THE EMC EFFECT
IN
HEAVY ION COLLISIONS

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**O U T L I N E**

**Motivation**
- We are testing small-$x$ physics in heavy-ion collisions
- Can we test the high-$x$ region in heavy-ion collisions?
- Is the $R_{dA}$ 'boring'='flat' at high-$p_T$?

**I. The EMC effect**
- The EMC effect in pQCD improved parton model
- Signatures for EMC effect in $dAu$ at RHIC

**II. Results, uncertainties, and errors**
- Results and the uncertainties of the theoretical model
- Slope comparison to existing $dAu$ and $AuAu$ data
M O T I V A T I O N – $\pi^0$

PHENIX $\pi^0$ data $p_T \leq 10$ GeV/c
- PRL 91 (2003) 072303
- $R_{dAu} \approx 1$ at highest $p_T$s
- Is there ’life’ above the Cronin region, $p_T \gtrsim 6 – 7$ GeV/c?

PHENIX has more precise data
- PRL 98 (2007) 172302
- Only huge errors at high $p_T$?
- $20 – 25\%$ suppression and slope structure at high $p_T$?
**M O T I V A T I O N − γ**

**PHENIX prelim. γ data in dAu**
- D. Peressounko, hep-ex/0609037
- Weak but, $R_{dAu}^\gamma \lesssim 1$, so negative slope at high $p_T$.

**PHENIX prelim. γ data in AuAu**
- T. Isobe, nucl-ex/0701040
- This is a 20 − 40% effect
- What effect is responsible for these slopes at high $p_T$?
THE EFFECT
First Measured by European Muon Collaboration

- EMC, BCDMS, SLAC E139 measured the ratio of $\sigma_{Fe}/\sigma_D$
  Benvenuti et al.: PL B189 483 (1987)
  J. Gomez et al.: PR D49 4348 (1994)

- Various nuclei were measured:
  $^4He, ^9Be, ^{12}C, ^{27}Al, ^{40}Ca, ^{56}Fe, ^{108}Ag, ^{197}Au$

- Strong dependence on targets:
  $\sigma_A/\sigma_D = C(x)A^{\alpha(x)}$ or
  $\sigma_A/\sigma_D = D(x)[1 + \beta(x)\rho(A)]$
- Suppression were found at $x > 0.3$
- No significant $Q^2$ dependence
- Measured $Q^2$ bins:
  $Q^2 = 2$ and $5$ (GeV/c)$^2$ for $x < 0.3$;
  $Q^2 = 2, 5, \text{ and } 10$ (GeV/c)$^2$ for $0.3 \leq x \leq 0.5$;
  $Q^2 = 5 \text{ and } 10$ (GeV/c)$^2$ for $x > 0.5$
Nominate Nuclear Modifications

EMC were measured by many experimental collaborations

- Strict def.: EMC effect is in $[0.3; 0.8] \ni x$, where $F_2^A/F_2^D \lesssim 1$
- Non-strict: Where the slope is negative: $[0.1; 0.7] \ni x$
- at RHIC these are $[30; 80]$ and $[10; 70]$ GeV/c \ni p_T$ respectively
The pQCD Improved Parton Model for $pA$ Collisions

\[
E_\pi \frac{d\sigma_{pA}^\pi}{d^3p_\pi} \sim f_{a/p}(x_a, Q^2; k_T) \otimes f_{b/A}(x_b, Q^2; k_T, b) \otimes \frac{d\sigma_{ab\to cd}}{dt} \otimes \frac{D_{\pi/c}(z_c, \hat{Q}^2)}{\pi z_c^2}.
\]

- $f_{b/A}(x_a, Q^2; k_T, b)$: Parton Dist. Function (PDF), at scale $Q^2$
- $D_{\pi/c}(z_c, \hat{Q}^2)$: Fragmentation Function for $\pi$ (FF), at scale $\hat{Q}^2$
- $\frac{d\sigma_{ab\to cd}}{dt}$: Partonic cross section
The Origin of the EMC – Shadowing inside the Nucleus

Shadowing – PDFs are modified inside the nucleus:

– PDF based: general, but model dependent (HIJING)
– True NPDFs: only for special nuclei, more precise (HKN)

\[ f_{a/A}(x, Q^2) = S_{a/A}(x, b) \left[ \frac{Z}{A} f_{a/p}(x, Q^2) + \left(1 - \frac{Z}{A}\right) f_{a/n}(x, Q^2) \right] \]

\( S_{a/A}(x, b) \): Shadowing function (e.g.: HIJING);
\( A \) atomic- and \( Z \) the proton number
Nuclear effects at very high-$p_T$ in central $dAu$ collision

**Multiple scattering**

**Nuclear shadowing or anti-shadowing**

**The EMC Effect**

**MULTIPLE SCATTERING:** $2 \text{ GeV/c} \leq p_T \leq 7 \text{ GeV/c}$

**(GLUON) SHADOWING:** $p_T \leq 1 - 5 \text{ GeV/c}$

**THE EMC REGION:** $p_T \geq 10 - 20 \text{ GeV/c}$
THEORETICAL RESULTS WITH

Unknown error.

Close
THEORETICAL RESULTS WITH ERRORS AND UNCERTAINTIES
Results: different shadowing parameterizations in $dAu$


Good agreement with fitted EPS09 shadowing in $dAu$

EPS09: Eskola et al., JHEP04 065 (2009)
Uncertainties of HKN parameterizations in $R_{dA}(p_T)$

Scale uncertainty at low-$p_T$

Errors of HKN $\mapsto \pm 10\%$

Extracting the slope of $R_{dAu}$ in $dAu$ collision at PHENIX

Comparing different shadowing parameterizations

Fit linear for the $\sim \log(p_T)$ in the $8 < p_T < 30$ GeV/c range

What is missing in the EMC region for $\pi^0$?
Extracting the slope of $R_{dAu}$ in $dAu$ collision at PHENIX

Further test on preliminary $dAu \rightarrow \gamma$ PEHNIX data

LO direct photon calculations, without FSI (suppression)

Negative slope is hopefully seen . . .
Extracting the slope of $R_{AuAu}$ in $AuAu$ collision at PHENIX

Test on preliminary $AuAu \rightarrow \gamma$ PEHNIX data

LO direct photon calculations, still NO FSI (suppression)

Clear slope, but more than linear power (double effect)
Extracting the slope of $R_{AuAu}$ in $AuAu$ collision at PHENIX

What if we would include FSI for $\pi^0$ in $dAu$ at RHIC

GLV-like suppression: shifts down $R_{dAu} \sim 10\%$

in this simple case no relevant change in the high-$p_T$ slope
Cold Quenching in $dAu$ collision at PHENIX

Barnaföldi, Fai, Levai, Papp

Calculations for $dAu$ with HKN shadowing

Cold quenching in $dAu$ collision at a small n~1 opacity

better model: (weak color matter) might be seen on slopes at RHIC, but this effect is stronger at LHC energies...
**SUMMARY**

\( R_{dAu} \) and HKN EMC slopes are close to parallel at high \( p_T \)

\[ \Rightarrow \] ...but, non equal, so room for final state effects

\[ \Rightarrow \] \( \pi^0 \) and \( \gamma \) in \( dAu \) and \( AuAu \) has similar suppression at high \( p_T \)

\[ \Rightarrow \] Errors and uncertainties are well handled

**Summarized in** arXiv: hep-ph/0702101 and 0805.3360
Nuclear effects in our model at:

CERN SPS ENERGIES

Old and new data from Fermilab, WA98, NA49 ...
Nuclear effects in our model at:

- **“Shadowing”**
  - Systems: $pA, AA$
  - Small-$x$, mostly low-$p_T$ but EMC, anti-shadowing at high-$p_T$

- **Jet-Quenching**
  - Systems: $(pA), AA$
  - Real high-$p_T$

- Intrinsic $k_T$
  - Systems: $pp, pA, AA$
  - Low- or intermediate-$p_T$

... high precision data by RHIC experiments ...
“Shadowing”
Systems: pA, AA
Small-x, mostly low-\(p_T\)
but EMC, anti-shadowing at high-\(p_T\)

Jet-Quenching
Systems: (pA), AA
Real high-\(p_T\)

LHC ENERGIES

... and predictions for LHC energies!
Suppression or Enhancement at LHC?

C.M. Energy dependence of GLV jet energy loss

\[ \Delta E_{GLV} \approx \frac{C_R \alpha_s}{N(E)} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu} = \frac{C_R \alpha_s}{N(E)} \frac{1}{A_{\perp}} \frac{dN}{dy} \langle L \rangle \log \frac{E}{\langle \mu \rangle} \]

- For central \( AuAu \) collision at RHIC \( \frac{1}{A_{\perp}} \frac{dN}{dy} \approx \frac{680}{\pi R_{dAu}^2} = 5.1 \)

- For \( dAu \) collision at RHIC \( \frac{1}{A_{\perp}} \frac{dN}{dy} \approx \frac{18}{\pi R_{dAu}^2} = 2.54 \)

- Without suppression \( \frac{dN}{dy} \sim \ln \sqrt{s} \)

- At LHC this \( \frac{dN}{dy} \) will be \( \sim 1500 - 2000 \)
Two main initial state effects:

Suppression can be strong at high-$p_T$ at the LHC energies. Cronin peak is slightly moving towards higher-$p_T$ values.
Two main initial state effects:
Suppression is stronger at low-$p_T$ at the LHC energies.
Cronin peak is slightly moving towards higher-$p_T$ values.