Nuclear PDFs
and
D-meson production in the GM-VFNS

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"France-Japan Workshop on physics analysis in the ALICE experiment"
Strasbourg, May 9, 2017

Part I: Nuclear PDFs

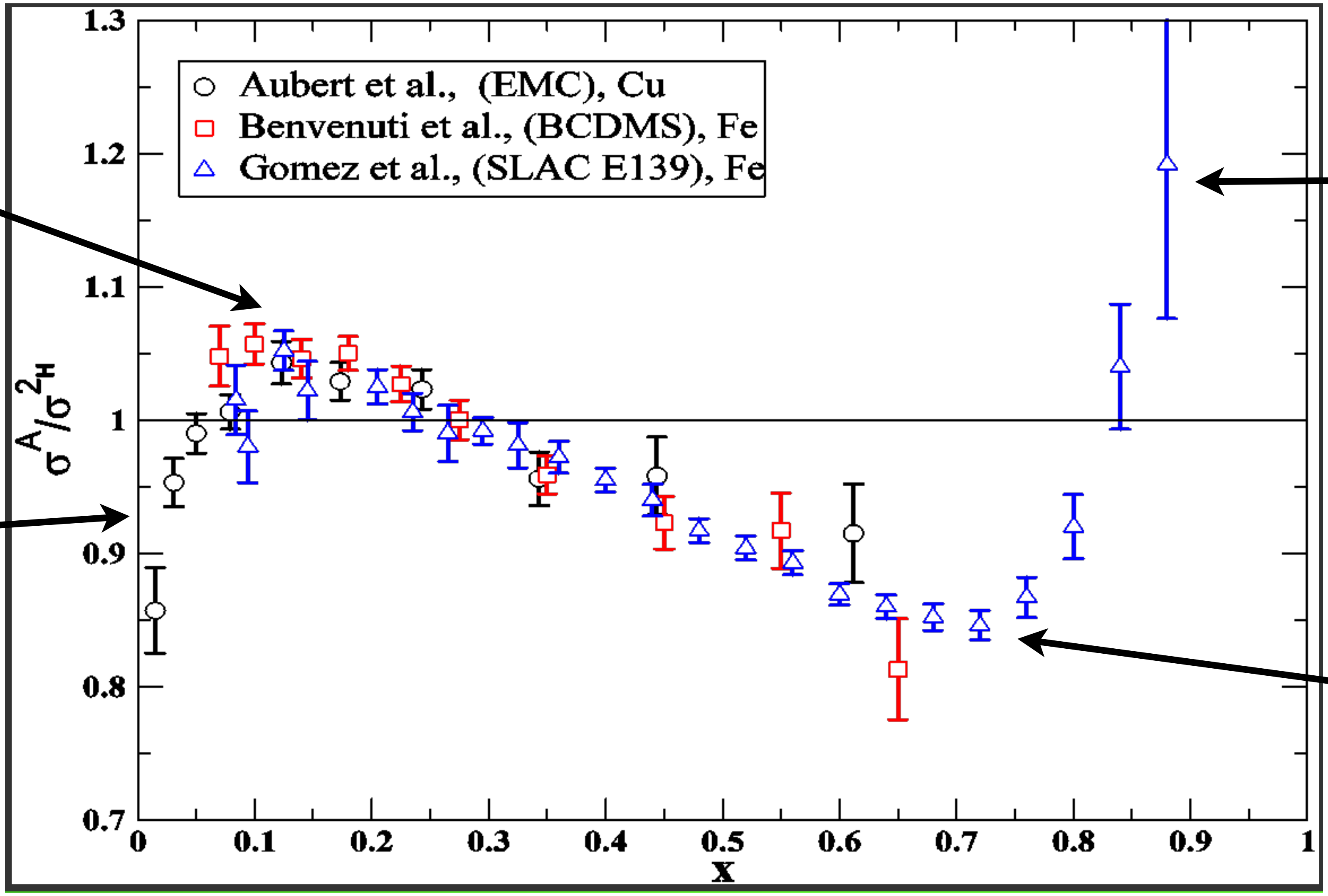
Outline

- Introduction
- Brief review of available nuclear PDFs
- LHC pPb data useful for constraining nPDF

Introduction

Nuclear modifications of DIS structure functions

$$F_2^A(x) \neq Z F_2^p(x) + N F_2^n(x)$$



Anti-shadowing enhancement

Shadowing suppression at small x

Rise due to Fermi motion

EMC effect

Can we translate these modifications into universal nuclear PDFs?

Nuclear PDFs

- There are at least two motivations for NPDFs:

  1. They encode **information on the partonic structure** of nuclei

  2. They are **crucial tools** for the description of pA and AA collisions at RHIC/LHC and lepton-A DIS

- Predictions for observables have to include **reliable estimates of the uncertainties** due to the NPDFs

- So far NPDFs are determined by performing **global analyses of data** similar to global analyses of proton PDFs

Theoretical Framework

- Factorization theorems
    - provide (field theoretical) definitions of universal PDFs
    - make the formalism predictive
    - make a statement about the error
- PDFs and predicitions for observables+uncertainities **refer to this standard pQCD framework**
- There might be breaking of QCD factorization, deviations from DGLAP evolution — in particular in a nuclear environment

  Still need solid understanding of standard framework to establish deviations!

In the nuclear case, consider factorization as a working assumption to be tested phenomenologically

Theoretical Framework

- Factorization theorems
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  - make the formalism predictive
  -
- PDI … this sta
- The … DGLAP evo

Stil to e

Factorization:

pp : Yes

pA: probably Yes

AA: ???

Need careful analysis of data in pp, pA, and AA!

Questions:

In pA: How big are higher twist terms?

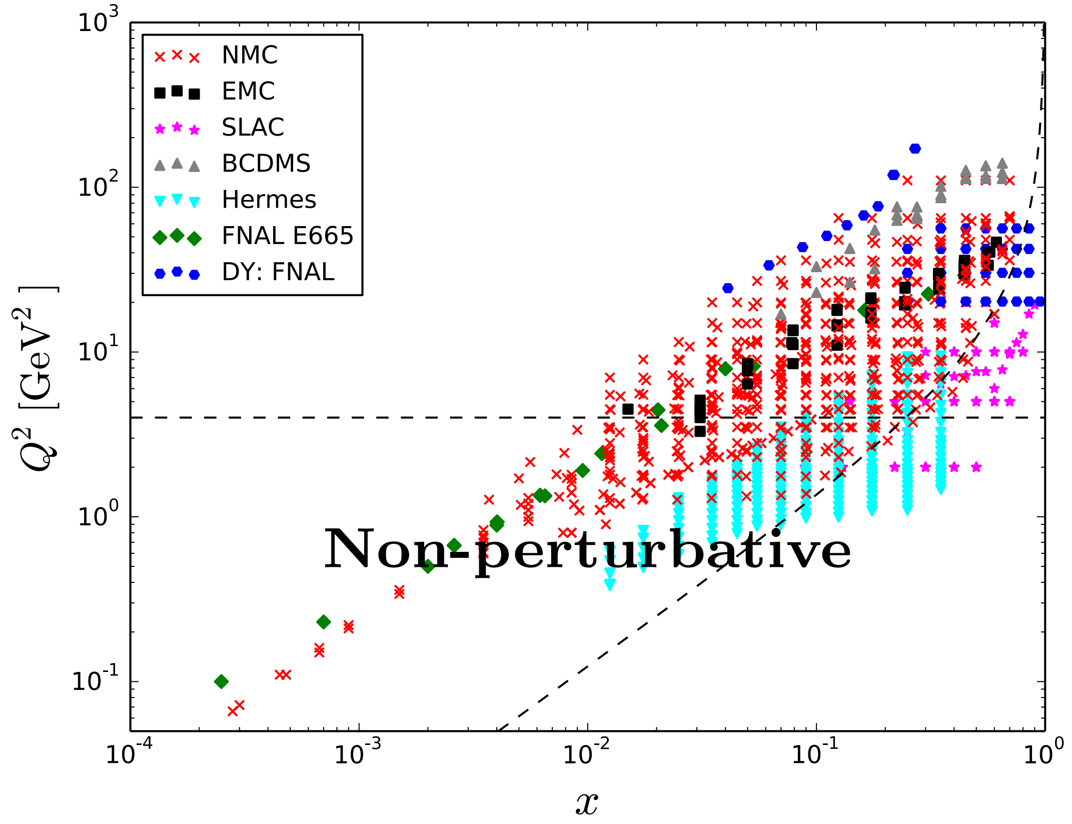
In AA: If factorization breaking, how big?

Is there an alternative to the factorization approach?

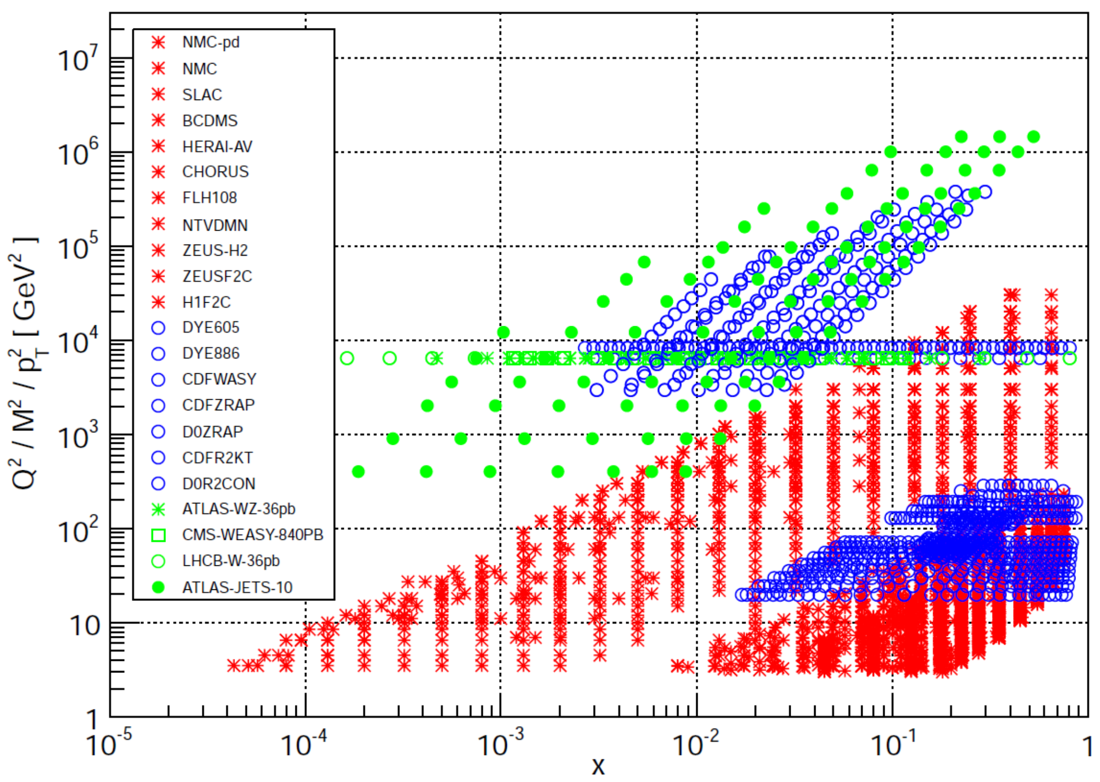
In the nuclear case, consider factorization as a working assumption to be tested phenomenologically

Main differences with free-proton PDFs

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



nCTEQ15 dataset



NNPDF2.3 dataset

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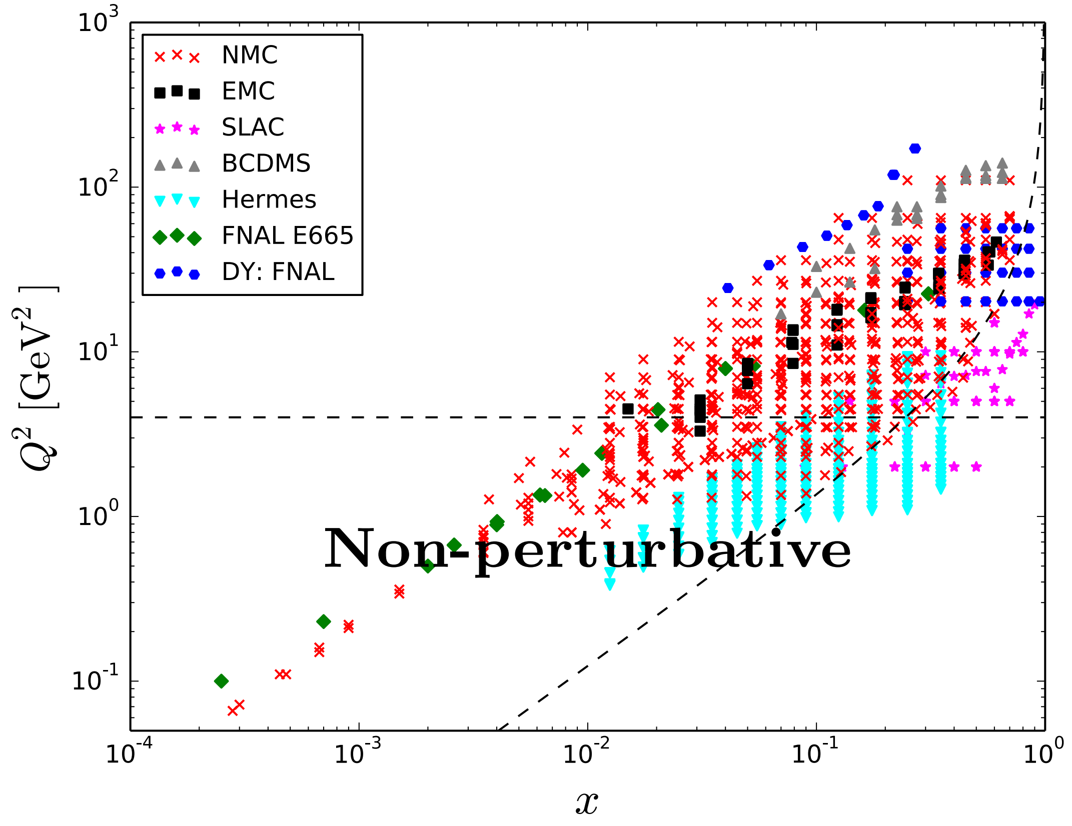

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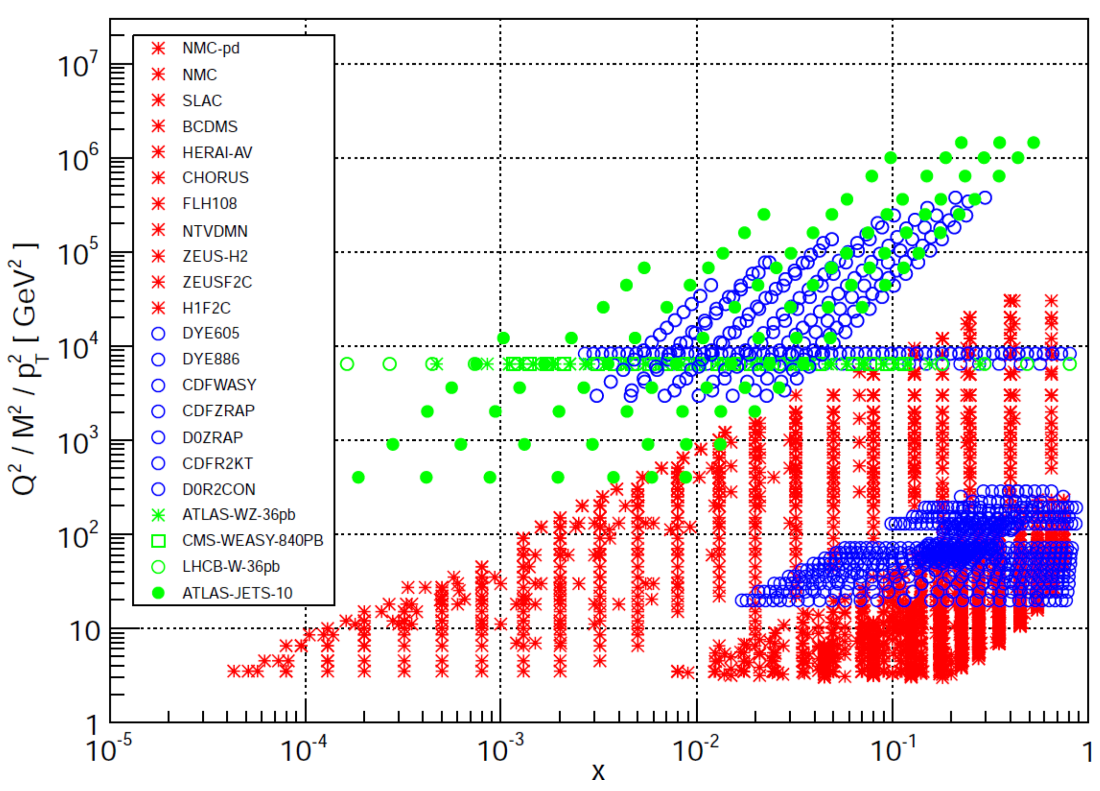

NNPDF2.3 dataset

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

Brief review of available nuclear PDFs

Available nuclear PDFs (NLO)

NEW

- 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

Available nuclear PDFs (NNLO)

- 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

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- **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

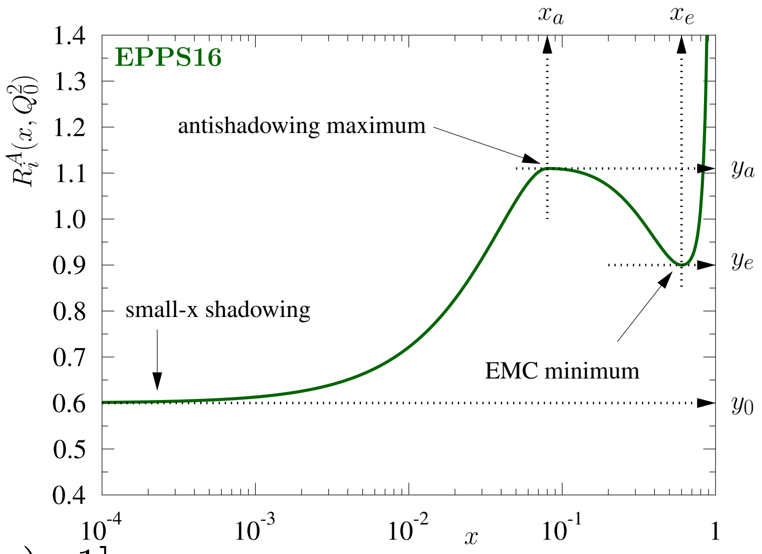
EPPS'16 framework

- NLO PDFs with errors (Hessian method, $\Delta\chi^2 = 52$)

- Parametrization ($x_N<1$, $Q_0=1.3$ GeV, $i=u_v,d_v,\bar{u},\bar{d},s,g$)

$$f_i^{p/A}(x_N,\mu_0) = R_i(x_N,\mu_0,A,Z)\, f_i(x_N,\mu_0),$$

$$R_i(x,A,Z) = \begin{cases} a_0 + (a_1 + a_2 x)(e^{-x} - e^{-x_a}) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1 \end{cases}$$



A-dependence of fit parameters: $y_i(A) = y_i(A_{\rm ref})\left(\frac{A}{A_{\rm ref}}\right)^{\gamma_i[y_i(A_{\rm ref})-1]}$

- CT14NLO free proton baseline, D (A=2) taken as free

- Data: lA DIS, DY, nu-A DIS, π^0@RHIC, LHC:dijets, W/Z

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

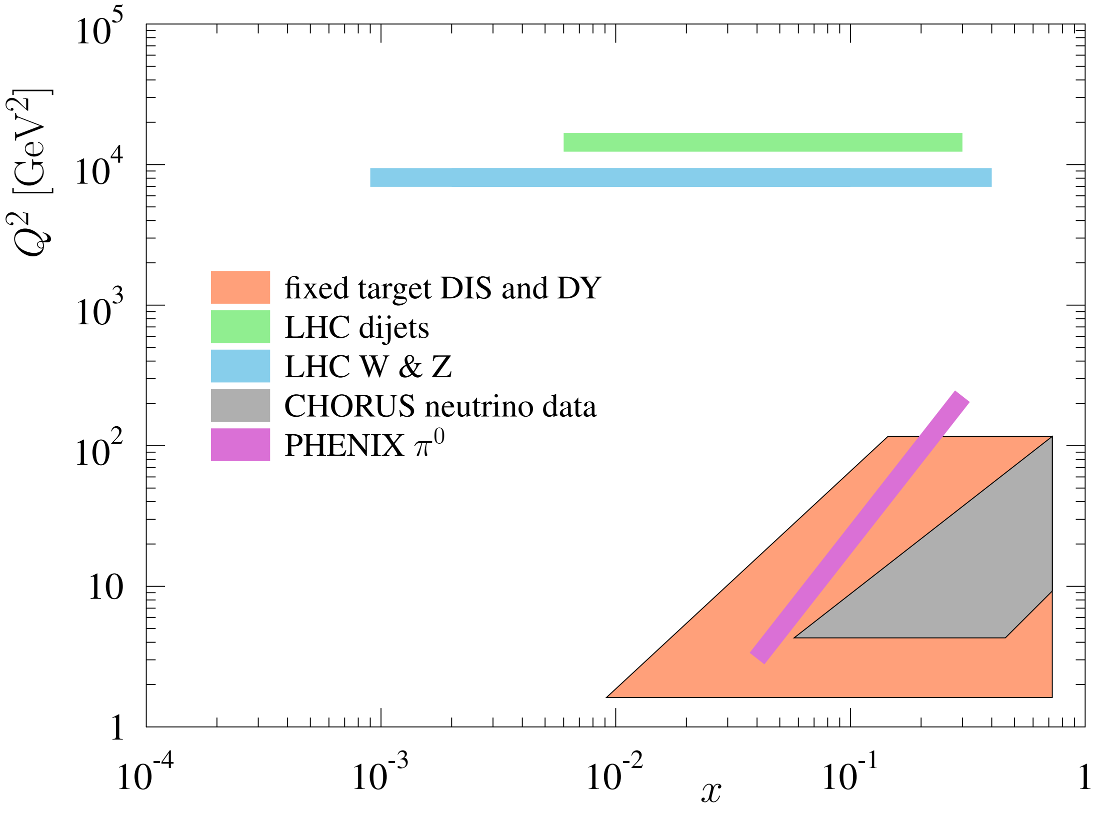
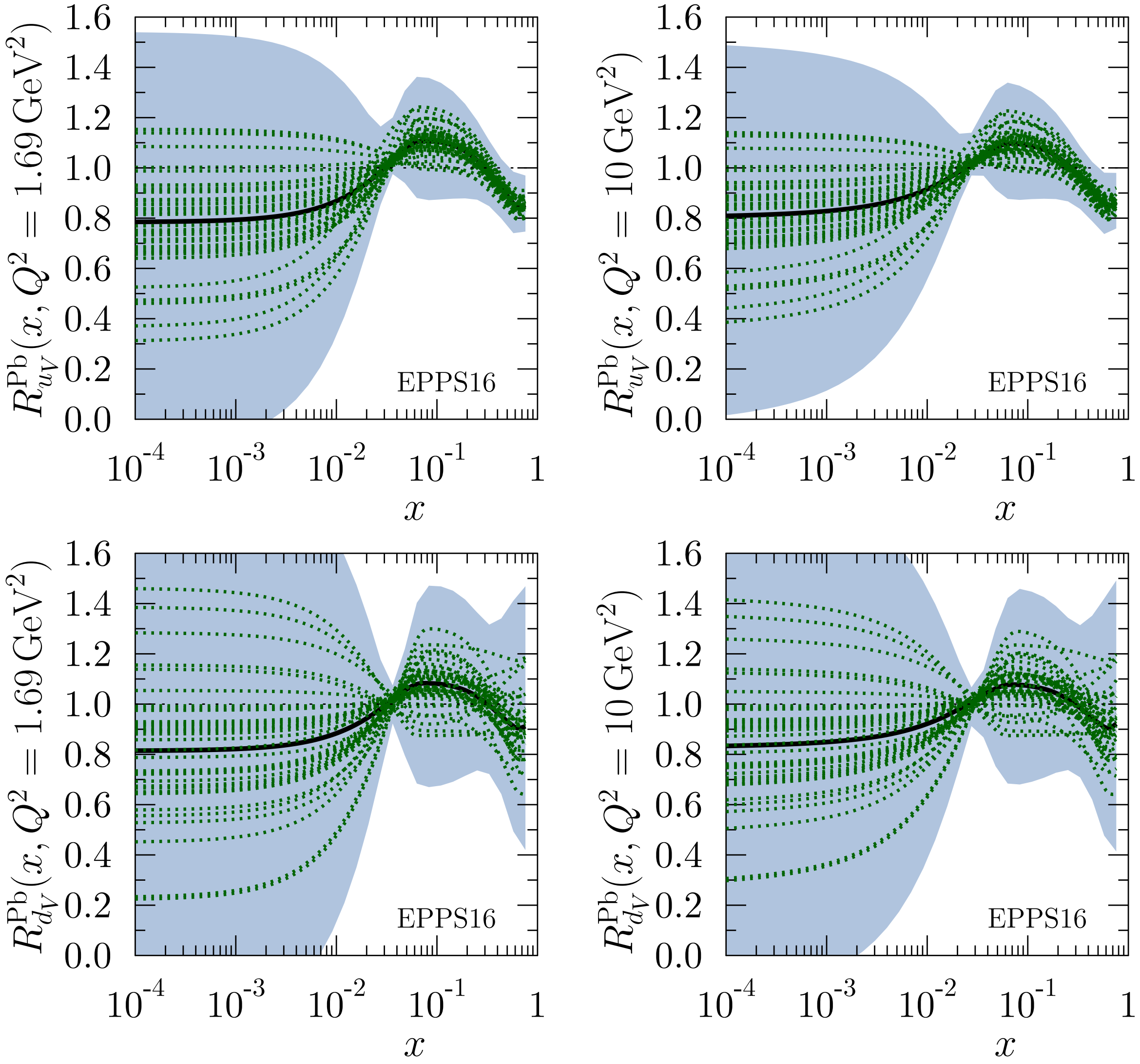
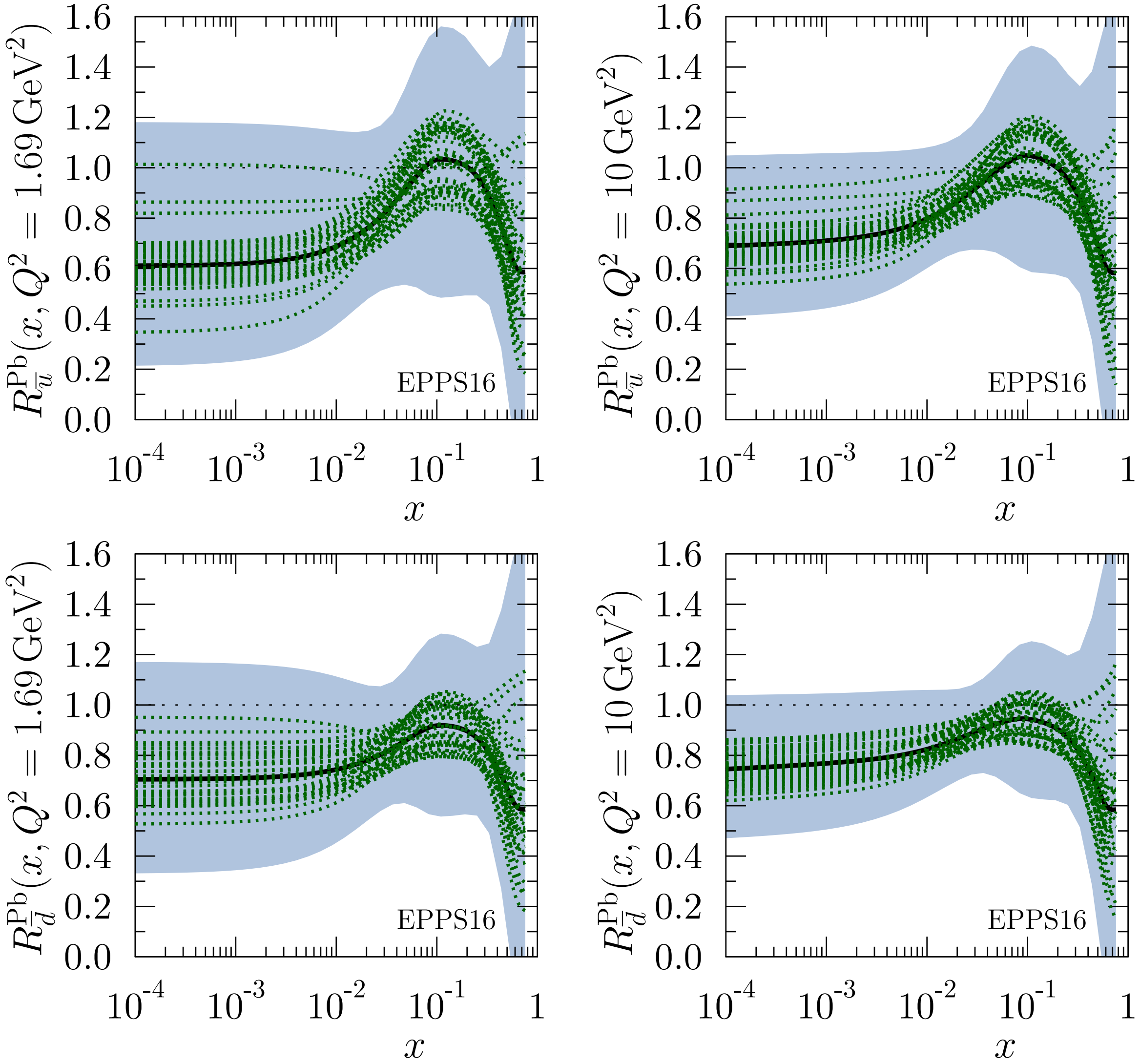


Fig. 2 The approximate regions in the (x, Q^2) plane at which different data in the EPPS16 fit probe the nuclear PDFs.

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), $\overline{\nu}$Pb(208)	824	998.6
Total			1811	1789

EPPS'16 framework: Results

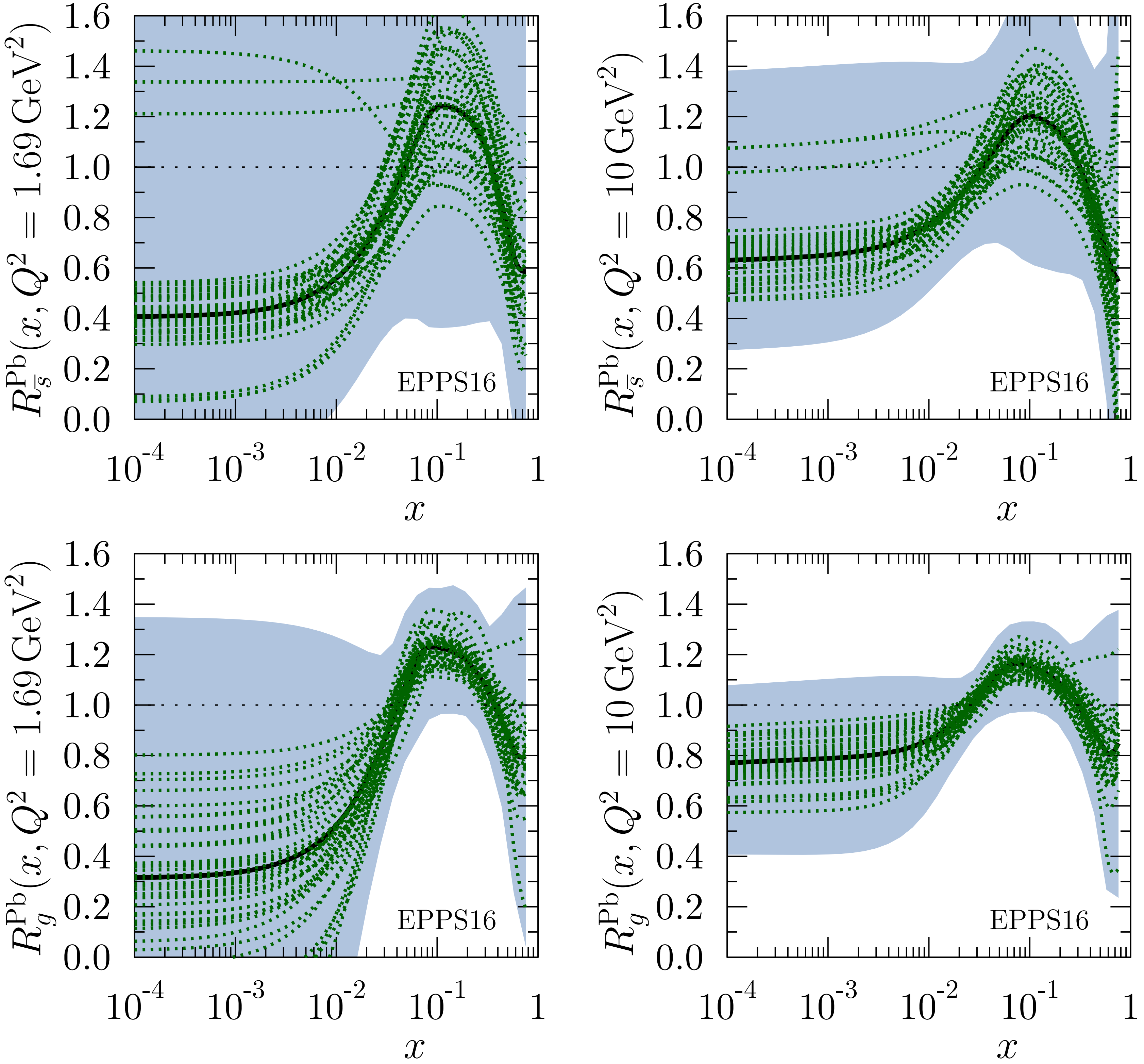




- Considerably larger uncertainties than EPS'09 despite more data (more flexible param., larger tolerance). Main impact from CHORUS and CMS dijet data.
- No notable tensions with previous data sets. **Supports validity of theoretical framework!**
- Still some parametrization bias (shape of PDFs), still quite a number of assumptions on parametrization
- Some aggressive choices (low DIS cuts, π-A DY data, RHIC π^0 data)

EPPS'16 framework: Results

- Large uncertainties for nuclear gluon distribution
- Nuclear strange PDF poorly constrained
- Clearly more LHC pPb data required
    - from LHC5
    - from LHC8 (much higher statistics)



nCTEQ'15 framework

PRD93(2016)085037

- Functional form of the bound proton PDF same as for the free proton (`CTEQ6M`, x restricted to $0 < x < 1$)

$$xf_i^{p/A}(x,Q_0) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}, \qquad i = u_v, d_v, g, \ldots$$
$$\bar{d}(x,Q_0)/\bar{u}(x,Q_0) = c_0 x^{c_1}(1-x)^{c_2} + (1+c_3 x)(1-x)^{c_4}$$

- A-dependent fit parameters (reduces to free proton for $A = 1$)

$$c_k \to c_k(A) \equiv c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right), \quad k = \{1, \ldots, 5\}$$

- PDFs for nucleus (A, Z)

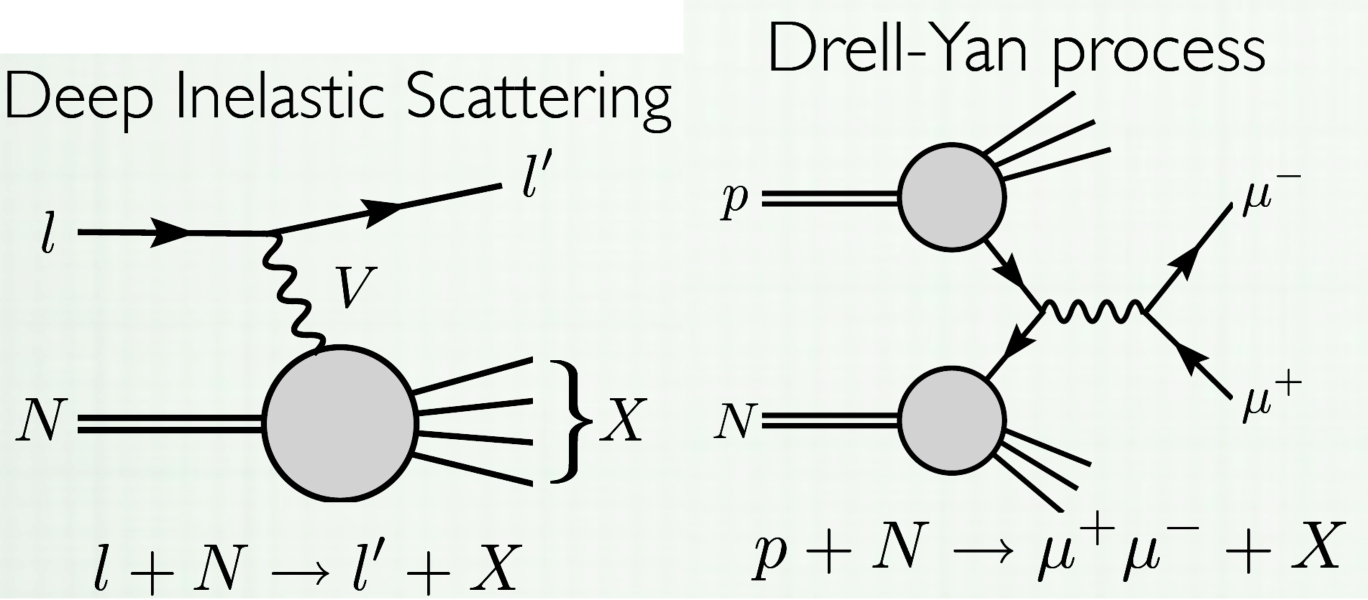
$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A} f_i^{p/A}(x,Q) + \frac{A-Z}{A} f_i^{n/A}(x,Q)$$

(bound neutron PDF $f_i^{n/A}$ by isospin symmetry)

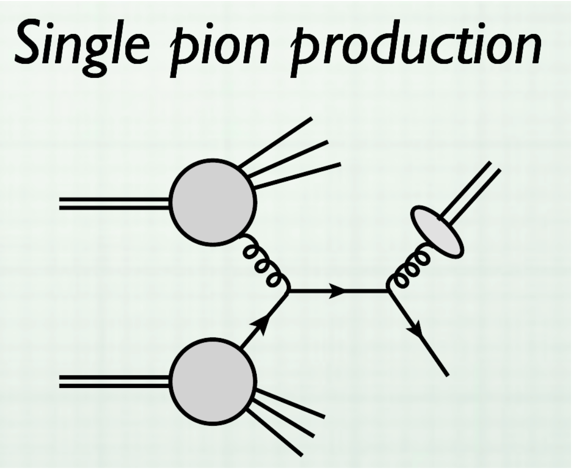
nCTEQ'15 framework: Data sets

- NC DIS & DY

CERN BCDMS & EMC & NMC
N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)
FNAL E-665
N = (D, C, Ca, Pb, Xe)
DESY Hermes
N = (D, He, N, Kr)
SLAC E-139 & E-049
N = (D, Ag, Al, Au, Be,C, Ca, Fe, He)
FNAL E-772 & E-886
N = (D, C, Ca, Fe,W)



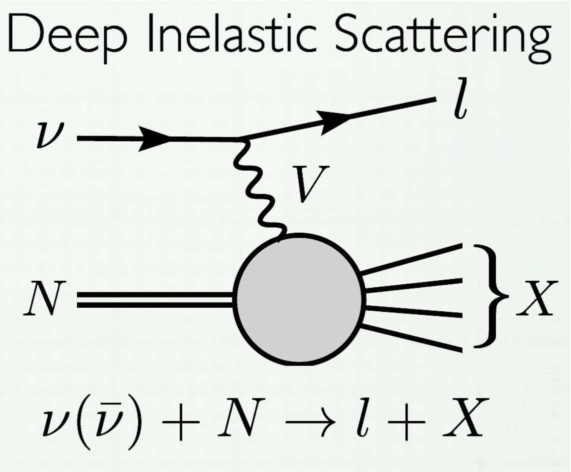
- Single pion production (new)



RHIC - PHENIX & STAR

N = Au

- Neutrino (to be included later)



CHORUS CCFR & NuTeV

N = Pb N = Fe

Fit details

PRD93(2016)085037

Fit properties:

- fit @NLO
- $Q_0 = 1.3\text{GeV}$
- using ACOT heavy quark scheme
- kinematic cuts:
  $Q > 2\text{GeV},\ W > 3.5\text{GeV}$
  $p_T > 1.7$ GeV
- 708 (DIS & DY) + 32 (single π^0) = 740 data points after cuts
- 16+2 free parameters
  - 7 gluon
  - 7 valence
  - 2 sea
  - 2 pion data normalizations
- $\chi^2 = 587$, giving $\chi^2/\text{dof} = 0.81$

Error analysis:

- use Hessian method

$$\chi^2 = \chi_0^2 + \frac{1}{2} H_{ij}(a_i - a_i^0)(a_j - a_j^0)$$

$$H_{ij} = \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}$$

- tolerance $\Delta\chi^2 = 35$ (every nuclear target within 90% C.L.)
- eigenvalues span 10 orders of magnitude → require numerical precision
- use noise reducing derivatives

Fit details

PRD93(2016)085037

Fit propert

- fit @N … od
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- 708 (I … arget within 90% C.L.)
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- 16+2 … reducing derivatives
- $\chi^2 =$

Kinematic cuts

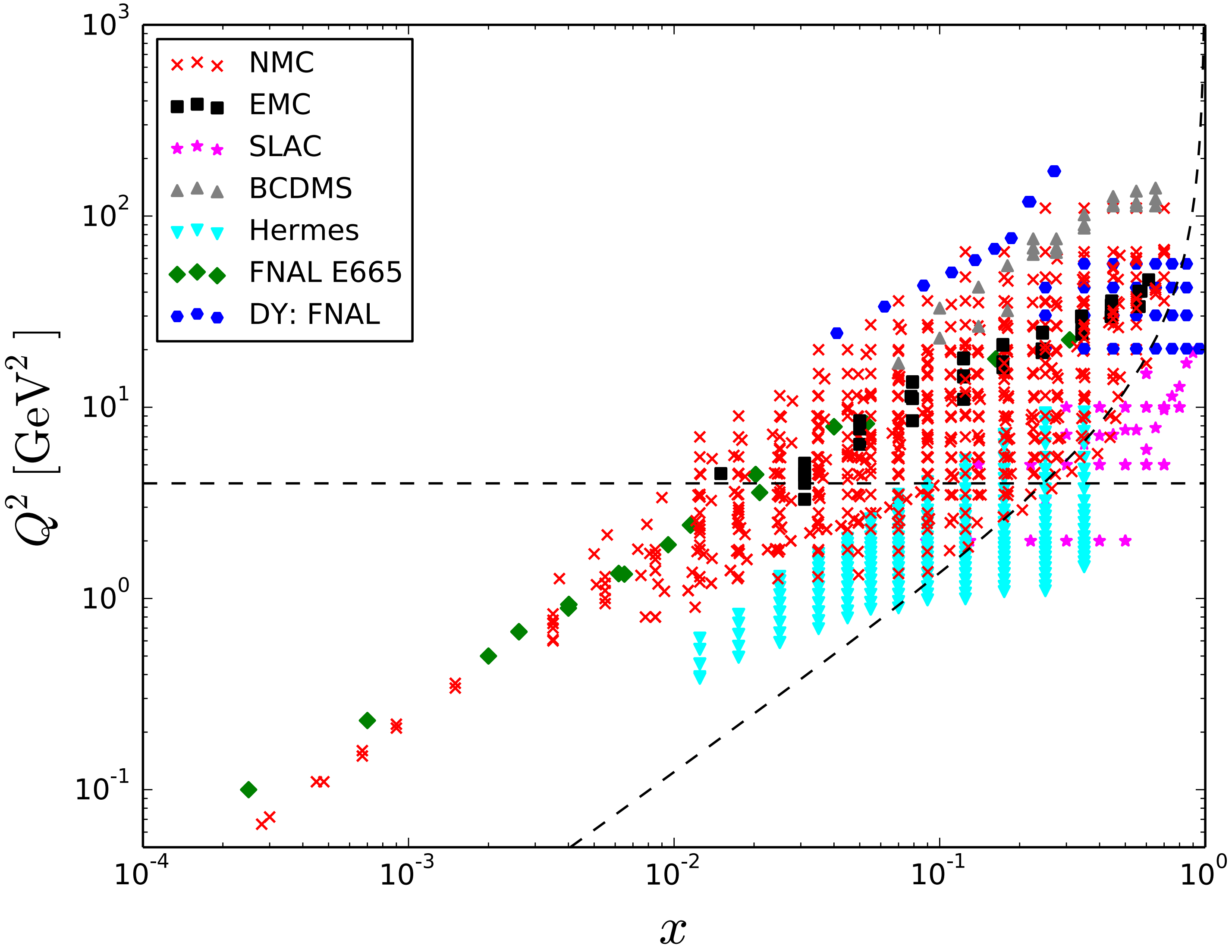
nCTEQ:

$$\begin{cases} Q > 2 \text{ GeV} \\ W > 3.5 \text{ GeV} \end{cases}$$

EPS: $Q > 1.3$ GeV

HKN: $Q > 1$ GeV

DSSZ: $Q > 1$ GeV



nCTEQ: 740 data points

EPS09: 929 data points

Fit details

PRD93(2016)085037

Fit properties:

- fit @NLO

Fit quality

- $\chi^2/dof = 0.81$

sc

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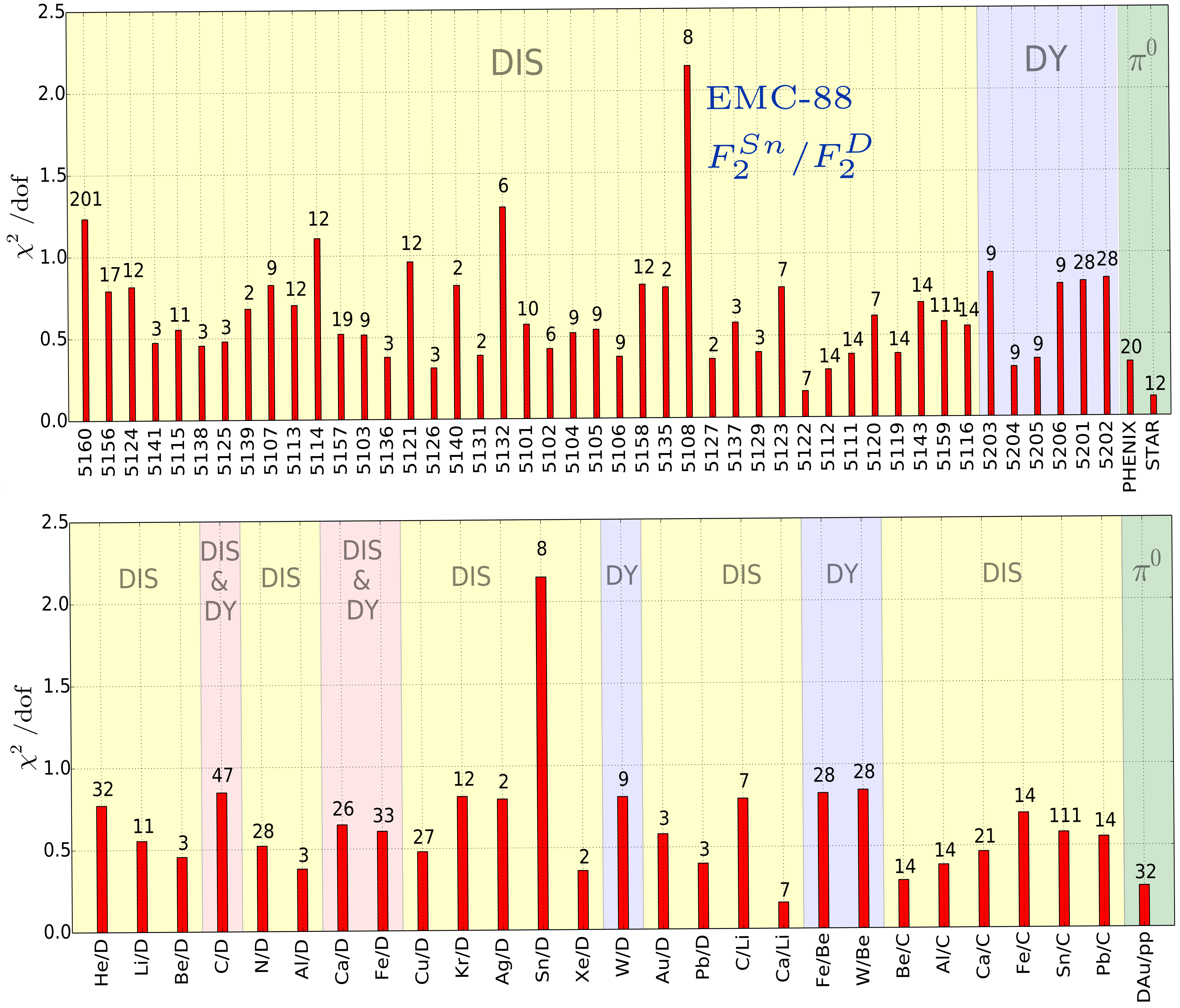
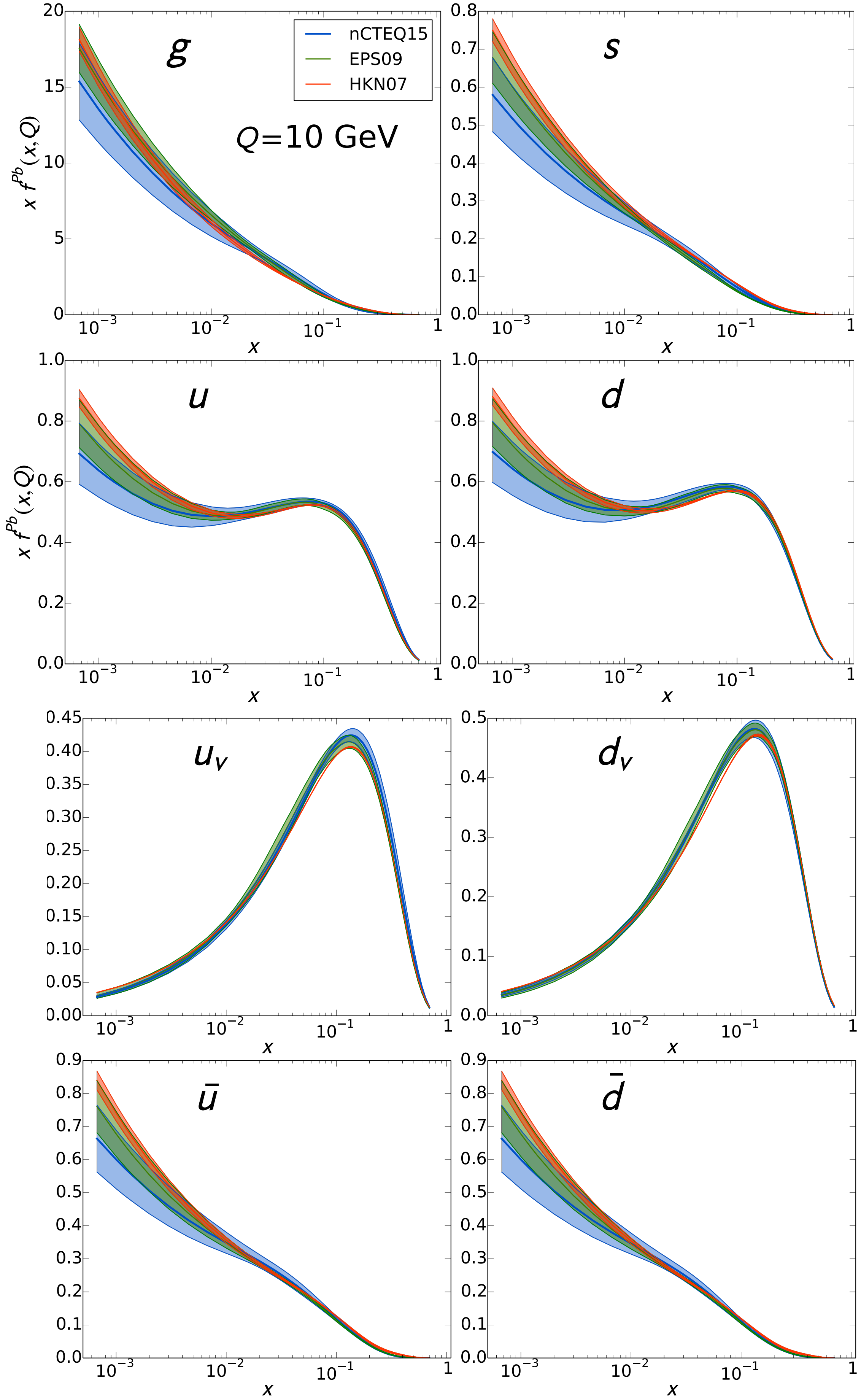


nCTEQ results

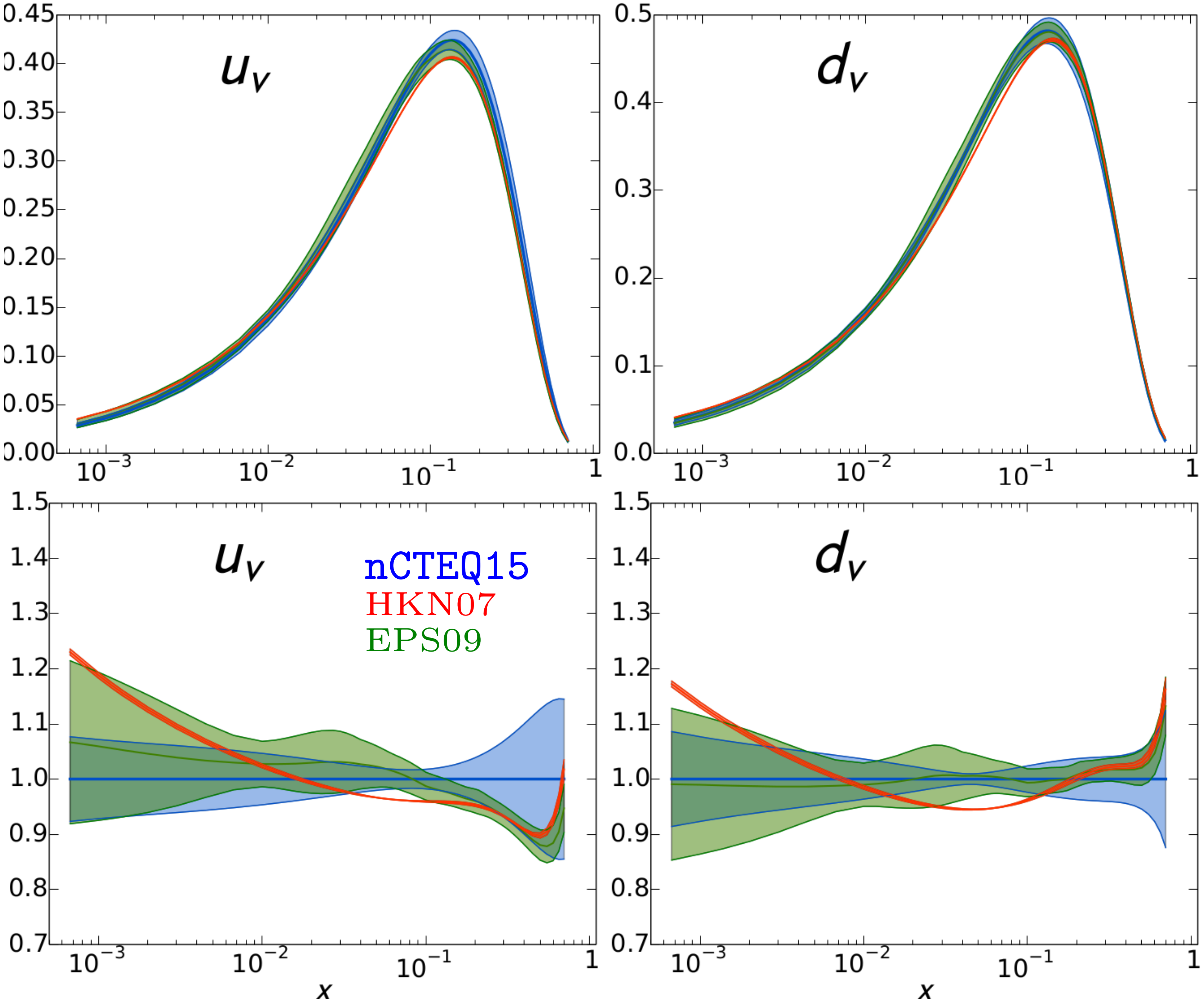
- First global analysis with Hessian error PDFs: [PRD93(2016]085037]
- Figure: PDFs inside lead at Q=10 GeV vs x
- nCTEQ features larger uncertainties than previous nPDFs
- better agreement between different groups



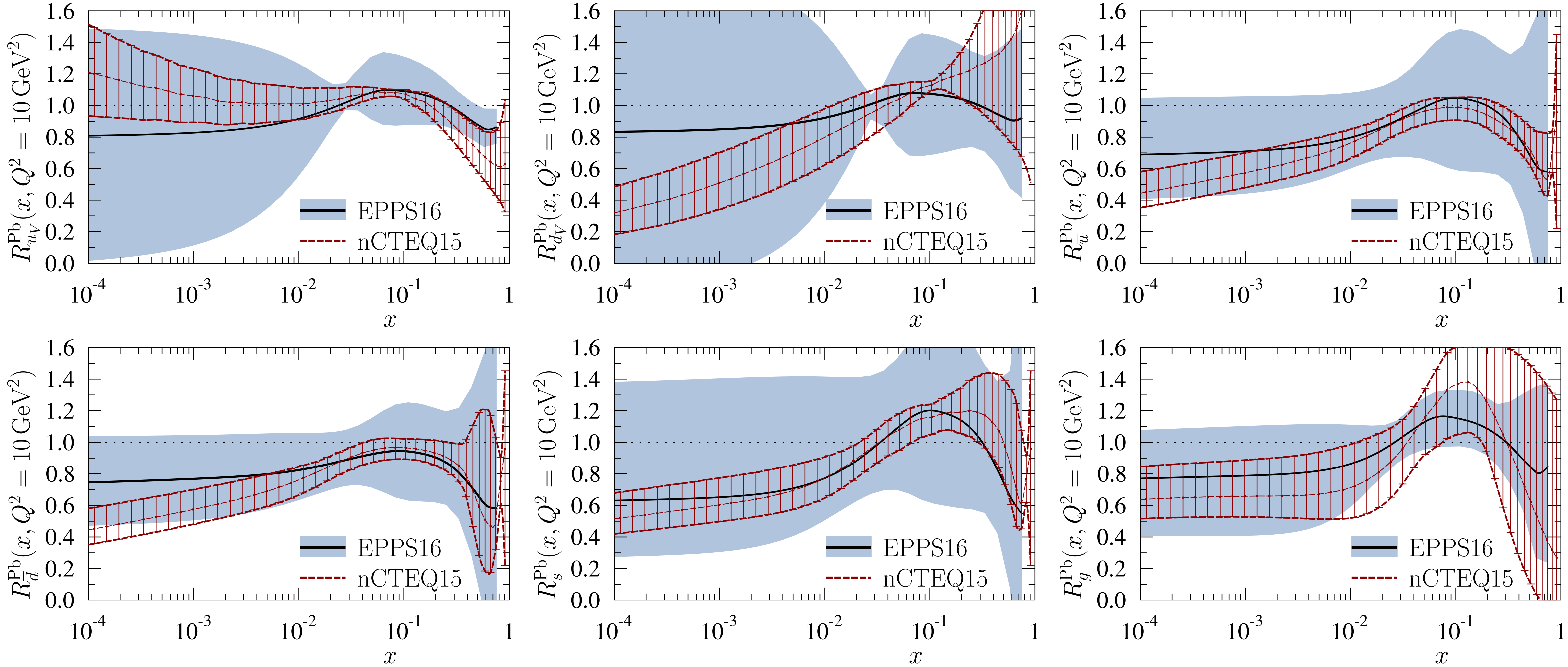
Valence distributions

Full lead nucleus distribution:

$$f^{Pb} = \frac{82}{208} f^{p/Pb} + \frac{208-82}{208} f^{n/Pb}$$

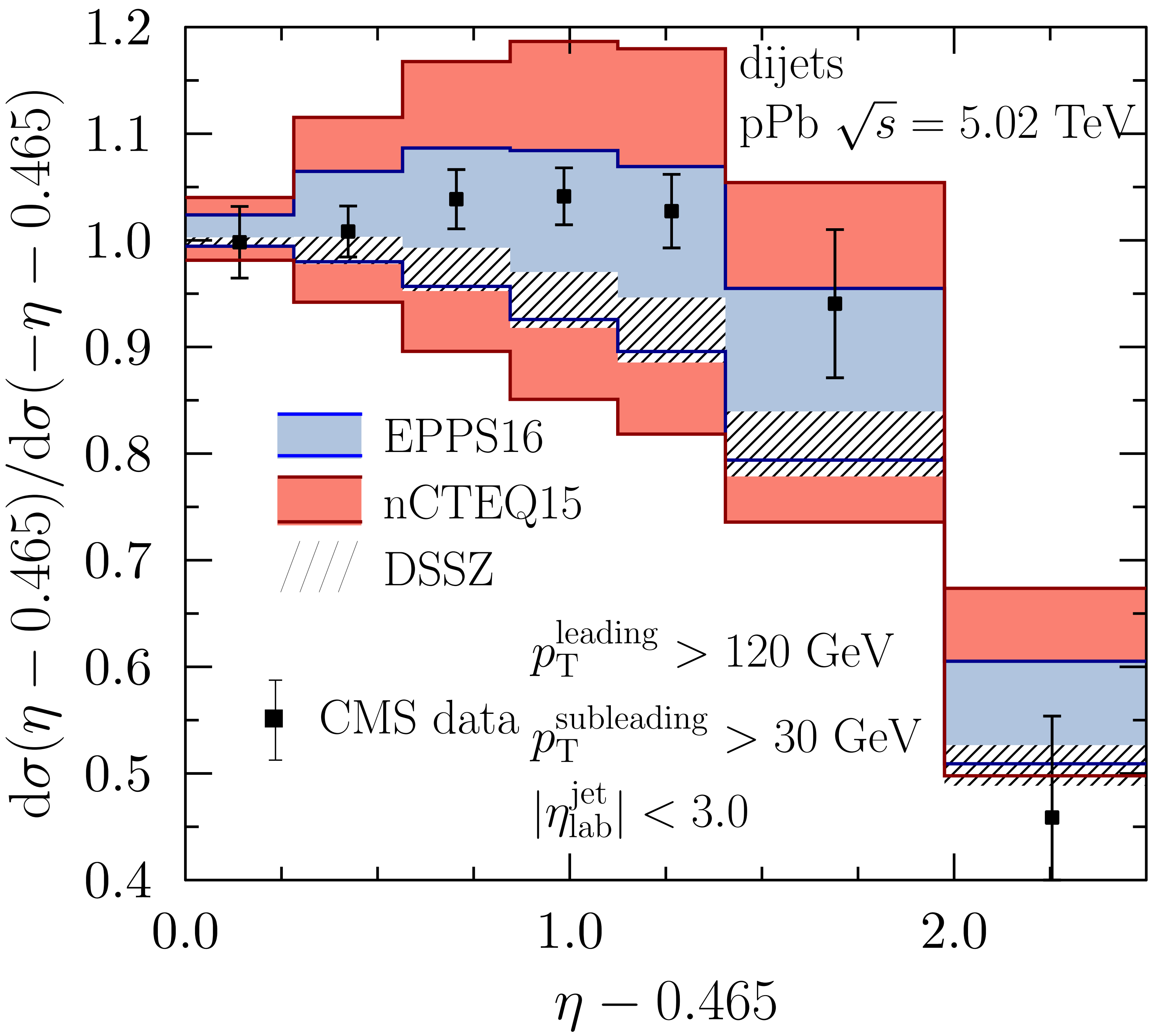


EPPS'16 vs nCTEQ'15 @Q^2=10 GeV^2



- 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?

LHC p-Pb data useful for constraining nPDF

Available pPb LHC data useful for nPDF fits

- 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]
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  - ALICE [arXiv:1509.07324]

Available pPb LHC data useful for nPDF fits

light sea,
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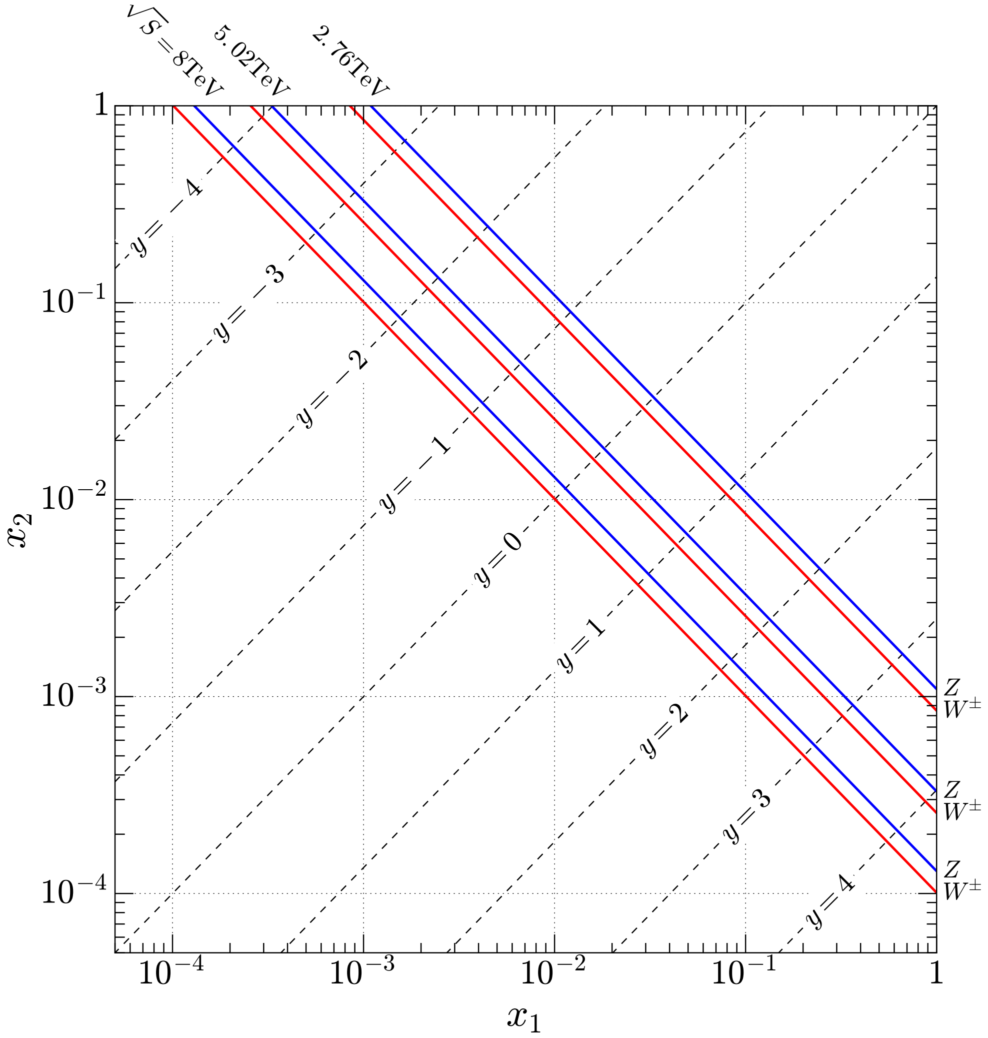
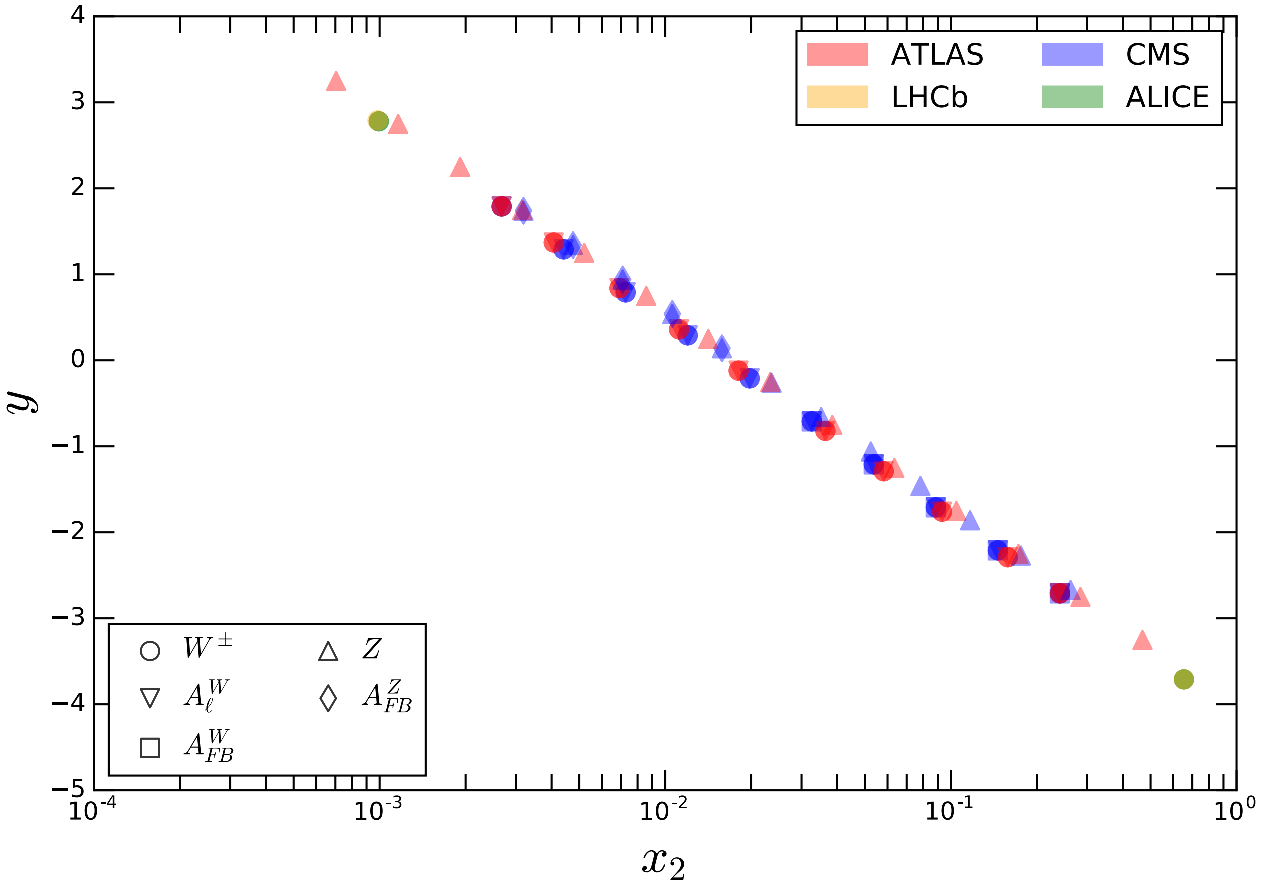
nCTEQ study of W,Z production at LHC



arXiv:1610.02925

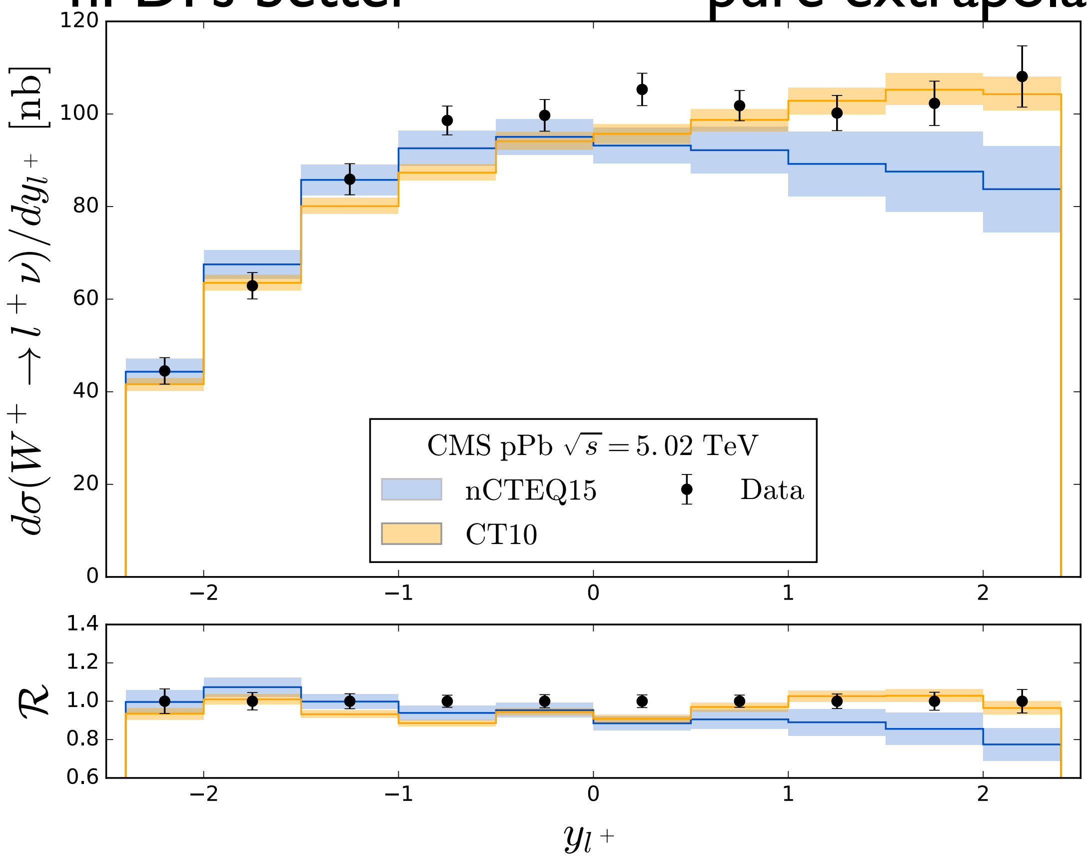


- $y < -1$: $x > 5\ \mathrm{x}10^{-2}$ ... 0.3 (region where nPDFs are constrained by data in global analysis)
- $|y| < 1$: $x \sim 10^{-2}$ (transition region from anti-shadowing to shadowing)
- $y > 1$: $x < 5\ \mathrm{x}\ 10^{-3}$ (pure extrapolation!)

W-boson rapidity distributions

nPDFs better

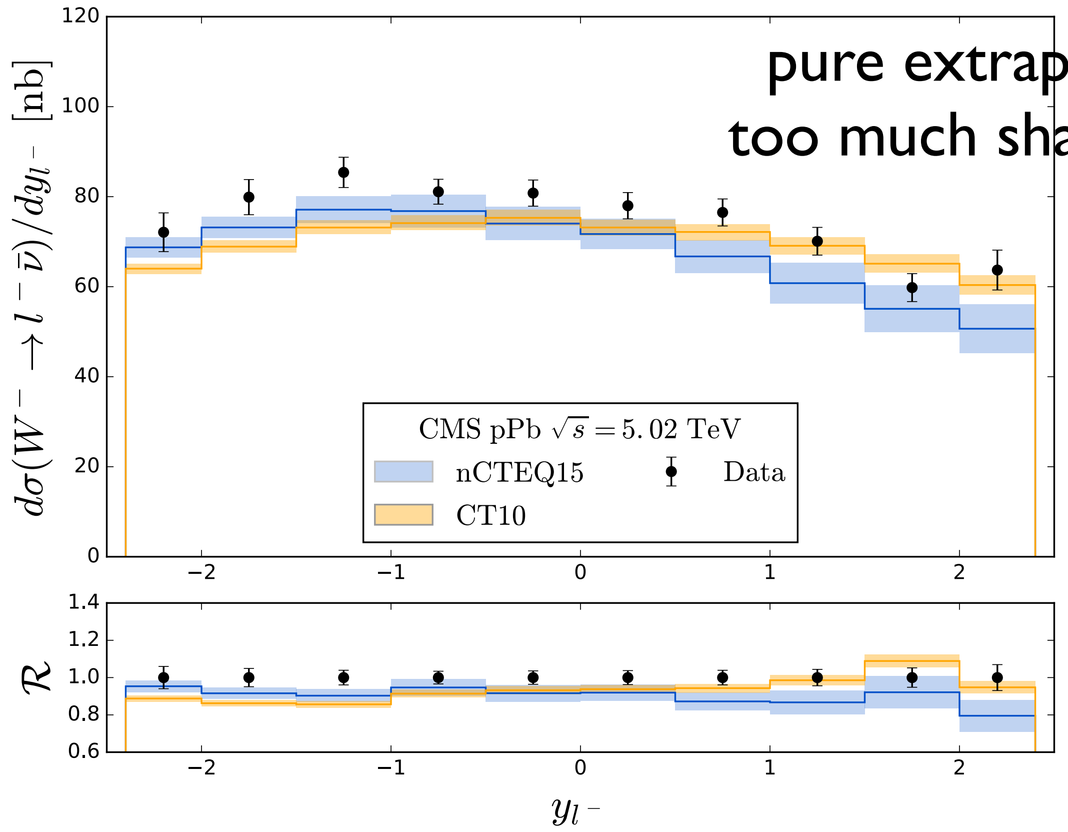
pure extrapolation



nPDFs better

pure extrapolation

too much shadowing?



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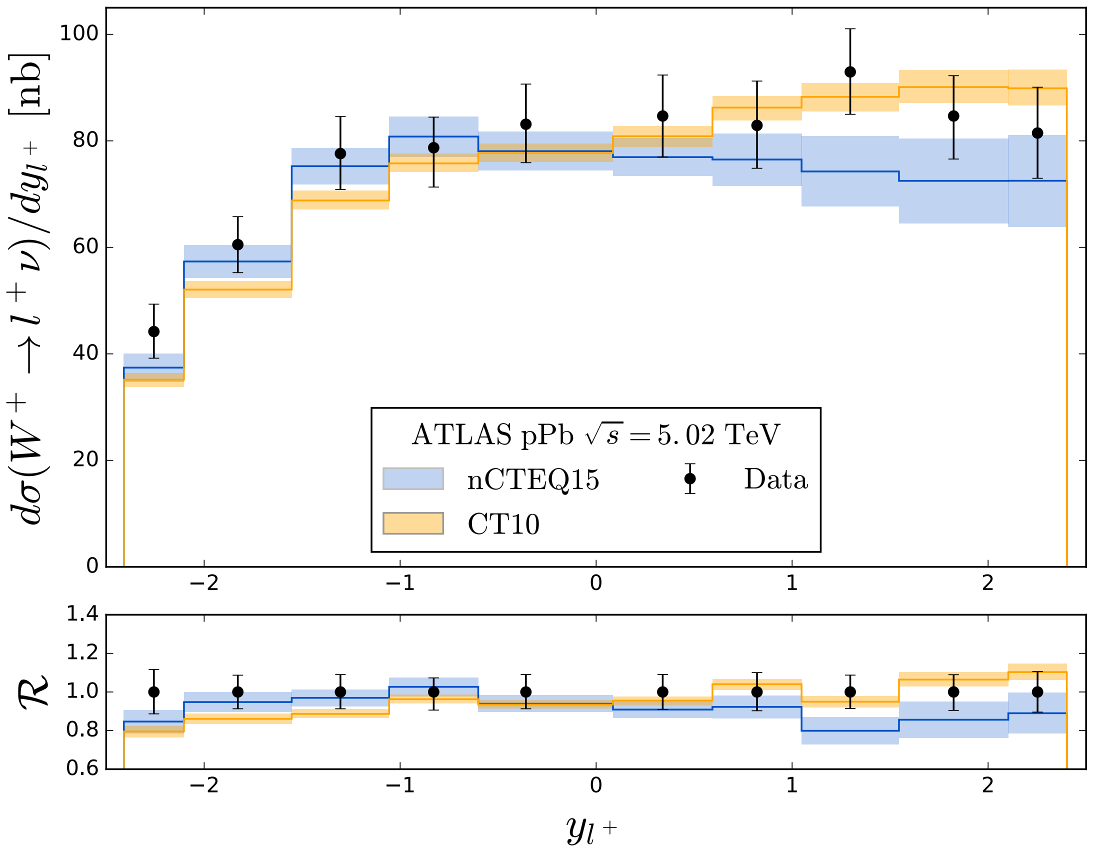
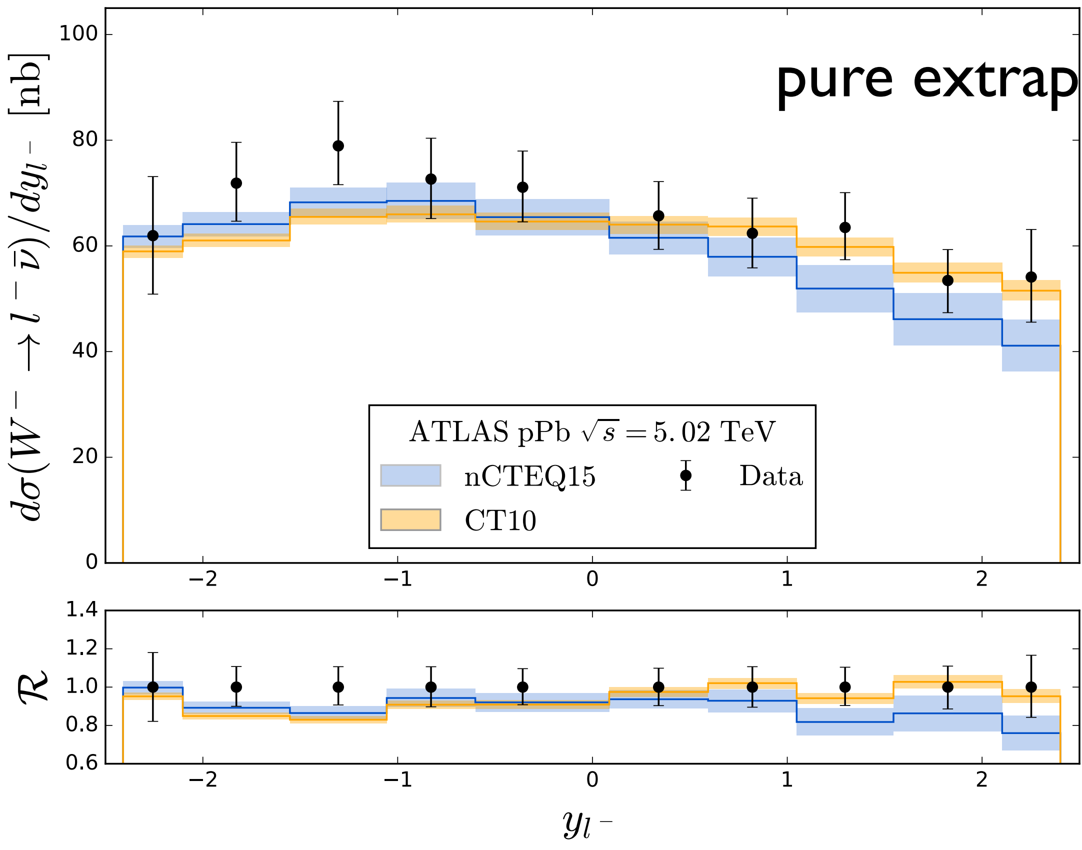


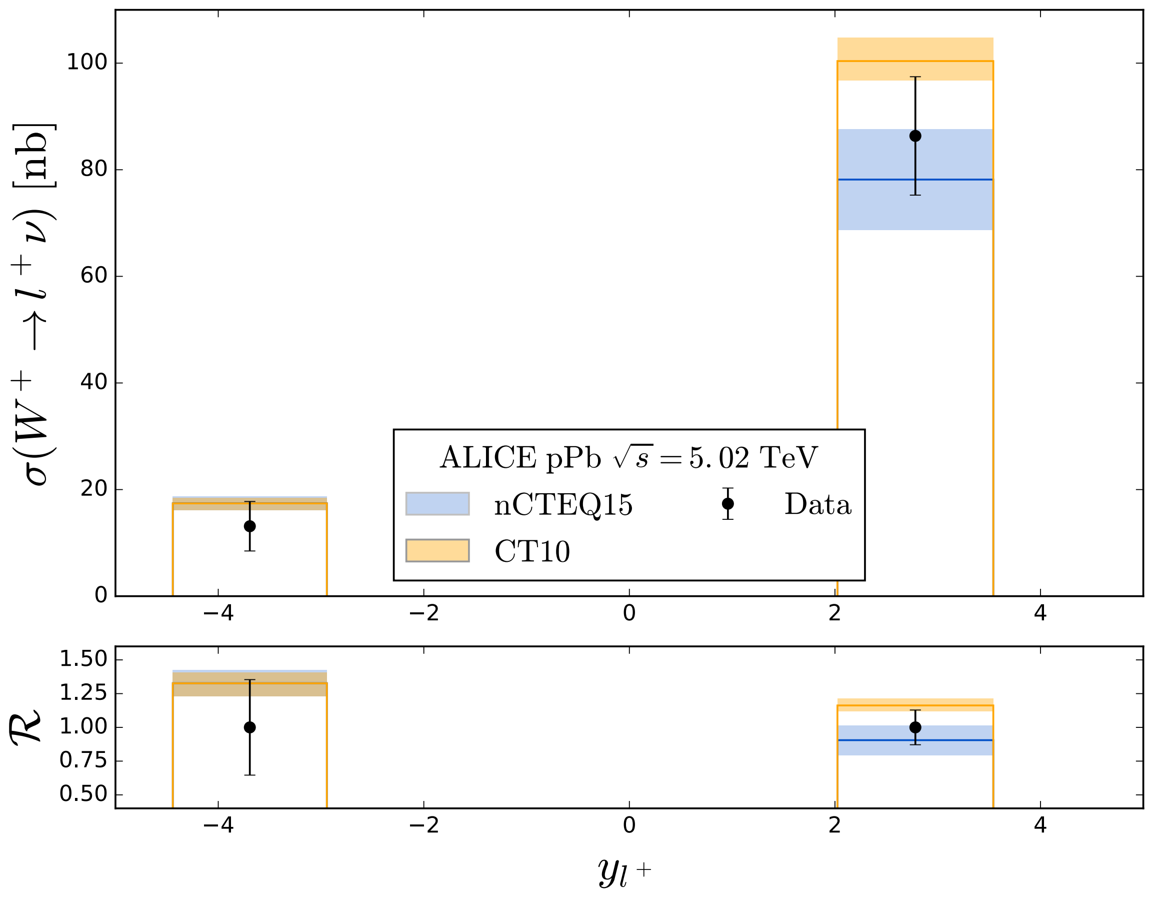
nPDFs better

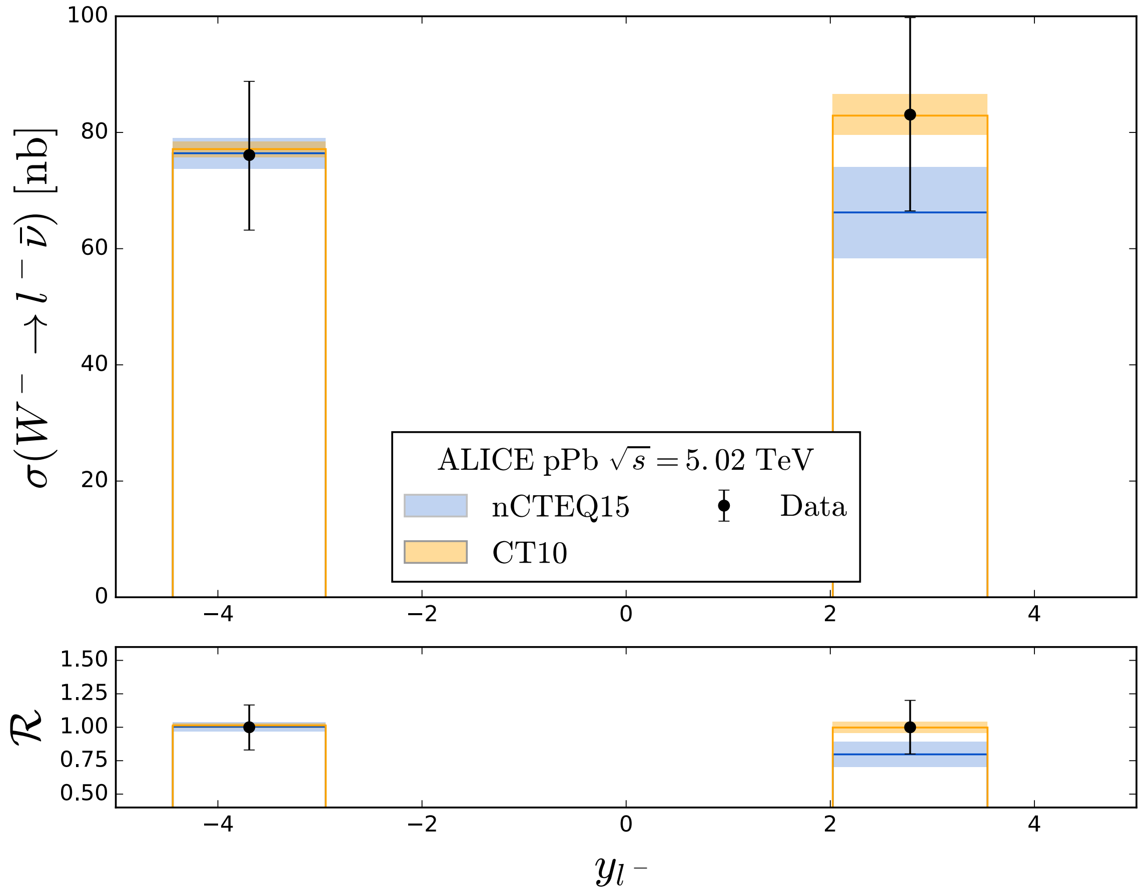
pure extrapolation



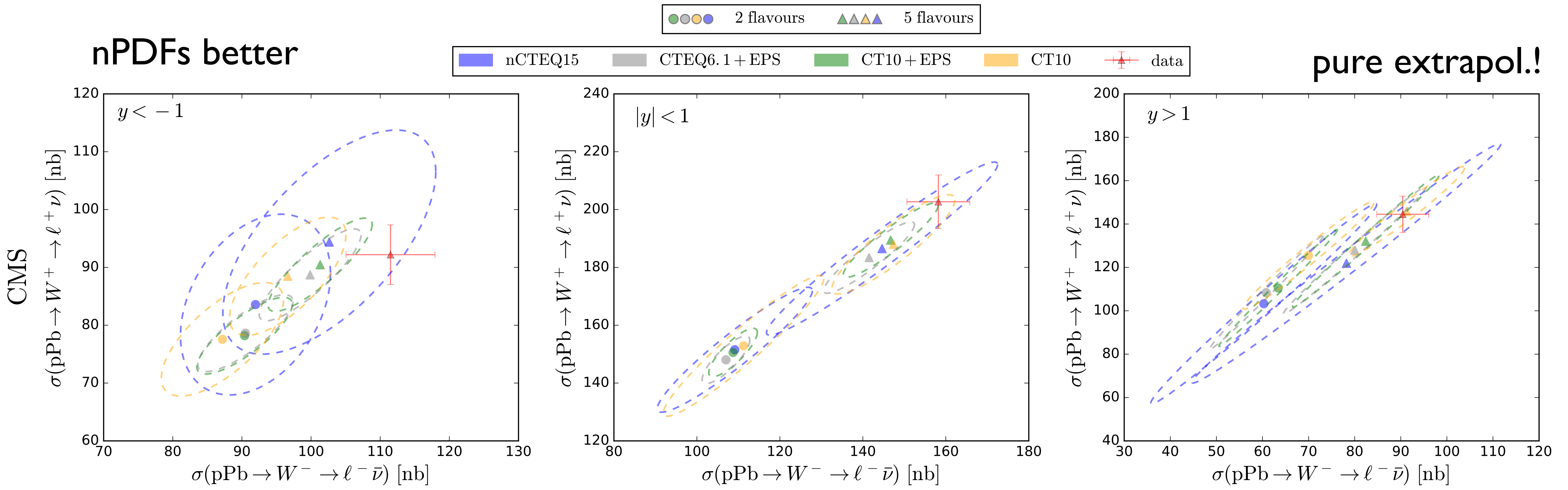
W-boson rapidity distributions

ALICE data:





Importance of strange PDF

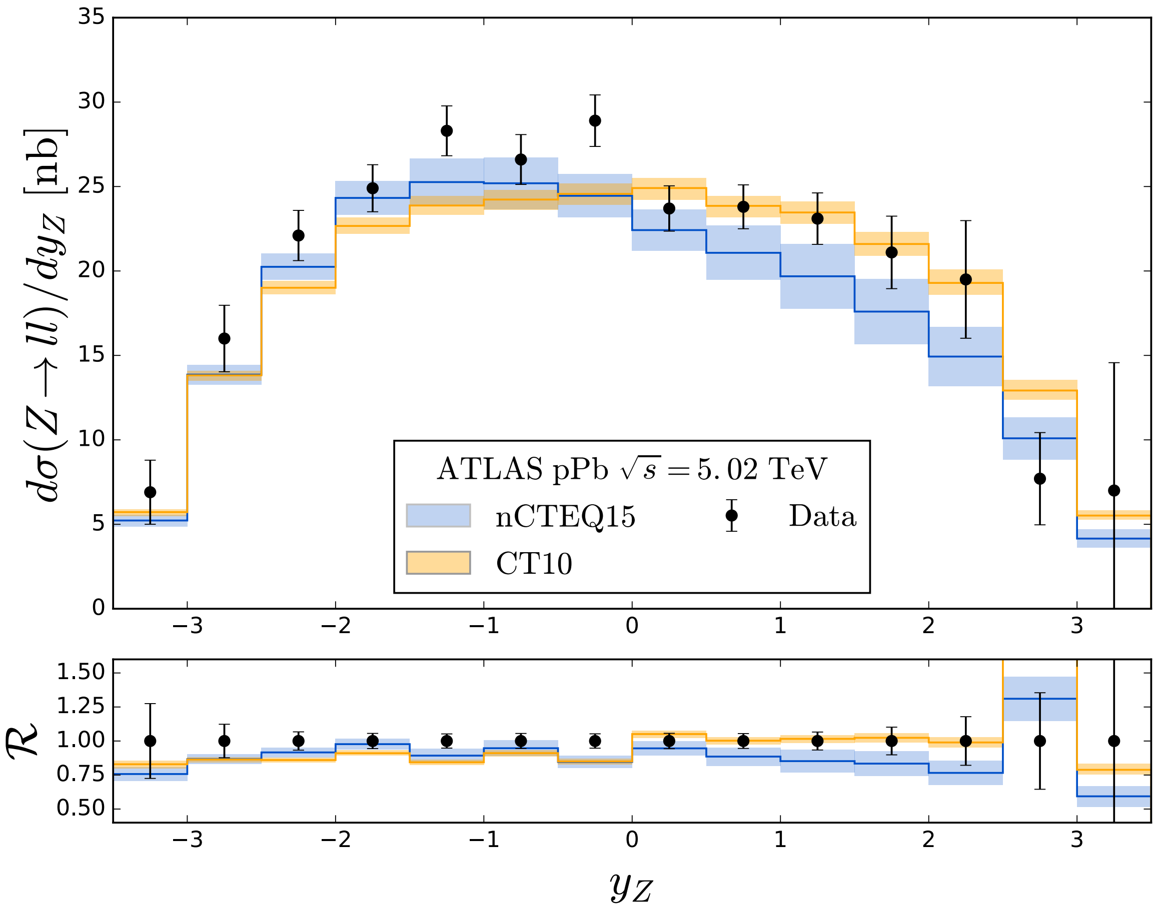


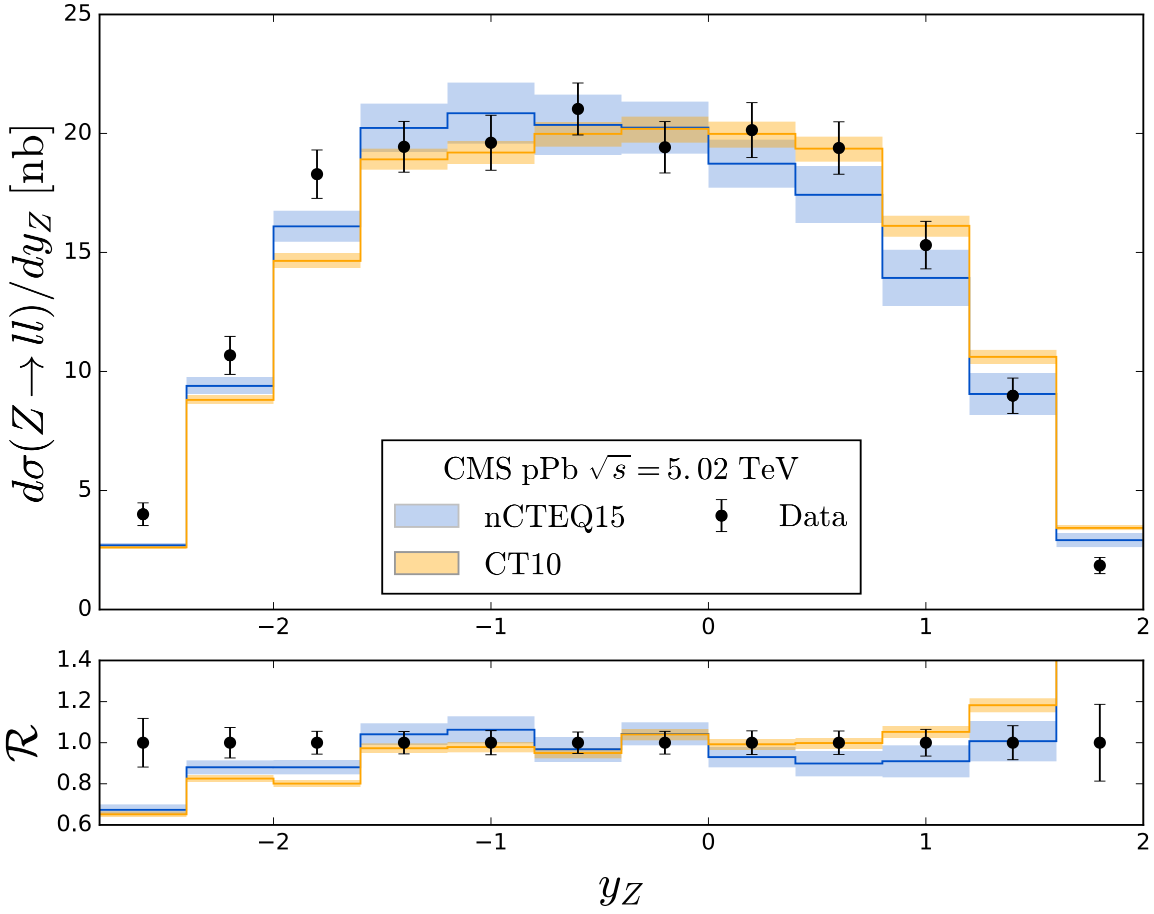
nPDFs better

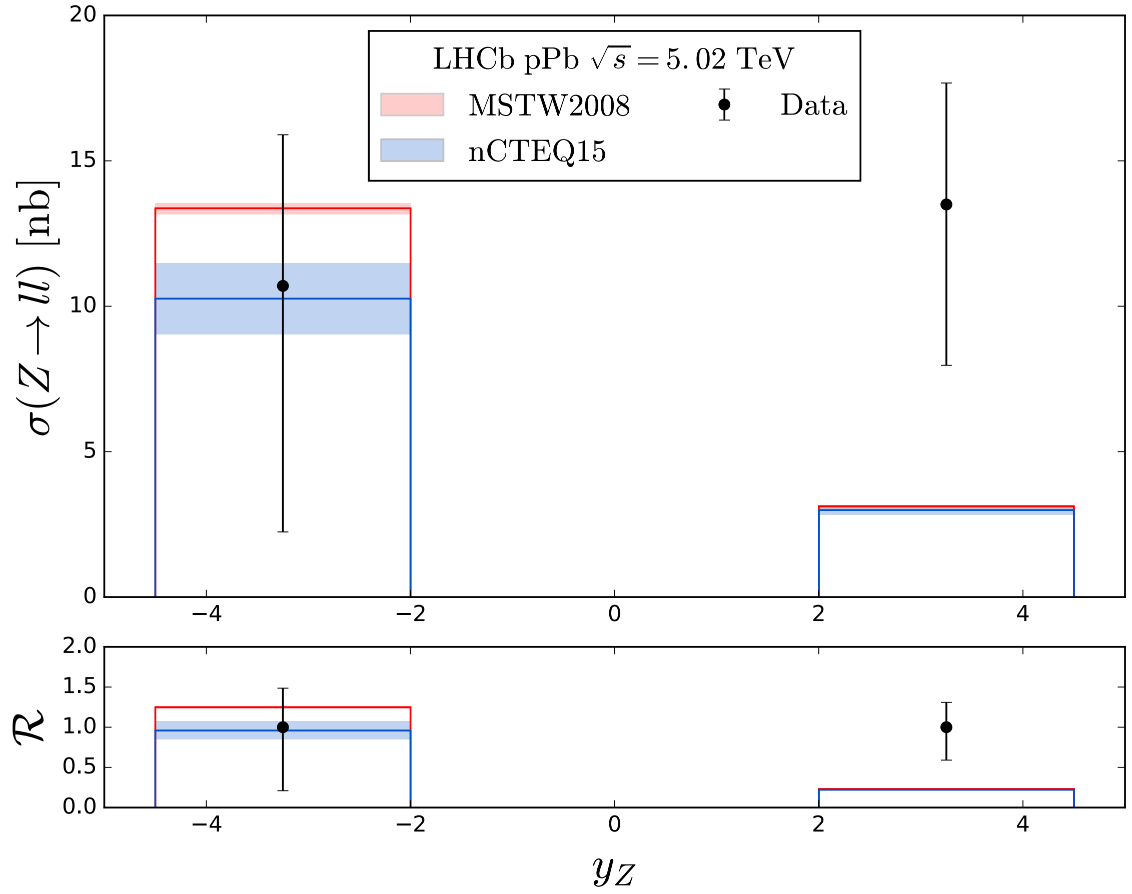
pure extrapol.!

- **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 very small x?

Z-boson rapidity distributions







What about heavy quarks?

- Charmonium production
  - Probes **gluon at small-x**
  - Theory under control?
- Inclusive D-meson production

  works in pp case!

  - Very sensitive to **gluon at small-x**!
    see PROSA study (for the gluon in the proton): EPJC75(2015)396, arXiv: 1503.04581
  - at large p_T and forward rapidites: probe of IC
- Inclusive photon+charm production
  - **probe of intrinsic charm**

work by T. Stavreva et al.

Conclusions

- Much recent progress (EPPS'16, NCTEQ'15, W/Z analysis)
- nPDF uncertainties still substantial
  (more realistic larger uncertainties now with EPPS'16)
- Need more precise LHC pA data from as many hard processes as possible! Lead-only analysis possible!
- Coloured and un-coloured final states to test shadowing vs energy loss effects
- Bright future: future fixed target experiments, EIC, LHeC, π-A data from COMPASS
- A lot of room for theoretical progress

Part II: D-meson production in the GM-VFNS

GM-VFNS

Factorization Formula: [1]

$$d\sigma(p\bar{p} \to D^\star X) = \sum_{i,j,k} \int dx_1\, dx_2\, dz\, f_i^p(x_1)\, f_j^{\bar{p}}(x_2) \times$$

$$\mathrm{d}\hat{\sigma}(ij \to kX)\, D_k^{D^\star}(z) + \mathcal{O}(\alpha_s^{n+1}, (\tfrac{\Lambda}{Q})^p)$$

Q: hard scale, $p = 1, 2$

- $\mathrm{d}\hat{\sigma}(\mu_F, \mu_F', \alpha_s(\mu_R), \frac{m_h}{p_T})$: hard scattering cross sections free of long-distance physics $\longrightarrow$ m_h kept
- PDFs $f_i^p(x_1, \mu_F)$, $f_j^{\bar{p}}(x_2, \mu_F)$: $i, j = g, q, c \quad [q = u, d, s]$
- FFs $D_k^{D^\star}(z, \mu_F')$: $k = g, q, c$

$\Rightarrow$ need short distance coefficients including heavy quark masses

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[1] J. Collins, 'Hard-scattering factorization with heavy quarks: A general treatment', PRD58(1998)094002

List of subprocesses in the GM-VFNS

	Only light lines	Heavy quark initiated ($m_Q = 0$)	Mass effects: $m_Q \neq 0$
❶	$gg \to qX$	-	$gg \to QX$
❷	$gg \to gX$	-	-
❸	$qg \to gX$	$Qg \to gX$	-
❹	$qg \to qX$	$Qg \to QX$	-
❺	$q\bar{q} \to gX$	$Q\bar{Q} \to gX$	-
❻	$q\bar{q} \to qX$	$Q\bar{Q} \to QX$	-
❼	$qg \to \bar{q}X$	$Qg \to \bar{Q}X$	-
❽	$qg \to \bar{q}'X$	$Qg \to \bar{q}X$	$qg \to \bar{Q}X$
❾	$qg \to q'X$	$Qg \to qX$	$qg \to QX$
❿	$qq \to gX$	$QQ \to gX$	-
⓫	$qq \to qX$	$QQ \to QX$	-
⓬	$q\bar{q} \to q'X$	$Q\bar{Q} \to qX$	$q\bar{q} \to QX$
⓭	$q\bar{q}' \to gX$	$Q\bar{q} \to gX$, $q\bar{Q} \to gX$	-
⓮	$q\bar{q}' \to qX$	$Q\bar{q} \to QX$, $q\bar{Q} \to qX$	-
⓯	$qq' \to gX$	$Qq \to gX$, $qQ \to gX$	-
⓰	$qq' \to qX$	$Qq \to QX$, $qQ \to qX$	-

$\oplus$ charge conjugated processes

Limiting cases

- **GM-VFNS → ZM-VFNS for $p_T >> m$**
  (this is the case by construction)

- **GM-VFNS → FFNS for $p_T \sim m$**
  (formally this can be shown; numerically problematic in the S-ACOT scheme)

Termes in the perturbation series

$L = \ln(m/p_T)$
$a = \alpha_s/(2\pi)$

Resummed ↓

Fixed Order →

	LL	NLL	NNLL	...
LO	1			
NLO	aL	a		
NNLO	$(aL)^2$	$a(aL)$	a^2	
...	...	...	...	...

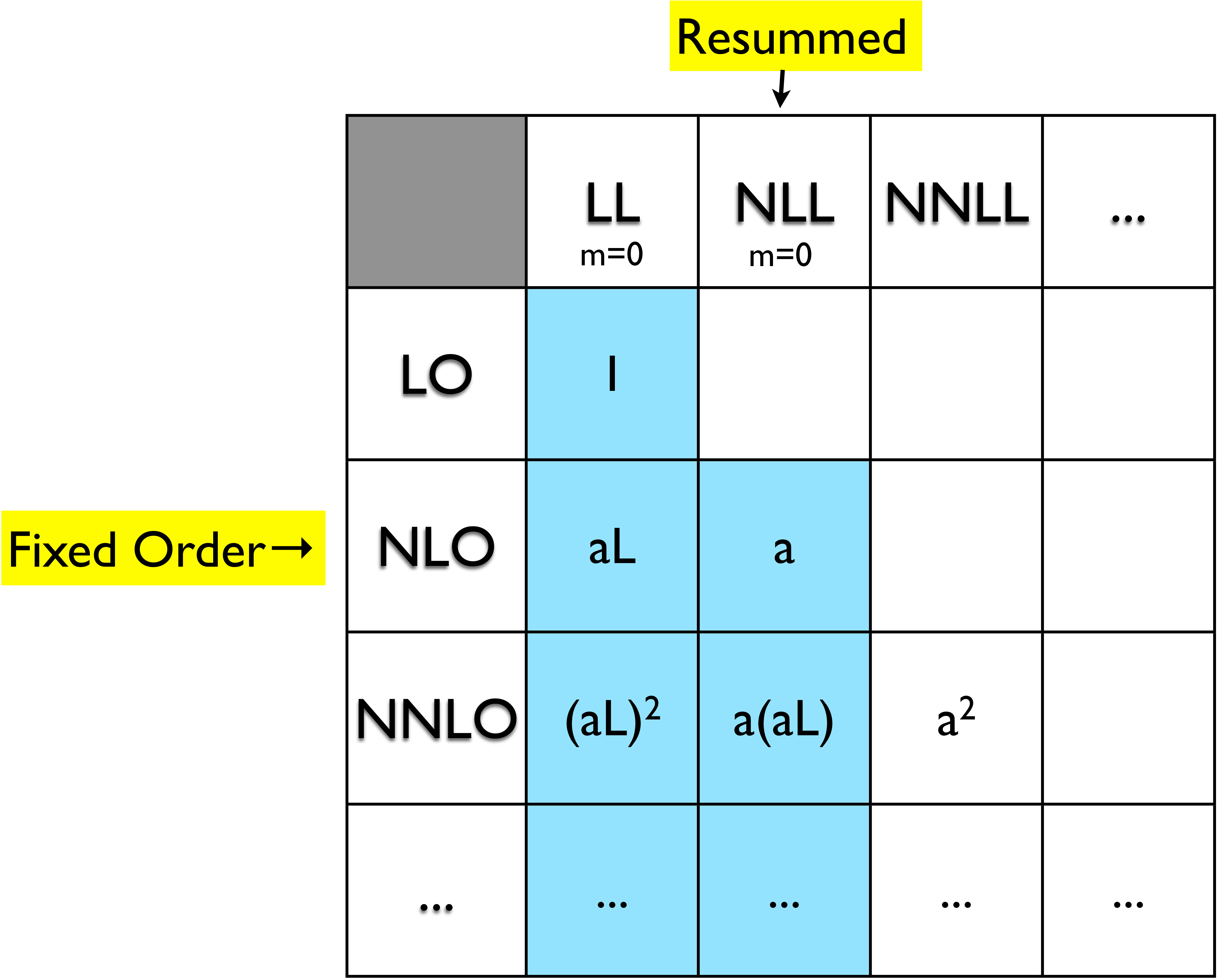
FFNS/Fixed Order NLO

Resummed ↓

Fixed Order→

	LL	NLL	NNLL	...
LO $m\neq0$	1			
NLO $m\neq0$	aL	a		
NNLO	$(aL)^2$	$a(aL)$	a^2	
...	...	...	...	...

ZM-VFNS/Resummed NLO



Resummed

Fixed Order→

	LL m=0	NLL m=0	NNLL	...
LO	1			
NLO	aL	a		
NNLO	$(aL)^2$	a(aL)	a^2	
...	...	...	...	...

GM-VFNS/FONLL (NLO+NLL)

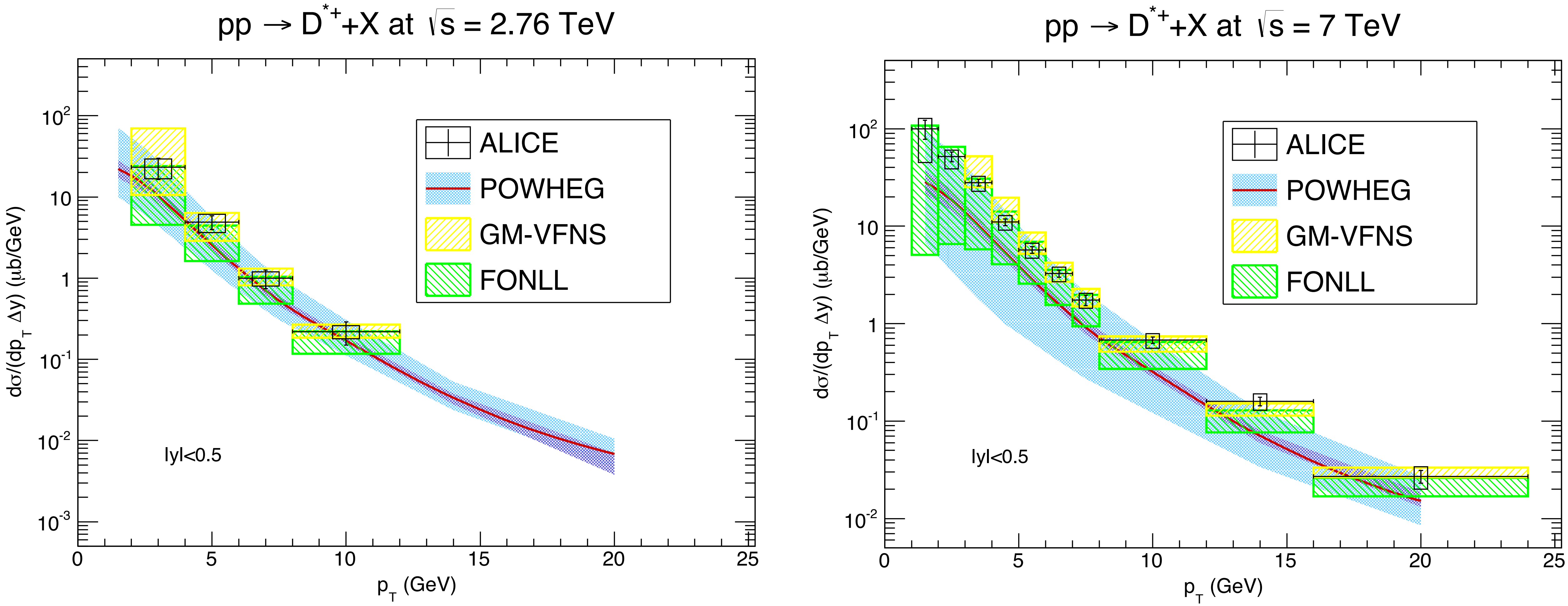
Resummed ↓

Fixed Order →

	LL	NLL	NNLL	...
LO	1 $m\neq0$			
NLO	aL $m\neq0$	a $m\neq0$		
NNLO	$(aL)^2$ $m=0$	$a(aL)$ $m=0$	a^2	
...	... $m=0$	... $m=0$	...	...

Comparison with ALICE data

arXiv:1405.3083



Central scale choice: $\mu_R=\mu_F=\mu_F'=m_T$

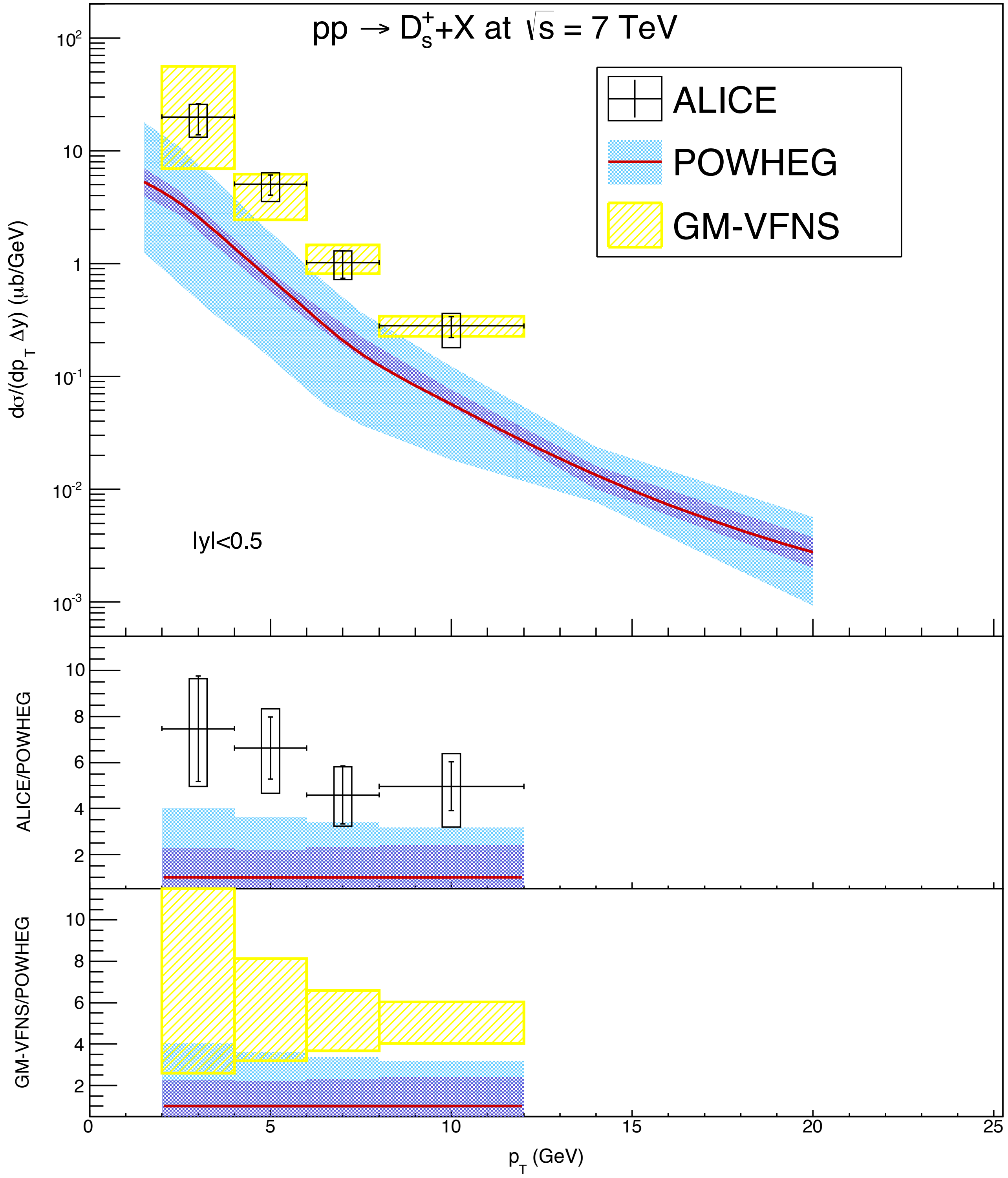
Uncertainty band: varying the scales by a factor 2 up/down

CT10 PDFs, KKKS FFs, m_c = 1.5 GeV

Comparison with ALICE data

D_s FFs from Kniehl, Kramer'06

arXiv:1405.3083

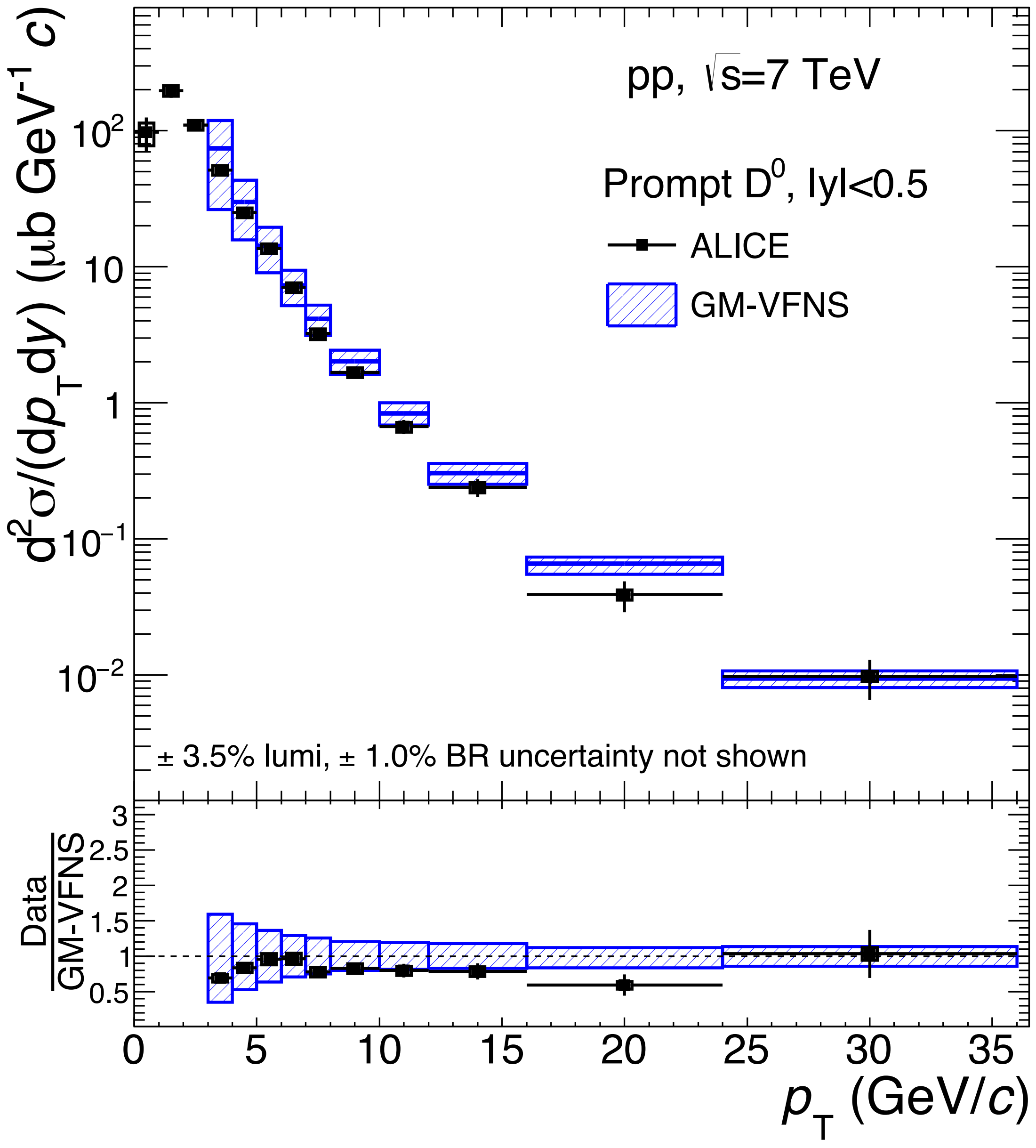


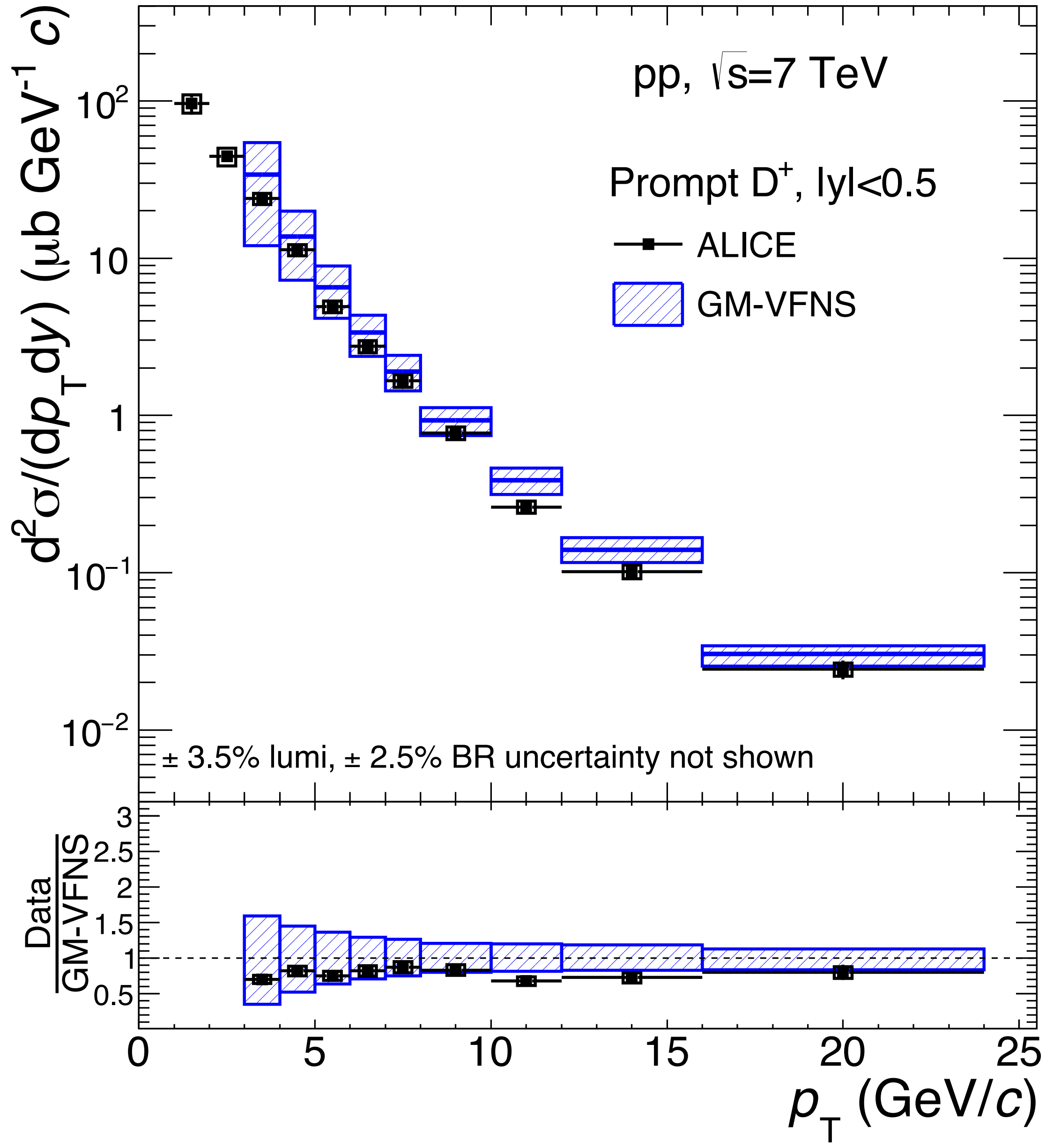
Recent numerical results

- a (D^*,D^0,D^+, D_s) in pp@7 TeV, |y|<0.5, pT=
- Ratio of D^0/D^+ (etc) predicted to be flat at p_T>2 m
- Λ_c in pp@5 TeV
- Results for p-Pb in progress
  - $d\sigma/dp_T$ sensitive to small-x nuclear gluon but large scale uncertainty
  - R_{pA} will be sensitive to small-x nuclear gluon PDF with reduced scale uncertainty; careful study required

Comparison with most recent ALICE data

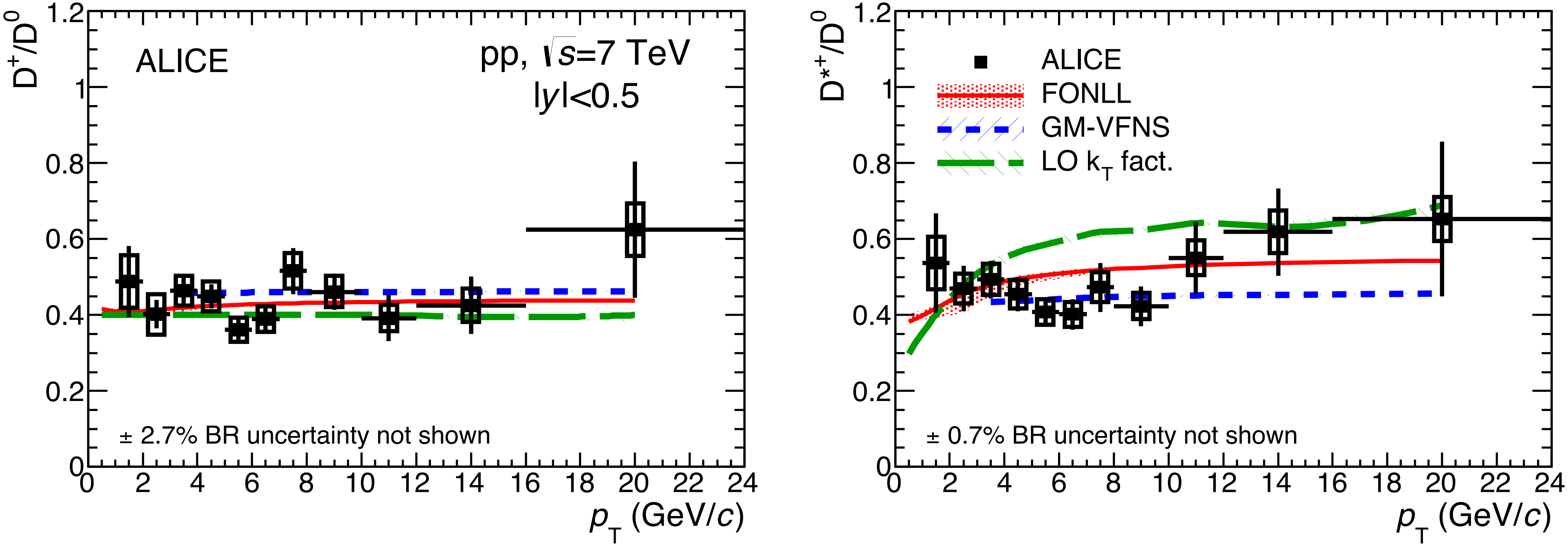
arXiv:1702.00766





Comparison with most recent ALICE data

arXiv:1702.00766

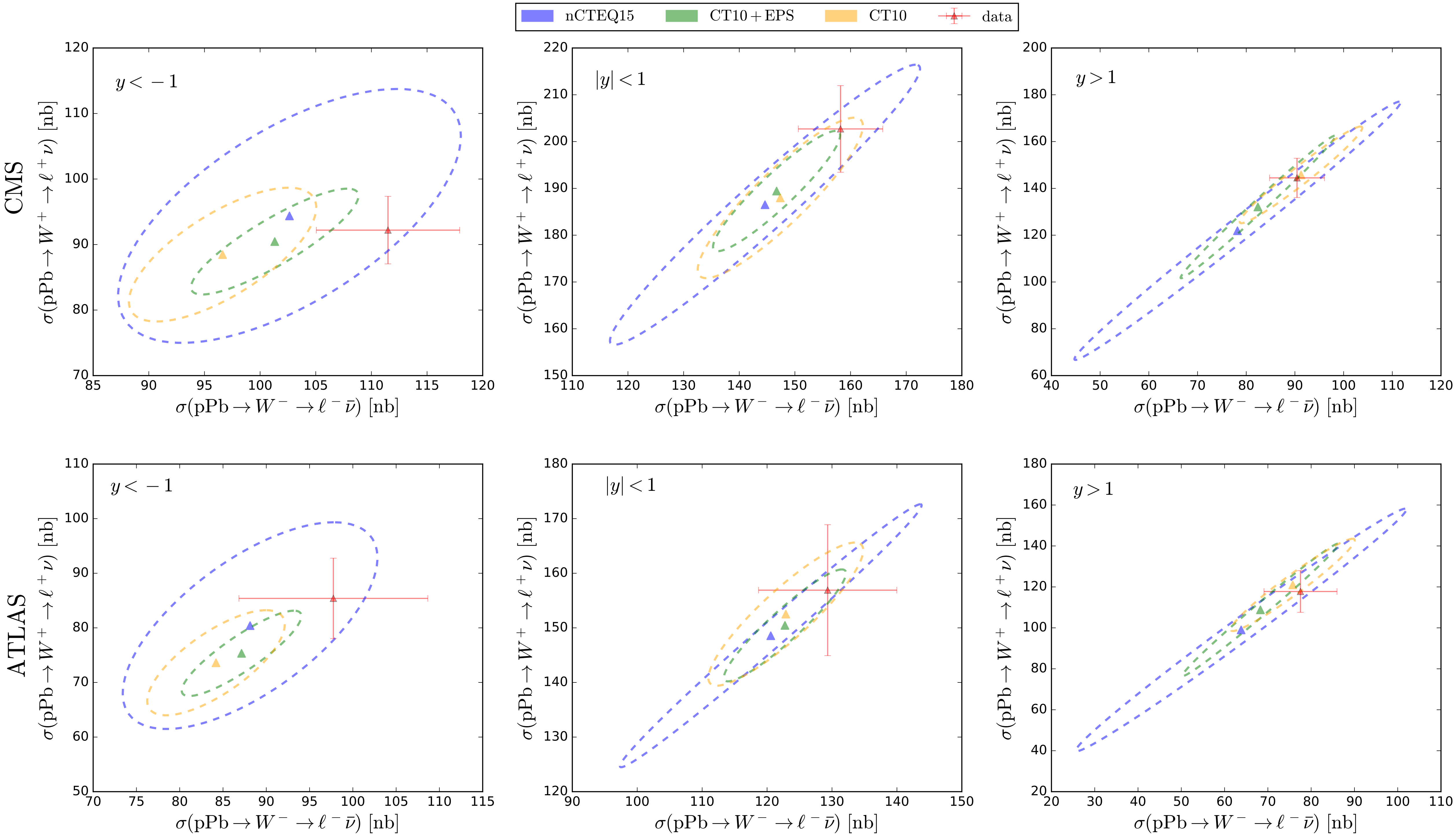


Conclusion

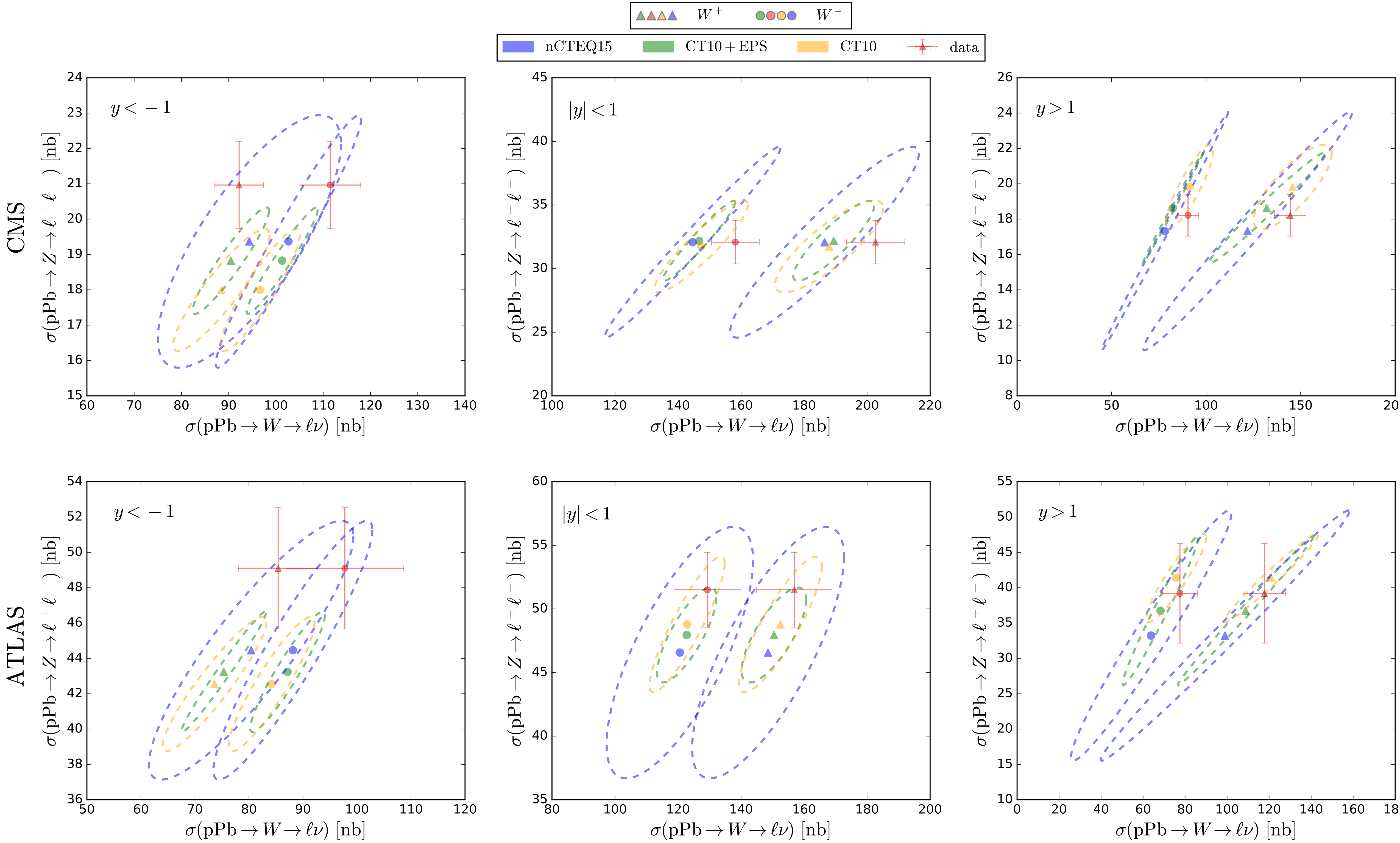
- GM-VFNS in good agreement with ALICE data for inclusive D meson production
- Large scale uncertainties!
  To make progress need NNLO
- p-Pb heavy quark data (D,B) interesting to constrain the small-x nuclear gluon distribution
- More results to come. Stay tuned.

Backup

(W^+, W^-) Correlation



(Z,W) Correlation



FONLL=FO+NLL [1]

$$\mathrm{FONLL} = \mathrm{FO} + (\mathrm{RS} - \mathrm{FOM0})\mathrm{G}(\mathrm{m}, \mathrm{p_T})$$

FO: Fixed Order; FOM0: Massless limit of FO; RS: Resummed

$$G(m, p_T) = \frac{p_T^2}{p_T^2 + 25m^2} \simeq \begin{cases} 0.04 & : \quad p_T = m \\ 0.25 & : \quad p_T = 3m \\ 0.50 & : \quad p_T = 5m \\ 0.66 & : \quad p_T = 7m \\ 0.80 & : \quad p_T = 10m \end{cases}$$

$$\Rightarrow \mathrm{FONLL} = \begin{cases} \mathrm{FO} & : \quad \mathrm{p_T} \lesssim 3\mathrm{m} \\ \mathrm{RS} & : \quad \mathrm{p_T} \gtrsim 10\mathrm{m} \end{cases}$$

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[1] Cacciari, Greco, Nason, JHEP05(1998)007

FONLL

- FFs in N-space in the PFF approach
- RS-FOM0 gets very large at small p_T:

  $G(m,p_T) = p_T^2/(p_T^2 + a^2\ m^2)$ with **a=5**

  needed to suppress this contribution sufficiently rapidly
- Central scale choice for FO, RS, FOM0: m_T
- Error bands: $\mu_F = \mu_F'$ (only two scales varied)
- Predictions for LHC7 in arXiv:1205.6344