nCTEQ PDFs and LHC nuclear scattering data

Challenges and Opportunities for QCD

T.J. Hobbs
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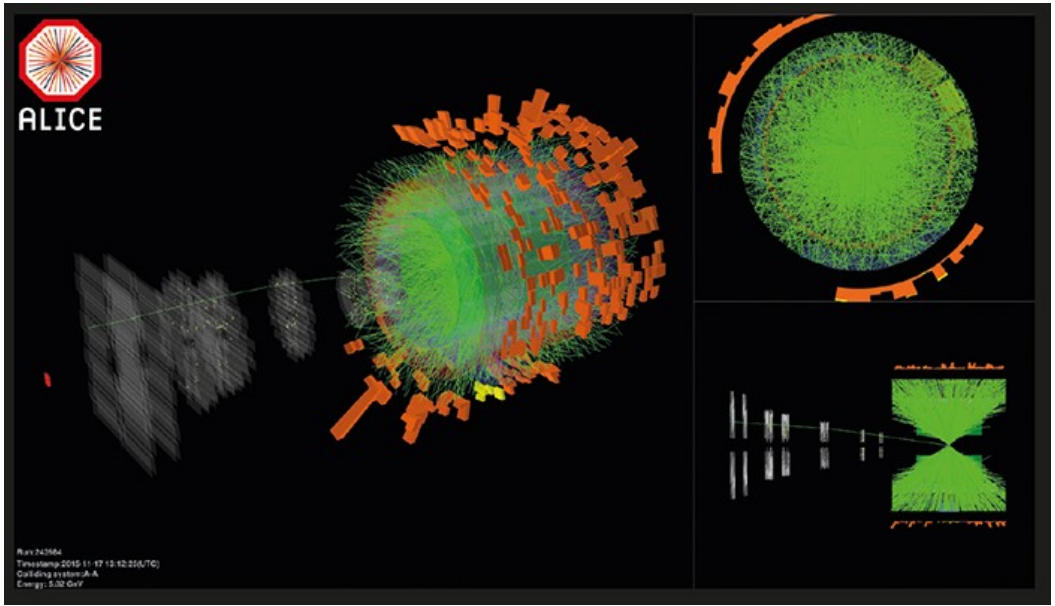
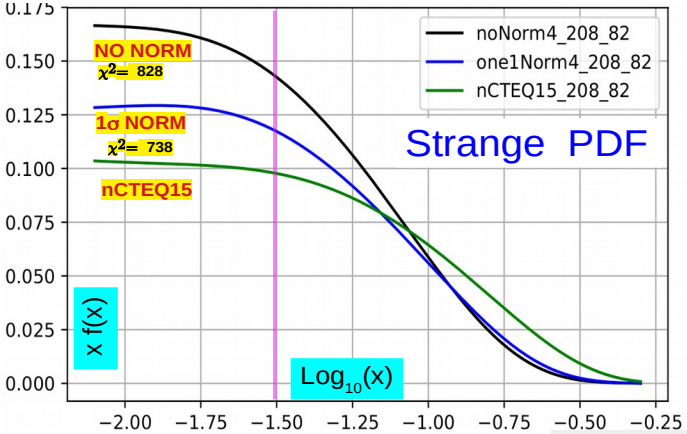
nCTEQ
nuclear parton distribution functions

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





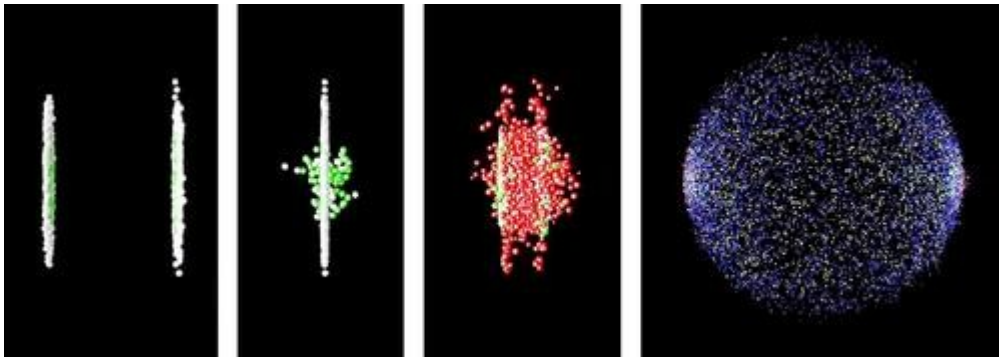
GHP2019
Denver
April 10-13, 2019

why bother with nuclear PDFs? (i)

...they are **crucial** for heavy-ion programs at

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

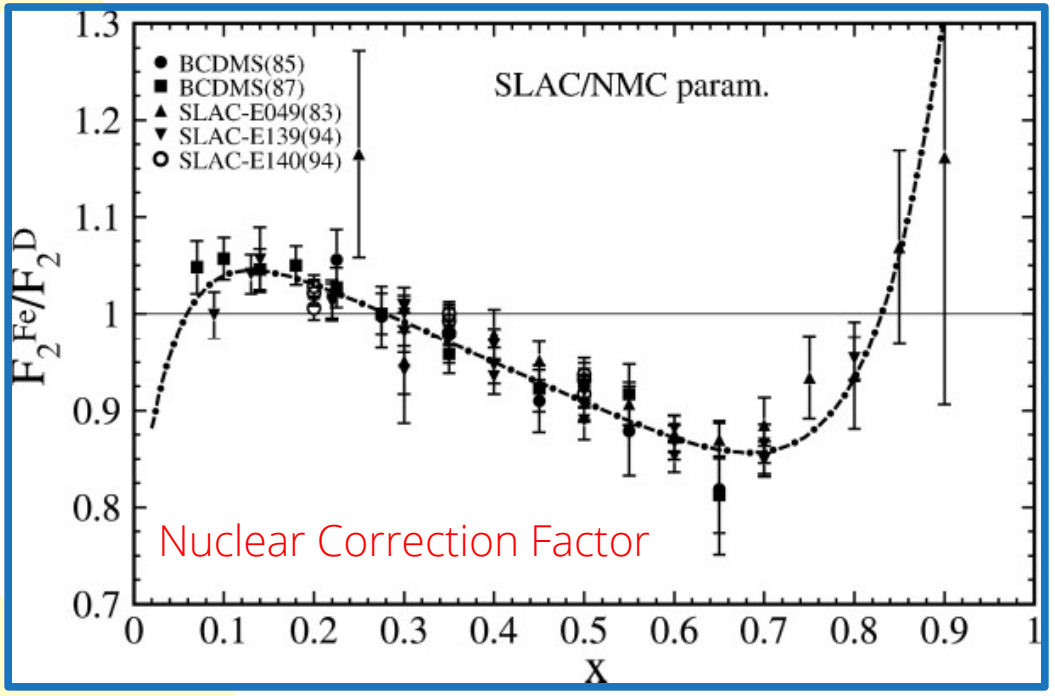
LHC (pPb, PbPb)



AND, to perform detailed flavor separations:

neutrino DIS

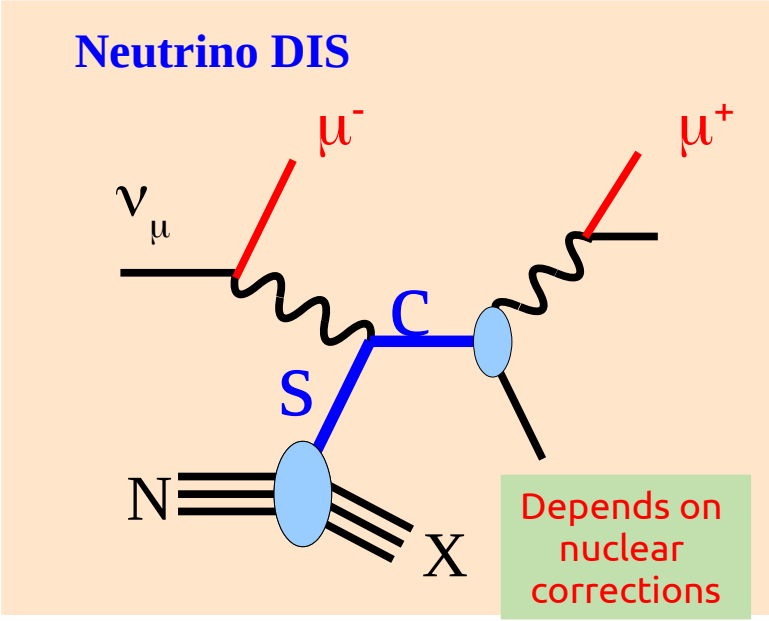
$$F_2^{\nu} \sim \left[d + s + \bar{u} + \bar{c}\right]$$
$$F_2^{\bar{\nu}} \sim \left[\bar{d} + \bar{s} + u + c\right]$$
$$F_3^{\nu} \sim 2\left[d + s - \bar{u} - \bar{c}\right]$$
$$F_3^{\bar{\nu}} \sim 2\left[u + c - \bar{d} - \bar{s}\right]$$

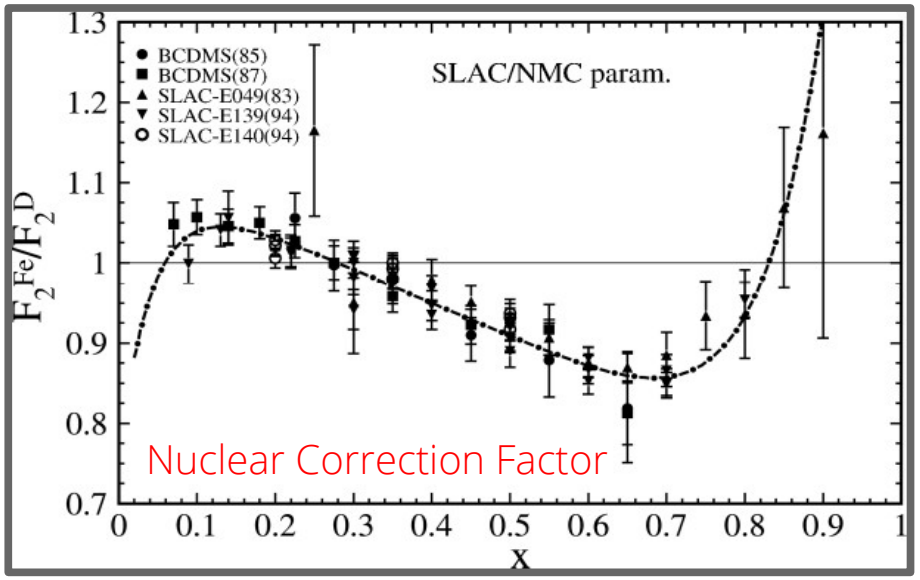


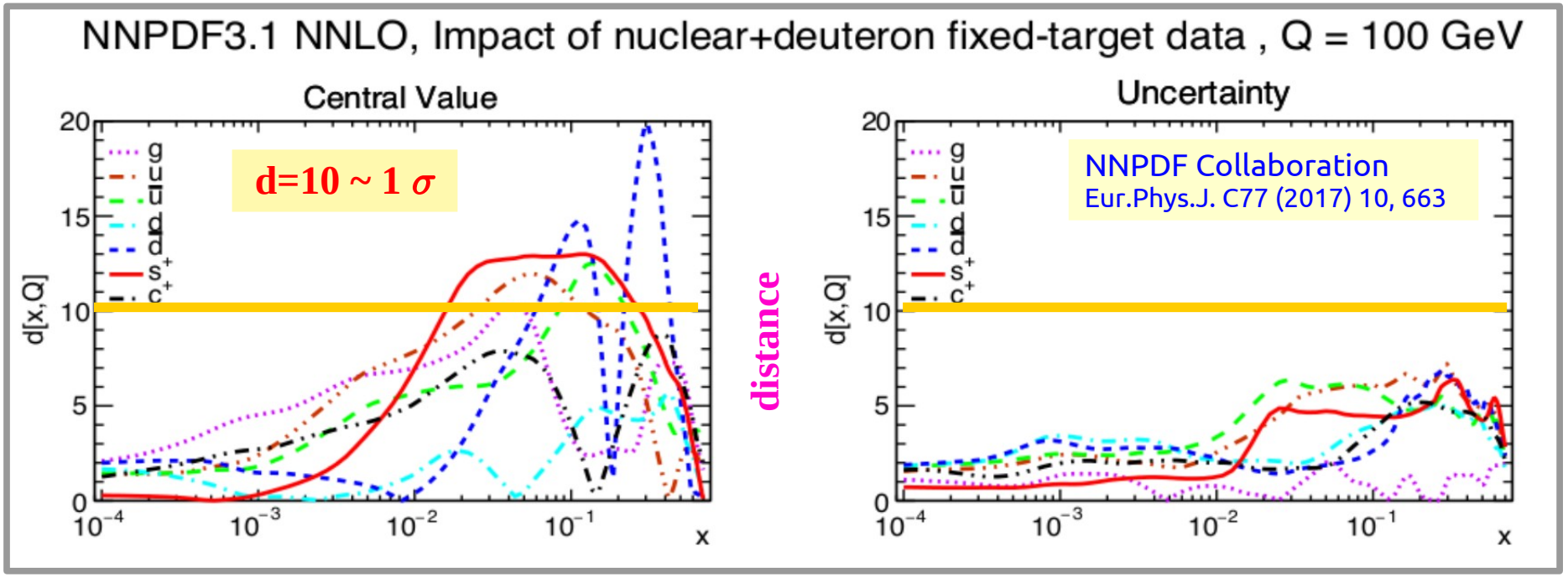
charged lepton DIS

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

impact of Nuclear Corrections on Proton PDFs







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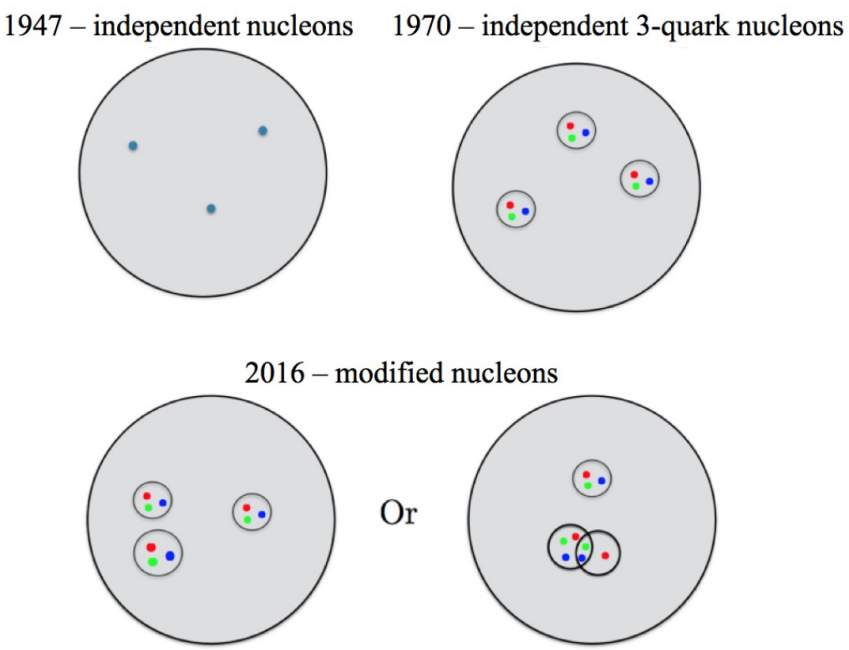
"... for the time being it is still appears advantageous to retain nuclear target data in the global dataset for general-purpose PDF determination"

why bother with nuclear PDFs? (ii)

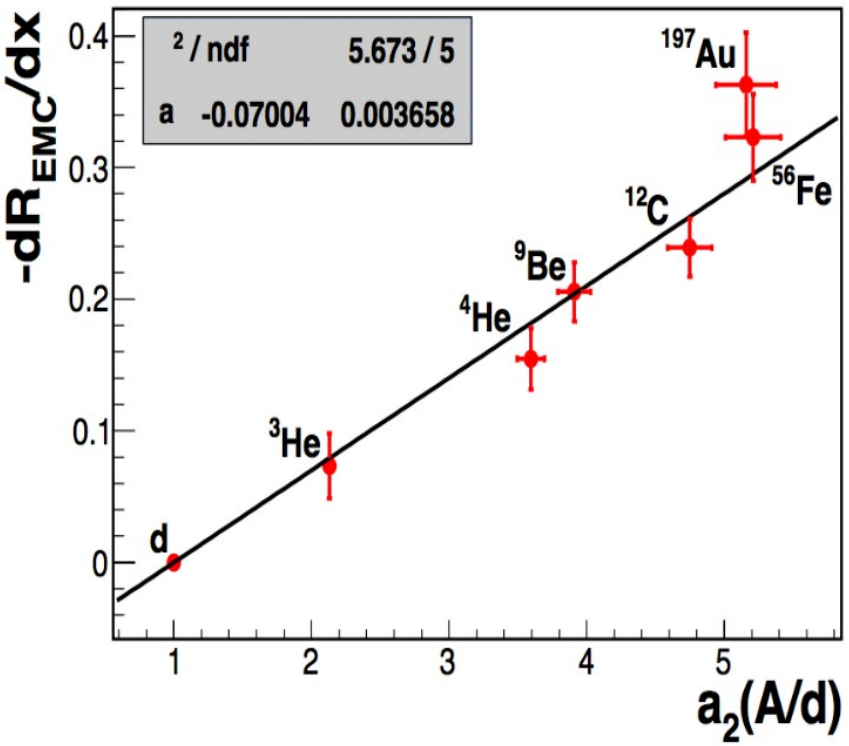
nPDFs are informative of the **dynamics** at work in the nuclear medium!

→ short-range correlations?

→ mean-field picture?



Hen et al., Rev. Mod. Phys. **89** (2017) no.4, 045002



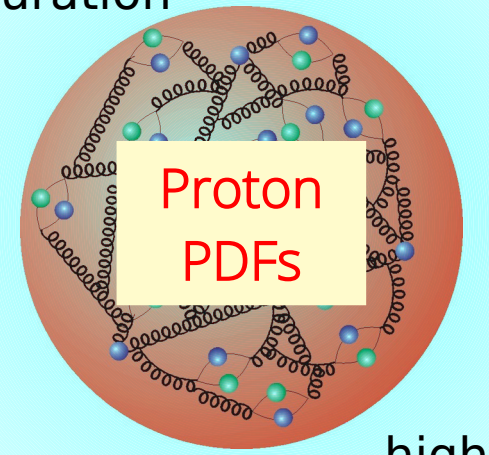
… the motivation for nCTEQ

DGLAP violation?

saturation

resummation

QCD
QED



hi-x

low-Q^2

higher twist

non-linear
QCD

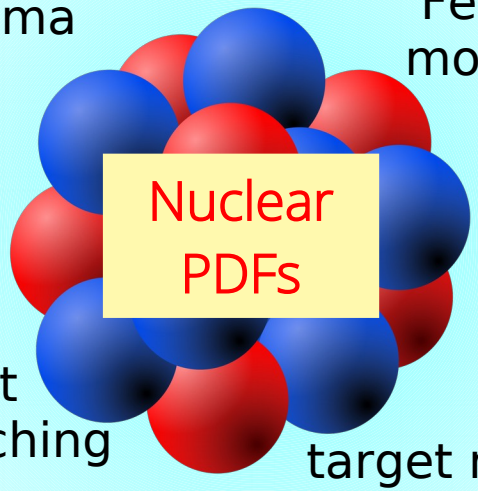
communication

e.g., flavor
differentiation

isospin
violation

quark-gluon
plasma

Fermi
motion



jet
quenching

target mass
corrections

shadowing

A. Kusina,
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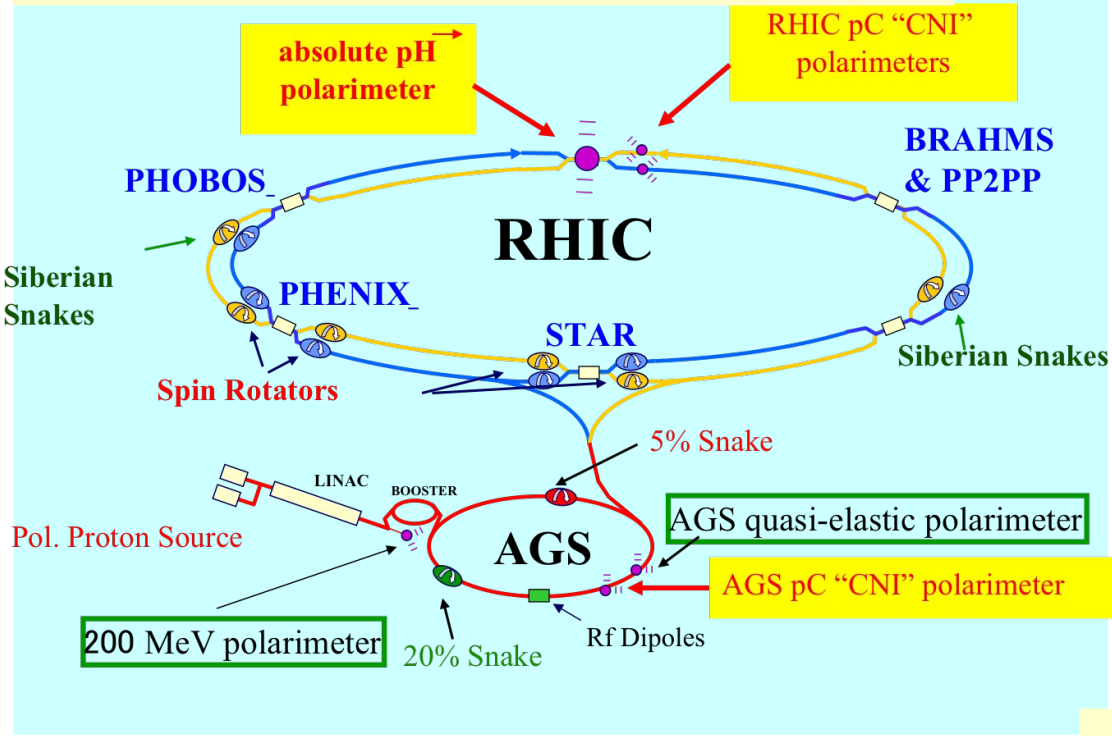
E. Godat

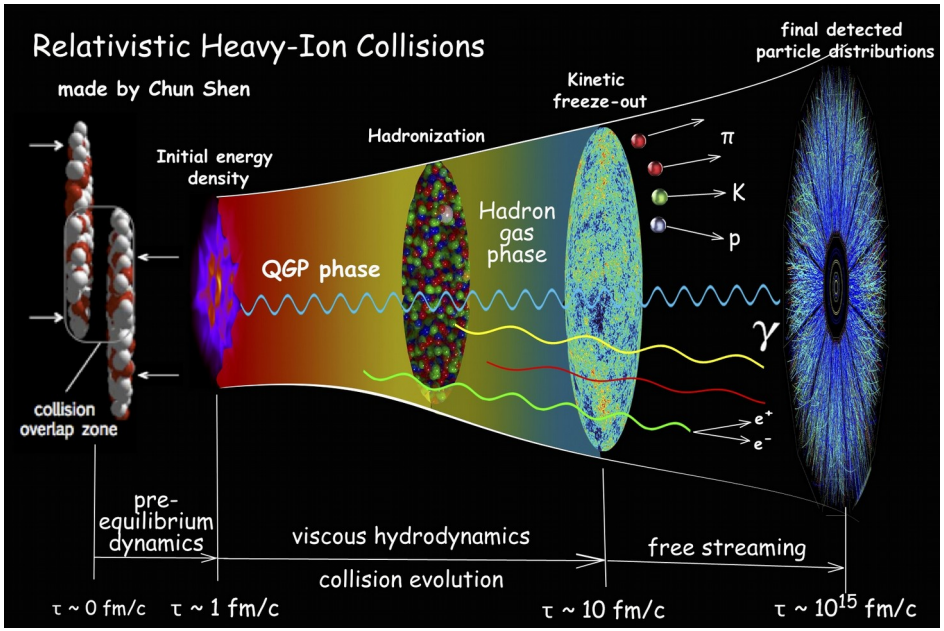
Data from nuclear targets play a key role in the flavor differentiation

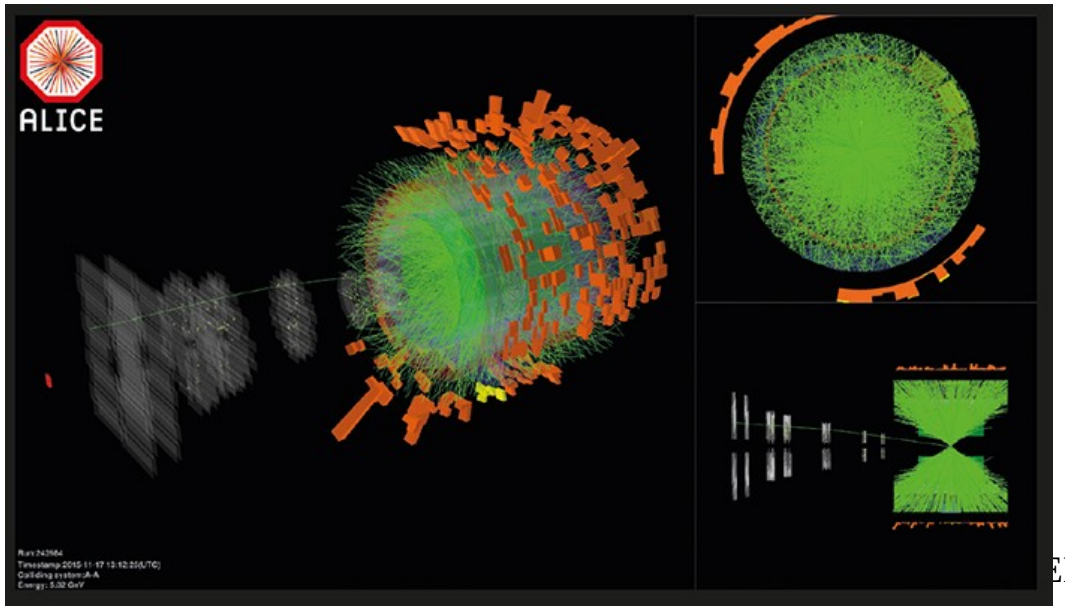
nCTEQ

nuclear parton distribution functions

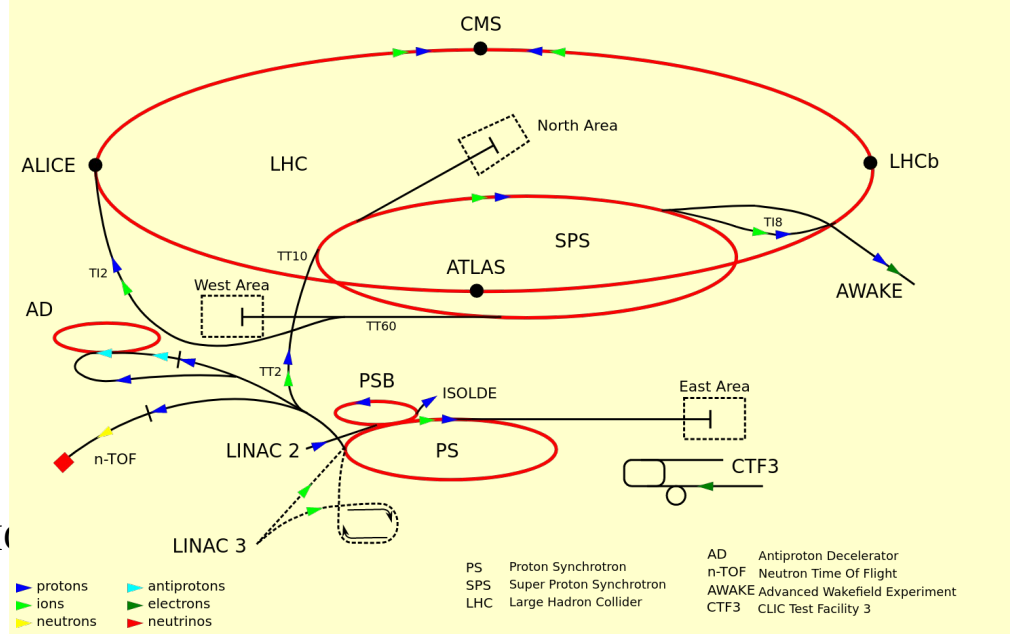
nPDFs of Current Interest





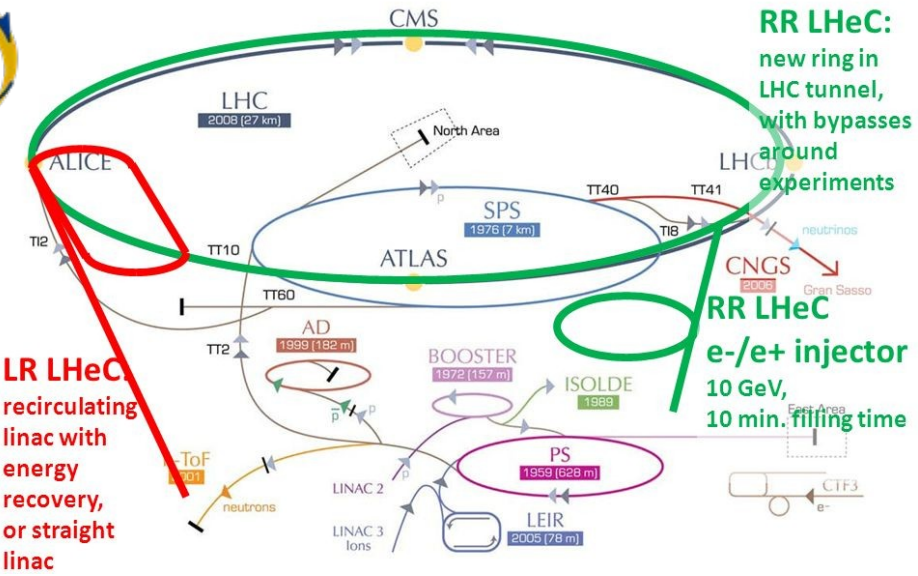


Heavy Ions at the LHC

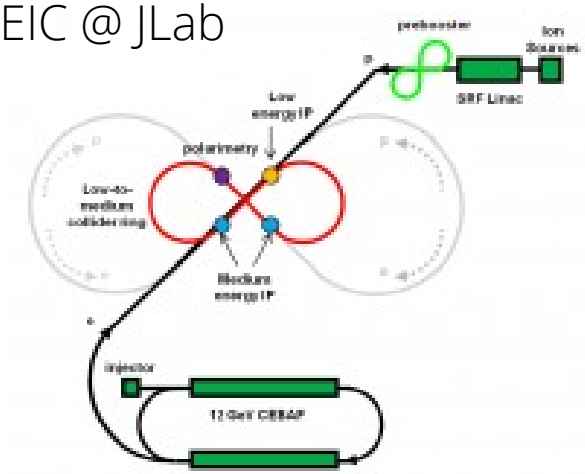


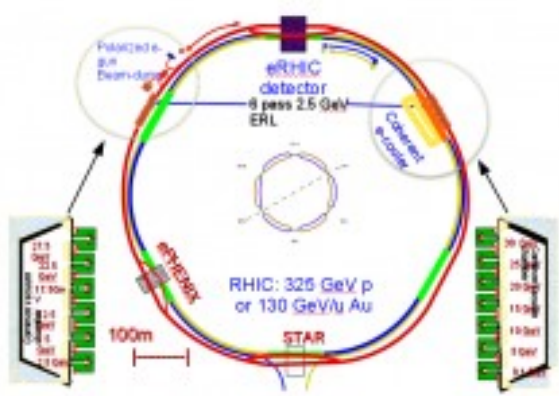
nPDFs and future interest

LHeC – several options

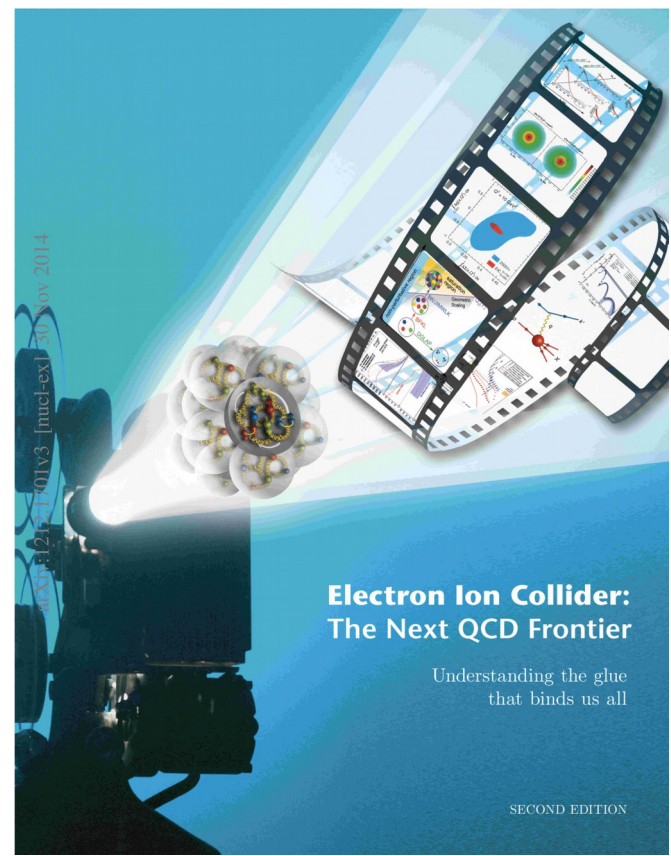


JLEIC @ JLab





eRHIC @ BNL



nuclear PDFs

...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

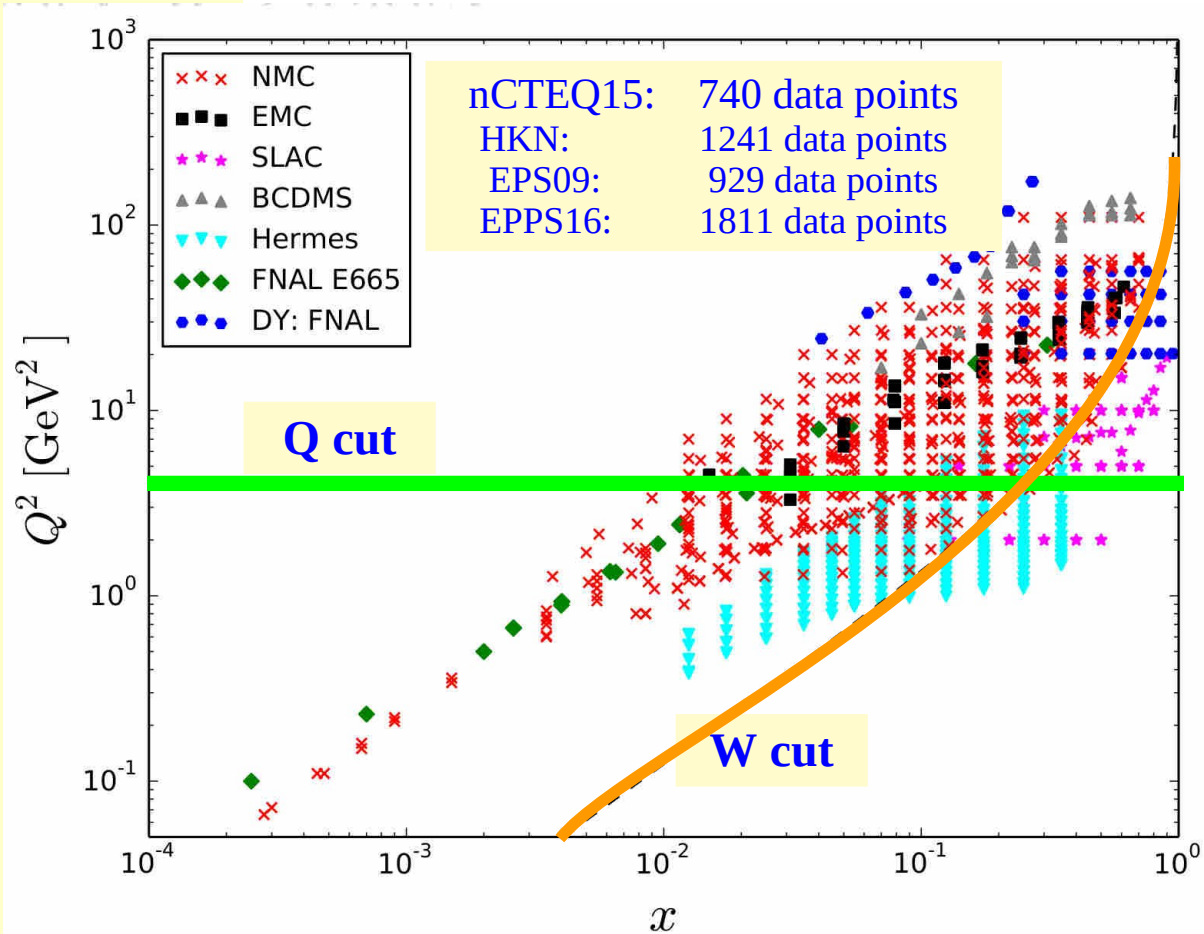
Pion Production:

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

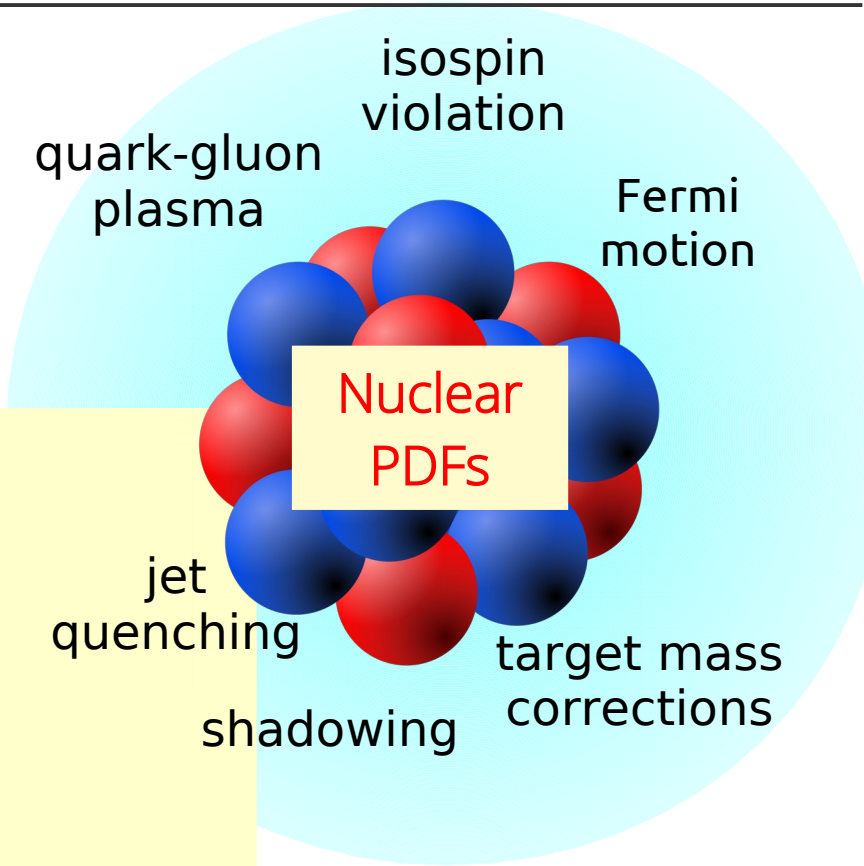


proton vs nuclear: fewer data and more DOF ... impose assumptions on nPDFs

... selected NLO Nuclear PDF Fits

nPDFs

nuclear parton distribution functions



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

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

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

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

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

nNNPDF1.0: NNPDF Group (talk by J. Ethier later this session)
[arXiv:1904.00018]

nPDF framework and parametrization

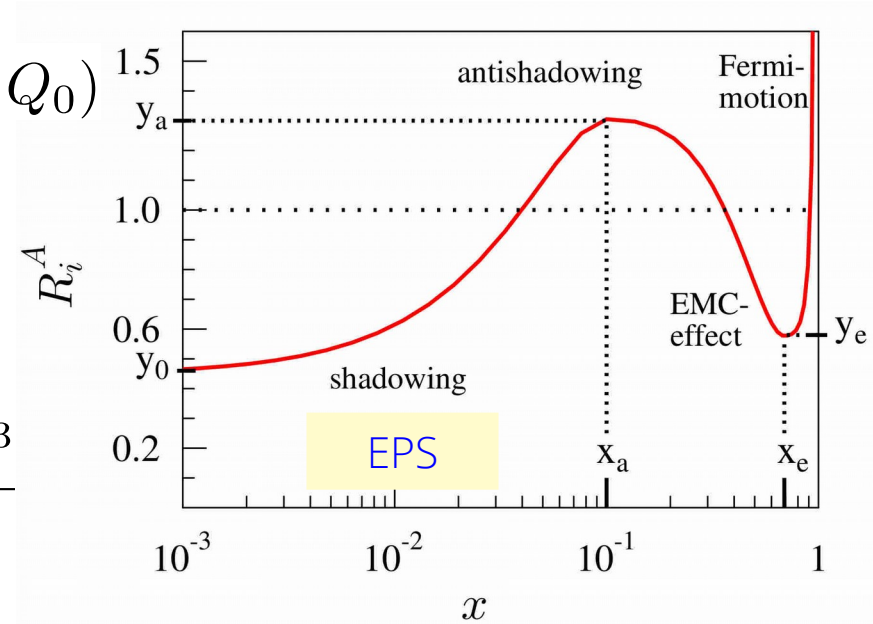
1) Multiplicative nuclear correction factors (HKN, EPPS, DSSZ)

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

... 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)

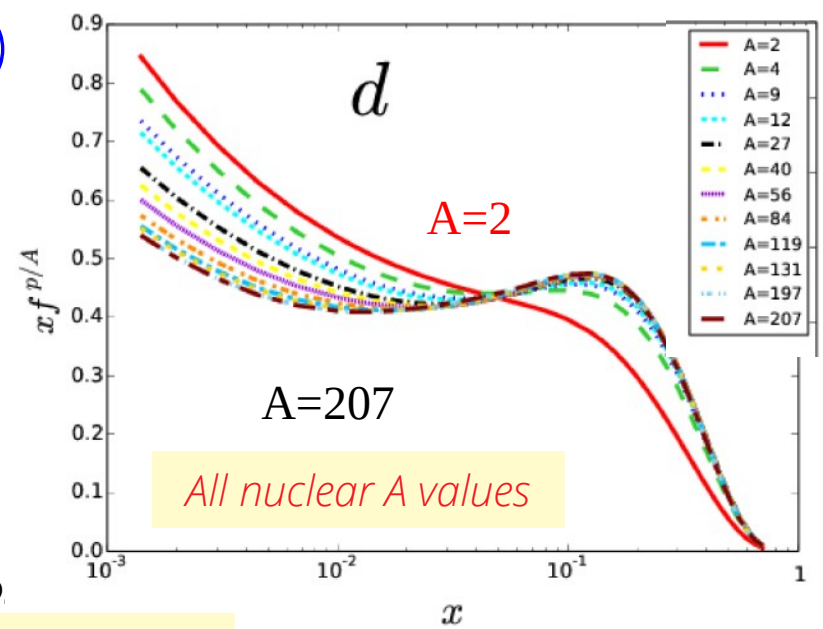
$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

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

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

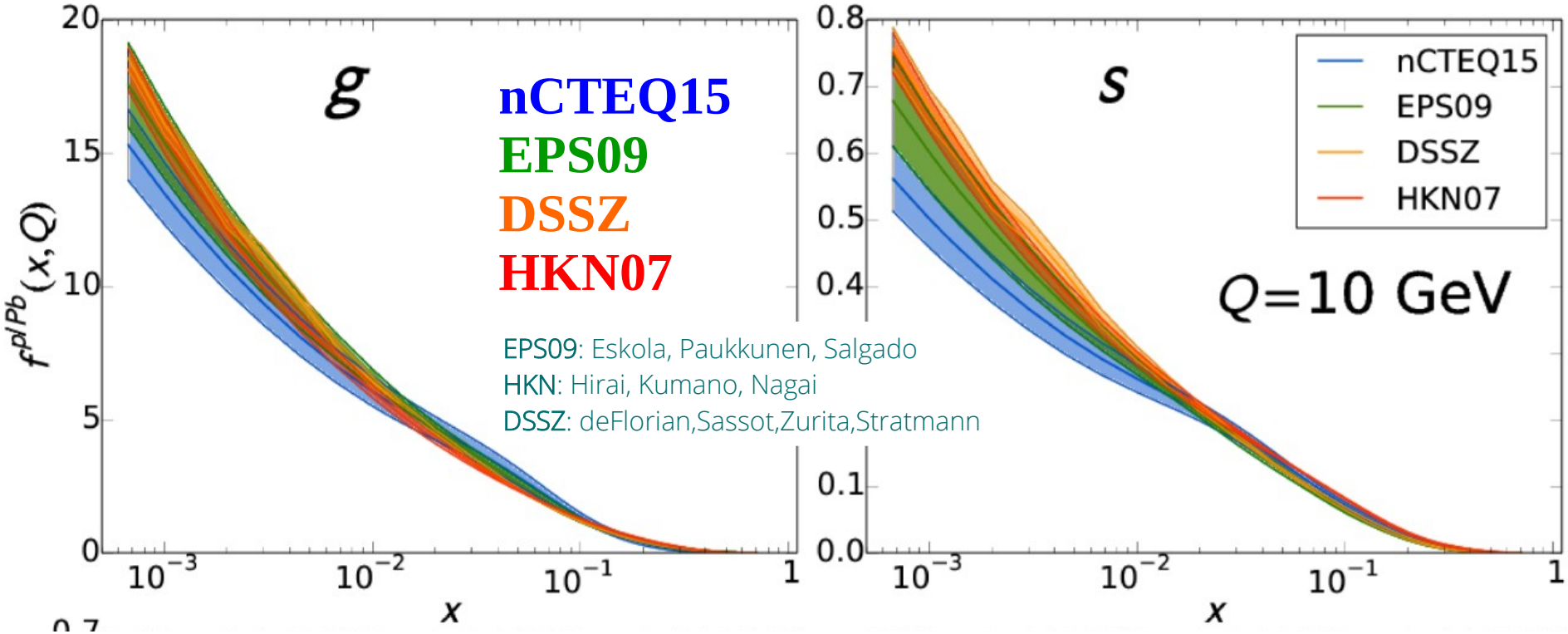
Proton

Nuclear



use proton as a Boundary Condition

Nuclear PDFs: Complementary efforts in general agreement



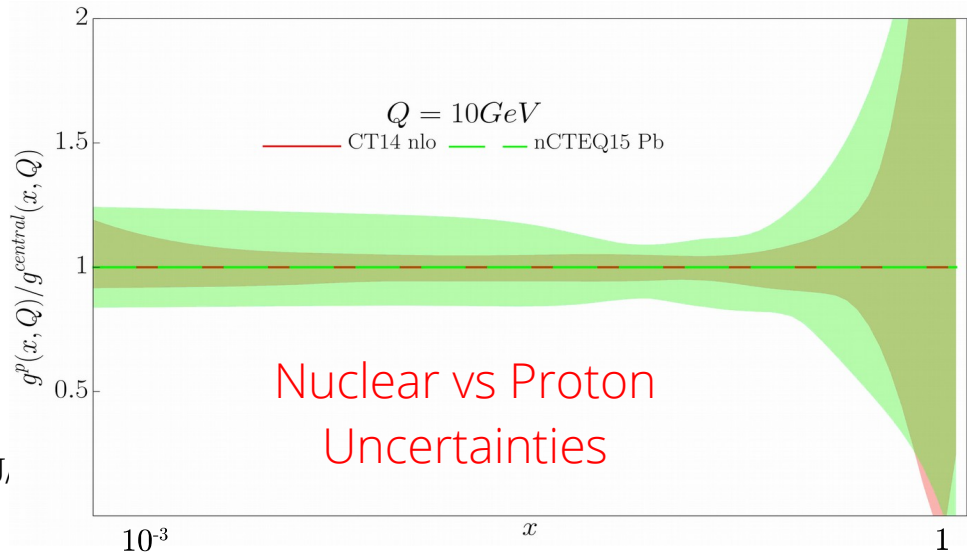
EPS09: Eskola, Paukkunen, Salgado
HKN: Hirai, Kumano, Nagai
DSSZ: deFlorian,Sassot,Zurita,Stratmann

Nuclear PDFs are more complex

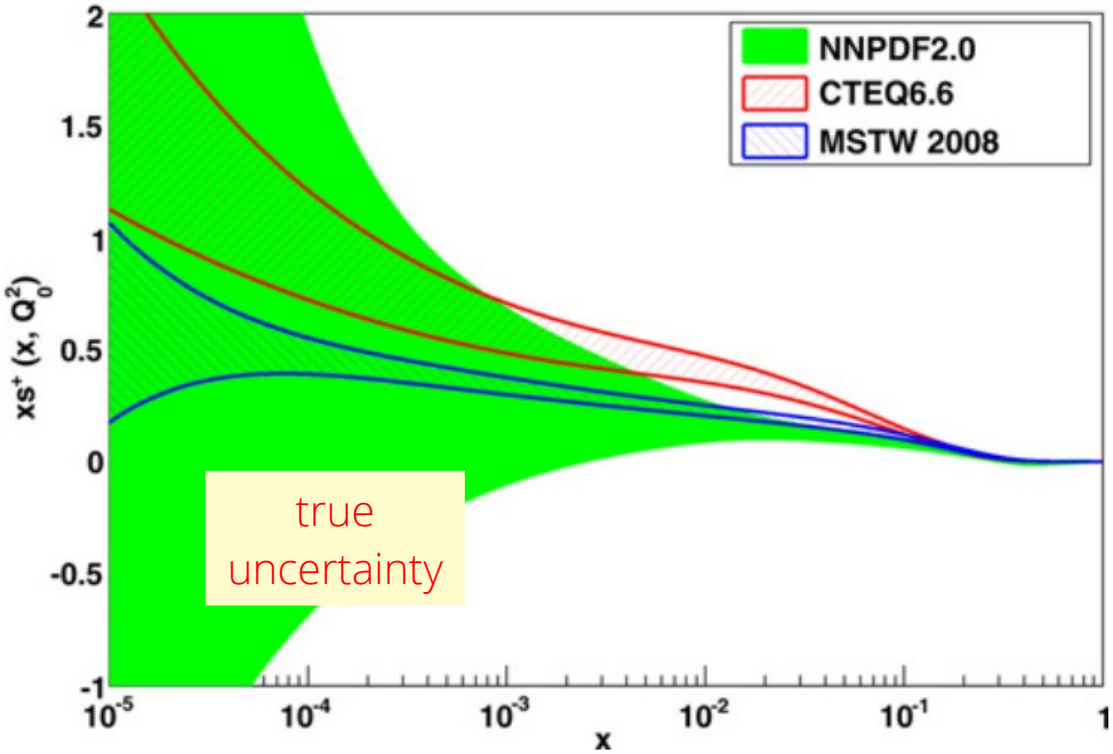
more DOF than Proton case

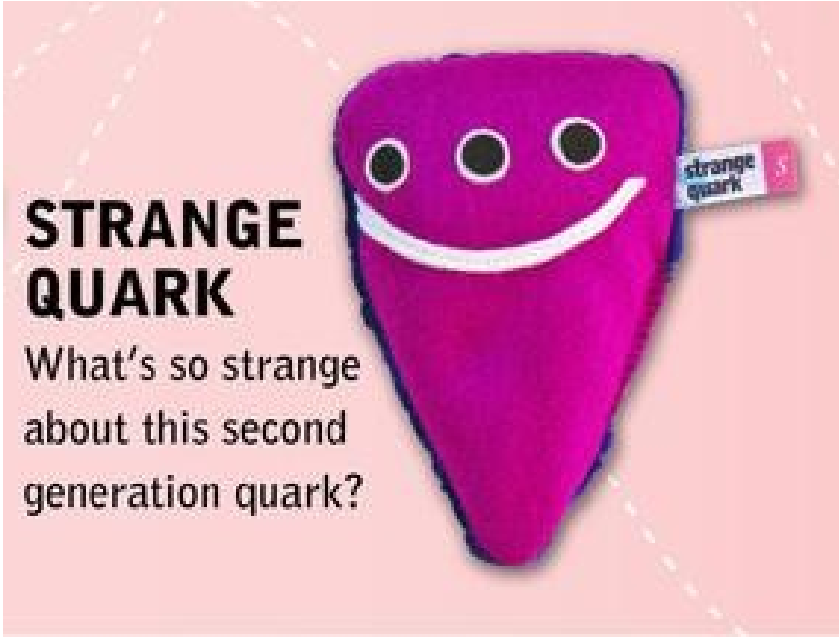
more complicated dynamically

(much) more work to do...



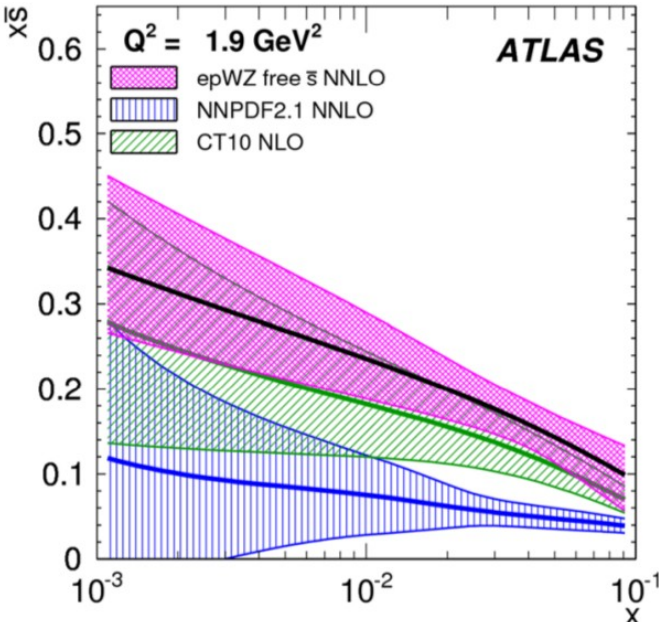
recent progress on strangeness





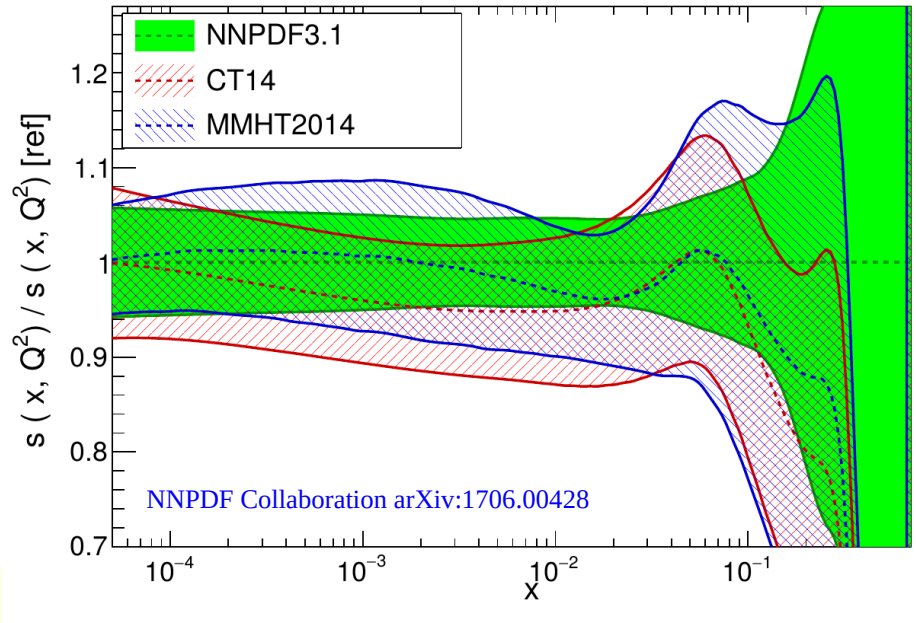
constraints on nucleon strangeness remain fairly loose

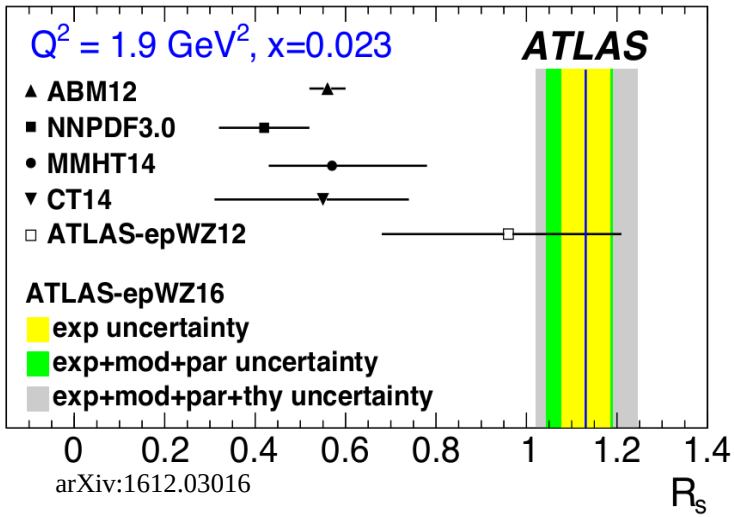
$$\kappa(Q) = \frac{\int_0^1 x\,[s(x,Q)+\bar{s}(x,Q)]\;dx}{\int_0^1 x\,[\bar{u}(x,Q)+\bar{d}(x,Q)]\;dx} \qquad r^s(x,Q) = \frac{\bar{s}(x,Q)+s(x,Q)}{2\bar{d}(x,Q)} \qquad R^s(x,Q) = \frac{s(x,Q)+\bar{s}(x,Q)}{\bar{u}(x,Q)+\bar{d}(x,Q)}$$



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

NNLO, Q = 100 GeV





arXiv:1612.03016

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

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

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

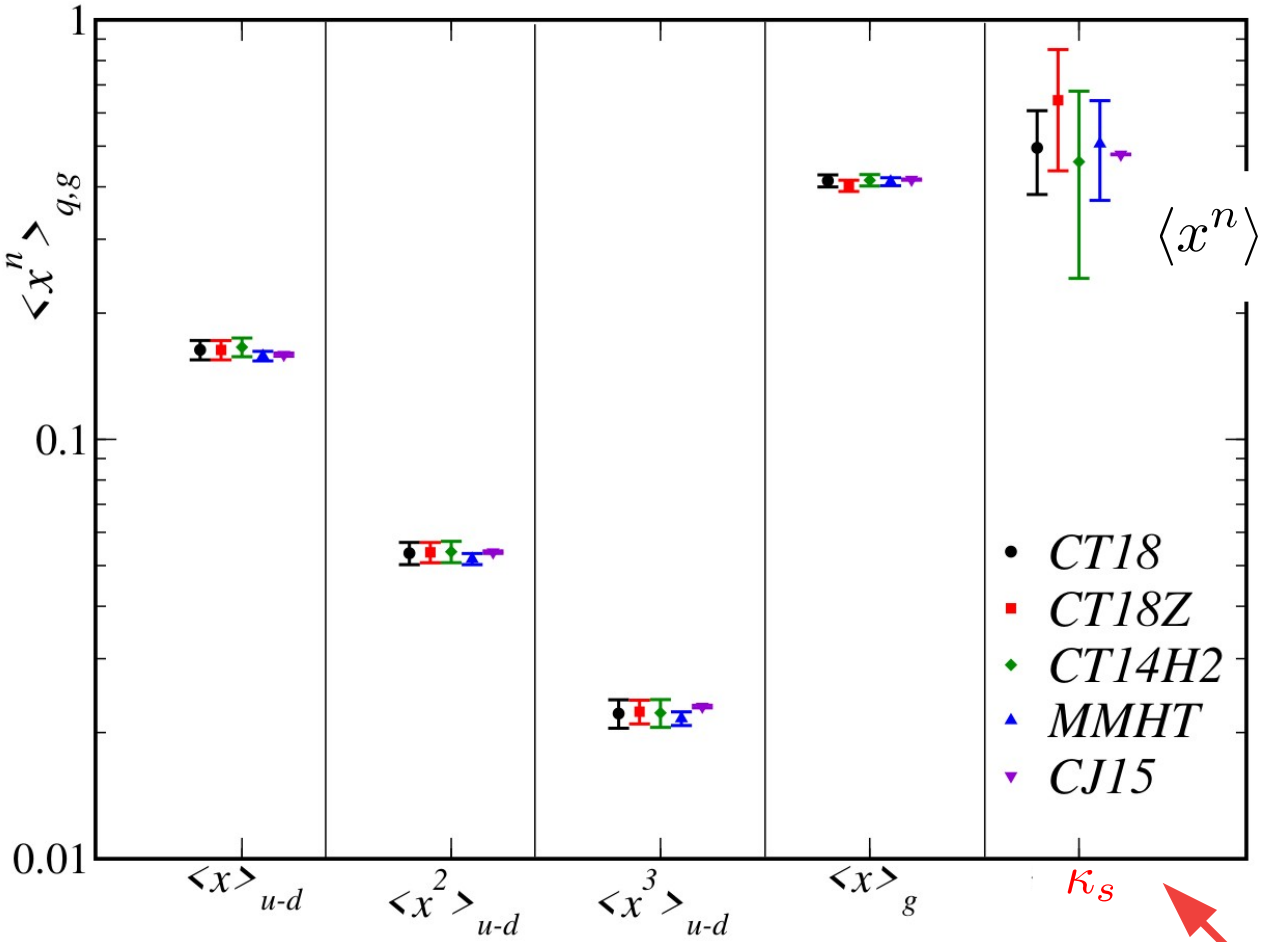
PhysRevD.90.032004
(exp)(model)(param)

$$\text{ATLAS } R_s = 1.13 \pm 0.05 \pm 0.02\;{}^{+0.01}_{-0.06}$$

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

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

PDF moments from CT18



$$\langle x^n \rangle_{q,g} = \int dx\, x^n f_{q,g}(x, \mu = 2\,\mathrm{GeV})$$

- progress in lattice QCD is compelling PDF phenomenologists to sharpen their benchmarks – especially for lower moments of light quarks

→ good agreement among phenom. predictions of isovector, gluon moments!

→ constraints are significantly weaker for moments of the light quark sea distributions, *e.g.*, the **strangeness suppression ratio**,

$$\kappa_s(\mu^{\mathrm{lat}}) \equiv \langle x \rangle_{s+\bar{s}} \big/ \langle x \rangle_{\bar{u}+\bar{d}} \big|_{\mu=2\,\mathrm{GeV}}$$

preliminary CT results

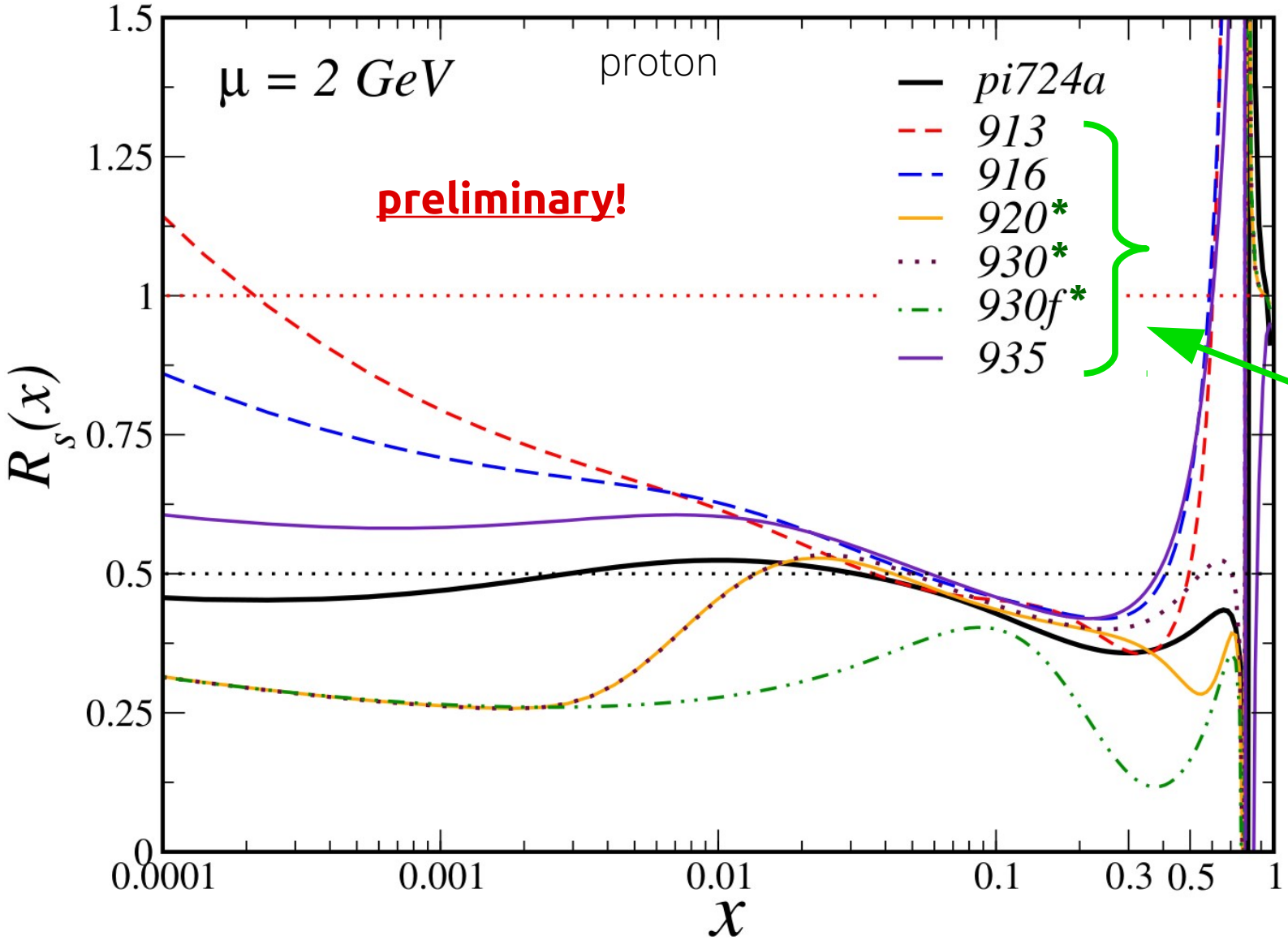
PDF moment	CT18	CT18Z	CT14H2
$\langle x \rangle_{u-d}$	0.163 ± 0.009	0.163 ± 0.009	0.166 ± 0.008
$\langle x^2 \rangle_{u-d}$	0.054 ± 0.003	0.054 ± 0.003	0.054 ± 0.003
$\langle x^3 \rangle_{u-d}$	0.022 ± 0.002	0.022 ± 0.001	0.022 ± 0.002
$\langle x \rangle_g$	0.413 ± 0.014	0.402 ± 0.012	0.415 ± 0.013
κ_s	0.496 ± 0.112	0.643 ± 0.206	0.459 ± 0.217

models may also enlighten PDF parametrization dependence

$$^{*}|\Psi_P^\lambda(P^+,\mathbf{P}_\perp)\rangle = \frac{1}{16\pi^3}\sum_{q=c,\bar{c}}\int \frac{dx d^2\mathbf{k}_\perp}{\sqrt{x(1-x)}}\psi^\lambda_{q\lambda_q}(x,\mathbf{k}_\perp)\,|q;xP^+,x\mathbf{P}_\perp+\mathbf{k}_\perp\rangle$$

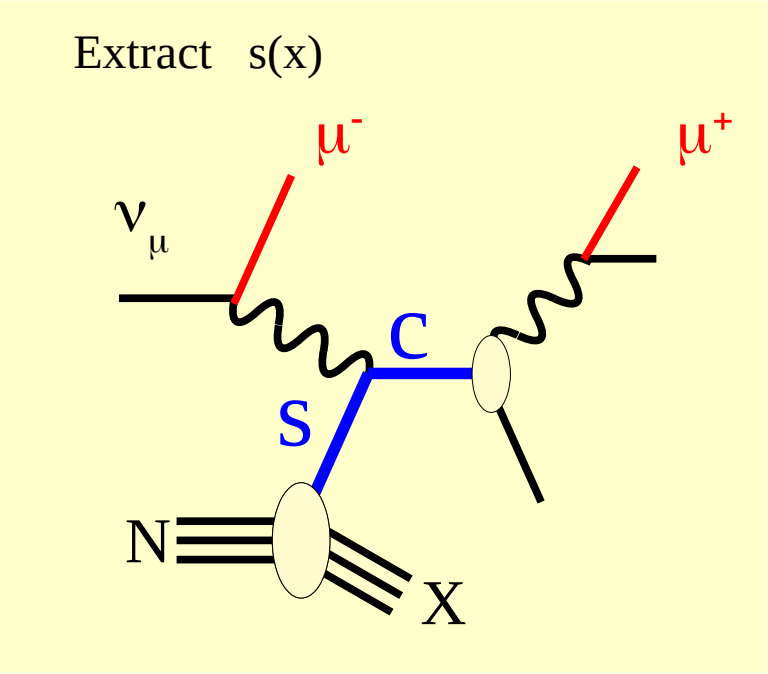
$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$

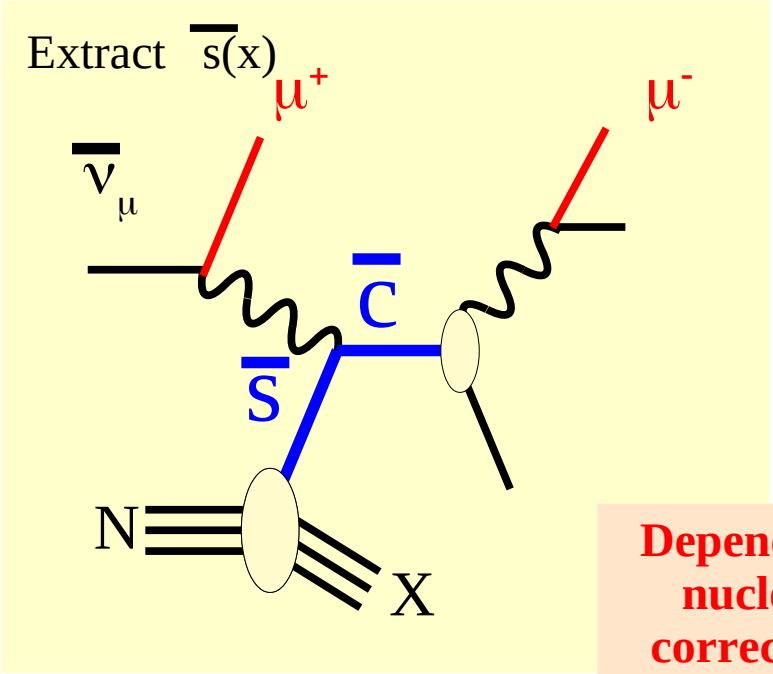
TJH, M. Alberg, and G. A. Miller; PRC**91**, 035205 (2015).
TJH, M. Alberg, and G. A. Miller; PRC**93**, 052801 (2016).
TJH, M. Alberg, and G. A. Miller; PRD**96**, 074023 (2017).



- results of fits with different parametric forms for symmetric strangeness motivated by models, e.g., on the QCD light front*
- fitted parameters in this instance are identified with quantities like constituent quark masses

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





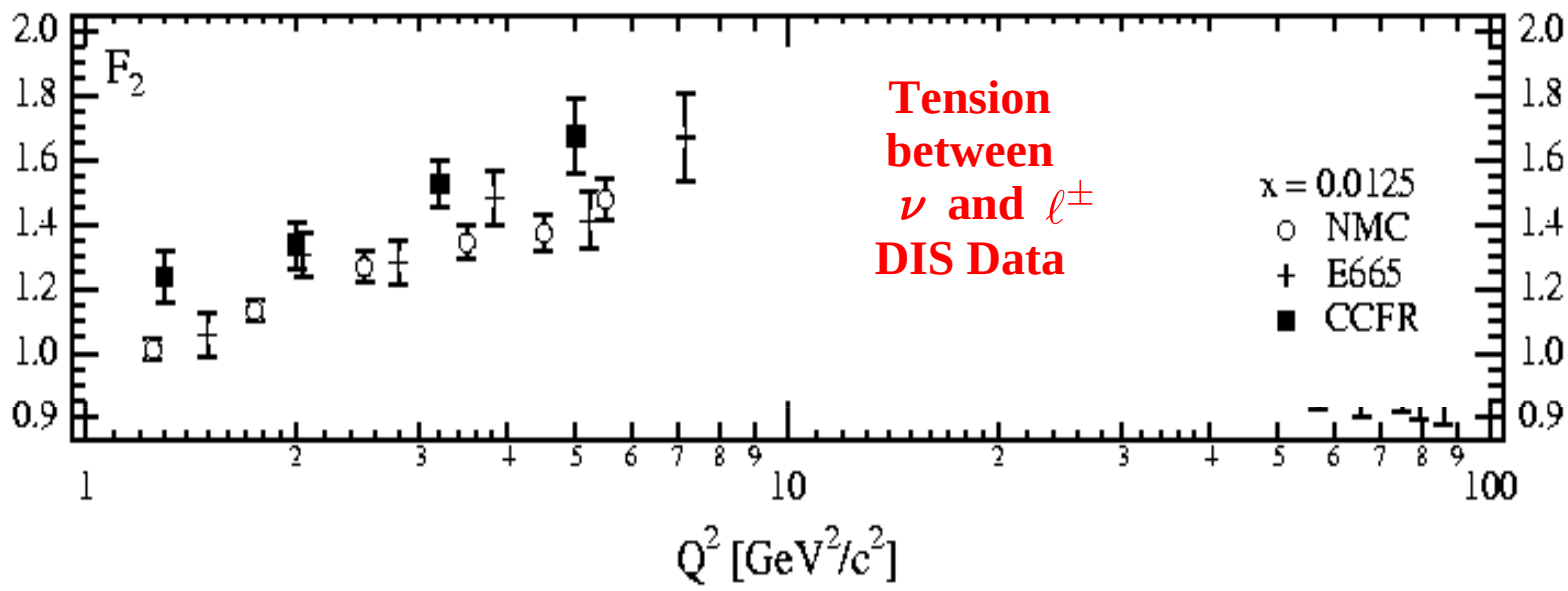
Depends on nuclear corrections

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

Used in CTEQ Fits

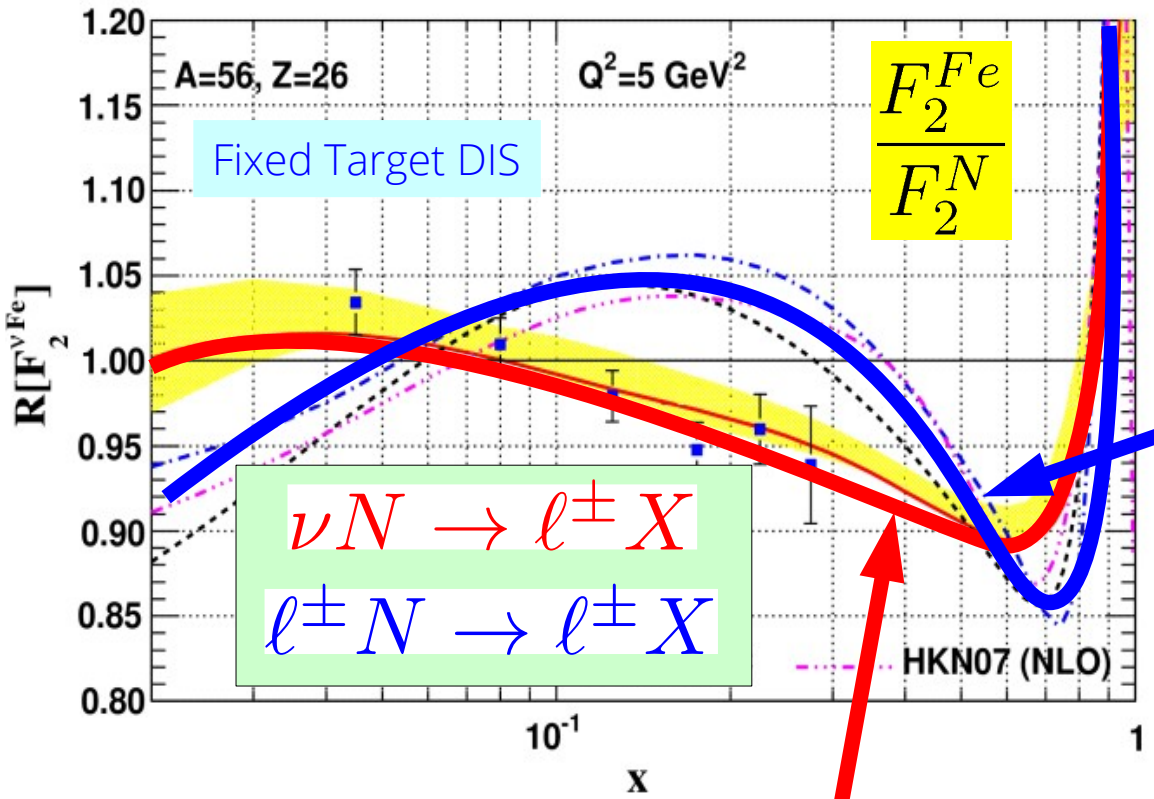
The CTEQ List of Challenges in Perturbative QCD

~1995

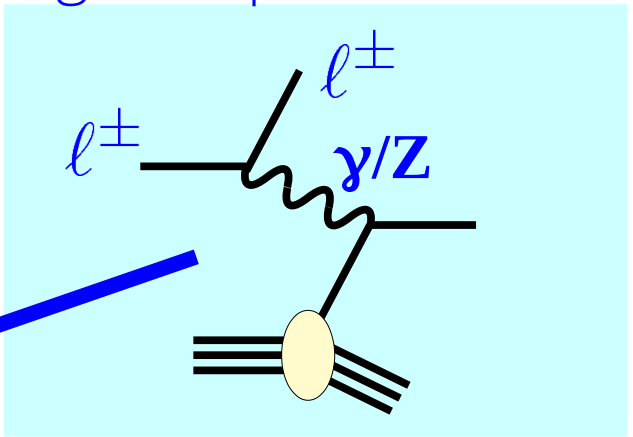


C T E Q

Strange Quark PDF & Nuclear Corrections

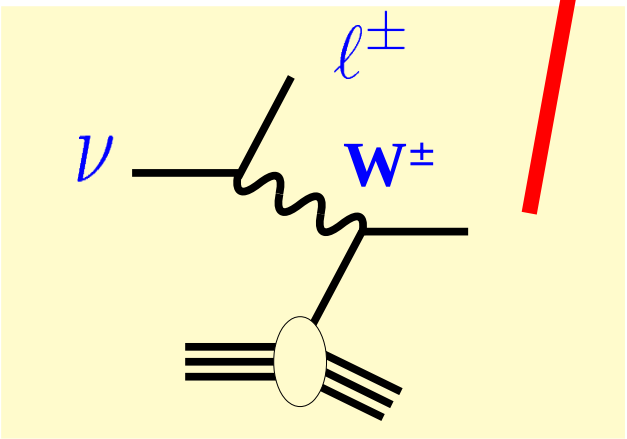


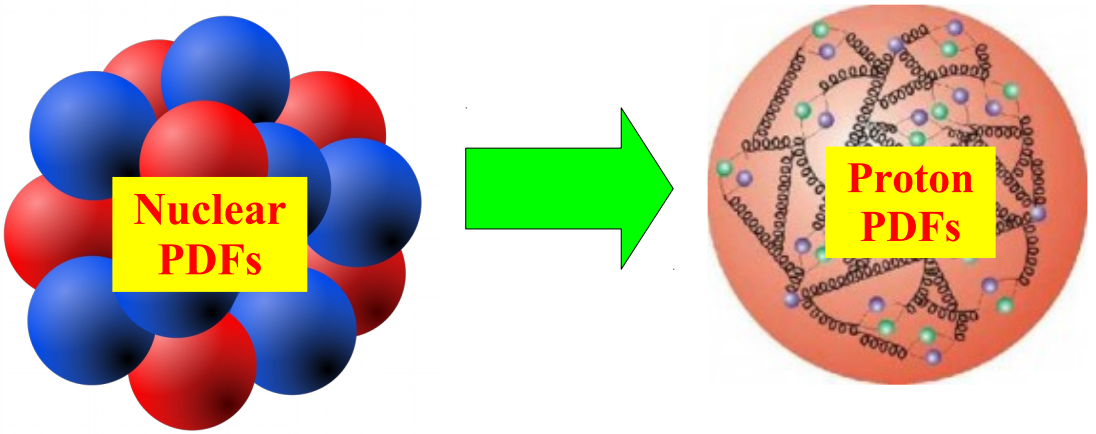
Charged Lepton DIS



some caveats
... correlated errors

Depends on nuclear corrections





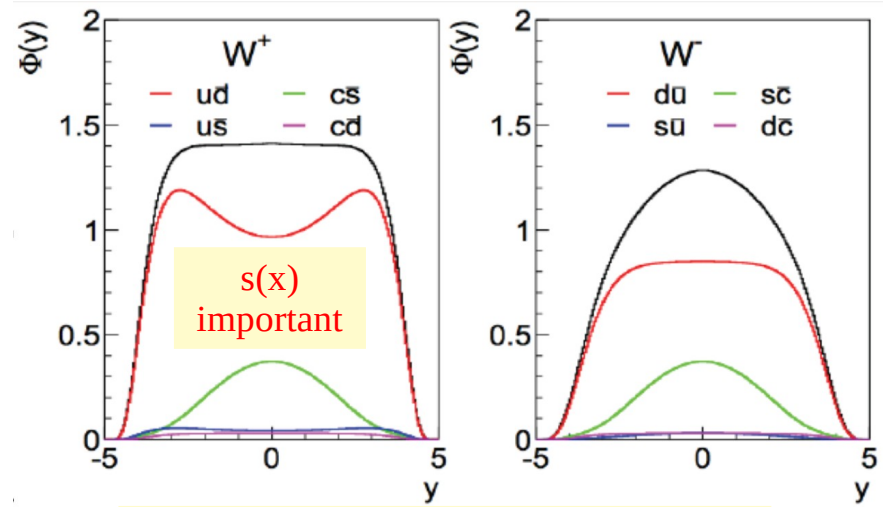
Neutrino DIS

(...see talk by Jorge Morfin!)

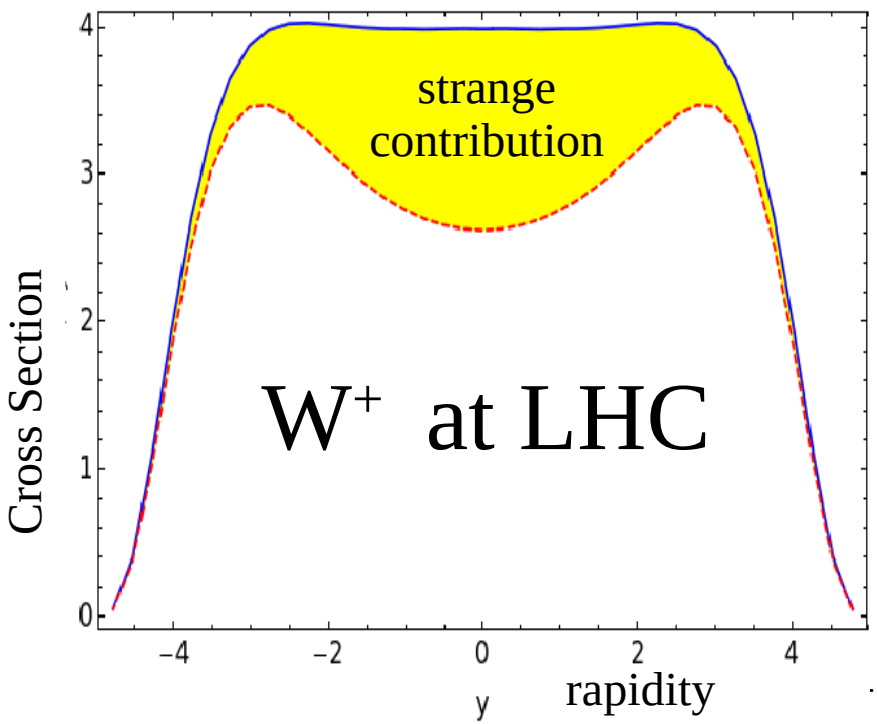
W/Z Production at LHC and the strange PDF

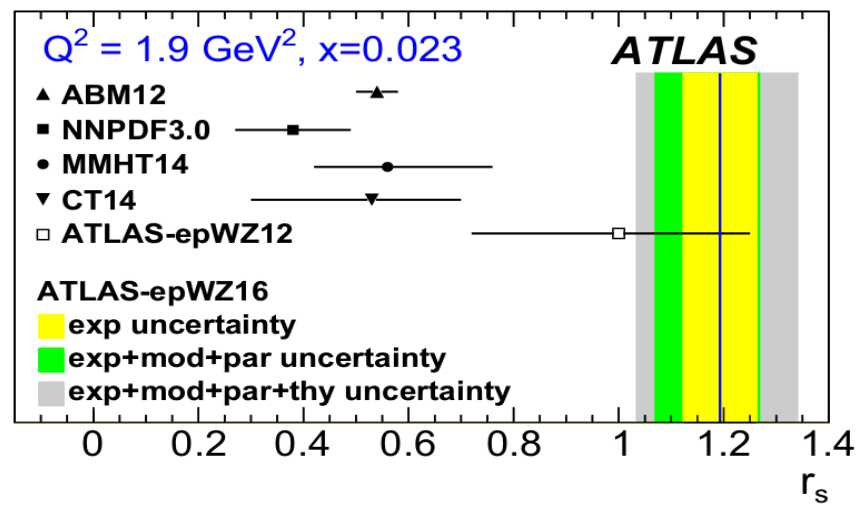
W/Z Production Channels

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



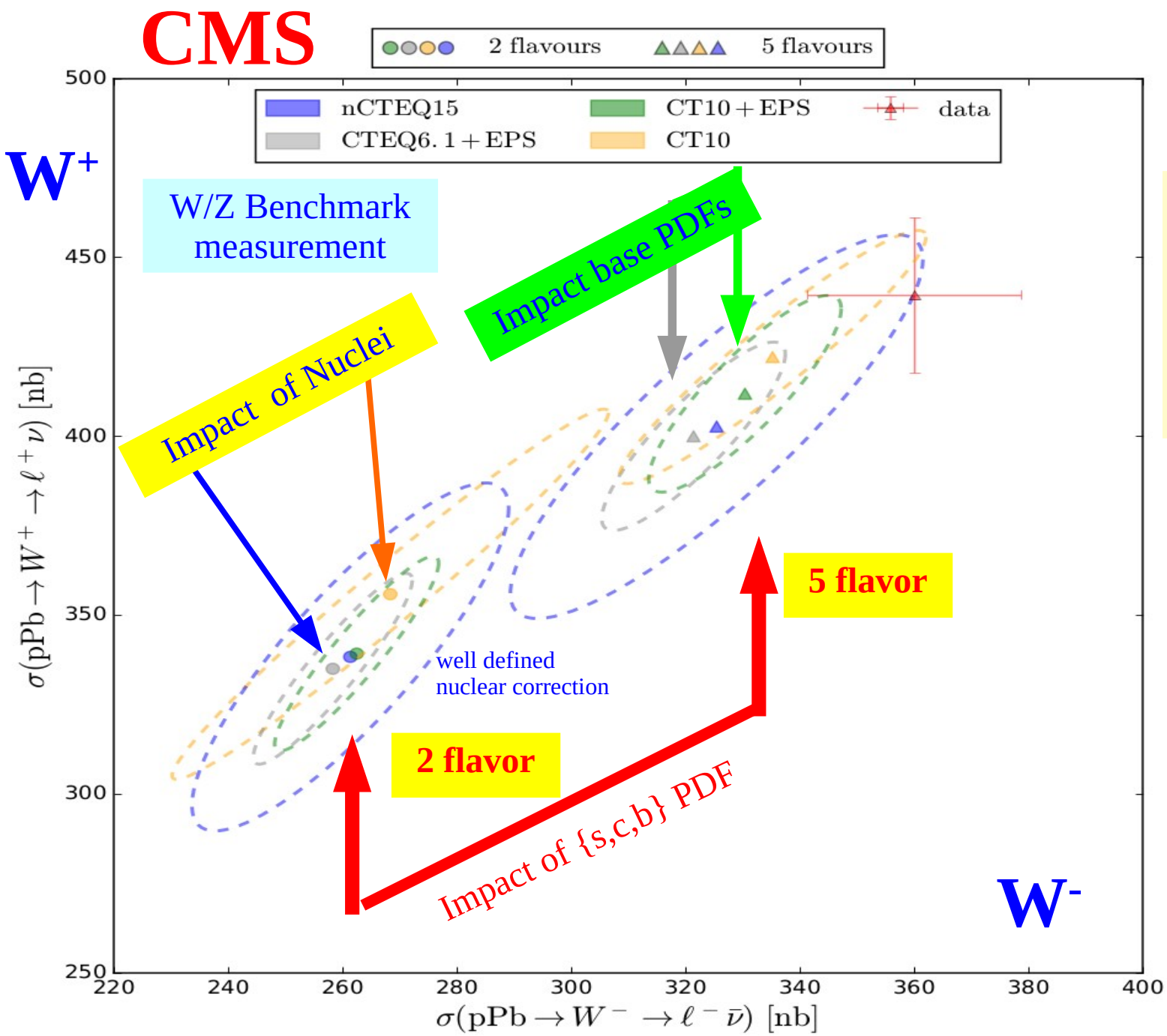
ATLAS: Eur. Phys. J. C 77 (2017) 367





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

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



Entangled:

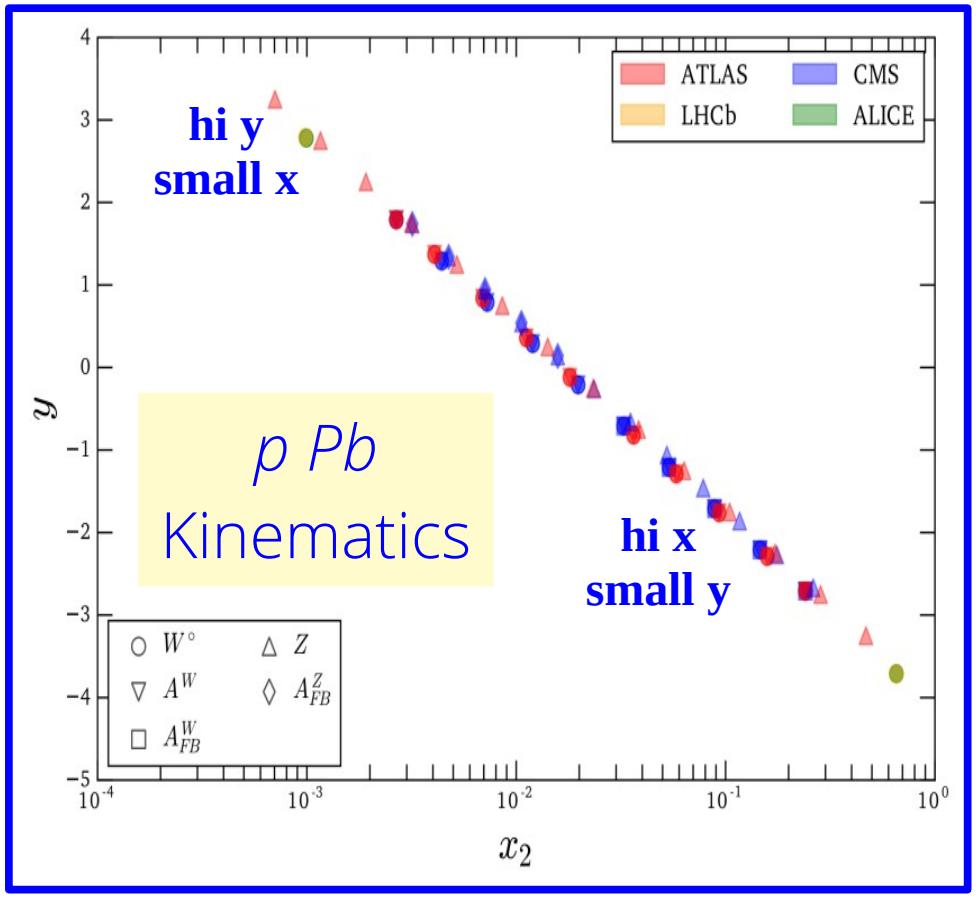
- Nucl. Corrections
- Base PDF
- PDF Flavors

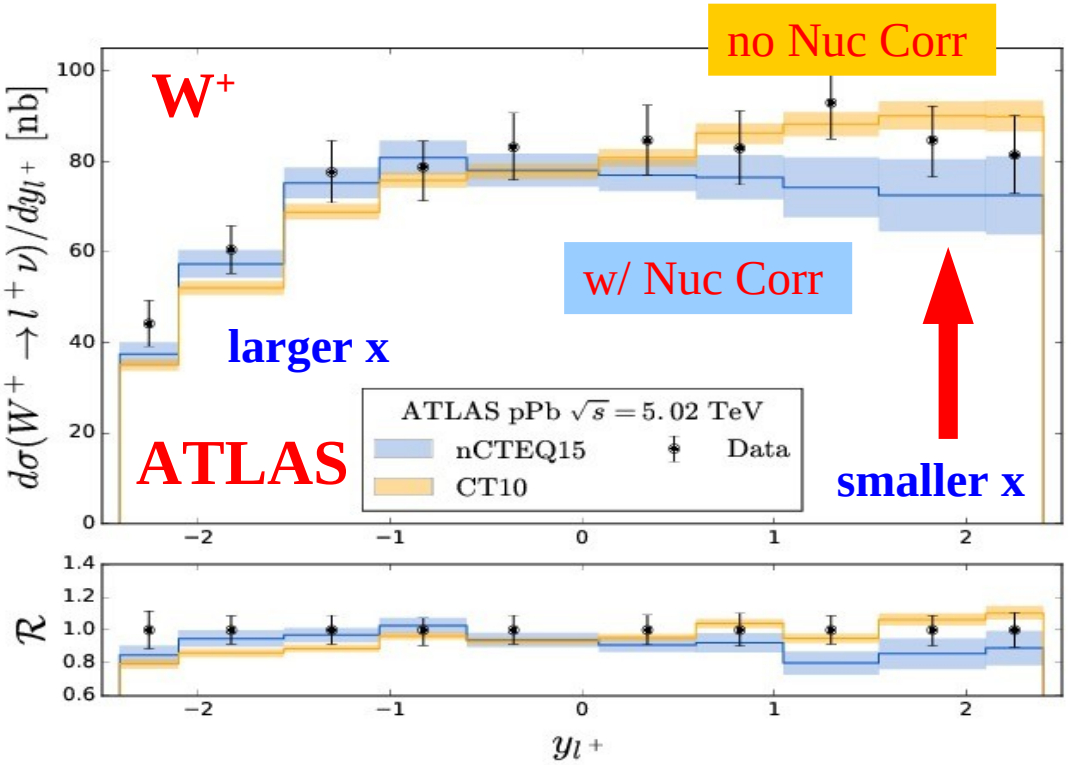
This is an area where LHeC is particularly suited to help

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

Could p Pb → W/Z Help?

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





lead kinematics

larger x ⟷ **smaller x**

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. C**77** (2017) no.7, 488.

...but how can we include these new processes into the fit directly???

nCTEQ++

what is nCTEQ++?

- a complete re-write of the nCTEQ FORTRAN fitting code in C++
- changed the code to allow for modules when building a PDF

  Evolution

  Interpolation

  Parameterization

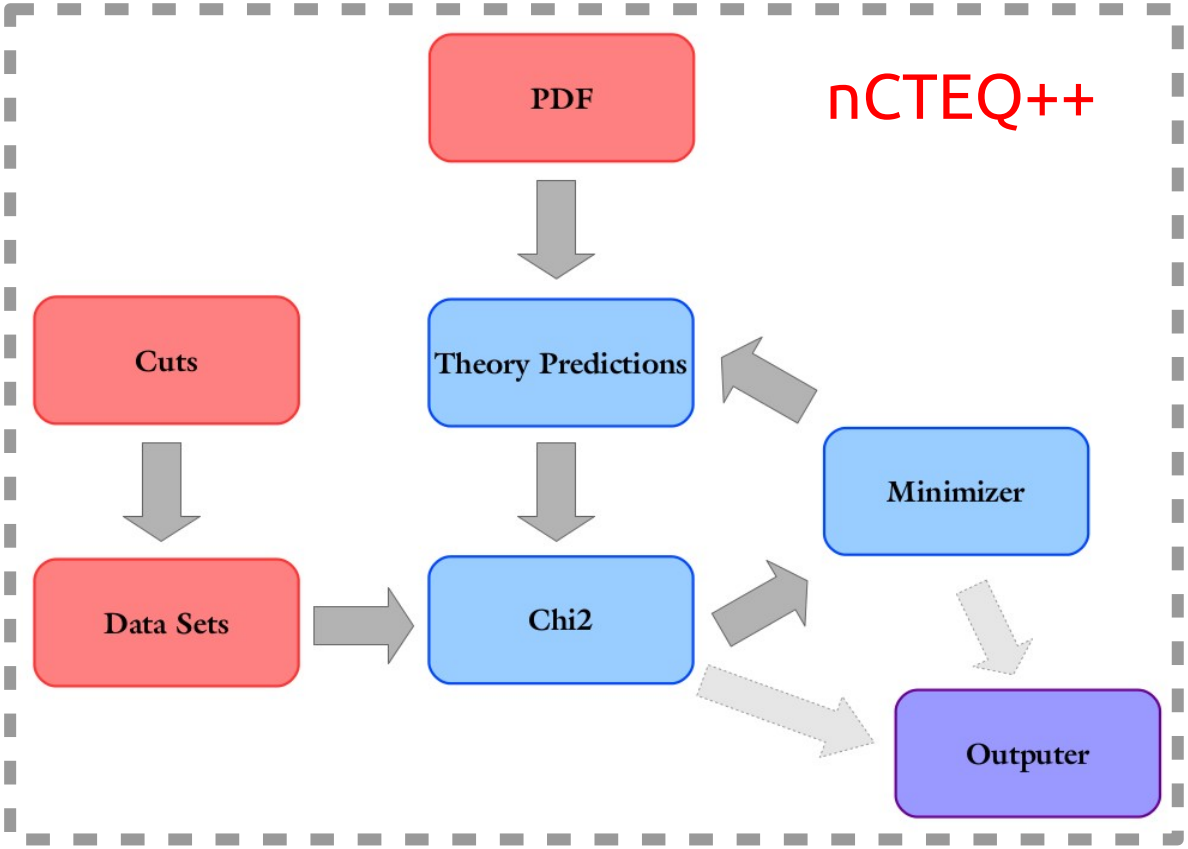
- **Use external programs**

  → Minuit

  → HOPPET

  → MCFM

  → APPLgrid



Special thanks to:

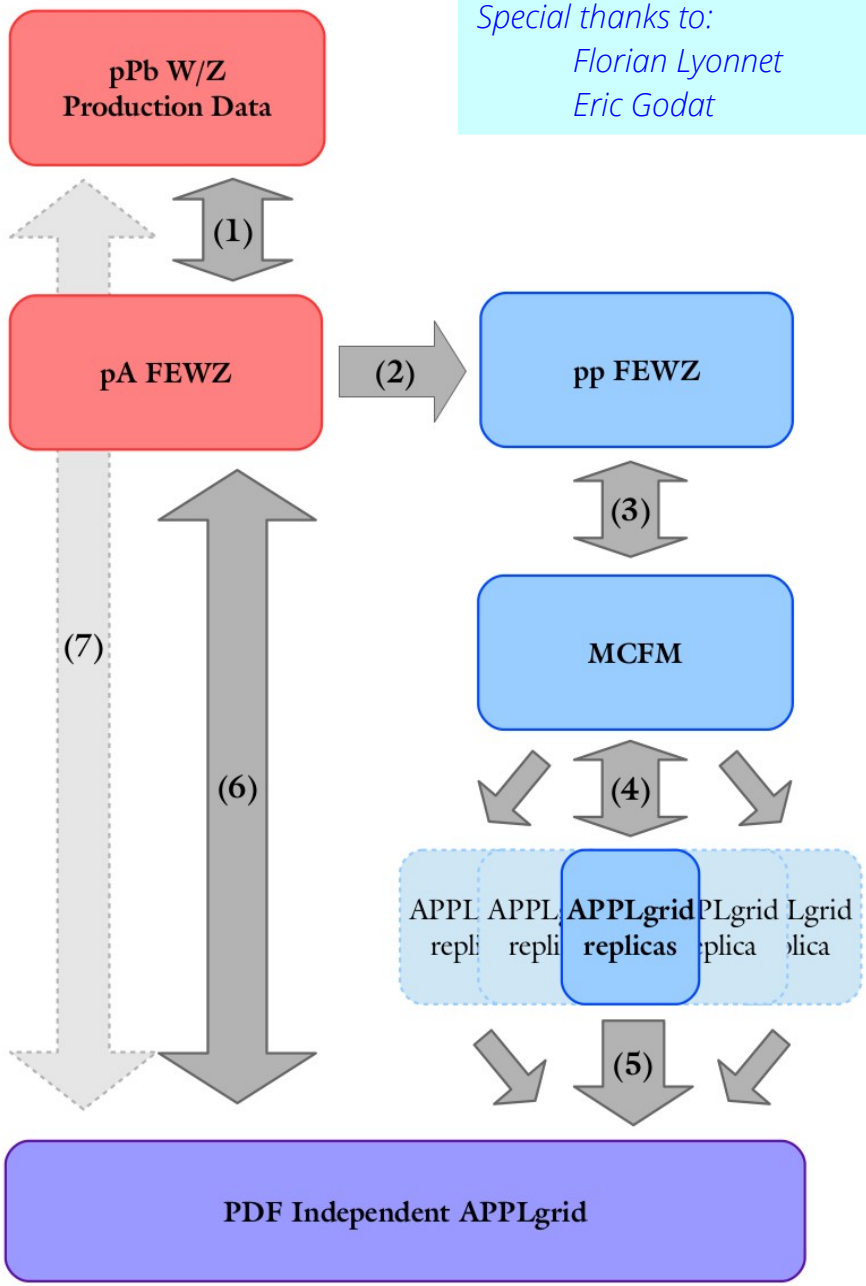
Florian Lyonnet

Tomas Jezo

Aleksander Kusina

Use MCFM + APPLgrid for pPb

Special thanks to:
Florian Lyonnet
Eric Godat



(1) Data matched to pA-FEWZ in reweighting

(2) Run FEWZ in symmetric pp - mode

(3) Compare pp FEWZ to pp MCFM

(4) Generate APPLgrid grids

- Using mcfm-bridge
- Different Monte Carlo seeds

(5) Combine replica grids into a single PDF-independent grid

- Using applgrid-combine

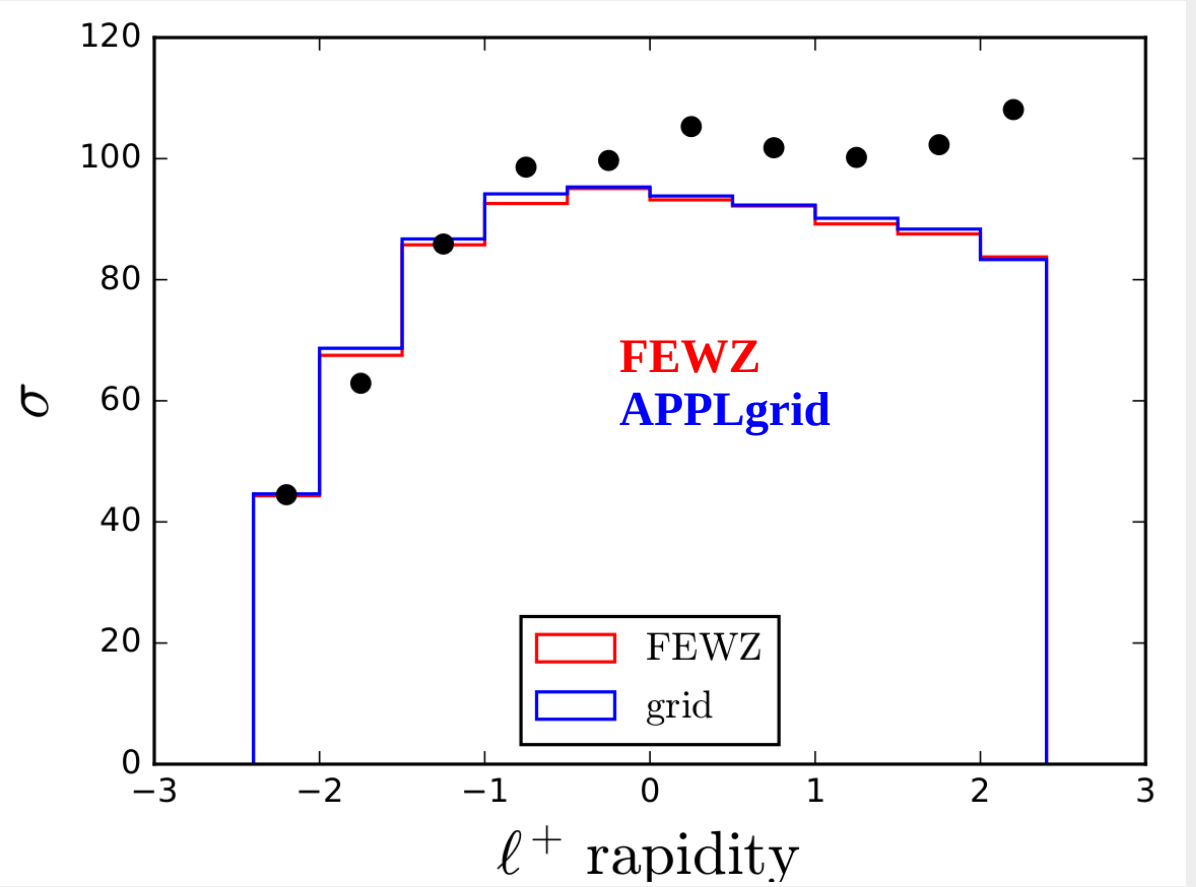
(6) Convolute PDF independent grid with asymmetric PDFs to compare to pAFEWZ

(7) Add data and grid in nCTEQ++ to fit W/Z LHC data

results match!

Grids generated for pp can be used for pPb !!!

Convoluted grids can be compared to data and used in nCTEQ++ as theory predictions

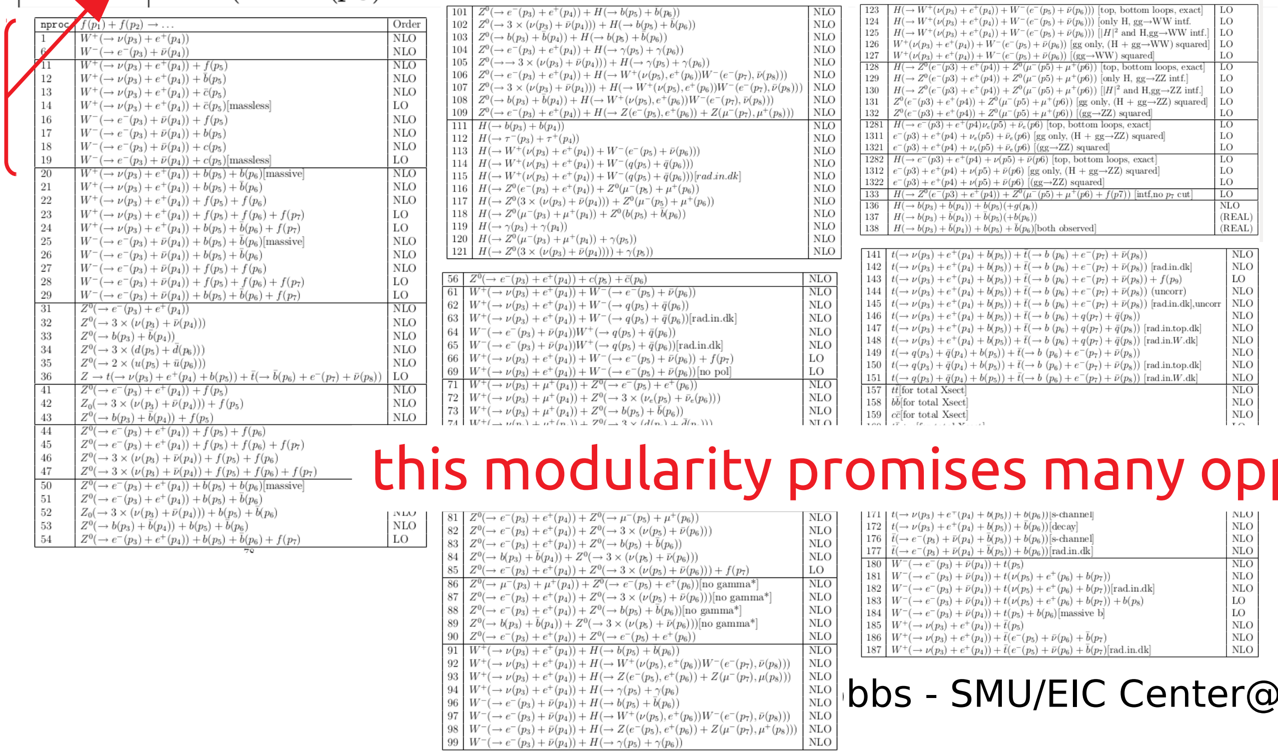


MCFM Processes Library (v6.8)

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. C**66** (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

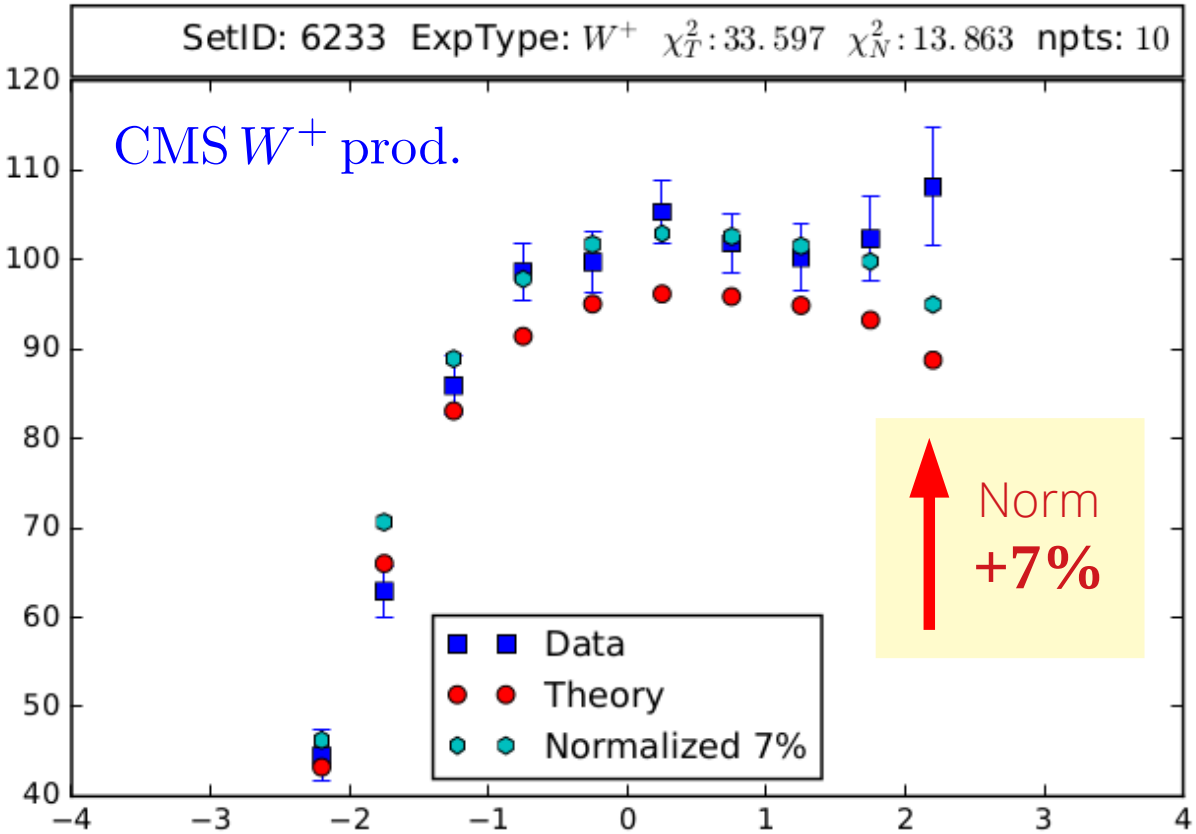


this modularity promises many opportunities for expansion!

we are now positioned to include LHC data directly into nPDF fits

nCTEQ+LHC

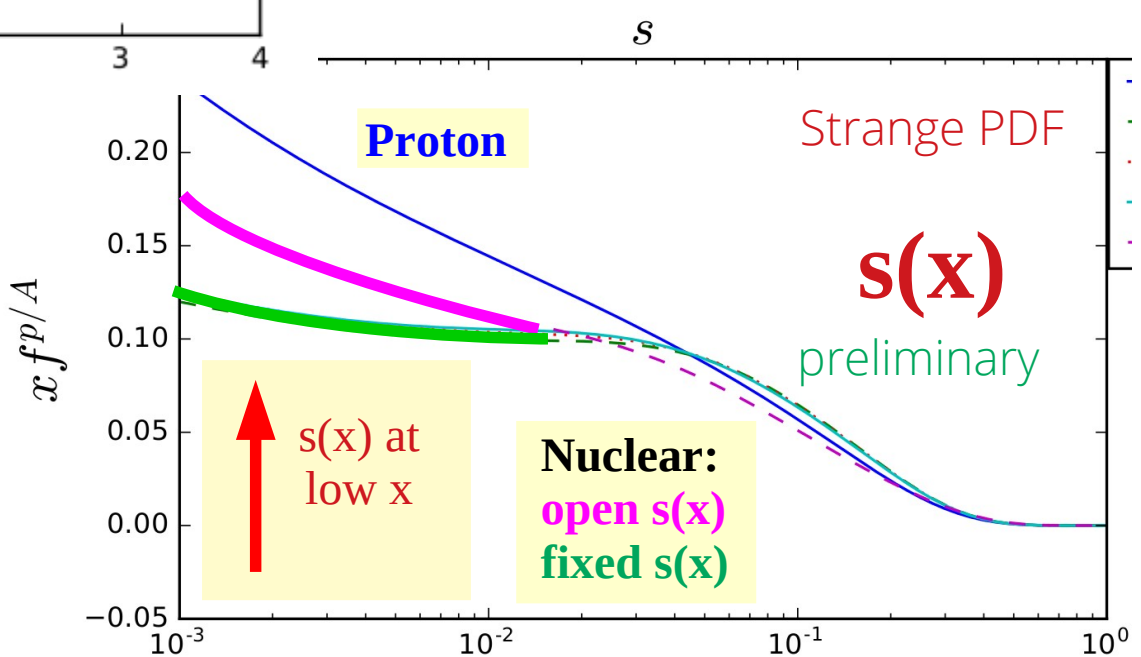
Fit to LHC W/Z Data w/ Normalization



Fit + Normalization

- Improved χ^2/d.o.f.
- Seems to prefer larger strange PDF

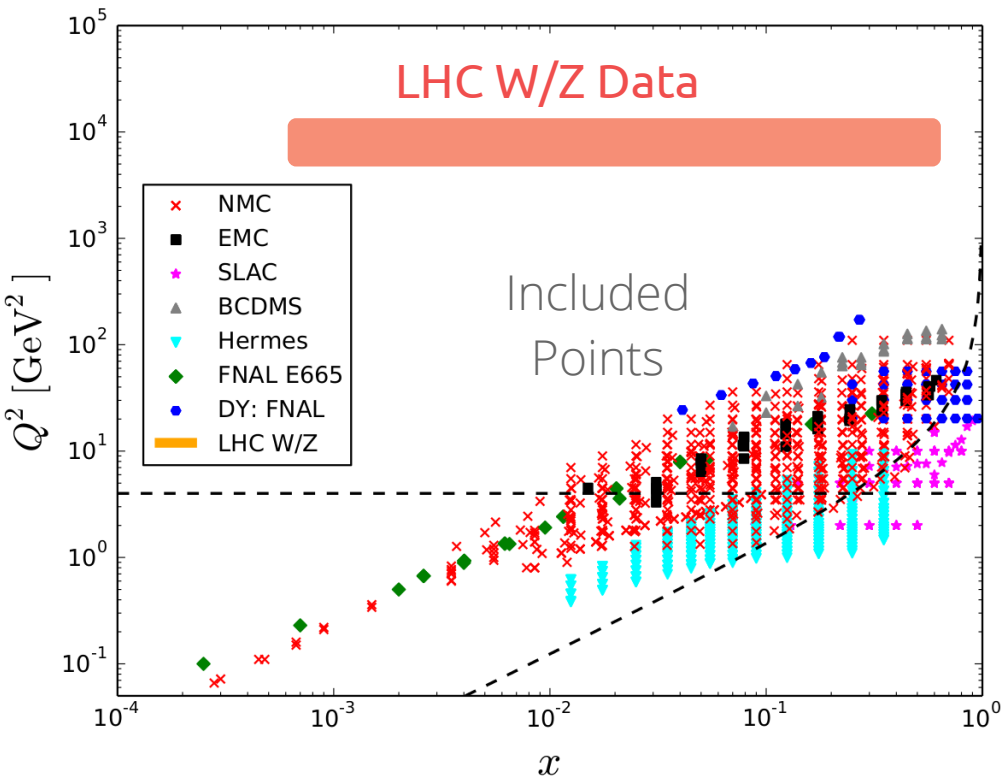
The preliminary result is
if we fit strange,
the data prefers a larger s(x)



pPb Data for nCTEQ+LHC

No LHC data in any previous nCTEQ fit

- New gridded theory predictions make this possible



ATLAS: $\sqrt{s} = 5.02\,\mathrm{TeV}$

- $d\sigma(W^- \to \ell^- \nu)/dy$

  ID: 6211 Npts: 10

- $d\sigma(Z \to \ell^+ \ell^-)/dy$

  ID: 6215 Npts: 14

CMS:

- $d\sigma(W^- \to \ell^- \nu)/dy$

  ID: 6231 Npts: 10

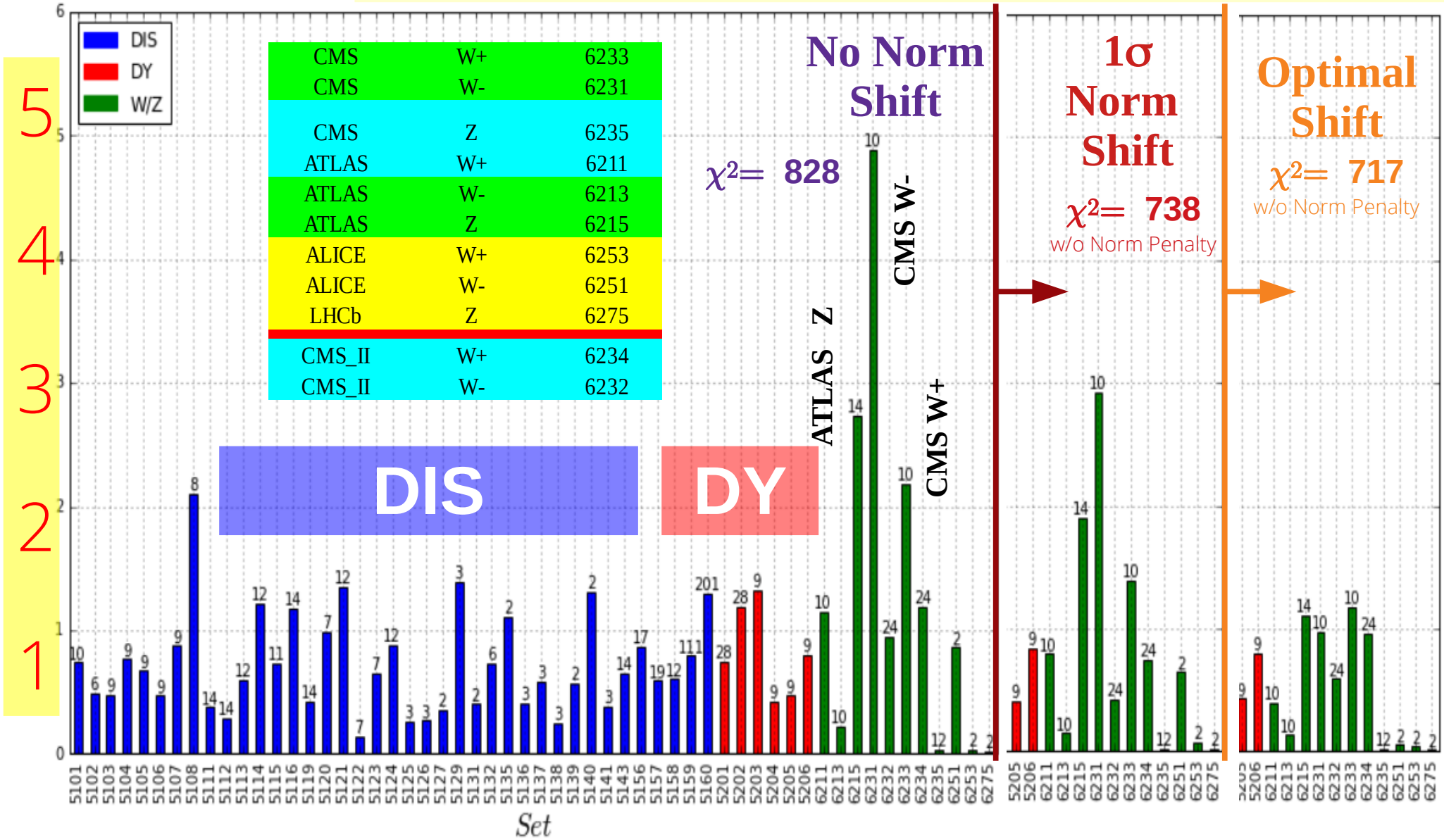
- $d\sigma(W^+ \to \ell^+ \nu)/dy$

  ID: 6233 Npts: 10

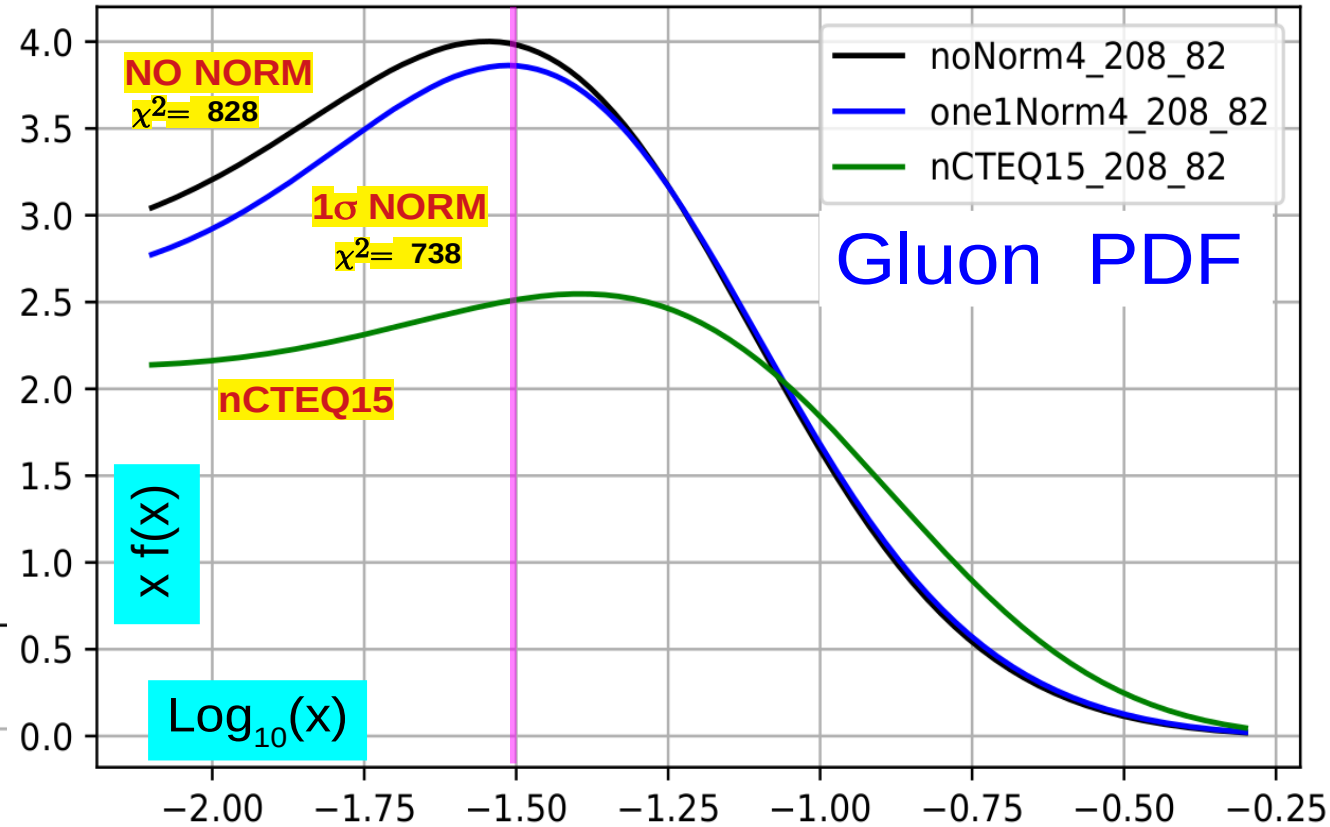
Fit to LHC W/Z Data w/ Normalization

nCTEQ++ with LHC W/Z Data

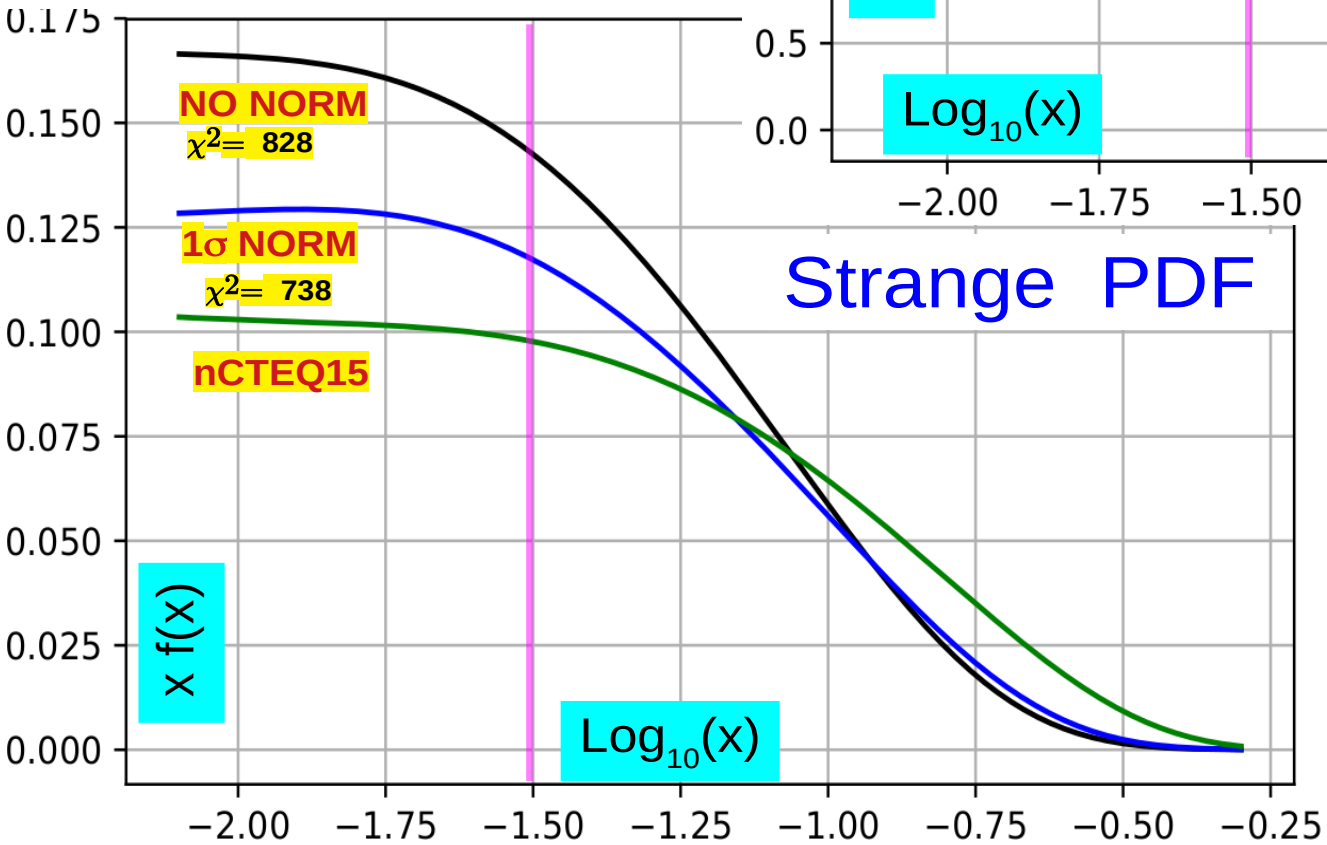
- Fit+Normalization dramatically reduce χ^2



unlike the gluon, strangeness is very sensitivity to our treatment of the LHC W/Z data



preliminary



this sensitivity is most pronounced about x ~ 0.01, determined from LO kinematics of pPb data

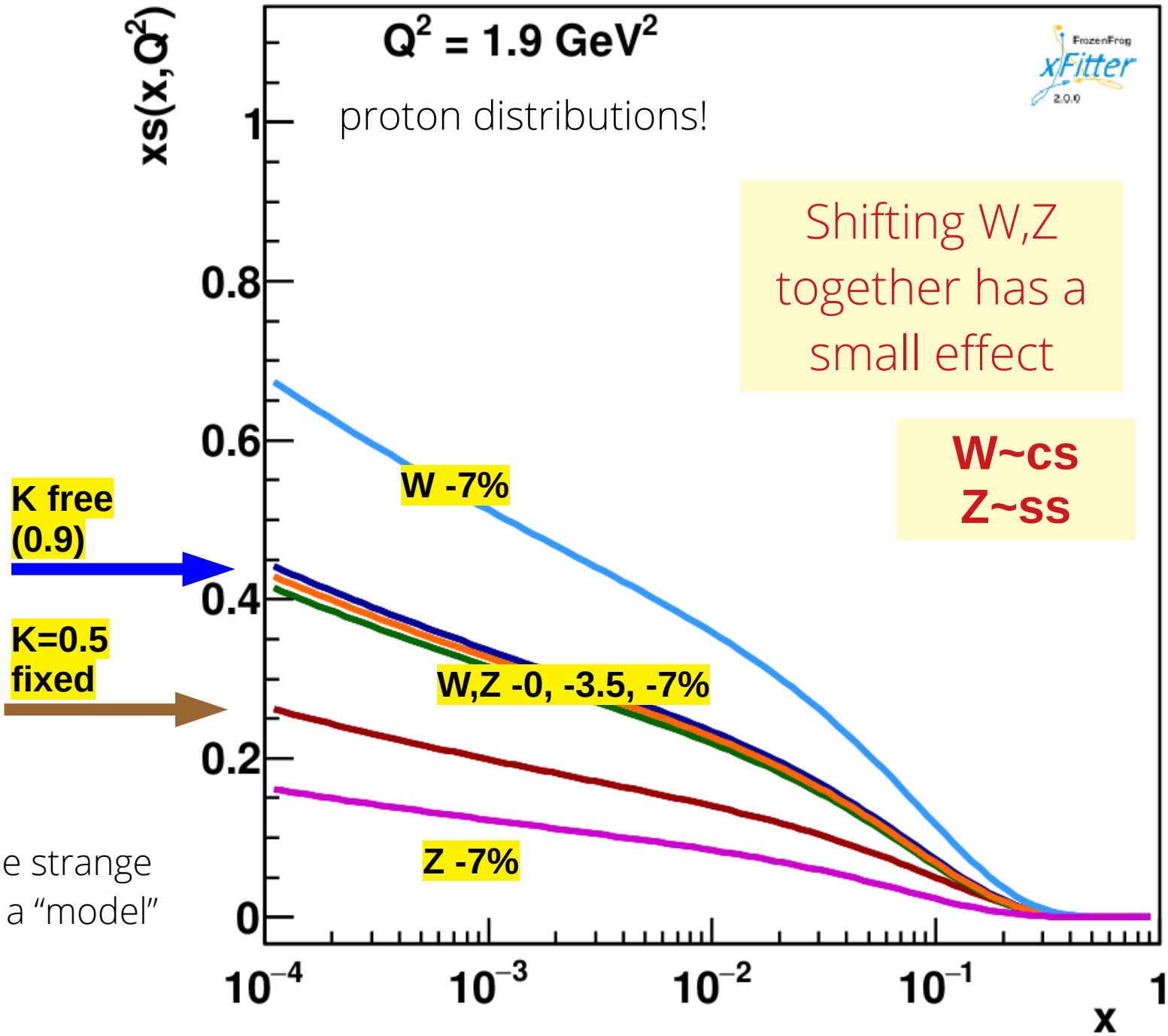
full fit is currently in production

pp @ LHC
xFitter Tutorial
w/ 2010 ATLAS
W/Z data

1-parameter fit
(kappa)

$$\kappa = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

→ download
and try!



we can study the
dependence of the strange
distribution using a "model"
nucleon fit

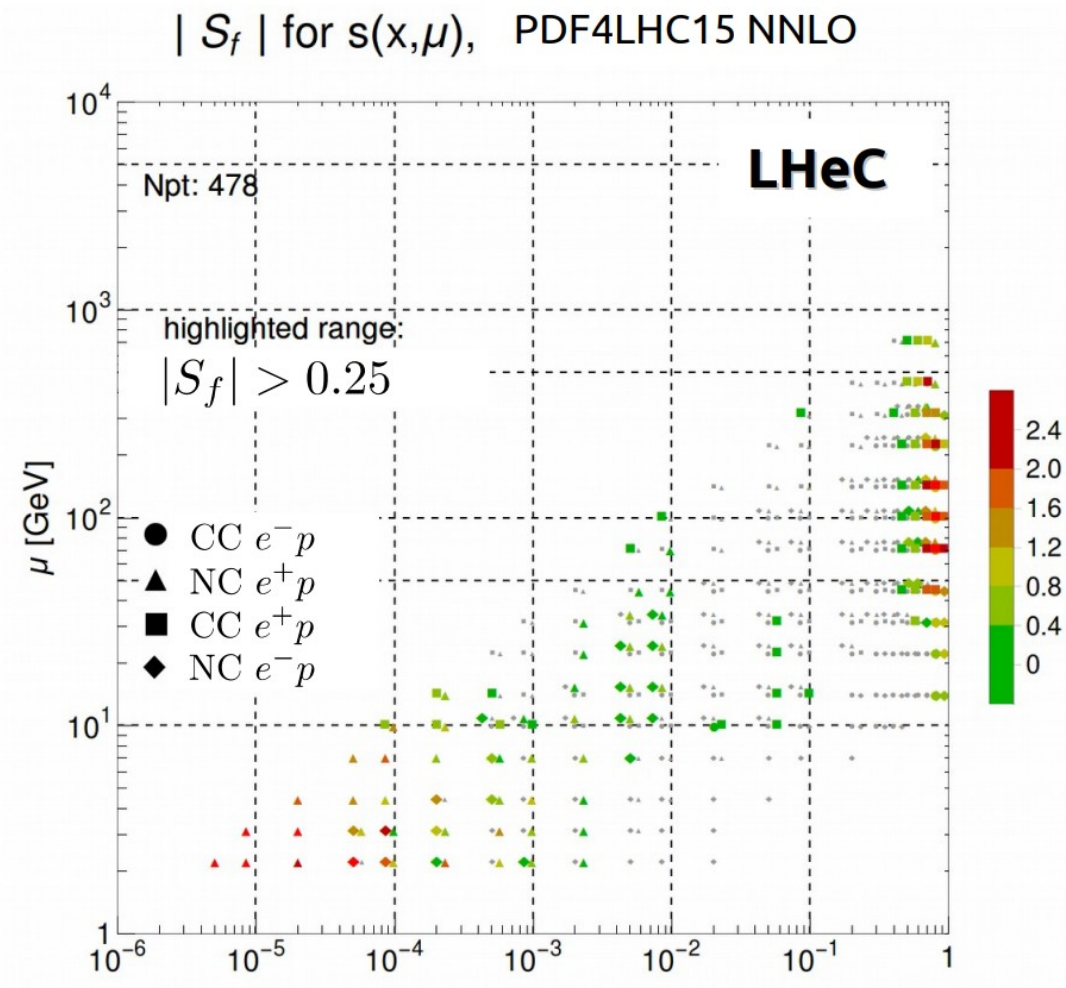
future facilities will be well-poised to constrain nucleon (nuclear) strangeness

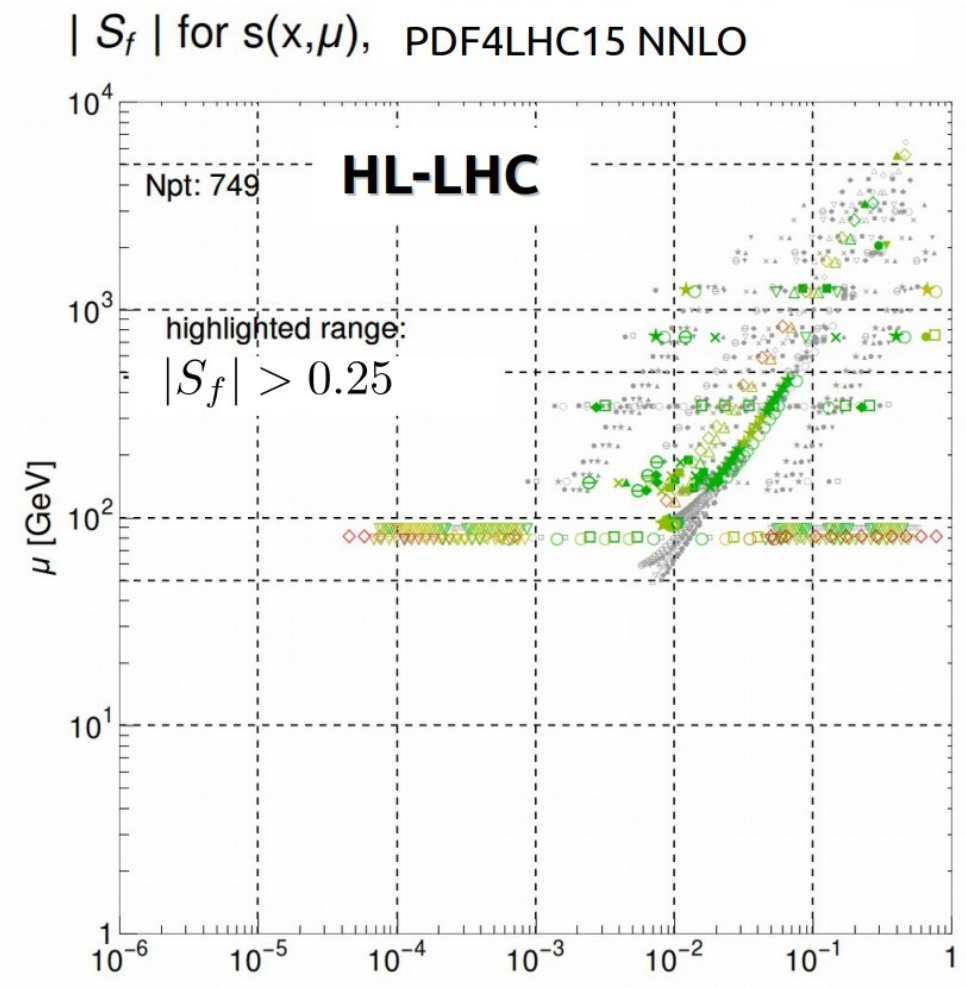
Wang, TJH, Doyle, Gao, Hou, Nadolsky, Olness, PRD**98**, 094030 (2018).

http://metapdf.hepforge.org/PDFSense/

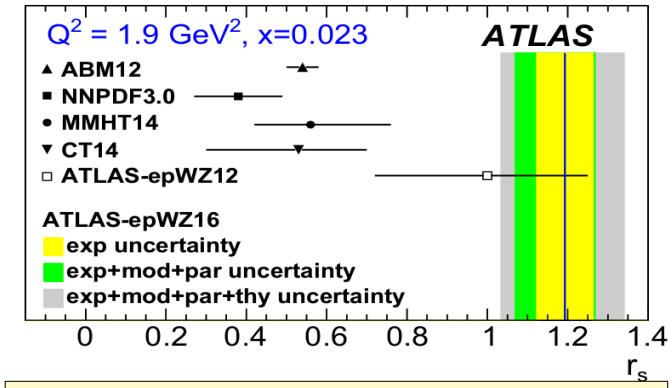
can make projections for PDF impact of LHeC, HL-LHC, EIC, AFTER@CERN, ...

→ for more, **later today** (PDF-lattice) AND Session **C09**: Sat., April 13th – 1:30pm

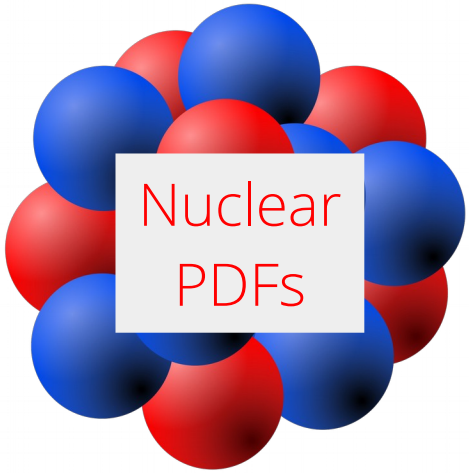




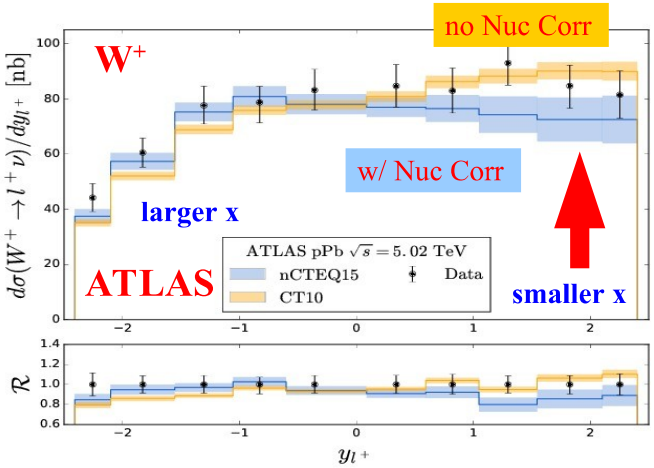
conclusions: we face **new data**, but with **new theoretical tools**



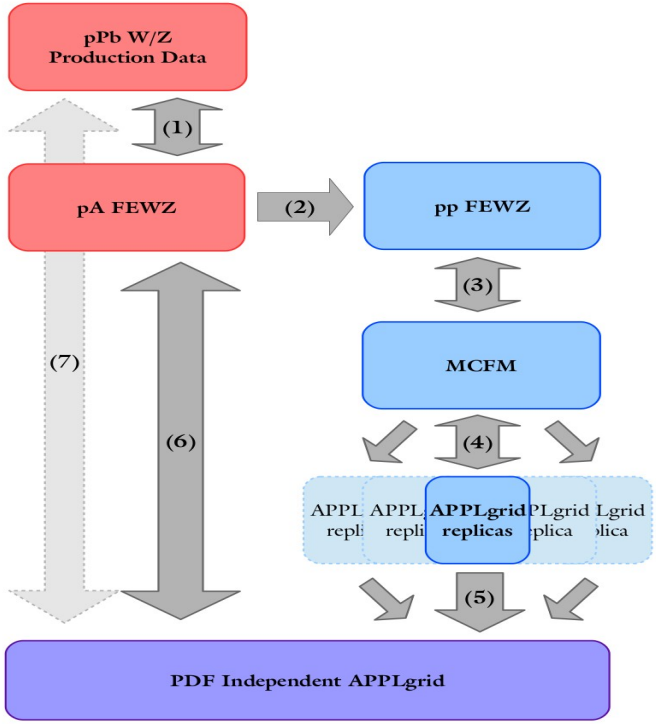
The Strange PDF Puzzle



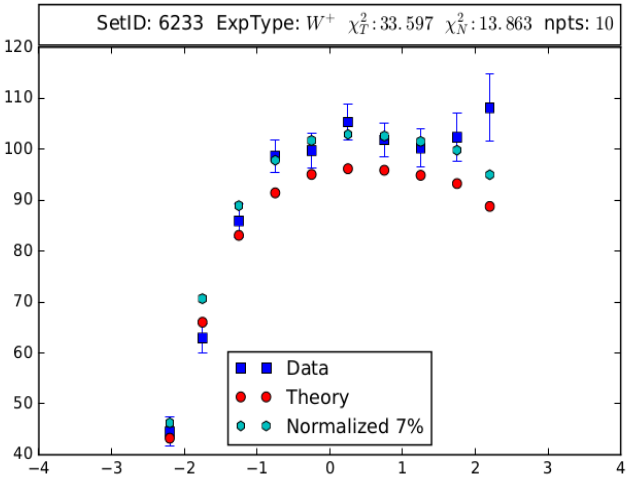
Nuclear Data Essential for PDFs



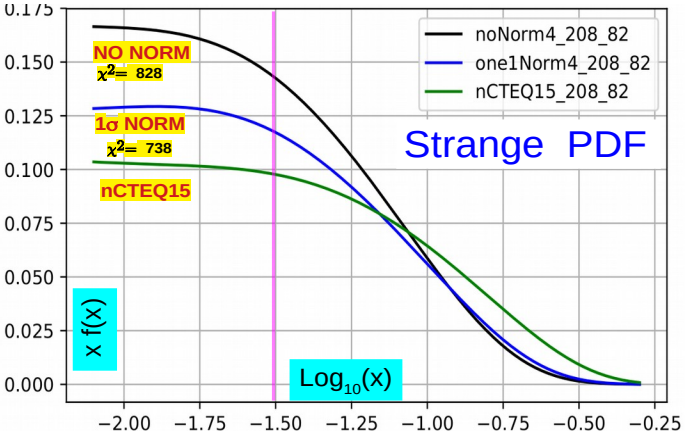
Tensions Evident



New Theory Tools!

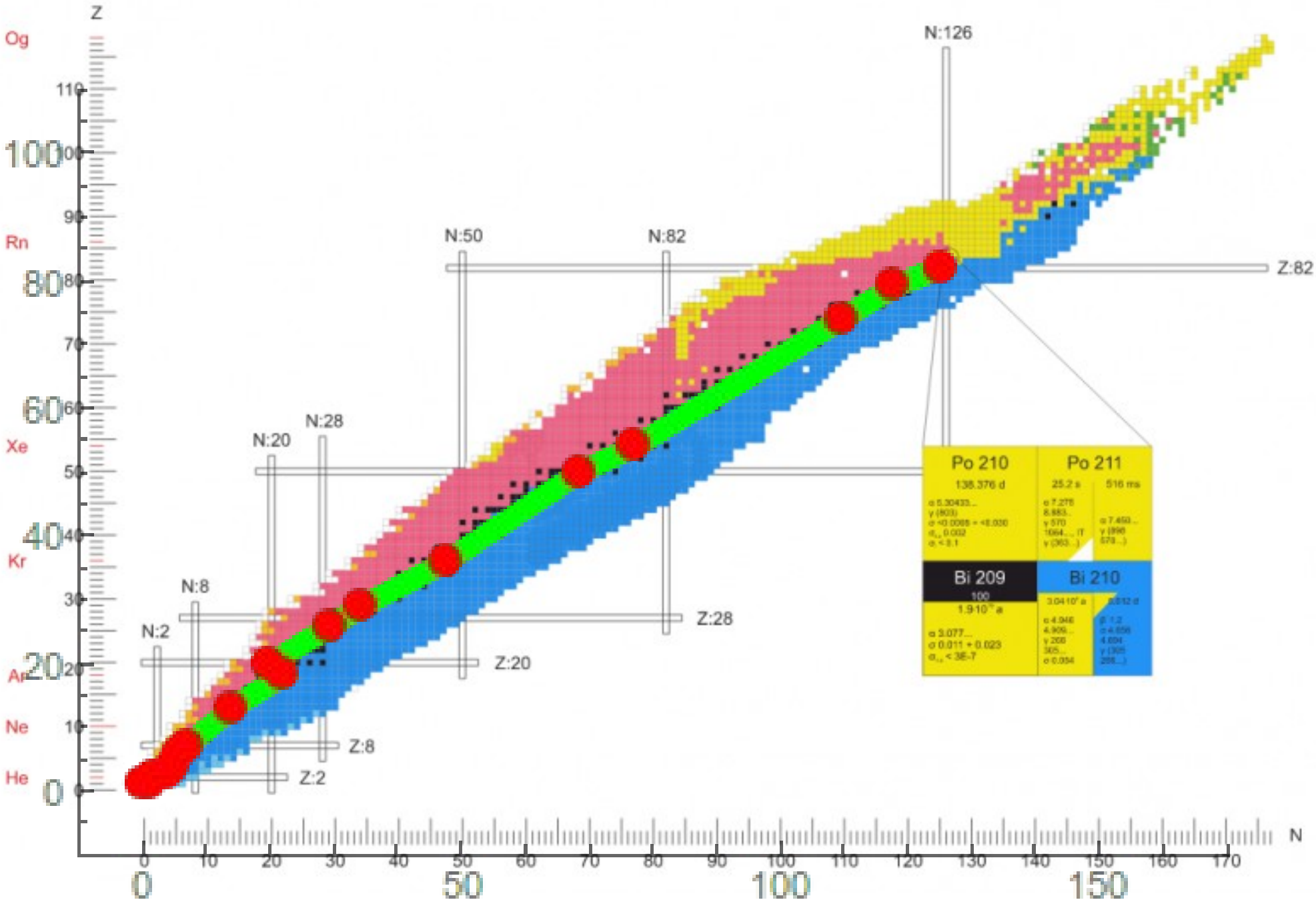


New Analyses in progress

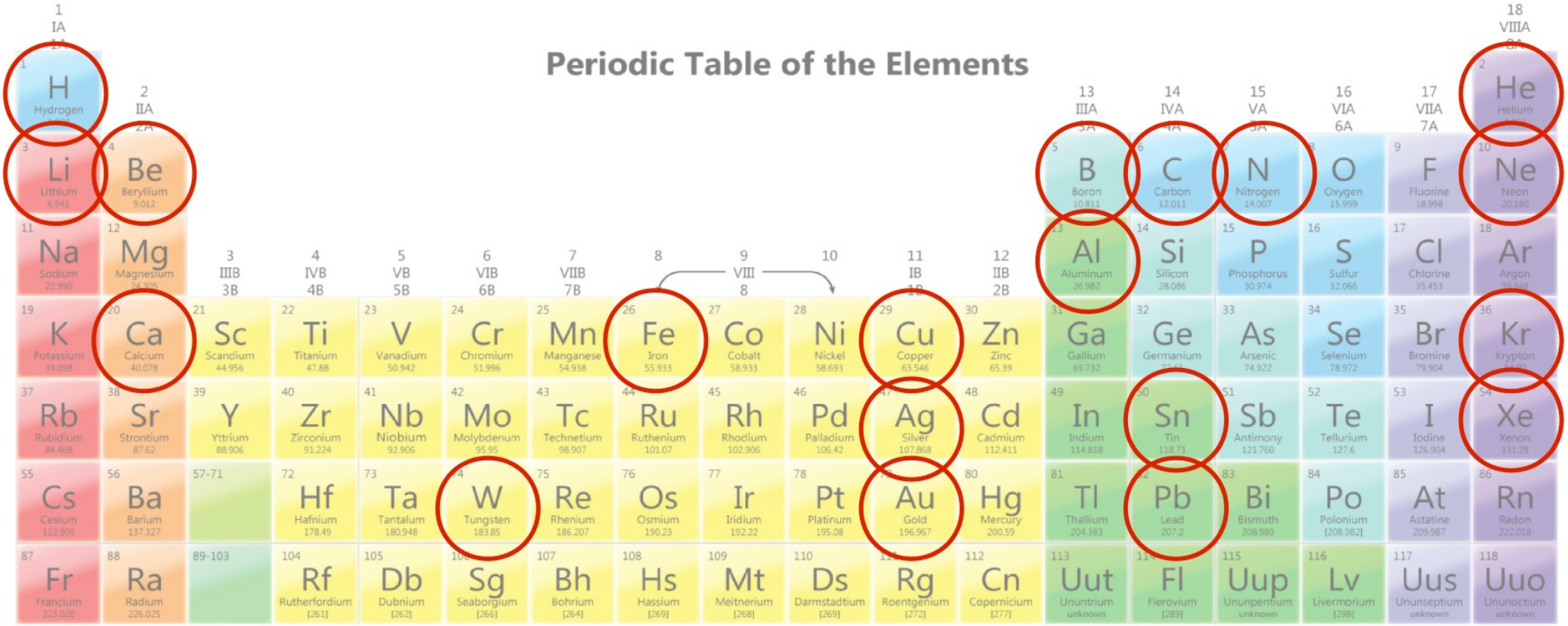


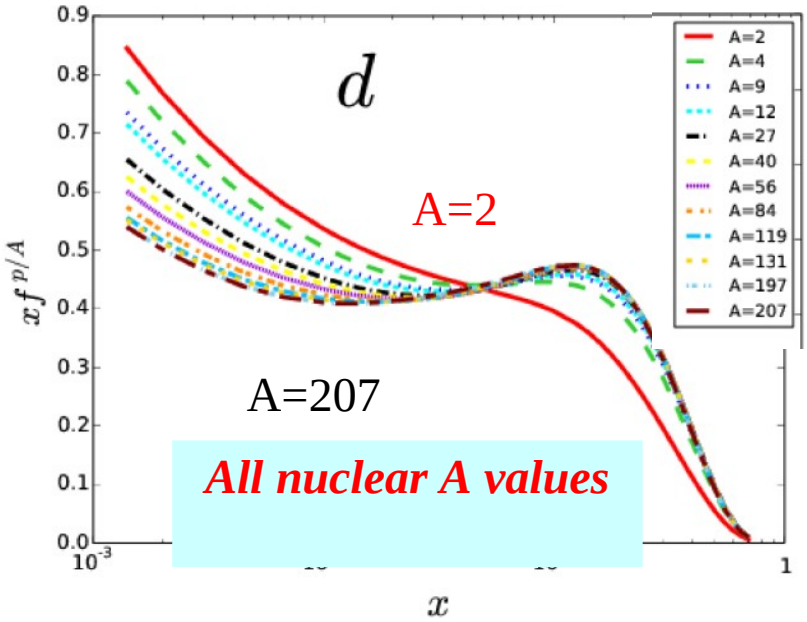
New Perspectives – e.g., on nucleon strangeness

BACKUP

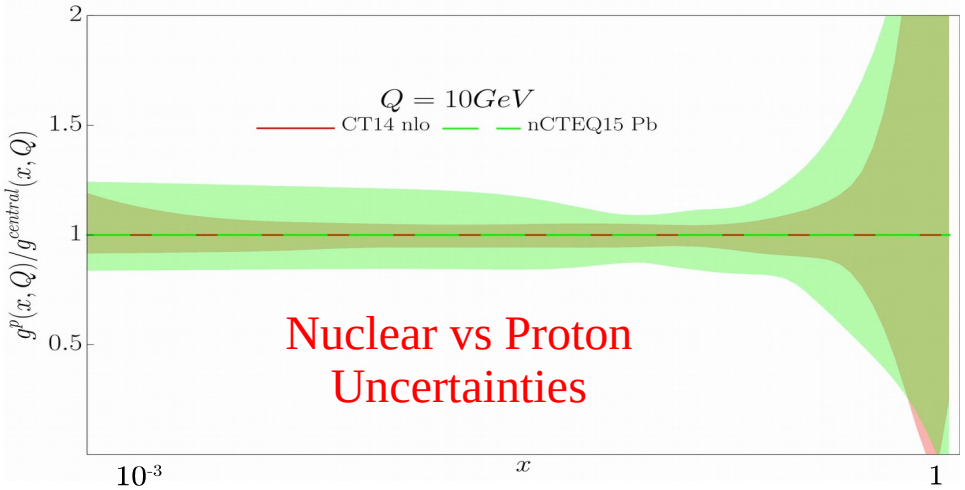

Z
Og
Rn
Xe
Kr
Ar
Ne
He
N
N:2
N:8
N:20
N:28
N:50
N:82
N:126
Z:2
Z:8
Z:20
Z:28
Z:82
Po 210
138.376 d
Po 211
25.2 s
516 ms
Bi 209
100
Bi 210

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





All nuclear A values



EIC can expand our knowledge of the nuclear A dimension

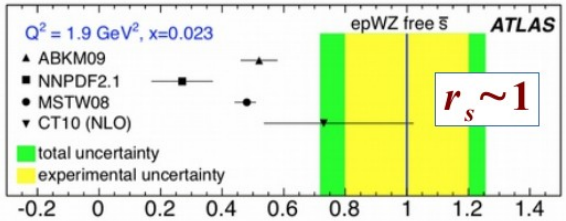
… on Monday we heard …

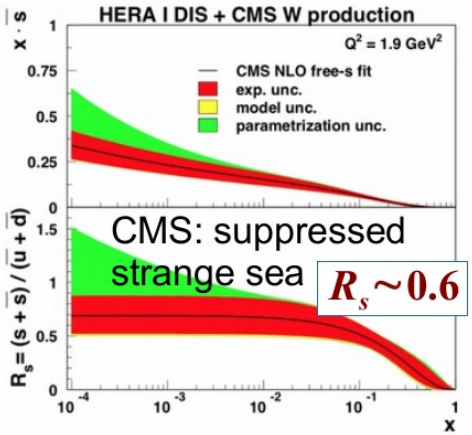
Recap: LHC data and the strange sea

- Global fits+NuTeV/CCFR, NOMAD, CHORUS: “suppressed” strange sea, r_s<1
- HERMES 2014: r_s is x-dependent (leading-order analysis)
- ATLAS 2012 fit of W and Drell-Yan +HERA: “unsuppressed” strange sea r_s=1
- CMS 2013 data on W asymmetry plus PDF fit: “suppressed” strange sea
- CMS 2013 data on c+W compatible with “suppressed” strange sea
- ATLAS 2014 data on c+W compatible with with “unsuppressed” ATLAS fit

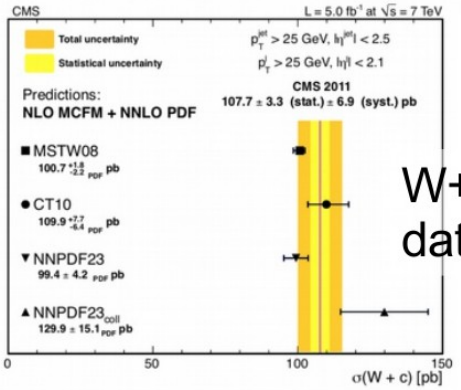
HERMES: Phys.Rev. D89 (2014) 097101 [arXiv:1312.7028]
ATLAS fit: Phys.Rev.Lett. 109 (2012) 012001 [arXiv:1203.4051]
CMS c+W: JHEP 1402 (2014) 013 [arXiv:1310.1138]
CMS W asym: Phys.Rev. D90 (2014) 032004 [arXiv:1312.6283]
ATLAS c+W: JHEP 1405 (2014) 068 [arXiv:1402.6263]

ATLAS: unsuppressed strange sea

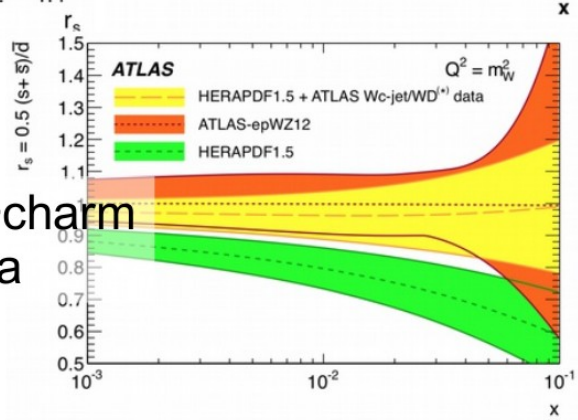




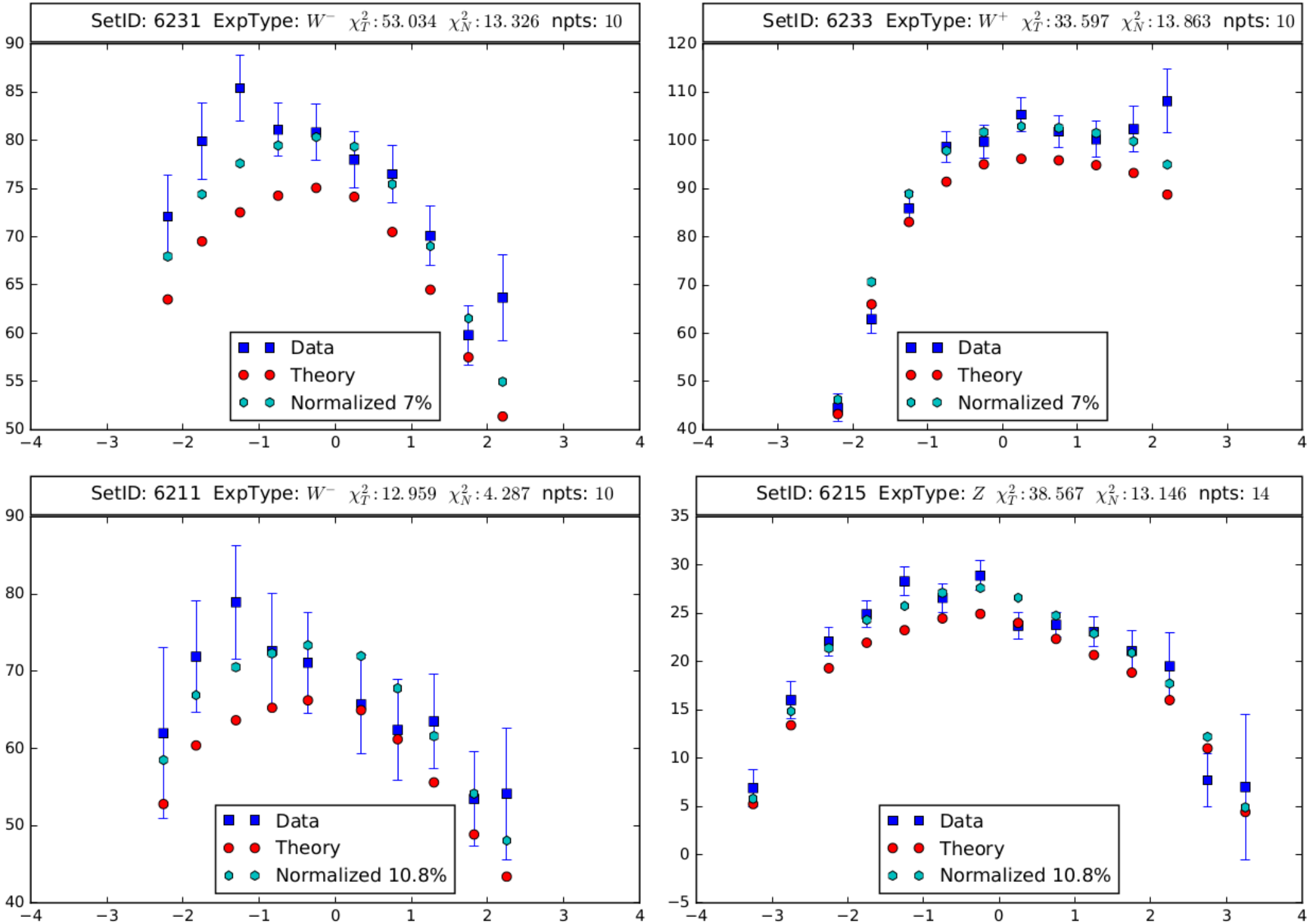
CMS: suppressed strange sea



W+charm data

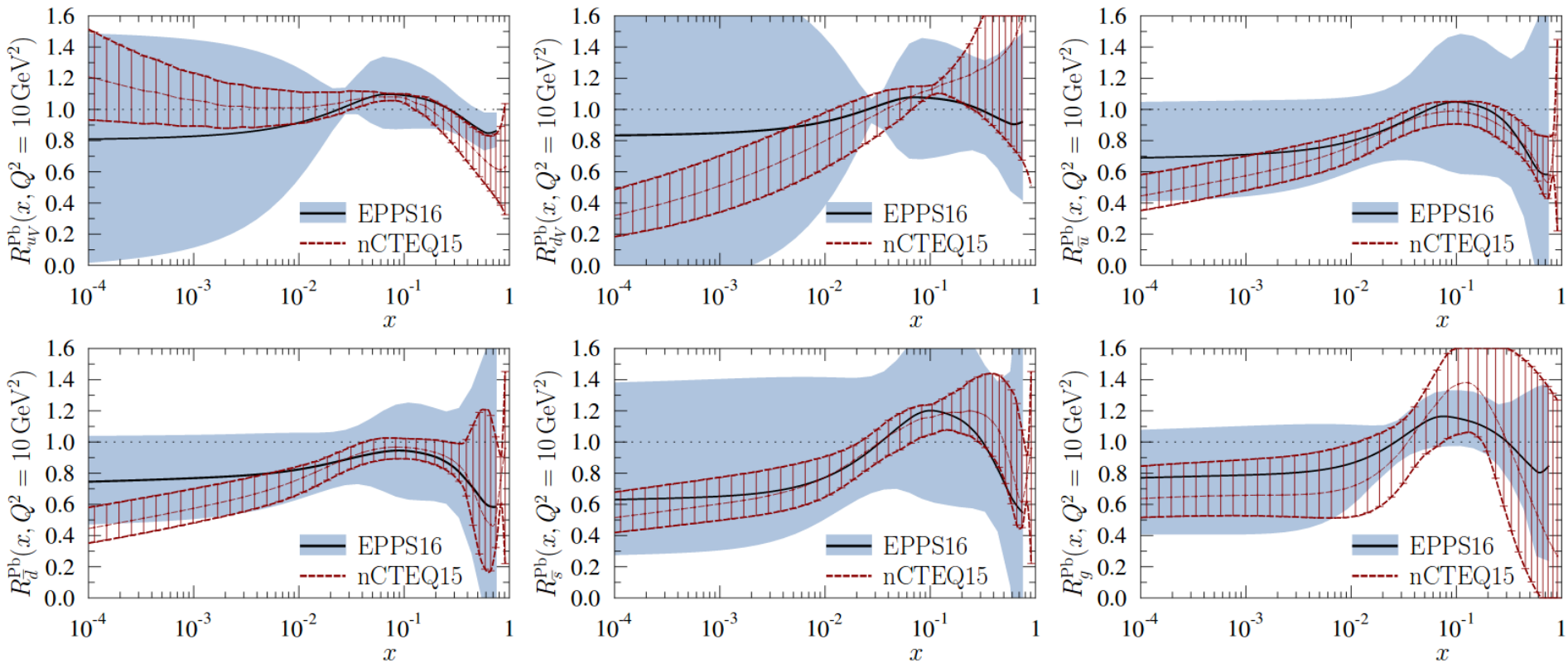


Do it yourself!!!
Try **xFitter**


SetID: 6231 ExpType: W^- χ^2_T: 53.034 χ^2_N: 13.326 npts: 10
Data
Theory
Normalized 7%
SetID: 6233 ExpType: W^+ χ^2_T: 33.597 χ^2_N: 13.863 npts: 10
Data
Theory
Normalized 7%
SetID: 6211 ExpType: W^- χ^2_T: 12.959 χ^2_N: 4.287 npts: 10
Data
Theory
Normalized 10.8%
SetID: 6215 ExpType: Z χ^2_T: 38.567 χ^2_N: 13.146 npts: 14
Data
Theory
Normalized 10.8%

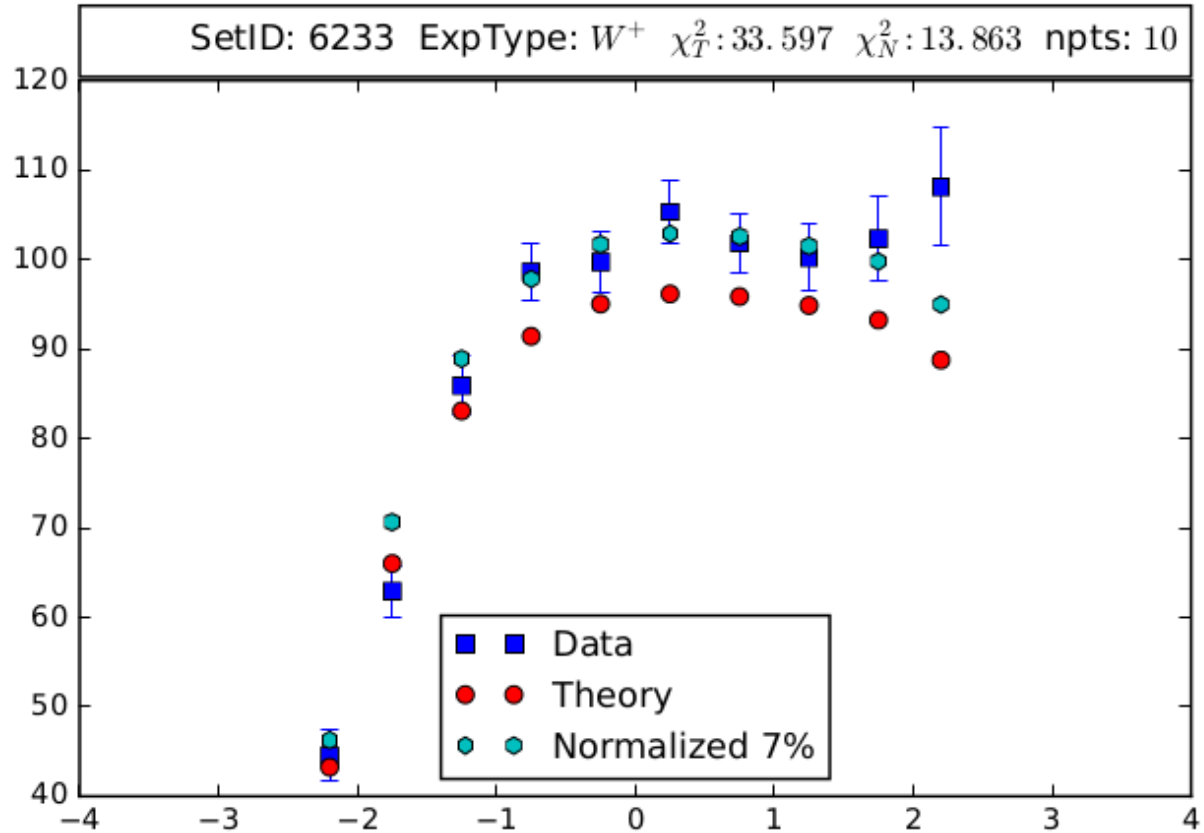
EPPS16

- EPPS fits nuclear ratios, not nuclear PDFs
  - EPPS16 includes LHC data
    - CMS Di-jets
    - W/Z Production from CMS, Z Production from ATLAS
  - Also includes large number of CHORUS Pb Fixed Target DIS points (824)
- More than double the data points in nCTEQ15 (1789)



Source: arXiv 1612.05741

Fit to LHC W/Z Data w/ Normalization



2σ normalization applied to LHC sets

- Improved χ^2/d.o.f.
- Additional normalization could improve χ^2 more

	Data ID:	6211	6231	6233	6215
nCTEQ15-np	χ^2per d.o.f:	1.55	6.91	7.73	3.16
Reweighting	χ^2per d.o.f:	0.87	3.27	2.95	1.76
nCTEQ+LHC	χ^2per d.o.f:	1.30	5.30	3.36	2.75
nCTEQ+LHC $(1 \times \sigma_N)$	χ^2per d.o.f:	0.92(+0.10)	2.77(+0.10)	1.66(+0.10)	1.96(+0.07)
nCTEQ+LHC $(4\sigma_N^{ATLAS},\ 2\sigma_N^{CMS})$	χ^2per d.o.f:	0.42(+1.60)	1.33(+0.40)	1.39(+0.40)	0.94(+1.14)

Normalized

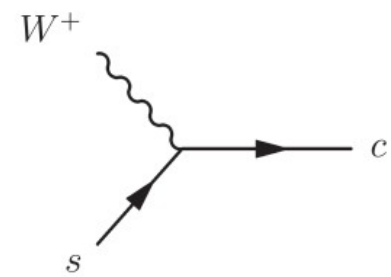
Penalty

… earlier this week we heard …

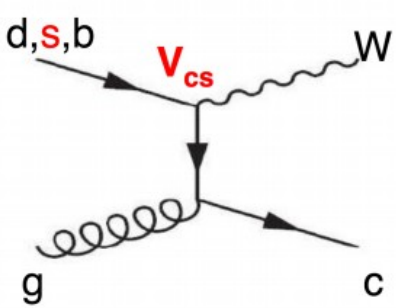
LHC Physics and EIC

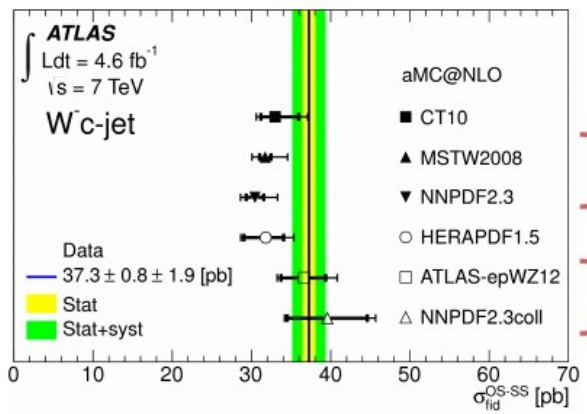
Shima Shimizu (KEK 協力研究員)

Charm-tagged Charged Current DIS



- If a charm is tagged in CC DIS, the cross section has a sensitivity to the intrinsic strange.
- Strange quark distribution is not well determined.
  - ATLAS data prefers more strangeness than fixed target data?





JHEP05(2014)068

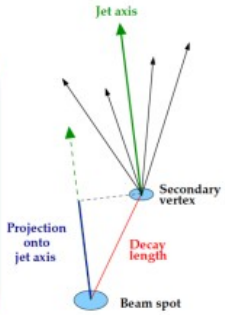
Asymmetric s and sbar, derived from CCFR and NuTeV (neutrino−nucleon DIS)

LHC data included

- Charm-tagged CC DIS at EIC would be interesting.
  - Free from the nuclear/target correction.
  - Requires charm tagging in the Central-Forward region.

Y. Furletova

At EIC
($\sqrt{s}$~70 GeV, Q^2>100GeV^2):
$\sigma(e^+p \to \nu_e + c + X) \sim 0.1$ pb
⇒ with 10fb^{-1} /year
⇒ ~ 1000 events/year

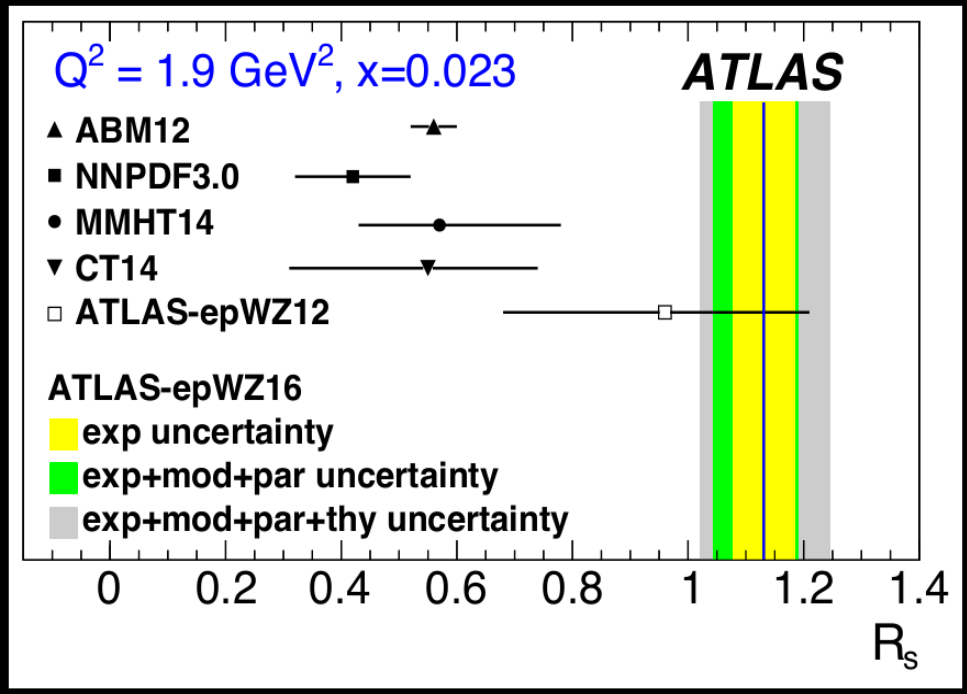


… at DIS2017 we heard …

Electroweak and QCD Measurements at the Large Hadron Collider

Strangeness in the Proton

arXiv:1612.03016



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

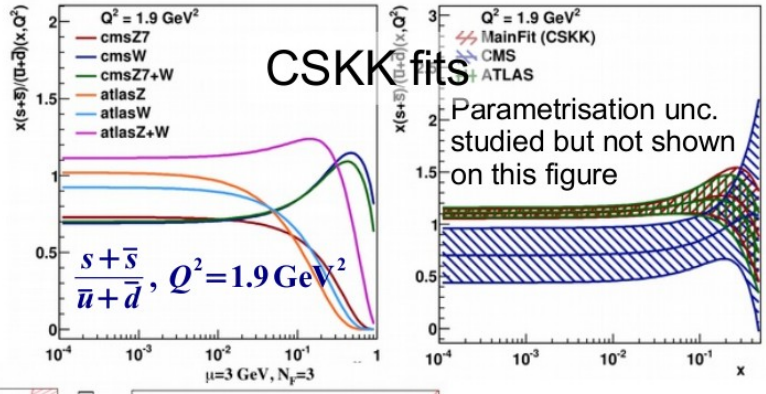
Do it yourself!!!
Try **xFitter**

João Guimarães da Costa
IHEP, Chinese Academy of Sciences

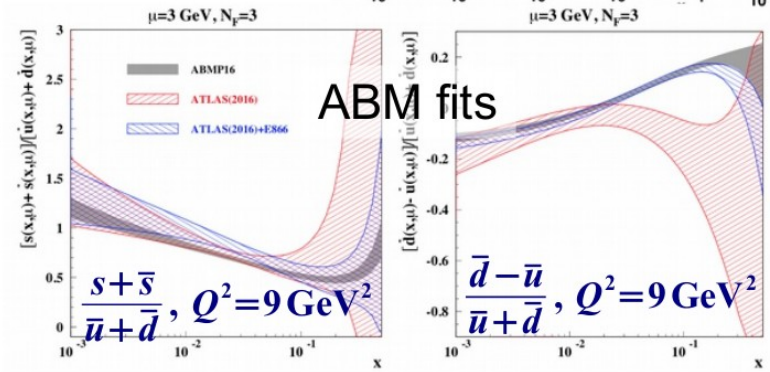
Birmingham, 3 April 2017

Fits using ATLAS and CMS W+DY data

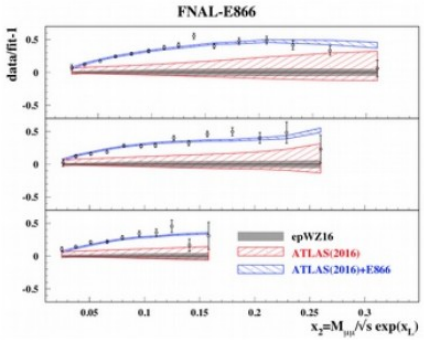
- Cooper-Sarkar & Wichmann (CSKK fit): compatibility of ATLAS and CMS data
- ABM group: revisit PDF parametrisation and compatibility with other data
- Not shown: NNPDF3.1 also investigates strangeness



CSKK (using "ATLAS" parametrisation): ATLAS and CMS data are compatible. Fit results in unsuppressed strange sea. Parametrisation and d(bar)-u(bar) are also studied.



Comparison to E866

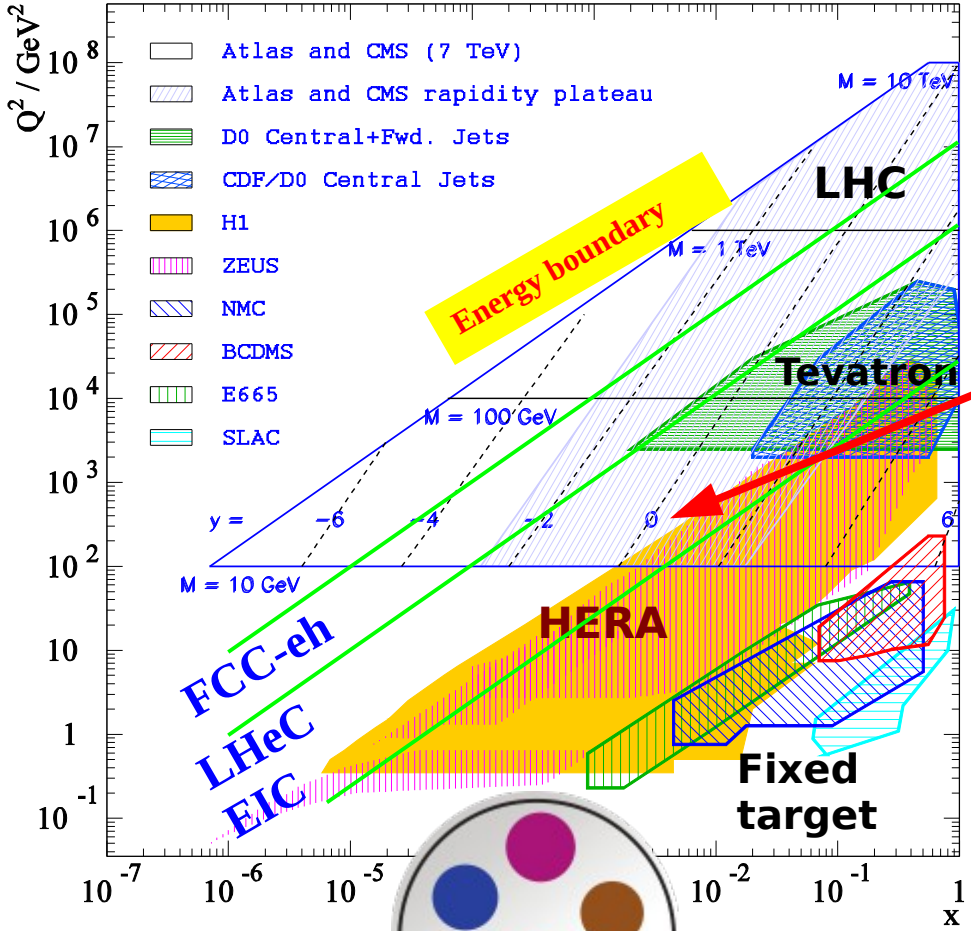


ABM: "ATLAS" central parametrisation is not flexible enough to accommodate E866 [NuSea] data.
have to use different parametrisation and study d(bar)-u(bar) and strangeness together.

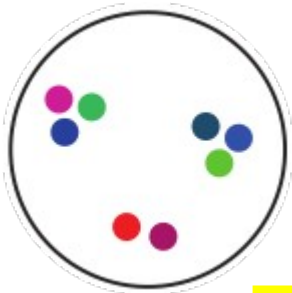
→ can improved d(bar)/u(bar) data help?

CSKK: arXiv:1803.00968; **WG1(227) 17.4. 15:20**
ABM: Phys.Lett. B777(2018) 134 [arXiv:1708.01067]; **WG1(153) 17.4. 14:00**
NNPDF3.1: EPJ C77 (2017) 663 [arXiv:1706.00428]; **WG1(252) 17.4. 15:00**

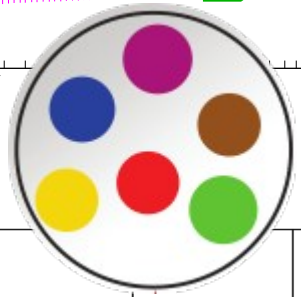
The Future Frontier: Pushing Kinematic Boundaries + Innovative Ideas



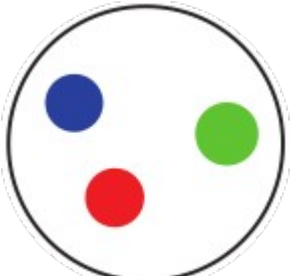
Precision

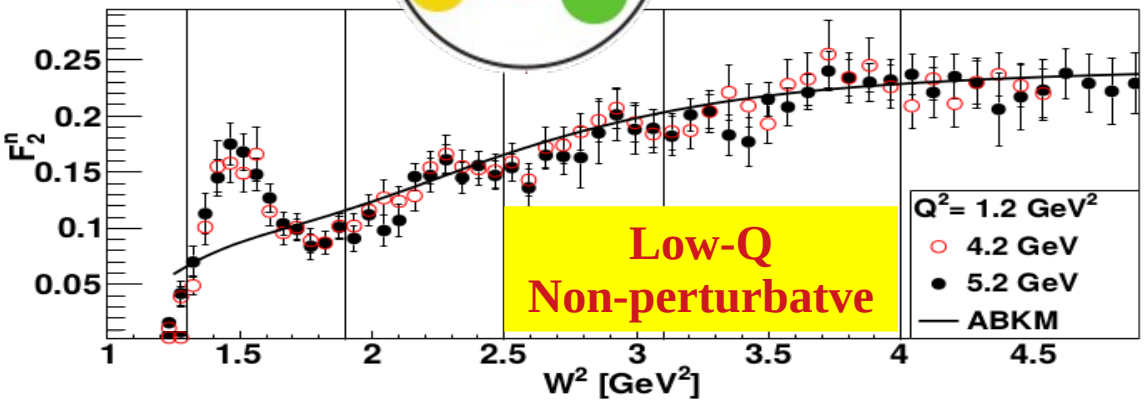


Low-x
Shadowing
Recombination
Resummation



Hi-x
Higher Twist





Precise knowledge of the PDFs are essential for predictions

QCD factorization:

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

Experimental Data:

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

Theory:

→ intense theoretical developments

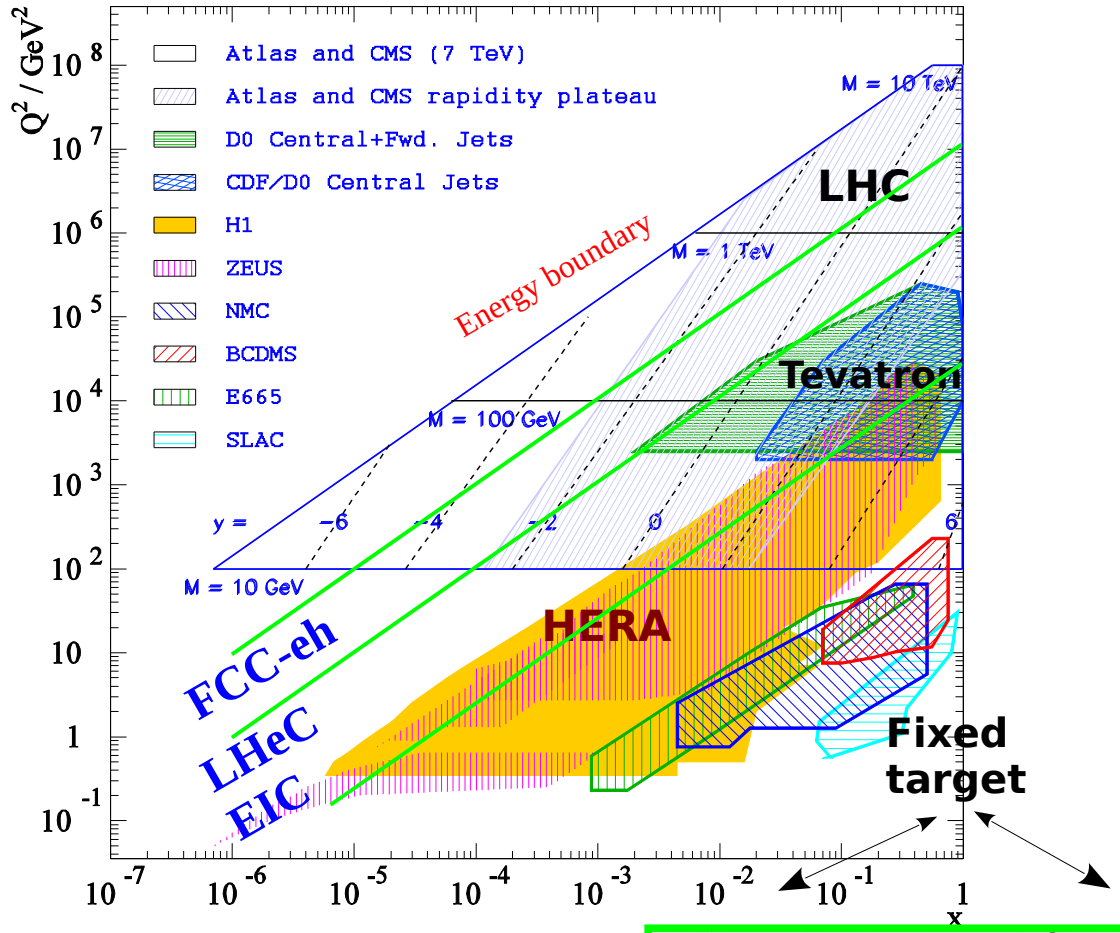
Tevatron + HERA
essential complementary components

LHC alone cannot maximize PDF precision

nuclear dimension essential!!!

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

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



Precision!!!