Nuclear Correction and the nCTEQ PDFs:

Progress, Puzzles, and Challenges

Fred Olness
SMU

Thanks for substantial input
from my friends & colleagues

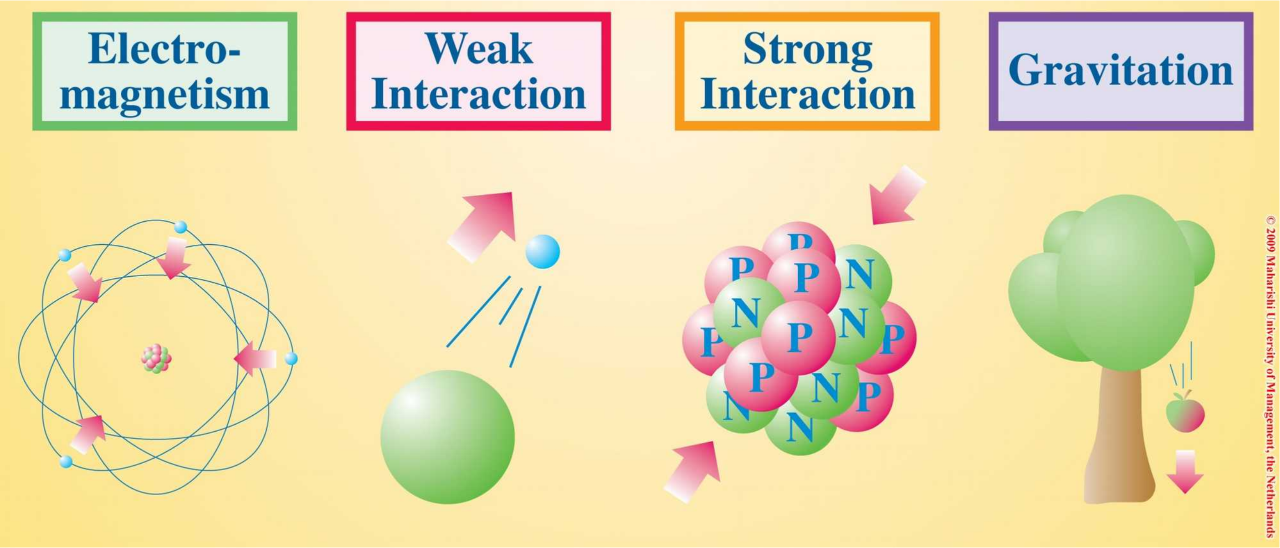
C T E Q

xFitter

nCTEQ
nuclear parton distribution functions

2nd JETSCAPE Winter School and Workshop
9-13 January 2019
Texas A&M University

“QCD is our most perfect physical theory” *Frank Wilczek*



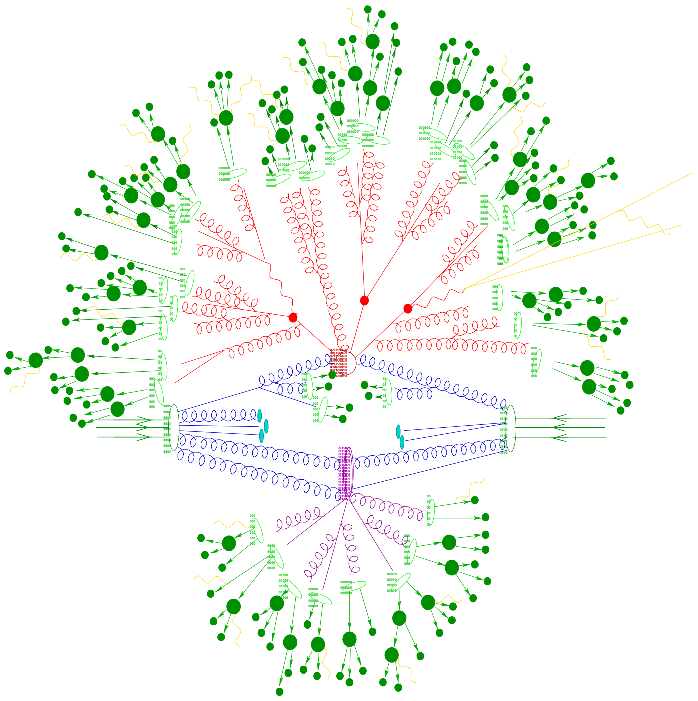
QCD is our most perfect physical theory

What QCD Tells Us About Nature – and Why We Should Listen. *Frank Wilczek*

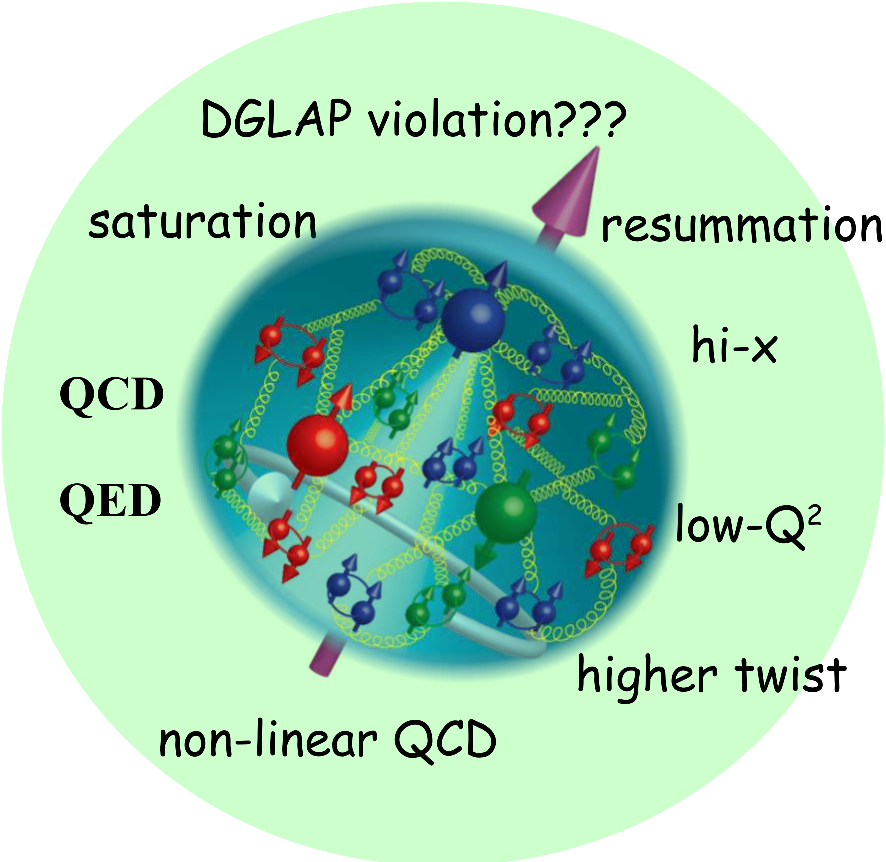
In many respects, our most complex
- asymptotic freedom
- strong color confinement
- … associated manifestations

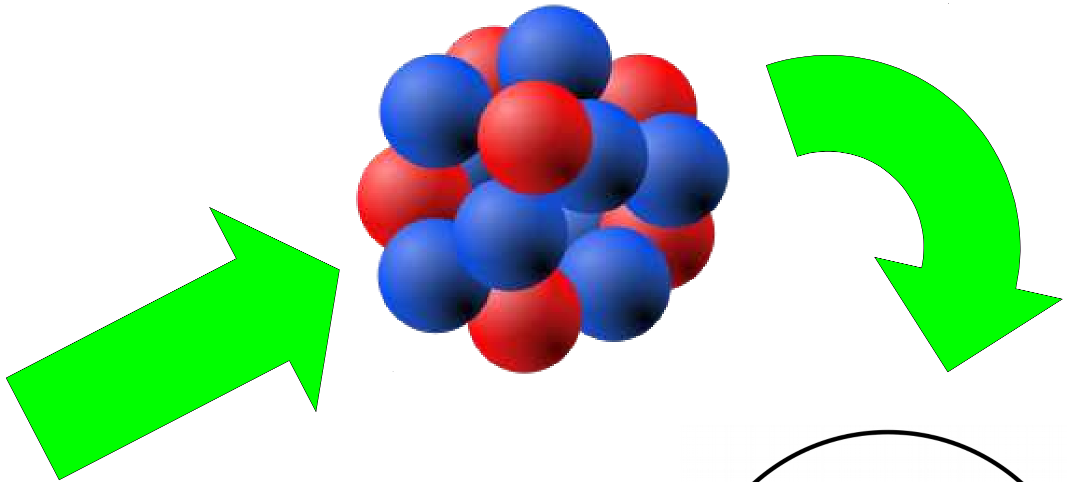
Lessons: The Nature of Nature

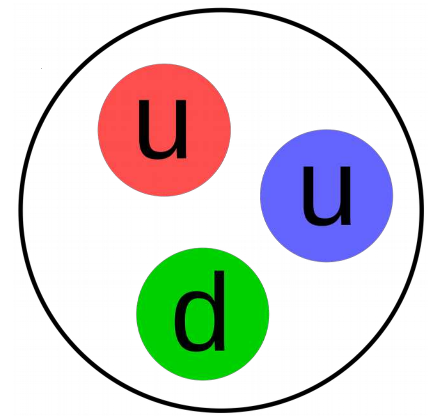
“… alien, simple, beautiful, weird, & comprehensible"



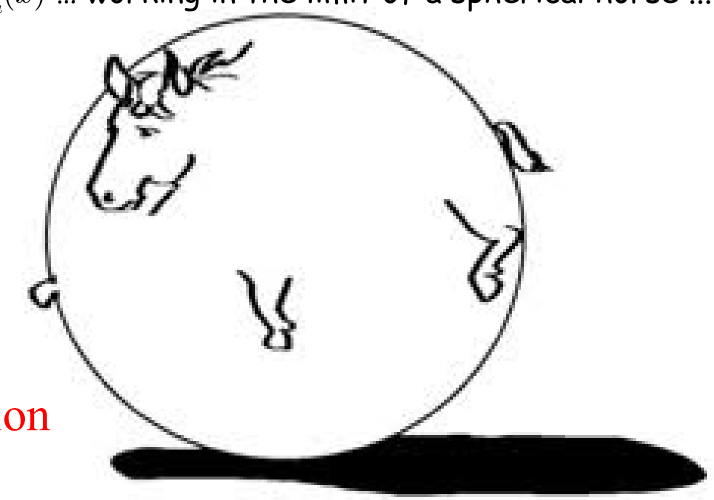
PDFs & the Parton Model ... *a few simpifications*







$f_a(x)$ ... working in the limit of a spherical horse ...



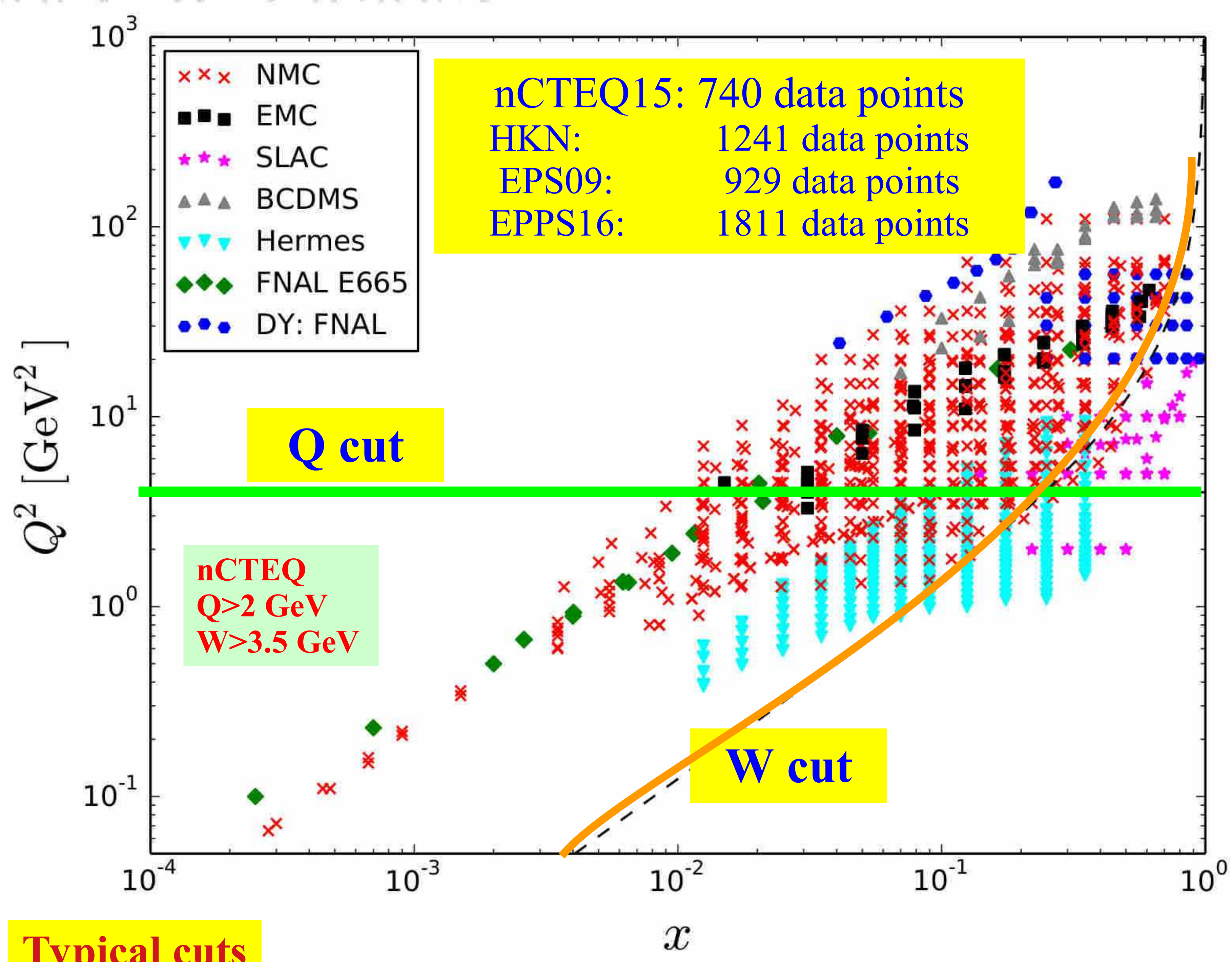
The QCD Parton Model

$$d\sigma = f_a(x) \otimes \widehat{\sigma}$$

Parameterized in terms of a single variable x, the momentum fraction

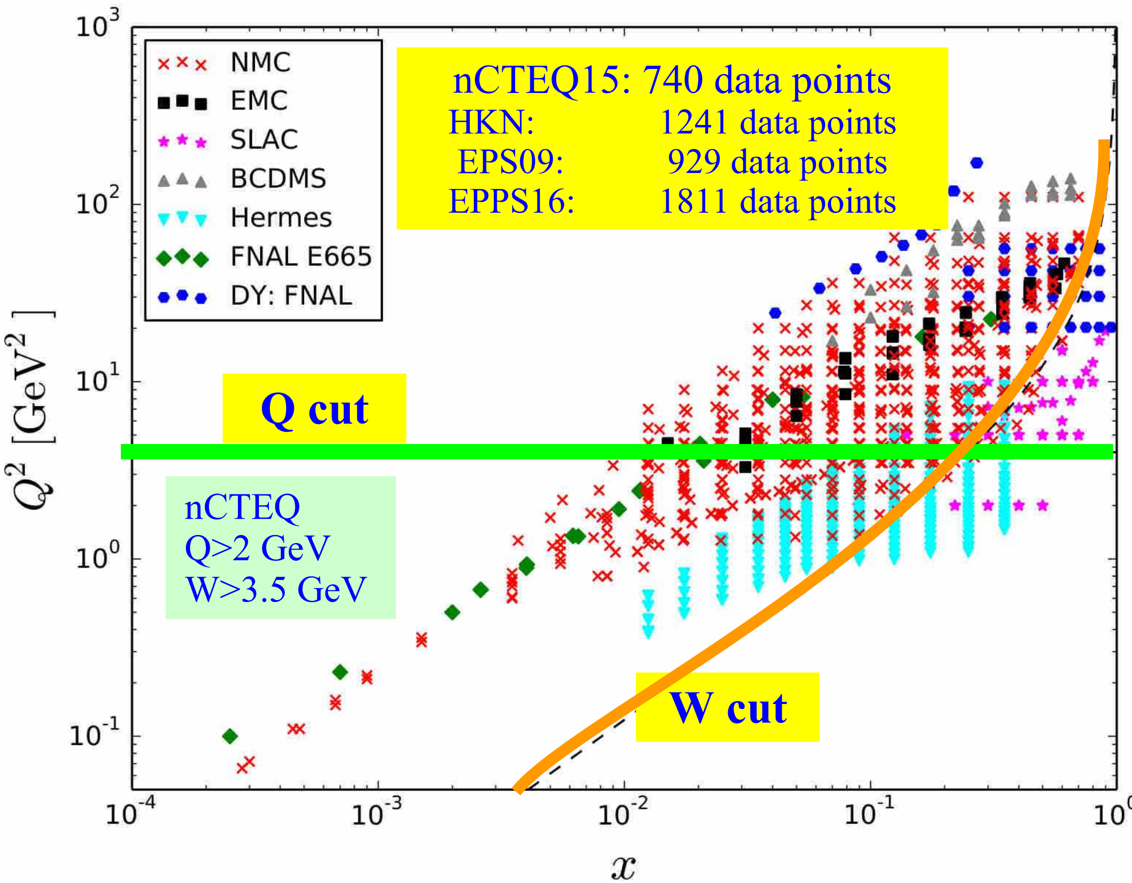
... use DGLAP to determine μ dependence

Input Data for Global nPDF Fits



Typical cuts

Hadron / Parton Transition:

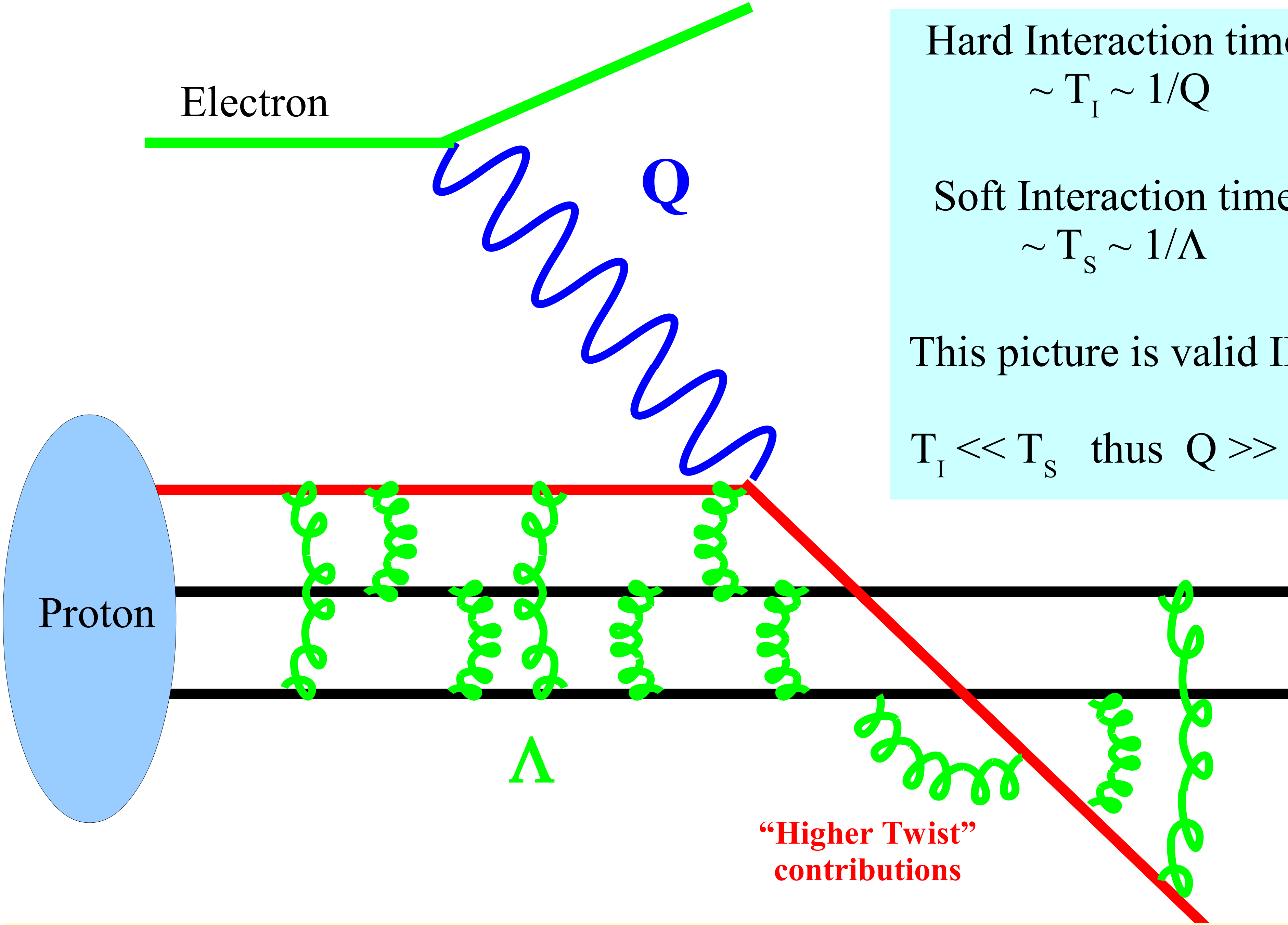


We're leaving half the data on the floor

- Higher Twist,
- many body problem,
- duality,
- hi-x,
- mass corrections ...

EIC can push these boundaries

Quarks are not quite free



Hard Interaction time
$\sim T_I \sim 1/Q$

Soft Interaction time
$\sim T_S \sim 1/\Lambda$

This picture is valid IF:

$T_I \ll T_S$ thus $Q \gg \Lambda$

Corrections to this picture (non-factorizable/ higher twist) terms are suppressed by powers of Λ/Q

These are hard problems

…

we need good ideas

Accurately modeling ultra-relativistic heavy ion collisions

Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Nuclear Physics A 00 (2018) 1–4
Nuclear Physics A
www.elsevier.com/locate/procedia

JETSCAPE v1.0 Quickstart Guide

Kolja Kauder for the JETSCAPE Collaboration

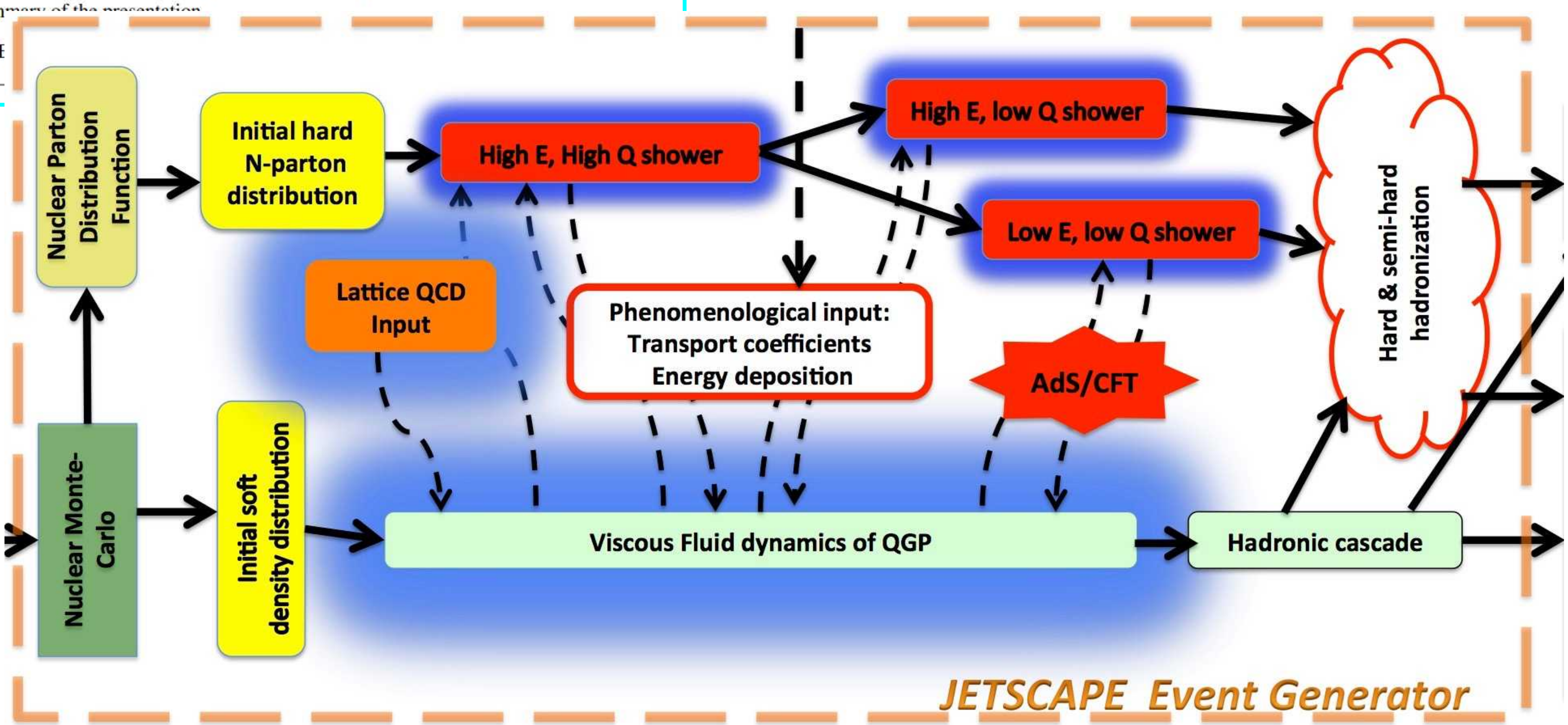
Dept. of Physics, Brookhaven National Lab, Upton, New York 11973

Abstract

The JETSCAPE collaboration announced the first public release of its framework and Monte Carlo event generator at this conference, providing a unified interface and a comprehensive suite of model implementations for all stages of ultra-relativistic heavy ion collisions. This release focuses on validation of the framework and the *pp* reference. A full manual is under development. In the mean-time, these proceedings will provide a guide for installation and simulation runs in lieu of the more traditional sum

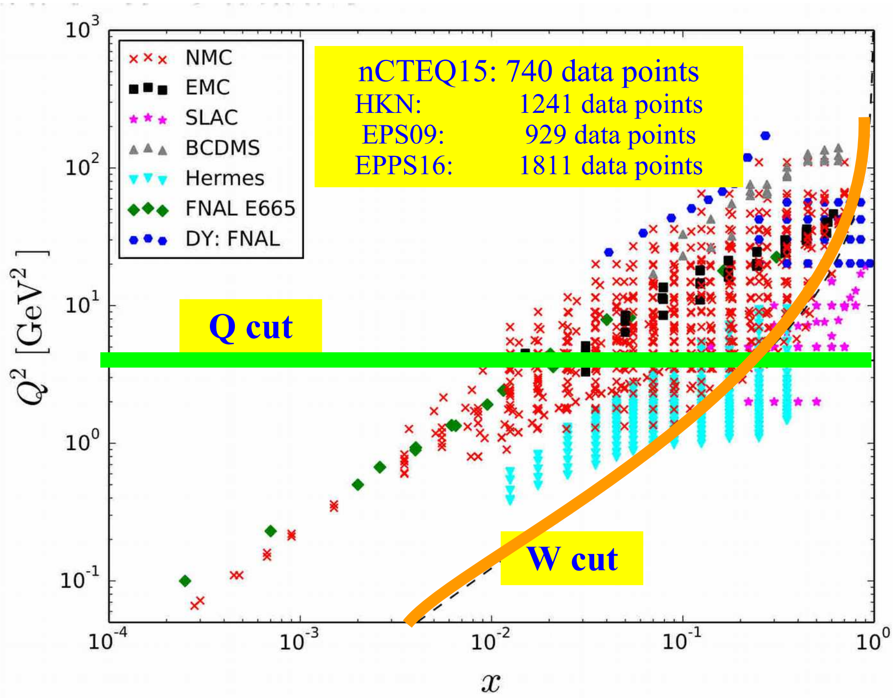
Keywords: Heavy-Ion Collisions, Jet E

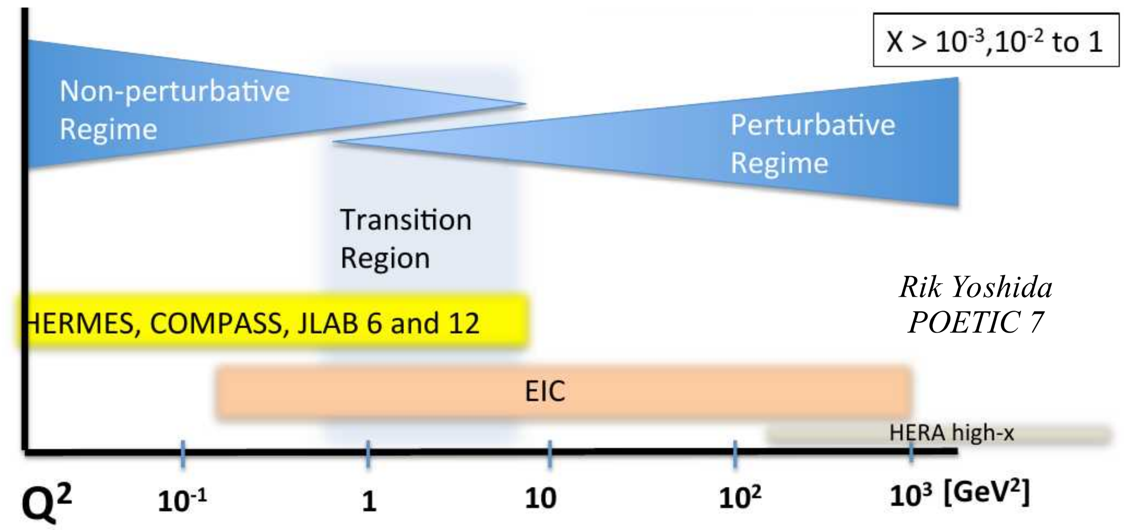
Jet
Energy-loss
Tomography with a
Statistically and
Computationally
Advanced
Program
Envelope
(JETSCAPE)
collaboration



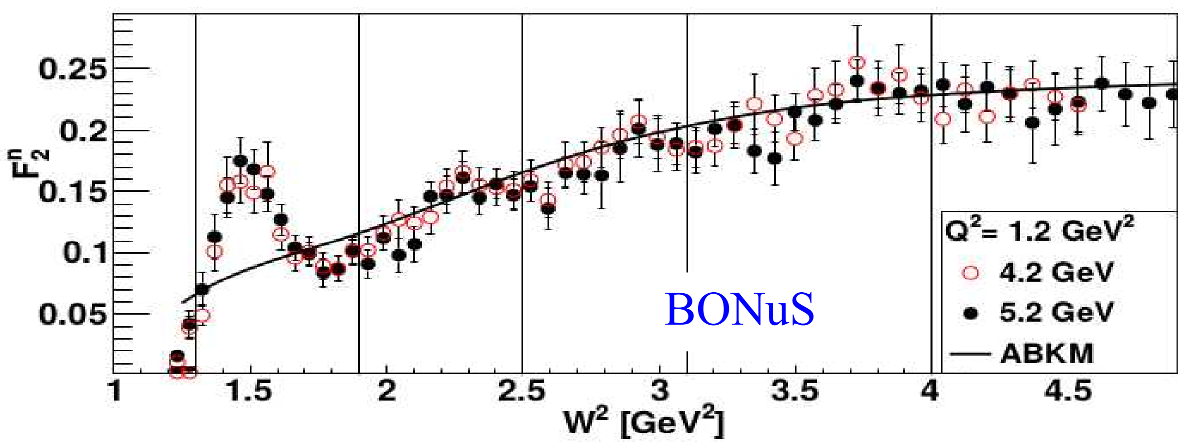
Hadron / Parton Transition: Extending the boundaries

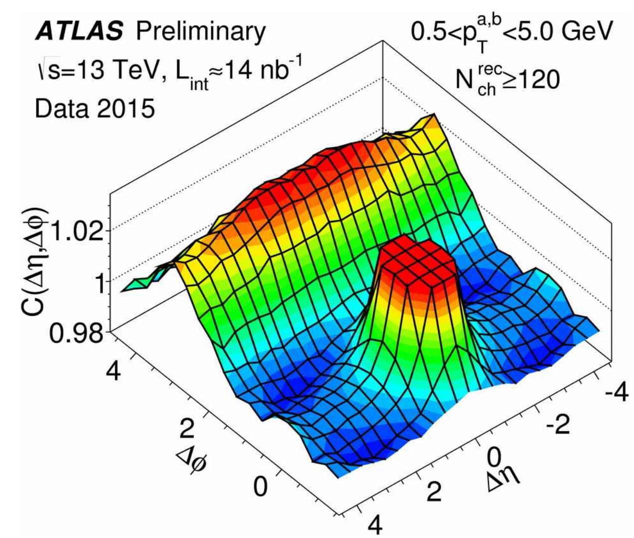
Higher Twist, many body problem, duality, hi-x, mass corrections ...





Rik Yoshida
POETIC 7

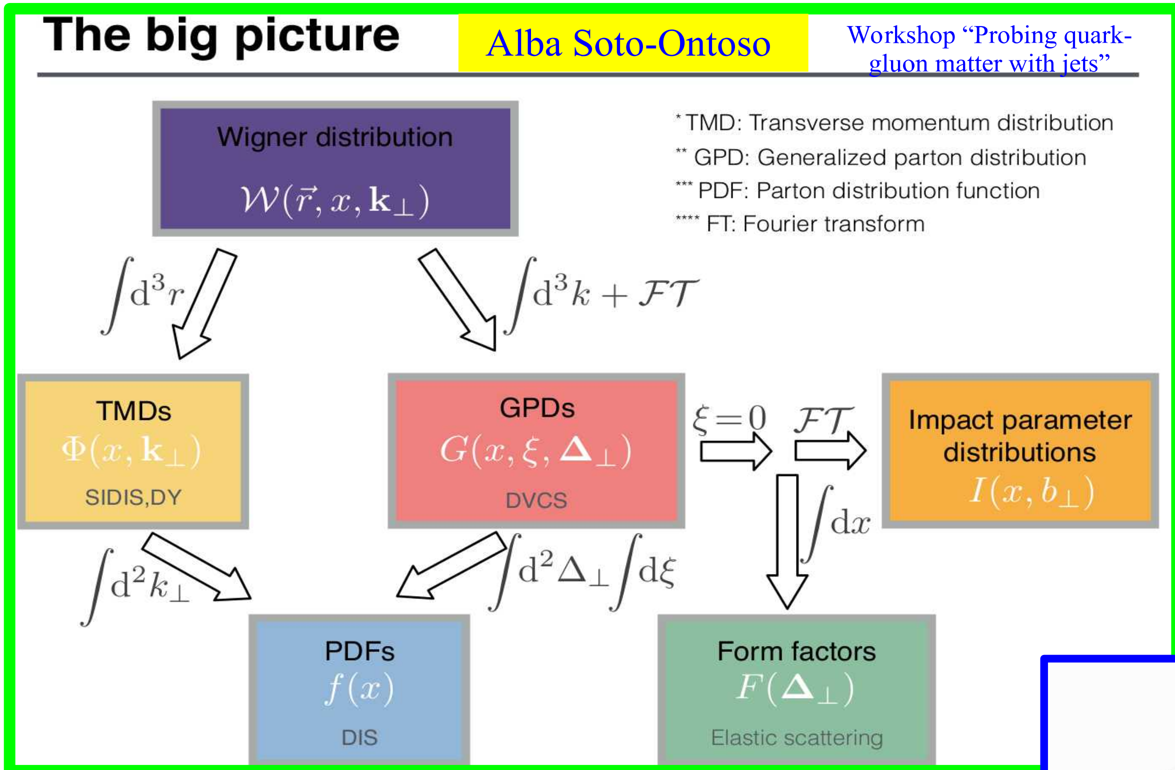


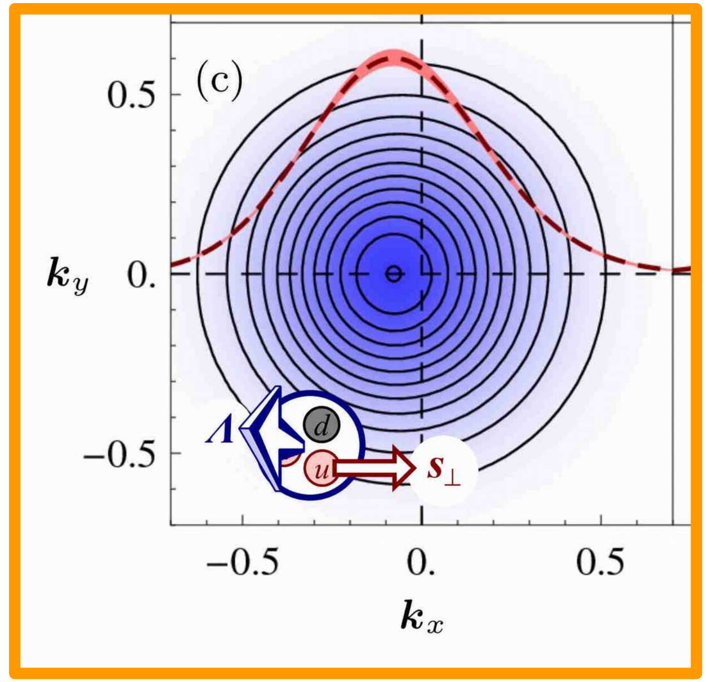


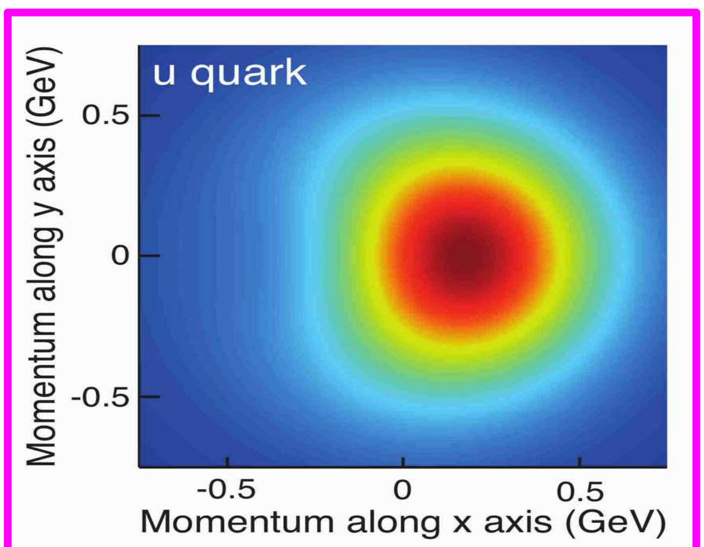
EIC can push these boundaries

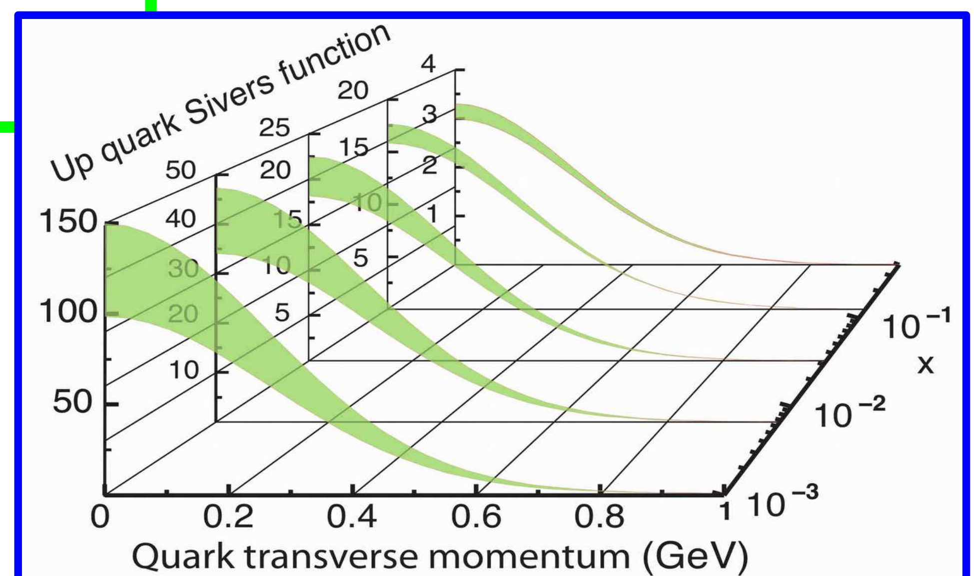
Thinking outside 1-Dimension *f(x)* ...

Hadron structure is much richer than f(x) conveys



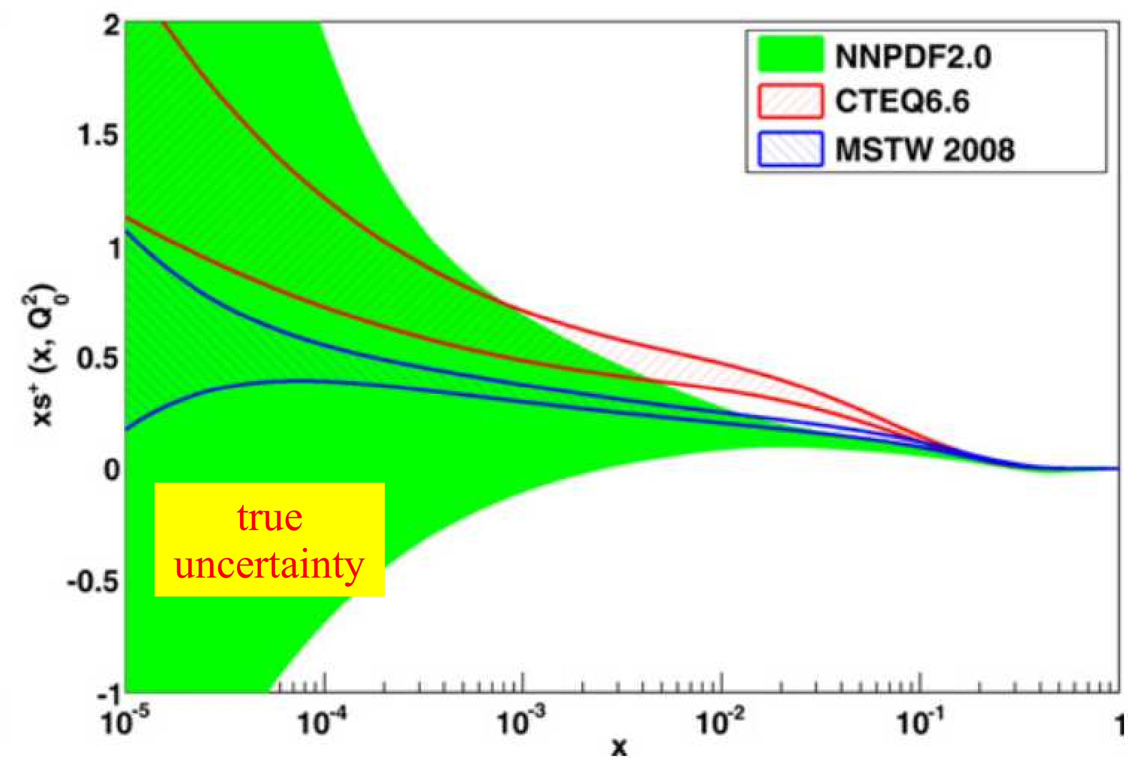


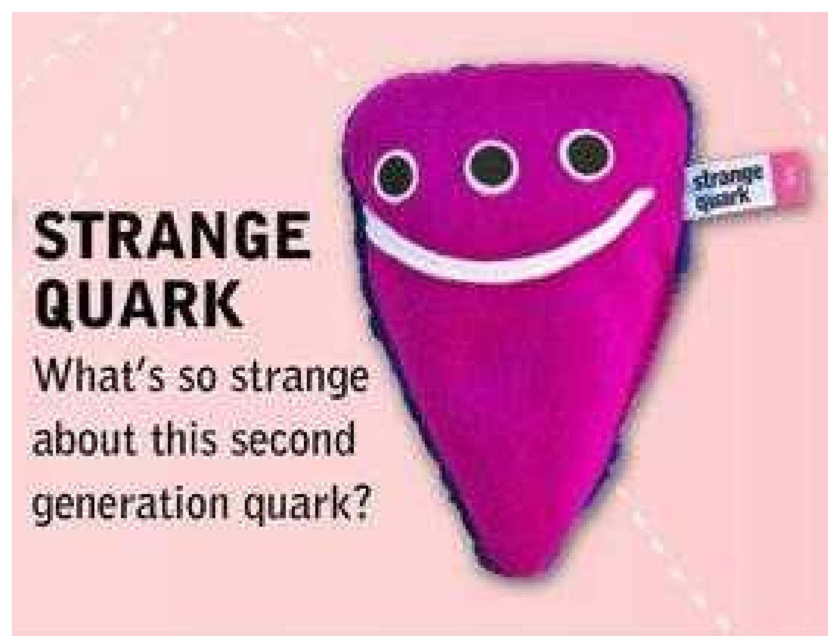




Conventional PDFs f(x) are the Boundary Conditions

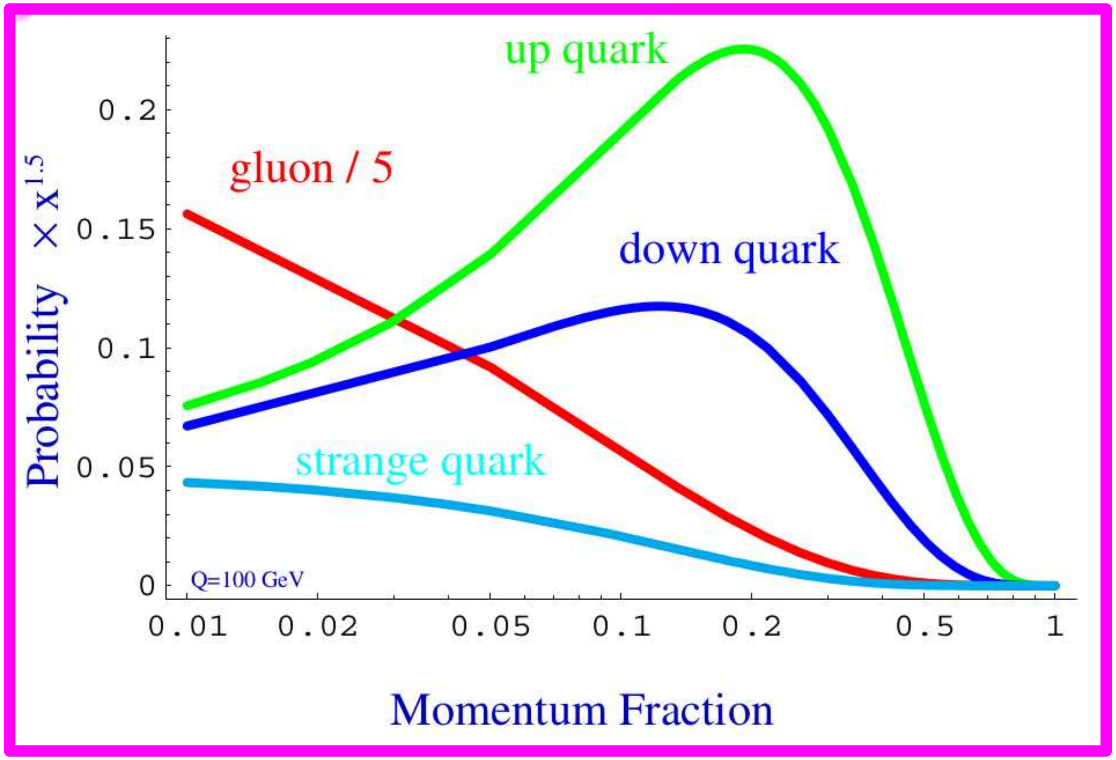
Case Study: The Strange PDF



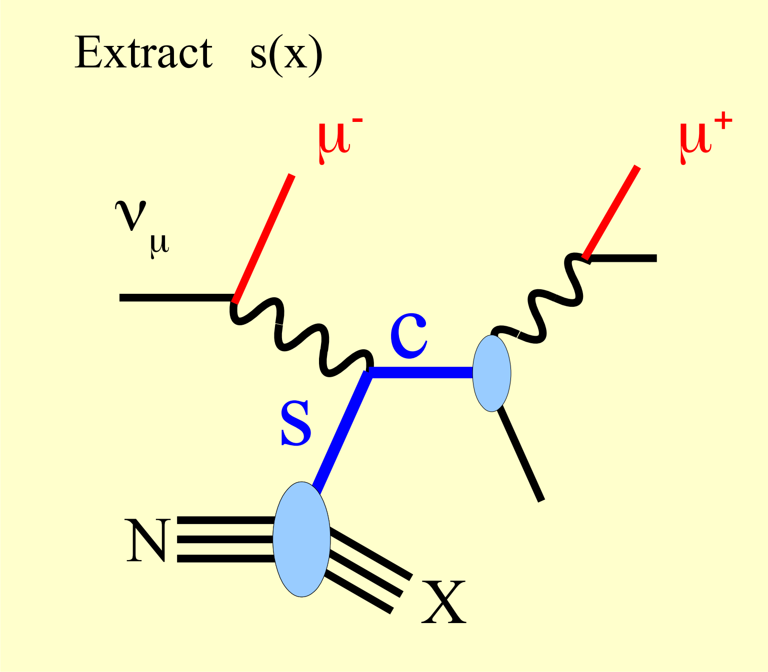


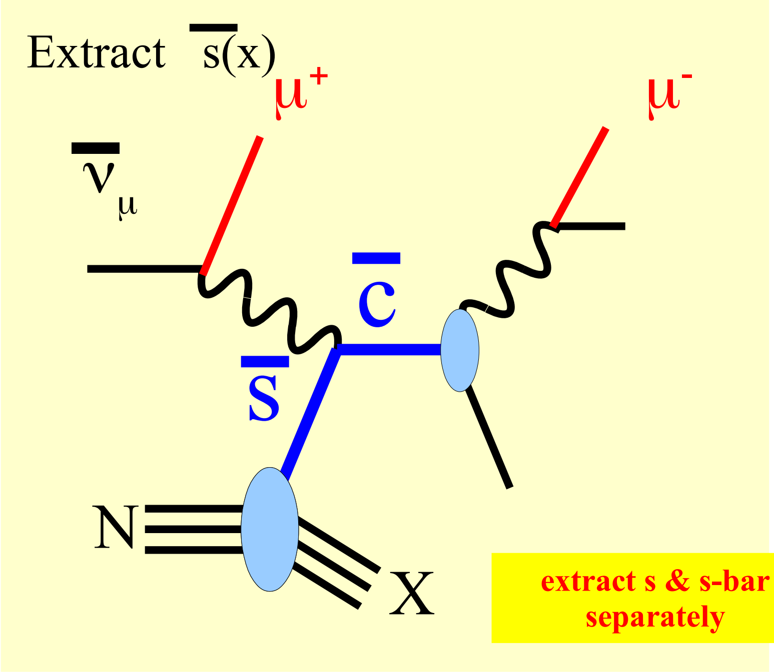
... where JETSCAPE tools could help out

Strange PDF: ν N di-muon Production



Need to "dig out" s(x) underneath d(x)

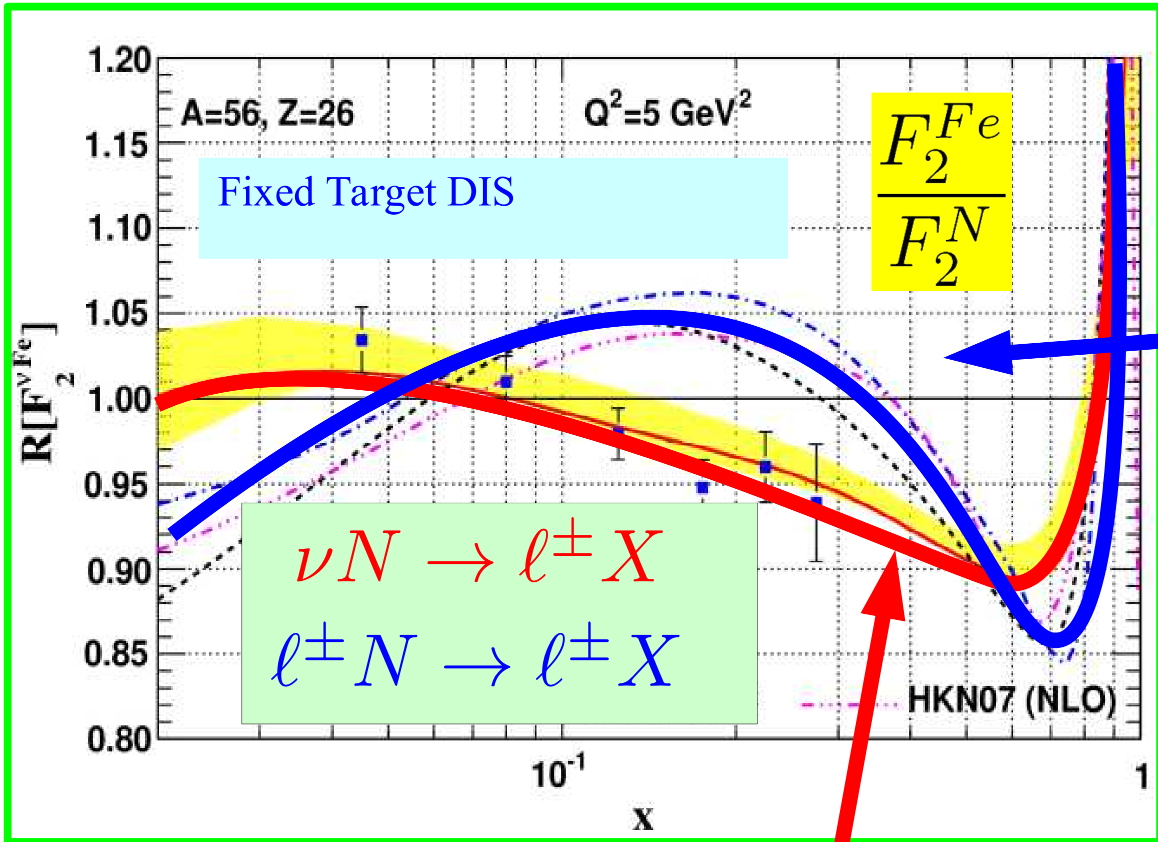


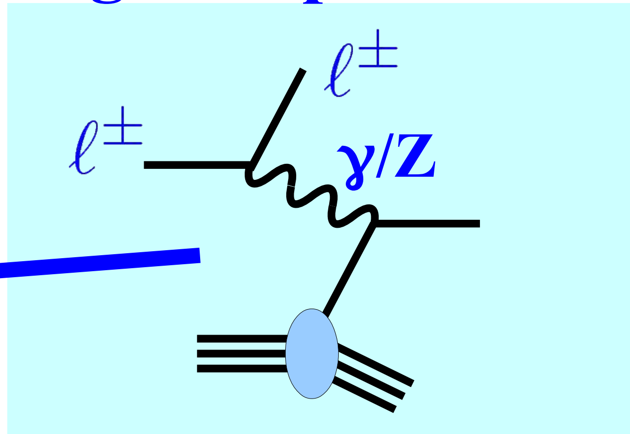


extract s & s-bar separately

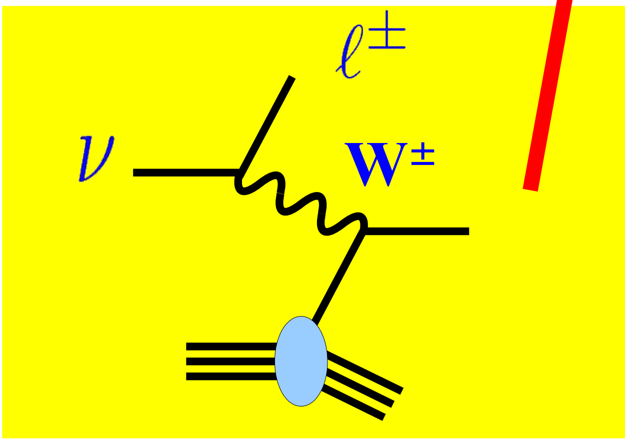
Puzzle: What is the Nuclear Correction

Charged Lepton DIS



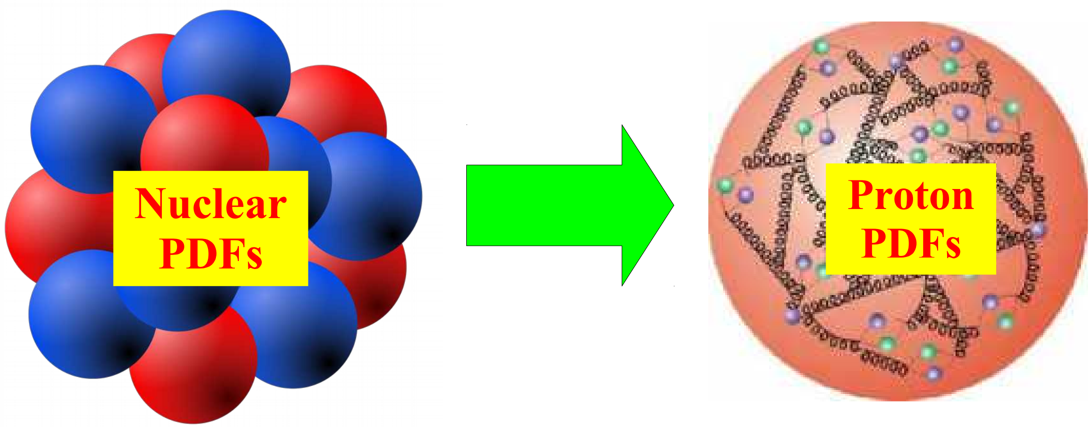


some caveats
... correlated errors



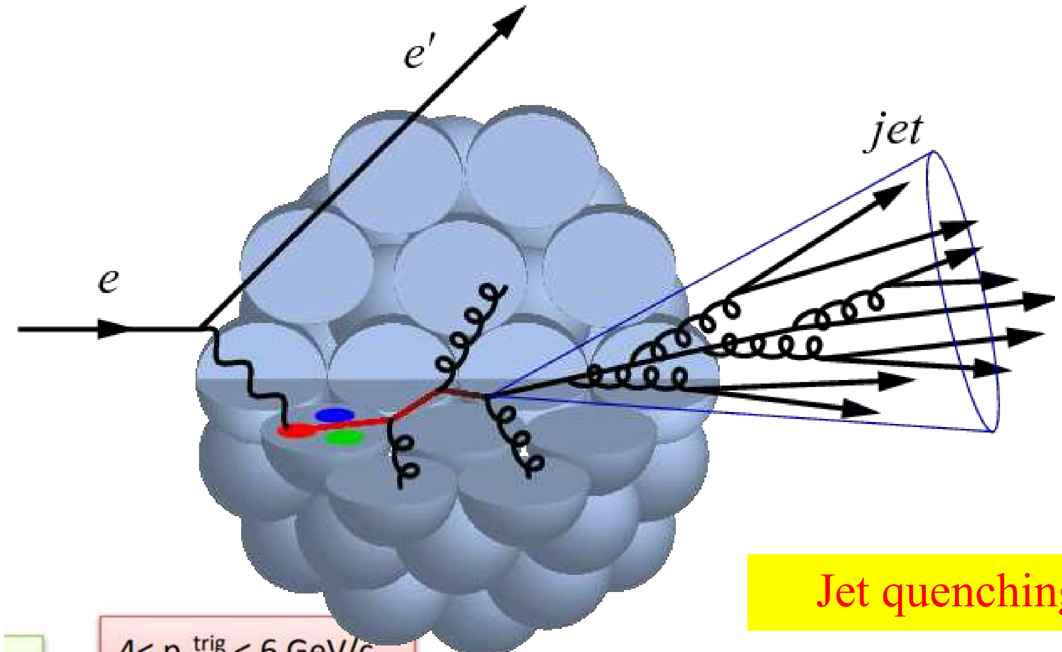
Neutrino DIS

Depends on nuclear corrections

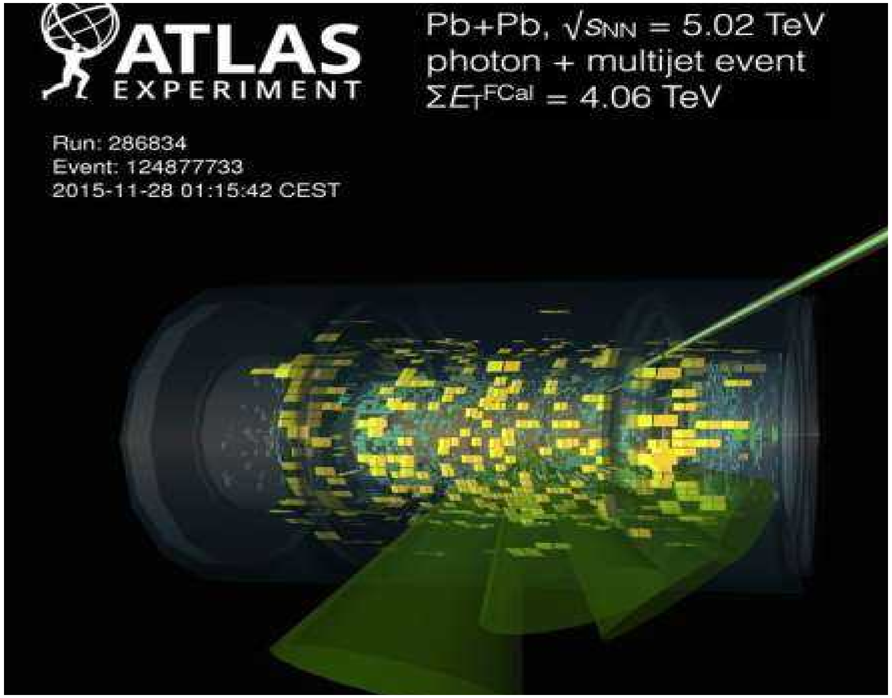


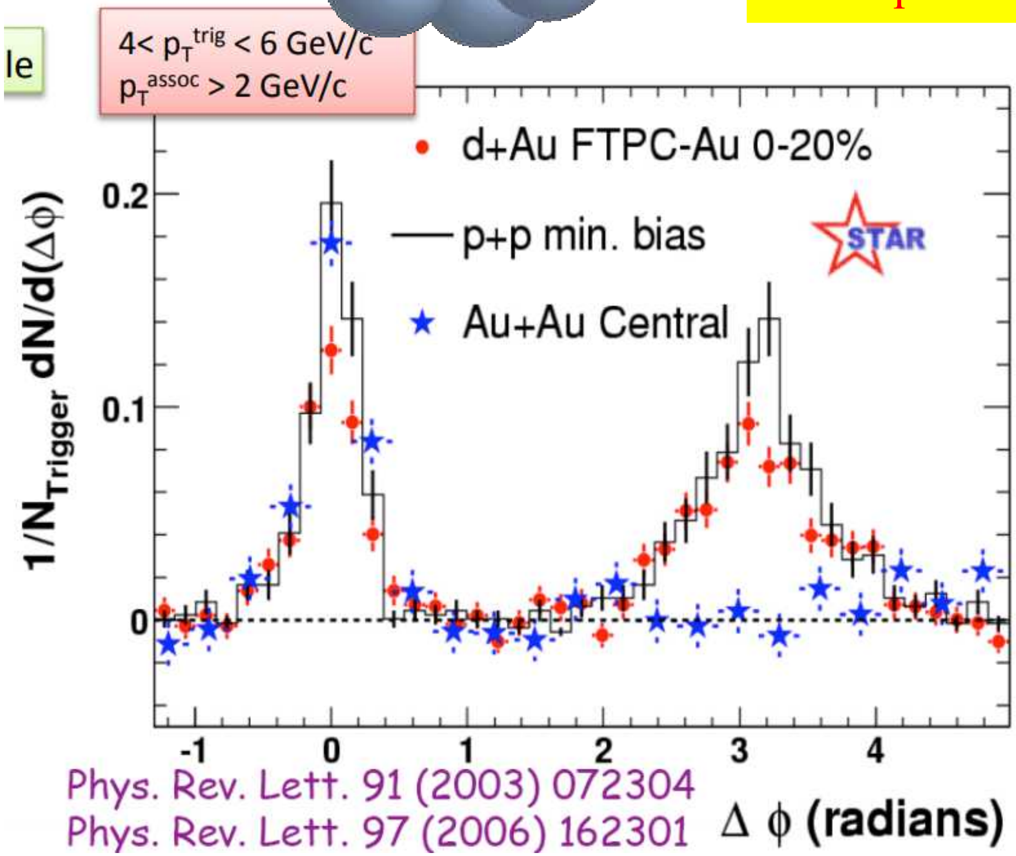
Propagation of γ/W thru nuclei

Propagation of γ/W thru nuclei

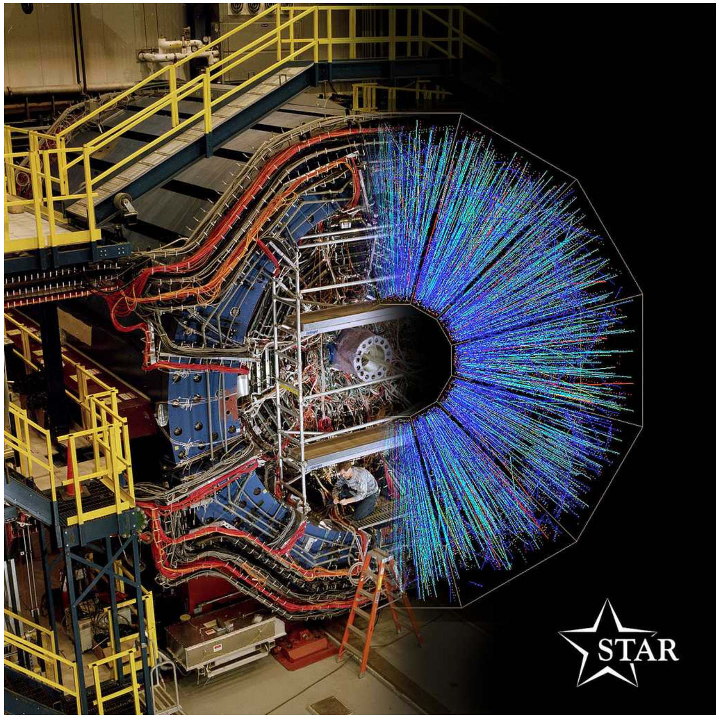


Jet quenching





Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

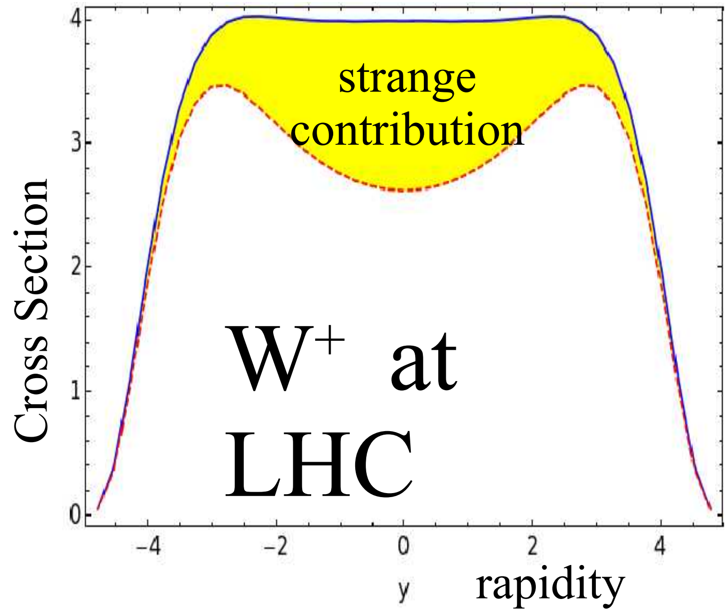


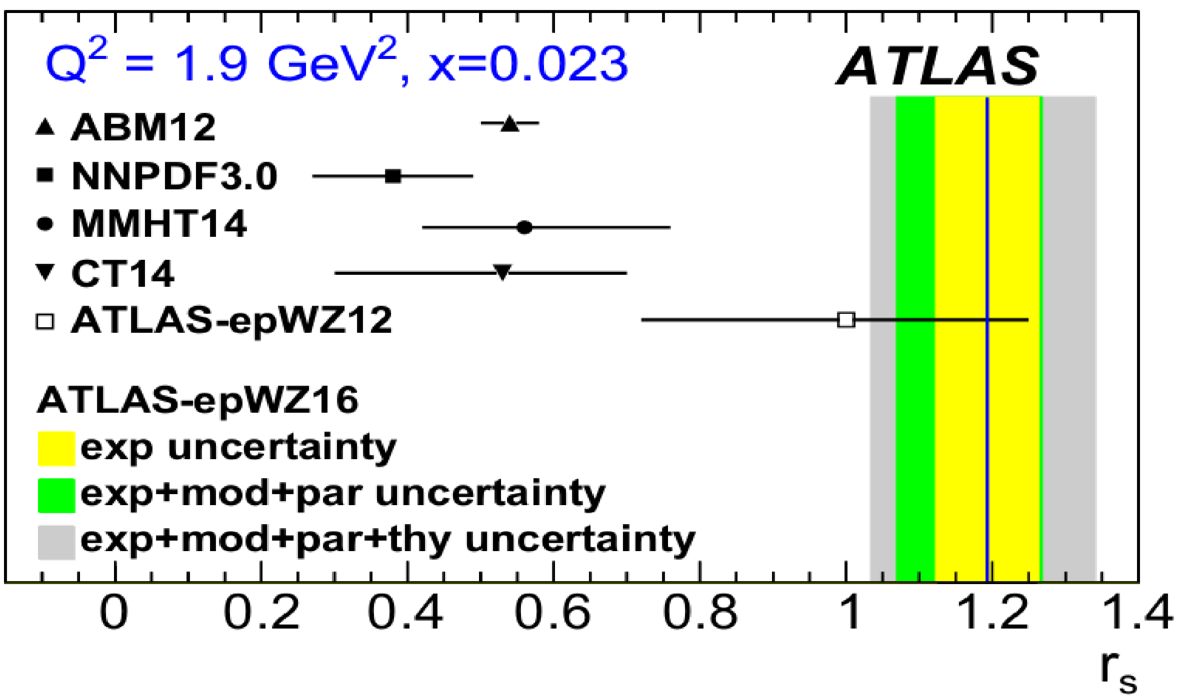
Nuclear PDFs

... are we modeling them accurately?

High Energy Insight: *W/Z Production at LHC and the strange PDF*

$$
\begin{aligned}
u\bar{d} + u\bar{s} + c\bar{d} + c\bar{s} &\rightarrow W^+ \\
\bar{u}d + \bar{u}s + \bar{c}d + \bar{c}s &\rightarrow W^- \\
u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} &\rightarrow Z
\end{aligned}
$$



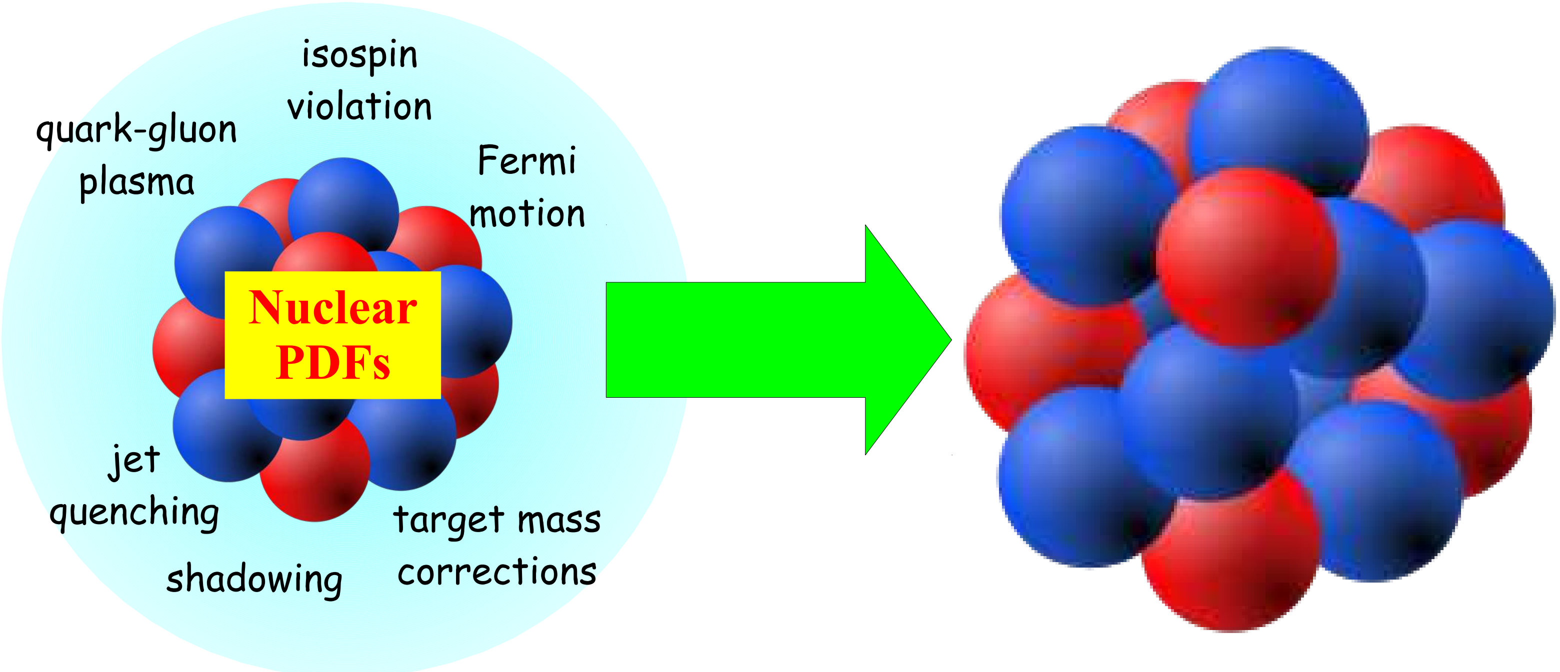


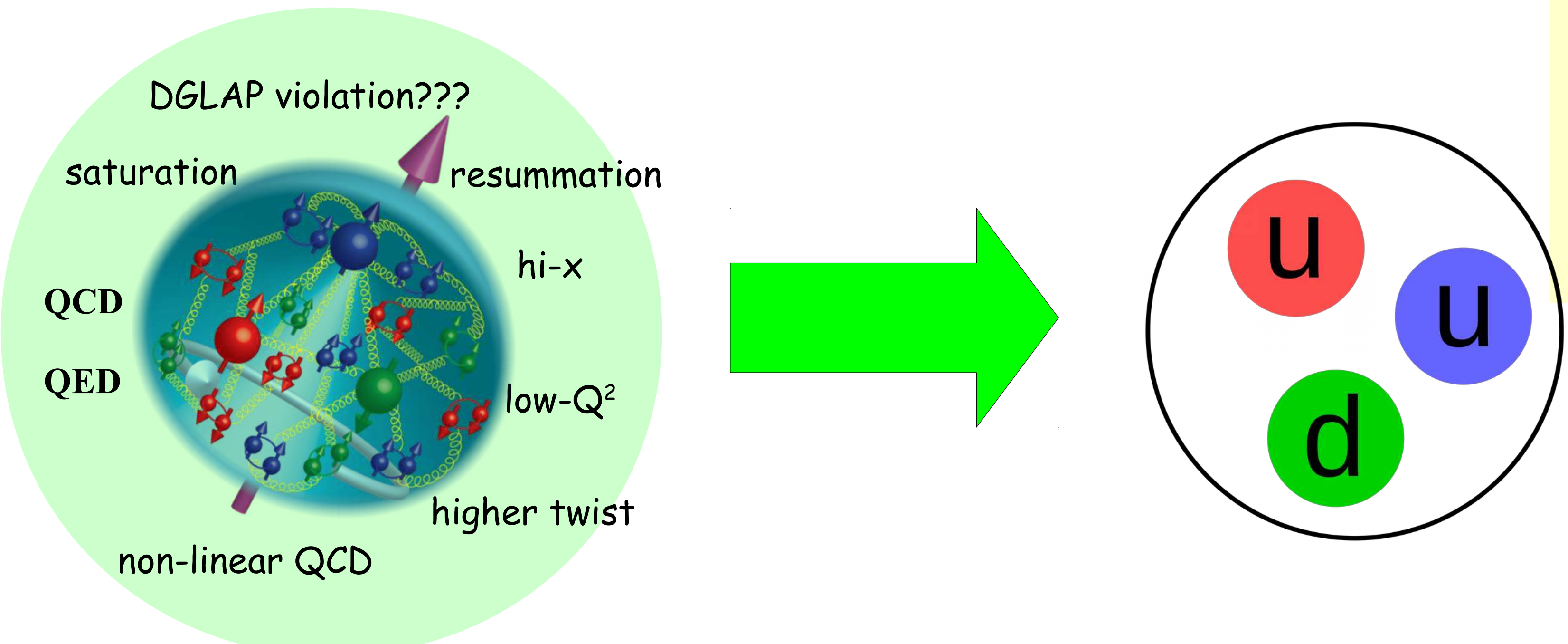
$$r^s(x,Q) = \frac{\bar{s}(x,Q) + s(x,Q)}{2\bar{d}(x,Q)}$$

Do it yourself!!!
Try xFitter

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

Nuclear PDFs & the Parton Model … *a few simpifications*





Limited data in nuclear dimension

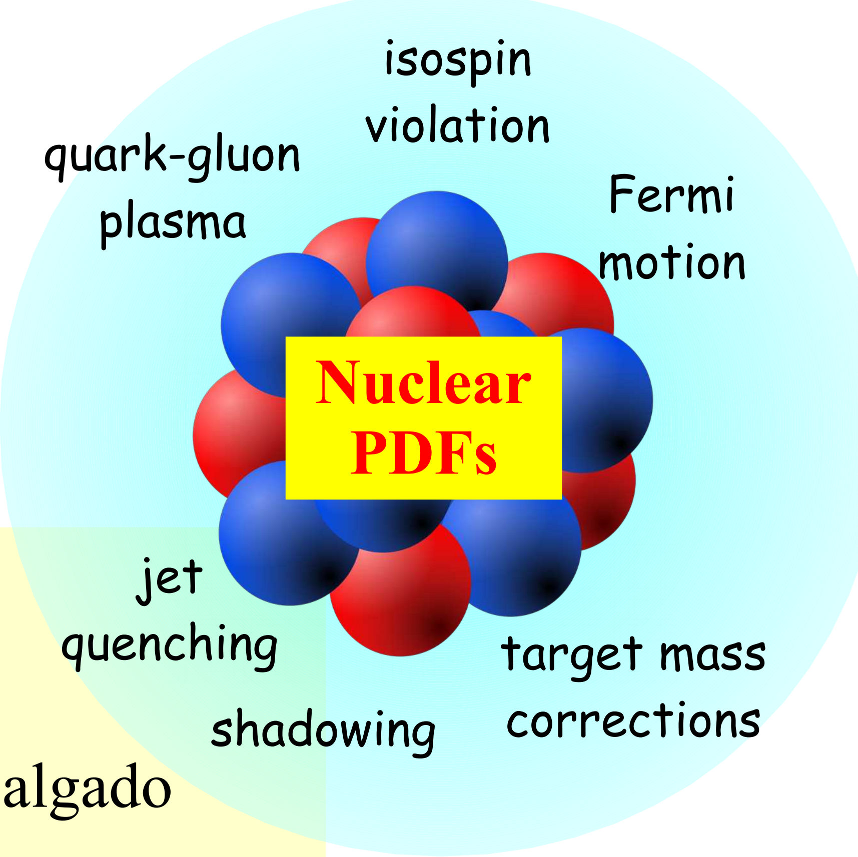
This is where EIC can contribute!!!

Nuclear PDF

The Players
The Ingredients

nPDFs

nuclear parton distribution functions



HKN'07: Hirai, Kumano, Nagai
[PRC 76, 065207 (2007)]

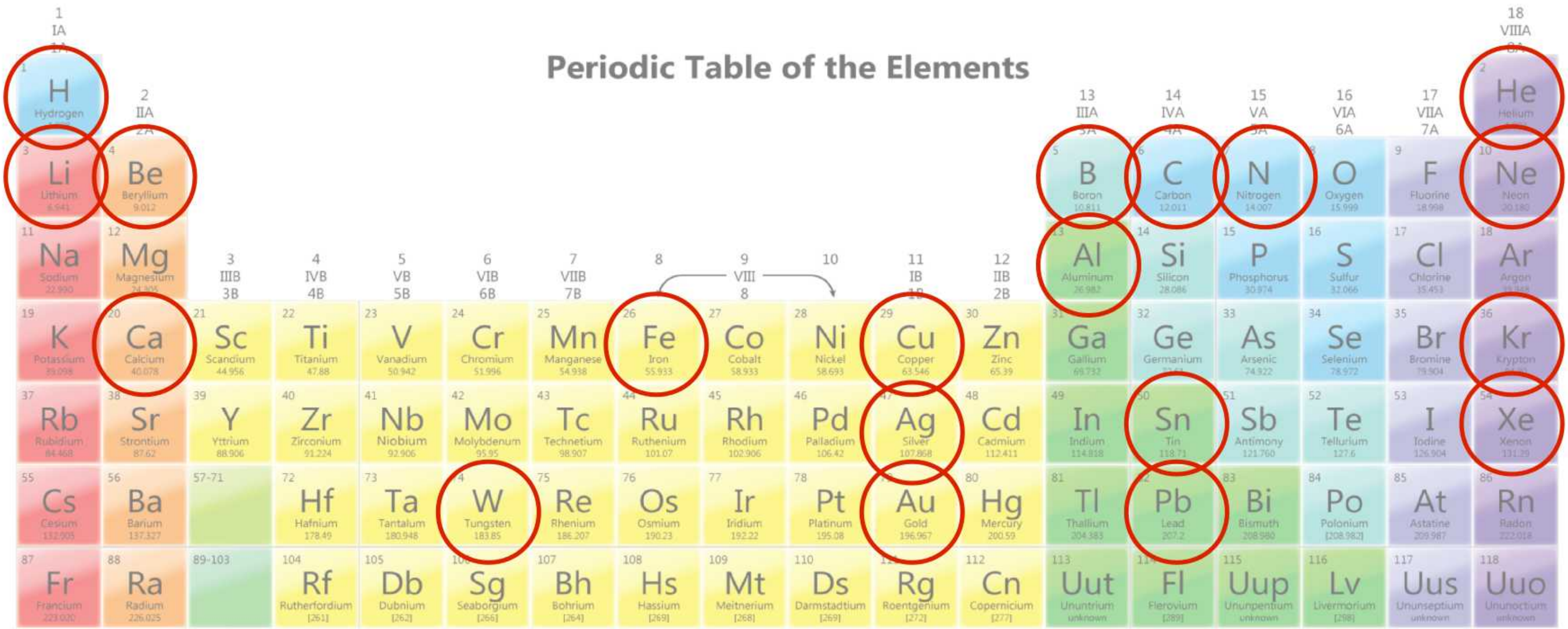
EPPS'16: Eskola, Paakkinen, Paukkunen, Salgado
Eur.Phys.J. C77 (2017) no.3, 163
(supersedes EPS'09)

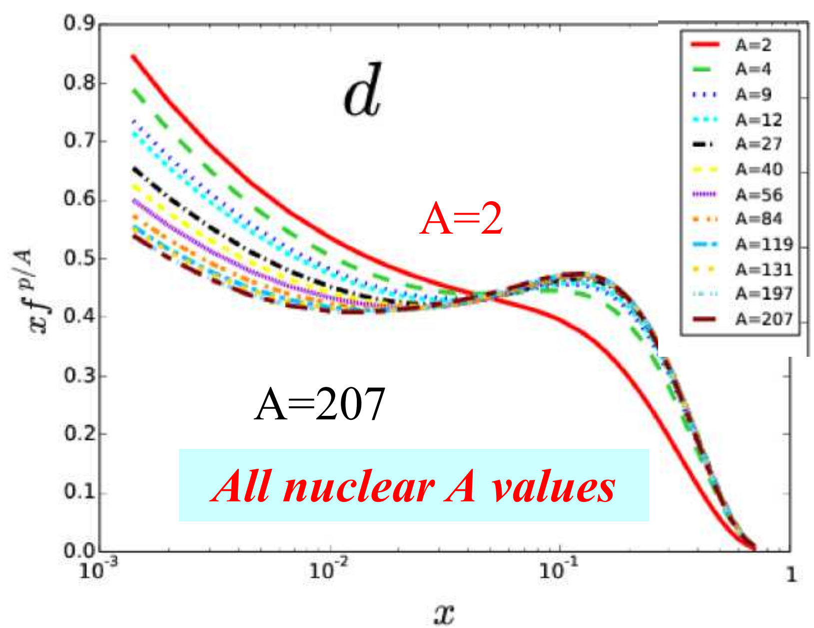
EPS'09: Eskola, Paukkunen, Salgado
[JHEP 04 (2009)]

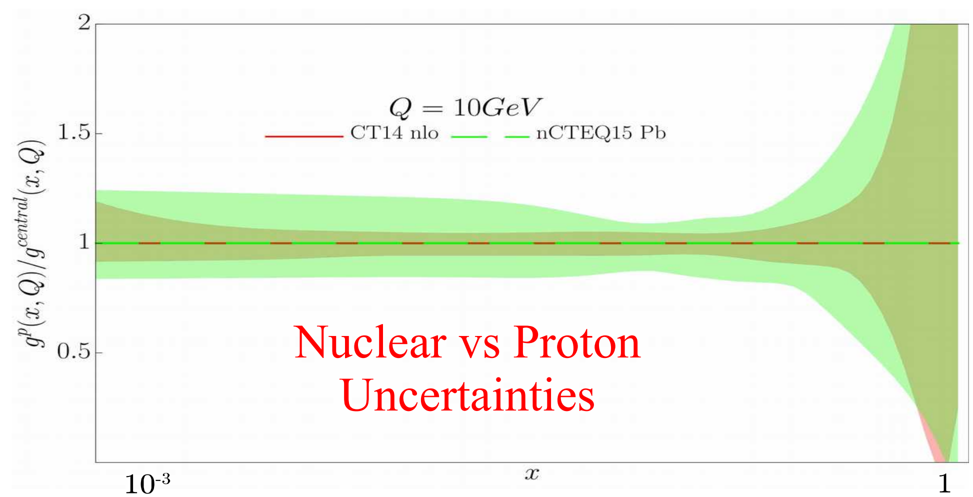
DSSZ'11: de Florian, Sassot, Stratmann, Zurita
[PRD 85, 074028 (2012)]

nCTEQ'15: nCTEQ Collaboration
[PRD 93, 085037 (2016)]

Nuclear PDFs: DIS, DY, π Prod, *(new)* Di-Jet







EIC can expand our knowledge of the nuclear A dimension

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*

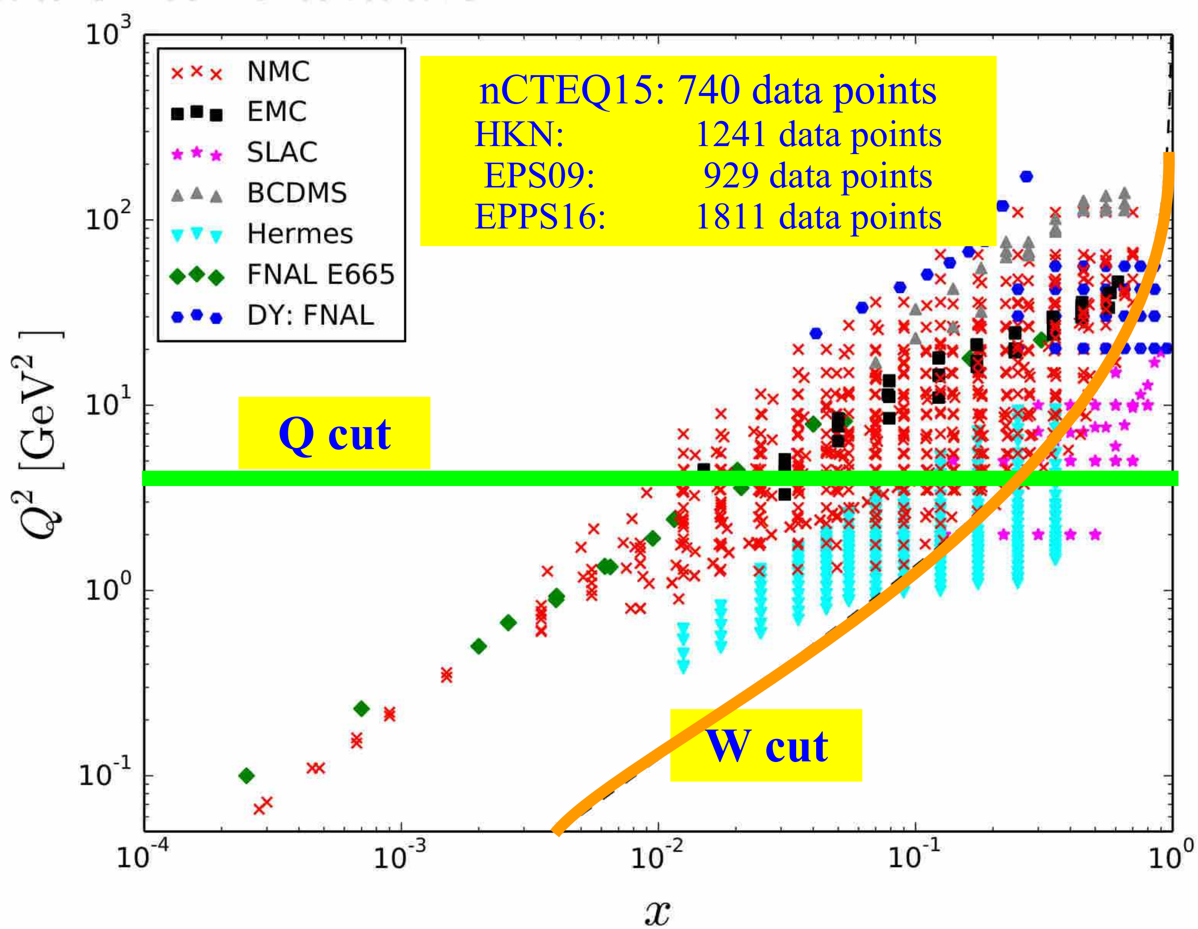
NuTeV CHORUS CCFR & NuTeV
N = Pb & Fe

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

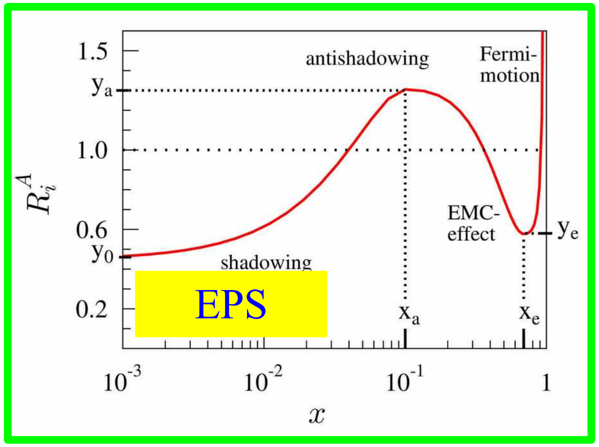
1) Multiplicative nuclear correction factors (HKN, EPPS, DSSZ)

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

... for example

HKN

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



2) Generalized A-parameterization (nCTEQ)

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

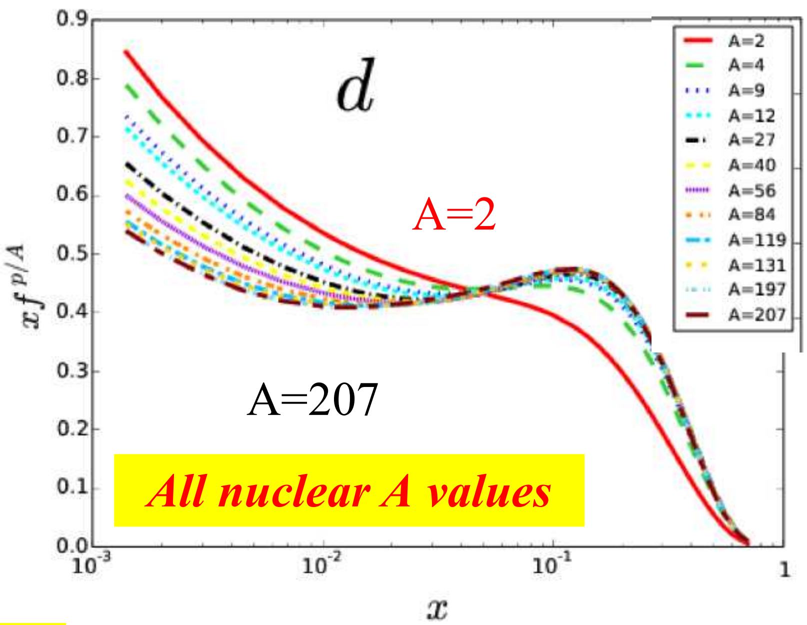
$$f \sim \ldots x^{c_1(A)}(1-x)^{c_2(A)} \ldots$$

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

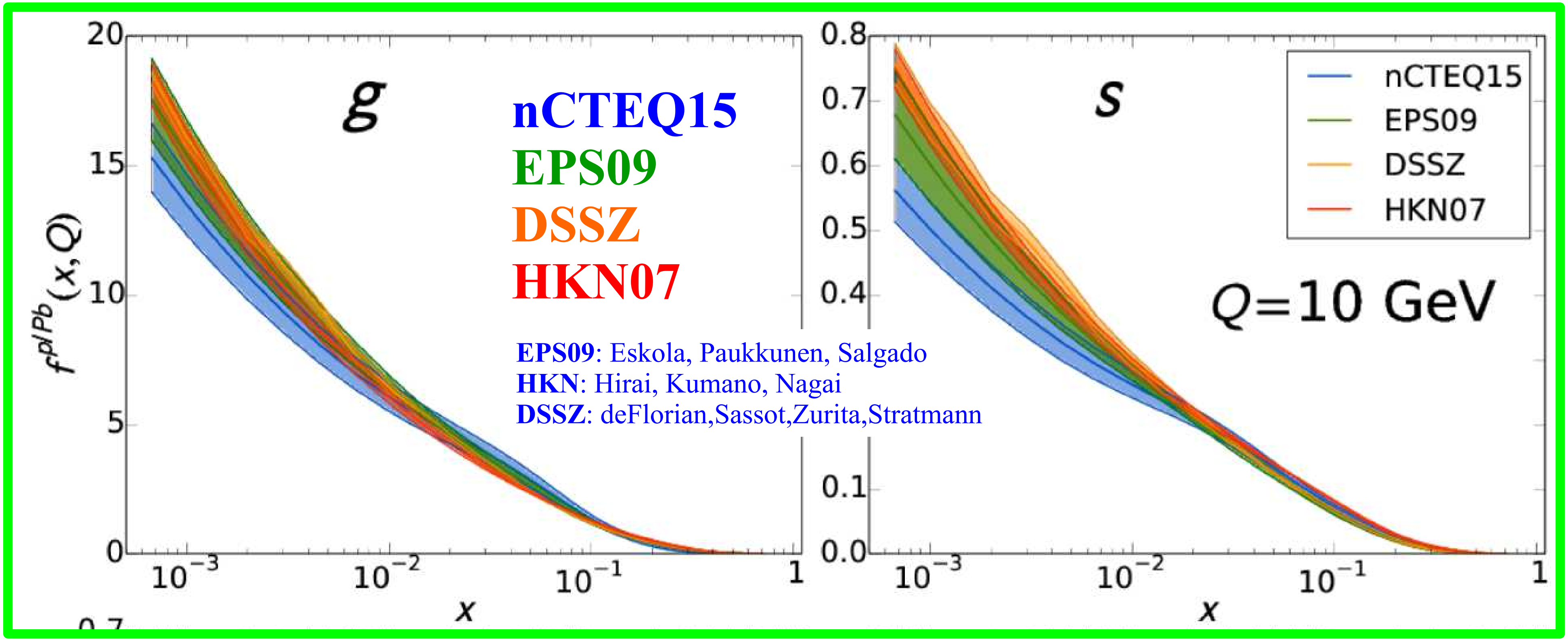
Proton

Nuclear

use proton as a Boundary Condition



Nuclear PDFs: Complementary efforts in general agreement

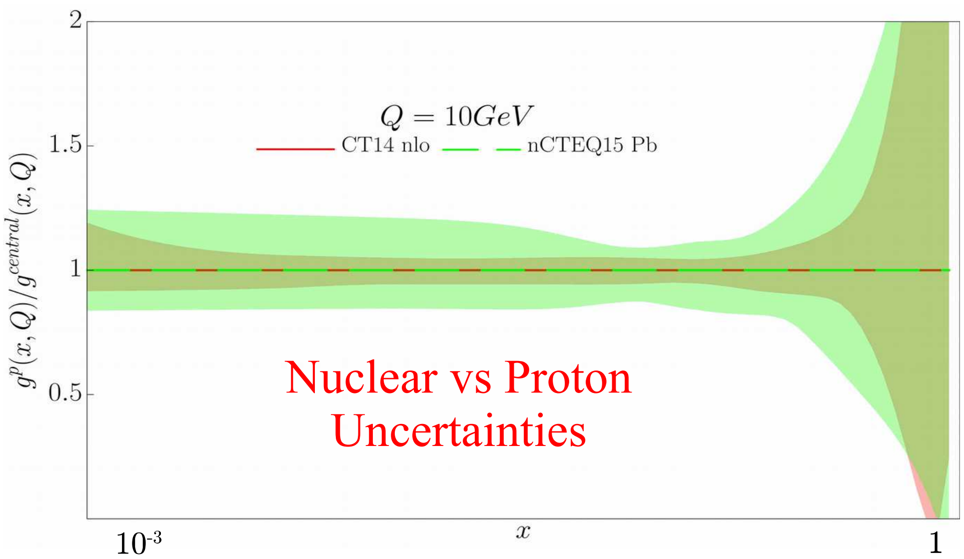


Nuclear PDFs are more complex

more DOF than Proton case

more "issues" to consider

more work to do ...

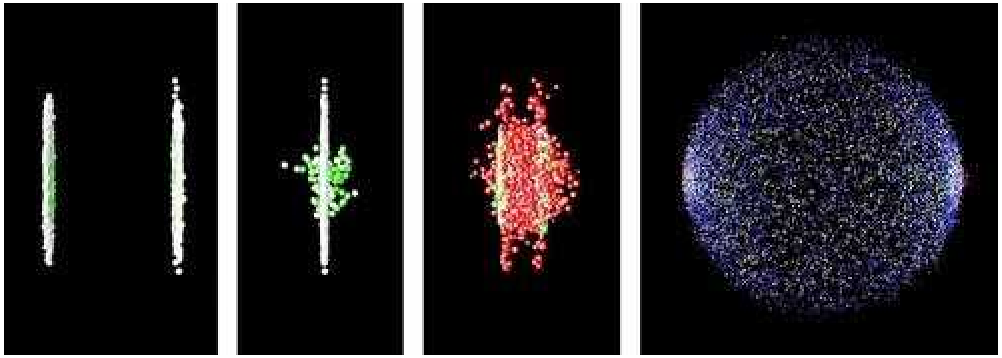


Motivation for nPDFs???

Make predictions for heavy ion collisions at:

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

LHC (pPb, PbPb)



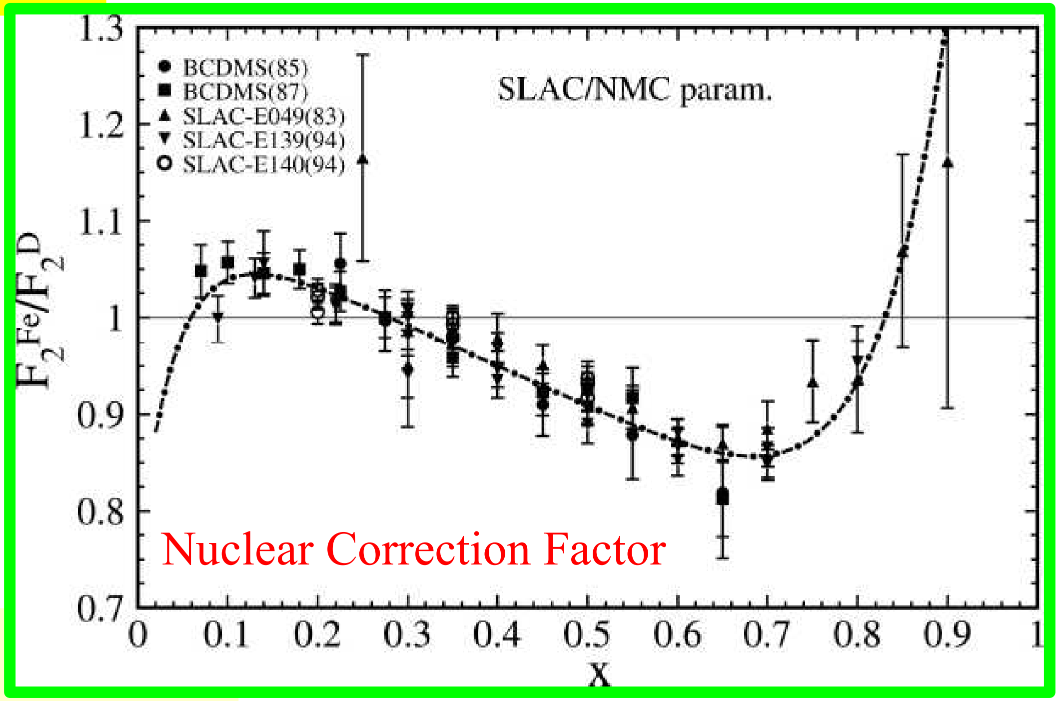
Differentiate flavors of free-proton PDFs:

neutrino DIS

$$F_2^{\nu} \sim \left[d + s + \bar{u} + \bar{c}\right]$$
$$F_2^{\bar{\nu}} \sim \left[\bar{d} + \bar{s} + u + c\right]$$
$$F_3^{\nu} \sim 2\left[d + s - \bar{u} - \bar{c}\right]$$
$$F_3^{\bar{\nu}} \sim 2\left[u + c - \bar{d} - \bar{s}\right]$$

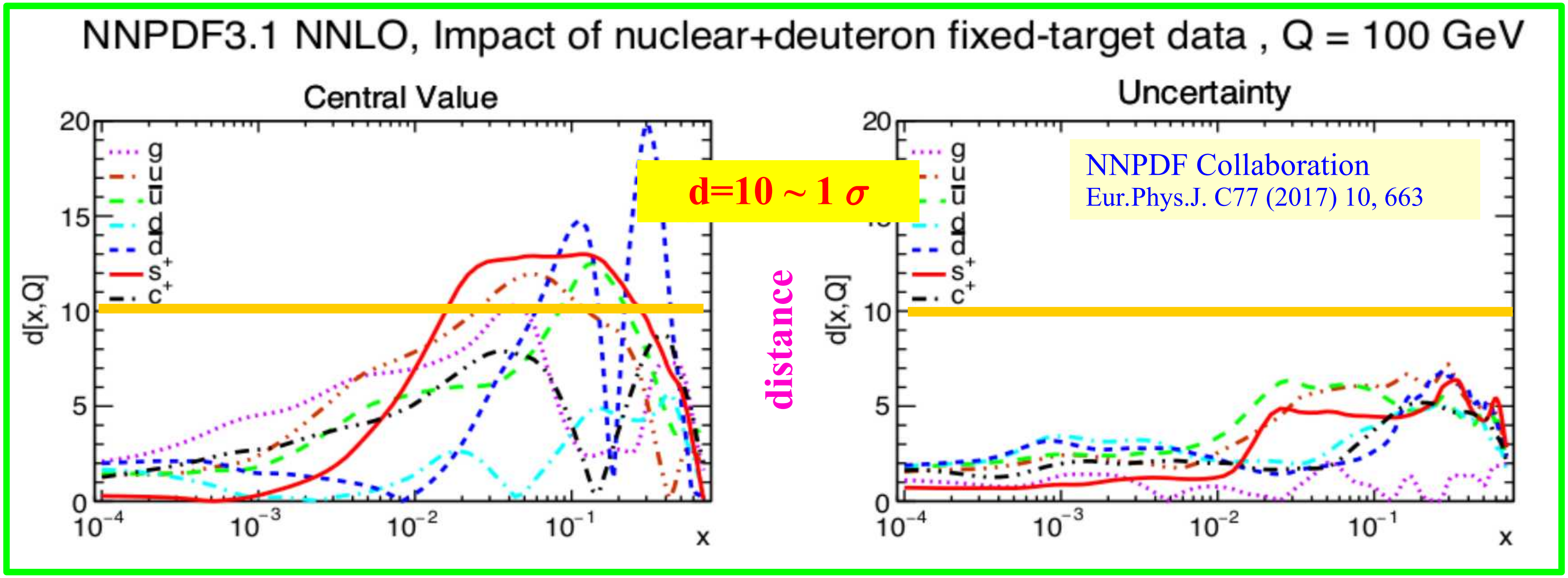
charged lepton DIS

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



Impact of Nuclear Corrections on Proton PDF

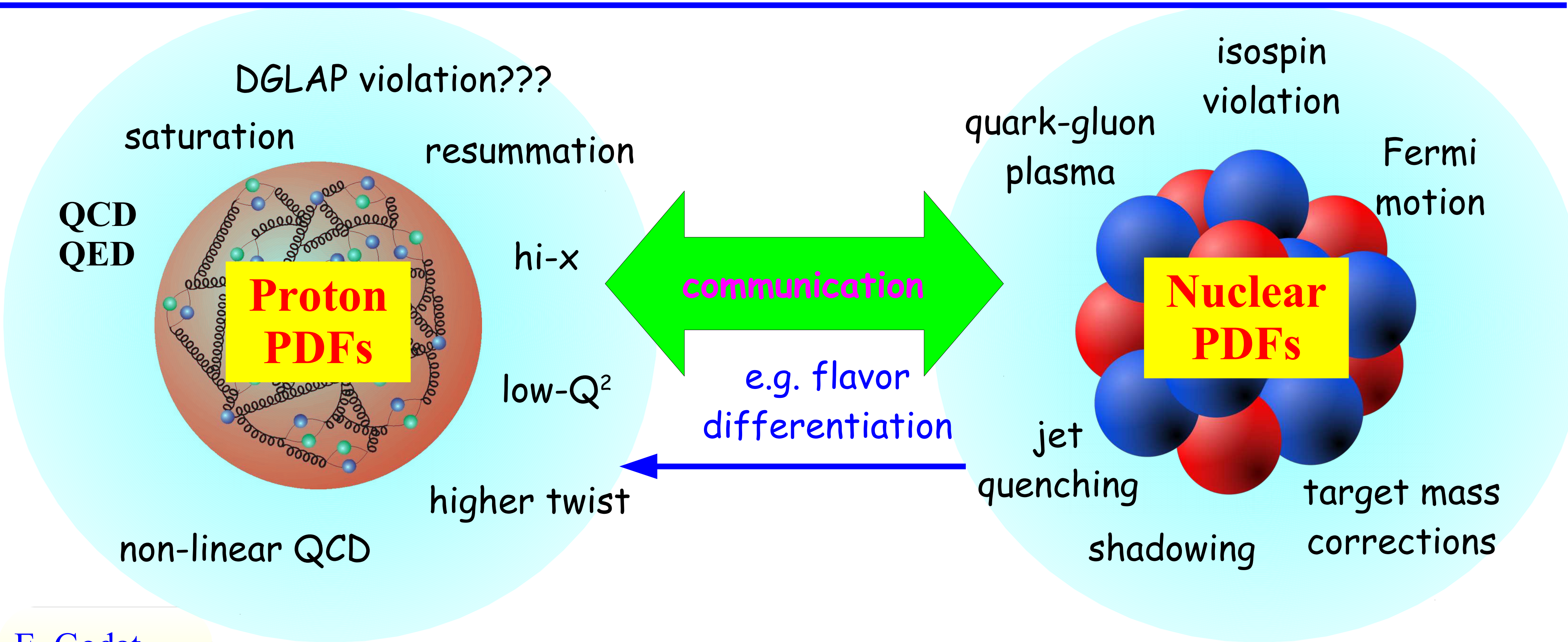
"... for the time being it is still appears advantageous to retain nuclear target data in the global dataset for general-purpose PDF determination"



Nuclear PDFs are ESSENTIAL for proton PDFs

nCTEQ++

… the motivation for nCTEQ



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

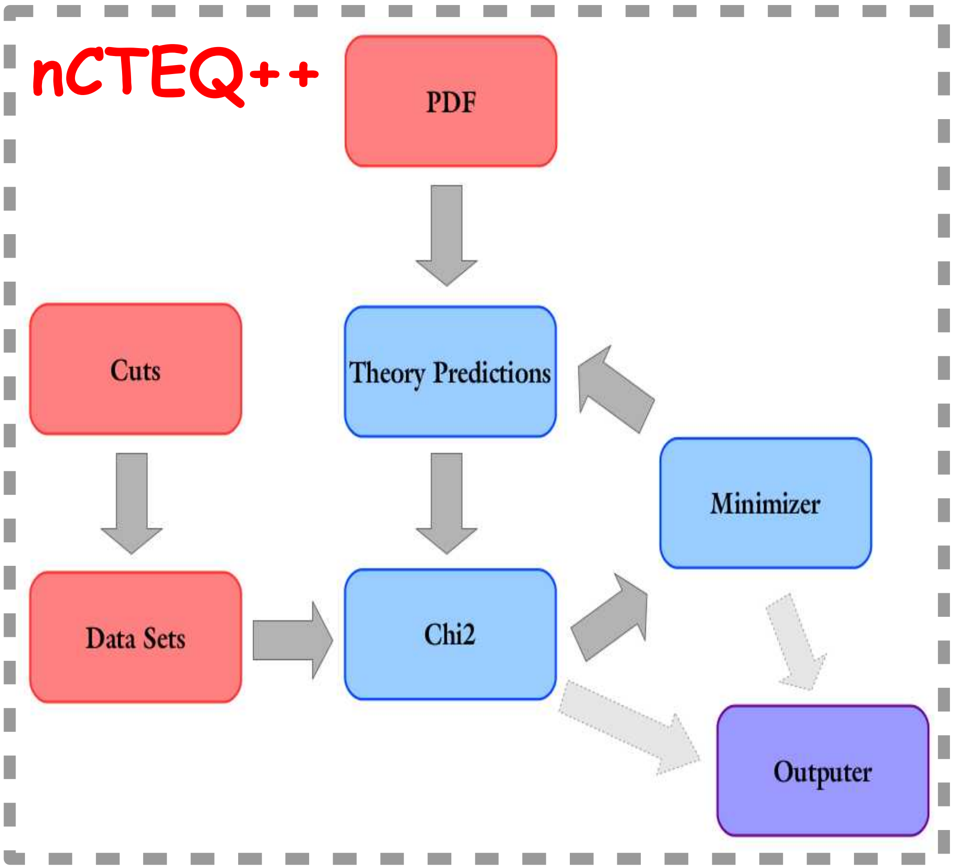
Data from nuclear targets play a key role in the flavor differentiation

nCTEQ

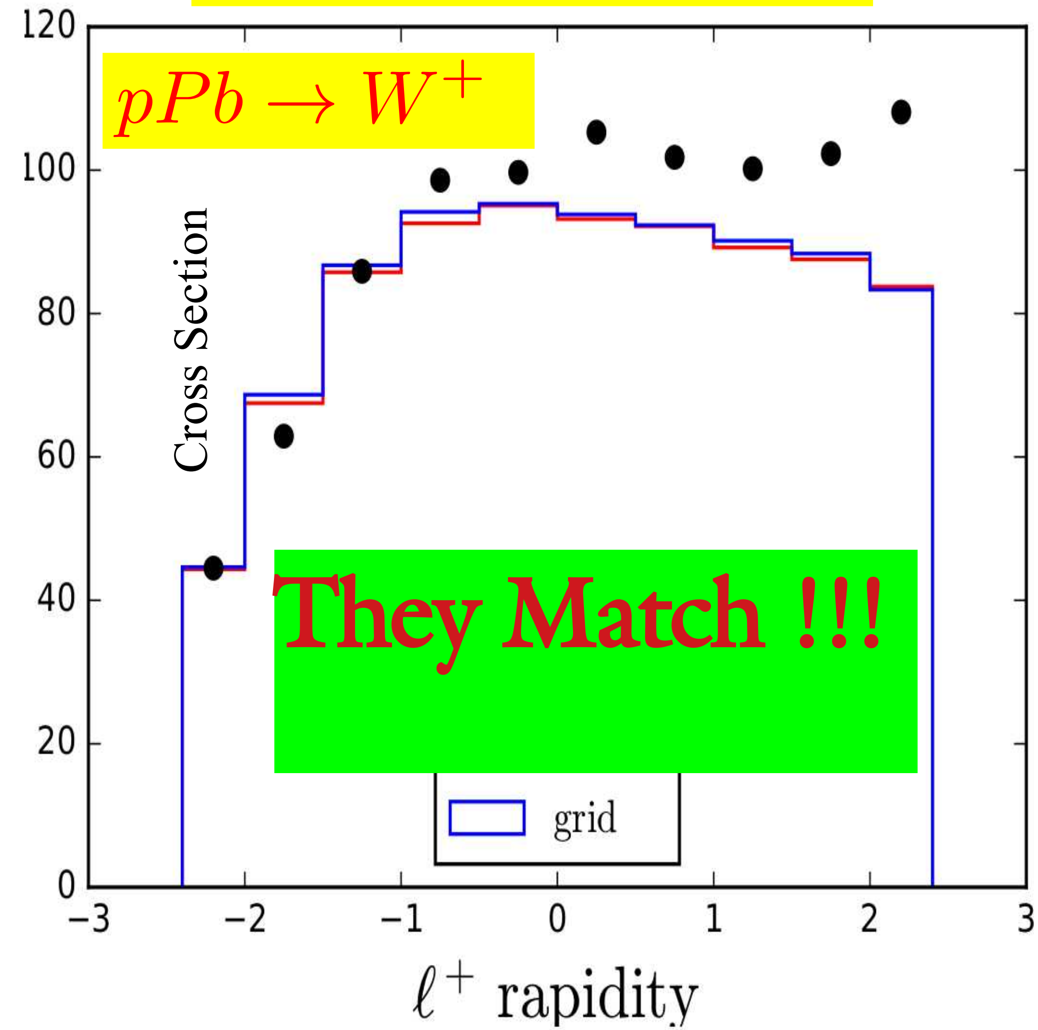
nuclear parton distribution functions

nCTEQ++ … a complete rewrite in C++

Top level C++, modular structure, output to YAML & Python scripts
Use external programs: Minuit, HOPPET, MCFM, APPLgrid, ...



LHC Heavy Ion Data:
Grids generated for pp
can be used for pPb !!!



Special thanks to:
Eric Godat
Florian Lyonnet
Tomas Jezo
Aleksander Kusina

MCFM Processes Library (v6.8)

MCFM: Vector boson pair production at the LHC, J. M.Campbell, R. K.Ellis and C.Williams, JHEP 1107, 018 (2011)

The APPLGRID Project: Tancredi Carli, Dan Clements, Amanda Cooper-Sarkar, Claire Gwenlan, Gavin P. Salam, Frank Siegert, Pavel Starovoitov, Mark Sutton. Eur.Phys.J. C66 (2010) 503-524

nproc	$f(p_1) + f(p_2) \to \dots$	Order
1	$W^+(\to \nu(p_3) + e^+(p_4))$	NLO
6	$W^-(\to e^-(p_3) + \bar{\nu}(p_4))$	NLO
11	$W^+(\to \nu(p_3) + e^+(p_4)) + f(p_5)$	NLO
12	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar{b}(p_5)$	NLO
13	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar{c}(p_5)$	NLO
14	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar{c}(p_5)$[massless]	LO
16	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + f(p_5)$	NLO
17	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + b(p_5)$	NLO
18	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + c(p_5)$	NLO
19	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + c(p_5)$[massless]	LO

xFitter

xFitter release xfitter-2.0.0

www.xFitter.org

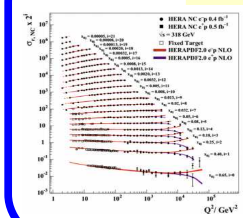
xFitter

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



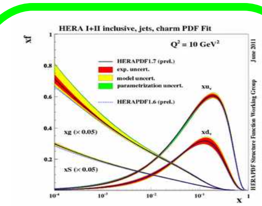
Data: HERA, Tevatron, LHC, fixed target experiments

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

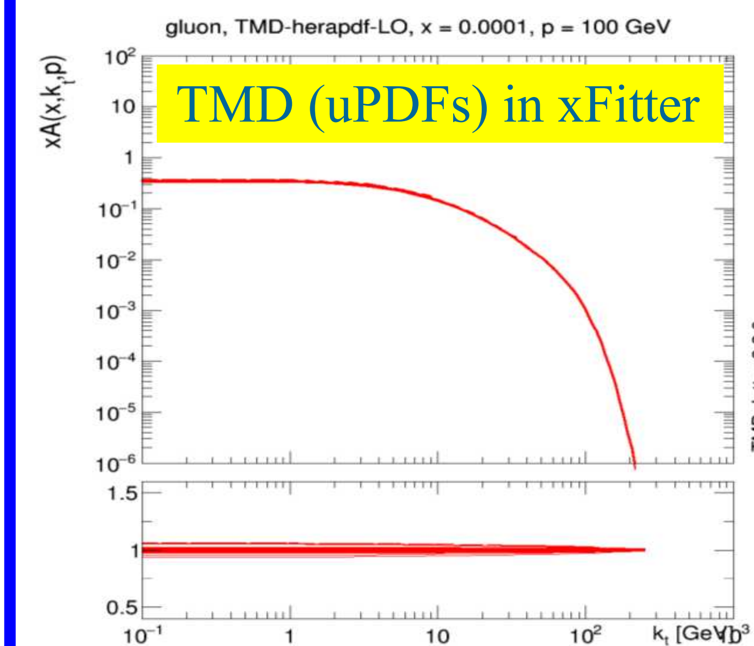
Features & Recent Updates:

- 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*

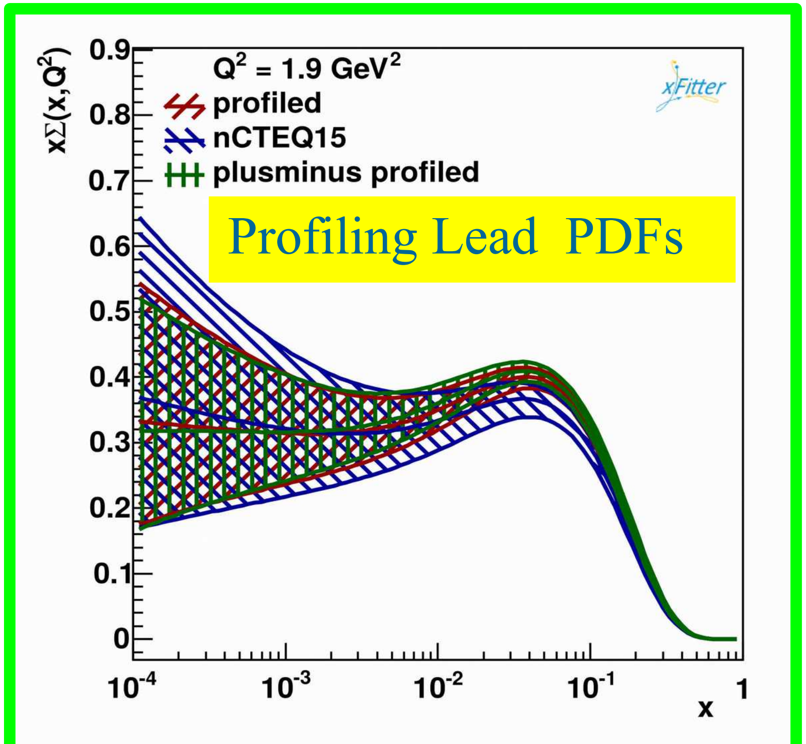
Versatility of xFitter

www.xFitter.org

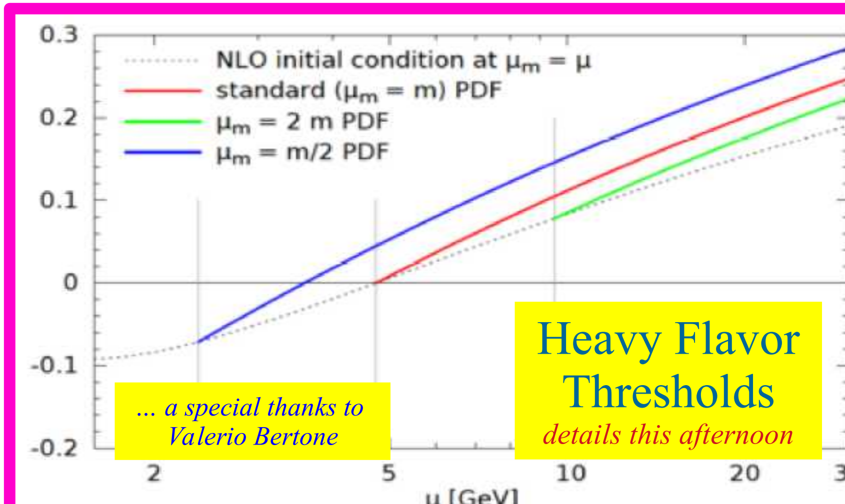
TMDs from fits - comparison of LO and NLO



TMDs with experimental uncertainties.



nPDFs with xFitter
Marina Walt
U. Tuebingen

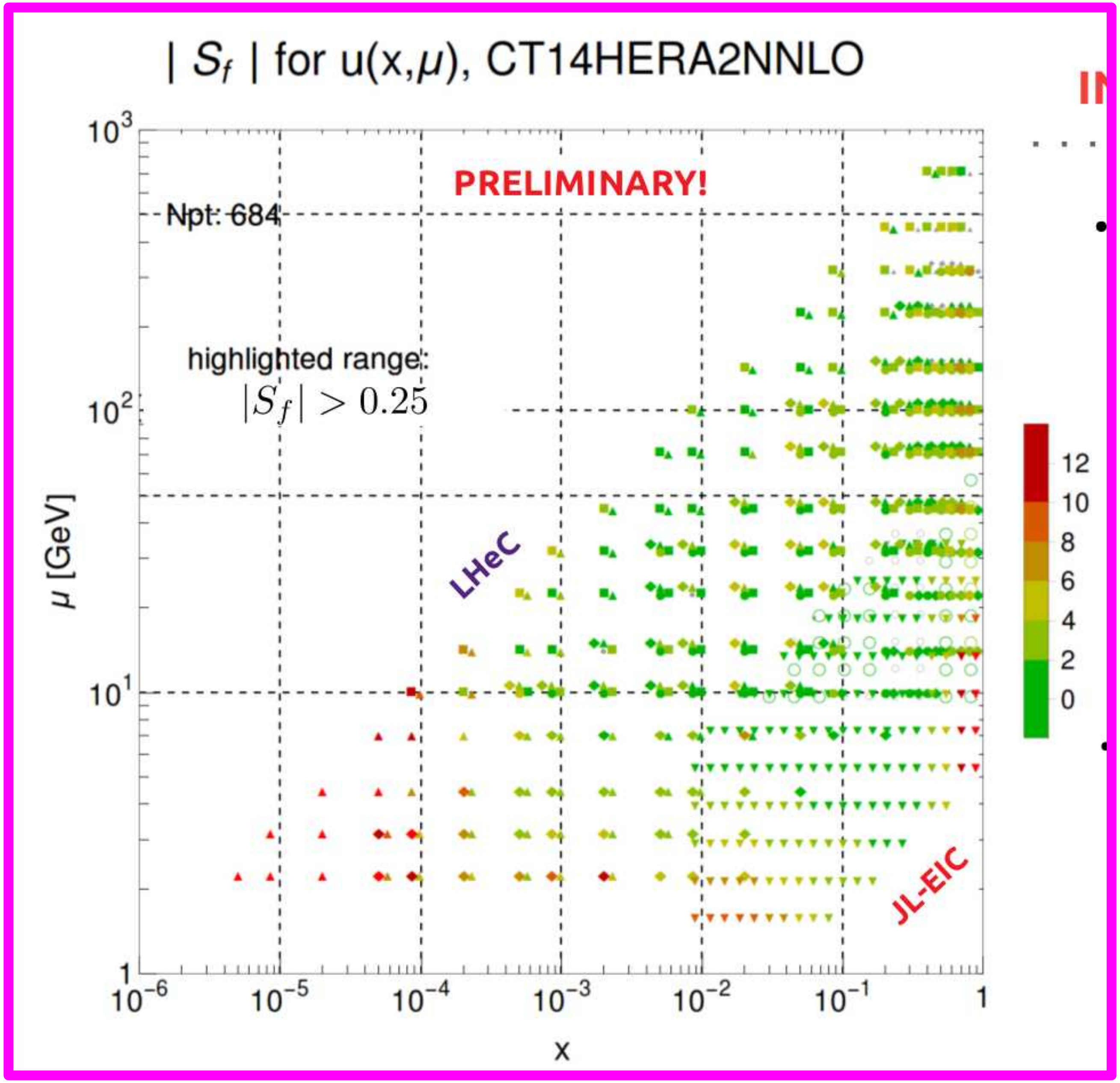


New Tools

PDFSense

&

… borrowing from AI



A new measure:

Sensitivity S_f

Extend concept of correlation (C) to include both pull and precision of experiment.

(Technically, weight by scaled residual.)

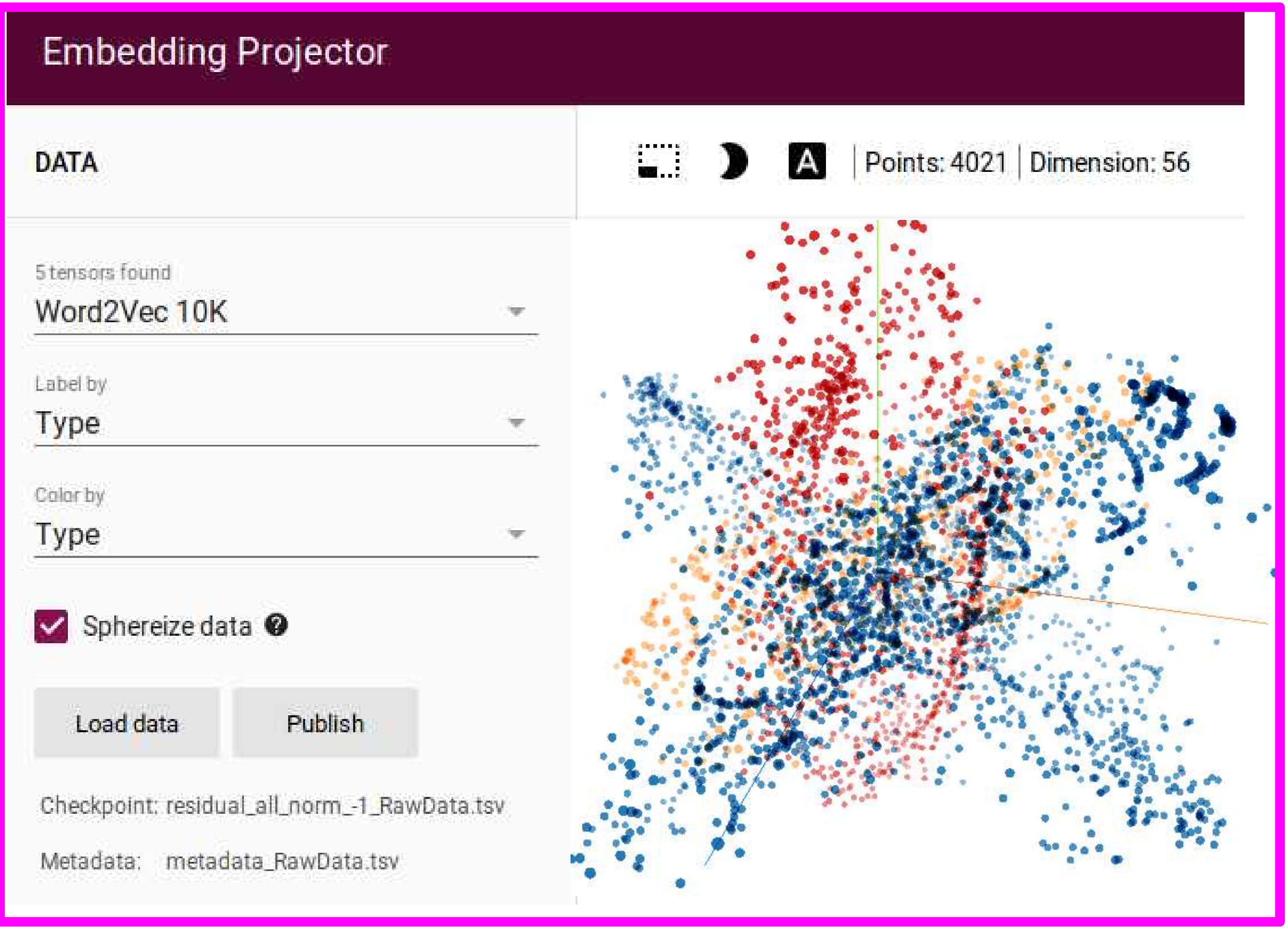
New insights on experimental impacts

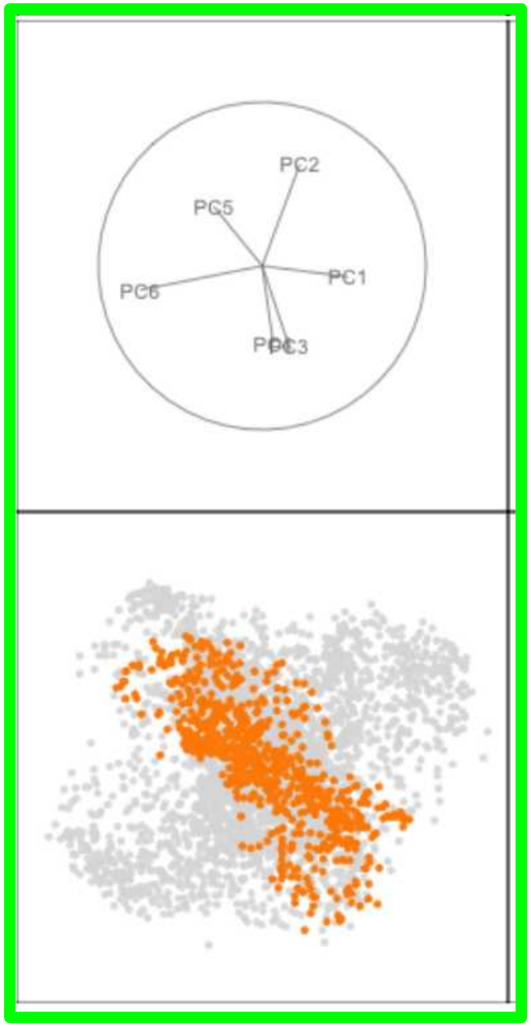
See Talk By:
Tim Hobbs (SMU)

Linked from:
https://metapdf.hepforge.org/

Applications of PDFSense:

Artificial Intelligence Tools: Projector tool of Google TensorFlow





Dynamical projections for the visualization of PDFSense data

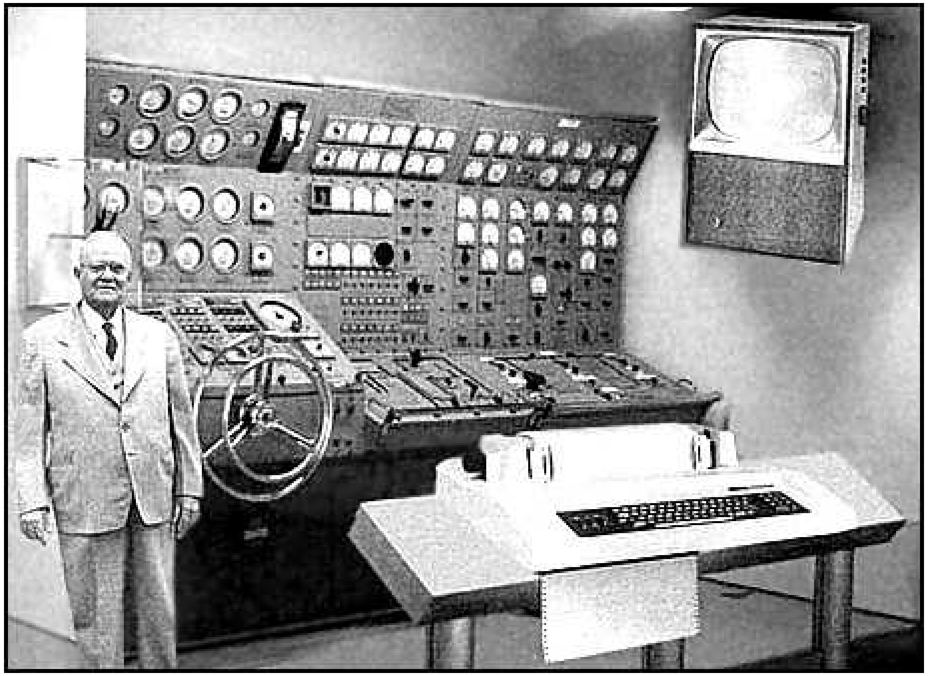
Dianne Cook, Ursula Laa, German Valencia arXiv:1806.09742

Conclusion

Updated tools are essential

Mobile Phone Circa 1950's

Vintage TV



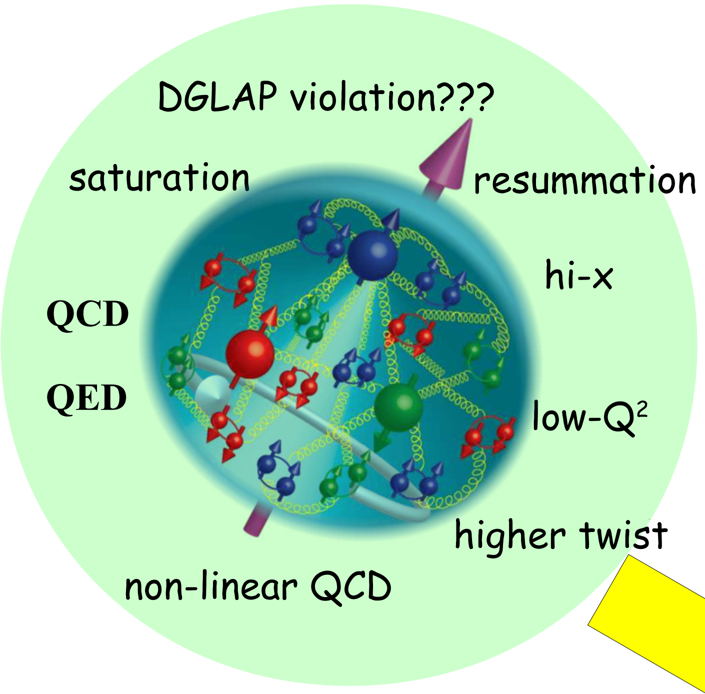
A (hoaxed) photo portraying a 1950's computer

Smarrt Phone
Circa 2019

IMac

Modern
Laptop

EIC *an ideal QCD Laboratory*



JETSCAPE