Overview of low $x$ physics with electrons, protons and nuclei

Carlos A. Salgado
Universidade de Santiago de Compostela

DIS2012 - Bonn

[Disclaimer: Mostly nuclear and saturation-motivated]

carlos.salgado@usc.es  http://cern.ch/csalgado
The heavy-ion community plans to move forward...

[for the more nuclear/QCD oriented experiments...
Interesting upgrades also in ATLAS, CMS and LHCb]
New lepton-proton/nucleus colliders being planned

LHC and RHIC experiment upgrades will precede the (eventual) operation of LHeC and/or EIC - Complementarity
Proton-nucleus at the LHC

Feasibility checks performed - estimate luminosity

\[ L = 10^{29} \text{ cm}^{-2} \text{ s}^{-1} \] (full energy) \[ \text{[Integrated in } 10^6 \text{ s : } L = 100 \text{ nb}^{-1}] \]

LHC two-in-one magnet

- Equal rigidity :: \( p_{\text{Pb}} = Z p_{\text{proton}} \)
- Center of mass shifted in rapidity \( \Delta y = 0.46 \)
- Top LHC energy for pPb: 8.8 TeV

Unequal revolution freq. at injection and ramp

- RF locked in physics to avoid movement of collision points

First pPb run scheduled in 2012 - max. energy 5 TeV

- A new physics system just before the 2013-2014 shutdown
Kinematical reach in nuclear collisions

\[ Q^2 (\text{GeV}^2) \]

\[ Q^2_{\text{sat,Pb}}(x) \]

Present nuclear DIS
and Drell-Yan in p+A

Present DIS+DY

\[ x_A \]

DIS2012, Bonn, March 2012 Low-x with electrons, protons and nuclei
Kinematical reach in nuclear collisions

Present nuclear DIS and Drell-Yan in p+A

d+Au @ RHIC

$0 < y < 3.2$

$Q^2_{sat,Pb}(x)$

$Q^2$ (GeV$^2$)

$x_A$
Kinematical reach in nuclear collisions

\[ \mathbf{Q}^2 (\text{GeV}^2) \]

- \( p+\text{Pb} @ \text{LHC (7 TeV+2.75 TeV)} \)
- Present nuclear DIS and Drell-Yan in \( p+A \)
- \( \text{d+Au} @ \text{RHIC} \)
- \( 0 < y < 3.2 \)
- \( \text{LHeC} \)
- \( 50 \text(e)+2750 \text(Pb) \)

\[ Q_{\text{sat,Pb}}^2 (x) \]

- \( y_{\text{lab}} = 6.6 \)
- \( y_{\text{lab}} = 6 \)
- \( y_{\text{lab}} = 4 \)
- \( y_{\text{lab}} = 2 \)
- \( y_{\text{lab}} = 0 \)

Present DIS+DY
Kinematical reach in nuclear collisions

New regions never explored in HIC
small-x and large-Q

DIS2012, Bonn, March 2012
Low-x with electrons, protons and nuclei
Kinematical reach in nuclear collisions

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS

and Drell-Yan in p+A

d+Au @ RHIC

0 < y < 3.2

Constrain PDFs

Check expected saturated region

Present DIS+DY

LHeC (50(e)+2750(Pb))

p+Pb @ LHC (7 TeV+2.75 TeV)

Nuclear DIS
Why proton-nucleus?

[To study the structure of a large object make collisions with smaller objects (Rutherford experiment...)]

The proton structure is constrained by DIS + other data

— HERA data of utmost importance

Need pA to study the high-energy nuclear structure

— DIS data is old (90’s) and with limited range

— pA@LHC is the only experimental condition available before an eventual lepton-A collider (LHeC, eRHIC?)

— Needed as benchmark for the AA program

— High-density effects (saturation) enhanced in nuclei
Low-x Physics with electrons, protons and nuclei

One of the basic questions:
Low-x Physics with electrons, protons and nuclei

One of the basic questions:

DGLAP or not DGLAP

— Saturation of partonic densities
— Resummation
— Signs of BFKL

[For hot QCD studies this is an essential question: Initial state of the system]
Some historical perspective

Global DGLAP fits work

- Essential for the phenomenology
- In particular LHC
Some historical perspective

Global DGLAP fits work
- Essential for the phenomenology
- In particular LHC

Also for nuclei
- Reduced amount of data
Geometric scaling as a qualitative signature

\[ Q_{sat}^2 \propto x^{-\lambda} A^{1/3\delta} \]

\[
\frac{2}{N_{part}} \frac{dN^{AA}}{d\eta} \bigg|_{\eta \sim 0} = N_0 \sqrt{s}^\lambda N_{part}^{\frac{1-\delta}{3}}
\]

Energy and centrality dependences fixed by lepton-nucleus data

[Stasto, Golec-Biernat, Kwiecinski 2001; Armesto, Salgado, Wiedemann 2004]

DIS2012, Bonn, March 2012

Low-x with electrons, protons and nuclei
Combined HERA data: unprecedented precision

Still, uncertainties large at small-\( x \)
Non-linear BK equations also fit small-x

Fit including heavy quarks

Fit with running coupling Balitsky-Kovchegov equations

DIS2012, Bonn, March 2012
We find evidence for deviations which are qualitatively consistent with the behaviour predicted by small $x$ perturbative resummation, and possibly also by nonlinear evolution effects, but incompatible with next-to-next-to-leading order corrections. [Caola, Forte, Rojo 2009]

Excluding the small-$x$ data from the fits would result in larger uncertainties at the LHC.
**nPDFs: global analyses. Status**

Main goals

- Check the factorization of nPDFs for hard processes
- Fix the benchmark for HI hot matter or saturation

[ Talks by R. Sassot and K. Kovarik ]

![Graph](image)

EKS98 [Eskola, Kolhinen, Ruuskanen, Salgado 1998]

HKM [Hirai, Kumano, Miyama, 2001]

nDS [de Florian, Sassot, 2003]

HKN [Hirai, Kumano, Nagai, 2004; 2007]

EPS08, EPS09 [Eskola, Paukkunen, Salgado, 2008; 2009]

nCTEQ [Kovarik et al, 2011]

DSSZ [de Florian, Sassot, Stratmann, Zurita, 2011]
How?: follow free proton approach

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

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

DGLAP

Compute observables \( \{ R_i^A(x, Q^2) \} \) for \( \{a_i\} \)

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

Minimum?

\( \{a_i\} \)

Compute observables \( \{ R_i^A(x, Q^2) \} \) for \( \{a_i\} \)

DGLAP

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

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

Final answer

Minimum?

\( \{a_i\} \)

Compute observables \( \{ R_i^A(x, Q^2) \} \) for \( \{a_i\} \)

DGLAP

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

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

Final answer

\( \{a_i\} \)
**Included data**

[EPS09]

**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

---

DIS2012, Bonn, March 2012
Included data
[EPS09]

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

 INCLUDED DATA 

<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>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>He(4)/D</td>
<td>18</td>
<td>2.0</td>
<td>1</td>
<td>[25]</td>
</tr>
<tr>
<td>NMC 95, reanalysis</td>
<td>DIS</td>
<td>He/D</td>
<td>16</td>
<td>12.1</td>
<td>1</td>
<td>[26]</td>
</tr>
<tr>
<td>NMC 95</td>
<td>DIS</td>
<td>Li(6)/D</td>
<td>15</td>
<td>30.7</td>
<td>1</td>
<td>[27]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Be(9)/D</td>
<td>17</td>
<td>5.5</td>
<td>1</td>
<td>[25]</td>
</tr>
<tr>
<td>NMC 96</td>
<td>DIS</td>
<td>Be(9)/C</td>
<td>15</td>
<td>4.2</td>
<td>1</td>
<td>[28]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>C(12)/D</td>
<td>7</td>
<td>3.5</td>
<td>1</td>
<td>[25]</td>
</tr>
<tr>
<td>NMC 95, reanalysis</td>
<td>DIS</td>
<td>C/Li</td>
<td>7</td>
<td>10.5</td>
<td>5</td>
<td>[29]</td>
</tr>
<tr>
<td>NMC 96</td>
<td>DIS</td>
<td>C/L</td>
<td>20</td>
<td>17.8</td>
<td>5</td>
<td>[26]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>C(Li)/D</td>
<td>7</td>
<td>36.4</td>
<td>10</td>
<td>[26]</td>
</tr>
<tr>
<td>NMC 95, reanalysis</td>
<td>DIS</td>
<td>C/L</td>
<td>20</td>
<td>36.4</td>
<td>10</td>
<td>[26]</td>
</tr>
<tr>
<td>NMC 96</td>
<td>DIS</td>
<td>C/L</td>
<td>20</td>
<td>36.4</td>
<td>10</td>
<td>[26]</td>
</tr>
<tr>
<td>FNAL-E772</td>
<td>DY</td>
<td>C/D</td>
<td>9</td>
<td>8.9</td>
<td>10</td>
<td>[29]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Al(27)/D</td>
<td>17</td>
<td>3.6</td>
<td>1</td>
<td>[25]</td>
</tr>
<tr>
<td>NMC 95</td>
<td>DIS</td>
<td>Al/C</td>
<td>15</td>
<td>6.7</td>
<td>1</td>
<td>[28]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Ca(40)/D</td>
<td>7</td>
<td>1.3</td>
<td>1</td>
<td>[29]</td>
</tr>
<tr>
<td>NMC 95, reanalysis</td>
<td>DIS</td>
<td>Ca/D</td>
<td>16</td>
<td>27.9</td>
<td>1</td>
<td>[27]</td>
</tr>
<tr>
<td>NMC 96</td>
<td>DIS</td>
<td>Ca/Li</td>
<td>20</td>
<td>26.1</td>
<td>1</td>
<td>[26]</td>
</tr>
<tr>
<td>NMC 96</td>
<td>DIS</td>
<td>Ca/C</td>
<td>15</td>
<td>6.3</td>
<td>1</td>
<td>[26]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Ca(25)/D</td>
<td>32</td>
<td>16.5</td>
<td>1</td>
<td>[26]</td>
</tr>
<tr>
<td>FNAL-E772</td>
<td>DY</td>
<td>Ca/D</td>
<td>9</td>
<td>5.0</td>
<td>10</td>
<td>[29]</td>
</tr>
<tr>
<td>NMC 95, reanalysis</td>
<td>DIS</td>
<td>Ca/Li</td>
<td>20</td>
<td>26.1</td>
<td>1</td>
<td>[26]</td>
</tr>
<tr>
<td>NMC 96</td>
<td>DIS</td>
<td>Ca/C</td>
<td>15</td>
<td>6.3</td>
<td>1</td>
<td>[26]</td>
</tr>
<tr>
<td>FNAL-E772</td>
<td>DY</td>
<td>Fe/D</td>
<td>9</td>
<td>5.0</td>
<td>10</td>
<td>[29]</td>
</tr>
<tr>
<td>FNAL-E866</td>
<td>DY</td>
<td>Fe/C</td>
<td>10</td>
<td>21.9</td>
<td>1</td>
<td>[29]</td>
</tr>
<tr>
<td>FNAL-E866</td>
<td>DY</td>
<td>Fe/Be</td>
<td>28</td>
<td>21.6</td>
<td>1</td>
<td>[30]</td>
</tr>
<tr>
<td>CERN EMC</td>
<td>DIS</td>
<td>Cu(64)/D</td>
<td>19</td>
<td>12.3</td>
<td>1</td>
<td>[31]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Cu(64)/D</td>
<td>7</td>
<td>2.3</td>
<td>1</td>
<td>[25]</td>
</tr>
<tr>
<td>NMC 95, Q^2 dep. $x \leq 0.025$</td>
<td>DIS</td>
<td>Sn(137)/C</td>
<td>15</td>
<td>10.0</td>
<td>1</td>
<td>[32]</td>
</tr>
<tr>
<td>NMC 96</td>
<td>DIS</td>
<td>Sn/C</td>
<td>24</td>
<td>9.4</td>
<td>10</td>
<td>[32]</td>
</tr>
<tr>
<td>FNAL-E772</td>
<td>DY</td>
<td>W(184)/D</td>
<td>9</td>
<td>10.0</td>
<td>10</td>
<td>[29]</td>
</tr>
<tr>
<td>FNAL-E866</td>
<td>DY</td>
<td>W/Be</td>
<td>28</td>
<td>26.5</td>
<td>1</td>
<td>[30]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Au(197)/D</td>
<td>18</td>
<td>6.1</td>
<td>1</td>
<td>[33]</td>
</tr>
<tr>
<td>RHIC-BRAHMS</td>
<td>$\Lambda$ prod.</td>
<td>dAu/pp</td>
<td>6</td>
<td>2.2</td>
<td>10</td>
<td>[11]</td>
</tr>
<tr>
<td>RHIC-HERMES</td>
<td>$\pi^+ + \pi^-$ prod.</td>
<td>dAu/pp</td>
<td>10</td>
<td>3.5</td>
<td>1</td>
<td>[16]</td>
</tr>
<tr>
<td>RHIC-STAR</td>
<td>$\pi^+ + \pi^-$ prod.</td>
<td>dAu/pp</td>
<td>10</td>
<td>3.5</td>
<td>1</td>
<td>[16]</td>
</tr>
<tr>
<td>NMC 96</td>
<td>DIS</td>
<td>Pb/C</td>
<td>15</td>
<td>5.1</td>
<td>1</td>
<td>[28]</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td></td>
<td>627</td>
<td>448</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Low-x with electrons, protons and nuclei

DIS2012, Bonn, March 2012
### Included data

**[EPS09]**

#### 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

#### Data Table

<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>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>He(4)/D</td>
<td>18</td>
<td>2.0</td>
<td>1</td>
<td>[25]</td>
</tr>
<tr>
<td>NMC 95, reanalysis</td>
<td>DIS</td>
<td>He/D</td>
<td>16</td>
<td>12.1</td>
<td>1</td>
<td>[26]</td>
</tr>
<tr>
<td>NMC 95</td>
<td>DIS</td>
<td>Li(6)/D</td>
<td>15</td>
<td>30.7</td>
<td>1</td>
<td>[27]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Be(9)/D</td>
<td>17</td>
<td>5.5</td>
<td>1</td>
<td>[25]</td>
</tr>
<tr>
<td>NMC 95</td>
<td>DIS</td>
<td>Be(9)/C</td>
<td>15</td>
<td>4.2</td>
<td>1</td>
<td>[28]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>C(12)/D</td>
<td>7</td>
<td>3.5</td>
<td>1</td>
<td>[25]</td>
</tr>
<tr>
<td>NMC 95</td>
<td>DIS</td>
<td>C(12)/C</td>
<td>15</td>
<td>10.5</td>
<td>5</td>
<td>[29]</td>
</tr>
<tr>
<td>NMC 95, reanalysis</td>
<td>DIS</td>
<td>C(12)/D</td>
<td>7</td>
<td>17.8</td>
<td>5</td>
<td>[29]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Al(27)/D</td>
<td>17</td>
<td>3.6</td>
<td>1</td>
<td>[25]</td>
</tr>
<tr>
<td>NMC 95</td>
<td>DIS</td>
<td>Al/C</td>
<td>15</td>
<td>6.7</td>
<td>1</td>
<td>[28]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Ca(40)/D</td>
<td>7</td>
<td>1.3</td>
<td>1</td>
<td>[29]</td>
</tr>
<tr>
<td>NMC 95</td>
<td>DIS</td>
<td>Ca/C</td>
<td>15</td>
<td>6.3</td>
<td>1</td>
<td>[29]</td>
</tr>
<tr>
<td>NMC 95, reanalysis</td>
<td>DIS</td>
<td>Ca/C</td>
<td>15</td>
<td>6.3</td>
<td>1</td>
<td>[29]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Fe(56)/D</td>
<td>17</td>
<td>27.9</td>
<td>1</td>
<td>[29]</td>
</tr>
<tr>
<td>NMC 95</td>
<td>DIS</td>
<td>Fe/C</td>
<td>15</td>
<td>26.1</td>
<td>1</td>
<td>[29]</td>
</tr>
<tr>
<td>NMC 95</td>
<td>DIS</td>
<td>Fe/Be</td>
<td>28</td>
<td>21.6</td>
<td>1</td>
<td>[30]</td>
</tr>
<tr>
<td>CERN EMC</td>
<td>DIS</td>
<td>Cu(64)/D</td>
<td>19</td>
<td>12.3</td>
<td>1</td>
<td>[30]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Si(28)/D</td>
<td>7</td>
<td>2.3</td>
<td>1</td>
<td>[25]</td>
</tr>
<tr>
<td>NMC 96</td>
<td>DIS</td>
<td>Sn(117)/C</td>
<td>15</td>
<td>19.0</td>
<td>1</td>
<td>[31]</td>
</tr>
<tr>
<td>NMC 96, $Q^2$ dep. $x \leq 0.025$</td>
<td>DIS</td>
<td>Sn/C</td>
<td>24</td>
<td>9.4</td>
<td>10</td>
<td>[32]</td>
</tr>
<tr>
<td>NMC 96, $Q^2$ dep. $x &gt; 0.025$</td>
<td>DIS</td>
<td>Sn/C</td>
<td>120</td>
<td>78.2</td>
<td>10</td>
<td>[32]</td>
</tr>
<tr>
<td>FNAL-E772</td>
<td>DY</td>
<td>Ca/D</td>
<td>9</td>
<td>5.0</td>
<td>10</td>
<td>[29]</td>
</tr>
<tr>
<td>FNAL-E772</td>
<td>DY</td>
<td>Fe/D</td>
<td>9</td>
<td>5.0</td>
<td>10</td>
<td>[29]</td>
</tr>
<tr>
<td>FNAL-E866</td>
<td>DY</td>
<td>Fe/C</td>
<td>10</td>
<td>11.3</td>
<td>1</td>
<td>[29]</td>
</tr>
<tr>
<td>FNAL-E866</td>
<td>DY</td>
<td>Fe/Be</td>
<td>28</td>
<td>21.6</td>
<td>1</td>
<td>[30]</td>
</tr>
<tr>
<td>CERN EMC</td>
<td>DIS</td>
<td>Cu(64)/D</td>
<td>19</td>
<td>12.3</td>
<td>1</td>
<td>[31]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Si(28)/D</td>
<td>7</td>
<td>2.3</td>
<td>1</td>
<td>[25]</td>
</tr>
<tr>
<td>NMC 96</td>
<td>DIS</td>
<td>Sn(117)/C</td>
<td>15</td>
<td>19.0</td>
<td>1</td>
<td>[31]</td>
</tr>
<tr>
<td>NMC 96, $Q^2$ dep. $x \leq 0.025$</td>
<td>DIS</td>
<td>Sn/C</td>
<td>24</td>
<td>9.4</td>
<td>10</td>
<td>[32]</td>
</tr>
<tr>
<td>NMC 96, $Q^2$ dep. $x &gt; 0.025$</td>
<td>DIS</td>
<td>Sn/C</td>
<td>120</td>
<td>78.2</td>
<td>10</td>
<td>[32]</td>
</tr>
<tr>
<td>FNAL-E772</td>
<td>DY</td>
<td>W(184)/D</td>
<td>9</td>
<td>10.0</td>
<td>10</td>
<td>[29]</td>
</tr>
<tr>
<td>FNAL-E866</td>
<td>DY</td>
<td>W/Be</td>
<td>28</td>
<td>26.5</td>
<td>10</td>
<td>[30]</td>
</tr>
<tr>
<td>SLAC E-139</td>
<td>DIS</td>
<td>Au(197)/D</td>
<td>18</td>
<td>6.1</td>
<td>1</td>
<td>[32]</td>
</tr>
<tr>
<td>RHIC-BRAHMS</td>
<td>$\tilde{p}$ prod.</td>
<td>dAu/pp</td>
<td>6</td>
<td>2.2</td>
<td>40</td>
<td>[11]</td>
</tr>
<tr>
<td>RHIC-BRAHMS</td>
<td>$\pi^+ + \pi^-$ prod.</td>
<td>dAu/pp</td>
<td>10</td>
<td>3.5</td>
<td>10</td>
<td>[16]</td>
</tr>
<tr>
<td>NMC 96</td>
<td>DIS</td>
<td>Pb/C</td>
<td>15</td>
<td>5.1</td>
<td>1</td>
<td>[28]</td>
</tr>
</tbody>
</table>

**Total**

| Experiment   | DIS | Pb/C | 15 | 5.1 | 1 | [28] |

**Low-x with electrons, protons and nuclei**

---

DIS2012, Bonn, March 2012
Approximate ranges and constrains in EPS09

Valence

Sea quarks

Gluons

$R_A G(x, Q^2)$

$x A = 208$ $Q_0^2 = 2.25 \text{ GeV}^2$

$x A = 208$ $Q_0^2 = 2.25 \text{ GeV}^2$

$x A = 208$ $Q_0^2 = 2.25 \text{ GeV}^2$

Low-x with electrons, protons and nuclei

DIS2012, Bonn, March 2012
Approximate ranges and constrains in EPS09

Valence

Sea quarks

Gluons

Constrained by DIS
Approximate ranges and constrains in EPS09

Valence

Sea quarks

Gluons

Constrained by DIS

Constrained by DY
Approximate ranges and constrains in EPS09

Valence

Sea quarks

Gluons

Constrained by DIS

Constrained by DY

Sum rules and dAu@RHIC

DIS2012, Bonn, March 2012
Approximate ranges and constrains in EPS09

Valence

Sea quarks

Gluons

Constrained by DIS

Constrained by DY

Sum rules and dAu@RHIC

Unconstrained
Approximate ranges and constraints in EPS09

Valence

Sea quarks

Gluons

Constrained by DIS
Constrained by DY
Sum rules and dAu@RHIC
Unconstrained

[these ranges are very approximative... but valid in general for other analyses]
Nuclear PDFs

Initial conditions and error analysis for different NLO sets

This work, EPS09NLO
HKN07 (NLO)
nDS (NLO)

Large uncertainties especially for gluons - smaller at large virtuality
Notice that parametrization bias effects are present
Bands to be considered as lower bounds

<table>
<thead>
<tr>
<th>PDF Set</th>
<th>Chi$^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS09</td>
<td>0.79</td>
</tr>
<tr>
<td>HKN</td>
<td>1.58</td>
</tr>
<tr>
<td>nCTEQ</td>
<td>0.89</td>
</tr>
<tr>
<td>DSSZ</td>
<td>0.99</td>
</tr>
</tbody>
</table>

DIS2012, Bonn, March 2012
Comparison with data included in the fit

No tension among data in the fit
Checks of factorization: forward@RHIC

[CTEQ6.1M PDFs fDSS FFs] inelastic = 40 mb

CTEQ6.1M PDFs fDSS FFs

ετ ετ = 40 mb

μfac = μfrag = μren = pT

μfac = μfrag = μren = pT

BRAHMS pp

BRAHMS dAu

Inclusive h^-

Inclusive h^-

η = 2.2

η = 3.2

η = 3.2

 kob, Paukkunen, Salgado, 2010]

Good description except for pp @ y=3.2

Not conclusive, LHC will indeed help by reaching smaller-x

DIS2012, Bonn, March 2012

Low-x with electrons, protons and nuclei
Checks of factorization: forward@RHIC

[Escola, Paukkunen, Salgado, 2010]

Ratios not well described

Data/Theory

\[ R_{d{Au}} \]

\[ \frac{d^3N}{d^3p} \text{ [GeV}^2] \]

\[ 1 \]

\[ 10^{-1} \]

\[ 10^{-2} \]

\[ 10^{-3} \]

\[ 10^{-4} \]

\[ 10^{-5} \]

\[ 10^{-6} \]

\[ 10^{-7} \]

\[ 0.5 \]

\[ 1.0 \]

\[ 1.5 \]

\[ 2.0 \]

\[ \eta = 2.2 \]

\[ \eta = 3.2 \]

BRAHMS \( h^- \)

EPS09NLO

Good description except for pp @ \( y=3.2 \)

Not conclusive, LHC will indeed help by reaching smaller-x

DIS2012, Bonn, March 2012

Low-x with electrons, protons and nuclei
Additional checks of factorization: neutrino DIS

NuTeV: 2618 data
CDHSW: 1533 data
CHORUS: 1214 data

Non-trivial check (neutrino data not included in the fit)
Result agrees with DSSZ (data included in the fit)
CONCLUSIONS

- 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 $\chi^2$ 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?

[Slide stolen from K. Kovari’s talk]
More on neutrino DIS: NuTeV

Our analysis points to systematic differences in NuTeV data as a function of the neutrino energy [only present for neutrino and for NuTeV]

This cannot be fixed by nuclear PDFs [Notice: ratios with theoretical proton DIS. CTEQ6.6 used here]
W/Z bosons in pA: a very promising tool

The rapidity asymmetry in pA can be exploited for nPDF studies

Small isospin effects on Z production
  - Asymmetry provides constraints without pp reference
  - PbPb much less constraining

Z-Spectrum, pPb at $\sqrt{s} = 8.8$TeV, $M=M_Z$

Z Asymmetry Pb at $\sqrt{s} = 8.8$TeV, $M=M_Z$

Z Production, $M=M_Z$

[Paukkunen, Salgado 2011]
W/Z bosons in pA: a very promising tool

Isospin effects important in W production
pA useful for proton PDFs fits?

DIS2012, Bonn, March 2012

Low-x with electrons, protons and nuclei
DGLAP global fits provide the technology
— One of the most standardized methods in HEP

Provide the data and checks of (collinear) factorization will be performed
— (& sets of nPDF released)
Saturation of partonic densities

(Color Glass Condensate)

pA as a benchmark for the bulk particle production

Only theoretically controlled tool to compute the initial state of the system
(essential for Hot QCD phenomenology)
Hits of saturation: RHIC@forward rapidities

- Suppression of yields
- Small-x evolution
- Disappearance of back-to-back
- Broadening

PHENIX: forward-forward and central-forward studied

DIS2012, Bonn, March 2012
Extrapolation to pA@LHC

\[ R_{pA}(p_T) \]

- 4.4 TeV, \( \eta = 0 \)
- \( Q^2_{0s} = 0.5 \text{ GeV}^2 \)
- \( Q^2_{0s} = 0.67 \text{ GeV}^2 \)

\[ N_{\text{coll}} = 6.5 \]

- Set 1, \( b < 8 \text{ fm} \), \( \sqrt{s} = 7 \text{ TeV} \)
- \( \gamma = 1.119 ? \)

\[ R_{pA}(p_T) \]

- 4.4 TeV, \( \eta = 2 \)
- \( Q^2_{0s} = 0.336 \text{ GeV}^2 \)
- \( Q^2_{0s} = 0.5 \text{ GeV}^2 \)

\[ N_{\text{coll}} = 6.5 \]

- Set 2, \( b < 8 \text{ fm} \), \( \sqrt{s} = 7 \text{ TeV} \)
- \( \gamma = 1.119 ? \)

[Albacete, LPCC workshop on pA, October 2011]

Low-x with electrons, protons and nuclei
Limited predicting power due to uncertainties in the initial conditions of the evolution (as in DGLAP...)

pA as benchmark for the initial state of the created system in AA

Rapidity evolution is a prediction in BK
Forward rapidities universal behavior reached?
GGC: Short list of theoretical developments

Evolution Equations BK-JIMWLK:
\[ \frac{\partial \phi(x, k)}{\partial \ln(1/x)} = K \otimes \phi(x, k) - \phi^2(x, k); \quad \frac{\partial W[\rho]}{\partial Y} = \ldots \]

- Running coupling corrections [Balitsky, Kovchegov-Weigert, Gardi et al]
- Full NLO kernel [Balitsky]
- High-Q^2 effects (CCFM + saturation) [Avsar-Iancu]
- Kinematic constraints & b-dependence in BK evolution [Berger-Stasto]
- Subleading-N(c) corrections [kovchegov-Weigert]
  - ...

Production processes:
\[ \frac{dN^{AB \rightarrow X}}{d^3p_1 \ldots} [\phi(x, k); W_Y[\rho]] \]

- Factorization of multiparticle production processes [Gelis-Lappi-Venugopalan]
- Analytic solutions to Yang-Mills EOM [Blaizot-Mehtar Tani-Lappi]
- Running coupling corrections to kt-factorization [Kovchegov-Horowitz]
- DIS NLO photon impact factors [Balitsky-Chirilli]
- Di-hadron correlations [Dumitru-Jalilian Marian, Dominguez et al]
- Progress in the hybrid formalism (CGC+pdf’s) [Altinoluk-Kovner]
- New observables beyond the large-Nc limit [Marquet-Weigert]
  - ...

Used in phenomenological works? ✓ Yes × No ✓ A bit :)
Summary

Small-\(x\) physics interesting QCD testing ground

— Departure from DGLAP?
— Potentially important phenomenological consequences (LHC)
— Precision of the data high, more to come from LHC

Nuclear PDFs badly constrained at small-\(x\)

— \(pA\) only possibility to reduce uncertainties
— Very standard technology but data needed

Saturation of partonic densities

— \(pA@LHC\) arguably the best experimental option before LHeC, etc
— Phenomenology applicable to the proton case
— Only theoretical controlled way to compute IS of the produced matter