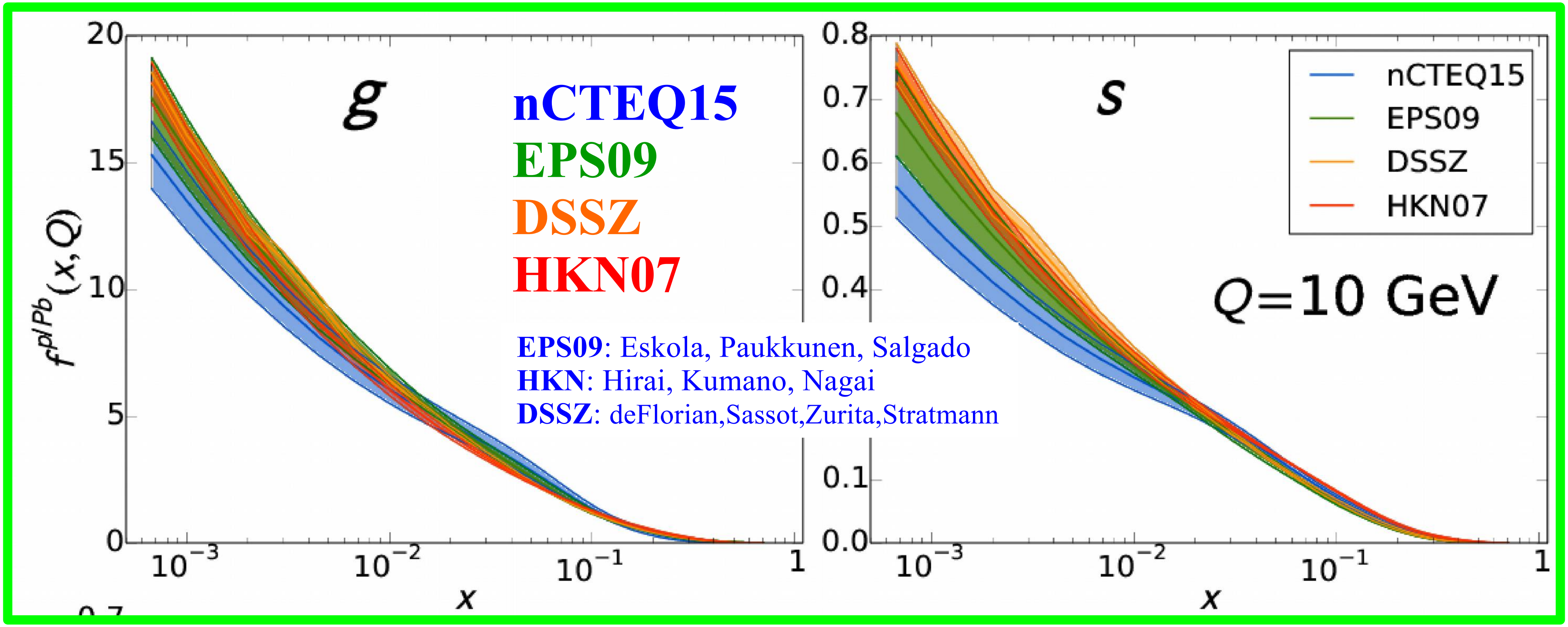
PDF Flavor Determination with LHC W/Z

challenges and opportunities

updates from the nCTEQ collaboration

Fred Olness

SMU



Thanks to:

P. Nadolsky, F. Lyonnet, B. Clark, E. Godat, A. Kusina,, I. Schienbein, K. Kovarik, J.Y. Yu, T. Jezo, J.G. Morfin, J.F. Owens, P. Nadolsky, M. Guzzi, V. Radescu, C. Keppel, xFitter Collaboration

CERN

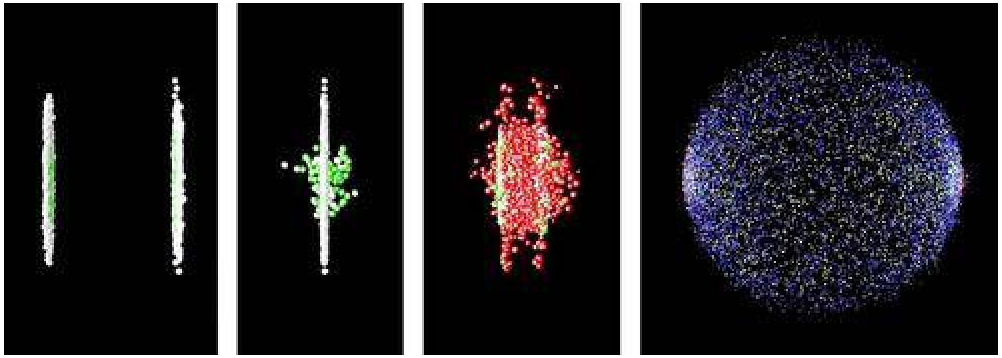
16 June 2017

Motivation for nPDFs???

Make predictions for heavy ion collisions at:

RHIC (Al, Au, Cu, U, ...)

LHC (pPb, PbPb)



Differentiate flavors of free-proton PDFs:

neutrino DIS

$$F_2^{\nu} \sim [d + s + \bar{u} + \bar{c}]$$

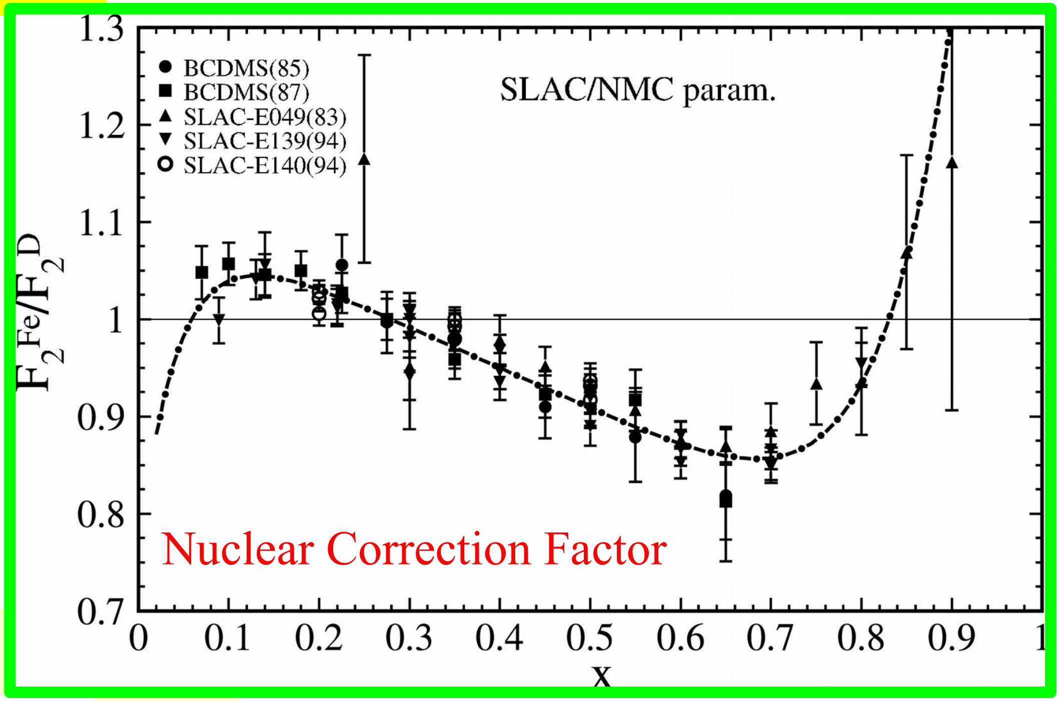
$$F_2^{\bar{\nu}} \sim [\bar{d} + \bar{s} + u + c]$$

$$F_3^{\nu} \sim 2[d + s - \bar{u} - \bar{c}]$$

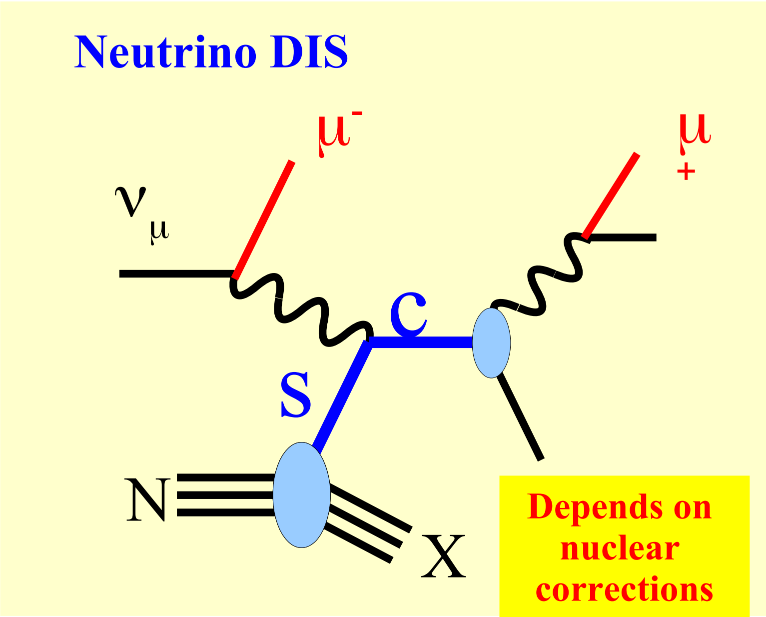
$$F_3^{\bar{\nu}} \sim 2[u + c - \bar{d} - \bar{s}]$$

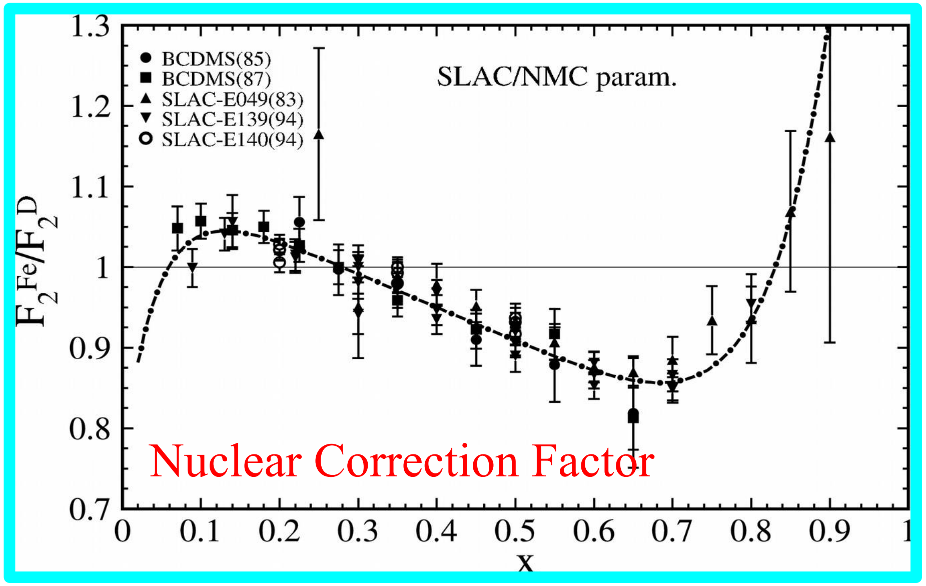
charged lepton DIS

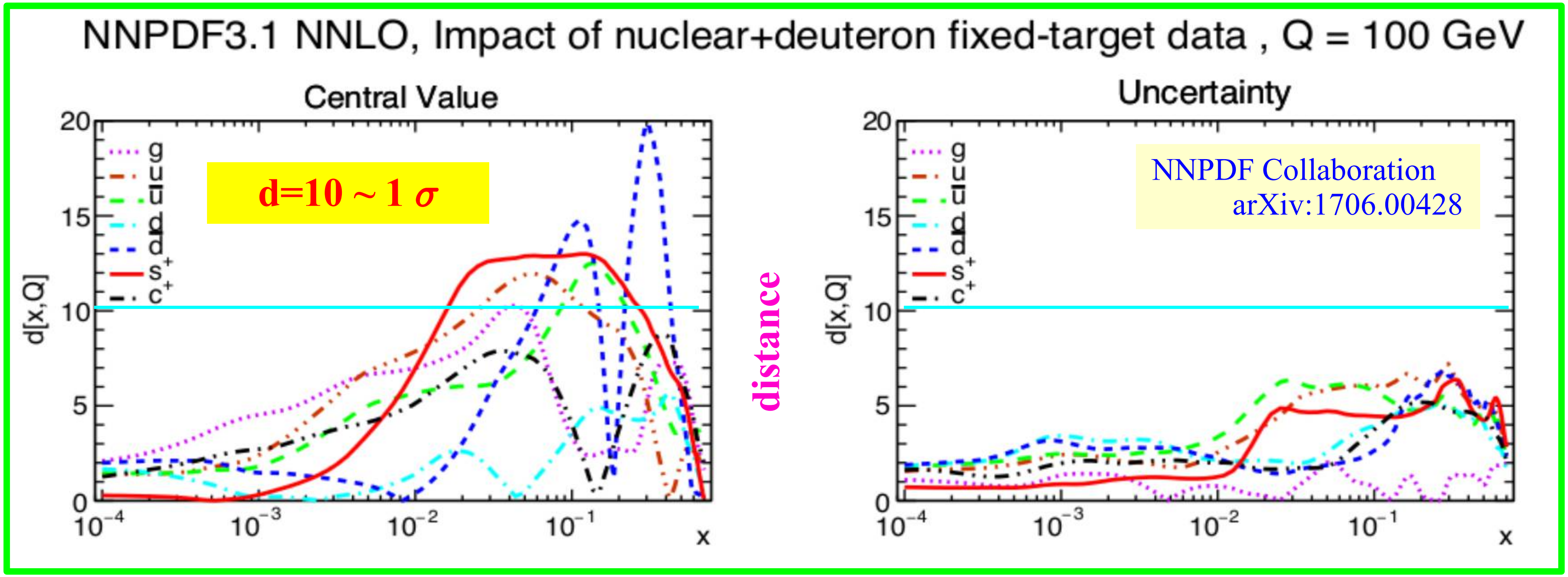
$$F_2^{l^\pm} \sim \left(\frac{1}{3}\right)^2 [d + s] + \left(\frac{2}{3}\right)^2 [u + c]$$



Impact of Nuclear Corrections on Proton PDF

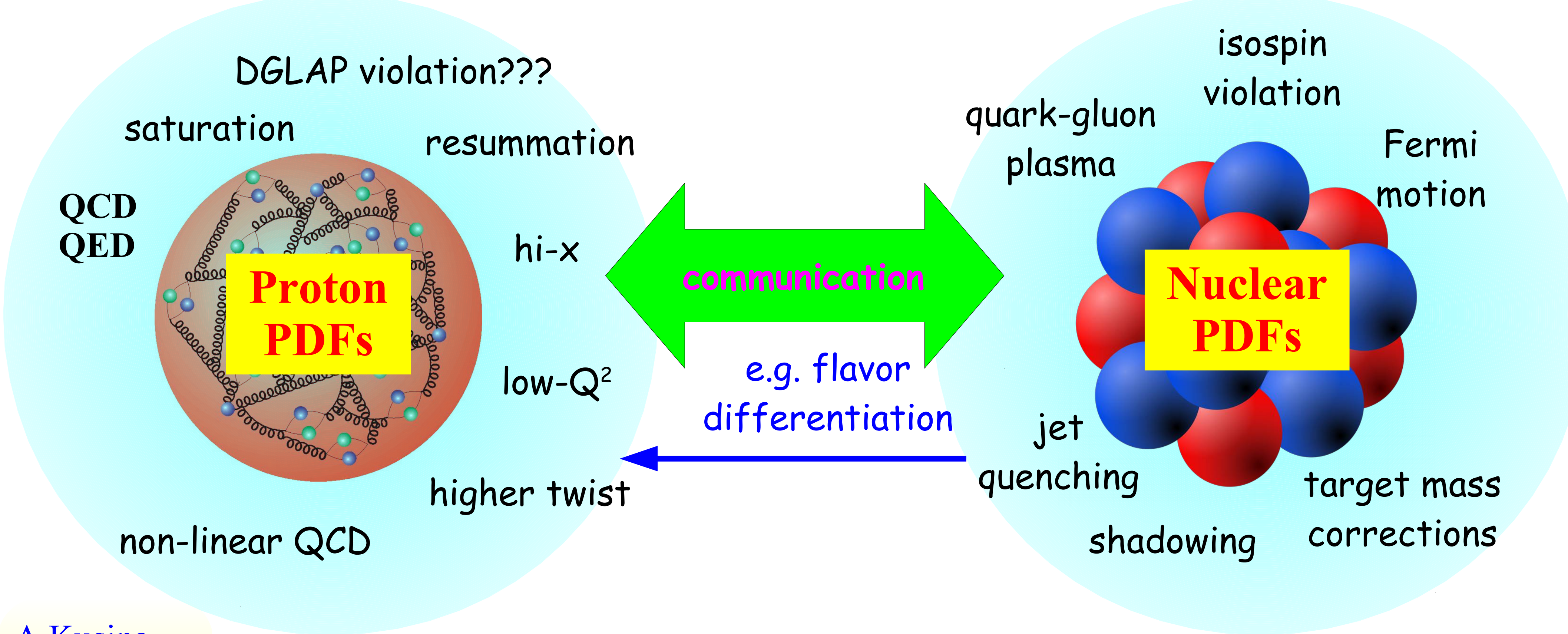






"... for the time being it is still appears advantageous to retain nuclear target data in the global dataset for general-purpose PDF determination"

… the original motivation for nCTEQ



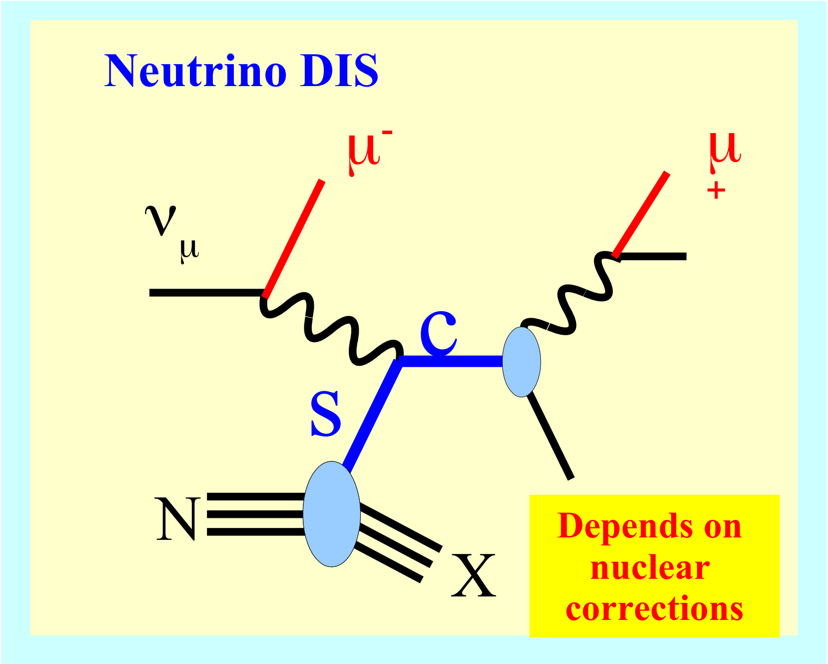
A Kusina,
K. Kovarik
T. Jezo,
D. Clark,
C. Keppel,
F. Lyonnet,
J. Morfin,
F. Olness
J. Owens,
I. Schienbein,
J. Yu
E. Godat

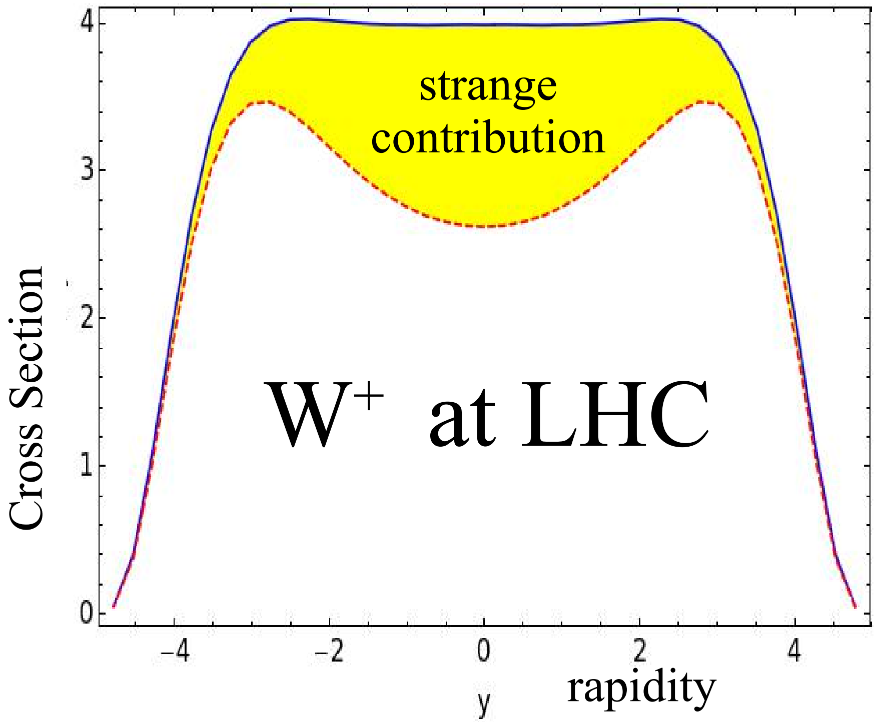
Data from nuclear targets play a key role in the flavor differentiation

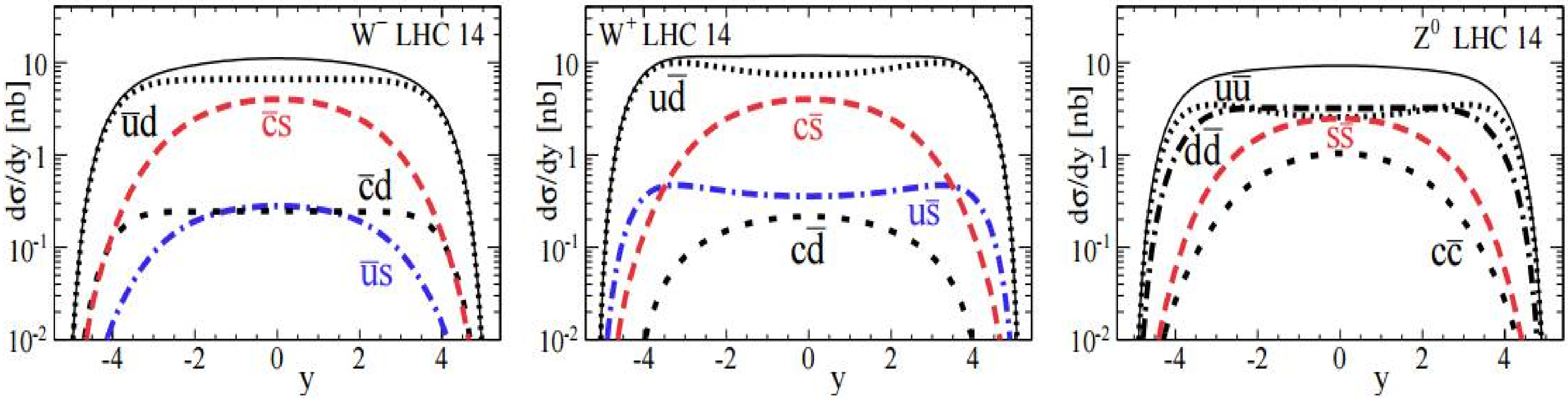
nCTEQ-15

nuclear parton distribution functions

$p\,p \rightarrow W/Z$ Production







LHC 14 TeV

(c) $d\sigma/dy$ for W^- (left), W^+ (middle), Z^0 (right) boson production at the LHC with $\sqrt{S} = 14$ TeV.

Strange Quark PDFs and Implications for Drell-Yan Boson Production at the LHC. A. Kusina, et al.., Phys.Rev. D85 (2012) 094028

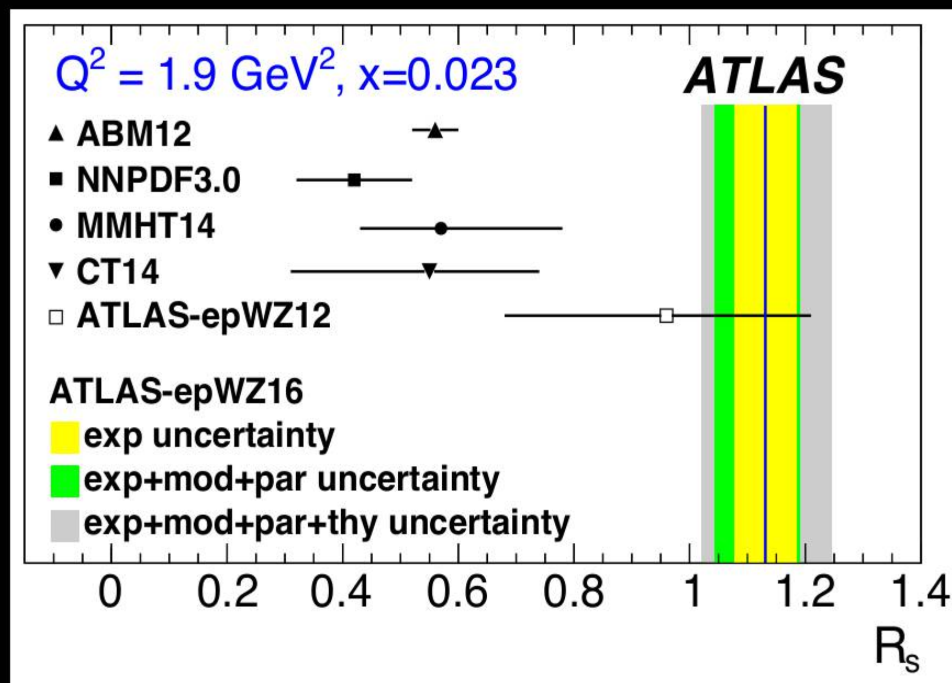
… at DIS2017 we heard …

Electroweak and QCD Measurements at the Large Hadron Collider

DIS17

Strangeness in the Proton

arXiv:1612.03016



$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}} = 1.13 \pm 0.05\,(\mathrm{exp}) \pm 0.02\,(\mathrm{mod})\ ^{+0.01}_{-0.06}\,(\mathrm{par})$$

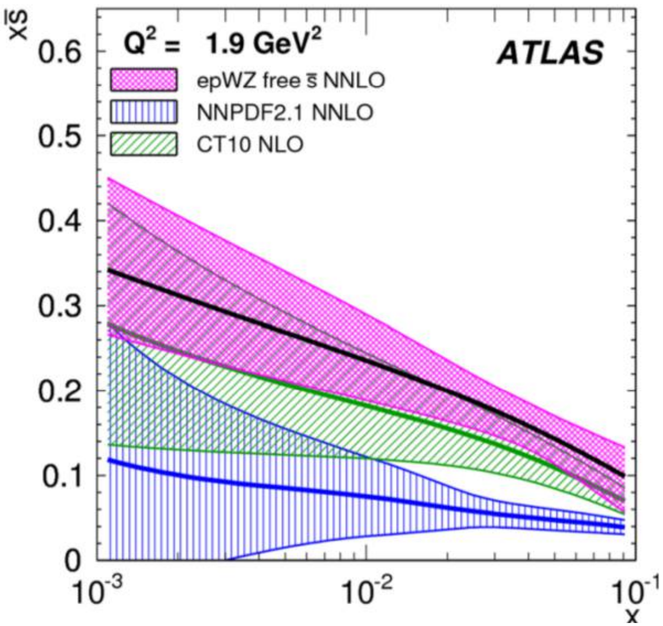
João Guimarães da Costa
IHEP, Chinese Academy of Sciences

Birmingham, 3 April 2017

Do it yourself!!!
Try **xFitter**

… I want a second opinion, ...

$$\kappa(Q) = \frac{\int_0^1 x\,[s(x,Q)+\bar{s}(x,Q)]\,dx}{\int_0^1 x\,[\bar{u}(x,Q)+\bar{d}(x,Q)]\,dx} \qquad r^s(x,Q) = \frac{\bar{s}(x,Q)+s(x,Q)}{2\bar{d}(x,Q)} \qquad R^s(x,Q) = \frac{s(x,Q)+\bar{s}(x,Q)}{\bar{u}(x,Q)+\bar{d}(x,Q)}$$



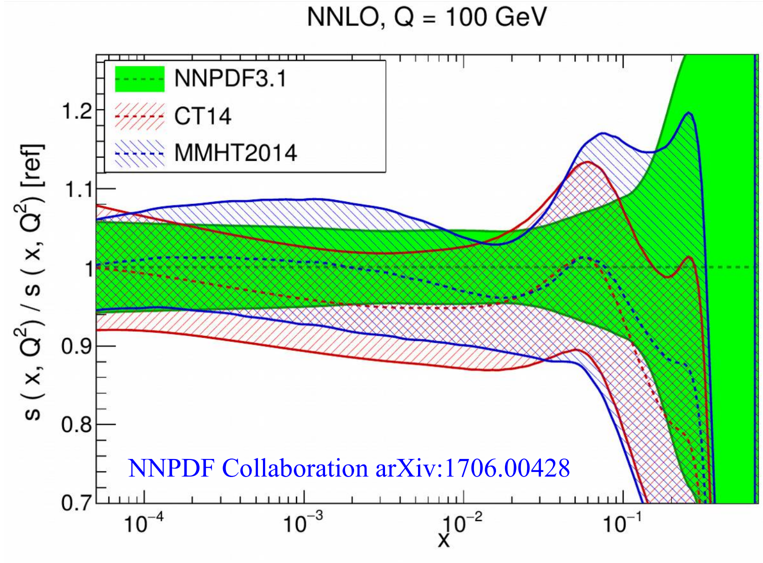
HERAFitter, Open Source QCD Fit Project
Eur. Phys. J. C (2015) 75: 304.

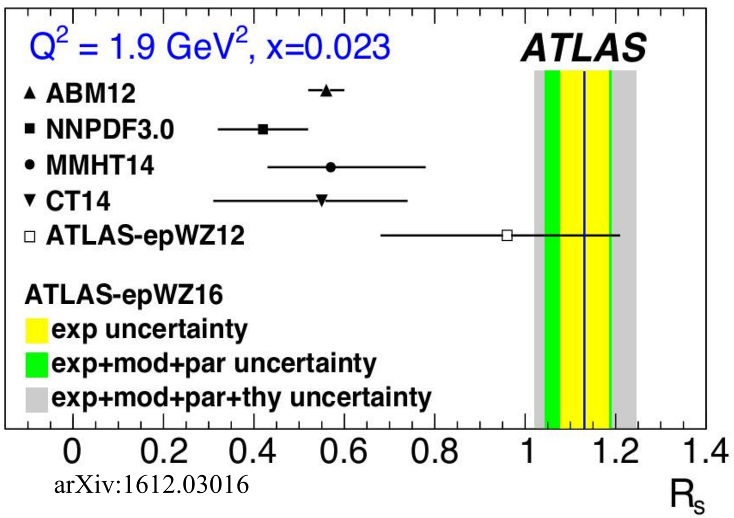
$$\kappa^s_{CT14NNLO} = 0.62 \pm 0.14$$

$$\kappa^s_{CT10NNLO} = 0.73 \pm 0.11$$

Carl Schmidt October 2015: INT Workshop

… whatever you want it to be





arXiv:1612.03016

$$\text{NuTeV } \kappa = 0.477^{+0.063}_{-0.053}$$ Z.Phys.C65:189-198,1995

$$\text{NOMAD } \kappa = 0.591 \pm 0.019$$ arXiv:1308.4750

$$\text{CMS } \kappa = 0.52^{+0.12}_{-0.10}{}^{+0.05}_{-0.06}{}^{+0.13}_{-0.10}$$ Q^2=20 GeV^2

PhysRevD.90.032004
(exp)(model)(param)

$$\text{ATLAS } r_s = 1.19 \pm 0.07 \pm 0.02^{+0.02}_{-0.10}$$

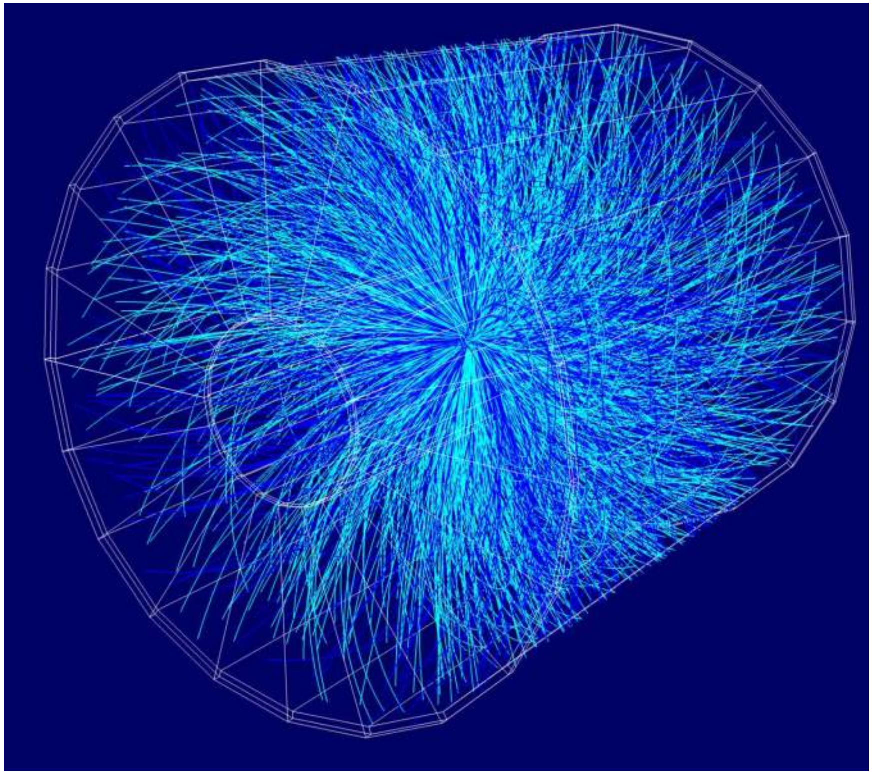
Q_0^2=1.9 GeV^2 at x=0.023

EPJC (2107) 77:367
(exp)(model)(param)

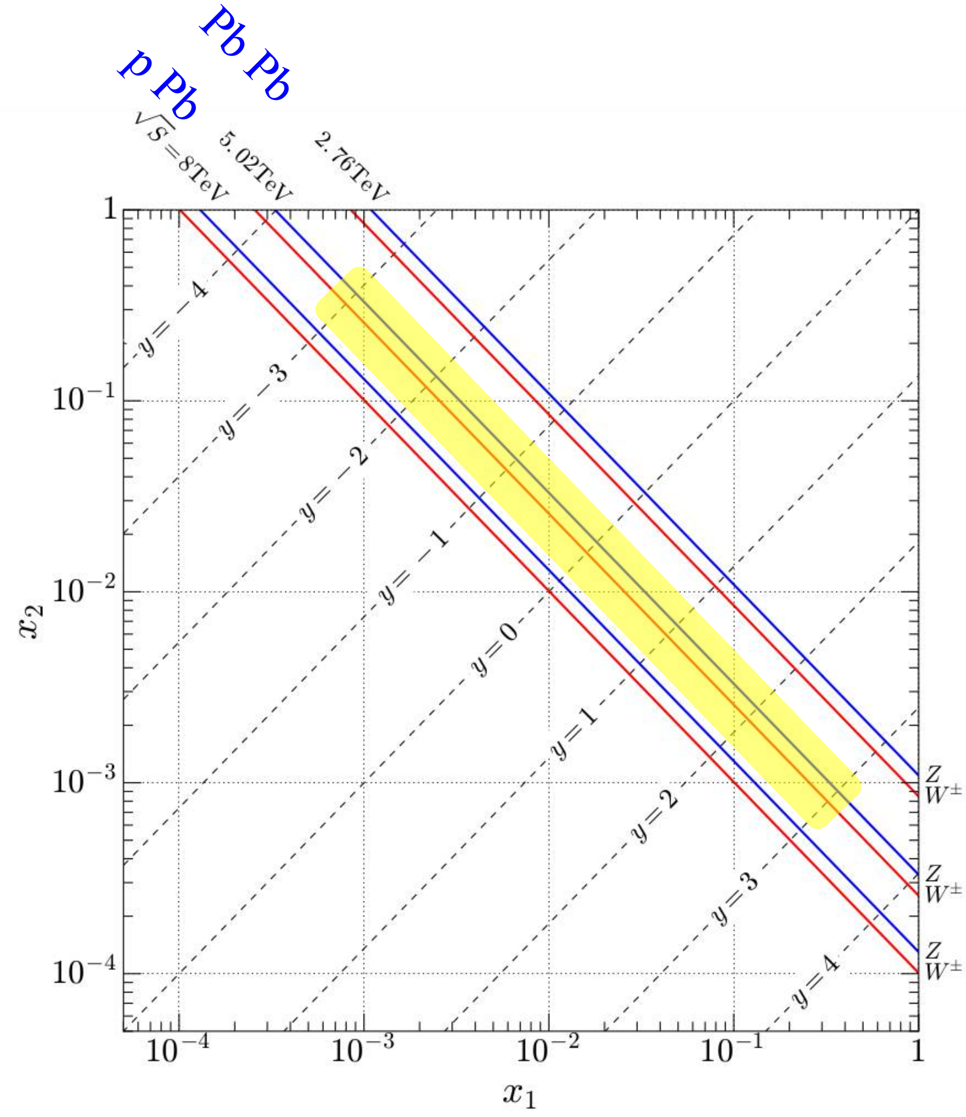
W/Z Production in Proton-Lead and Lead-Lead

* Sensitive to s(x) in new kinematic range with new A

* Provide complementary information to proton-proton W/Z production



One of the first lead-lead collisions at the LHC, recorded by the ALICE detector in November 2010. Note the large number of particle tracks (Image: ALICE)



nCTEQ15

The Ingredients

Data sets & cuts for nPDF fits

NC DIS & DY

SLAC E-139 & E-049
N = (D, Ag, Al, Au, Be,C, Ca, Fe, He)

CERN BCDMS & EMC & NMC
N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)

DESY Hermes
N = (D, He, N, Kr)

FNAL E-665
N = (D, C, Ca, Pb, Xe)

FNAL E-772 & E-886
N = (D, C, Ca, Fe,W)

Neutrino DIS*

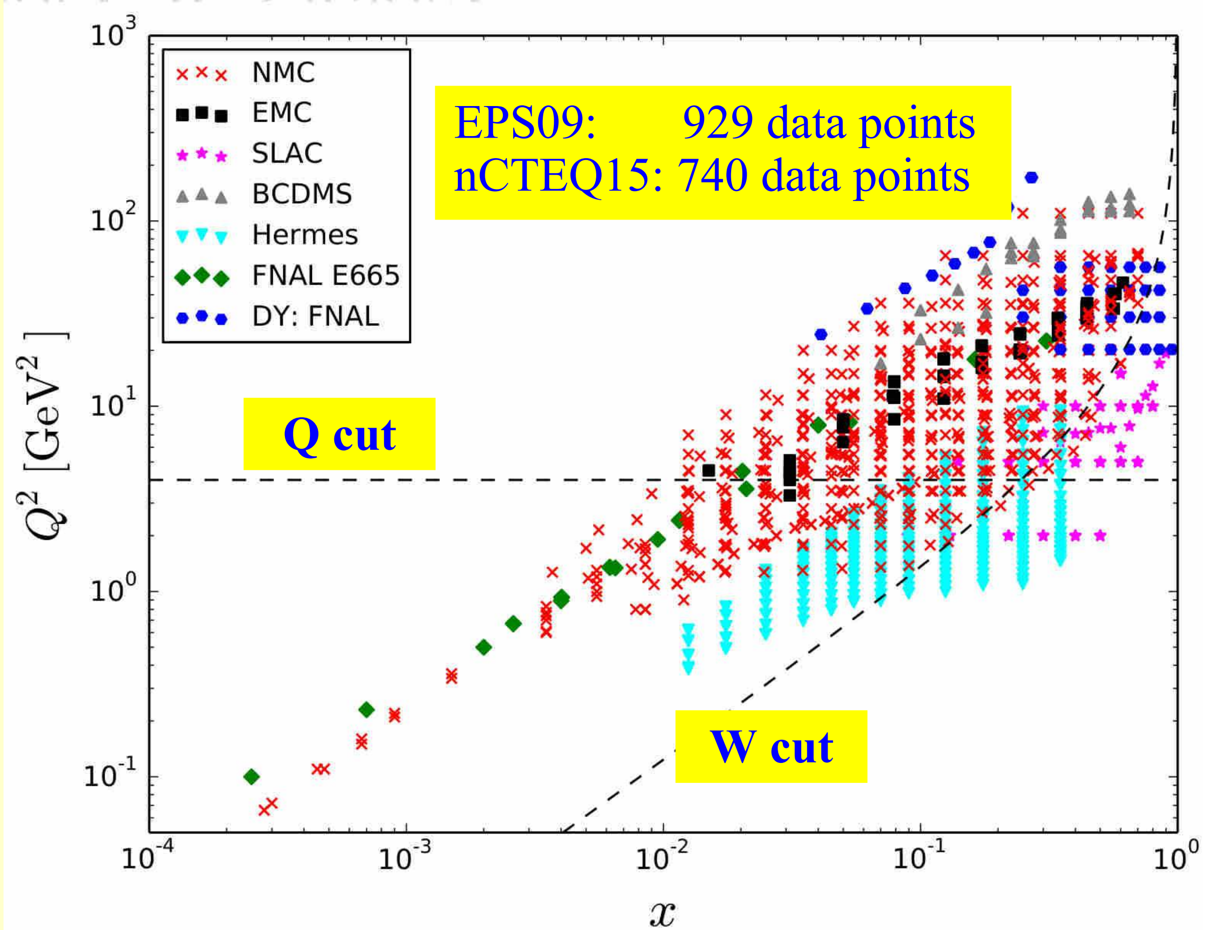
NuTeV CHORUS CCFR & NuTeV
N = Pb & Fe

Pion Production:

RHIC: PHENIX & STAR
N = Au

will show comparision w/ LHC pPb

DIS Cuts:
EPS: Q>1.3
HKN: Q>1.0
DSSZ: Q>1.0
nCTEQ: Q>2.0 & W>3.5



proton vs nuclear: fewer data and more DOF … impose assumptions on nPDFs

Mechanics of nPDFs

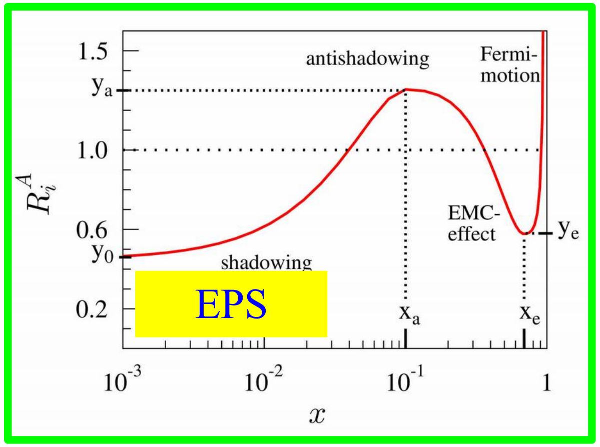
1) Multiplicative nuclear correction factors (HKN, EPS, DSSZ)

$$f_i^{p/A}(x_N, Q_0) = R_i(x_N, Q_0, A)\ f_i^{free\ proton}(x_N, Q_0)$$

… for example

HKN

$$R_i(x, Q_0, A) = 1 + \left(1 - \frac{1}{A^\alpha}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$



2) Generalized A-parameterization (nCTEQ)

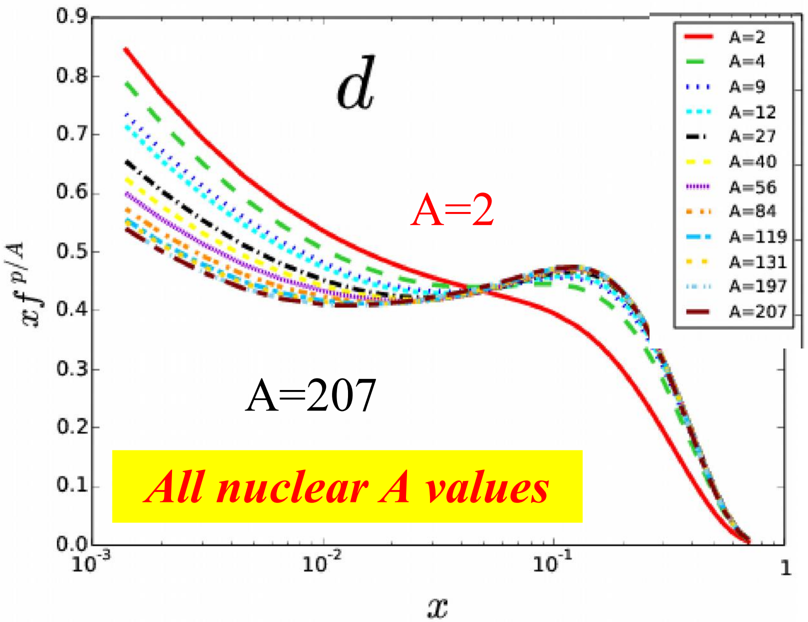
$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

$$f \sim \ldots x^{c_1(A)} (1-x)^{c_2(A)} \ldots$$

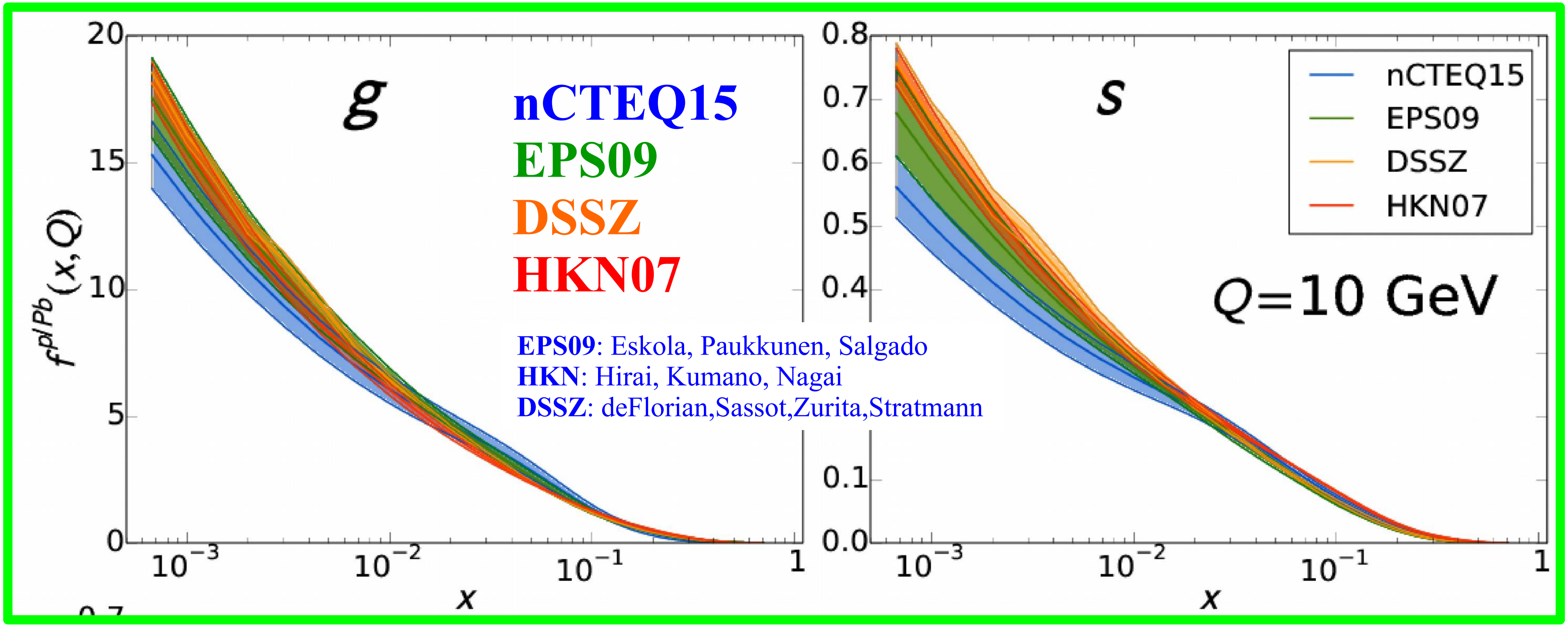
$$c_k \sim c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right)$$

Proton ($c_{k,0}$) — Nuclear ($c_{k,1}$, $c_{k,2}$)

use proton as starting point

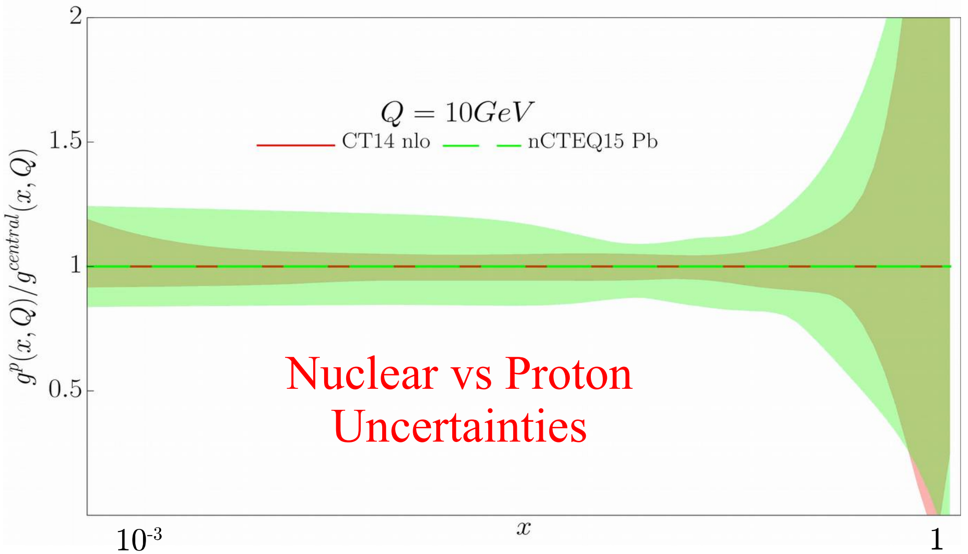


Nuclear PDFs: Complementary efforts in general agreement



Nuclear PDFs are more complex

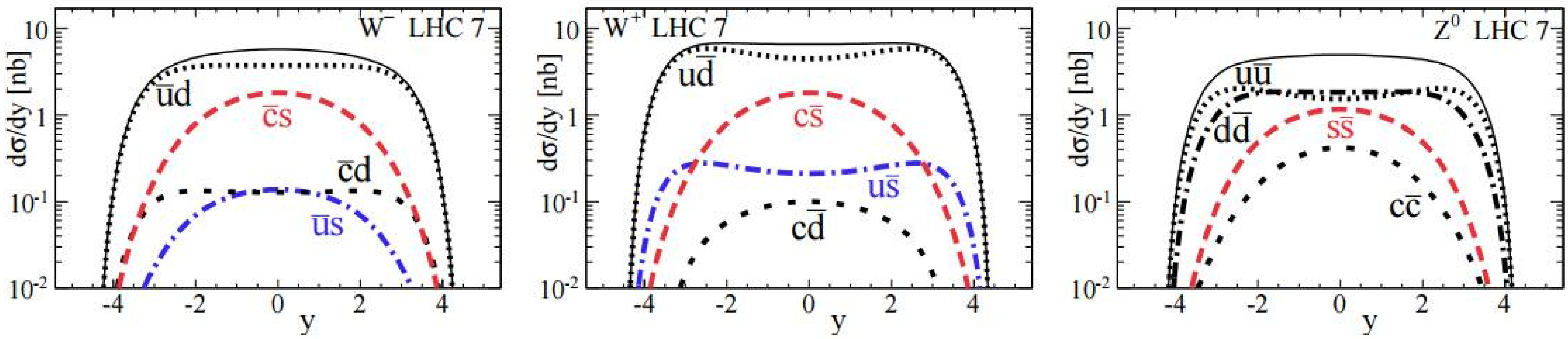
- more DOF than Proton case
- more "issues" to consider
- more work to do ...



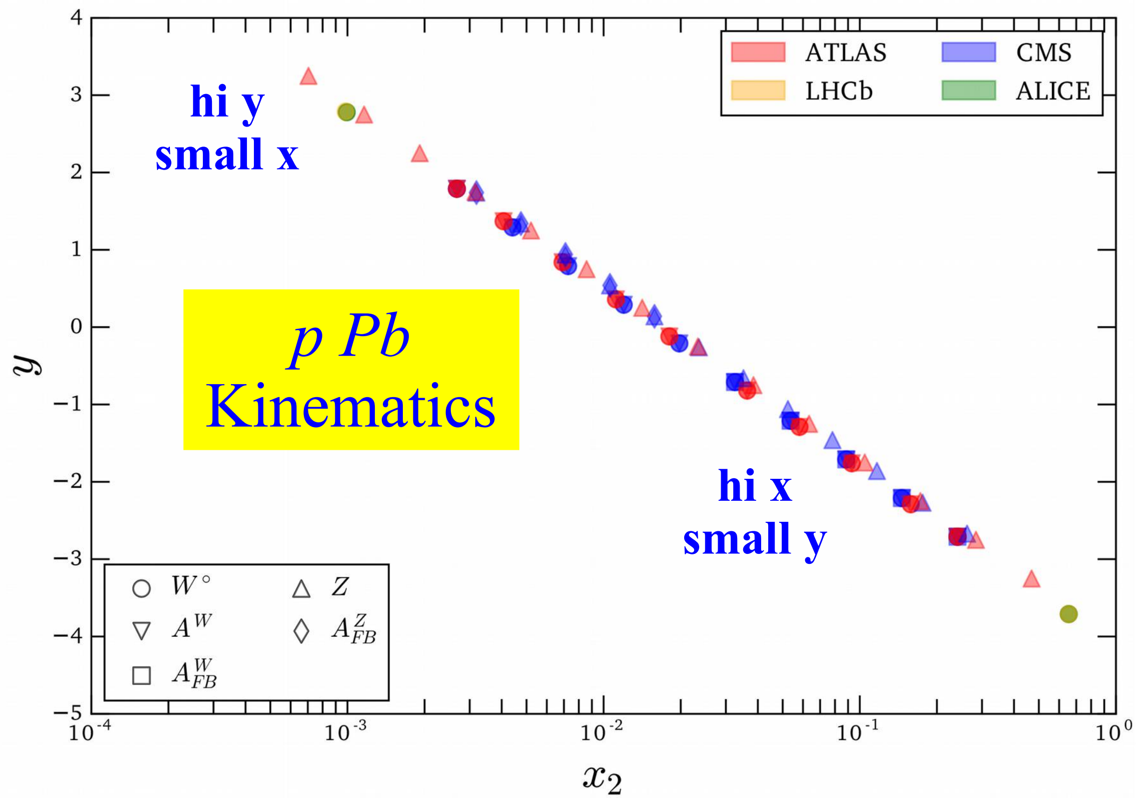
W/Z Cross Sections & Flavor Determination

Vector boson production in pPb & PbPb
A. Kusina, F. Lyonnet, D. B. Clark, E. Godat, T. Jezo, K. Kovarik, F. I. Olness, I. Schienbein, J. Y. Yu, arXiv:1610.02925 [nucl-th]

W/Z Production



(b) $d\sigma/dy$ for W^- (left), W^+ (middle), Z^0 (right) boson production at the LHC with $\sqrt{S} = 7$ TeV.

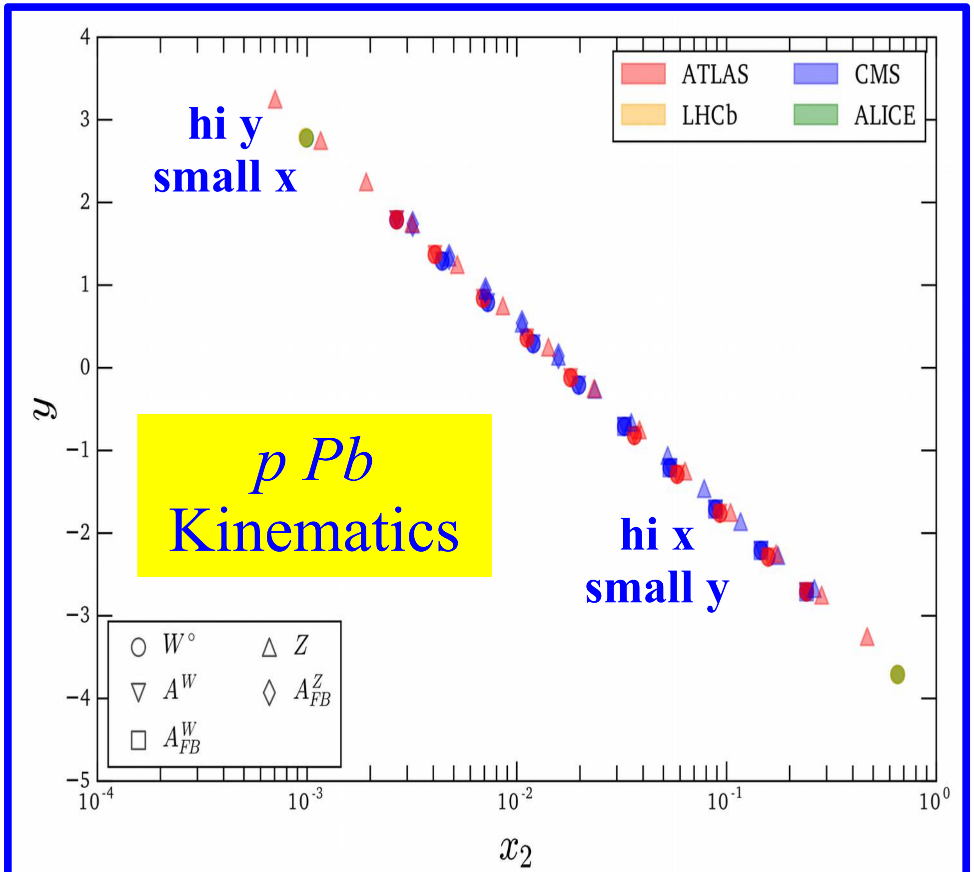


$$W^+ \sim c(x)\,\bar{s}(x)$$
$$W^- \sim s(x)\,\bar{c}(x)$$
$$Z \sim s(x)\,\bar{s}(x)$$

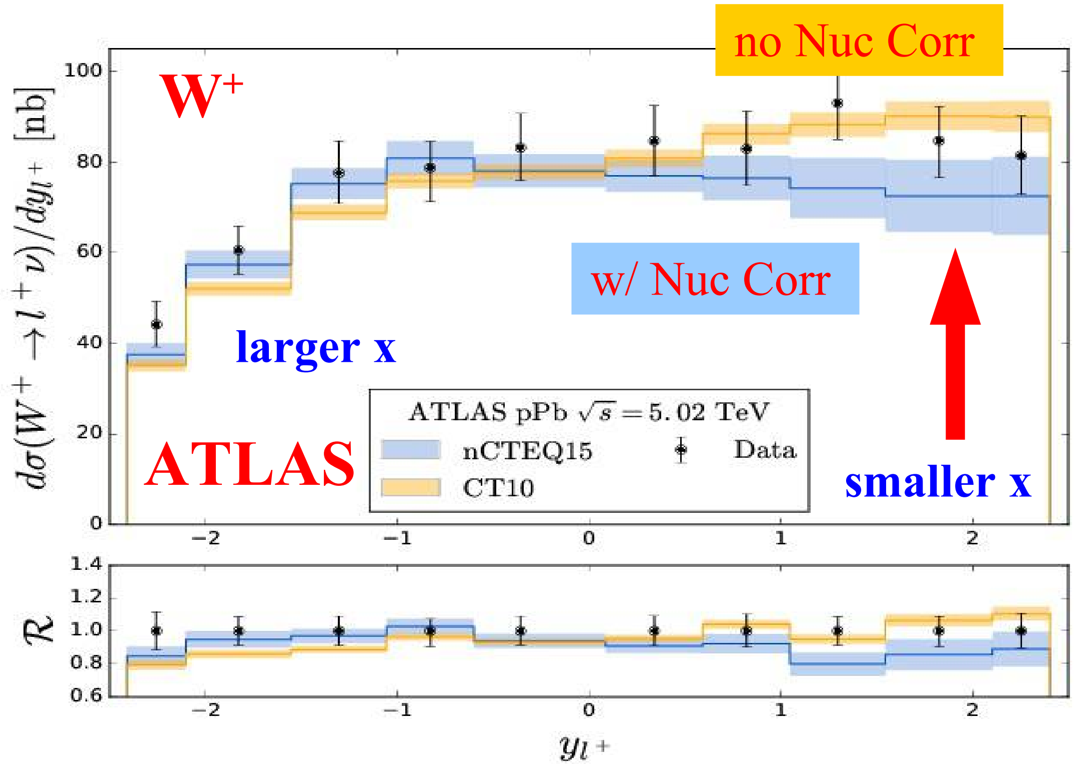
Strange Quark PDFs and Implications for Drell-Yan Boson Production at the LHC. A. Kusina, et al.., Phys.Rev. D85 (2012) 094028

$p\,Pb \to W/Z$ and Nuclear Corrections

$$\frac{d\sigma(p\,Pb \to W^+)}{dy}$$



Vector boson production in pPb & PbPb
A. Kusina, F. Lyonnet, D. B. Clark, E. Godat, T. Jezo, K. Kovarik, F. I. Olness, I. Schienbein, J. Y. Yu, arXiv:1610.02925 [nucl-th]

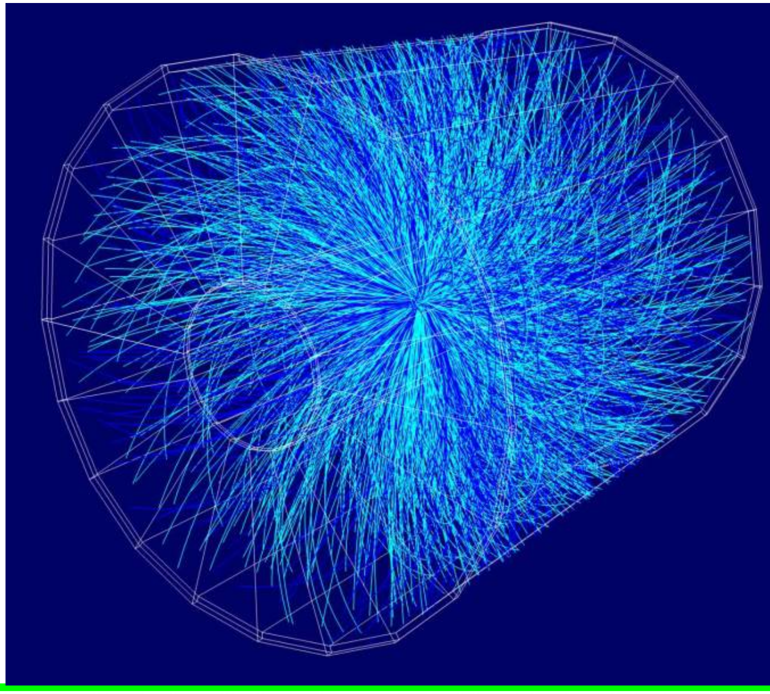


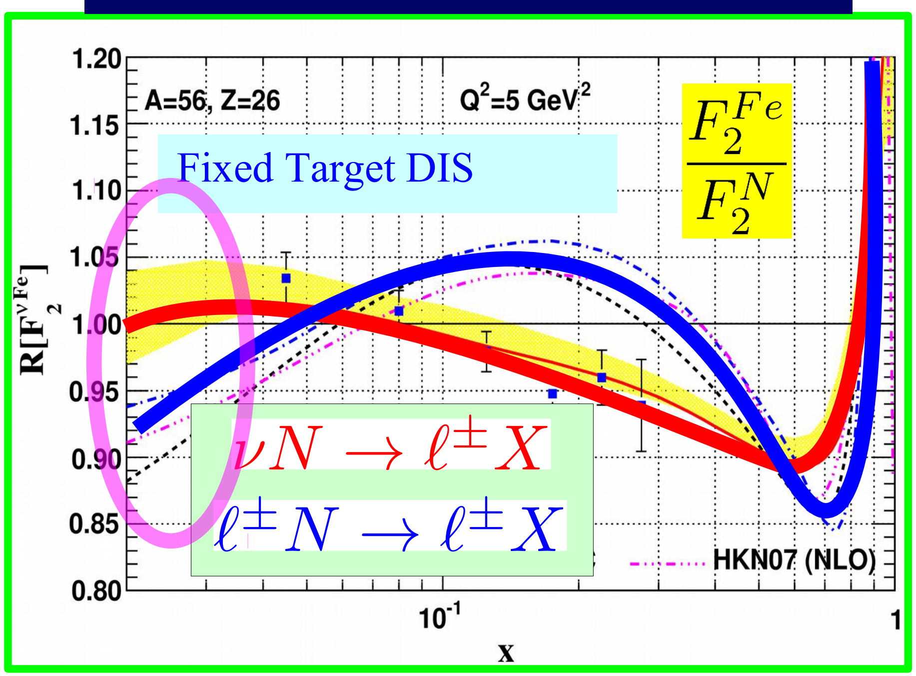
lead kinematics

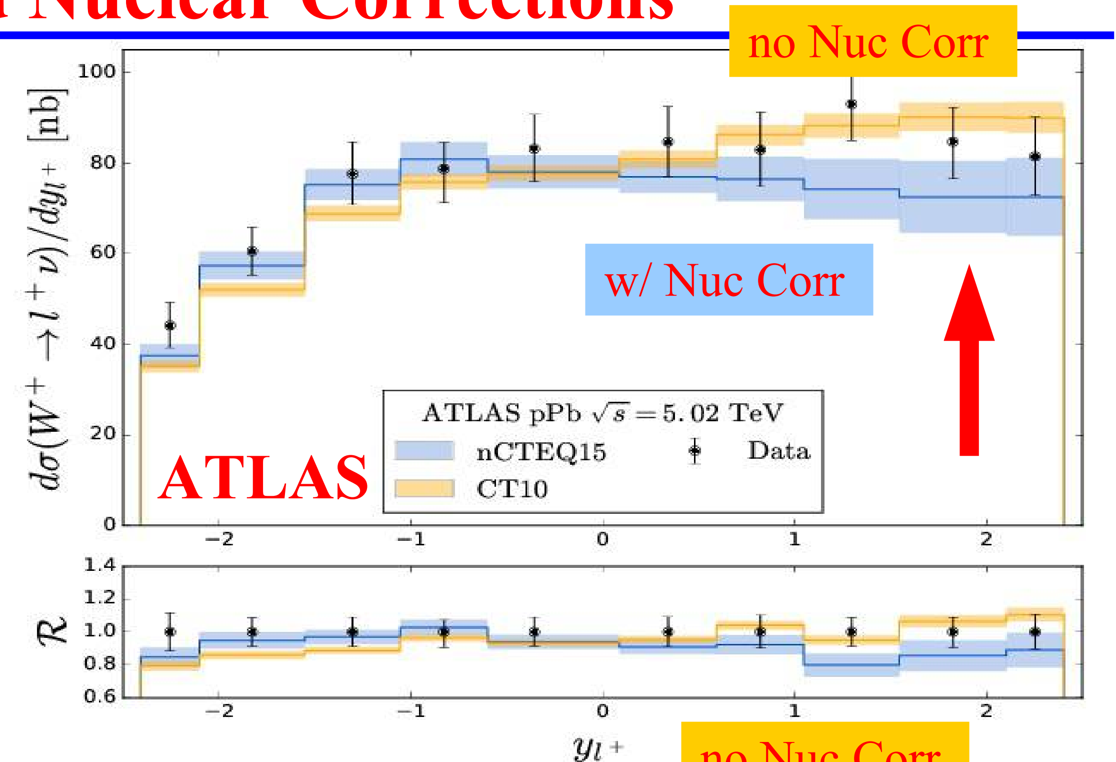
larger x ⟷ **smaller x**

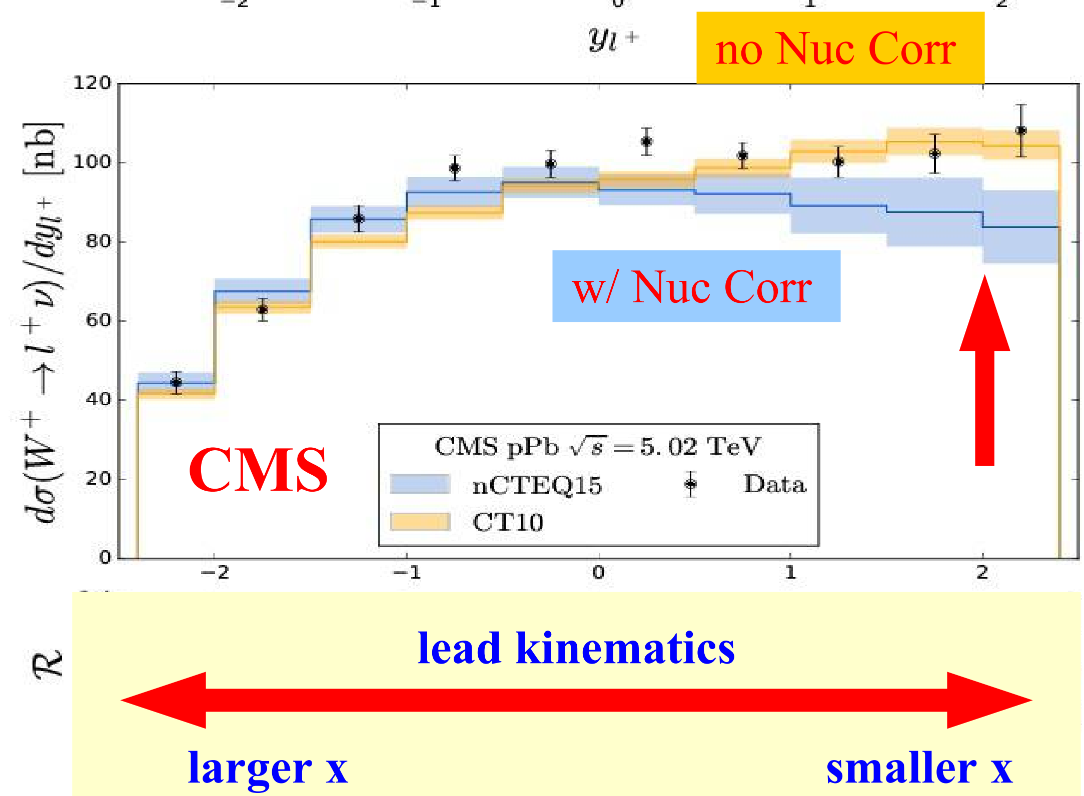
"OK" nuclear correction	**too much suppression**
previous data constraints	**minimal data constraints**

$p\,Pb \rightarrow W/Z$ and Nuclear Corrections



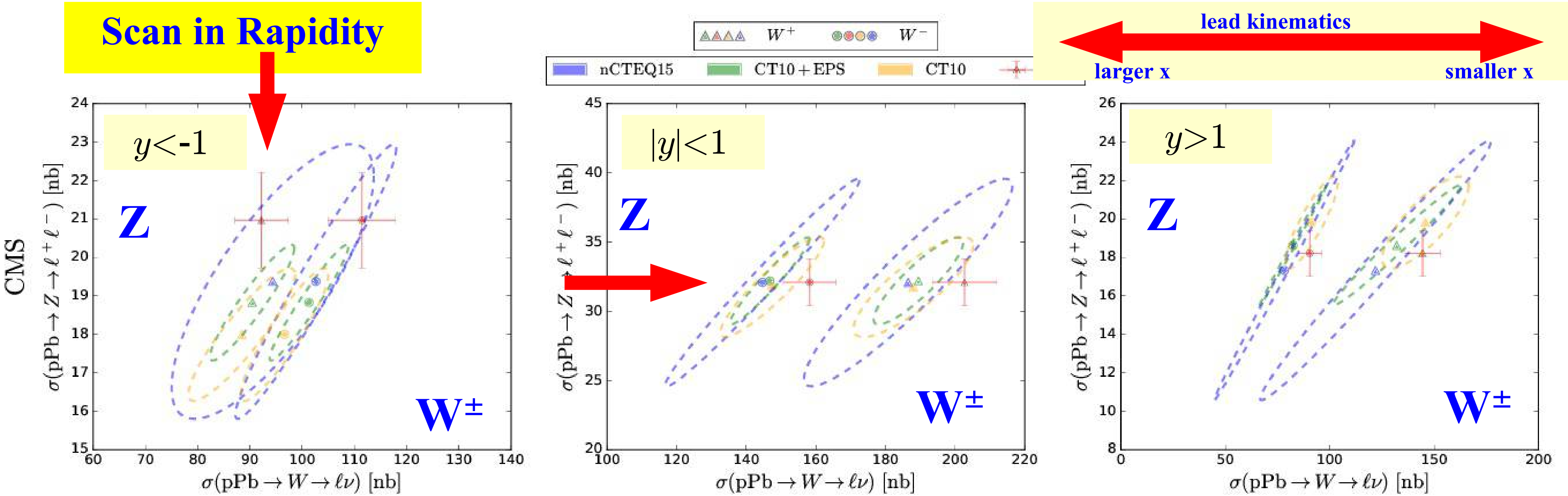




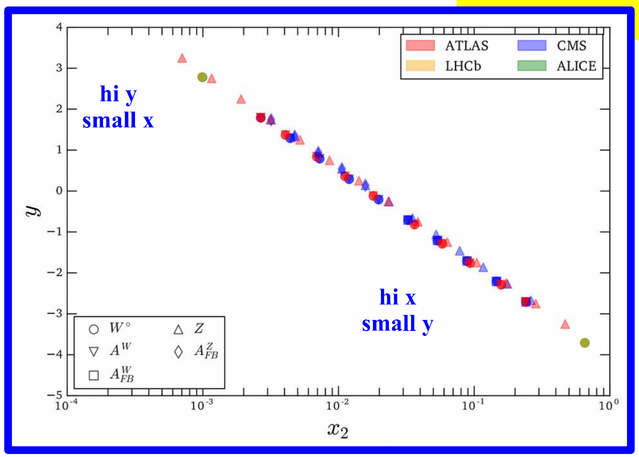


A. Kusina, et al., arXiv:1610.02925 [nucl-th]

σ Correlations: Scan in "x" and flavor combinations



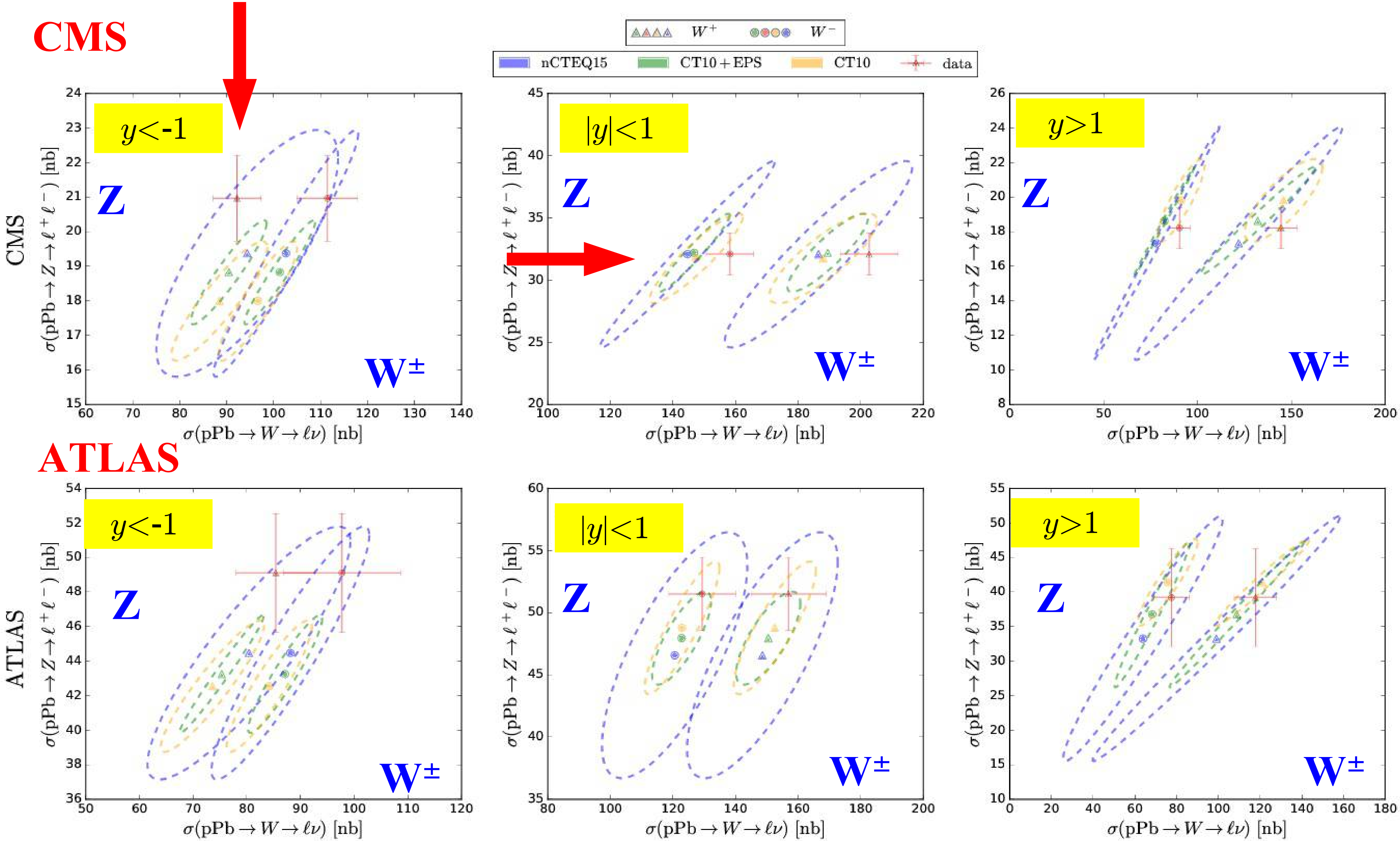
- $W^\pm / Z$ provide different linear combinations
- Rapidity scans different x regions



$$W^+ \sim c(x)\,\bar{s}(x)$$
$$W^- \sim s(x)\,\bar{c}(x)$$
$$Z \sim s(x)\,\bar{s}(x)$$

A. Kusina, et al., arXiv:1610.02925 [nucl-th]

σ Correlations: Scan in "x" and flavor combinations



lead kinematics

larger x ⟷ **smaller x**

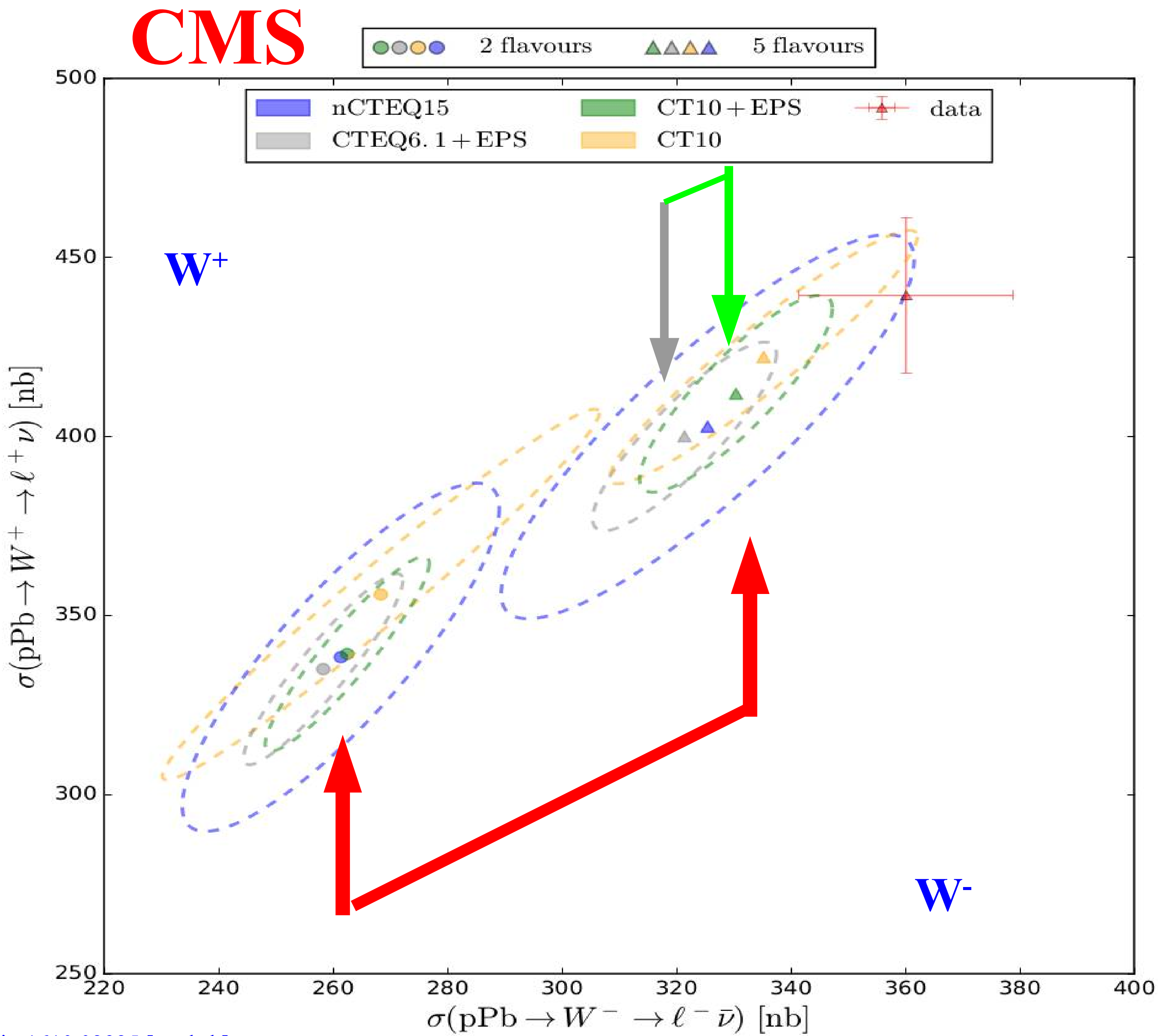
A. Kusina, et al., arXiv:1610.02925 [nucl-th]

W/Z Cross Sections

Compare
2 vs. 5 Flavors

Vector boson production in pPb & PbPb
A. Kusina, F. Lyonnet, D. B. Clark, E. Godat, T. Jezo,
K. Kovarik, F. I. Olness, I. Schienbein, J. Y. Yu,
arXiv:1610.02925 [nucl-th]

Impact of {s,c,b} PDF

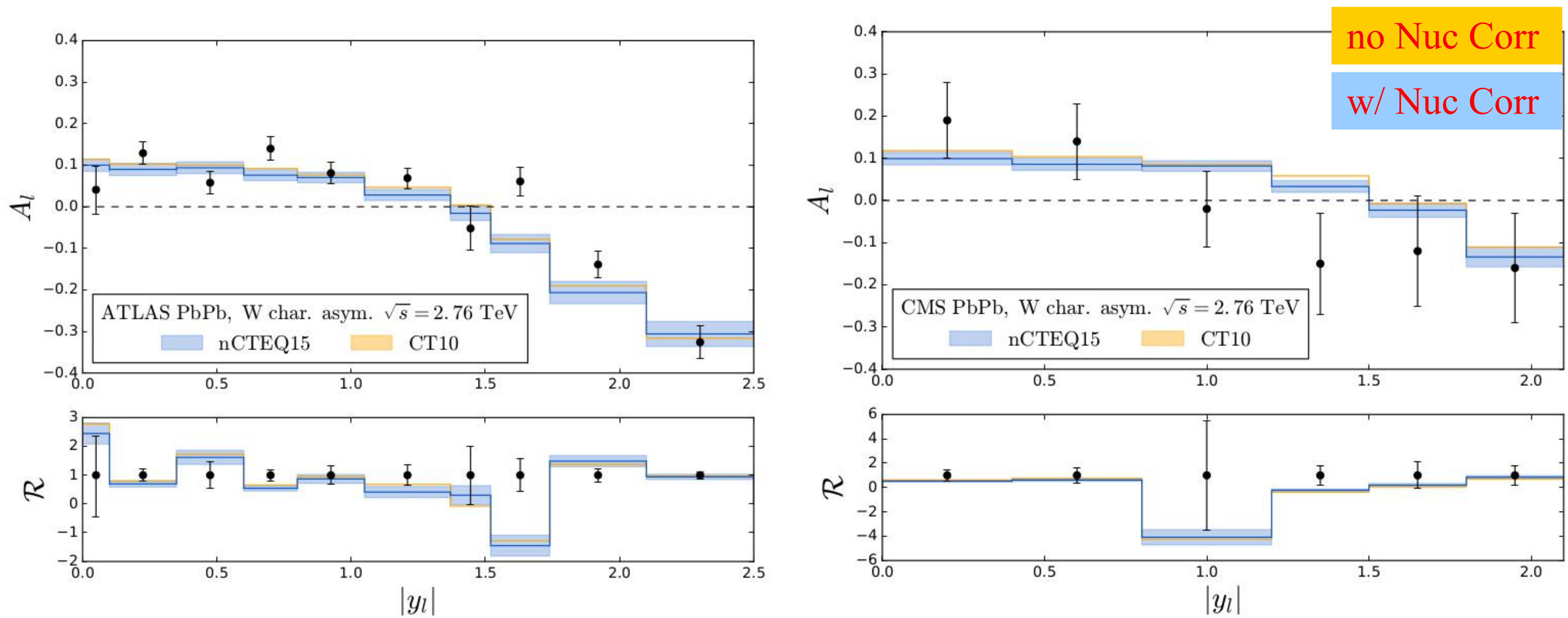


A. Kusina, et al., arXiv:1610.02925 [nucl-th]

Pb Pb Asymmetries

PbPb W Charge Asymmetry

$$A_\ell(y_\ell) = \frac{dN(W^+ \to \ell^+\nu_\ell) - dN(W^- \to \ell^-\bar{\nu}_\ell)}{dN(W^+ \to \ell^+\nu_\ell) + dN(W^- \to \ell^-\bar{\nu}_\ell)}$$



(a) ATLAS (b) CMS

Fig. 10: W charge asymmetry for PbPb collisions at the LHC with $\sqrt{s} = 2.76$ TeV as measured by the ATLAS and CMS collaborations. Corresponding predictions obtained with `nCTEQ15` and CT10 PDFs are also shown.

EPS09 & EPPS16

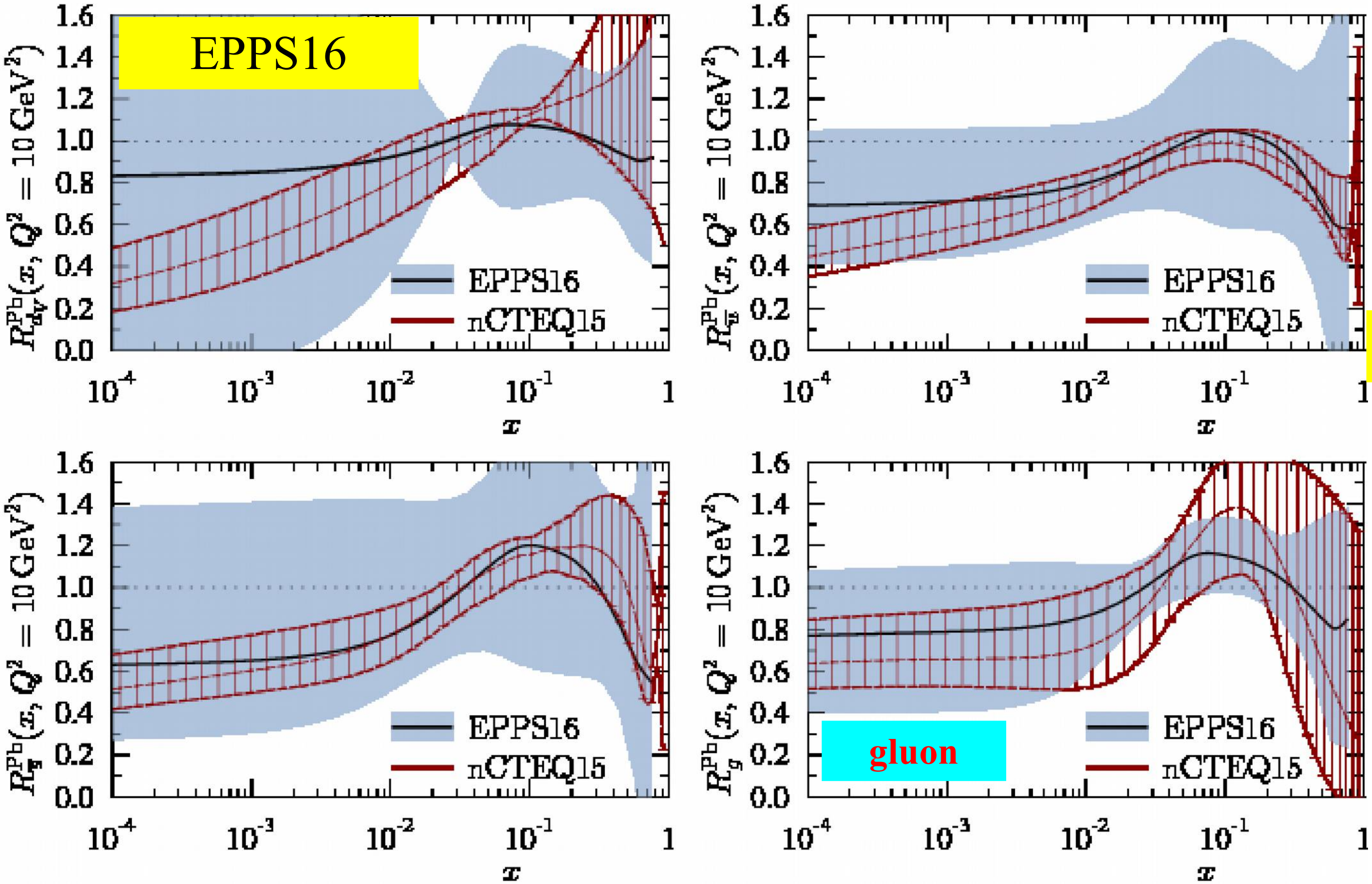
nPDFs

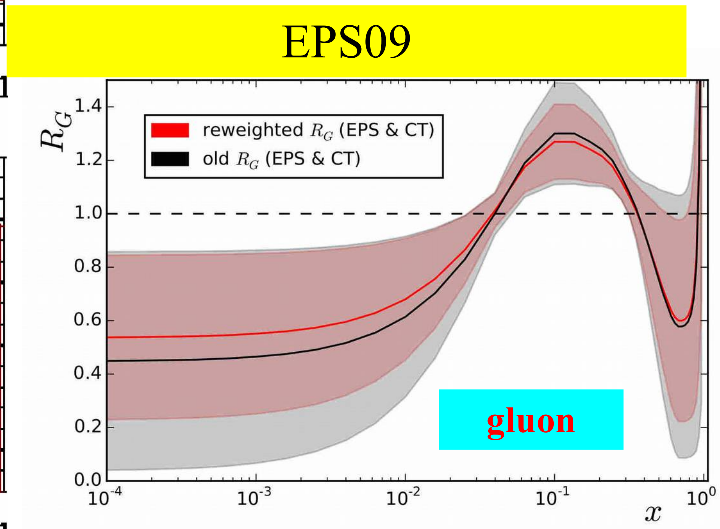
Nuclear Corrections: Pb vs. x

EPS09:
χ^2/DOF 731/929
15 total parameters
5 Parameters for R_{sea}
Fit Ratios

EPPS16:
χ^2/DOF 1789/1811
20 Parameters
9 Parameters for sea PDFs
LHC pPb W/Z & dijet
Fit Ratios

nCTEQ15:
χ^2/DOF 587/740
18 Parameters *(inc. 2 norm.)*
2 Parameters for s(x) PDF
Fit PDFs (w/ base proton)

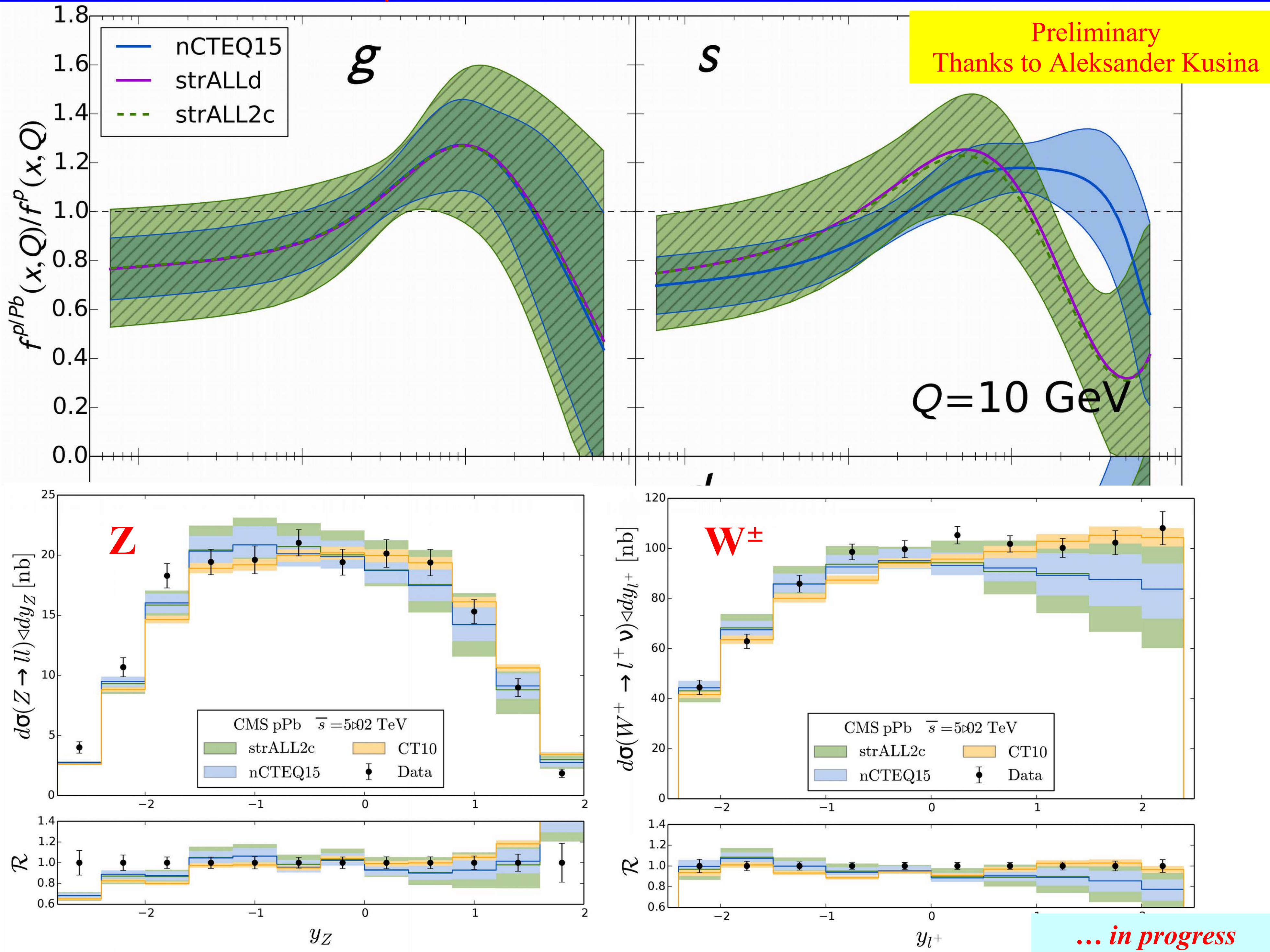




EPS09: HEP 0904 (2009) 065

EPPS16:Eur.Phys.J. C77 (2017) no.3, 163

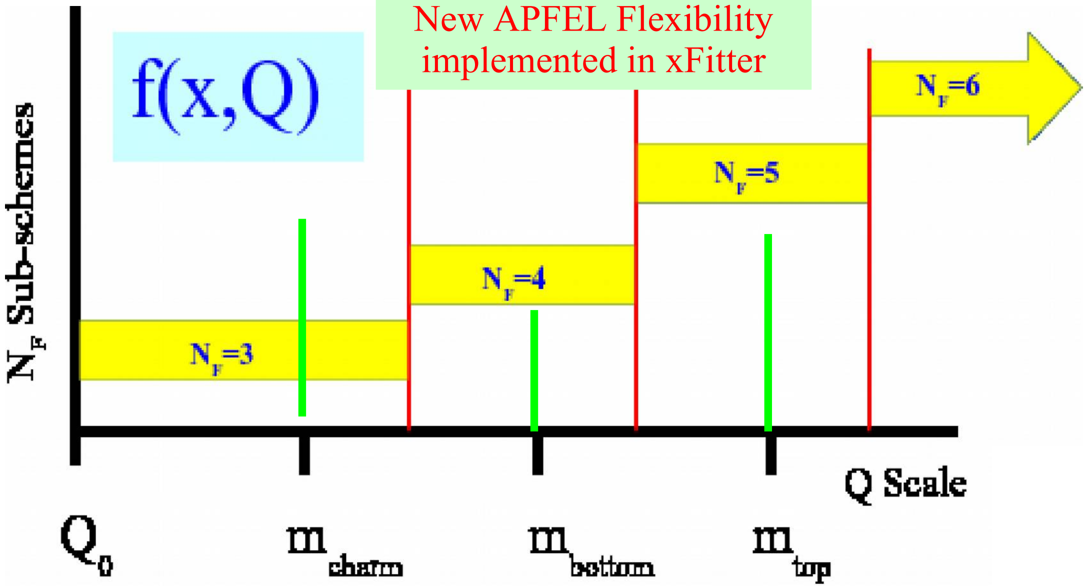
$p\,Pb \rightarrow W/Z$: Free the Strange Quark s(x)



Almost done ...

VFNS: Heavy quark matching scale freedom … implemented in xFitter

New APFEL Flexibility implemented in xFitter

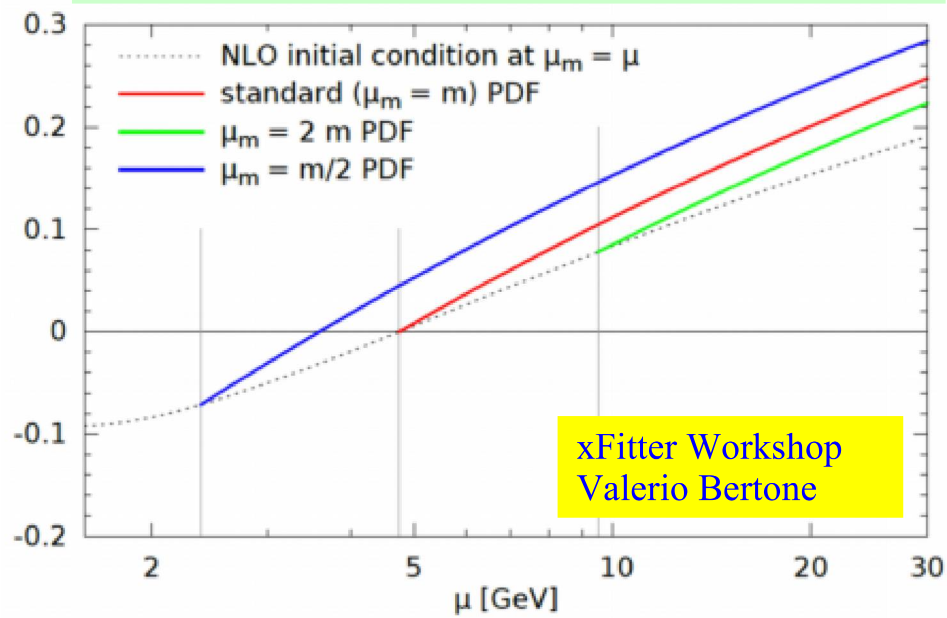


What are the advantages?

1) shift discontinuities

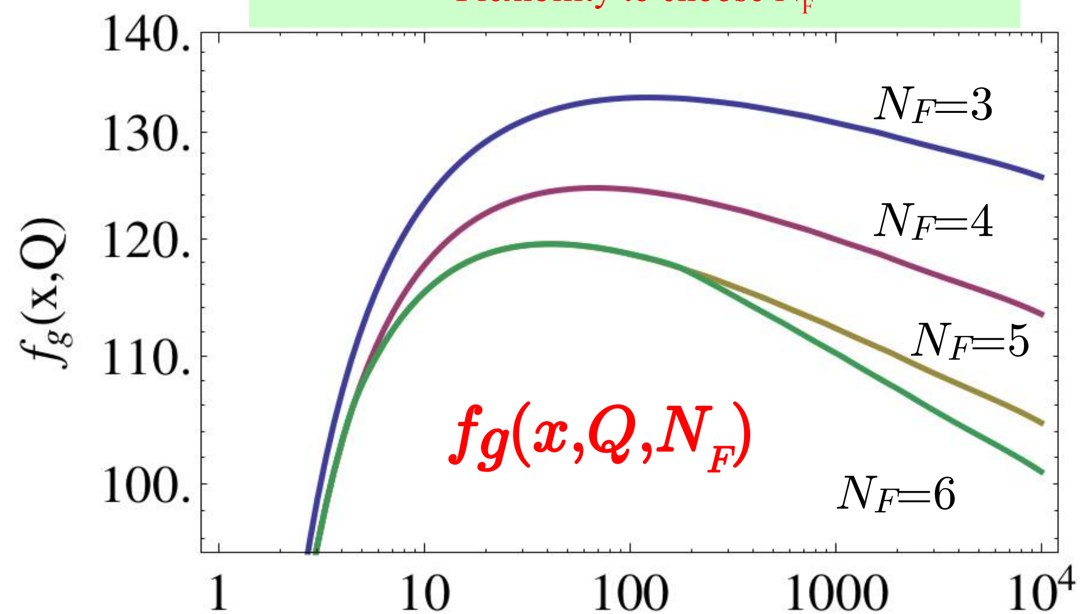
2) avoid delicate matching ~m

Boundary Conditions implemented at NLO & NNLO



xFitter Workshop
Valerio Bertone

Flexibility to choose N_F



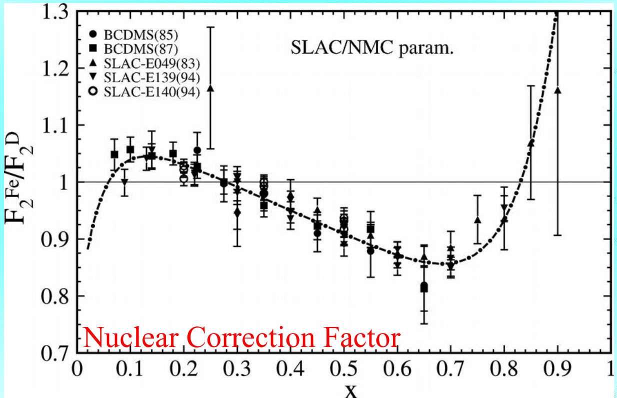
… for example, simultaneously

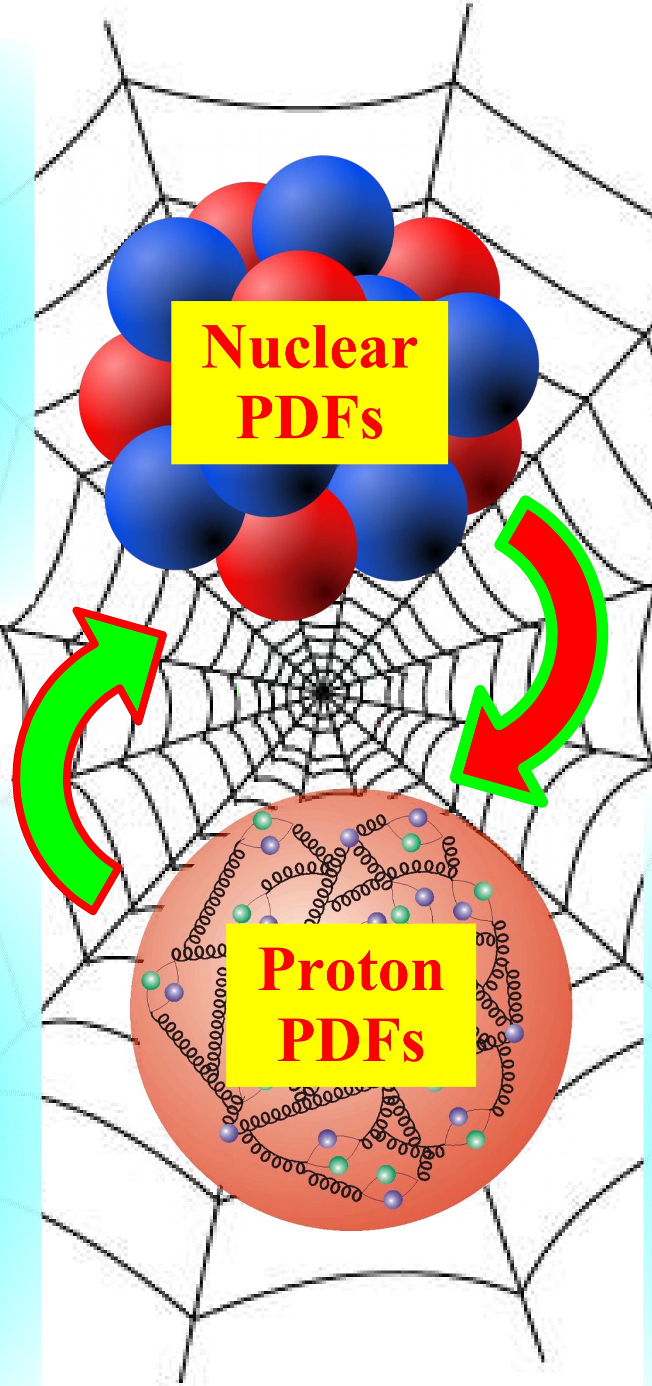
1) analyze HERA in N_F=4

2) analyze LHC in N_F=5

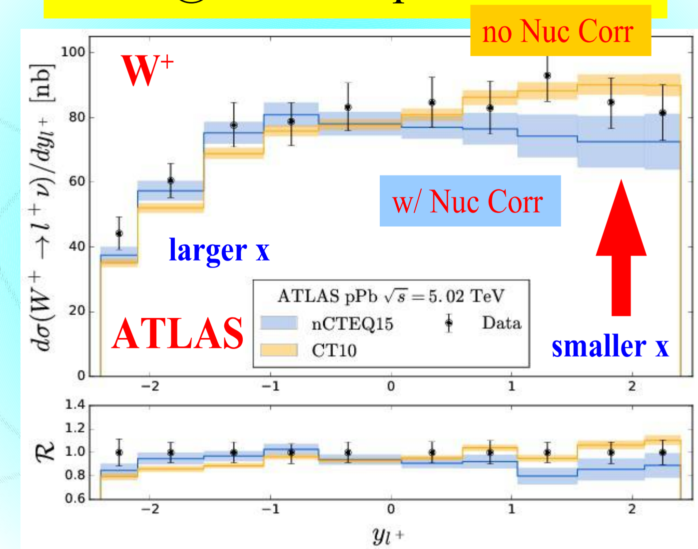
Conclusions

Nuclear Correction Factor

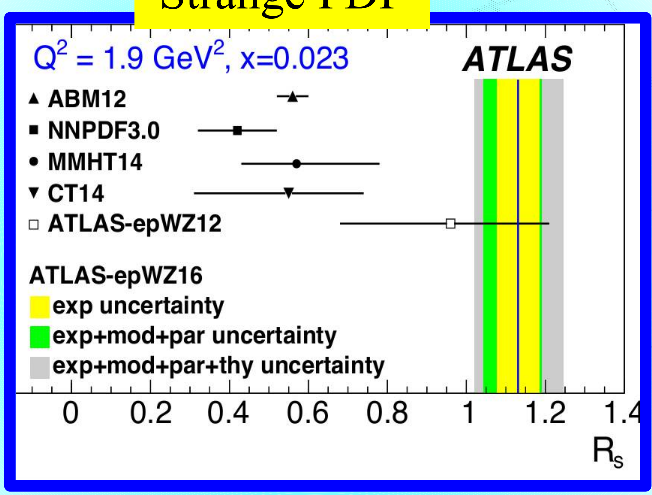




W/Z @ LHC w/ pPb & PbPb

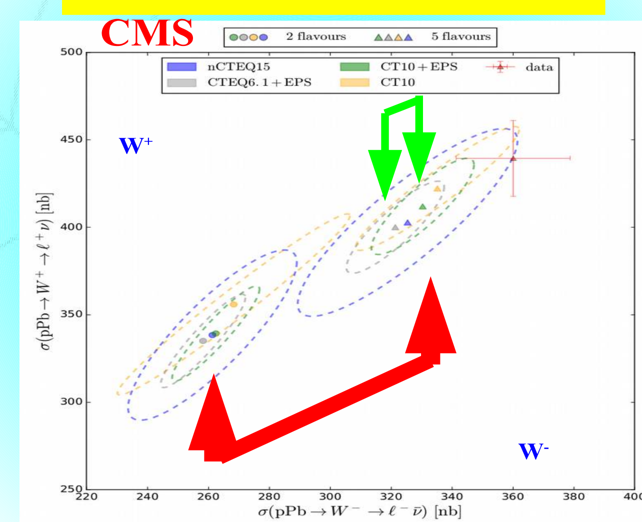


Strange PDF



ATLAS Collaboration arXiv:1612.03016

W/Z Correlations



backup

LHeC Workshop: 11-13 September 2017 @ CERN

cern.ch/lhec

LHeC Workshop

11-13 September 2017
CERN
Europe/Zurich timezone

Search...

- Overview
- Registration
- Participant List
- Access and transport
- Accommodation
- Internet access
- LHeC website

Support

lhec.ws@cern.ch

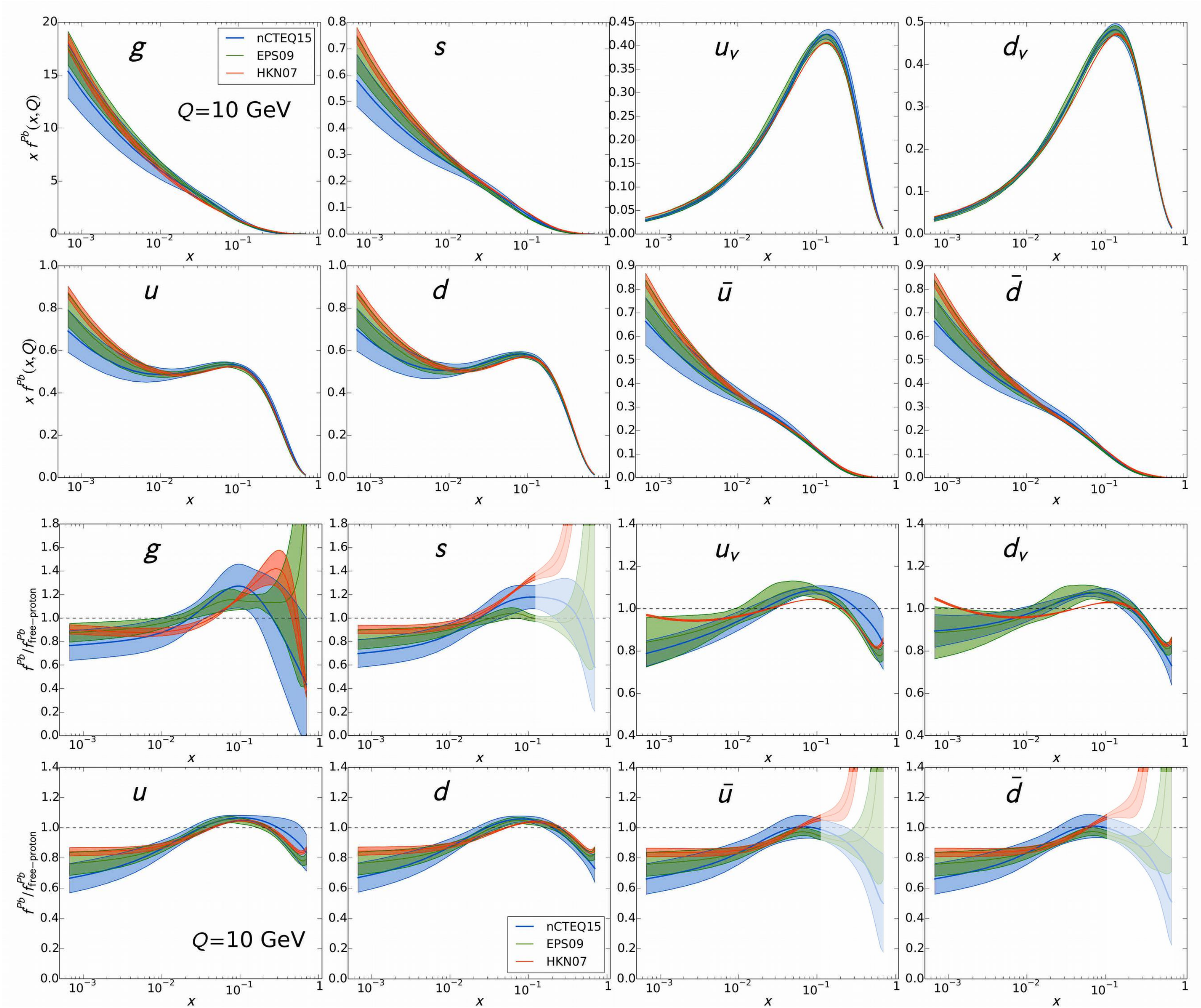
September Workshop on the LHeC and FCC-eh

The LHeC is a proposed upgrade of the LHC to enable luminous electron-proton and electron-ion collisions to take place in the final phase of LHC operation. Its design is based on a high current, multi-turn energy recovery electron linac, arranged tangentially to the LHC. A small ERL facility, PERLE, is under design to possibly be built at Orsay. The ERL is considered to serve also as the baseline for electron-hadron collisions at the future circular collider, the FCC-eh. The workshop discusses the physics, accelerator, test facility and detector developments in view of the updated documents, on the LHeC and FCC-eh, to be prepared for the deliberations of the forthcoming European and global strategy debates in the next years. It takes place at CERN, in a three day plenary session format, combining invited overview talks with shorter, topical contributions. The goal of the workshop is to review the update and to progress on the various developments which have taken place following the LHeC workshop in 2015.

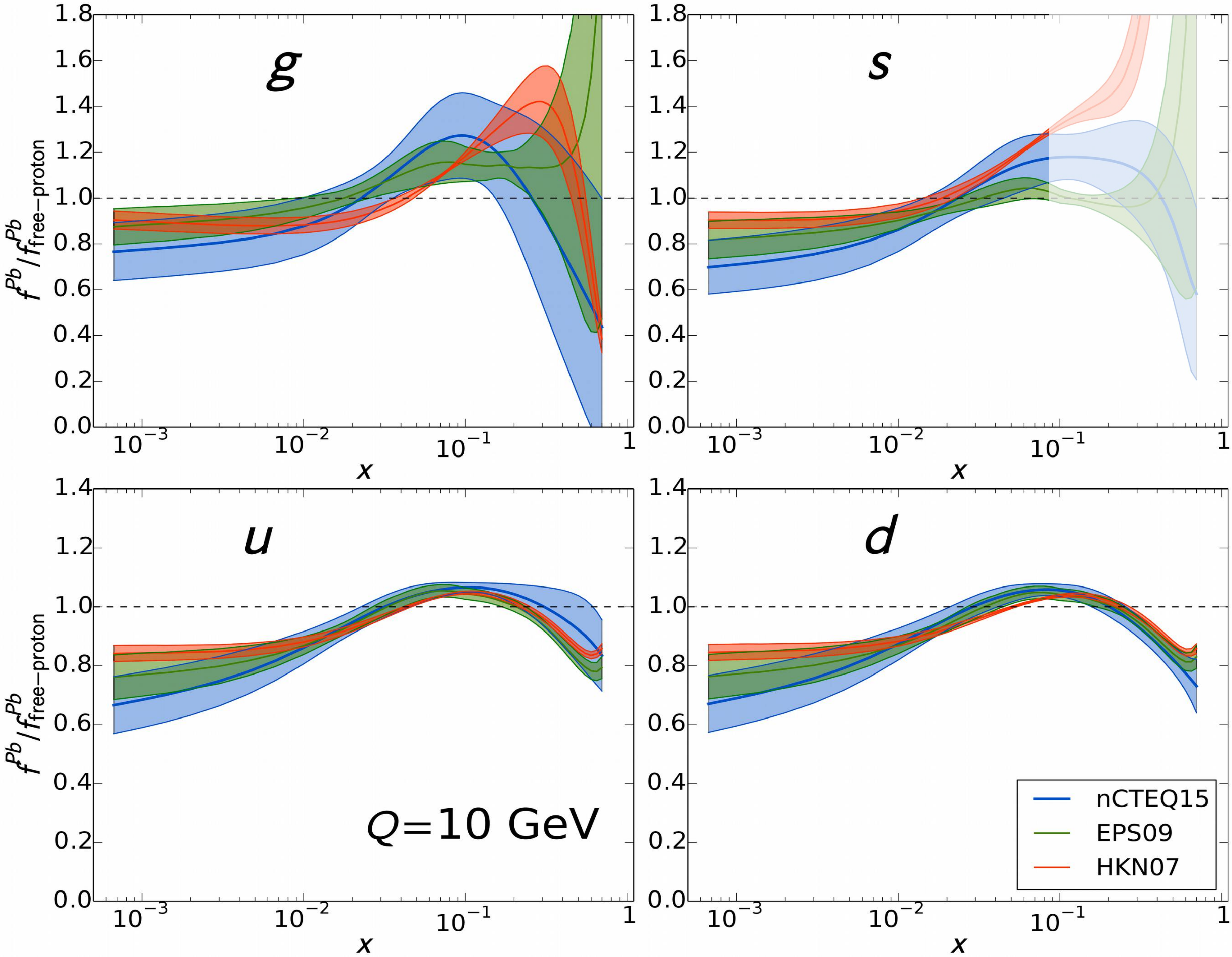
The

PDFs

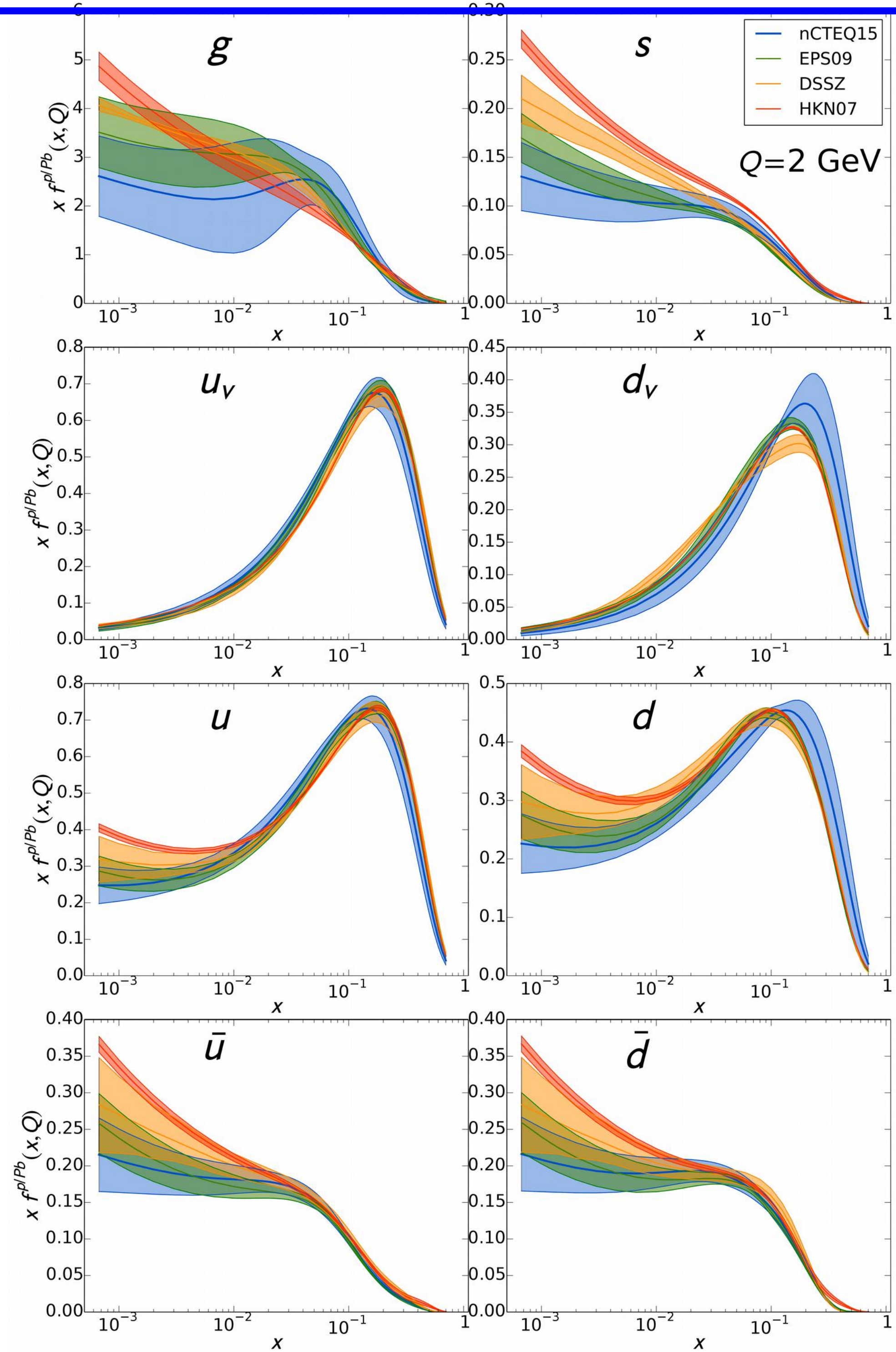
Nuclear Corrections: Lead PDFs & Ratios to Proton

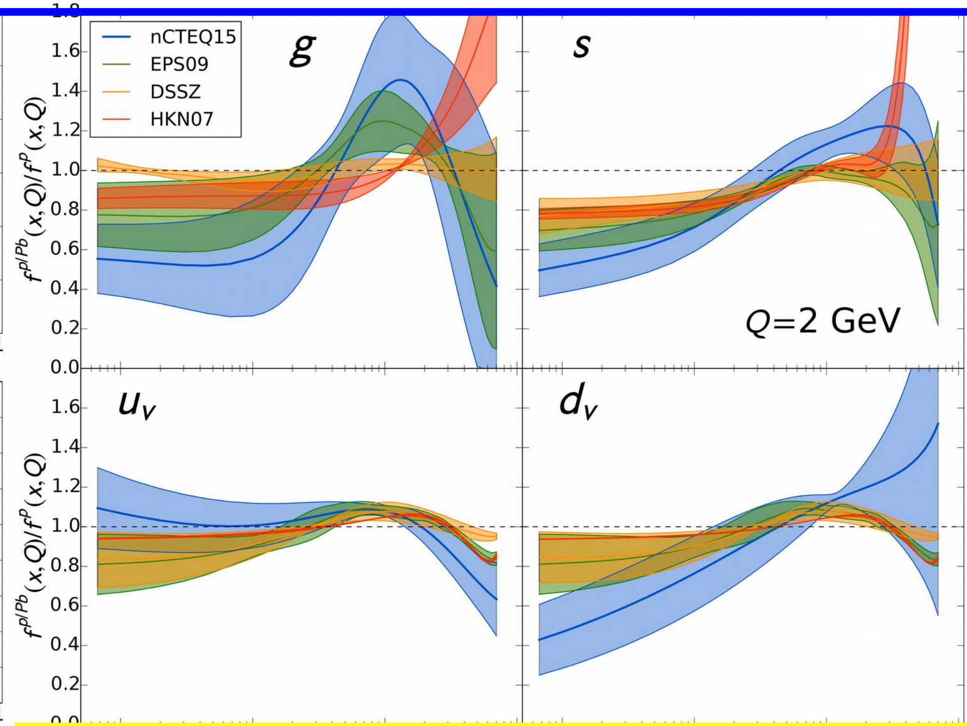


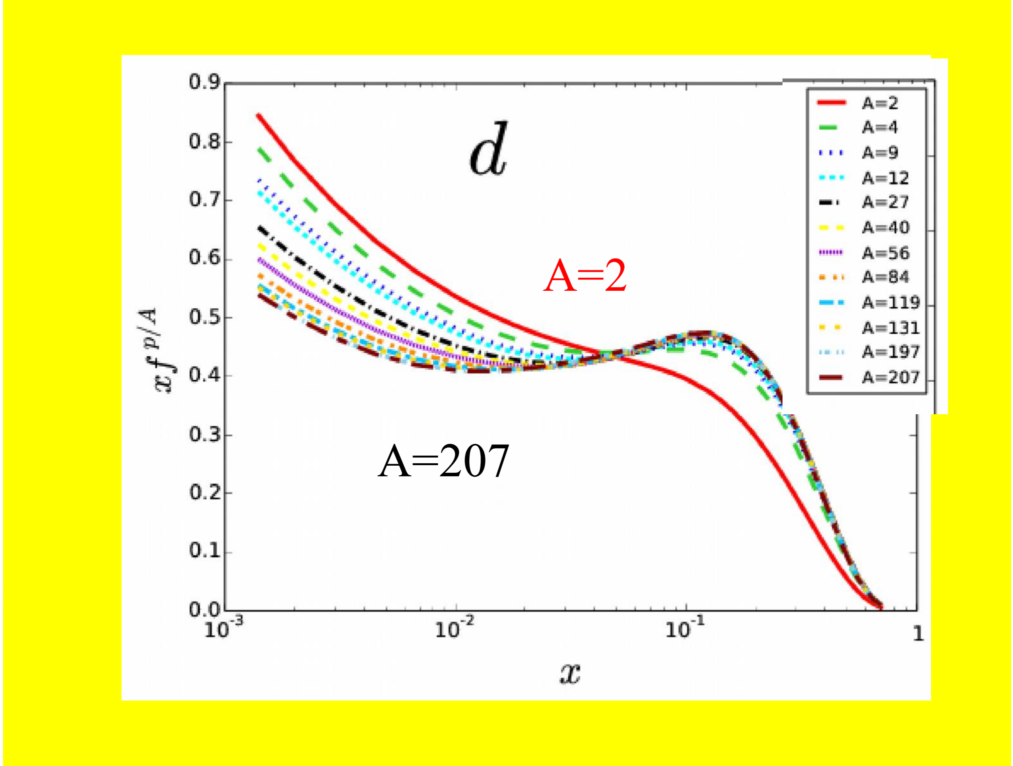
Nuclear Corrections: Lead PDFs & Ratios to Proton



Nuclear Corrections: Lead PDFs & Ratios to Proton at lower scale: 2 GeV







Differences with the free-proton PDFs

$$f^N = \frac{Z}{A} f^{p/N} + \frac{A-Z}{A} f^{n/N}$$

Factorization & DGLAP Evolution:

- Assume factorization & universal PDFs
- Assume bound protons have same evolution & sum rules as free protons
  - We neglect contributions from $x_N > 1$

Higher Order Corrections:

- Currently working at NLO
  - NNLO in future, but current precision does not warrant
- Assume isospin symmetry to construct nPDFs
  - NLO EW corrections will spoil isospin

Parametrization:

- More parameters & Less data/DOF
  - Need to make assumptions
- Complex χ^2 surface; potentially multiple minima

nCTEQ Framework

PRD80, 094004 (2009)

NLO PDFs with errors
Error PDFs with Hessian method
Parametrization (Q_0=1.3 GeV)

~CTEQ6.1M free proton baseline
Neglects x_N>1
Data: DIS, DY, & π^0 @ RHIC

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

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

$$\frac{\bar{d}(x,Q_0)}{\bar{u}(x,Q_0)} = c_0 x^{c_1}(1-x)^{c_2} + (1+c_3 x)(1-x)^{c_4}$$

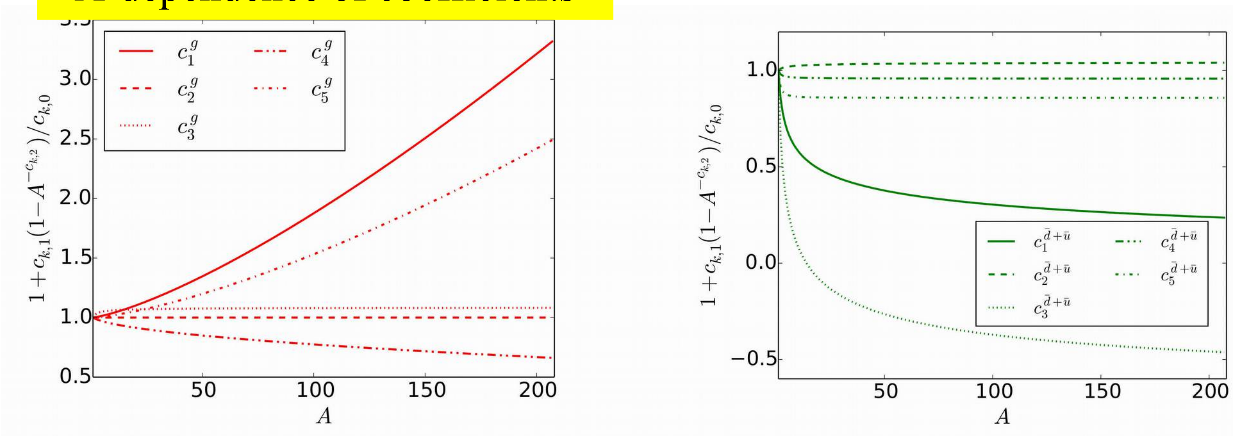
$$c_k \to c_k(A) \equiv c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right), \quad k = \{1,\ldots,5\}$$

Proton ($c_{k,0}$)

Nuclear ($c_{k,1}$, $c_{k,2}$)

nCTEQ Framework PRD80, 094004 (2009)

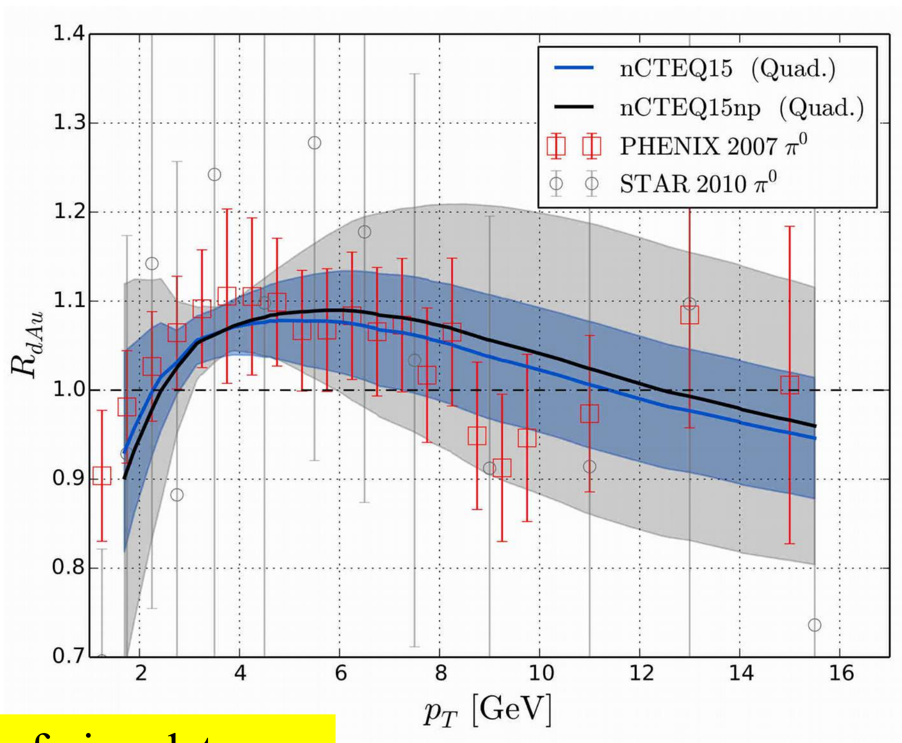
A-dependence of coefficients



(a) Gluon (b) $\bar{d}+\bar{u}$

Sample data sets

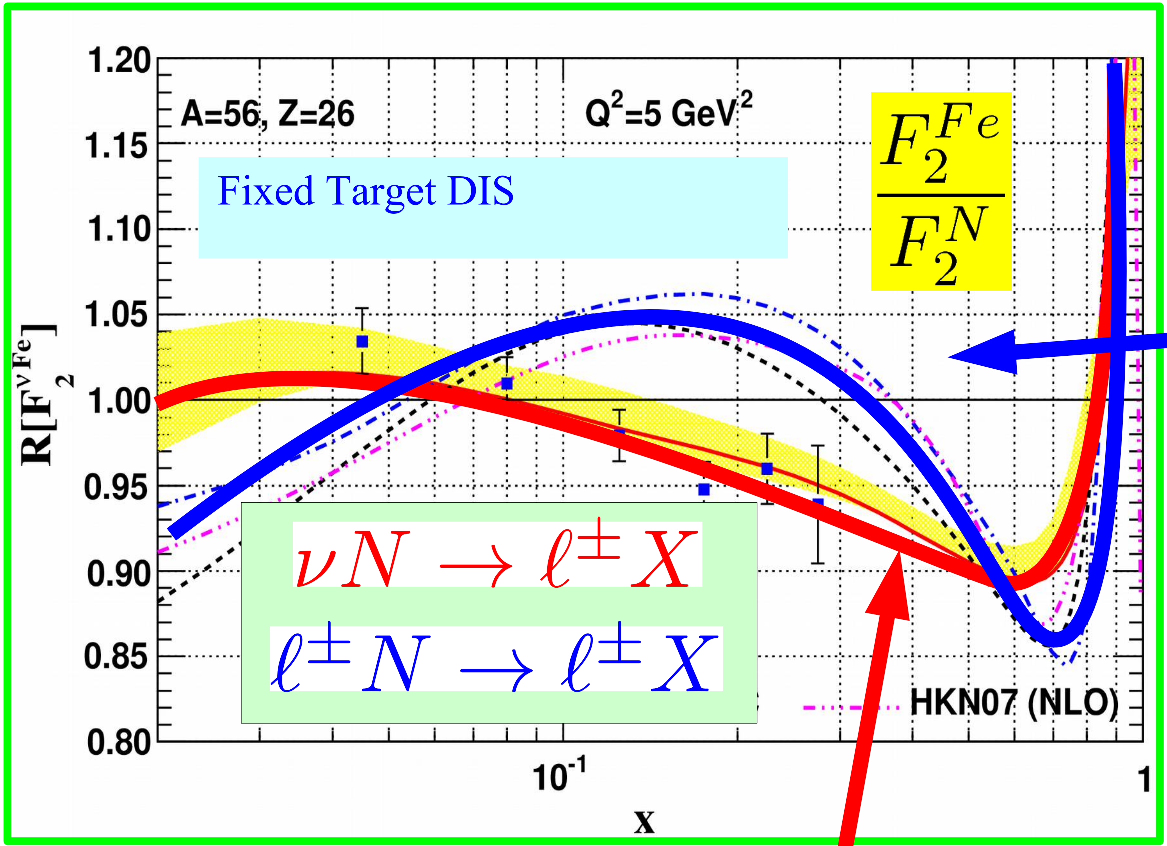
F_2^A/F_2^D : Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
D	NMC-97	5160	[48]	292	201	247.73
He/D	Hermes	5156	[49]	182	17	13.45
	NMC-95,re	5124	[50]	18	12	9.78
	SLAC-E139	5141	[51]	18	3	1.42
Li/D	NMC-95	5115	[52]	24	11	6.10
Be/D	SLAC-E139	5138	[51]	17	3	1.37
C/D	FNAL-E665-95	5125	[53]	11	3	1.44
	SLAC-E139	5139	[51]	7	2	1.36
	EMC-88	5107	[54]	9	9	7.41
	EMC-90	5110	[55]	9	0	0.00
	NMC-95	5113	[52]	24	12	8.40
	NMC-95,re	5114	[50]	18	12	13.29
N/D	Hermes	5157	[49]	175	19	9.92
	BCDMS-85	5103	[56]	9	9	4.65
Al/D	SLAC-E049	5134	[57]	18	0	0.00
	SLAC-E139	5136	[51]	17	3	1.14
Ca/D	NMC-95,re	5121	[50]	18	12	11.54
	FNAL-E665-95	5126	[53]	11	3	0.94
	SLAC-E139	5140	[51]	7	2	1.63
	EMC-90	5109	[55]	9	0	0.00
Fe/D	SLAC-E049	5131	[58]	14	2	0.78
	SLAC-E139	5132	[51]	23	6	7.76
	SLAC-E140	5133	[59]	10	0	0.00
	BCDMS-87	5101	[60]	10	10	5.77
	BCDMS-85	5102	[56]	6	6	2.56
Cu/D	EMC-93	5104	[61]	10	9	4.71
	EMC-93(chariot)	5105	[61]	9	9	4.88
	EMC-88	5106	[54]	9	9	3.39
Kr/D	Hermes	5158	[49]	167	12	9.79
Ag/D	SLAC-E139	5135	[51]	7	2	1.60
Sn/D	EMC-88	5108	[54]	8	8	17.20
Xe/D	FNAL-E665-92	5127	[62]	10	2	0.72
Au/D	SLAC-E139	5137	[51]	18	3	1.74
Pb/D	FNAL-E665-95	5129	[53]	11	3	1.20
Total:				1205	414	403.70

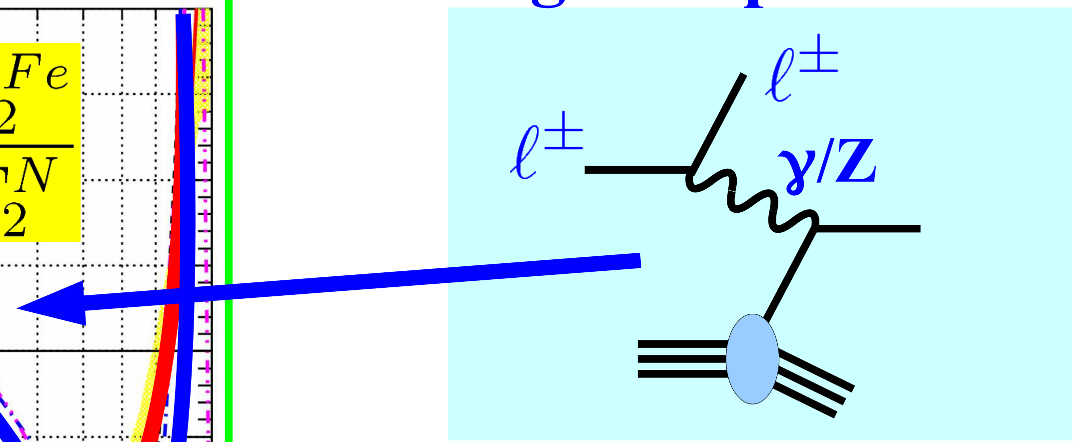


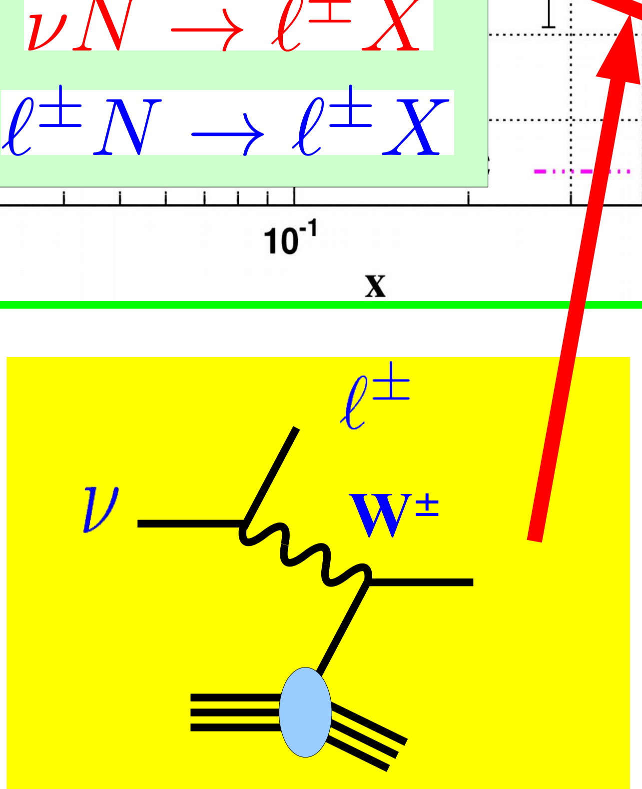
Impact of pion data

Strange Quark PDF & Nuclear Corrections

Charged Lepton DIS

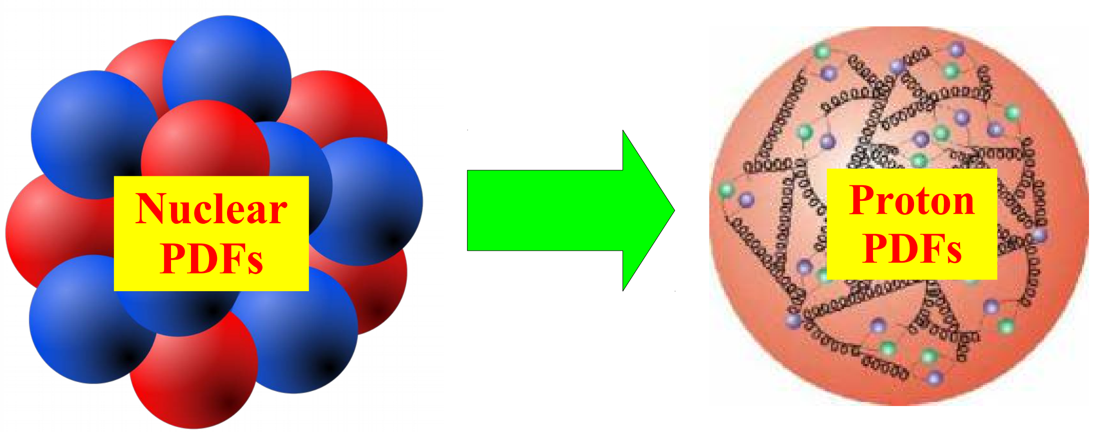




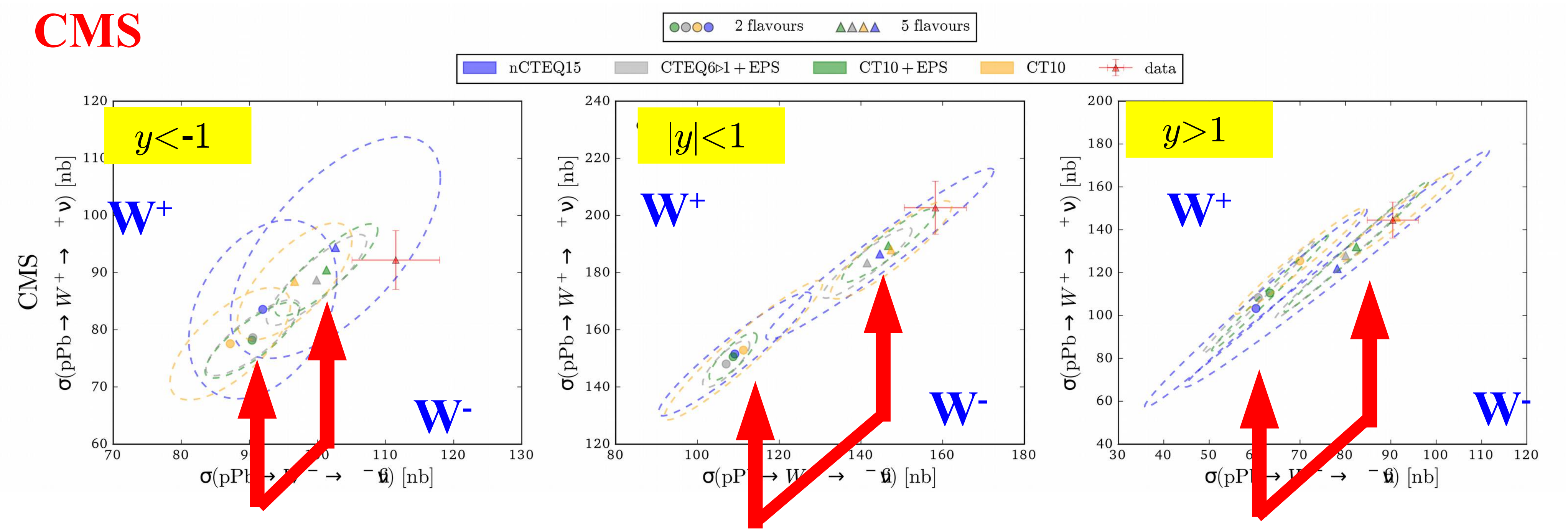


Neutrino DIS

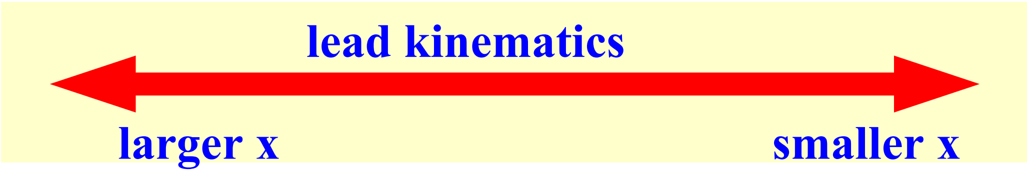
Depends on nuclear corrections



Impact of Strange PDF s(x)

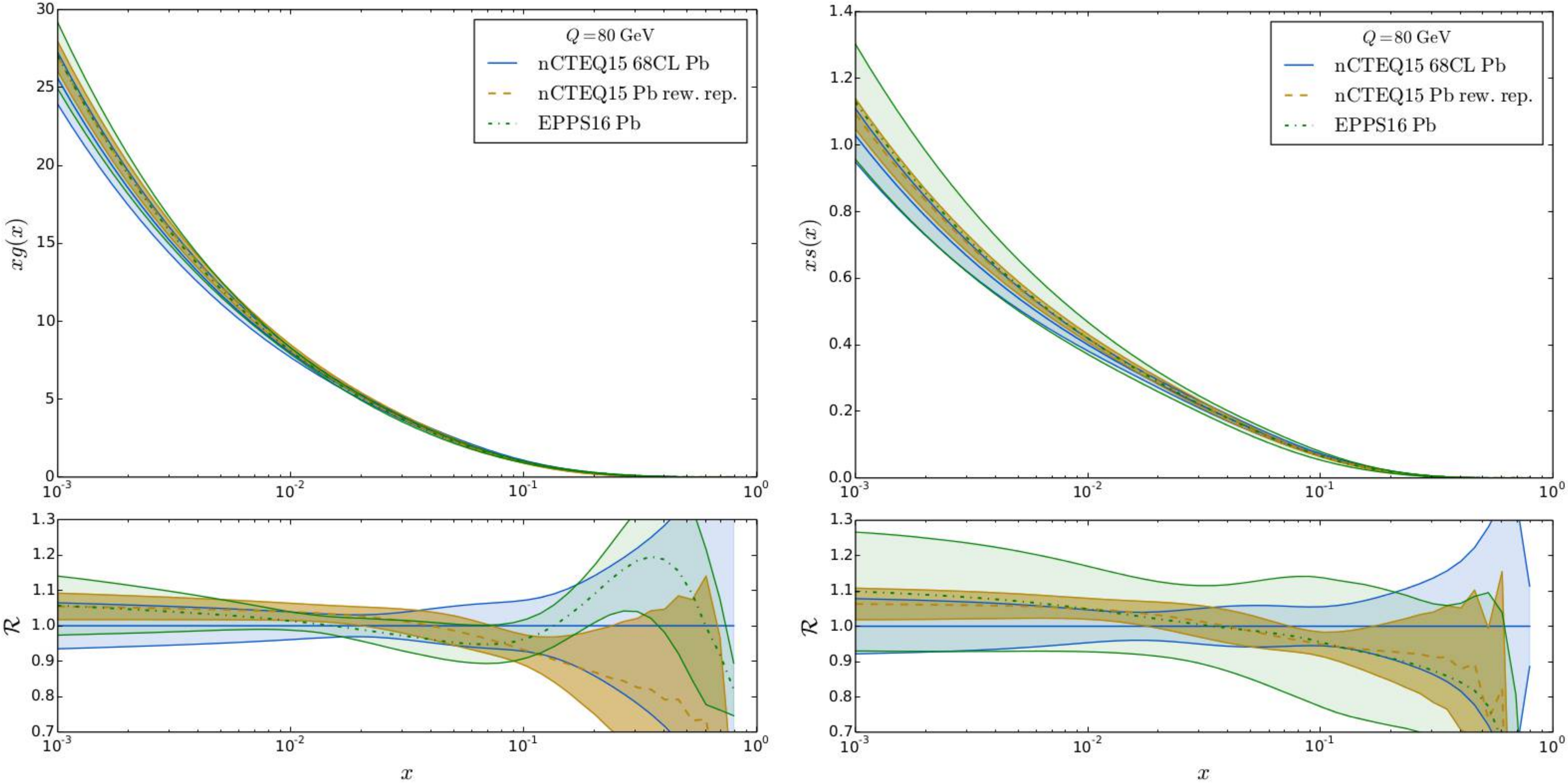


Strange PDF important in this kinematic region



A. Kusina, et al., arXiv:1610.02925 [nucl-th]

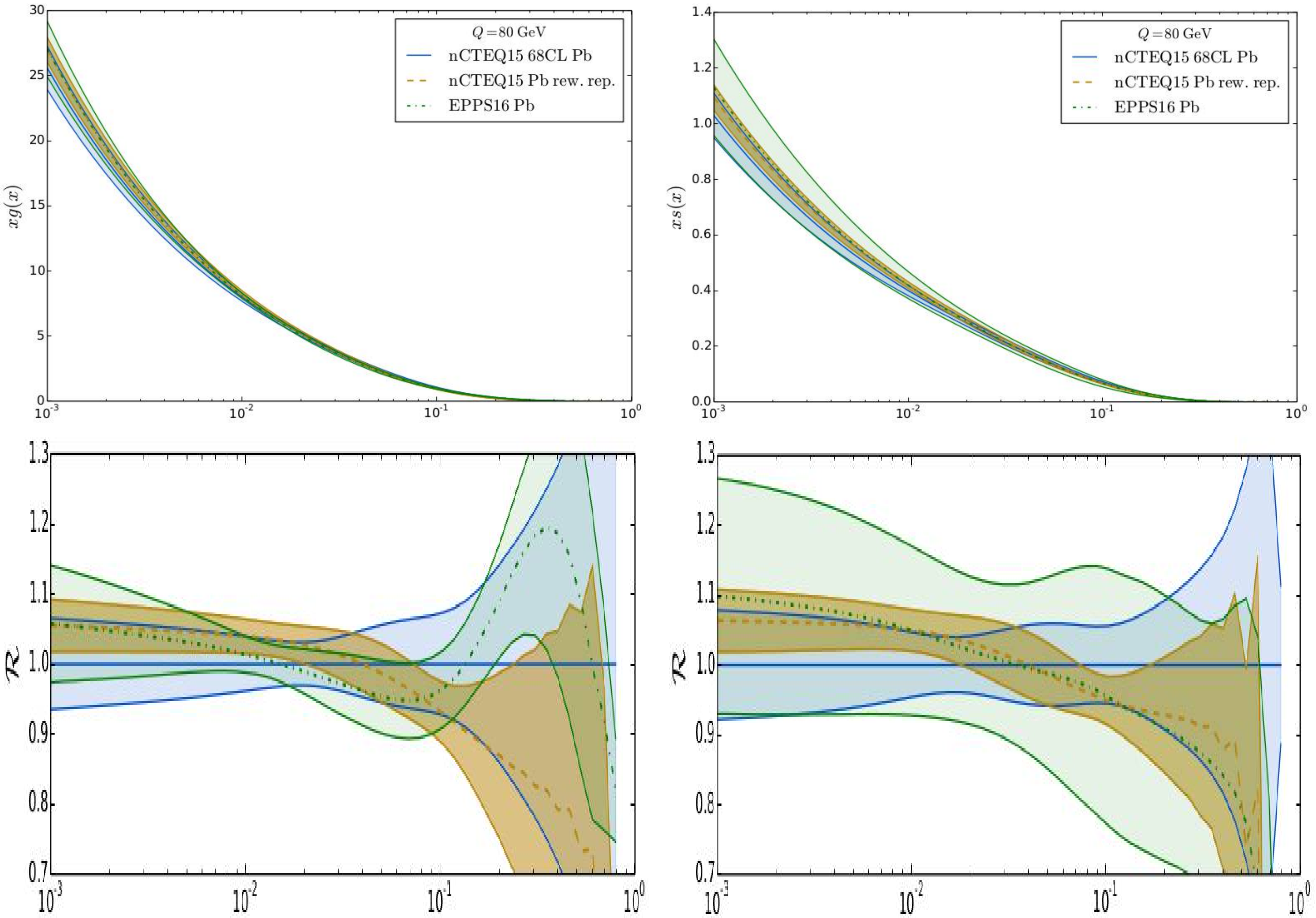
$p\ Pb \rightarrow W/Z$ and Nuclear Corrections



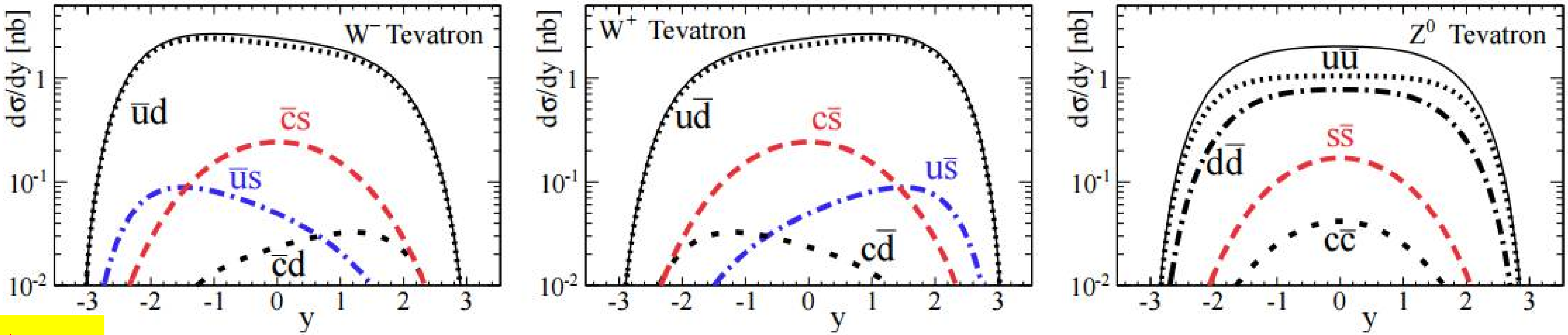
(a) g PDF

(b) s PDF

$p\ Pb \rightarrow W/Z$ and Nuclear Corrections

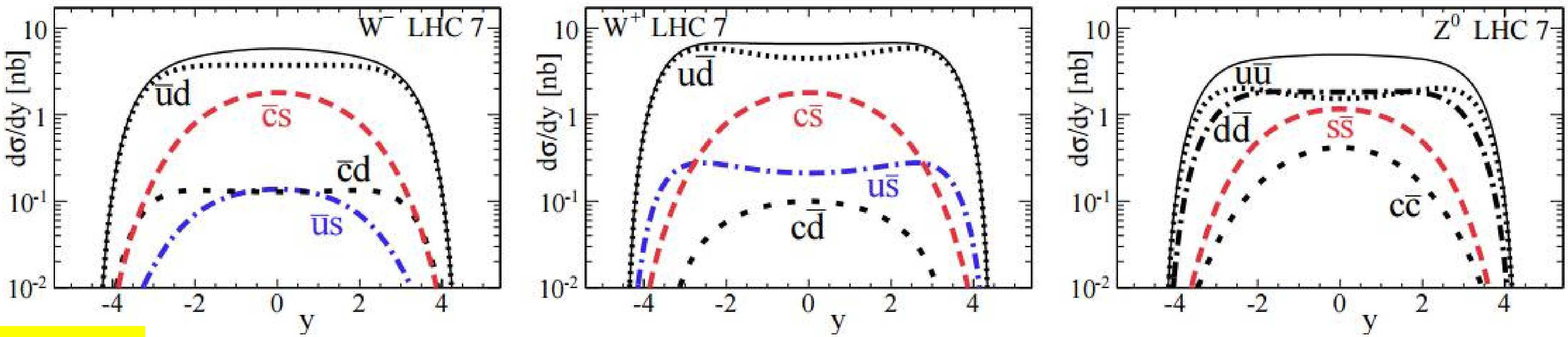


$p\,p \rightarrow W/Z$ Production



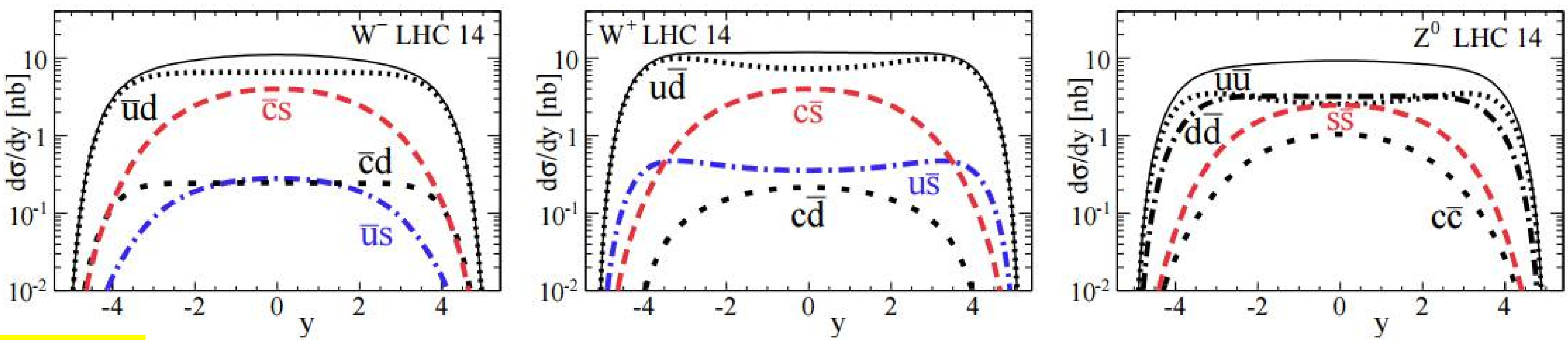
Tevatron

(a) $d\sigma/dy$ for W^- (left), W^+ (middle), Z^0 (right) boson production at the Tevatron.



LHC 7 TeV

(b) $d\sigma/dy$ for W^- (left), W^+ (middle), Z^0 (right) boson production at the LHC with $\sqrt{S} = 7$ TeV.



LHC 14 TeV

(c) $d\sigma/dy$ for W^- (left), W^+ (middle), Z^0 (right) boson production at the LHC with $\sqrt{S} = 14$ TeV.

Strange Quark PDFs and Implications for Drell-Yan Boson Production at the LHC. A. Kusina, et al.., Phys.Rev. D85 (2012) 094028

Heavy Quark

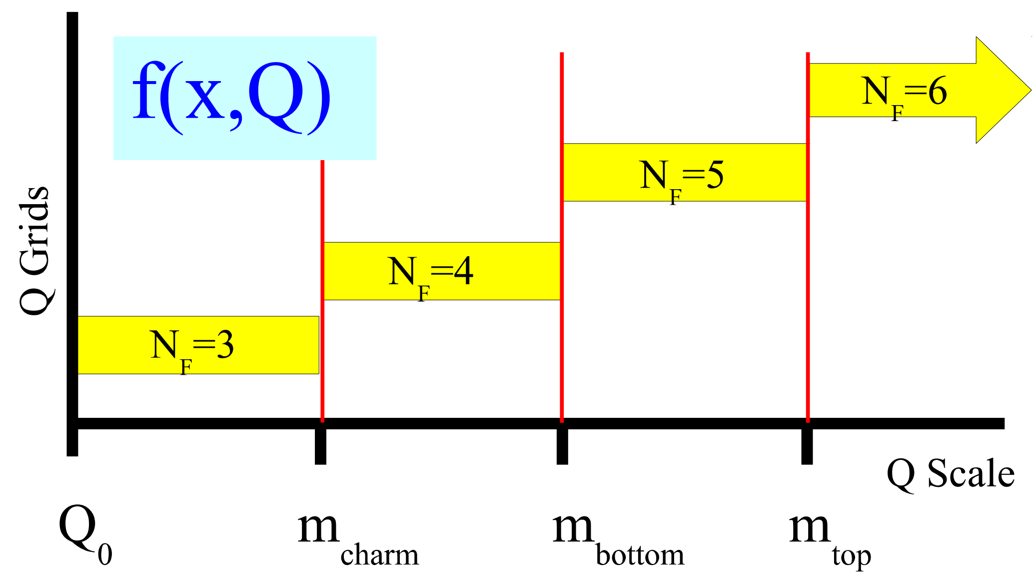
PDFs

Impact of heavy quark matching scale dependence in global PDF fits

APFEL has a new feature

We can adjust the matching scale for the heavy quark PDF transition

Traditional VFNS

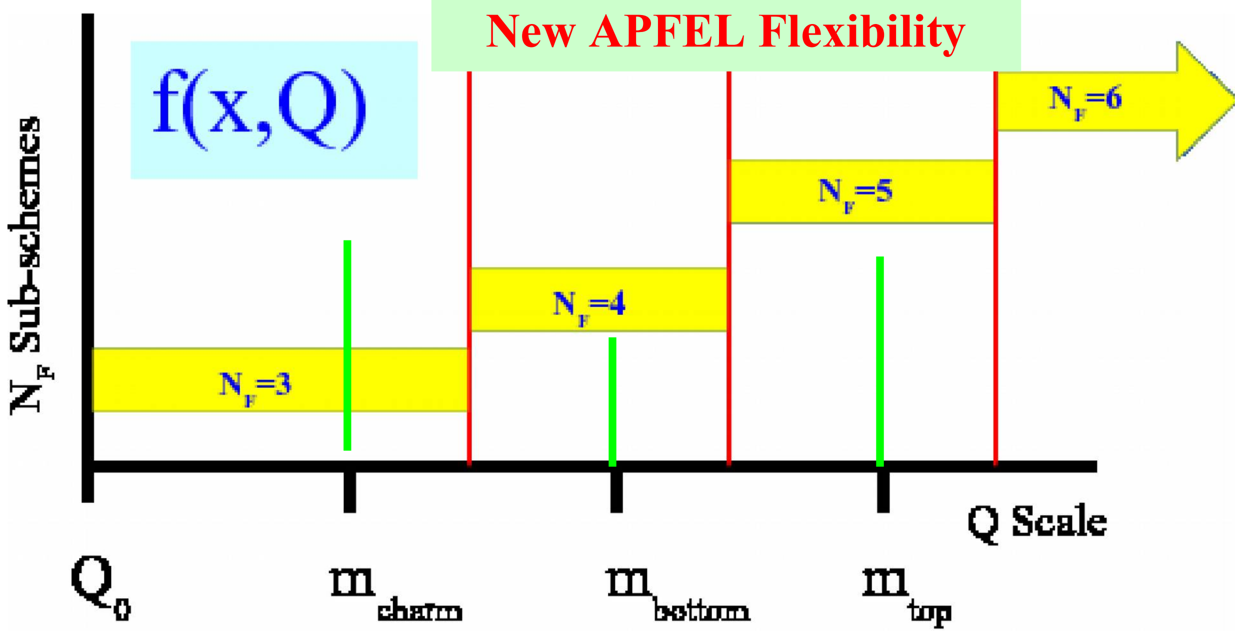


What are the benefits?

1) **avoid discontinuities in the middle of data sets**

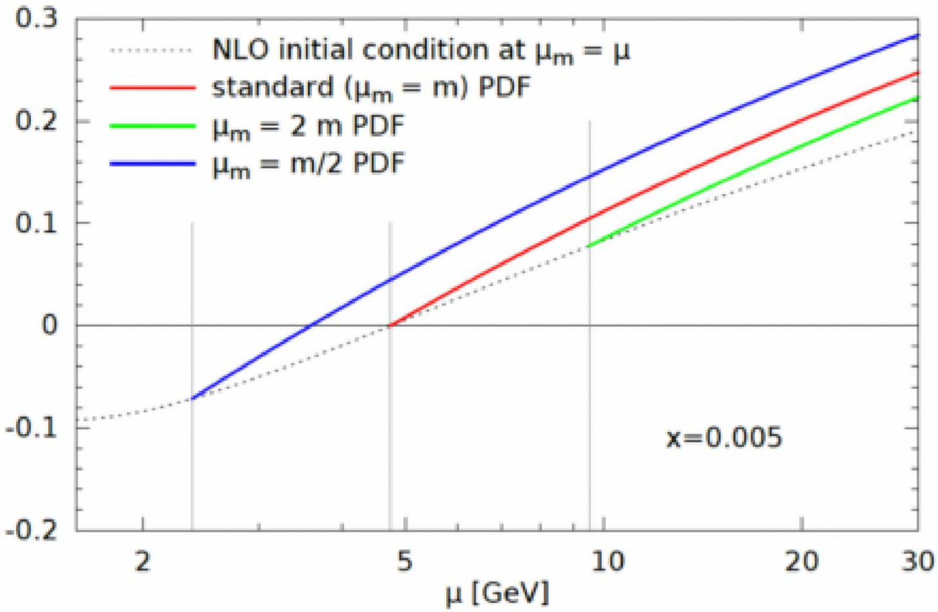
2) **avoid delicate matching in region $\mu \sim m_{c,b}$**

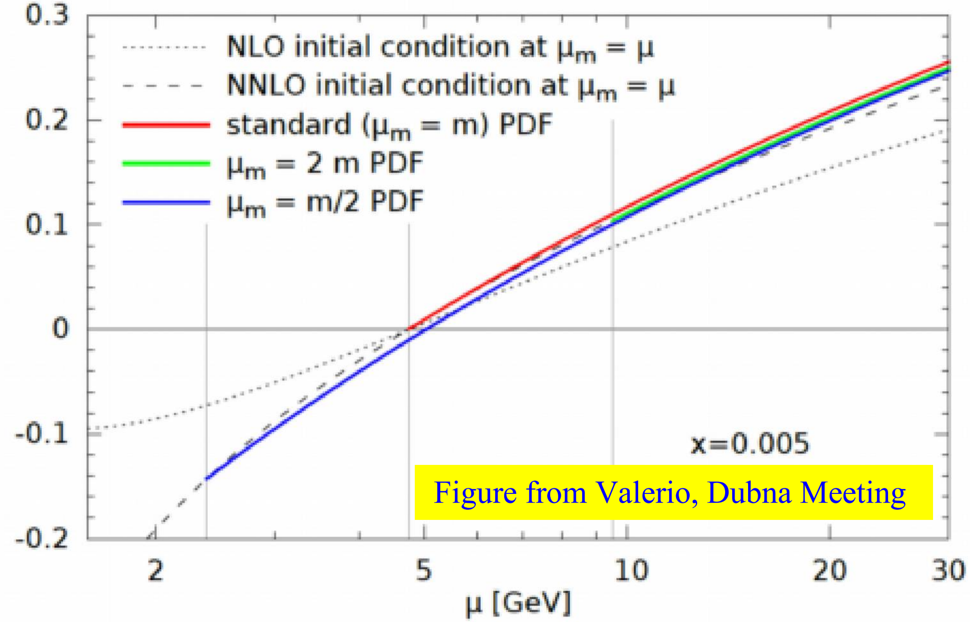
New APFEL Flexibility



Based on an idea of John Collins

The matching conditions are non-trivial, especially at NNLO





NLO Matching Condition

$$f_b^5(x,\mu) = \left(\frac{\alpha_S}{2\pi}\right)\left[P_{1,0} + P_{1,1}\log\left(\frac{\mu^2}{m_b^2}\right)\right] \otimes f_g^4(x,\mu)$$

A proposal: Consider N_F dependent PDF

Provides some of the benefits & flexibility of displaced matching, but with a compromise.

Disadvantages:

Match at $\mu_{c,b} \sim m_{c,b}$,

but switch at higher scale

How much do we "lose" in χ^2 ???

Advantages:

* avoid discontinuities in data
* avoid delicate cancellations

and

* minimal set of PDF grids