From EPS09 to EPPS16 nPDFs

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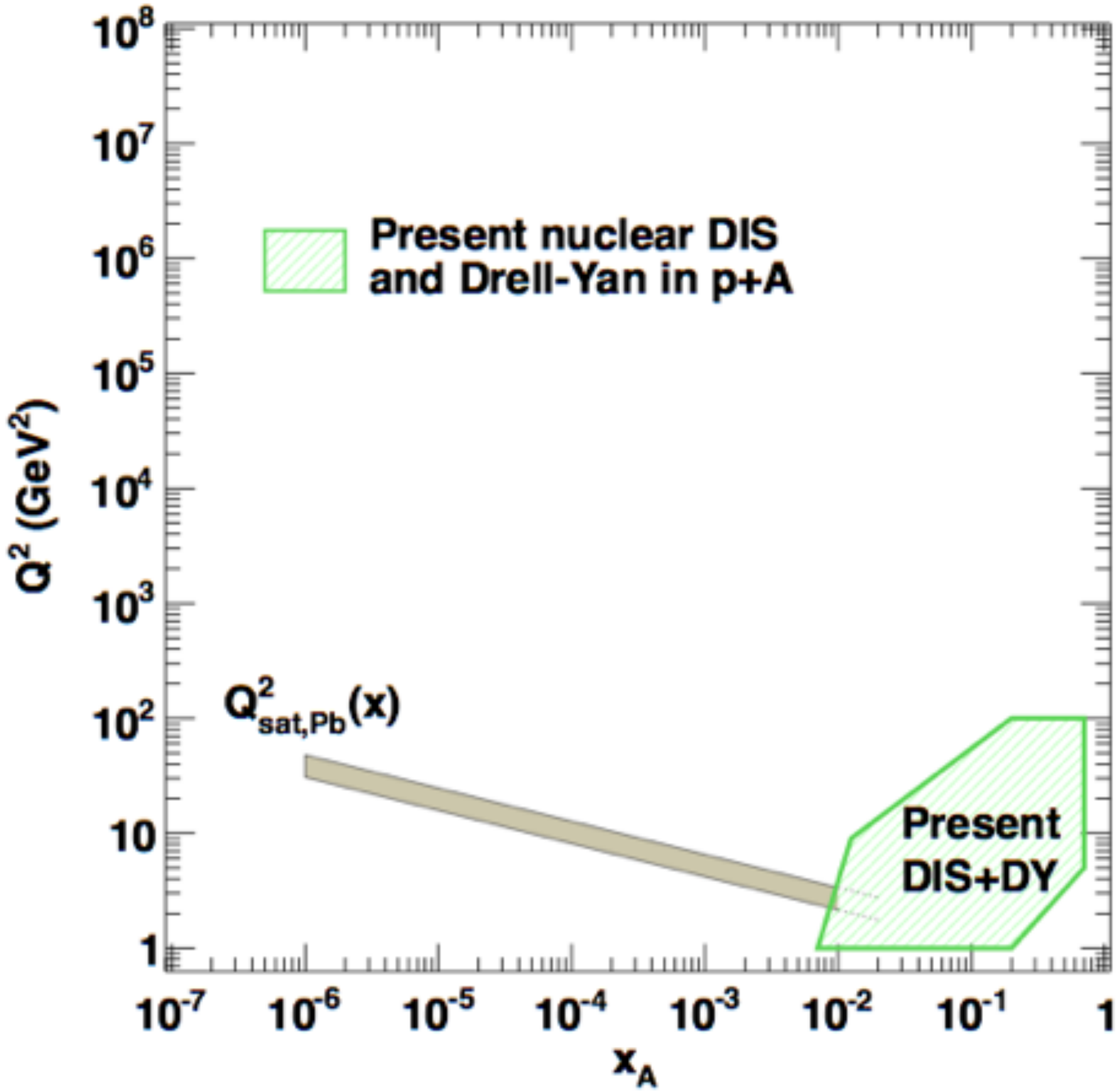
IPN - Orsay - June 2017

@CASSalgado @HotLHC

nPDFs vs time



EKS98

[Eskola, Kolhinen, Ruuskanen, Salgado]

HKM01, HKN04

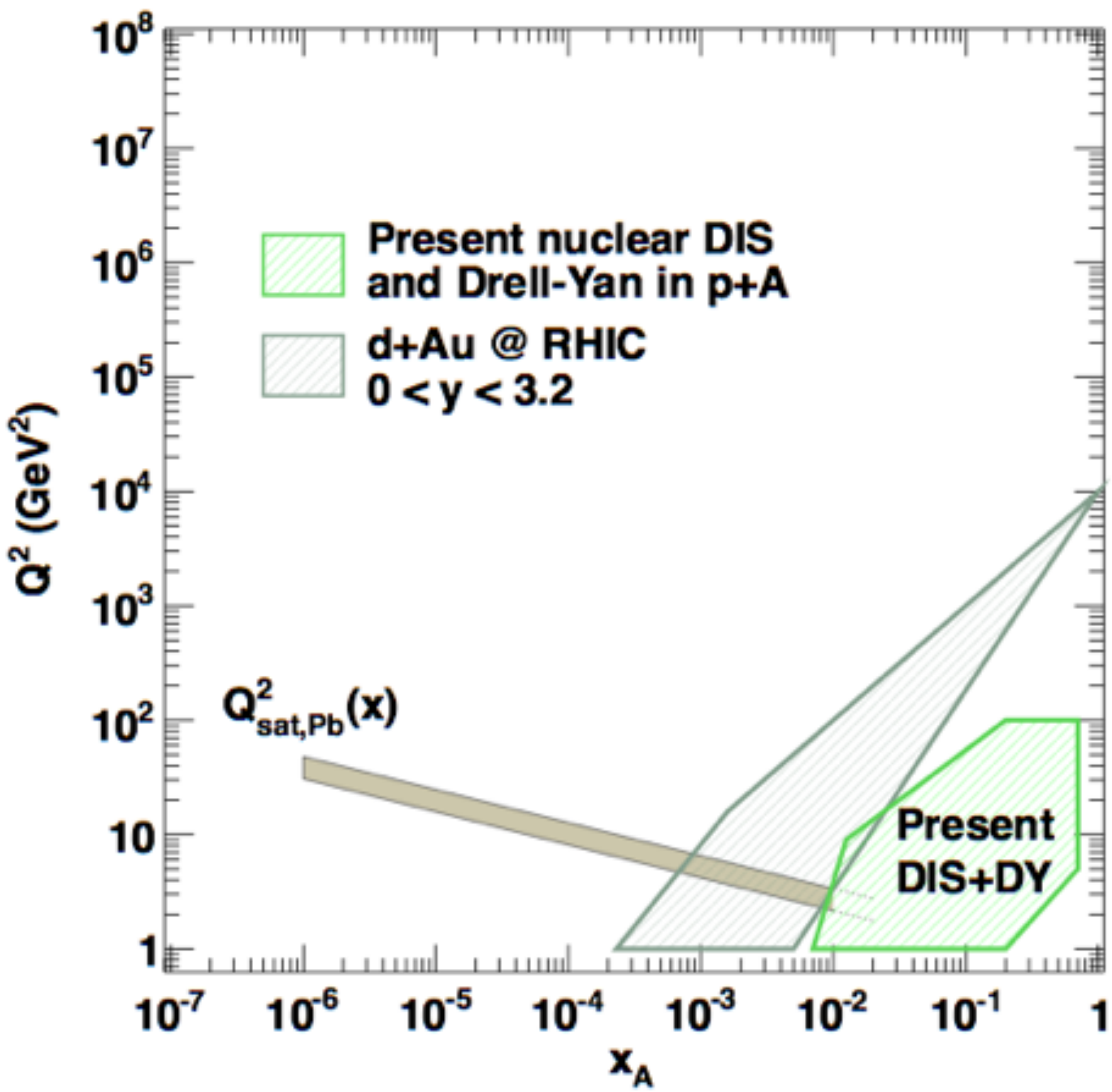
[Hirai, Kumano, Miyama, Nagai]

HKN04 - **first Hessian error analysis**

de Florian, Sassot 2004

First NLO analysis

nPDFs vs time



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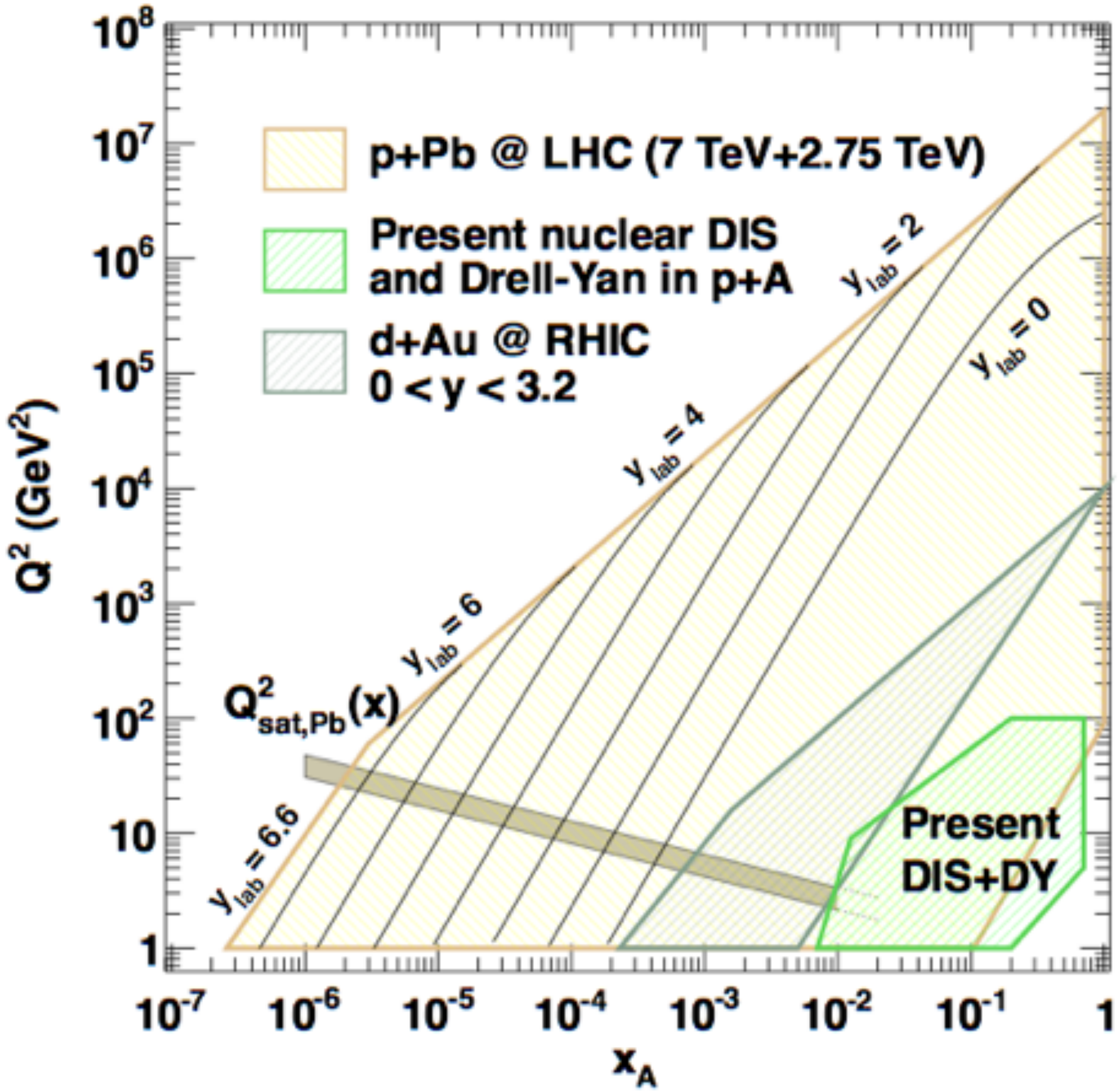
RHIC data included for 1st time

DSSZ-2012
[de Florian, Sassot, Stratmann, Zurita]
Neutrino data included in fit

nCTEQ - 2015
[Kovarik et al.]

nPDFs vs time



LHC: large extension in kinematic reach: **proton-lead**

EKS98

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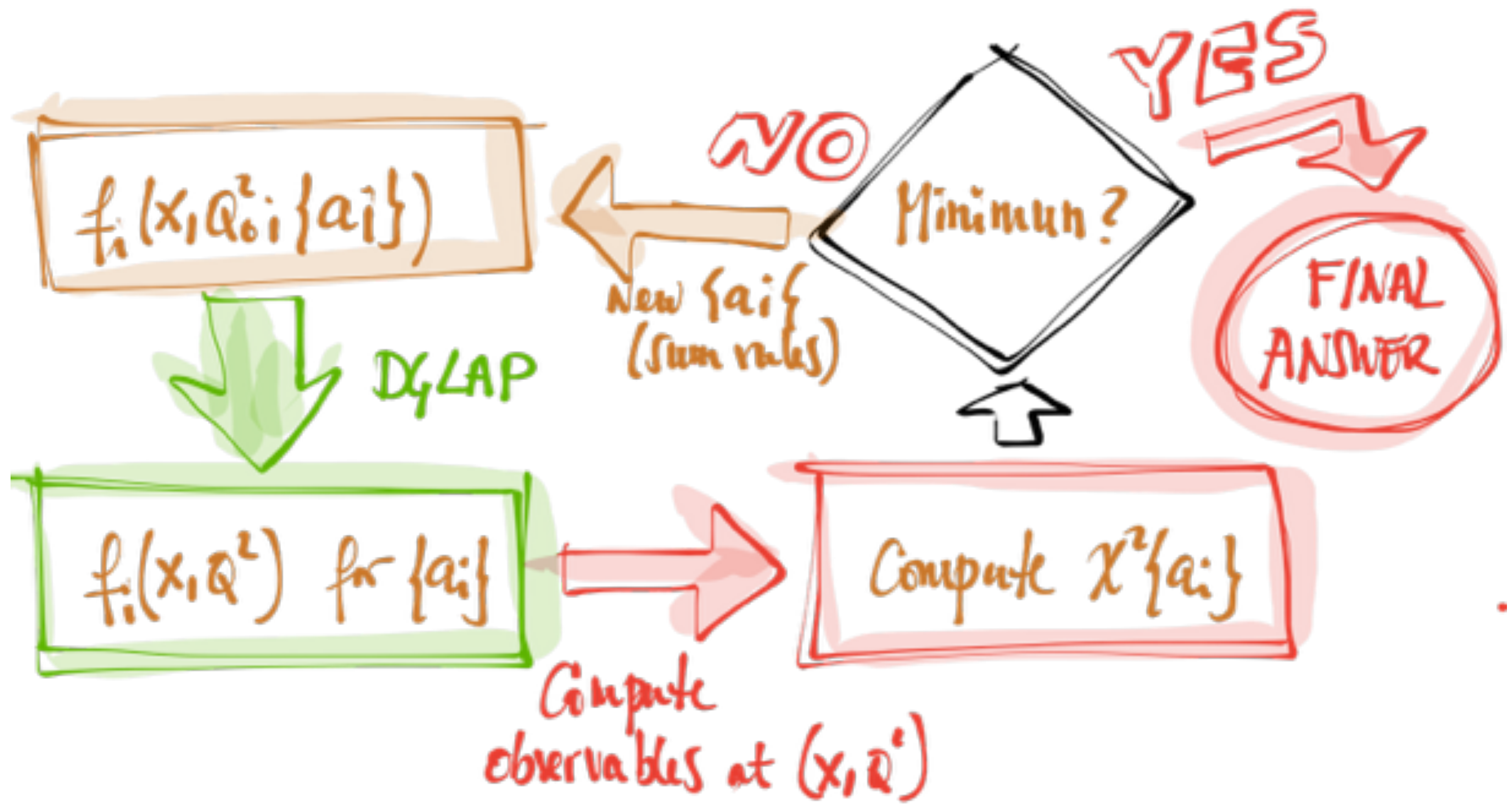
EPPS16

[Eskola,Paakkinen,Paukkunen,Salgado]

LHC data included for first time

Global (nuclear) PDF fit

- **One of the most standardized procedures in High-Energy Physics.**
- Main goal: provide a set of Parton Distribution Functions (PDFs)

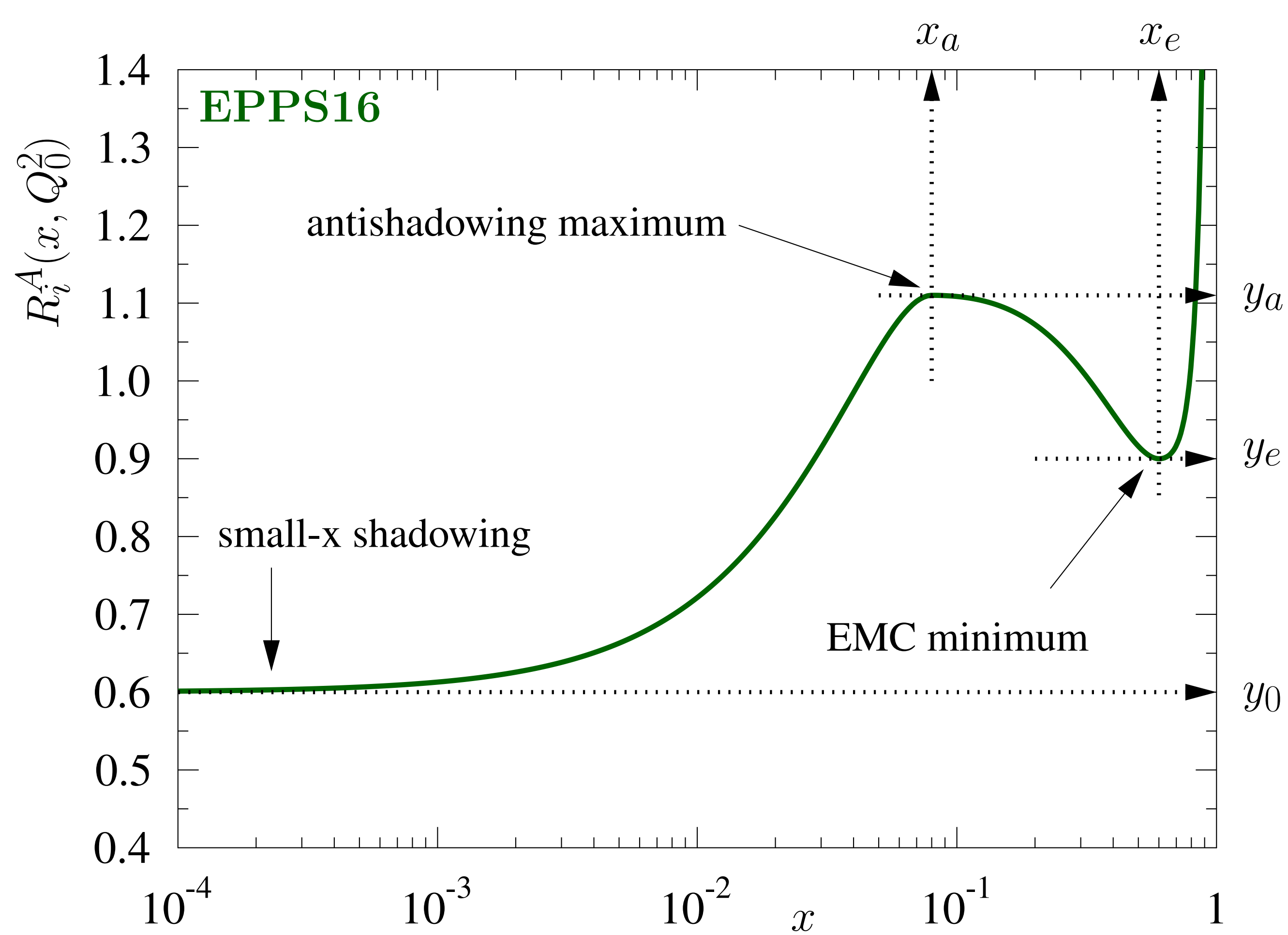


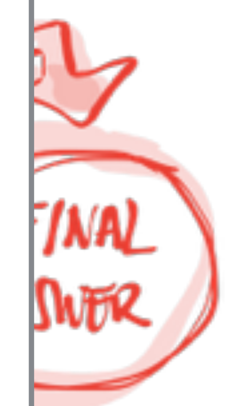
Main difference in the nuclear case:
**Normally ratios with free proton used due to lack of constraints

Global (nuclear) PDF fit

- **One of t** ... **gy Physics.**
- Main go ... DFs)

EPPS16 fitting function





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

Main dif

**Normal ... k of constraints

Recent sets

		EPS09 JHEP0904 (2009) 065	DSSZ PRD85 (2012) 074028	nCTEQ PRD93 (2016) 085037	EPPS16 EPJC77 (2017) 163
data included	e-DIS				
	Drell-Yan pA				
	RHIC hadrons			also without	
	neutrino DIS				
	LHC data				
Flavor decomposition				(partial)	
# data points		929	1579	740	1811
accuracy		NLO	NLO	NLO	NLO
proton PDF		CTEQ6.1	MSTW2008	~CTEQ6.1	CT14NLO

[Also Khanpour, Atashbar 2016 (NNLO)]

What is new?

EPPS16 supersedes our previous EPS09 analysis
[most widely used of nuclear PDFs to date]

Neutrino DIS	**Flavor decomposition**
LHC W/Z production **pion-nucleus DY**	
LHC dijet data	**More constraints on gluons** [with no extra weights to specific data sets]

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Also improvements on the error analysis, heavy-flavor prescription, isospin corrections to old DIS data…

Experimental data sets

Main addition is information on **lead nuclei** [whole data table in backup]

CERN NMC 96	DIS	μ^-Pb(207), μ^-C(12)	15	4.1	[75]
CERN CMS★	$W^\pm$	pPb(208)	10	8.8	[43]
CERN CMS★	Z	pPb(208)	6	5.8	[45]
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Only this set (15 points) for Pb in EPS09

+ 41 data points for Au

Notice that in addition to x and Q^2, **a new variable for nuclei: A**

The dependence on the atomic number A is also parametrized in nPDFs (as x in proton PDFs)

Neutrino DIS data

In conclusion, we have demonstrated that disposing the overall normalization by dividing the data by the integrated cross section in each neutrino energy bin separately, all large-Q^2 neutrino data show practically identical nuclear effects, consistent with the present nuclear PDFs. Our numerical consistency test based on the Hessian method of propagating uncertainties confirms that these data could be included in a global fit without causing disagreement with the other data.

[Paukkunen, Salgado arXiv:1302.2001 / PRL110 (2013) 212301]

Neutrino data had a problem

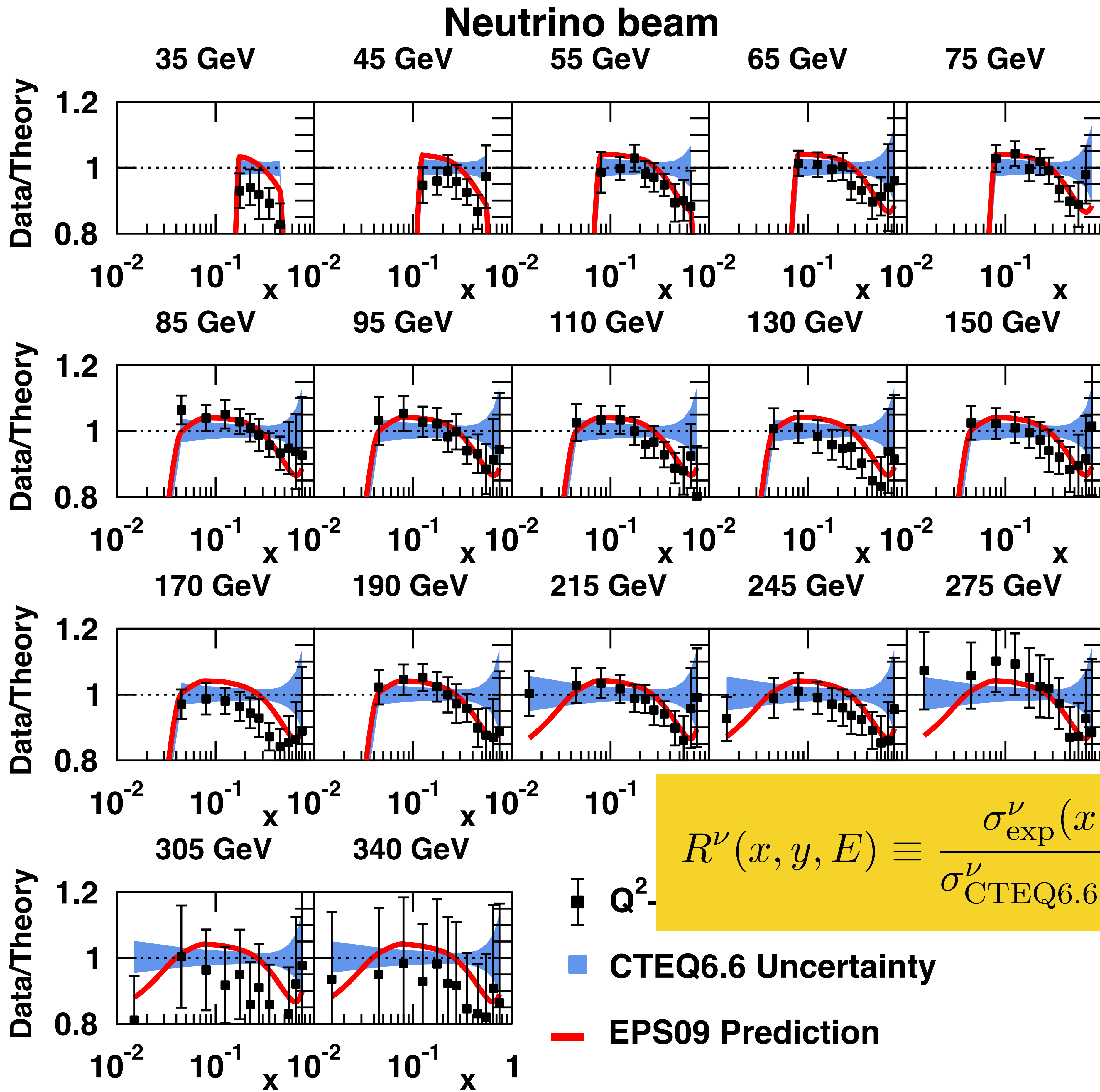
CONCLUSIONS

[Slide stolen from K. Kovari's talk at DIS 2012]

- Incompatibility of neutrino DIS with charged lepton DIS (?)
  - conclusions heavily rely on only NuTeV data - most precise
  - incompatibility a "precision" effect - the result changes e.g. when using uncorrelated errors
  - tension in NuTeV data → high χ^2 of the fit to NuTeV alone → problem of NuTeV data ?
  - NOMAD data can help decide
- The impact of nuclear PDF from neutrino DIS on proton PDF
  - how does the incompatibility of neutrino DIS impact the uncertainty of strange quark PDF ?

Karlsruhe Institute of Technology

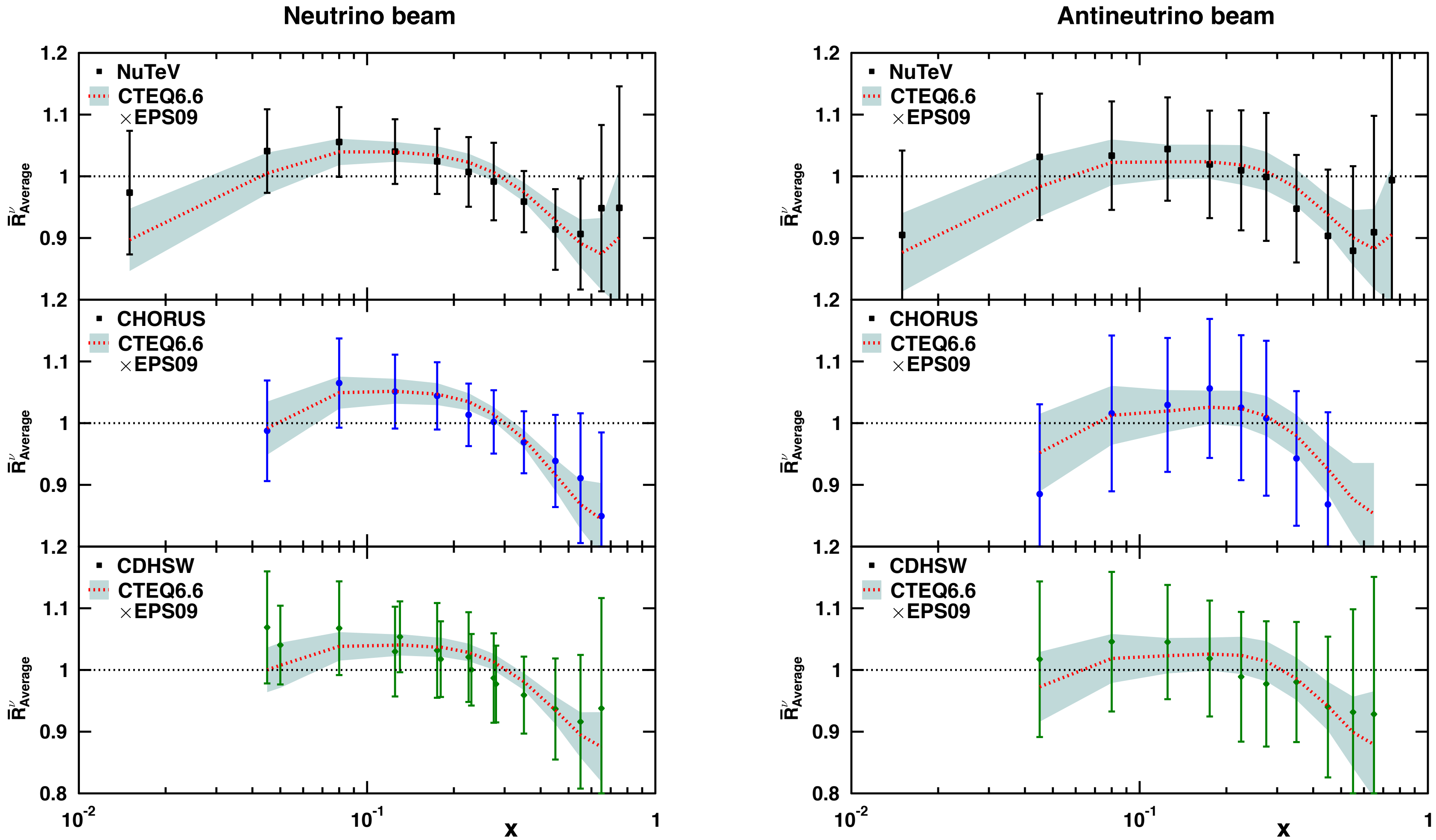
[Paukkunen, Salgado / arXiv:1004.3140,1302.2001]



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

The neutrino DIS data

Neutrino DIS data on Pb or Fe - **no ratios**.
Good description of **normalized cross-sections** with EPS09



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

NuTeV data not used in EPPS16

[Paukkunen, Salgado / arXiv:1004.3140,1302.2001]

LHC data

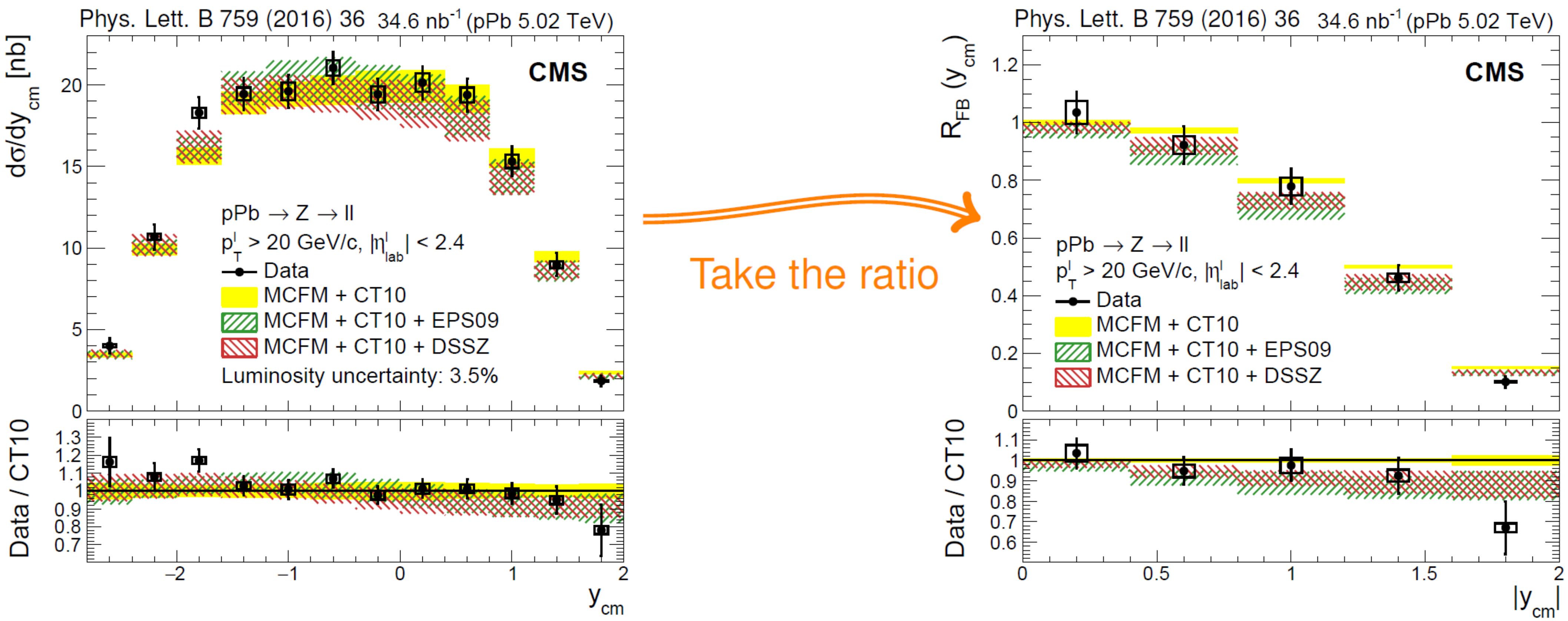
large impact. In general, these new LHC data may allow to implement more flexibility into the fit functions and also to release restrictions related to the flavour dependence of the quark nuclear effects. Also, the EPS09 analysis used an additional weight to emphasise the importance of the data set (neutral pions at RHIC) sensitive to gluon nPDF. Now, with the use of the new LHC data, such artificial means are likely to be unnecessary. Therefore, for understanding the true significance of these data, new global fits including these and upcoming data are thus required.

[Armesto, Paukkunen, Penin, Salgado, Zurita arXiv:1512.01528]

Treatment of LHC data

To avoid (large) sensitivity to proton PDFs: two solutions

- Use neutrino DIS method (self-normalize cross sections)
- Use forward-backward ratios



Cancel some experimental/theoretical uncertainties but **some information is lost - pp benchmark** (same energy) **needed**

Reweighting

Page 1

Hessian

Most PDF fits in Hessian approach

↓

Issue - tolerance factor
$\Delta\chi^2 > 1$

↓ diagonalize H

Compute errors with Error sets PDFs

Bayesian

Use Monte Carlo techniques
→ used by NNPDF

↓

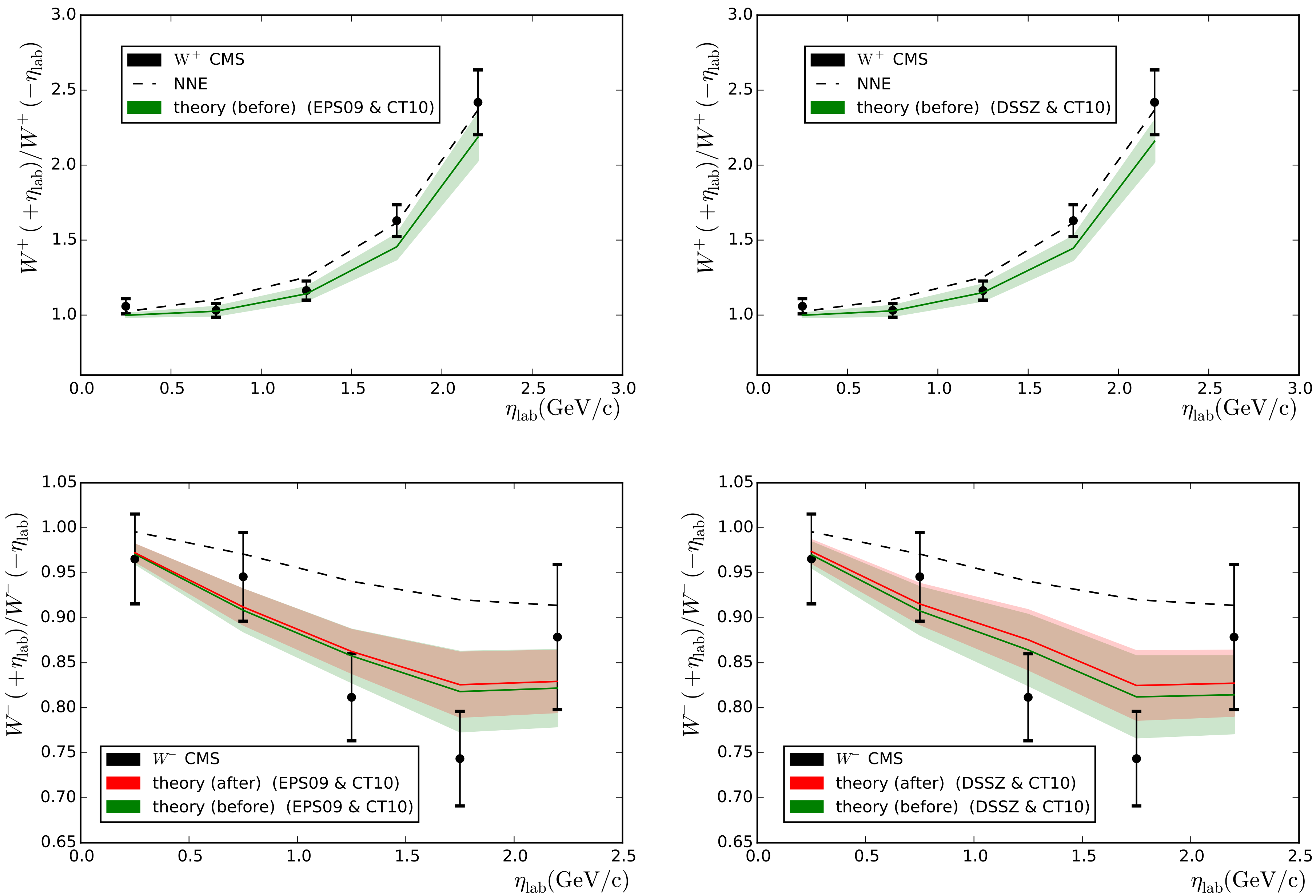
Build MC replicas &
χ^2-fit each replica

↓

Compute errors with MC replicas

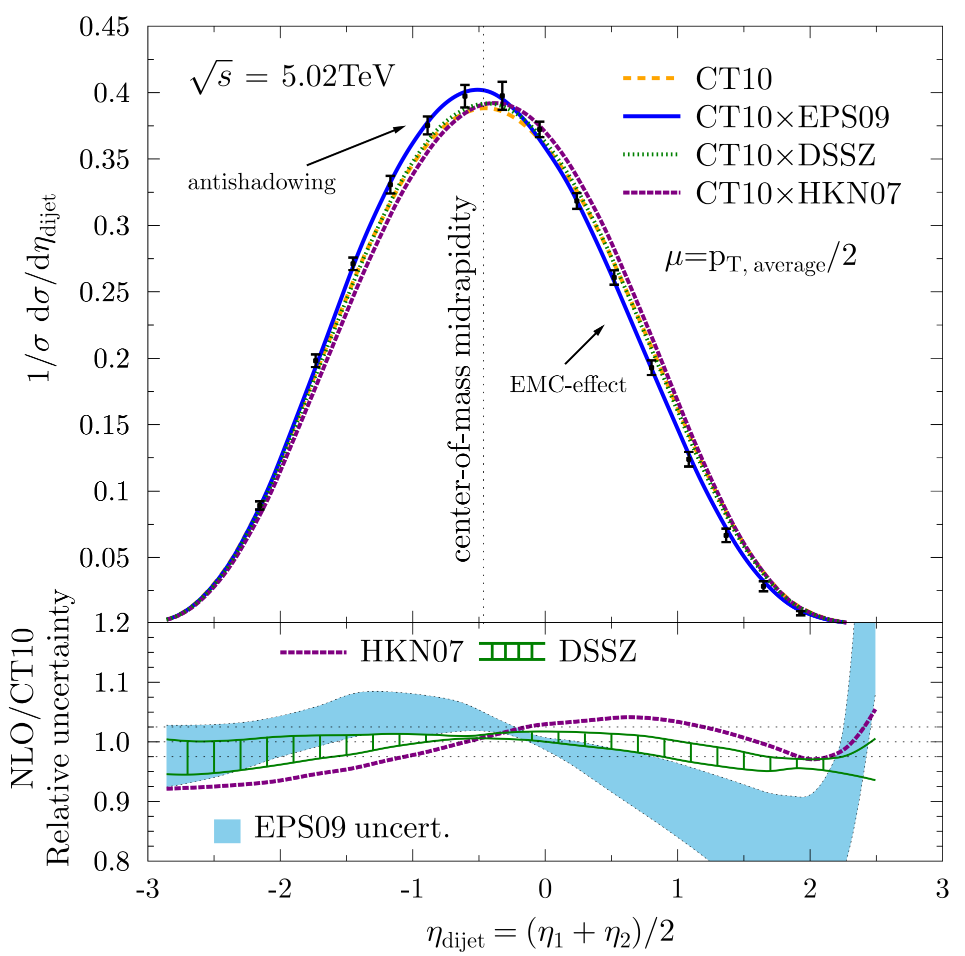
Reweighting to check impact on new data before a global fit

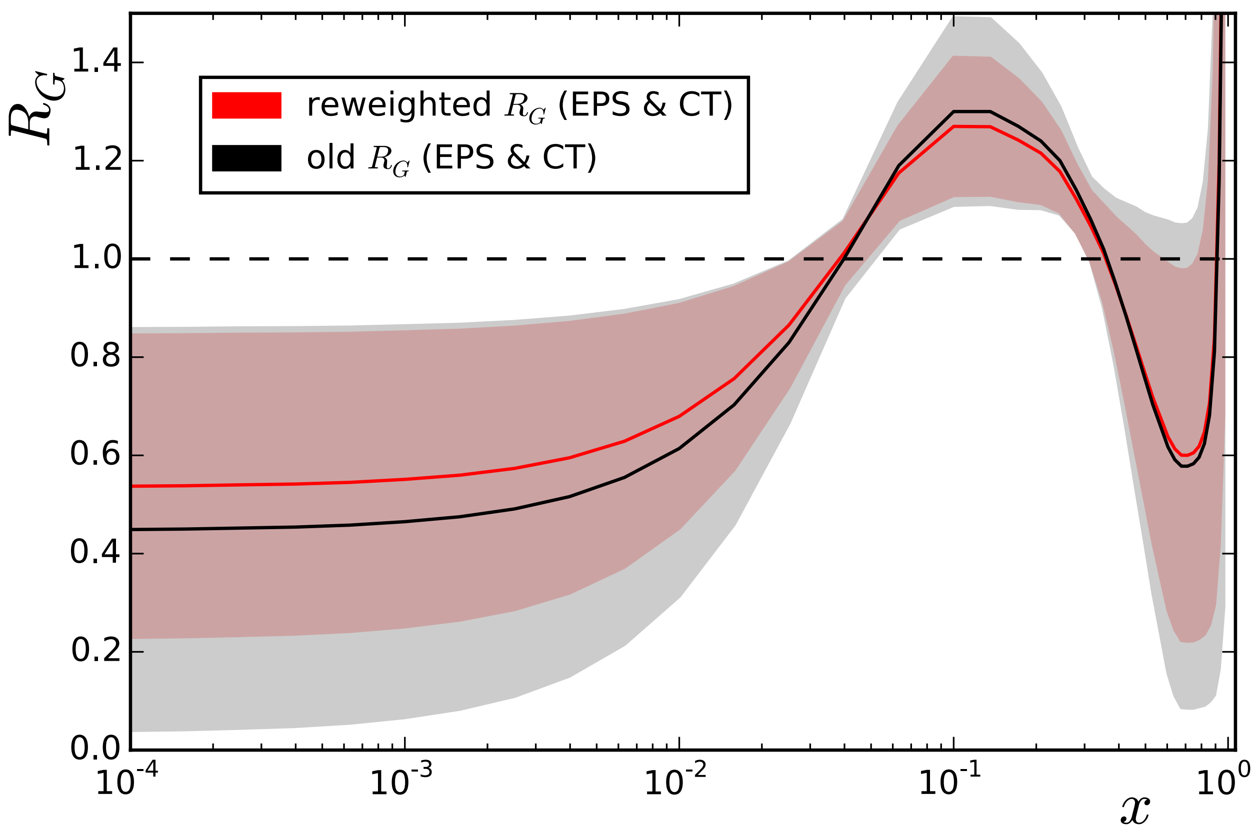
Reweighting EW bosons



Mild effect

Reweighting Gluons

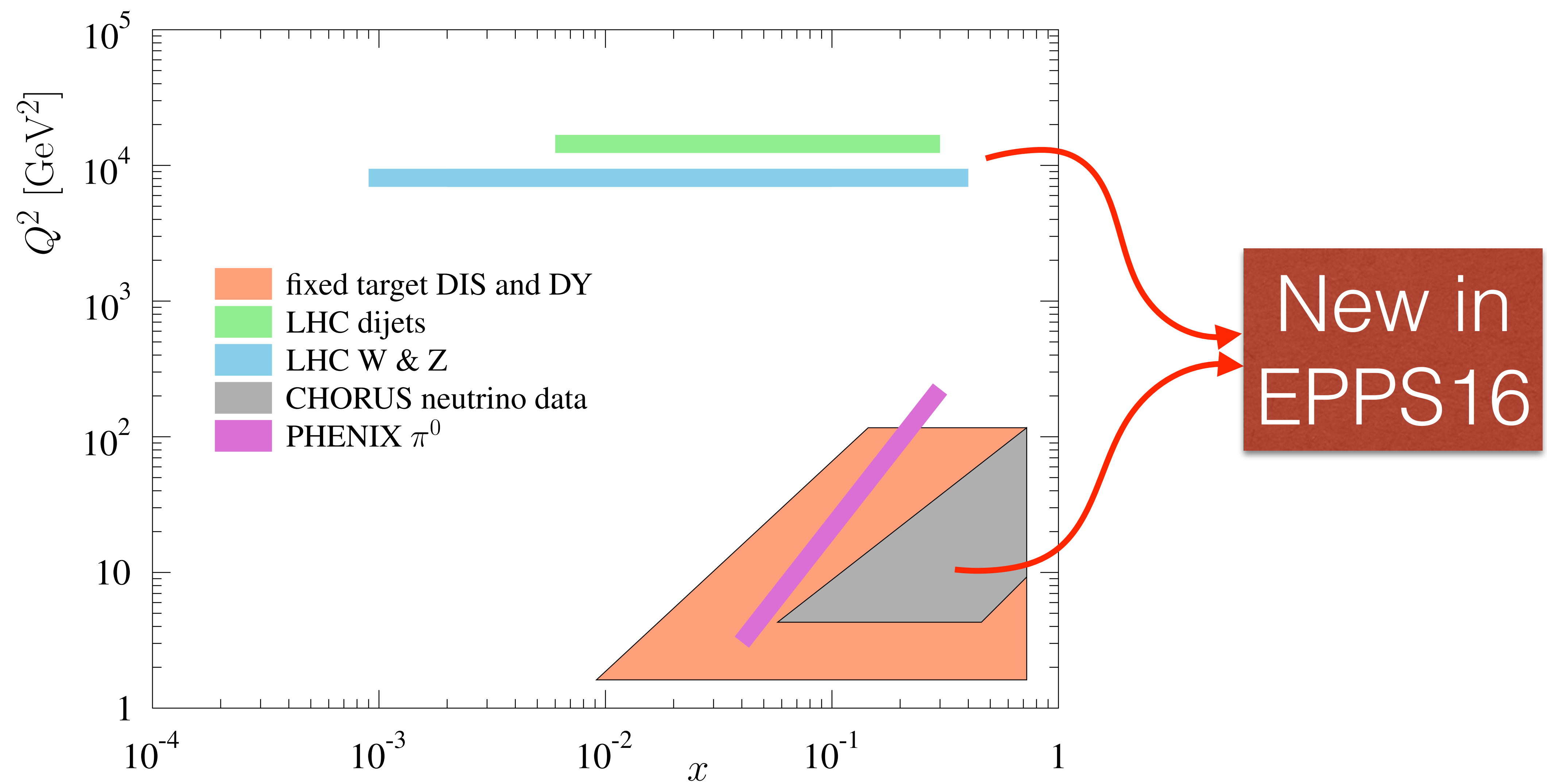




Some extra constraints - no need of weights in global fit

EPPS16

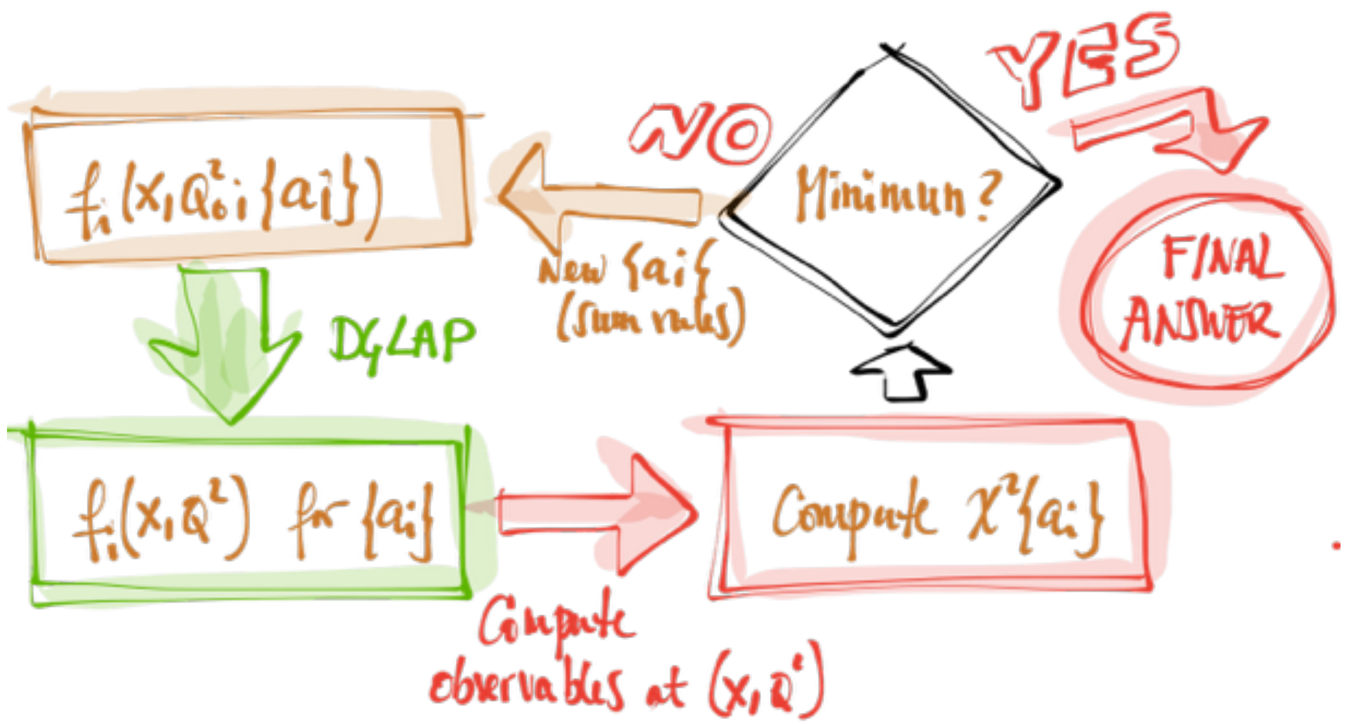
Kinematic reach

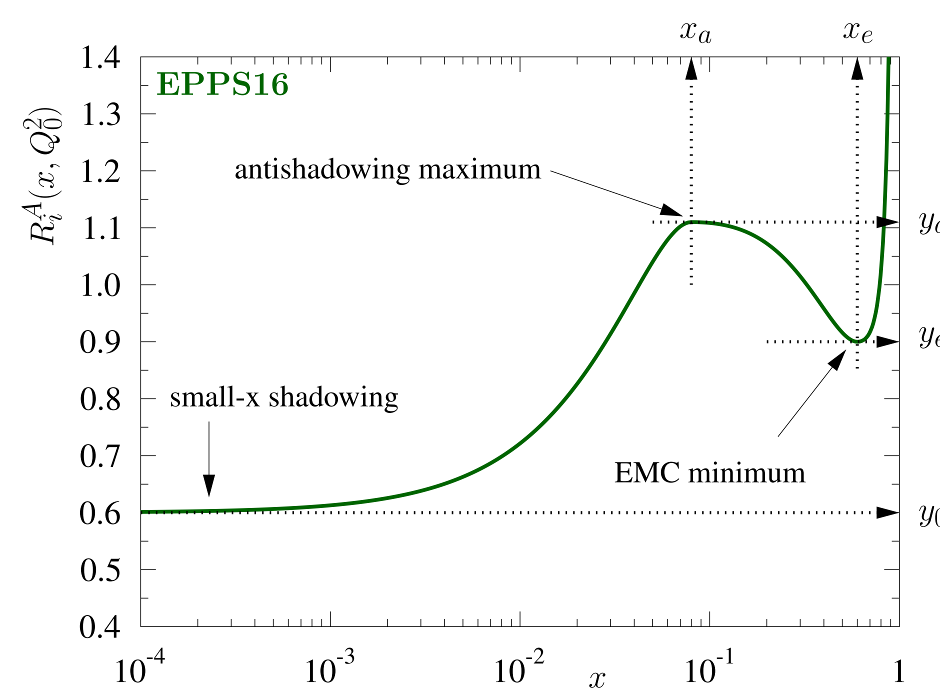


Larger kinematic reach in *x* (and Q) and new constraints at large-*x*

More data from 2016 pPb run - large impact expected

EPPS16 global analysis





$$R_i^A(x, Q_0^2) = \begin{cases} a_0 + a_1 (x - x_a)^2 & x \le x_a \\ b_0 + b_1 x^{\alpha} + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)\,(1 - x)^{-\beta} & x_e \le x \le 1, \end{cases}$$

A-dep implicit
Total 40 param

Error analysis: needed to check compatibility of (new) different sets of data

(Hessian) Error analysis

Define chi2 in terms of the initial parameters **a** (N-dim vector)

$$\chi^2(\mathbf{a}) \equiv \sum_k \chi_k^2(\mathbf{a}) \equiv \sum_{i,j} [T_i(\mathbf{a}) - D_i] C_{ij}^{-1} [T_j(\mathbf{a}) - D_j] .$$

Compute the Hessian matrix and diagonalize

$$\chi^2(\mathbf{a}) \approx \chi_0^2 + \sum_{ij} \delta a_i H_{ij} \delta a_j , \quad \longrightarrow \quad \chi^2(\mathbf{z}) \approx \chi_0^2 + \sum_i z_i^2 .$$

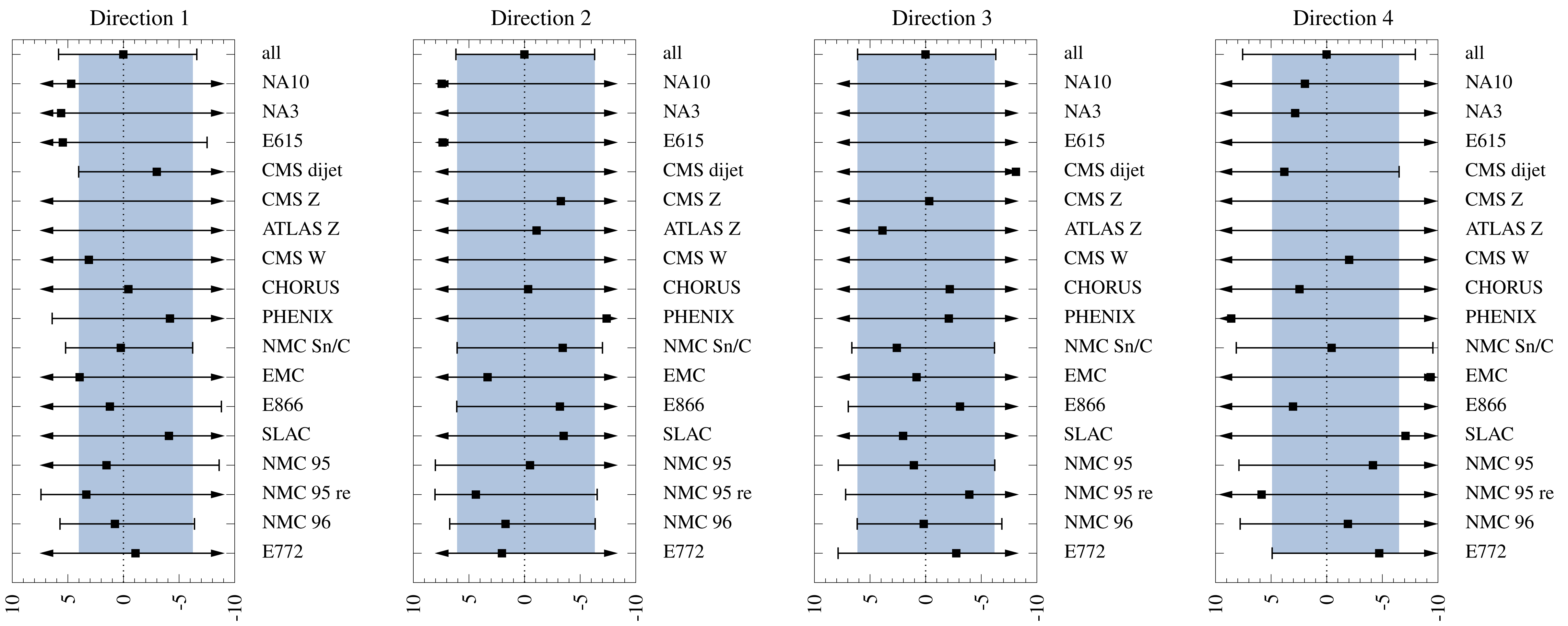
vectors **z** are linear combinations of original **a** now **uncorrelated**

$$\int_0^{M_k} \frac{d\chi^2}{2\Gamma(N_k/2)} \left(\frac{\chi^2}{2}\right)^{N_k/2-1} \exp\left(-\chi^2/2\right) = 0.90,$$

→ **Tolerance factor** $\Delta\chi^2$

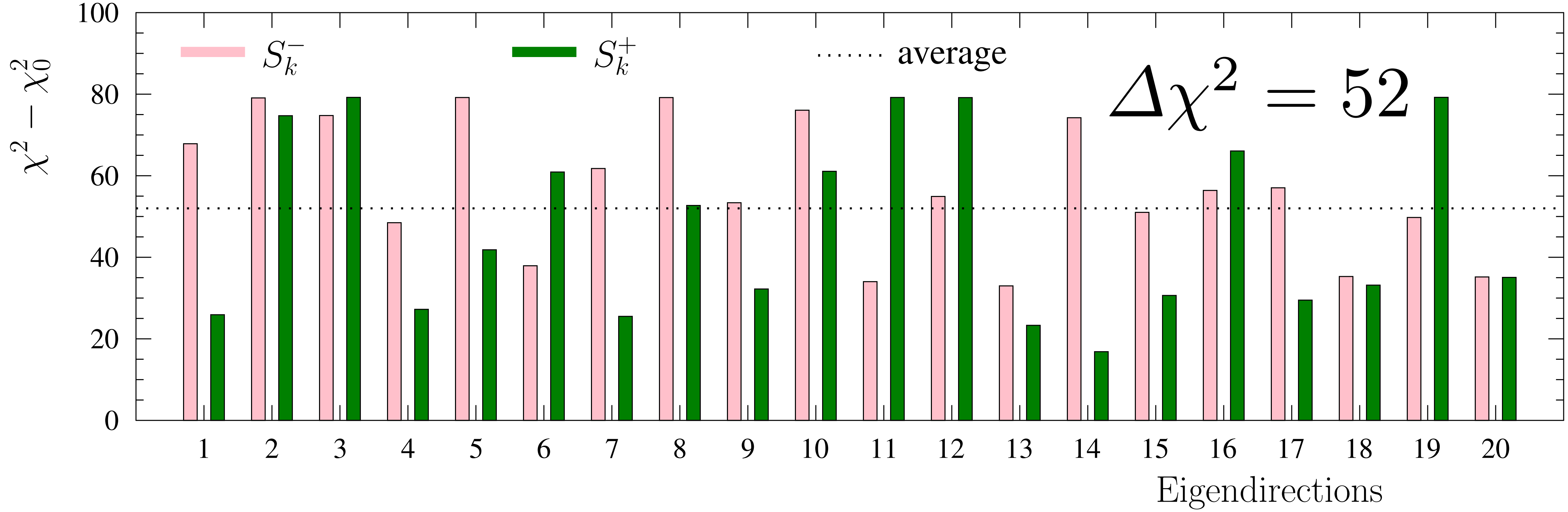
Torelance factor

Compute for each z-direction (only 1-4 here)



Torelance factor

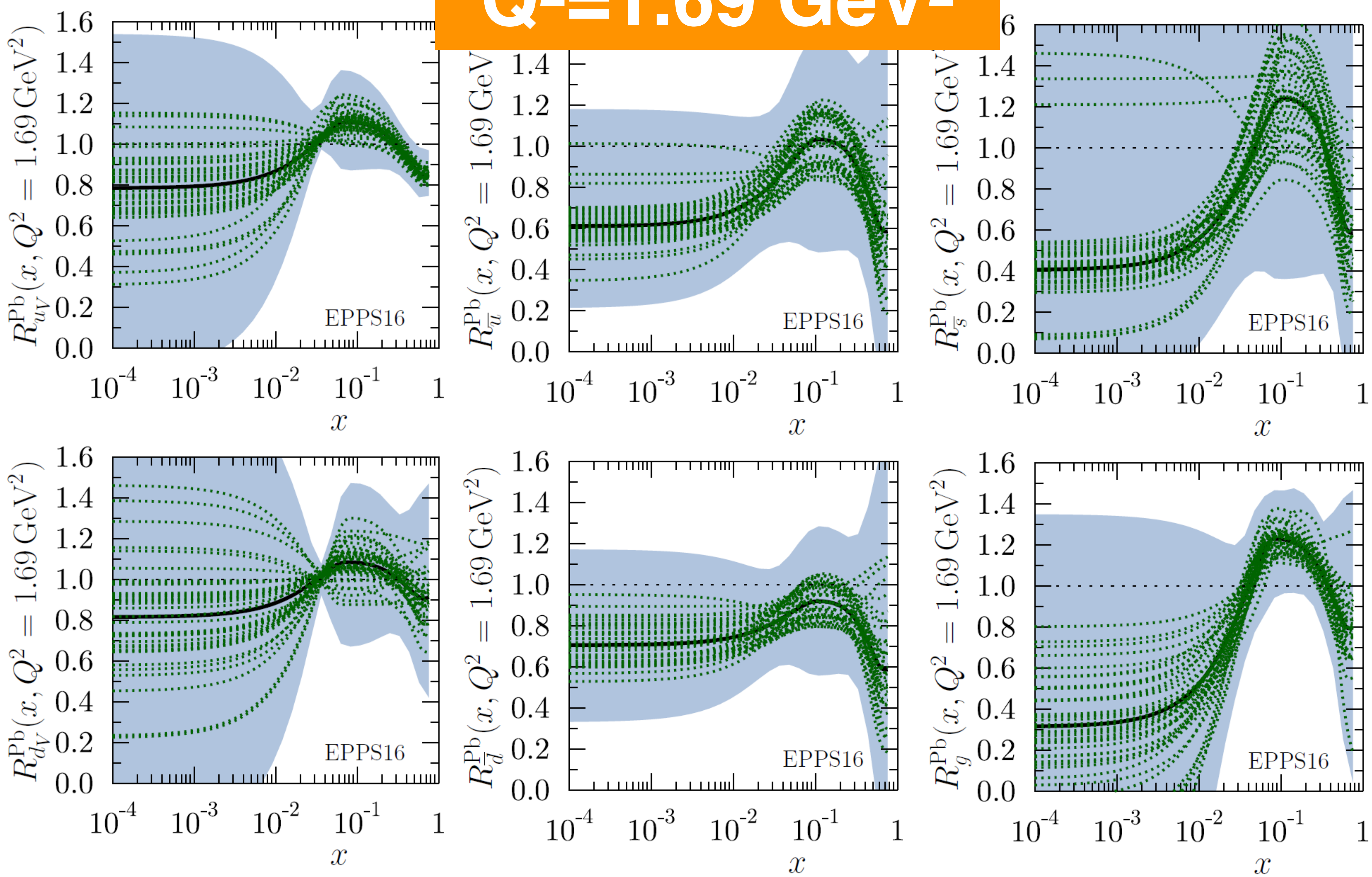
All directions in a single plot compared to the average



Using average provides results almost indistinguishable from dynamical tolerance

EPPS16 - results

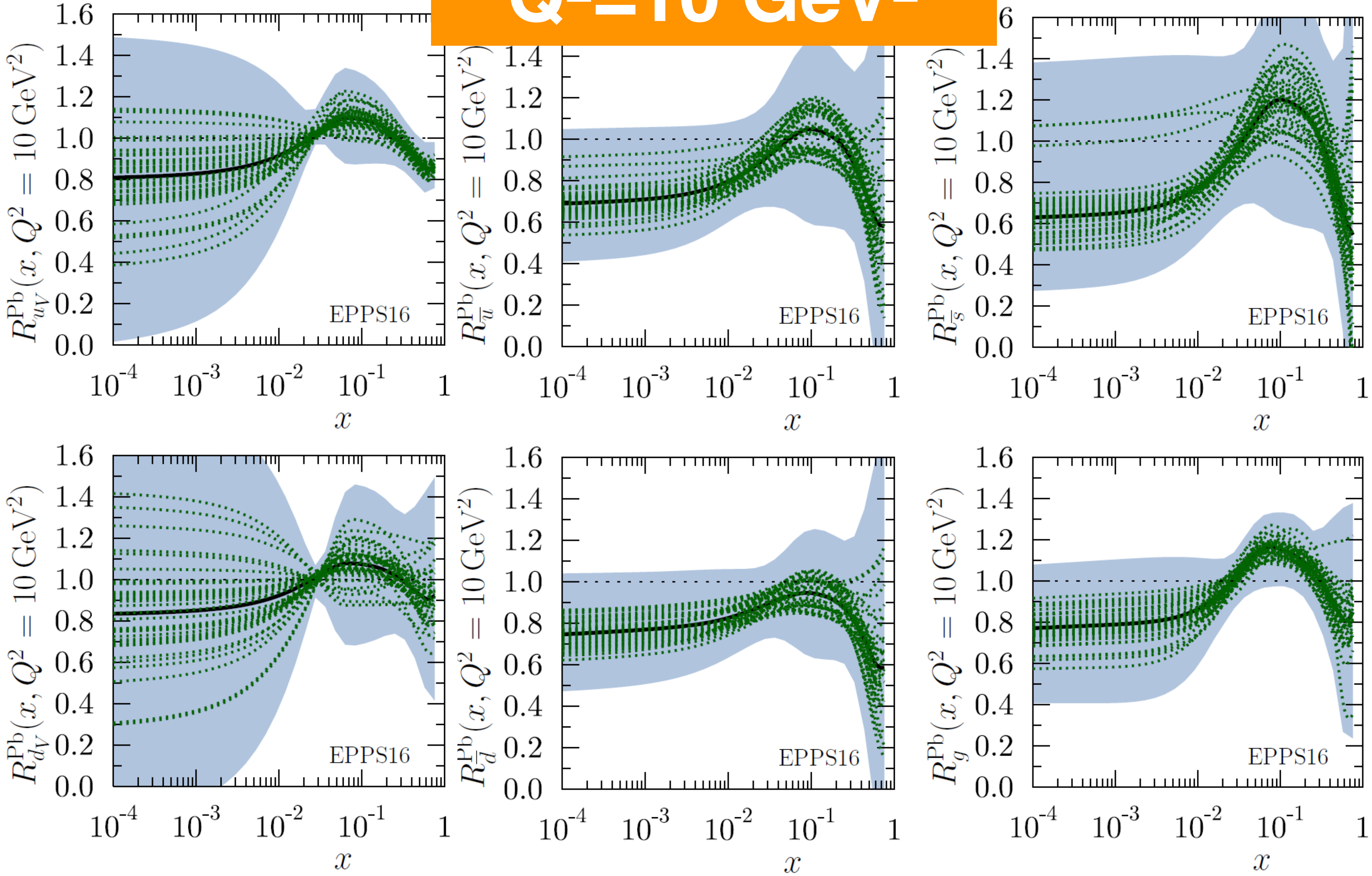
Q^2=1.69 GeV^2



Best fit + 40 error sets. **Large uncertainties,** decrease with evolution

EPPS16 - results

Q^2=10 GeV^2

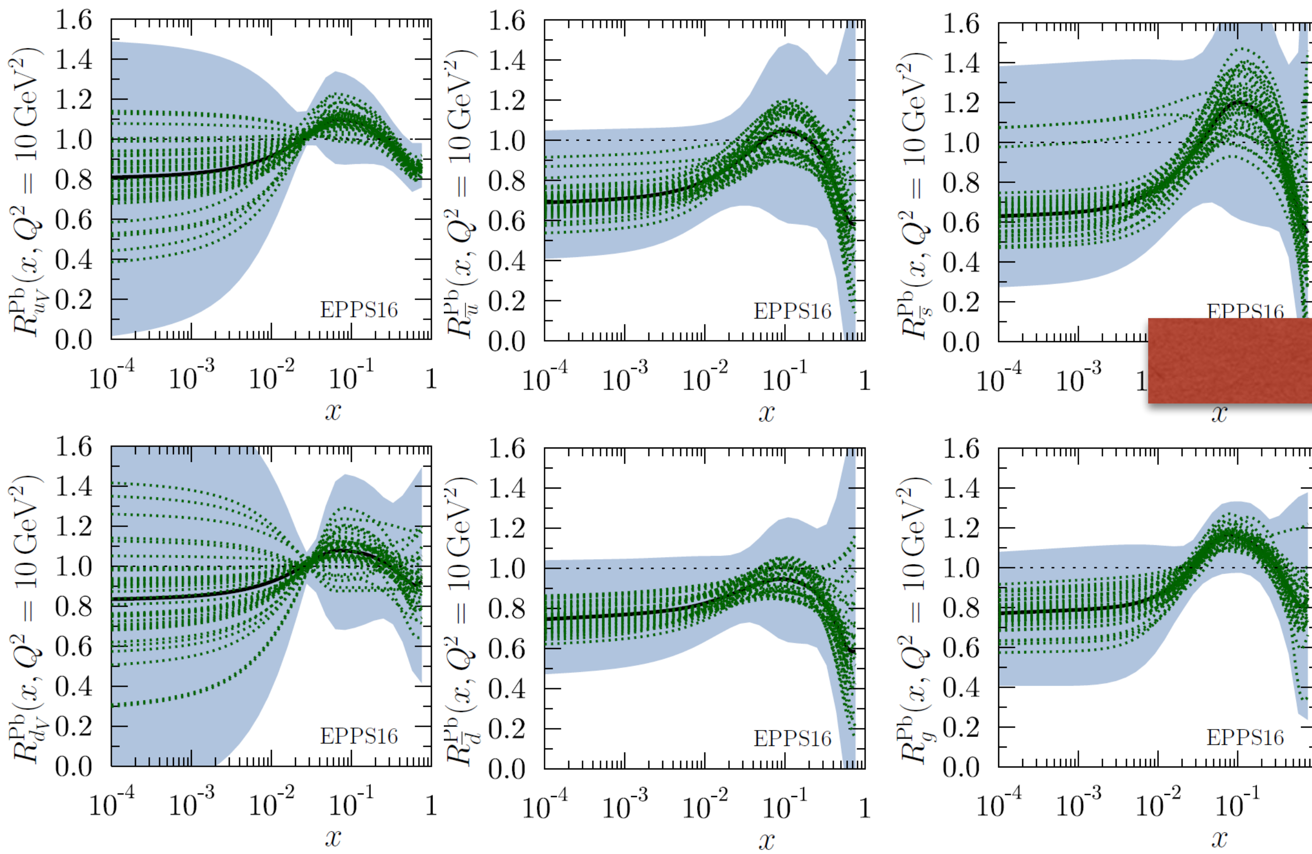


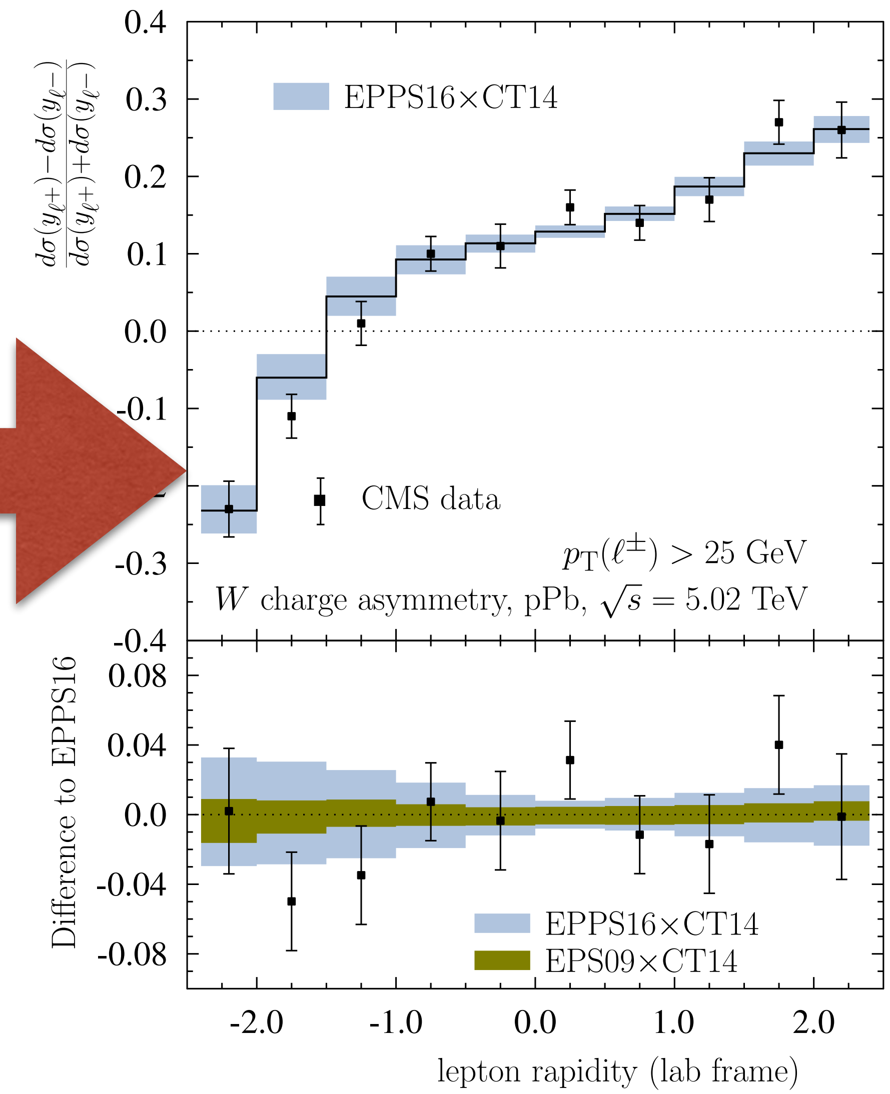
Best fit + 40 error sets. **Large uncertainties,** <u>decrease with evolution</u>

Computing errors

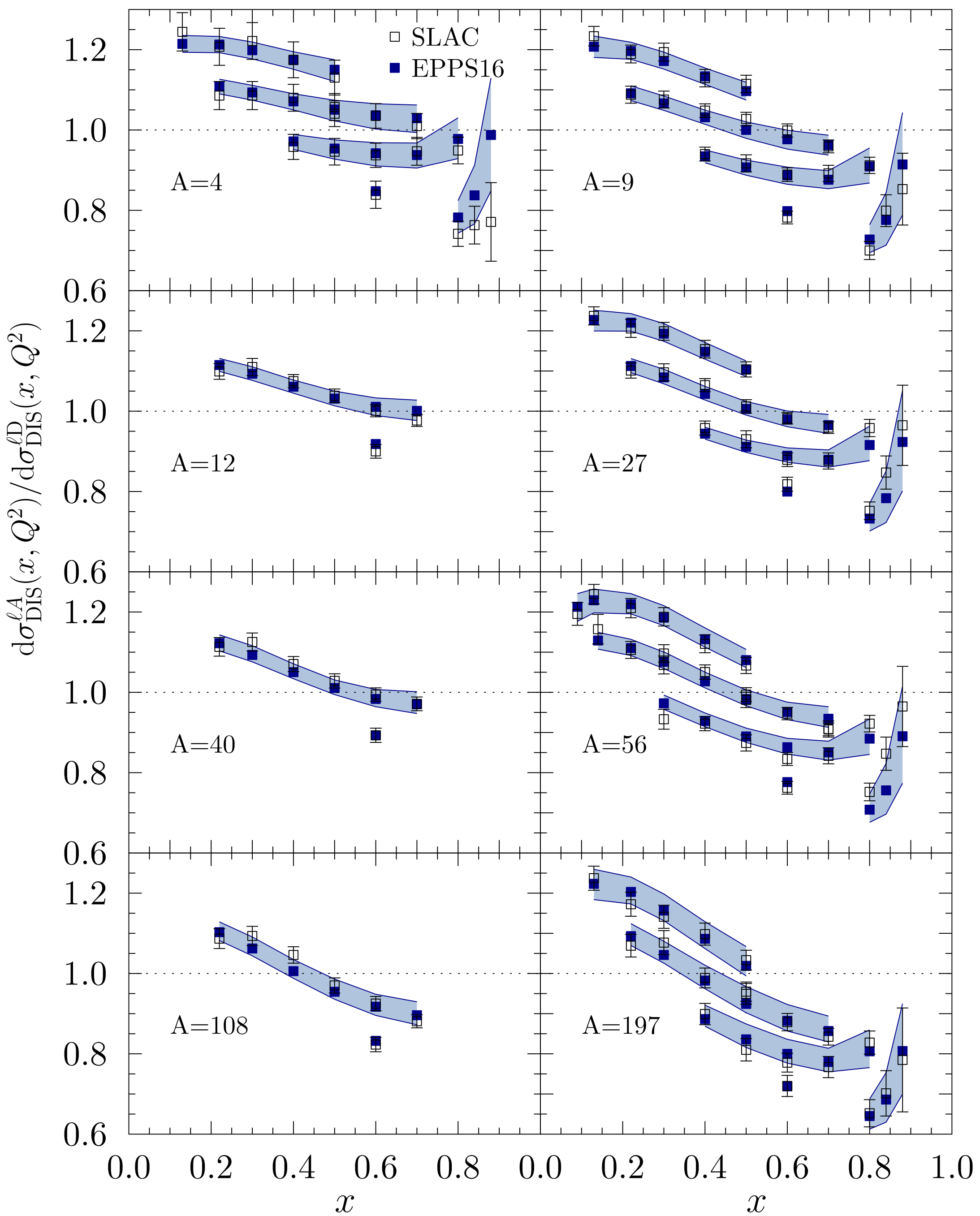
EPPS16 provides nPDF error sets. To compute the uncertainty

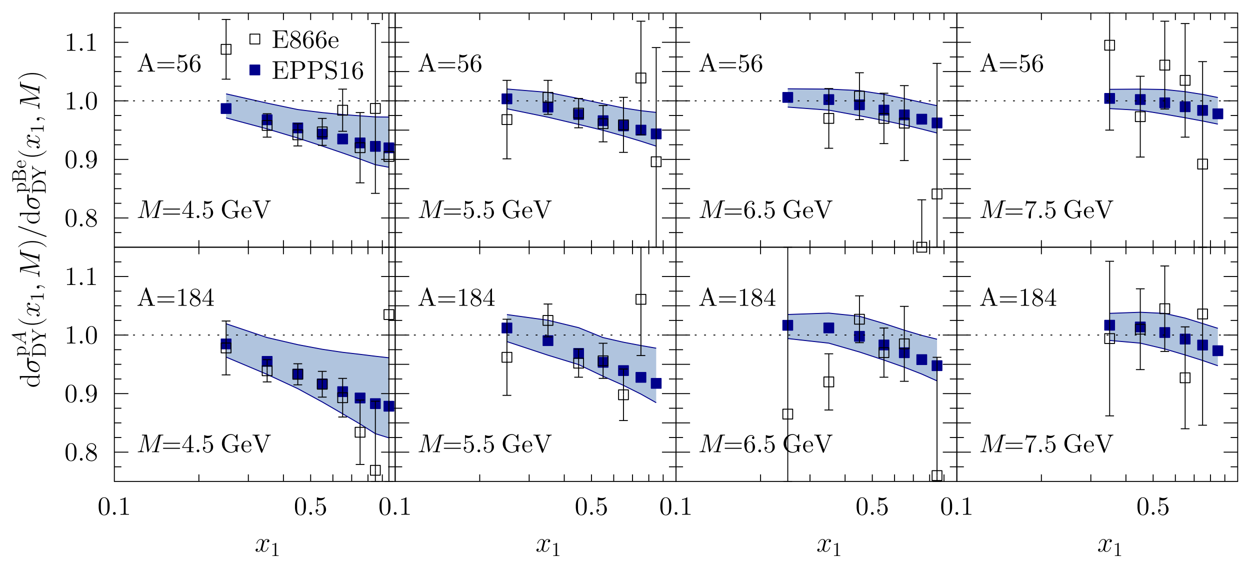
$$\left(\delta\mathcal{O}^{\pm}\right)^2 = \sum_i \left[{}^{\max}_{\min} \left\{ \mathcal{O}\left(S_i^{+}\right) - \mathcal{O}\left(S_0\right), \mathcal{O}\left(S_i^{-}\right) - \mathcal{O}\left(S_0\right), 0 \right\} \right]^2,$$





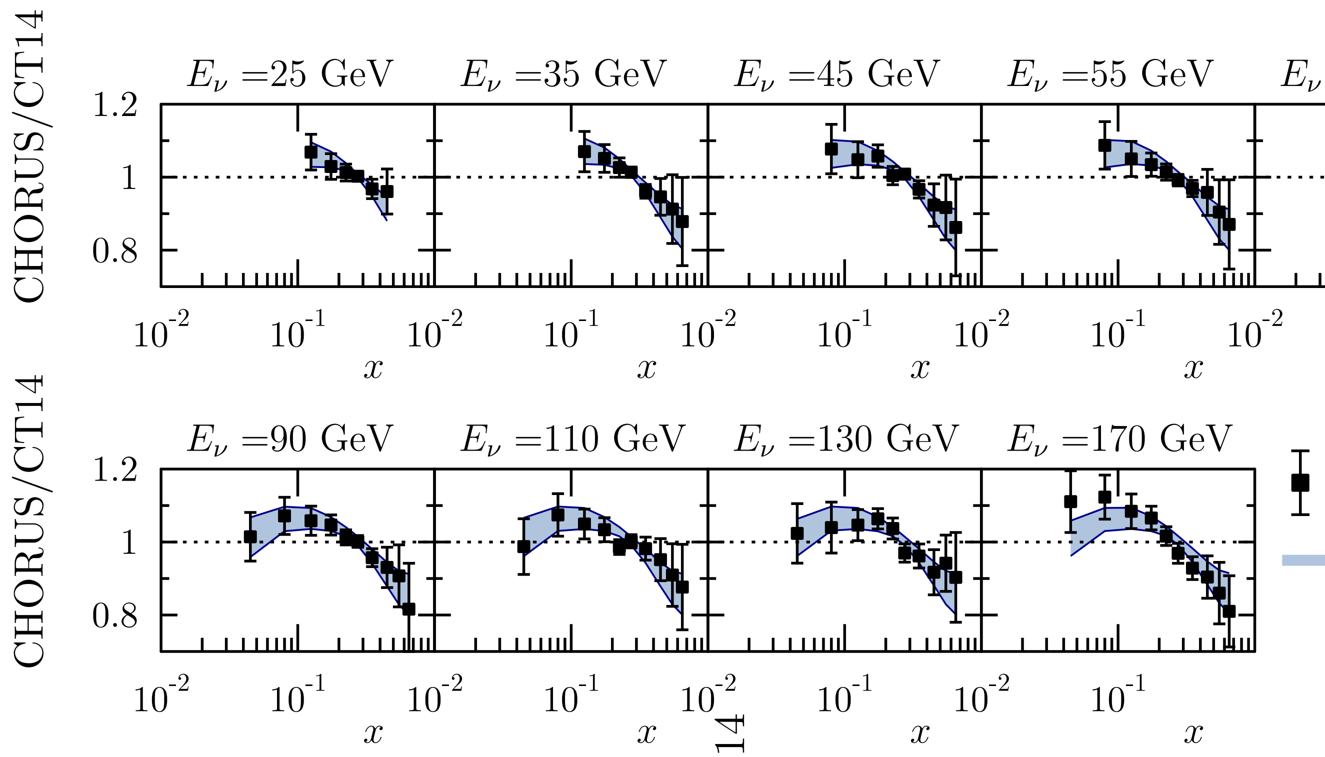
EPPS16 vs DIS/DY



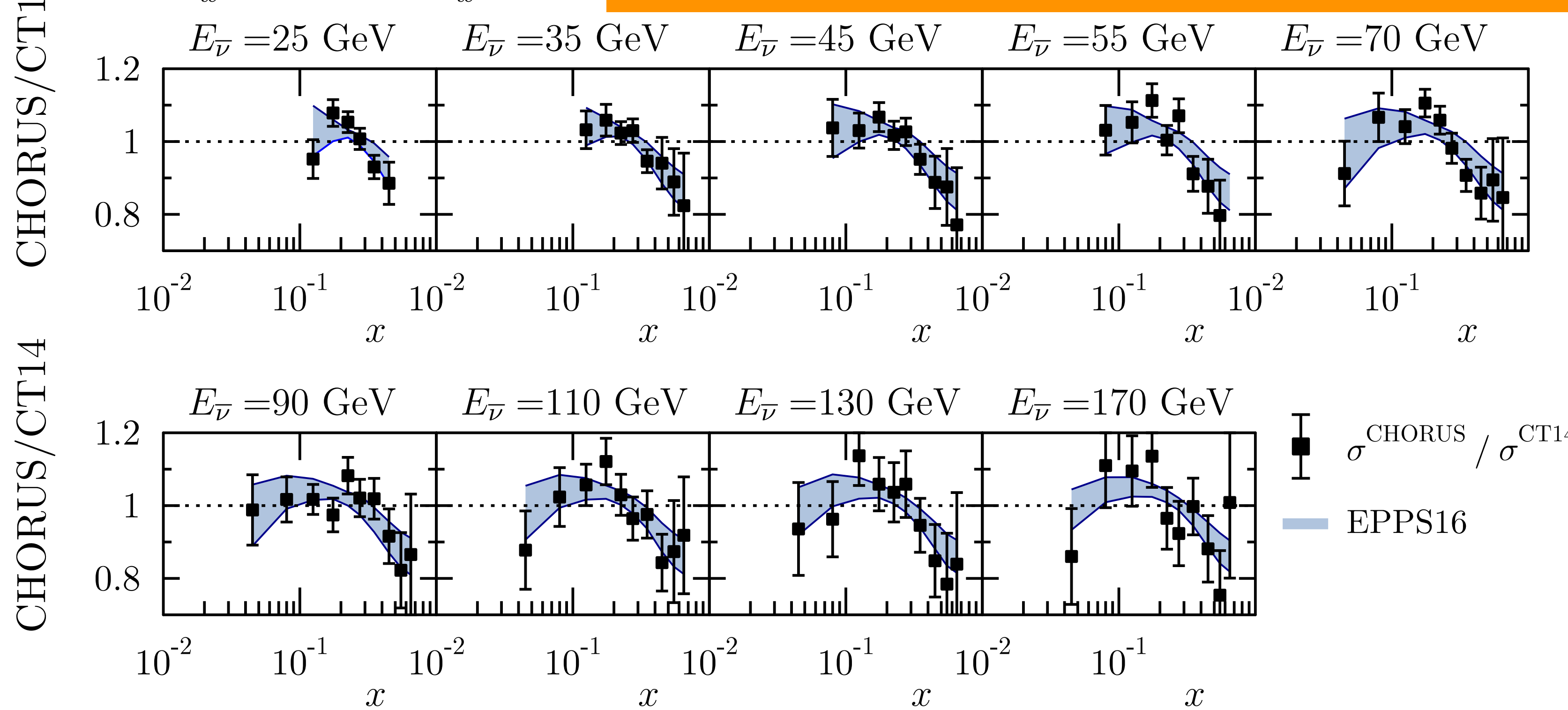


(Just a sample of plots)
Good description, these data were already included in the previous analyses.

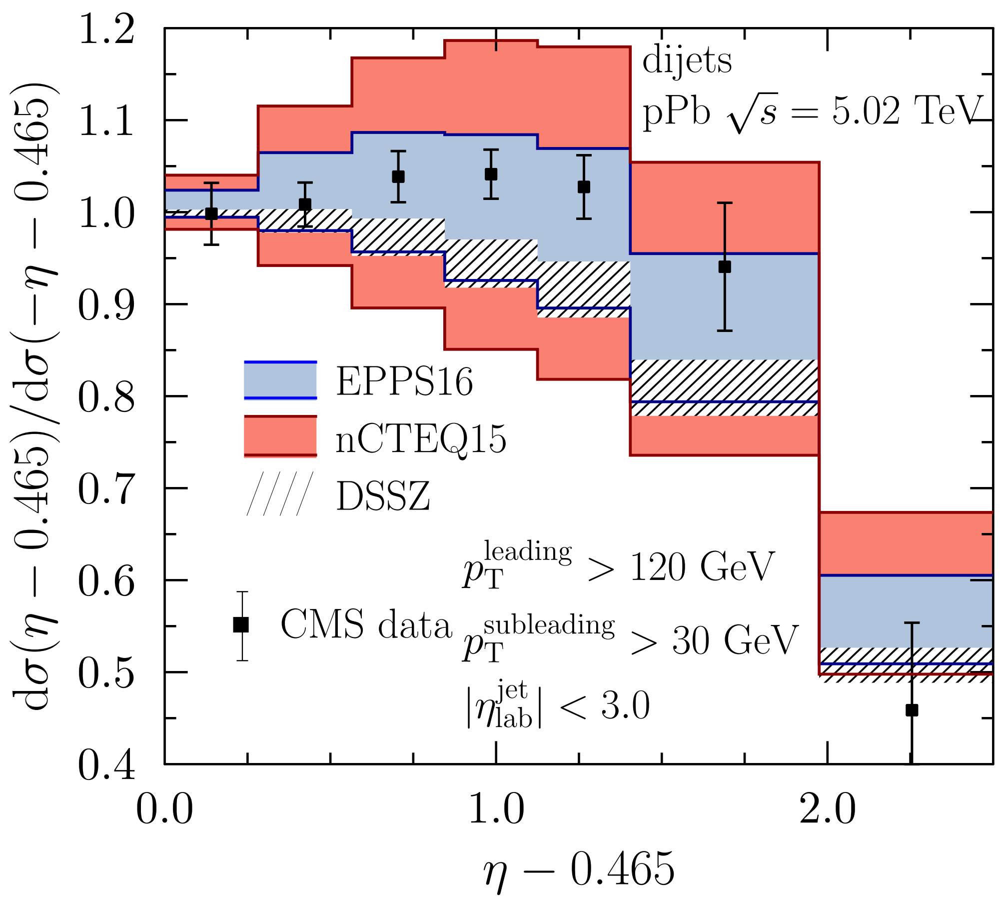
EPPS16 vs neutrinos

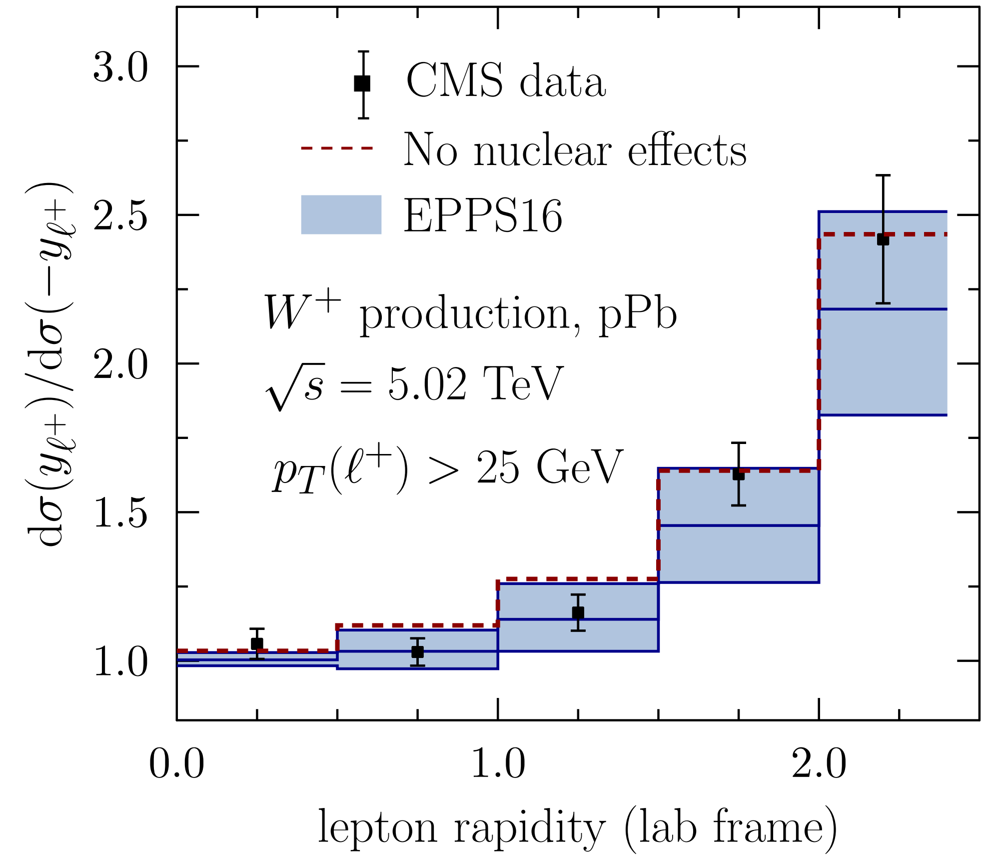


Neutrino data essential for flavor decomposition in EPPS16



EPPS16 vs LHC

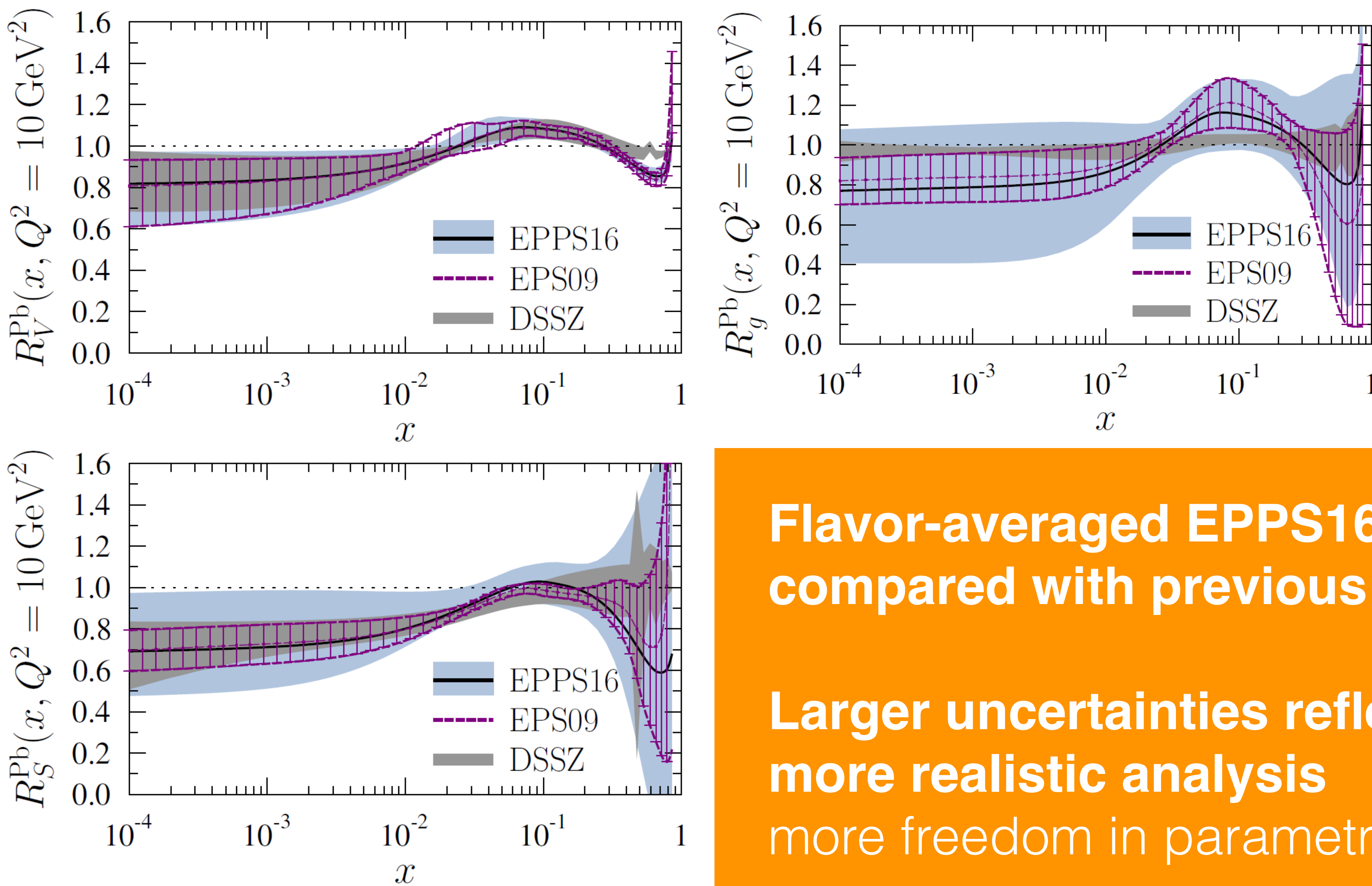




Dijet data constrains gluon distributions

Good description of heavy boson production but limited constraining power on the fit

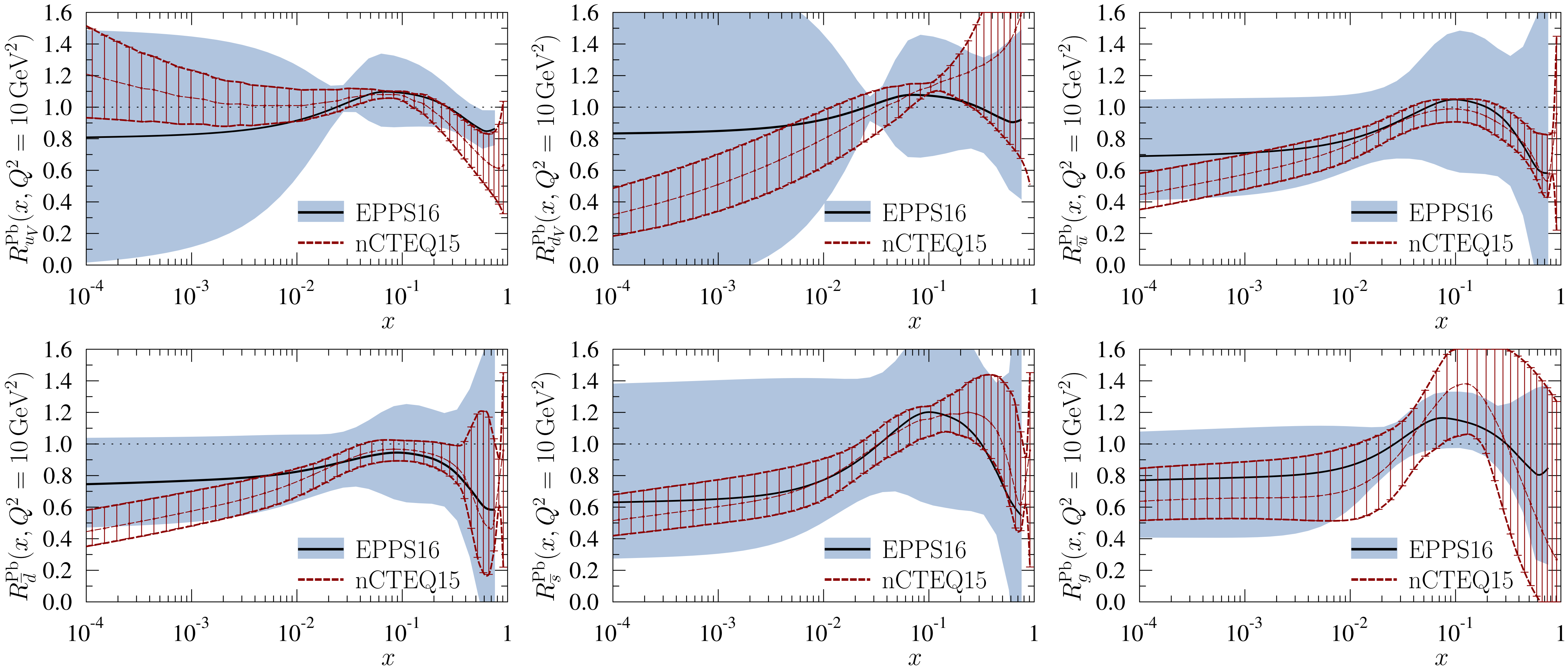
Comparison



Flavor-averaged EPPS16 compared with previous sets

Larger uncertainties reflect more realistic analysis
more freedom in parametrization

EPPS16 vs nCTEQ



Neutrino DIS and LHC data provide more constraints in EPPS16

More realistic uncertainties and flavor decomposition

Conclusions

- A **new set** of nuclear PDFs **EPPS16** is presented
- Larger number of data sets to date (first with LHC)

New sets

  - Neutrino DIS - allows flavor decomposition
  - LHC **pPb** dijet data - constrain gluons
  - LHC **pPb** Z/W data
  - pion-nucleus DY
- **No tension** between data sets exist - universality
- **Proton-Lead run in 2016** expected to have strong impact in nPDFs
- **nPDFs with uncertainties publicly available**

https://www.jyu.fi/fysiikka/en/research/highenergy/urhic/EPPS16%20download

Total list of experimental data in EPPS16

Experiment	Observable	Collisions	Data points	χ^2	Ref.
SLAC E139	DIS	e^-He(4), e^-D	21	12.2	[72]
CERN NMC 95, re.	DIS	μ^-He(4), μ^-D	16	18.0	[73]
CERN NMC 95	DIS	μ^-Li(6), μ^-D	15	18.4	[74]
CERN NMC 95, Q^2 dep.	DIS	μ^-Li(6), μ^-D	153	161.2	[74]
SLAC E139	DIS	e^-Be(9), e^-D	20	12.9	[72]
CERN NMC 96	DIS	μ^-Be(9), μ^-C	15	4.4	[75]
SLAC E139	DIS	e^-C(12), e^-D	7	6.4	[72]
CERN NMC 95	DIS	μ^-C(12), μ^-D	15	9.0	[74]
CERN NMC 95, Q^2 dep.	DIS	μ^-C(12), μ^-D	165	133.6	[74]
CERN NMC 95, re.	DIS	μ^-C(12), μ^-D	16	16.7	[73]
CERN NMC 95, re.	DIS	μ^-C(12), μ^-Li(6)	20	27.9	[73]
FNAL E772	DY	pC(12), pD	9	11.3	[76]
SLAC E139	DIS	e^-Al(27), e^-D	20	13.7	[72]
CERN NMC 96	DIS	μ^-Al(27), μ^-C(12)	15	5.6	[75]
SLAC E139	DIS	e^-Ca(40), e^-D	7	4.8	[72]
FNAL E772	DY	pCa(40), pD	9	3.33	[76]
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-D	15	27.6	[73]
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-Li(6)	20	19.5	[73]
CERN NMC 96	DIS	μ^-Ca(40), μ^-C(12)	15	6.4	[75]
SLAC E139	DIS	e^-Fe(56), e^-D	26	22.6	[72]
FNAL E772	DY	e^-Fe(56), e^-D	9	3.0	[76]
CERN NMC 96	DIS	μ^-Fe(56), μ^-C(12)	15	10.8	[75]
FNAL E866	DY	pFe(56), pBe(9)	28	20.1	[77]
CERN EMC	DIS	μ^-Cu(64), μ^-D	19	15.4	[78]
SLAC E139	DIS	e^-Ag(108), e^-D	7	8.0	[72]
CERN NMC 96	DIS	μ^-Sn(117), μ^-C(12)	15	12.5	[75]
CERN NMC 96, Q^2 dep.	DIS	μ^-Sn(117), μ^-C(12)	144	87.6	[79]
FNAL E772	DY	pW(184), pD	9	7.2	[76]
FNAL E866	DY	pW(184), pBe(9)	28	26.1	[77]
CERN NA10★	DY	π^-W(184), π^-D	10	11.6	[52]
FNAL E615★	DY	π^+W(184), π^-W(184)	11	10.2	[53]
CERN NA3★	DY	π^-Pt(195), π^-H	7	4.6	[51]
SLAC E139	DIS	e^-Au(197), e^-D	21	8.4	[72]
RHIC PHENIX	π^0	dAu(197), pp	20	6.9	[28]
CERN NMC 96	DIS	μ^-Pb(207), μ^-C(12)	15	4.1	[75]
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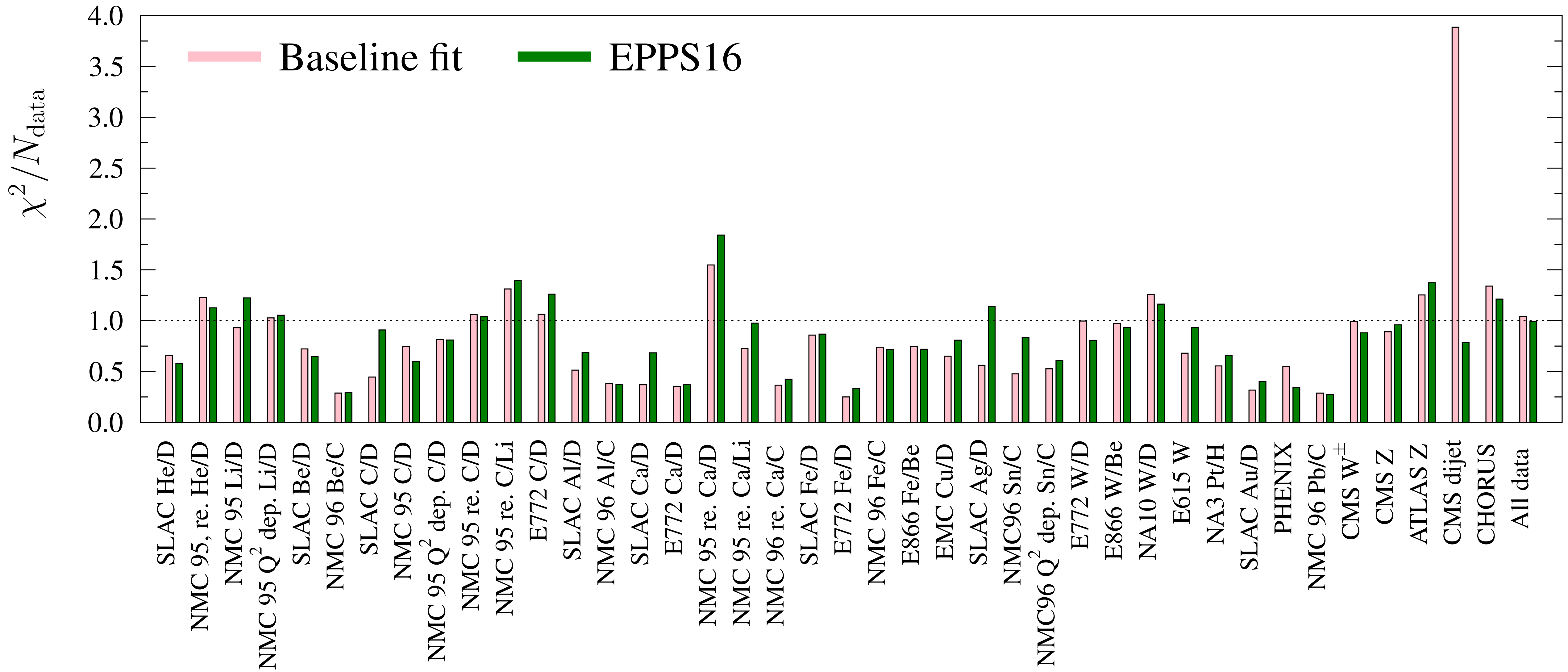
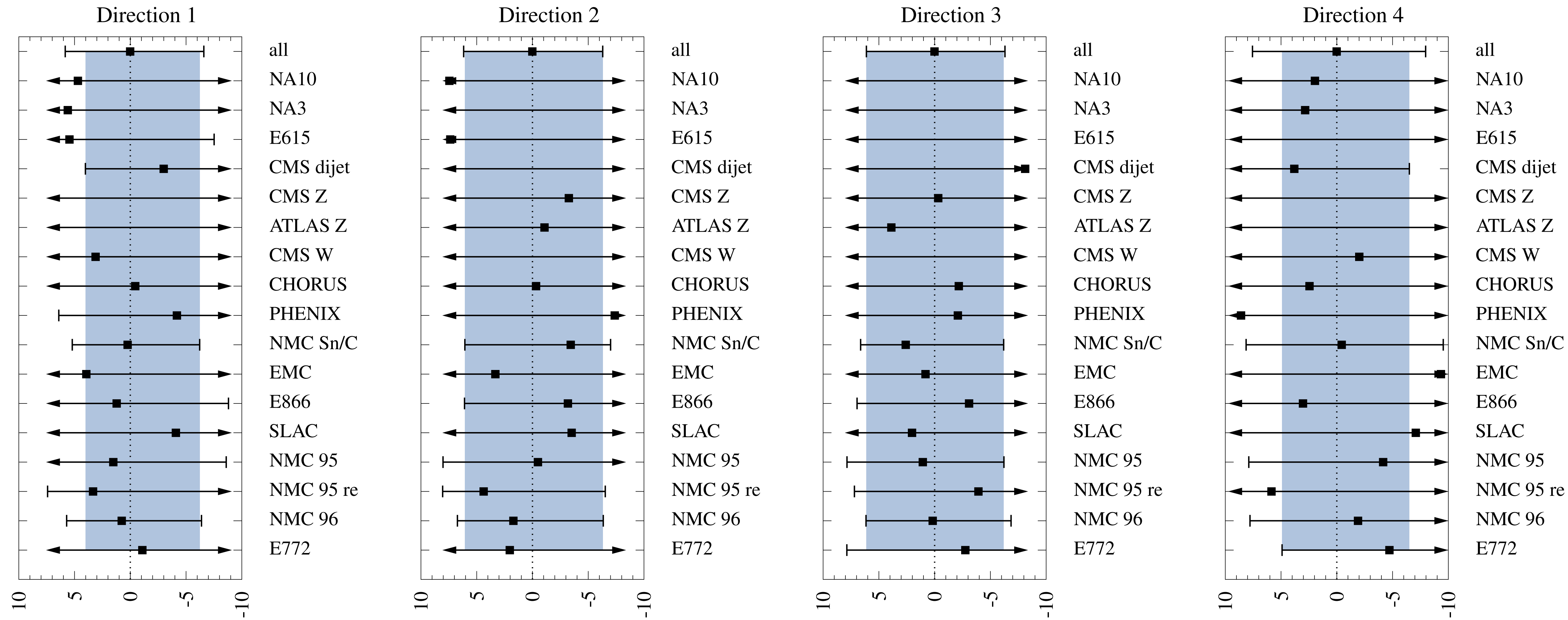
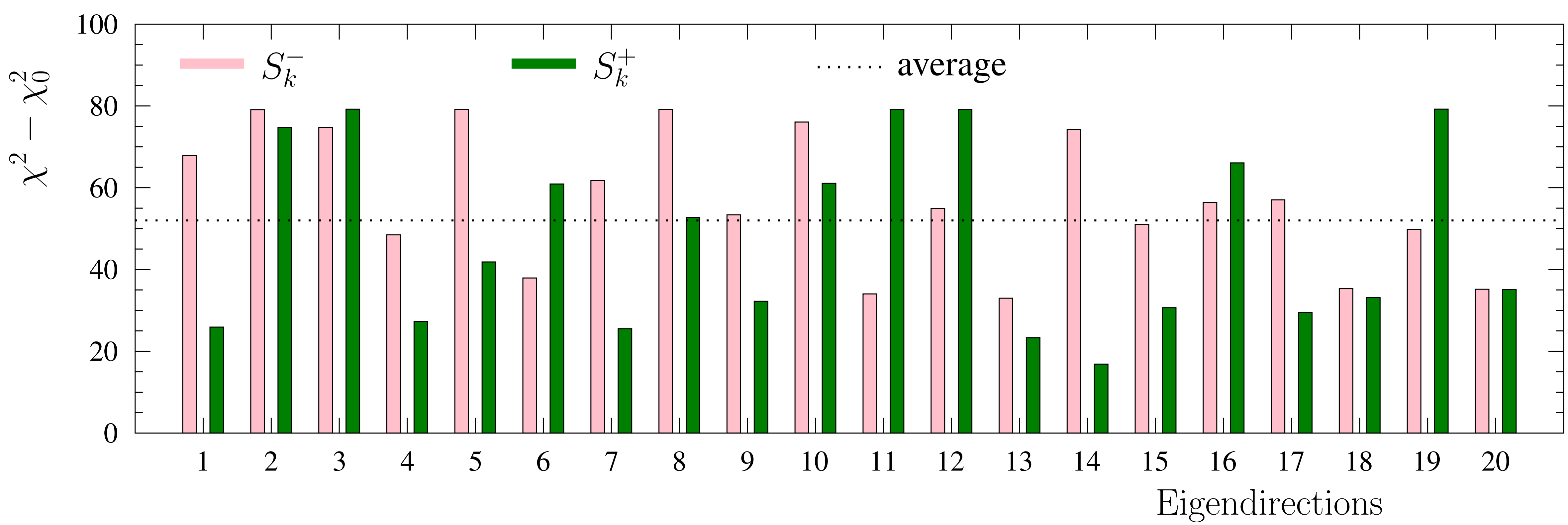
CERN CHORUS★	DIS	νPb(208), $\bar{\nu}$Pb(208)	824	998.6	[50]
Total			1811	1789	



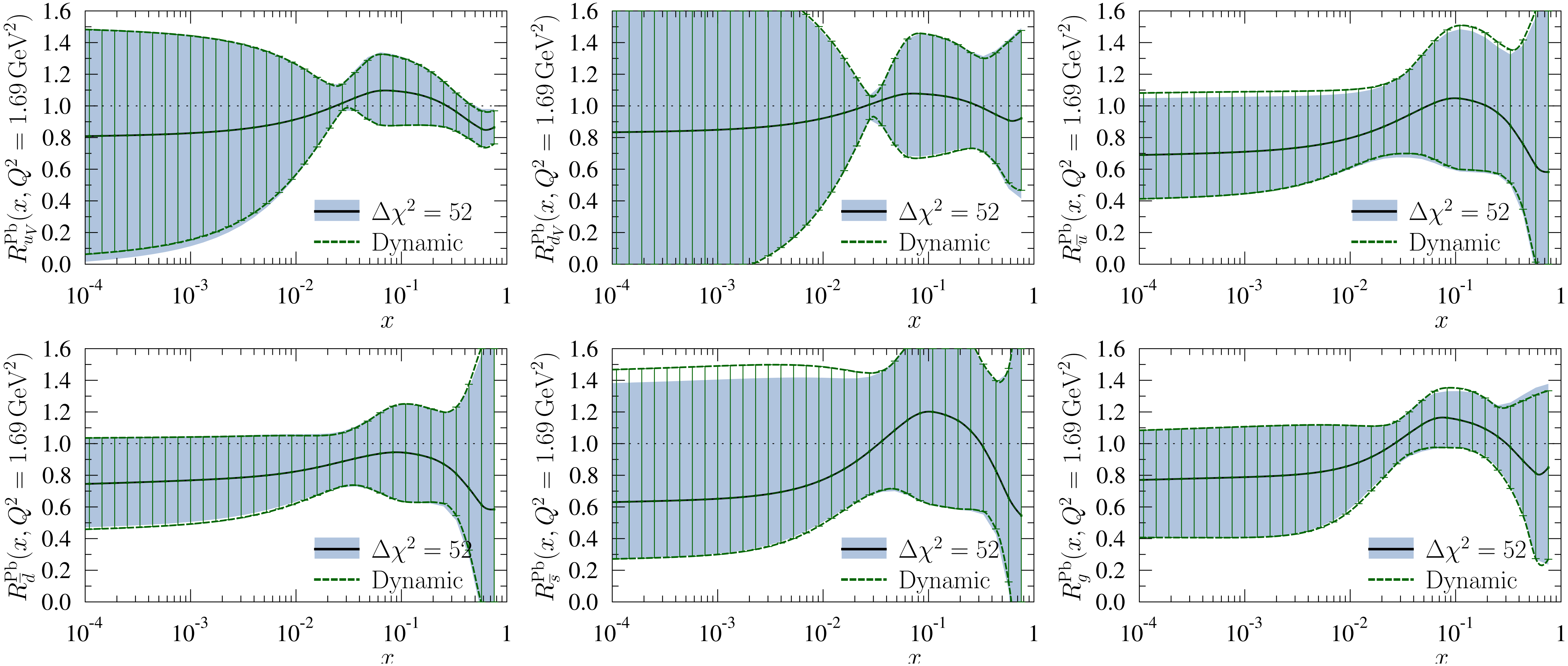
Baseline fit
EPPS16
$\chi^2/N_{\rm data}$
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
SLAC He/D
NMC 95, re. He/D
NMC 95 Li/D
NMC 95 Q^2 dep. Li/D
SLAC Be/D
NMC 96 Be/C
SLAC C/D
NMC 95 C/D
NMC 95 Q^2 dep. C/D
NMC 95 re. C/D
NMC 95 re. C/Li
E772 C/D
SLAC Al/D
NMC 96 Al/C
SLAC Ca/D
E772 Ca/D
NMC 95 re. Ca/D
NMC 95 re. Ca/Li
NMC 96 re. Ca/C
SLAC Fe/D
E772 Fe/D
NMC 96 Fe/C
E866 Fe/Be
EMC Cu/D
SLAC Ag/D
NMC96 Sn/C
NMC96 Q^2 dep. Sn/C
E772 W/D
E866 W/Be
NA10 W/D
E615 W
NA3 Pt/H
SLAC Au/D
PHENIX
NMC 96 Pb/C
CMS W$^\pm$
CMS Z
ATLAS Z
CMS dijet
CHORUS
All data



Direction 1
Direction 2
Direction 3
Direction 4
all
NA10
NA3
E615
CMS dijet
CMS Z
ATLAS Z
CMS W
CHORUS
PHENIX
NMC Sn/C
EMC
E866
SLAC
NMC 95
NMC 95 re
NMC 96
E772
10
5
0
-5
-10

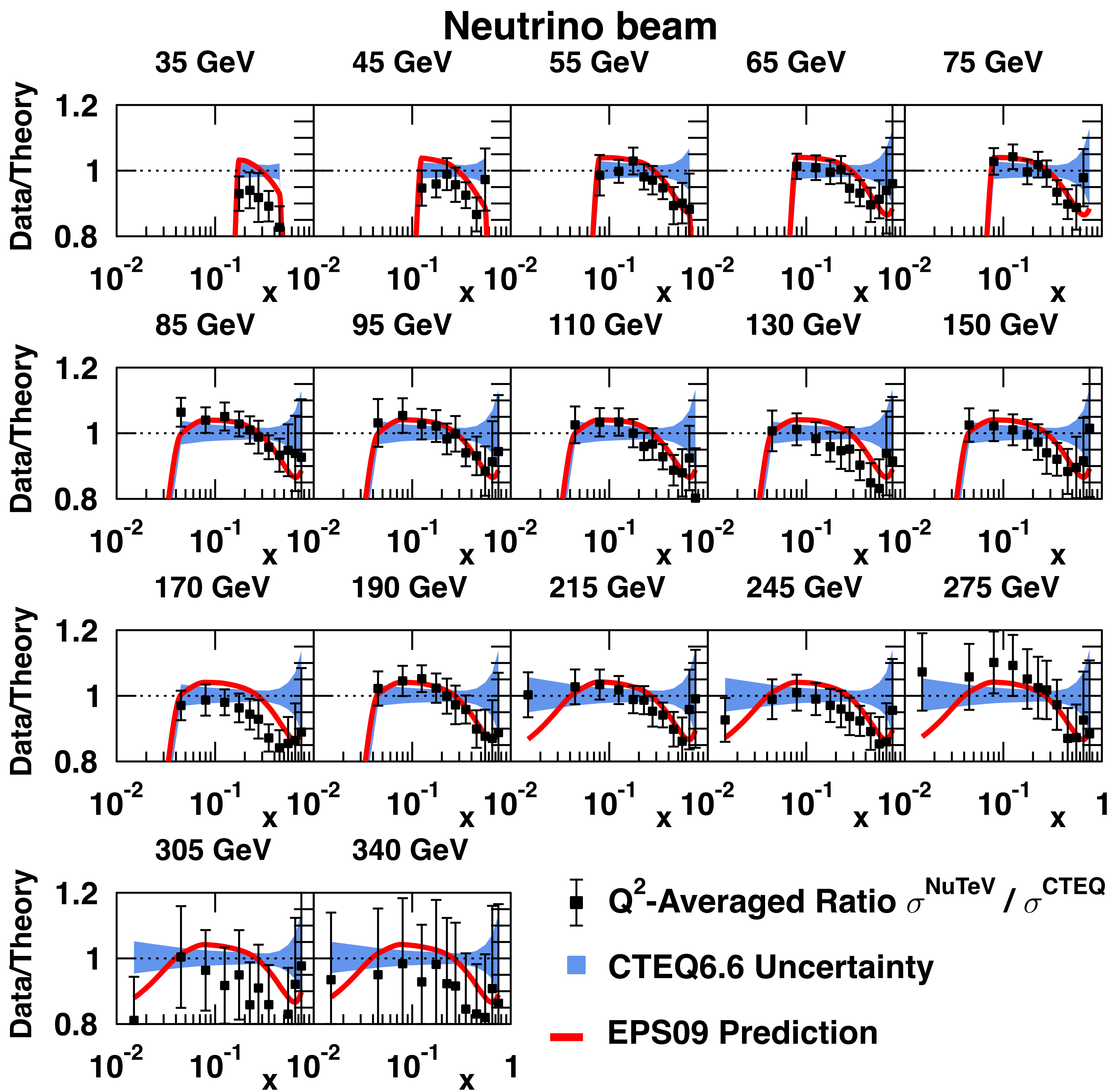


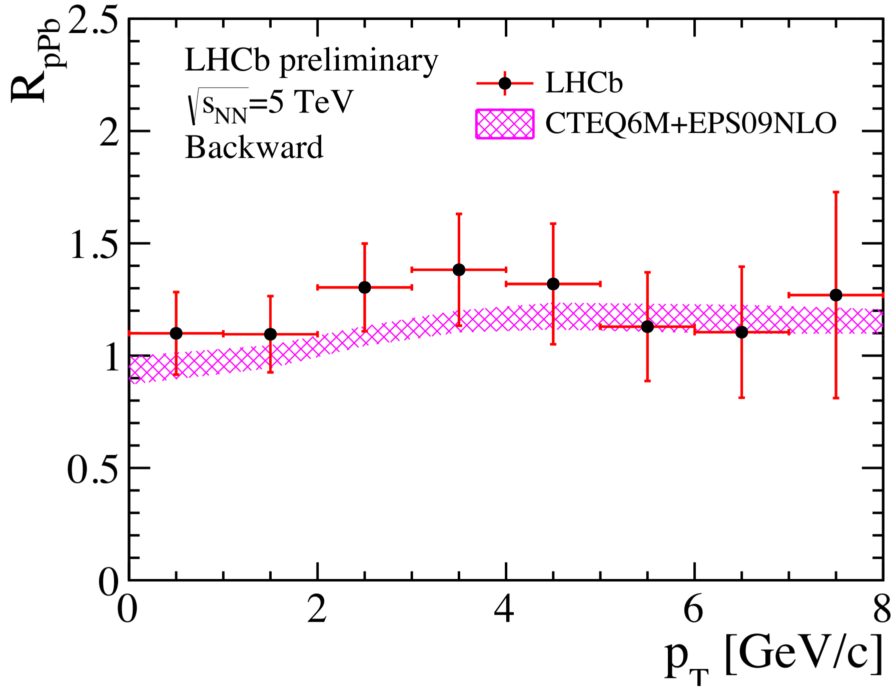
$\chi^2 - \chi_0^2$
S_k^-
S_k^+
average
Eigendirections
0
20
40
60
80
100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20



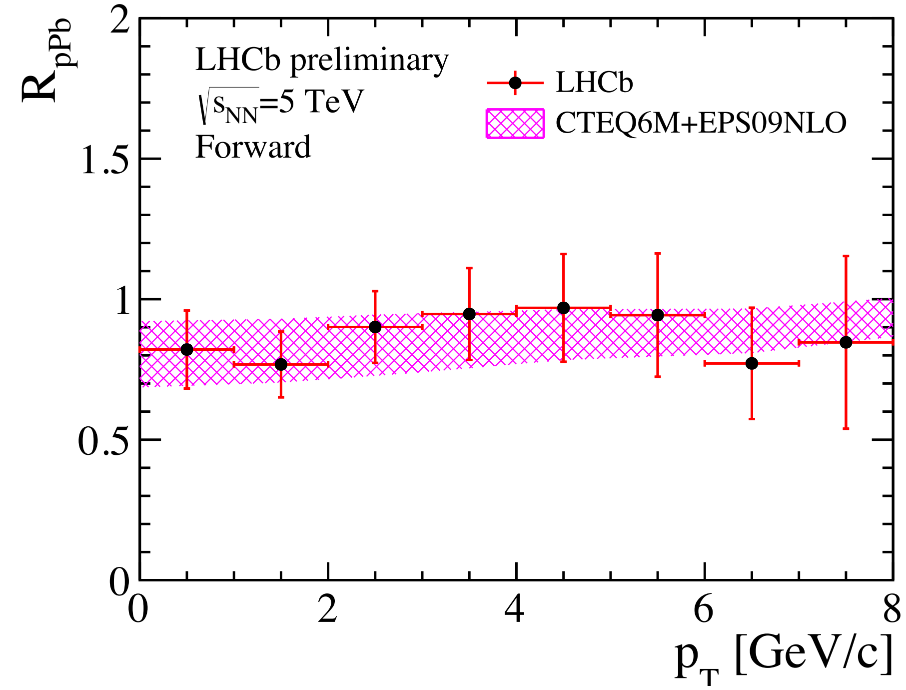
$R^{\mathrm{Pb}}_{u_V}(x, Q^2 = 1.69\,\mathrm{GeV}^2)$
$R^{\mathrm{Pb}}_{d_V}(x, Q^2 = 1.69\,\mathrm{GeV}^2)$
$R^{\mathrm{Pb}}_{\bar{u}}(x, Q^2 = 1.69\,\mathrm{GeV}^2)$
$R^{\mathrm{Pb}}_{\bar{d}}(x, Q^2 = 1.69\,\mathrm{GeV}^2)$
$R^{\mathrm{Pb}}_{\bar{s}}(x, Q^2 = 1.69\,\mathrm{GeV}^2)$
$R^{\mathrm{Pb}}_{g}(x, Q^2 = 1.69\,\mathrm{GeV}^2)$
$\Delta\chi^2 = 52$
Dynamic
x

Paukkunen, Salgado / arXiv:1004.3140,1302.2001

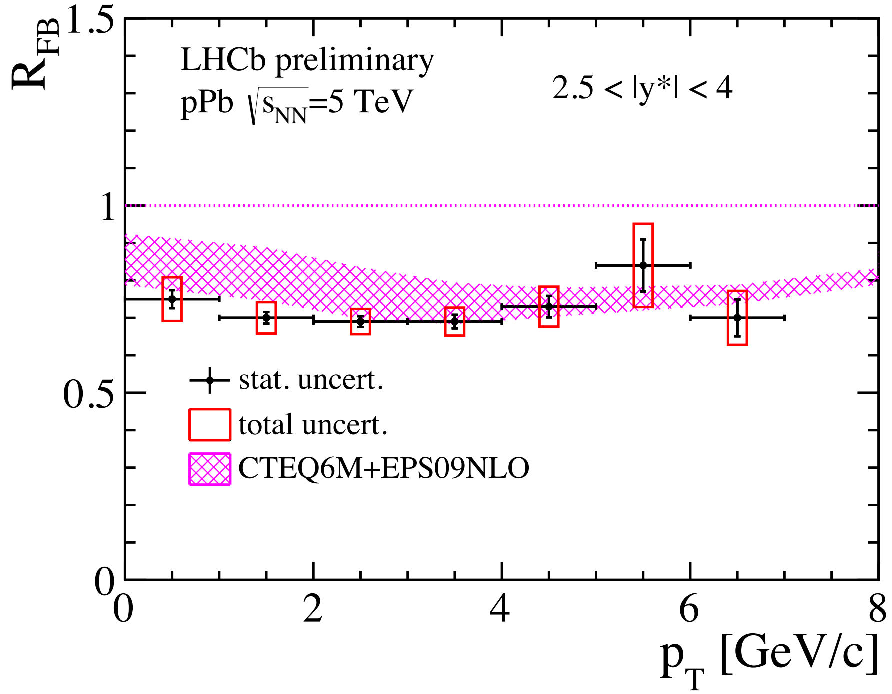




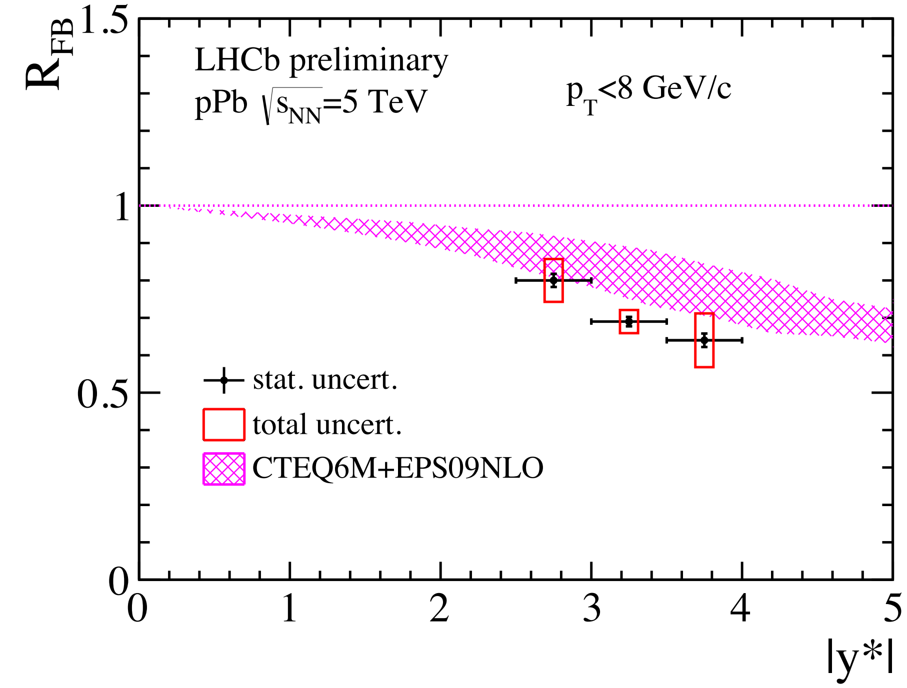
R_{pPb}
LHCb preliminary
$\sqrt{s_{NN}}$=5 TeV
Backward
LHCb
CTEQ6M+EPS09NLO
p_T [GeV/c]



R_{pPb}
LHCb preliminary
$\sqrt{s_{NN}}$=5 TeV
Forward
LHCb
CTEQ6M+EPS09NLO
p_T [GeV/c]



R_{FB}
LHCb preliminary
pPb $\sqrt{s_{NN}}$=5 TeV
2.5 < |y*| < 4
stat. uncert.
total uncert.
CTEQ6M+EPS09NLO
p_T [GeV/c]



R_{FB}
LHCb preliminary
pPb $\sqrt{s_{NN}}$=5 TeV
p_T<8 GeV/c
stat. uncert.
total uncert.
CTEQ6M+EPS09NLO
|y*|

Parameter	u_V	d_V	$\overline{u}$
$y_0(A_{\rm ref})$	sum rule	sum rule	**0.844**
γ_{y_0}	sum rule	sum rule	**0.731**
x_a	**0.0717**	as u_V	**0.104**
x_e	**0.693**	as u_V	as u_V
$y_a(A_{\rm ref})$	**1.06**	**1.05**	**1.03**
γ_{y_a}	**0.278**	as u_V	0, fixed
$y_e(A_{\rm ref})$	**0.908**	**0.943**	**0.725**
γ_{y_e}	**0.288**	as u_V	as u_V
β	1.3, fixed	1.3, fixed	1.3, fixed

Parameter	$\overline{d}$	s	g
$y_0(A_{\rm ref})$	**0.889**	**0.723**	sum rule
γ_{y_0}	as $\overline{u}$	as $\overline{u}$	sum rule
x_a	as $\overline{u}$	as $\overline{u}$	**0.0820**
x_e	as u_V	as u_V	as u_V
$y_a(A_{\rm ref})$	**0.919**	**1.24**	**1.12**
γ_{y_a}	0, fixed	0, fixed	as u_V
$y_e(A_{\rm ref})$	as $\overline{u}$	as $\overline{u}$	**0.874**
γ_{y_e}	as u_V	as u_V	as u_V
β	1.3, fixed	1.3, fixed	1.3, fixed