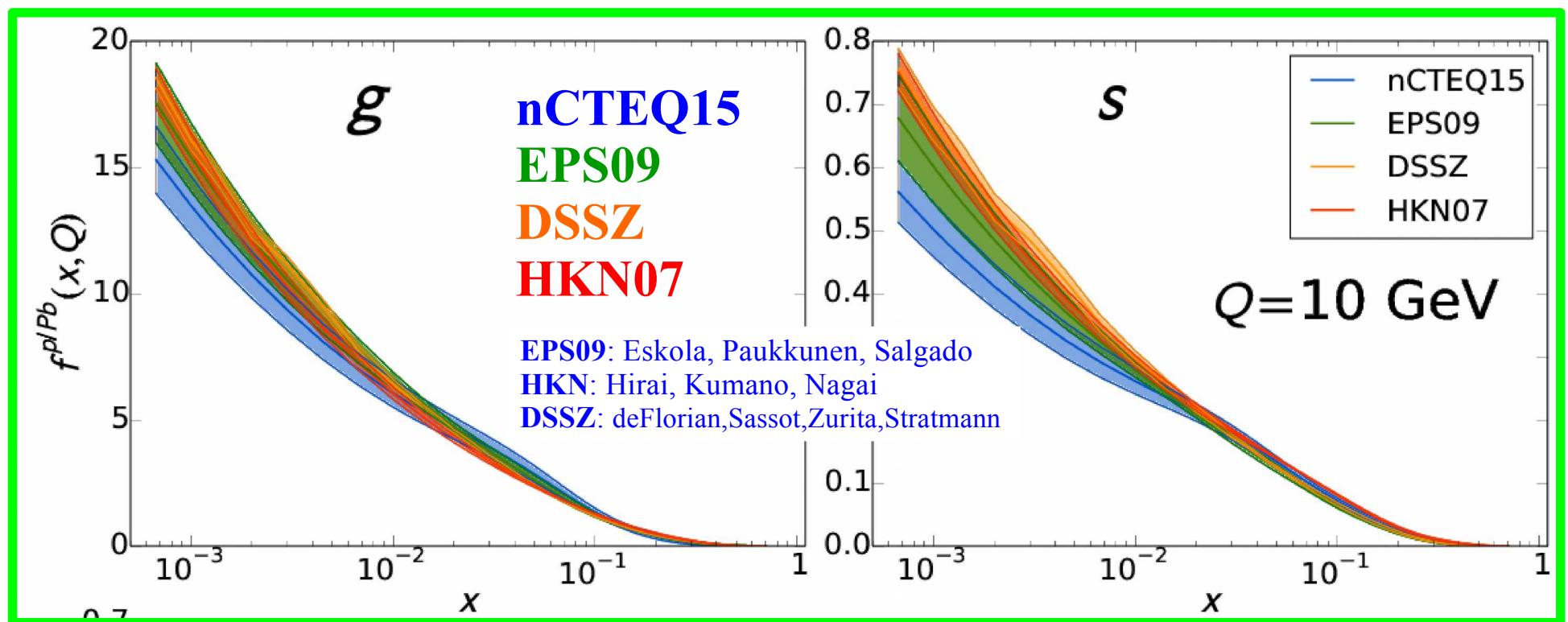


PDF flavor determination and the nCTEQ15 PDFs

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

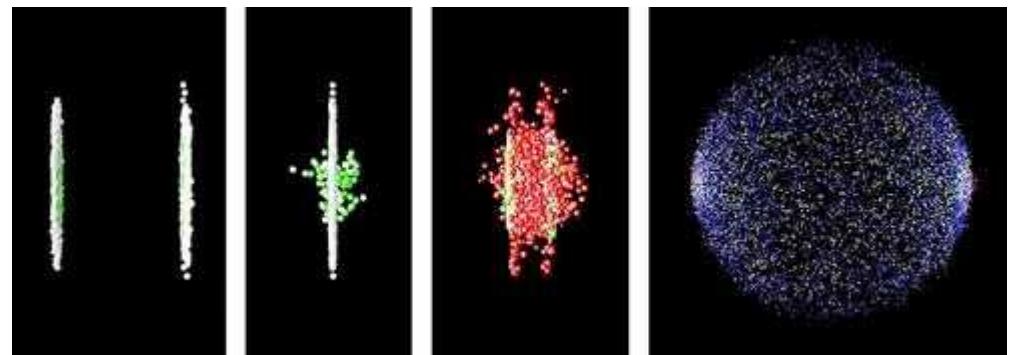
The Santa Fe
Jets & Heavy Flavor Workshop
January 29-31, 2018

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

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

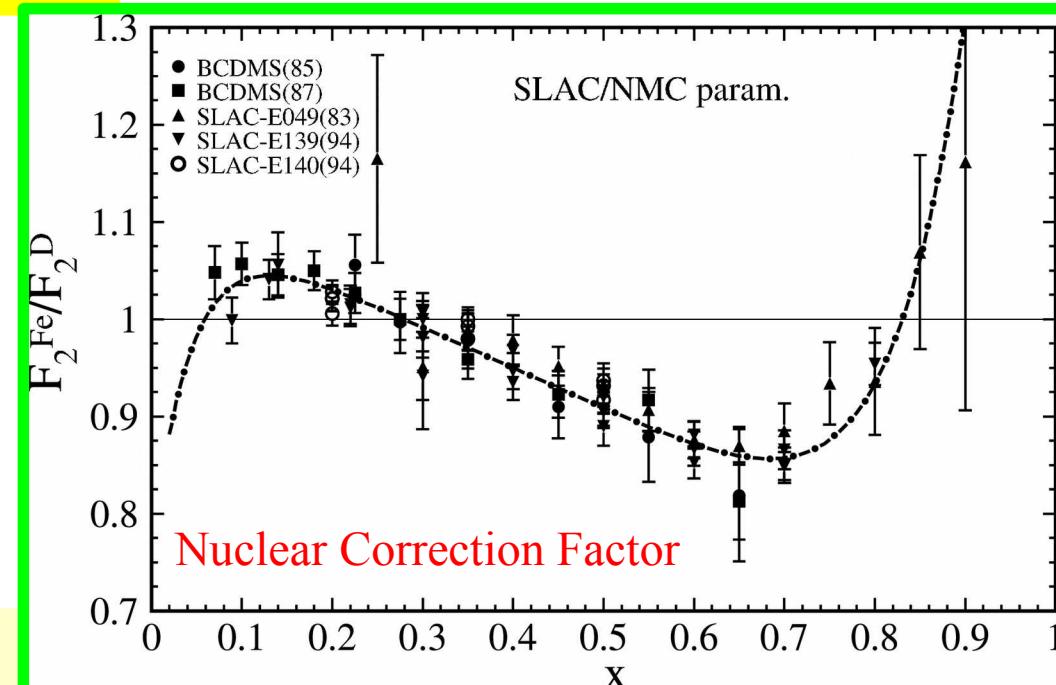
$$F_2^{\bar{\nu}} \sim [\bar{d} + \bar{s} + u + c]$$

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

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

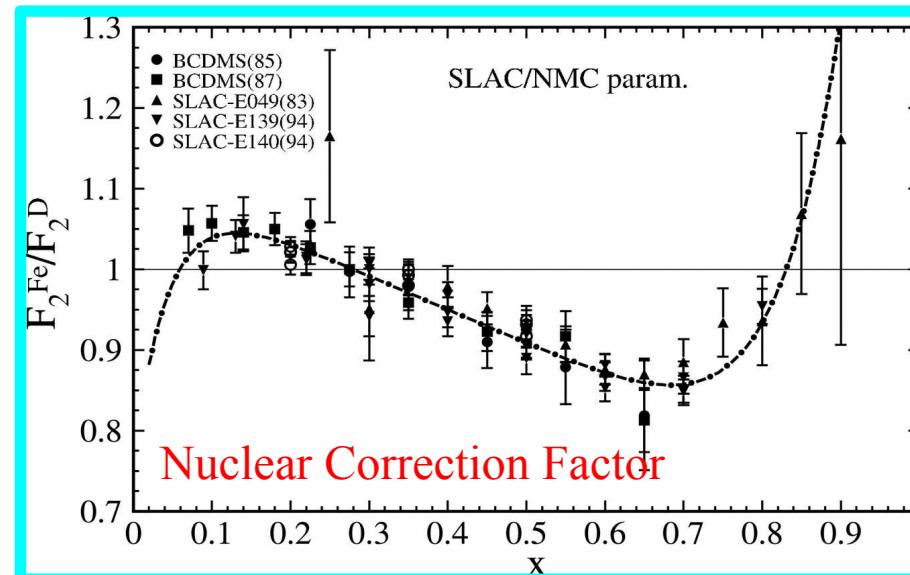
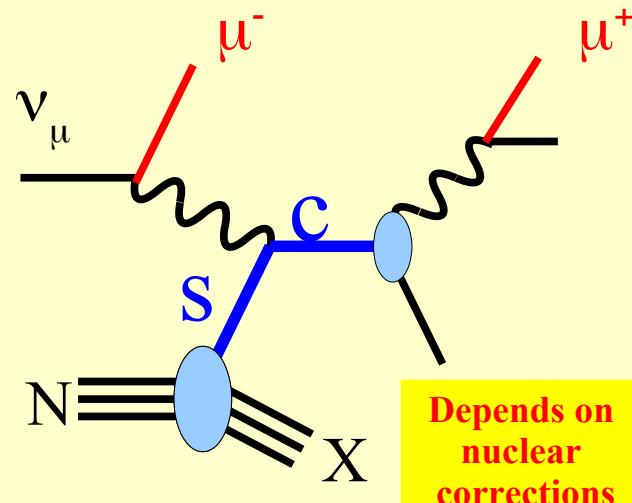
charged lepton DIS

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

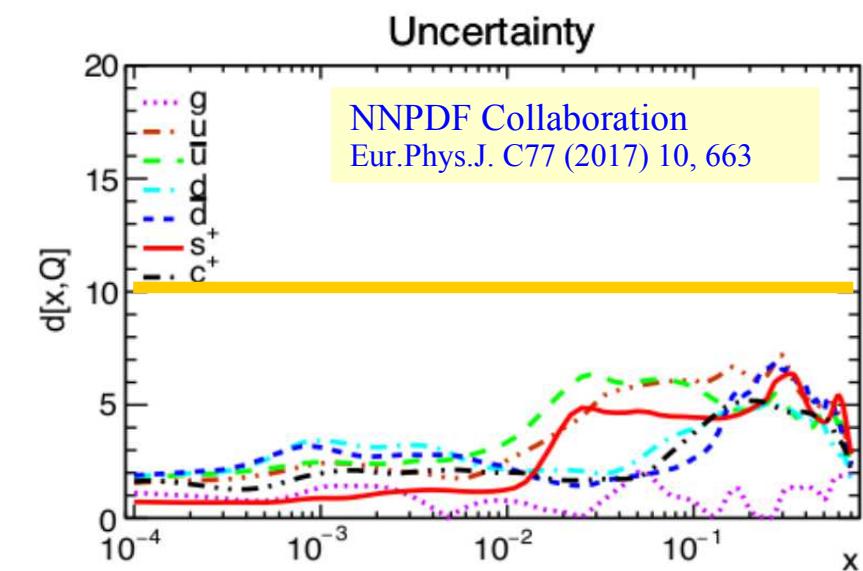
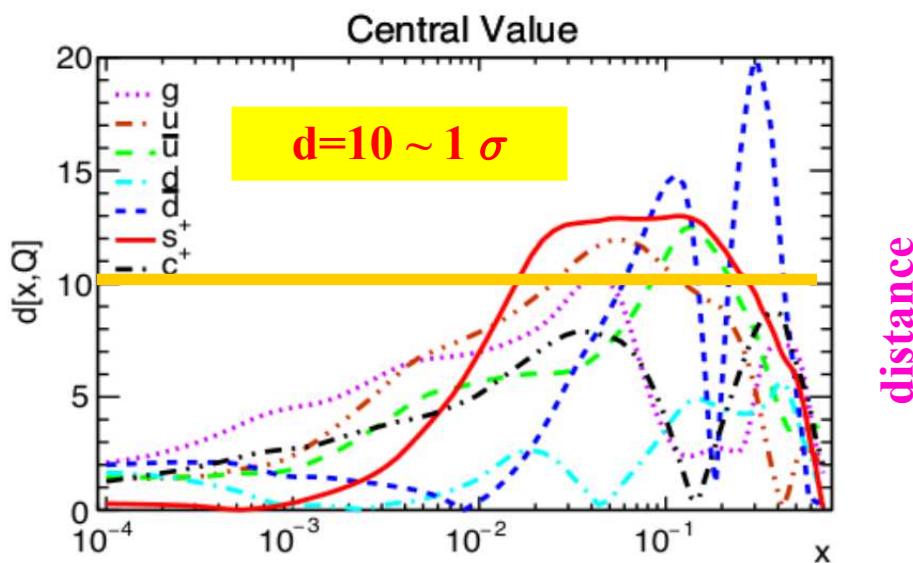


Impact of Nuclear Corrections on Proton PDF

Neutrino DIS

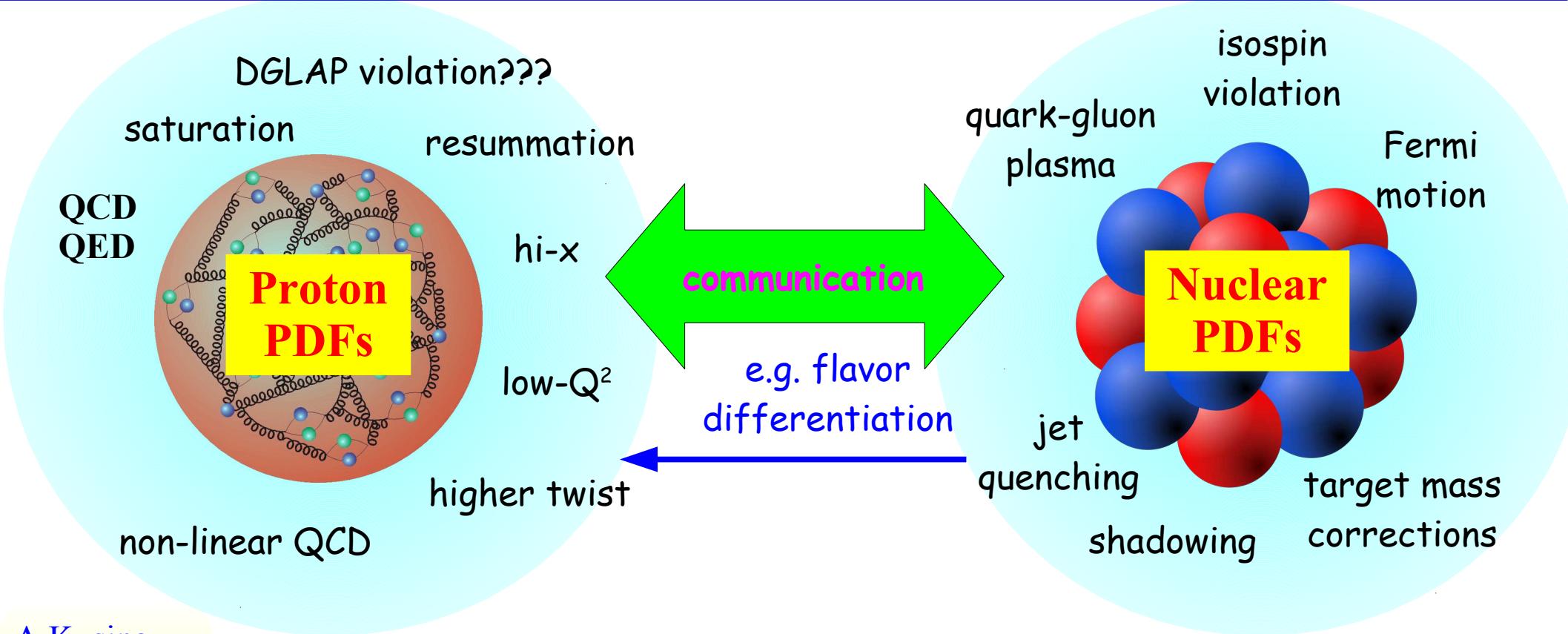


NNPDF3.1 NNLO, Impact of nuclear+deuteron fixed-target data , $Q = 100 \text{ GeV}$



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

... the motivation for nCTEQ

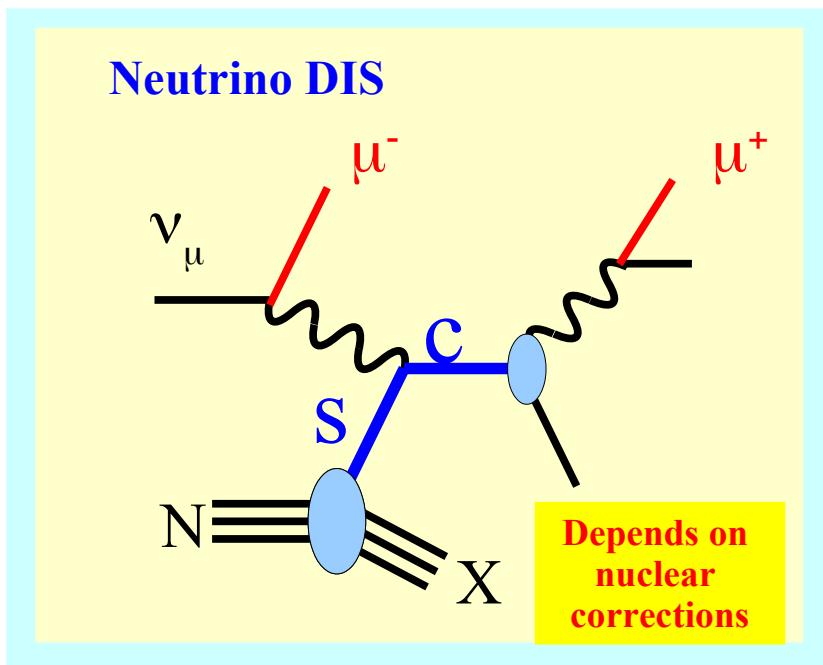


A Kusina,
K. Kovarik
T. Jezo,
D. Clark,
C. Keppel,
F. Lyonnet,
J. Morfin,
F. Olness
J. Owens,
I. Schienbein,
J. Yu
E. Godat

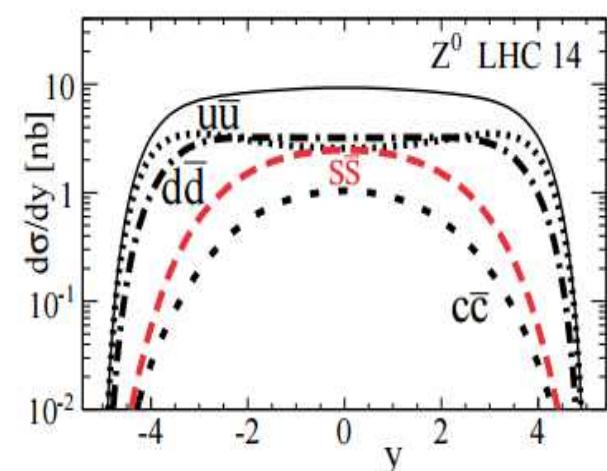
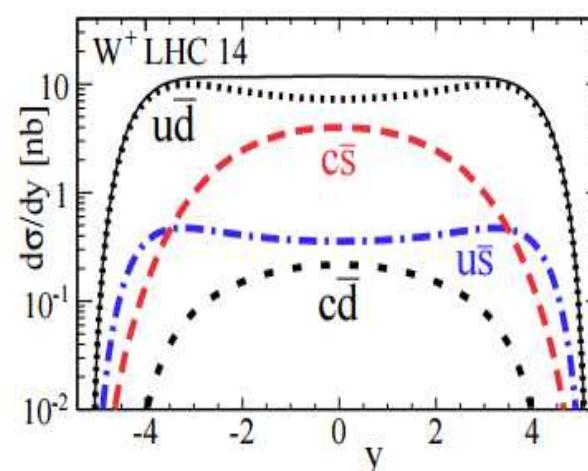
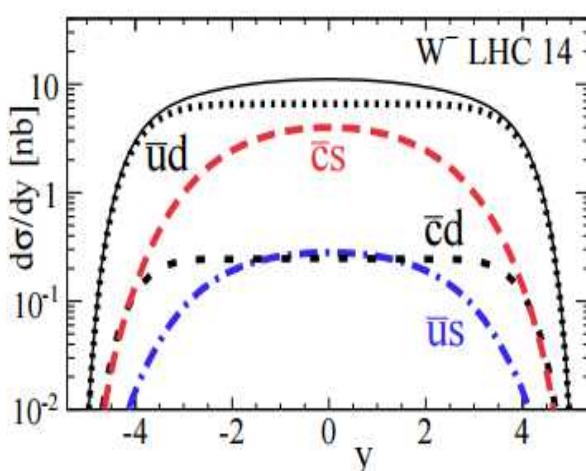
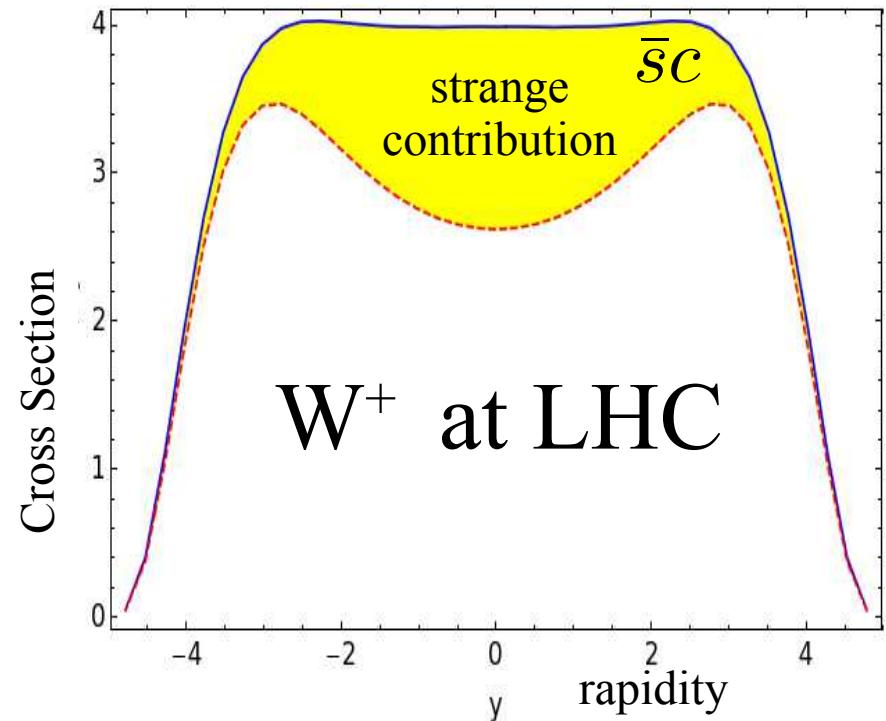
Data from nuclear targets play a key role in the flavor differentiation

nCTEQ

nuclear parton distribution functions



... stepping stone to charm, bottom, ...



LHC 14 TeV

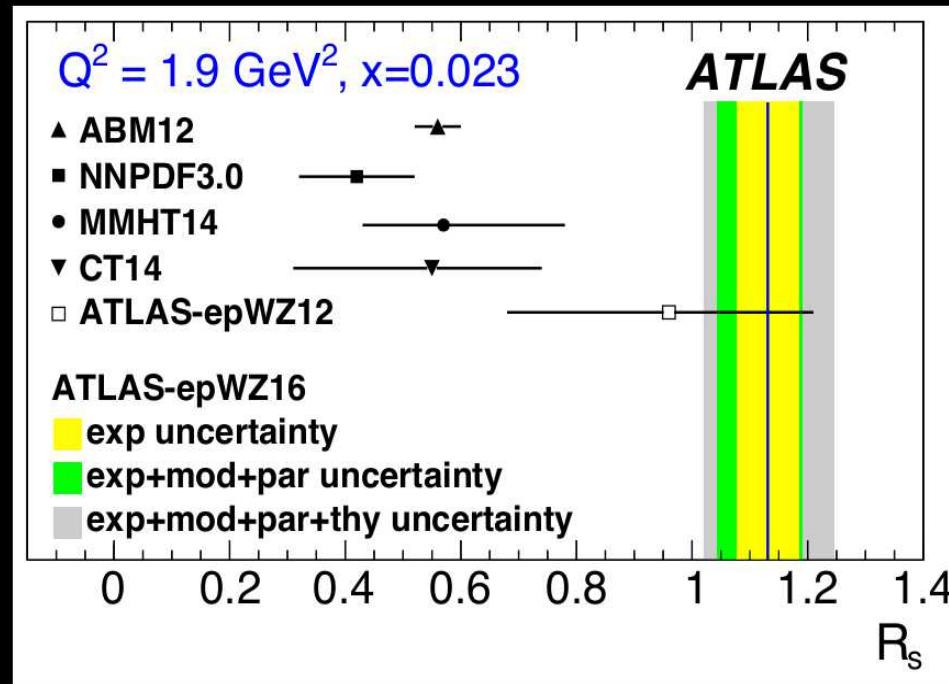
(c) $d\sigma/dy$ for W^- (left), W^+ (middle), Z^0 (right) boson production at the LHC with $\sqrt{S} = 14$ TeV.

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 Strangeness in the Proton

arXiv:1612.03016



$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}} = 1.13 \pm 0.05 \text{ (exp)} \pm 0.02 \text{ (mod)} \stackrel{+0.01}{\scriptscriptstyle (-0.06)} \text{ (par)}$$

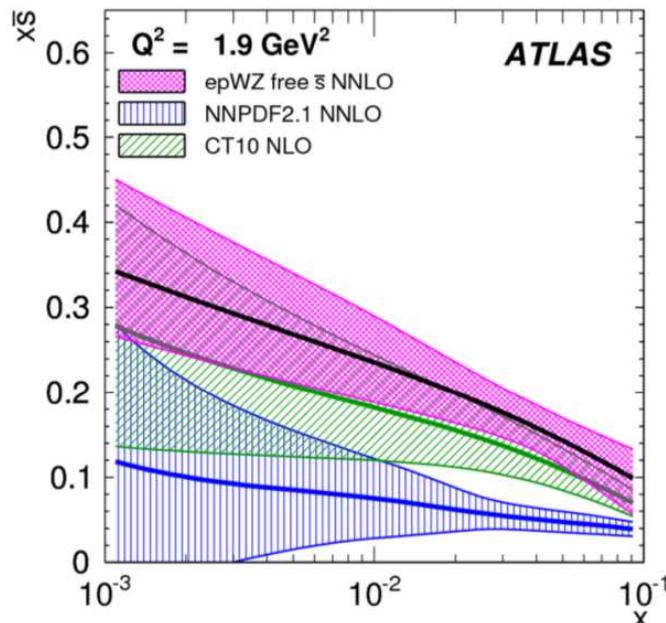
... I want a second opinion, ...

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

$$r^s(x, Q) = \frac{\bar{s}(x, Q) + s(x, Q)}{2\bar{d}(x, Q)}$$

$$R^s(x, Q) = \frac{s(x, Q) + \bar{s}(x, Q)}{\bar{u}(x, Q) + \bar{d}(x, Q)}$$

NNLO, $Q = 100 \text{ GeV}$

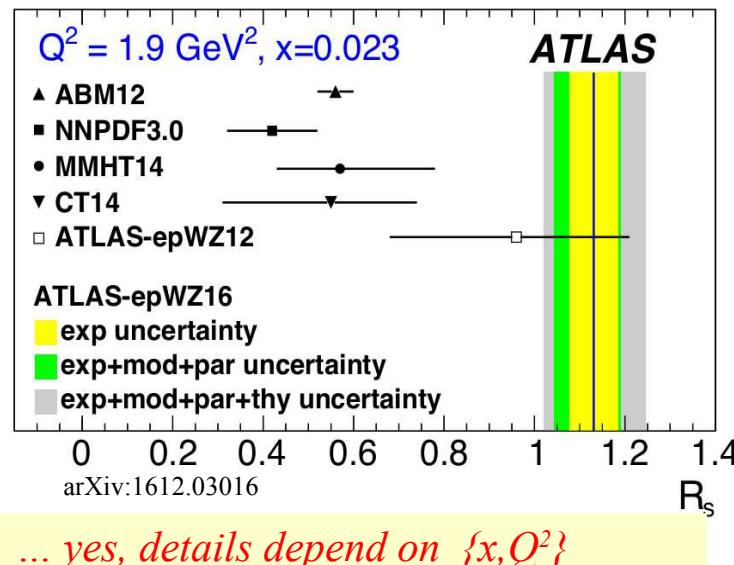
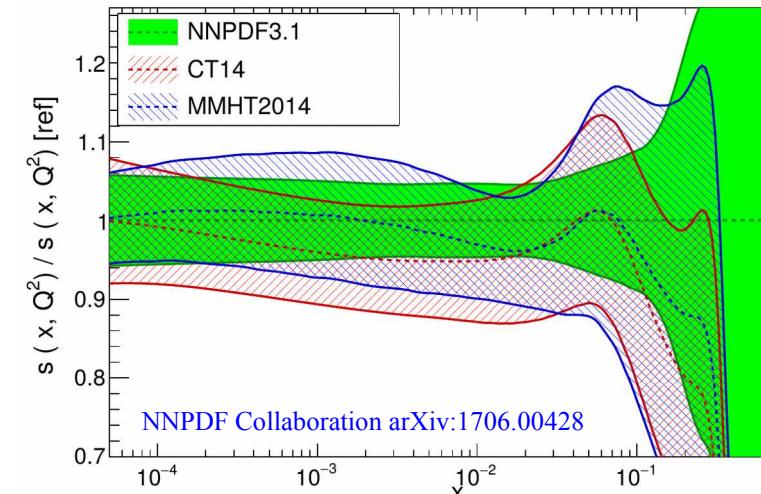


HERAFitter, Open Source QCD Fit Project
Eur. Phys. J. C (2015) 75: 304.

$K_{\text{CT14NNLO}}^s = 0.62 \pm 0.14$
 $K_{\text{CT10NNLO}}^s = 0.73 \pm 0.11$

Carl Schmidt October 2015: INT Workshop

*... whatever you
want it to be*



NuTeV $\kappa = 0.477^{+0.063}_{-0.053}$

Z.Phys.C65:189-198,1995

NOMAD $\kappa = 0.591 \pm 0.019$

arXiv:1308.4750

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

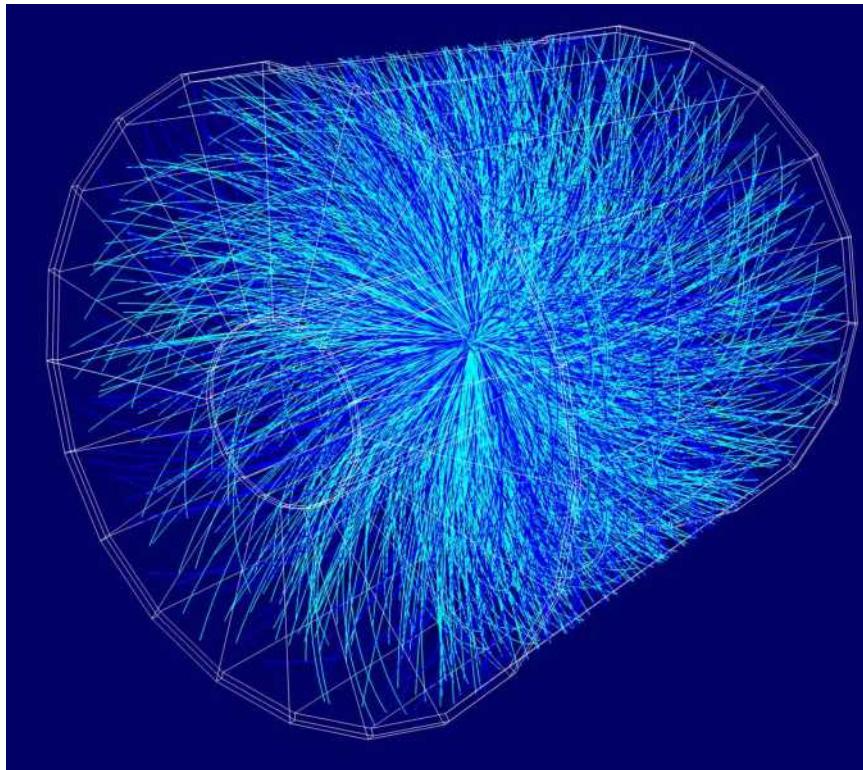
PhysRevD.90.032004
(exp)(model)(param)

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

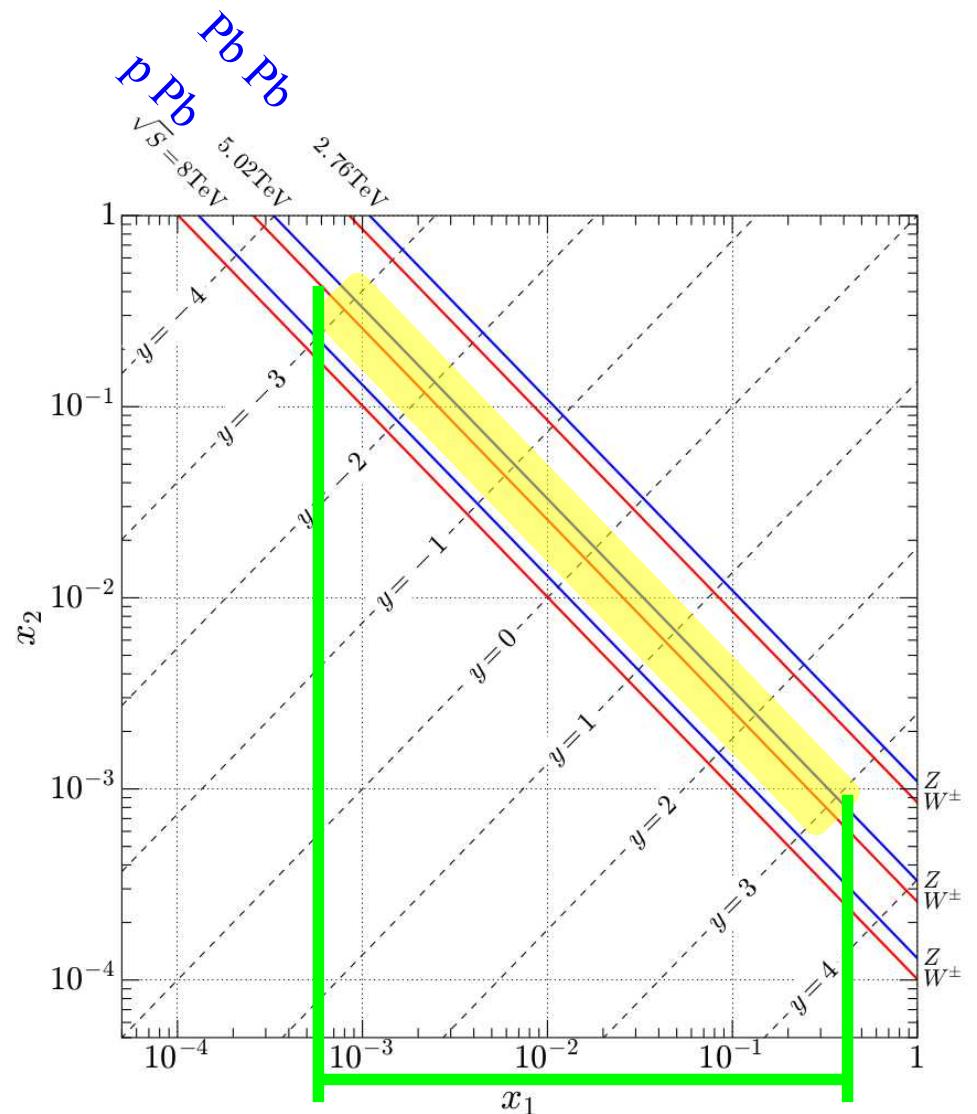
$Q_0^2=1.9 \text{ GeV}^2$ at $x=0.023$

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

- * 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

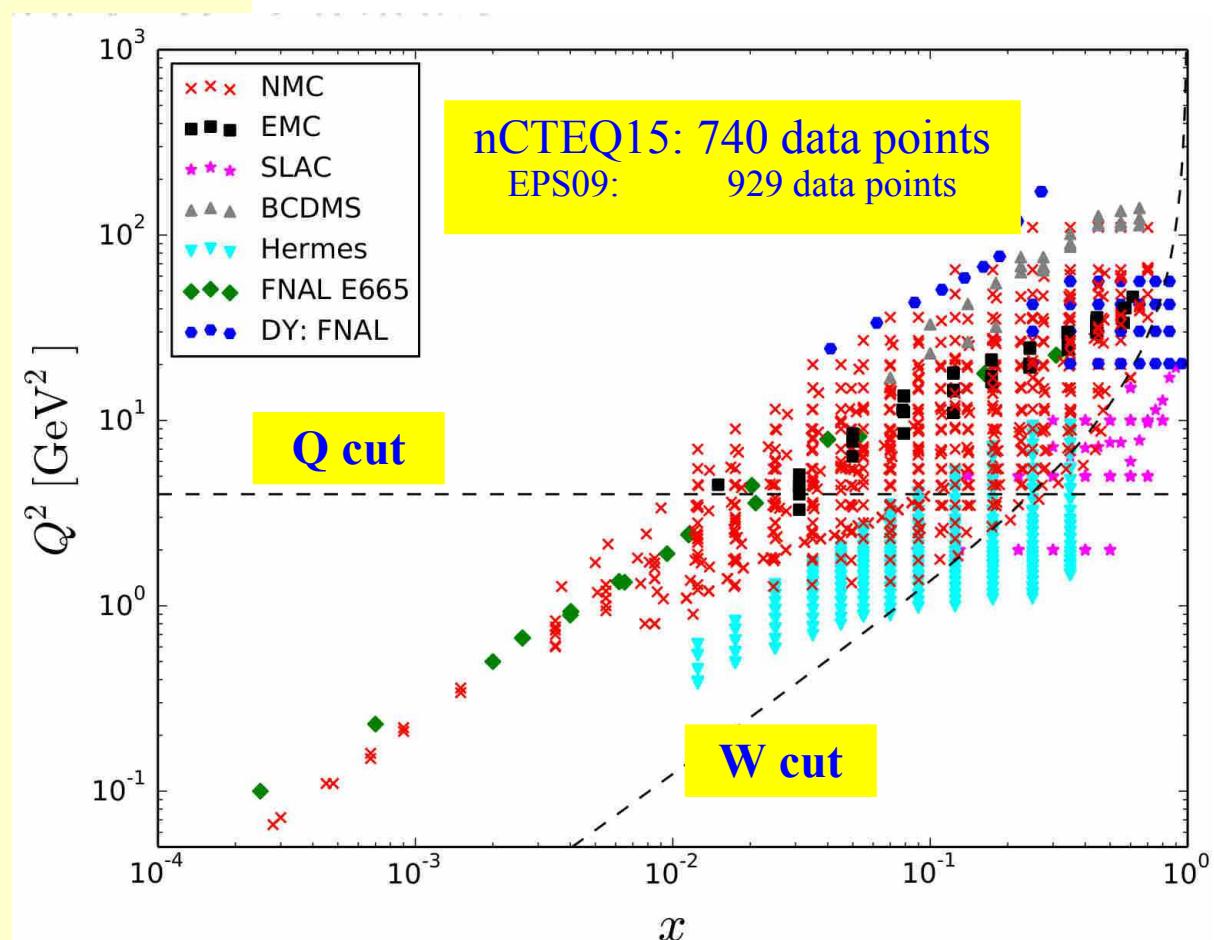
DIS Cuts:

nCTEQ: Q>2.0 & W>3.5

EPS: Q>1.3

HKN: Q>1.0

DSSZ: Q>1.0



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

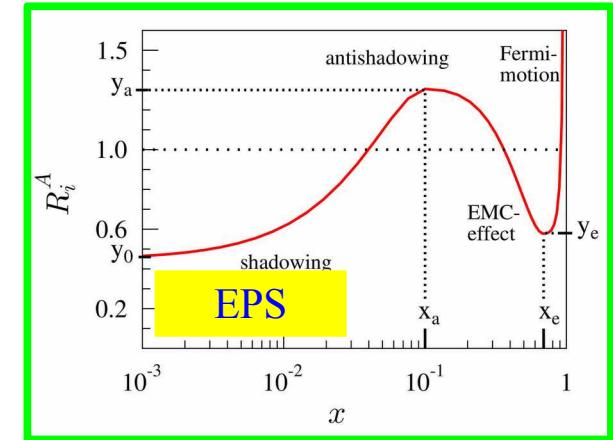
1) Multiplicative nuclear correction factors (HKN, EPS, DSSZ)

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

... 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)

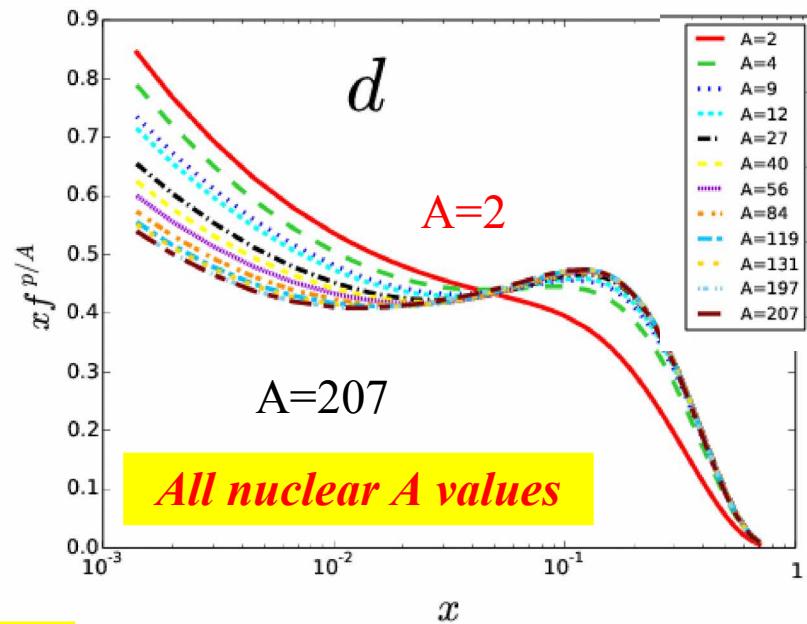
$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

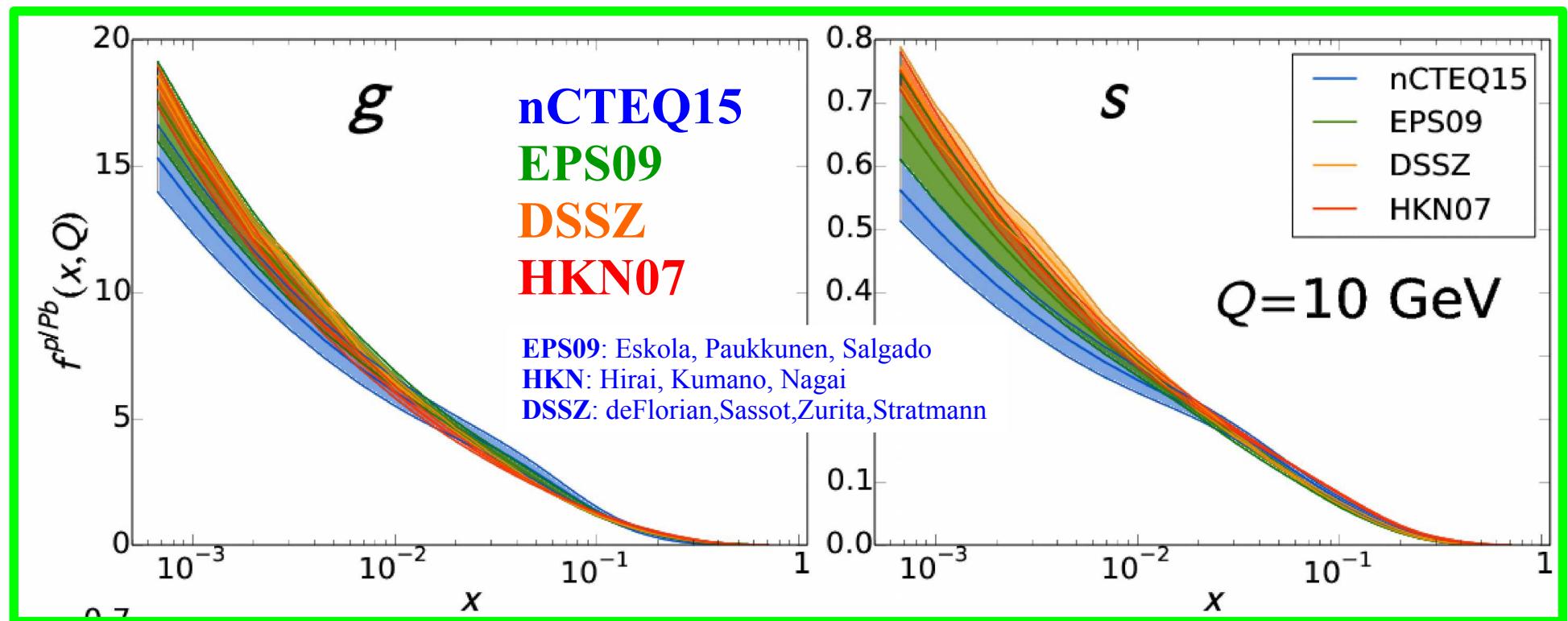
$$f \sim \dots x^{c_1(A)} (1-x)^{c_2(A)} \dots$$

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

Proton

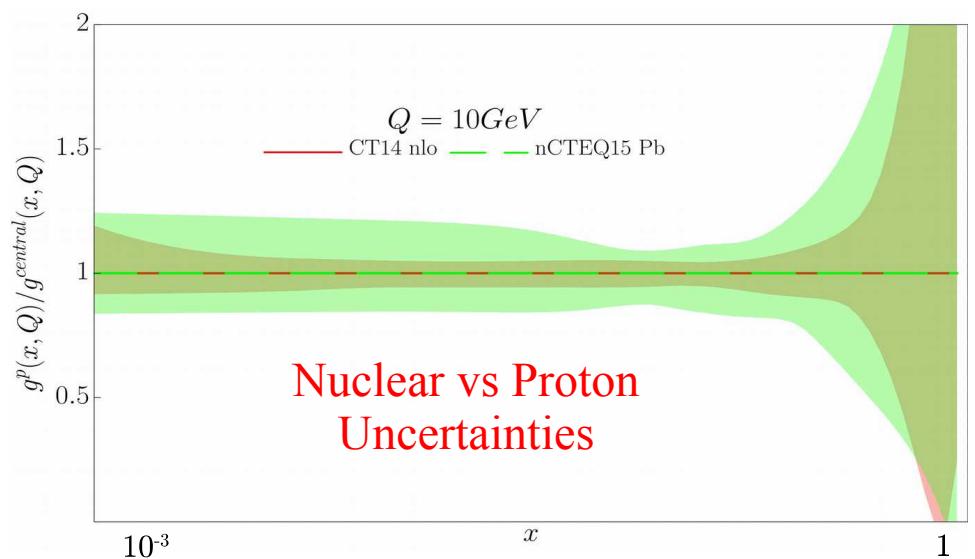
use proton as a Boundary Condition





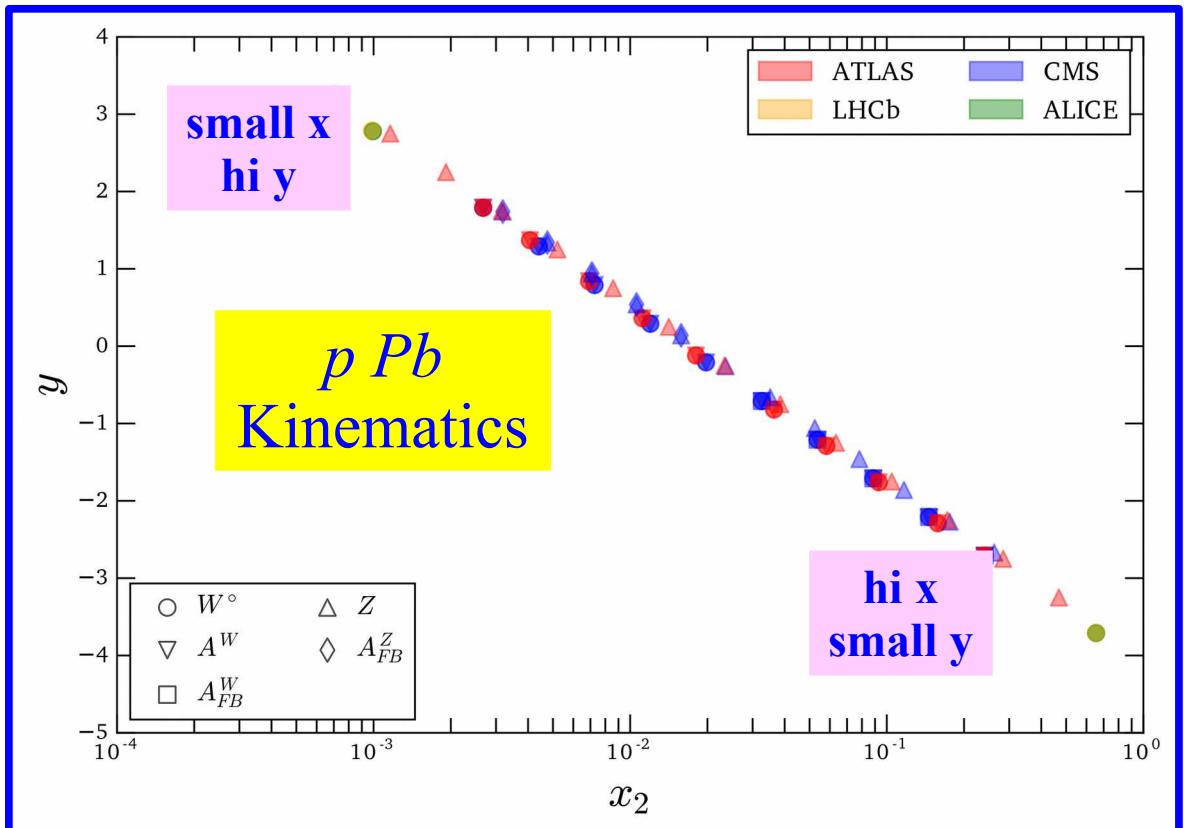
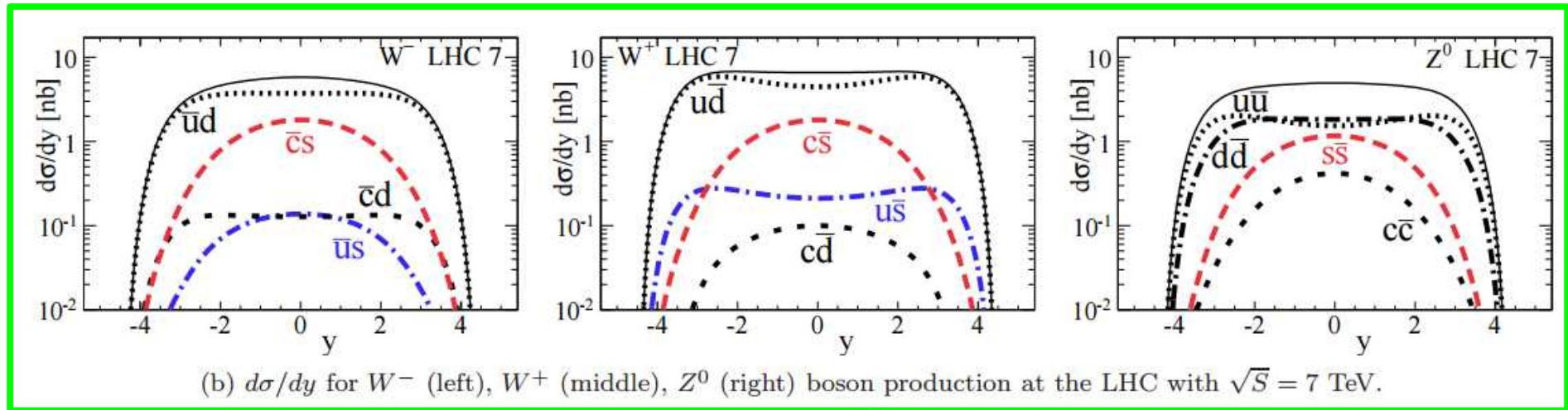
Nuclear PDFs are more complex

- 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. Lyonne, D. B. Clark, E. Godat, T. Jezo,
K. Kovarik, F. I. Olness, I. Schienbein, J. Y. Yu,
arXiv:1610.02925 [nucl-th]



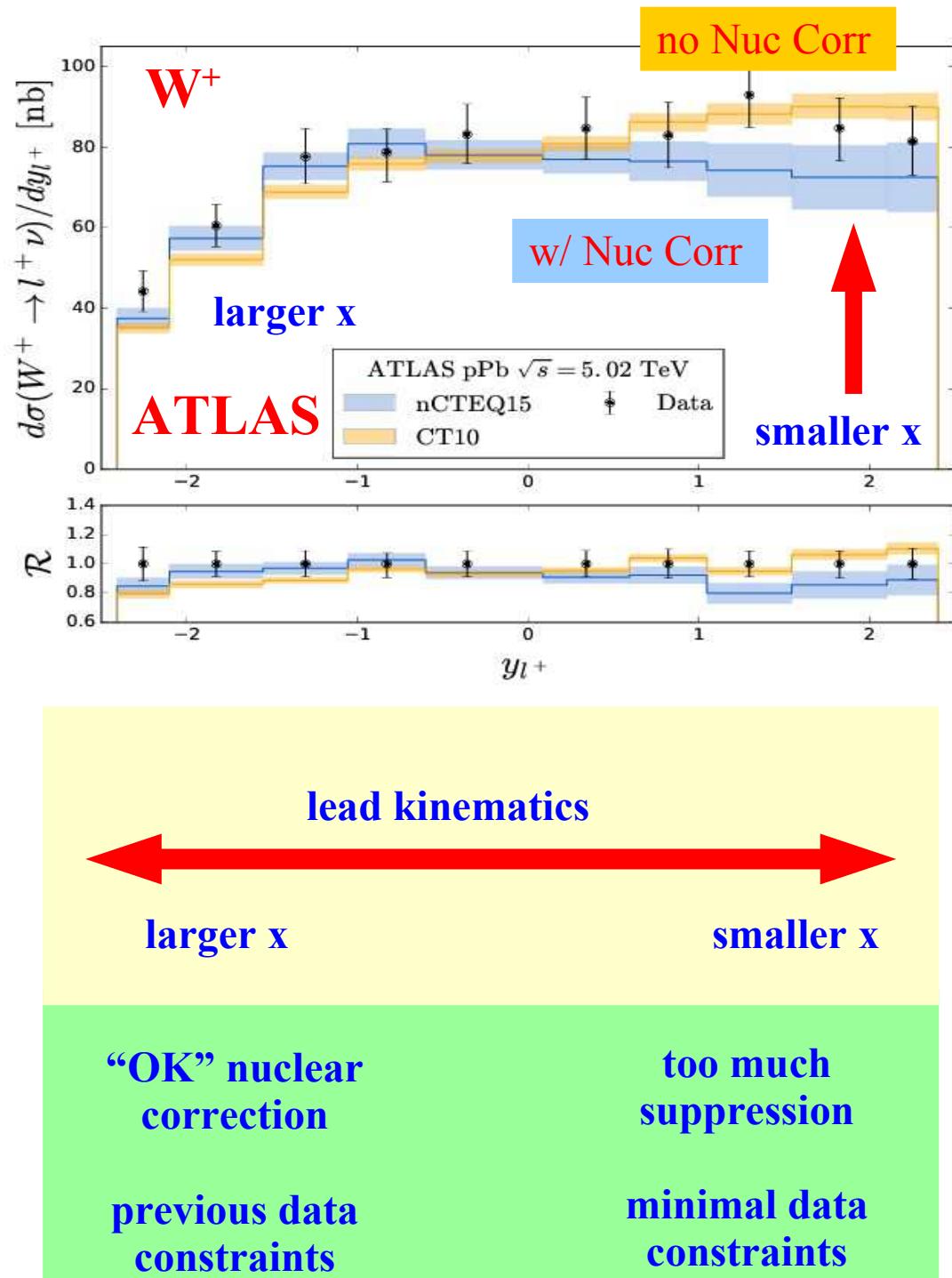
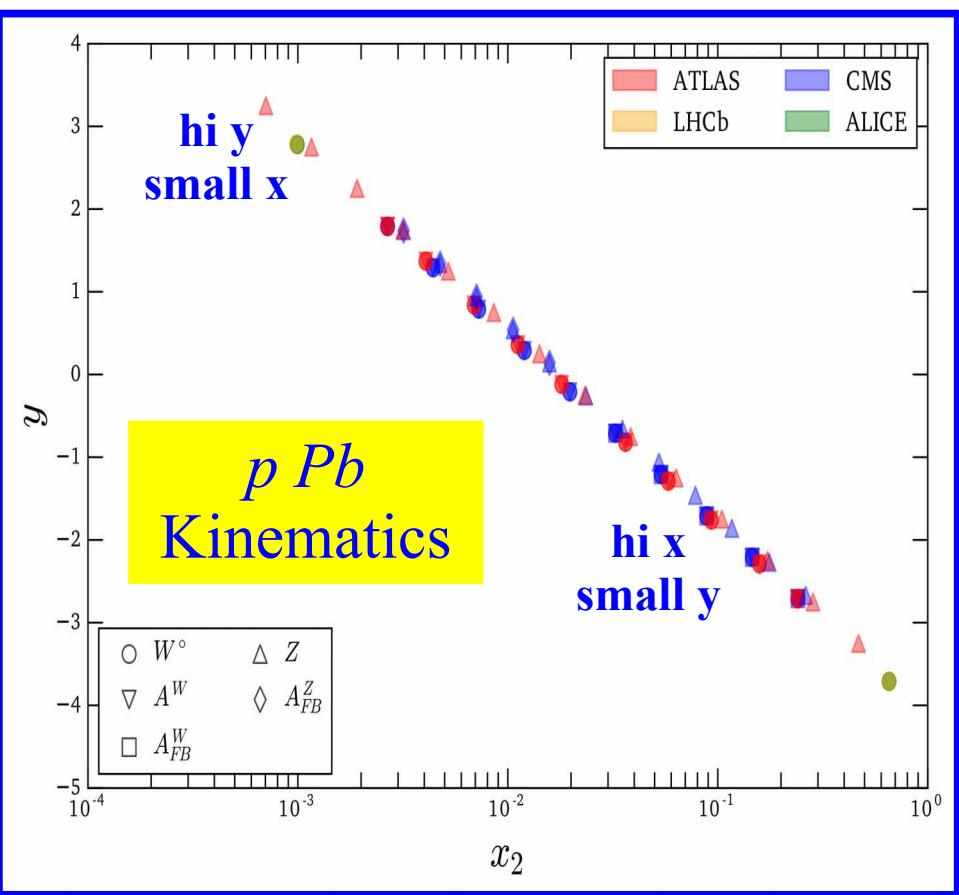
$$W^+ \sim c(x) \bar{s}(x)$$

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

$$Z \sim s(x) \bar{s}(x)$$

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

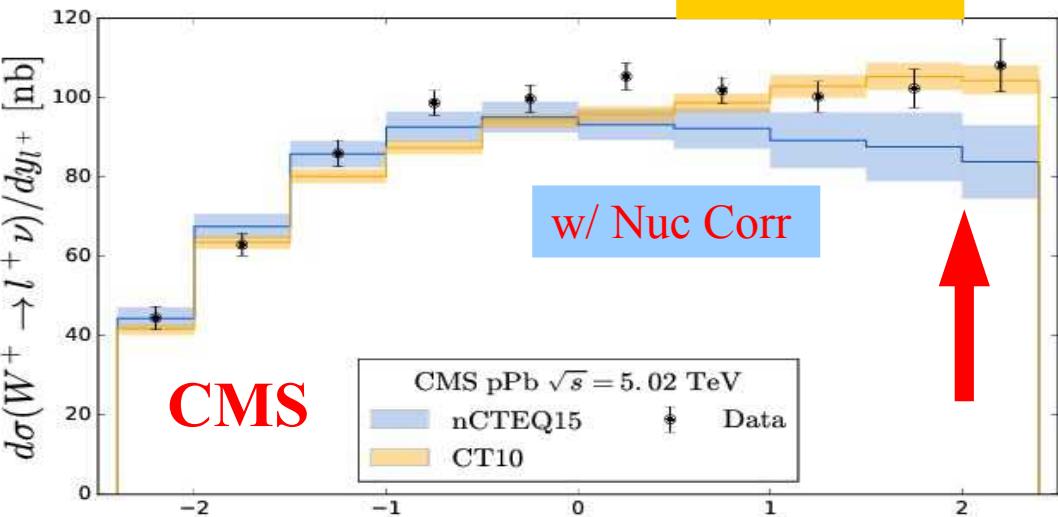
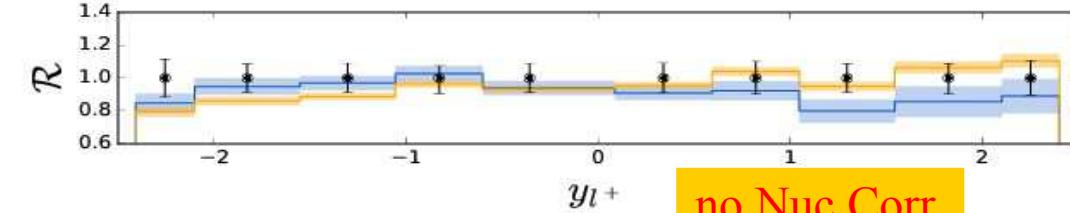
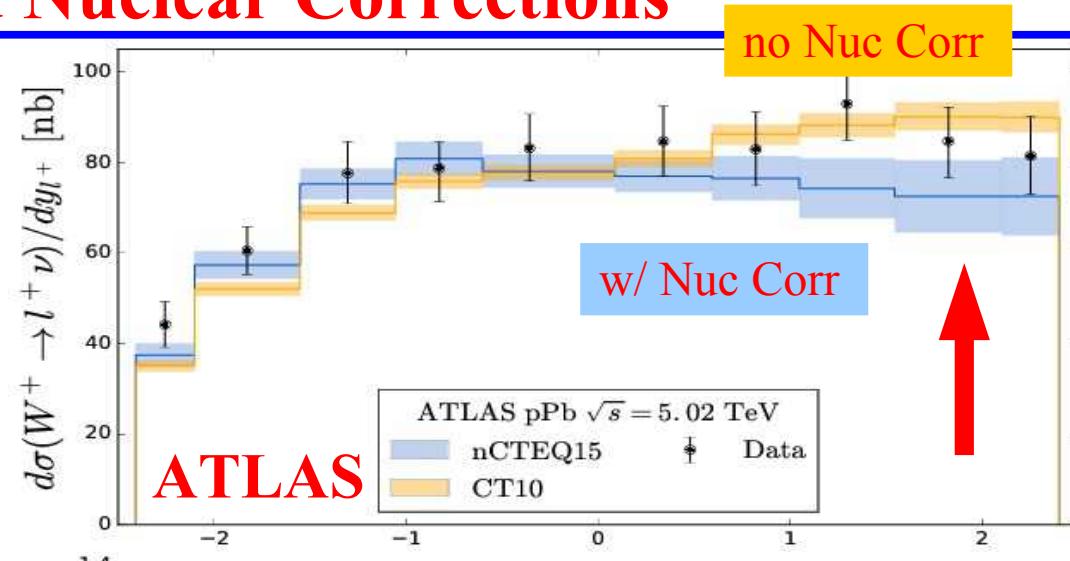
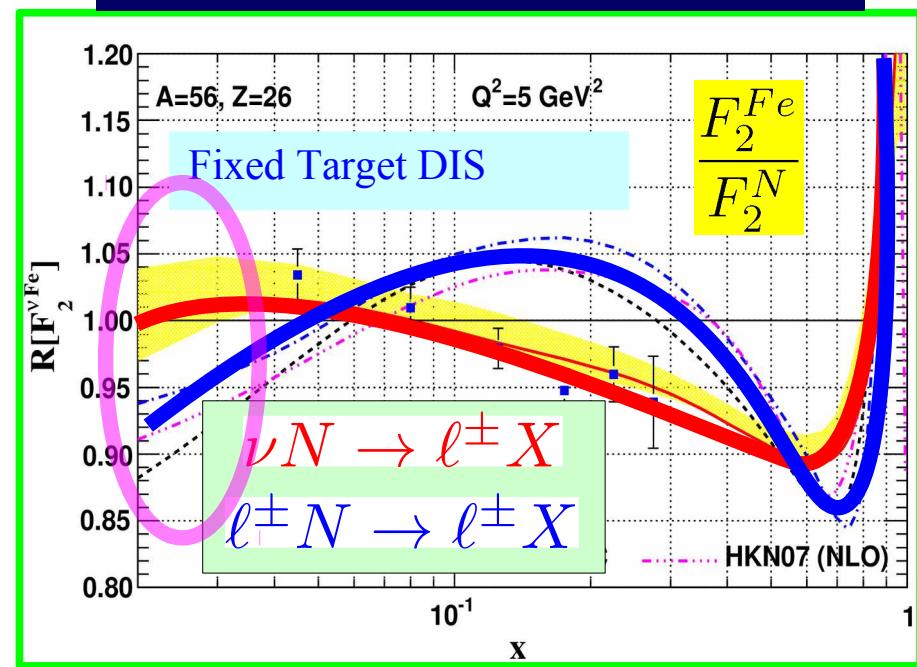
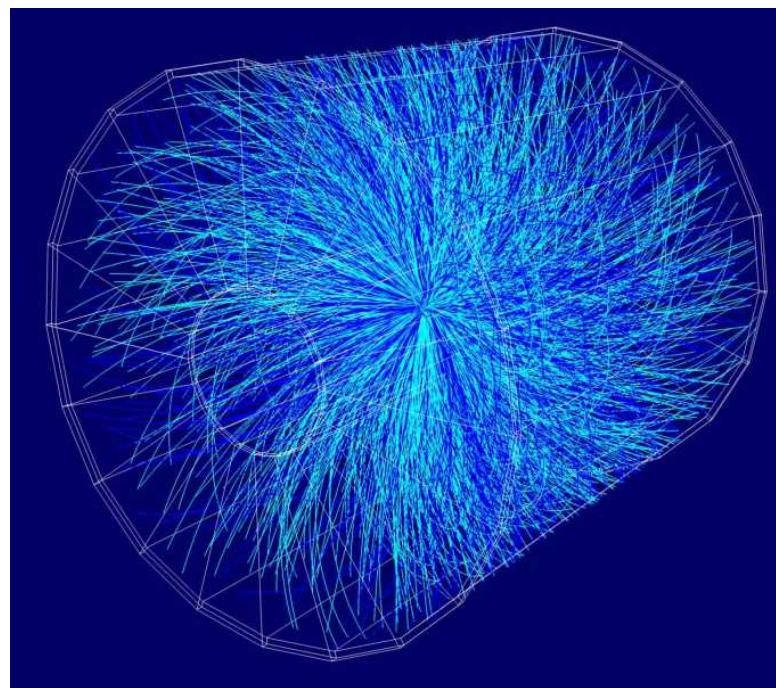
$$\frac{d\sigma(p\,Pb \rightarrow W^+)}{dy}$$



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]

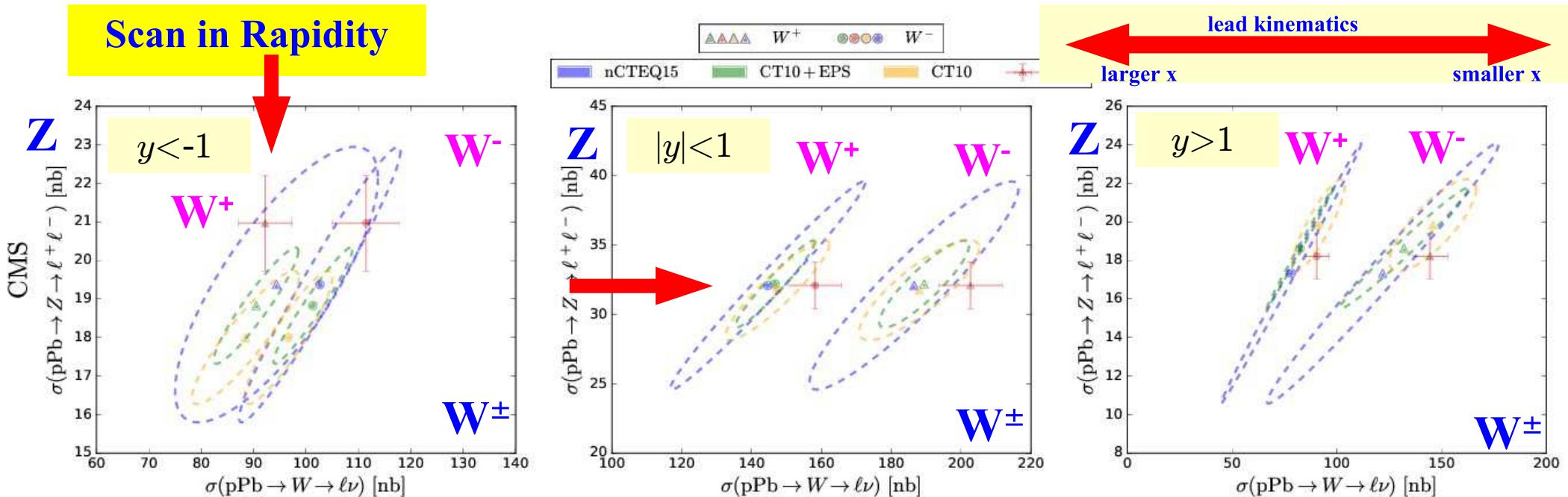
$p\,Pb \rightarrow W/Z$ and Nuclear Corrections



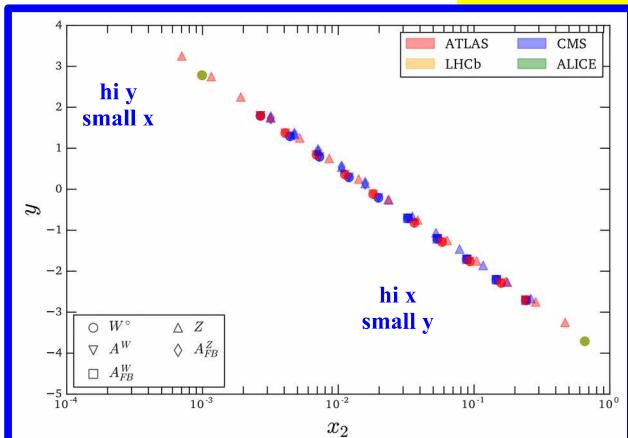
lead kinematics

larger x ← → smaller x

σ Correlations: Scan in “x” and flavor combinations



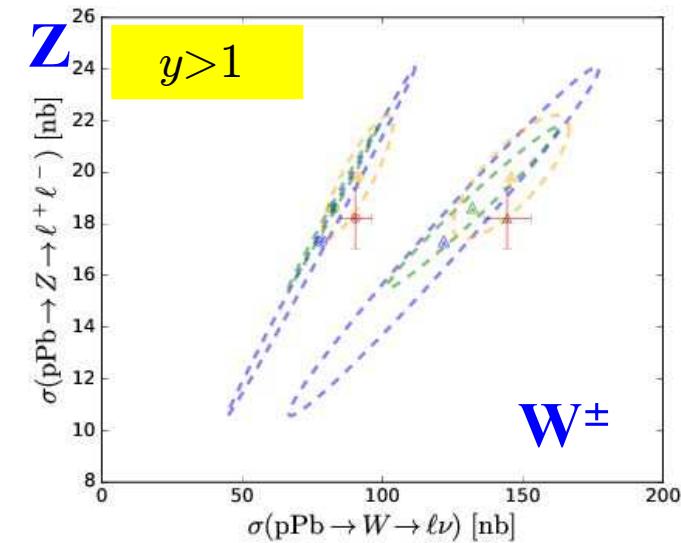
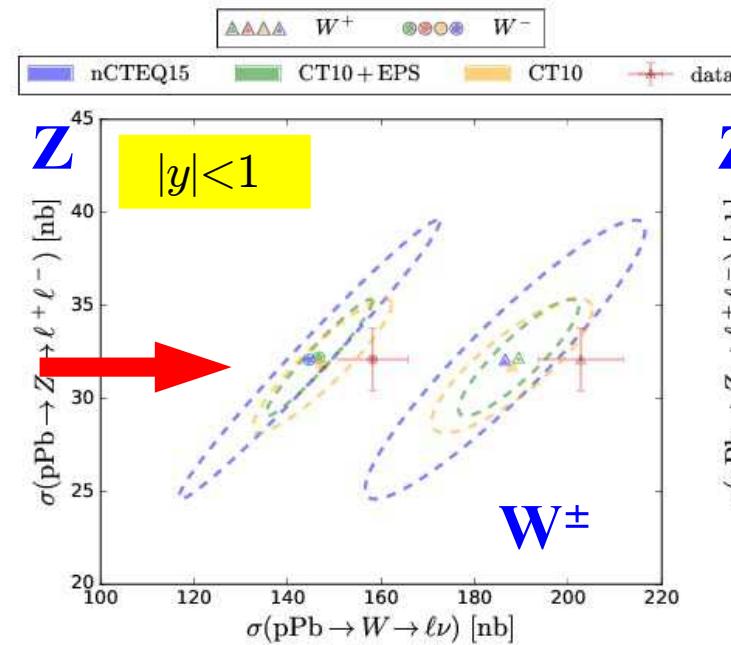
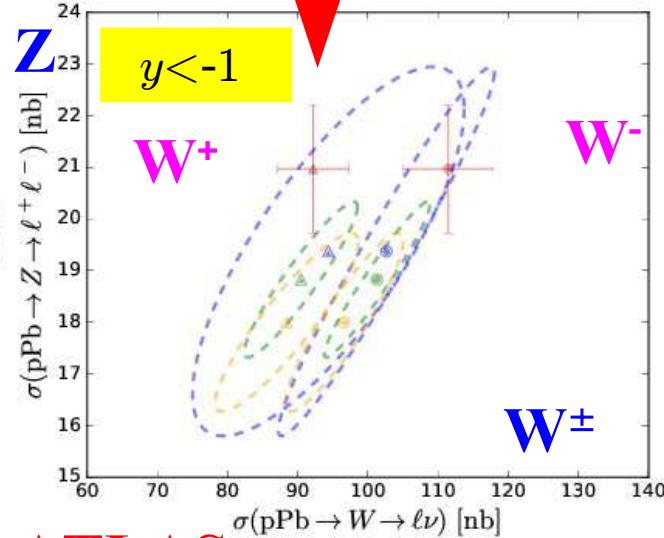
- W^\pm / Z provide different linear combinations
- Rapidity scans different x regions



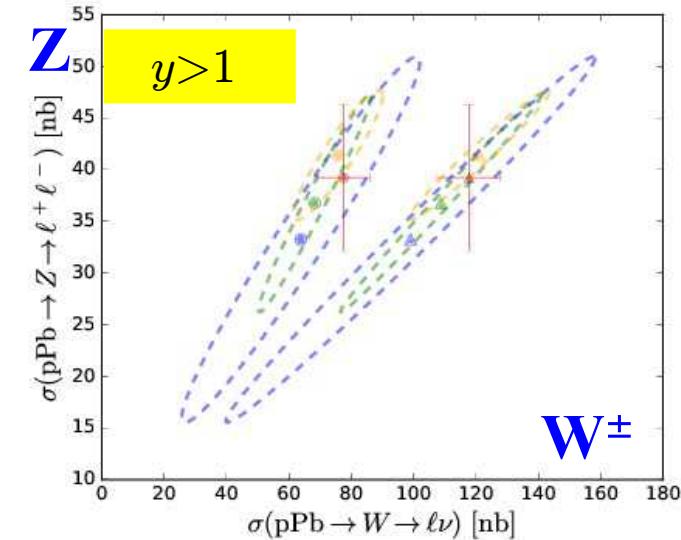
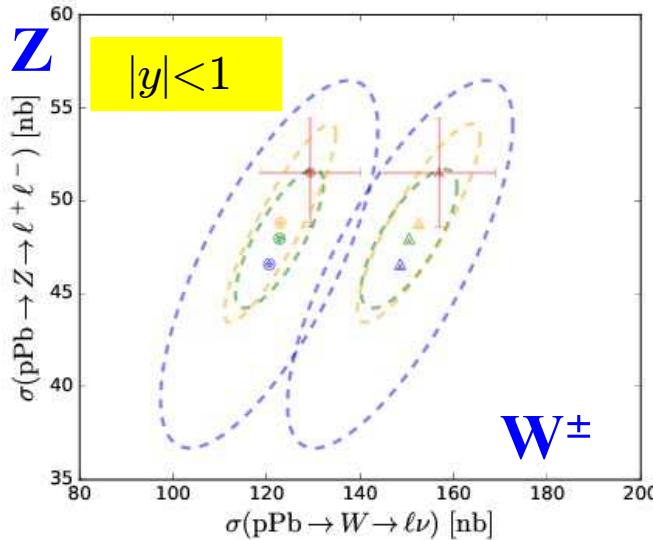
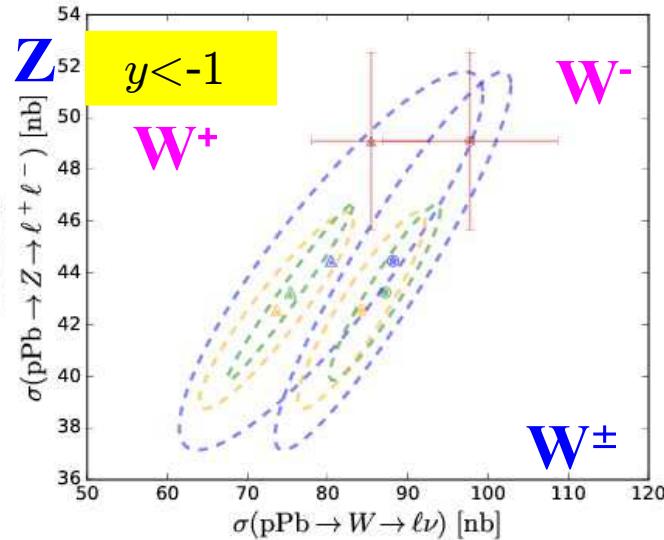
$$\begin{aligned} W^+ &\sim c(x) \bar{s}(x) \\ W^- &\sim s(x) \bar{c}(x) \\ Z &\sim s(x) \bar{s}(x) \end{aligned}$$

σ Correlations: Scan in “x” and flavor combinations

CMS



ATLAS



lead kinematics

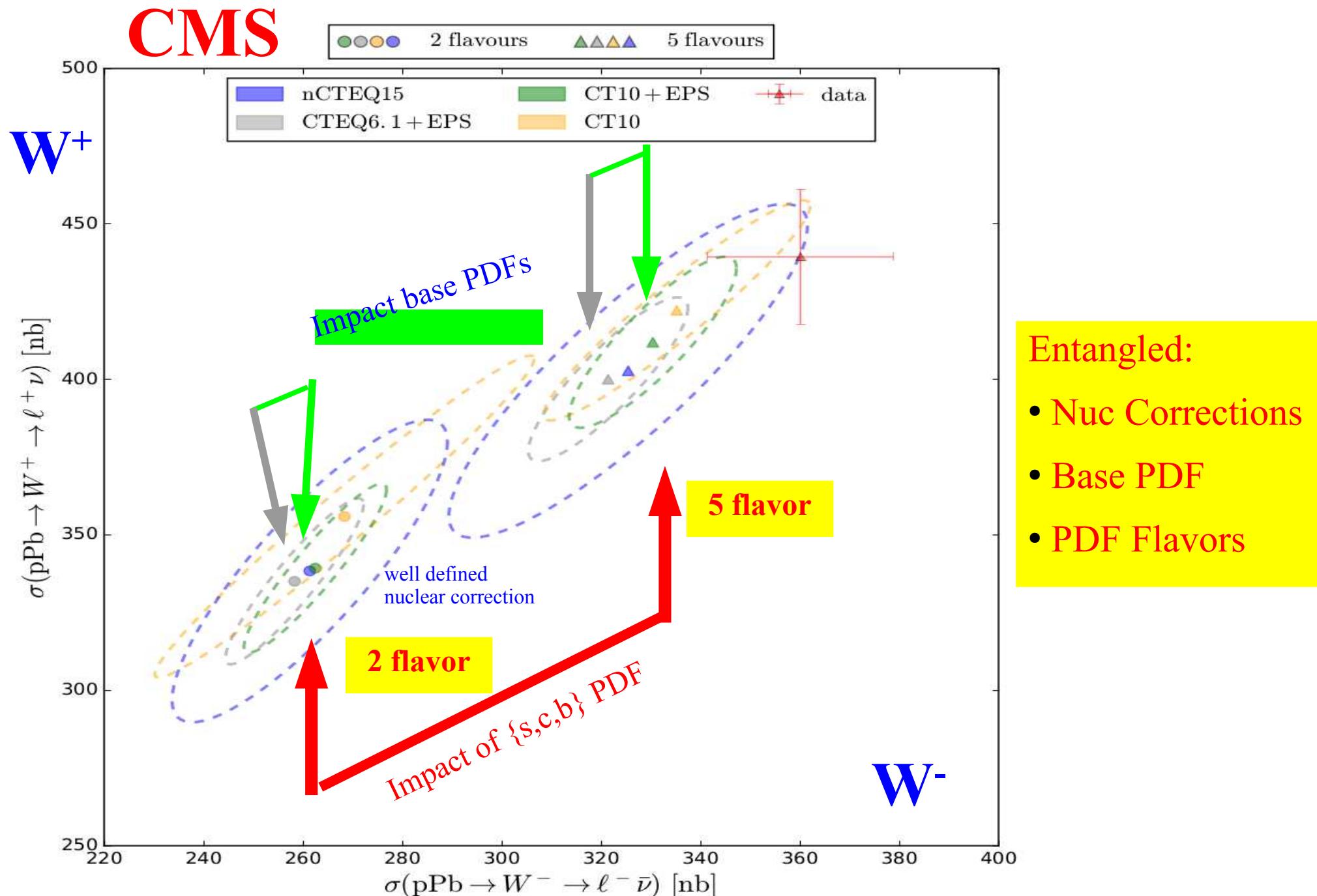
larger x smaller x

W/Z Cross Sections

Compare
2 vs. 5 Flavors

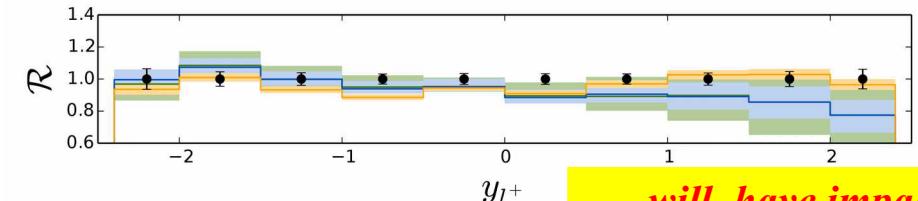
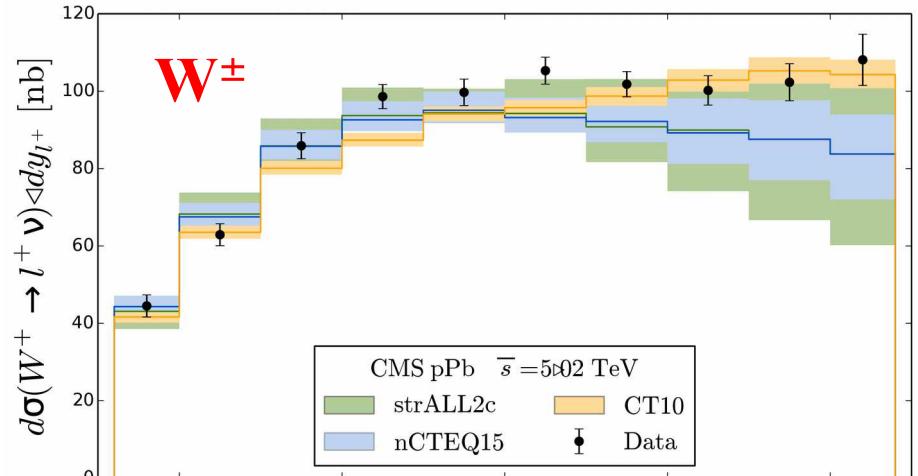
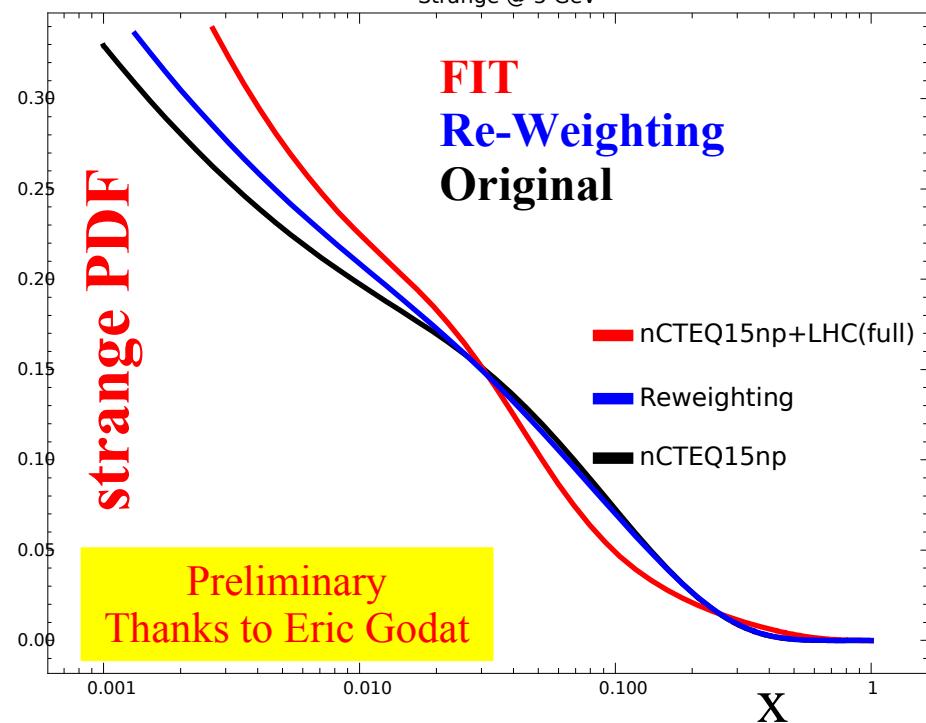
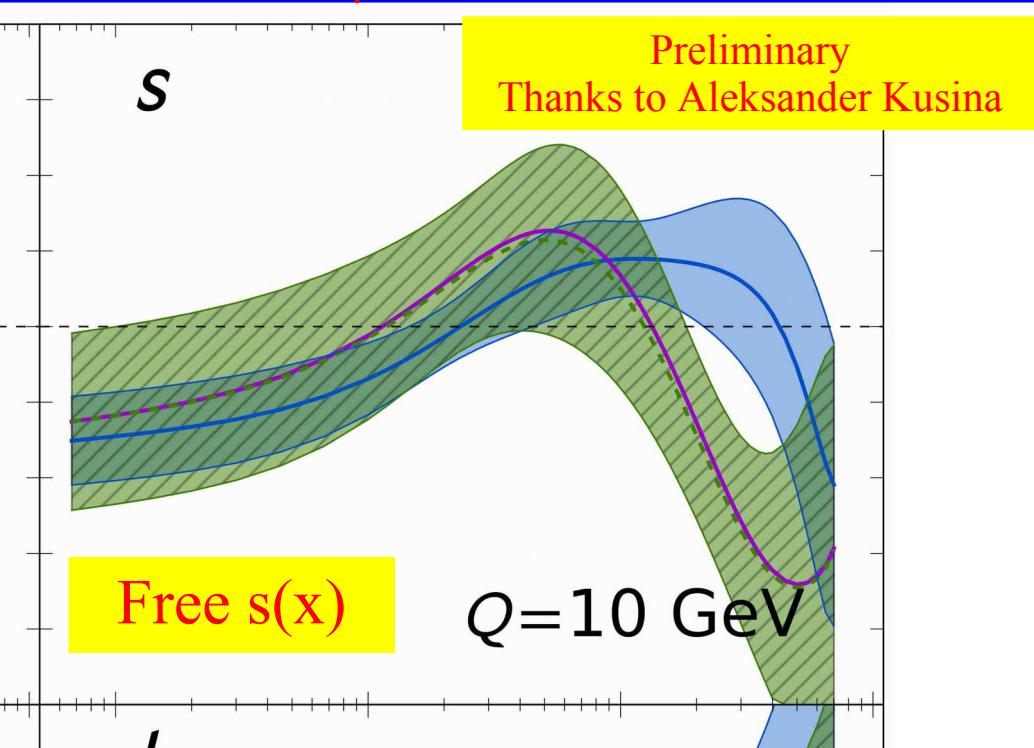
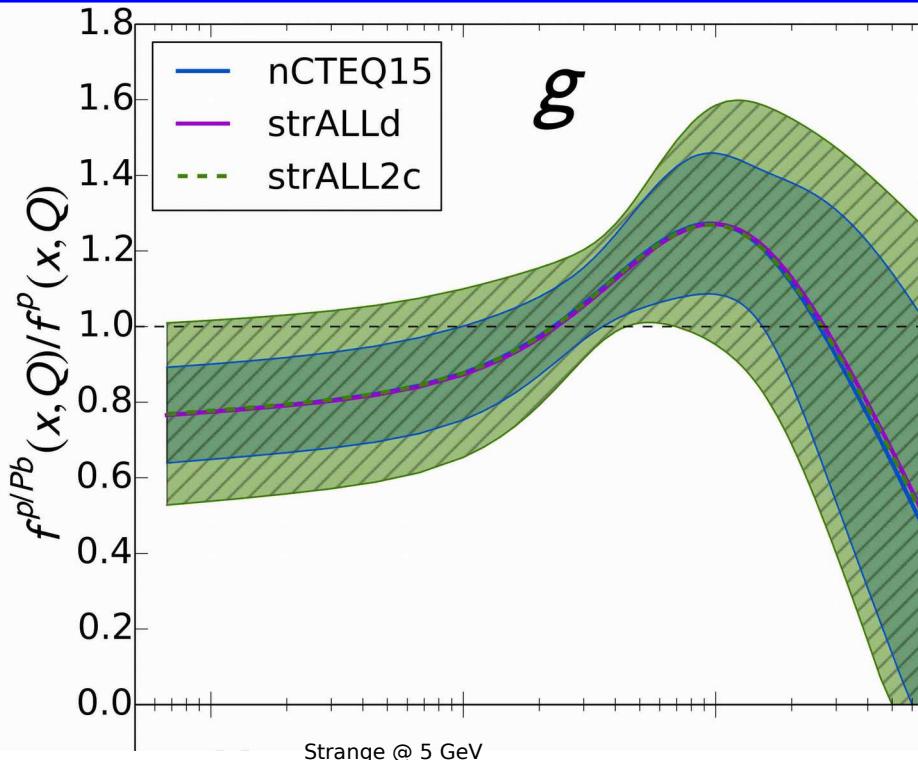
Vector boson production in pPb & PbPb
A. Kusina, F. Lyonne, D. B. Clark, E. Godat, T. Jezo,
K. Kovarik, F. I. Olness, I. Schienbein, J. Y. Yu,
arXiv:1610.02925 [nucl-th]

Impact of {s,c,b} PDF



... work in progress

In Progress: Add $p\text{ }Pb \rightarrow W/Z$

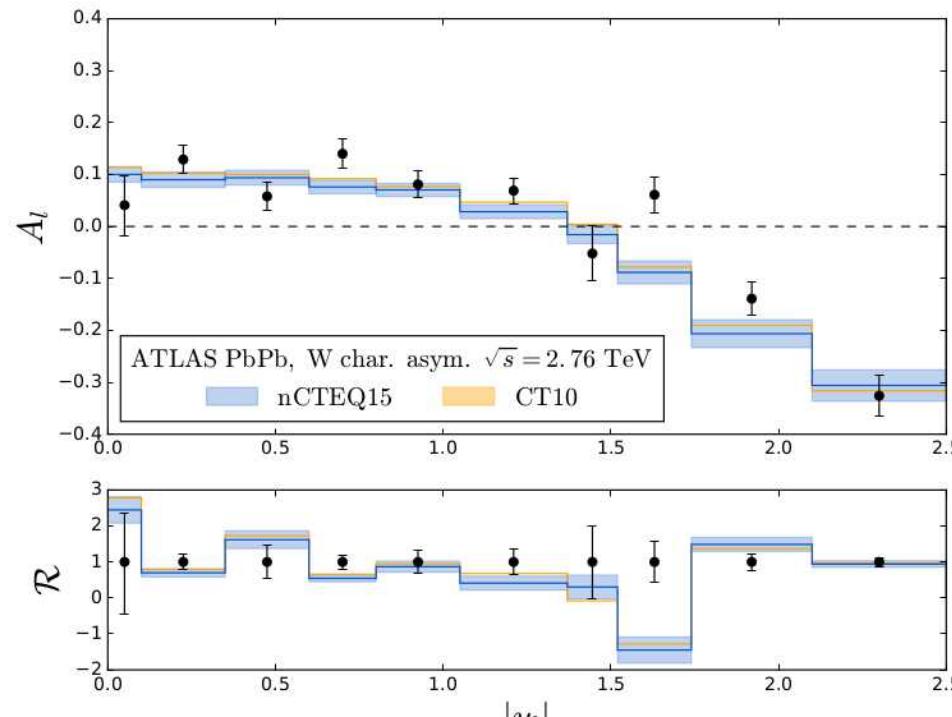


...will have impact!!!

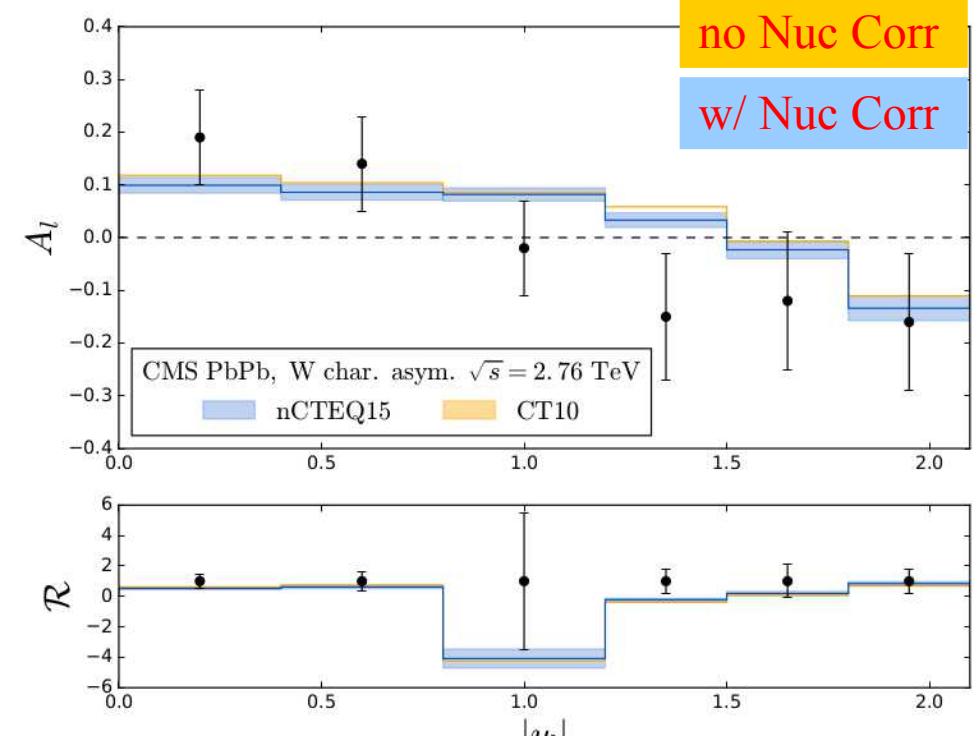
Pb Pb Asymmetries

Pb-Pb W Charge Asymmetry

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



(a) ATLAS



(b) CMS

Nuclear Corrections
also cancel in ratio

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.

Compare w/ EPS09 & EPPS16:

EPS09:

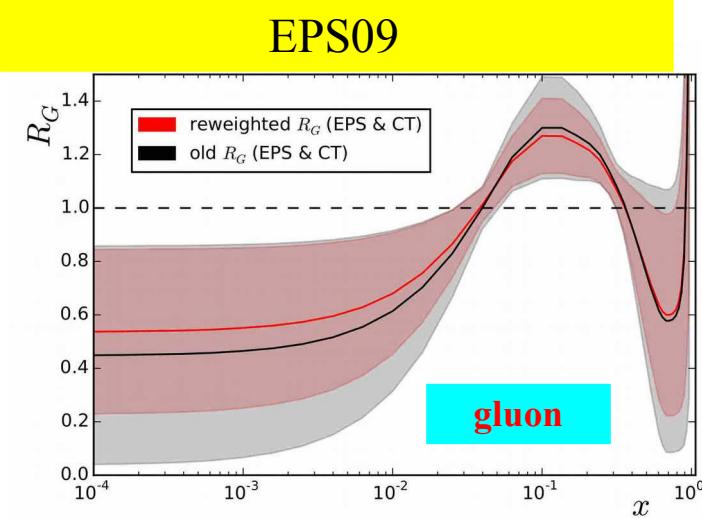
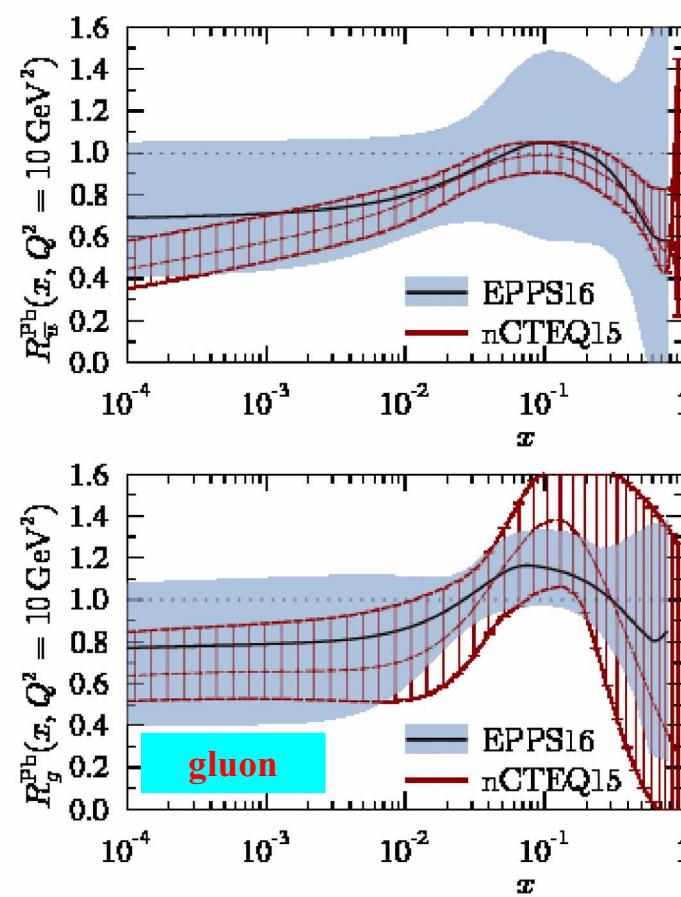
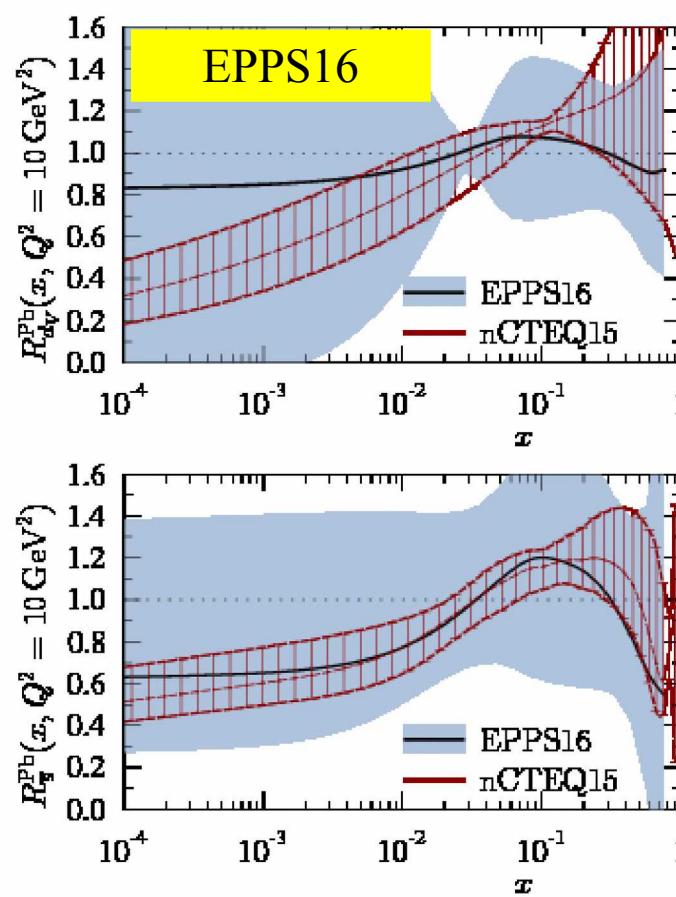
χ^2/DOF 731/929
 15 total parameters
 5 Parameters for R_{sea}
 Fit Ratios

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

nCTEQ15 generally compatible with EPPS16

... progress on

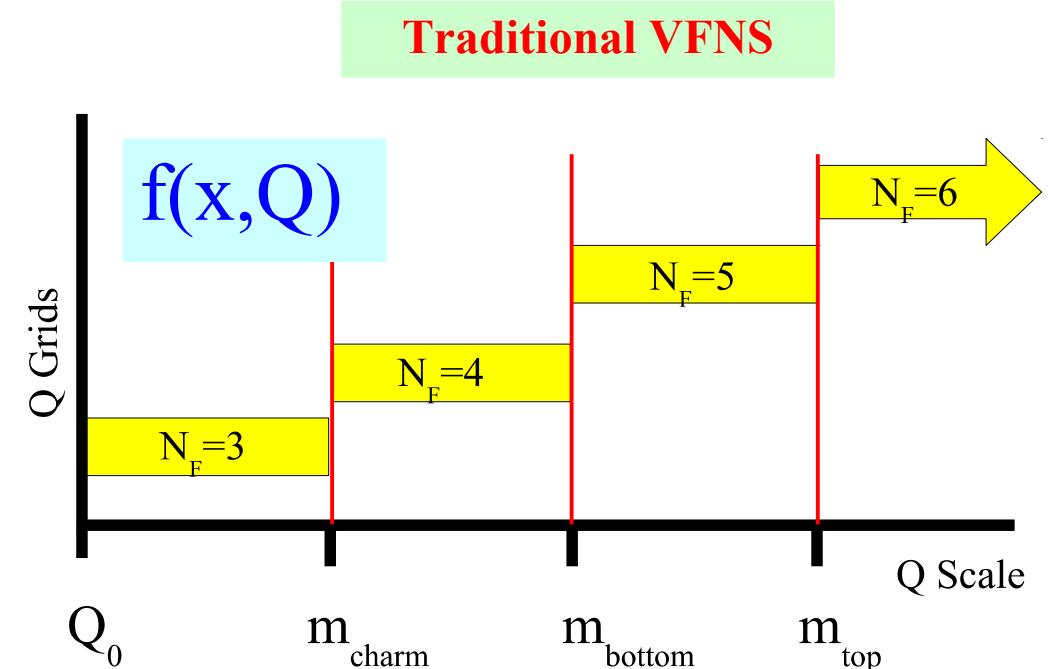
$c(x)$ & $b(x)$

PDFs

APFEL has a new feature

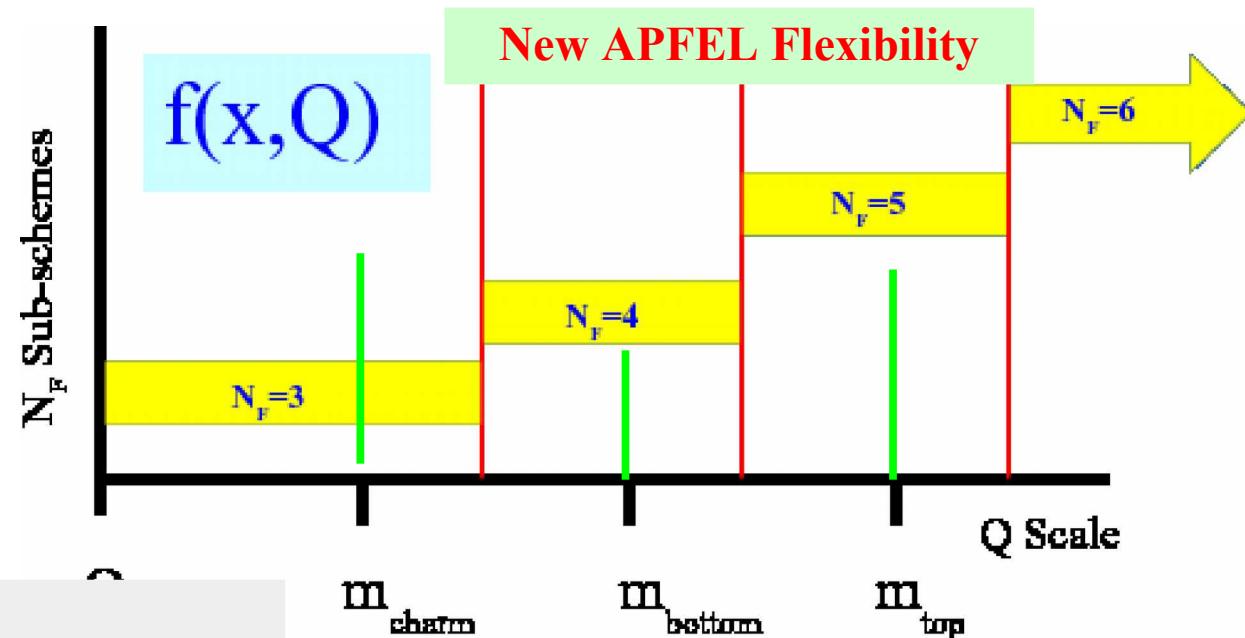
included in xFitter

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

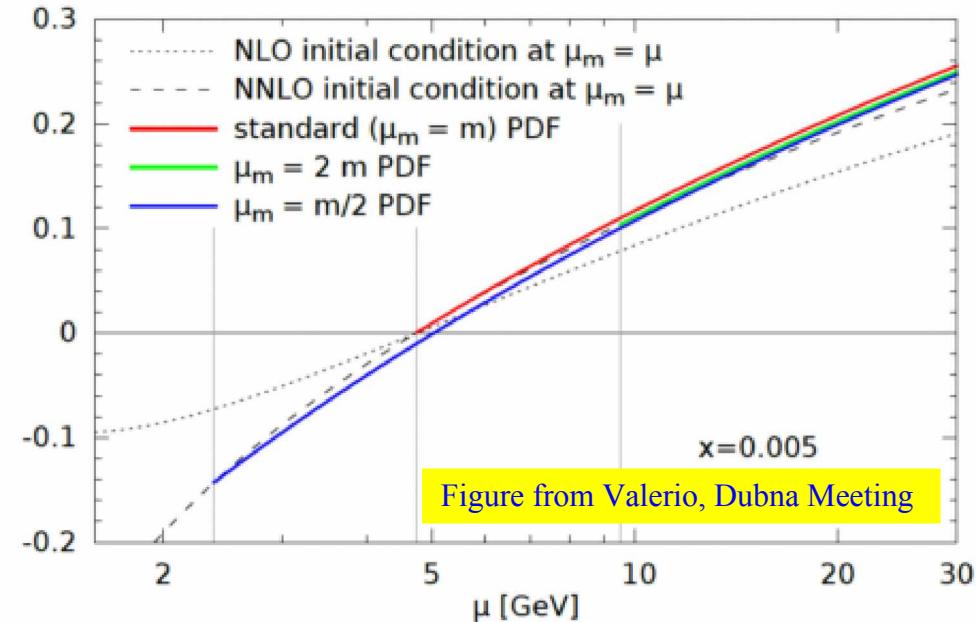
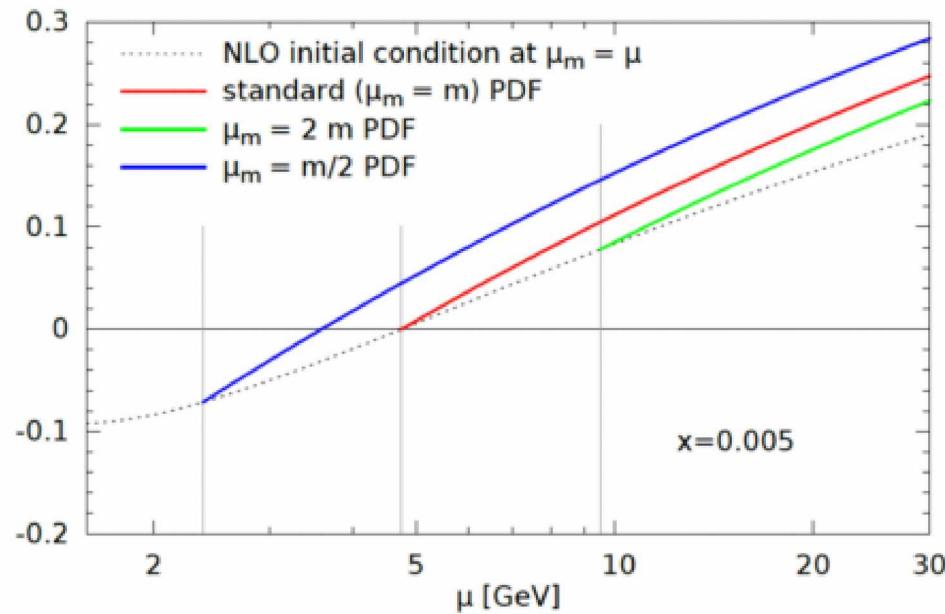


What are the benefits?

- 1) avoid discontinuities in the middle of data sets
- 2) avoid delicate matching in region $\mu \sim m_{c,b}$



The matching conditions are non-trivial, especially at NNLO



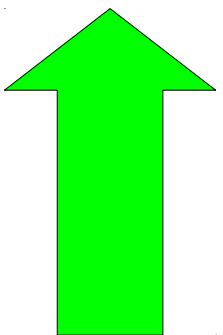
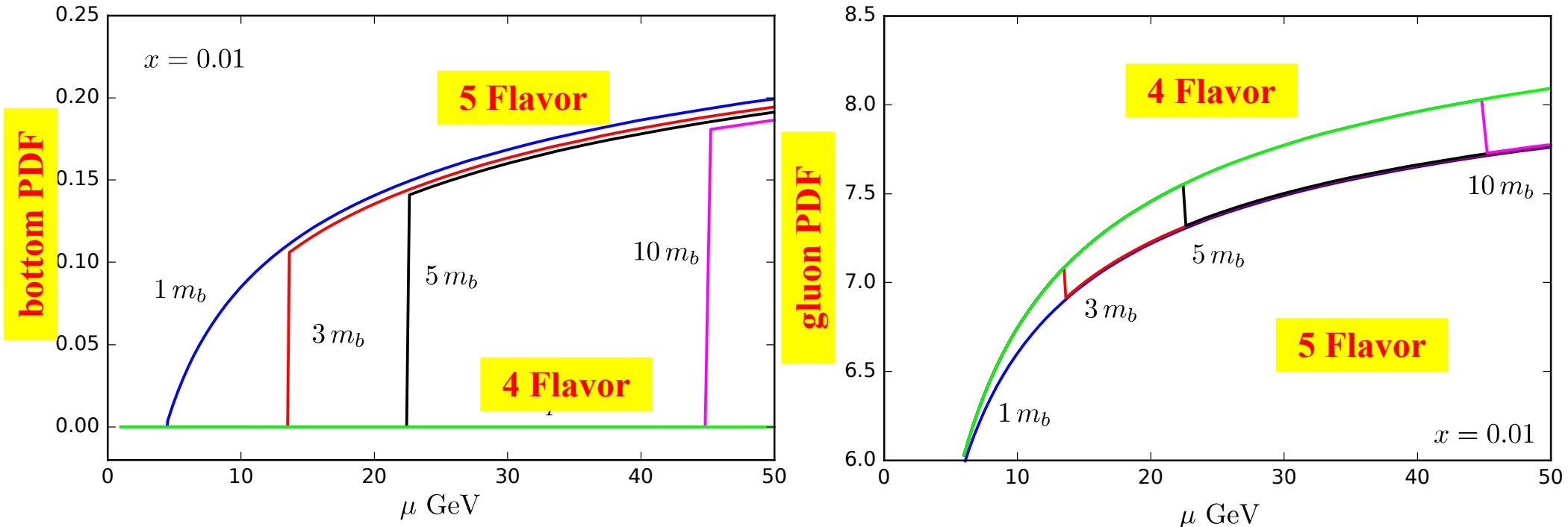
NLO Matching Condition

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

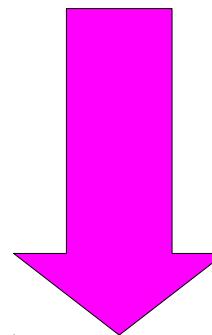
Zero at
Leading Order

Leading
DGLAP
contribution

Turn on Bottom PDF at arbitrary scale μ_b :



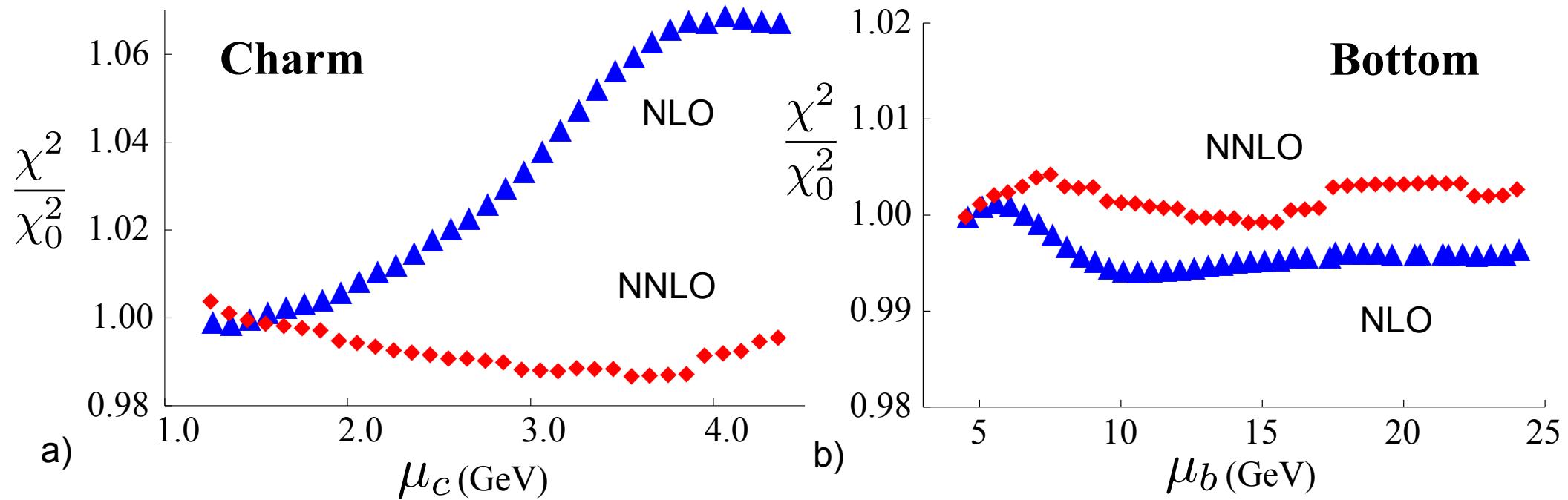
**Turn on
bottom PDF**



**Depletes
gluon PDF**

Impact of Flavor Transition on χ^2

30



A proposal: Consider N_F dependent PDF

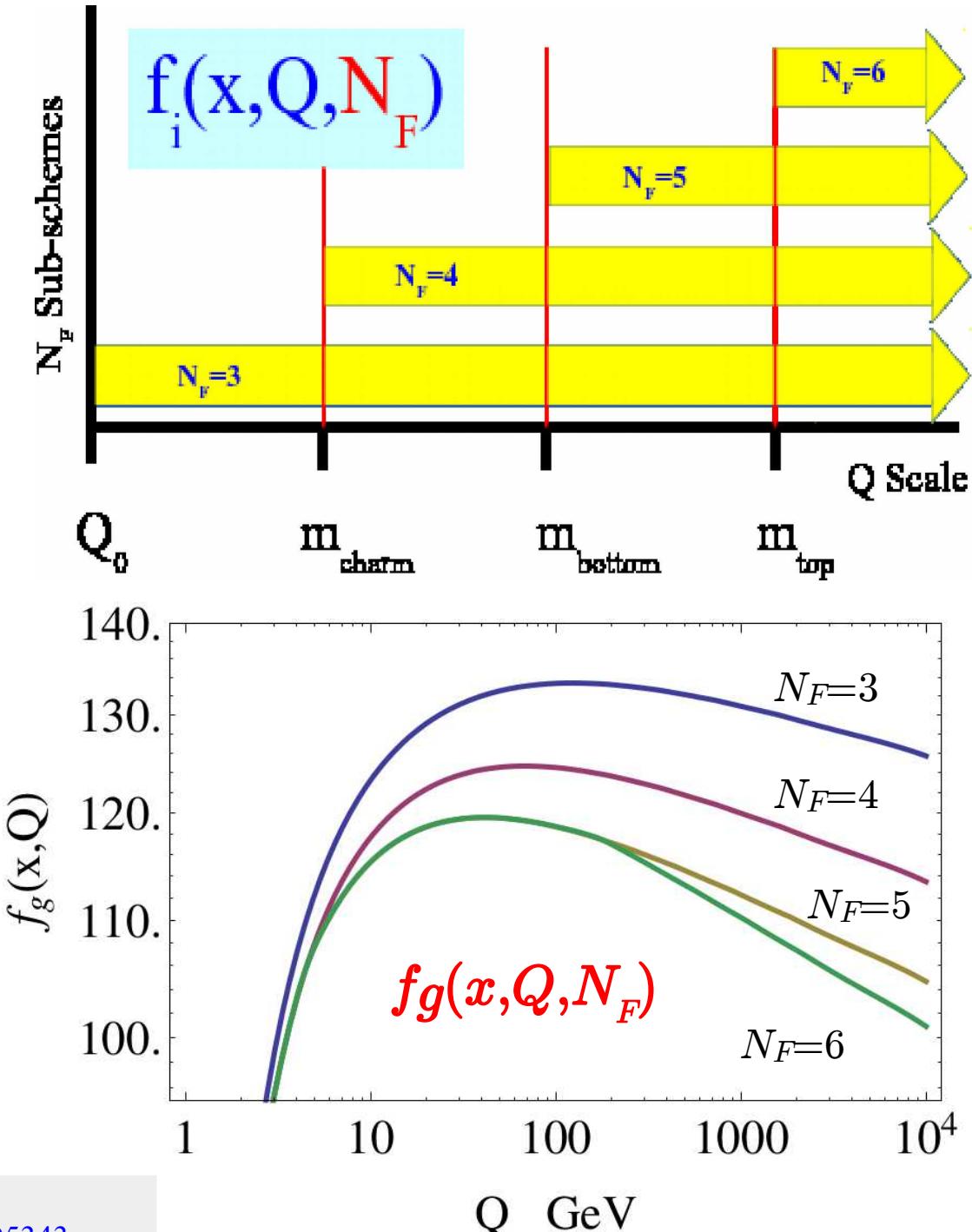
Provides some of the benefits & flexibility of flexible matching,

Advantages:

- * avoid discontinuities in data
- * avoid delicate cancellations
- * minimal set of PDF grids

... for example, simultaneously

- 1) analyze HERA in $N_F=4$
- 2) analyze LHC in $N_F=5$



LHeC/FCCeh/PERLE Workshop:

27-29 June2018 @ LAL Orsay, France

cern.ch/lhec



LHeC Workshop

Overview

Registration

Participant List

Access and transport

Accommodation

Internet access

LHeC website

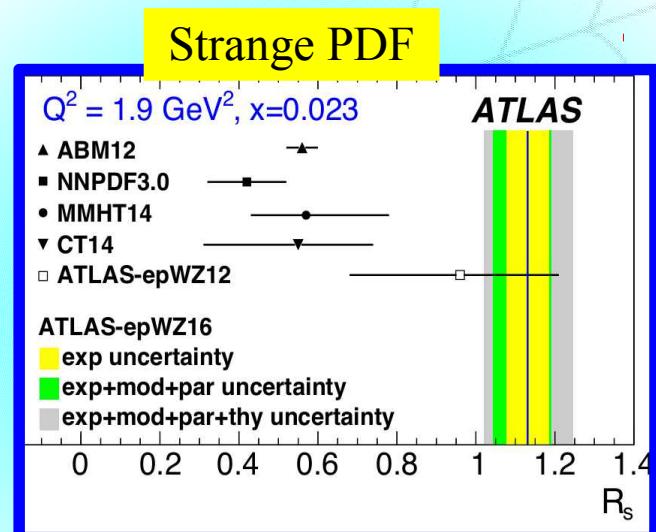
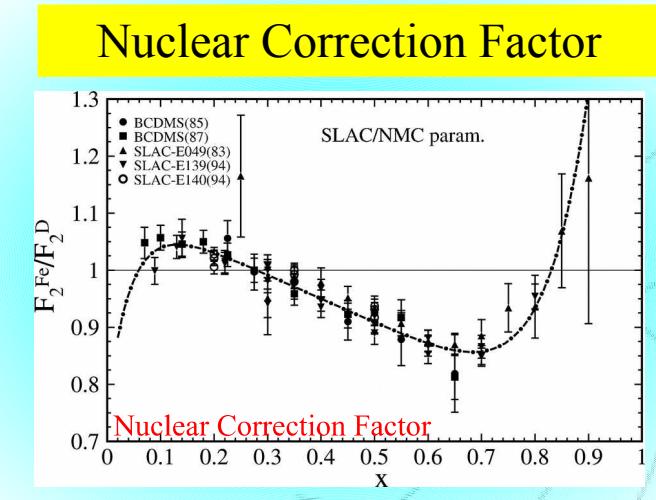
Support

lhec.ws@cern.ch

27-29 June2018 @ LAL Orsay, France

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.

Conclusions



ATLAS Collaboration arXiv:1612.03016

