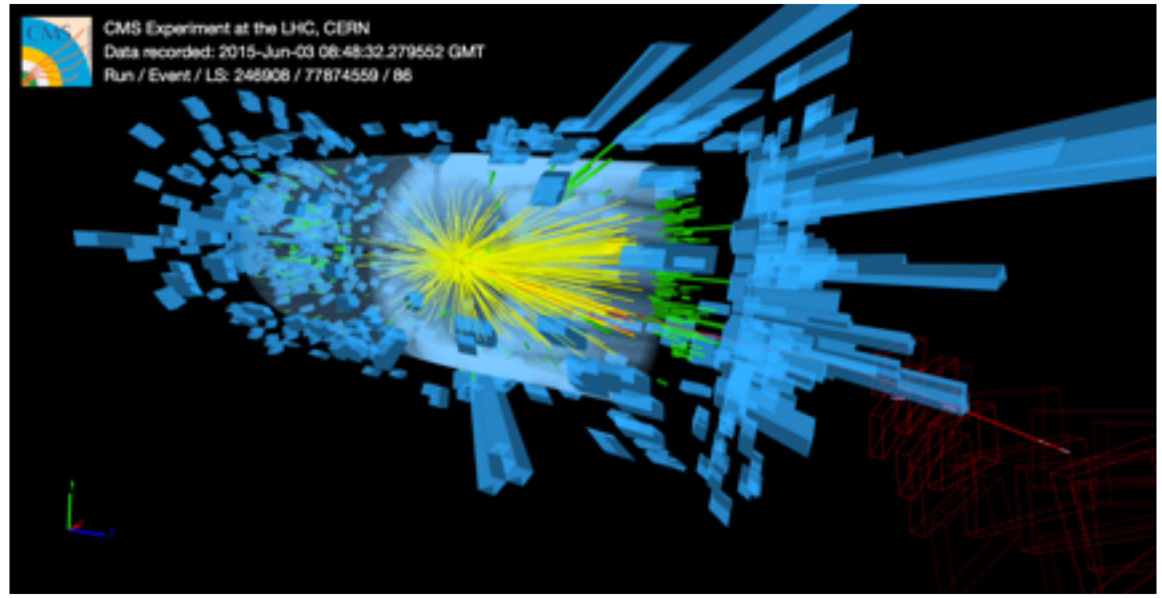


QCD measurements at high P_T

Simon de Visscher (CERN)

Lepton-Photon 2015, Ljubljana

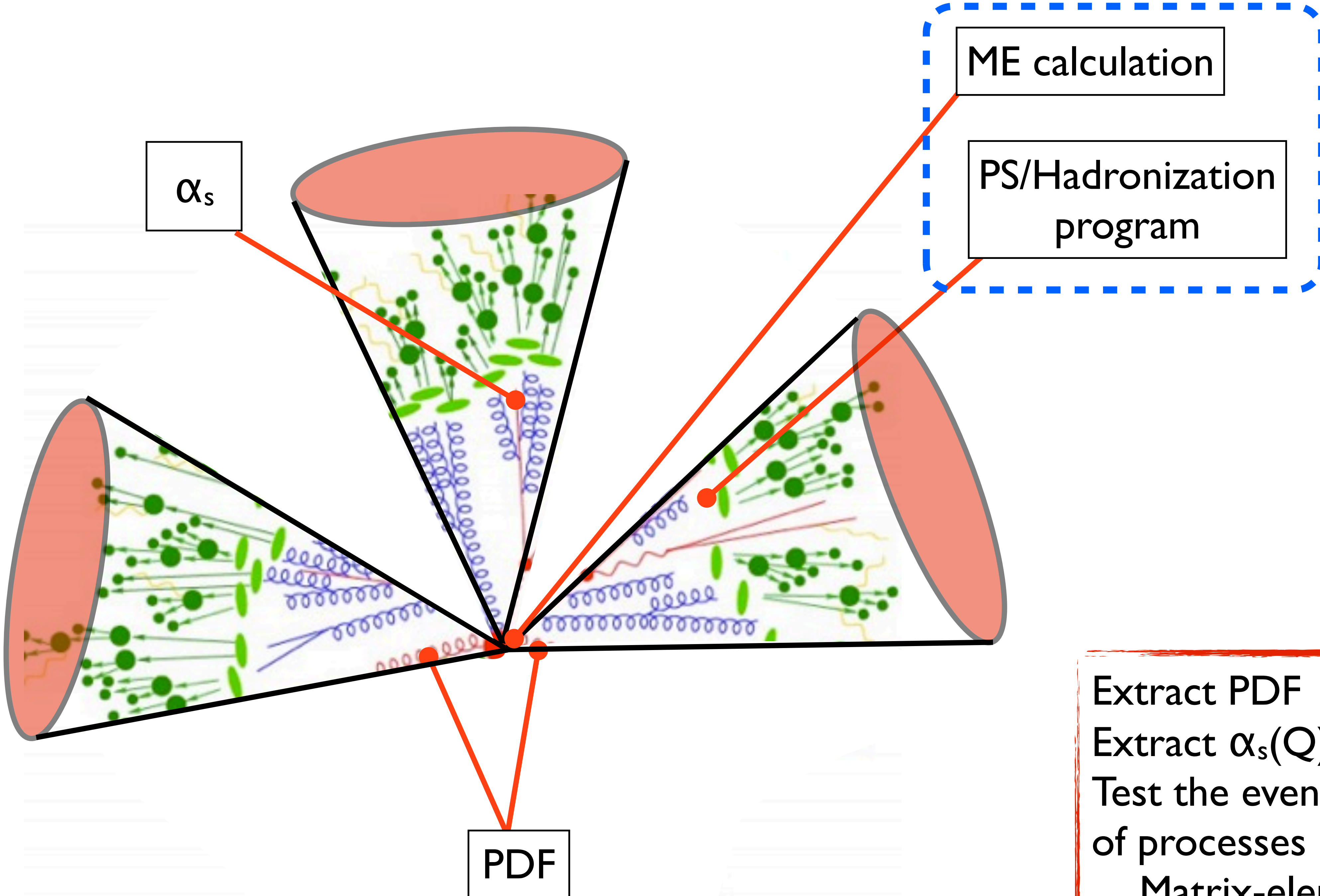
Disclaimer

- ATLAS, CMS, DO, CDF, LHCb: a *lot* of jets- and V+jets-related results...
- This talk: only recent and/or representative studies.
  - No soft QCD discussed here (see next talk from J.F. Grosse-Oetrinhaus)
  - No Top result discussed here (see Top session on thrusday morning)
- For detailed public results:
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  - CDF: http://www-cdf.fnal.gov/physics/new/qcd/QCD.html
  - D0: http://www-d0.fnal.gov/Run2Physics/WWW/results.htm
  - LHCb: http://cds.cern.ch/collection/LHCb%20Papers?ln=en

Outline

- PDF, α_s, jets
- Data/MC comparisons for V+jets
  - V+jets
  - V+ HF jets
- Run II preliminaries

QCD at hadron collider

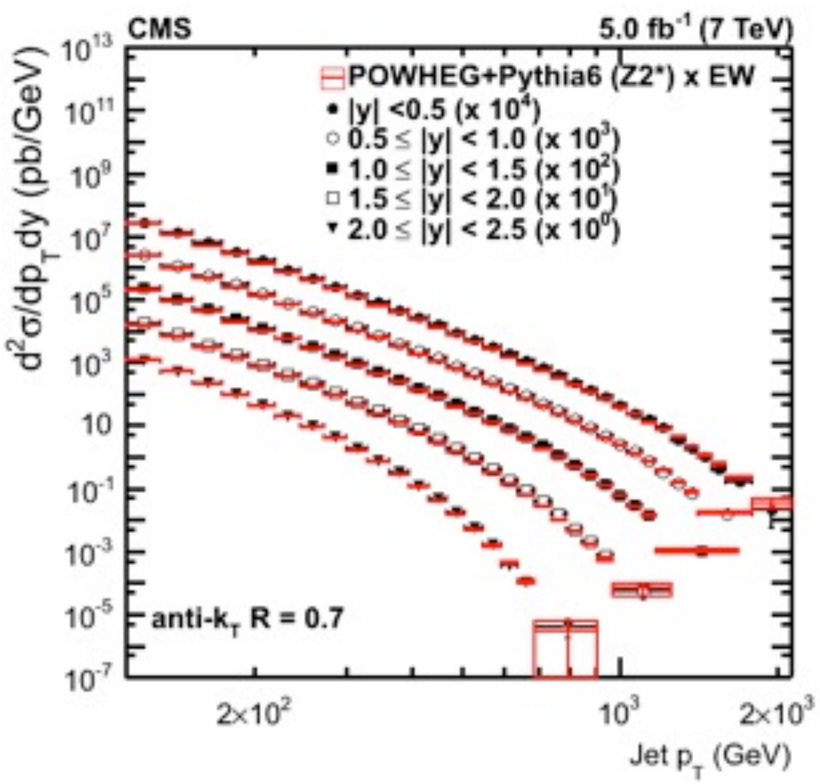


Extract PDF
Extract $\alpha_s(Q)$
Test the event generators: all types of processes
- Matrix-element calc.
- Parton Shower
- ME+PS interface
- ...

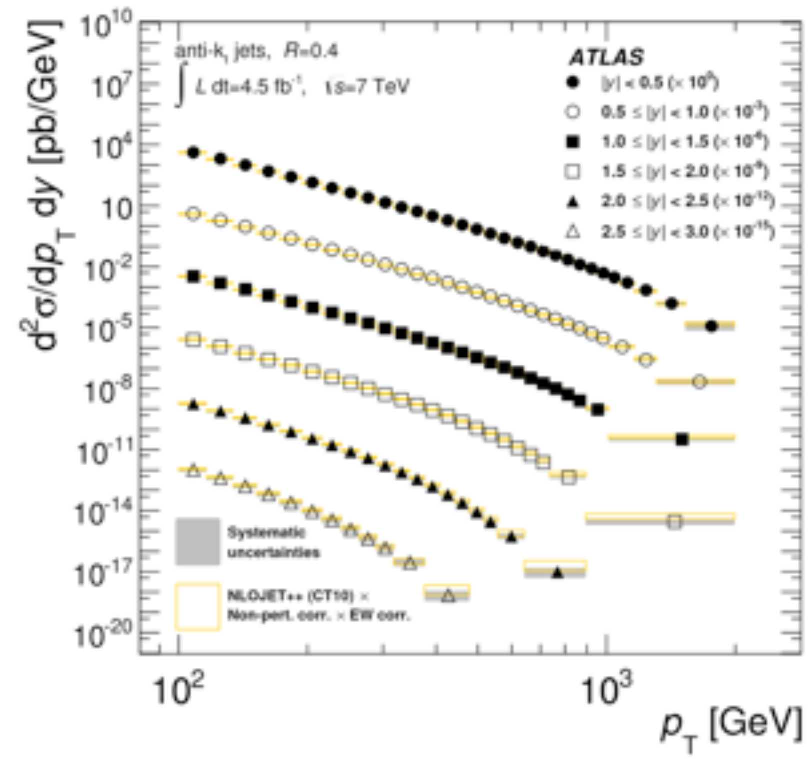
PDF, α_s, jets

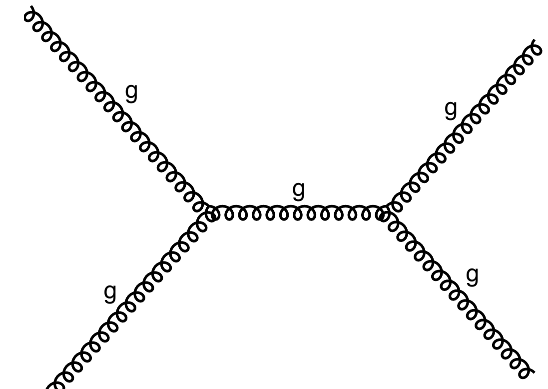
PDF from >=2-jet cross-section

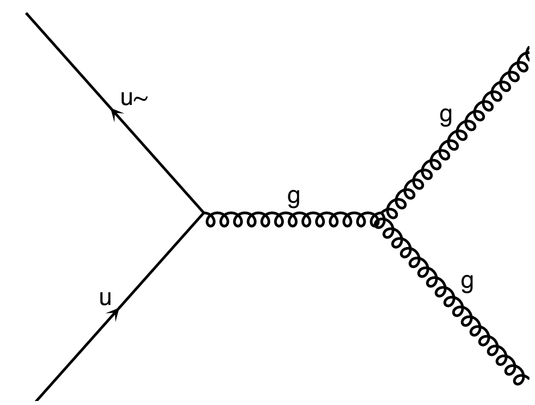
[Eur.Phys.J.C (2015) 75:288]

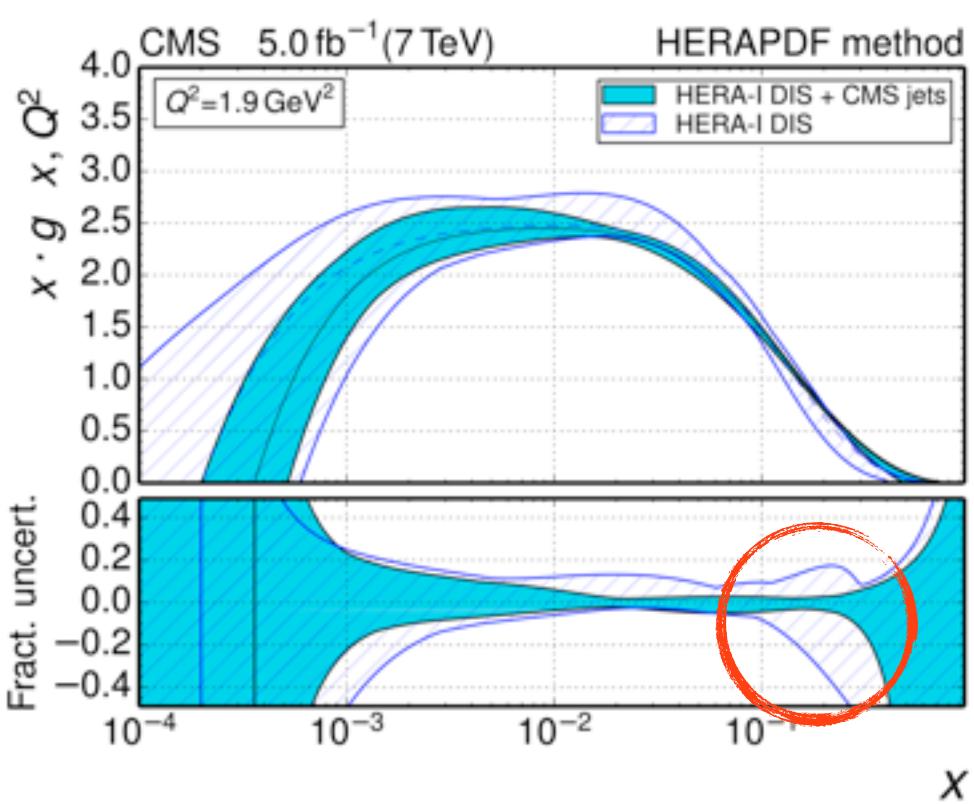


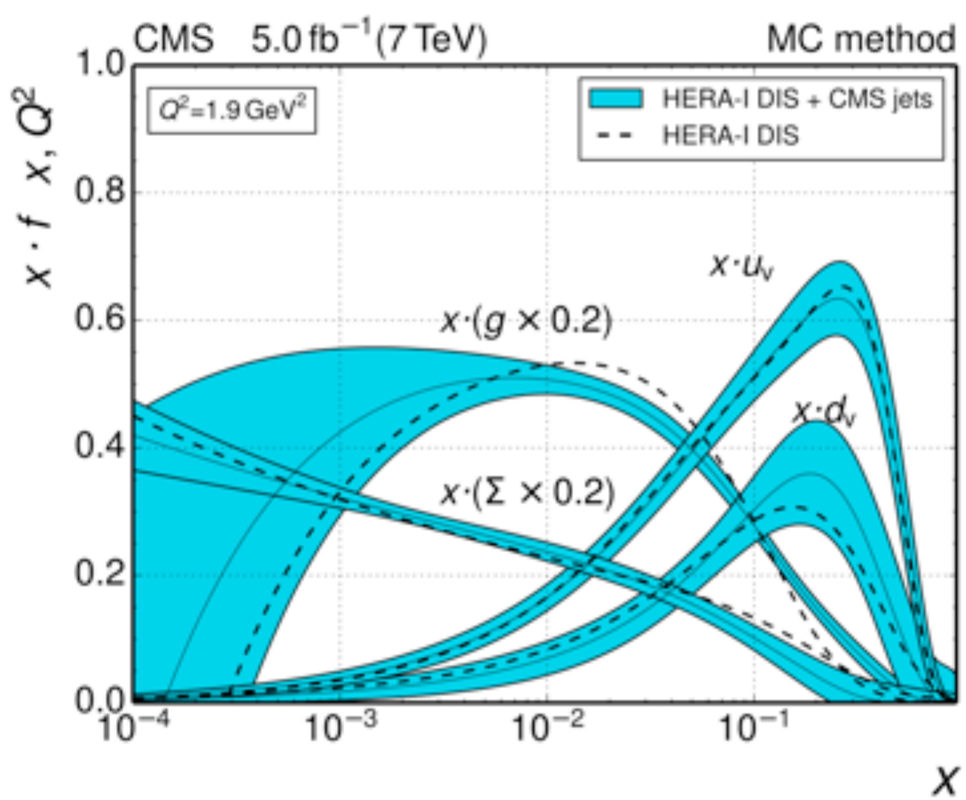
[JHEP02(2015)153]







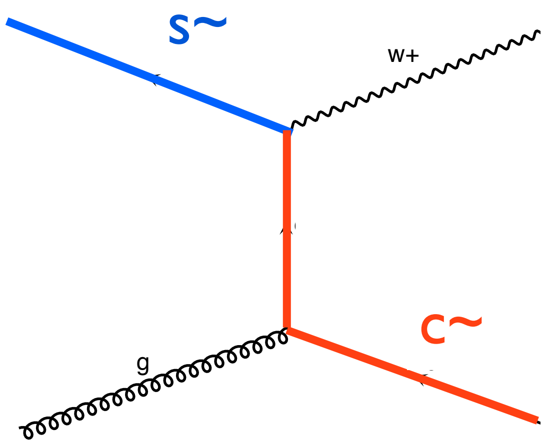




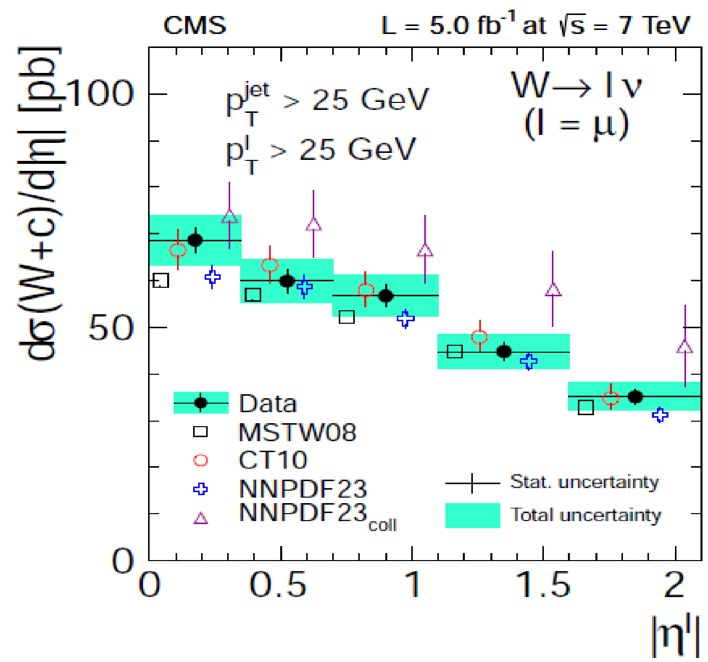
Impact on all PDFs (significant reduction of uncertainties for g-PDF at high x)

s-PDF from W+c

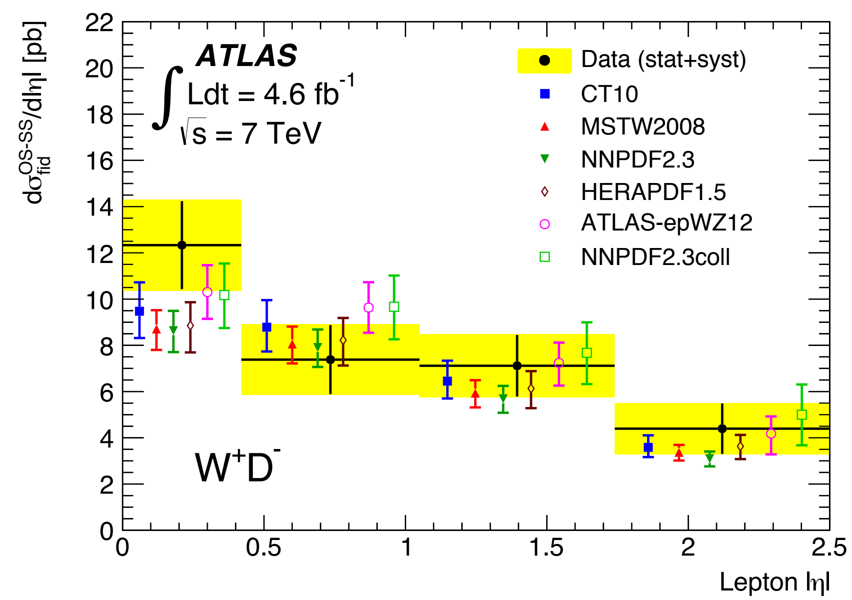
W+c: probe s-quark PDF



[JHEP 02 (2014) 013]

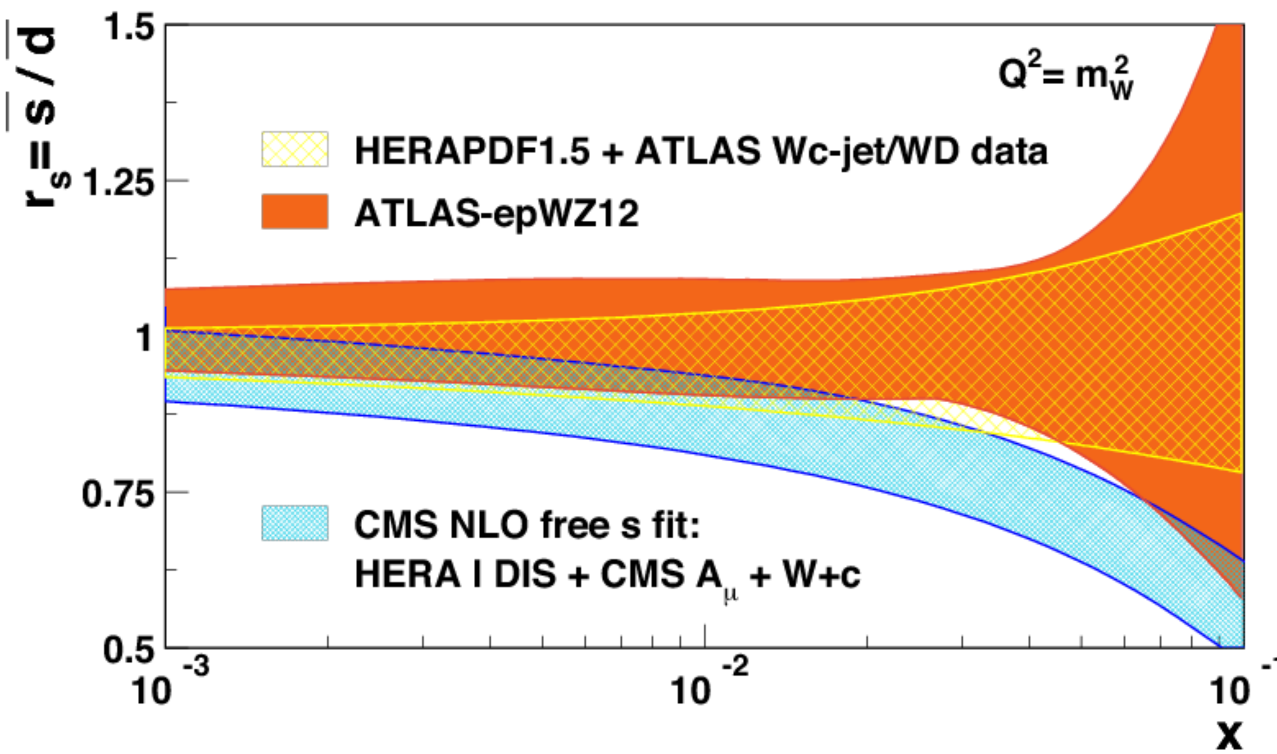


[JHEP 05 (2014) 068]



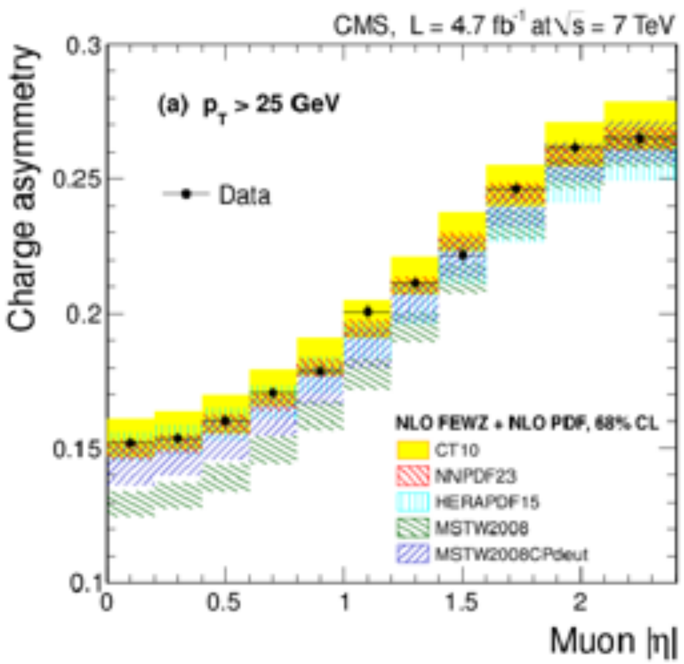
Strategy: OS-SS to remove tt, single-top, Wcc, Wbb, ...

[JHEP 05 (2014) 068]
+
[PRD 90 (2014) 032004]



(small) tension between CMS and ATLAS results

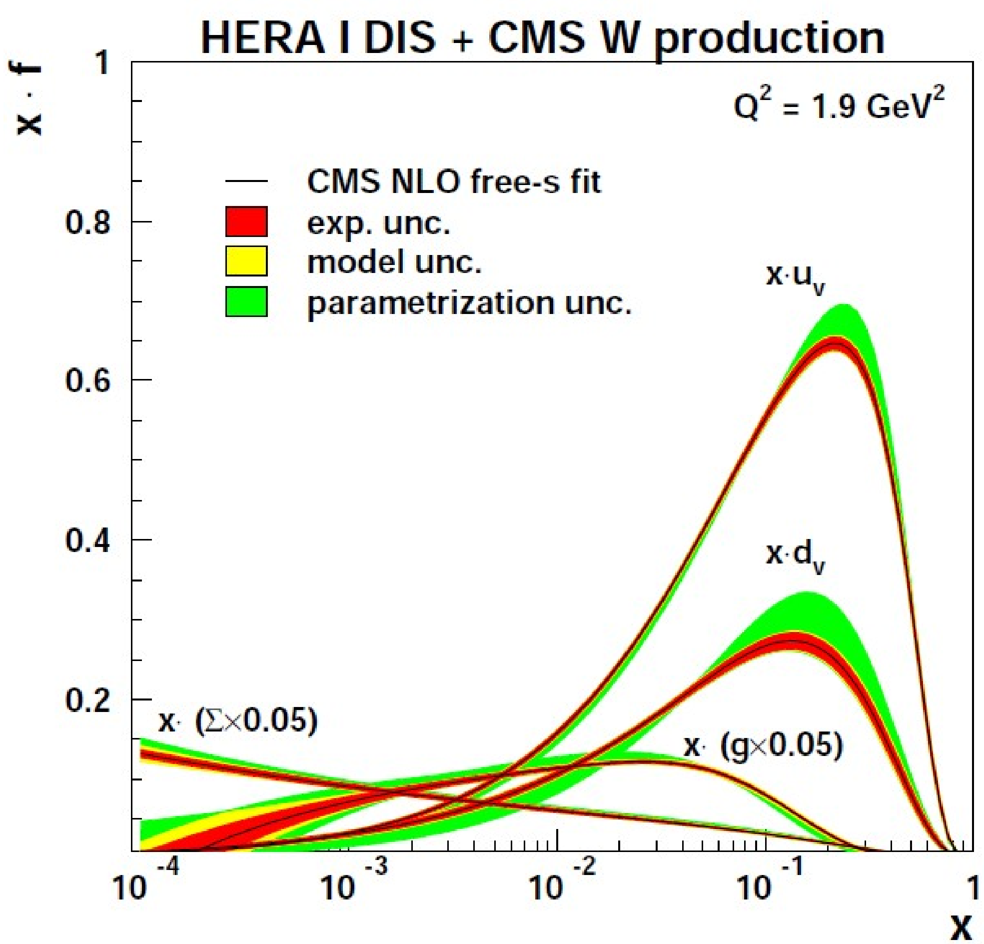
q-PDF from W+c and A_W

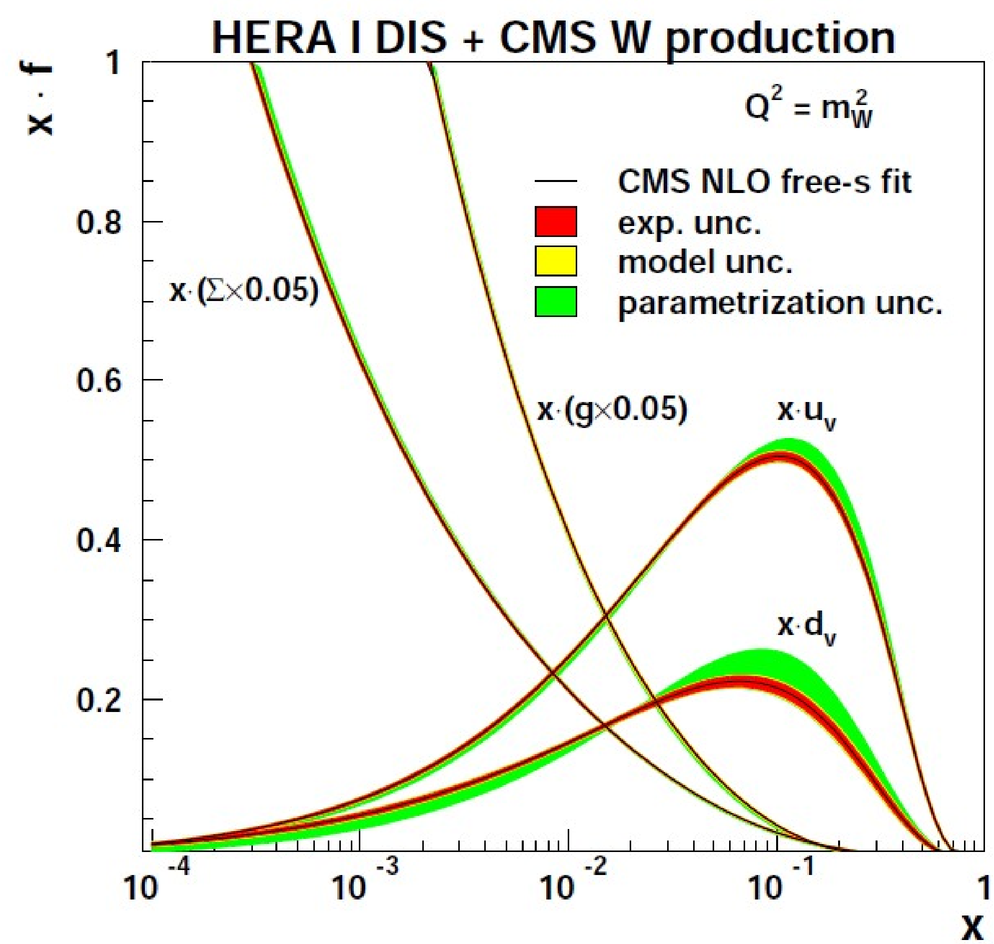


+ W+C + Hera

[PRD 90 (2014) 032004]

⇒





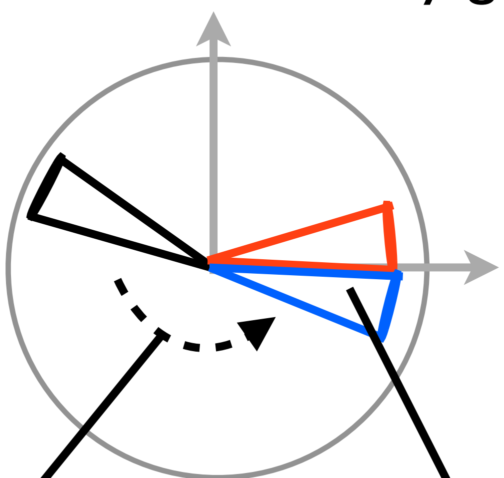
Included in NNPDF 3.0

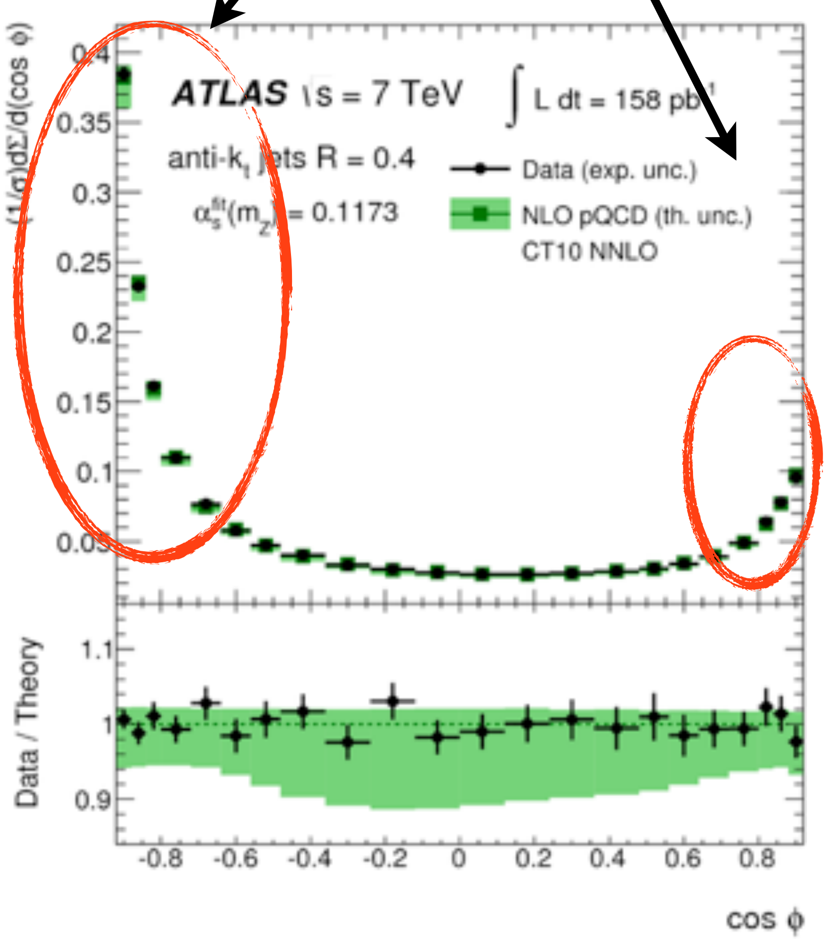
$\alpha_s(M_Z)$ from TEEC/ATEEC

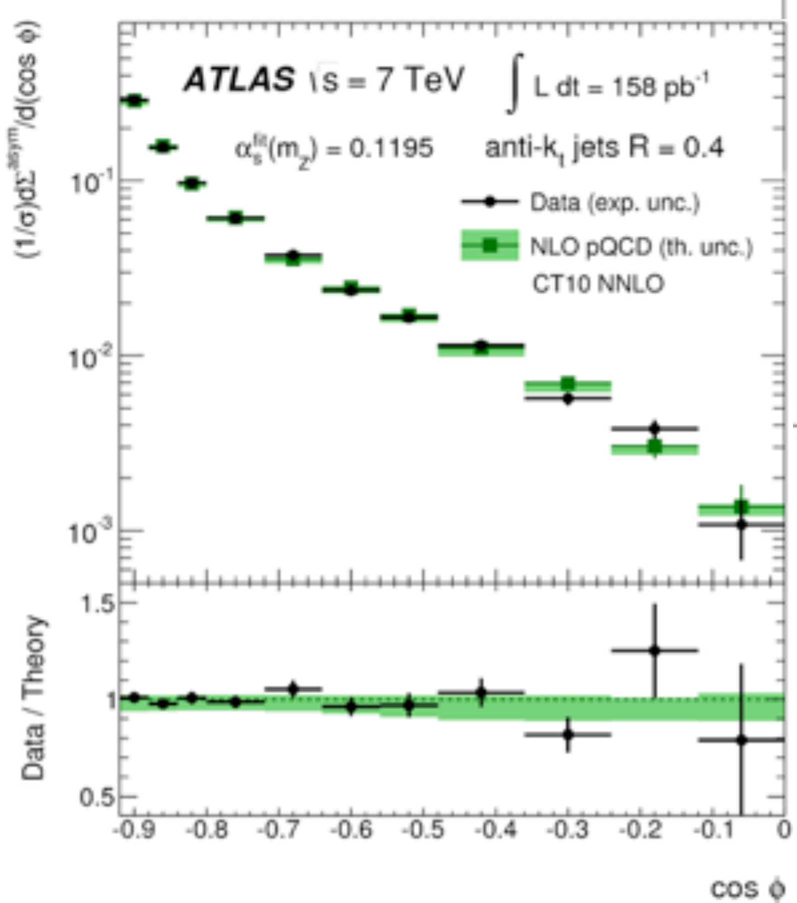
TEEC: angles between all (energy-weighted) combinations of jets.

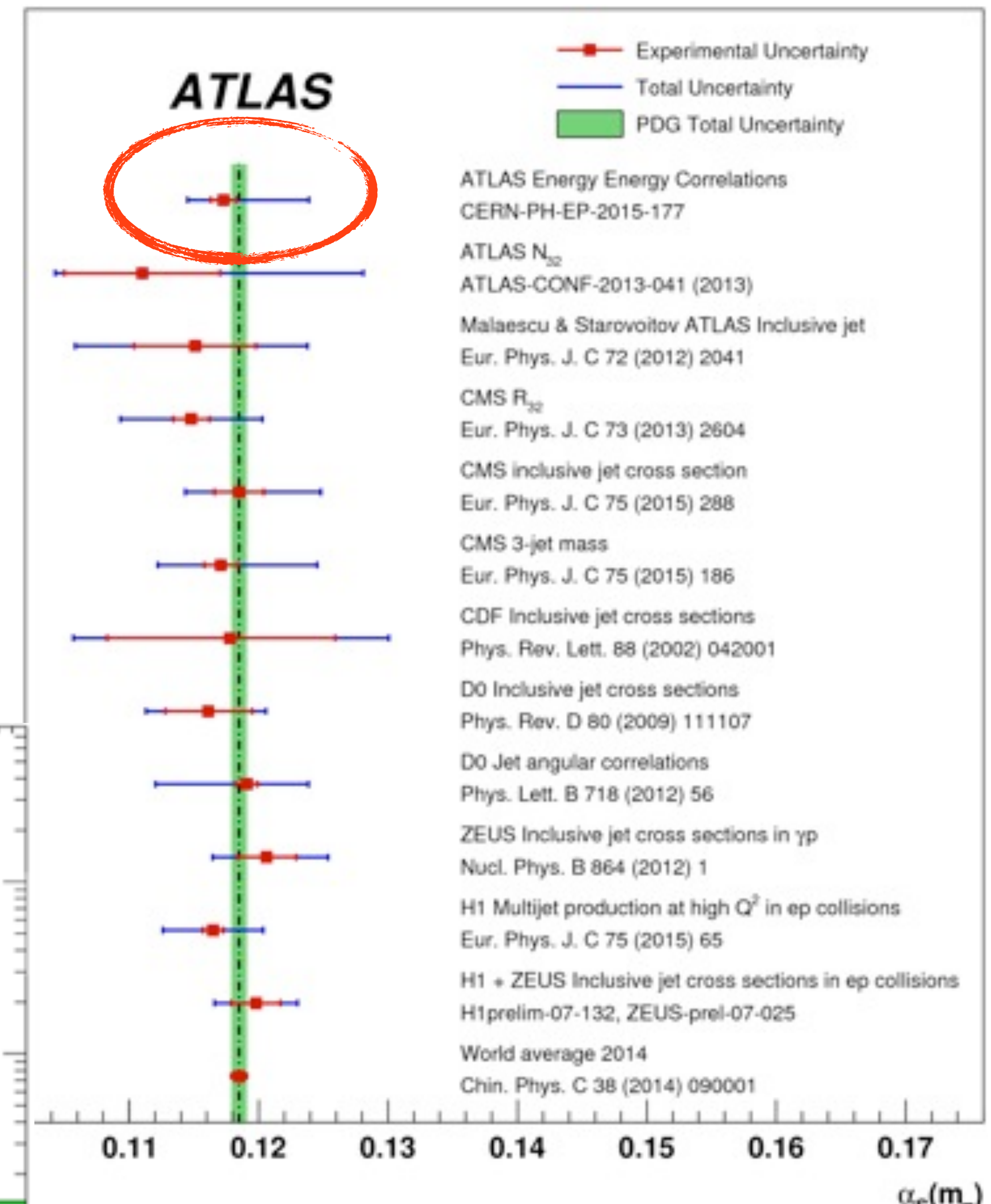
ATEEC: removes contribution from 2 jets events. What remains is dominated by gluon contribution ⇒ α_s

[arxiv:1508.01579v1.pdf]



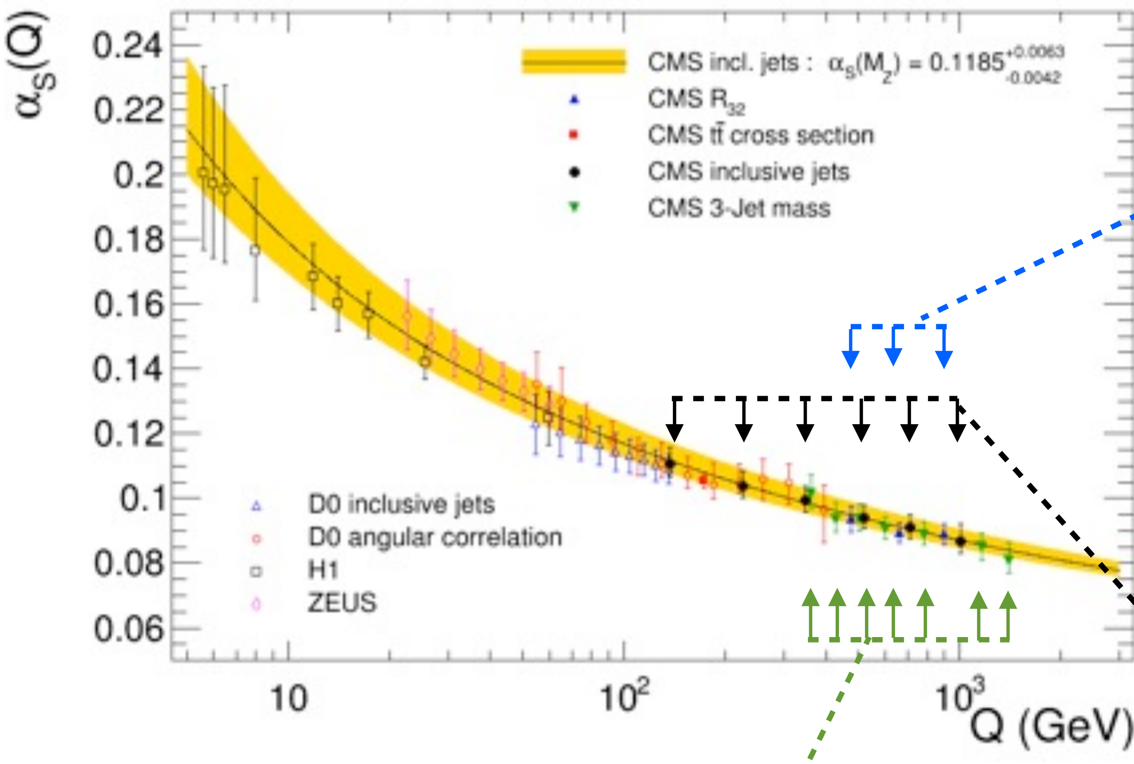




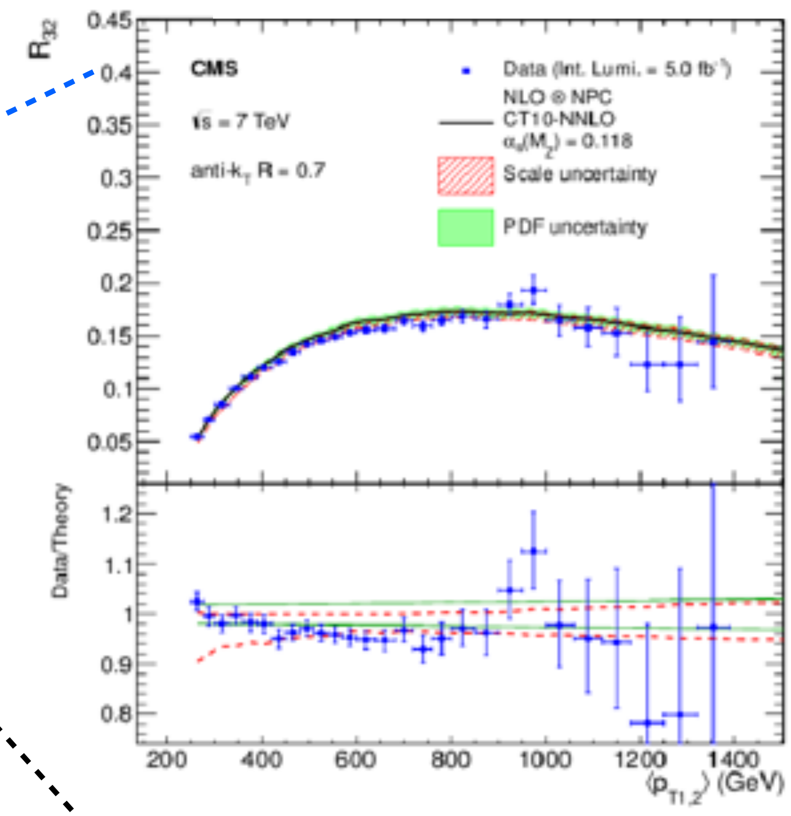


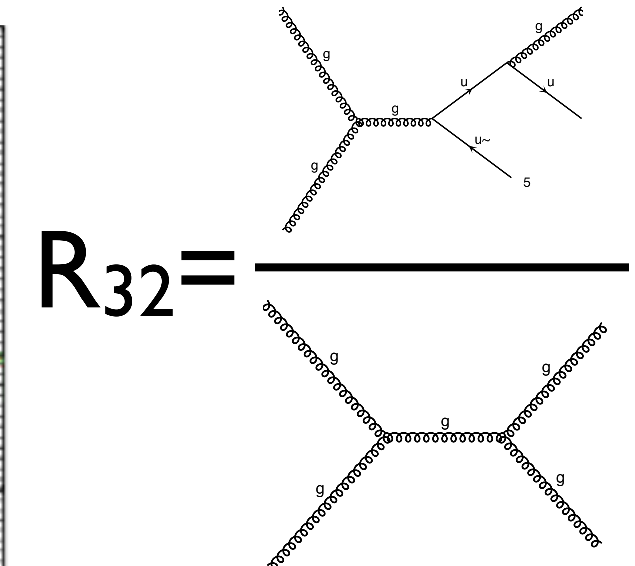
Excellent agreement with the world average (2014) α_s=0.1185+-0006

$\alpha_s(Q)$

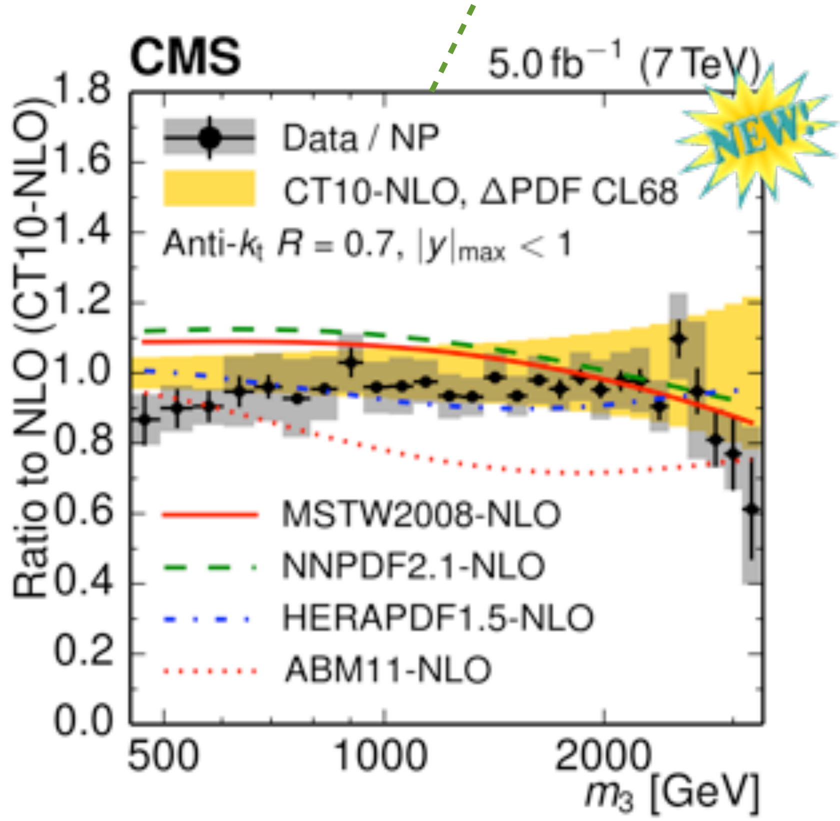


[Eur. Phys. J. C 73 (2013) 2604]

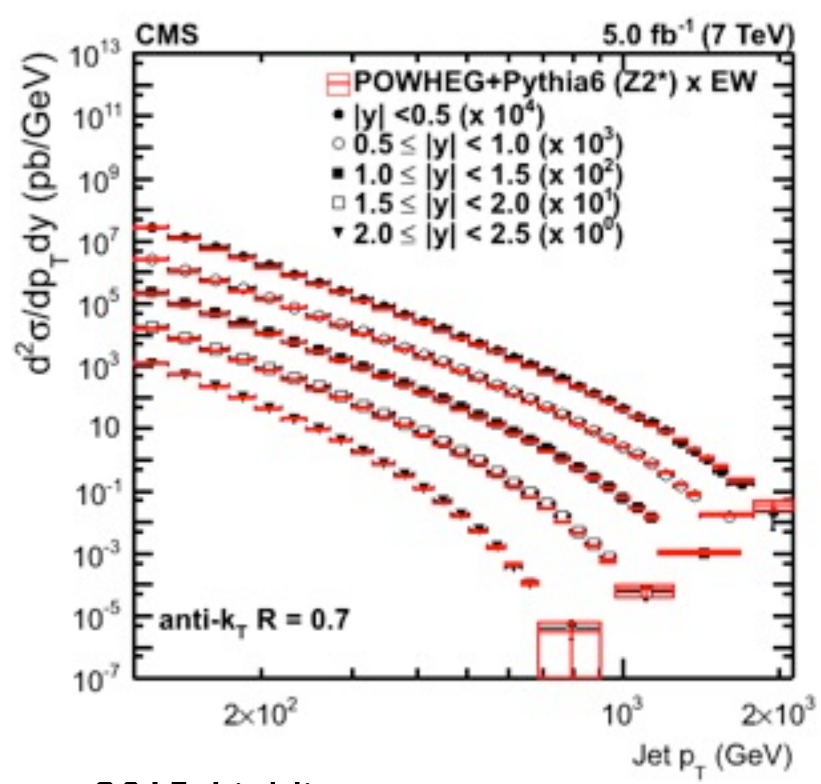




[Eur. Phys. J.C75(2015)186]



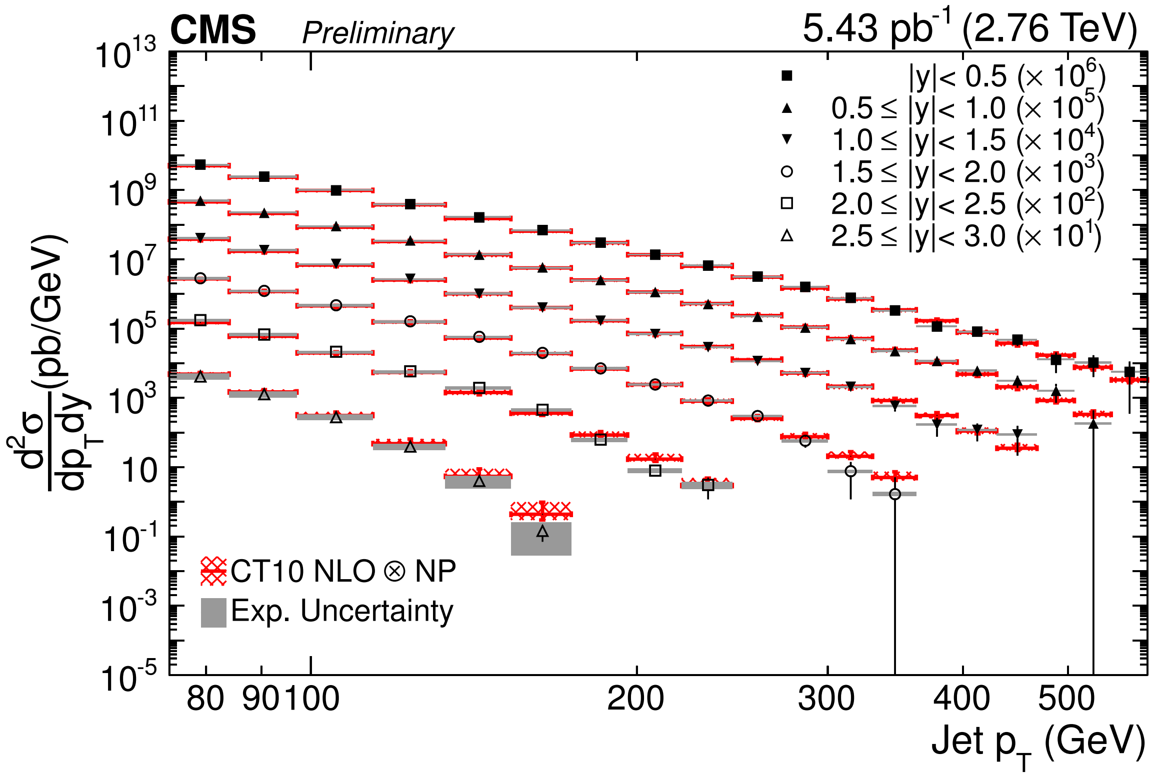
[Eur. Phys. J.C75(2015)288]

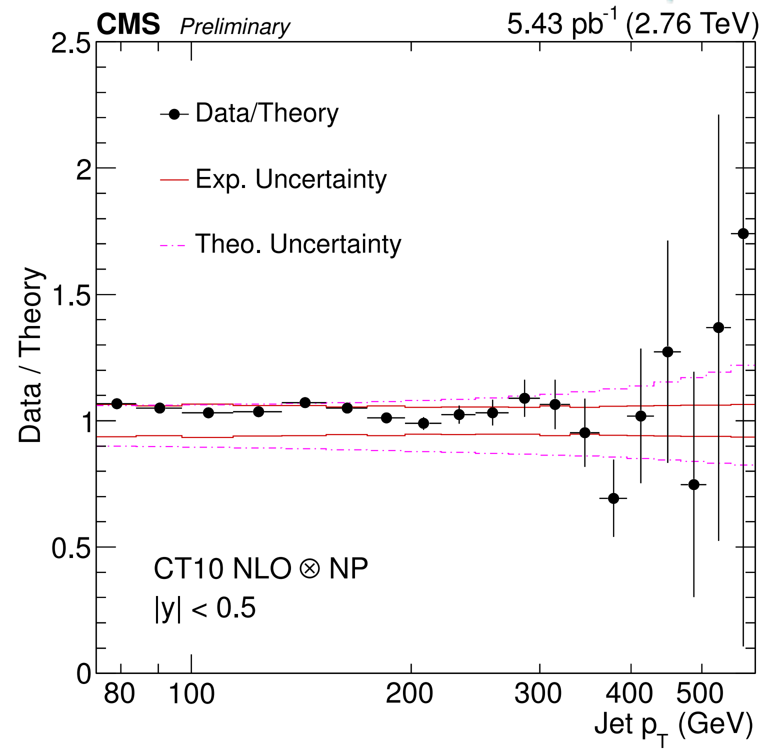


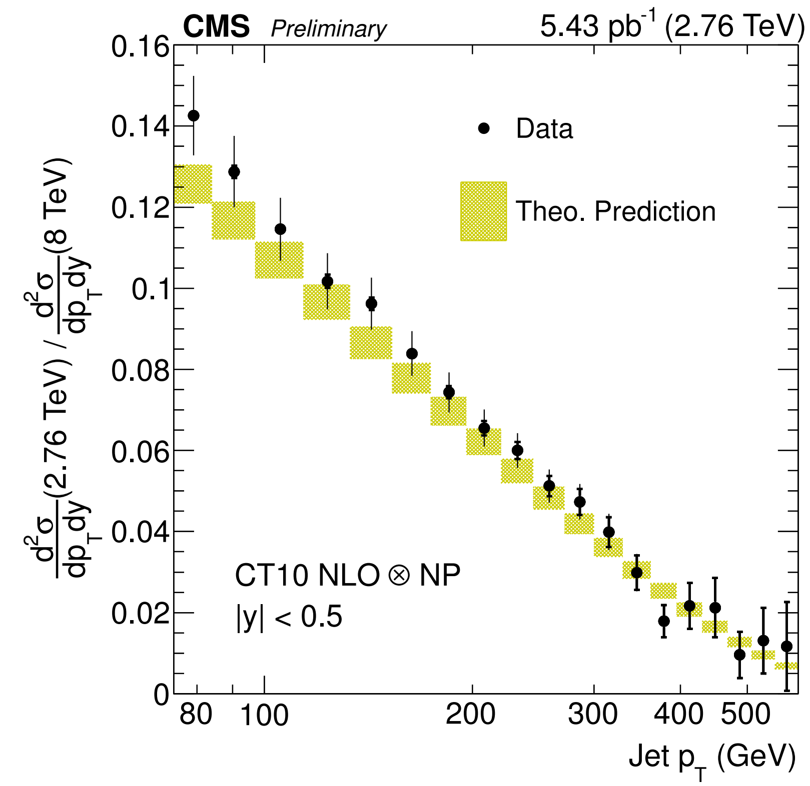
2.76 TeV (+ ratio to 8 TeV)

NEW!

[CMS-PAS-SMP-14-017]

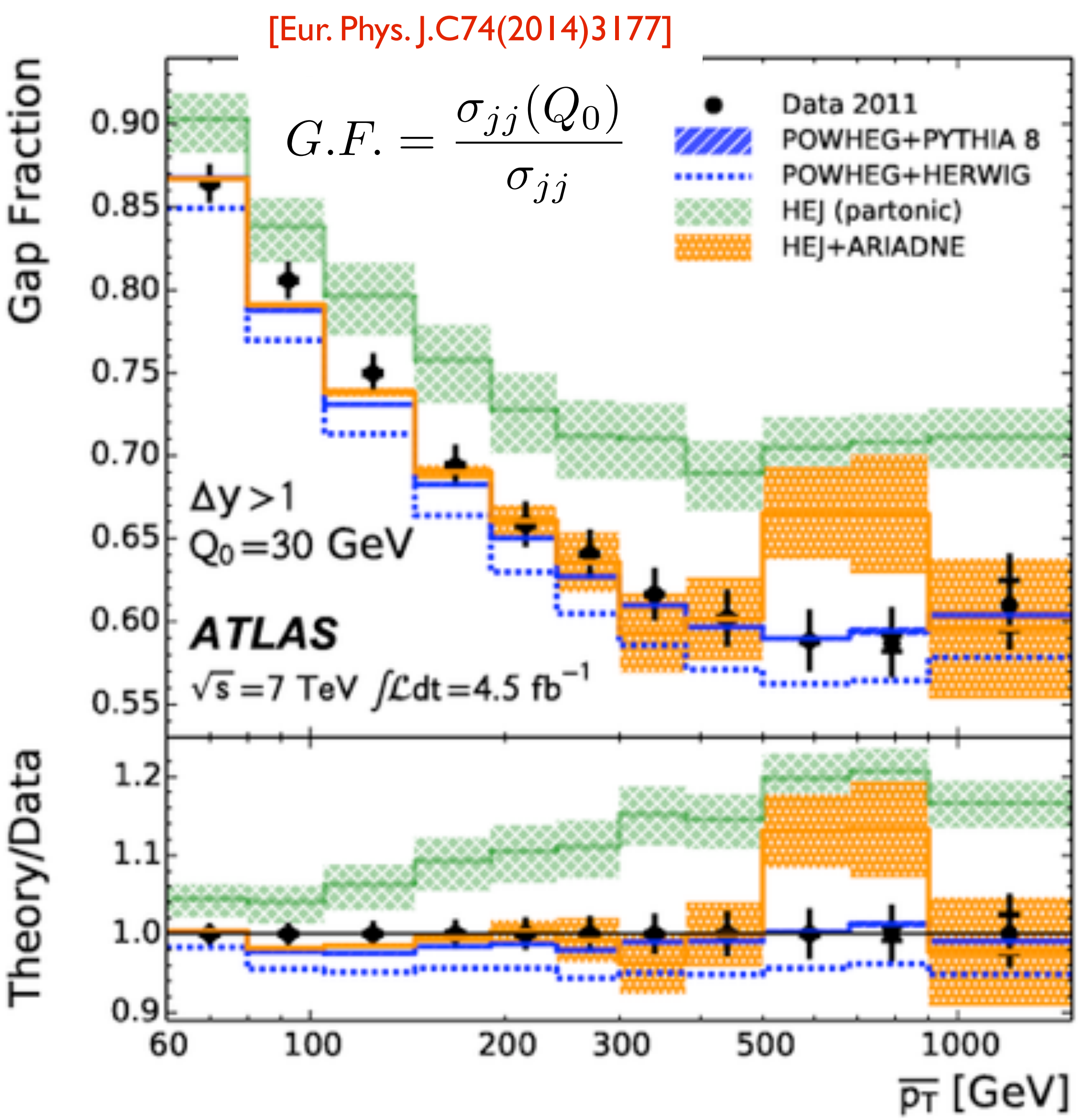


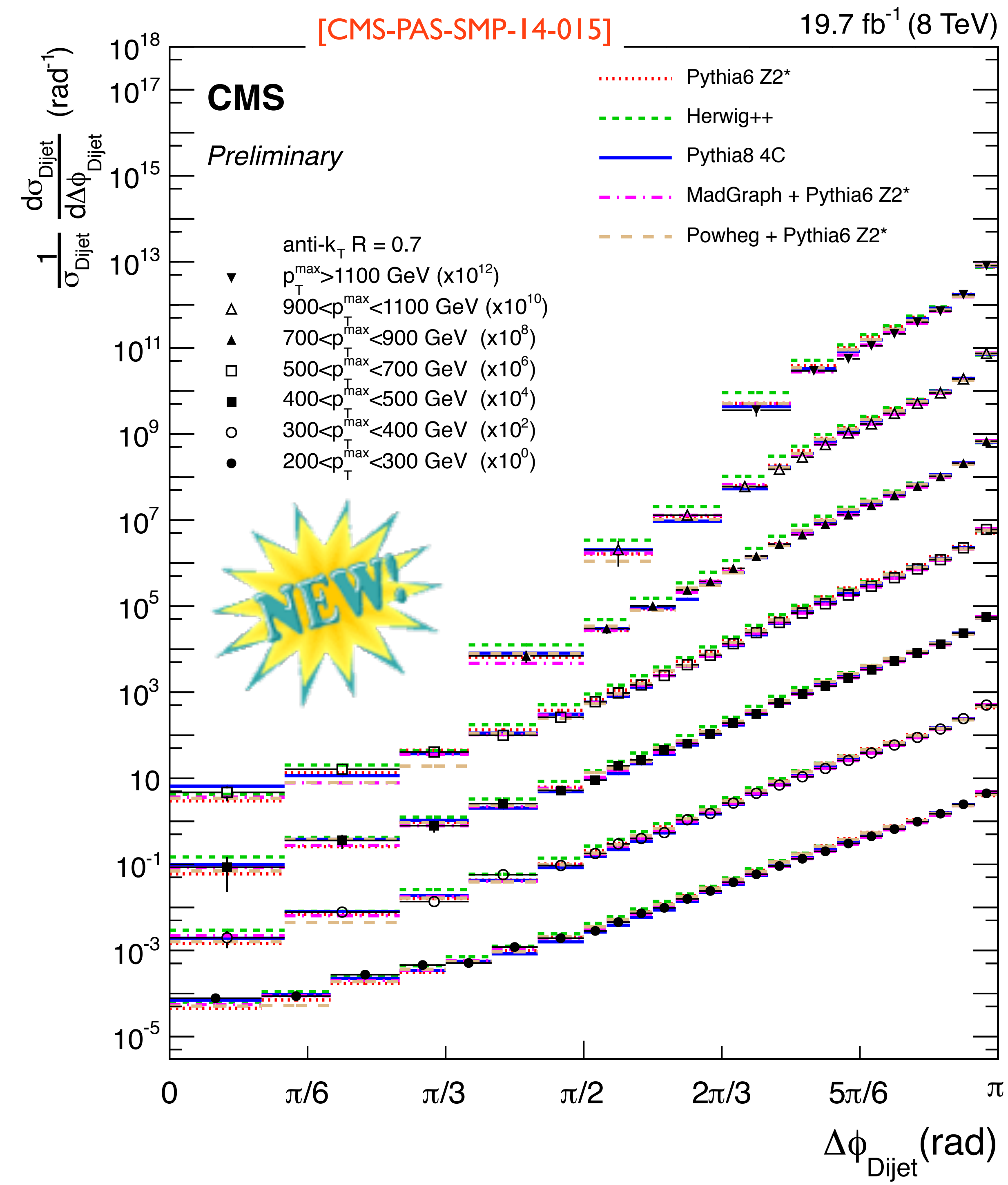




Additional measurement useful for PDF and α_s
Ratio cancels partially the exp. uncertainties, no significant deviation from NLOJet prediction

Azimuthal (de)correlation and jet veto



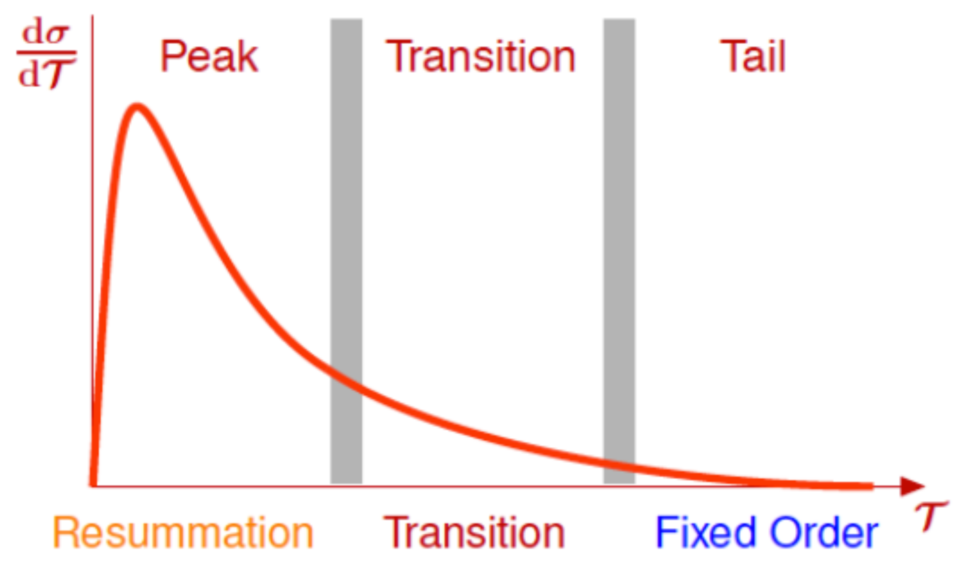


Generally an good agreement with multileg+PS predictions

Data/MC comparisons for V+jets

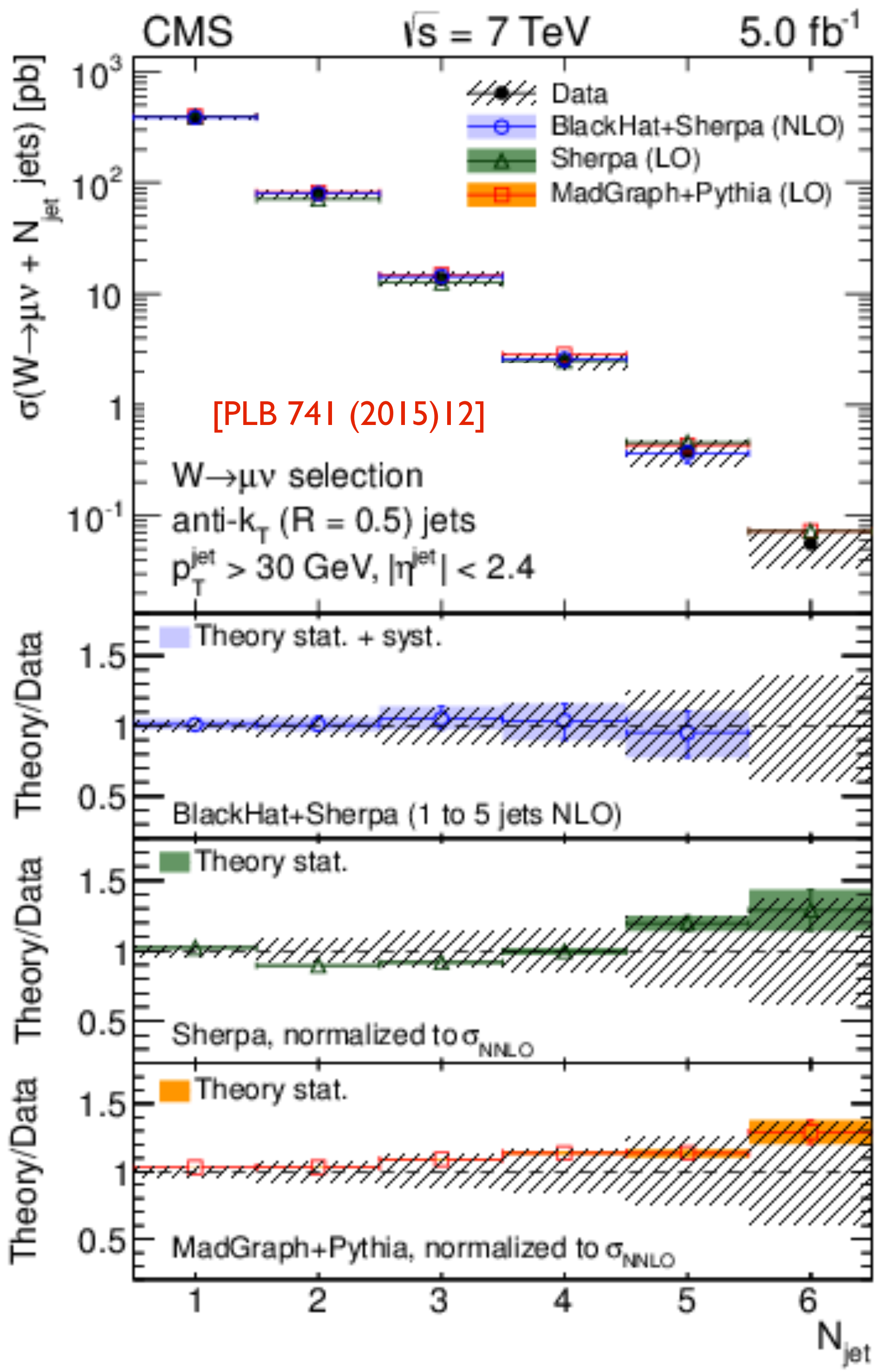
V, V+jets

- Why study the emission of a vector boson, with or without associated jets ?
  - Background for searches
  - Sensitivity to
    - soft physics description
    - merging techniques in soft/mid-scales
    - QCD/QED corrections at harder scales

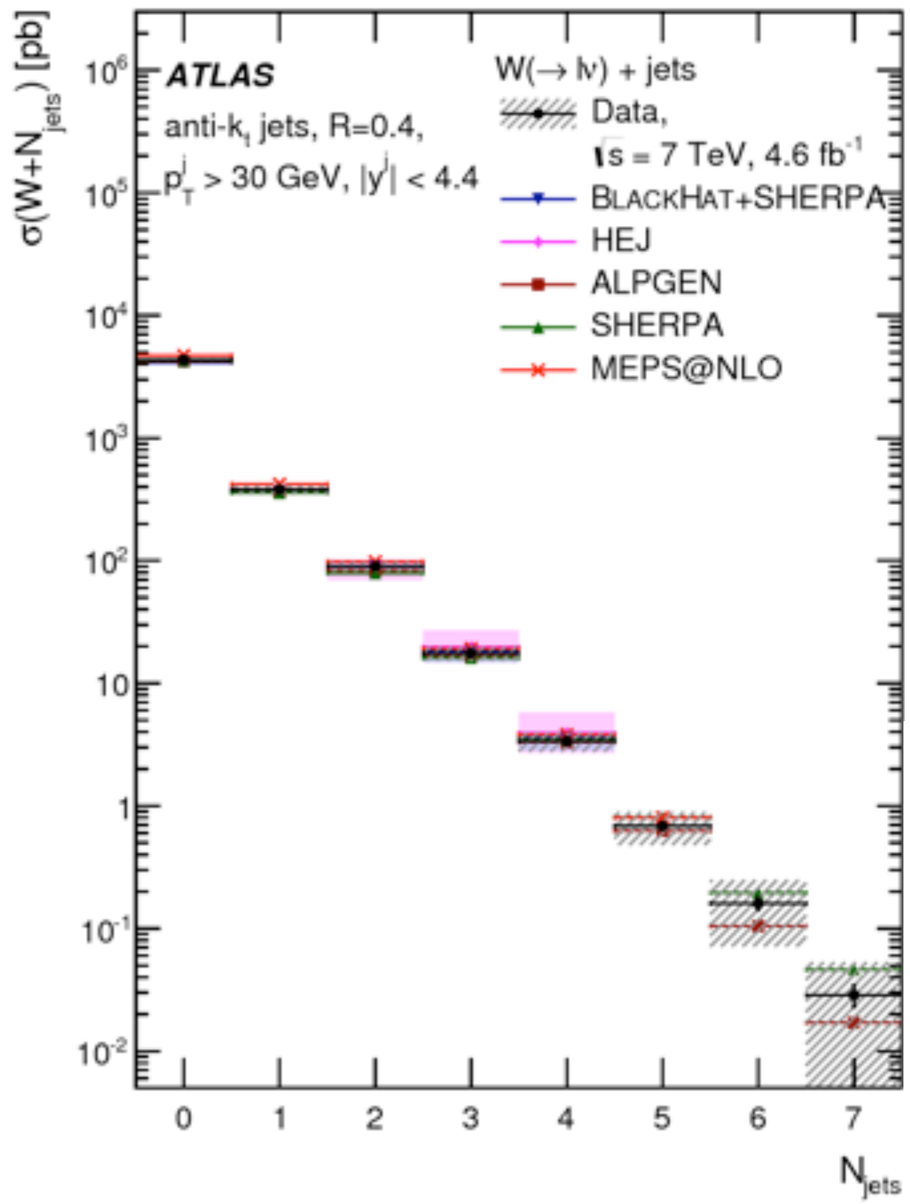


- stress test of event generators/calculations
  - tree-level vs NLO vs NNLO
    - Madgraph_aMC@NLO, Powheg, Sherpa, BlackHat, MEPS@NLO, ALPGEN
  - Parton shower algos (+Tunes)
    - Pythia6 vs Pythia8 vs Herwig vs... ...
  - Merging schemes (scale dependencies,...)
    - KtMLM vs ShowerKt vs CKKW-L vs FxFx vs UMEPS vs UNLOPS vs...

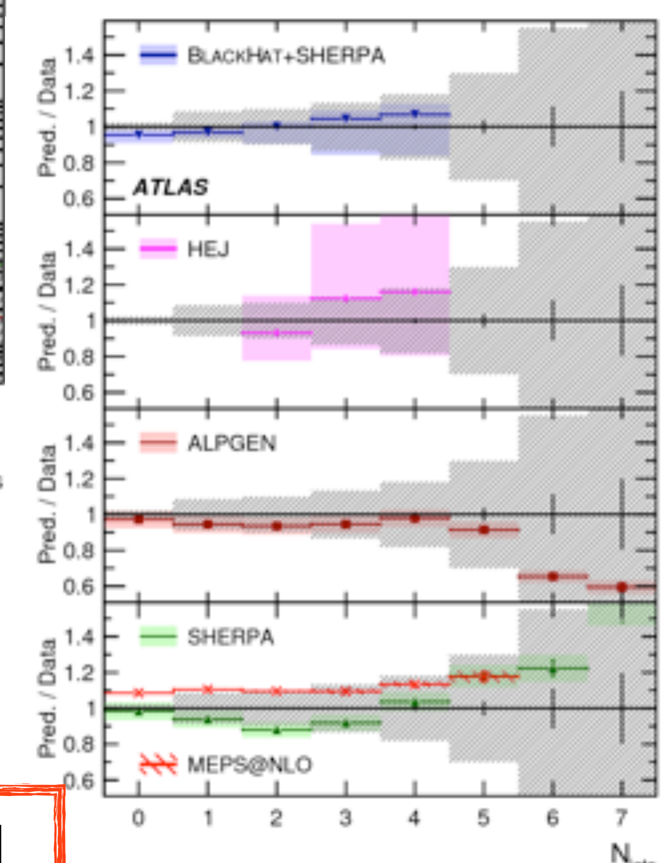
Number of jets: W+jets @ 7 teV



[PLB 741 (2015)12]

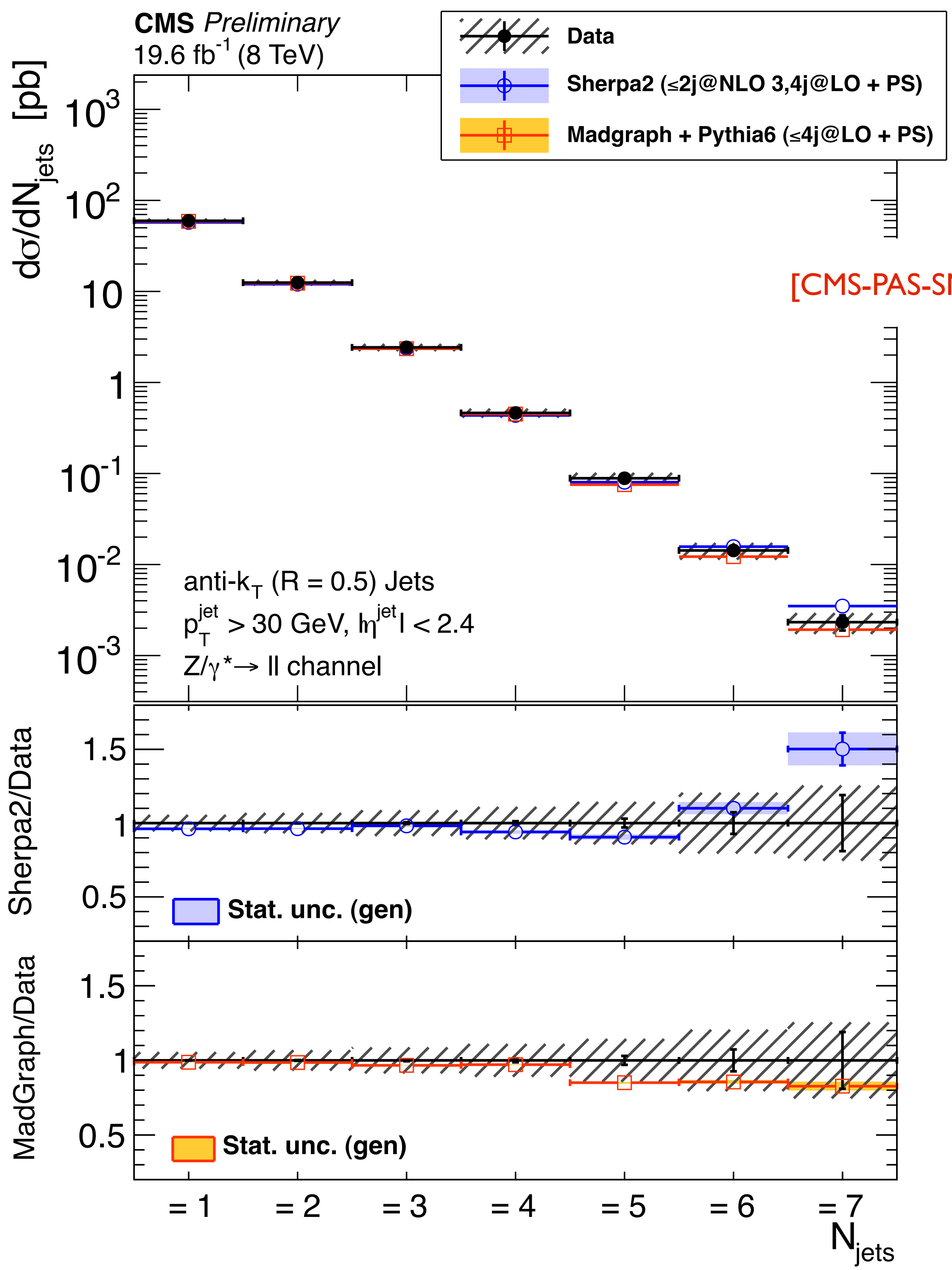


[Eur. Phys. J.C75(2015)82]

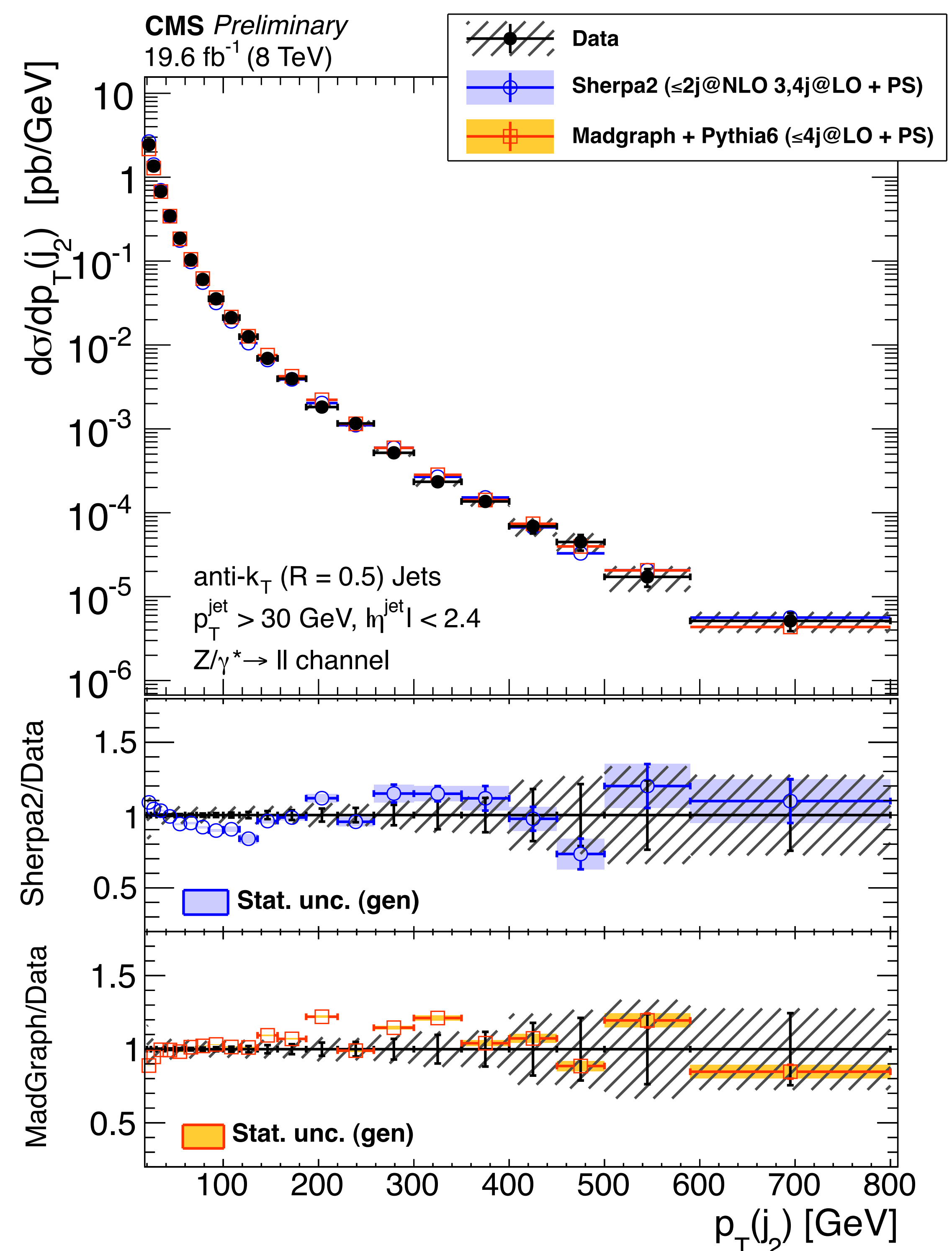


Final state up to 6/7 jets. Data generally well described

Z+jets @ 8 TeV

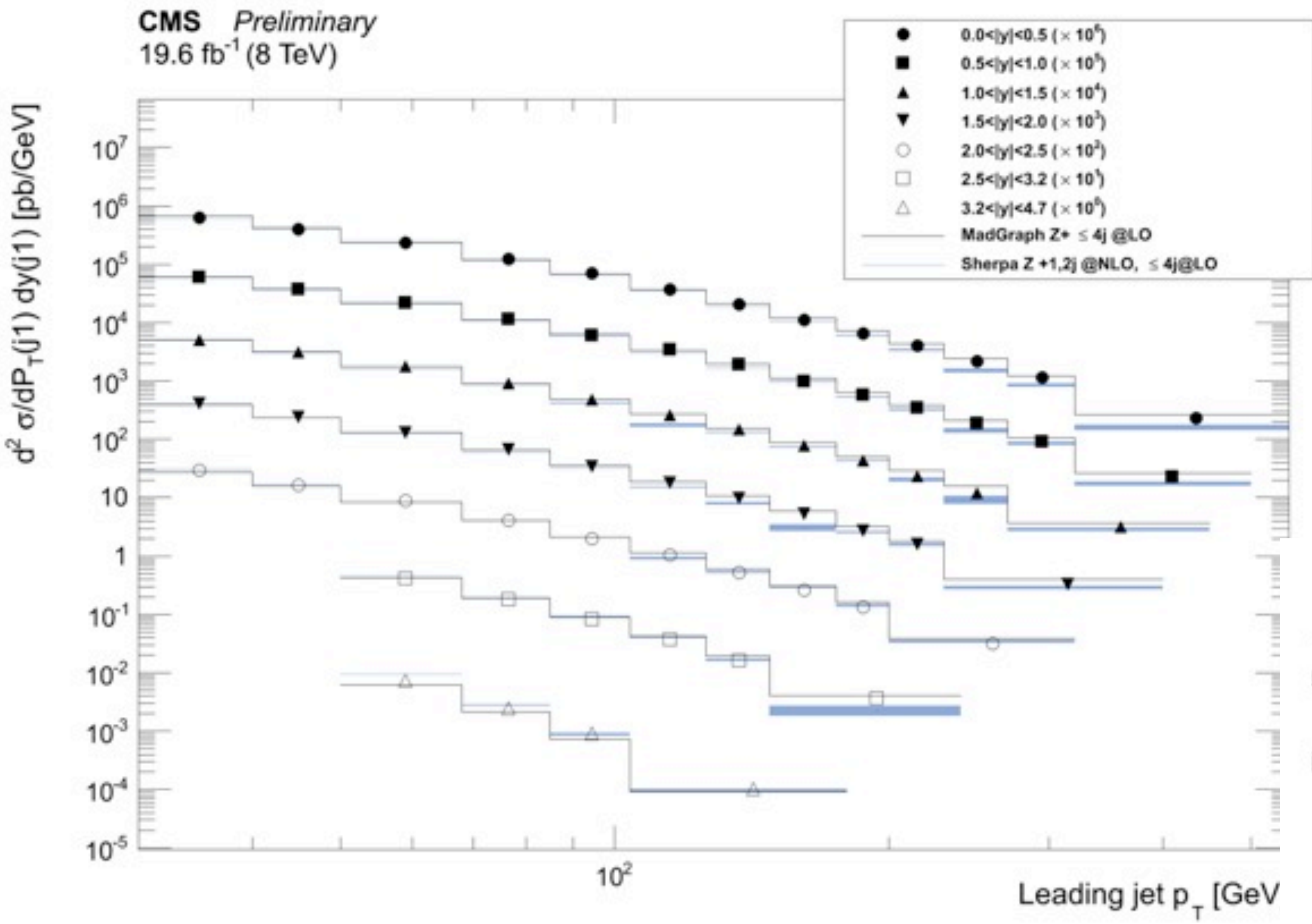


[CMS-PAS-SMP-13-007]



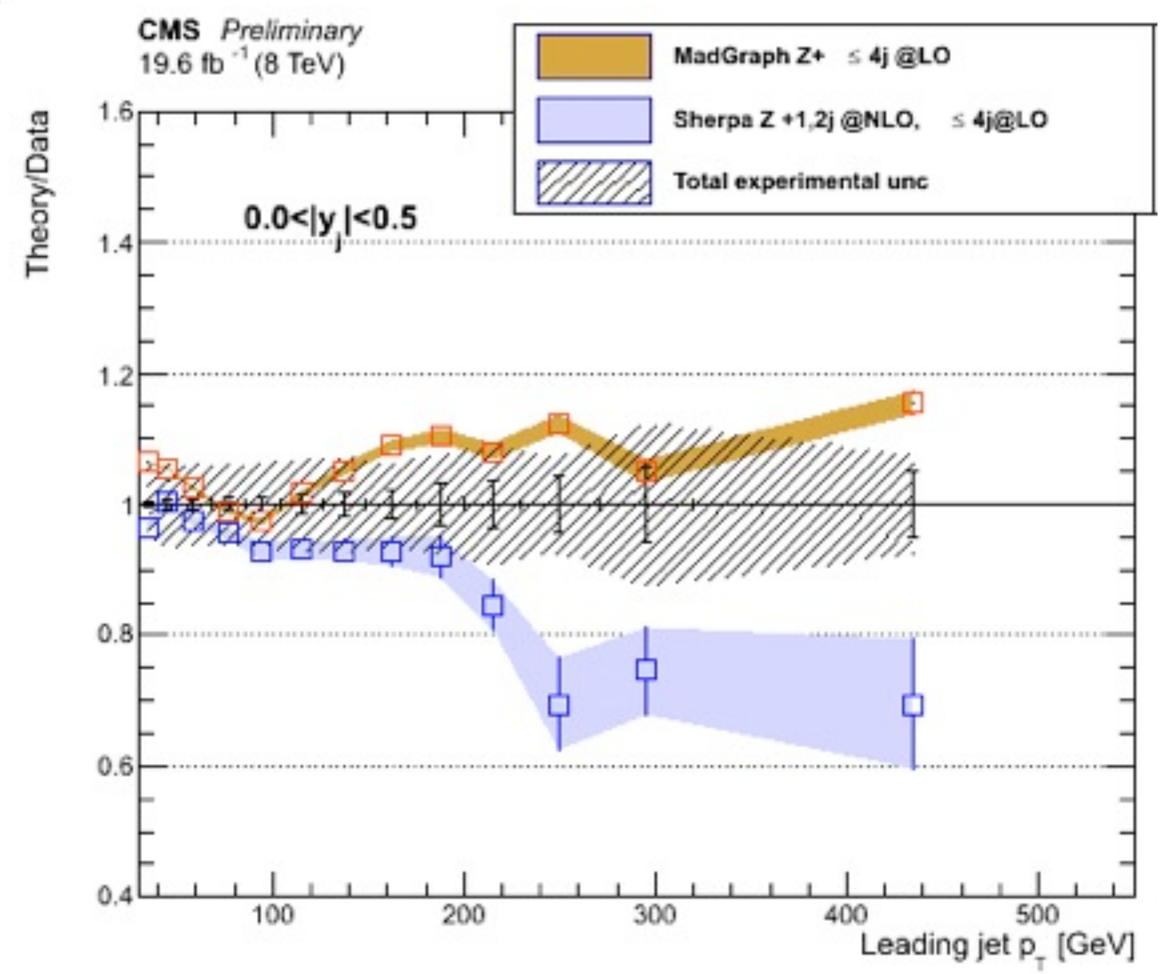
Trend observed for both Sherpa2@NLO and MG prediction
Slighly better job by Sherpa2@NLO for Pt(Jet)

Z+jets @ 8 TeV



[CMS-PAS-SMP-14-009]

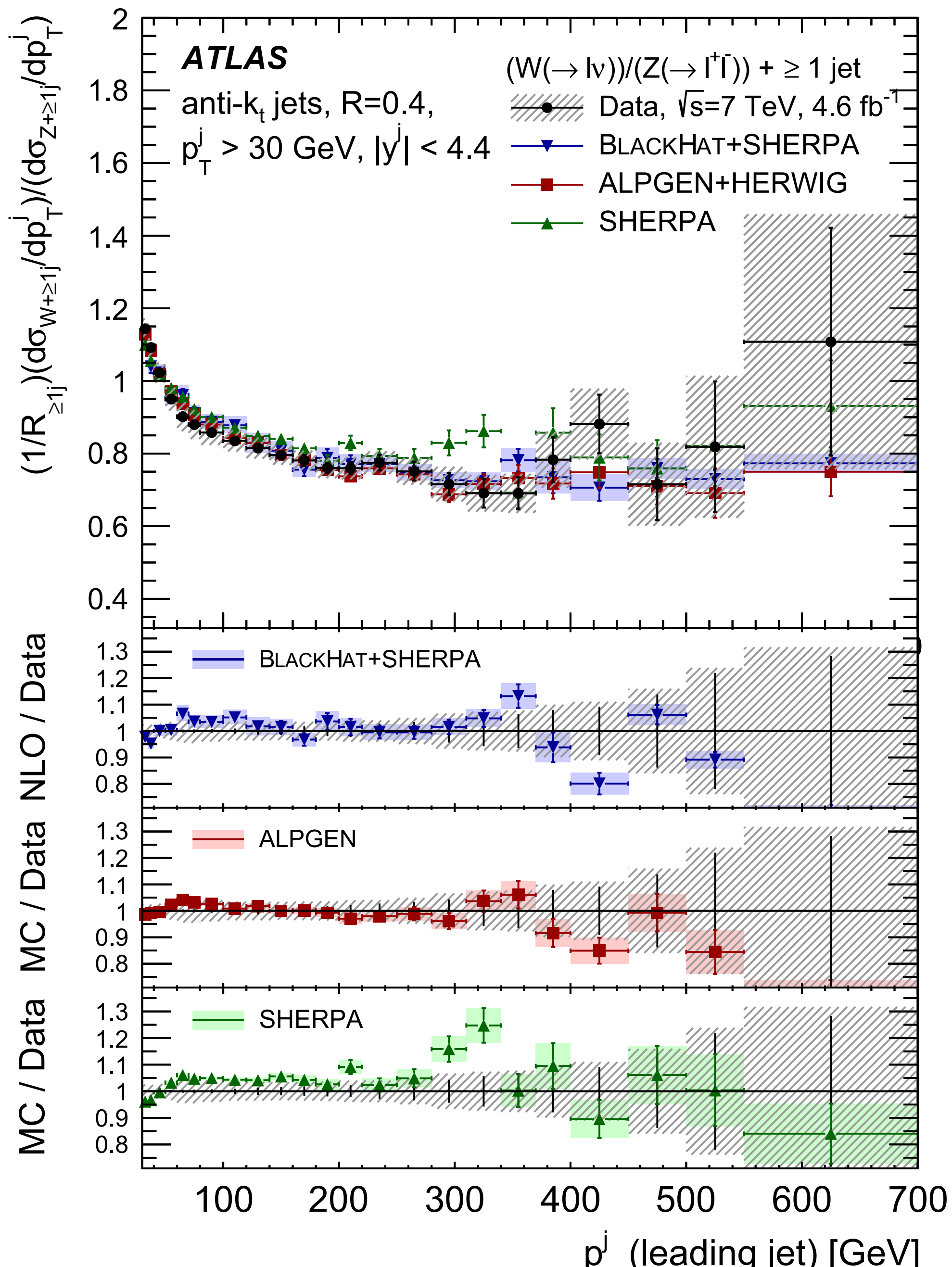
Double differential measurement of jet kinematics.
Eta coverage extended to 4.7



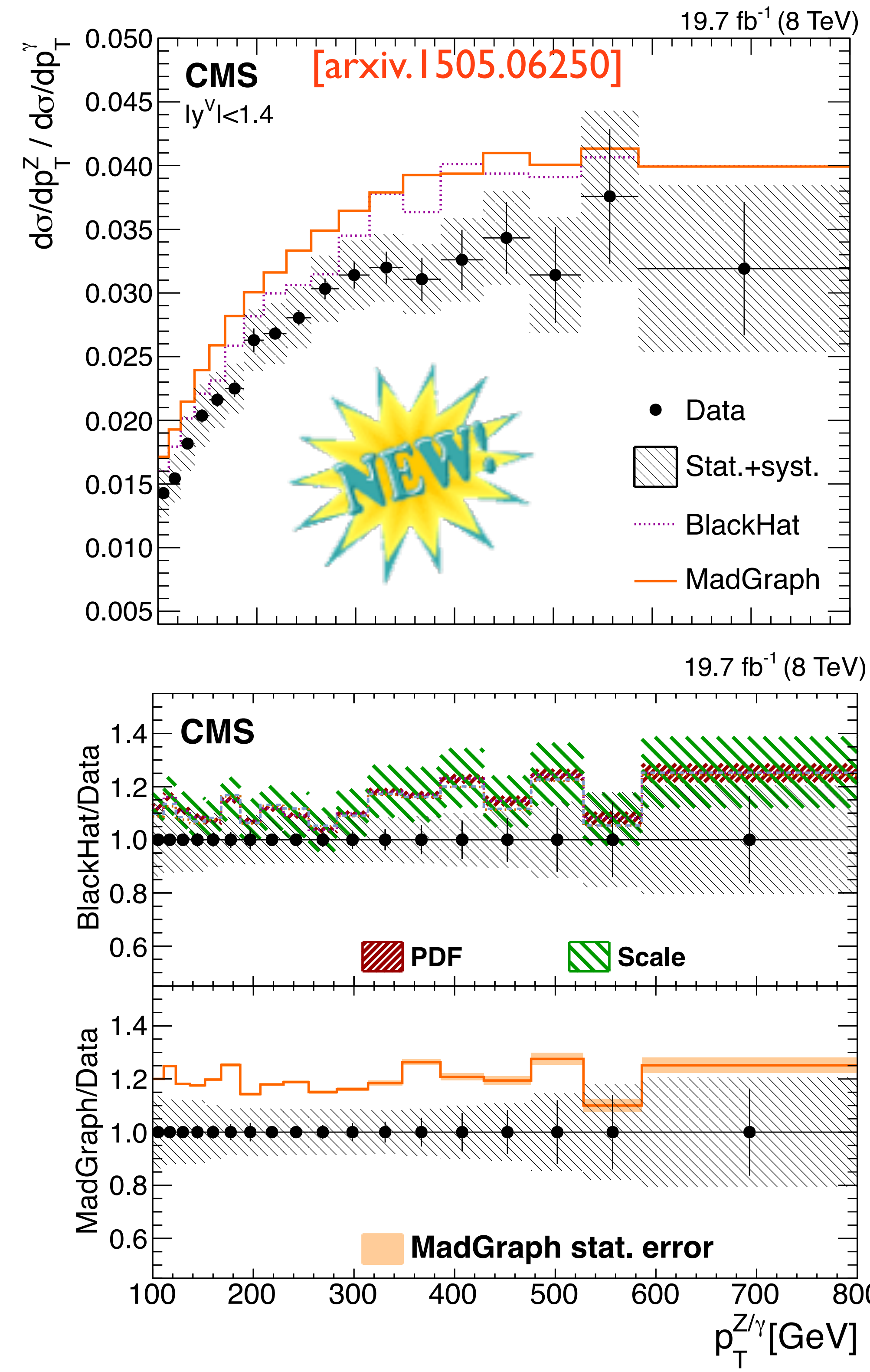
Severe trend for Sherpa
More reasonable for MG

W/Z and Z/γ+jets ratio

[PLB708(2012)221-240]



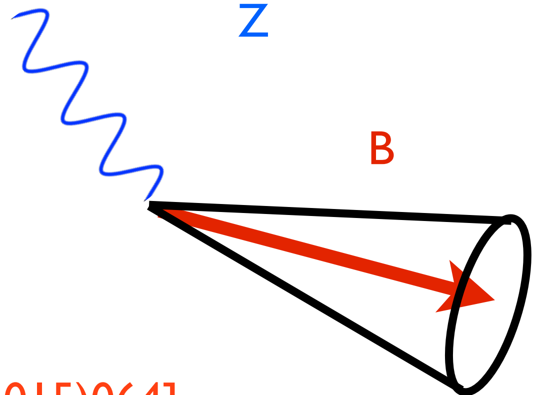
[arxiv.1505.06250]



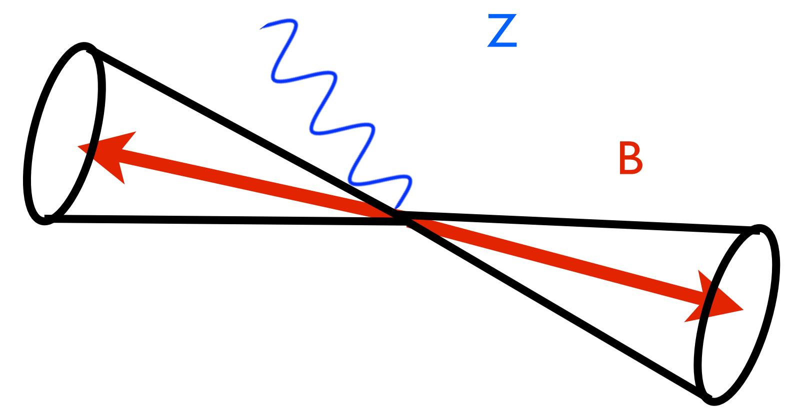
No severe disagreement between data and MC Tree-Level and NLO predictions show very similar behaviour

Data and MC agree within uncertainties.

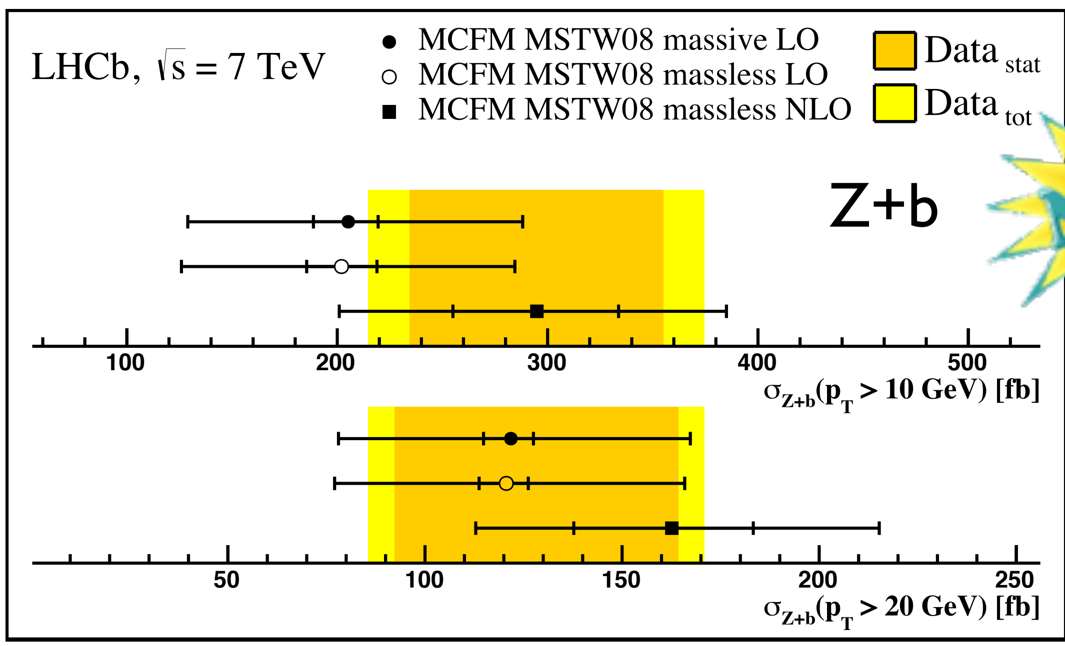
Z+1, 2 b



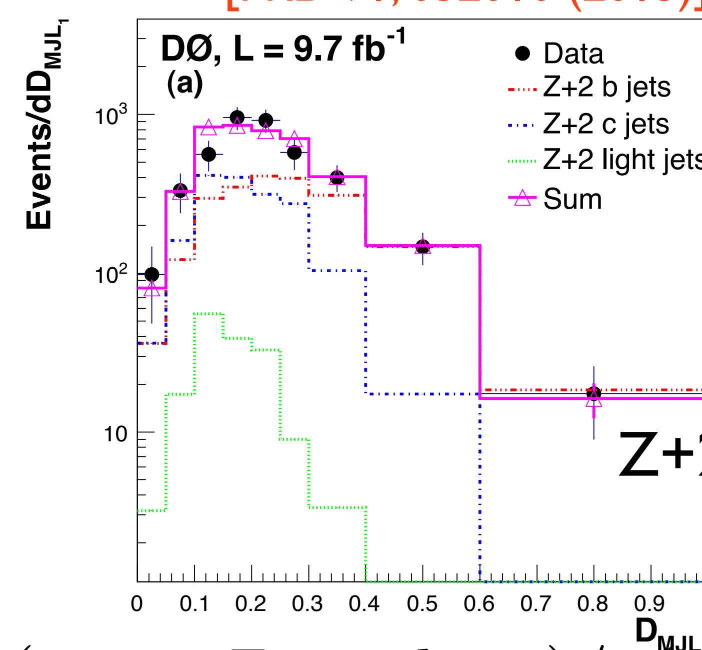
[JHEP 01(2015)064]



[PRD 91, 052010 (2015)]



Z+b



Z+2bj/Z+2j

$$\sigma(p\bar{p} \to Z + 2\ b\ \text{jet})/\sigma(p\bar{p} \to Z + 2\ \text{jet})$$

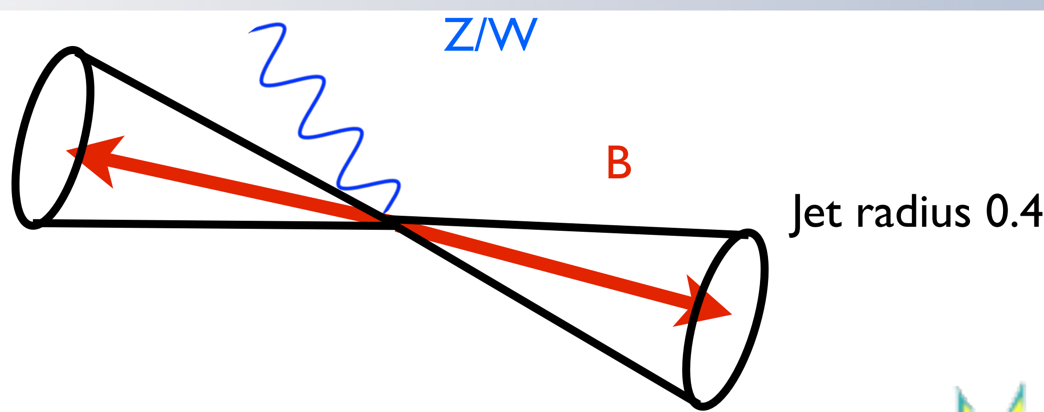
$$(2.36 \pm 0.32 \pm 0.35) \times 10^{-2}$$

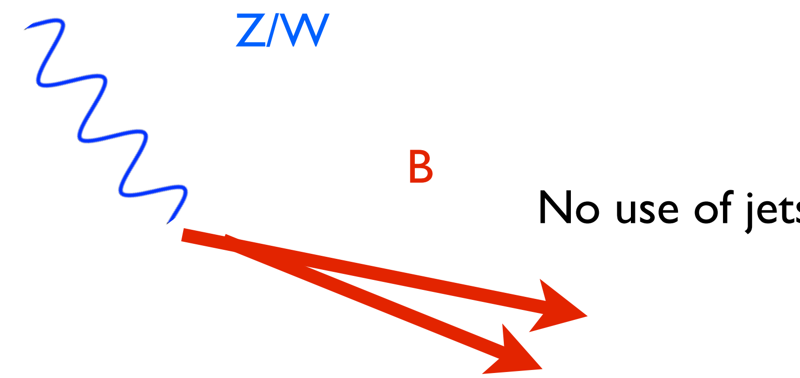
NLO QCD(MSTW)	PYTHIA	ALPGEN
$(1.76 \pm 0.26) \times 10^{-2}$	2.42×10^{-2}	2.21×10^{-2}

Generally MCFM agrees quite well with data small deviation for LO Z+b prediction and soft Pt regime

Pythia and ALPGEN predictions match the data

Z+2b

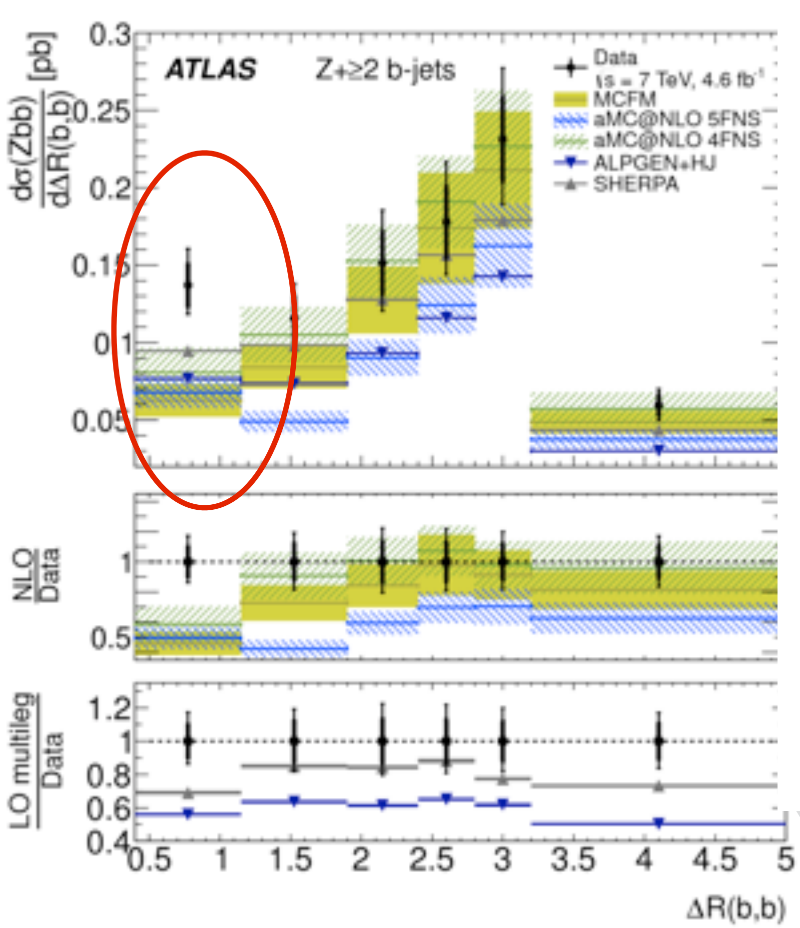


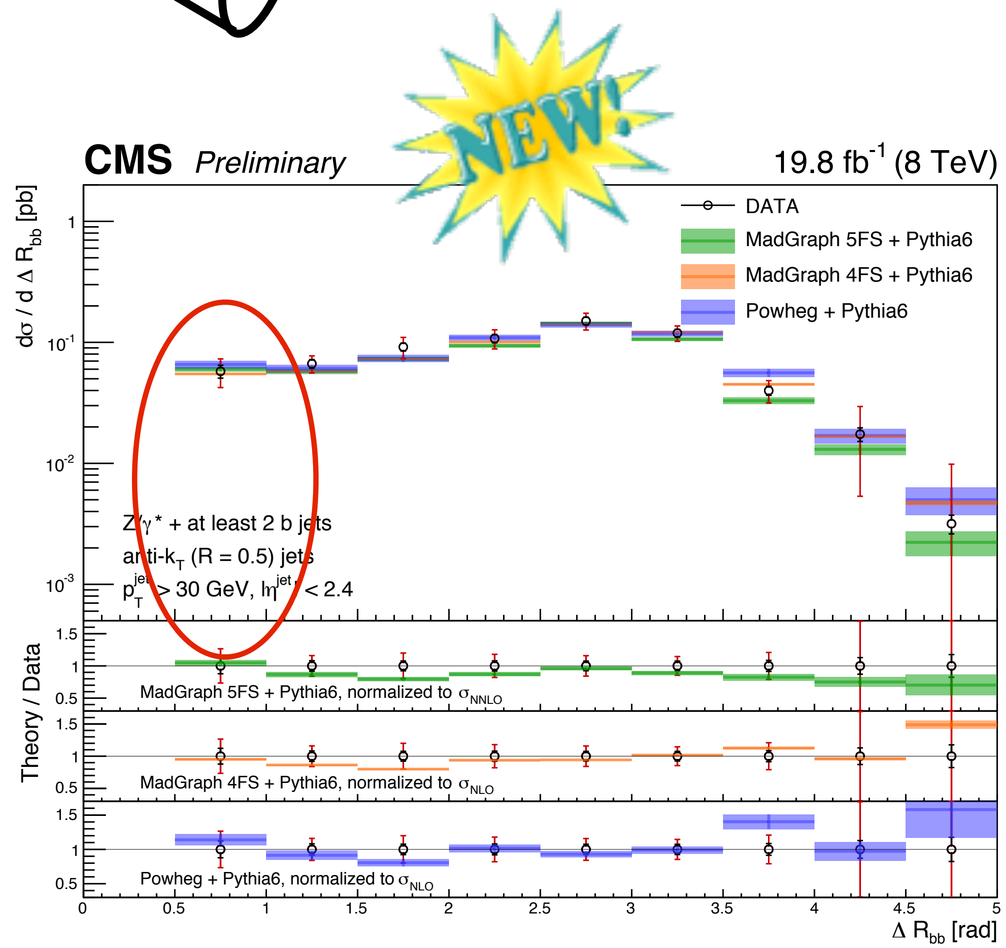


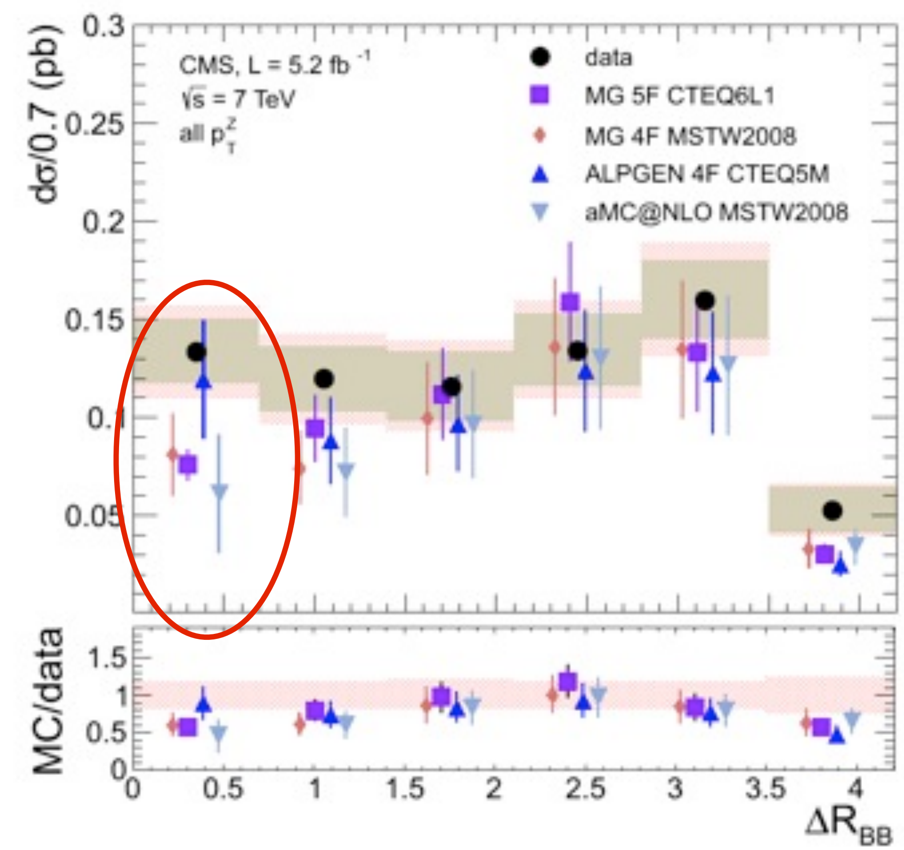
Z+2bj

[JHEP 10 (2014) 141]

[JHEP 12 (2013) 39]





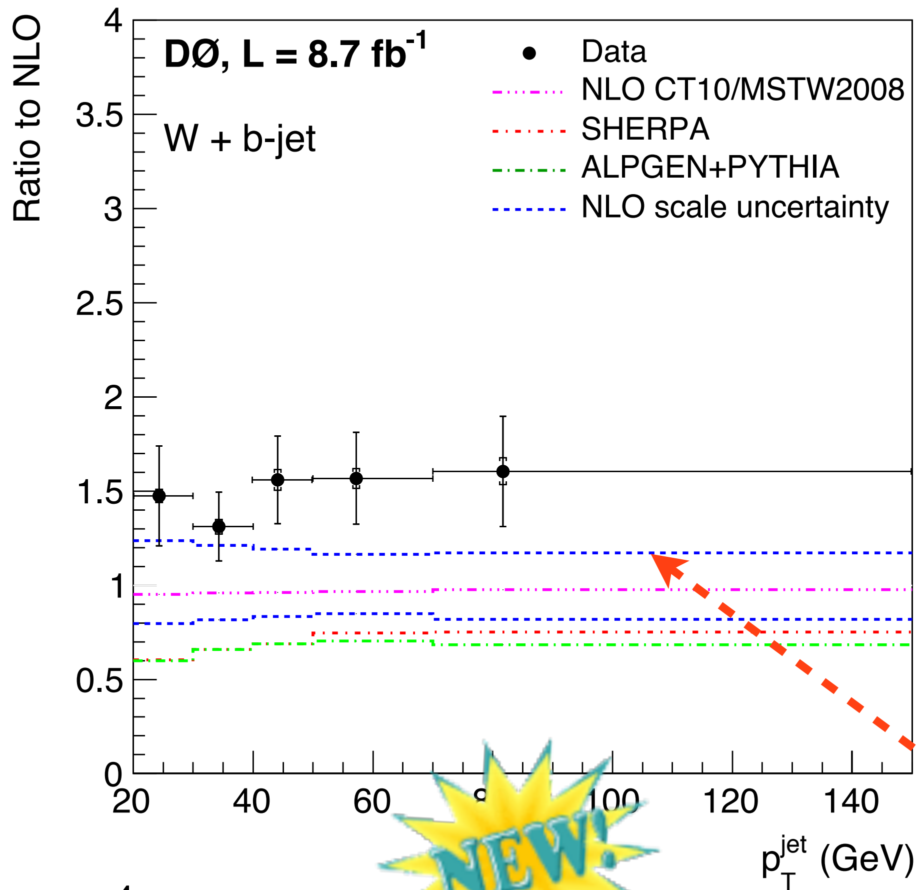


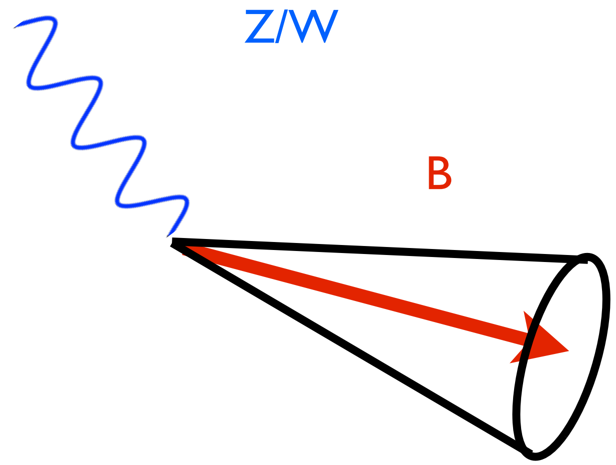
Z+2B

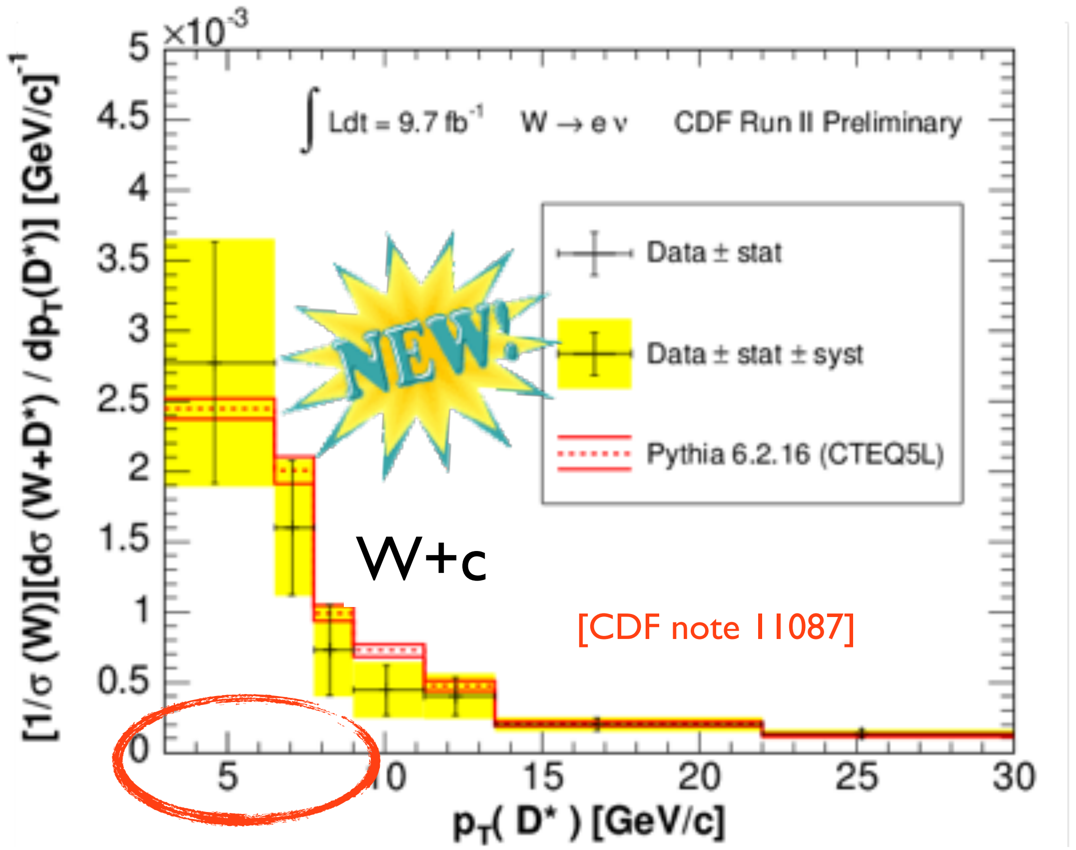
ATLAS and CMS 7 TeV measurements: excess of data around ~0.5 CMS (except ALPGEN)
Zbb @ 8 TeV: excess unseen with jet radius=0.5

W+1 b/c

[PLB 743, 6 (2015)]

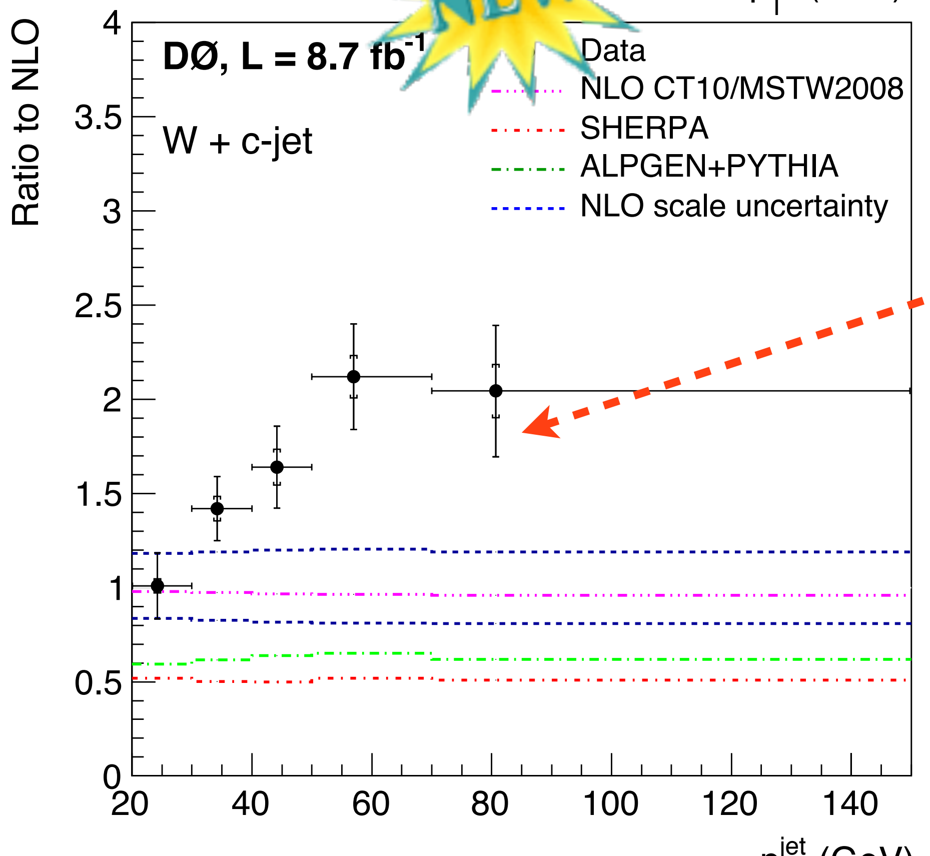


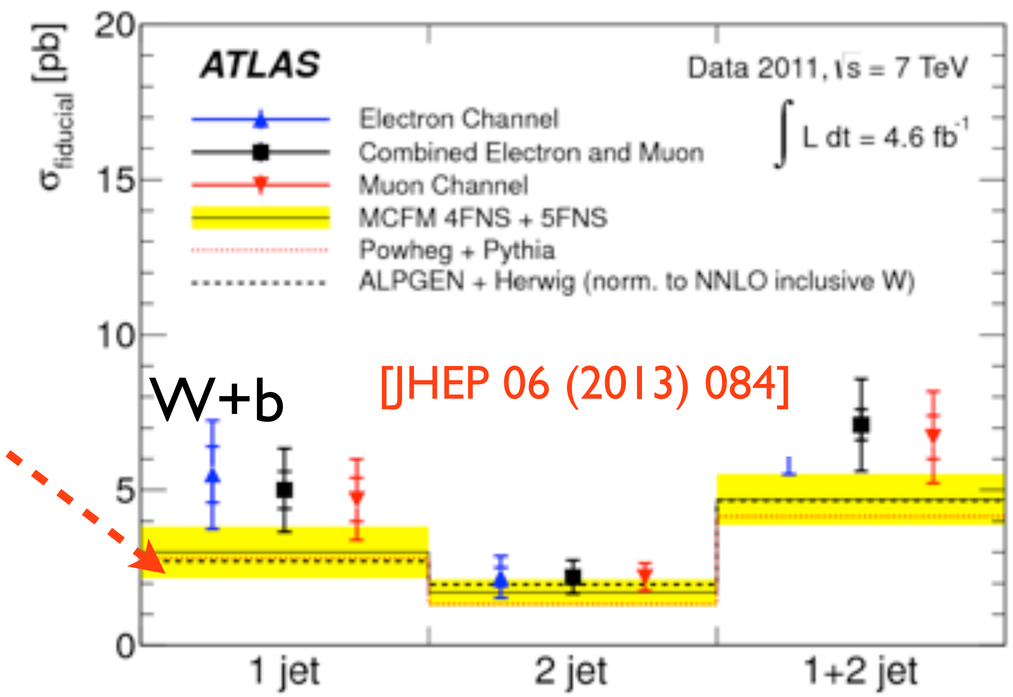




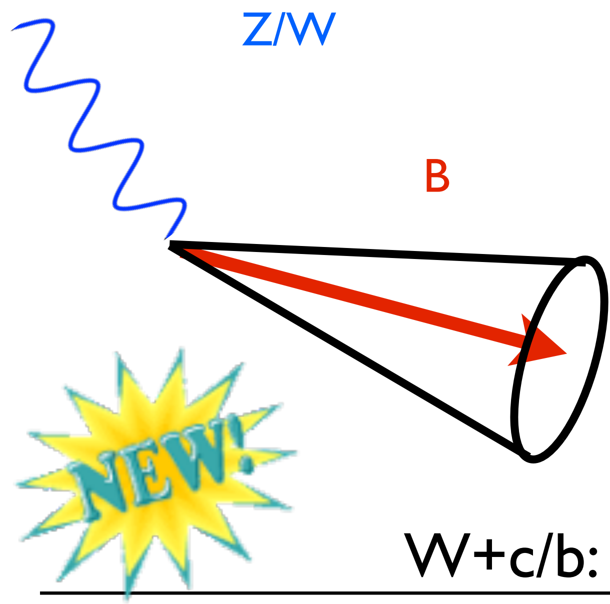
Data/MC~1

Large data/MC excess





W+b/c, W+2b

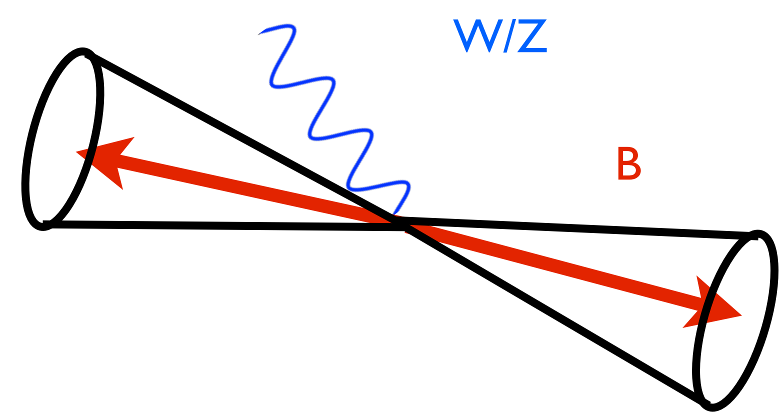


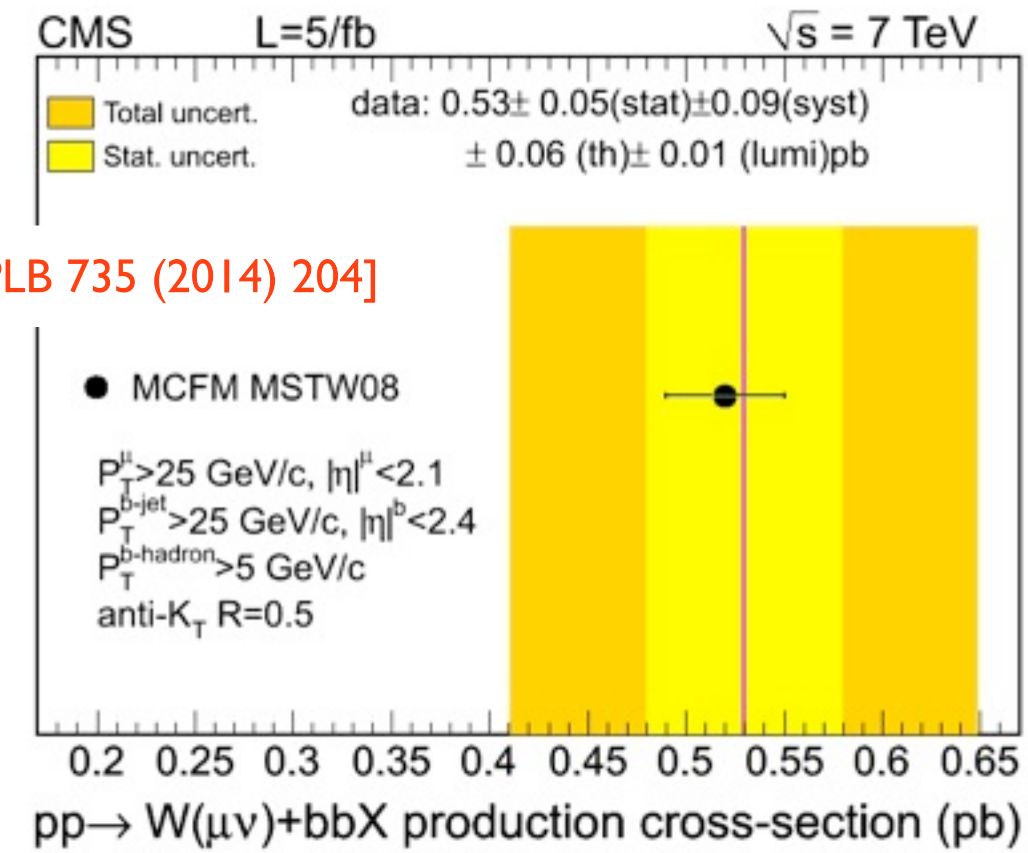
[CERN-PH-EP-2015-118]

W+c/b: LHCb

	Results 7 TeV	Results 8 TeV	SM prediction 7 TeV	SM prediction 8 TeV
$\frac{\sigma(Wb)}{\sigma(Wj)} \times 10^2$	$0.66 \pm 0.13 \pm 0.13$	$0.78 \pm 0.08 \pm 0.16$	$0.74^{+0.17}_{-0.13}$	$0.77^{+0.18}_{-0.13}$
$\frac{\sigma(Wc)}{\sigma(Wj)} \times 10^2$	$5.80 \pm 0.44 \pm 0.75$	$5.62 \pm 0.28 \pm 0.73$	$5.02^{+0.80}_{-0.69}$	$5.31^{+0.87}_{-0.52}$
$\mathcal{A}(Wb)$	$0.51 \pm 0.20 \pm 0.09$	$0.27 \pm 0.13 \pm 0.09$	$0.27^{+0.03}_{-0.03}$	$0.28^{+0.03}_{-0.03}$
$\mathcal{A}(Wc)$	$-0.09 \pm 0.08 \pm 0.04$	$-0.01 \pm 0.05 \pm 0.04$	$-0.15^{+0.02}_{-0.04}$	$-0.14^{+0.02}_{-0.03}$
$\frac{\sigma(W^+j)}{\sigma(Zj)}$	$10.49 \pm 0.28 \pm 0.53$	$9.44 \pm 0.19 \pm 0.47$	$9.90^{+0.28}_{-0.24}$	$9.48^{+0.16}_{-0.33}$
$\frac{\sigma(W^-j)}{\sigma(Zj)}$	$6.61 \pm 0.19 \pm 0.33$	$6.02 \pm 0.13 \pm 0.30$	$5.79^{+0.21}_{-0.18}$	$5.52^{+0.13}_{-0.25}$

Good agreement between data and MCFM



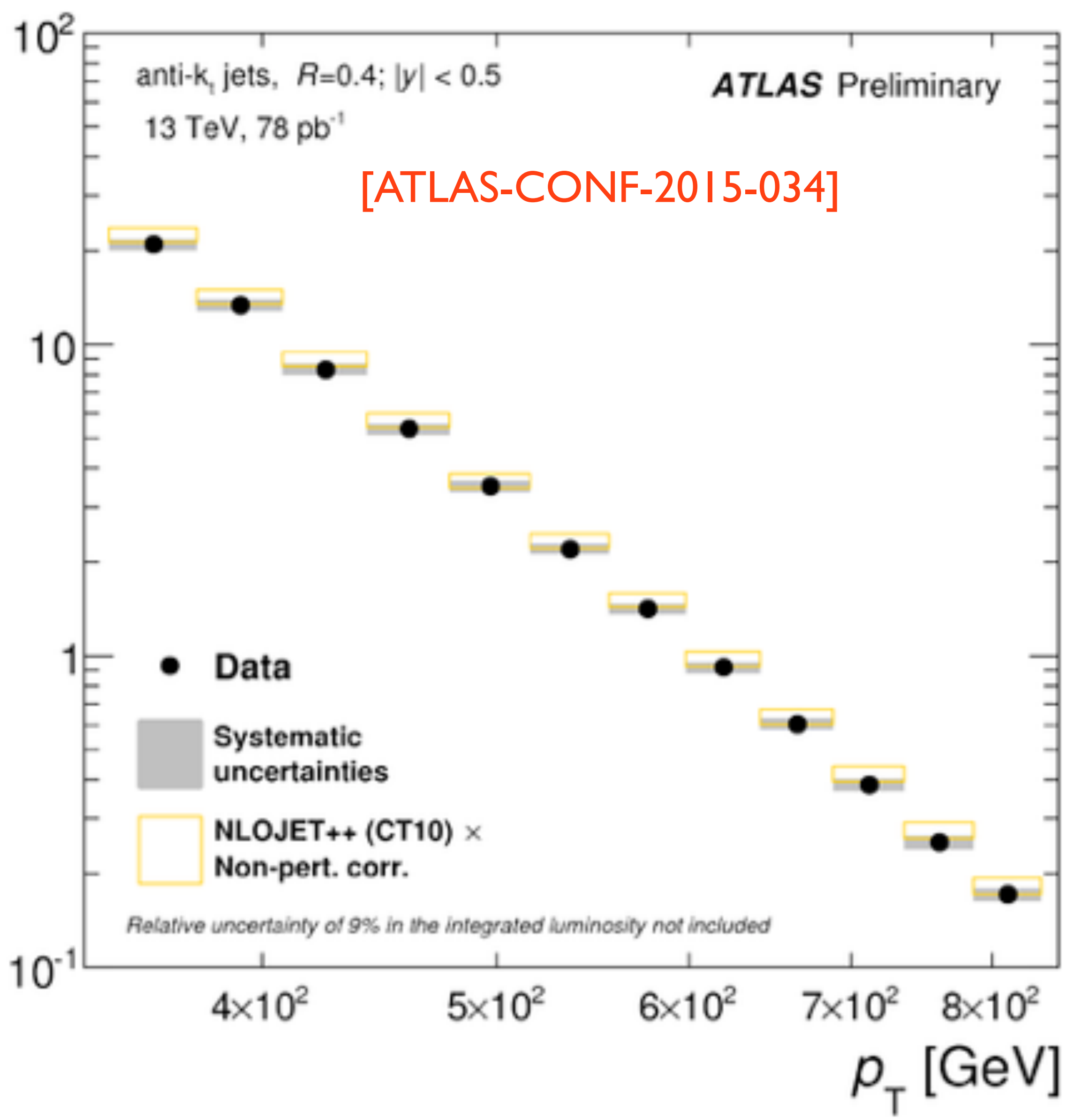


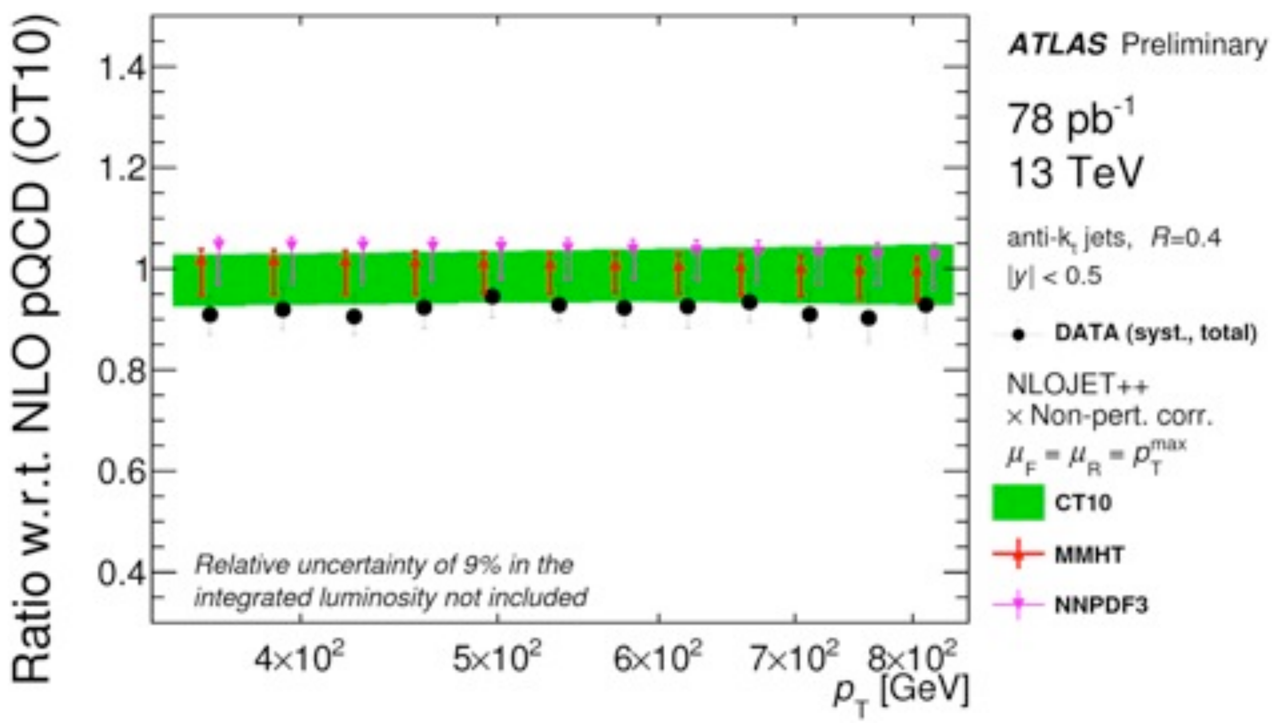
[PLB 735 (2014) 204]

Good agreement MCFM

LHC Run II preliminaries

LHC Run II first QCD results

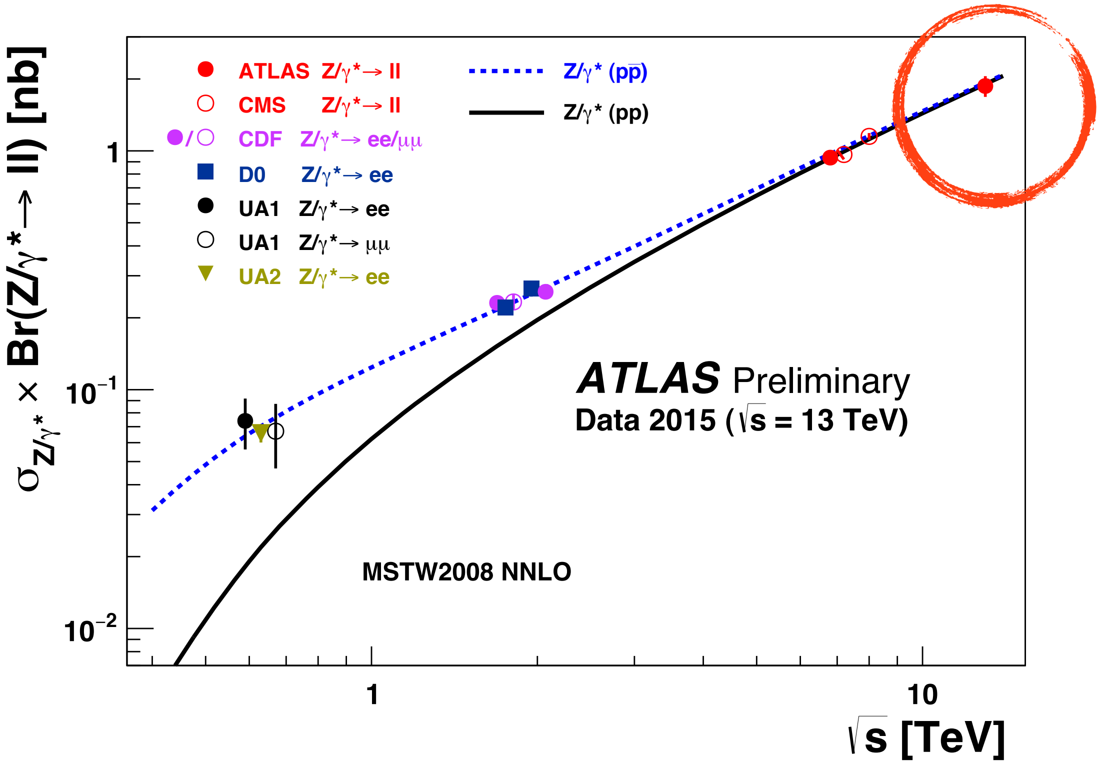




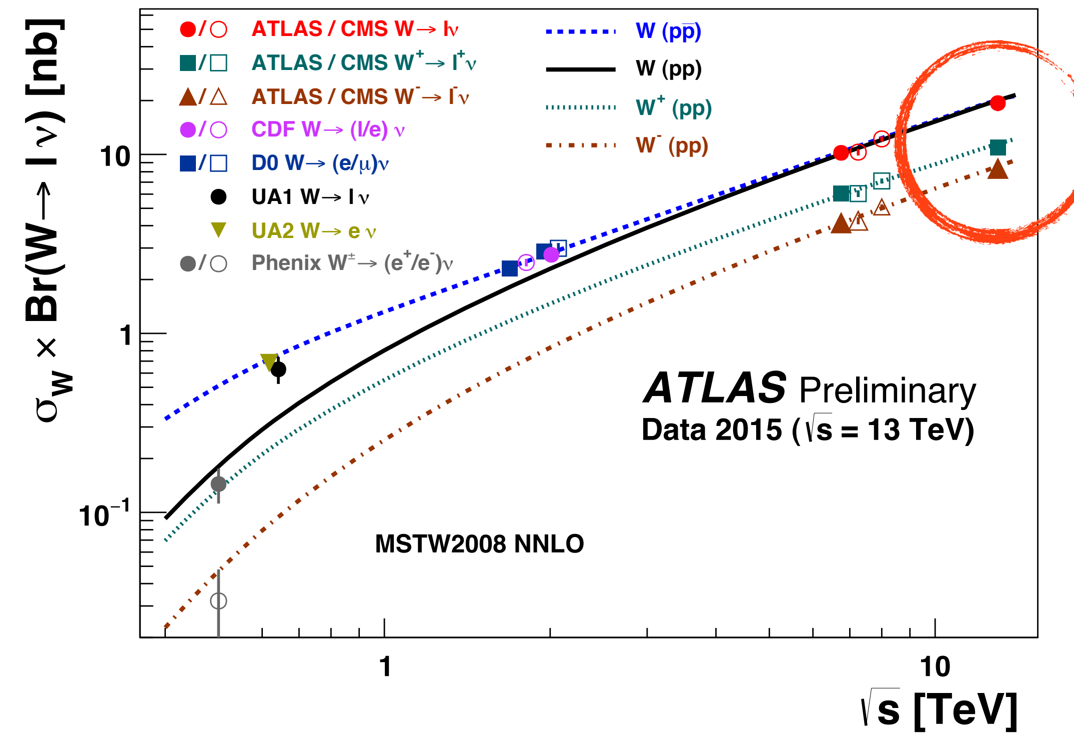
Normalisation: data and MC are in a reasonable agreement
Shape: very good agreement

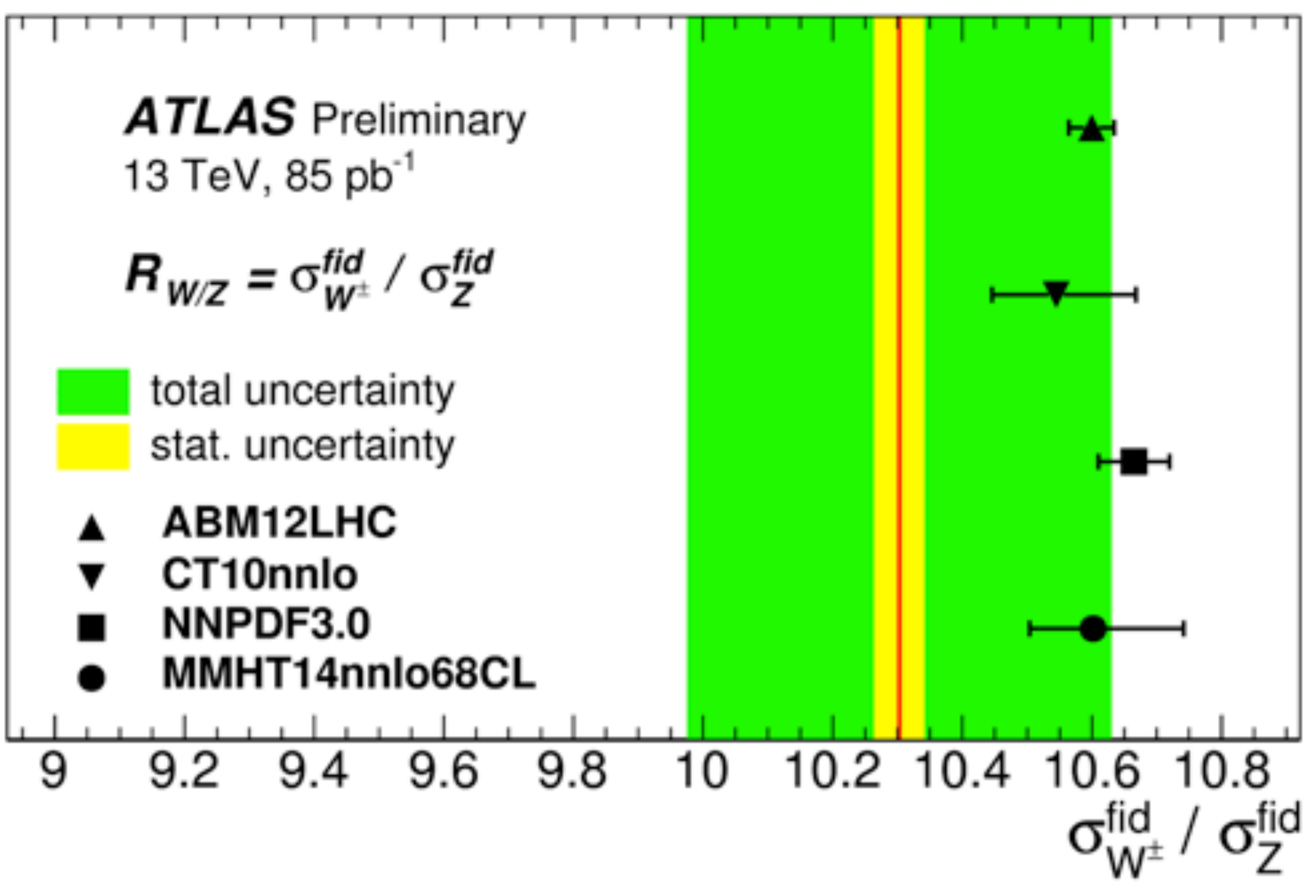
LHC Run II first QCD results: W/Z

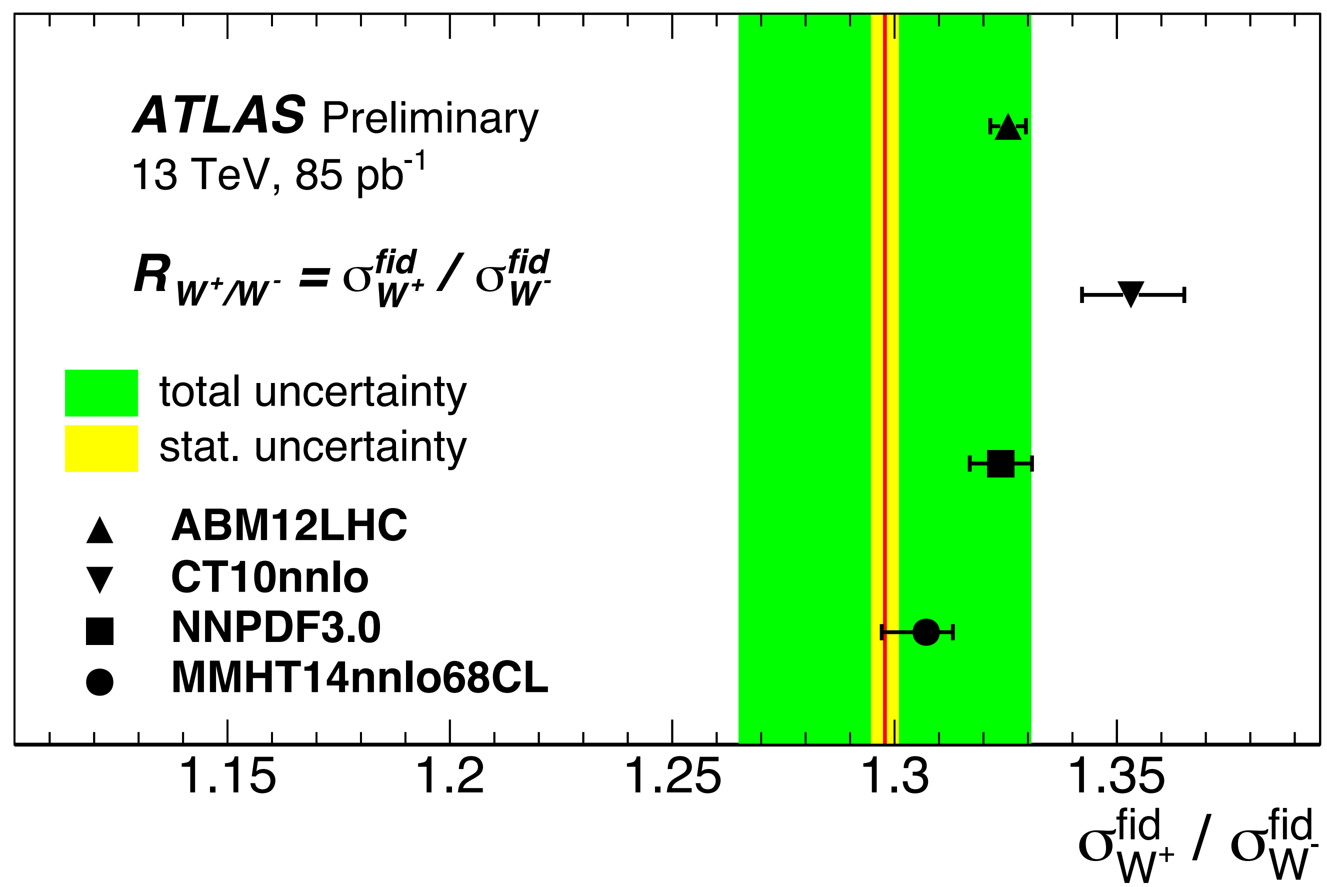
[ATLAS-CONF-2015-039]



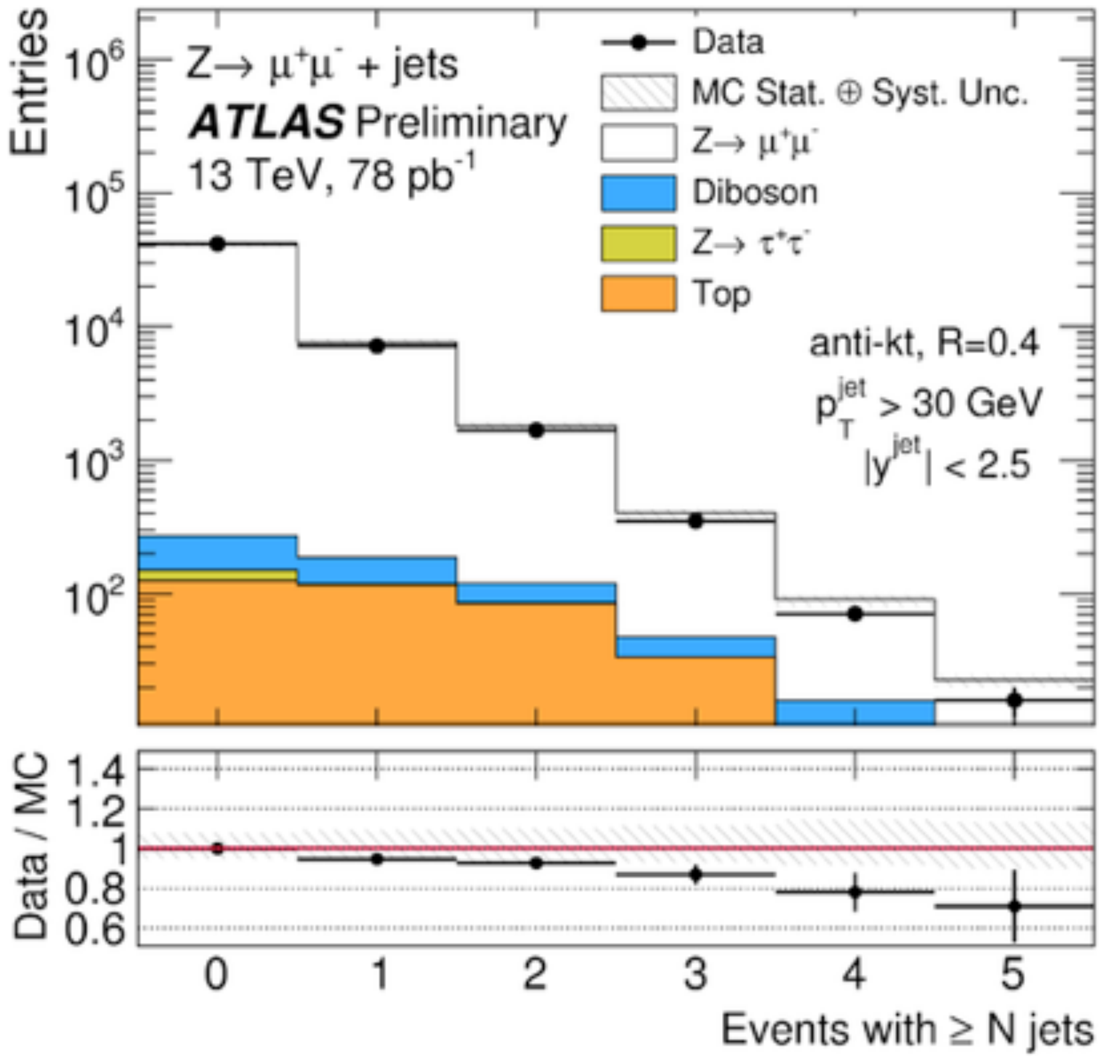
Early result allow to already check if a dependence to V's inclusive xsec ratio.

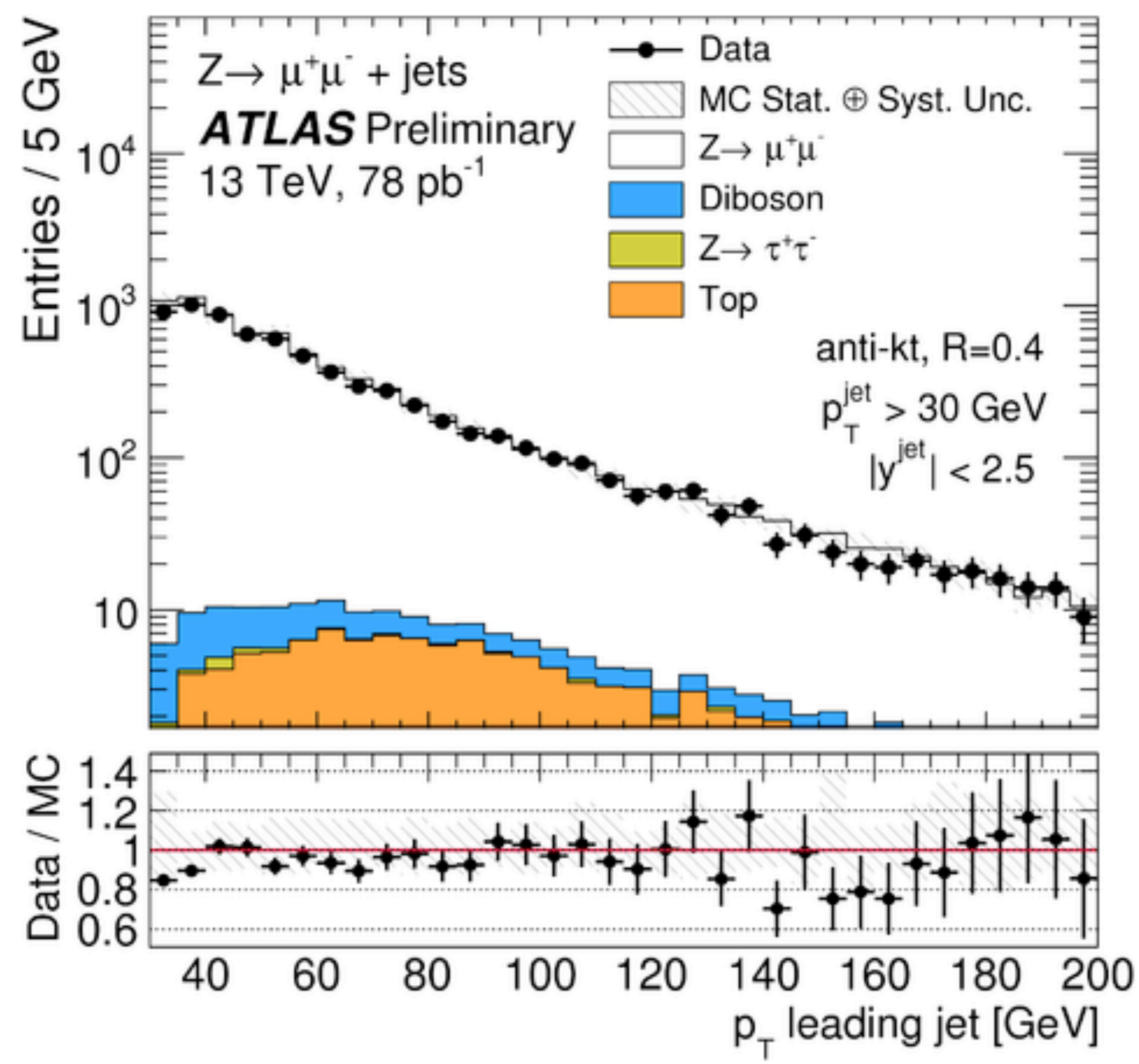






[ATLAS-PHYS-PUB-2015-021]





First detector-level comparison between data and MC!

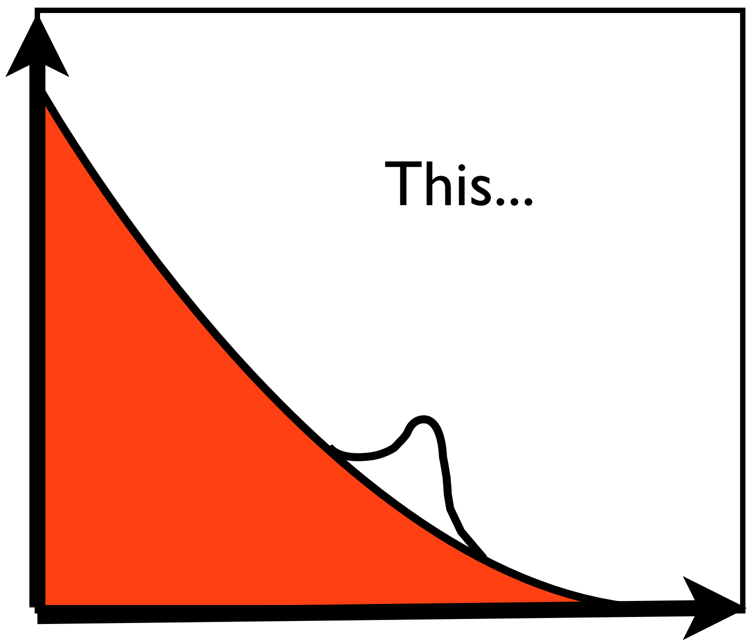
Conclusion

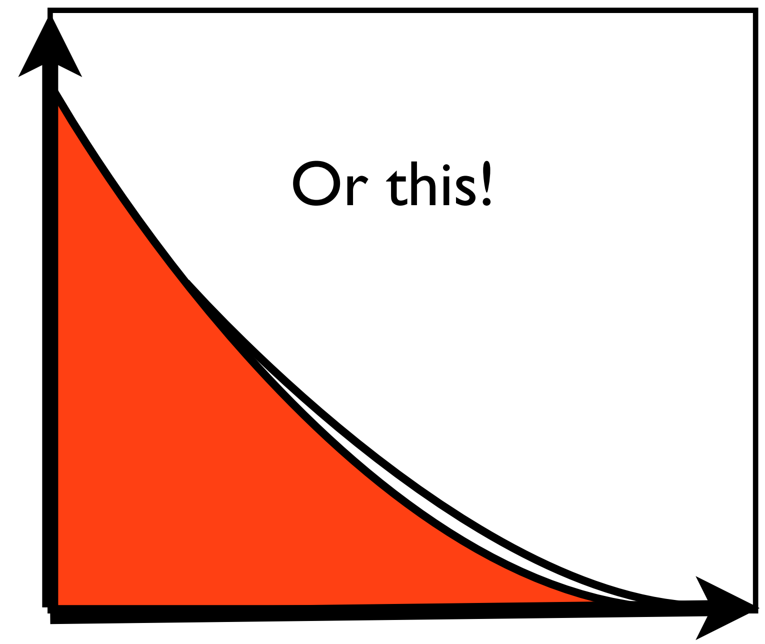
- Run I has allowed to push forward our knowledge on QCD, on many fronts. Impacts on
  - PDF, α_s
  - Generator:
    - Leading Order vs Tree-Level vs Next-to-Leading Order
    - merging techniques: (Kt-)MLM, CKKW(-L), FxFx
  - Light and heavy flavour jets production
- With expected Run II statistics
  - PDF: higher x, ratio between diff. energies, exploitation of Z+jets,...
  - Probe more efficiently regions where QCD and EWK higher order correction becomes larger
  - Probe collinear production of heavy hadrons (D and B)
  - ...

Backup

QCD at hadron collider

Discover a new signature at the LHC, can be...

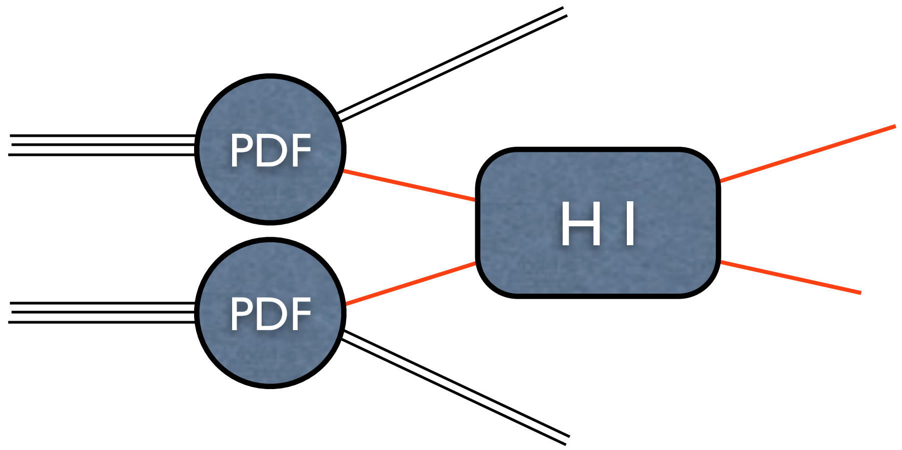




«Easy» discovery case:
data-driven estimation
of the background.
MC not absolutely needed
for the signal

Much more complicated!
Needs accurate prediction from
simulation for both signal and
background normalizations AND shapes

QCD plays a central role for *all* kinds predictions at hadron colliders. You need to make sure you have it well under control!
True also for precision measurement (Top,...)

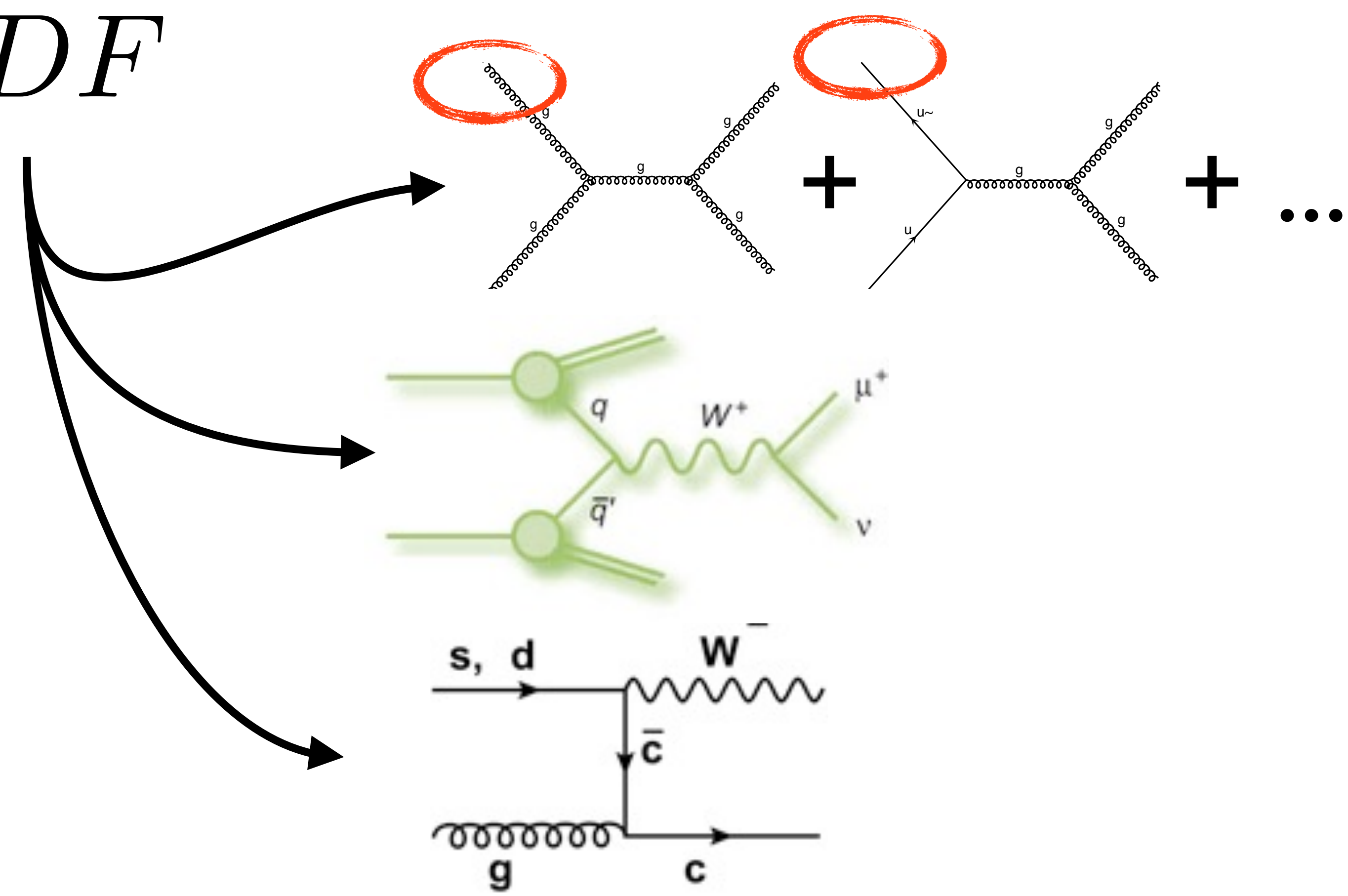


Good agreement between unfolded data and prediction from theory.

Small differences should result on PDF choice
⇒ allows to constrains PDF

quark or gluon-PDF?

$$\sigma \sim \sigma_{HI} \times PDF$$



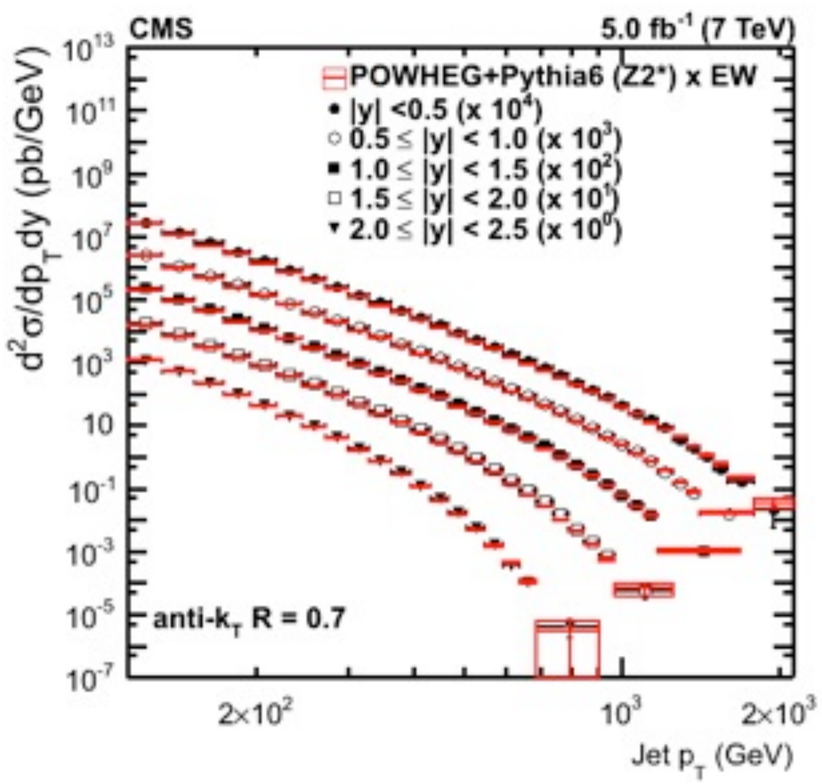
g,q-PDF

u,d-PDF

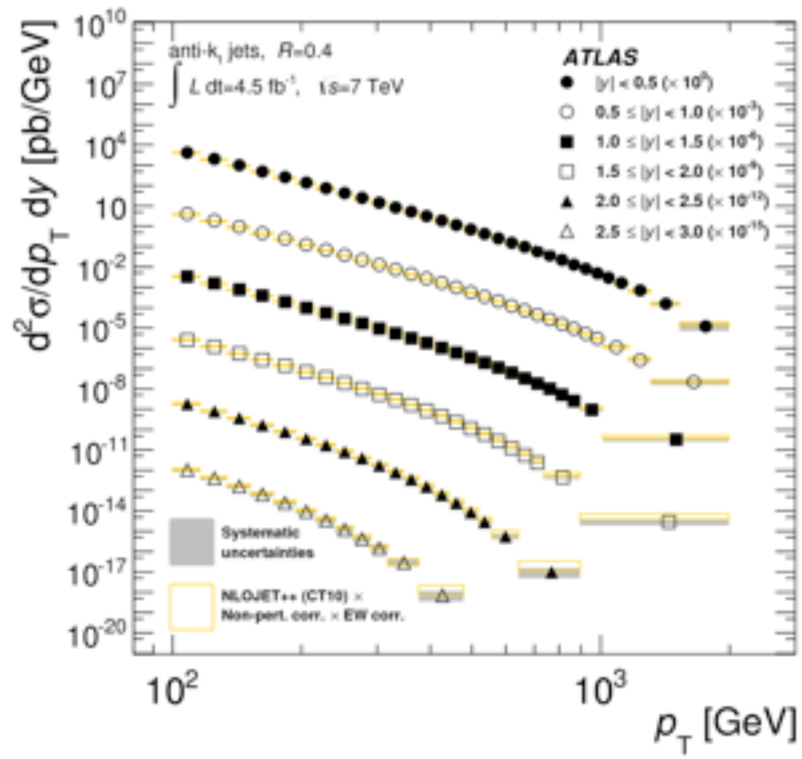
s-PDF

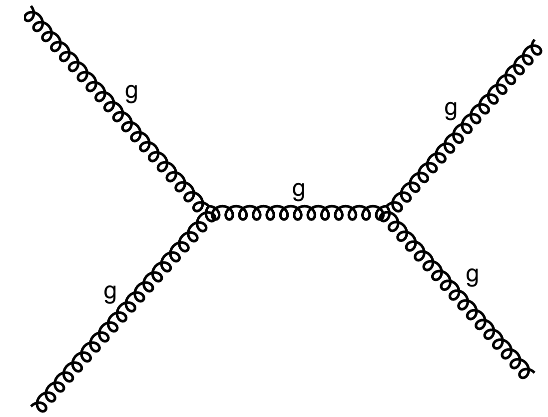
PDF from >=2-jet cross-section

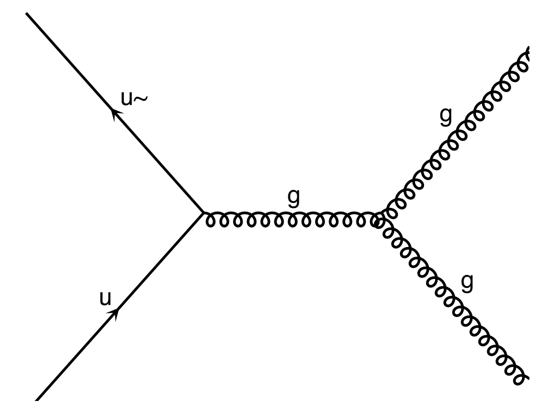
[Eur.Phys.J.C (2015) 75:288]



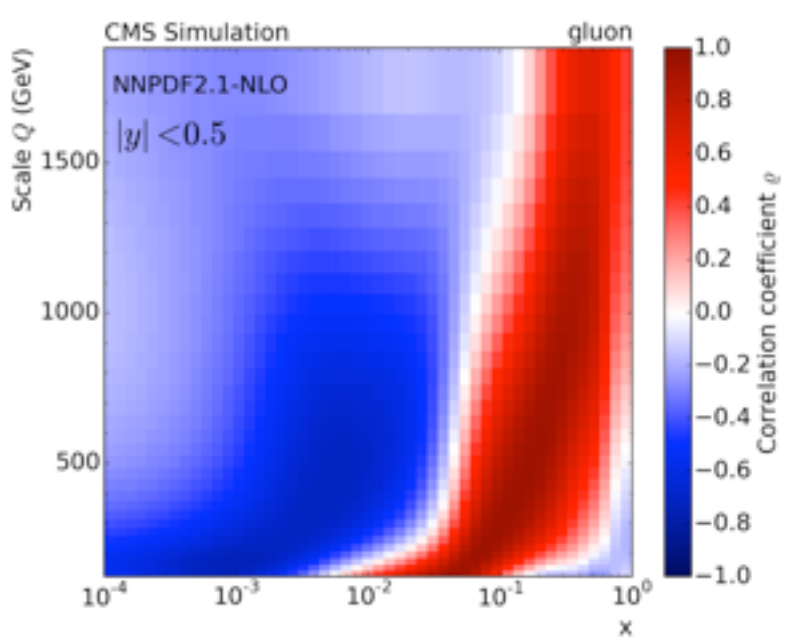
[JHEP02(2015)153]







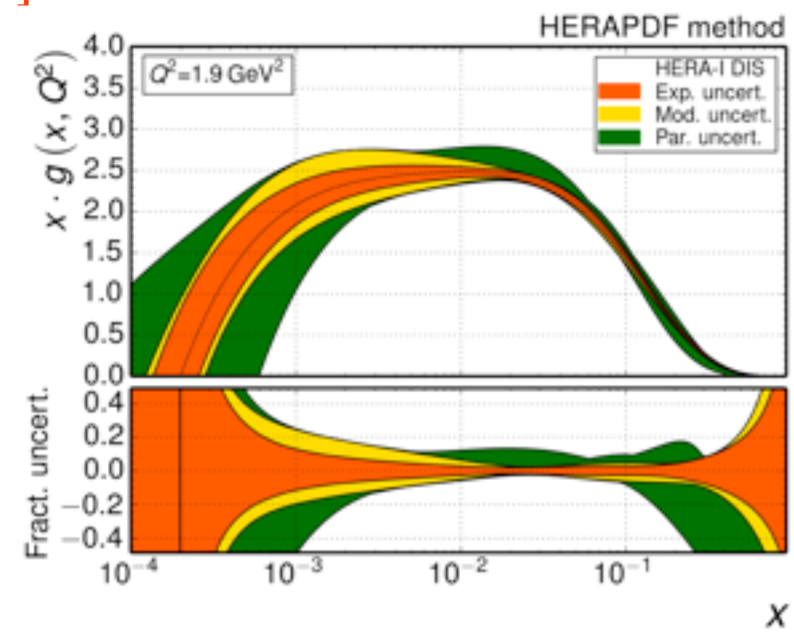
Strong correlation in (x,Q)
⇒good to constrain PDF



PDF from n-jet cross-section

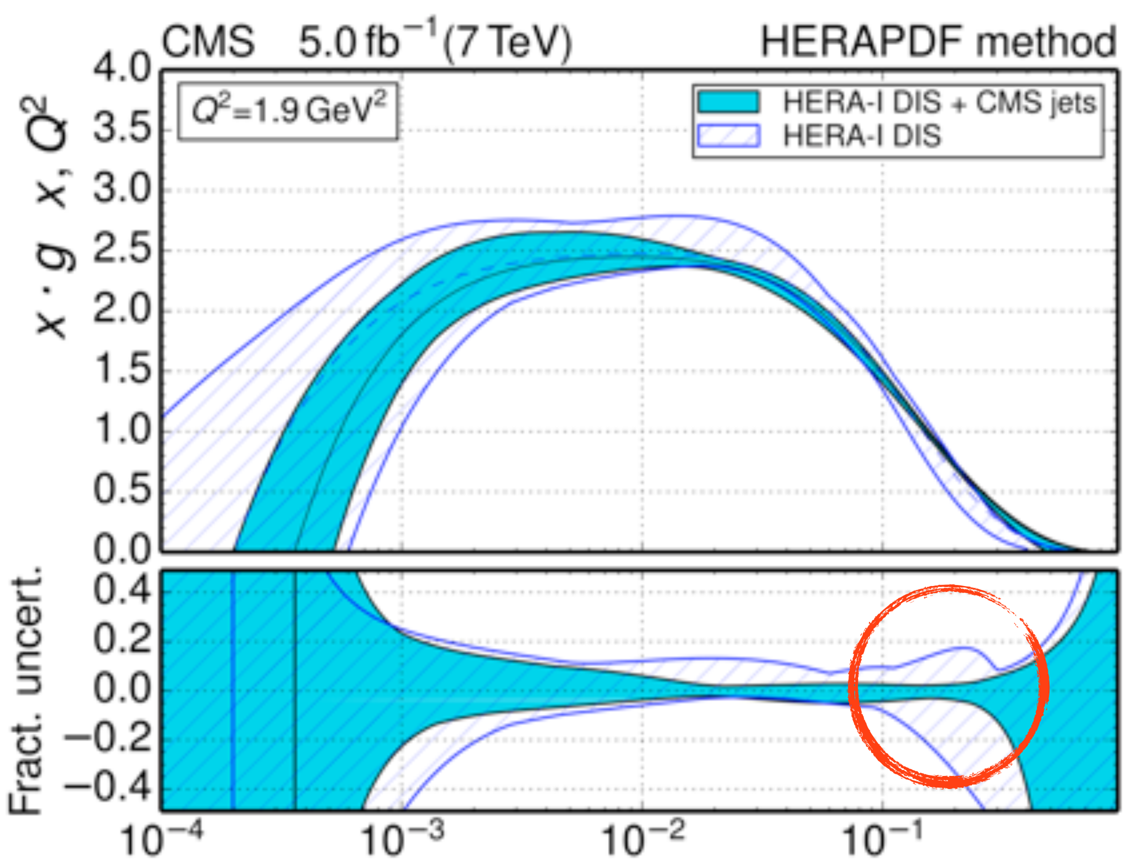
[Eur.Phys.J.C (2015) 75:288]

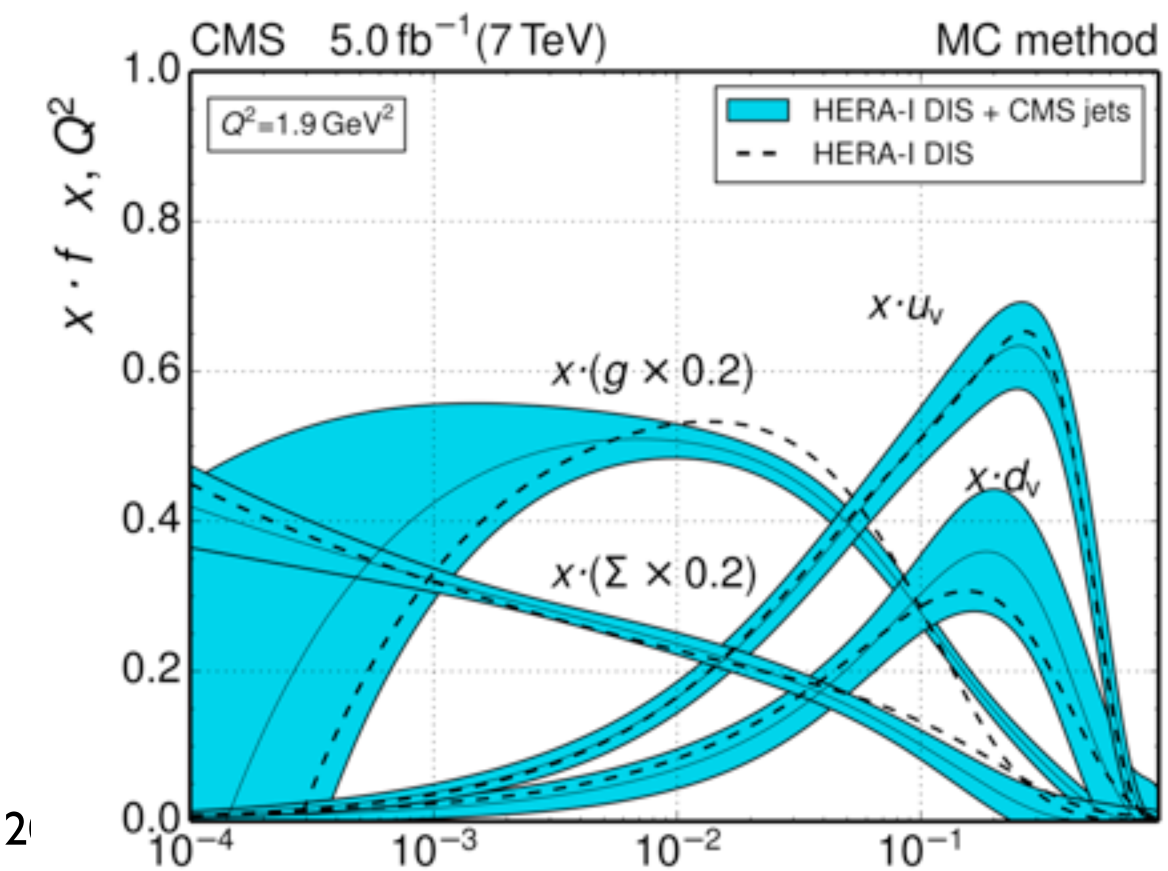
HeraFitter package used to constraint the PDFs
- CMS Jet Pt data: input
- input compared with prediction from theory (NLOJet)
- PDF parameters chosen to fit the theory to the data



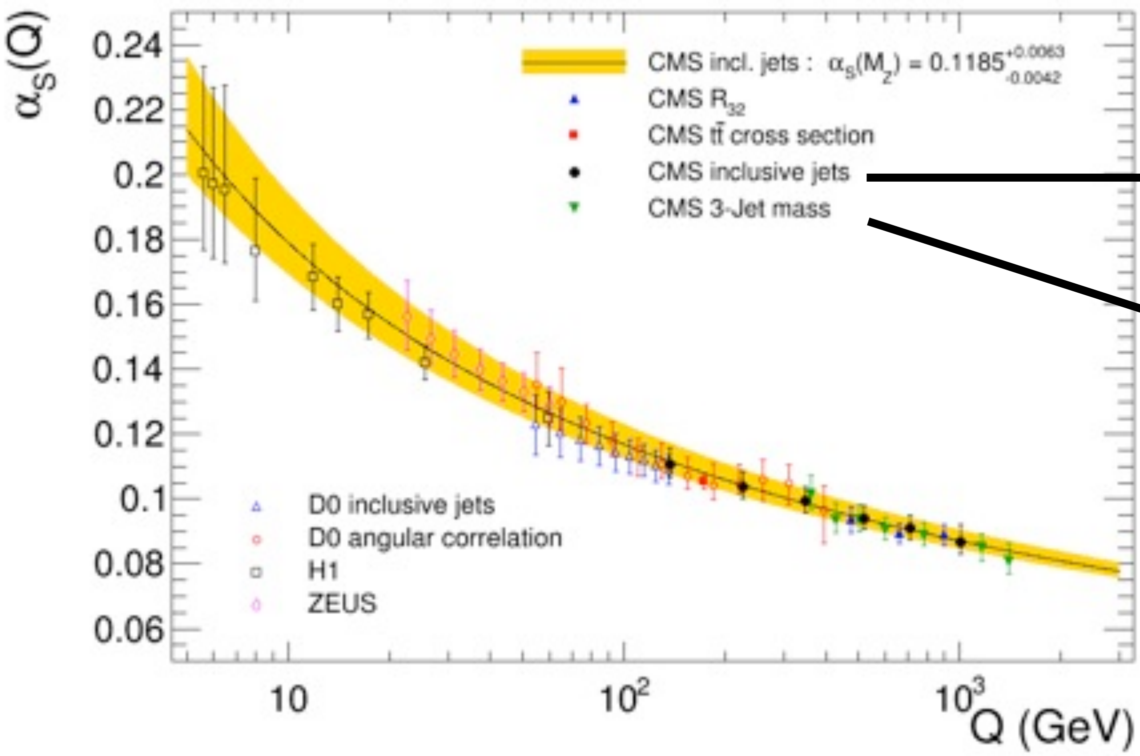
Reduction of uncertainties, especially for g-PDF

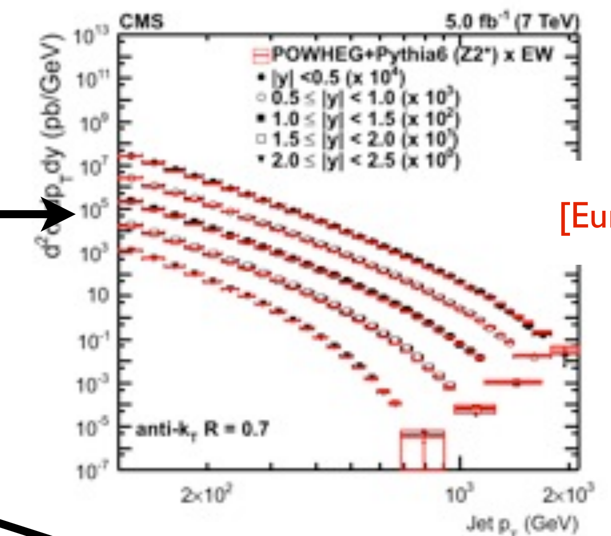
Impact on all PDF's is present, here at Q^2=1.9 GeV^2



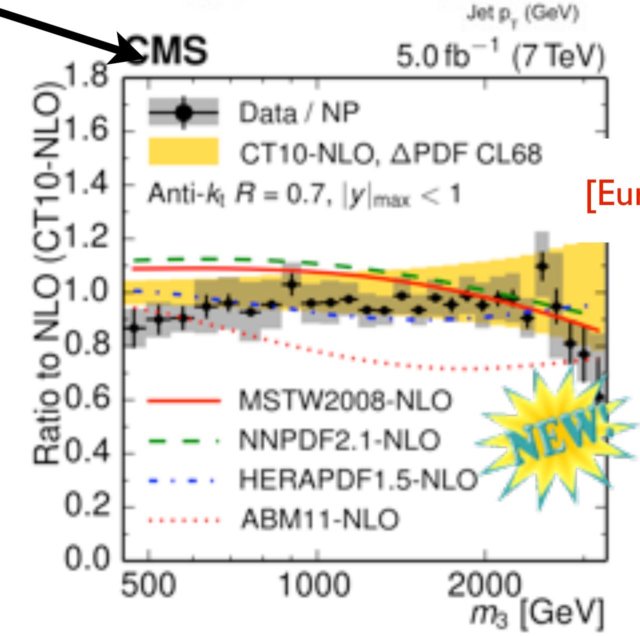


$\alpha_s(Q)$

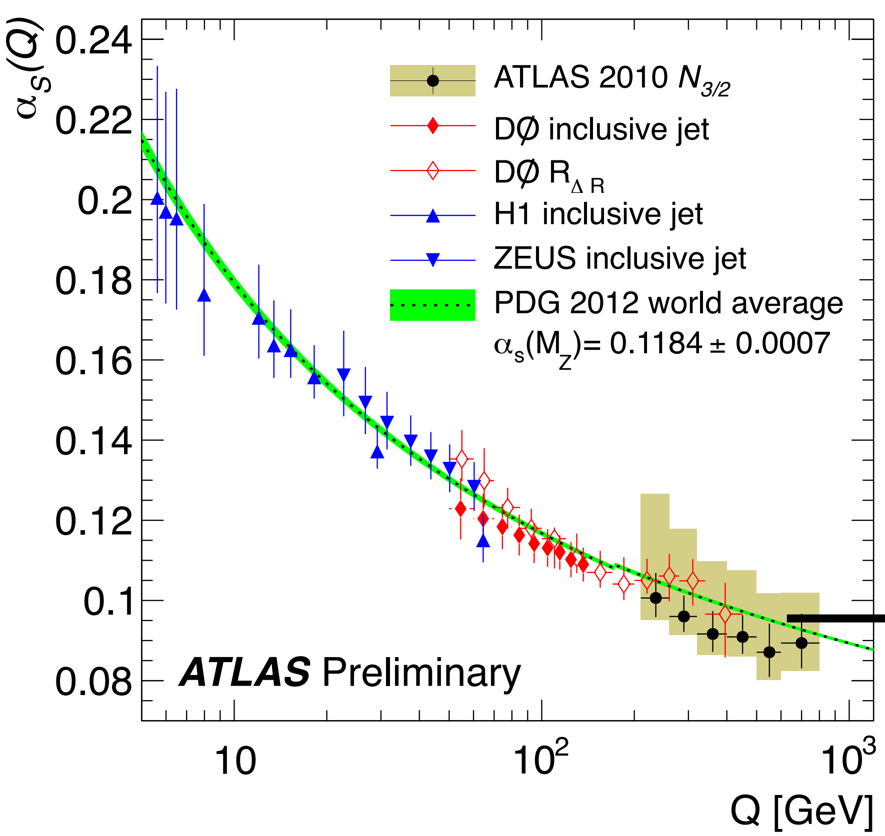


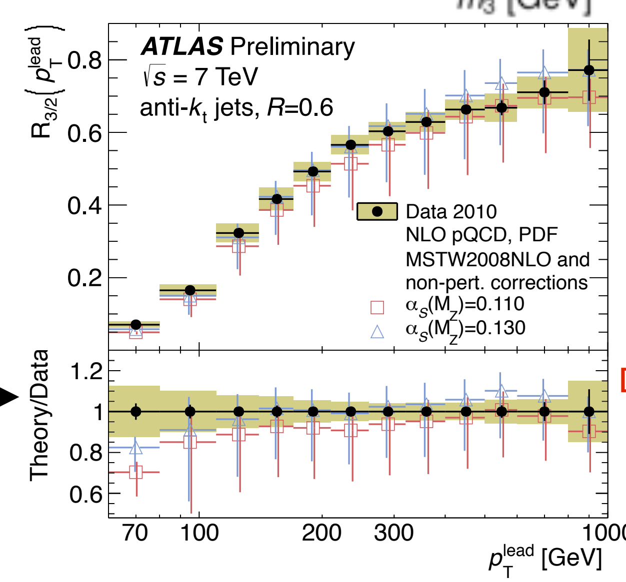


[Eur. Phys. J.C75(2015)288]



[Eur. Phys. J.C75(2015)186]

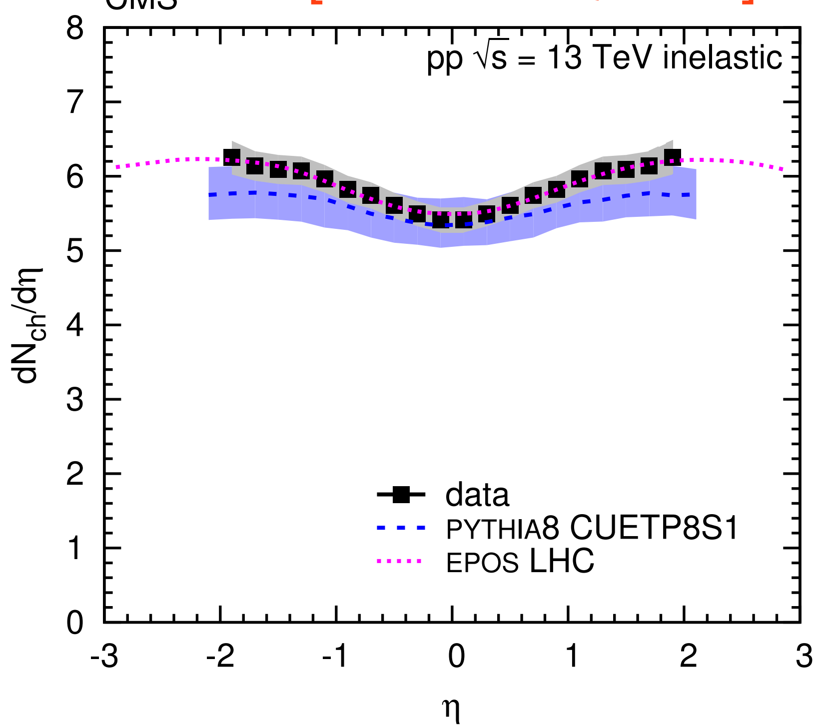


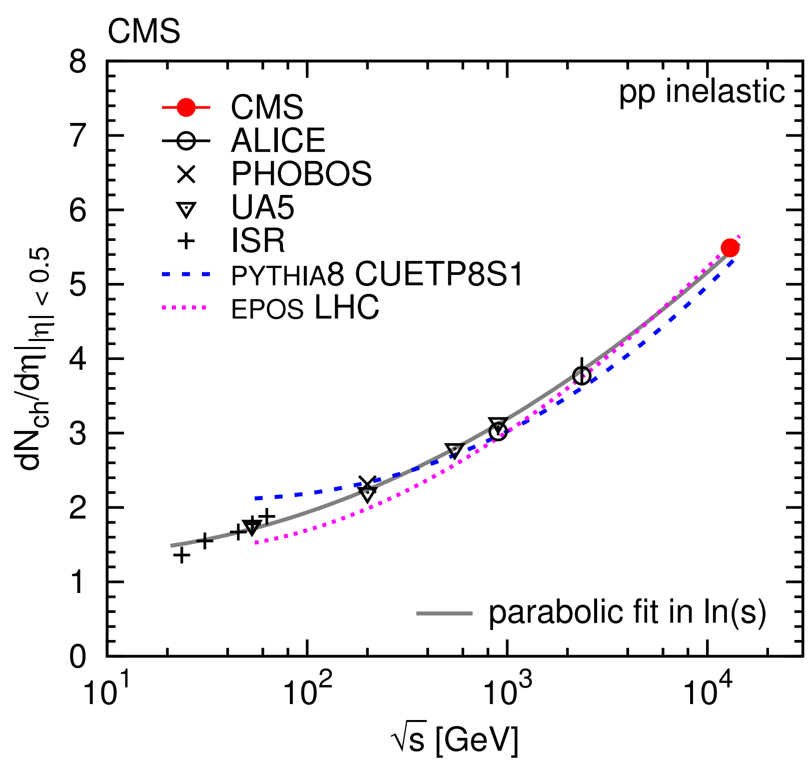


[ATLAS-CONF-2013-041]

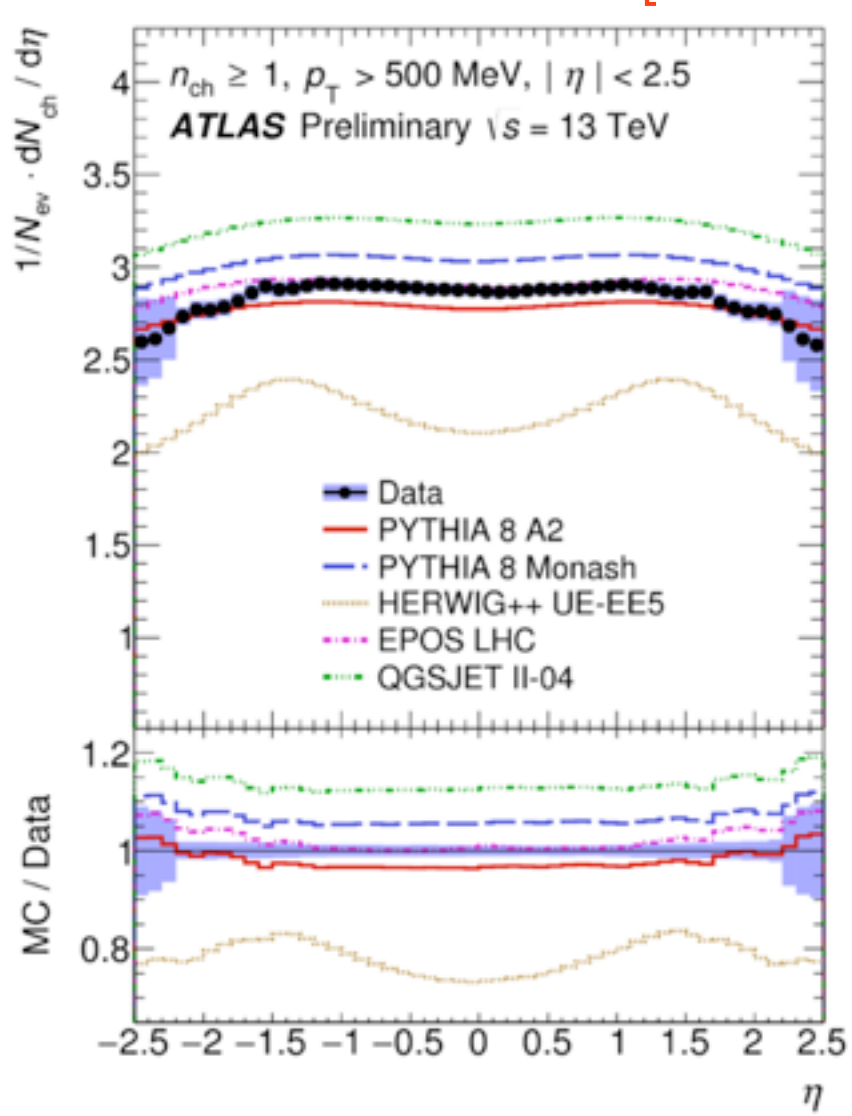
LHC Run II QCD preliminaries... NEW!

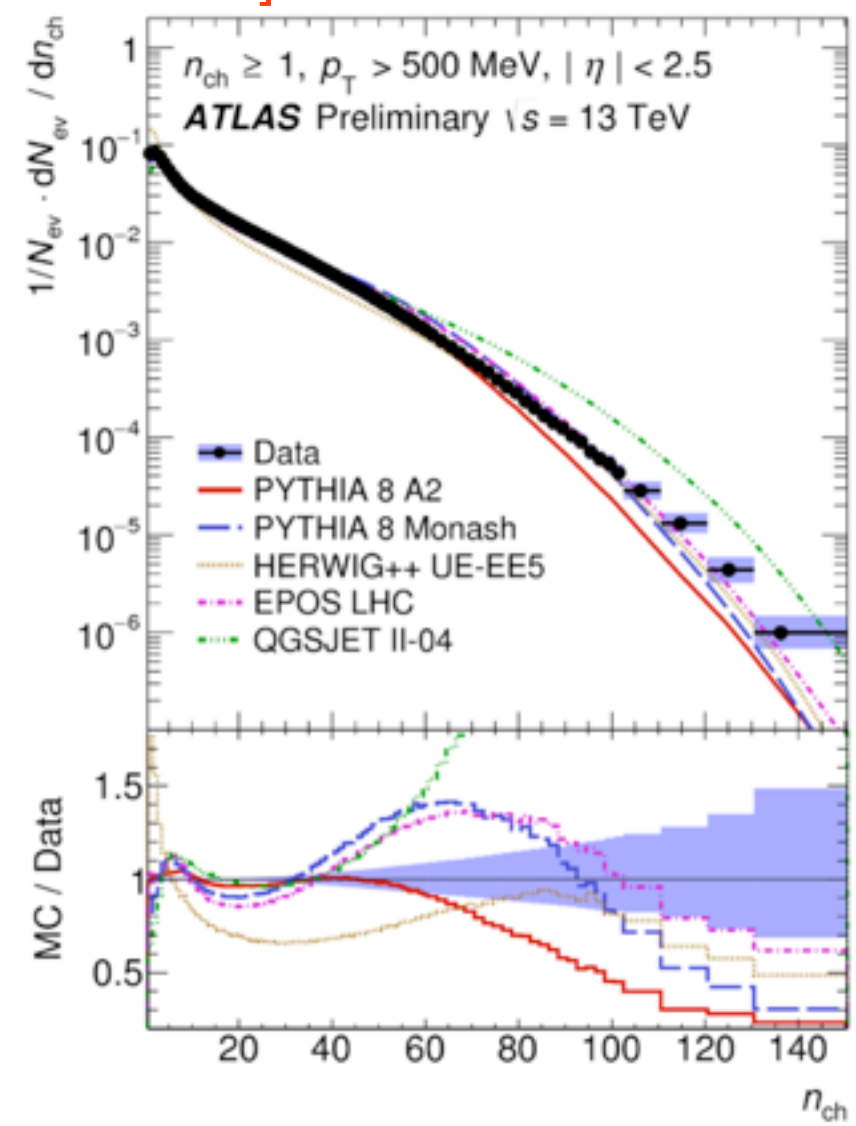
[CMS-PAS-FSQ15-001]





[ATLAS-CONF-2015-028]

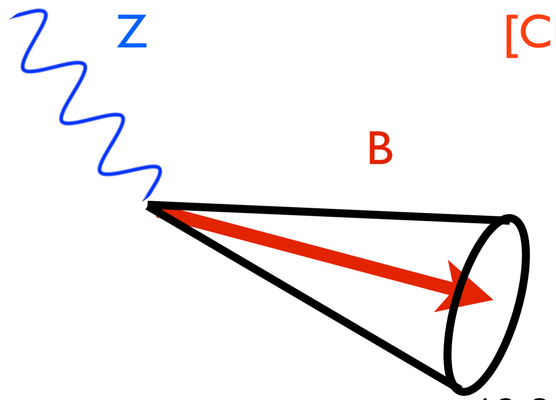


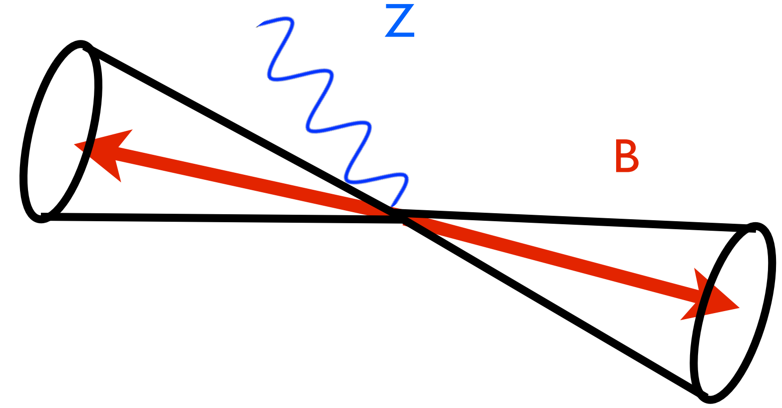


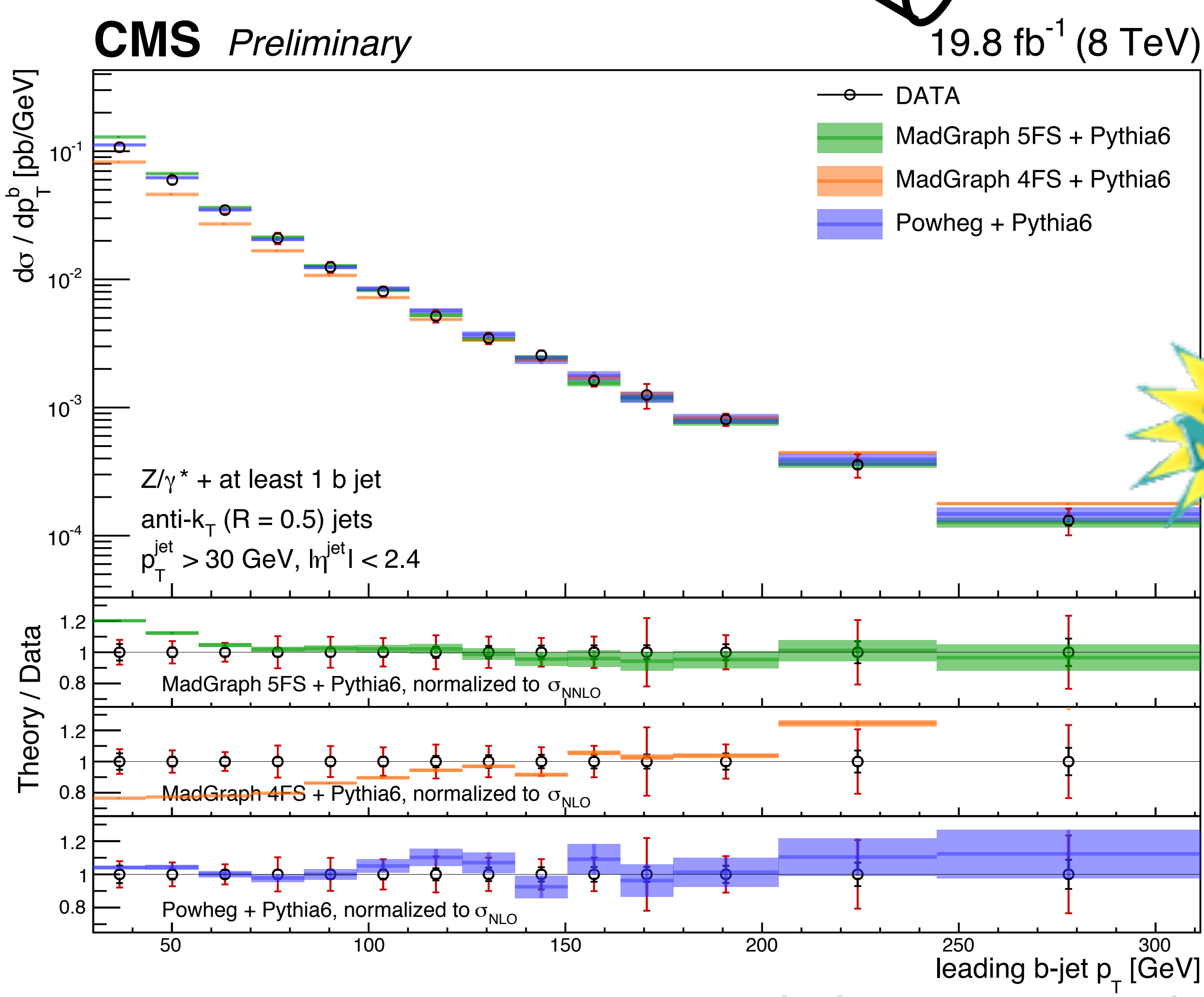
Important to understand the soft activity (track multiplicity in jets, MPI,...)

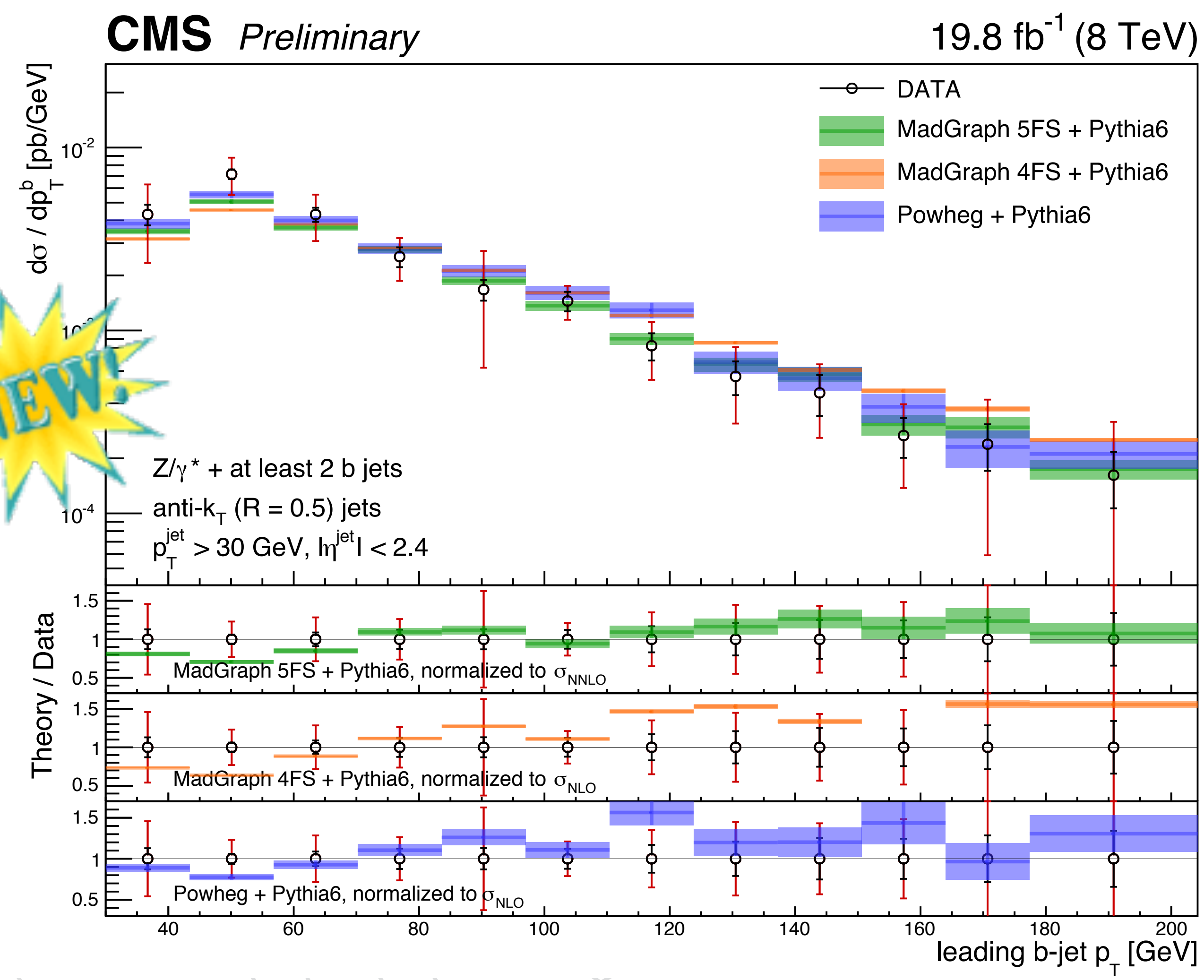
Z+2b

[CMS-PAS-SMP-14-10]









Z+>1b: powheg does the best job, MG 4F and 5F (P6) show trends
Z+2b: MG and PWG show the same trends

α_s from >2-jets cross-section

Use jet Pt to extract $\alpha_s(Q)$. Fit on different eta ranges to extract $\alpha_s(M_Z)$

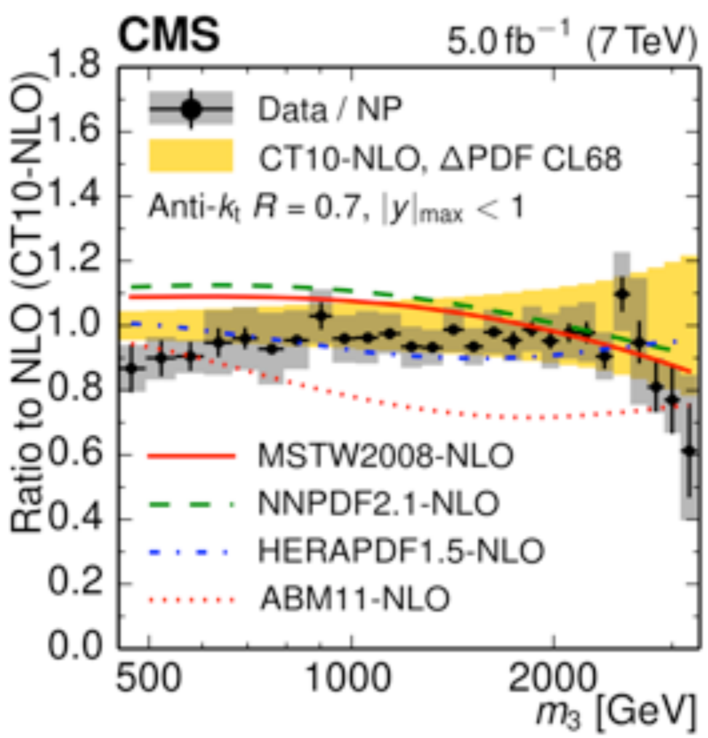
CMS

$$\alpha_S(M_Z) = 0.1185 \pm 0.0019\,(\text{exp}) \pm 0.0028\,(\text{PDF}) \pm 0.0004\,(\text{NP})^{+0.0053}_{-0.0024}\,(\text{scale})$$

ATLAS

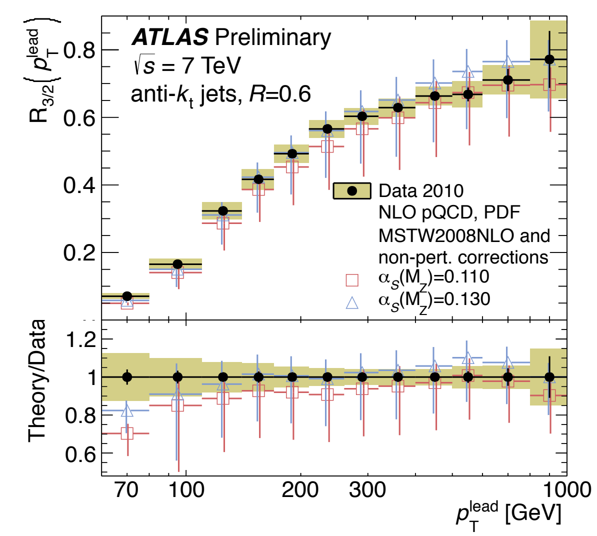
$$\begin{aligned}\alpha_S(M_Z^2) \;=\; & 0.1151 \pm 0.0001\ (\text{stat.}) \pm 0.0047\ (\text{exp. syst.}) \\ & \pm 0.0014\ (p_T\ \text{range}) \pm 0.0060\ (\text{jet size}) \\ & ^{+0.0044}_{-0.0011}\ (\text{scale})^{+0.0022}_{-0.0015}\ (\text{PDF choice}) \\ & \pm 0.0010\ (\text{PDF eig.})^{+0.0009}_{-0.0034}\ (\text{NP corrections})\end{aligned}$$

α_s from 3-jet mass cross-section



$$\alpha_S(M_Z) = 0.1171 \pm 0.0013\,(\text{exp}) \pm 0.0024\,(\text{PDF}) \pm 0.0008\,(\text{NP})\ ^{+0.0069}_{-0.0040}\,(\text{scale})$$

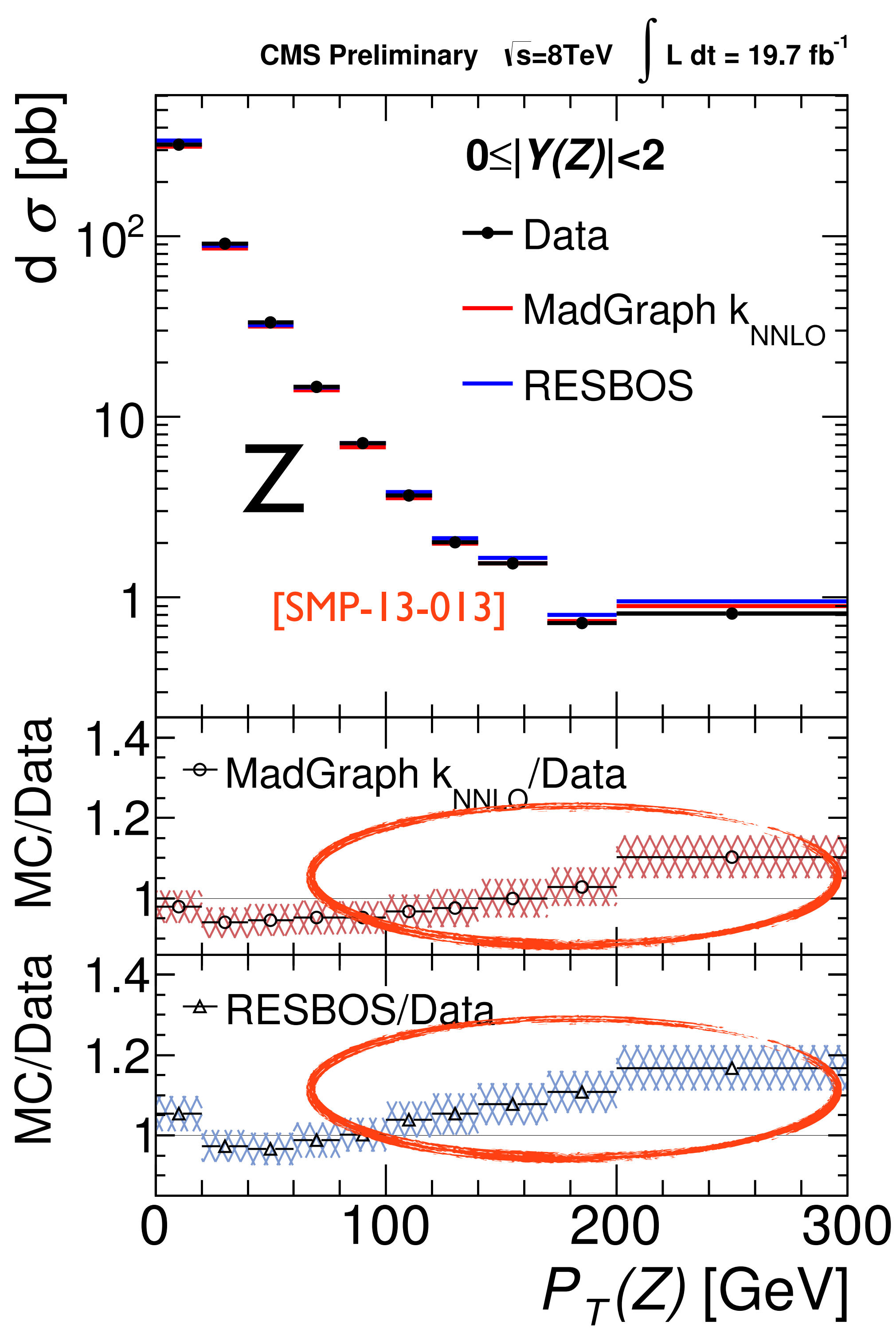
α_s from 3/2-jet cross-section



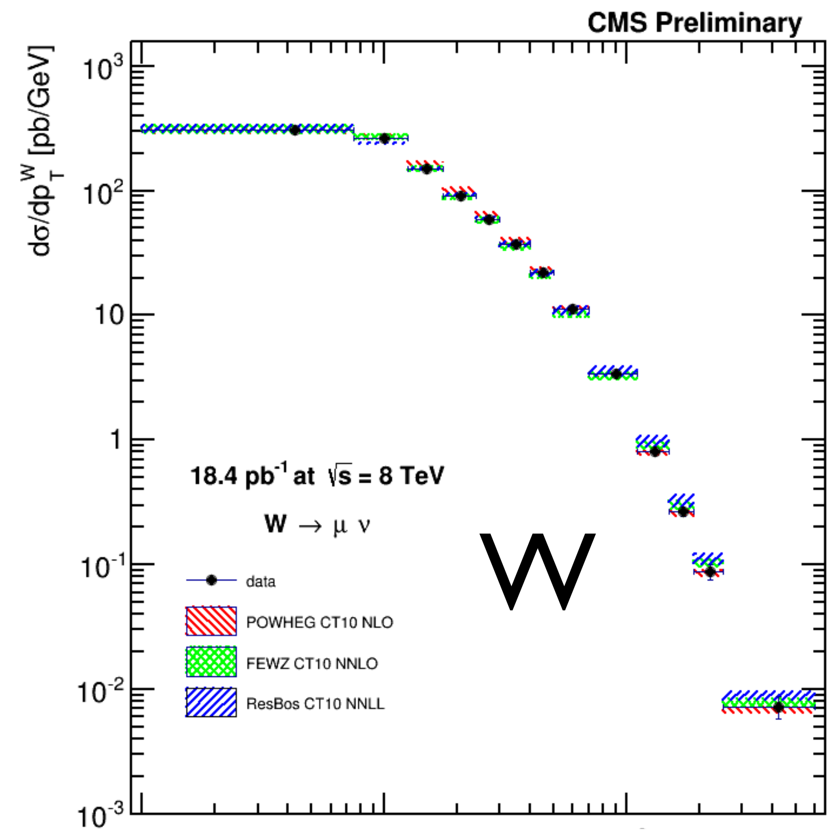
$$\alpha_s(M_Z) = 0.111 \pm 0.006(\text{exp.})\ ^{+0.016}_{-0.003}(\text{theory}).$$

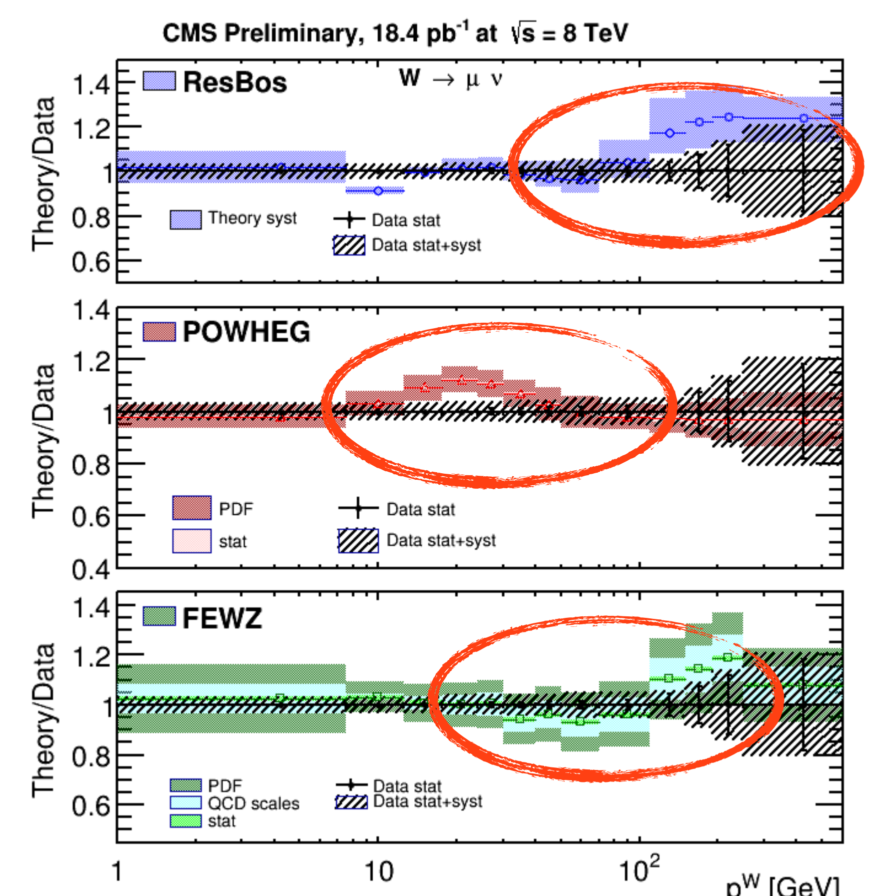
Dynamics of W, Z bosons: $d\sigma/dp_T$

[SMP-13-006]



- Very simple final state
  - 1 or 2 leptons
- Large statistics
  - ~% level uncertainty



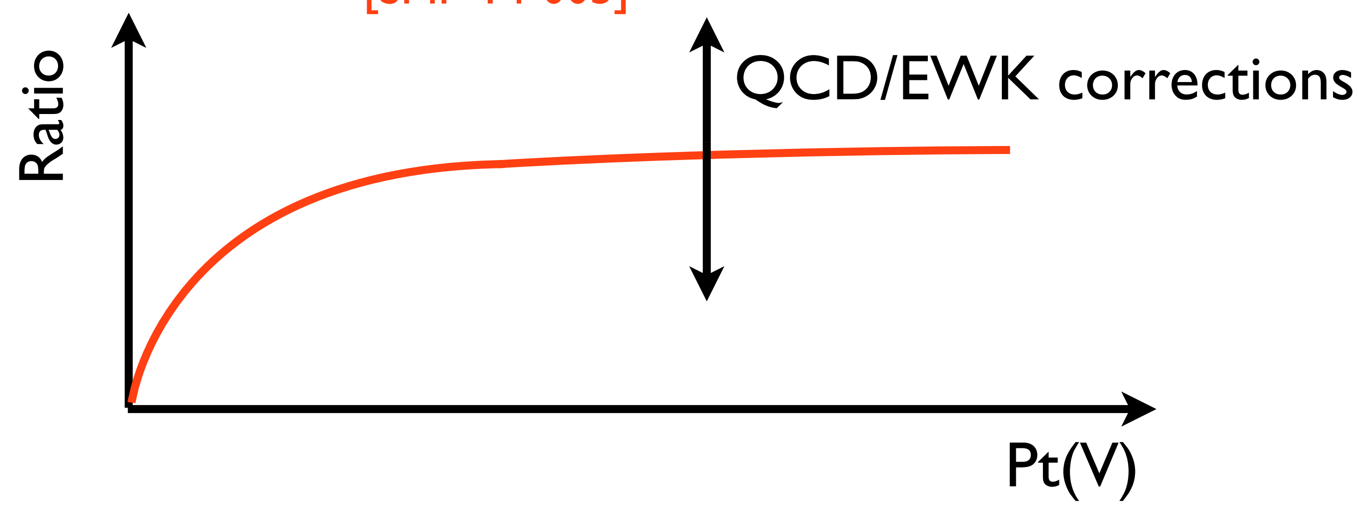


No prediction matches the data, LO or NLO

Z/γ+jets ratio

- Why Z/γ?
  - In high Pt

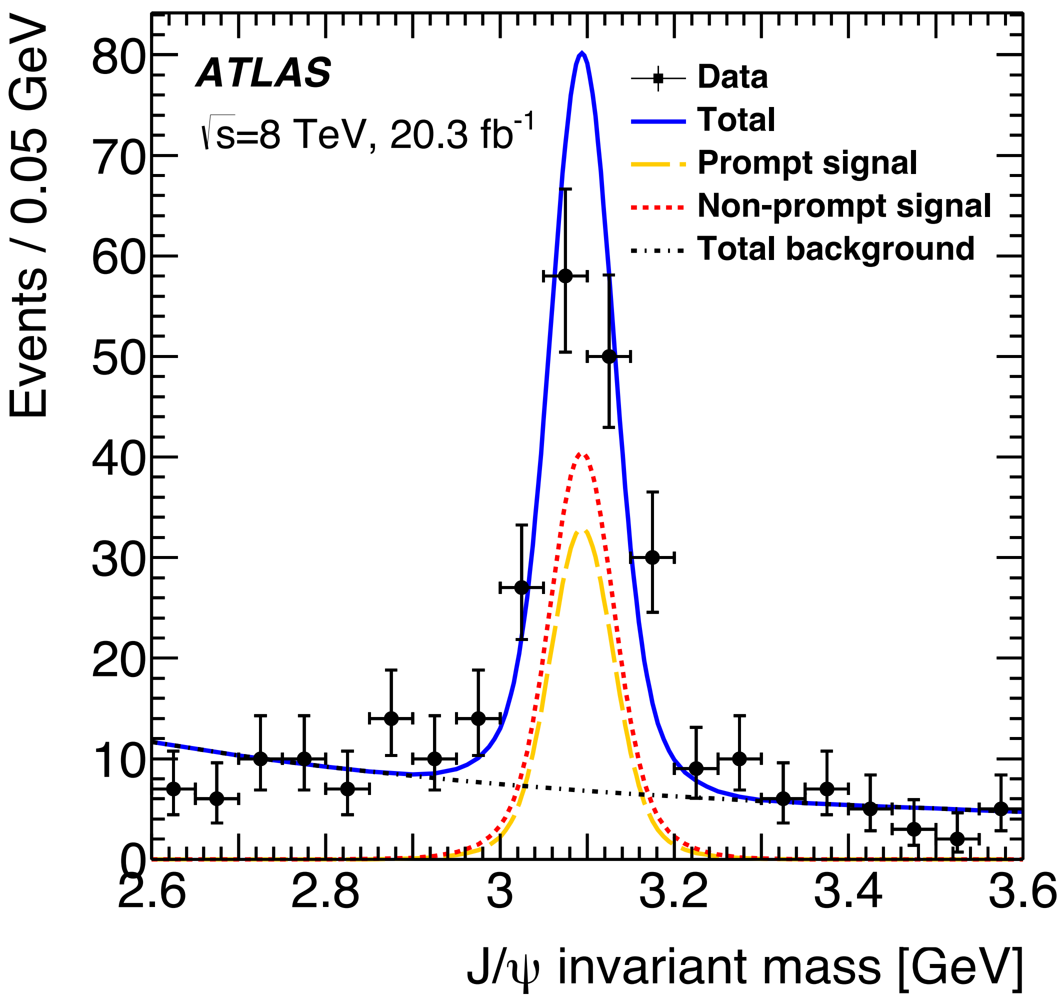
[SMP-14-005]



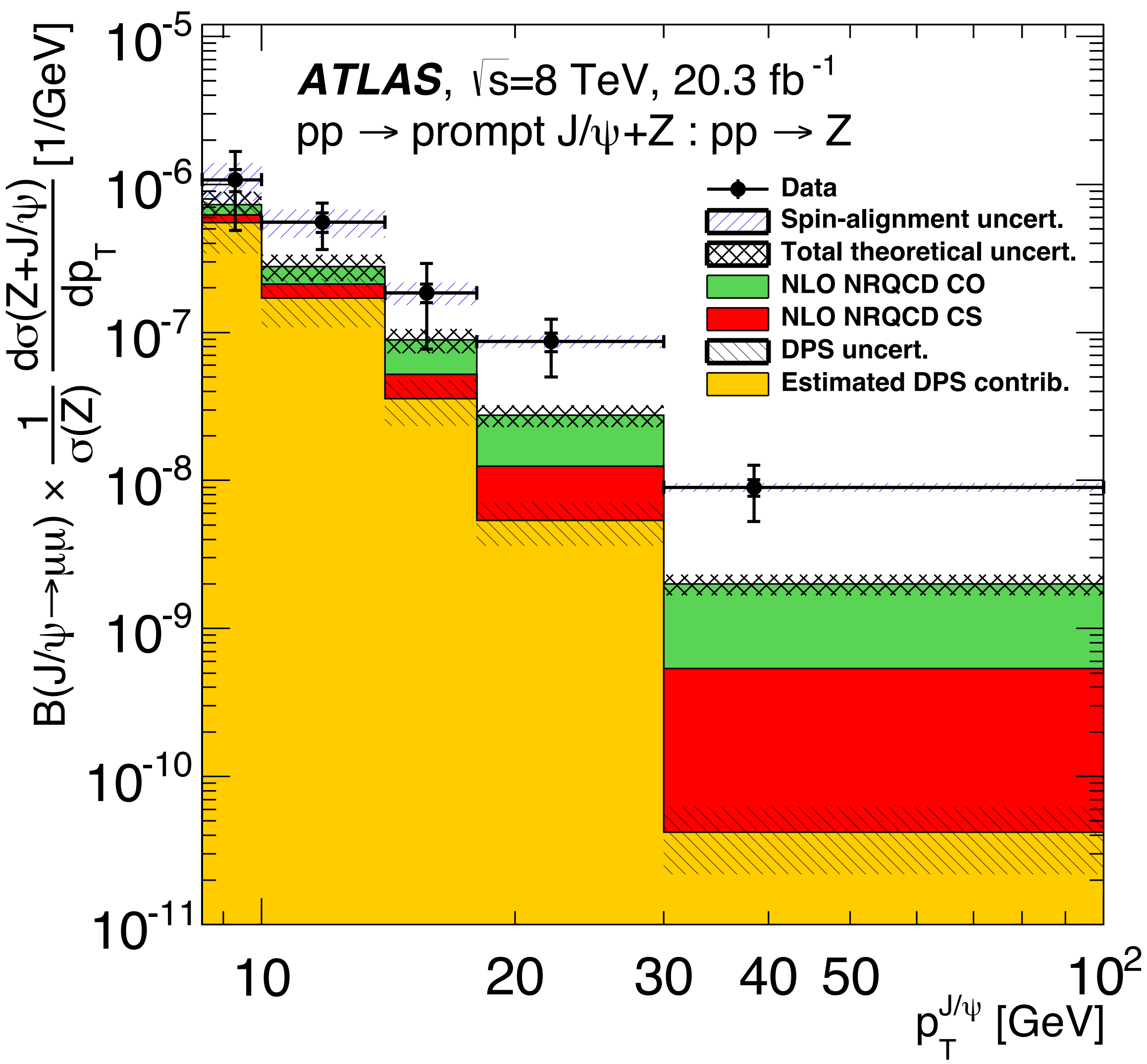
  - Both Z and γ+jets are large background processes for many searches
    - Particularly relevant for the modeling of $Z \rightarrow \nu\nu$+jets (SUSY) in MET+jets final state

- Exp. final state:
  - 2 lept + >=1 jet, Pt>20 GeV, $|\eta|<2.4$, trigger match, M(ll)∈[81,101] GeV
  - γ + >=1 jet, Pt>100 GeV, $|\eta_\gamma|<1.4$
  - >= 1 jets: pt>30 GeV, $|\eta|<2.4$
  - DeltaR(photon, γ OR lepton)>0.5

Z+J/Psi



ATLAS
√s=8 TeV, 20.3 fb-1
Data
Total
Prompt signal
Non-prompt signal
Total background
Events / 0.05 GeV
J/ψ invariant mass [GeV]



ATLAS, √s=8 TeV, 20.3 fb-1
pp → prompt J/ψ+Z : pp → Z
Data
Spin-alignment uncert.
Total theoretical uncert.
NLO NRQCD CO
NLO NRQCD CS
DPS uncert.
Estimated DPS contrib.
B(J/ψ→μμ) × 1/σ(Z) dσ(Z+J/ψ)/dpT [1/GeV]
pTJ/ψ [GeV]