Deciphering QCD:

…

From PDFs to the underlying QCD characteristics

Fred Olness
SMU

Thanks for substantial input
from my friends & colleagues

C T E Q

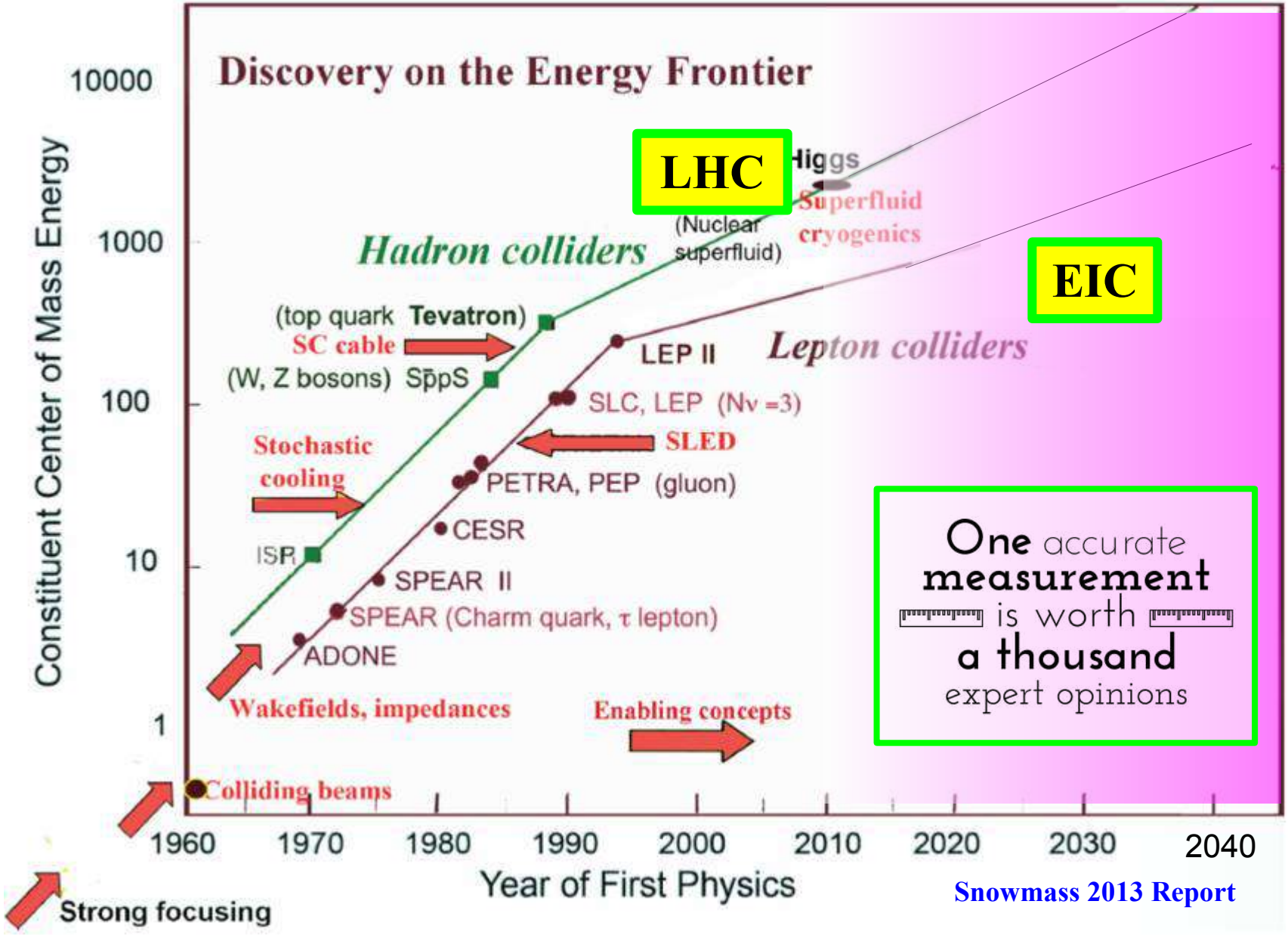
xFitter

nCTEQ
nuclear parton distribution functions

EIC opportunities for Snowmass

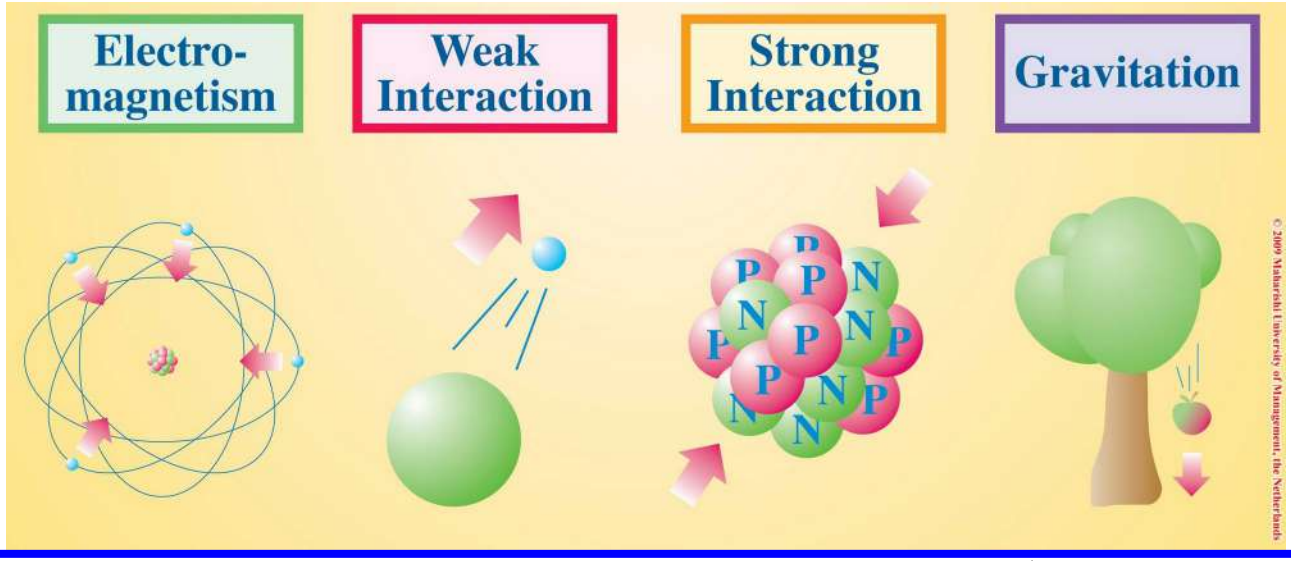
25 January 2021

Landscape of the Physics Frontier



We've reached the peak energy. Future searches require precision!!!

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



PDFs & nPDFs

Generalized PDFs

Spin Structure

Lattice QCD

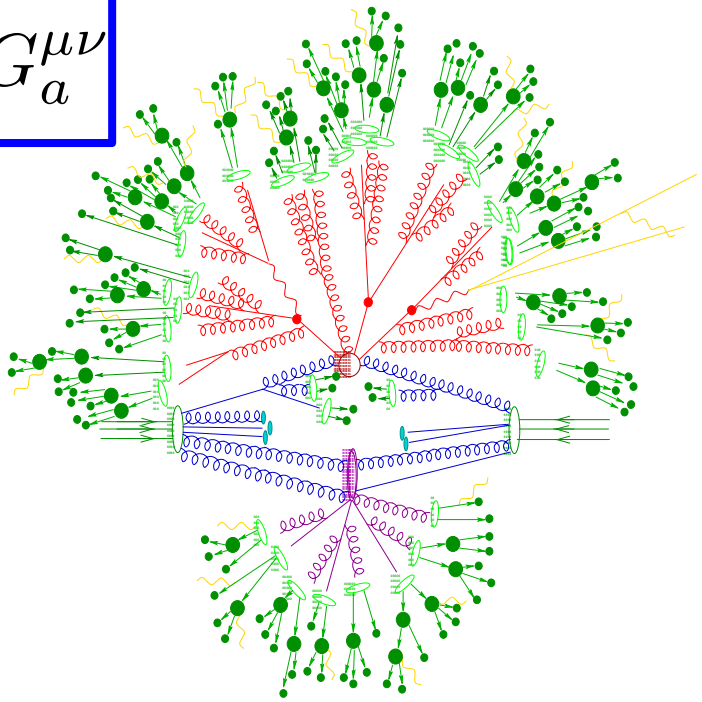
Quark-Gluon Plasma

$$\mathcal{L}_{QCD} = \overline{\psi}_q \left(i\gamma_\mu D^\mu - m_q \right) \psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

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

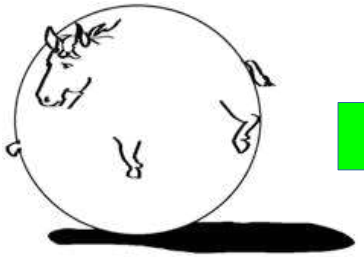
"… alien, simple, beautiful, weird, & comprehensible"

Combines HEP + NUC

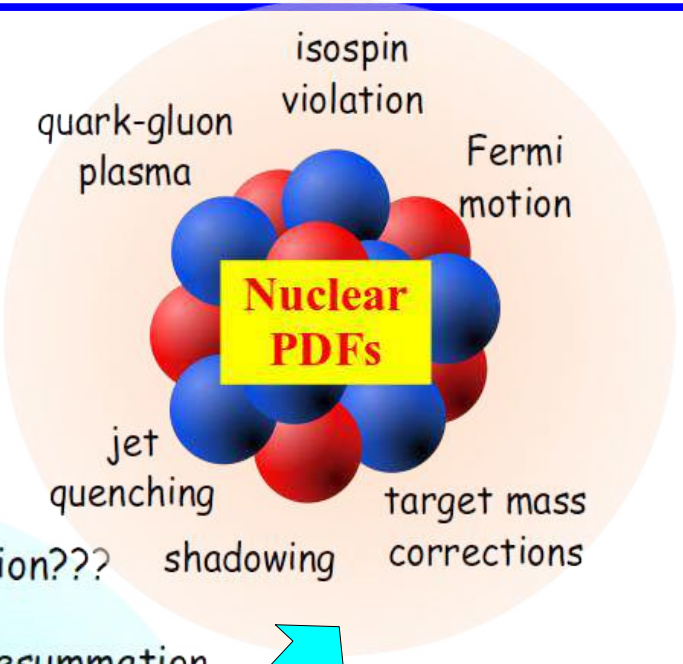
interdisciplinary

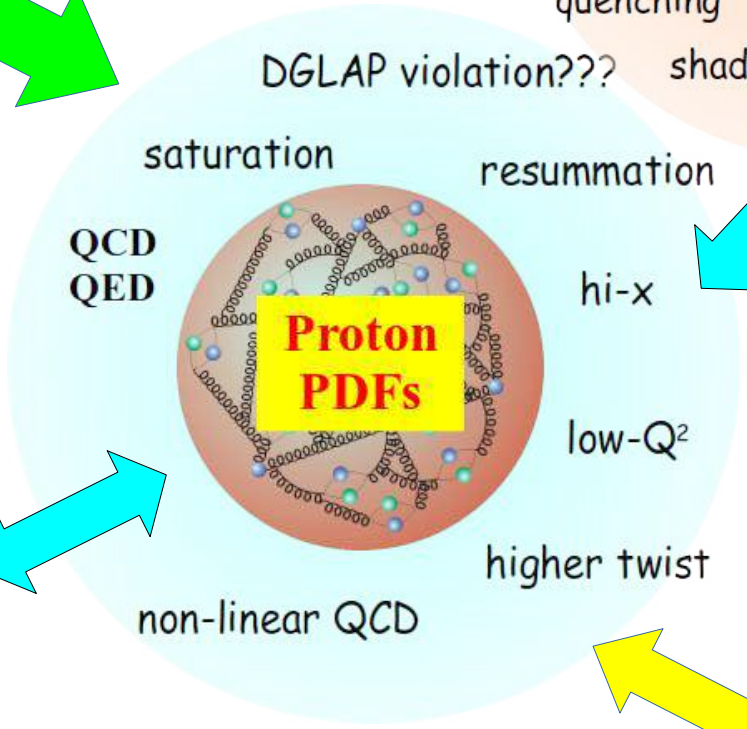
From Parameterization to a Deep Understanding … LHC + EIC

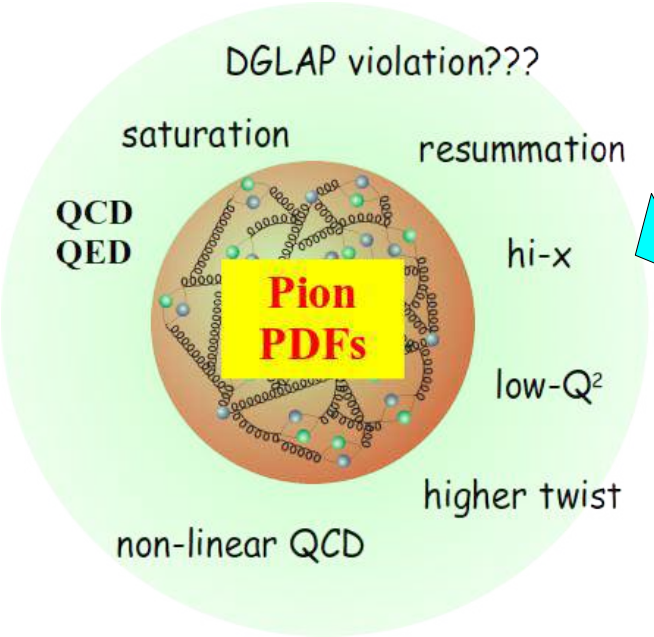
QCD
Lagrangian

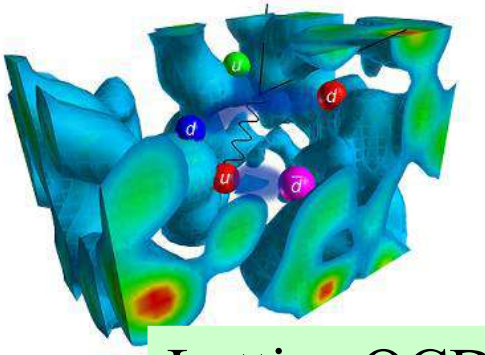


$$\mathcal{L}_{QCD} = \overline{\psi}_q \left(i\gamma_\mu D^\mu - m_q \right) \psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$









Lattice QCD

- **Hadron Spin**
- **Generalized PDFs**
- **Fragmentation**

… the motivation for nCTEQ

DGLAP violation???

saturation

resummation

QCD

QED

hi-x

Proton PDFs

low-Q^2

higher twist

non-linear QCD

intricate connections

e.g. flavor differentiation

isospin violation

quark-gluon plasma

Fermi motion

Nuclear PDFs

jet quenching

target mass corrections

shadowing

E. Godat
T.J. Hobbs
T. Jezo,
C. Keppel,
M. Klasen
K. Kovarik
A Kusina,
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

The Physics

nCTEQ Wish List

nCTEQ
nuclear parton distribution functions

www.ncteq.org

CTEQ

www.cteq.org

PDF General Issues:

- Proton PDF; nuclear corrections for interpreting heavy target DIS (Ar, Fe, Pb).

Strange quark PDF: s(x)

- Resolve tension between fixed-target (νN, ℓN) and collider expectations ($W^{\pm}$,Z)

Charm & Bottom: c(x) & b(x)

- Multi-scale & resummation issues: $\mathrm{Log}(m_{c,b}/Q)$
- "Fitted" charm: $c(x) \neq 0$ at m_c
- Intrinsic heavy flavors: $c(x) \neq 0$ at $Q < m_c$

Neutrino cross sections on heavy targets (Ar, Fe, Pb)

- Universality of Neutral Current (γ) and Charged Current ($W^{\pm}$) processes

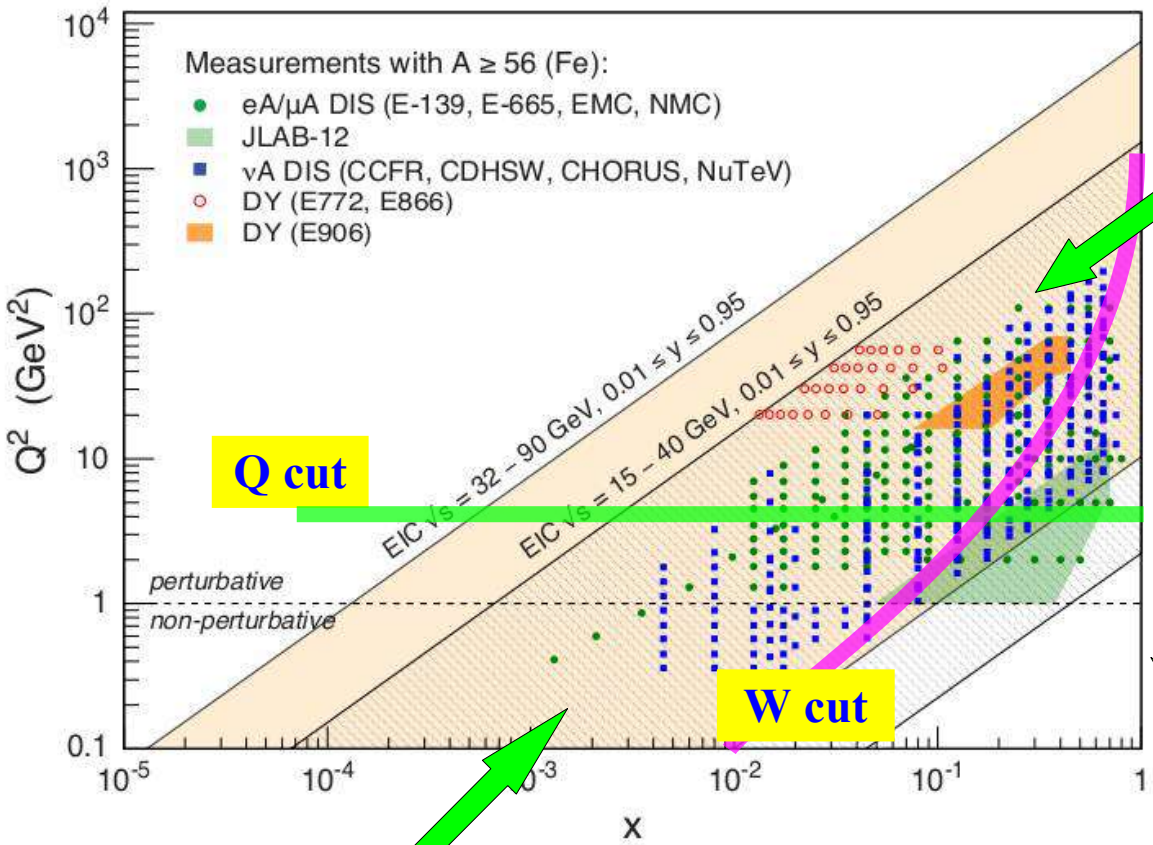
Expanded $\{x,Q^2\}$ Kinematic Regime

- Small-x saturation, resummation: $\mathrm{Log}[1/x]$
- Large-x higher twist: (M^2/Q^2)
- Low Q^2 non-perturbative effects

Compilation by Fred Olness with helpful feedback from: Alberto Accardi, Tim Hobbs, Tomas Jezo, Thia Keppel, Michael Klasen, Karol Kovarik, Aleksander Kusina, Jorge Morfin, Pavel Nadolsky, Jeff Owens, Ingo Schienbein, Efrain Segarra, Steve Sekula, Ji-Young Yu

nPDFs: Extend Kinematic Reach in {x,Q²} nCTEQ15HIX

arXiv:2012.11566



High-x:

Nuclear PDFs: x>1 allowed;

impacts F_2^{Nuc}/F_2^{Iso} in Fermi region

Target Mass Corrections

pick up M^2/Q^2 higher twist

Deuteron Corrections

impacts $F_2^{Nuc}/F_2^{Deuteron}$ ratio

Low-Q²:

Non-Perturbative inteface

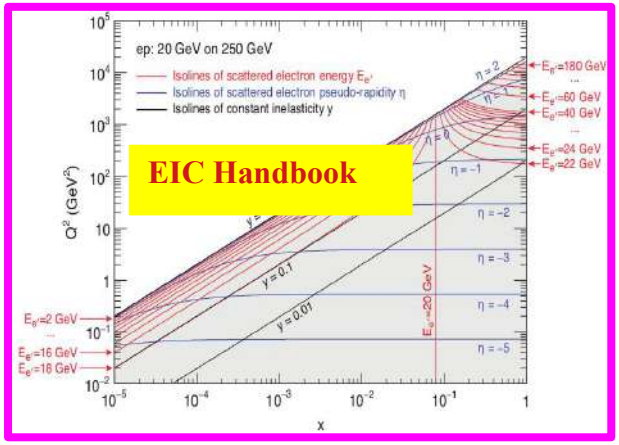
collective effects

Target Mass Corrections

pick up M^2/Q^2 higher twist

F_L at low Q^2 access to g(x)

Run at multiple energies



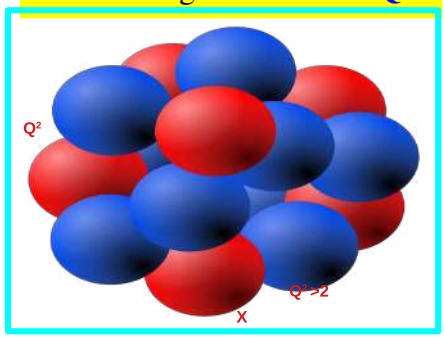
Warm-up:

JLab Data @ Hi-X Low-Q²

extend nCTEQ framework for this region

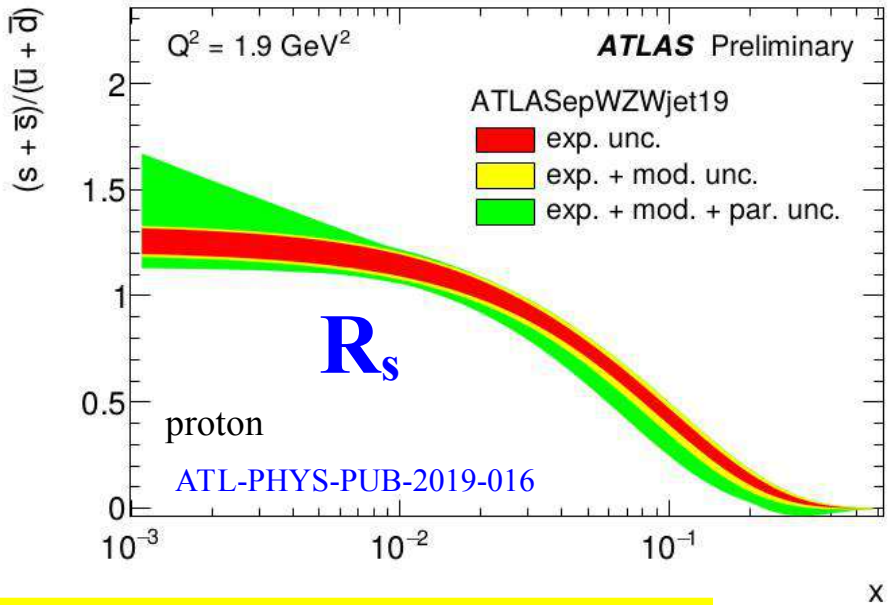
& prepare for EIC

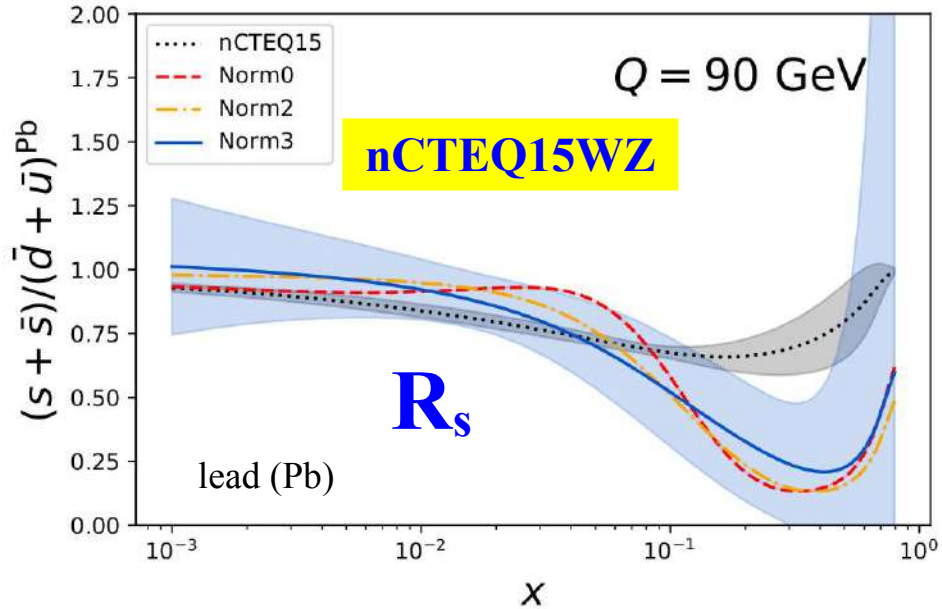
Efrain Segarra w/ **nCTEQ**



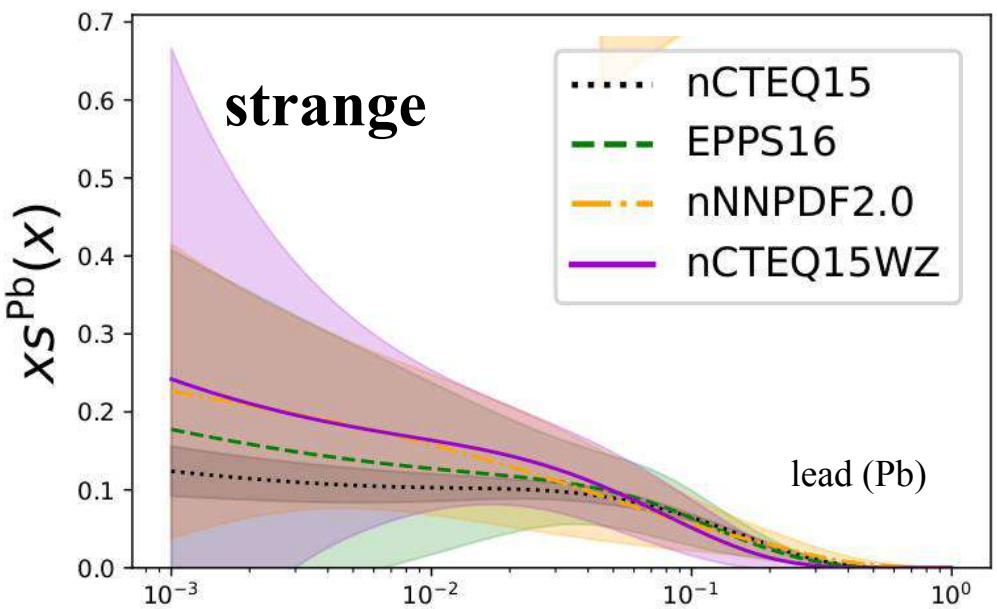
nuclear PDFs for lead (Pb)

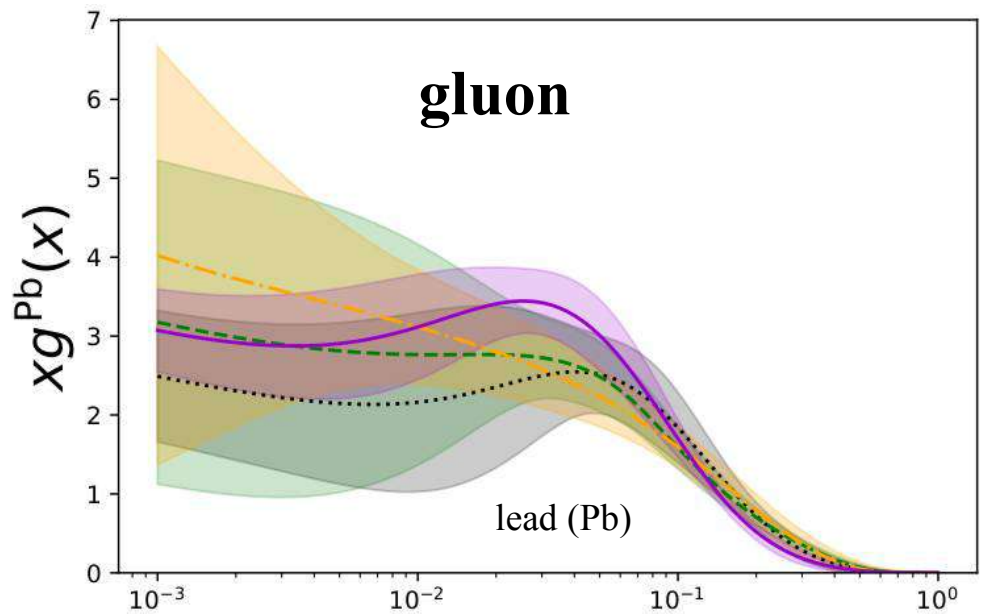
Eur.Phys.J.C 80 (2020) 10, 968
e-Print: 2007.09100 [hep-ph]





W/Z influence nPDF s(x) and g(x)





Challenging problems require good ideas & tools

nCTEQ++

nCTEQ++ … *modular w/ standard interfaces*

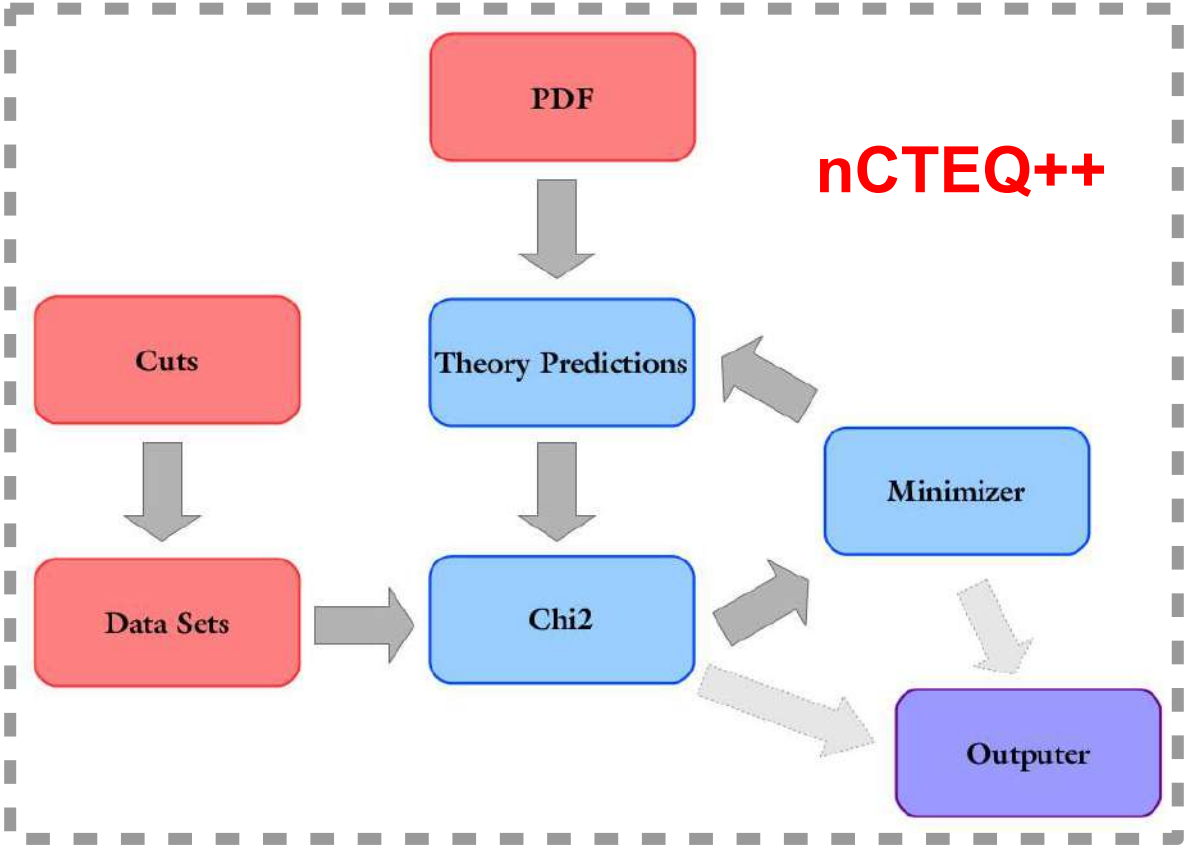
- A complete rewrite of the nCTEQ FORTRAN fitting code in C++
- Changed the code to allow for modules when building a PDF

  Evolution

  Interpolation

  Parameterization

- **Use external programs**
  - **Minuit**
  - **HOPPET**
  - **MCFM**
  - **APPLgrid**



I/O in standard LHAPDF
and YAML format

Interface to Python Analysis tools &
Jupyter notebooks

Special thanks to:
Florian Lyonnet
Tomas Jezo
Aleksander Kusina

Strategy: use case studies to validate new nCTEQ++ framework

Grid Technology: … to NLO and Beyond: ApplGrid, FastNLO, …

APPLGRID method

Eur.Phys.J.C66:503-524,2010.

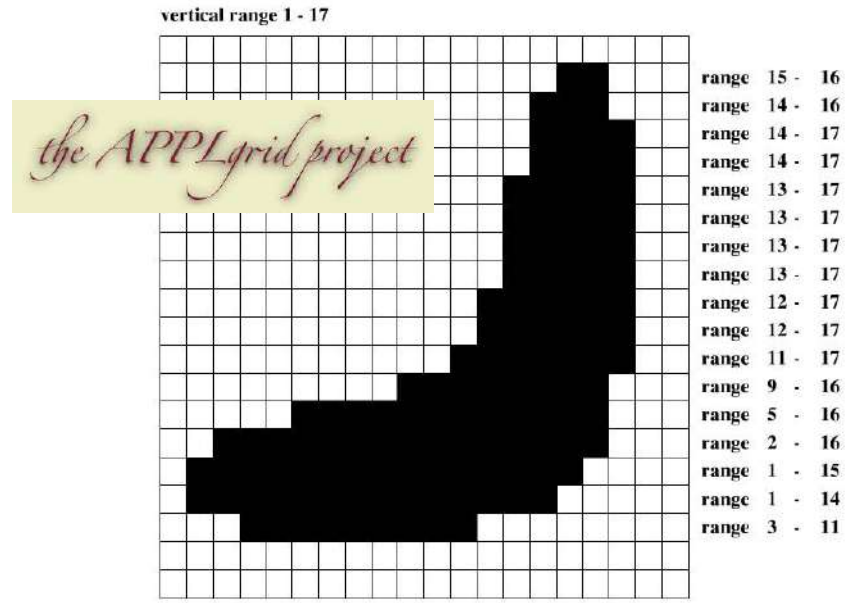
- Step 1 (long run): Collect perturbative weights to grids .
  - binning (x_1, x_2, Q^2)
  - interpolation
  - initial flavours decomposition : $13 \times 13 \rightarrow \mathcal{L}$ $(\mathcal{L} \sim 10)$

$$\frac{d\hat{\sigma}^{ij}_{(p)}}{dX}(x_1, x_2, Q_F^2, Q_R^2;\ S) \xrightarrow{3D-grid} w^{(p)(l)}(x_1^m, x_2^n, Q^{2^k})\ (Q_R^2 \equiv Q_F^2)$$

- Step 2 ($\sim$ 10–100 ms): Convolute grid with PDF's .
  - integral $\rightarrow$ sum
  - any coupling, PDF

$$\frac{d\sigma}{dX} = \sum_p \sum_{l=0}^{L} \sum_{m,n,k} w^{(p)(l)}_{m,n,k} \left(\frac{\alpha_s(Q_k^2)}{2\pi}\right)^{p_l} F^{(l)}\left(x_{1m}, x_{2n}, Q_k^2\right)$$

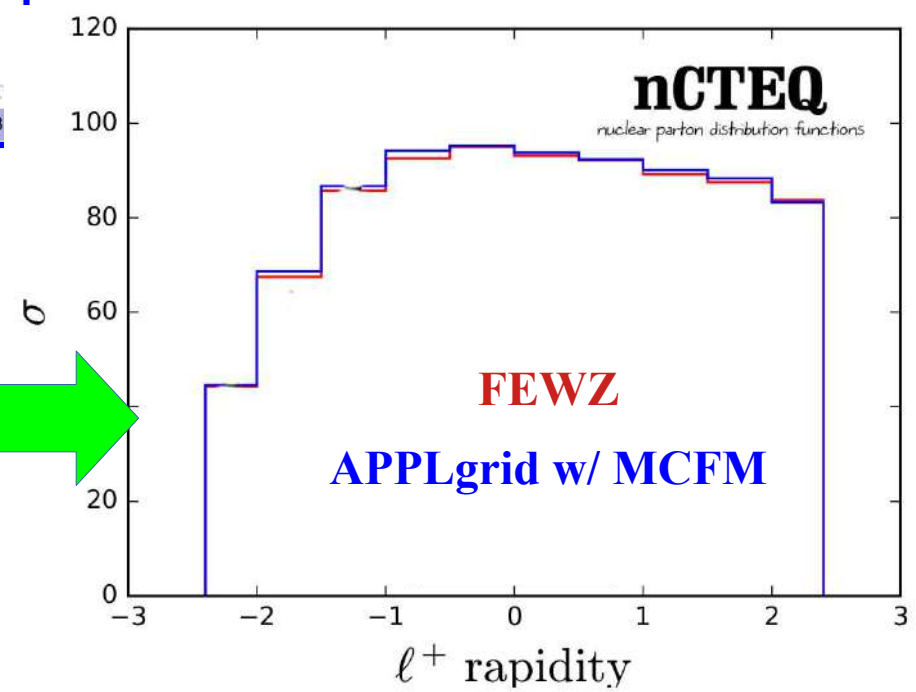
Pavel Starovoitov (Kirchhof-Institut für Physik) APPLGRID project zFitter@JINR 4 / 18



Validation:

Compare Grid to Full Calculation

Works for both proton & **nuclear**

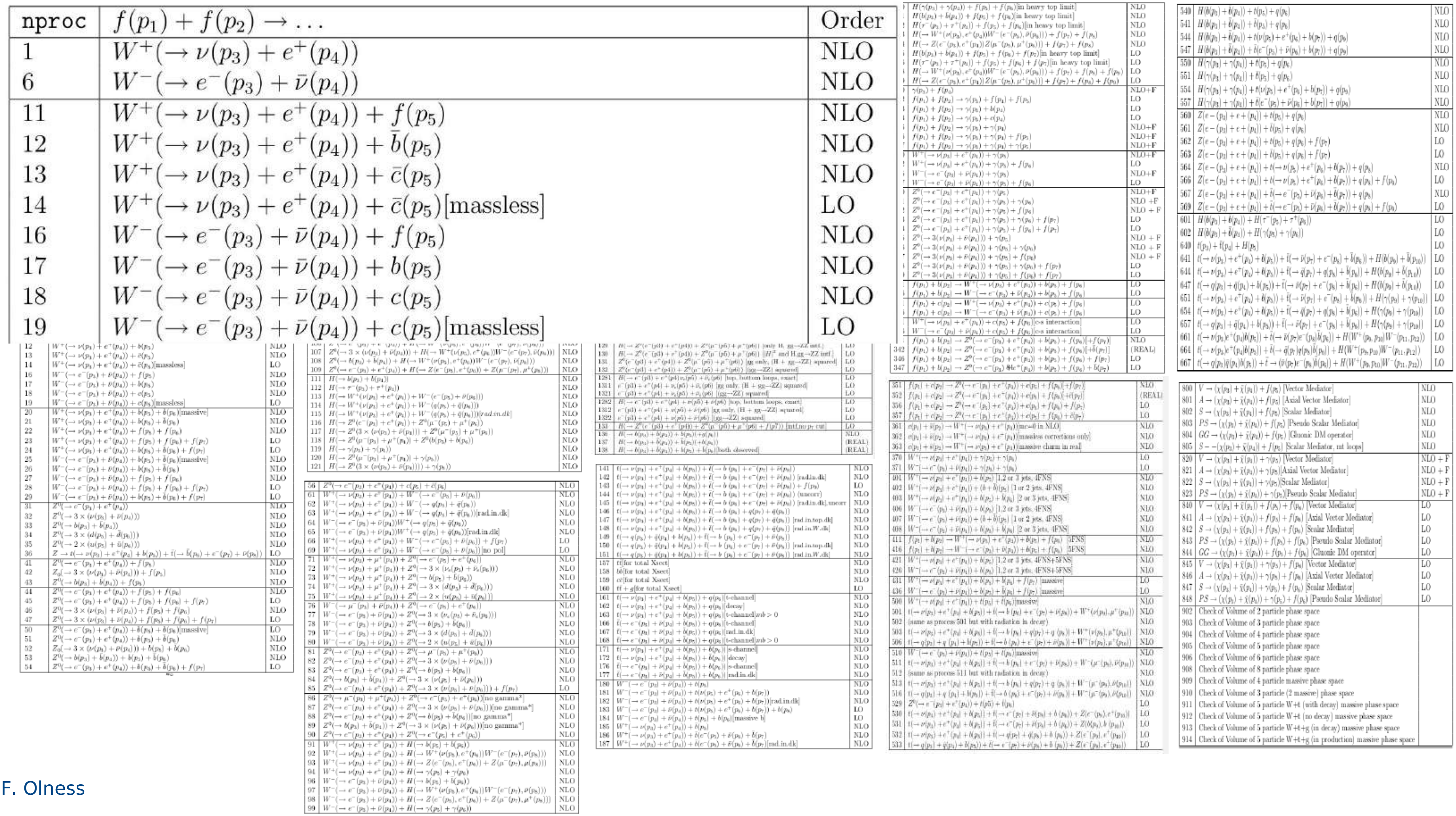


… can now access all MCFM Processes

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	$f(p_1) + f(p_2) \to \ldots$	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

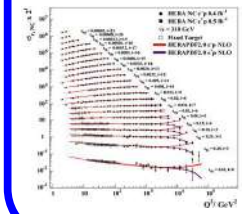
PROTON NUCLEON MESON

www.xFitter.org

Sample data files:

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

Experimental Data



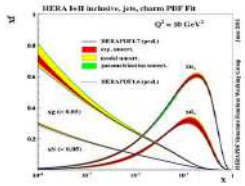
Data: HERA, Tevatron, LHC, fixed target experiments

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)

extensions include nuclear PDFs

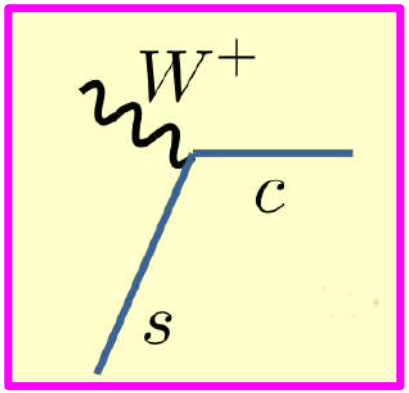
Features & Recent Updates:

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

xFitter 2.0.1
Old Fashioned

Charged Current Charm Production Constrains Strange PDF

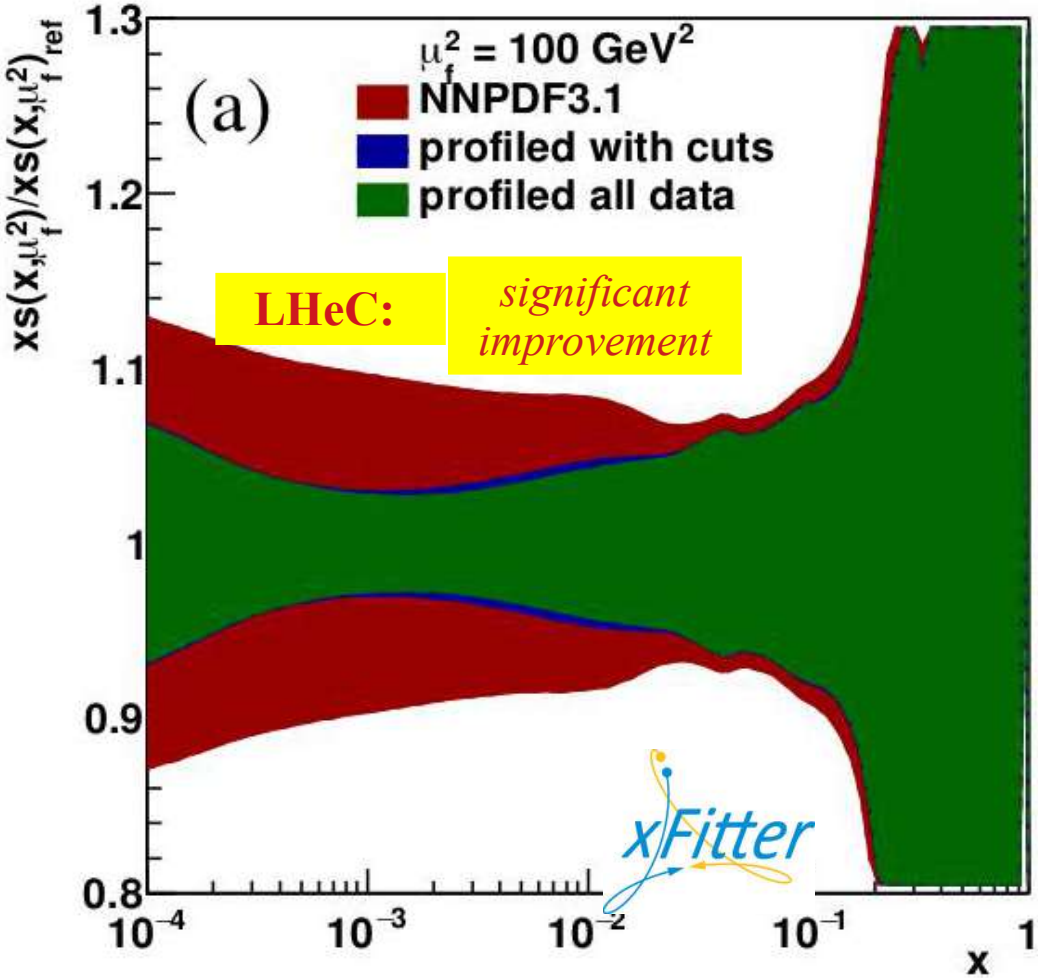


Probing the strange content of the proton with charm production in charged current at LHeC

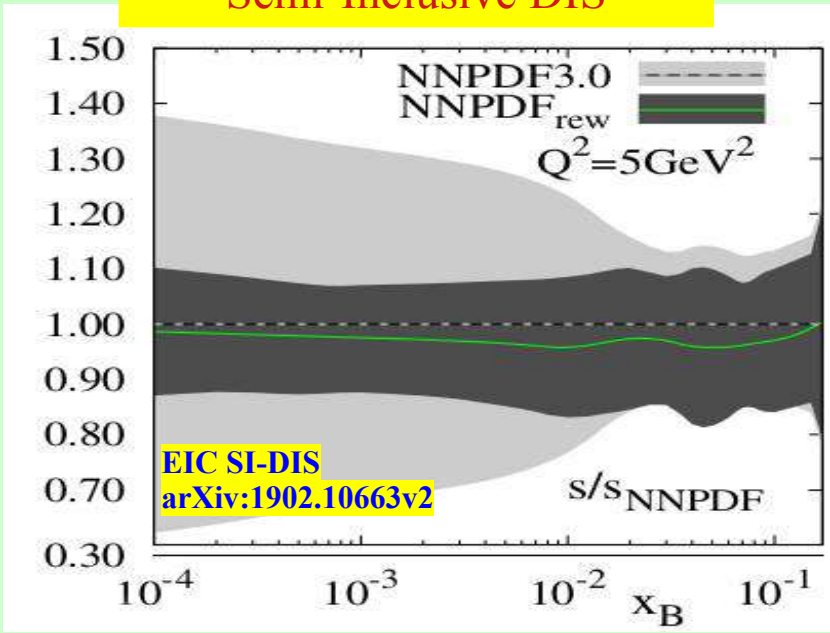
xFitter Developers' team: Hamed Abdolmaleki[1], Valerio Bertone[2], Daniel Britzger[3], Stefano Camarda[4], Amanda Cooper-Sarkar[5], Achim Geiser[6], Francesco Giuli[7], Alexander Glazov[6], Agnieszka Luszczak[8], Ivan Novikov[9], Fred Olness[10], Andrey Sapronov[9], Oleksandr Zenaiev[11]

xFitter Developers' Team;
arXiv:1907.01014 [hep-ph]

xFitter:
Docker & Singularity images available
details in extra slides



Potential EIC improvement
Semi-Inclusive DIS



See also: R.A. Khalek, S. Bailey, J.Gao, L. Harland-Lang, J. Rojo, arXiv:1906.10127 [hep-ph] *w/ additional channels*

... how can we nail this!
would also elucidate LHC issues

New Tools

PDFSense

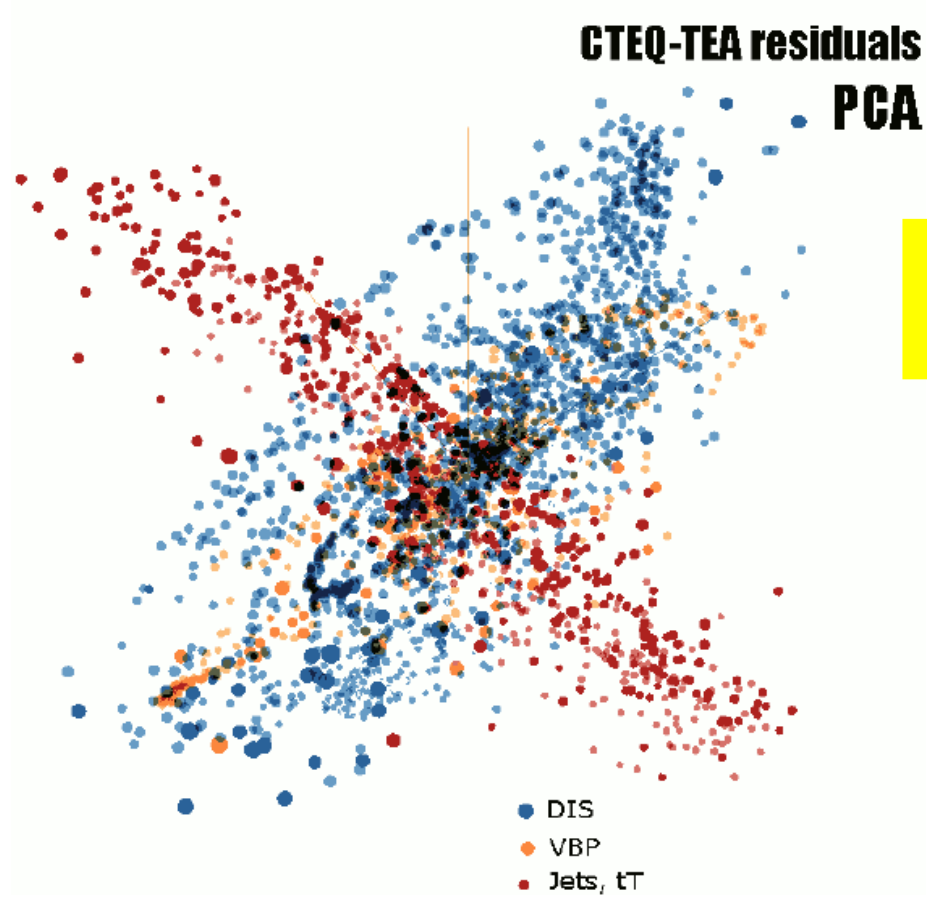
&

… borrowing from AI

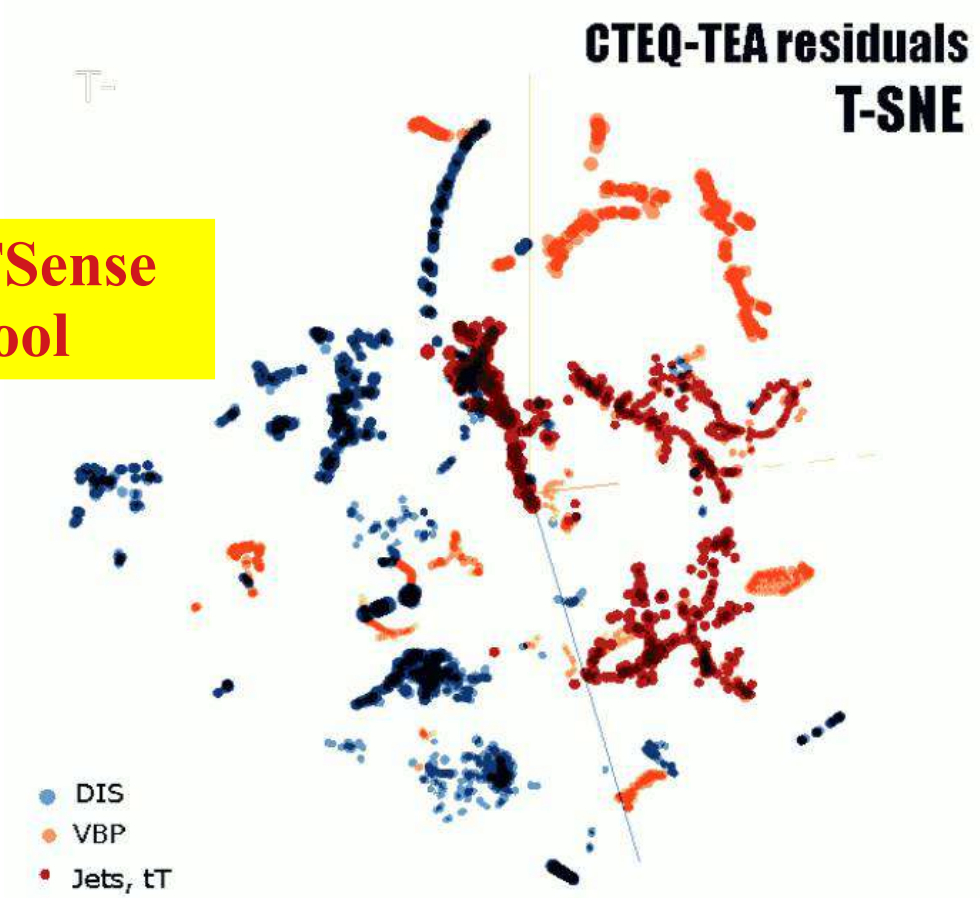
TensorFlow Embedding Projector

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

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



PDFSense tool



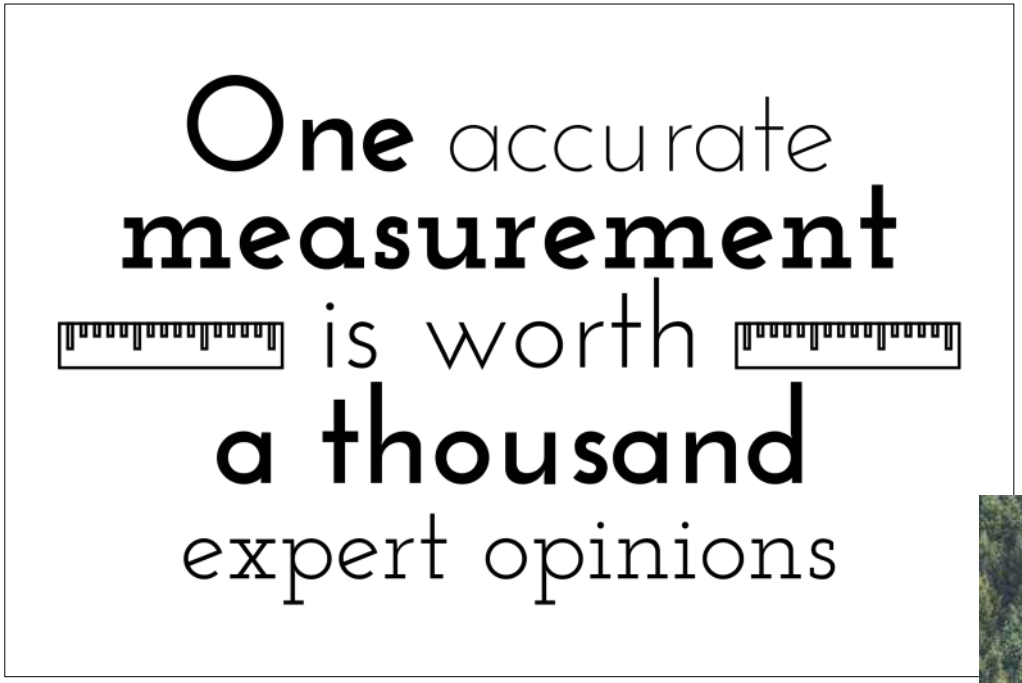
Principal Component Analysis (PCA) visualizes the 56-dim. manifold by reducing it to 10 dimensions (à la META PDFs)

http://projector.tensorflow.org

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

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

Conclusion

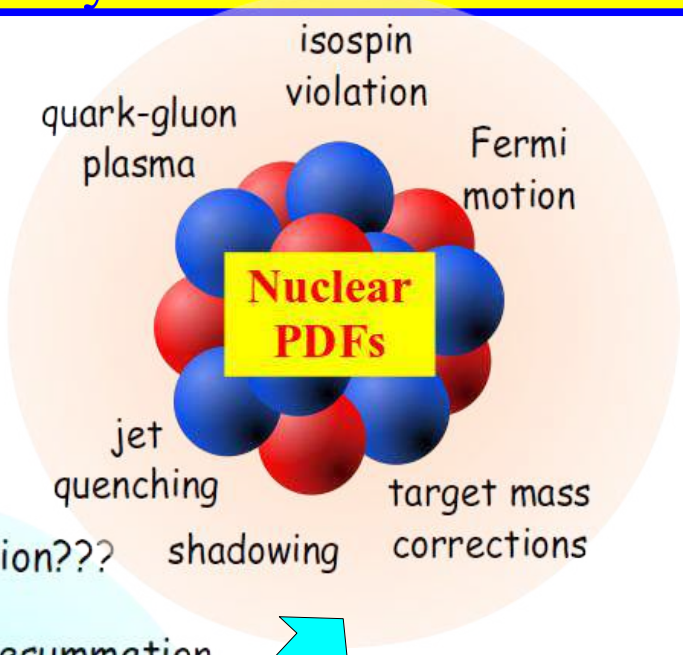

One accurate
measurement
is worth
a thousand
expert opinions

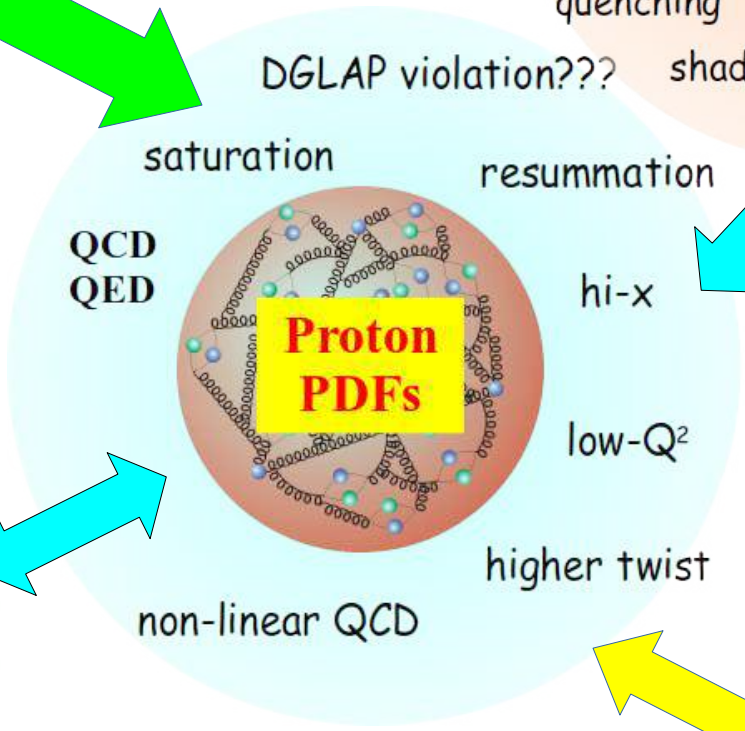

The heart of science is
measurement.
Erik Brynjolfsson
BrainyQuote

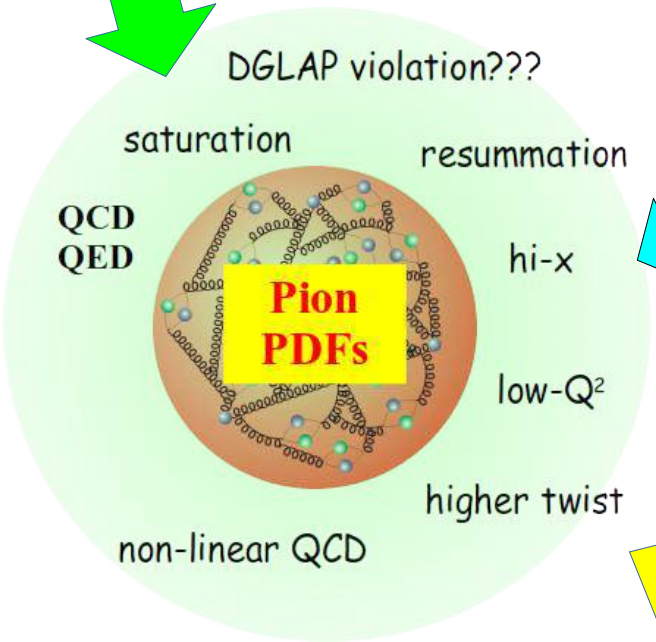
Deciphering QCD: ... concerted interdisciplinary effort across HEP & NUC

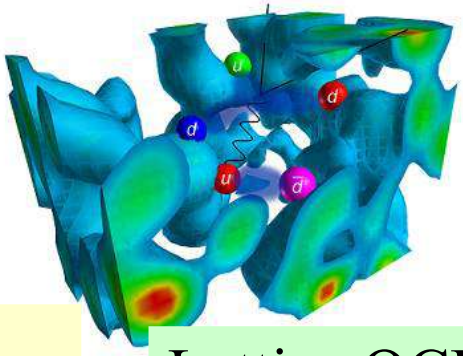
QCD
Lagrangian

$$\mathcal{L}_{QCD} = \overline{\psi}_q \left(i\gamma_\mu D^\mu - m_q \right) \psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$









Lattice QCD

- Hadron Spin
- Generalized PDFs