Nuclear Parton Distribution Functions

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Structure of Hadrons and Nuclei at an Electron Ion Collider
ECT* Trento July 2008

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I will talk about nPDFs in a DGLAP (linear) approach
Several other talks at this meeting address other aspects
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With special attention to our new analysis EPS08

[Eskola, Paukkunen, Salgado arXiv:0802.0139]
What are HIC about?

Fundamental Interactions
Searches – Higgs, SUSY, extra-dimensions...

Increase energy density
simple systems

Collective properties
of the fundamental interactions

Increase extended energy density
“less simple” systems
High-energy HI experiments

⇒ SPS at CERN
  ↘ pA, SU and PbPb at $\sqrt{s} \simeq 20$ AGeV/c
  ↘ Most of experiments finished. New experiment NA61.

⇒ RHIC at BNL
  ↘ Dedicated HI collider
  ↘ pp, dAu, CuCu and AuAu at $\sqrt{s} = 20 \ldots 200$ AGeV

⇒ LHC at CERN
  ↘ Will collide PbPb $\sqrt{s} \simeq 5500$ AGeV and pA $\sqrt{s} \simeq 8800$ AGeV
  ↘ ALICE (dedicated experiment)
  ↘ CMS and ATLAS strong HI program

With the LHC the energy frontier of HIC equals for the first time that of the more traditional high-energy physics (dilute systems)
Access to hard probes in HIC

- SPS $\sqrt{s} = 20$ GeV ($Q \sim 1$ GeV) $\rightarrow$ marginal access to HP
- RHIC $\sqrt{s} = 200$ GeV ($Q \sim 10$ GeV) $\rightarrow$ access to HP
- LHC $\sqrt{s} = 5500$ GeV ($Q \gtrsim 100$ GeV) $\rightarrow$ HP and QCD evolution

$$\sigma^{pp \rightarrow h} = f_p(x_1, Q^2) \otimes f_p(x_2, Q^2) \otimes \sigma(x_1, x_2, Q^2) \otimes D(z, Q^2) + \left( \frac{1}{Q^2} \right)^n$$

- The extension of the medium modifies the long-distance terms
- New evolution equations for $f_A(x, Q^2); D(z, Q^2)$?
- Modification of non-perturbative input?
- Kinematical access to evolution: large-$Q^2$, small-$x$ $\rightarrow$ LHC
Nuclear effects in DIS

\[ R_{F_2}^A(x, Q^2) = \frac{F_2^A(x, Q^2)}{AF_2^p(x, Q^2)} \]

Nuclear parton distribution functions \( f_{i/A}(x, Q^2) \neq Af_{i/p}(x, Q^2) \)
Nuclear effects in DIS

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antishadowing

EMC effect

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Nuclear effects in DIS

\[ R_{F_2}^A (x, Q^2) = \frac{F_2^A(x, Q^2)}{AF_2^p(x, Q^2)} \]

- Shadowing
- Antishadowing
- Fermi motion
- EMC effect

Nuclear parton distribution functions

\[ f_{i/A}(x, Q^2) \neq Af_{i/p}(x, Q^2) \]
Global analyses of nPDFs

Main goals

- Check the factorization of nPDFs for hard processes
- Fix the benchmark for HI hot matter studies
- Fix the benchmark for other processes (saturation...)

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Benchmarking role of nPDFs

Examples: J/ψ or high-pT particle suppression observed in AA

Proposed as signals of the produced hot medium

What are the effects due to cold nuclear matter? in particular PDFs

Essential for a correct characterization of the medium properties

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Kinematical reach

- Present DIS+DY data constrains only a small region of the phase space
  - Constrains for RHIC at central rapidities
  - LHC kinematics in a completely unexplored region of phase space
  - Use pA/dAu data to improve the situation
Present DIS+DY data constrains only a small region of the phase space.

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RHIC at forward rapidities: kinematical bound plotted - actual relevant values of $x$ are larger.
Kinematical reach

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RHIC at forward rapidities: kinematical bound plotted - actual relevant values of x are larger
Comparison to proton global fits

- Experimental data
  - Experimental data for nuclei much less abundant
  - New variable (A) complicates the analysis
  - Including hadronic data (pp, pA...) slows the computations

- Role of different sets of data in the analysis
  - Some physically important observables (e.g. to constrain gluons) could have limited effect in the fit for being small number of data
  - Weights are used

- Determination of the uncertainties
  - Hessian method - error matrix computed in the minimization
  - Gives biased effects (depending on the parametrization)

- Usual approach in the nuclear case: parallel as much as possible the analyses for free protons (well developed technology exists)
How?

- Cross sections computed in collinear factorization
- Define
  \[ R_i^A(x, Q^2) = \frac{f_i^A(x, Q^2)}{f_i^p(x, Q^2)} \]
- Using a known set for free protons (CTEQ, MRST....)
- and DGLAP evolution of the nuclear and free proton PDFs
- Find the minimum of \( \chi^2 \)

\[ \{ R_i^A(x, \{ a_i \}) \} \quad \text{at} \quad Q_0^2 \]

DGLAP

\[ \{ R_i^A(x, Q^2) \} \quad \text{for} \quad \{ a_i \} \]

Compute observables at \((x, Q^2)\)

Compute \( \chi^2 [\{ a_i \}] \)

Minimum?

vary \( \{ a_i \} \)

(fulfilling sum rules)

NO

YES

Final answer

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Global analyses of nPDFs

- **EKS98** [Eskola, Kolhinen, Ruuskanen, Salgado, 1998]
  - 1st global analysis of nPDFs (LO)
  - Good description of DIS+DY data: factorization works
  - Parametrization released: widely used by the RHIC community

- **nDS** [de Florian, Sassot, 2003]
  - 1st NLO analysis
  - Computer code also released

- **HKM, HKN** [Hirai, Kumano, Miyama, Nagai, 2001; 2004; 2007]
  - 1st $\chi^2$-minimization and uncertainty analysis
  - LO and NLO and computer codes released

- **EKPS** [Eskola, Kolhinen, Paukkunen, Salgado, 2007]
  - Uncertainty analysis within the EKS98 framework
  - First look at RHIC data

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Parametrize $R_{F^2}^A(x)$ at $Q_0^2 = 2.25 \text{ GeV}^2$

Valence quarks $R_{uV}^A = R_{dV}^A = R_V^A(x)$
- Large-x fixed to $R_V^A \simeq R_{F^2}^A$
- Intermediate-x by DY
- Rest: Baryon number sum rule

Sea quarks $R_{\bar{u}}^A = R_{\bar{d}}^A = R_S^A = R_S^A(x)$
- Small-x fixed to $R_S^A \simeq R_{F^2}^A$
- Intermediate-x by DY
- Large-x: assumption

Gluons
- Large/small-x fixed to $R_g^A \simeq R_{F^2}^A$
- Intermediate-x: DGLAP
Approximate ranges and constraints in EKS98

Valence

Sea quarks

Gluons

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Approximate ranges and constraints in EKS98

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Constrained by DIS
Approximate ranges and constraints in EKS98

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Assumptions
Approximate ranges and constraints in EKS98

Valence

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Constrained by Sum rules

Assumptions

[these ranges are very approximative... but valid in general for other analyses]
Very good overall NLO and LO fits
Solve DGLAP in moments space
Less control over the shape of the function

\[ R^\text{Ca}_{\nu} Q^2 = 2.25 \text{ GeV}^2 \]
\[ R^\text{Ca}_{\pi} \]
\[ R^\text{Ca}_g \]
\[ Q^2 = 100 \text{ GeV}^2 \]

\[ x = 0.0125 \]
\[ x = 0.0175 \]
\[ x = 0.025 \]
\[ x = 0.035 \]
\[ x = 0.045 \]
\[ x = 0.055 \]
\[ x = 0.070 \]
\[ x = 0.090 \]
\[ x = 0.125 \]
\[ x = 0.175 \]
\[ x = 0.25 \]
\[ x = 0.35 \]
\[ x = 0.45 \]
\[ x = 0.55 \]
\[ x = 0.70 \]
Very good overall NLO and LO fits
Solve DGLAP in moments space
Less control over the shape of the function

Much less effect for gluons than EKS98
Uncertainty estimates using the Hessian method

\begin{align*}
Q^2 = 1 \text{ GeV}^2
\end{align*}
Uncertainty estimates within the EKS98 framework. Goals:

- Check the goodness of EKS98 and uncertainties
- Later: check compatibility with BRAHMS forward rapidity

- Large-x errors treated separately for sea and glue
- Small-x errors dominated by systematics
- Common to all approaches
- Much stronger gluon shadowing required by BRAHMS

\[ A = 208, \quad Q_0^2 = 1.69 \text{ GeV}^2 \]
Uncertainty estimates within the EKS98 framework. Goals:
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- Small-\(x\) errors dominated by systematics
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Error analysis

⇒ Hessian method assumes quadratic deviations from the minimum

\[ \Delta \chi^2 = \chi^2(\hat{\xi} + \delta \xi) - \chi^2(\hat{\xi}) = \sum_{i,j} H_{ij} \delta \xi_i \delta \xi_j. \]

⇒ Linear propagation of errors allows to compute the uncertainty as

\[ [\delta F(x, \hat{\xi})]^2 = \Delta \chi^2 \sum_{i,j} \left( \frac{\partial F(x, \hat{\xi})}{\partial \xi_i} \right) H_{ij}^{-1} \left( \frac{\partial F(x, \hat{\xi})}{\partial \xi_j} \right), \]

⇒ The value of \( \Delta \chi^2 \) for a given confidence level \( P \) can be obtained

\[ P = \int_0^\Delta \chi^2 \frac{1}{2 \Gamma(N/2)} \left( \frac{S}{2} \right)^{N/2 - 1} \exp \left( -\frac{S}{2} \right) dS, \]

⇒ However, some other values, based on experience are also taken
Differences in fitting functions

EKPS use a piecewise fitting function

\[ R_1^A(x) = c_0^A + (c_1^A + c_2^A x)\left[\exp(-x/x_s^A) - \exp(-x_{a}^A/x_s^A)\right], \quad x \leq x_{a}^A \]
\[ R_2^A(x) = a_0^A + a_1^A x + a_2^A x^2 + a_3^A x^3, \quad x_{a}^A \leq x \leq x_{e}^A \]
\[ R_3^A(x) = \frac{b_0^A - b_1^A x}{(1 - x)^{\beta^A}}, \quad x_{e}^A \leq x \]

Where each parameter depends on A: \[ z_i^A = z_i^{A_{\text{ref}}} \left( \frac{A}{A_{\text{ref}}} \right)^{p_{z_i}} \]

HKN use a simpler functional form

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

and fix \[ \alpha = 1/3 \]

Convergence needs several parameters to be fixed in both cases
All lines give a good description of experimental data.

In particular, for EKPS strong gluon shadowing $\chi^2/d.o.f. < 1$.

Clear limitation of the Hessian method to constrain uncertainties.

Results biased by the chosen form of the fitting functions.
Similar problems appear in proton PDF analyses

Less dramatic for most of the regions of interest: more data exists

Uncertainty of gluon from Hessian method

Non-singlet
Stronger gluon shadowing needed to agree with BRAHMS

(This was not the result of a fit)
Try to obtain more constrains for the gluons from RHIC

Question to be answer:

Is it possible to reproduce high-pT inclusive data within the collinear factorization approach (universal nPDFs) and at the same time maintain the good fit for DIS and DY?
Some technical points

- Including inclusive hadron production is time consuming

$$\frac{d\sigma^{AB\rightarrow h}}{dp_T^2 dy} = \sum_{i,j,k=q,\bar{q},g} \int \frac{dx_2}{x_2} \int \frac{dz}{z} x_1 f_i^A(x_1, Q^2) x_2 f_j^B(x_2, Q^2) \frac{d\sigma^{ij\rightarrow k}}{dt} D_{k\rightarrow h}^{med}(z, Q^2)$$

- The number of data points from RHIC is very small compared with the total number of data points
  - The effects of these data in the total $\chi^2$ is negligible
  - Needs a redefinition of the fitting procedure

- Given the limitations of the Hessian method we decided not to give results on uncertainties

- We consider only pions and negative hadrons to avoid baryons
Fitting procedure I

In the usual definition

\[ \chi^2_N({\{z\}}) \equiv \sum_{i \in N} \left[ \frac{D_i - T_i({\{z\}})}{\sigma_i} \right]^2 \]

where \( N \) labels the experimental data sets, \( D_i, \sigma_i \) are the central value and error of the data point and \( T_i({\{z\}}) \) is the theoretical value.

We use the generalized definition [Stump et al, hep-ph/0101051]

\[ \chi^2({\{z\}}) \equiv \sum_N w_N \chi^2_N({\{z\}}) \]

Where each set of data is given a different weight \( w_N \) and

\[ \chi^2_N({\{z\}}) \equiv \left( \frac{1 - f_N}{\sigma_{\text{norm}}^N} \right)^2 + \sum_{i \in N} \left[ \frac{f_N D_i - T_i({\{z\}})}{\sigma_i} \right]^2. \]
Fitting procedure II

\[ \chi^2_N(\{z\}) \equiv \left( \frac{1 - f_N}{\sigma_N^{\text{norm}}} \right)^2 + \sum_{i \in N} \left[ \frac{f_N D_i - T_i(\{z\})}{\sigma_i} \right]^2, \]

Contains a normalization factor, that allows to fit experimental data in which all points have a common normalization error.

- \( f_N \) is fitted for each set of parameters within the experimental range, with a penalty factor for \( f_N \neq 1 \)
- Specially important for uncertainties in number of collisions
- The weights are essential to emphasize those sets of data important for physical reasons but unimportant in number
Two relevant sets of data for gluons

Gluons are indirectly constrained in DIS by DGLAP at low-x

\[ \frac{\partial R^A_{F_2}(x, Q^2)}{\partial \log Q^2} \approx \frac{10\alpha_s}{27\pi} \frac{xg(2x, Q^2)}{F^D_2(x, Q^2)} \times [R^A_G(2x, Q^2) - R^A_{F_2}(x, Q^2)] \]

Only one set of data measured \( Q^2 \)-dependence for fixed \( x \)

Positive slopes indicate not very large shadowing for \( x \gtrsim 0.02 \)

Gluons enter directly in the computation of the inclusive high-pT hadrons

Central rapidity data overlaps with DIS: check of universality

Forward rapidity needs of a much stronger shadowing

Delicate interplay between the two data sets
Initial condition

We use CTEQ6L1 as the reference free proton PDF

The initial parametrization for the ratios is similar to EKPS

\[
R_1^A(x) = c_0^A + (c_1^A + c_2^A x^{\alpha^A}) \left[ \exp(-x/x_s^A) - \exp(-x_a^A/x_s^A) \right], \quad x \leq x_a^A
\]

\[
R_2^A(x) = a_0^A + a_1^A x + a_2^A x^2 + a_3^A x^3, \quad x_a^A \leq x \leq x_e^A
\]

\[
R_3^A(x) = \frac{b_0^A - b_1^A x}{(1 - x)^{\beta^A}} + b_2^A (x - x_e^A)^2, \quad x_e^A \leq x \leq 1.
\]

Main changes:

- Small-x: stronger shadowing \[ R_i^A(x, Q_0^2) \xrightarrow{x \to 0} x^{\alpha^A}, \quad \alpha^A > 0. \]
- EMC, Large-x: new term improves the agreement

A-dependences as previously:

\[ z_i^A = z_i^{A_{\text{ref}}} \left( \frac{A}{A_{\text{ref}}} \right)^{p_{z_i}} \]

After imposing sum rules this gives a total of 44 parameters

\[ \text{reduced to 15 by fixing most of them} \]
Data sets

**DIS:** (484 points)
- SLAC-E-139
- NMC 95, 95re, 96 + EMC
  - leave E665 out

**DY in p+A (92 points)**
- E772 & E866

**RHIC inclusive dAu**
(51 points)
- PHENIX/STAR: midrapidity
- BRAHMS: forward
  - Include only $p_T > 2$ GeV

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## Sea quarks

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Process</th>
<th>Nuclei</th>
<th>Data points</th>
<th>$\chi^2$</th>
<th>Weight</th>
<th>Ref.</th>
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<td>He(4)/D</td>
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## Gluons

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<tr>
<td>total</td>
<td></td>
<td></td>
<td>627</td>
<td>448</td>
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</table>
Parameters

\( \alpha^A \) the power according to which \( R_1^A \rightarrow 0 \) at \( x \rightarrow 0 \),

\( x_s^A \) a slope factor in the exponential,

\( x_a^A, y_a^A \) position and height of the antishadowing maximum

\( x_e^A \) position of the EMC minimum

\( \Delta_e^A \) difference of the antishadowing maximum and the EMC minimum

\( \beta^A, b_2^A \) slope factors in the Fermi-motion part \( R_3 \) at \( x > x_e \).
### Fitted value of the parameters

<table>
<thead>
<tr>
<th>Param.</th>
<th>Valence $R^A_V$</th>
<th>Sea $R^A_S$</th>
<th>Gluon $R^A_G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\alpha$</td>
<td>$\alpha^A$ from baryon sum</td>
<td>$2.67 \times 10^{-2}$</td>
</tr>
<tr>
<td>2</td>
<td>$p_\alpha$</td>
<td>—</td>
<td>$3.47 \times 10^{-1}$</td>
</tr>
<tr>
<td>3</td>
<td>$x_s$</td>
<td>0.1, fixed</td>
<td>1.0, fixed</td>
</tr>
<tr>
<td>4</td>
<td>$p_{x_s}$</td>
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<td>0, fixed</td>
</tr>
<tr>
<td>5</td>
<td>$x_a$</td>
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<td>$0.580$</td>
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<tr>
<td>6</td>
<td>$p_{x_a}$</td>
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<td>0, fixed</td>
</tr>
<tr>
<td>7</td>
<td>$x_e$</td>
<td>0.751</td>
<td>as valence</td>
</tr>
<tr>
<td>8</td>
<td>$p_{x_e}$</td>
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<td>0, fixed</td>
</tr>
<tr>
<td>9</td>
<td>$y_a$</td>
<td>1.04</td>
<td>0.997</td>
</tr>
<tr>
<td>10</td>
<td>$p_{y_a}$</td>
<td>$1.55 \times 10^{-2}$</td>
<td>$-1.51 \times 10^{-2}$</td>
</tr>
<tr>
<td>11</td>
<td>$\Delta_e$</td>
<td>0.138</td>
<td>0, fixed</td>
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<tr>
<td>12</td>
<td>$p_{\Delta e}$</td>
<td>0.257</td>
<td>0, fixed</td>
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<tr>
<td>13</td>
<td>$b_2$</td>
<td>13.3</td>
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<tr>
<td>14</td>
<td>$p_{b_2}$</td>
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<tr>
<td>15</td>
<td>$\beta$</td>
<td>0.3, fixed</td>
<td>0.3, fixed</td>
</tr>
<tr>
<td>16</td>
<td>$p_\beta$</td>
<td>0, fixed</td>
<td>0, fixed</td>
</tr>
</tbody>
</table>

Trento, July 2008
Results for the initial conditions

\[ R_1^A(x, Q_0^2) \]

\( A = 12 \), \( A = 40 \), \( A = 117 \), \( A = 208 \)

\( x \) vs. \( R \)

EPS08
Description of the data: DIS

Trento, July 2008
Description of the data: DY

Improvement here
Normalization important to have a good description of data

Notice that, the Cronin enhancement is just antishadowing

PHENIX
\[ \sigma^{\text{NORM}} = 10\% \]

STAR
\[ \sigma^{\text{NORM}} = 17\% \]

Notice that, the Cronin enhancement is just antishadowing
Strong gluon shadowing in EPS08 improves the agreement
Still compatible with DIS?

Recall that at small-$x$

\[
\frac{\partial R_{F_2}^A(x, Q^2)}{\partial \log Q^2} \approx \frac{10\alpha_s}{27\pi} \frac{xg(2x, Q^2)}{F_2^D(x, Q^2)} \times [R_G^A(2x, Q^2) - R_{F_2}^A(x, Q^2)].
\]

Positive slopes required by data

EPS08 have the strongest gluon shadowing still compatible with this set of DIS data

Trento, July 2008
The DGLAP evolution removes the nuclear effects very efficiently.
The DGLAP evolution removes the nuclear effects very efficiently.
The DGLAP evolution removes the nuclear effects very efficiently.
Comparison with previous analyses

This work, EPS08

EKS98

HKN07 (LO)

EKPS

nDS (LO)

<table>
<thead>
<tr>
<th>Set</th>
<th>$Q_0^2$/GeV$^2$</th>
<th>$N_{\text{data}}$</th>
<th>$N_{\text{params}}$</th>
<th>$\chi^2$</th>
<th>$\chi^2/N$</th>
<th>$\chi^2$/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS08</td>
<td>1.69</td>
<td>627</td>
<td>15</td>
<td>445.2</td>
<td>0.71</td>
<td>0.73</td>
</tr>
<tr>
<td>EKPS</td>
<td>1.69</td>
<td>514</td>
<td>16</td>
<td>410.15</td>
<td>0.798</td>
<td>0.824</td>
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<tr>
<td>EKS98</td>
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<td>479</td>
<td>–</td>
<td>387.39</td>
<td>0.809</td>
<td>–</td>
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<tr>
<td>HKN07, LO</td>
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<td>12</td>
<td>1653</td>
<td>1.33</td>
<td>1.35</td>
</tr>
<tr>
<td>HKN07, NLO</td>
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<td>1241</td>
<td>12</td>
<td>1486</td>
<td>1.20</td>
<td>1.21</td>
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<tr>
<td>HKM</td>
<td>1.0</td>
<td>309</td>
<td>9</td>
<td>546.6</td>
<td>1.769</td>
<td>1.822</td>
</tr>
<tr>
<td>HKN</td>
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<td>951</td>
<td>9</td>
<td>1489.8</td>
<td>1.567</td>
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<tr>
<td>nDS, LO</td>
<td>0.4</td>
<td>420</td>
<td>27</td>
<td>316.35</td>
<td>0.753</td>
<td>0.806</td>
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<tr>
<td>nDS, NLO</td>
<td>0.4</td>
<td>420</td>
<td>27</td>
<td>300.15</td>
<td>0.715</td>
<td>0.764</td>
</tr>
</tbody>
</table>
Comparison with previous analyses

The disagreement with error analyses at small-x is more dramatic.
The weight for the BRAHMS data affects the gluon shadowing.

With our choice, the weight times the number of data points for the two sets of data of relevance for gluons is the same. The amount of shadowing is the maximum to maintain the positive slopes in NMC data.
Strong gluon shadowing in other approaches

This leads in general to a strong gluon shadowing due to the gluon dominance in the diffractive PDFs.

[Frakfurt, Guzey, Strikman 2003; Tywoniuk, Arsene, Bravina, Kaidalov, Zabrodin 2007; also Armesto, Capella, Kaidalov, Albacete, Salgado 2003]

[For a review see Armesto hep-ph/0604108]
Strong gluon shadowing in other approaches

In Gribov’s theory nuclear shadowing is related with diffraction

Different parametrizations for diffractive PDFs used

This leads in general to a strong gluon shadowing due to the gluon dominance in the diffractive PDFs

[Frakfurt, Guzey, Strikman 2003; Tywoniuk, Arsene, Bravina, Kaidalov, Zabrodin 2007; also Armesto, Capella, Kaidalov, Albacete, Salgado 2003]

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LHeC
Benchmarking is one of the main roles of nPDF global analyses
- In particular for hot matter studies in AA
- A universal set of nuclear PDFs able to accommodate present data
  - DIS+DY and also single inclusive high-pT in dAu
- Gluon PDF remain the less constrained
  - BRAHMS forward data favors strong gluon shadowing
  - Delicate interplay with DIS data in the fit
  - Strongest gluon shadowing still compatible with DIS
- Improvements in EPS08
  - New fitting procedure including weights and normalization factors
  - RHIC data included for the first time
Summary

- This analysis probes the feasibility of pA @ LHC to constrain nPDFs
- Error analysis tend to underestimate uncertainties
  - Errors dominated by the actual shape of the fitting function
- We are likely to push collinear factorization to a limit
  - Use EPS08 in parallel with EKS98, nDS, HKM, FGS...
  - This was the old method in proton PDFs and we should probably use it before we have more data in the unexplored kinematical regions
- Code for EPS08 available
- Next
  - NLO analysis in progress
  - Include more data photons from RHIC
- pA @ LHC, eRHIC, ELIC, LHeC !!!