Nuclear PDFs at the beginning of the LHC era

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Outline

I A brief overview of the existing nuclear PDFs

II The case of neutrino-nucleus DIS data

III The first glimpse of nuclear PDFs in the LHC p+Pb data?

IV Summary

I A brief overview of the exisiting nuclear PDFs

The theoretical foundation

- **The framework of collinear factorization**

The coeffcient functions – perturbatively calculable in strong & electroweak couplings

$$d\sigma^{A+B\to\mathcal{O}} = \sum_{ij} f_i^A \otimes d\hat{\sigma}^{i+j\to\mathcal{O}} \otimes f_j^B \quad + \mathrm{highertwist}$$

Parton distribution functions obeying the DGLAP evolution equations

$$Q^2 \frac{\partial f_i(x,Q^2)}{dQ^2} = \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z) f_j(x/z,Q^2)$$

Splitting functions – perturbatively calculable in strong & electroweak couplings. Known up to NNLO in α_{strong} and LO in α_{QED}

The PDF fit merry-go-round

Parametrize the PDFs f(x,Q_0) at intial scale

↓

Solve the DGLAP equations $$Q^2\frac{\partial f_i(x,Q^2)}{dQ^2} = \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z) f_j(x/z,Q^2)$$

↓

Calculate the cross sections assuming the factorization

$$d\sigma^{A+B\to\mathcal{O}} = \sum_{ij} f_i^A \otimes d\hat{\sigma}^{i+j\to\mathcal{O}} \otimes f_j^B$$

↓

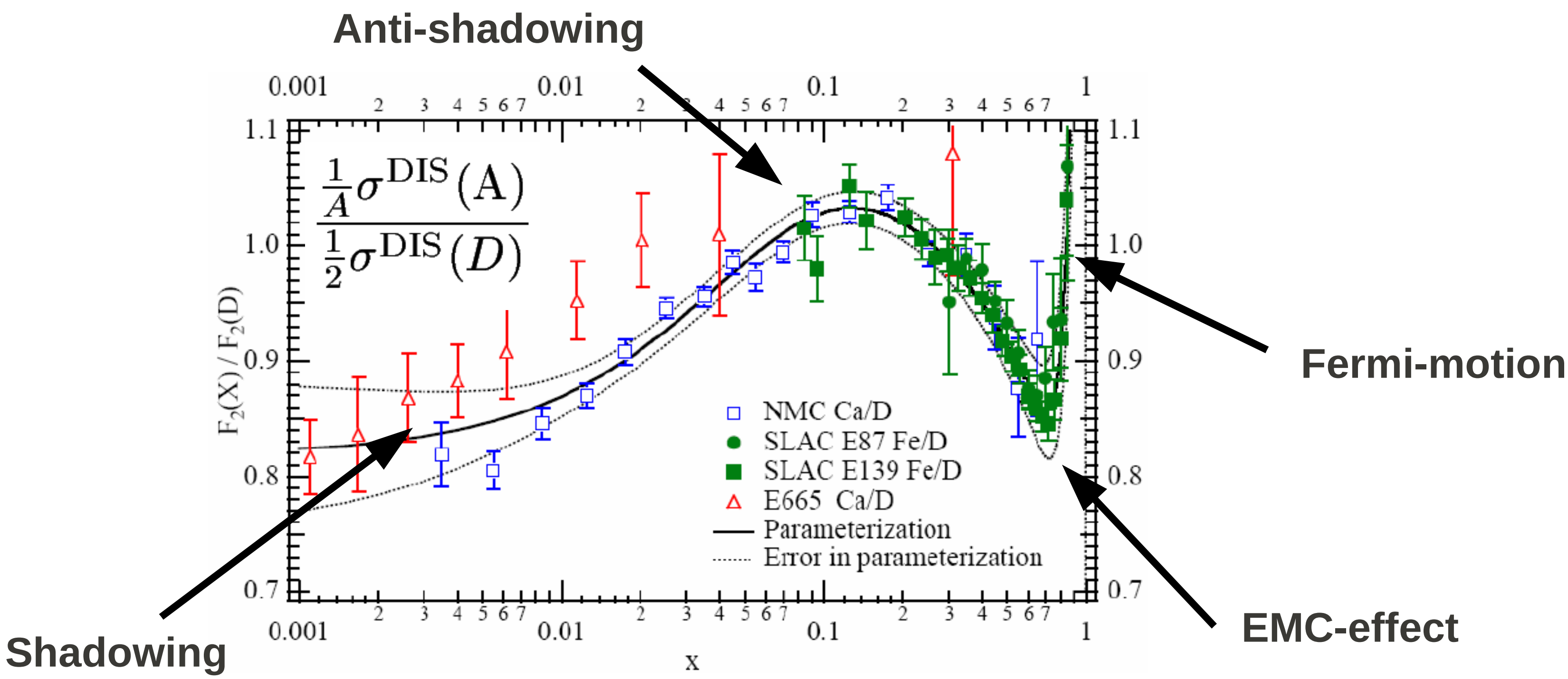
$$\chi^2 = \sum_{i=1}^{N_{\rm data}} \left(\frac{{\rm data}_i - {\rm theory}_i}{\Delta_i}\right)^2$$

Vary the parameters and find the minimum

↓

Estimate the tolerance $\Delta\chi^2$ and construct the PDF error sets

Global nPDF fits – tests of factorization



- **General observation:** $\sigma^{\text{bound nucleon}} \neq \sigma^{\text{free nucleon}}$
- **Search for <u>process independent</u> nPDFs to realize such differences**

$$\sigma_{\text{DIS}}^{\ell+A\to\ell+X} = \sum_{i=q,\bar{q},g} f_i^A(\mu^2) \otimes \hat{\sigma}_{\text{DIS}}^{\ell+i\to\ell+X}(\mu^2)$$

Nuclear PDFs, obeying the standard DGLAP

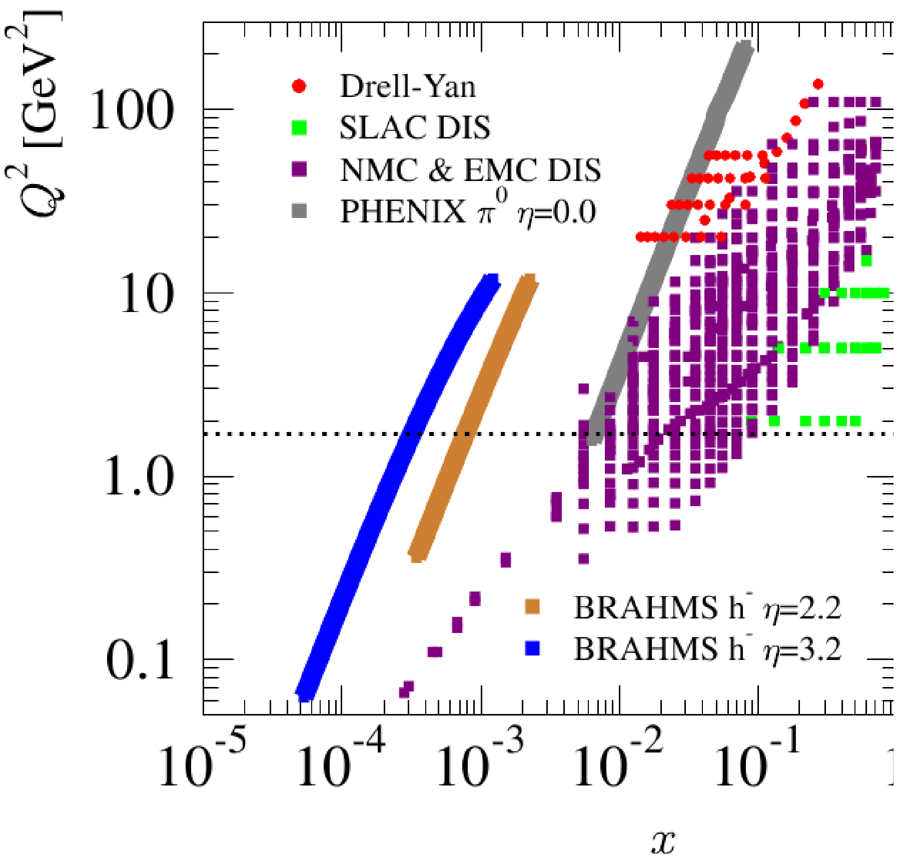
Usual perturbative coefficient functions

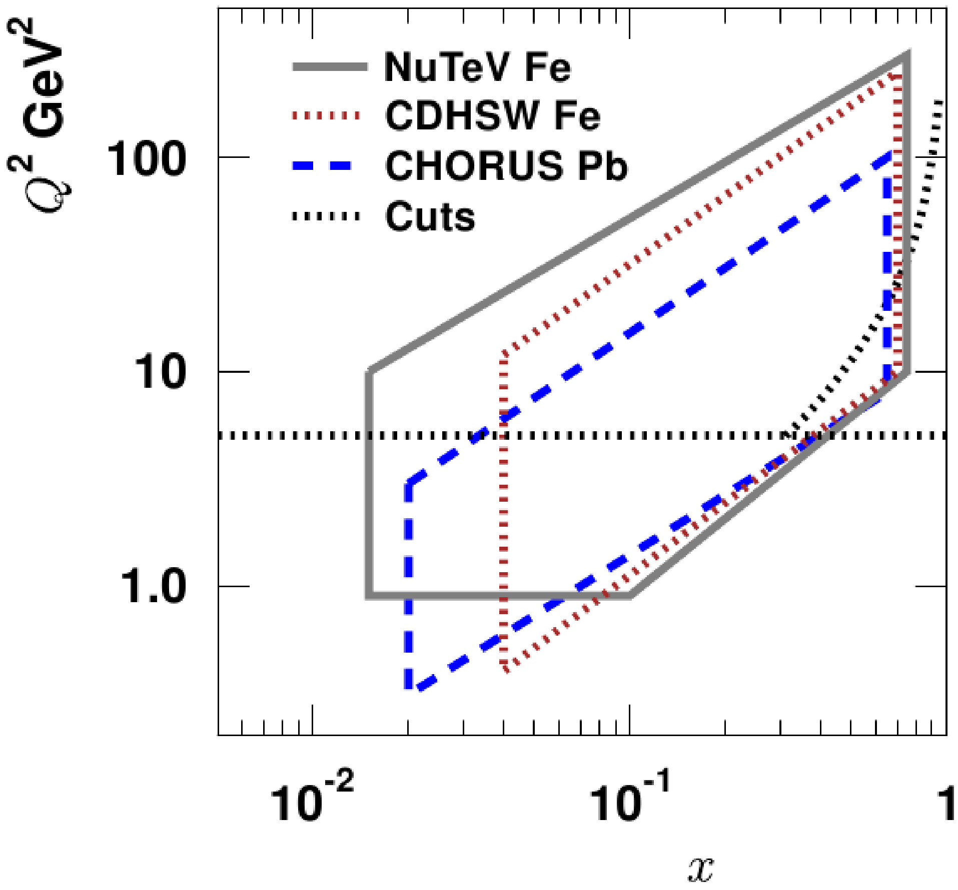
The contemporary NLO nPDF fits

$$f_i^{p,A}(x,Q^2) = R_i^A(x,Q^2) f_i^p(x,Q^2)$$

	HKN07	EPS09	DSSZ	nCTEQ prelim.
Ref.	Phys. Rev. C76 (2007) 065207	JHEP 0904 (2009) 065	Phys.Rev. D85 (2012) 074028	arXiv:1307.3454
Order	LO & NLO	LO & NLO	NLO	NLO
Neutral current e+A / e+d DIS	√	√	√	√
Drell-Yan dileptons in p+A / p+d	√	√	√	√
RHIC pions in d+Au / p+p		√	√	
Neutrino-nucleus DIS			√	
Q^2 cut in DIS	1GeV	1.3GeV	1GeV	2GeV
# of data points	1241	929	1579	708
Free parameters	12	15	25	17
Error sets available		√	√	√
Error tolerance $\Delta\chi^2$	13.7	50	30	35
Baseline	MRST98	CTEQ6.1	MSTW2008	CTEQ6M
Heavy quark treatment	ZM_VFNS	ZM_VFNS	GM_VFNS	GM_VFNS

Kinematical coverage of the data

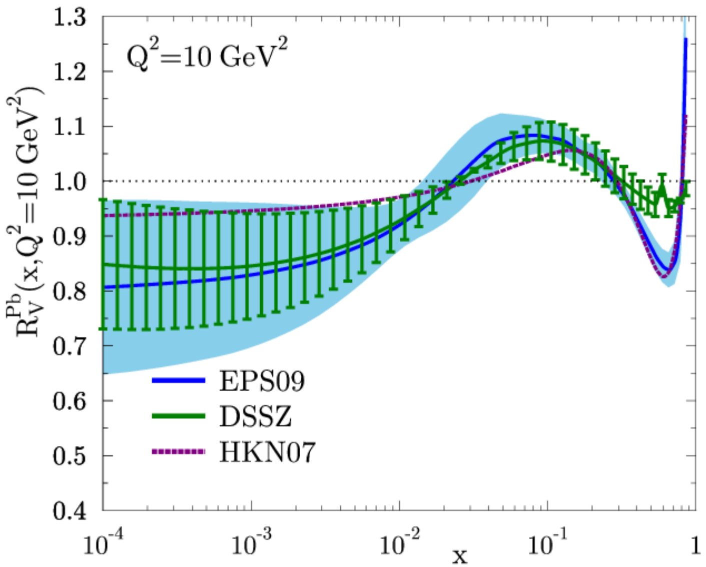




- Only a handful of different observables & quite restricted kinematic coverage. To be changed along the LHC p+Pb measurements?

Comparison: Valence quarks

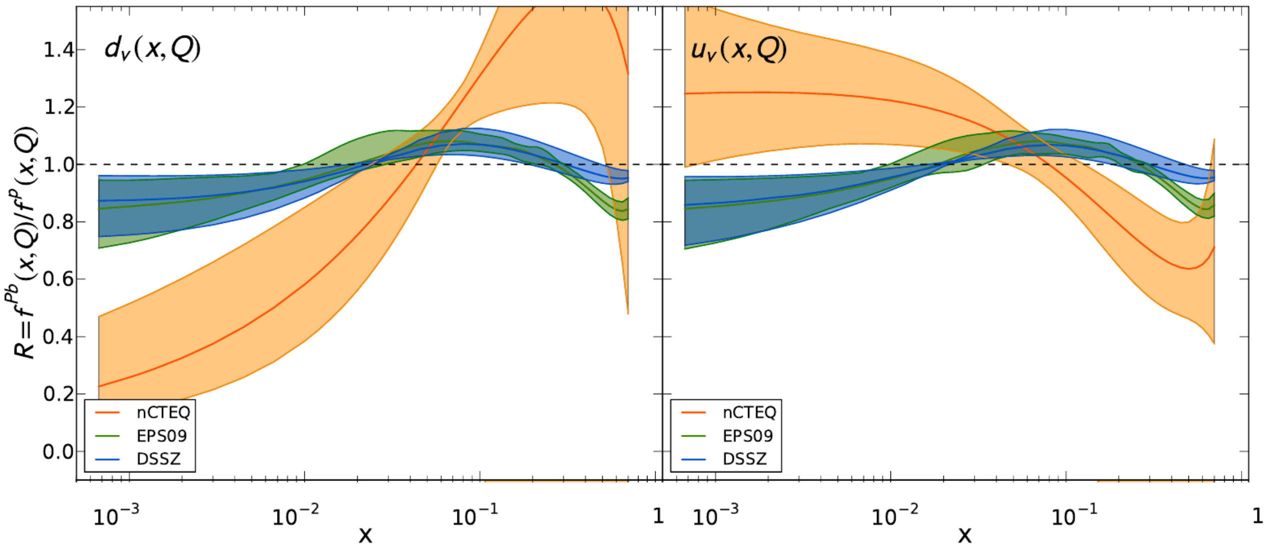
- **Some differences between EPS09, HKN07 & DSSZ.... (data constraints for x=0.1...1)**



(R_{uV} & R_{dV} almost the same for EPS09, DSSZ, HKN07)

Clear diasgreement at large x. An isospin effect?

- **…but the preliminary nCTEQ curves show a really drastic difference**



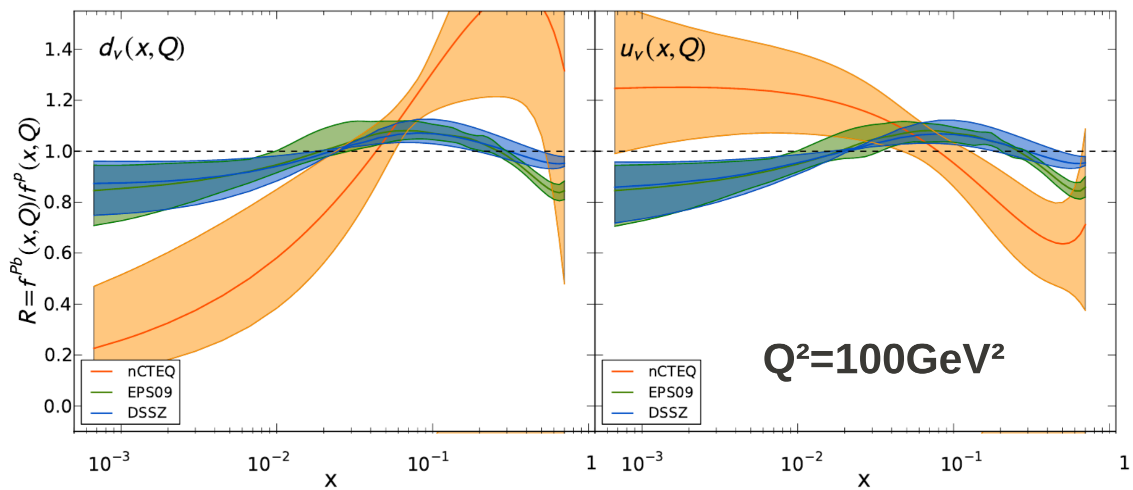
Q^2=100GeV^2

Comparison: Valence quarks

$$d\sigma^{\text{DIS}} \sim \left(\frac{4}{9}\right) u_v^A + \left(\frac{1}{9}\right) d_v^A$$

$$\sim u_v^A \left[R_{u_v} + R_{d_v} \frac{d_v^p}{u_v^p} \frac{Z+4N}{N+4Z} \right]$$

$$\approx u_v^A \left[R_{u_v} + \frac{1}{2} R_{d_v} \right]$$

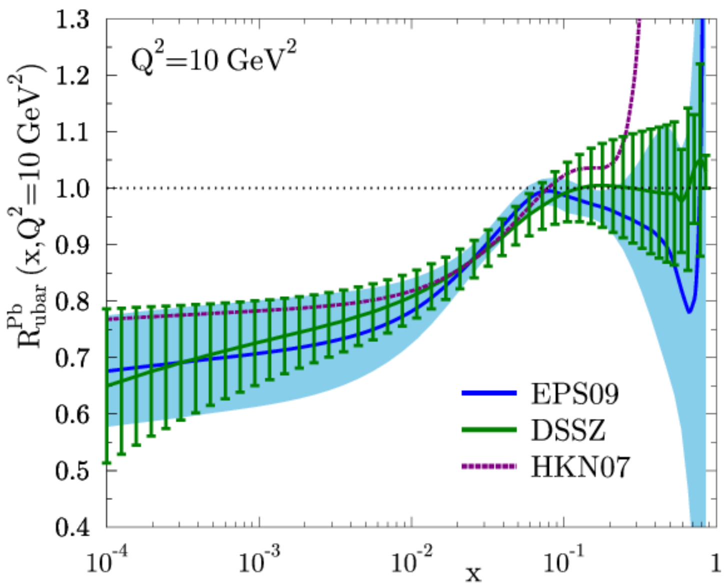


Some variations depending on the nucleus and x

- **The data does not constraint both R_{uV} & R_{dV} separately - only a linear combination of them.**
- **Need another observable for more reliable flavor separation**

Comparison: Sea Quarks

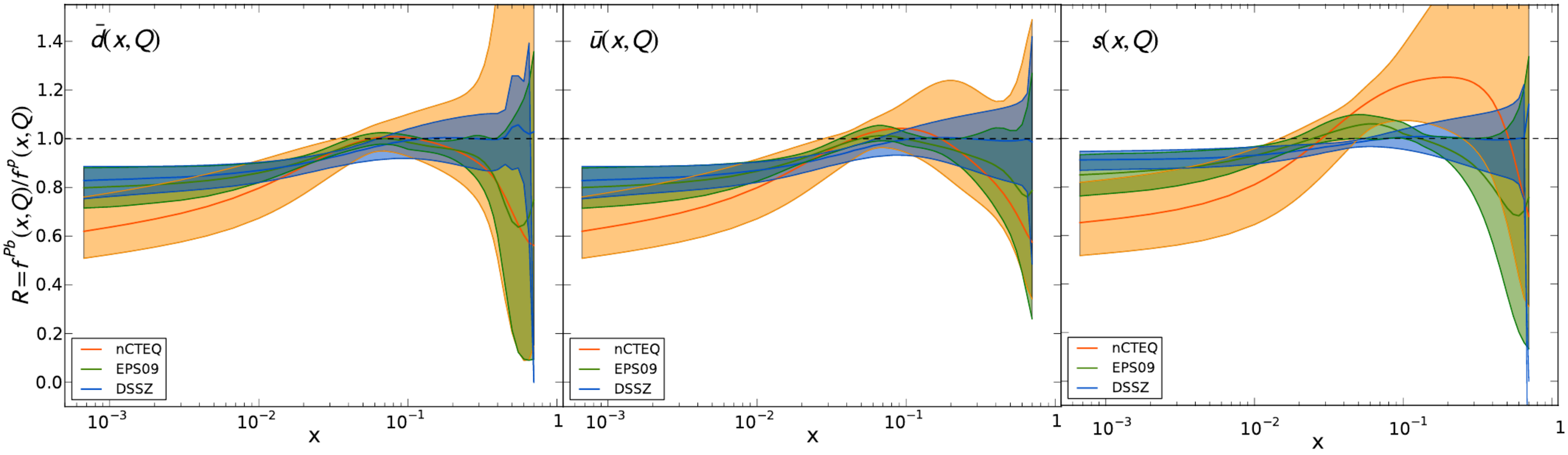
- **No qualitative disagreements in the data constrained region (x=0.01...0.1)**



The large-x behaviour reflects the gluons (above the parametrization scale)

- **No qualitative disagreements to preliminary nCTEQ results either**

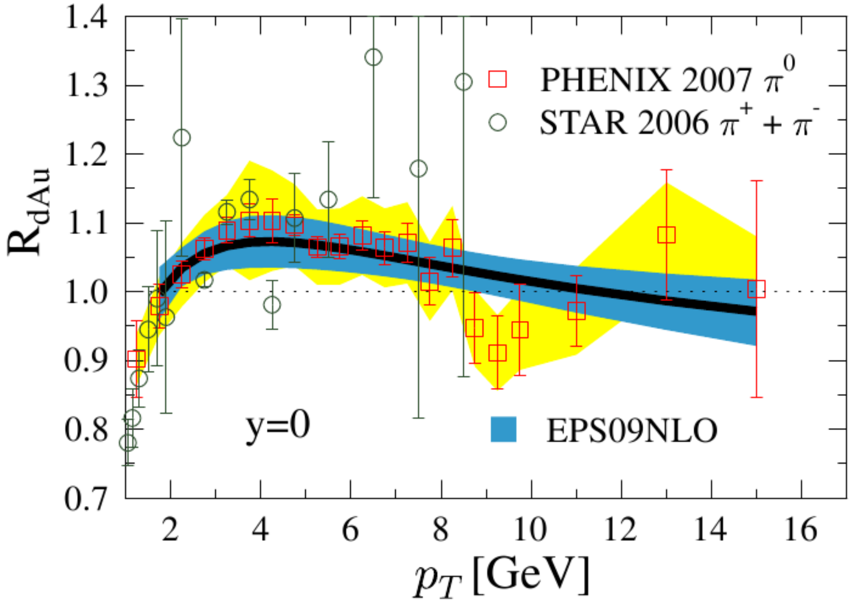
Q^2=100GeV^2

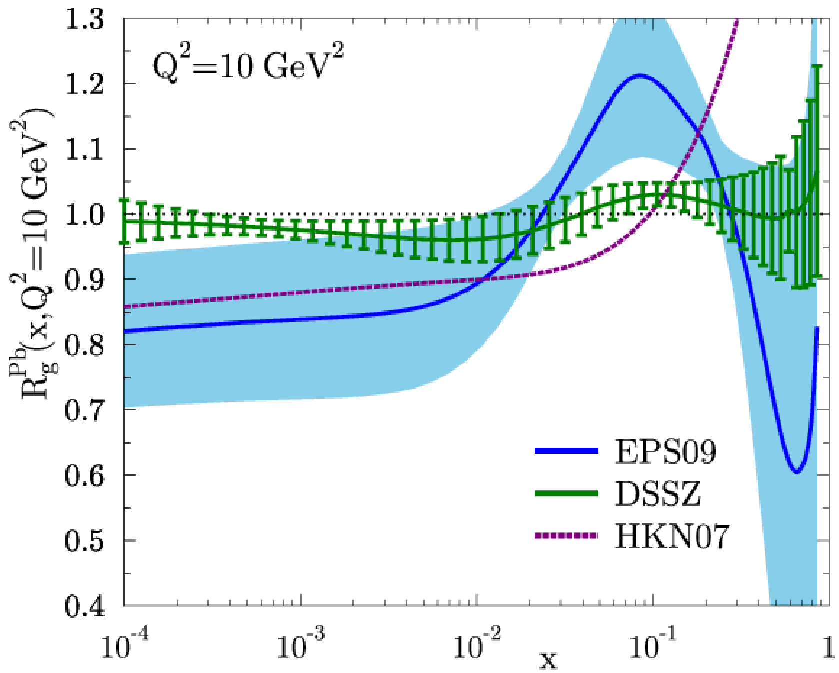


Comparison: Gluons

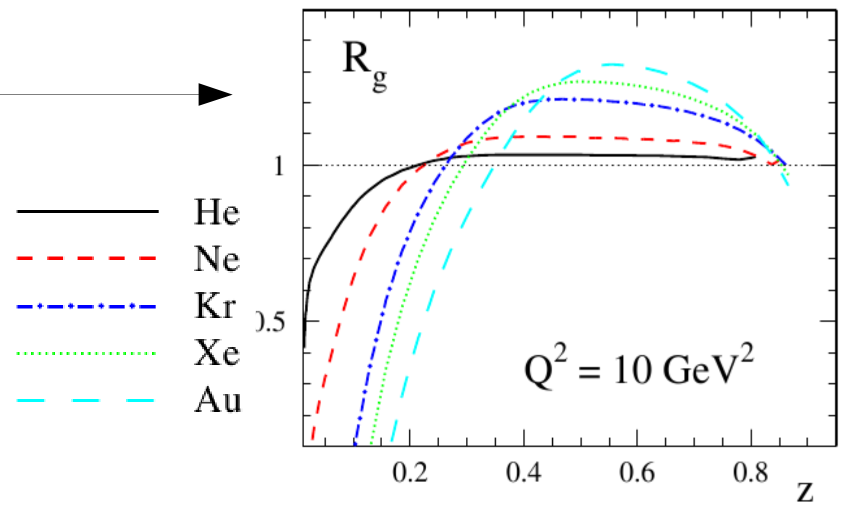
- **Difference between EPS09 & DSSZ:**

*The antishadowing and EMC effect in **EPS09** comes from the RHIC pion data*





FF(g→pion,A) / FF(g→pion,p)



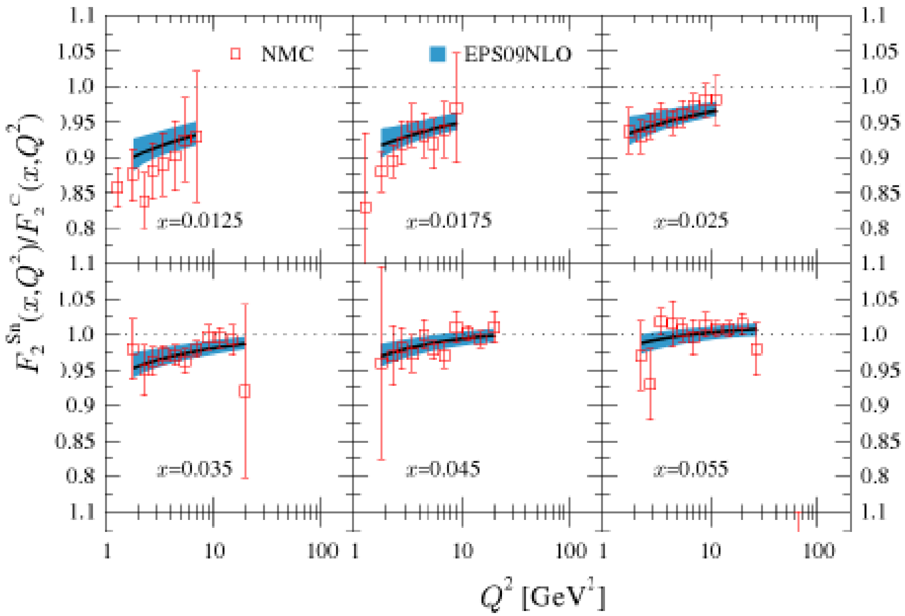
***DSSZ** advocated nuclear modifications in the fragmentation functions. No antishadowing nor EMC effect.*

Both can fit the pion data, but the origin of the effect is different.

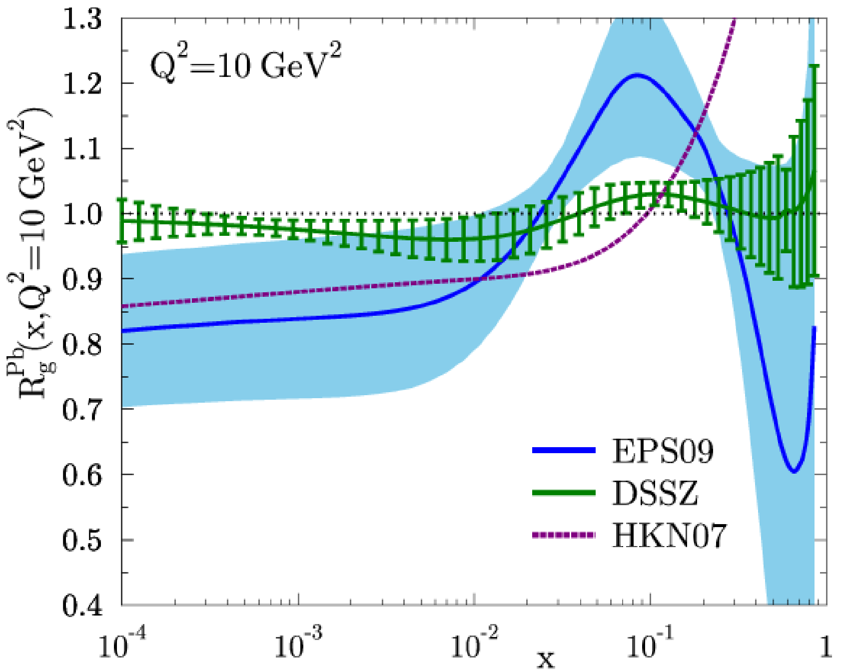
Comparison: Gluons

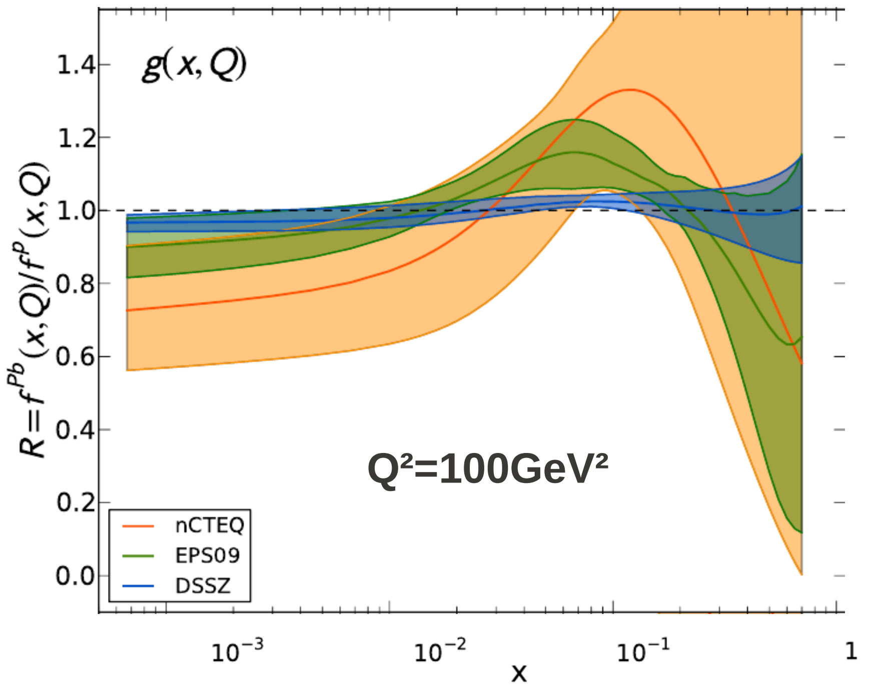
- ***Strongest shadowing and largest error band in nCTEQ***

  Higher Q^2 cut has removed part of the small-Q^2 DIS data (largest DGLAP effects).



  No pion data included yet





- ***These differences are to be clarified by the LHC data***

  (See also talk by P. Zurita, Session 2B)

II The combatibility of neutrino-nucleus DIS data

Some remarks regarding neutrino DIS

- **Neutrino DIS probes different partonic combinations than e.g. the charged lepton DIS**

  → **Complemtentary information on the PDFs (especially the strange quark)**

$$d^2\sigma^{\nu A} \propto \left(d^A + s^A + b^A\right) + (1-y)^2 \left(\overline{u}^A + \overline{c}^A\right)$$
$$d^2\sigma^{\overline{\nu} A} \propto \left(\overline{d}^A + \overline{s}^A + \overline{b}^A\right) + (1-y)^2 \left(u^A + c^A\right)$$

vs.

$$d^2\sigma^{\ell^\pm A} \propto \frac{4}{9}\left(u^A + c^A + \overline{u}^A + \overline{c}^A\right) + \frac{1}{9}\left(d^A + s^A + b^A + \overline{d}^A + \overline{s}^A + \overline{b}^A\right)$$

- **Data taken with heavy targets (Fe, Pb)**

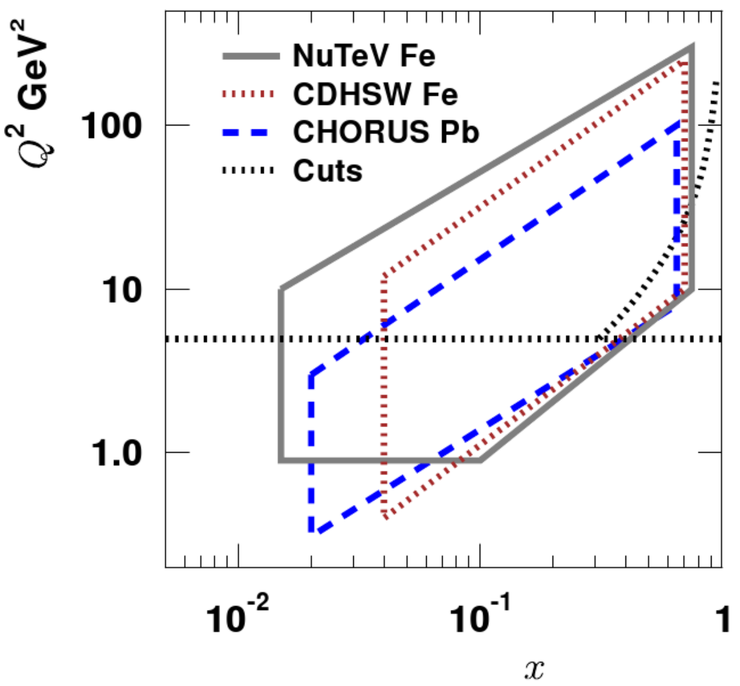
  A test of the nPDF universality

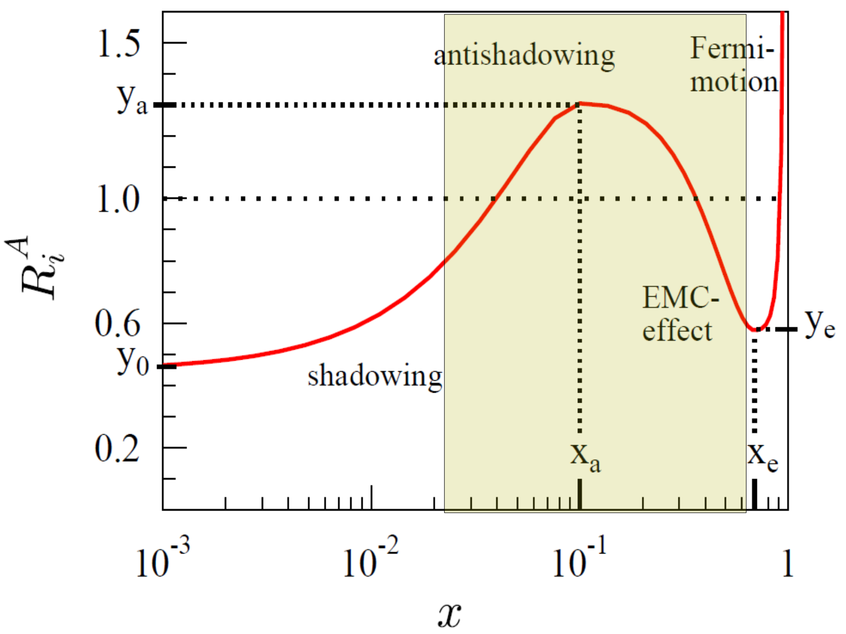
- **The adequacy of the factorization in nuclear neutrino DIS has been studied by independent groups. The conclusions contradictory.**

  nCTEQ: **No** ; *Paukkunen & Salgado*: **Yes** ; *De Florian et.al (DSSZ)*: **Yes**

The high-energy neutrino data

- **Three independent data sets:** **NuTeV (Fe), CDHSW (Fe) and CHORUS (Pb) (absolute cross sections)**





- **Typical kinematical cuts:** $Q^2_{\rm cut} > 4\,{\rm GeV}^2$, and $W^2_{\rm cut} > 12.25\,{\rm GeV}^2$

→ **~ 2000 NuTeV, 1000 CHORUS, 1000 CDHSW datapoints**

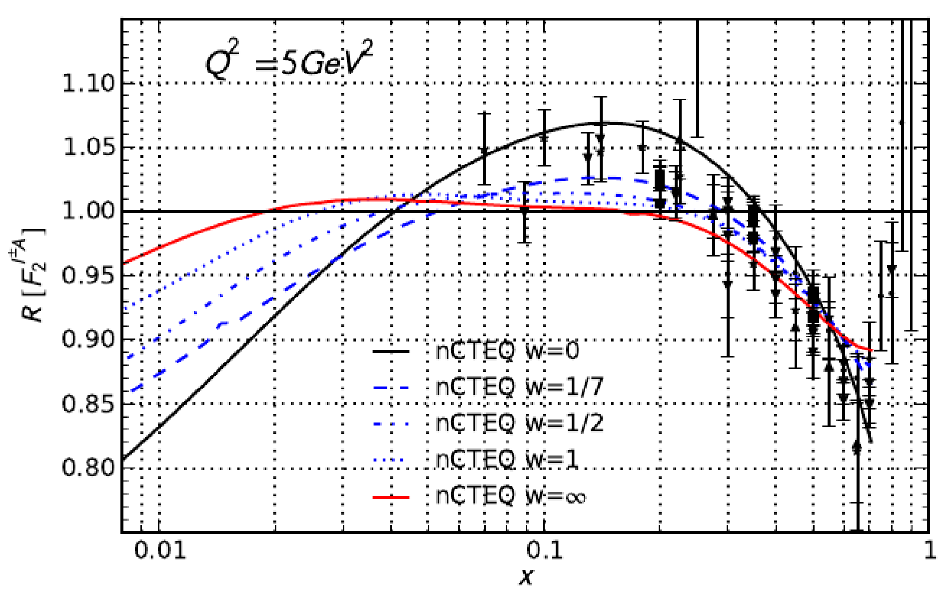
- **The large kinematical overlap should enable to check the mutual compatibility**

Neutrinos: The nCTEQ work

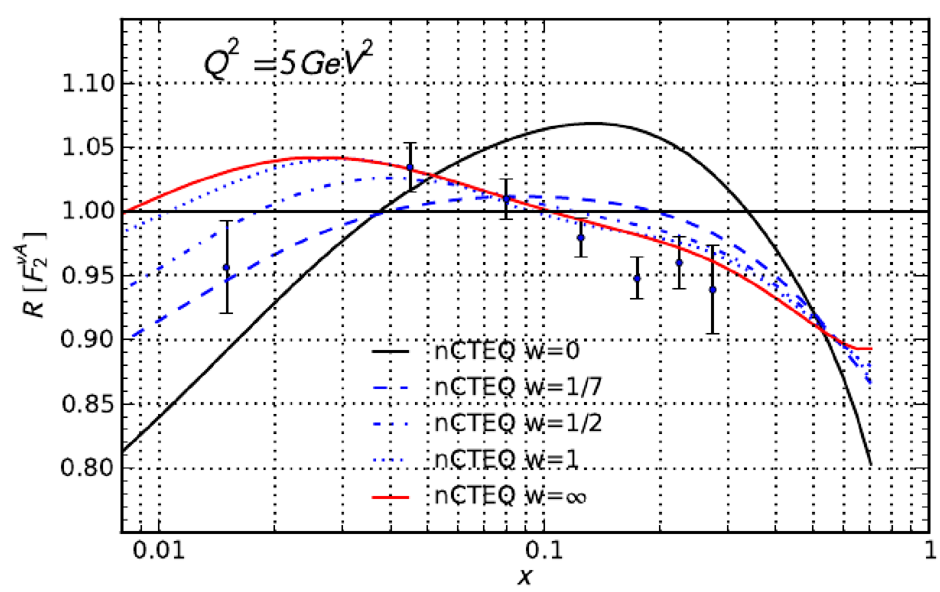
- **The nCTEQ claimed for having observed non-universal nuclear effects in the NuTeV cross-section data**

Phys. Rev. D77 054013 (2008) & Phys. Rev. D80 094004 (2009)

Some charged lepton data



Some NuTeV neutrino data data



Fit to the NuTeV neutrino data

Neutrinos: The nCTEQ work

- A global nPDF analysis including NuTeV & CHORUS neutrino cross-section data

$$\chi^2 = \sum_{l^\pm A \text{ data}} \chi_i^2 + \sum_{\nu A \text{ data}} w\chi_i^2$$

$l^\pm A$ gets worse as w is increased

Phys. Rev. Lett. 106, 122301 (2011)

TABLE II. Summary table of a family of compromise fits.

w	$l^\pm A$	χ^2 (/pt)	νA	χ^2 (/pt)	total χ^2(/pt)
0	708	638 (0.90)	...	...	638 (0.90)
1/7	708	645 (0.91)	3134	4710 (1.50)	5355 (1.39)
1/2	708	680 (0.96)	3134	4405 (1.40)	5085 (1.32)
1	708	736 (1.04)	3134	4277 (1.36)	5014 (1.30)
∞	...	...	3134	4192 (1.33)	4192 (1.33)

νA gets worse as w is decreased

- No satisfactory simultaneous fit to both $l^\pm A$ and νA data
- The use of correlated NuTeV errors was underscored (the same conclusion was, however, reached when adding all errors in quadrature)

Neutrinos: Paukkunen & Salgado

JHEP 1007 (2010) 032

- **An independent systematic comparison**

  - More diverse set of neutrino DIS data: **NuTeV (Fe), CDHSW (Fe) and CHORUS (Pb)**
  - The target mass corrections according to Accardi & Qiu *[JHEP 0807 (2008) 090]*

$$\int_x^1 \frac{dz}{z}\omega_{ik}(z)\, f_k^A\left(\frac{x}{z}\right) \to \int_x^1 \frac{dz}{z}\omega_{ik}(z)\, f_k^A\left(\frac{\xi}{z}\right) \qquad \xi \equiv 2x/(1+\sqrt{1+4x^2M^2/Q^2})$$

  - Electroweak radiation Bardin et.al *[JHEP 0506 (2005) 078]* as a part of the cross-sections

$$F_i^A = \sum_k \left[\omega_{ik}^{\rm LO}\left(1+\Delta_k^{\rm radiative}\right) + \omega_{ik}^{\rm NLO}\right] \otimes f_k^A$$

  - No PDF-fitting involved, just a systematic comparison employing CTEQ6.6 & EPS09

- **Present the data as a weighted average**

$$R_{\rm Average}^{\rm CTEQ6.6} \equiv \left(\sum_{i\in{\rm fixed}\,x}^{N} \frac{R_i^{\rm CTEQ6.6}}{\sigma_i}\right)\left(\sum_{i\in{\rm fixed}\,x}^{N}\frac{1}{\sigma_i}\right)^{-1} \pm N \times \left(\sum_{i\in{\rm fixed}\,x}^{N}\frac{1}{\sigma_i}\right)^{-1}$$

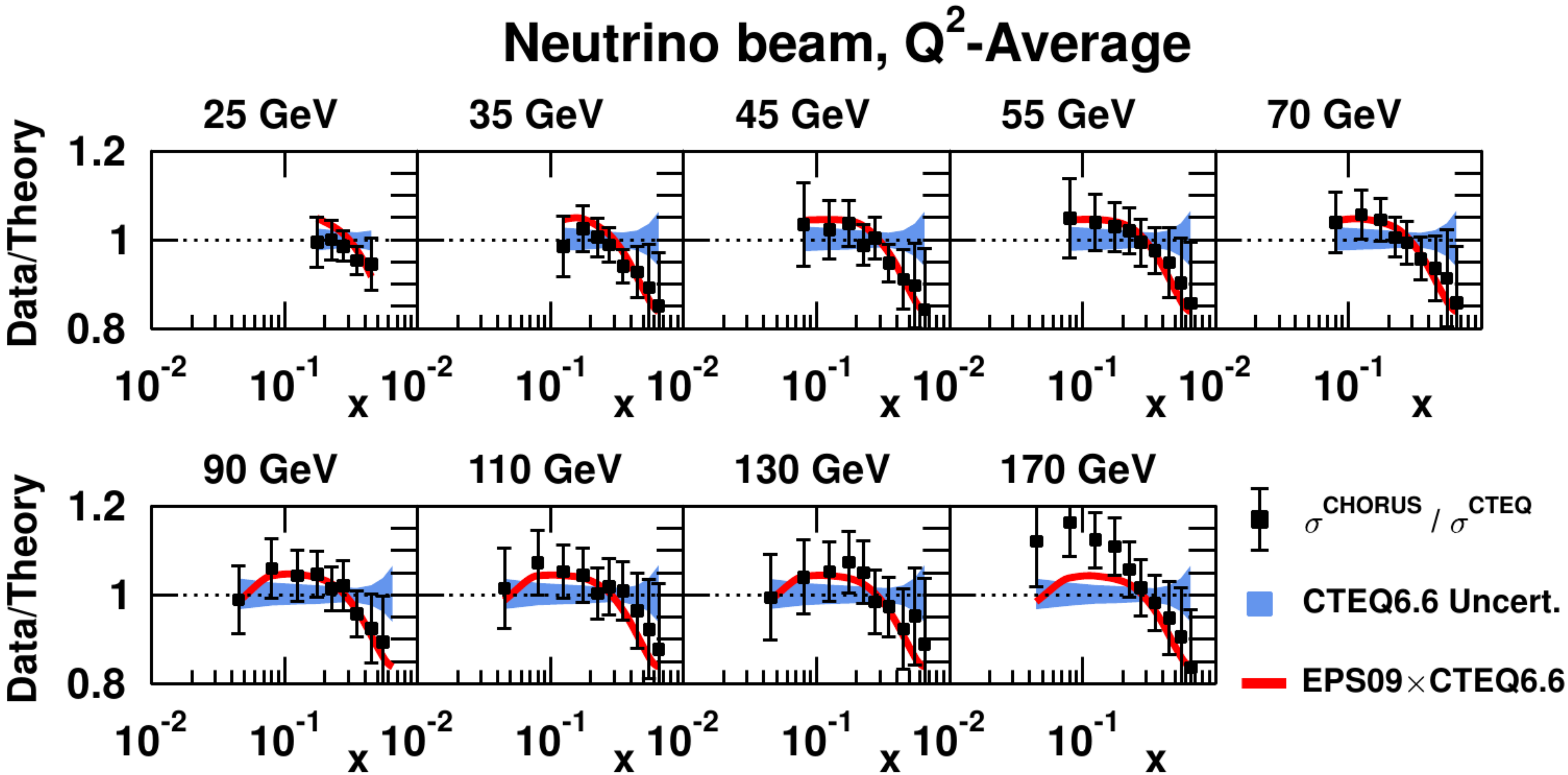
$$R^{\rm CTEQ6.6} \equiv \frac{\sigma^{\nu,\overline{\nu}}\,({\rm Experimental})}{\sigma^{\nu,\overline{\nu}}\,({\rm CTEQ6.6})}$$

← *virtually independent of Q^2*

Neutrinos: Paukkunen & Salgado

JHEP 1007 (2010) 032

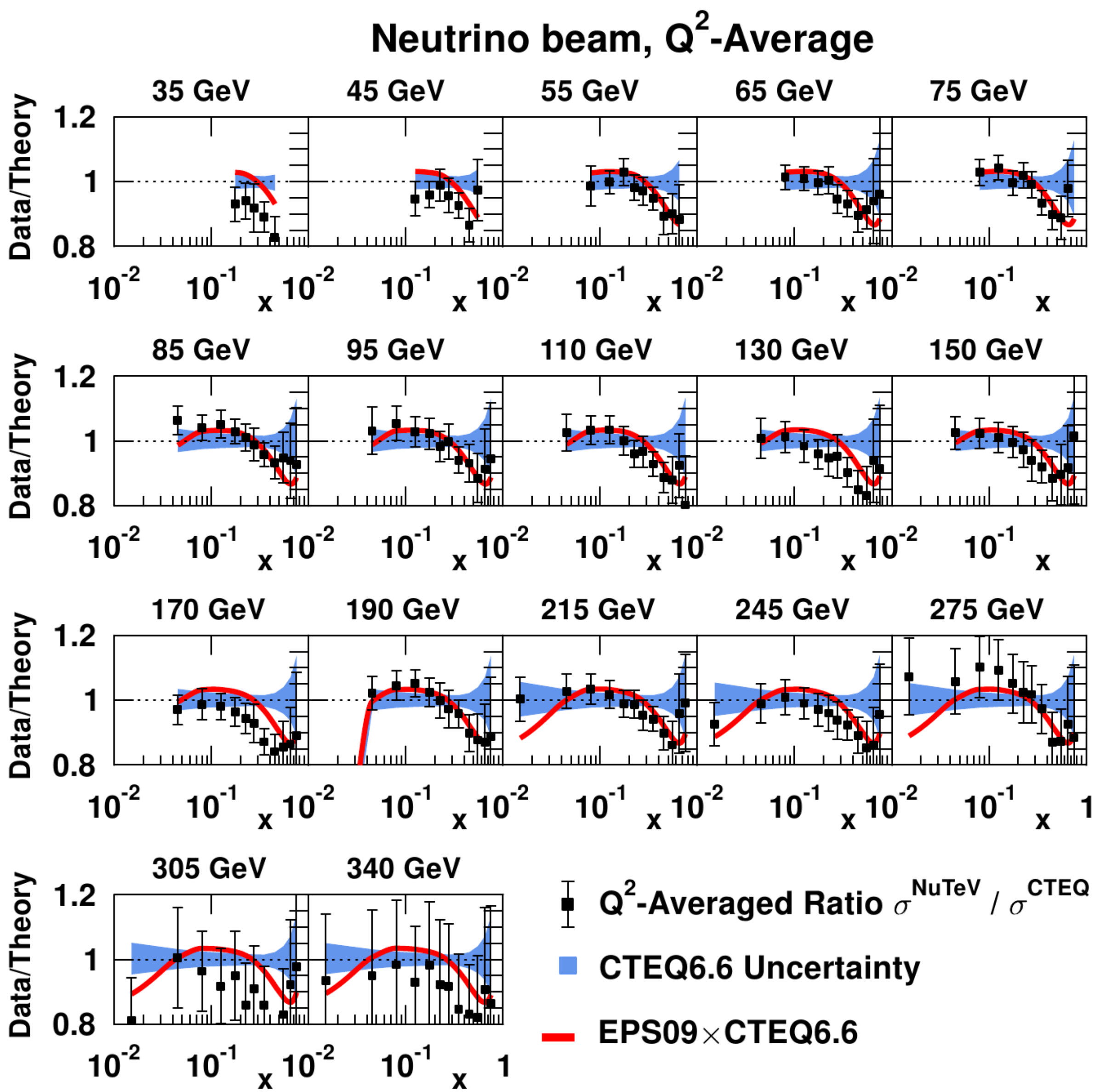
- For example, the CHORUS data in an excellent agreement with the EPS09 and CTEQ6.6



Neutrinos: Paukkunen & Salgado

JHEP 1007 (2010) 032

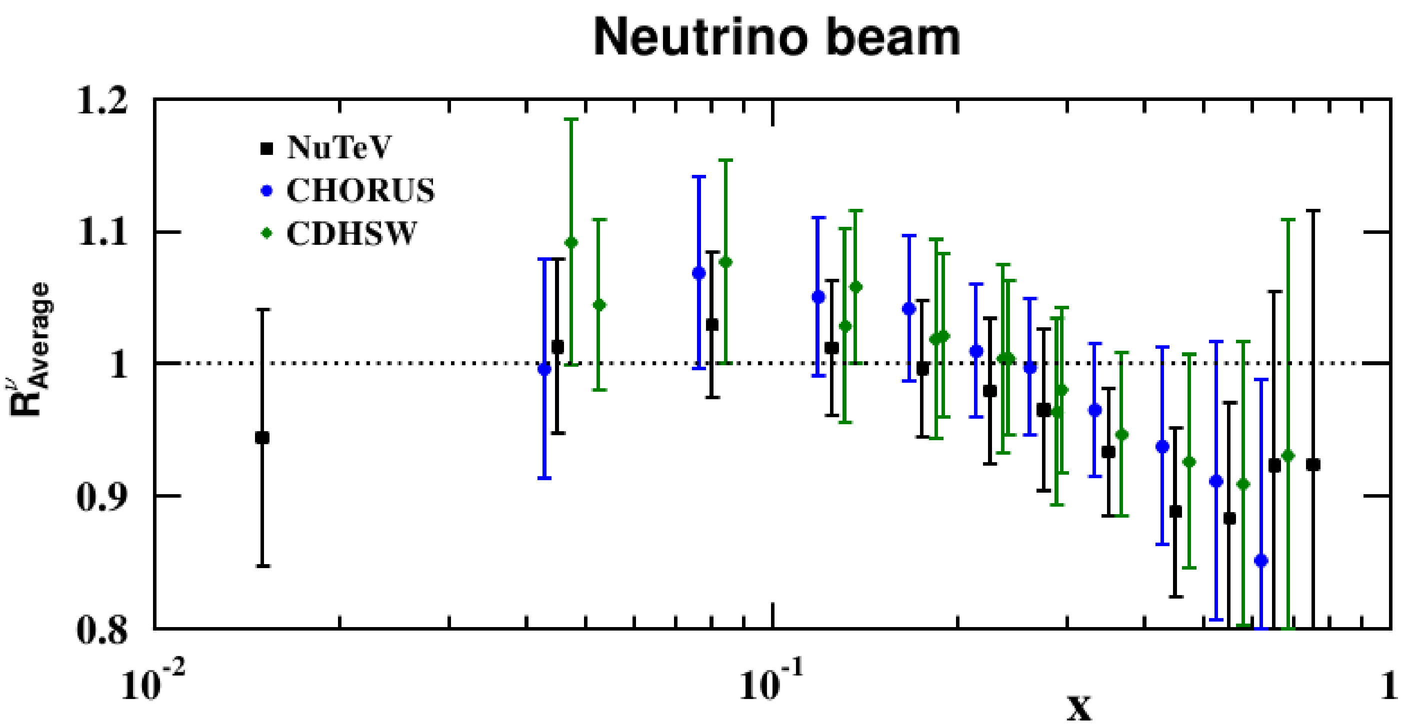
- Neutrino-energy-dependent inconsistencies in the NuTeV data



Neutrinos: Paukkunen & Salgado

Phys.Rev.Lett. 110 (2013) 212301

- Average also over the neutrino energy



- The NuTeV data systematically below the rest

  → Tension in a global fit

- The shape appears similar in all independent data sets

Neutrinos: Paukkunen & Salgado

Phys.Rev.Lett. 110 (2013) 212301

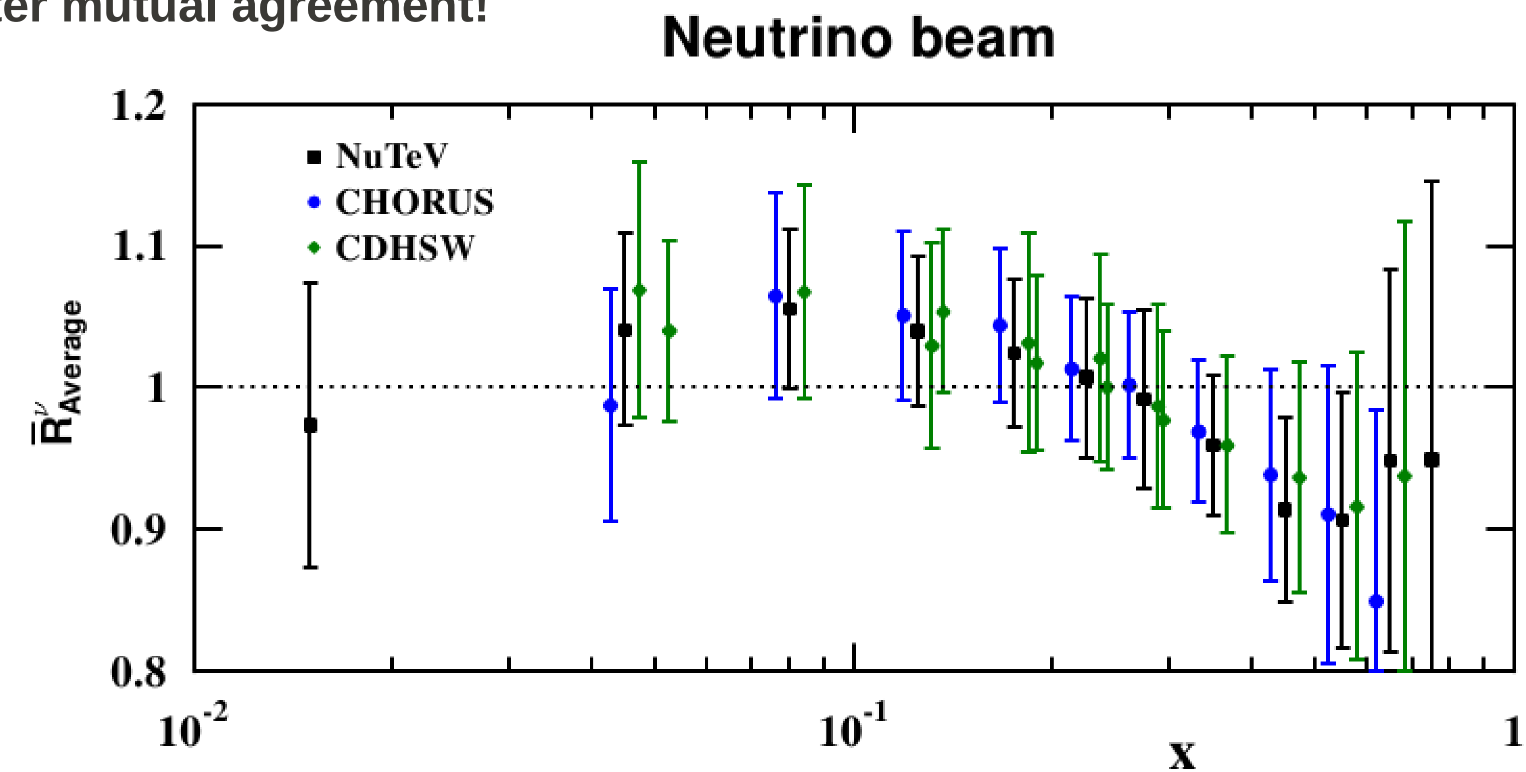
- Dispose the absolute normalization dividing by the total cross-section for each E

$$I^{\nu}_{\rm exp}(E) \equiv \sum_{i \in {\rm fixed}\, E} \sigma_{{\rm exp},i}(x,y,E) \times B_i(x,y)$$

Size of the experimental bin

$$\overline{R}^{\nu}(x,y,E) \equiv \frac{\sigma^{\nu}_{\rm exp}(x,y,E)/I^{\nu}_{\rm exp}(E)}{\sigma^{\nu}_{\rm CTEQ6.6}(x,y,E)/I^{\nu}_{\rm CTEQ6.6}(E)}.$$

- Much better mutual agreement!



Neutrinos: Paukkunen & Salgado

Phys.Rev.Lett. 110 (2013) 212301

- An excellent agreement with e.g. CTEQ6.6 & EPS09

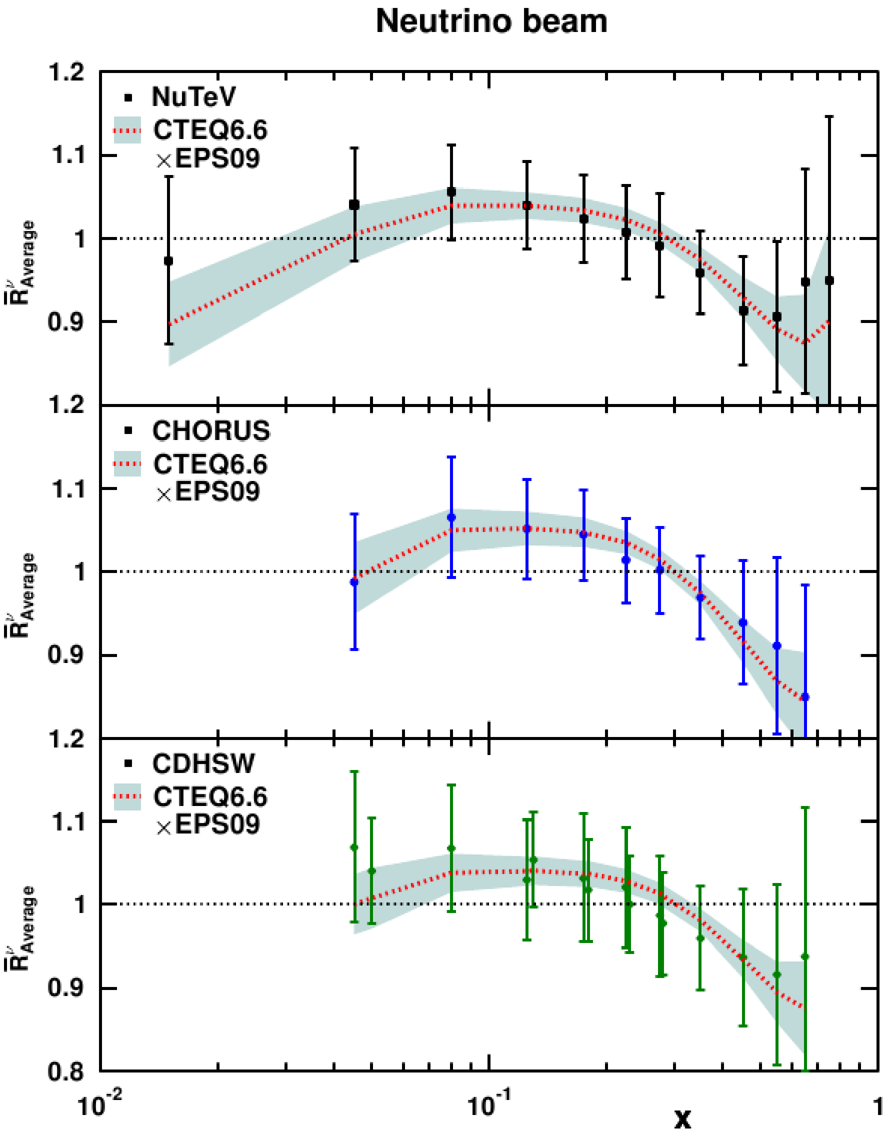
- A novel PDF re-weighting method was devised to reinforce the compatibilty with these fits

  With the normalization, OK

  Without the normalization the result of nCTEQ was “recovered” (for the NuTeV data).

- No reason to believe that the factorization would be violated.

- Points to an underestimation of the experimental errors (NuTeV)



Neutrinos: DSSZ

- **The DSSZ global fit included the neutrino data with no obvious difficult:**

Included neutrino structure function data from NuTeV, CHORUS & CDHSW

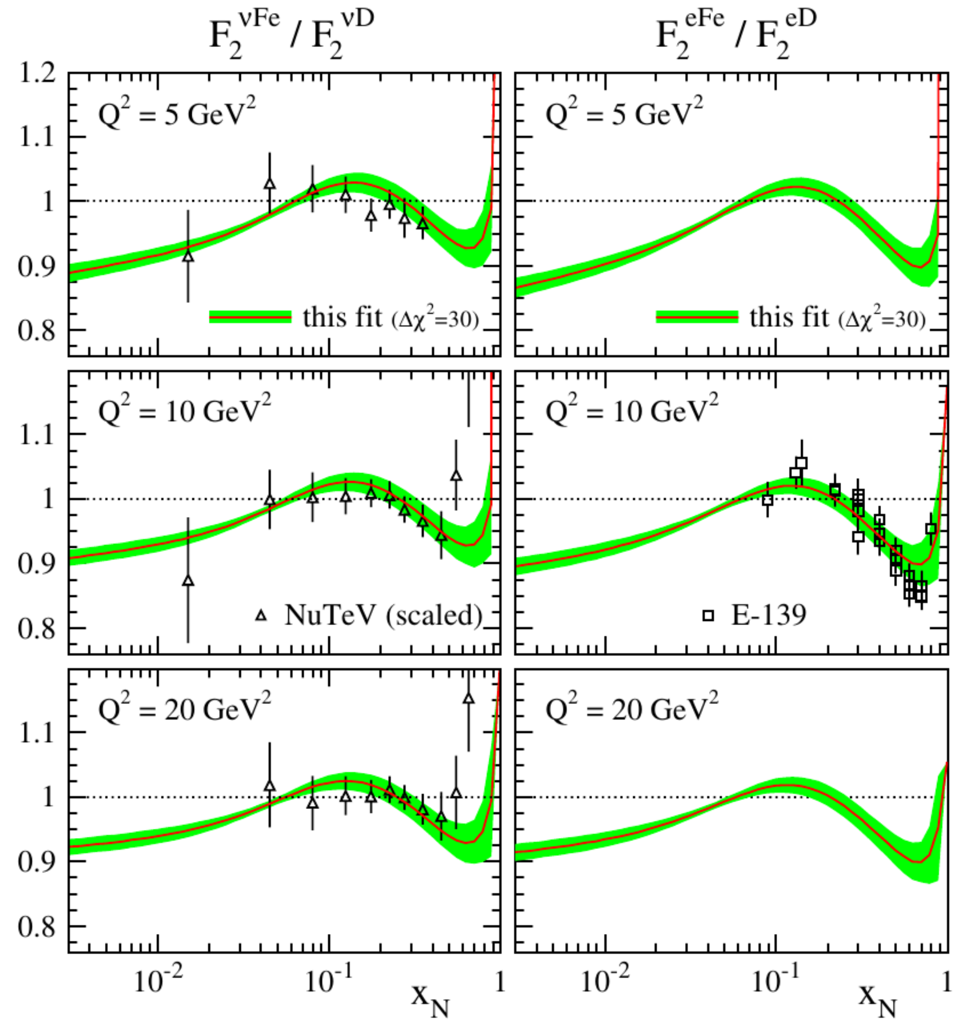
much more scarce than the absolute cross-section data

Used MSTW2008 free proton PDFs as a baseline

this set was already constrained by the NuTeV data

Added the MSTW2008 uncertainties in quadrature to the experimental errors

as point-to-point uncorrelated errors.



- Given all this, the neutrino data did not carry as large weight as e.g. in the nCTEQ work

III The first glimpse of nuclear PDFs in the LHC p+Pb data?

The CMS dijets in p+Pb

- CMS has measured dijets using the 2013 p+Pb data
- Data binned in dijet “pseudorapidity”

$$\eta_{\rm dijet} \equiv (\eta_1 + \eta_2)/2,$$

pseudorapidities of
the individual jets

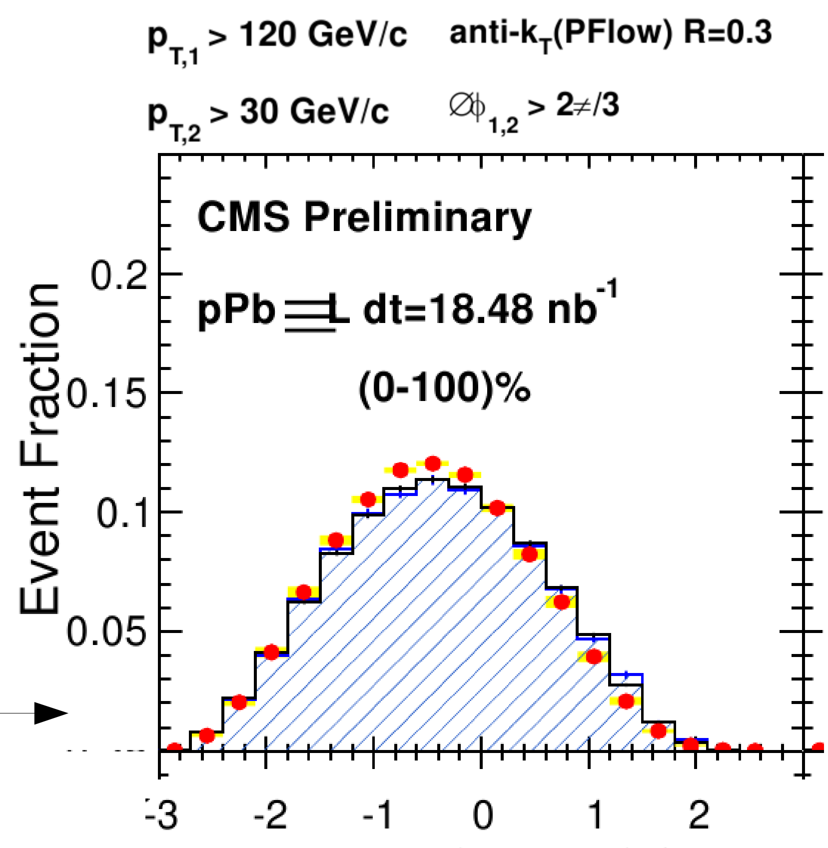
- Note the rapidity shift

$$\eta_{\rm shift} \equiv 0.5 \log\left(E_{\rm Pb}/E_{\rm p}\right) \approx -0.465$$

Pb → ← p

(results presented in the collider frame)

CMS PAS HIN-13-001



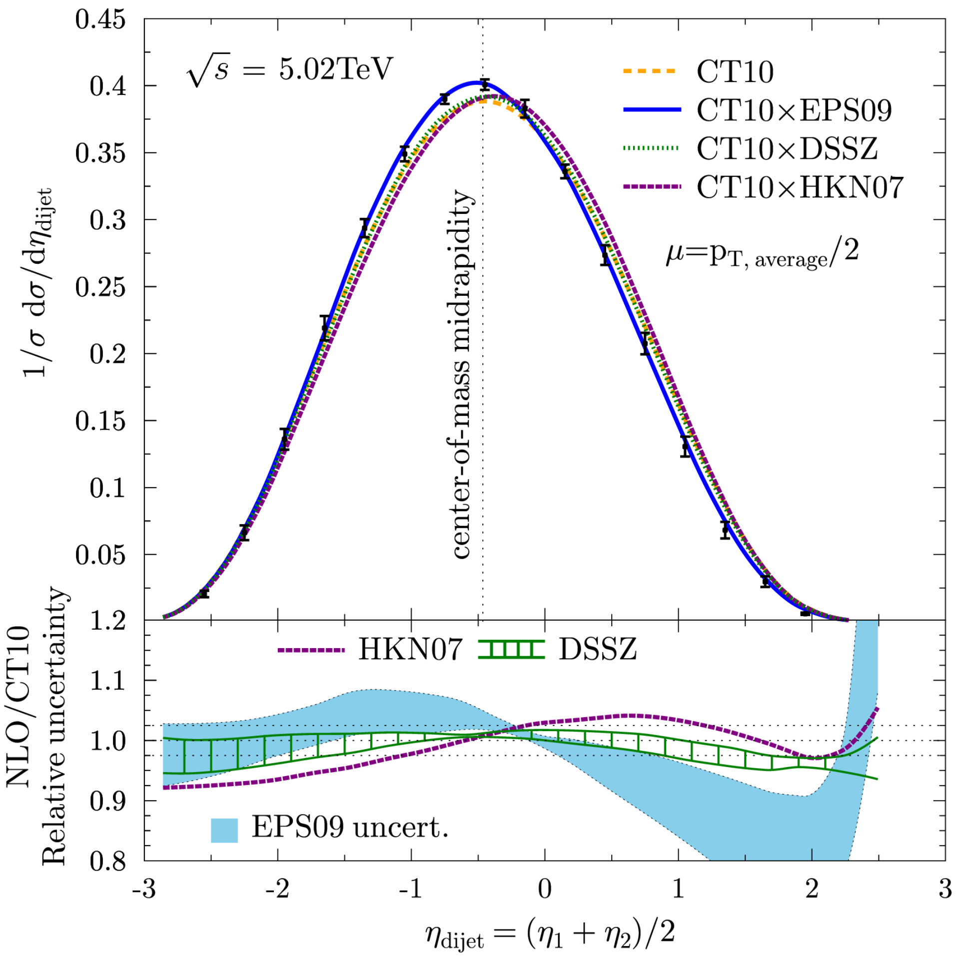
$$\eta_{\rm dijet} \equiv (\eta_1 + \eta_2)/2,$$

- Large minimum leading jet pT! (compare to leading pT > 60 GeV in CMS pp data)
- Should be well in the realm of pQCD and coll. factorization and does not depend on the Glauber.

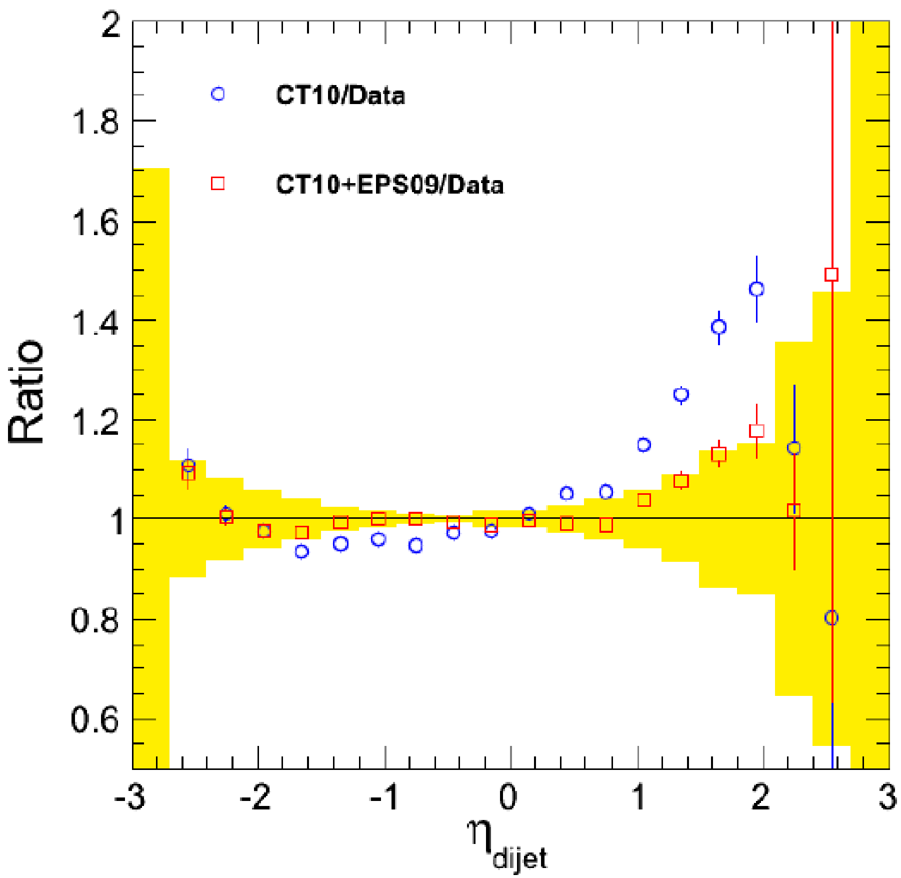
The CMS dijets in p+Pb

- **Comparison to the NLO calculations – the gluon PDFs make a difference!**

Eskola, Paukkunen, Salgado, arXiv:1308.6733



Doga Gulhan, Jet workhop, 2013 Paris



- **Exciting agreement with the preliminary data (Doga G's talk on session 4B)**

Summary

- **Presented comparison of current nPDFs**

  Large differences among independent fits.
  The LHC p+Pb data are expected to change this.

- **Discussed the issue of neutrino-nucleus DIS**

  The recent controversy could be explained
  by underestimation of the experimental errors in NuTeV

- **Flashed the first hard process data from LHC p+Pb runs**

  Already this first data could discriminate between
  different sets of nPDFs – and this is just the beginning!