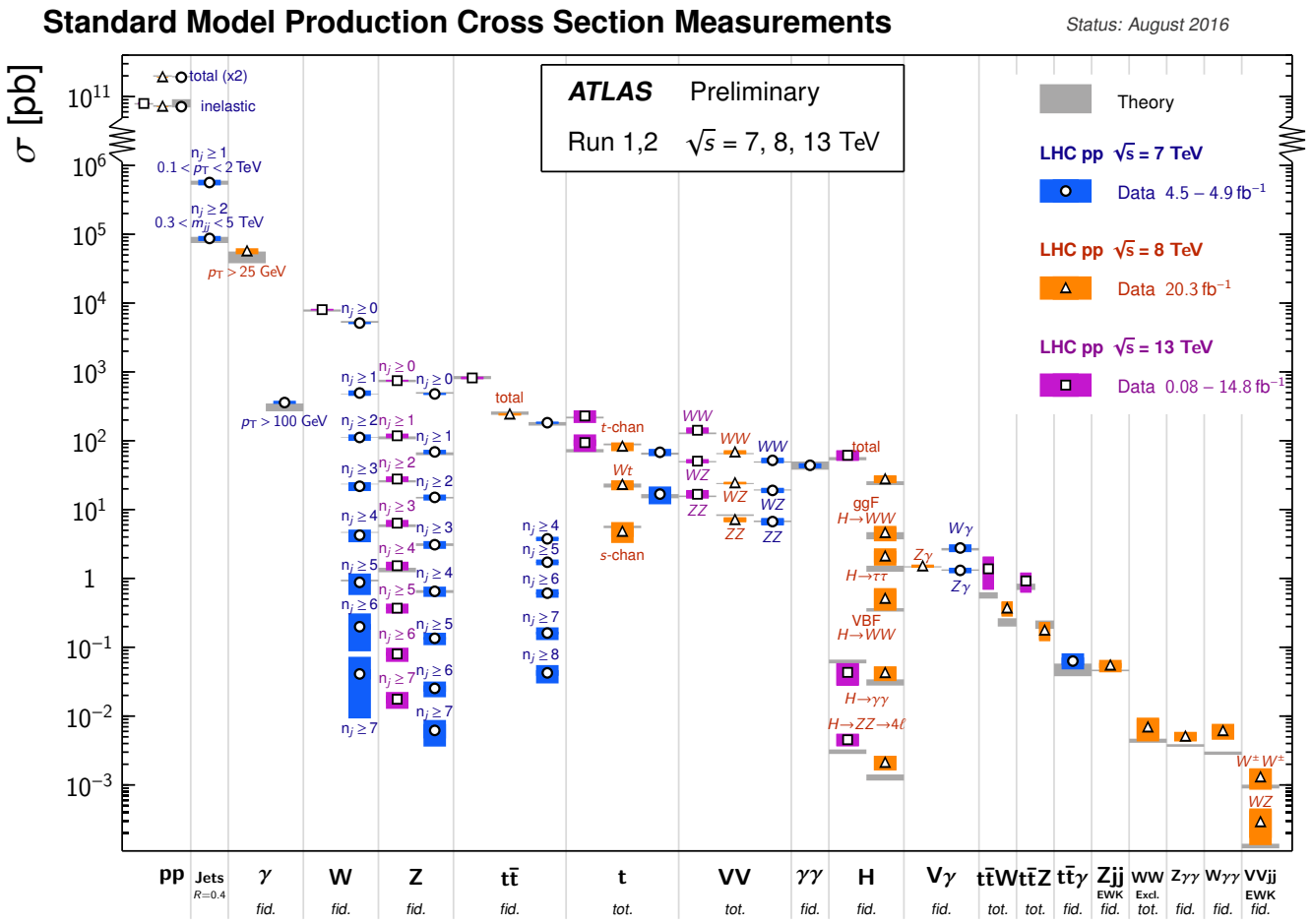




Protons are not elementary, "hard collisions" involve partons carrying fraction of the beam energy, $x_1 P$ and $x_2 P$. The effective centre of mass energy is $\sqrt{\hat{s}} = 2P\sqrt{x_1 x_2}$.

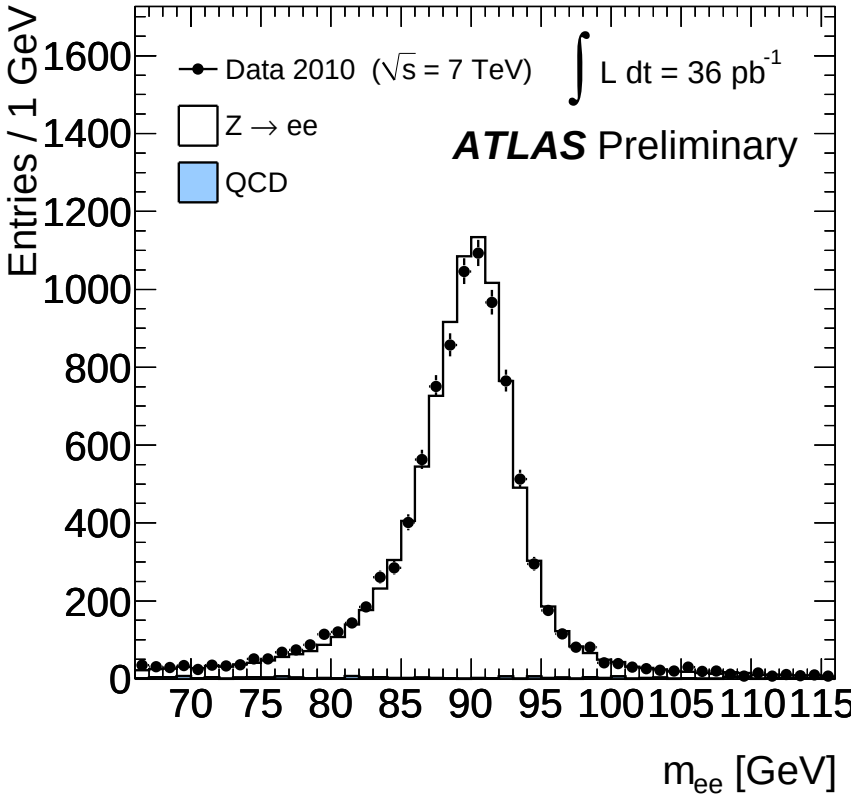
At large $x > 0.1$, valence u_v and d_v quarks play dominant role. For low x, LHC is the gluon-gluon and gluon-(anti)quark collider.

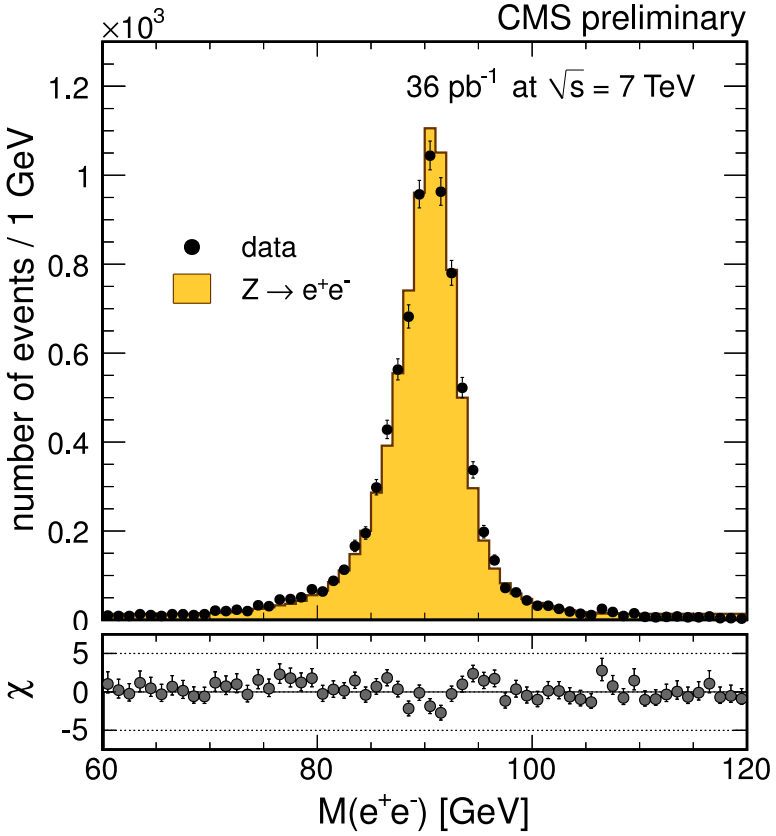
The measured processes



- Many new measurements from the LHC experiments.
- From first results at $\sqrt{s} = 13$ TeV to precision analyses of run I data.

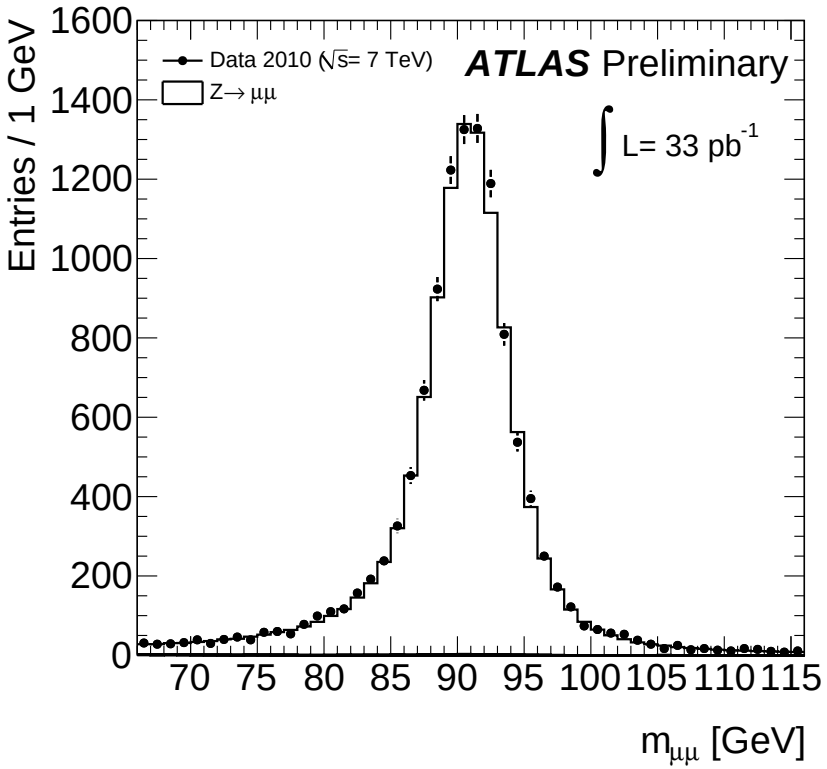
Reconstruction of Electron(s) — Energy scale

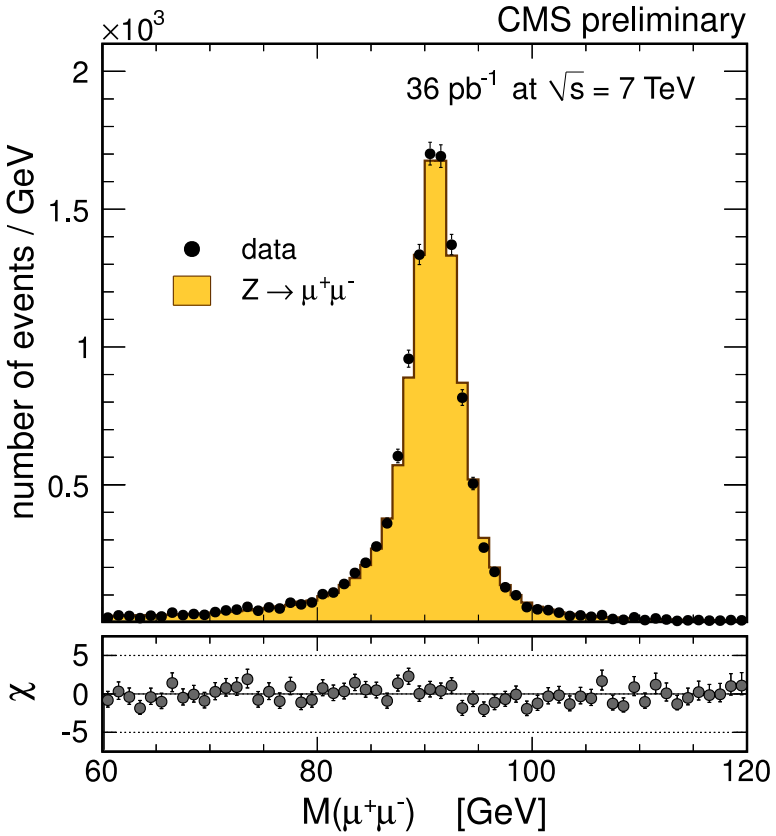




- Energy scale is important to reconstruct event kinematics.
- Calibrated using $Z \rightarrow e^+e^-$ events.
- Comparable resolution for ATLAS and CMS detectors.

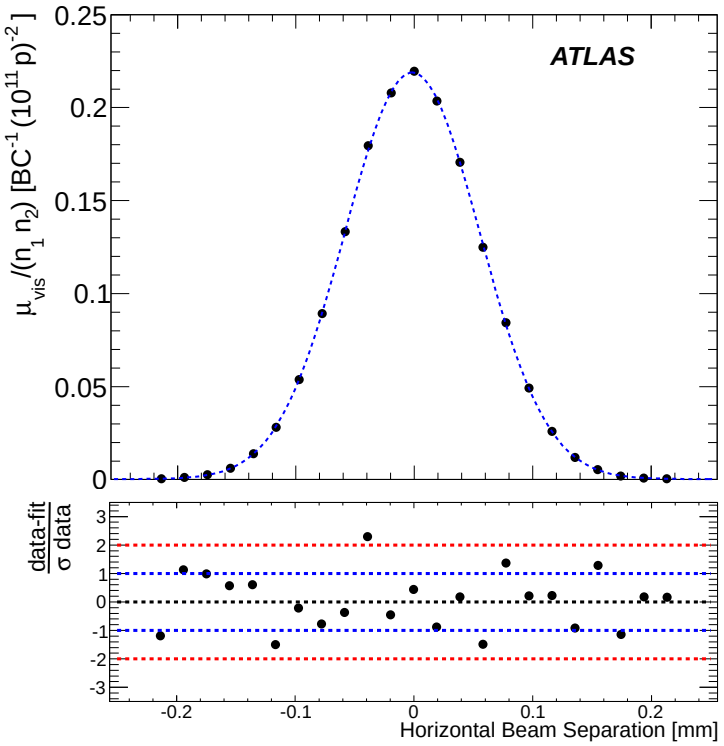
Reconstruction of Muon(s) — Alignment and p_t scale





- Muon momentum reconstruction critically depends on detector alignment, checked by comparing inner detector/muon system standalone measurements.
- Comparable resolution for ATLAS and CMS detectors.

Luminosity Measurement



Determine luminosity from direct measurements of machine parameters:

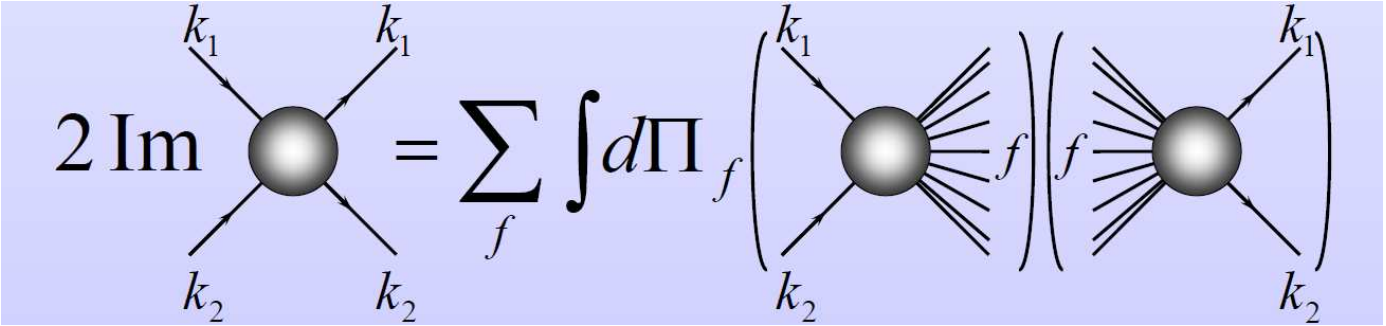
$$\mathcal{L} = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y},$$

where n_b — number of bunch crossings $n_{1,2}$ — bunch populations, f_r — revolution frequency, $\Sigma_{x,y}$ — horizontal/vertical profiles of the beams.

$n_{1,2}$ are determined from the machine measurement of beam currents, $\Sigma_{x,y}$ — from Van der Meer scans, where distance scale between beams is calibrated by ATLAS primary vertex position reconstruction.

→ Total luminosity uncertainty: 1.8% for ATLAS 2011 data.
(Eur. Phys. J. C (2013) 73)

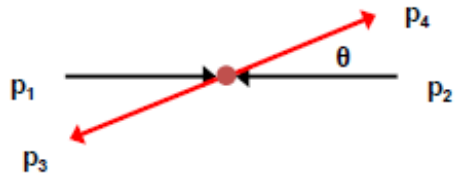
Total pp cross section measurement



Use optical theorem to calculate the total cross section from the elastic forward scattering amplitude:

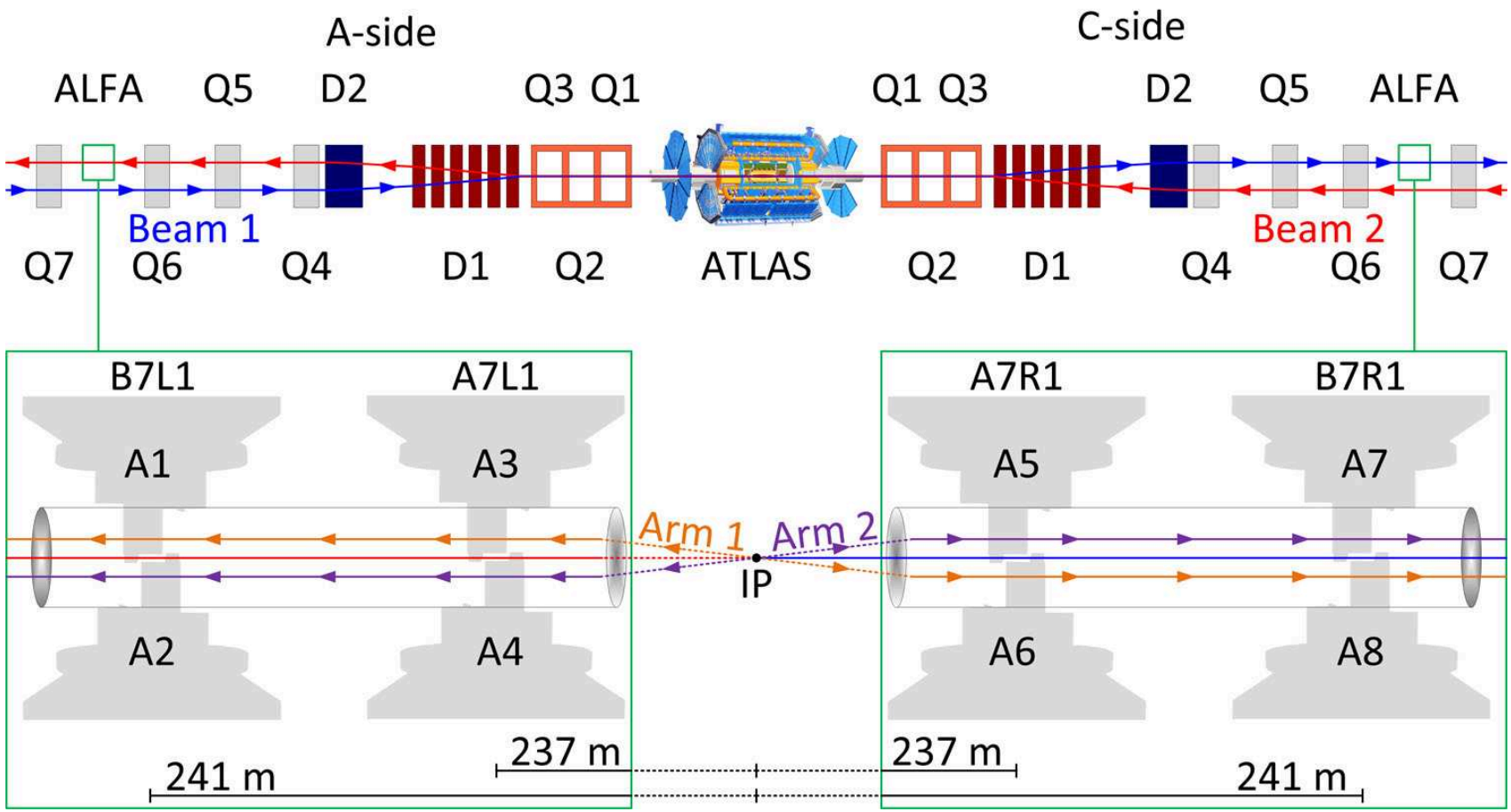
$$\sigma_{tot} \sim 4\pi \Im\,(f_{el})_{t\to 0}$$

Here $t = (p_1 - p_3)^2 \approx -(p\theta)^2$



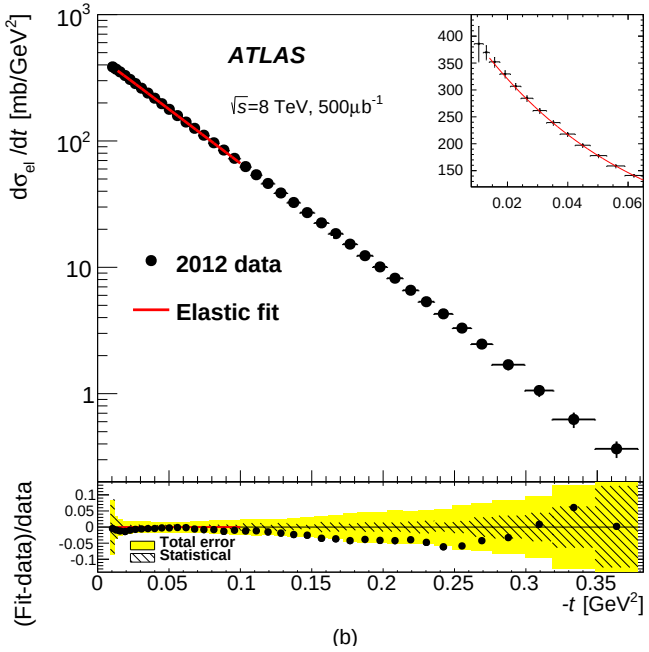
→ Need a dedicated detector to measure t spectrum close to 0, extrapolate to $t = 0$.

The ALFA detector

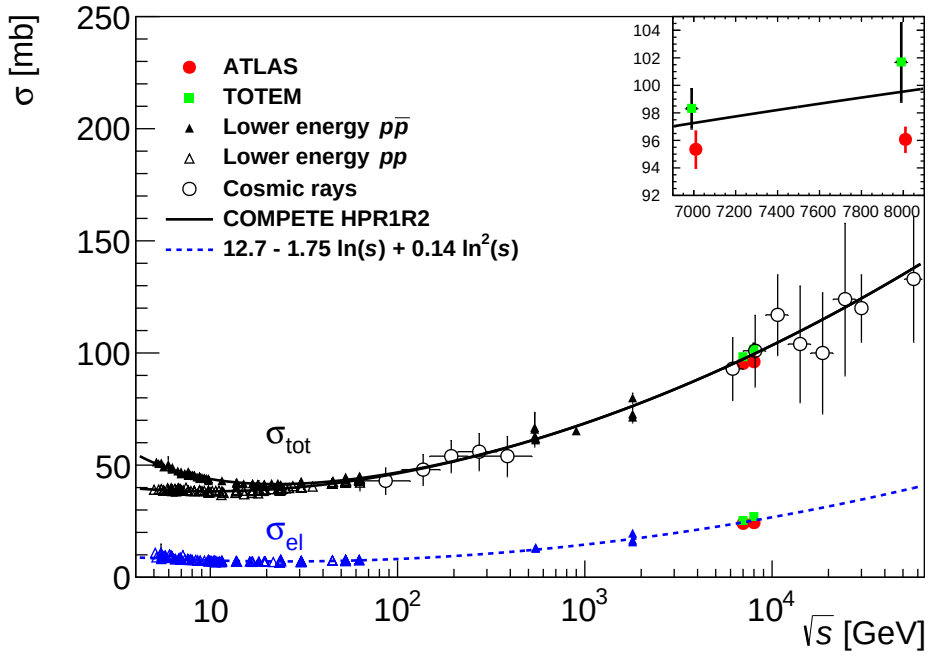


- Roman Pot detector, with $\sim 30\mu$m resolution approaching the proton beams.
- Dedicated beam optics with small emittance of $2-3\mu$m and small beam divergence of $\sim 3\mu$rad.

Total pp cross section at $\sqrt{s}$ = 8 TeV



(b)



(a)

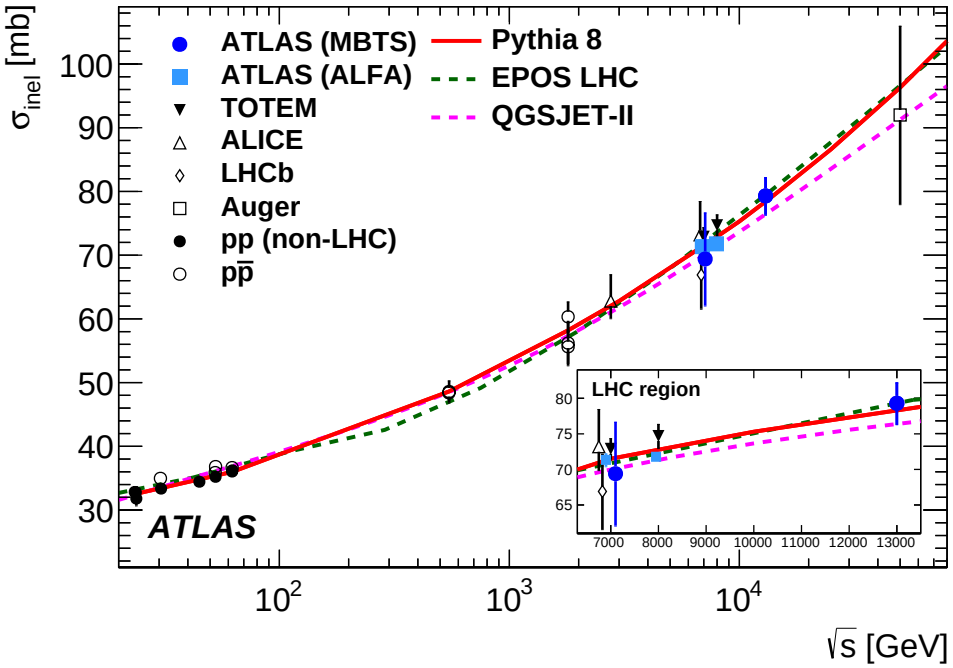
Measurement of elastic cross section at small t using special LHC run and dedicated ALFA detector and employing optical theorem

$$\sigma_{\mathrm{tot}}^2 = \frac{16\pi}{1+\rho^2}\left.\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}t}\right|_{t\to 0}$$

Lower but consistent with TOTEM, within TOTEM uncertainties.

ATLAS, arXiv:1607.06605

Inelastic pp cross section at $\sqrt{s} = 13$ TeV

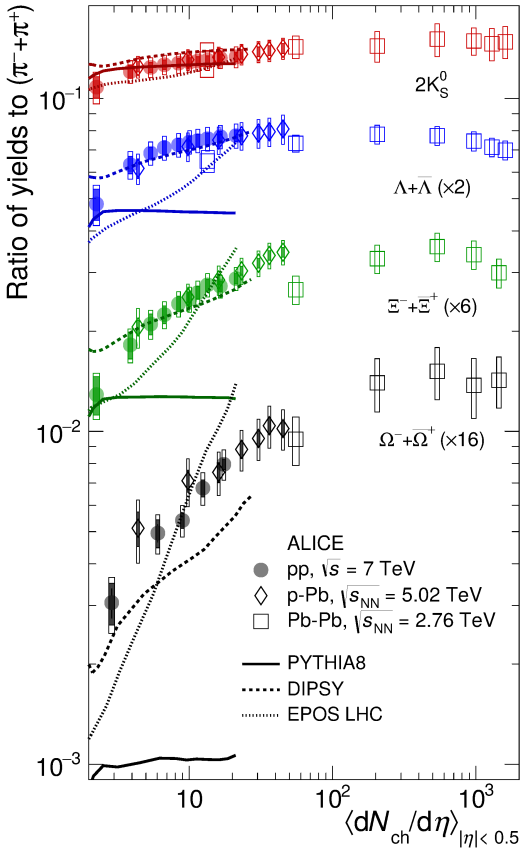


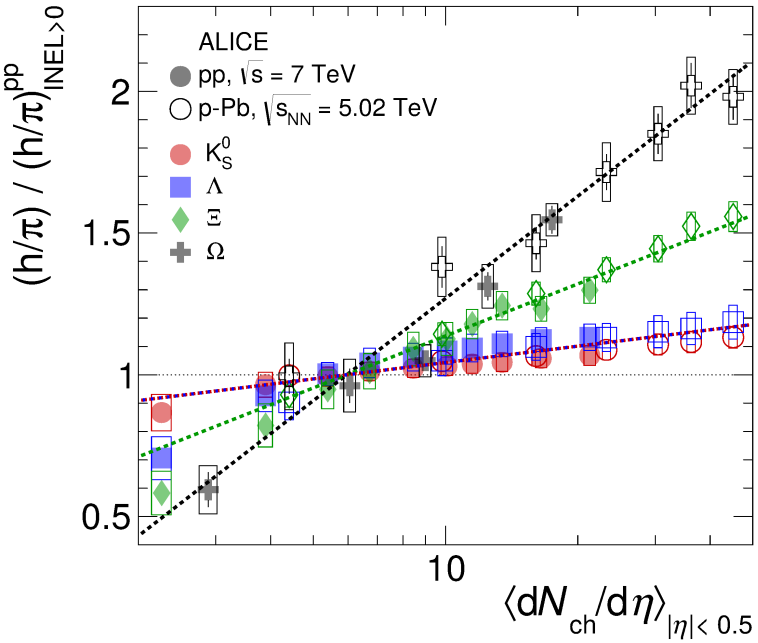
ATLAS: Measurement based on MBTS covering charged particles in $2.07 < |\eta| < 3.86$ range, corresponding to $\xi = M_x^2/s > 10^{-6}$, relies on extrapolation to full phase-space. For experimental volume,
$\sigma(\xi > 10^{-6}) = 68.1 \pm 0.6(\text{exp.}) \pm 1.3(\text{lum})$.

CMS prelim.: HF and CASTOR calorimeters, up to $\eta < 5.2$
$\sigma(\xi > 10^{-6}) = 65.77 \pm 0.76(\text{exp.}) \pm 1.78(\text{lum})$.

ATLAS, arXiv:1606.02625, CMS PAS FSQ-15-005

Strangeness production at high multiplicities

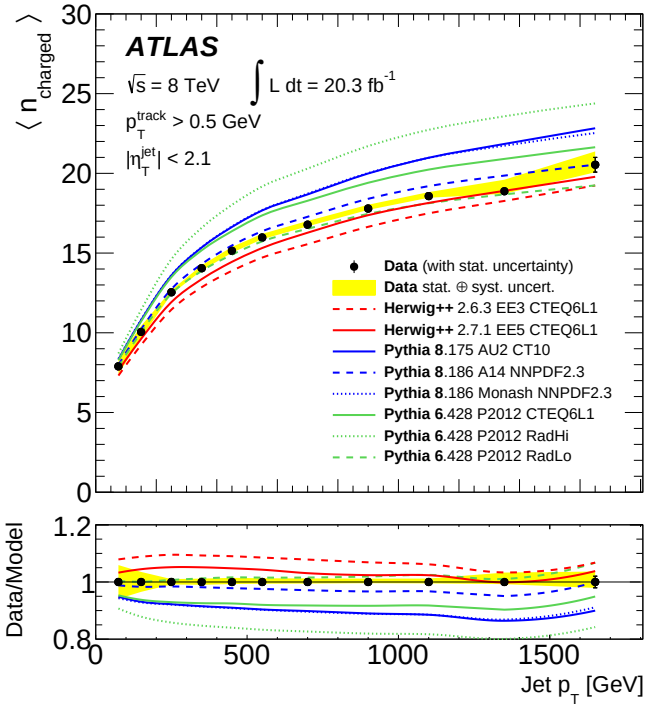


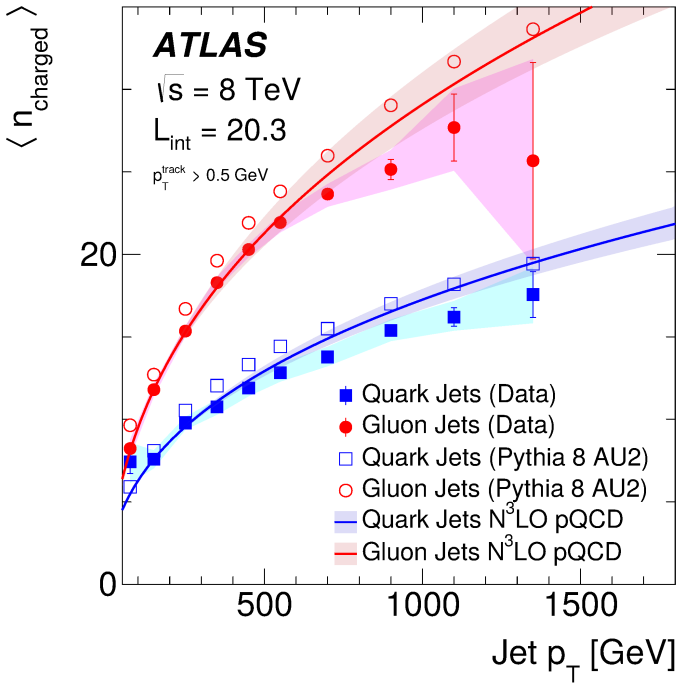


- Measurement of strange and multi-strange particles production vs charge particle multiplicity in *pp* and *pPb* collisions.
- Strong increase is observed vs pion production, stronger for multi-strange particles.

ALICE arXiv:1606.07424

Charged-particle multiplicity inside jets

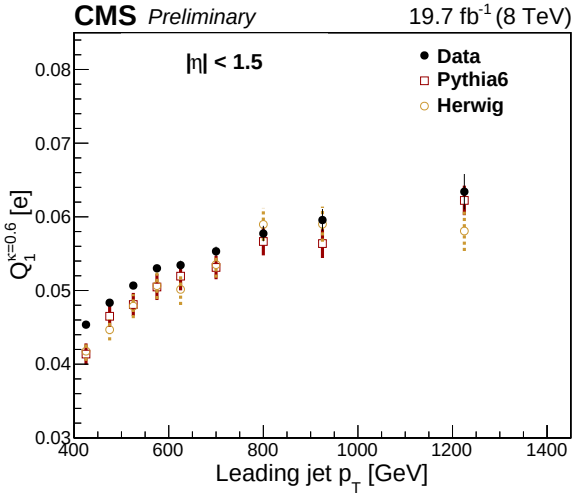


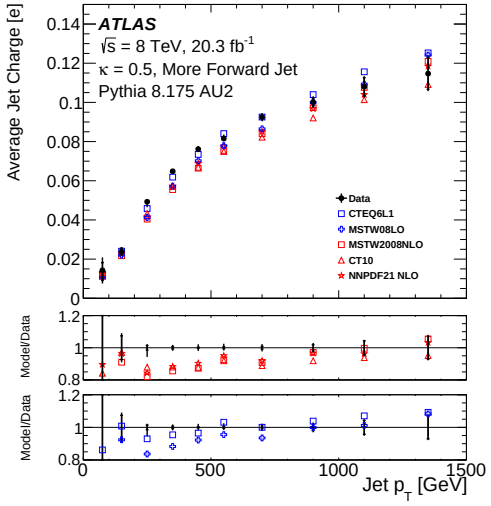


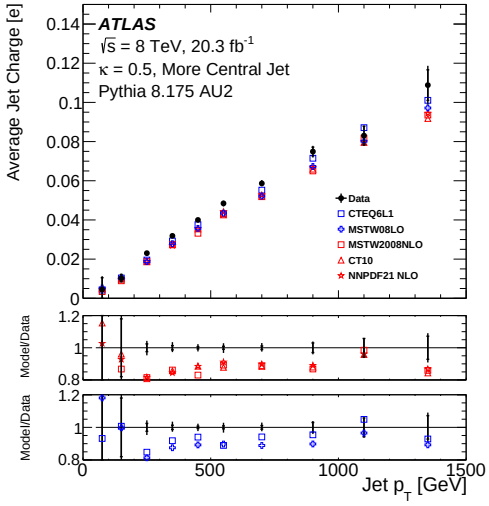
- Unfolded number of charged tracks with p_T > 500 MeV, > 2 GeV, and > 5 GeV in high p_T jets for dijet events.
- Best agreement with A14 Pythia (which includes previous ATLAS result at low p_T) and HERWIG EE5 tunes.
- Compare forward (more q-like) and central (more g-like) and use MC label to extract multiplicity for q- and g-like jets.

ATLAS Eur. Phys. J. C76(6), 1 (2016)

Jet charge observables







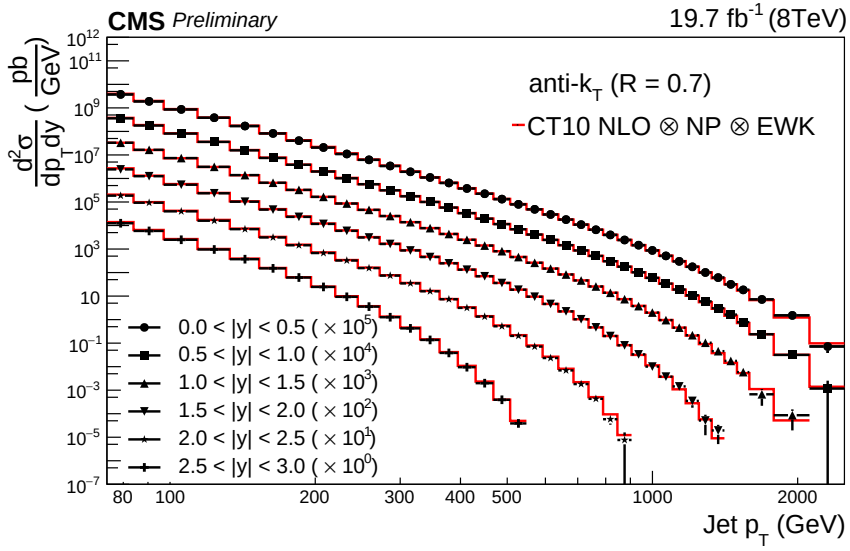
Define jet charge as

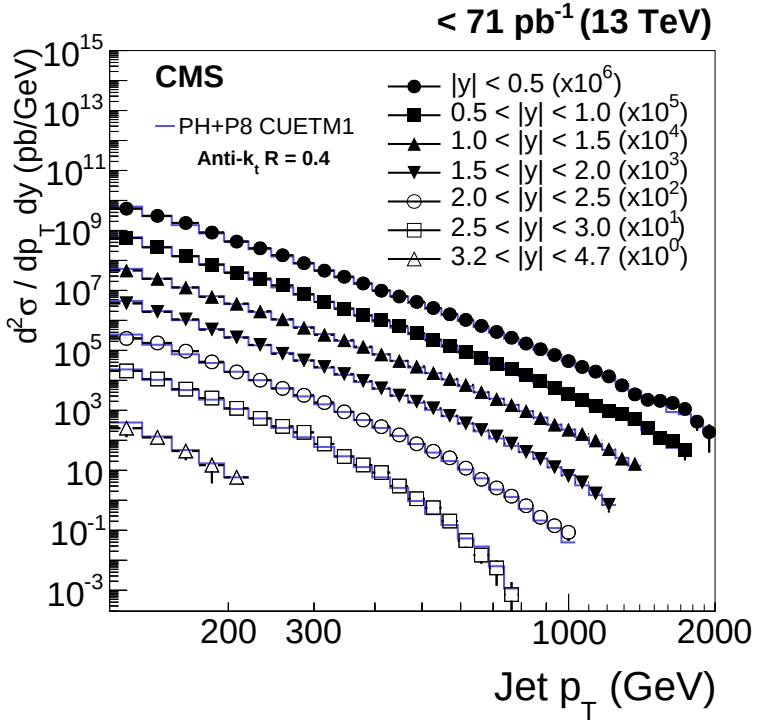
$$Q_J = \frac{1}{(P_{\mathrm{T}_j})^k} \sum_{j \in \mathrm{Tracks}} q_i \times (P_{\mathrm{T},i})^k$$

Increase of the charge for high p_{T} is due to valence quarks. Spread of predictions from different models comparable to spread from different PDFs.

ATLAS Phys. Rev. D93 (2016) 052003, CMS-PAS-SMP-15-003

Jet measurements at $\sqrt{s} = 8$ TeV and 13 TeV

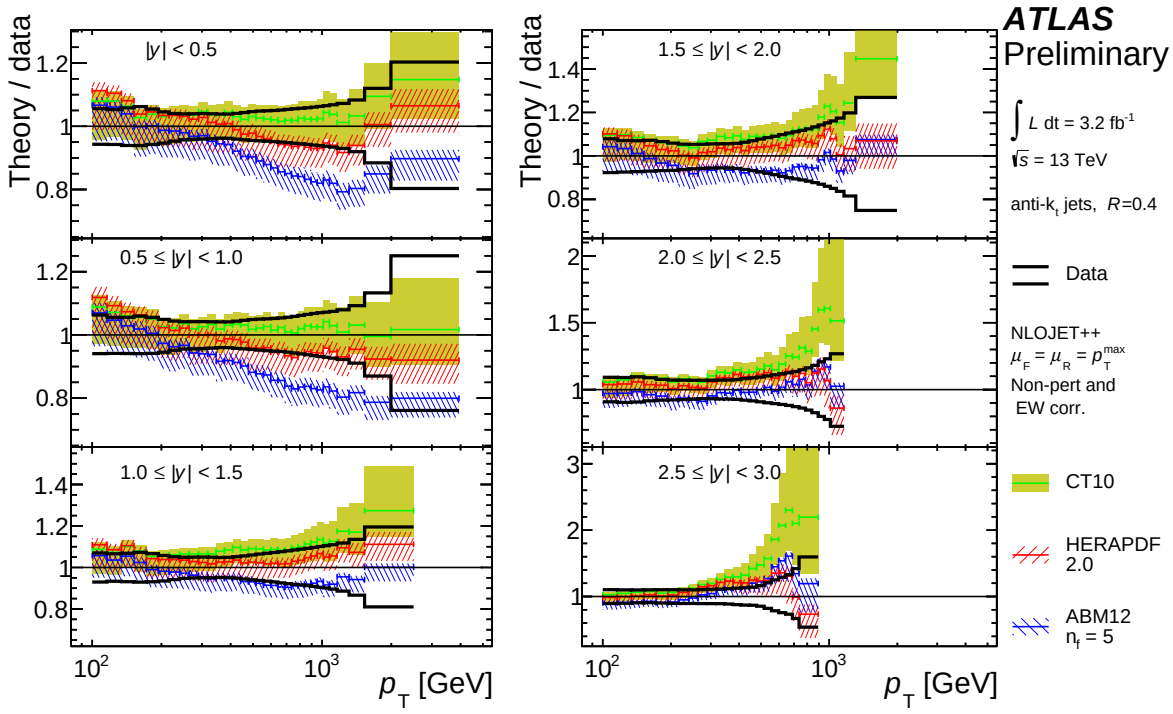




- Precision measurement of jet production for $\sqrt{s} = 8$ TeV, including determination of $\alpha_S = 0.1164^{+0.0060}_{-0.0043}$
- First results based on $\sqrt{s} = 13$ TeV data.

  CMS-PAS-SMP-14-001, EPJC 76 (2016) 451

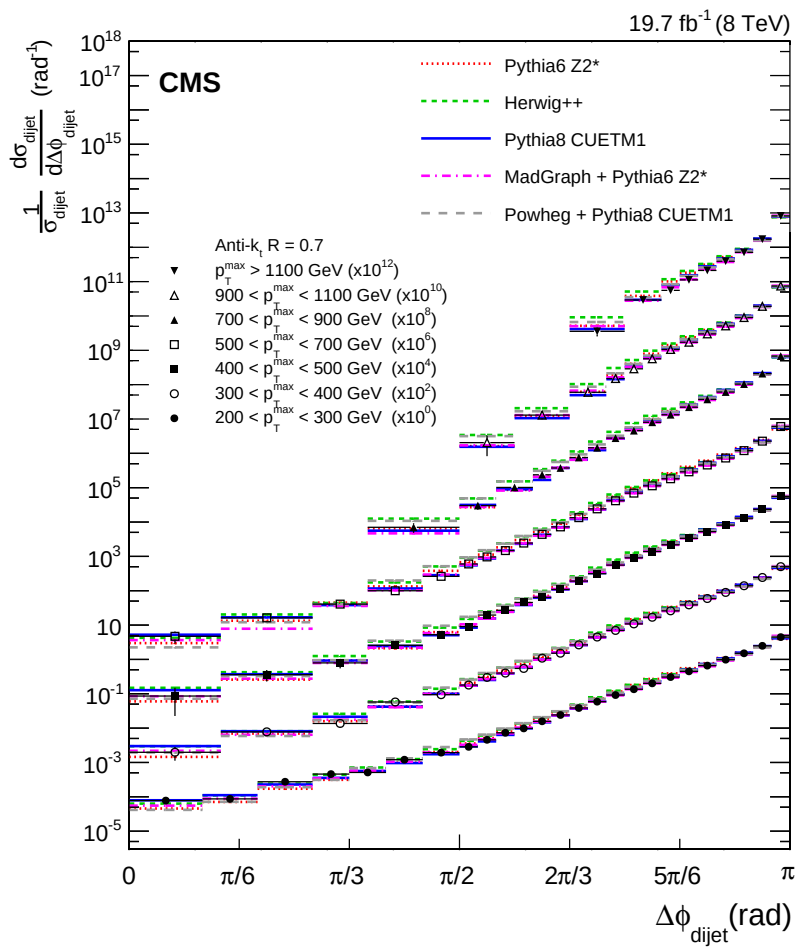
Inclusive jets at $\sqrt{s}$ = 13 TeV

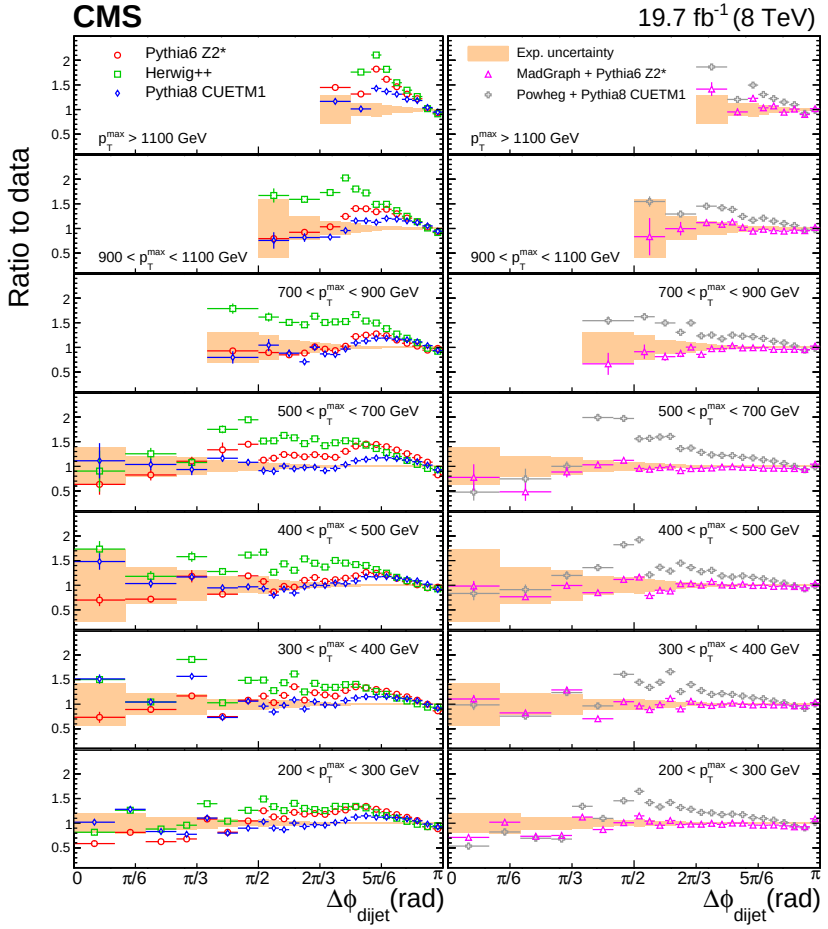


- New measurement of inclusive jet cross section using $\sqrt{s}$ = 13 TeV data
- The dominant JES uncertainty is at 5% level for $|y| < 0.5$ and $p_T < 1$ TeV.
- Compared to predictions using NLOJET++ plus EWK corrections to modern PDF sets.

ATLAS-CONF-2016-092

Dijet azimuthal decorrelations at $\sqrt{s} = 8$ TeV

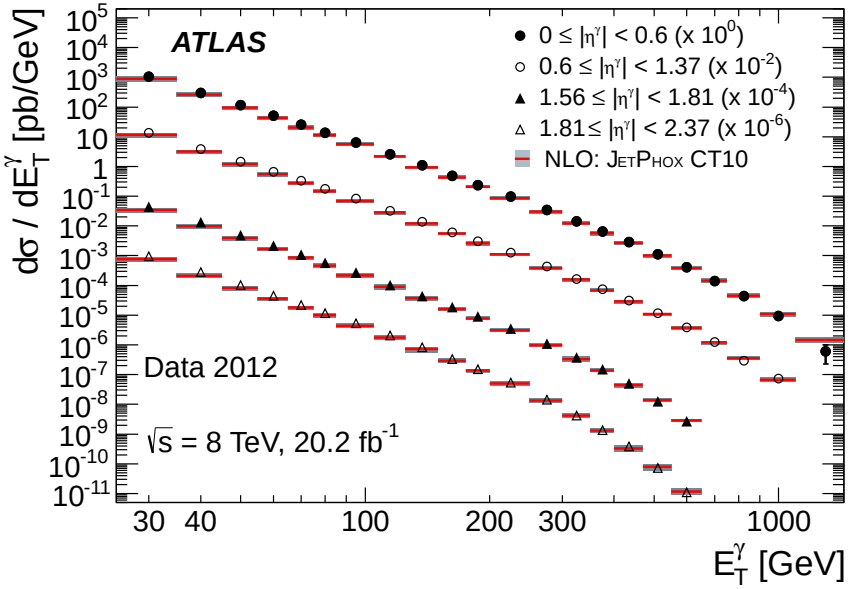


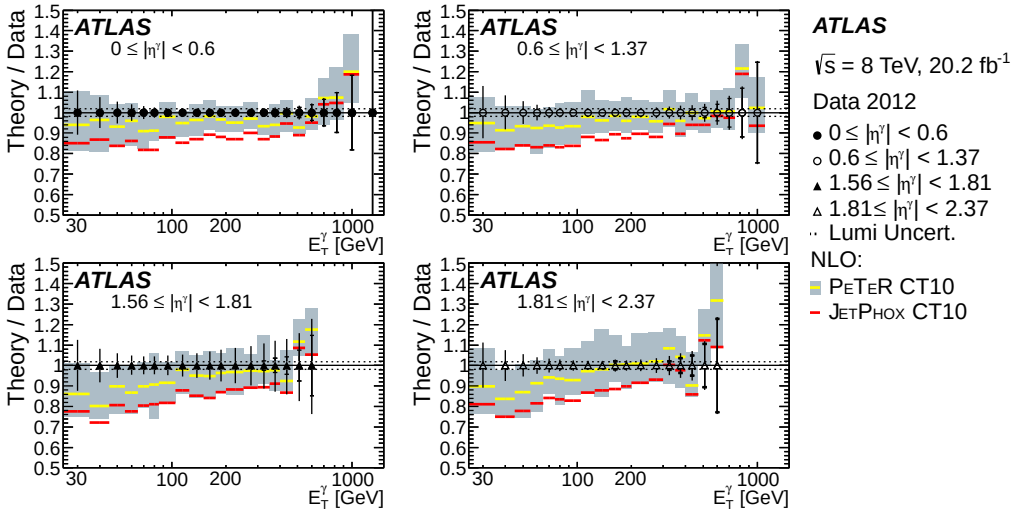


Need multiparton generators to get reasonable description of the data.

CMS arXiv:1602.04384

Inclusive photons at $\sqrt{s}$ = 8 TeV

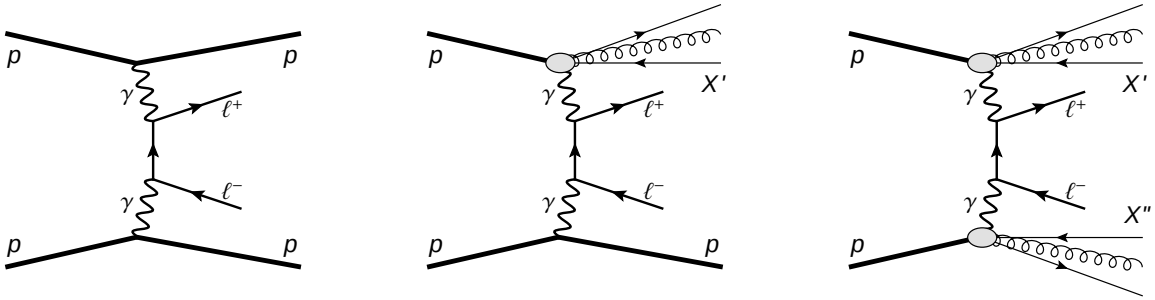


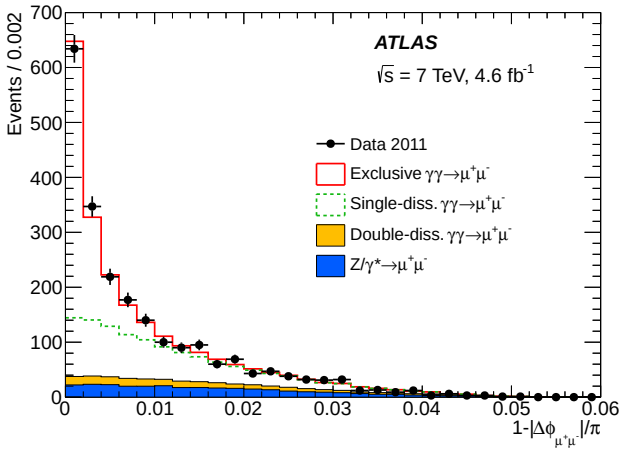


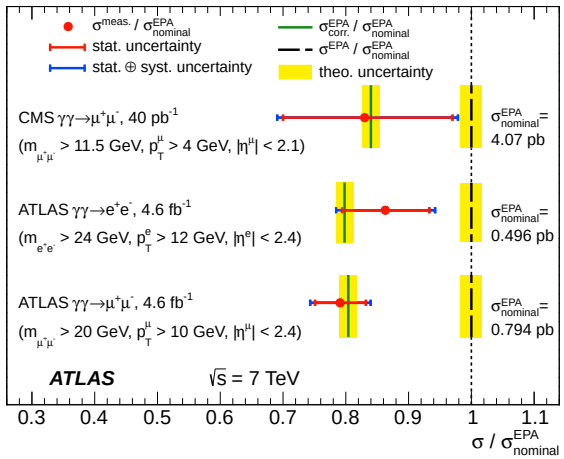
- Inclusive γ production measurement, for $25 < E_T < 1500$ GeV, double differential in E_T and η
- Measurements compared to NLO JetPhox and NLO+threshold resummation + EWK Sudakov logs PeTeR predictions.
- PeTeR matches data better, theory errors are larger vs experimental uncertainties.

ATLAS, JHEP 06 (2016) 005

Exclusive $\gamma\gamma \rightarrow \ell\ell$



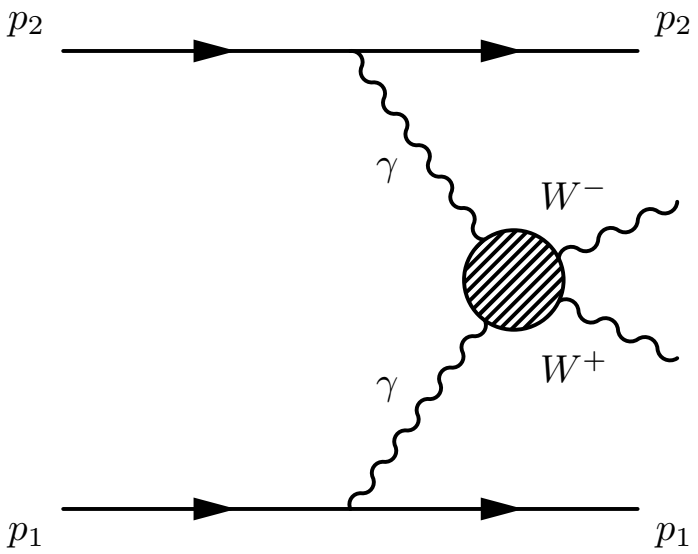


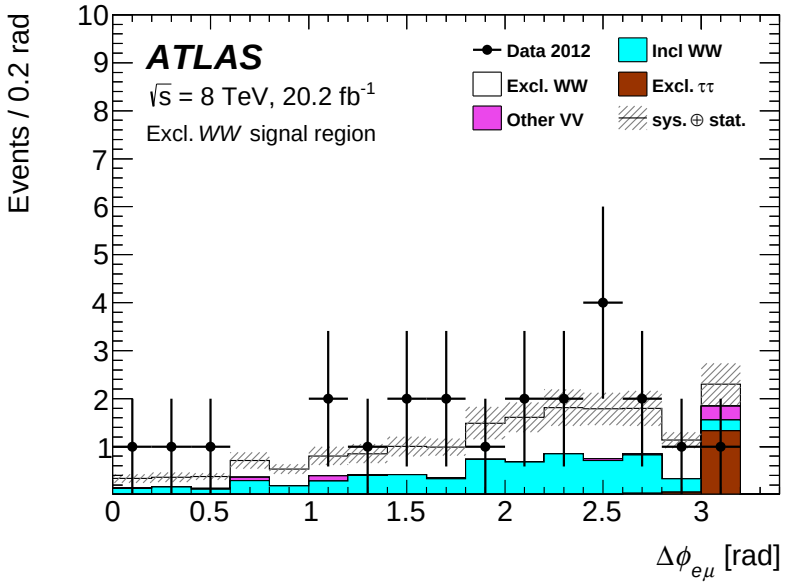


- $\gamma\gamma$ scattering has a significant cross section for process in which proton remains intact having simple experimental signature.
- Requiring exactly two ee or $\mu\mu$ tracks at the vertex with back-to-back signature reduces background significantly.
- Measured cross sections are inline with expectations which include absorptive corrections.

  ATLAS, PLB749 (2015) 242

Exclusive $W^{\pm}W^{\mp}$ production

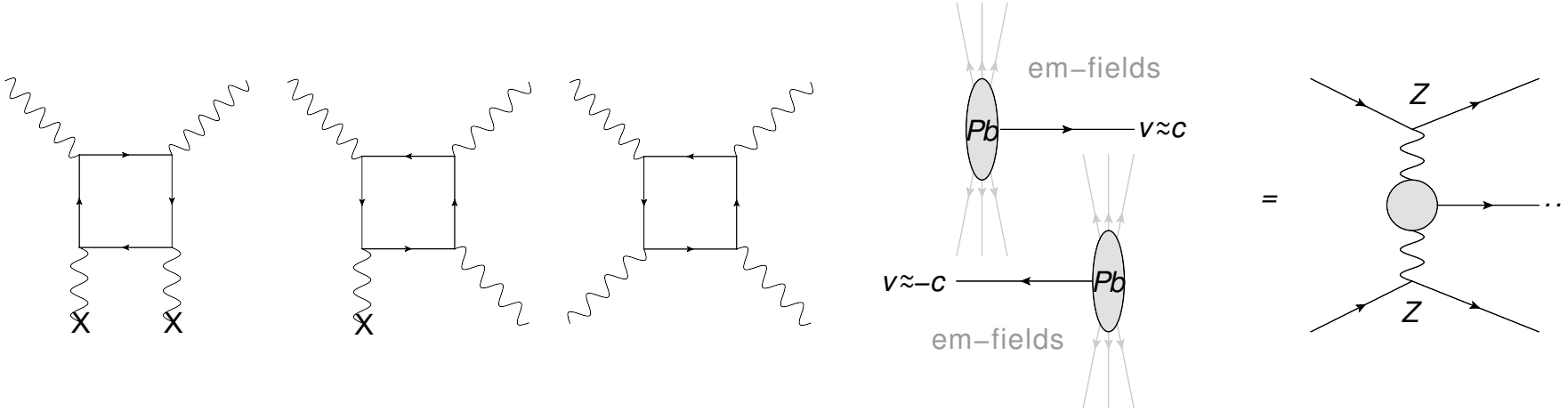




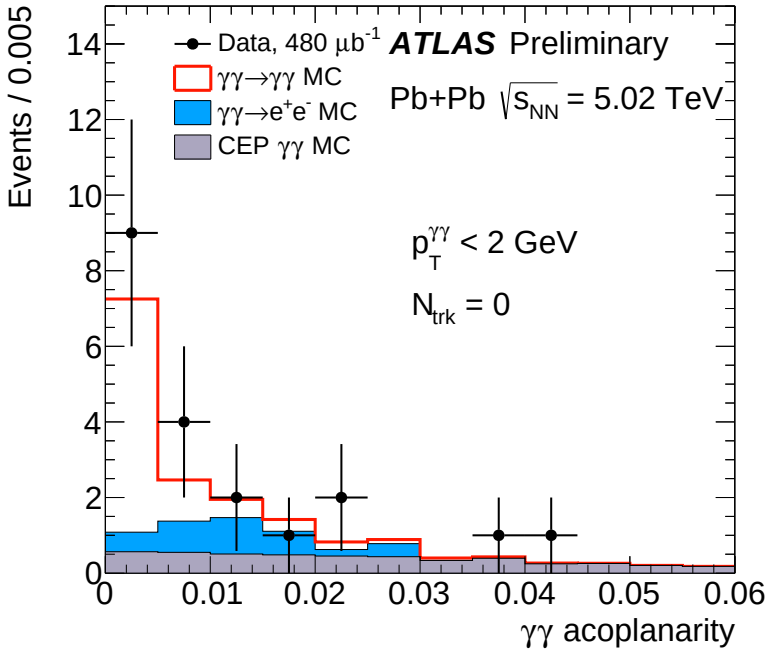
- $\gamma\gamma \to WW$ process probes interesting quartic gauge coupling.
- Use $e\mu$ final state to reduce $\gamma\gamma \to \ell\ell$ background.
- The observed cross section $6.9 \pm 2.2_{\text{stat}} \pm 1.4_{\text{sys}}$ fb is consistent with SM expectation of 4.4 ± 0.3 fb.

ATLAS, Phys. Rev. D 94 (2016) 032011

Light-by-light scattering

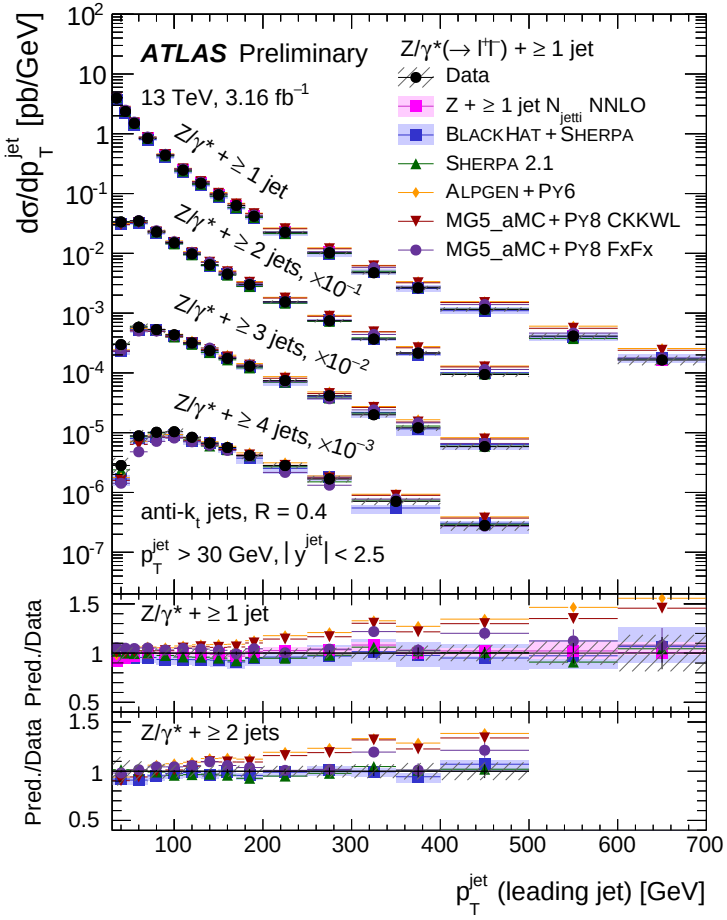


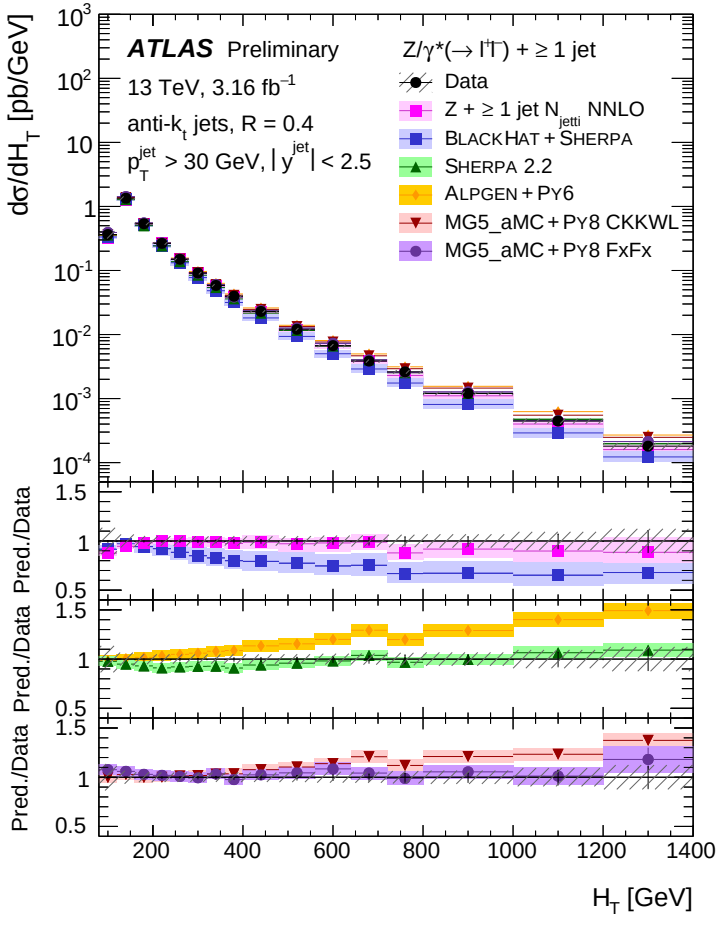
- $\gamma\gamma \to \gamma\gamma$ scattering is $O(\alpha_{em}^4)$ QED process, sensitive to BSM contributions.
- Use PbPb collisions to obtain $Z^4 = 82^4$ cross-section enchantment factor. Trigger on "empty" events with total calorimeter $5 < E_T^{\text{tot}} < 200$ GeV. Lower offline E_T^{γ} cut to 3 GeV. Use large $\gamma\gamma \to e^+e^-(\gamma)$ samples for calibration, efficiency studies.
- Observed $\gamma\gamma \to \gamma\gamma$ yield agrees with expectations.



ATLAS-CONF-2016-111

Z plus jets at $\sqrt{s}$ = 13 TeV

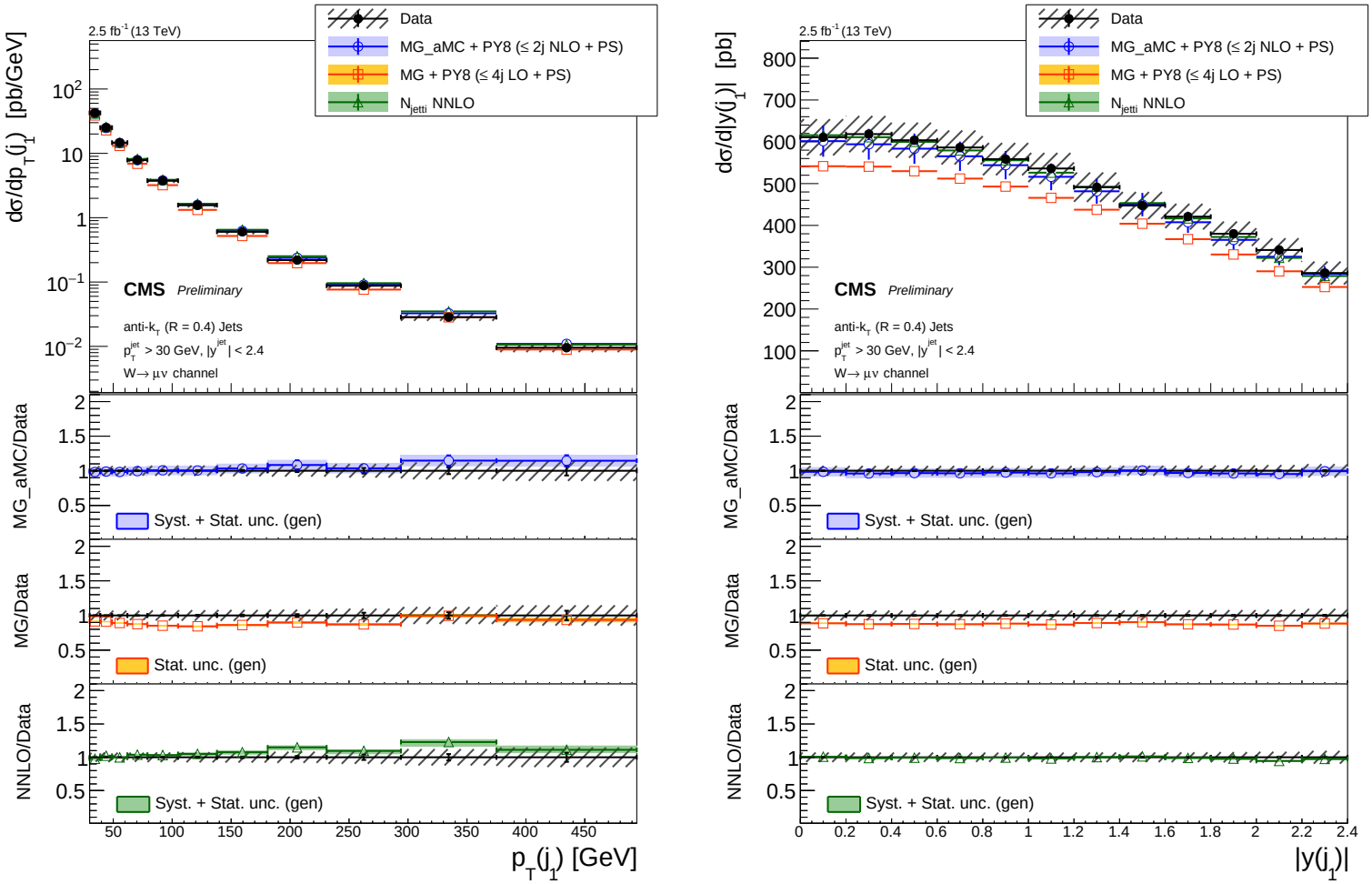




- New extensive study of Z plus jet events using $\sqrt{s}$ = 13 TeV data
- Comparisons to NNLO predictions show good agreement.

ATLAS-CONF-2016-046

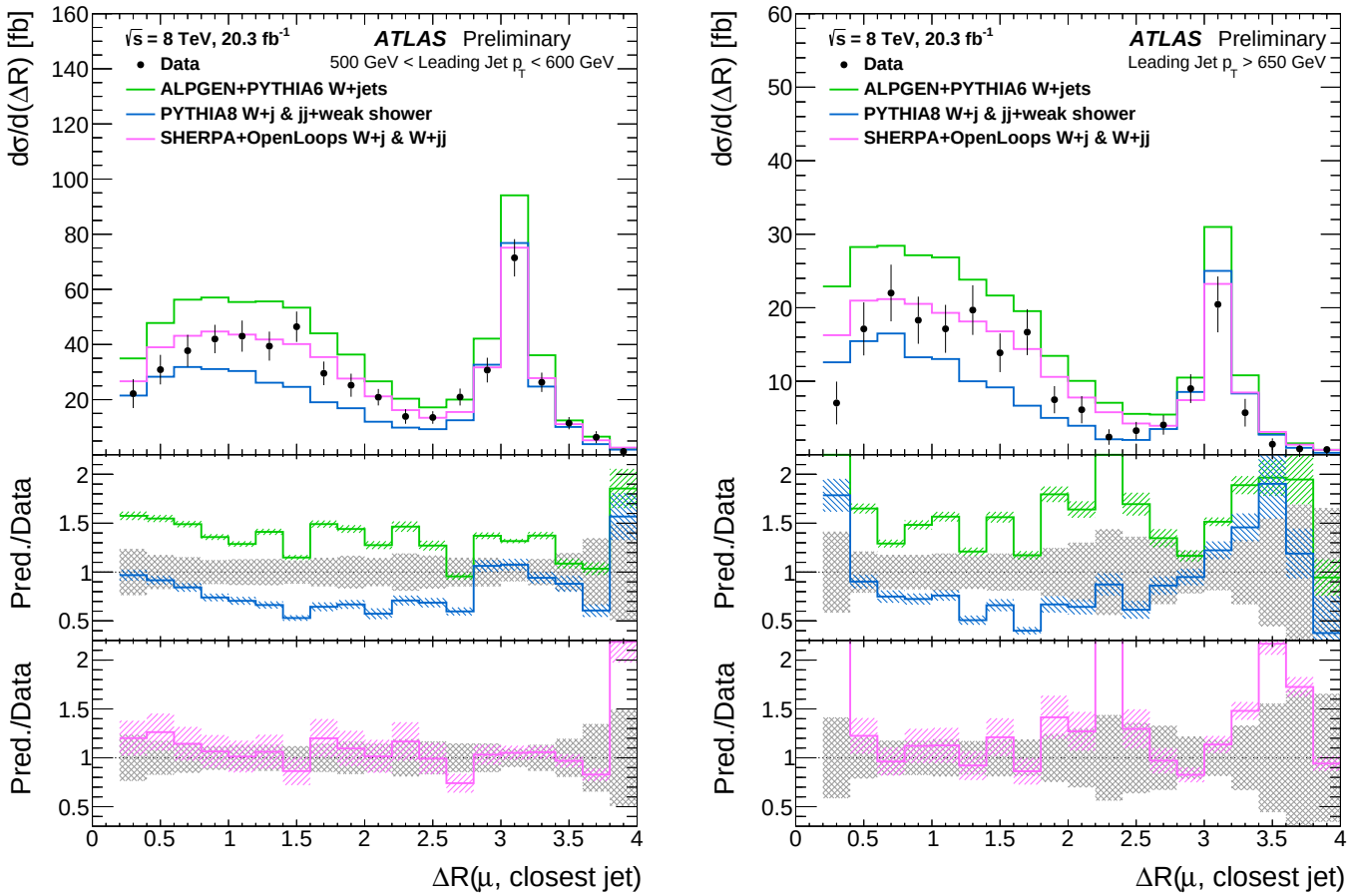
W plus jets at $\sqrt{s}$ = 13 TeV



- Similar study from CMS for W plus jet data, NNLO comparisons look good.

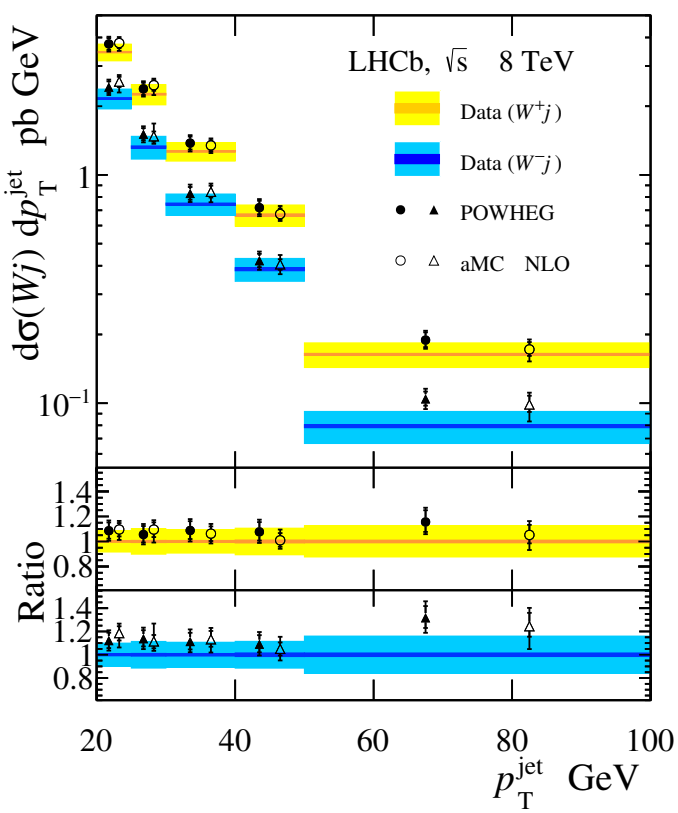
CMS-PAS-SMP-16-005

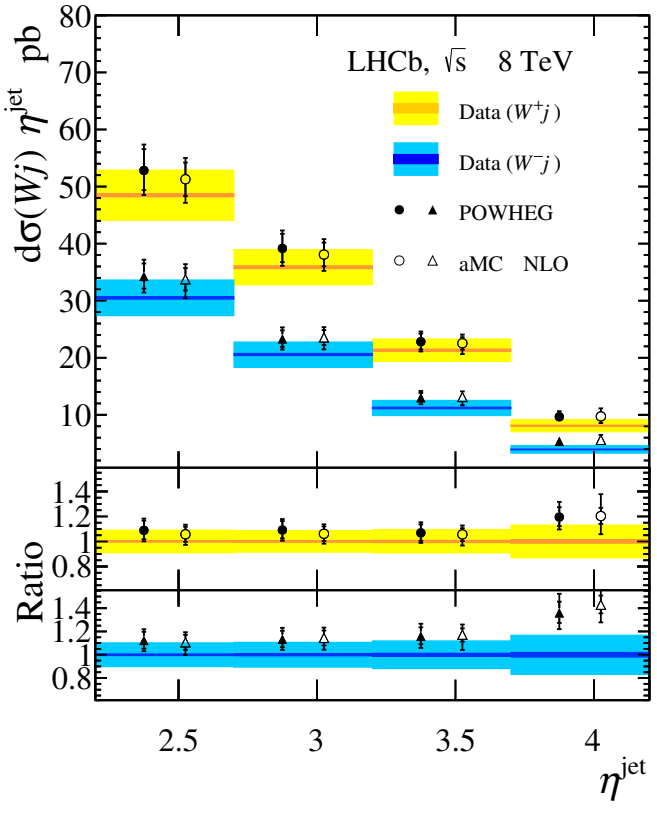
W production close to jets



- Measurement of *W* production vs distance to high p_T jets.
- Reasonable agreement with SHERPA+Openloops NLO QCD+EW prediction.

W and *Z* plus jets in forward region

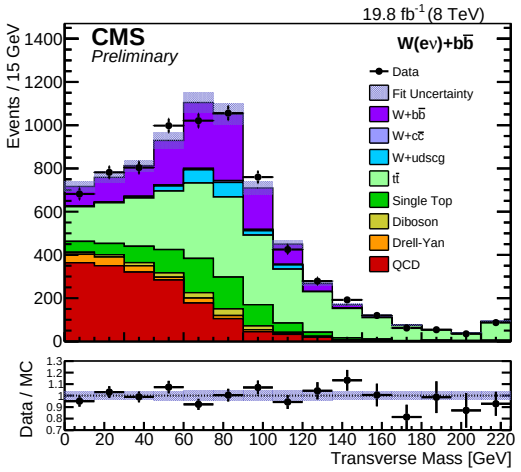


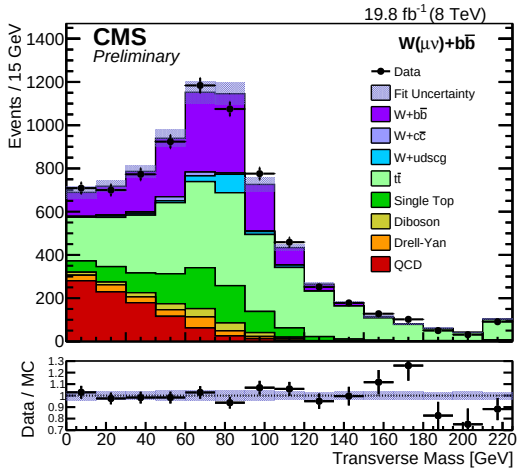


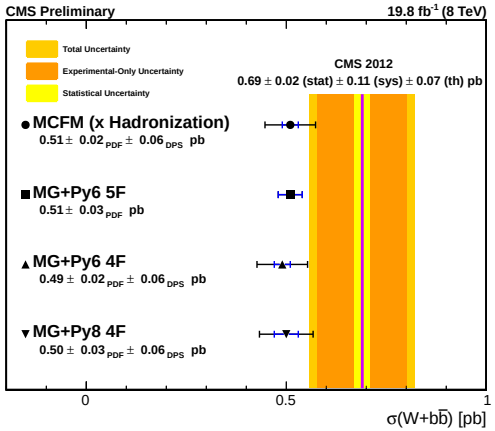
- Jets are reconstructed using particle-flow algorithm.
- Fiducial and differential plus various ratios are considered, overall a good agreement with predictions is observed.

LHCb arXiv:1605.00951

$W + b\bar{b}$ jet production



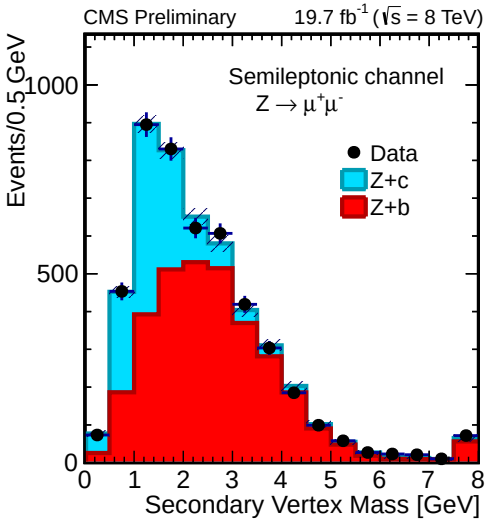


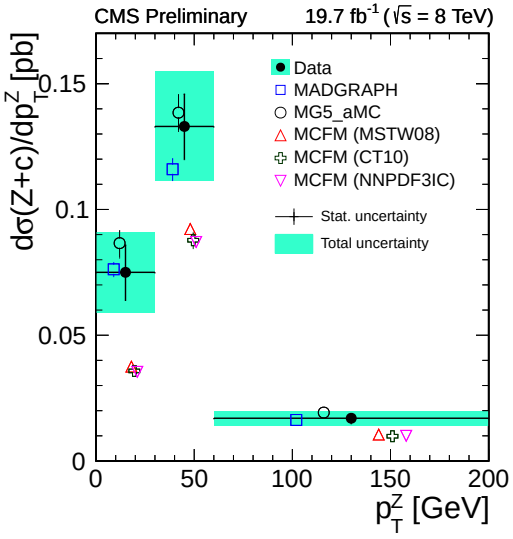


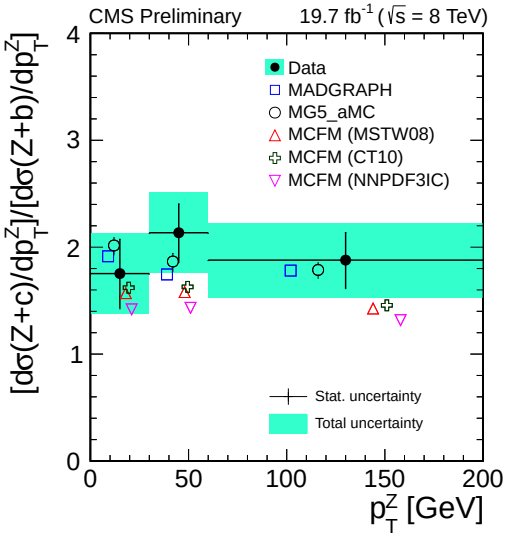
- Measurement of W production with exactly two b-tagged jets with $R = 0.5$, $p_T > 25$ GeV and $|\eta| < 2.4$ (3rd jet veto).
- Fit to M_T distribution, backgrounds are also fixed in control region.
- Predictions based on MCFM (+ hadr. and DPS corrections) as well as MadGraph+Pythia with 4- and 5-flavour PDFs agree with each other and about 1σ below the data.

CMS-PAS-SMP-14-020

$Z + c$ production at $\sqrt{s} = 8$ TeV



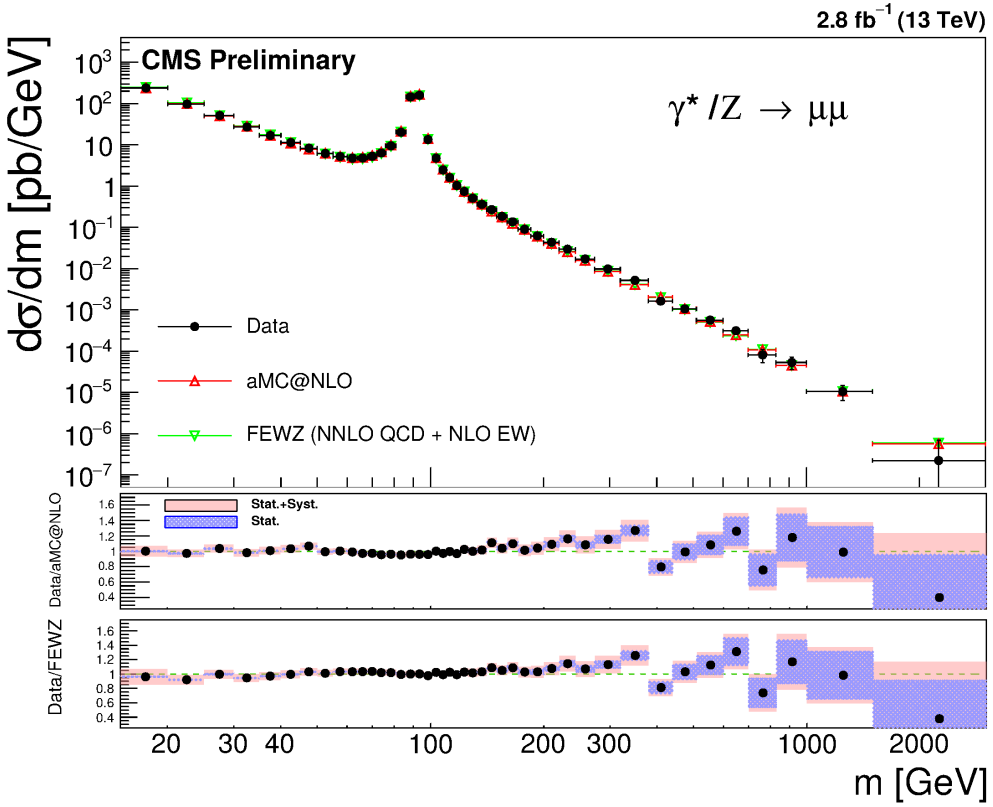




- Measurement of $Z + c$, differential in Z and jet p_{T} and the ratio of $\sigma_{Z+b}/\sigma_{Z+c}$ with at least one jet with $P_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$.
- Several tagging methods used: μ in jets; displaced vertex consistent with $D^{(*)}$ meson decays.
- $Z + b$ and $Z + c$ are determined using fits to flavour-sensitive variables which discriminate their contributions.
- Predictions agree with the data within uncertainties.

CMS-PAS-SMP-15-009

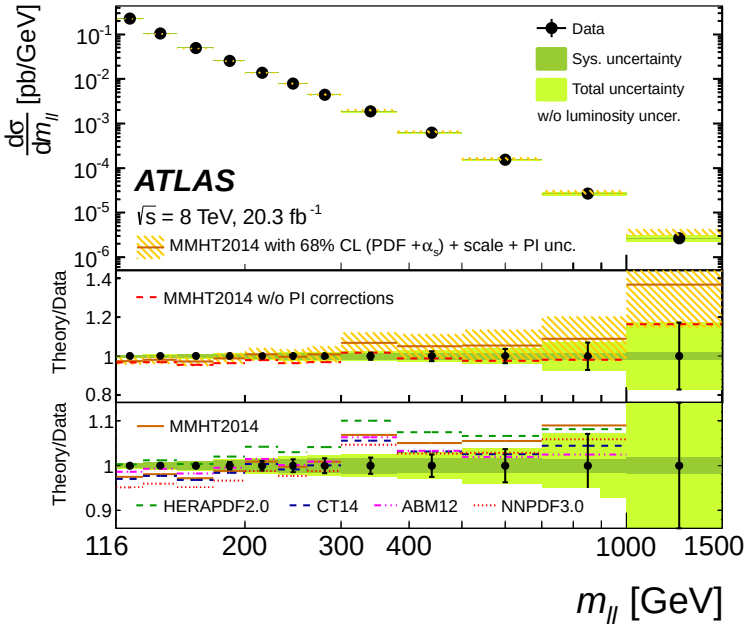
Inclusive Z/γ^* production as $\sqrt{s} = 13$ TeV

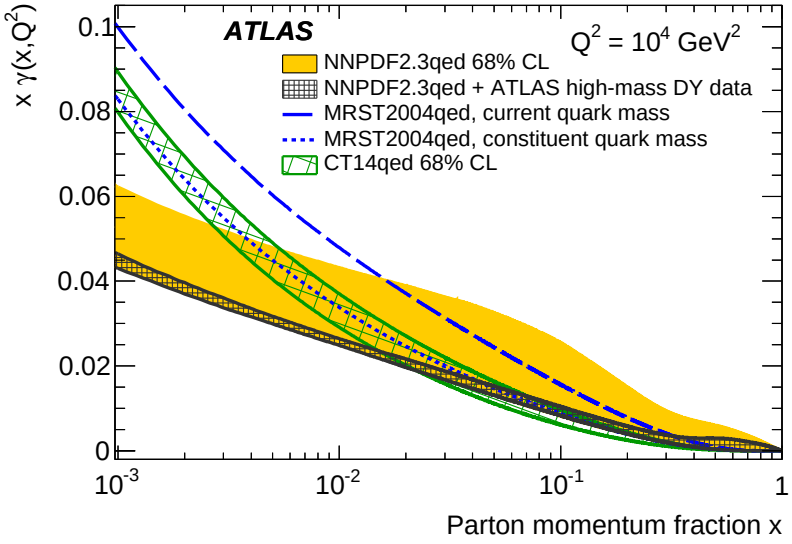


- Measurement of $d\sigma/dM_{\mu\mu}$ in $15 < M_{\mu\mu} < 3000$ GeV range, with $\sim 2\%$ systematic uncertainties for the peak region (plus 2.7% lumi).
- Agrees well with NLO and NNLO expectations.

CMS-PAS-SMP-16-009

High mass DY measurement at $\sqrt{s} = 8$ TeV

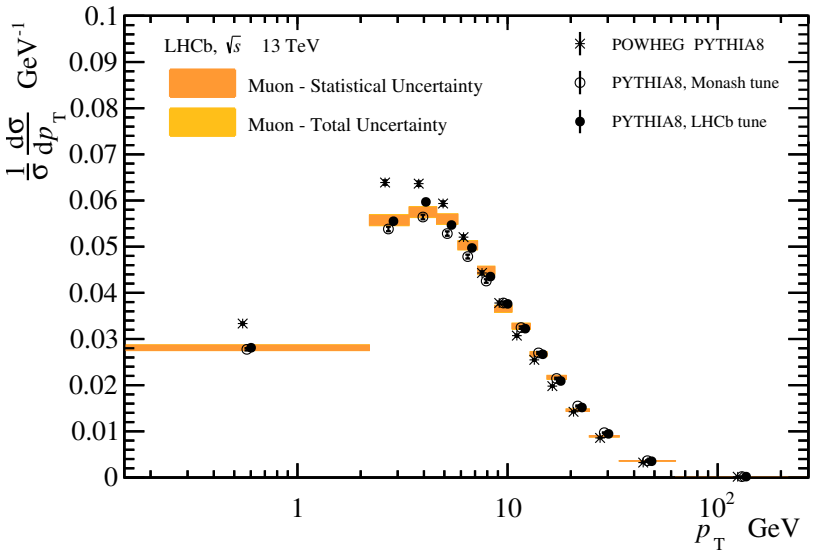


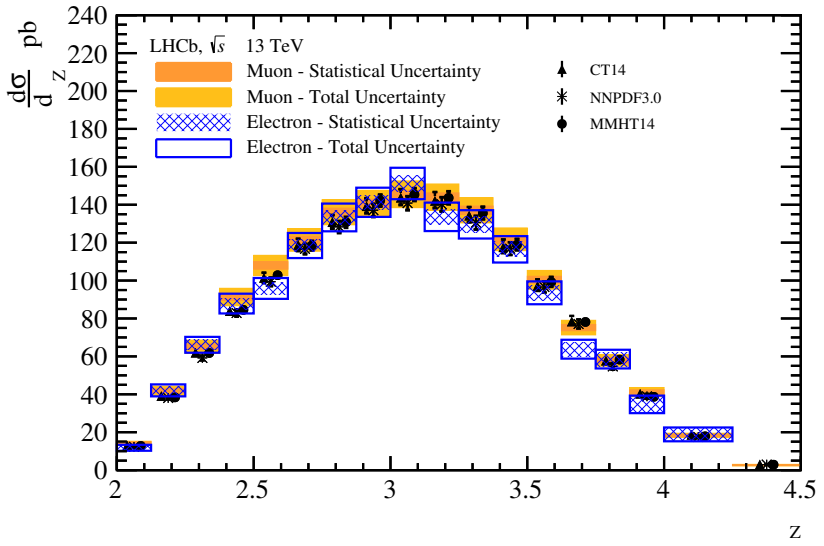


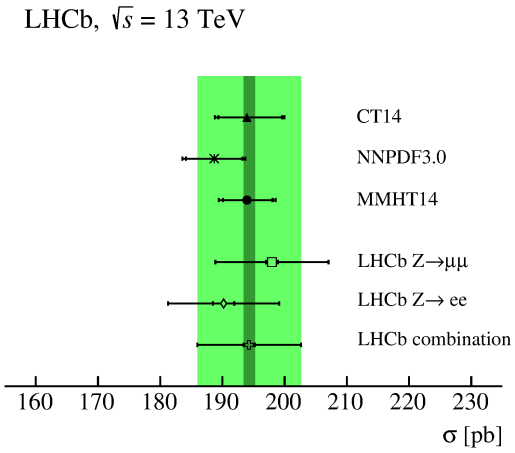
- Measurement in e and μ channels with combined experimental precision better than 1% for low $M_{\ell\ell}$ (plus 1.9% lumi), double differential in $M_{\ell\ell}$ and $y_{\ell\ell}$ and $\delta\eta_{\ell\ell}$.
- Sensitive to $\gamma\gamma \to \ell\ell$ with significant constraining power vs NNPDF2.3QED.

ATLAS, JHEP 08 (2016) 009

Measurements of Z-boson at forward rapidities



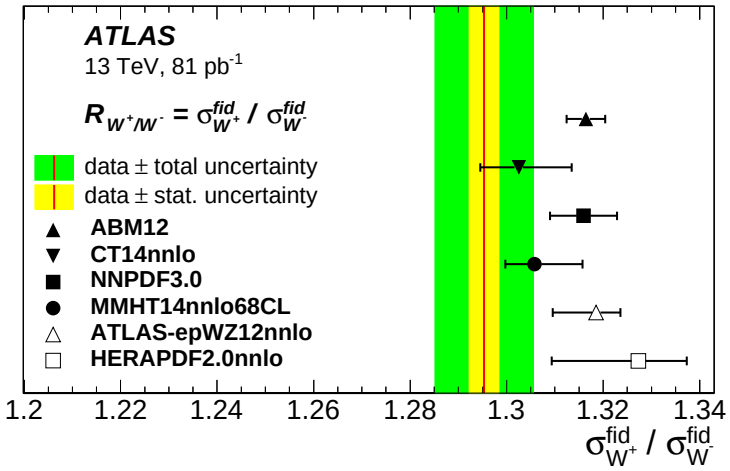


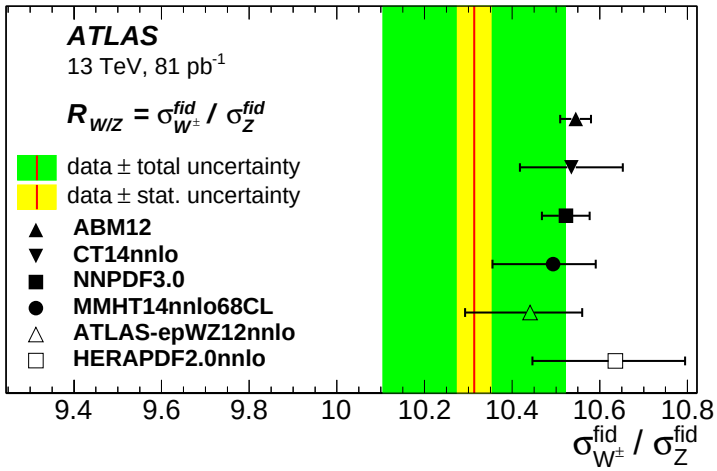


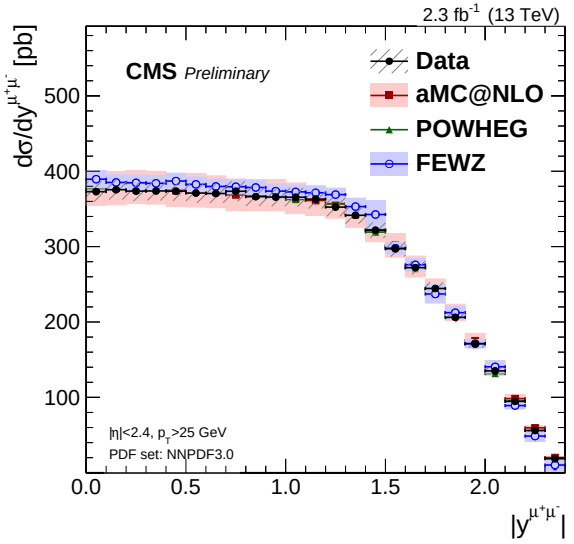
- Measurement using both e and μ channels at $\sqrt{s} = 13$ TeV for leptons with $2 < \eta < 4.5$ and $p_T > 20$ GeV
- Fiducial cross section and differential in $y_{\ell\ell}$, ϕ^* and $p_{\mathrm{T},\ell\ell}$.

LHCb-PAPER-2016-021

W, Z production at $\sqrt{s} = 13$ TeV



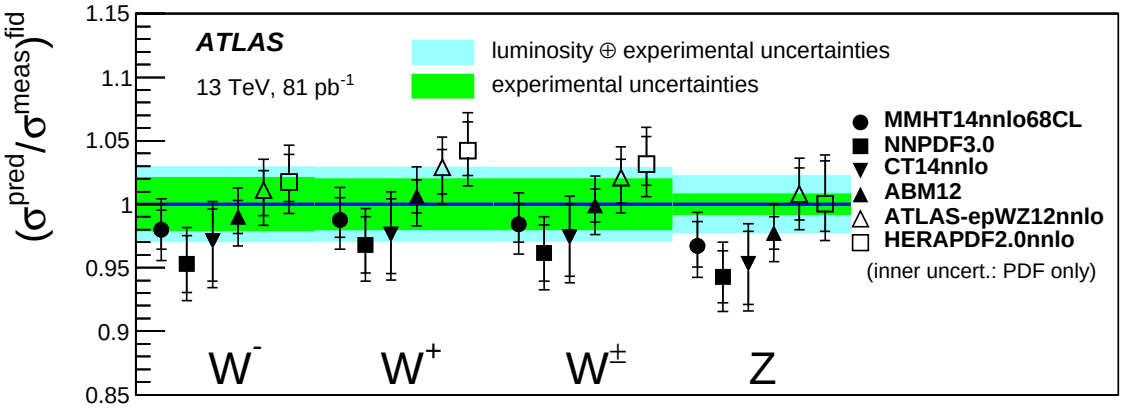




- Measurements by ATLAS of W, Z-boson production cross sections and ratios
- Measurements by CMS of Z-boson cross section and differential distribution.

ATLAS Phys. Lett. B 759 (2016) 601, CMS-PAS-SMP-15-01, CMS-PAS-SMP-15-011

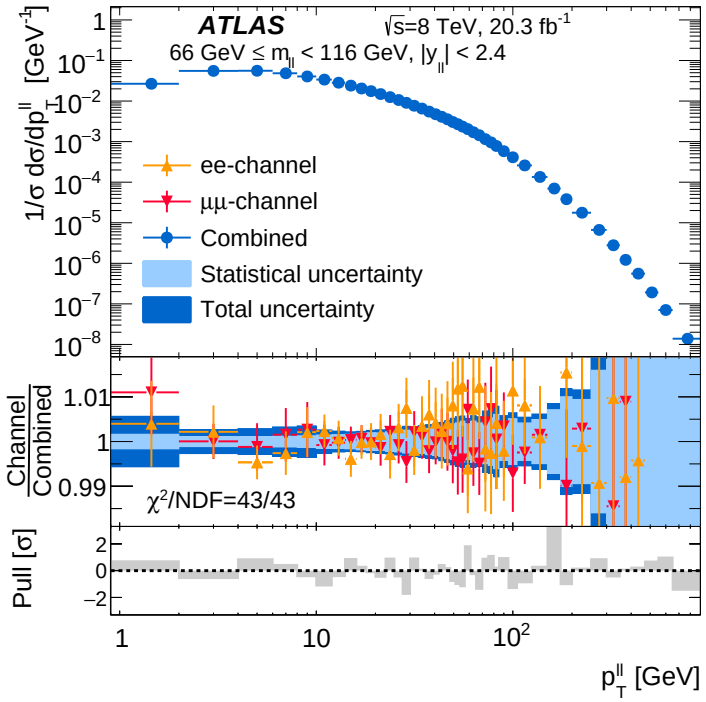
W, Z production at $\sqrt{s} = 13$ TeV

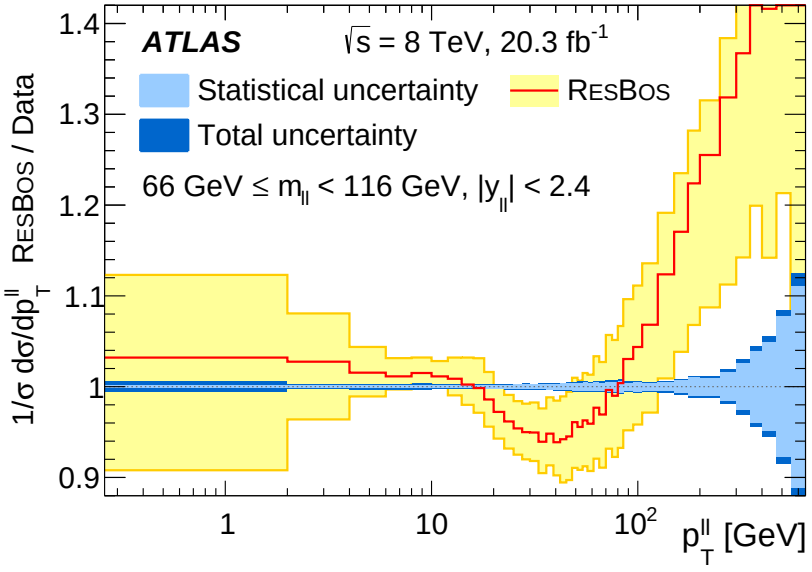


- Even for early $\sqrt{s} = 13$ TeV data the dominant uncertainty on the fiducial Z-boson production cross section comes from the luminosity.
- The luminosity uncertainty is improved for $\sqrt{s} = 8$ TeV data to 1.9%. For $\sqrt{s} = 13$ TeV data it is now at 2.1% and 1.8% for $\sqrt{s} = 7$ TeV data.

ATLAS luminosity at $\sqrt{s} = 8$ TeV: arXiv:1608.03953

Measurement of Z_{p_T}

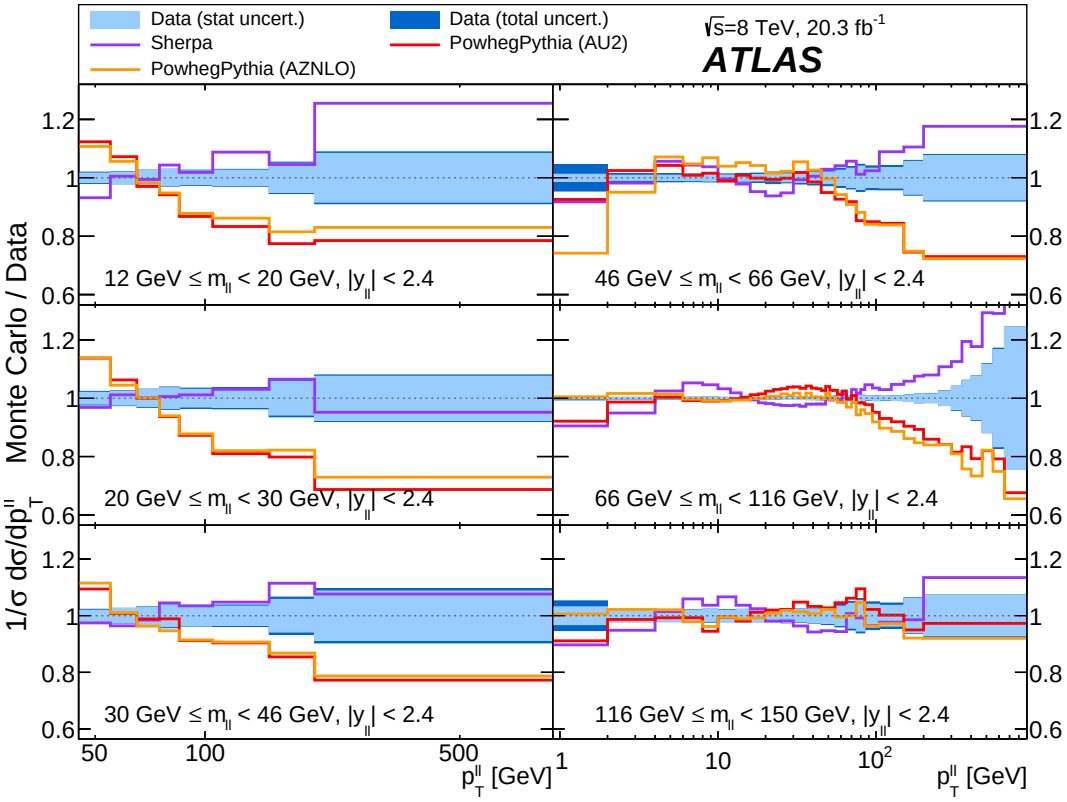




- Several measurements of Z_{p_T} at $\sqrt{s} = 7$ and 8 TeV by ATLAS and CMS.
- ATLAS measurements use both $Z \to ee$ and $Z \to \mu\mu$ channels, which have comparable accuracy. The combined result is accurate to better than 0.5% for $P_T < 100$ GeV range.

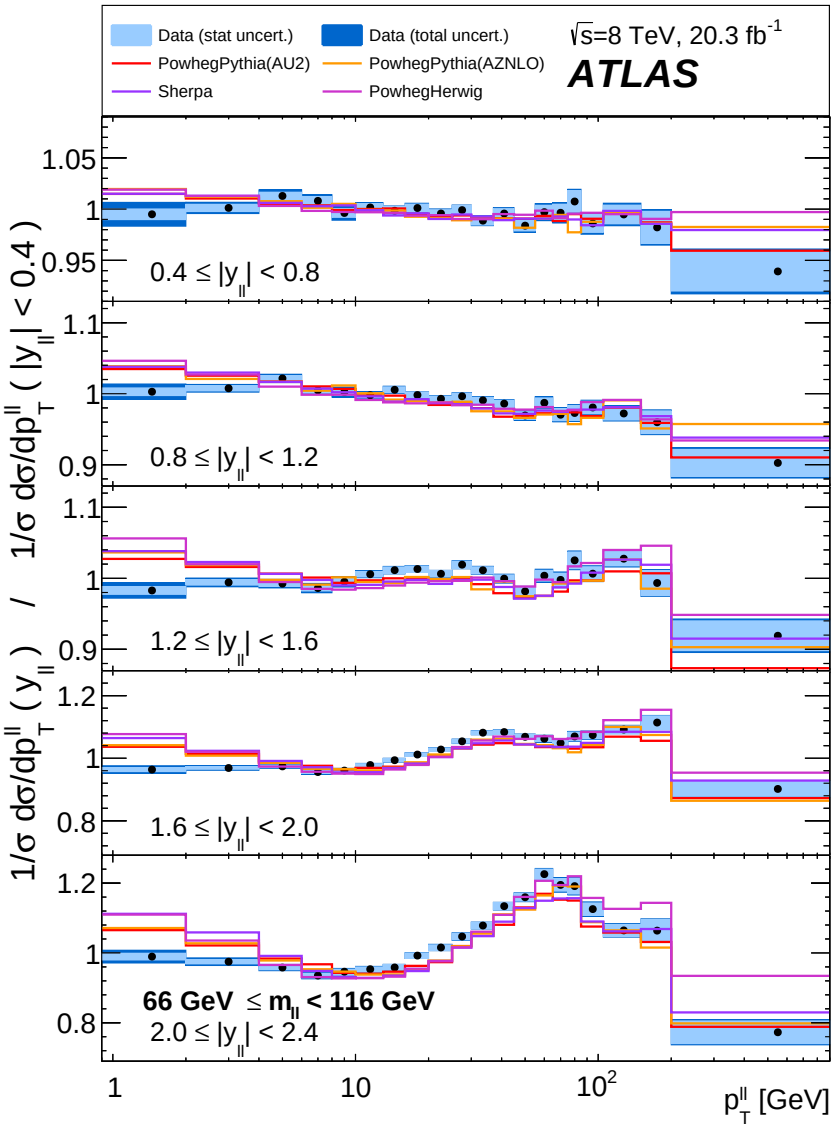
ATLAS, arXiv:1512.02192

Off-peak p_T measurements



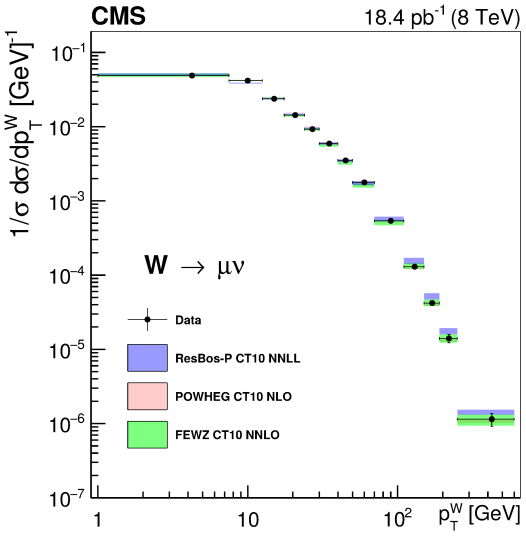
- Large $\sqrt{s} = 8$ TeV samples can be used to probe distributions double differentially. Studying dependence in mass can probe different PDF decomposition, scale dependence, electroweak effects.
- Dedicated Powheg+Pythia tune AZNLO, developed using Z_{p_T} $\sqrt{s} = 7$ TeV data, works very well for the peak range but deviates at low masses.

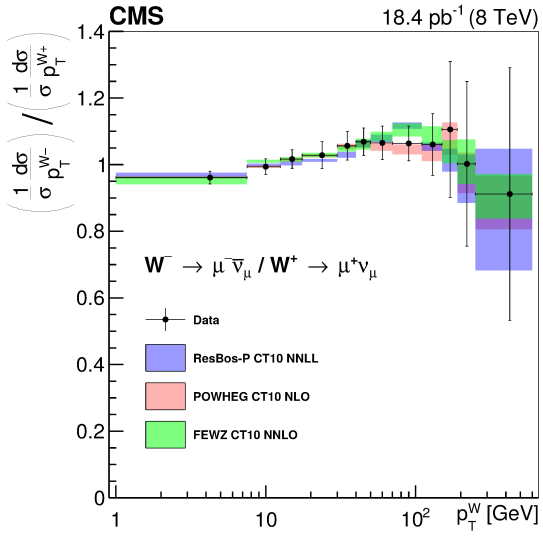
Z_{p_T} as a function of y_Z

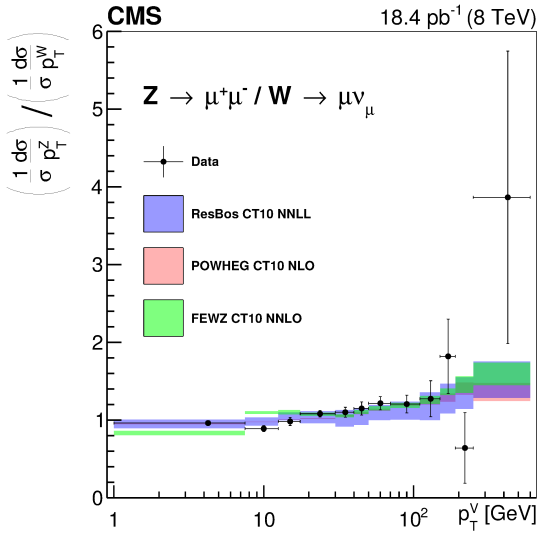


- Additional stringent tests can be performed using double ratios, e.g. to explore y_Z dependence.
- NLO+PS MC samples struggle to describe p_T dependence as a function of y_Z.

Measurement of $p_T(Z)$ and $p_T(W)$ by CMS



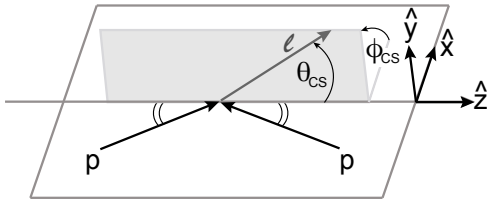


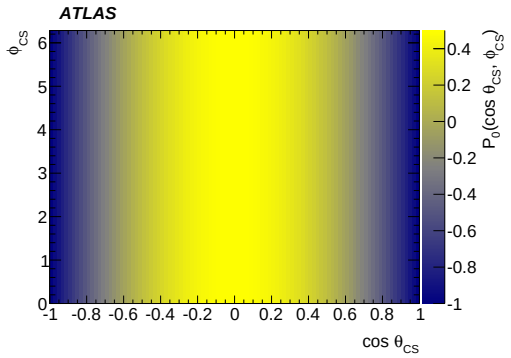


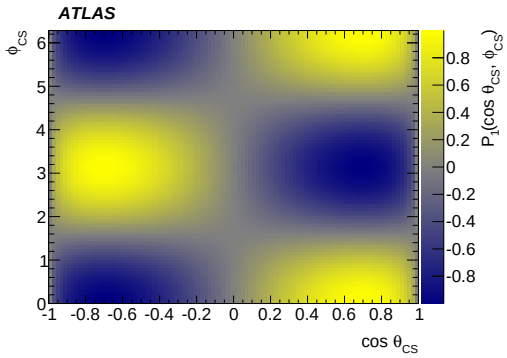
- Measurement of the W-boson p distribution and the ratios of $p_{\mathrm{T}}^{W^+}/p_{\mathrm{T}}^{W^-}$ and $p_{\mathrm{T}}^{Z}/p_{\mathrm{T}}^{Z}$ using a dedicated low pileup run at $\sqrt{s} = 8$ TeV.
- Important to understand transfer from precise p_{T}^{Z} to p_{T}^{W} for the W-boson mass measurement.

  CMS, arXiv:1606.05864, also CMS-PAS-15-002

Z-boson polarisation



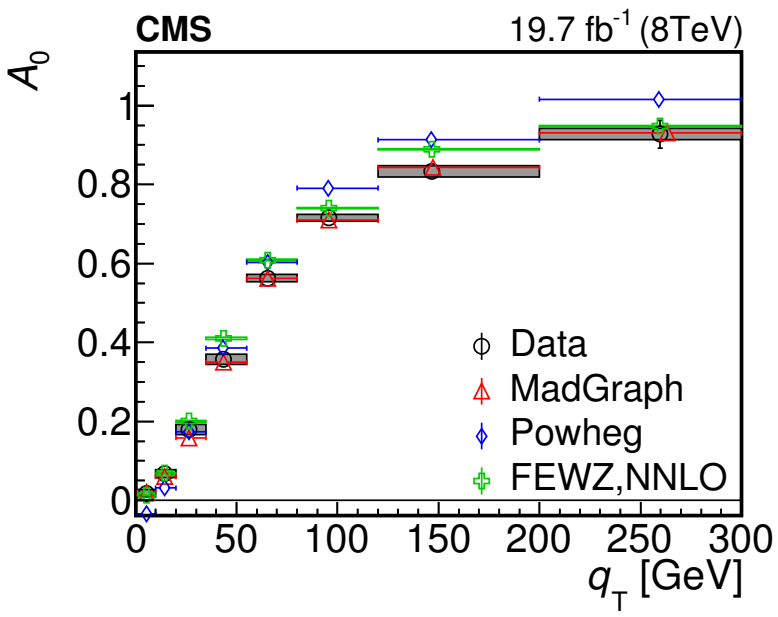


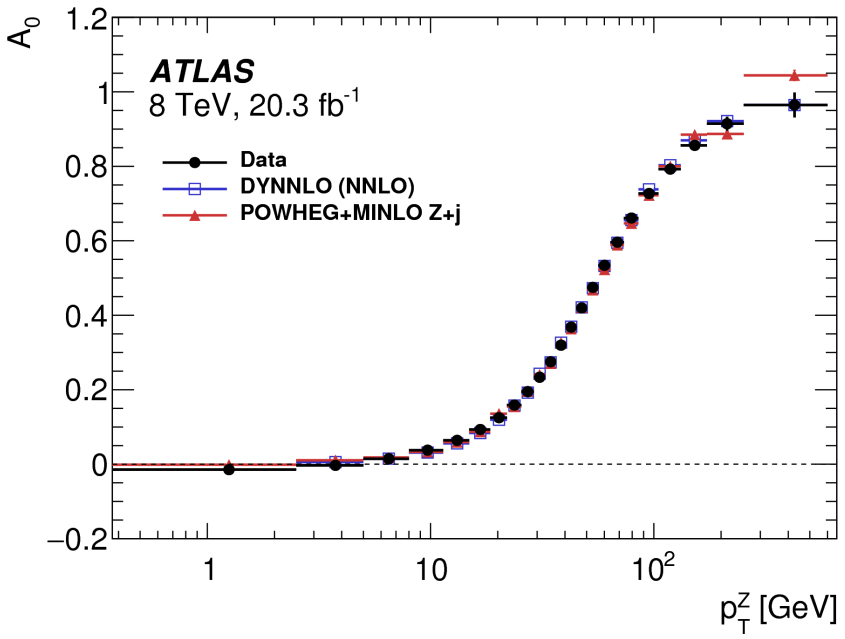


$$\frac{d\sigma}{d\cos\theta d\phi} = (1+\cos^2\theta) + A_0\tfrac{1}{2}(1-3\cos^2\theta) + A_1\sin 2\theta + \tfrac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi$$
$$+A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\,.$$

- W, Z bosons are vector particles and are produced polarised. Decay distributions can be described by spherical harmonics with eight parameters.
- At leading order QCD, only A_4, corresponding to forward-backward asymmetry is present
- At NLO, due to new gq and $g\bar{q}$ diagrams, $A_0 - A_4$ are not zero.
- All coefficients are not zero at NNLO.

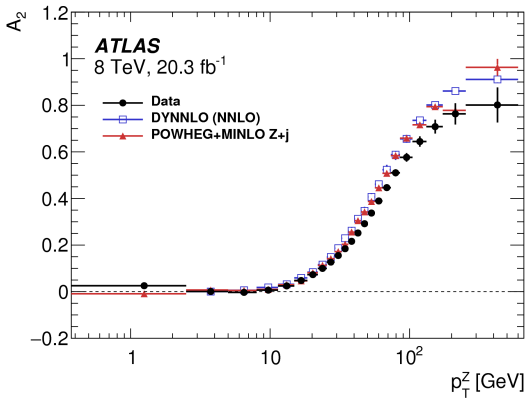
Z polarisation results

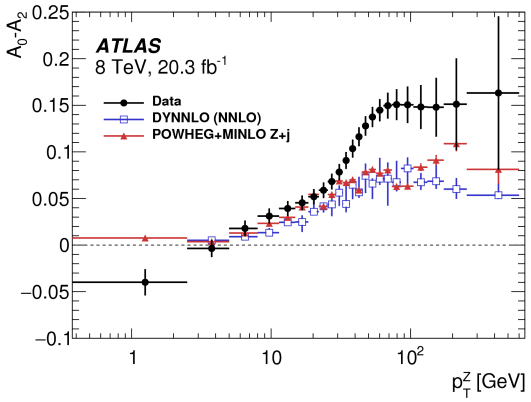


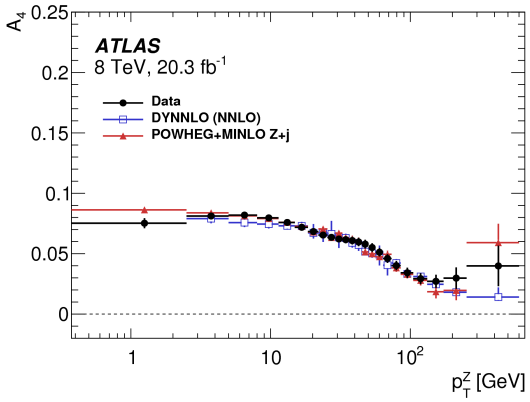


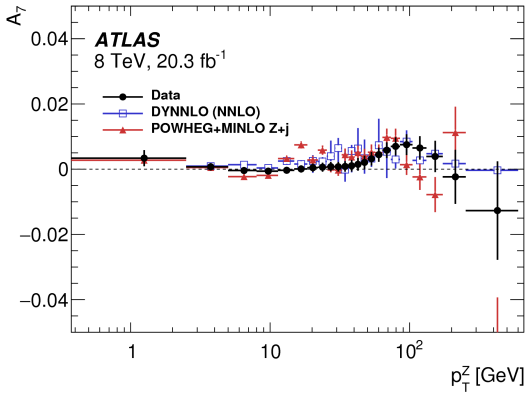
- Measurement of Z polarisation coefficients from ATLAS and CMS.
- ATLAS measures all $A_0 - A_8$ polynomials using data from both electron and muon channel and their combination.
- Excellent agreement for A_0 with NNLO QCD.
  CMS, PLB 750 (2015) 154, ATLAS arXiv:1606.00689

Z angular coefficients









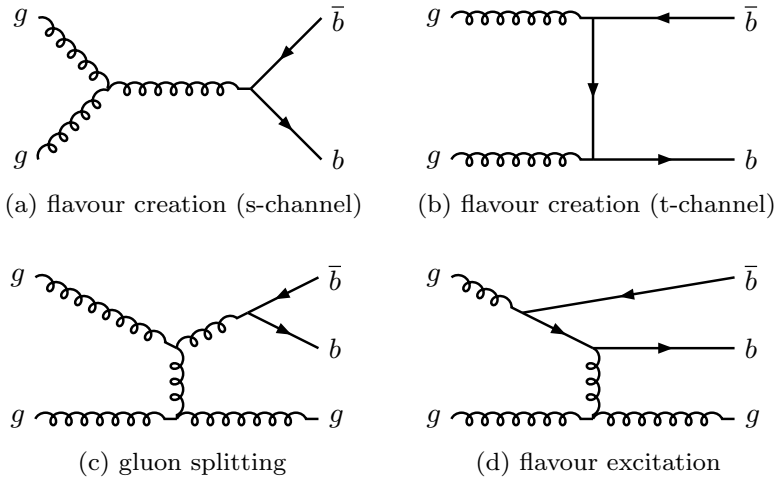
- $A_0 - A_0$ is expected to become non-zero at NNLO, data confirms that
- Data deviates from NNLO expectations for A_2 (and $A_0 - A_2$) at high p_T.
- A_4 measures forward-backward asymmetry, can be used to extract $\sin^2 \theta_W$
- Higher order coefficients appear from NNLO, evidence of them in data.

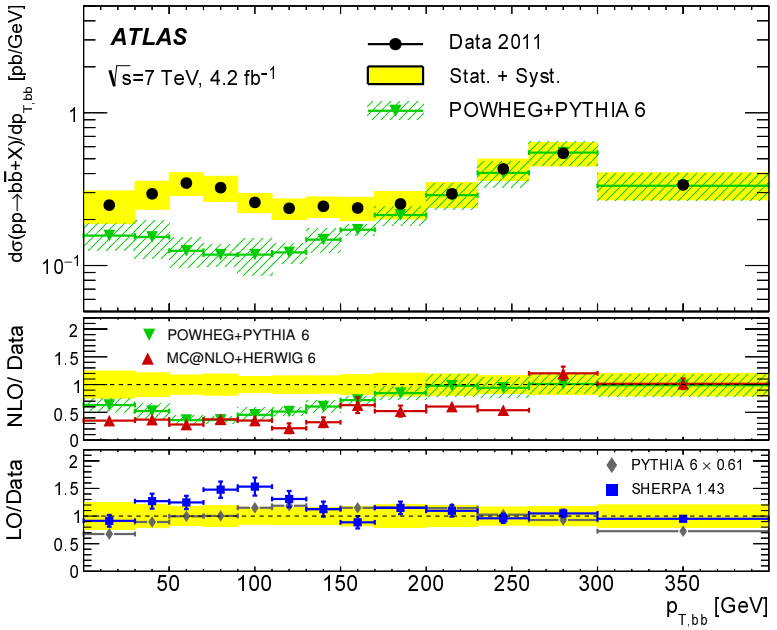
ATLAS arXiv:1606.00689

Summary

- A number of interesting QCD measurements from the LHC experiments.
- A few new ideas explored in jet studies.
- Precision measurements based on Run-I data, with high constraining power, probing latest QCD theory developments.
- First new measurements at $\sqrt{s} = 13$ TeV, sometimes with surprisingly good accuracy.

$b\bar{b}$ jets at $\sqrt{s} = 7$ TeV

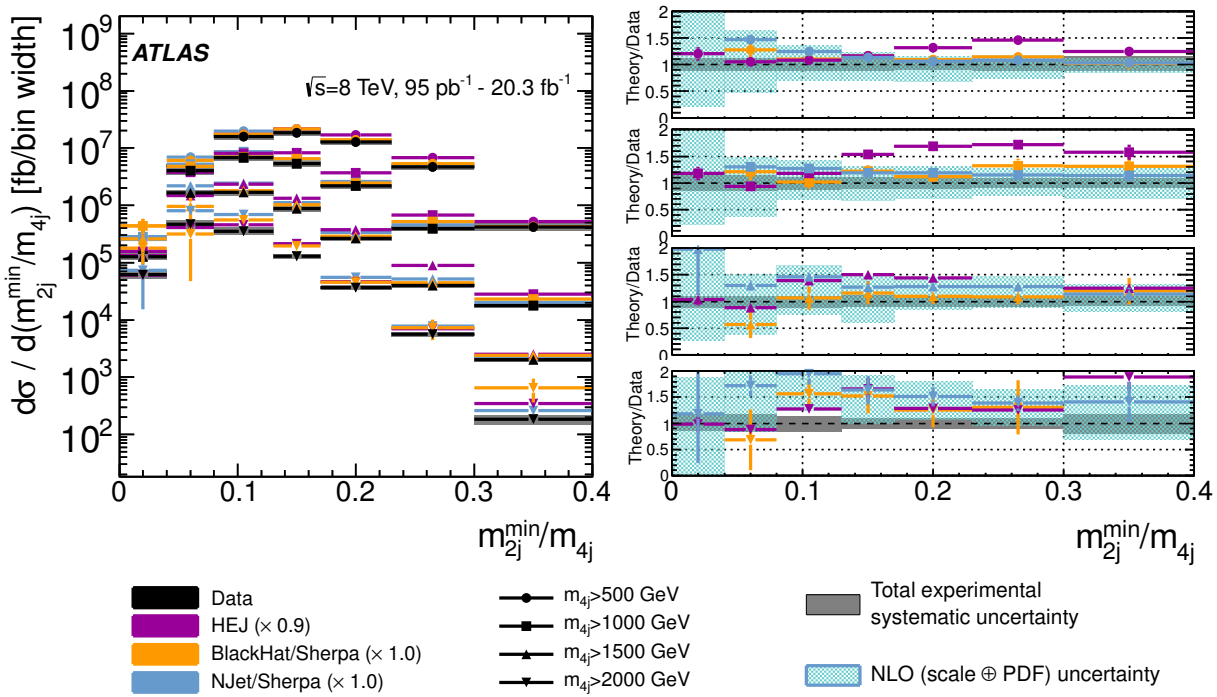




- Study of b-tagged dijet system with $p_{\mathrm{T},1} > 270$ GeV, $p_{\mathrm{T},2} > 20$ GeV, $\Delta R > 0.4$.
- Focus on dijet observables, m_{bb}, $p_{\mathrm{T},bb}$ and Δ_ϕ.
- Compared to LO and NLO predictions which have difficulties to describe the data in this specific phase space.

ATLAS arXiv:1607.08430

Multijet differential cross sections



- Extensive study of multijet observables for ≥ 4 jets with $p_{\mathrm{T}} > 64$ GeV, anti-k_T $R = 0.4$, well separated $\Delta R > 0.65$, and leading jet $p_{\mathrm{T}} > 100$ GeV.
- NLO predictions give reasonable description of the data, for the most of observables.

ATLAS, JHEP 12 (2015) 105