Review of nuclear PDFs

Ingo Schienbein
Université Grenoble Alpes/LPSC Grenoble

UNIVERSITÉ
Grenoble
Alpes

Laboratoire de Physique
Subatomique et de Cosmologie

CPTGA meeting “Heavy Flavour Issues at the LHC”
LPSC Grenoble, September 26, 2017

Current status in a nutshell

Available nuclear PDFs

- EPPS'16 (supersedes EPS'09)
  Eskola, Paakkinen, Paukkunen, Salgado, arXiv:1612.0574

NEW

- nCTEQ'15
  nCTEQ collaboration, PRD93(2016)085037, arXiv:1509.00792

- DSSZ'11
  de Florian, Sassot, Stratmann, Zurita, PRD85(2012)074028, arXiv:1509.00792

- HKN'07
  Hirai, Kumano, Nagai, PRC76(2007)065207, arXiv:0709.3038

- AT'12
  Atashbar Tehrani, PRC86(2012)064301

- KA'15
  Khanpour, Atashbar Tehrani, PRD93(2016)014026, arXiv:1601.00939

Available nuclear PDFs

- EPPS'16 (supersedes EPS'09)
  Eskola, Paakkinen, Paukkunen, Salgado, arXiv:1612.0574

- nCTEQ'15
  nCTEQ collaboration, PRD93(2016)085037, arXiv:1509.00792

- DSSZ'11
  de Florian, Sassot, Stratmann, Zurita, PRD85(2012)074028, arXiv:1509.00792

- HKN'07
  Hirai, Kumano, Nagai, PRC76(2007)065207, arXiv:0709.3038

- AT'12
  Atashbar Tehrani, PRC86(2012)064301

- KA'15
  Khanpour, Atashbar Tehrani, PRD93(2016)014026, arXiv:1601.00939

Main differences

- **Used data sets**

  - **charged lepton-nucleus DIS, pA DY**: All groups (but **different cuts!**) (EPPS'16 uses also π-A DY data)

  - **RHIC single pion production**: EPPS'16, nCTEQ'15, DSSZ'11 (EPPS now with weigth = 1; DSSZ includes nuclear corrections to FFs)

  - **neutrino-Pb DIS** (CHORUS): EPPS'16

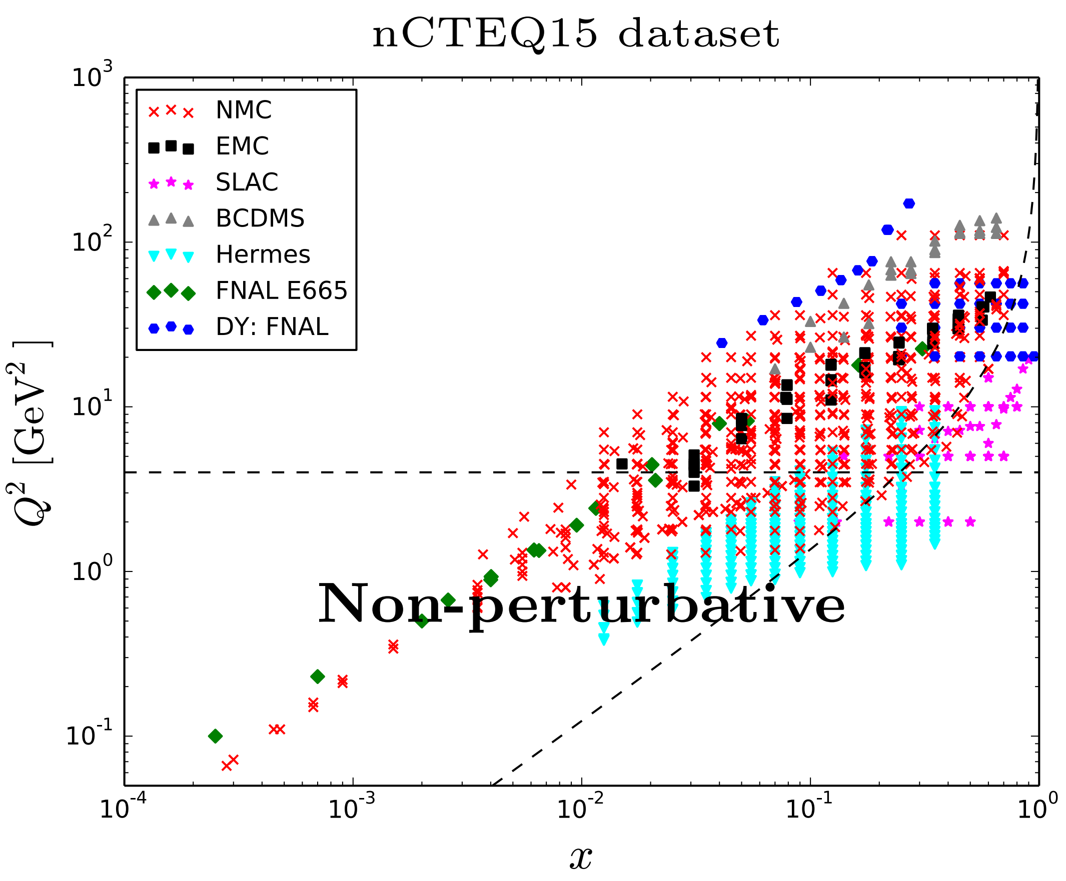
  - **LHC data** (dijet production, W/Z production): EPPS'16

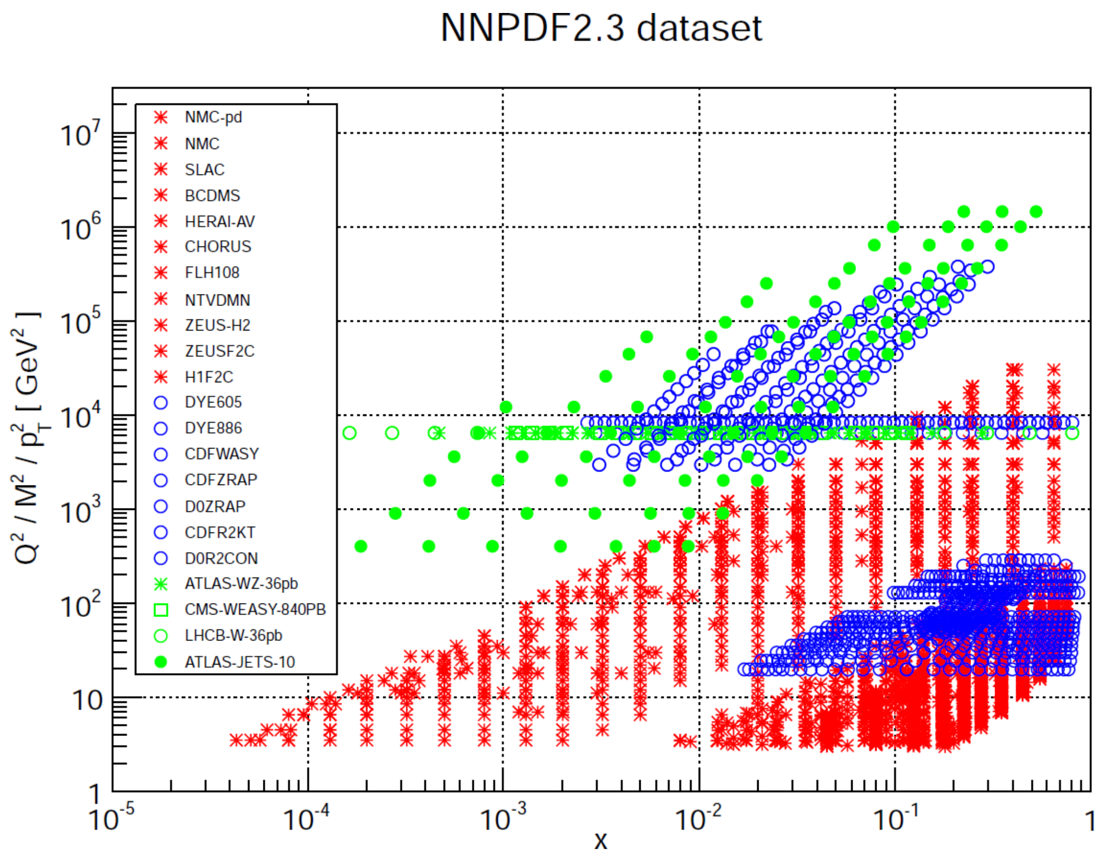
Main differences

- **Used data sets**
  - **charged lepton-nucleus DIS, pA DY**: All groups (but **different cuts!**) (EPPS'16 uses also π-A DY data)
  - **RHIC single pion production**: EPPS'16, nCTEQ'15, DSSZ'11 (EPPS now with weigth = 1; DSSZ includes nuclear corrections to FFs)
  - **neutrino-Pb DIS** (CHORUS): EPPS'16
  - **LHC data** (dijet production, W/Z production): EPPS'16
- **Parametrization**
  - Multiplicative nuclear correction factors: EPPS'16, DSSZ'11, HKN'07, AT'12, KA'15 (requires proton baseline, parametrization can be quite complicated)
  - Native nuclear PDFs (same treatment as proton PDFs): nCTEQ'16

Main differences with free-proton PDFs

- Theoretical status of factorization
- Parametrization: more parameters to model A-dependence
- Less data constraints, much(!) smaller kinematic coverage





- Less data constraints → more **assumptions** about input PDFs
- Assumptions "hide" uncertainties!

EPPS'16 framework: Data

- DIS cut: Q > 1.3 GeV
- No cut on W
- Underlying assumption: structure function ratios less sensitive to higher twist and TMC

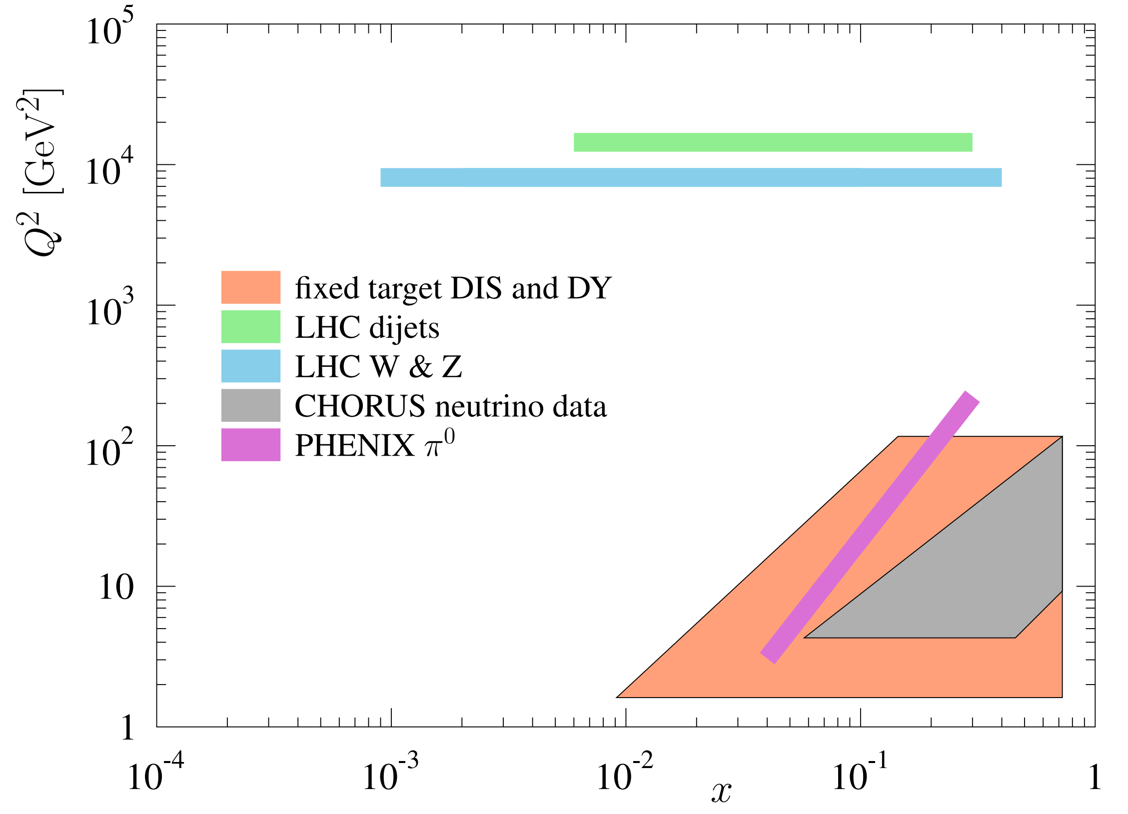
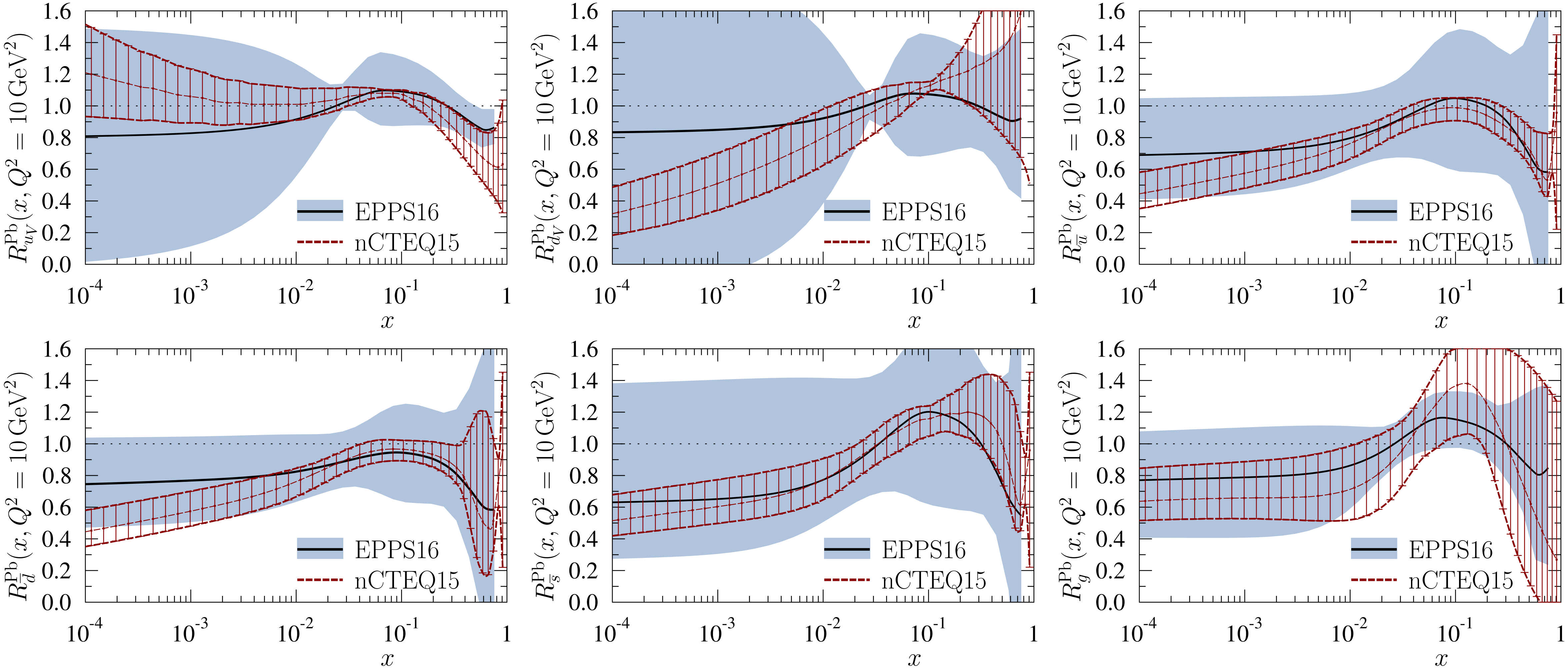


Fig. 2 The approximate regions in the (x, Q^2) plane at which different data in the EPPS16 fit probe the nuclear PDFs.

Experiment	Observable	Collisions	Data points	χ^2
SLAC E139	DIS	e^-He(4), e^-D	21	12.2
CERN NMC 95, re.	DIS	μ^-He(4), μ^-D	16	18.0
CERN NMC 95	DIS	μ^-Li(6), μ^-D	15	18.4
CERN NMC 95, Q^2 dep.	DIS	μ^-Li(6), μ^-D	153	161.2
SLAC E139	DIS	e^-Be(9), e^-D	20	12.9
CERN NMC 96	DIS	μ^-Be(9), μ^-C	15	4.4
SLAC E139	DIS	e^-C(12), e^-D	7	6.4
CERN NMC 95	DIS	μ^-C(12), μ^-D	15	9.0
CERN NMC 95, Q^2 dep.	DIS	μ^-C(12), μ^-D	165	133.6
CERN NMC 95, re.	DIS	μ^-C(12), μ^-D	16	16.7
CERN NMC 95, re.	DIS	μ^-C(12), μ^-Li(6)	20	27.9
FNAL E772	DY	pC(12), pD	9	11.3
SLAC E139	DIS	e^-Al(27), e^-D	20	13.7
CERN NMC 96	DIS	μ^-Al(27), μ^-C(12)	15	5.6
SLAC E139	DIS	e^-Ca(40), e^-D	7	4.8
FNAL E772	DY	pCa(40), pD	9	3.33
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-D	15	27.6
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-Li(6)	20	19.5
CERN NMC 96	DIS	μ^-Ca(40), μ^-C(12)	15	6.4
SLAC E139	DIS	e^-Fe(56), e^-D	26	22.6
FNAL E772	DY	e^-Fe(56), e^-D	9	3.0
CERN NMC 96	DIS	μ^-Fe(56), μ^-C(12)	15	10.8
FNAL E866	DY	pFe(56), pBe(9)	28	20.1
CERN EMC	DIS	μ^-Cu(64), μ^-D	19	15.4
SLAC E139	DIS	e^-Ag(108), e^-D	7	8.0
CERN NMC 96	DIS	μ^-Sn(117), μ^-C(12)	15	12.5
CERN NMC 96, Q^2 dep.	DIS	μ^-Sn(117), μ^-C(12)	144	87.6
FNAL E772	DY	pW(184), pD	9	7.2
FNAL E866	DY	pW(184), pBe(9)	28	26.1
CERN NA10⋆	DY	π^-W(184), π^-D	10	11.6
FNAL E615⋆	DY	π^+W(184), π^-W(184)	11	10.2
CERN NA3⋆	DY	π^-Pt(195), π^-H	7	4.6
SLAC E139	DIS	e^-Au(197), e^-D	21	8.4
RHIC PHENIX	π^0	dAu(197), pp	20	6.9
CERN NMC 96	DIS	μ^-Pb(207), μ^-C(12)	15	4.1
CERN CMS⋆	W$^\pm$	pPb(208)	10	8.8
CERN CMS⋆	Z	pPb(208)	6	5.8
CERN ATLAS⋆	Z	pPb(208)	7	9.6
CERN CMS⋆	dijet	pPb(208)	7	5.5
CERN CHORUS⋆	DIS	νPb(208), $\bar{\nu}$Pb(208)	824	998.6
Total			1811	1789

EPPS’16 vs nCTEQ’15 @Q^2=10 GeV^2



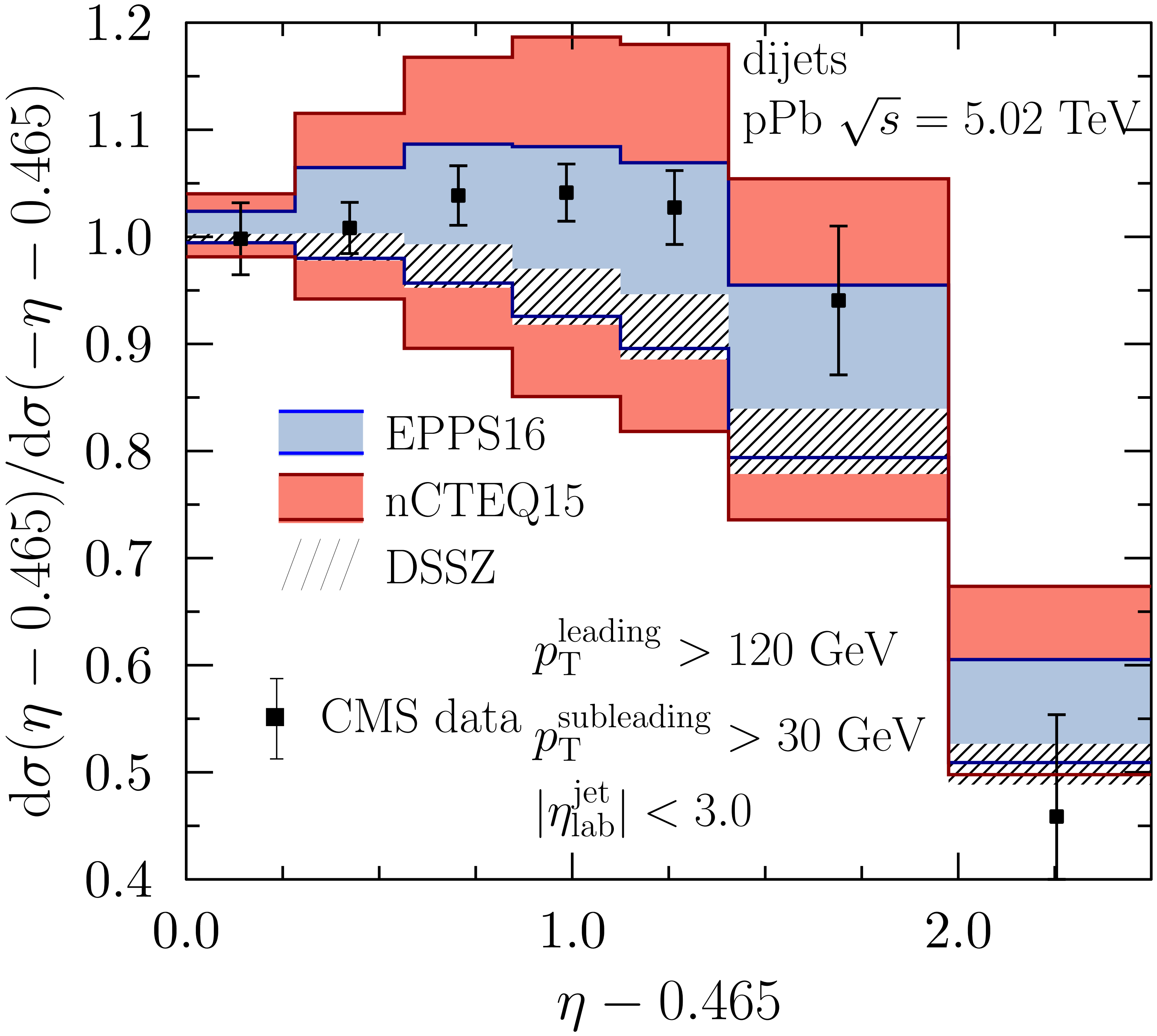
- Generally good agreement for x>0.01 (nCTEQ has no data constraints for x<0.01)
  $\Delta\chi^2 = 35$ (nCTEQ’15), $\Delta\chi^2 = 52$ (EPPS’16)

- Valence bands at large-x partly differ (valence at small-x <10^{-2} irrelevant); influence from CHORUS data?

- EPPS’16 bands for light sea more realistic; nCTEQ’15 has fewer fit parameters for sea

- Still quite some parametrization bias even for EPPS’16

Comparison with dijet data



- nCTEQ'15 in agreement with CMS data; including CMS dijet data in global analysis will help

- DSSZ gluon needs to be revised since not enough shadowed **OR** energy loss effects need to be included?

Conclusions I

- Paradox: The inclusion of LHC data allowed EPPS'16 to have a more flexible parametrization leading to much(!) larger uncertainty bands

- Even still regions where EPPS16 and nCTEQ15 bands don't overlap pointing to a systematic bias (mostly parametrization bias)

- Need more and more precise LHC pA data from as many hard processes as possible! Lead-only analysis possible!

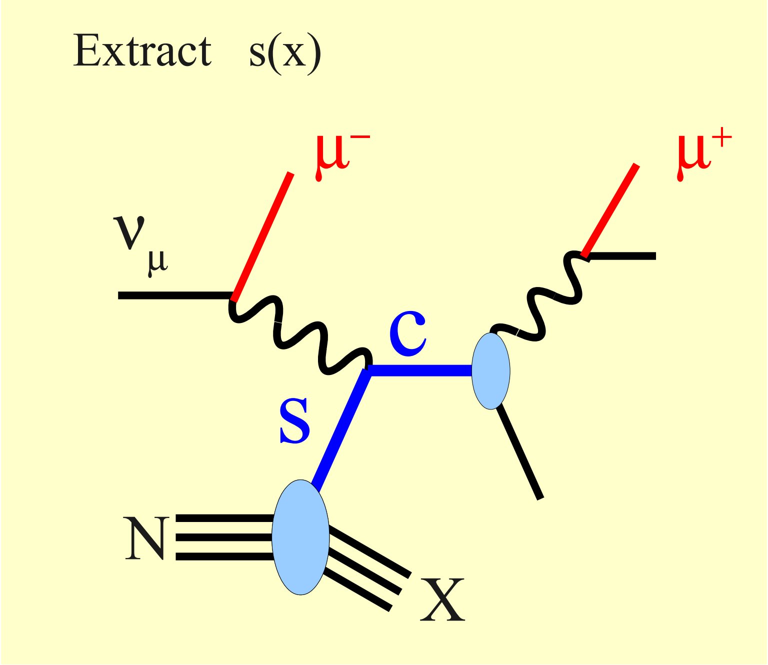
Vector boson production and the strange PDF

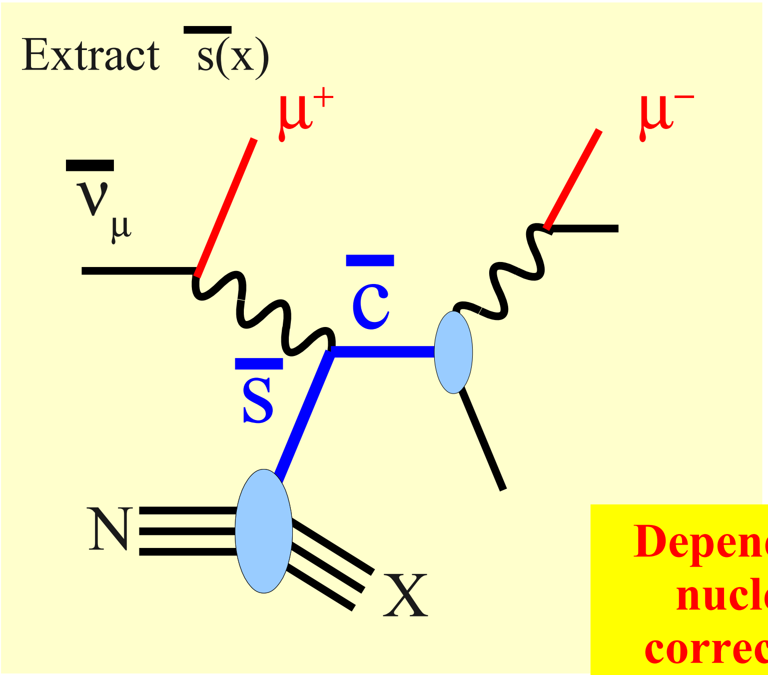
see nCTEQ analysis, arXiv:1610.02925

see also arXiv:1203.1290 for a discussion of experimental constraints on the strange PDF

Strange PDF: experimental constraints

Opposite sign dimuon production in neutrino DIS: $\nu N \rightarrow \mu^+ \mu^- X$



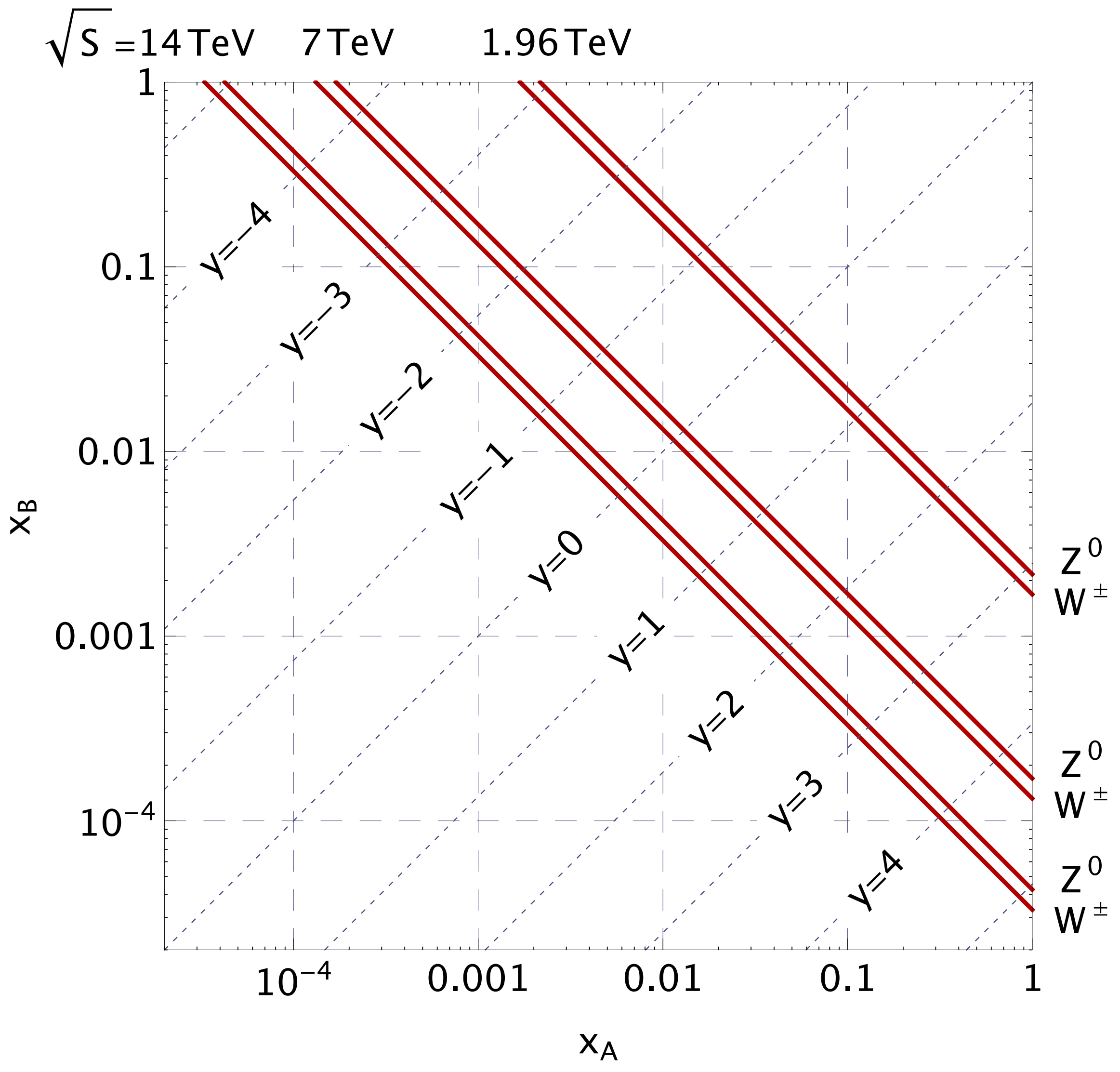


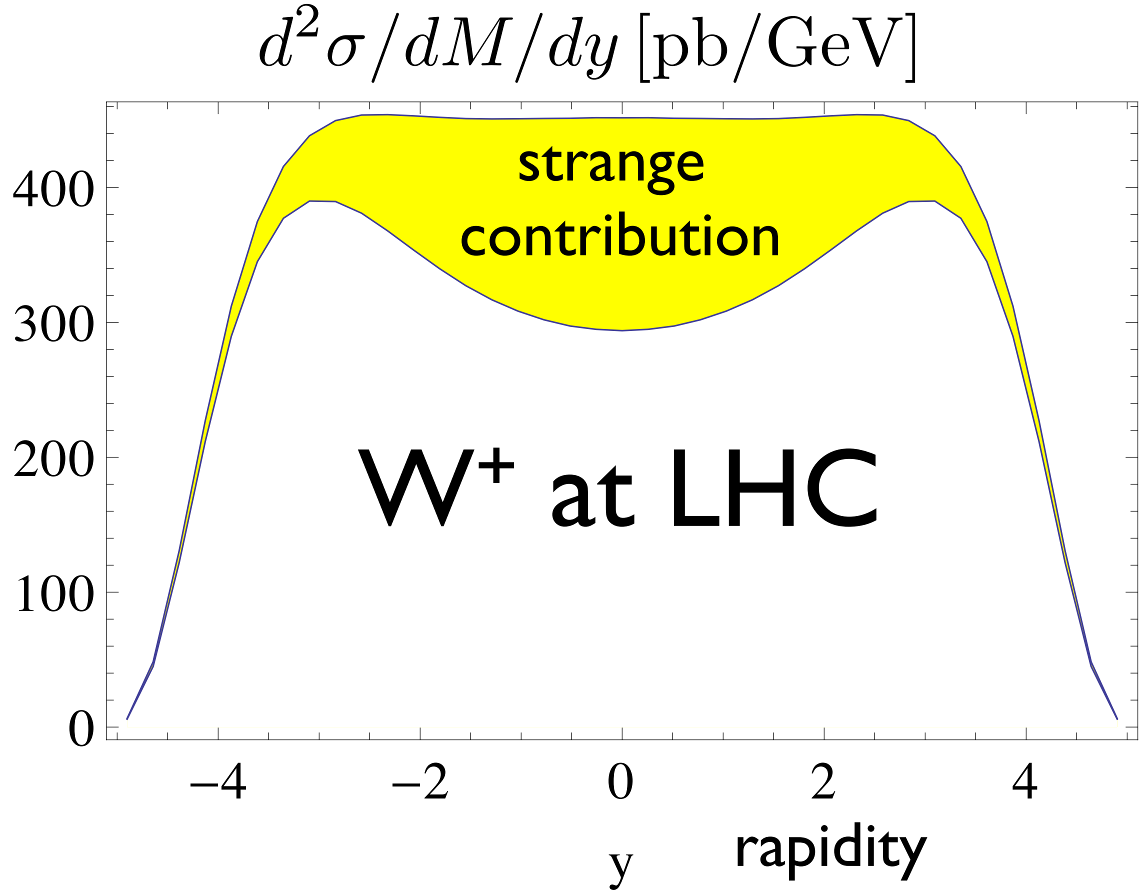
Depends on nuclear corrections

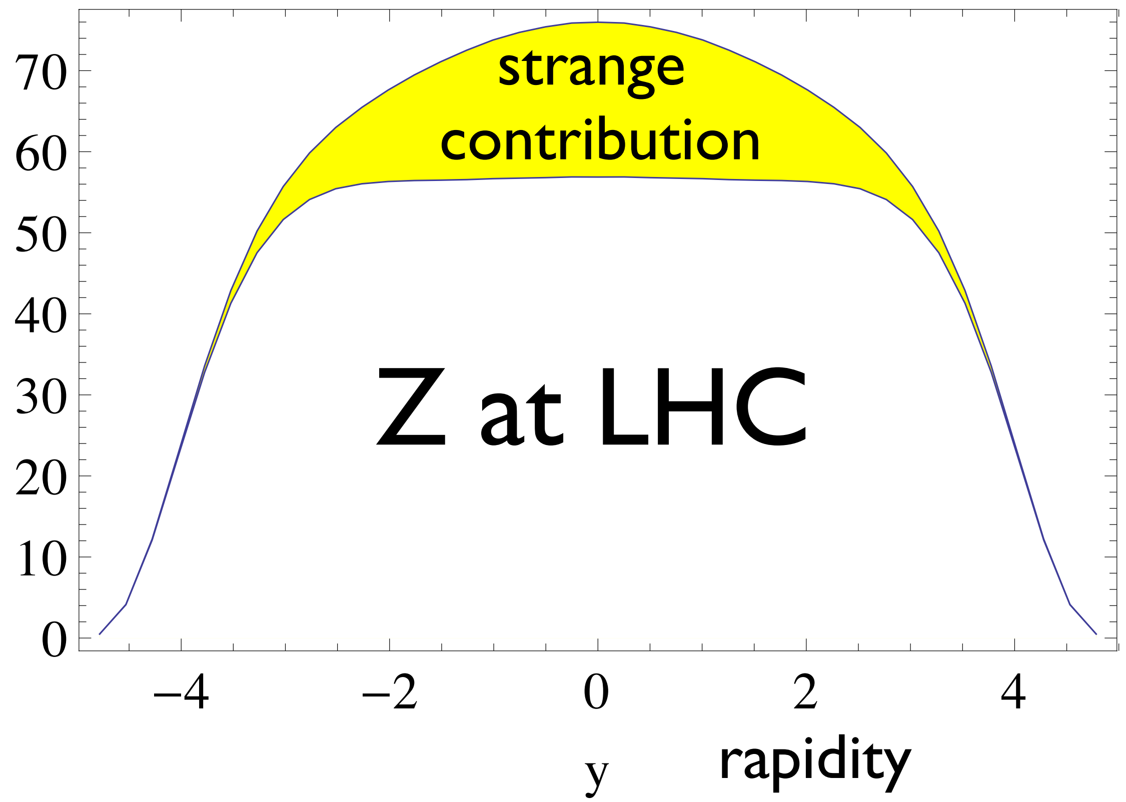
- High-statistics data from CCFR and NuTeV: **Main source** of information!
- x~[0.01,0.4]
- νFe DIS: need nuclear corrections! Problem: Final State Interactions (FSI)
- CHORUS (νPb): compatible with NuTeV, could be included
- NOMAD (νFe): data not yet published, in principle very interesting

Drell-Yan production of W/Z at the LHC

Kinematic plane





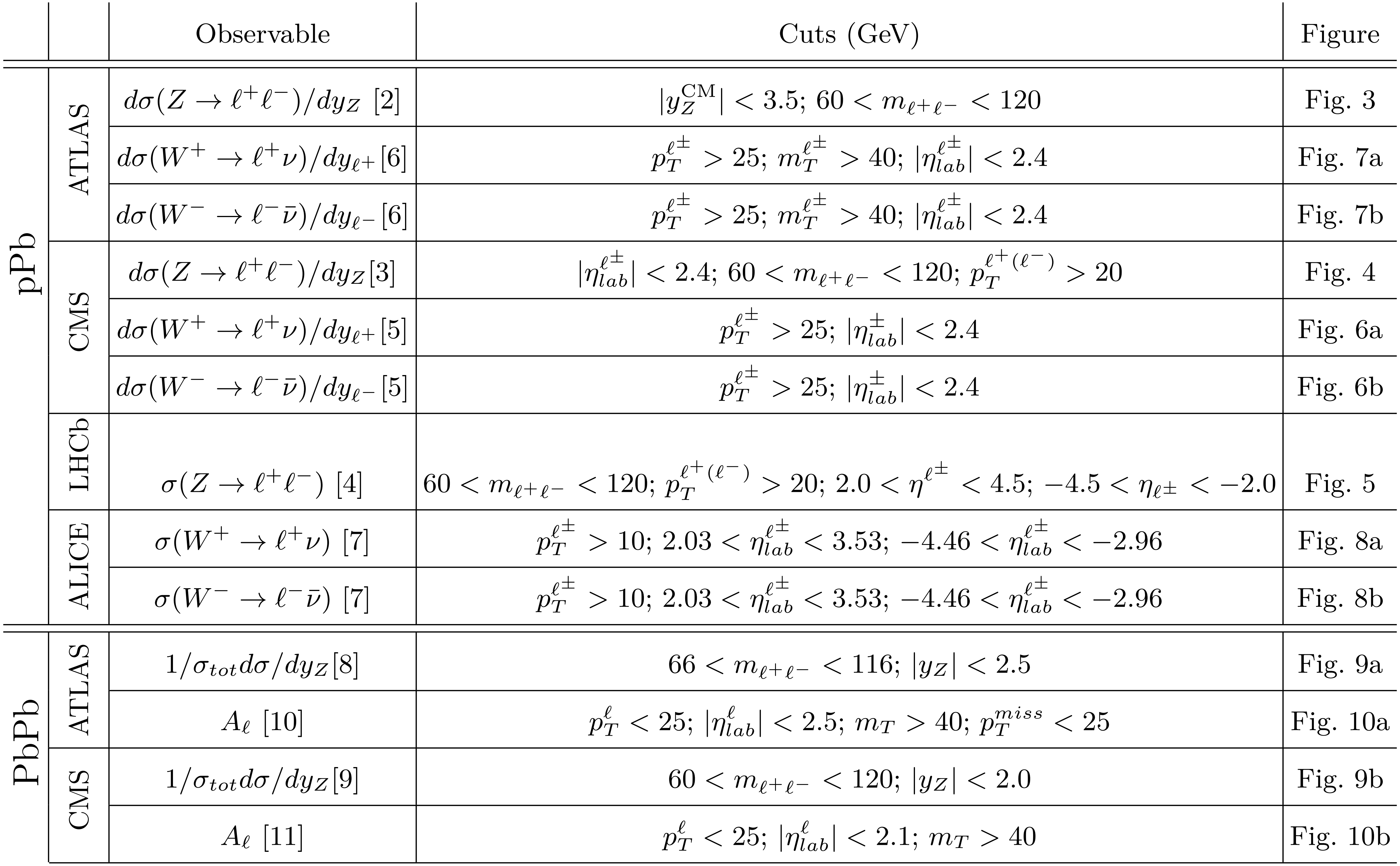


Uncertainty of strange-PDF will feed into benchmark process

VRAP code: Anastasiou, Dixon, Melnikov, Petriello, PRD69(2004)094008

nCTEQ study of W,Z production at LHC

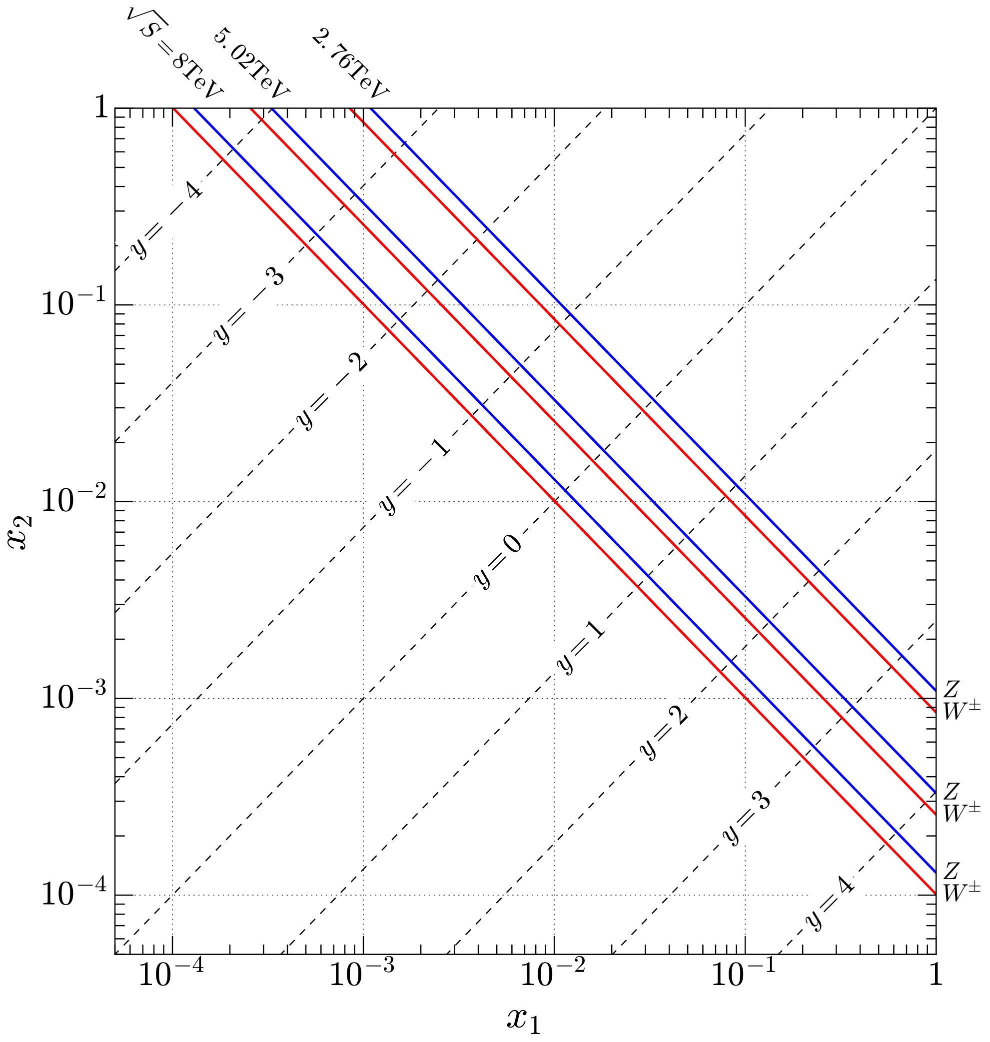
arXiv:1610.02925

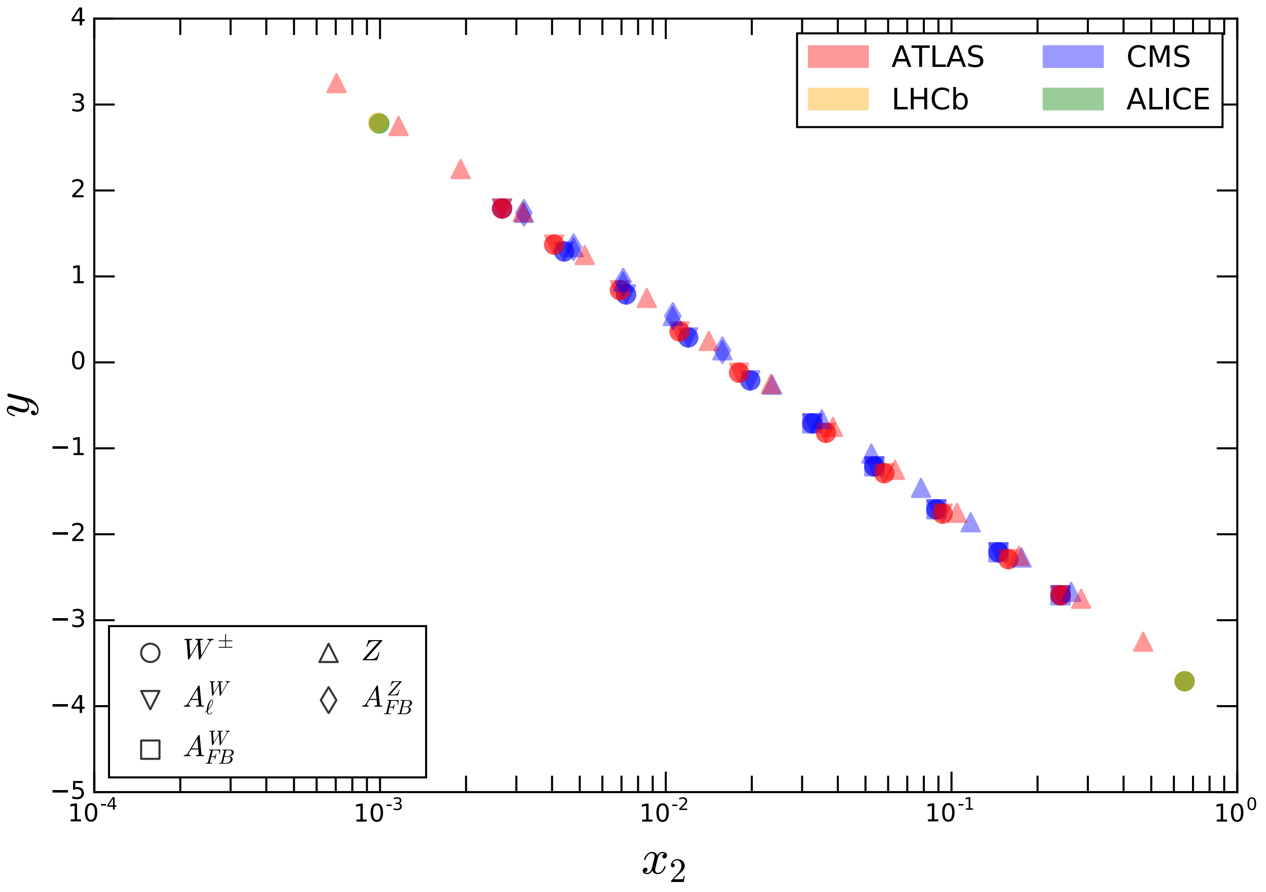


		Observable	Cuts (GeV)	Figure
pPb	ATLAS	$d\sigma(Z \to \ell^+\ell^-)/dy_Z$ [2]	$\lvert y_Z^{\rm CM}\rvert < 3.5$; $60 < m_{\ell^+\ell^-} < 120$	Fig. 3
		$d\sigma(W^+ \to \ell^+\nu)/dy_{\ell^+}$ [6]	$p_T^{\ell^\pm} > 25$; $m_T^{\ell^\pm} > 40$; $\lvert\eta_{lab}^{\ell^\pm}\rvert < 2.4$	Fig. 7a
		$d\sigma(W^- \to \ell^-\bar{\nu})/dy_{\ell^-}$ [6]	$p_T^{\ell^\pm} > 25$; $m_T^{\ell^\pm} > 40$; $\lvert\eta_{lab}^{\ell^\pm}\rvert < 2.4$	Fig. 7b
	CMS	$d\sigma(Z \to \ell^+\ell^-)/dy_Z$ [3]	$\lvert\eta_{lab}^{\ell^\pm}\rvert < 2.4$; $60 < m_{\ell^+\ell^-} < 120$; $p_T^{\ell^+(\ell^-)} > 20$	Fig. 4
		$d\sigma(W^+ \to \ell^+\nu)/dy_{\ell^+}$ [5]	$p_T^{\ell^\pm} > 25$; $\lvert\eta_{lab}^{\pm}\rvert < 2.4$	Fig. 6a
		$d\sigma(W^- \to \ell^-\bar{\nu})/dy_{\ell^-}$ [5]	$p_T^{\ell^\pm} > 25$; $\lvert\eta_{lab}^{\pm}\rvert < 2.4$	Fig. 6b
	LHCb	$\sigma(Z \to \ell^+\ell^-)$ [4]	$60 < m_{\ell^+\ell^-} < 120$; $p_T^{\ell^+(\ell^-)} > 20$; $2.0 < \eta^{\ell^\pm} < 4.5$; $-4.5 < \eta_{\ell^\pm} < -2.0$	Fig. 5
	ALICE	$\sigma(W^+ \to \ell^+\nu)$ [7]	$p_T^{\ell^\pm} > 10$; $2.03 < \eta_{lab}^{\ell^\pm} < 3.53$; $-4.46 < \eta_{lab}^{\ell^\pm} < -2.96$	Fig. 8a
		$\sigma(W^- \to \ell^-\bar{\nu})$ [7]	$p_T^{\ell^\pm} > 10$; $2.03 < \eta_{lab}^{\ell^\pm} < 3.53$; $-4.46 < \eta_{lab}^{\ell^\pm} < -2.96$	Fig. 8b
PbPb	ATLAS	$1/\sigma_{tot} d\sigma/dy_Z$ [8]	$66 < m_{\ell^+\ell^-} < 116$; $\lvert y_Z\rvert < 2.5$	Fig. 9a
		A_ℓ [10]	$p_T^\ell < 25$; $\lvert\eta_{lab}^\ell\rvert < 2.5$; $m_T > 40$; $p_T^{miss} < 25$	Fig. 10a
	CMS	$1/\sigma_{tot} d\sigma/dy_Z$ [9]	$60 < m_{\ell^+\ell^-} < 120$; $\lvert y_Z\rvert < 2.0$	Fig. 9b
		A_ℓ [11]	$p_T^\ell < 25$; $\lvert\eta_{lab}^\ell\rvert < 2.1$; $m_T > 40$	Fig. 10b

Table I: LHC data sets considered in this analysis.

nCTEQ study of W,Z production at LHC



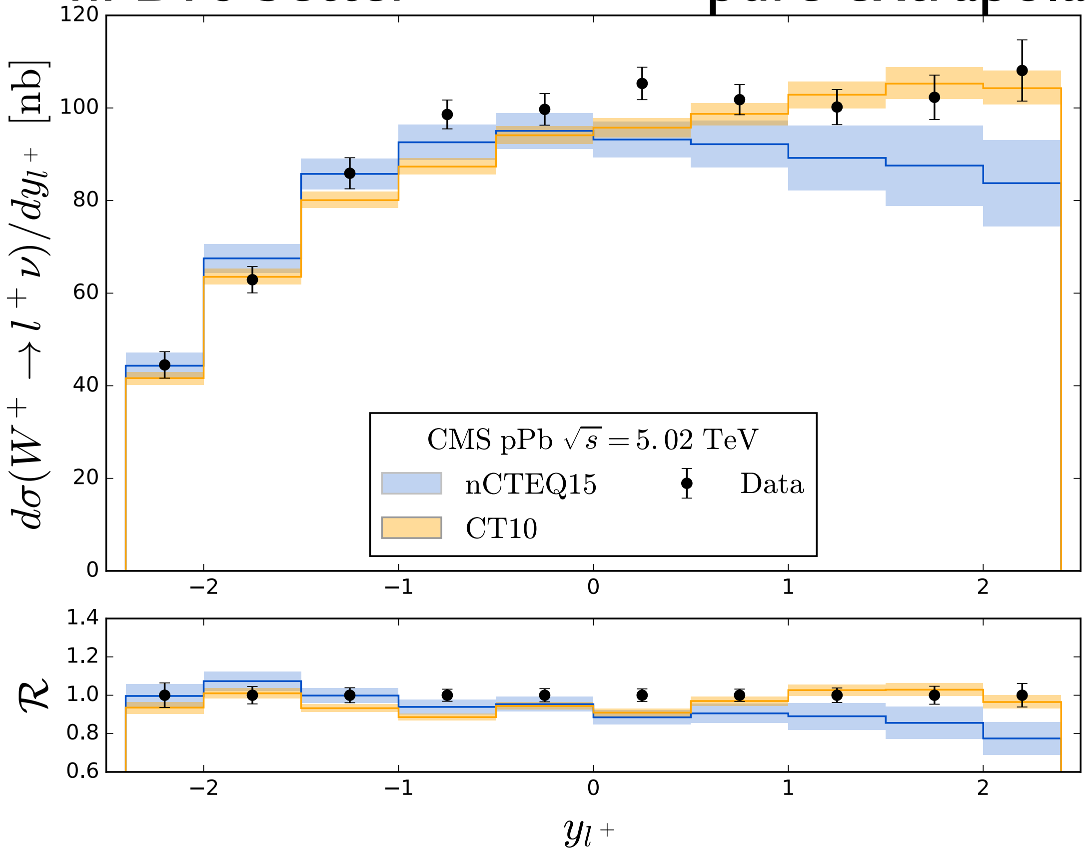


- y < -1: x > 5 x10^{-2} ... 0.3 (region where nPDFs are constrained by data in global analysis)

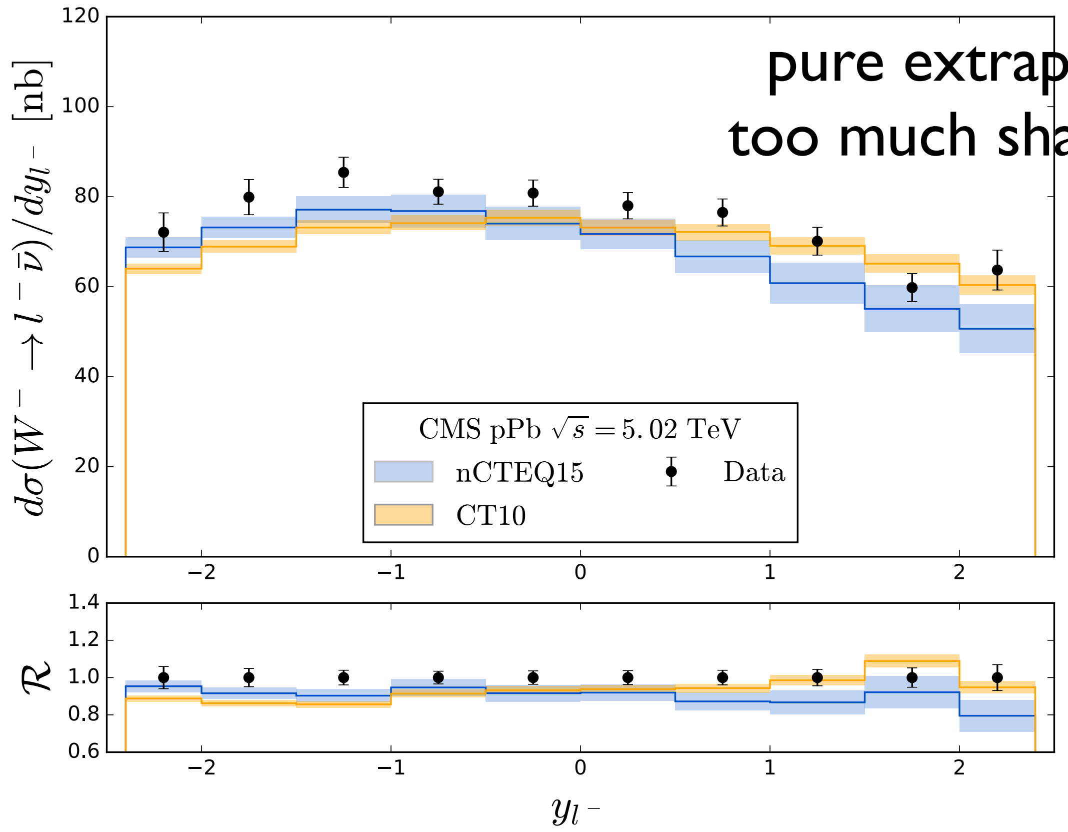
- |y| < 1: x ~ 10^{-2} (transition region from anti-shadowing to shadowing)

- y > 1: x < 5 x 10^{-3} (pure extrapolation!)

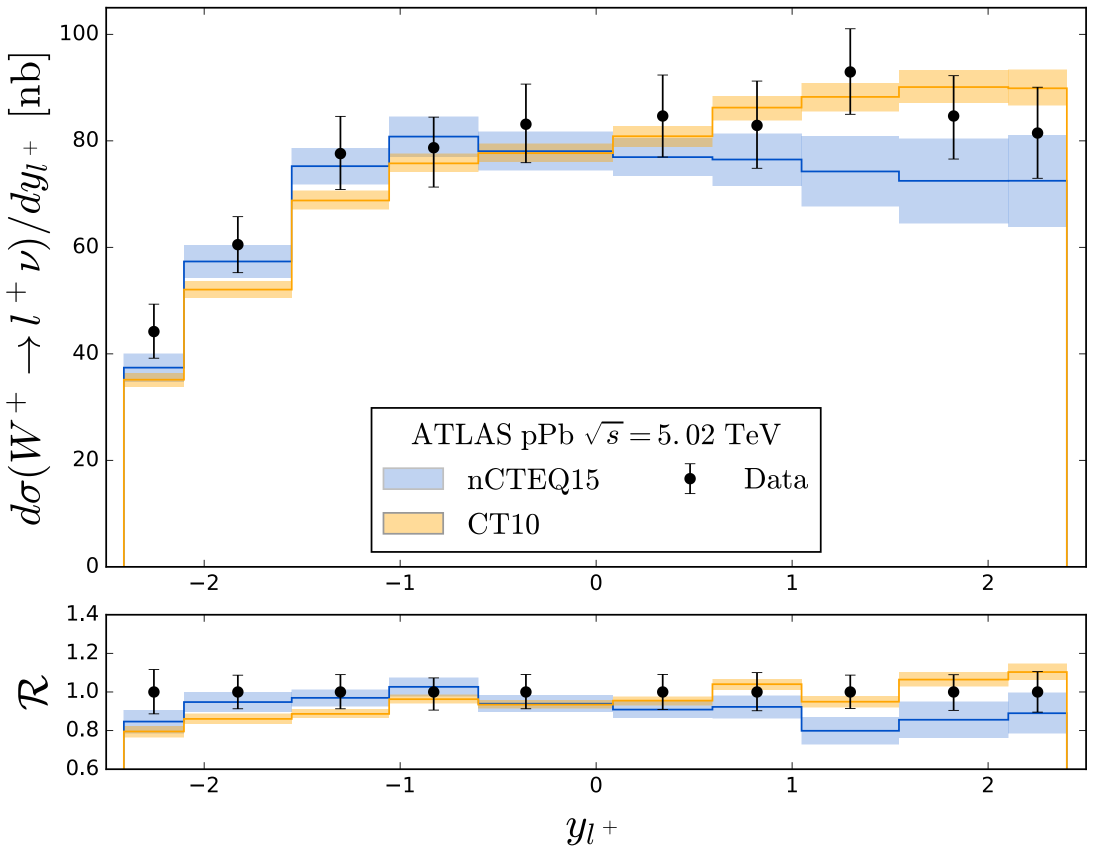
W-boson rapidity distributions


nPDFs better

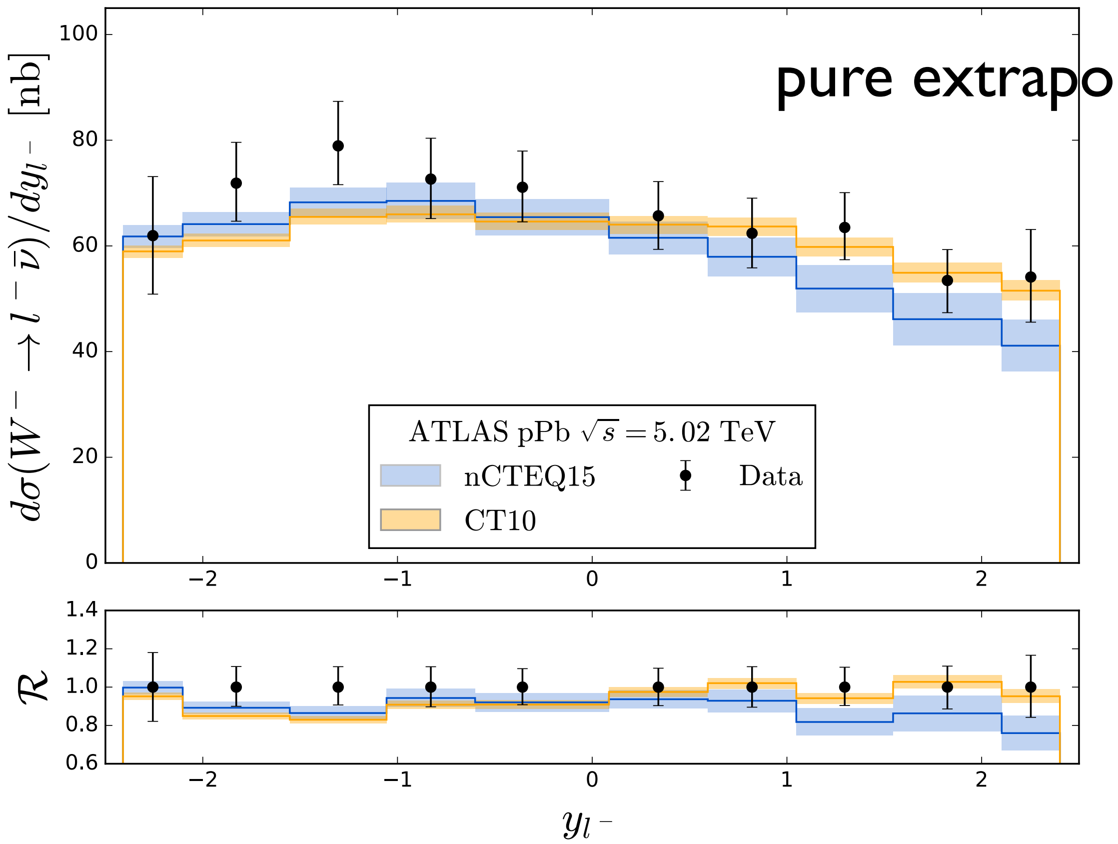
pure extrapolation


nPDFs better

pure extrapolation
too much shadowing?

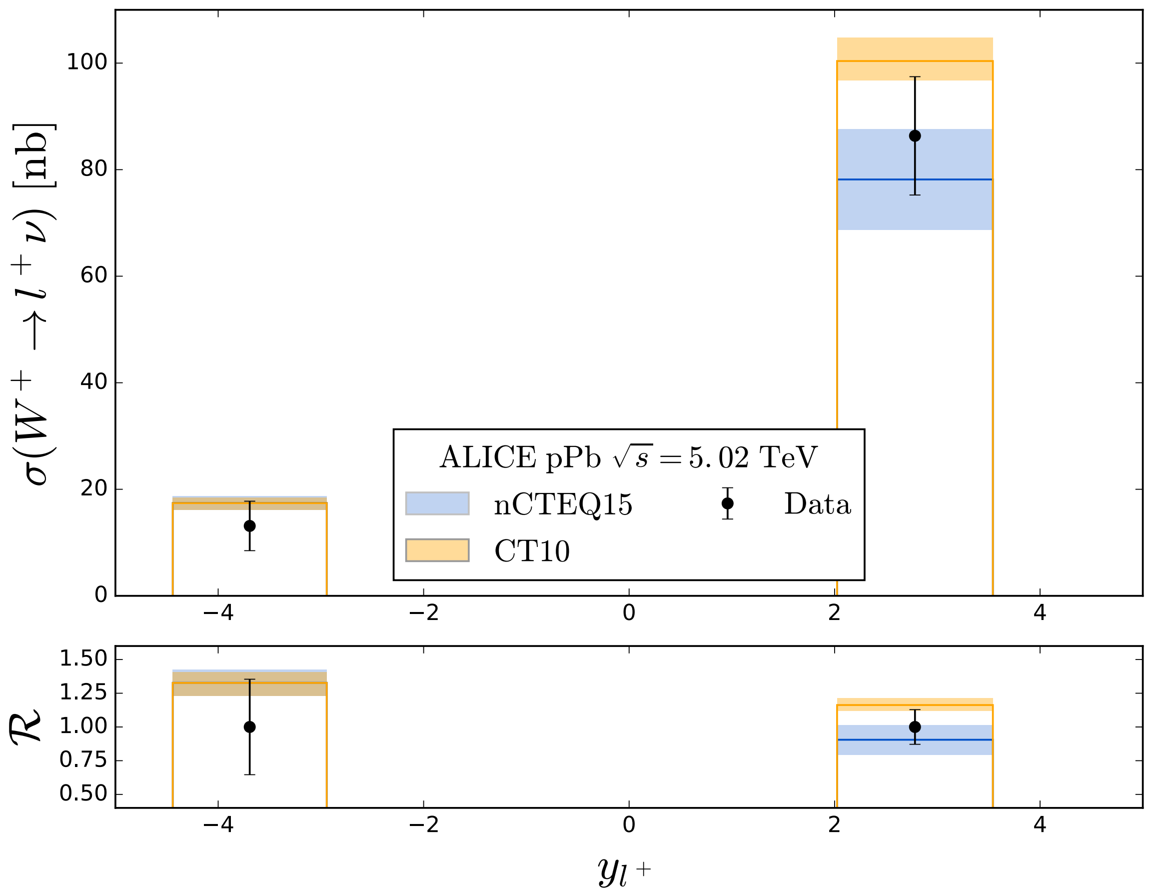

nPDFs better

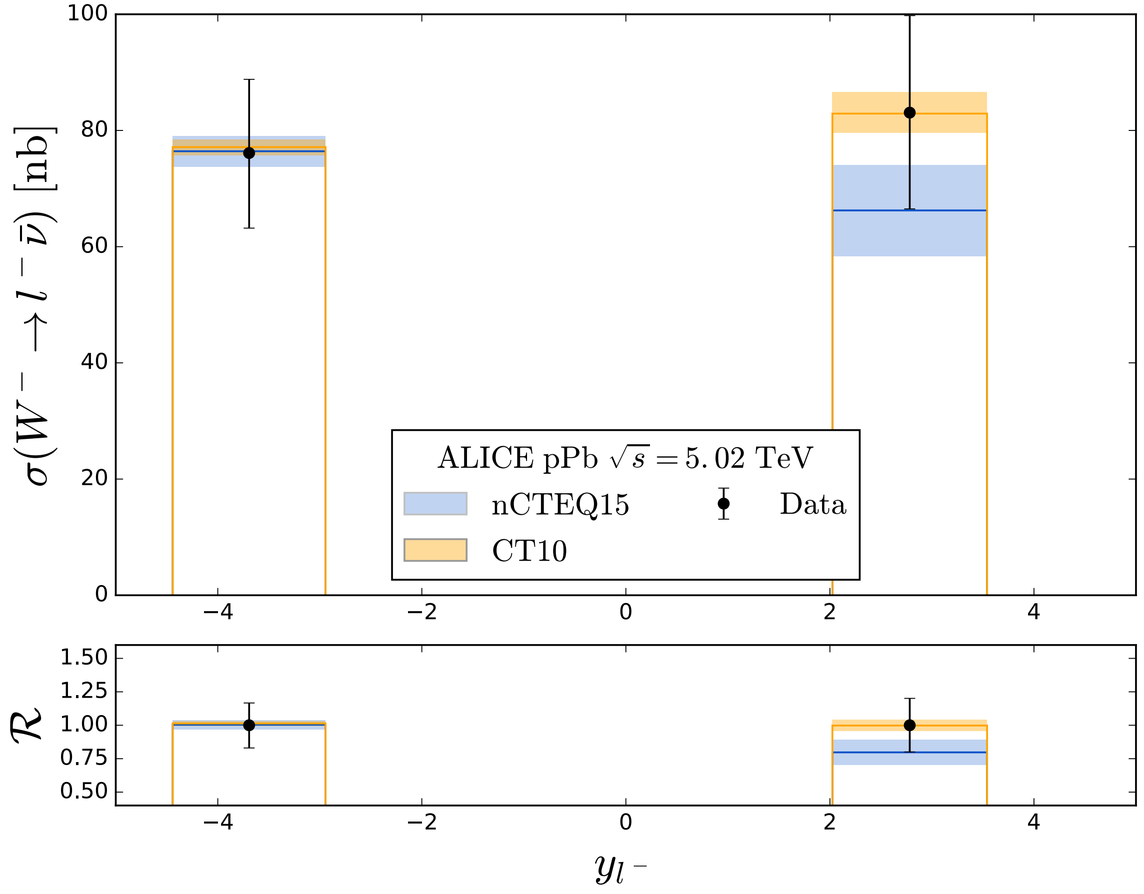
pure extrapolation


nPDFs better

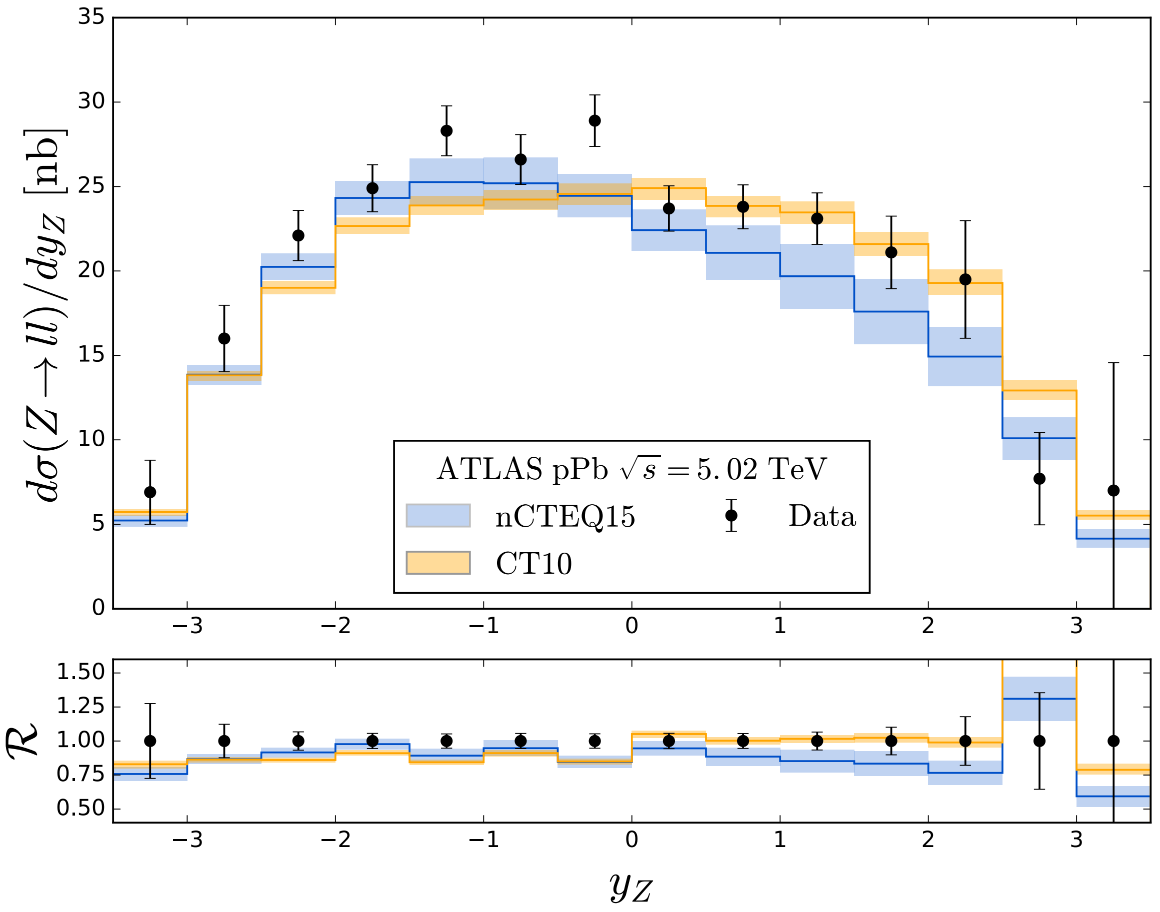
pure extrapolation

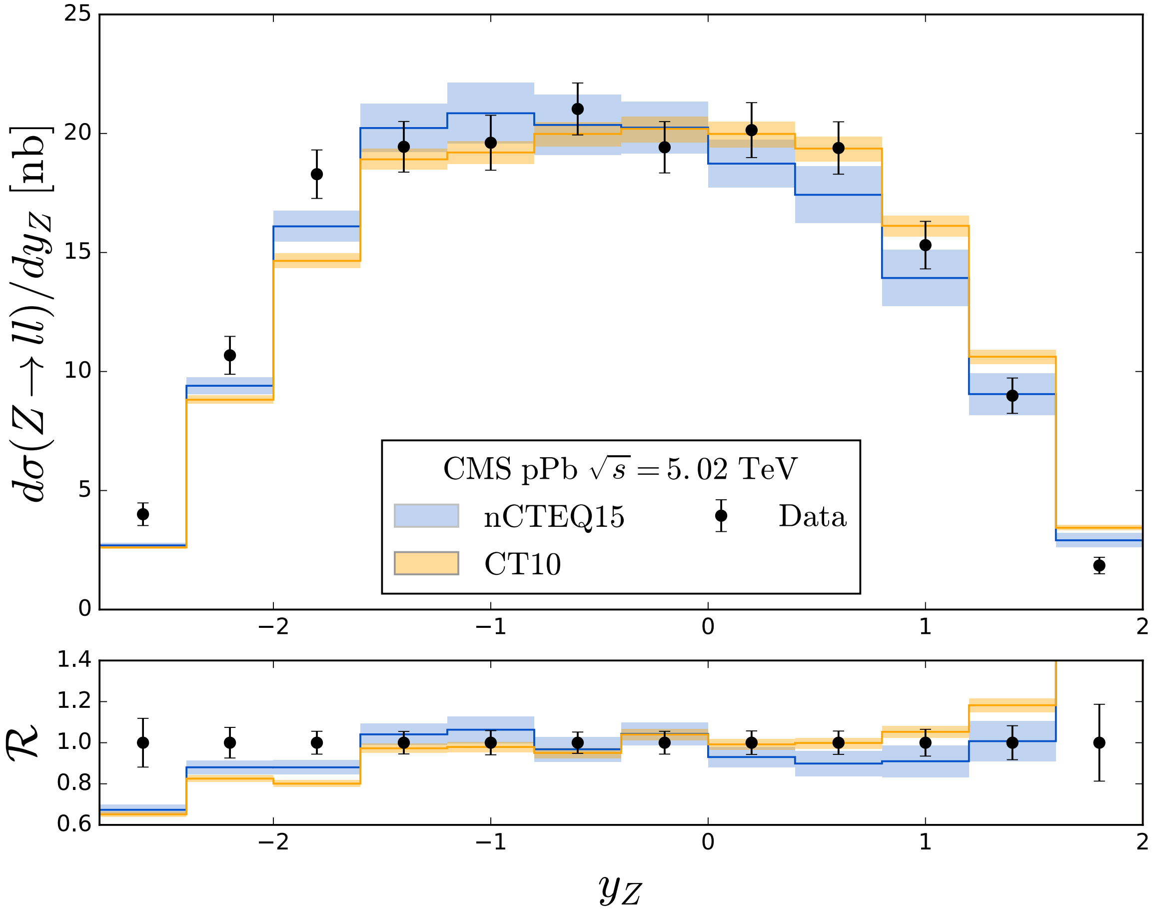
W-boson rapidity distributions from ALICE

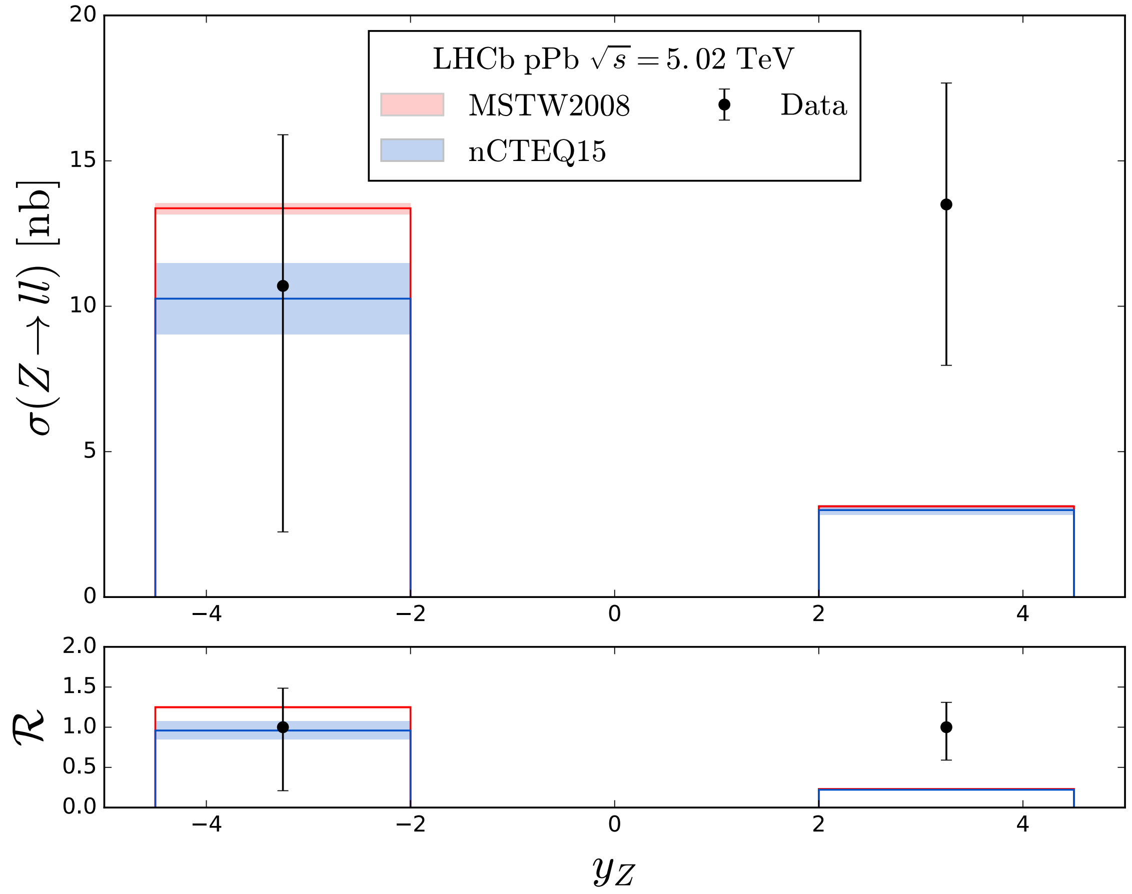




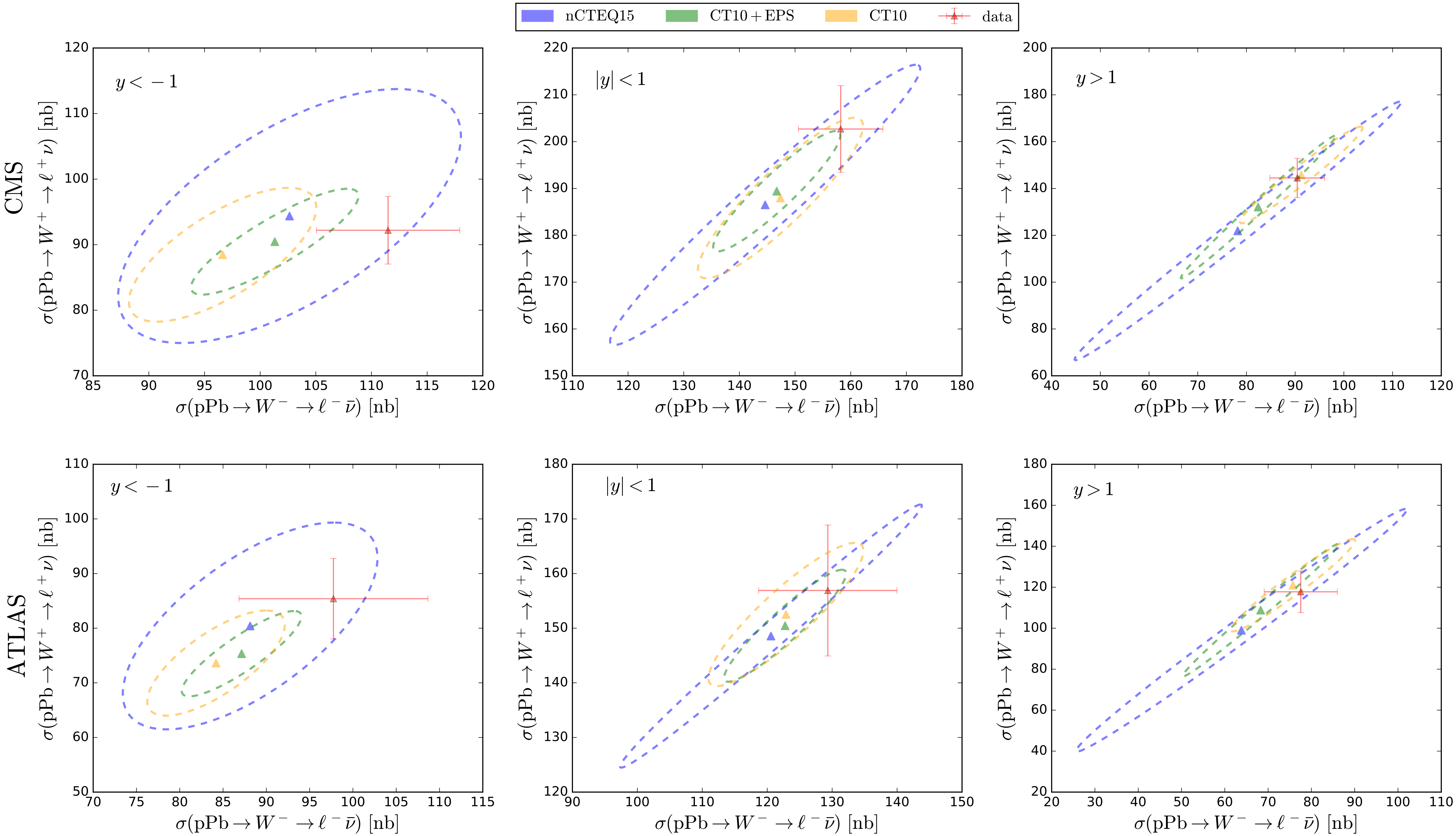
Z-boson rapidity distributions



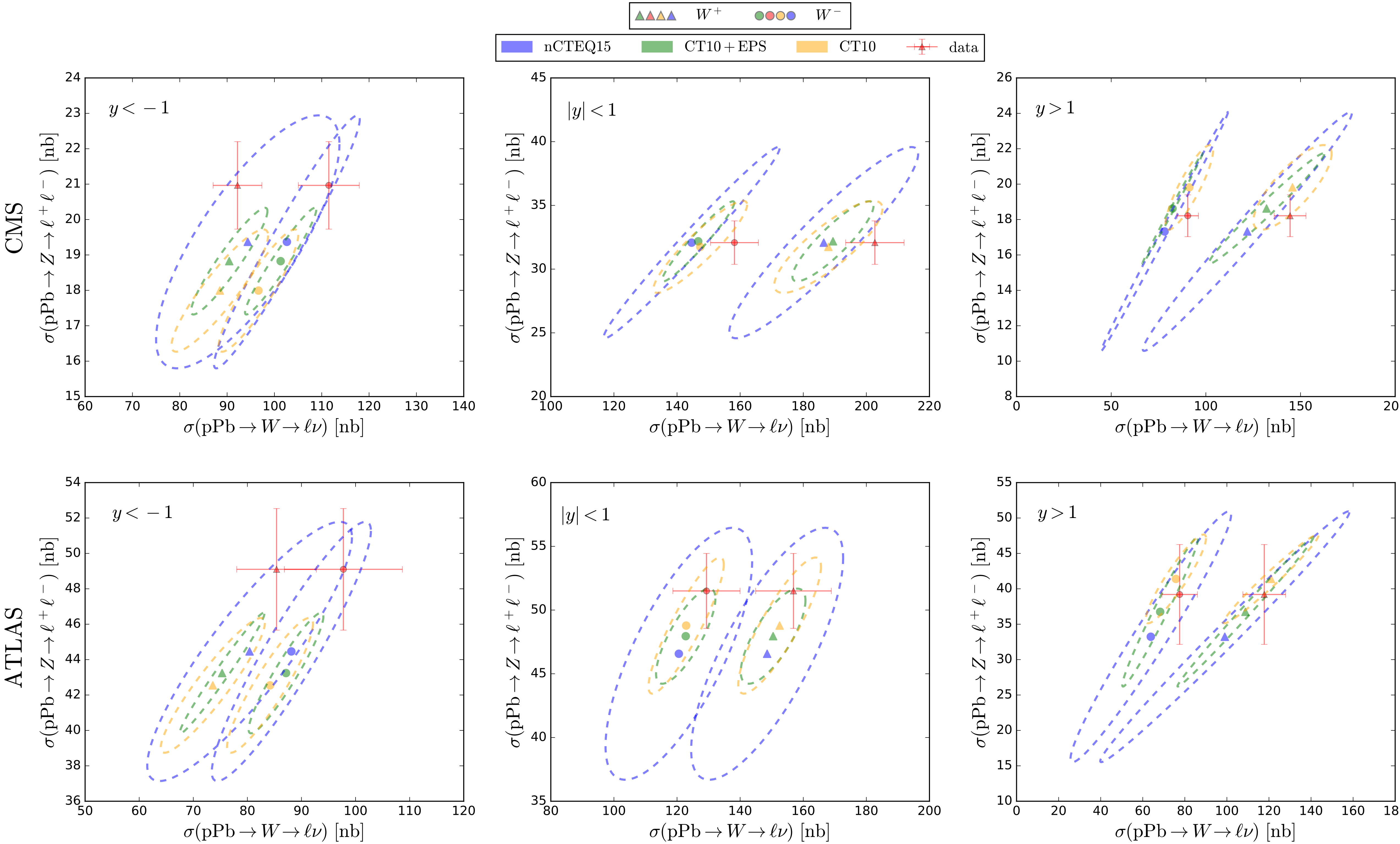




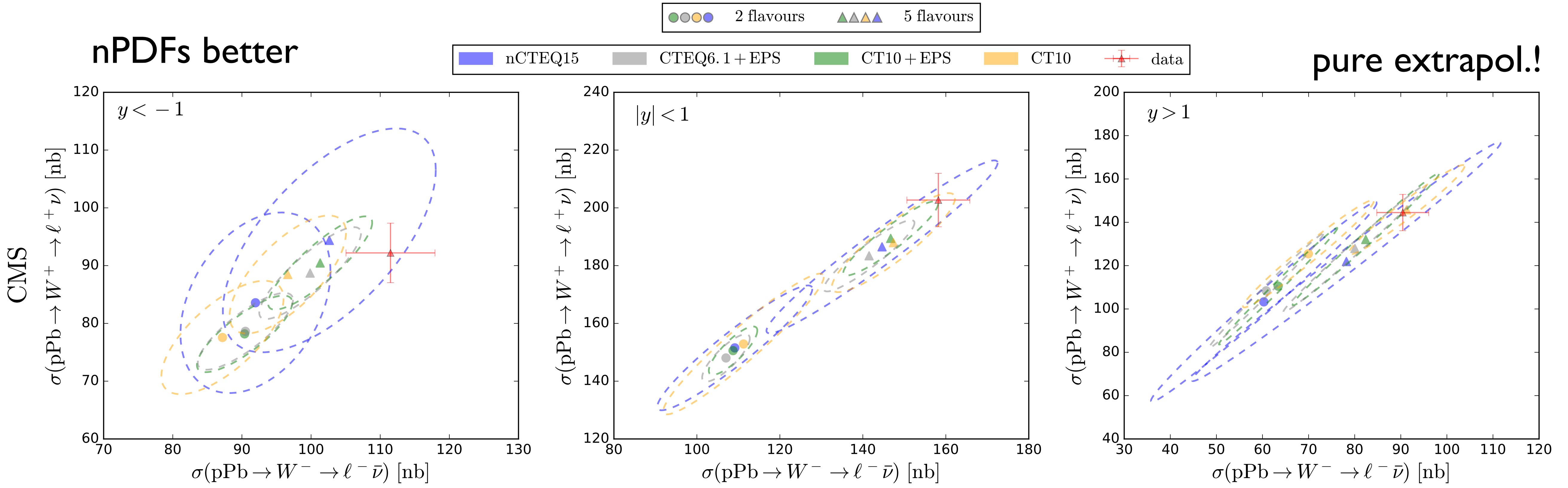
(W^+,W^-) Correlation



(Z,W) Correlation



Importance of strange PDF

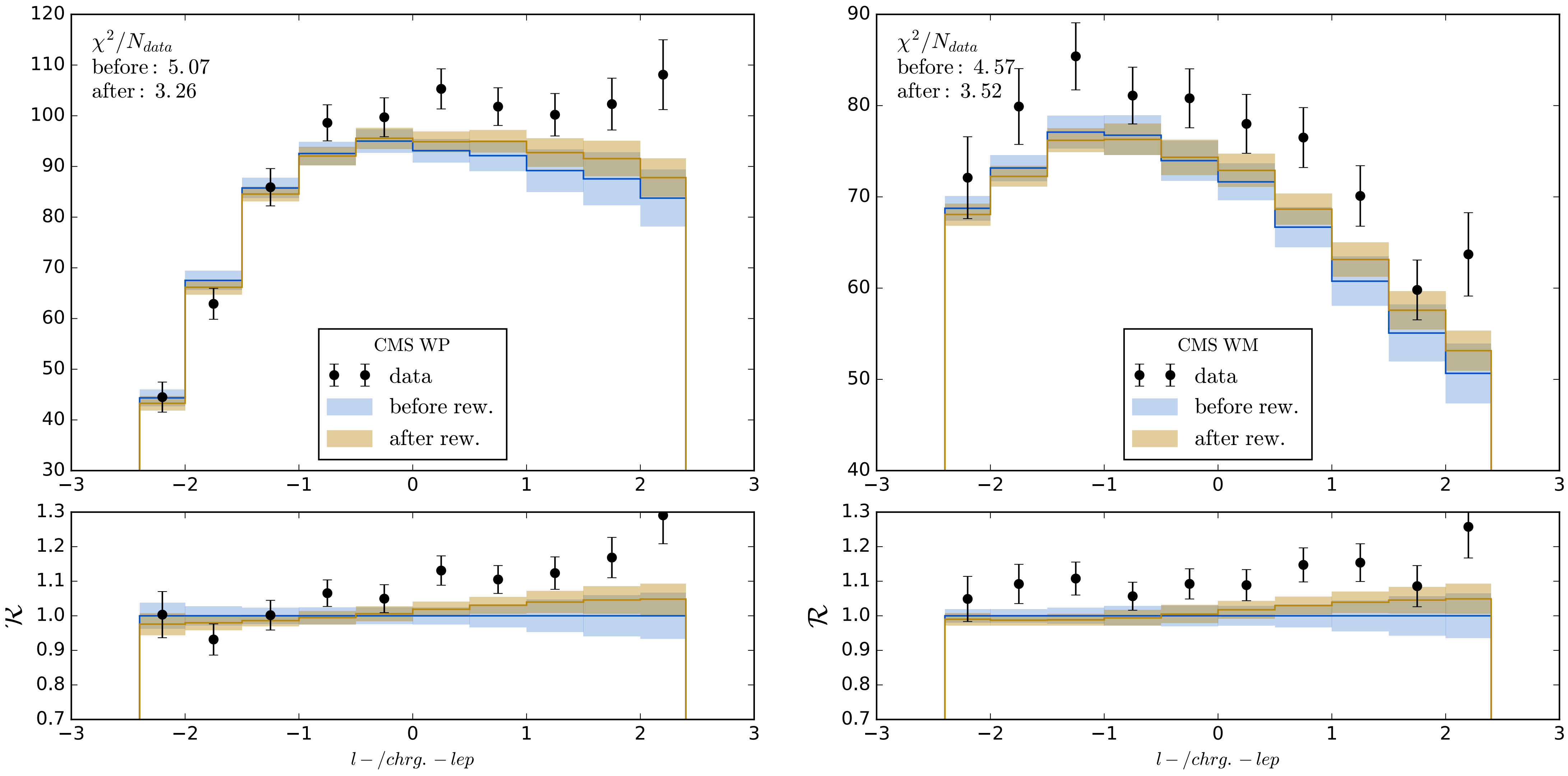


nPDFs better

pure extrapol.!

- **y<-1** (large x): s > sbar could help!
- **|y|<1**: delayed transition from anti-shadowing to shadowing could help **as seen in NuTeV neutrino data**
- **y>1**: Extrapolation, rather no shadowing at small x~10^{-3}?

Reweighting



(a) W^+ (b) W^-

- Improvements after reweighting
- However, strange PDF not fitted independently in nCTEQ15
- Need to include data in global analysis and open up strange PDF

Conclusions II

- LHC W/Z production data provide important constraints on the light quarks AND the strange quark
- Data favor an unsuppressed quark sea at small $x\sim 10^{-3}$!
- nCTEQ has performed a reweighting analysis and plans to include these data in the next global analysis

Impact of LHC heavy quark data on NPDFs

Shao, Cacciari, Kusina, Lansberg, IS, work in progress

Introduction

- Use data for D^0, J/Ψ, B →J/Ψ, ϒ(1S) production in p-Pb collsions at LHC at 5.02 and 8.16 TeV
- Comparison with predictions from nCTEQ15 and EPPS16
- Perform reweighting analysis of nuclear effects
- Goal: constrain small-x gluon in lead (down to $x{\sim}10^{-6}$)

Data-driven approach

Lansberg & Shao arXiv:1610.05382

- Parameterize the squared amplitude for the partonic scattering process g+g→H+X

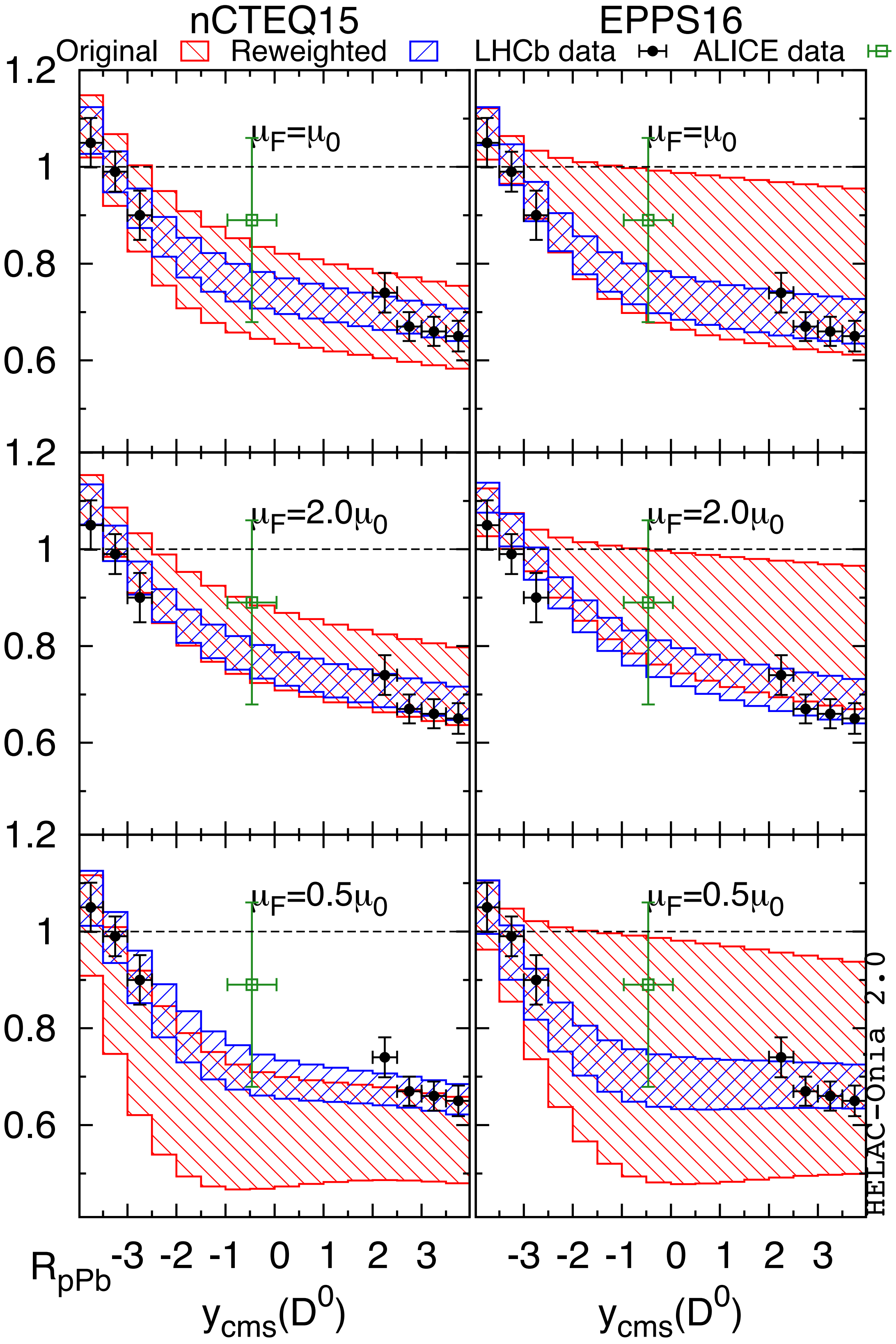
- Convolute with modern proton PDFs

- Use data for D^0, J/Ψ, B →J/Ψ, Υ(1S) production in pp collisions at the LHC to determine the squared amplitude

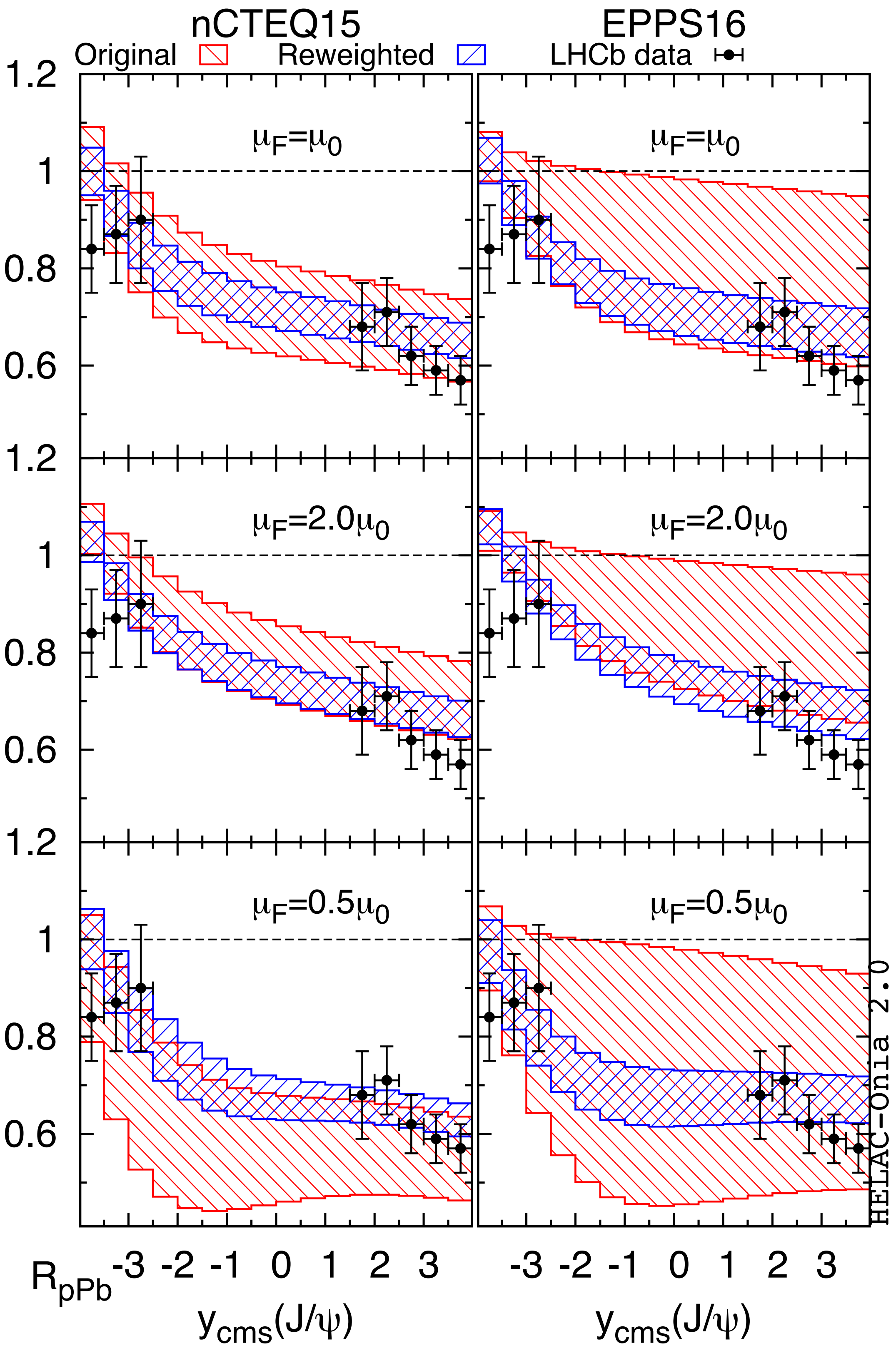
- Depends on the framework of proton PDF (scheme, order, scale choice, ...)

- Convolute squared amplitude with nuclear PDFs (same scheme, order, scale choice) to obtain predictions for p-Pb collisions

Results for R_{pA} vs rapidity

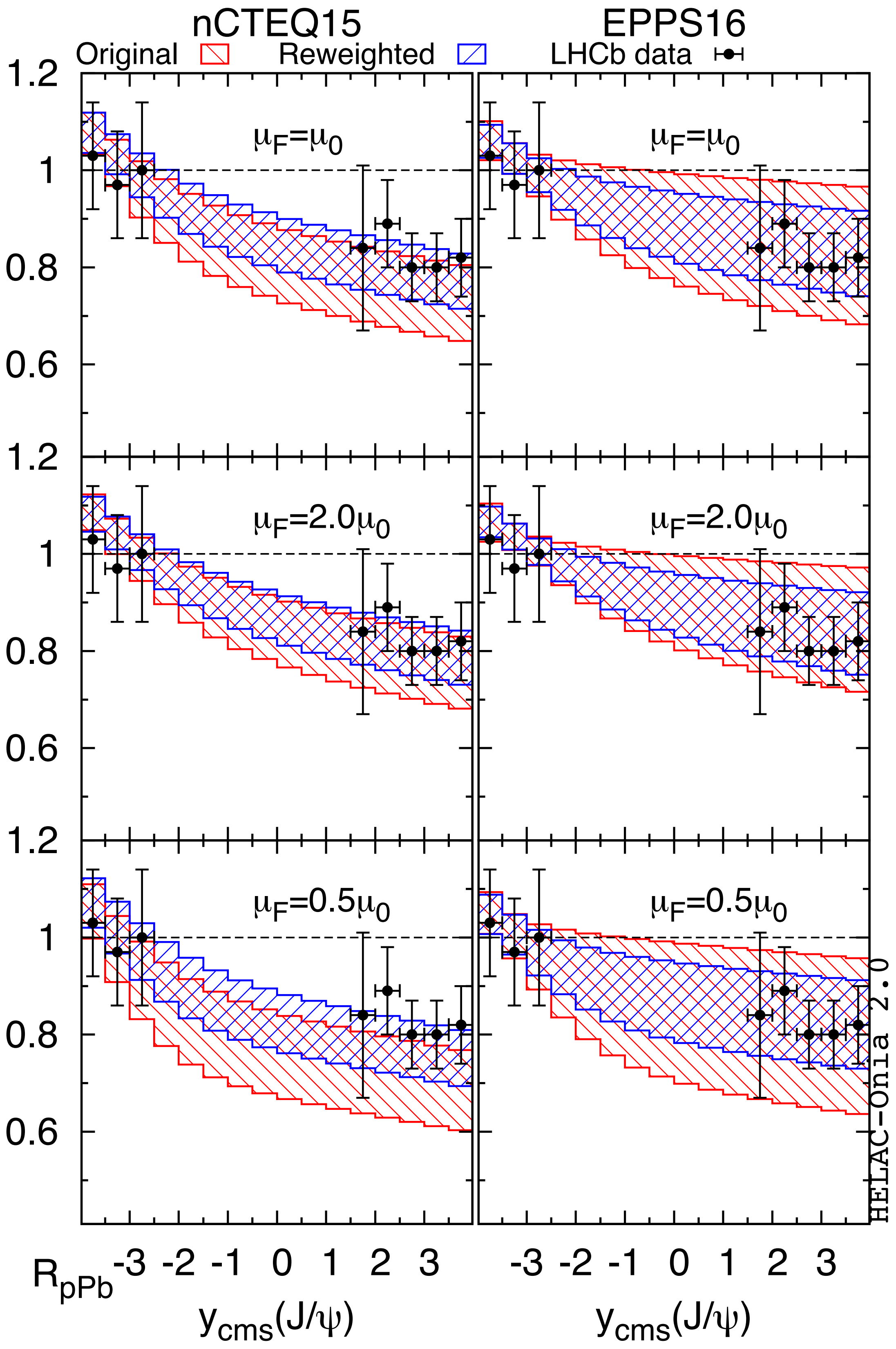


(a) Prompt D^0

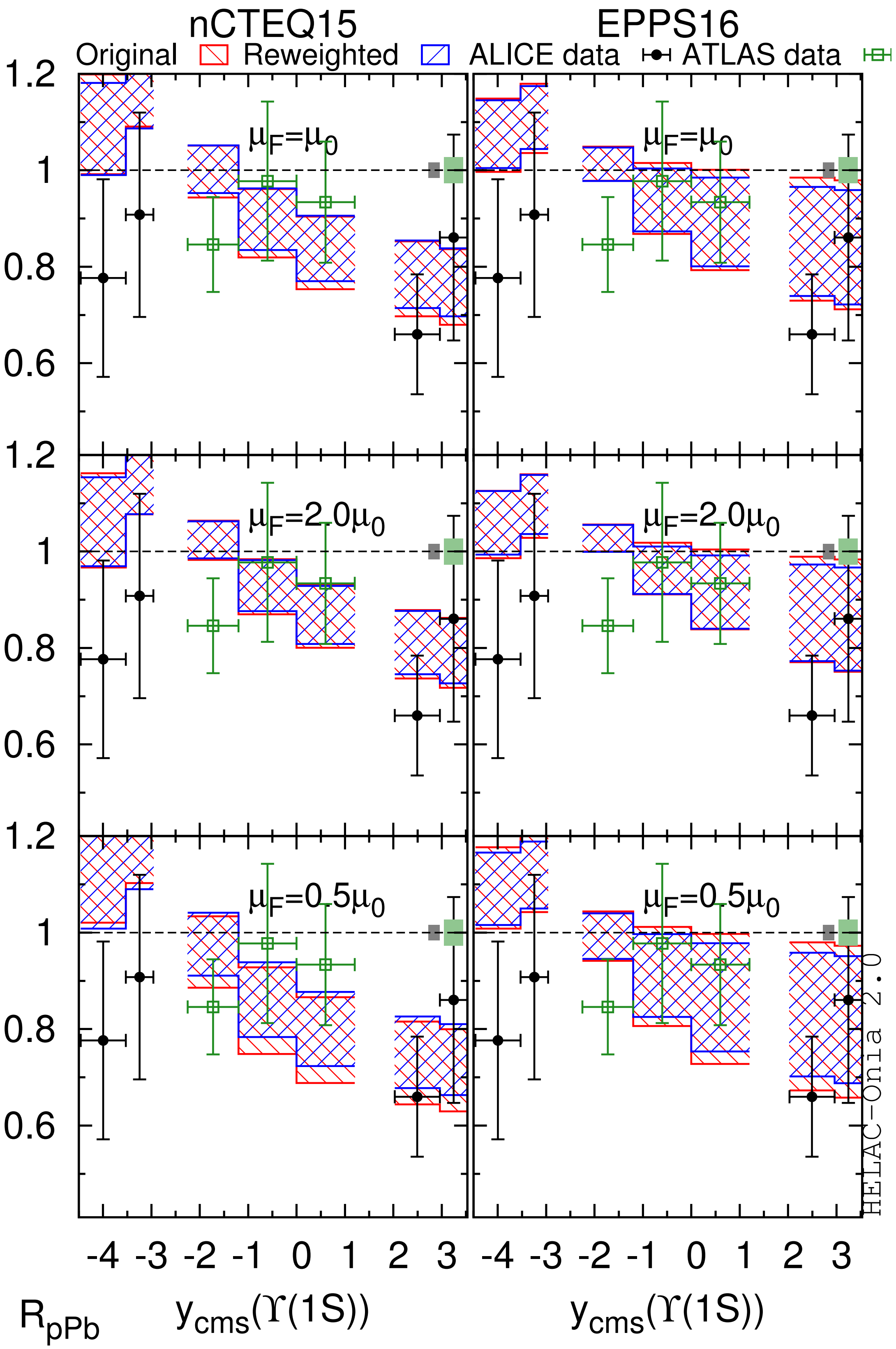


(b) Prompt J/ψ

Results for R_{pA} vs rapidity

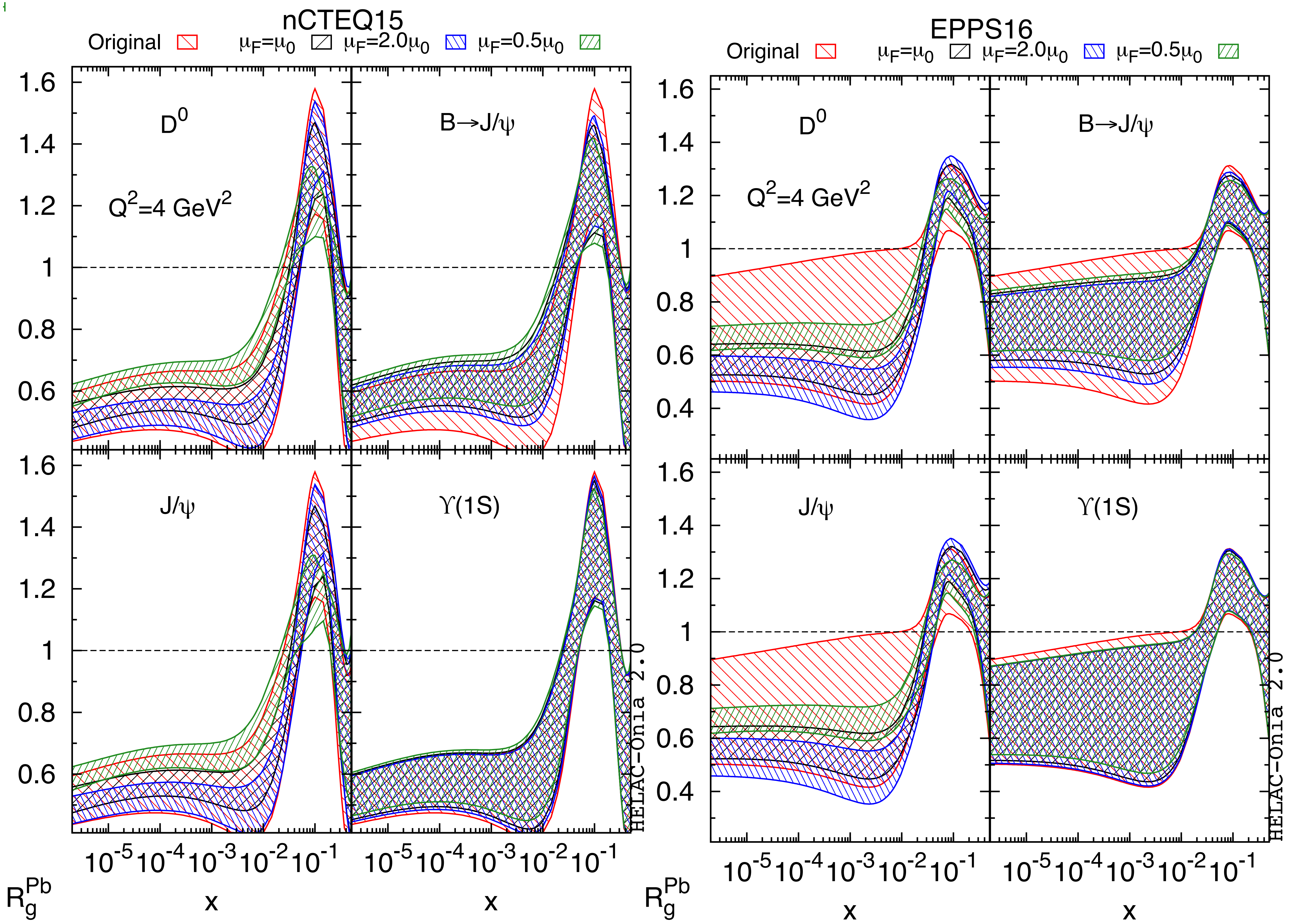


(c) $B \to J/\psi$



(d) $\Upsilon(1S)$

R_g^{Pb} vs x



(e) nCTEQ15 nPDF (f) EPPS16 nPDF

Conclusions III

- A consistent description of LHC heavy quark data p-Pb data is possible in the standard pQCD framework
- Reweighting of nCTEQ15 and EPPS'16 nPDF shows unambiguosly a suppressed ('shadowed') gluon for x<10-2
- Much reduced uncertainty band for **both** EPPS'16 and nCTEQ'15+gluons in arXiv:1012.1178
- Interesting situation since W/Z data seem to prefer unsuppressed quark distributions at small x~10^-3.

Outlook/Discussion

- Perform global anlysis of heavy quark data
- **Other cold nuclear matter effects** have been proposed which should be tested in a global analysis and which might drastically change the nuclear effects, for example:
    - Energy loss in p-A collisions proposed by Arleo & Peigne
    - Gluon saturation
- To test the standard pQCD framework one should include gluon-dominated processes with **uncolored** final states (where little or no energy loss effects are expected)
    - inclusive prompt photon production (with little energy loss expected)
    - di-photon production (no energy loss)
    - photon + heavy quark production (heavy quark energy loss in p-Pb?)

Backup

Available pPb LHC data

- W/Z production
  - ATLAS [arXiv:1507.06232, ATLAS-CONF-2015-056]
  - CMS [arXiv:1512.06461, arXiv:1503.05825]
  - LHCb [arXiv:1406.2885]
  - ALICE [arXiv:1511.06398]
- Jets
  - ATLAS [arXiv:1412.4092]
  - CMS [arXiv:1401.4433, CMS-PAS-HIN-14-001]
- Charged particle production (FFs dependence)
  - CMS [CMS-PAS-HIN-12-017]
  - ALICE [arXiv:1405.2737, arXiv:1505.04717]
- Isolated photons (PbPb)
  - ATLAS [arXiv:1506.08552]
  - CMS [arXiv:1201.3093]
  - ALICE [arXiv:1509.07324]

Constraining the small-x gluon in the proton

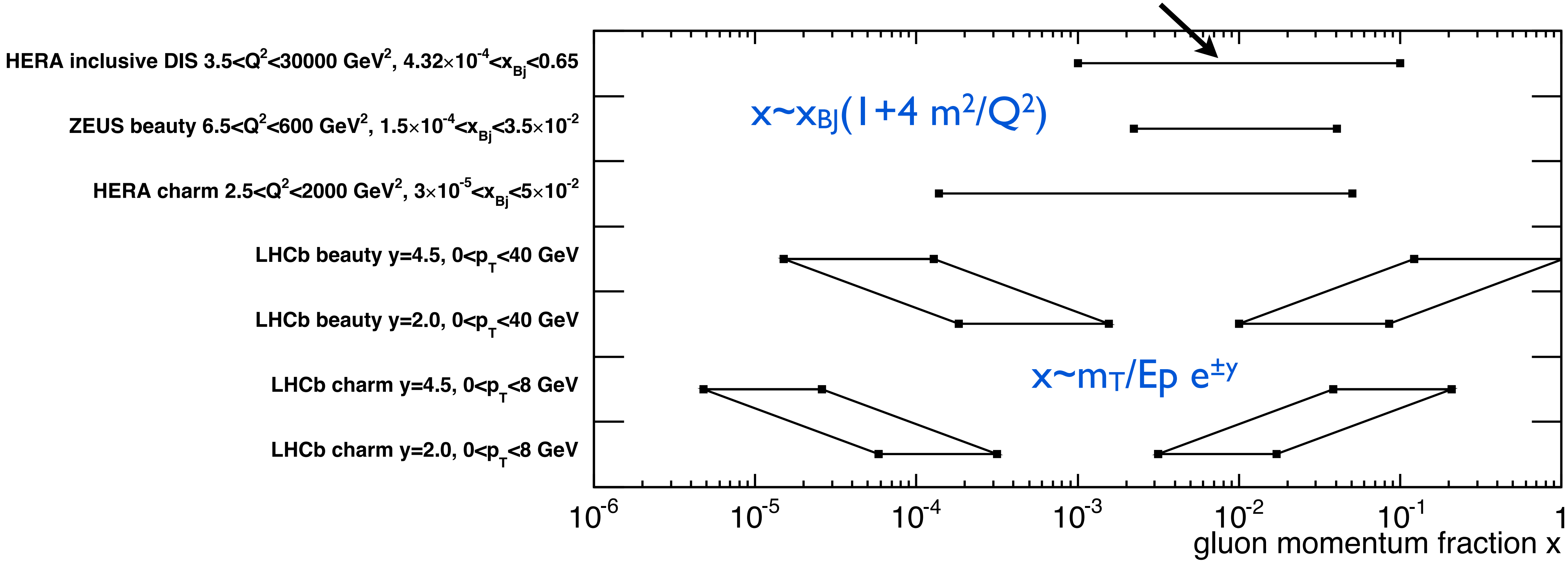
PROSA study

O. Zenaiev et al, EPJC75(2015)396

- NLO QCD analysis of impact of data for heavy quark production in ep and pp collisions on PDFs
- Theory for heavy quark production in ep, pp: FFNS at NLO
- Data:
  - HERA: Inclusive DIS cross sections in ep
  - HERA: Heavy flavour production cross sections in ep
  - LHCb: Differential cross sections for c (D^0, D^+, D^{*+}, D_s^+, Λ_c) and b (B^+, B^0, B_s^0) production in pp at LHC7
- Result:
  LHCb data impose constraints on low-x gluon and quark sea

Kinematic range

O. Zenaiev et al, EPJC75(2015)396

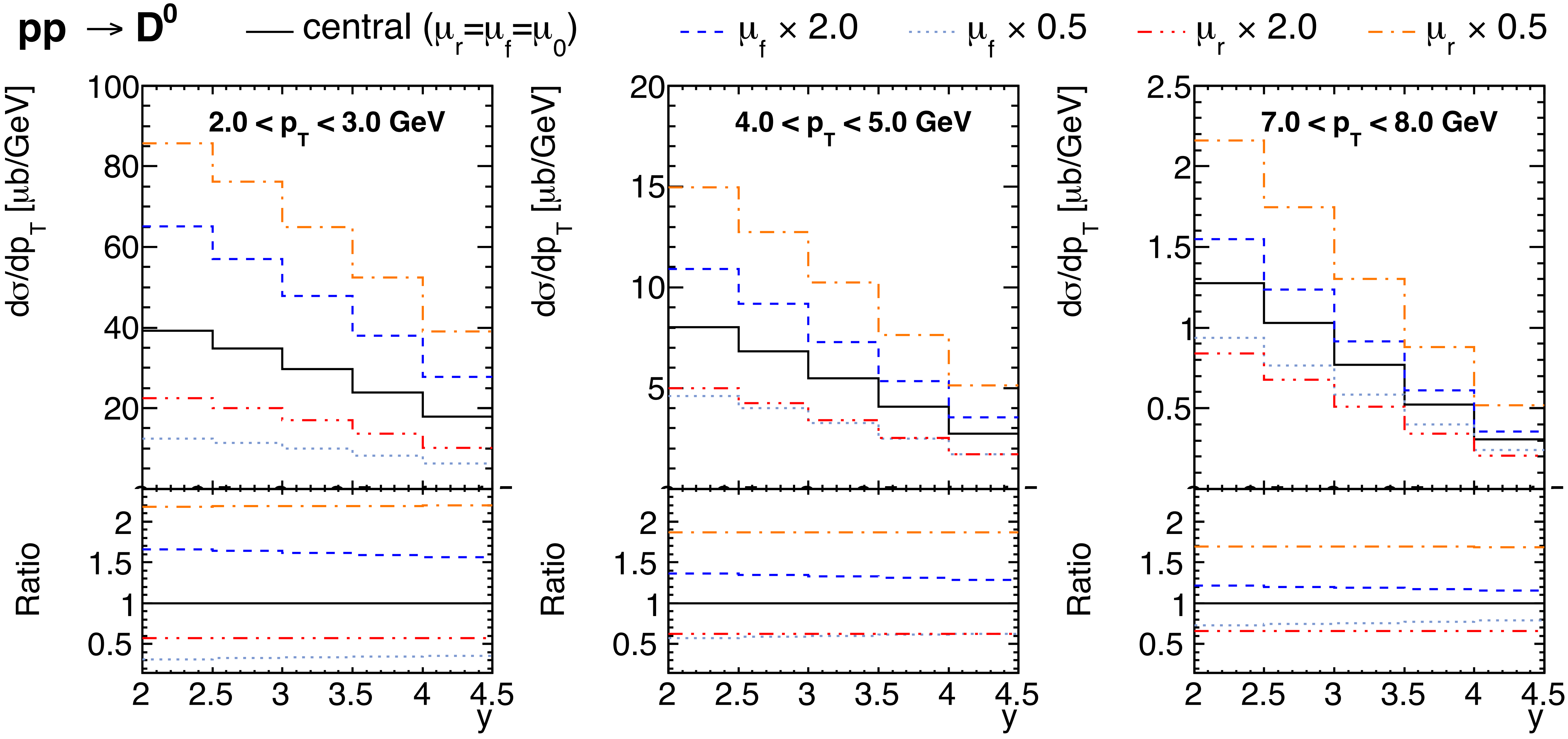


gluon well known in this range

- HERA inclusive DIS data: x-range is indicated where the gluon PDF uncertainties are less than 10% (at $\mu_F^2=10$ GeV^2)

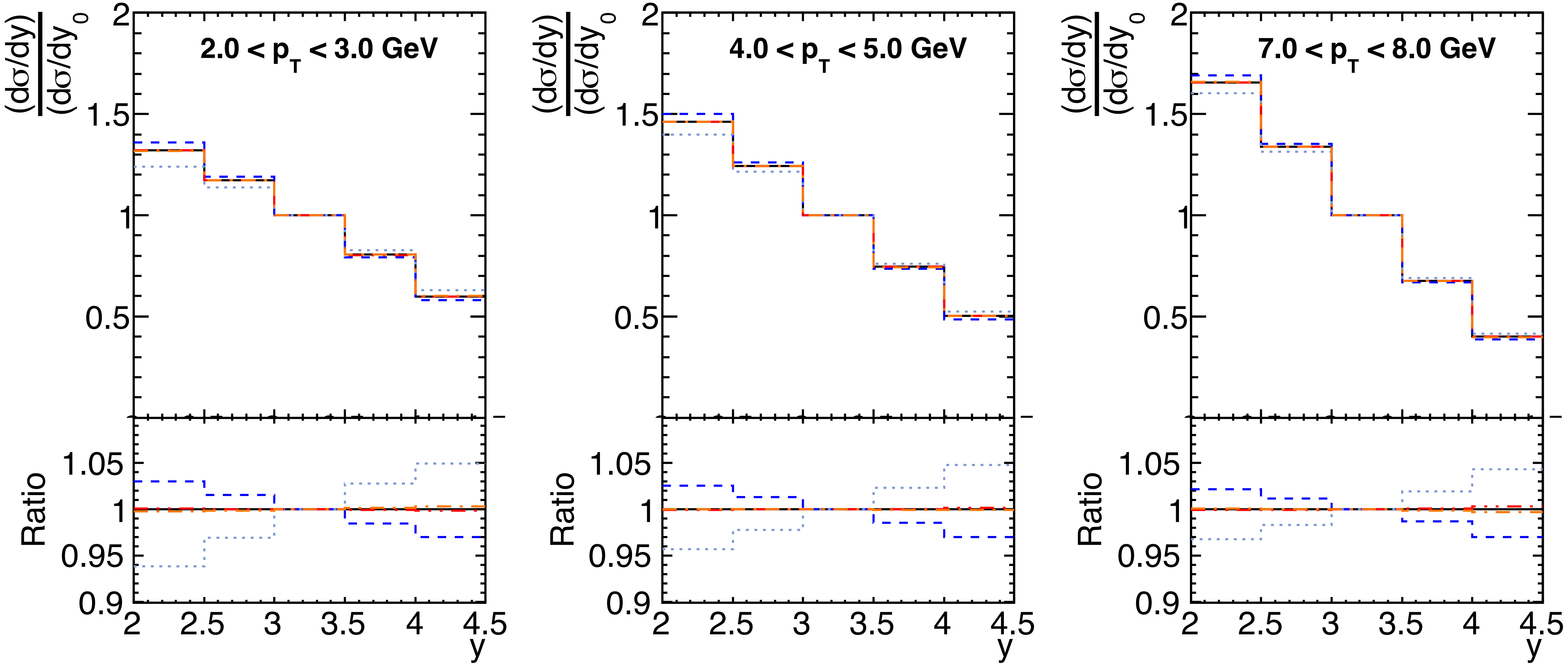
- Mayor impact of LHCb data expected at $5\times10^{-6} < x < 10^{-4}$

NLO QCD predictions for charm LHCb data



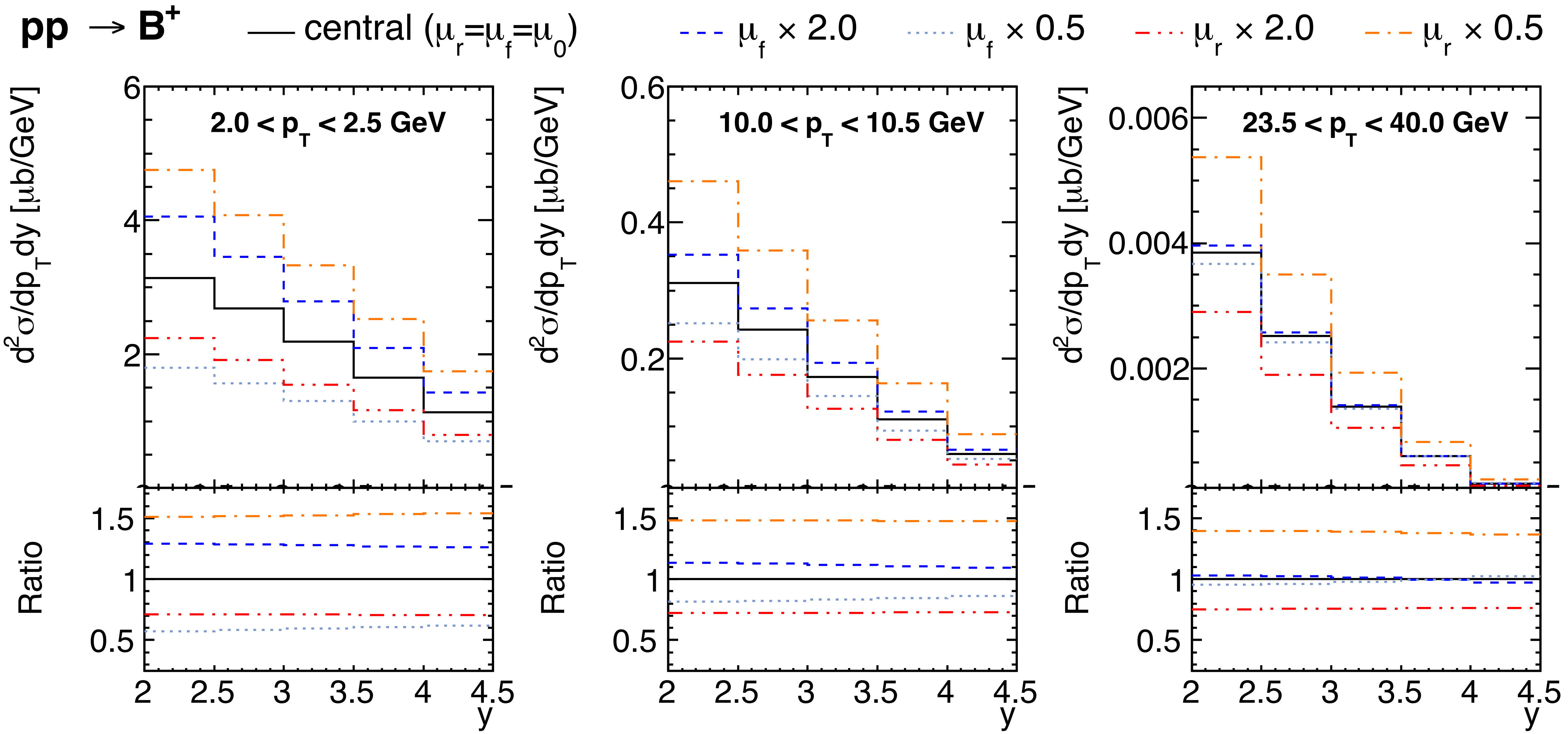
- Central scale $\mu_0 = m_T$
- Large scale uncertainties!
- Mostly change the normalization, shape less affected

NLO QCD predictions for charm LHCb data



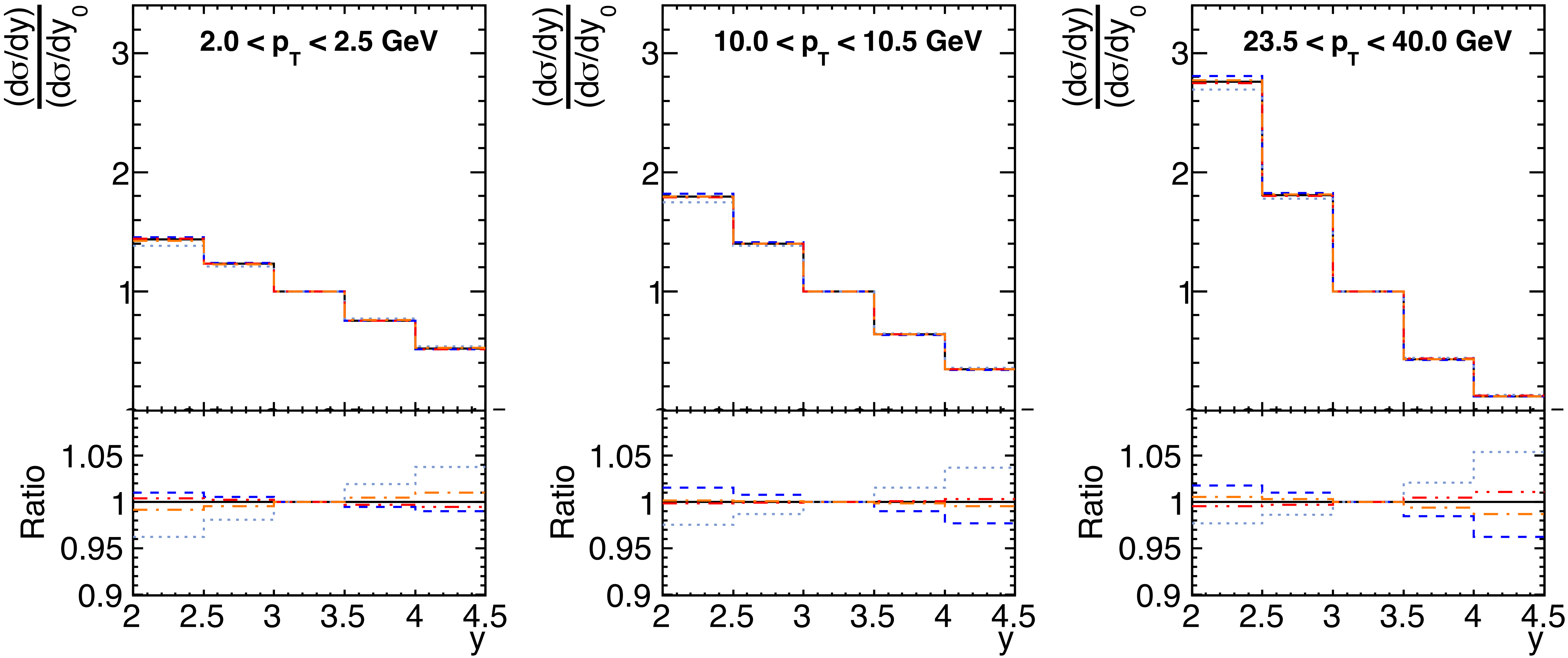
- Normalized cross sections w.r.t. dσ/dy in the bin 3<y<3.5
- Very small scale uncertainties now!
- Shape remains sensitive to gluon

NLO QCD predictions for beauty LHCb data



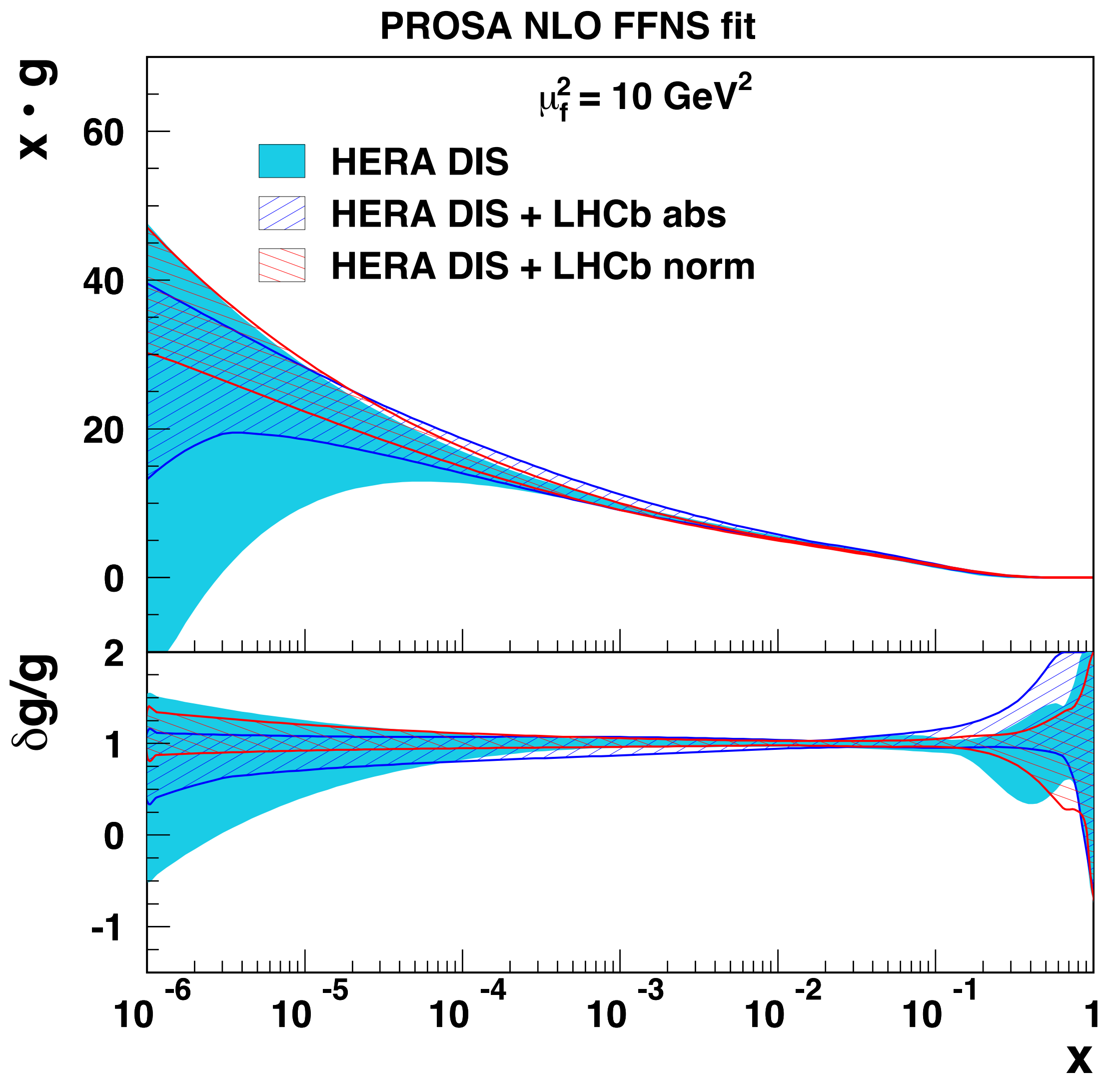
- Central scale $\mu_0 = m_T$
- Large scale uncertainties!
- Mostly change the normalization, shape less affected

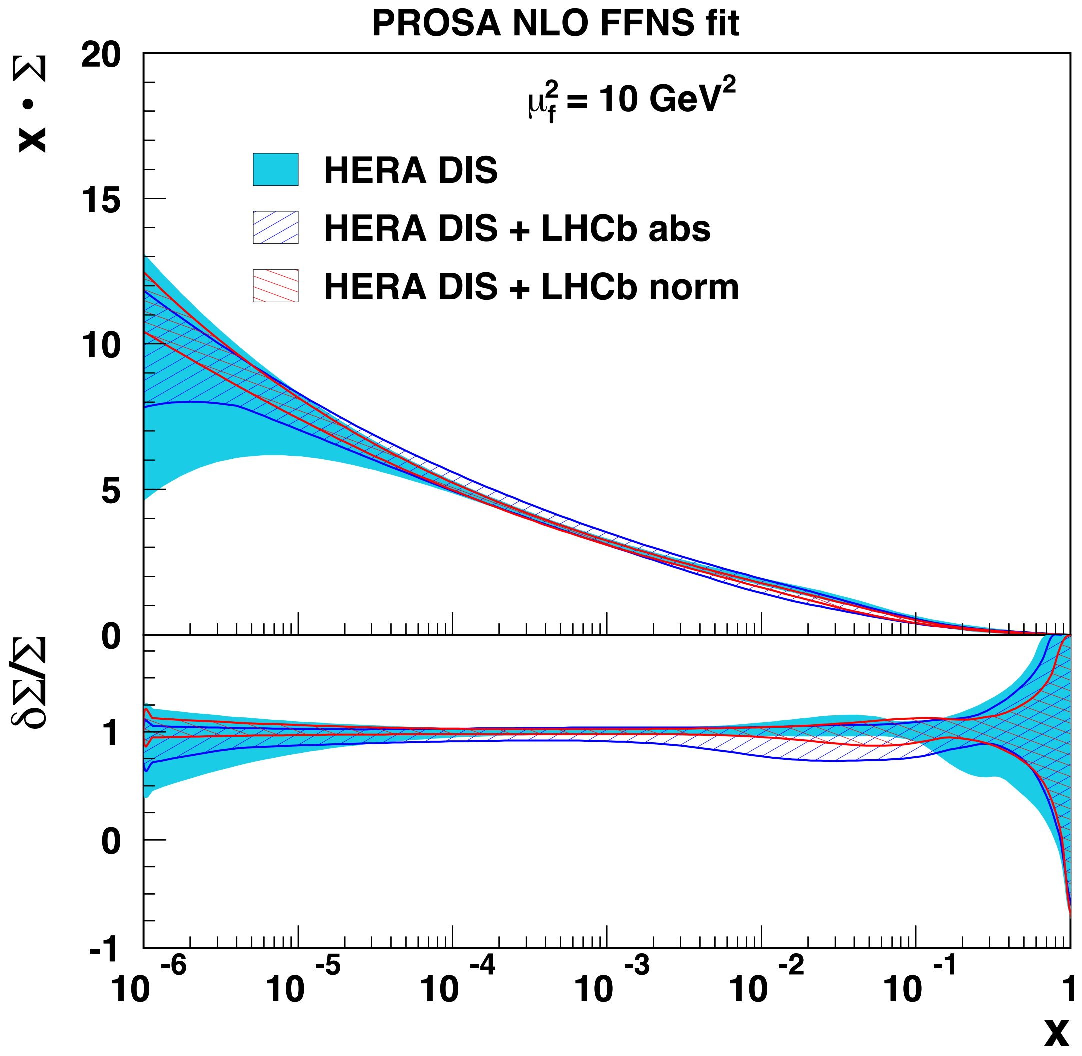
NLO QCD predictions for beauty LHCb data



- Normalized cross sections w.r.t. dσ/dy in the bin 3<y<3.5
- Very small scale uncertainties now!
- Shape remains sensitive to gluon

Results for the gluon and the sea





- The uncertainties on the gluon and the sea are significantly reduced using LHCb data

- In the normalised case by a factor 3 at $x \sim 5 \times 10^{-6}$