Hard QCD measurements @ LHC

Gabriella Pásztor

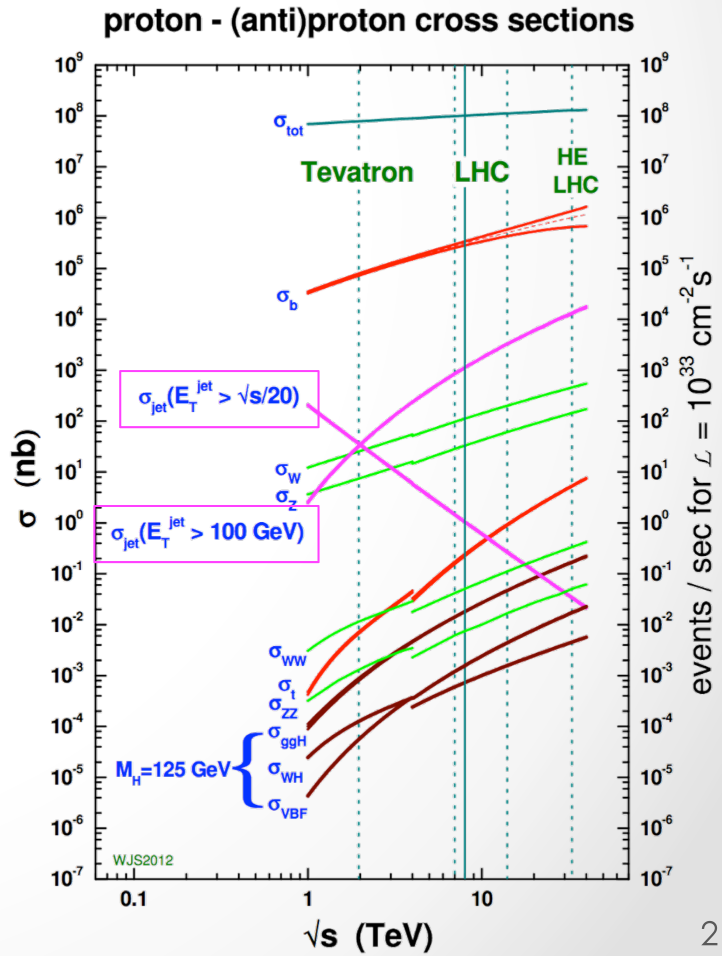
MTA-ELTE Lendület Particle and Nuclear Physics Group, Budapest

on behalf of

the ATLAS, CMS and LHC-b Collaborations

What can we learn from LHC data?

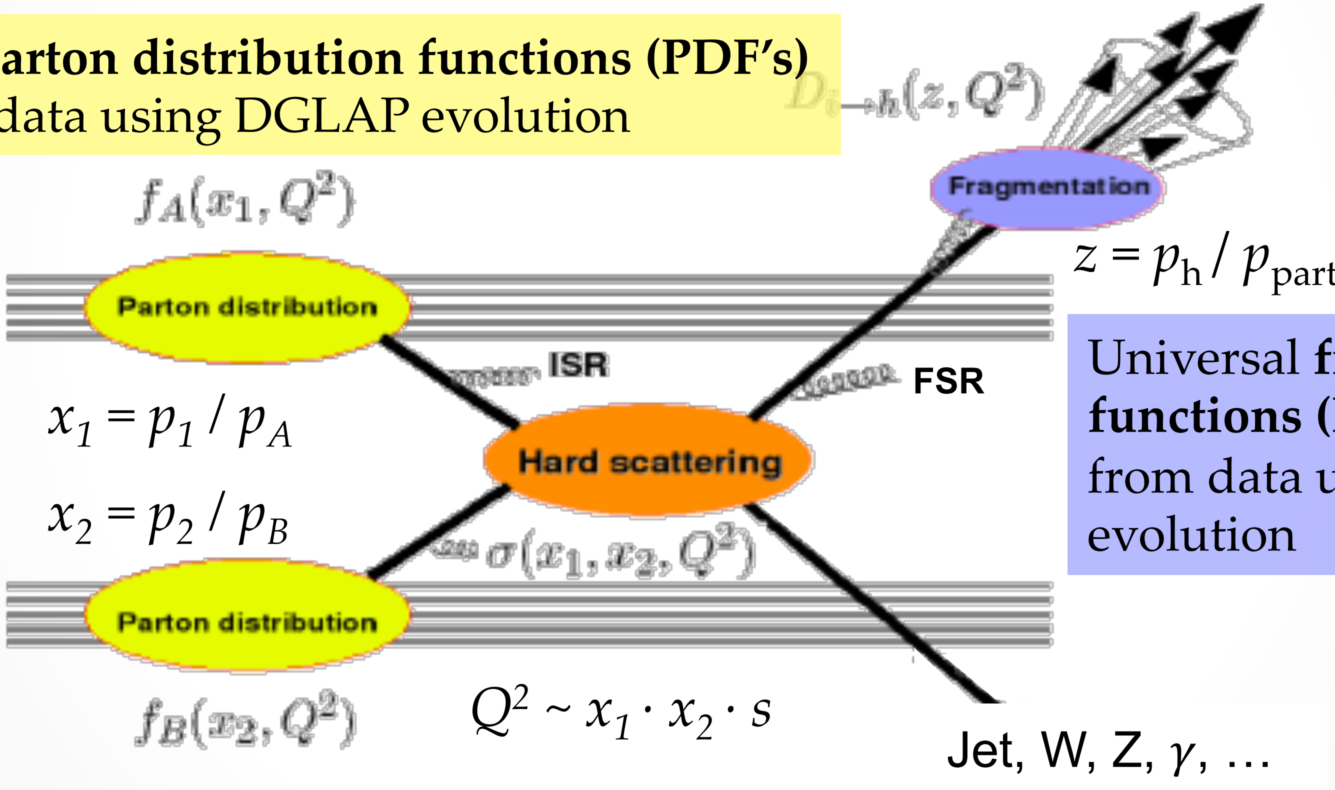
- QCD processes dominant at LHC → **LHC: a jet factory**
- Study pQCD in a previously unexplored region
- QCD processes give significant background to new physics searches
- Cross-sections (Including new physics such as SUSY particle, dark matter, V', … production) affected by QCD processes



Interlude: cross-sections at LHC

$$\sigma(AB \to h) = f_A(x_1,Q^2) \otimes f_B(x_2,Q^2) \otimes \sigma(x_1,x_2,Q^2) \otimes D_{i\to h}(z,Q^2)$$

Universal **parton distribution functions (PDF's)** fitted from data using DGLAP evolution



$z = p_h / p_{parton}$

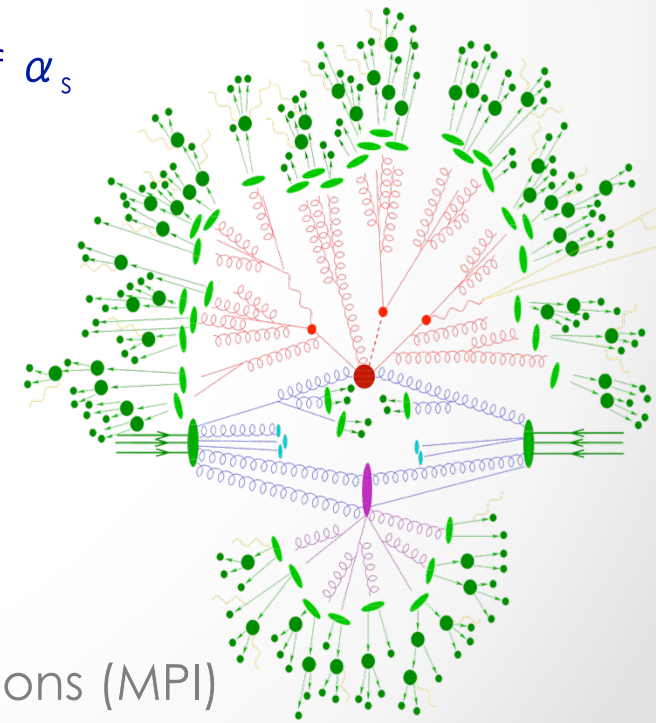
Universal **fragmentation functions (FF's)** fitted from data using DGLAP evolution

Hard scattering matrix element calculated at (N)NLO in pQCD α_s expansion with (N)NLL resummation of large logs

What can we learn from LHC data?

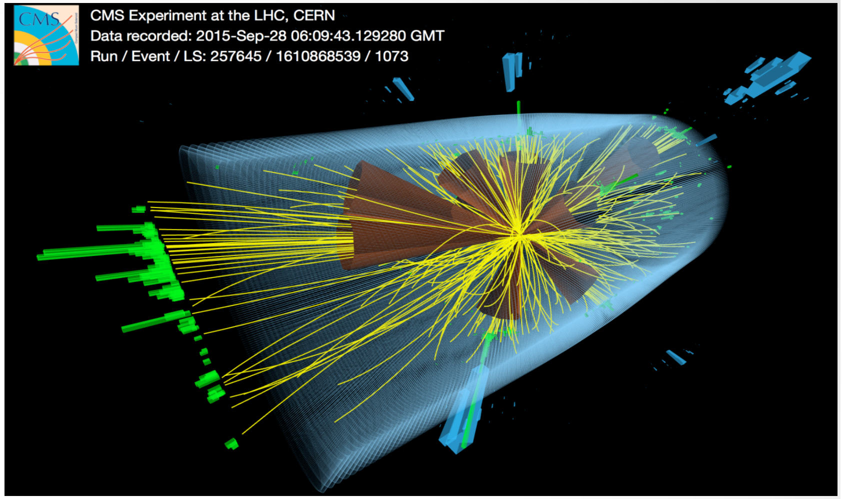
- QCD processes dominant at LHC → **LHC: a jet factory**
- Study pQCD in a previously unexplored region
- QCD processes give significant background to new physics searches
- Alll cross-sections (also of new physics such as SUSY particle, dark matter, V', … production) affected by QCD processes

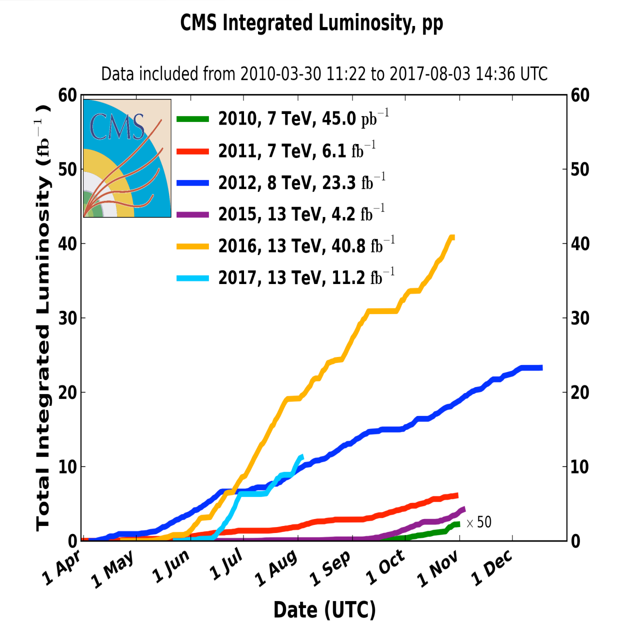
- Extract α_s, PDF's, FF's
  - New colored particles would change the running of α_s
  - PDF uncertainty is dominant systematics for Higgs, top production, limits precision measurements (m_W, α_s) and searches for heavy particles
- Test precision calculations with higher order corrections and soft- and collinear gluon resummation
- Validate sophisticated Monte Carlo tools, parton shower modelling, ME&PS matching
- Study underlying event (UE), multi-parton interactions (MPI)

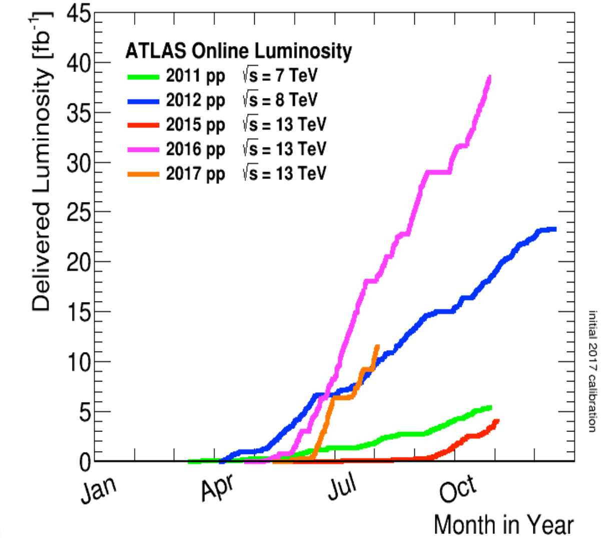


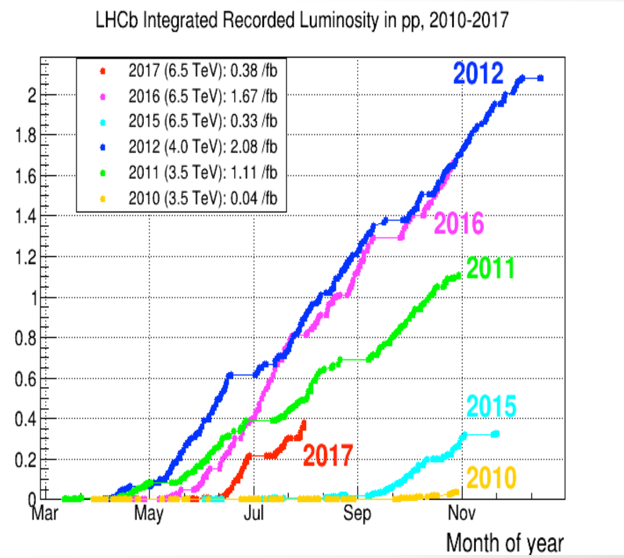
Outline

- **Concentrate on recent jet and V+jet measurements at 8 and 13 TeV**
- Comparison to theoretical calculations, MC predictions
- Impact on PDF's, determination of α_s
- Only representative results (+ some more in backup)
- All public results:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
  - http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_QEE.html





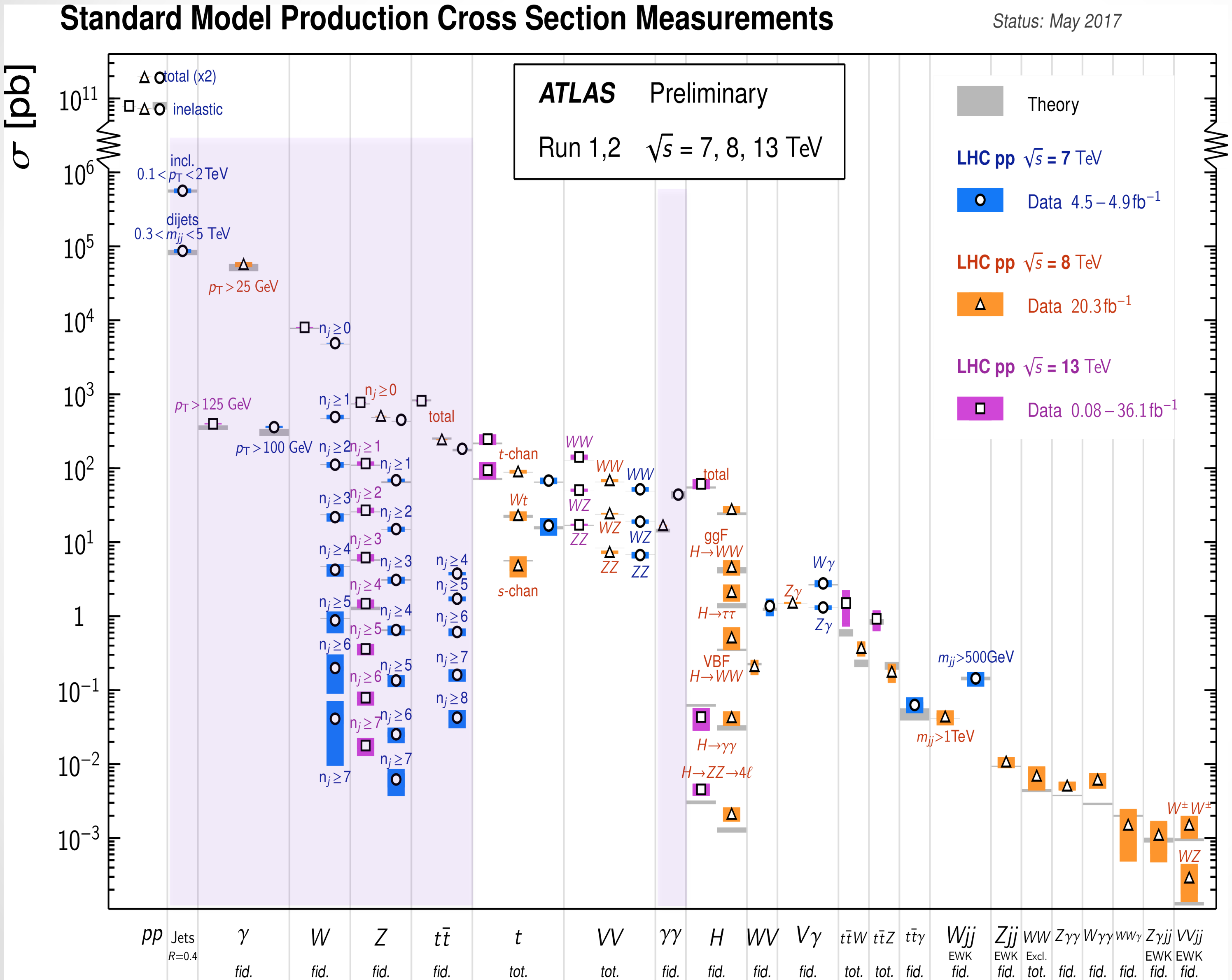




LHCb: luminosity-leveled

At a glance

Impressive data – theory agreement over many orders of magnitude in cross-section



Thanks to advances in experimental methods

- Improved object reconstruction, calibration
- Pile-up robustness
- Better triggers
- Data-driven background
- Boosted techniques
- …

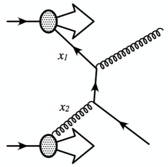
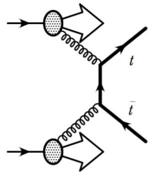
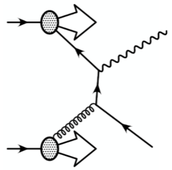
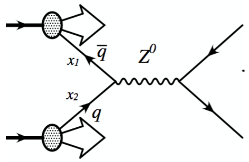
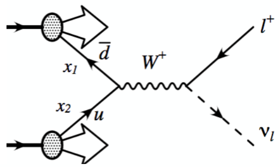
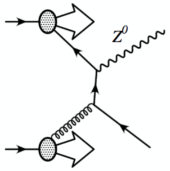
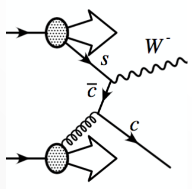
and theoretical calculations

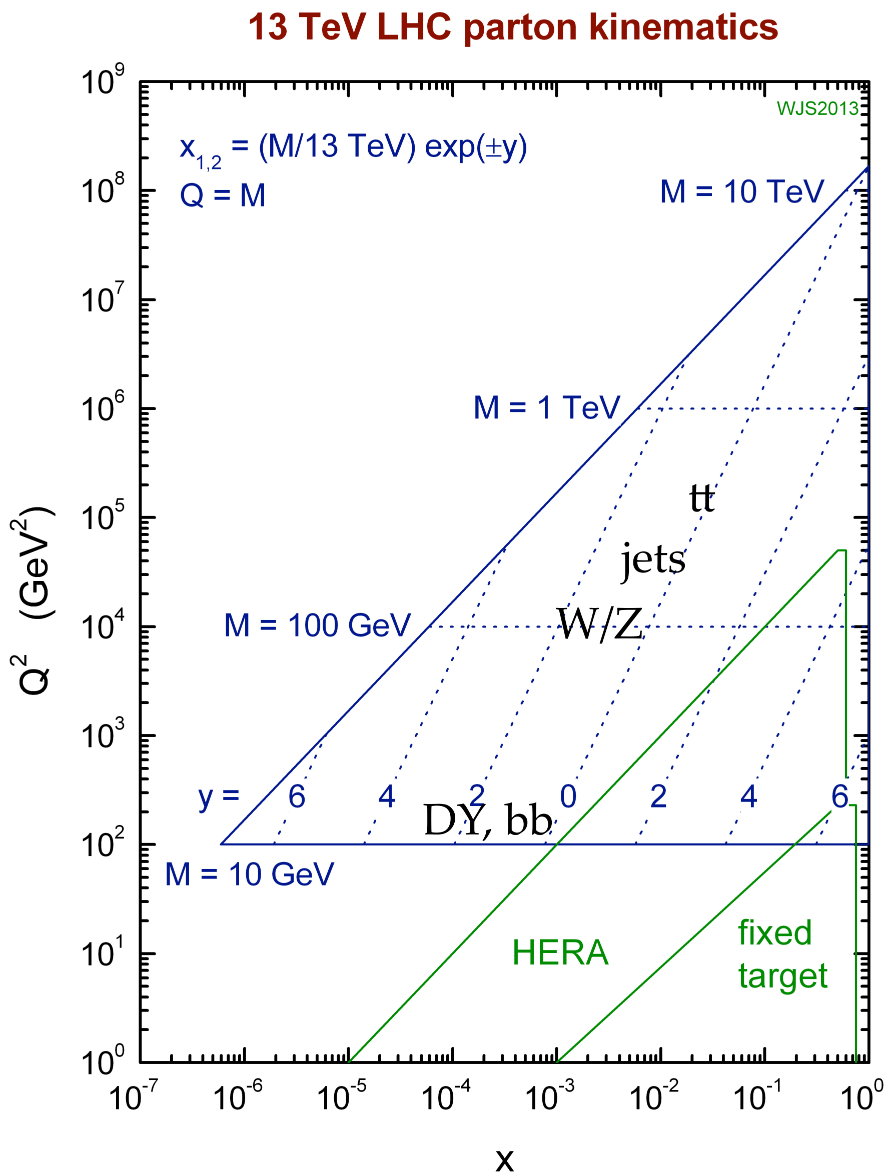
- NNLO (N³LO)
- Resummation of large logs
- EW corrections
- Improved treatment of parton showers, ME&PS matching
- MC tools
- …

PDF constraints from LHC

Many handles:

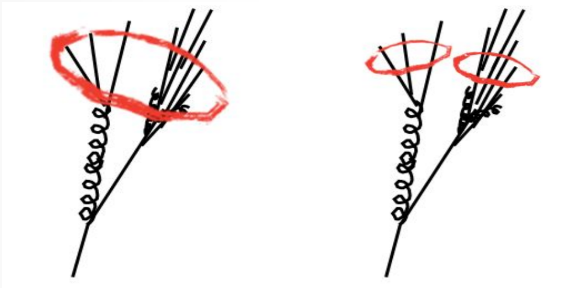
- Jets:
  gluon, valence q's, α_s
- Top pairs:
  gluon, valence q's, α_s
- Prompt photon:
  gluon, valence q's, α_s
- W, Z, ratios:
  q flavour separation
- Off-peak Drell-Yan:
  u,d at low, high x
- Z+jets:
  gluon
- V+Q:
  s quark,
  charm

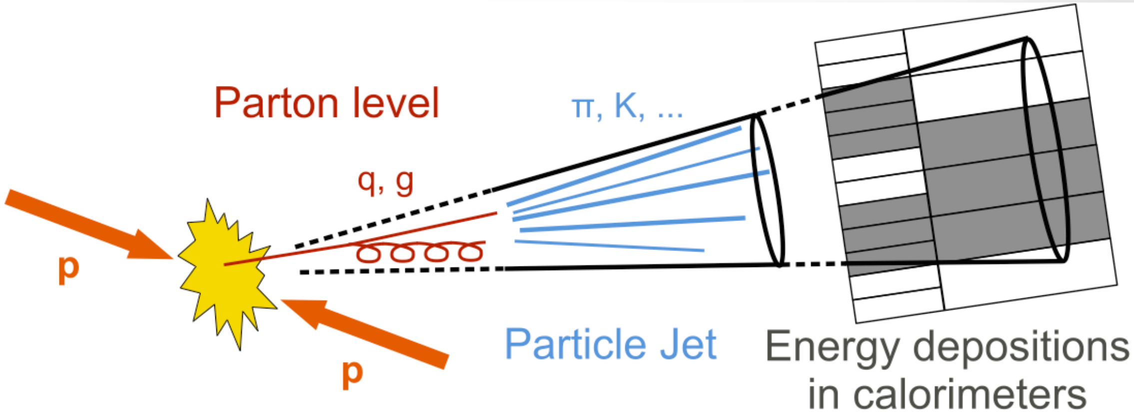










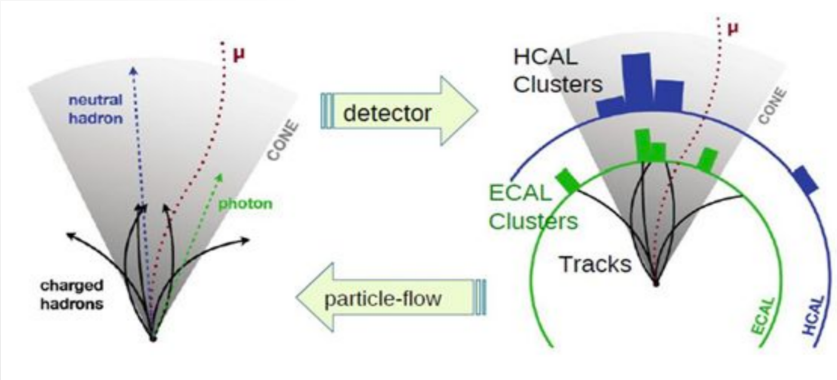
Jet reconstruction @ LHC

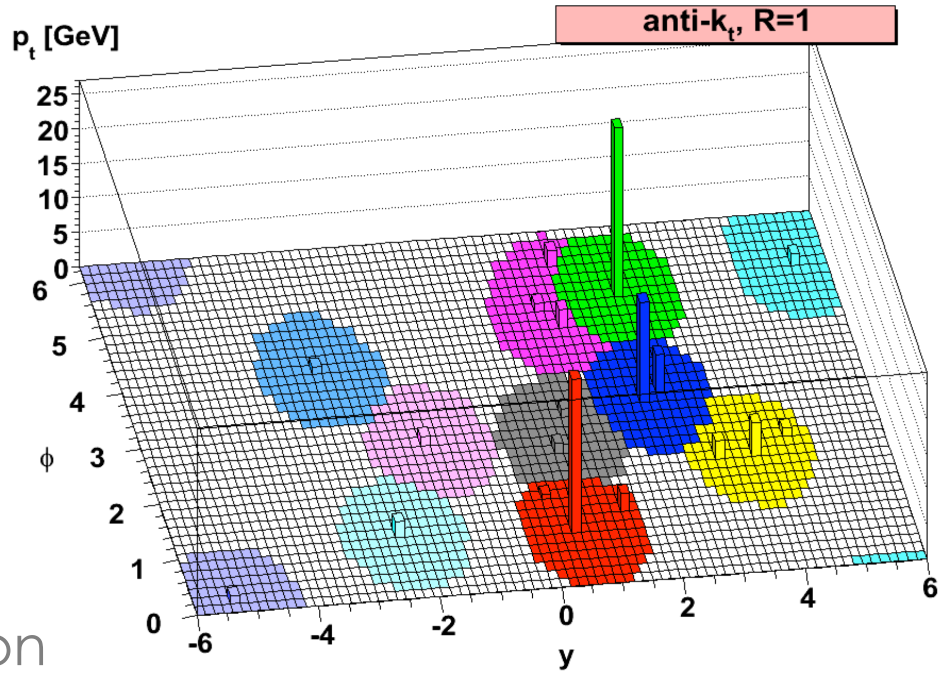
- Anti-kt algorithm
  - Infrared- and collinear-safe
  - Typically R = 0.4 – 0.8 in analyses presented here





- Particle-flow objects





- Dominant experimental systematics: jet energy calibration

Inclusive jet cross-section @ 8 TeV

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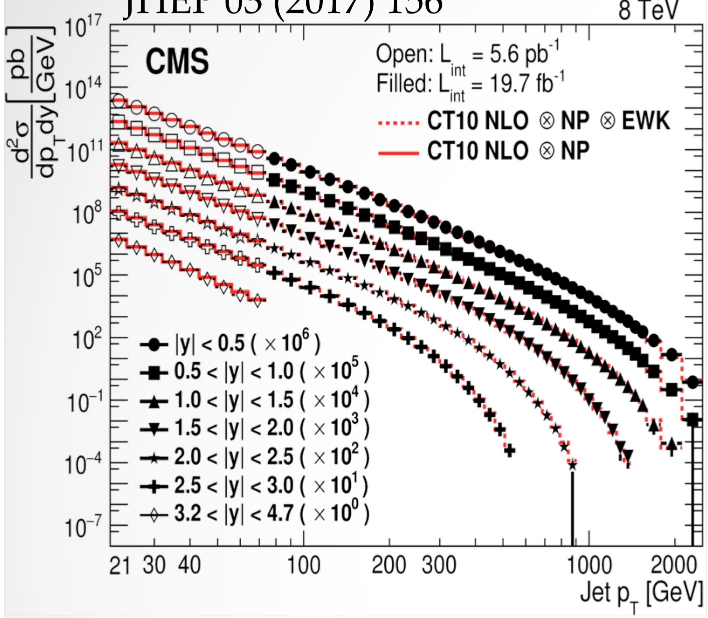
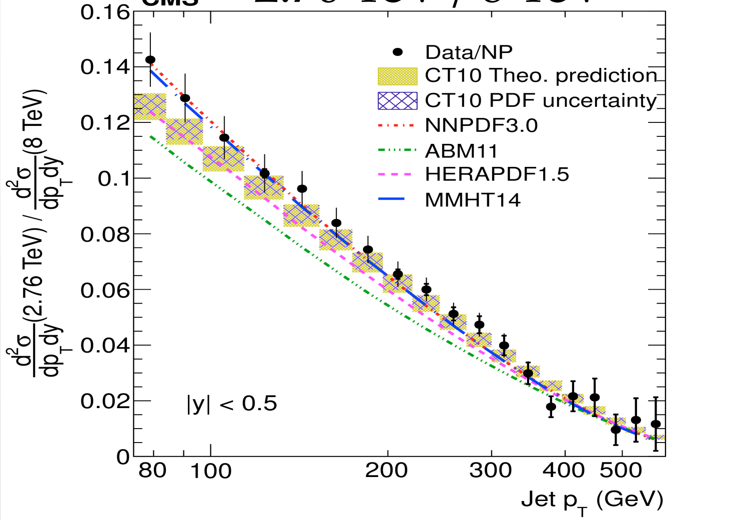
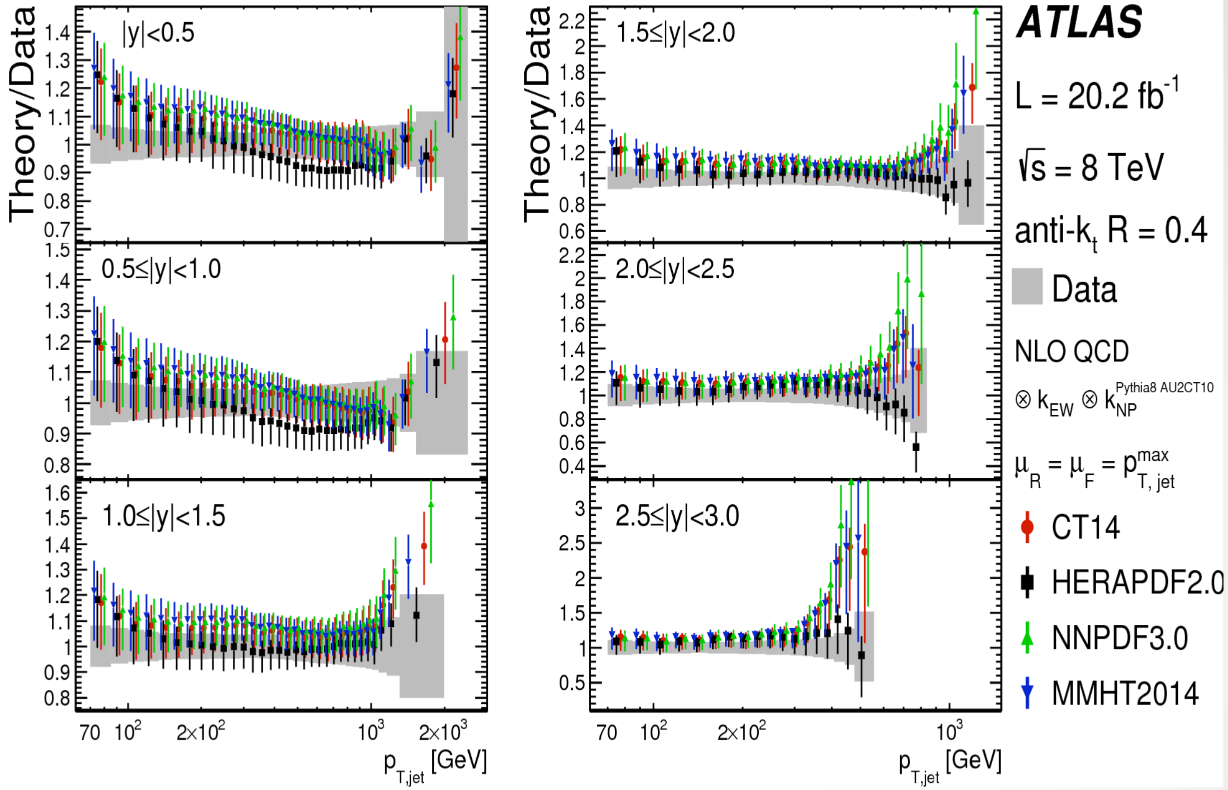


2.76 TeV / 8 TeV



arXiv:1706.03192



- Data covers more than 12 orders of magnitude in cross-section
- Experimental < theory uncertainty → power to constrain PDF's
- Quantitative test: reasonable agreement in individual p_T and y bins but tension when fitting all bins
- ABM11 clearly disfavoured

PDF constraints at 8 TeV

- Gluon density at high x poorly constrained
- gq production dominates jet production for almost the full kinematic range except at high pT where qq takes over

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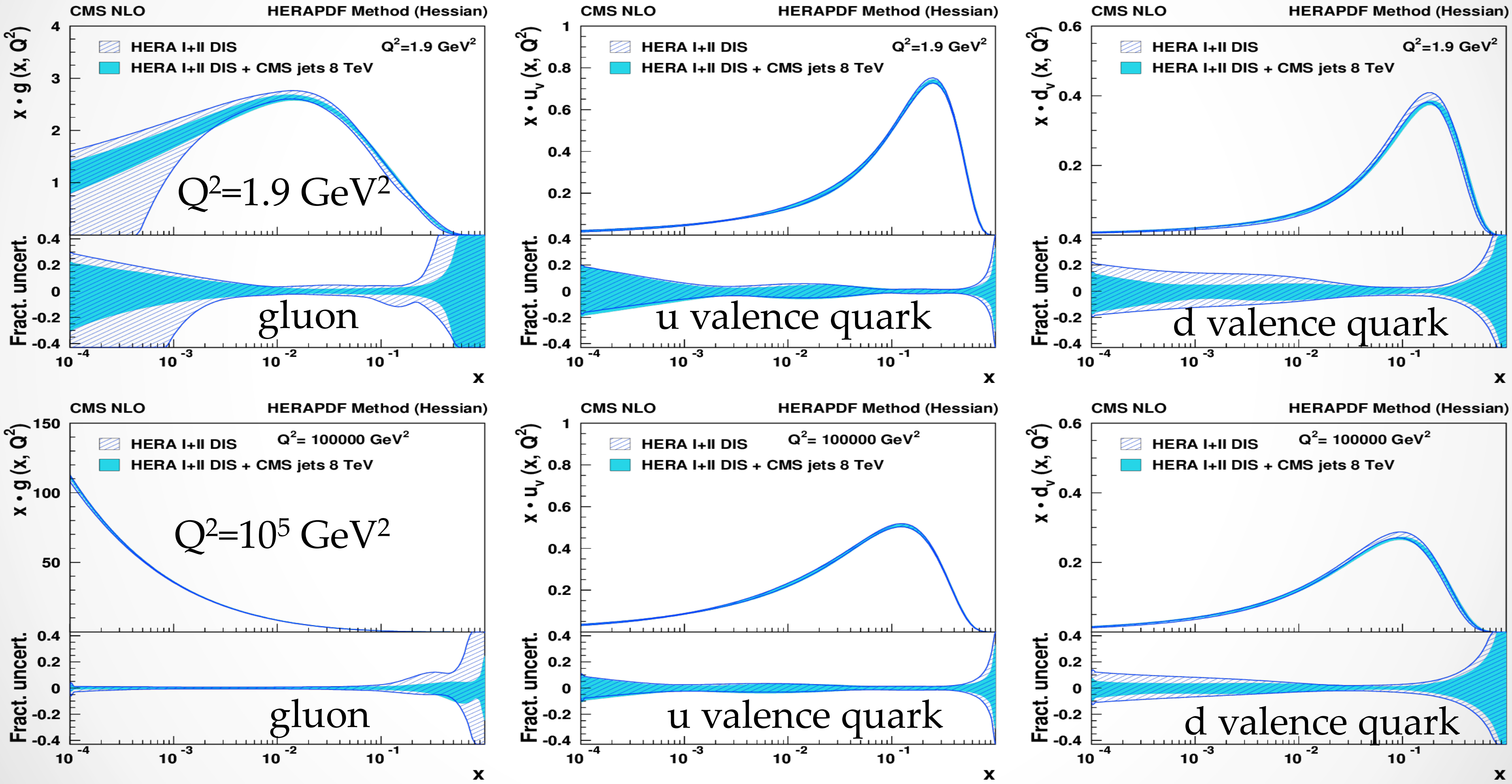


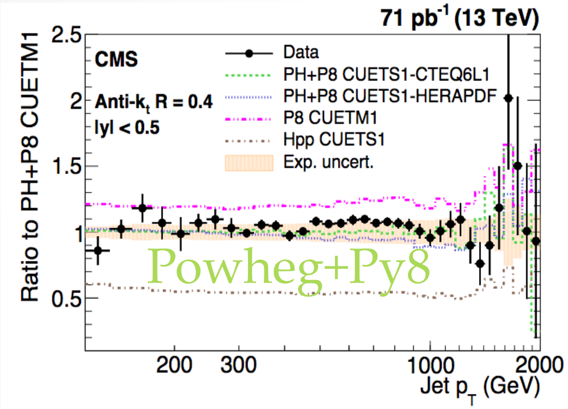
If α_s left free in fit: $\alpha_S(M_Z) = 0.1185^{+0.0019}_{-0.0021}\,(\mathrm{exp})^{+0.0002}_{-0.0015}\,(\mathrm{model})^{+0.0000}_{-0.0004}(\mathrm{param})^{+0.0022}_{-0.0018}\,(\mathrm{scale})$

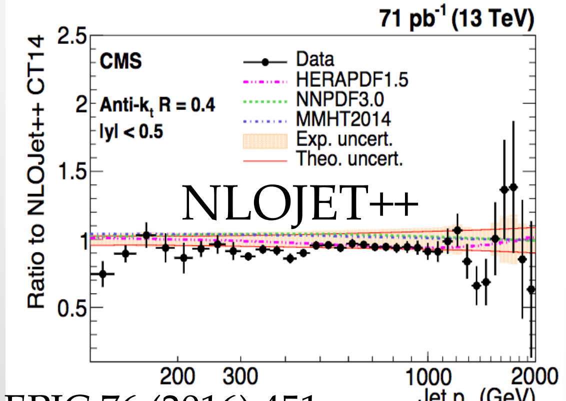
Compatible with world average: α_s=0.1181±0.0011

Inclusive jet cross-section @ 13 TeV

NEW!!

- For R=0.4, Powheg + Py8 better describes data than NLOJET++
- NLOJET++ description improves somewhat for R=0.7
- NNLO scale uncertainty generally improved but prediction rather sensitive to central scale choice





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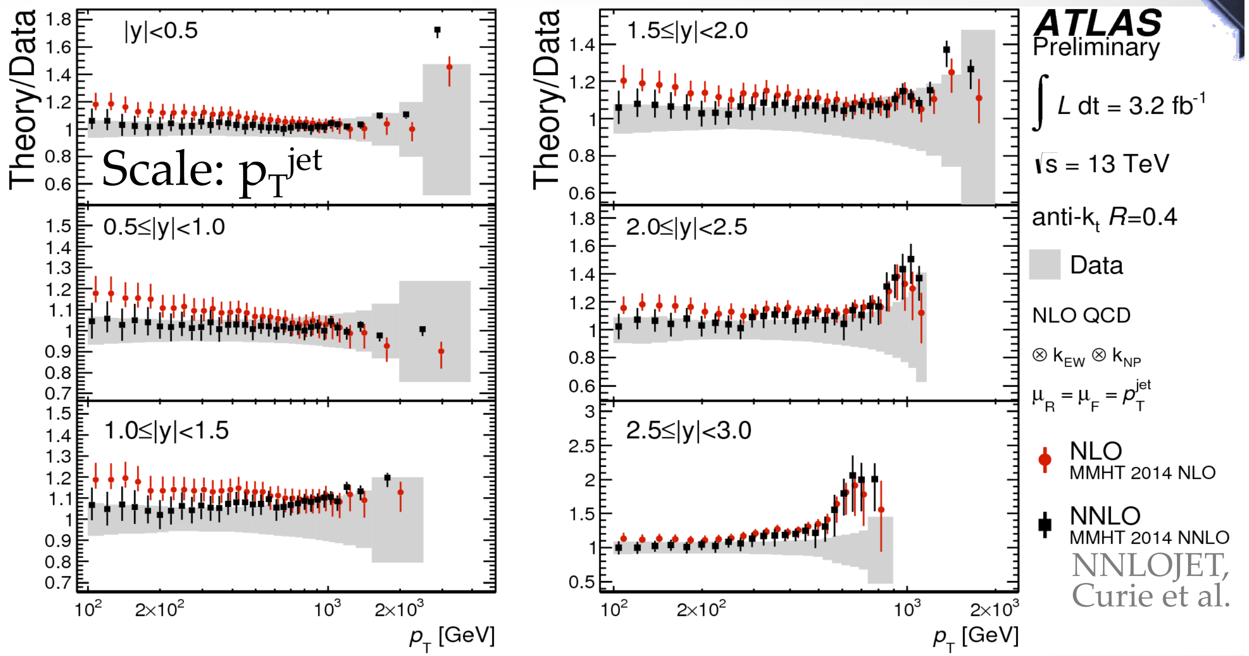
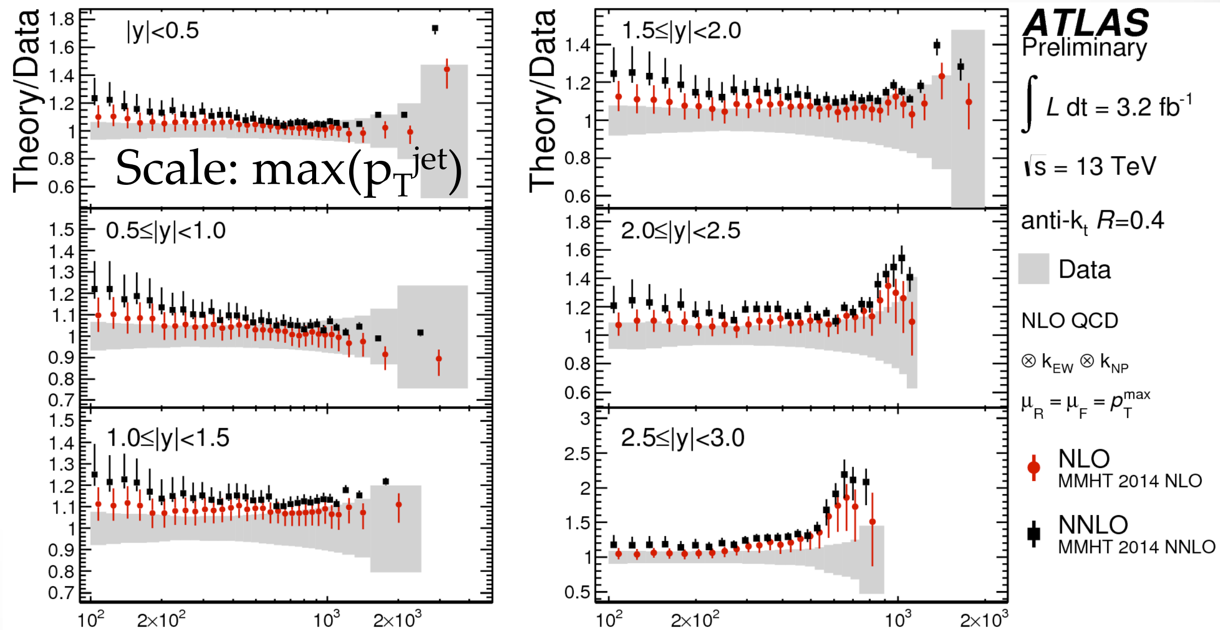


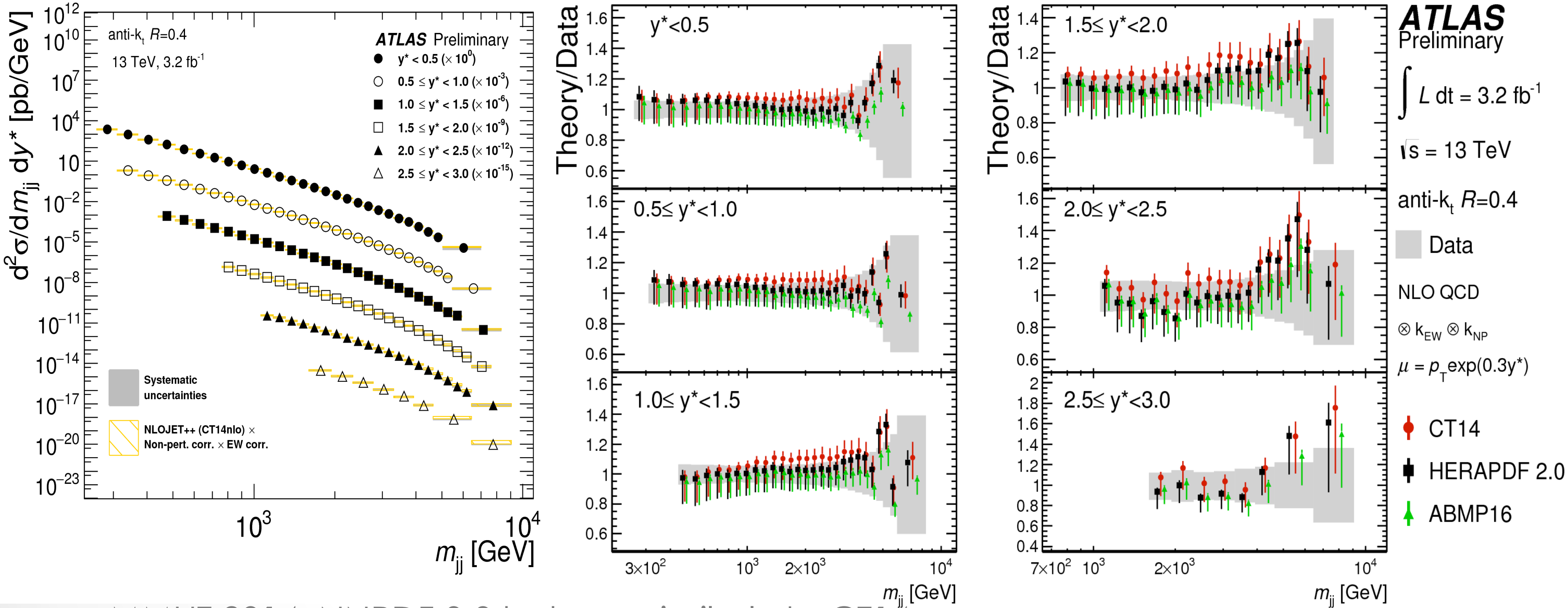


ATLAS-CONF-2017-048

Dijet cross-section @ 13 TeV

NEW!!

ATLAS-CONF-2017-048

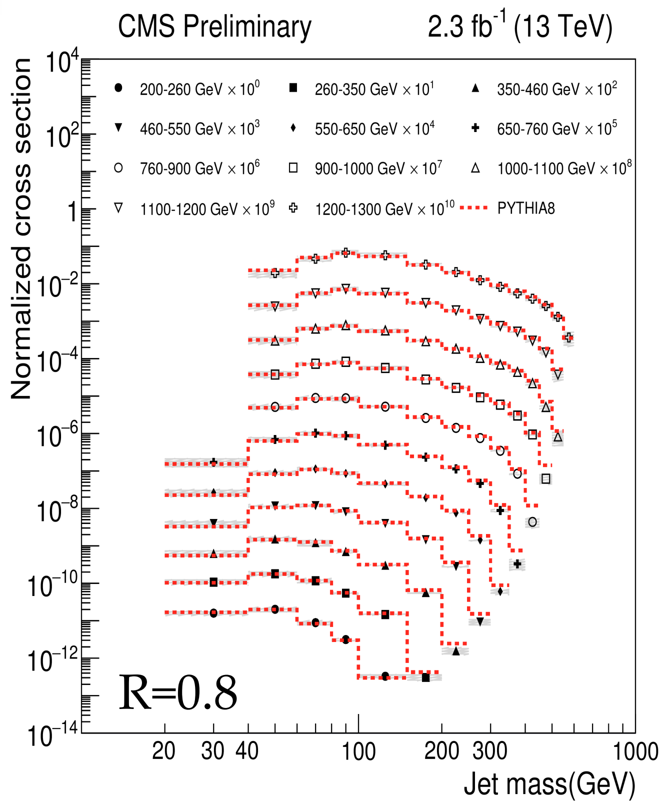


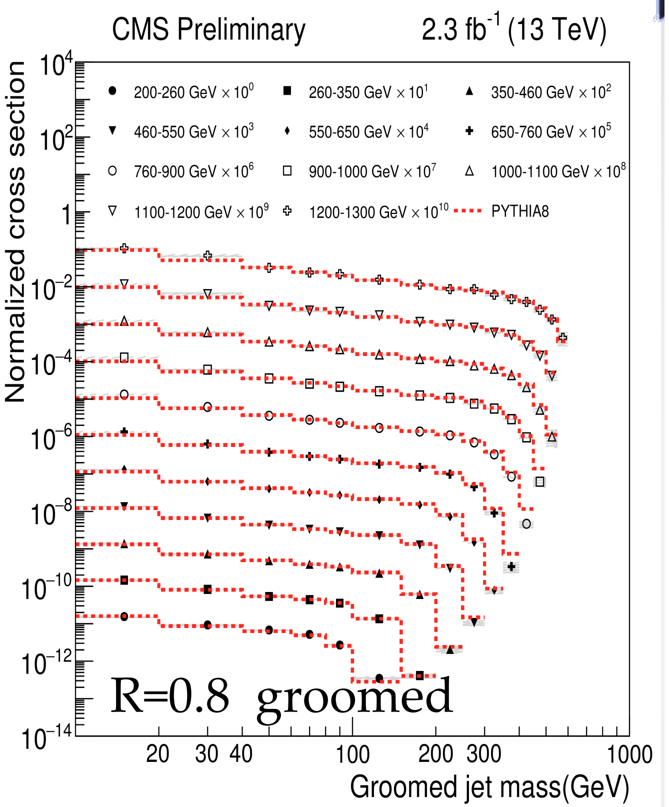
- MMHT 2014, NNPDF 3.0 behave similarly to CT14
- Quantitative test: reasonable agreement with NLO pQCD in individual p_T and y bins as well as fitting all bins

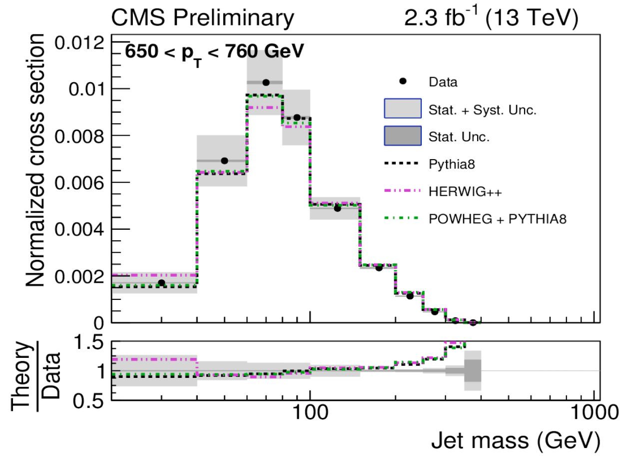
Dijet mass distribution @ 13 TeV

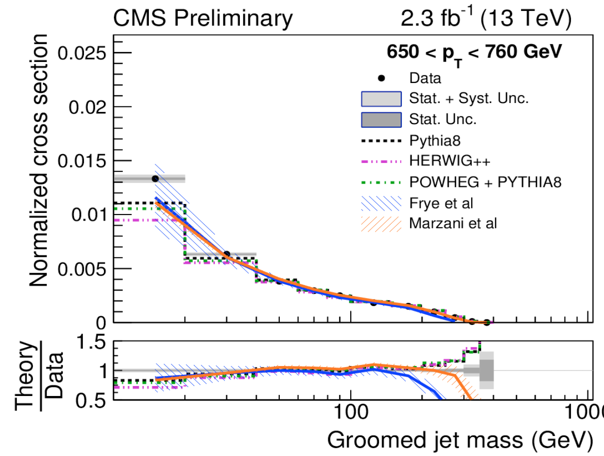
NEW!!

- Sensitive to PS modelling
- Important for "boosted" searches
- Unfolded in jet p_T and mass
- Py8 better agrees with data
- "Soft drop" jet grooming
- Sudakov peak suppressed
- Better agreement at mid-m/p_T as soft radiation portion removed
- Semi-analitical NNLL calculations predict data well except at high m/p_T



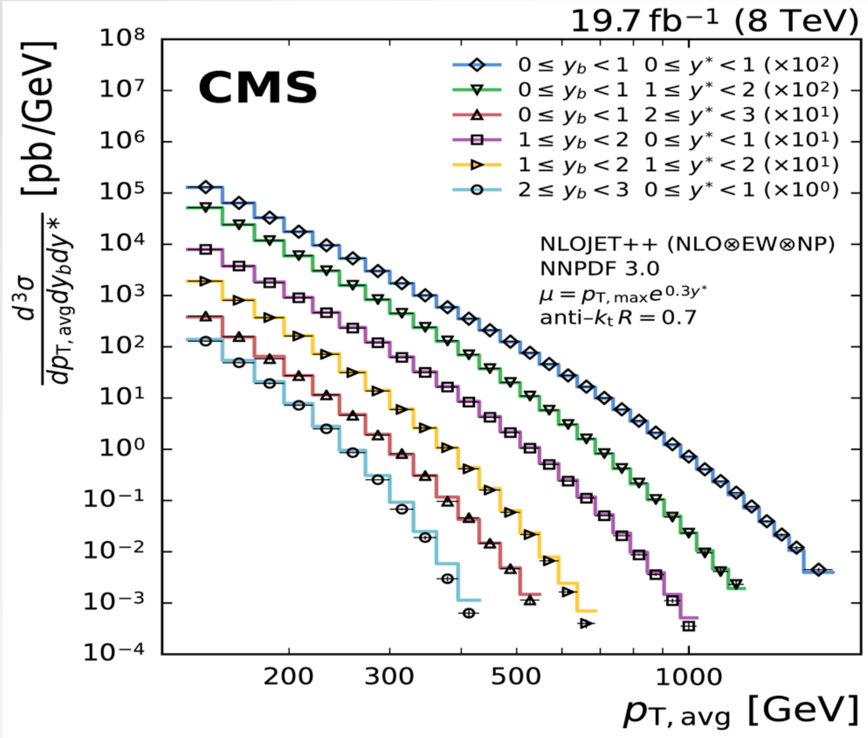


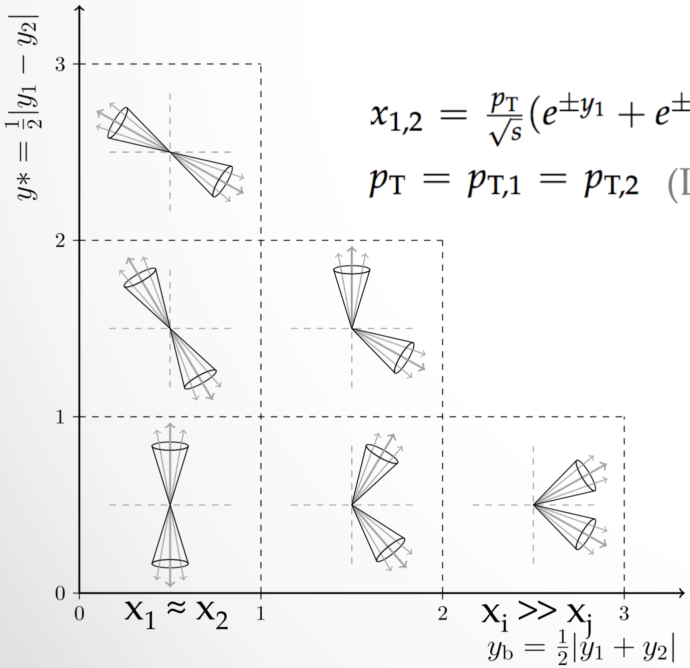




CMS PAS SMP-16-010

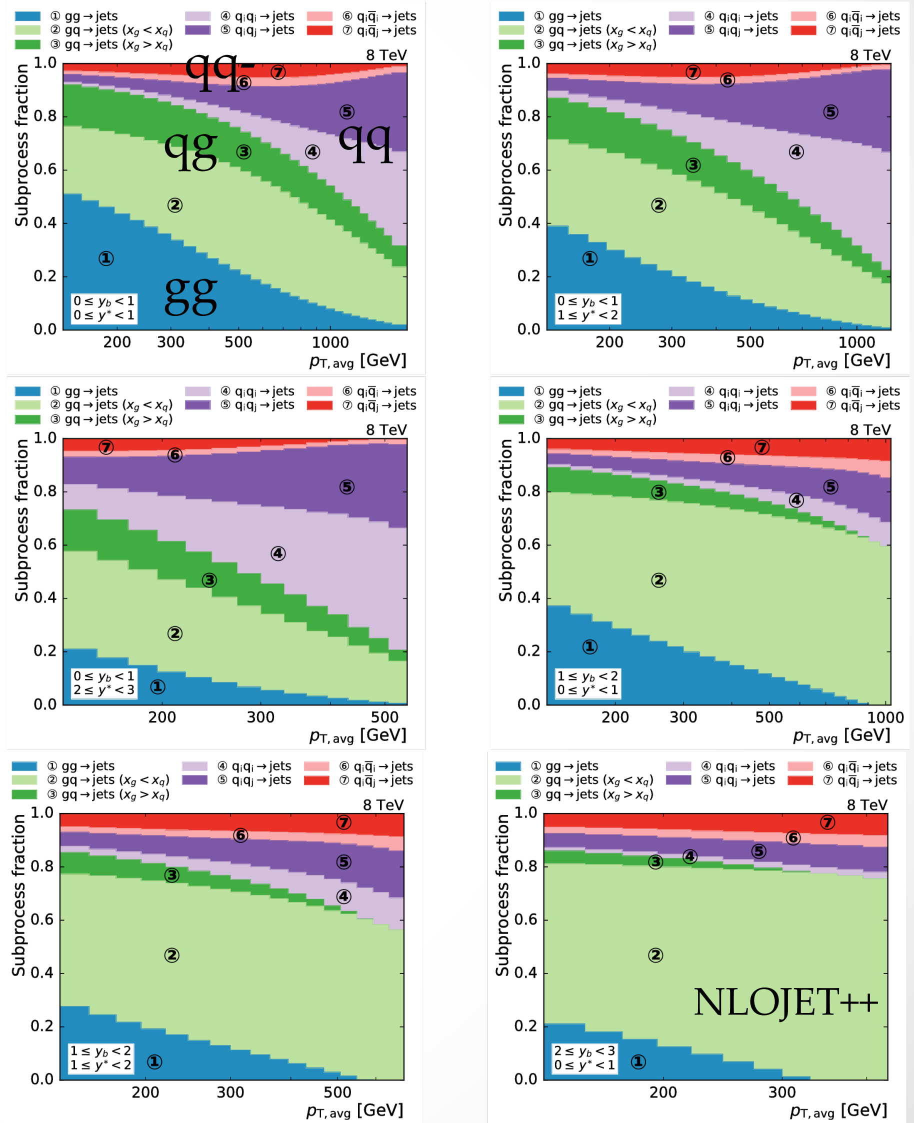
Triple differential dijet cross-section





$$x_{1,2} = \frac{p_T}{\sqrt{s}}(e^{\pm y_1} + e^{\pm y_2})$$

$$p_T = p_{T,1} = p_{T,2} \quad \text{(LO)}$$

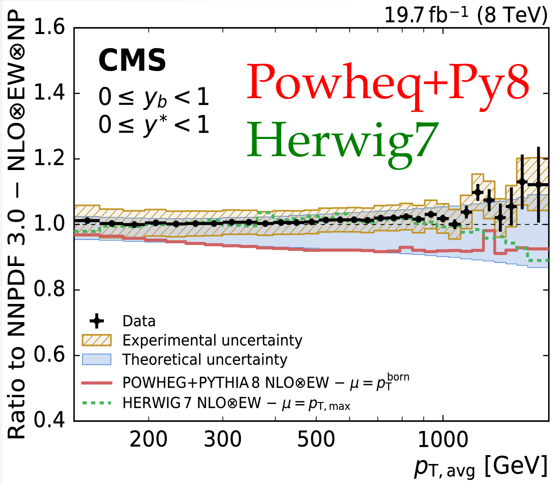


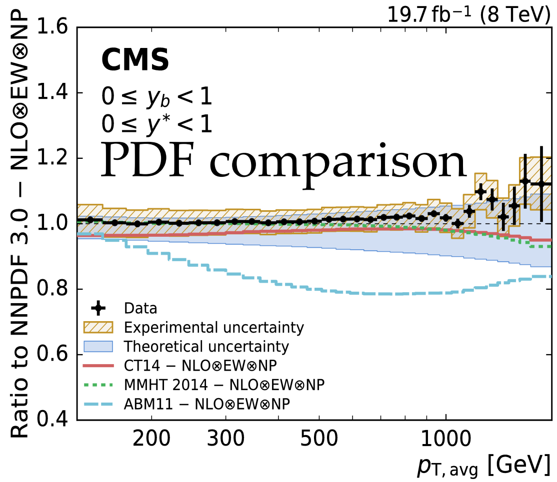
arXiv:1705.02628

$$p_{T,avg} = (p_{T,1} + p_{T,2})/2$$

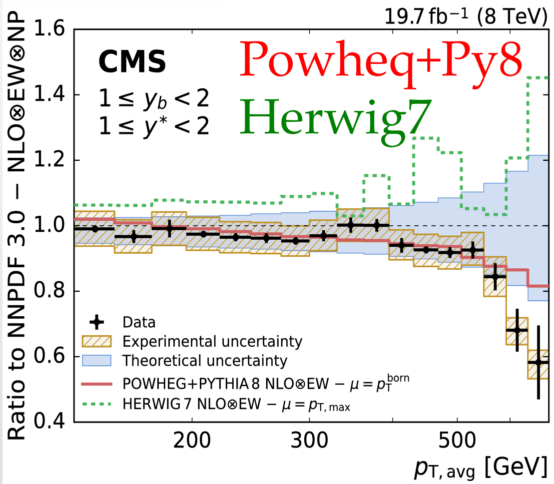
Triple differential dijet cross-section

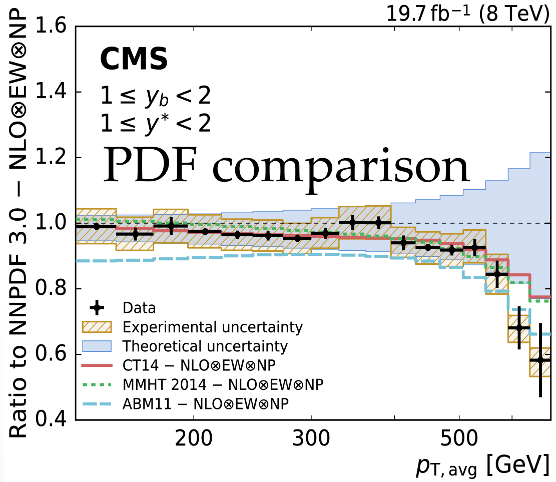
- At high y_b and large p_T (less known high x region) differences observed
- Both Powheg+Py8 (CT10) and Herwig7 (MMHT 2014) show differences
  - Central region better described by Herwig7, boosted region by Powheg+Py8
- Smaller data uncertainty → possible to constrain pdf
- AMB11 underestimates data for $y_b < 2$ due to soft gluon pdf and low α_s

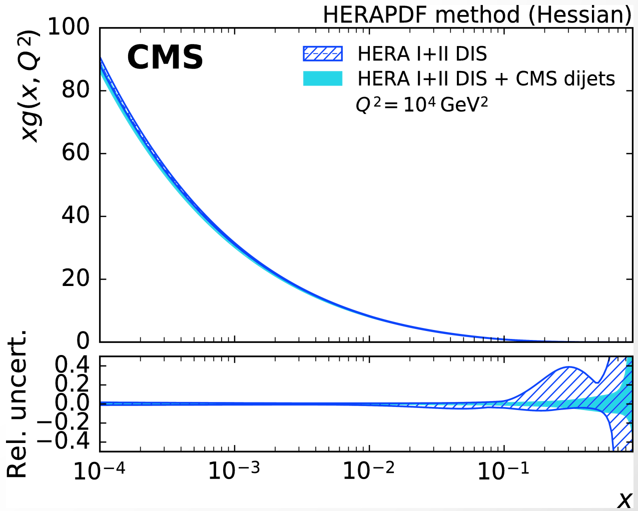




- Improves uncertainty on gluon pdf
- Also causes change in shape, especially at low Q^2
- Similar constraint as from inclusive jet data





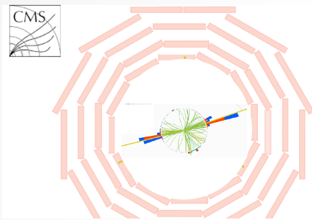


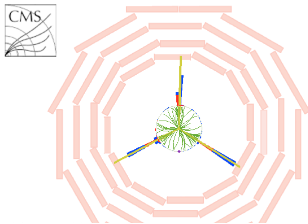
arXiv:1705.02628

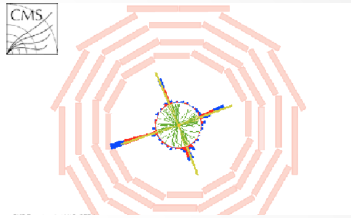
Azimuthal correlations in 2/3/4-jet topologies

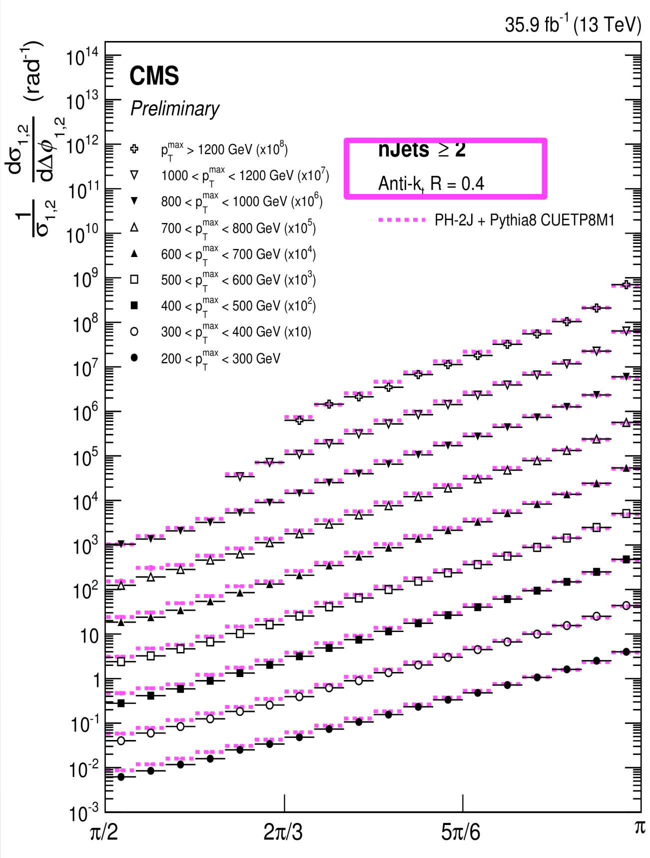
Normalised to total dijet cross-section within each region of leading jet p_T (p_T^{max})

Large data – MC differences









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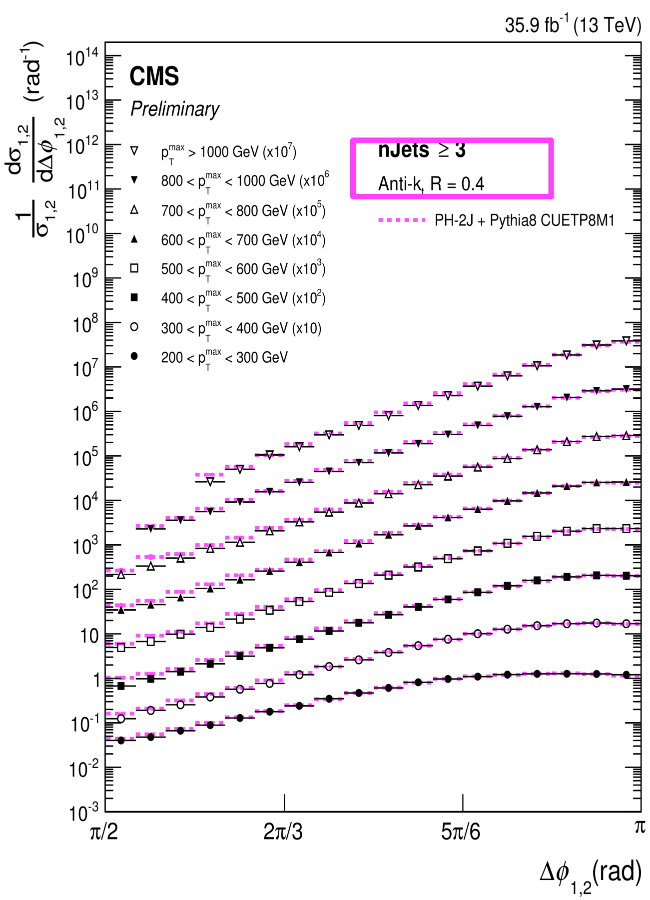
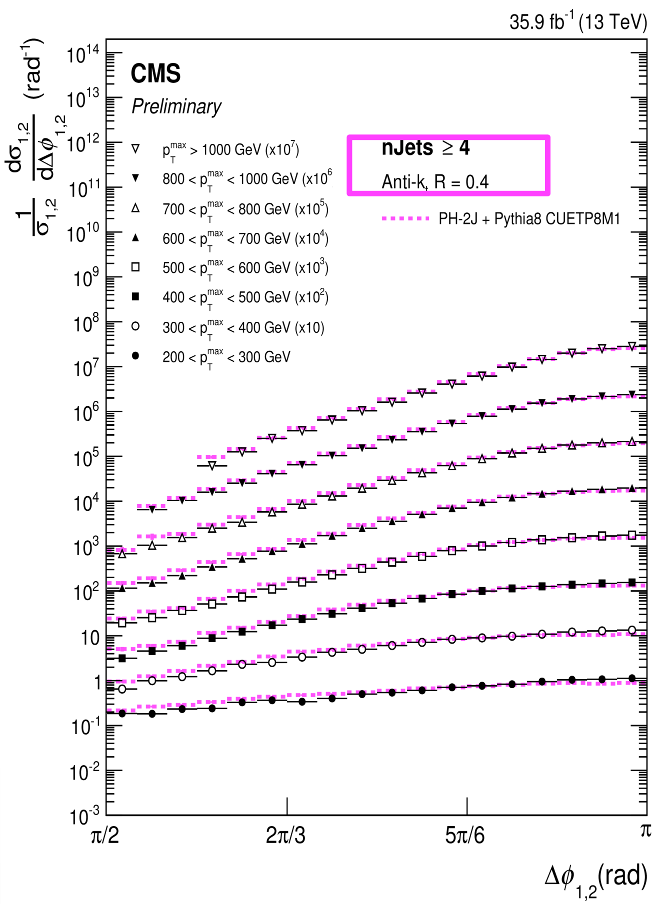
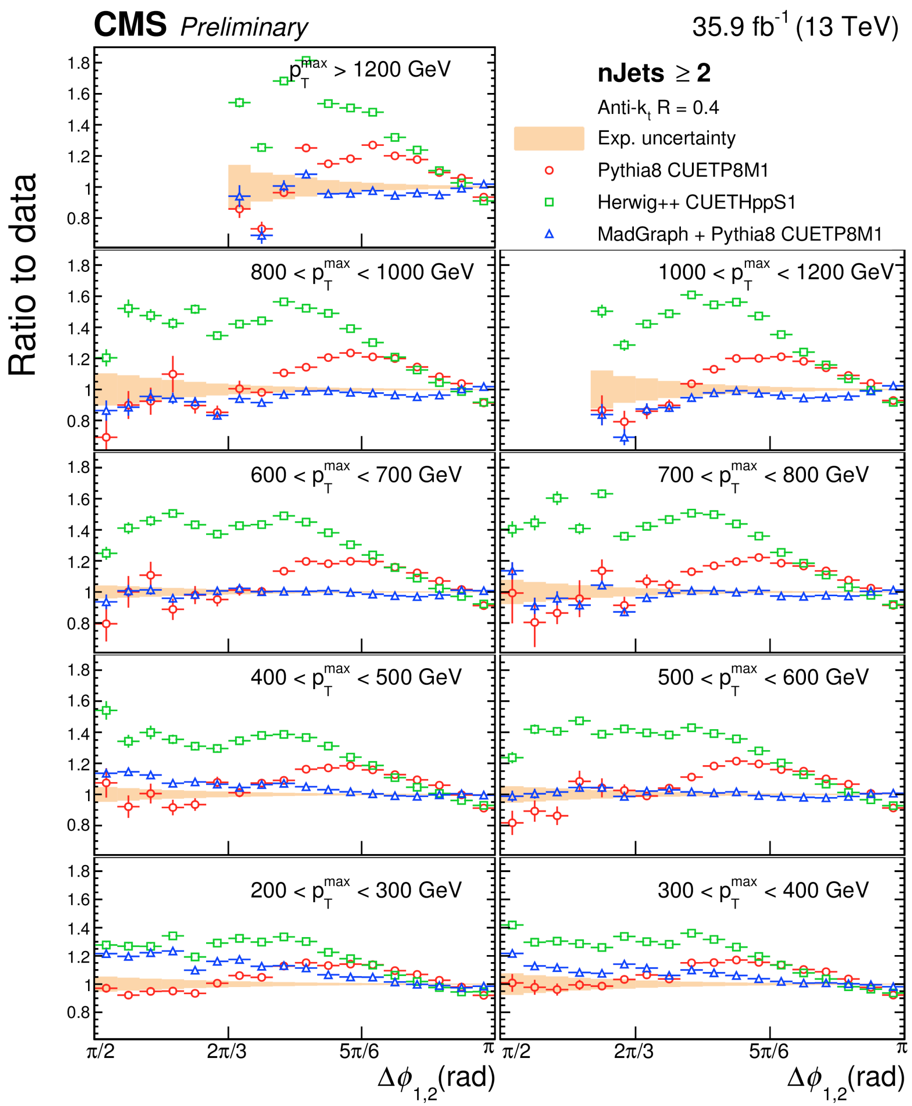


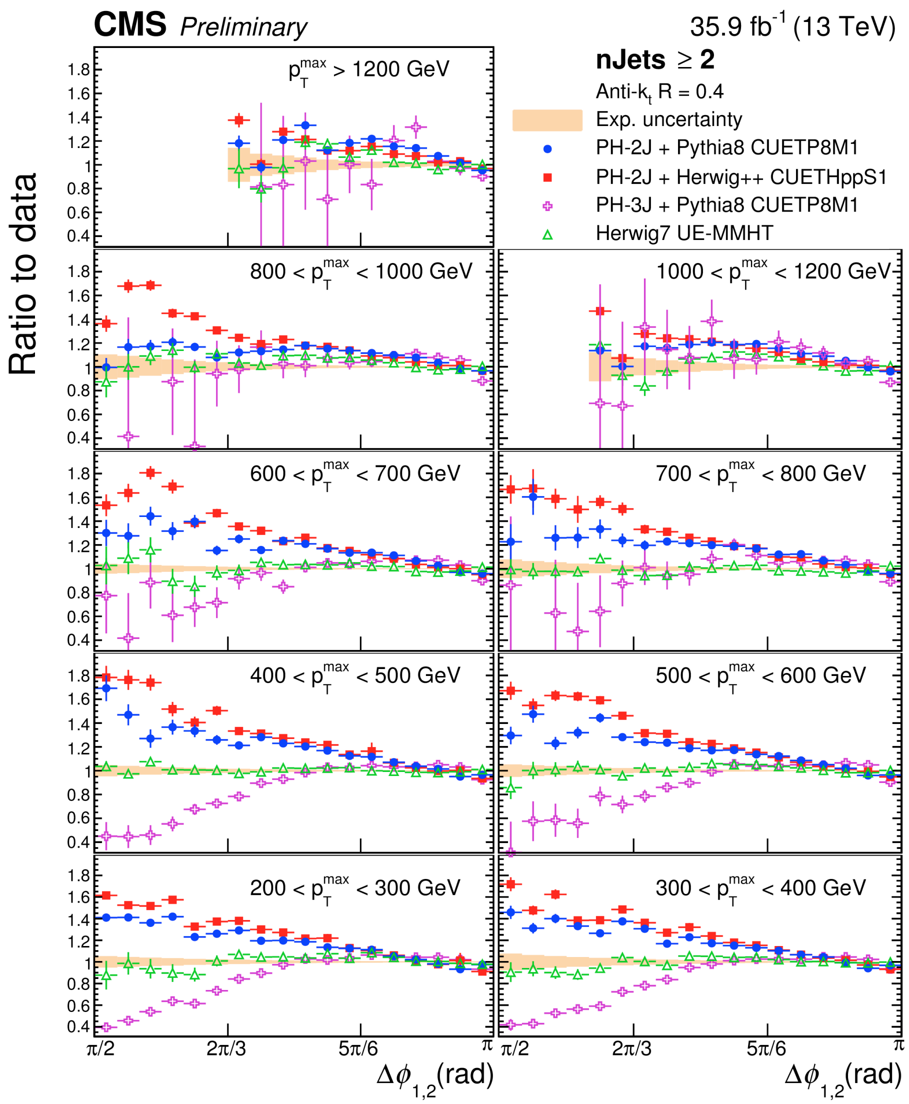


Azimuthal correlations in 2-jet topologies

Two leading jets' azimuthal difference

CMS-PAS-SMP-16-014

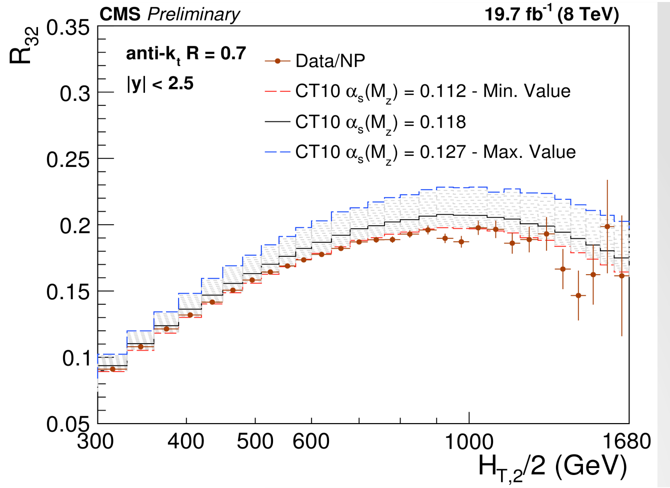


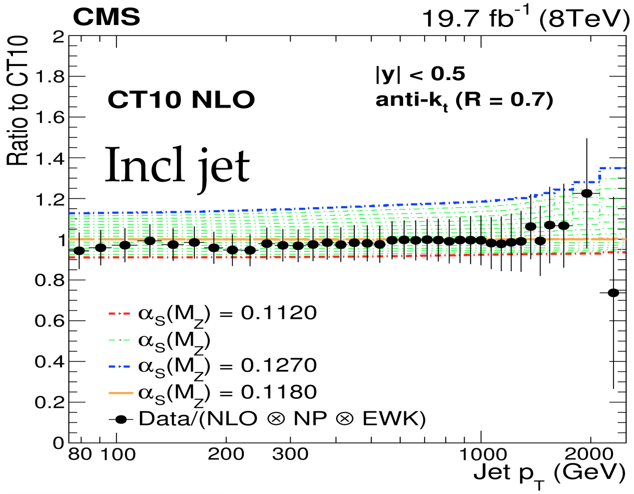


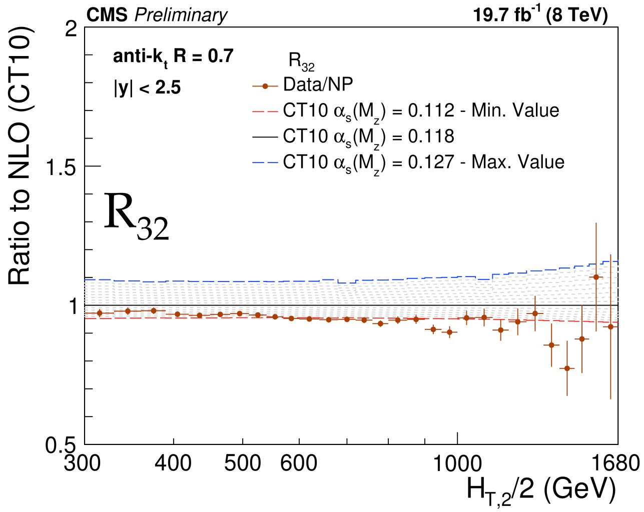
Best description by Madgraph (except 4-jet $\Delta\phi_{2j}^{min}$) and Herwig7

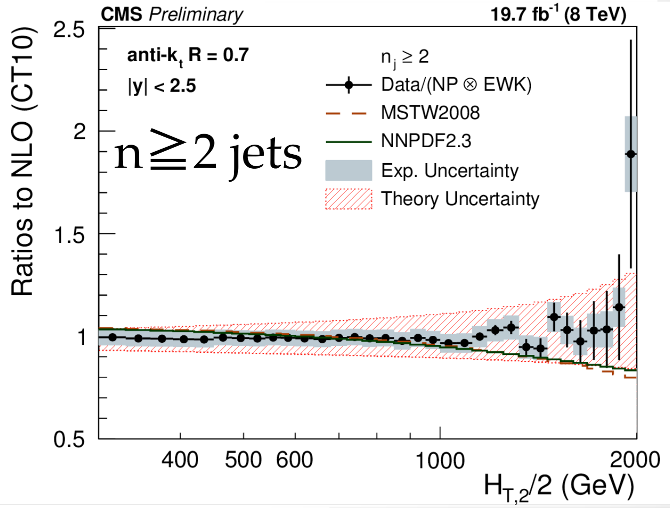
α_s determination from jet rates

- Inclusive jet cross-section: $d^2\sigma/dp_T d\eta \propto \alpha_s^2$
- Various experimental and theoretical errors cancel in inclusive cross-section ratios for n jets: $R_{mn} = \sigma_m / \sigma_n \propto \alpha_s^{m-n}$









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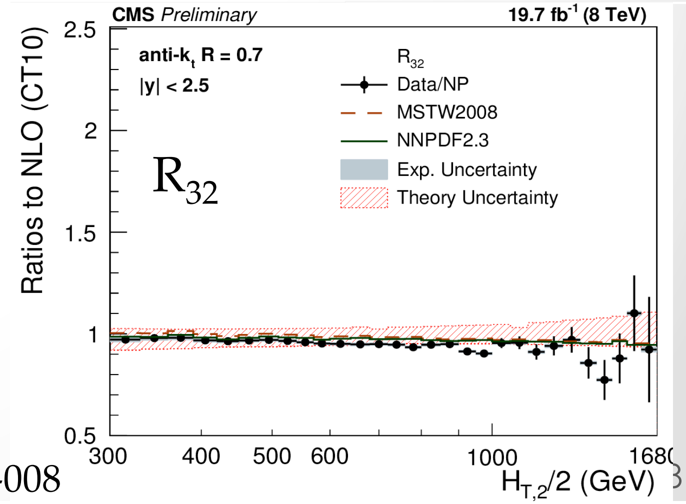
R_{32}:

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

Inclusive jet cross-section:

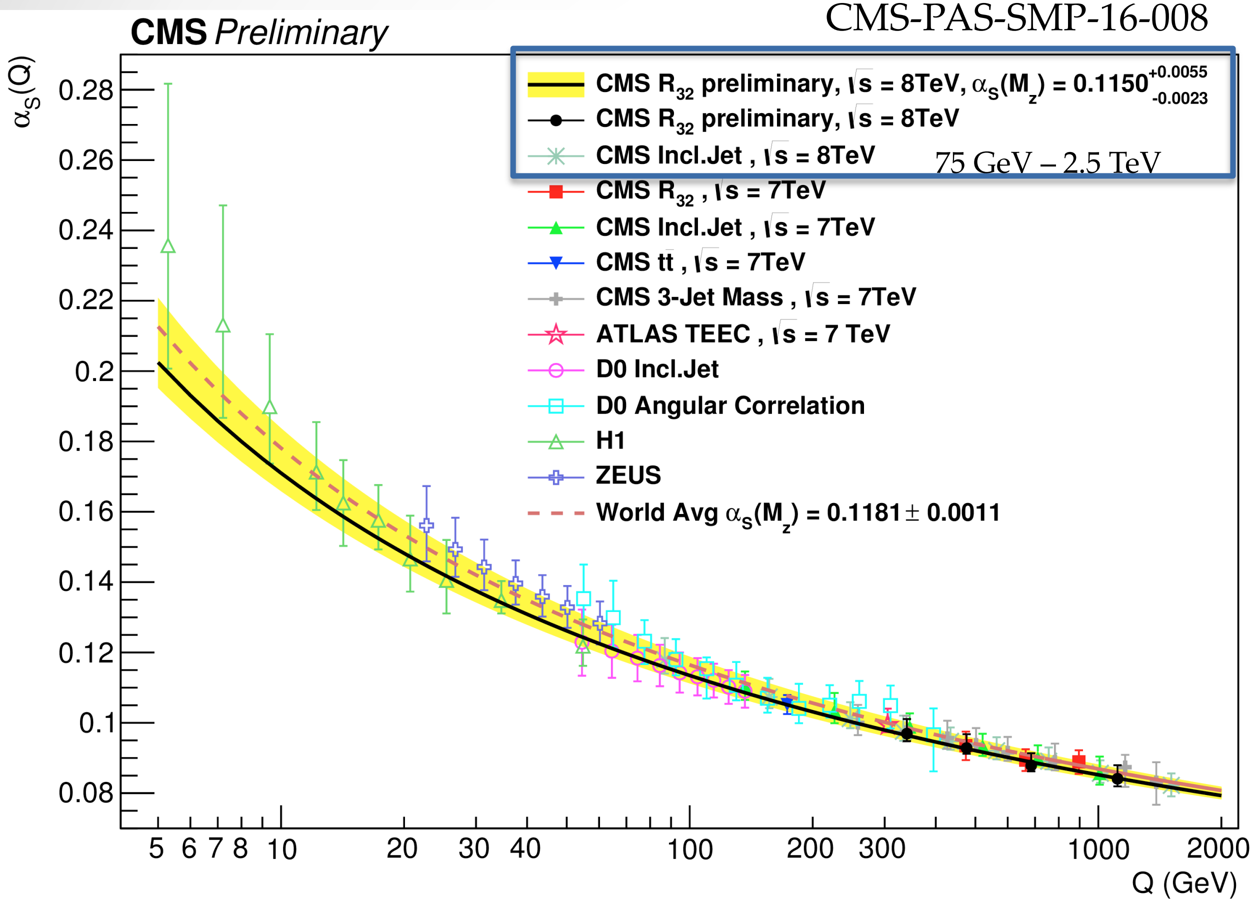
$$\alpha_s = 0.1162 \,{}^{+0.0014}_{-0.0015}\,(\text{exp}) \,{}^{+0.0025}_{-0.0029}\,(\text{PDF}) \pm 0.0001\,(\text{NP}) \,{}^{+0.0053}_{-0.0028}\,(\text{scale})$$

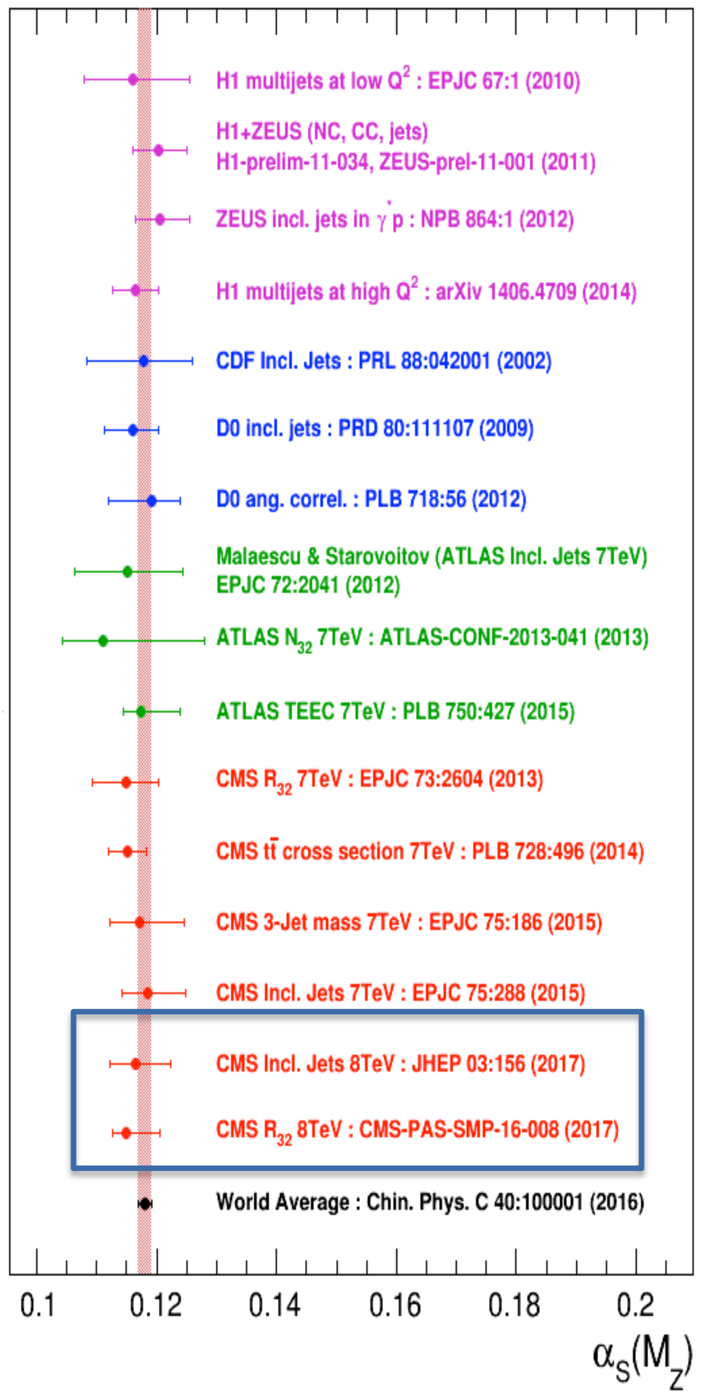


CMS-PAS-SMP-16-008

α_s determination

CMS-PAS-SMP-16-008





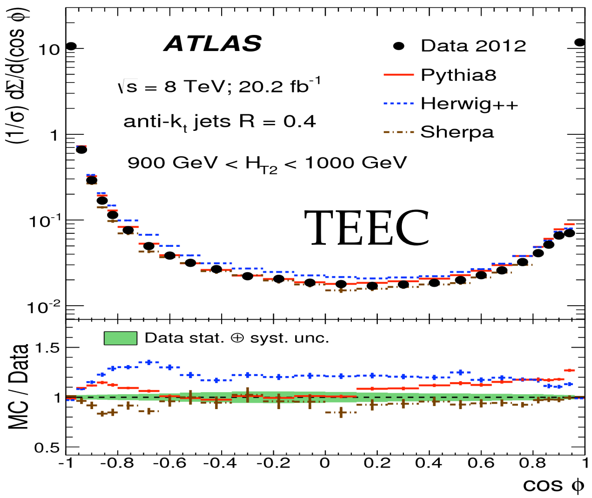
- Determined at NLO
- 4-5% total uncertainty
- Dominated by missing higher-order terms (scale)

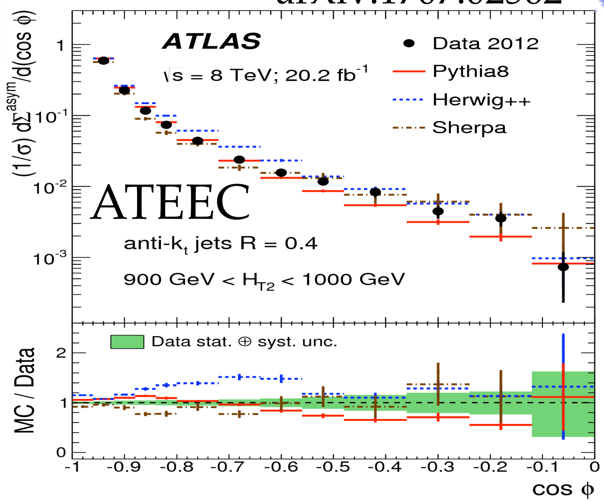
α_s determination from (A)TEEC

NEW!!

arXiv:1707.02562

- TEEC, transverse energy-energy correlation (energy-weighted angular distribution of jet pairs) gets moderate NLO corrections (NLOJET++), robust wrt experimental uncertainties
  → precision test of pQCD
- ATEEC: asymmetry between forward and backward parts of TEEC
- TEEC, ATTEC ∝ α_s^2 at NLO



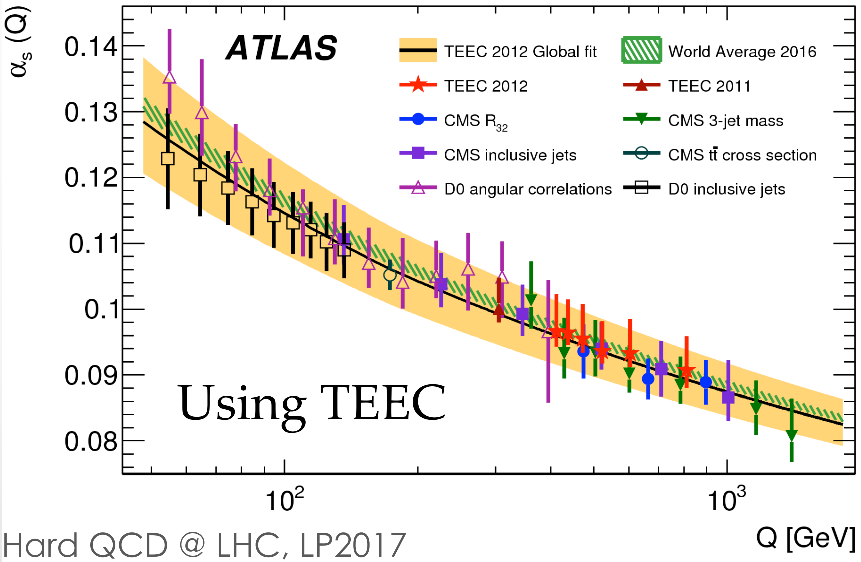


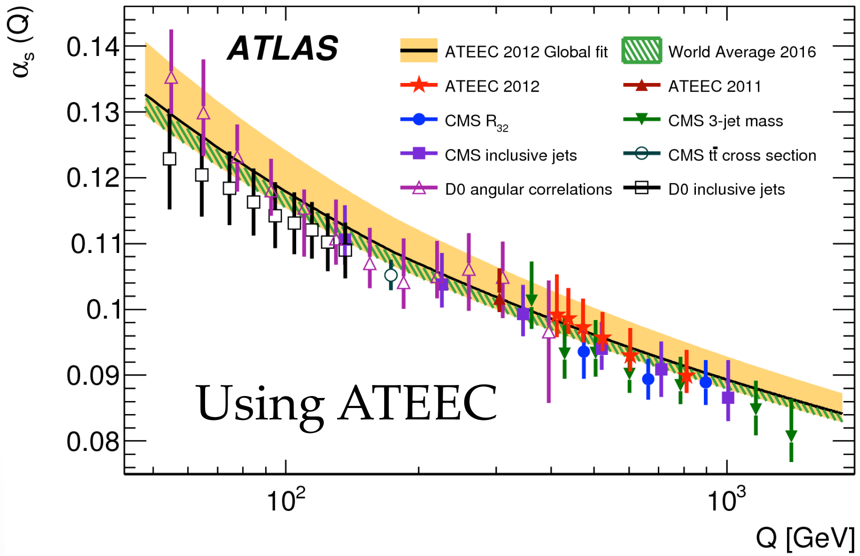
TEEC:

$$\alpha_s(m_Z) = 0.1162 \pm 0.0011\ (\text{exp.})\ {}^{+0.0076}_{-0.0061}\ (\text{scale}) \pm 0.0018\ (\text{PDF}) \pm 0.0003\ (\text{NP})$$

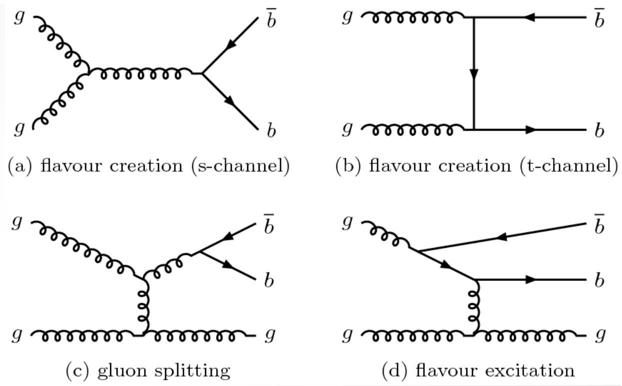
ATEEC:

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

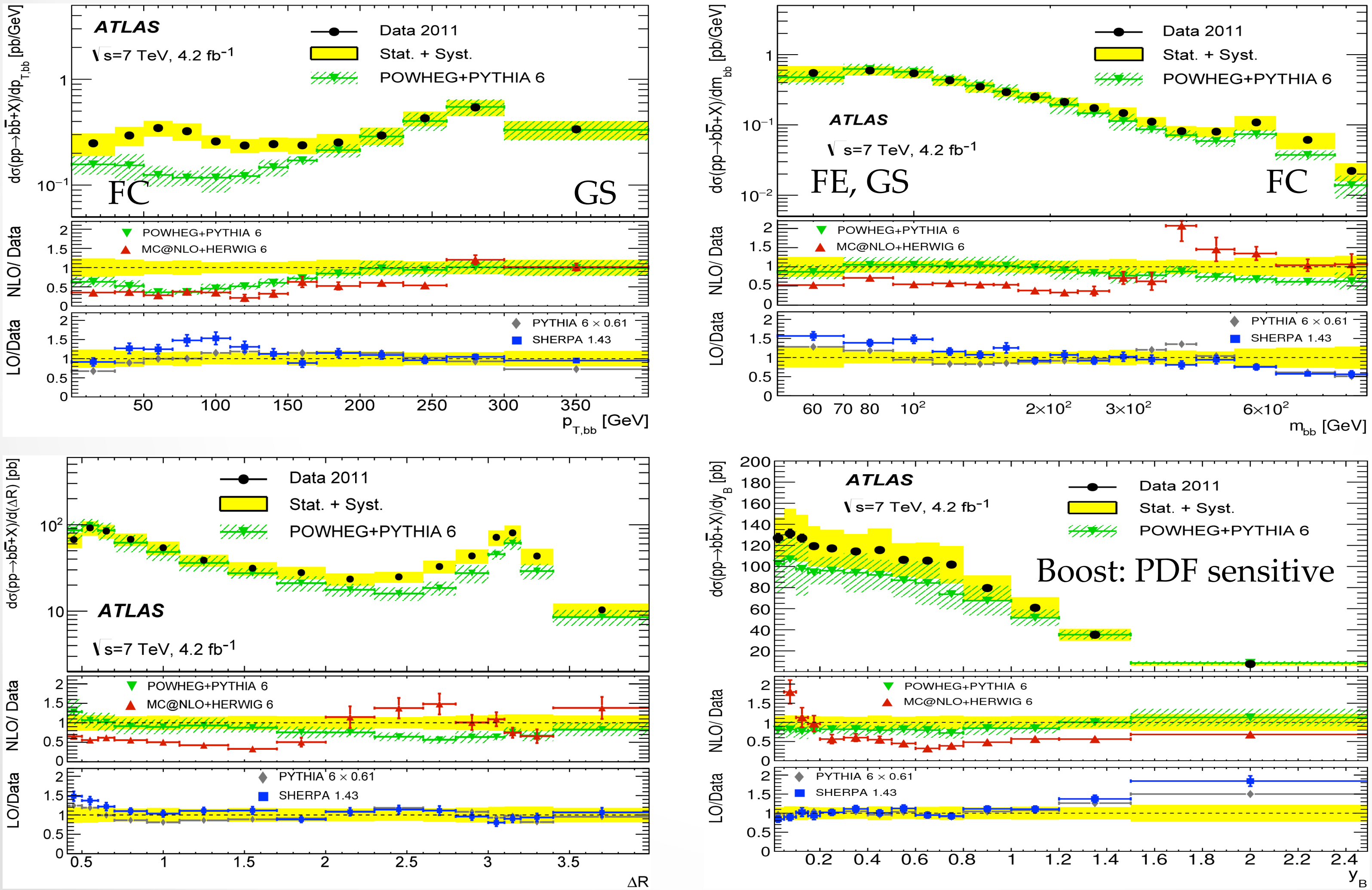




bb-dijet cross-section at 7 TeV



- Require a jet with pT>270 GeV → 3-jet topology enhanced
- $\Delta R(bb)>0.4$, $p_{T,b}>20$ GeV, $|\eta_b|<2.5$
- All MC generators have difficulty reproducing data



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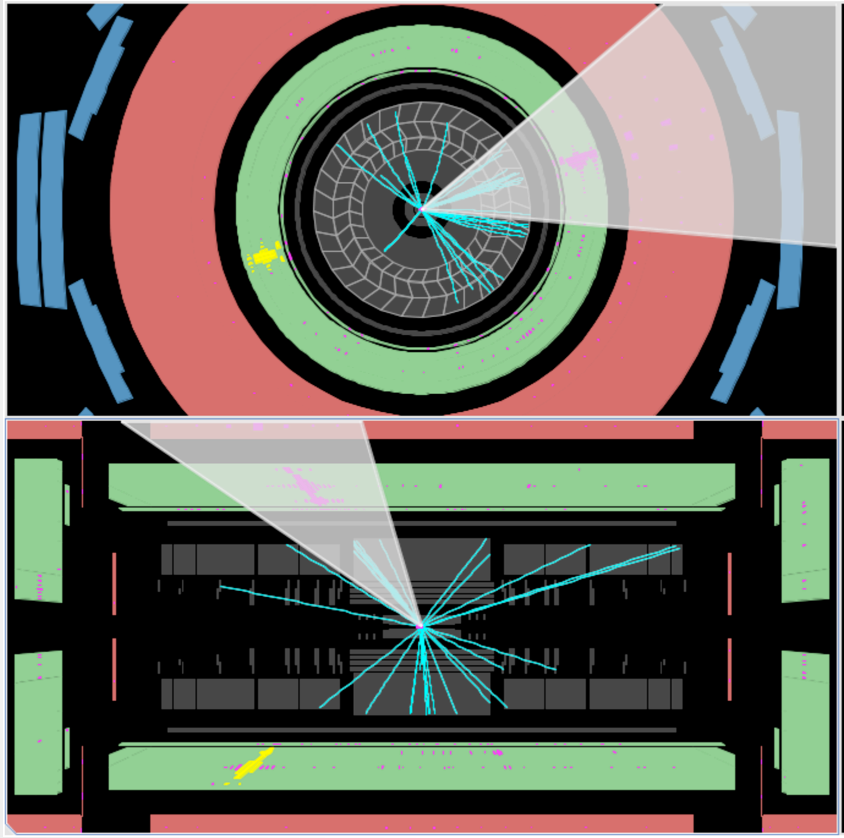
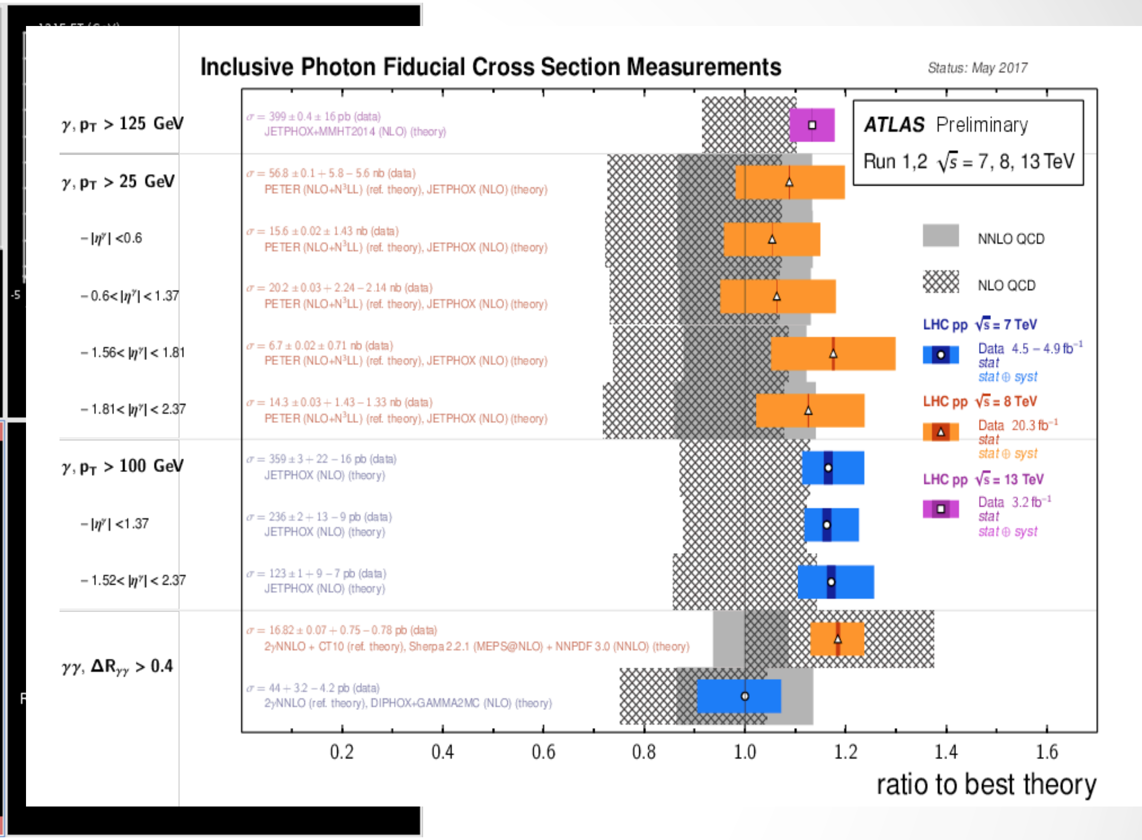
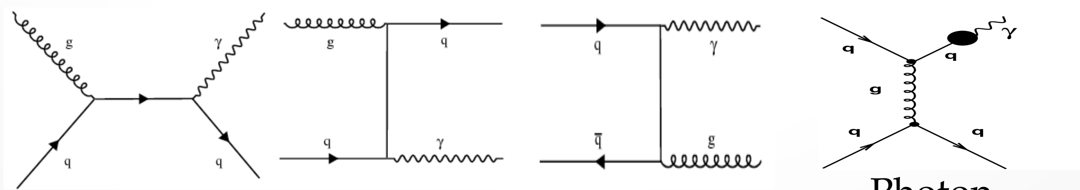
Inclusive photon cross-section





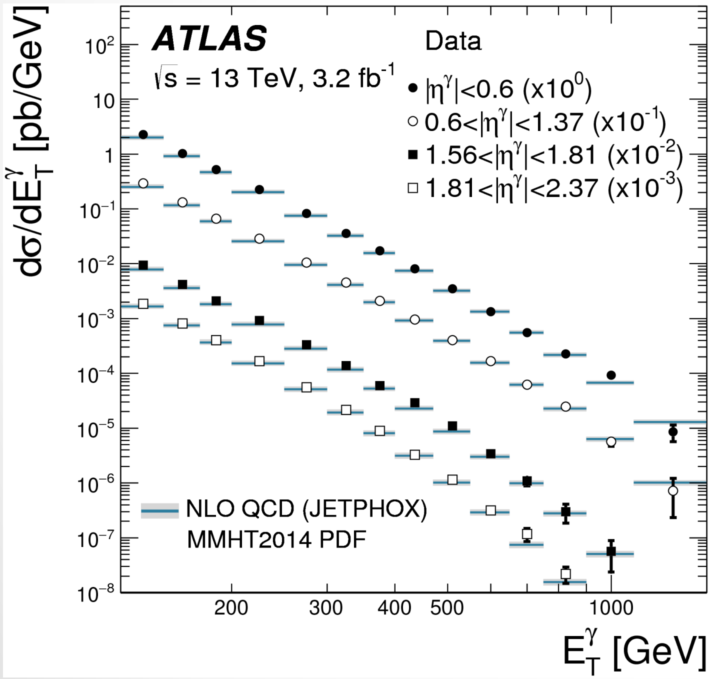
- Tests pQCD with hard colorless probe
- Sensitive to gluon PDF at LO

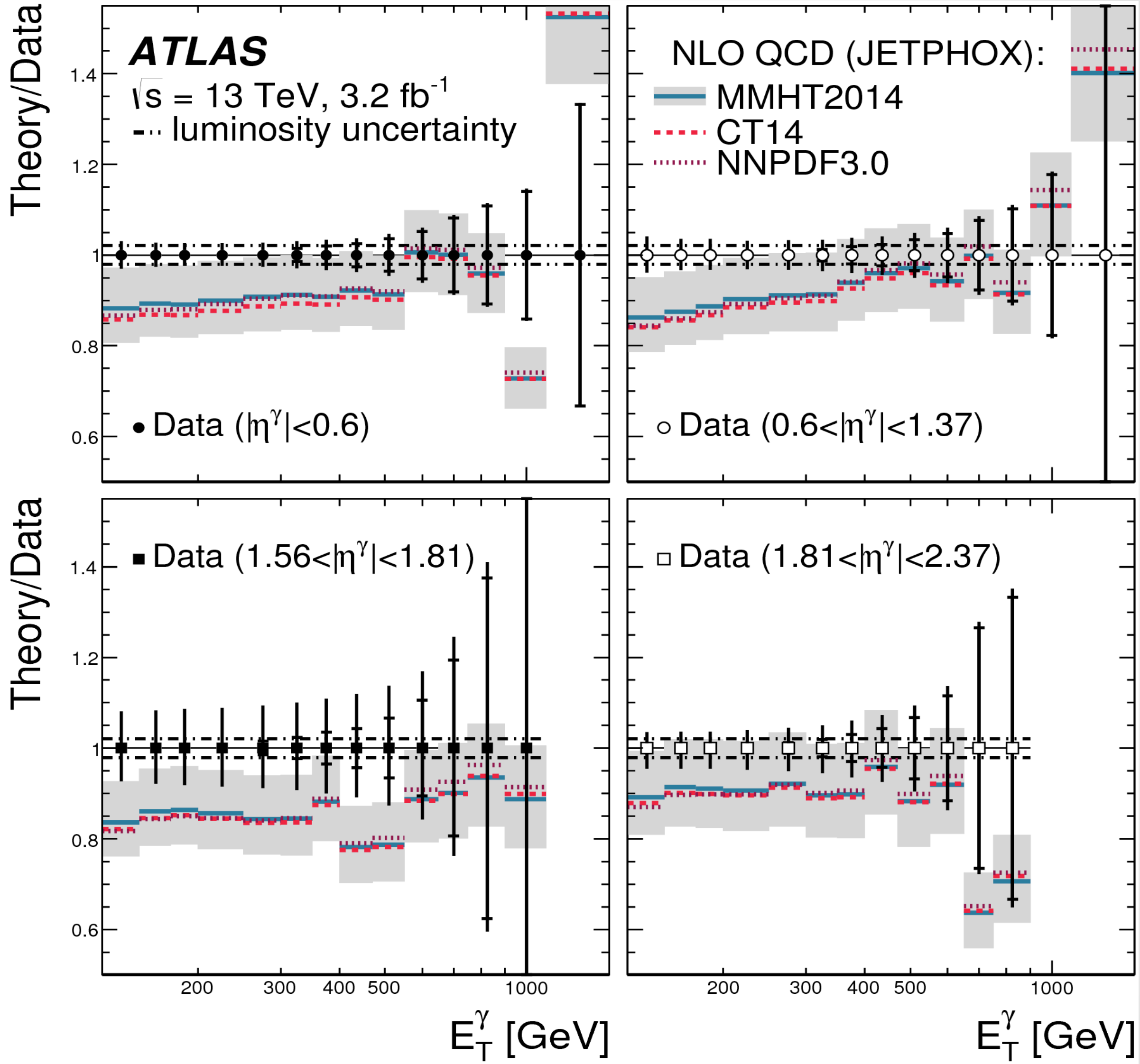


Photon fragmentation

Inclusive photon cross-section @ 13 TeV

- NLO prediction provide reasonable description
- Experimental uncertainty smaller than theoretical
- Need NNLO pQCD





$$\sigma = 399 \pm 13(\text{exp.}) \pm 8(\text{lumi})\ \text{pb} \qquad \sigma_{\text{JETPHOX}} = 352^{+36}_{-29}(\text{scale}) \pm 3(\text{pdf}) \pm 6(\alpha_s) \pm 4(\text{non-pert})\ \text{pb}$$

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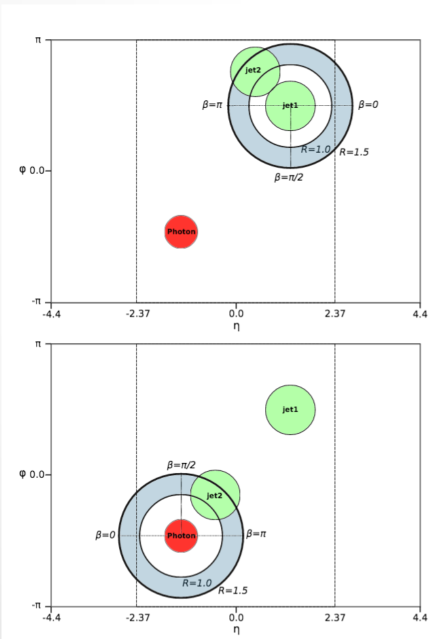
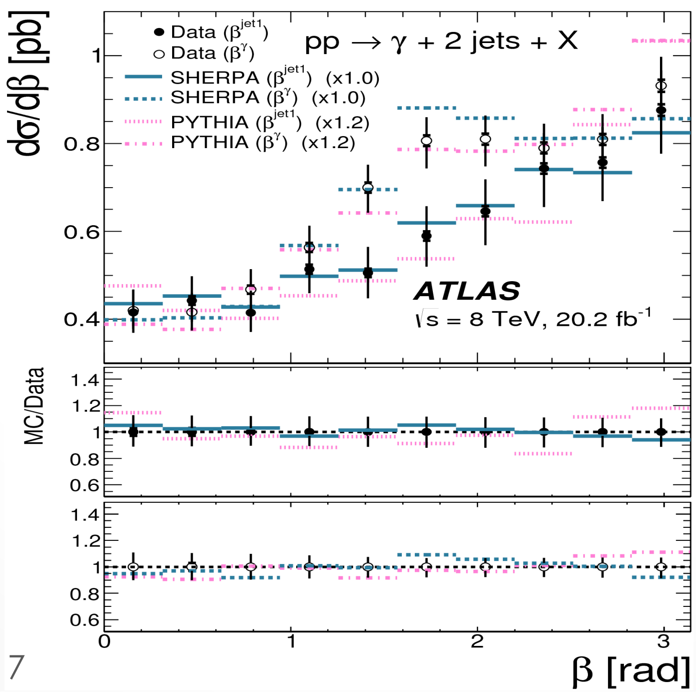
Photon + jet

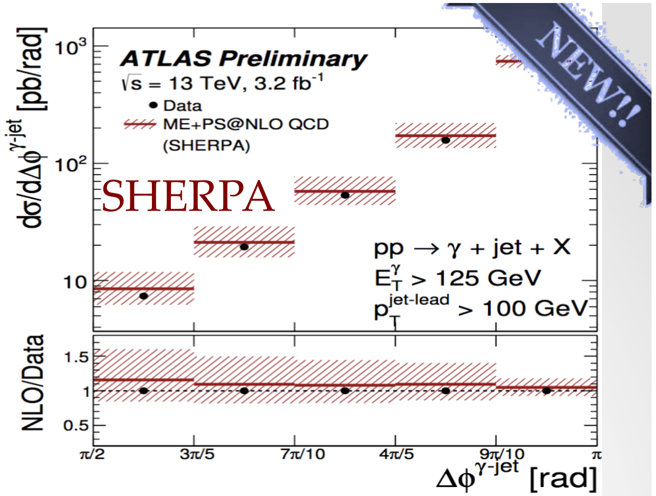
- NLO JETFOX can not describe $\Delta\phi(\gamma,\text{jet})$ due to limitations in the number of final state partons
- SHERPA ME 2→4/5 @NLO agrees well with data
- Jet pT better described by SHERPA@LO than @NLO
- Theory uncertainties larger than experimental due to missing corrections beyond NLO
- At 8 TeV, observed different QCD radiation pattern around leading jet and photon for 1st time

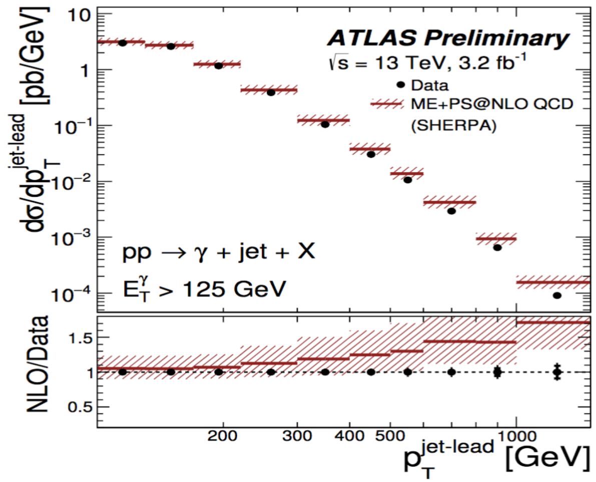


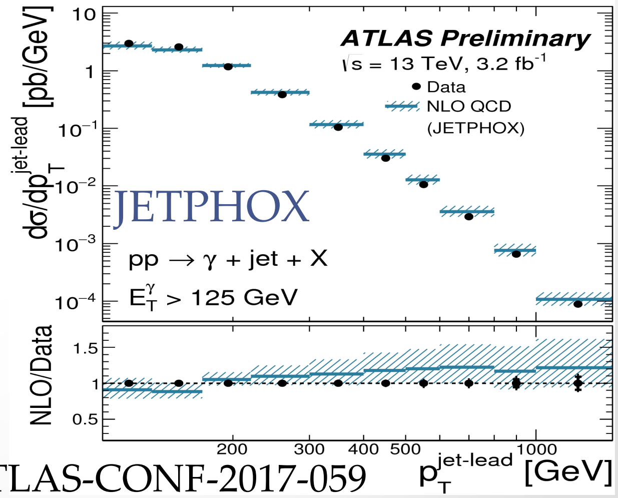
arXiv:1611.06586

$$\beta^{\gamma} = \tan^{-1}\frac{|\phi^{\text{jet2}} - \phi^{\gamma}|}{\text{sign}(\eta^{\gamma})\cdot(\eta^{\text{jet2}} - \eta^{\gamma})}$$





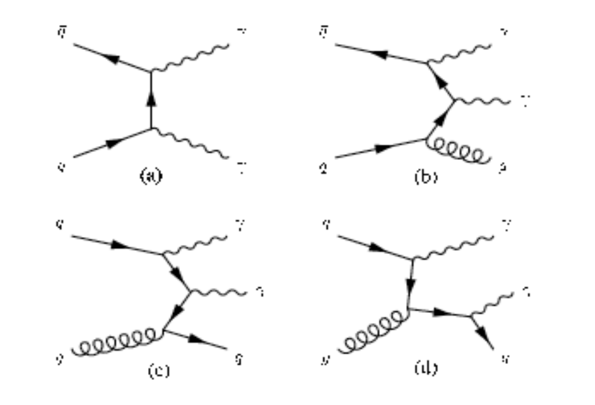


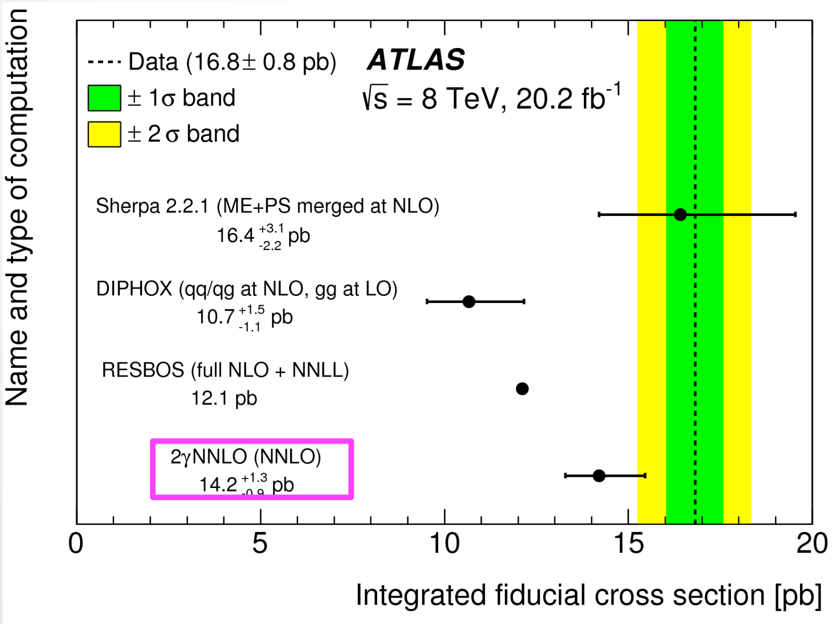


ATLAS-CONF-2017-059

Diphoton cross-section

- Sensitive to α_s corrections, QCD infrared emission
- Fixed order calculations lower than data, improved at NNLO
- Fixed order predictions can not reproduce data
- Especially in regions sensitive to infrared emissions (low $p_{T,\gamma\gamma}$, ϕ^*_η, a_T, $\Delta\phi_{\gamma\gamma} \sim \pi$)
  → need soft-gluon resummation at NNLL





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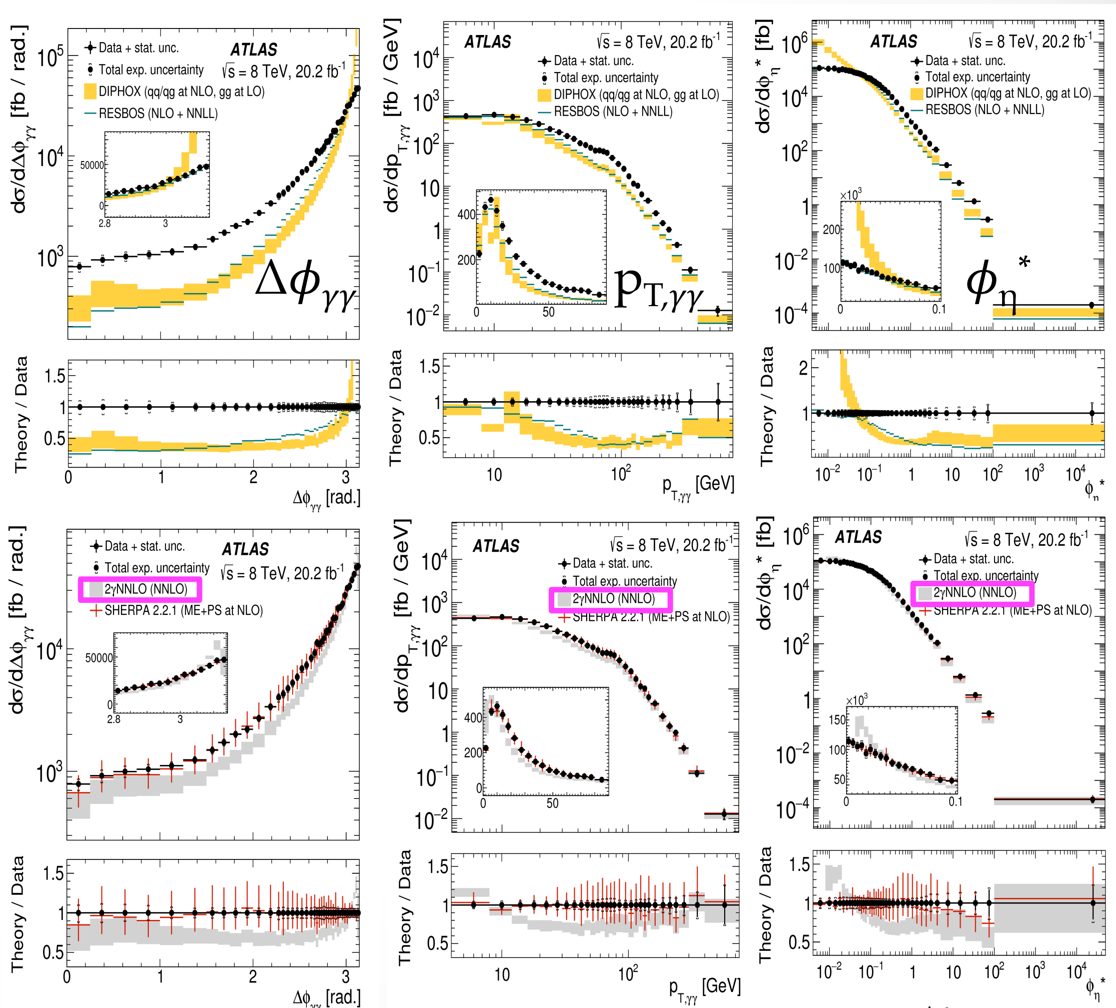
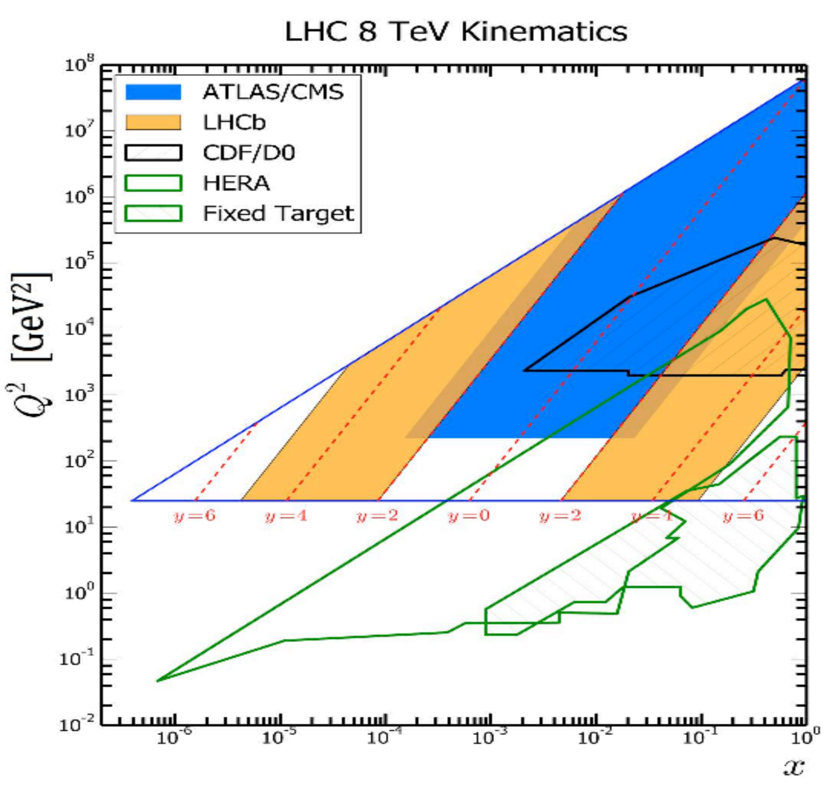


DIPHOX
Resbos
2γNNLO
Sherpa

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

Drell-Yan production

- Large number of measurements
  - Total and differential cross-sections in boson (lepton) kinematics (y, p_T, ϕ^*,…)
  - Cross-section ratios (W^+/W^-, W/Z, …)
  - Jet distributions
- ATLAS/CMS and LHC-b complementary
- Low & high x accessed by off-shell data



Drell-Yan production

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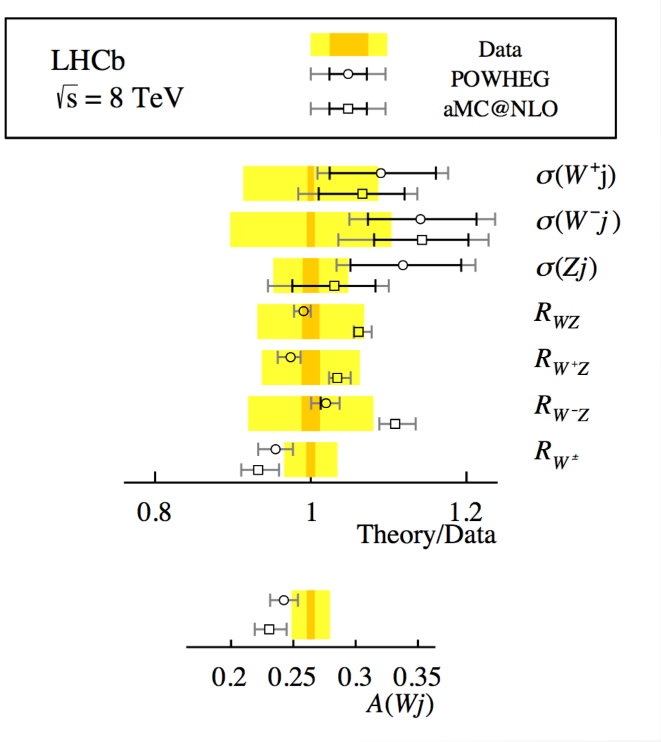
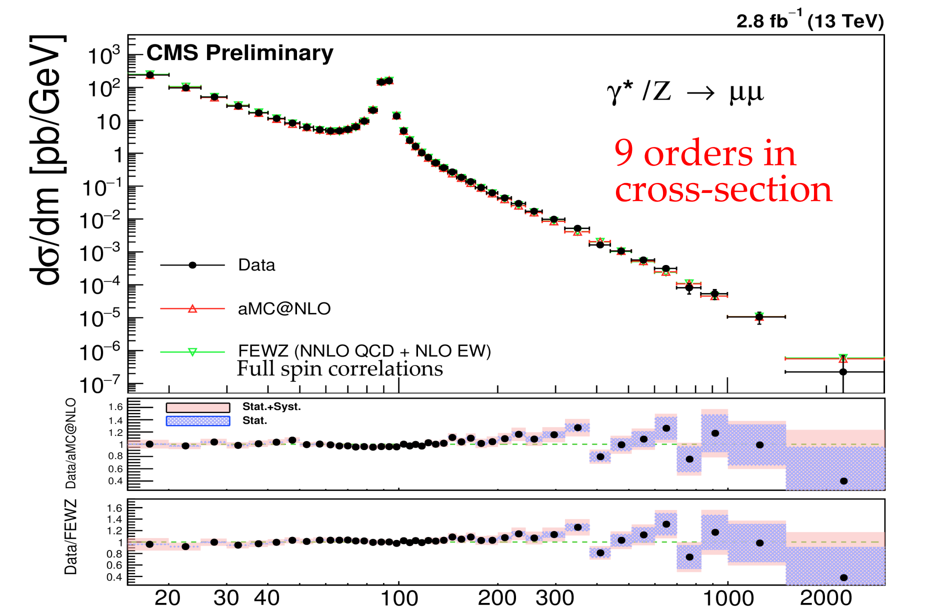
  - Cross-section ratios (W^+/W^-, W/Z, ...)
  - Jet distributions
- ATLAS/CMS and LHC-b complementary
- Low & high x accessed by off-shell data
- Large statistics, clean signature, excellent detector calibration → typical experimental systematics ~1%
- Luminosity systematics (2-3%) and also other contributions cancel in ratios



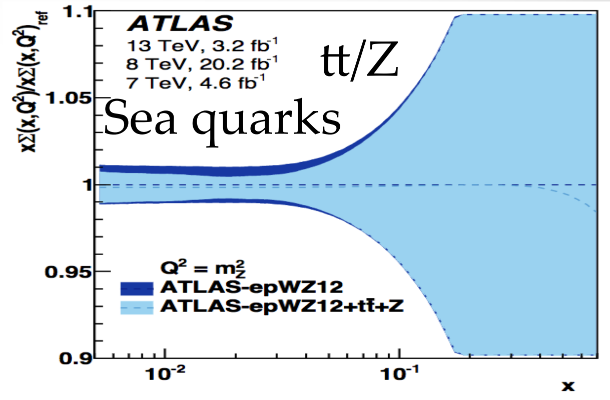


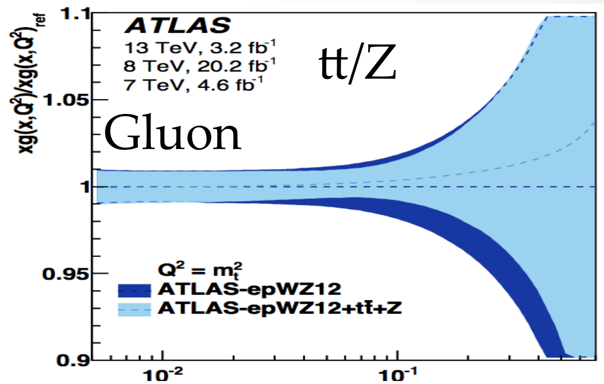
CMS-PAS-SMP-16-009

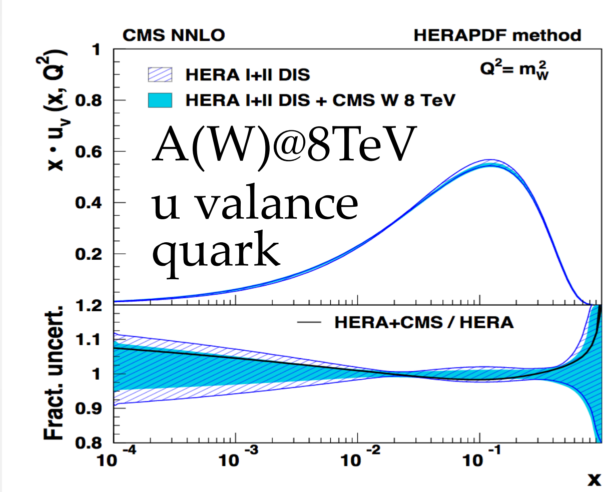
- Understand proton structure: constrain PDFs
- Probe higher-order pQCD calculations
- Study non-perturbative efffects, soft gluon resummation, parton shower modelling
- Test Monte Carlo tools
- Essential for precision physics at LHC

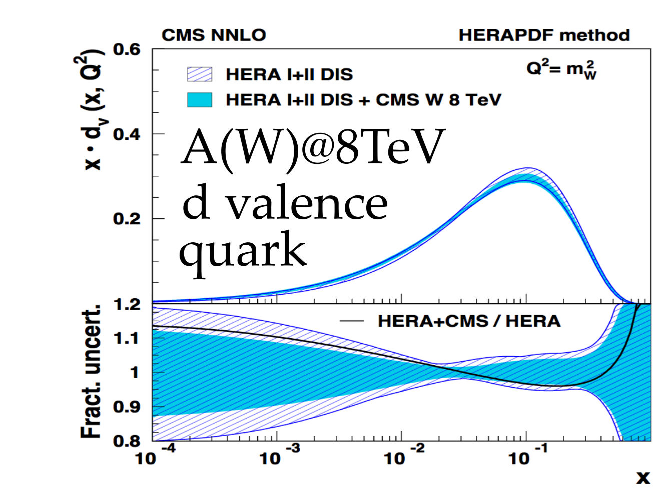
Constraints on PDF's from W/Z

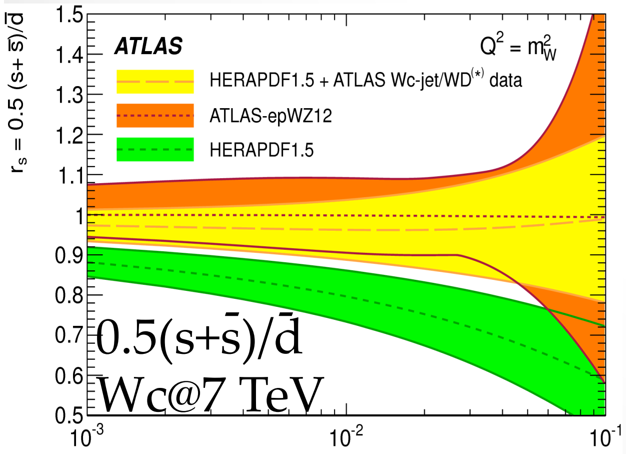
- More details on W/Z(+jets) and W/Z+HF production in backup
- See also Quiang Lee's presenation (Tuesday)

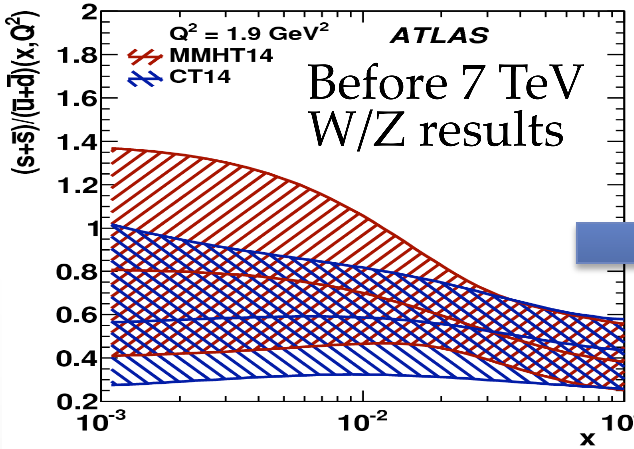


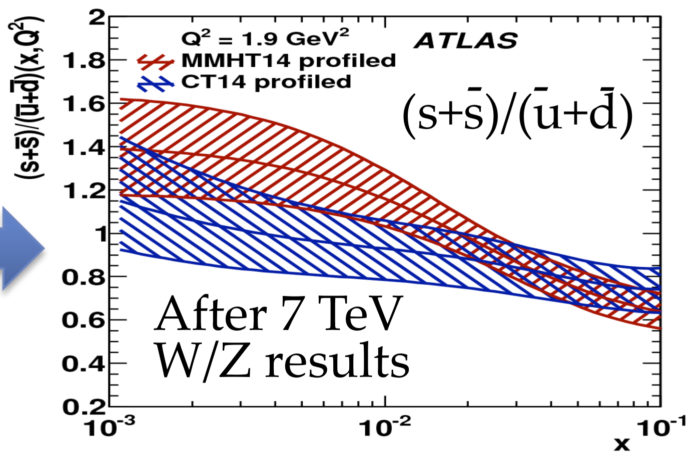




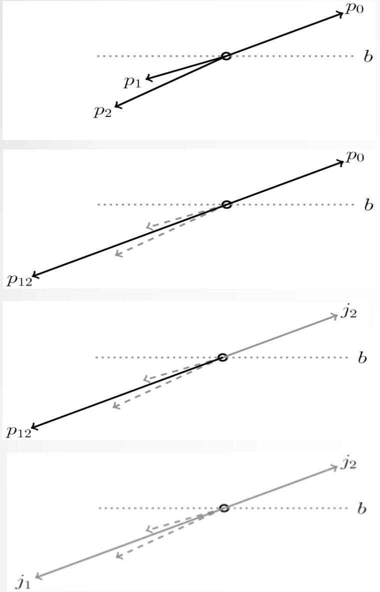








kt-splitting in Z(ll)+jets



Distance measures:

$$d_{ij} = \min\left(p_{\mathrm{T},i}^2, p_{\mathrm{T},j}^2\right) \times \frac{\Delta R_{ij}^2}{R^2},$$

$$d_{ib} = p_{\mathrm{T},i}^2,$$

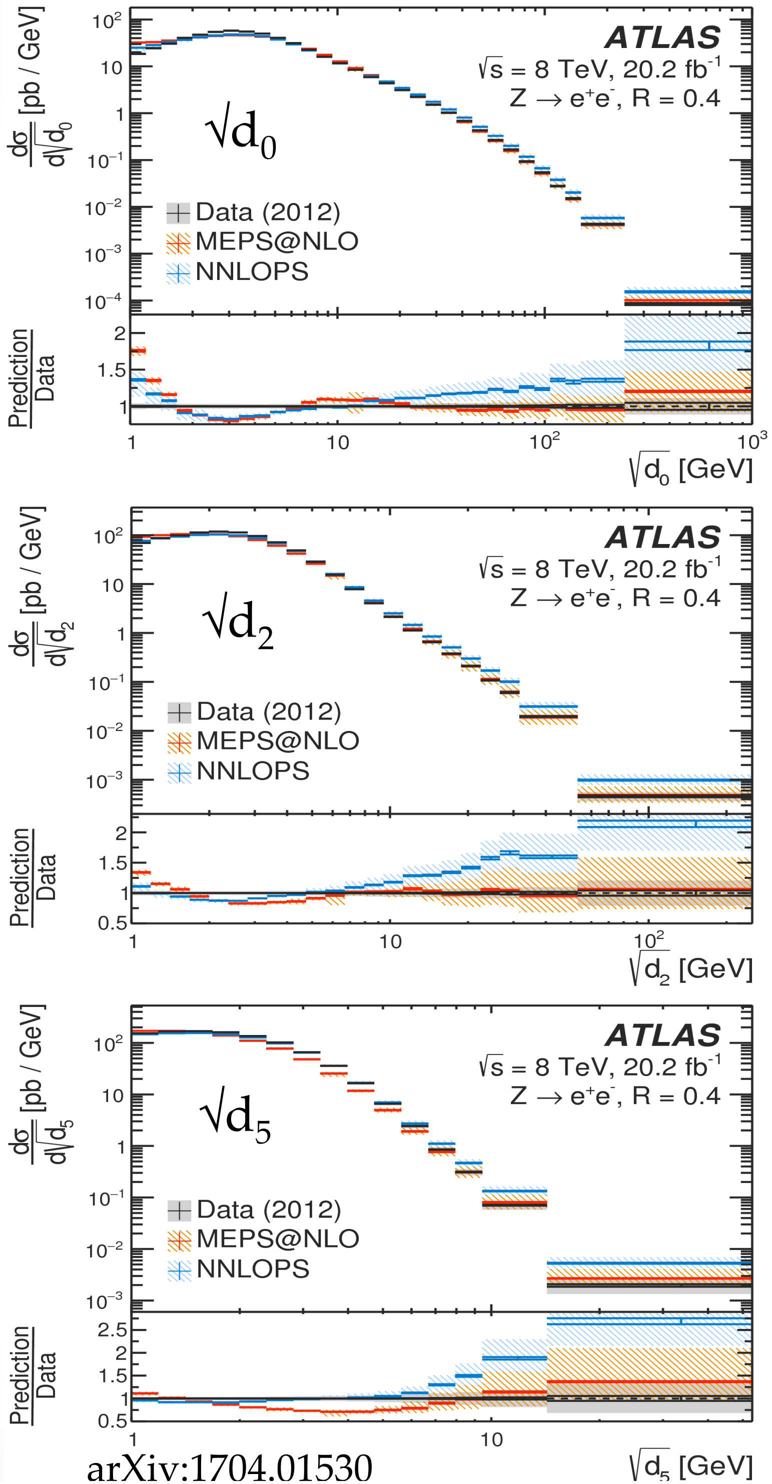
#particles from k+1 → k:

$$d_k = \min_{i,j}(d_{ij}, d_{ib}).$$

$\sqrt{d_0}$: p_T of leading kt jet

$\sqrt{d_N}$: distance where N-jet event resolves to N+1 jets

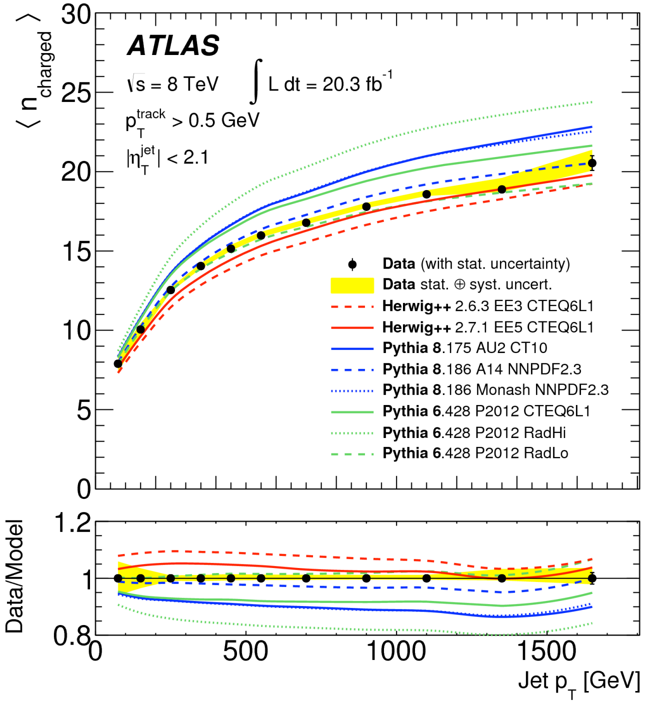
- Anti-kt jets of charged particle tracks with R=0.4, 1.0
- Extrapolation for charged+neutral distributions
- At higher k values, SHERPA (NLO for up to 2 jets, LO for up to 4) performs better, ME-PS matching with improved CKKW (MEPS@NLO)
- **At high √d, perturbative modeling tested**
- **At low √d (soft region), non-perturbative effects as hadronisation, MPI, PS also play a role**
    - DYNNLO + Powheg + Py8 underestimates less the data
- Data can be used for MC tuning of NP stages

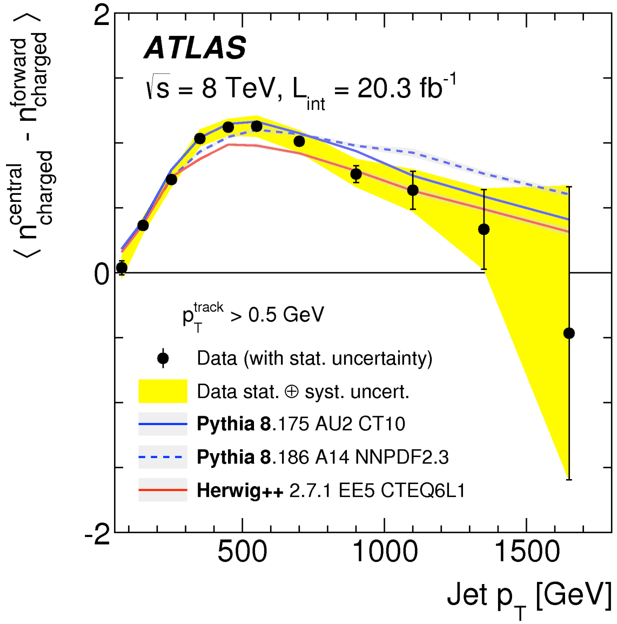


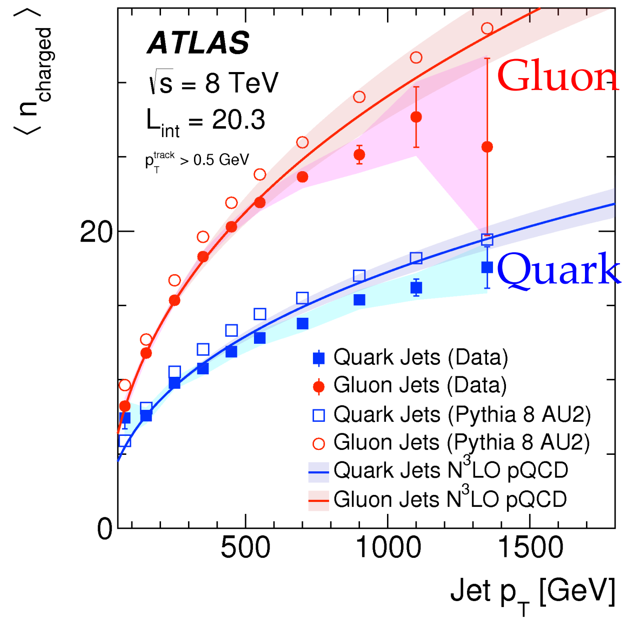
arXiv:1704.01530

Charged particle multiplicity inside jets

- **Jet properties depend on parton type**
- **Gluon jets: higher (charged) particle multiplicity** due to the gluons larger color charge, and multiplicity grows faster with jet energy
- Dijet topologies selected
- **More forward jet** typically belongs to the parton with higher longitudinal momentum fraction x, **less likely to come from gluon**
- **Run2 tunes give better description**







NNLO: 5FS, $\mu_R=0.4p_T$ (caveat: n_{ch} not IR safe)
Predicts scale dependence
Can not give absolute prediction, normalized to 2nd bin

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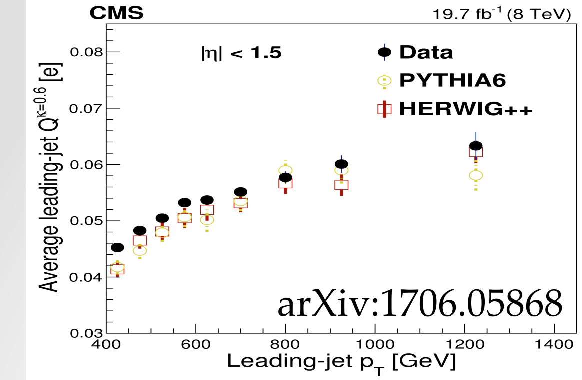
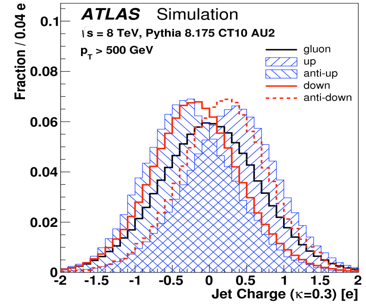


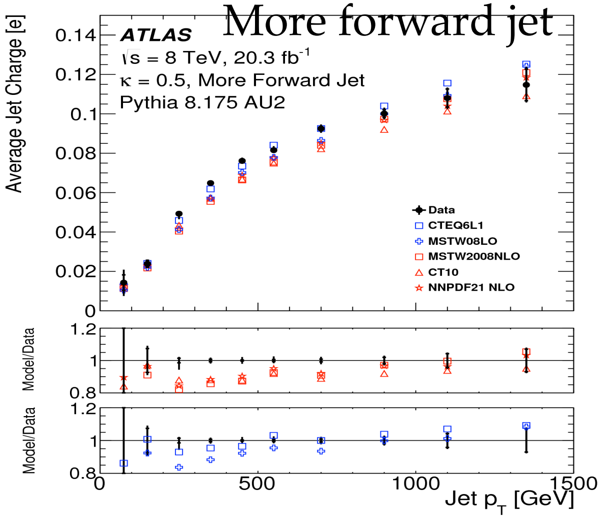
Jet charge in dijet events

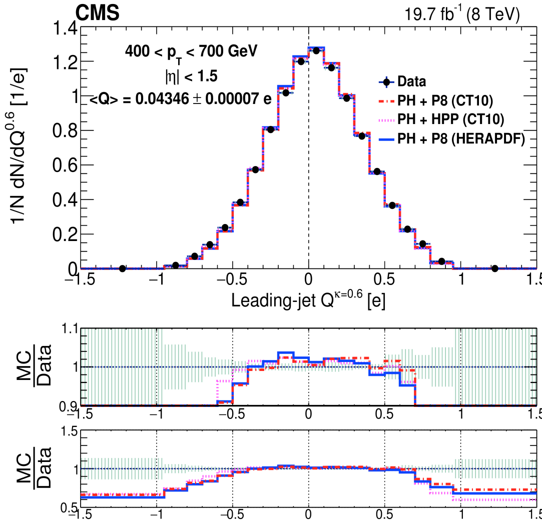
- Momentum-weighted sum of particle charges above some p_T threshold, e.g.

$$Q_J = \frac{1}{(p_{T\,J})^{\kappa}} \sum_{i \in Tracks} q_i \times (p_{T,i})^{\kappa},$$

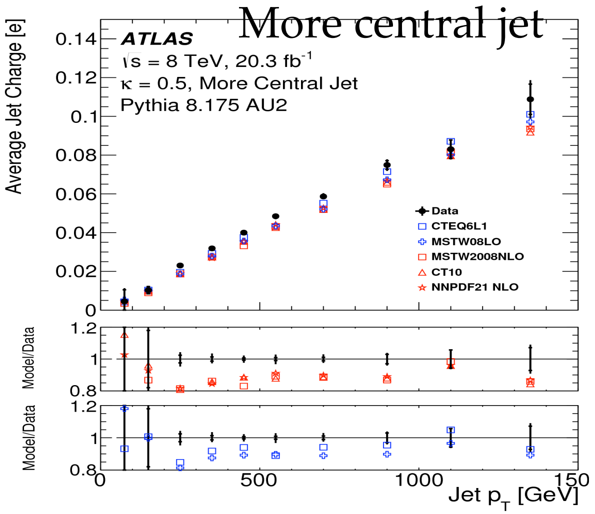
- Aim: determine origin of jet
- **Average jet charge** should **increase with s-hat** if correlated with quark charge (increasing valence-u quark fraction)
- **Sensitive to pdf and fragmentation modeling**, both contributes to jet charge p_T dependence

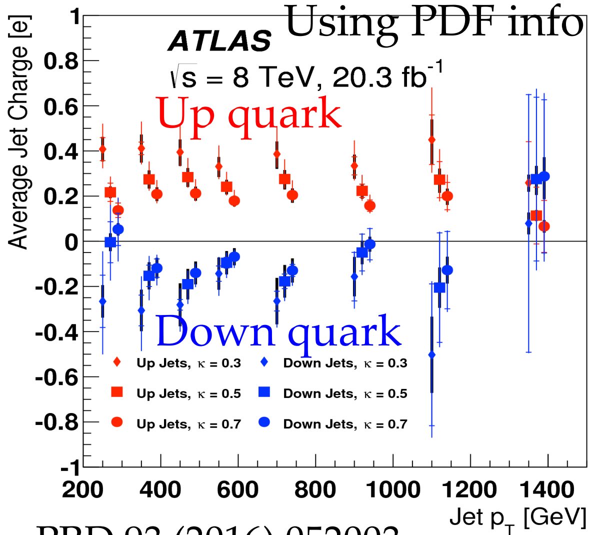






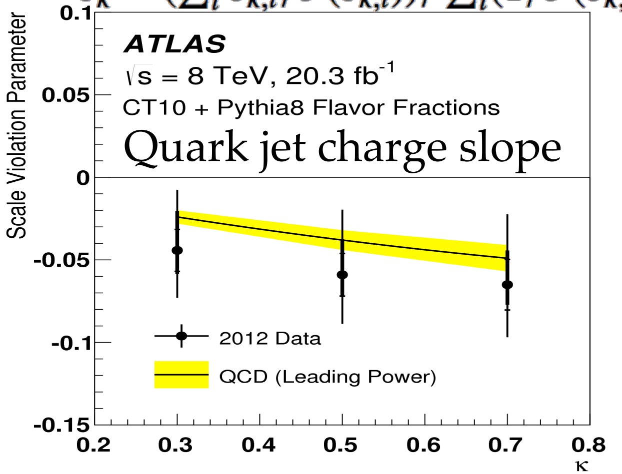
$$\langle Q_i \rangle_{\text{measured}} = \sum_f \beta_{f,i} \bar{Q}_f (1 + c_{\kappa,i} \ln(p_{T,i}/\bar{p}_T))$$





PRD 93 (2016) 052003

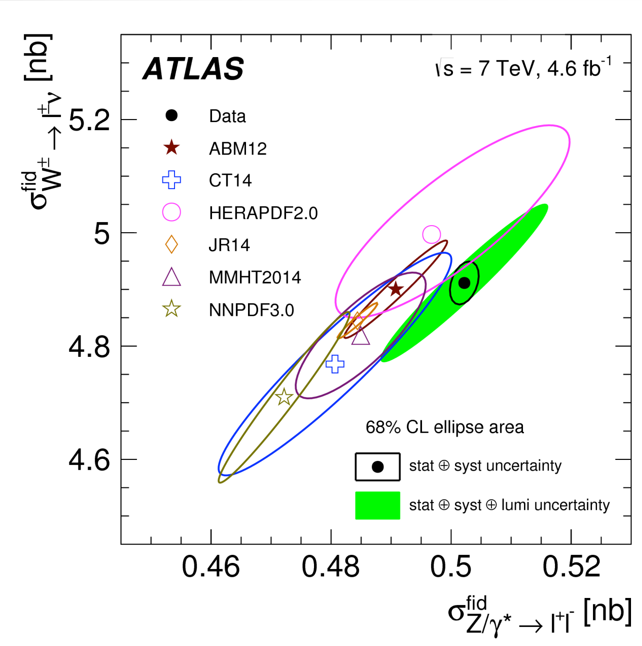
$$c_\kappa = \left(\sum_i c_{\kappa,i}/\sigma(c_{\kappa,i})\right) / \sum_i \left(1/\sigma(c_{\kappa,i})\right).$$

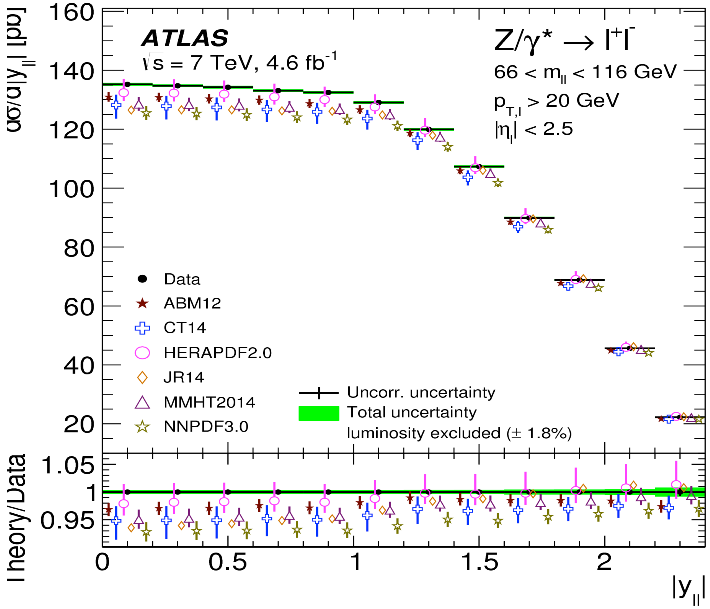


Conclusion

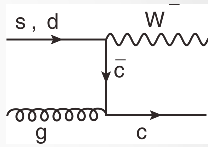
- Presented a selection of hard QCD results
- LHC data provides a wealth of precise information, accessing new regions in the phase space → LHC entered precision era
- Generally good agreement with theory but deviations present in certain kinematic regions
- As expected, (N)NLO predictions typically provide a better description of data
- Experimental precision for certain processes better than theoretical
  - Need for further improvements in calculation
  - Placing significant constraints on PDF's
- New measurements of α_s at high Q

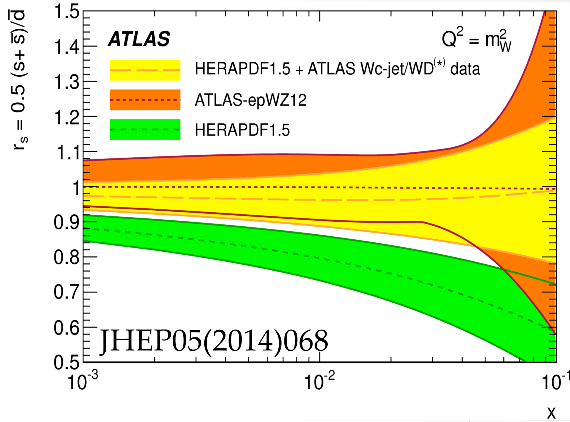
Precision measurements @ 7 TeV

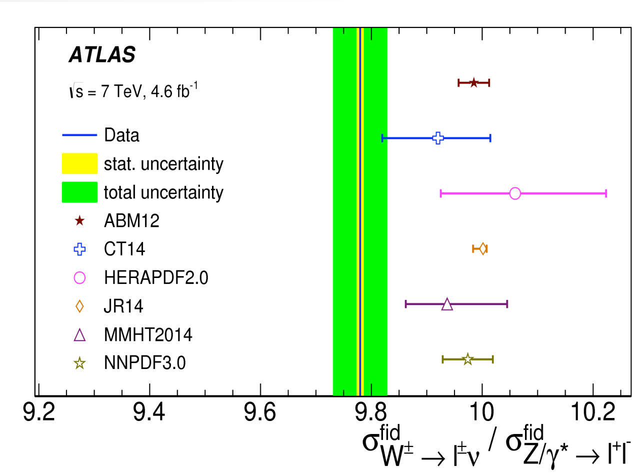




- Good agreement in general with a few exceptions
- Enhanced s-quark content
  - Not evident in Wc results







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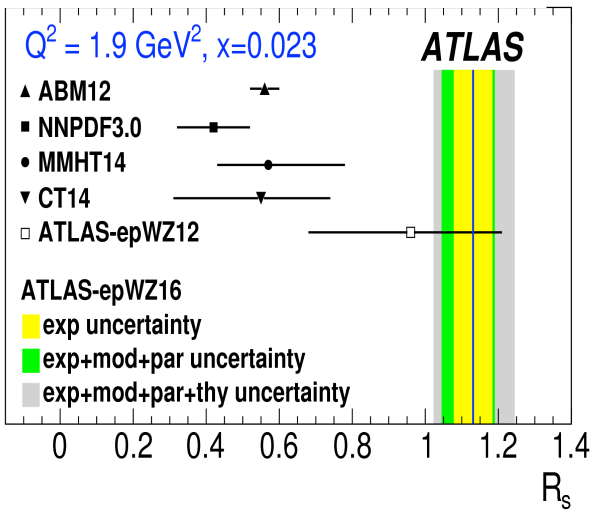
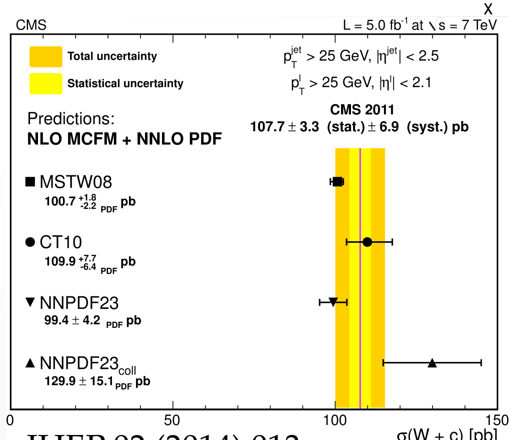
$$R_s(x) = (s(x) + \bar{s}(x))/(\bar{u}(x) + \bar{d}(x))$$

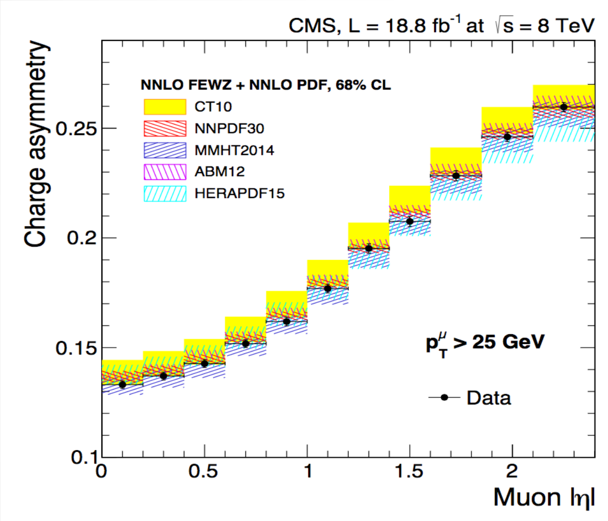


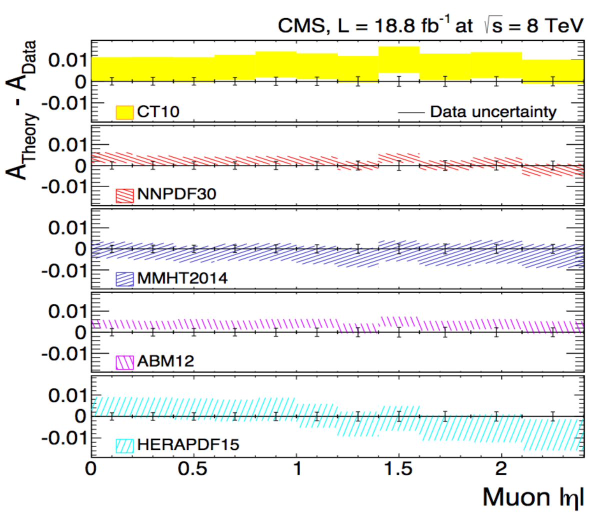


JHEP 02 (2014) 013

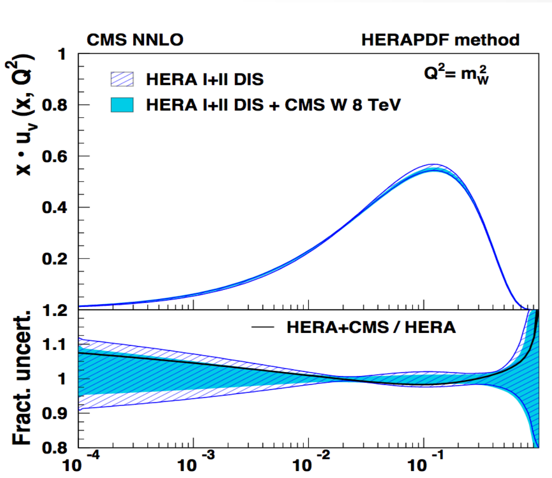
W charge asymmetry at 8 TeV

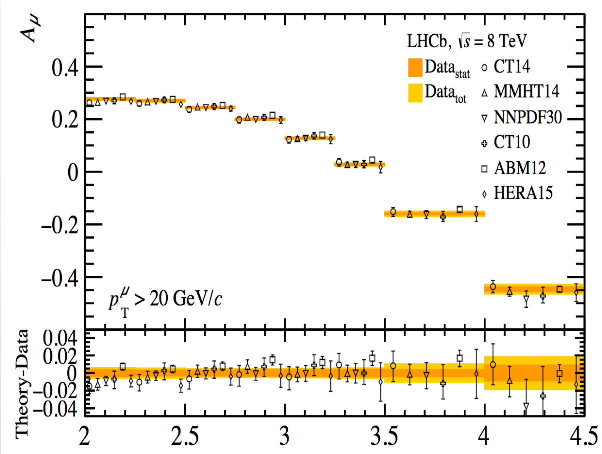
- $\mathcal{A}(\eta) = \frac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-}$ with $\sigma_\eta^\pm = \frac{d\sigma}{d\eta}(pp \to W^\pm + X \to \mu^\pm \nu + X)$
- PDF sensitive as main production mechanisms for W's: $u\bar{d} \to W^+$ $d\bar{u} \to W^-$
- Constrains u(x)/d(x) ratio



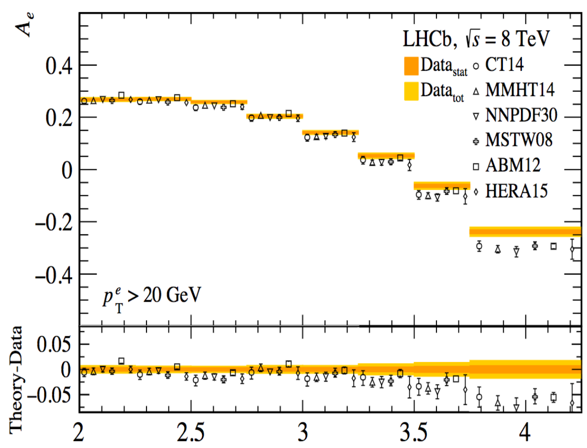


Effect of CMS data on PDFs:

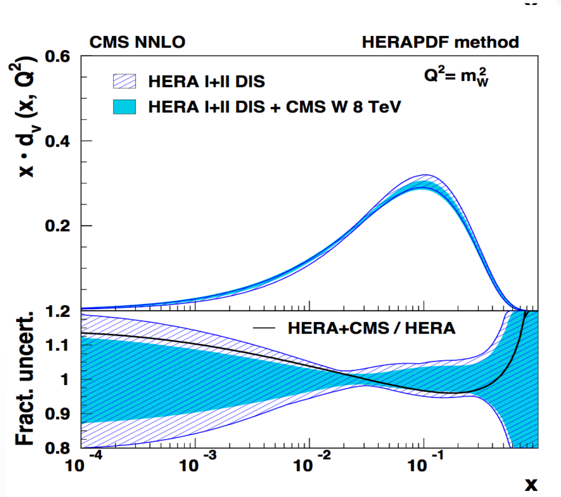




JHEP 01 (2016) 155



JHEP 10 (2016) 030



EPJC 76 (2016) 469

$t\bar{t}$ / Z cross-section ratio

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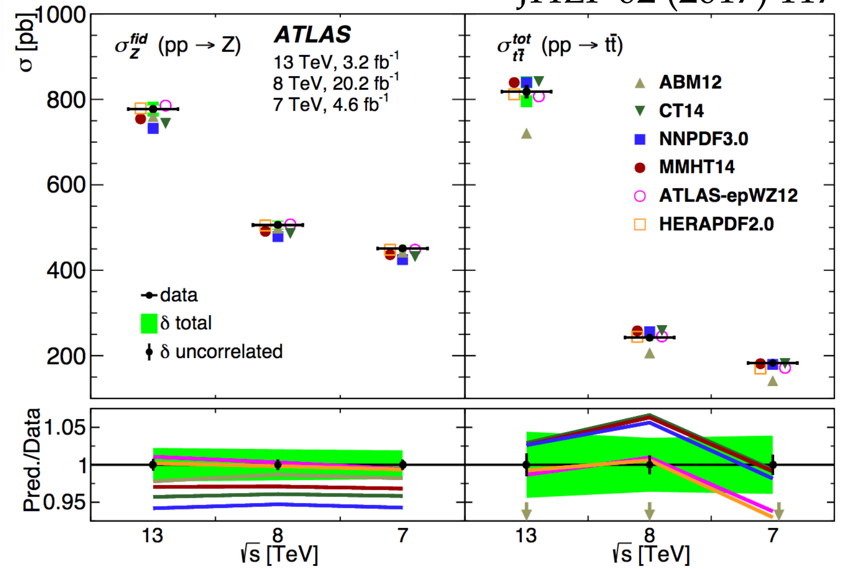
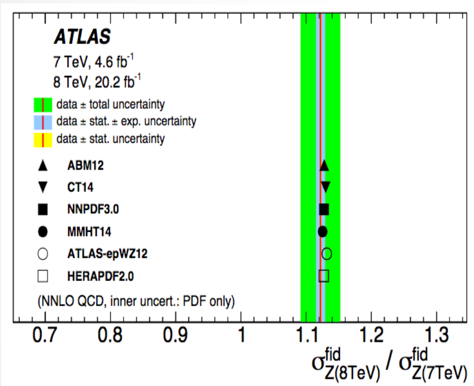
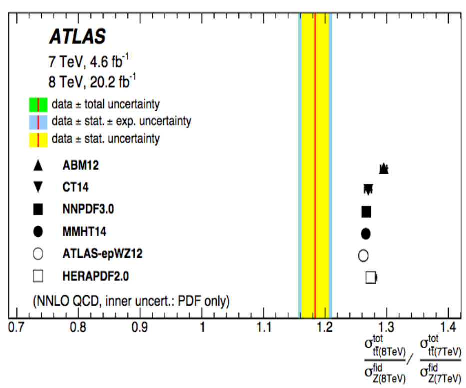
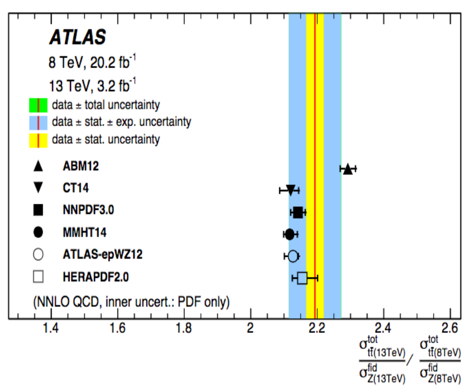
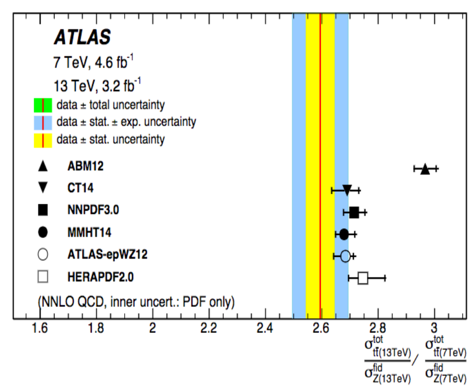


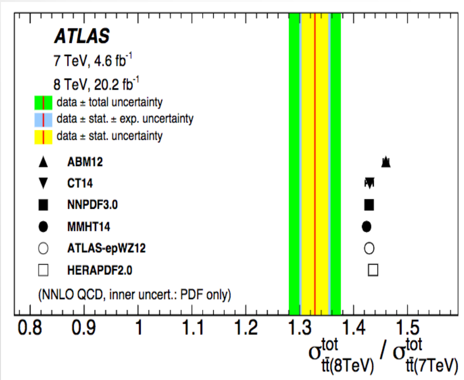
- Luminosity uncertainty cancels out
- High precision (stat, syst, beam, lumi):
  σ_Z^{fid}(13 TeV) = 777 ± 1 ± 3 ± 5 ± 16
  $\sigma_{t\bar{t}}^{tot}$(13 TeV) = 818 ± 8 ± 27 ± 12 ± 19
- Challenging to take correlations precisely into account
- In double ratio most uncertainties cancel out





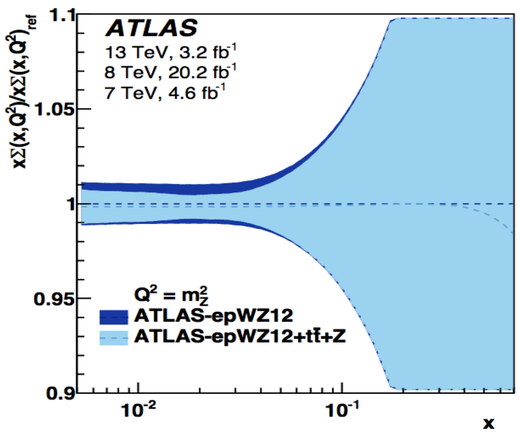


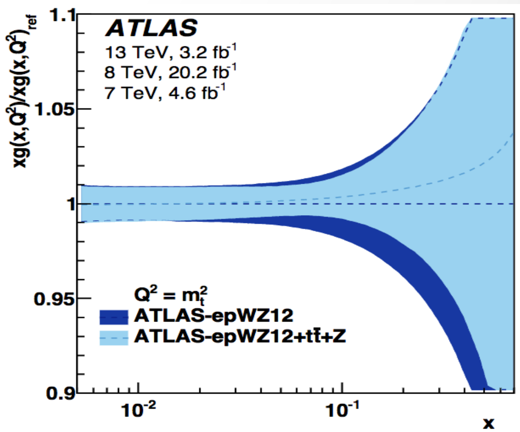




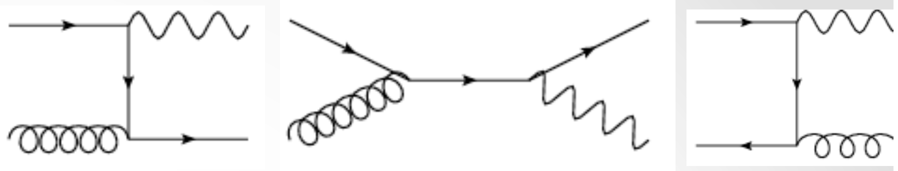
σ($t\bar{t}$) ratios of X TeV / 7 TeV are lower than predicted

Effect on PDF





Z+jets production



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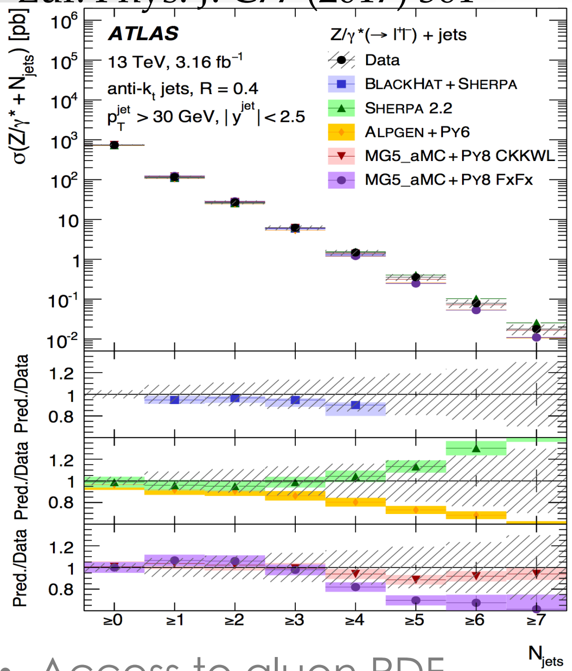
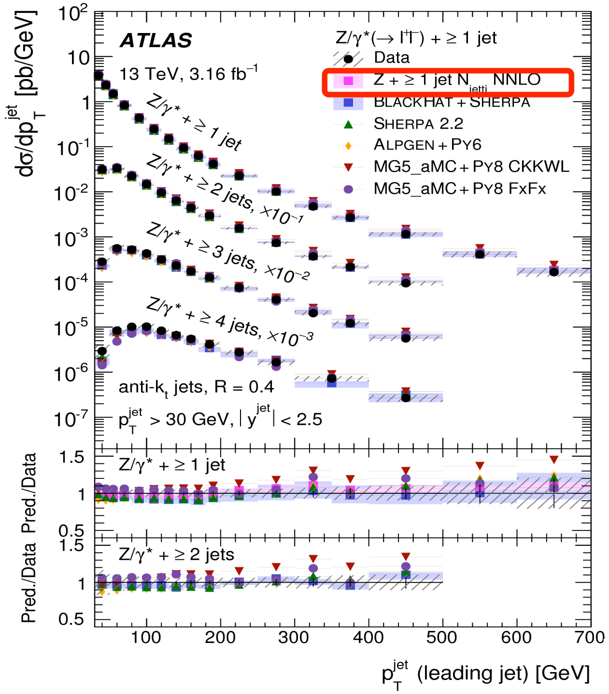
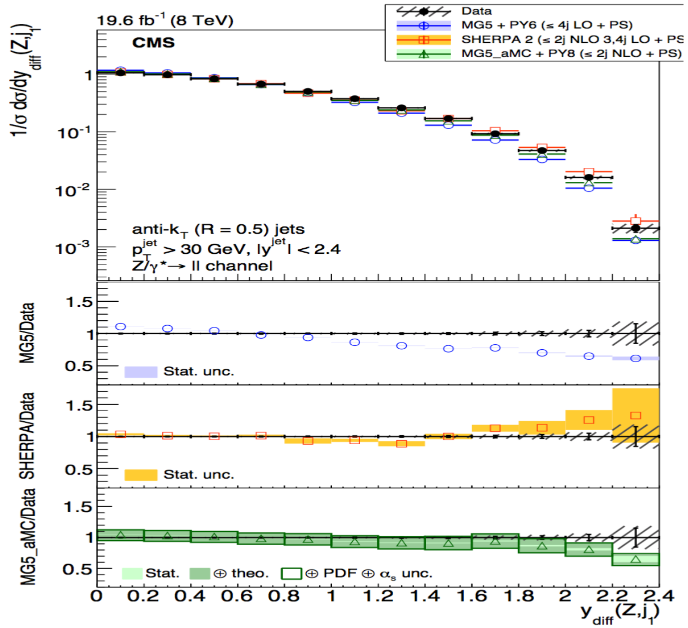
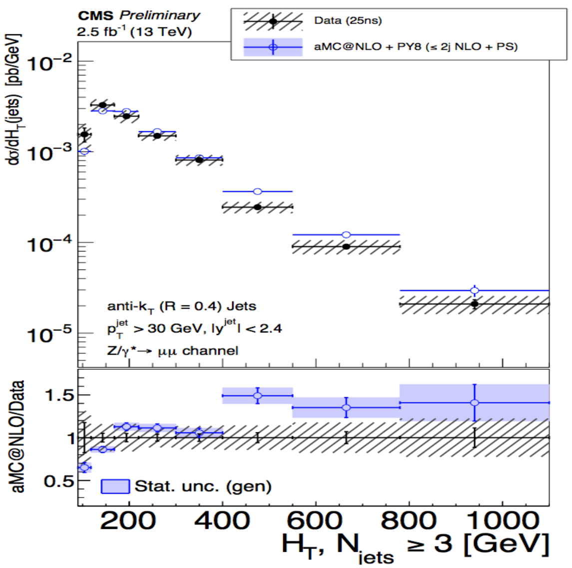


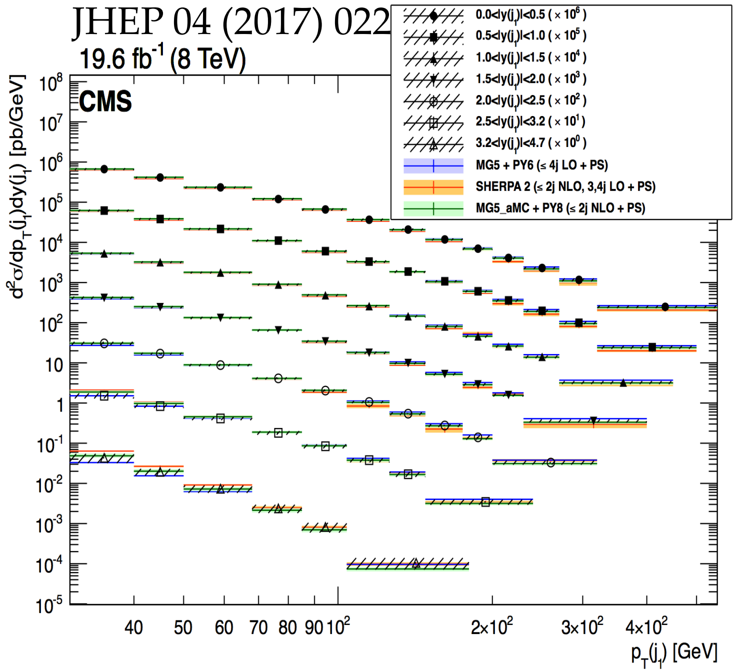




JHEP 04 (2017) 022

- Access to gluon PDF
- Two scale problem at NLO
- Good description of most variables
- Deviation for high jet multiplicities, high jet p_T, HT, rapidity correlations
- y_{diff} sensitive to matching procedure for ME and PS
  - Smaller tension at higher Z p_T
  - NLO better due to extra diagrams with t-channel gluon propagator



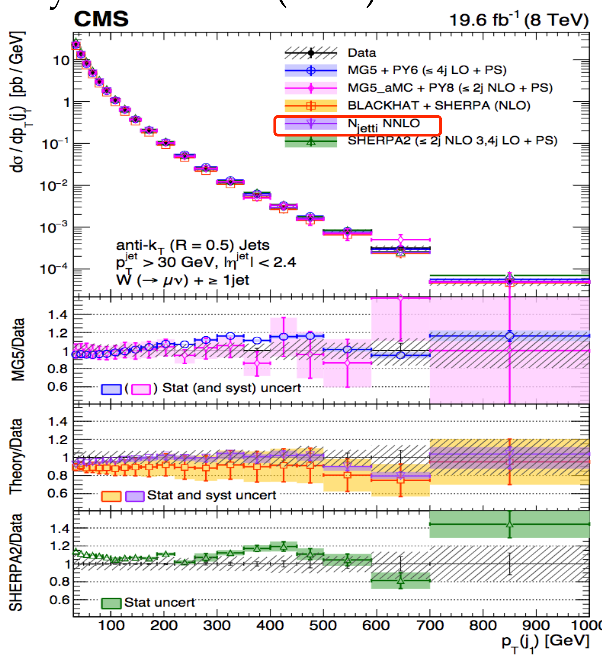


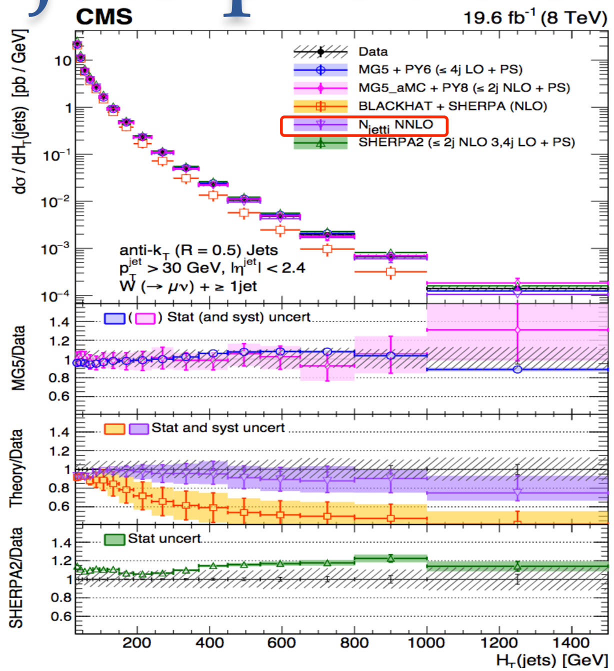
CMS-PAS-SMP-15-010

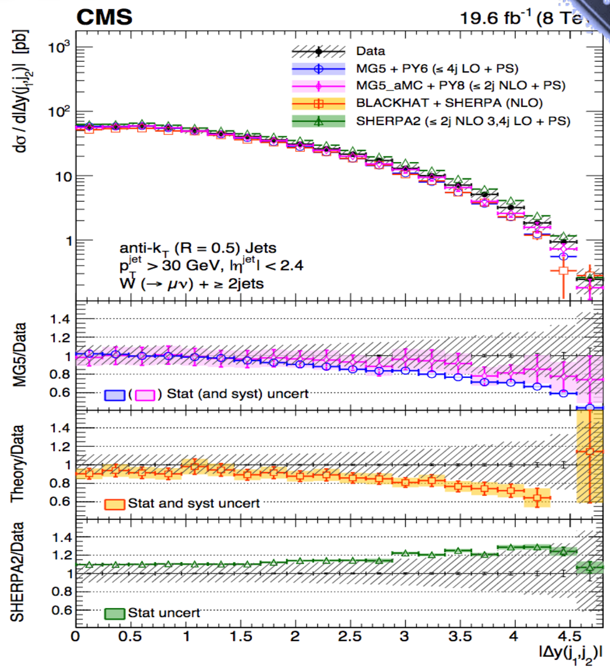
W+jets production

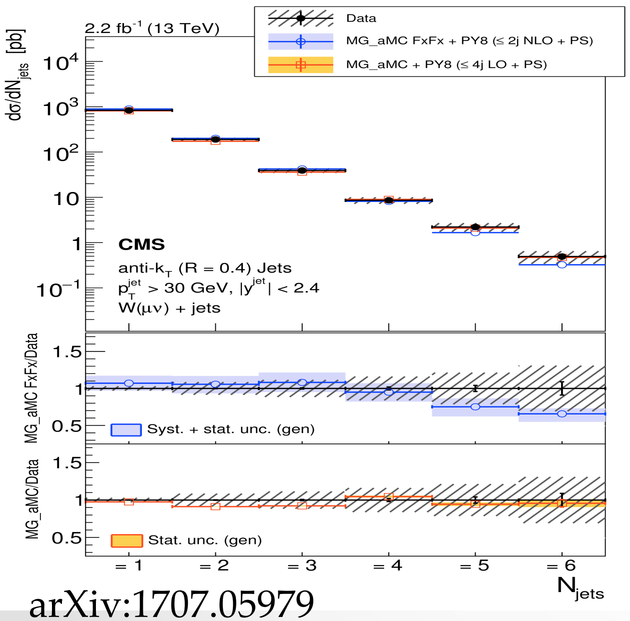
NEW!!

Phys. Rev. D 95 (2017) 052002

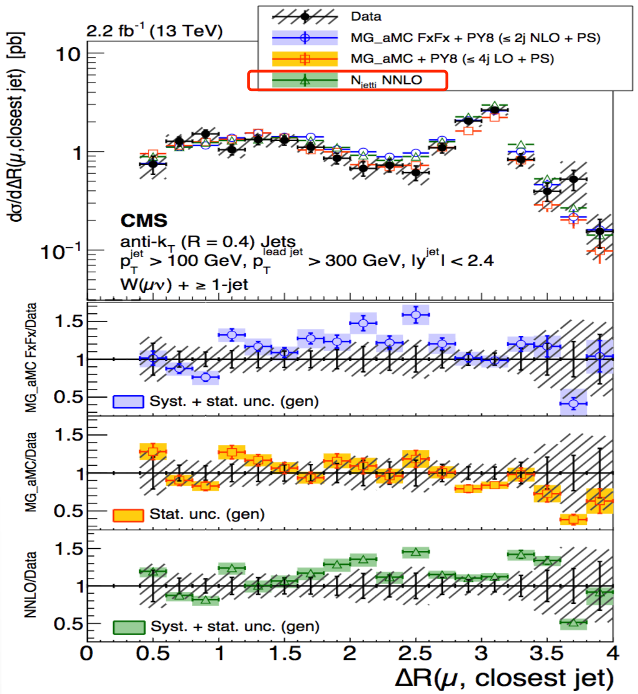






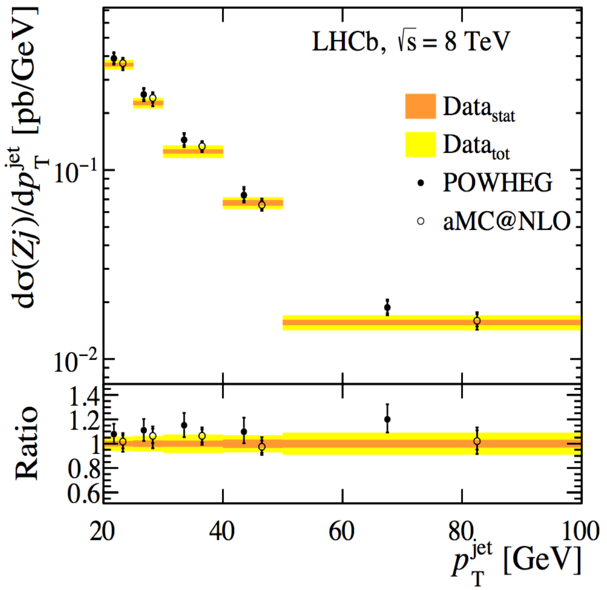


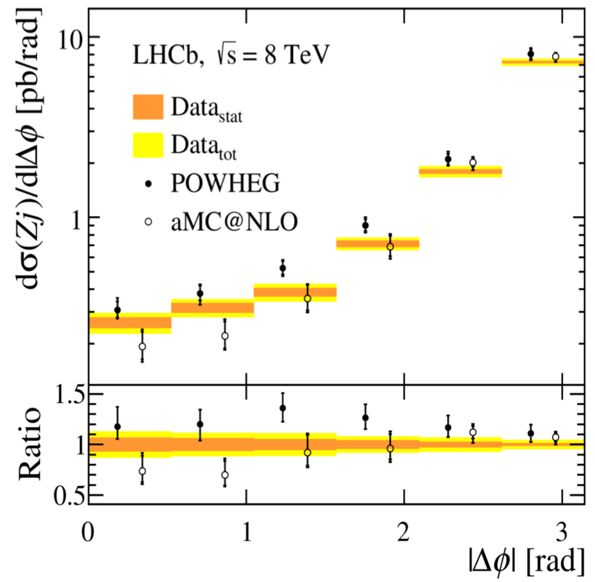
arXiv:1707.05979

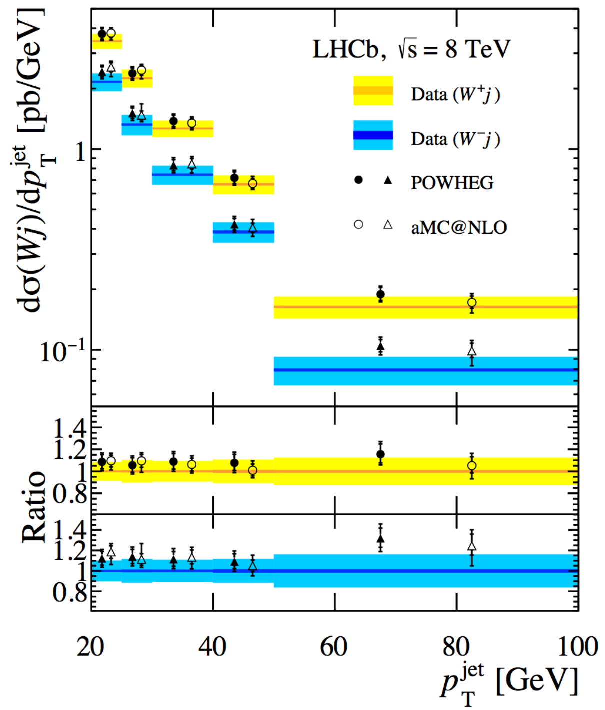


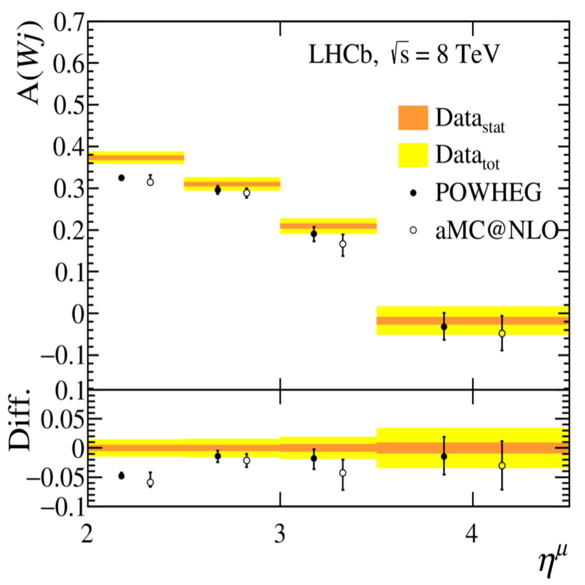
- Important background for other measurements
- Essential test of QCD radiation modelling
- Angular correlation $\Delta R(\mu j)$ fairly well described
- Collinear region (low ΔR) sensitive to W ISR and FSR from quarks
- Peak region (high ΔR): back-to-back W + ≥1 jet

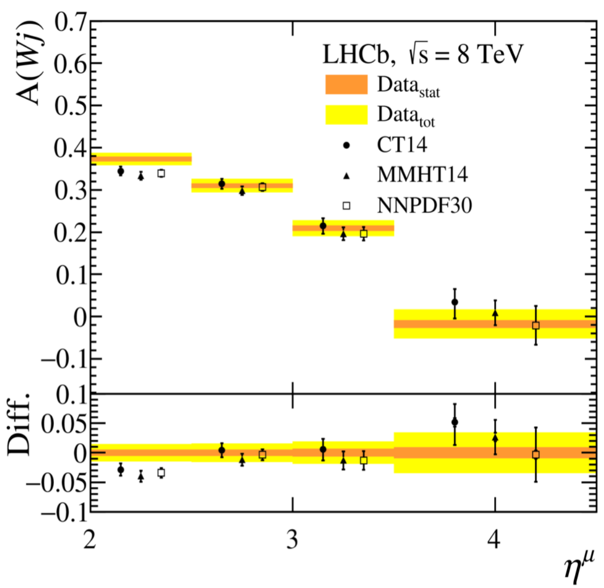
Forward V+jets production

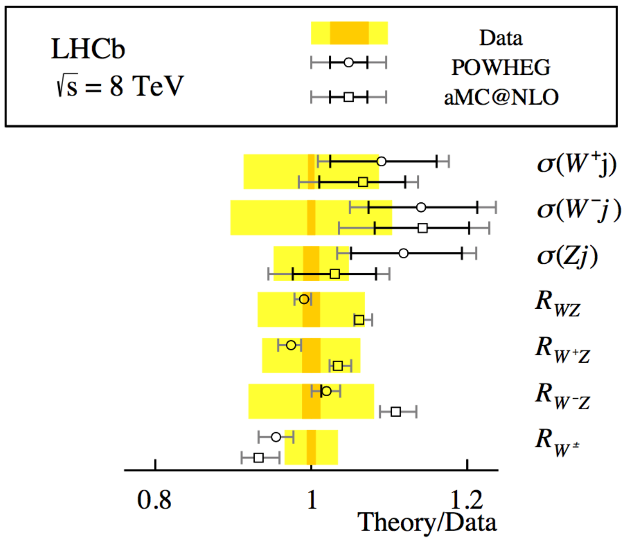


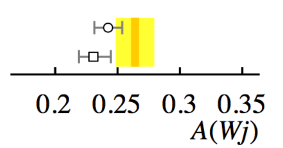












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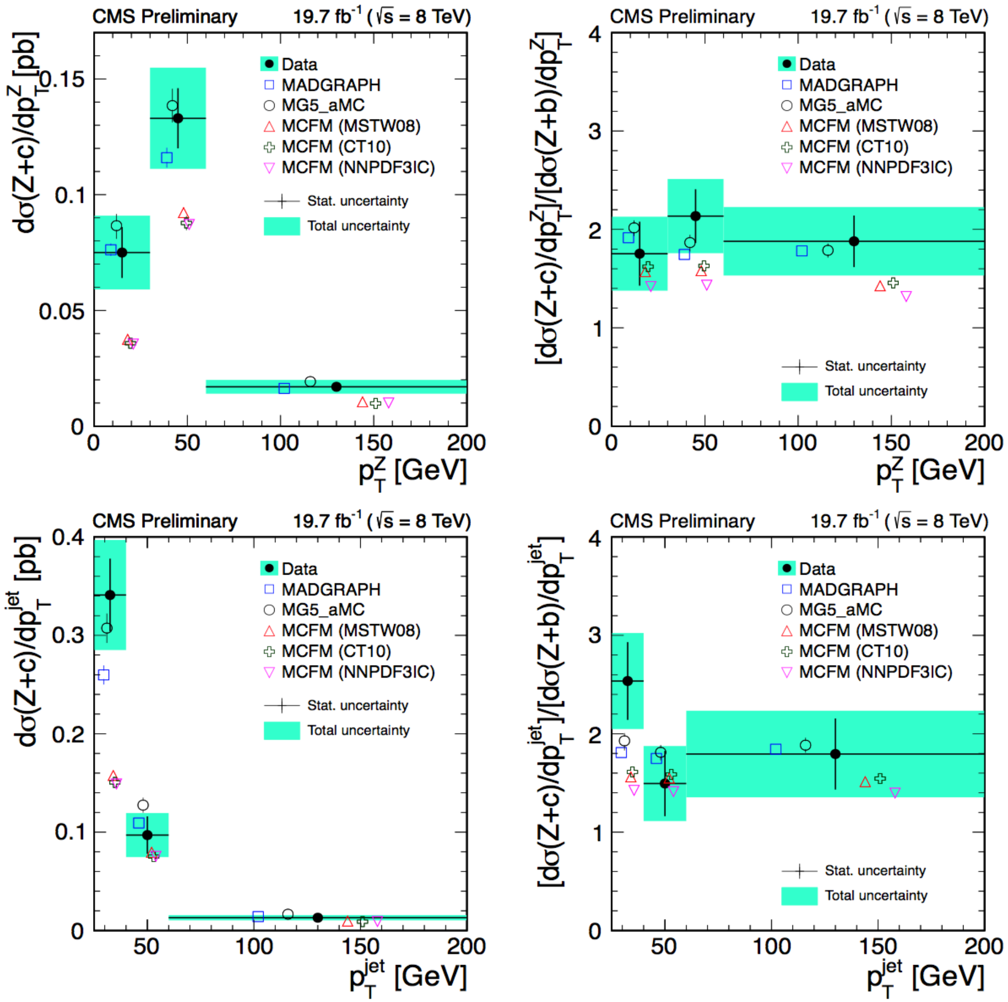
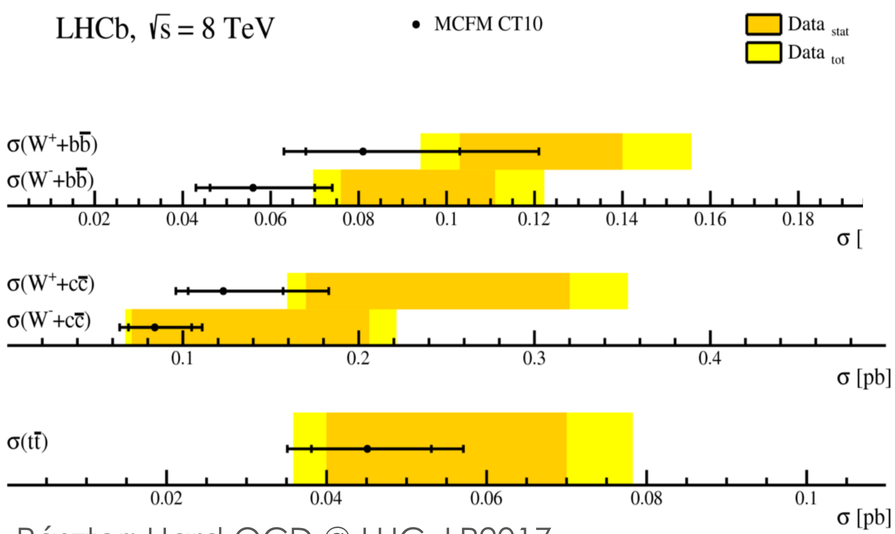
V+charm production

- Z+c: search for non-perturbative intrinsic charm component
- NLO MCFM underpredicts at low jet p_T

- Simultaneous measurement of $W^{\pm}cc$, $W^{\pm}bb$, tt in 4 samples ($e^{\pm}$, $\mu^{\pm}$) fitting in 4D to m_{jj}, j_1 and j_2 BDT(b|c), and a kinematic MVA variable
- Good agreement with NLO theory (corrected to particle level)



CMS-PAS-SMP-15-009



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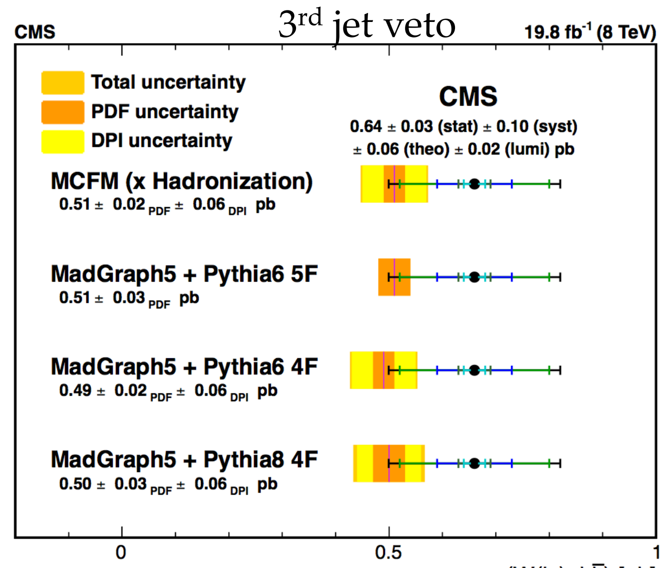
V+b(b) production

- Test of pQCD, beauty production
- Background for searches, other (eg. Higgs) measurements
- Z+b(b) differential in various observables
  - Z(≧1b) low-pT region not well described
  - Z(bb) generally agree with predictions



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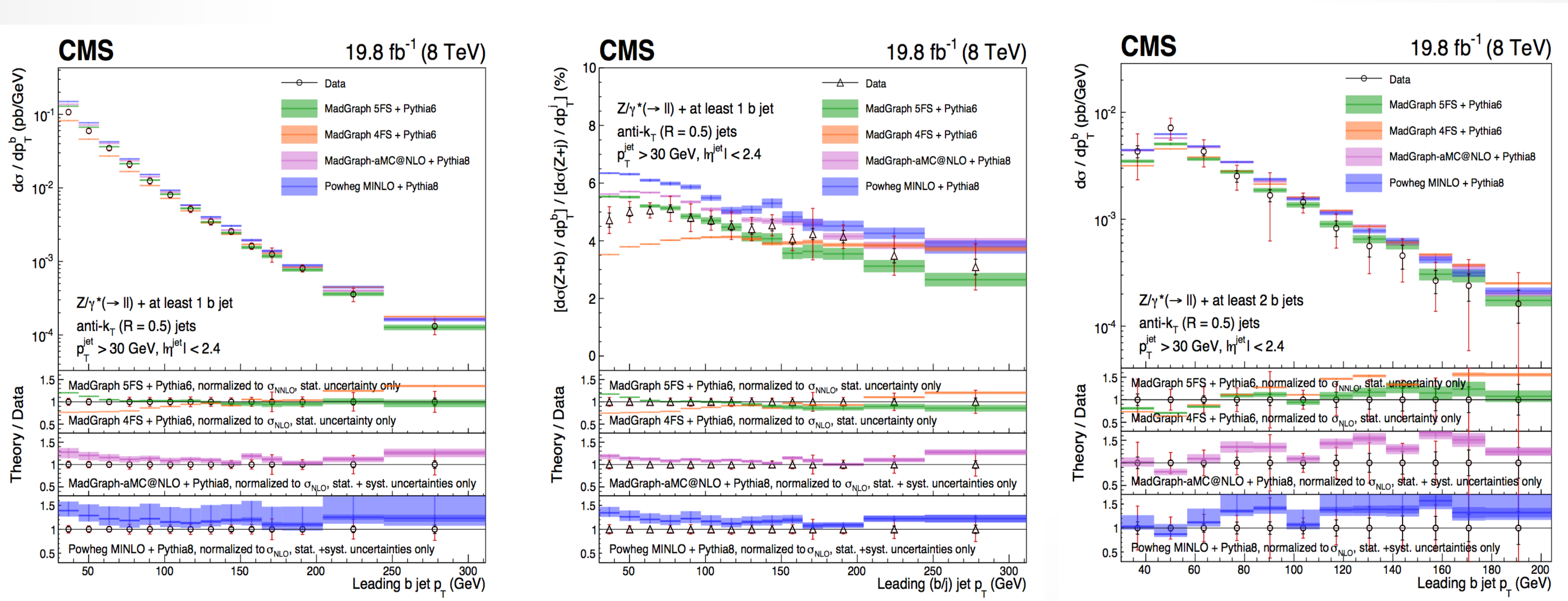


arXiv:1611.06507

Extra

Jet energy

CMS @ 8 TeV

- Multiplicative jet energy correction ~ 10% at 100 GeV, decreases with pT
- Jet energy resolution 15% / 8% / 4% at 10 GeV / 100 GeV / 1 TeV
- Effect on cross-section:
    - JES: 2-4% @ sub-TeV, 20% @ highest pT, $1<|\eta|<2$
    - JER: 1-5% @ high pT, can exceed 30% @ low pT

Event and jet cleaning (99% efficiency for true jets)

- MET/SumET < 0.3
- Tight jet ID: min 2 PF particle / jet, min 1 charged hadron / jet, $E_{neutral}/E < 0.9$
- Min 1 jet above trigger threshold

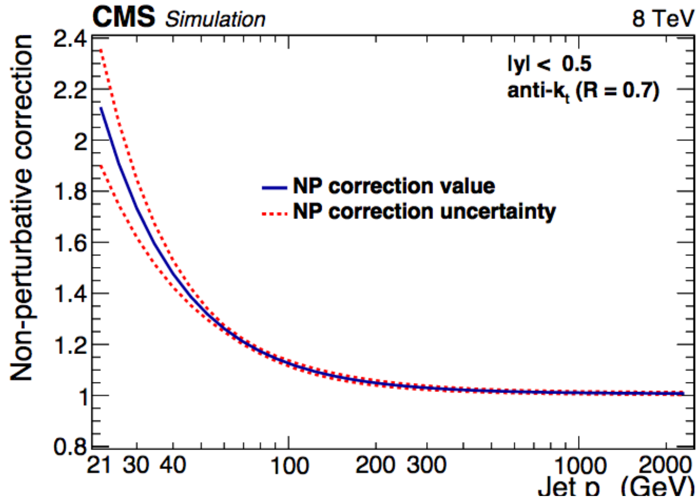
Theory cross-section

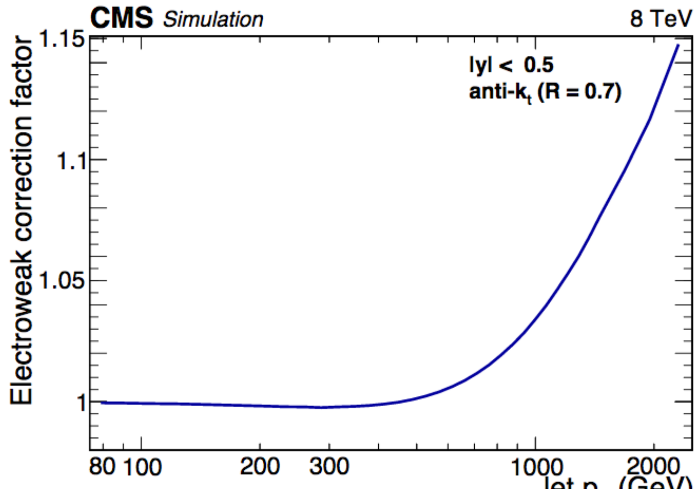
Incl jet 8 TeV:

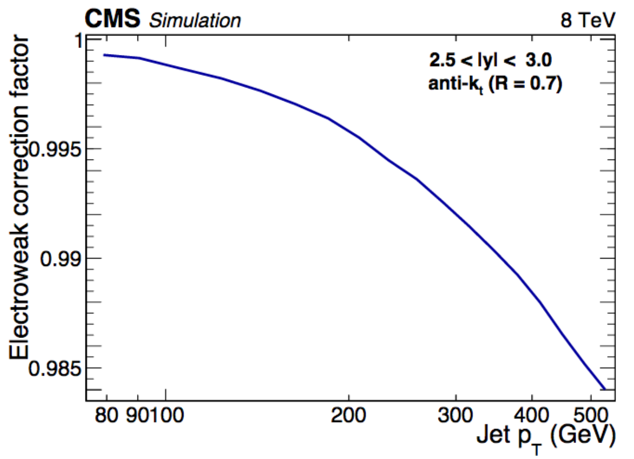
- NLO QCD (NLOJET++, FastNLO package), scale = highest jet pT, NLO PDFs with typically 5 (NNPDF2.1: 6) massless flavours , variable (ABM11: fixed) flavour number scheme

PDF set	Refs.	Order	N_f	M_t (GeV)	M_Z (GeV)	$\alpha_S(M_Z)$	$\alpha_S(M_Z)$ range
ABM11	[41]	NLO	5	180	91.174	0.1180	0.110–0.130
CT10	[36]	NLO	≤ 5	172	91.188	0.1180	0.112–0.127
HERAPDF1.5	[40]	NLO	≤ 5	180	91.187	0.1176	0.114–0.122
MSTW2008	[37]	NLO	≤ 5	10^{10}	91.1876	0.1202	0.110–0.130
NNPDF2.1	[38]	NLO	≤ 6	175	91.2	0.1190	0.114–0.124
NNPDF3.0	[39]	NLO	≤ 5	175	91.2	0.1180	0.115–0.121

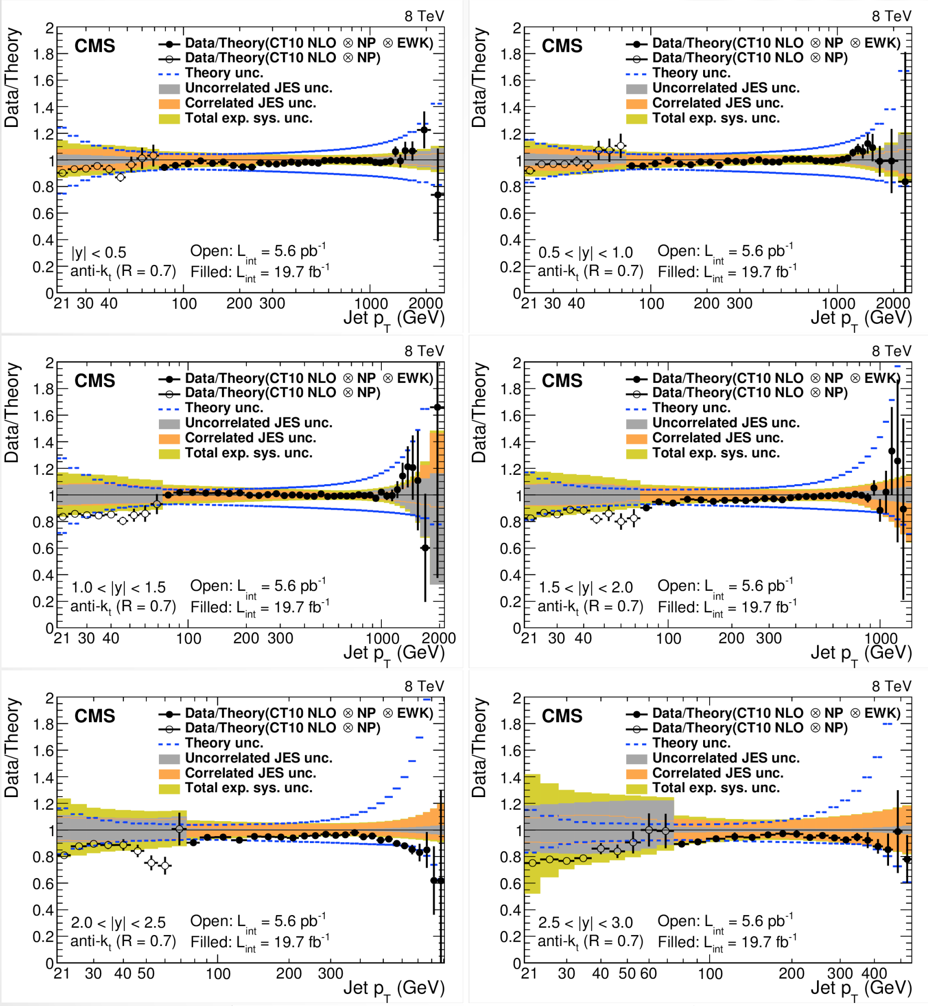
  - Uncertainty: scale 5-10% in central y, 40% outer y, high pT
  - PDF: 5-30% in central y,
- Parton level NLO corrected for non-perturbative effects (hadronization, MPI) estimated from LO and NLO MC : 20% at low pT,1% at 2.5 TeV
  - Uncertainty: 1.4% @100 GeV, 0.06% @ 2.5 TeV
- EW correction for W, Z exchange ~ $\alpha_W \ln^2(Q^2/m_W^2)$, for high pT jet large correction

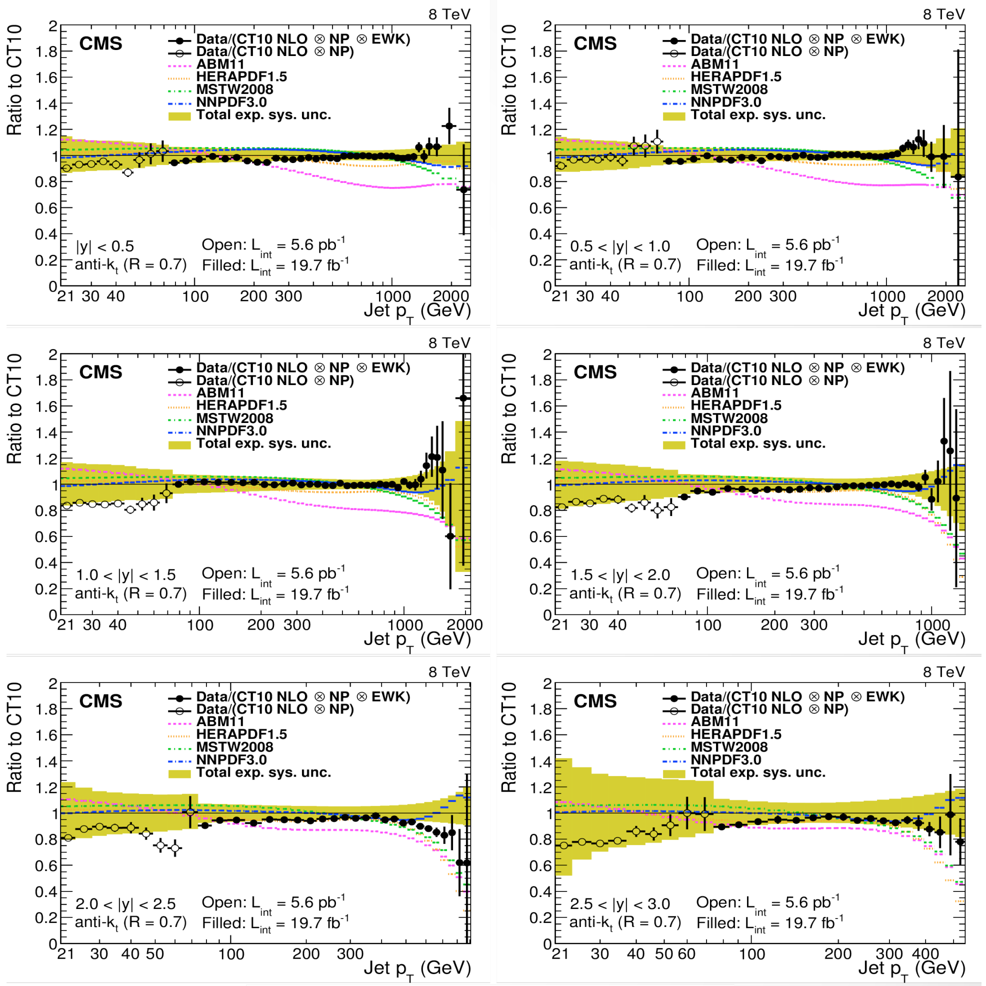


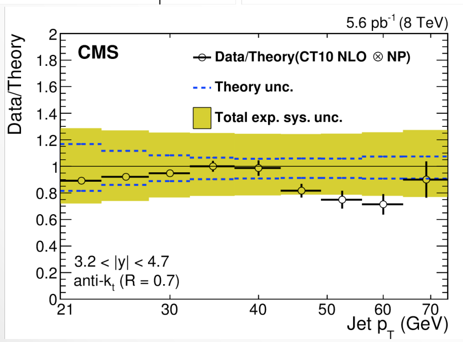


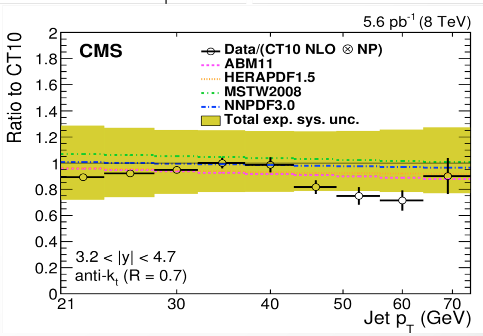


Uncertainties



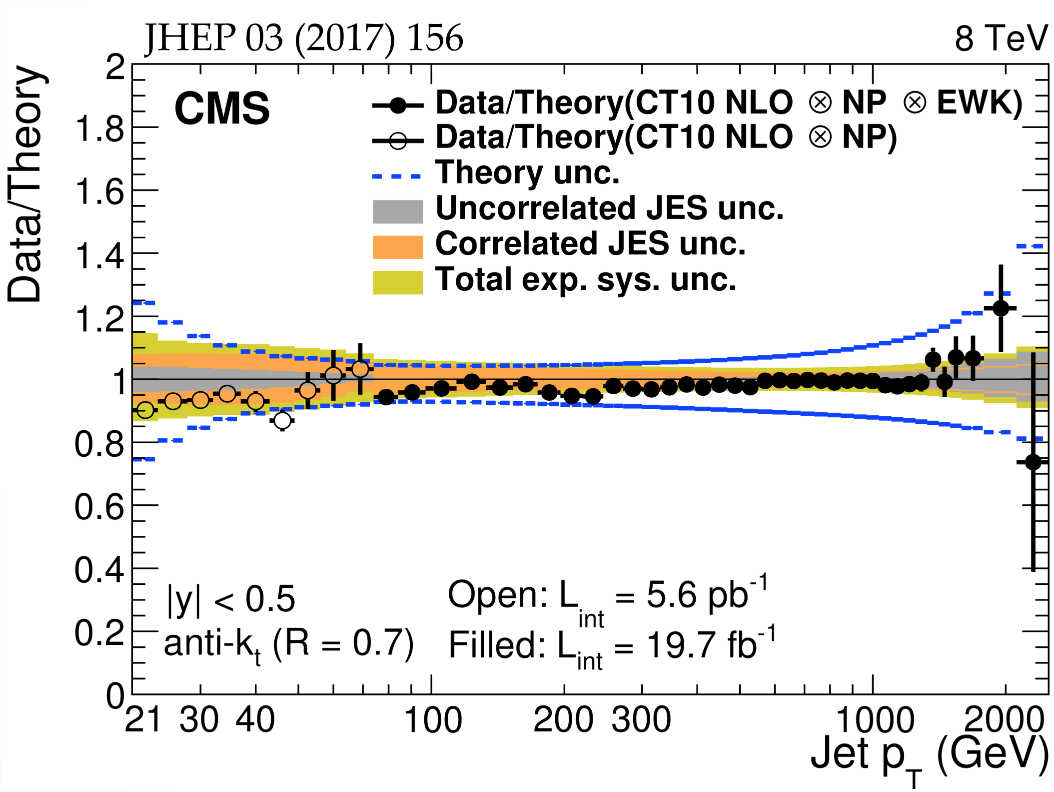




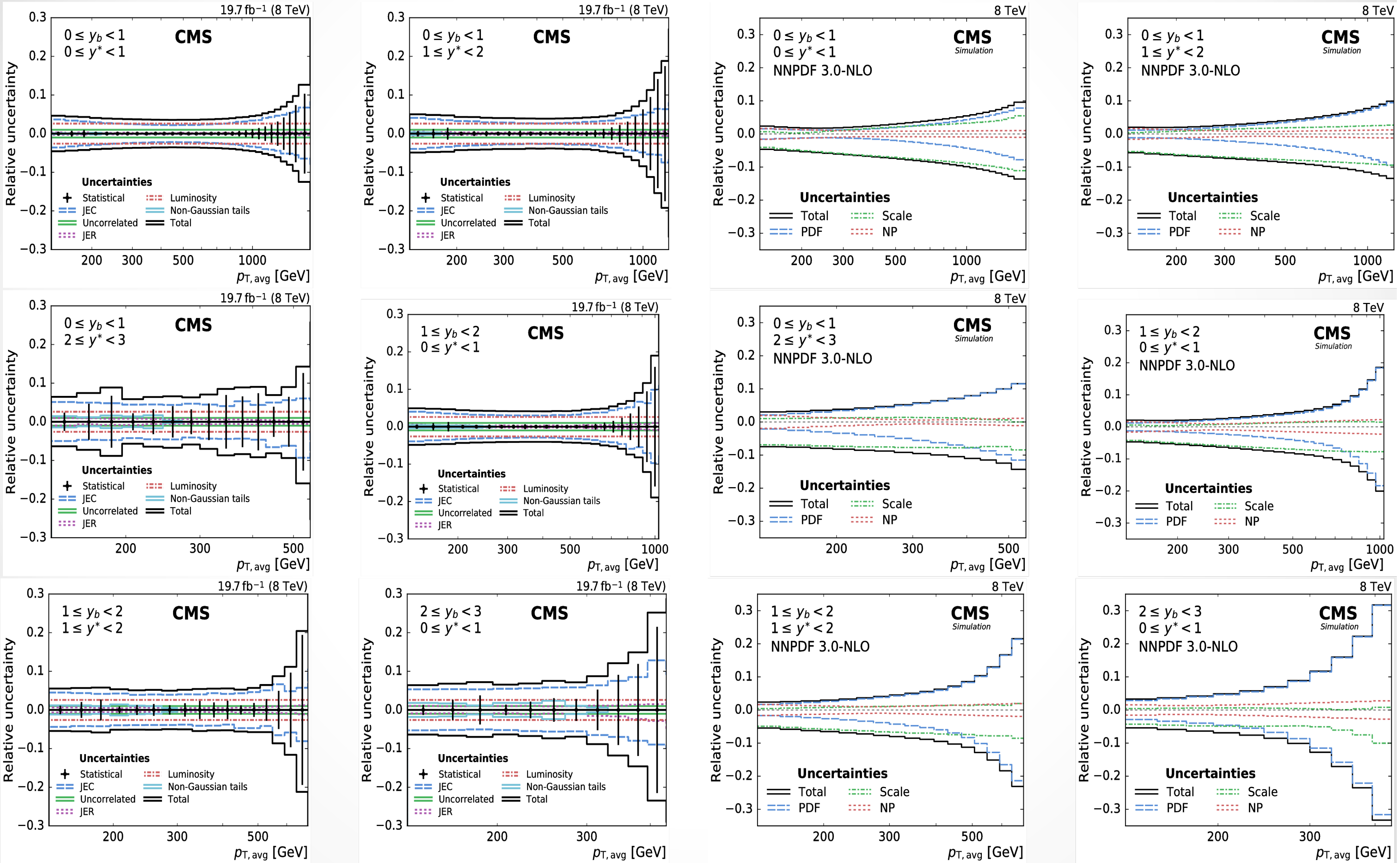


Inclusive jet cross-section @ 8 TeV

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \mathcal{L}_{\text{int,eff}}} \frac{N_{\text{jets}}}{\Delta p_T \, (2\Delta|y|)}$$

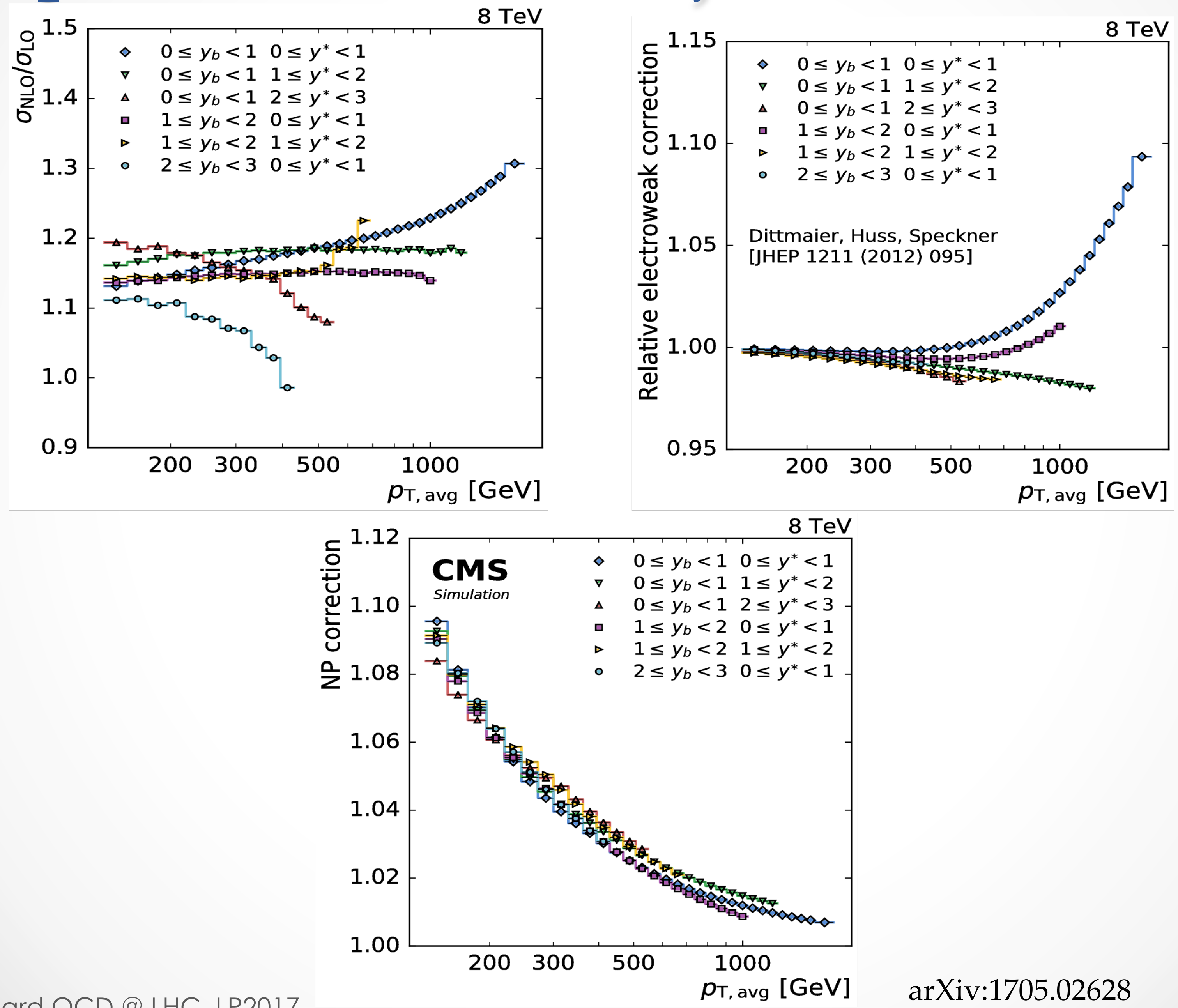


Triple differential dijet cross-section



arXiv:1705.02628

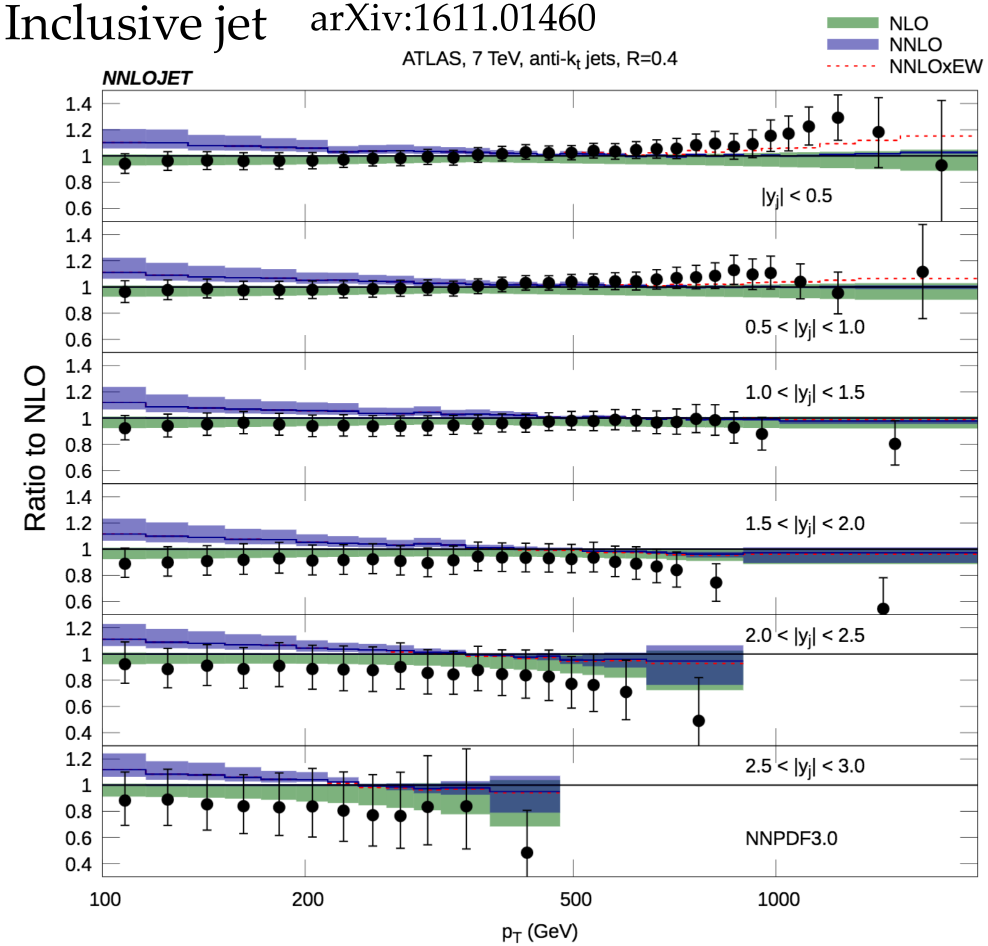
Triple differential dijet cross-section



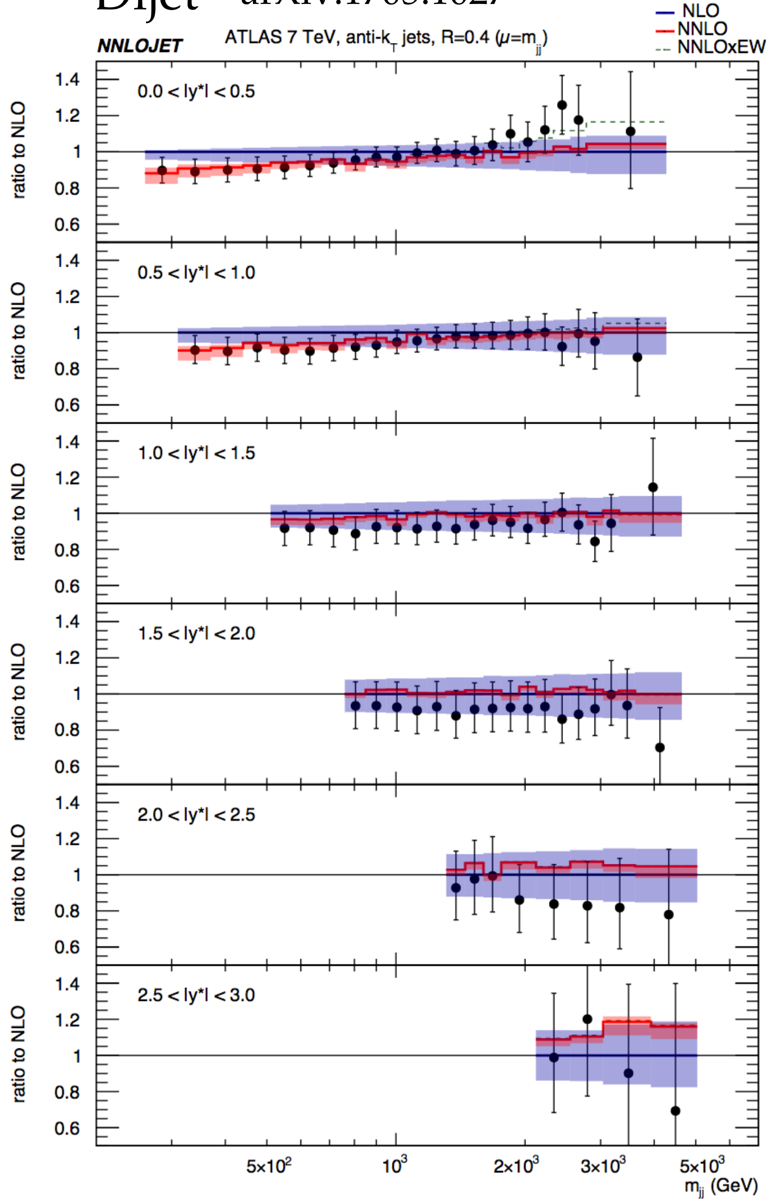
arXiv:1705.02628

NNLOJET

Inclusive jet arXiv:1611.01460

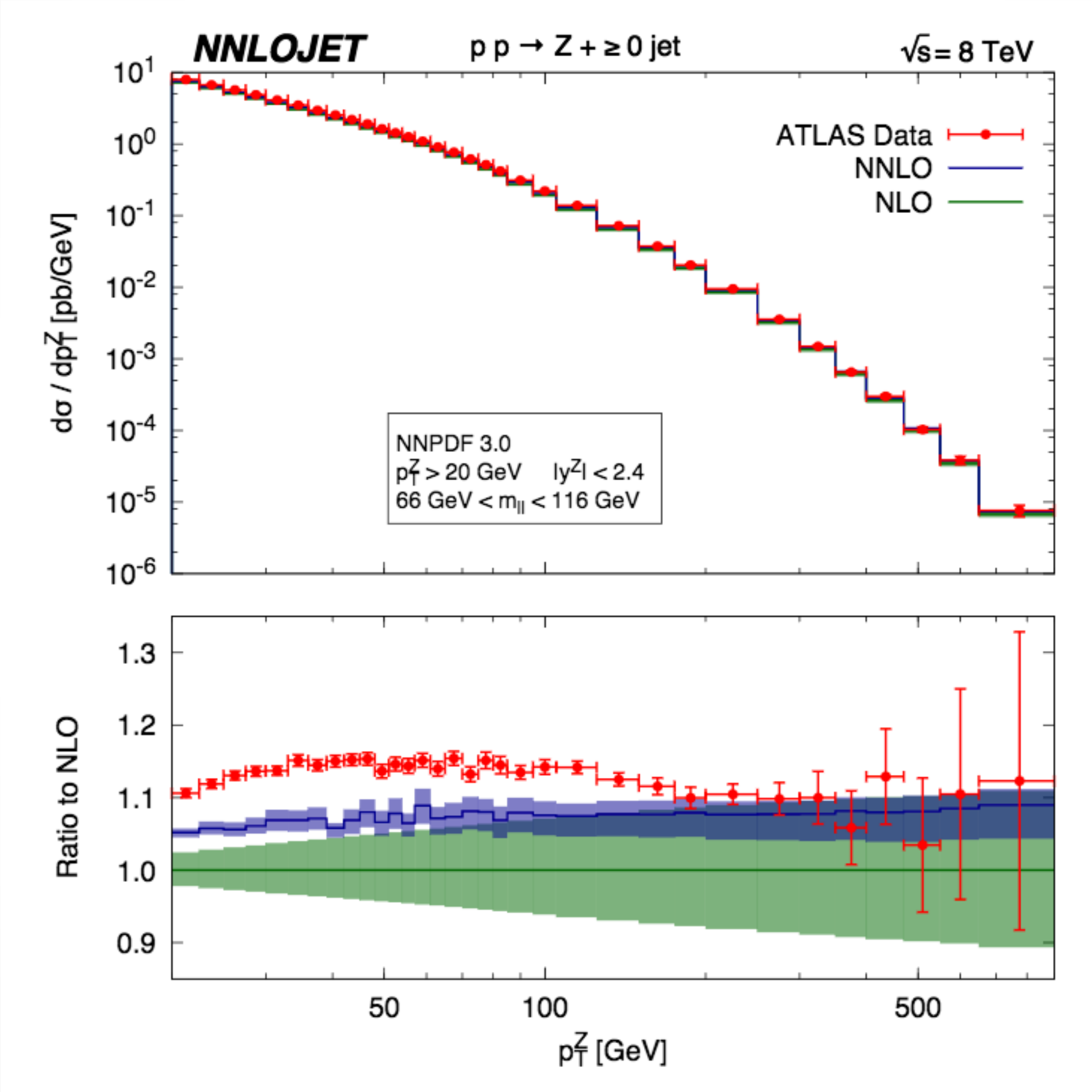


Dijet arXiv:1705.1027



- Long awaited NNLO jet cross-sections from Curie et al.
- Will be interesting to include in a full QCD fit of the data

NNLO Z+jets

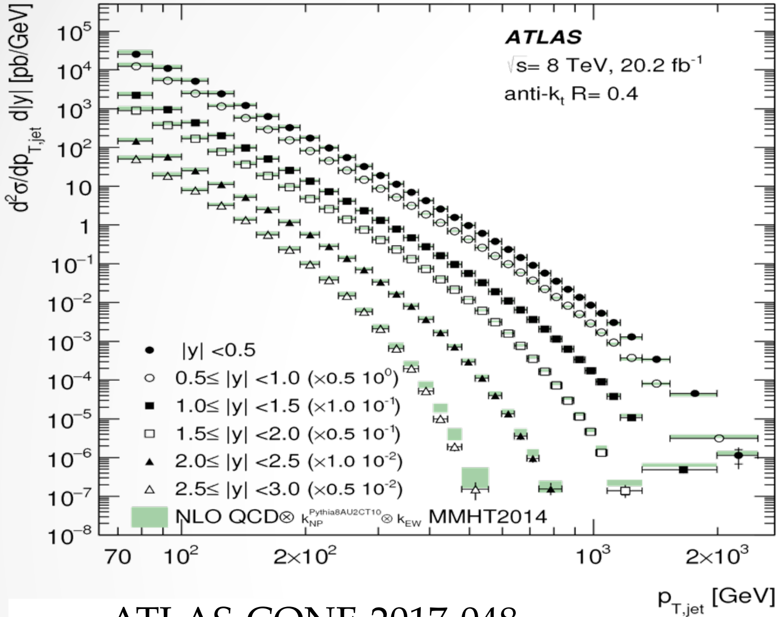


arXiv: 1607.01749

Inclusive jet cross-section

Data covers more than 12 orders of magnitude in cross-section, anti-kt jet, R=0.4-0.7

arXiv:1706.03192



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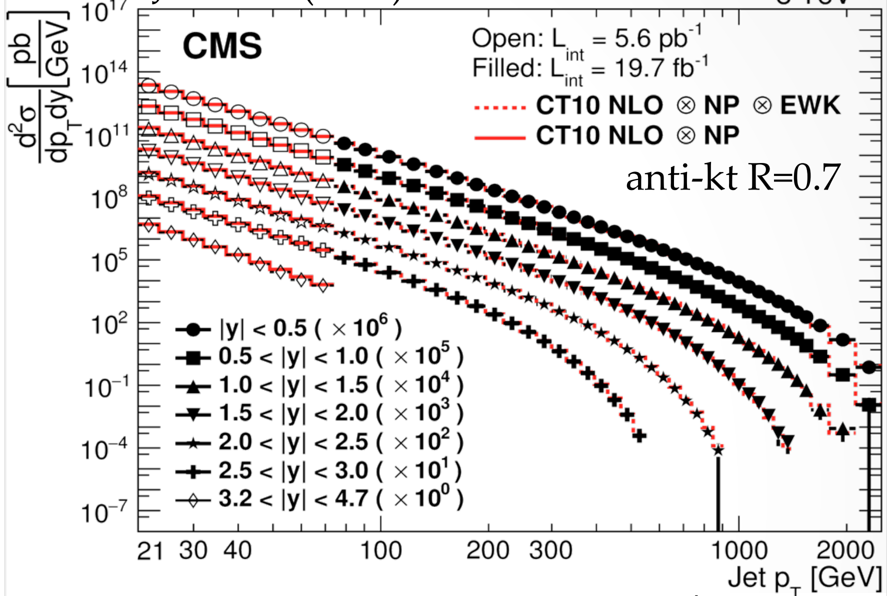
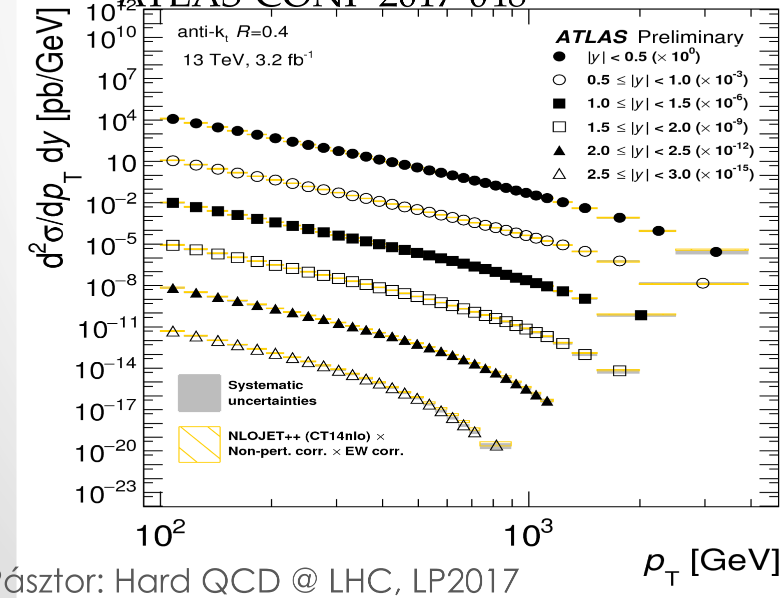
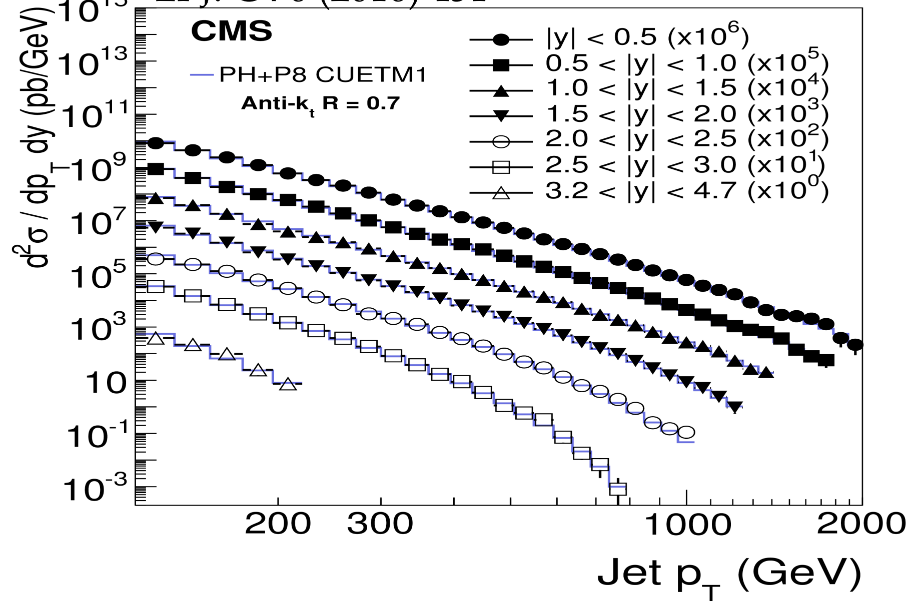


ATLAS-CONF-2017-048

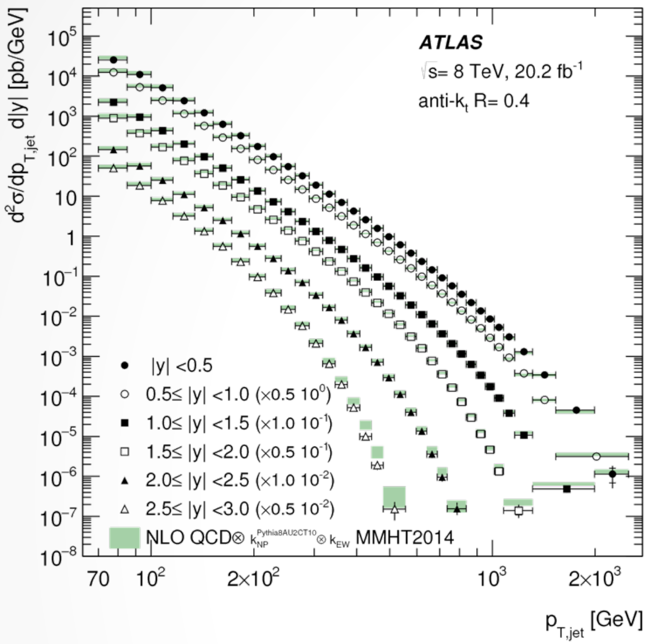


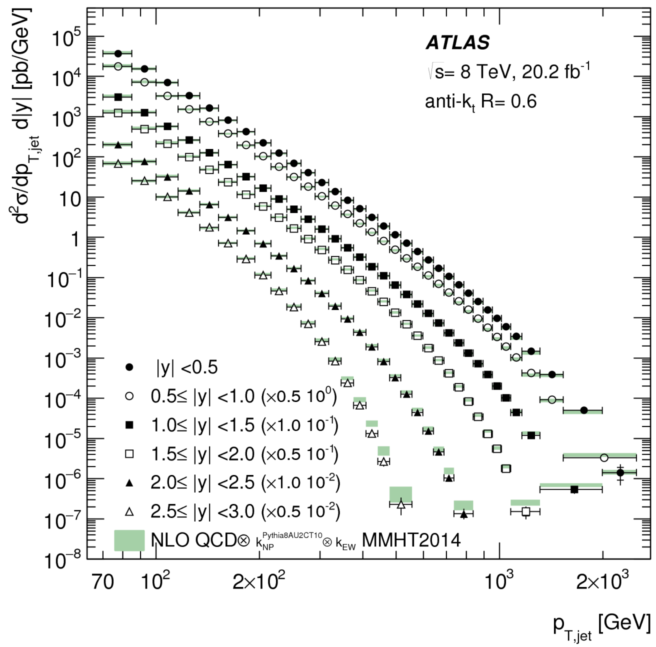
EPJ. C 76 (2016) 451

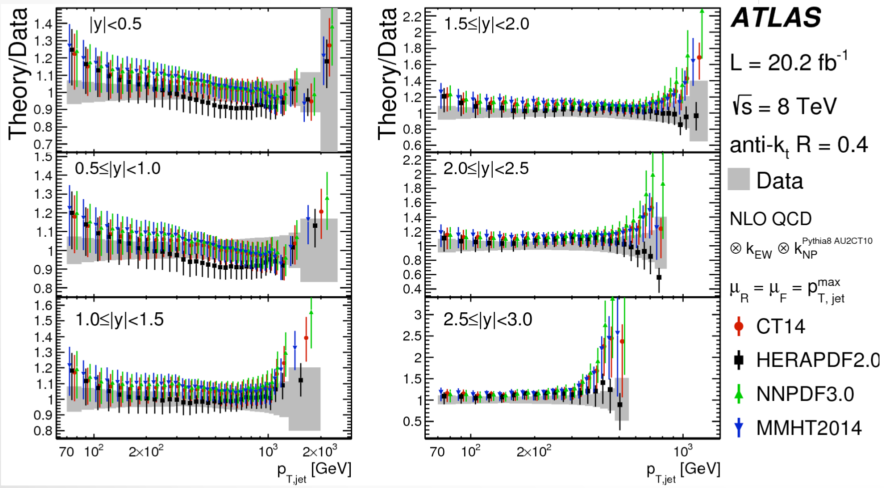


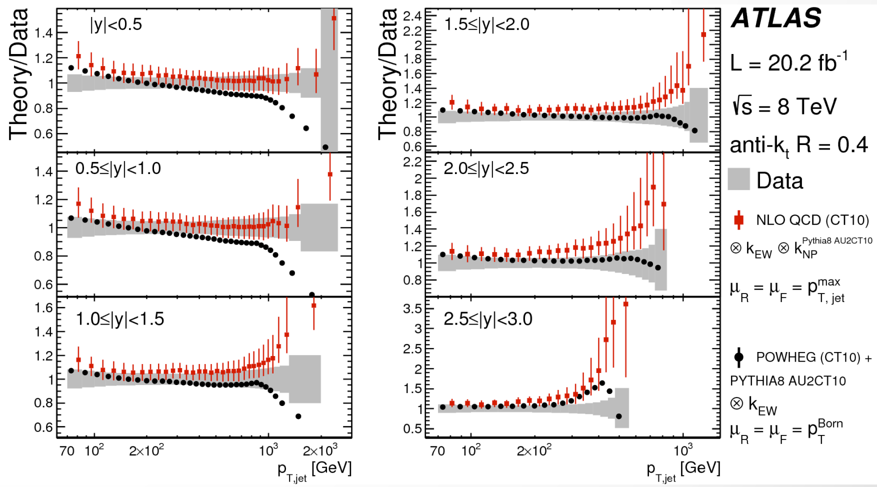
Inclusive jet cross-section @ 8 TeV

arXiv:1706.03192









α_s determination @ 8 TeV (Incl jet)

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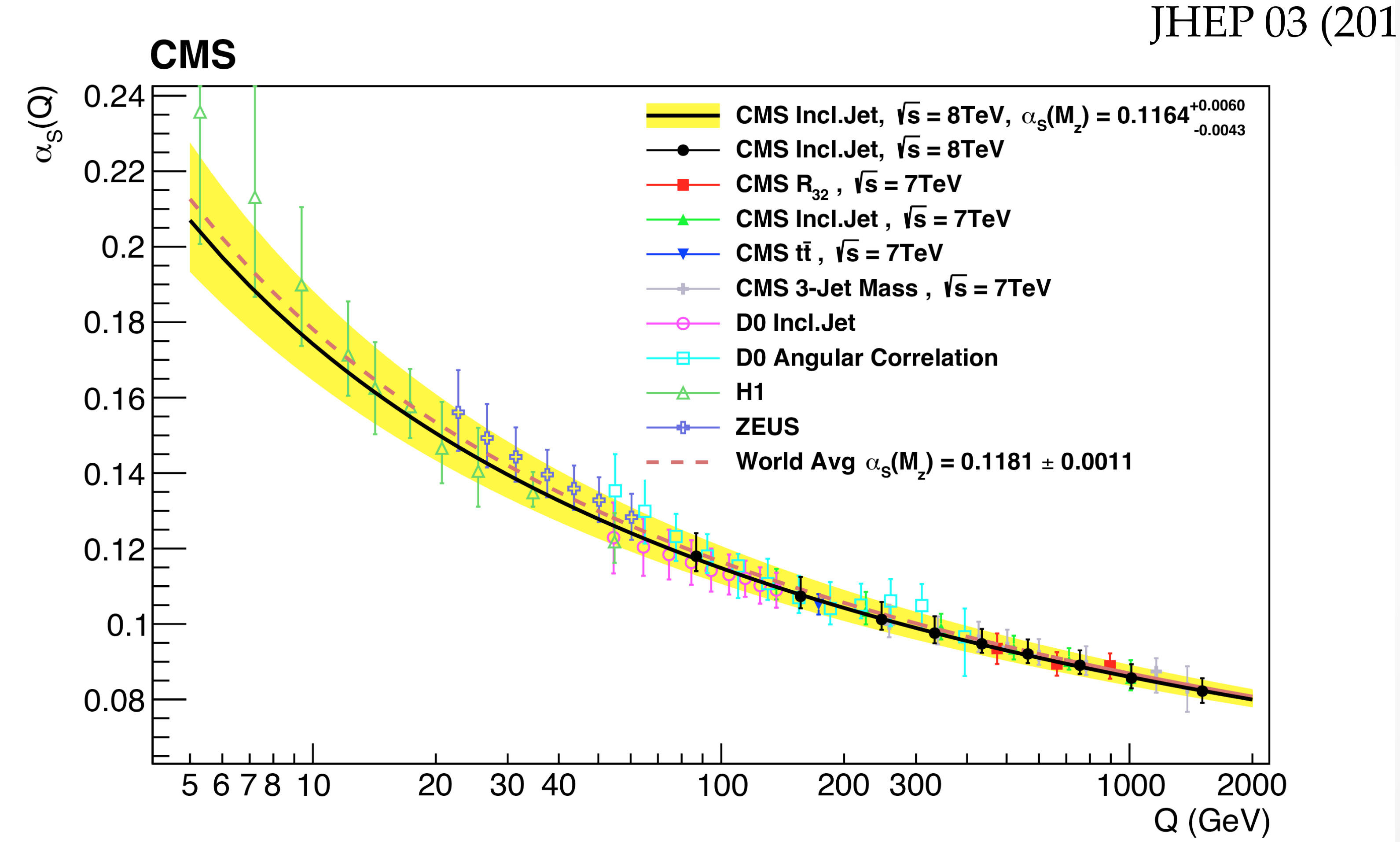


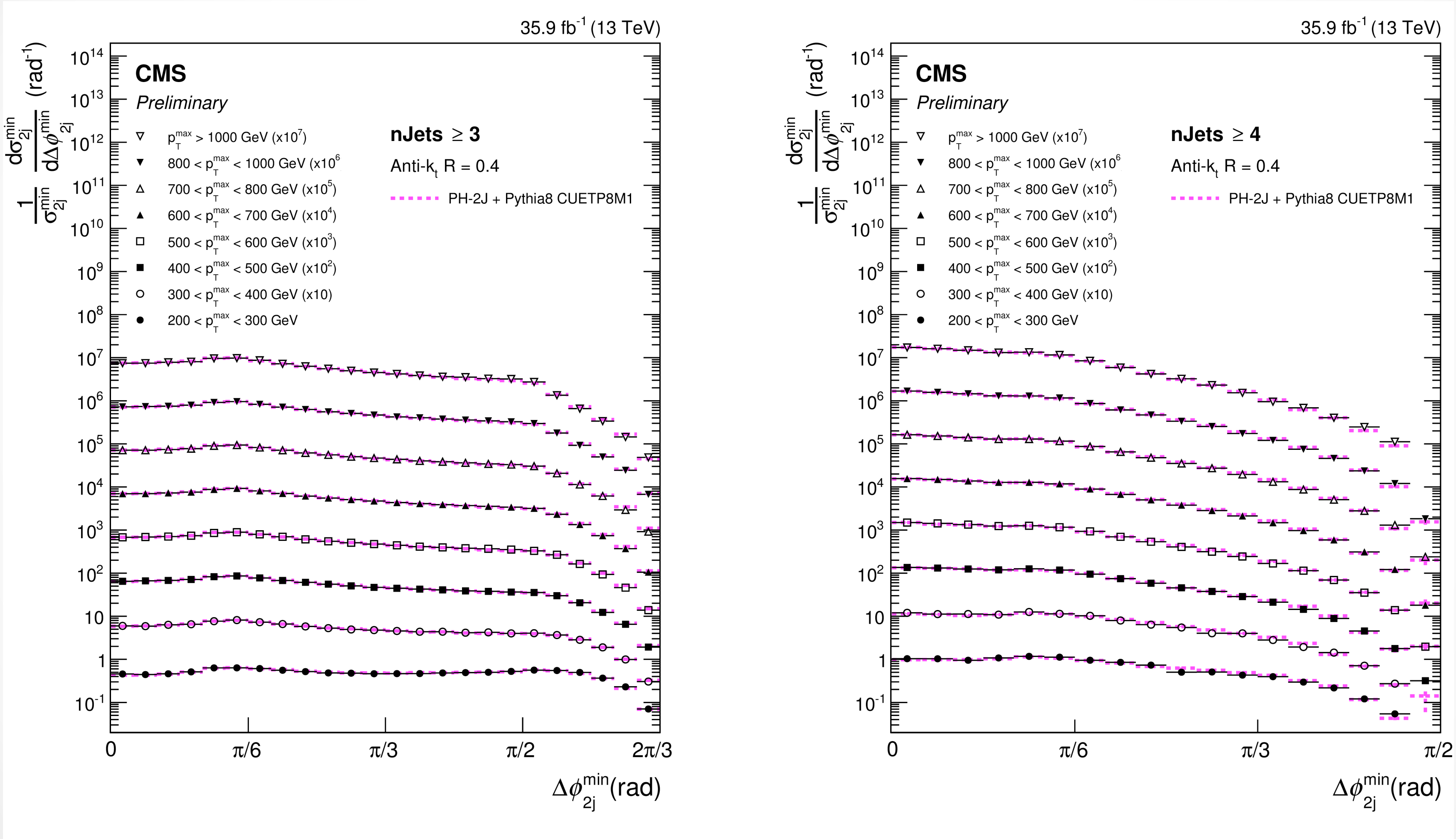
Azimuthal correlations in 2/3/4-jet topologies

- Pythia8 LO 2→2, p_T-ordered PS, Lund string hadronisation, MPI interleaved with PS, CUETP8M1 tune based on NNPDF2.3LO
- Herwig++ LO 2→2, angular-ordered PS, cluster fragmentation, MPI, CUETHppS1 tune based on the CTEQ6L1
- Madgraph LO up to 2→4, interfaced with Pythia8 for PS, hadronization, MPI, kT-MLM matching to remove double counting between ME and PS, NNPDF2.3LO
- Powheg NLO, interfaced with Pythia8 with tune CUETP8M1 or Herwig++ with tune CUETHppS1, matching with MC@NLO procedure (angular-ordered emission)
  - PH-2J: NLO 2-jet (min p_T for real parton emission of 10 GeV)
  - PH-3J: NLO 3-jet (min p_T for real parton emission of 100 GeV)
- Herwig7 NLO 2-jet, similar to Herwig++ for PS, hadronisation, MPI, MMHT 2014 PDF, default tune H7-UE-MMHT

Matrix element generator	Simulated diagrams	PDF set	Tune
PYTHIA8.219 [15]	2→2 (LO)	NNPDF2.3LO [26, 27]	CUETP8M1 [25]
HERWIG++ 2.7.1 [21]	2→2 (LO)	CTEQ6L1 [28]	CUETHppS1 [25]
MADGRAPH5 2.3.3 [29] + PYTHIA8.219 [15]	2→2, 2→3, 2→4 (LO)	NNPDF2.3LO [26, 27]	CUETP8M1 [25]
POWHEG V2_Sep2016 [31–33] + PYTHIA8.219 [15]	2→2 (NLO), 2→3 (LO)	NNPDF3.0nlo [37]	CUETP8M1 [25]
POWHEG V2_Sep2016 [31–33] + HERWIG++ 2.7.1 [21]	2→2 (NLO), 2→3 (LO)	NNPDF3.0nlo [37]	CUETHppS1 [25]
POWHEG V2_Sep2016 [31–33] + PYTHIA8.219 [15]	2→3 (NLO), 2→4 (LO)	NNPDF3.0nlo [37]	CUETP8M1 [25]
HERWIG7.0.4 [34]	2→2 (LO)	MMHT2014 [38]	H7-UE-MMHT [34]

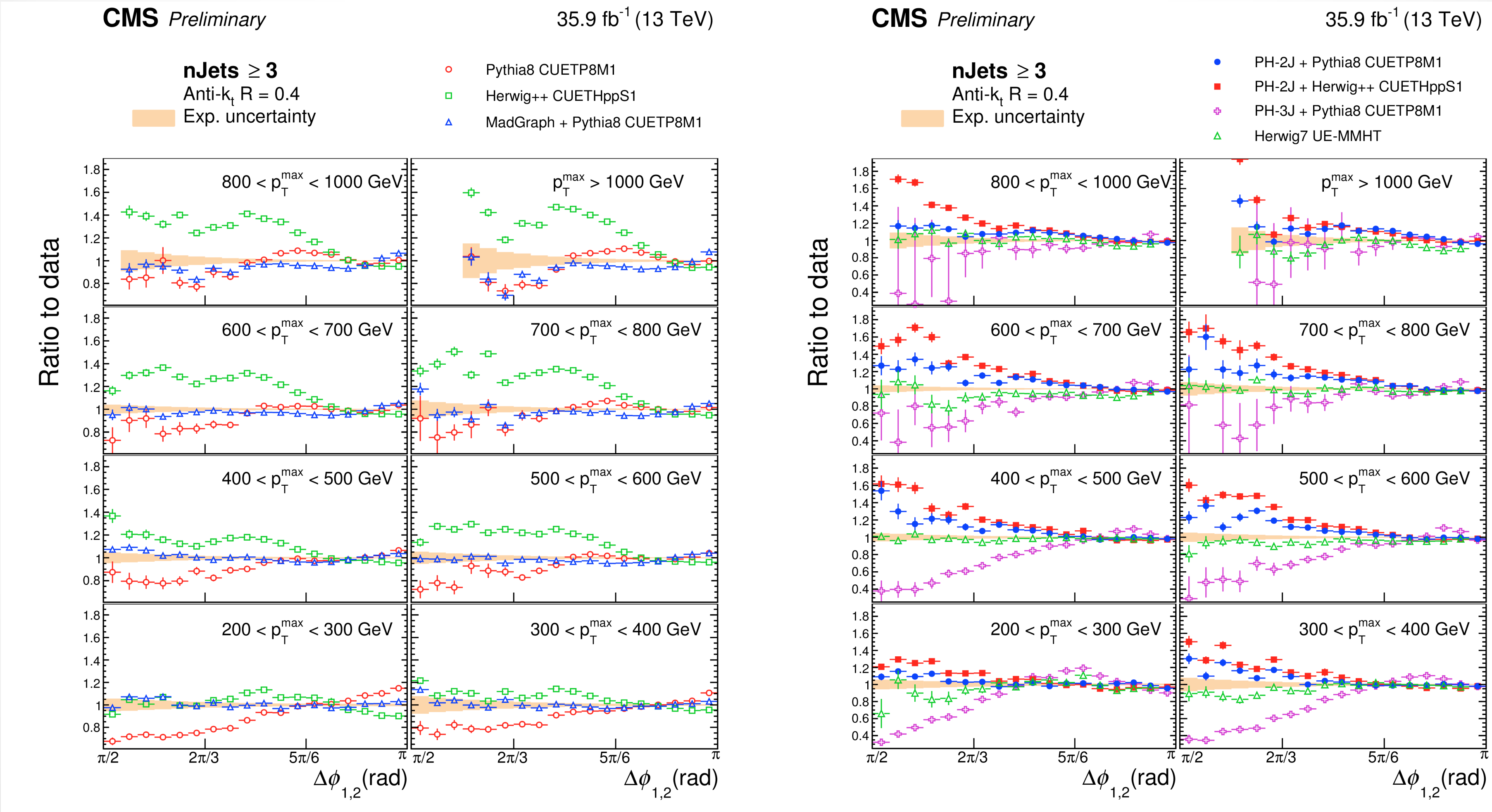
CMS-PAS-SMP-16-014

Azimuthal correlations in 3/4-jet topologies



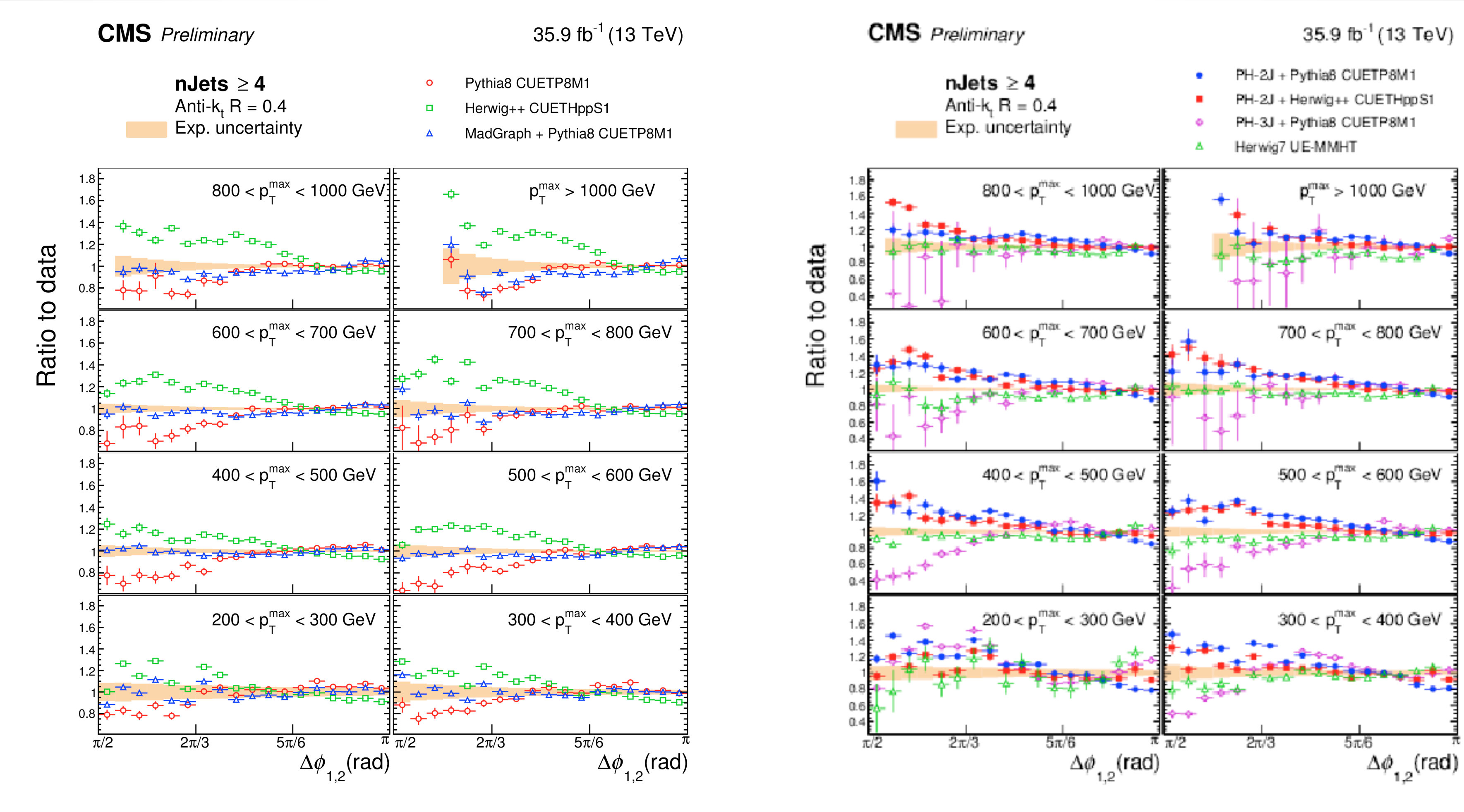
CMS-PAS-SMP-16-014

Azimuthal correlations in 3-jet topologies



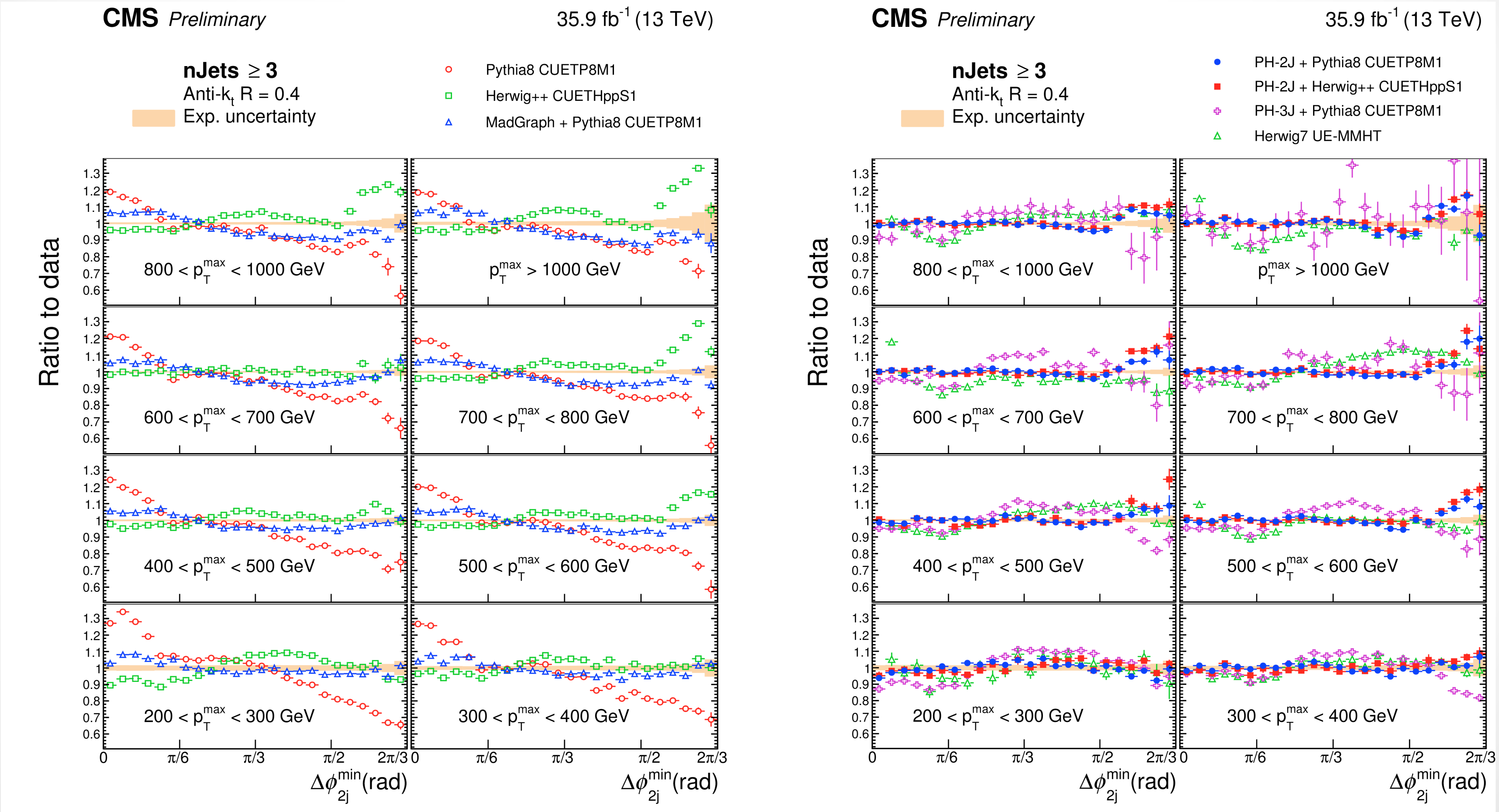
CMS-PAS-SMP-16-014

Azimuthal correlations in 4-jet topologies



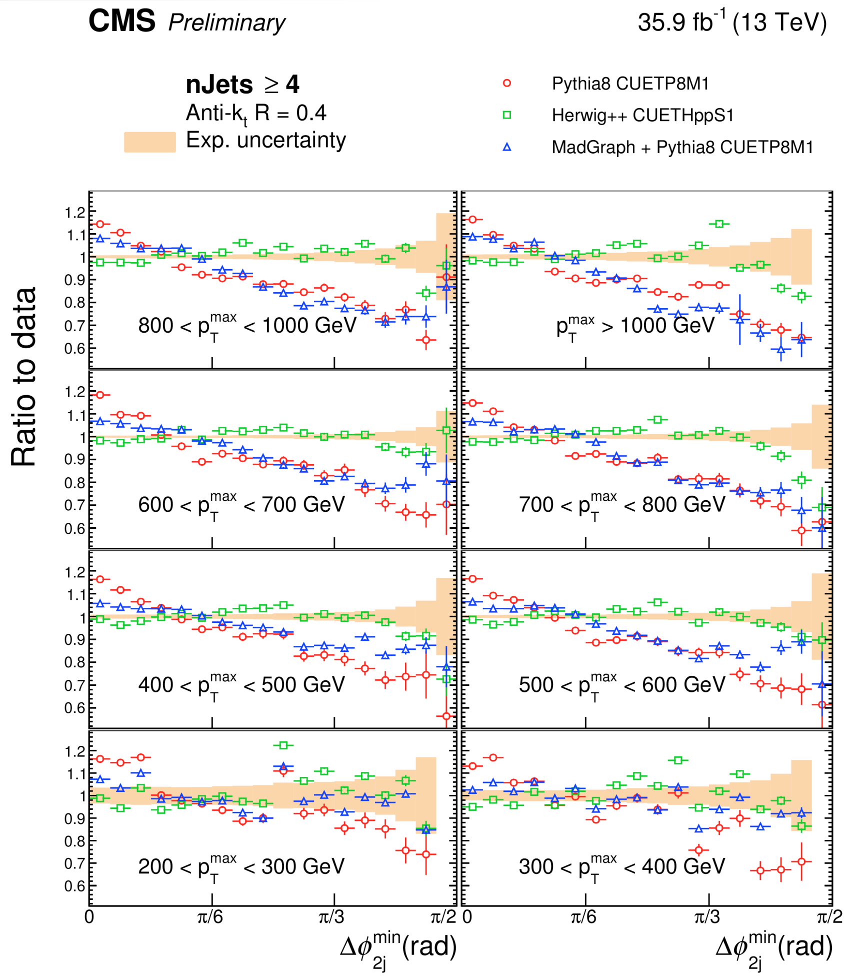
CMS-PAS-SMP-16-014

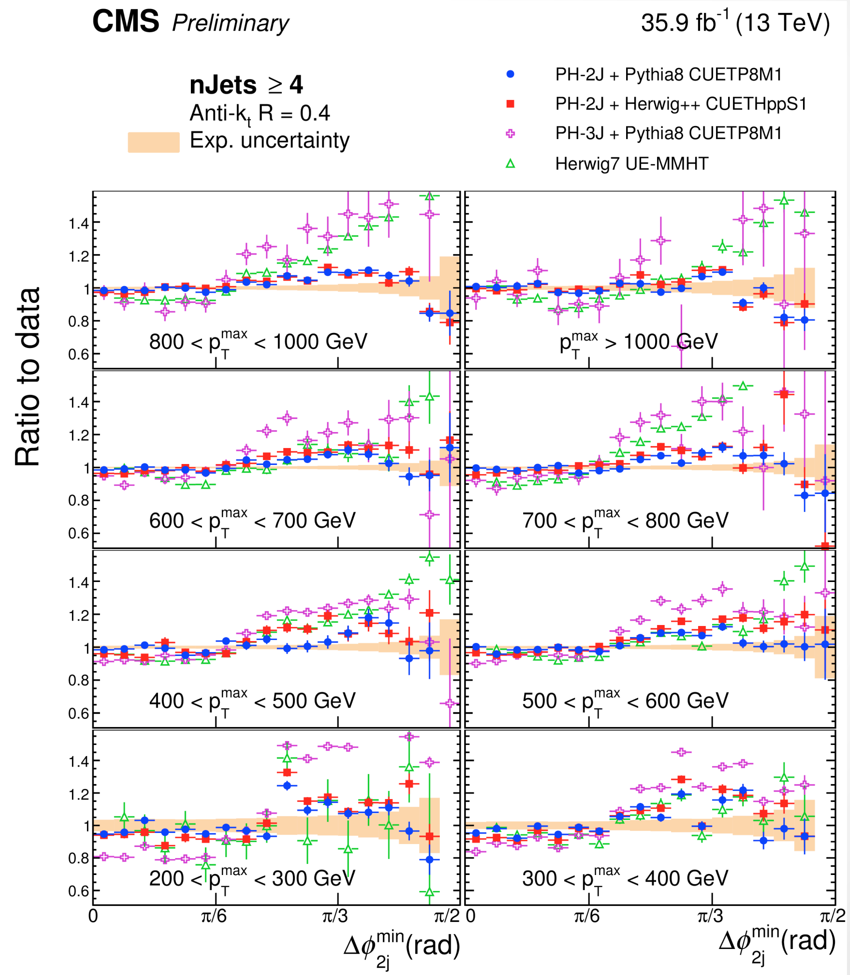
Azimuthal correlations in 3-jet topologies



CMS-PAS-SMP-16-014

Azimuthal correlations in 4-jet topologies





CMS-PAS-SMP-16-014

Transverse energy-energy correlation

- TEEC: Energy-weighted angular distribution of jet pairs

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d\cos\phi}\, x_{Ti}x_{Tj}dx_{Ti}dx_{Tj} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{Ti}E^A_{Tj}}{\left(\sum_k E^A_{Tk}\right)^2}\delta(\cos\phi-\cos\phi_{ij})$$

jet indices in event

$x_{Ti} = E_{Ti}/\sum_k E_{Tk}$

jet E_T

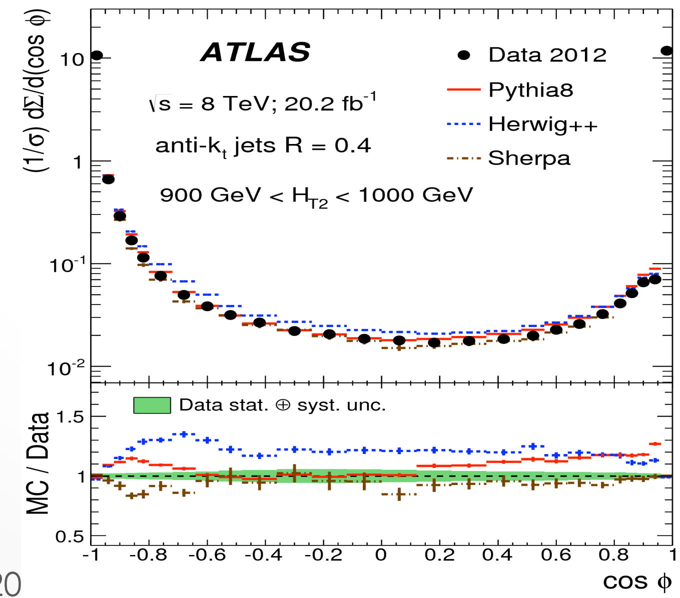
# of multijet events

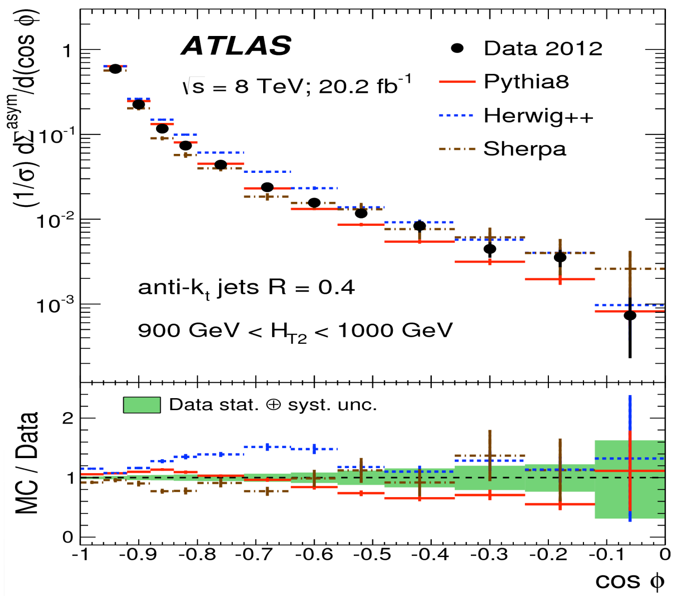
angle in transverse plane between jets

- ATEEC: asymmetry between forward ($\cos\phi>0$) and backward ($\cos\phi<0$) parts of TEEC

$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} \equiv \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

- Moderate NLO corrections (NLOJET++) → precision test of pQCD
- At NLO, TEEC ∝ α_s^2 ATTEC ∝ α_s^2
- Stable wrt experimental uncertainties





arXiv:1707.02562

α_s determination

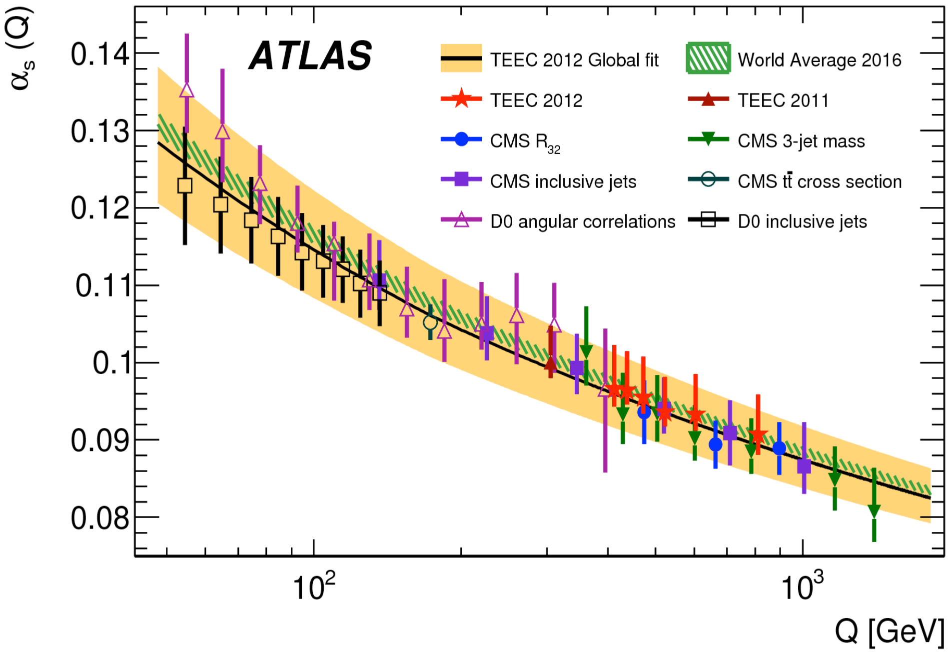
arXiv:1707.02562

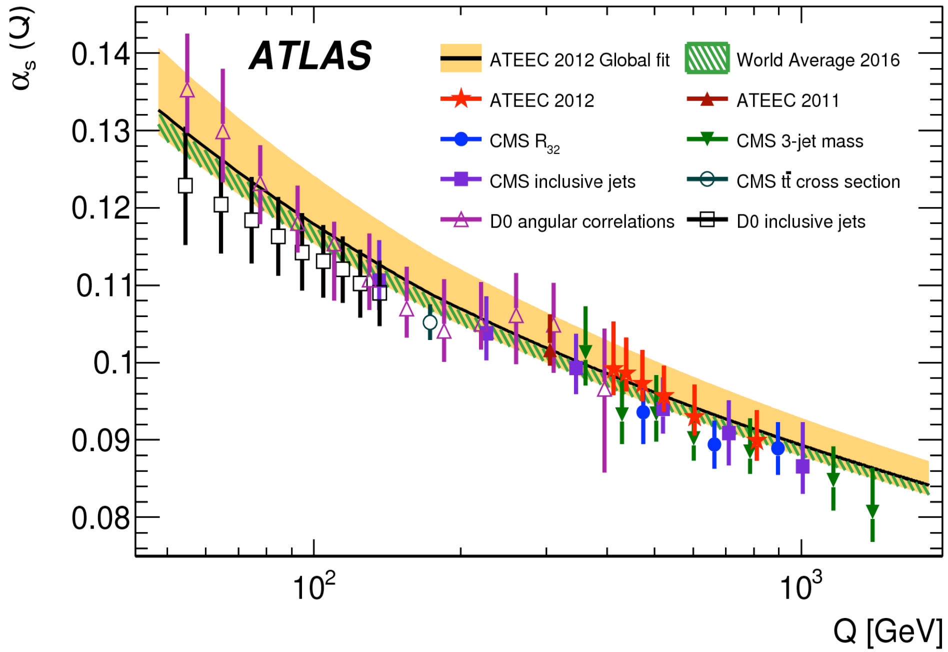
TEEC

PDF	$\alpha_s(m_Z)$ value	χ^2/N_{dof}
MMHT 2014	0.1151 ± 0.0008 (exp.) $^{+0.0064}_{-0.0047}$ (scale) ± 0.0012 (PDF) ± 0.0002 (NP)	173 / 131
CT14	0.1165 ± 0.0010 (exp.) $^{+0.0067}_{-0.0061}$ (scale) ± 0.0016 (PDF) ± 0.0003 (NP)	161 / 131
NNPDF 3.0	0.1162 ± 0.0011 (exp.) $^{+0.0076}_{-0.0061}$ (scale) ± 0.0018 (PDF) ± 0.0003 (NP)	174 / 131
HERAPDF 2.0	0.1177 ± 0.0008 (exp.) $^{+0.0064}_{-0.0040}$ (scale) ± 0.0005 (PDF) ± 0.0002 (NP) $^{+0.0008}_{-0.0007}$ (mod)	169 / 131

ATEEC

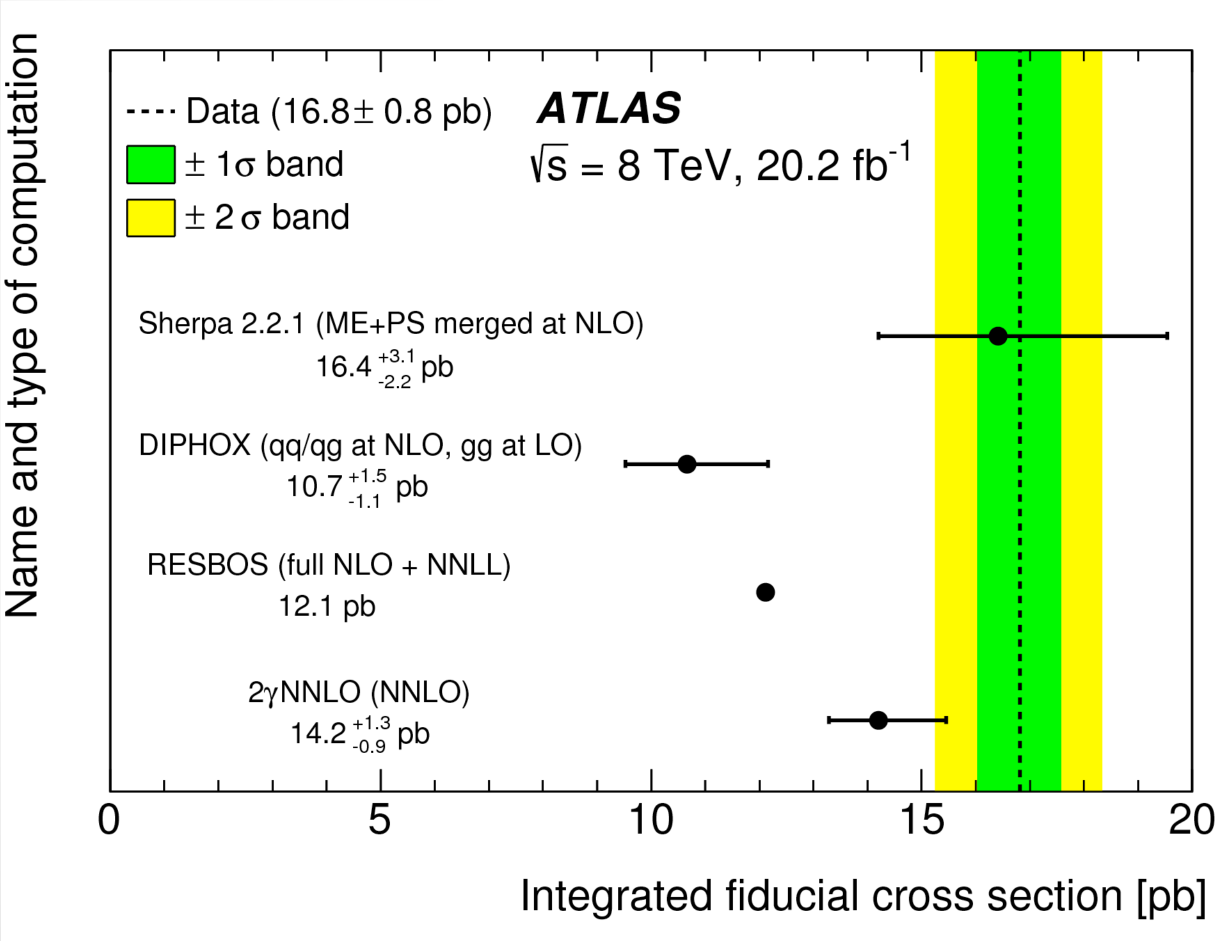
PDF	$\alpha_s(m_Z)$ value	χ^2/N_{dof}
MMHT 2014	0.1185 ± 0.0012 (exp.) $^{+0.0047}_{-0.0010}$ (scale) ± 0.0010 (PDF) ± 0.0004 (NP)	57.0 / 65
CT14	0.1203 ± 0.0013 (exp.) $^{+0.0053}_{-0.0014}$ (scale) ± 0.0015 (PDF) ± 0.0004 (NP)	55.4 / 65
NNPDF 3.0	0.1196 ± 0.0013 (exp.) $^{+0.0061}_{-0.0013}$ (scale) ± 0.0017 (PDF) ± 0.0004 (NP)	60.3 / 65
HERAPDF 2.0	0.1206 ± 0.0012 (exp.) $^{+0.0050}_{-0.0014}$ (scale) ± 0.0005 (PDF) ± 0.0002 (NP) ± 0.0007 (mod)	54.2 / 65

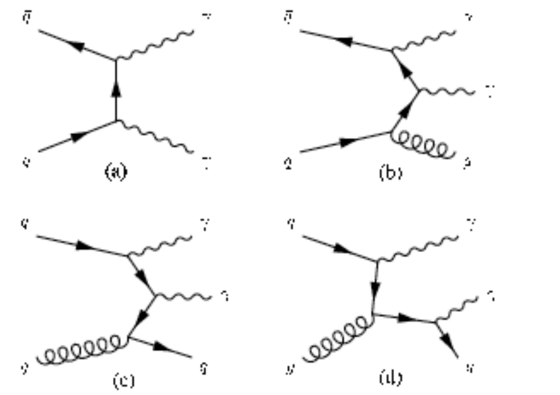




Diphoton cross-section

- Sensitive to α_s corrections, QCD infrared emission





Particle level
Sherpa (NNPDF3.0 NNLO):
- $\gamma\gamma$ + 0-1 parton: NLO
- $\gamma\gamma$ + 2-3 partons: LO

Parton level
DIPHOX NLO (CT10 NLO)
Resbos NLO+NLL (CT10 NLO)
- No uncertanity provided

2γNNLO (CT10 NNLO)

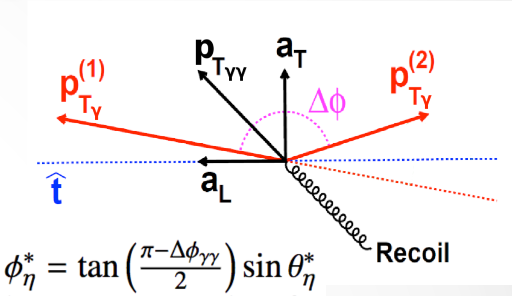
Fixed order calculations lower than data
Improved at NNLO

Di-photon sample composition

Process	Event fraction [%] Two-dimensional template fit	Event fraction [%] Matrix method
$\gamma\gamma$	75.3 ± 0.3 (stat) $^{+2.6}_{-2.8}$ (syst)	73.9 ± 0.3 (stat) $^{+3.1}_{-2.7}$ (syst)
γj	14.5 ± 0.2 (stat) $^{+2.7}_{-2.8}$ (syst)	14.4 ± 0.2 (stat) $^{+2.0}_{-2.4}$ (syst)
jγ	6.0 ± 0.2 (stat) $^{+1.4}_{-1.5}$ (syst)	5.8 ± 0.1 (stat) ± 0.6 (syst)
jj	1.6 ± 0.2 (stat) $^{+0.9}_{-0.4}$ (syst)	2.4 ± 0.1 (stat) $^{+0.6}_{-0.5}$ (syst)
ee	2.6 ± 0.2 (stat) $^{+0.9}_{-0.4}$ (syst)	3.5 ± 0.1 (stat) ± 0.4 (syst)

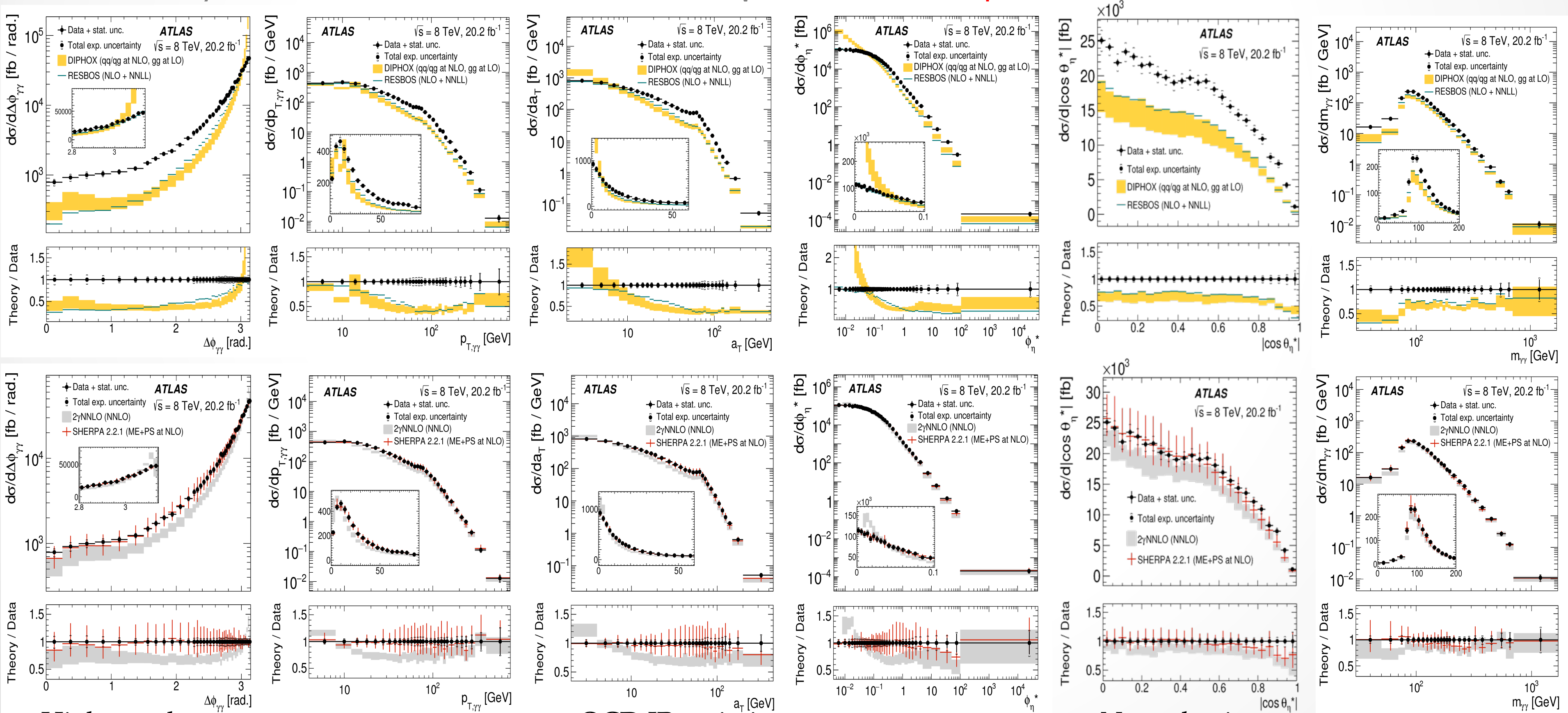
Diphoton cross-section

- Improvement from NLO to NNLO
- Fixed order predictions can not reproduce data
- Especially in regions sensitive to infrared emissions (low $p_{T,\gamma\gamma}$, ϕ^*_η, a_T, $\Delta\phi_{\gamma\gamma} \sim \pi$)
  - Need soft-gluon resummation at NNLL
- Theory curves: DIPHOX, Resbos, 2γNNLO, Sherpa



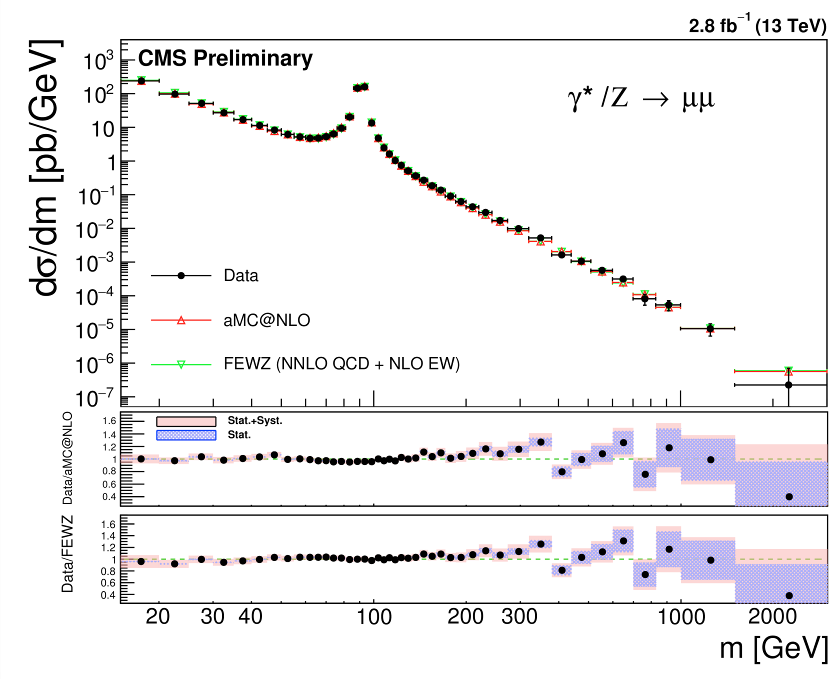
$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi_{\gamma\gamma}}{2}\right) \sin\theta^*_\eta$$

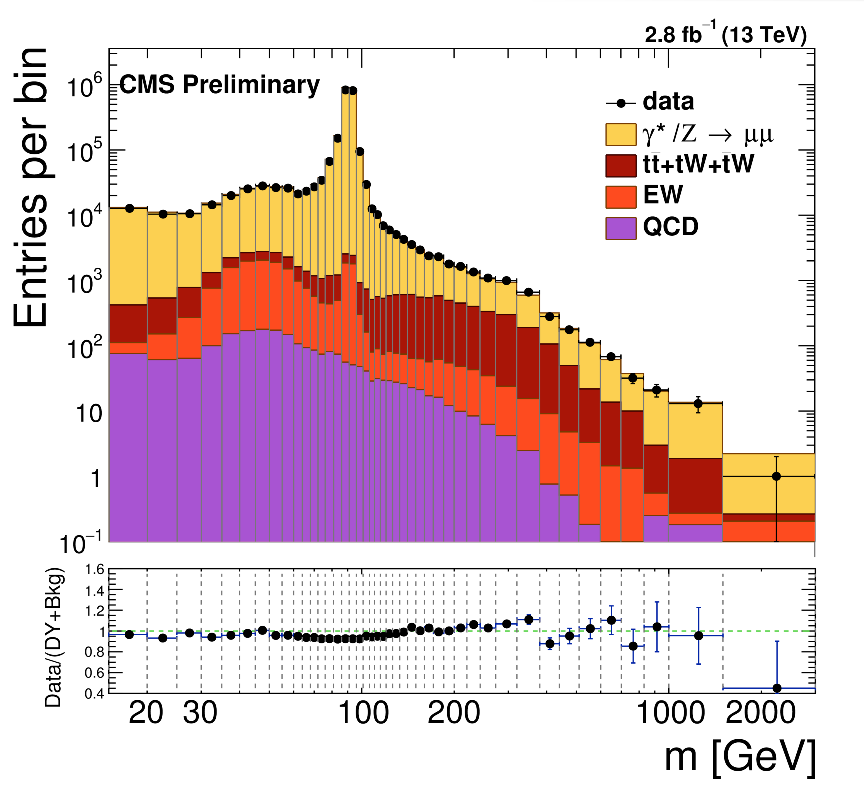
$$|\cos\theta^*_\eta| = \tanh\frac{|\Delta\eta_{\gamma\gamma}|}{2}$$



Higher order QCD IR emission New physics

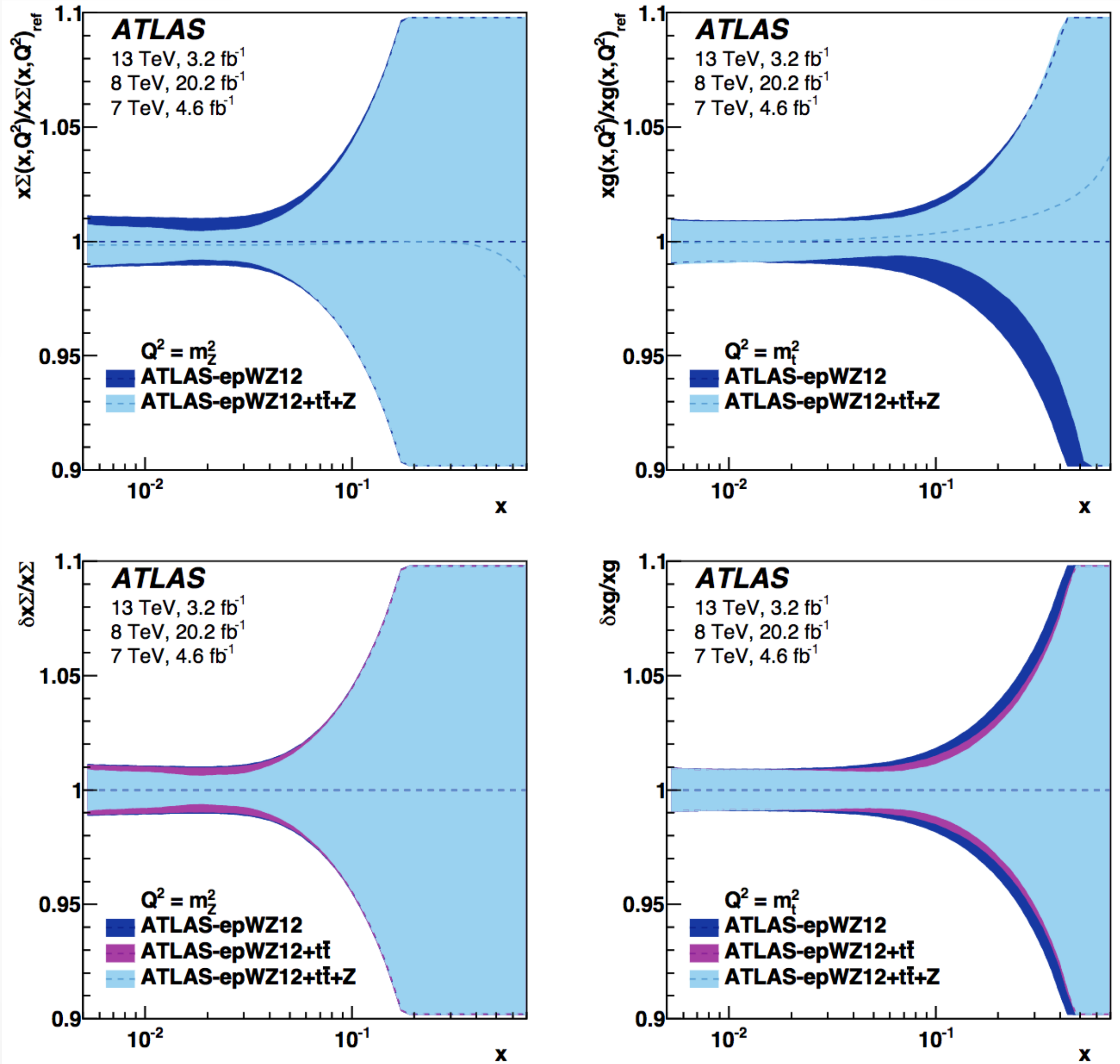
DY @ 13 TeV





CMS-PAS-SMP-16-009

tt, Z data: effect on PDF



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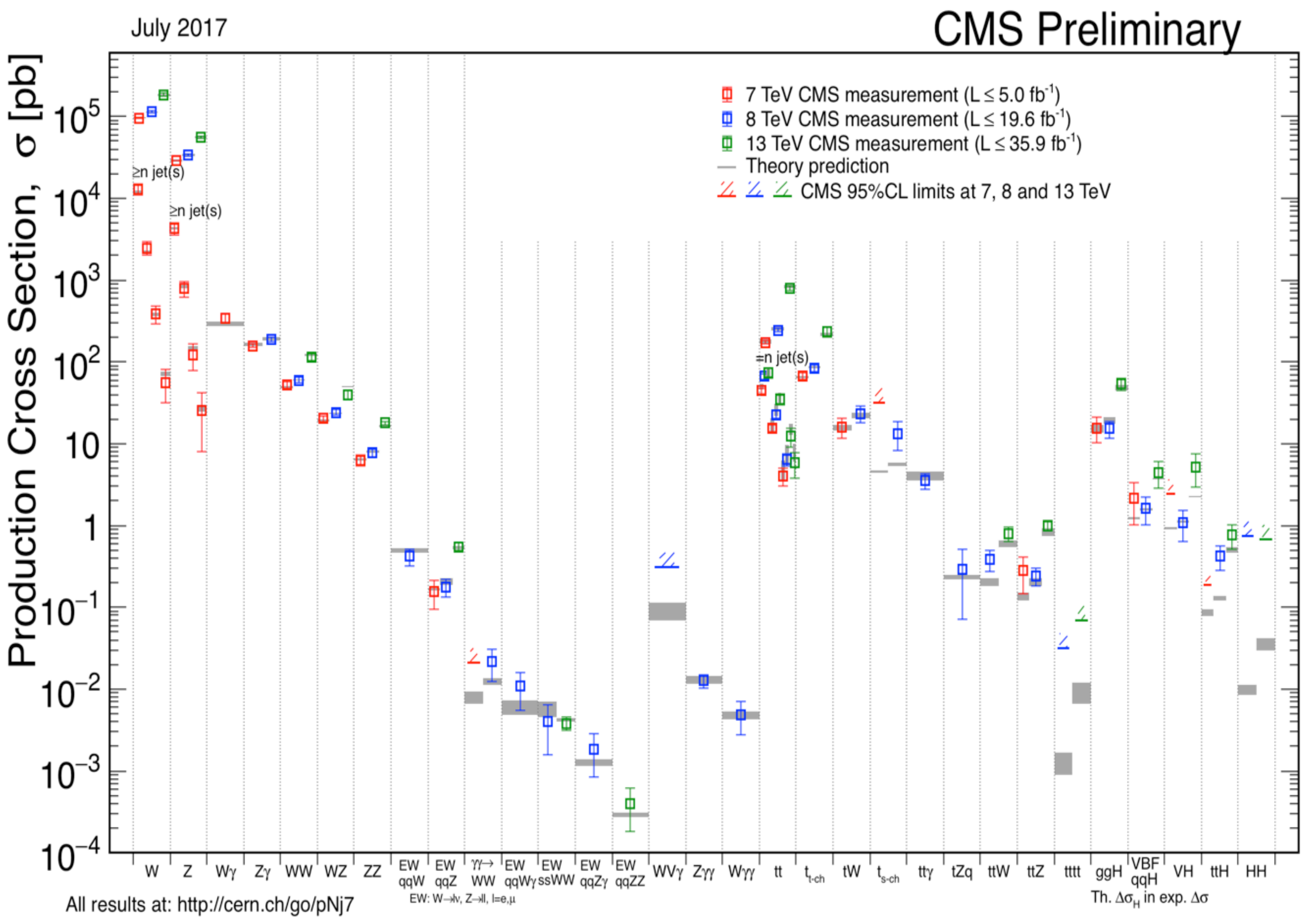
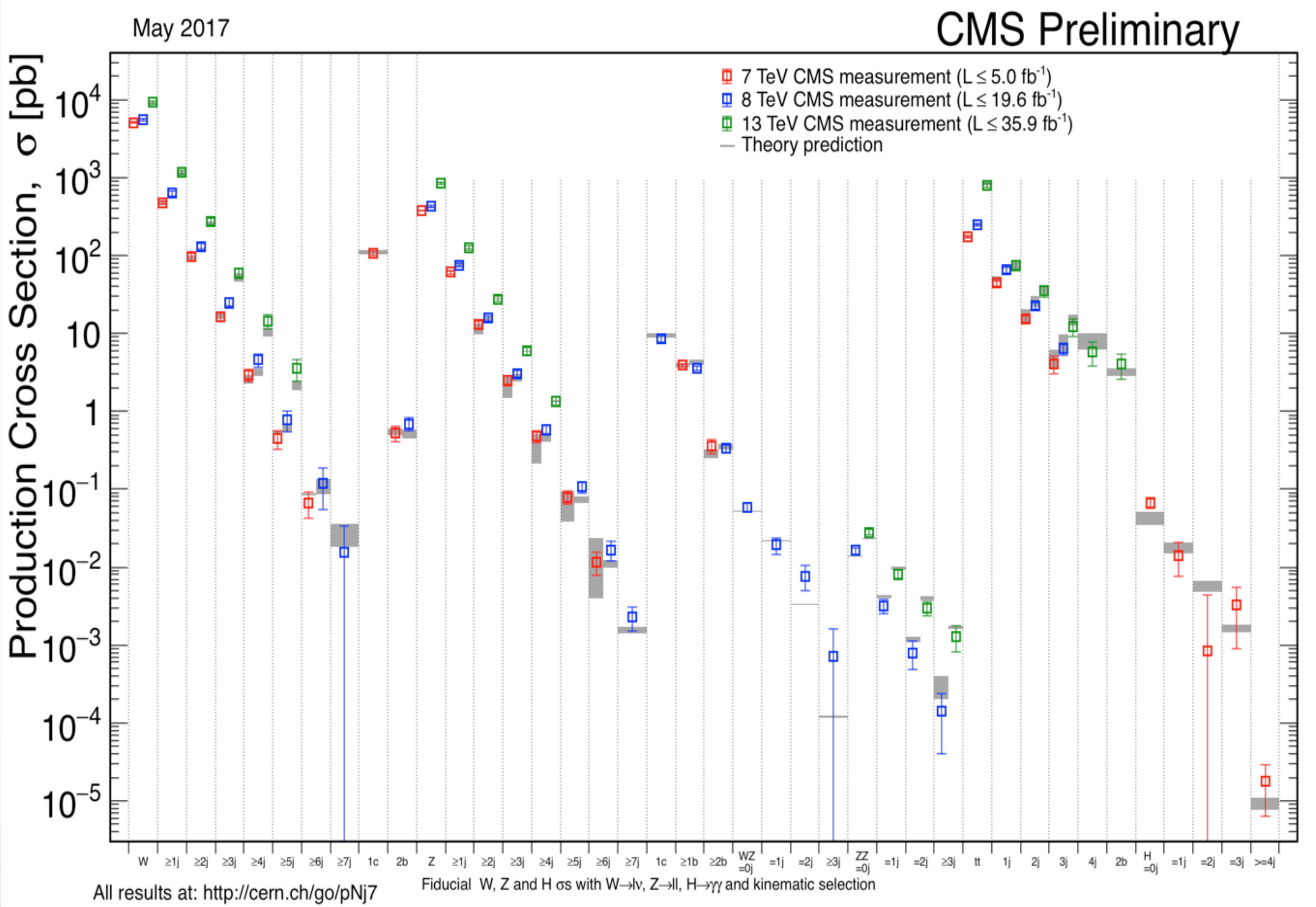
Summary plots

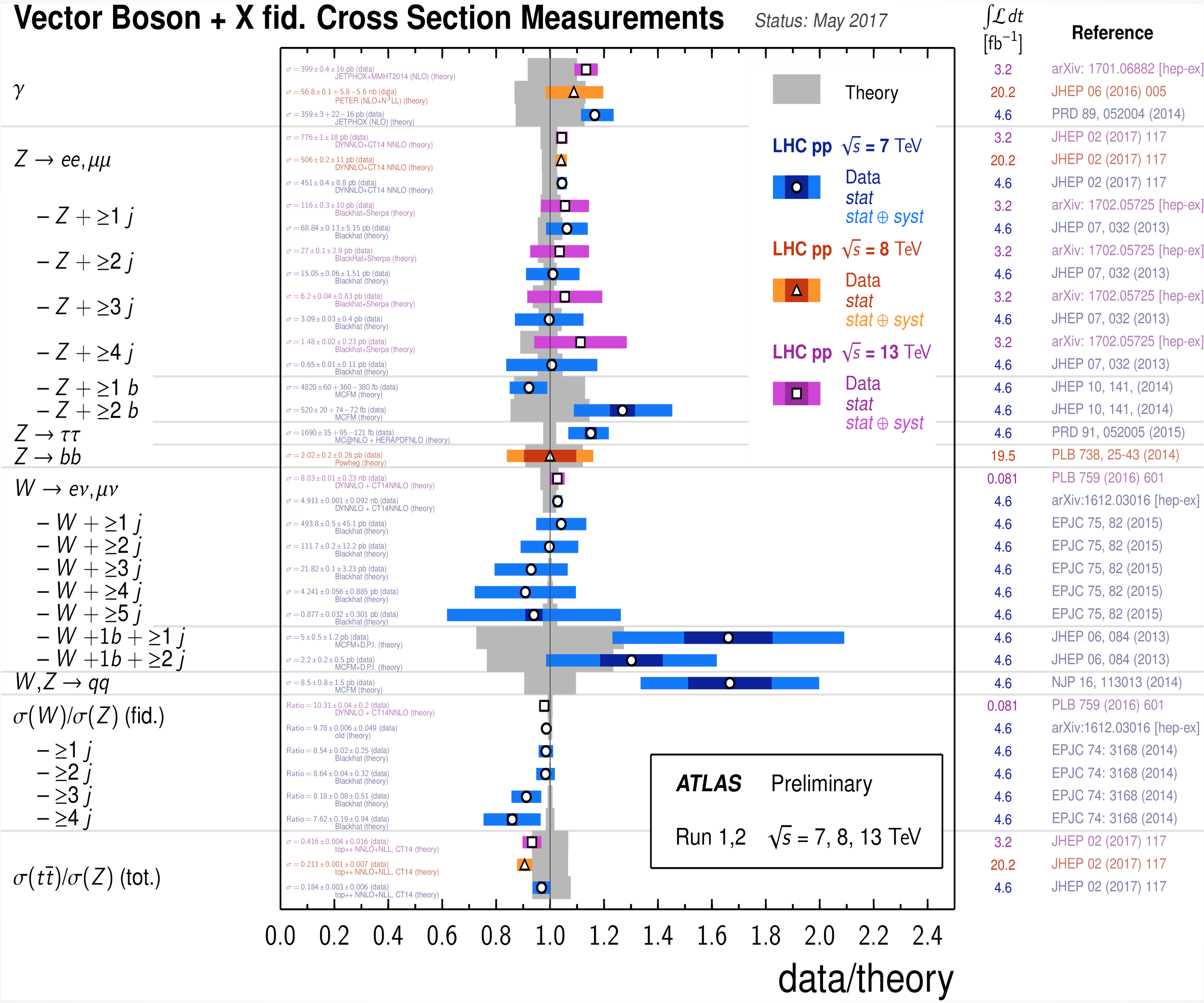
SM results


July 2017
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
13 TeV CMS measurement (L ≤ 35.9 fb⁻¹)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
=n jet(s)
W Z Wγ Zγ WW WZ ZZ EW qqW EW qqZ γγ→WW EW qqWγ EW ssWW EW qqZγ EW qqZZ WVγ Zγγ Wγγ tt t-ch tW ts-ch ttγ tZq ttW ttZ tttt ggH VBF qqH VH ttH HH
EW: W→lν, Z→ll, l=e,μ
Th. ΔσH in exp. Δσ
All results at: http://cern.ch/go/pNj7

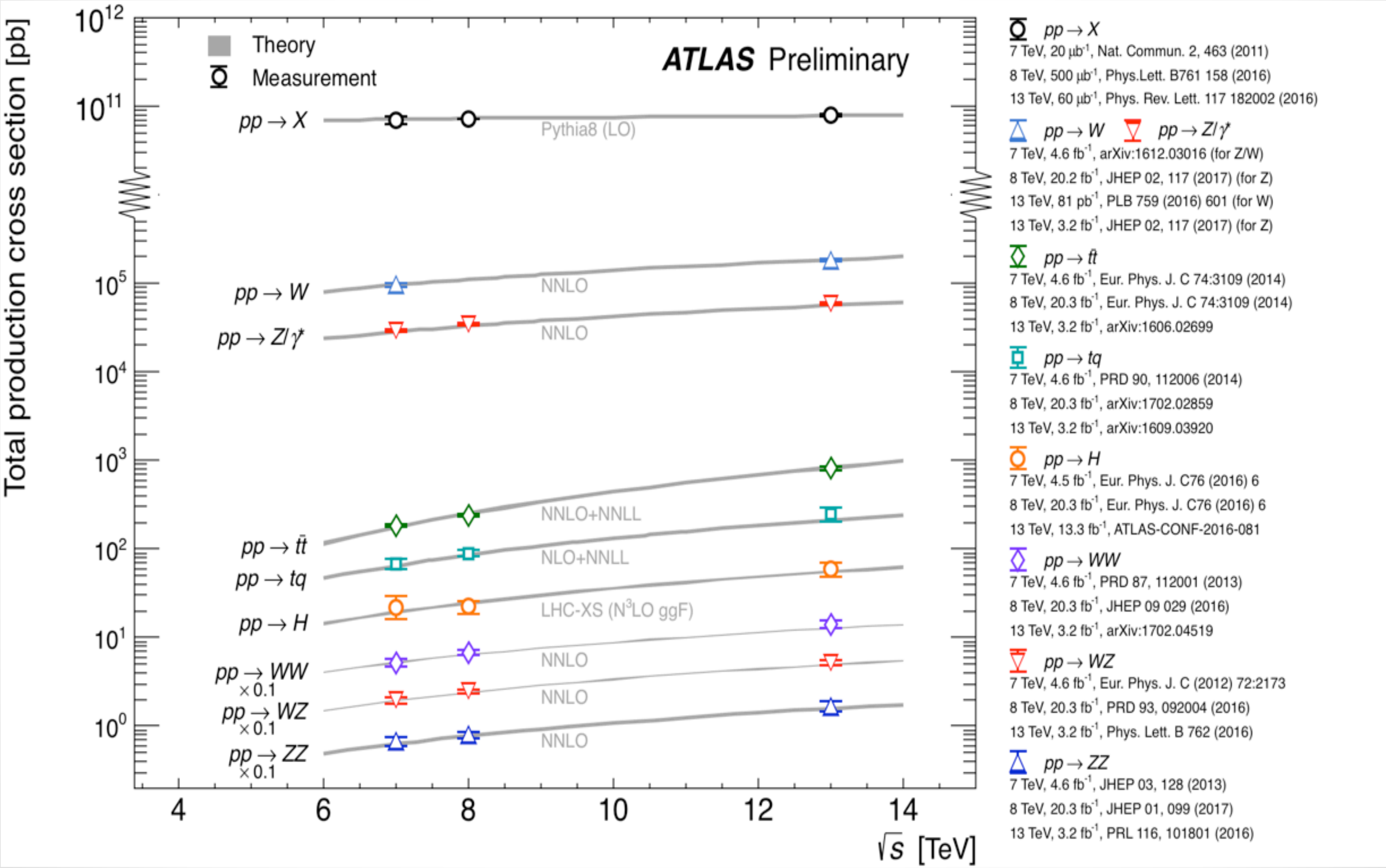
SM results with boson + jets



SM results with X+jets



SM results



Total production cross section [pb]
Theory
Measurement
ATLAS Preliminary
pp → X
Pythia8 (LO)
pp → W
NNLO
pp → Z/γ*
NNLO
pp → tt̄
NNLO+NNLL
pp → tq
NLO+NNLL
pp → H
LHC-XS (N³LO ggF)
pp → WW ×0.1
NNLO
pp → WZ ×0.1
NNLO
pp → ZZ ×0.1
NNLO
√s [TeV]
pp → X
7 TeV, 20 μb⁻¹, Nat. Commun. 2, 463 (2011)
8 TeV, 500 μb⁻¹, Phys.Lett. B761 158 (2016)
13 TeV, 60 μb⁻¹, Phys. Rev. Lett. 117 182002 (2016)
pp → W pp → Z/γ*
7 TeV, 4.6 fb⁻¹, arXiv:1612.03016 (for Z/W)
8 TeV, 20.2 fb⁻¹, JHEP 02, 117 (2017) (for Z)
13 TeV, 81 pb⁻¹, PLB 759 (2016) 601 (for W)
13 TeV, 3.2 fb⁻¹, JHEP 02, 117 (2017) (for Z)
pp → tt̄
7 TeV, 4.6 fb⁻¹, Eur. Phys. J. C 74:3109 (2014)
8 TeV, 20.3 fb⁻¹, Eur. Phys. J. C 74:3109 (2014)
13 TeV, 3.2 fb⁻¹, arXiv:1606.02699
pp → tq
7 TeV, 4.6 fb⁻¹, PRD 90, 112006 (2014)
8 TeV, 20.3 fb⁻¹, arXiv:1702.02859
13 TeV, 3.2 fb⁻¹, arXiv:1609.03920
pp → H
7 TeV, 4.5 fb⁻¹, Eur. Phys. J. C76 (2016) 6
8 TeV, 20.3 fb⁻¹, Eur. Phys. J. C76 (2016) 6
13 TeV, 13.3 fb⁻¹, ATLAS-CONF-2016-081
pp → WW
7 TeV, 4.6 fb⁻¹, PRD 87, 112001 (2013)
8 TeV, 20.3 fb⁻¹, JHEP 09 029 (2016)
13 TeV, 3.2 fb⁻¹, arXiv:1702.04519
pp → WZ
7 TeV, 4.6 fb⁻¹, Eur. Phys. J. C (2012) 72:2173
8 TeV, 20.3 fb⁻¹, PRD 93, 092004 (2016)
13 TeV, 3.2 fb⁻¹, Phys. Lett. B 762 (2016)
pp → ZZ
7 TeV, 4.6 fb⁻¹, JHEP 03, 128 (2013)
8 TeV, 20.3 fb⁻¹, JHEP 01, 099 (2017)
13 TeV, 3.2 fb⁻¹, PRL 116, 101801 (2016)

Higgs cross-section