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Rescattering effects in p-nucleus and heavy-ion collisions

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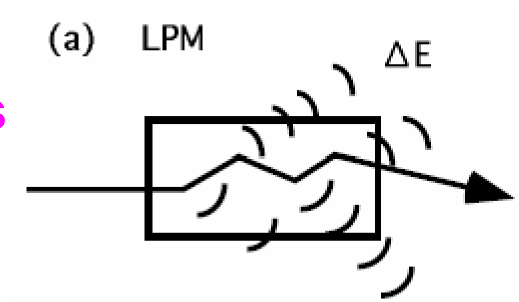
based work done with X. Guo, Ma Luo, G. Stermen, I. Vitev, X. Zhang, et al.

Outline of the Talk

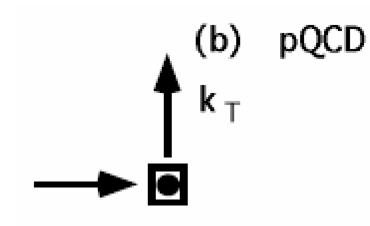
- Our approach to QCD rescattering
- Characteristic scale of QCD rescattering: $\langle F^{+\alpha} F_{\alpha}^{\ +} \rangle$
- Extract $\langle F^{+\alpha} F_{\alpha}^{\ +} \rangle$ from Drell-Yan k_T-broadening
- Extract $\langle F^{+\alpha} F_{\alpha}^{\ +} \rangle$ from DIS nuclear shadowing data
- Universality of the characteristic scale
- Low mass Drell-Yan and power corrections
- Summary and outlook

Our approach to the rescattering

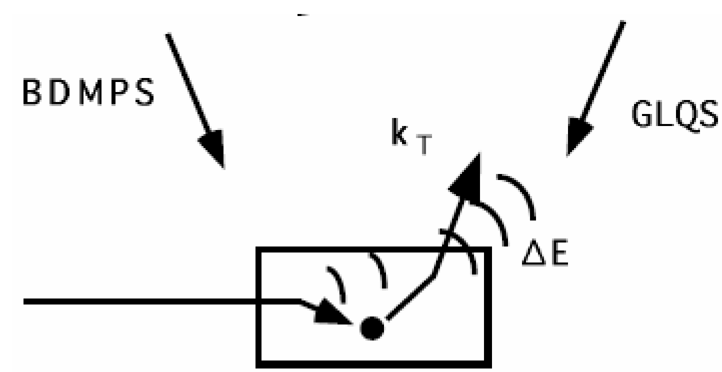
- Baier et al (BDMPS) treat energy lose due to many soft rescatterings
  Not hard scale is required



- We (Guo, et al) calculate coherent multiple scatterings in terms of perturbative QCD factorization
  A hard scale is required



- A complete analysis of hard probe in a large target involves both energy lose and hard momentum transfer
  e.g., Guo and Wang (PRL 85, 2000)



Our approach to the rescattering

❑ Advantage:

- ❖ factorization approach enables us to quantify the high order corrections
- ❖ express non-perturbative quantities in terms of matrix elements of well-defined operators – universality
- ❖ better predictive power

❑ Disadvantage:

- ❖ Rely on the factorization theorem – not easy to prove
- ❖ Hard probe might limit the region of coherence – small target

❑ Helper:

- ❖ Hard probe at small x could cover a large nuclear target

Size of the hard probes

- Size of a hard probe is very localized and much smaller than a typical hadron at rest

$$1/Q \ll 2R \sim \text{fm}$$

- But, it might be larger than a Lorentz contracted hadron:

$$1/Q > 2R\left(m/p\right)$$

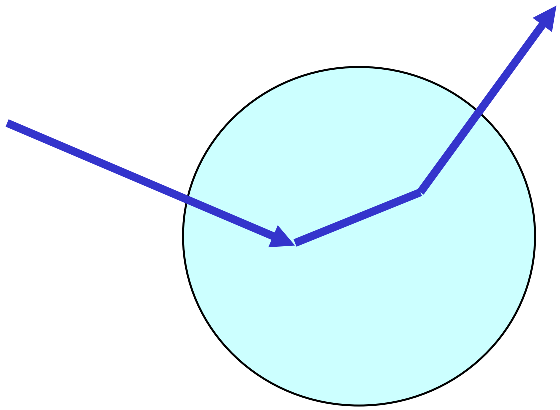
- low x: uncertainty in locating the parton is much larger than the size of the boosted hadron (a nucleon)

$$\frac{1}{Q} \sim \frac{1}{xp} \gg 2R\,\frac{m}{p} \quad \Rightarrow \quad x \ll x_c \equiv \frac{1}{2mR} \approx 0.1$$

If the active *x* is small enough
a hard probe could cover several nucleons
In a Lorentz contracted large nucleus!

Dynamical power corrections

- Coherent multiple scattering leads to dynamical power corrections:



$$\frac{d\sigma^{(D)}}{d\sigma^{(S)}} \sim \alpha_s \frac{1/Q^2}{R^2} \left\langle F^{+\alpha} F_\alpha^{+} \right\rangle A^{1/3}$$

$$d\sigma \approx d\sigma^{(S)} + d\sigma^{(D)} + \ldots$$

- Characteristic scale for the power corrections: $\left\langle F^{+\alpha} F_\alpha^{+} \right\rangle$

- For a hard probe: $\frac{\alpha_s}{Q^2 R^2} \ll 1$

- To extract the universal matrix element, we need new observables more sensitive to $\left\langle F^{+\alpha} F_\alpha^{+} \right\rangle$

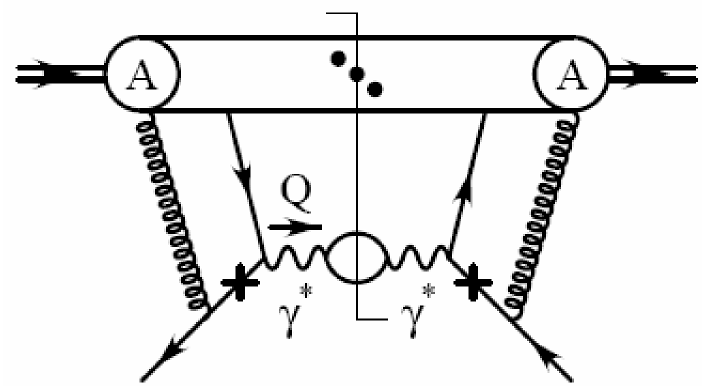
Drell-Yan Q_T broadening

Guo, PRD 58 (1998)

❑ **Drell-Yan Q_T average:** $\langle Q_T^2 \rangle \equiv \int dQ_T^2 \left(Q_T^2\right) \left(\frac{d\sigma}{dQ^2 dQ_T^2} \right) \Big/ \int dQ_T^2 \left(\frac{d\sigma}{dQ^2 dQ_T^2} \right)$

❑ **Drell-Yan Q_T broadening:** $\Delta \langle Q_T^2 \rangle \equiv \langle Q_T^2 \rangle^{hA} - A \langle Q_T^2 \rangle^{hN} \propto \sigma^{(D)}$

$$\frac{d\sigma}{dQ^2 dQ_T^2} \Big/ \frac{d\sigma}{dQ^2} \propto \frac{\alpha_s}{Q_T^2} T_q(x, A)$$



❑ **Four-parton correlation:**

$$T_q(x,A) = \int \frac{dy^-}{2\pi} e^{ixp^+y^-} \int dy_1^- dy_2^- \theta\left(y^- - y_1^-\right)\theta\left(-y_2^-\right)$$
$$\times \langle p_A | F_\alpha^+ \left(y_2^-\right) \bar{\psi}(0) \frac{\gamma^+}{2} \psi\left(y^-\right) F^{+\alpha}\left(y_1^-\right) | p_A \rangle \approx \frac{9A^{1/3}}{16\pi R^2} \langle F^{+\alpha} F_\alpha^+ \rangle q_A(x)$$

❑ **Characteristic scale:**

$$\langle F^{+\alpha} F_\alpha^+ \rangle \equiv \frac{1}{p^+} \int dy_1^- \langle N | F^{+\alpha}(0) F_\alpha^+ \left(y_1^-\right) | N \rangle \theta\left(y_1^-\right)$$

$\langle F^{+\alpha} F_{\alpha}^{+} \rangle$ from Drell-Yan Q_T broadening

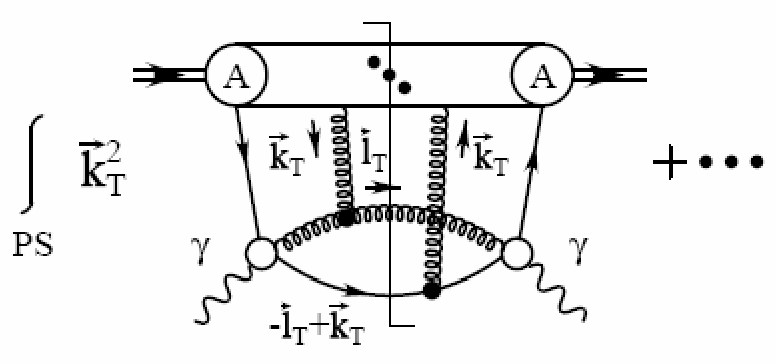
- **Drell-Yan Q_T broadening:**

$$\Delta\langle Q_T^2 \rangle \equiv \langle Q_T^2 \rangle^{hA} - A\langle Q_T^2 \rangle^{hN} = \left(\frac{3\pi\alpha_s}{4R^2}\right)\langle F^{+\alpha} F_{\alpha}^{+} \rangle A^{1/3}$$

E772 and NA10 data: ⟹ $\langle F^{+\alpha} F_{\alpha}^{+} \rangle \sim 3-4$ Guo, PRD 58 (1998)

In cold nuclear matter

- **Di-jet momentum imbalance in $\gamma + A$ collisions**



⟹ $\langle F^{+\alpha} F_{\alpha}^{+} \rangle_{Di-jet} \sim 15-40$

Luo et al, PRD 49 (1994)

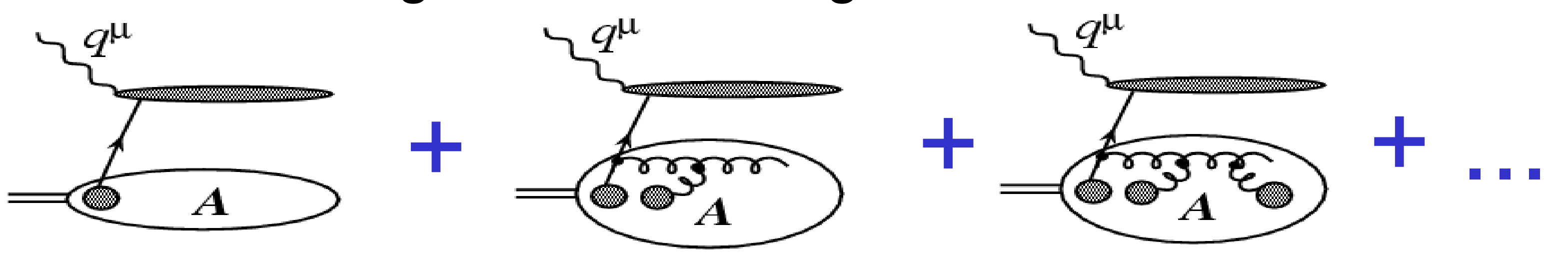
Need more independent measurements to test the universality!

Inclusive deep inelastic scattering

- **Nuclear shadowing data are available for $x_B < 0.1$**
- **Interpretation:**

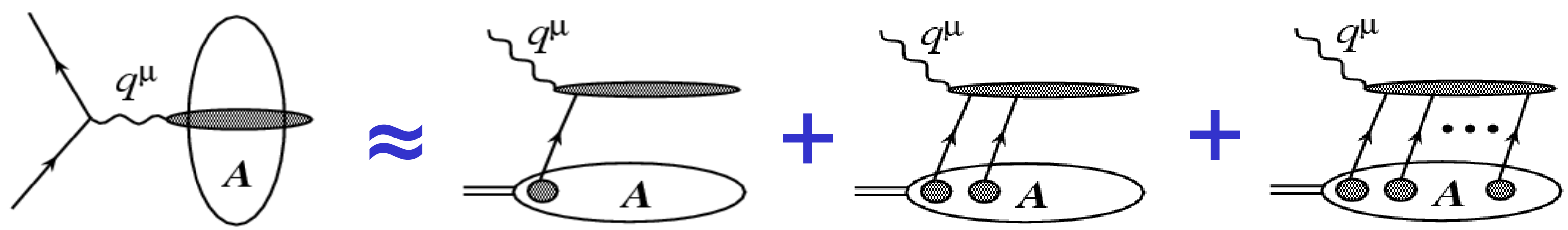
Parton recombination and saturation, color glass condensate to parton density in a larger nucleus

⇨ **Leading twist shadowing**



- **But, experiments measure cross sections, not parton distributions:**

At small x, the hard probe covers several nucleons, coherent multiple scattering could be equally important at relatively low Q



Coherent multiple scattering in DIS

- **Collinear factorization to DIS cross section:**

Leading twist

$$d\sigma_{DIS}^{\gamma^* h} = d\hat{\sigma}_2^i \otimes [1 + C^{(1,2)}\alpha_s + C^{(2,2)}\alpha_s^2 + \ldots] \otimes T_2^{i/h}(x)$$

$$+ \frac{d\hat{\sigma}_4^i}{Q^2} \otimes [1 + C^{(1,4)}\alpha_s + C^{(2,4)}\alpha_s^2 + \ldots] \otimes T_4^{i/h}(x)$$

$$+ \frac{d\hat{\sigma}_6^i}{Q^4} \otimes [1 + C^{(1,6)}\alpha_s + C^{(2,6)}\alpha_s^2 + \ldots] \otimes T_6^{i/h}(x)$$

$$+ \ldots$$

Power corrections

Factorization breaks in hadronic collisions beyond $1/Q^2$ terms

- **Nonperturbative contributions:**

$T_{4,\ldots}^{i/h}(x)$ should include both $\langle k_T^2 \rangle$ and multiple scattering effect $\langle F^{+\alpha} F_\alpha^{\ +} \rangle$

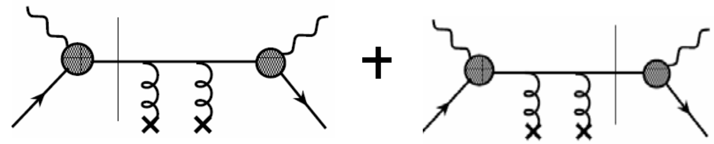
Resummation of leading power corrections: $\sum_N \left(\frac{\alpha_s}{Q^2 R^2} \langle F^{+\alpha} F_\alpha^{\ +} \rangle A^{1/3} \right)^N$

Resummation of multiple scattering

- **LO contribution to DIS cross section:**

$$\Longrightarrow \quad \delta(x - x_B)$$

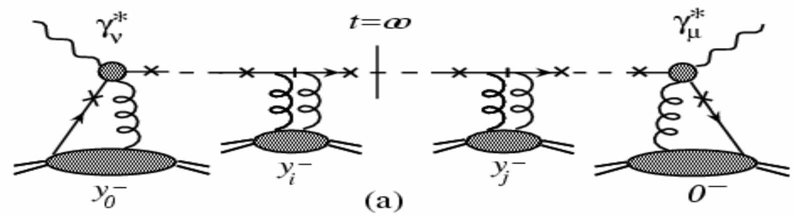
- **NLO contribution:**



$$\Longrightarrow \quad \frac{g^2}{Q^2}\left(\frac{1}{2N_c}\right)\left[2\pi^2\tilde{F}^2(0)\right] x_B \lim_{x_1\to x}\left[\frac{1}{x-x_1}\delta(x_1-x_B)+\frac{1}{x_1-x}\delta(x-x_B)\right]$$

$$\int\frac{dy_2^-\,dy_1^-}{(2\pi)^2}\left[F^{+\alpha}(y_2^-)F_\alpha^{\ +}(y_1^-)\right]\theta(y_2^-) \qquad x_B\left[-\frac{d}{dx}\delta(x-x_B)\right]$$

- **Nth order contribution:**



$$\Longrightarrow$$

$$\left[\frac{g^2}{Q^2}\left(\frac{1}{2N_c}\right)\left[2\pi^2\tilde{F}^2(0)\right]\right]^N x_B^N \lim_{x_i\to x}\sum_{m=0}^{N}\delta(x_m-x_B)\left[\prod_{i=1}^{m}\left(\frac{1}{x_{i-1}-x_m}\right)\right]\left[\prod_{j=1}^{N-m}\left(\frac{1}{x_{m+j}-x_m}\right)\right]$$

Infrared safe!

$$x_B^N\left[(-1)^N\frac{1}{N!}\frac{d^N}{dx^N}\delta(x-x_B)\right]$$

Contributions to DIS structure functions

- **Transverse structure function:**

Qiu and Vitev, PRL (in press)

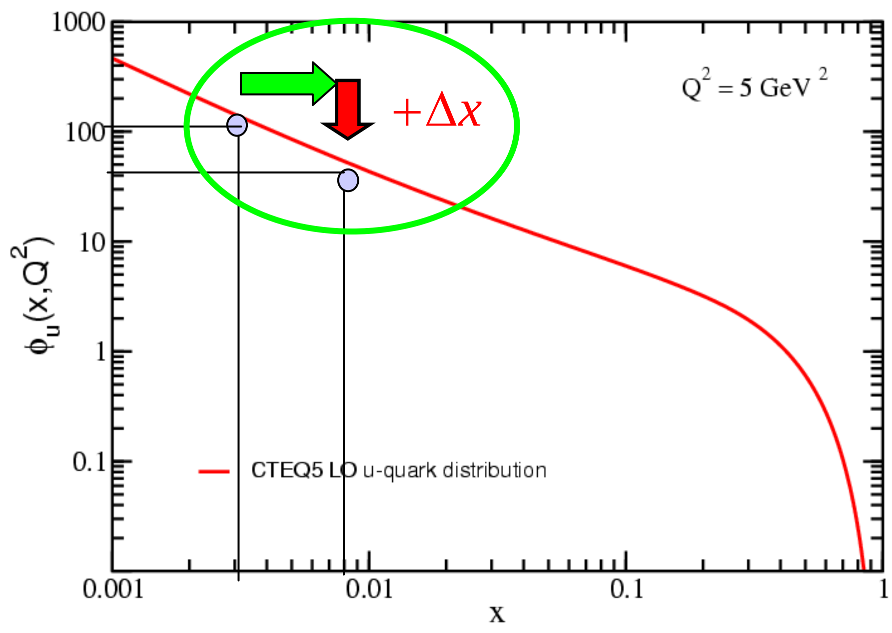
$$F_T(x_B,Q^2)=\sum_{n=0}^{N}\frac{1}{n!}\left[\frac{\xi^2}{Q^2}\left(A^{1/3}-1\right)\right]^n x_B^n\frac{d^n}{dx_B^n}F_T^{(0)}(x_B,Q^2)$$

$$\approx F_T^{(0)}(x_B(1+\Delta),Q^2)$$

Similar expression of F_L

$$\Delta\equiv\frac{\xi^2}{Q^2}\left(A^{1/3}-1\right)$$

$$\xi^2=\frac{3\pi\alpha_s}{8R^2}\langle F^{+\alpha}F_\alpha{}^{+}\rangle$$



Single parameter for the power correction, and is proportional to the same characteristic scale

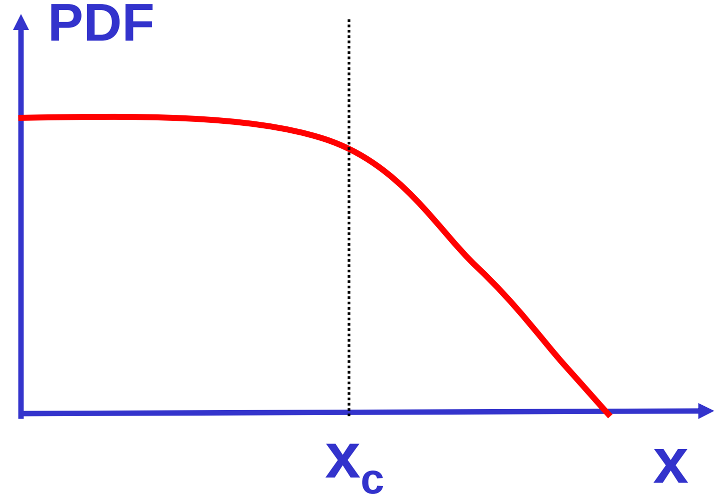
Leading twist shadowing

- **Power corrections complement to the leading twist shadowing:**
  - **Leading twist shadowing changes the x- and Q-dependence of the parton distributions**
  - **Power corrections to the DIS structure functions (or cross sections) are effectively equivalent to a shift in x**
  - **Power corrections vanish quickly as hard scale Q increases while the leading twist shadowing goes away much slower**

- **If leading twist shadowing is so strong that x-dependence of parton distributions saturates**

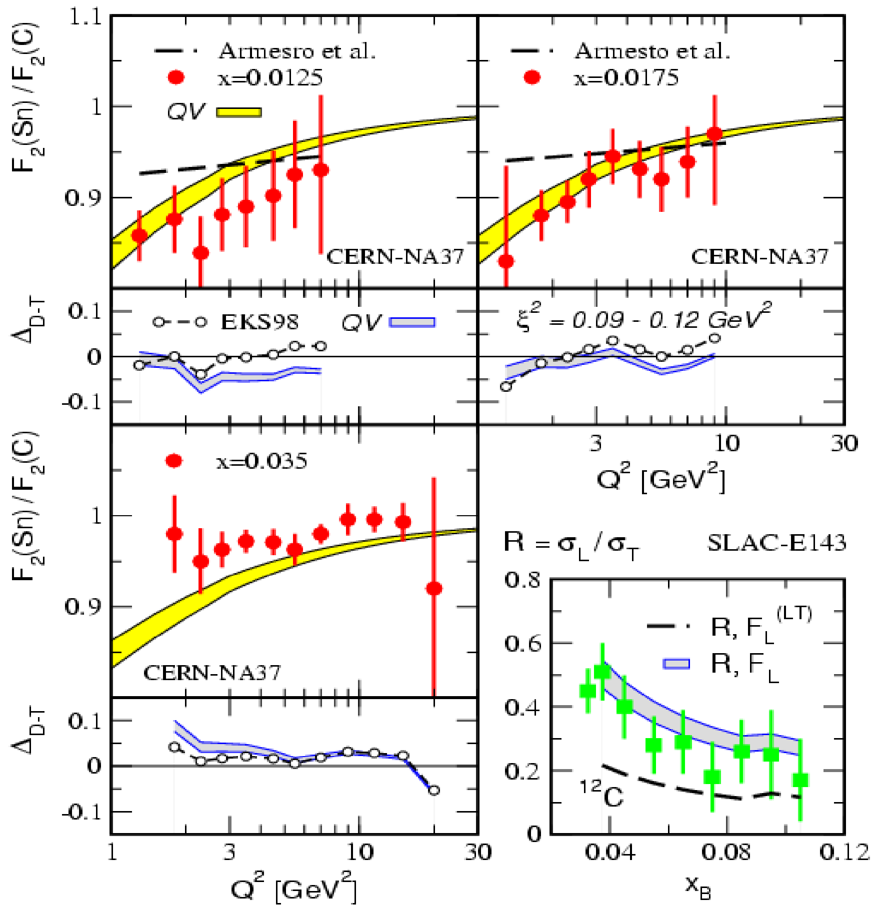
  for $x < x_c$,

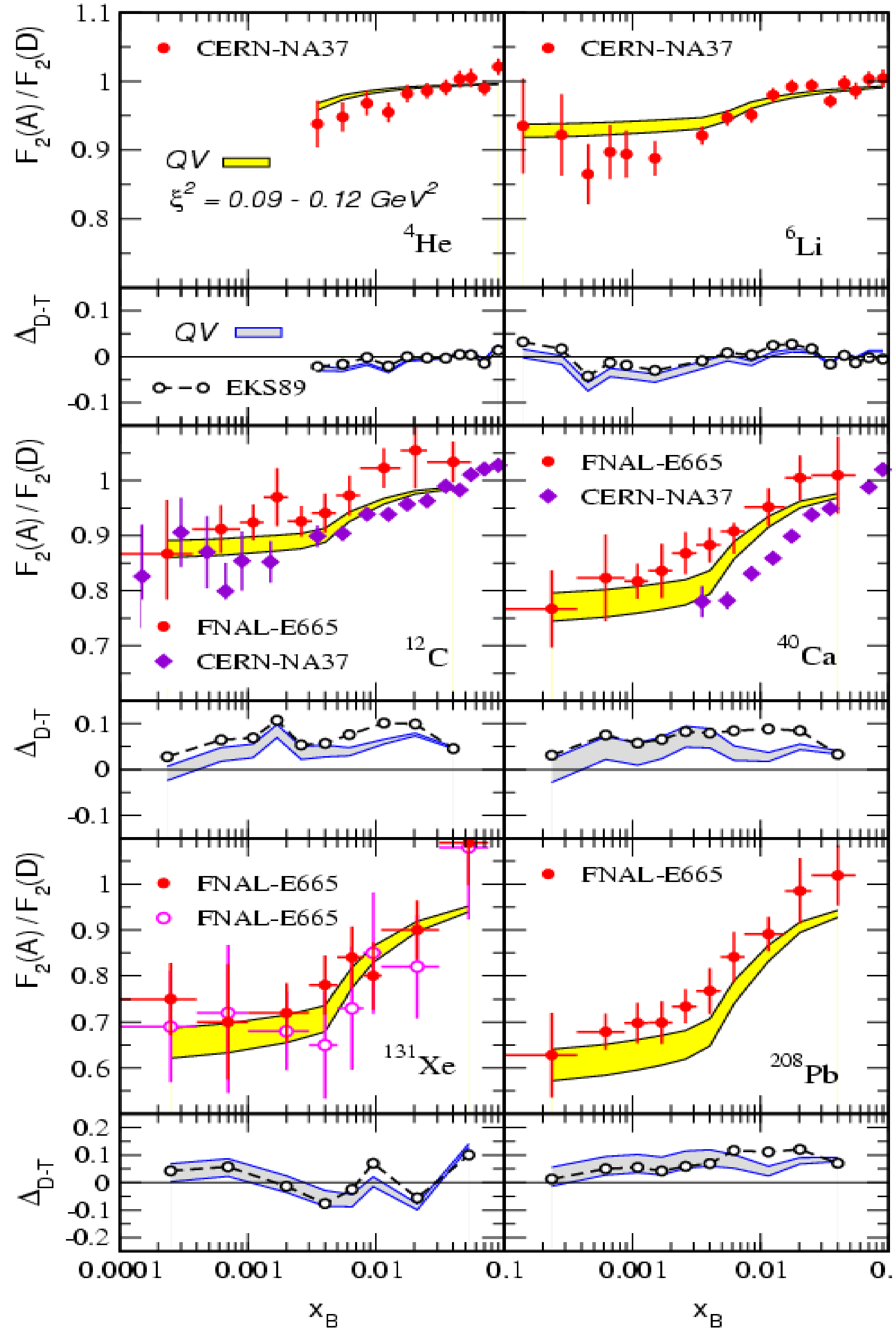
  additional power corrections, the shift in x, should have no effect to the cross section!



Neglect LT shadowing upper limit of ξ^2

$\xi^2 \sim$ 0.09 - 0.12 GeV^2





Upper limit of $\langle F^{+\alpha} F_\alpha^{+} \rangle$ from DIS data

- Drell-Yan Q_T-broadening data:

$$\Longrightarrow \langle F^{+\alpha} F_\alpha^{+} \rangle_{DY} \sim 3-4 \quad \Longrightarrow \quad \xi^2 \approx 0.05-0.06 \text{ GeV}^{-2}$$

- Upper limit from the shadowing data:

$$\Longrightarrow \quad \xi^2_{Max} \approx 0.09 \text{ - } 0.12 \text{ GeV}^{-2} \quad \Longrightarrow \quad \langle F^{+\alpha} F_\alpha^{+} \rangle_{DIS} < 6$$

- "Saturation" scale of cold nuclear matter:

$$Q_s^2 \sim \xi^2 A^{1/3} \leq 0.3 \text{ GeV}^2 \text{ seen by quarks}$$

$$\leq 0.6 \text{ GeV}^2 \text{ seen by gluons}$$

- Physical meaning of these numbers:

$$\langle F^{+\alpha} F_\alpha^{+} \rangle \equiv \frac{1}{p^+} \int dy_1^- \langle N | F^{+\alpha}(0) F_\alpha^{+}(y_1^-) | N \rangle \theta(y_1^-) \approx \frac{1}{2} \lim_{x \to 0} xG(x, Q^2)$$

$$\Longrightarrow \langle xG(x \to 0, Q_s^2) \rangle \leq 8 \text{ in cold nuclear matter(?)}$$

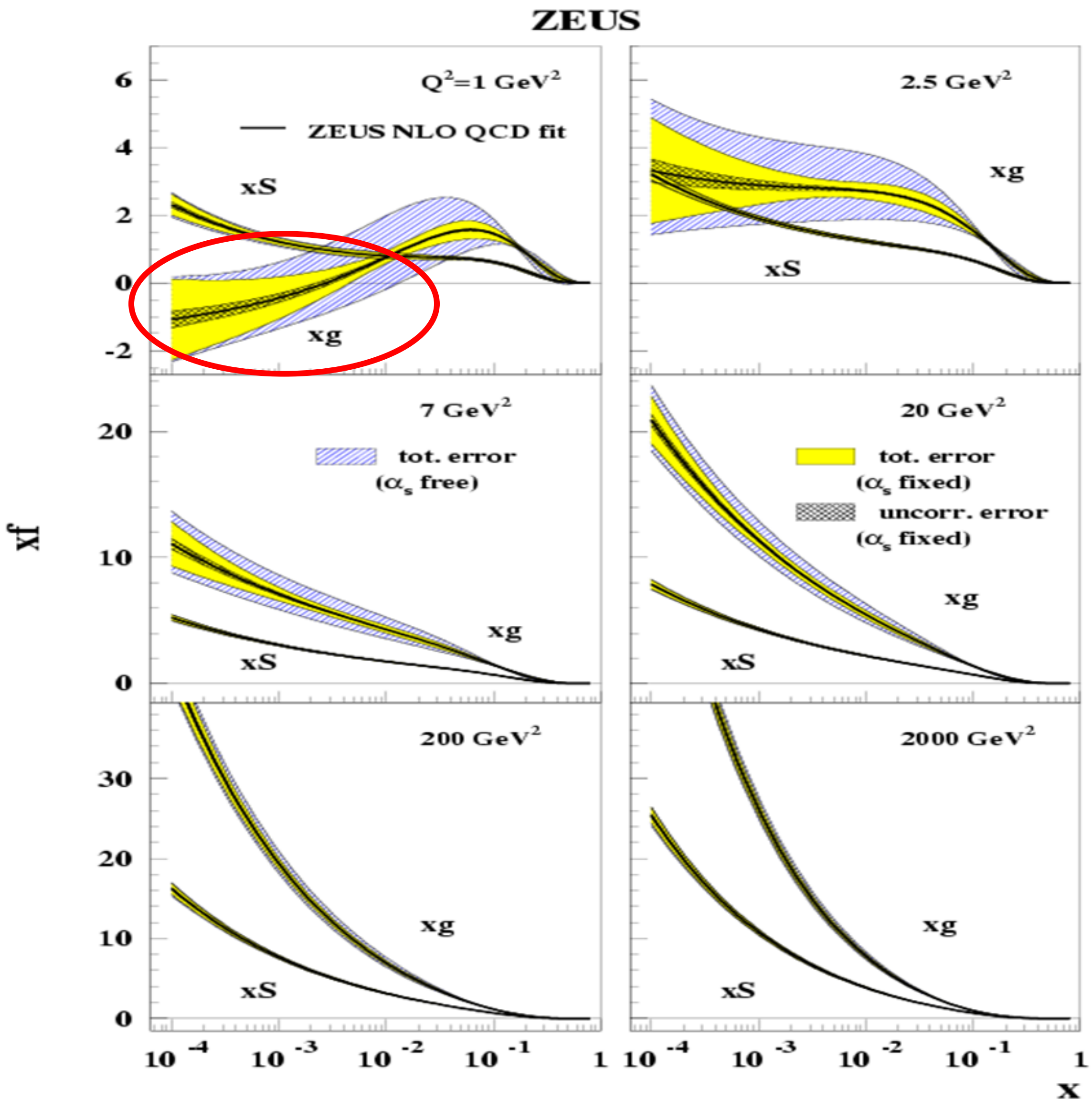
Negative gluon distribution at low Q

- ❑ NLO global fitting based on leading twist DGLAP evolution leads to negative gluon distribution

- ❑ MRST PDF's have the same features

Does it mean that we have no gluon for $x < 10^{-3}$ at 1 GeV?

No!



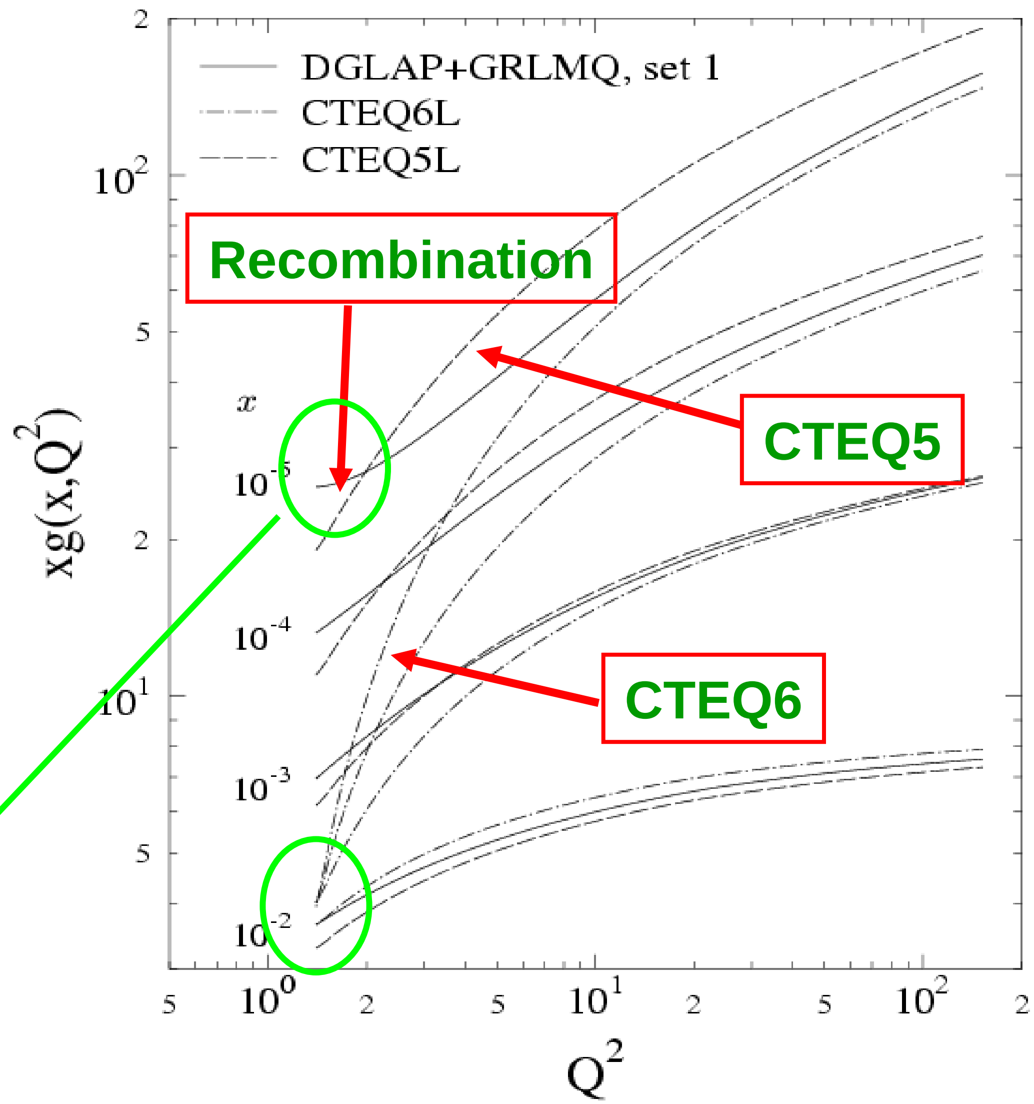
Recombination prevents negative gluon

- In order to fit new HERA data, like MRST PDF's, CTEQ6 gluon has to be much smaller than CTEQ5, even negative at Q = 1 GeV

- The power correction to the evolution equation slows down the Q^2-dependence, prevents PDF's to be negative

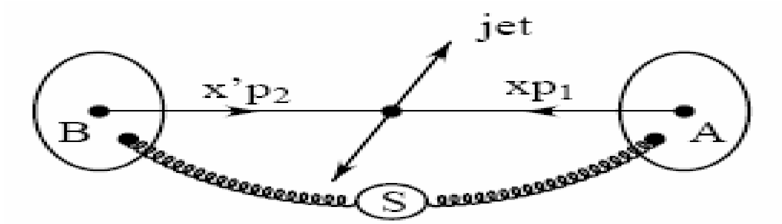
$$\langle xG(x \to 10^{-5}) \rangle \sim 3$$

Eskola et al. NPB660 (2003)

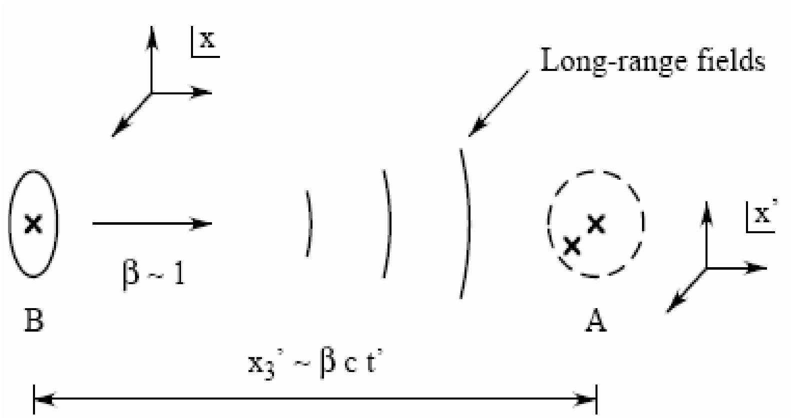


Factorization in hadron-hadron collisions

- Soft-gluon interactions take place **all the time:**



- Factorization = Soft-gluon interactions are powerly **suppressed**



x-Frame	x'-Frame
$A^-(x) = \frac{e}{\lvert\vec{x}\rvert}$	$A'^-(x') = \frac{e\gamma(1+\beta)}{(x_T^2+\gamma^2\Delta^2)^{1/2}}$ $\Longrightarrow 1$ "not contracted!"
$E_3(x) = \frac{e}{\lvert\vec{x}\rvert^2}$	$E_3(x') = \frac{-e\gamma\Delta}{(x_T^2+\gamma^2\Delta^2)^{3/2}}$ $\Longrightarrow \frac{1}{\gamma^2}$ "strongly contracted!"

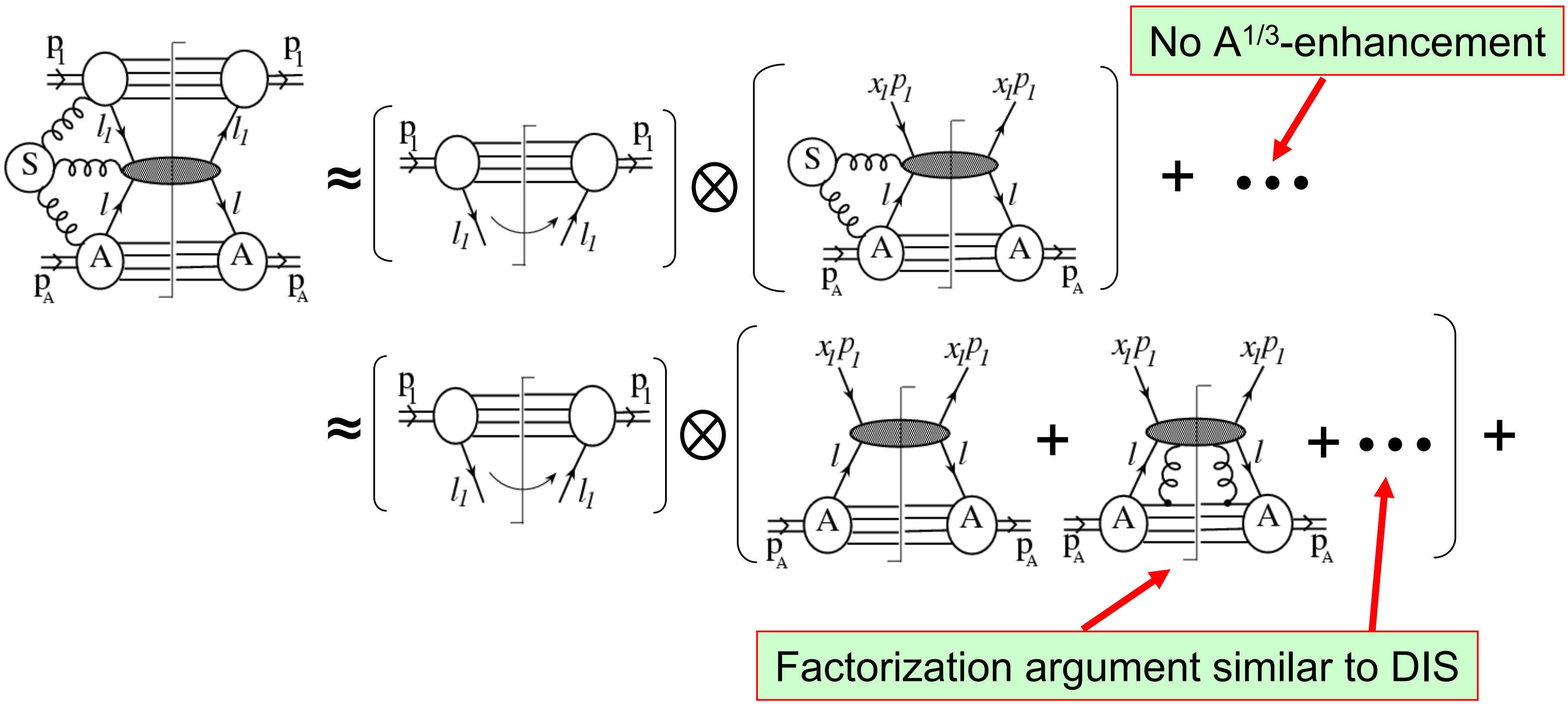
- Factorization **breaks** beyond 1/Q^2 term:

$$\sigma(Q) = H^0 \otimes f_2 \otimes f_2 + \left(\frac{1}{Q^2}\right) H^1 \otimes f_2 \otimes f_4 + O\left(\frac{1}{Q^4}\right)$$

Doria, et al (1980)
Basu et al. (1984)
Brandt, et al (1989)

Role of $\langle F^{+\alpha} F_{\alpha}^{+} \rangle$ in p-nucleus collisions

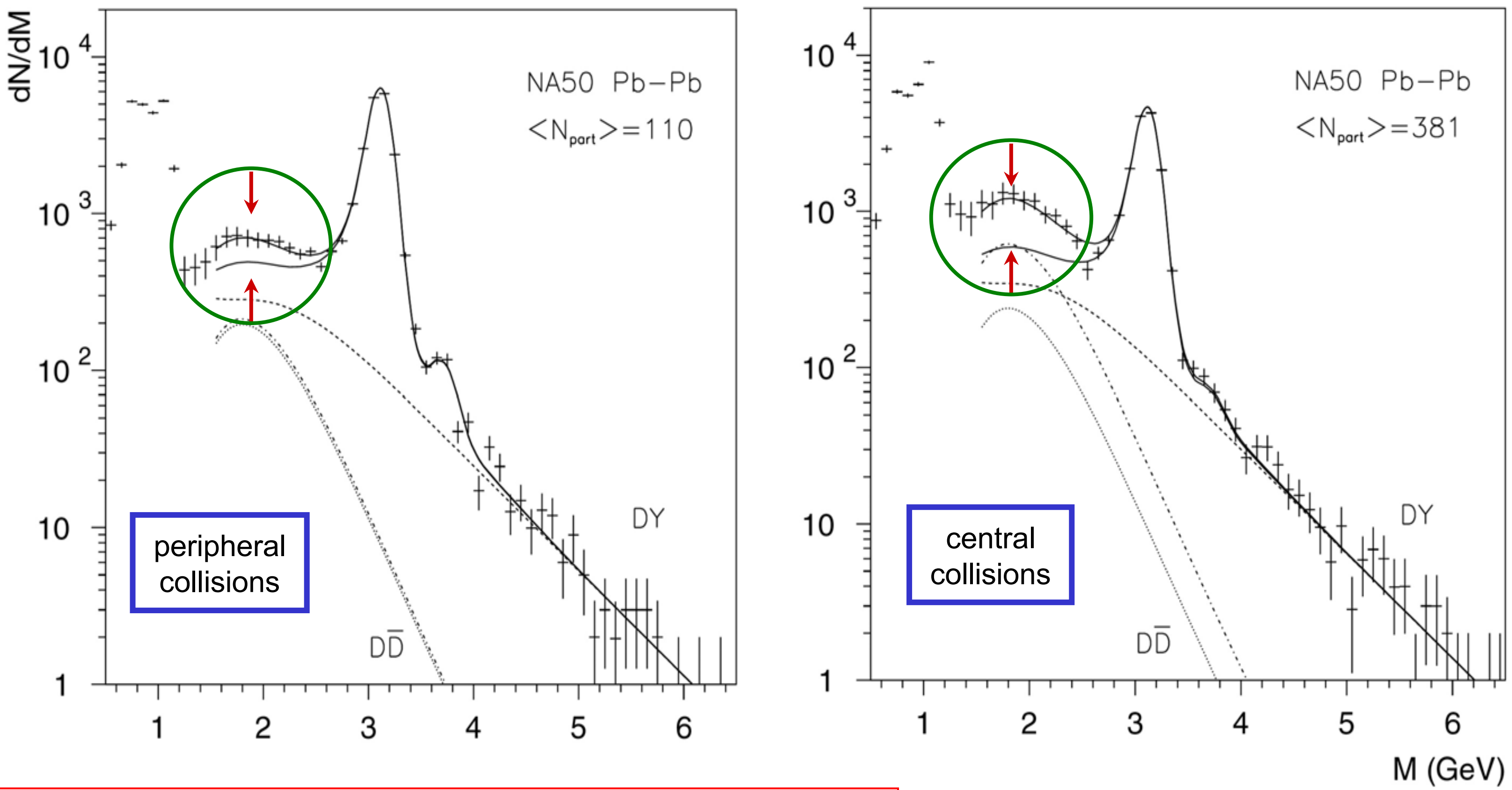
- A-enhanced power corrections, $A^{1/3}/Q^2$, are factorizable:



- But, power corrections are process-dependent, and they are different from DIS

Drell-Yan at low mass

❑ **Enhancement of low mass dileptons in heavy ion collisions:**



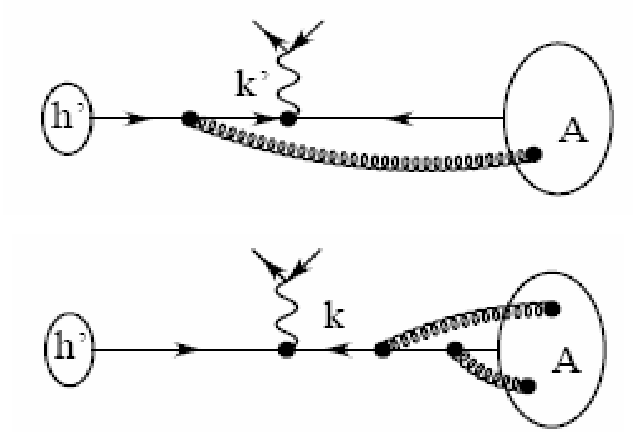
Unlike DIS, coherent power corrections to Drell-Yan cross section are positive!

Figures from Shahoyan's talk

Predicted power corrections to DY

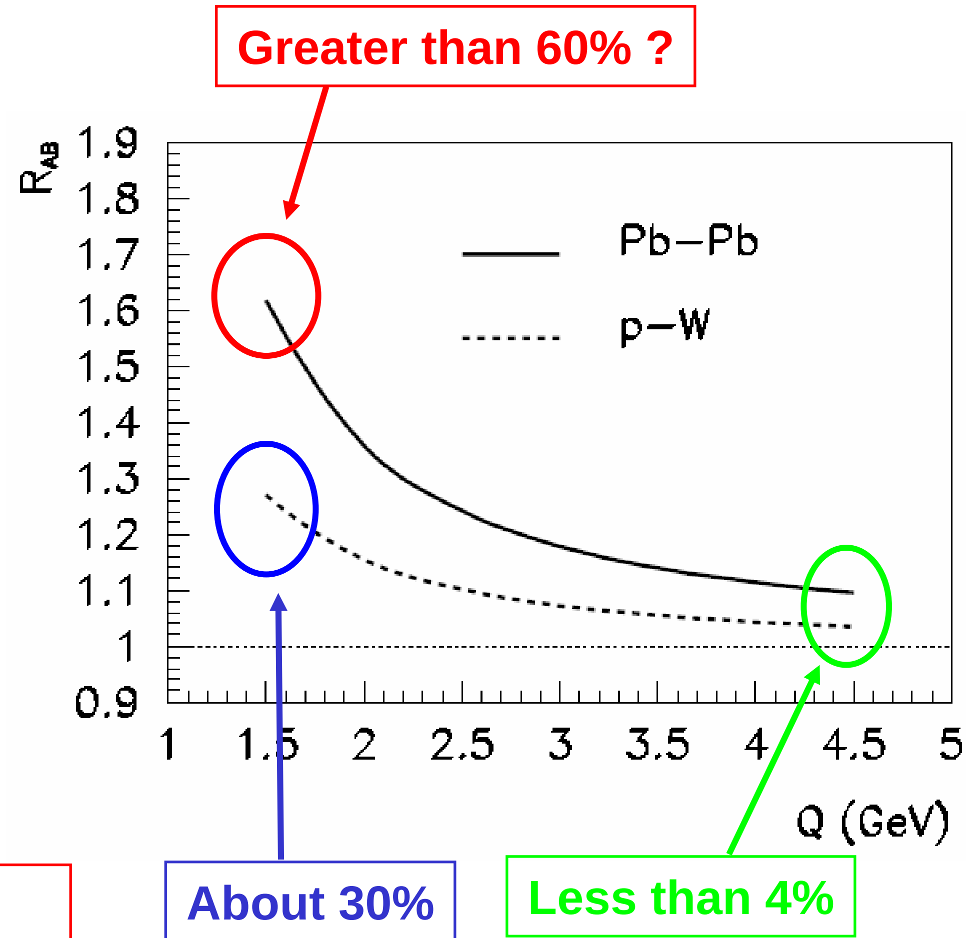
- Drell-Yan in h-nucleus collisions:

Qiu and Zhang, PLB525 (2002)



$$\frac{d\sigma_{AB}}{dQ^2} \approx AB\frac{d\sigma_{NN}^{(s)}}{dQ^2} + \frac{d\sigma_{AB}^{(d)}}{dQ^2} + $$

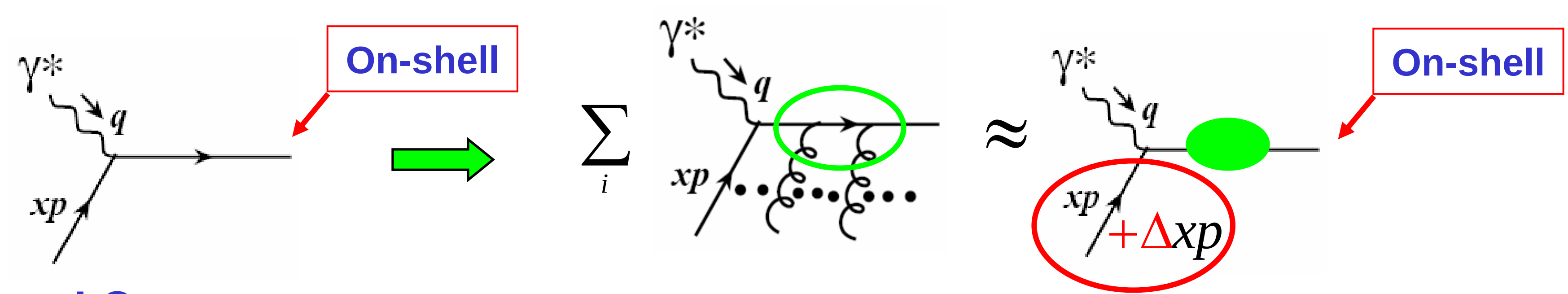
$$\equiv AB\frac{d\sigma_{NN}^{(s)}}{dQ^2} R_{AB}(Q)$$



Depends on the same $\langle F^{+\alpha} F_{\alpha}^{+} \rangle_{DY}$ **and no additional free parameters**

Intuition for the power corrections

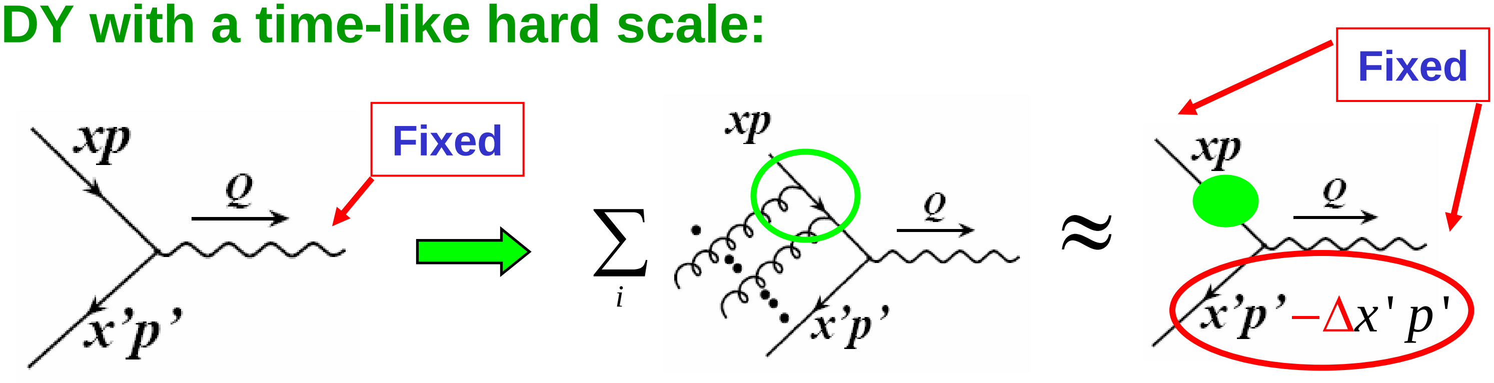
❑ DIS with a space-like hard scale:



LO

Resum all powers

❑ DY with a time-like hard scale:



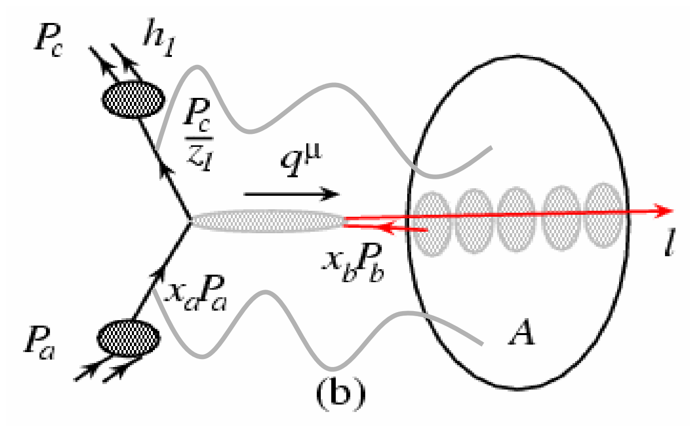
LO

Resum all powers

Power Corrections in p+A Collisions

- Hadronic factorization fails for power corrections of the order of $1/Q^4$ and beyond
- Medium size enhanced dynamical power corrections in p+A could be factorized

⇨ **to make predictions for p+A collisions**



- Single hadron inclusive production:

Once we fix the incoming parton momentum from the beam and outgoing fragmentation parton, we uniquely fix the momentum exchange, q^μ, and the probe size

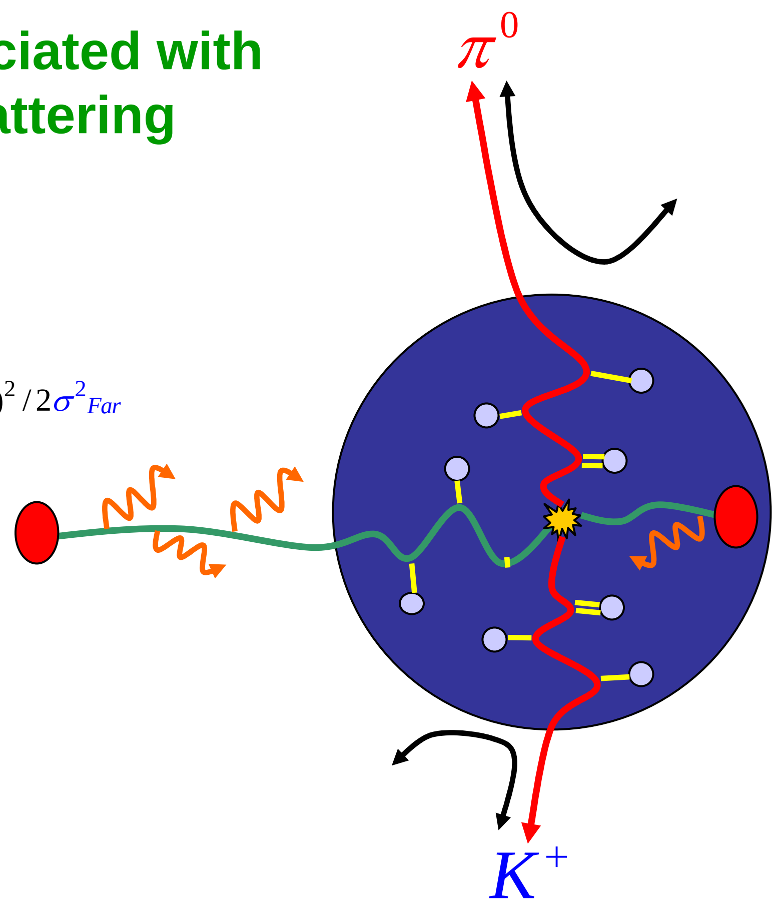
⇔ coherence along the direction of $q^\mu - p^\mu$

Acoplanarity and power corrections

- Consider di-hadron correlations associated with hard (approximately) back-to-back scattering

$$C_2(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN^{h_1h_2}{}_{dijet}(|y_1 - y_2|)}{d\Delta\phi}$$

$$\approx \frac{A_{Near}(|y_1 - y_2|)}{\sqrt{2\pi}\sigma_{Near}} e^{-\Delta\phi^2/2\sigma^2{}_{Near}} + \frac{A_{Far}}{\sqrt{2\pi}\sigma_{Far}} e^{-(\Delta\phi-\pi)^2/2\sigma^2{}_{Far}}$$



- Coherent scattering reduces:

$$A_{Far}(p+A) = R^{h_1h_2}(p_T) < 1$$

- Incoherent scattering broadens:

$$\langle k_\perp{}^2 \rangle_{pair} = \langle k_\perp{}^2 \rangle_{vac} + \sum_i \langle k_\perp{}^2 \rangle_i^{broad}$$

$$\langle k_T{}^2 \rangle_{IS} = 2\xi \frac{\mu^2}{\lambda_{q,g}} \langle L \rangle \qquad \langle k_T{}^2 \rangle_{FS} = \begin{cases} 2\xi \dfrac{\mu^2}{\lambda_{q,g}} \langle L \rangle & \text{Cold} \\ 2\xi \dfrac{3C_R \pi \alpha_s^2}{2} \dfrac{1}{A_\perp} \dfrac{dN^g}{dy} \ln \dfrac{\langle L \rangle}{\tau_0} & \text{Hot 1+1D} \end{cases}$$

Dihadron Correlation Broadening and Attenuation

Mid-rapidity and moderate p_T

- Only small broadening versus centrality
- Looks rather similar at forward rapidity of 2
- The reduction of the area is rather modest

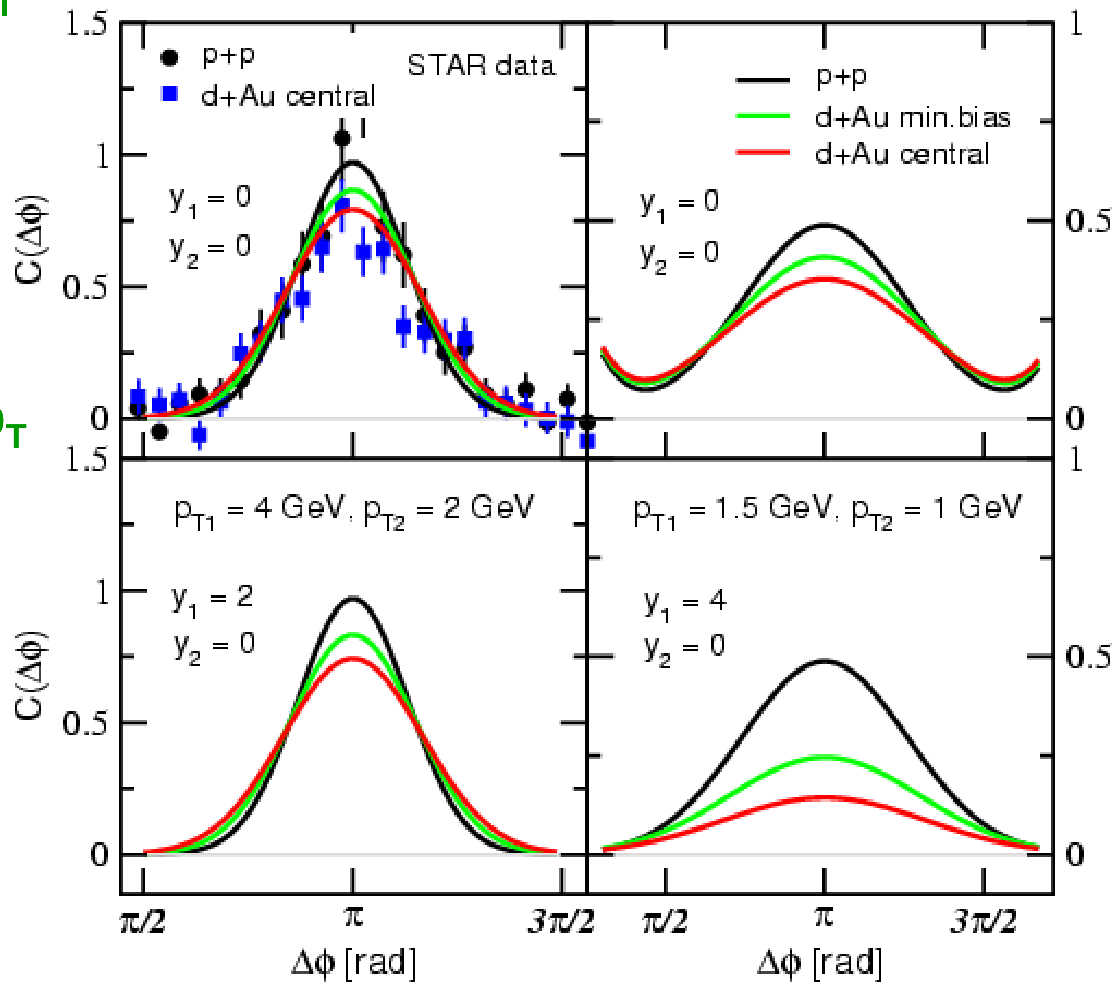
Forward rapidity and small p_T

- Apparently broader $\Delta\phi$ distribution
- Even at midrapidity a small reduction of the area
- Factor of 2-3 reduction of the area at forward rapidity of 4

Trigger bias can also affect:

$$A_{Far} \sim (-t) \sim 1/z_1$$

J.Adams *et al*., Phys.Rev.Lett. 91 (2003)



Qiu and Vitev, Phys.Lett.B 570 (2003); hep-ph/0405068

Summary and outlook

- Introduce a systematic factorization approach to coherent QCD rescattering in nuclear medium.
- Leading medium size enhanced nuclear effects due to power corrections can be systematically calculated, and they complement to the leading twist (universal) nuclear effects
- Identify a characteristic scale for the QCD rescattering: $\left\langle F^{+\alpha} F_{\alpha}^{+} \right\rangle$ which corresponds to a mass scale 0.6 GeV^2 (seen by gluons) in cold nuclear matter
- The characteristic scale depends on the medium and could have temperature dependence
- Many applications:

  Guo and Wang, PRL85 (2000)

  power (or non-linear) corrections to fragmentation functions

  jet broadening and suppression of jet correlation in p-A

  …

  Qiu and Vitev, PLB587 (2004) hep-ph/0405068

Backup transparencies

The Gross-Llewellyn Smith Sum Rules

$$S_{GLS} = \int_0^1 dx\ \frac{1}{2x}\left(xF_3^{\nu N}(x,Q^2) + xF_3^{\bar{\nu} N}(x,Q^2)\right)$$

$$\approx \#U + \#D = 3$$

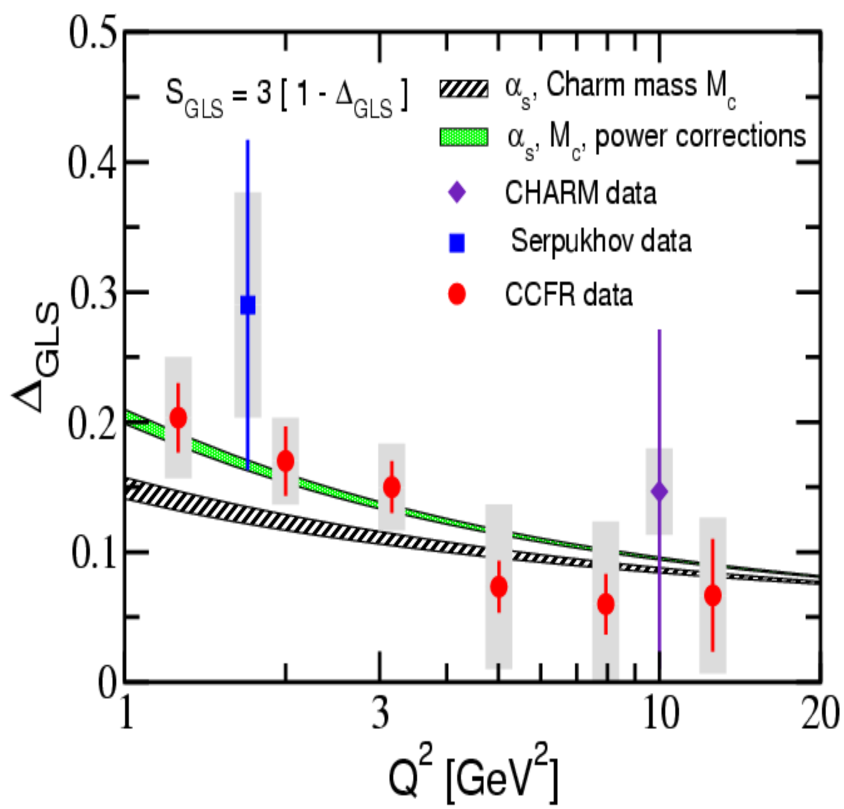
D.J.Gross and C.H Llewellyn Smith , Nucl.Phys. B 14 (1969)

$$\Delta_{GLS} \equiv \frac{1}{3}(3 - S_{GLS}) = \frac{\alpha_s(Q)}{\pi} + \frac{\kappa}{Q^2} + O\left(\frac{1}{Q^4}\right)$$

Fully coherent final-state power corrections to the sum rule almost cancel due to the unitarity:

$$\int_{-\infty}^{+\infty} dx\ \varphi(x + \Delta x) = \int_{-\infty}^{+\infty} dx\ \varphi(x)$$

But, nuclear enhanced power corrections only for a limited values of $x \in (0, 0.1)$



Qiu and Vitev, Phys.Lett.B 587 (2004)

Prediction is compatible with the trend in the current data

Process-dependent power corrections are important!

Numerical results for the power corrections

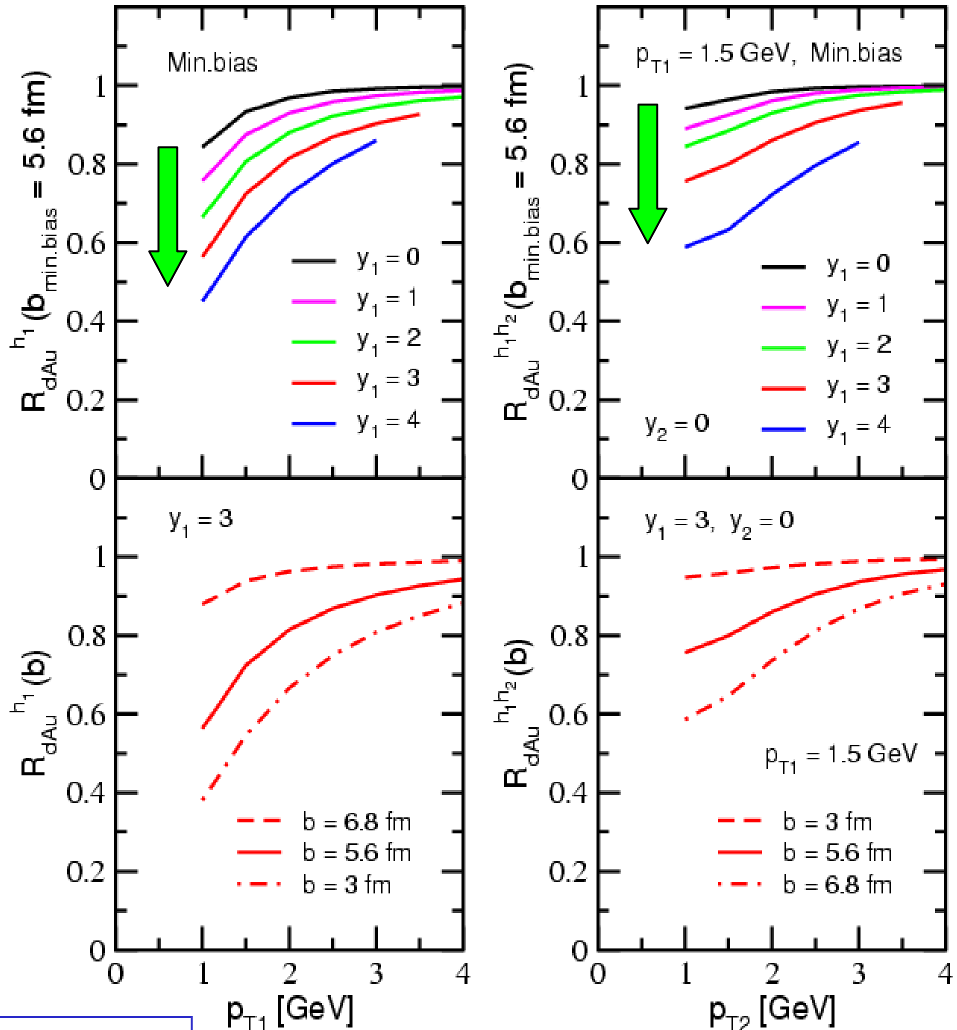
❖ **Similar power correction modification to single and double inclusive hadron production**

- **increases with rapidity**
- **increases with centrality**
- **disappears at high p_T in accord with the QCD factorization theorems**
- **single and double inclusive shift in ~ ξ^2 /t**

$$s = 2\frac{p_T^2}{z^2}(1+\cosh(y_1 - y_2)),$$

$$t = -\frac{p_T^2}{z^2}(1+\exp(-y_1 + y_2)),$$

$$u = -\frac{p_T^2}{z^2}(1+\exp(y_1 - y_2))$$



Small at mid-rapidity C.M. energy 200 GeV
Even smaller at mid-rapidity C.M. energy 62 GeV

Qiu and Vitev, hep-ph/0405068