PDF Flavor Determination

...

Fred Olness
SMU

Thanks to 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

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

and also
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Huey-Wen Lin, Kostas Orginos, Juan Rojo, J. Thomas

nCTEQ
nuclear parton distribution functions

The Flavor Structure of Nucleon Sea
INT Workshop October 2-13, 2017

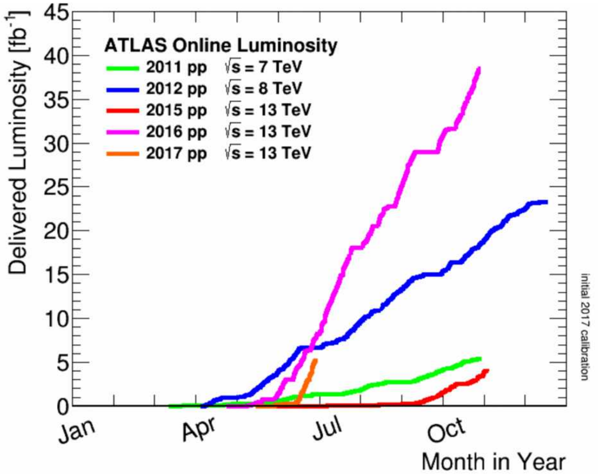
The Key to Understanding: The Parton Model and Factorization

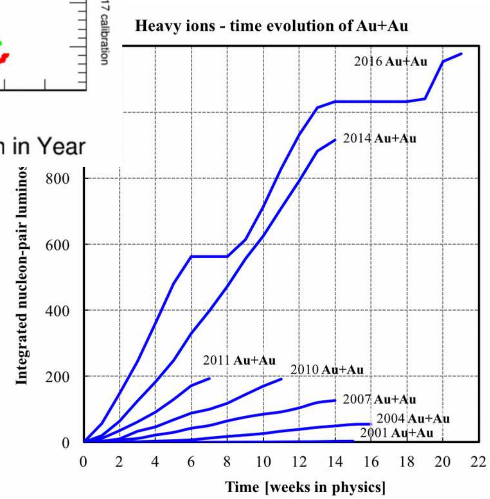
$$\sigma_{N\gamma\to c} = f_{N\to a} \otimes \hat{\sigma}_{a\gamma\to c}$$

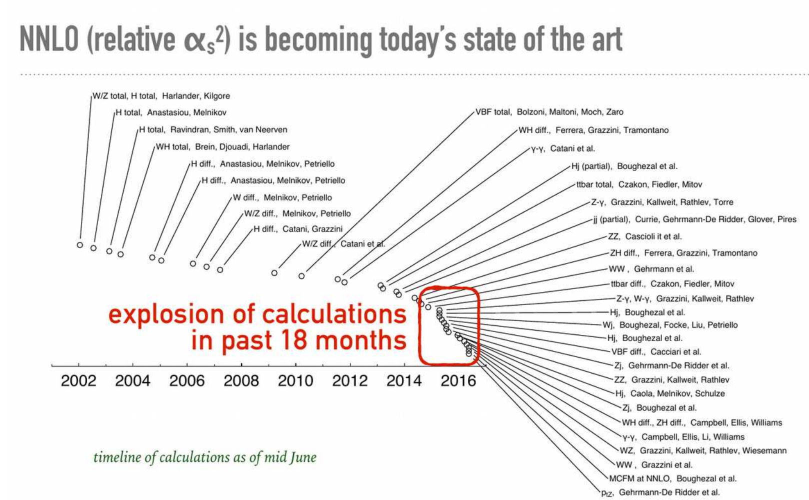
Experimental Observables

WHAT ABOUT PDF'S ???

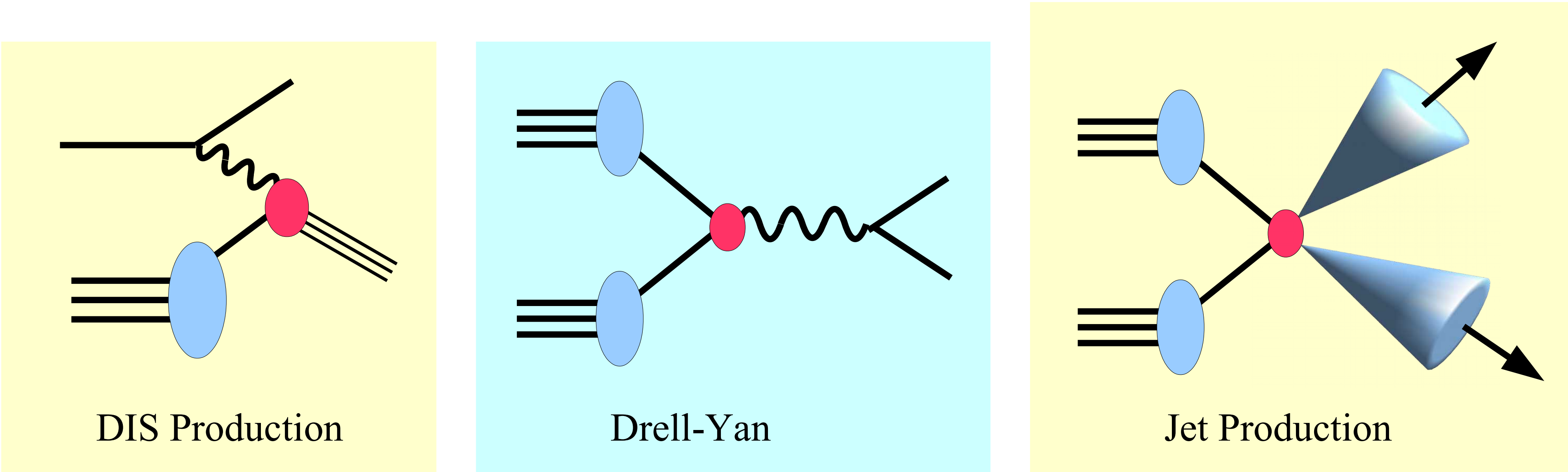
Theoretical Calculations







Key Data Sets for Global PDF Fits



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

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

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

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

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

In particular, the DIS combinations have historically been particularly useful

Different linear combinations – key for flavor differentiation

The ν-DIS data typically use heavy targets, and this requires the application of ***nuclear corrections***

Precise knowledge of the PDFs are essential for predictions

QCD factorization:

$$\sigma = \hat{\sigma} \otimes PDF$$

"PDF uncertainties are among the leading uncertainties in the first LHC precision measurements by CMS" *Jan Kretzschmar*

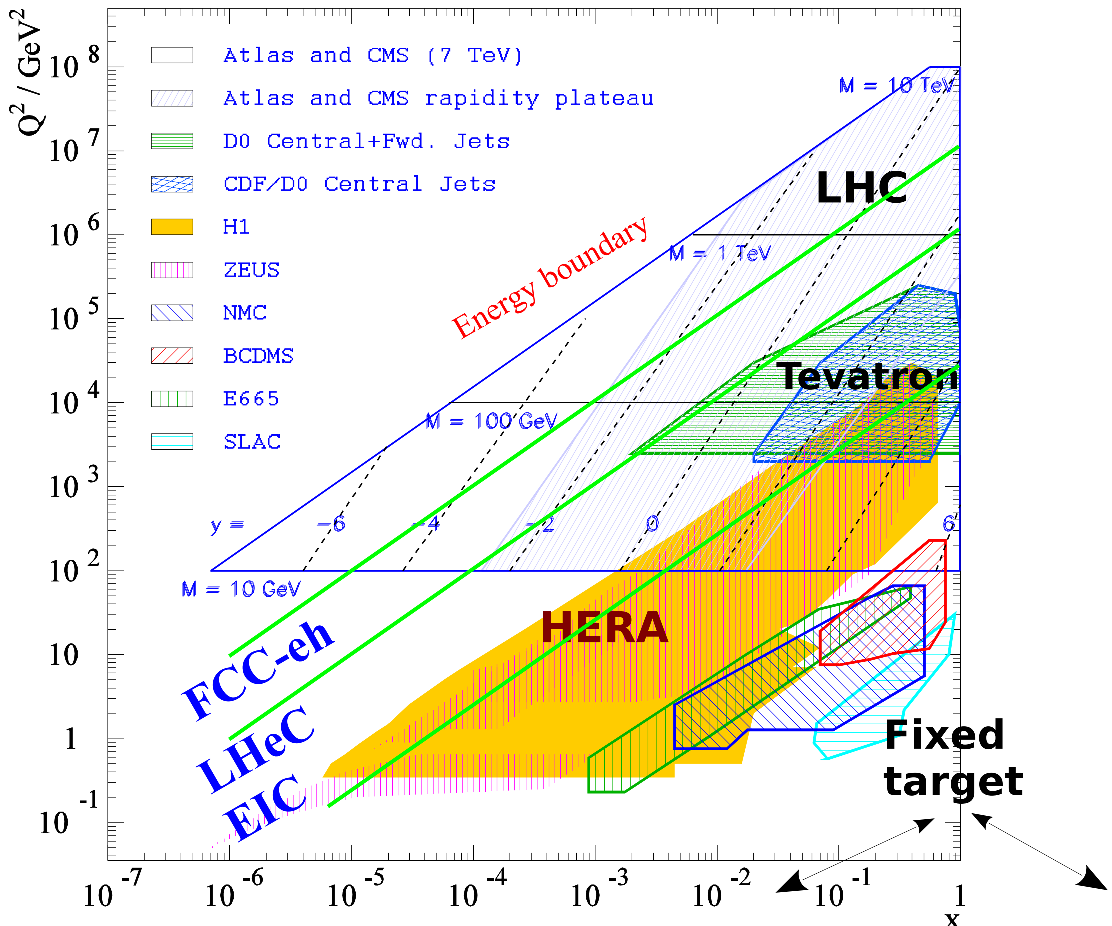
Experimental Data:

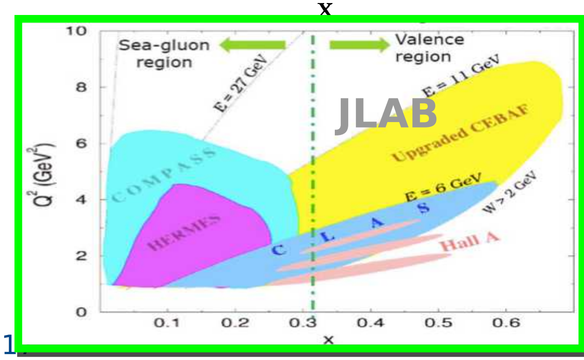
→ **requires** a large variety of data from fixed-target and collider experiments

Theory:

→ intense theoretical developments

kinematic plane of the experimental data (in x,Q^2)





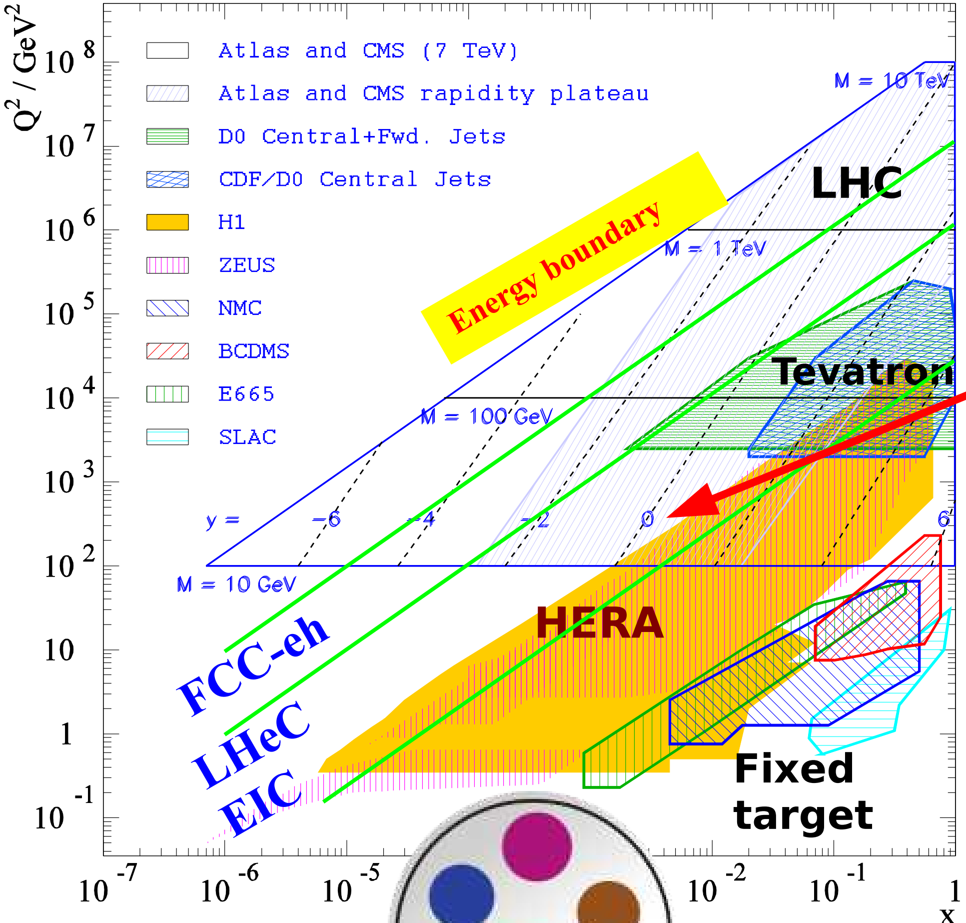
Tevatron + HERA
essential complementary components

LHC alone cannot maximize PDF precision

nuclear dimension essential!!!

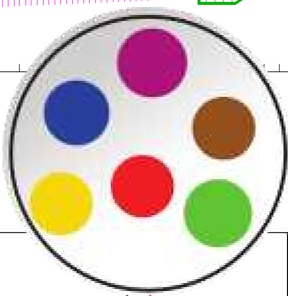
Precision!!!

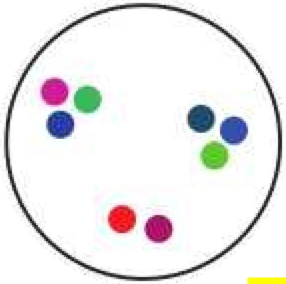
Frontier: Precison, Hi-x, Low-x, Low-Q



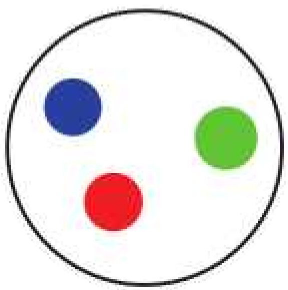
Precision

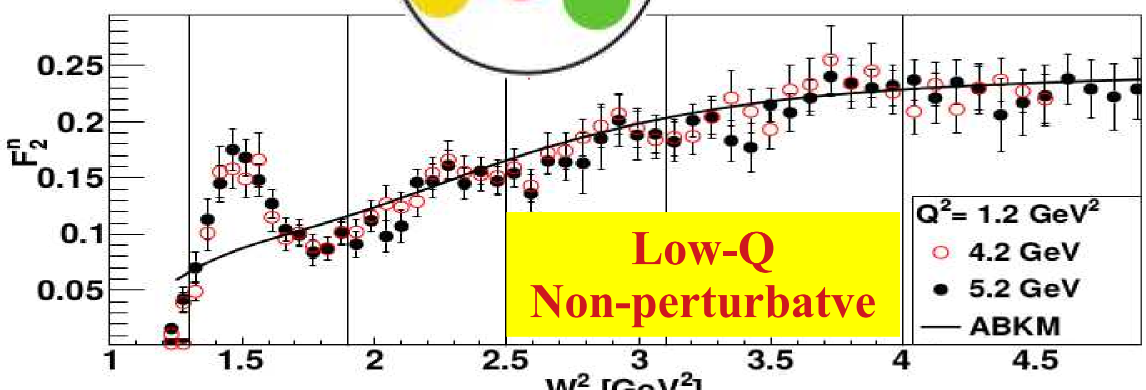
Low-x
Shadowing
Recombination
Resummation





Hi-x
Higher Twist



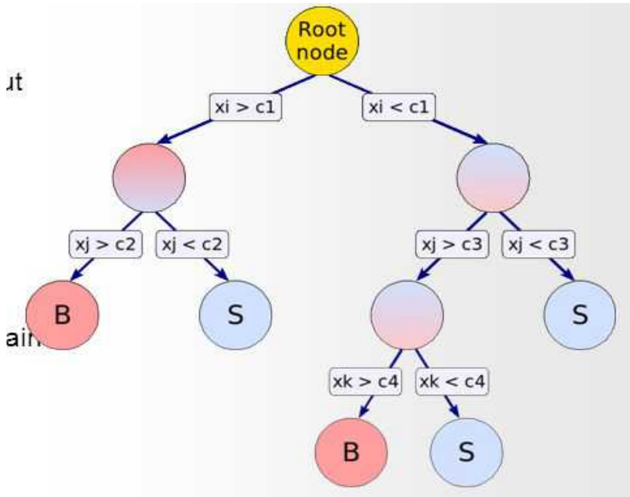


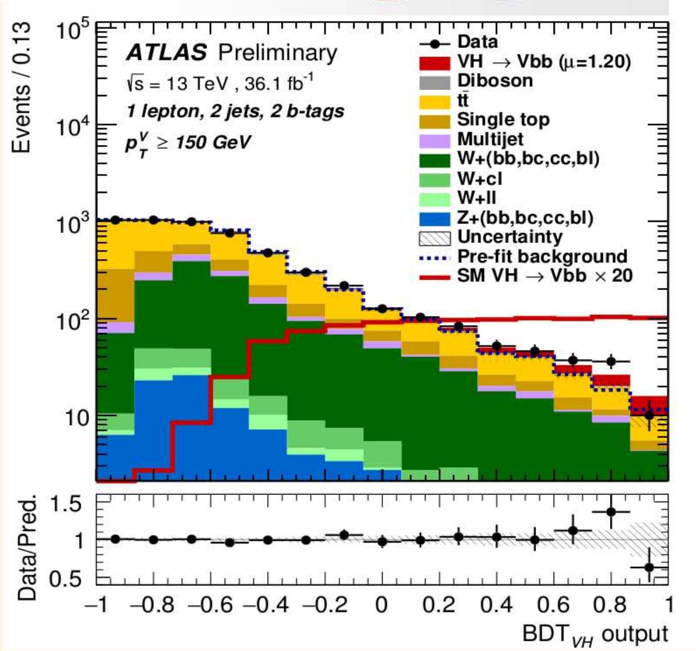
Low-Q
Non-perturbatve

INNOVATIVE IDEAS

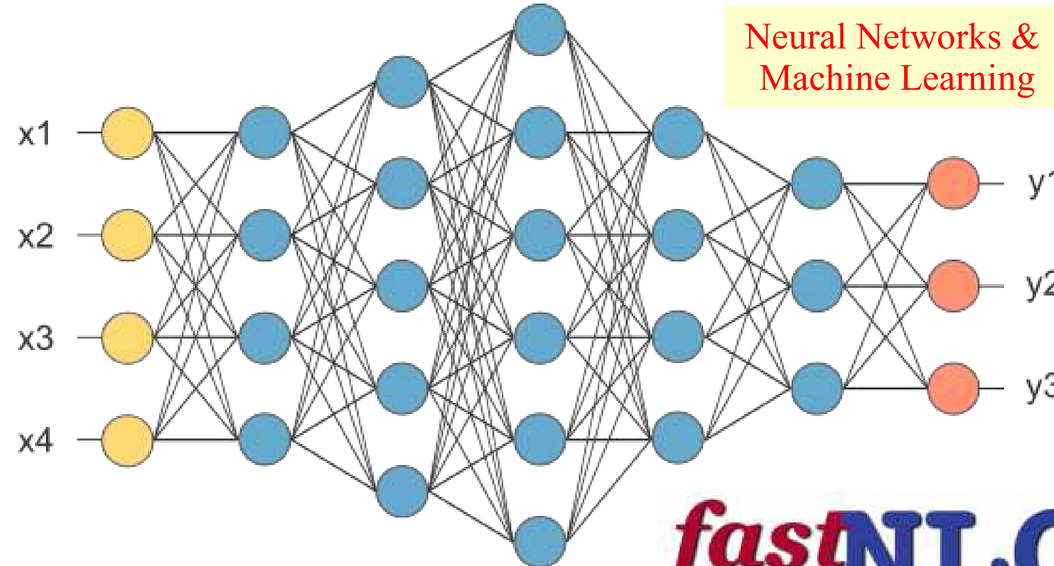
Innovative Ideas

Boosted Decision Trees (BDT)





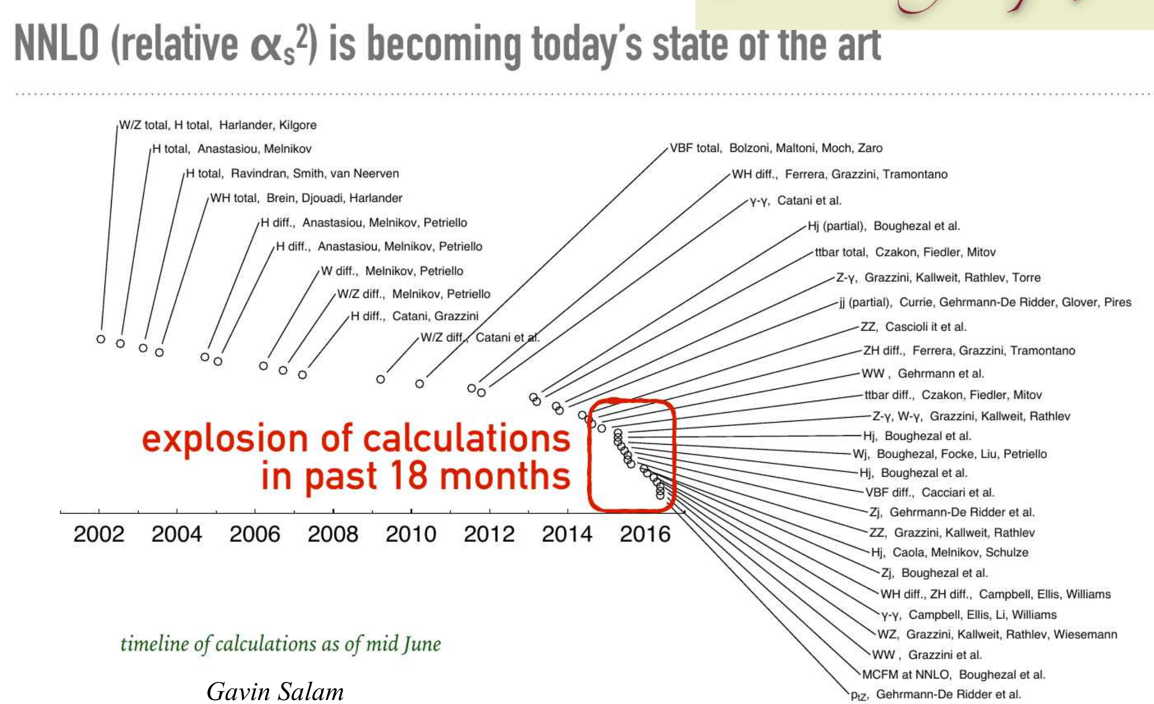
Neural Networks & Machine Learning



fastNLO

… variety of new techniques

the APPLgrid project



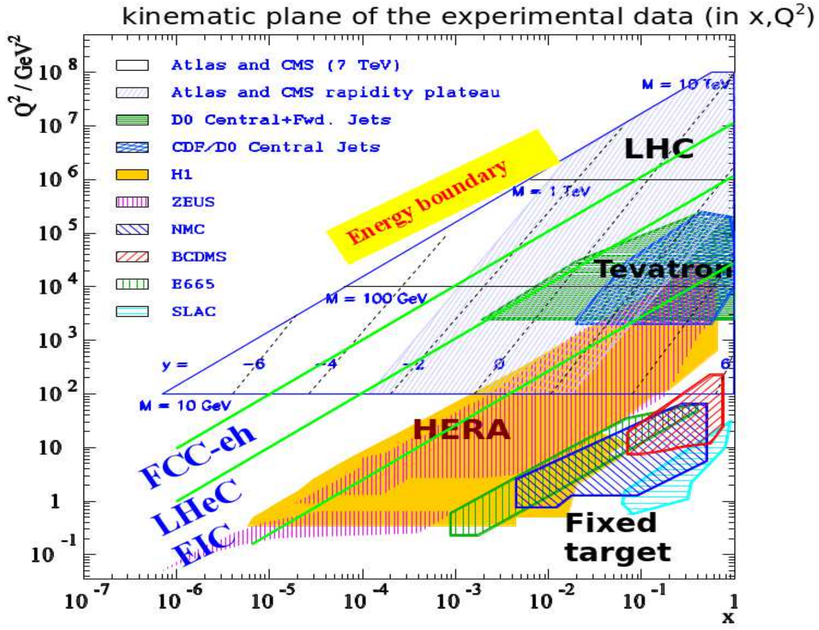
Gavin Salam

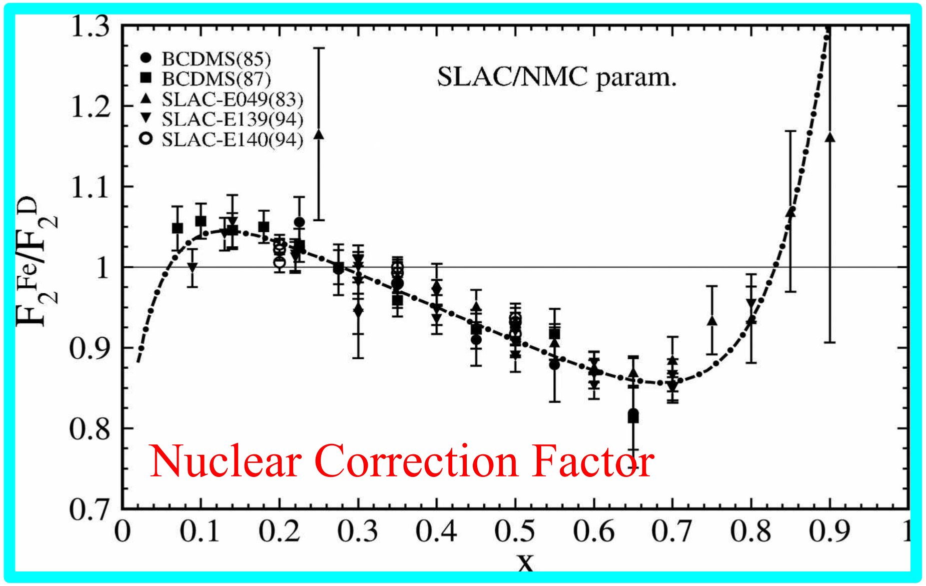
input from Lattice QCD

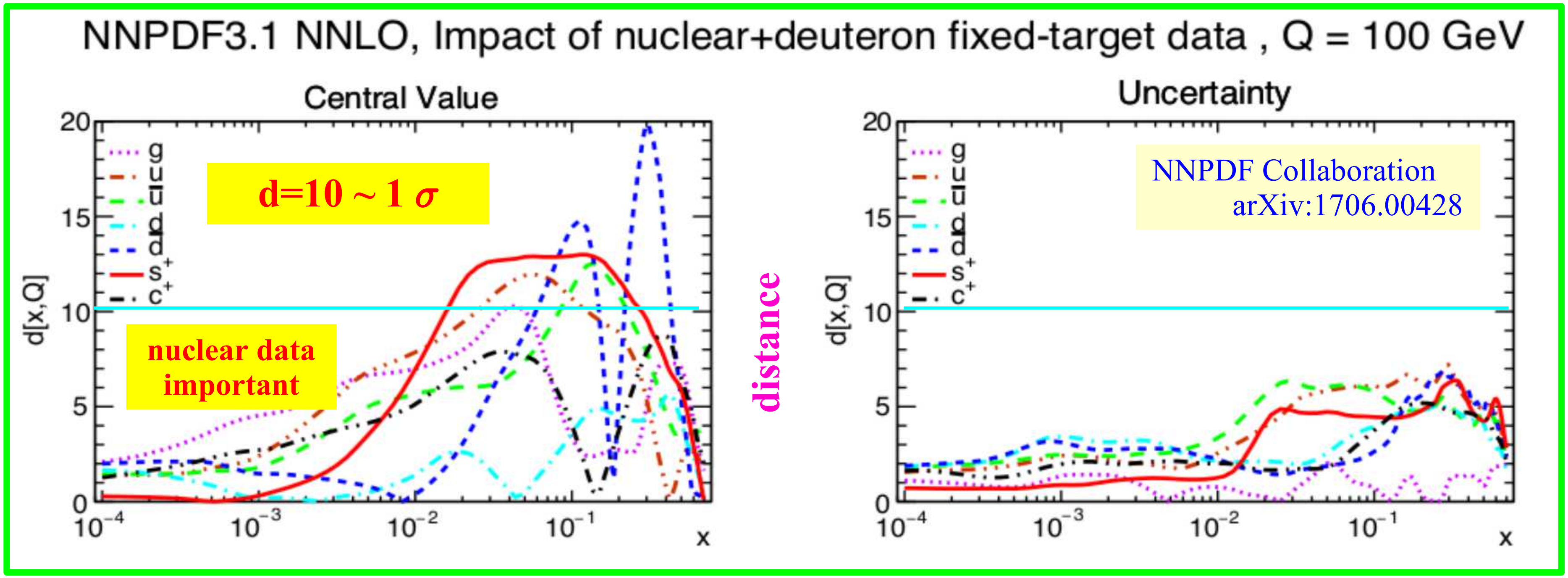
Cf. talk by Huey-Wen Lin

Why the nuclei are important

Impact of Nuclear Corrections on Proton PDF

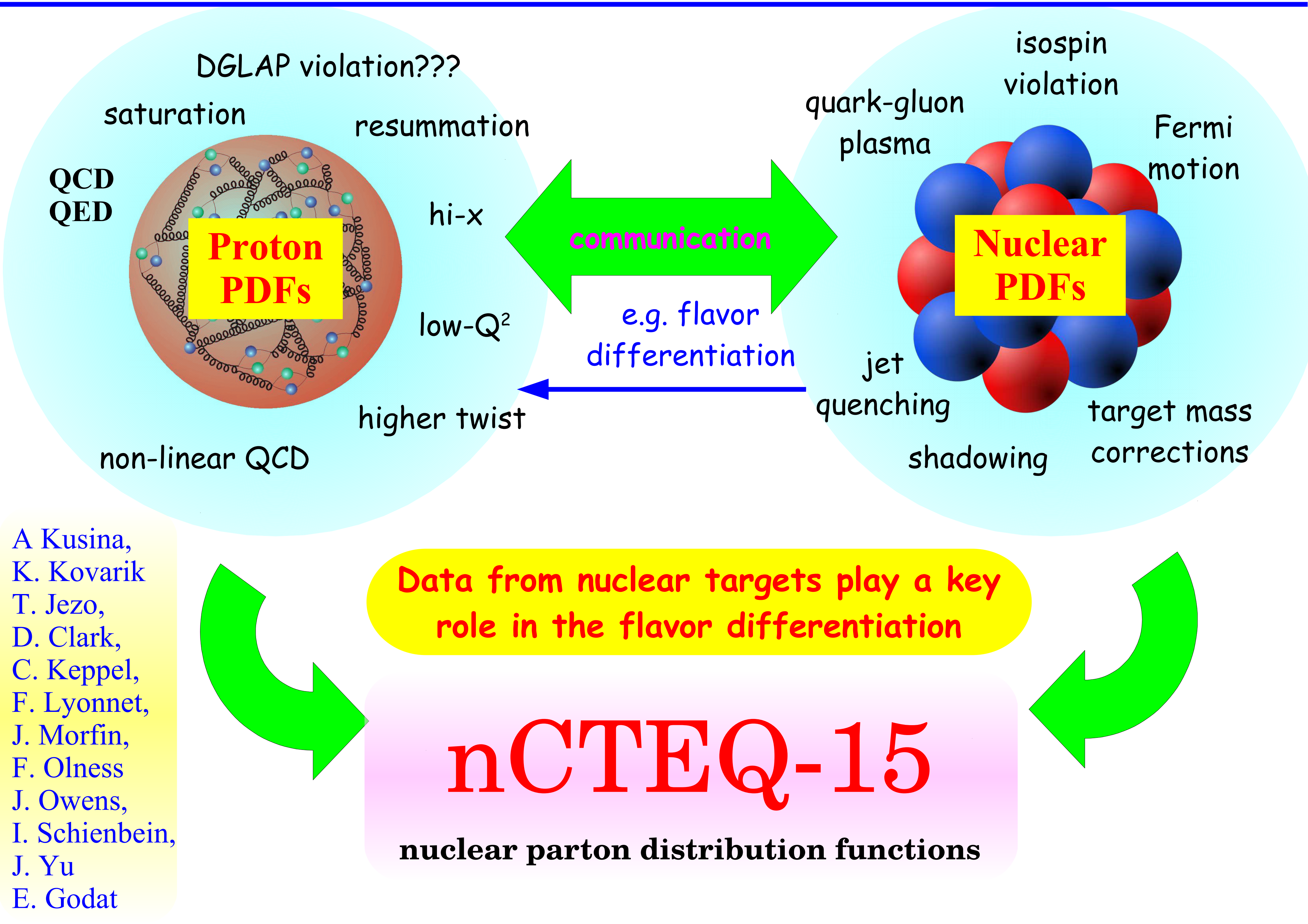






"... for the time being it is still appears advantageous to retain nuclear target data in the global dataset for general-purpose PDF determination"

… the motivation for nCTEQ



Nuclear PDF

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*

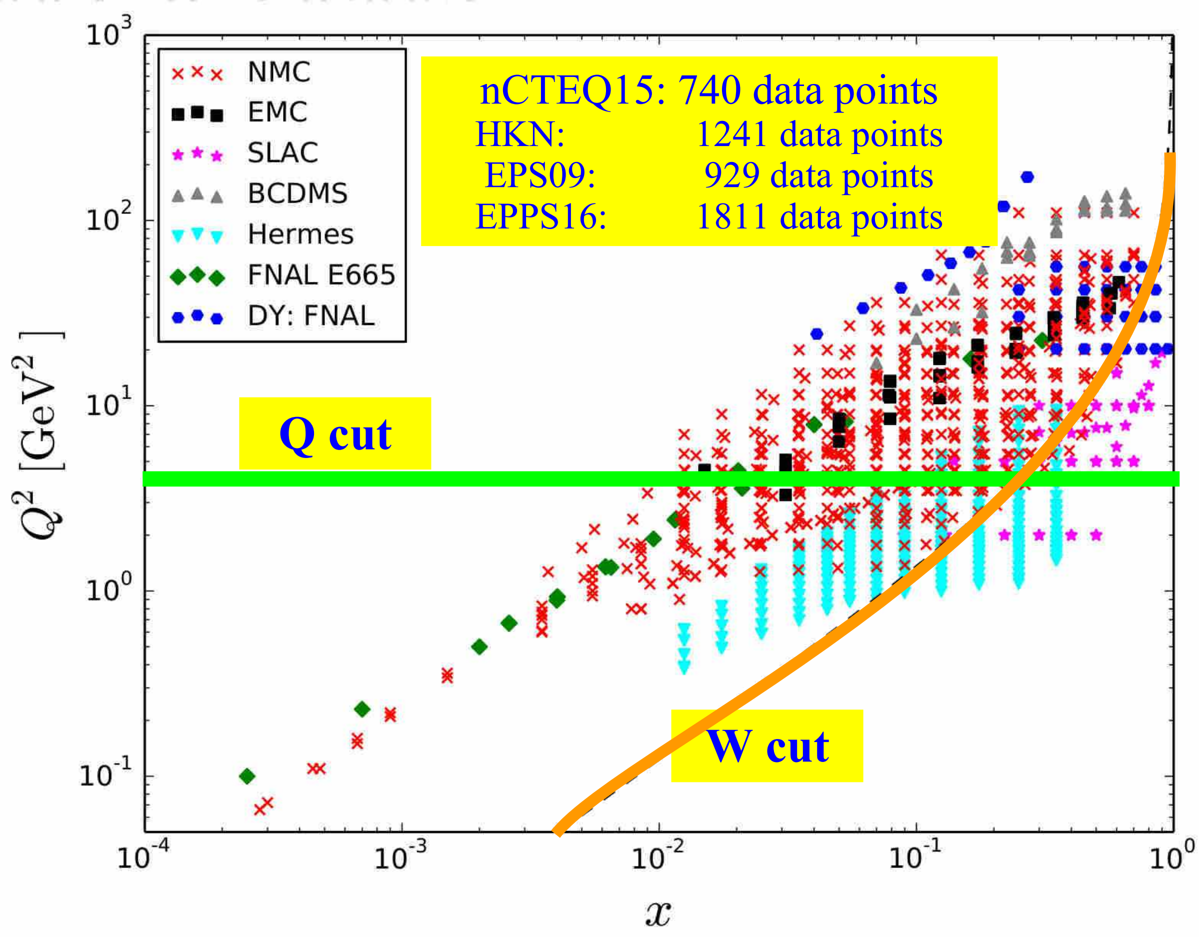
NuTeV CHORUS CCFR & NuTeV
N = Pb & Fe

Pion Production:

RHIC: PHENIX & STAR
N = Au

will show comparision w/ LHC pPb

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



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

Mechanics of nPDFs

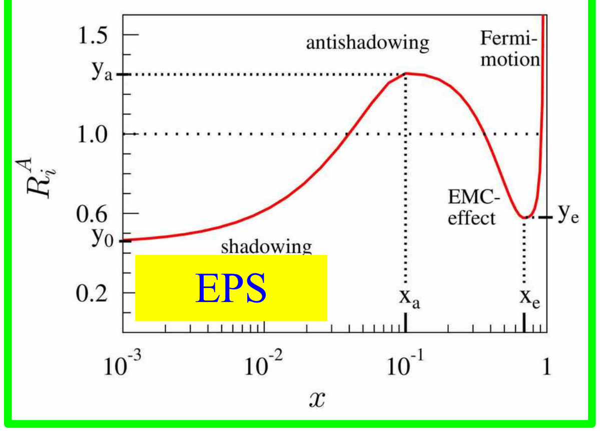
1) Multiplicative nuclear correction factors (HKN, EPPS, DSSZ)

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

... for example

HKN

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



Cf. talks by:
Shunzo Kumano
Rodolfo Sassot

2) Generalized A-parameterization (nCTEQ)

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

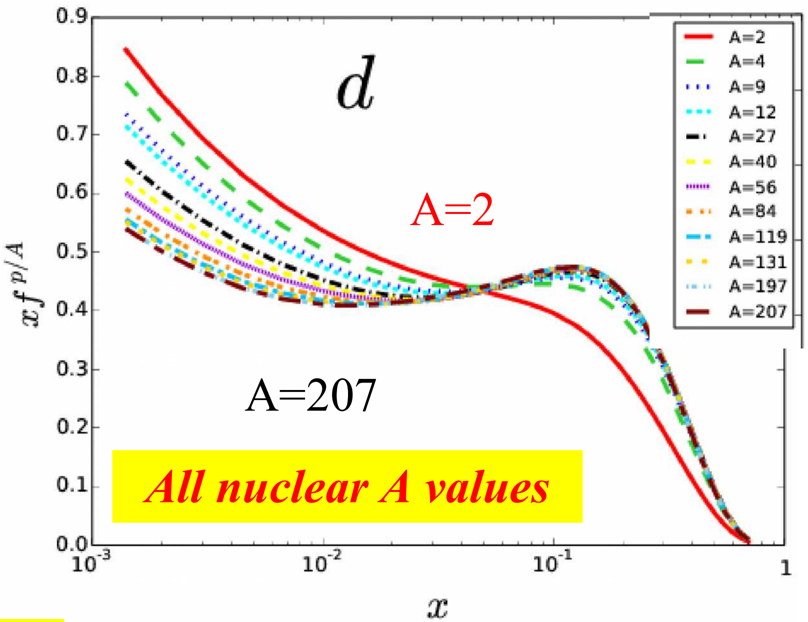
$$f \sim \ldots x^{c_1(A)}(1-x)^{c_2(A)} \ldots$$

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

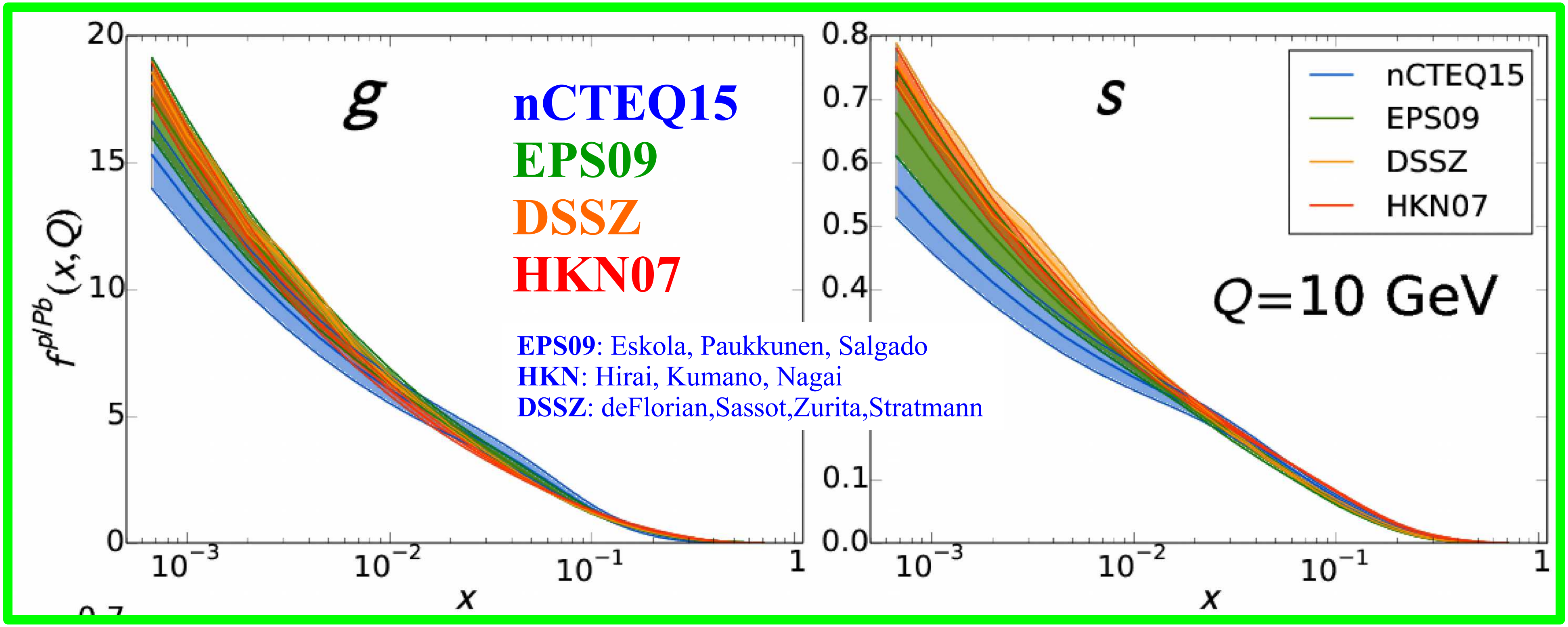
Proton

Nuclear

use proton as a Boundary Condition



Nuclear PDFs: Complementary efforts in general agreement

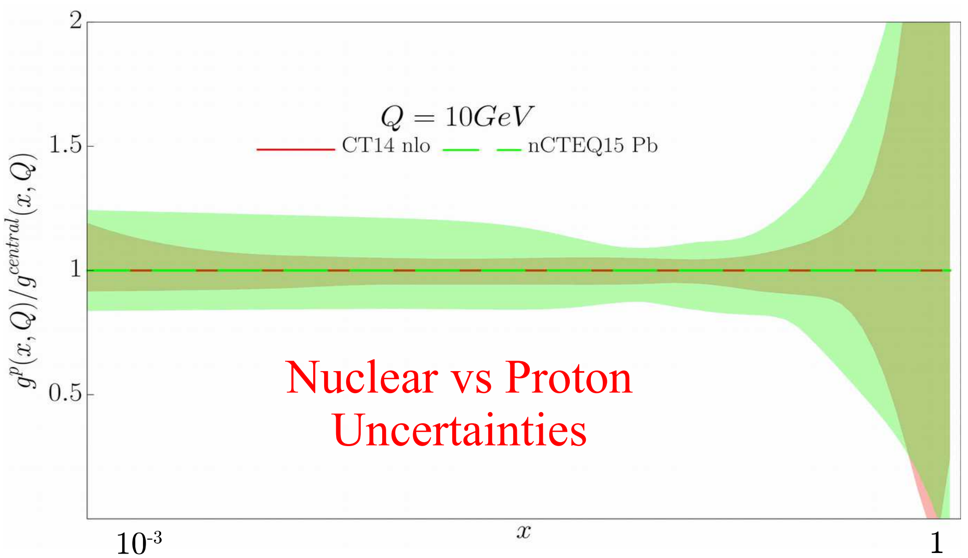


Nuclear PDFs are more complex

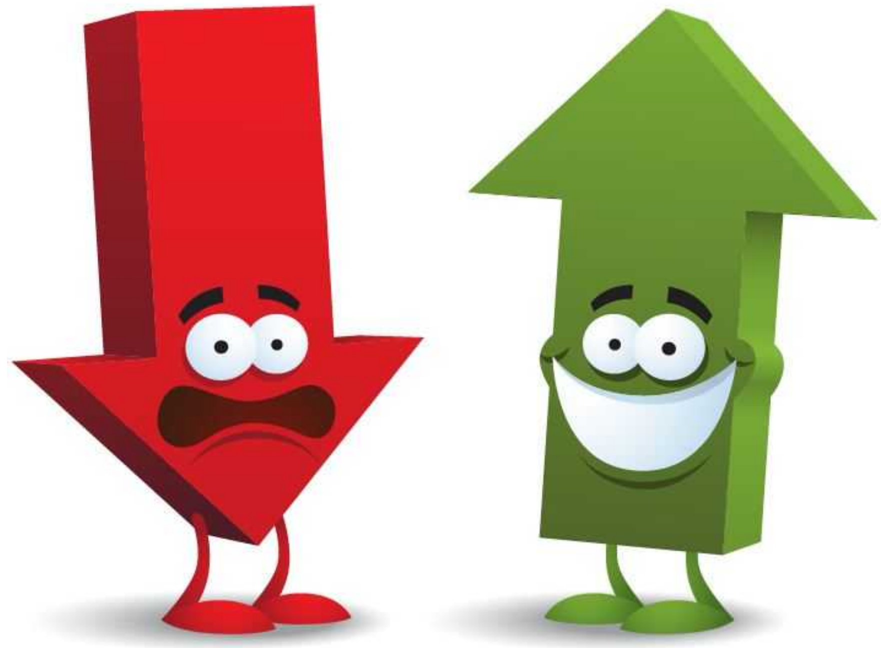
more DOF than Proton case

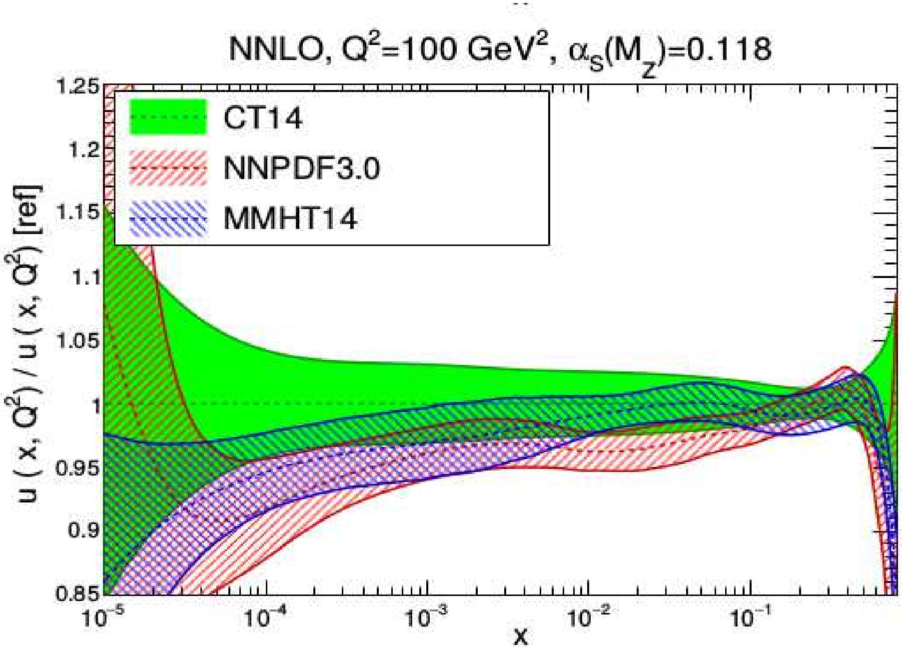
more "issues" to consider

more work to do ...

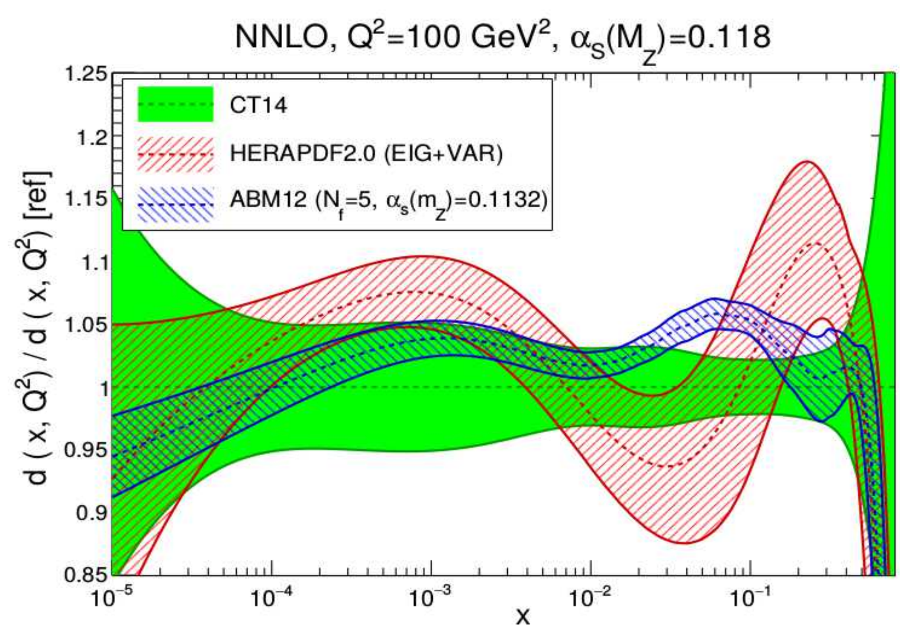


Down & Up



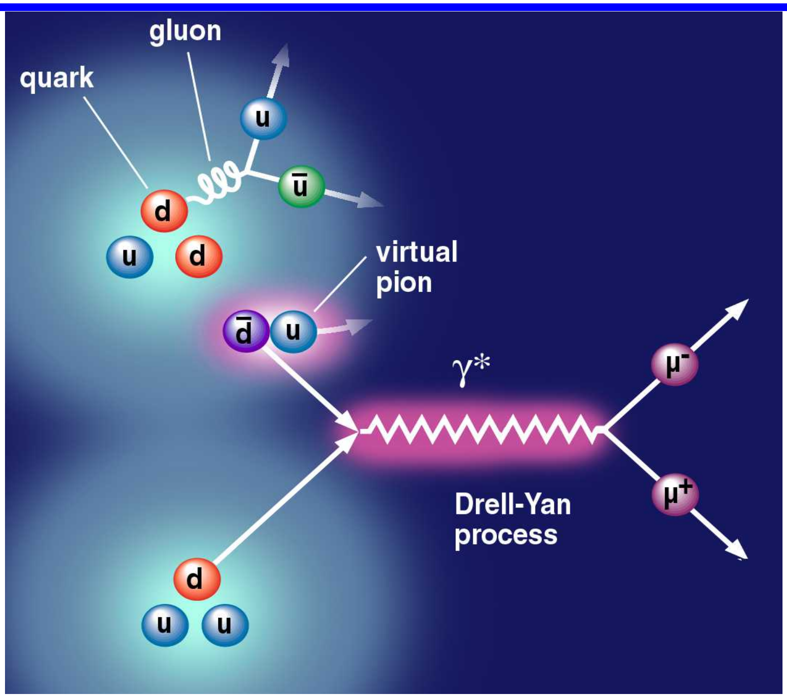


NNLO, Q²=100 GeV², αS(MZ)=0.118
CT14
NNPDF3.0
MMHT14
u (x, Q²) / u (x, Q²) [ref]
x



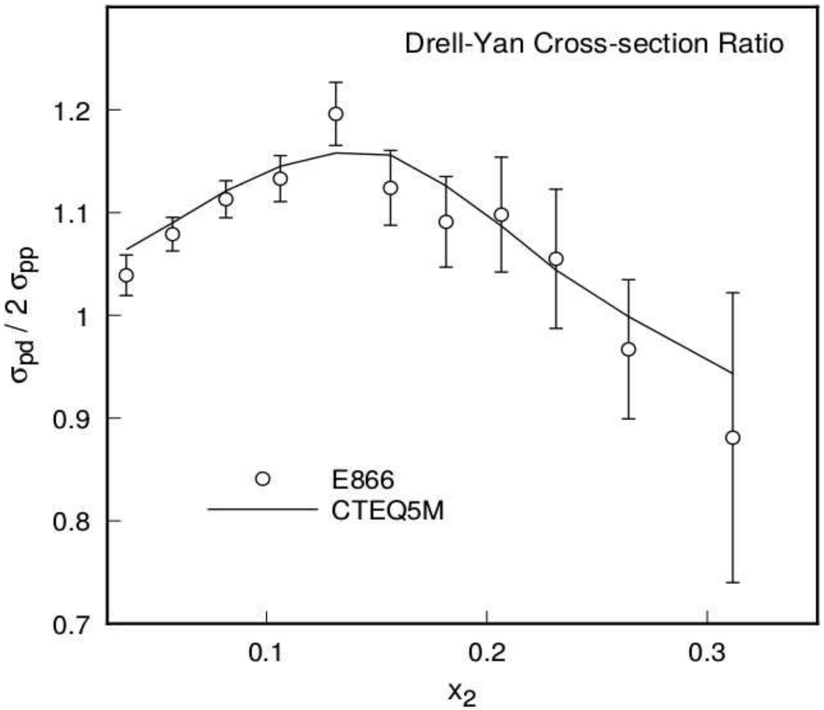
NNLO, Q²=100 GeV², αS(MZ)=0.118
CT14
HERAPDF2.0 (EIG+VAR)
ABM12 (Nf=5, αs(mZ)=0.1132)
d (x, Q²) / d (x, Q²) [ref]
x

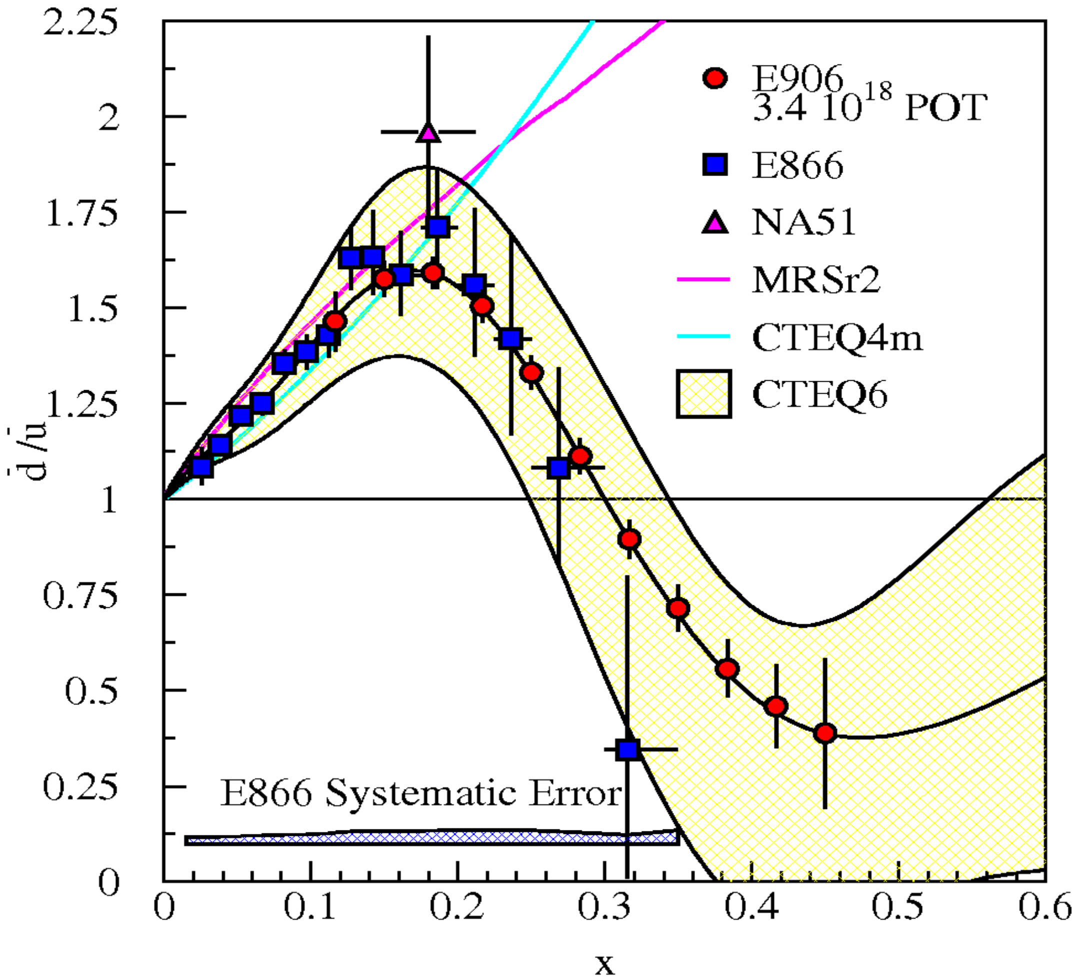
d-bar/u-bar Ratio: A Longstanding Puzzle



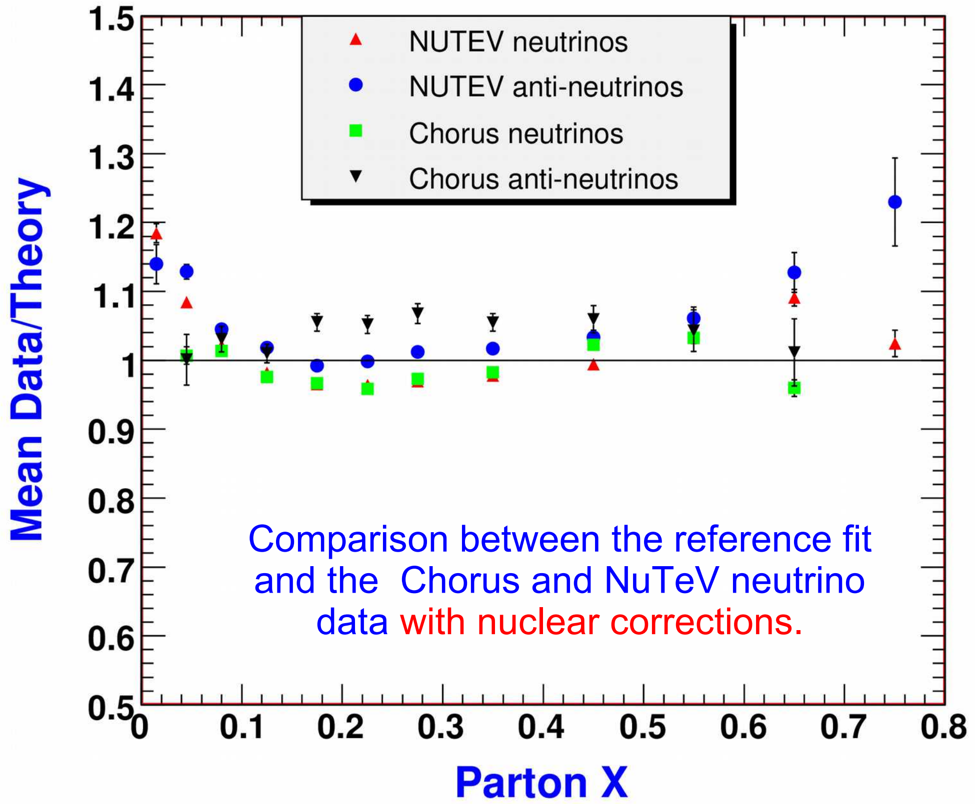
Fermilab E866/NuSea
E906 SeaQuest

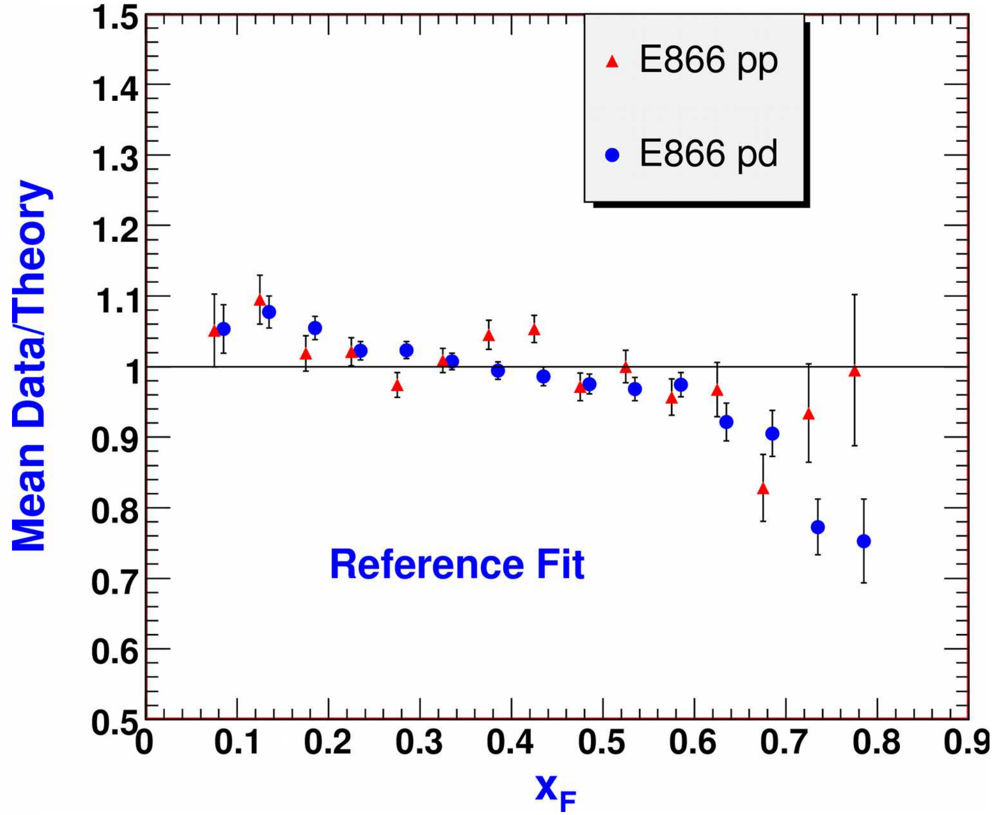
800 GeV $p+p$ and $p+d \to \mu^+\mu^- X$





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





"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.

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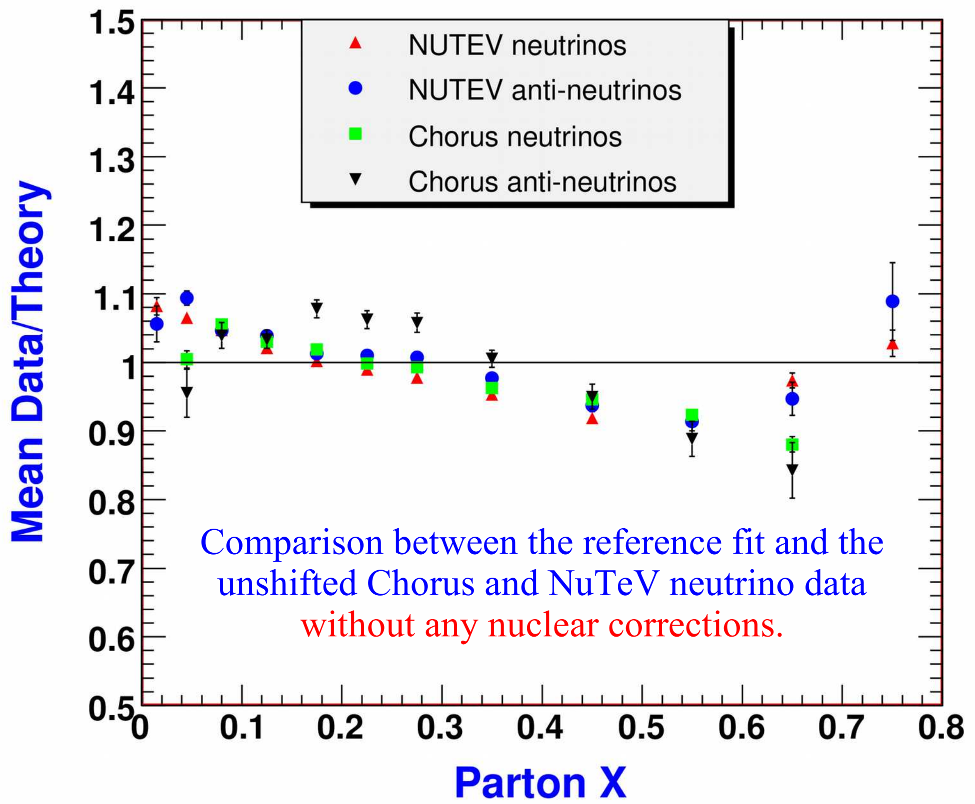

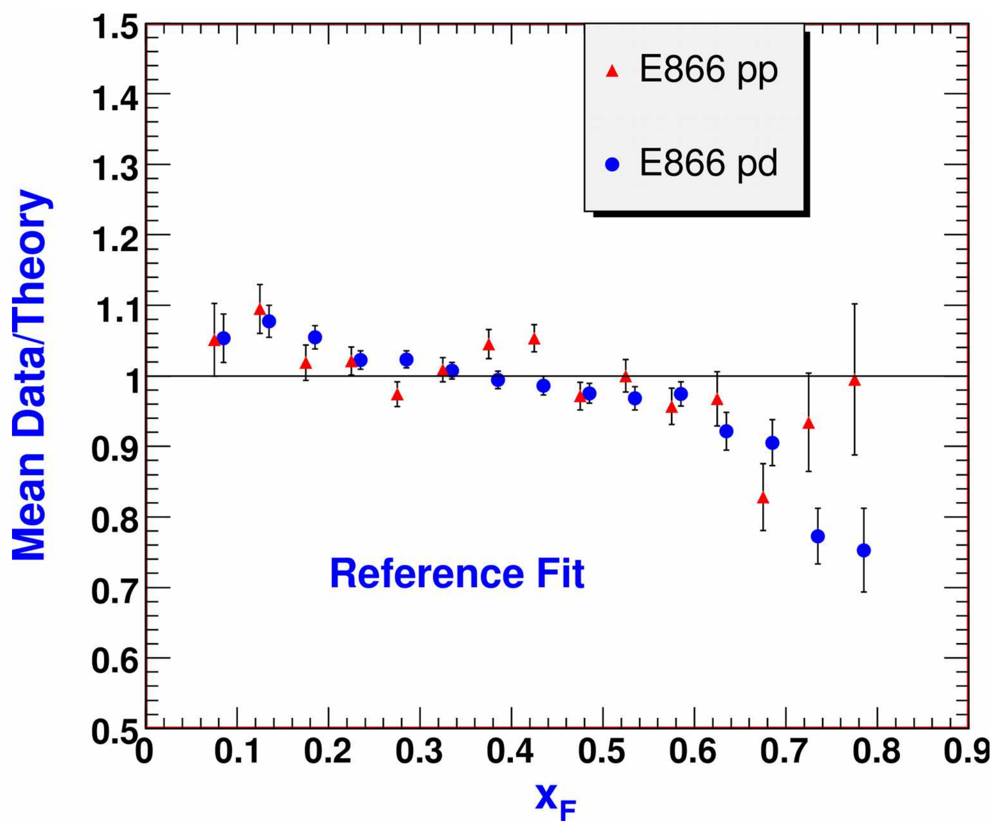

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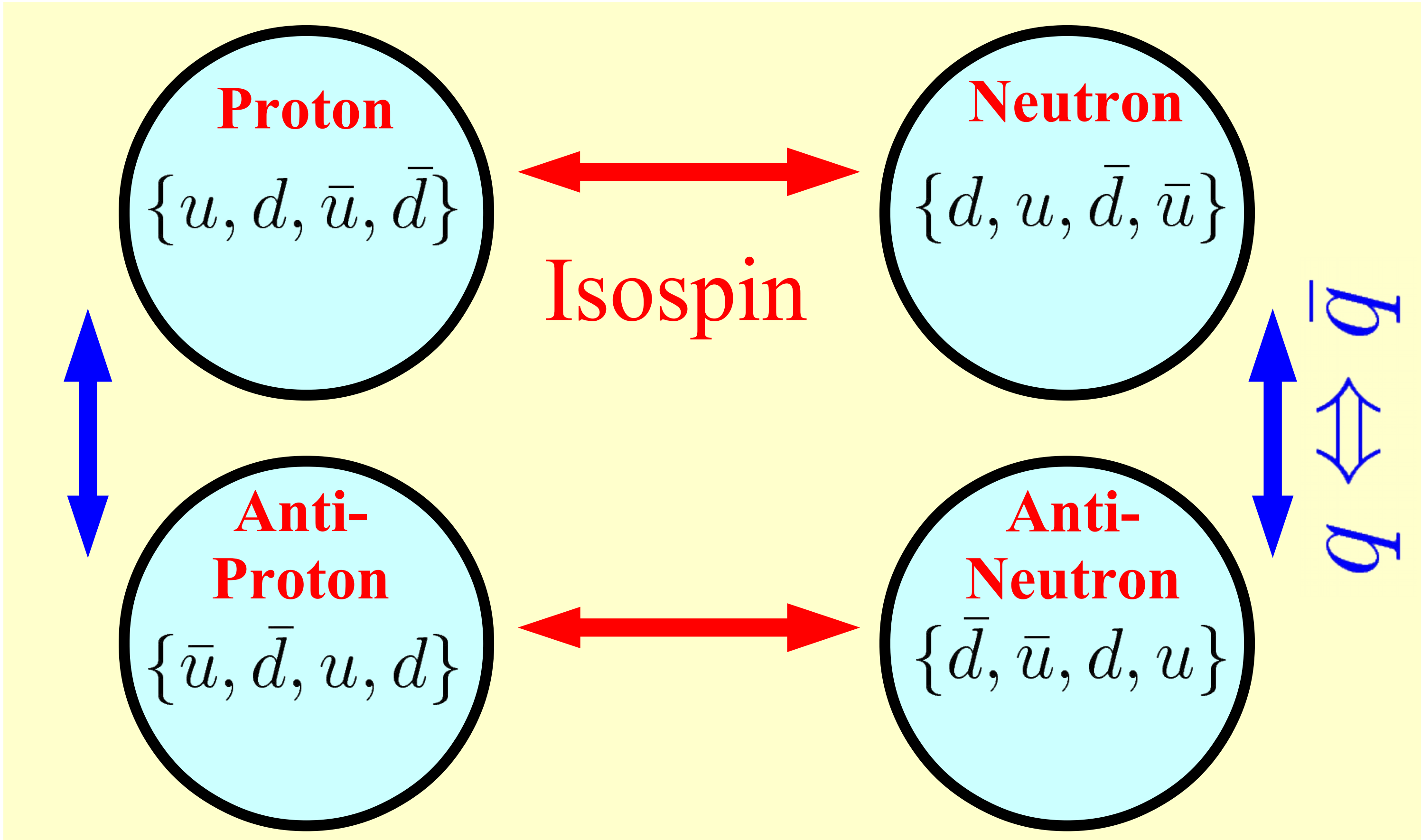
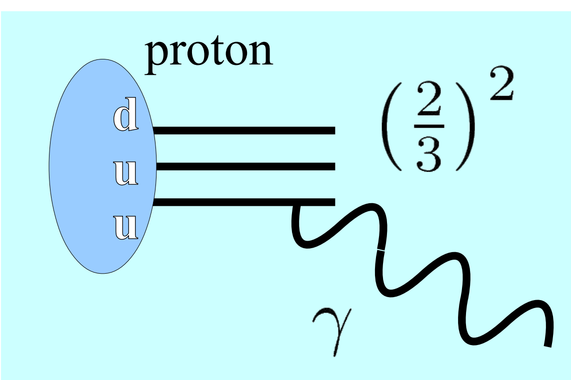
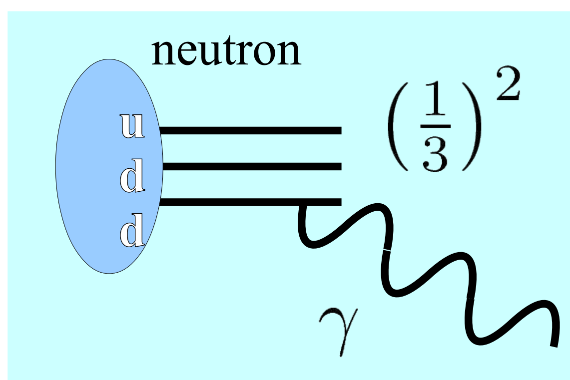
More interesting things, particularly at large-x

Isospin Symmetry used to relate PDFs





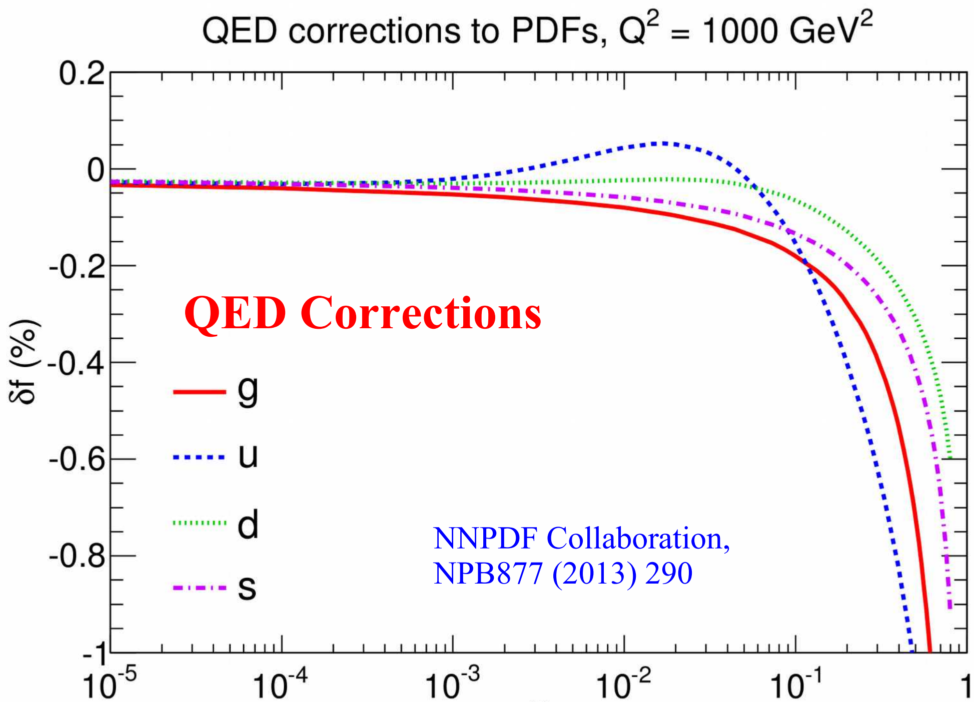


Isospin terms are comparable to NNLO QCD

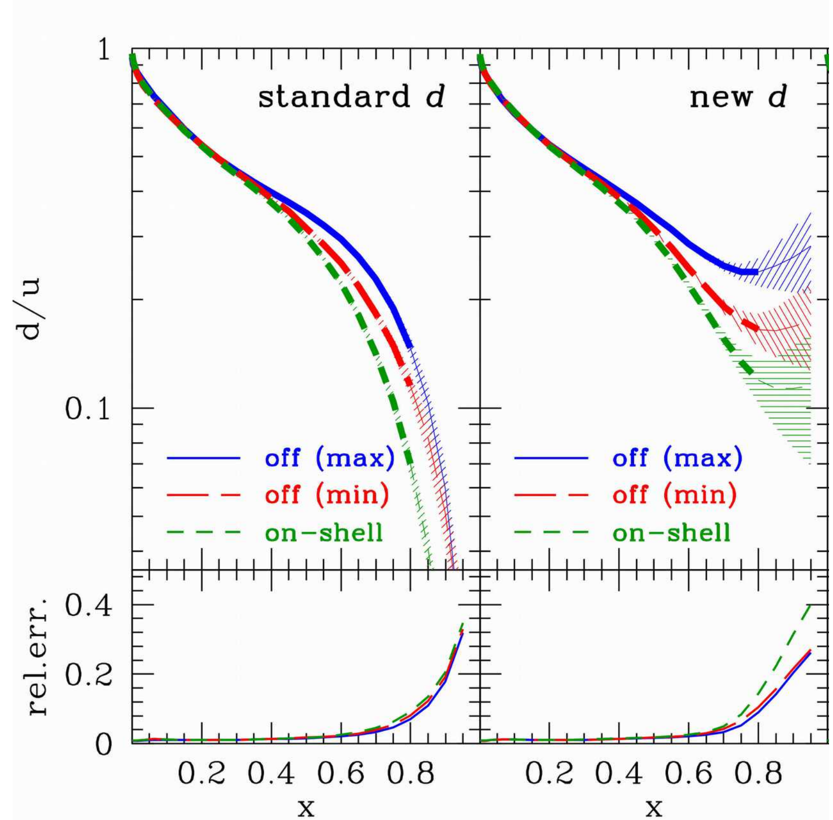
QCD & EW Corrections do NOT factorize

A Review of Target Mass Corrections.
Ingo Schienbein et al,
J.Phys.G35:053101,2008.

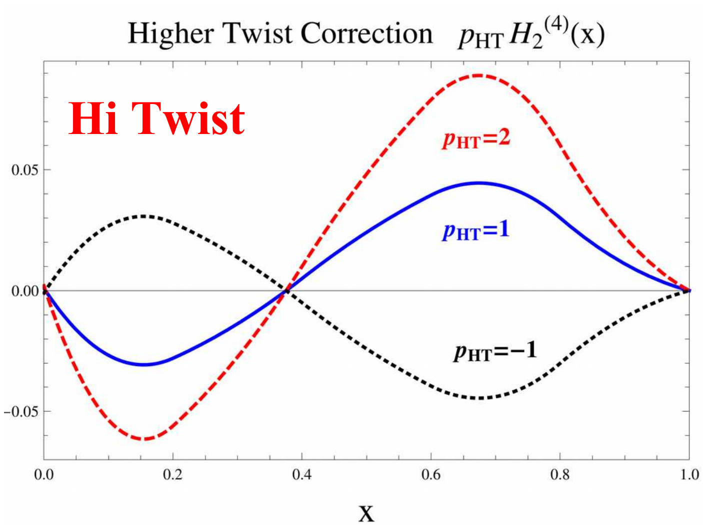
Hi-x Issues: Isospin Symmetry Violation, Higher Twist, ...

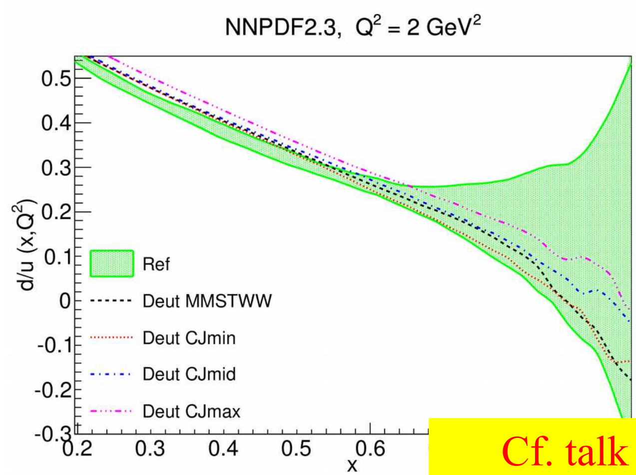


Hi-x is a "Gold Mine" for EIC

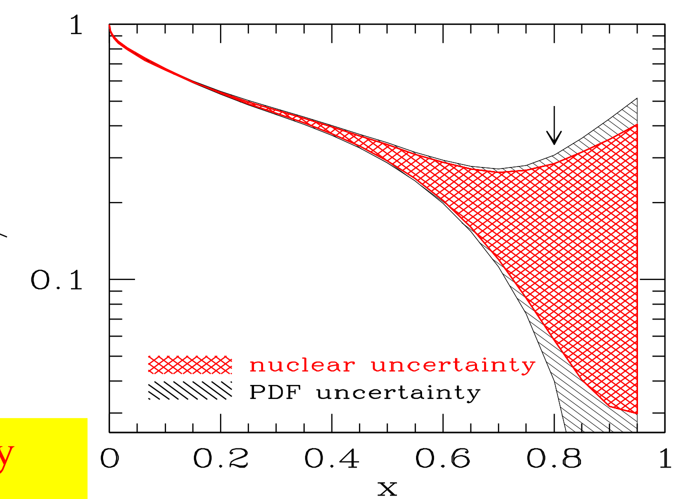


Clever Parameterization at large x





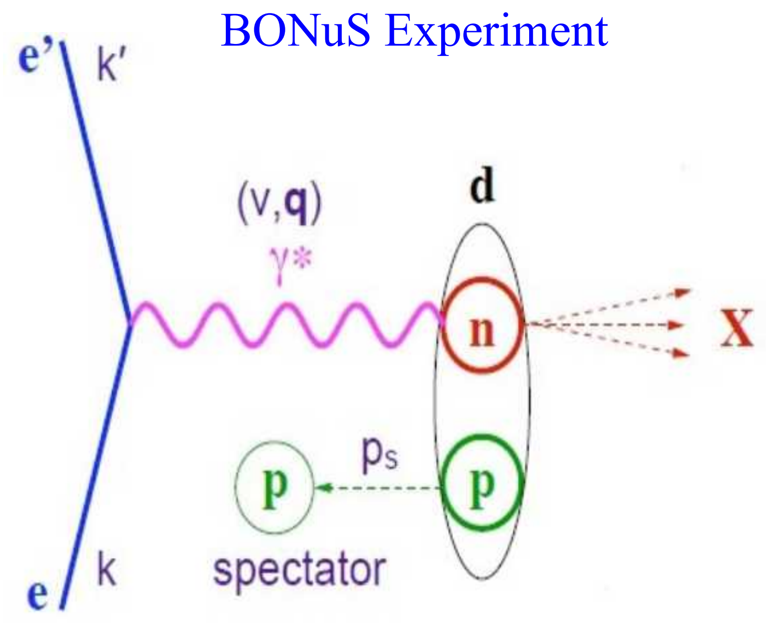
Cf. talk by Wally Melnitchouk



The NNPDF Collaboration, PLB723 (2013) 330

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

The BONuS Experiment: Clever way to get a neutron target



Effective Neutron beam

Push to large x region

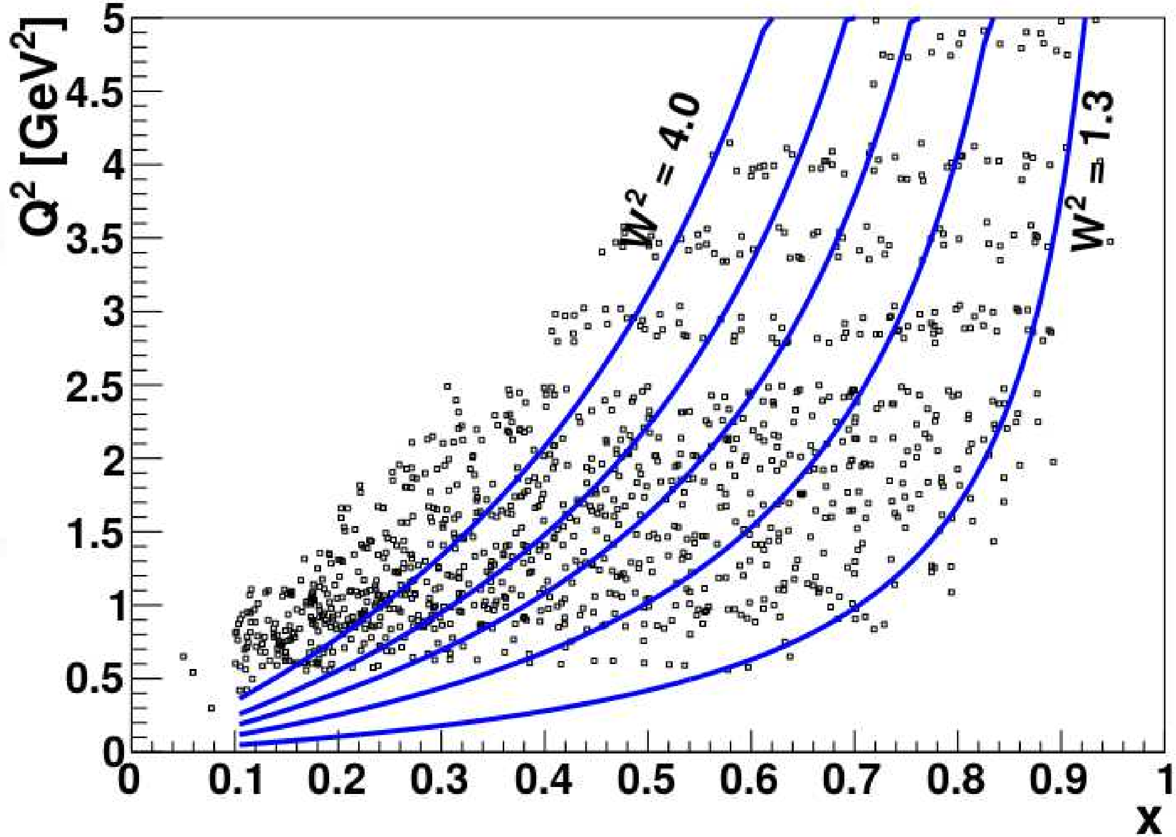
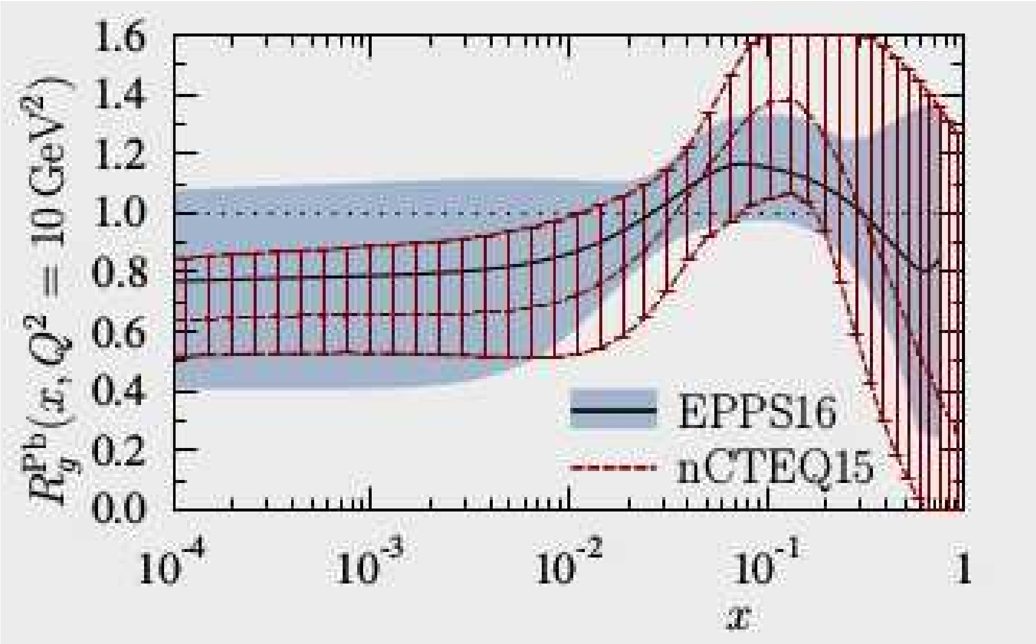


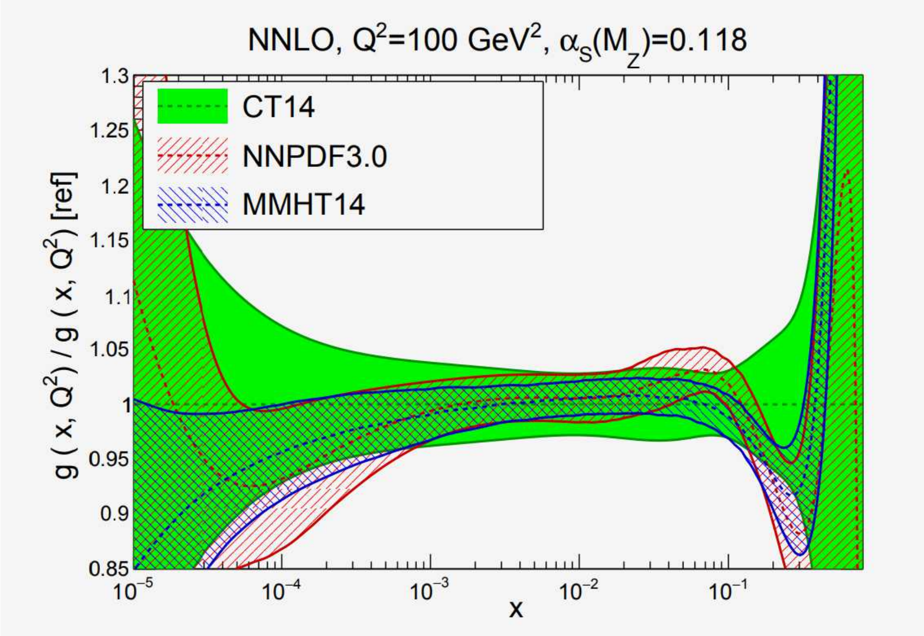
FIG. 1: Kinematic coverage of the BONuS data. The solid lines denote the fixed-W^2 thresholds for the four final state mass regions in Eq. (2), from $W^2 = 1.3$ to 4.0 GeV^2.

Phys.Rev. C91 (2015) no.5, 055206, (BONUS)
Direct observation of quark-hadron duality in the free neutron F 2 structure function. I. Niculescu, et al.,

GLUON

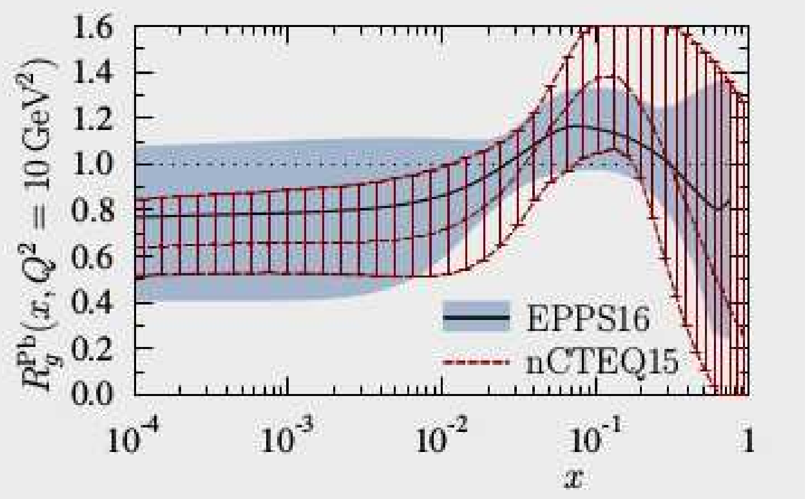


$R_g^{Pb}(x, Q^2 = 10\,GeV^2)$
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
EPPS16
nCTEQ15

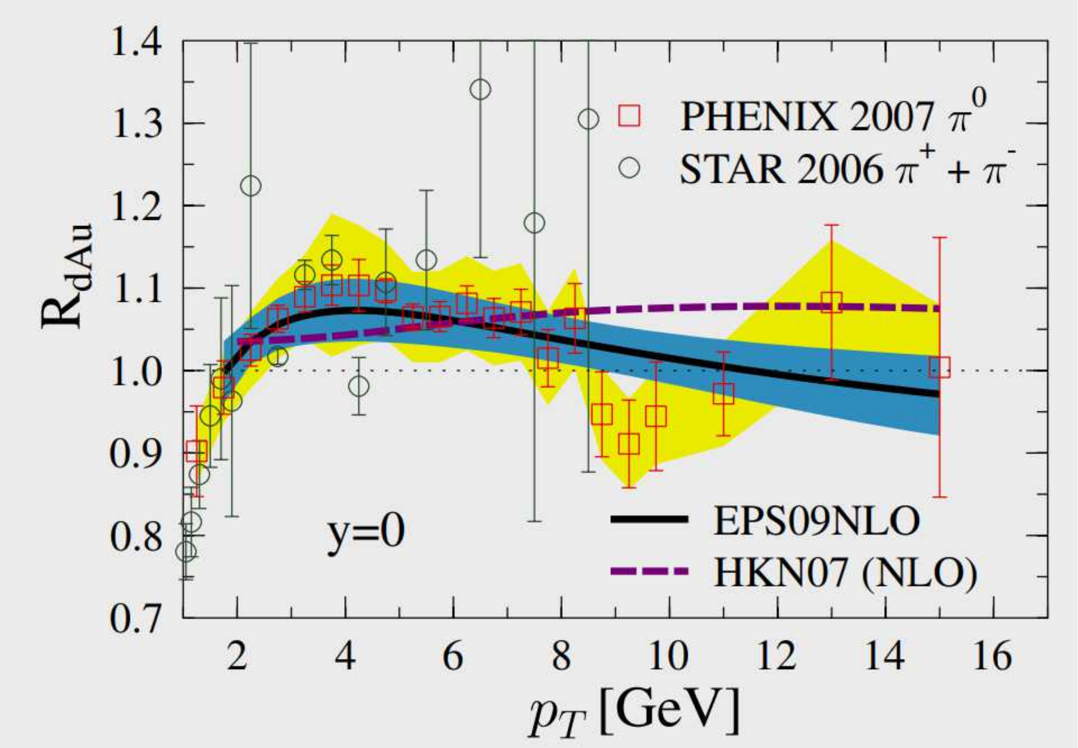


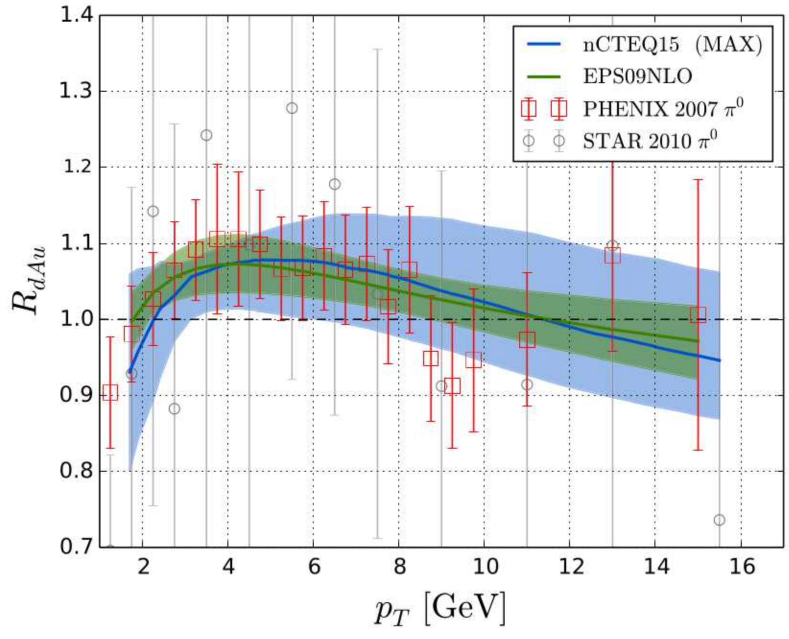
NNLO, Q^2=100 GeV^2, $\alpha_S(M_Z)$=0.118
CT14
NNPDF3.0
MMHT14
g (x, Q^2) / g (x, Q^2) [ref]
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x

Nuclear Gluon: Challenging! RHIC Pion Production



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

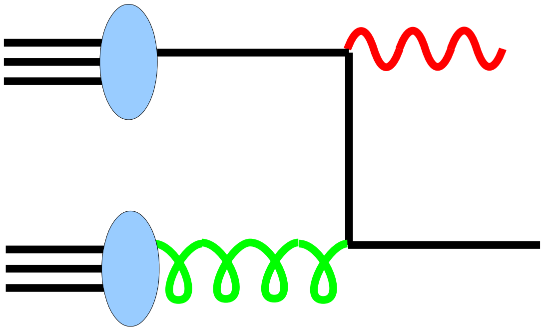




depends on fragmentation function

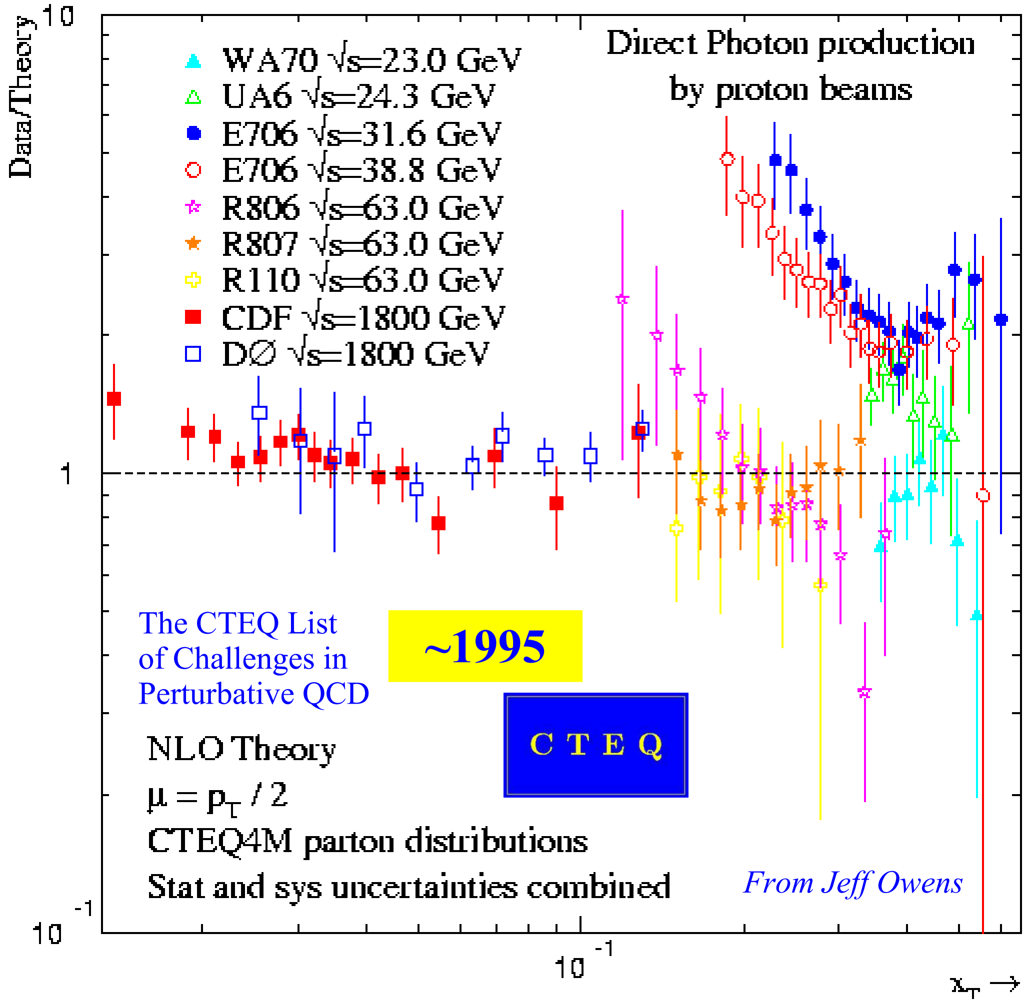
Cf. talks by:
Shunzo Kumano
Rodolfo Sassot

Nuclear Gluon: Could we use Direct Photon???

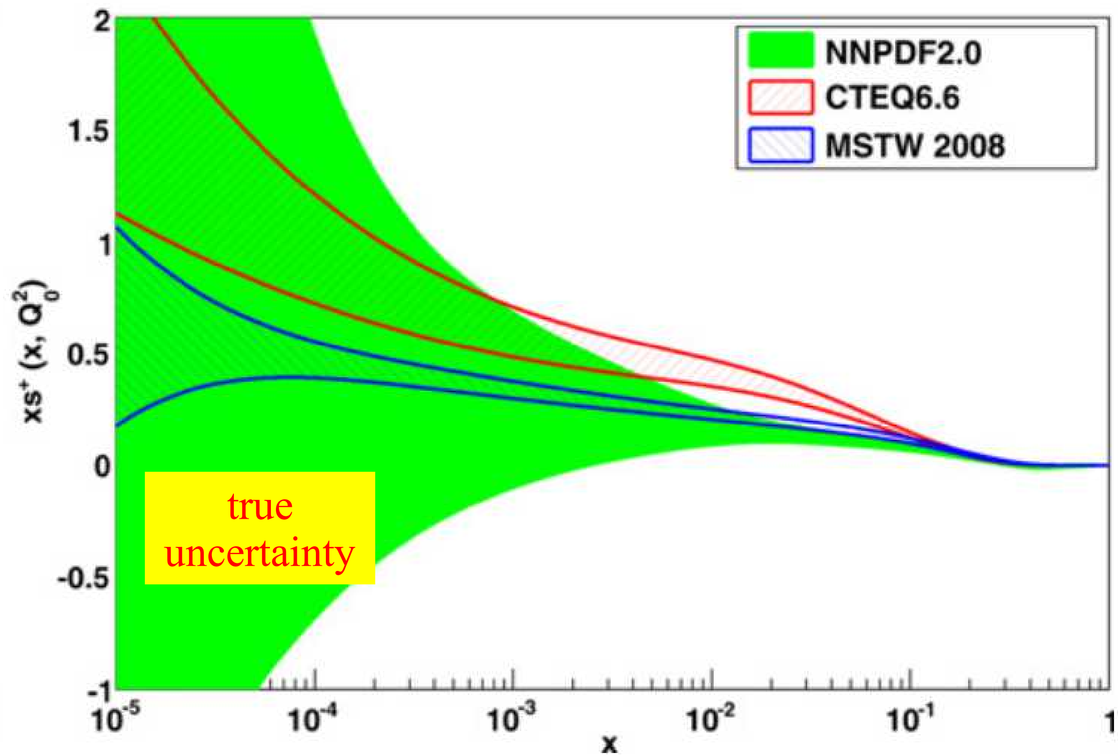


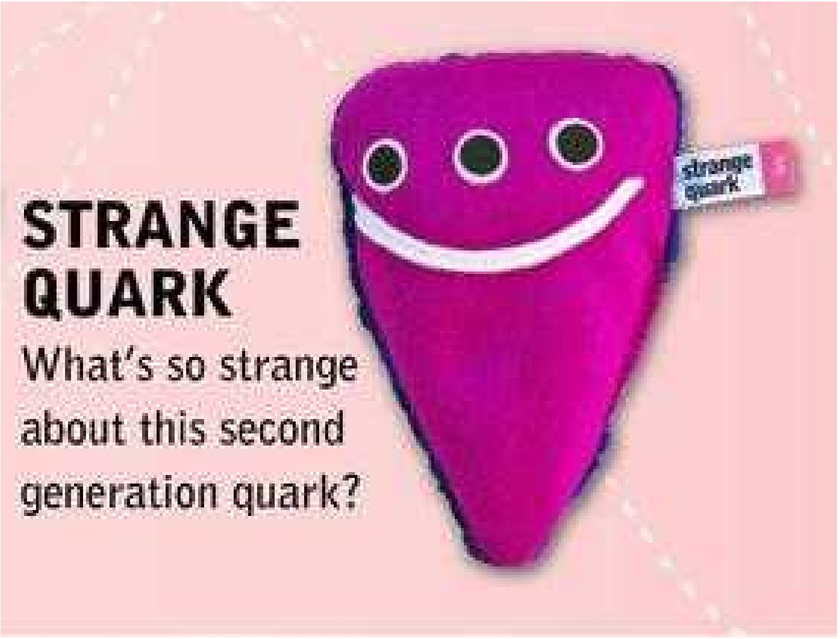
Historically Challenging Intrinsic K_T Issues

Recent improvements in resummation techniques



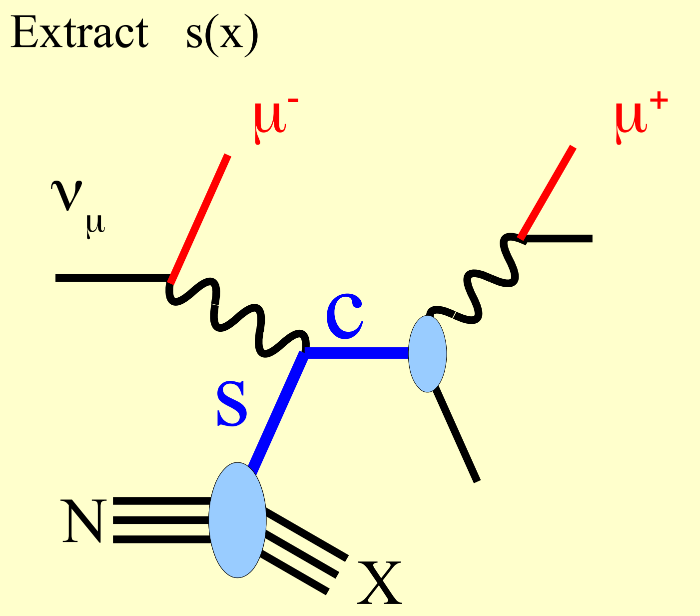
Progress on strange PDF

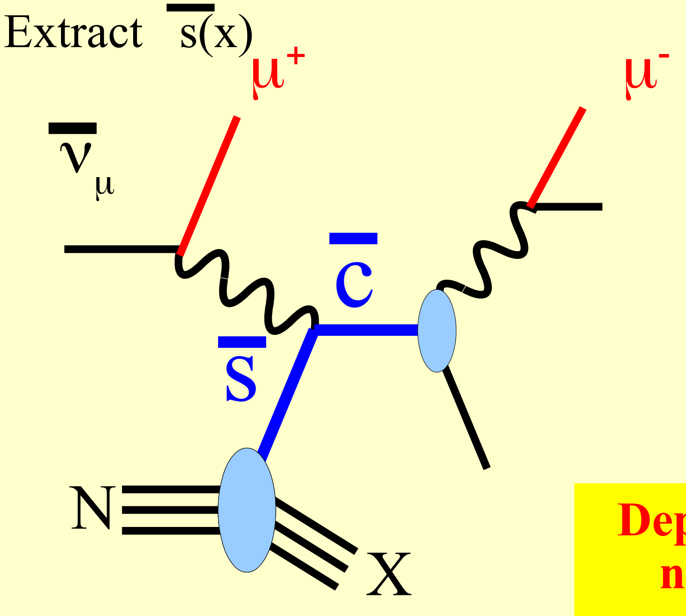




Cf. talk by Sergey Alekhin

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

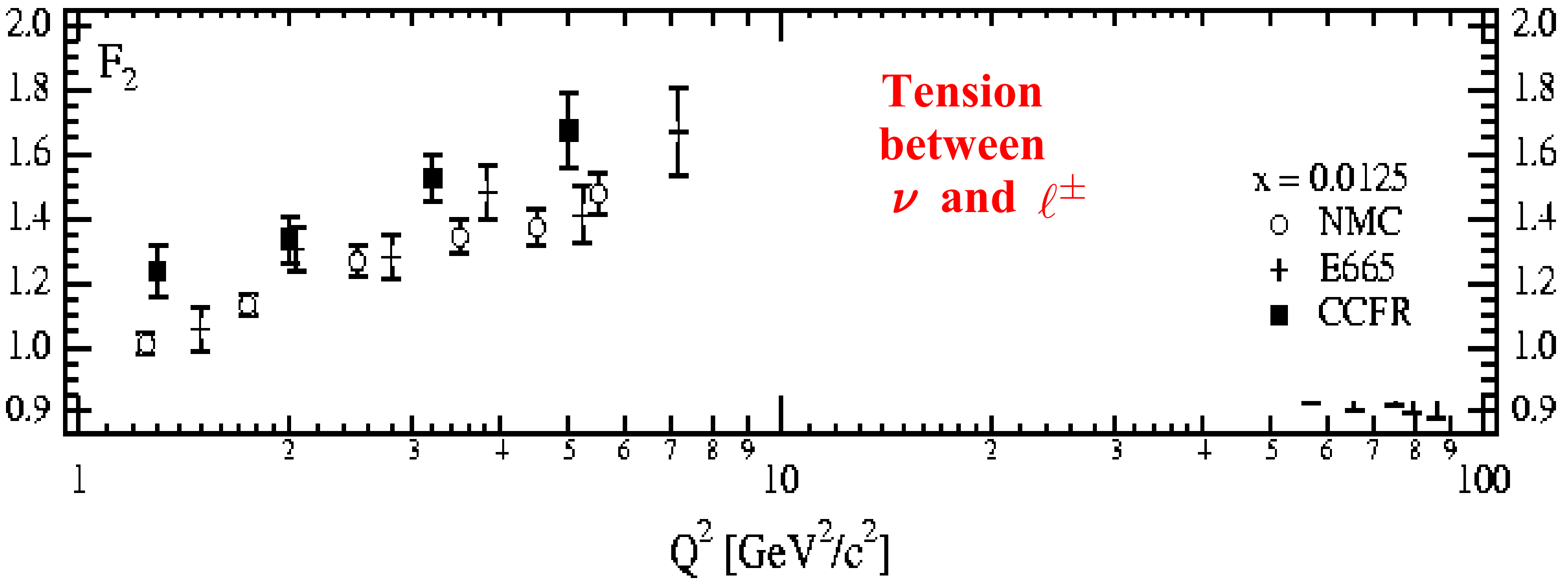




Depends on nuclear corrections

Can extract s(x) and s̄(x) separately

Used in CTEQ Fits

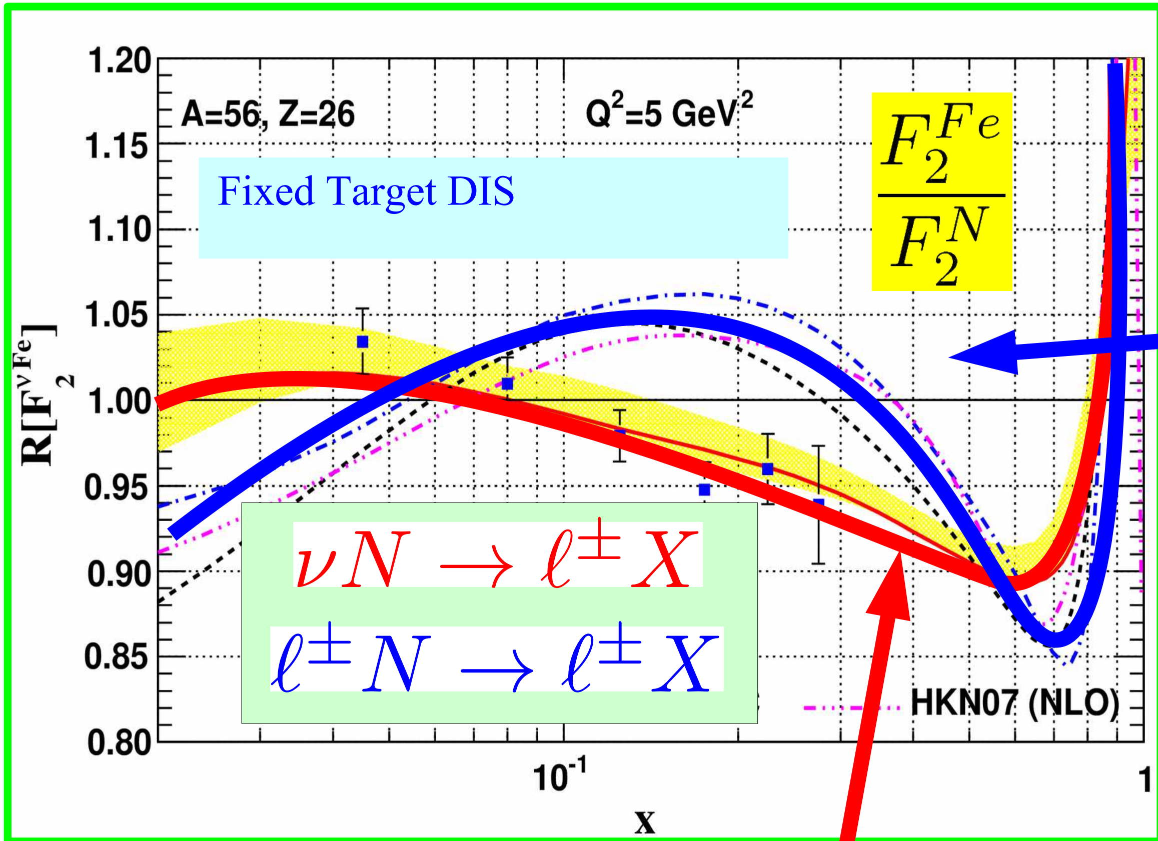


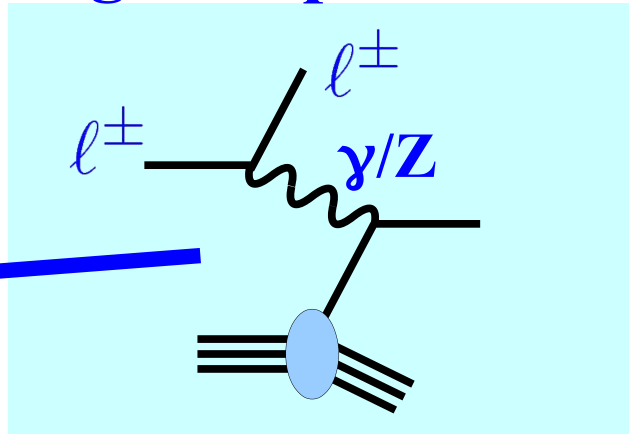
The CTEQ List of Challenges in Perturbative QCD

~1995

C T E Q

Charged Lepton DIS

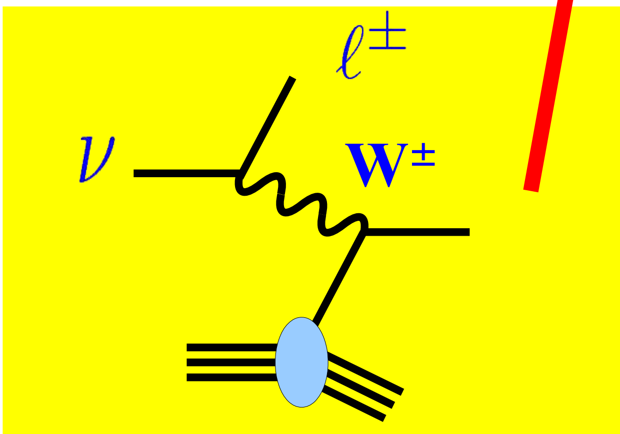




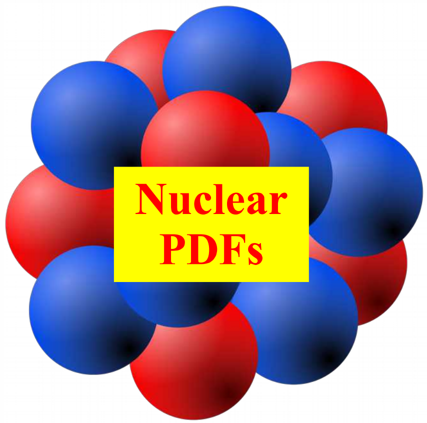
some caveats

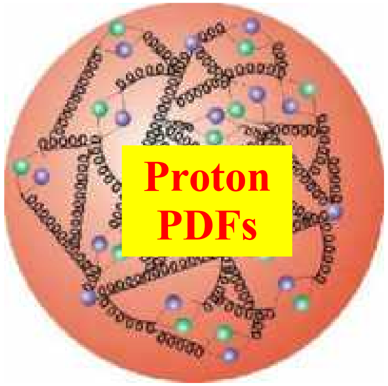
... correlated errors

Depends on nuclear corrections



Neutrino DIS



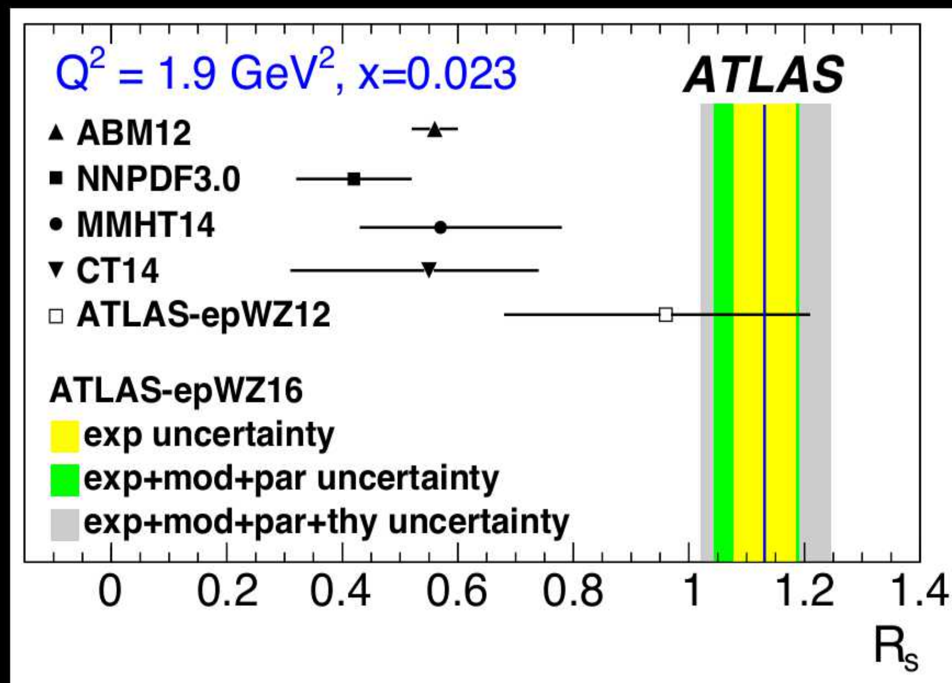


… at DIS2017 we heard ...

Electroweak and QCD Measurements at the Large Hadron Collider

Strangeness in the Proton

arXiv:1612.03016



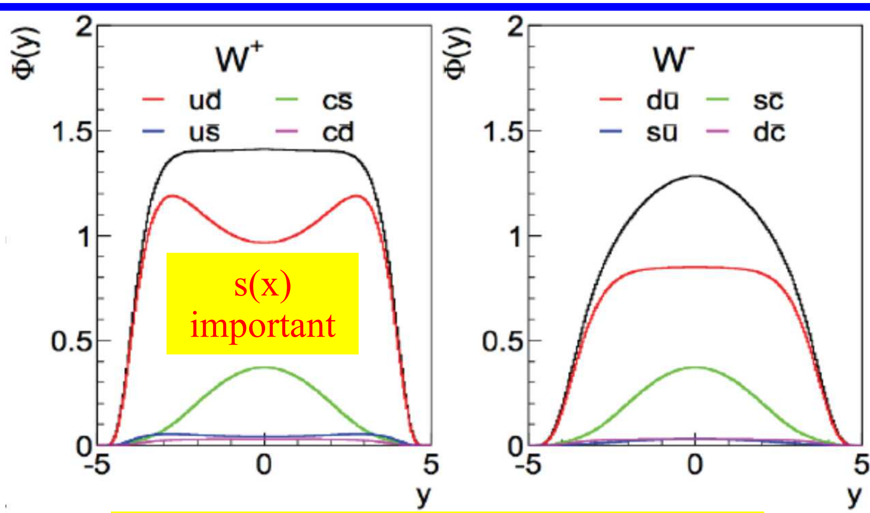
$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}} = 1.13 \pm 0.05\,(\text{exp}) \pm 0.02\,(\text{mod})\;{}^{+0.01}_{-0.06}\,(\text{par})$$

João Guimarães da Costa
IHEP, Chinese Academy of Sciences

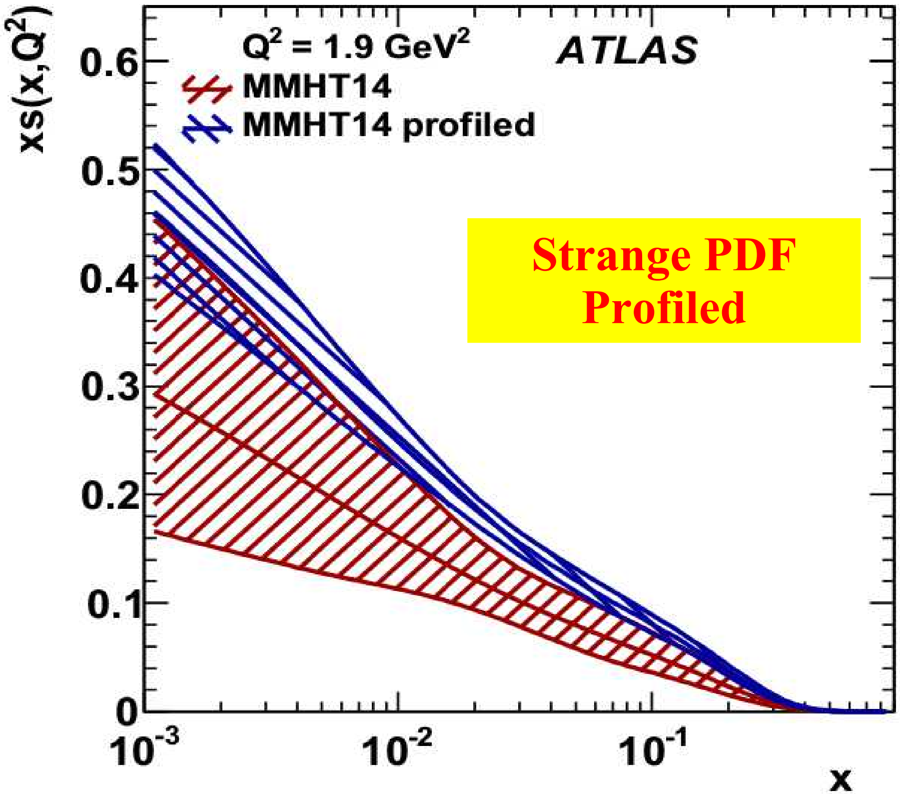
Birmingham, 3 April 2017

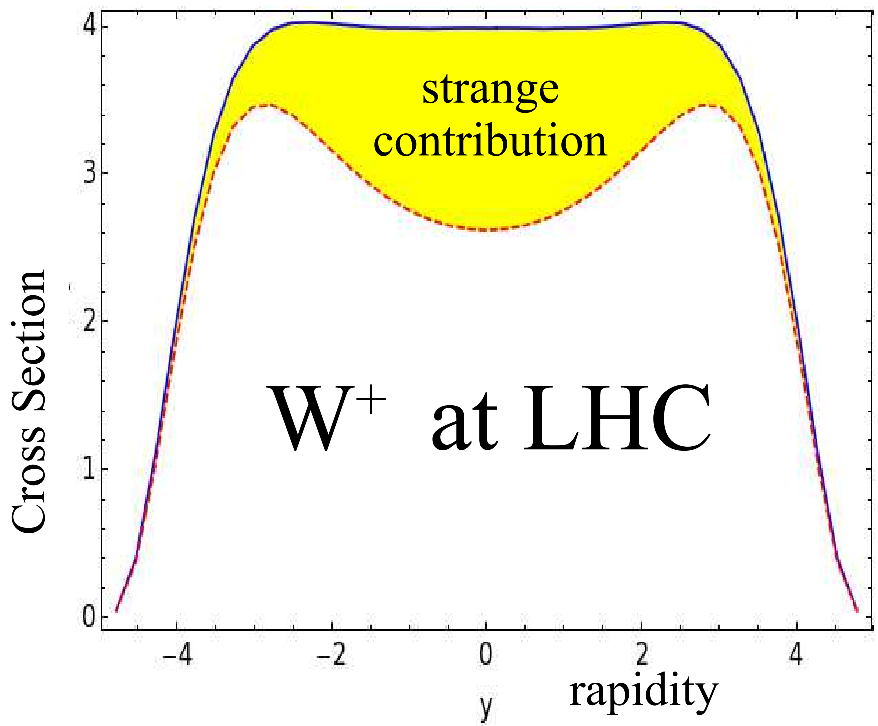
Do it yourself!!!
Try xFitter

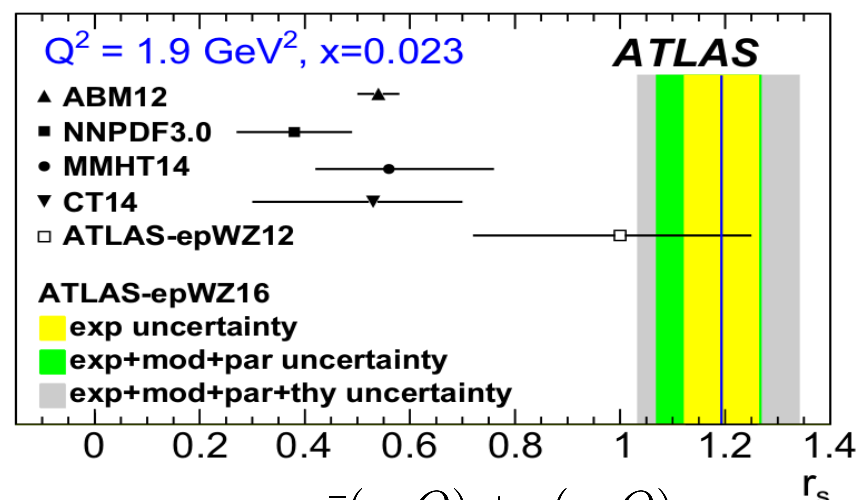
W/Z Production at LHC and the strange PDF



ATLAS: Eur. Phys. J. C 77 (2017) 367



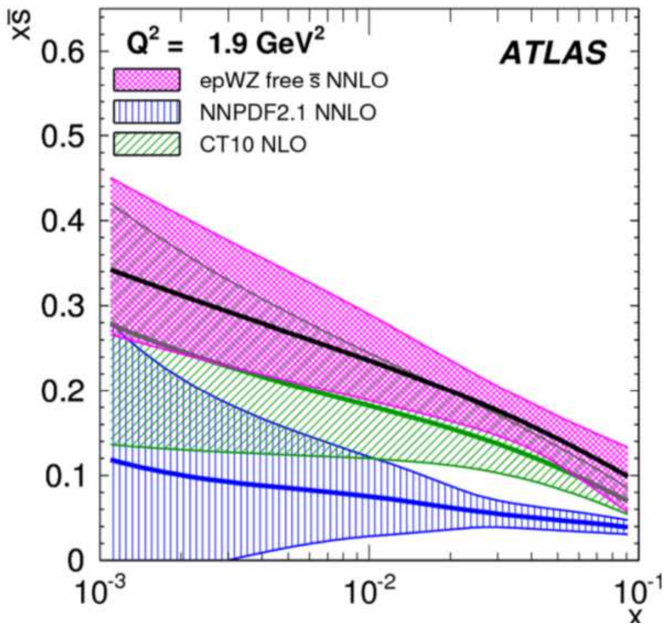




$$r^s(x,Q) = \frac{\bar{s}(x,Q) + s(x,Q)}{2\bar{d}(x,Q)}$$

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

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

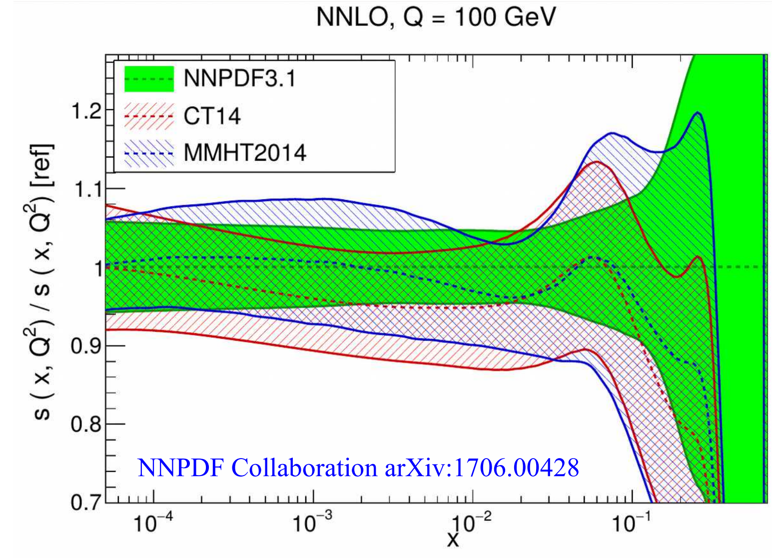


HERAFitter, Open Source QCD Fit Project
Eur. Phys. J. C (2015) 75: 304.

$$\kappa^s_{CT14NNLO} = 0.62 \pm 0.14$$
$$\kappa^s_{CT10NNLO} = 0.73 \pm 0.11$$

Carl Schmidt October 2015: INT Workshop

… whatever you want it to be

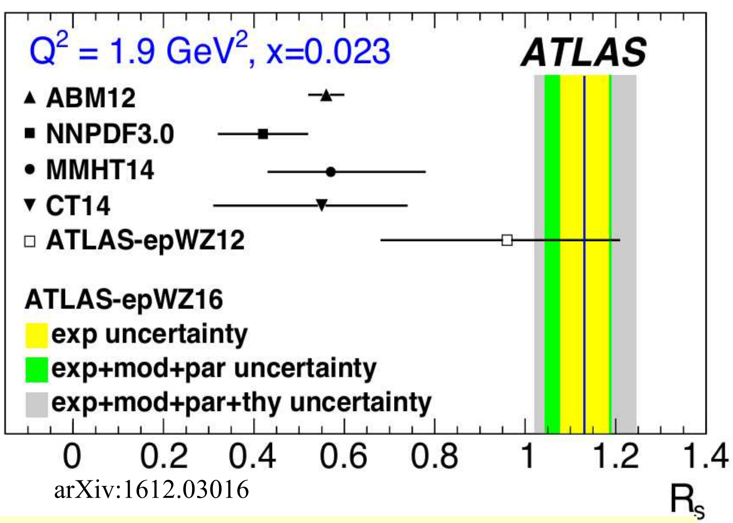


$$\text{NuTeV}\ \kappa = 0.477^{+0.063}_{-0.053}$$ Z.Phys.C65:189-198,1995

$$\text{NOMAD}\ \kappa = 0.591 \pm 0.019$$ 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)



arXiv:1612.03016

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

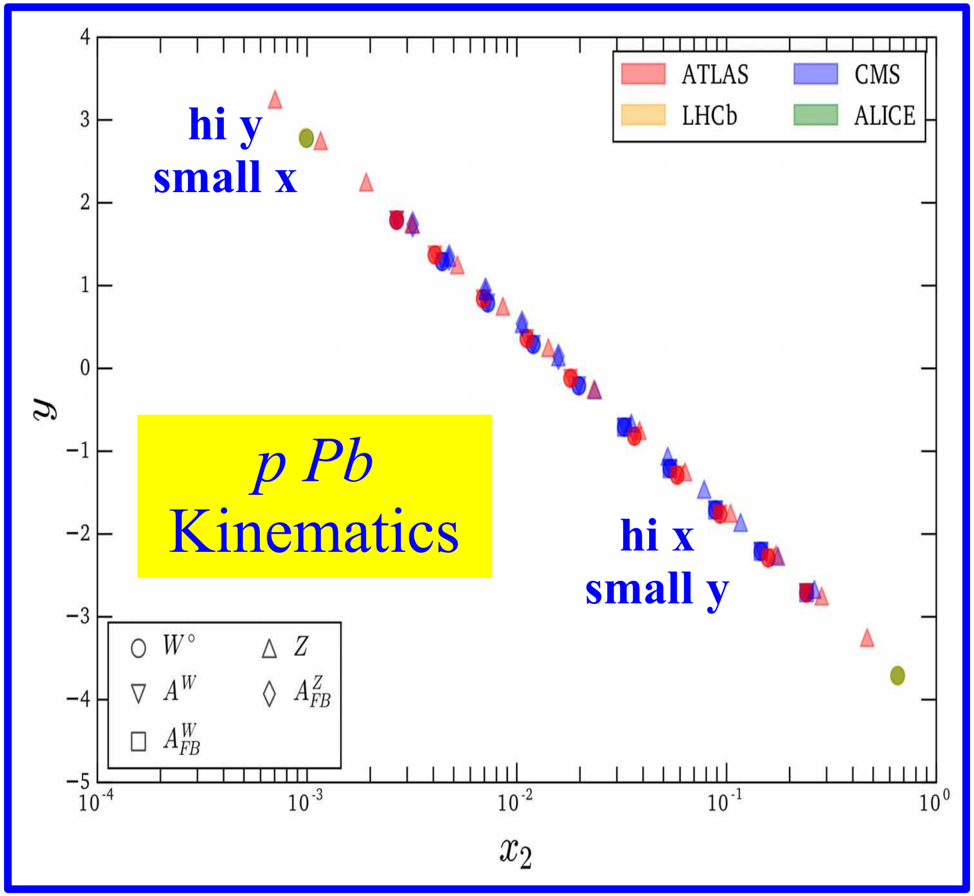
Q_0^2=1.9 GeV^2 at x=0.023

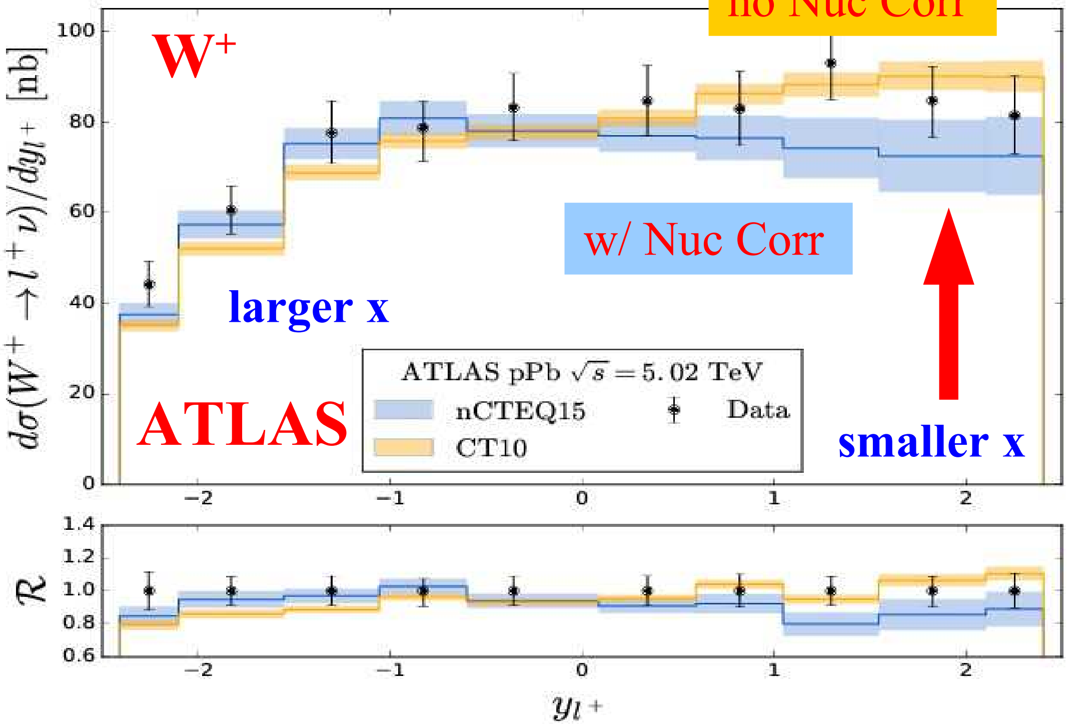
EPJC (2107) 77:367
(exp)(model)(param)

… yes, details depend on {x,Q²}

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

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





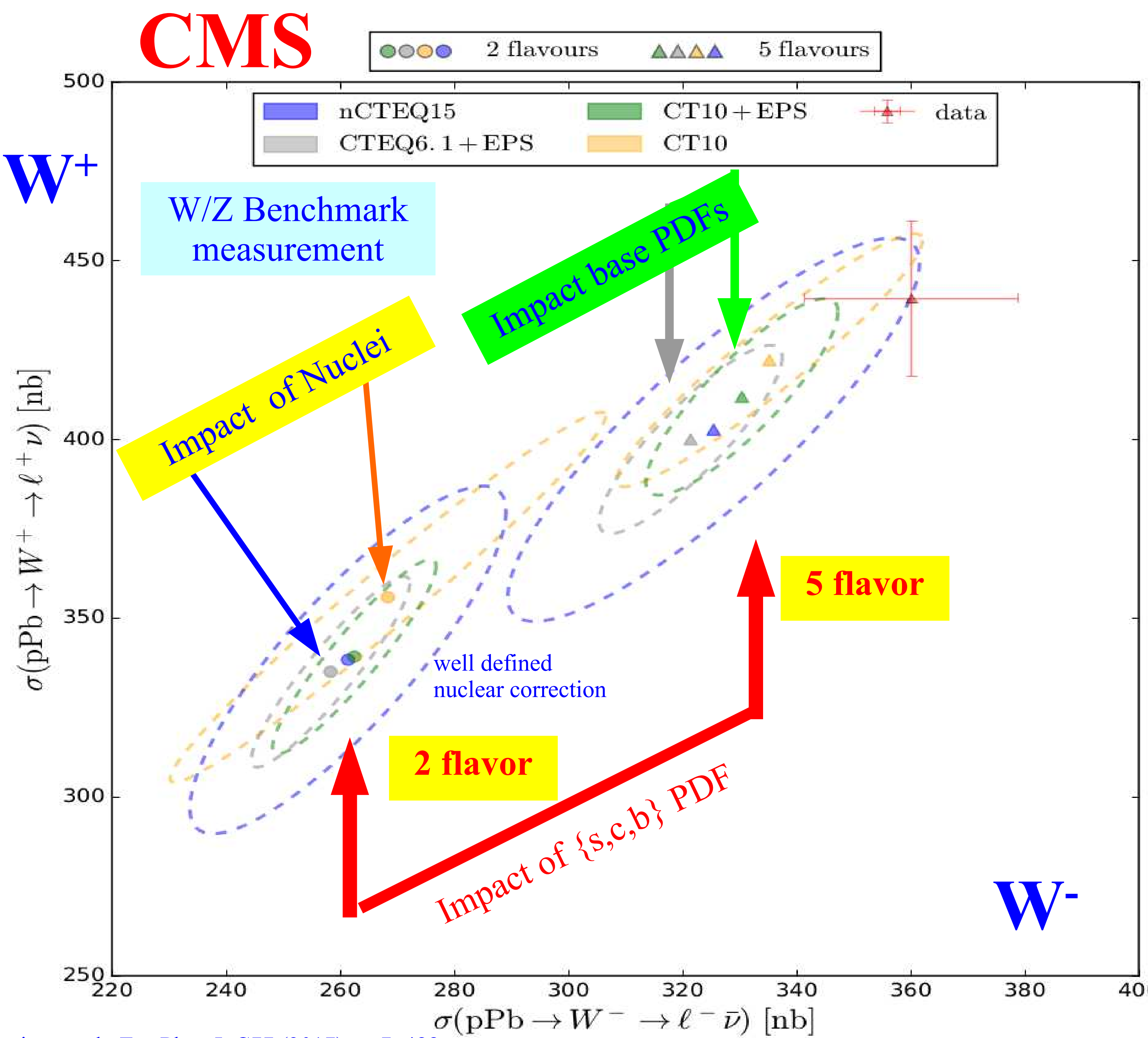
lead kinematics

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

p Pb → *W/Z*: Impact of {s,c,b} PDF



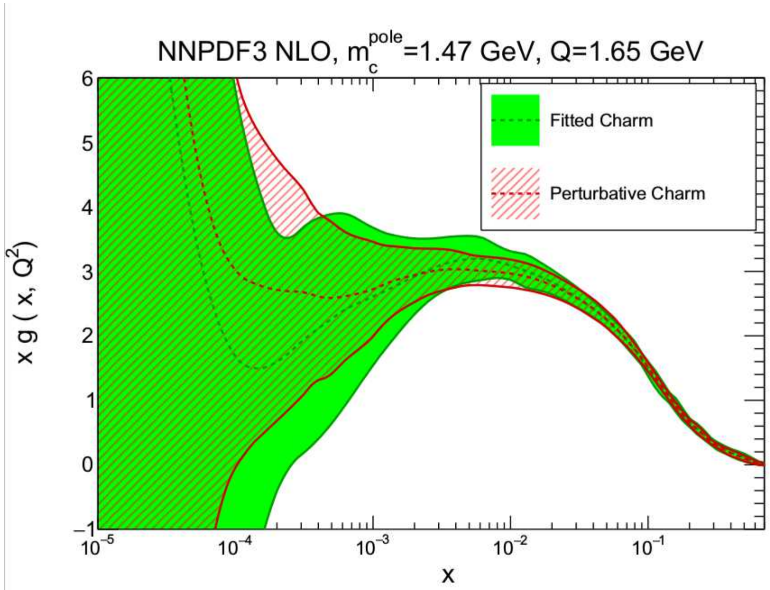
Entangled:

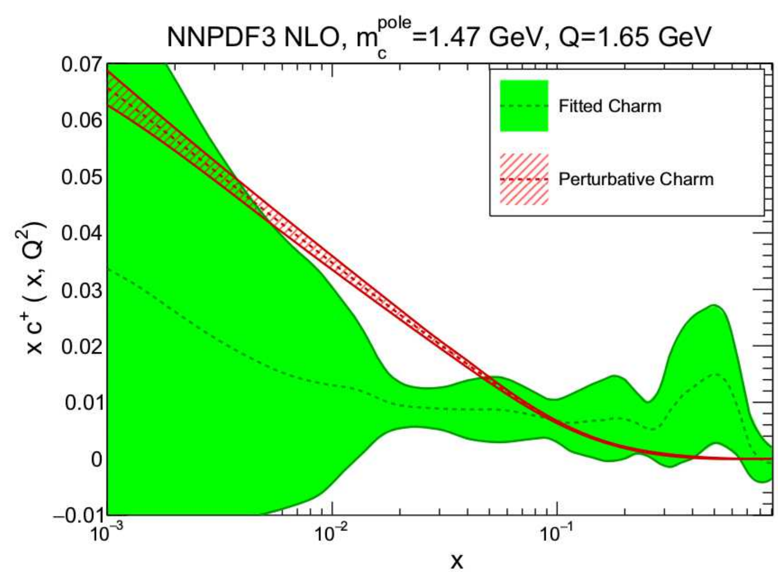
- Nuc Corrections
- Base PDF
- PDF Flavors

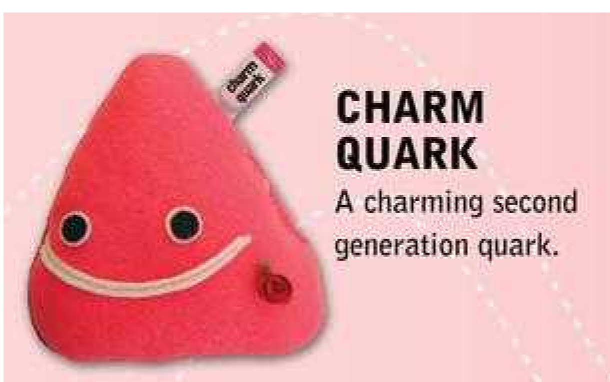
This is an area where LHeC is particularly suited to help

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

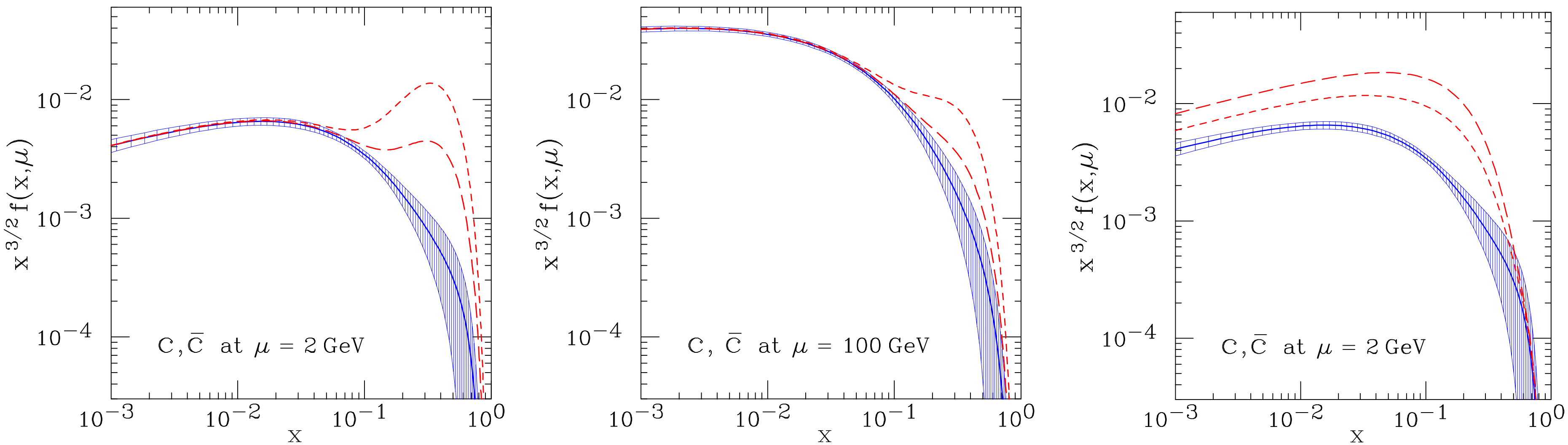
Charm & Bottom



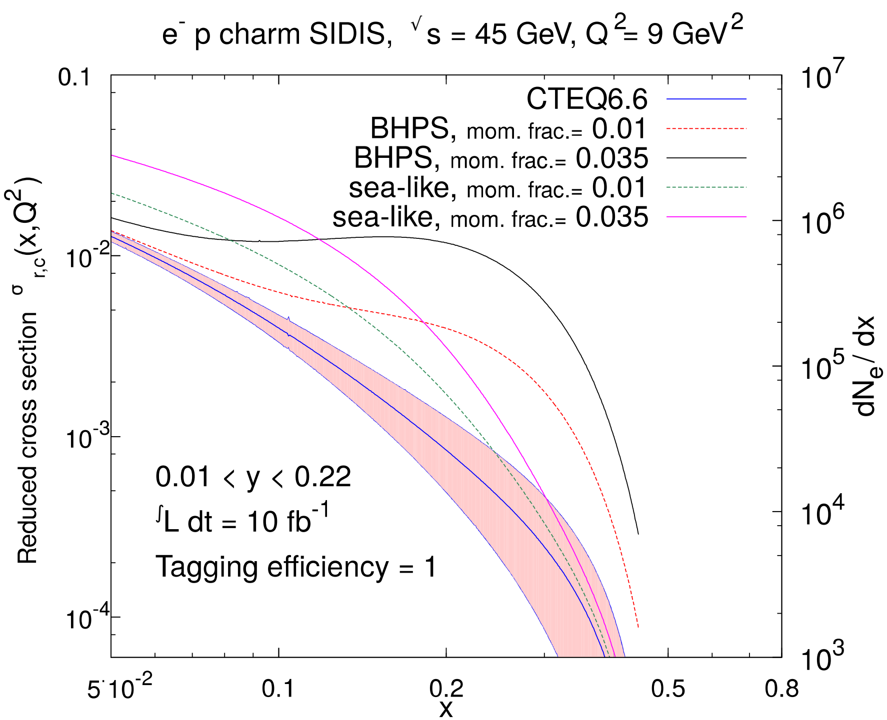


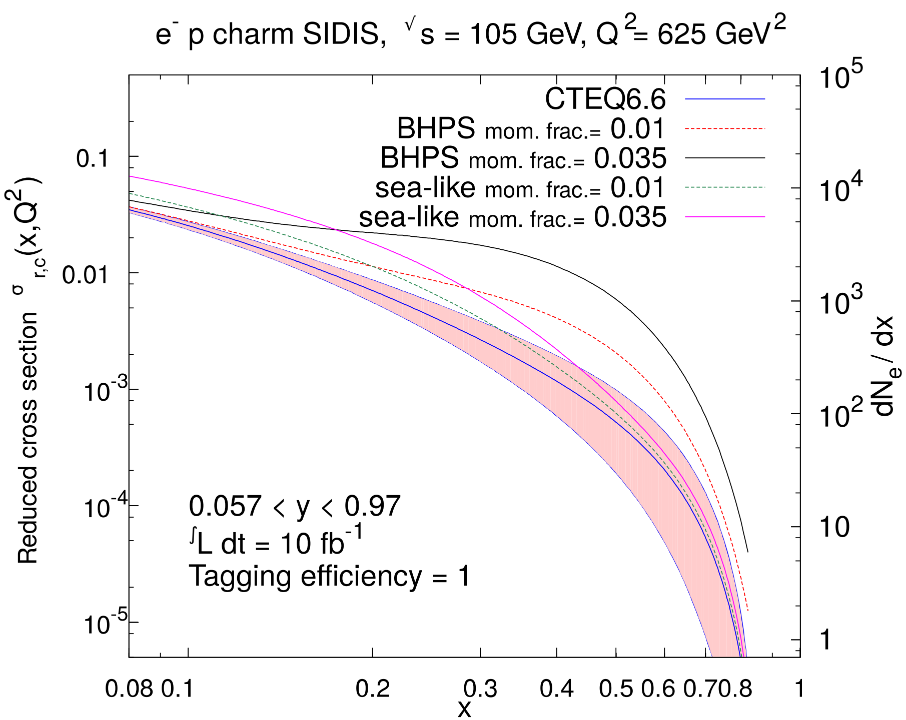


Intrinsic Charm PDFs

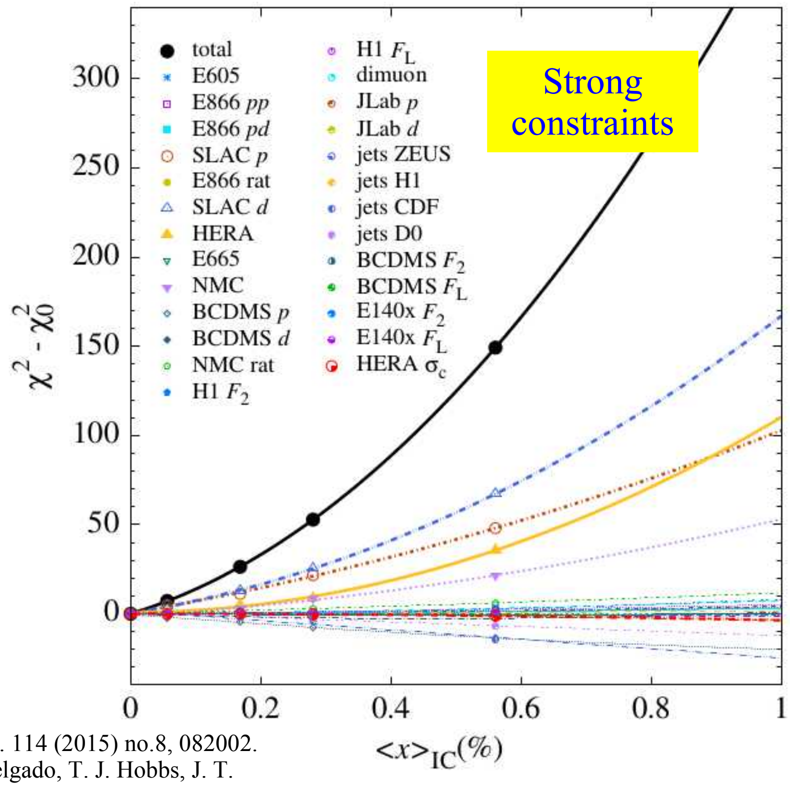


Gluons and the quark sea at high-energies

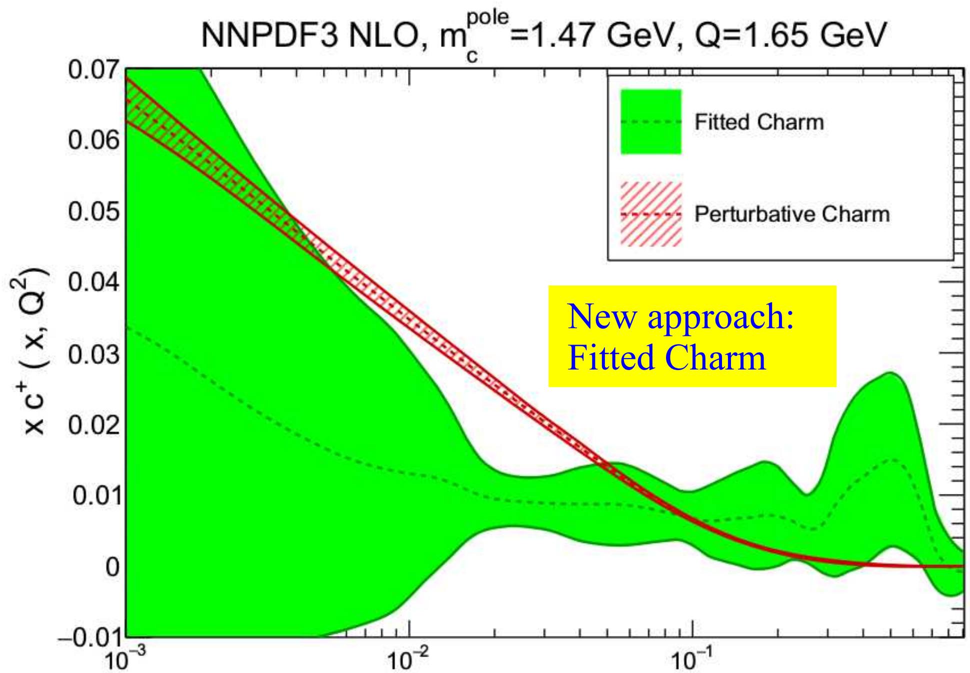




Charm: Variety of Recent Developments



Phys.Rev.Lett. 114 (2015) no.8, 082002.
P. Jimenez-Delgado, T. J. Hobbs, J. T. Londergan, W. Melnitchouk,



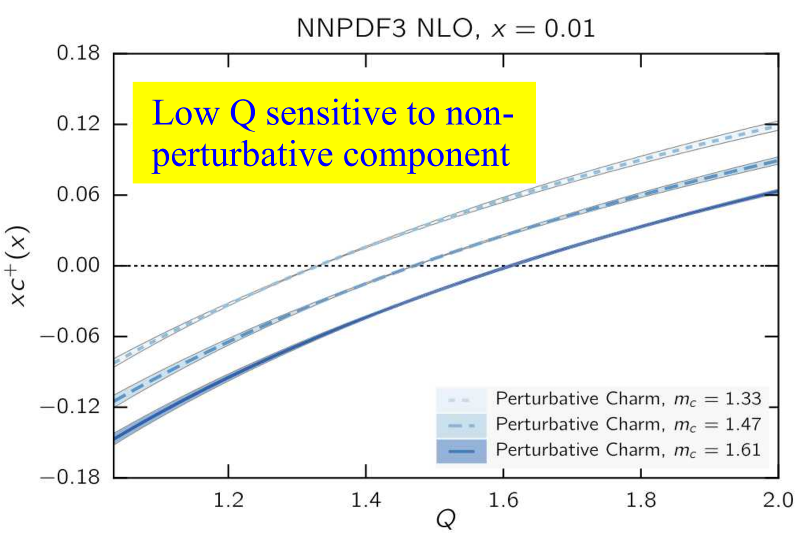


Table 3 The charm momentum fraction $C(Q^2)$ at a low scale $Q = 1.65$ GeV with perturbative charm, and with fitted charm with and without the EMC data included. The momentum fractions for several CT14IC PDF sets are also given for comparison (see text)

PDF set	$C(Q = 1.65\ \text{GeV})$
NNPDF3 perturbative charm	$(0.239 \pm 0.003)\%$
NNPDF3 fitted charm	$(0.7 \pm 0.3)\%$
NNPDF3 fitted charm (no EMC)	$(1.6 \pm 1.2)\%$
CT14IC BHPS1	1.3%
CT14IC BHPS2	2.6%
CT14IC SEA1	1.3%
CT14IC SEA2	2.2%

"Turn on" heavy quarks (c,b) at an arbitrary scale $\mu_{c,b}$

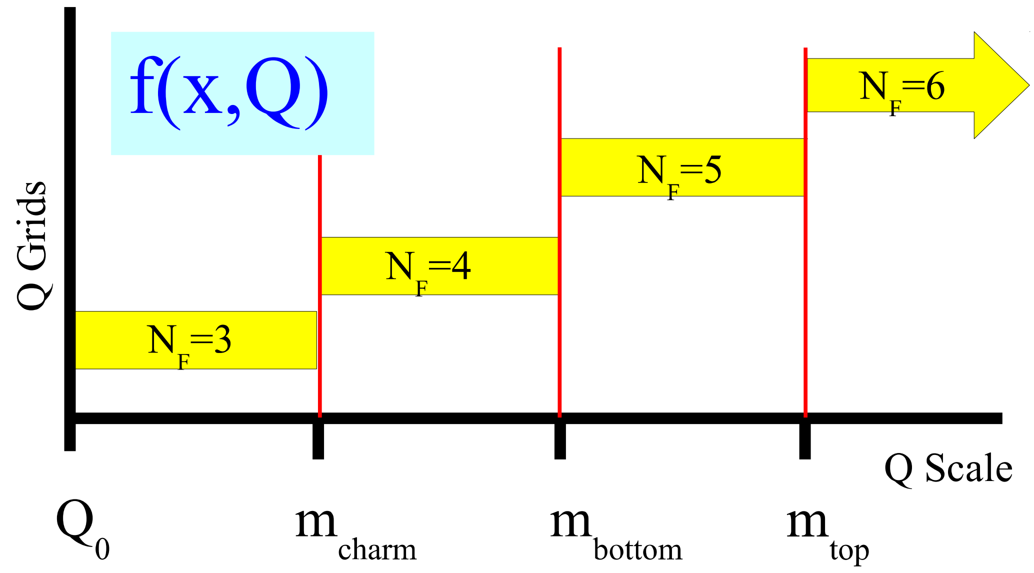
xFitter

APFEL has a new feature

included in xFitter

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

Traditional VFNS

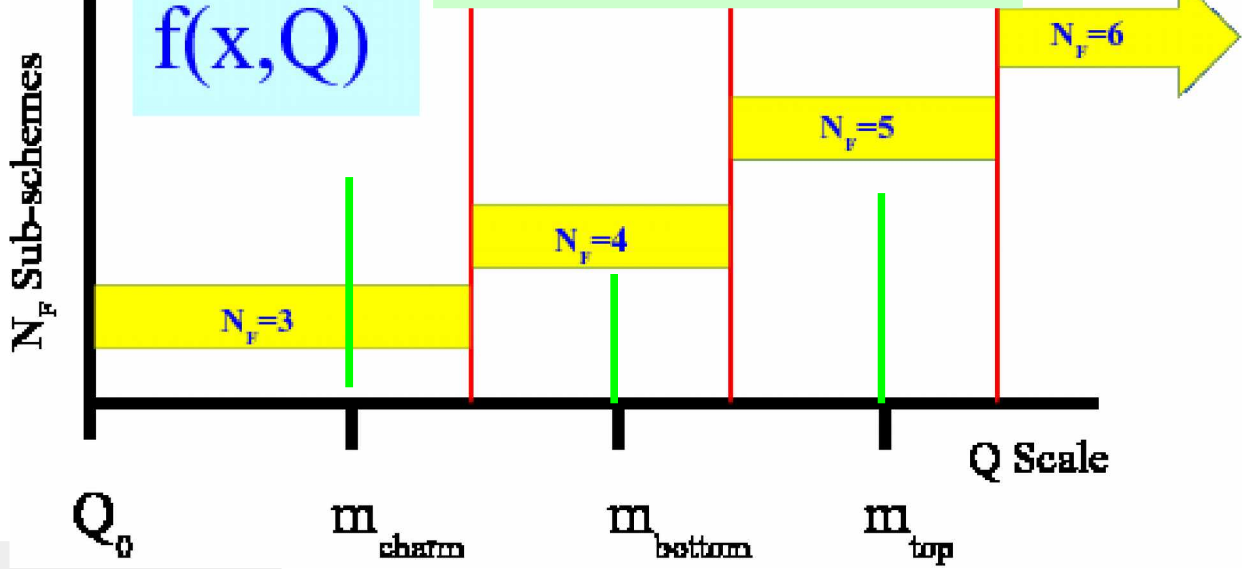


What are the benefits?

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

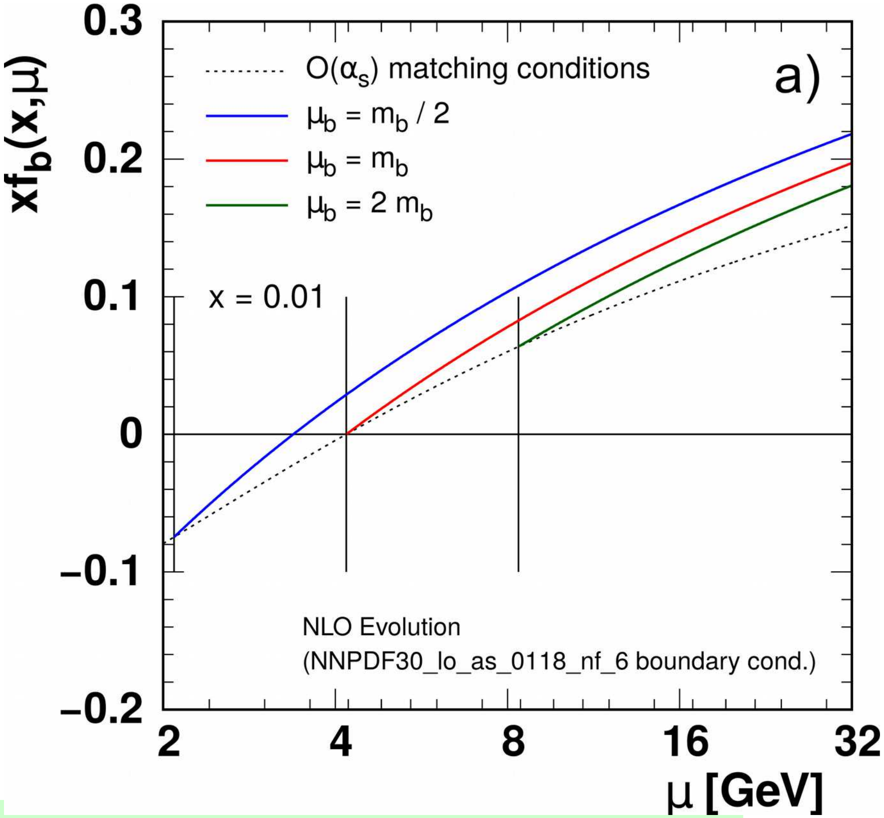
2) **avoid delicate matching in region $\mu \sim m_{c,b}$**

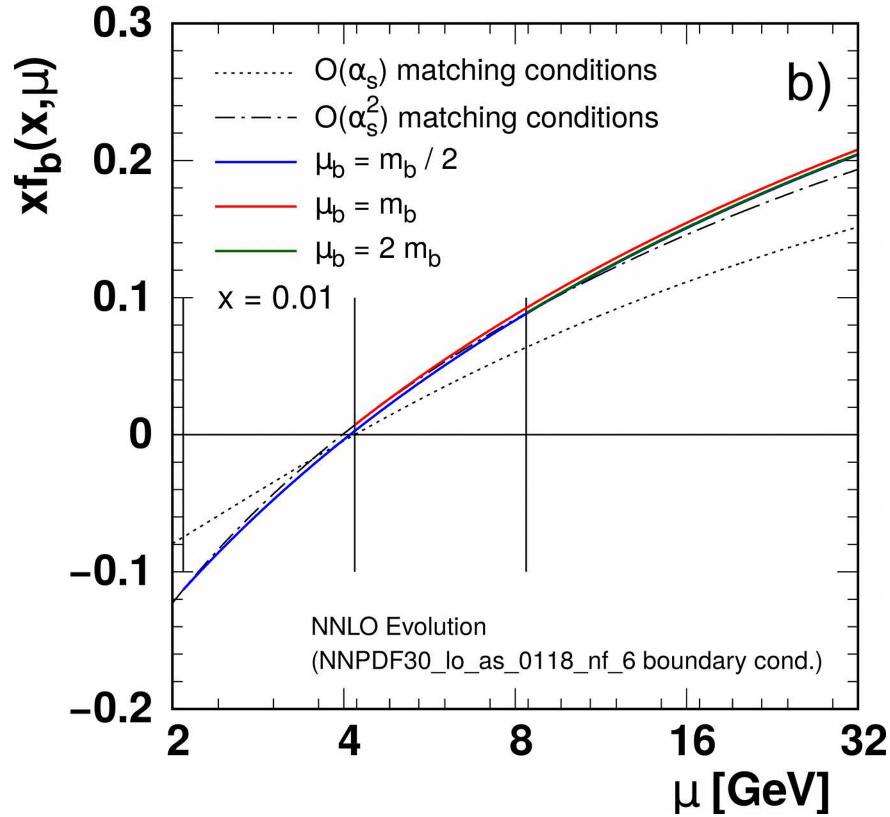
New APFEL Flexibility



Impact of the heavy quark matching scales in PDF fits
The xFitter Developers Team: V. Bertone, et al., arXiv:1707.05343

The matching conditions are non-trivial, especially at NNLO





NLO Matching Condition

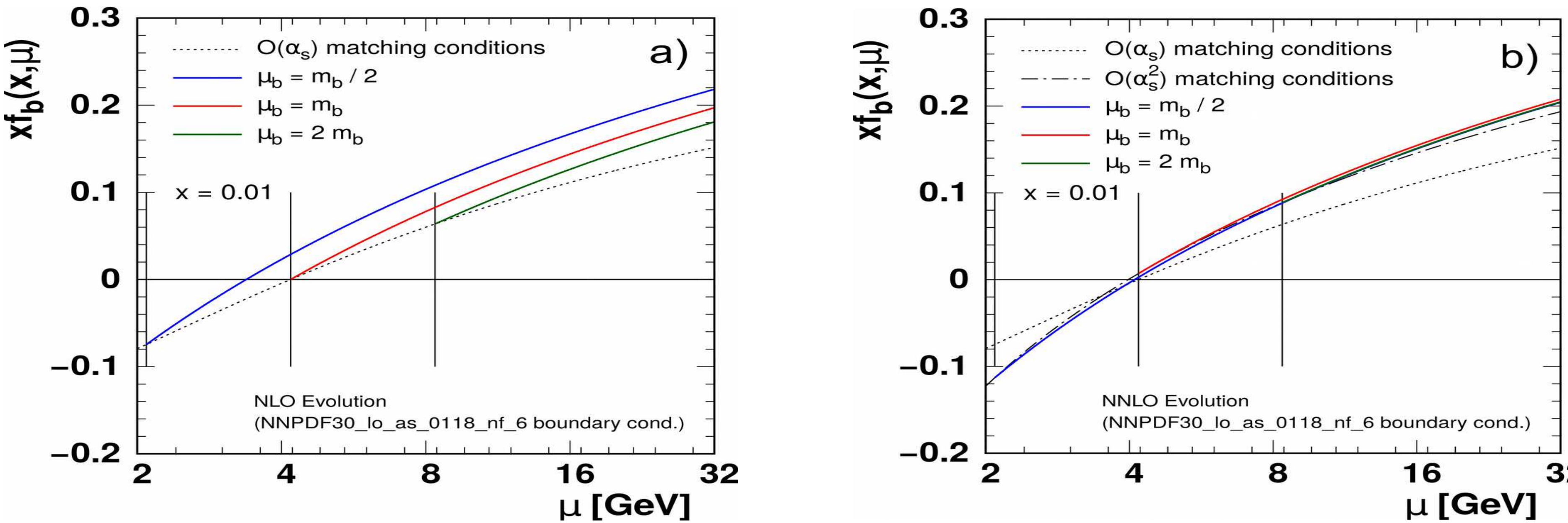
$$f_b^5(x,\mu) = \left(\frac{\alpha_S}{2\pi}\right)\left[P_{1,0} + P_{1,1}\log\left(\frac{\mu^2}{m_b^2}\right)\right] \otimes f_g^4(x,\mu)$$

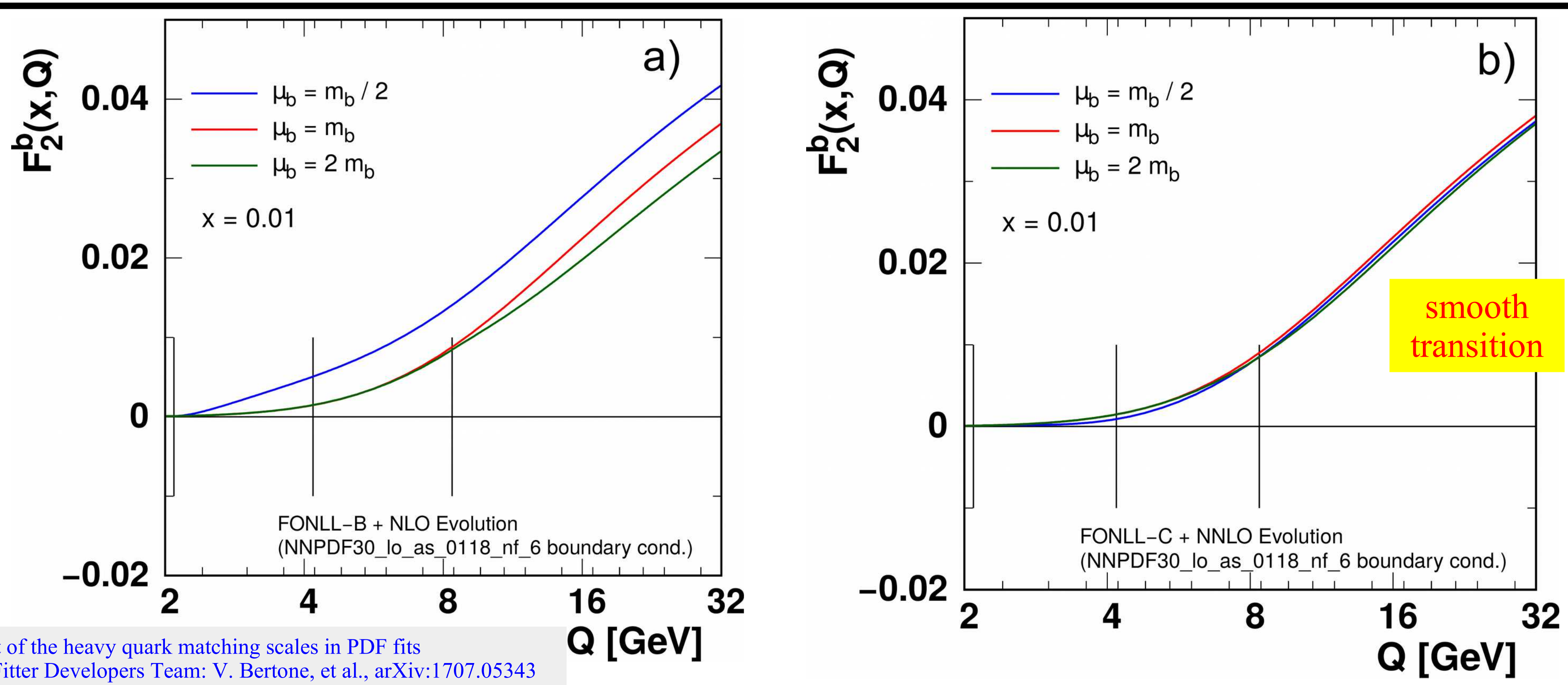
Zero at Leading Order

DGLAP contribution

Impact of the heavy quark matching scales in PDF fits
The xFitter Developers Team: V. Bertone, et al., arXiv:1707.05343

The matching conditions are non-trivial, especially at NNLO





Impact of the heavy quark matching scales in PDF fits
The xFitter Developers Team: V. Bertone, et al., arXiv:1707.05343

A proposal: Consider N_F dependent PDF

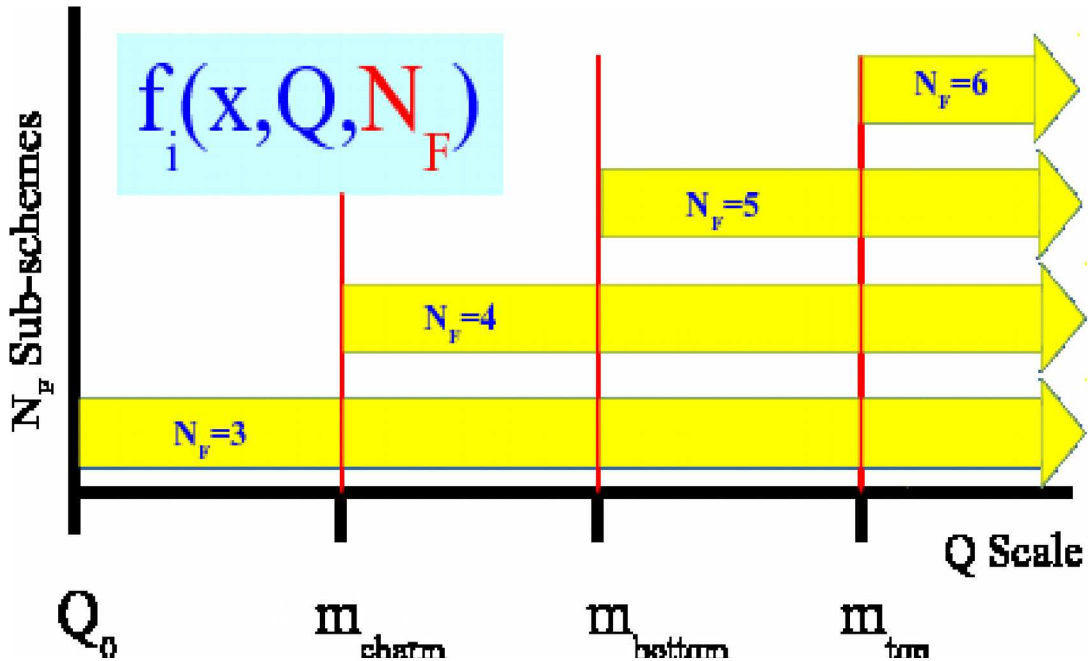
Provides some of the benefits & flexibility of flexible matching,

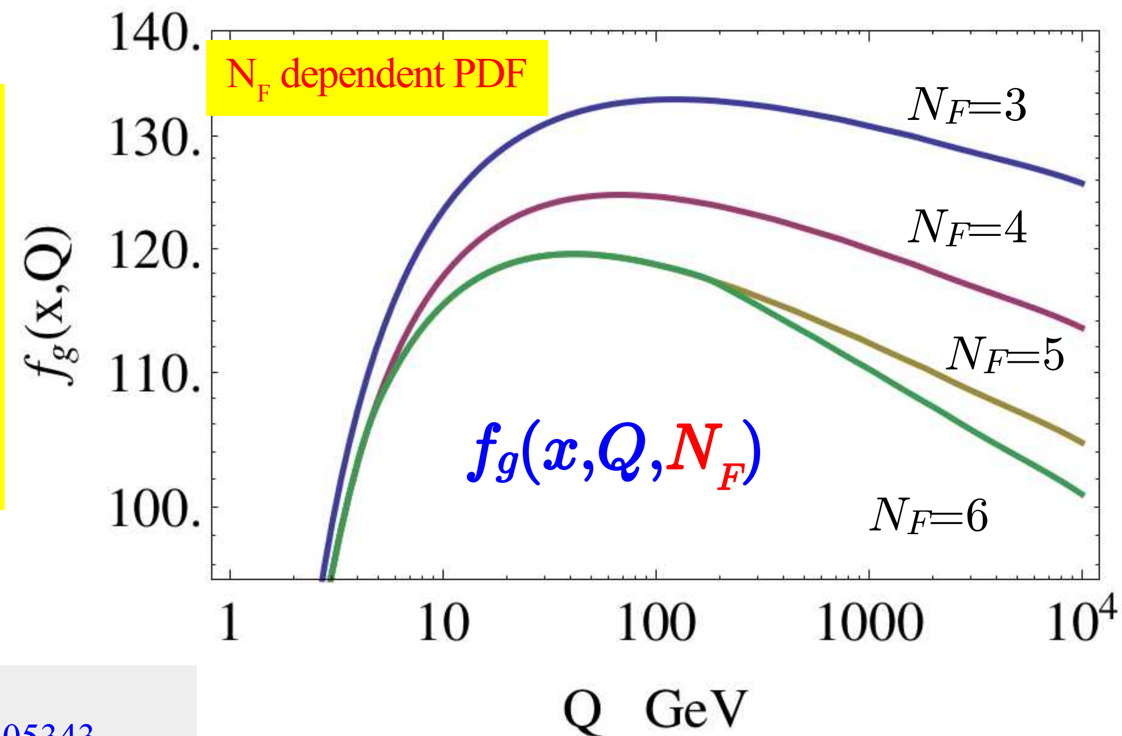
Advantages:
* avoid discontinuities in data
* avoid delicate cancellations
* minimal set of PDF grids

… for example, simultaneously

1) analyze HERA in N_F=4

2) analyze LHC in N_F=5





Impact of the heavy quark matching scales in PDF fits
The xFitter Developers Team: V. Bertone, et al., arXiv:1707.05343

TOP


top quark
TOP QUARK
This heavyweight champion doesn't live long enough to make friends with anyone.

Top Quark Production at LHC

Observation of top quark production in proton-nucleus collisions
The CMS Collaboration
arXiv:1709.07411

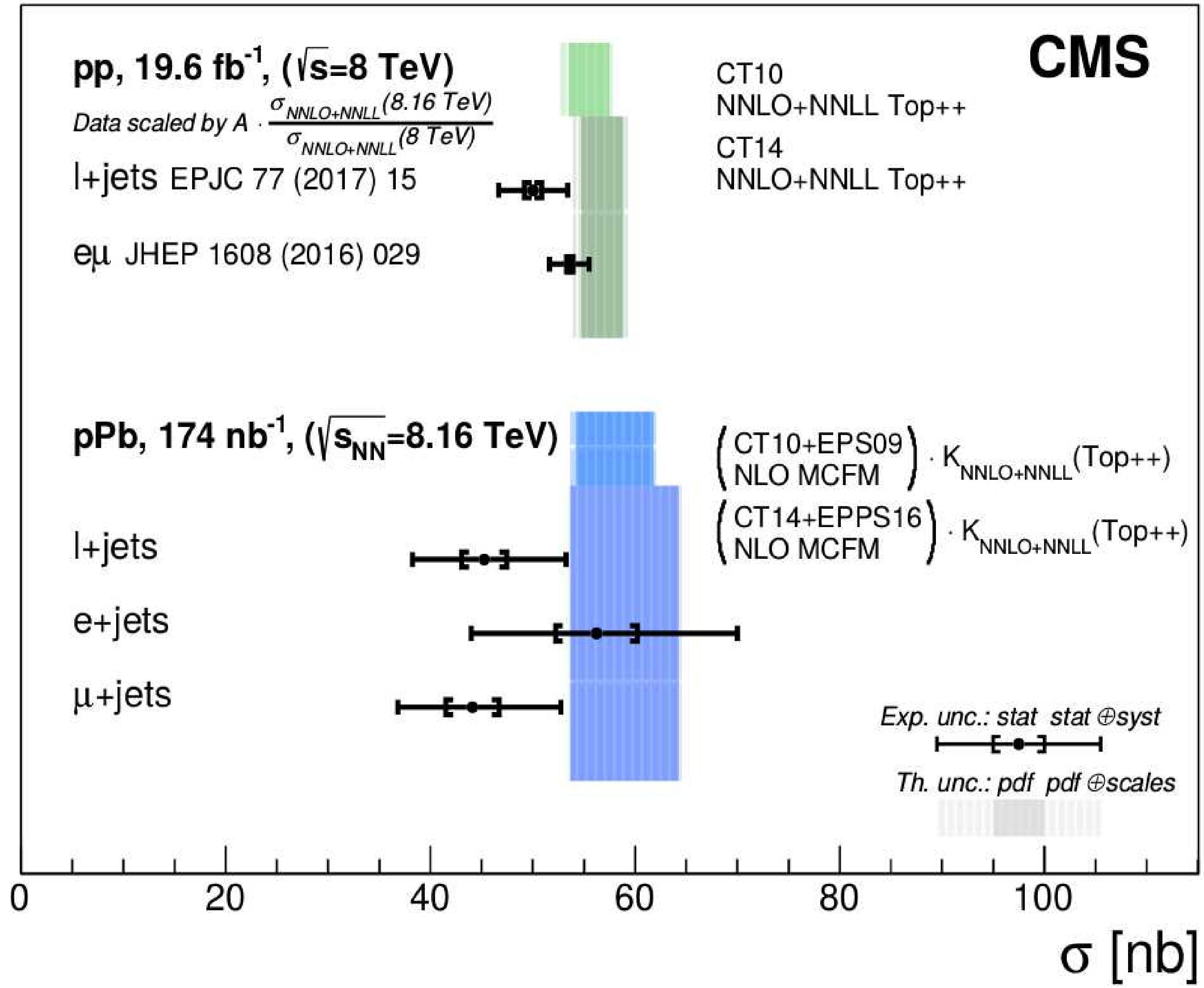


Figure 3: Total $t\bar{t}$ cross sections measured in the e+jets, μ+jets, and combined ℓ+jets channels in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV, compared to theoretical NNLO+NNLL predictions, and to scaled $\sqrt{s} = 8$ TeV pp results [38, 39]. The total experimental error bars (theoretical error bands) include statistical and systematic (PDF and scale) uncertainties added in quadrature.

xfitter

NEW

xFitter release xfitter-2.0.0

www.xFitter.org

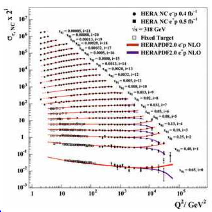
xFitter

xFitter/xFitterTalks » xFitter/../xFitterDevel.. » xFitter/../Meeting2017-.. » xFitter » xFitter/DownloadPage

Sample data files:

- **LHC:** ATLAS, CMS, LHCb
- **Tevatron:** CDF, D0
- **HERA:** H1, ZEUS, Combined
- **Fixed Target:** …
- **User Supplied:** ...

Experimental Data



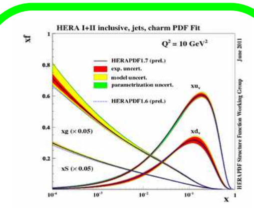
Data: HERA, Tevatron, LHC, fixed target experiments

Processes:
Inclusive DIS, Jets, Drell-Yan, Diffraction, Top production W and Z production

Theory Calculations

HQ Schemes:	MSTW, NNPDF, ABM, ACOT
Jets, W, Z:	FastNLO, ApplGrid
Top:	Hathor
Evolution:	QCDNUM, APFEL, k_T
Other:	NNPDF reweighting
	TMDs, Dipole Model, ...

xFitter



Parton Distribution Functions: PDF, Updf, TMD

$\alpha_S(M_Z)$, m_c,m_b,m_t ...

Theoretical Cross Sections

Comparisons to other PDFs (LHAPDF)

xFitter 2.0.0
FrozenFrog

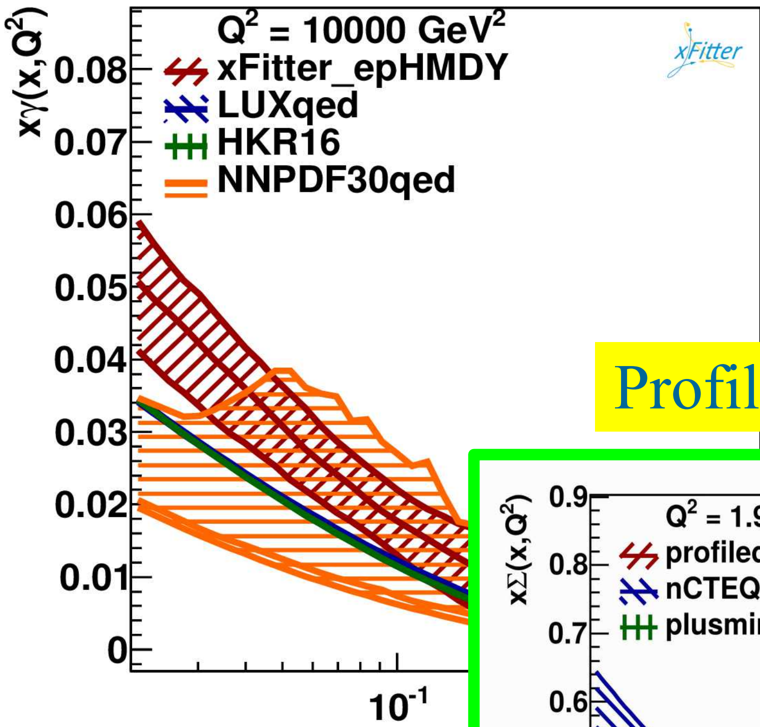
Features & Recent Updates:

- Photon PDF & QED
- Pole & MS-bar masses
- Profiling and Re-Weighting
- Heavy Quark Variable Treshold
- Improvements in χ^2 and correlations
- TMD PDFs (uPDFs)
- *... and many other*

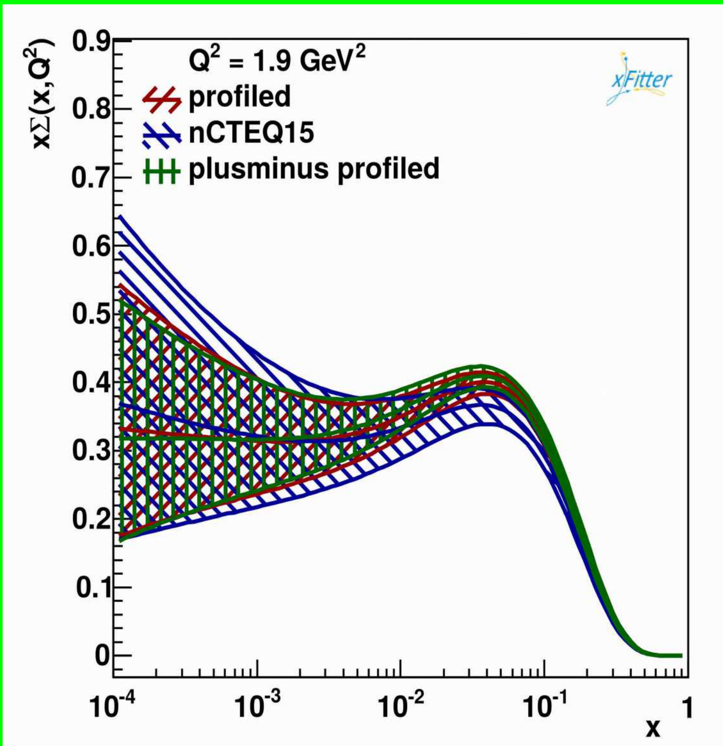
NEW xFitter release xfitter-2.0.0

www.xFitter.org

Photon PDF

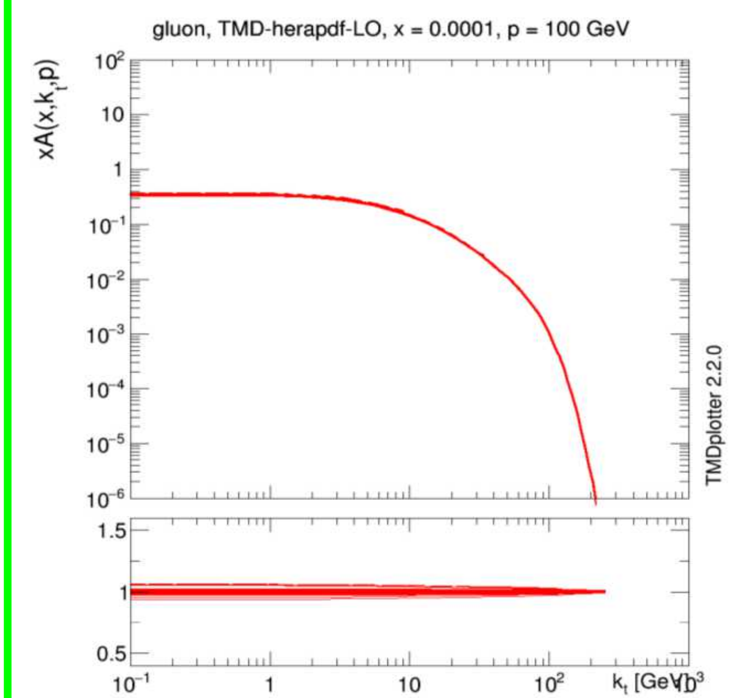


Profiling Lead PDFs



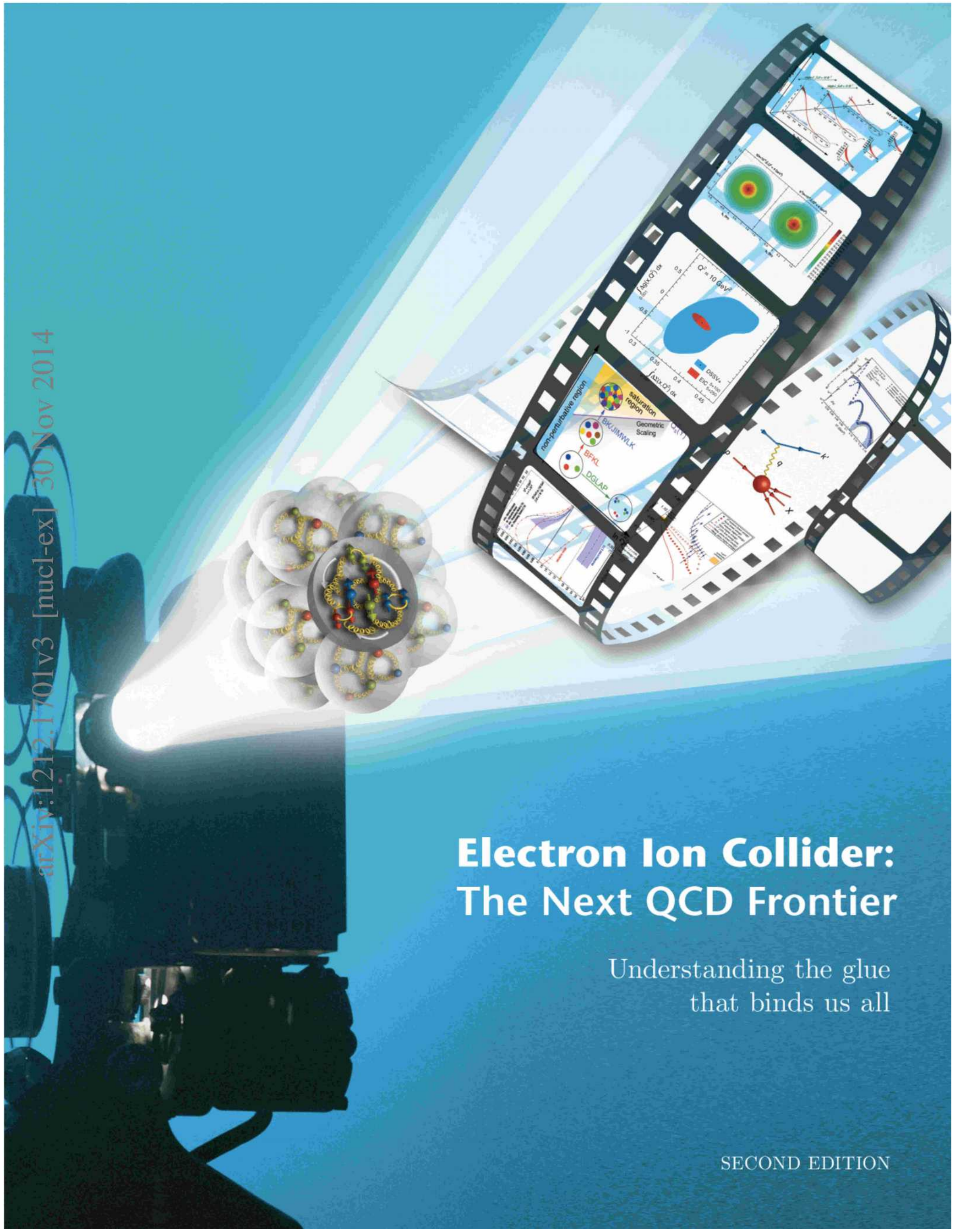
TMD (uPDFs) in xFitter

TMDs from fits - comparison of LO and NLO



TMDs with experimental uncertainties.

Future Facilities


Electron Ion Collider:
The Next QCD Frontier
Understanding the glue
that binds us all
SECOND EDITION


http://cern.ch/lhec
lhec.ws@cern.ch
Workshop on the LHeC
Electron-proton and electron-ion collisions at the LHC
24 June 2015 CERN
25-26 June 2015 Chavannes-de-Bogis, Switzerland
International Advisory Committee
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Sergio Bertolucci (CERN)
Nicola Bianchi (INFN)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago and Fermilab)
Victor A. Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
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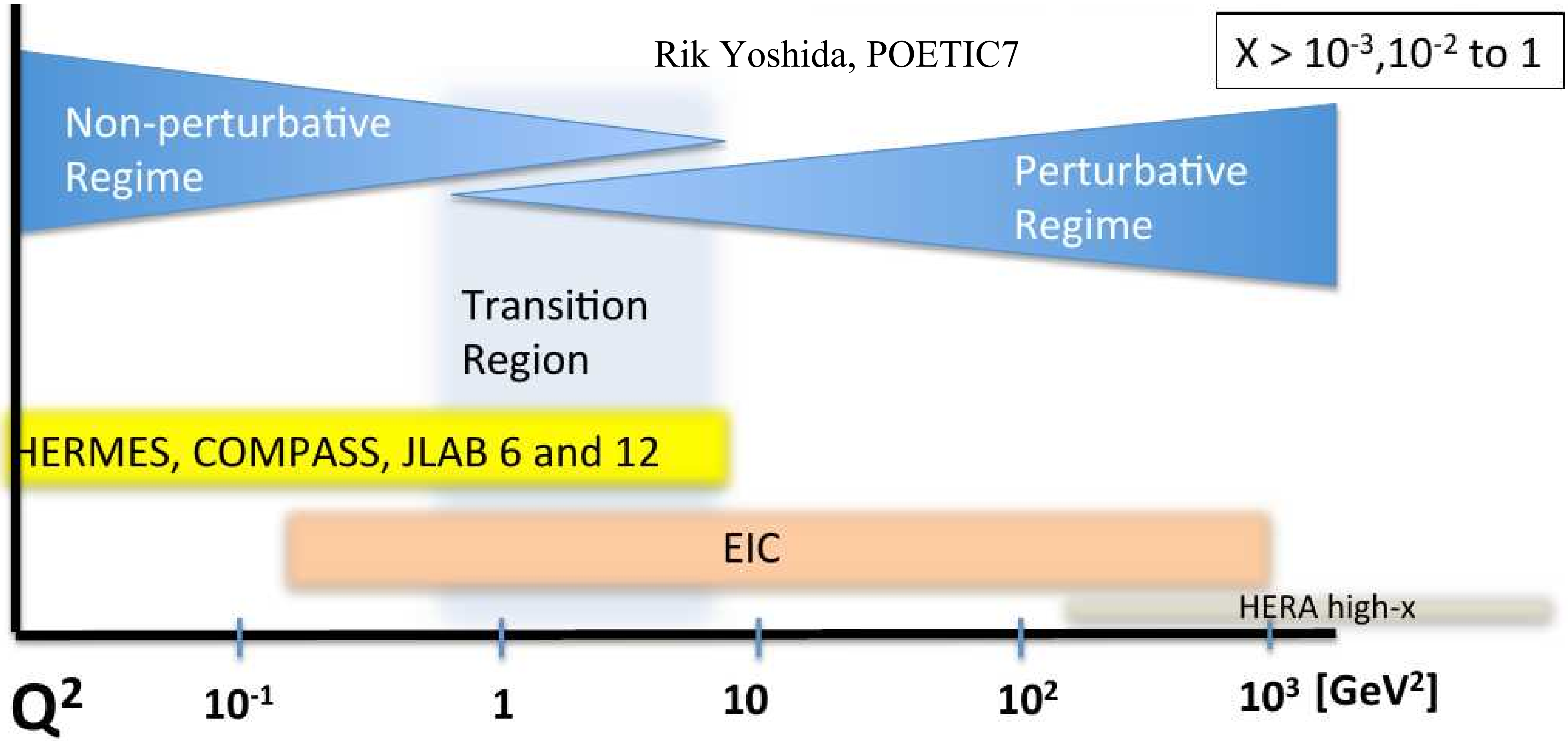
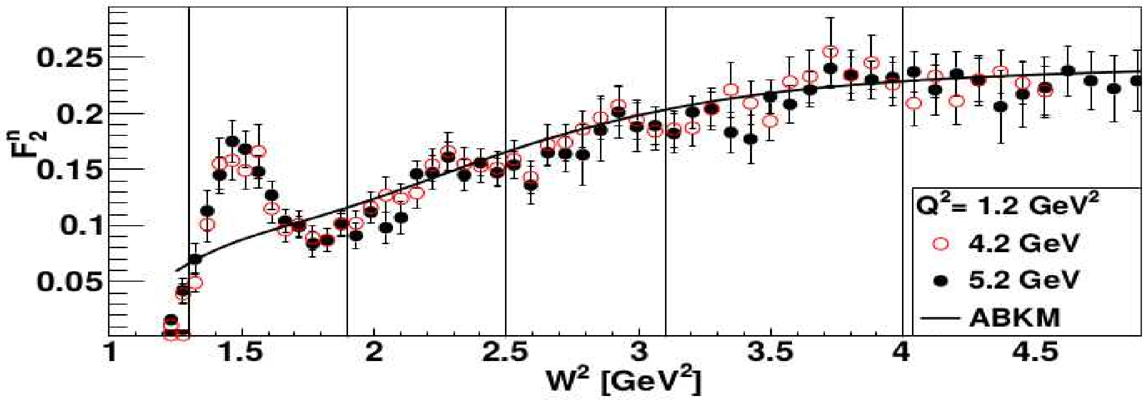
Electron Ion Collider





The Physics Programme of the LHeC

arXiv:1206.2913 (CDR) 1211.4831 and 5102

QCD Discoveries	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$
Higgs	WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate
Substructure	electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H?
New and BSM Physics	leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s
Top Quark	top PDF, $xt = x\overline{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c
Precision DIS	$\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure	Proton, Deuteron, Neutron, Ions, Photon
Quark Distributions	valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \overline{s}$?, charm, beauty, top
QCD	N^{3}LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing
Heavy Ions	initial QGP, nPDFs, hadronization inside media, black limit, saturation
Modified Partons	PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

Thanks to my xFitter & nCTEQ colleagues

xFitter Meeting: Oxford March 2017

A special thanks to
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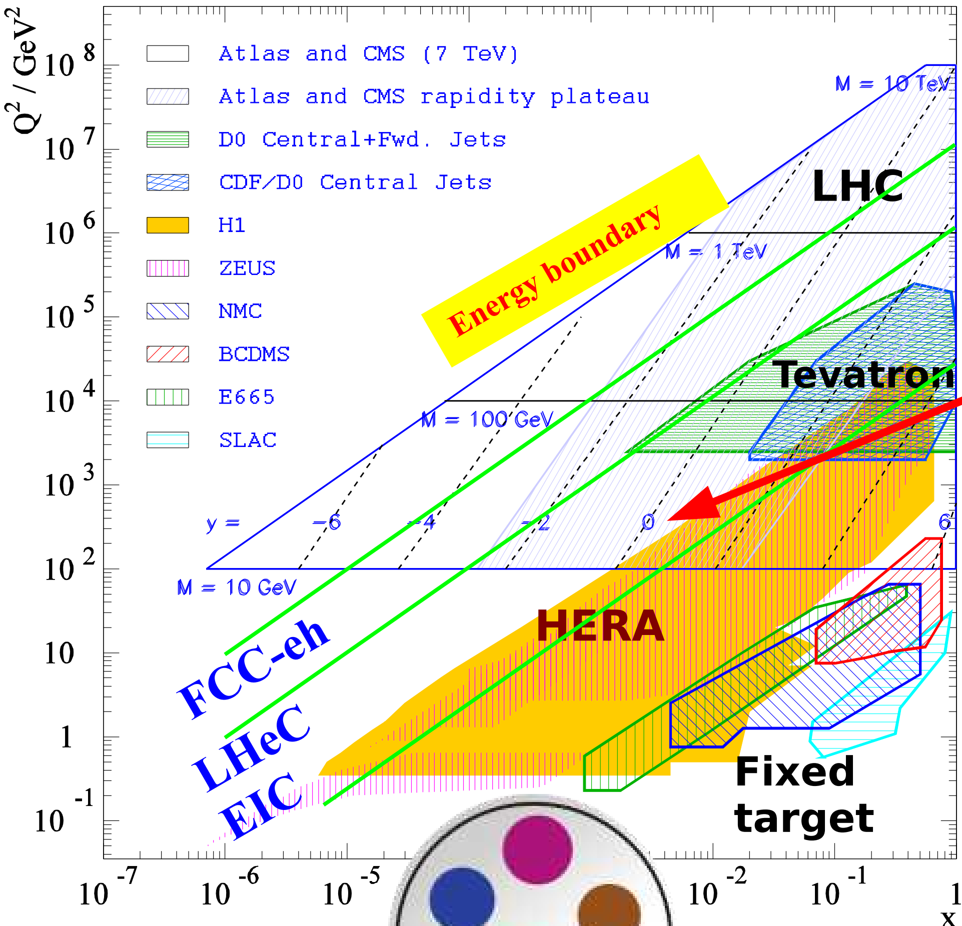
Ringaile Placakyte & Voica Radescu

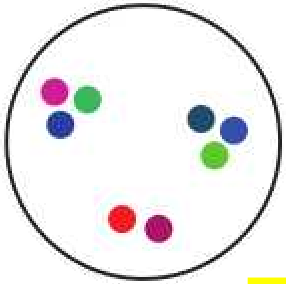
nCTEQ & friends @ Grenoble

nCTEQ
nuclear parton distribution functions

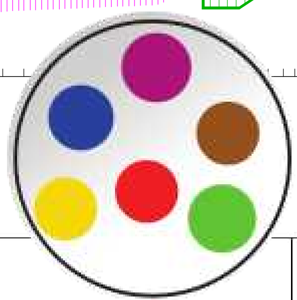
The Future Frontier: Pushing Kinematic Boundaries + Innovative Ideas



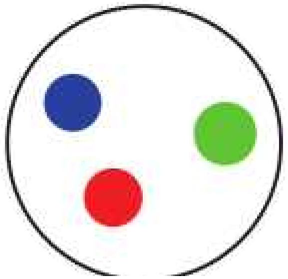
Precision

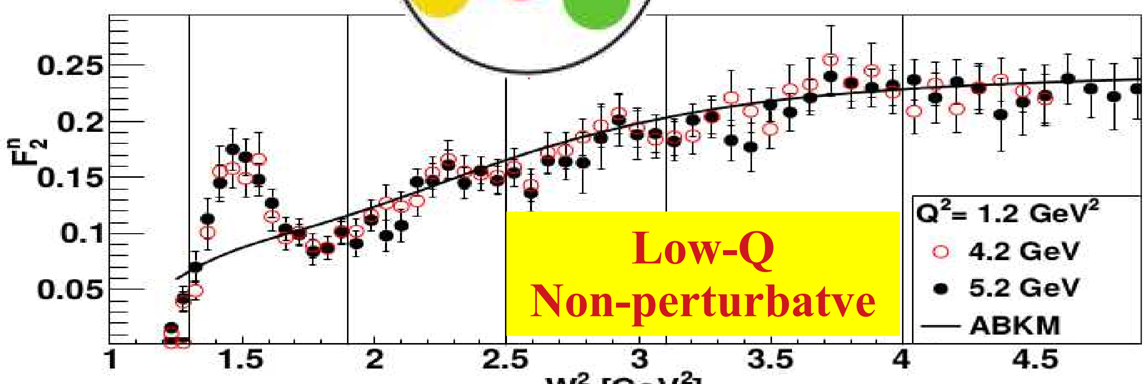


Low-x
Shadowing
Recombination
Resummation



Hi-x
Higher Twist





Low-Q
Non-perturbatve