Hard Probes 2012
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Global analysis of nuclear PDFs – latest developments

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I will discuss

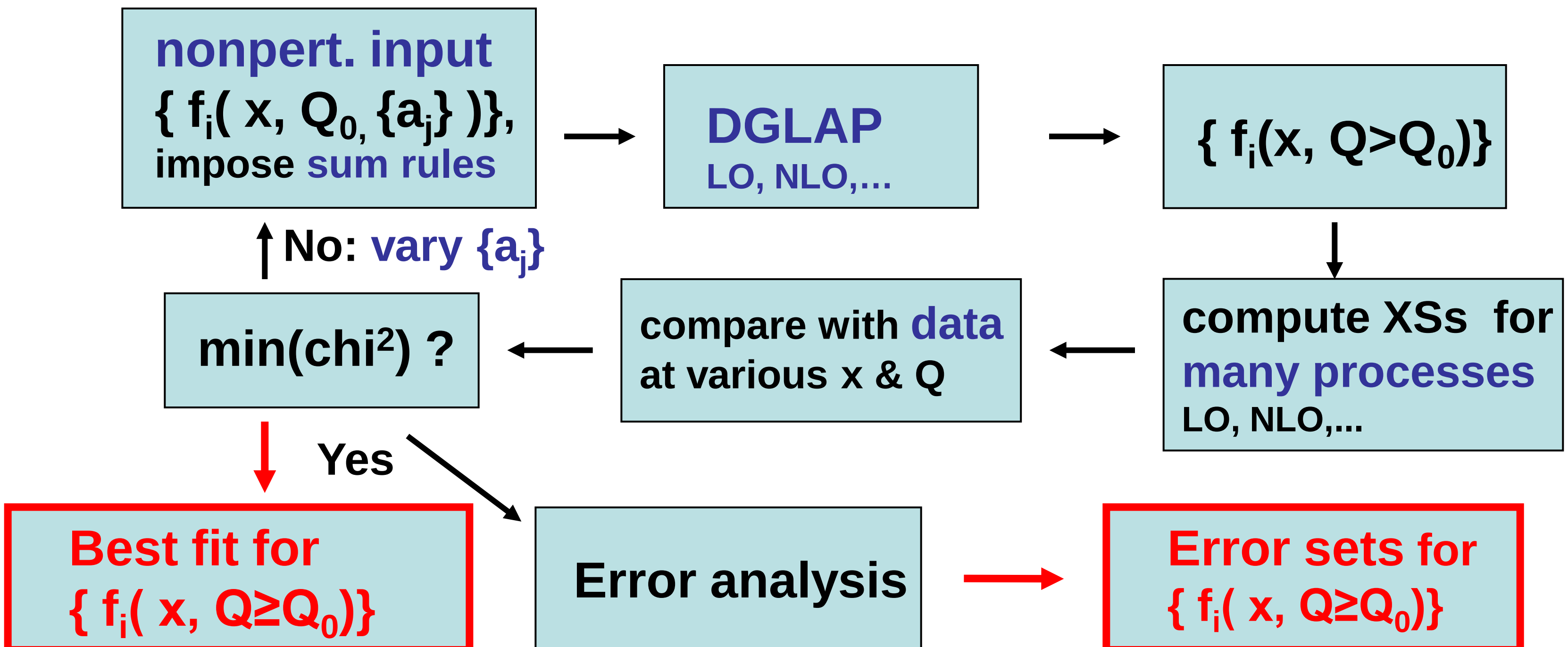
- **global DGLAP analyses of nPDFs**
  → **EPS09 (2009), nCTEQ (2011), DSZS (2012)**
- **impact-parameter dependence in these nPDFs?**
  → **EKS98s and EPS09s**
  Helenius, KJE, Honkanen, Salgado, 1205.5359 hep-ph

I. Global DGLAP analyses of nuclear PDFs

- **test pQCD & collinear factorization**

$$\sigma_{AB\to h+X} = \sum_{i,j} f_i^A(Q^2) \otimes \hat{\sigma}_{ij\to h+X} \otimes f_j^B(Q^2) + \mathcal{O}\left(Q^2\right)^{-n}$$

- **study whether a universal set $\{f_i^A(x,Q^2)\}$ at $Q^2 \gg \Lambda^2_{QCD}$ can be found through the following procedure**



- **Quantification of the nPDF uncertainties**

Interesting and important topics not addressed here:

- **QCD-origin of nuclear effects in PDFs** in different x-regions
  → **various models**, lots of work by many people
  e.g. shadowing models in multiple scattering frameworks
  → see, e.g., Armesto's review, hep-ph/0604108,
  Tywoniuk et al, 0705.1596 [hep-ph]
  Frankfurt, Guzey, Strikman, hep-ph/0303022, G&S 0908.1149 [hep-ph],
  recent review: FGS, **arXiv:1106.2091 [hep-ph], Phys. Rept. 512 (2012)**
  FGS nPDFs are b-dependent!

- **nonlinear effects in PDFs** in the small-x, small-Q2 region,
  saturation and CGC phenomena & **other evolution eqs**
  (BFKL, BK, JIMWLK, nonlinearities to DGLAP/BFKL,…)

- **power corrections** $\sim(1/Q^2)^n$ to the cross sections,
  → see e.g. Qiu&Vitev, hep-ph/0309094

Challenges in global analysis of (n)PDFs

- data (=constraints) at limited & correlated (x, Q^2) regions
- how to account for the experim. statistical/systematic/normalization uncertainties
- parameter space 15-30 d & NLO XSs require multi-d numerical integrations

→ need <u>very</u> fast DGLAP & XS solvers

<u>Free p PDFs</u>

excellent global fits [CTEQ: CT09, CT10; MRST, MSTW,…]

→ factorization theorem seems to hold well

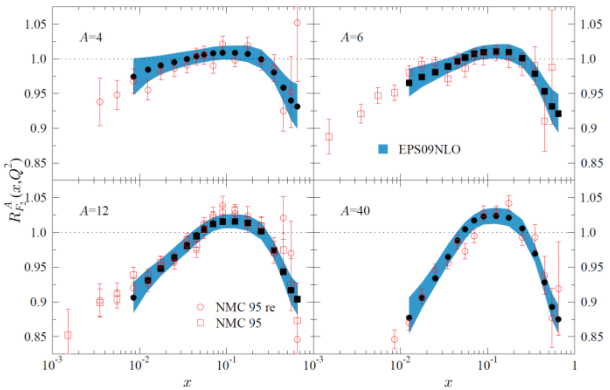
→ PDF uncertainties have been quantified & error sets available

<u>Nuclear PDFs,</u> spatially averaged:

$$f_i^A(x,Q) \neq f_i^p(x,Q)$$

Challenges relative to free-p PDFs

- less data
- fewer types of data
- **smaller kinematical (x,Q) range**
- **A dependence**



arXiv:0902.4154 [hep-ph]

- **impact parameter dependence?**

  → **no global analysis so far…**

$$f_i^A(x,Q,\text{center}) \neq f_i^A(x,Q,\text{edge})$$

Progress in the global nPDF analyses

year	set	Authors	order	data	error analysis
1998	EKS98	Eskola, Kolhinen, Ruuskanen, Salgado hep-ph/9802350, hep-ph/9807297	LO	l+A DIS, p+A DY	no
2001	HKM	Hirai, Kumano, Miyama hep-ph/0103208	LO	DIS	yes
2004	HKN04	Hirai, Kumano, Nagai hep-ph/0404093	LO	DIS, DY	yes
2004	nDS	de Florian, Sassot hep-ph/0311227	NLO	DIS, DY	no
2007	EKPS	Eskola, Kolhinen, Paukkunen, Salgado hep-ph/0703104	LO	DIS, DY	yes
2007	HKN07	Hirai, Kumano, Nagai 0709.3038 hep-ph	NLO	DIS, DY	yes
2008	EPS08	Eskola, Paukkunen, Salgado 0802.0139 hep-ph	LO	DIS, DY, d+Au h,pi	no

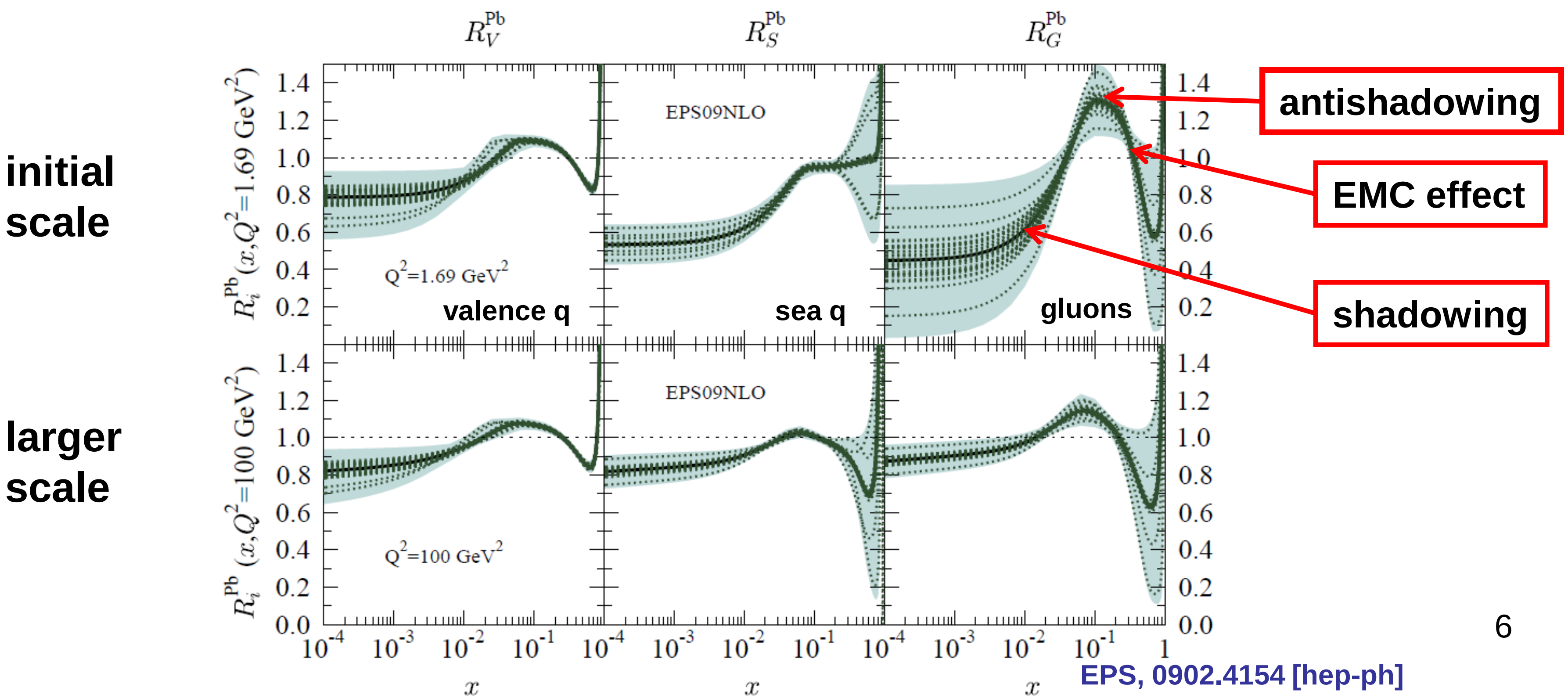
- - - - - - - - - - In this talk:

year	set	Authors	order	data	error analysis
2009	EPS09	Eskola, Paukkunen, Salgado, 0902.4154 hep-ph	NLO	DIS, DY, d+Au pi	yes→ error sets
2009	nCTEQ	Schienbein, Yu, Kovarik, et al. 0907.2357 hep-ph; also Stavreva et al, 1012.1178 hep-ph	NLO	DIS, DY	yes
2010	nCTEQ	Kovarik, Schienbein, Olness, et al, 1012.0286 hep-ph	NLO	l+A&nu+A DIS, DY	yes
2012	DSZS	de Florian, Sassot, Zurita, Stratmann 1112.6324 hep-ph	NLO	l+A&nu+A DIS, DY, d+Au pi, nFFs	yes→ error sets

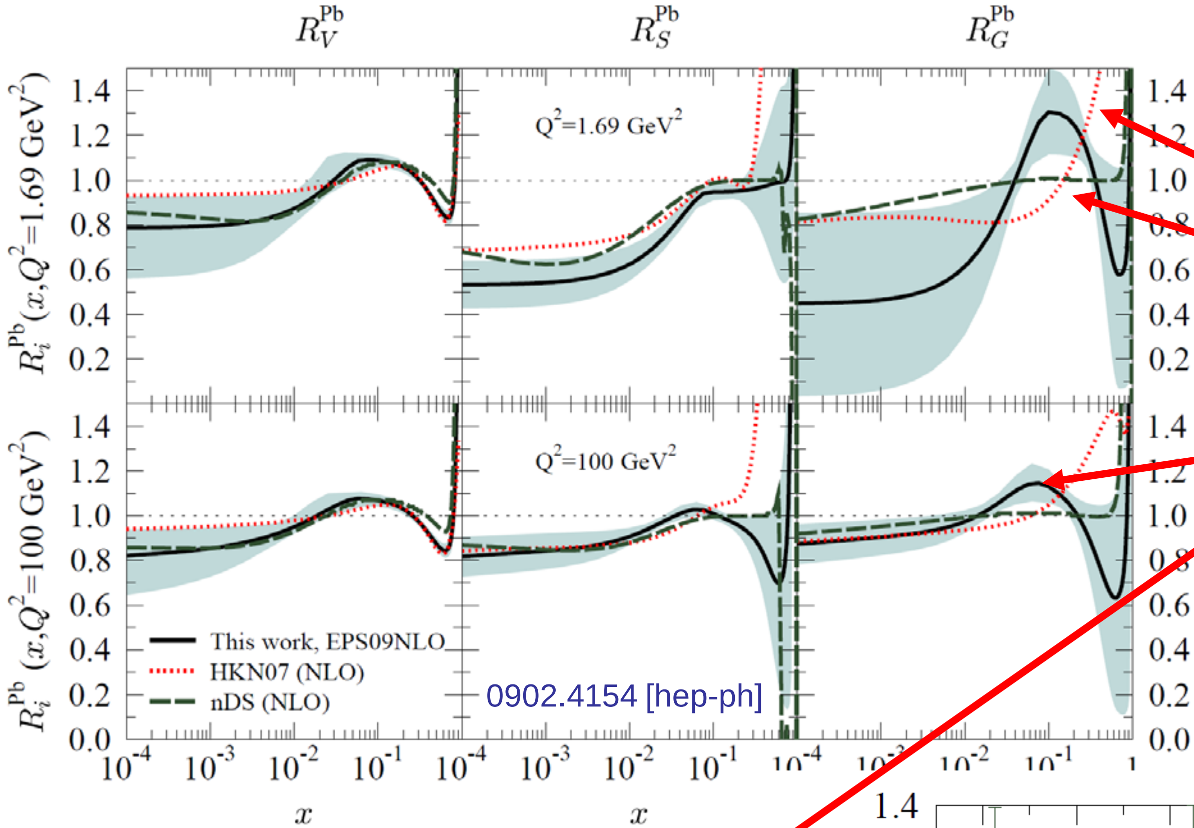
EPS09 nPDFs

$$f_i^A(x,Q^2) \equiv R_i^A(x,Q^2) f_i^{\mathrm{CTEQ6.1M}}(x,Q^2)$$

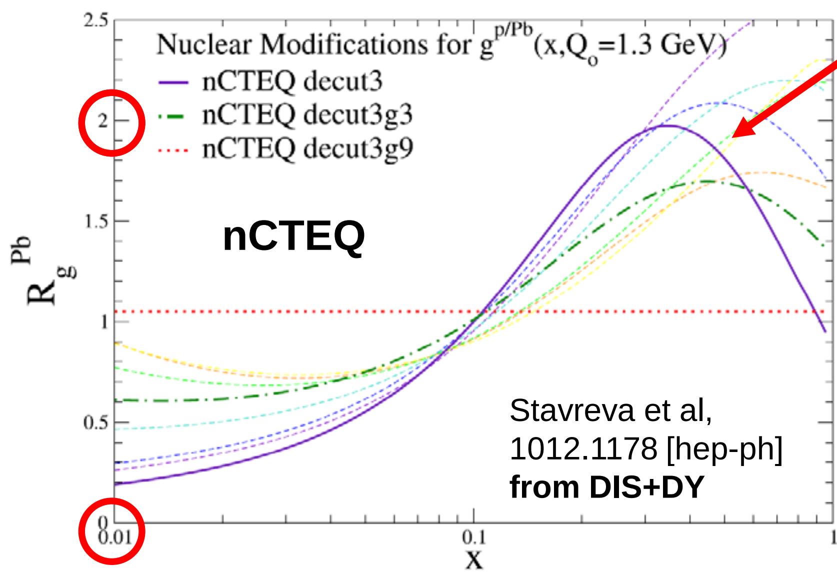
- defined vs. CTEQ6.1M Free p PDFs; parametrize $R_i^A(x,Q_0^2)$
- MSbar & zero-mass variable flavor-number sceme
- initial scale **Q_0=1.3 GeV**
- uncertainties in the free-p PDFs **not** considered
- **weights** for small data sets → check that **no significant tension** arises!
- 31 data sets from charged **l+A** [E139,NMC] **&** p+A **DY** [E772,E866] & 1 set **R_{dAu}**(pi0) [PHENIX] → 929 data points; chi2 = 731
- Hessian error analysis; "90 % confidence criterion" → deltaChi2 = 50 → best fit + <u>**30 error sets**</u>

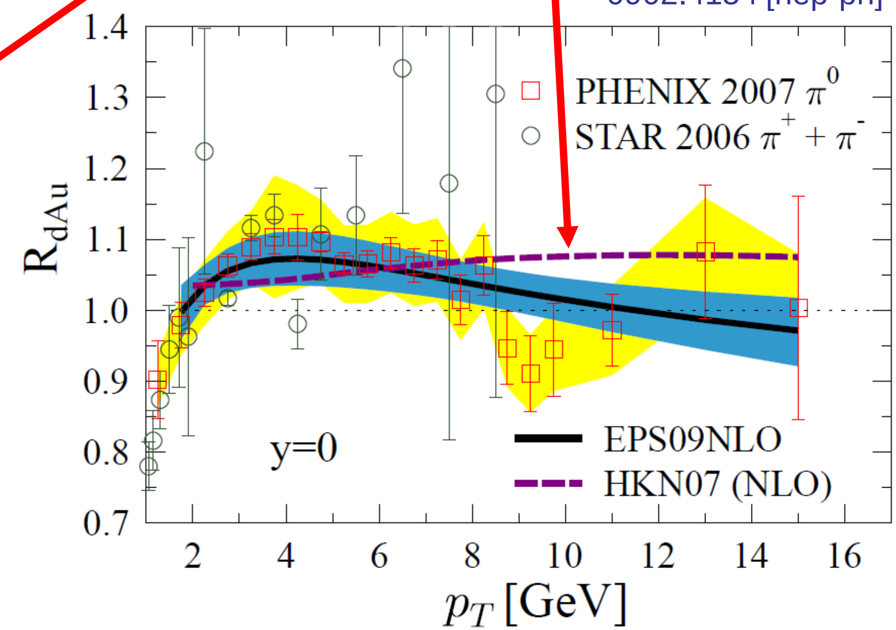


EPS, 0902.4154 [hep-ph]



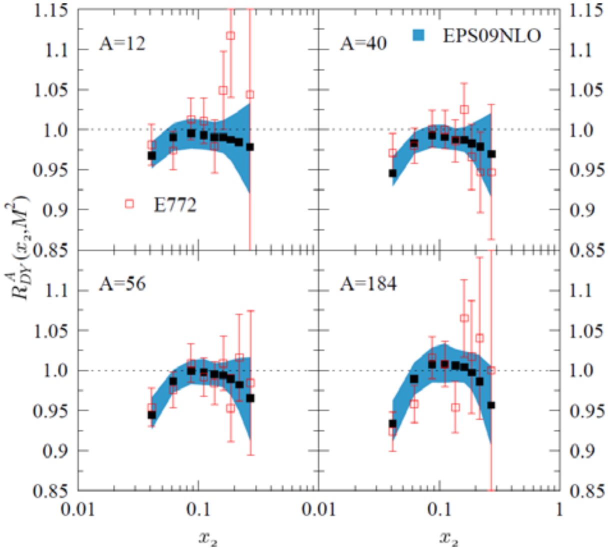
Difference here
→ R_{dAu} constrains gluons!





$$R^{A}_{DY}(x_{1,2}, M^2) \equiv \frac{\frac{1}{A} d\sigma^{pA}_{DY}/dM^2 dx_{1,2}}{\frac{1}{2} d\sigma^{pd}_{DY}/dM^2 dx_{1,2}}$$

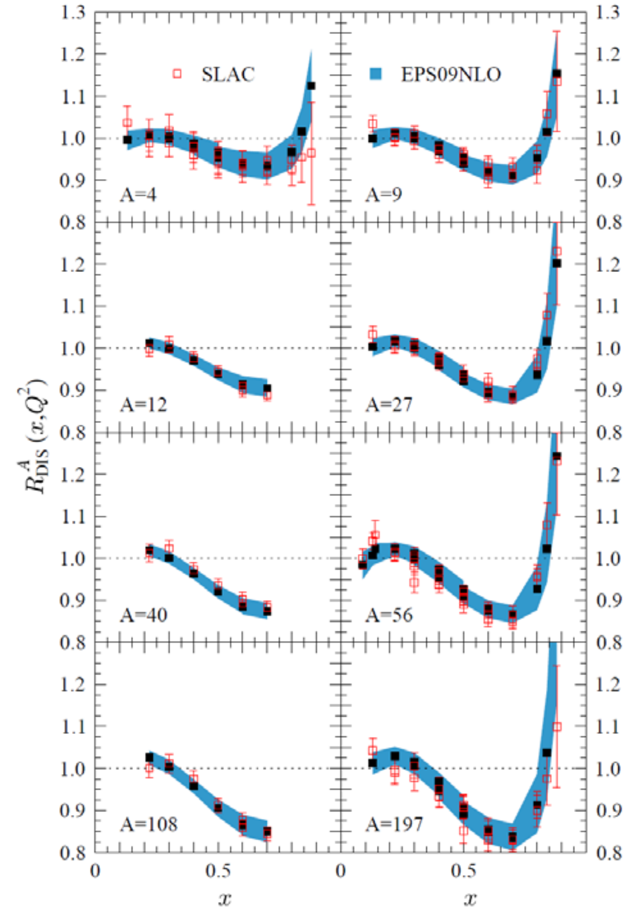
arXiv:0902.4154 [hep-ph]



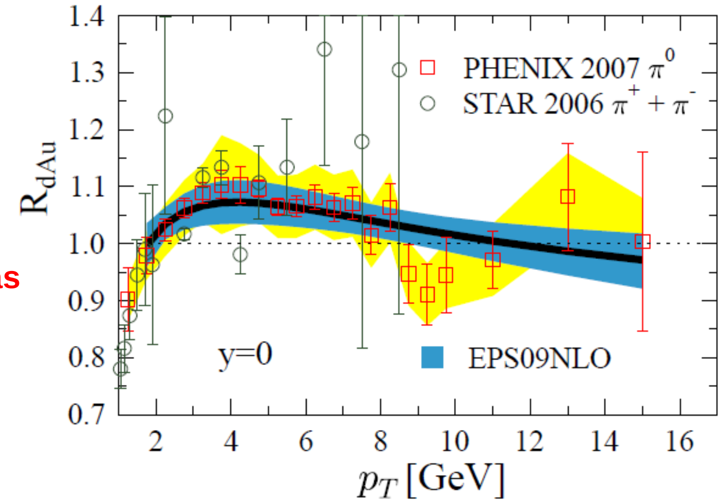
$$R^{A}_{DIS}(x, Q^2) \equiv \frac{\frac{1}{A} d\sigma^{lA}_{DIS}/dQ^2 dx}{\frac{1}{2} d\sigma^{ld}_{DIS}/dQ^2 dx}$$

EPS09 summary:

- Good & tensionless fits
- error propagation OK
- factorization OK, nPDFs seem universal at x≳0.005, Q≳1.3 GeV



Min. bias



$$R^{\pi}_{dAu} \equiv \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N^{dAu}_{\pi}/dp_T dy}{d^2 N^{pp}_{\pi}/dp_T dy} \overset{\text{min.bias}}{=} \frac{\frac{1}{2A} d^2\sigma^{dAu}_{\pi}/dp_T dy}{d^2\sigma^{pp}_{\pi}/dp_T dy}$$

We account for the R_{dAu} overall normalization uncertainty & use vacuum FFs

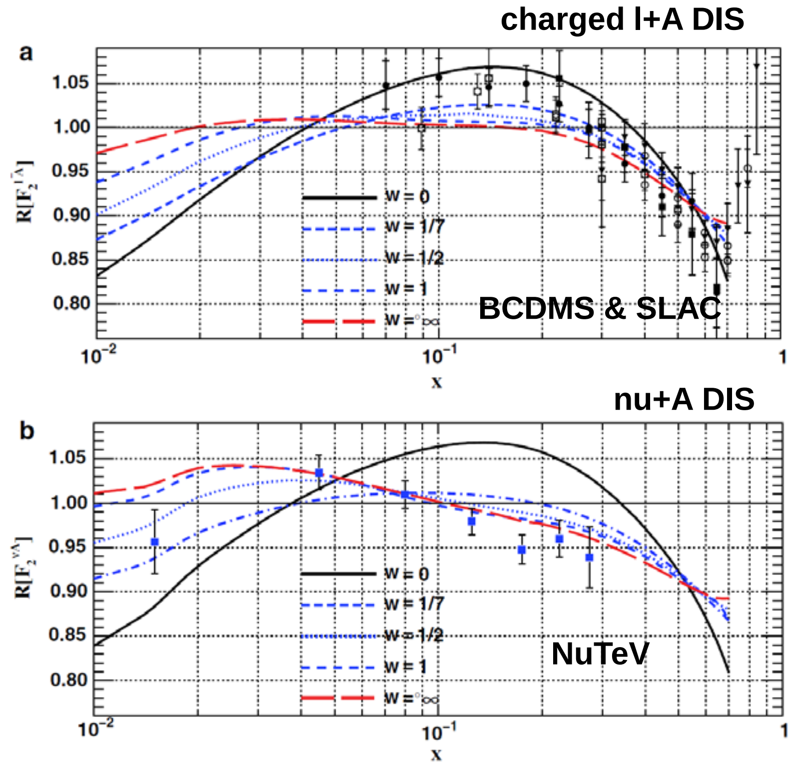
nCTEQ nPDFs

Kovarik et al. 1012.0286 hep-ph, PRL106(2011)

- setup based on CTEQ6M: parametrize $f_i^A(x,Q_0^2)$
- initial scale **Q_0=1.3 GeV**
- heavy-Q effects included: GM-VFNS
- 31 charged lepton+A **DIS** & p+A **DY** data sets → 708 data points
  \+ **8 nu+A DIS data sets** [CHORUS,NuTeV,CCFR] → 3134 (!) data points
- chi2/pt = 0.9 – 1.30 – 1.33 for nuDIS-weight 0,1,infinity

nCTEQ summary [Kovarik at DIS2012]

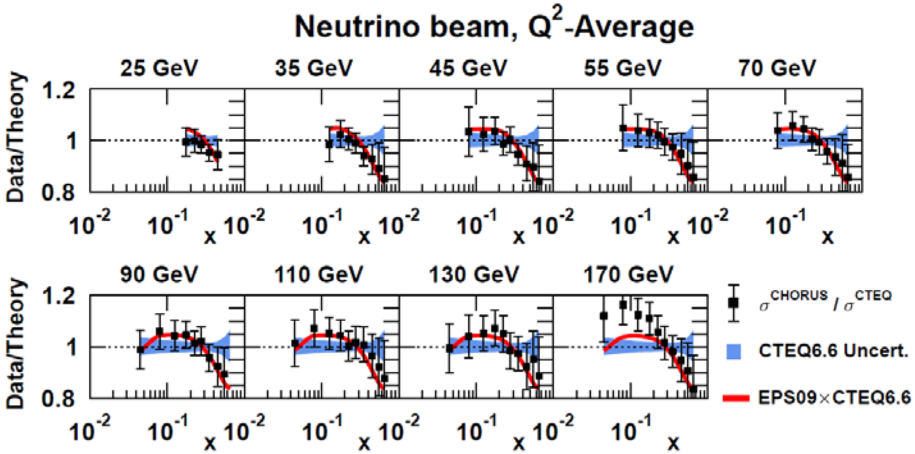
- nu DIS **incompatible** with charged l DIS
= a "precision" effect: the result changes when using uncorrelated errors
- **tension in NuTeV data**
  & high-chi2 fit to NuTeV alone
  → problem with NuTeV data ?
- future nu-A data [NOMAD] can help

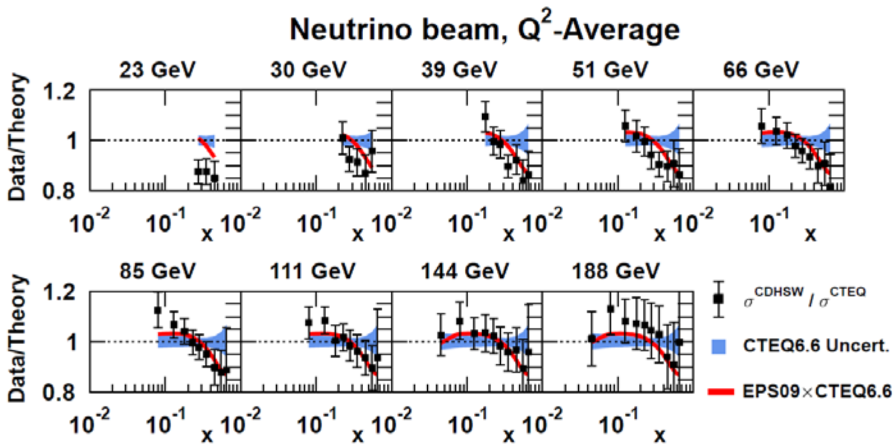


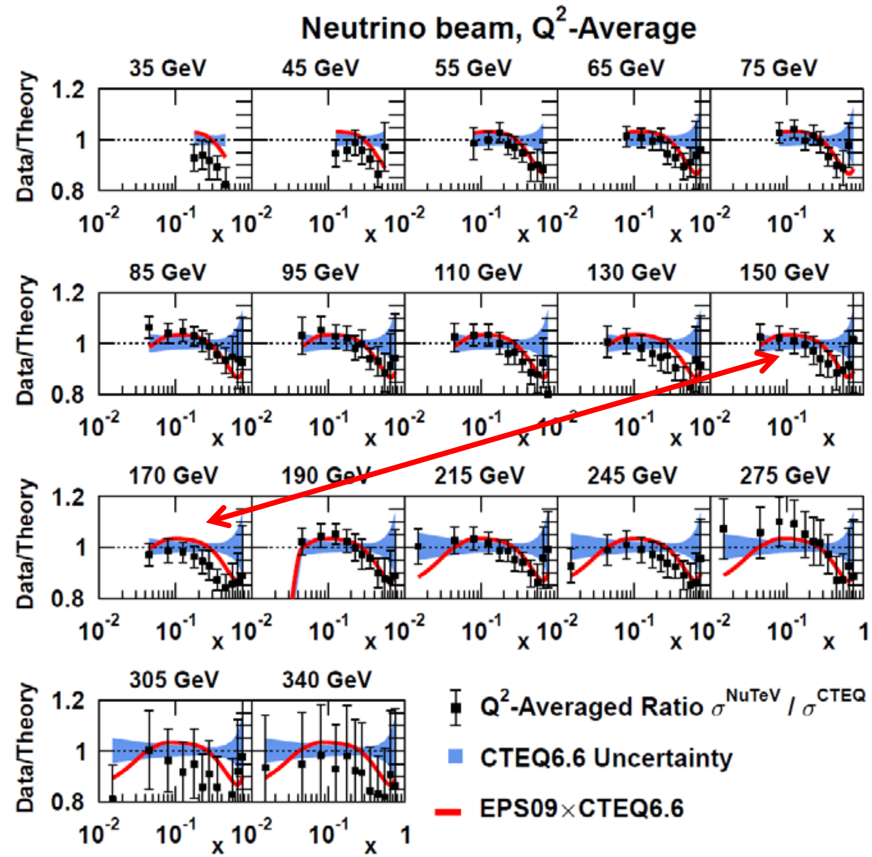
1012.0286 hep-ph

[Paukkunen & Salgado, JHEP 007:032,2010]: **EPS09 vs neutrino-beam DIS**

(these data not included in EPS09 fits)







Agreement good with CHORUS and CDHSW data, also with most of NuTeV data

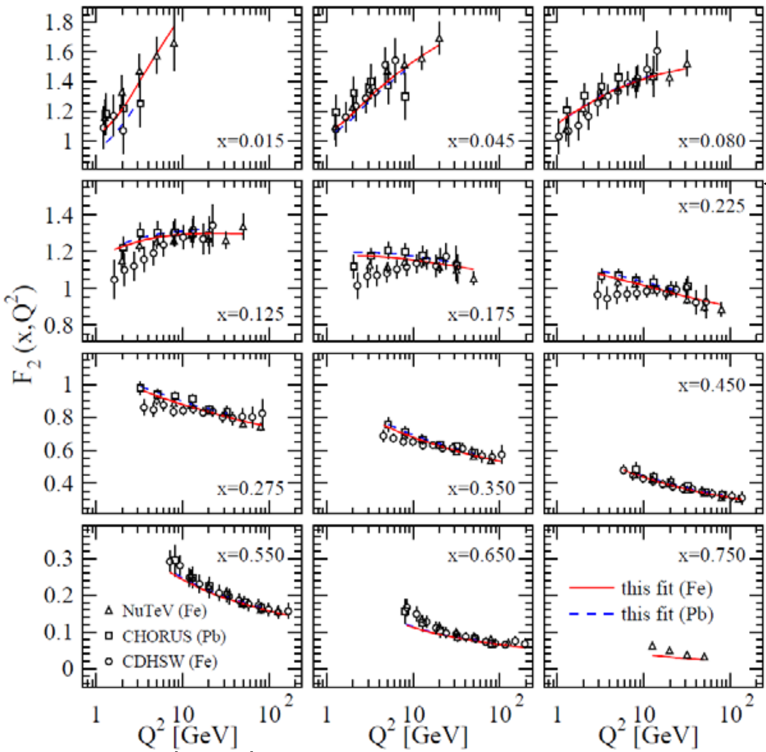
My conclusion: Factorization seems to work OK, nPDFs look universal in the (x,Q) region of global DGLAP fits

DSZS nPDFs

de Florian, Sassot, Zurita, Stratmann, 1112.6324 hep-ph, Phys.Rev.D85 (2012)

- defined vs. MSTW free p PDFs; parametrize $R_i^A(x,Q_0^2)$
- MSbar & heavy-Q with GM-VFNS
- initial scale **Q_0=1 GeV**
- data sets: 27 charged l+A **DIS** [NMC,E139,EMC] & 6 p+A **DY** [E772, E866] & 6 nu+A **DIS** [NuTeV, CDHSW,CHORUS] & 3 pion **R_{dAU}** [PHENIX, STAR]
  → 1579 data points; chi2 = 1545
- **no weights** for datasets
- for R_{dAu}, use **nuclear FFs!**
- Hessian error analysis → deltaChi2 = 30 → 2x25 **error sets**

The most important differences wrt EPS09 !



- clever idea for treating the absolute nu+A XSs:

$error^2 = stat^2 + syst^2 + errMSTW^2$

measurement	collaboration	ref.	# points	χ^2
$F_2^{\nu Fe}$	NuTeV	[18]	78	109.65
$F_3^{\nu Fe}$	NuTeV	[18]	75	79.78
$F_2^{\nu Fe}$	CDHSW	[19]	120	108.20
$F_3^{\nu Fe}$	CDHSW	[19]	133	90.57
$F_2^{\nu Pb}$	CHORUS	[20]	63	20.42
$F_3^{\nu Pb}$	CHORUS	[20]	63	79.58

DSZS conclusions:

- **good fits; also to most nu+A DIS data, no tension!**
  →Factorization OK, nPDFs seem universal in the fitted (x,Q) range
- **gluons differ significantly from those in EPS09!**

DSZS vs. EPS09

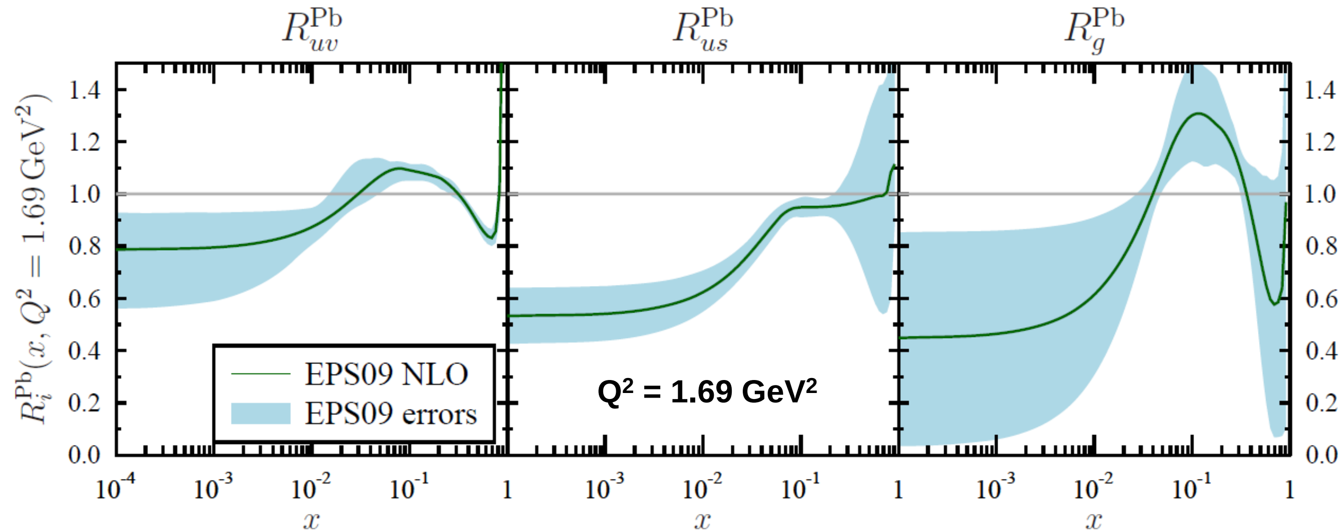
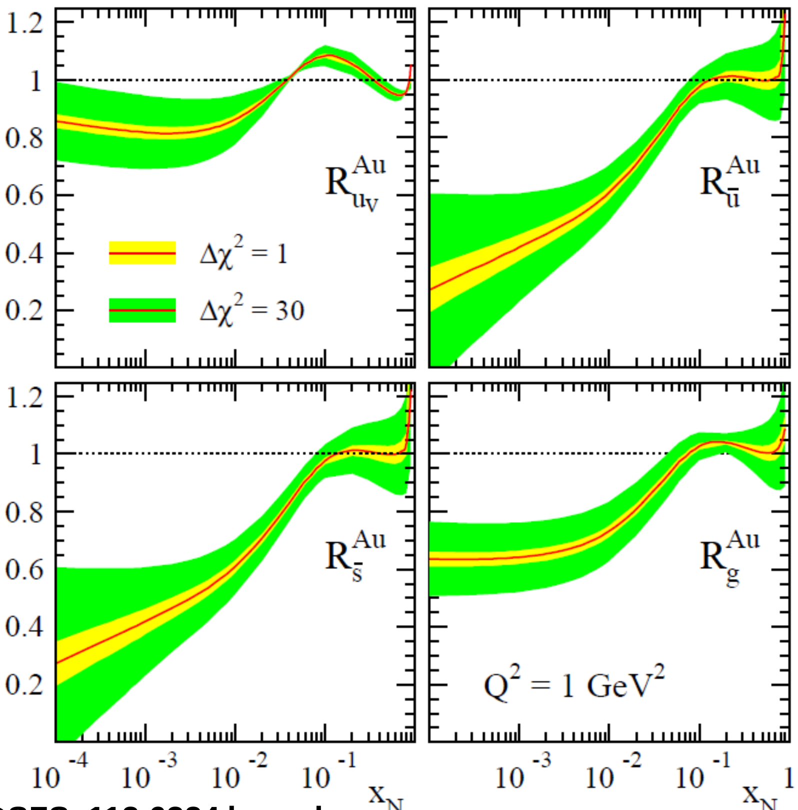


Fig. from 1205.5359 hep-ph

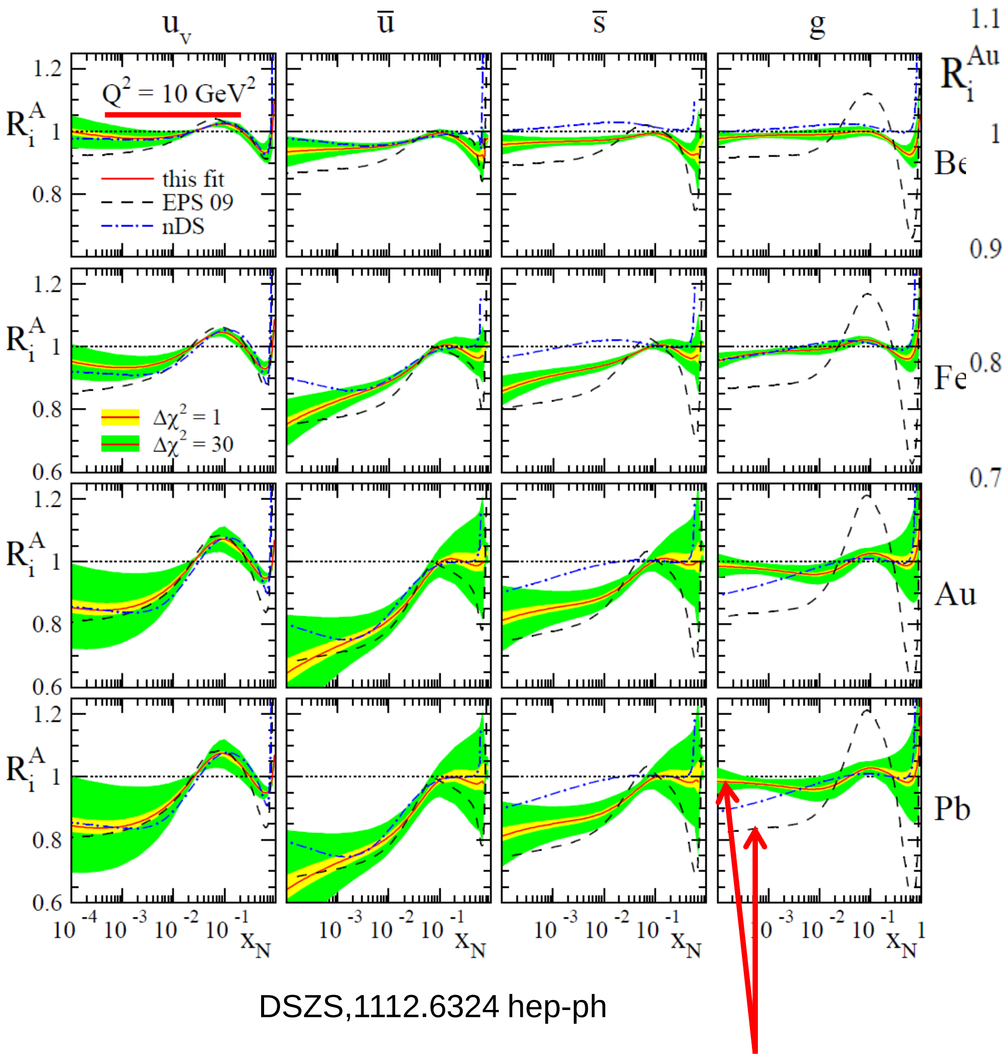


DSZS, 112.6324 hep-ph

The input modifications at Q_0

- **slightly <u>different</u> initial scales;**
  Q_0(EPS09) = 1.3 GeV
  Q_0(DSZS) = 1.0 GeV
- deltachi2 (DSZS) < deltachi2 (EPS09)
  → smaller error bands in DSZS?
- seem similar in gluon shadowings
  … but after scale evolution they differ →
- **<u>no</u> gluon antishadowing in DSZS!** → →

DSZS vs. EPS09: what's going on with gluons?

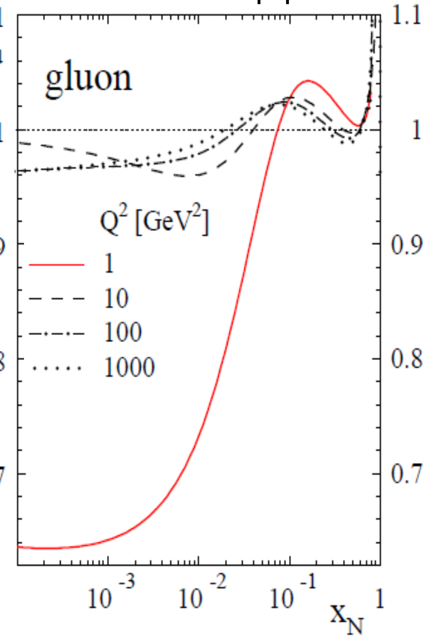


DSZS,1112.6324 hep-ph

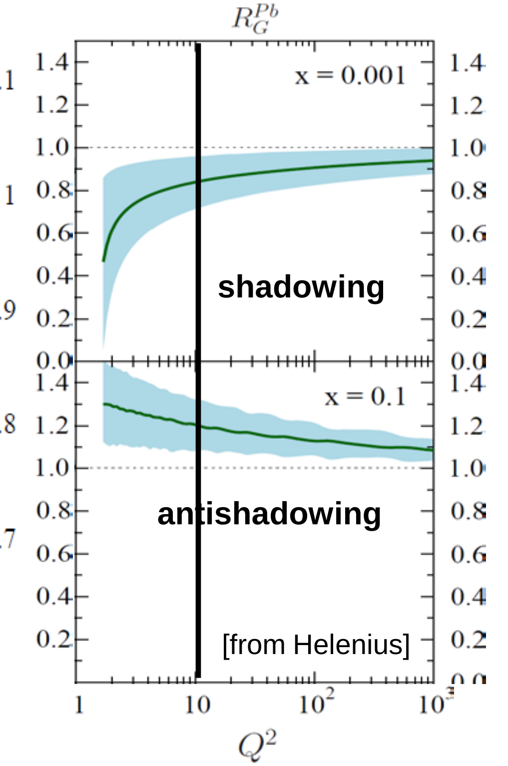
Difference here

DSZS

1112.6324 hep-ph



EPS09



gluon shadowing:

very rapid Q2-evolution

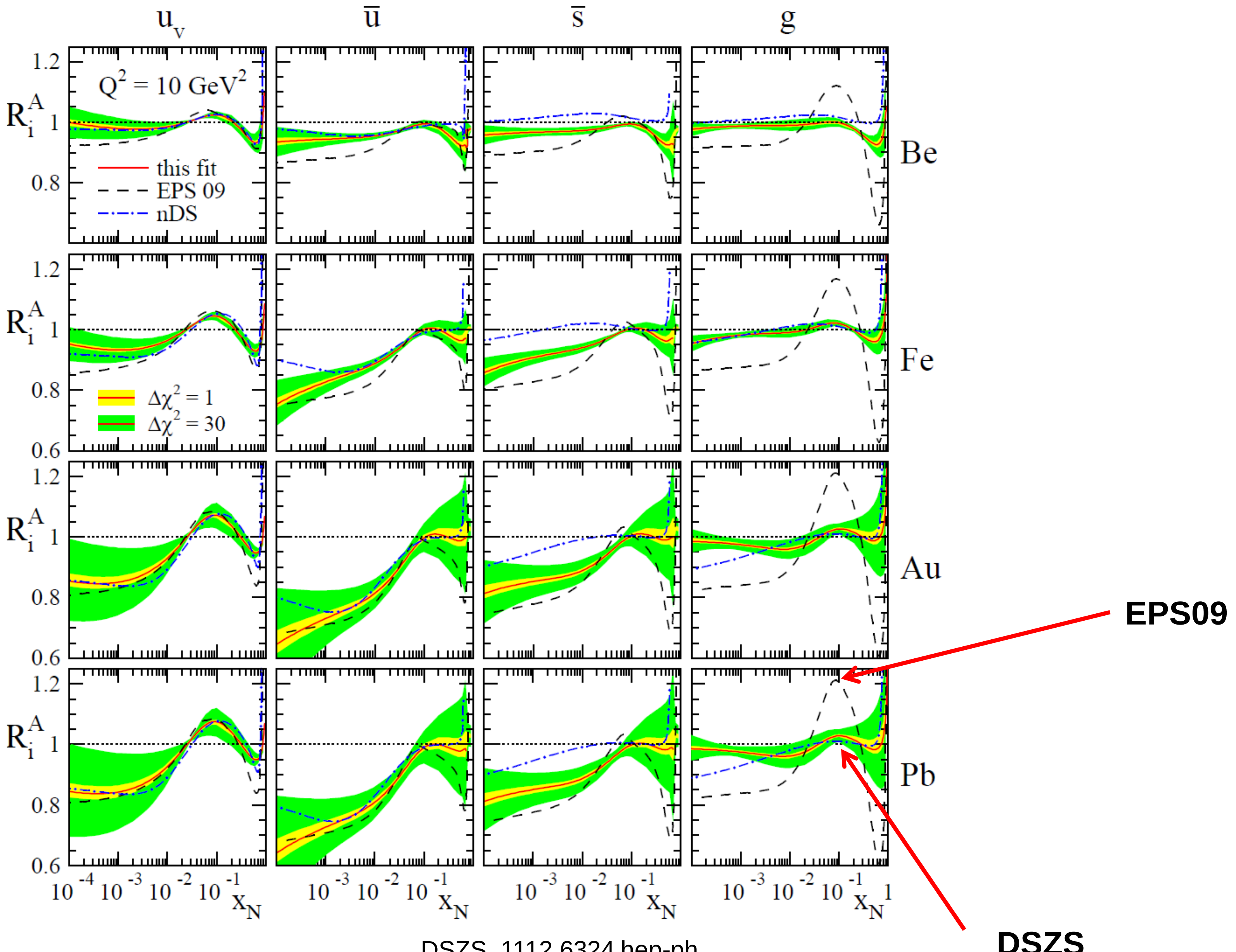
in the DSZS shadowing region;

EPS09 more stable

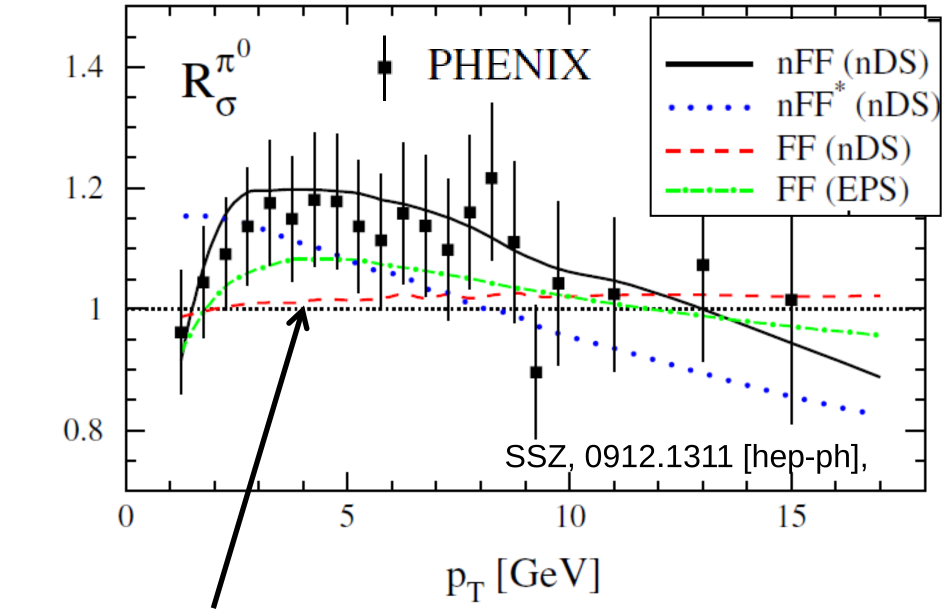
⟷ Rg shape & lower input scale in DSZS

also xg<0 at smallest x in MSTW&DSZS

DSZS vs. EPS09
what's going on with gluons: antishadowing or not?



DSZS, 1112.6324 hep-ph

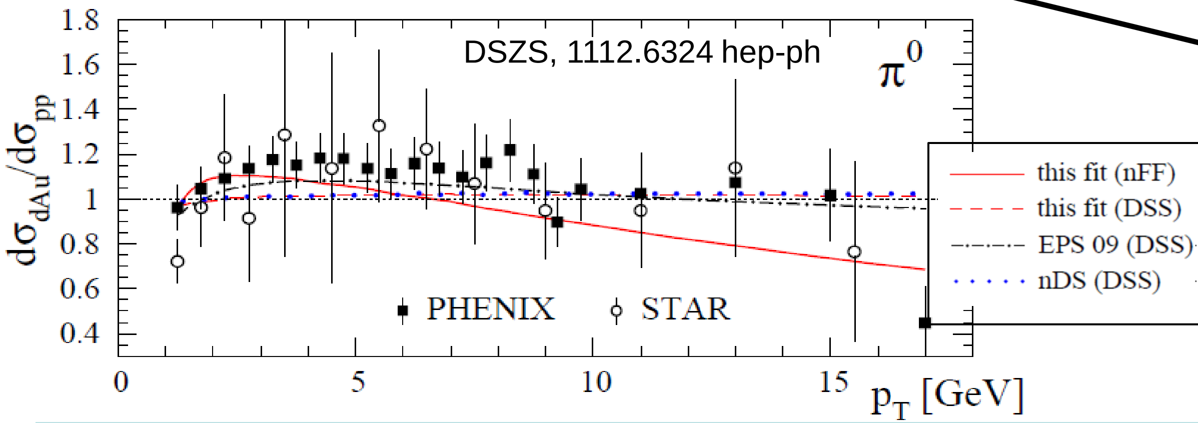


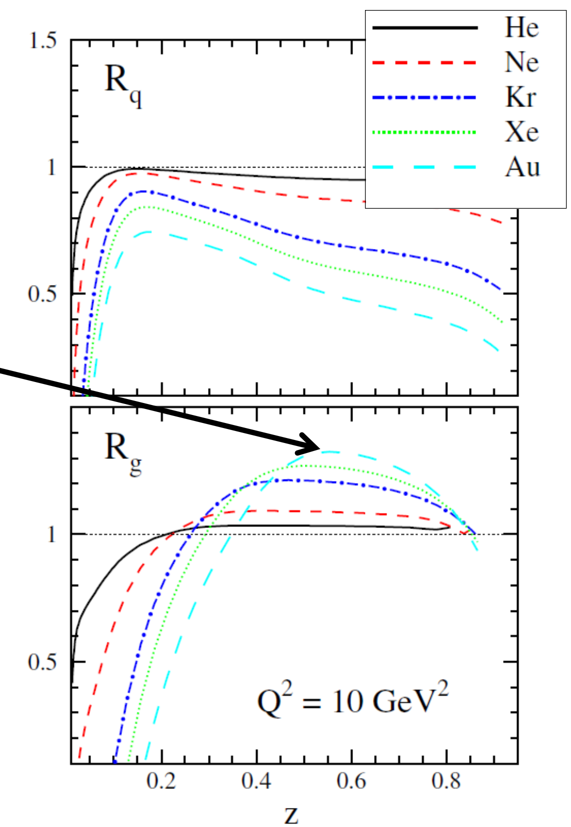
Nuclear FFs:

Sassot, Stratmann, Zurita
0912.1311 hep-ph, PRD81 (2010)

- HERMES SIDIS data
  → suppression for the nuclear quark D(z)
- PHENIX data on RdAu(pi0)
  STAR data on RdAu(pi)
  → **nuclear modifications for the gluon D(z)**

~No gluon antishadowing in the old nDS nPDFs used here
→The ~**entire** enhancement in R_{dAu} is translated
into an **enhancement of nuclear $D_g(z)$**

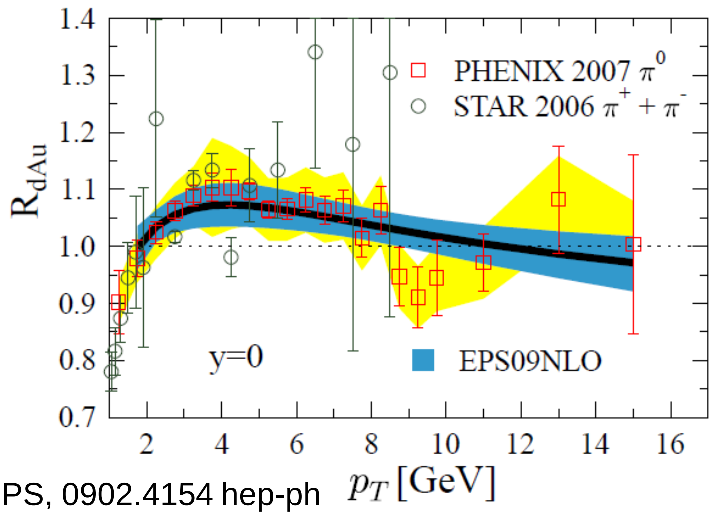




SSZ, 0912.1311 [hep-ph]

Same data are used in DSZS global nPDF fit
→**by construction, with nFF (or w. FF w/o data weights) no antishadowing for DSZS gluons**

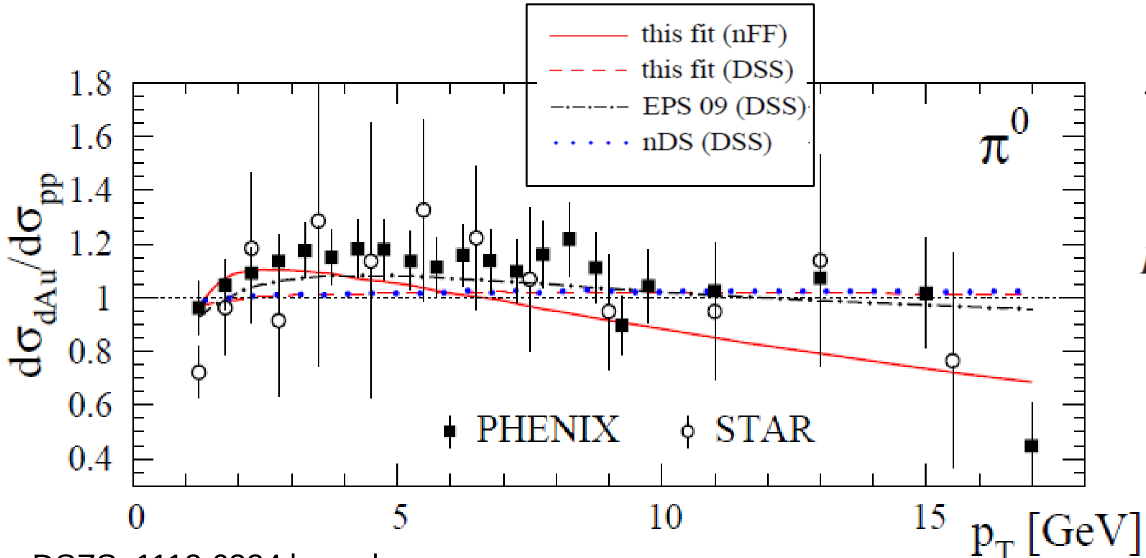
Observation: DSZS have fitted to different min. bias pion modifications than EPS09



EPS, 0902.4154 hep-ph

EPS09:

- **Minimum bias ratio R_{dAu}(pi0) as quoted by PHENIX** [PRL98(2007)172302]
  — a good fit with data x 1.04
- Vacuum FFS used here
  → the enhancement & shape in R_{dAu} maps into gluon antishadowing & EMC effect



DSZS, 1112.6324 hep-ph

DSZS form the following ratio from the PHENIX [PRL98(2007)172302] and STAR **min bias data for XSs**:

$$R_\sigma^H(A, p_T) \equiv \frac{1}{2A} \frac{Ed^3\sigma^H/dp^3|_{dA}}{Ed^3\sigma^H/dp^3|_{pp}}$$

→ **larger enhancement than in R_{dAu}**

My conclusions from these global DGLAP nPDF fits

- In the (x,Q) region probed by the fits,
  factorization & universal nPDFs seem OK

- the NLO analyses with error sets have brought the nPDF global fits
  to the ~same (NLO) sophistication level as the free-p PDF analyses

- Still large uncertainties in the gluon sector
  → Role of nuclear FFs in understanding R_{dAu} should be clarified
  → would need a **simultaneous global fit of nPDFs and nFFs**

- Still only partially included the free-p PDF uncertainties in the nPDF analysis
  → Ultimately, would need a **combined global analysis of PDFs and nPDFs**

- Further hard-process data from RHIC d+Au and LHC p+Pb
  will help in constraining the nPDFs
  → direct photons, heavyQ+photon, pions, Z/W asymmetries,…

- small-x, hi-Q DIS data from future e+A colliders(?)
  → resolve the gluon problem, especially at small x

II. Impact-parameter dependence of globally analysed nPDFs?

Helenius, Eskola, Honkanen, Salgado, 1205.5359 [hep-ph] – **see Helenius today, in Parallel session VC**

$$f_i^A\,(x,Q,\text{center}) \neq f_i^A\,(x,Q,\text{edge})$$

- need these for computing **centrality-dependent hard-process observables**, e.g.

$$R_{\mathrm{d}A}^{\pi^0}(p_T,y;b_1,b_2) \equiv \frac{\left\langle \dfrac{\mathrm{d}^2 N_{\mathrm{d}A}^{\pi^0}}{\mathrm{d}p_T\mathrm{d}y} \right\rangle_{b_1,b_2}}{\langle N_{bin}^{\mathrm{d}A}\rangle_{b_1,b_2} \dfrac{1}{\sigma_{inel}^{NN}} \dfrac{\mathrm{d}^2\sigma_{\mathrm{pp}}^{\pi^0}}{\mathrm{d}p_T\mathrm{d}y}} = \frac{\int_{b_1}^{b_2} \mathrm{d}^2\mathbf{b}\, \dfrac{\mathrm{d}^2 N_{\mathrm{d}A}^{\pi^0}(\mathbf{b})}{\mathrm{d}p_T\mathrm{d}y}}{\int_{b_1}^{b_2} \mathrm{d}^2\mathbf{b}\, T_{\mathrm{d}A}(\mathbf{b}) \dfrac{\mathrm{d}^2\sigma_{\mathrm{pp}}^{\pi^0}}{\mathrm{d}p_T\mathrm{d}y}}$$

$$\mathrm{d}N^{AB\to k+X}(\mathbf{b}) = \sum_{i,j,X'} \frac{1}{AB} \sum_{N_A,N_B} \int \mathrm{d}^2\mathbf{s_1}\, T_A(\mathbf{s_1})\, r_i^A(x_1,Q^2,\mathbf{s_1})\, f_i^{N_A}(x_1,Q^2) \otimes \int \mathrm{d}^2\mathbf{s_2}\, T_B(\mathbf{s_2})\, r_j^B(x_2,Q^2,\mathbf{s_2})\, f_j^{N_B}(x_2,Q^2) \otimes \mathrm{d}\hat{\sigma}^{ij\to k+X'}\, \delta(\mathbf{s_2}-\mathbf{s_1}-\mathbf{b}).$$

Spatially dependent nuclear PDF modifications

• assume the following form, motivated by [FGS] modeling of shadowing

$$r_i^A(x,Q^2,\mathbf{s}) = 1 + \sum_{j=1}^{n} c_j^i(x,Q^2)\,[T_A(\mathbf{s})]^j$$

$$R_i^A(x,Q^2) \equiv \frac{1}{A}\int d^2\mathbf{s}\, T_A(\mathbf{s})\, r_i^A(x,Q^2,\mathbf{s})$$

Standard nuclear overlap function

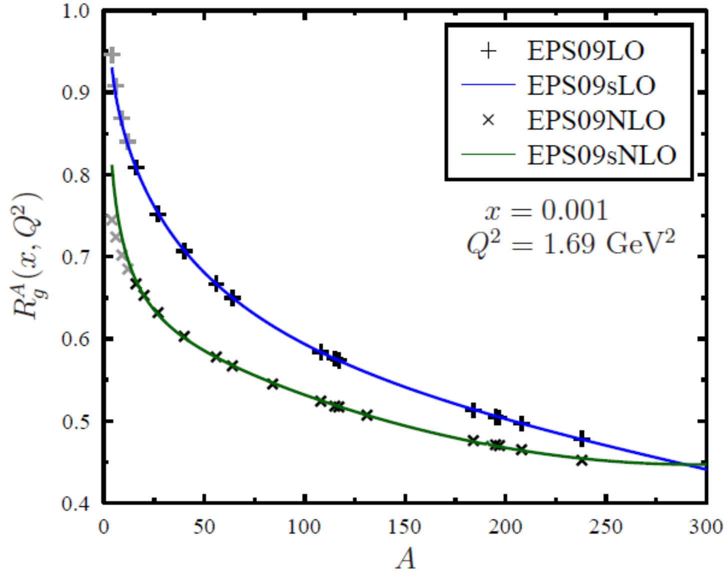
A-independent fit coefficients

• to **reproduce the A-systematics** in the EPS09 & EKS98 nPDFs, at all x & Q, need **n=4** (e.g. n=1 is not sufficient)

• **Fit c^i_j** for each x, Q, parton flavor i, using the spatially independent **EKS98** LO set & **EPS09** NLO & LO **best fits+30 error sets**

$$\chi_i^2(x,Q^2) \equiv \sum_A \left[\frac{R_i^A(x,Q^2) - \frac{1}{A}\int d^2\mathbf{s}\, T_A(\mathbf{s})\, r_i^A(x,Q^2,\mathbf{s})}{W_i^A(x,Q^2)}\right]^2$$

→**outcome: impact-parameter dependent nPDFs** EKS98s & EPS09s



HEHS, 1205.5359 [hep-ph]

[See Helenius's talk]

A-systematics reproduced OK, at all x&Q

By construction, nuclear modifications vanish at the edge of the nucleus

f_i^A (x,Q,center) ≠ f_i^A (x,Q,edge)

In the center of the nucleus the modifications are slightly stronger than the average

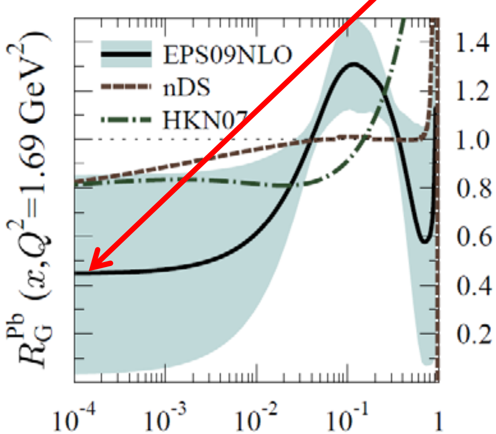
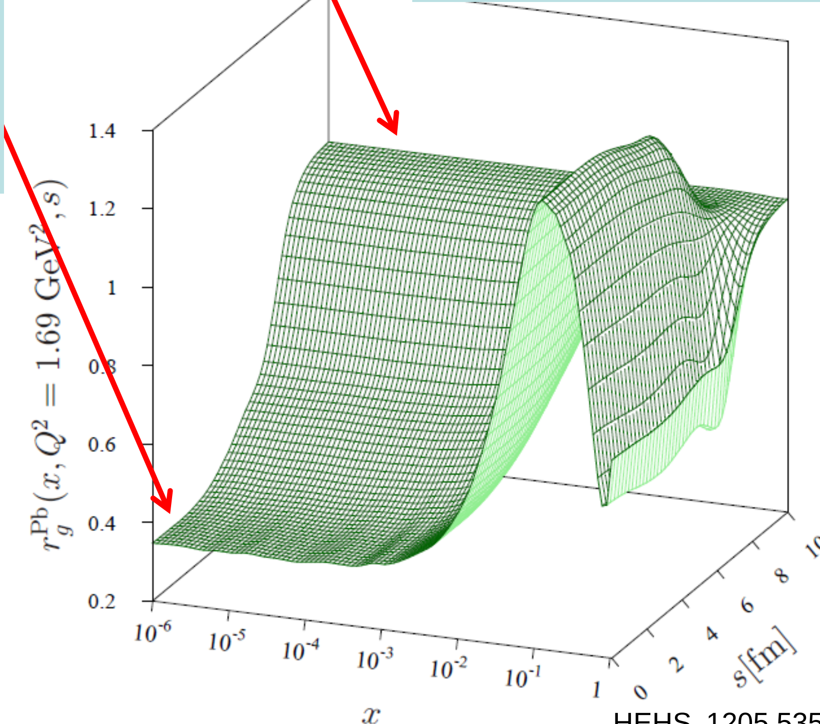
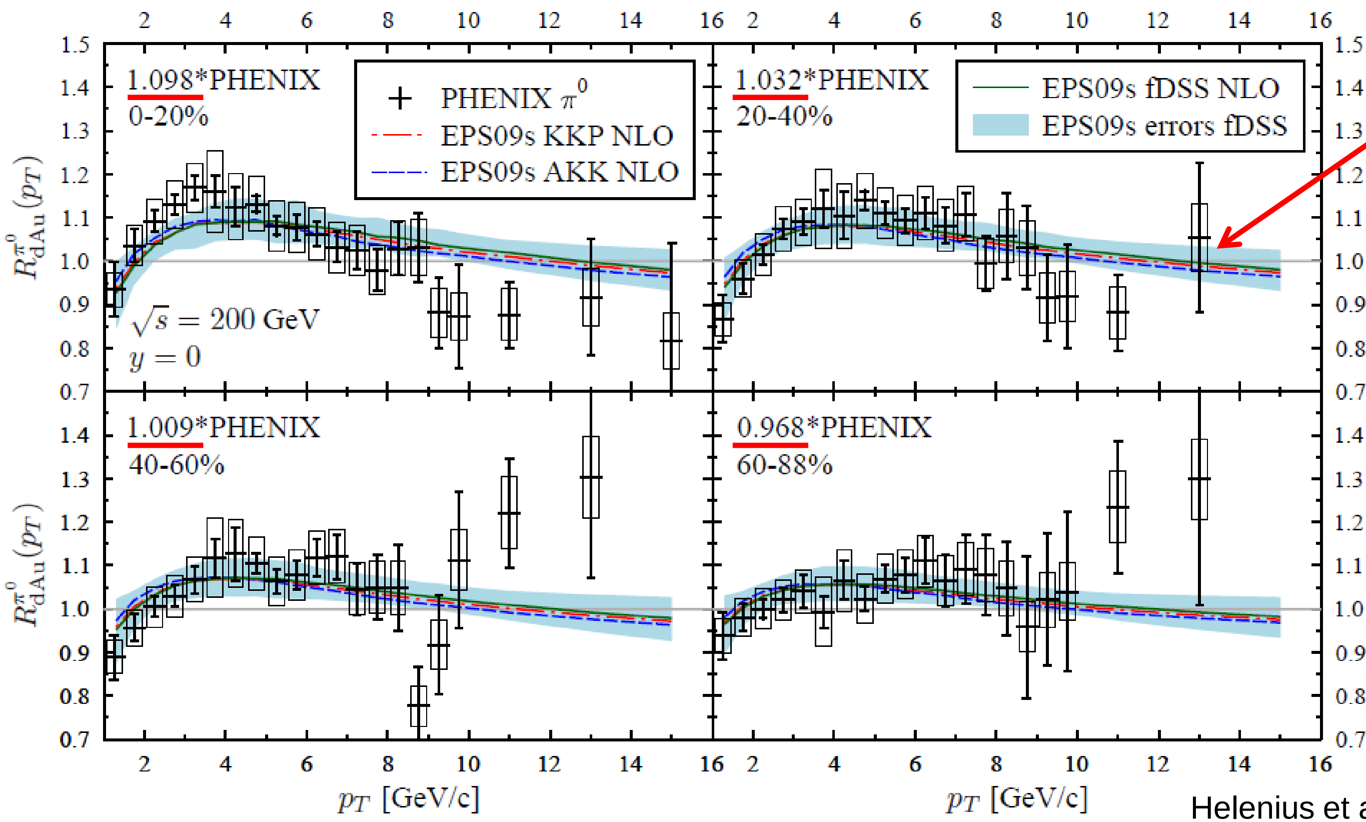


fig. from Arleo et al, 1103.1471 [hep-ph]



HEHS, 1205.5359 [hep-ph]

Centrality dependence of R_{dAu}(pi0) at RHIC – EPS09sNLO vs. PHENIX data



Also these error bands are from EPS09s !

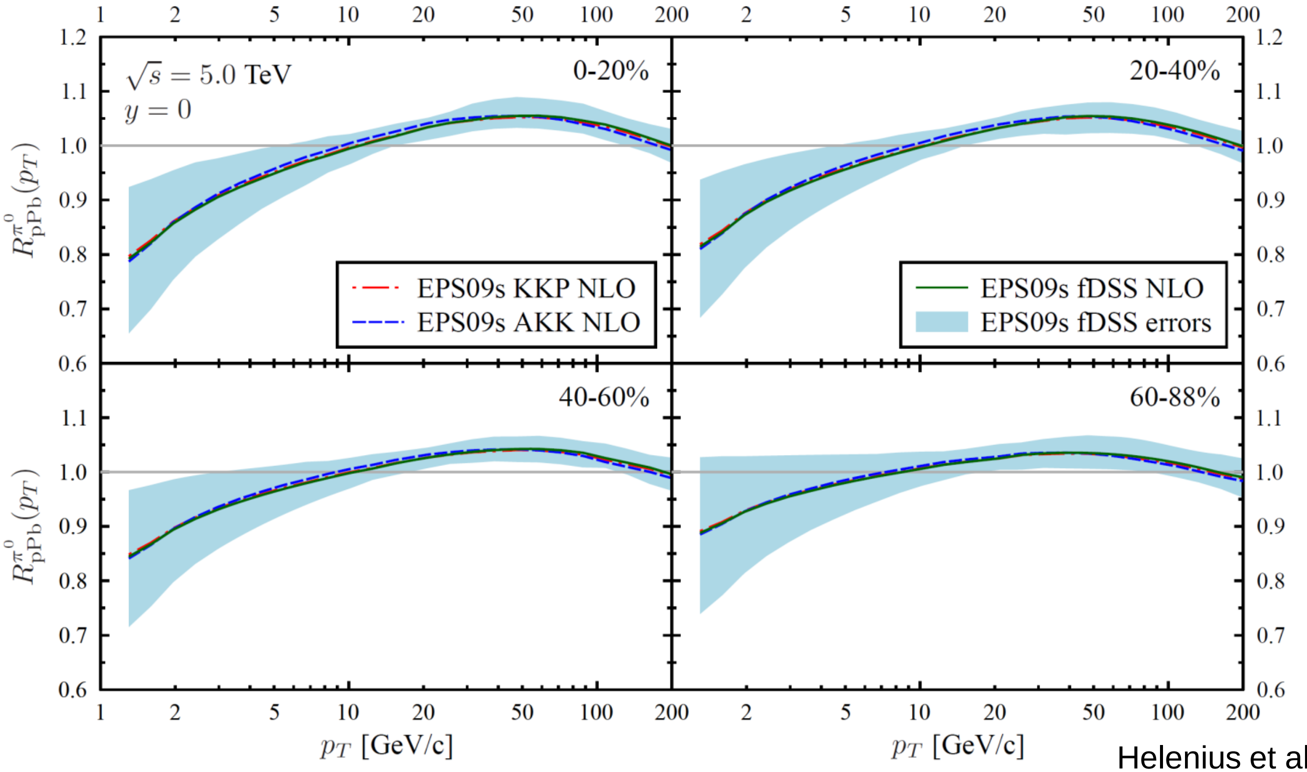
Helenius et al, 1205.5359 [hep-ph]

Magnitude & small-pT slope consistent with the data, given

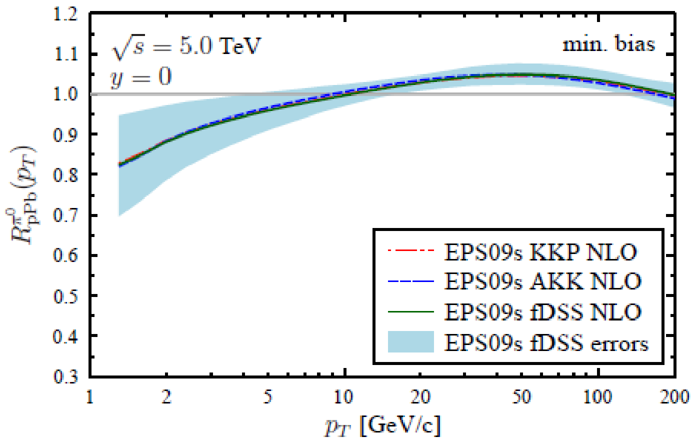
- the overall normalization uncertainties in the data [9.7% p+p baseline + 6.6-9.6% Glauberization]
- EPS09s error bands
- differences btw. theor. (optical Glauber) and experim. centrality-class definitions

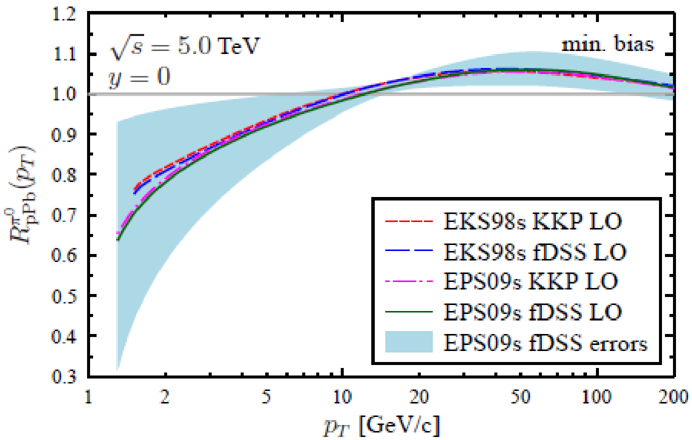
Note the multiplicative factors which we have applied to the data and which are well within the experim. overall norm. errors

Centrality dependence of R_{pPb}(pi0) at LHC — EPS09sNLO predictions



Helenius et al, 1205.5359 [hep-ph]





Min. bias ratios

EPS09s and EKS98s summary

- impact parameter dependence of globally analysed nPDFs has now been determined (in a specific framework) for the first time consistently with their A-systematics

- impact-parameter dependent nPDFs **EPS09s** (NLO&LO + error sets) and **EKS98s** (LO) available for public use, codes will be soon downloadable at https://www.jyu.fi/fysiikka/en/research/highenergy/urhic/

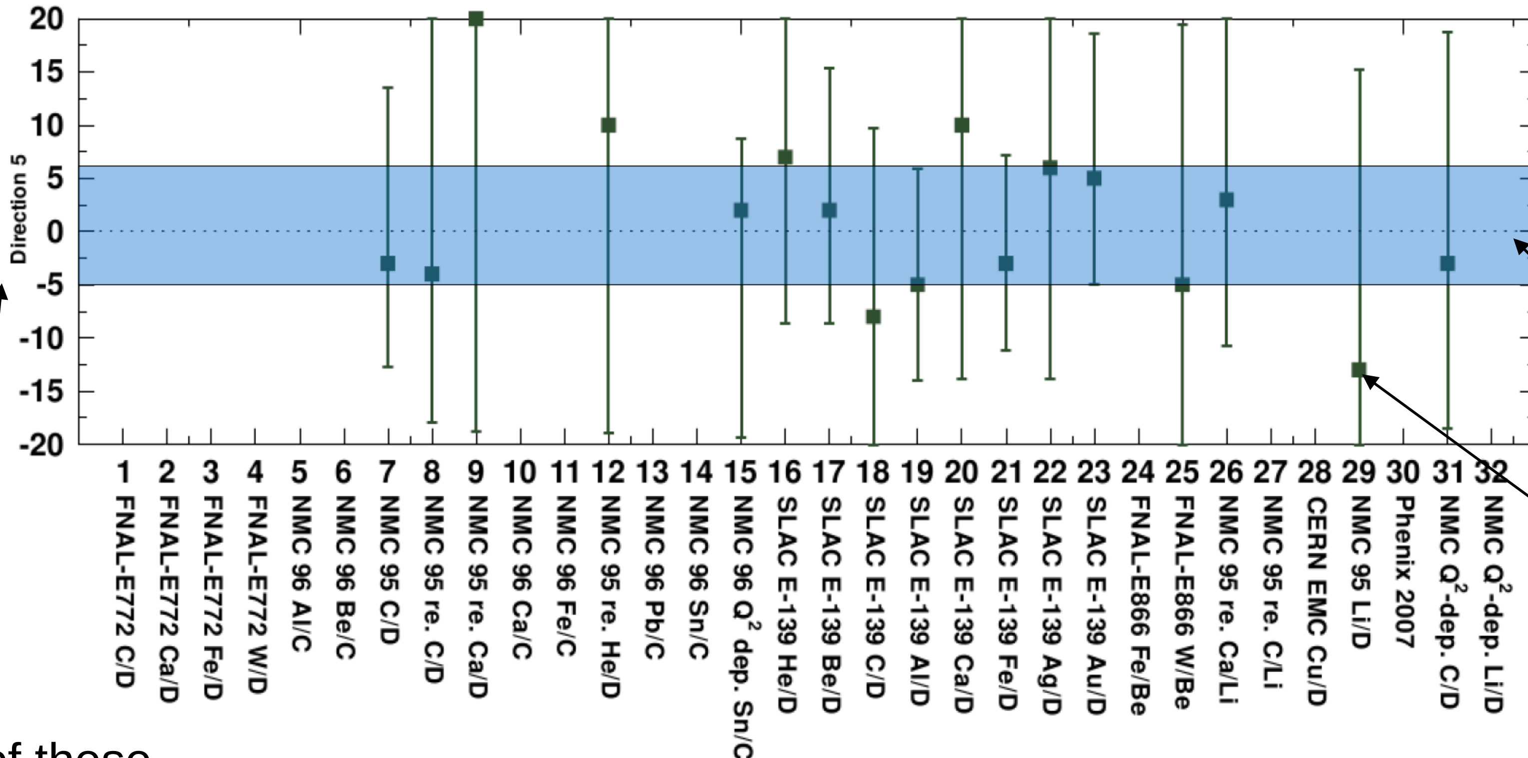
- instructions of how to implement the spatial nPDFs into existing codes are given in 1205.5359 [hep-ph] → **see Helenius's talk!**

- **Computation of nuclear hard-process cross-sections in different centrality classes is now possible consistently with EPS09 and EKS98**

- **Future task:** implement this framework directly into the global fits

Extra slide

- We take $\Delta\chi^2$ = 50 based on requiring the χ^2-contribution of each data set to stay within its 90% confidence range.



total chi2 min

Min chi2 for data set 29

15 of these

- $$\Delta\chi^2 \equiv \sum_i \frac{\Delta\chi^2(z_i^+) + \Delta\chi^2(z_i^-)}{2N}$$ **= 50**

[from HP]