NUCLEAR PARTON DISTRIBUTION FUNCTIONS

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OUTLINE

1. Motivation for nuclear PDFs
2. Review of available nPDFs
3. Details of nuclear CTEQ analysis
4. Future experiments and nPDF needs

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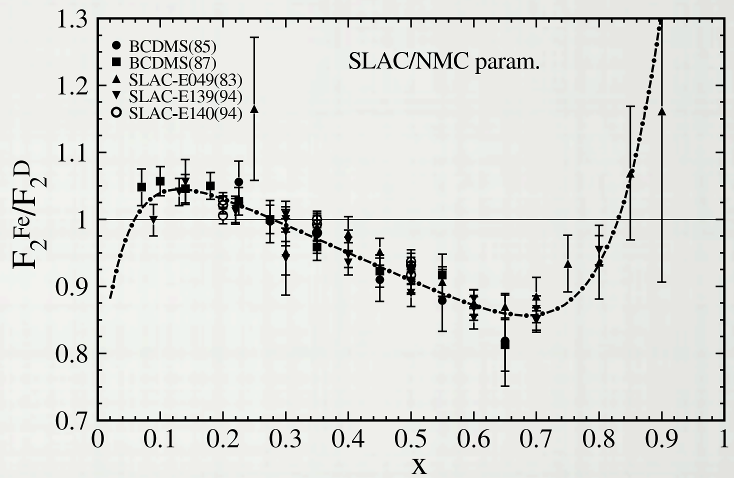
MOTIVATION

- What are nuclear parton density functions (nPDF) ?
  - parton densities for partons in bound proton & neutron



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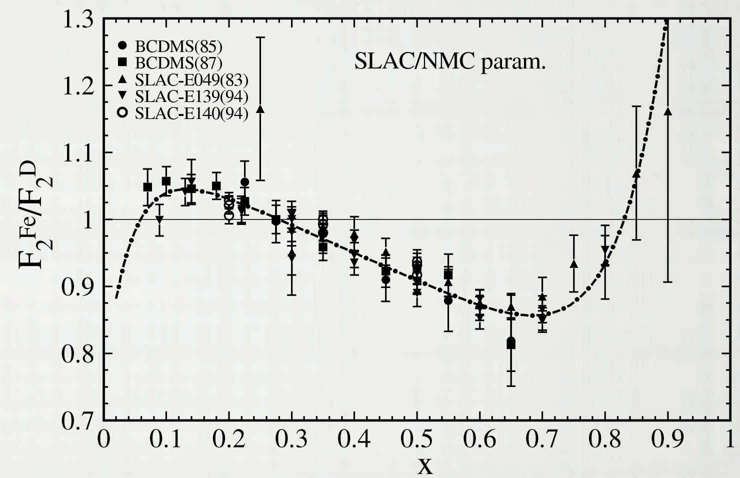
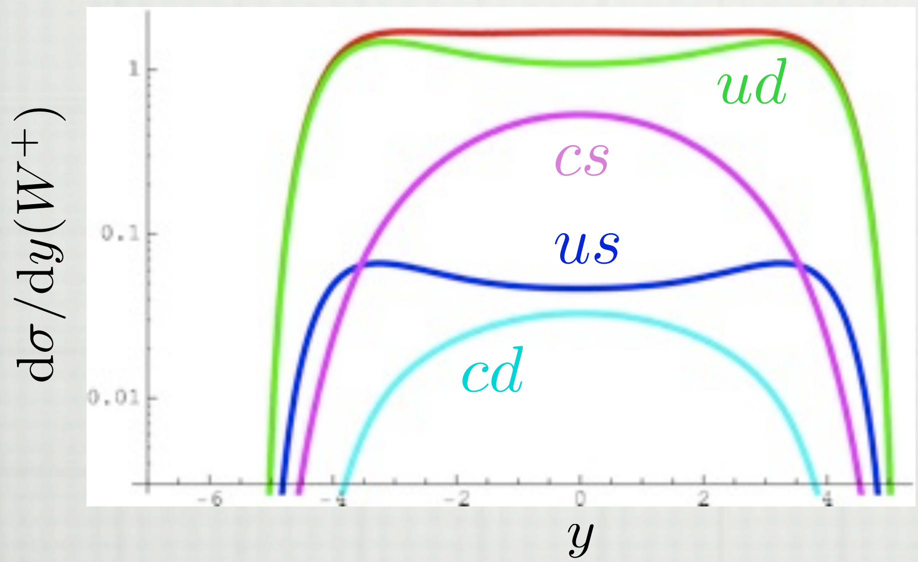


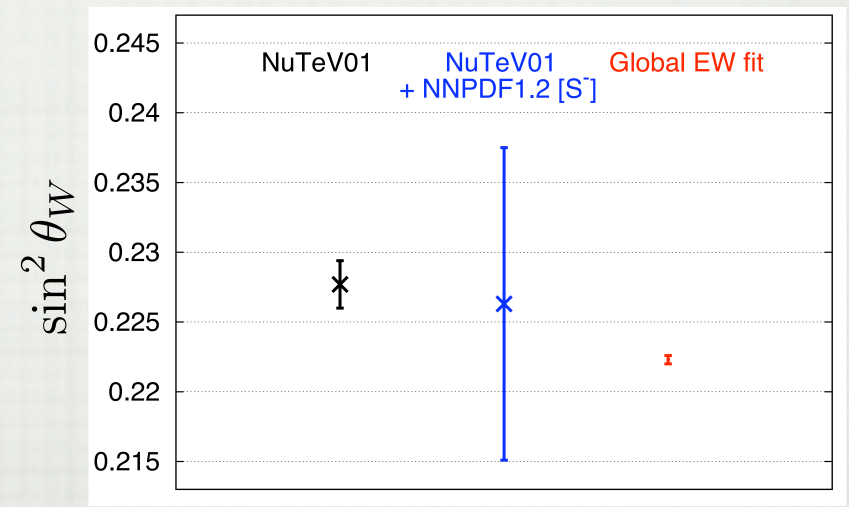
- Where are nuclear parton density functions useful ?

1. **Strange quark content of the proton**

   (anti-)strange PDF from (anti-)neutrino DIS with heavy nuclei - nuclear effects important



W-boson production @ LHC



weak mixing angle from NuTeV experiment

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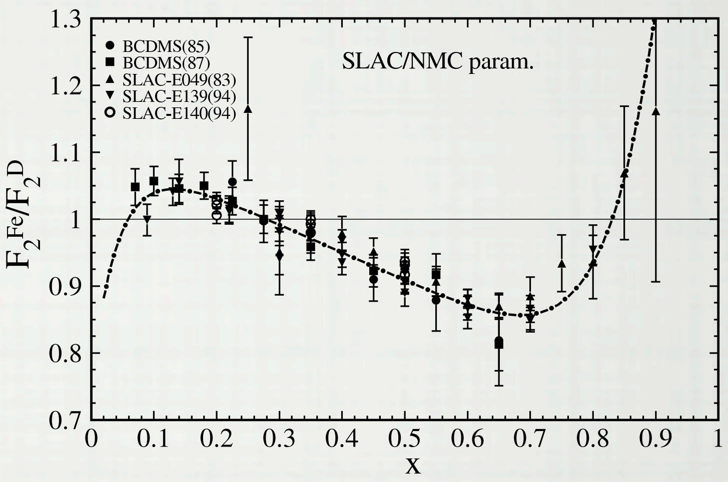

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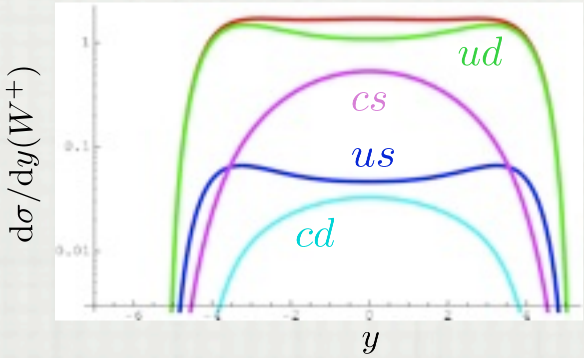

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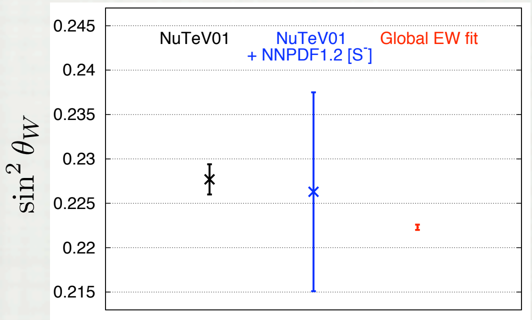

weak mixing angle from NuTeV experiment

2. **Heavy ion collisions @ RHIC, LHC**

   lead & gold heavy nuclei - nuclear effects in gluon PDF substantial

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NPDF REVIEW

- Review of existing global analyses of nuclear PDF

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NPDF REVIEW

- Review of existing global analyses of nuclear PDF

1. Multiplicative nuclear correction factor

$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i(x_N, Q_0^2)$$

free parton density

Hirai, Kumano, Nagai [PRC76(2007)065207] arXiv: 0709.0338

Eskola, Paukkunen, Salgado [JHEP0904(2009)065] arXiv: 0902.4154

de Florian, Sassot, Stratmann, Zurita [PRD85(2012)074028]arXiv: 1112.6324

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2. Convolution relation

$$f_i^A(x_N, Q_0^2) = \int_{x_N}^{A} \frac{\mathrm{d}y}{y} W_i(y, A, Z) f_i(x_N/y, Q_0^2)$$

nucleon density in nucleus with y/A mom.fraction

de Florian, Sassot [PRD69(2004)074028] hep-ph/0311227

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3. Native nuclear PDF

$$f_i^A(x_N, Q_0^2) = f_i(x_N, A, Q_0^2) \qquad f_i(x_N, Q_0^2) = f_i(x_N, A = 1, Q_0^2)$$

bound parton density

free parton density

nCTEQ [PRD80(2009)094004] arXiv: 0907.2357

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NPDF REVIEW

- Review of existing global analyses of nuclear PDF

DE FLORIAN, SASSOT'04 [PRD69(2004)074028]
LO, NLO

χ^2/dof = 0.76

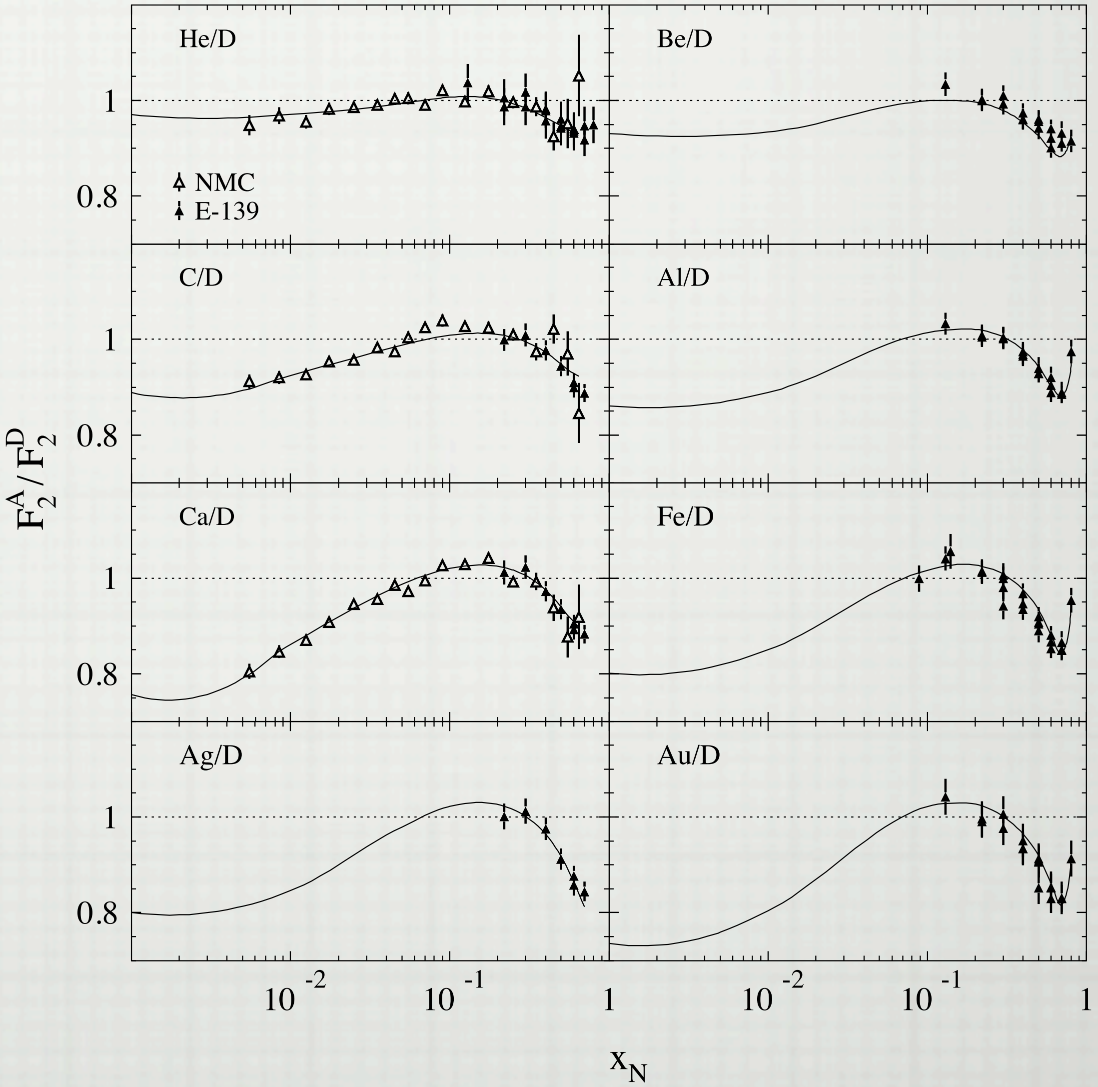
- first NLO analysis of nuclear data
- the only group using convolution relation

$$f_i^A(x_N, Q_0^2) = \int_{x_N}^{A} \frac{\mathrm{d}y}{y} W_i(y, A, Z) f_i(x_N/y, Q_0^2)$$

- typical nucleon density for valence quarks

$$W_v(y, A, Z) = A[a_v \delta(1 - \epsilon_v - y) + (1 - a_v)\delta(1 - \epsilon_{v'} - y)]$$
$$+ n_v \left(\frac{y}{A}\right)^{\alpha_v} \left(1 - \frac{y}{A}\right)^{\beta_v} + n_s \left(\frac{y}{A}\right)^{\alpha_s} \left(1 - \frac{y}{A}\right)^{\beta_s}$$

- the only framework using evolution in Mellin space & have PDFs also for $x_N > 1$
- only standard DIS data sets (semi-global)
- no error analysis

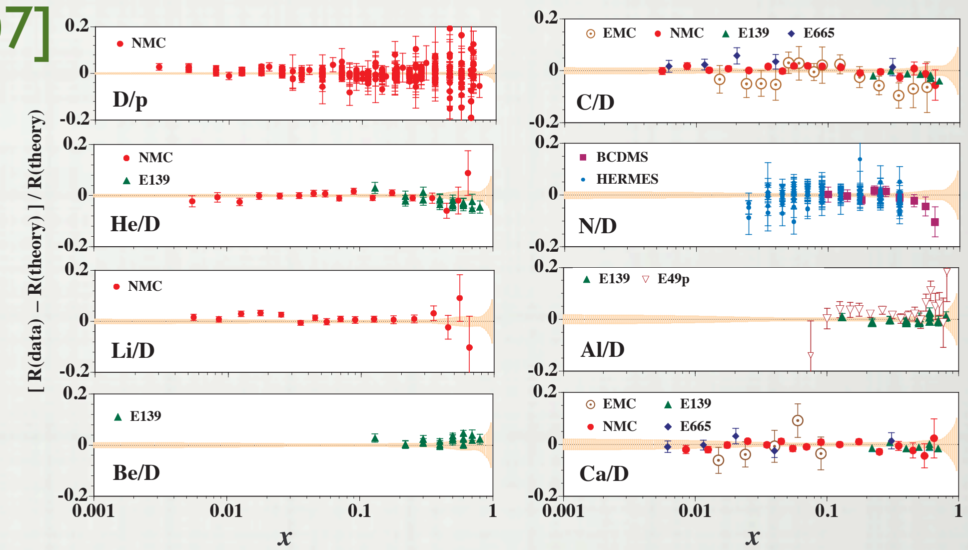


NPDF REVIEW

- Review of existing global analyses of nuclear PDF

χ^2/dof = 1.2

HIRAI, KUMANO, NAGAI'07 [PRC76(2007)065207]
LO, NLO, ERROR PDFS



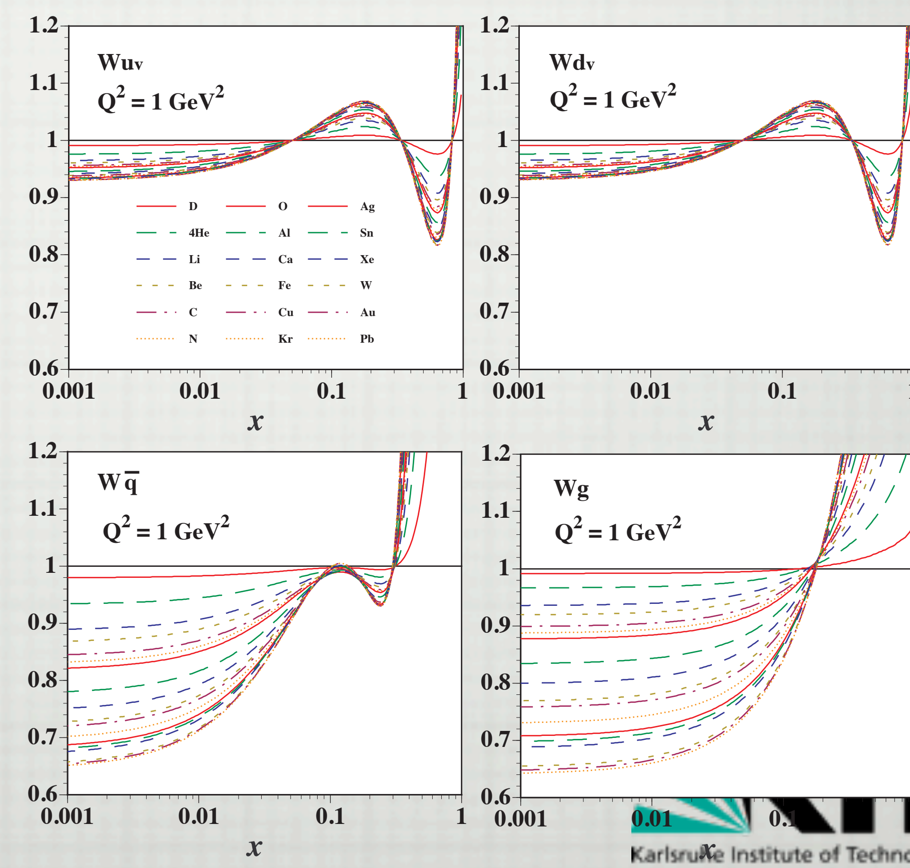
- uses multiplicative factor

$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i(x_N, Q_0^2)$$

where proton PDF in MRST 1998 and factor

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

- neglects region x>1
- includes all current DIS & DY data set (same as our analysis - discussed later)
- use Hessian method to produce error PDFs



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NPDF REVIEW

- Review of existing global analyses of nuclear PDF

ESKOLA, PAUKKUNEN, SALGADO'09 [JHEP0904(2009)065]
LO, NLO, ERROR PDFS

$\chi^2/\mathrm{dof} = 0.8$

- uses multiplicative factor

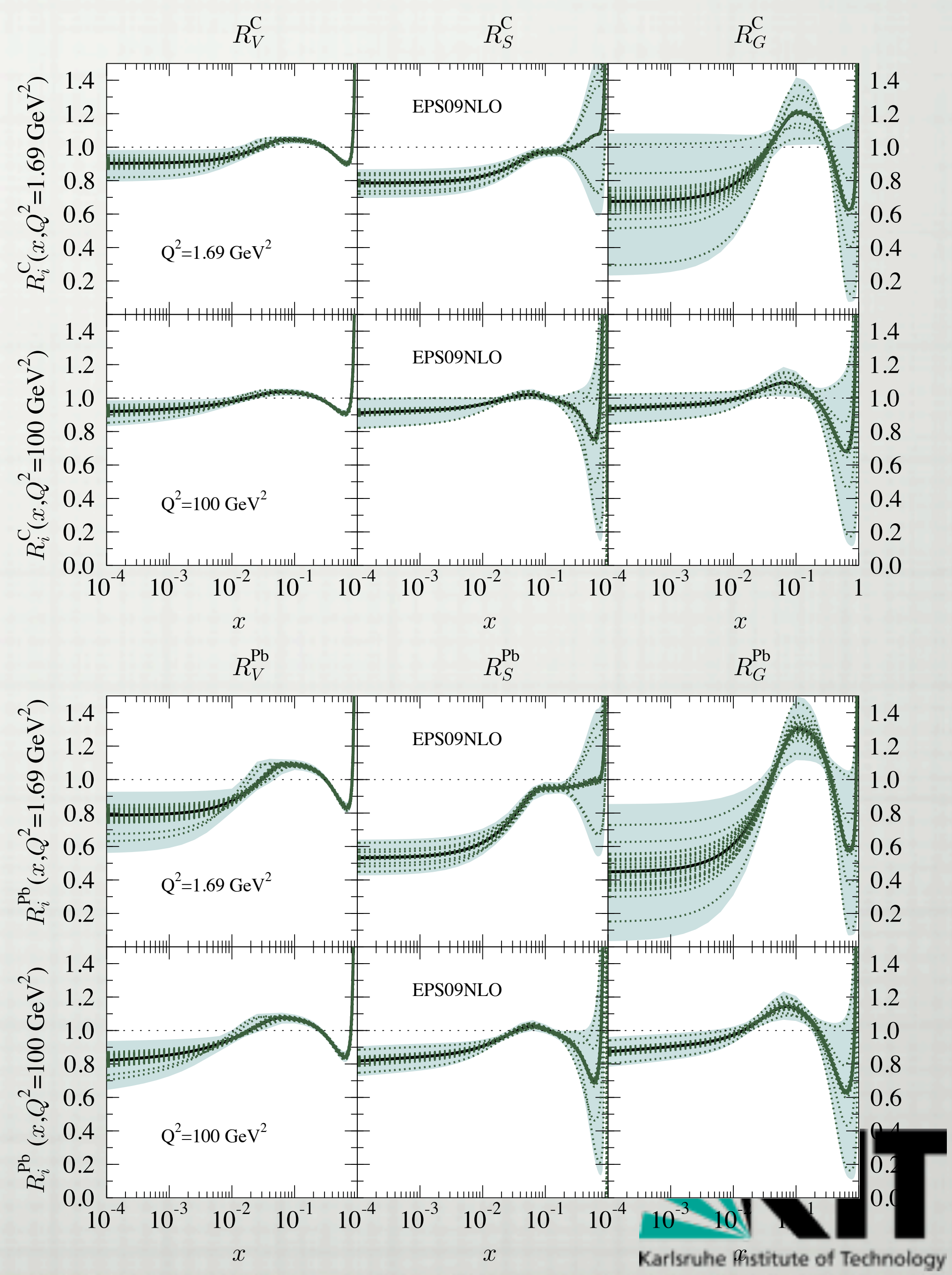
$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i(x_N, Q_0^2)$$

where proton PDF in CTEQ6.1M and factor is a complicated piecewise defined function

$$R_i(x, A, Z) = \begin{cases} a_0 + (a_1 + a_2 x)(e^{-x} - e^{-x_a}) & x \leq x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \leq x \leq x_e \\ c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x_e \leq x \leq 1 \end{cases}$$

with A-dependent parameters

- neglects region x>1
- includes all current DIS & DY data set & π^0 RHIC data to constrain gluon
- use Hessian method to produce error PDFs



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NPDF REVIEW

- Review of existing global analyses of nuclear PDF

DE FLORIAN, SASSOT, STRATMANN, ZURITA [PRD85(2012)074028]
LO, NLO, ERROR PDFS

- uses multiplicative factor

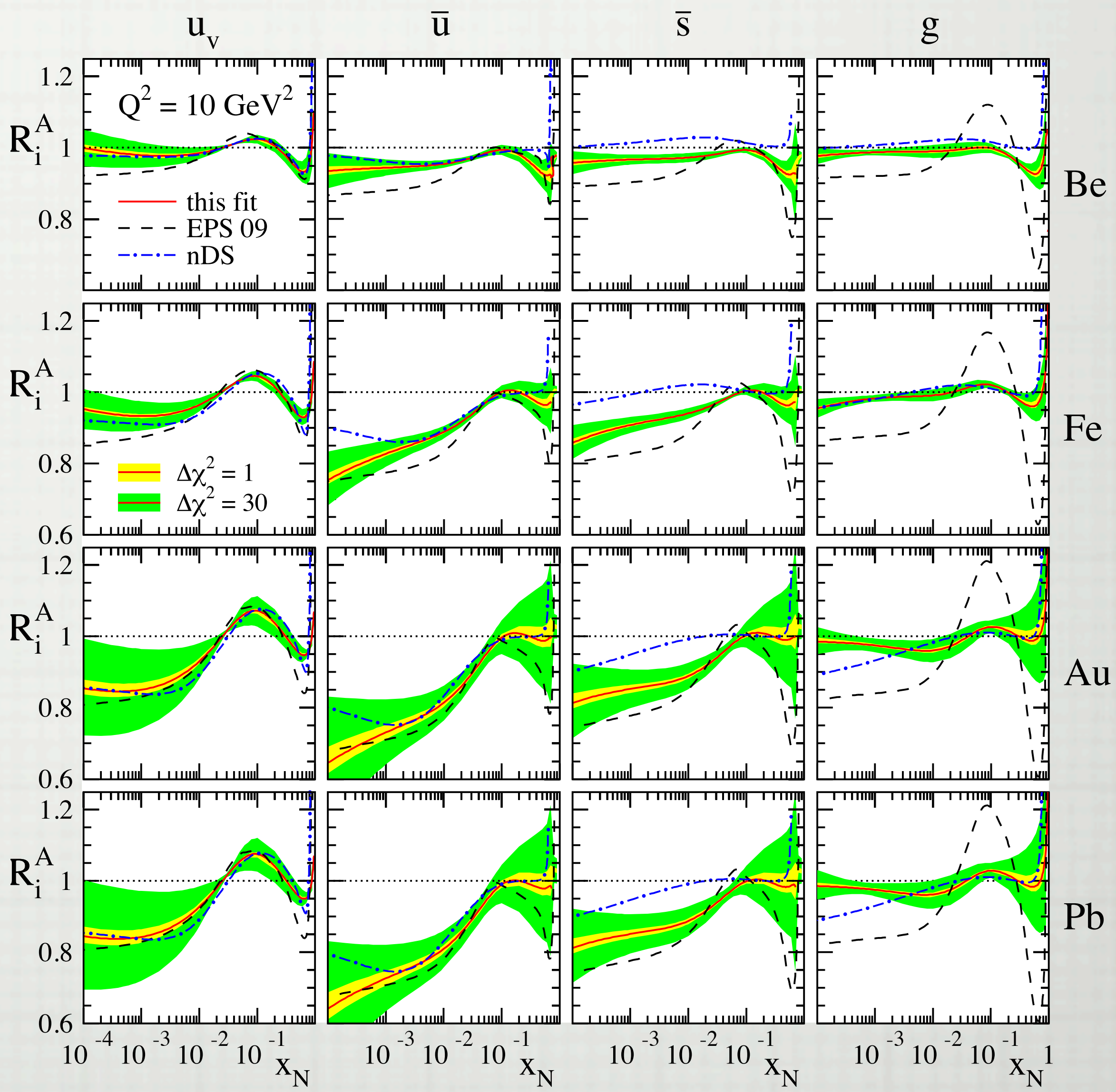
$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i(x_N, Q_0^2)$$

where proton PDF in MSTW08 and factor is a complicated function different for each flavour

$$R_v^A(x, Q_0^2) = \epsilon_1\, x^{\alpha_v} (1-x)^{\beta_1} \left(1 + \epsilon_2 (1-x)^{\beta_2}\right) \times \times \left(1 + a_v (1-x)^{\beta_3}\right)$$

$$R_s^A(x, Q_0^2) = R_v^A(x, Q_0^2)\, \frac{\epsilon_s}{\epsilon_1} \frac{1 + a_s x^{\alpha_s}}{a_s + 1}$$

$$R_g^A(x, Q_0^2) = R_v^A(x, Q_0^2)\, \frac{\epsilon_g}{\epsilon_1} \frac{1 + a_g x^{\alpha_g}}{a_g + 1}$$



- includes all current DIS & DY data set & π^0 RHIC data and $F_2^{\nu A}$ from neutrino data
- use Hessian method to produce error PDFs

nCTEQ

- CTEQ framework for nuclear PDF - based on CTEQ6M proton fit
  - functional form for bound protons same as for free proton PDF (restrict x to 0<x<1)

$$x\, f_k(x,Q_0) = c_0\, x^{c_1} (1-x)^{c_2} e^{c_3 x} (1+e^{c_4} x)^{c_5} \qquad k = u_v, d_v, g, \bar{u}+\bar{d}, s, \bar{s}$$

$$\bar{d}(x,Q_0)/\bar{u}(x,Q_0) = c_0\, x^{c_1} (1-x)^{c_2} + (1+c_3 x)(1-x)^{c_4}$$

  - coefficients with A-dependance (reduces to proton for A=1)

$$c_k \to c_k(A) \equiv c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right), \quad k = \{1,\ldots,5\}$$

  - proton coefficients $c_{k,0}$ fixed to special CTEQ6M fit without much of nuclear data
  - PDF for a nucleus with A-nucleons out of which Z-protons

$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A} f_i^{p/A}(x,Q) + \frac{A-Z}{A} f_i^{n/A}(x,Q)$$

  - Input scale and other input parameters as in CTEQ6M proton analysis

$$Q_0 = m_c = 1.3\mathrm{GeV} \qquad m_b = 4.5\,\mathrm{GeV} \qquad \alpha_s(m_Z) = 0.118$$

  - Kinematic cuts on data

$$Q > 2\,\mathrm{GeV} \qquad W > 3.5\,\mathrm{GeV}$$

nCTEQ [PRD80(2009)094004] arXiv: 0907.2357

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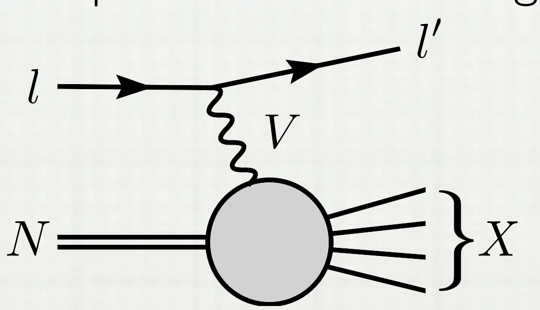
NCTEQ

- Experiments included in the analysis

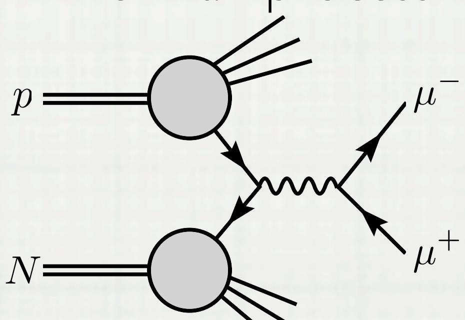
Charged lepton

Deep Inelastic Scattering



$$l + N \to l' + X$$

Drell-Yan process



$$p + N \to \mu^+\mu^- + X$$

CERN BCDMS & EMC & NMC
$N = (\mathrm{D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W})$

FNAL E-665
$N = (\mathrm{D, C, Ca, Pb, Xe})$

DESY Hermes
$N = (\mathrm{D, He, N, Kr})$

SLAC E-139 & E-049
$N = (\mathrm{D, Ag, Al, Au, Be, C, Ca, Fe, He})$

FNAL E-772 & E-886
$N = (\mathrm{D, C, Ca, Fe, W})$

1233 data points (708 after cuts)

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NCTEQ

- NPDF fit properties:
  - we fit nuclear data with NLO QCD predictions & include heavy quark effects (ACOT)
  - added nuclear observables to CTEQ fitting routines (need to treat 2 nuclei at once)

DIS: $F_2^A/F_2^{A'}$ Drell-Yan: $\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$

  - applied standard CTEQ kinematical cuts Q>2GeV & W>3.5GeV

- NPDF fit results:
  - 708 (1233) data points after (before) cuts
  - 32 free parameters - 675 degrees of freedom
  - overall χ^2/dof = 0.95
  - individually for different data sets
    - for F_2^A/F_2^D χ^2/pt = 0.92
    - for $F_2^A/F_2^{A'}$ χ^2/pt = 0.69
    - for $\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$ χ^2/pt = 1.08

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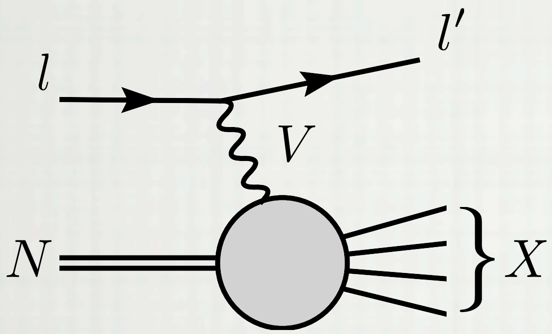
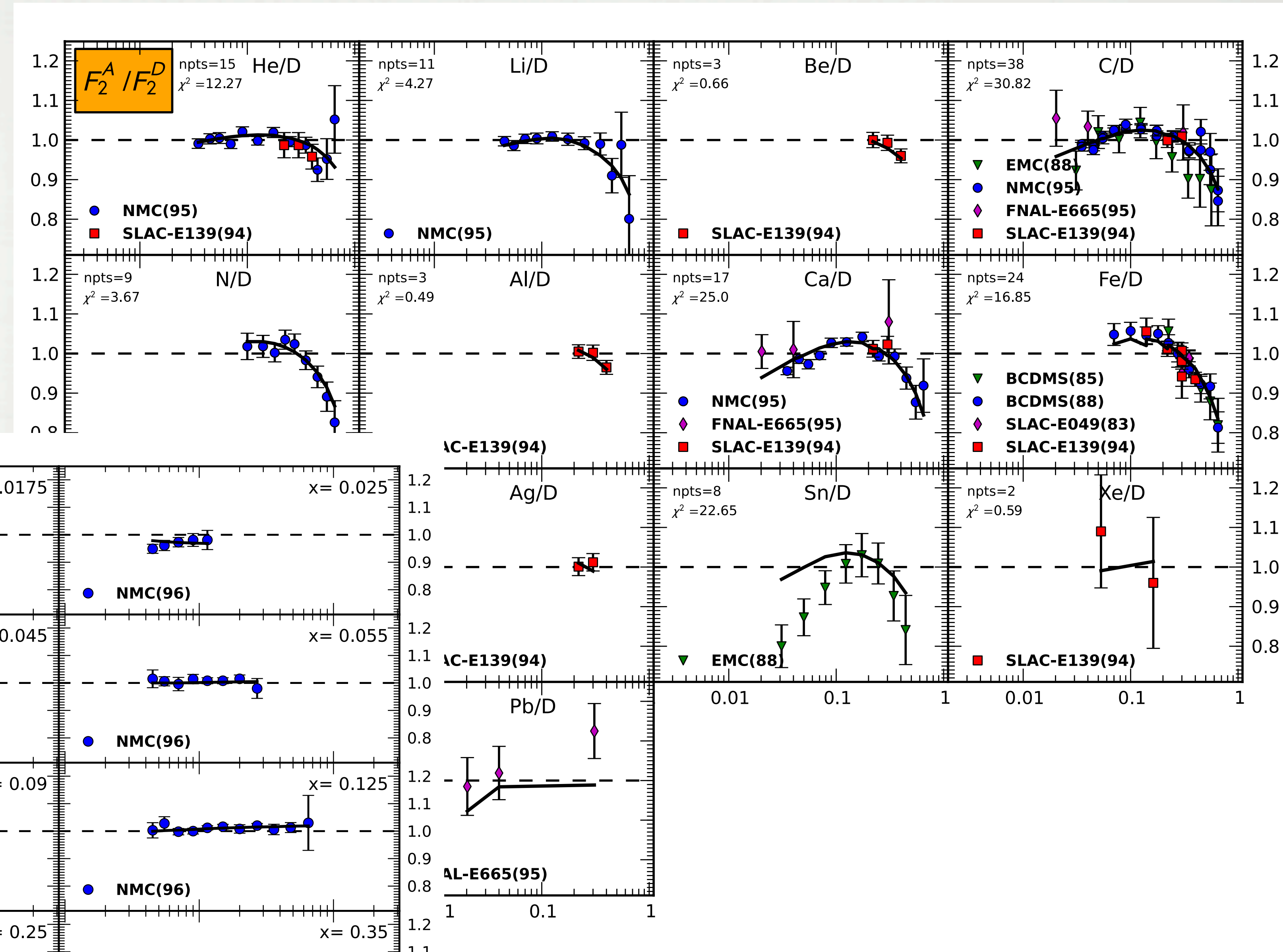
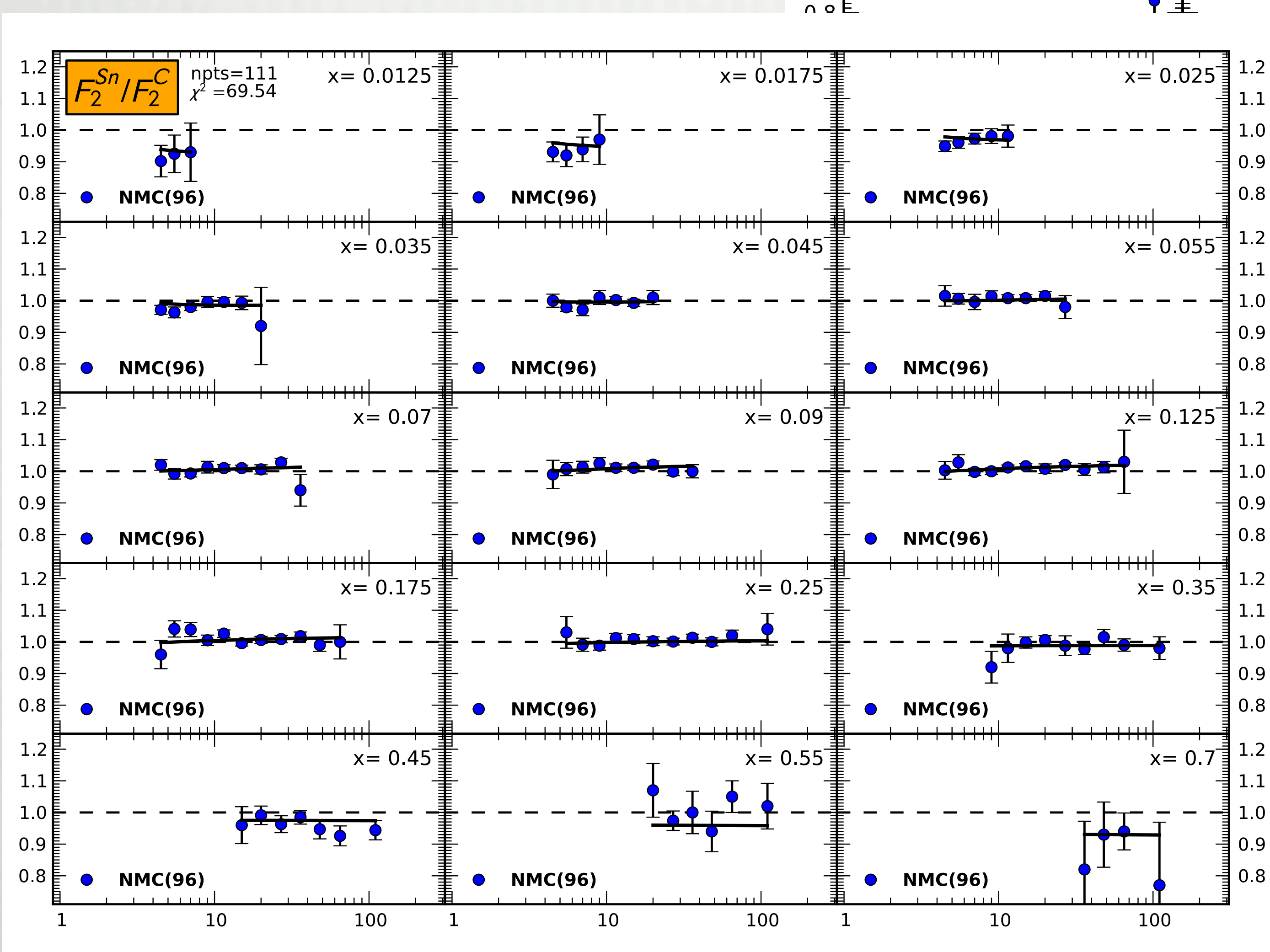
NCTEQ

- Deep Inelastic Scattering







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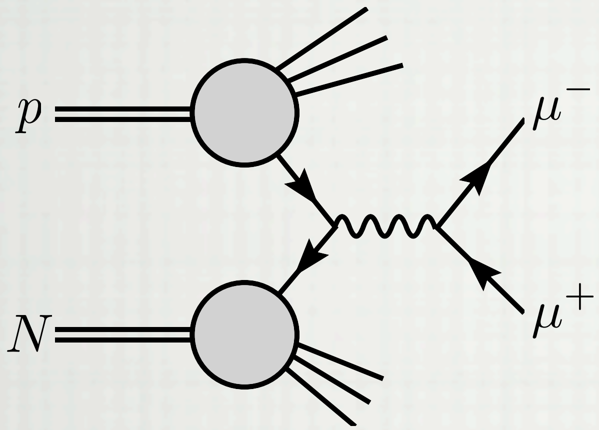
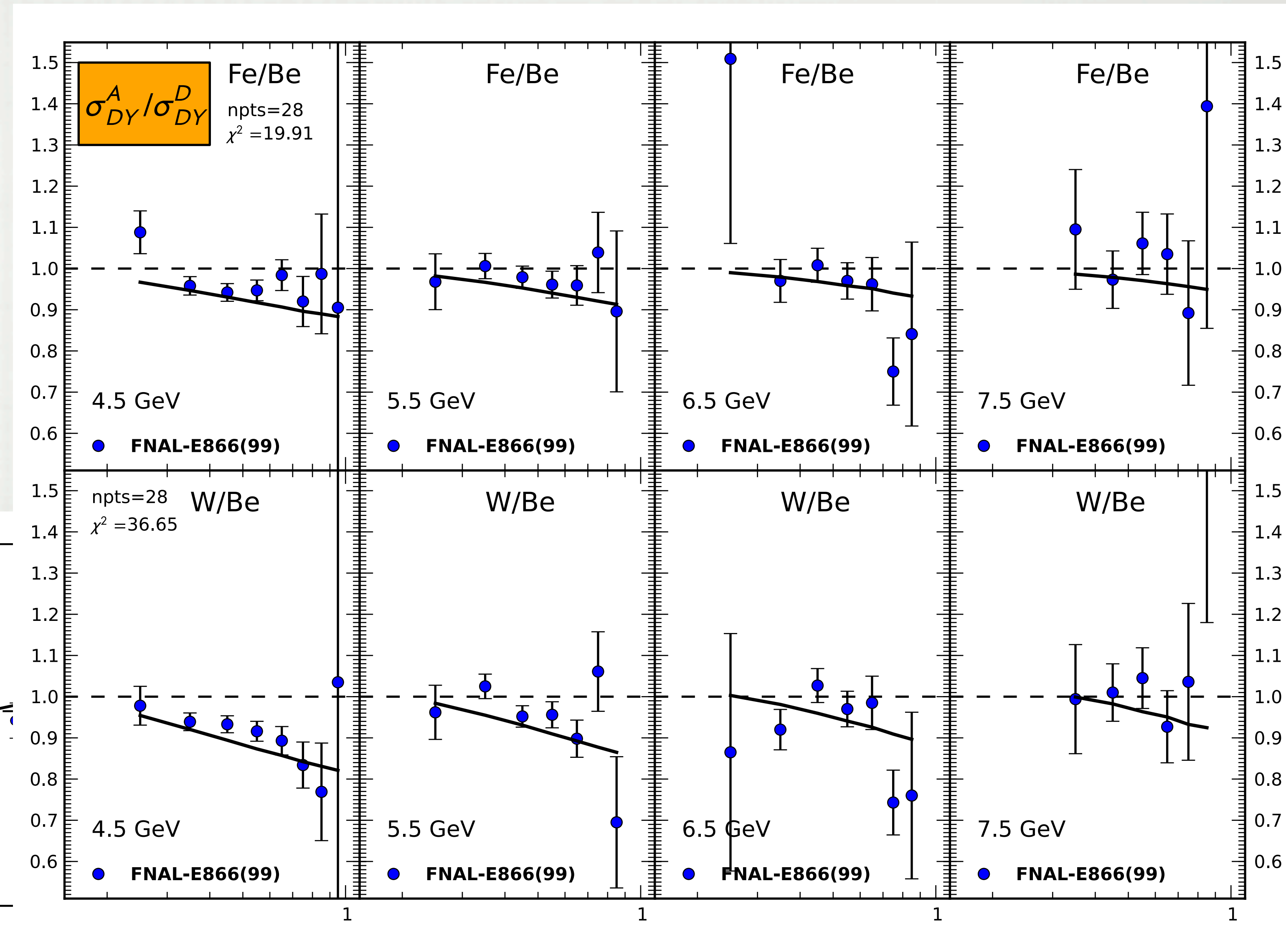
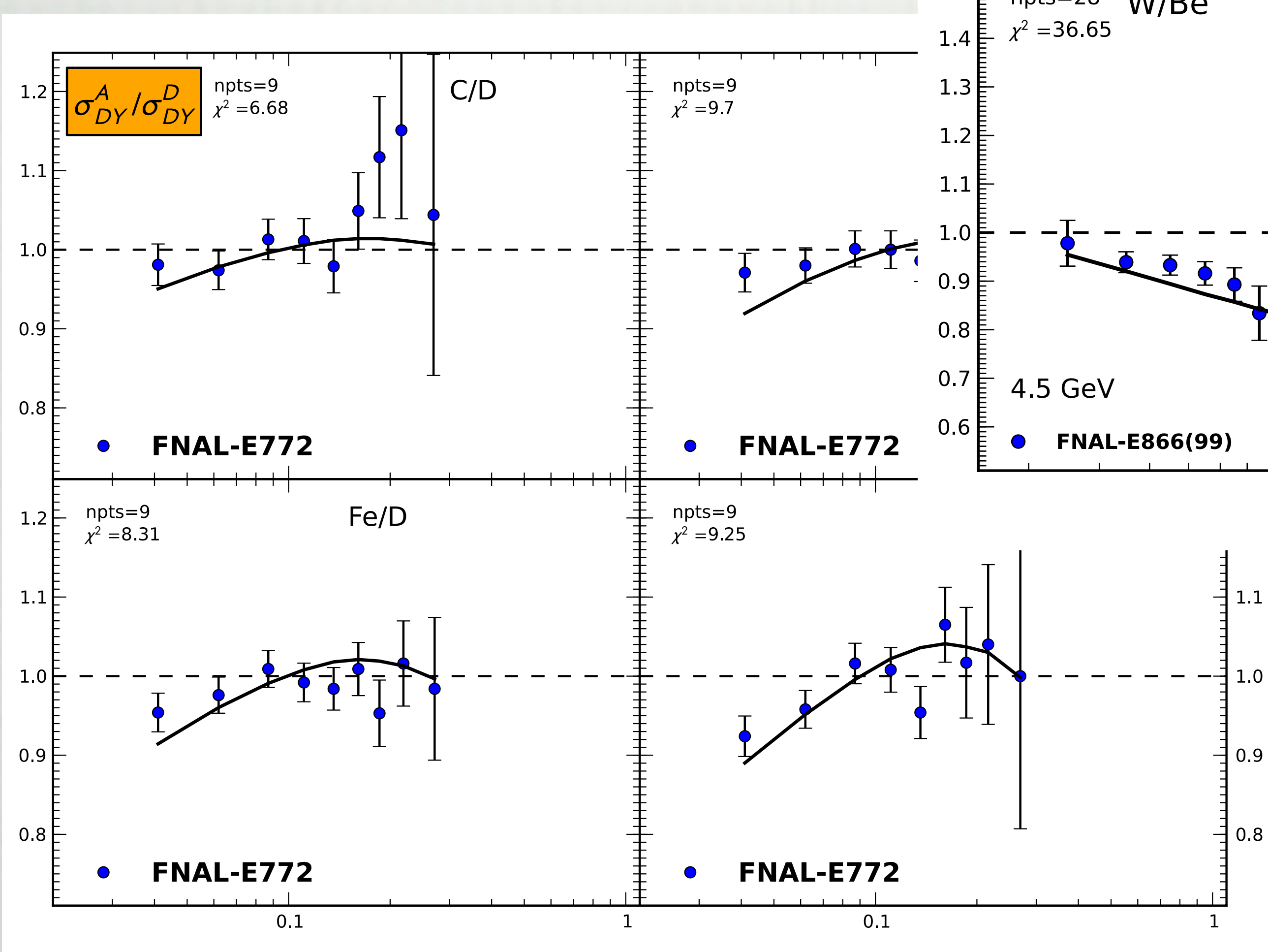
- Drell-Yan process







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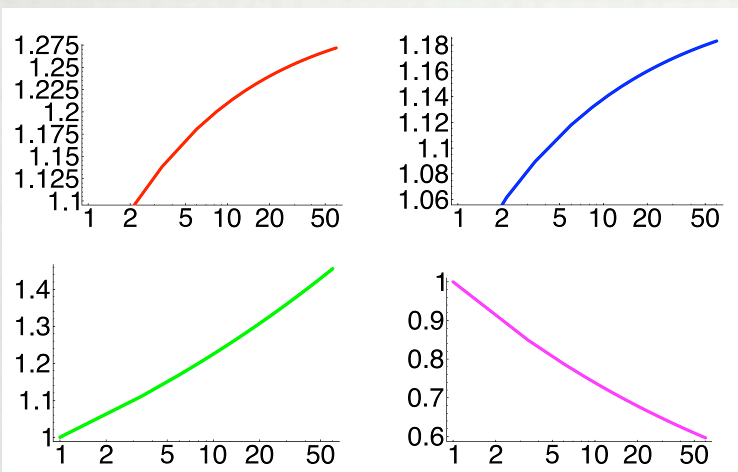
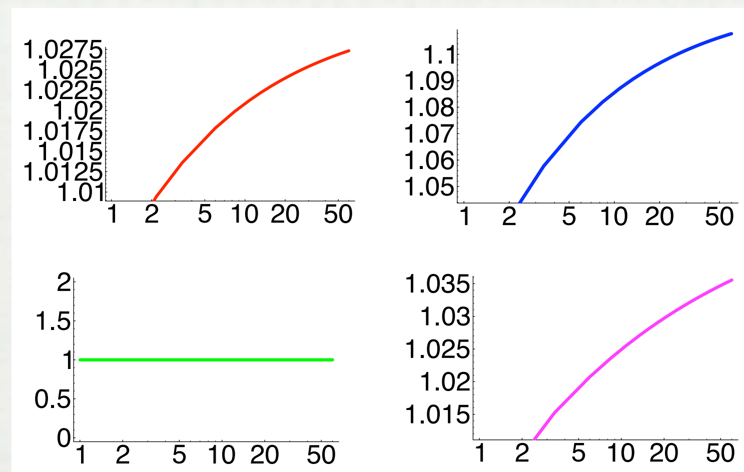
NCTEQ

- CTEQ A-dependent parameter $c_k(A)/c_{k,0}$ for parton distributions $\begin{pmatrix} d_v & u_v \\ g & \bar{u}+\bar{d} \end{pmatrix}$

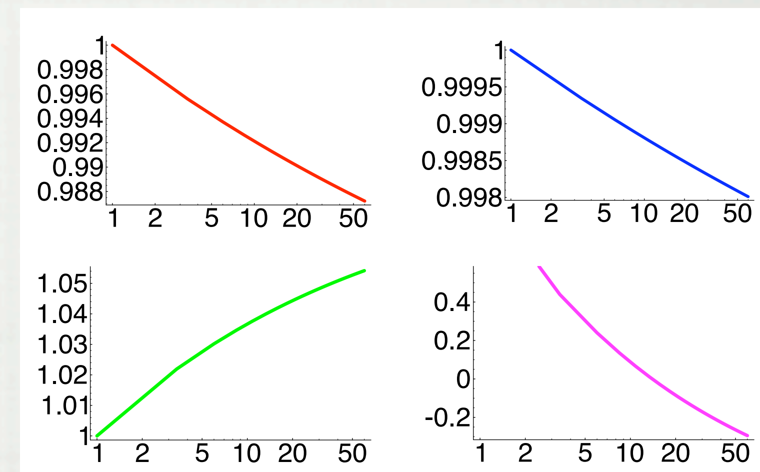
$c_1(A)/c_{k,0}$



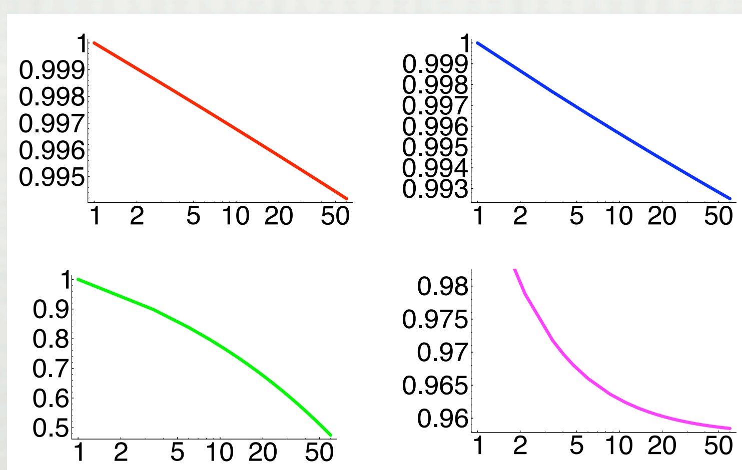
$c_2(A)/c_{k,0}$



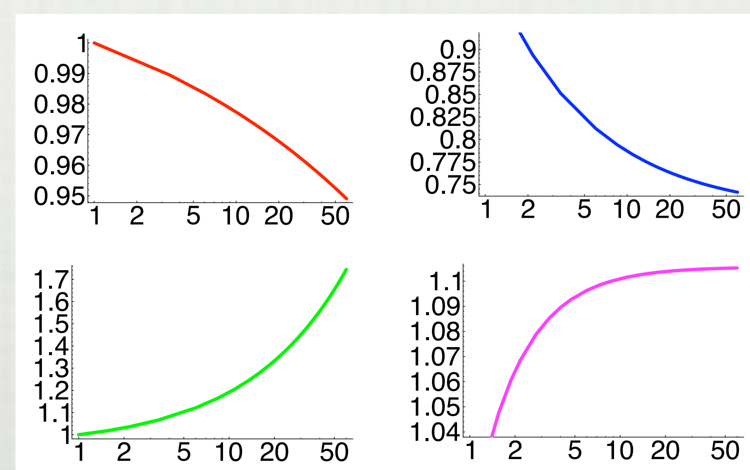
$c_3(A)/c_{k,0}$



$c_4(A)/c_{k,0}$



$c_5(A)/c_{k,0}$



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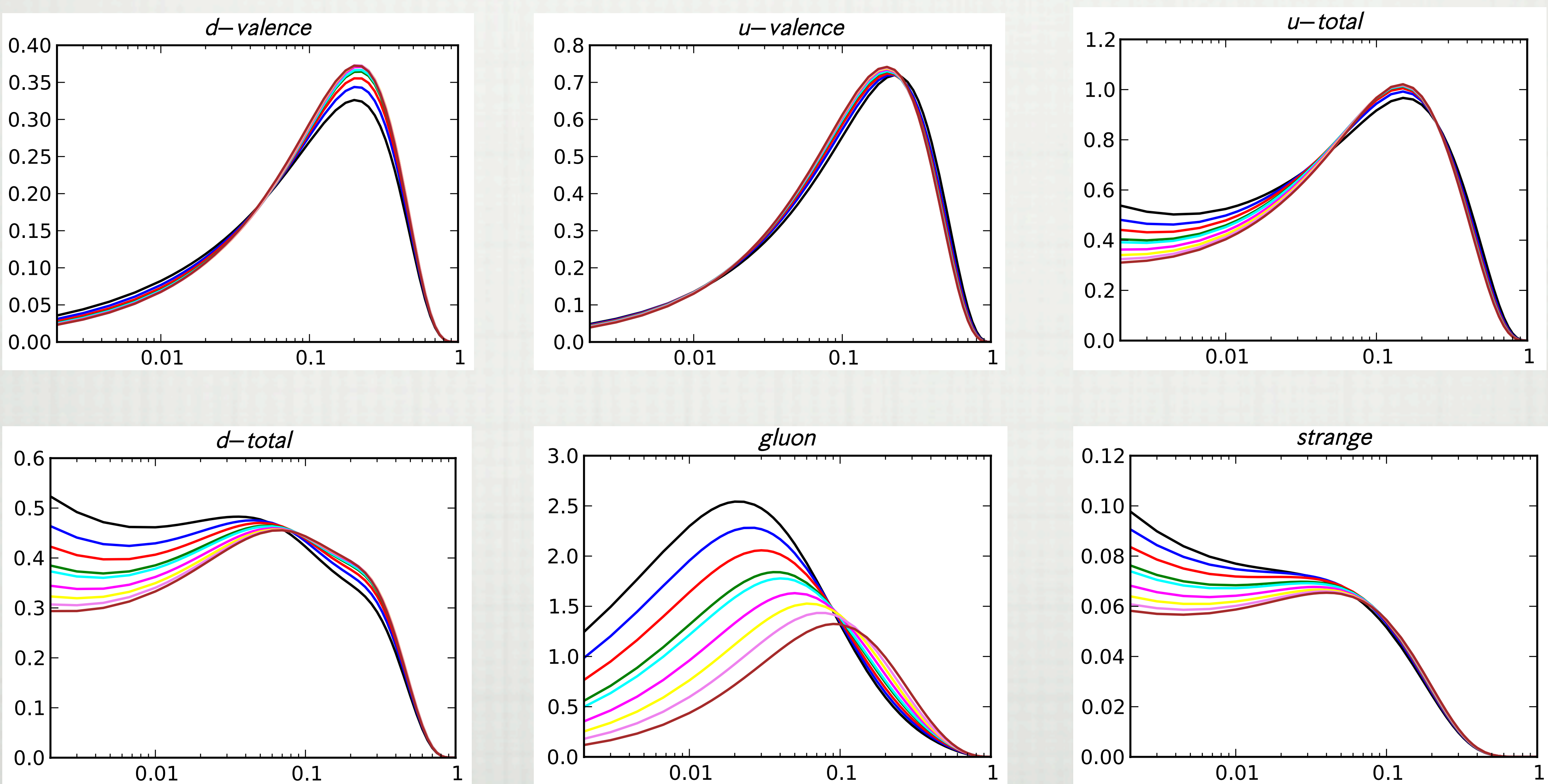
NCTEQ

- Parton density functions for bound partons as a function of x

black yellow brown

$$x\, f_k^A(x,Q) \ \text{for} \ A = (1, 2, 4, 9, 12, 27, 56, 108, 207)$$

red purple



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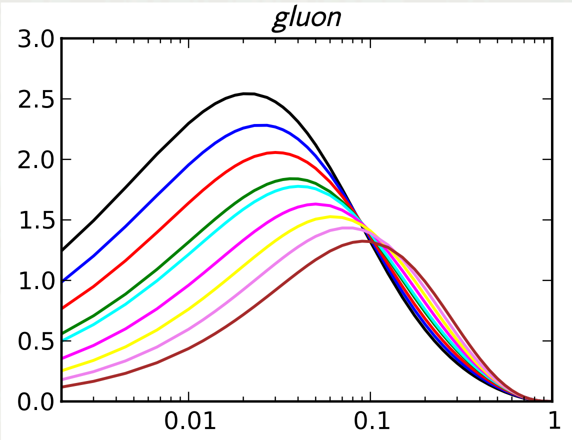
NCTEQ

- Problems associated with nuclear PDF

nCTEQ

- Problems associated with nuclear PDF
    - largely unconstrained nuclear gluon PDF
      - low-x behavior, insufficient data



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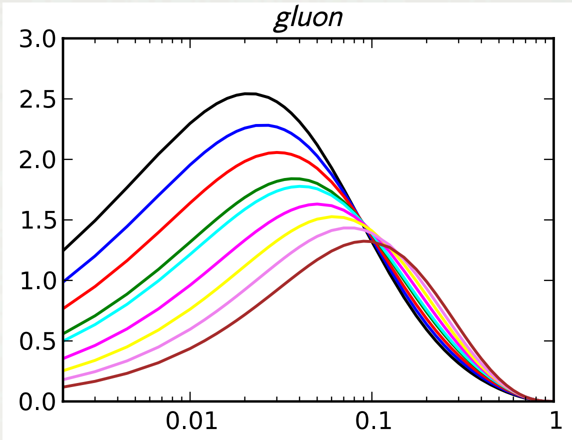
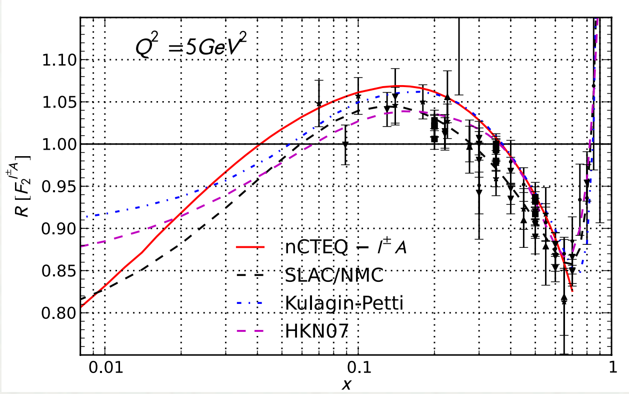
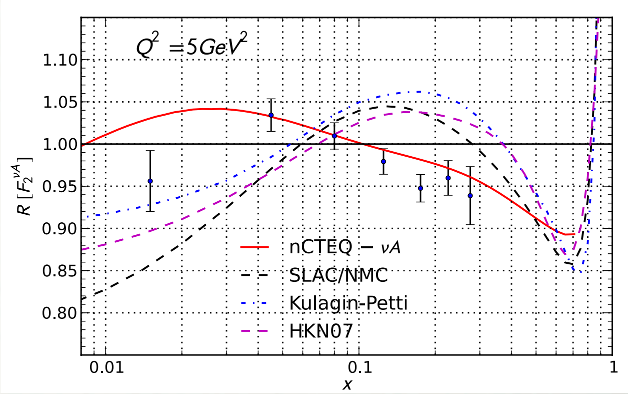
- Problems associated with nuclear PDF
  - largely unconstrained nuclear gluon PDF
    - low-x behavior, insufficient data
  - problematic flavor separation for nuclear PDF
    - neutrino DIS data & nuclear strange quark

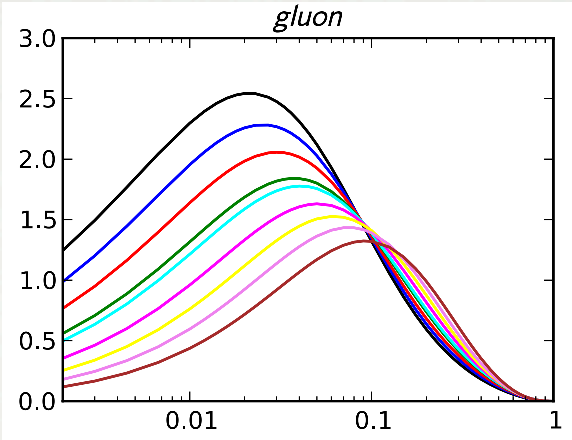


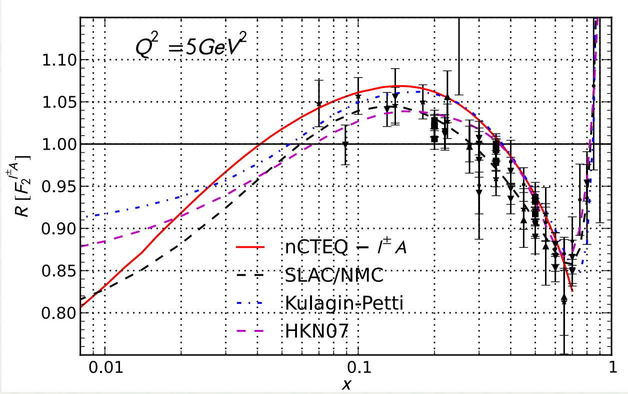


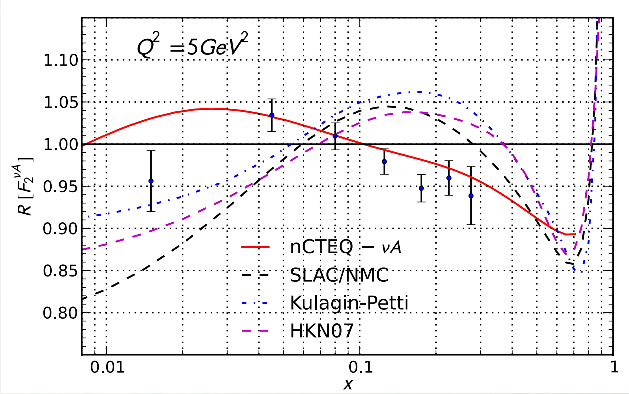


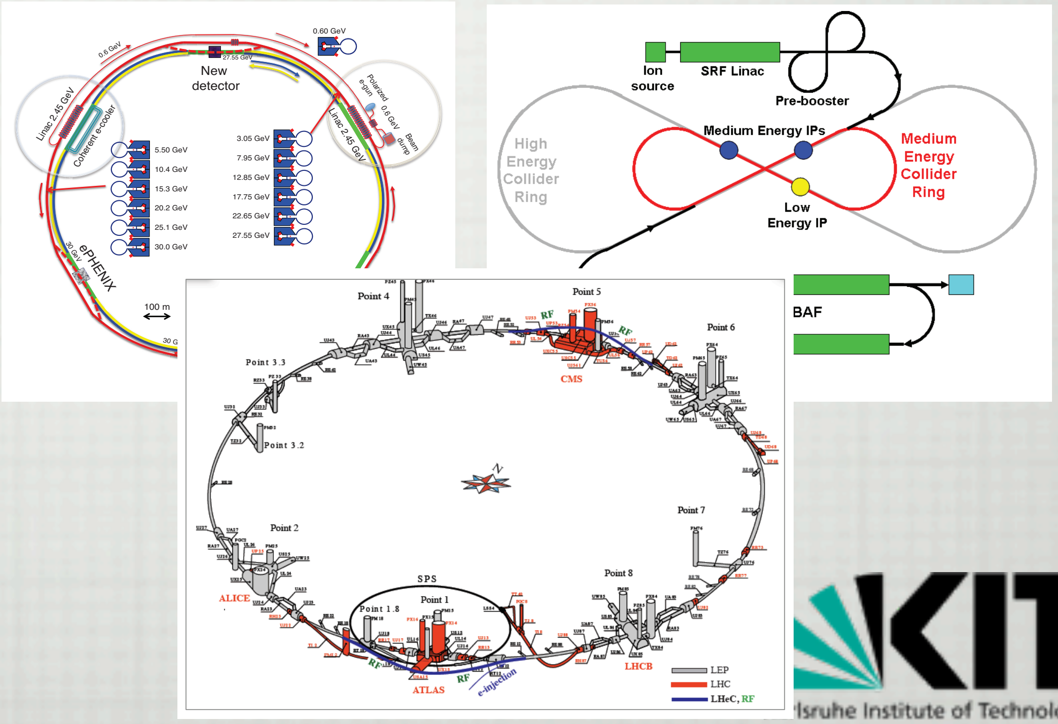
NCTEQ

- Problems associated with nuclear PDF
  - largely unconstrained nuclear gluon PDF
    - low-x behavior, insufficient data
  - problematic flavor separation for nuclear PDF
    - neutrino DIS data & nuclear strange quark
  - lacking data (4x less data than proton PDF)
    - need low-x & precise data, for several nuclei



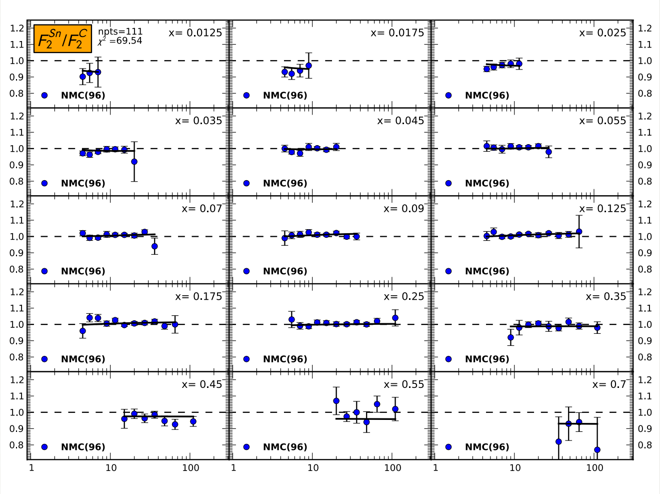






GLUON NPDF

- Nuclear modifications in the gluon PDF
  - important for predictions @ LHC for AA or pA collisions
  - only data 'directly' constraining gluon Sn/C from NMC
  - data from RHIC have to include fragmentation functions



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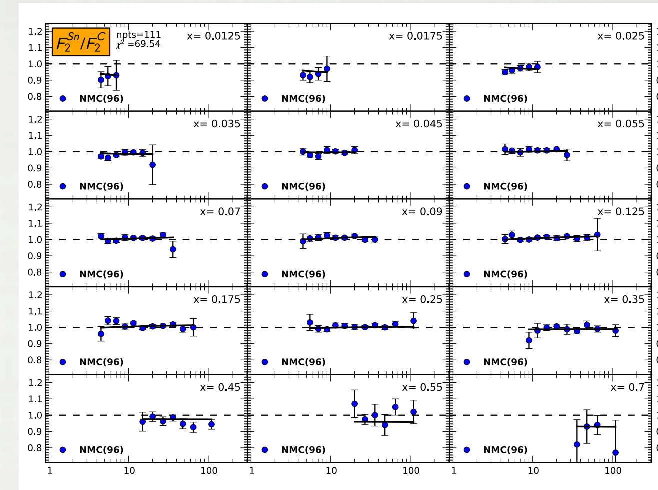
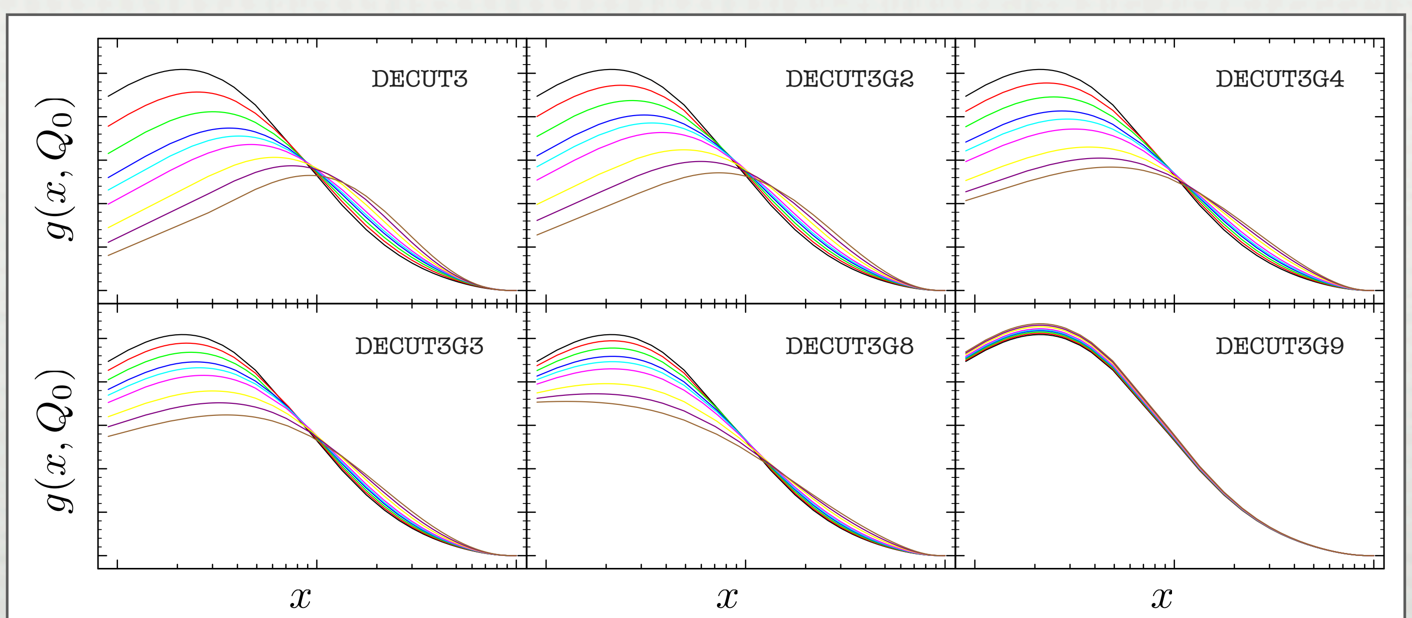


- nCTEQ estimate of gluon nPDF uncertainty
    - vary gluon nPDF assumptions & parameterizations
    - large uncertainty for low x<0.1 in nCTEQ framework
    - need further data to constrain gluon nPDF

Stavreva, Schienbein, Arleo, KK, Olness, Yu, Owens
[JHEP 1101 (2011) 152] arXiv: 1012.1178



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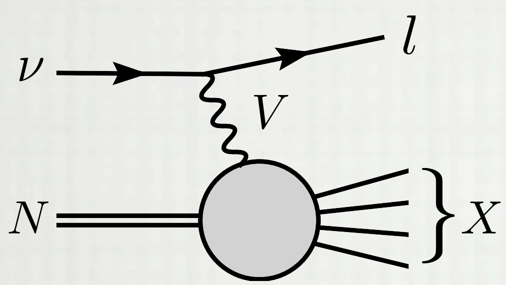
NEUTRINO DIS

- Neutrino DIS cross-section data



$\nu + N \rightarrow l + X$

NuTeV & di-muon
$N = \mathrm{Fe}$ → 2310 data points

CHORUS
$N = \mathrm{Pb}$ → 824 data points

All charged lepton
DIS & Drell-Yan data
→ 708 data points

- Challenges in combining the neutrino & charged lepton data
  - deal with the disparity of number of data points - assigning weights to neutrino data
  - neutrino DIS data only with 2 heavy nuclei - insufficient to get a reliable A-dependance
  - do all neutrino data show the different behavior or only NuTeV ?
- Different neutrino observables

$$\frac{d\sigma^{\nu A}}{dx dQ^2} \; \& \; \frac{d\sigma^{\bar{\nu} A}}{dx dQ^2} \quad \text{vs.} \quad F_2^{\nu+\bar{\nu}}(x, Q^2) \; \& \; xF_3^{\nu+\bar{\nu}}(x, Q^2)$$

needs theory assumptions to extract

- Nuclear correction factors
  - we show correction factors defined e.g. as $R[F_2^{\nu}] = F_2^{\nu A} / F_2^{\nu A,\mathrm{free}}$

from free proton PDF

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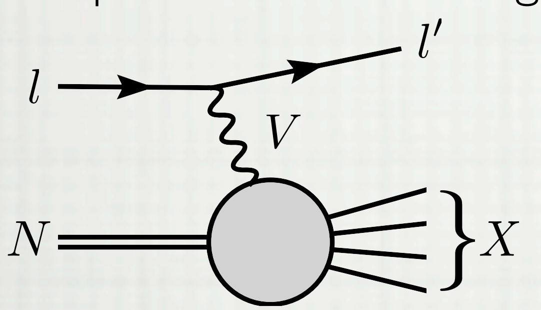
NEUTRINO DIS

- Experiments included in the analysis

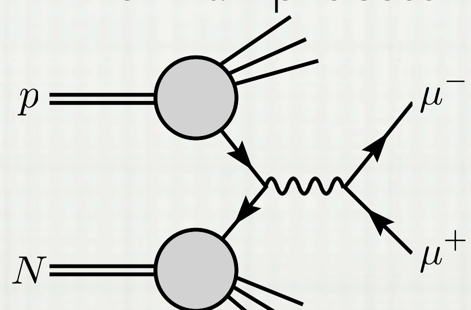
Charged lepton

Deep Inelastic Scattering



$$l + N \to l' + X$$

Drell-Yan process



$$p + N \to \mu^+\mu^- + X$$

CERN BCDMS & EMC & NMC
$N = (\mathrm{D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W})$

FNAL E-665
$N = (\mathrm{D, C, Ca, Pb, Xe})$

DESY Hermes
$N = (\mathrm{D, He, N, Kr})$

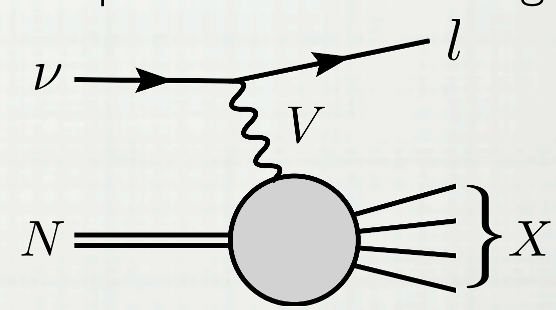
SLAC E-139 & E-049
$N = (\mathrm{D, Ag, Al, Au, Be, C, Ca, Fe, He})$

FNAL E-772 & E-886
$N = (\mathrm{D, C, Ca, Fe, W})$

1233 data points (708 after cuts)

Neutrino

Deep Inelastic Scattering



$$\nu(\bar{\nu}) + N \to l + X$$

CHORUS
$N = \mathrm{Pb}$

CCFR & NuTeV
$N = \mathrm{Fe}$

3832 data points (3134 after cuts)

NEUTRINO DIS

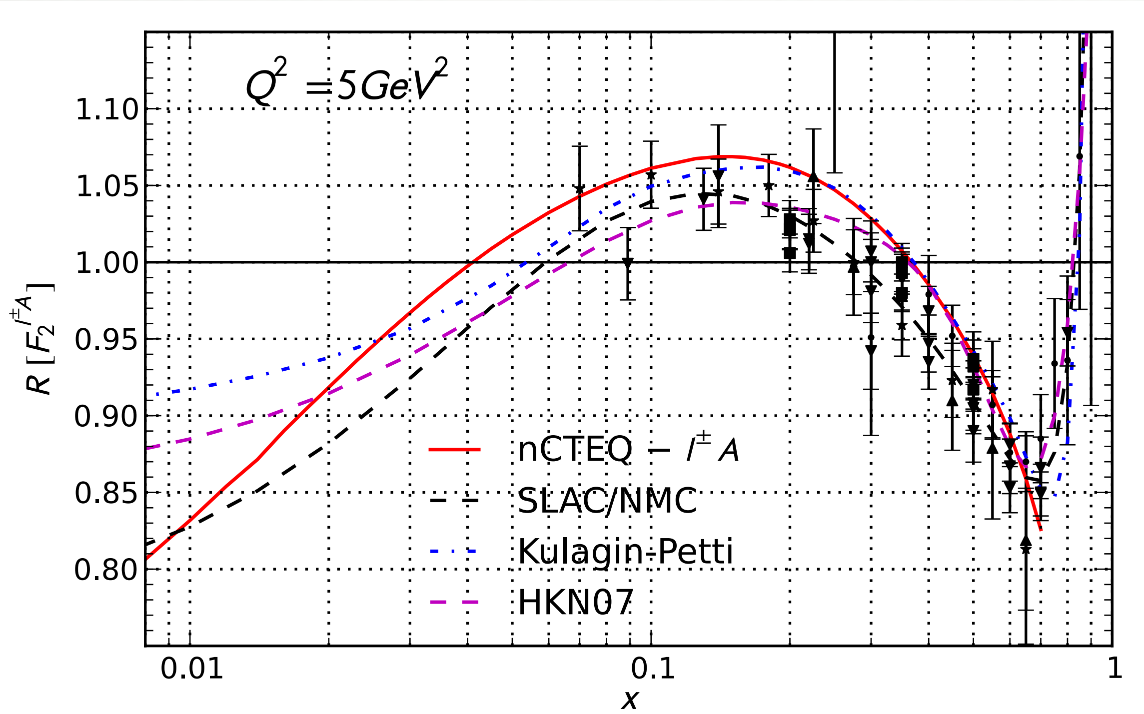
- Comparison of charged lepton and neutrino fits

KK et al.
[Phys.Rev.Lett. 106(2011) 122301] arXiv: 1012.1178

Fit to charged lepton data

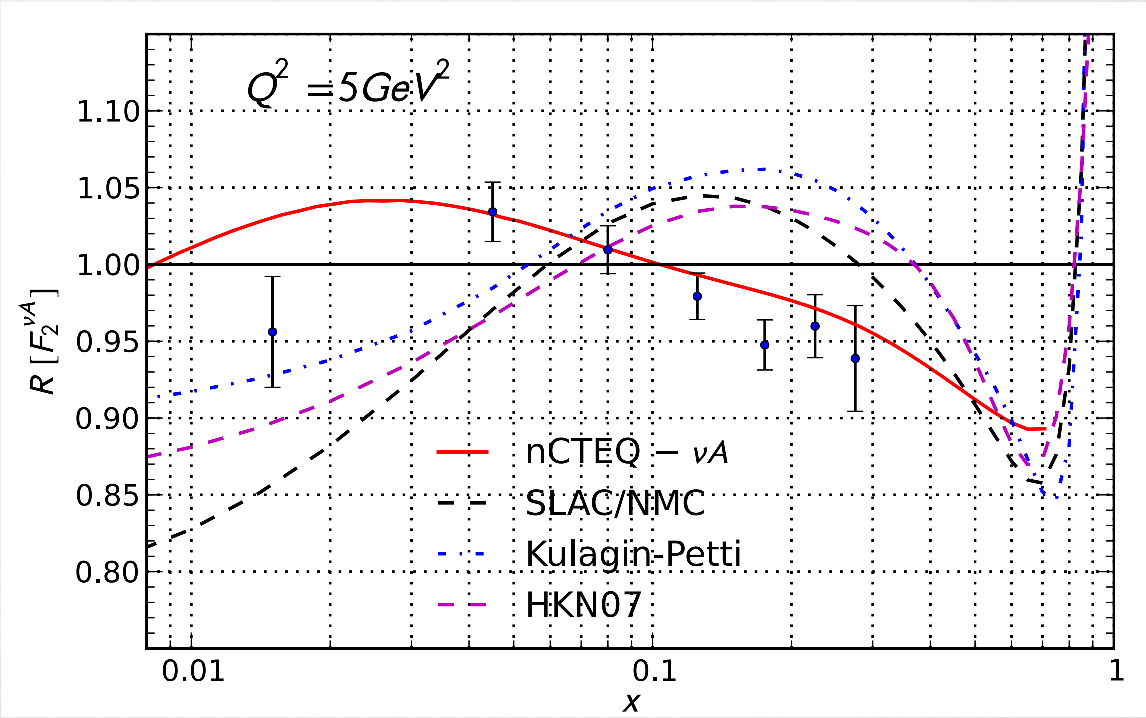
DIS & DY

$\chi^2/\text{d.o.f} = 0.89$



Fit to only neutrino DIS

$\chi^2/\text{d.o.f} = 1.33$



- can we explain the difference and fit all data together in a global fit ?

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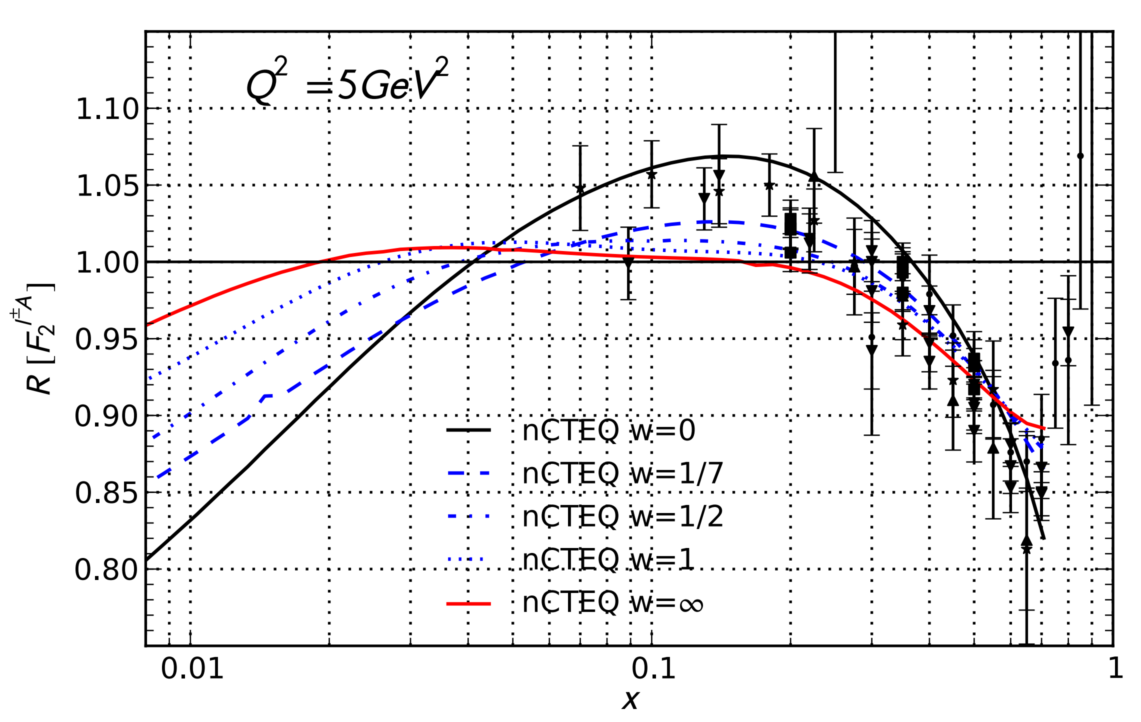
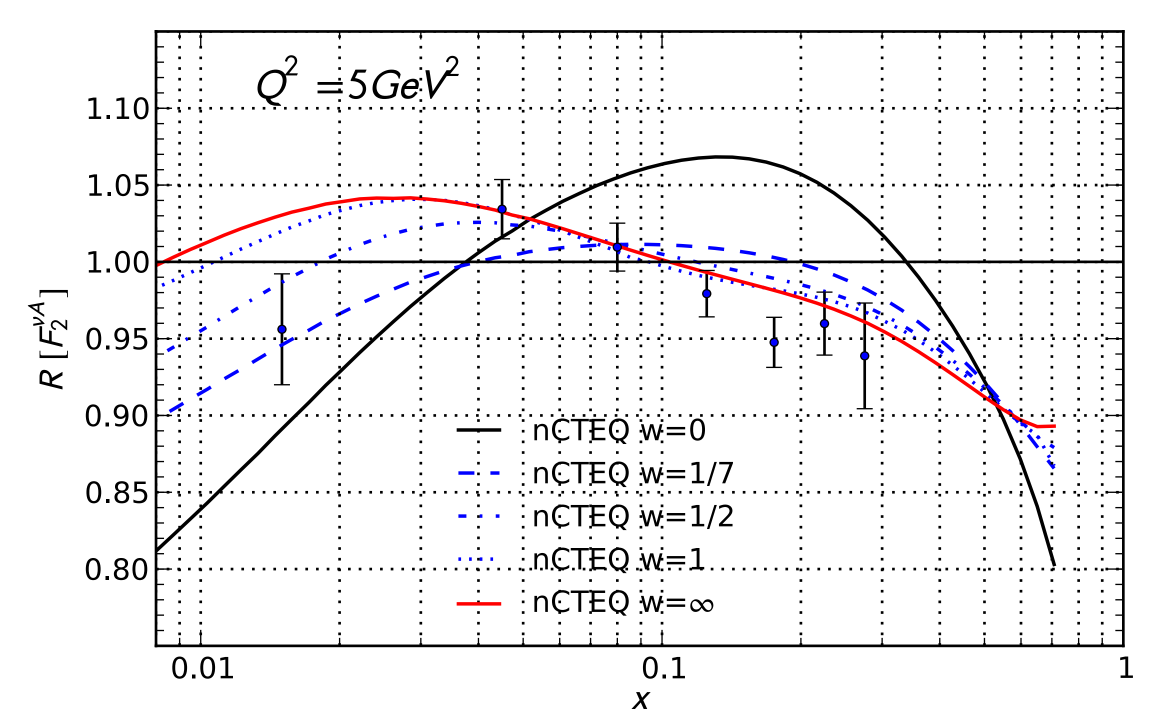
NEUTRINO DIS

- Analysis of fits with different weights of neutrino DIS (correlated errors)

w	$l^{\pm}A$	χ^2 (/pt)	νA	χ^2 (/pt)	total χ^2(/pt)
0	708	630 (0.89)	-	-	630 ± 58
1/7	708	645 (0.91)	3134	4681 (1.50)	5326 ± 203
1/2	708	680 (0.96)	3134	4375 (1.40)	5055 ± 192
1	708	736 (1.04)	3134	4246 (1.36)	4983 ± 190
∞	-	-	3134	4167 (1.33)	4167 ± 176

$$P(\chi^2, N) = \frac{(\chi^2)^{N/2-1}e^{-\chi^2/2}}{2^{N/2}\Gamma(N/2)}$$





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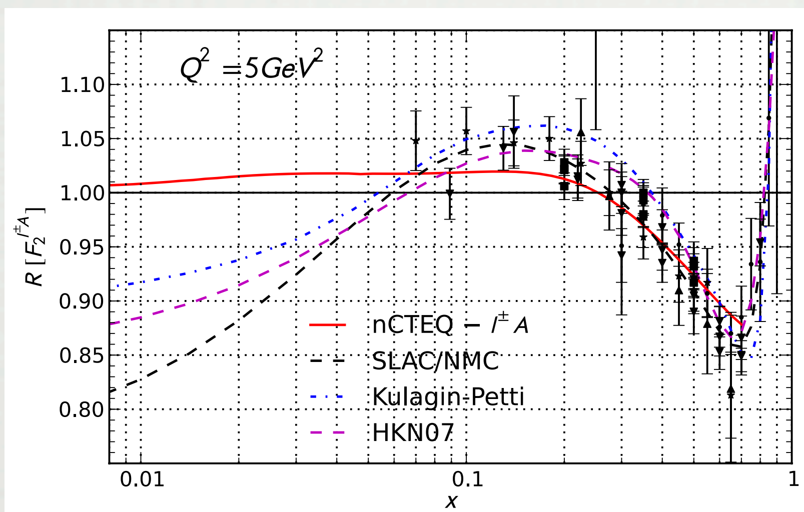
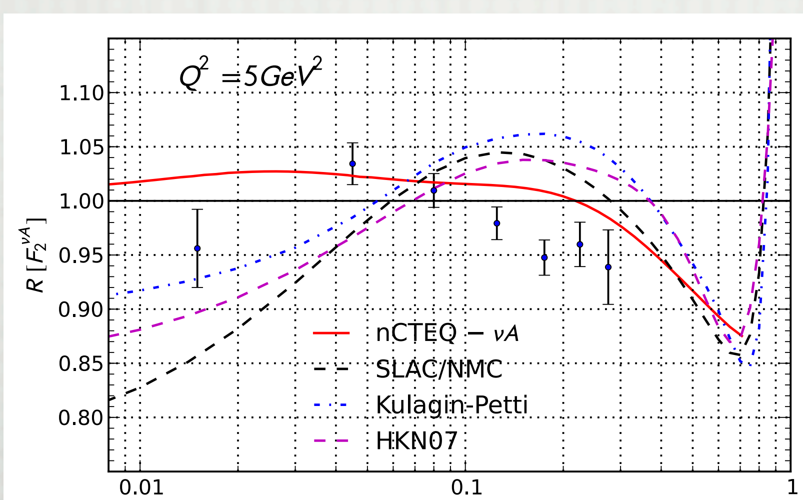
NEUTRINO DIS

- Analysis of fits with neutrino DIS (uncorrelated errors)

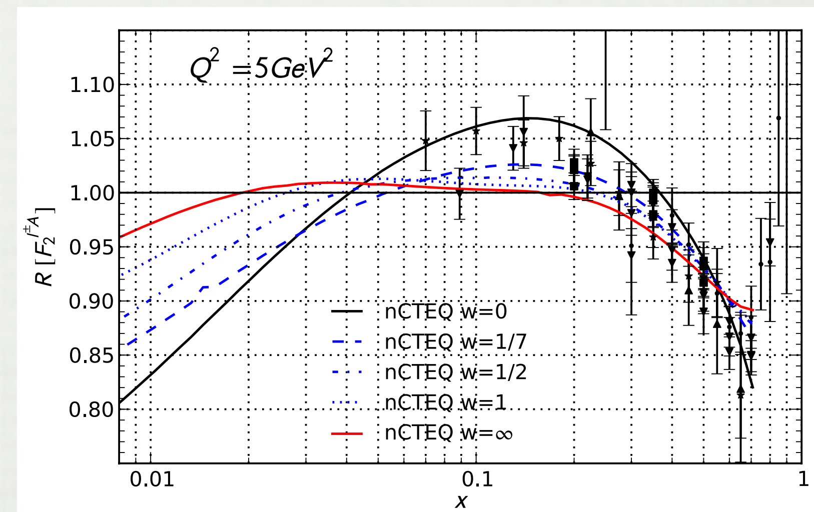
w	$l^{\pm}A$	χ^2 (/pt)	νA	χ^2 (/pt)	total χ^2(/pt)
1-corr	708	736 (1.04)	3134	4246 (1.36)	4983 (1.30)
1-uncorr	708	809 (1.14)	3110	3115 (1.00)	3924 (1.02)

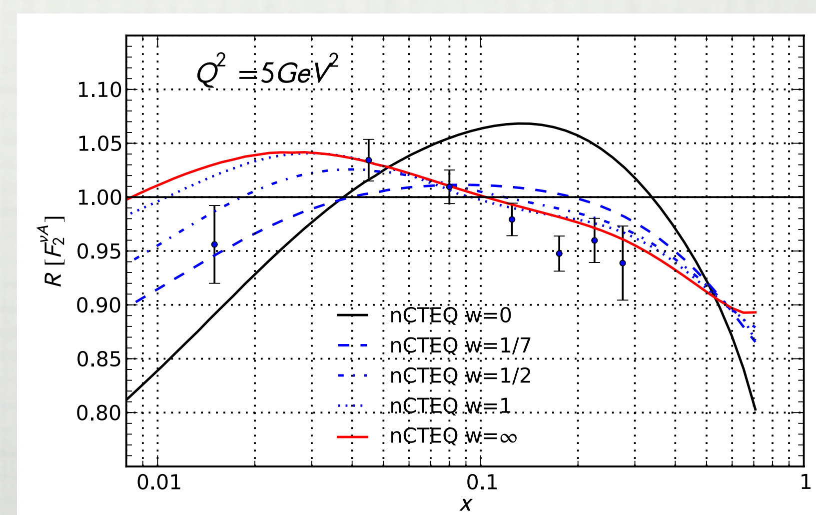
uncorrelated errors





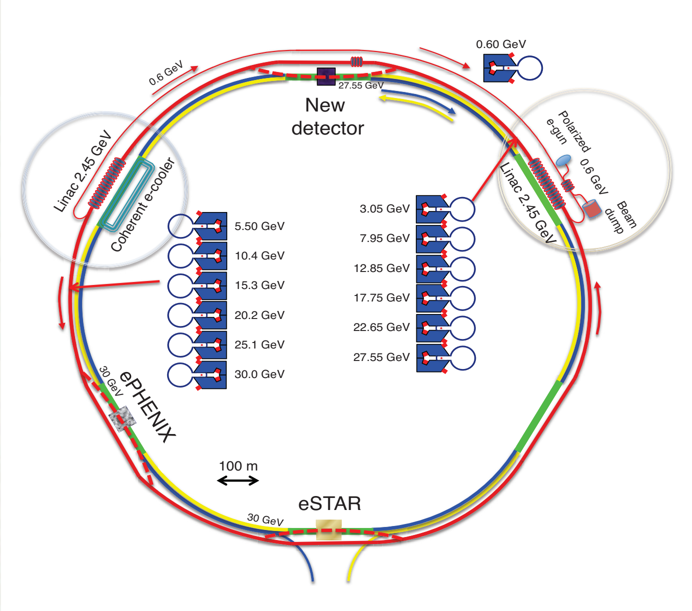
correlated errors

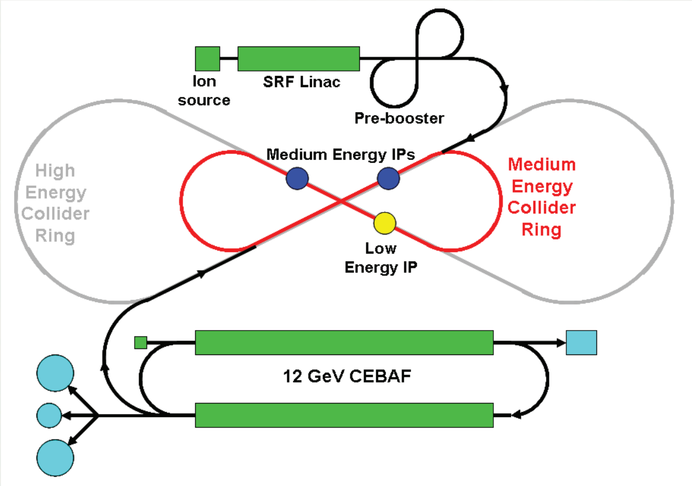




FUTURE EXPERIMENTS

- Electron-Ion-Collider (EIC)
  - 2 different proposals - JLab & RHIC
  - multiple nuclear targets
  - reach to small-x





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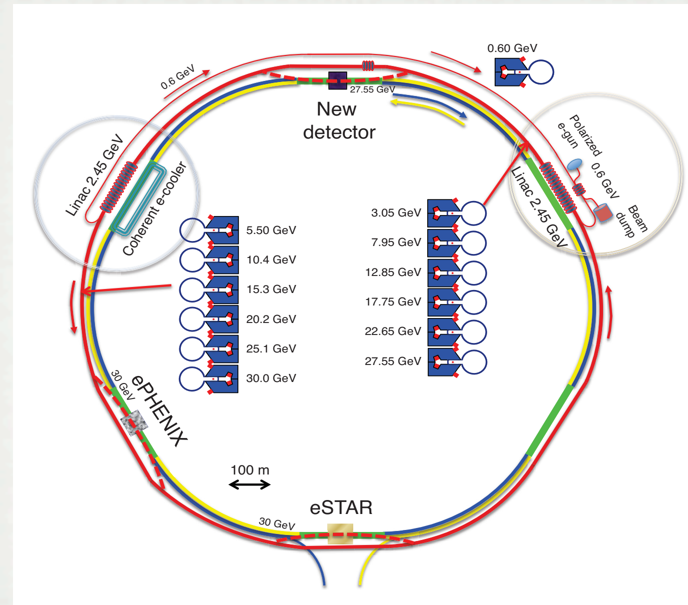
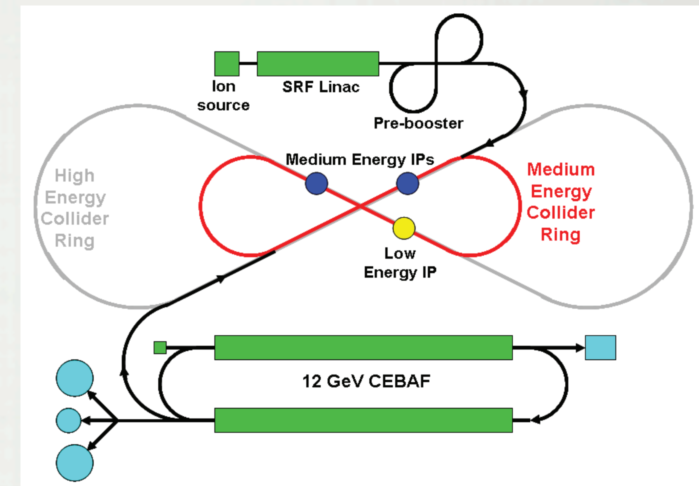
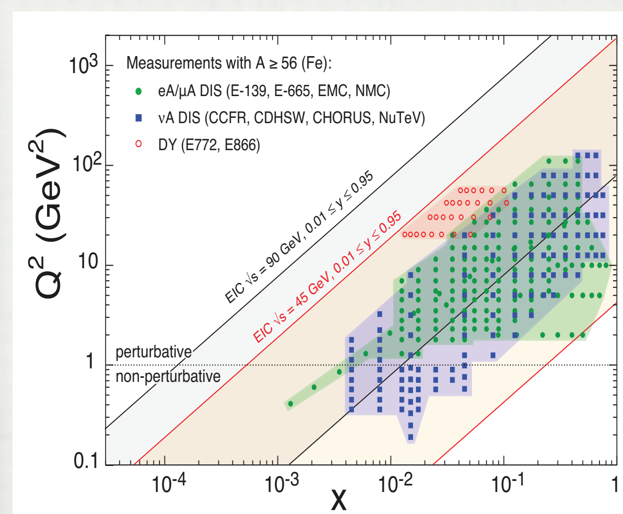
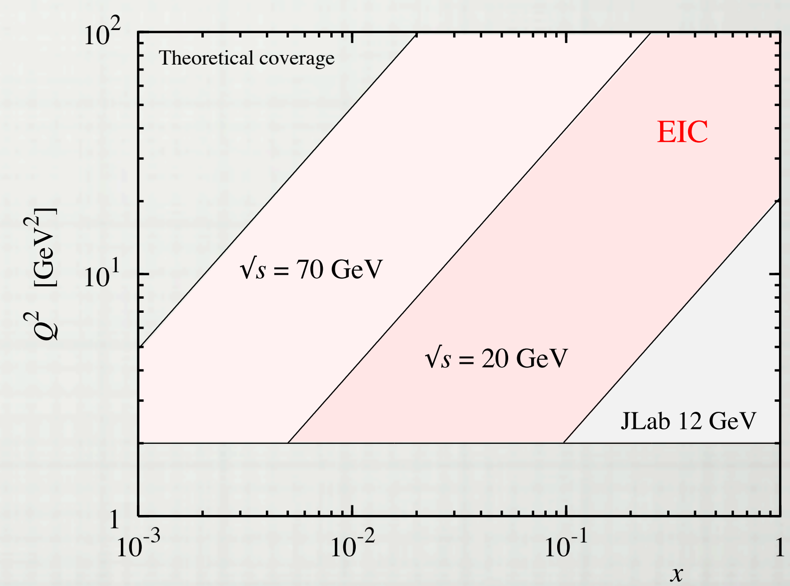




- nPDF requirements on EIC
  - coverage in x-Q^2 plane (small-x)
  - precision (e.g. for gluon PDF)
  - # nuclei





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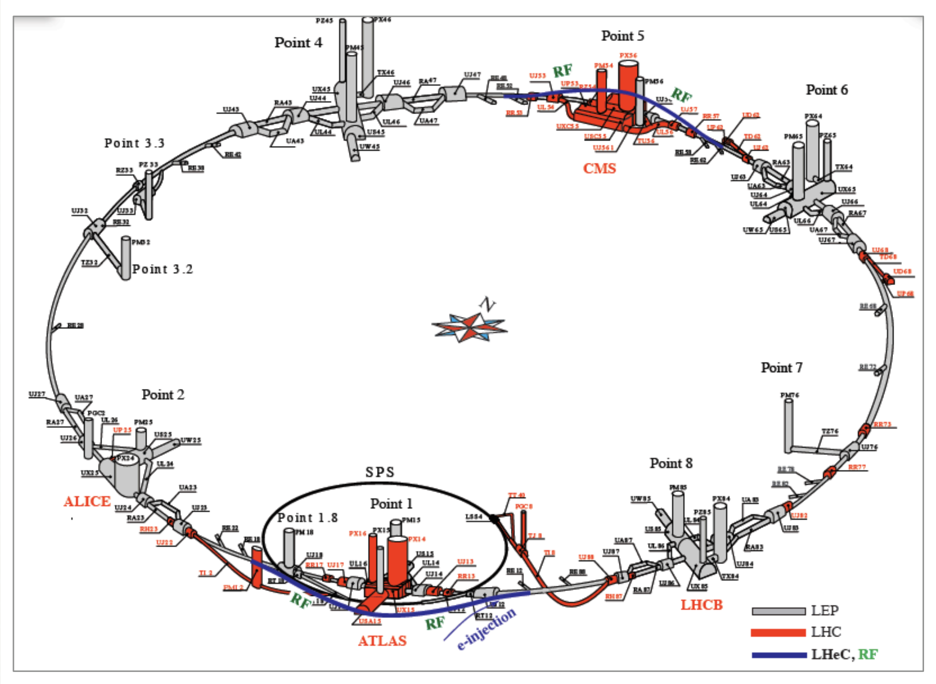
FUTURE EXPERIMENTS

- LHeC
  - 2 different proposals - ring-ring and linac-LHC
  - only Pb (possibly Ca) targets
  - reach to very small-x



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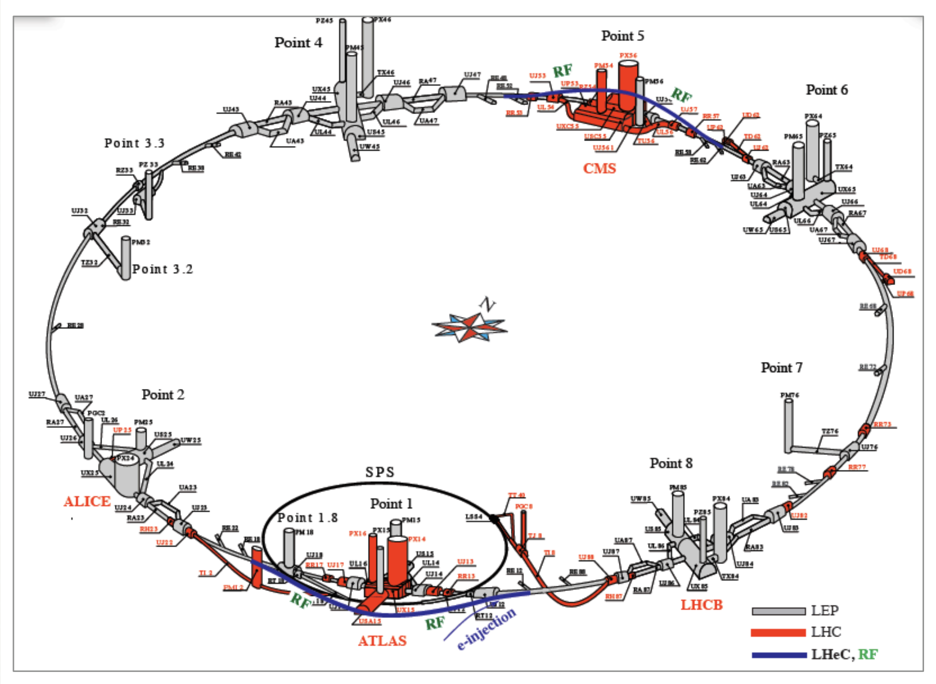

- nPDF requirements on LHeC
  - coverage in x-Q^2 plane (small-x)
  - precision (e.g. for gluon PDF)
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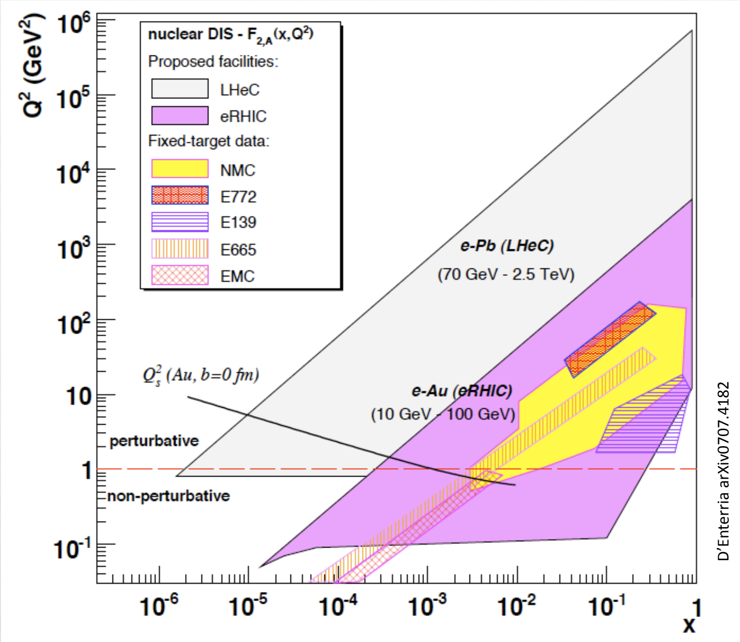

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CONCLUSIONS & OUTLOOK

- nPDF analysis put to test @ LHC in pA & AA collisions
- Some important open questions remain (all can be solved by having more data)
  - uncertainty in nuclear gluon PDF at small-x
    - need HERA-like measurements for many nuclear targets covering also small-x (EIC & LHeC)
  - neutrino DIS on nuclei
    - at the moment NuTeV incompatible with the rest of charged lepton data
    - proton strange quark information from LHC vital
    - new(old) data would solve the problem - NOMAD or NuSonG

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THANK YOU