Parton distribution functions for heavy ion collisions @ LHC

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Outline

1. Introduction to PDFs
2. Motivations & review of available nPDFs
3. Details of nuclear CTEQ analysis
4. Future experiments and nPDF outlook

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1. Introduction to PDFs

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PDF intro

- Scattering - *THE tool to study inner structure of atoms, nuclei & proton*
- Parton distribution functions & the inner structure of the proton
  - direct descendants of Rutherford's experiments

- ***Rutherford's scattering***

  spin-0 non-relativistic projectile with very heavy target (no recoil)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Ruth.}} = \frac{(\alpha Z)^2}{4E^2 \sin^4 \frac{\theta}{2}} \, .$$

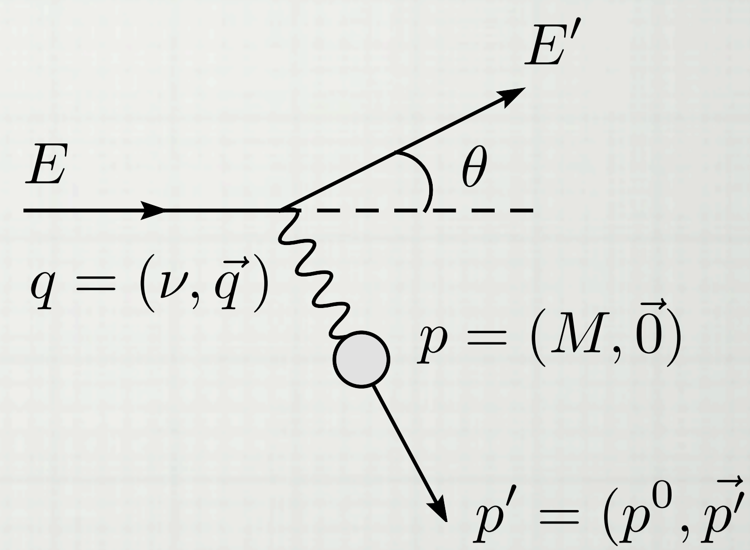
E.Rutherford – nobel prize in chemistry – 1908

- ***Mott's scattering***

  spin-0 relativistic projectile with recoil of the target

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} = \frac{(\alpha Z)^2}{4E^2 \sin^4 \frac{\theta}{2}} \frac{E'}{E} \cos^2 \frac{\theta}{2}$$

- ***Kinematics of elastic scattering***



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PDF intro

- Scattering - *THE tool to study inner structure of atoms, nuclei & proton*
- Parton distribution functions & the inner structure of the proton

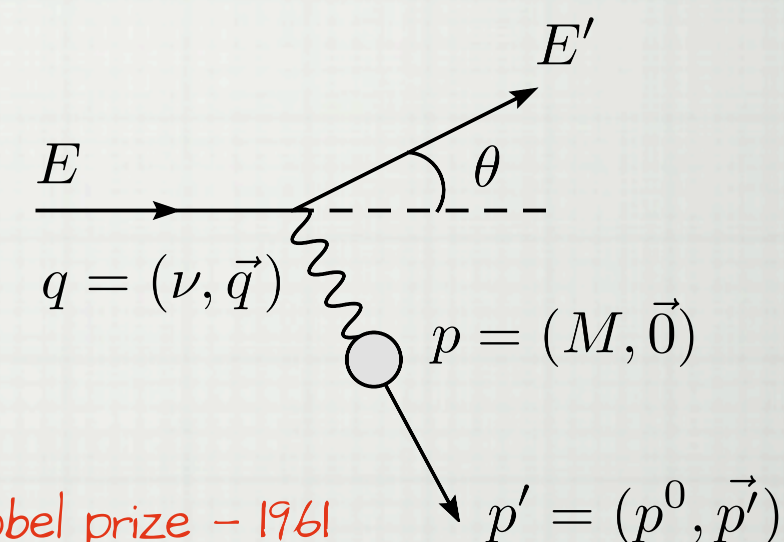
  - direct descendants of Rutherford's experiments

- ***Scattering of electrons on muons***

  spin-1/2 relativistic projectile scattering on muons

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\frac{E'}{E}\left[\cos^2\frac{\theta}{2} - \frac{q^2}{2M^2}\sin^2\frac{\theta}{2}\right]$$

- ***Kinematics of elastic scattering***



- ***Rosenbluth's scattering***

  spin-1/2 relativistic projectile scattering on
  non-point like target with spin-1/2 (proton)

R.Hofstadter – nobel prize – 1961

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\frac{E'}{E}\left[\left(F_1(q)^2 - \frac{\kappa^2 q^2}{4M^2}F_2(q)^2\right)\cos^2\frac{\theta}{2} - \frac{q^2}{2M^2}(F_1(q)+\kappa F_2(q))^2\sin^2\frac{\theta}{2}\right]$$

electric form-factor

magnetic form-factor

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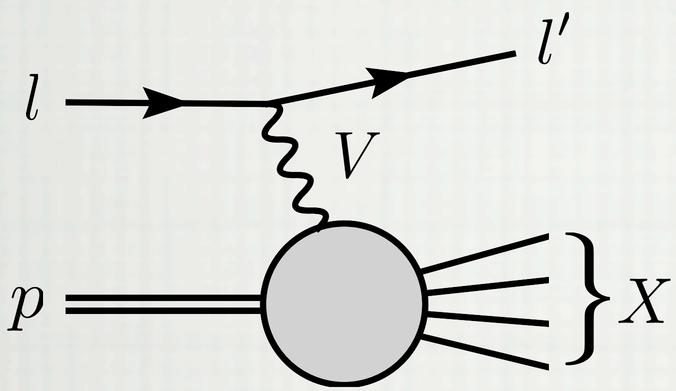
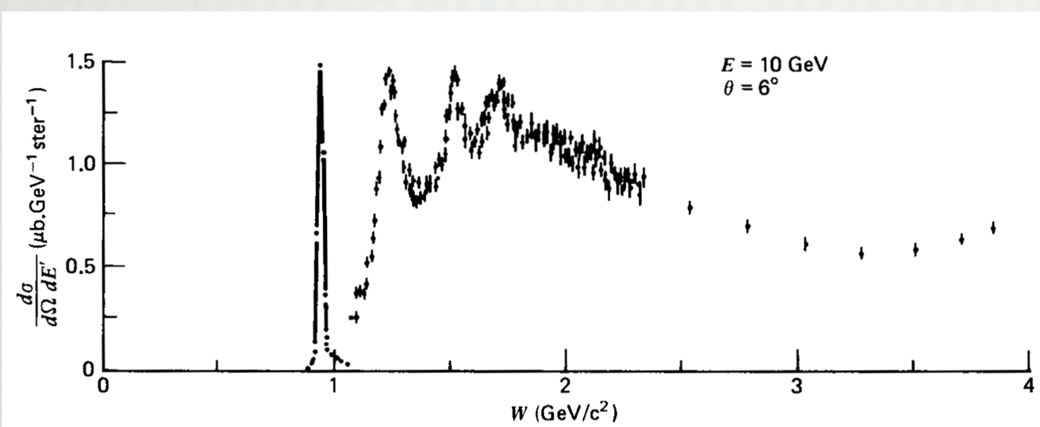
PDF intro

- Deep Inelastic Scattering

R.Taylor, H.Kendall, J.Friedman – nobel prize – 1990



$$l(k) + p(p) \to l'(k') + X$$



- Kinematic variables

$$q = k - k' \qquad Q^2 = -q^2 \qquad x = \frac{Q^2}{2p.q} \qquad x \in (0,1)$$

- Distinguishing between elastic & inelastic scattering

$$W^2 = (p_1' + p_2' + \ldots + p_n')^2$$

- if $W^2 = m_p^2$ elastic scattering
- if $W^2 \gg m_p^2$ inelastic scattering

- DIS cross-section & structure functions

$$\frac{d\sigma}{dE' d\Omega} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left(\frac{2F_1(x,Q^2)}{M} \sin^2 \frac{\theta}{2} + \frac{F_2(x,Q^2)}{E - E'} \cos^2 \frac{\theta}{2} \right)$$

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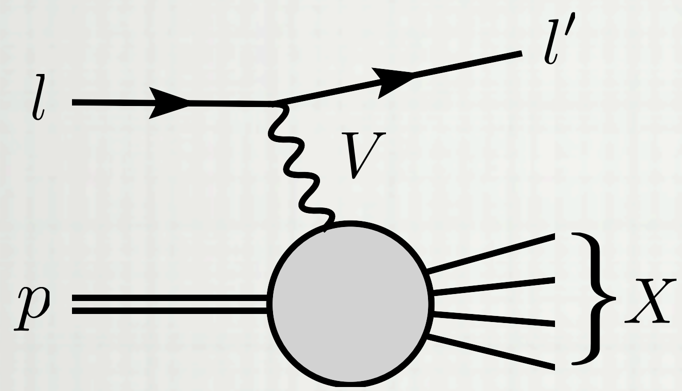
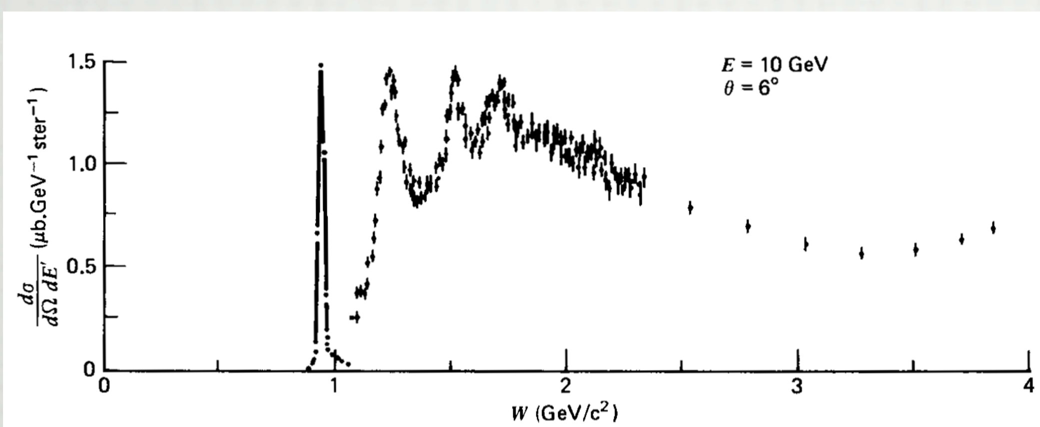
PDF intro

- Deep Inelastic Scattering

R.Taylor, H.Kendall, J.Friedman – nobel prize – 1990



$$l(k) + p(p) \rightarrow l'(k') + X$$



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- if $W^2 = m_p^2$ elastic scattering
- if $W^2 \gg m_p^2$ inelastic scattering

- Assuming elastic scattering on partons in the proton (in LO)

$$F_2(x, \cancel{Q^2}) = \sum_i e_i^2 \int \mathrm{d}\xi\, \xi\, f_i(\xi)\, \delta\left(\xi - \frac{Q^2}{2p.q}\right)$$

mom. fraction $\xi = x$ kinematic variable

parton distribution function

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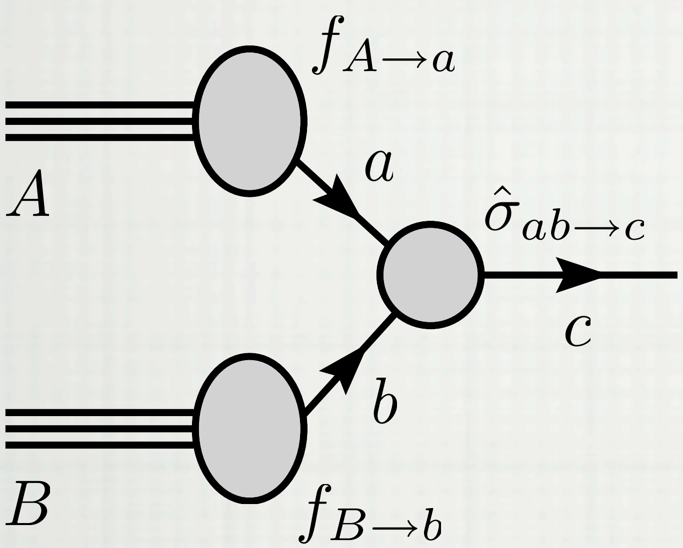
PDF intro

- Factorization & PDFs



$$\sigma = \int dx_1 dx_2\ f_{A\to a}(x_1, Q^2) f_{B\to b}(x_2, Q^2)\ \hat{\sigma}_{ab\to c}(x_1 x_2 s)$$

from experiment

from pQCD

- Parton distribution functions (PDFs)

$$f_{A\to a}(x, Q^2)$$

  - universal, non-perturbative objects
  - describe the structure of hadrons

    in terms of partons - quarks & gluons
  - Q-dependance governed by the DGLAP evolution equations

$$\frac{\mathrm{d} f_i(x, Q^2)}{\mathrm{d}\ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi} \int_x^1 \frac{\mathrm{d}y}{y} P_{ij}(y) f_j(x/y, Q^2)$$

  - x-dependance determined from a fit to the data

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PDF intro

- CTEQ framework to fit PDFs from experimental data

CTEQ6M hep-ph/0201195

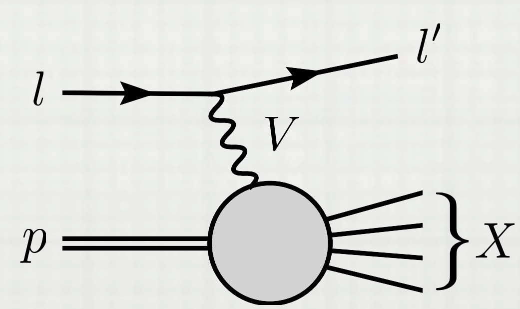
  - the input scale set to $Q_0 = 1.3\,\mathrm{GeV}$
  - parameterisation of the PDFs in x

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

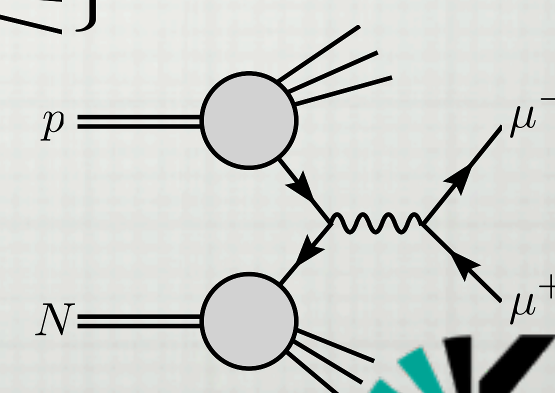
$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0\, x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4}$$

  - make sure # of free parameters not too high - CTEQ approx. 20 free params
  - carefully choose data sets & kinematic cuts to constrain free parameters
  - perform χ^2 fit to data

- Which data sets are included ?



  - Deep Inelastic Scattering ($l^{\pm}p, l^{-}d, \nu N, \bar{\nu}N$)
  - Neutrino DIS di-muon production
  - Drell-Yan & vector boson production ($W^{\pm}, Z^{0}, \gamma$)
  - hadronic jet data



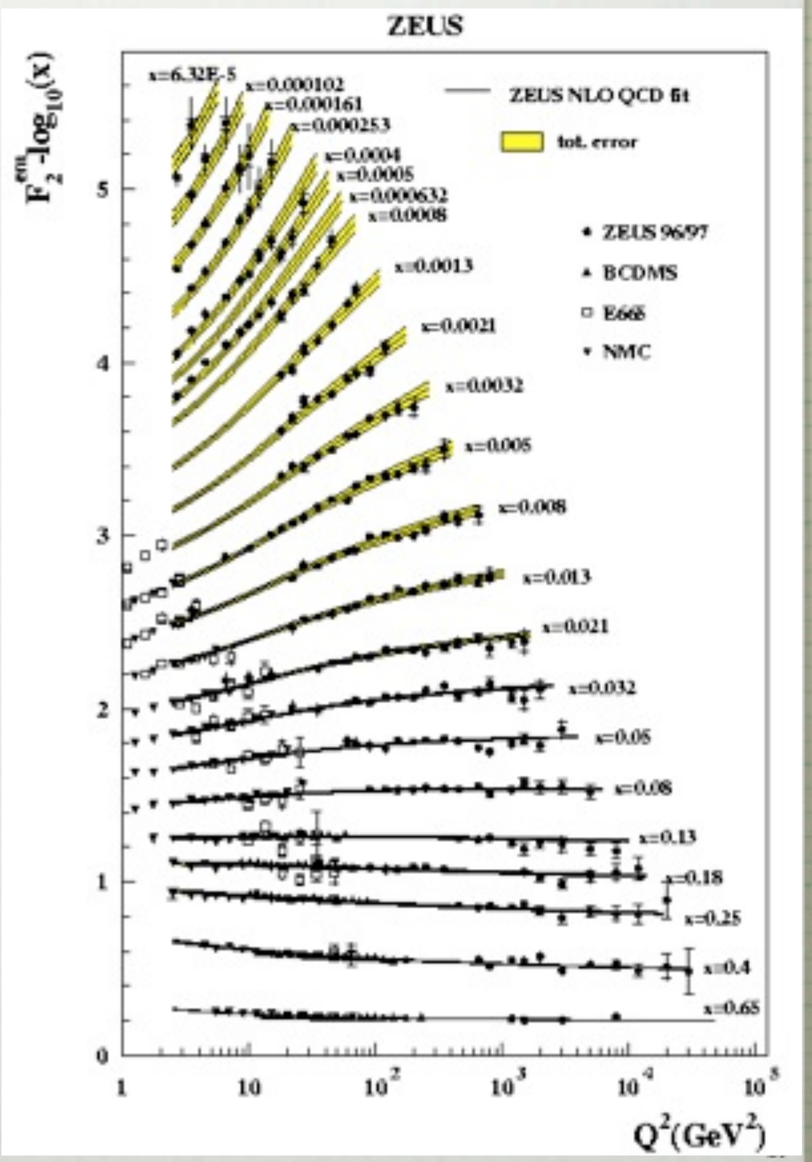
PDF intro

- Some details of PDF determination
  - which data constrain what distribution ?

charged DIS: $$F_2(x,\mu^2) = x\sum_i e_q^2\left[q_i(x,\mu^2)+\bar{q}_i(x,\mu^2)\right]$$

quark & anti-quark distributions

neutrino DIS:
$$F_2(x,\mu^2) = x\sum_i \left[q_i(x,\mu^2)+\bar{q}_i(x,\mu^2)\right]$$
$$xF_3(x,\mu^2) = x\sum_i \left[q_i(x,\mu^2)-\bar{q}_i(x,\mu^2)\right]$$



DIS scaling violations & jet data - gluon distribution

- breaking of Bjorken scaling at small x driven by gluon PDF

$$\mu^2\frac{\mathrm{d}F_2}{\mathrm{d}\mu^2} = \frac{\alpha_S}{2\pi}\sum e_i^2\int_x^1\frac{\mathrm{d}y}{y}\,P_{qg}(y)f_g(x/y,\mu^2)$$

- high x behaviour constrained by jet data

2. Nuclear PDFs

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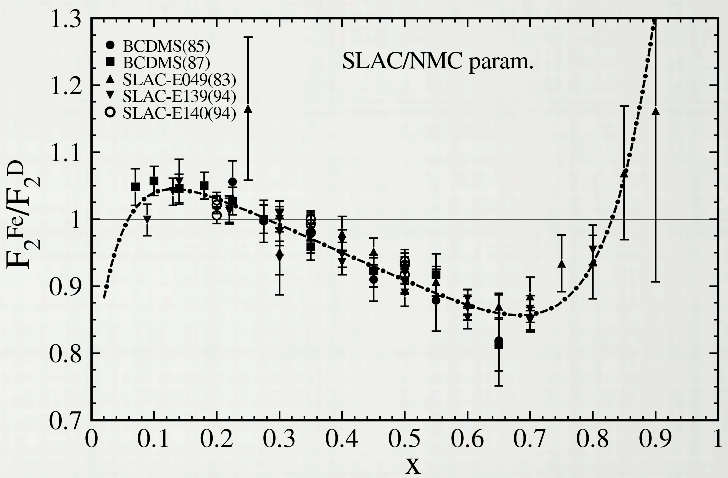
nPDF motivation

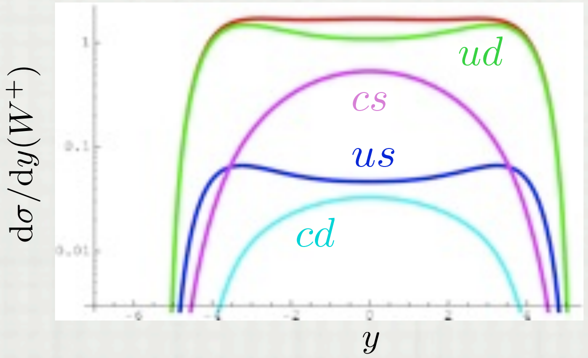
- What are nuclear parton density functions (nPDF) ?
  - parton densities for partons in bound proton & neutron



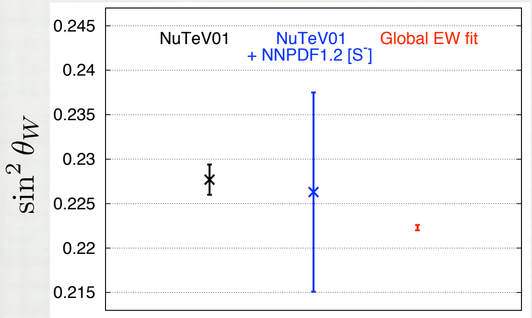
- Where are nuclear parton density functions useful ?

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

2. Heavy ion collisions @ RHIC, LHC

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

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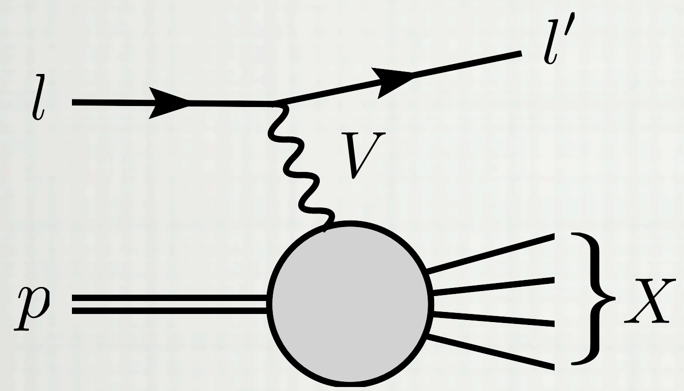
nPDF motivation

- Deep Inelastic Scattering on nuclei



$$l(k) + N(p_N) \to l'(k') + X$$

- Kinematic variables of the nucleus

$$q = k - k'$$
$$Q^2 = -q^2$$
$$x_N = \frac{Q^2}{2p_N.q} \qquad x_N \in (0,1)$$

- New kinematic variables for the bound protons

$$p_A = \frac{p_N}{A}$$ average momentum of a nucleon

$$x_A = \frac{Q^2}{2p_A.q} = A\,x_N \qquad x_A \in (0, A)$$

momentum fraction of a single nucleon

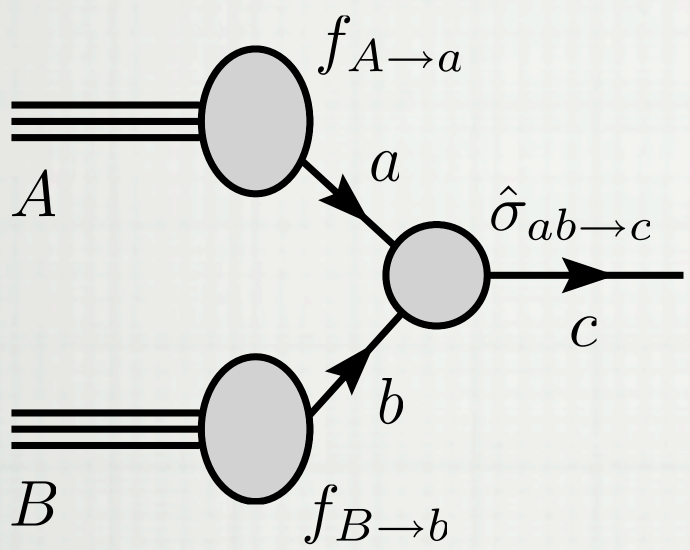
- Distinguishing between elastic & inelastic scattering (assuming interaction only with one nucleon)

$$W^2 = (p'_1 + p'_2 + \ldots + p'_n)^2$$

- if $W^2 = m_p^2$ elastic scattering
- if $W^2 \gg m_p^2$ inelastic scattering

nPDF motivation

- Factorization & PDFs



$$\sigma = \int dx_1 dx_2 \; f_{A\to a}(x_1, Q^2) f_{B\to b}(x_2, Q^2) \; \hat{\sigma}_{ab\to c}(x_1 x_2 s)$$

from experiment

from pQCD

- Parton distribution functions (PDFs)

$$f_{A\to a}(x, Q^2)$$

  - universal, non-perturbative objects
  - describe the structure of hadrons (in terms of partons - quarks & gluons)
  - obey DGLAP evolution equations

- Nuclear parton distribution functions (nPDFs)
  - distributions of partons bound inside protons & neutrons in nuclei
  - simple assumption that nuclear modifications of proton PDF depends on A - # of nucleons

nPDF review

- Review of existing global analyses of nuclear PDF

1. Multiplicative nuclear correction factor

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

bound parton density

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

2. 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

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

- uses multiplicative factor

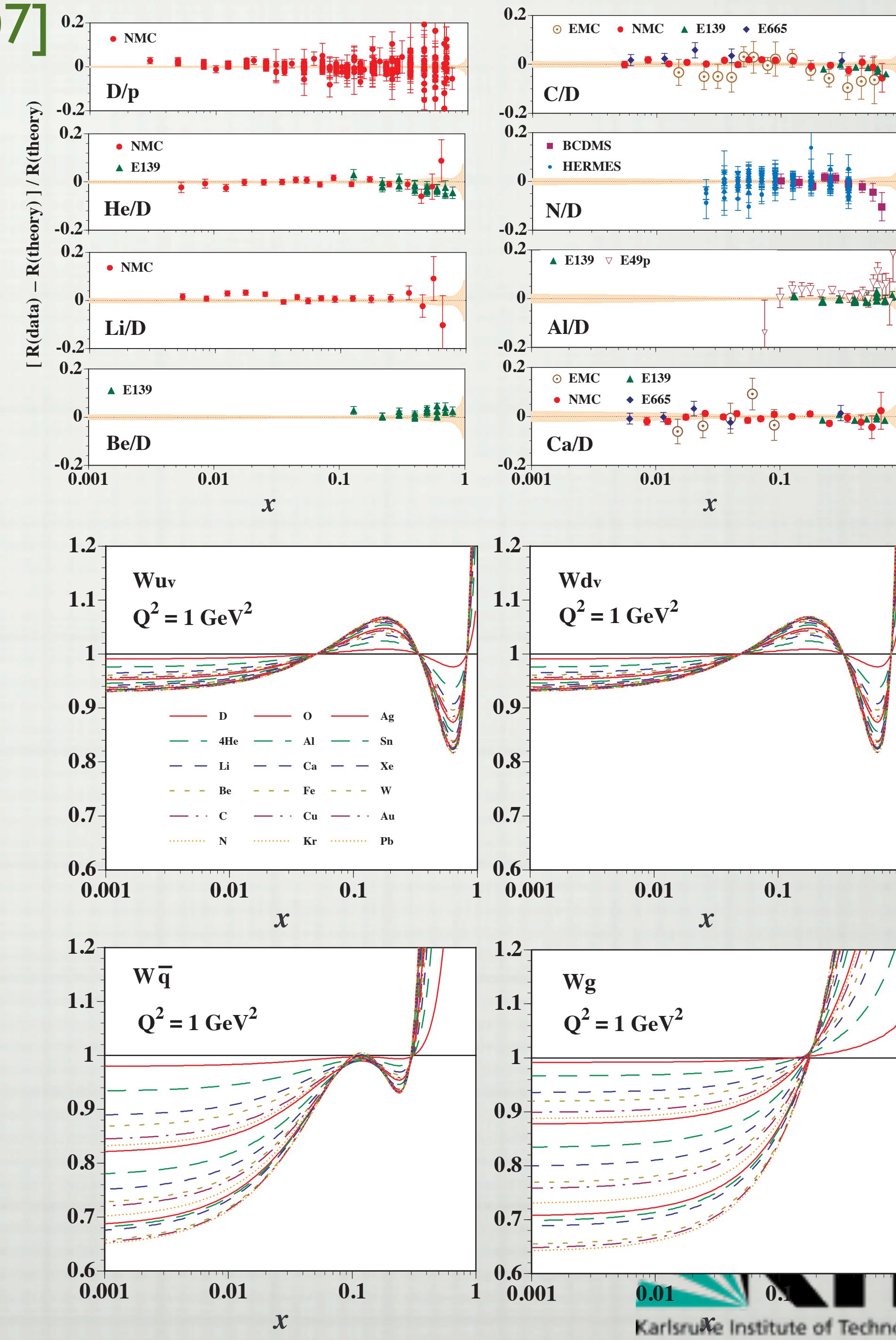
$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i(x_N, Q_0^2)$$

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

χ^2/dof = 1.2



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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

χ^2/dof = 0.8

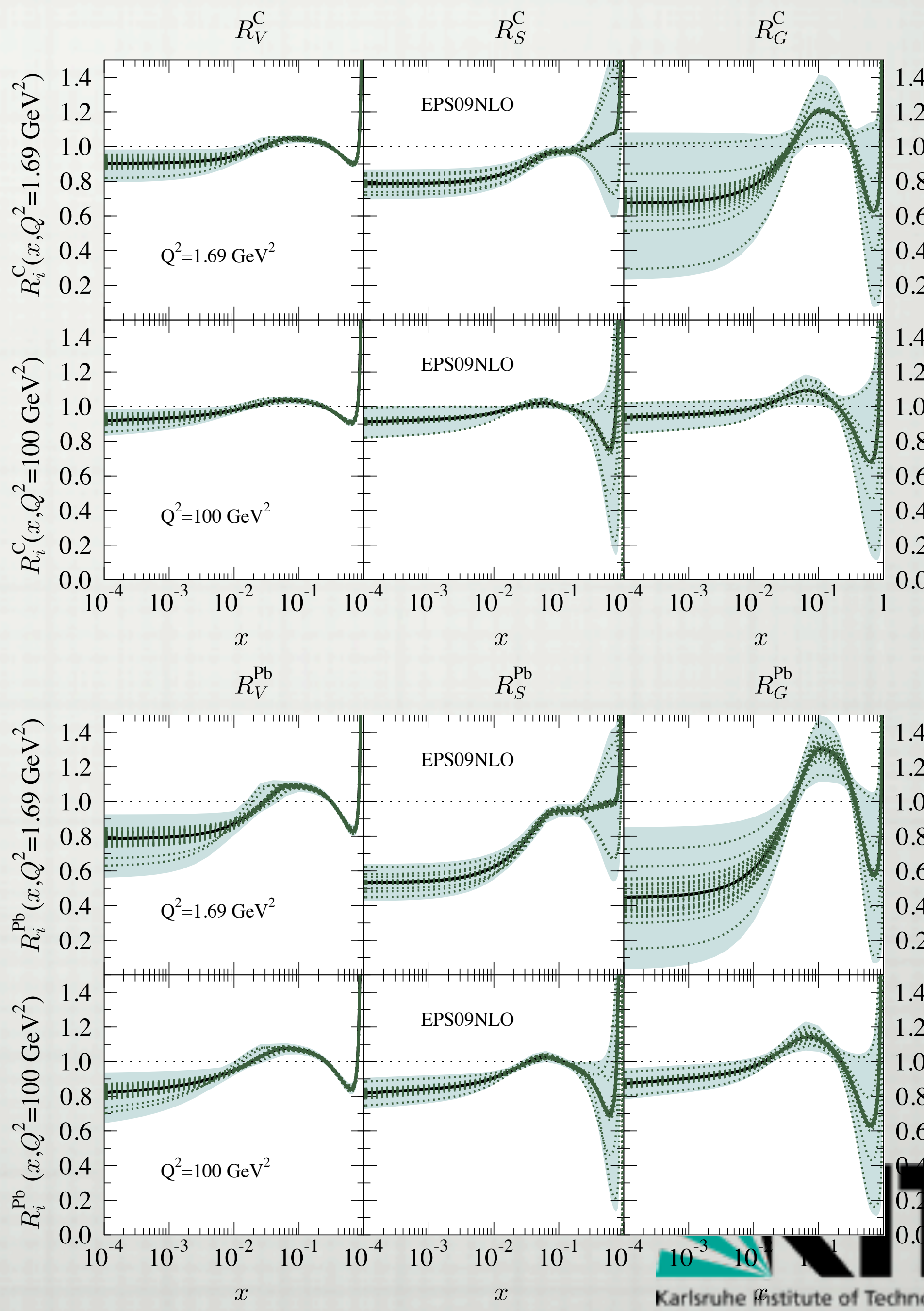
- uses multiplicative factor

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

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

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

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

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

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

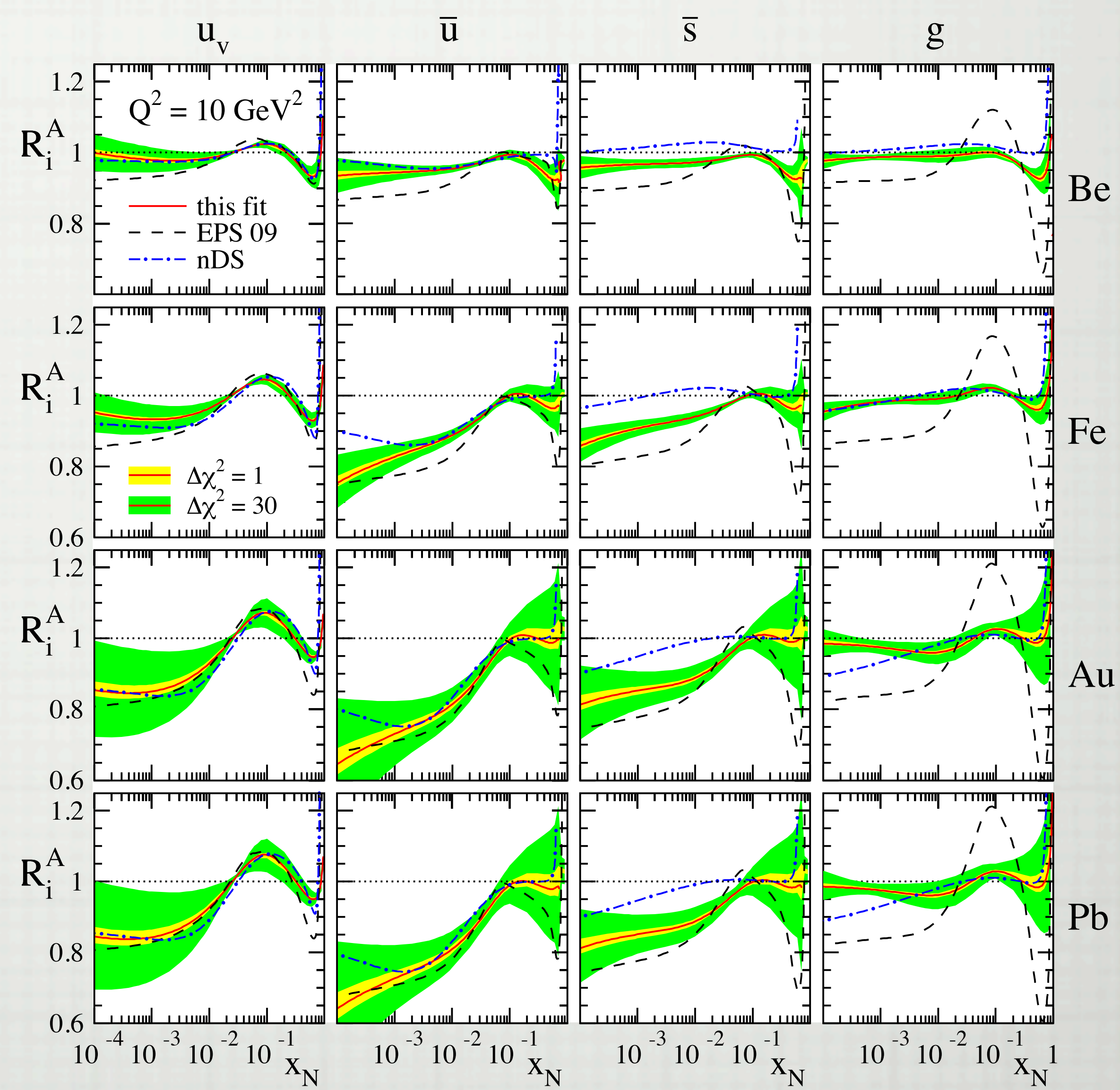
where proton PDF in MSTW08 and factor is a complicated function different for each flavour

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

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

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

- 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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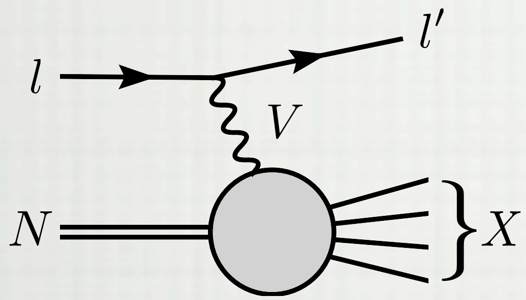
- Experiments included in the analysis

NOT (YET) INCLUDED

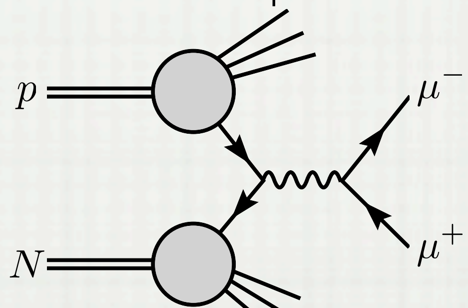
Charged lepton

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

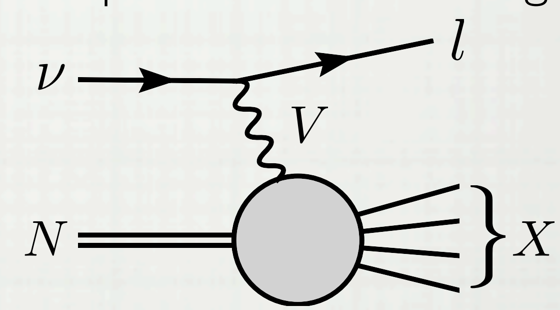
SLAC E-139 & E-049
$N = (\mathrm{D, Ag, Al, Au, Be, C, Ca, Fe, He})$

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

1233 data points (708 after cuts)

Neutrino

Deep Inelastic Scattering

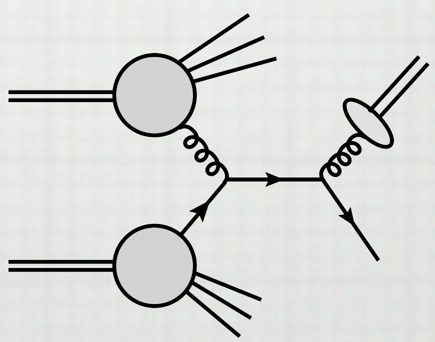


$\nu(\bar{\nu}) + N \to l + X$

CHORUS
$N = \mathrm{Pb}$

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

Single pion production



RHIC - PHENIX & STAR
$\mathrm{N} = \mathrm{Au}$

nCTEQ

- NPDF fit properties:
  - we fit nuclear data with NLO QCD predictions
  - we include heavy quark effects (ACOT)
  - applied standard CTEQ kinematical cuts **Q>2GeV & W>3.5GeV**
- NPDF fit results:
  - 708 (1233) data points after (before) cuts
  - 17 free parameters - 691 degrees of freedom
  - overall χ^2/dof = 0.87
  - individually for different data subsets
    - for F_2^A/F_2^D χ^2/pt = 0.80
    - for $F_2^A/F_2^{A'}$ χ^2/pt = 0.51
    - for $\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$ χ^2/pt = 0.85

$\mathbf{F_2^A/F_2^{A'}}$: Observable	Experiment	# data
Be/C	NMC-96	15
Al/C	NMC-96	15
Ca/C	NMC-95	20
	NMC-96	15
Fe/C	NMC-95	15
Sn/C	NMC-96	144
Pb/C	NMC-96	15
C/Li	NMC-95	20
Ca/Li	NMC-95	20
Total:		279

$\sigma_{\mathbf{DY}}^{\mathbf{pA}}/\sigma_{\mathbf{DY}}^{\mathbf{pA'}}$: Observable	Experiment	# data
C/D	FNAL-E772-90	9
Ca/D	FNAL-E772-90	9
Fe/D	FNAL-E772-90	9
W/D	FNAL-E772-90	9
Fe/Be	FNAL-E866-99	28
W/Be	FNAL-E866-99	28
Total:		92

$\mathbf{F_2^A/F_2^D}$: Observable	Experiment	# data
D	NMC-97	275
He/D	SLAC-E139	18
	NMC-95,re	16
	Hermes	92
Li/D	NMC-95	15
Be/D	SLAC-E139	17
C/D	EMC-88	9
	EMC-90	2
	SLAC-E139	7
	NMC-95,re	16
	NMC-95	15
	FNAL-E665-95	4
N/D	BCDMS-85	9
	Hermes	92
Al/D	SLAC-E049	18
	SLAC-E139	17
Ca/D	EMC-90	2
	SLAC-E139	7
	NMC-95,re	15
	FNAL-E665-95	4
Fe/D	BCDMS-85	6
	BCDMS-87	10
	SLAC-E049	14
	SLAC-E139	23
	SLAC-E140	6
Cu/D	EMC-88	9
	EMC-93(addendum)	10
	EMC-93(chariot)	9
Kr/D	Hermes	84
Ag/D	SLAC-E139	7
Sn/D	EMC-88	8
Xe/D	FNAL-E665-92	4
Au/D	SLAC-E139	18
Pb/D	FNAL-E665-95	4
Total:		862

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nCTEQ

- NPDF Hessian analysis:

$$\chi^2 = \chi_0^2 + \frac{1}{2} H_{ij}(a_i - a_i^0)(a_j - a_j^0) \qquad H_{ij} = \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}$$

  - 17 free parameters - 7 gluon parameters
    - 8 valence parameters
    - 2 sea parameters
  - Eigenvalues span 10 orders of magnitude → numerical precision required
  - Use improved derivatives - less sensitive to noise

$$\frac{\partial f}{\partial x} = \frac{f_1 - f_{-1}}{2h}$$

central differences

$$\frac{f_1 - f_{-1} + 2(f_2 - f_{-2}) + 3(f_3 - f_{-3})}{28h}$$

noise robust Lanczos 3, 5-point derivative

$$\frac{f_1 - f_{-1} + 2(f_2 - f_{-2}) + 3(f_3 - f_{-3}) + 4(f_4 - f_{-4}) + 5(f_5 - f_{-5})}{110h}$$

  - $\Delta\chi^2 = 35$ determined so that every nuclear target is described within 90% C.L.

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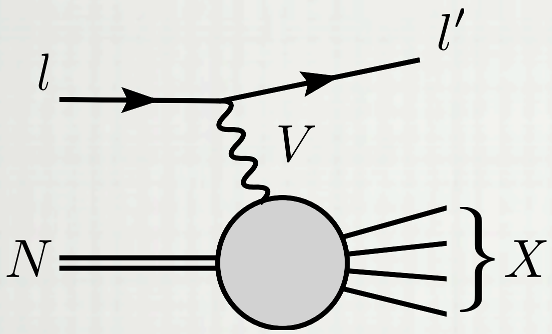
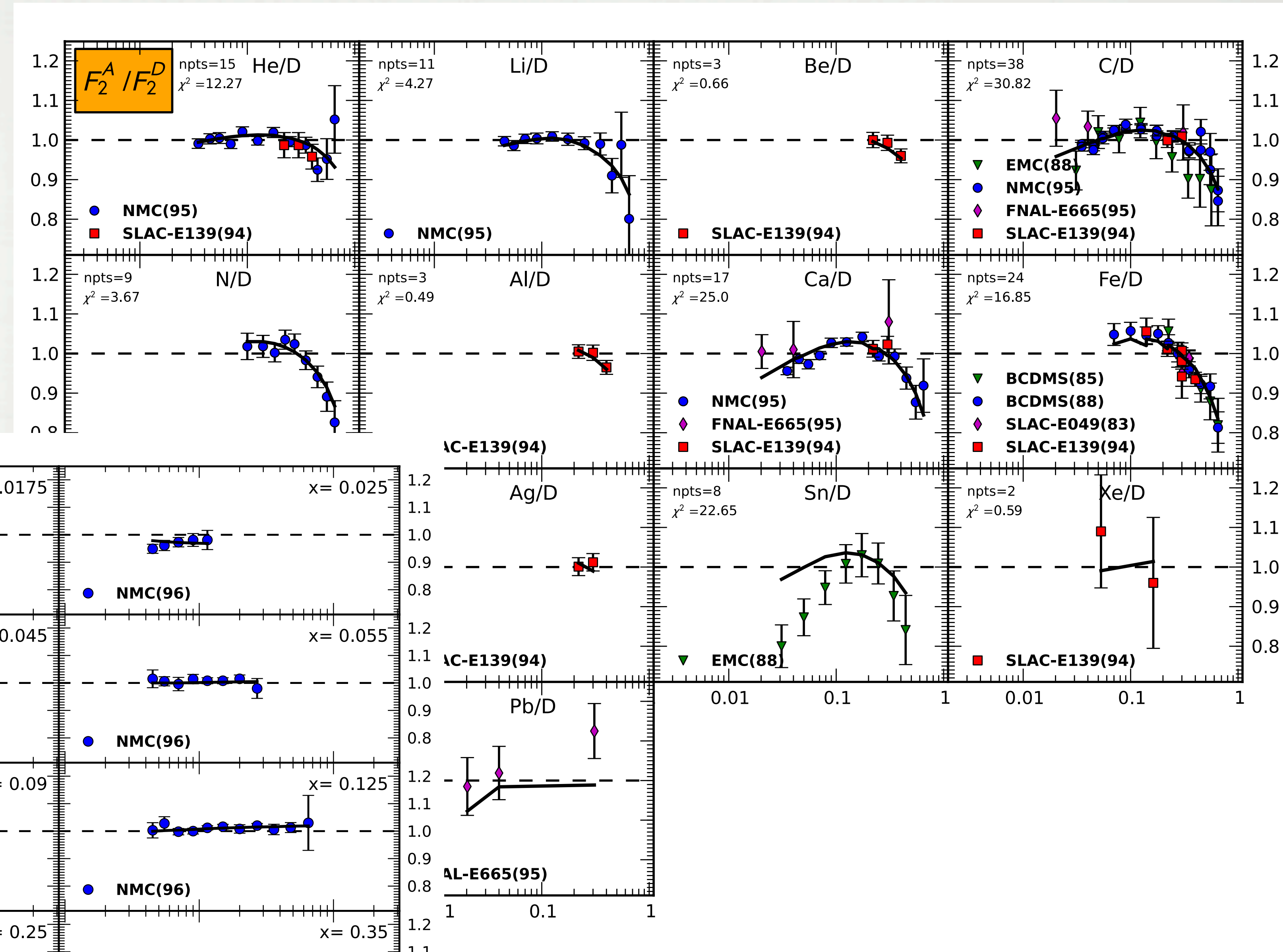
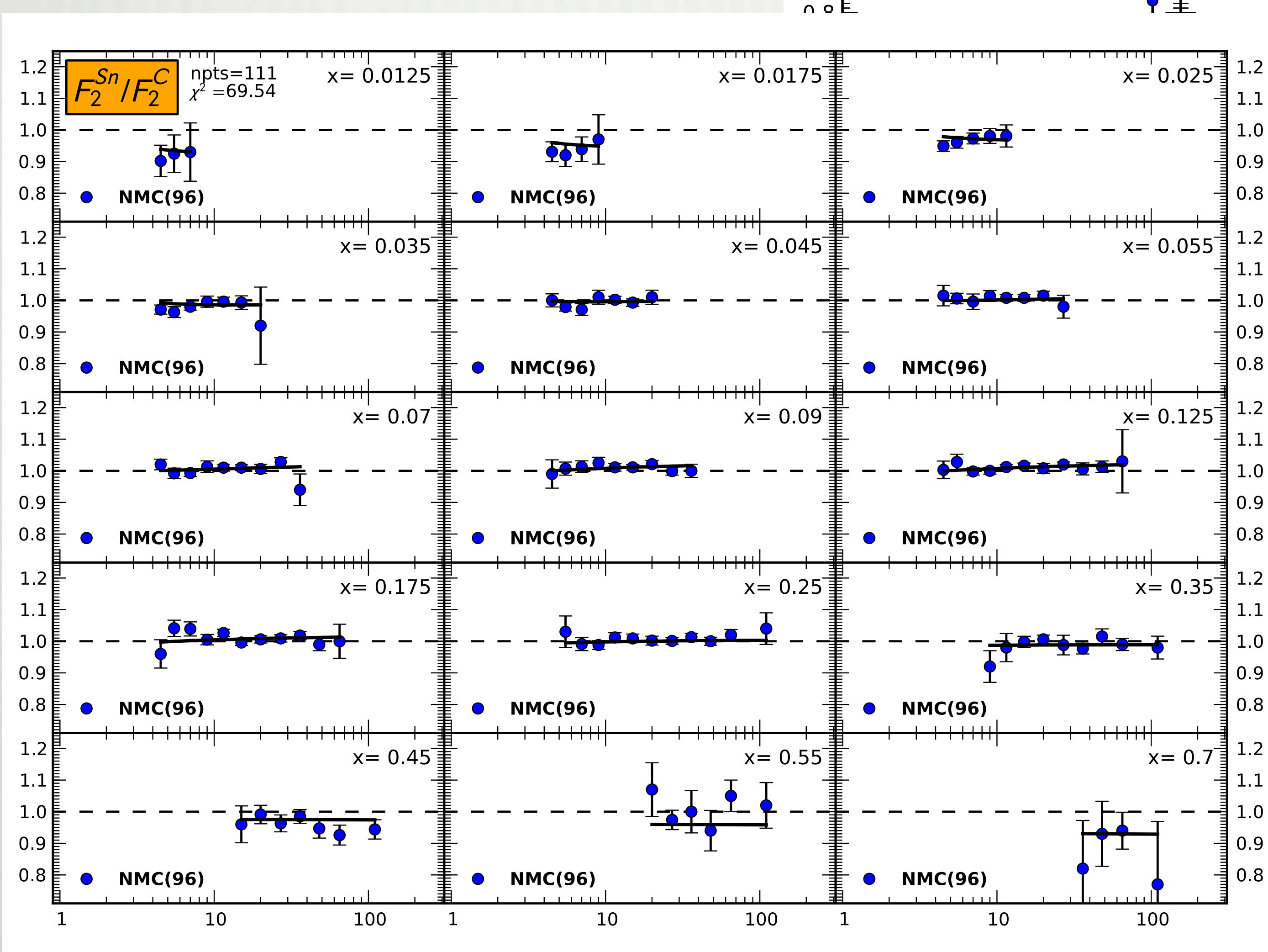
nCTEQ

- Deep Inelastic Scattering

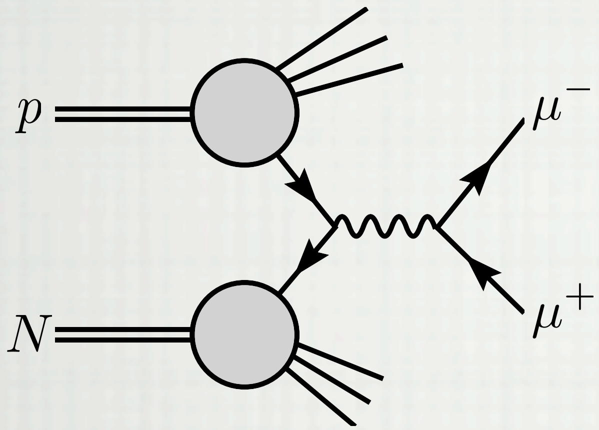


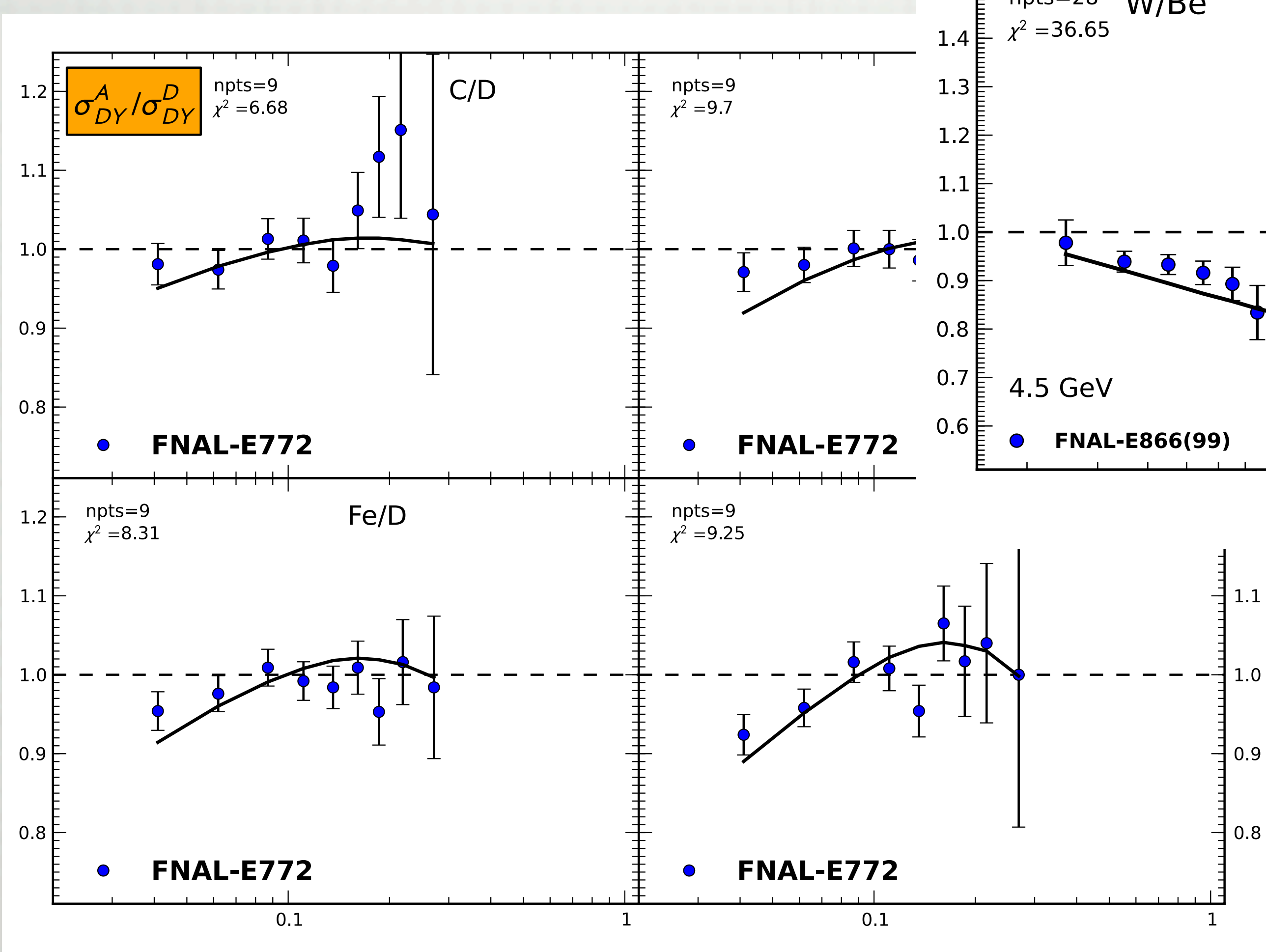


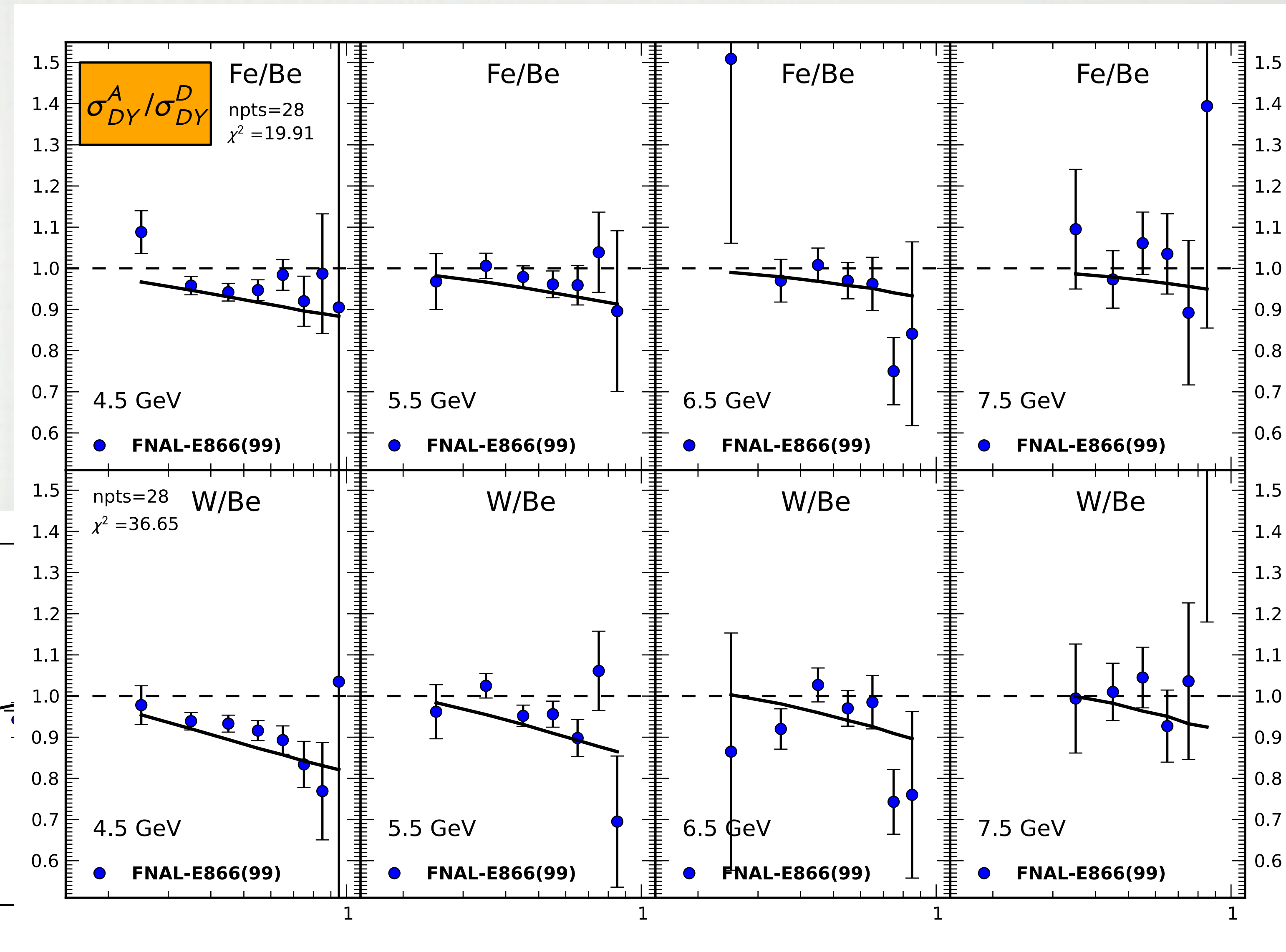


nCTEQ

- Drell-Yan process







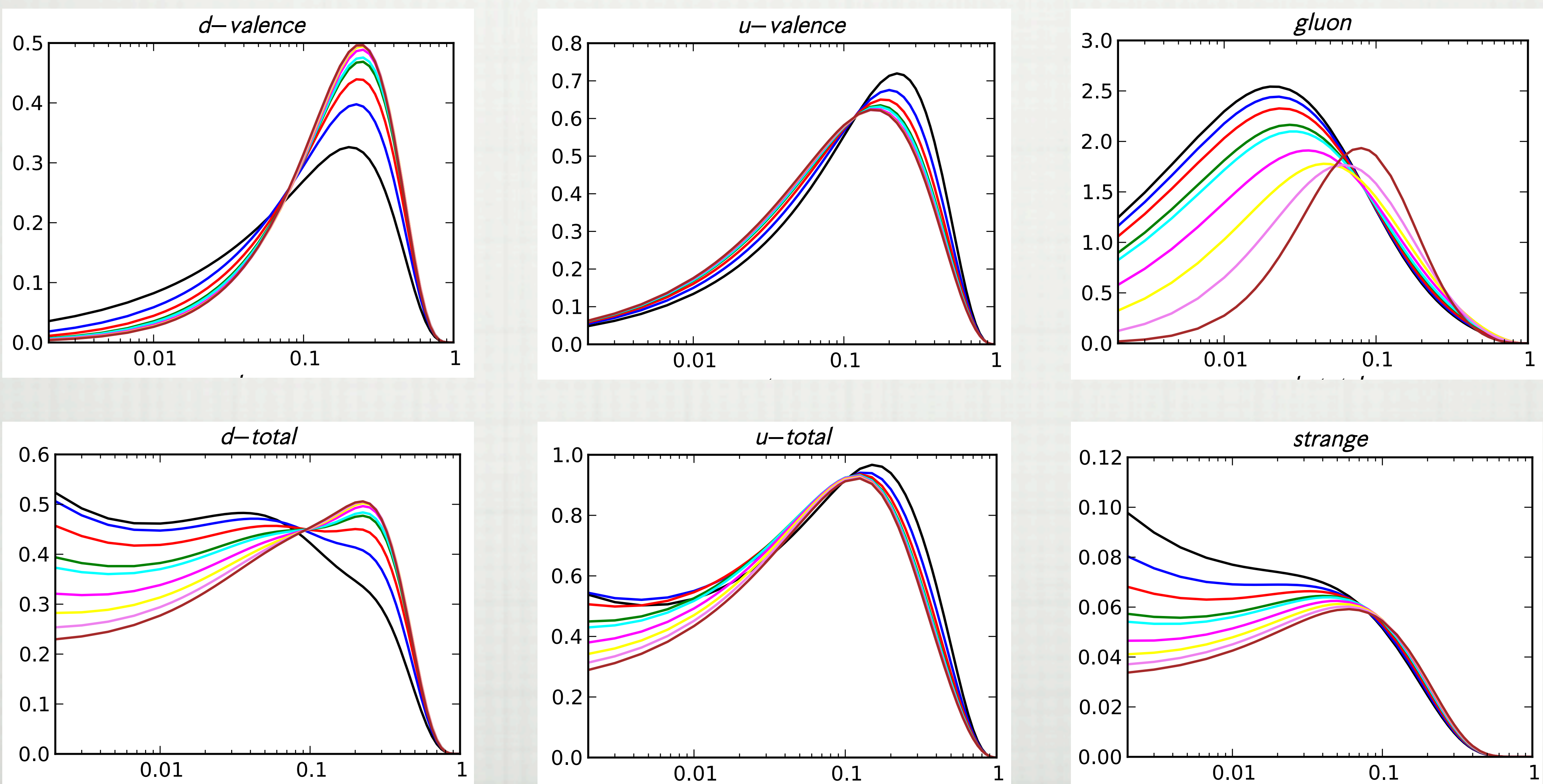
nCTEQ

- 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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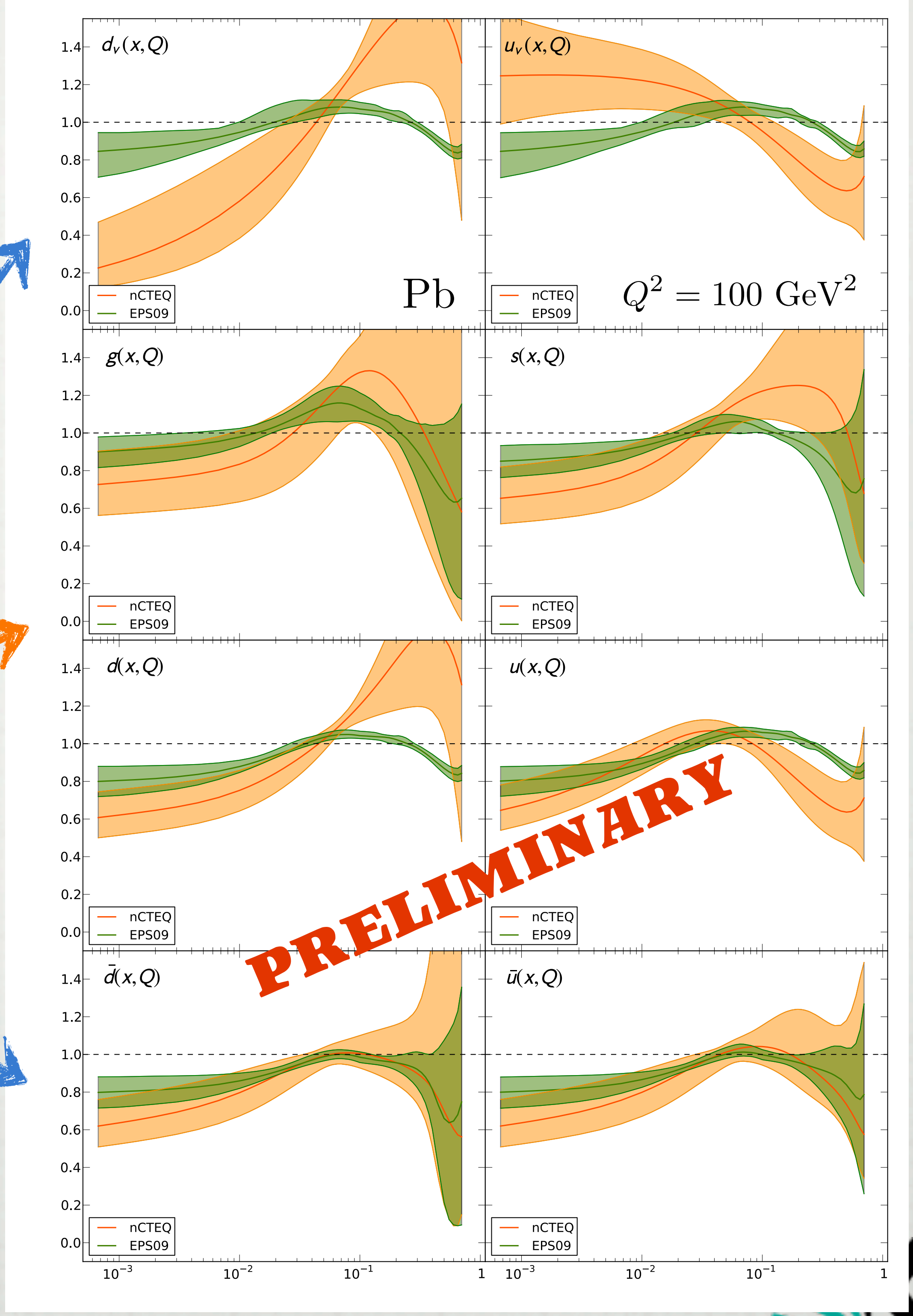
- nCTEQ nuclear correction factors with uncertainties

$$R_i(\text{Pb}) = \frac{f_i^{Pb}(x,Q)}{f_i^{p}(x,Q)} \quad @ \;\; Q^2 = 100 \text{ GeV}^2$$

- different solution for d-valence & u-valence compared to EPS09
- larger uncertainty @ gluon nuclear correction factor & bigger low-x suppression
- sea quark nuclear correction factors similar to EPS09
- nuclear correction factors depend largely on underlying proton baseline



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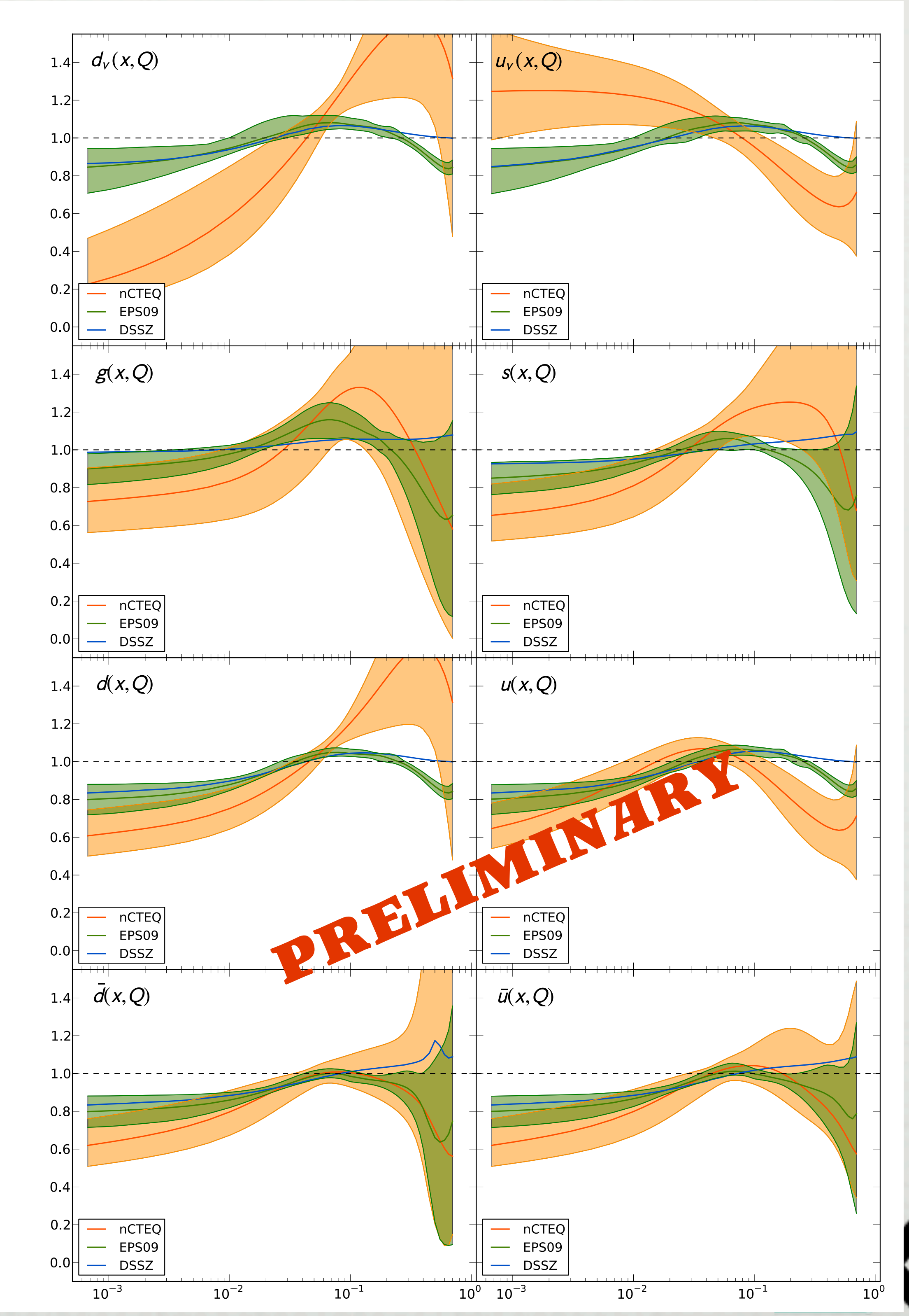
nCTEQ

- nCTEQ nuclear PDFs with uncertainties

$$x f_i^{\mathrm{Pb}}(x,Q) \quad @ \quad Q^2 = 100 \ \mathrm{GeV}^2$$

  - nCTEQ d-valence & u-valence solution between HKN07 & EPS09
  - nCTEQ nuclear uncertainties larger than previous nPDF analyses
  - nPDFs not dependant on proton baseline - better agreement between different nPDFs
  - Results still very preliminary



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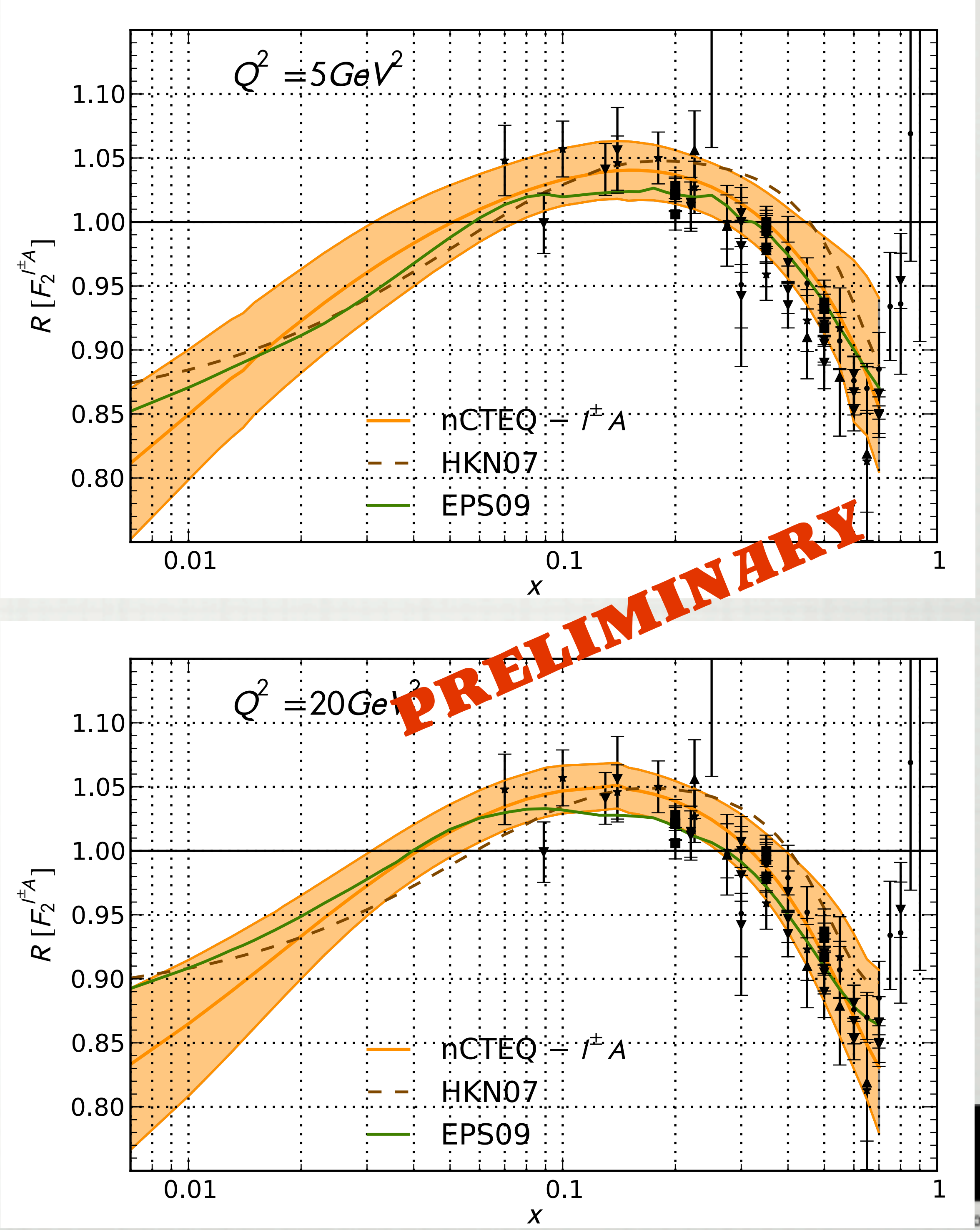
nCTEQ

- nCTEQ structure function ratios with uncertainties

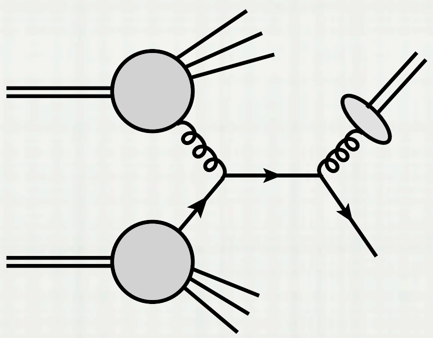
$$R = \frac{F_2^{Fe}(x,Q)}{F_2^{D}(x,Q)}$$

- Structure function ratios are fitted observables
- Despite different d-valence & u-valence solutions - ratio of structure functions remain very similar
- Good description of data & differences between nCTEQ and other nPDFs appear at low-x where there's no data



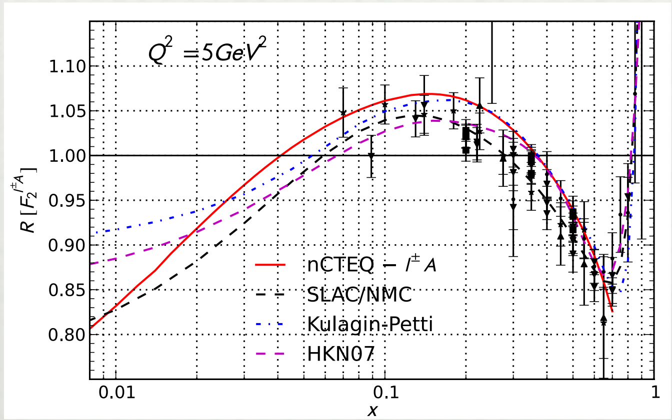
nCTEQ

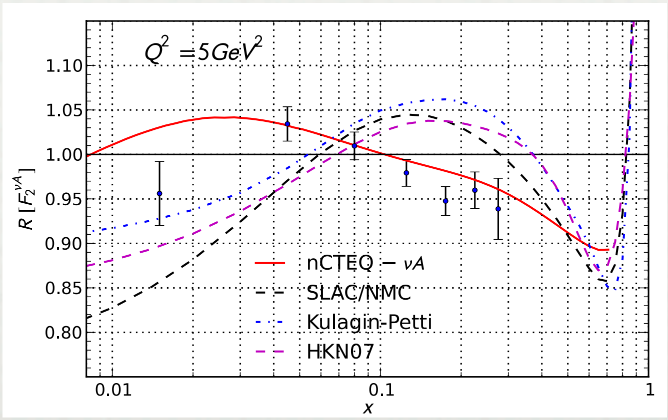
- Why is the nCTEQ analysis still **PRELIMINARY ?**
    - On-going work - inclusion of single inclusive pion production data from d-Au from RHIC



- more realistic estimate of the nuclear gluon correction factor @ intermediate & high-x

    - In discussion - inclusion of neutrino DIS data (inconsistencies within NuTeV data)





- better flavour separation for nuclear effects

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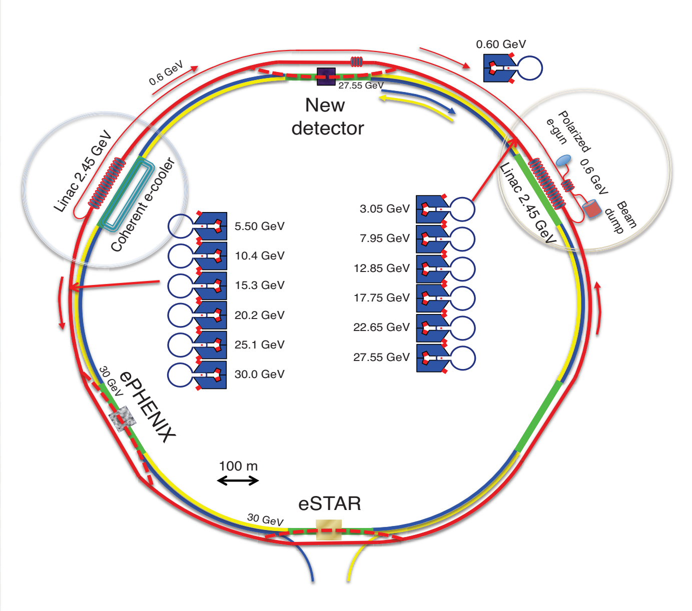
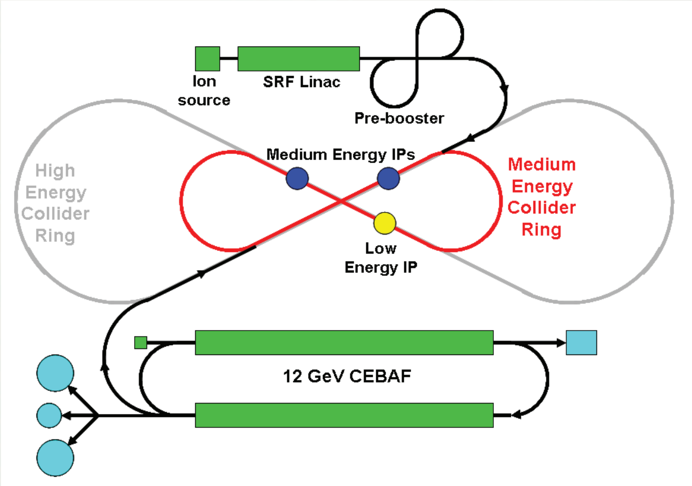
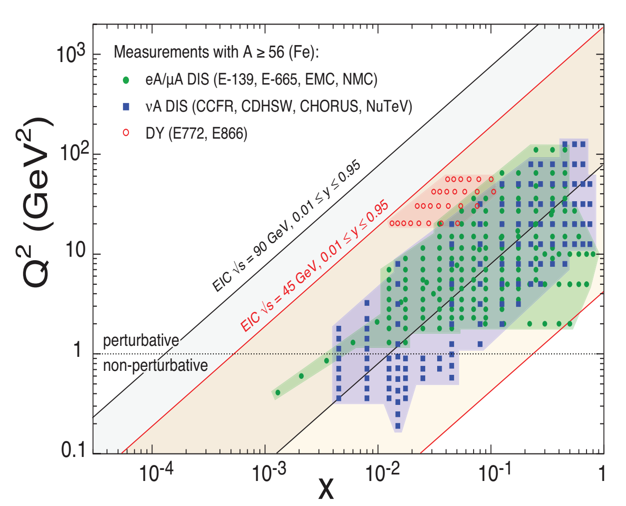
Future experiments

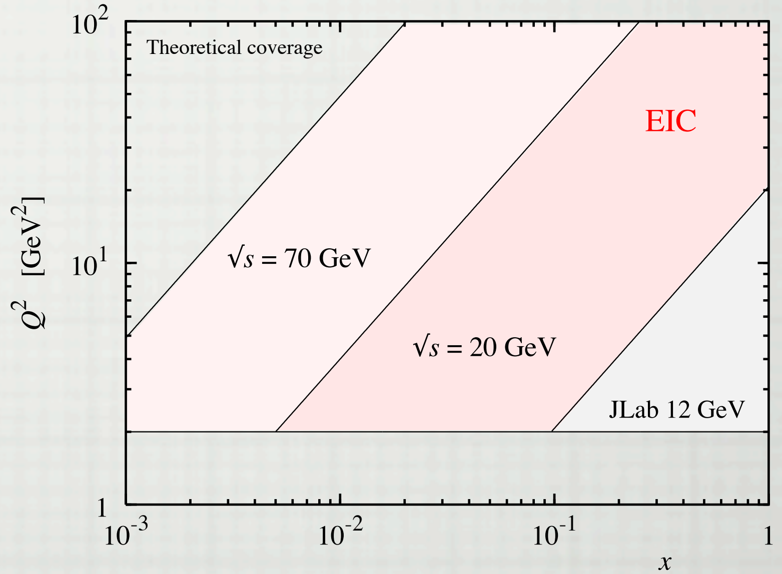
- Electron-Ion-Collider (EIC)
  - 2 different proposals - JLab & RHIC
  - multiple nuclear targets
  - reach to small-x





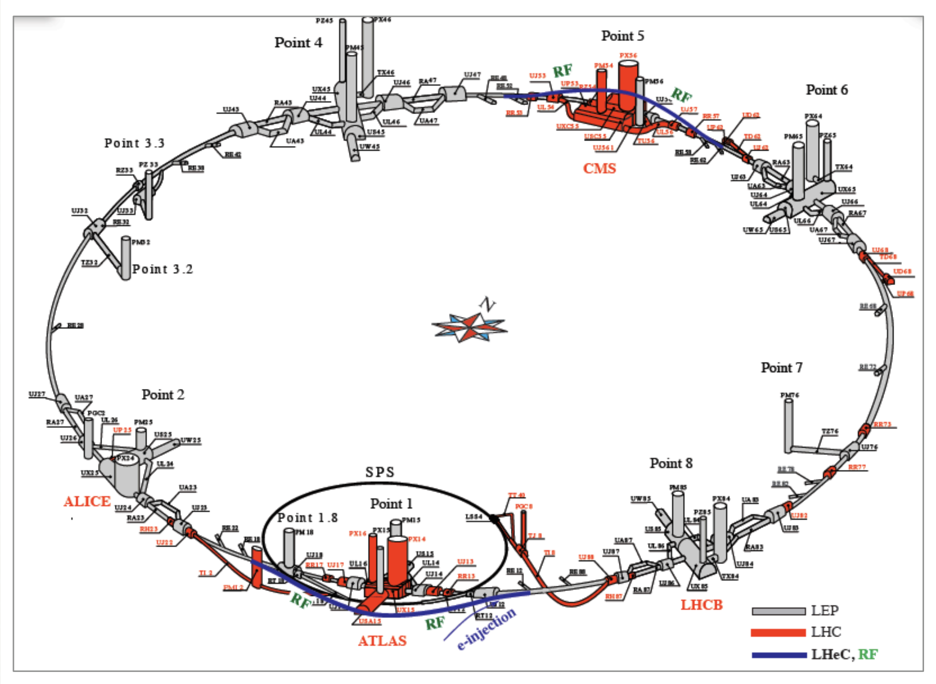
- nPDF requirements on EIC
  - coverage in x-Q^2 plane (small-x)
  - precision (e.g. for gluon PDF)
  - # nuclei



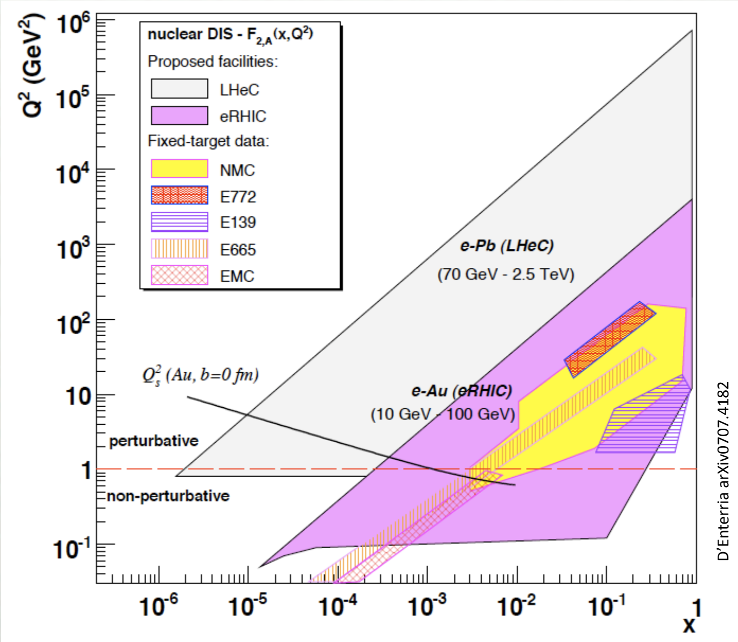


Future experiments

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



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



Conclusions & Outlook

- nCTEQ analysis still preliminary - RHIC data being included & analysed at the moment
- nCTEQ has larger uncertainties & larger nuclear suppression for gluon @ low-x
- Some important open questions remain (all can be solved by having more data)
  - uncertainty in nuclear gluon PDF (especially at small-x)
    - important contribution from LHC pA data
    - 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