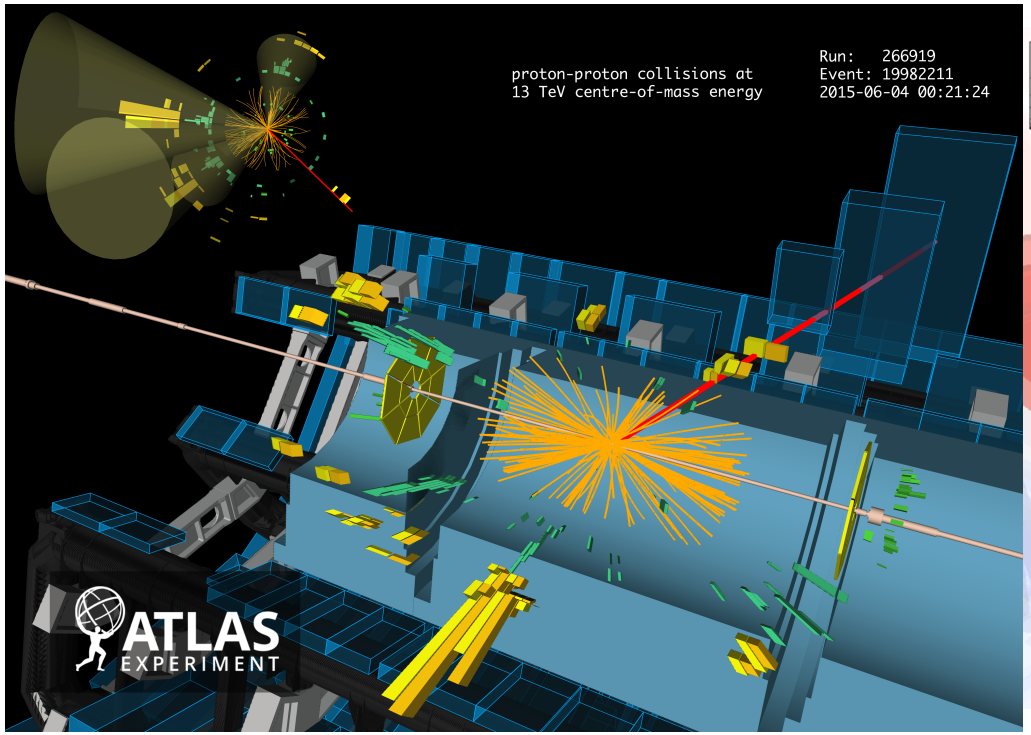
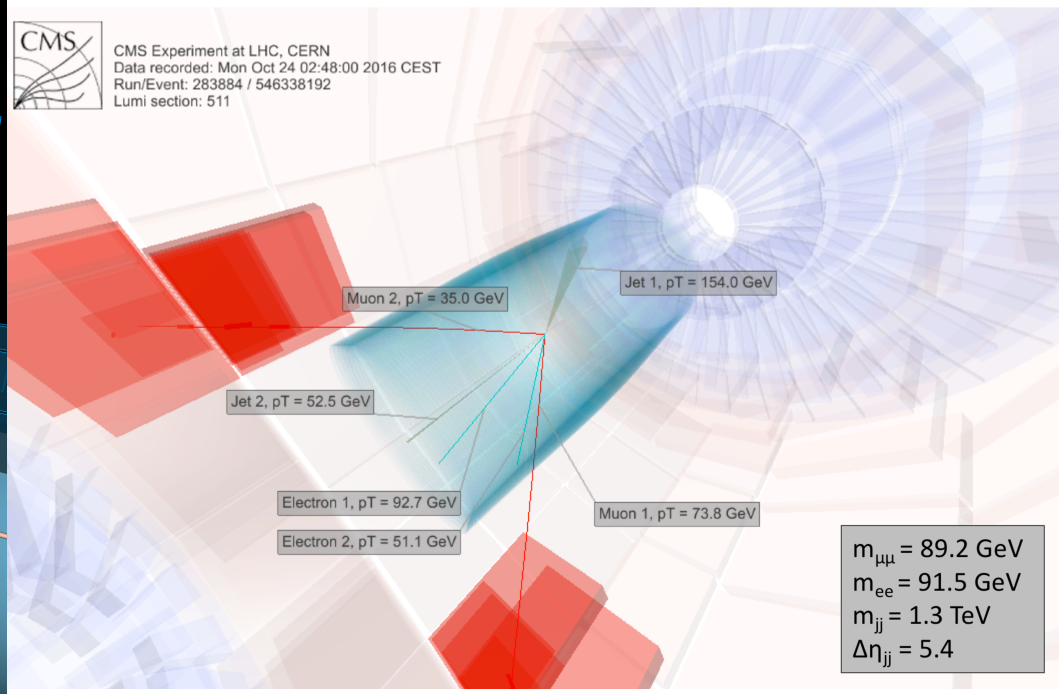
Latest LHC results on Standard Model measurements

Emanuela Barberis
Northeastern University
for the ATLAS and CMS Collaborations





Outline

Jet Production
- Inclusive jet cross sections
- Dijet cross sections
- PDFs constraints
- Extraction of α_s
- 2-, 3-, 4-jet azimuthal correlations

Photons
- Inclusive photon cross sections
- Photon pair production
- Photon + jets

W,Z Production
- Inclusive W,Z cross sections
- Differential cross sections and PDFs
- W mass

V (W,Z) + jets
- W,Z + jets differential cross sections
- W,Z + b(b)-jet
- Z + charm
- Electroweak W,Z + 2 jets

Multi-bosons
- Diboson cross-sections
- VV+jets
- aTGC and aQGC

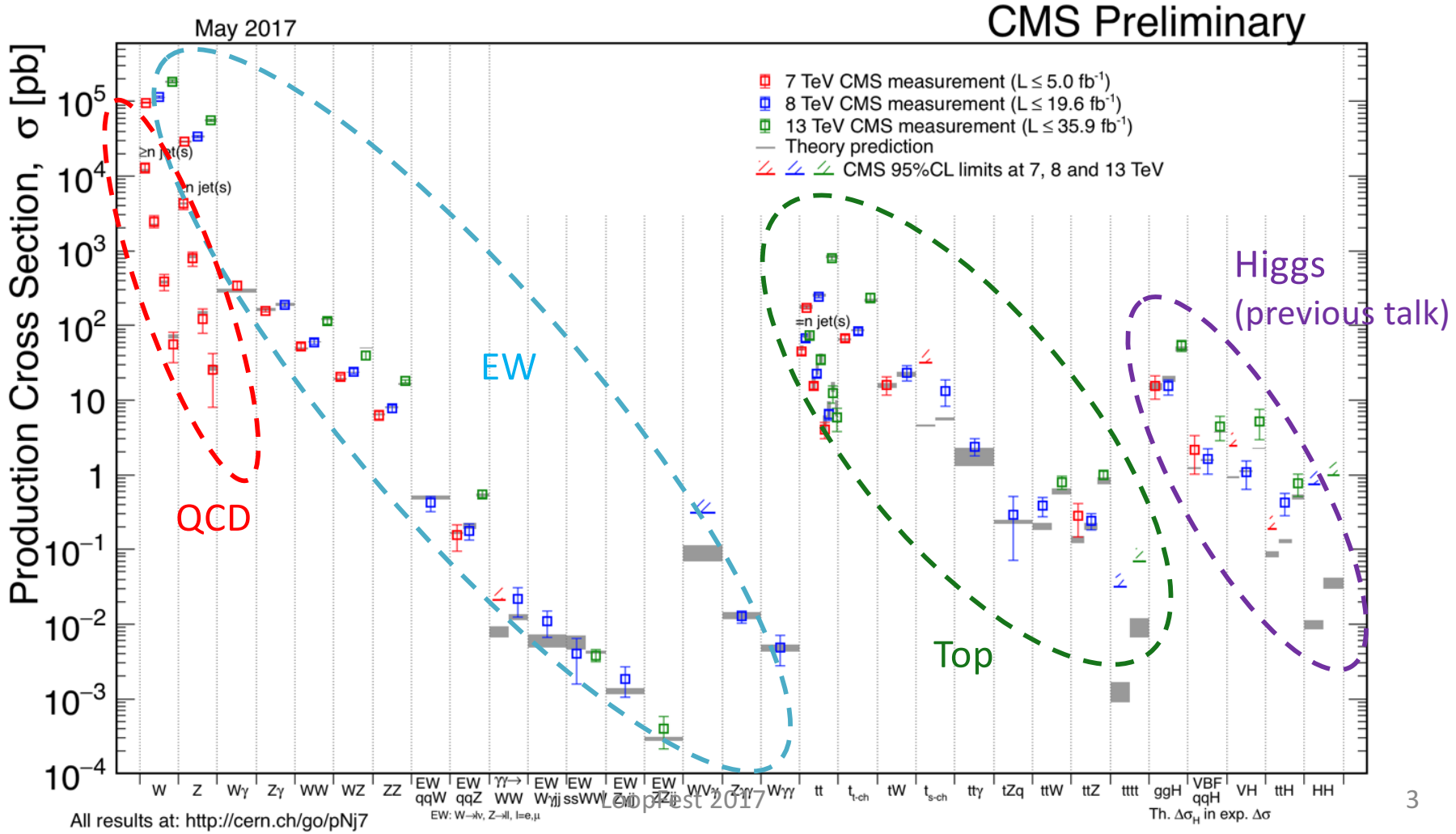
Top quark production
- Pair production cross-sections
- Associated pair production
- Constraints on PDFs
- Single top production
- Top mass

*Selected list of recent results. By no means a complete list.

Standard Model Measurements

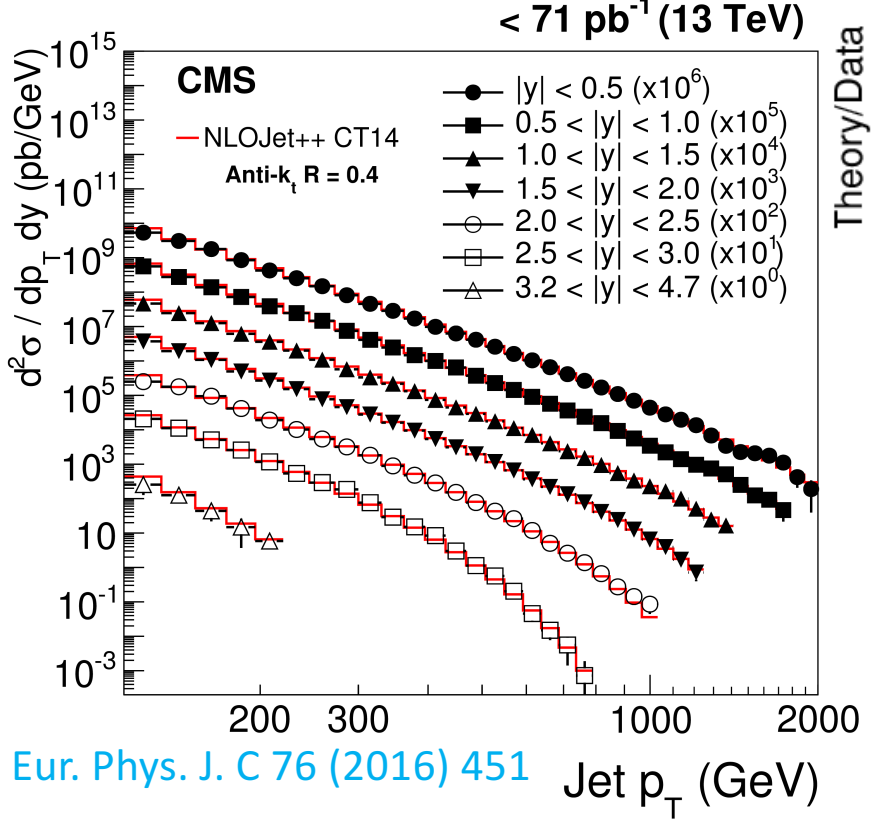
SM precision measurements allow us to test a wide range of QCD and EW predictions, and to extract fundamental parameters such as α_s.

They are also important for understanding the backgrounds to rare/new processes and can be sensitive themselves to the effects of new physics.

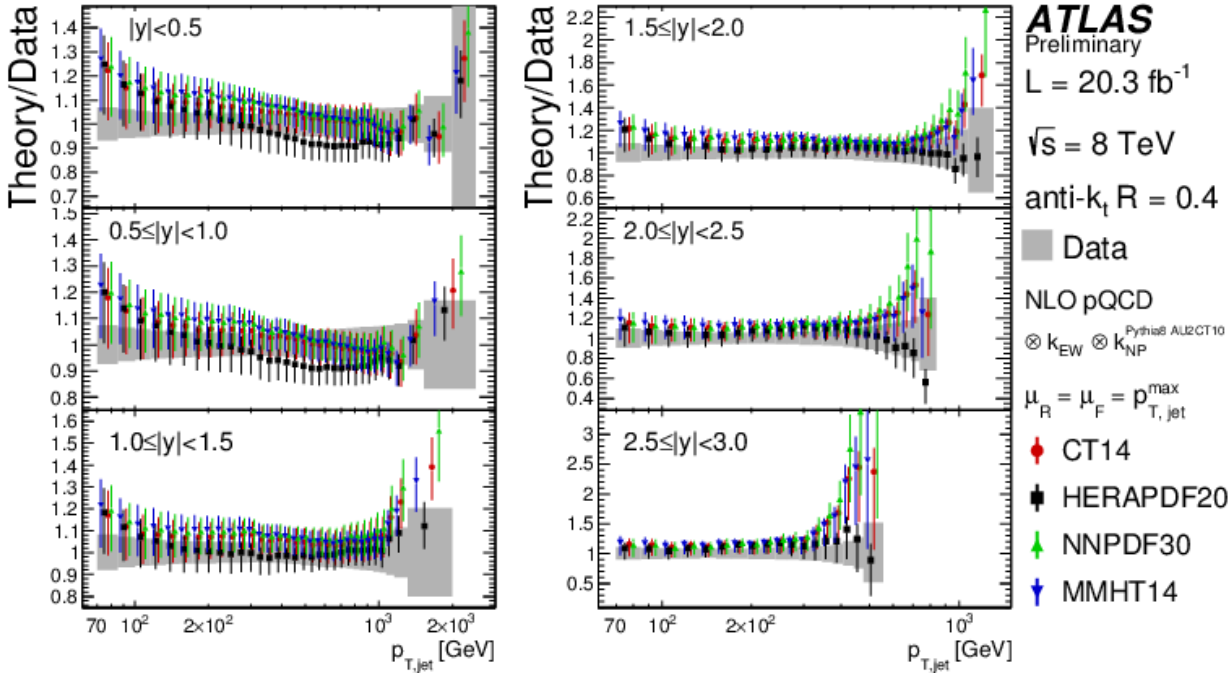


Inclusive Jet Production

Inclusive jets cross-section: double differential (p_T, y) measurements over several orders of magnitude, up 3.2 TeV and |y|=4.7, compared with fixed-order NLO calculations, NLOJet++ and POWHEG+PY8 (corrected for non perturbative and EW effects). Main tool for jet energy calibration.



Eur. Phys. J. C 76 (2016) 451



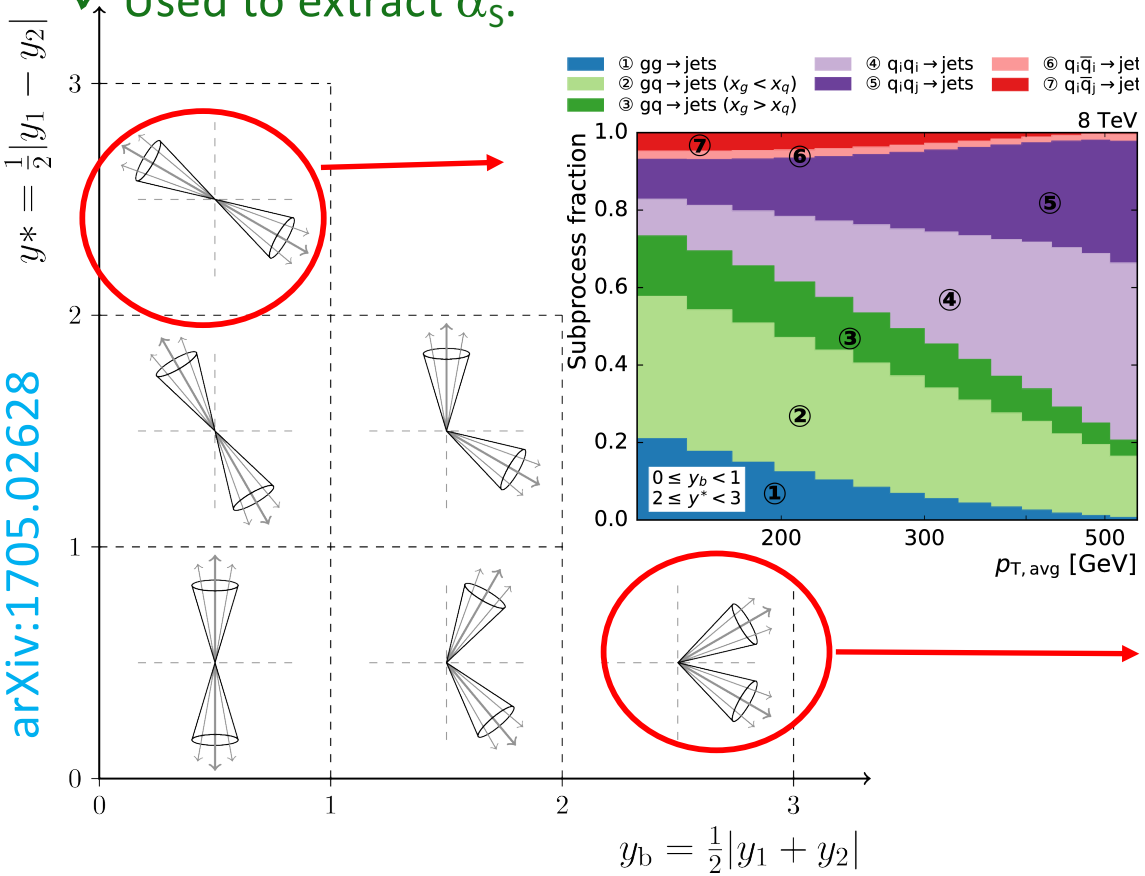
ATLAS-STDM-2015-01

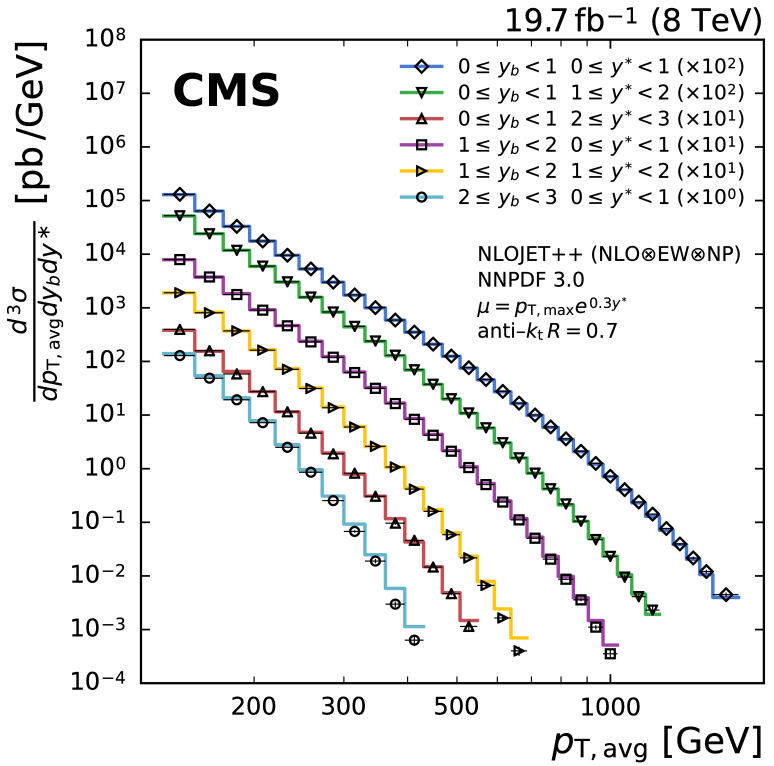
- ✓ Overall good agreement with NLO QCD predictions.
- ✓ Two cone sizes to test radiative and NP effects (smaller cone size needs NLO+PS).
- ✓ Sensitive to PDFs over a wide (x,Q) range, in particular high-x gluon and valence quark.
- ✓ Used to extract α_S.

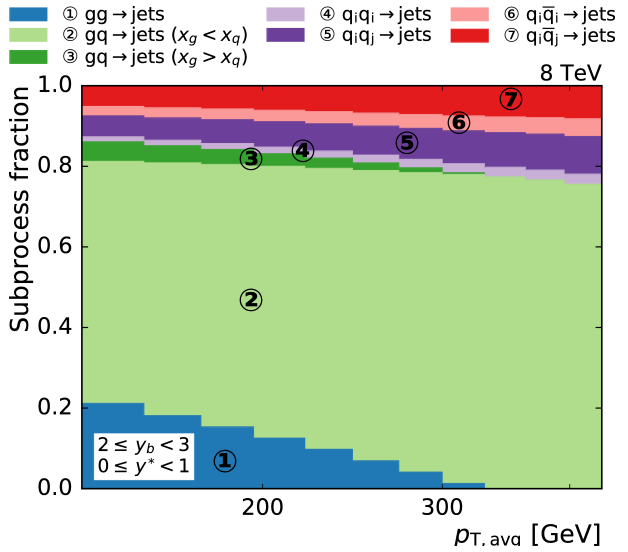
Dijet Production

Dijets cross-sections: Triple differential cross sections ($p_{T,avg}$, y^*, y_b), sensitive to different sub-processes and overlapping (x,Q) regions in PDFs. Compared to NLOJet++ (with NP and EW effects).

- ✓ In agreement with NLO predictions.
- ✓ Used to constraint PDFs.
- ✓ Used to extract α_S.





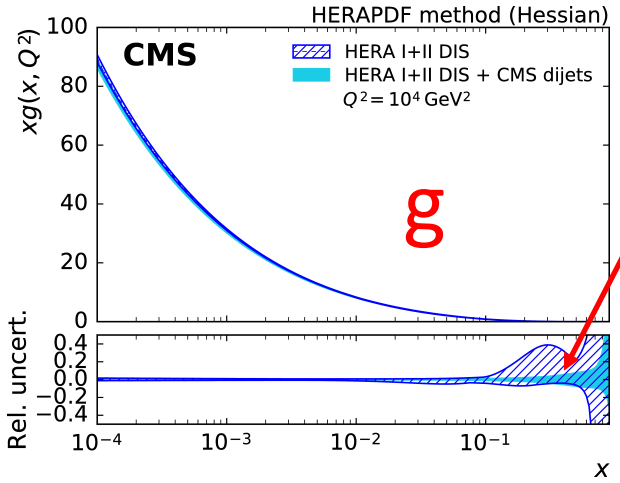


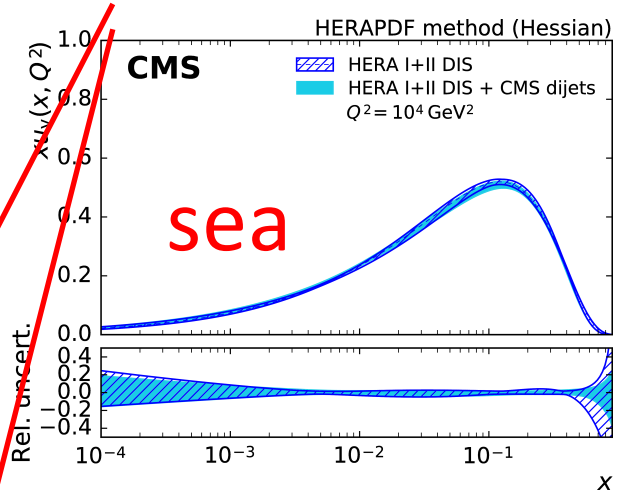
arXiv:1705.02628

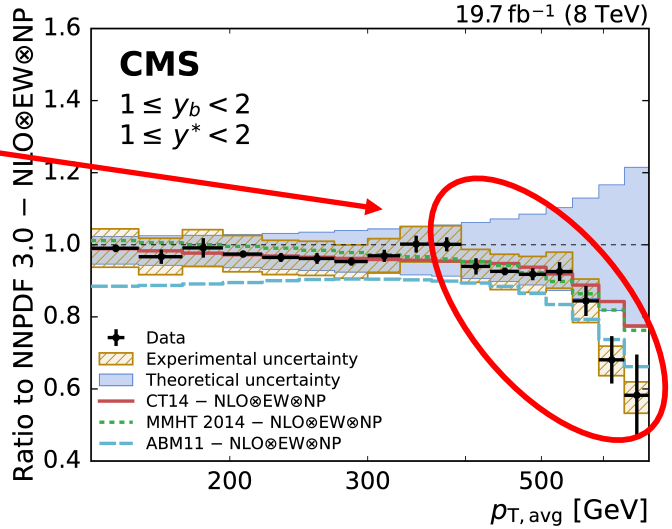
PDFs constraints

Precision constraints of the PDFs: Inclusive jet, dijet cross sections, and other precision measurements of jet processes are fitted to constrain PDFs (and determine α_S).

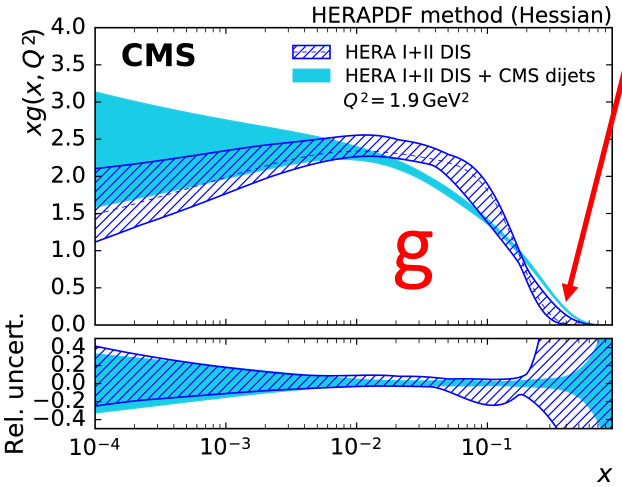
- ✓ Reduces PDF uncertainties, specially the gluon PDF, in the boosted regime (high $|y_1+y_2|$, high $p_{T,avg}$), where large x are probed.
- ✓ It also changes the gluon PDF shape for low Q^2.

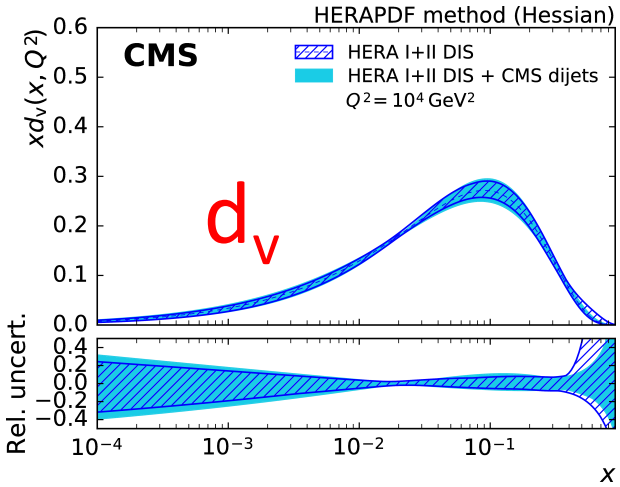


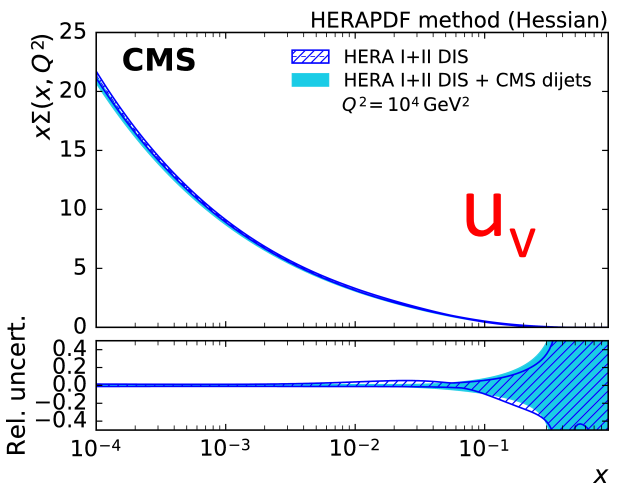




arXiv:1705.02628



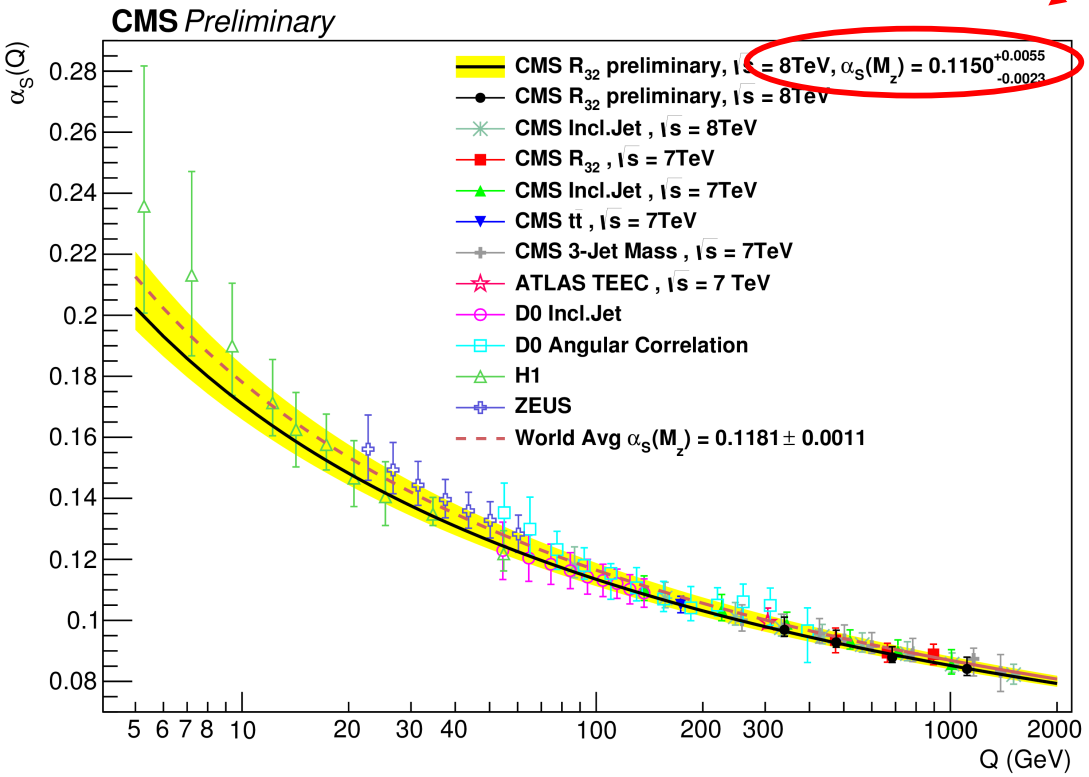




Measurement of strong coupling α_S

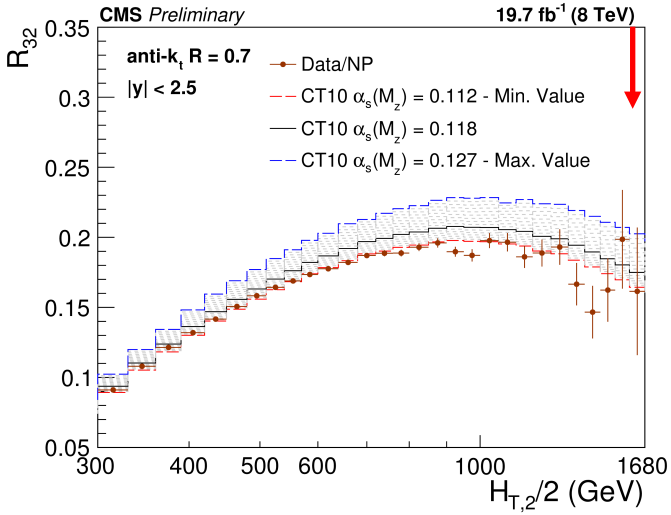
Evolution of strong coupling extracted from different measurements up to Q=2TeV: α_S is a fundamental parameter in SM, modifications of running at higher scale could occur due to new physics.

CMS-PAS-SMP-16-008



Measurement from ratio of inclusive 3- to 2- jet cross sections (R_{32}) as a function of $H_T/2=1/2(p_{T1}+p_{T2})$.

✓Compared to NLOJet++ to extract α_S with FastNLO framework.



CMS R_{32}

$\alpha_s(M_Z)= 0.1150\pm0.0010\ (\text{exp})\pm0.0013\ (\text{PDF})\pm0.0015\ (\text{NP})^{+0.0050}_{-0.0000}\ (\text{scale})$

ATLAS TEEC

$\alpha_s(M_Z)= 0.1162\pm0.0008\ (\text{exp})\pm0.0018\ (\text{PDF})\pm0.0003\ (\text{NP})^{+0.0050}_{-0.0000}\ (\text{scale})\pm0.0007\ (\text{other})$

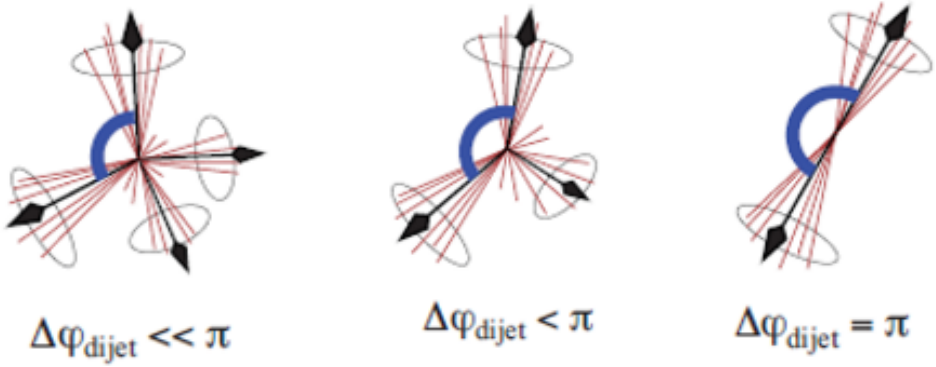
ATLAS-STDM-2016-10

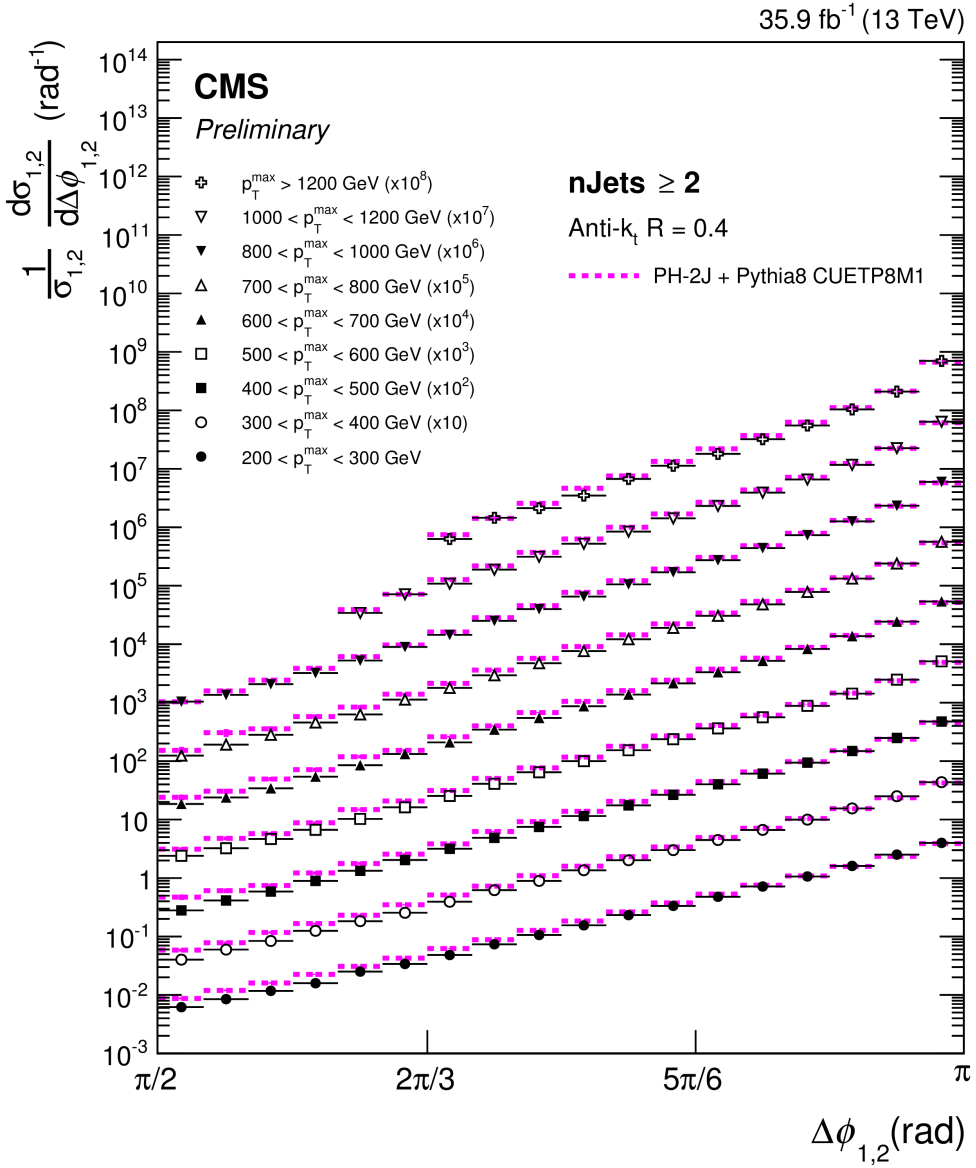
2- 3- 4-jet azimuthal correlations

Multi-jet azimuthal correlations: normalized differential cross-section in $\Delta\phi_{1,2}$ of the two leading p_T jets in inclusive 2-, 3-, 4- jets, and in $\Delta\phi_{2j}^{min}$, the minimum azimuthal angular separation between any two jets in 3-, 4- jet topologies.

- ✓Sensitive to the radiation of additional jets .
- ✓Probes the dynamics of multijet production.
- ✓Results compared to LO and NLO MC generators with various PS tunes.

Decorrelation from π of $\Delta\phi_{1,2}$

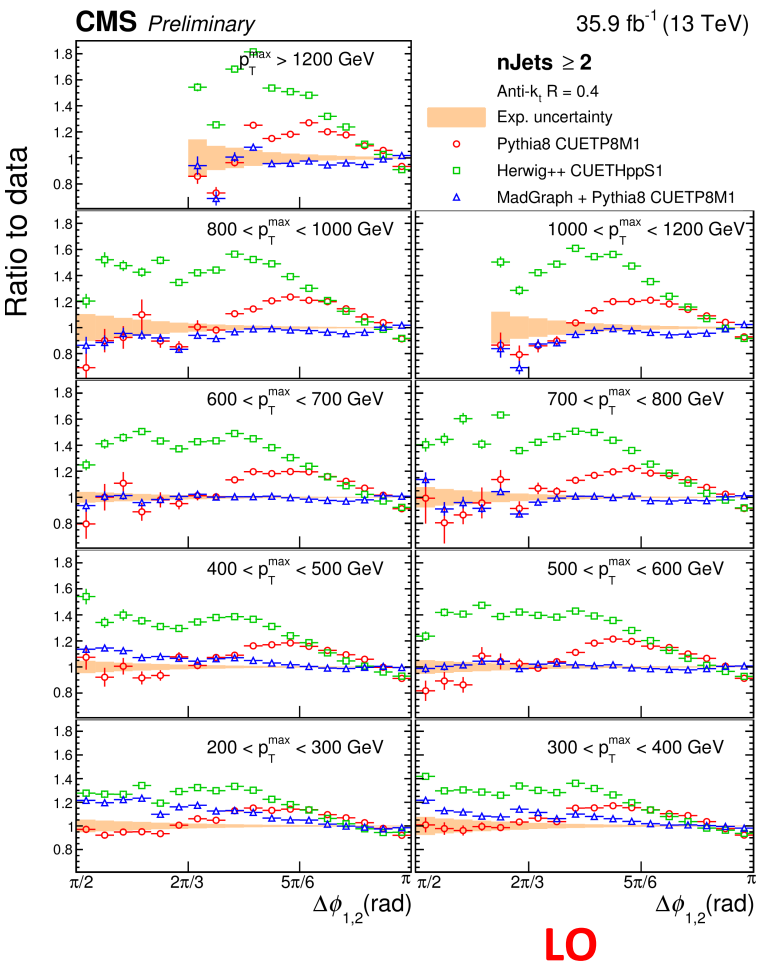




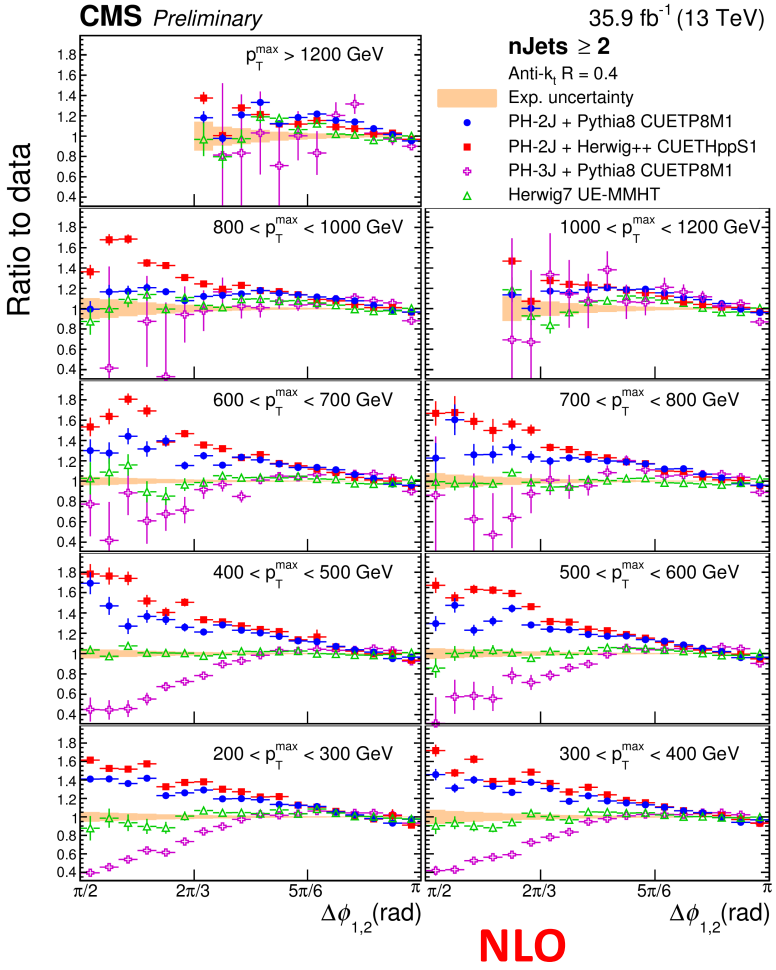
CMS-PAS-SMP-16-014

2- 3- 4-jet azimuthal correlations

CMS-PAS-SMP-16-014

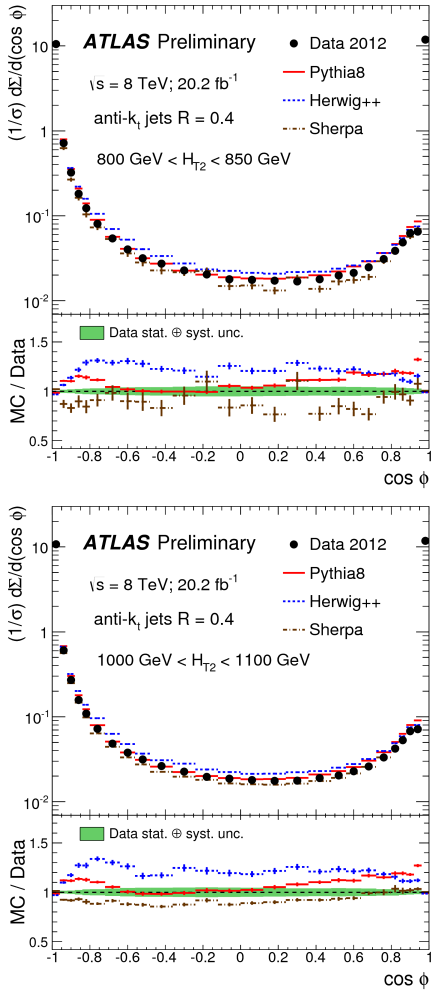


LO



NLO

ATLAS-STDM-2016-10



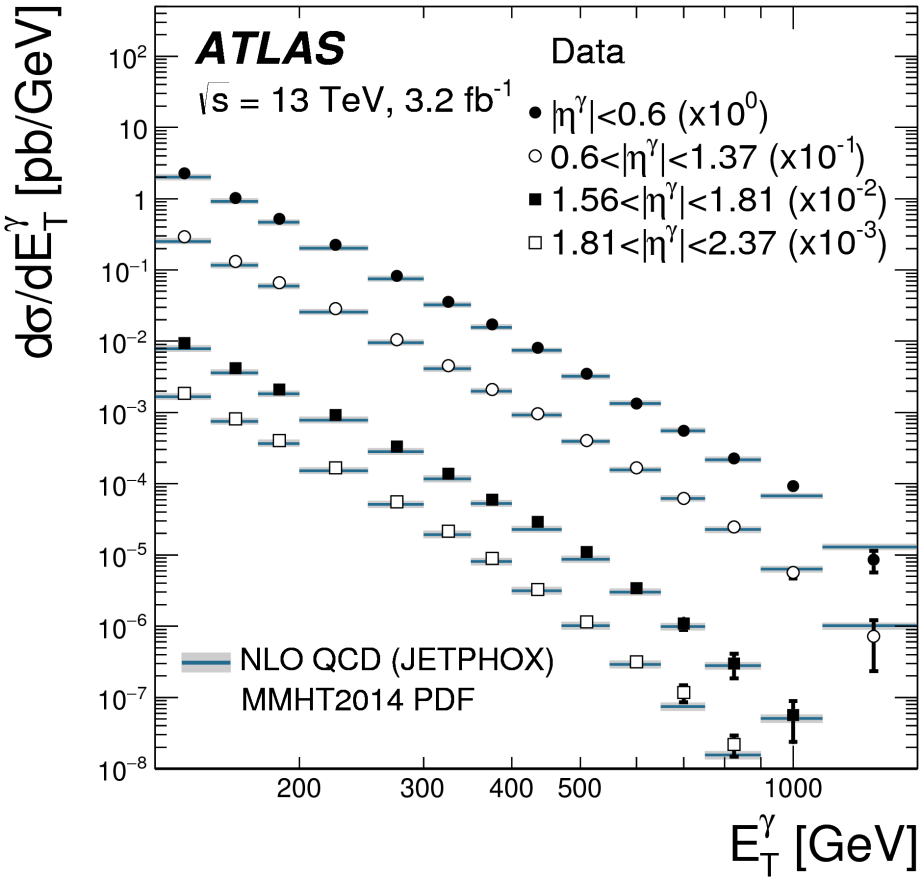
✓Improved description from NLO. Herwig7 describes the $\Delta\phi_{1,2}$ cross sections best, while PH2J (POWHEG matched to Herwig++ or Pythia8) describes the $\Delta\phi_{2j}^{min}$ data best.

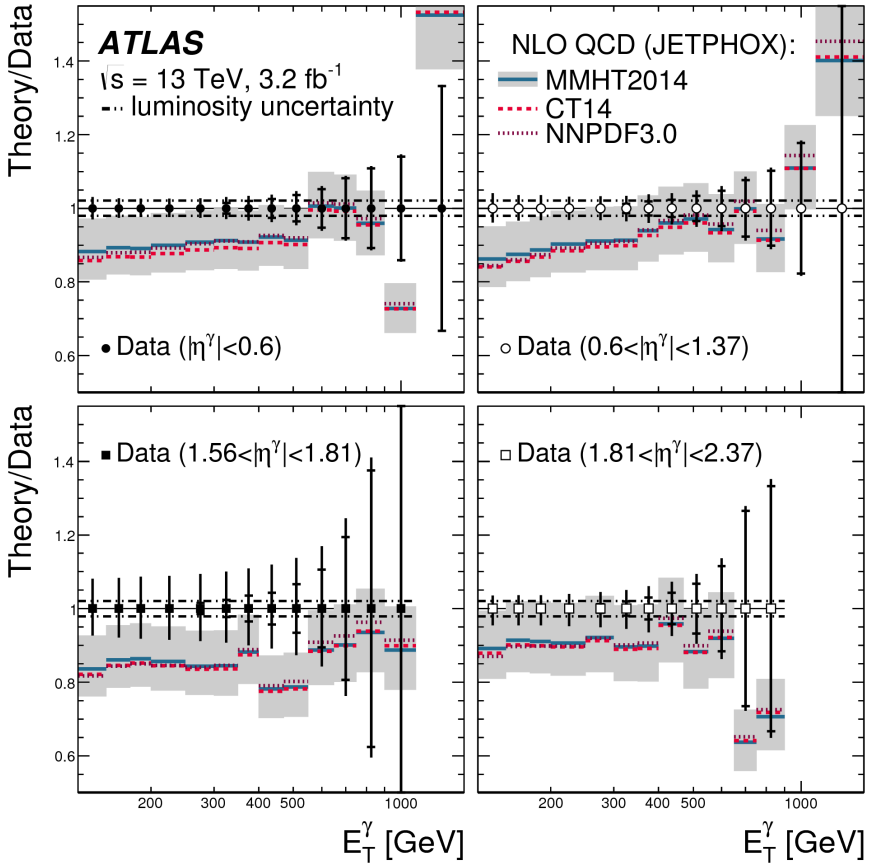
✓Transverse energy-energy correlations best described by Pythia8 and Sherpa.

Inclusive Photon Production

Inclusive isolated photon cross-section: double differential (E^{γ}_{T},η^{γ}) measurement compared with pQCD NLO calculation (JETPHOX), and LO MC generators (PYTHIA8 and SHERPA).

arXiv: 1701.06882



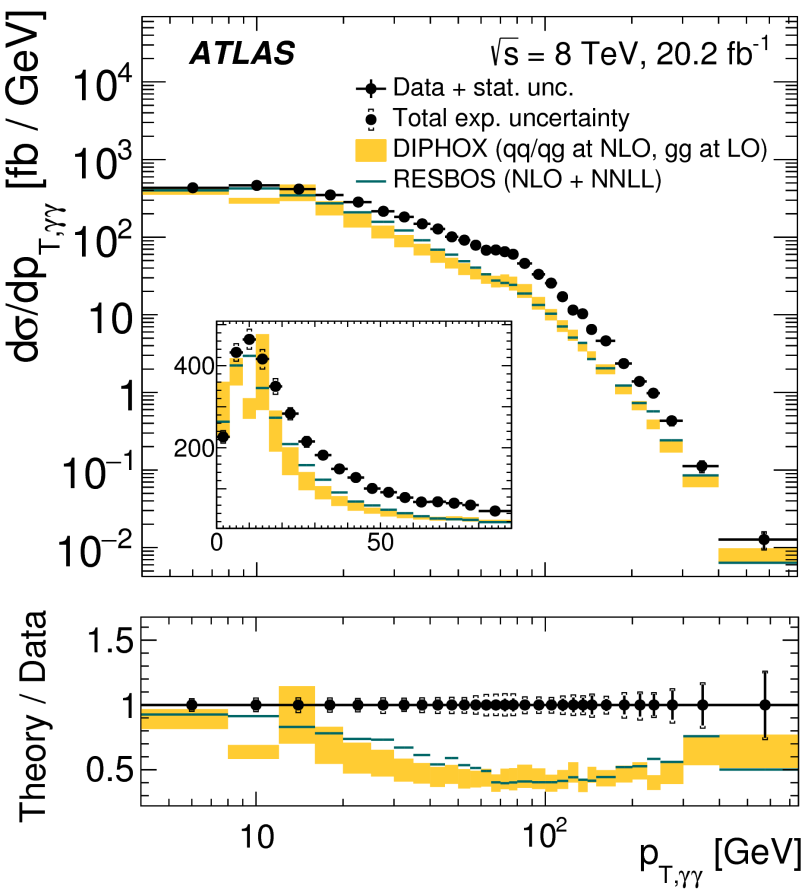


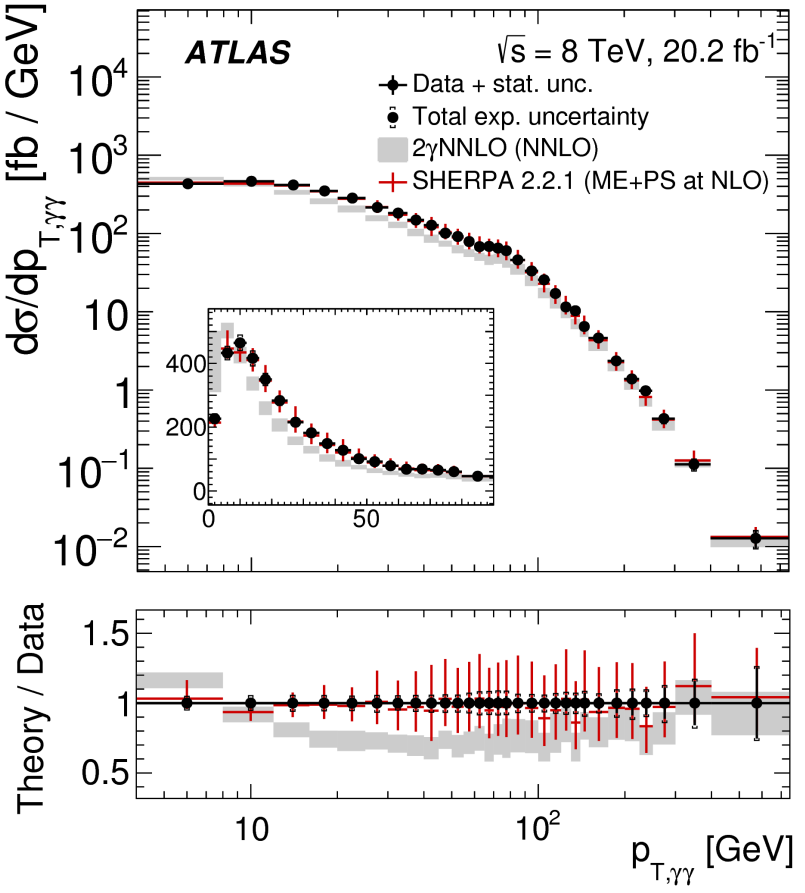
- ✓ Good shape agreement with LO predictions, except for E^{γ}_{T}>500 GeV and $|\eta^{\gamma}|$<1.38.
- ✓ Adequate description from JETPHOX, within uncertainties (which are still large).
- ✓ Can be used to constrain gluon PDF.

Isolated Photon Pairs

Production of pairs of isolated photons: fiducial and differential cross section measurements as functions of $\Delta\phi_{\gamma\gamma}$,$m_{\gamma\gamma}$,$p_{T\gamma\gamma}$ and other angular variables. Compared with NLO (DIPHOX), NNLO pQCD (2γNNLO), NLO+PS (Sherpa 2.2.1), NLO+resummation of soft gluons at NNLL (RESBOS).

arXiv: 1704.03839



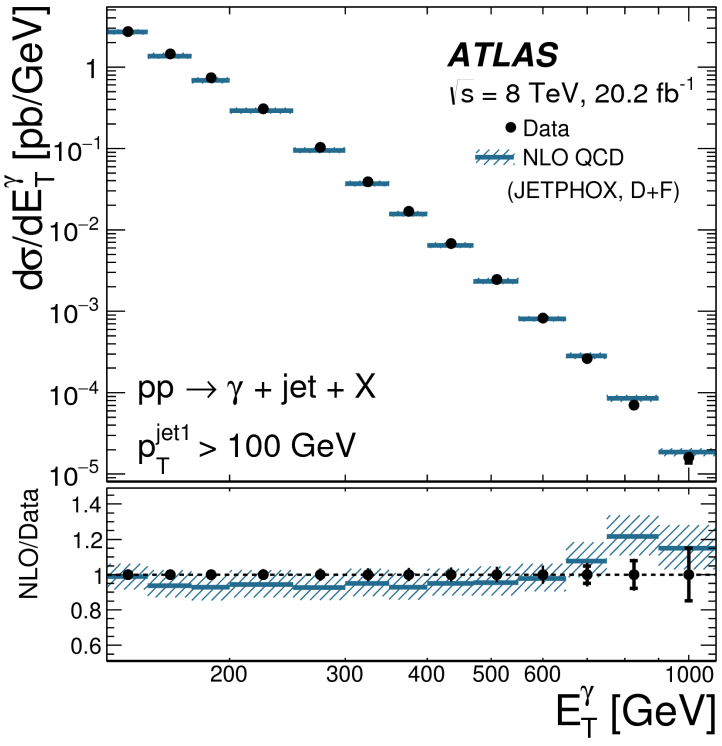


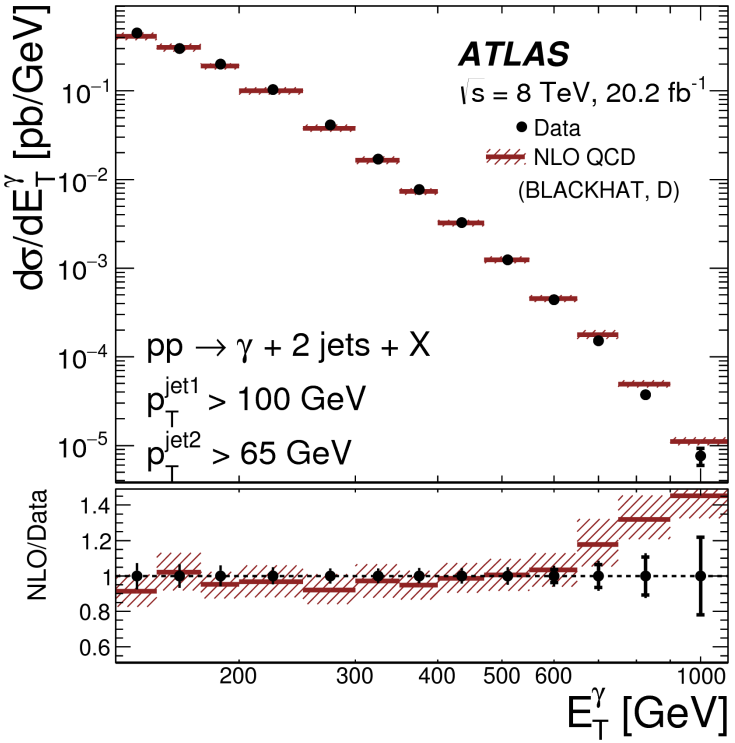
✓ DIPHOX and RESBOS do not reproduce the data. Discrepancies also observed for 2γNNLO. Best description from SHERPA.

Photon + jets

Photon + jets cross sections : differential in E_T^{γ}, p_T^{jet}, $\Delta\phi_{\gamma j}$ $m_{\gamma j}$ and other angular variables. Compared with NLO predictions of JETPHOX and BLACKHAT and LO predictions of SHERPA and PYTHIA. The pattern of QCD radiation around the photon and the leading jet is also studied by measuring jet production in a region centered on each object.

Nucl.Phys. B918 (2017) 257-316

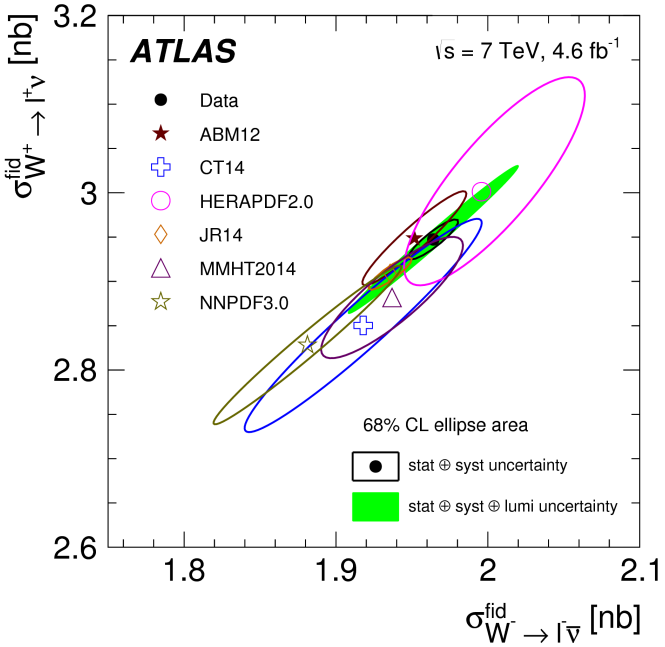


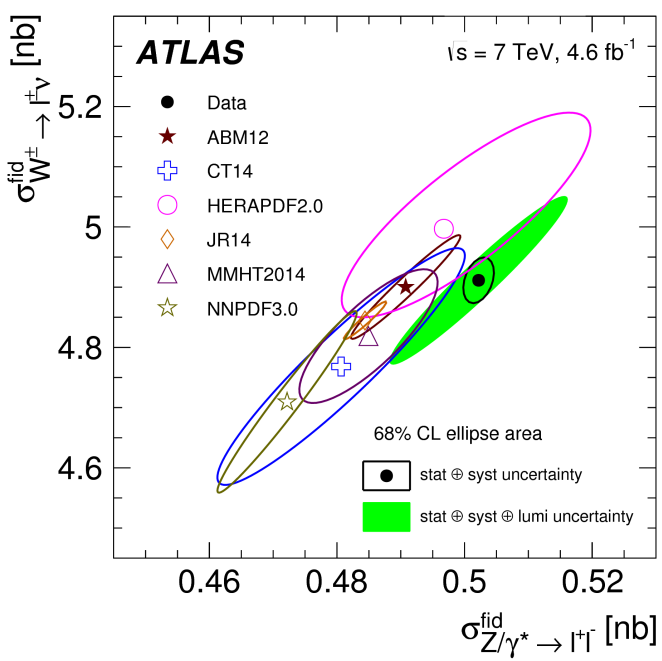


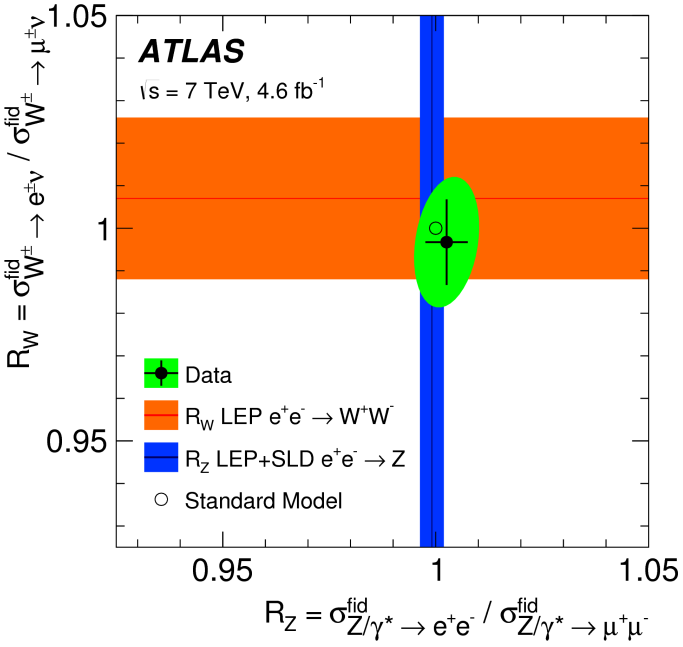
✓ Best description of γ+jet with JETPHOX. γ+2 jets is described by BLACKHAT up to 750 GeV.

W and Z production

Inclusive W and Z cross section measurements: High precision determination of W^+,W^-,Z and Drell-Yan production cross-sections, fundamental tests of EW theory. Differential cross-sections. Tests of lepton universality. NNLO QCD analysis (with HERA data) to constrain PDFs.





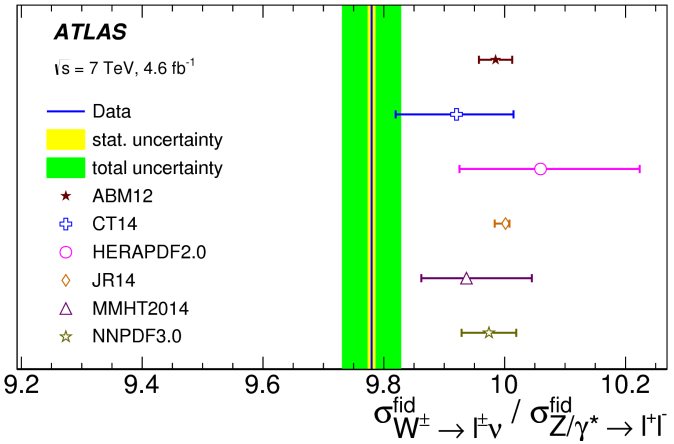


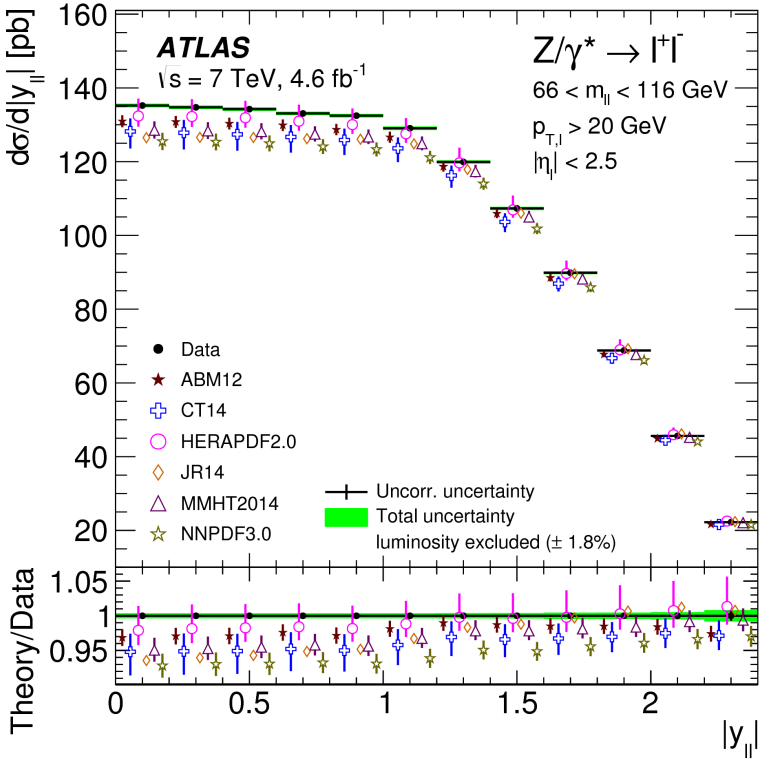
- ✓ High precision (uncertainty <2.8%) fiducial cross-sections calculated and compared to NNLO QCD (DYNNLO/FEWZ)+ NLO EWK (FEWZ/SANC) with different PDFs. Potential for PDF discrimination is visible.
- ✓ Constraints to the strange quark PDF and measurement of $|V_{cs}|$.
- ✓ Test of lepton universality for 1st and 2nd generation in agreement with SM.

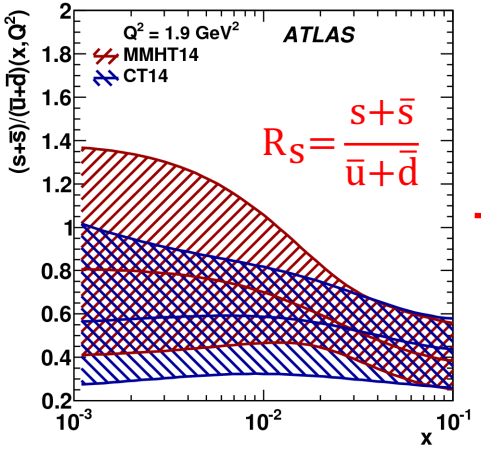
arXiv:1612.03016

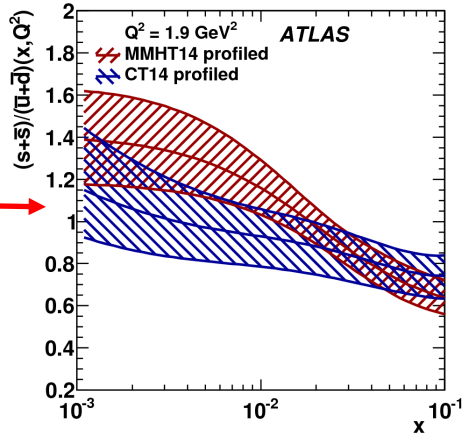
W and Z differential cross sections and PDFs

Differential W and Z cross sections: Ratio of $\sigma(W)/\sigma(Z)$ significantly lower in data. Differential cross-sections in $|\eta|$ are sensitive to PDFs, the impact on PDF is assessed with profiling.









$$R_S = \frac{s+\bar{s}}{\bar{u}+\bar{d}} = 1.13 \pm 0.05(\text{exp}) \pm 0.02(\text{mod})^{+0.01}_{-0.06}(\text{par})$$

- ✓ The uncertainty on the strange quark density in the proton, s(x), is reduced.
- ✓ Strange quarks are not suppressed w.r.t. up and down sea quarks.
- ✓ A value for $|V_{cs}|$ is extracted, assuming unitarity. Compatible with previous results.
- ✓ A new PDF set is produced, ATLAS-epWZ16.

arXiv:1612.03016

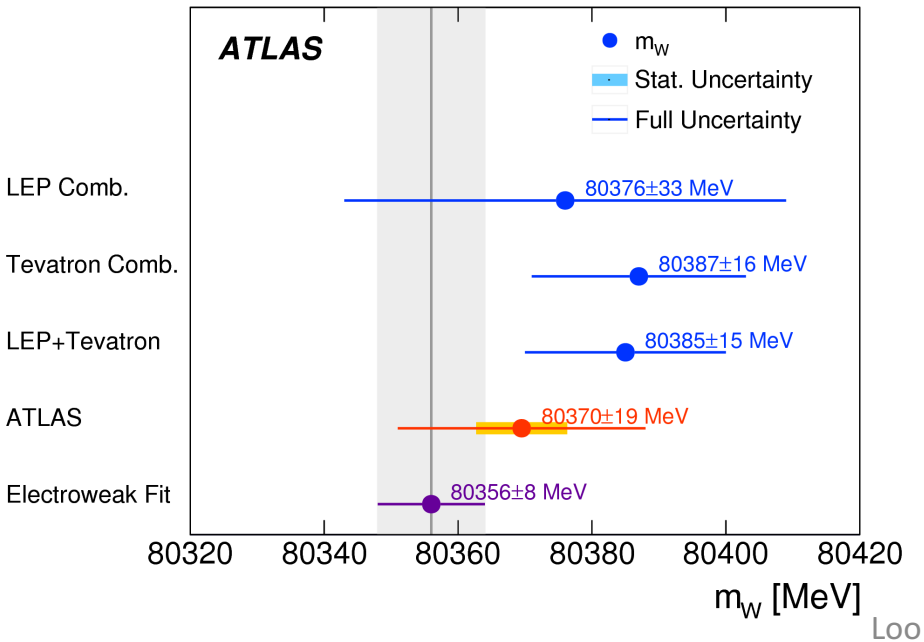
W mass

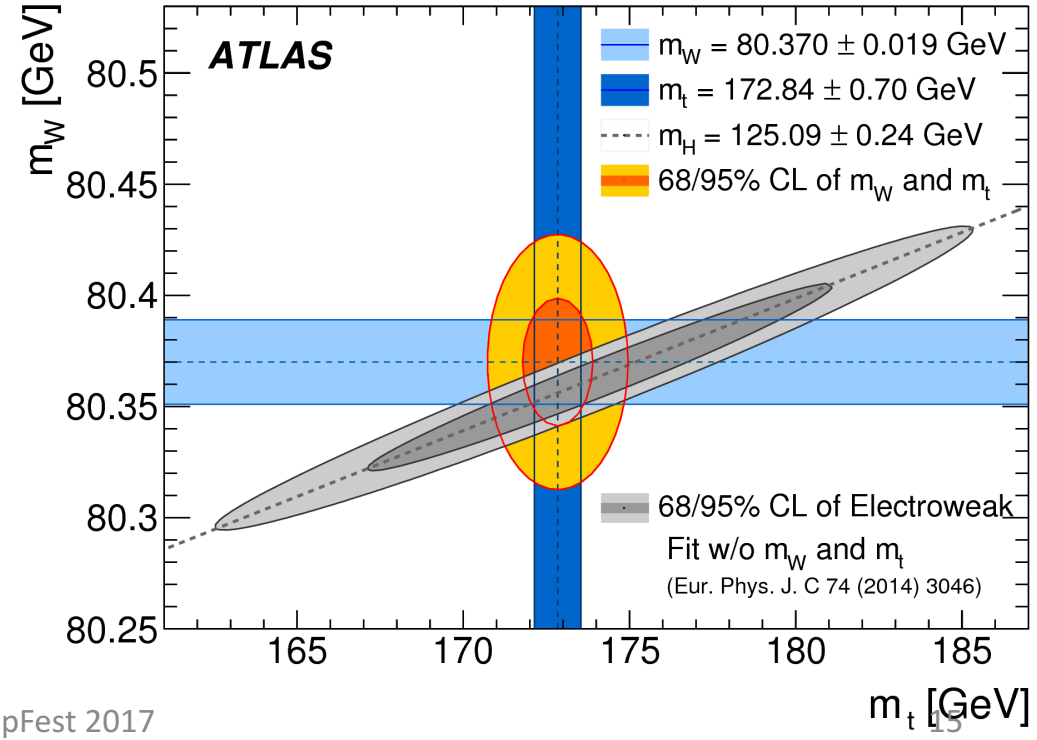
W mass measurement: Precision consistency test of the SM. Mass extracted from M_T and lepton p_T. First measurement of M_W at the LHC. Relies on Z events for calibration and modelling. Largest sources of uncertainty are theoretical (Z cross section angular coefficients, p^W_T modelling, PDFs) and instrumental (lepton energy scale and resolution).

$m_W = 80370 \pm 7$ (stat.) ± 11 (exp. syst.) ± 14 (mod. syst.) MeV
$= 80370 \pm 19$ MeV

arXiv:1701.07240

- ✓ Precision close to previous best measurements.
- ✓ Consistent with EW fit.

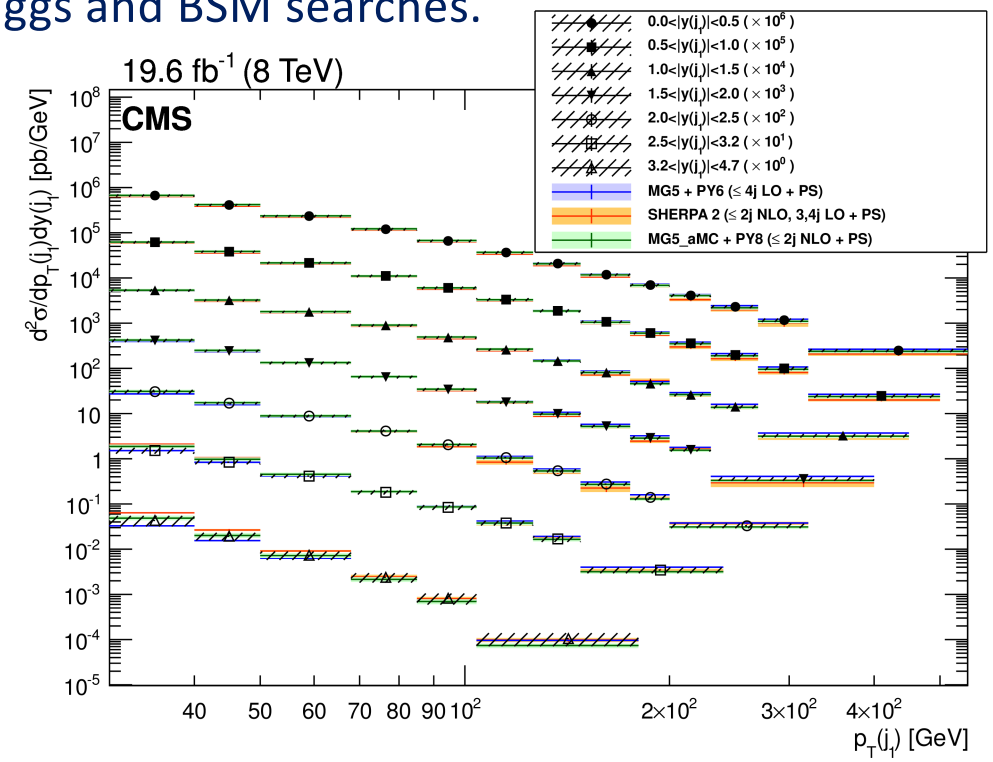




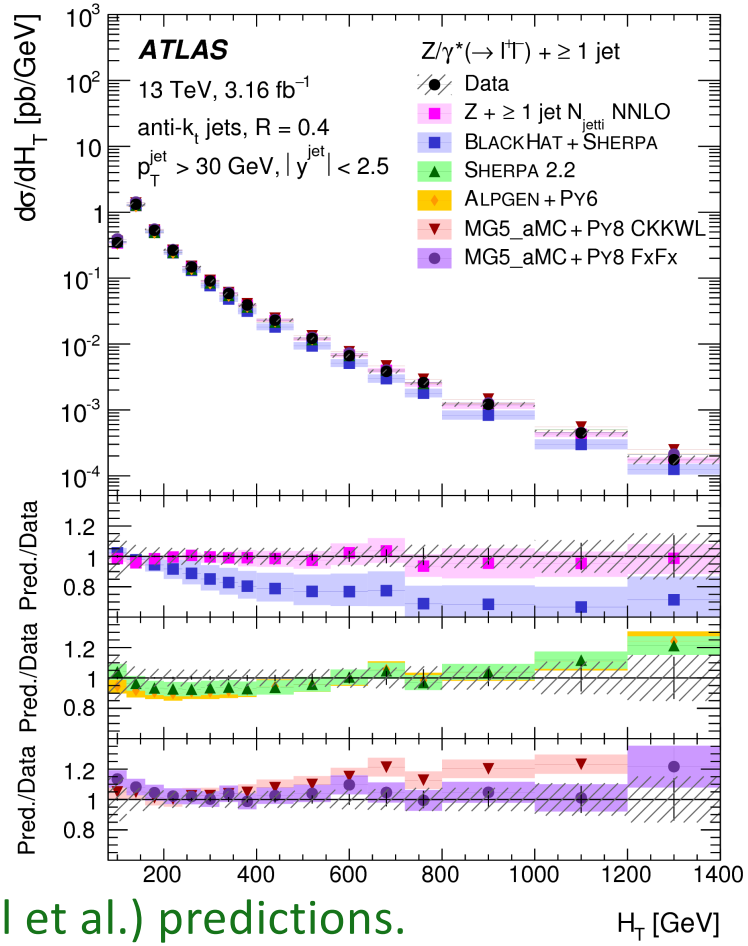
Z+jets

Z+jets differential cross sections: test QCD fixed-order calculations and MCs, sensitive to higher order effects but also soft QCD effects (particle emission, PS). Background to top, Higgs and BSM searches.

arXiv:1611.03844, accepted by JHEP



arXiv:1702.05725

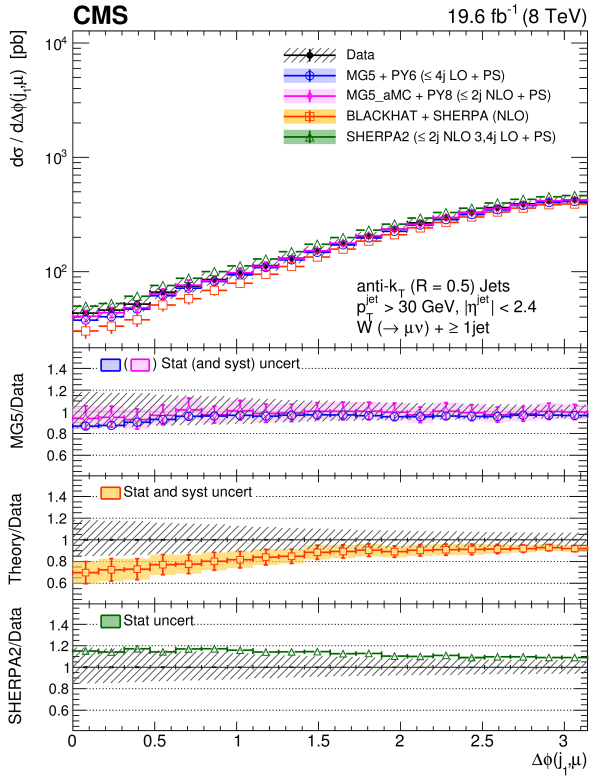


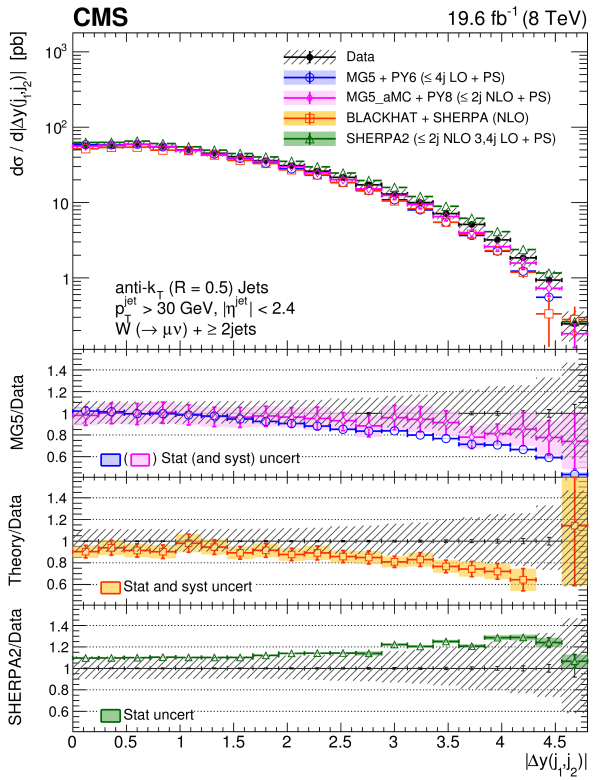
- ✓NLO improves upon LO (spectra, merging schemes).
- ✓Very good agreement with NLO and NNLO (R. Boughezal et al.) predictions.
- ✓With large datasets, extend to 2D differential, higher jet |y|.
- ✓Measurements drive/benefit from advancements in MC generators, e.g. multileg NLO interfaced with PS, and in fixed-order calculations.

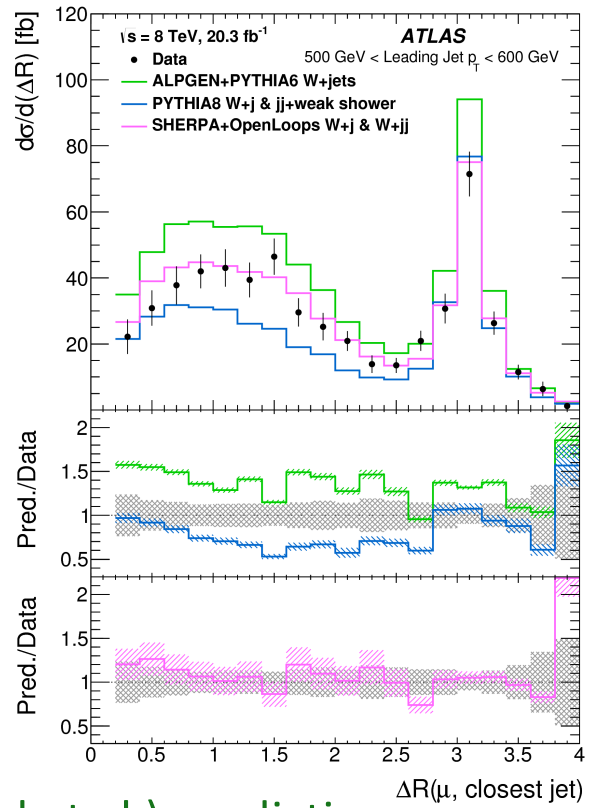
W+jets

W+jets differential cross sections: Similarly to Z+jets, the measurements are sensitive to higher order corrections and radiative effects. With large statistics, detailed analysis of angular correlations among final state particles.

PRD 95 (2017) 052002







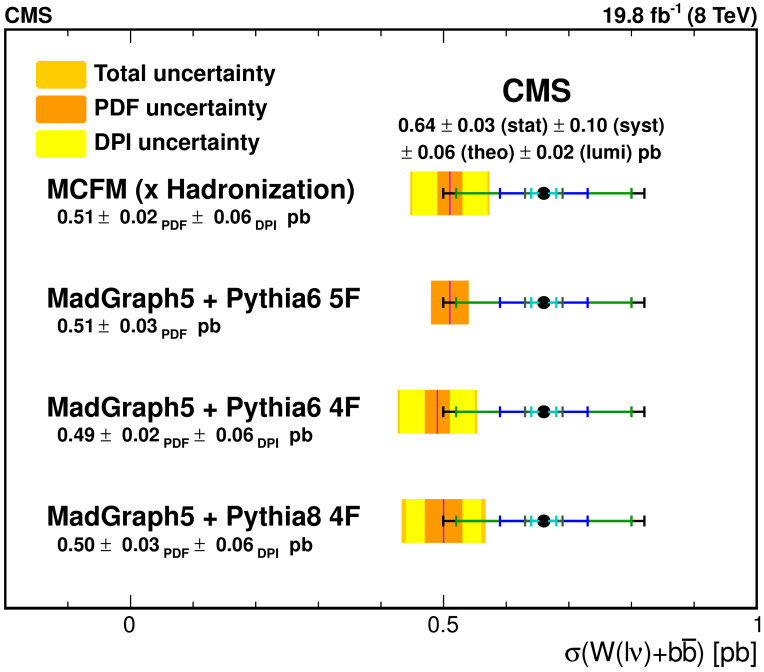
Phys. Lett. B 765 (2017) 132

- ✓ Very good agreement with NLO and NNLO (R. Boughezal et al.) predictions.
- ✓ Deviations observed for large values of jet |y| and of |Δy| among p_T- and y-ordered jets) and for small values of azimuthal separation between the muons and jets.
- ✓ Starting to test EW effects of real W radiative emission. Effects well described by NLO QCD+EW predictions.

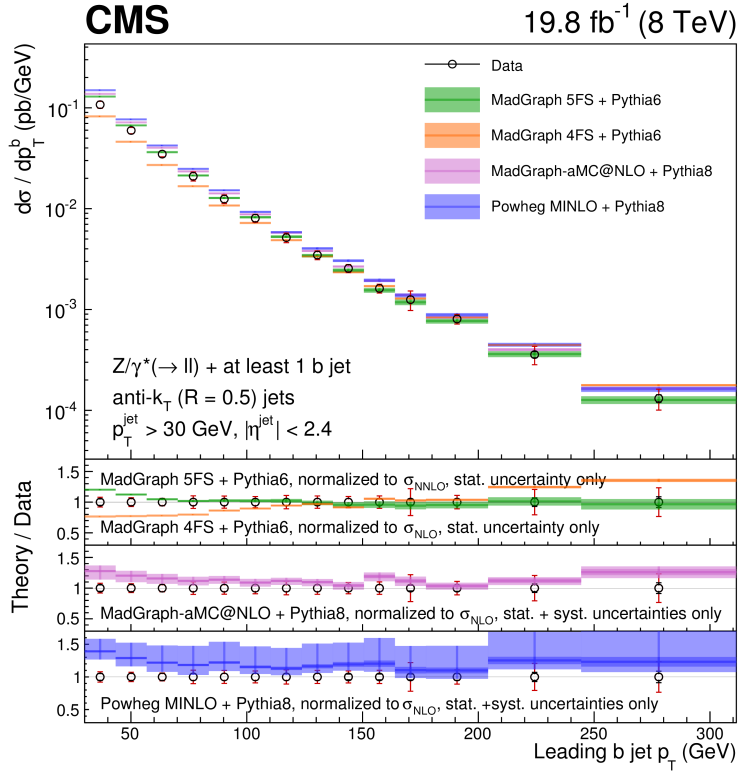
Z,W+b jets

Z+(b)b and W+bb cross sections: Sensitive to gluon splitting, can probe b-quark PDF, important background to Higgs and BSM searches.

W+bb Cross section obtained by fitting M_T. Compared to LO (4FS/5FS) and NLO.



Z+(b)b Fiducial Z+≥1b,≥ 2b cross sections and ratio. Differential in jet p_T and Z p_T. Compared to LO (4FS/5FS) and NLO.



EPJC (2017) 77:92

arXiv:1611.06507 , submitted to EPJC

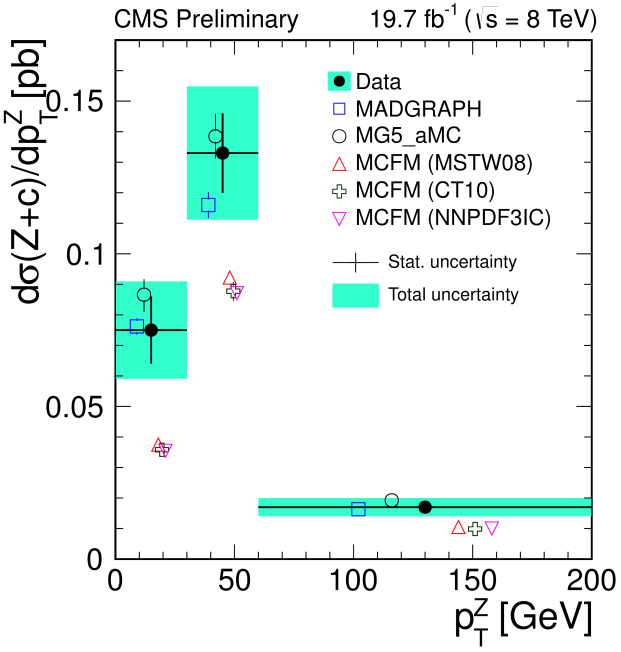
✓ For W+bb, in agreement with predictions.

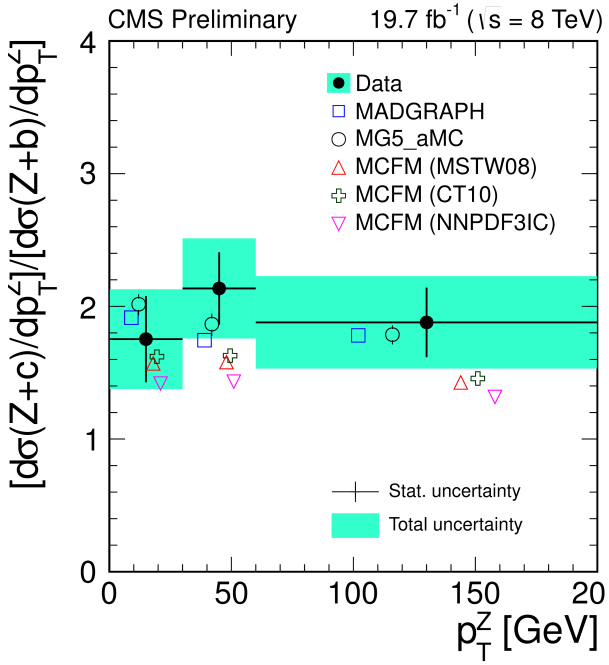
✓ For Z+(b)b 20% discrepancy for 4FS LO. 5FS LO overestimates data at low b-jet p_T.

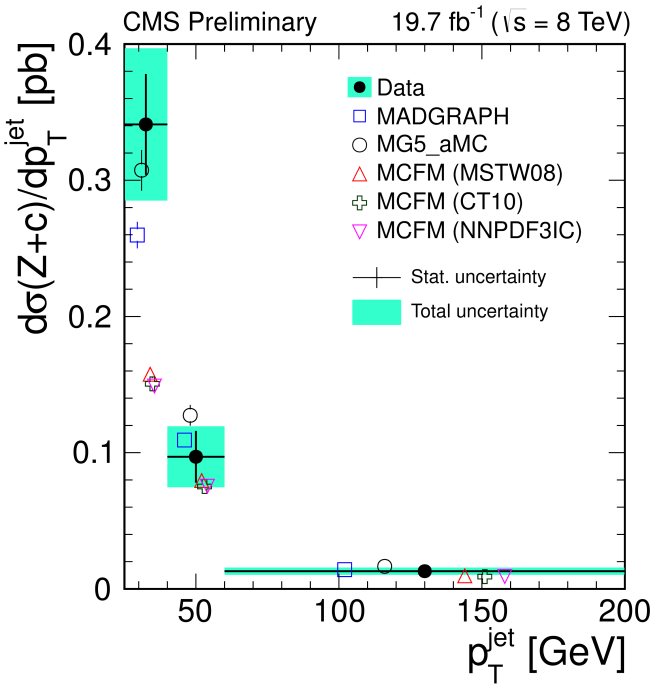
Z+c

Z+c production: **T**est of QCD predictions, sensitive to charm content in the proton. Test modelling of Z+HF in searches (e.g. FCNC top decays). Signal isolated with:

- Selection with a muon from decay of a HF quark, participating in a displaced vertex.
- Selection of exclusive final states from D meson resonant peaks (either $D^{\pm}$ or $D^{*\pm}$)







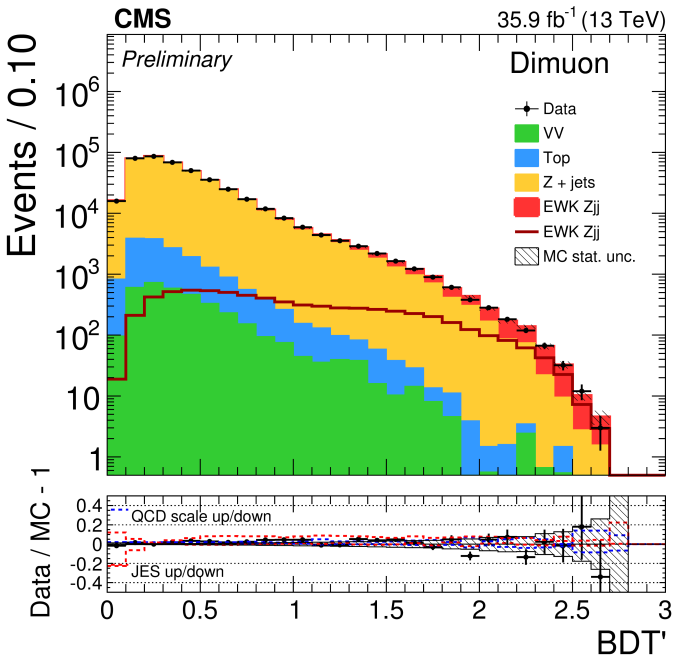
CMS-PAS-SMP-15-009

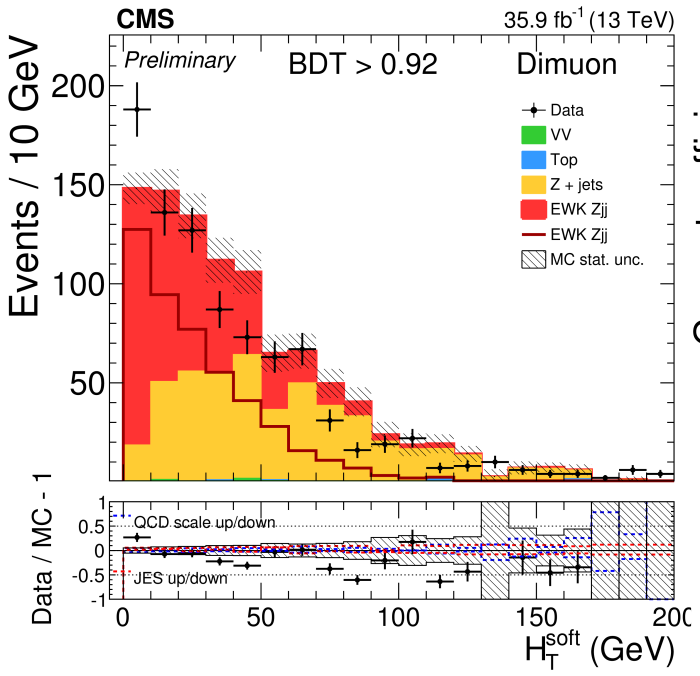
Fiducial cross sections (Z+c, Z+c/Z+b) measured, also differentially in p_T(Z) and p_T(jet). Comparison with LO and NLO predictions.

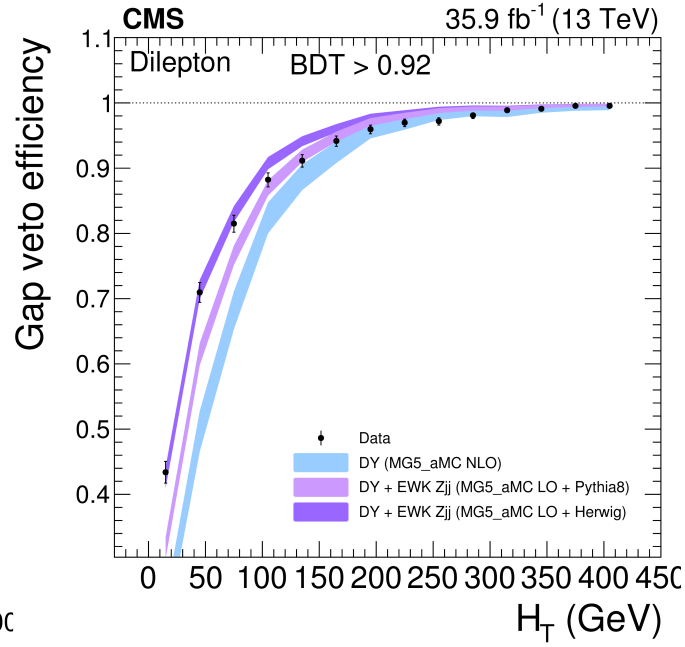
✓ Generally in good agreement, except in the low jet p_T region (wr.t. MCFM).

EW production of Z+2 jets

EW Z+2 jets production (VBF): Probes EWSB. Background to VBF Higgs. Characterized by 2 forward jets separated in rapidity, with low hadronic activity in between. Main background: QCD Z+2 jets. Signal extraction with BDT (M_{jj}, $\Delta\eta_{jj}$, p_{Tjj}, quark-gluon jet likelihood, angular, and event balance variables). Gap activity is studied in signal enriched region (BDT>0.92).





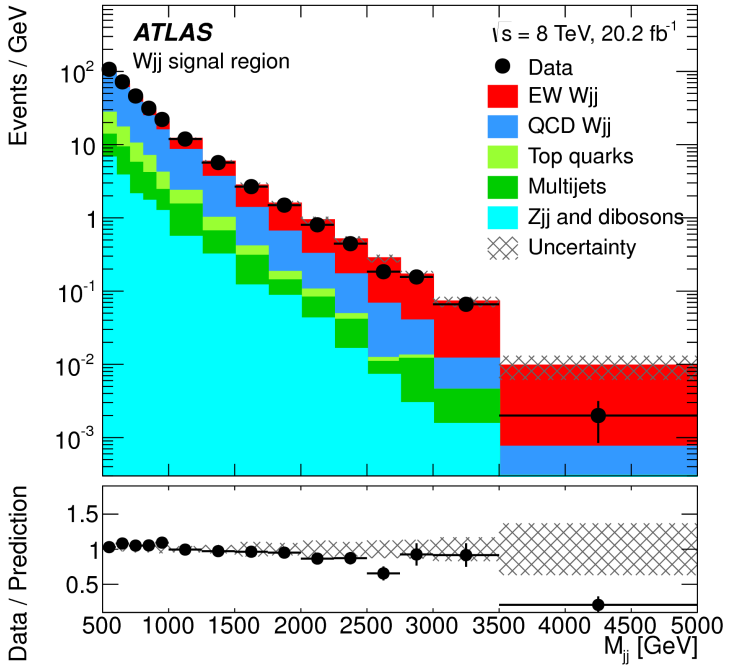


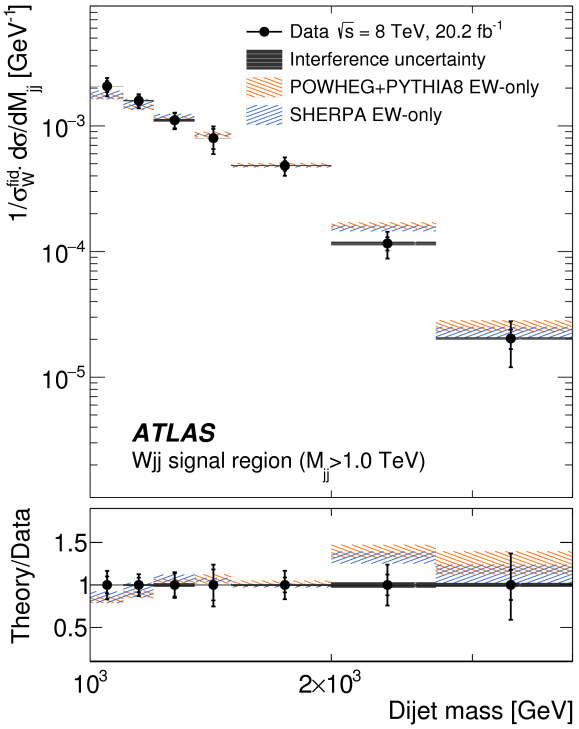
CMS-PAS-SMP-16-018

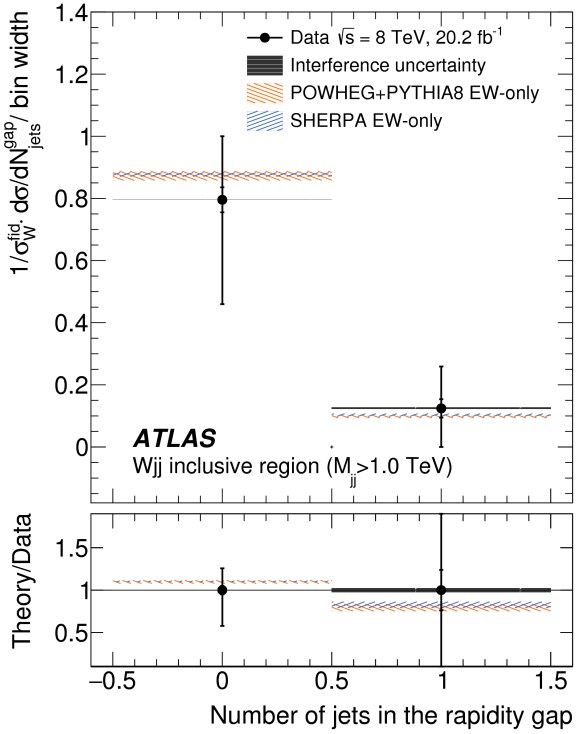
- ✓ The cross section, σ(EW lljj)=552±19(stat)±55(syst)fb agrees with LO SM predictions.
- ✓ Data favor a signal model with HERWIG(PYTHIA8) PS for low(larger) gap activity.
- ✓ Similar measurement recently performed by ATLAS on 13 TeV (ATLAS-STDM-2016-09) also agrees with SM predictions.

EW production of W+2 jets

EW W+2 jets production (VBF): Characterized by forward-backward jets (plus W) topology. The signal is extracted with a likelihood fit of M_{jj} in signal and control regions. Cross sections are unfolded in EW- and QCD-dominated regions. It is used to probe for anomalous Triple Gauge Couplings.





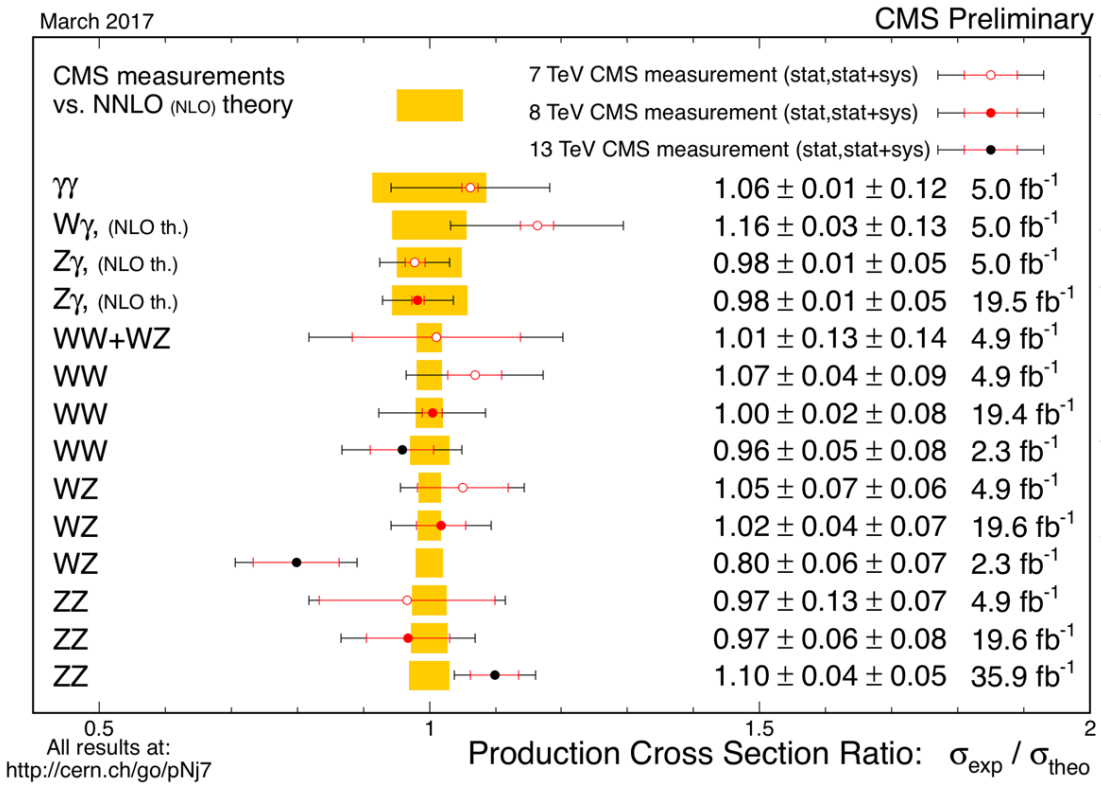


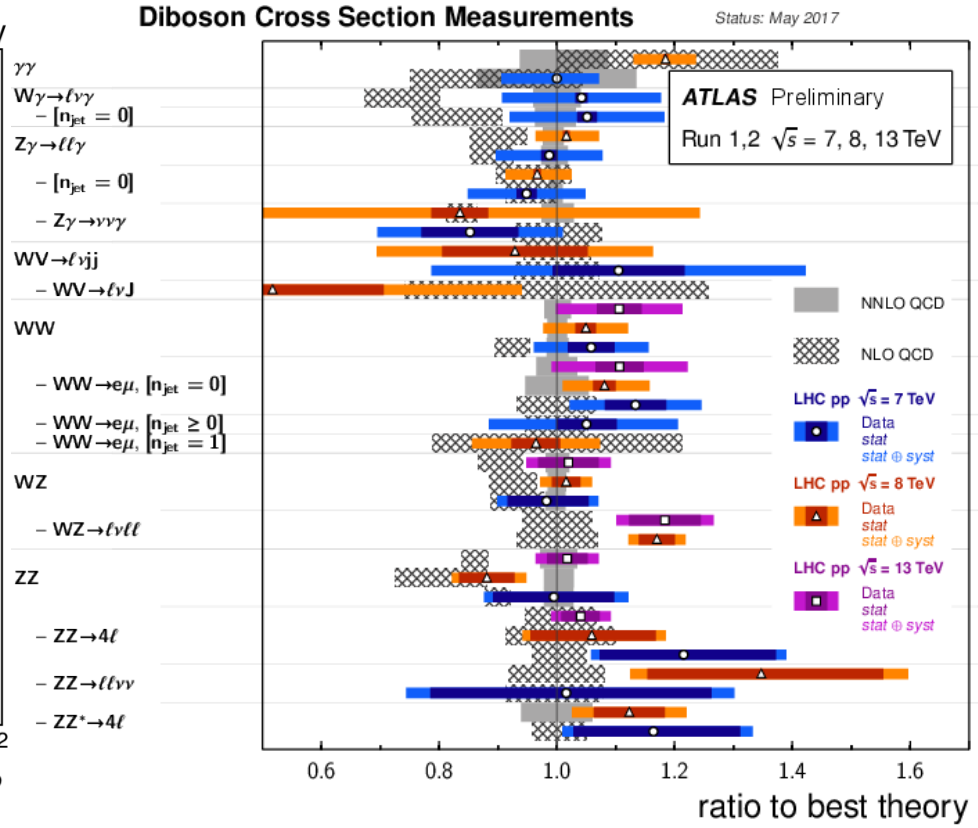
arXiv:1703.04362

- ✓ Fiducial cross sections in agreement with NLO SM predictions.
- ✓ Differential cross-sections well described in regions of different admixture of EW and QCD. EW NLO corrections needed for some spectra.
- ✓ aTGC limits extracted from extended SM Lagrangian (effective Lagrangian or effective field theory) containing non-SM operators and anomalous coupling parameters.

Multi-bosons

Multi-bosons production: Important test of EWSB. Backgrounds to Higgs and BSM searches, sensitive to higher order corrections (QCD and QED). Processes can be rare (e.g. tri-bosons), they test the SM gauge structure and are sensitive to new physics.



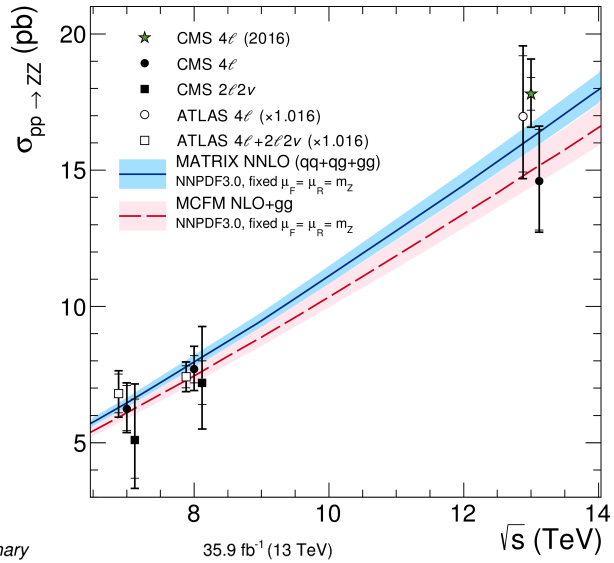


✓ New 13 TeV results in good agreement with SM expectations. Inclusive diboson cross section measurements are dominated by systematic uncertainties.

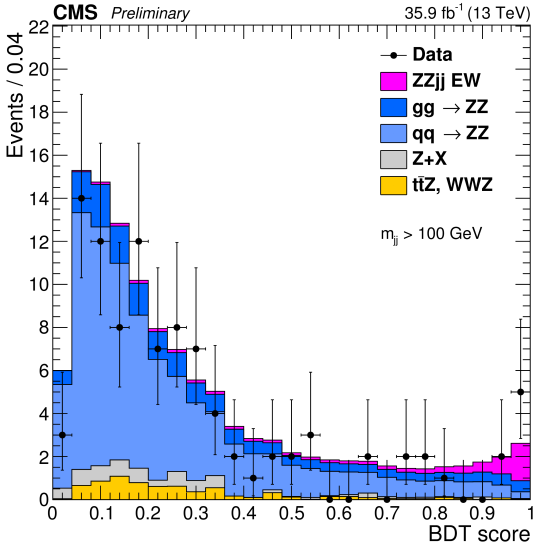
ZZ production

ZZ inclusive production: First diboson measurement with 2016 13 data. Main channel: ZZ→ 4ℓ, clean signature and background to H → 4ℓ. Differential cross sections (with and w/o jets)to test higher order effects (NNLO QCD and NLO QED).

CMS-PAS-SMP-16-017

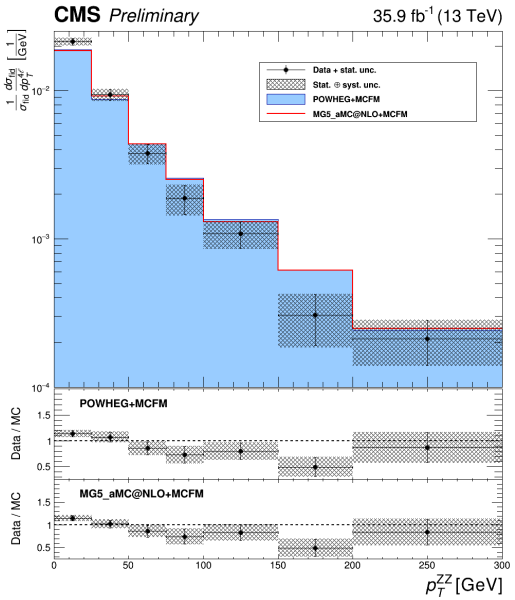


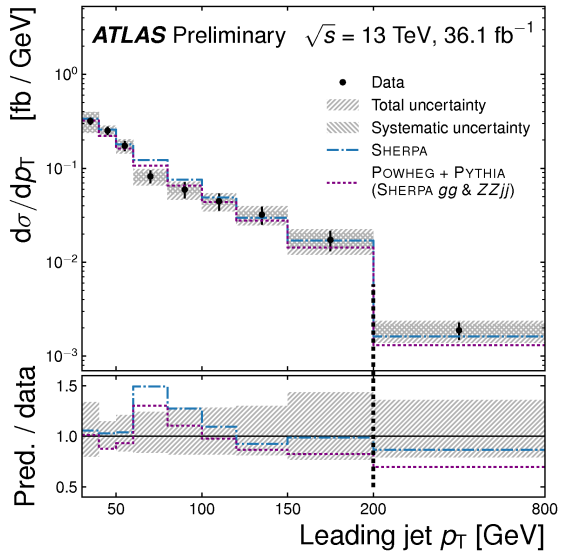
ZZ+jets: differential measurement needed for the study of EW ZZjj (VBS)



CMS-PAS-SMP-16-019

ATLAS-CONF-2017-031





$\sigma_{EW}=0.40^{+0.21}_{-0.16}(stat)^{+0.13}_{-0.09}(syst)fb$

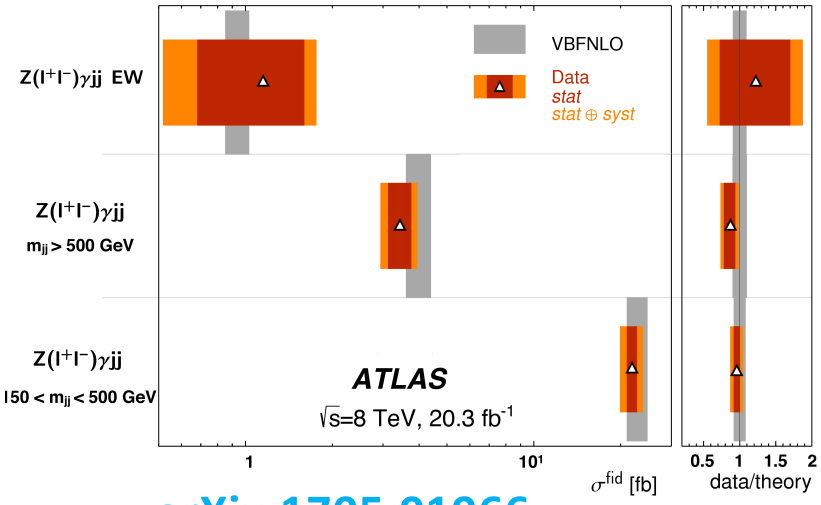
- ✓ Inclusive and differential ZZ and ZZjj cross sections in agreement with SM.
- ✓ First measurement of σ_{EW} ZZjj in agreement with SM.
- ✓ Extraction of aTGC and aQGC couplings.

EW production, WWjj and Zγjj

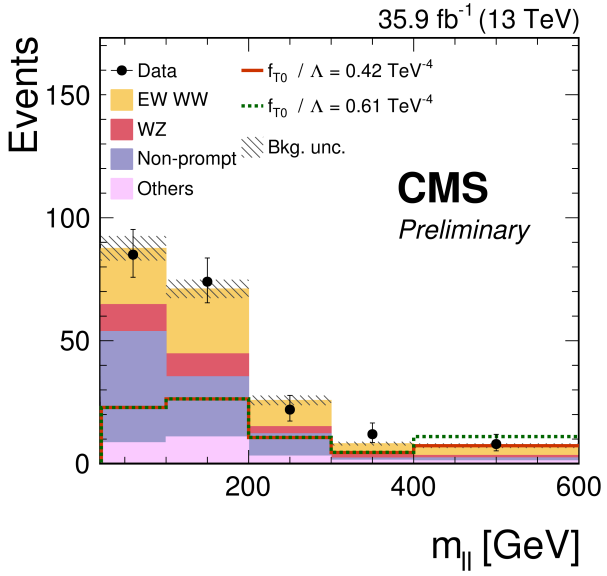
EW VV+2 jets production (VBS): Probes EWSB. Characterized by 2 forward jets separated in rapidity, with low hadronic activity in between. New results for Zγ and WW.

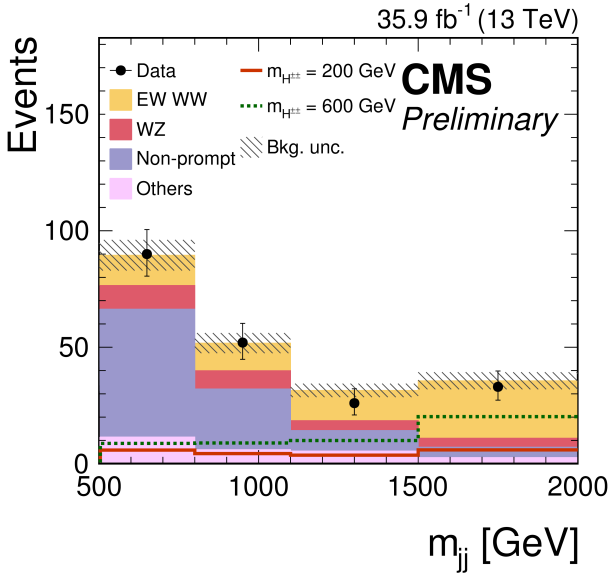
Zγ: uses $Z \to \ell\ell$ and $Z \to \nu\nu$ decays and a high mass dijet system. EW (at 2σ) and inclusive Zγjj cross sections are extracted in several fiducial regions. aQGC are determined.

$W^{\pm}W^{\pm}$: same sign lepton selection, two jets with large y separation and m_{jj} leads to first observation of EW VV at 13 TeV (5.5σ)



arXiv:1705.01966





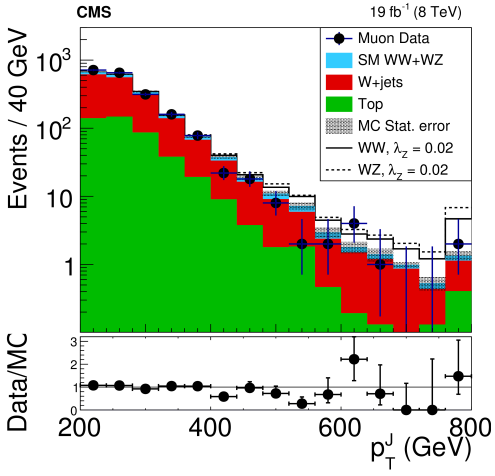
CMS-PAS-SMP-17-004

- ✓ Good agreement with SM predictions, first observation of EW VV at 13 TeV in $W^{\pm}W^{\pm}$ (fiducial cross section measured).
- ✓ Constraints are set on aQGC.

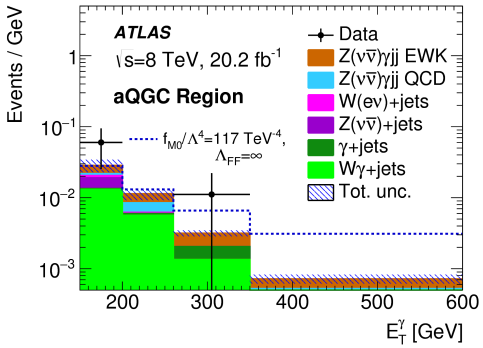
Anomalous Vector Boson Couplings

Anomalous vector boson couplings: New physics at higher scales can lead to modified couplings → probe for increase in cross sections.

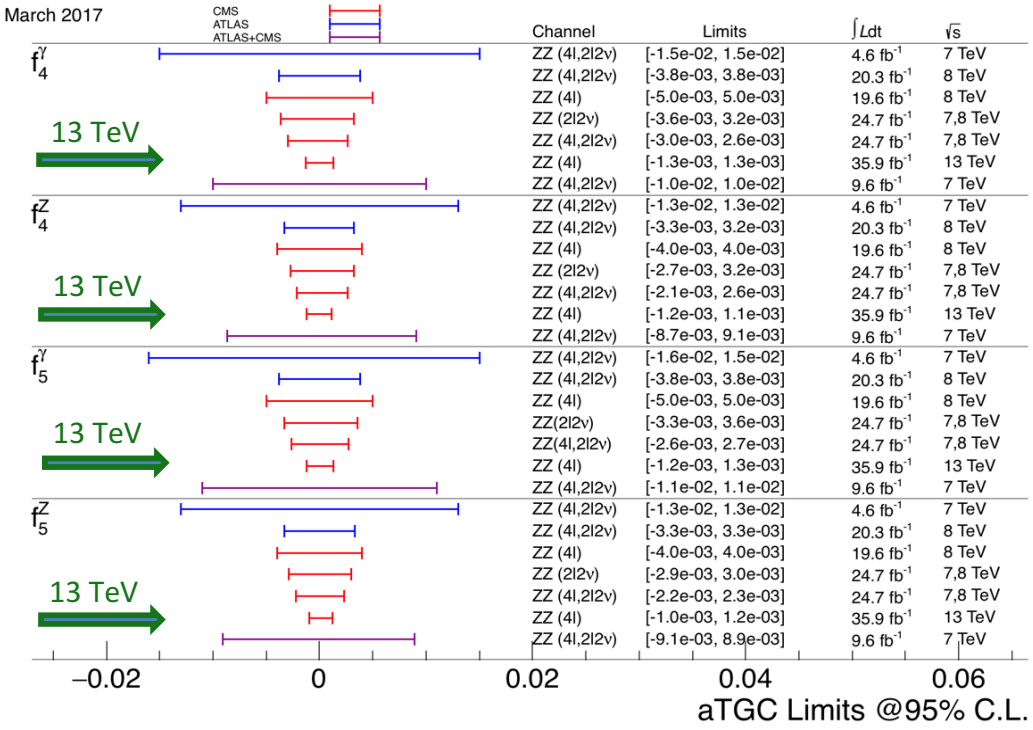
- ✓ aTGC constrained with inclusive diboson.
- ✓ aQGC constrained with EW VVjj and triboson.

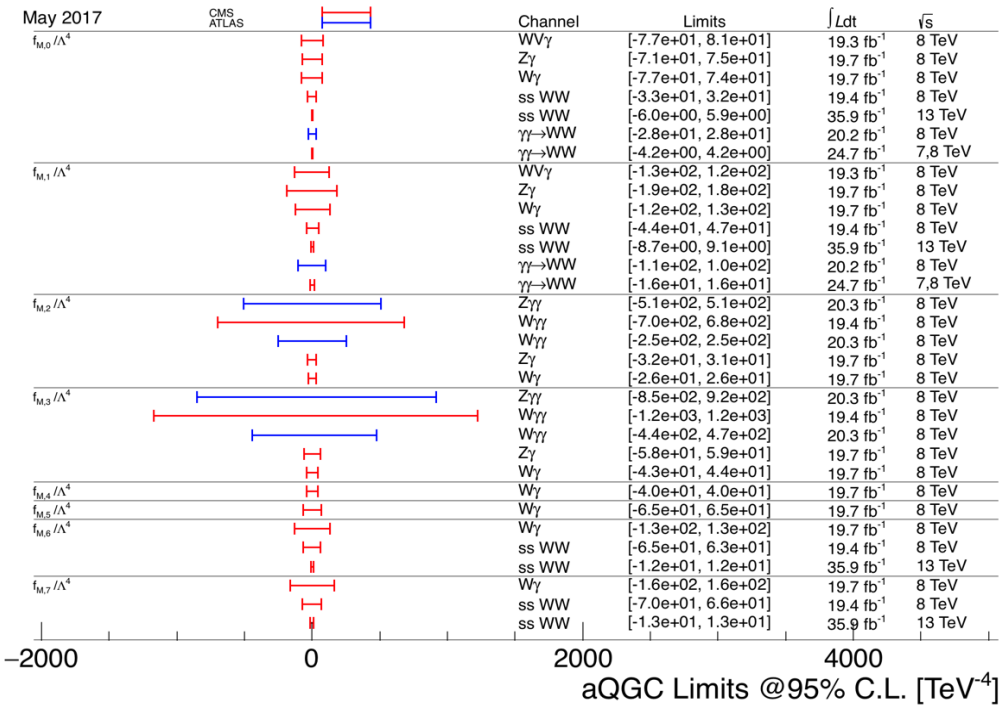


arXiv:1705.01966



arXiv:1703.06095





Limits on neutral aTGC ZZγ and ZZZ couplings

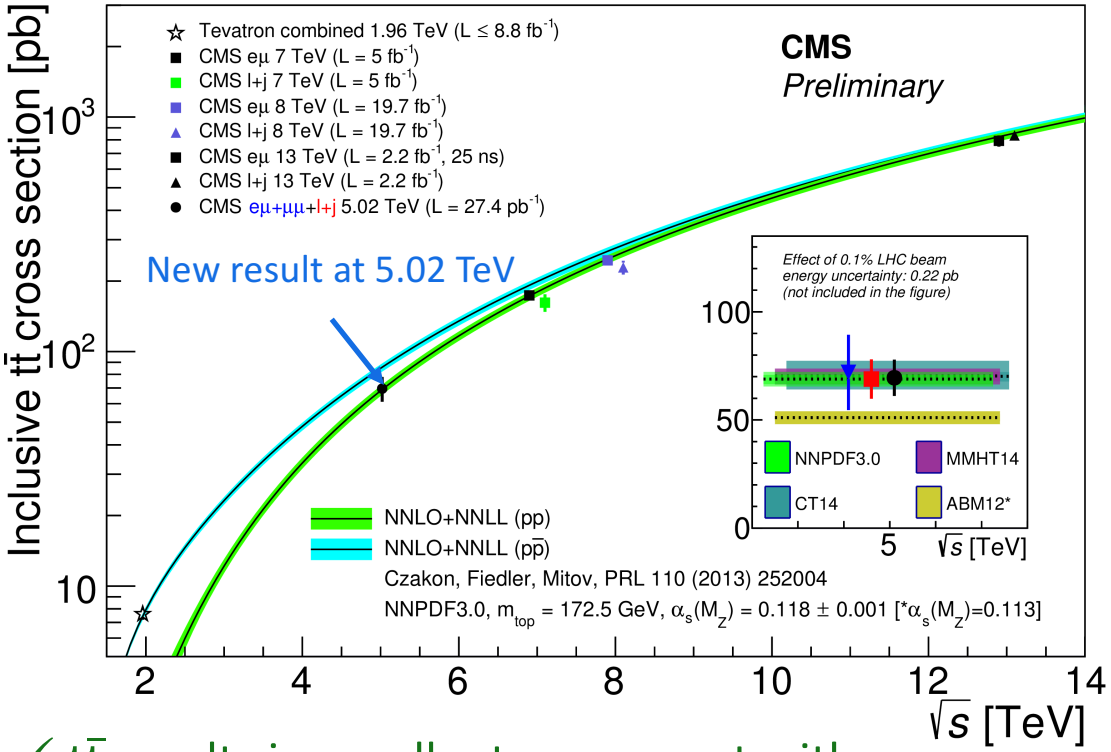
Limits on aQGC

Complete list at **https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC**

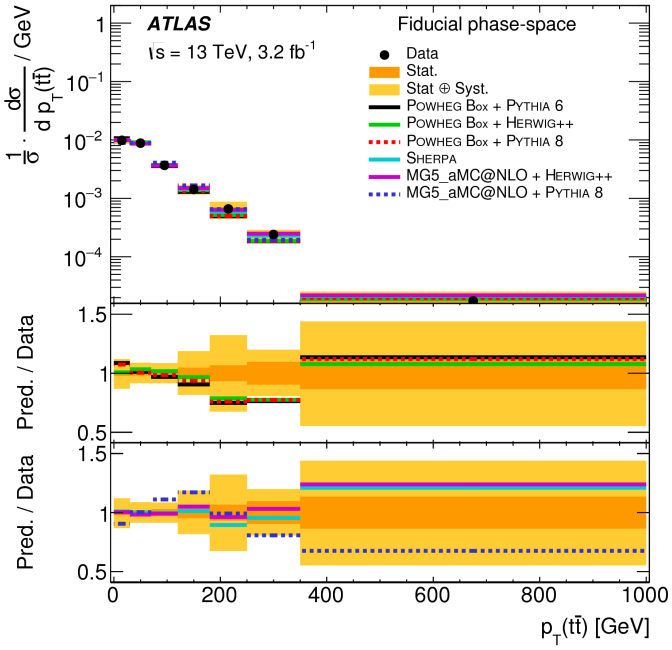
Top pair production

Production of top quarks: tests SM, special connection to EWSB? (heaviest know elementary particle). The LHC is a top factory, with enough statistics to perform precision measurements of differential cross-sections.

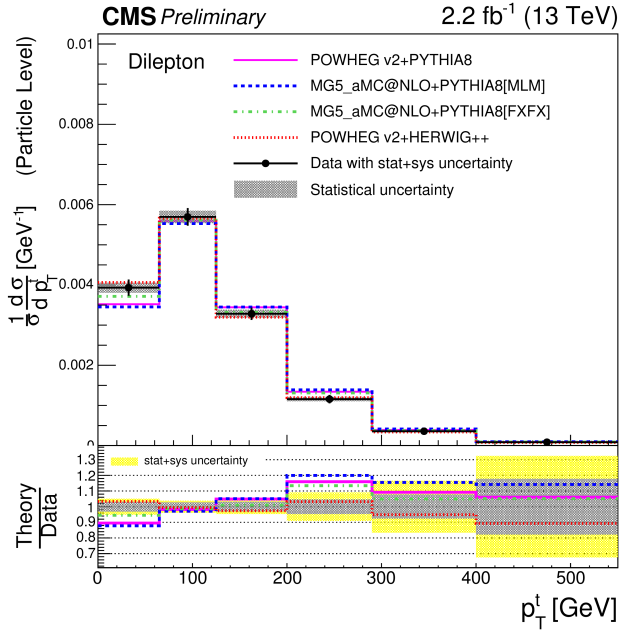
CMS-PAS-TOP-16-023



- ✓ tt̄ results in excellent agreement with NNLO+NNLL predictions.
- ✓ Starts constraining the gluon PDF.
- ✓ α_S determination (if m_{top} fixed).



Eur. Phys. J. C77 (2017) 299



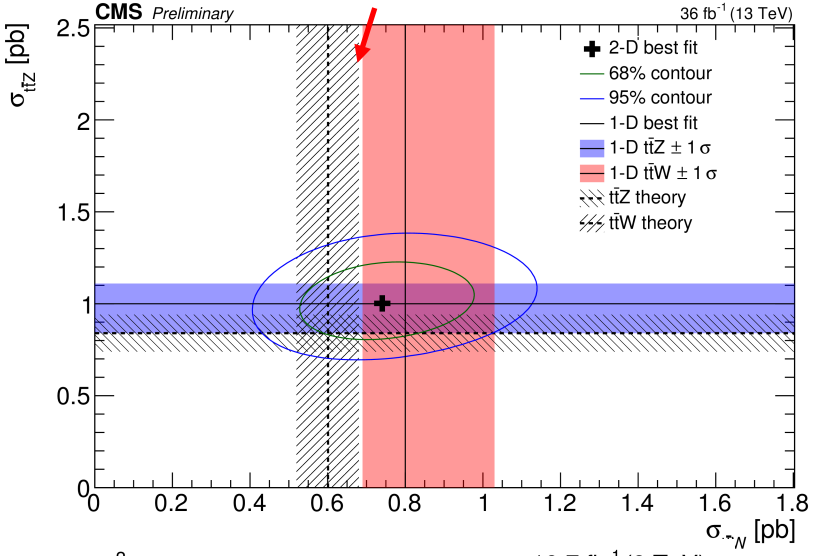
CMS-PAS-TOP-16-007

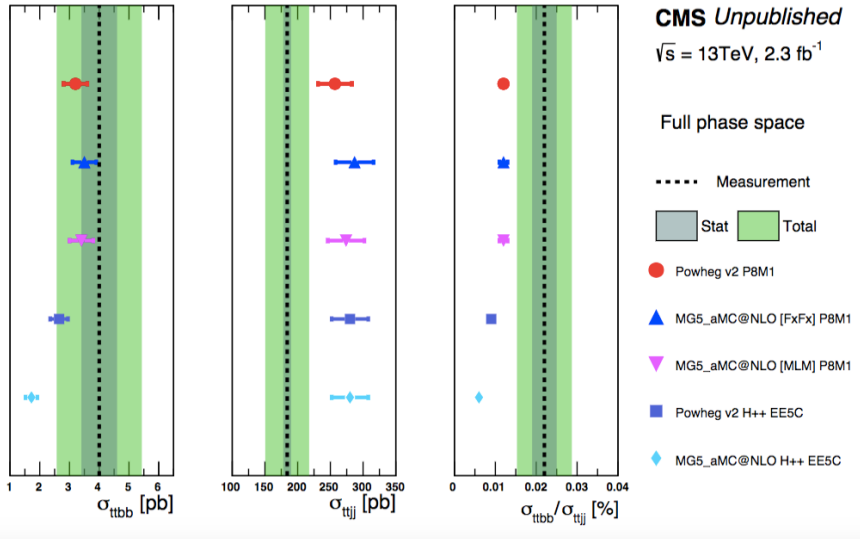
Associated $t\bar{t}X$ production

Associated production: $t\bar{t}(W,Z)$, $t\bar{t}\gamma$, ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ cross sections

$t\bar{t}(W,Z)$ observation at $(5.5,9.9)\sigma$

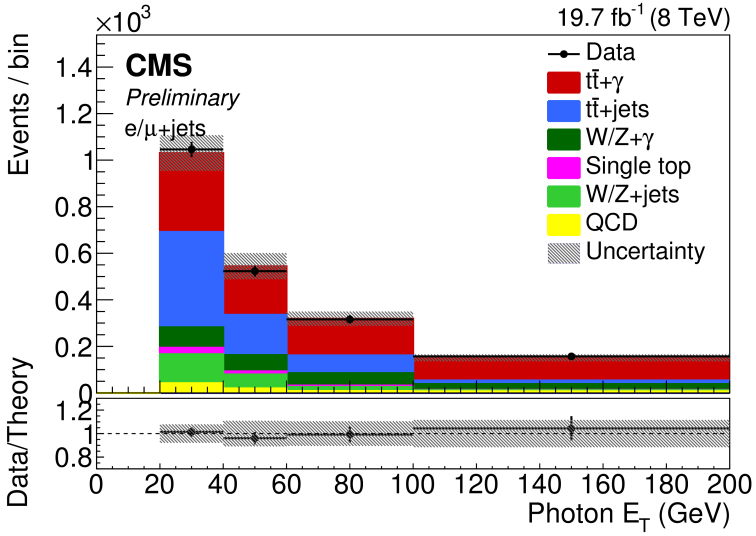
CMS-PAS-TOP-17-005

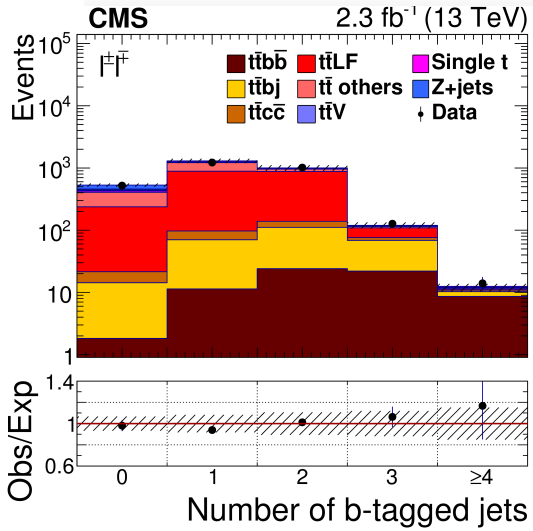




CMS-PAS-TOP-16-010

CMS-PAS-TOP-14-008





- ✓ Associated $t\bar{t}$ production consistent with SM predictions.
- ✓ Important background to $t\bar{t}H$ and to searches.
- ✓ $t\bar{t}W$ and $t\bar{t}Z$ observation.

Constraints on PDFs from $t\bar{t}$ cross sections

Ratio of $t\bar{t}$/Z production cross sections:

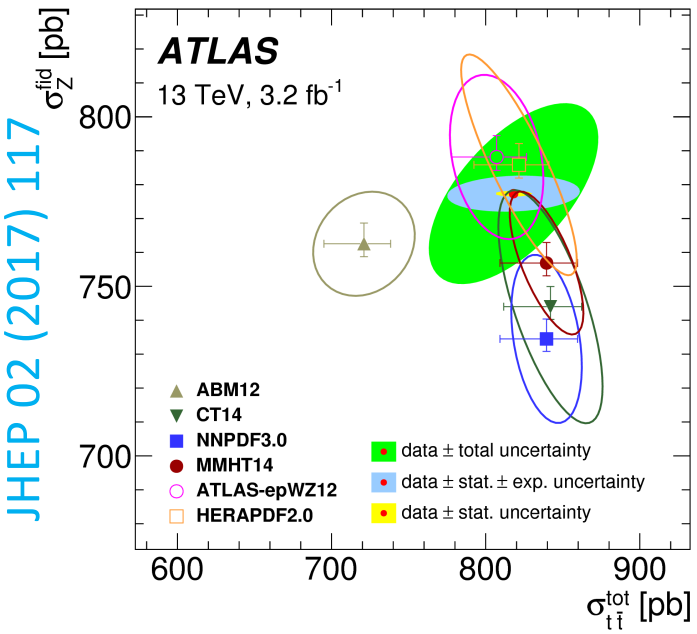
Systematics cancel in ratio measurements. Ratios of 7, 8, and 13 TeV inclusive Z and $t\bar{t}$ compared with NNLO (NLO EW) for Z and NNLO+NNLL for $t\bar{t}$, with different PDFs.

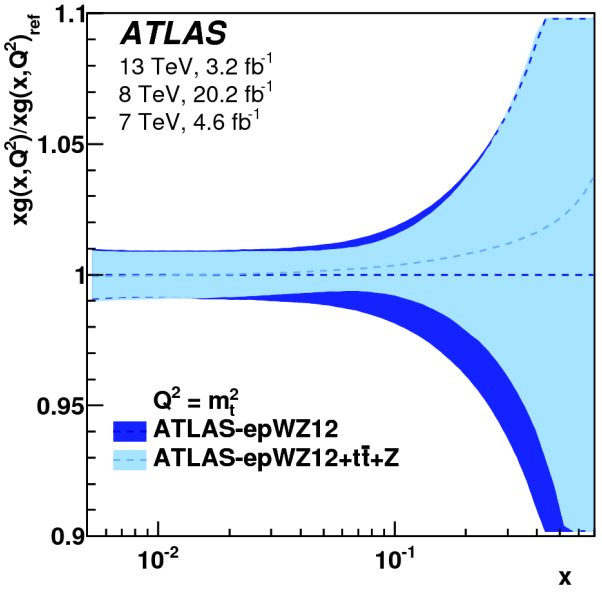
Double differential cross sections:

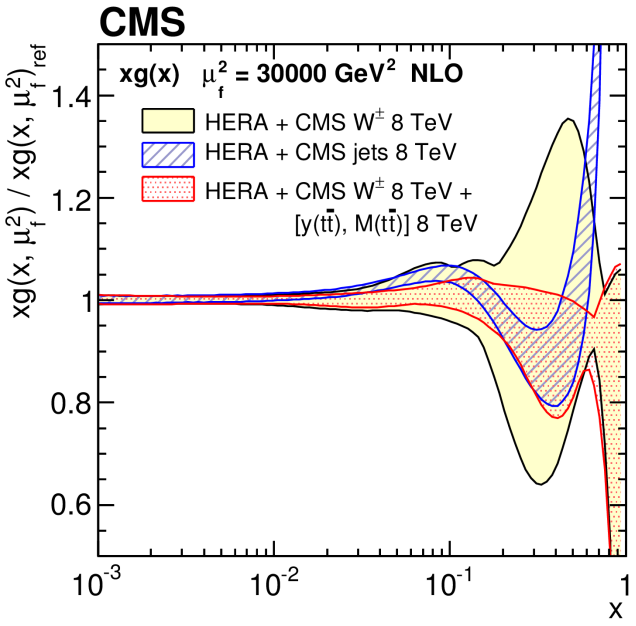
$e\mu$(+ jets) double differential vs. y($t\bar{t}$), M($t\bar{t}$)) included in a fit of parametrized PDFs.

arXiv.1703.01630

JHEP 02 (2017) 117



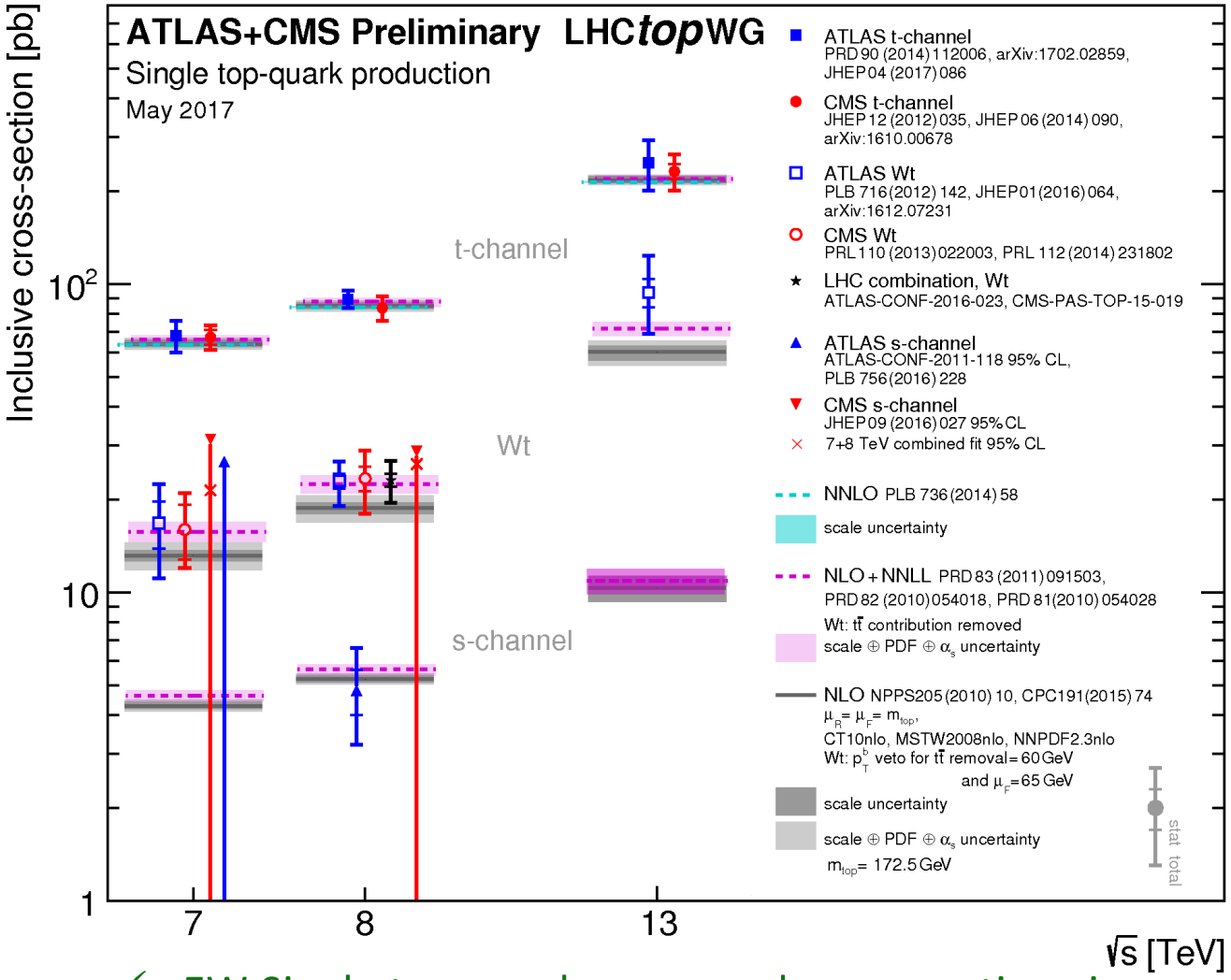




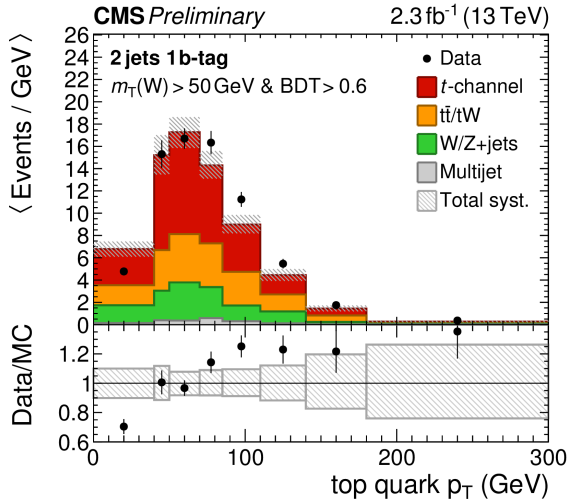
- ✓ Tension data/predictions in the $t\bar{t}$/Z double ratio 8/7 TeV, not ascribable to PDFs.
- ✓ Projected PDF uncertainties show significant impact on gluon (x~0.1) and light-quark sea (x<0.02) distributions

- ✓ Shows significant impact on gluon PDF. Measurement at 5.02 TeV further extends sensitivity to high-x gluons (CMS-PAS-TOP-16-023)

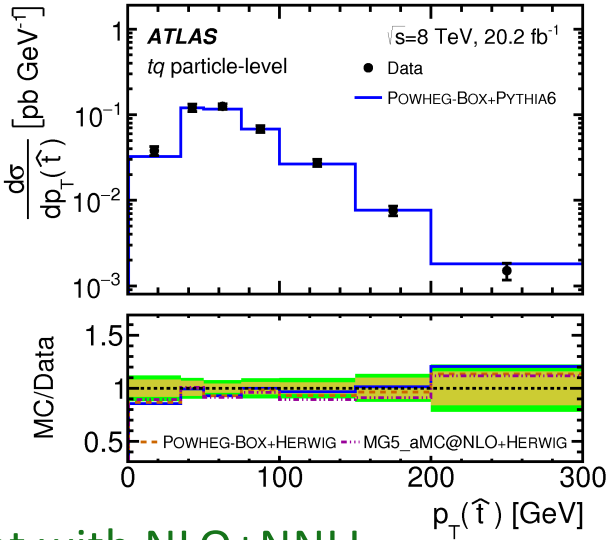
EW Single Top production



CMS-PAS-TOP-16-004



arXiv:1702.02859



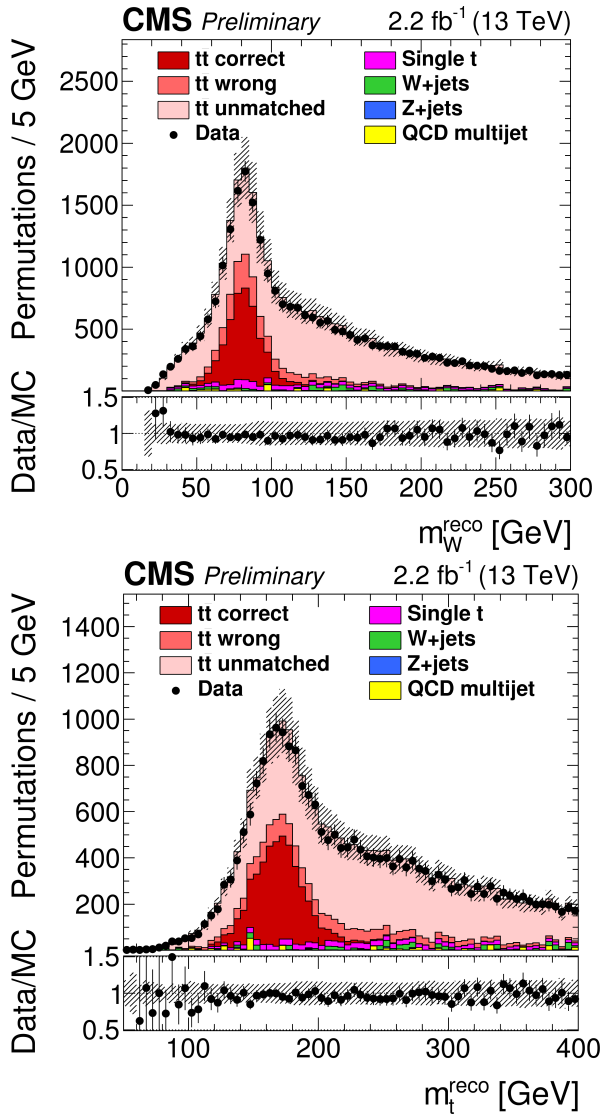
- ✓ EW Single top quark measured cross-sections in agreement with NLO+NNLL predictions. First 13 TeV measurements for the t-channel and Wt cross-sections.
- ✓ Differential cross-section measurements are available for the t-channel.

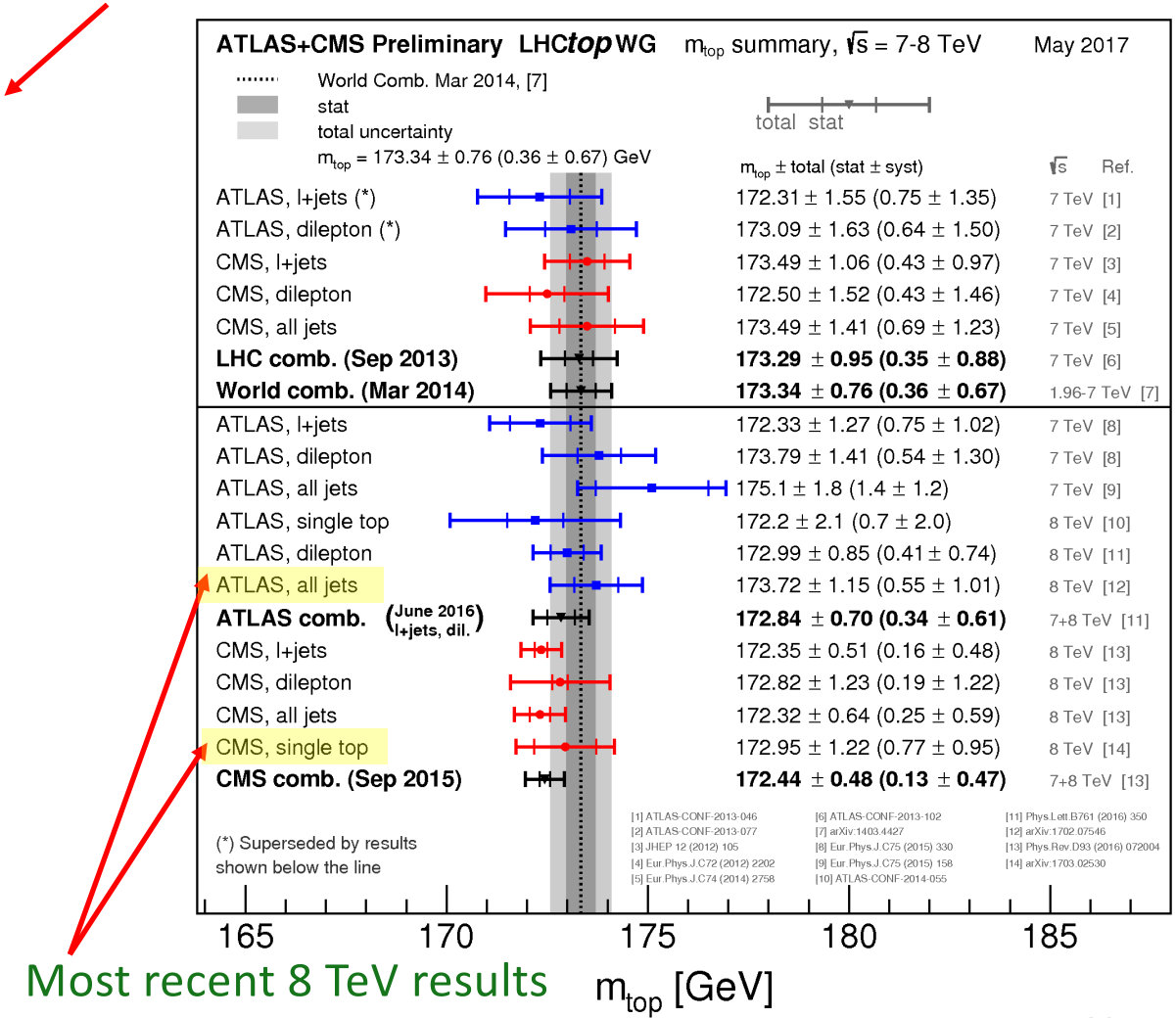
Top quark mass

Top quark mass: measured in many channels with many techniques.

- ✓ The combination of many mass measurements has a 0.3% precision.
- ✓ First measurement at 13 TeV (μ+jets final state).

CMS-PAS-TOP-16-022





Most recent 8 TeV results

Conclusions

Outstanding performance of the LHC in 2016.

Broad range of Standard Model analyses with 7, 8 , and 13 TeV data from the LHC experiments.

No significant deviations from the SM observed to date. Increasingly more precise and complex SM measurements will continue to play a complementary role to direct searches in probing for new physics.

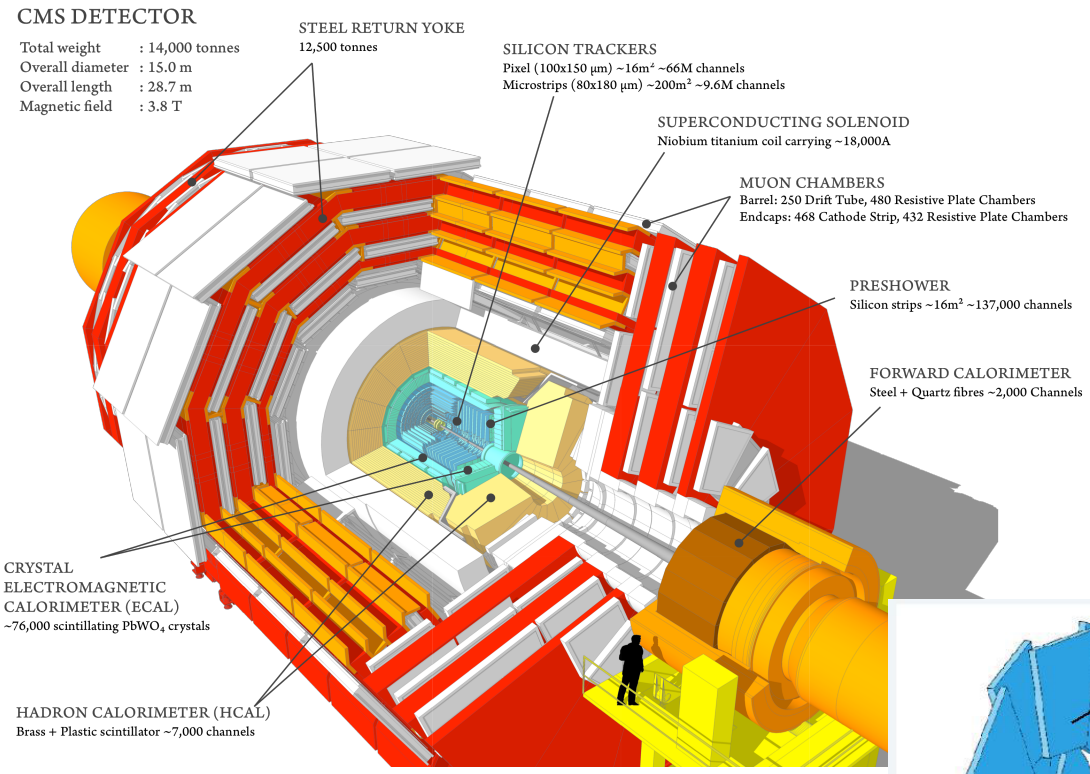
The full set of ATLAS and CMS results is available at
http://cms-results.web.cern.ch/cmsresults/public-results/publications/
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Recent_Results

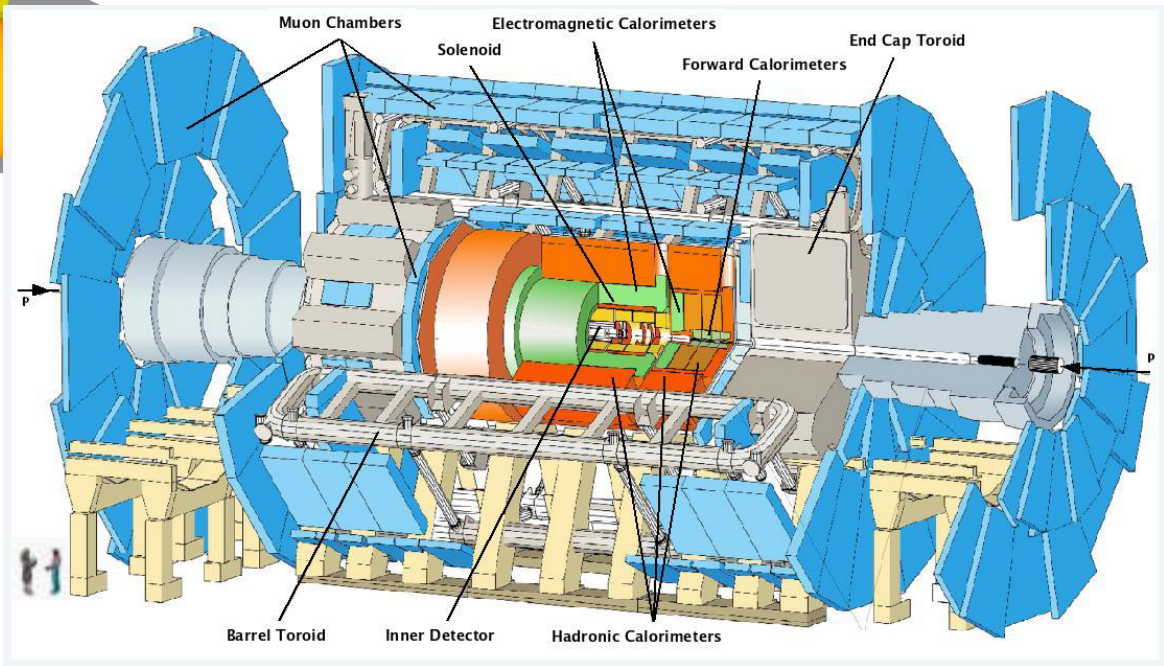
Thank you!

Photo credits: CERN

Backup

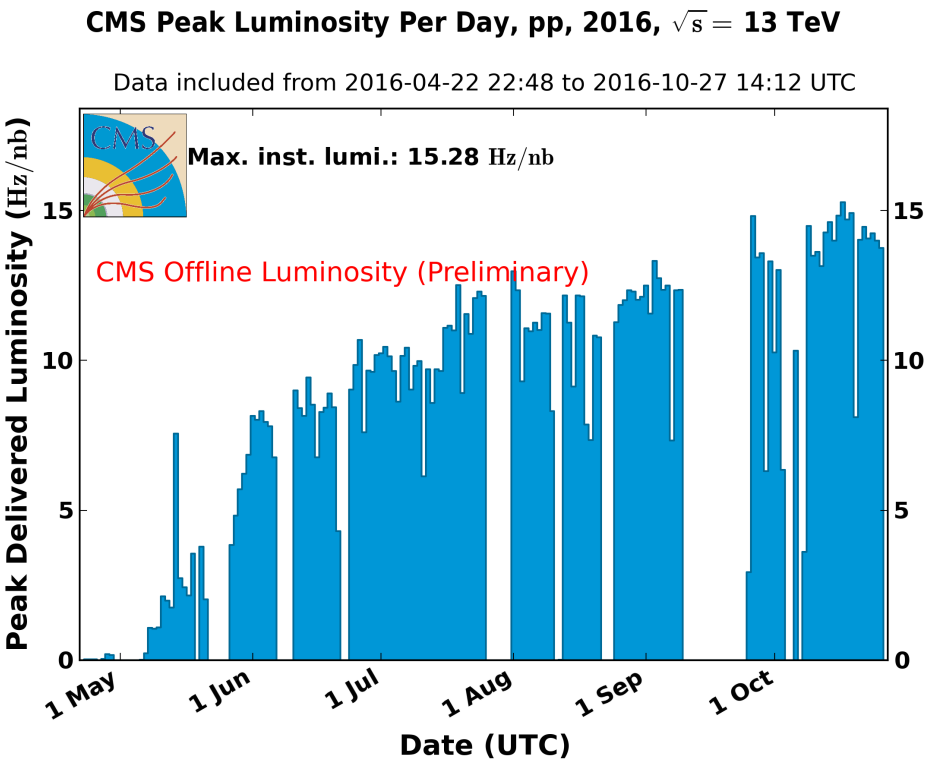
CMS and ATLAS



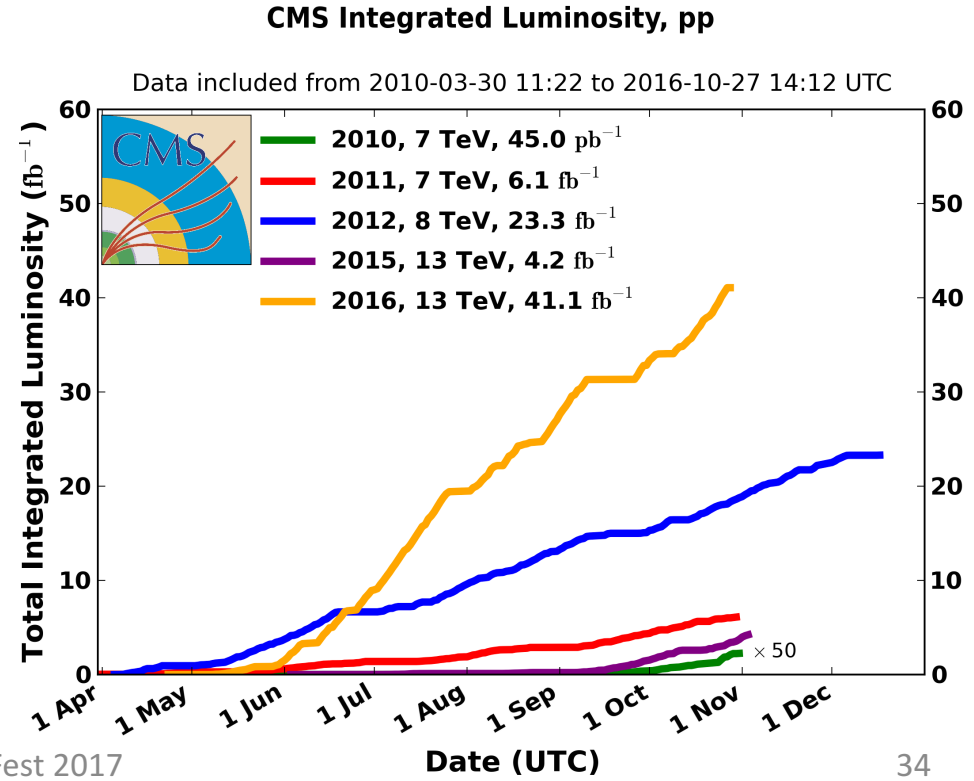


Data taking in 2016

An exceptional 2nd year of 13 TeV ("Run 2") running, exceeding expectations



15 Hz/nb goal in instantaneous luminosity reached early in the run and maintained throughout



CMS (ATLAS) recorded 38.27 (35.6) fb^{-1} of 13 TeV pp data in 2016.