Revealing the fundamental character of the strong force

nCTEQ
nuclear parton distribution functions

nuclear CTEQ

xFitter

C T E Q

Coordinated Theoretical-Experimental Project on QCD

Fred Olness
SMU

Thanks for substantial input from my friends & colleagues

2022 Mitchell Conference
May 24-27

WHY SCIENTISTS THINK PHYSICS COULD BE IN FOR A RECKONING

The evidence seems to be growing that some new physics is needed.

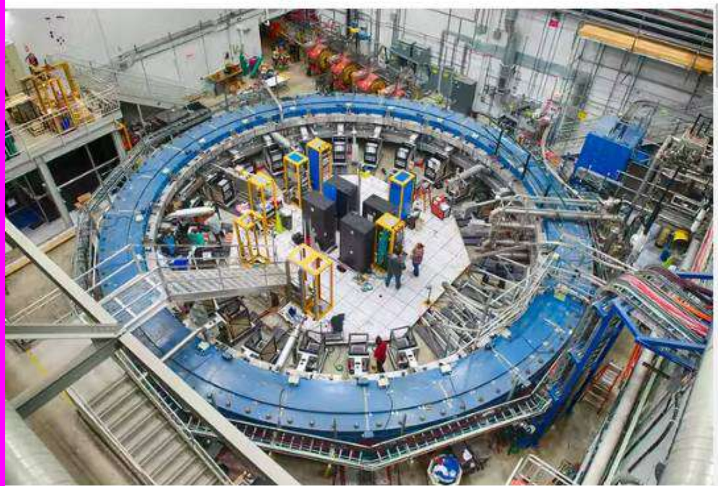
…HC) at CERN, one …ing to find …ide from the Higgs …nposite particles?" I … how we have

PHYSICS TODAY

W-boson mass hints at physics beyond the standard model

Nearly a decade of coll… fundamental particle's …

THE CONVERSATION



The storage-ring magnet for the Muon G-2 experiment at Fermilab. Reidar Hahn/wikipedia, CC BY-SA

The standard model of particle physics may be broken – an expert explains

HVP Hadronic Vacuum Polarization

Published: May 6, 2022 11.43am EDT

Roger Jones, *Lancaster University*

As a physicist working at the Large Hadron Collider (LHC) at Cern, one of the most frequent questions I am asked is "When are you going to find something?". Resisting the temptation to

W-Mass

g-2

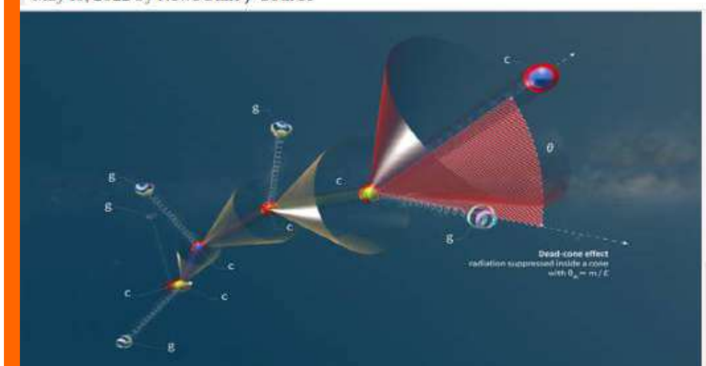
ALICE Dead-Cone

…

SCI NEWS

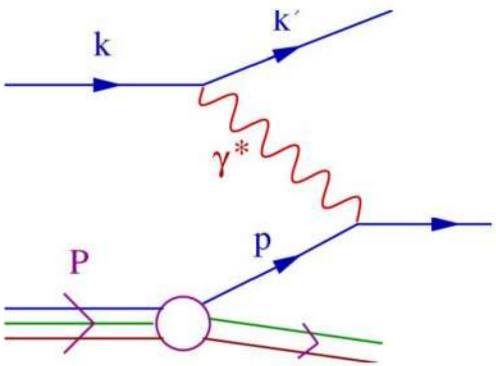
CERN Physicists Directly Observe Fundamental Phenomenon in Quantum Chromodynamics

May 19, 2022 by News Staff / Source

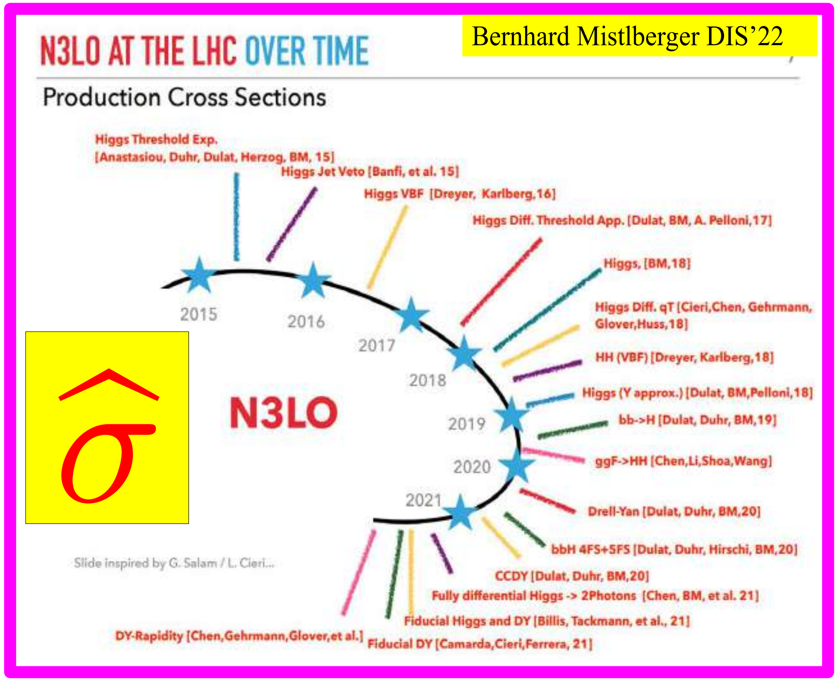


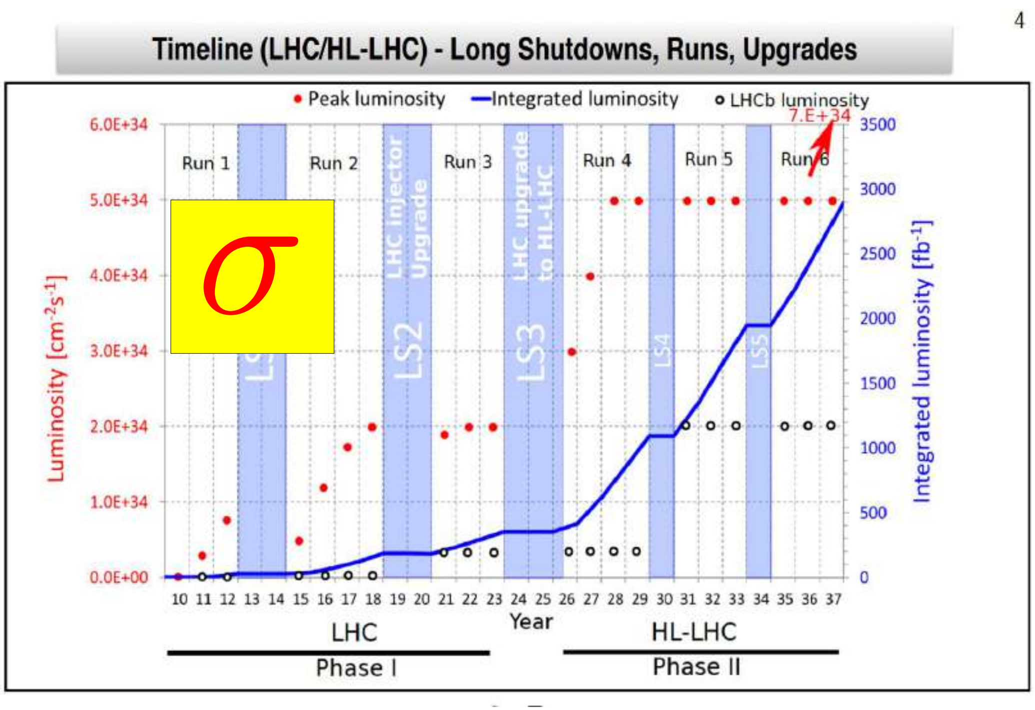
A charm quark (c) in a parton shower loses energy by emitting radiation in the form of gluons (g). The shower displays a dead cone of suppressed radiation around the quark for angles smaller than the ratio of the quark's mass (m) and energy (E). The energy decreases at each stage of the shower. Image credit: Daniel Dominguez / CERN.

We are entering the "Precision Era"

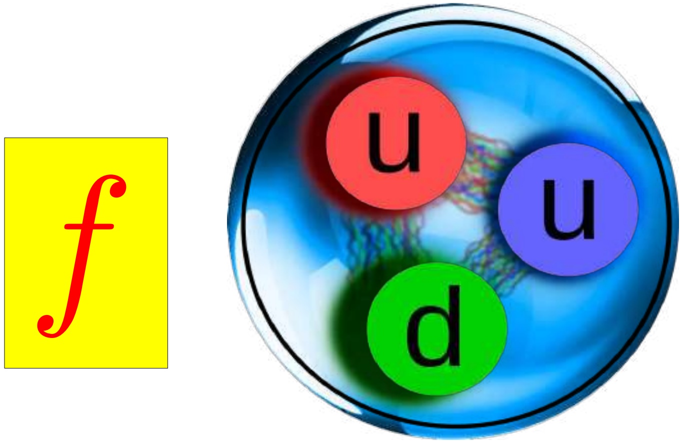


$$\sigma = f \otimes \hat{\sigma}$$

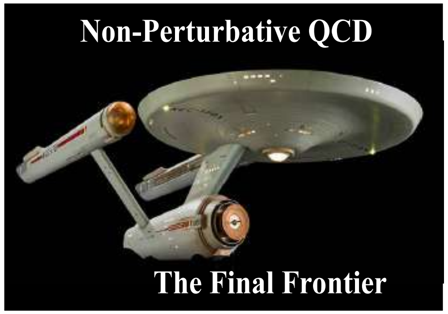


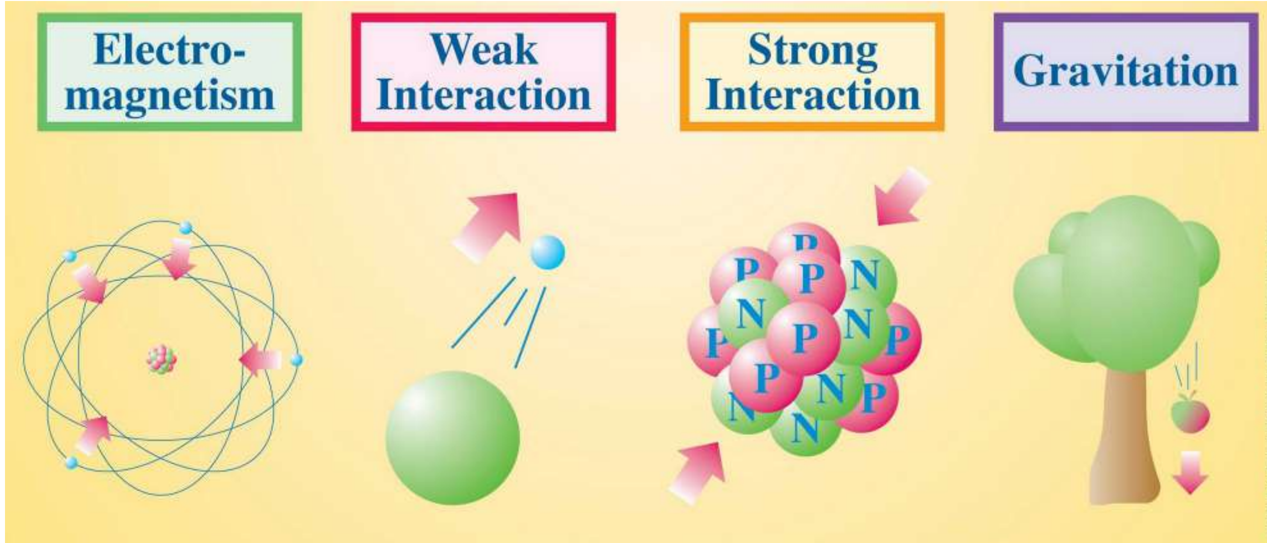


Challenge: hadronic component



arXiv:hep-ph/9907340 # "QCD is our most perfect physical theory" *Frank Wilczek*





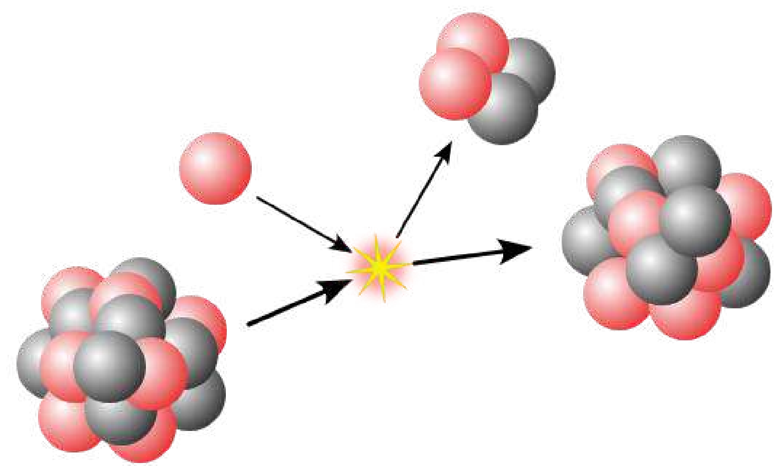
QCD:
Quantum
ChromoDynamics
… the strong nuclear force

Nobel Prizes: EW '79,'95,'99,'02,'08,'15 QCD '04 Gravity '11, '17, '20 Higgs '13

QCD is our most perfect physical theory

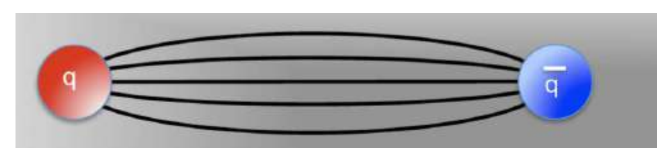
What QCD Tells Us About Nature – and Why We Should Listen. *Frank Wilczek*

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



Lessons: The Nature of Nature

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

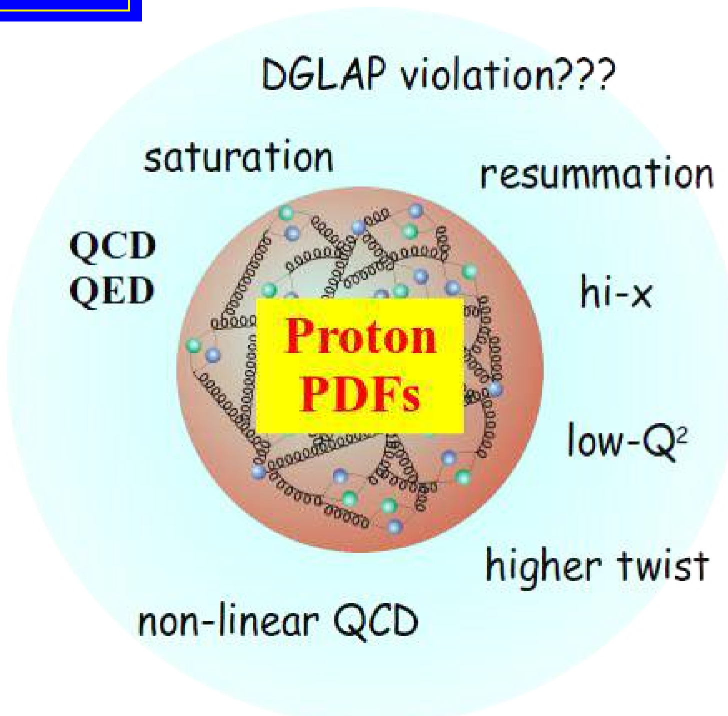


Quark Confinement
(Asymptotic Freedom)

C T E Q

Established 1991

Foster communication between experimentalists & theorists

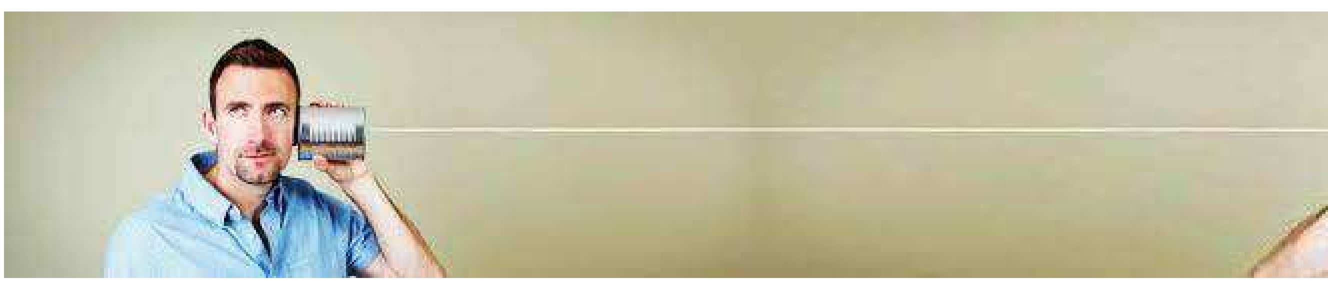


HERA
Tevatron
era

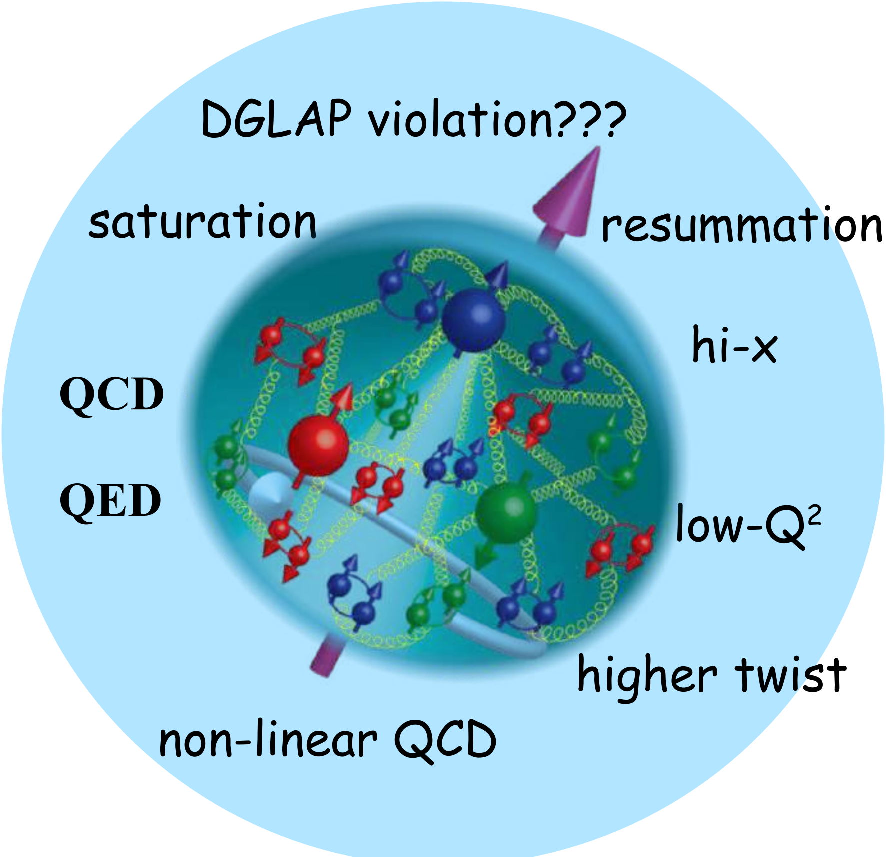
A History of CTEQ:

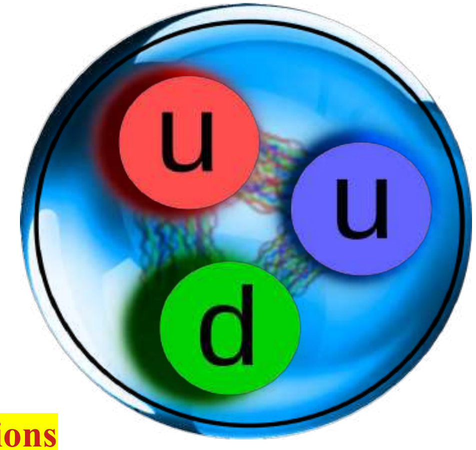
The Coordinated Project on Theoretical and Experimental Studies of QCD

The CTEQ Collaboration
Editor: Jeff Owens

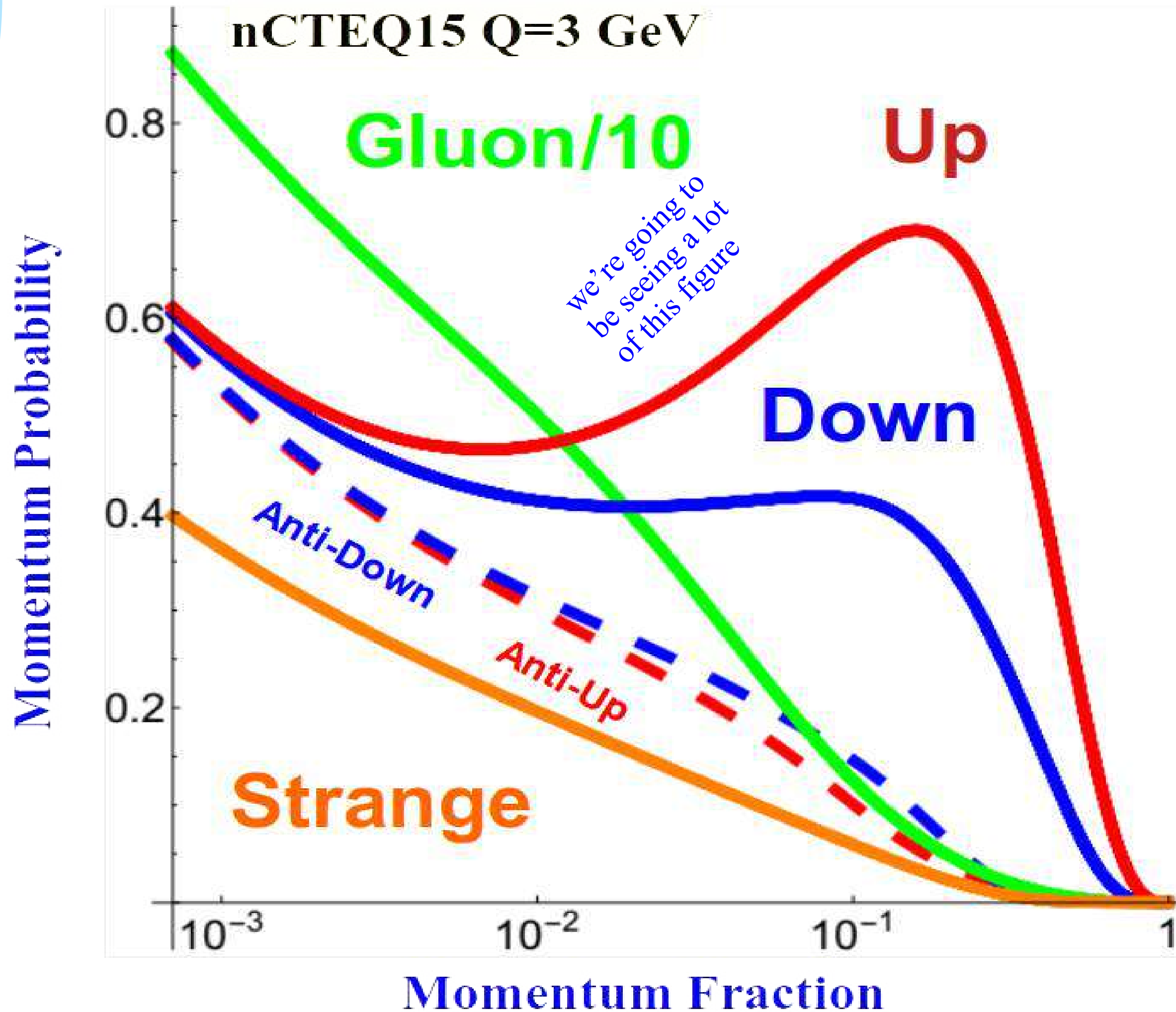


PROTON Parton Distribution Functions (PDFs)





Parton Distribution Functions



This description is
Universal

Applies to HERA, LHC, EIC …

a consequence of factorization

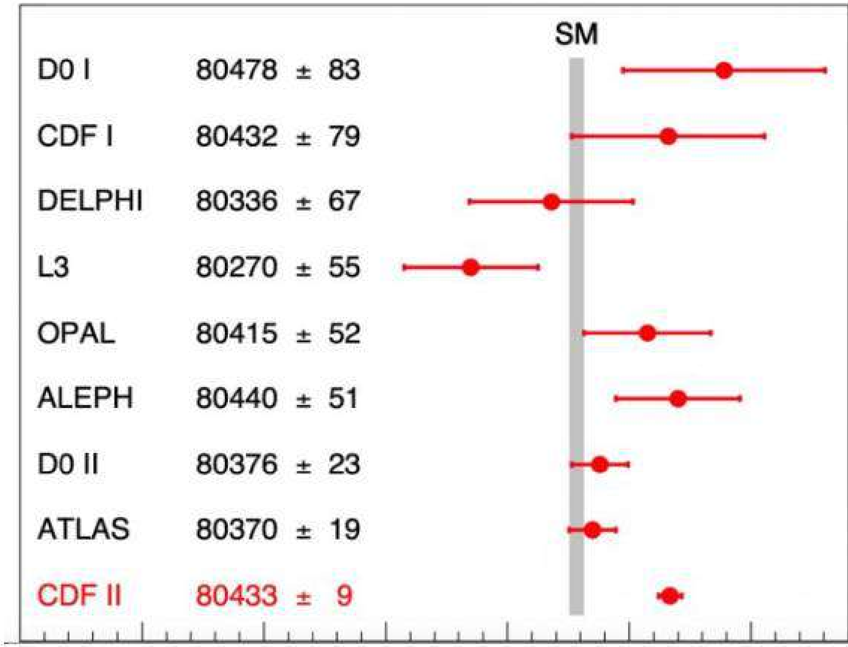
Precision Era: High Precision W Boson Mass

RESEARCH

PARTICLE PHYSICS

High-precision measurement of the *W* boson mass with the CDF II detector

CDF Collaboration†‡, T. Aaltonen[1,2], S. Amerio[3,4], D. Amidei[5], A. Anastassov[6]



1994

ICHEP'94

Table 1. Uncertainties in the W mass measurements, in MeV.

	CDF (e)	CDF (μ)	DØ(e)
Energy Scale	130	60	260
Resolution	140	120	70
Background	50	50	30
Fitting	20	20	30
PDF	100	100	70
p_T^W and und. evt.	120	145	120
Width	-	-	20
Total Sys.	250	240	307
Statistical	150	200	160
Total (Stat + Sys)	290	300	346

2022

Table 2. Uncertainties on the combined M_W result.

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

CSS Resummation

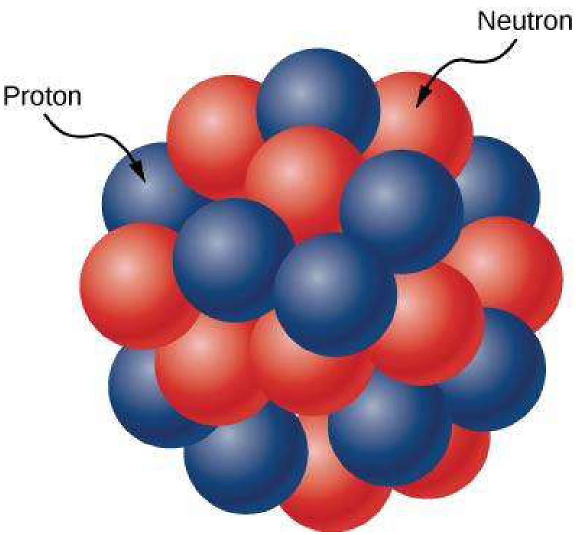
Strange PDF

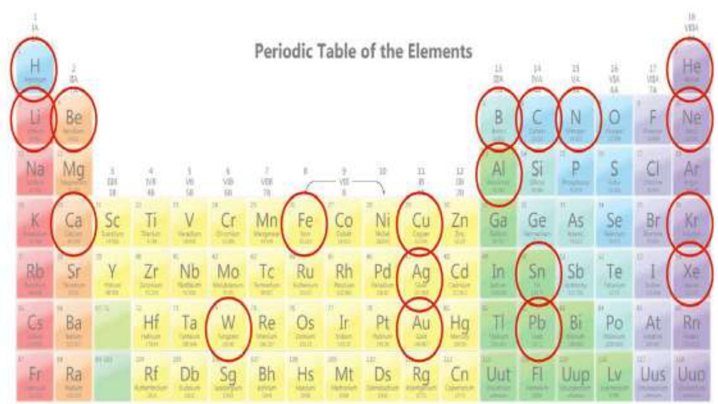
PDF Precision

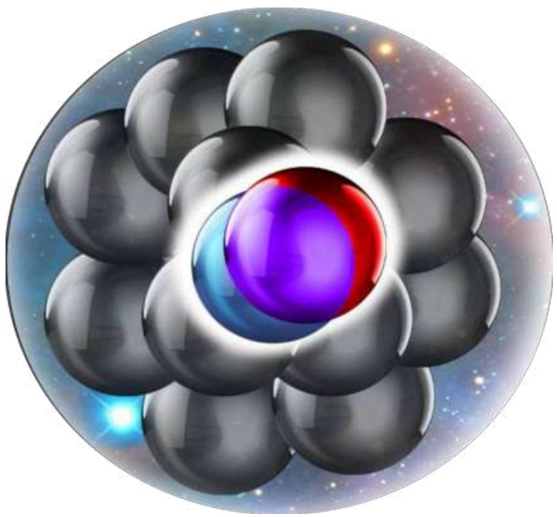
CDF Collaboration et al., Science 376, 170–176 (2022)

Nuclear PDFs

Parton Distribution Functions





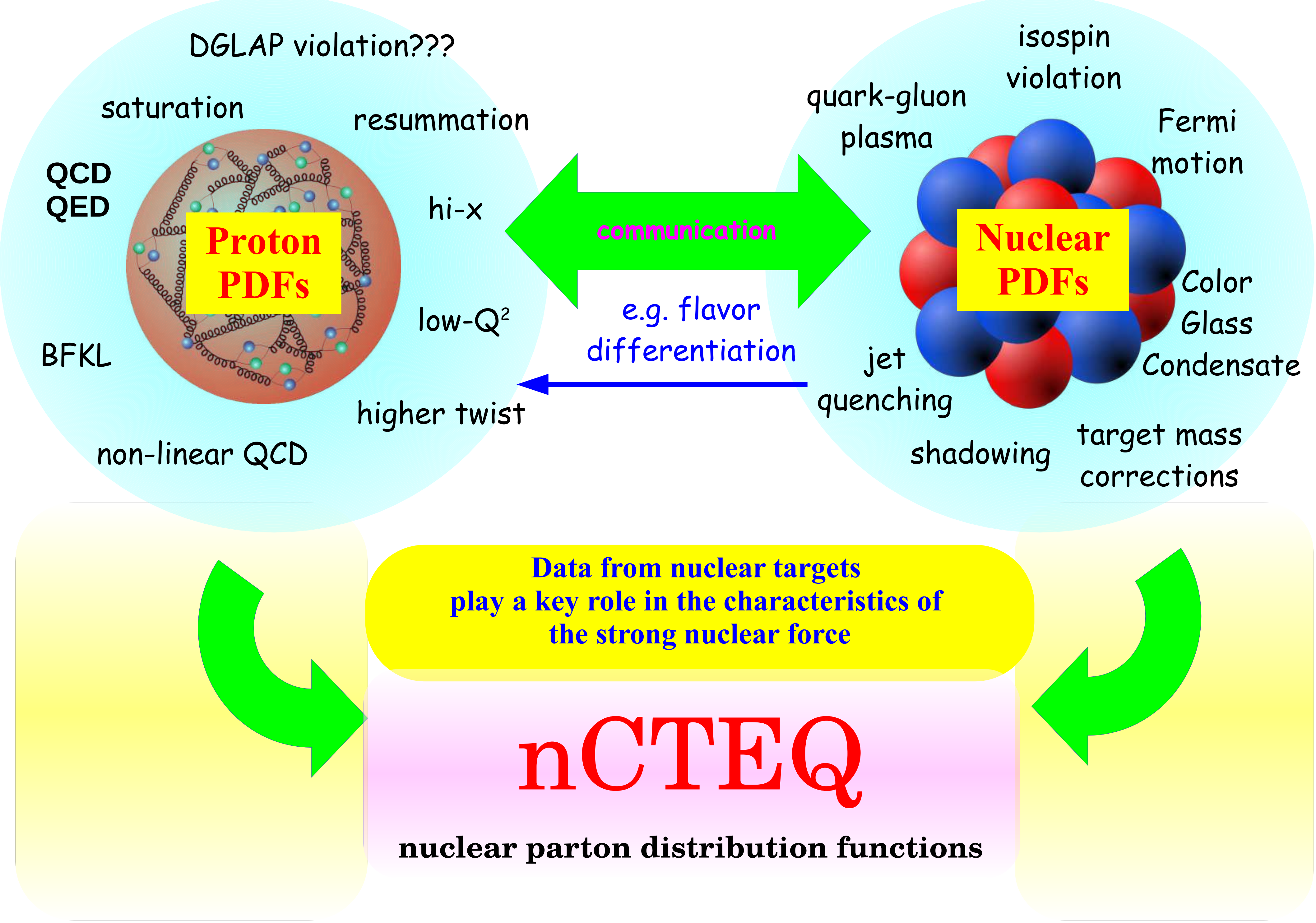


nCTEQ

nuclear parton distribution functions

nuclear Coordinated Theoretical-Experimental Project on QCD

… the ultimate goal for nCTEQ



nCTEQ
nuclear parton distribution functions

nCTEQ Projects

ν DIS: Muzakka, Kovarik, Klasen, …

W/Z: Jezo, Kusina, Olness, …

Gluons: Duwentaster, Klasen, …

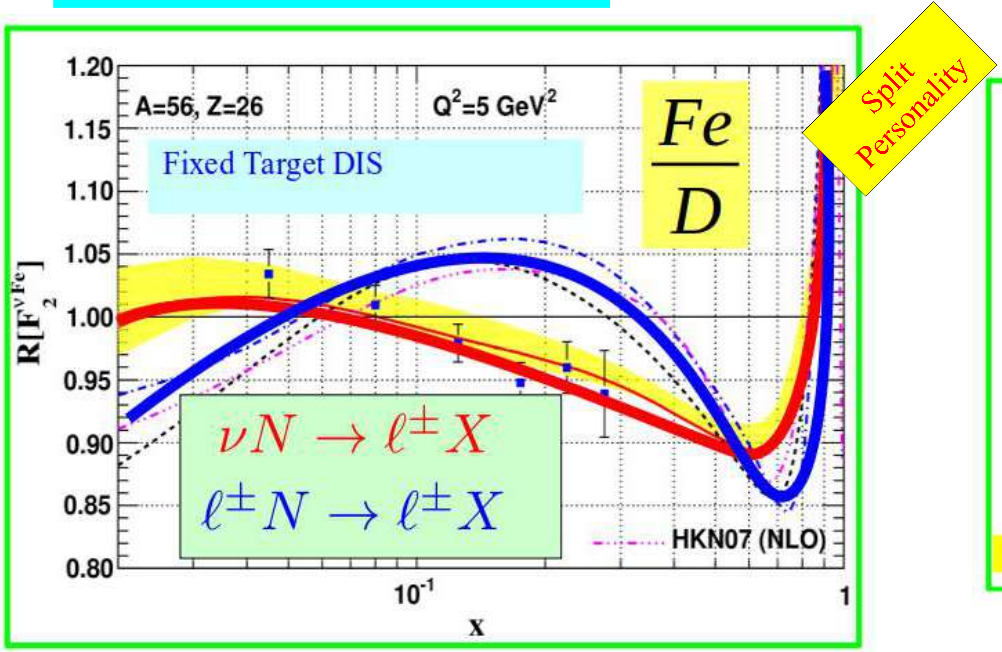
SRC: Jezo, Kusina, Olness, …

Masses: Schienbein, Leger, Ruiz, …

nCTEQ++: Jezo, Risse, Muzakka, DuwentasterWissmann...

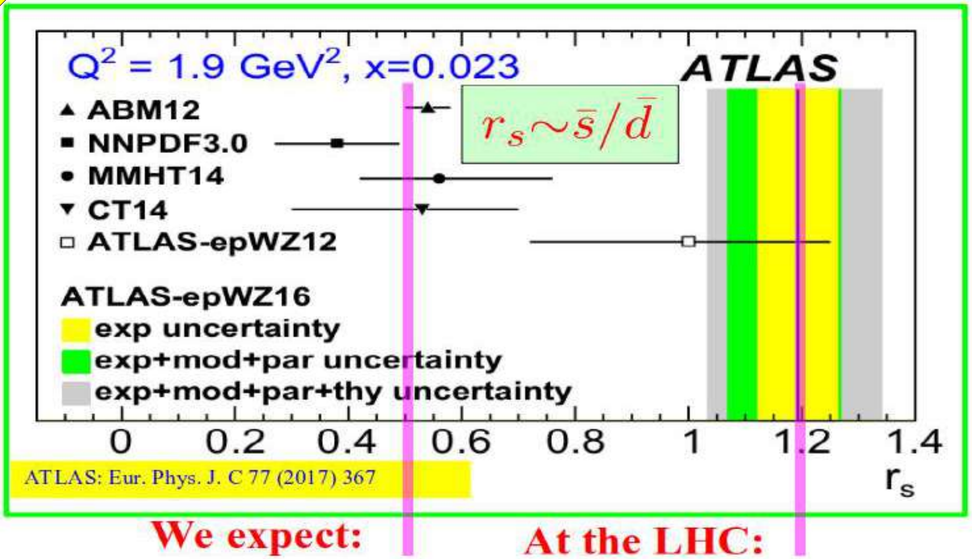
multifaceted approach

nCTEQ15ν



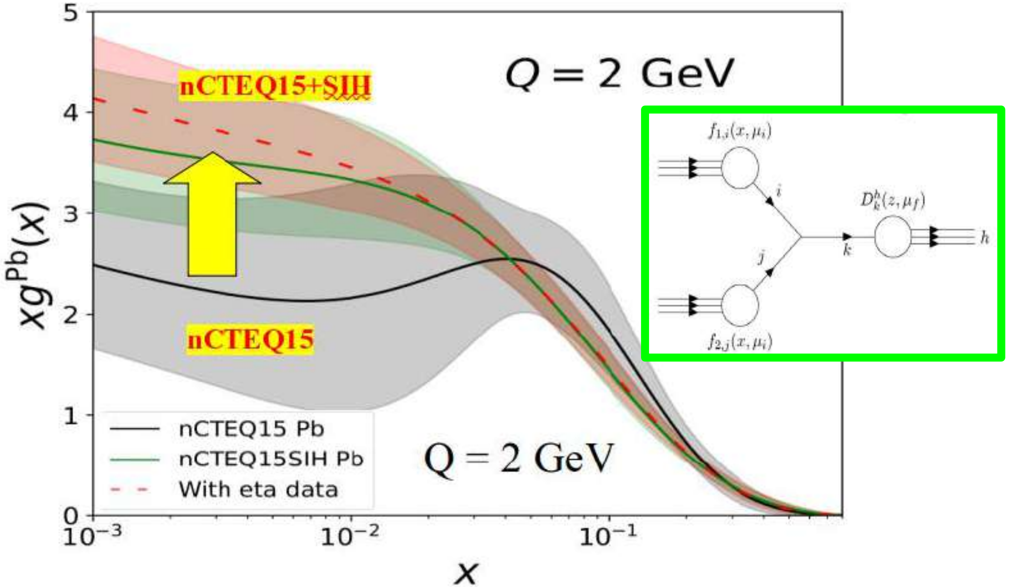
nCTEQ: arXiv: 2204.13157

nCTEQ15WZ



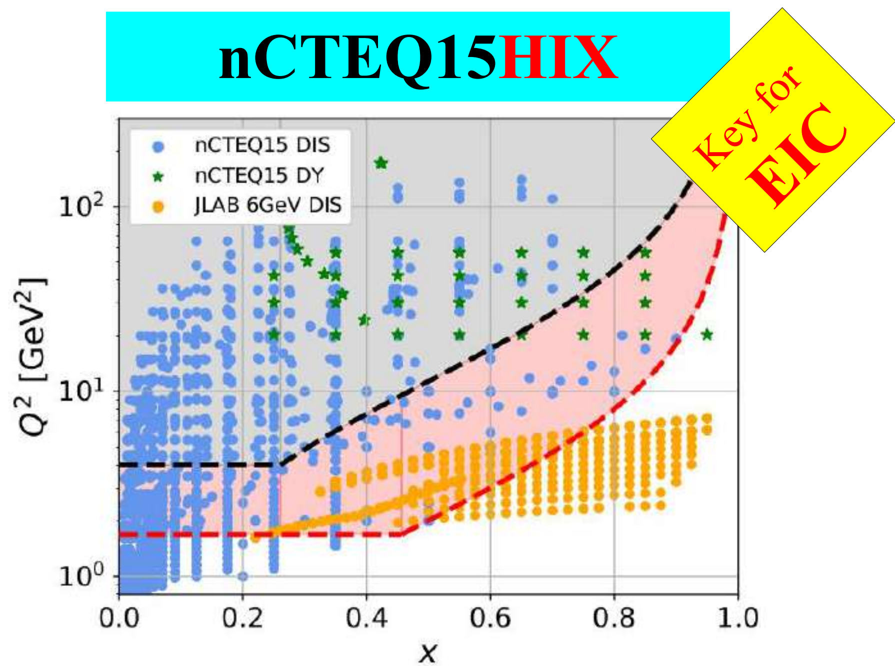
nCTEQ: Phys.Rev.D 104 (2021) 094005

nCTEQ15WZ+SIH



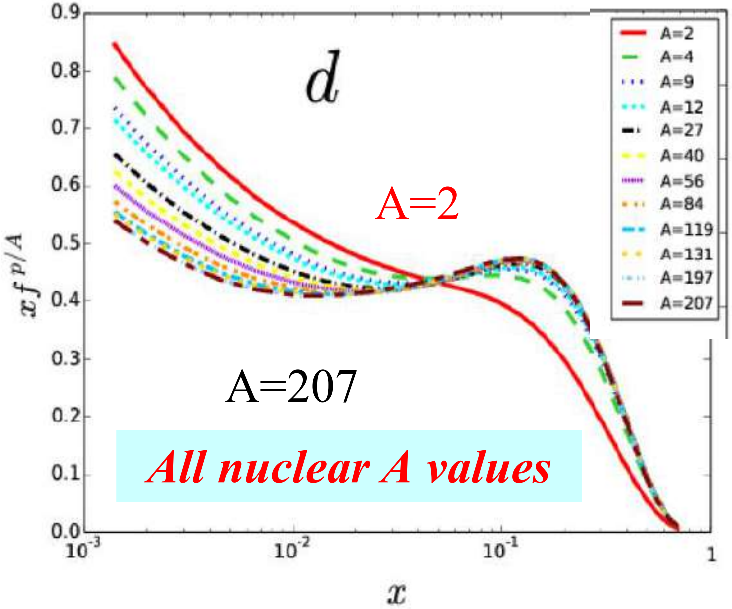
nCTEQ: PRD104 (2021) 094005.

nCTEQ15HIX



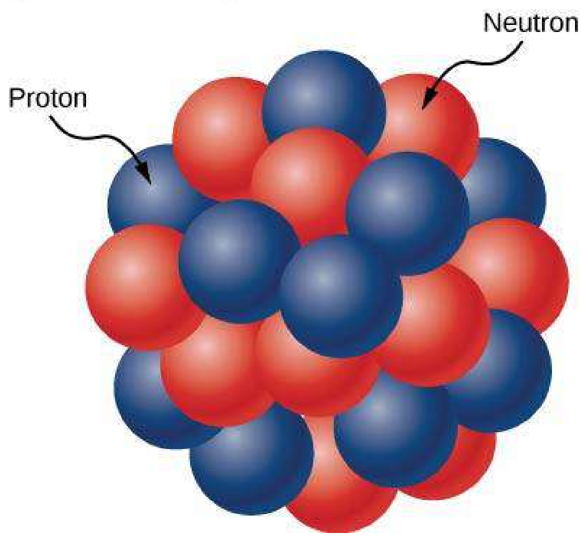
nCTEQ: Phys.Rev.D 103 (2021) 11, 114015

Short Range Correlations (SRC)

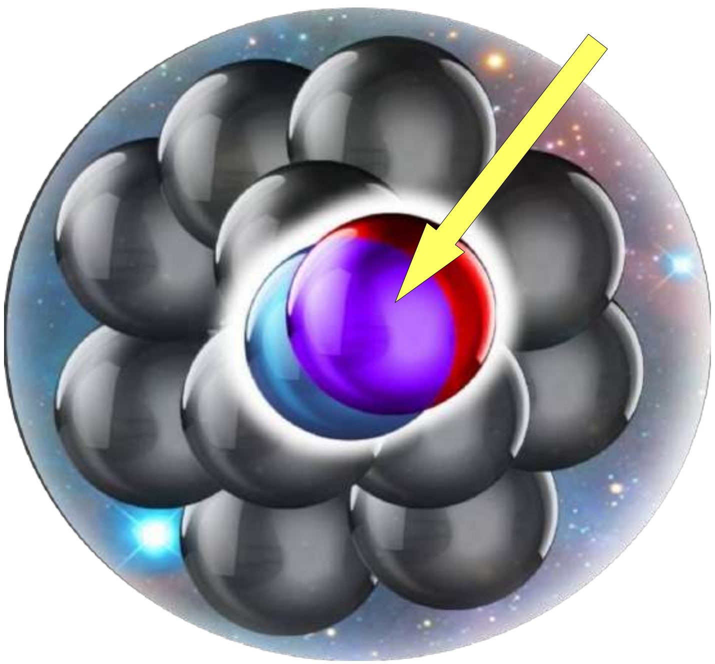


$$f_A = (1-c_A)\ f_p + c_A\ f_{SRC}$$

nuclear PDF — normal proton PDF — SRC modified PDF



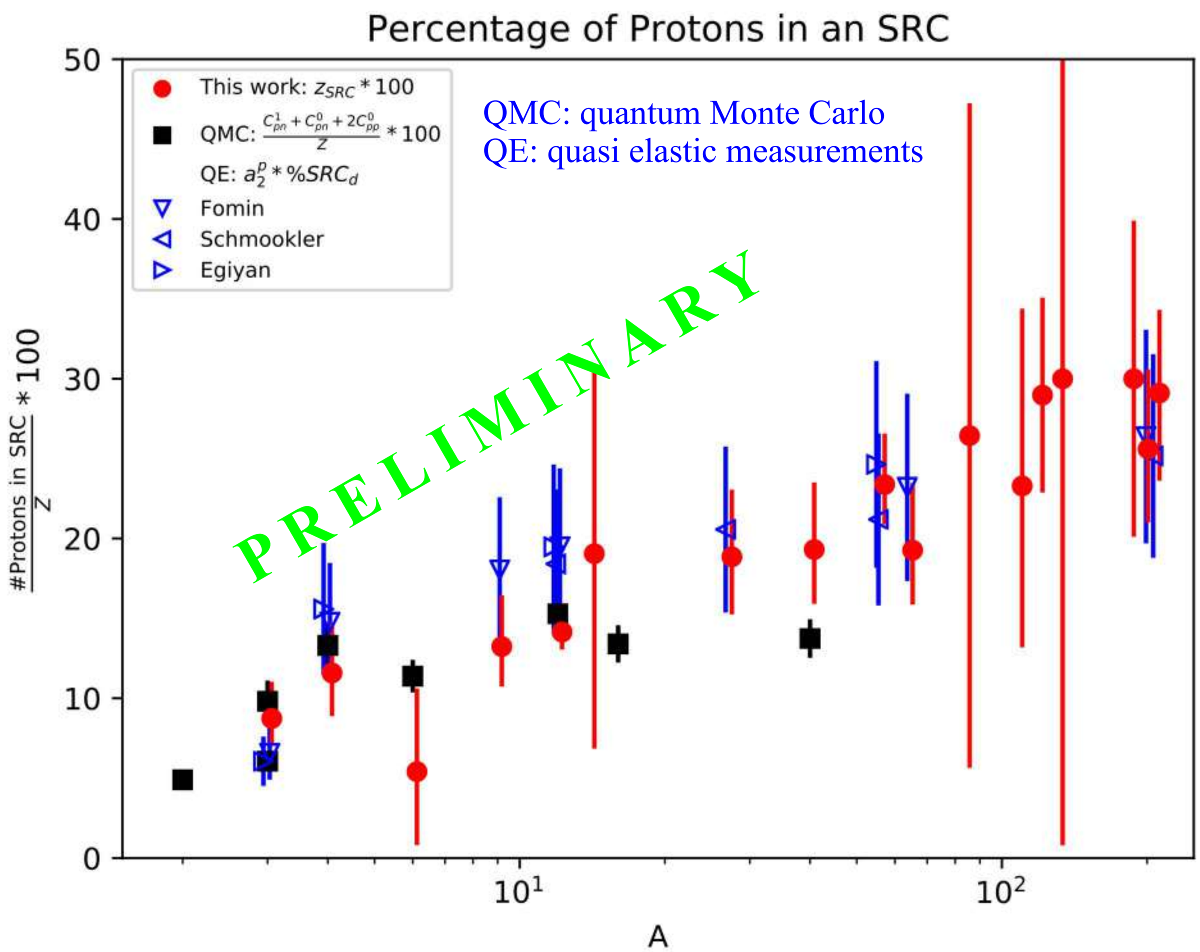
Short Range Correlations (SRC)

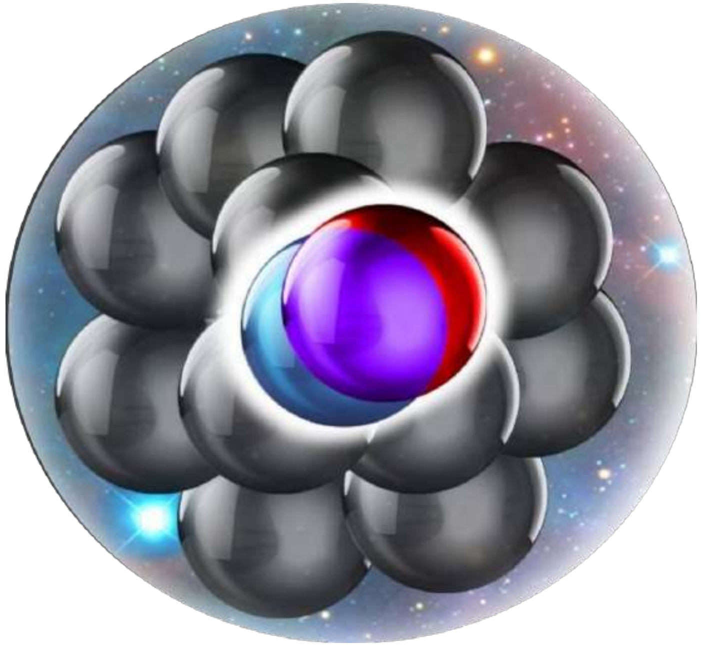


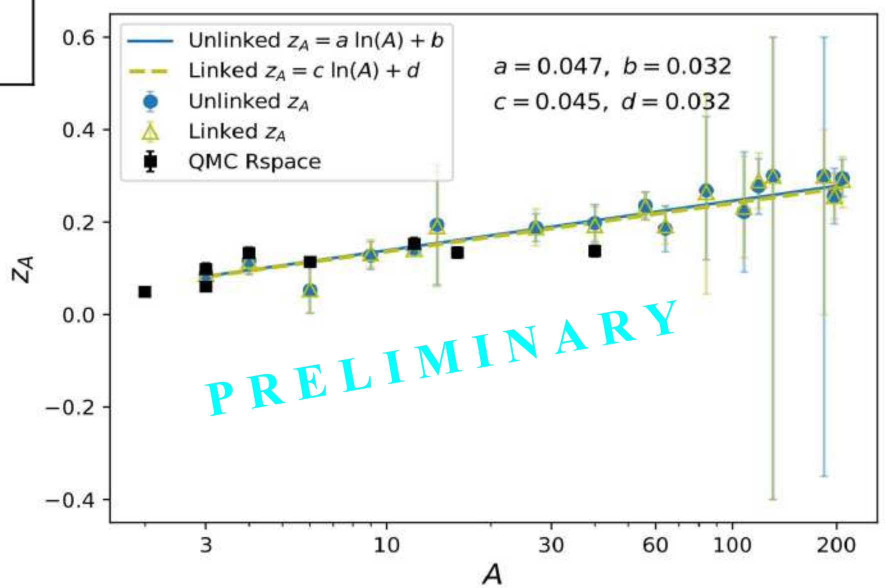
Hen Lab
Laboratory for Nuclear Science @ MIT

Tomas Jezo, Aleksander Kusina, ...

Short Range Correlations (SRC)







Preliminary results:

- Yields good fit: $\chi^2/N \sim 0.80$ vs. 0.85
- Compatible with (pn) SRC pairs

xFitter

www.xFitter.org

xFitter

PROTON

NUCLEON

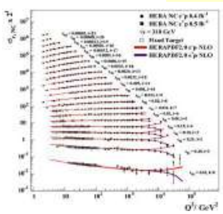
MESON

www.xFitter.org

Sample data files:

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

Experimental Data



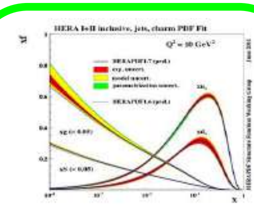
Data: HERA, Tevatron, LHC, fixed target experiments

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:

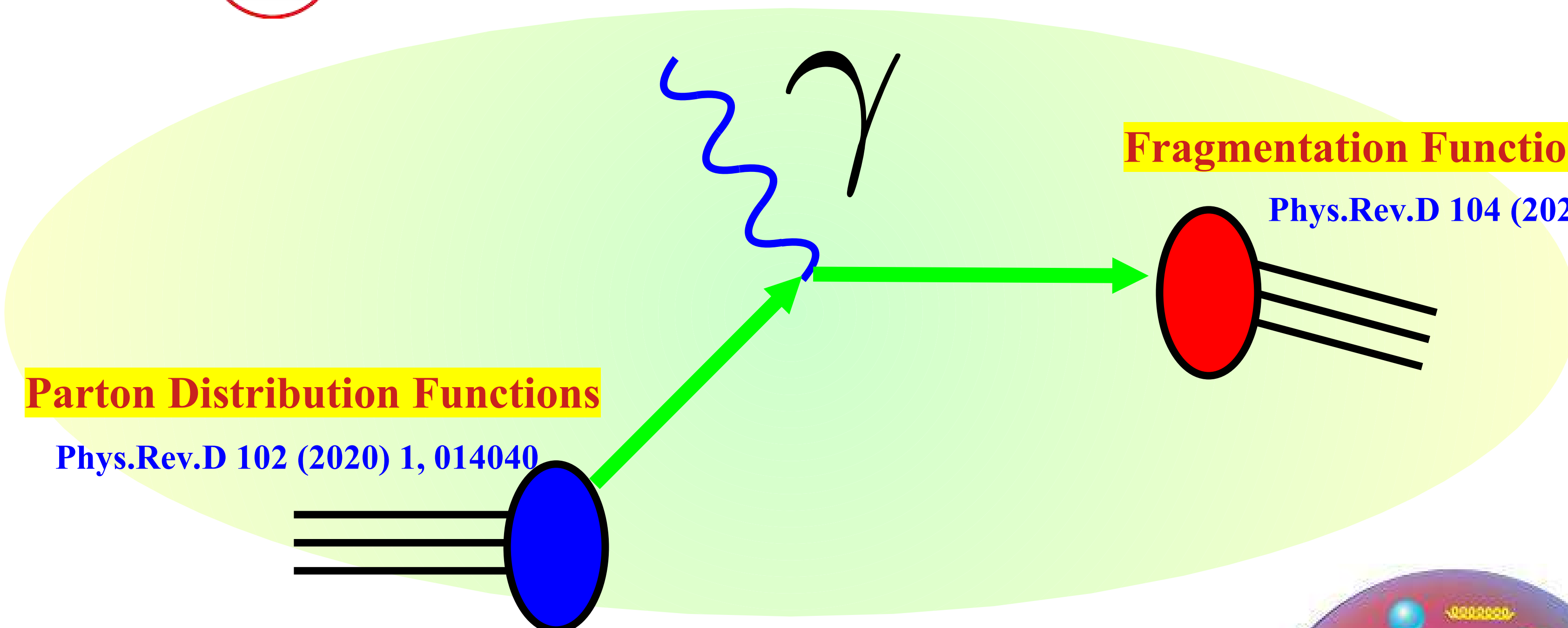
- Photon PDF & QED
- Pole & MS-bar masses
- Profiling and Re-Weighting
- Heavy Quark Variable Treshold
- Improvements in χ^2 and correlations
- TMD PDFs (uPDFs)
- *... and many other*

xFitter 2.2.0
Future Freeze

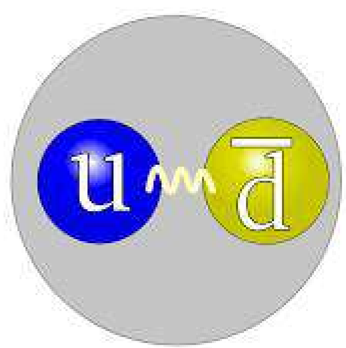
Pion PDFs & FFs

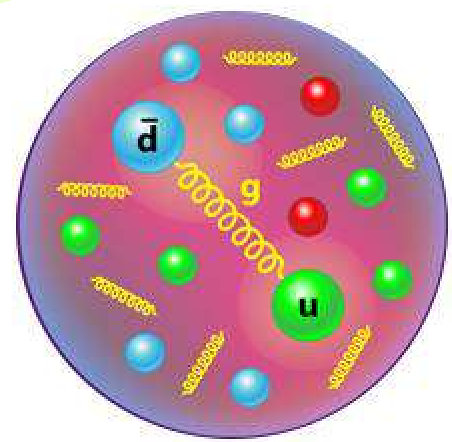
Parton Distribution Functions

Fragmentation Functions



$$\text{Pion } \pi^+ = u\bar{d}$$





Input from L-QCD

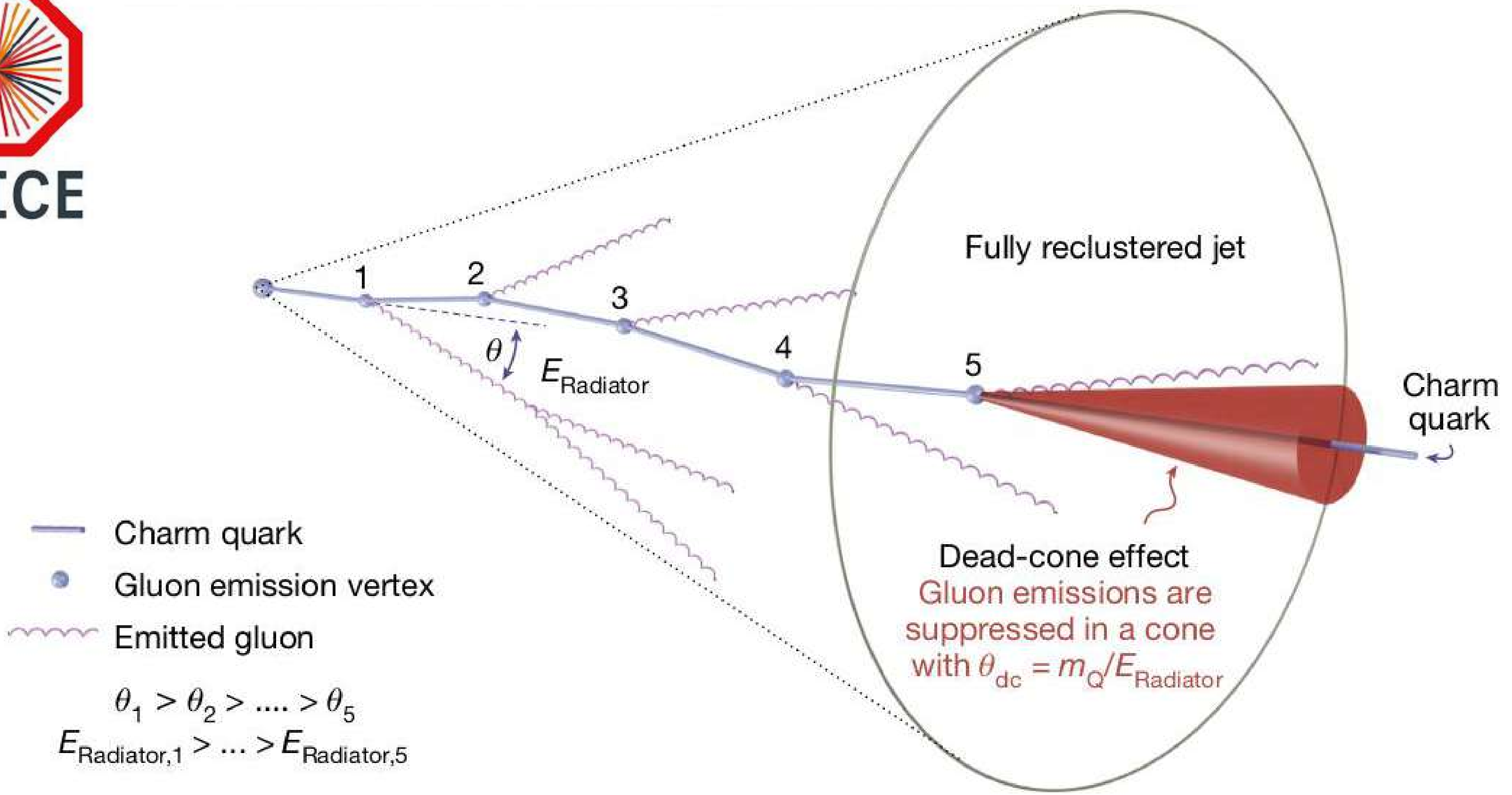
Dead Cone Effect: Charm quark parton shower reconstructed

Article

Direct observation of the dead-cone effect in quantum chromodynamics

https://doi.org/10.1038/s41586-022-04572-w
ALICE Collaboration*

- Detailed heavy quark shower reconstruction
- Dead Cone Observation
- Sensitive to **QUARK** mass *(not meson mass)*



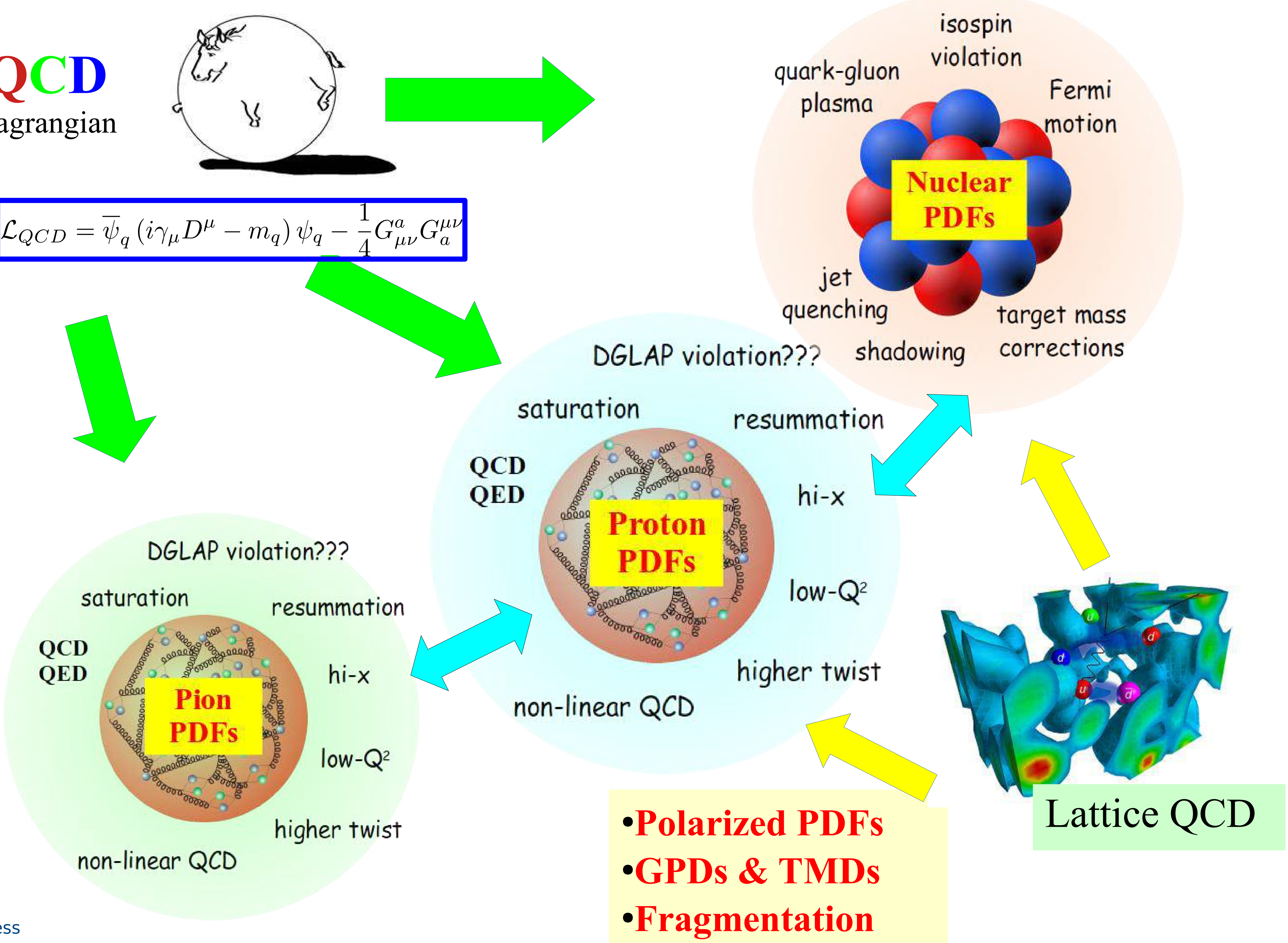
$$d\sigma \sim \frac{\theta^2}{(\theta^2 + \theta_D^2)^2} \qquad \theta_D \sim \frac{m}{E}$$

CONCLUSIONS

From Parameterization to a Deep Understanding … LHC + EIC

QCD Lagrangian

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



BACKUP

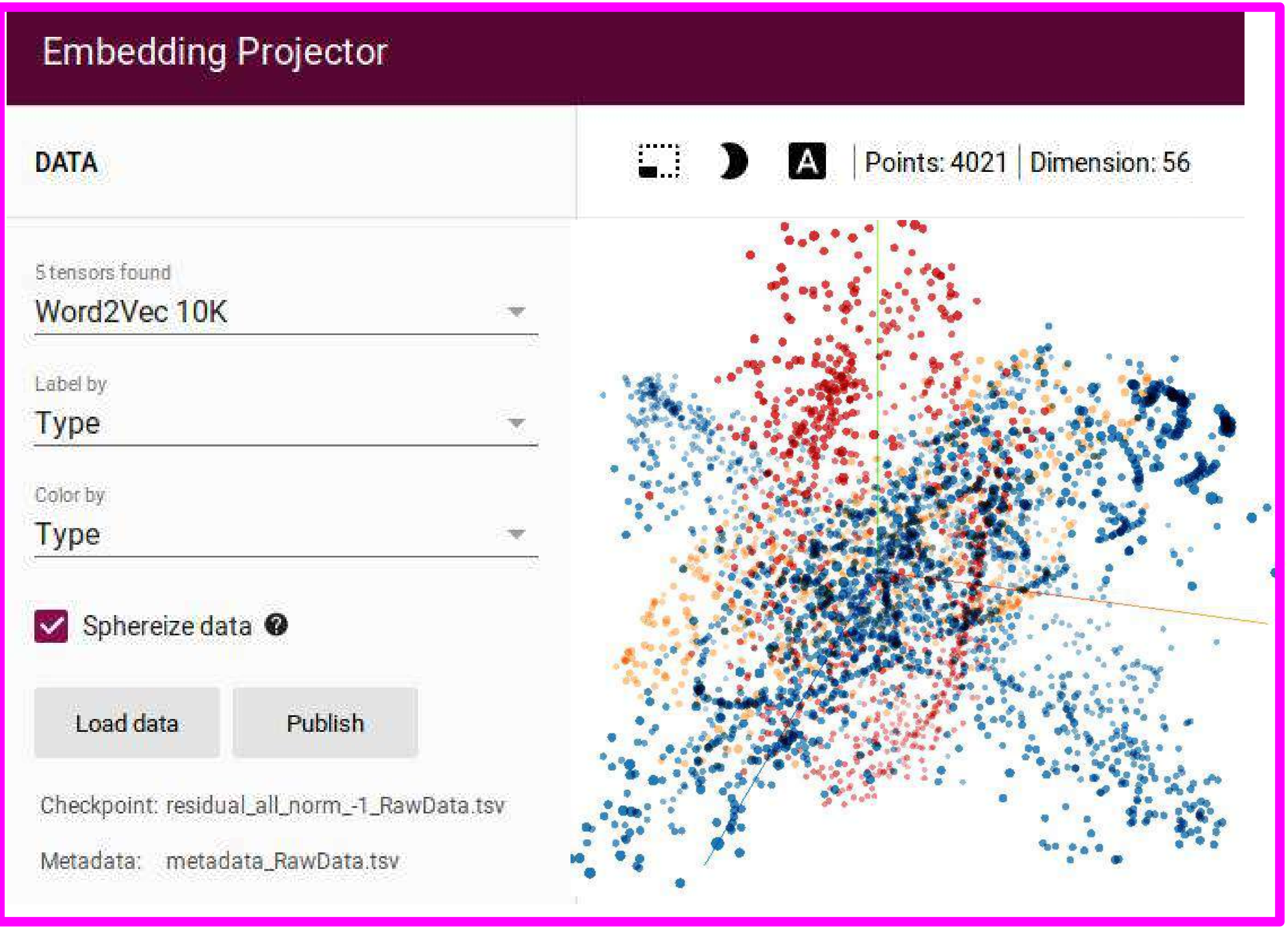
New Tools

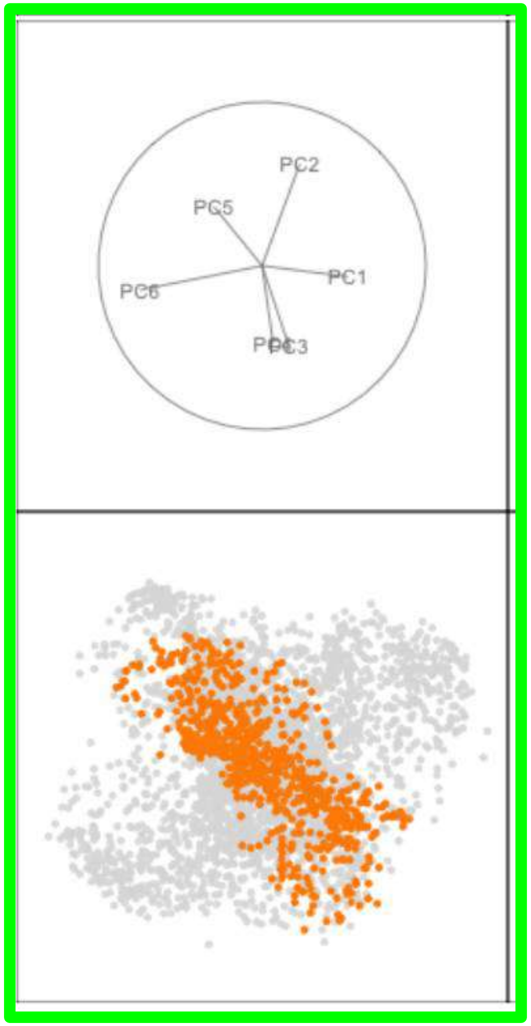
PDFSense

&

… borrowing from AI

Artificial Intelligence Tools: Projector tool of Google TensorFlow

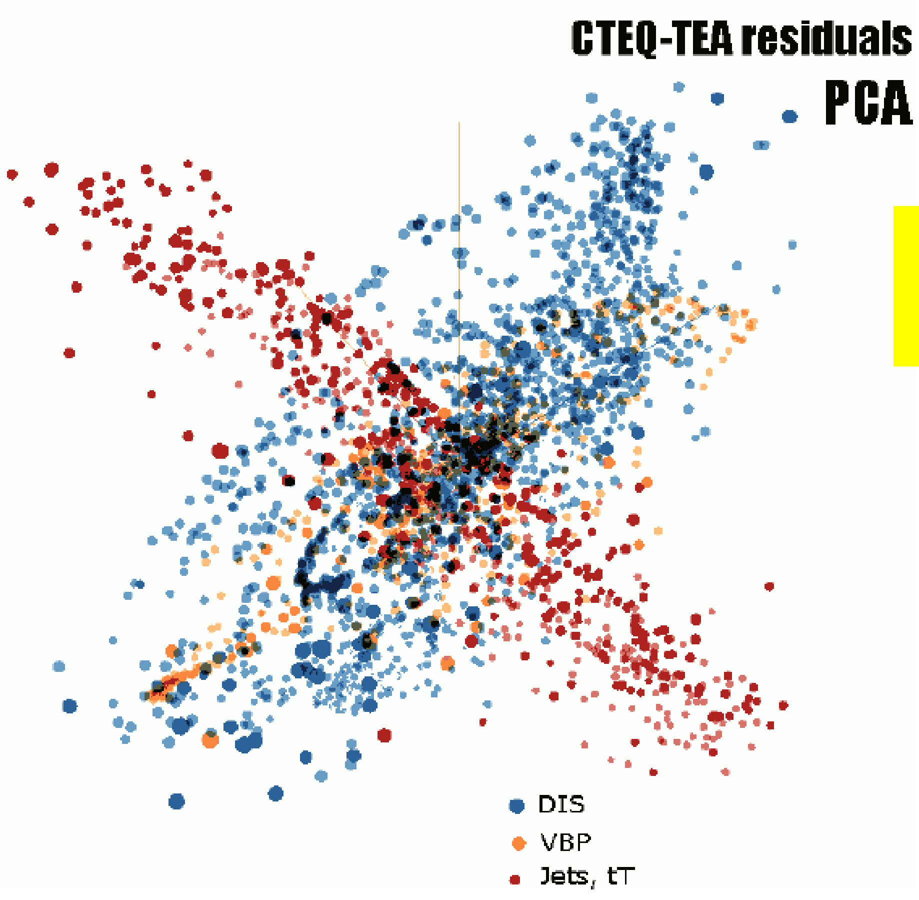




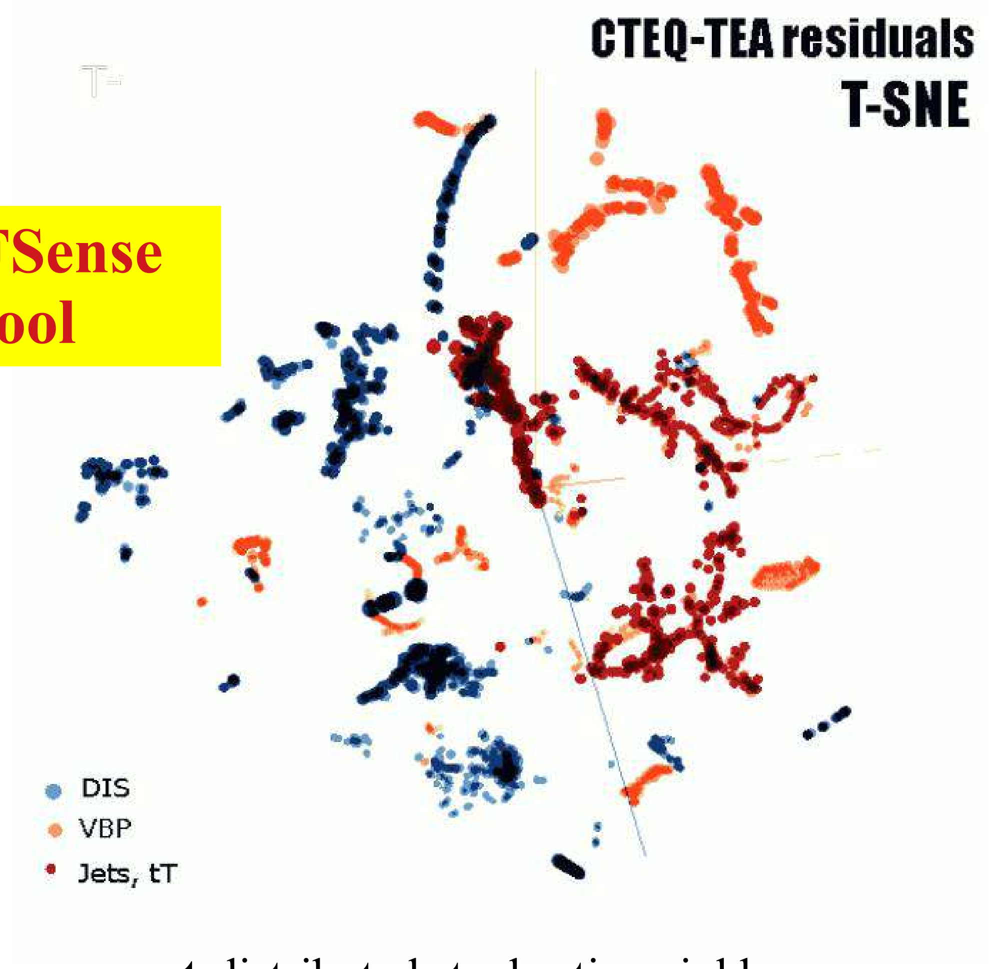
Dynamical projections for the visualization of PDFSense data
Dianne Cook, Ursula Laa, German Valencia arXiv:1806.09742

TensorFlow Embedding Projector

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



PDFSense tool



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

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

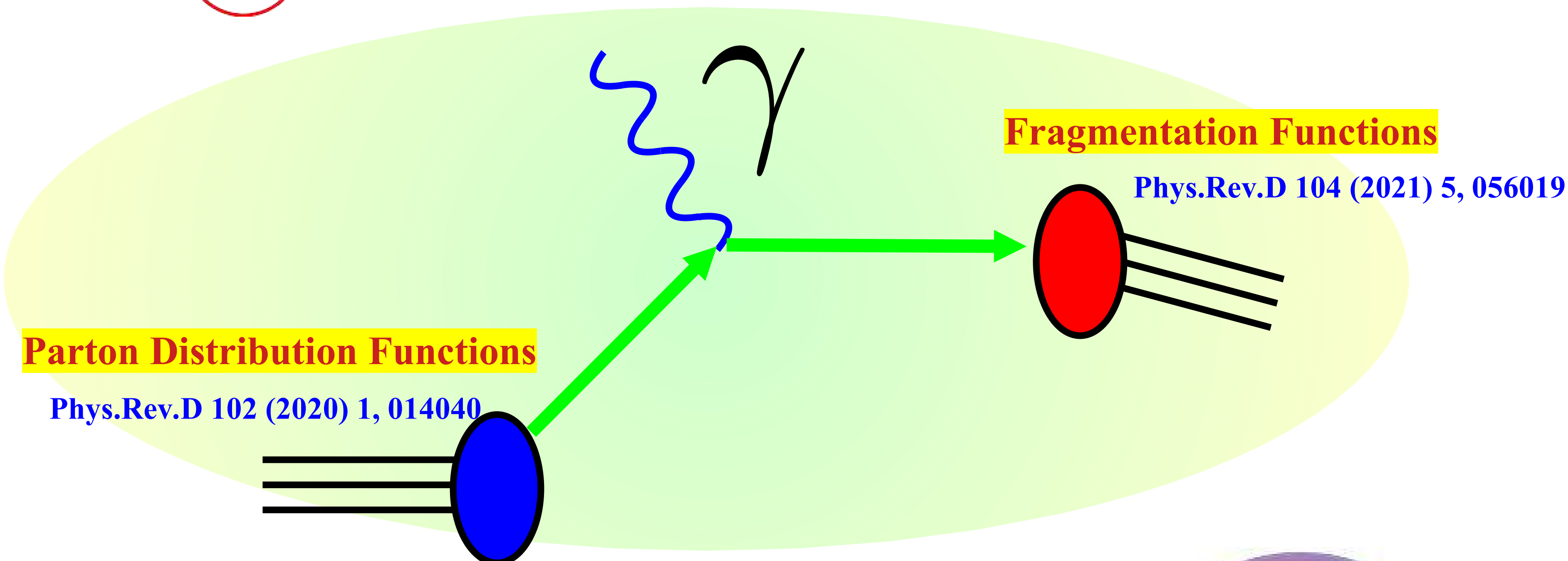
$$r_i(\vec{a}) = \frac{1}{s_i}\left(T_i(\vec{a}) - D_{i,sh}(\vec{a})\right).$$

http://projector.tensorflow.org

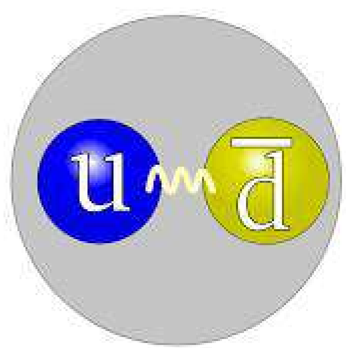
Pion PDFs & FFs

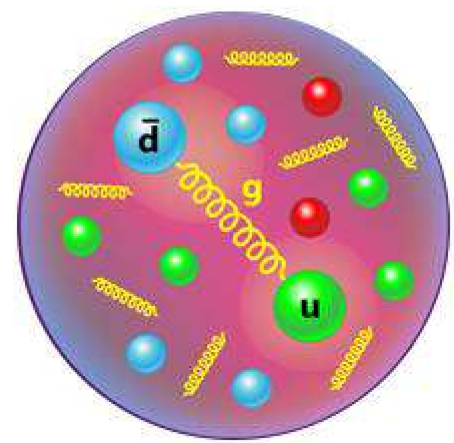
Parton Distribution Functions

Fragmentation Functions



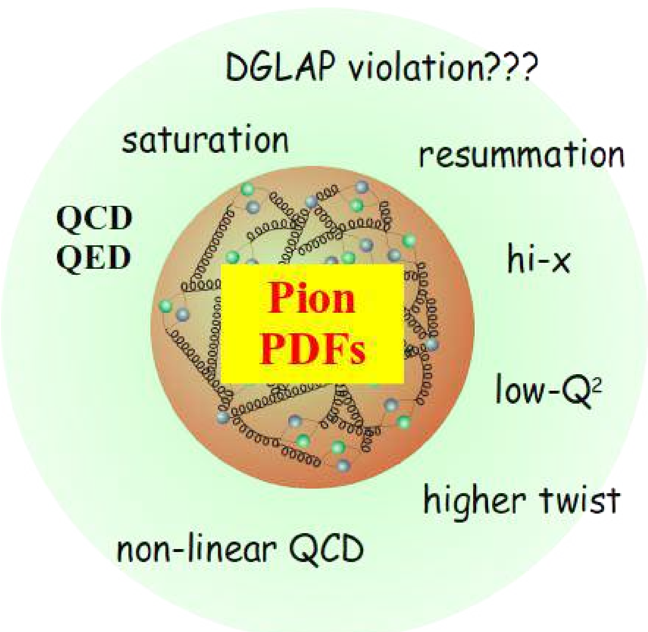
$$\text{Pion } \pi^+ = u\bar{d}$$





xFitter Pion Fit

Phys.Rev.D 102 (2020) 1, 014040



Special thanks to: Ivan Novikov, Alexander Glazov, Oleksandr Zenaiev

Parton Distribution Functions of the Charged Pion Within The xFitter Framework

xFitter Developers' team: Ivan Novikov,[1,2,*] Hamed Abdolmaleki,[3] Daniel Britzger,[4] Amanda Cooper-Sarkar,[5] Francesco Giuli,[6] Alexander Glazov,[2,†] Aleksander Kusina,[7] Agnieszka Luszczak,[8] Fred Olness,[9] Pavel Starovoitov,[10] Mark Sutton,[11] and Oleksandr Zenaiev[12]

e-Print: 2002.02902 [hep-ph]

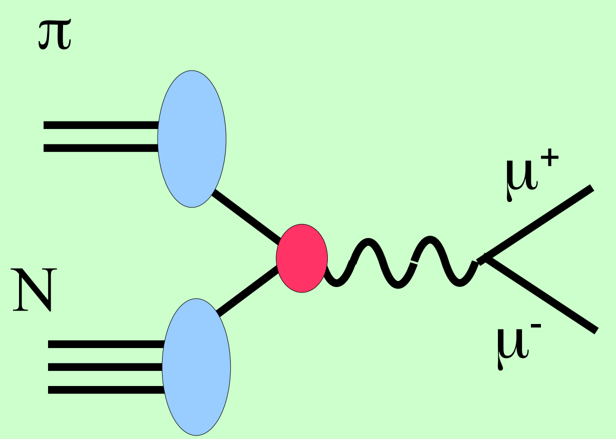
xFitter Meson PDFs

xFitter: open-source framework for global fits to meson PDFs

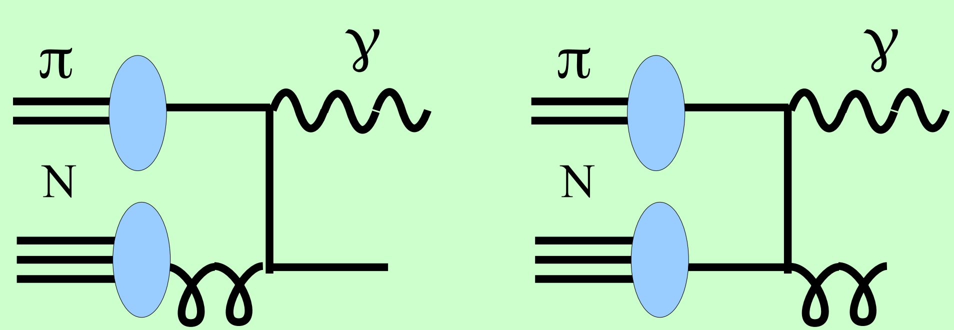
https://www.xfitter.org/

xFitter

Experiment	χ^2/N_{points}
E615	206/140
NA10 (194 GeV)	107/67
NA10 (286 GeV)	95/73
WA70	64/99



E615 & NA10
Pions on Tungsten



WA70
Pions on Proton

Parton Distribution Functions of the Charged Pion Within The xFitter Framework

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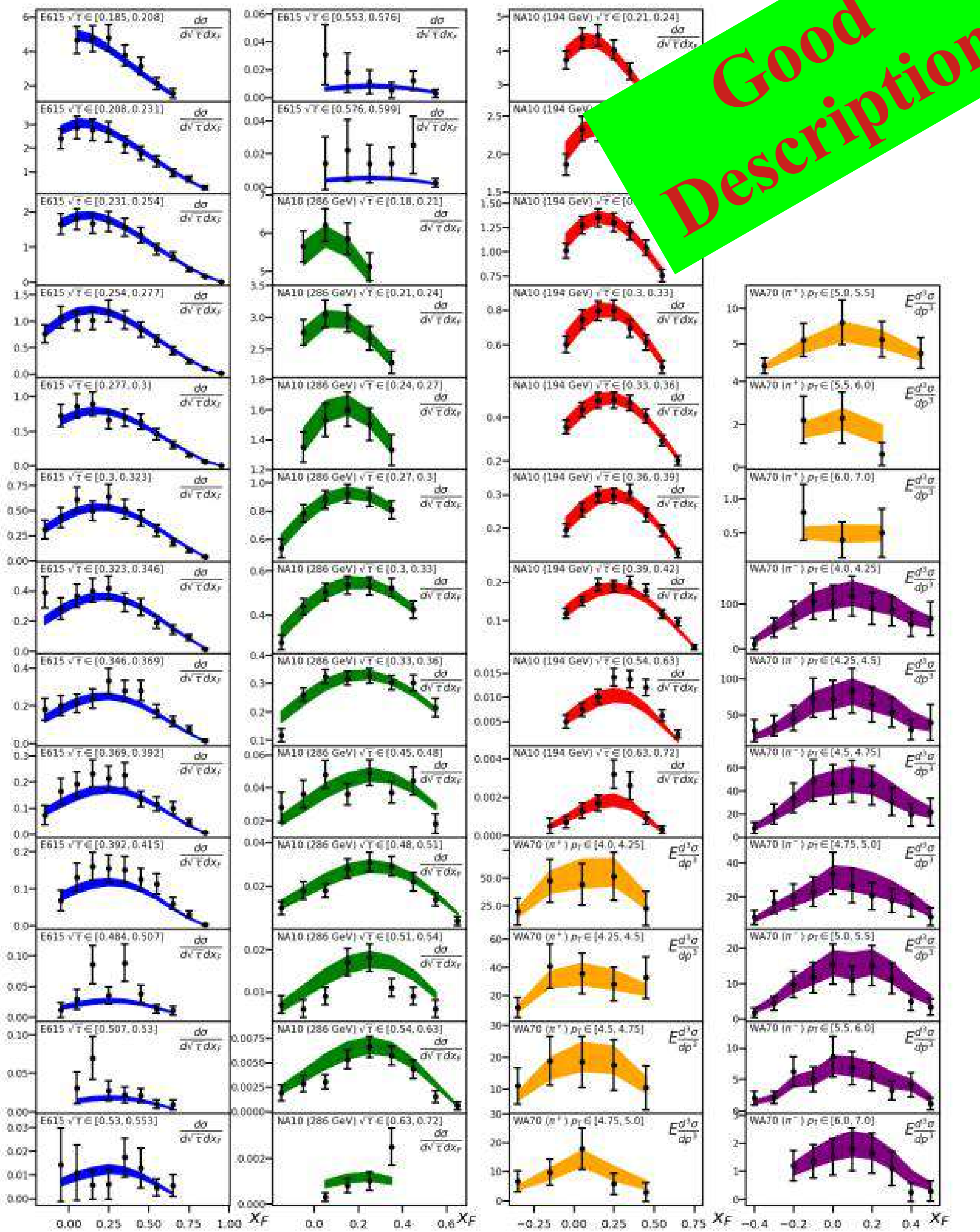
e-Print: 2002.02902 [hep-ph]

Pion Data:

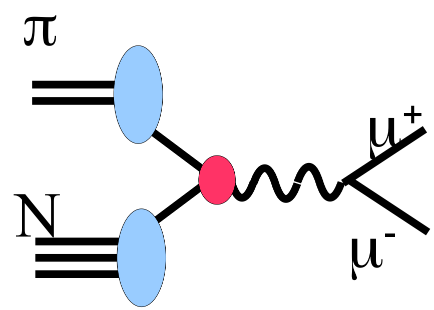


Good Description

Pions (π^{-}) on Tungsten

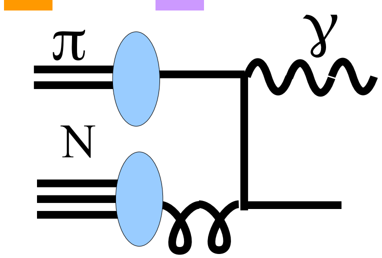
E615 E_π = **252 GeV**

NA10 E_π = **194 GeV** & **286 GeV**



Pions ($\pi^{\pm}$) on Proton

WA70 π^+ π^-



NLO computation with MCFM / APPLGRID

- theory errors from α_S, and nPDF uncert
- uncertainties include scale variations.
  - for factorization scale variation

modify APPLGRID for two PDFs

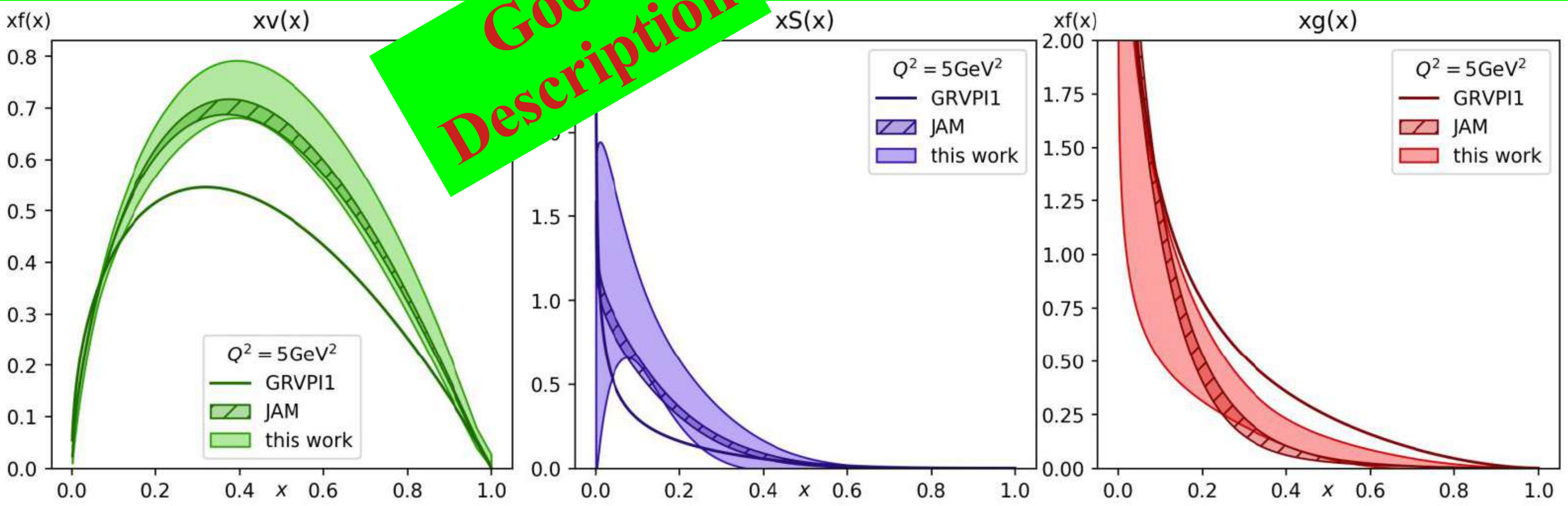
xFitter Pion PDFs

Experiment	Normalization uncertainty	χ^2/N_{points}
E615	15 %	206/140
NA10 (194 GeV)	6.4%	107/67
NA10 (286 GeV)	6.4%	95/73
WA70	32%	64/99

$$xv(x) = A_v x^{B_v}(1-x)^{C_v}(1+D_v x^{\alpha}),$$
$$xS(x) = A_S x^{B_S}(1-x)^{C_S}/\mathcal{B}(B_S+1, C_S+1),$$
$$xg(x) = A_g(C_g+1)(1-x)^{C_g},$$

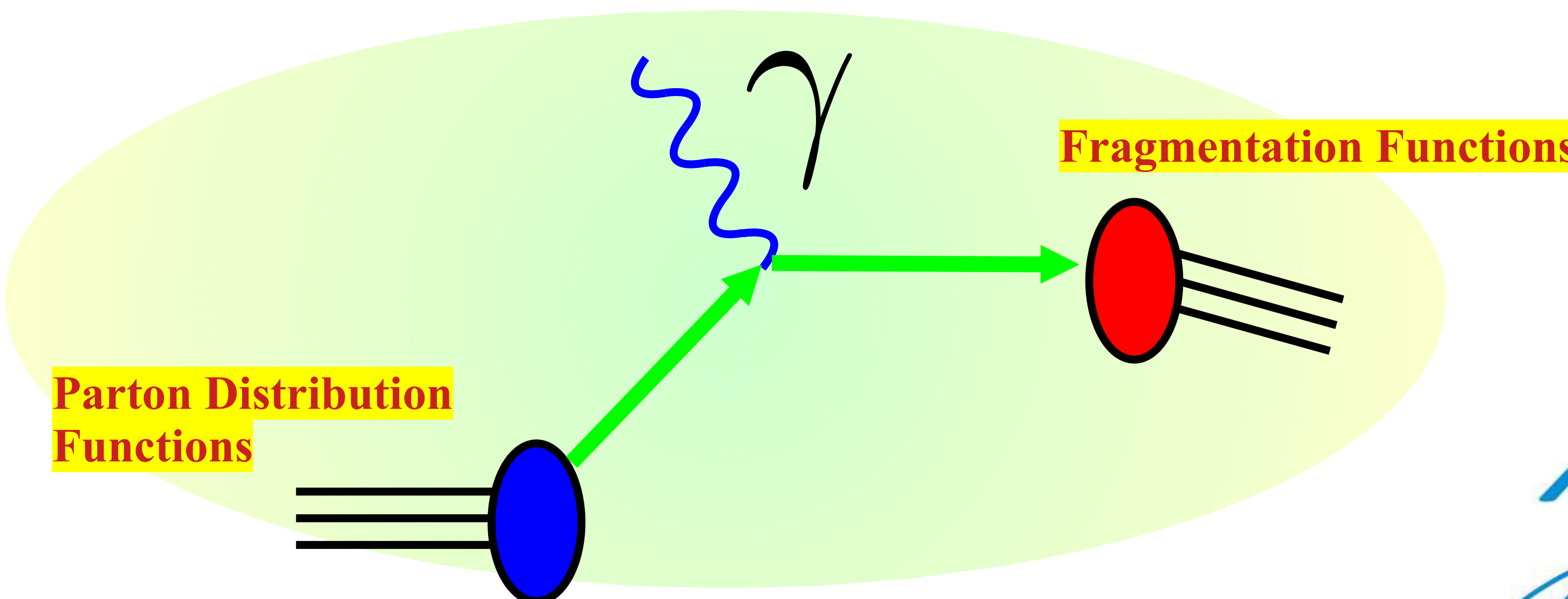
	$\langle xv\rangle$	$\langle xS\rangle$	$\langle xg\rangle$	Q^2 (GeV^2)
JAM [31]	0.54 ± 0.01	0.16 ± 0.02	0.30 ± 0.02	1.69
JAM (DY)	0.60 ± 0.01	0.30 ± 0.05	0.10 ± 0.05	1.69
this work	0.55 ± 0.06	0.26 ± 0.15	0.19 ± 0.16	1.69
Lattice-3 [18]	0.428 ± 0.030			4
SMRS [25]	0.47			4
Han et al. [44]	0.51 ± 0.03			4
GRVPI1 [27]	0.39	0.11	0.51	4
Ding et al. [11]	0.48 ± 0.03	0.11 ± 0.02	0.41 ± 0.02	4
this work	0.50 ± 0.05	0.25 ± 0.13	0.25 ± 0.13	4
JAM	0.48 ± 0.01	0.17 ± 0.01	0.35 ± 0.02	5
this work	0.49 ± 0.05	0.25 ± 0.12	0.26 ± 0.13	5
Lattice-1 [16]	0.558 ± 0.166			5.76
Lattice-2 [17]	0.48 ± 0.04			5.76
this work	0.48 ± 0.05	0.25 ± 0.12	0.27 ± 0.13	5.76
WRH [26]	0.434 ± 0.022			27
ChQM-1 [13]	0.428			27
ChQM-2 [15]	0.46			27
this work	0.42 ± 0.04	0.25 ± 0.10	0.32 ± 0.10	27
SMRS [25]	0.49 ± 0.02			49
this work	0.41 ± 0.04	0.25 ± 0.09	0.34 ± 0.09	49

Good Description



Pion Fragmentation Functions

Phys.Rev.D 104 (2021) 5, 056019



Hamed Abdolmaleki, Maryam Soleymaninia, Hamzeh Khanpour

PHYSICAL REVIEW D **104**, 056019 (2021)

QCD analysis of pion fragmentation functions in the xFitter framework

Hamed Abdolmaleki,[1,*] Maryam Soleymaninia,[1,†] Hamzeh Khanpour,[1,2,3,‡] Simone Amoroso,[4,§] Francesco Giuli,[5,∥] Alexander Glazov,[4,¶] Agnieszka Luszczak,[6,**] Fredrick Olness,[7,††] and Oleksandr Zenaiev[8,‡‡]
(xFITTER Developers' Team:)

xFitter: Multiple fits with a vast array of data sets

HAMED ABDOLMALEKI *et al.* PHYS. REV. D **104,** 056019 (2021)

TABLE I. The Single Inclusive electron-positron Annihilation (SIA) datasets used in the pion FFs analysis. The values of χ^2 per N data points for the individual SIA experiments are shown. The z range for each experiment is displayed in Fig. 8. The measured observable is also listed where $\sqrt{s}$ is the total CMS energy, $\beta = p_h/E_h$, and $z = 2E_h/\sqrt{s}$.

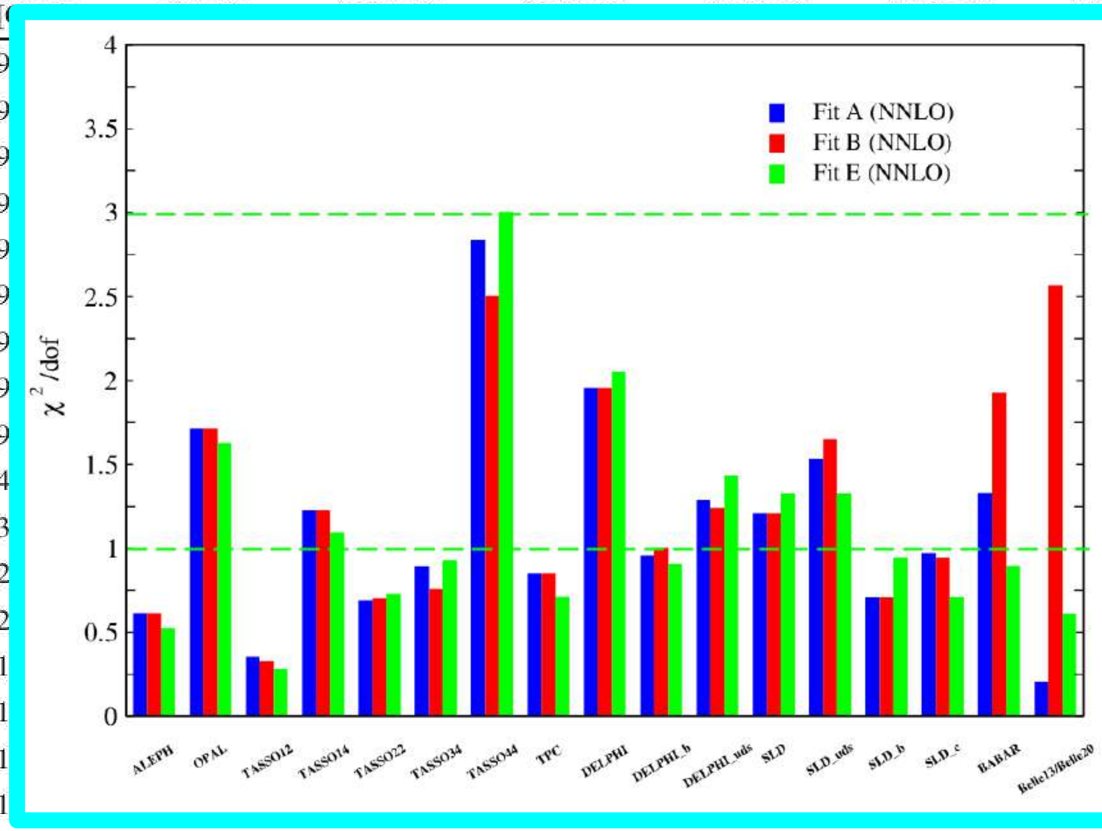
			χ^2/number of points					
Observable	Experiment	$\sqrt{s}$ [GeV]	Fit A (NLO)	Fit A (NNLO)	Fit B (NNLO)	Fit C (NNLO)	Fit D (NNLO)	Fit E (NNLO)
$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dz}$	SLD	91.20	57/34	41/34	41/34	48/34	39/34	45/34
$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dz}\big\|_{\text{uds}}$	SLD_{uds}	91.20	66/34	52/34	56/34	44/34	43/34	45/34
$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dz}\big\|_c$	SLD_c	91.20	35/34	33/34	32/34	32/34	32/34	32/34
$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dz}\big\|_b$	SLD_b	91.20	25/34	24/34	24/34	24/34	23/34	24/34
$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dp_h}$	OPAL	91.20	42/24	41/24	41/24	39/24	39/24	39/24
$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dp_h}$	DELPHI	91.20	37/21	41/21	41/21	44/21	44/21	43/21
$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dp_h}\big\|_{\text{uds}}$	$\text{DELPH}_{\text{uds}}$	91.20	25/21	27/21	26/21	30/21	31/21	30/21
$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dp_h}\big\|_b$	DELPH_b	91.20	20/21	20/21	21/21	19/21	20/21	19/21
$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dz}$	ALEPH	91.20	21/23	14/23	14/23	11/23	11/23	12/23
$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dz}$	TASSO44	44.00	15/6	17/6	15/6	18/6	16/6	18/6
$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dz}$	TASSO34	34.00	6.8/9	8.0/9	6.8/9	9.3/9	7.3/9	8.3/9
$\frac{1}{\beta\sigma_{\text{tot}}}\frac{d\sigma^h}{dz}$	TPC	29.00	6.3/13	11/13	11/13	11/13	7.1/13	9.2/13
$\frac{s}{\beta}\frac{d\sigma^h}{dz}$	TASSO22	22.00	5.7/8	5.5/8	5.6/8	6.1/8	5.9/8	5.8/8
$\frac{s}{\beta}\frac{d\sigma^h}{dz}$	TASSO14	14.00	11/9	11/9	11/9	9.9/9	11/9	9.8/9
$\frac{s}{\beta}\frac{d\sigma^h}{dz}$	TASSO12	12.00	1.4/4	1.4/4	1.3/4	0.96/4	1.4/4	1.1/4
$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^h}{dp_h}$	*BABAR*	10.52	71/40	53/40	77/40	...	...	33/37
$\frac{d\sigma^h}{dz}$	BELLE13	10.54	21/70	14/70	...	...	...	...
$\frac{d\sigma^h}{dz}$	BELLE20	10.58	...	...	82/32	32/32	9.2/28	17/28
Correlated χ^2			11	9.4	8.4	16	9.4	12
Log penalty χ^2			+4.2	+3.0	+4.2	+7.7	+5.6	+6.8
Total χ^2/dof			480/386	427/386	518/348	404/308	357/304	410/341

xFitter: Multiple fits with a vast array of data sets

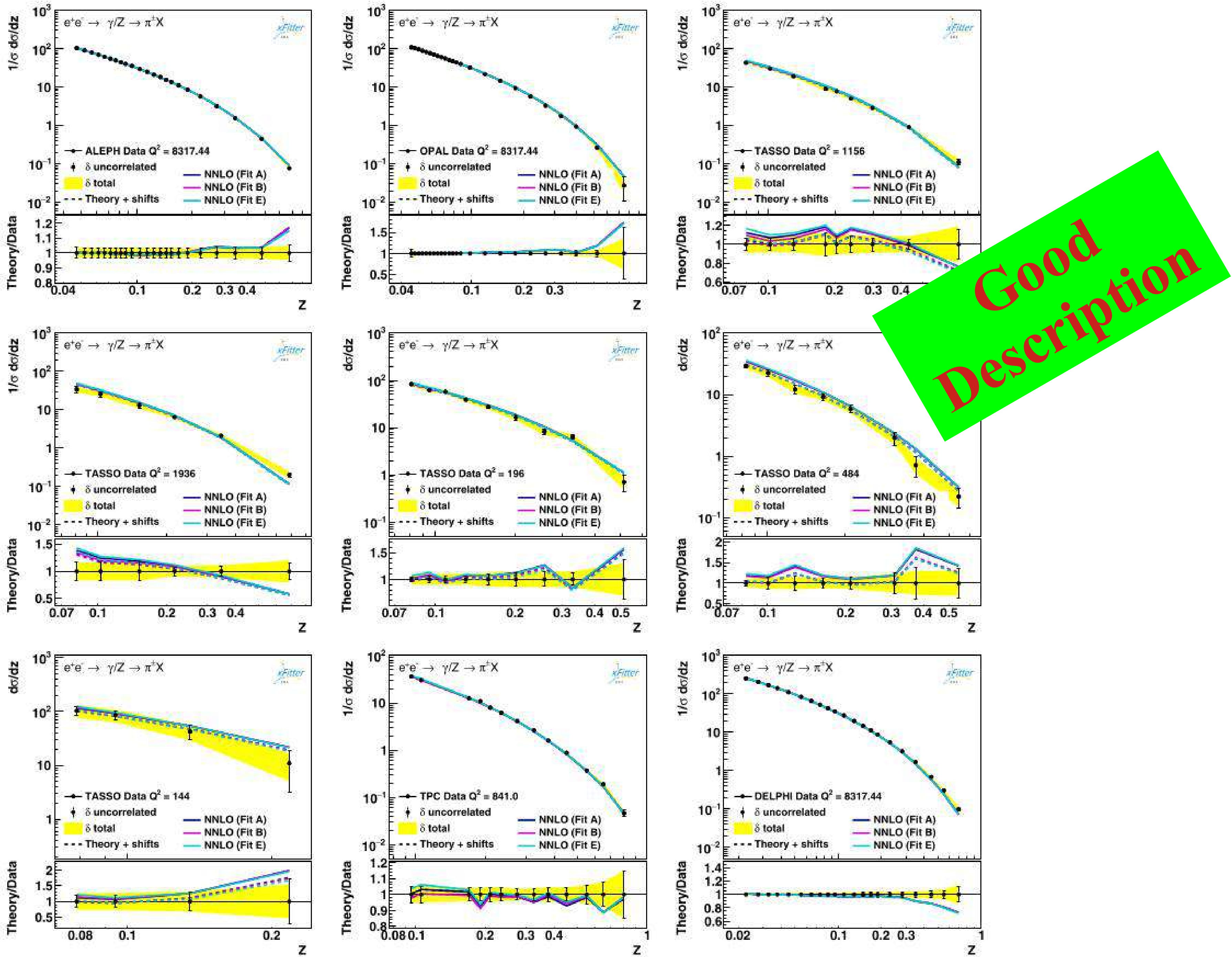
HAMED ABDOLMALEKI *et al.* PHYS. REV. D **104,** 056019 (2021)

TABLE I. The Single Inclusive electron-positron Annihilation (SIA) datasets used in the pion FFs analysis. The values of χ^2 per N data points for the individual SIA experiments are shown. The z range for each experiment is displayed in Fig. 8. The measured observable is also listed where $\sqrt{s}$ is the total CMS energy, $\beta = p_h/E_h$, and $z = 2E_h/\sqrt{s}$.

Observable	Experiment	$\sqrt{s}$ [	χ^2/number of points Fit A	Fit A	Fit B	Fit C	Fit D	Fit E LO)
$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dz}$	SLD	9						/34
$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dz}\|_{uds}$	SLD_{uds}	9						/34
$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dz}\|_{c}$	SLD_c	9						/34
$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dz}\|_{b}$	SLD_b	9						/34
$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dp_h}$	OPAL	9						/24
$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dp_h}$	DELPHI	9						/21
$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dp_h}\|_{uds}$	$DELPH_{uds}$	9						/21
$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dp_h}\|_{b}$	$DELPH_b$	9						/21
$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dz}$	ALEPH	9						/23
$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dz}$	TASSO44	4						3/6
$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dz}$	TASSO34	3						3/9
$\frac{1}{\beta\sigma_{tot}}\frac{d\sigma^h}{dz}$	TPC	2						/13
$\frac{s}{\beta}\frac{d\sigma^h}{dz}$	TASSO22	2						3/8
$\frac{s}{\beta}\frac{d\sigma^h}{dz}$	TASSO14	1						3/9
$\frac{s}{\beta}\frac{d\sigma^h}{dz}$	TASSO12	1						1/4
$\frac{1}{\sigma_{tot}}\frac{d\sigma^h}{dp_h}$	*BABAR*	1						/37
$\frac{d\sigma^h}{dz}$	BELLE13	1						..
$\frac{d\sigma^h}{dz}$	BELLE20	10.58	...	...	82/32	32/32	9.2/28	17/28
Correlated χ^2			11	9.4	8.4	16	9.4	12
Log penalty χ^2			+4.2	+3.0	+4.2	+7.7	+5.6	+6.8
Total χ^2/dof			480/386	427/386	518/348	404/308	357/304	410/341

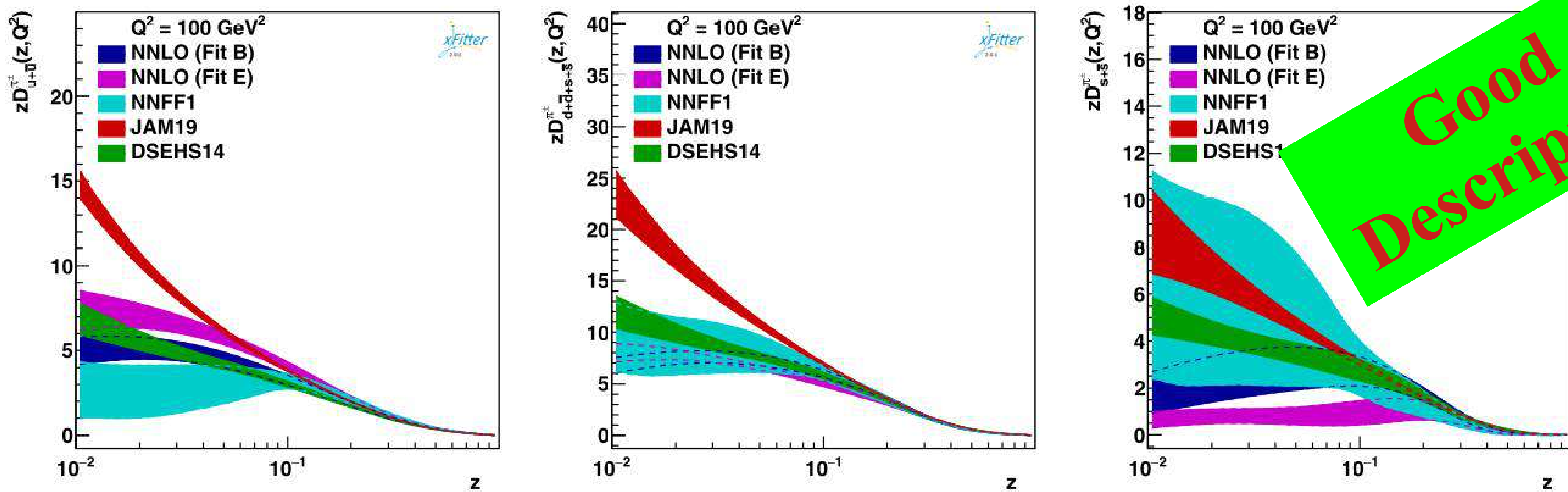


xFitter: Detailed comparison with data sets

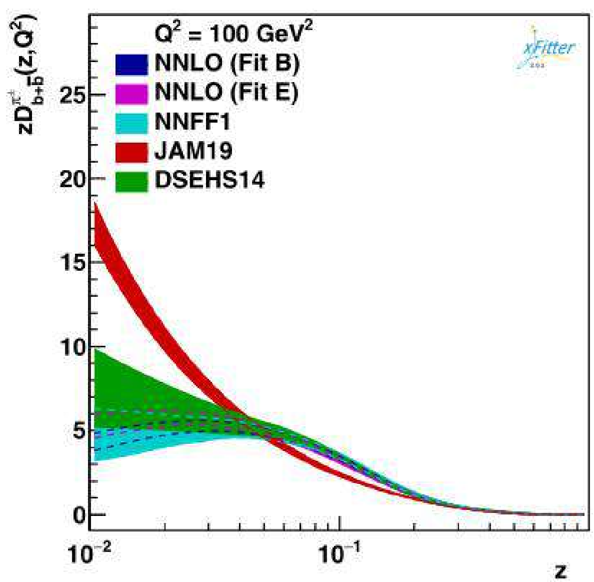


xFitter: Comparisons: … good overall … *more work needed*

HAMED ABDOLMALEKI *et al.* PHYS. REV. D **104,** 056019 (2021)



Good Description



Good description of the data in general

Deviations in the low-z region

BELLE and BaBar data pull in opposite directions

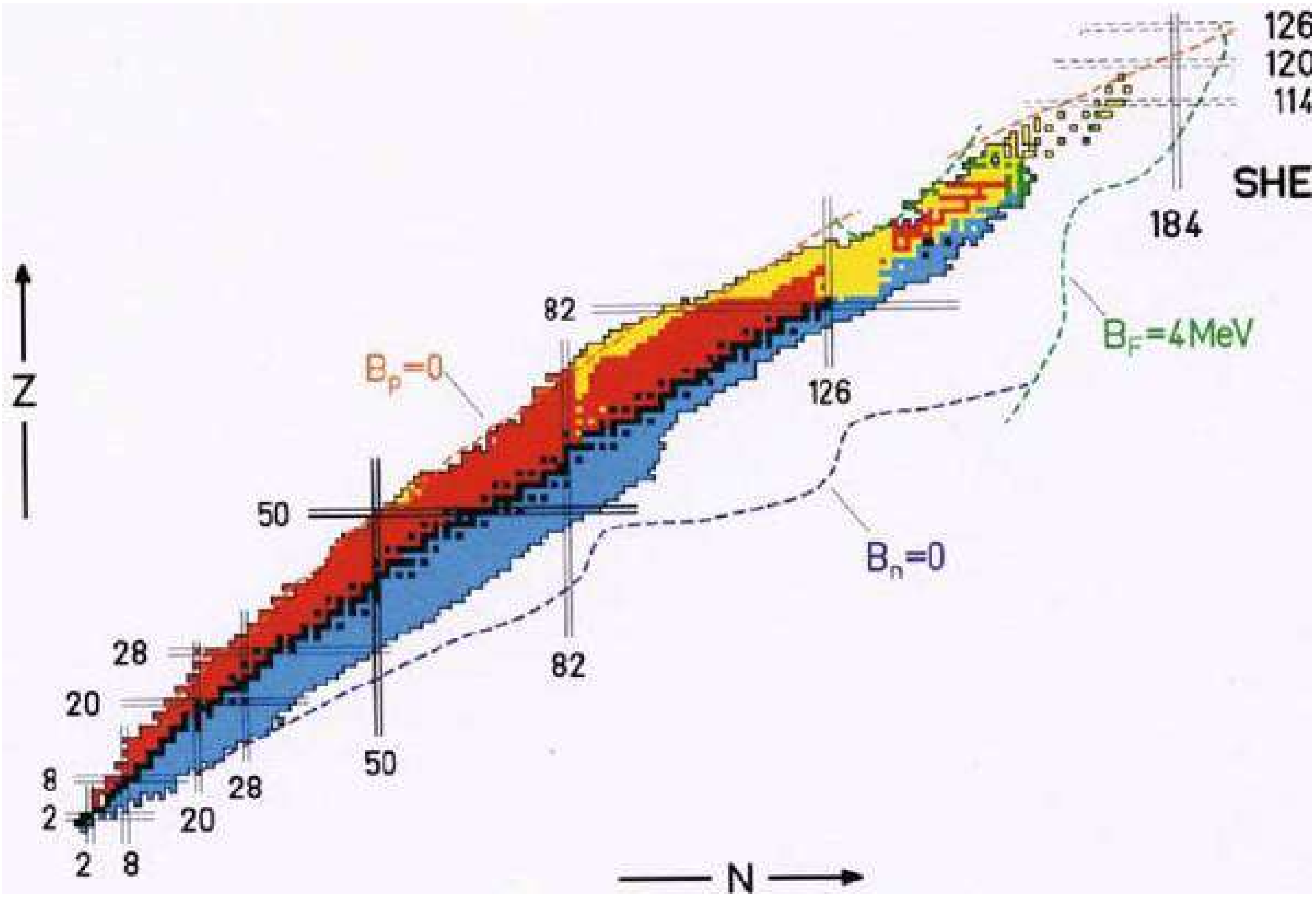
Clearly further investigation is warranted

Target Mass Corrections (TMC)

The challenge of a multi-scale problem

...

Ingo Schienbein, Chloe Leger, Richard Ruiz ...



Example #2: Multi-Scale Problems are Challenging

Two-Loop Total Cross Section: One Scale

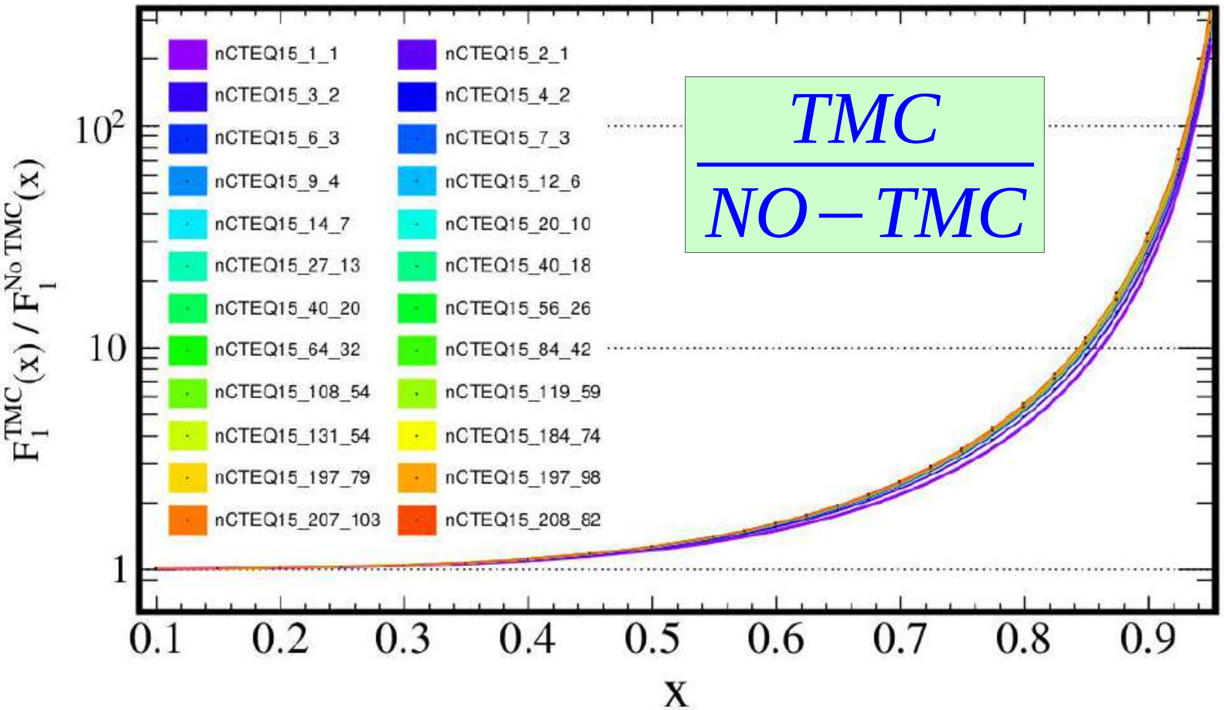
$$\sigma(Q^2)=\sigma_0\left\{1+\frac{\alpha_s(Q^2)}{4\pi}(3C_F)+\left[\frac{\alpha_s(Q^2)}{4\pi}\right]^2\left[-C_F^2\left[\frac{3}{2}\right]+C_FC_A\left[\frac{123}{2}-44\zeta(3)\right]+C_FTn_f(-22+16\zeta(3))\right]\right.$$

Two-Loop Drell-Yan Cross Section: Two Scales

$$\begin{aligned}
H_{q\bar{q}}^{(2),S+V}(z)=\left[\frac{\alpha_s}{4\pi}\right]^2\delta(1-z)\Big\{C_AC_F\Big[&[\tfrac{193}{3}-24\zeta(3)]\ln\left[\frac{Q^2}{M^2}\right]-11\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{12}{5}\zeta(2)^2+\tfrac{592}{9}\zeta(2)+28\zeta(3)-\tfrac{1535}{12}\Big]\\
+C_F^2\Big[&[18-32\zeta(2)]\ln^2\left[\frac{Q^2}{M^2}\right]+[24\zeta(2)+176\zeta(3)-93]\ln\left[\frac{Q^2}{M^2}\right]\\
&+\tfrac{8}{5}\zeta(2)^2-70\zeta(2)-60\zeta(3)+\tfrac{511}{4}\Big]\\
+n_fC_F\Big[&2\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{34}{3}\ln\left[\frac{Q^2}{M^2}\right]+8\zeta(3)-\tfrac{112}{9}\zeta(2)+\tfrac{127}{6}\Big]\Big\}\\
+C_AC_F\Big[&-\tfrac{44}{3}\mathcal{D}_0(z)\ln^2\left[\frac{Q^2}{M^2}\right]+\{[\tfrac{536}{9}-16\zeta(2)]\mathcal{D}_0(z)-\tfrac{176}{3}\mathcal{D}_1(z)\}\ln\left[\frac{Q^2}{M^2}\right]\\
&-\tfrac{176}{3}\mathcal{D}_2(z)+[\tfrac{1072}{9}-32\zeta(2)]\mathcal{D}_1(z)+[56\zeta(3)+\tfrac{176}{3}\zeta(2)-\tfrac{1616}{27}]\mathcal{D}_0(z)\Big]\\
+C_F^2\Big[&[64\mathcal{D}_1(z)+48\mathcal{D}_0(z)]\ln^2\left[\frac{Q^2}{M^2}\right]+\{192\mathcal{D}_2(z)+96\mathcal{D}_1(z)-[128+64\zeta(2)]\mathcal{D}_0(z)\}\ln\left[\frac{Q^2}{M^2}\right]\\
&+128\mathcal{D}_3(z)-(128\zeta(2)+256)\mathcal{D}_1(z)+256\zeta(3)\mathcal{D}_0(z)\Big]\\
+n_fC_F\Big[&\tfrac{8}{3}\mathcal{D}_0(z)\ln^2\left[\frac{Q^2}{M^2}\right]+[\tfrac{32}{3}\mathcal{D}_1(z)-\tfrac{80}{9}\mathcal{D}_0(z)]\ln\left[\frac{Q^2}{M^2}\right]+\tfrac{32}{3}\mathcal{D}_2(z)-\tfrac{160}{9}\mathcal{D}_1(z)+[\tfrac{224}{27}-\tfrac{32}{3}\zeta(2)]\mathcal{D}_0(z)\Big].
\end{aligned}$$

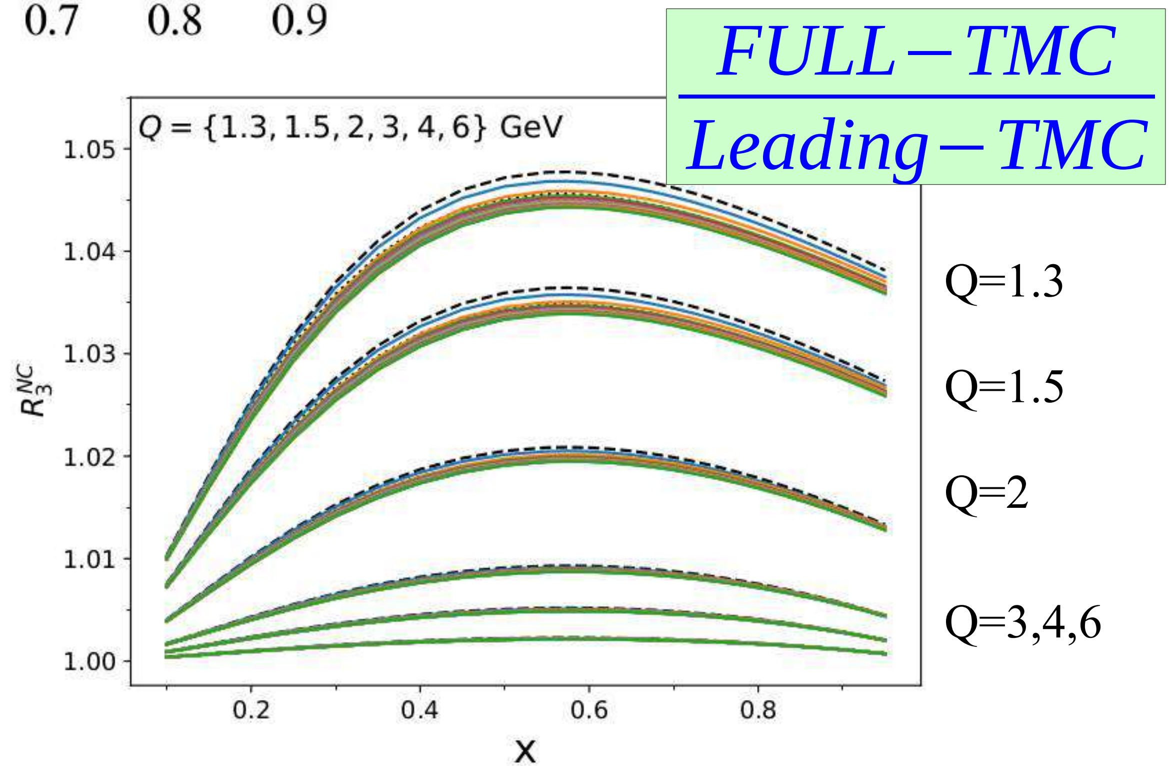
Ref: CTEQ Handbook

Target Mass Corrections (TMC) for nuclear processes



TMCs can be large

Corrections are nearly universal



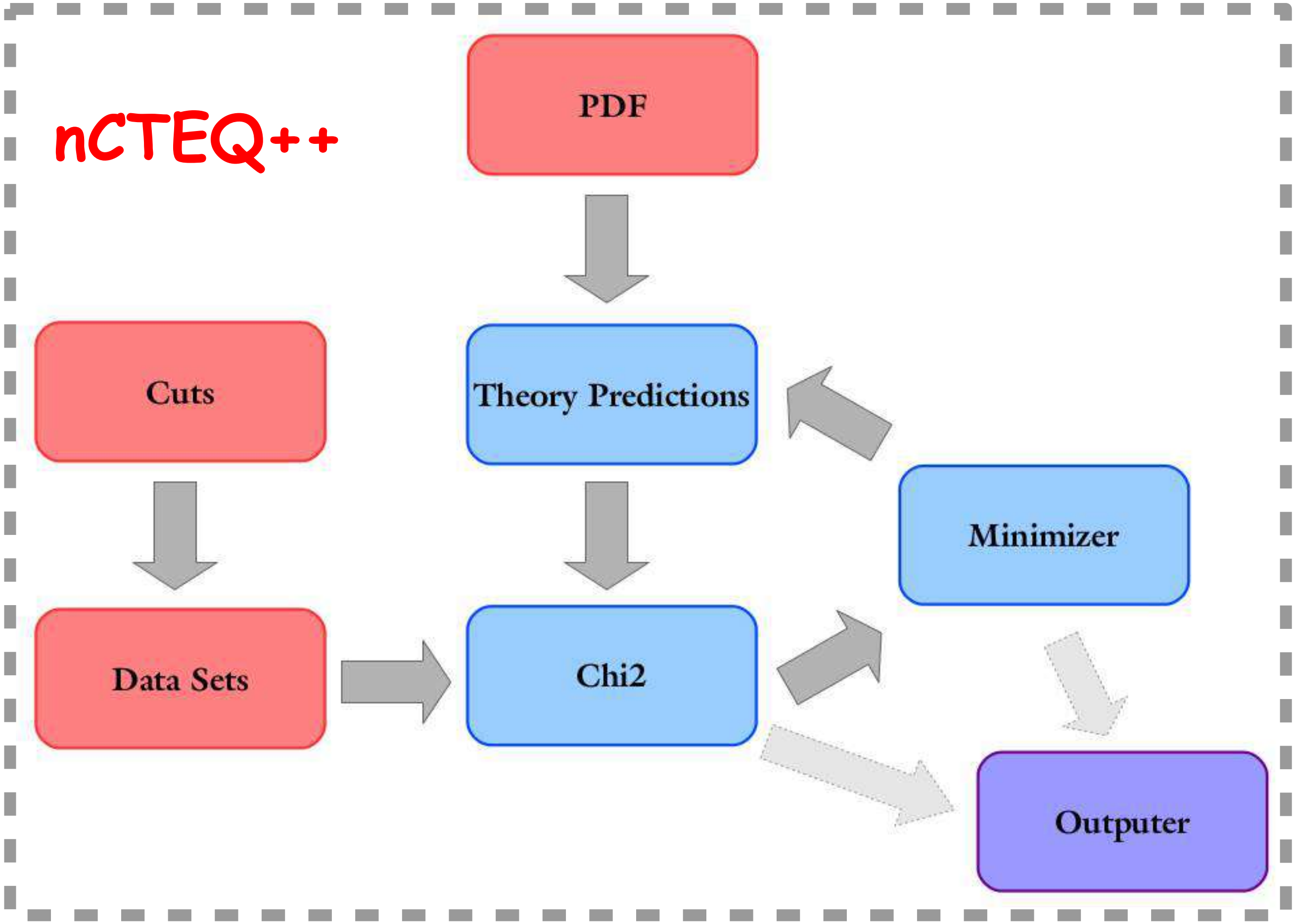
Ingo Schienbein, Chloe Leger, Richard Ruiz ...

nCTEQ++

a modern, modular code base

nCTEQ++ … a complete rewrite in C++

Top level C++, modular structure, output to YAML & Python scripts



Use external programs

- Minuit
- HOPPET
- MCFM
- APPLgrid

Pre-Computed Grids

Tremendous speed-up for higher order calculation

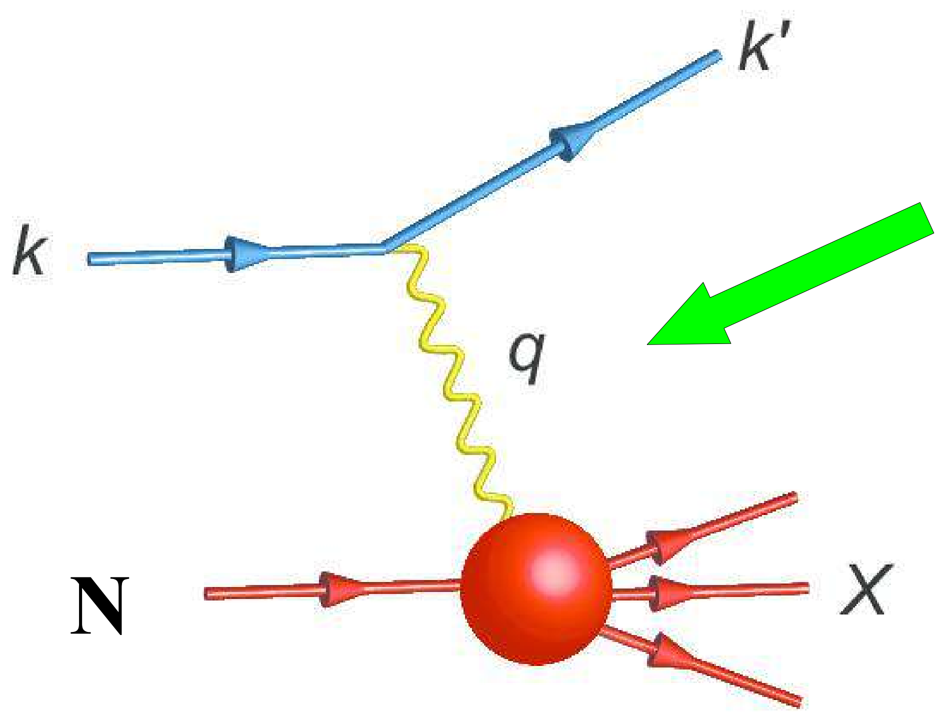
… for example …

High order DIS processes (Peter Risse)

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

Neutrino
Deep Inelastic Scattering (DIS)

Faiq Muzakka, Karol Kovarik, ...

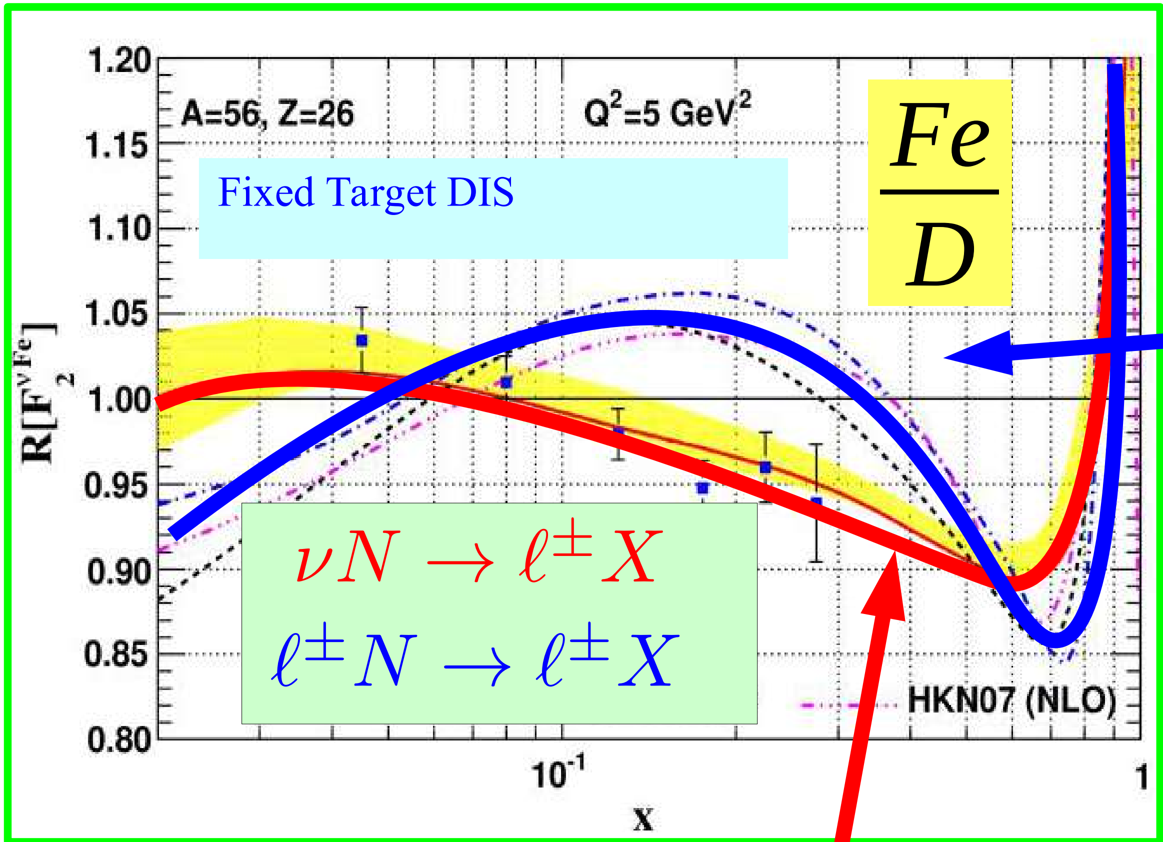


Could be:

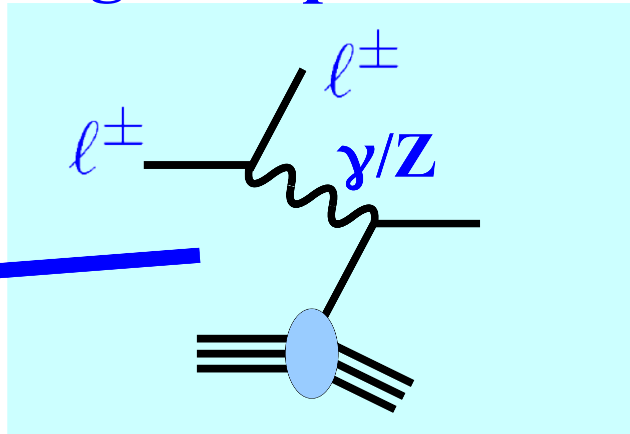
neutral photon γ

or charged $W^{\pm}$

Puzzle: **Split Personality …** *What is the correct Nuclear ratio*



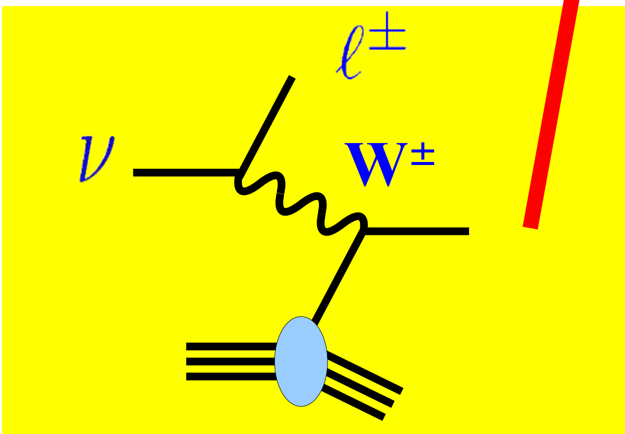
Charged Lepton DIS



some caveats
… correlated errors

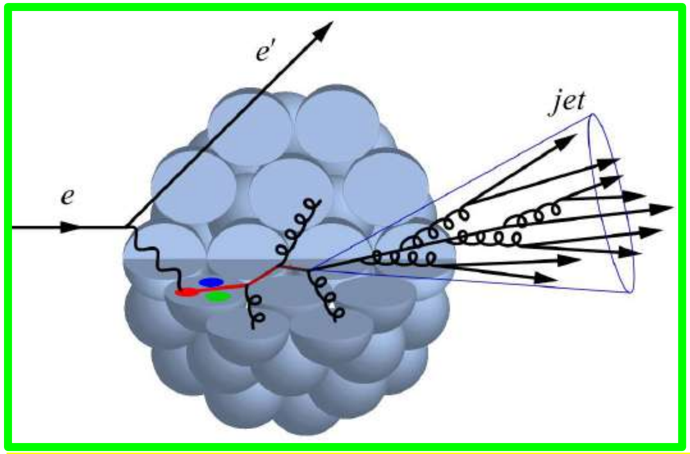
Ingo Schienbein, … (2007)

Karol Kovarik, … (2010)



Neutrino DIS

Depends on nuclear corrections

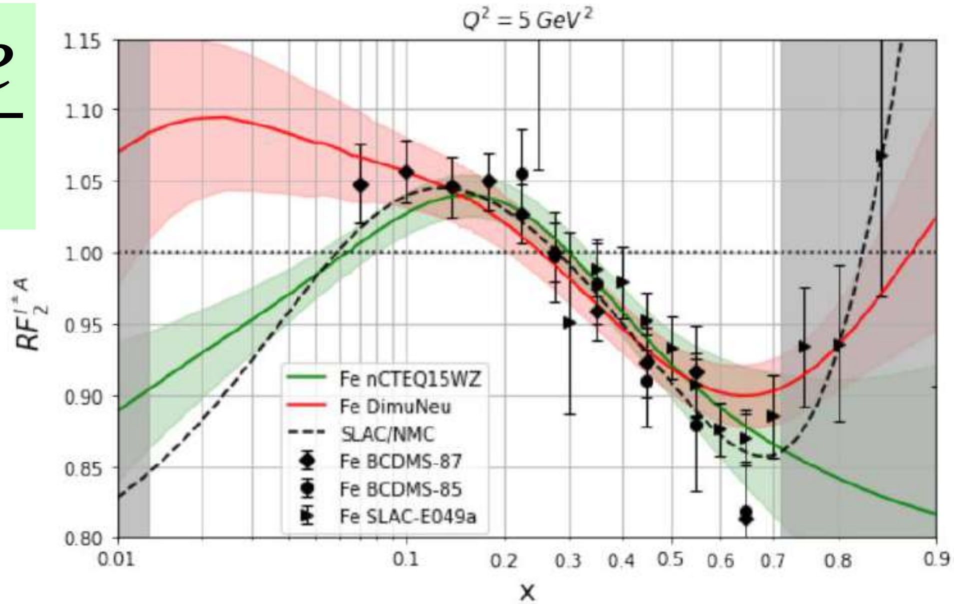


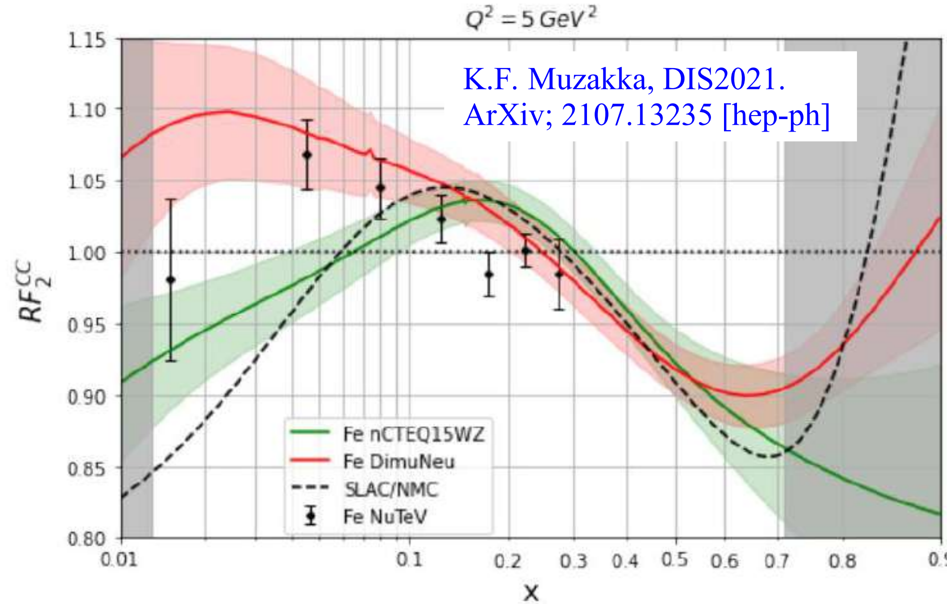
Propagation of γ/W thru nuclei

Puzzle: Split Personality … *What is the correct Nuclear ratio*

Faiq Muzakka, Karol Kovarik, ...

$$\frac{Fe}{D}$$

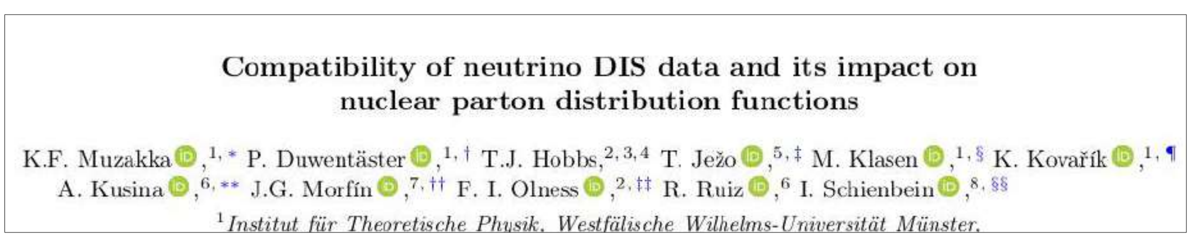




$$\frac{Iron}{(proton + neutron)}$$

What is the correct nuclear correction ???

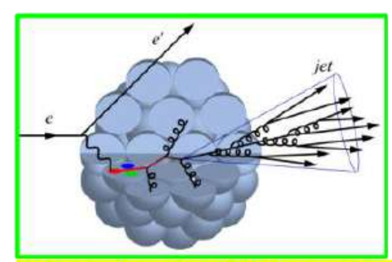
Are these data sets compatible???



Compatibility of neutrino DIS data and its impact on nuclear parton distribution functions

K.F. Muzakka,[1,*] P. Duwentäster,[1,†] T.J. Hobbs,[2,3,4] T. Ježo,[5,‡] M. Klasen,[1,§] K. Kovařík,[1,¶] A. Kusina,[6,**] J.G. Morfín,[7,††] F. I. Olness,[2,‡‡] R. Ruiz,[6] I. Schienbein,[8,§§]

[1]*Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster,*



Propagation of γ/W thru nuclei

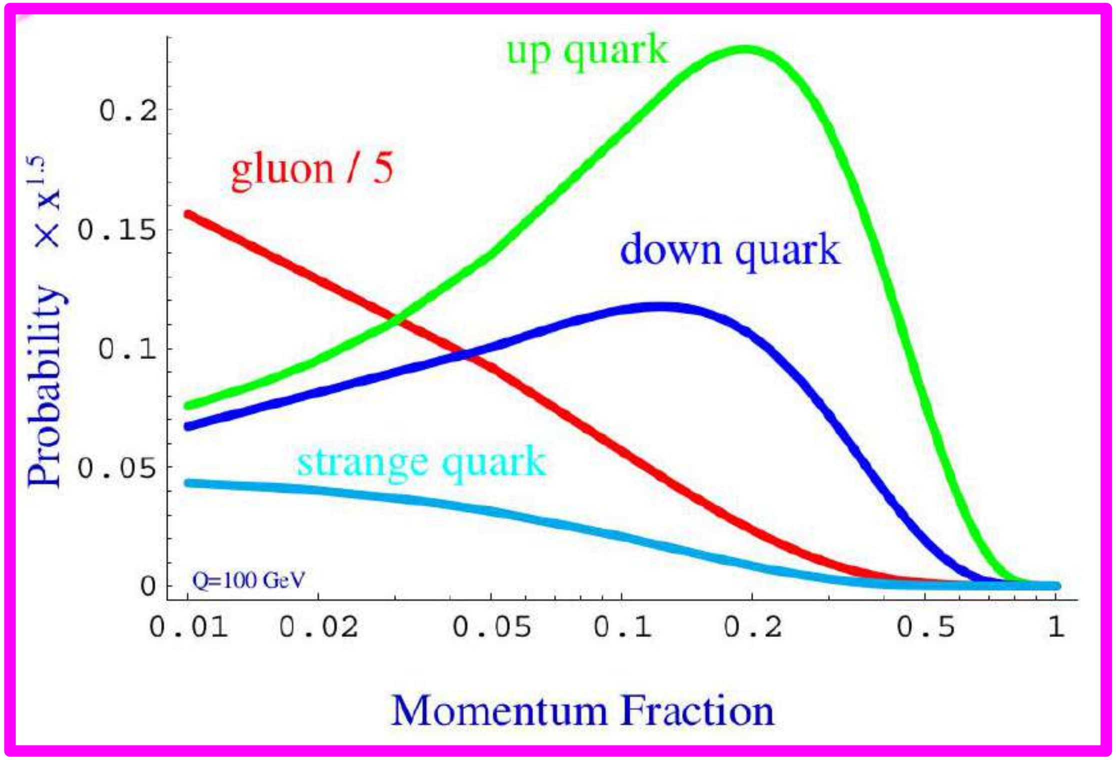
Strange PDF

Parton Distribution Functions

... this has a significant impact on the strange quark PDF

Strange PDF: ν Nucleon di-muon Production

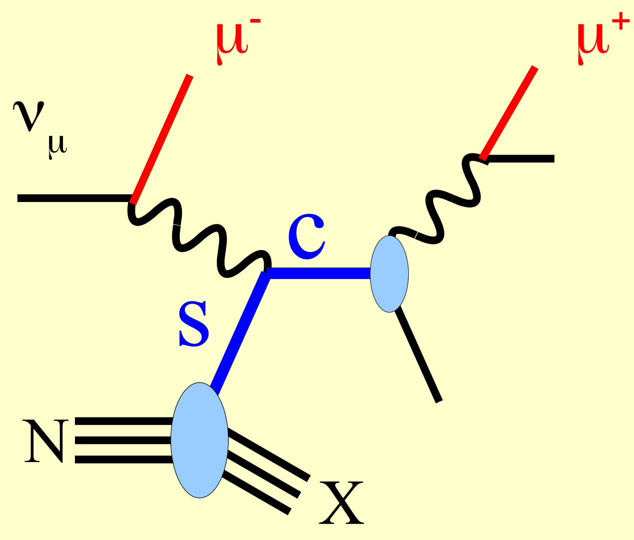
Need to "dig out" s(x) underneath d(x)



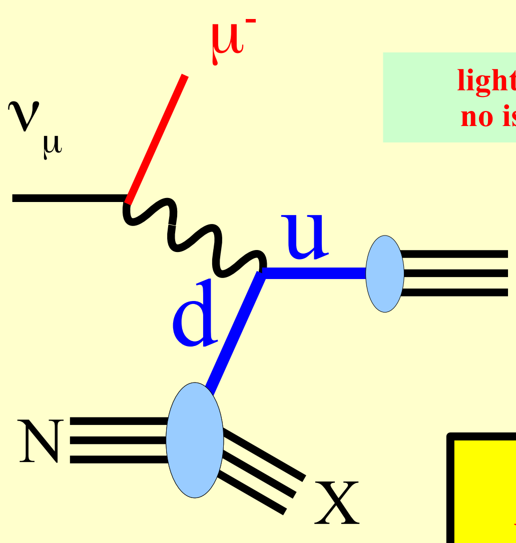
Result:

$$\bar{s}(x) \sim \frac{1}{2}\,\bar{d}(x)$$

Strange Quark



Down Quark

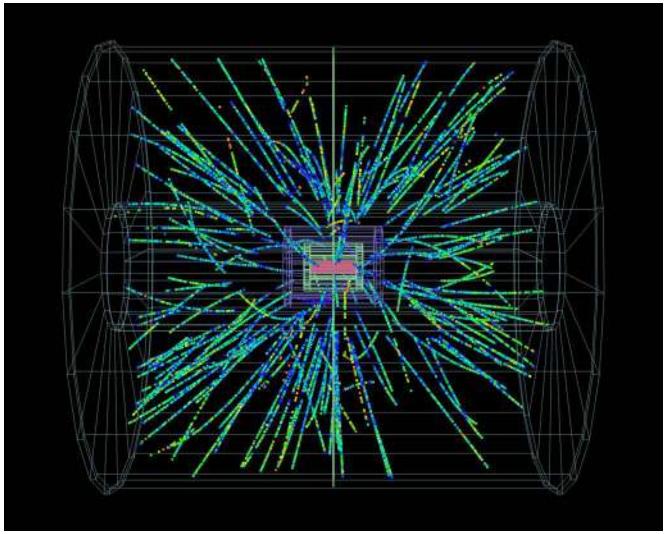


light u mass
no isolated μ

Depends on nuclear PDFs

W and Z Boson Production at the Large Hadron Collider (LHC)

Tomas Jezo, Aleksander Kusina, Fred Olness, ...



$$p\ p \to W, Z$$
$$p\, Pb \to W, Z$$

LHC Heavy Ion

… there's another way to measure the strange quark

nCTEQ: Eur.Phys.J.C 80 (2020) 10, 968

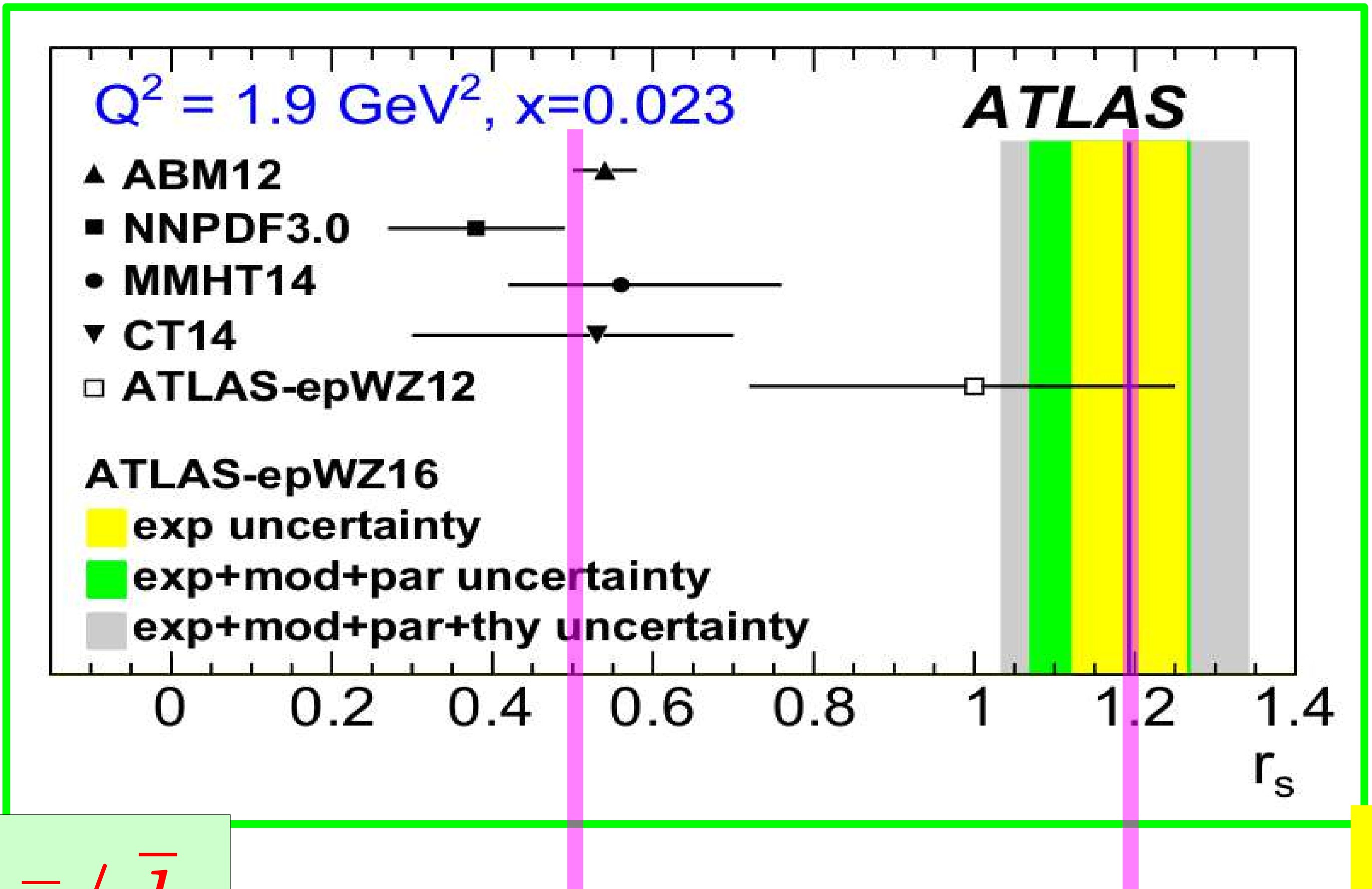
Surprise: … LHC sees more strange than expected

$$u\bar{d} + u\bar{s} + c\bar{d} + c\bar{s} \rightarrow W^+$$
$$\bar{u}d + \bar{u}s + \bar{c}d + \bar{c}s \rightarrow W^-$$
$$u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} \rightarrow Z$$

Surprise:

We expected $r_s = 1/2$

LHC finds $r_s > 1$



Proton case

$$r_s \sim \bar{s}/\bar{d}$$

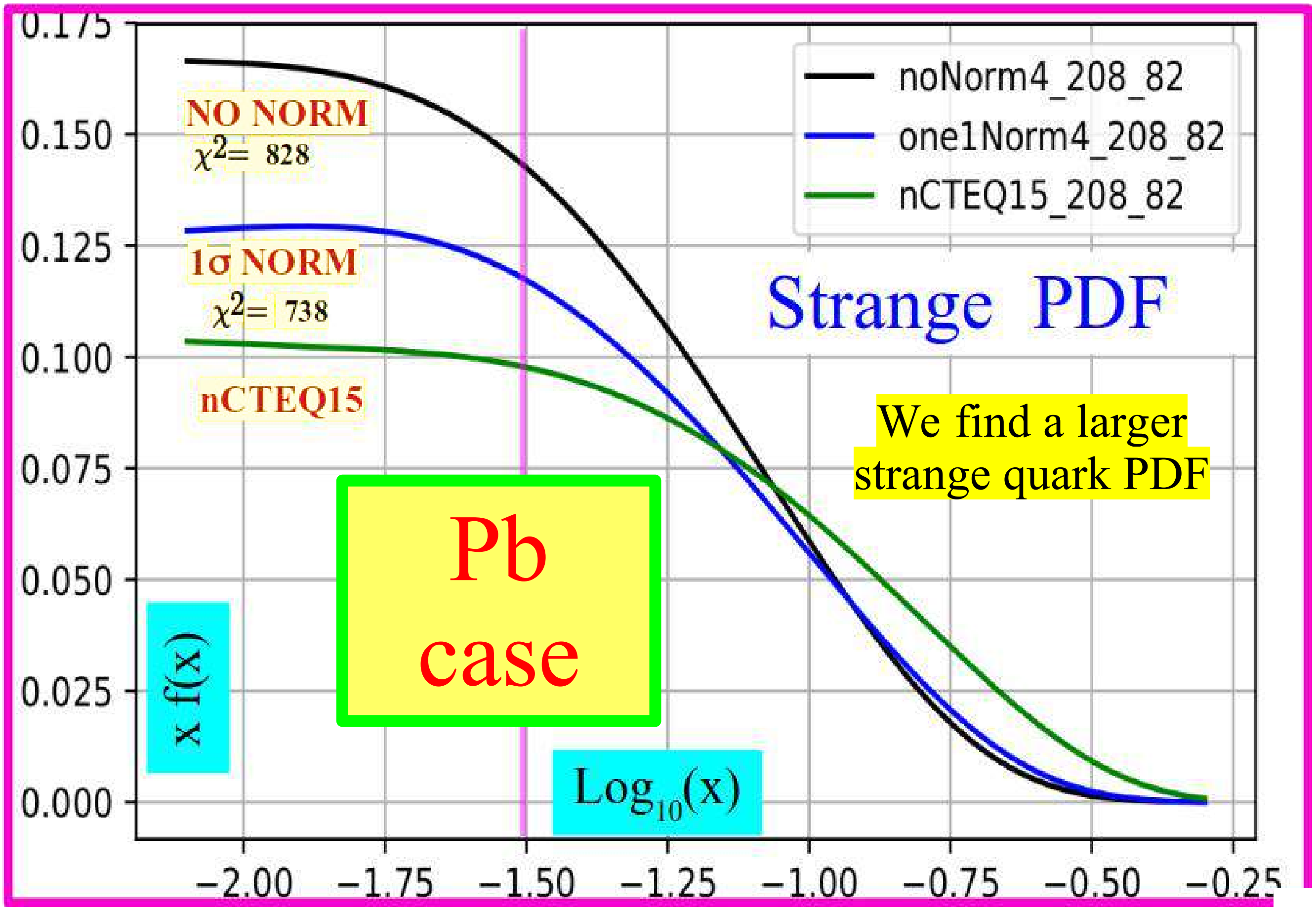
We expect:

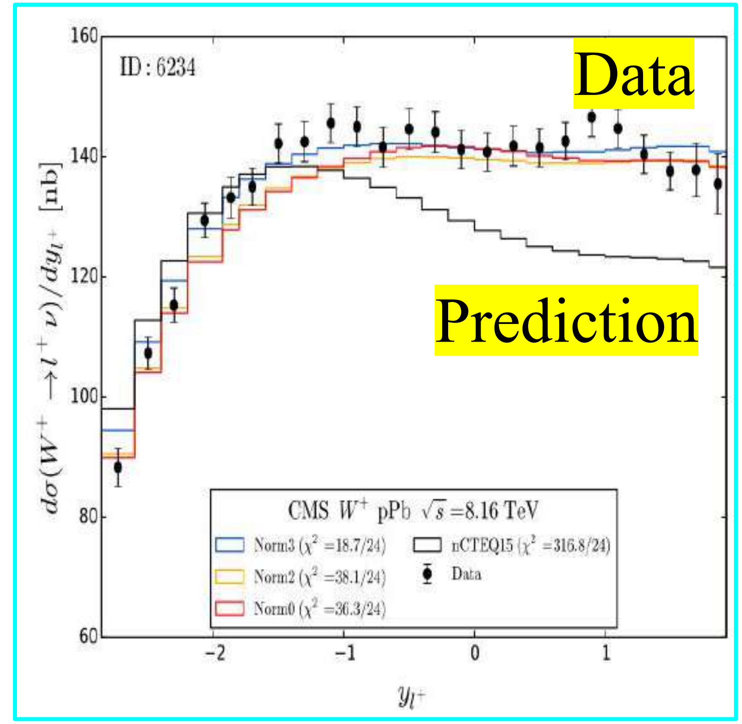
At the LHC:

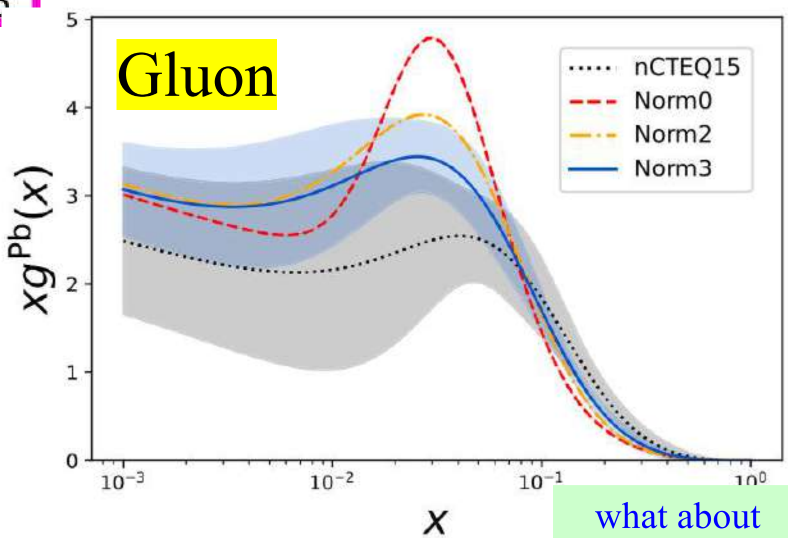
$$r_s = \frac{\bar{s} + s}{2\bar{d}}$$

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

Heavy Ion Case: … LHC STILL sees more strange than expected







Is the strange PDF driving the data ...

Or is the data driving the strange ???

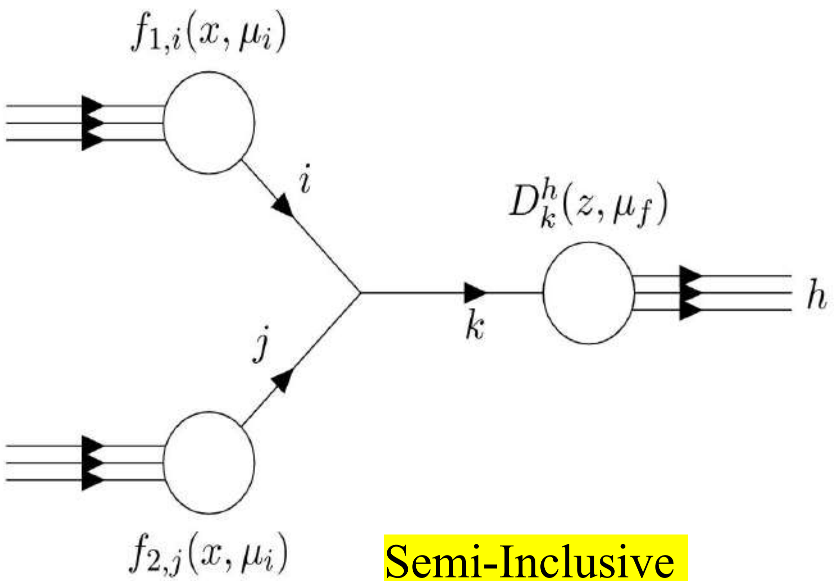
Tomas Jezo, Aleksander Kusina,

what about the gluon???

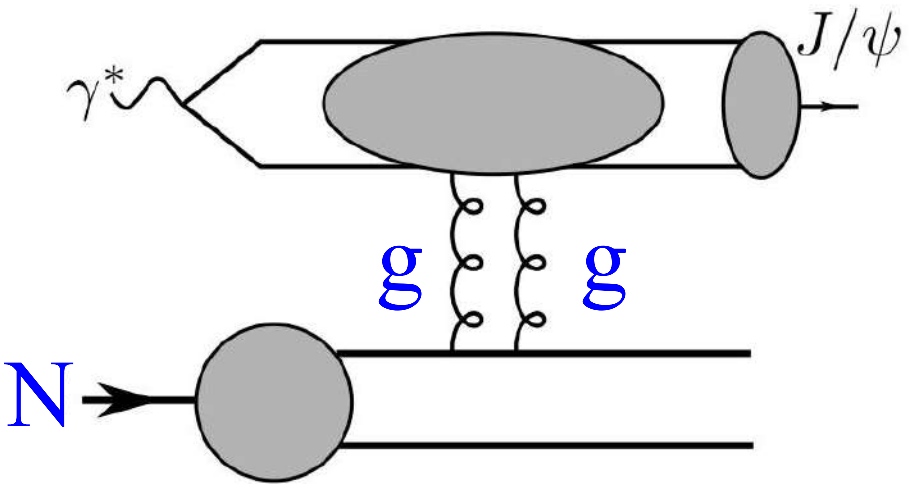
Measuring the nuclear Gluon PDF

Parton Distribution Functions

Pit Duwentaster, Michael Klasen, ...



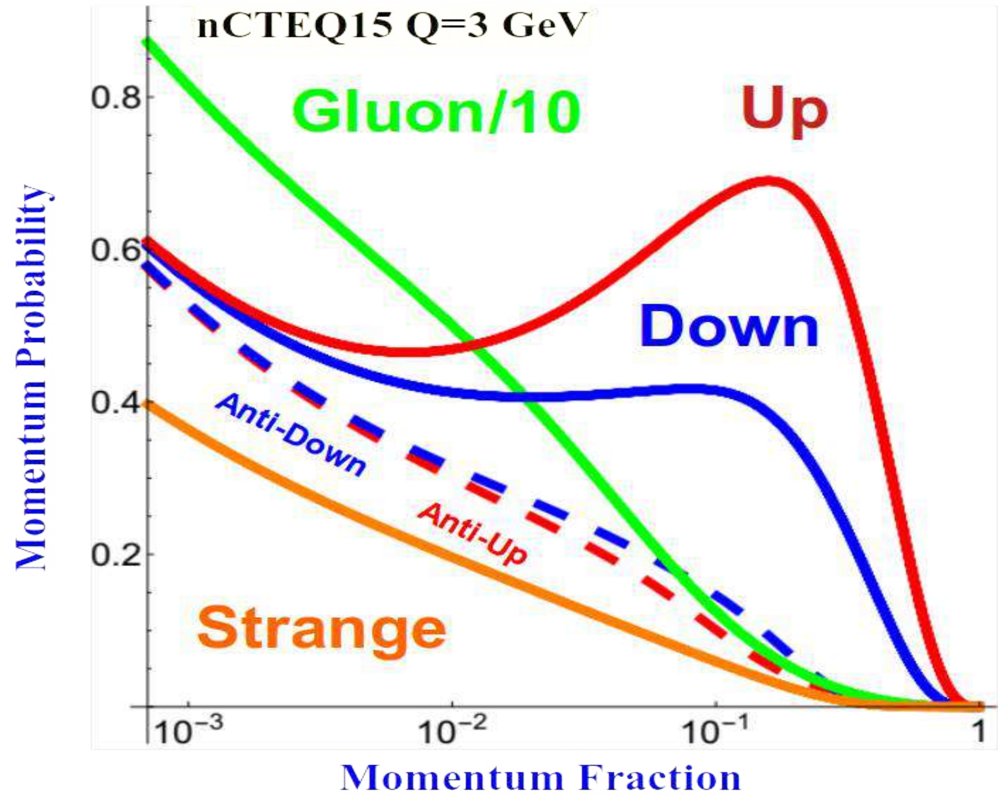
Semi-Inclusive
Hadron Production

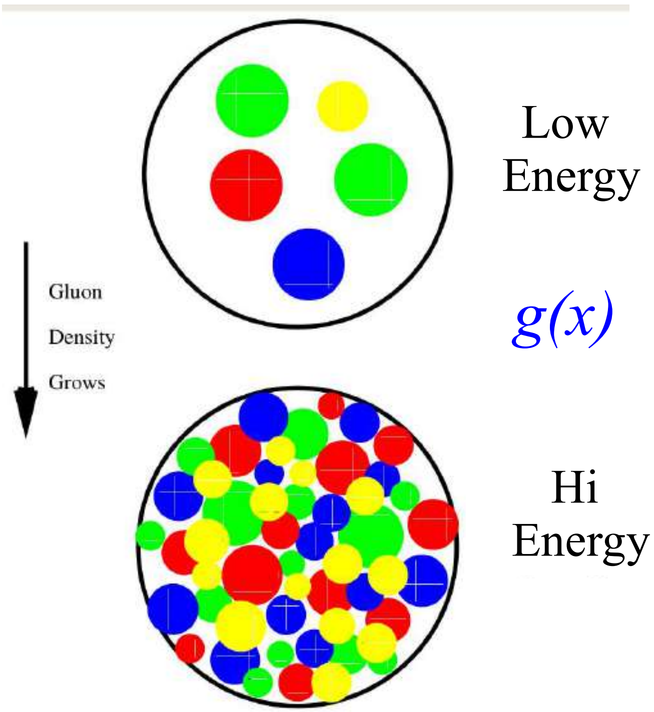


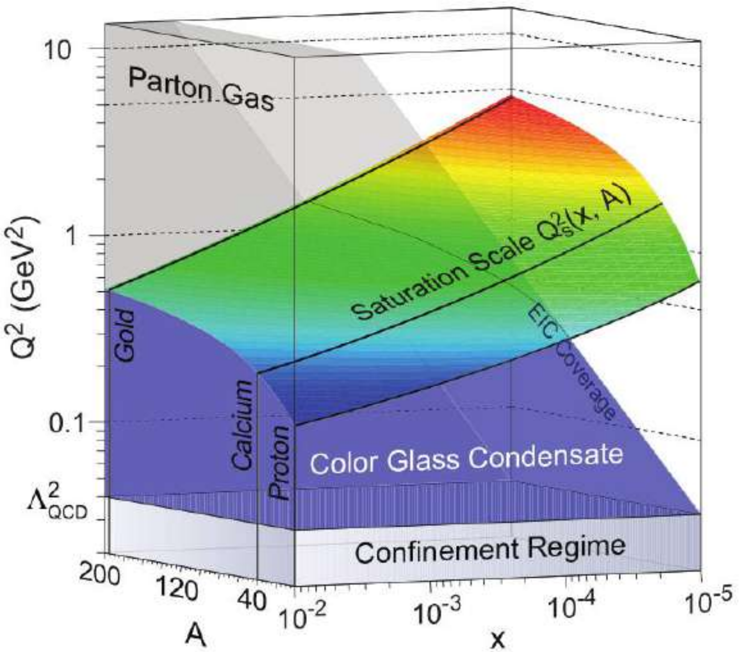
Quarkonia
Production

how can we determine the gluon

Nuclear Medium Effects at small momentum fraction (x)



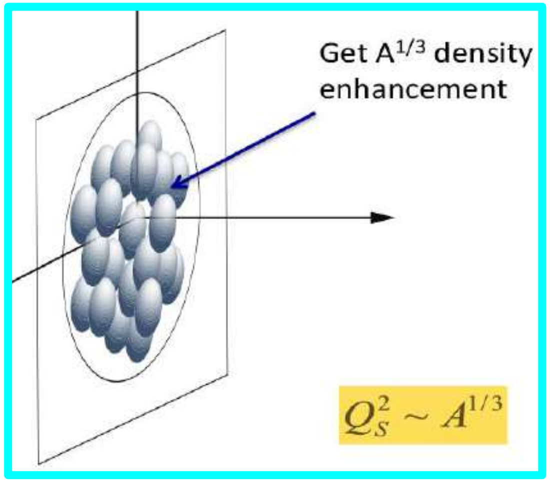




Nuclear medium effects:

- Quark Gluon Plasma
- Color Glass Condensate
- Recombination
- Saturation
- Resummation
- … *your theory here*

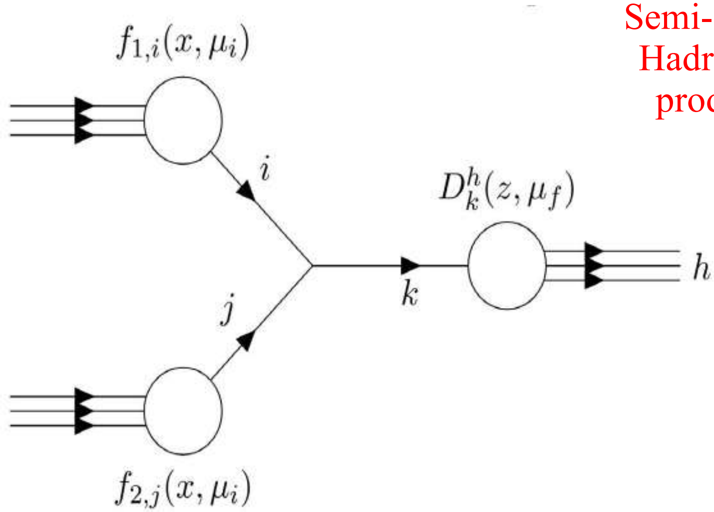
We gain a geometric factor of $A^{1/3}$



Review: Edmond Iancu & Raju Venugopalan: arXiv:0303204

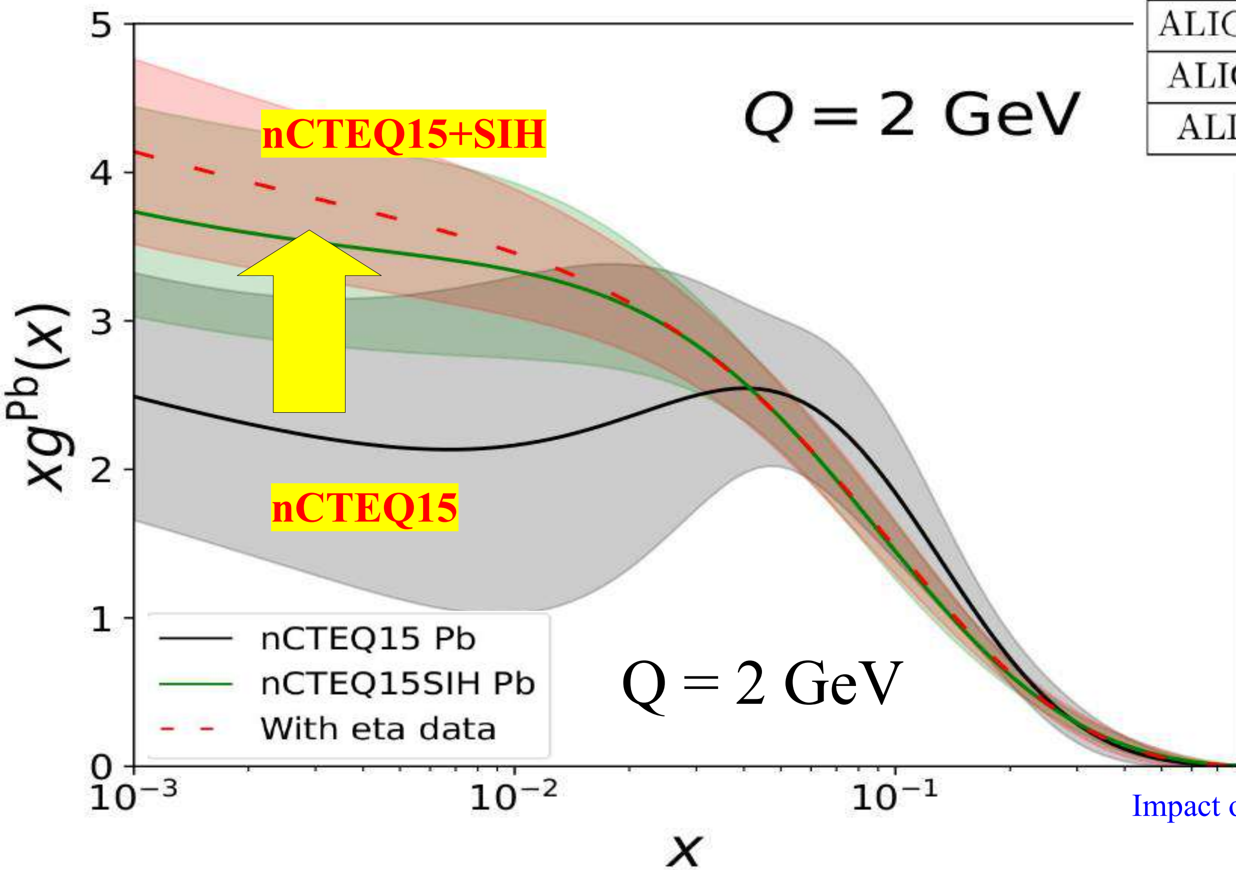
Precision Gluon can help study nuclear medium effects

Pit Duwentaster, Michael Klasen, ...



Semi-Inclusive Hadron (SIH) production

Data set	$\sqrt{s_{NN}}$ [GeV]	Observ.	No. points
PHENIX π^0	200	R_{dAu}	21
PHENIX η	200	R_{dAu}	12
PHENIX $\pi^\pm$	200	R_{dAu}	20
PHENIX $K^\pm$	200	R_{dAu}	15
STARπ^0	200	R_{dAu}	13
STAR η	200	R_{dAu}	7
STAR $\pi^\pm$	200	R_{dAu}	23
ALICE 5 TeV π^0	5020	R_{pPb}	31
ALICE 5 TeV η	5020	R_{pPb}	16
ALICE 5 TeV $\pi^\pm$	5020	R_{pPb}	58
ALICE 5 TeV $K^\pm$	5020	R_{pPb}	58
ALICE 8 TeV π^0	8160	R_{pPb}	30
ALICE 8 TeV η	8160	R_{pPb}	14



Semi-Inclusive Hadron (SIH) production

Determines gluon in small x region

Impact of inclusive hadron production data on nuclear gluon PDFs
nCTEQ: P. Duwentäster, et al., PRD104 (2021) 094005.

xFitter/xFitterTalks » xFitter/../xFitterDevel.. »

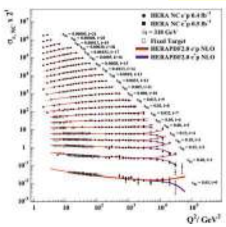
Features & Recent Updates:

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

Sample data files:

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

Experimental Data



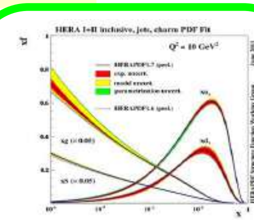
Data: HERA, Tevatron, LHC, fixed target experiments

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

xFitter 2.0.1
Old Fashioned

Date	Version
 02/2020	2.0.1N Nuclear Daiquiri

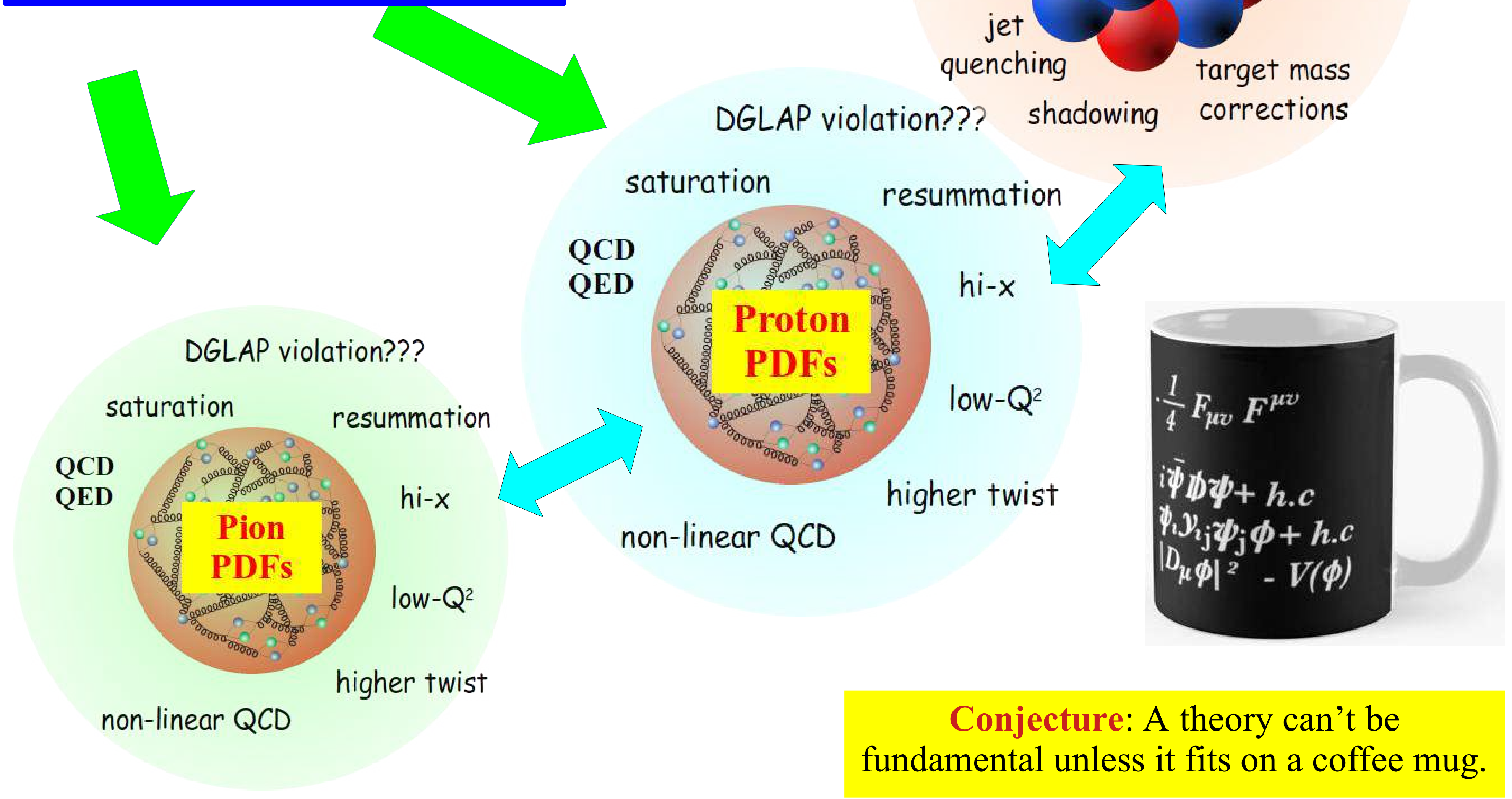
nCTEQ: A Deeper Understanding of the strong nuclear force

Quantum ChromoDynamics

QCD

Lagrangian

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



Conjecture: A theory can't be fundamental unless it fits on a coffee mug.