Impact of LHC measurements on parton density functions

QCD@LHC 2016, August 22-26

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Outline

recent results on production of

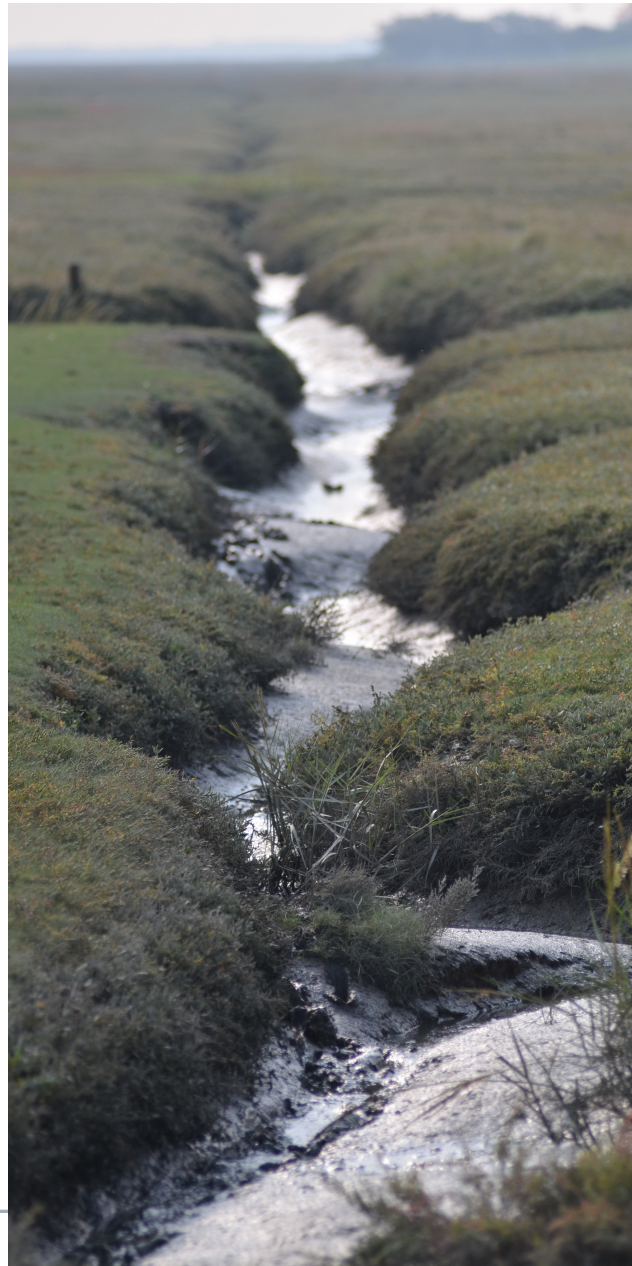
- jets
- isolated photons
- inclusive single vector bosons
- associated production of V-bosons
- central exclusive production
- heavy quarks

in pp collisions at LHC with

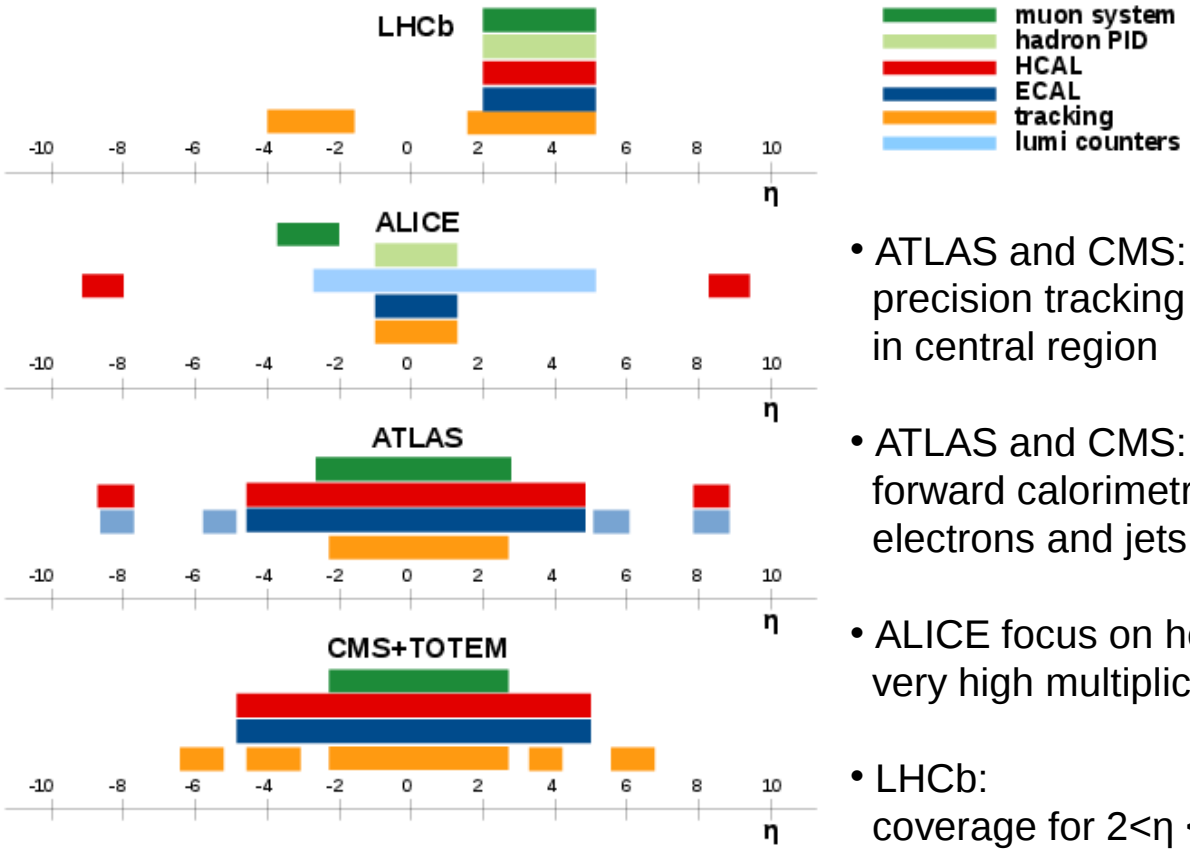
centre of mass energies of 8 and 13 TeV

more results at 7 and 2.76 TeV available

- nuclear PDFs: proton-lead collisions



Coverage of LHC detectors

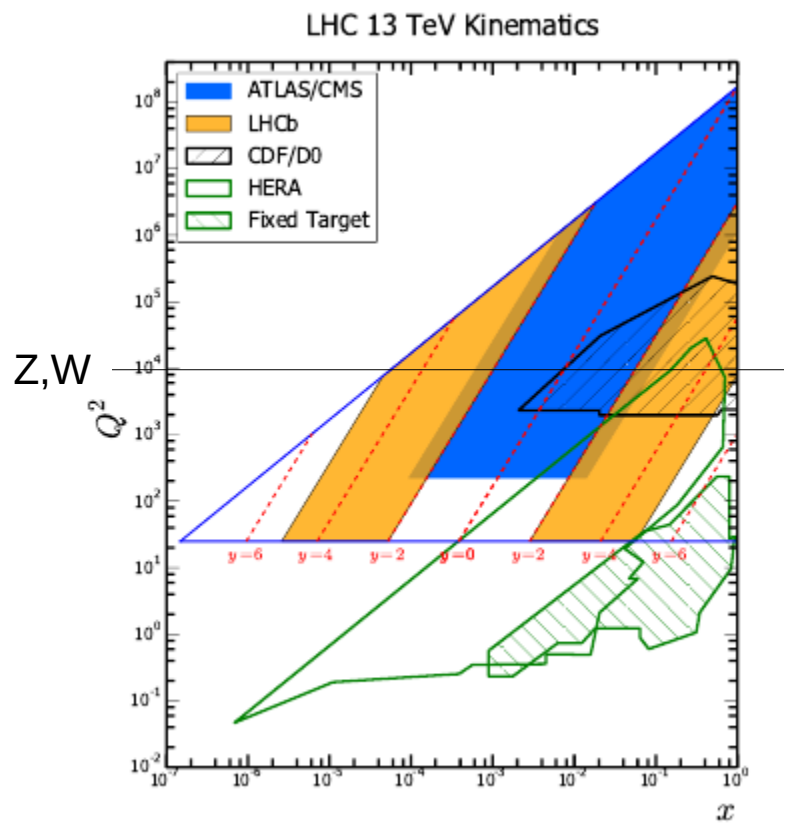


- ATLAS and CMS:
  precision tracking and muon identification in central region
- ATLAS and CMS:
  forward calorimetry - measurements of electrons and jets for $|\eta| < 5$
- ALICE focus on heavy ion physics
  very high multiplicity events
- LHCb:
  coverage for $2<\eta < 5$ – excellent tracking and particle identification
  low p_T, low mass triggers
  → complementary measurements

Kinematic region of LHC experiments

$$\underbrace{\sigma(x,Q^2)}_{hadronic\,x-sec.} = \sum_{a,b} \int_0^1 dx_1\, dx_2 \underbrace{f_a(x_1 Q^2) f_b(x_2 Q^2)}_{PDFs} \times \underbrace{\hat{\sigma}(x_1, x_2, Q^2)}_{partonic\,x-sec}$$

- x-section measurements and ratios sensitive to parton density functions (PDFs)
- measurements used to constrain PDFs → important for e.g. searches
- LHC, HERA, Tevatron and fixed target data: cover wide range in x-Q^2 plane



Jets

Jet production

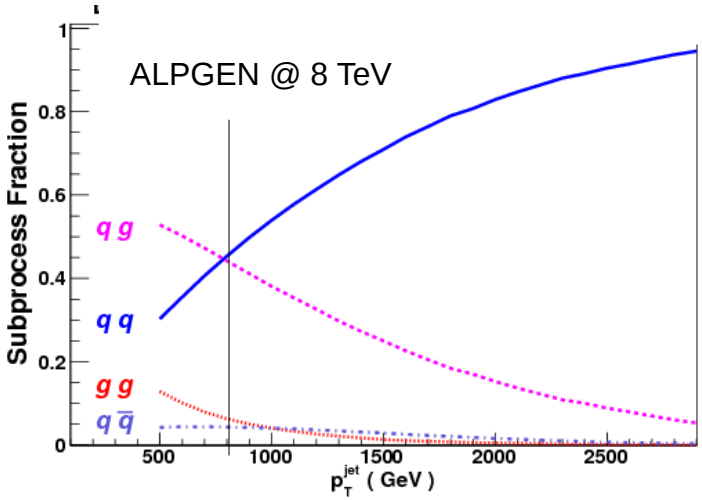
CMS-PAS-SMP-14-001

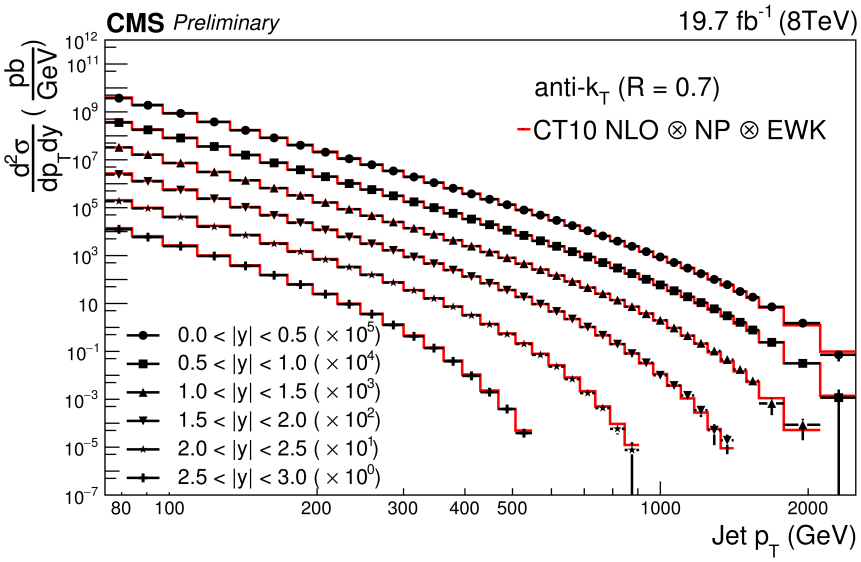
- p_T < 800 GeV, quark-gluon scattering

  → sensitivity to gluon
- p_T > 800 GeV: quark-quark scattering

  → sensitivity to quark

- constraints in medium and high-x region
- probe QCD at high scales
  → determination of α_s





inclusive jets @ 8 TeV

→ good agreement with NLO QCD over 12 orders of magnitude

jet p_T up to 2.5 TeV

2.76 TeV EPJC 76 (2016) 265

Talk: Mikko Voutilainen, Bora Isildak

Inclusive jets @ 8 TeV

CMS-PAS-SMP-14-001

p_T(jet)>74 GeV

sensitive to α_s and PDF

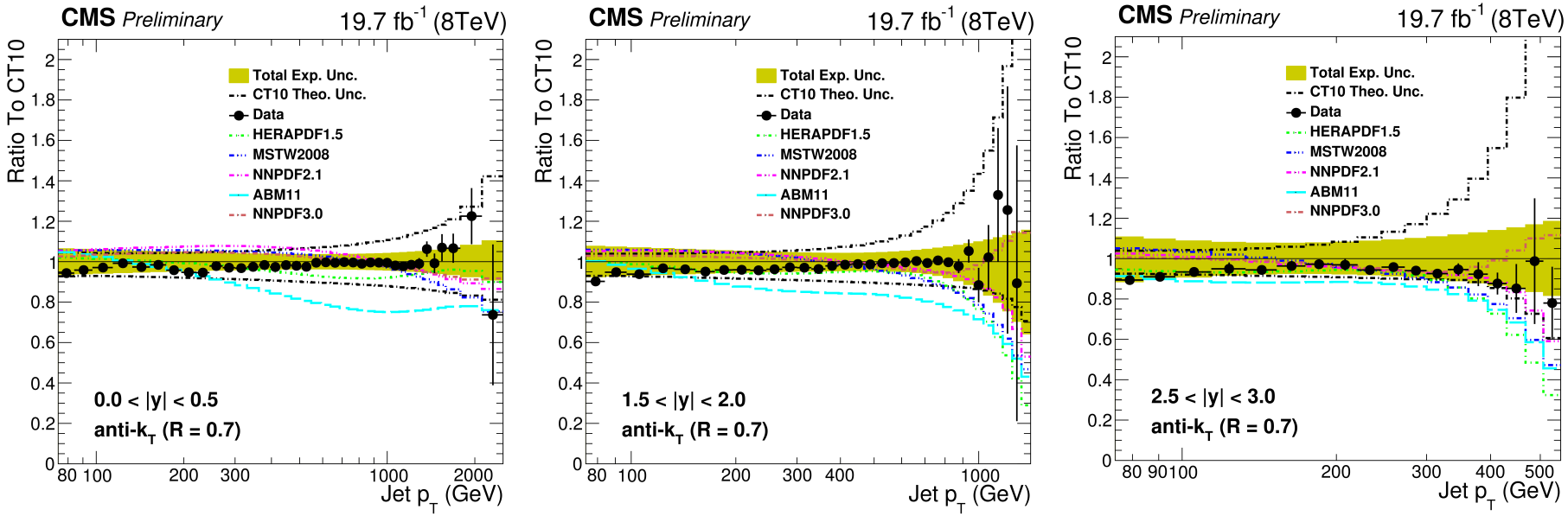
JES dominant uncertainty → highly correlated

theory predictions: NLOJet++, theoretical > experimental uncertainties

ratio to theory for different PDF sets → valuable input for PDFs

ABM11 significant discrepancies for p_T>200 GeV

different PDF sets differ from each other and data at high p_T



Talk: Mikko Voutilainen, Bora Isildak

Inclusive jets at 13 TeV

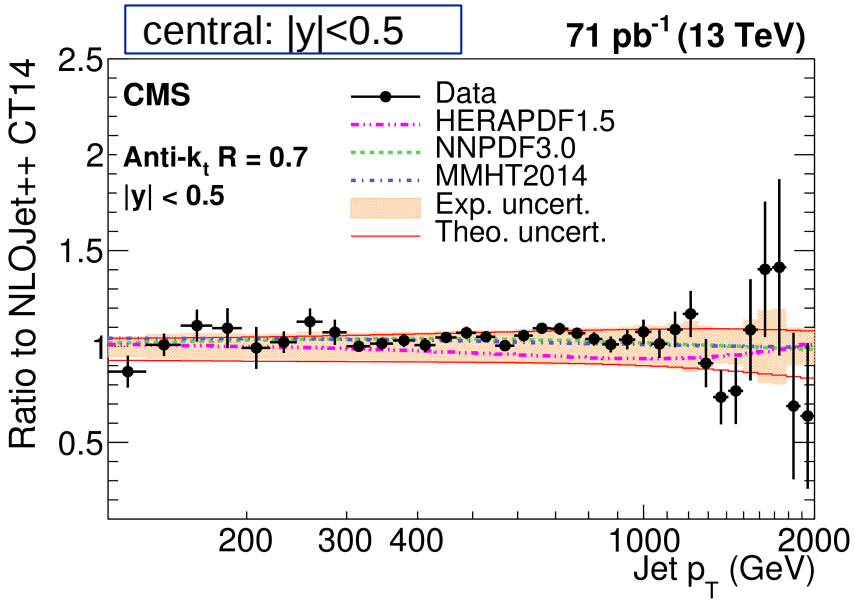
CMS: EPJC 76 (2016) 451

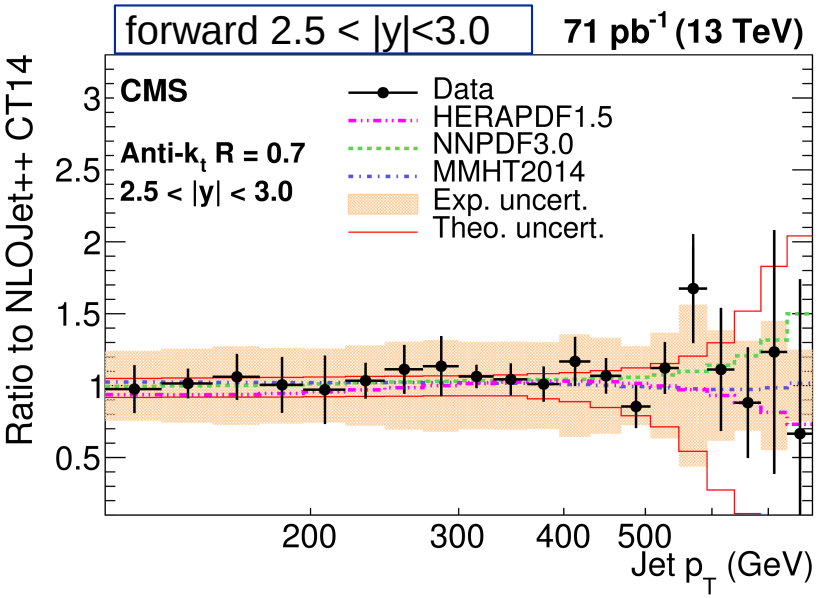
CMS: double differential x-sections with R=0.7 and 0.4

NLOJet++ corrected for NP and EWK effects

- central: different PDF sets agree
- sensitivity in forward region at high p_T
- JES: 1-3% (central), 7-8% (forward)

13 TeV: q-g scattering dominates for p_T<1.4 TeV





Talk: Mikko Voutilainen, Bora Isildak

Inclusive jets at 13 TeV

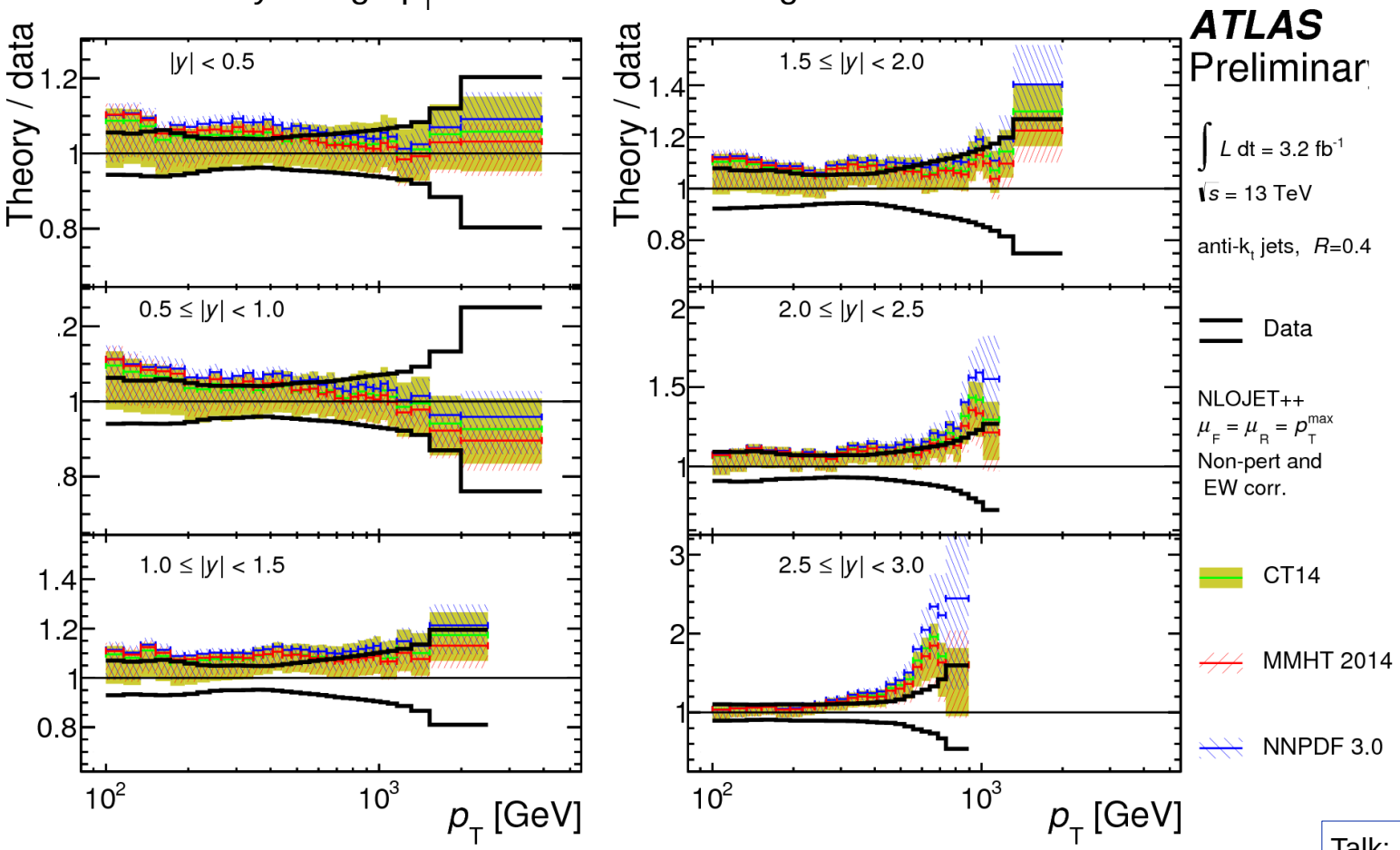
ATLAS-CONF-2016-092

ATLAS measurement with R=0.4, NLOJet++ corrected for NP and EWK effects

up to p_T=4 TeV – significant extension of kinematic range

predictions tend to overestimate in the forward region: indication of soft effects?

PDF sensitivity at high p_T and in the forward region



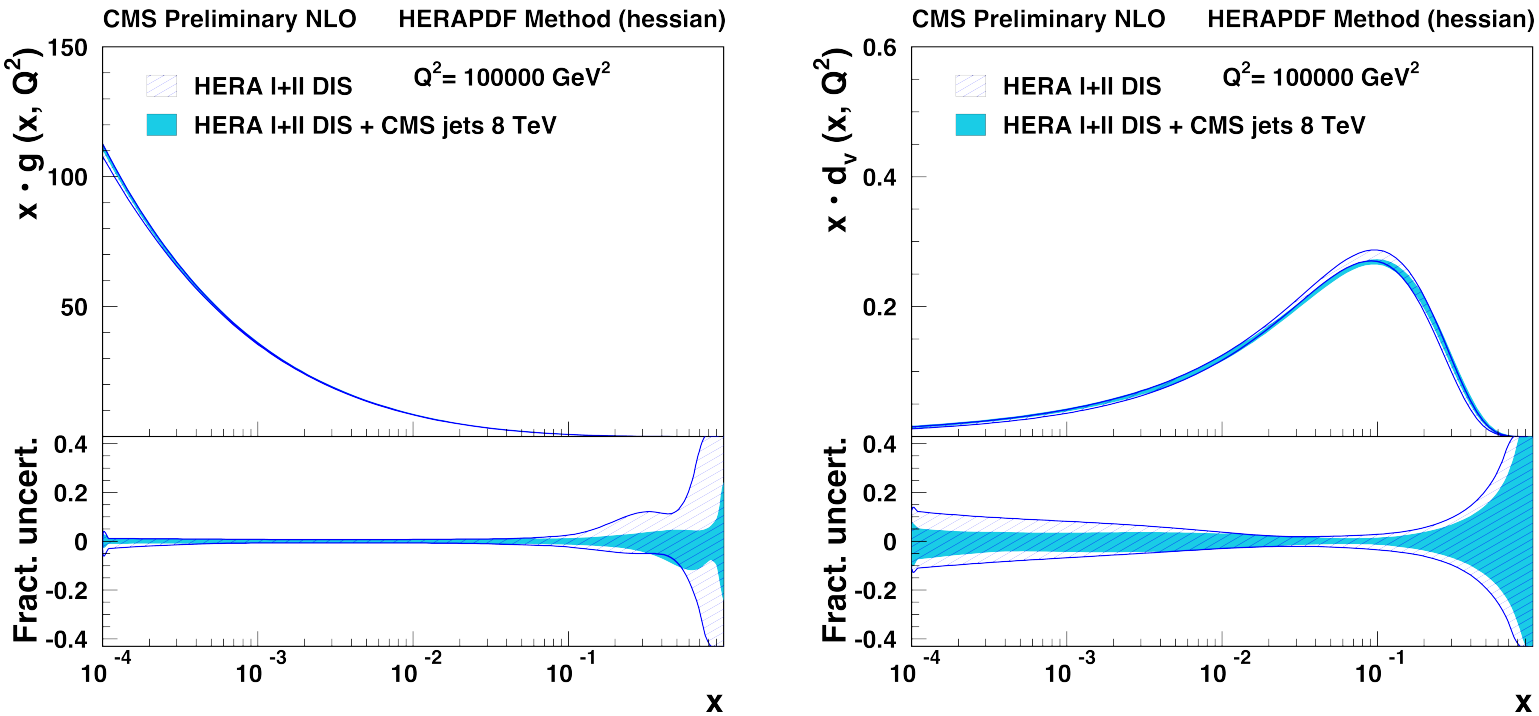
Talk: Jonathan Bossio

Impact of jet data on PDF

CMS-PAS-SMP-14-001

CMS jet cross sections at 8 TeV used as input to QCD fits to extract PDFs
→ sensitive to gluon and quarks (at high p_T)

NLO QCD analysis: HERA I+II DIS [Eur. Phys. J. C75 (2015) 2604] plus CMS jets



Isolated photons

Isolated photons @ 8 TeV

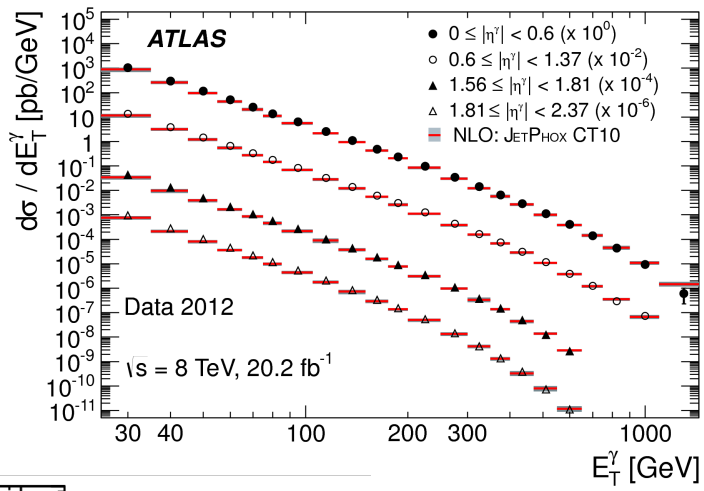
ATLAS: arXiv:1605.03495

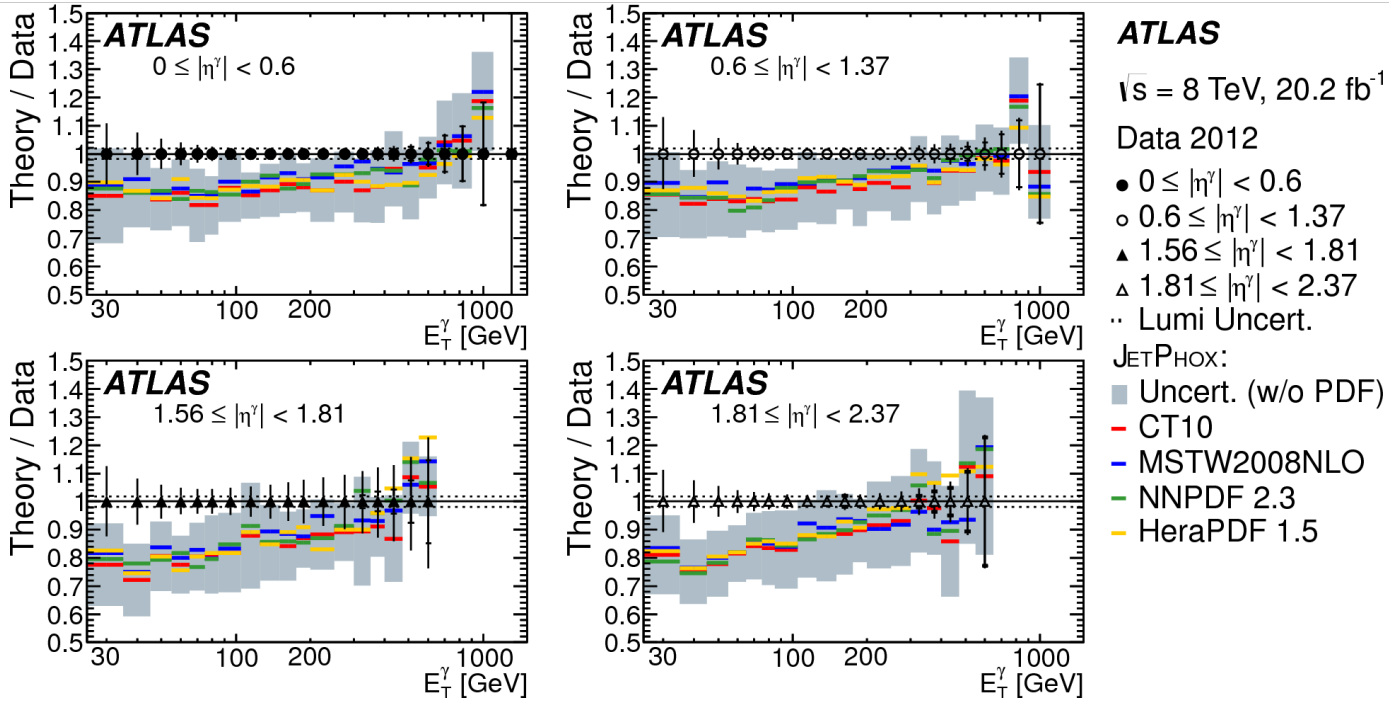
dominant production: q g → q γ
→ constrain on gluon at medium x (x~0.1)

25< E_T <1500 GeV

dominant systematic uncertainties:
energy scale, unknown admixture of fragmentation
background correlations

JetPhox: too low in normalisation
NLO predictions: large scale uncertainties





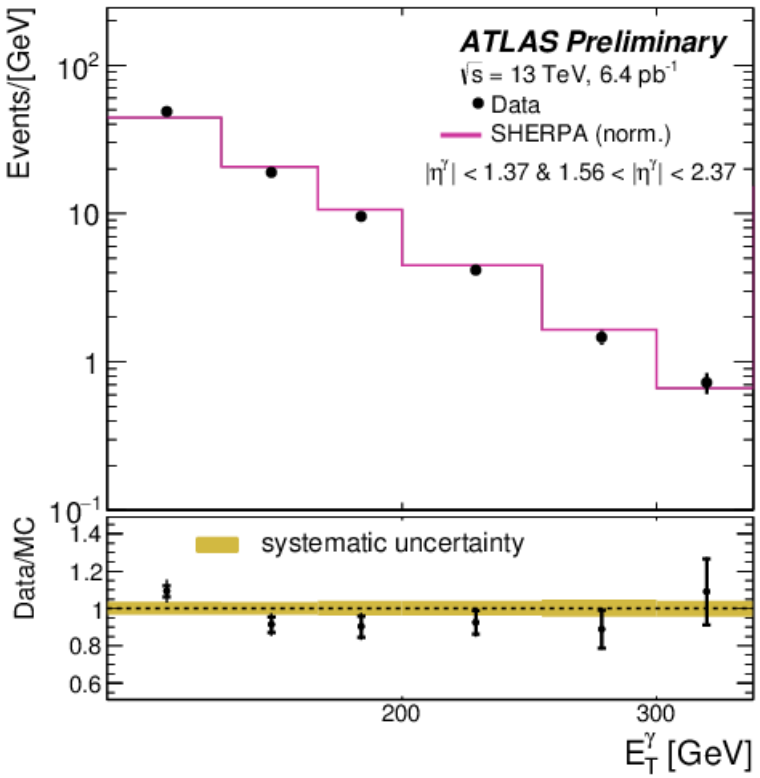
Talk: Jonathan Bossio

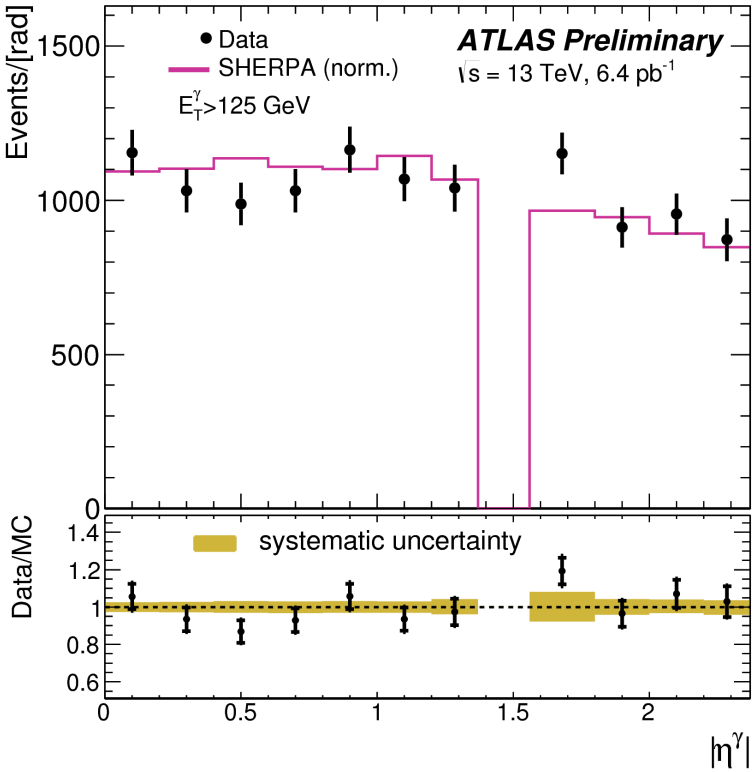
Inclusive photons @ 13 TEV

ATL-PHYS-PUB-2015-016

luminosity: 6.4± 0.6 pb^{-1} ,<μ>=20
E^{γ}_{T} = 125 GeV, $|\eta^{\gamma}| < 2.37$

no unfolding - detector level quantities

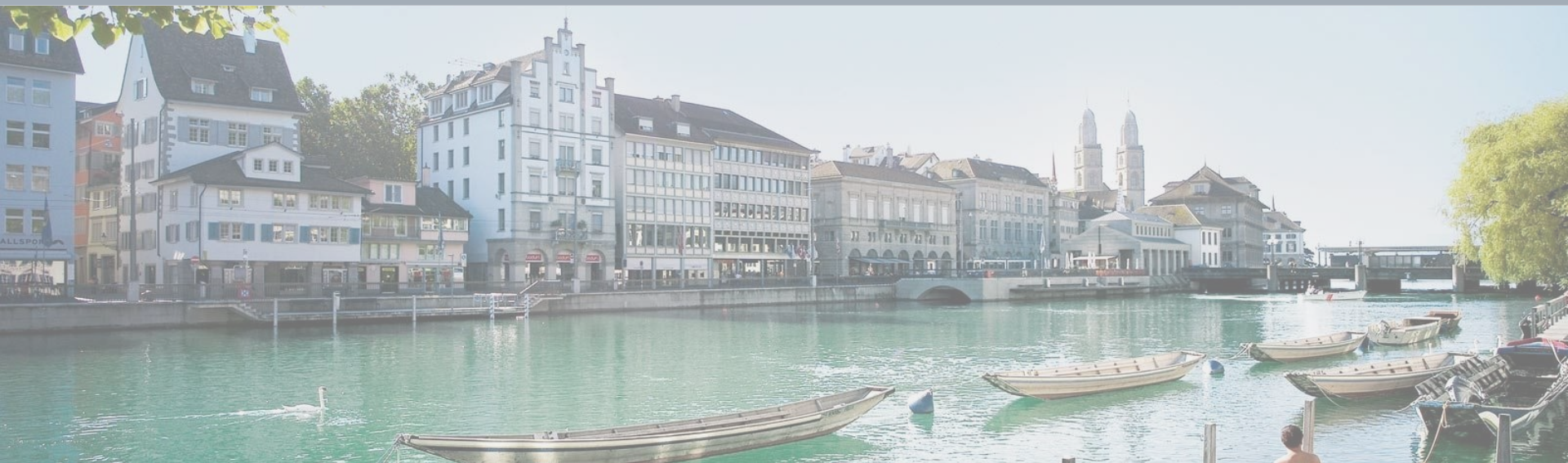




good description by Sherpa 2.1+ CT10 full simulation

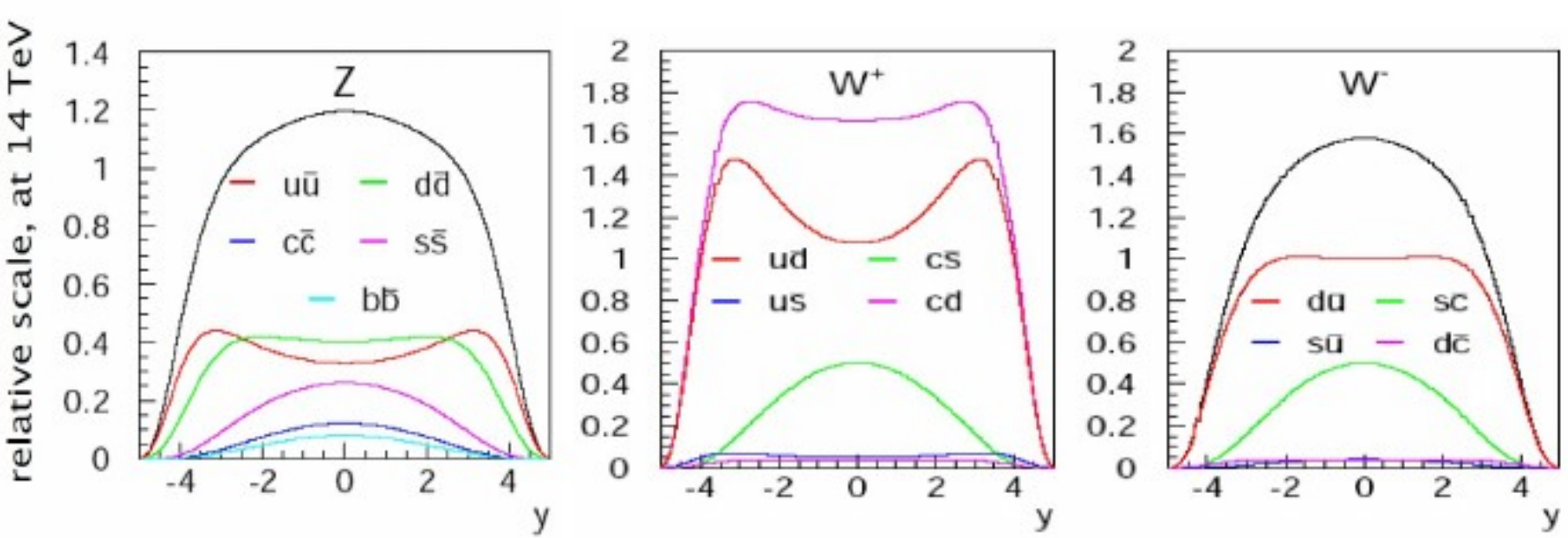
Talk: Jonathan Bossio

Inclusive W and Z bosons



Motivation

measurements with W and Z allow to distinguish different quark contributions

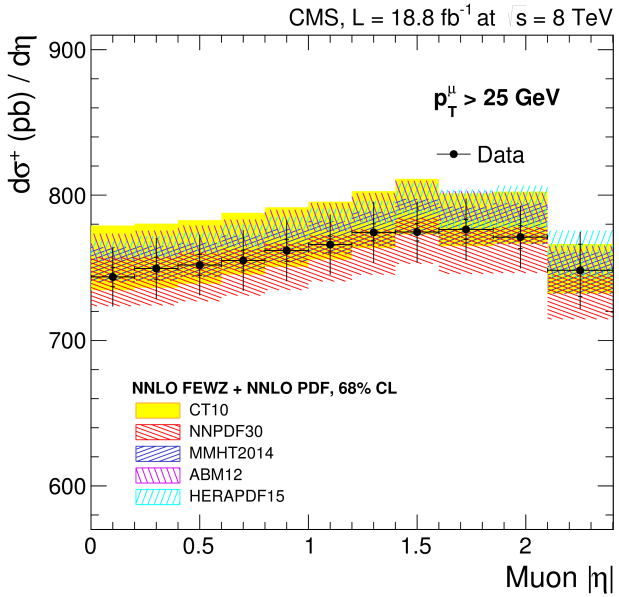


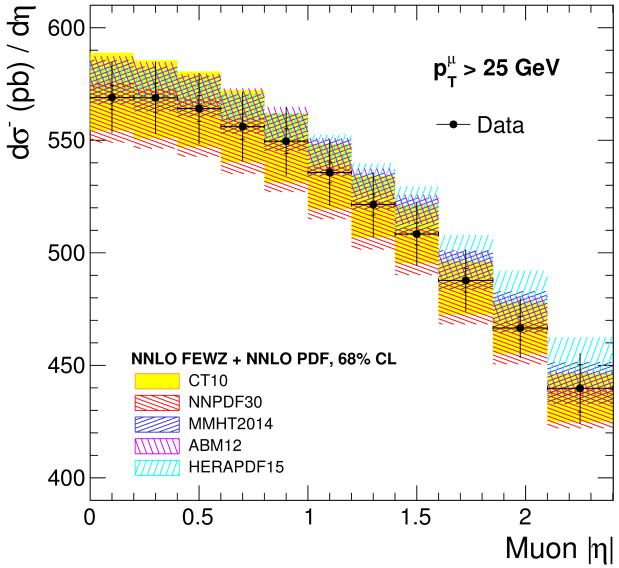
u and d quarks dominate for W production

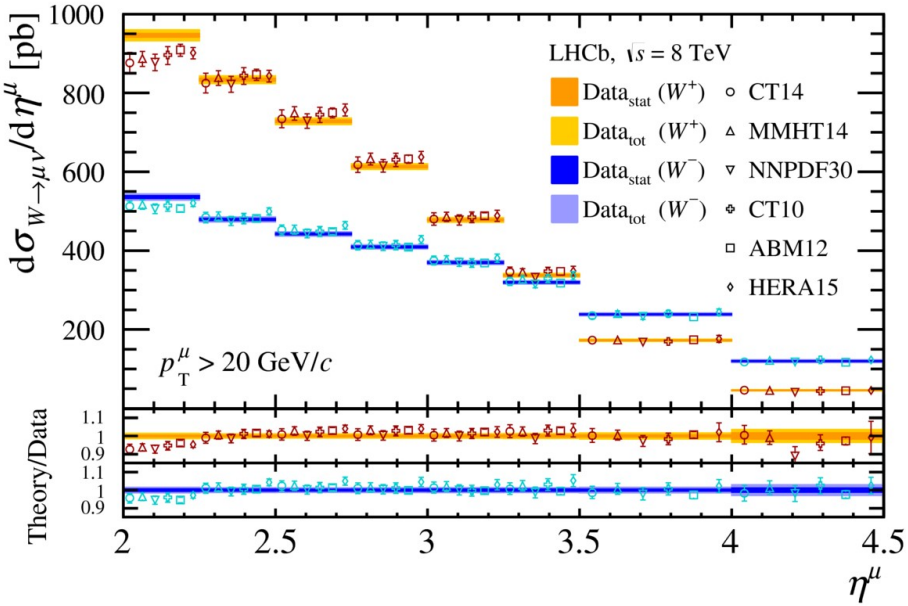
all flavours contribute for Z production

W @ 8 TeV: inclusive cross sections

LHCb JHEP 01 (2016) 155
CMS: arXiv:1603.01803







NNLO predictions with different PDF sets
forward: overall good description

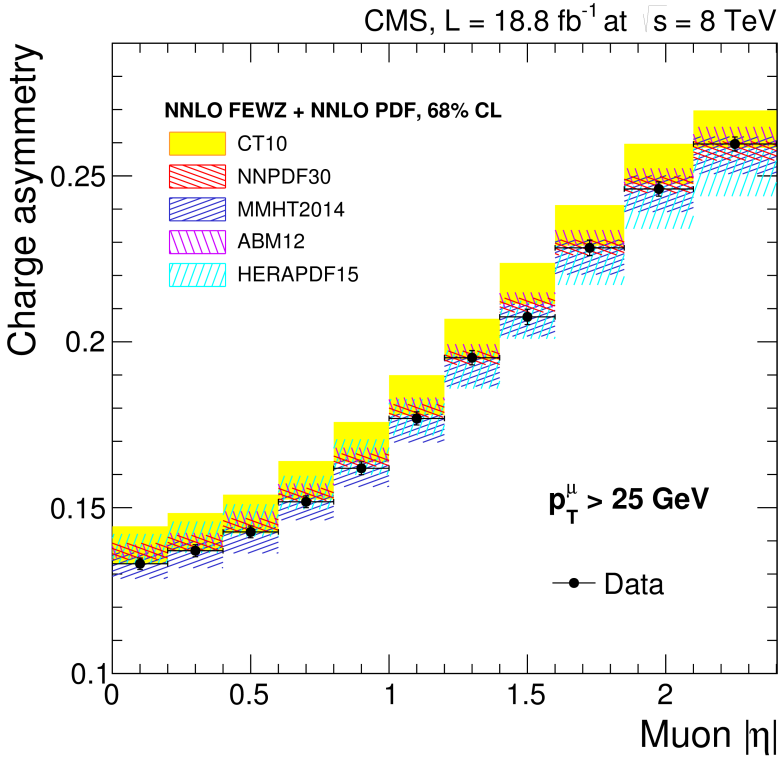
central: CT10, ABM12, HERA1.5 tend to be higher
NNPDF3.0 lower than the data

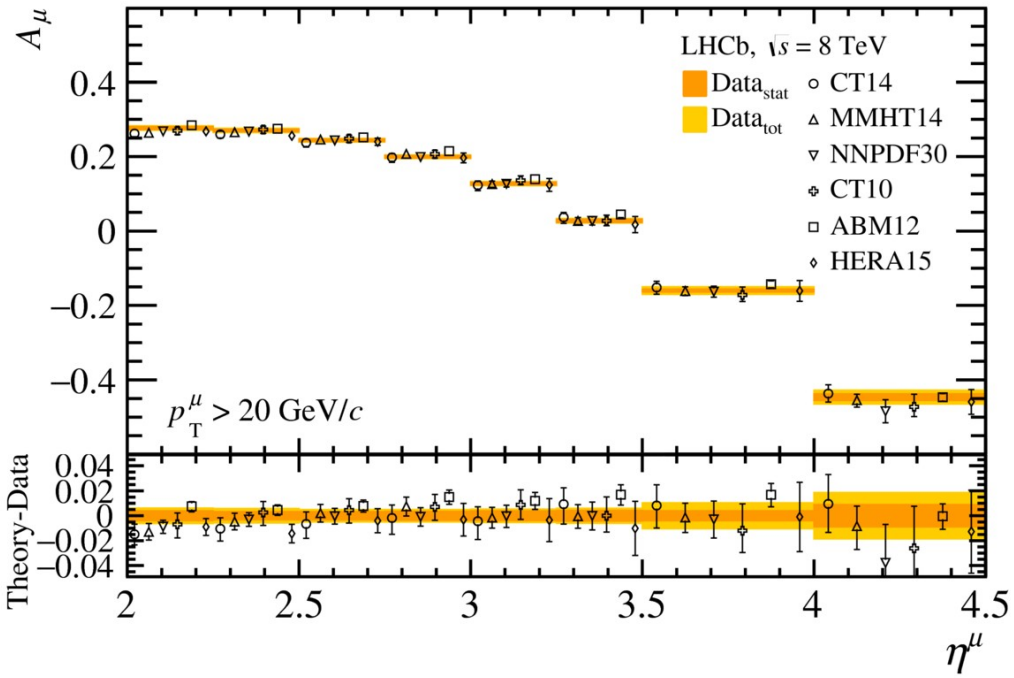
luminosity uncertainty: 2.6% (CMS), 1.6% (LHCb)
other systematic uncertainties sub%-level

Talks: Ringaile Placakyte, Xinmai Niu, Alex Grecu

W @ 8 TeV: lepton charge asymmetry

LHCb: JHEP 01 (2016) 155
CMS: arXiv:1603.01803





lepton charge asymmetry:

$$A_\mu(\eta_i) = \frac{\sigma_{W^+\to\mu^+\nu}(\eta_i) - \sigma_{W^-\to\mu^-\overline{\nu}}(\eta_i)}{\sigma_{W^+\to\mu^+\nu}(\eta_i) + \sigma_{W^-\to\mu^-\overline{\nu}}(\eta_i)}$$

high experimental precision – uncertainties at sub-% level

agreement with different PDF sets within 1-2%
most sensitive to PDF as most uncertainties cancel in the ratio

asymmetry constrains uv, dv, uv/dv PDF

Talks: Ringaile Placakyte, Xinmai Niu, Alex Grecu

W @ 8 TeV: lepton charge asymmetry

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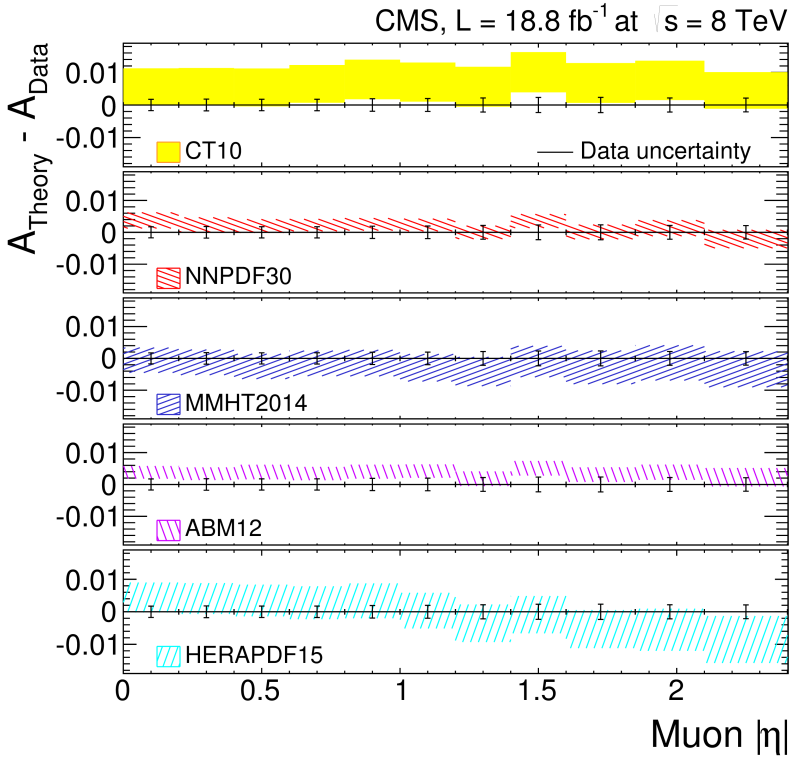

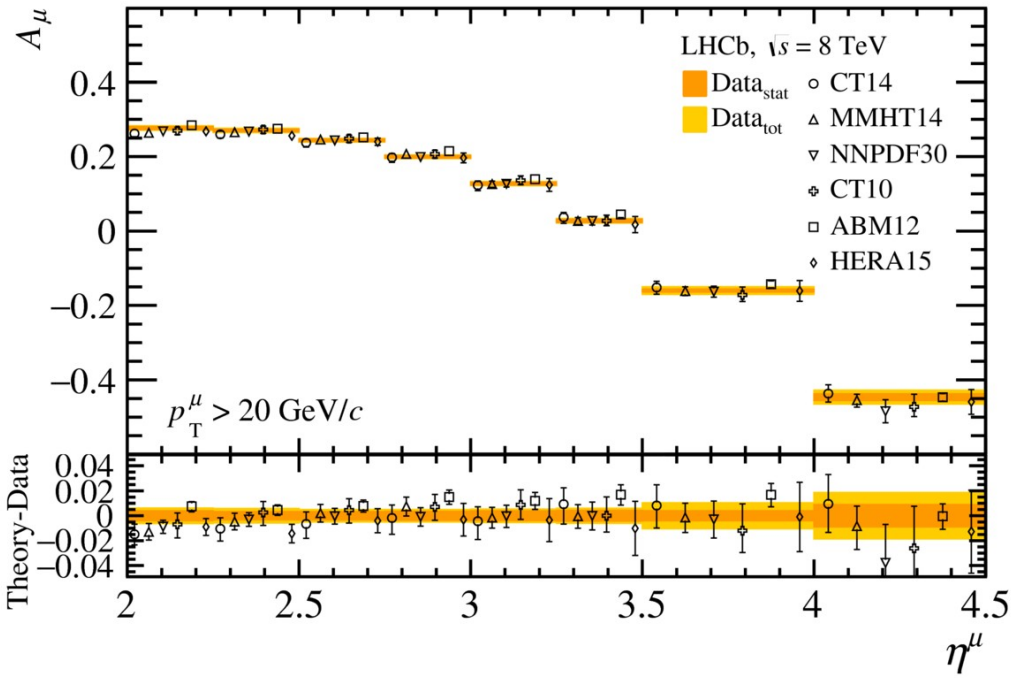

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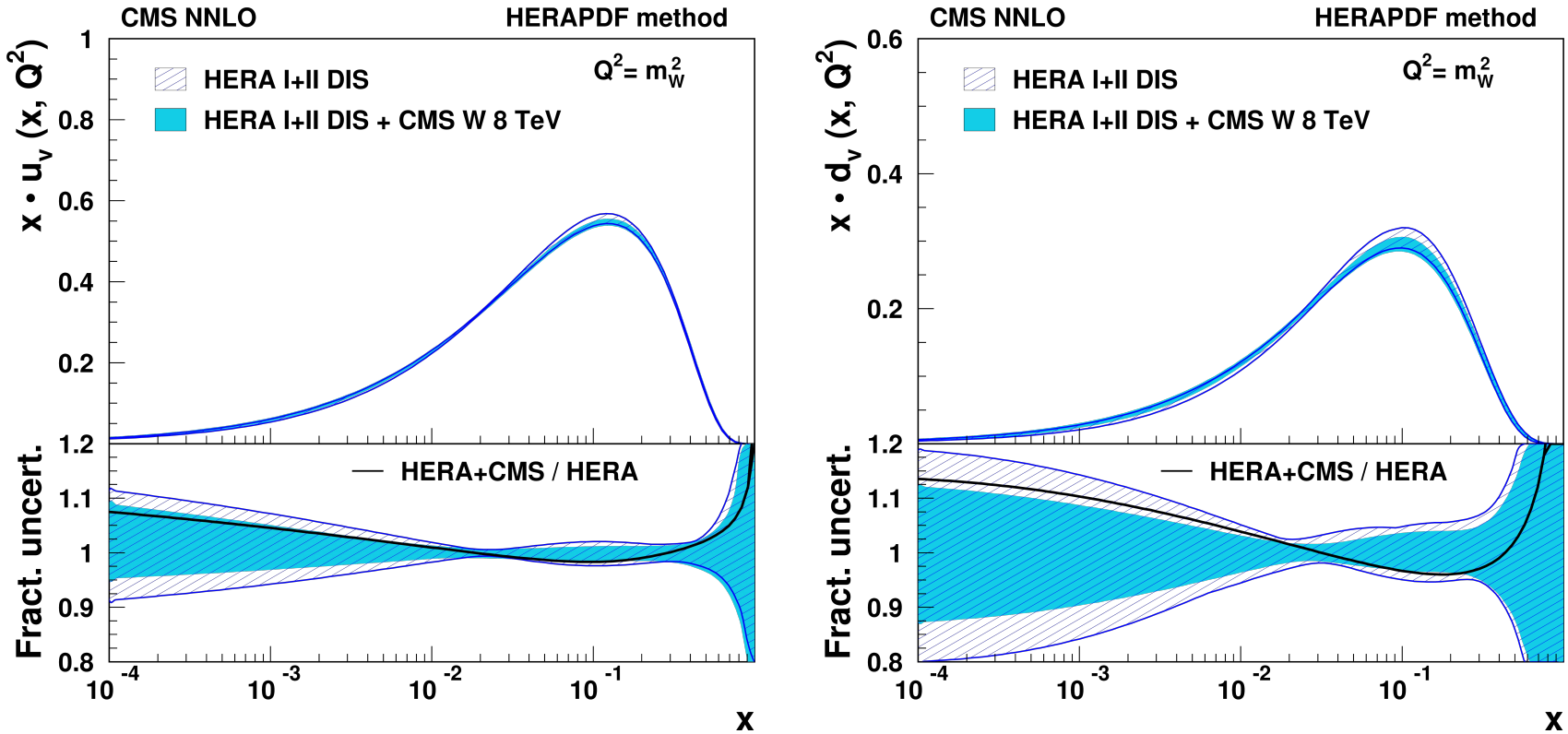
Talks: Ringaile Placakyte, Xinmai Niu, Alex Grecu

Impact of 8 TeV CMS data on PDF

CMS: arXiv:1603.01803



HERAFitter @ NNLO using the lepton charge asymmetry
heavy quark contribution: general mass variable flavor number scheme
$Q^2 \geq Q^2_{min} = 3.5\ GeV^2$

→ changes in shapes and reduction of the uncertainties of the valence quark distribution

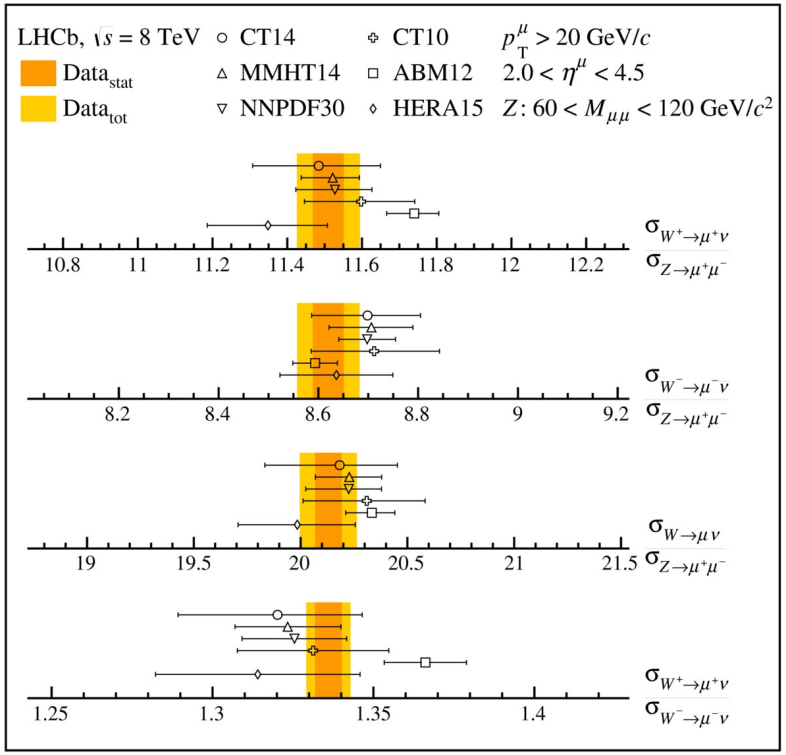
Talks: Ringaile Placakyte, Xinmai Niu

W, Z – ratios

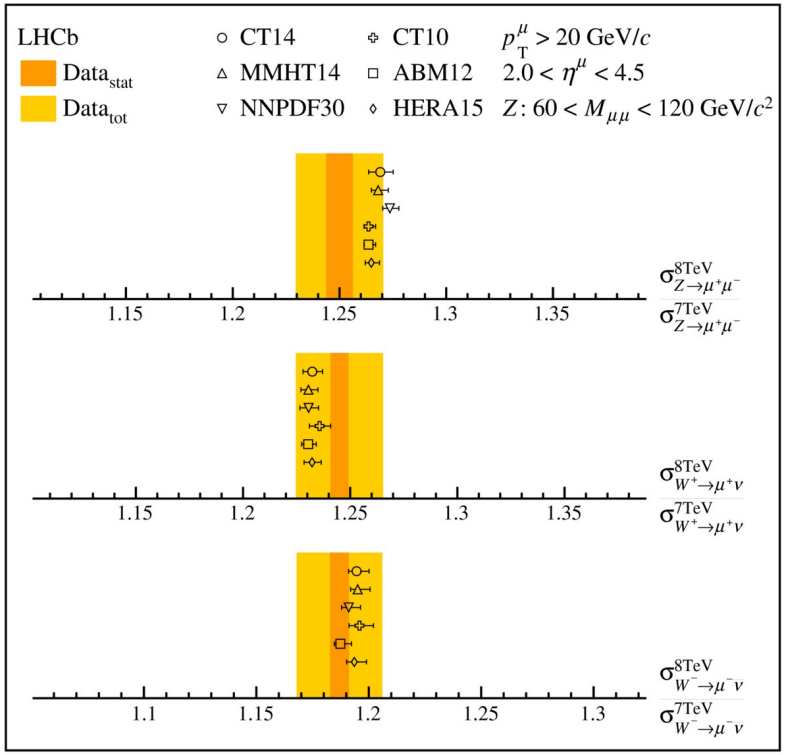
LHCb: JHEP 01 (2016) 155

- ratio W/Z or W^+/W^-: sensitive test of predictions
- ratio at different cm energies: less sensitive to higher order effects
  PDF uncertainties reduced but do not completely cancel as different x-regions are probed
  better PDF sensitivity with 13 TeV measurements

W/Z or W^+/W^-



ratio 7/8 TeV

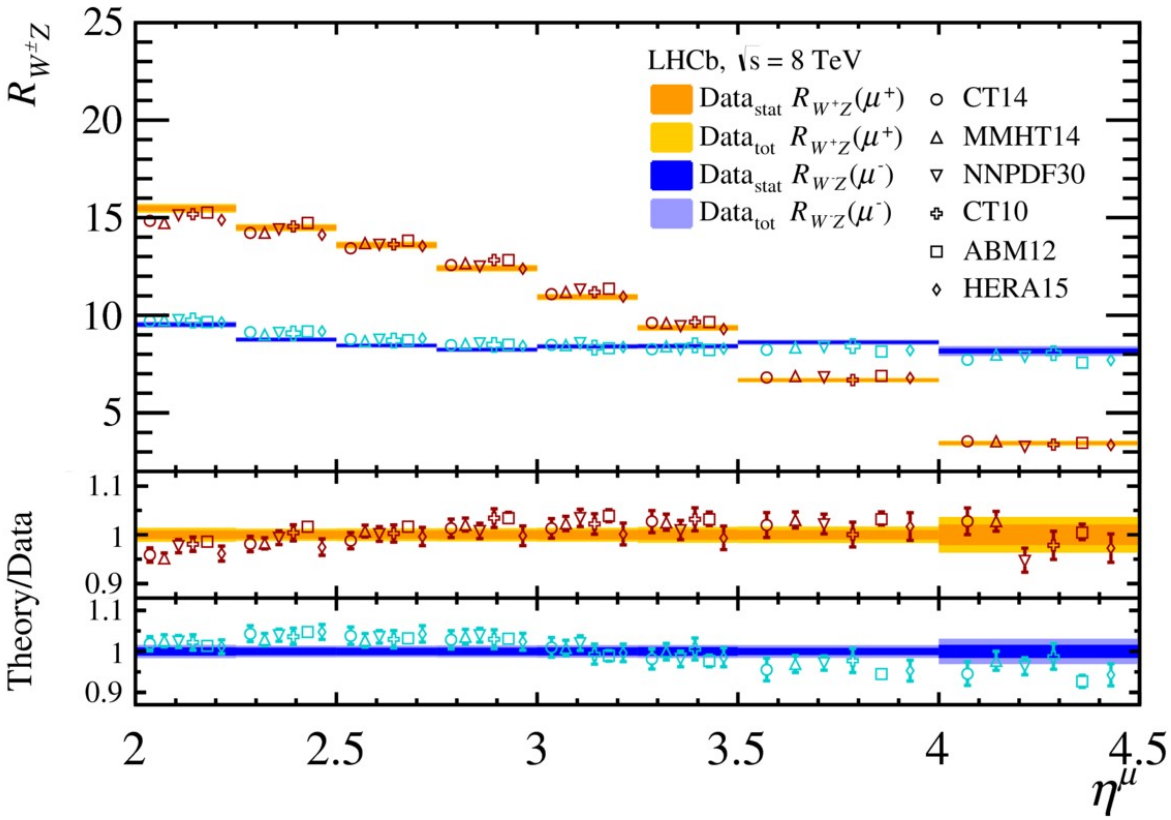


Talk: Alex Grecu

W/Z – ratio @ 8 TeV

LHCb: JHEP 01 (2016) 155

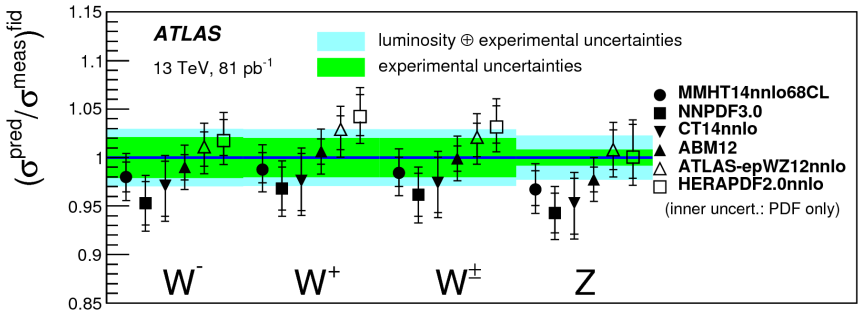
simultaneous measurement of W and Z, taking into account the correlations
→ sensitivity to strange quark (arXiv:1203.4051)



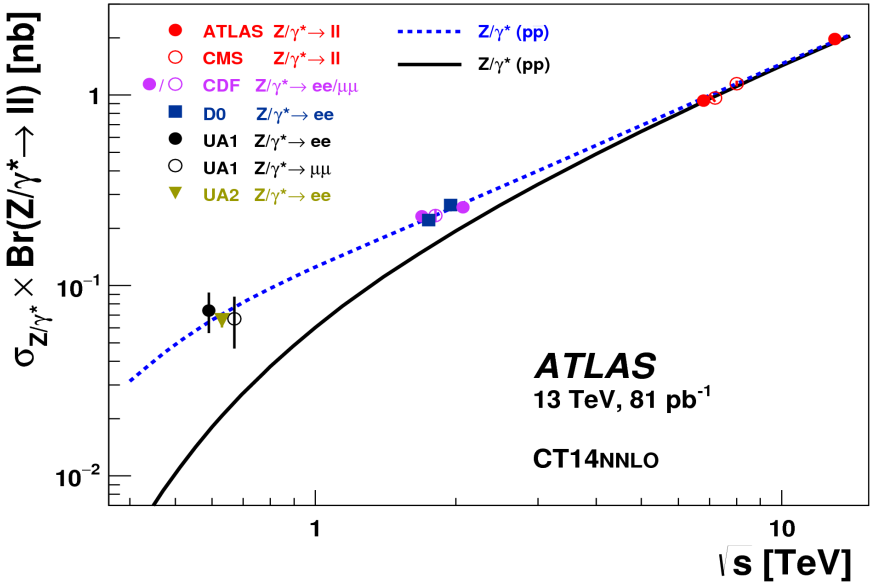
Talk: Alex Grecu

W, Z @ 13 TeV

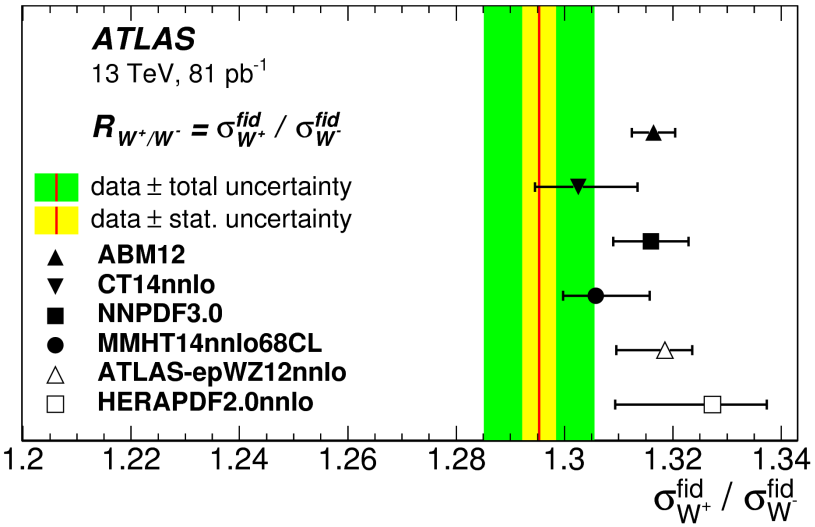
ATLAS: arXiv:1603.09222

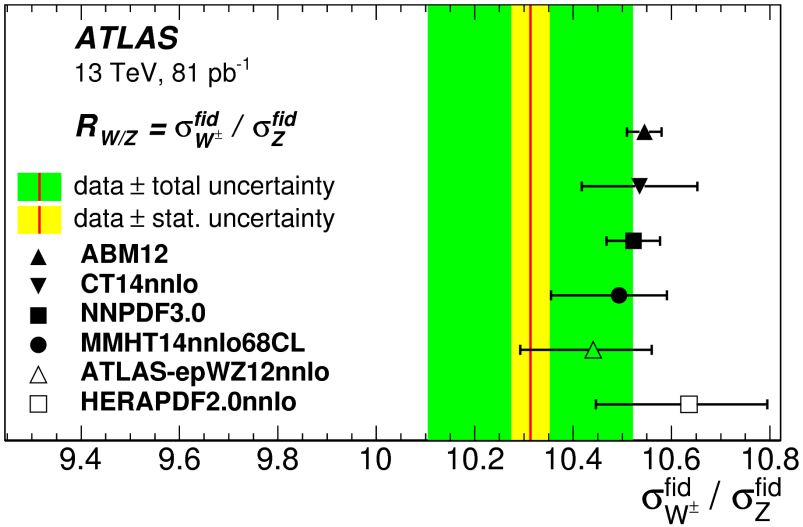


good agreement with predictions
luminosity uncertainty 2.1%
systematic uncertainties 2%(W), 1%(Z)



W^+/W^- ratio: uncertainty 0.8%

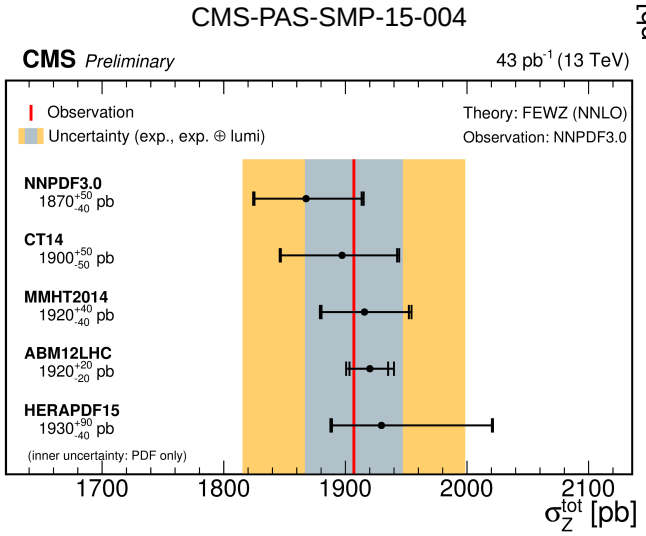


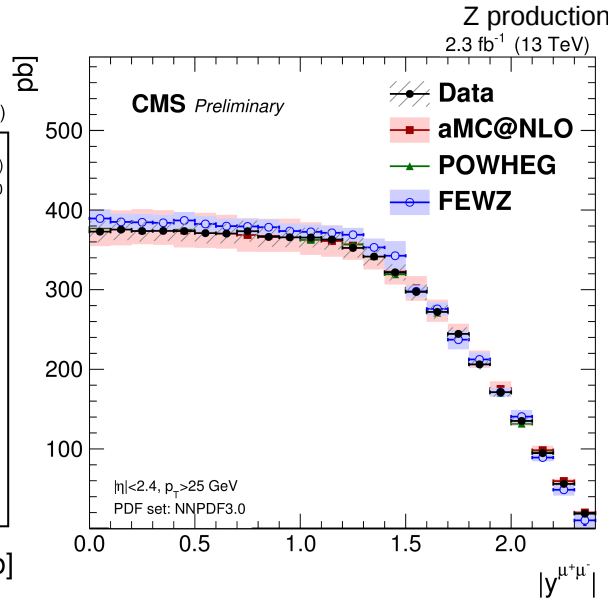


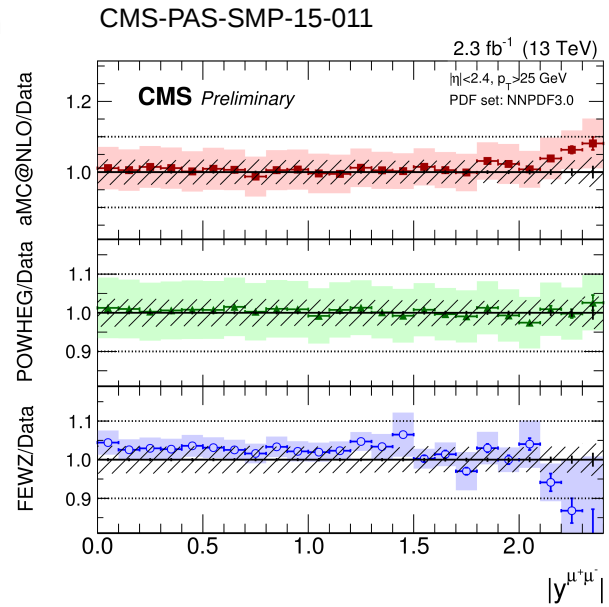
Talk: Stefano Camarda

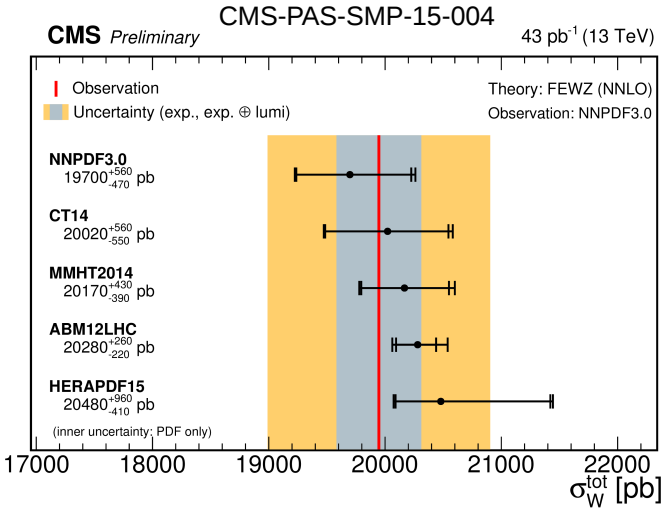
W, Z @13 TeV

CMS-PAS-SMP-15-004
CMS PAS SMP-15-011









luminosity uncertainty 4.8 (W), 2.7% (Z)

Z: inclusive and differential results

→ detector description well understood
→ x-sections well described by predictions

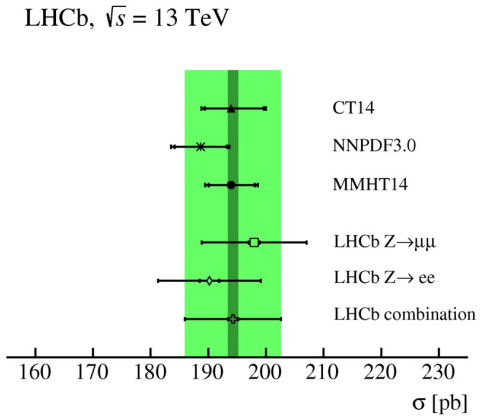
PDFs show differences depending on which data are used in the fit

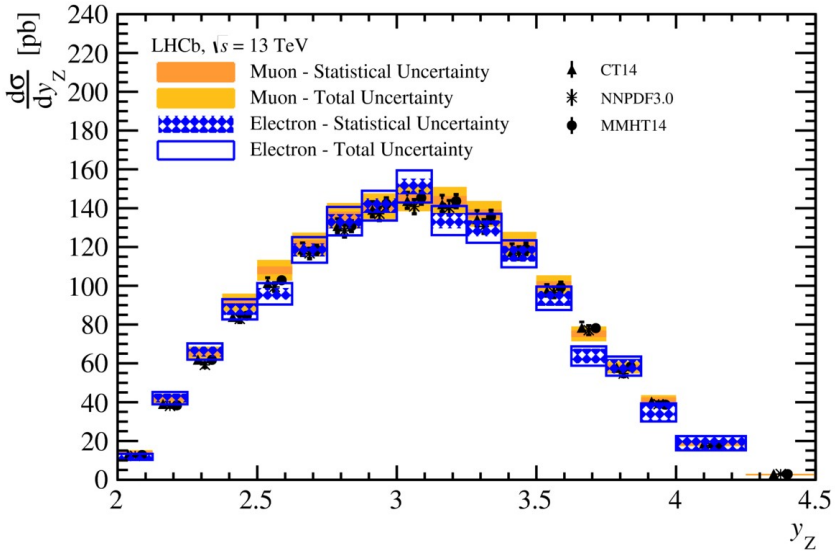
Talks: Ringaile Placakyte, Xinmai Niu

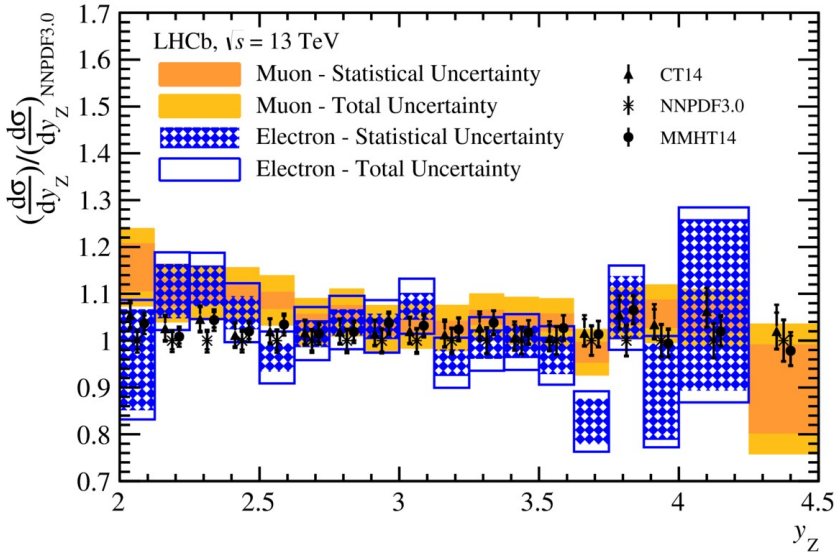
Z @ 13 TeV - forward

LHCb: arXiv 1607.06495

fiducial volume:
2.0<η<4.5, p_T>20 GeV
60 < M(μμ) < 120 GeV







luminosity uncertainty: 3.9%

other syst. uncertainties: statistical in nature
sensitivity to PDFs with more statistics
note: high rapidities are sensitive
to low and high x (close to one)

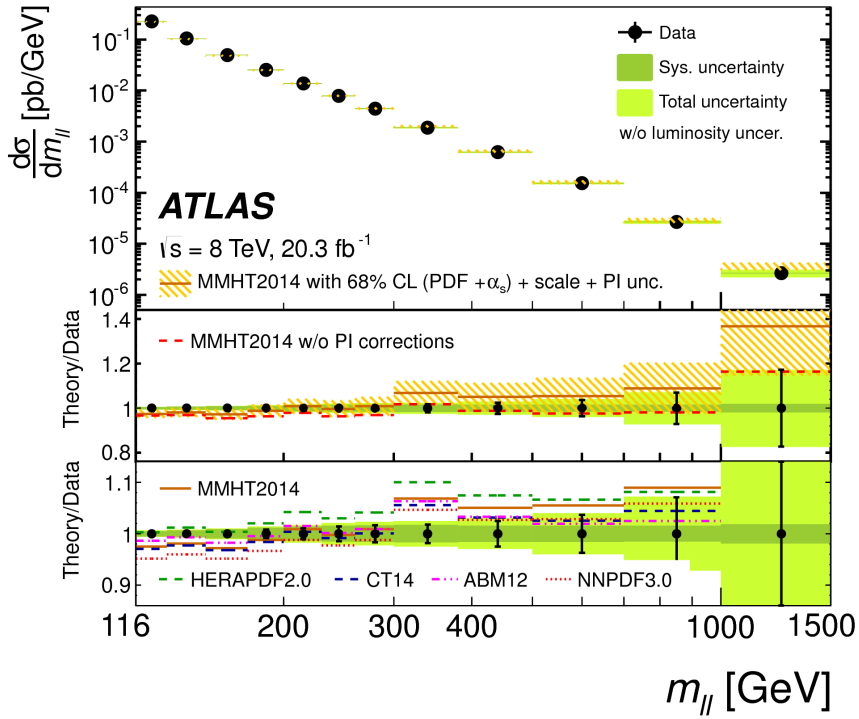
differences between PDF sets larger than
at smaller cm energies

Talk: Alex Grecu

High mass Drell-Yan production @ 8 TeV

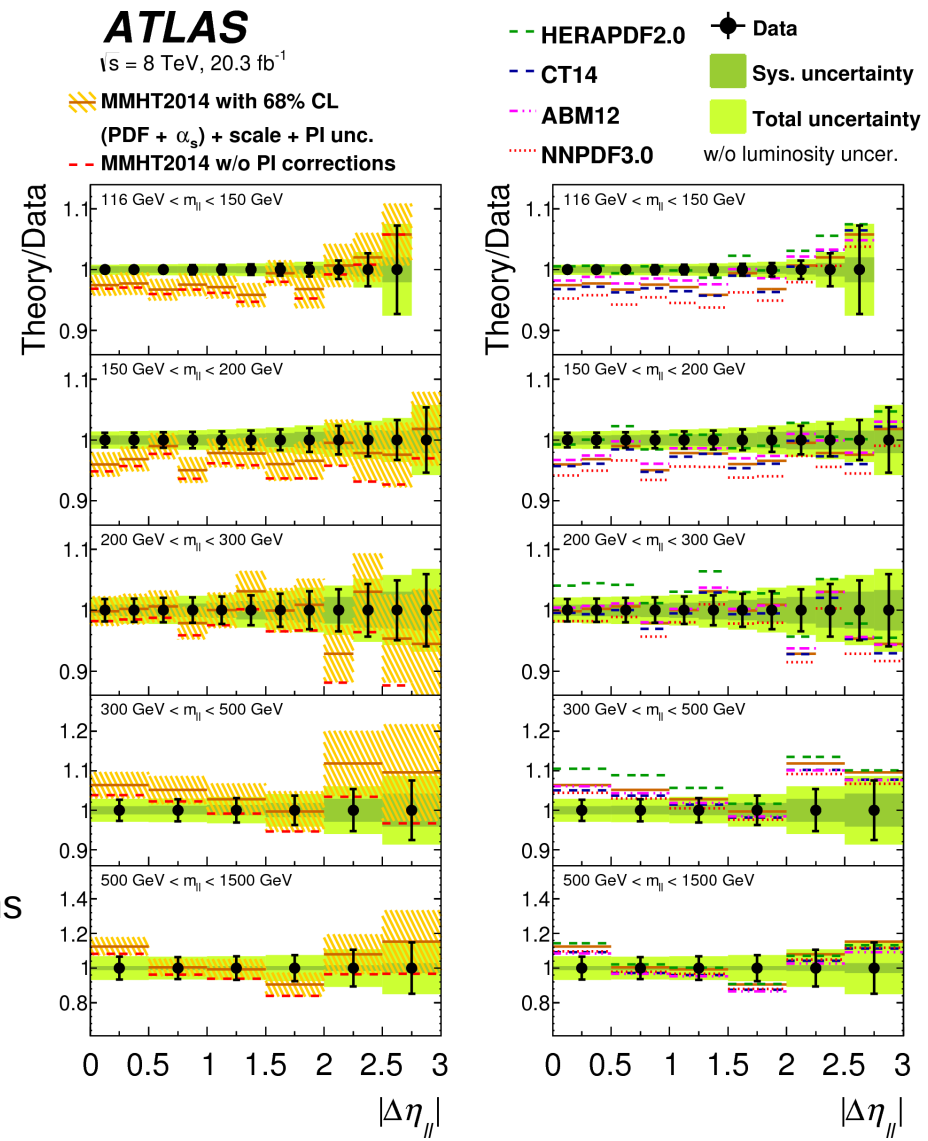
ATLAS arXiv:1606.01736

Drell-Yan lepton pair production: $Z/\gamma^* \rightarrow \ell\ell$
for $116 < M_{\ell\ell} < 1500$ GeV



predictions: NNLO plus electroweak corrections

→ general agreement with different PDF sets

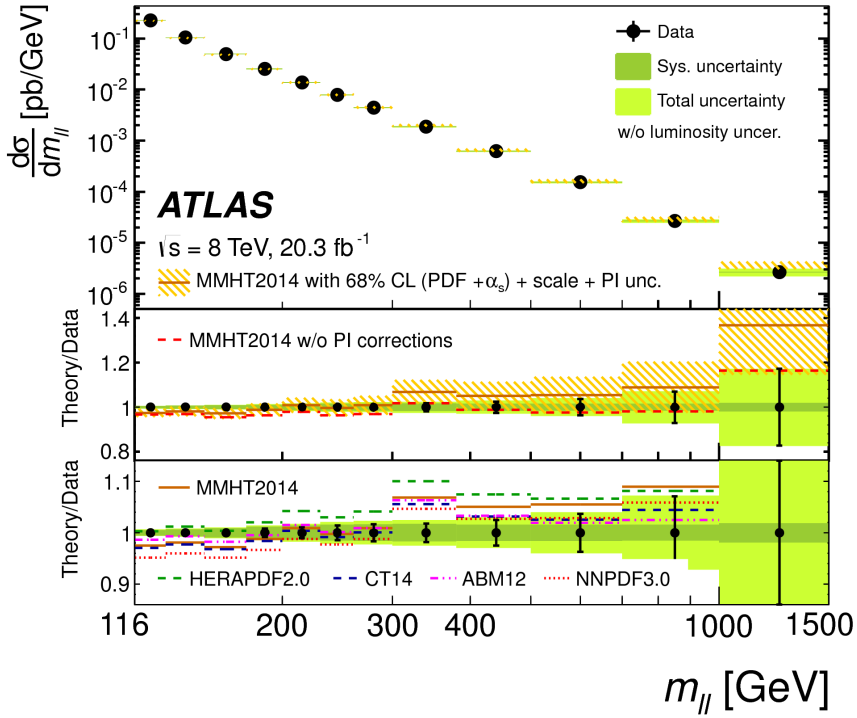


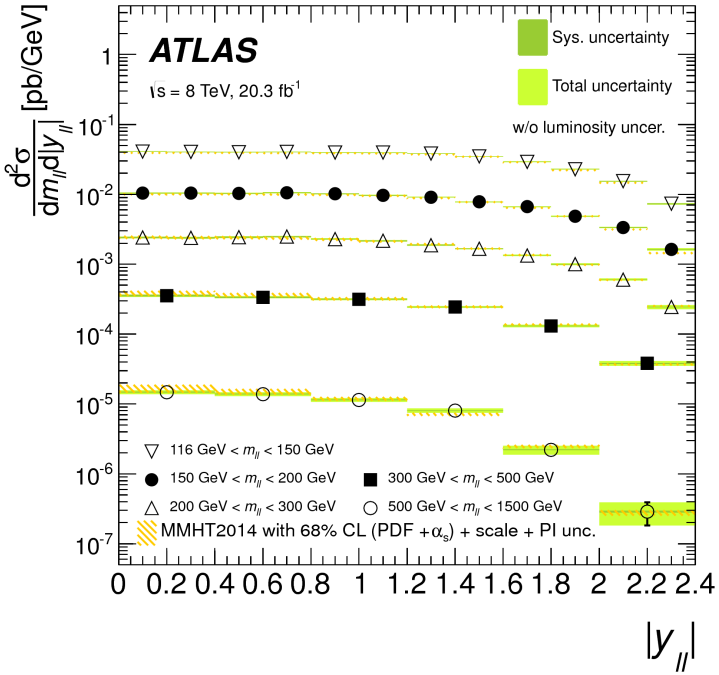
Talk: Stefano Camarda, Eram Rizvi

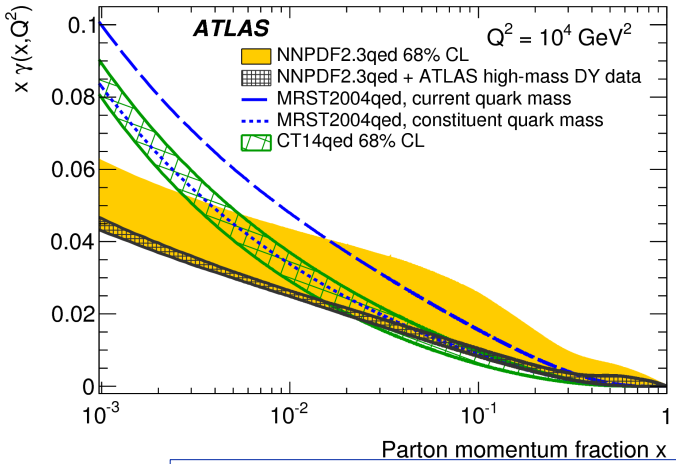
High mass Drell-Yan production @ 8 TeV

ATLAS: arXiv:1606.01736

DY can be used to constrain the photon PDF







→ photon induced (PI) processes up to 15% with large uncertainty of 60-90%
sensitivity to photon PDF via γγ → $\ell\ell$

Bayesian reweighting of qq and γγ predictions based on NNPDF2.3qed
→ significant reduction of PDF uncertainty

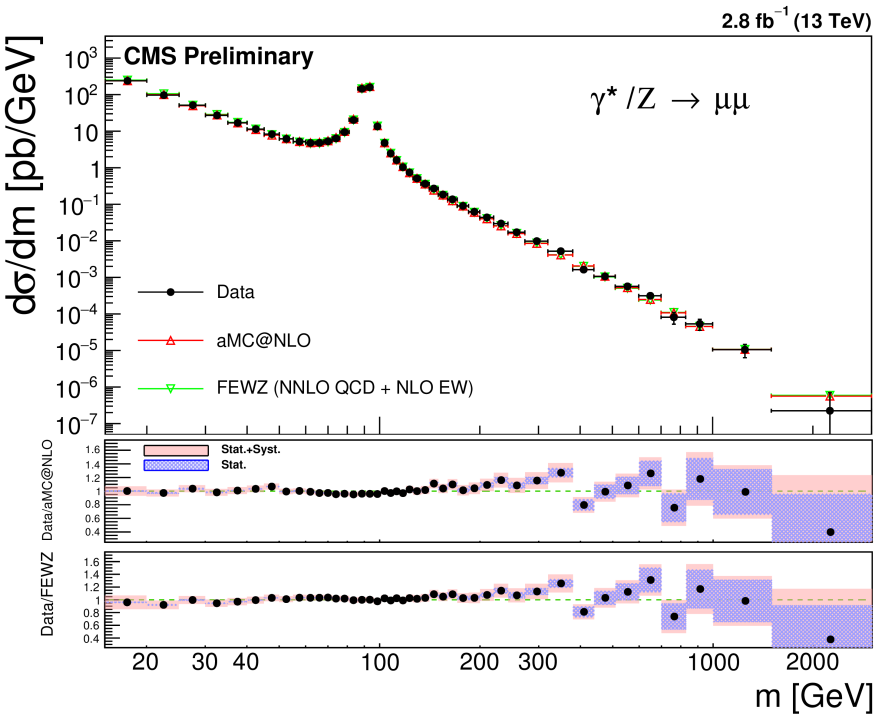
Talk: Stefano Camarda, Eram Rizvi

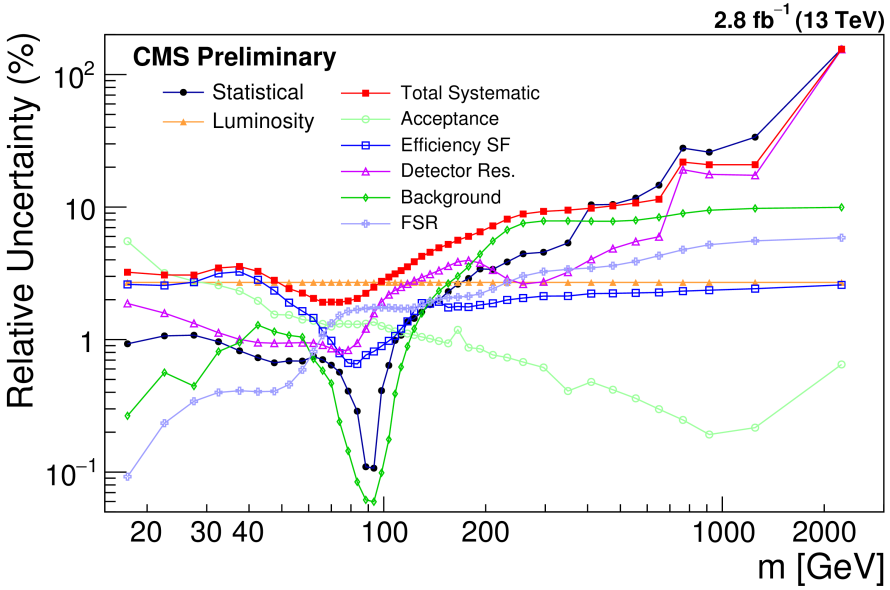
DY production @ 13 TeV

CMS PAS-SMP-16-009

mass range: 15 < M< 3000 GeV
comparison: aMC @NLO and FEWZ (NNLO) with NNPDF3.0 PDF and EW corrections

generally good agreement within uncertainties





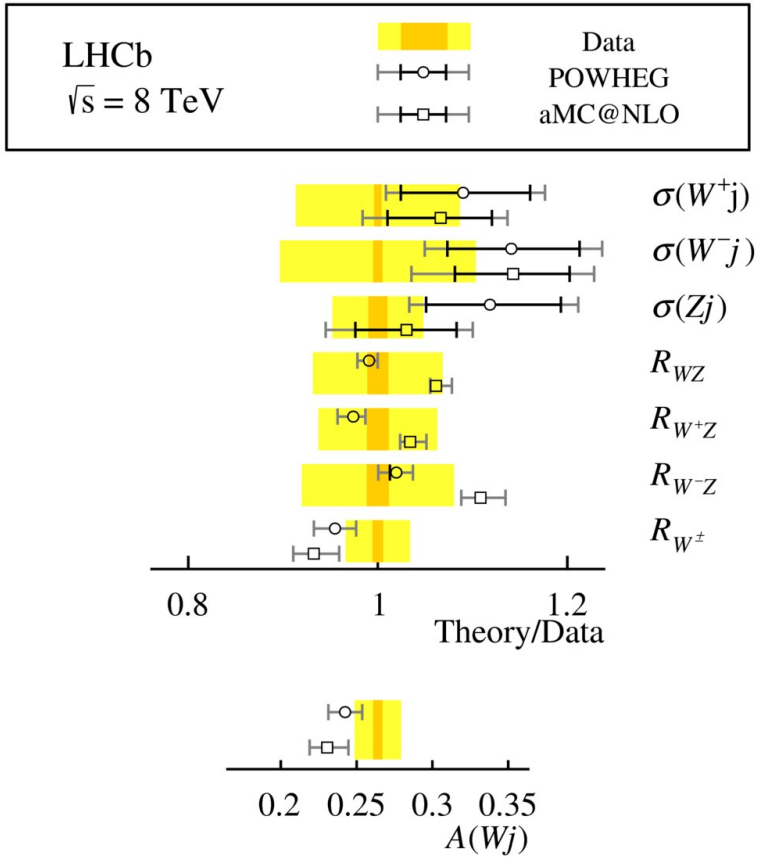
associated production of W and Z bosons

W, Z plus jet @ 8 TeV - forward

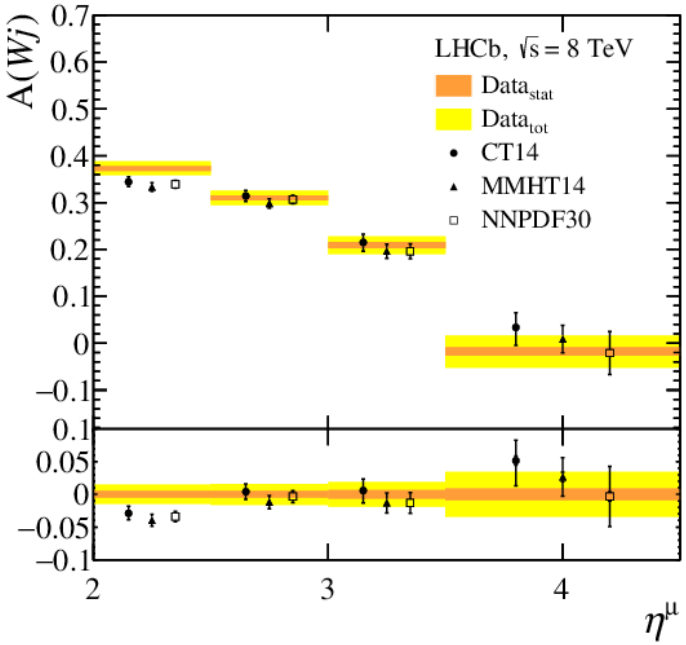
LHCb: arXiv:1605.00951

agreement with NLO (+PS)

many differential distributions available
general good description by predictions



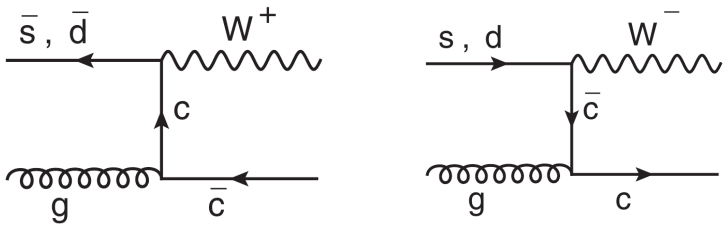
W + jet: lepton charge asymmetry
→ some sensitivity to PDFs at higher Q^2



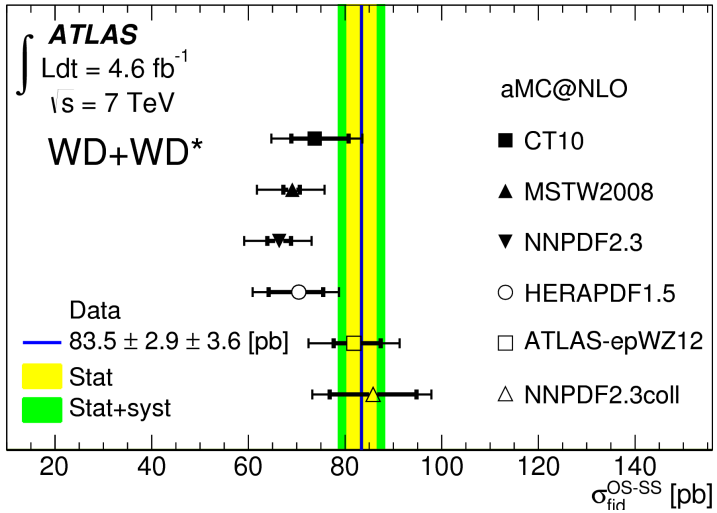
Talk: Wouter Hulsbergen

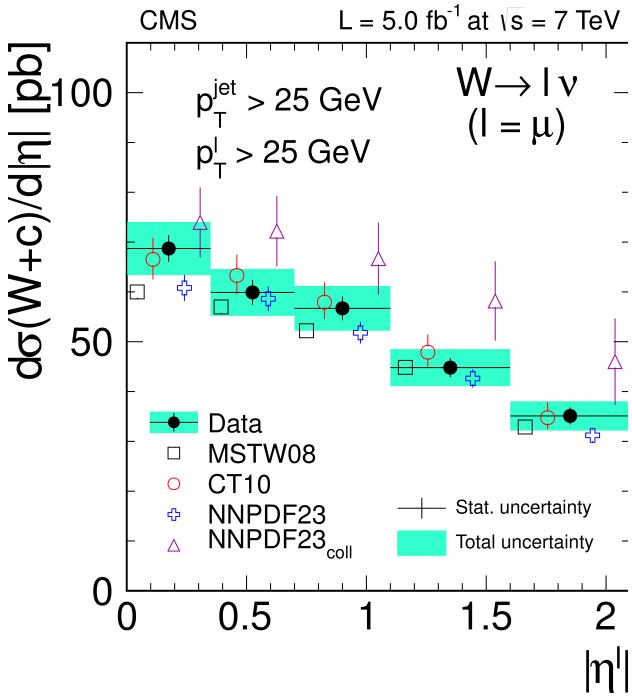
W plus charm

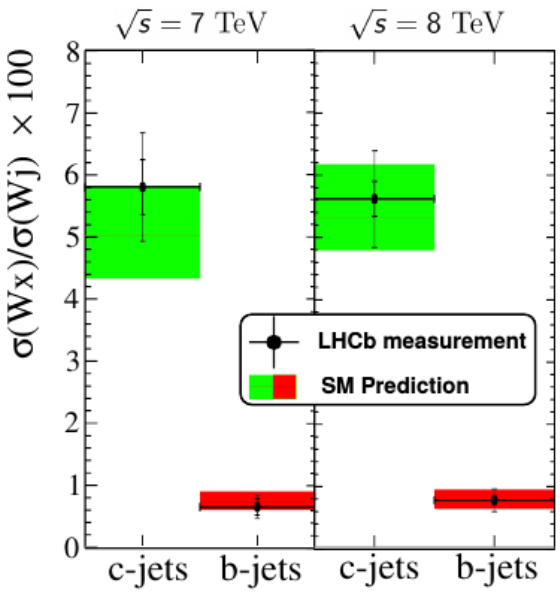
CMS: JHEP02 (2014) 013
ATLAS: JHEP05(2014)068
LHCb: PRD 92 (2015) 052001

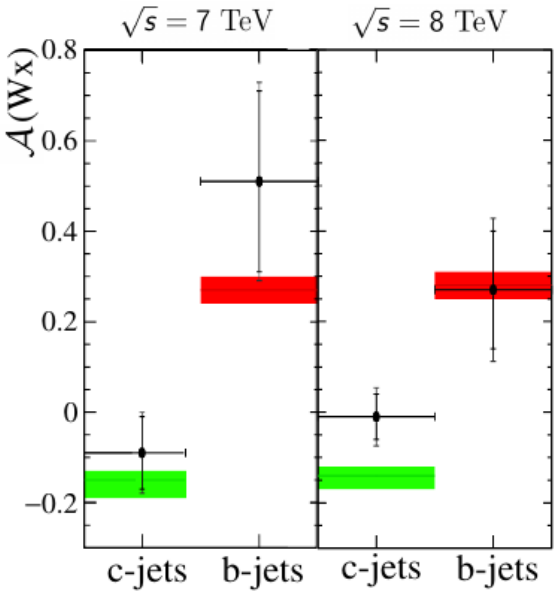


sg → W + c dominant
dg → W process is Cabibbo suppressed
→ σ(W + c-jet) direct probe of strangeness
complementary to low energy neutrino data









Talks: Gabriele Chiodini, Wouter Hulsbergen

Z plus charm

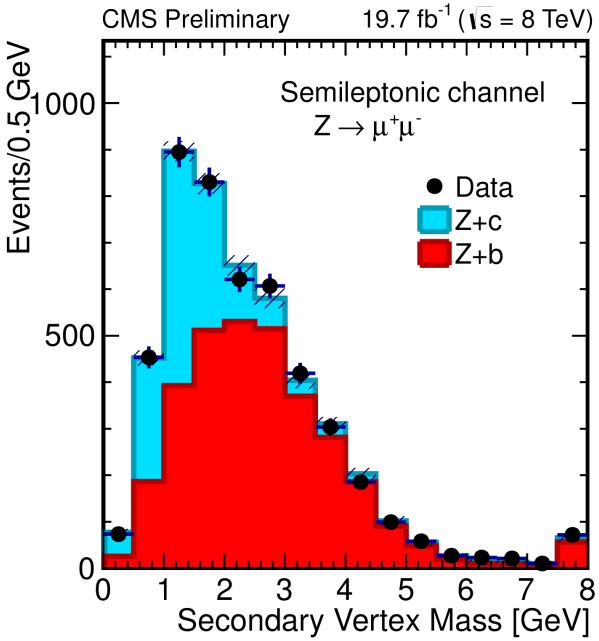
CMS-PAS-SMP-15-009

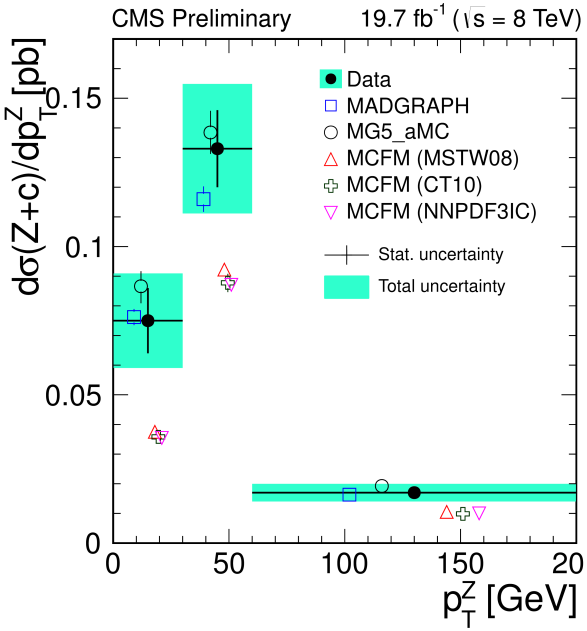
sensitivity to intrinsic charm and double parton scattering

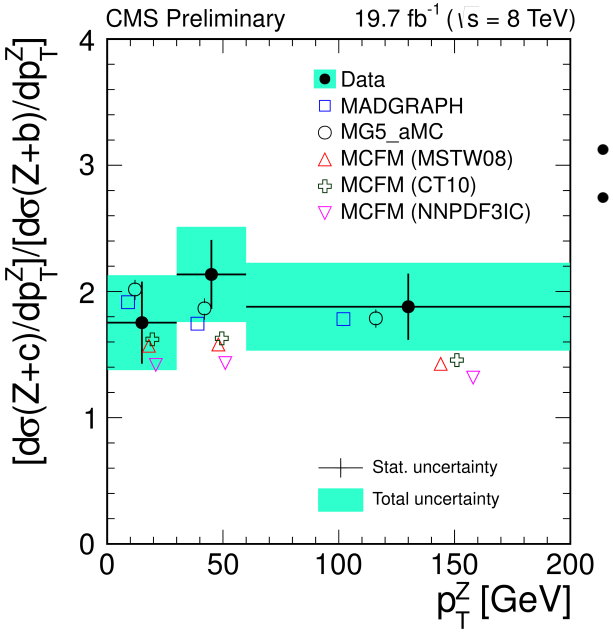
Z plus at least one jet originating from c quark

heavy flavour identification

- semileptonically (muon)
- displaced vertices
  three or two tracks vertices consistent with D decays
- discriminant to separate Z+b and Z+c:
  secondary mass (semileptonic channel)
  probability that jet tracks come from PV (D channels)







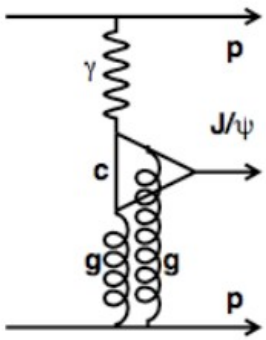
- MCFM too low
- MADGRAPH and MG5_AMC within uncertainties

Talk: Fengwangdong Zhang

Central Exclusive Production

Central exclusive production

LHCb: J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

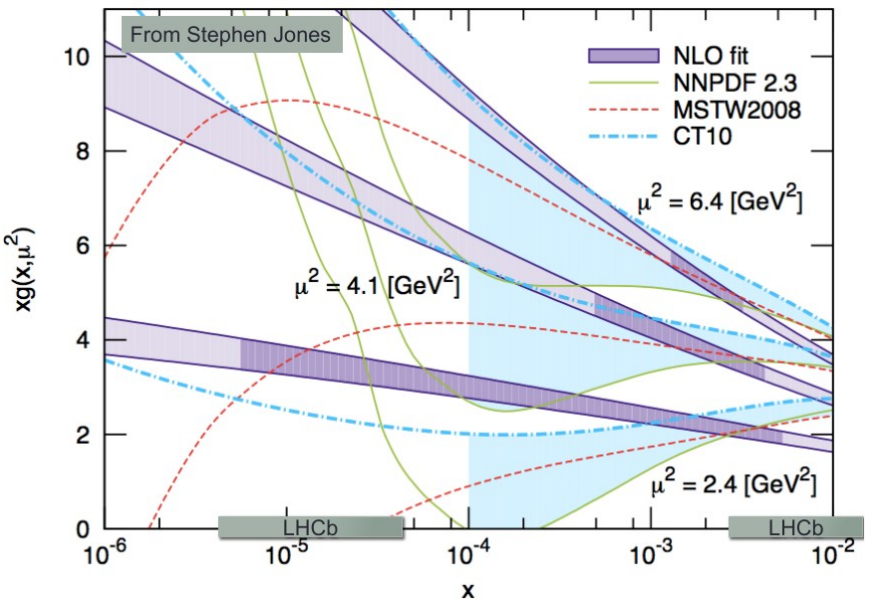


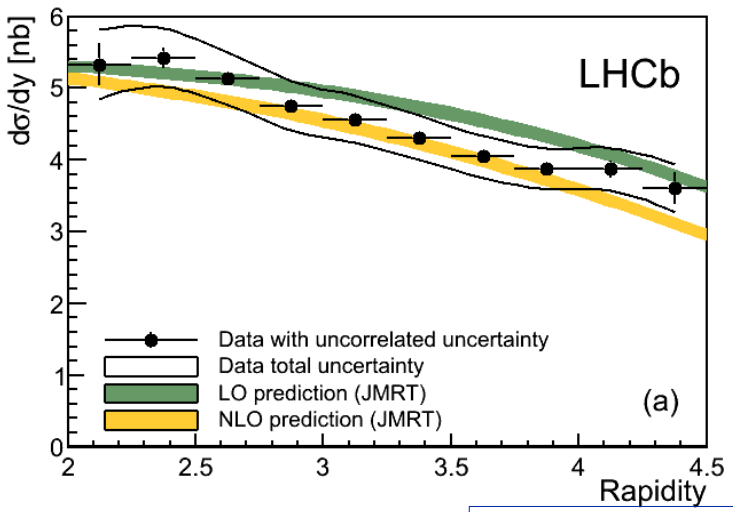
γ-pomeron fusion eg J/Ψ, Ψ(2S)

exchange of neutral, colourless particles - protons remain intact
very clean experimental final states

→ sensitivity to gluon distribution at low Bjorken-x ($5 \cdot 10^{-6}$)

NLO gluon resulting from a fit using LHCb exclusive J/Ψ production compared to the global fits (arXiv: 1307.7099) → gluon PDF may rise faster than predicted by global PDFs





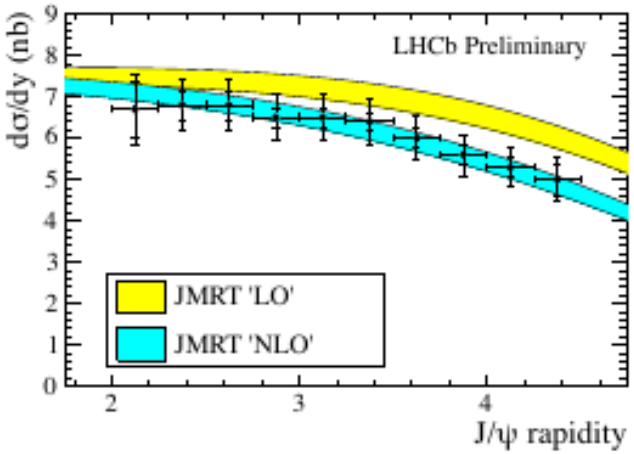
Talk: Tomasz Szumlak

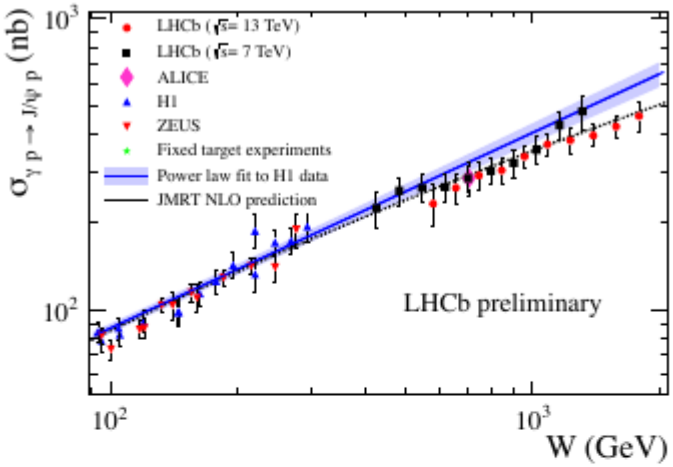
Central exclusive production @ 13 TeV

LHCb-CONF-2016-007

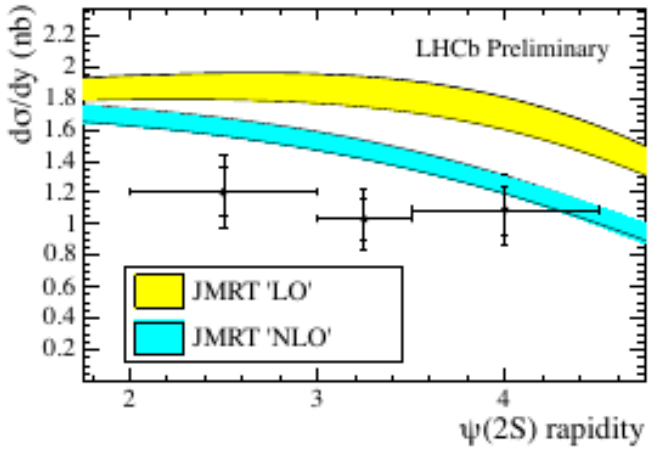
- new scintillators installed in the forward region
  → lower backgrounds (about half) from inelastic processes
- data agree better with NLO prediction
- comparison with HERA photoproduction data: deviation from simple power law for J/Ψ

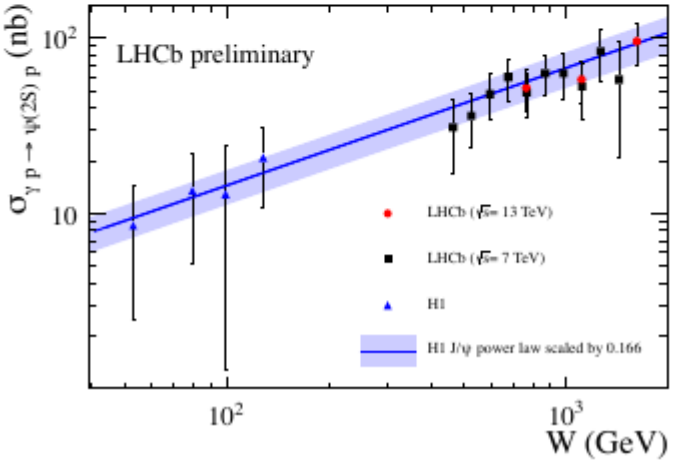
J/Ψ





Ψ(2S)





Talk: Tomasz Szumlak

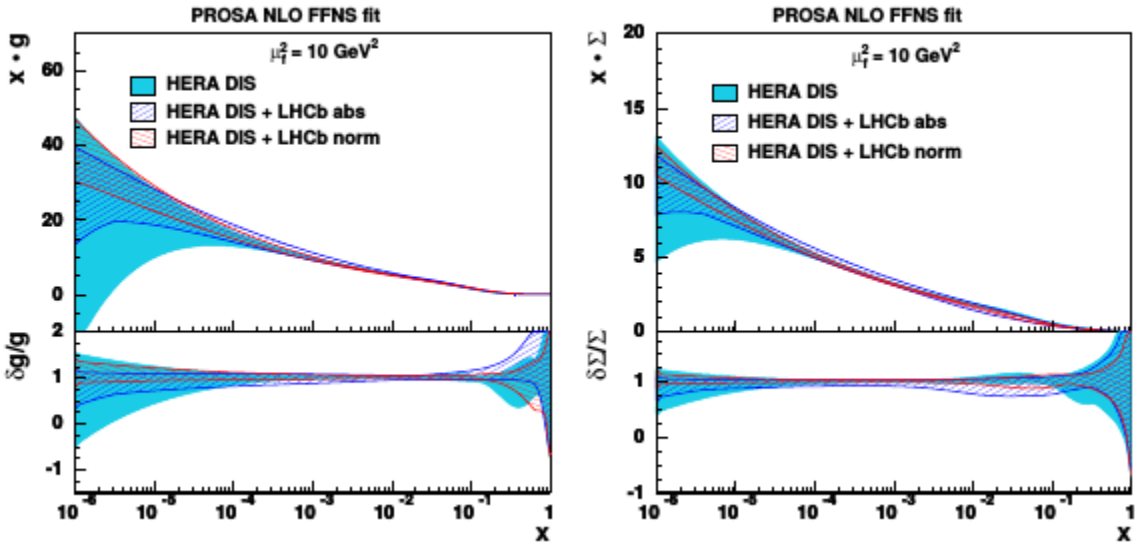
Heavy Quarks

Motivation

tt-bar cross sections are already used in PDF fits
→ improved constraints on large-x gluon, complementary to jets and photons

forward open charm and bottom production
→ p_T and rapidity distributions sensitive to low and high-x gluon, $x \sim 5 \times 10^{-6}$

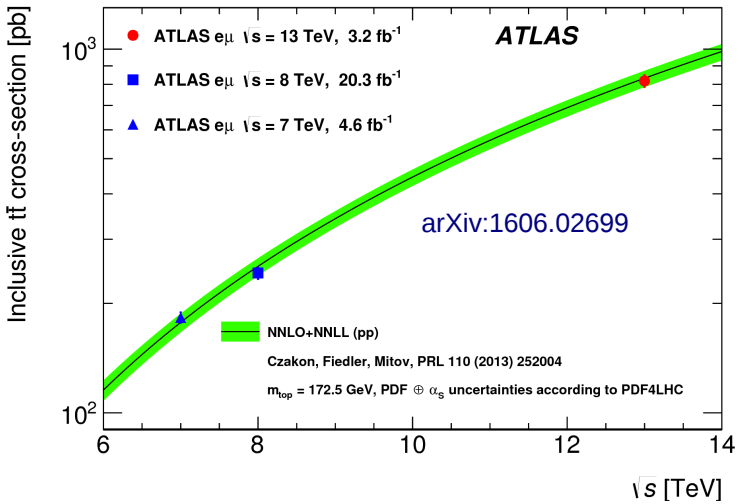
Example: impact of LHCb D^0 and B^+ differential cross section measurements on gluon and sea quark distribution NPB871 (2013) 1, JHEP08 (2013) 117



PROSA collaboration: arXiv: 1503.04581

Top @ 13 TeV

CMS-PAS-TOP-16-007
ATLAS-CONF-2016-040
ATLAS arXiv: 1606.02699

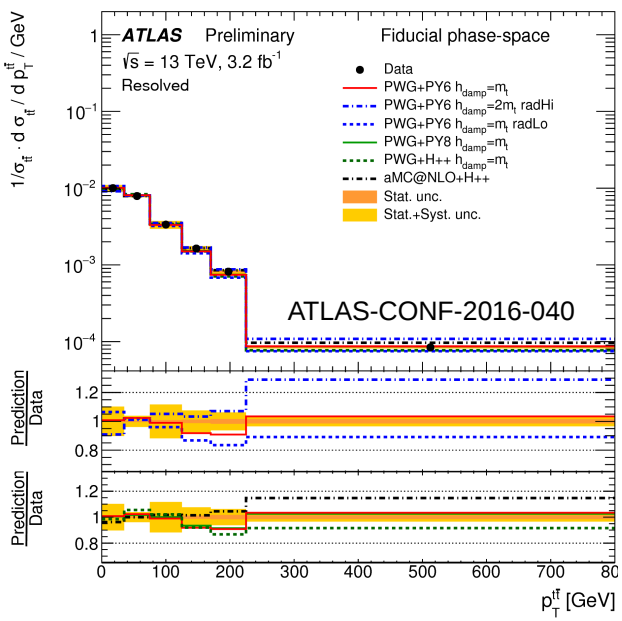


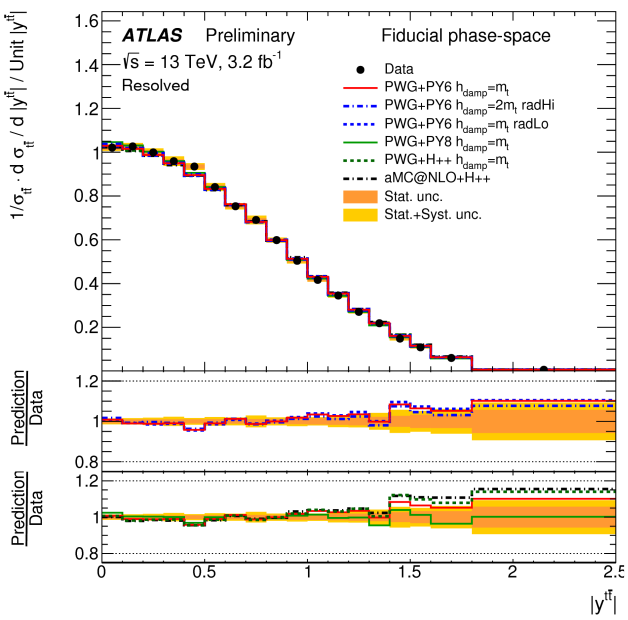
production mainly in gluon-gluon channel
→ sensitivity to gluon (x>0.1)

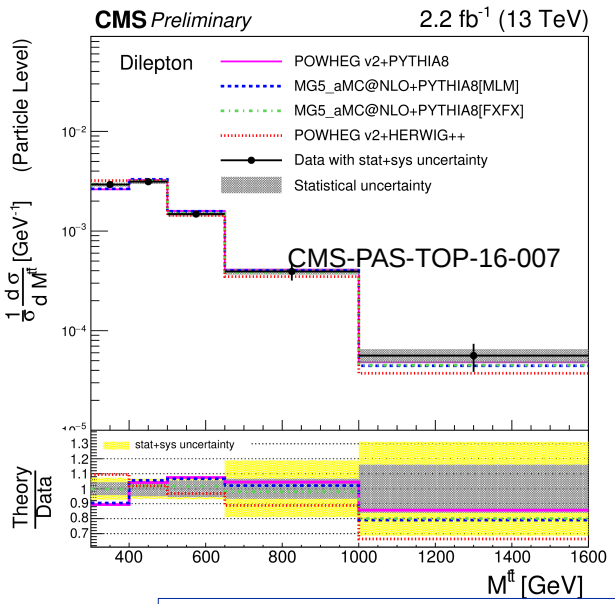
tails at large m_{tt} or high p_T sensitive to quarks

lepton plus jets channel: tt-bar → eμνν̄bb̄-bar
consistent with prediction based on NNLO+NNLL
or POWHEG & PYTHIA

new measurement @ 7 and 8 TeV arXiv:1607.00837







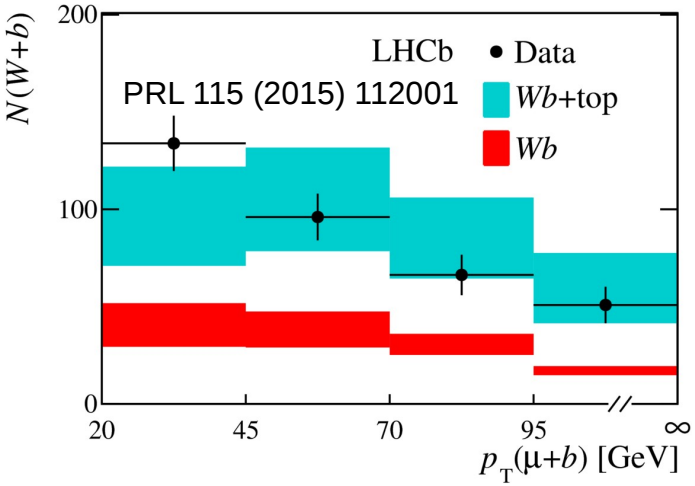
Talks: Ki Lie, Georgios Krintiras

Top in the forward region

LHCb: PRL 115 (2015) 112001
LHCb-PAPER-2016-038

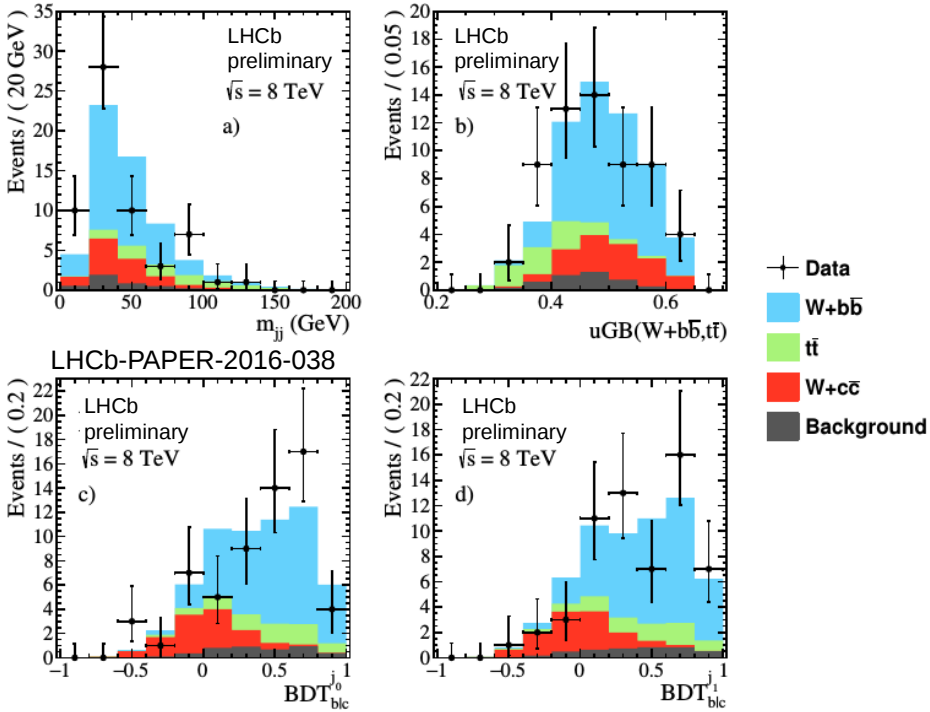
first observation of top quark in the forward region using Run I data:

final state: one isolated muon and a b-jet
$p_T(\mu + b)$: discrimination between top and W+b-jets



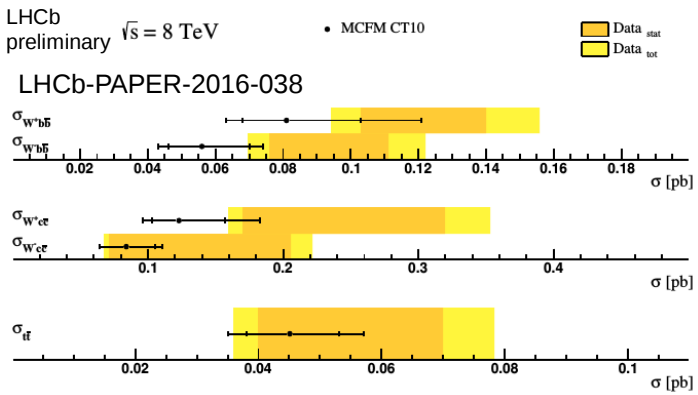
New: high p_T isolated lepton plus two b-jets
→ W+bb, W+cc and tt-bar production

discrimination: m_{jj},BDT(b|c) and MVA(W+bb|tt)



LHCb-PAPER-2016-038

results in agreement with NLO predictions



LHCb-PAPER-2016-038

Talk: Wouter Hulsbergen

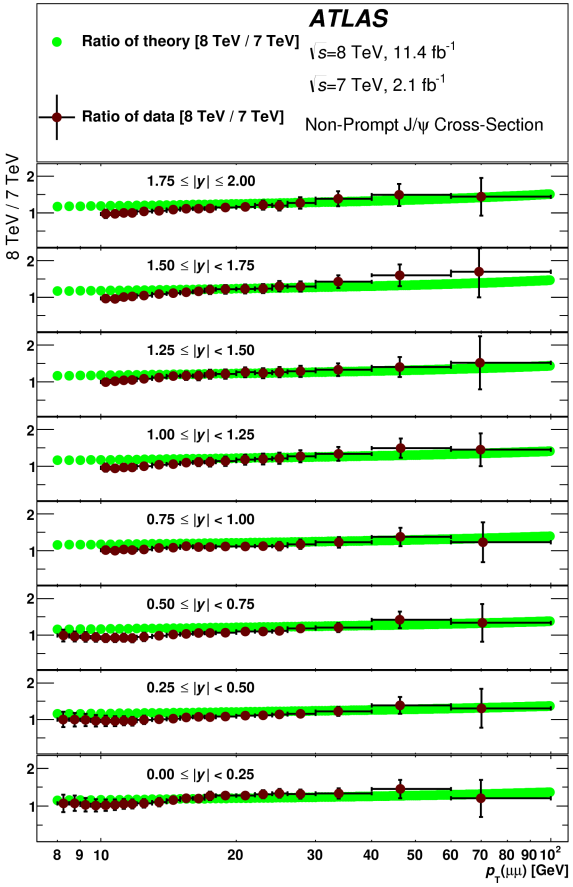
J/Ψ from b @13 TeV

LHCb: JHEP 10 (2015) 172
ATLAS: Eur. Phys. J. C 76(5), 1, (2016)

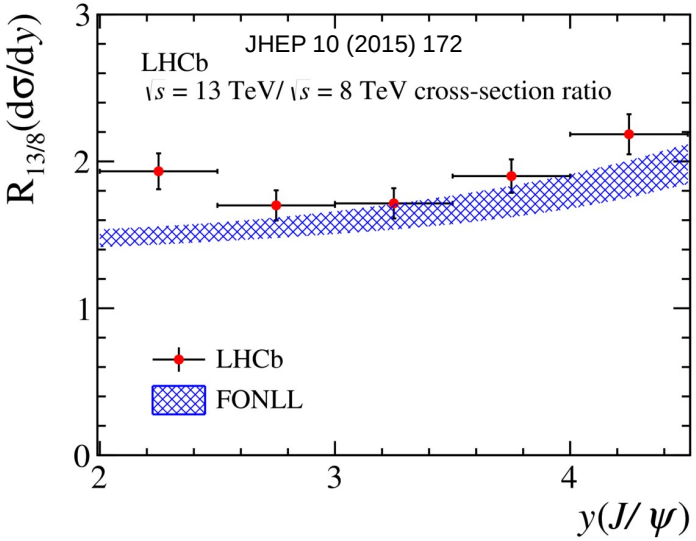
forward: x-section @ 13TeV is harder than @ 8 TeV
predictions describe p_T and y distributions

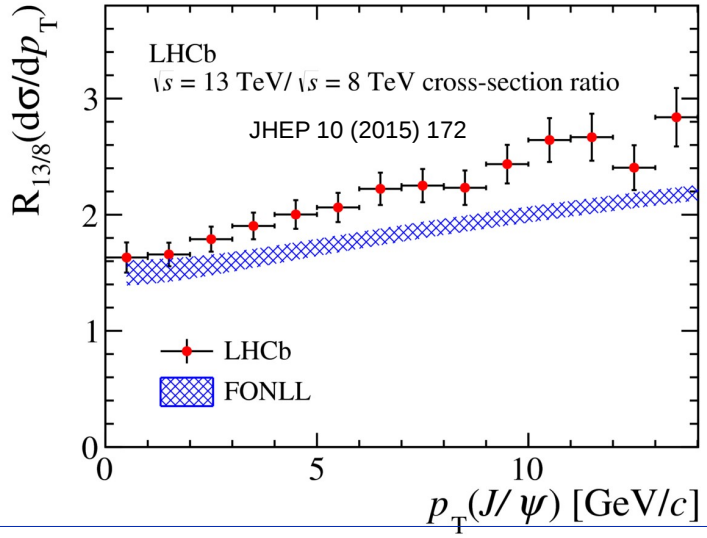
$R_{13/8}$: not described at low rapidity

$R_{8/7}$: data below predictions at low p_T



J/Ψ from b



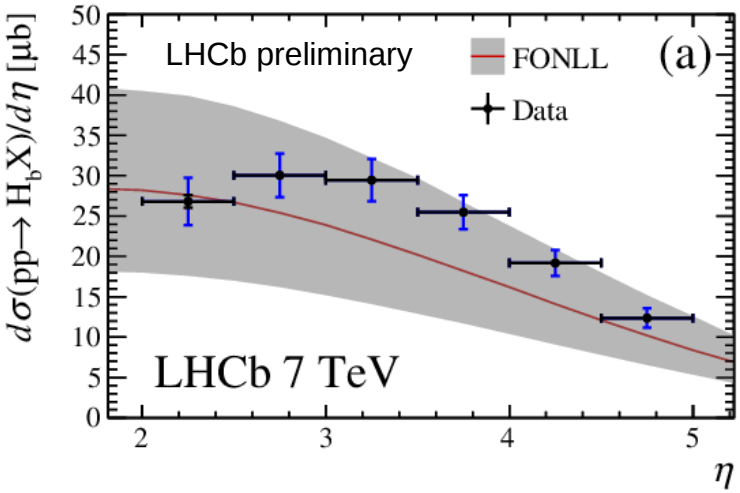


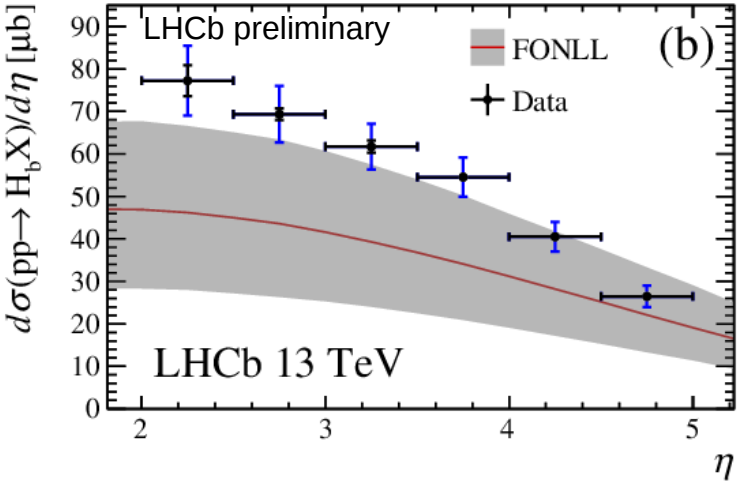
Talks: Matt Needham, Rafael Coutinho, Gabriele Chiodini

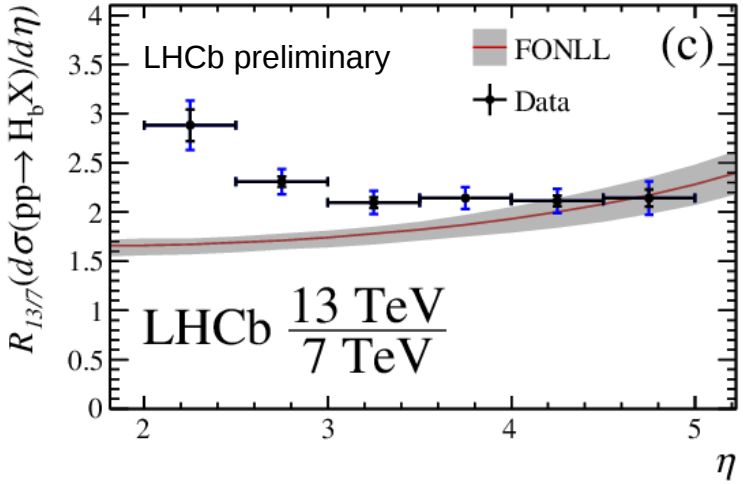
Bottom @ 7 and 13 TeV

LHCb-paper-2016-031

b quark production cross-section at 7 and 13 TeV from semi-leptonic decays of b-hadrons in pseudorapidity range 2<η<5







7 TeV: in agreement with FONLL prediction
13 TeV: tendency to be above
ratio: tension with theoretical predictions, especially at low η

Talks: Matt Needham, Rafael Coutinho

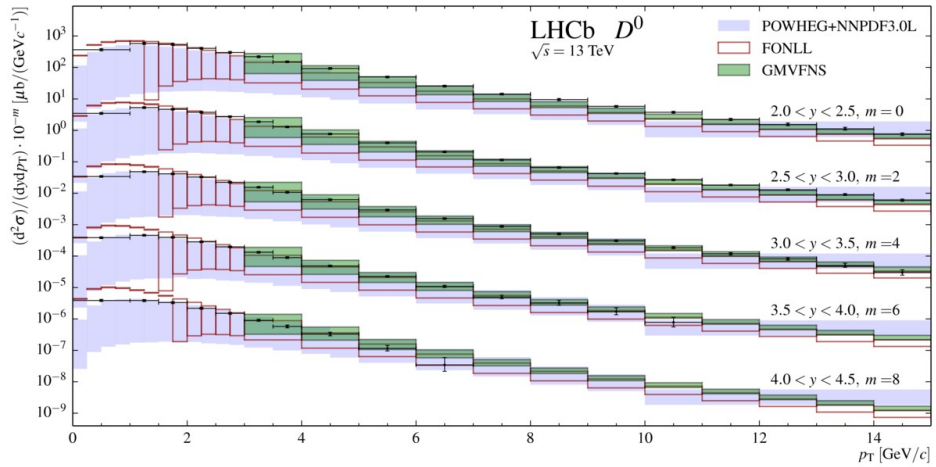
Charm @ 13 TeV

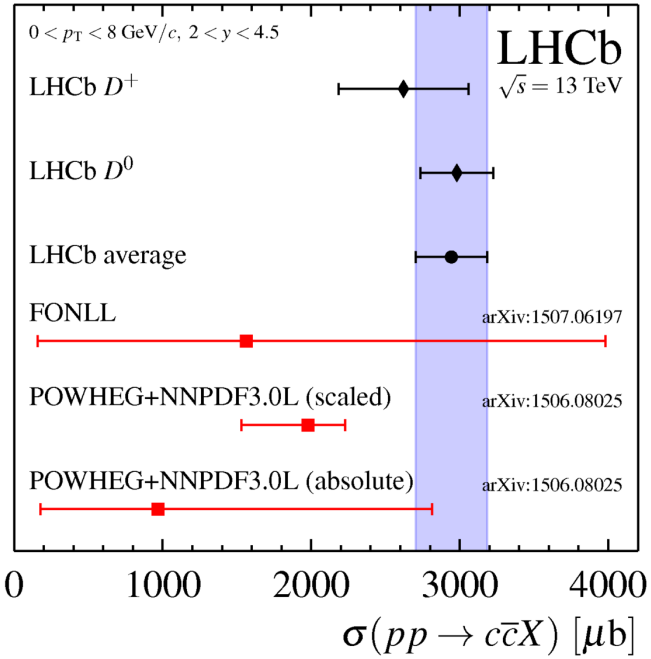
LHCb: arXiv:1510.01707

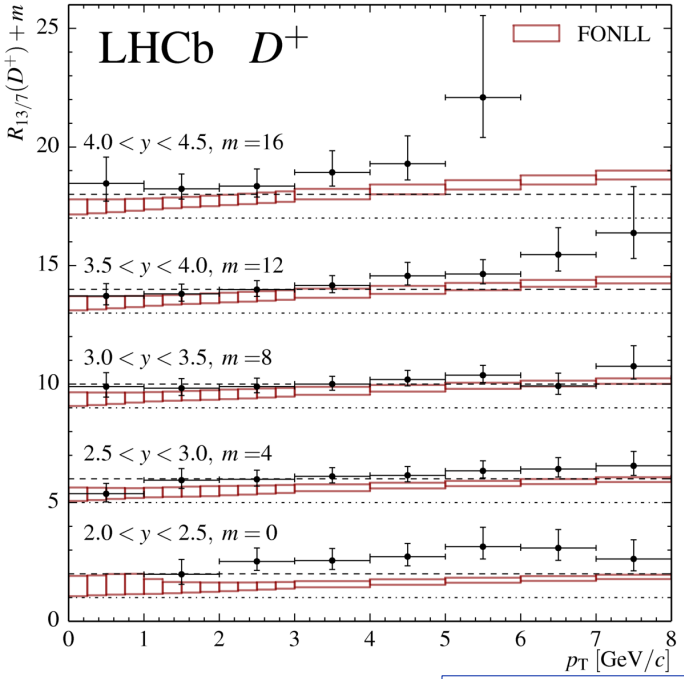
D^0, D^+, D^+_s, and D^{*+} production

$0 < p_T < 15$ GeV and $2.0 < y < 4.5$

- agreement with NLO predictions large uncertainties at low p_T
- ratios of x-sections for 13 and 7 TeV reduced uncertainties predictions show tendency to lie below the data

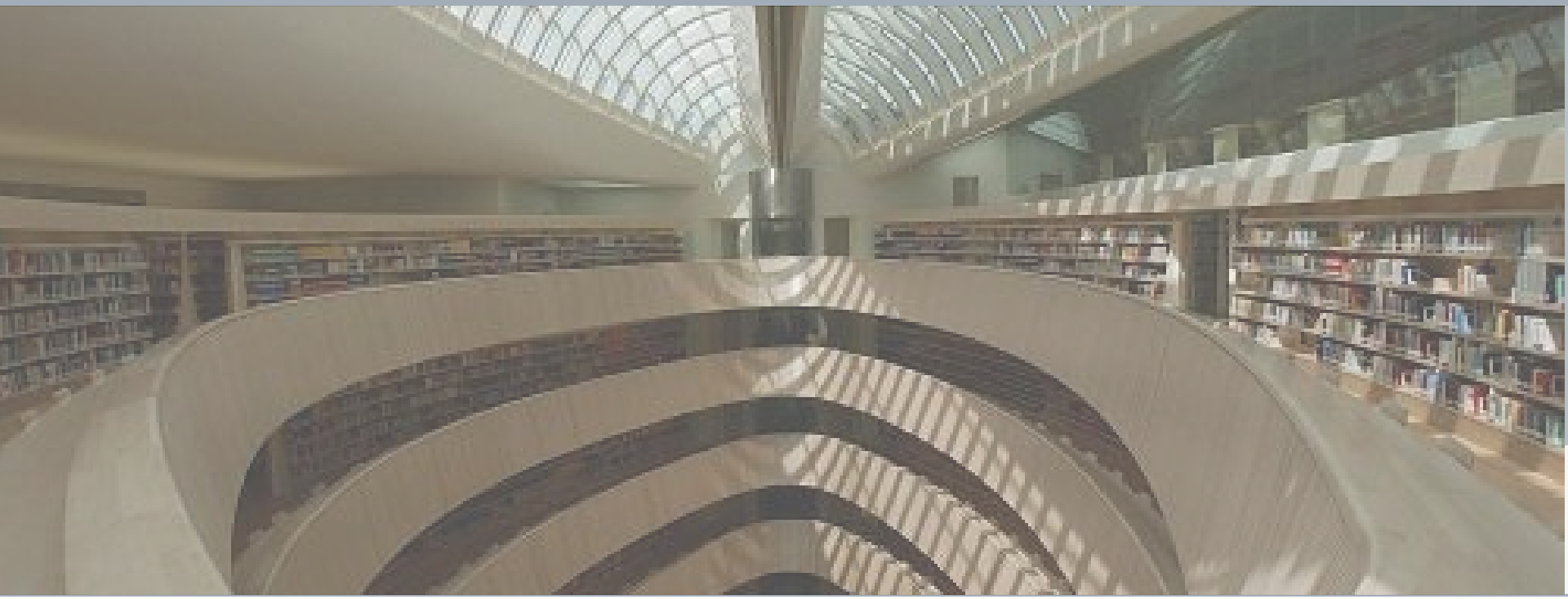






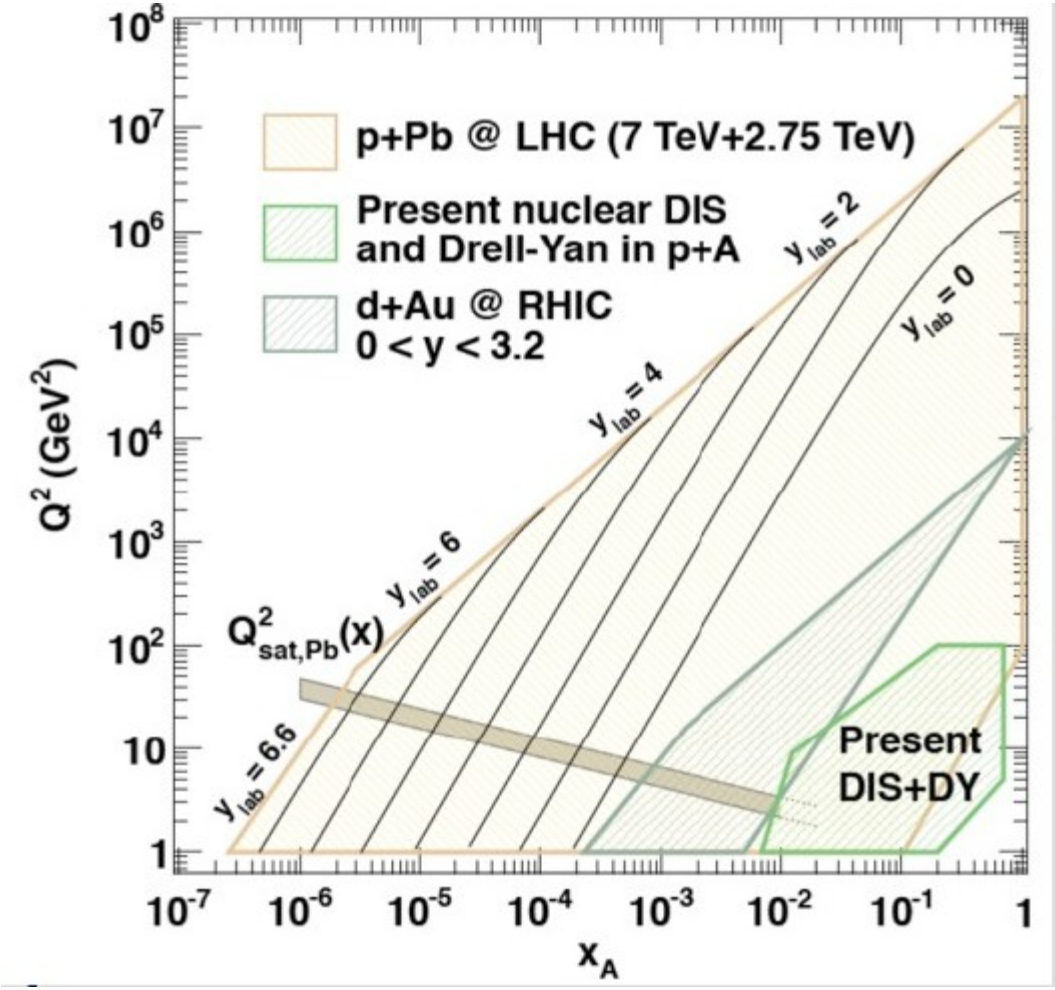
Talks: Matt Needham, Rafael Coutinho

Nuclear PDFs



Nuclear PDFs (nPDF)

LHC greatly extends kinematical range, especially if forward region is used



nPDF – Z production

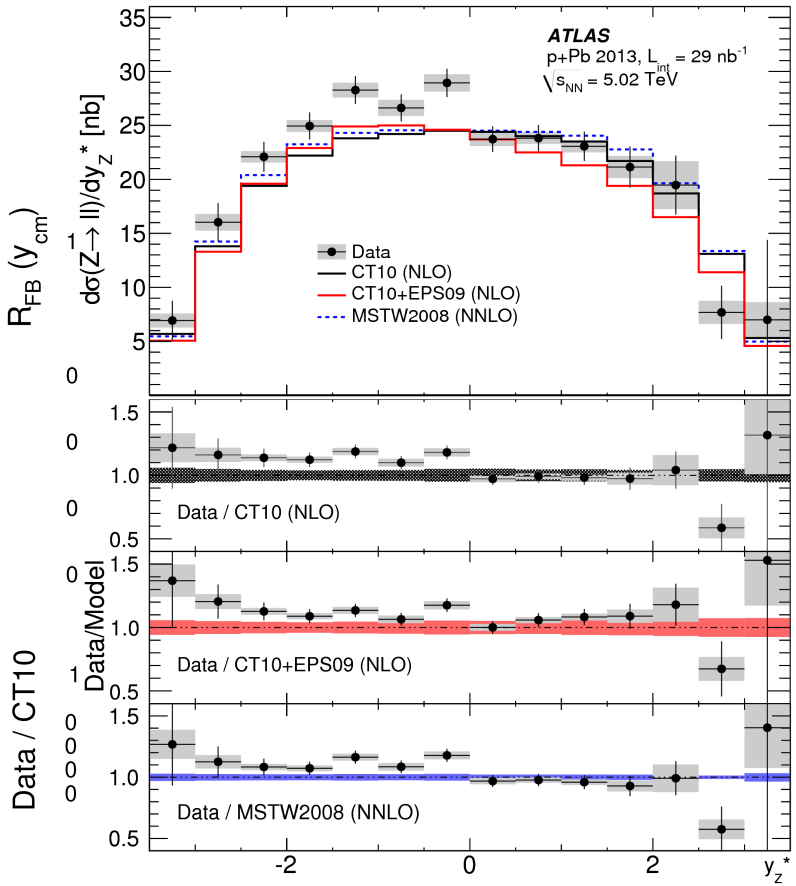
ATLAS: Phys Rev. C 92 044915 (2015)
CMS: PLB 759 (2016) 36

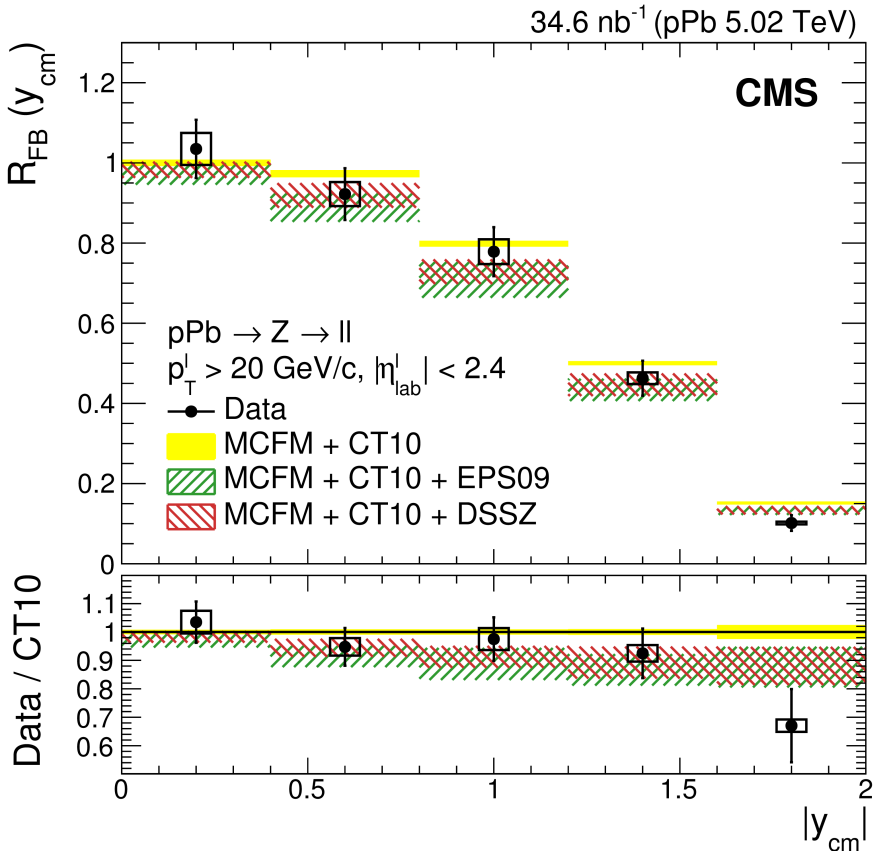
proton lead collisions with centre of mass energy per nucleon of 5.02 TeV

Z production: forward-backward asymmetry
positive: direction of the proton

$$R_{\mathrm{FB}}(y_{\mathrm{cm}}) = \frac{\mathrm{d}\sigma(+y_{\mathrm{cm}})/\mathrm{d}y_{\mathrm{cm}}}{\mathrm{d}\sigma(-y_{\mathrm{cm}})/\mathrm{d}y_{\mathrm{cm}}},$$

PDFs including nuclear corrections (EPS09, DSSZ) describe the data better



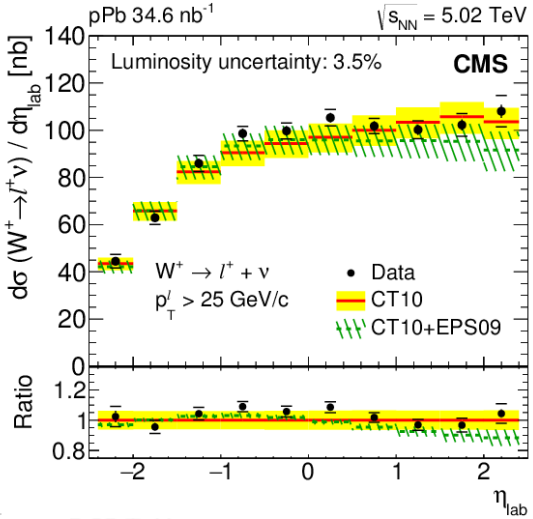


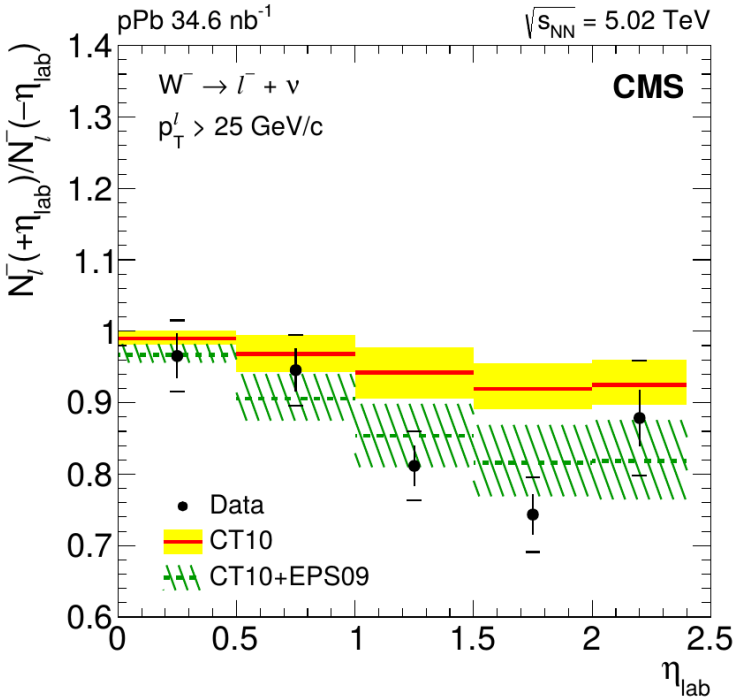
nPDF – W production

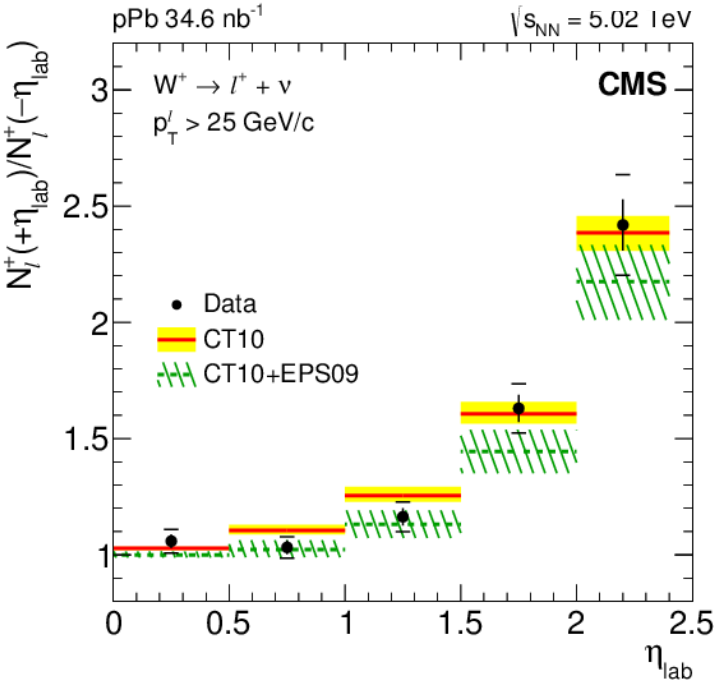
CMS: PLB 750 (2015) 565

modification of cross section of same order as theory uncertainties
→ increased sensitivity by taking ratios

- differential cross sections agree with both PDF sets
- AFW: negative W: prefers PDF with nuclear effects
  positive W: prefers unmodified PDF
  → no firm conclusion

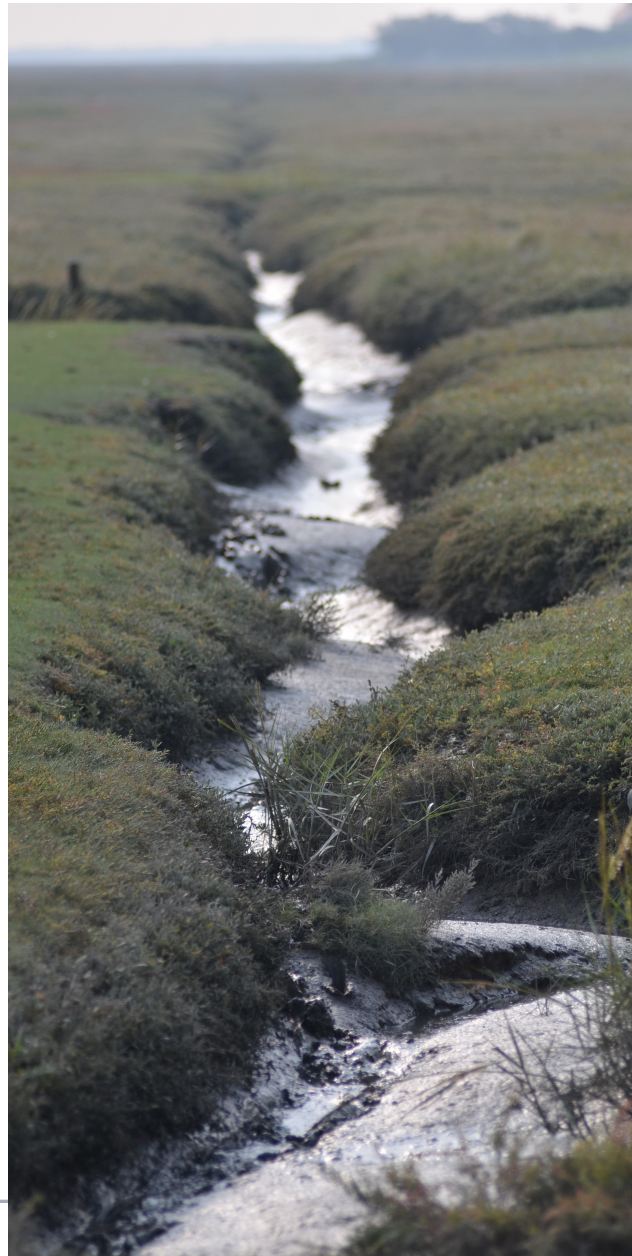






Conclusions

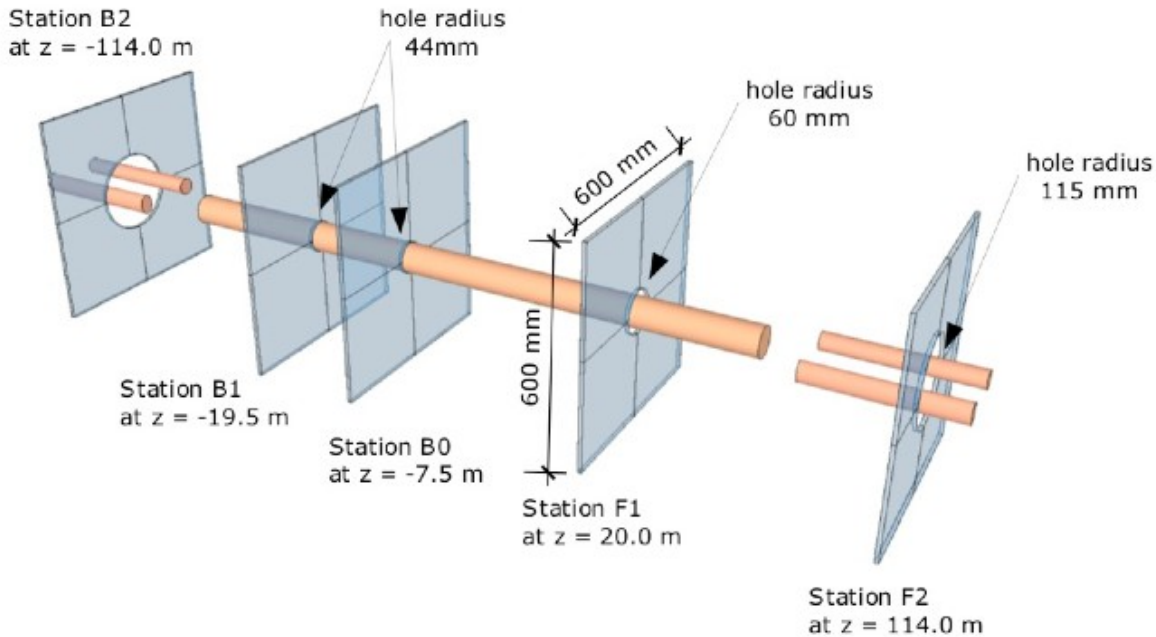
- LHC high-precision QCD measurements at 7 and 8 TeV being complemented by the first results at 13 TeV
- large variety of results with sensitivity to PDF
  in different kinematic regions
  different final states → different systematic uncertainties
  many different cm energies
- some Run I results still being completed
- new Run II results in the pipeline:
  jets, W&Z bosons
  central exclusive production
  ...



Backup

HERSCHEL

HeRSCheL: High Rapidity Shower Counters for LHCb



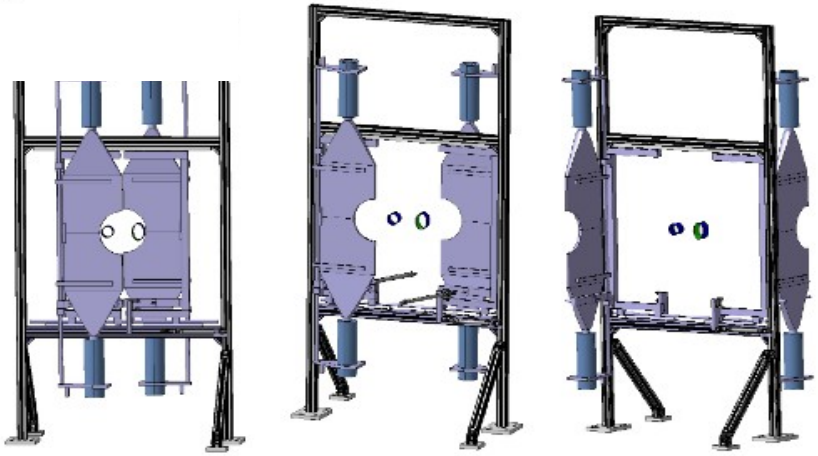
five stations: three backwards, two forward

detectors: four plastic scintillator plates,

20 mm thick - retractable

→ improvements in triggering and

background rejection for CEP events



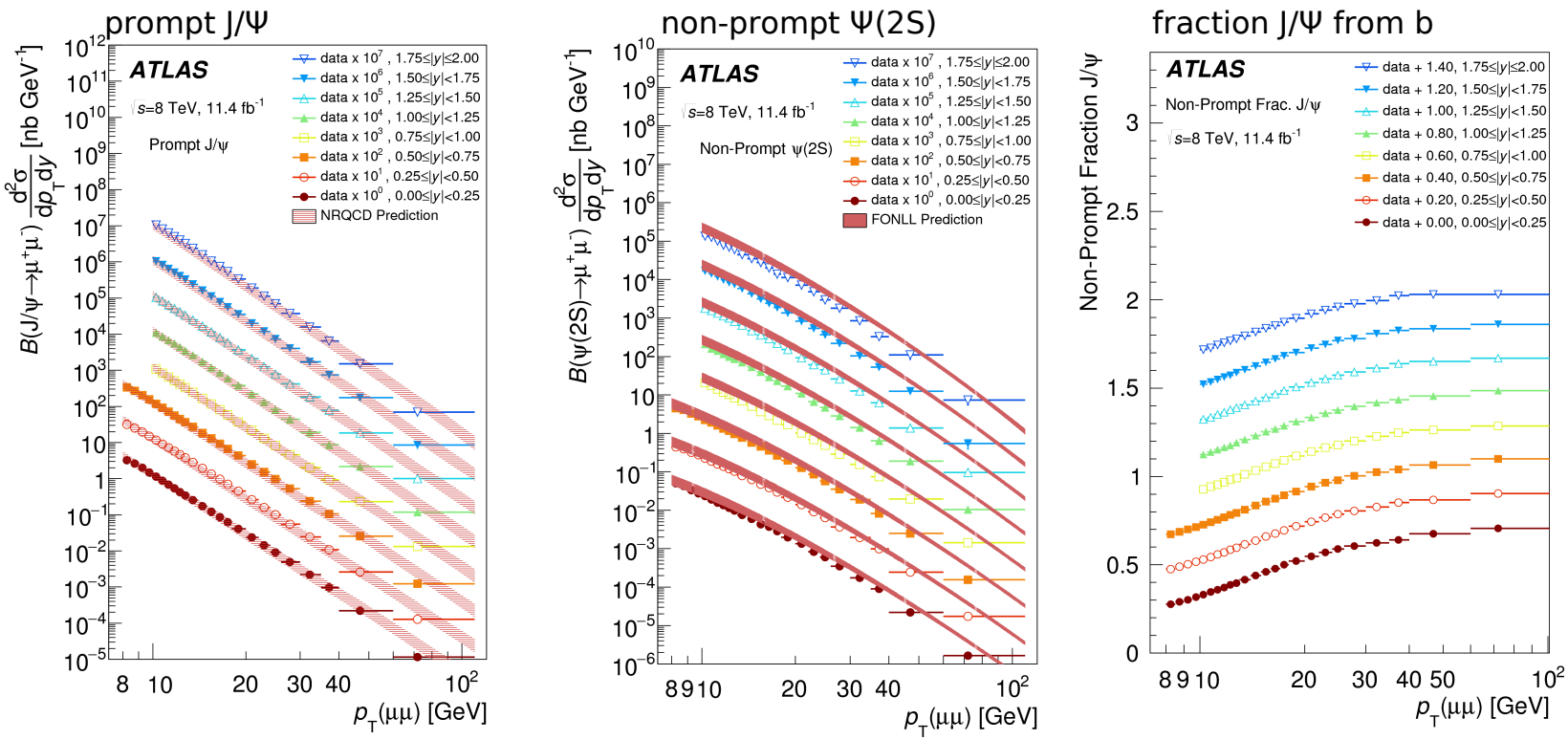
J/Ψ and Ψ(2S) @ 7 and 8 TeV

arXiv:1512.03657

extend previous measurements to higher p_T and cm energies

prompt: good agreement with NRQCD
non-prompt: fixed order NLL slightly overestimate at highest p_T

non-prompt fraction increases with p_T, constant p_T>40 GeV

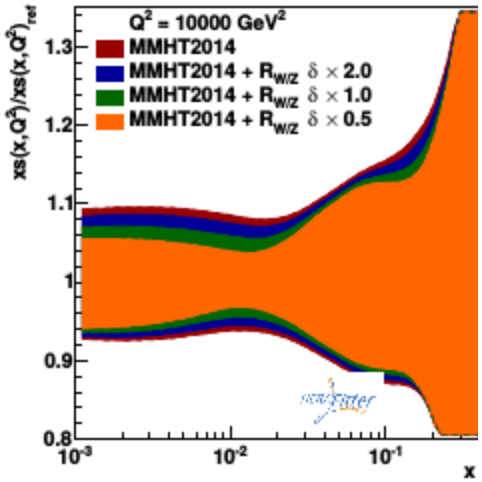


W,Z @ 13 TeV - motivation

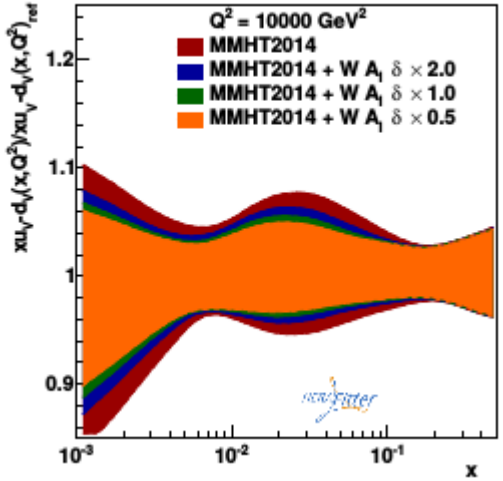
rediscover standard candles in the new kinematic regime

measure cross-section ratios: fully cancel lumi uncertainties and partially systematics

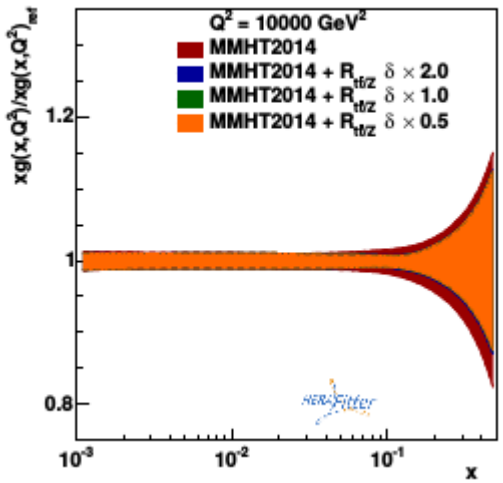
s from W/Z



u_v-d_v from W^+/W^-



g from tt/Z



Study of impact of 13 TeV results on PDF uncertainty
J. Rojo et al., J.Phys.G 42 (2015) 103103

W/Z: 2% experimental precision adds constraint on strange PDF

W^+/W^-: 2% constrains u_v-d_v PDF

tt/Z: 2-4% adds constraint on high-x gluon PDF

CMS: azimuthal decorrelations @ 8 TeV

arXiv:1602.04384

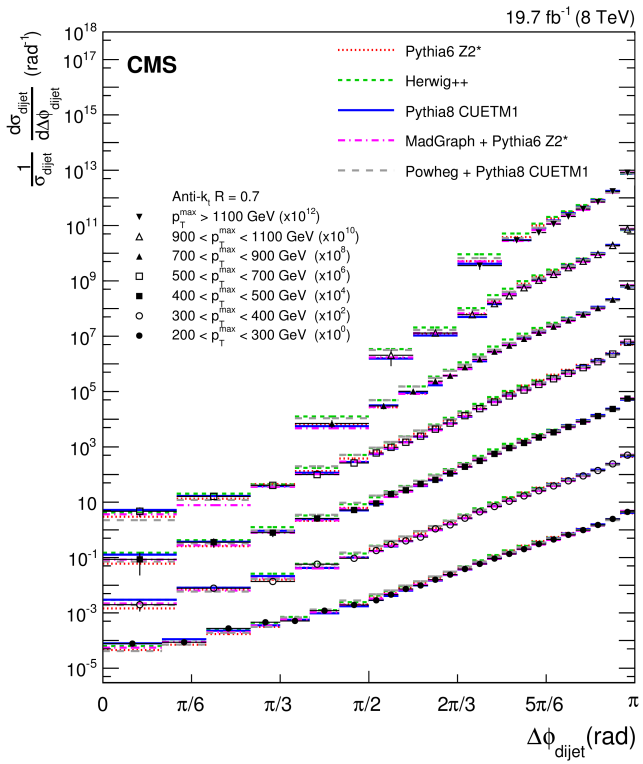
two leading jets with p_T>100 GeV, |y|<5

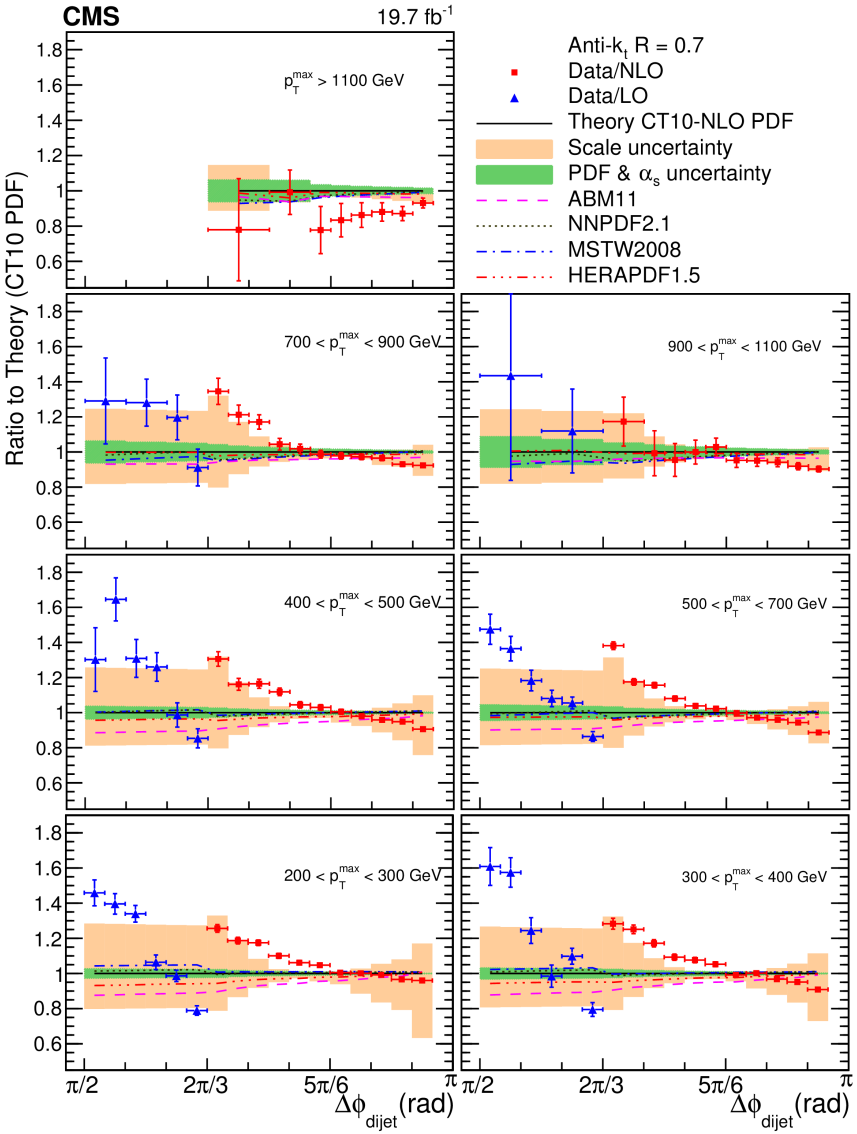
comparison to NLOJet++

LO precision $\pi/2<\Delta\Phi(\text{dijet})<2\pi/3$

NLO precision $2\pi/3<\Delta\Phi(\text{dijet})<\pi$

scale uncertainty too large
to have sensitivity to PDFs





J/Ψ and Ψ(2S) from b @ 7 and 8 TeV

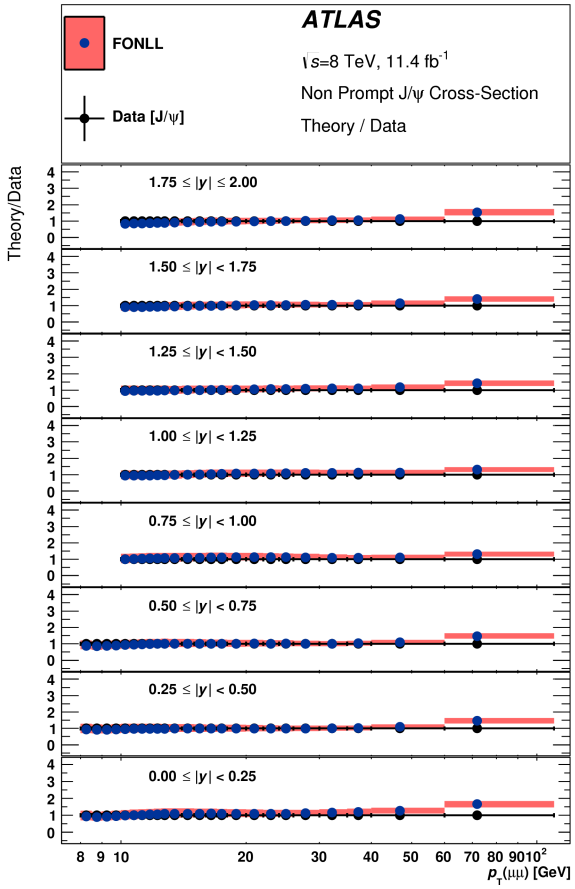
ATLAS: Eur. Phys. J. C 76(5), 1, (2016)

extend previous measurements to higher p_T and cm energies

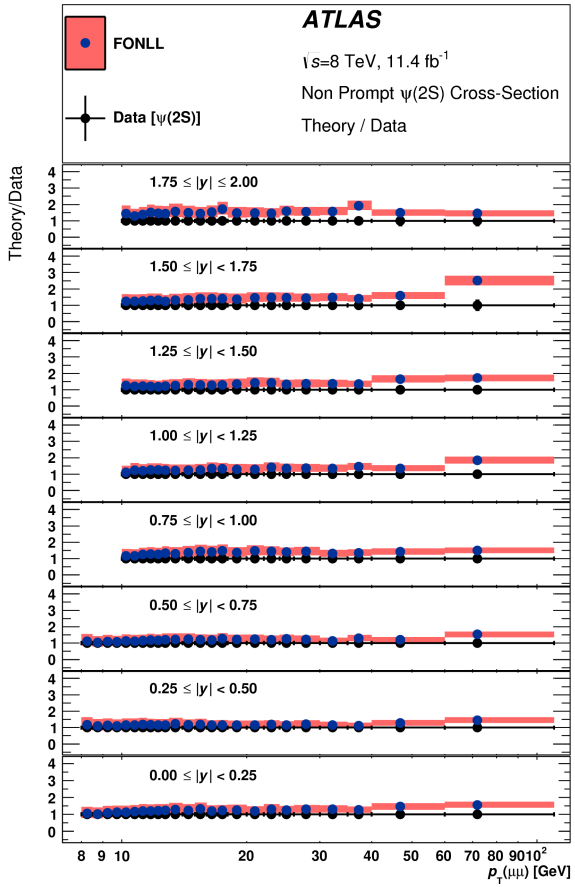
J/Ψ generally good agreement with FONLL, FONLL tends to predict larger R_{87}

Ψ(2S) FONLL tends to be too high

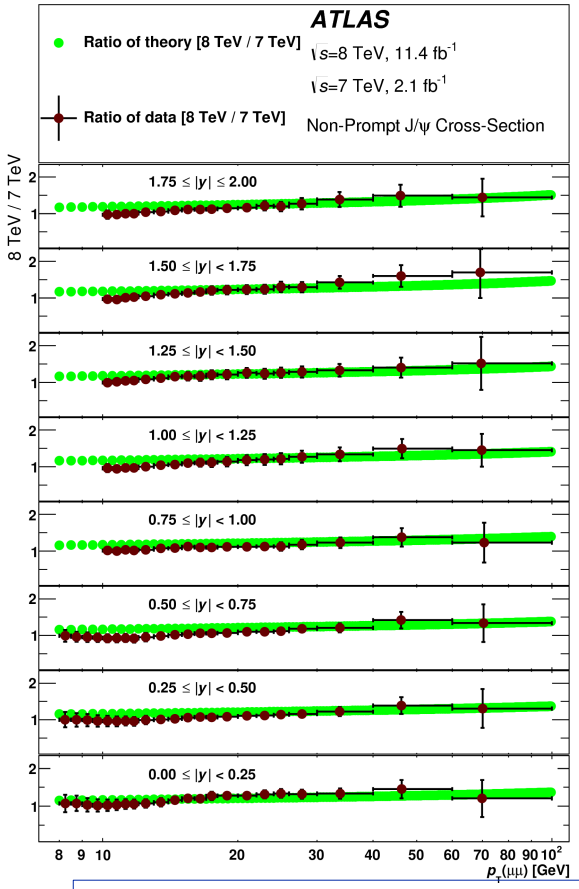
J/Ψ



Ψ(2S)



J/Ψ :R_{87}

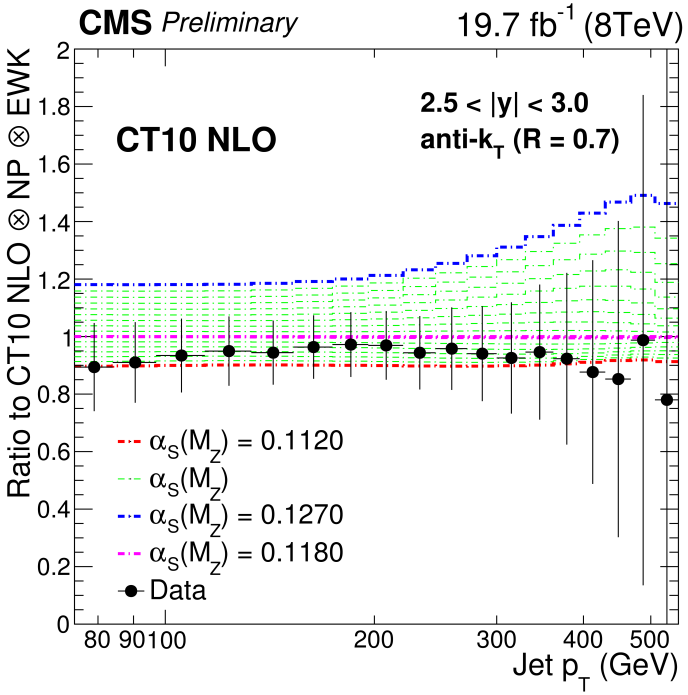


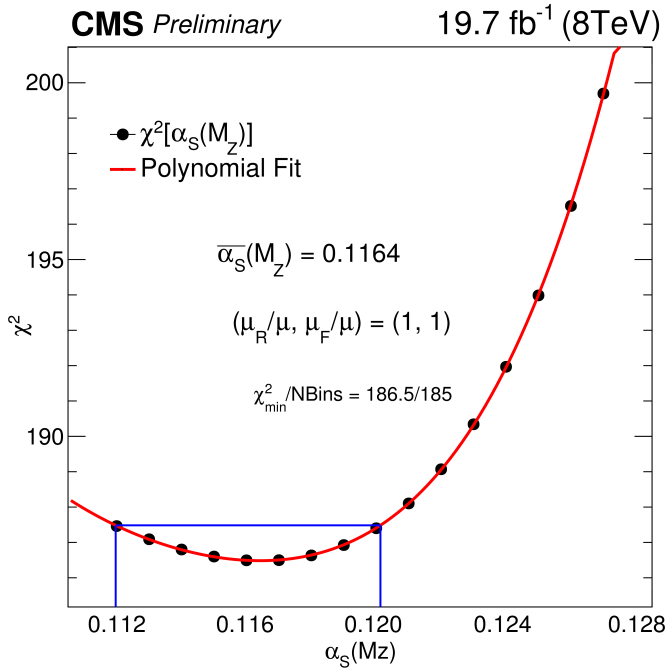
Talk: Roger Jones,Gabriele Chiodini

Strong coupling constant

CMS-PAS-SMP-14-001

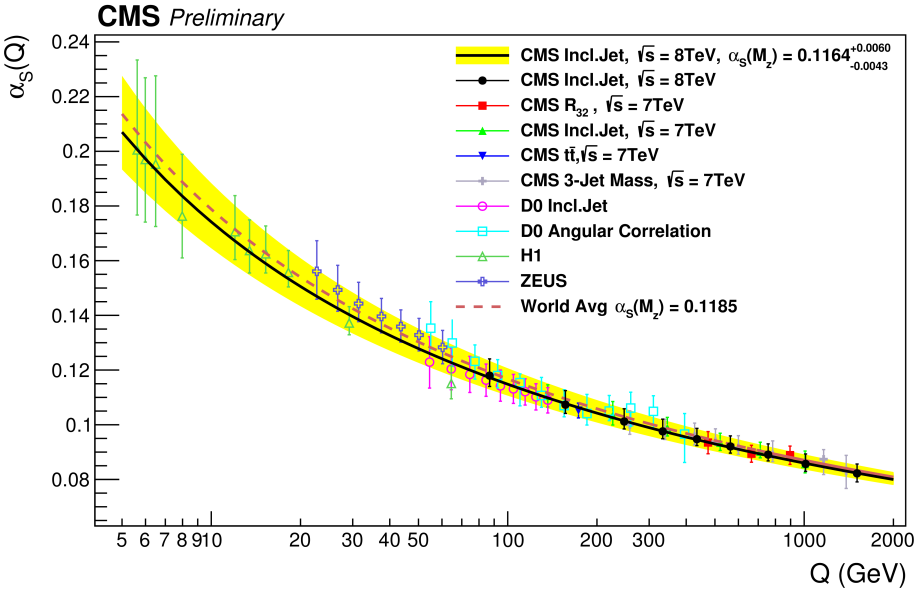
from CMS inclusive jet measurement at 8 TeV
theory recomputed with different $\alpha_s(M_Z)$ values
α_s determined by minimising chi² between data and NLO theory, using data from all rapidity bins



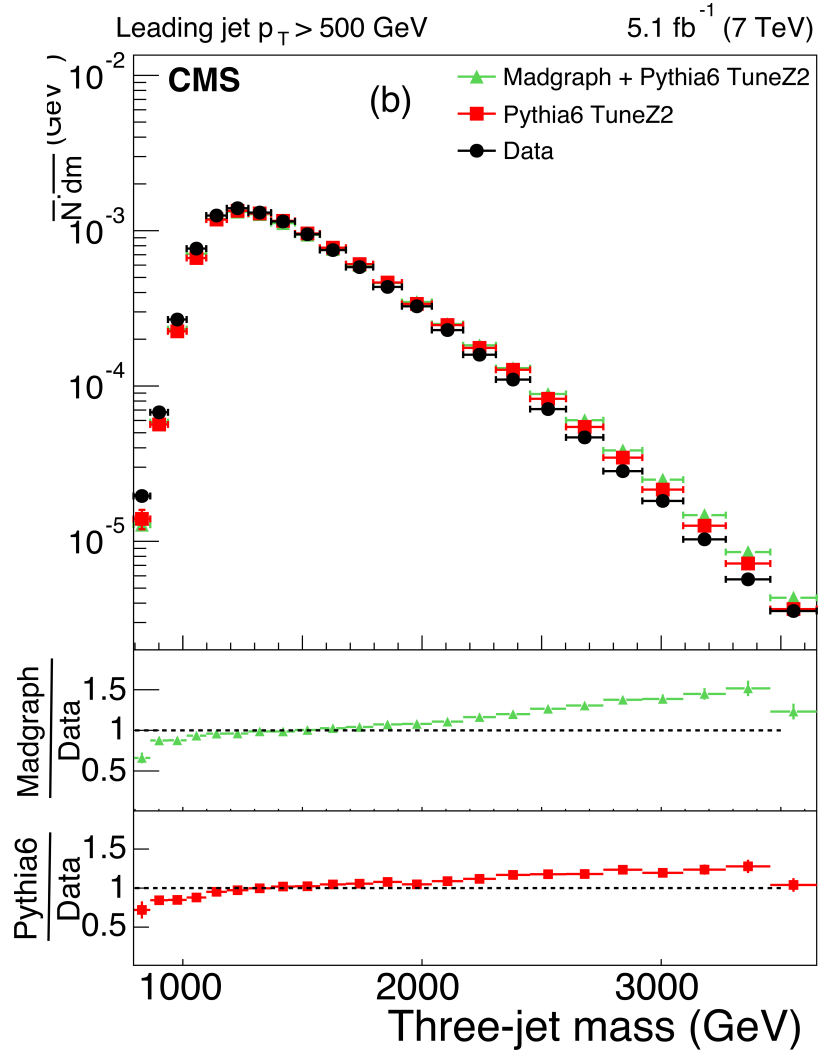


Strong coupling constant

CMS-PAS-SMP-14-001
CMS: Eur. Phys. J. C 75(2015) 302



Eur. Phys. J. C 75 (2015) 302



$\alpha_S(Q)$ evolution as determined from

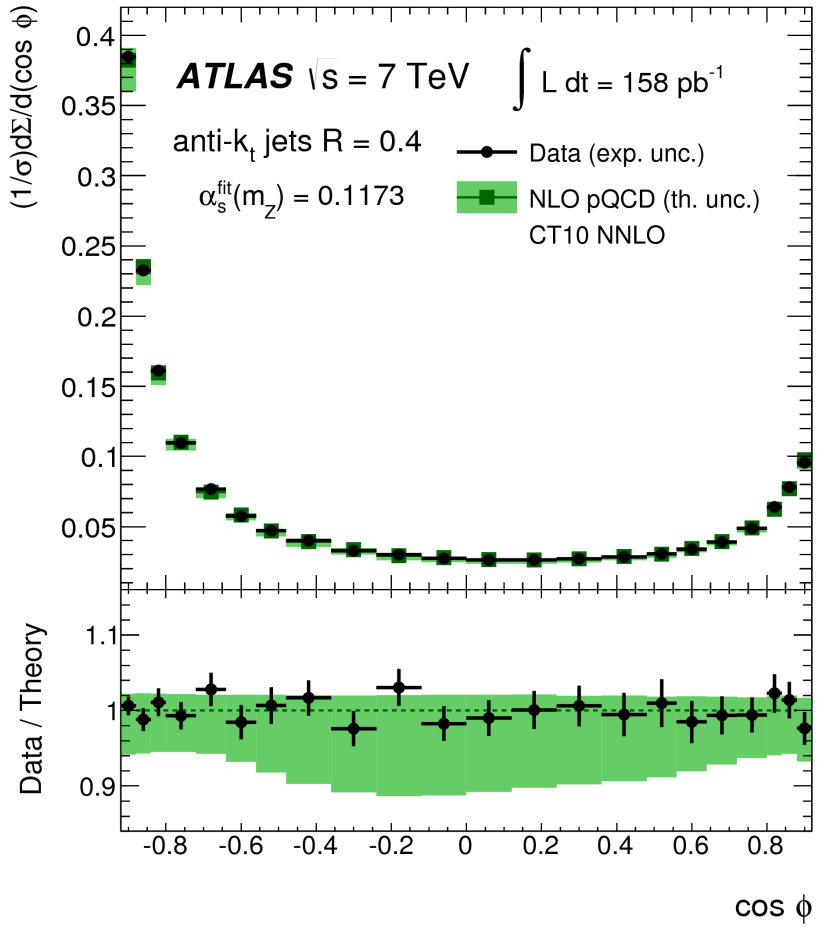
- inclusive jet analysis (7 and 8 TeV)
- R3/2 ratio of three jets over two jets events
- ttbar cross-section
- 3-jet mass

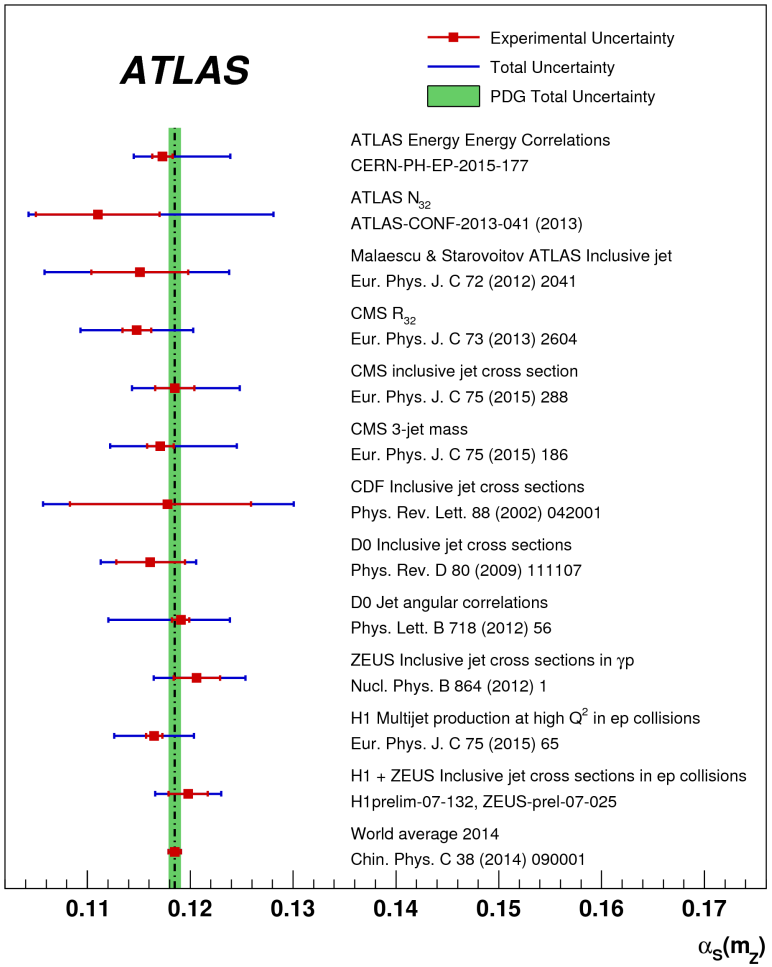
$$\alpha_S(M_Z) = 0.1164^{+0.0025}_{-0.0029}(PDF)^{+0.0053}_{-0.0028}(Scale) \pm 0.001(NP)^{+0.0014}_{-0.0015}(\exp)$$

Strong coupling constant

ATLAS Physics Letters B 750 (2015) 427-447

transverse energy-energy correlations





$$\alpha_S(M_Z) = 0.1173 \pm 0.0017(PDF)^{+0.0063}_{-0.0020}(Scale) \pm 0.002(NP) \pm 0.0010(\exp)$$

→ theoretical uncertainties dominating