

PDF Flavor Determination & nCTEQ PDFs

Challenges and Opportunities for QCD

Fred Olness
SMU

nCTEQ
nuclear parton distribution functions

Thanks to my nCTEQ colleagues

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



nCTEQ & friends @ Grenoble 2017

DIS2018

Kobe, Japan

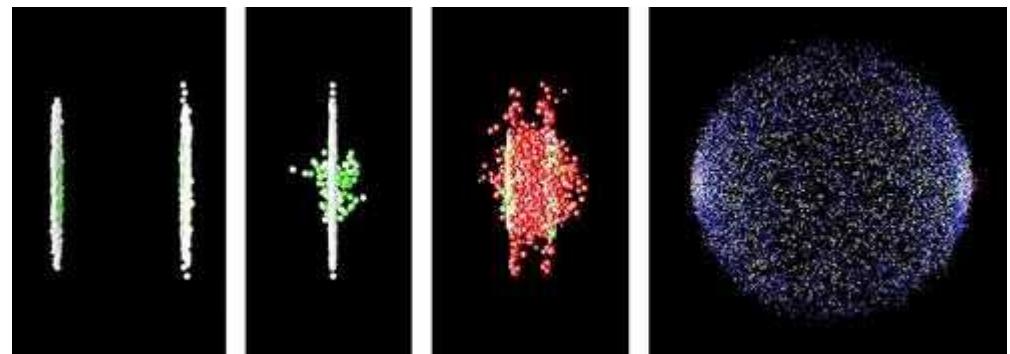
April 16-20, 2018

Motivation for nPDFs???

Make predictions for heavy ion collisions at:

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

LHC (pPb, PbPb)



Differentiate flavors of free-proton PDFs:

neutrino DIS

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

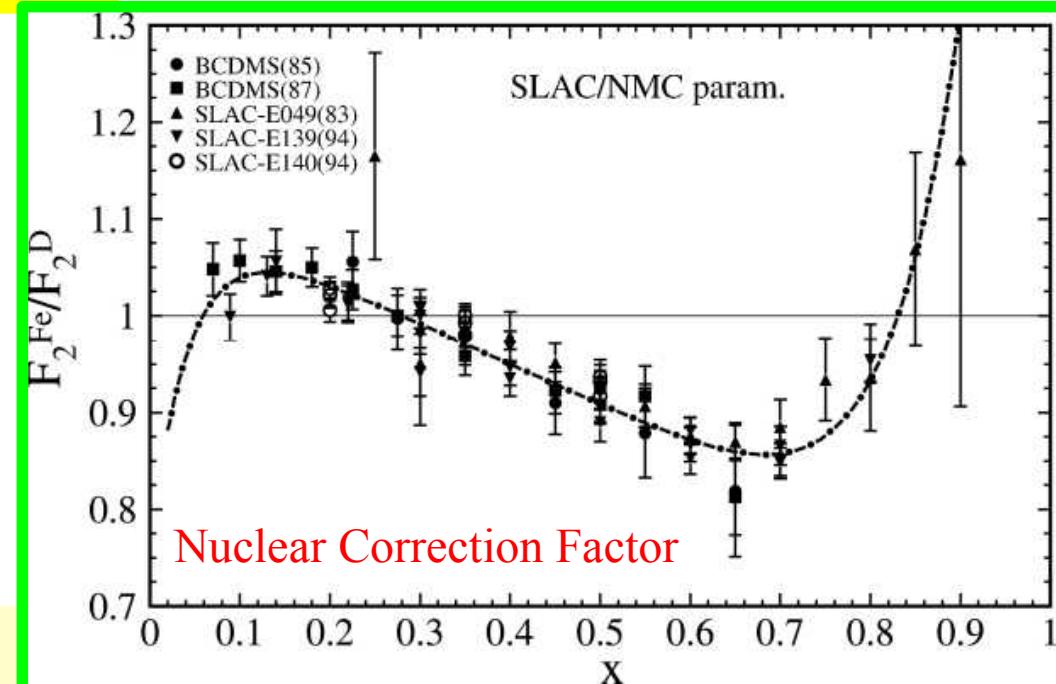
$$F_2^{\bar{\nu}} \sim [\bar{d} + \bar{s} + u + c]$$

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

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

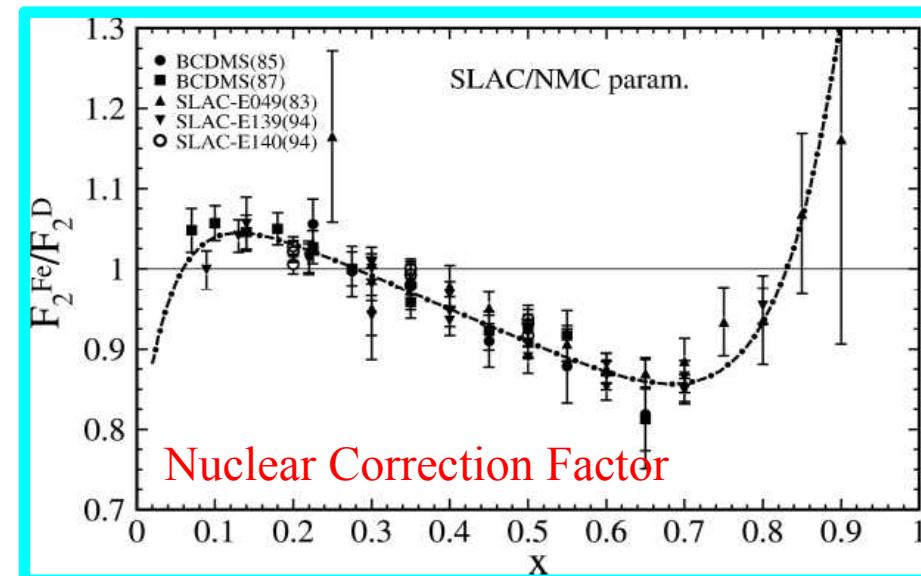
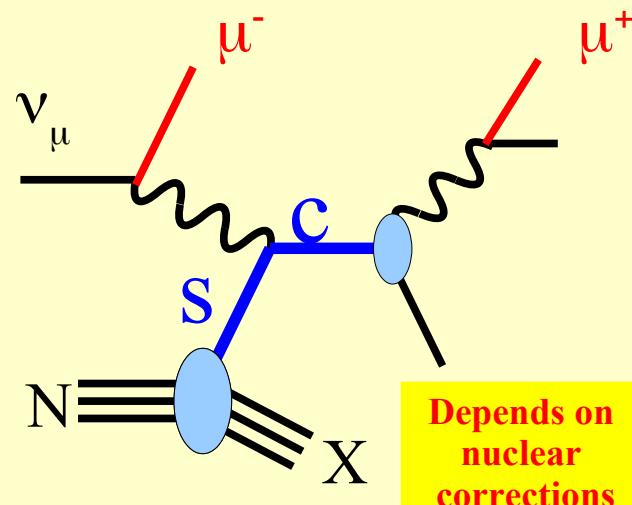
charged lepton DIS

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

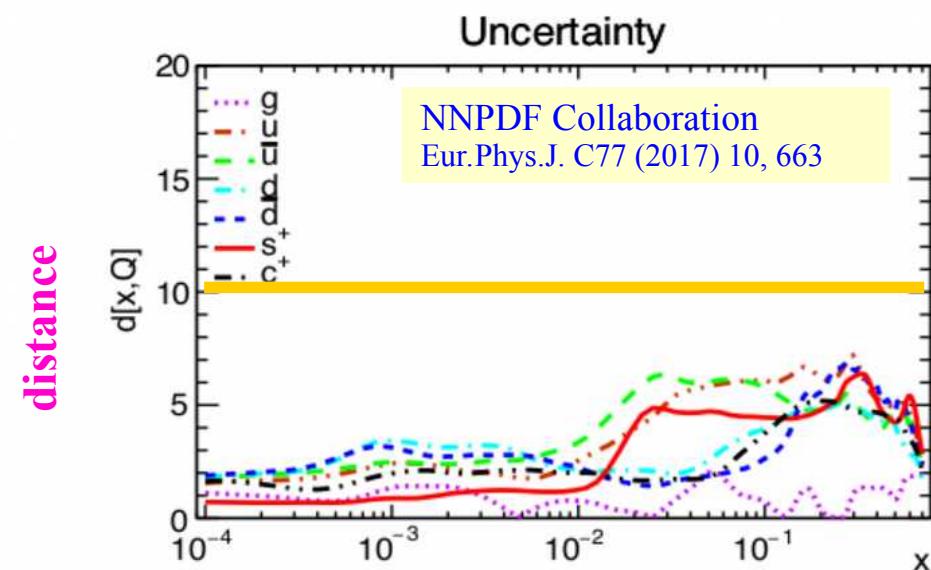
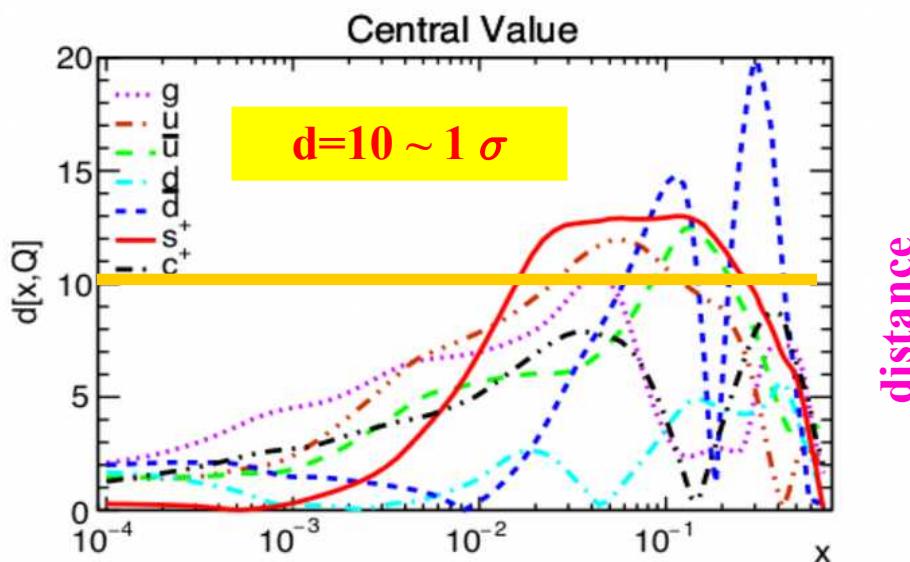


Impact of Nuclear Corrections on Proton PDF

Neutrino DIS

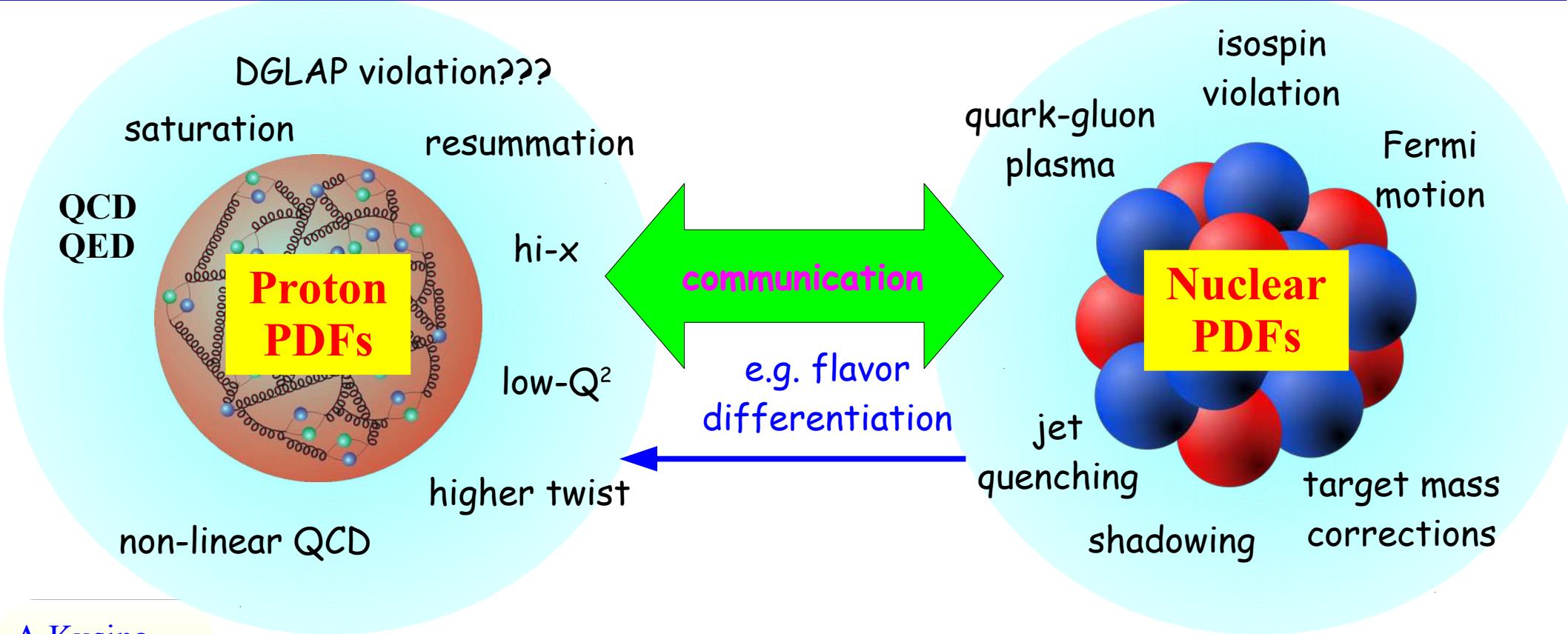


NNPDF3.1 NNLO, Impact of nuclear+deuteron fixed-target data , $Q = 100 \text{ GeV}$



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

... the motivation for nCTEQ



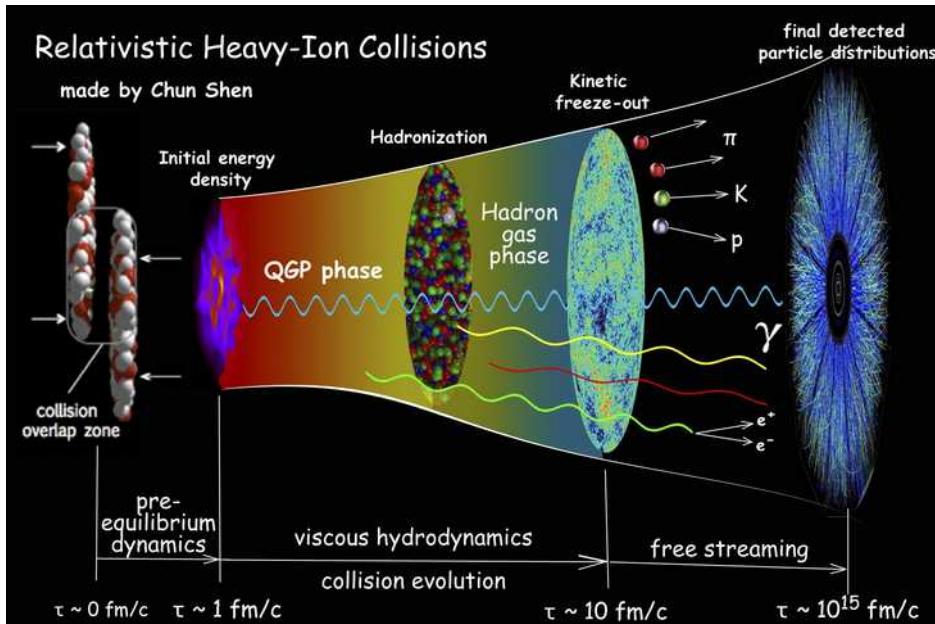
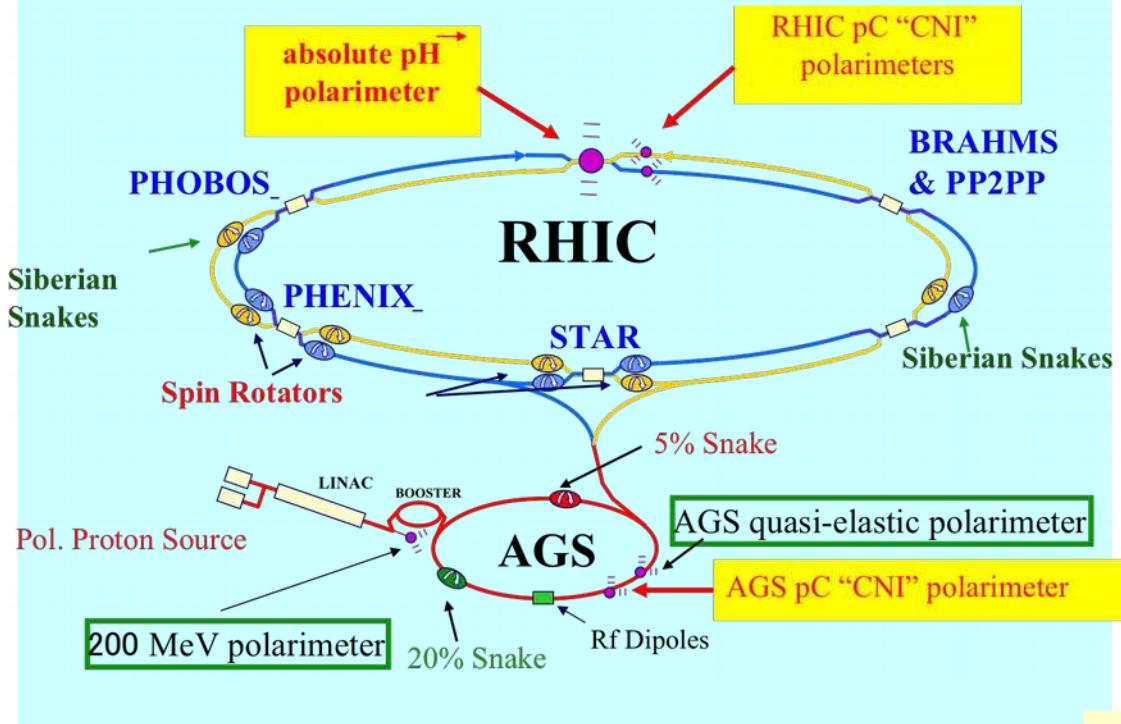
A Kusina,
 K. Kovarik
 T. Jezo,
 D. Clark,
 C. Keppel,
 F. Lyonnet,
 J. Morfin,
 F. Olness
 J. Owens,
 I. Schienbein,
 J. Yu
 E. Godat

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

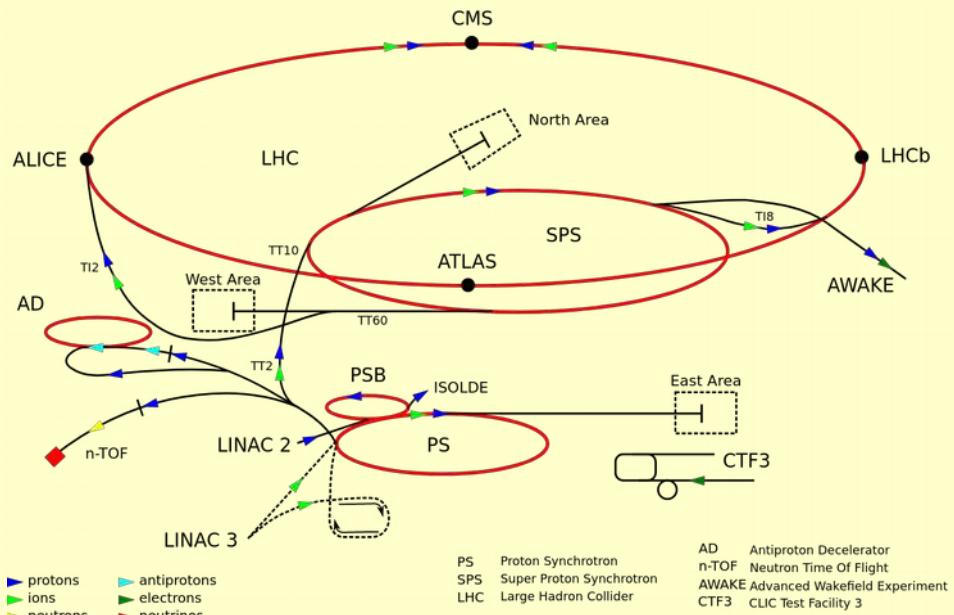
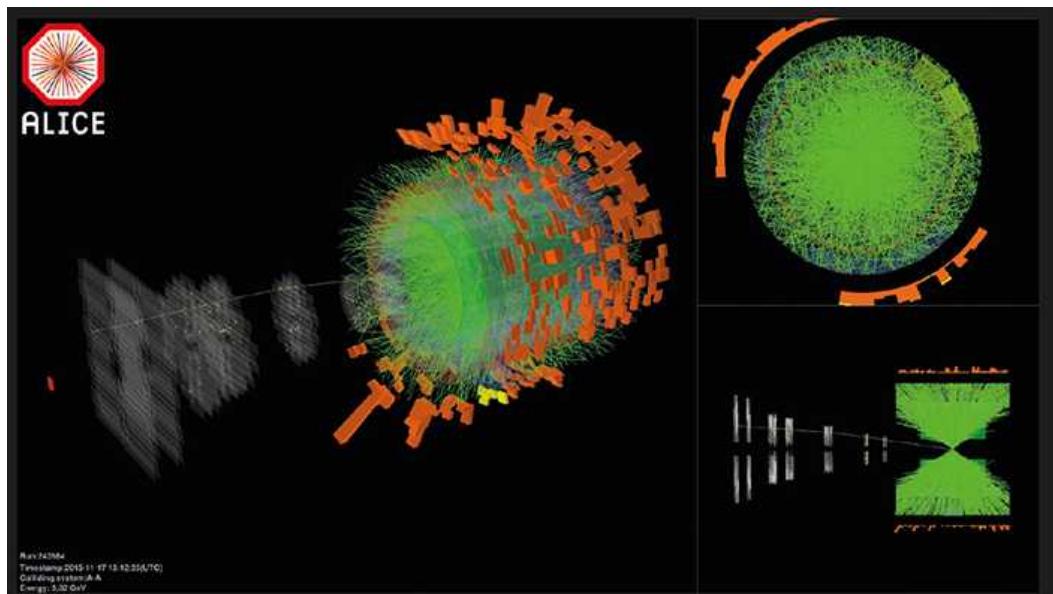
nCTEQ

nuclear parton distribution functions

nPDFs of Current Interest



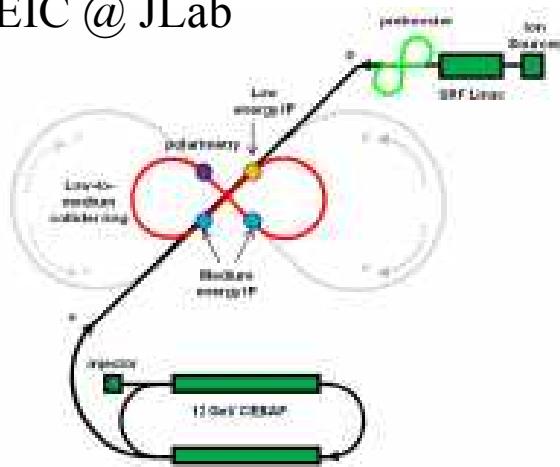
Heavy Ions at the LHC



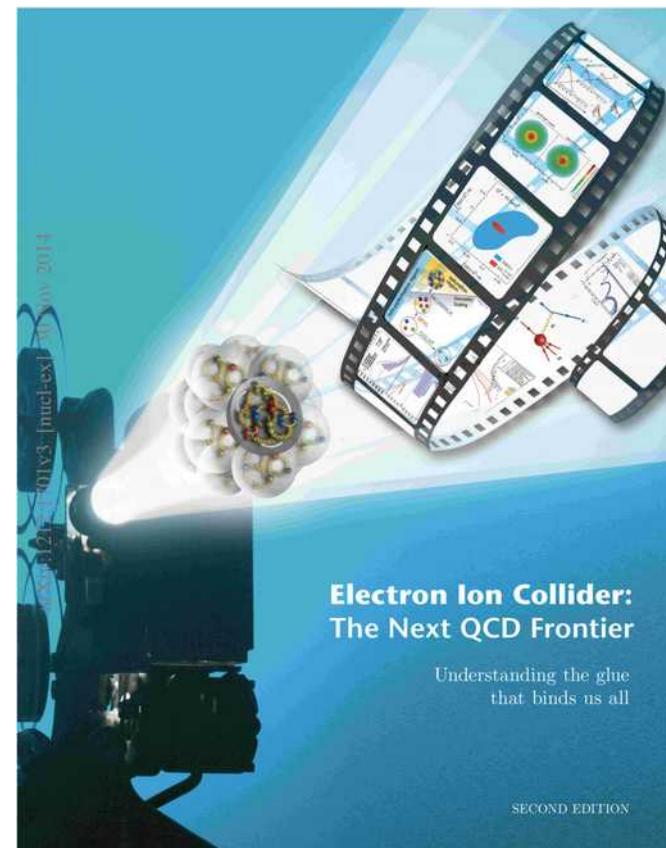
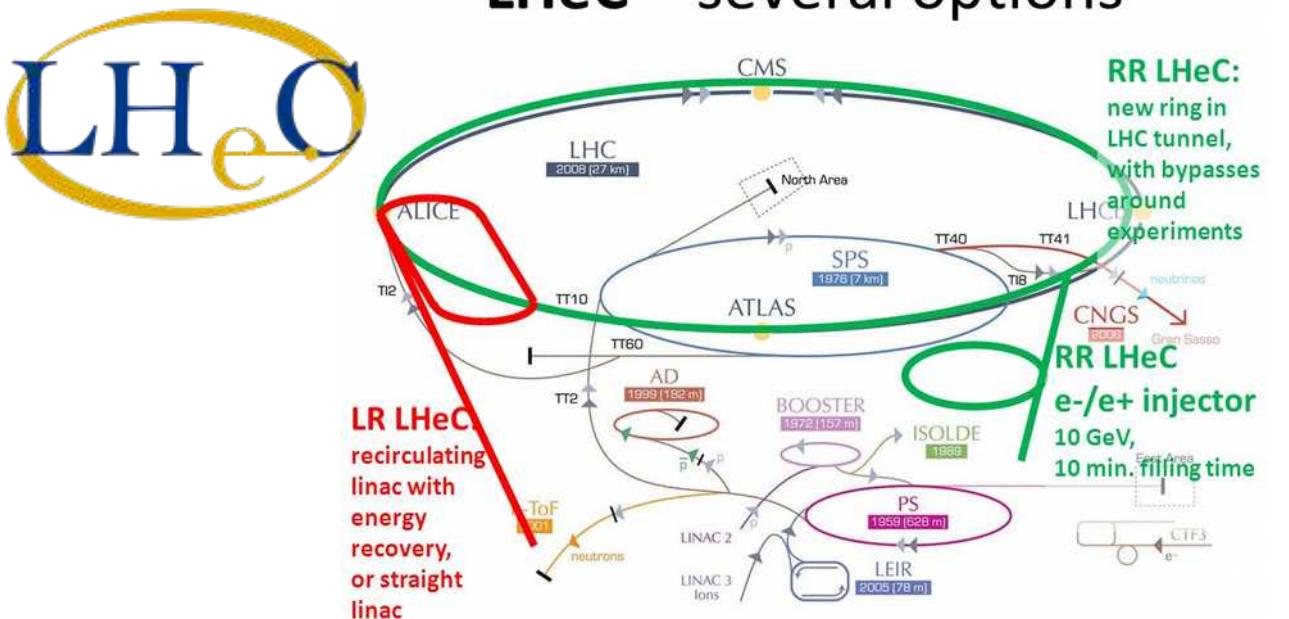
nPDFs and of Future Interest



JLEIC @ JLab



eRHIC @ BNL



Nuclear PDF

The Ingredients

Data sets & cuts for nPDF fits

NC DIS & DY

SLAC E-139 & E-049

N = (D, Ag, Al, Au, Be,C, Ca, Fe, He)

CERN BCDMS & EMC & NMC

N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)

DESY Hermes

N = (D, He, N, Kr)

FNAL E-665

N = (D, C, Ca, Pb, Xe)

FNAL E-772 & E-886

N = (D, C, Ca, Fe,W)

Neutrino DIS*

NuTeV CHORUS CCFR & NuTeV

N = Pb & Fe

Pion Production:

RHIC: PHENIX & STAR

N = Au

will show comparision w/ LHC pPb

DIS Cuts:

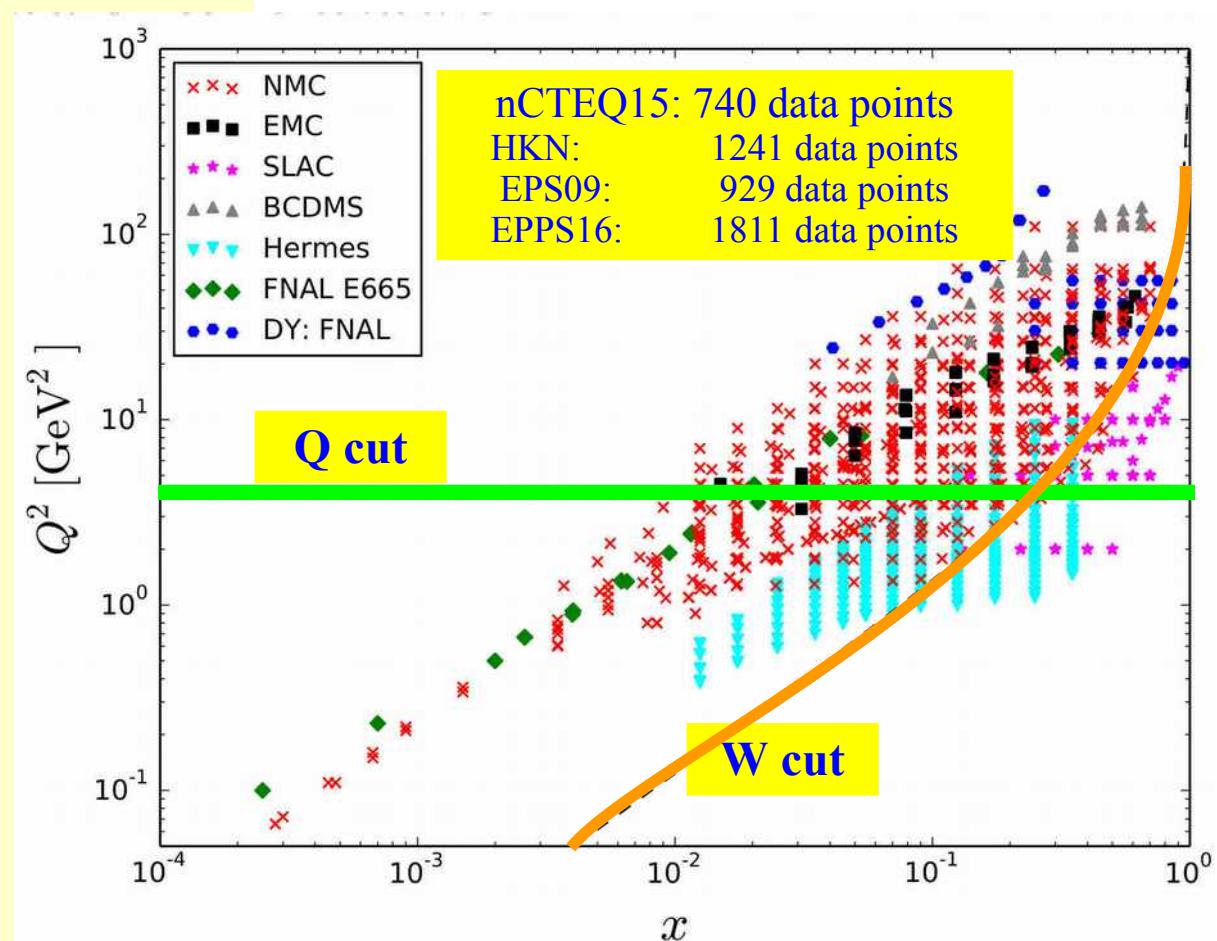
nCTEQ: $Q > 2.0 \text{ & } W > 3.5$

EPPS16: $Q > 2.0 \text{ & } W > 3.5$

EPS09: $Q > 1.3$

HKN: $Q > 1.0$

DSSZ: $Q > 1.0$



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

nPDFs

nuclear parton distribution functions

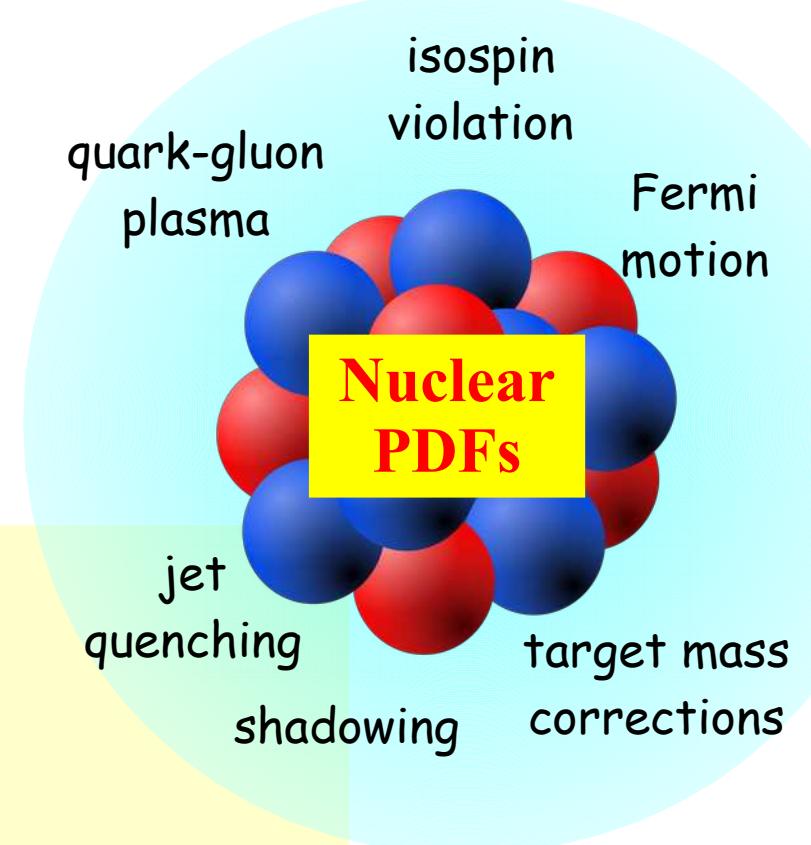
HKN'07: Hirai, Kumano, Nagai
 [PRC 76, 065207 (2007)]

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)]



Mechanics of nPDFs

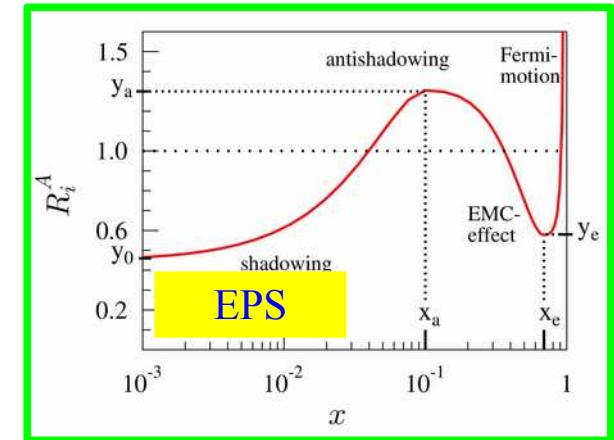
1) Multiplicative nuclear correction factors (HKN, EPPS, DSSZ)

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

... 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)

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

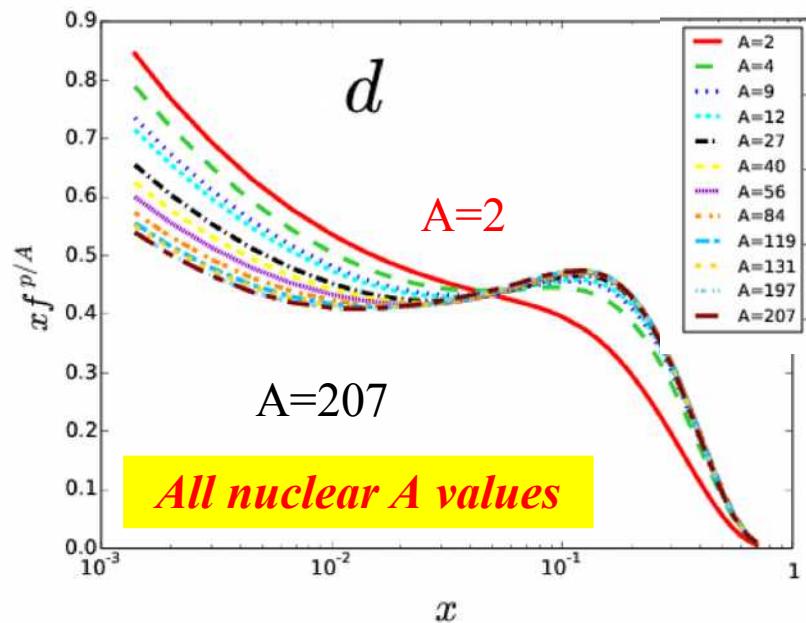
$$f \sim \dots x^{c_1(A)} (1-x)^{c_2(A)} \dots$$

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

Proton

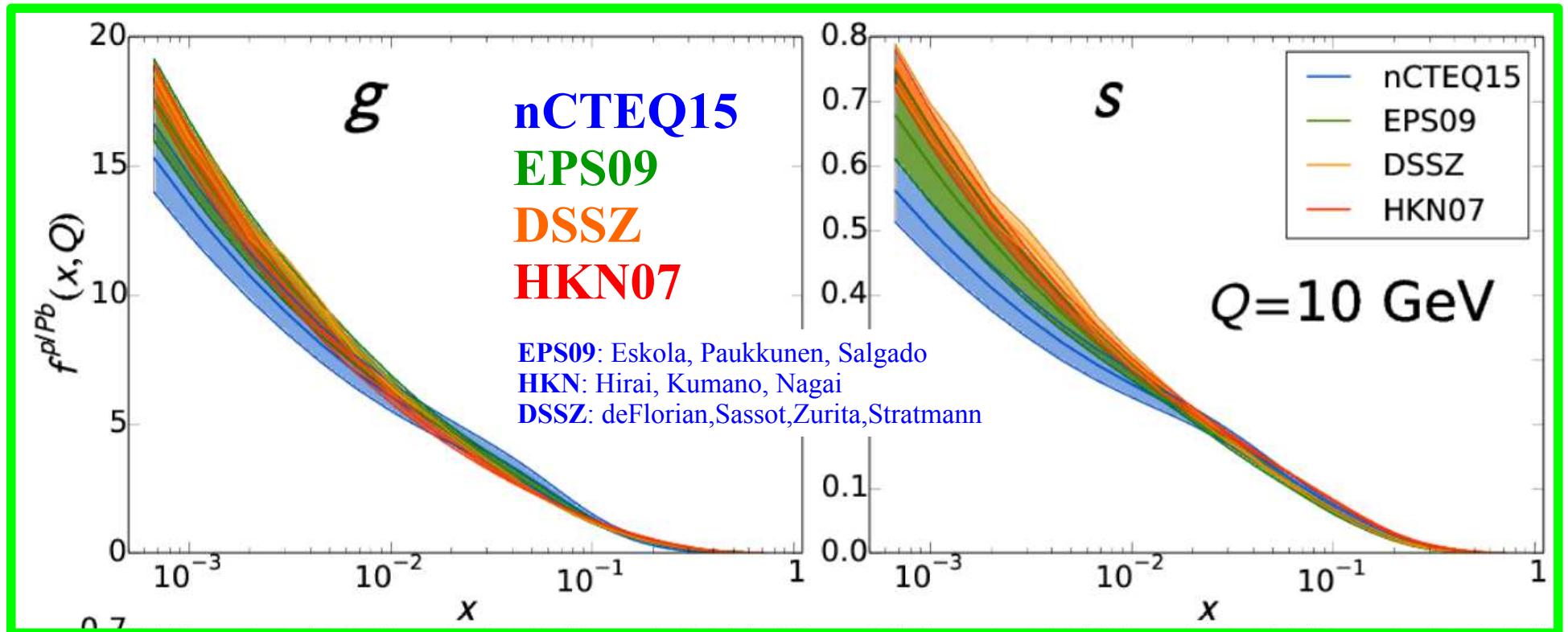
Nuclear

use proton as a Boundary Condition



Nuclear PDFs: Complementary efforts in general agreement

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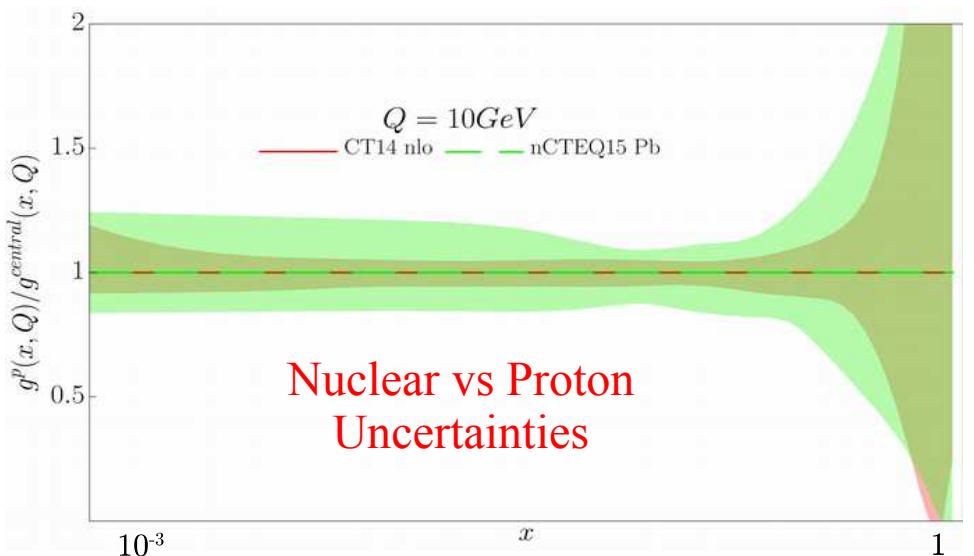


Nuclear PDFs are more complex

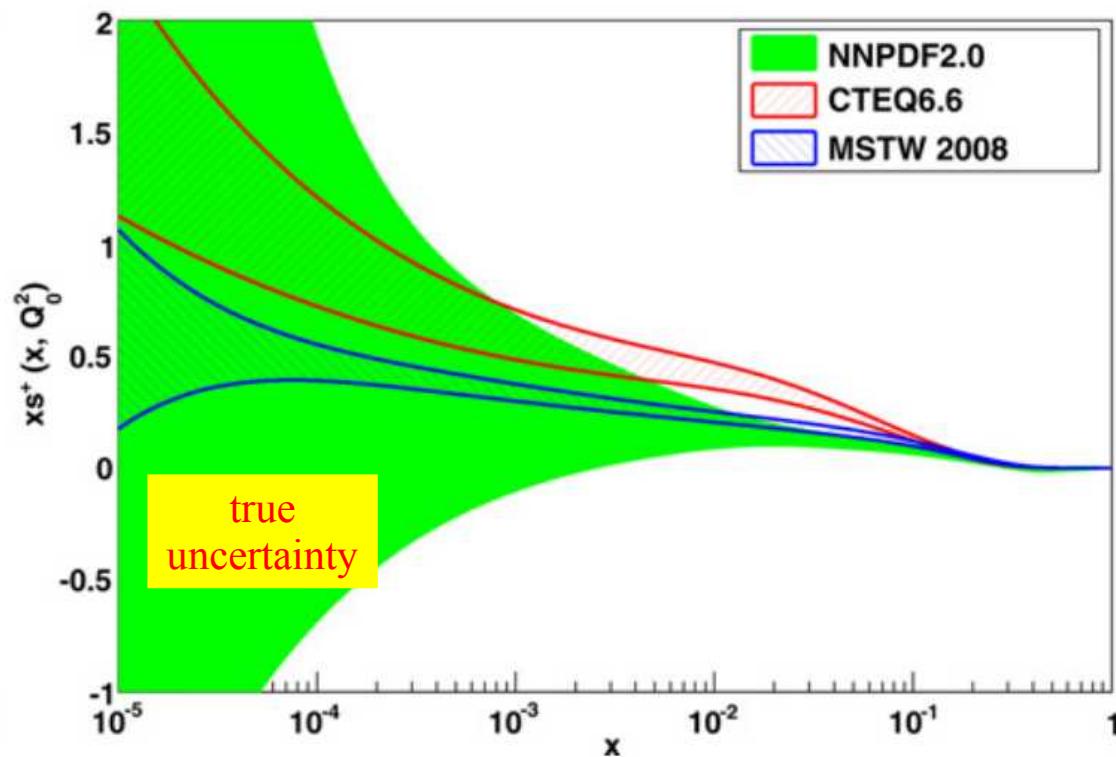
more DOF than Proton case

more “issues” to consider

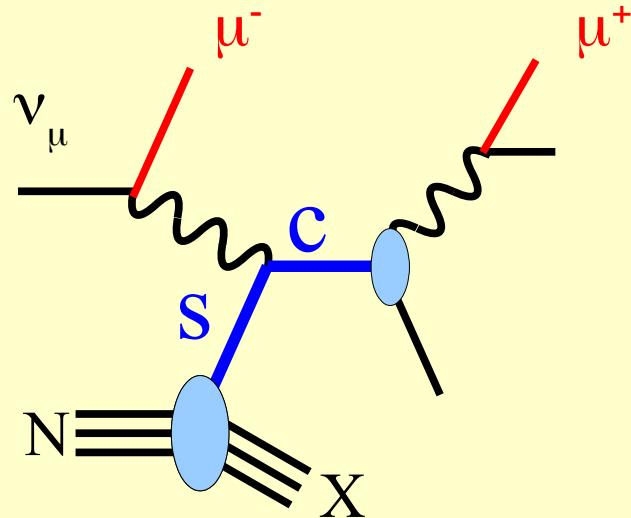
more work to do ...



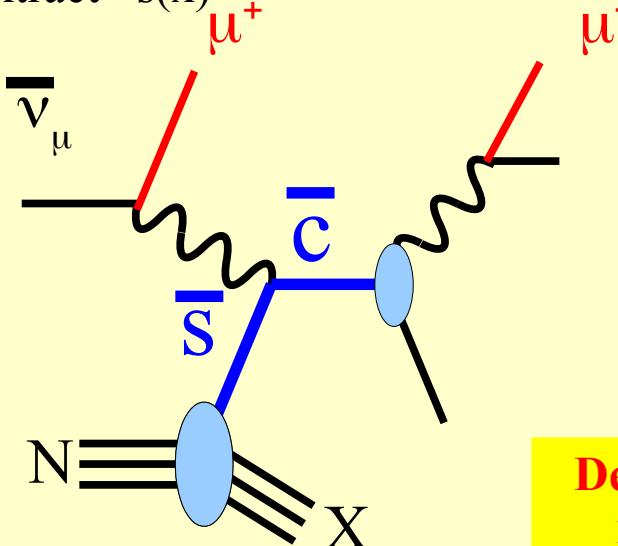
Progress on strange PDF



Extract $s(x)$



Extract $\bar{s}(x)$



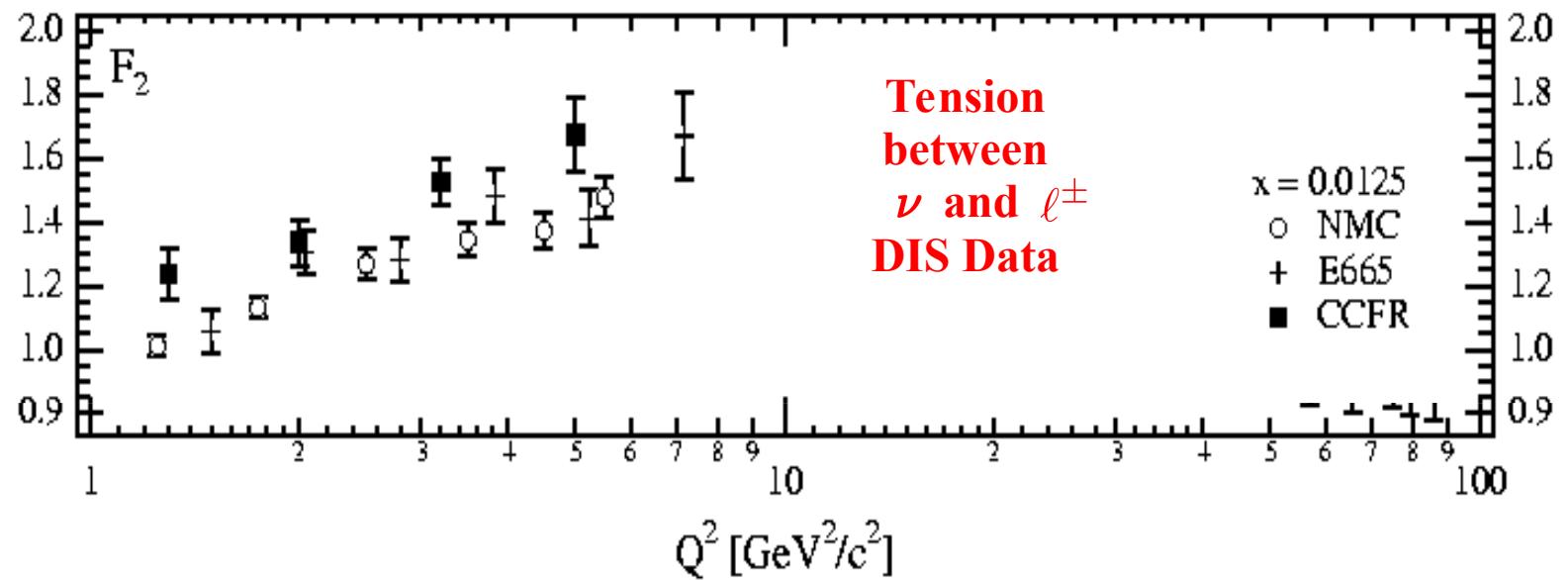
Depends on nuclear corrections

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

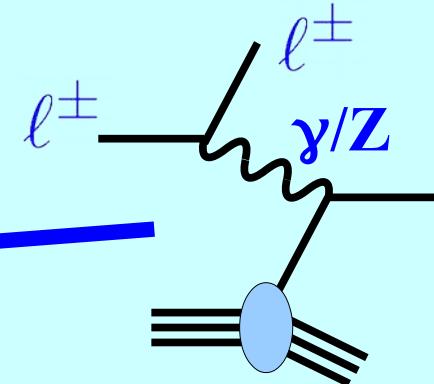
Used in CTEQ Fits

The CTEQ List of Challenges in Perturbative QCD

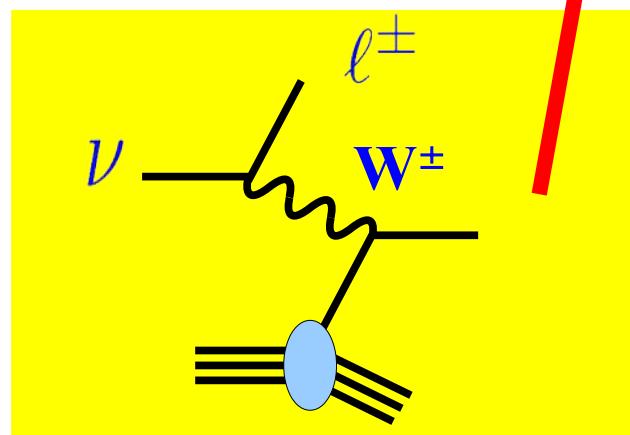
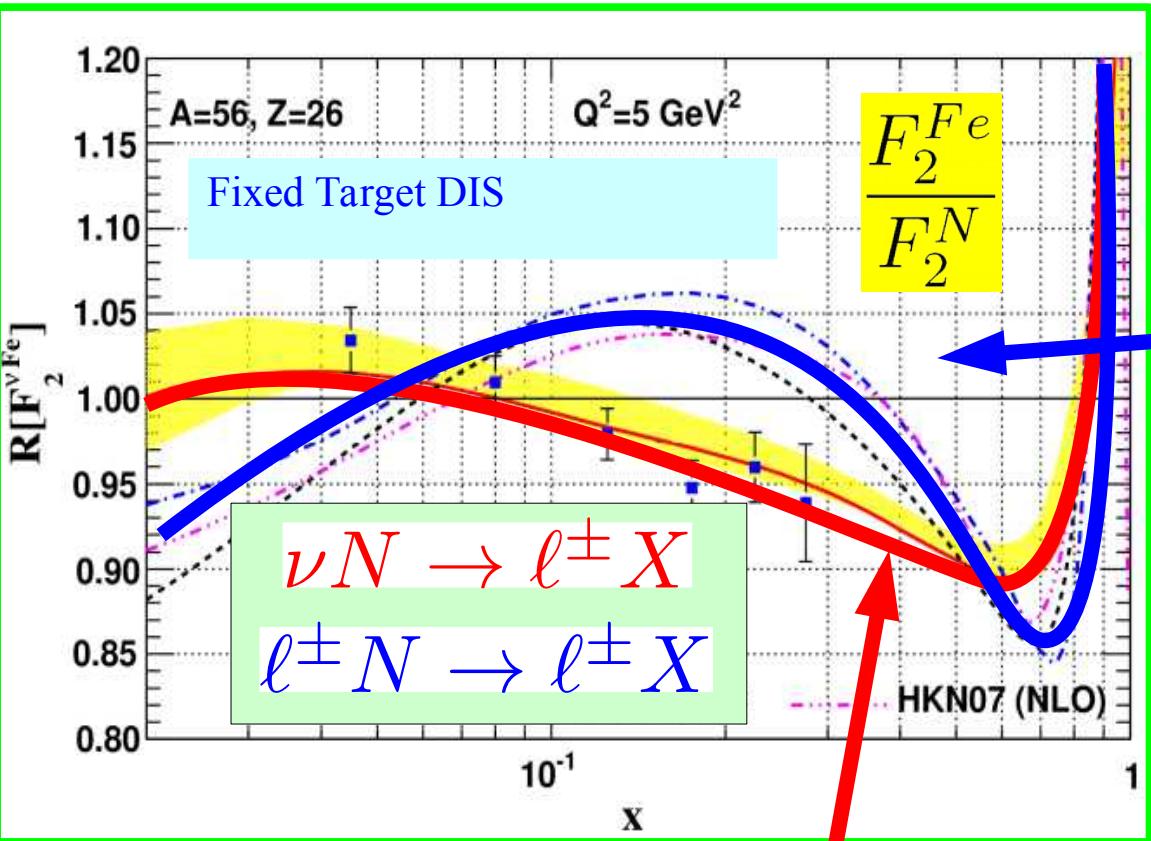
~1995



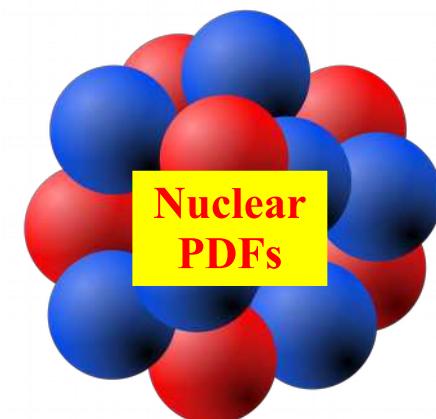
Charged Lepton DIS



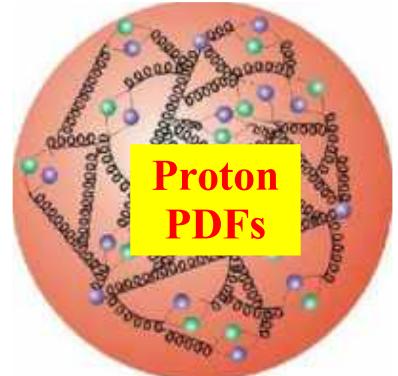
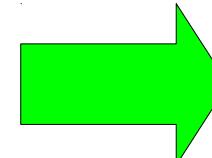
*some caveats
... correlated errors*



Neutrino DIS

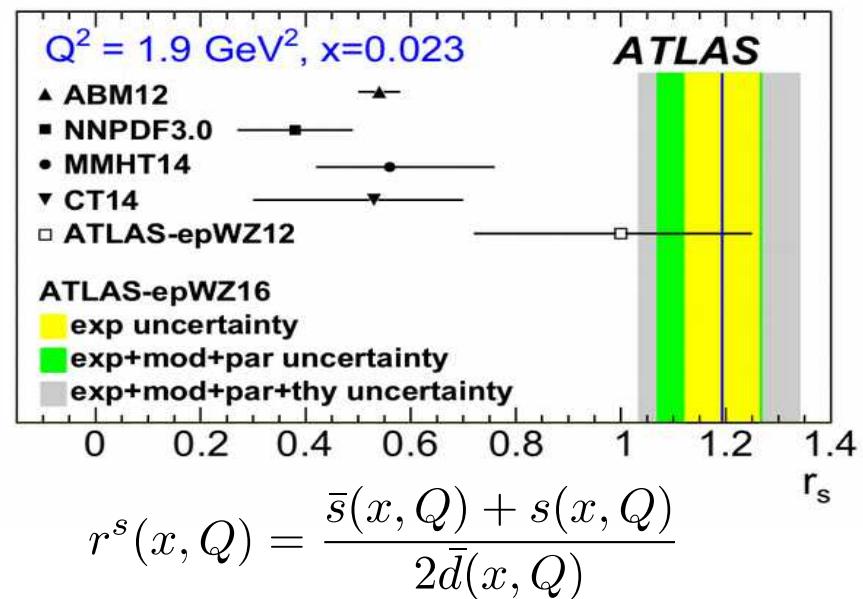
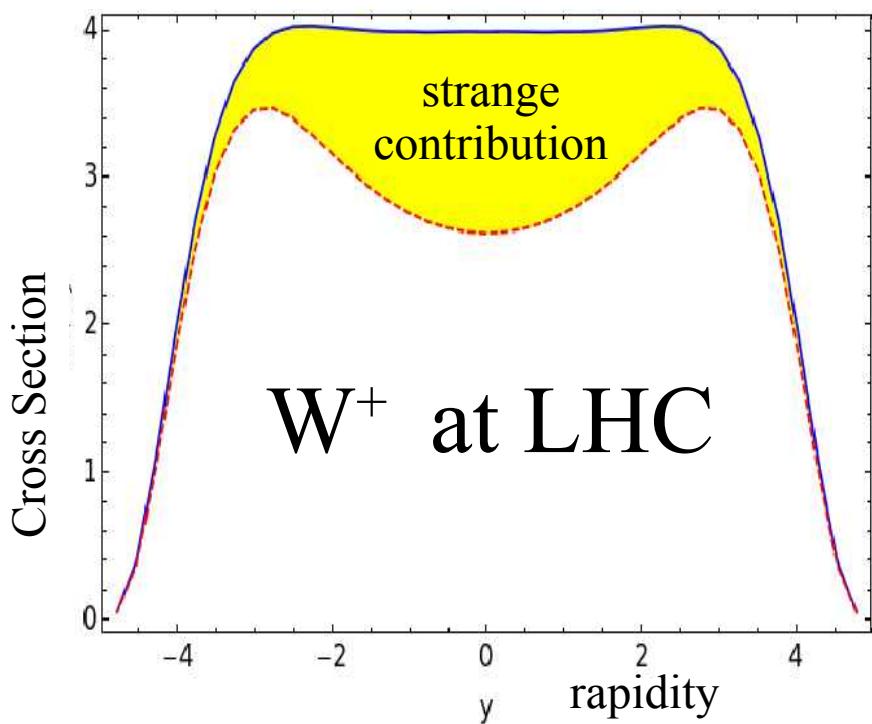
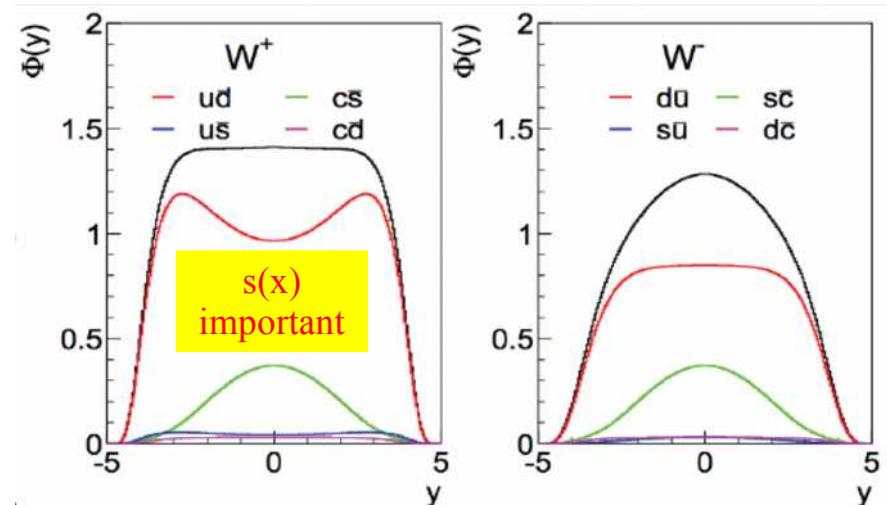
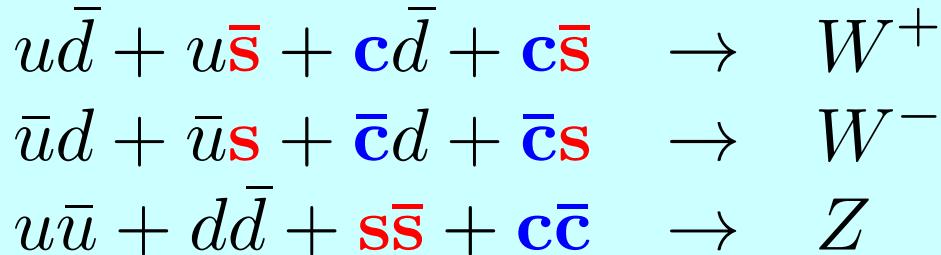


Depends on nuclear corrections



W/Z Production at LHC and the strange PDF

W/Z Production Channels

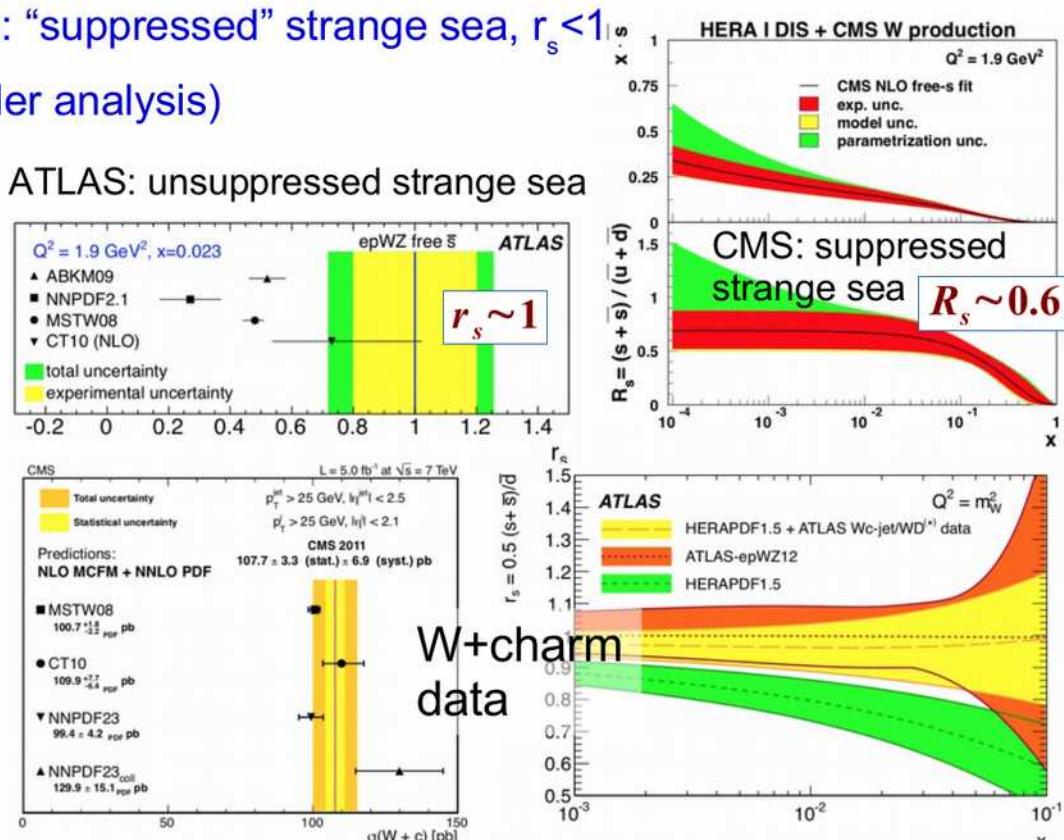




Recap: LHC data and the strange sea

- 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 “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]

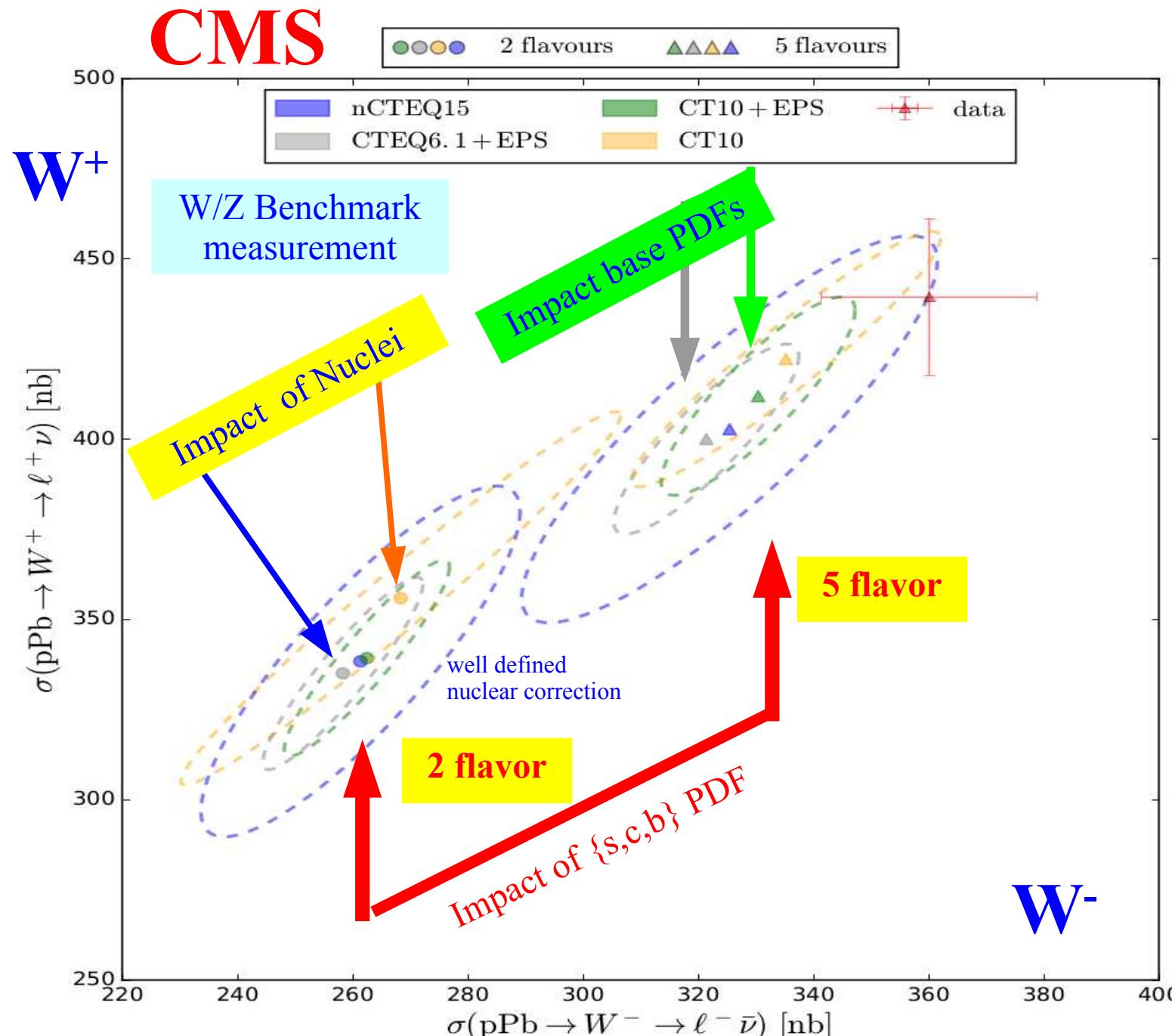


DIS conference, April 2018

S.Schmitt, Parton density results

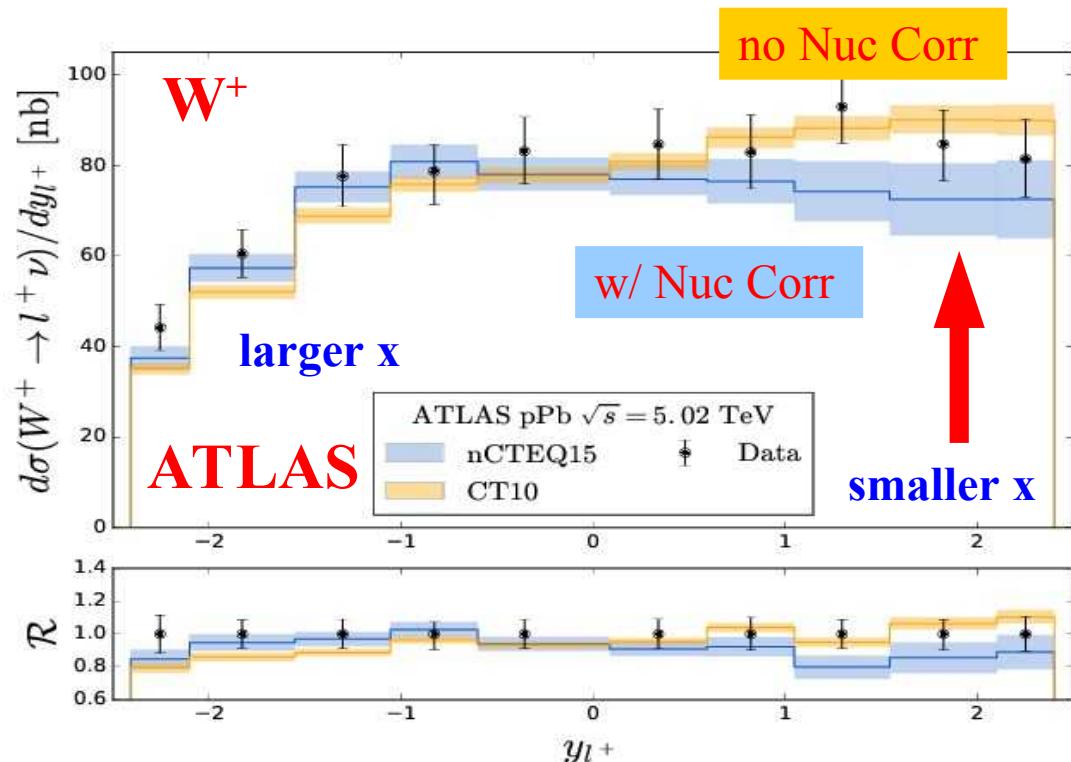
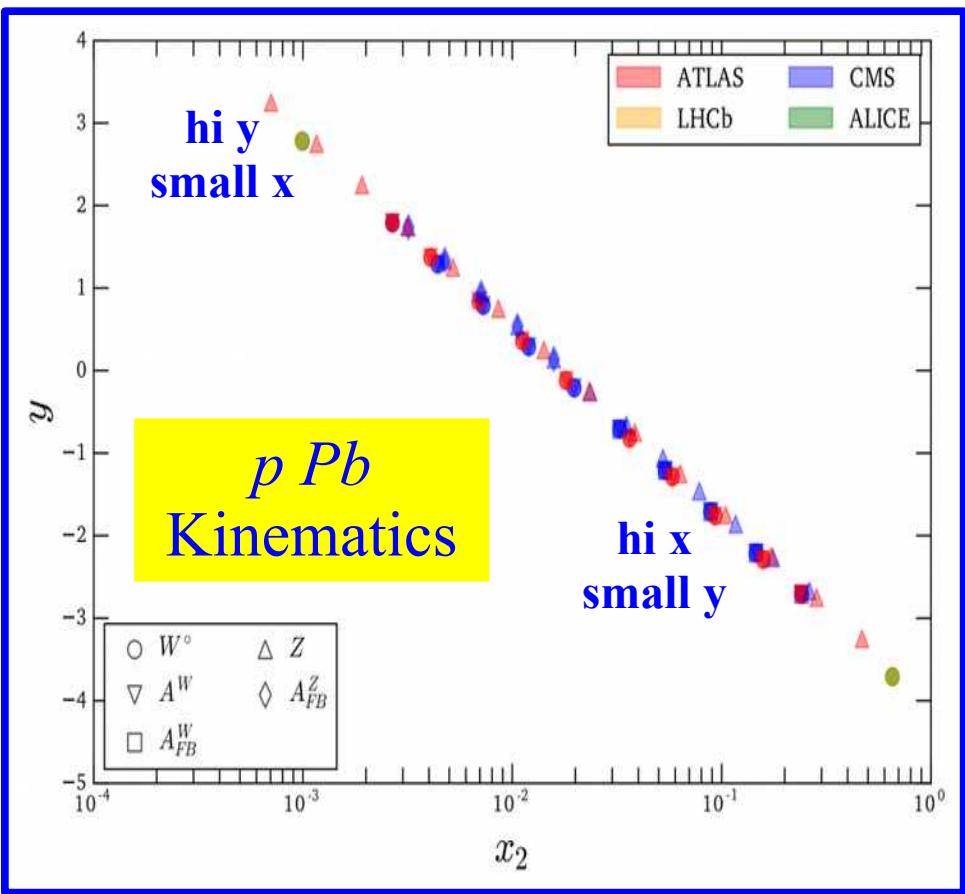
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p Pb → W/Z: Impact of {s,c,b} PDF



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

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



Vector boson production in pPb & PbPb

A. Kusina, F. Lyonnet, D. B. Clark, E. Godat, T. Jezo,
K. Kovarik, F. I. Olness, I. Schienbein, J. Y. Yu,
Eur.Phys.J. C77 (2017) no.7, 488

“OK” nuclear
correction

previous data
constraints

too much
suppression

minimal data
constraints

How can we include these new processes into the fit directly???

nCTEQ++

What is nCTEQ++?



- 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

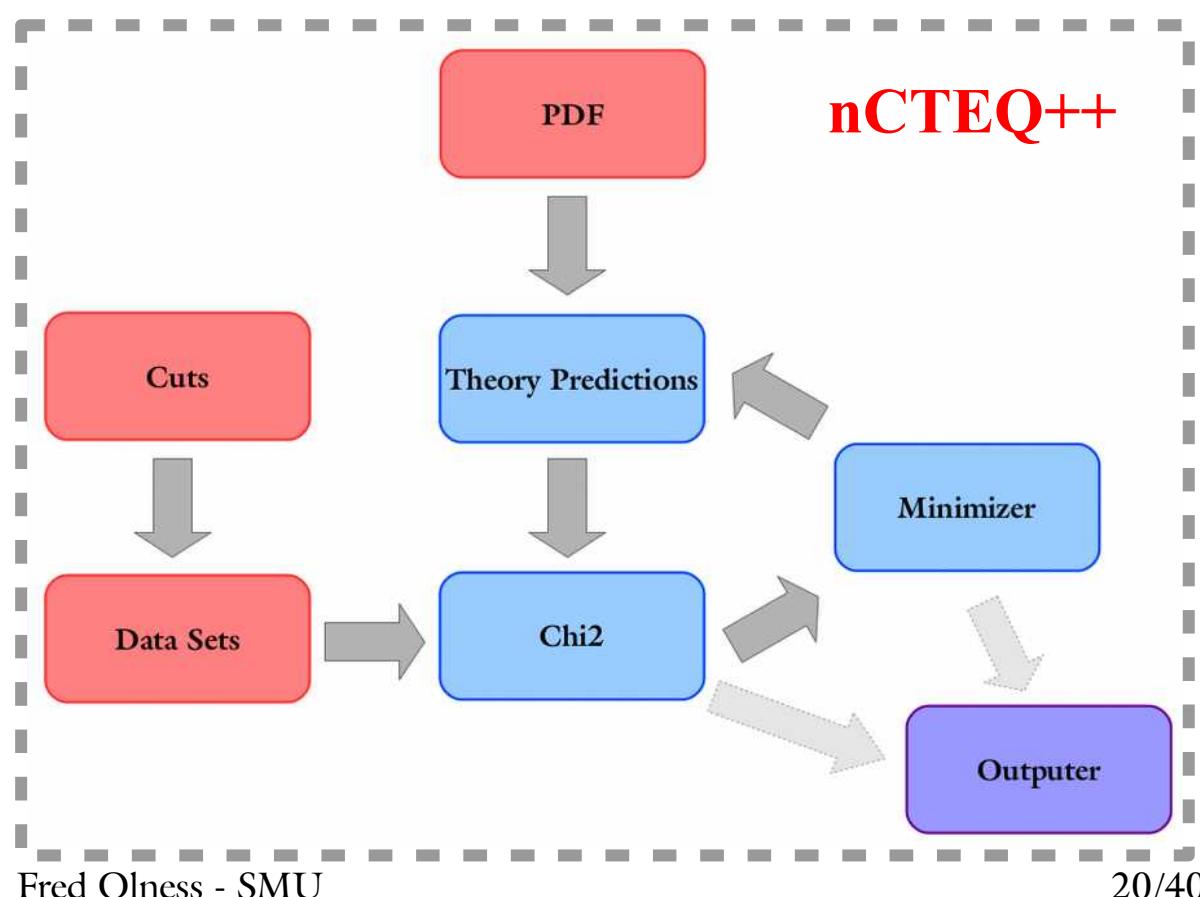
- Use external programs
 - Minuit
 - HOPPET
 - MCFM
 - APPLgrid

Special thanks to:

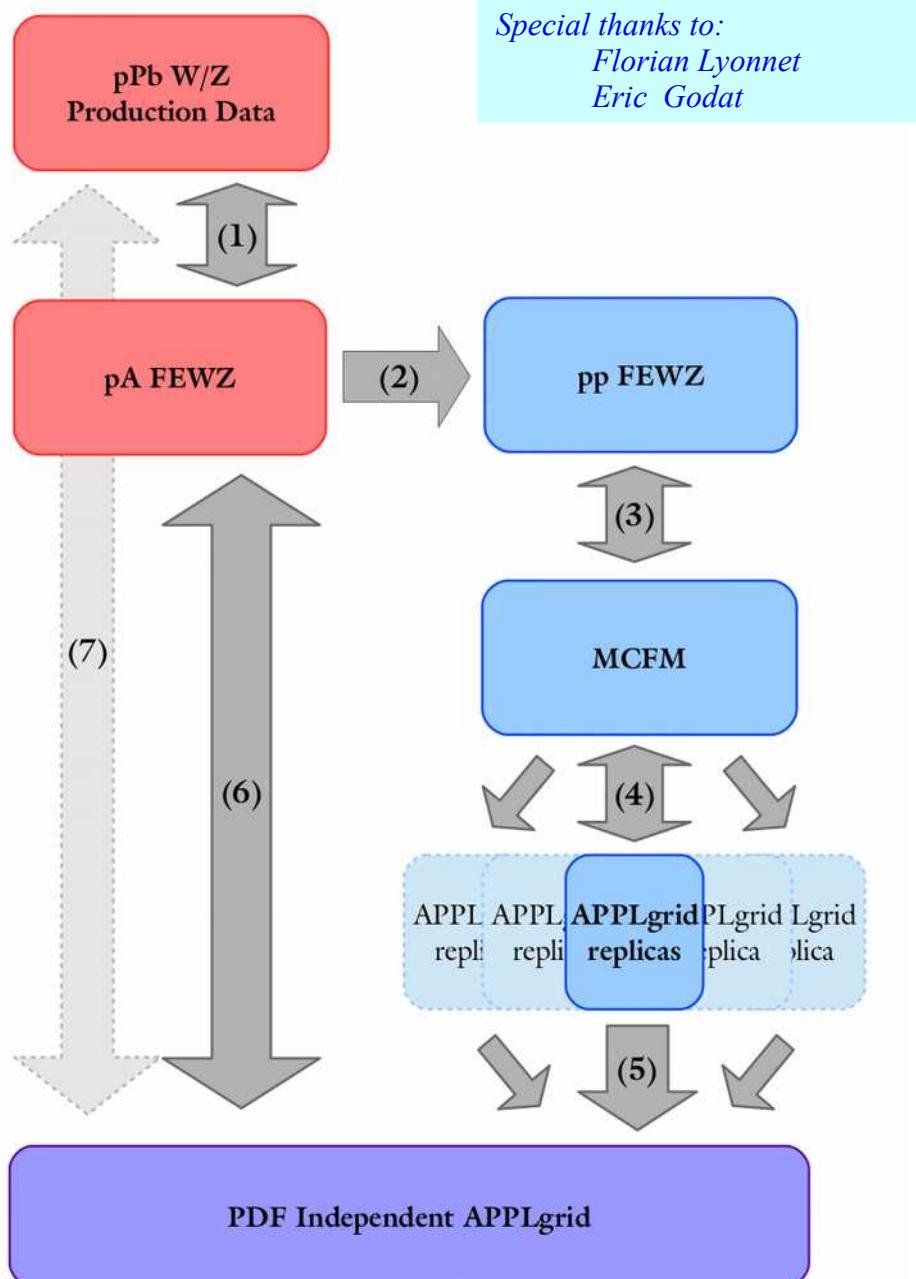
Florian Lyonnet

Tomas Jezo

Aleksander Kusina



Use MCFM + APPLgrid for pPb



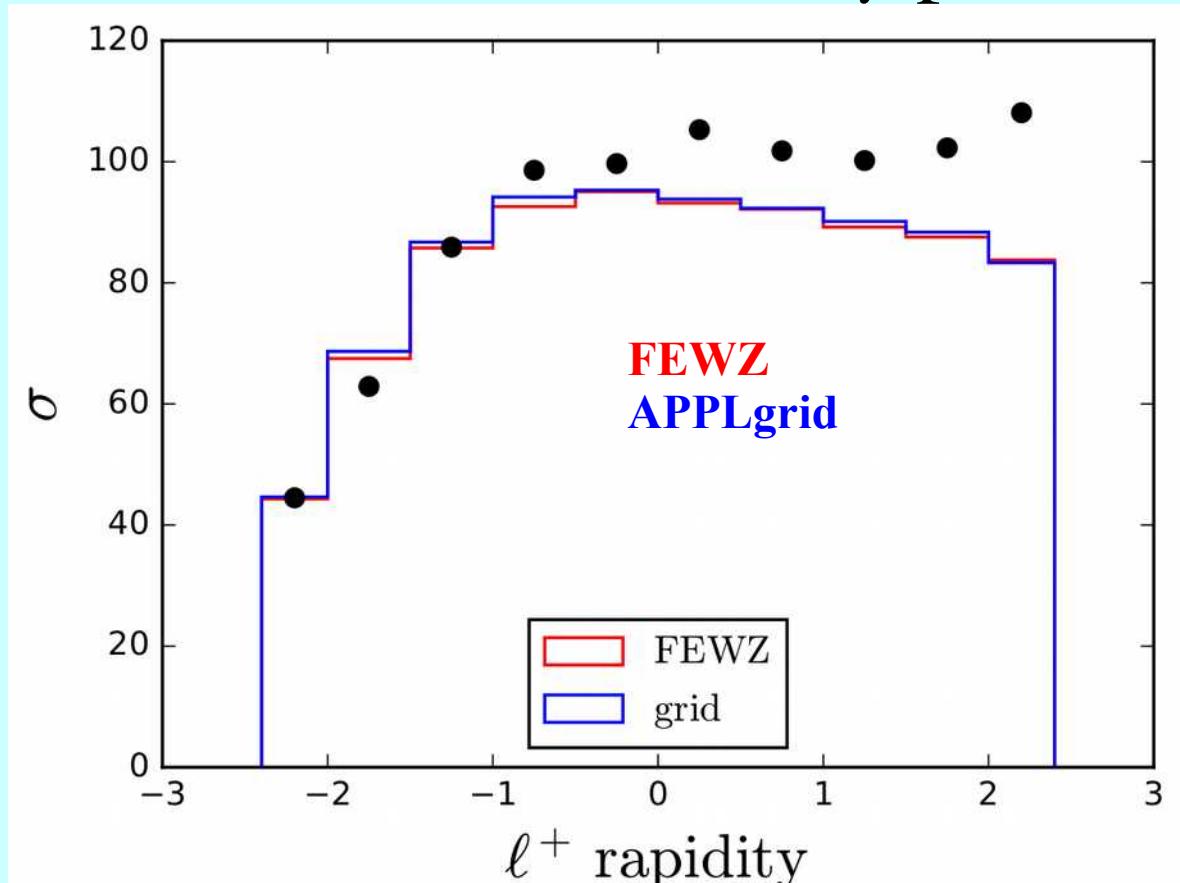
- (1) Data matched to pA-FEWZ in reweighting
- (2) Run FEWZ in symmetric pp - mode
- (3) Compare pp FEWZ to pp MCFM
- (4) Generate APPLgrid grids
 - Using mcfm-bridge
 - Different Monte Carlo seeds
- (5) Combine replica grids into a single PDF independent grid
 - Using applgrid-combine
- (6) Convolute PDF independent grid with asymmetric PDFs to compare to pAFEWZ
- (7) Add data and grid in nCTEQ++ to fit W/Z LHC data

They Match !!!



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

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



Let's include LHC data into the fit directly

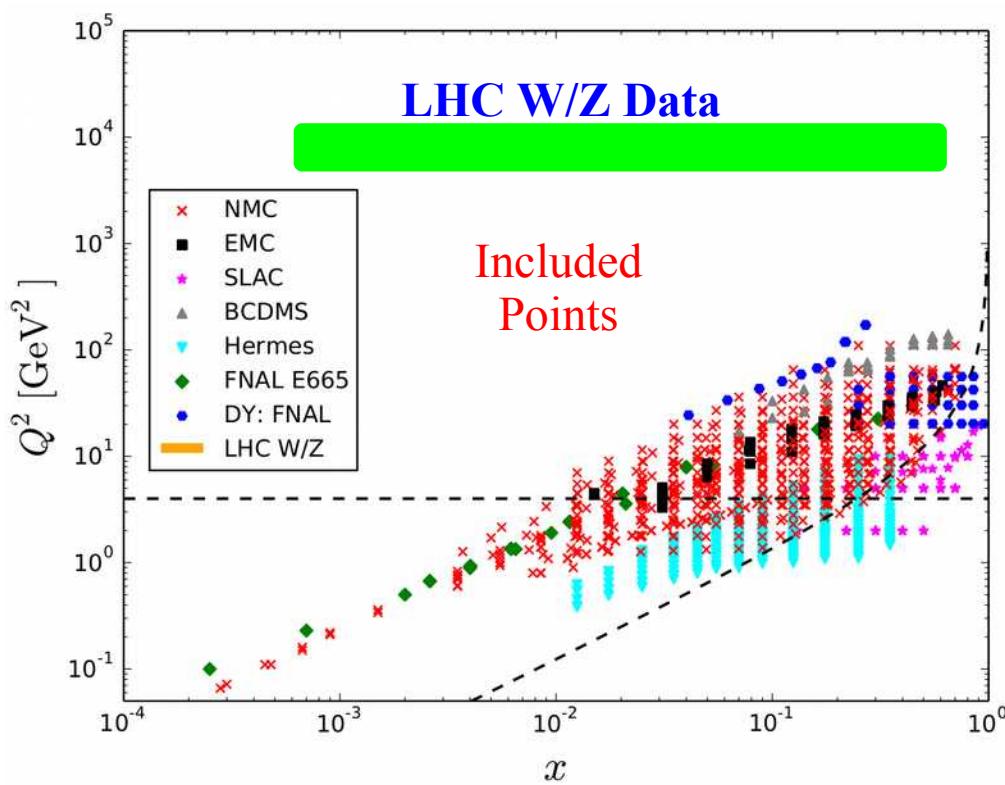
nCTEQ+LHC

pPb Data for nCTEQ+LHC



No LHC data in any previous nCTEQ fit

- New gridded theory predictions make this possible



Fred Olness - SMU

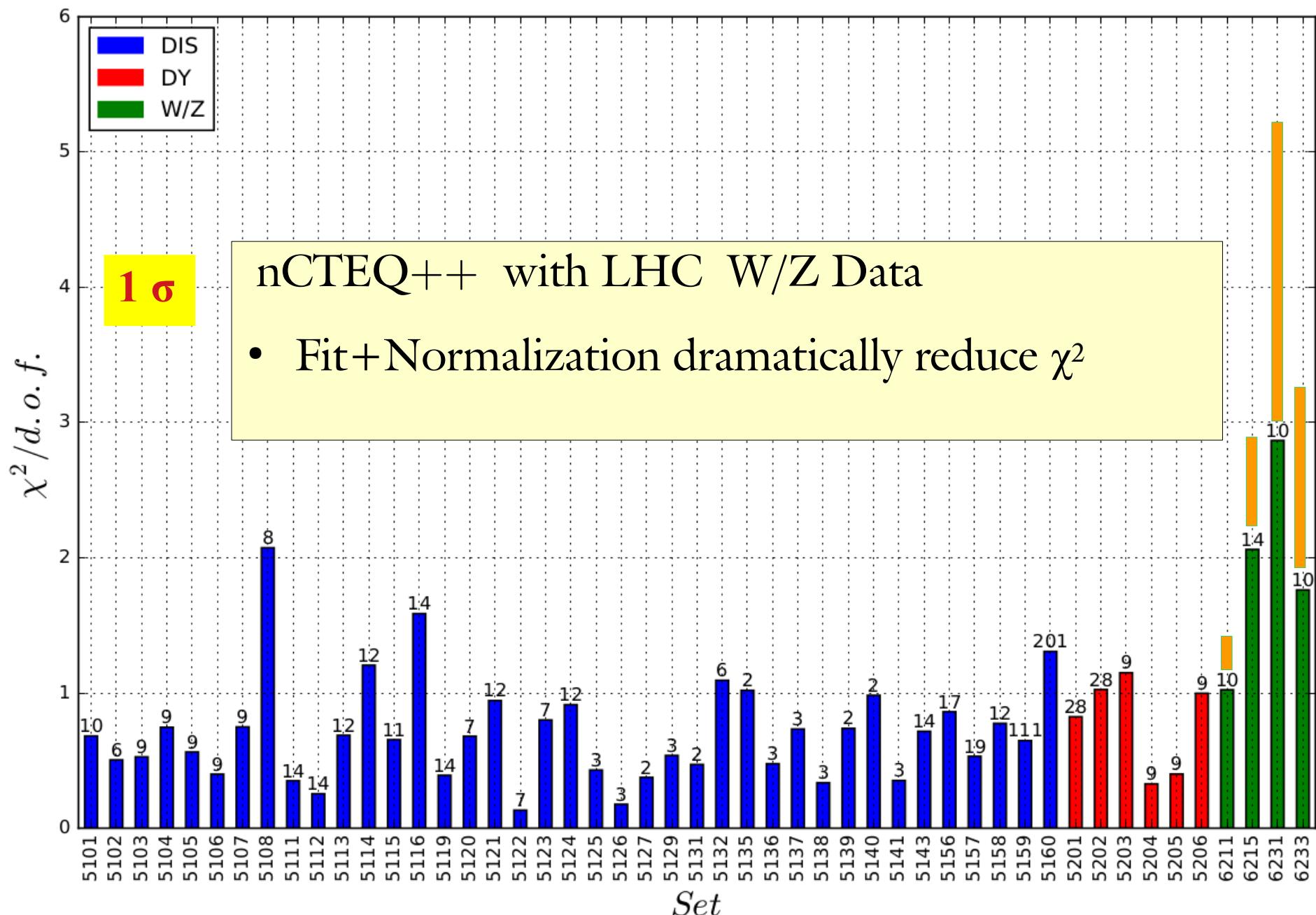
ATLAS:

- $d\sigma(W^- \rightarrow \ell^-\nu)/dy$
ID: 6211 Npts: 10
- $d\sigma(Z \rightarrow \ell^+\ell^-)/dy$
ID: 6215 Npts: 14

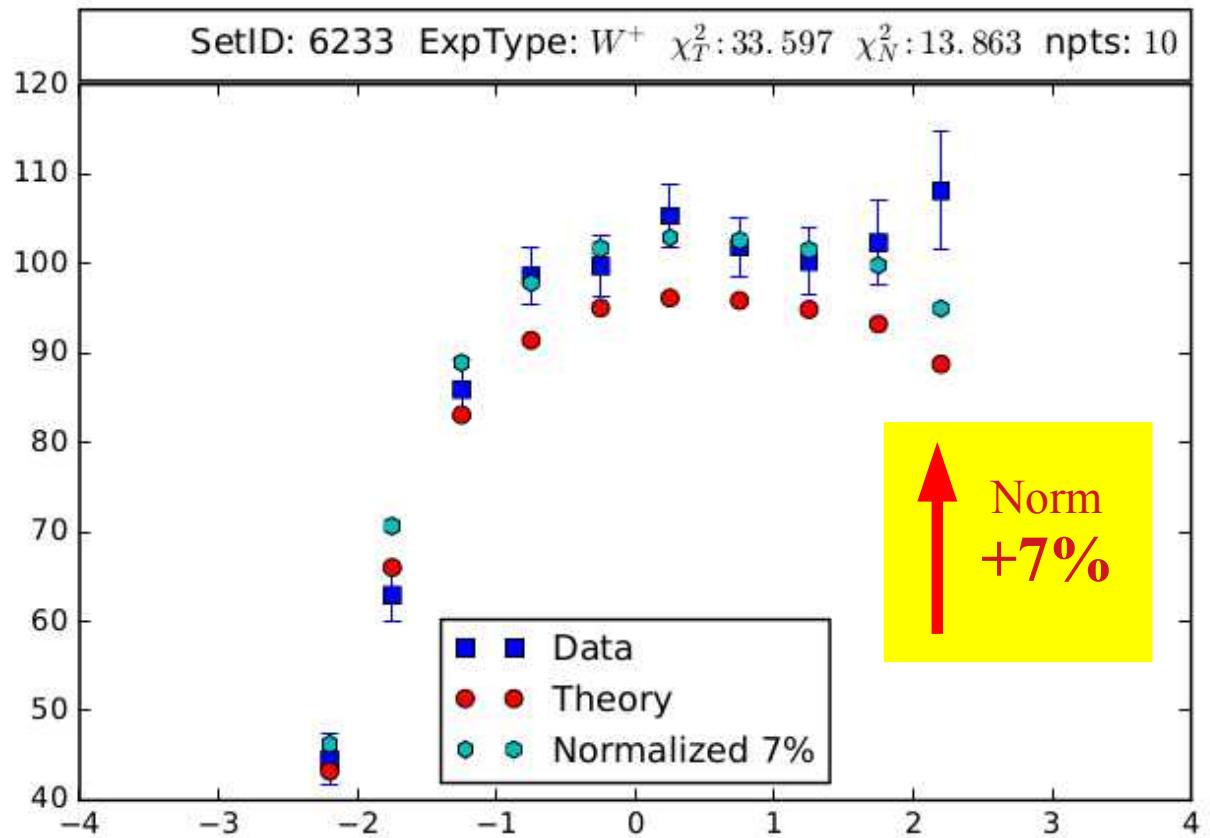
CMS:

- $d\sigma(W^- \rightarrow \ell^-\nu)/dy$
ID: 6231 Npts: 10
- $d\sigma(W^+ \rightarrow \ell^+\nu)/dy$
ID: 6233 Npts: 10

Fit to LHC W/Z Data w/ Normalization



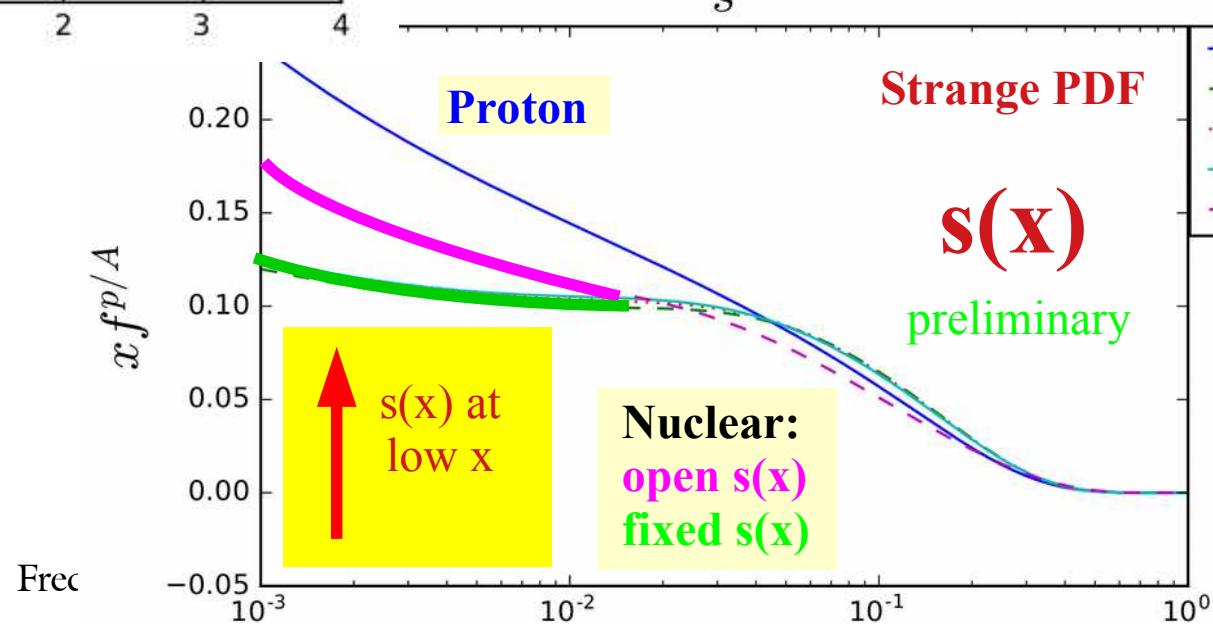
Fit to LHC W/Z Data w/ Normalization



Fit + Normalization

- Improved $\chi^2/\text{d.o.f.}$
- Seems to prefer larger strange PDF

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



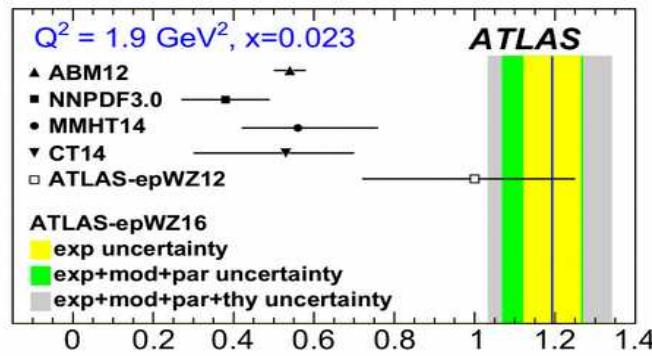
... thanks & conclusions

Thanks to my nCTEQ colleagues

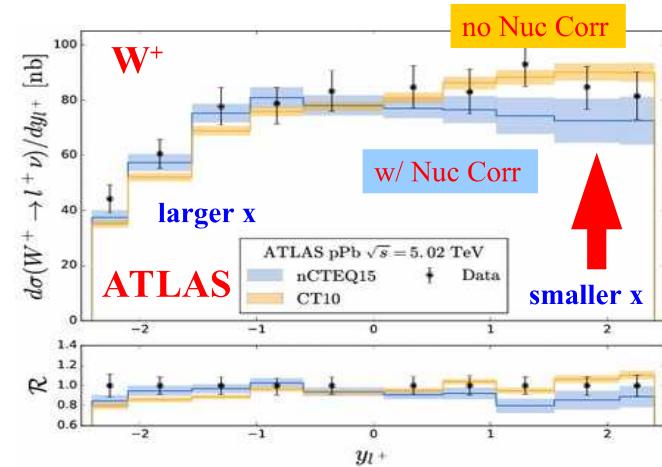
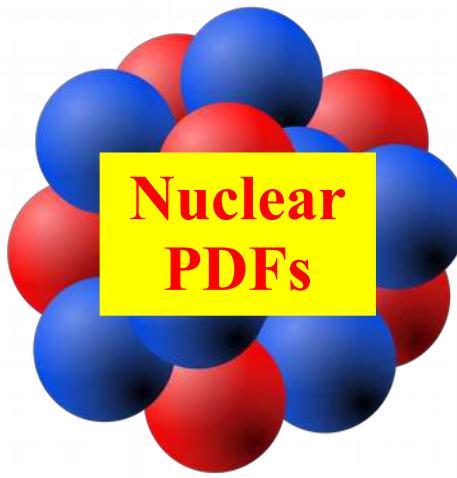
nCTEQ
nuclear parton distribution functions



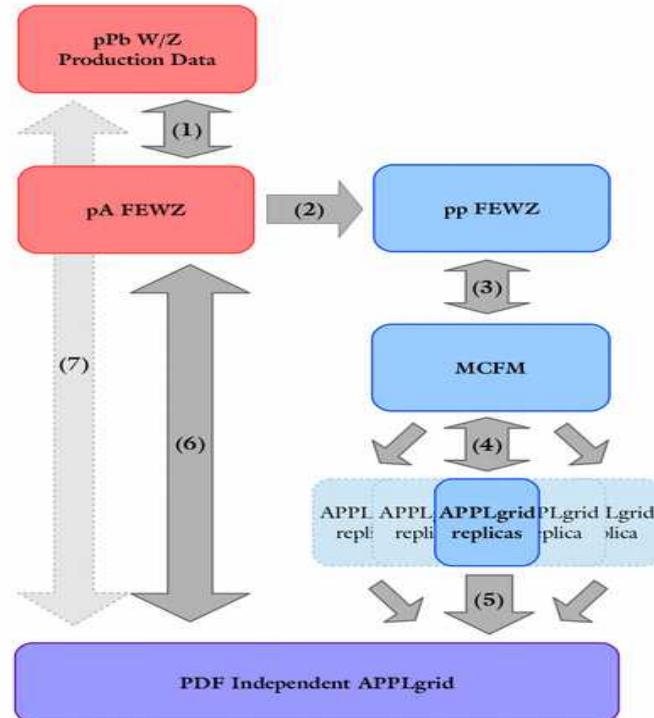
New Data & New Theoretical Tools



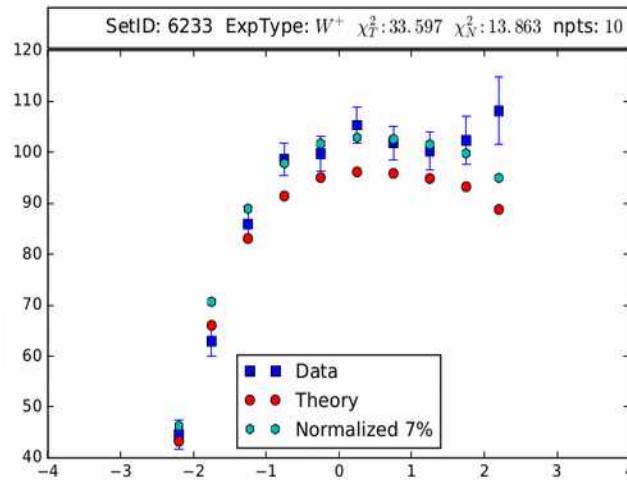
The Strange PDF Puzzle



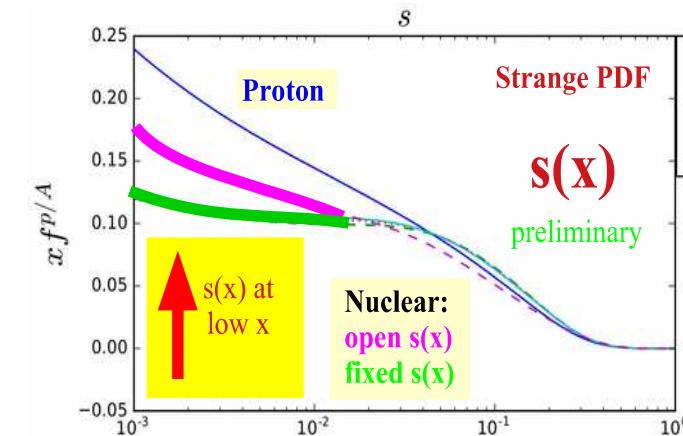
Tensions Evident



New Theory Tools

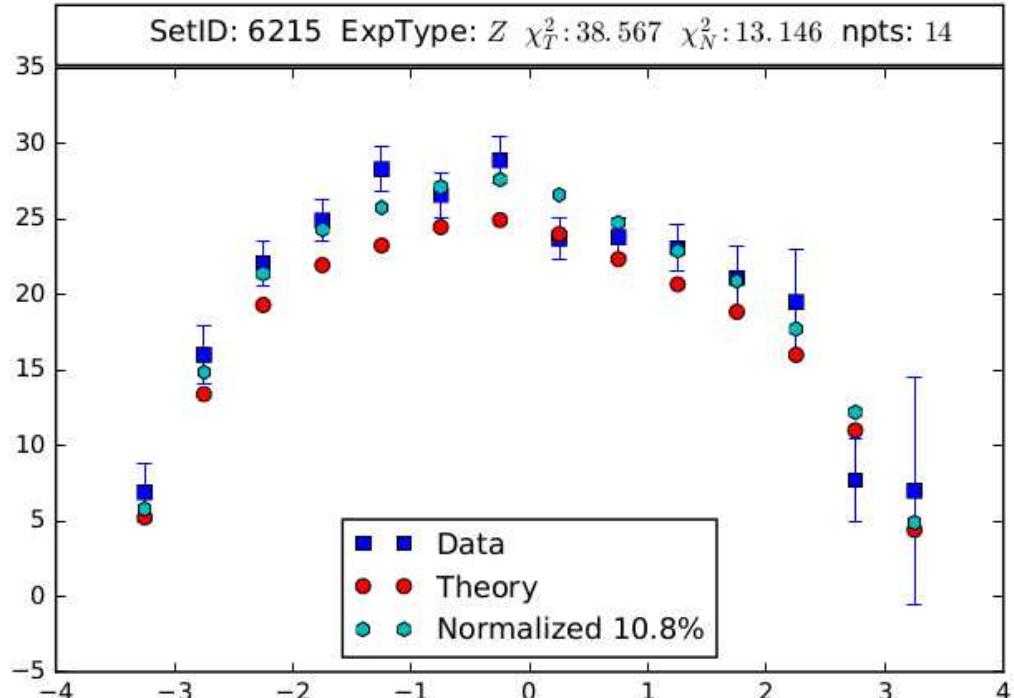
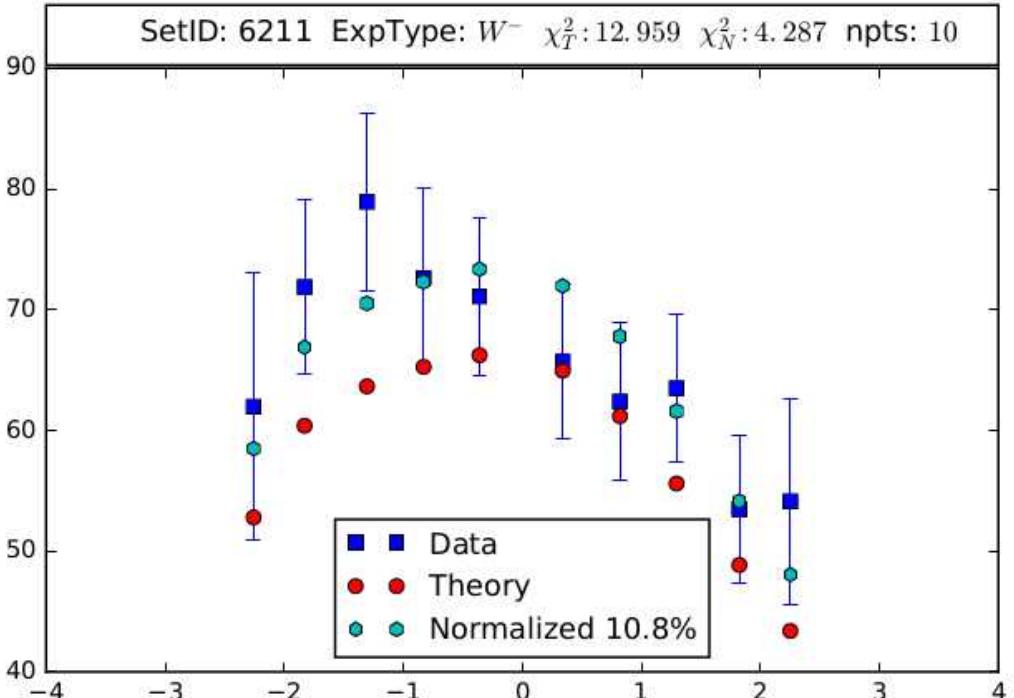
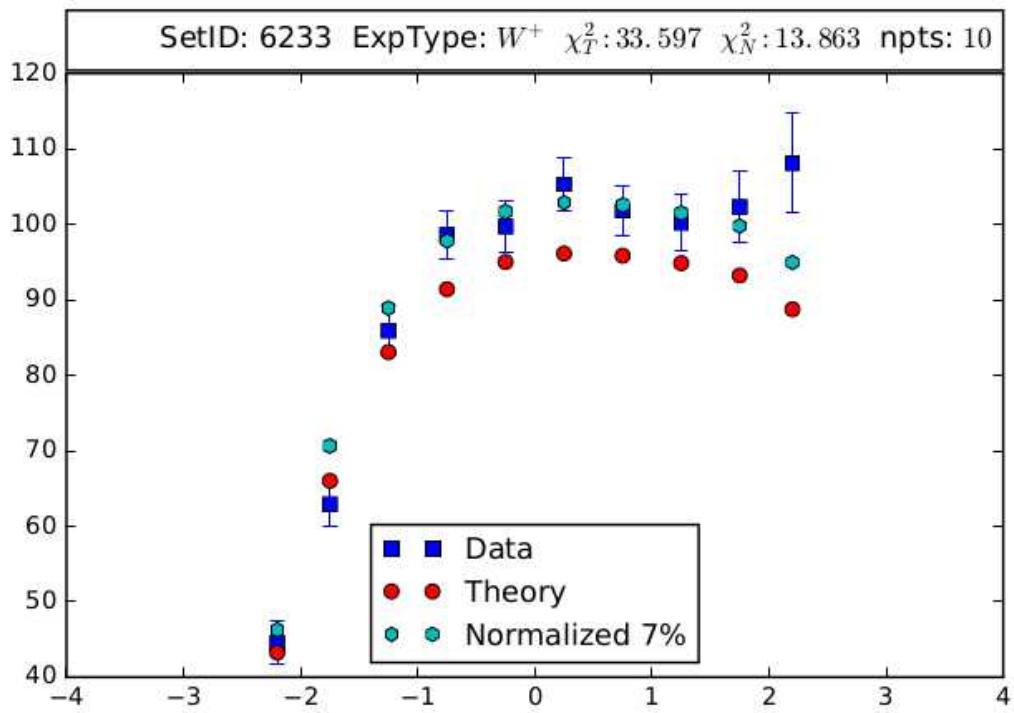
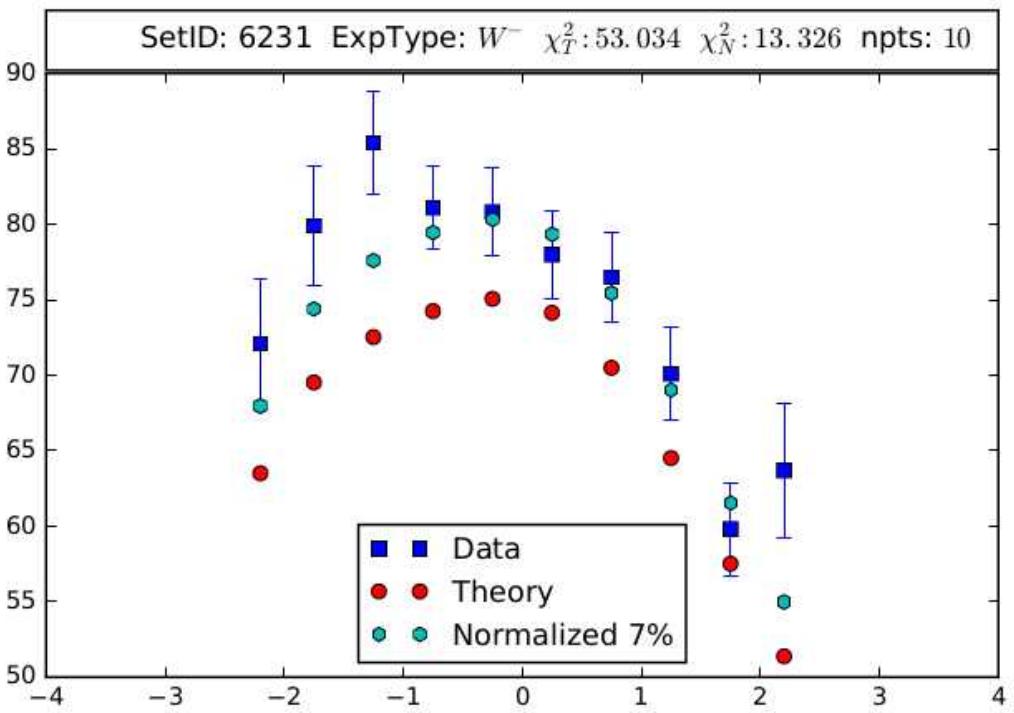


New Analyses



New Perspectives

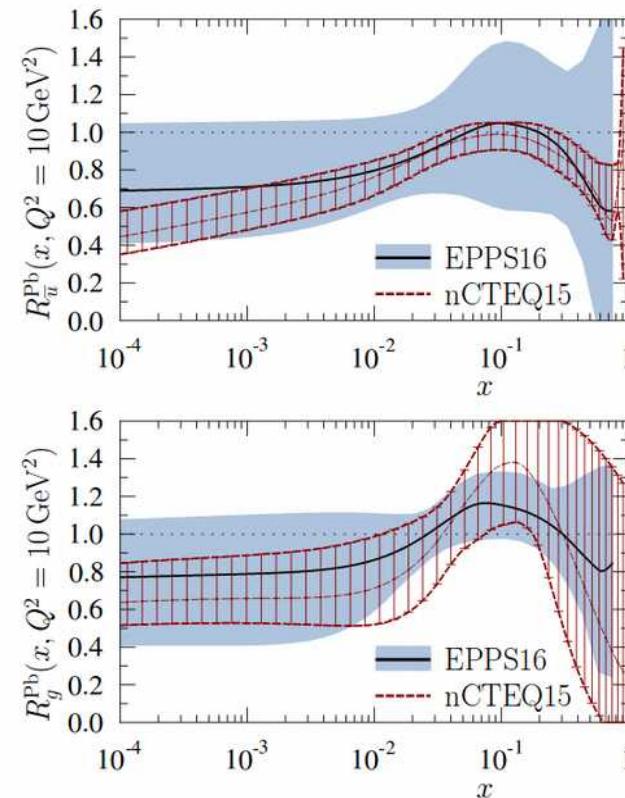
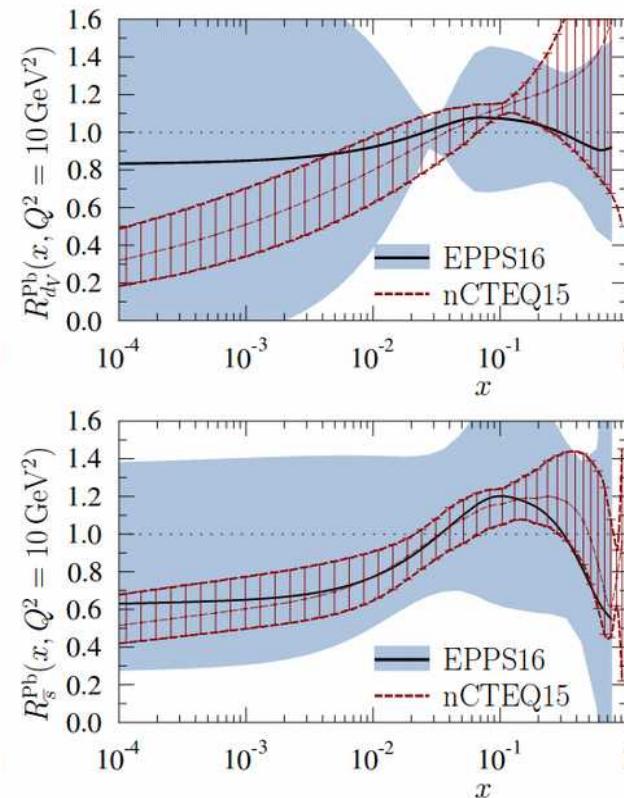
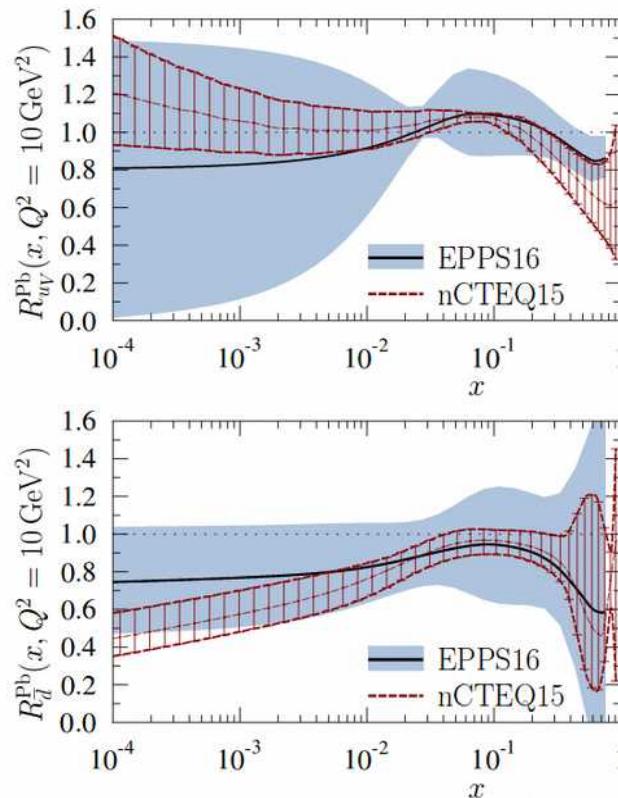
BACKUP



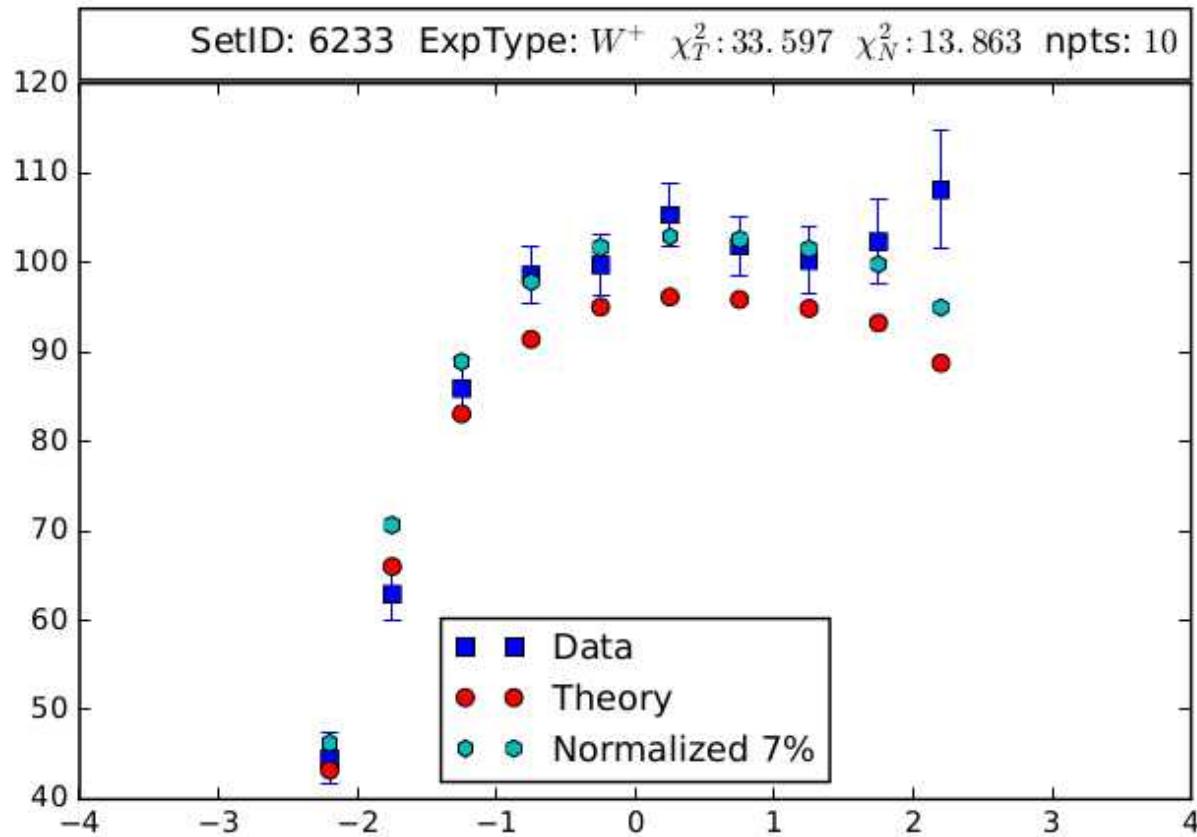
EPPS16



- 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)



Fit to LHC W/Z Data w/ Normalization



2 σ normalization
applied to LHC sets

- Improved $\chi^2/\text{d.o.f.}$
- Additional normalization could improve χ^2 more

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

Normalized {

Penalty

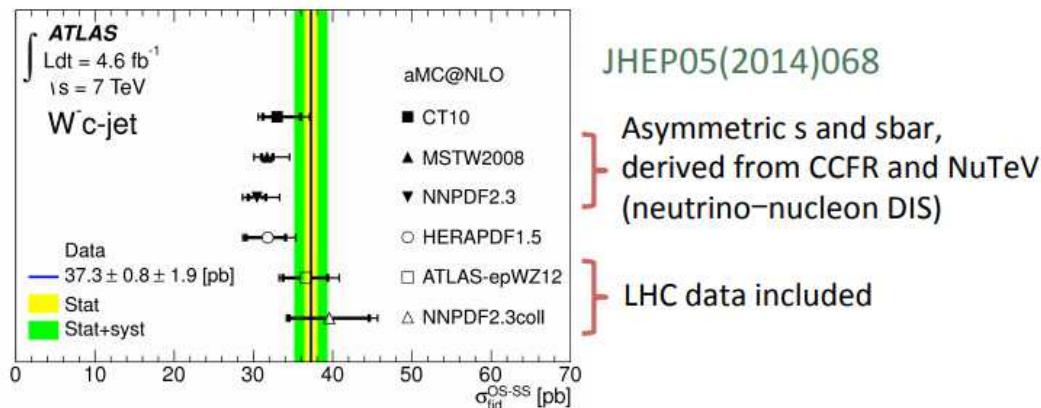
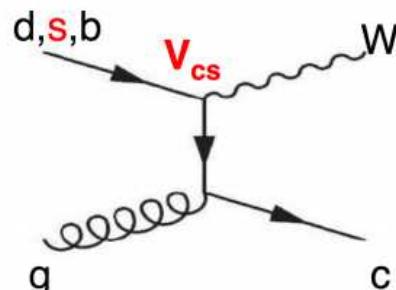
... earlier this week we heard ...

LHC Physics and EIC

Shima Shimizu (KEK 協力研究員)

Charm-tagged Charged Current DIS

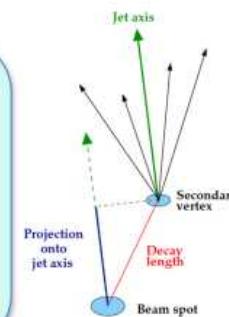
- ◆ If a charm is tagged in CC DIS, the cross section has a sensitivity to the intrinsic strange.
- ◆ Strange quark distribution is not well determined.
 - ATLAS data prefers more strangeness than fixed target data?



- ◆ 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

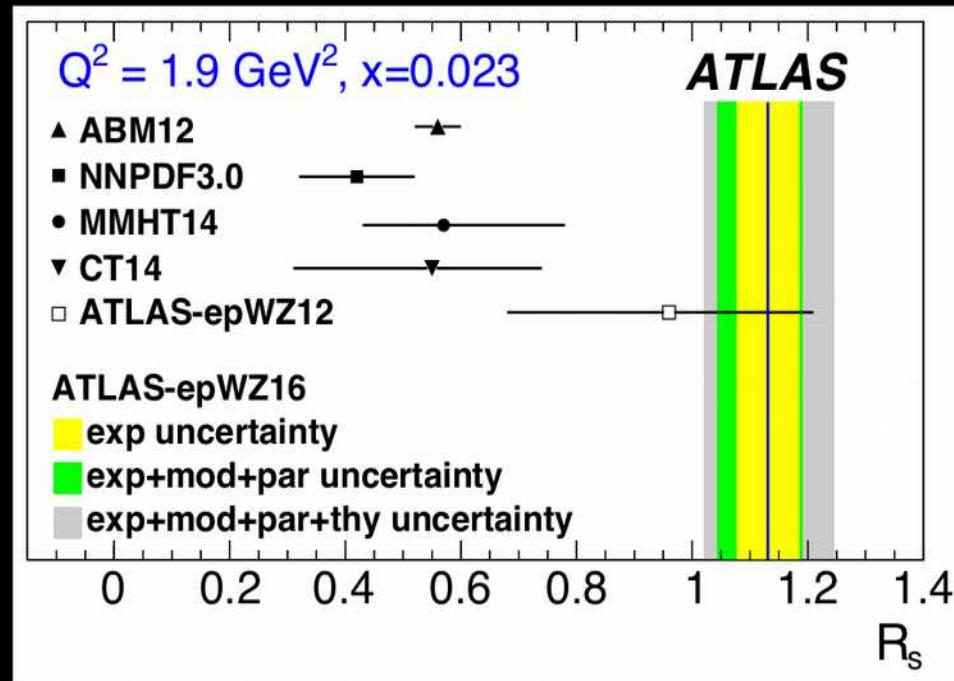
At EIC
($\sqrt{s} \sim 70 \text{ GeV}$, $Q^2 > 100 \text{ GeV}^2$):
 $\sigma(e^+p \rightarrow \nu_e + c + X) \sim 0.1 \text{ pb}$
 \Rightarrow with $10 \text{ fb}^{-1}/\text{year}$
 $\Rightarrow \sim 1000 \text{ events/year}$



... at DIS2017 we heard ...

Electroweak and QCD Measurements at the Large Hadron Collider Strangeness in the Proton

arXiv:1612.03016

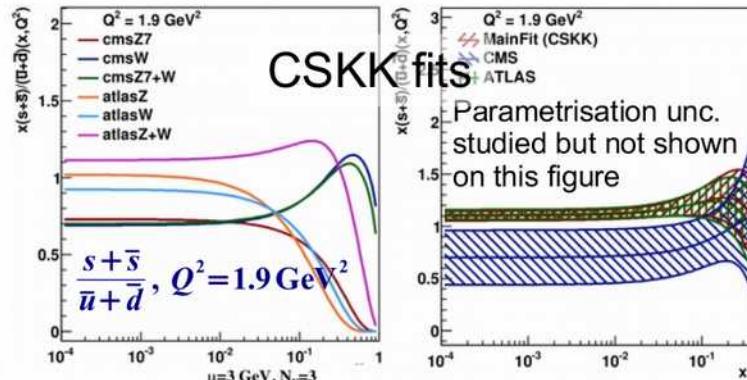


$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}} = 1.13 \pm 0.05 \text{ (exp)} \pm 0.02 \text{ (mod)} \stackrel{+0.01}{-0.06} \text{ (par)}$$

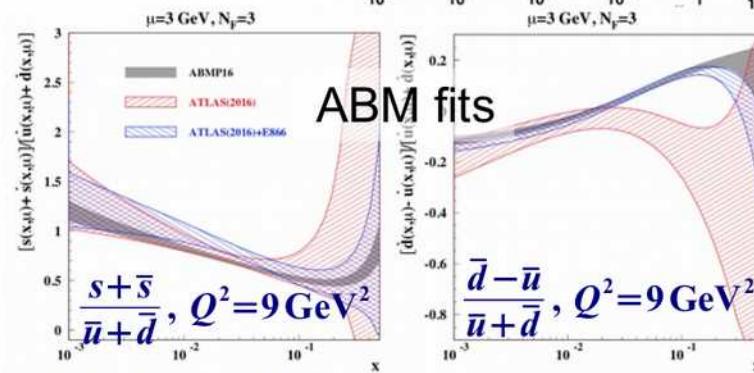
Fits using ATLAS and CMS W+DY data



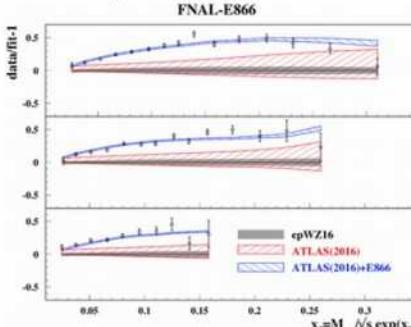
- Cooper-Sarkar & Wichmann (CSKK fit): compatibility of ATLAS and CMS data
- ABM group: revisit PDF parametrisation and compatibility with other data
- Not shown: NNPDF3.1 also investigates strangeness



CSKK (using “ATLAS” parametrisation): ATLAS and CMS data are compatible. Fit results in unsuppressed strange sea. Parametrisation and d(\bar{b})-u(\bar{b}) 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{b})-u(\bar{b}) and strangeness together.

→ can improved d(\bar{b})-u(\bar{b}) 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**

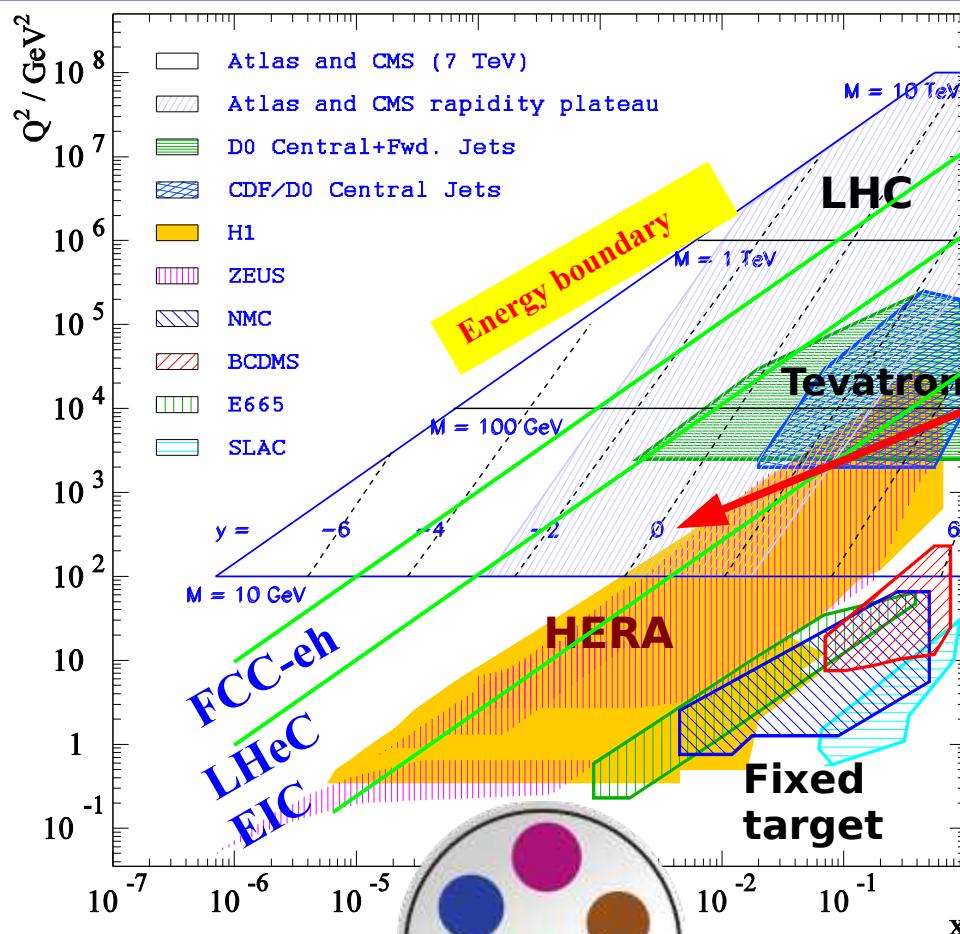
NNPDF3.1: EPJ C77 (2017) 663 [arXiv:1706.00428]; **WG1(252) 17.4. 15:00**

DIS conference, April 2018

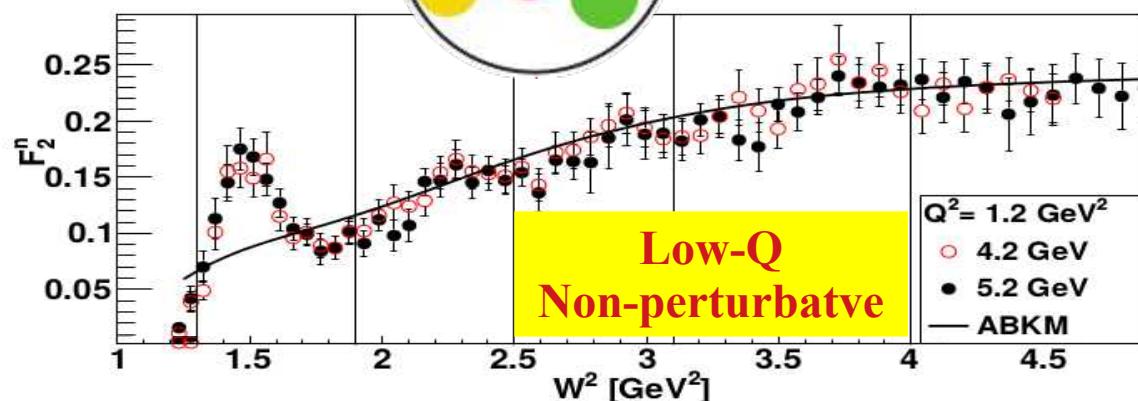
S.Schmitt, Parton density results

31

The Future Frontier: Pushing Kinematic Boundaries + Innovative Ideas³⁹

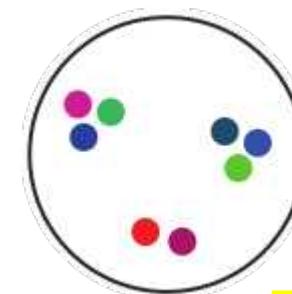


**Low-x
Shadowing
Recombination
Resummation**

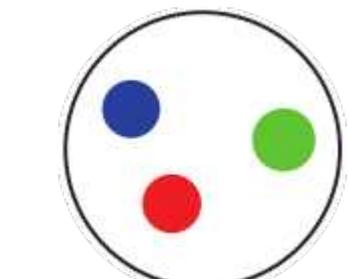


**Low-Q
Non-perturbative**

Precision



**Hi-x
Higher Twist**



QCD factorization:

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

Experimental Data:

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

Theory:

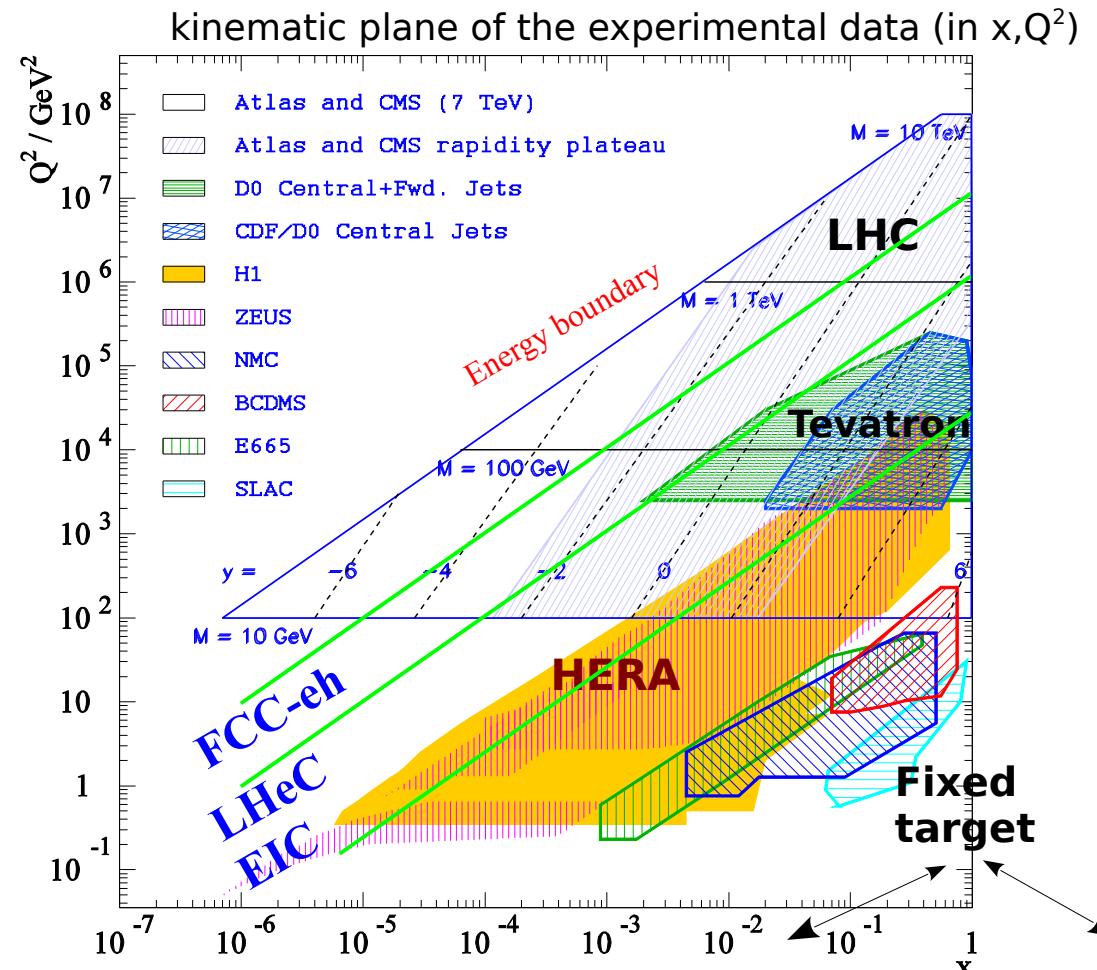
→ intense theoretical developments

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



Precision!!!

