nCTEQ PDF Update

What are the challenges & opportunities with an EIC

Fred Olness
SMU

nCTEQ
nuclear parton distribution functions

Thanks to my nCTEQ colleagues
B. Clark, E. Godat, T. Hobbs, T. Jezo, C. Keppel, A. Kusina, F. Lyonnet,
J.G. Morfin, M. Klasen, K. Kovarik, J.F. Owens, I. Schienbein, J.Y. Yu

and my xFitter colleagues
V. Bertone, M. Botje, D. Britzger, S. Camarda, A. Cooper-Sarkar, F. Giuli,
A. Glazov, A. Luszczak, R. Placakyte, V. Radescu, W. Slominksi, O. Zenaiev

and also
C. Bertulani, A. Geiser, C. Gwenlan, M. Guzzi, P. Nadolsky,
Emanuele R. Nocera, Huey-Wen Lin, Kostas Orginos, Juan Rojo

xFitter

EIC Users Group Meeting
Ecole Nationale Supérieure de Chimie
Paris, France July 22-26, 2019

Welcome to Paris

Alexander Cassatt
(1839-1906)

first electrified urban terminal station in the world,

Gare d'Orsay (1900)

Left: Wikimedia Commons (CC BY-SA 3.0)

Musée d'Orsay (today)

Right: Stock Photos from maziarz/Shutterstock

Pennsylvania Station (1910)

… join us in NYC

March 23 - 27, 2020

nCTEQ PDF Update

What are the challenges & opportunities with an EIC

It will have high statistics for a wide variety of NUCLEI

Nuclear corrections are inextricably linked
to the PDF flavor differentiation

It allows us to push to HI-X

At present, our W cuts eliminate much of this region
Explore issues of higher-twist, factorization violations, …
Test models in $x \to 1$ limit, e.g., d/u, …

It allows us to push to low Q

At present, our Q cuts eliminate much of this region
Explores the parton/hadron transition
Study non-perturbative collective phenomena

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)

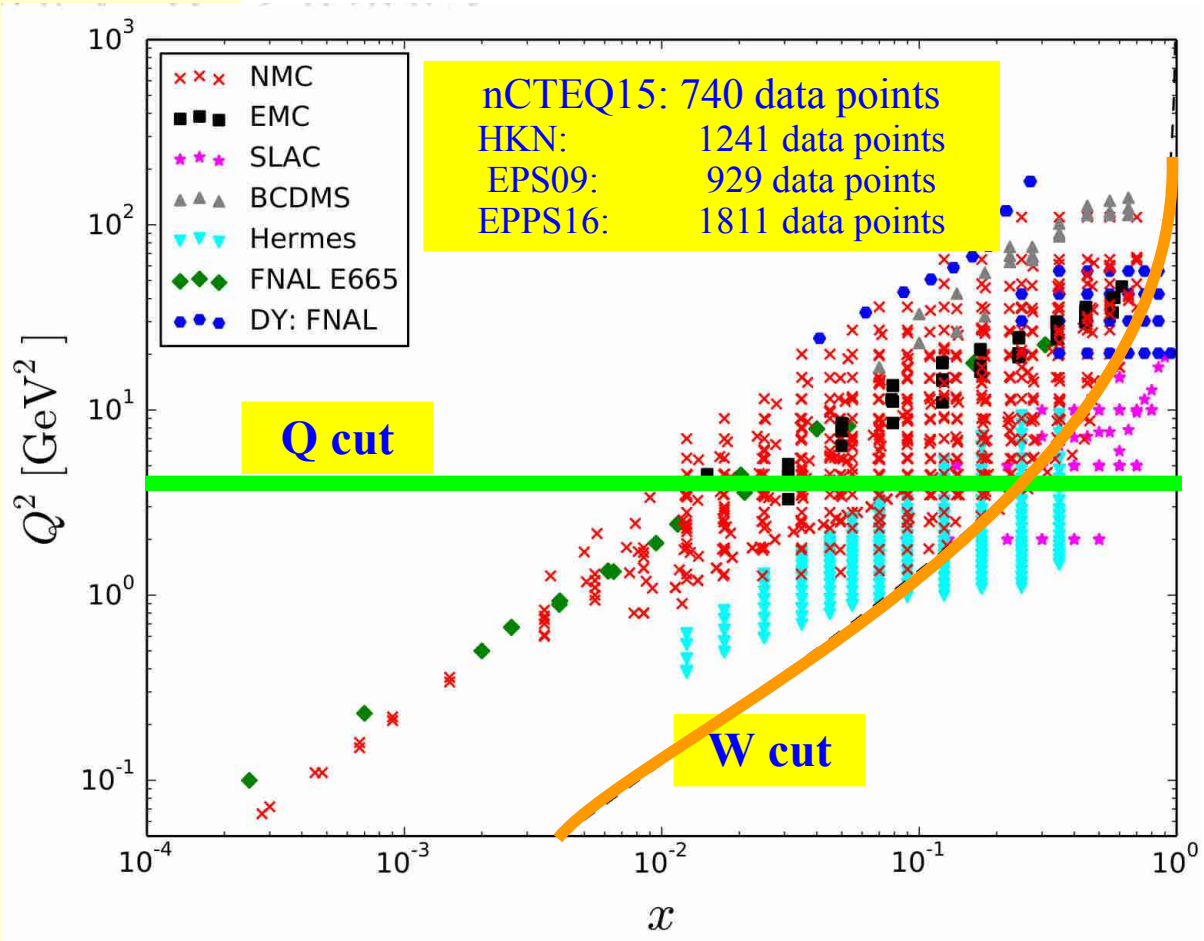
Neutrino DIS*

NuTeV CHORUS CCFR & NuTeV
N = Pb & Fe

Pion Production:

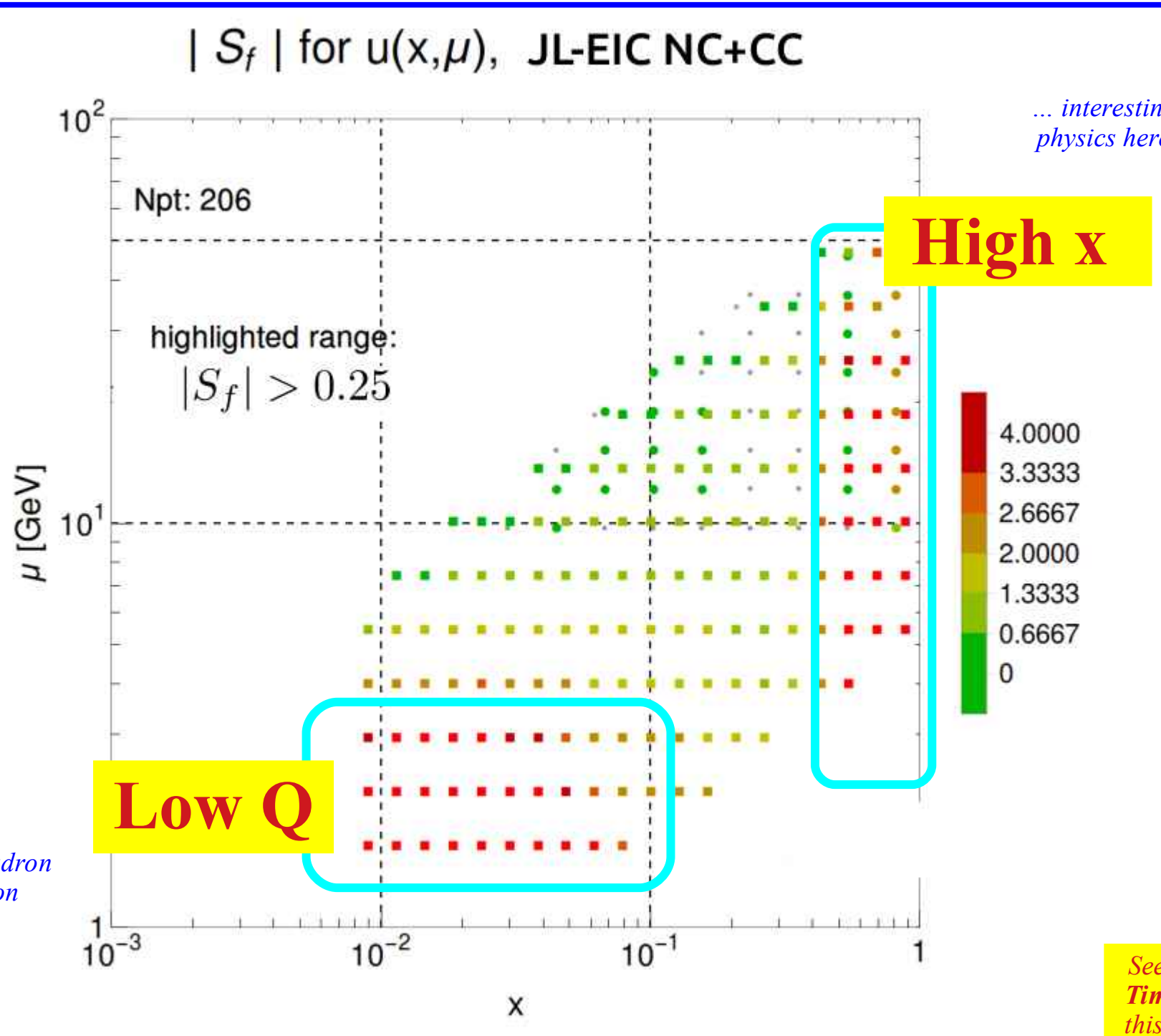
RHIC: PHENIX & STAR
N = Au

DIS Cuts:
nCTEQ: Q>2.0 & W>3.5
EPPS16: Q>2.0 & W>3.5
EPS09: Q>1.3
HKN: Q>1.0
DSSZ: Q>1.0



Q and W cuts exclude large portion of data

Sample Sensitivity in {x,Q} Plane with EIC Pseudodata



... interesting physics here

High x

Low Q

Parton / Hadron Transition

See talk by ***Tim Hobbs*** *this session*

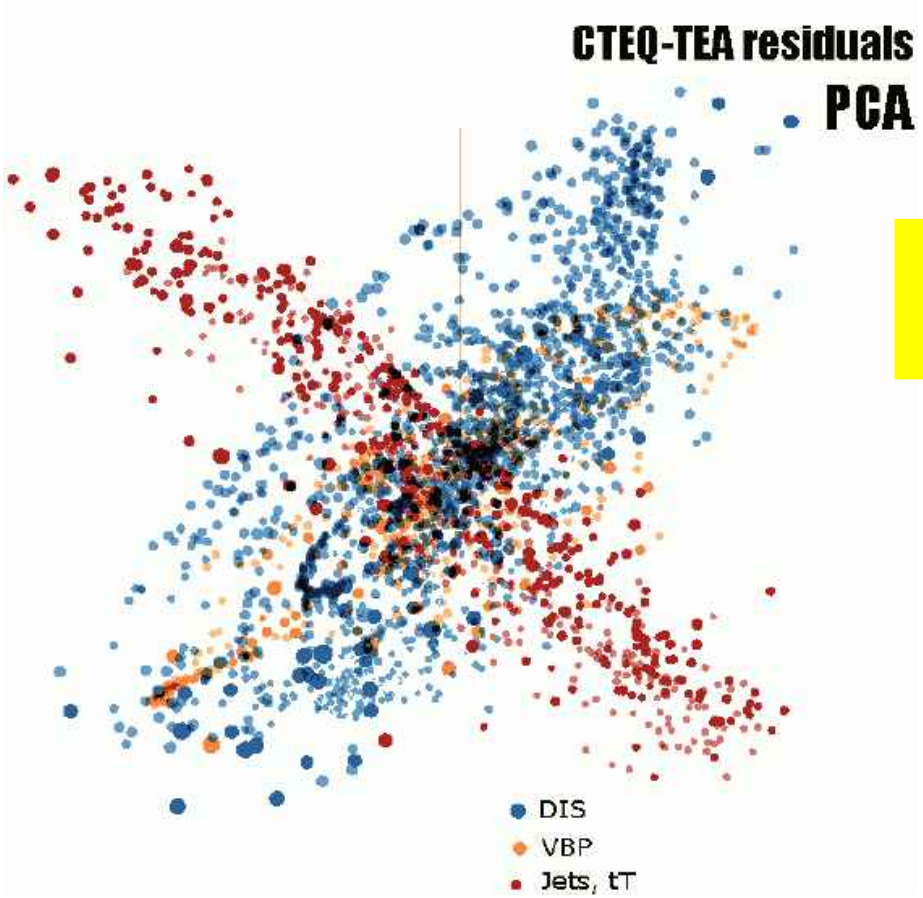
INNOVATIVE IDEAS

borrow from AI

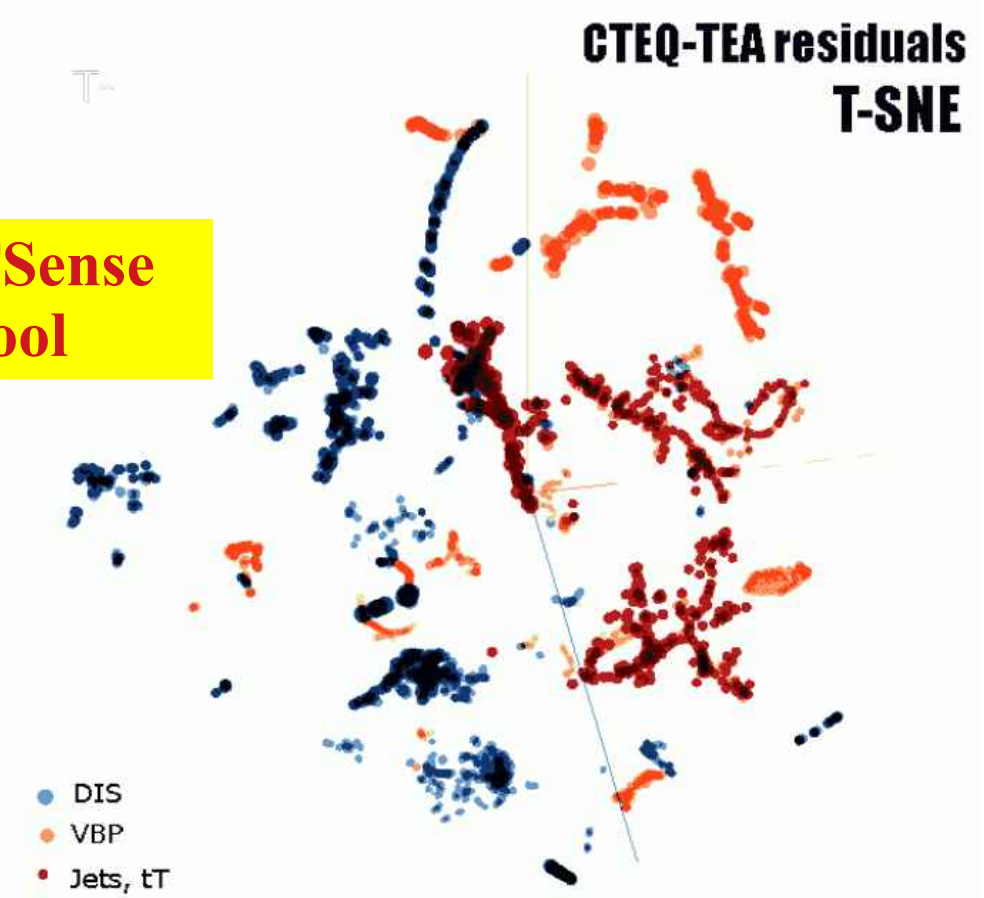
TensorFlow Embedding Projector

https://metapdf.hepforge.org/PDFSense/

Reads 2 .tsv files with vectors and metadata (descriptions of data points)



PDFSense tool



Principal Component Analysis (PCA) visualizes the 56-dim. manifold by reducing it to 10 dimensions (à la META PDFs)

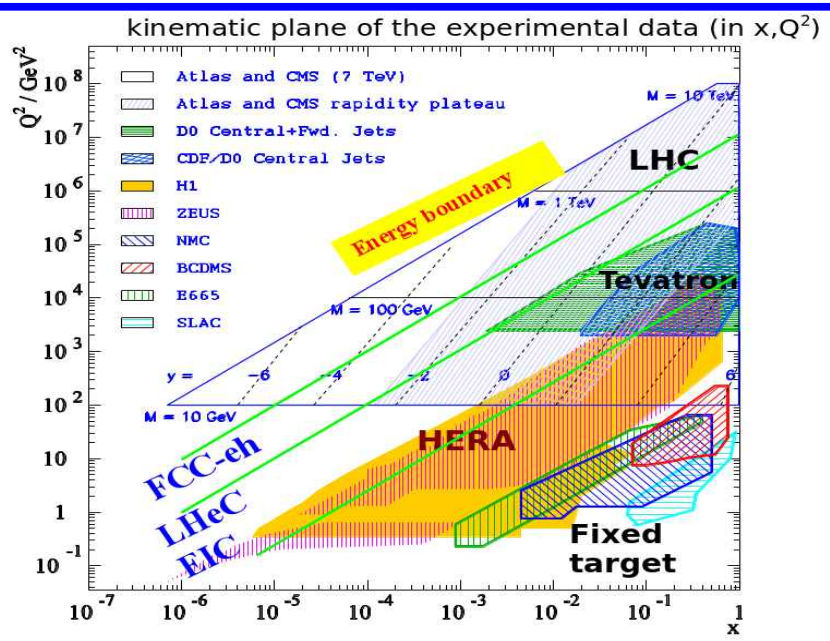
http://projector.tensorflow.org

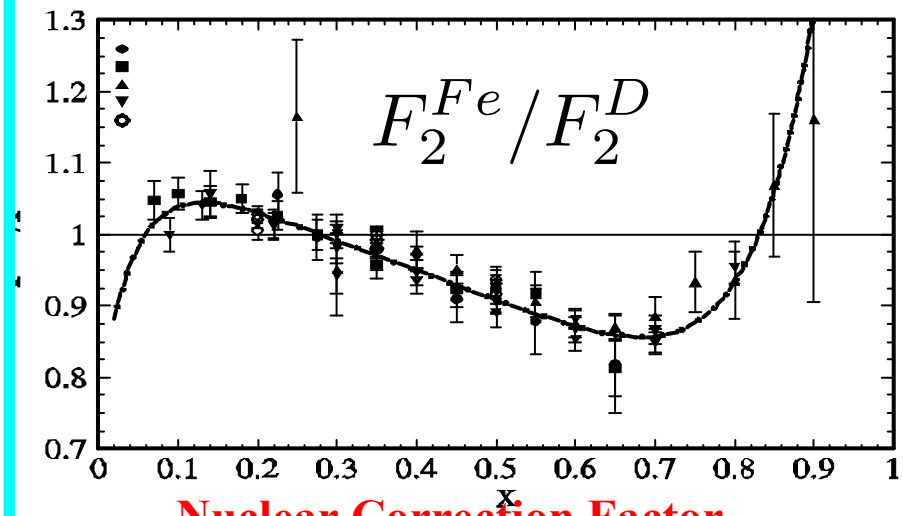
t-distributed stochastic neighbor embedding (**t-SNE**) sorts vectors according to their similarity

$$r_i(\vec{a}) = \frac{1}{s_i}\left(T_i(\vec{a}) - D_{i,sh}(\vec{a})\right),$$

Why are the nuclei important

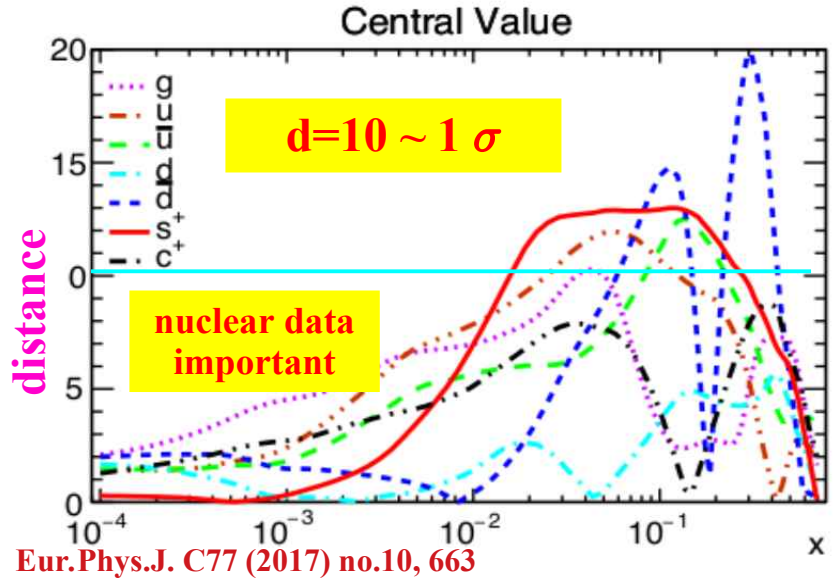
Impact of Nuclear Corrections on Flavor Decomposition *(including Proton)*





Nuclear Correction Factor

NNPDF3.1 NNLO, Impact of nuclear+deuteron fixed-target data , Q = 100 GeV



Eur.Phys.J. C77 (2017) no.10, 663

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

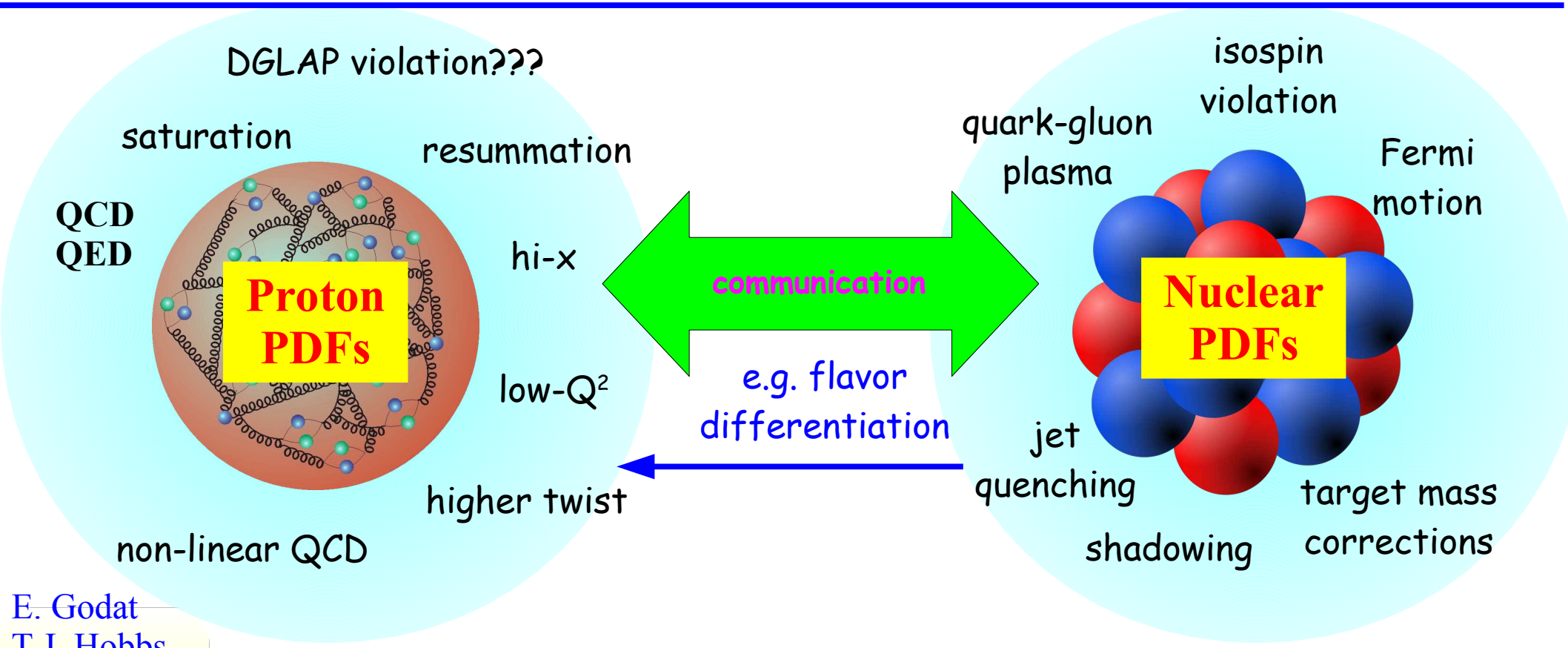
$$F_2^{\bar{\nu}} \sim [\bar{d} + \bar{s} + u + c]$$

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

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

Extraction of Proton PDF flavors is inextricably linked to the nuclear degrees of freedom

… the motivation for nCTEQ



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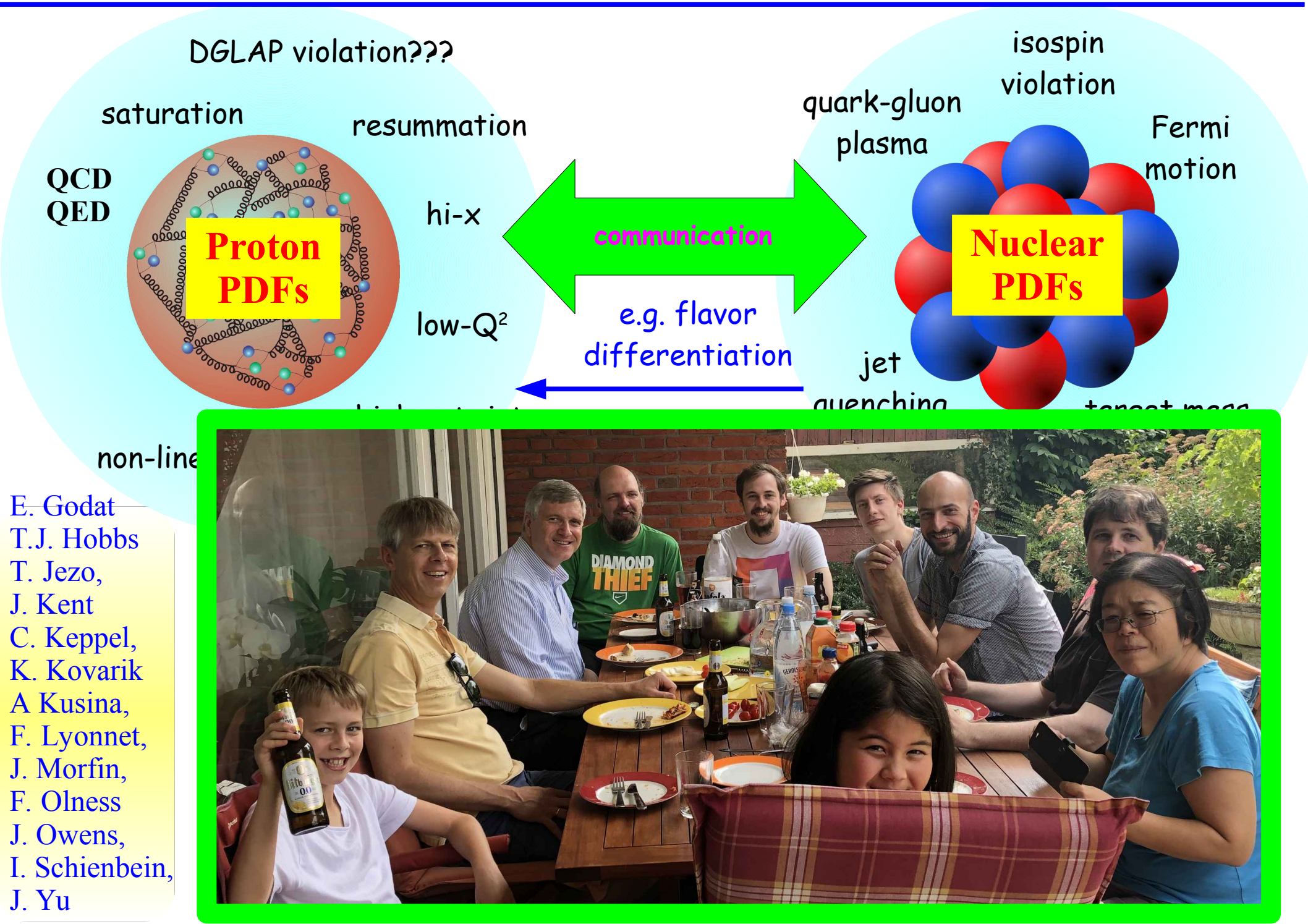
Data from nuclear targets play a key role in the flavor differentiation

nCTEQ

nuclear parton distribution functions

nCTEQ … *hard at work*



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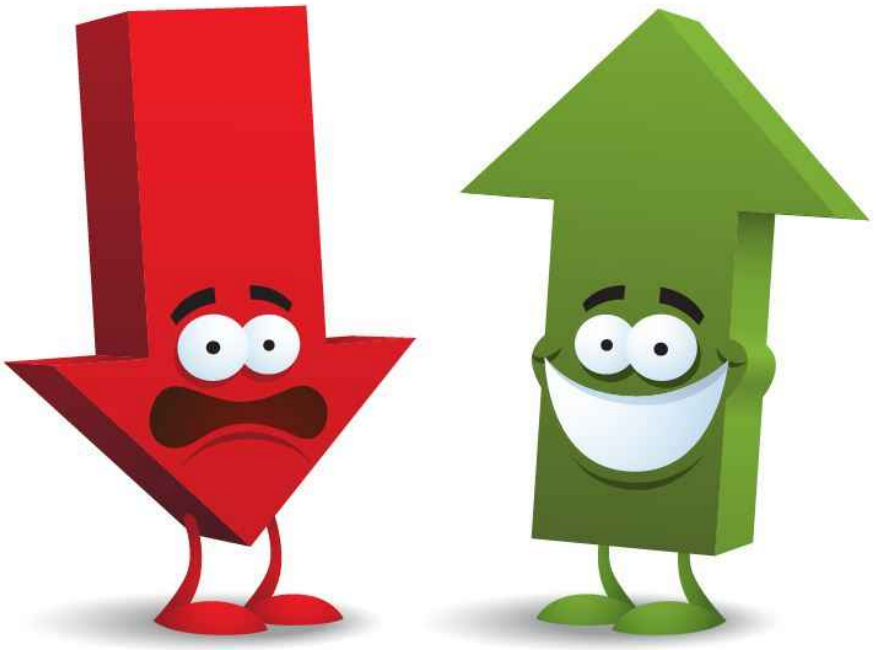
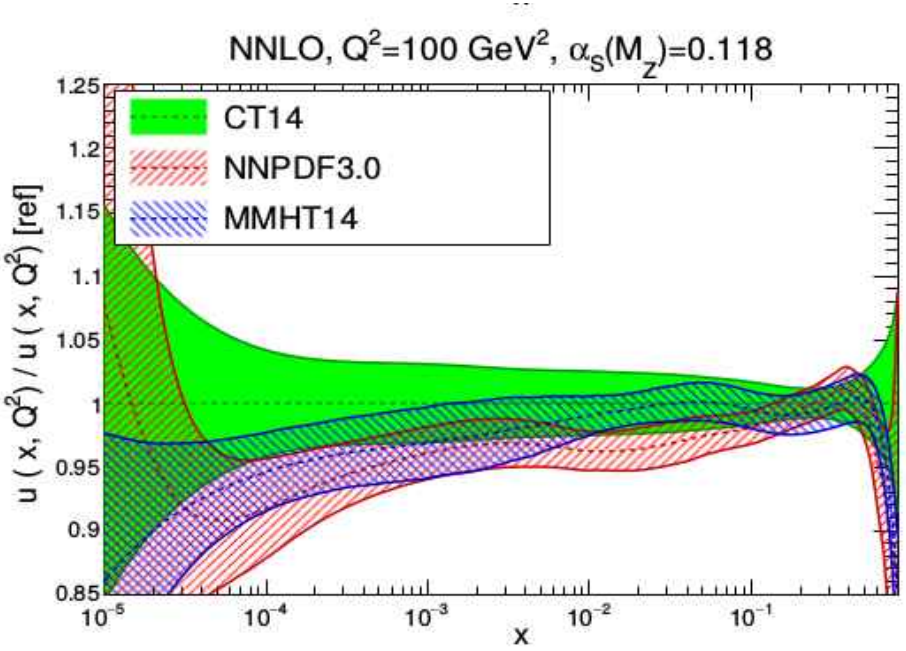
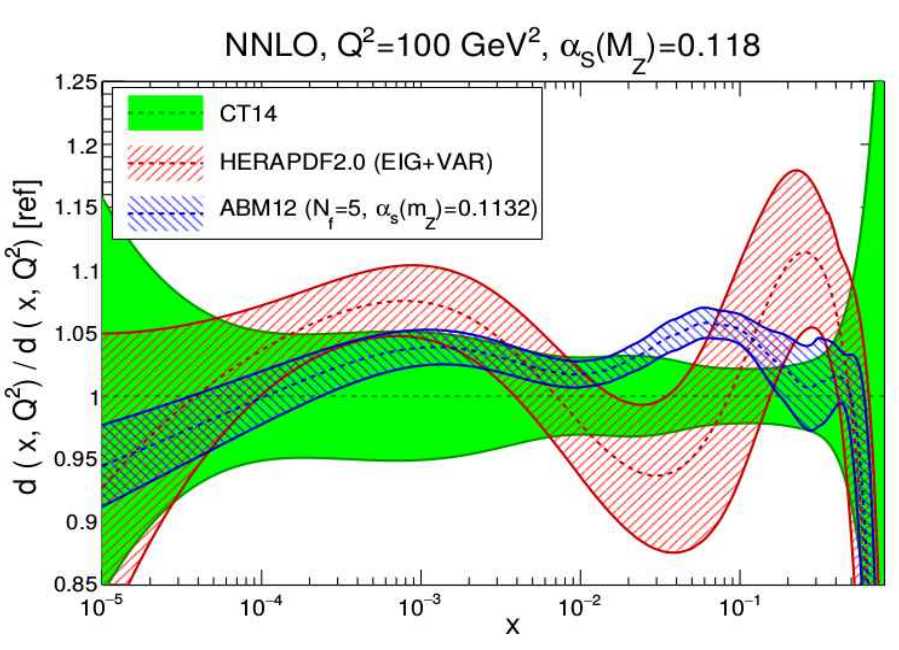
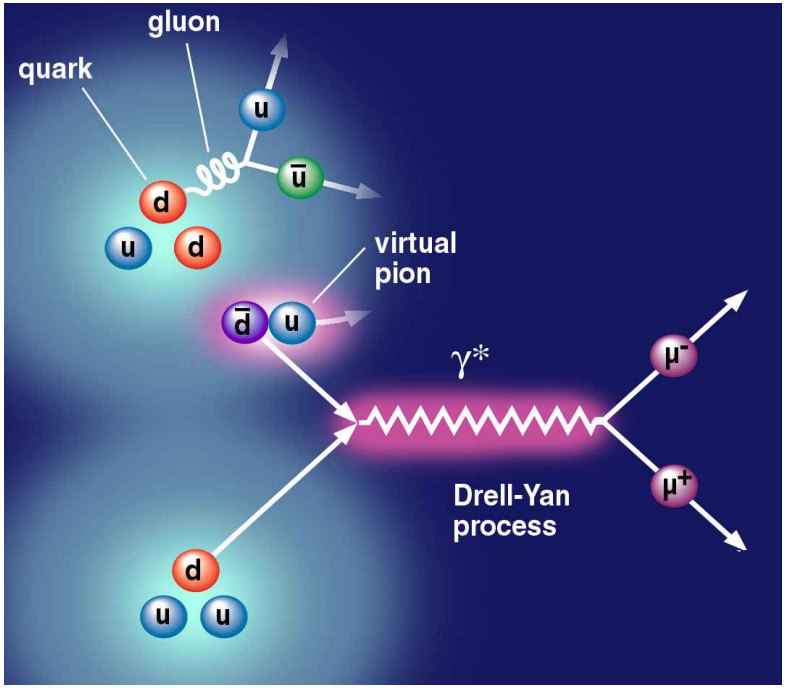
Down & Up




NNLO, Q^2=100 GeV^2, $\alpha_S(M_Z)$=0.118
CT14
NNPDF3.0
MMHT14
$u(x,Q^2)/u(x,Q^2)$ [ref]
x

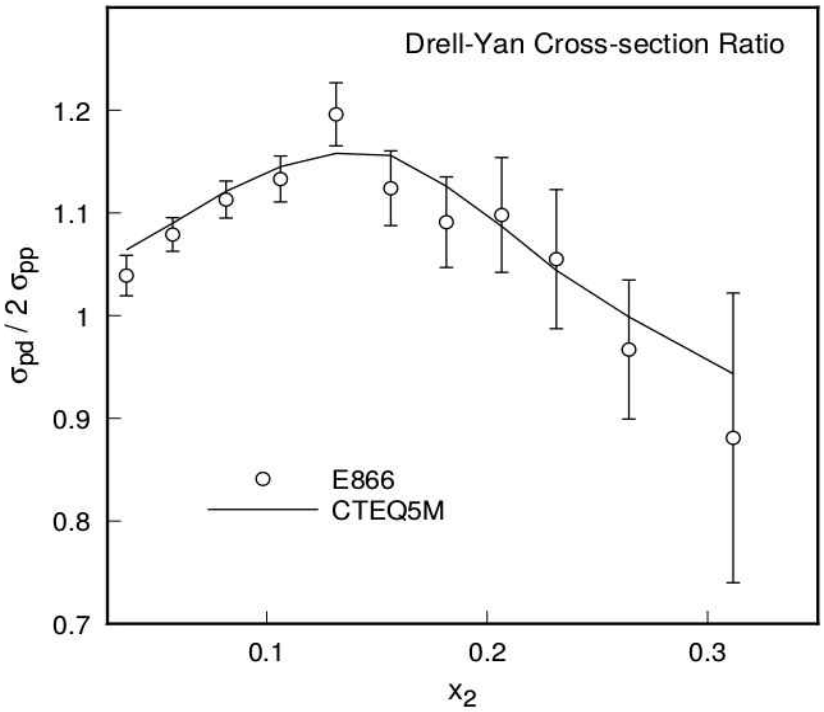

NNLO, Q^2=100 GeV^2, $\alpha_S(M_Z)$=0.118
CT14
HERAPDF2.0 (EIG+VAR)
ABM12 (N_f=5, $\alpha_s(m_Z)$=0.1132)
$d(x,Q^2)/d(x,Q^2)$ [ref]
x

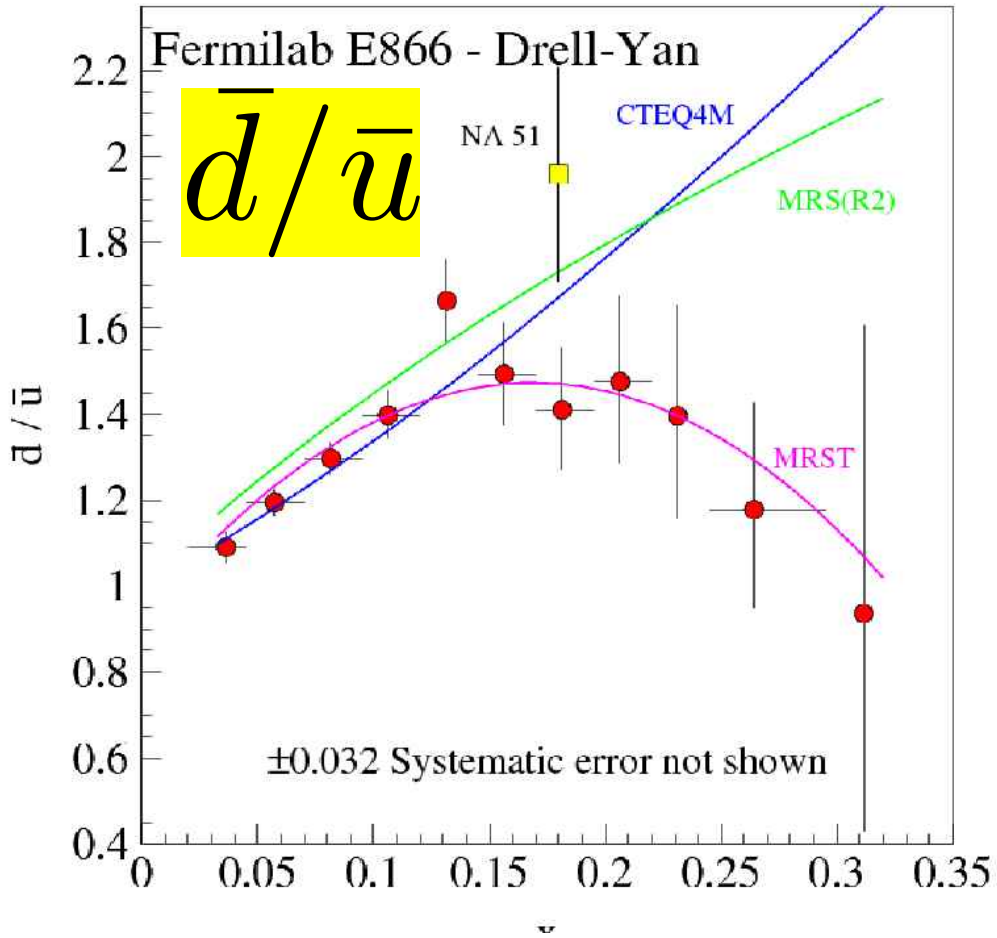
d-bar/u-bar Ratio: A Longstanding Puzzle



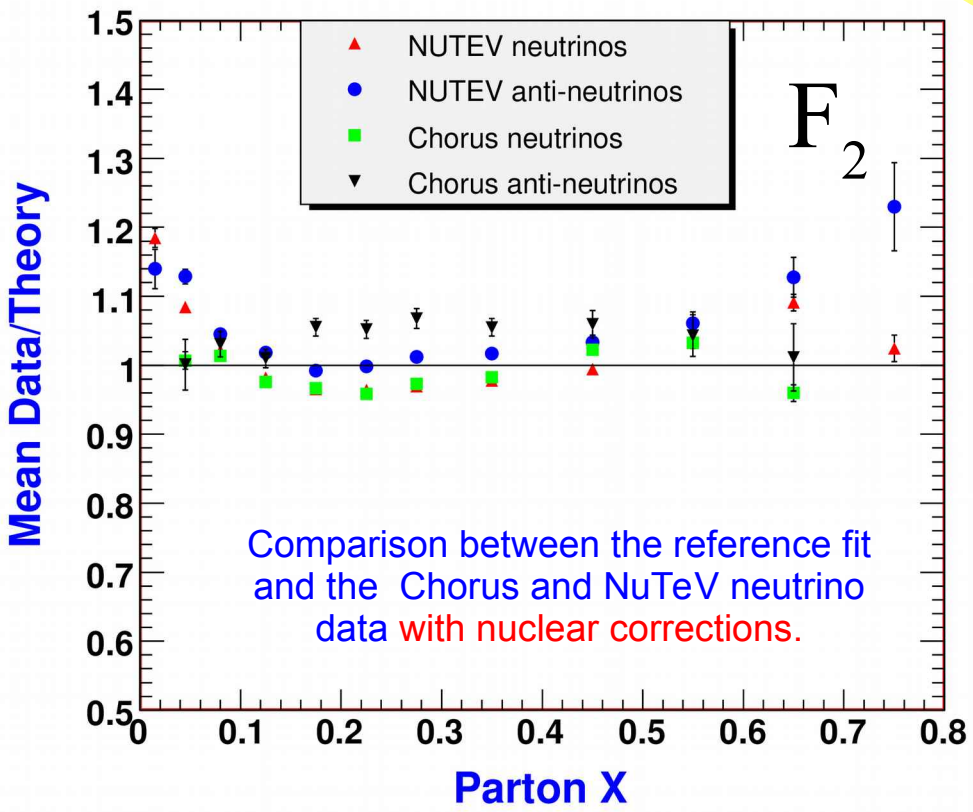
Fermilab E866/NuSea
E906 SeaQuest

800 GeV $p + p$ and $p + d \rightarrow \mu^+\mu^- X$

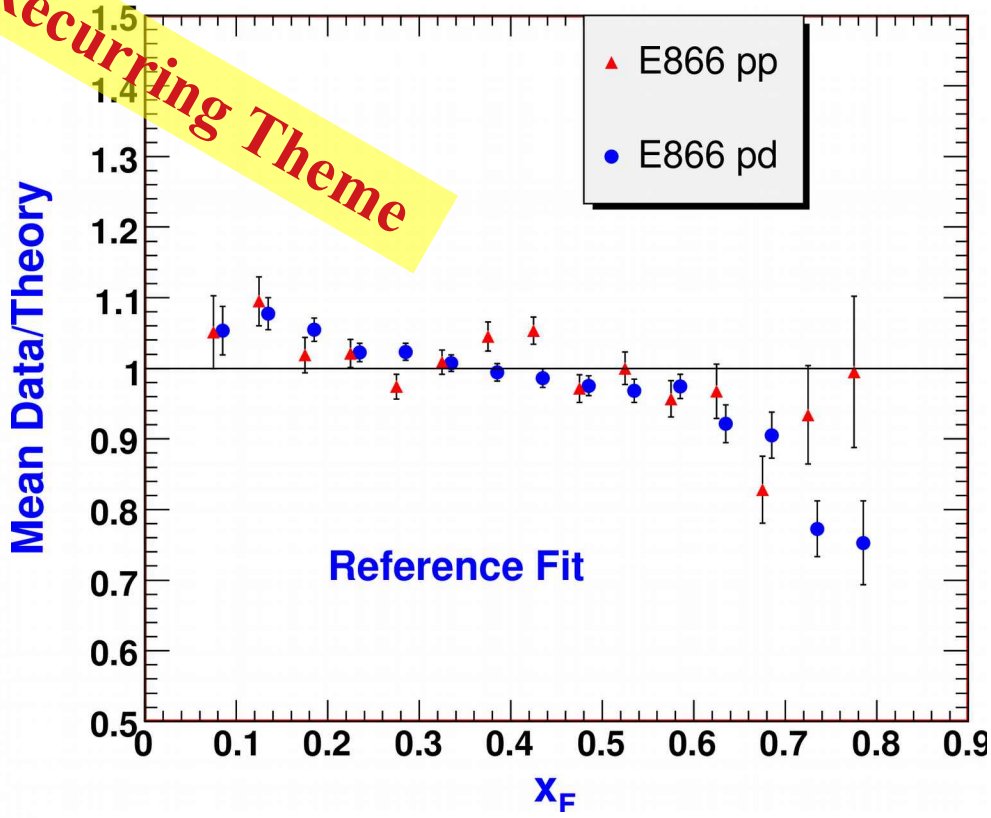




Could nuclear corrections be different for CC (W) or NC (γ,Z) processes???



Recurring Theme

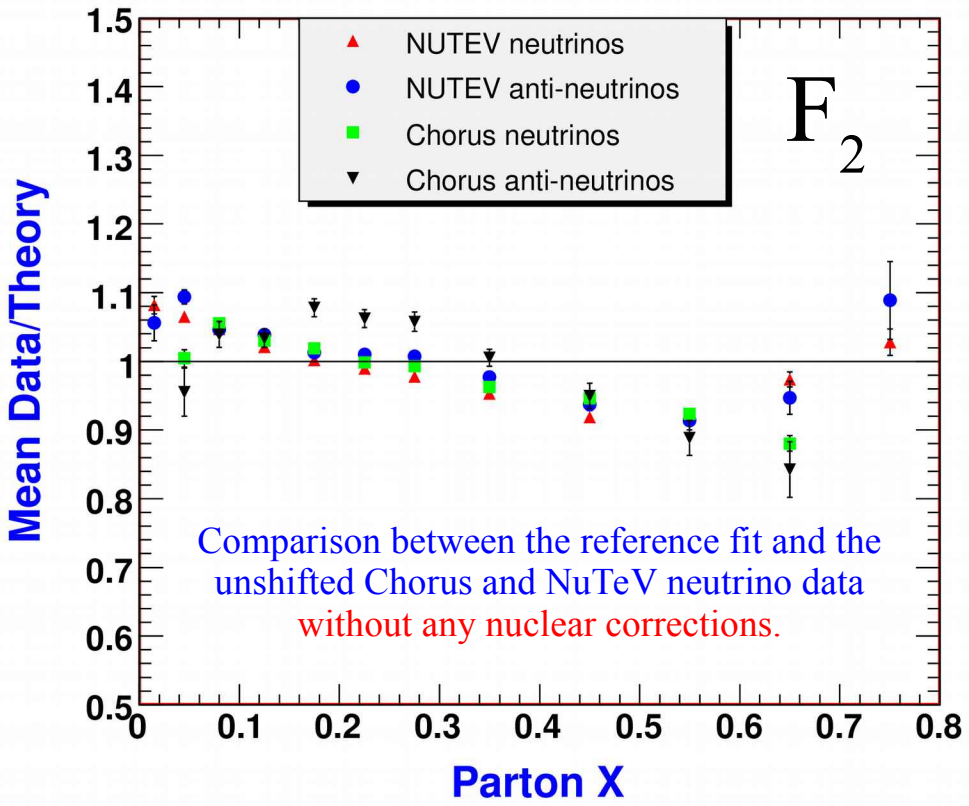


"Thus, these results suggest on a purely phenomenological level that the nuclear corrections may well be very similar for the nu and nubar cross sections and that the overall magnitude of the corrections may well be smaller than in the model used in this analysis."

χ=7453/5062 Reference Fit
χ=6606/5062 Mod Nuclear Fit

Owens, Huston, Keppel, Kuhlmann, Morfin, Olness, Pumplin, Stump. Phys.Rev.D75:054030,2007.

Could nuclear corrections be different for CC (W) or NC (γ,Z) processes???



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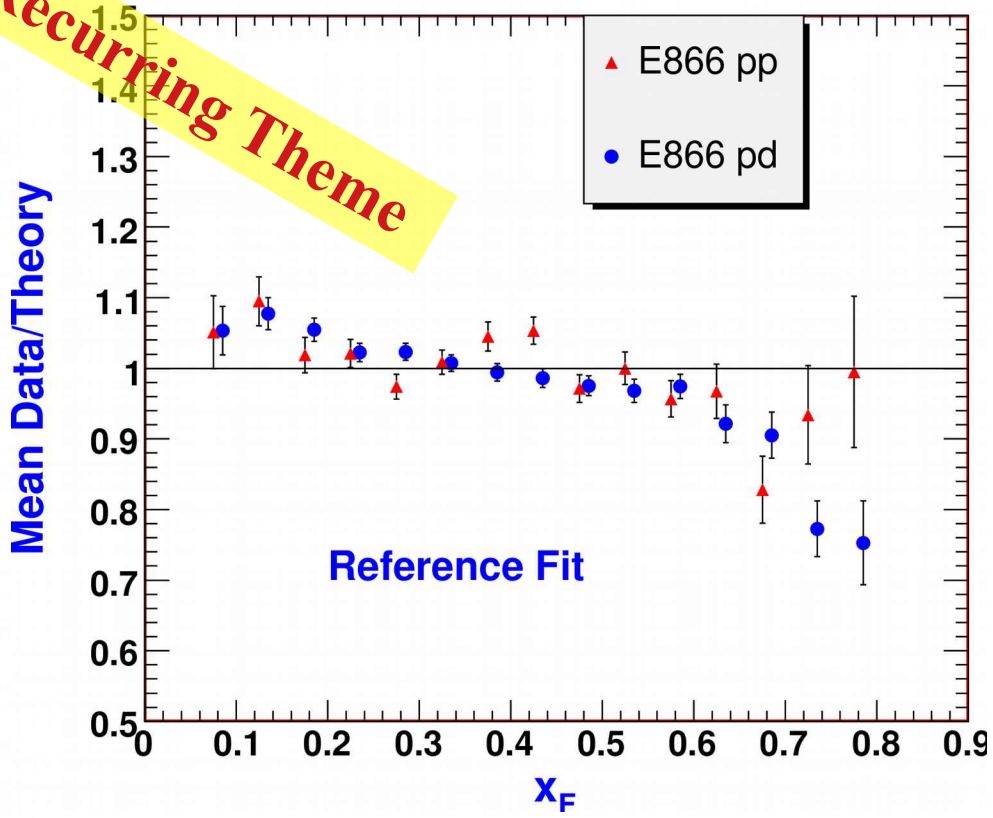

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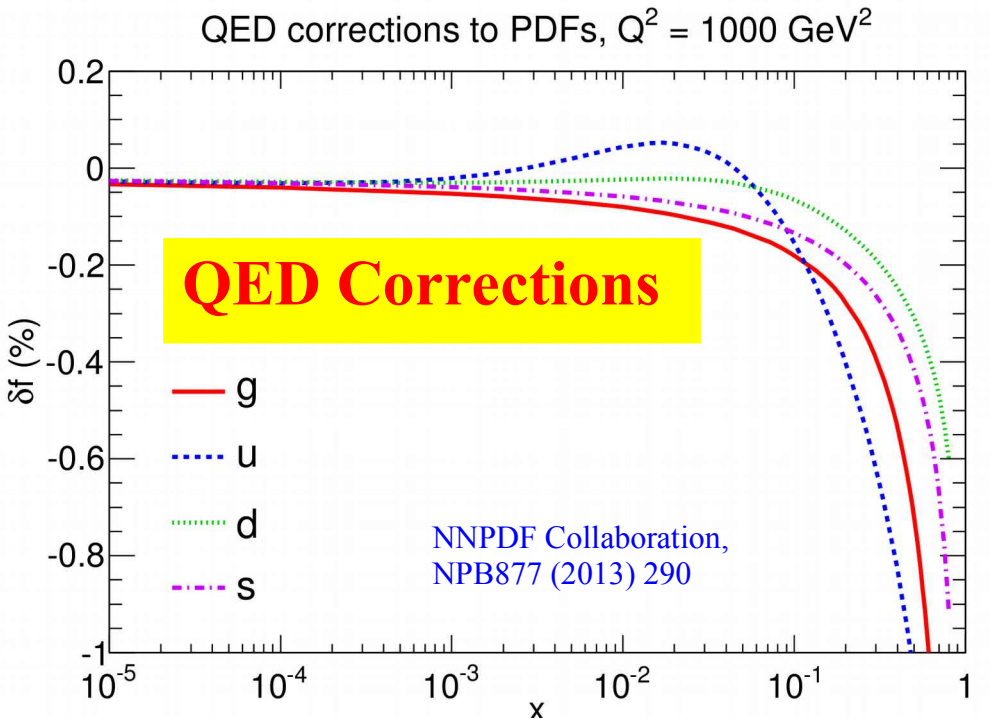
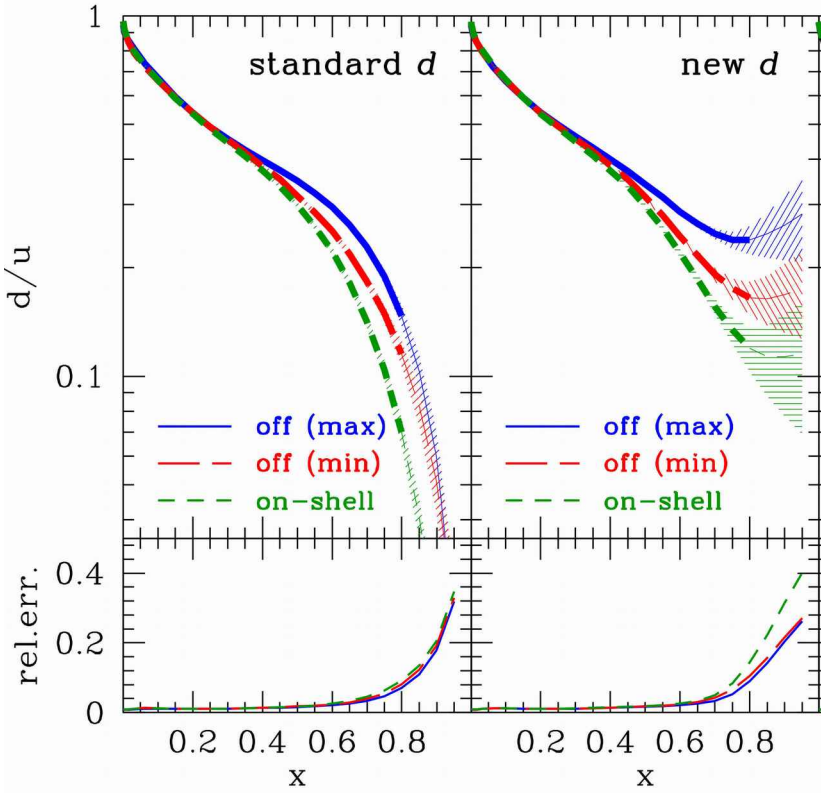
More interesting things, particularly at large-x

... an EIC strength

Hi-x Issues: Isospin Symmetry Violation, Higher Twist, ...

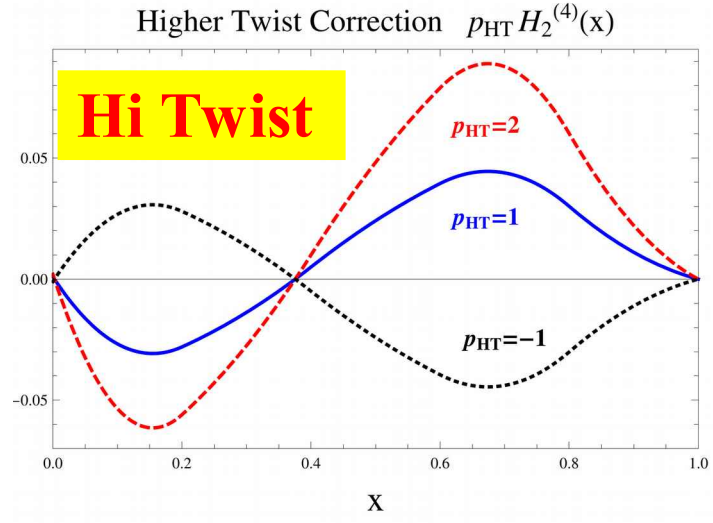


QED Corrections

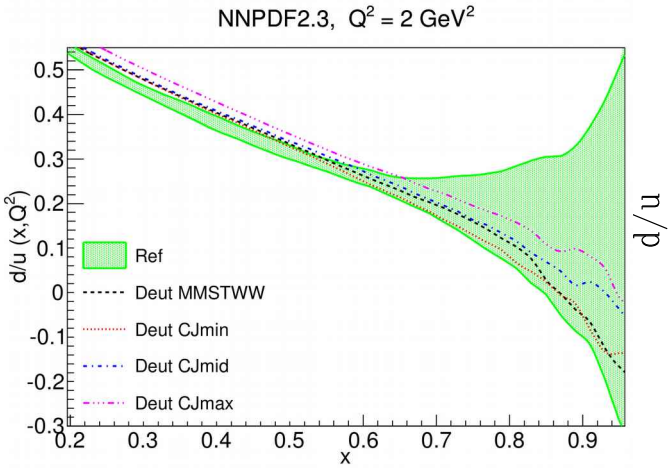


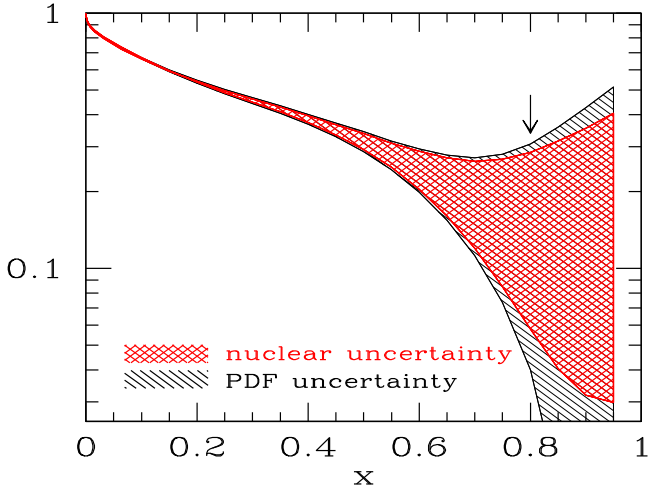
Hi-x is a "Gold Mine" for EIC

Clever Parameterization at large x



Hi Twist

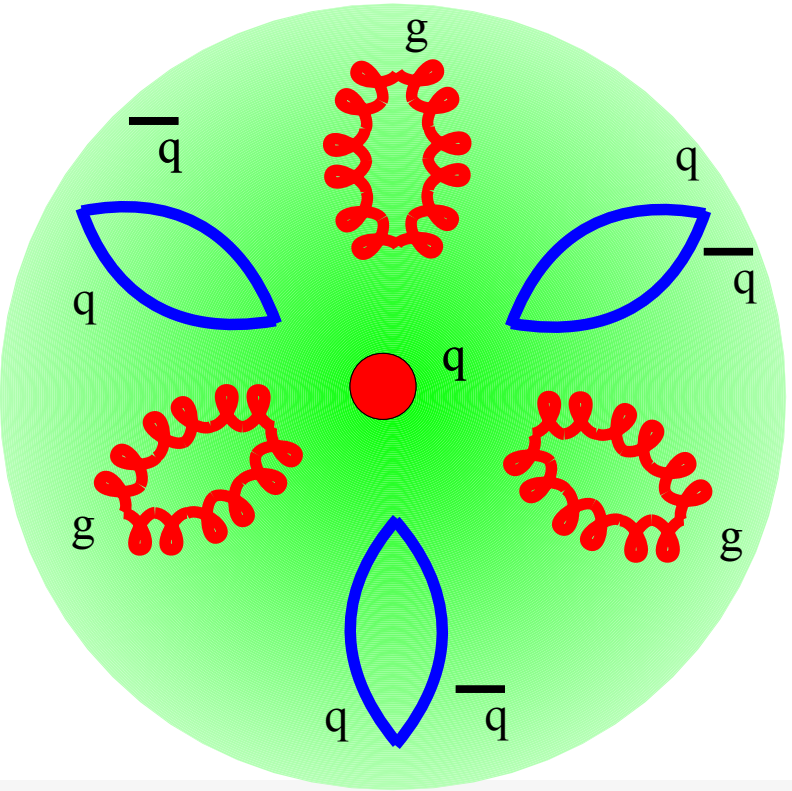


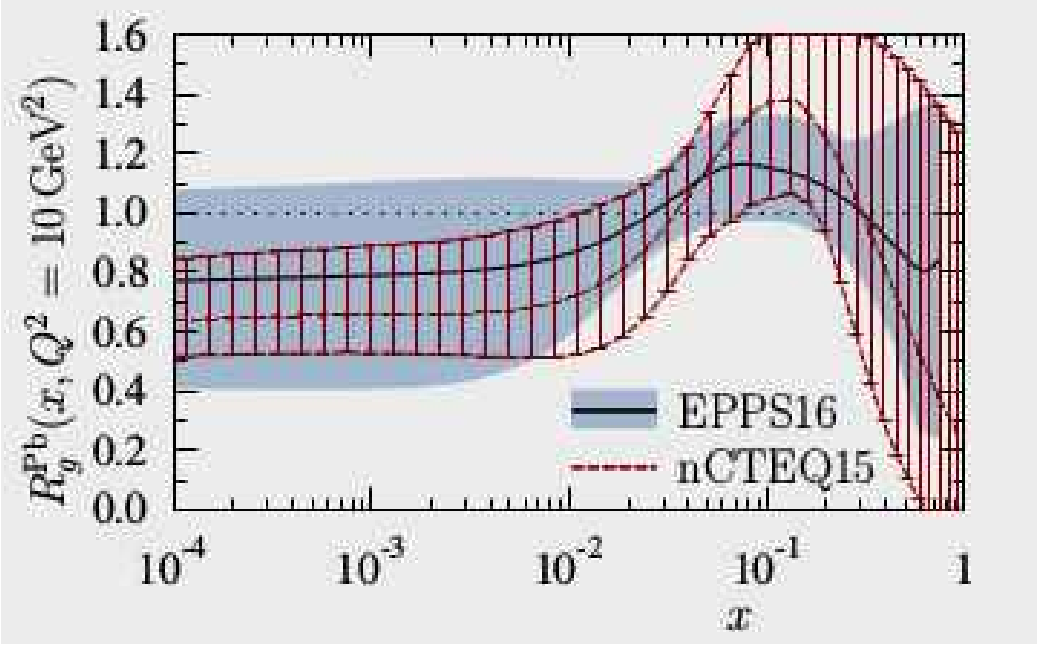


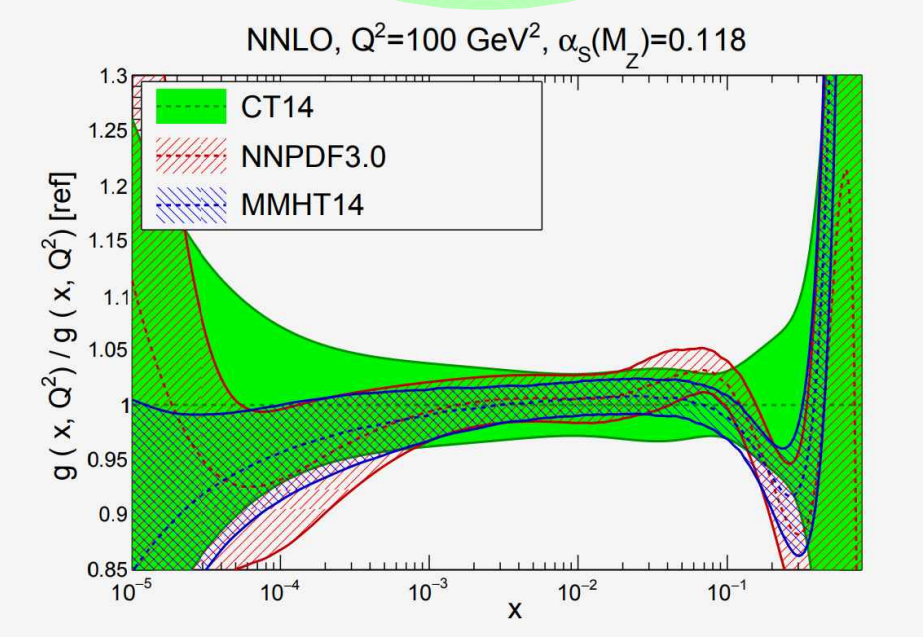
The NNPDF Collaboration, PLB723 (2013) 330

CTEQ-CJ: Phys.Rev. D84 (2011) 014008

GLUON

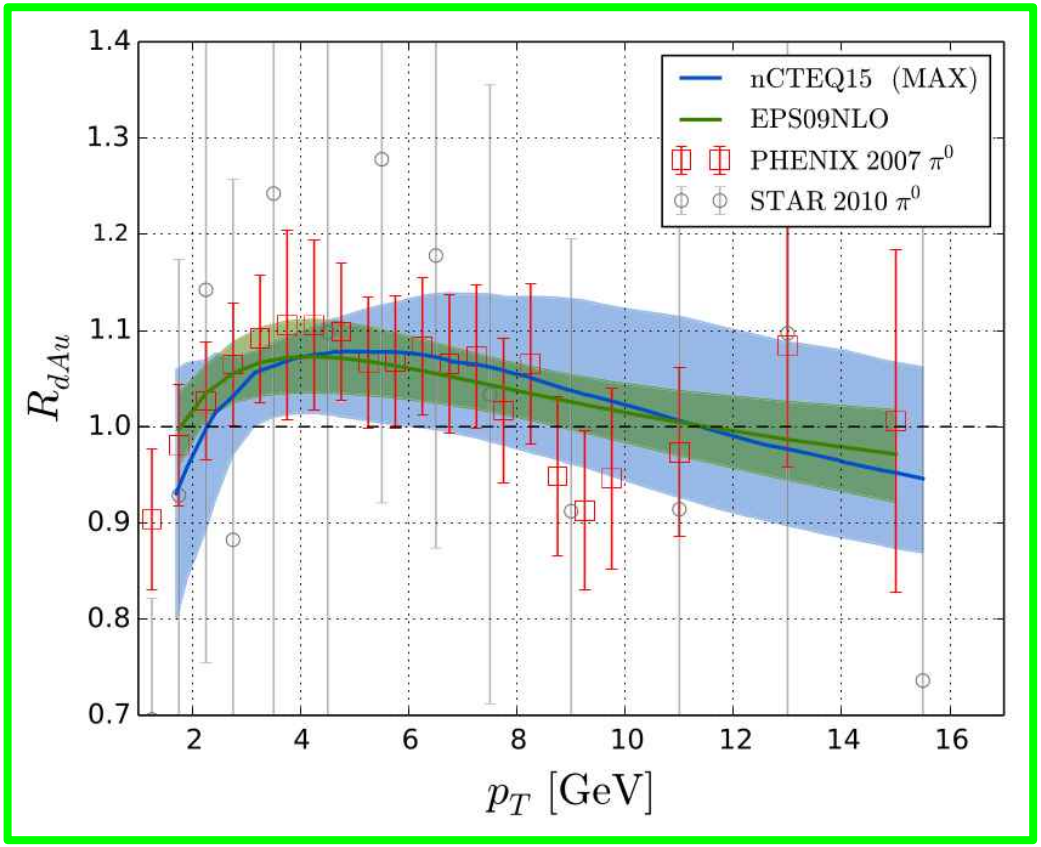

g
q
q
q
q
q
g
g
q
q

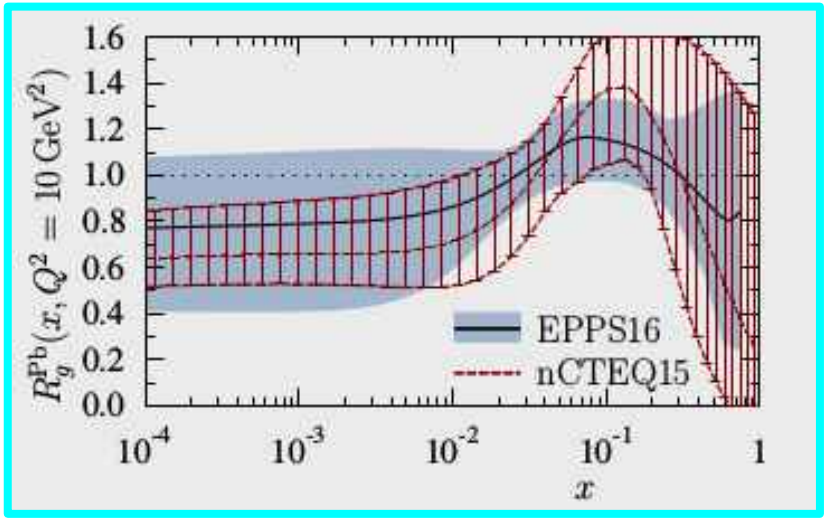

$R_g^{\mathrm{Pb}}(x, Q^2 = 10\ \mathrm{GeV}^2)$
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
EPPS16
nCTEQ15

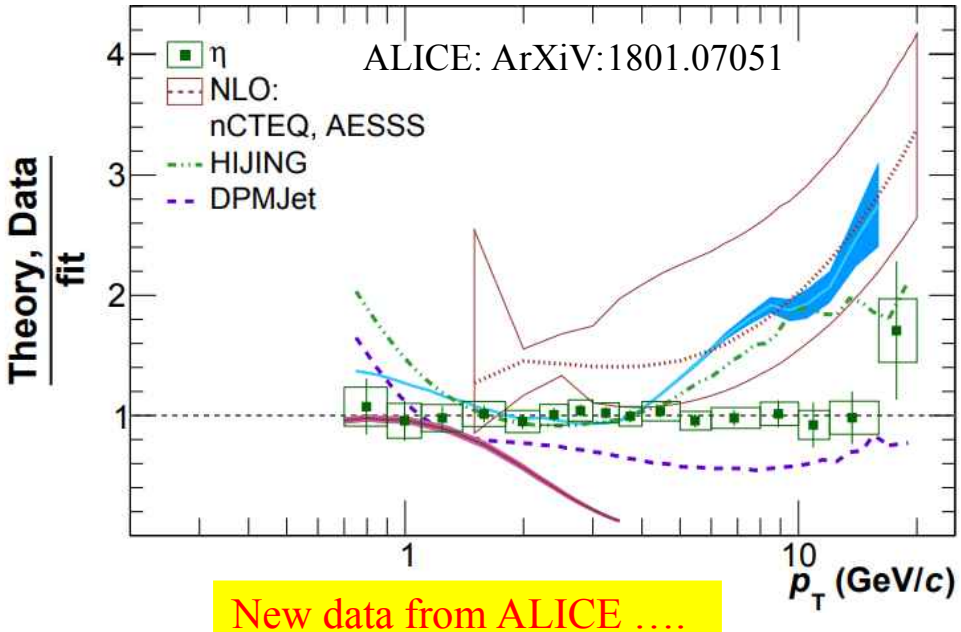

NNLO, Q^2=100 GeV^2, $\alpha_S(M_Z)$=0.118
g (x, Q^2) / g (x, Q^2) [ref]
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x
CT14
NNPDF3.0
MMHT14

Nuclear Gluon: CHALLENGING! RHIC Pion Production

PHENIX & STAR:
Pion Production in p+p and d+Au



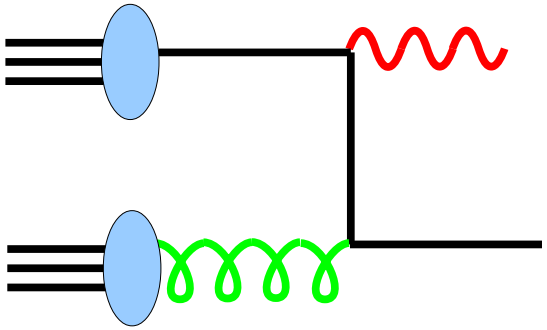


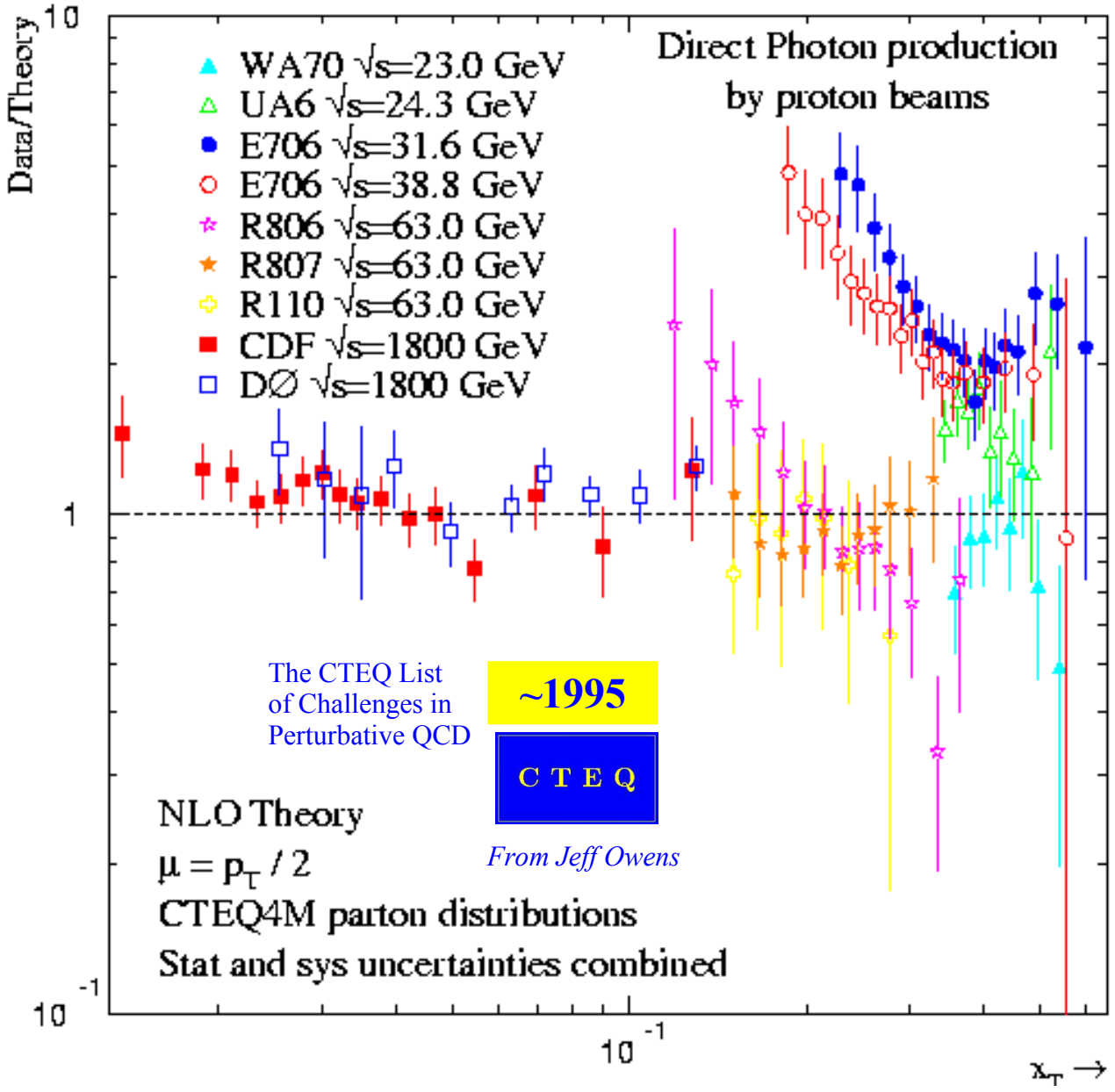


New data from ALICE ….

depends on fragmentation function

Nuclear Gluon: Could we use Direct Photon???

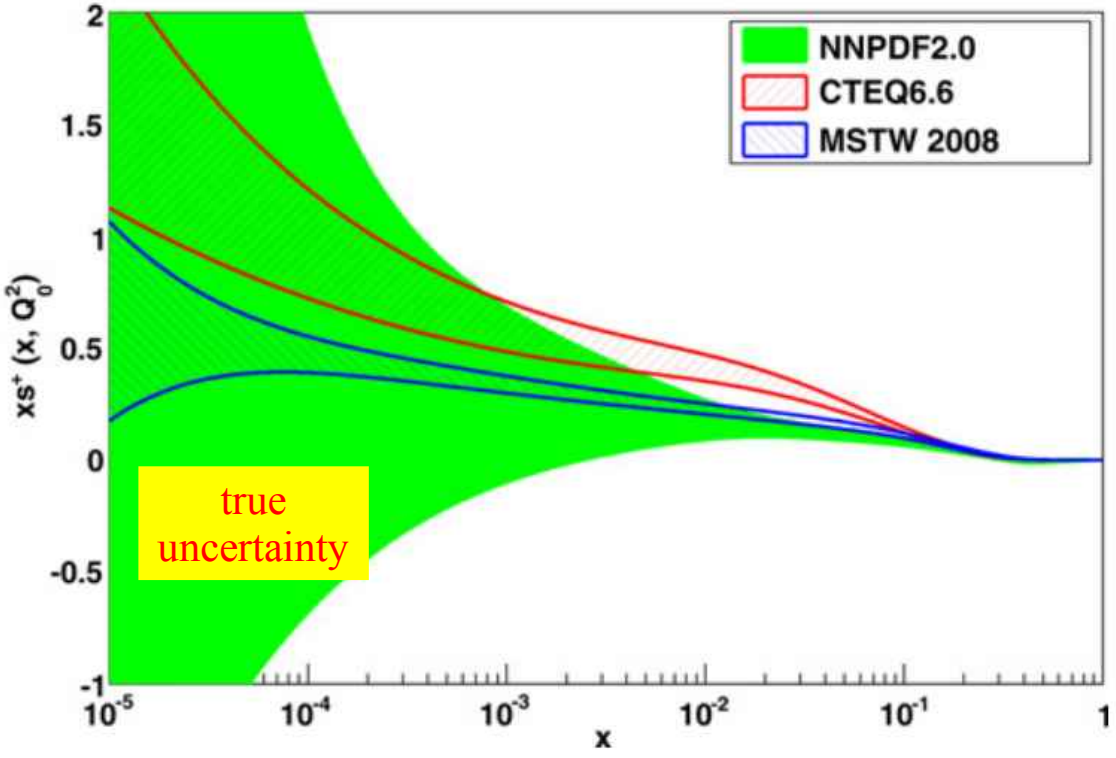


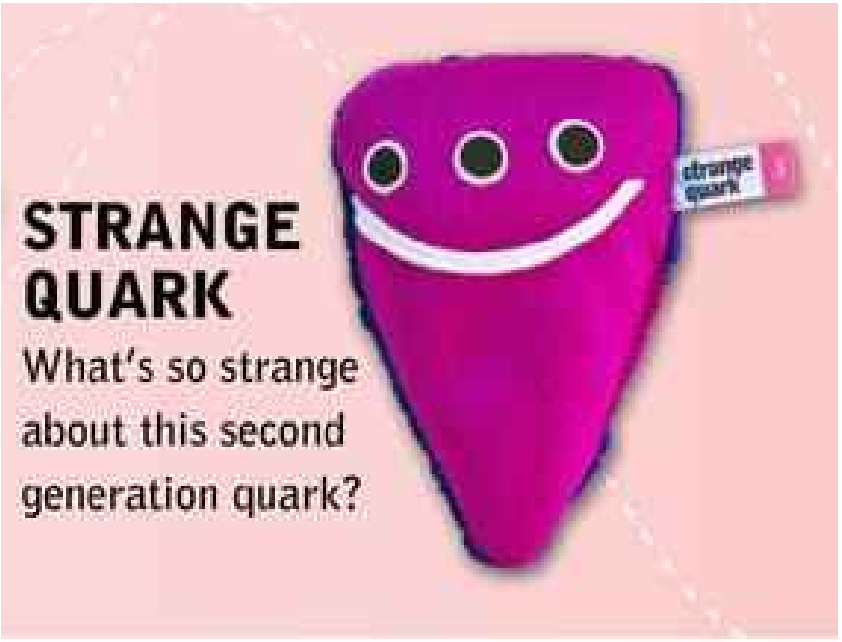


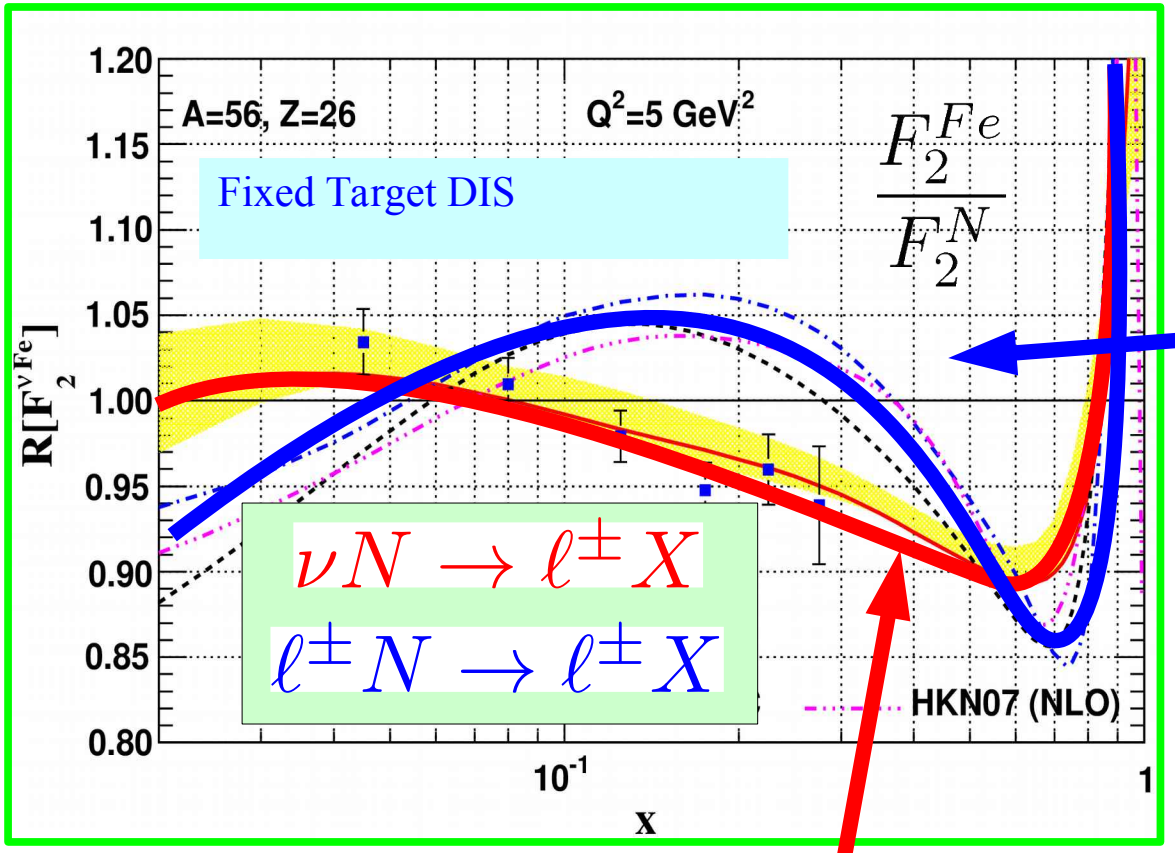
Historically Challenging Intrinsic K_T Issues

Recent improvements in resummation techniques

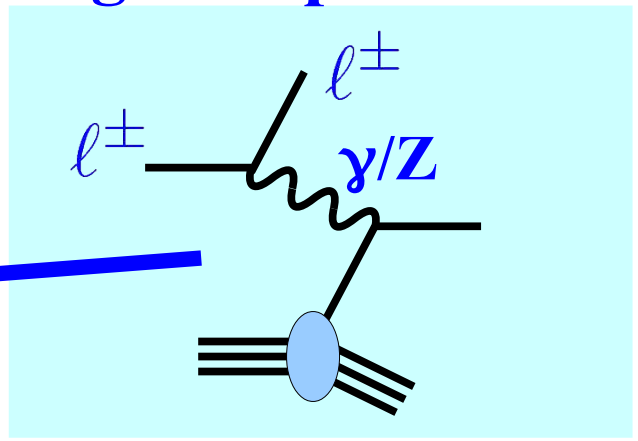
Progress on strange PDF







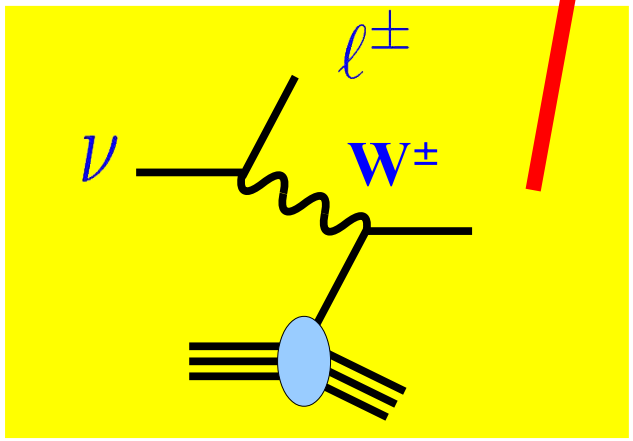
Charged Lepton DIS



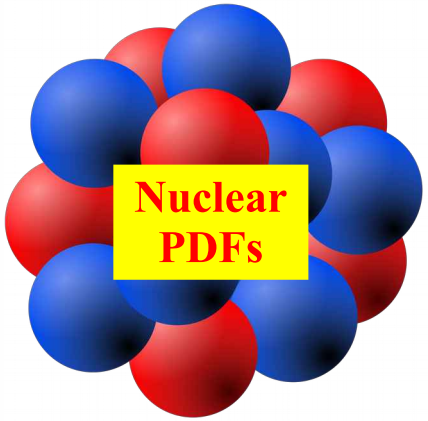
Recurring Theme

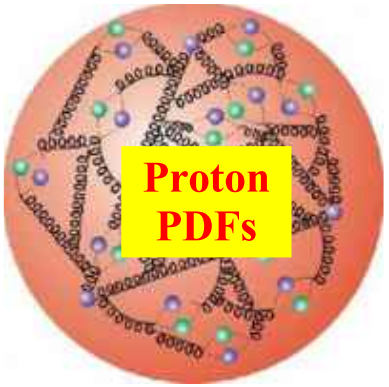
some caveats
... correlated errors

Depends on nuclear corrections



Neutrino DIS

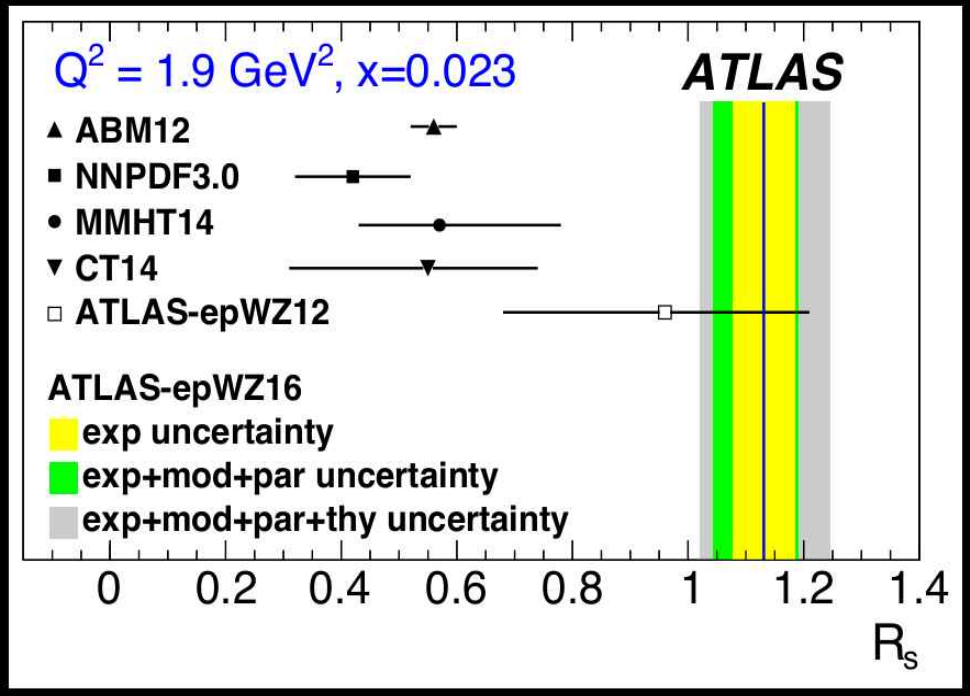




Electroweak and QCD Measurements at the Large Hadron Collider

Strangeness in the Proton

arXiv:1612.03016



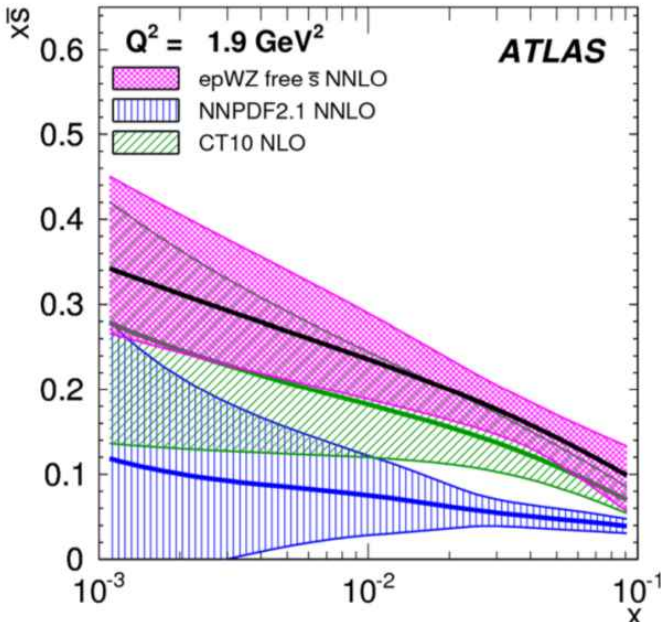
$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}} = 1.13 \pm 0.05\,(\text{exp}) \pm 0.02\,(\text{mod})\ ^{+0.01}_{-0.06}\,(\text{par})$$

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

João Guimarães da Costa
IHEP, Chinese Academy of Sciences

… do we know what the strange PDF is ???

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



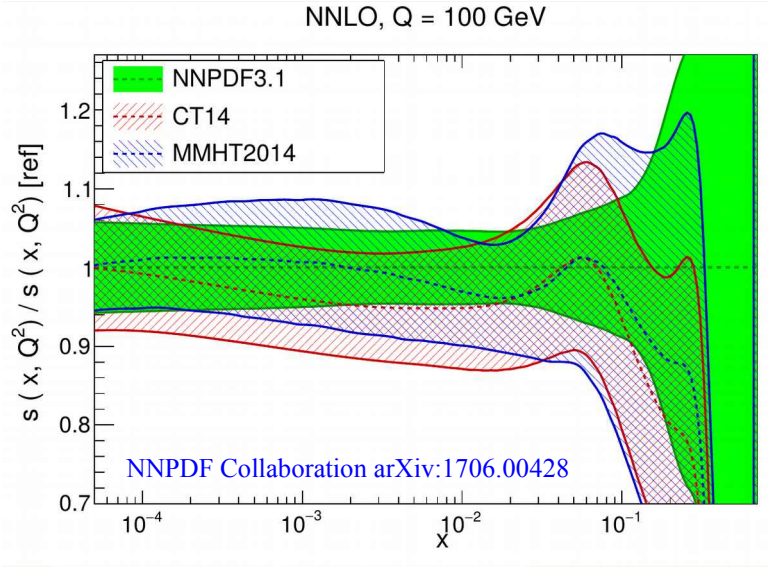
HERAFitter, Open Source QCD Fit Project
Eur. Phys. J. C (2015) 75: 304.

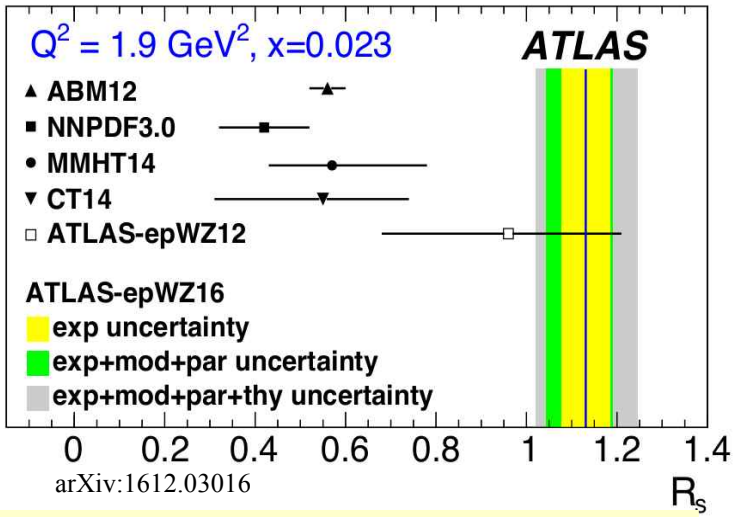
$$K^s_{\mathrm{CT14NNLO}} = 0.62 \pm 0.14$$

$$K^s_{\mathrm{CT10NNLO}} = 0.73 \pm 0.11$$

Carl Schmidt October 2015: INT Workshop

… whatever you want it to be





arXiv:1612.03016

… yes, details depend on {x,Q²}

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

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

$$\text{CMS } \kappa = 0.52^{+0.12+0.05+0.13}_{-0.10-0.06-0.10}$$ Q^2=20 GeV²

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

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

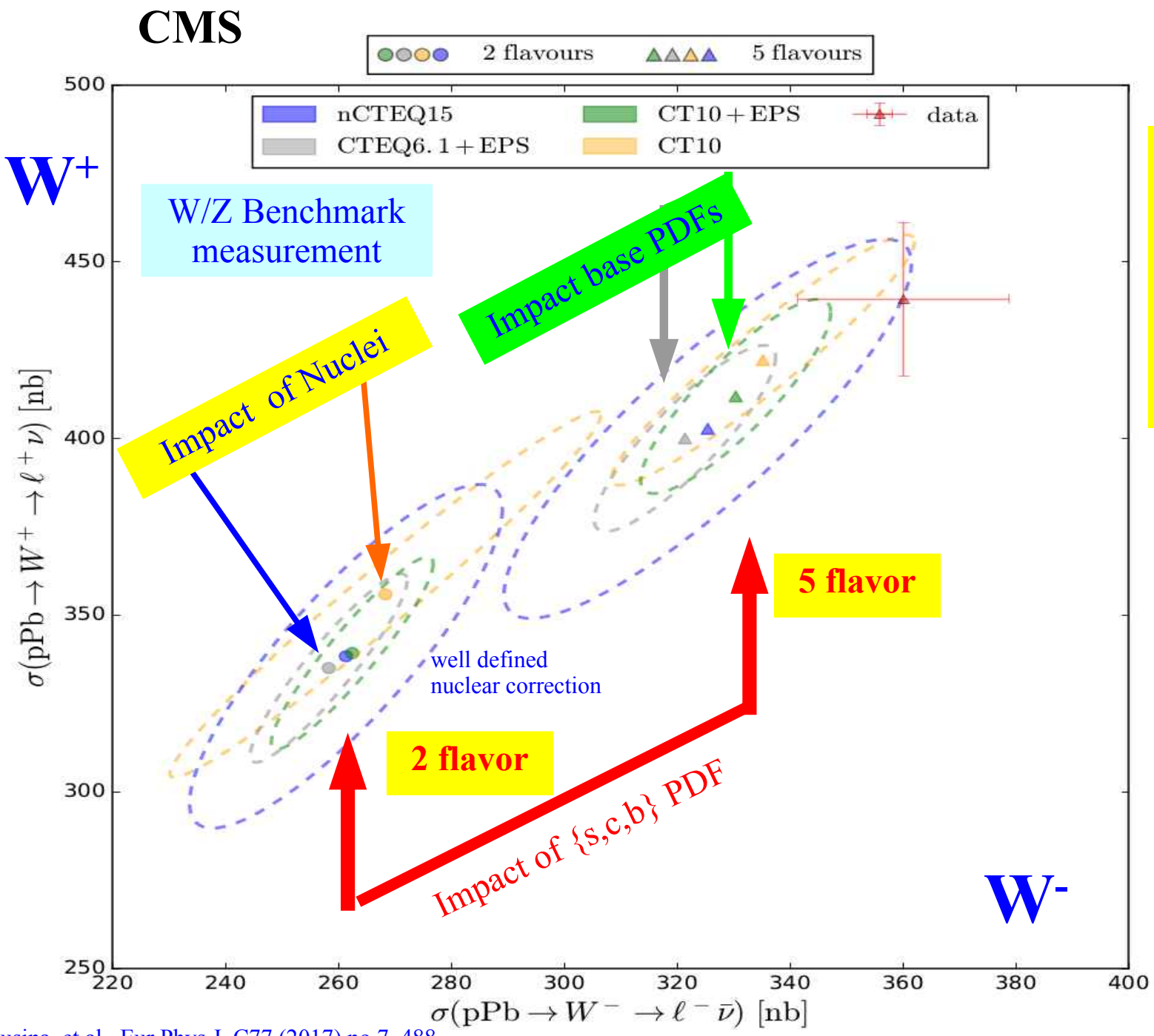
Q_0^2=1.9 GeV² at x=0.023

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

W/Z Heavy Ion Data

p-Pb

$p\,Pb \rightarrow W/Z$: Impact of {s,c,b} PDF

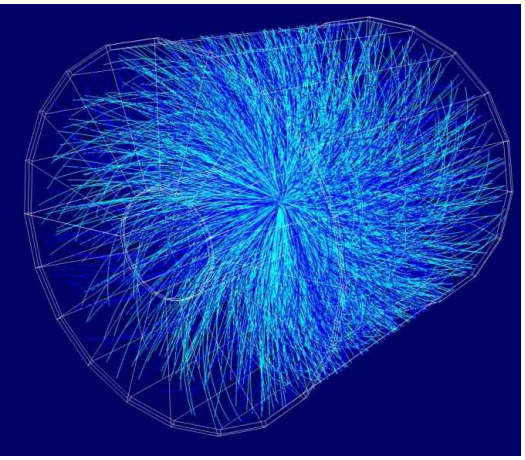


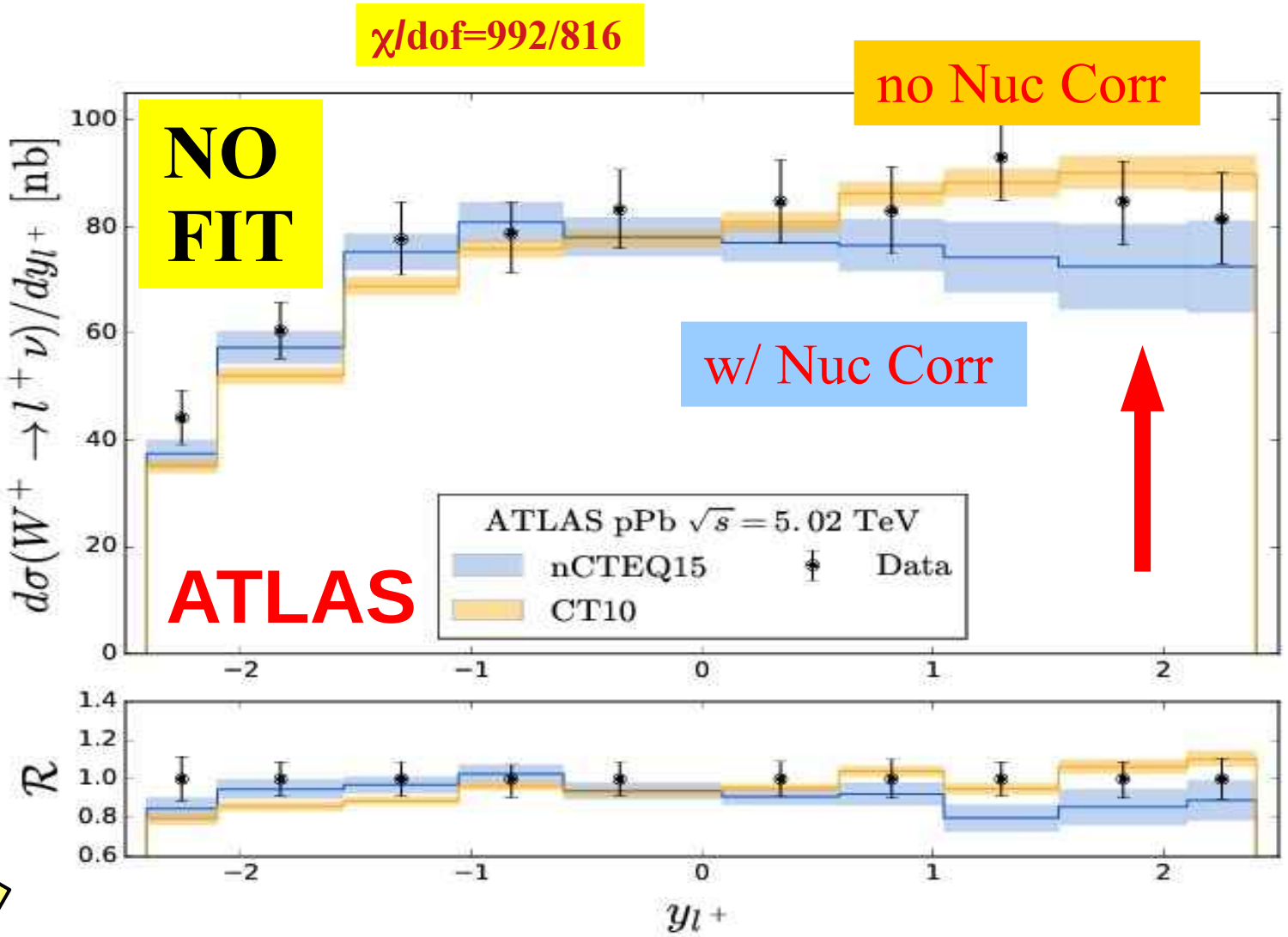
Entangled:

- Nuc Corrections
- Base PDF
- PDF Flavors

A. Kusina, et al., Eur.Phys.J. C77 (2017) no.7, 488

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





Recurring Theme

lead kinematics

larger x ⟵ ⟶ **smaller x**

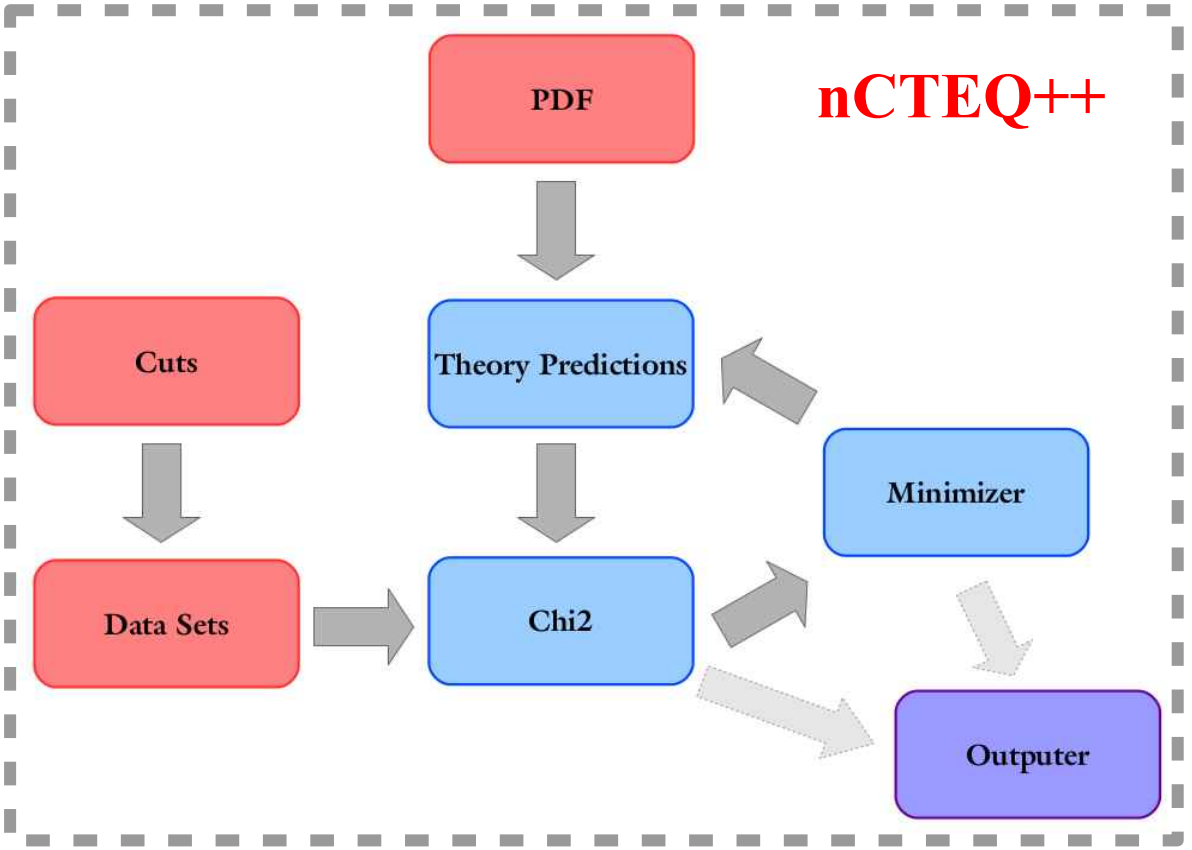
A. Kusina, et al., arXiv:1610.02925 [nucl-th]

Include W/Z Heavy Ion Data in fit *p-Pb*

With new tools we can now fit this data: nCTEQ++

nCTEQ++

- A complete rewrite of the nCTEQ FORTRAN fitting code in C++
- Changed the code to allow for modules when building a PDF
  - Evolution
  - Interpolation
  - Parameterization
- **Use external programs**
  - **Minuit**
  - **HOPPET**
  - **MCFM**
  - **APPLgrid**



Special thanks to:
Florian Lyonnet
Tomas Jezo
Aleksander Kusina

W/Z Data in fit: LHC p-Pb

nCTEQ++

χ^2/dof

χ^2: 992 → 828

CMS	W+	6233
CMS	W-	6231
CMS	Z	6235
ATLAS	W+	6211
ATLAS	W-	6213
ATLAS	Z	6215
ALICE	W+	6253
ALICE	W-	6251
LHCb	Z	6275
CMS_II	W+	6234
CMS_II	W-	6232

No Norm Shift

χ^2= 828

DOF=816

1σ Norm Shift

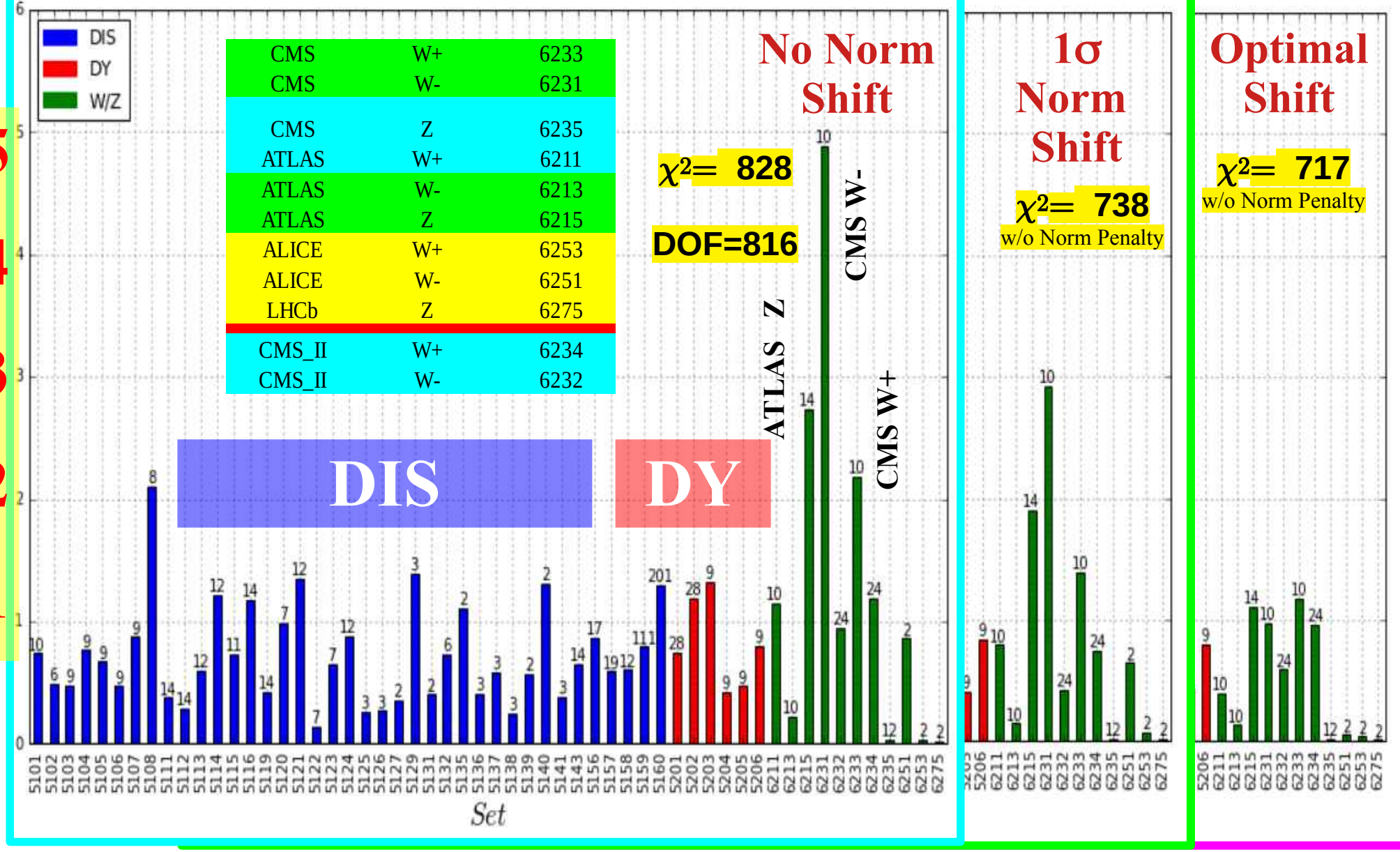
χ^2= 738

w/o Norm Penalty

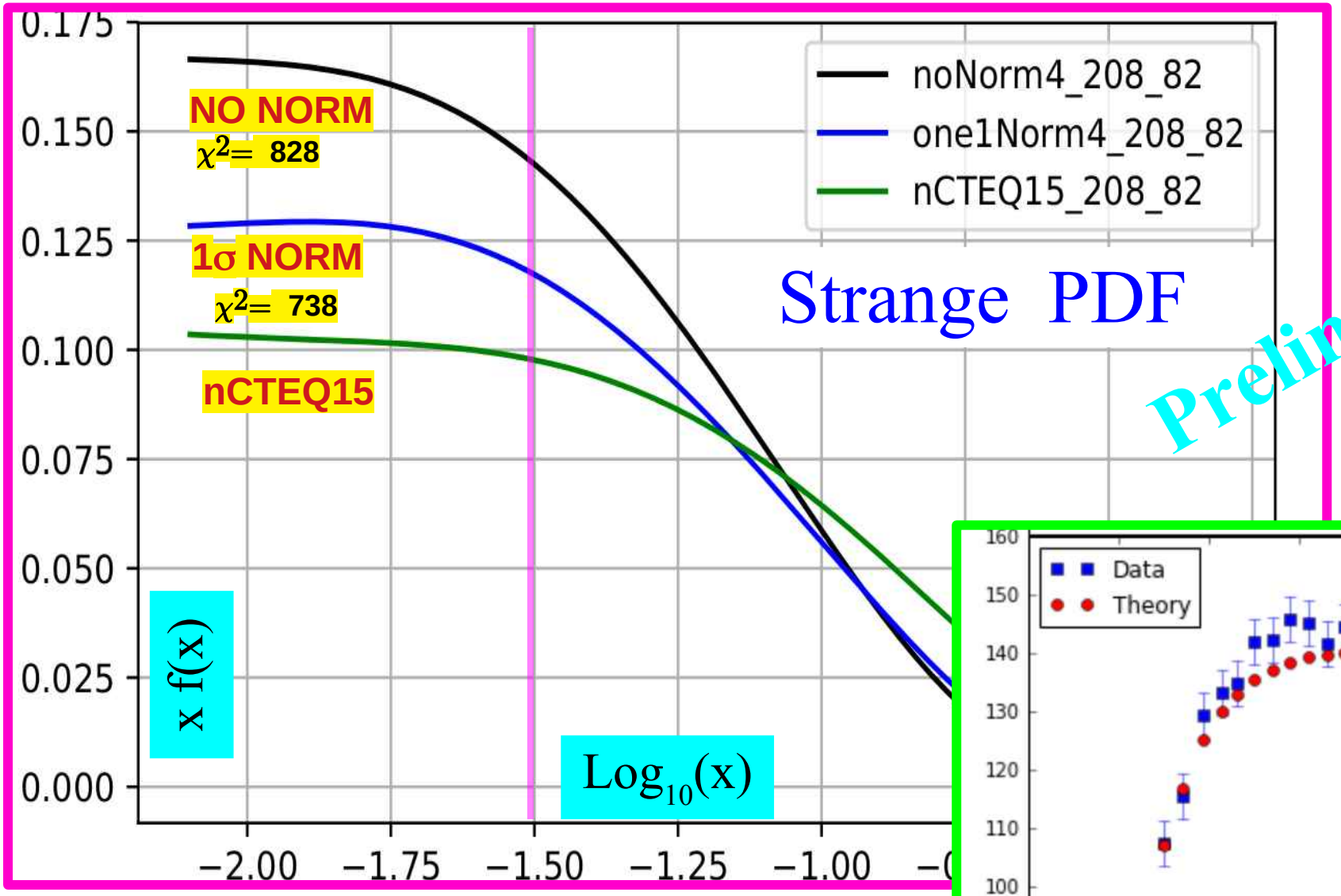
Optimal Shift

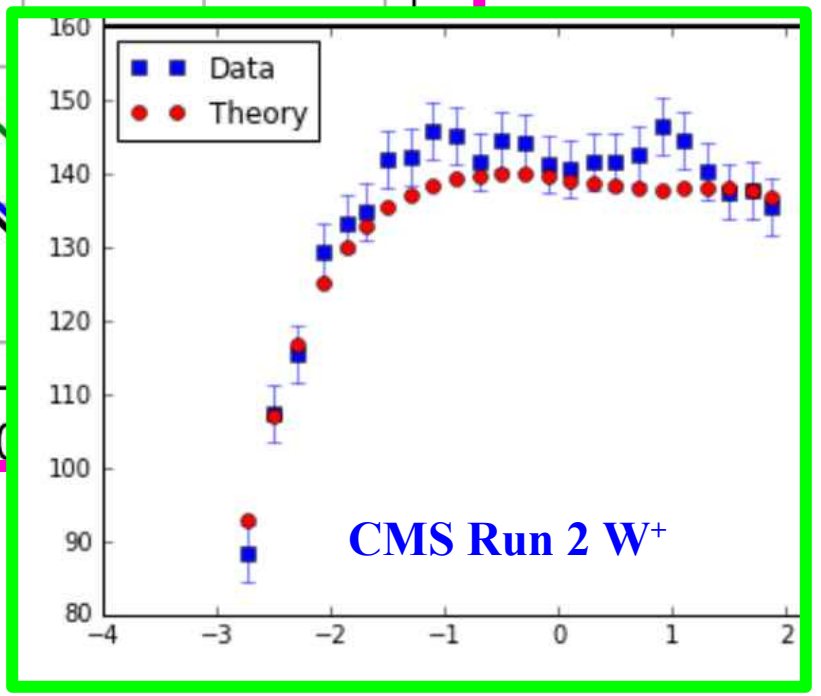
χ^2= 717

w/o Norm Penalty



W/Z Data in fit: LHC p-Pb





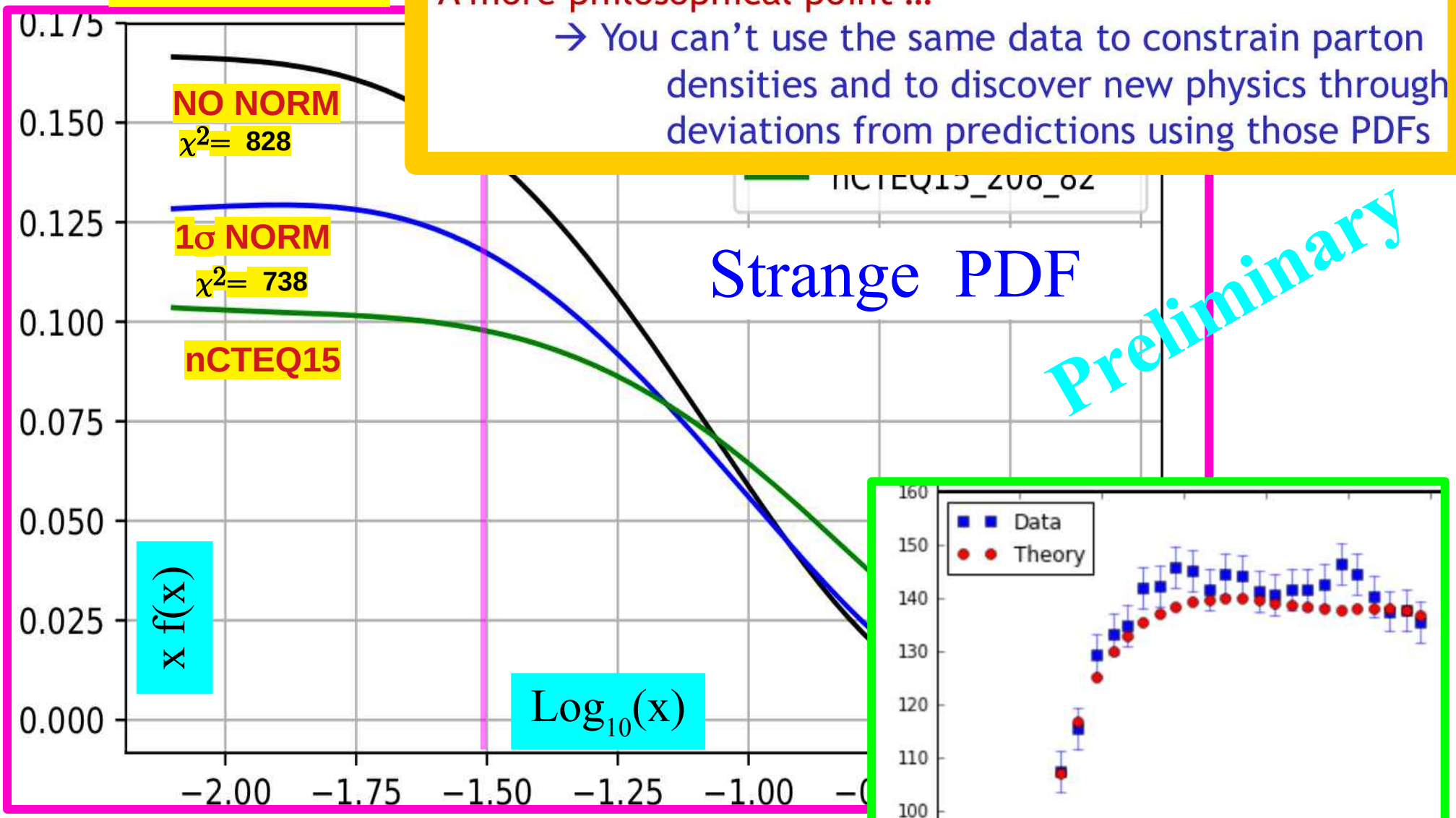
Is the strange PDF driving the data ….
Or is the data driving the strange ???

W/Z Data in fit: LHC p-Pb

… we heard on Monday from Paul Newman

A more philosophical point …

→ You can't use the same data to constrain parton densities and to discover new physics through deviations from predictions using those PDFs



Is the strange PDF driving the data ….
Or is the data driving the strange ???

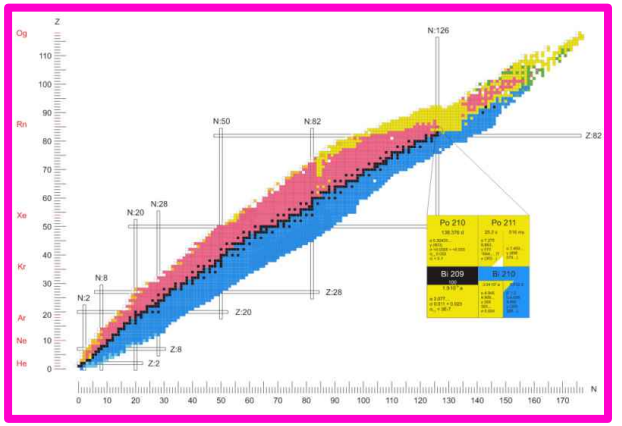
Conclusions

nCTEQ PDF Update

What are the challenges & opportunities with an EIC

It will have high statistics for a wide variety of NUCLEI

Nuclear corrections are inextricably linked
to the PDF flavor differentiation

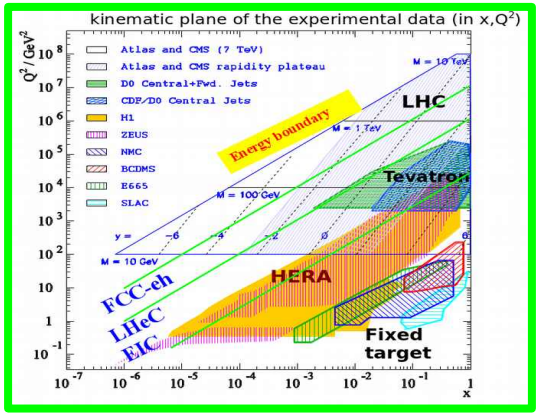


It allows us to push to HI-X

W cuts eliminate much of this region
Higher-twist, factorization violations, …
Test models in x→1 limit, e.g., d/u, …

It allows us to push to low Q

Q cuts eliminate much of this region
Explores the parton/hadron transition
Study non-perturbative collective phenomena



Nuclear PDF

The Ingredients

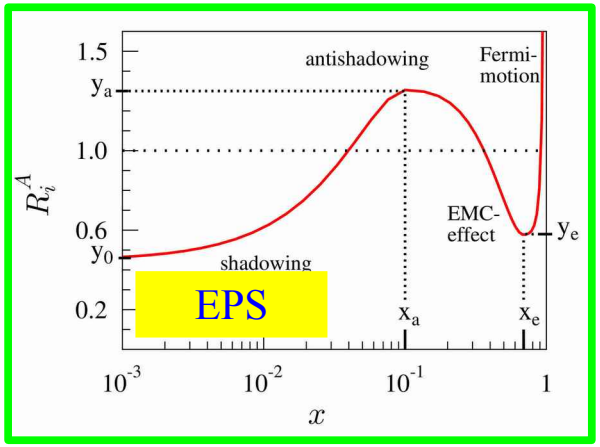
1) Multiplicative nuclear correction factors (HKN, EPPS, DSSZ)

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

... 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)

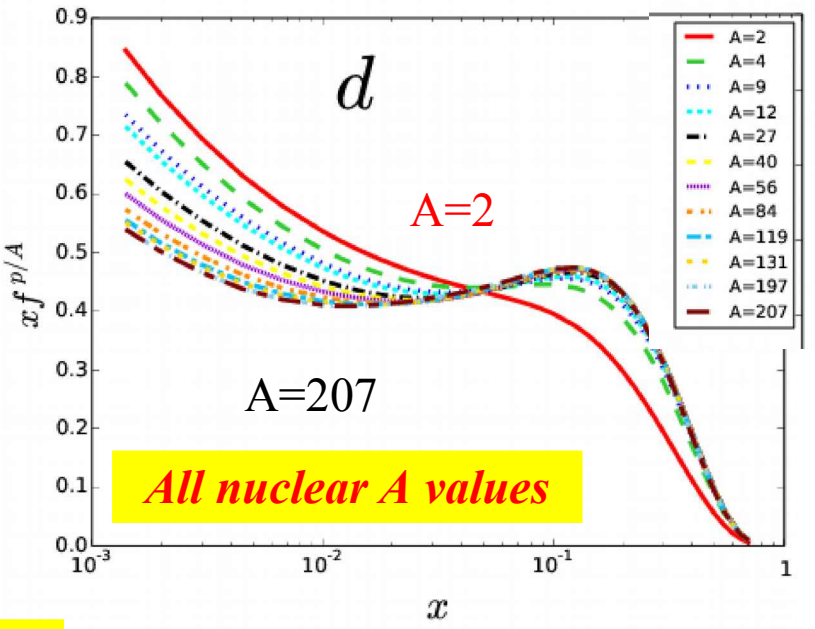
$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

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

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

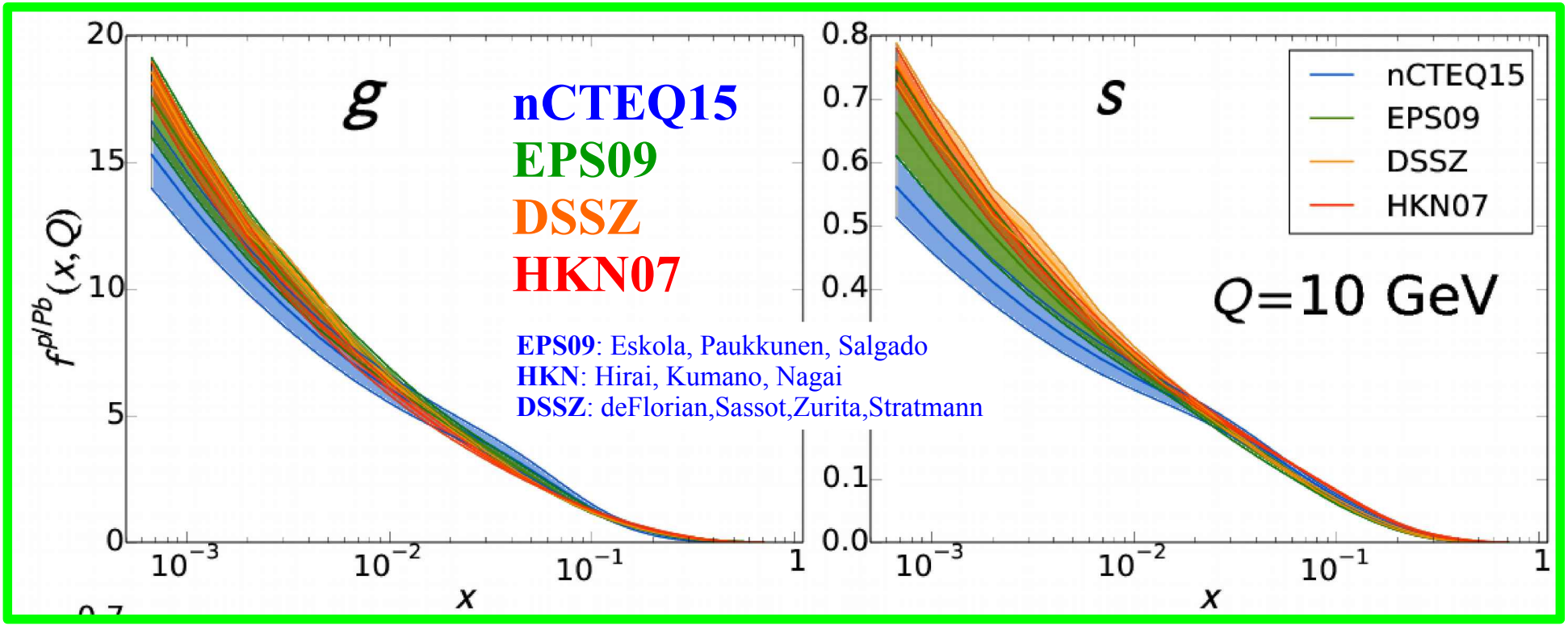
Proton

Nuclear



use proton as a Boundary Condition

Nuclear PDFs: Complementary efforts in general agreement

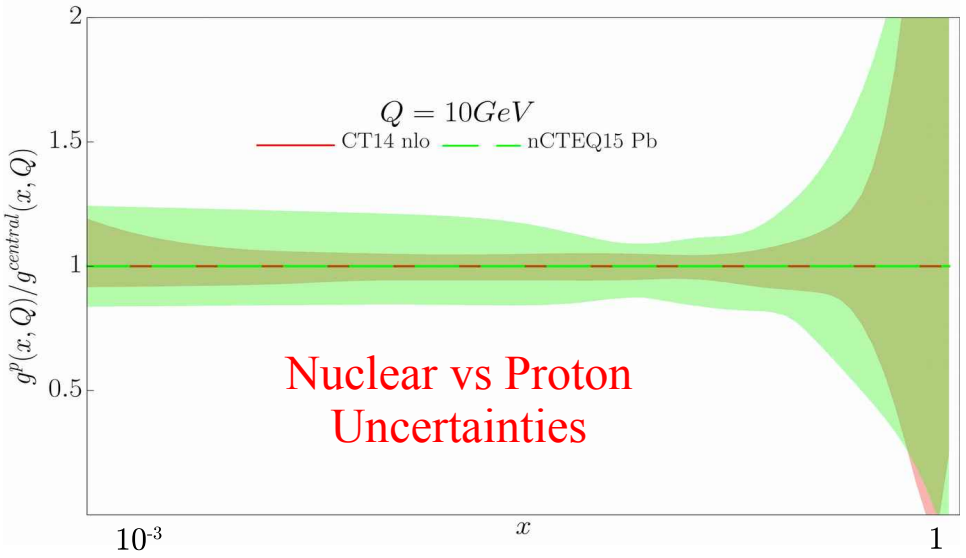


Nuclear PDFs are more complex

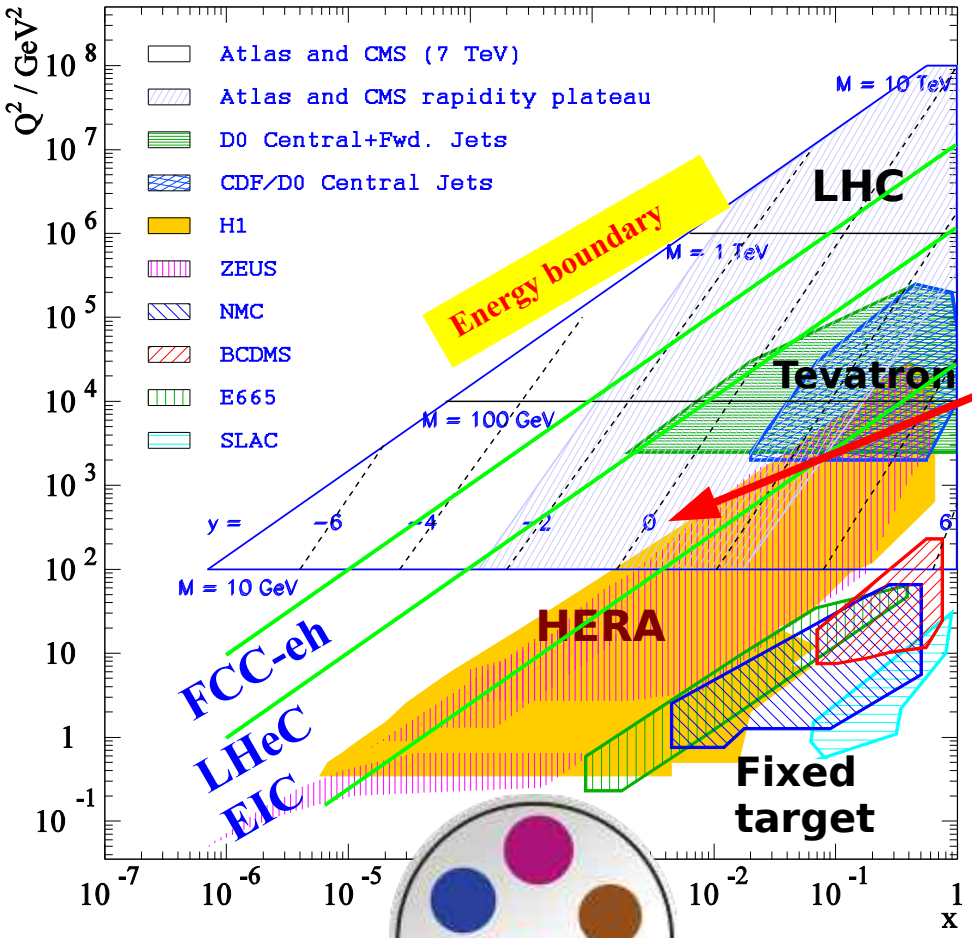
more DOF than Proton case

more "issues" to consider

more work to do ...



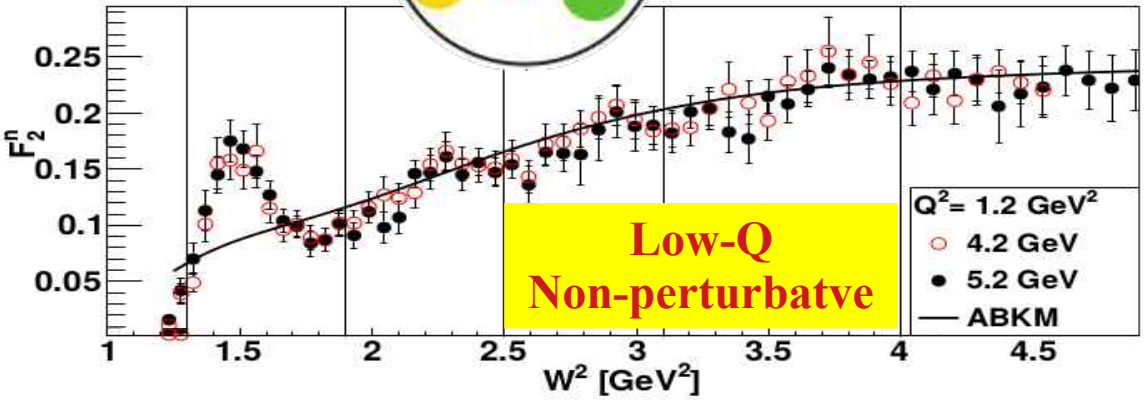
Frontier: Precison, Hi-x, Low-x, Low-Q



Precision

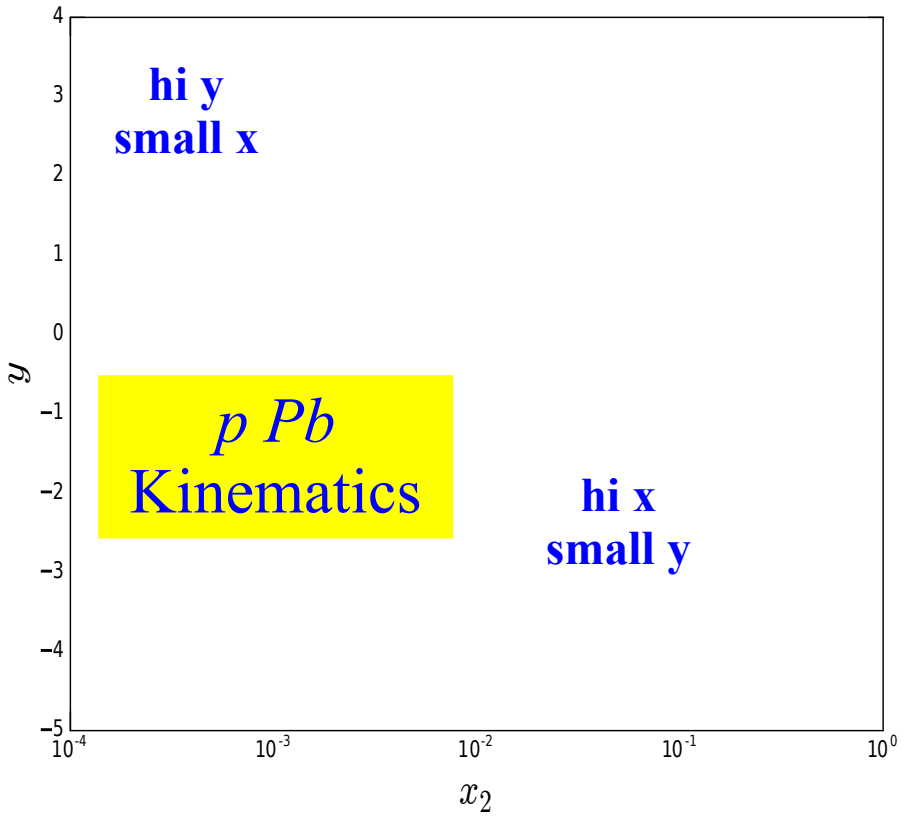
Low-x
Shadowing
Recombination
Resummation

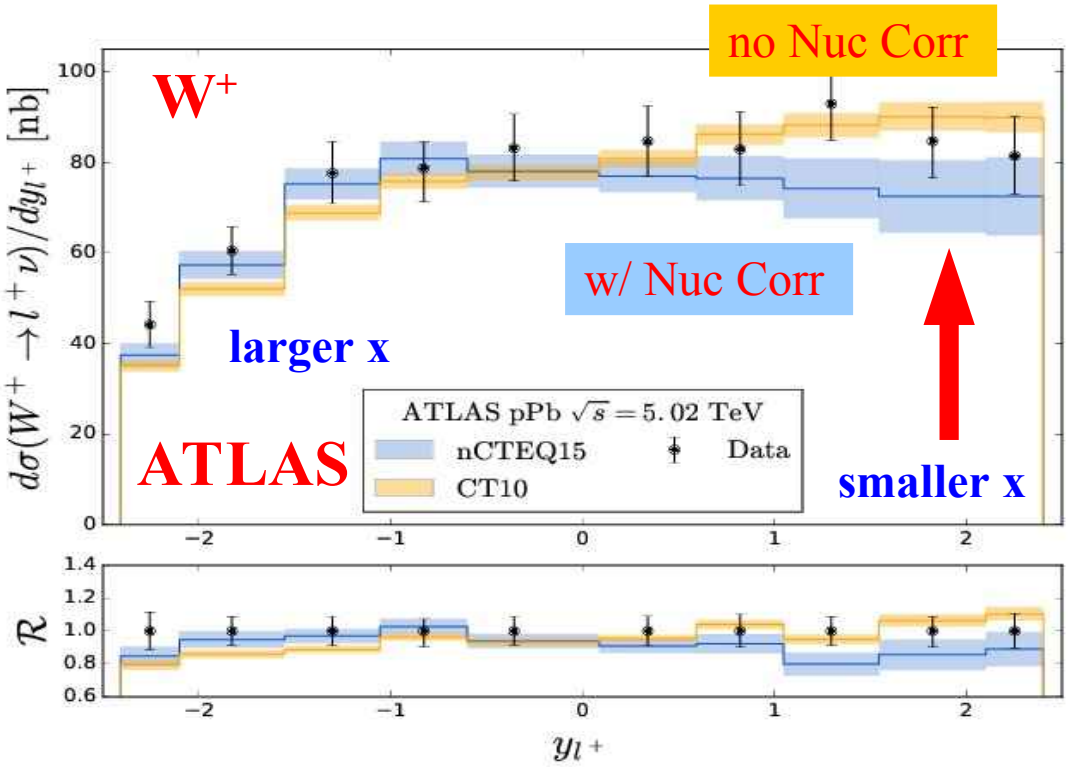
Hi-x
Higher Twist



Could $p\,Pb \to W/Z$ Help???

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





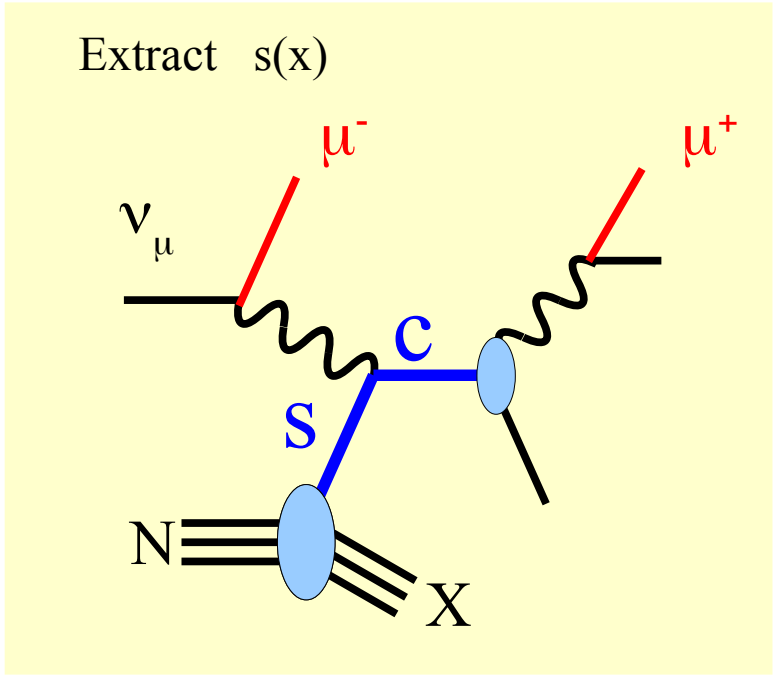
lead kinematics

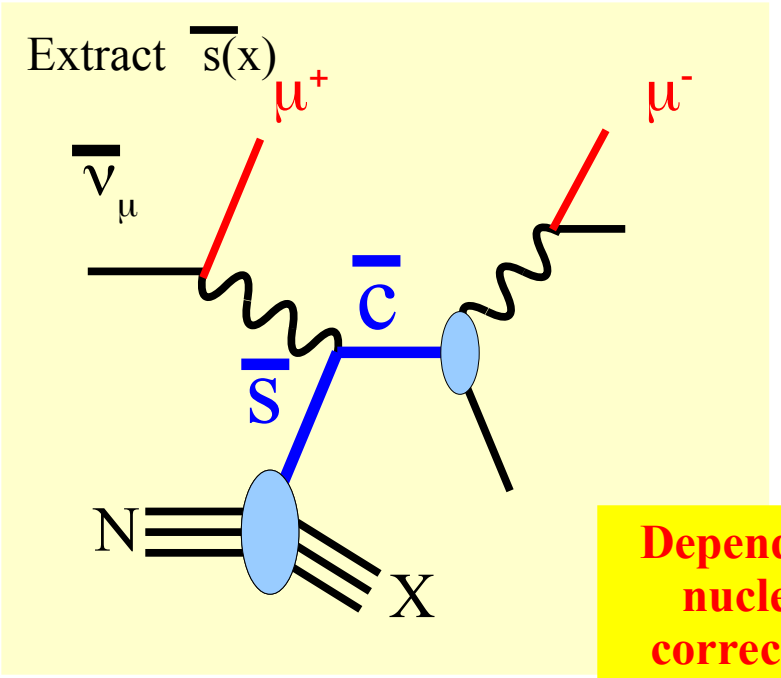
larger x — smaller x

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

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, Eur.Phys.J. C77 (2017) no.7, 488

Di-muon production ⇒ Extract s(x) Parton Distribution

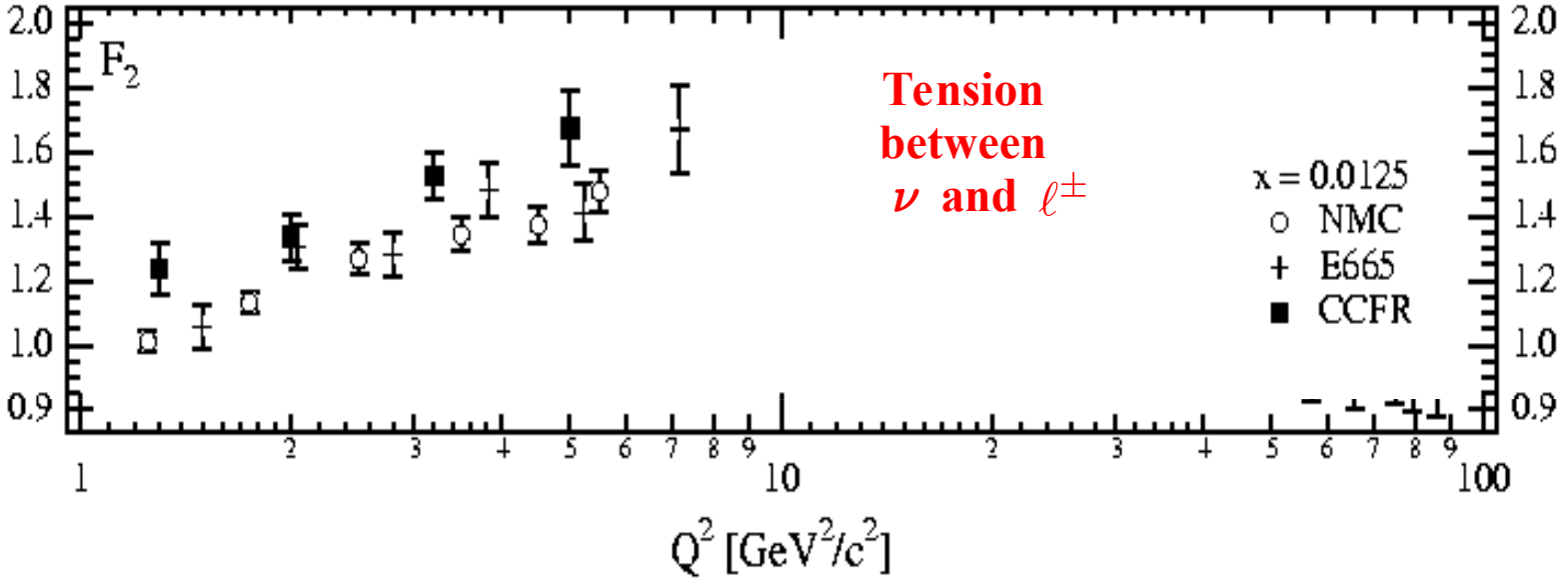




Depends on nuclear corrections

Can extract s(x) and $\bar{s}(x)$ separately

Used in CTEQ Fits



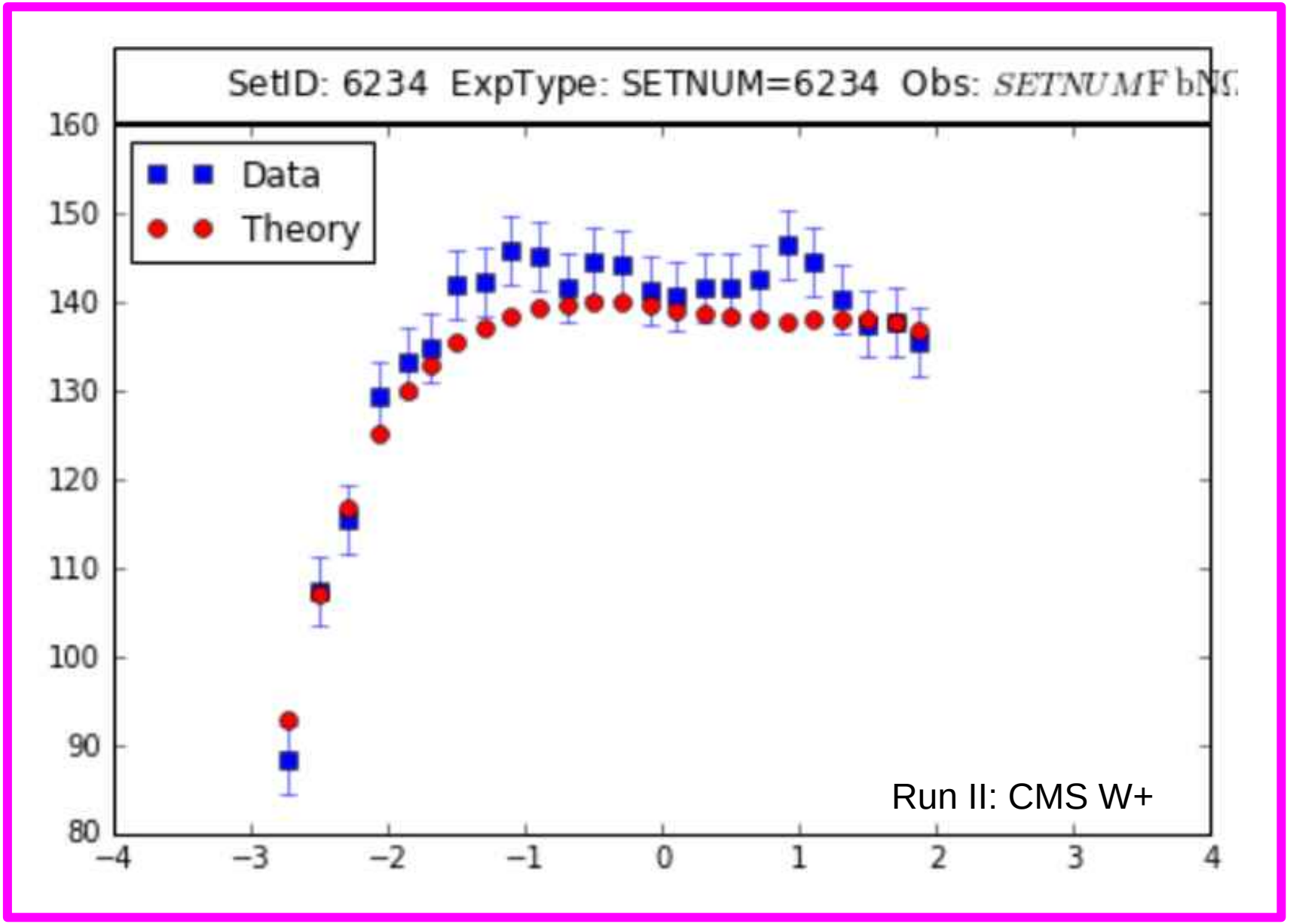
The CTEQ List of Challenges in Perturbative QCD

~1995

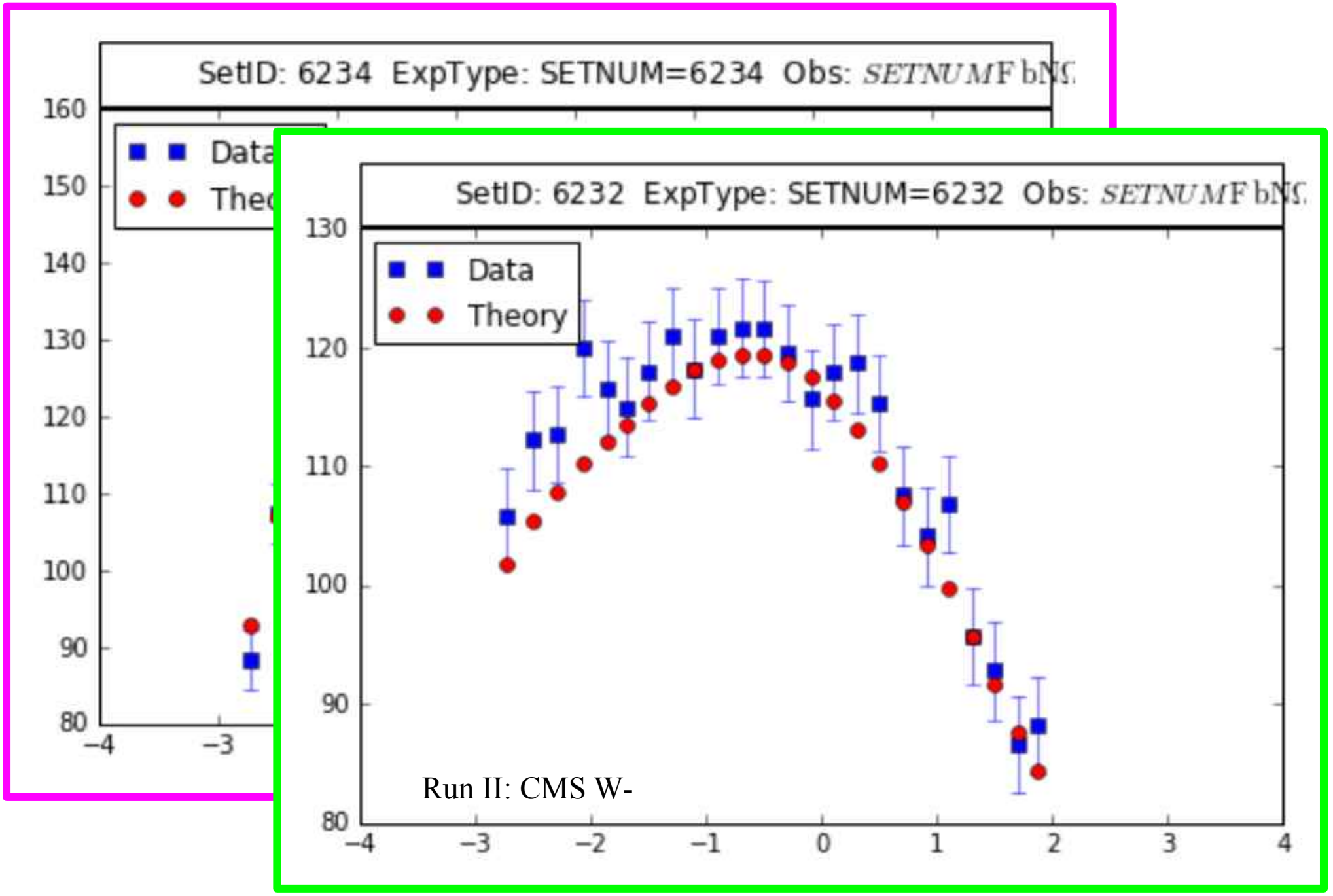
From Jeff Owens

C T E Q

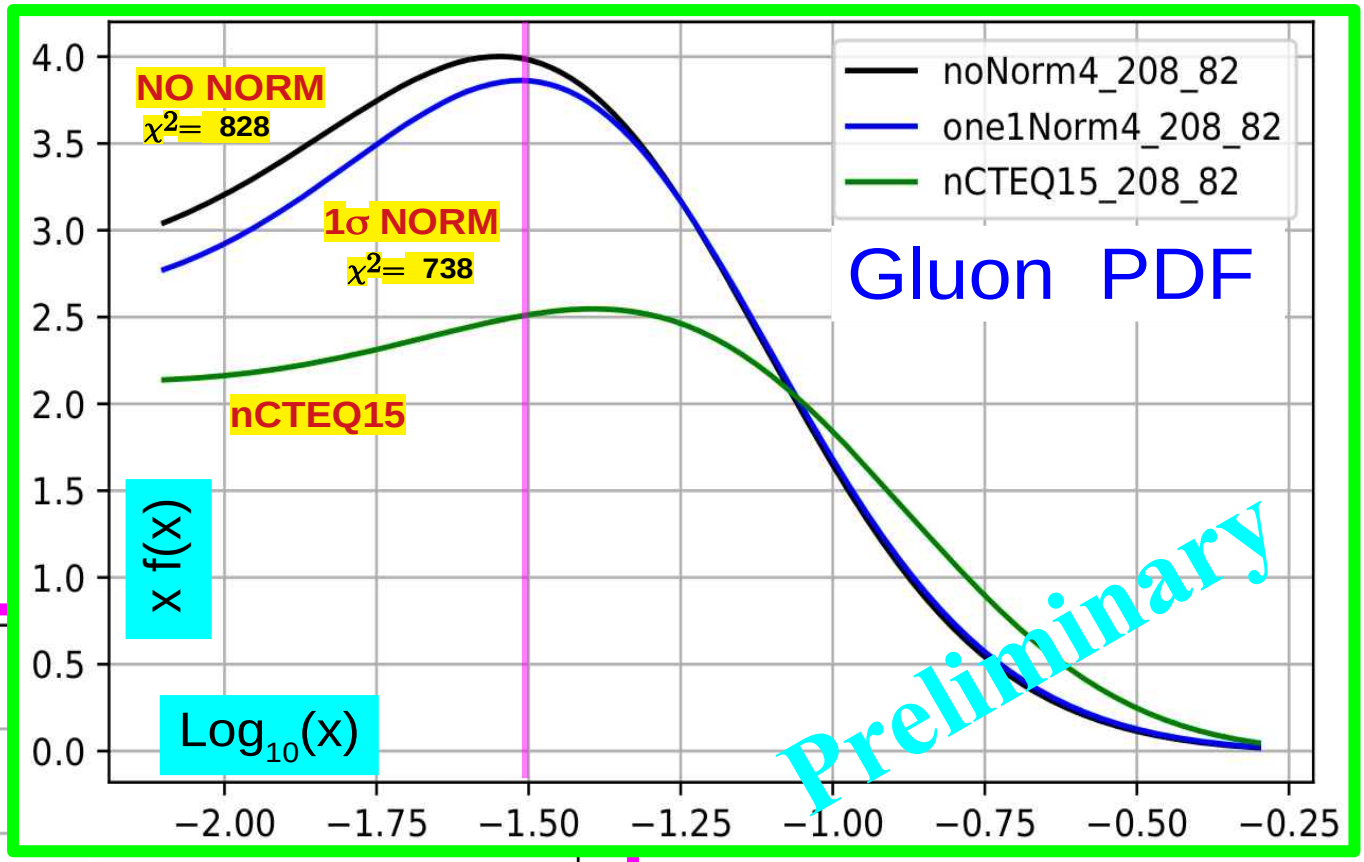
W/Z Data in fit: LHC p-Pb

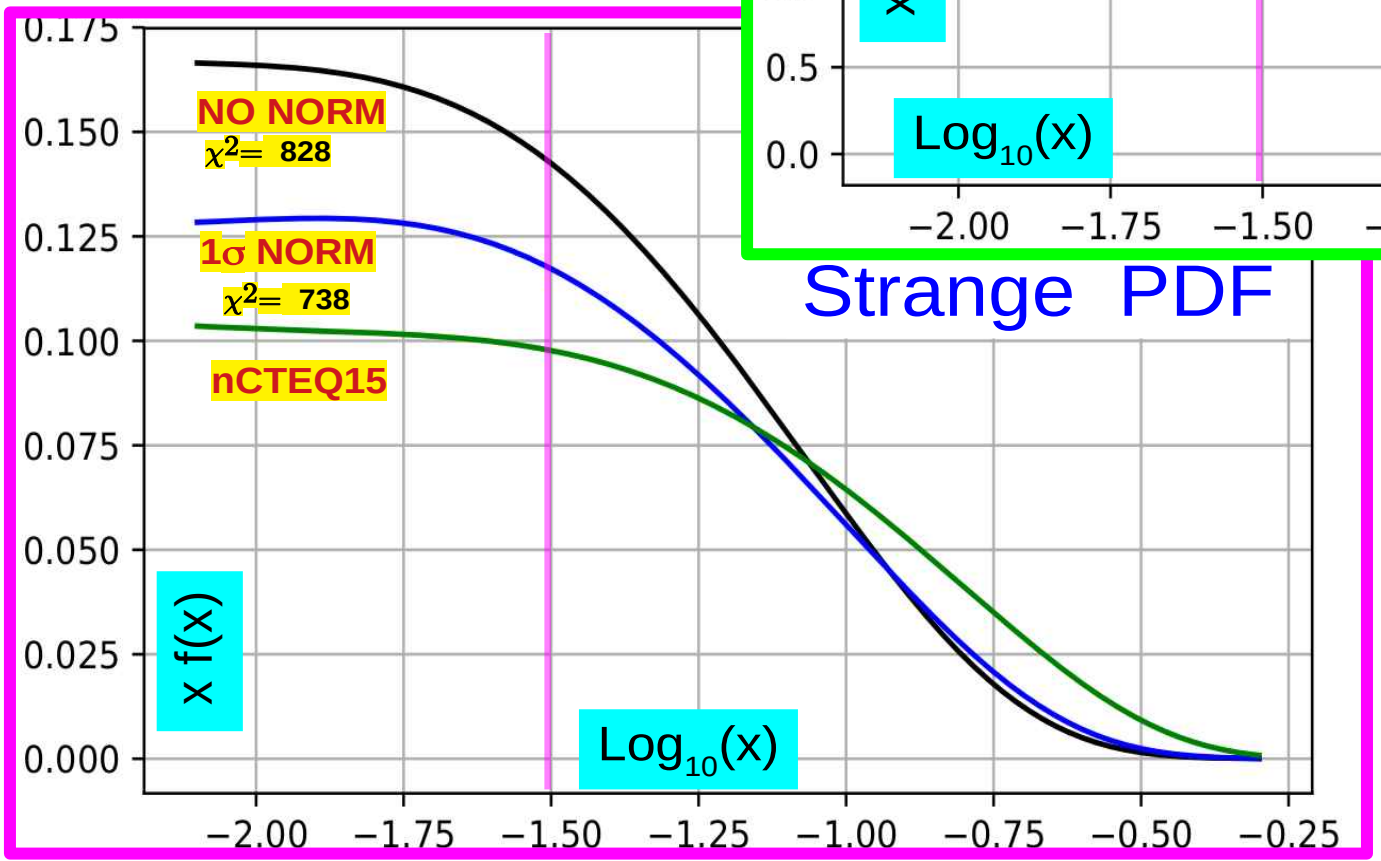


W/Z Data in fit: LHC p-Pb

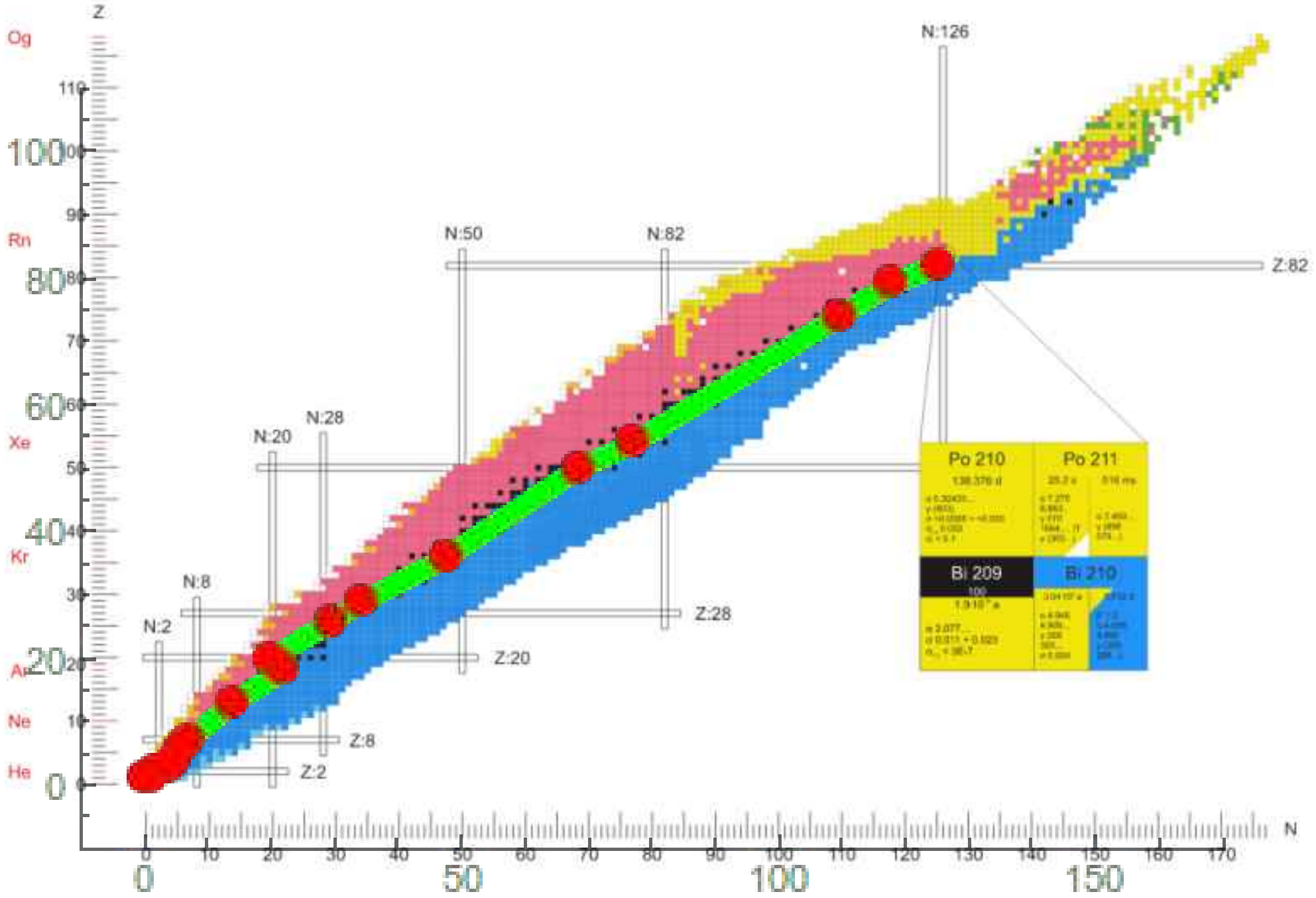


W/Z Data in fit: LHC p-Pb

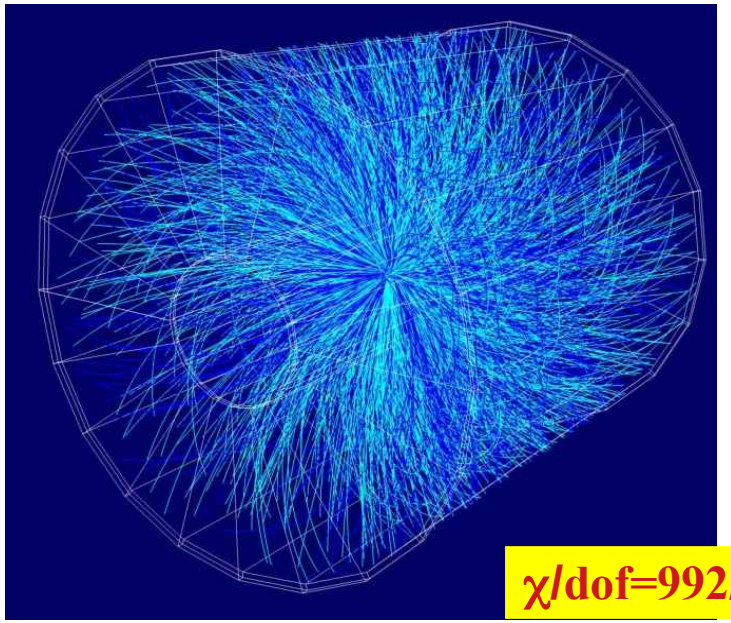




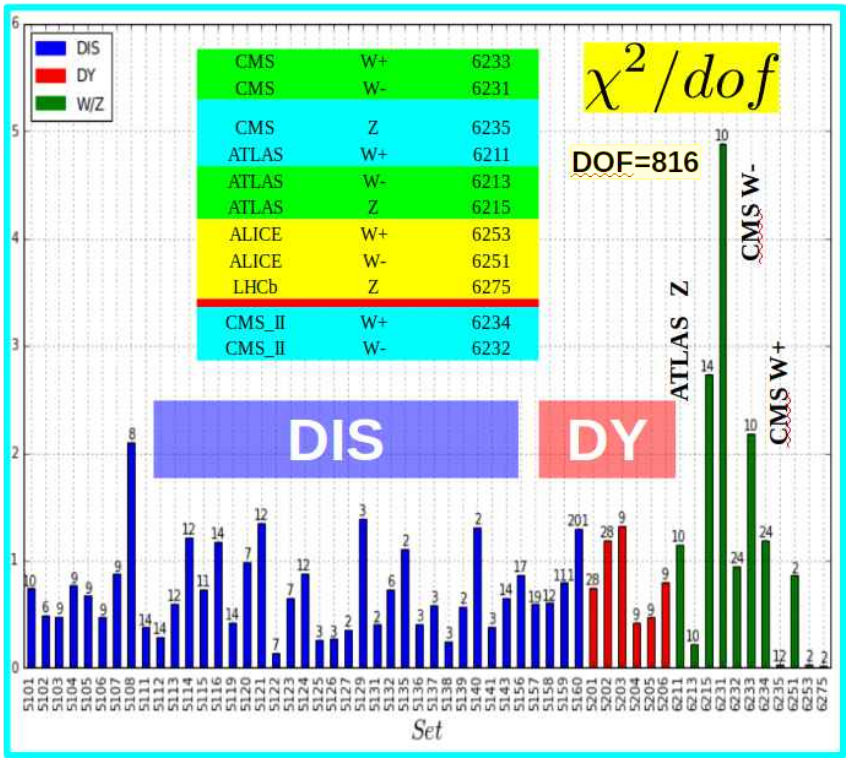
Combining these data sets can help clarify (and disentangle) both the strange PDF and the nuclear corrections


Z
Og
Rn
Xe
Kr
Ar
Ne
He
N
N:126
N:82
N:50
N:28
N:20
N:8
N:2
Z:82
Z:28
Z:20
Z:8
Z:2
Po 210
Po 211
Bi 209
Bi 210

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

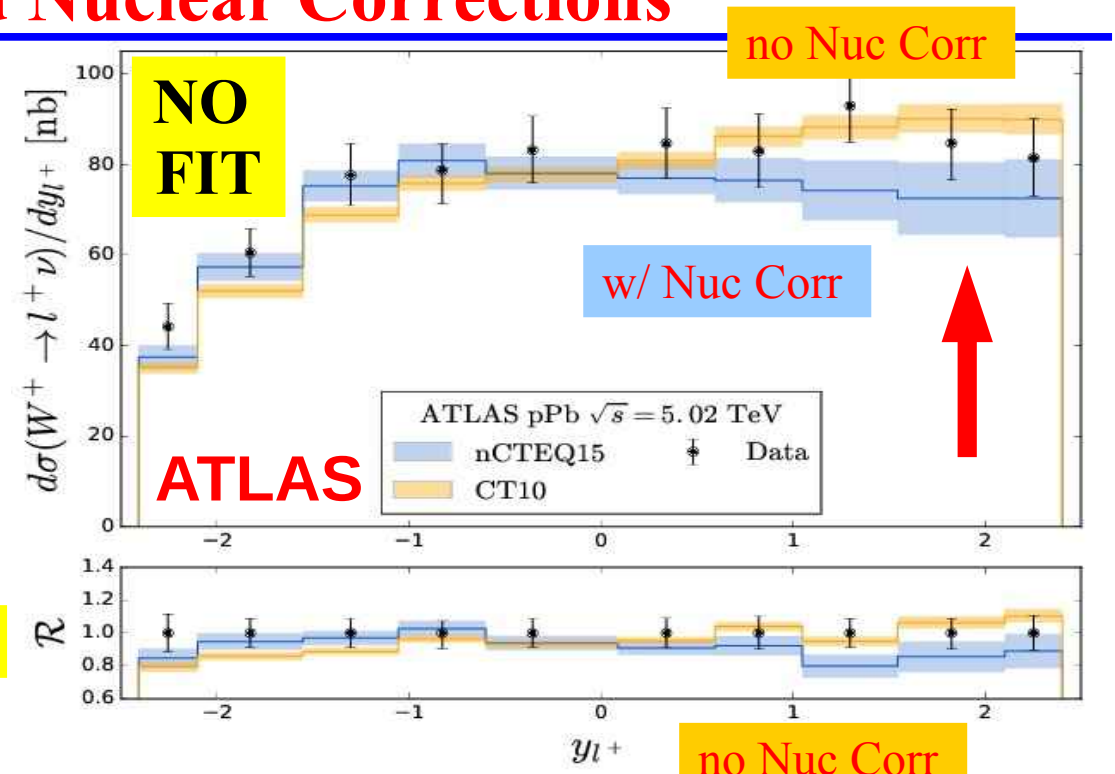


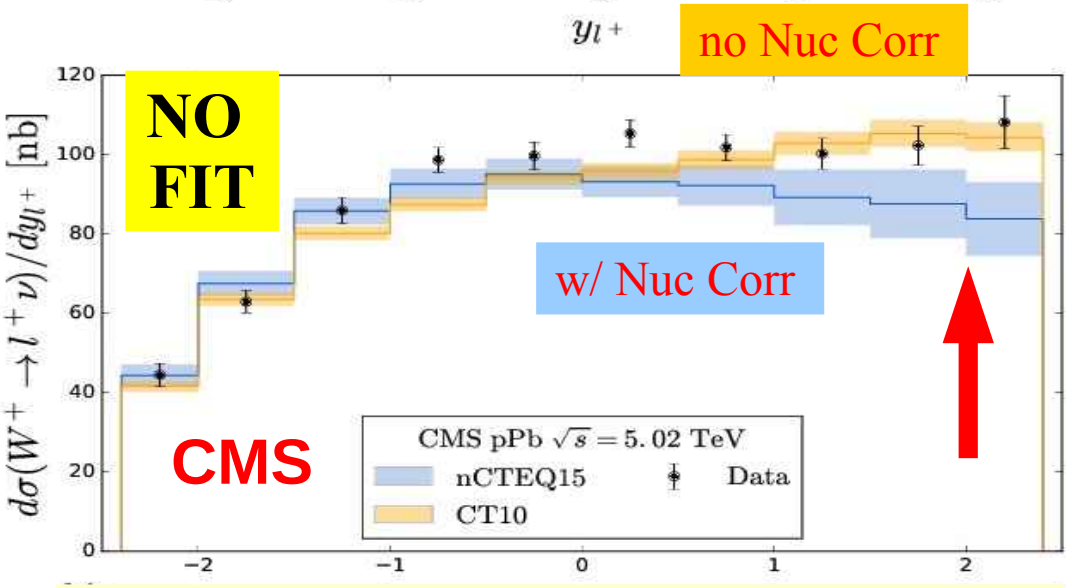
χ/dof=992/816



5 4 3 2 1

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





$\mathcal{R}$

lead kinematics

larger x — smaller x