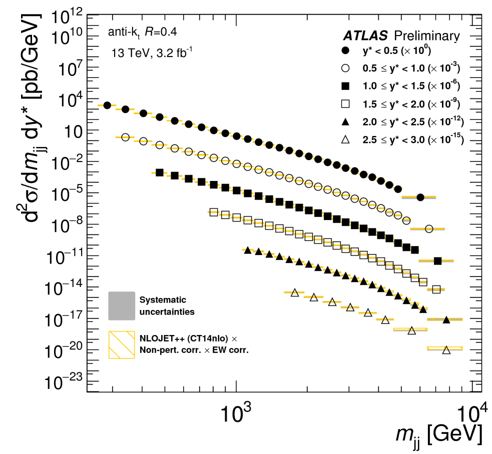
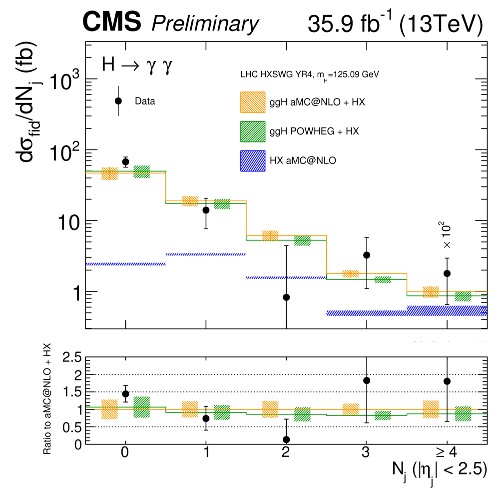
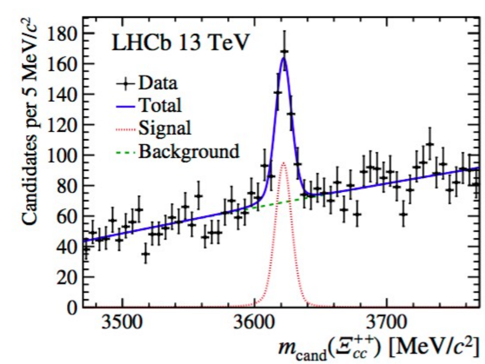
QCD measurements at the LHC

- Large field:
  - Hadron physics
    - HF spectroscopy
    - Quarkonia production
    - Exotic multi-quark states
  - Soft QCD
    - Exlusive, diffractive processes
    - Multi-parton interactions
    - Minimum bias interactions
    - Total pp cross section
  - Hard pQCD & PDFs
    - Jets, dijets, multijets
    - alpha_s measurements
    - W/Z +jets production
    - Photon production
    - Inclusve W/Z production
    - Boosted topologies





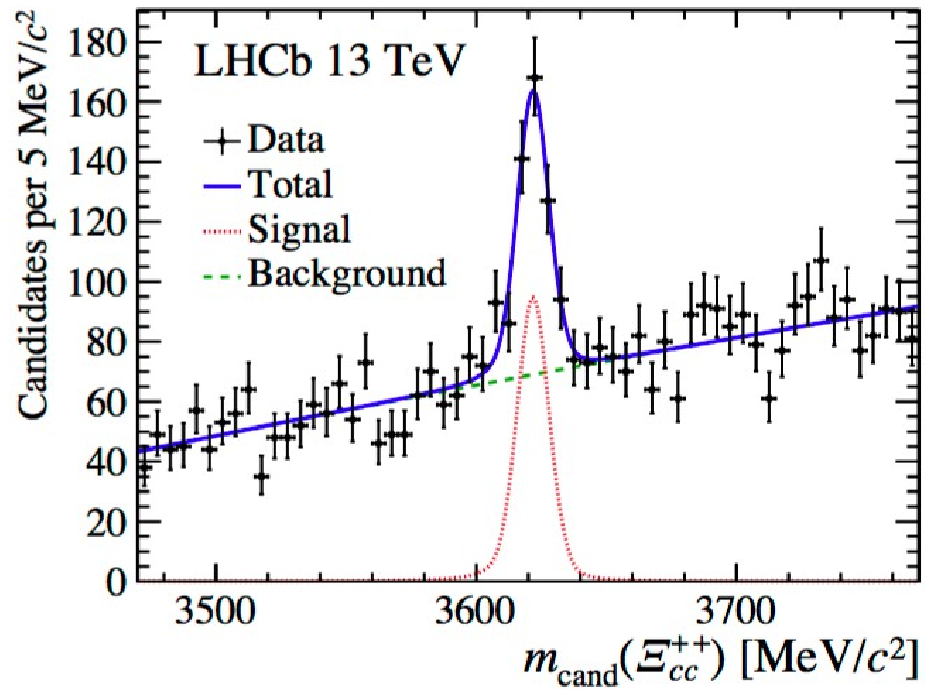


This talk constitutes a biased selection of recent measurements

Top and HF → see dedicated sessions

Observation of Ξ_{cc}^{++}

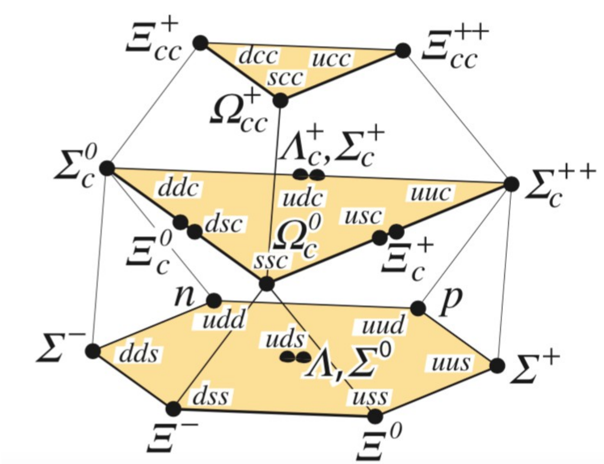
- Constituent quark model predicts three weakly decaying double-charmed states
- **LHCb 13TeV:** Reconstruct $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ with $\Lambda_c^+ \to p K^- \pi^+$
- Background estimate using wrong sign π π
- Selection exploits longer life time, Multivariate selector
- Local signal significance > 12 σ
  Confirmation in Run1 data set (8TeV)



arXiv:1707.01621

- Mass measurement:
  $$3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14\,(\Lambda_c^+)\ \text{MeV}/c^2$$

- Width determined by experimental resolution
  lifetime/width consistent with weak decay

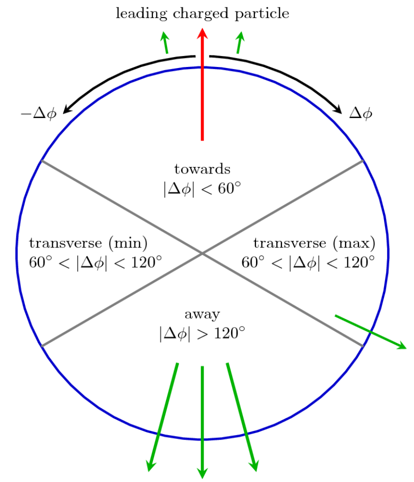


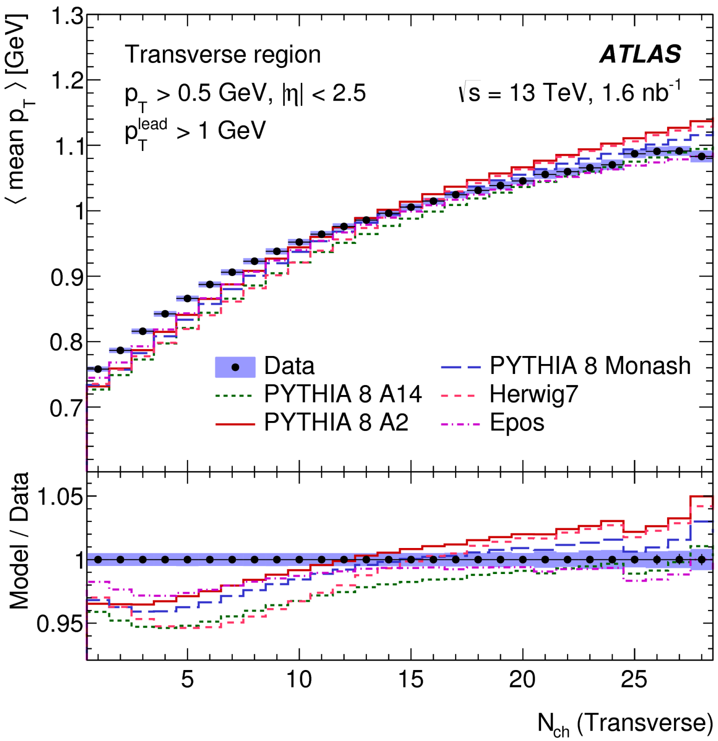
Particle Data Group: Quark model

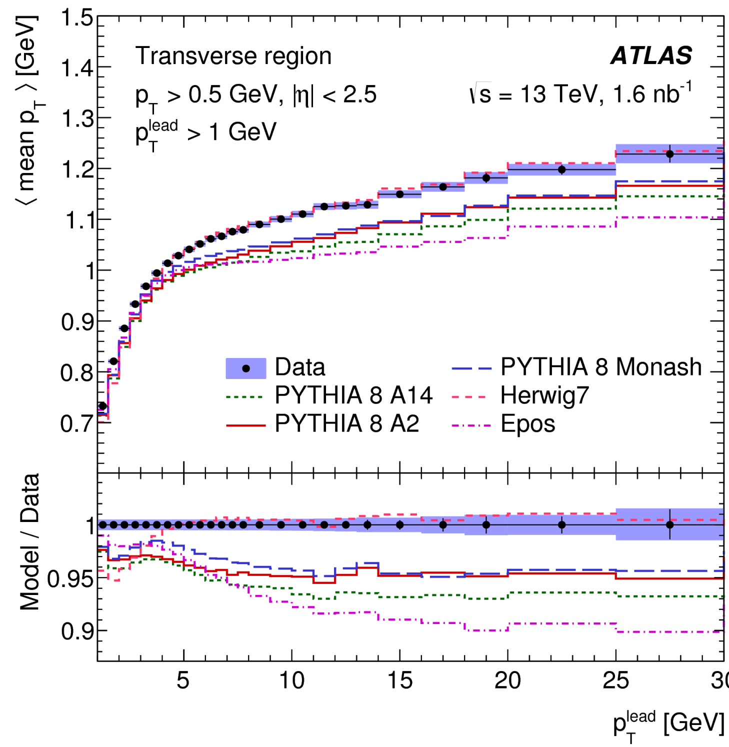
Track-based UE

Probe performance of Run1 MC tunes, provide data for new UE tuning

- **ATLAS 13TeV, 1.6/nb**
  - Angular distributions of energy /particle flow wrt pT(lead), ΔΦ, N(cha)
  - Track pT> 500 GeV, |η| < 2.5, pT(lead)>1GeV
  - Divide the phase space to discrimitate sources
  - Compare to Pythia8 (A2,A14,Monash), Herwig7 (UEMMHT), EPOS (LHC)
  - Measurement precision 1%, best models describe the data to 5%







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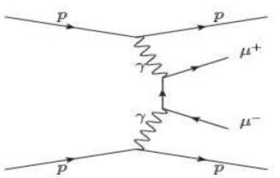
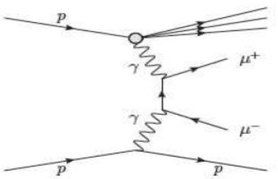
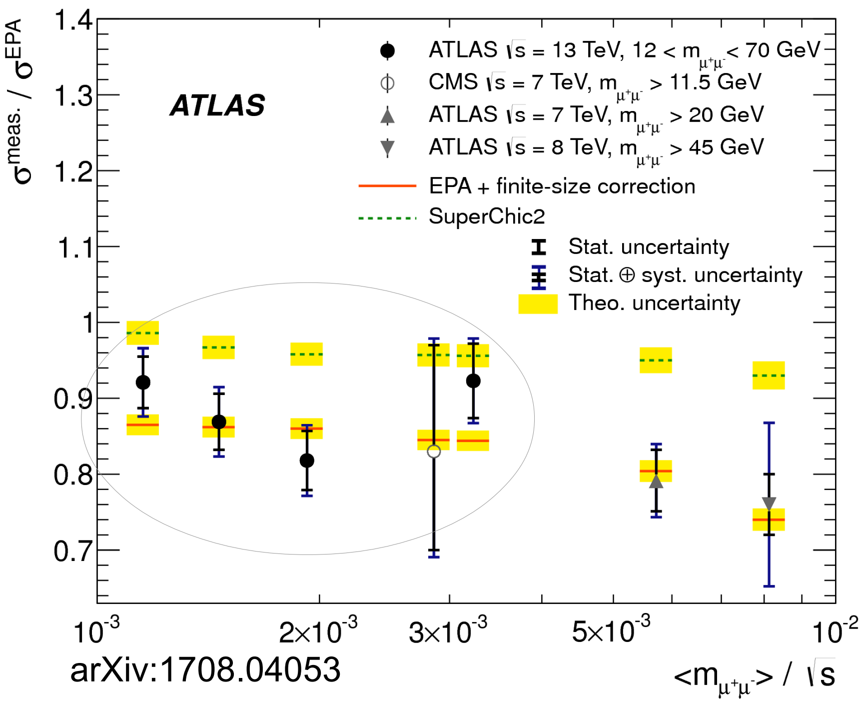
Exclusive di-muon production

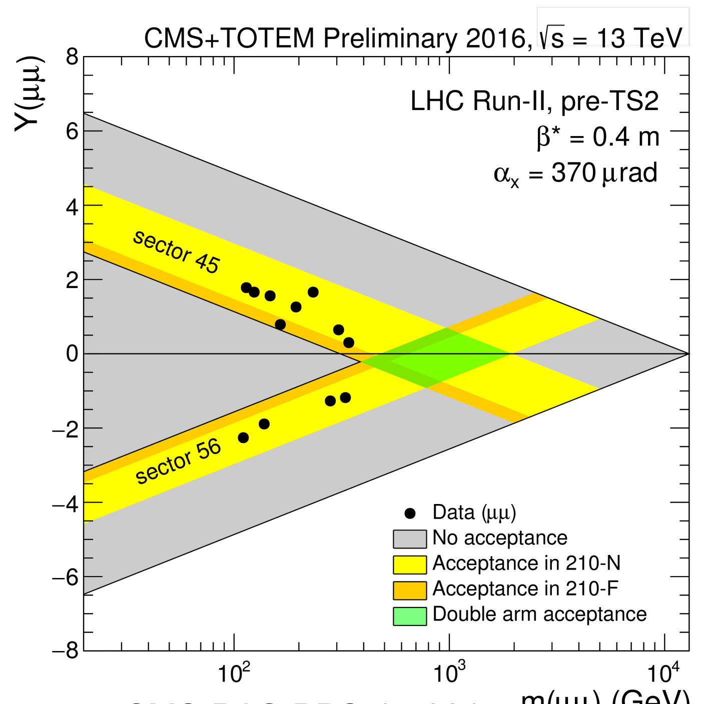




- Selections: 2 muons , avoid Z peak region
  track veto in z window around PV, acoplanarity fit
- **CMS 13 TeV:** matched with a proton tag in the new CMS-TOTEM CT-PPS
  protons close to beam detected in RP, 210m from IP
  → First evidence for proton-tagged semi-exl. dimuon production: 12 events
- **ATLAS 13 TeV:** insufficient suppression of absorptive effects in Superchic 2,
  data prefers finite-size corrections



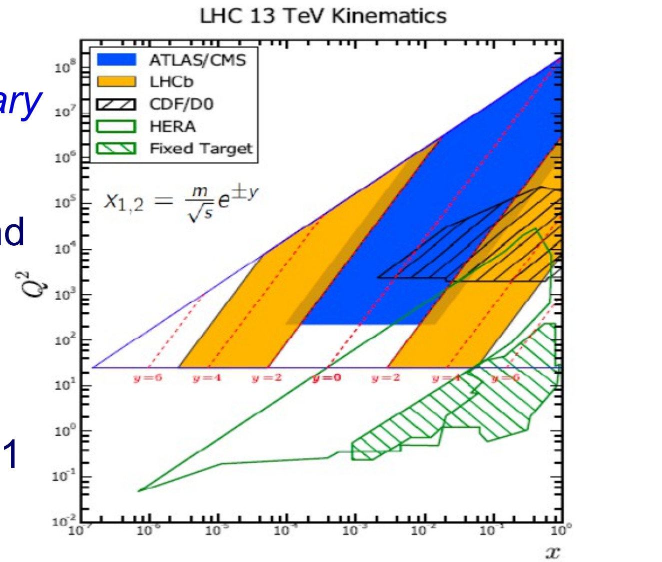
arXiv:1708.04053



CMS-PAS-PPS-17-001

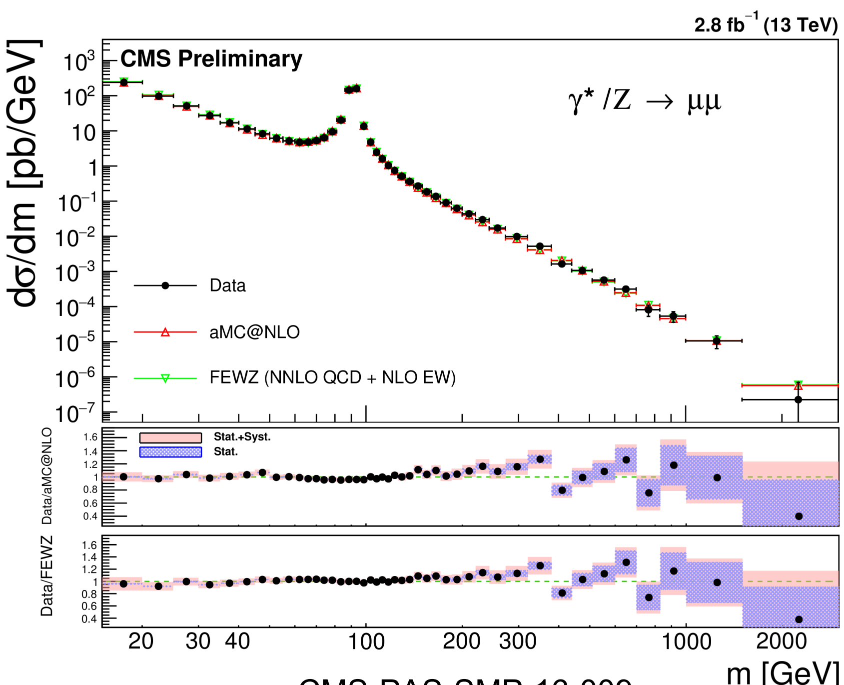
W/Z cross sections and PDF

ATLAS/CMS and LHCb measurements complementary

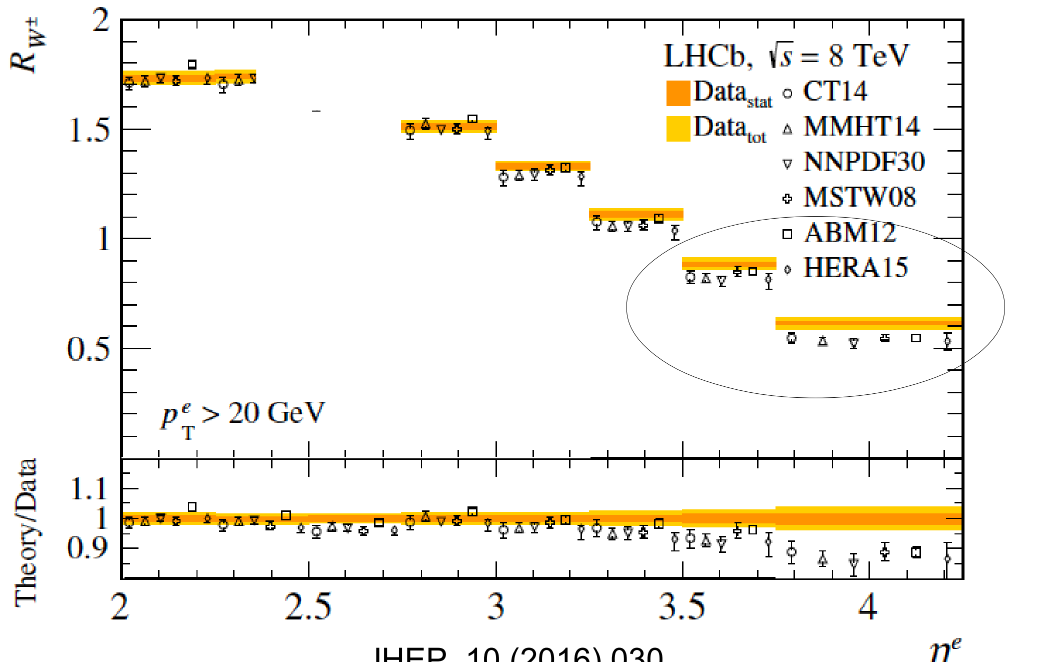


- **CMS: 13TeV** DY cross section
  - Probes 15 < m(ll) < 3000 GeV
  - Precision up to 2%
  - Probes for $10^{-4} < x < 1$
  - Compare to FEWZ+NNPDF3.0 +EW and MG_aMC + NNPDF3.0

- **LHCb: 8TeV** W cross section and W charge-asymmetry
  - η 2 - 4.5
  - Precision 2%
  - Constrains u/d PDF for x > 0.1



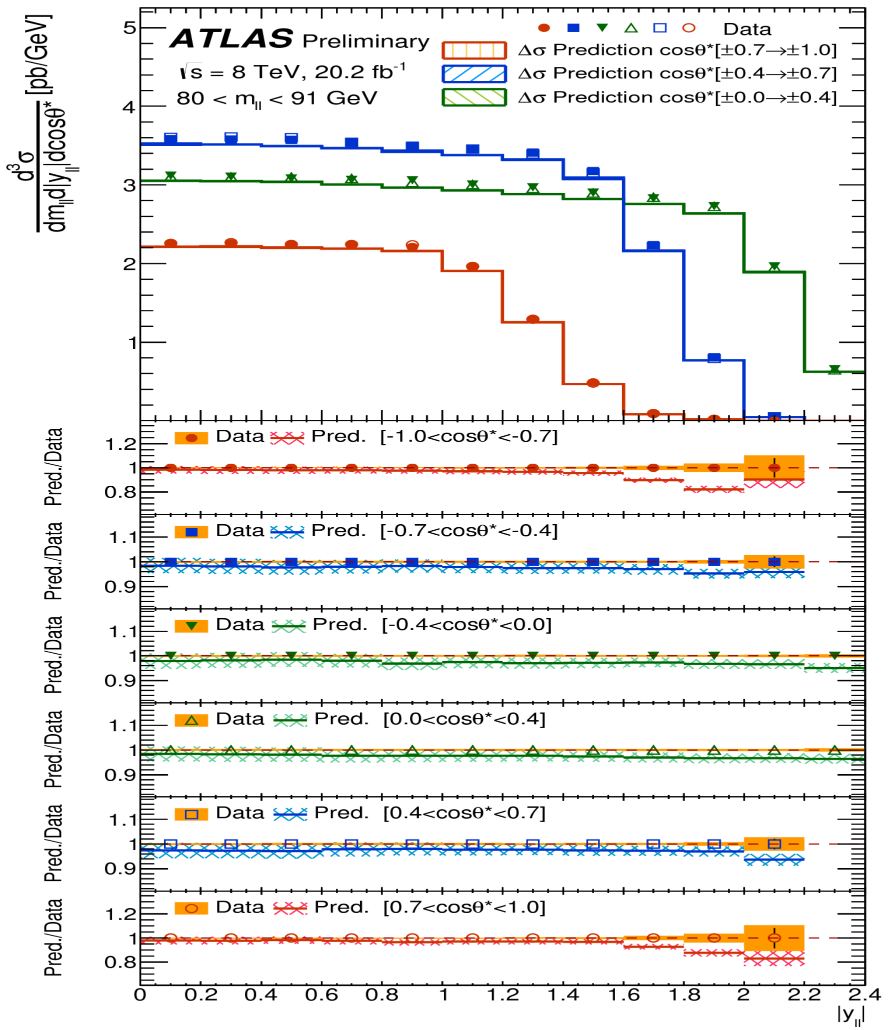
CMS-PAS-SMP-16-009



JHEP 10 (2016) 030

W/Z cross sections and PDF

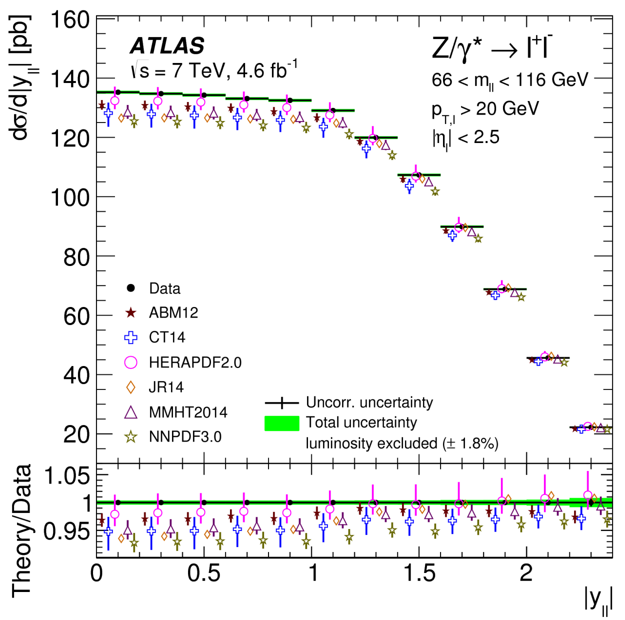
- **ATLAS 8TeV:** 3D DY (Z) cross section: m(ll), Y(ll), cosΘ*
  - m(ll) 46-200 GeV, Y(ll) <2.4(3.6), AFB in Y(ll) bins
  - Precision up to 0.5% for central, Z peak
  - Data agrees with Powheg v1+Pythia8 + CT10 + mass dependent NNLO +EW k-factor + A_i reweighting



CERN-EP-2017-152

- **ATLAS 7TeV:** DY cross sect. ($W^+/W^-/Z$) vs Y, m 46-150 GeV
  - Precision of 0.5%
  - QCD fit: unsuppressed strangeness ATLAS-epWZ16

    r_s = **1.19 ± 0.16** for Q^2=1.9 GeV^2 and x=0.023



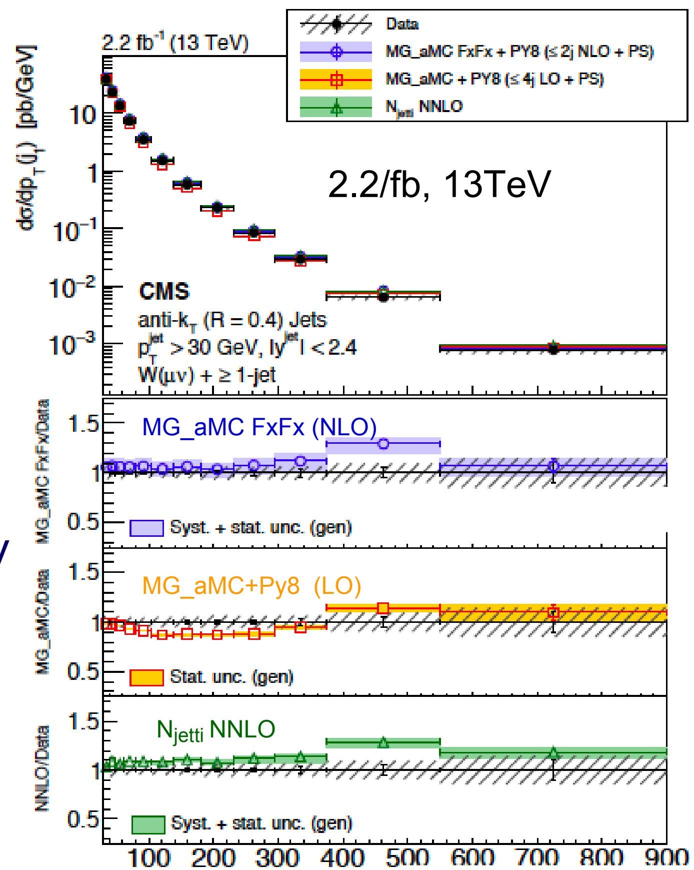
EPJC 77 (2017) 367

→ PDFs, $\sin^2\Theta_W$

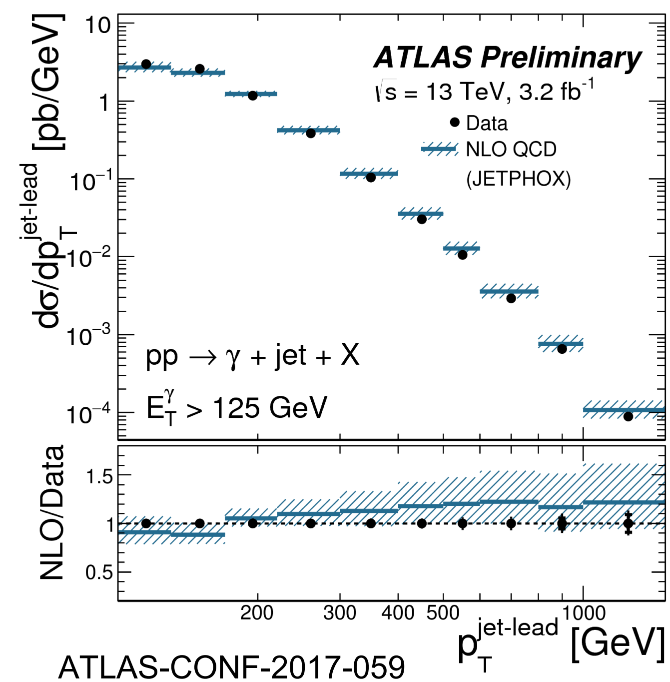
V+jets

- V+jets Important background for Top/Higgs/searches
- Probe pQCD, PDF
- Large theory progress: NLO revolution, NNLO calculations, ME+PS@NLO, EW corrections,..
- With higher cms energies and more data: sensitive to EW corrections and collinear V emissions

- **W+jets, CMS, 13TeV**
- Reduce top bkg with b-veto
- pT(j) > 30GeV
- NLO ME perform better
  Good agreeement with NNLO



- **Isol. γ+jets, ATLAS, 13TeV**
- ET(γ) >125GeV, pT(j) >100GeV
- Compare with LO+PS, Sherpa Multileg LO/NLO fixed-order NLO (Jetphox)
- NLO ME perform better
  LO Multileg better than LO+PS

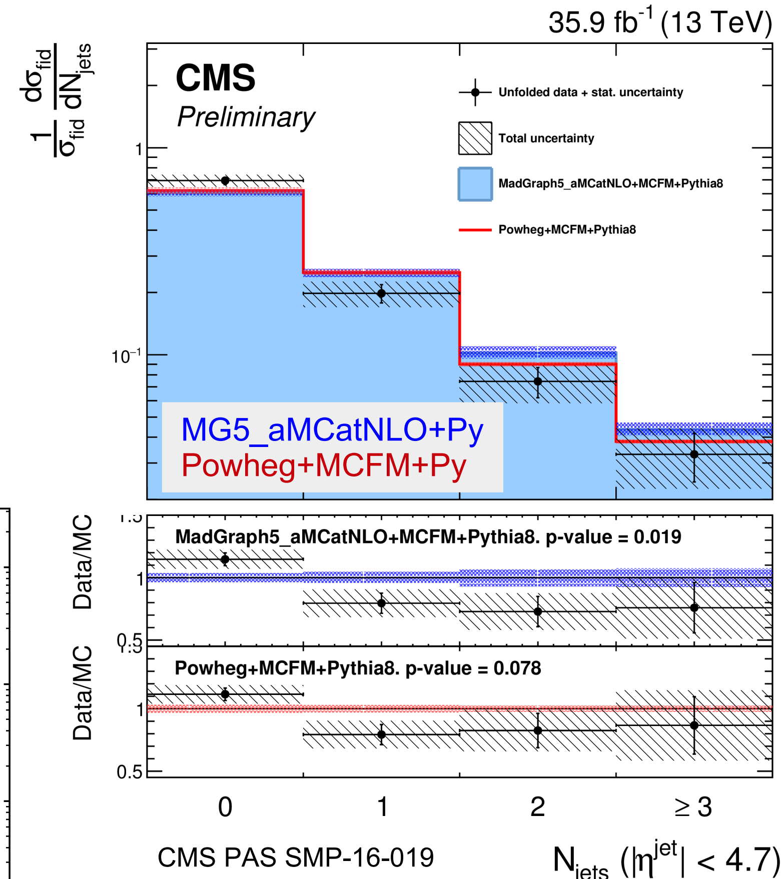


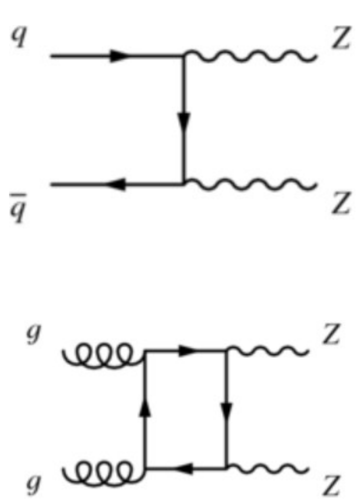
ATLAS-CONF-2017-059

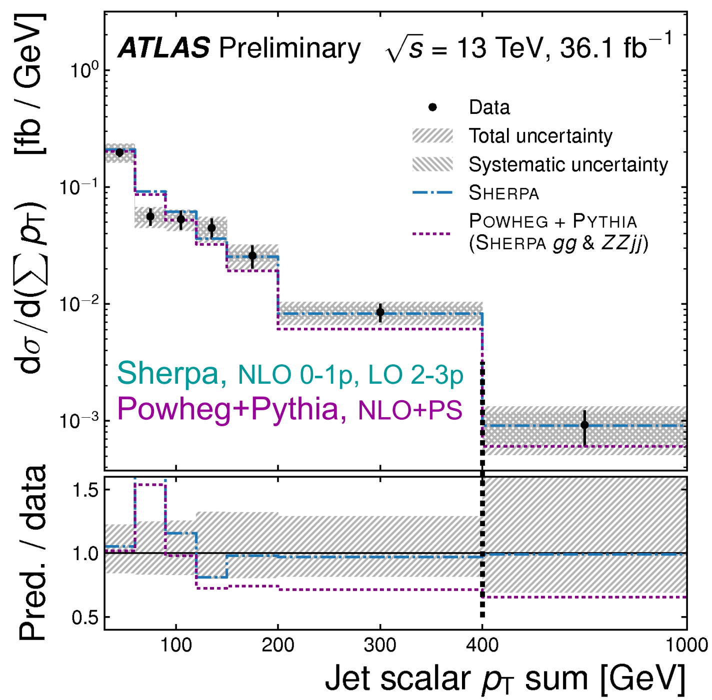
arXiv:1707.05979

Diboson + jets: ZZ at 13TeV

- **ATLAS,CMS 13TeV**
- Important background for VBS ZZ etc.
- Select two on-shell Z, leptonic decays
- Compare to generator predictions:
  - ME+PS with higher jet multipicities performs better than NLO+PS
  - More recent generator versions perform better





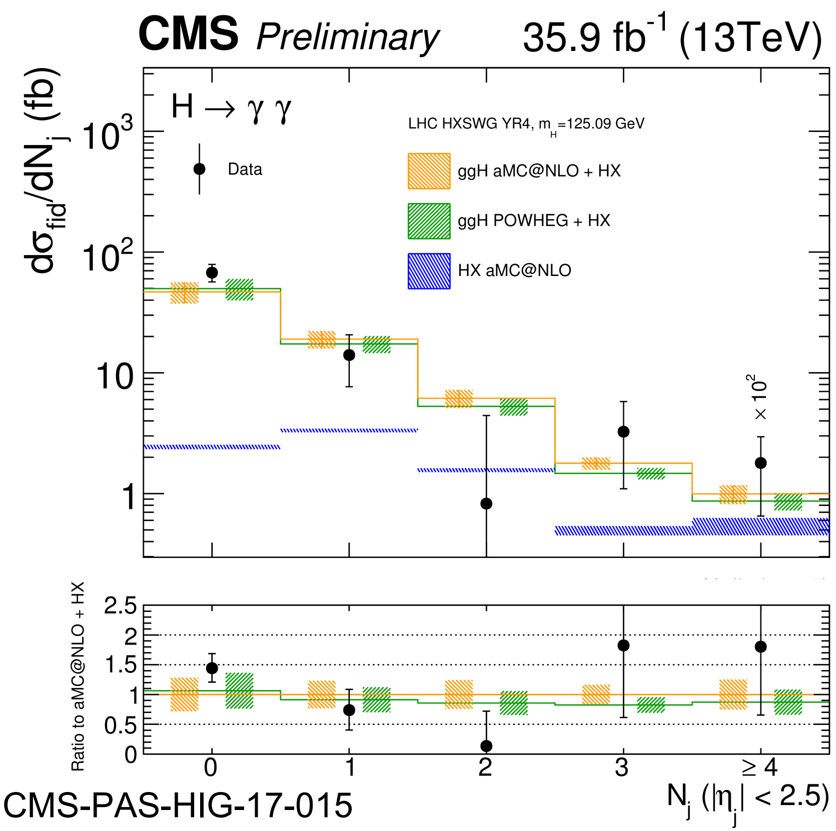


ATLAS-CONF-2017-031

QCD studies in Higgs events

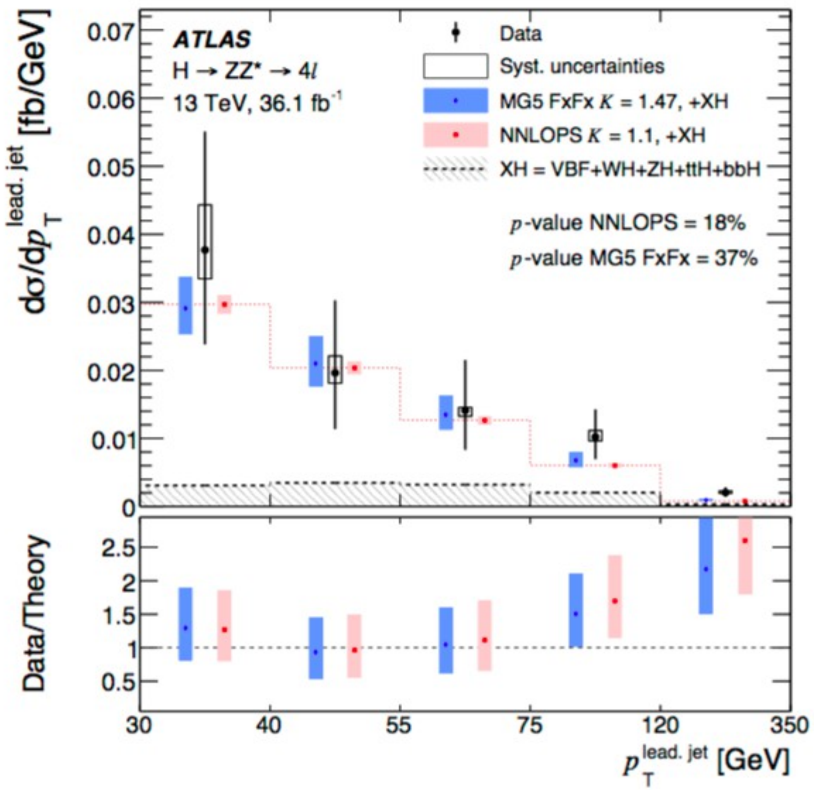
Probe pQCD, validate model assumptions used in H selection

- **CMS 13TeV:**
- Uncertainty statistically dominated
- Consistent with generator predictions:
  - Complete MG_aMCatNLO set
  - ggH modelled with Powheg



CMS-PAS-HIG-17-015

arXiv:1708.02810



- **ATLAS 13TeV**
- Uncertainty statistically dominated
- In general good agreements with
  - ggF MG5 FxFx (0-2p atNLO) * k-*N3LO*
  - ggF Powheg rew. with HNNLO * k-*N3LO*
- Worse for high Njet and high pT(jet)

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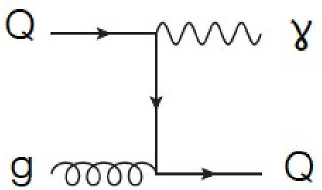
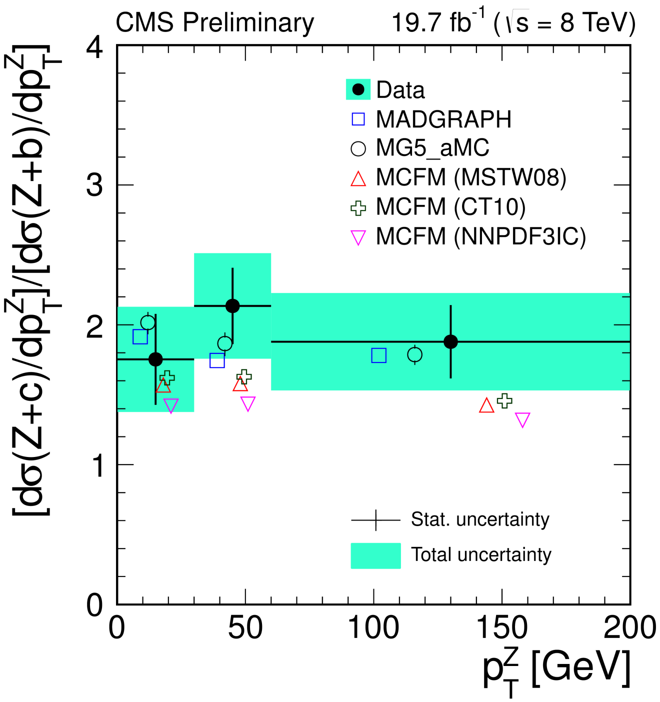
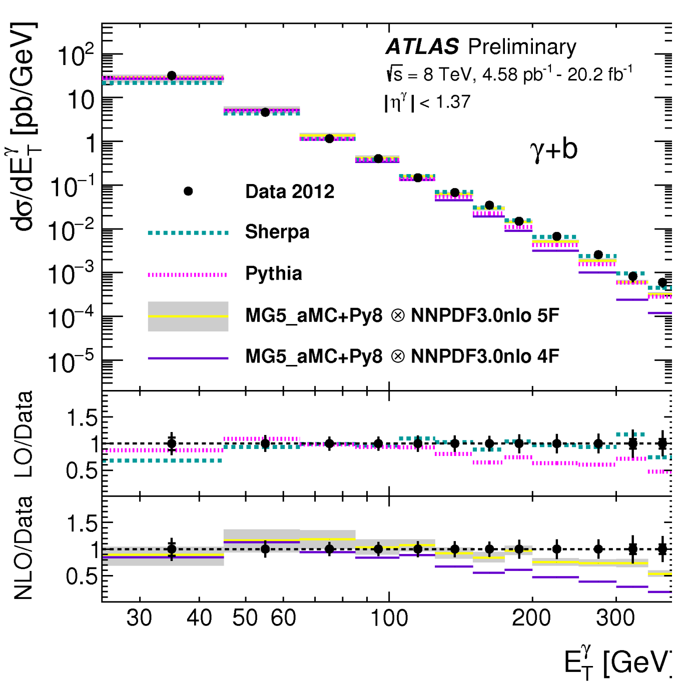
Z/γ+ c/b

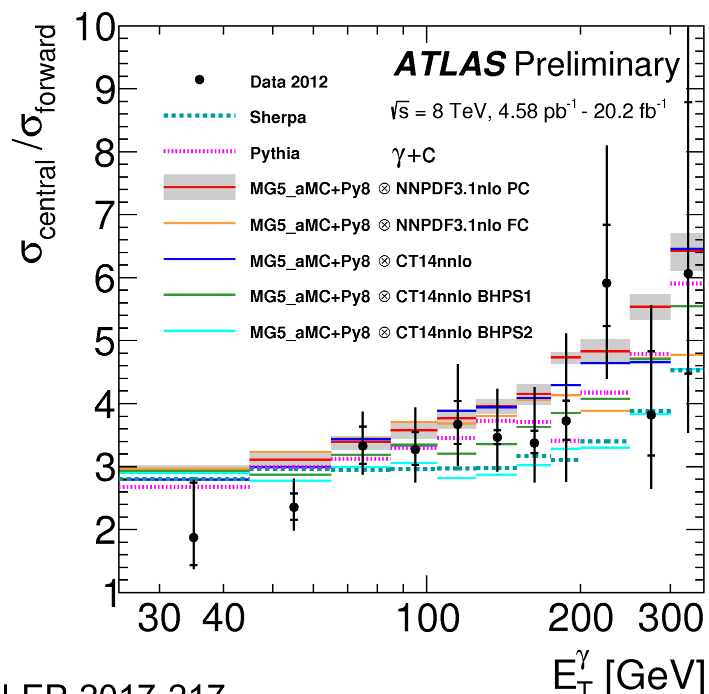


- c/b PDF, intrinsic charm, flavour scheme, background to searches.
- Extraction of signal:
  - **ATLAS, 8TeV:** γ+b/c, combined fit to b-tagging discriminant
  - **CMS, 8TeV:** Z+b/c, μ tagger, fit to vertex mass & D reco, fit to vertex probabiity
- pT(V), pT(q), pT V+b/V+c, central/forward
- Z+b/c: Good agreement with MG (LO, NLO) ME+PS, bad agreement with MCFM
- γ+b/c: 5F better than 4F, Sherpa best agreement, data agrees with all intrinsic c models



CMS-PAS-SMP-15-009





CERN-EP-2017-217

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2 and 3D jet cross sections

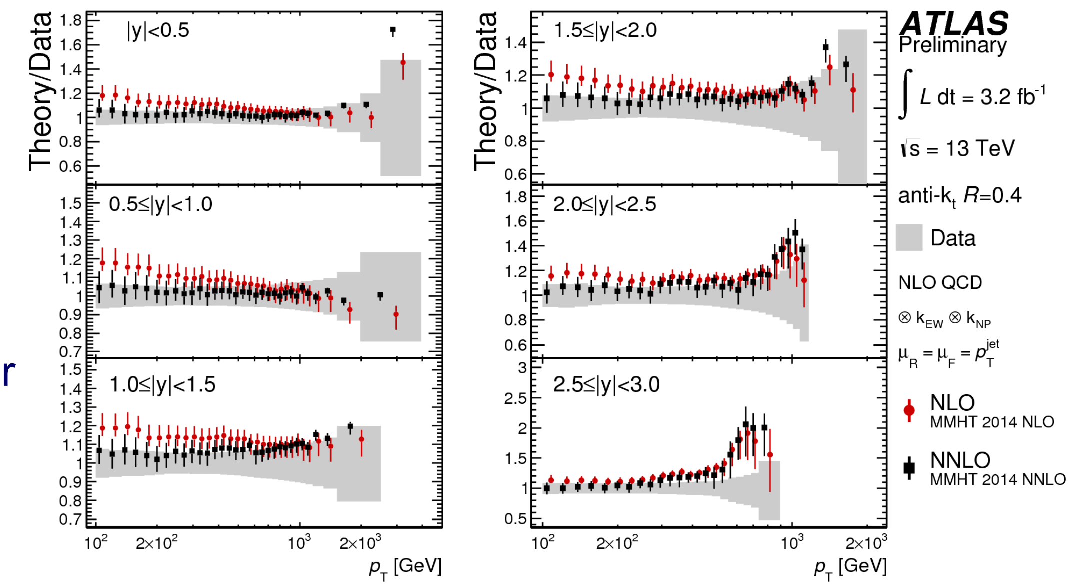
Sensitive to PDF, pQCD, α_S

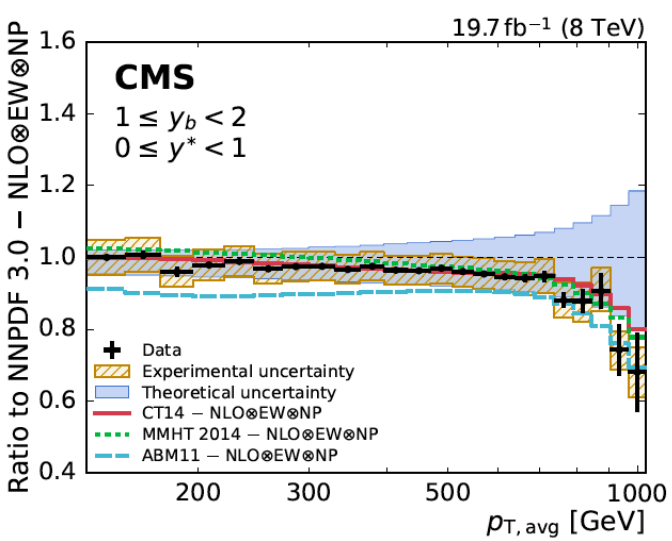
- **ATLAS 13TeV** 2D incl. Jet cross section (pT, Y),
- Probe NLO and NNLO (+EW+NP): (N)NLOJET
- Data agrees better with NNLO with pT(jet) scale
  Large sensititivy to central scale choice
- Fair agreement with NLO in individual y/pT bins
  Strong tensions when considering all bins together

→ similar to 8TeV results: *JHEP 09 (2017) 020*

ATLAS-CONF-2017-048

NLO, NNLO





arXiv:1705.02628

- **CMS 8TeV** 3D dijet ross sections:
  pT_{av}= (pT1+pT2)/2, y*= |y1-y2|/2, yb + |y1+y2|/2
- Compare to NLOjet (+EW+NP)
  NLO Powheg+Py8 +CT10, NLO Herwig7 + MMHT
- Central: Herwig7 better, Boosted: Powheg better
- Constrains PDF, in particular for high x (boosted)
- Very competitive measurement of α_S

Jet mass with jet grooming

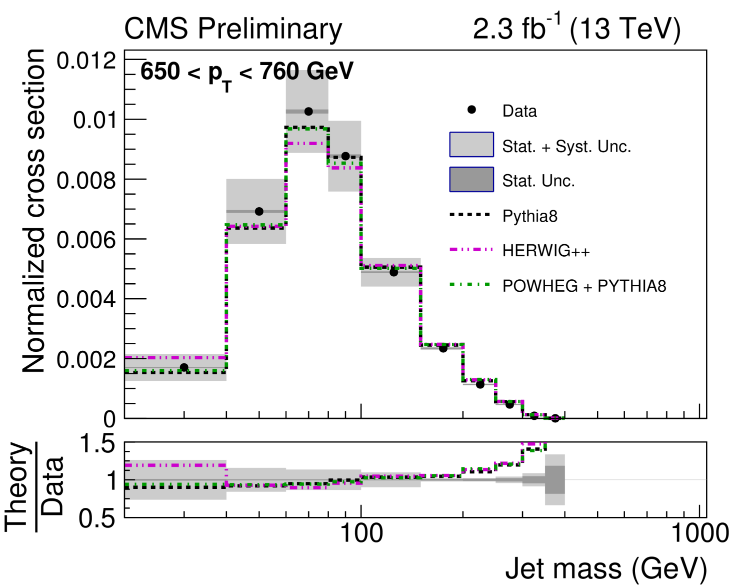
- Motivation: use jet mass to identify hadronically decaying heavy SM or BSM particles, ideally unbiased by soft effects and pileup
- **CMS 13TeV:** Select +- balanced dijets events, AntiKt8 (pFlow)
  - Recluster with C/A, decluster with soft drop condition:
  - Uncertaintes: JES, JER, JMS, JMR, MC model

$$\frac{\min(p_{t,i}, p_{t,j})}{(p_{t,i} + p_{t,j})} > z_{cut} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$

Here: z = 0.1, β = 0 ("mass drop")

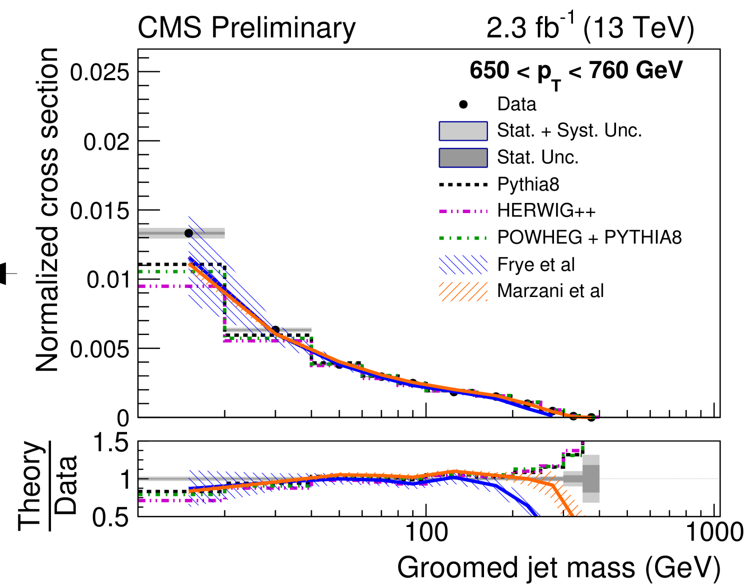
- Compare normalized cross sections to generators and
- fixed-order calculations: (SCEF) LO+NNLL, NLO +NLL+NPC
  - Good agreement for m/pT ~ 5-30%

Ungroomed AK8 jet mass: Sudakov peak



Groomed jet mass

NP

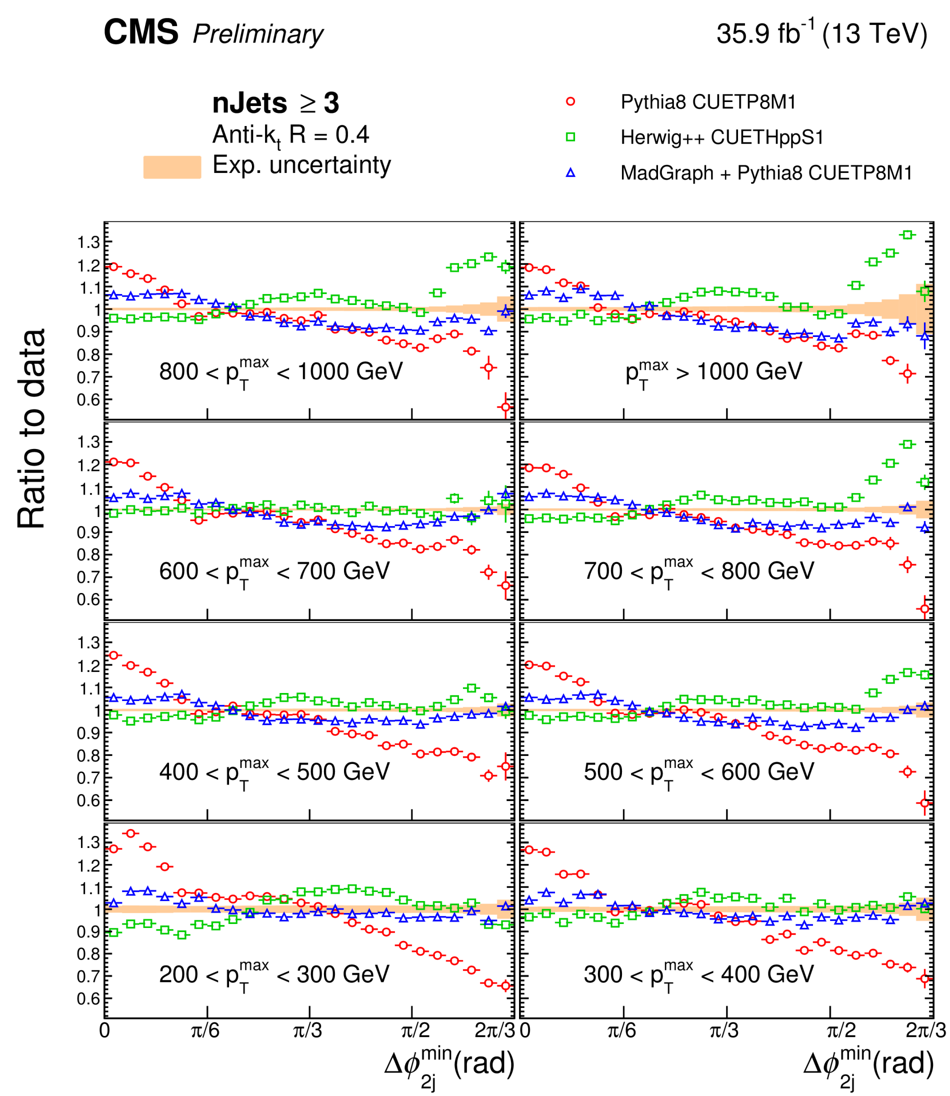


CMS-PAS-SMP-16-010

Multijets: azimuthal correlations

- **CMS 13TeV:**
  Test predictions for multijet production
- Normalized ΔΦ(j1,j2) for 2-4jets
  Normalized minΔΦ(j,j) for 3-4jets
- Dominating unc: JES,JER, ΔΦ resolution
- 2 → 2 LO, 2 → 2/3 NLO, 2 → 2/3/4 LO
- Prediction struggle to describe all distributions
- MG 2 → 2/3/4 (LO): Good overall description
  (at the limit for 4 jets)
- Herwig: NLO 2 → 2 better than LO 2 → 2

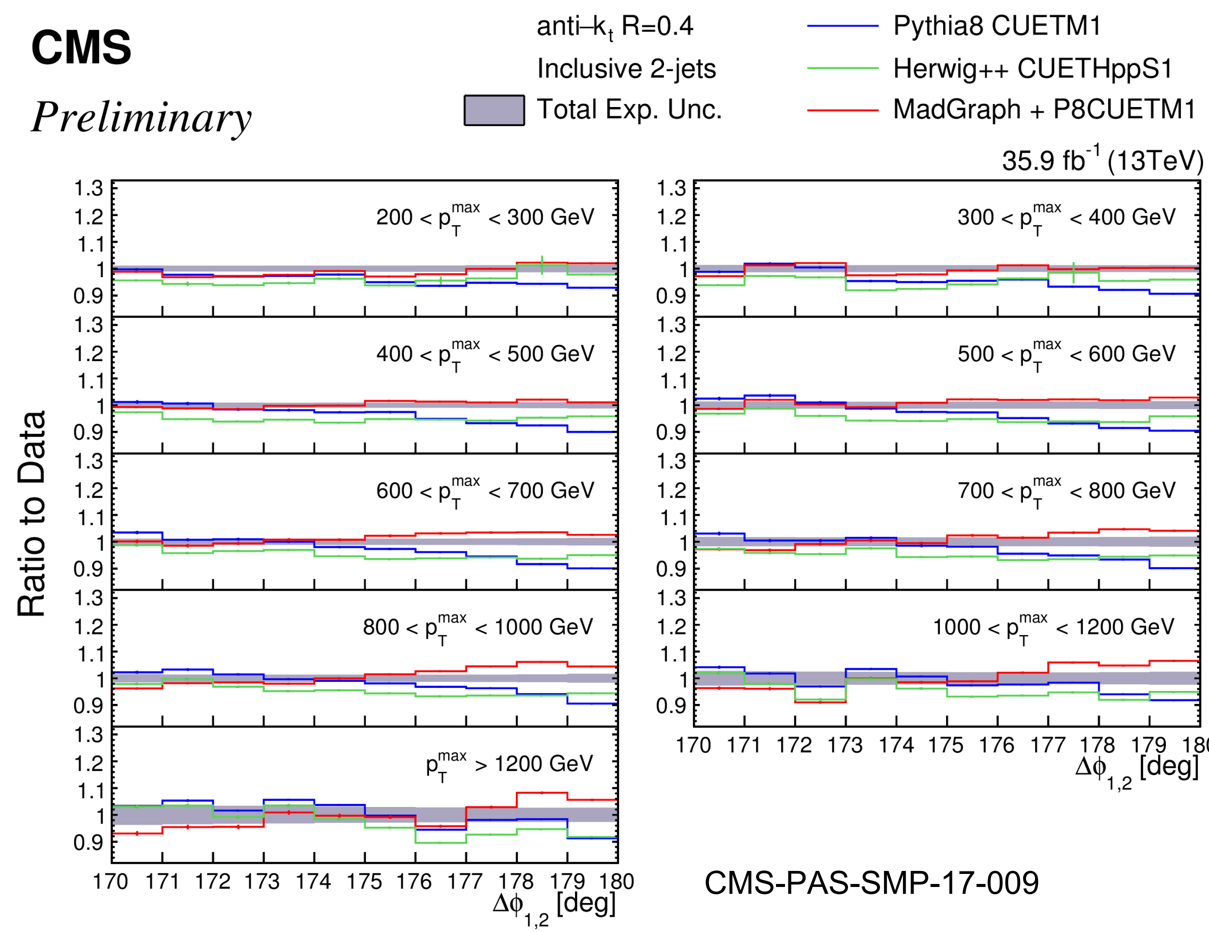
MG 2-> 2/3/4 LO,
Pythia LO+PS,
Herwig++ LP +PS



CMS PAS SMP-16-014

Soft radiation: Dijets azimuthal correlations

Zoom into ~180^o region



MG 2-> 2/3/4 LO, Pythia LO+PS, Herwig++ LP +PS

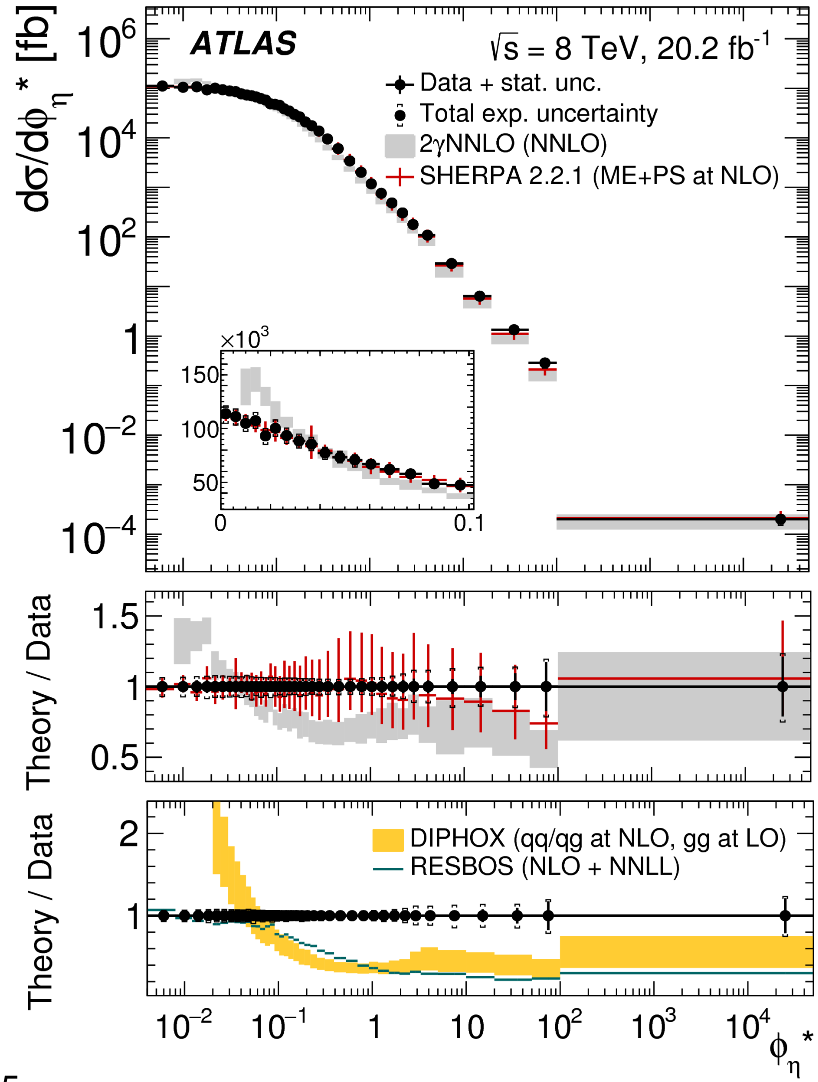
- **CMS 13TeV:** $\Delta\Phi$(j1,j2) for inclusive 2 jets and 3 jets for various pT^{max} . pTjets > 200/100/30 GeV
- Dominating unc: JES,JER
- Tested NLO fixed-order predictions and LO ME+PS
- Region close to 180^o sensitive to soft radiation: hard to model

Soft radiation: Di-photon cross sections

- **ATLAS 8TeV:** Sensitive to soft rad. for low-pT(γγ)
  Contributions from qq and qg initial states
- Select two isolated photons,
  ET > 40GeV/30GeV
- Probe m(γγ), cosΘ*η , ΔΦ(γγ), pT(γγ), aT(γγ)
- Typical uncertainties below 5%,
  dominated by photon ID and isolation modelling
- Good description by Sherpa ME+PS (NLO & LO)
- Problems with fixed-order calculations
- Resummation improves modelling of low-pT(γγ)

$$|\cos\theta^*_\eta| = \tanh\frac{|\Delta\eta_{\gamma\gamma}|}{2}$$

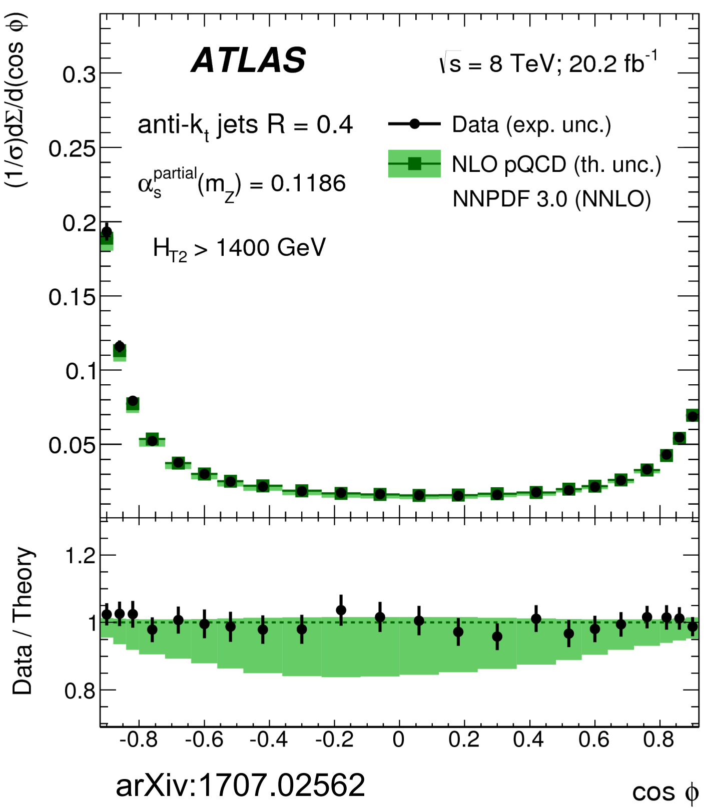
$$\phi^*_\eta = \tan\left(\frac{\pi-\Delta\phi_{\gamma\gamma}}{2}\right)\sin\theta^*_\eta$$



Phys. Rev. D 95 (2017) 112005

The strong coupling constant

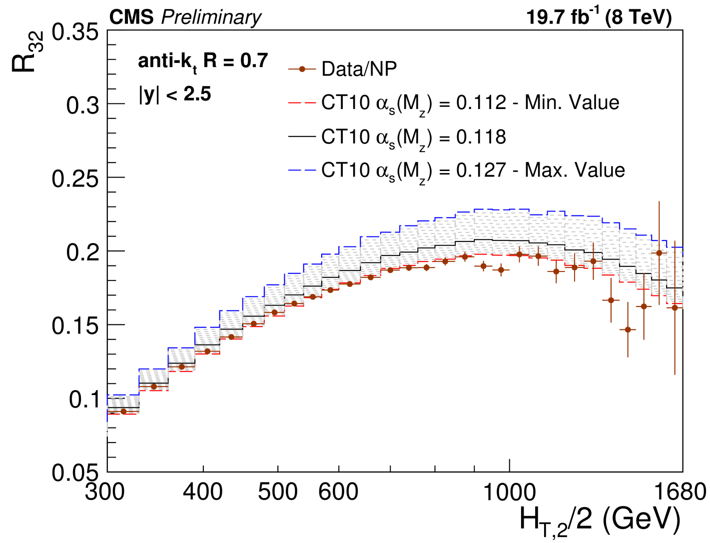
Example ATLAS: E_T weighted angular relation of jets (TEEC) and its asymmetry (ATEEC)



arXiv:1707.02562

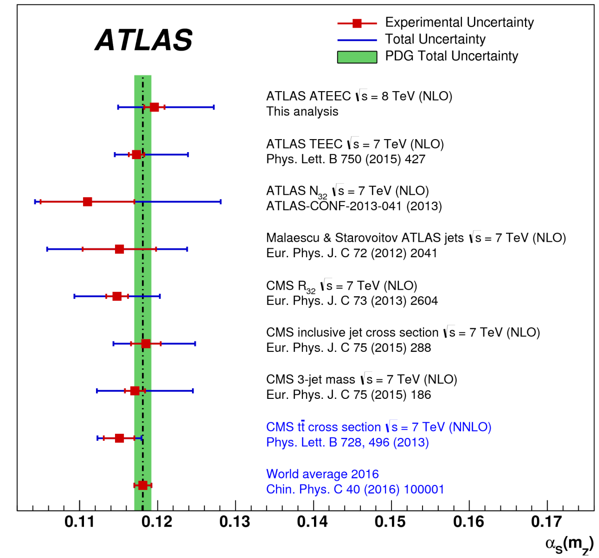
$$\alpha_s(m_Z) = 0.1196 \pm 0.0013\,(\text{exp.})\,^{+0.0061}_{-0.0013}\,(\text{scale}) \pm 0.0017\,(\text{PDF}) \pm 0.0004\,(\text{NP})$$

Example CMS: 3jets/2jets ratio



CMS PAS SMP-16-008

$$\alpha_s(M_Z) = 0.1142 \pm 0.0010\,(\text{exp}) \pm 0.0013\,(\text{PDF}) \pm 0.0014\,(\text{NP})\,^{+0.0049}_{-0.0006}\,(\text{scale})$$



- Probing α_S at high scales
- Experimental uncertainty at the order of 1%
- Main uncertainty: QCD scale choice: up to 5% → would improve with NNLO 2 → 3

Example CMS: 3D dijet cross section → combined α_S, PDF extraction

$$\alpha_S(M_Z) = 0.1199 \pm 0.0015\,(\text{exp})\,^{+0.0031}_{-0.0020}\,(\text{theo}).$$

Summary

- Very active field with lots of new ideas
- Still some modelling problems for some topologies/phase space regions
- In general adding higher orders or explicit real ME, improves the modelling
- Increased cross sections and data size enable us to do QCD measurements double and triple differentially and in rarer processes (diboson, Higgs,...)