R_{pA} for single hadron production

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Outline

- ✧ What do we know?
- ✧ What we want to know?
- ✧ What we expect to see?
- ✧ What could be surprises?
- ✧ What ...

CERN Workshop on "pA@LHC", June 4 - 8, 2012, Geneva, Switzerland

What do we know?

❑ Cronin effect:

Cronin et al., Phys. Rev. D11, 3105, (1975)

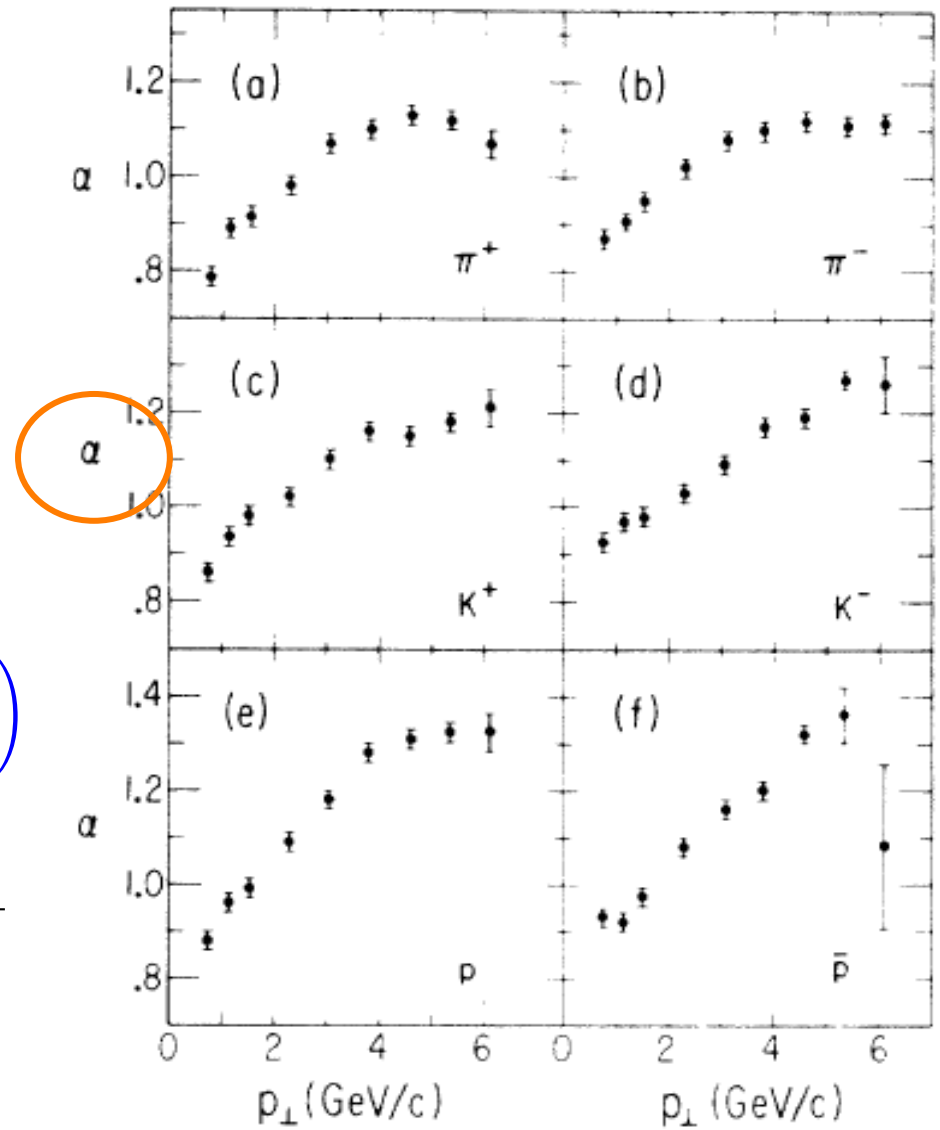
$$p + A \to \text{hadron(p)} + X$$

Fermilab fixed target with a proton beam of energy: 200, 300, 400 GeV

$$E\frac{d\sigma^{hA}}{d^3p} \equiv E\frac{d\sigma^{hN}}{d^3p}\, A^{\alpha(p)}$$

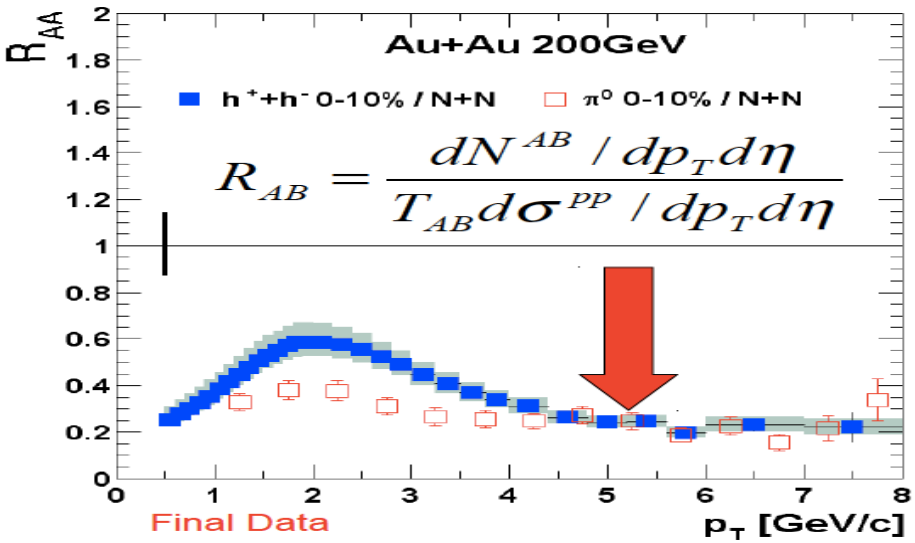
If $R_{pA} \equiv E\frac{d\sigma^{hA}}{d^3p} \Big/ \left(A \times E\frac{d\sigma^{hN}}{d^3p}\right)$

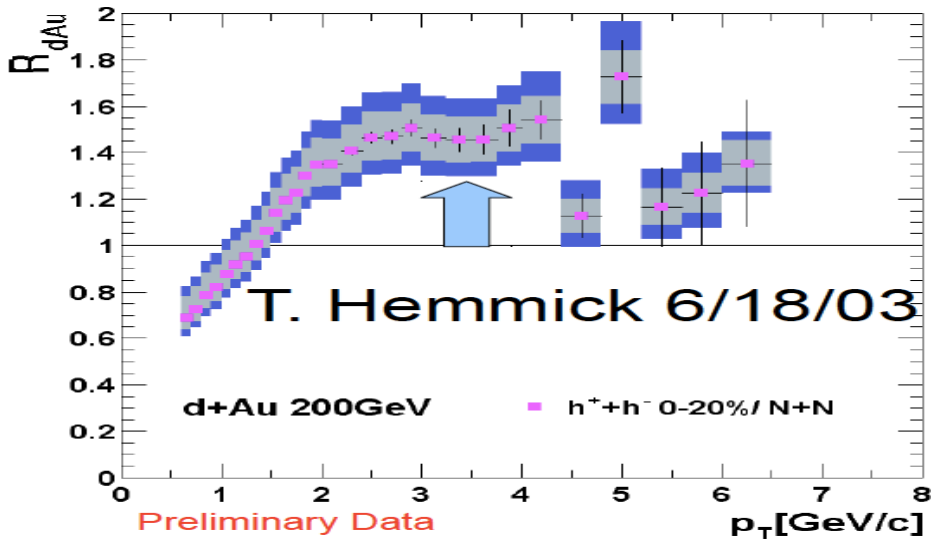
$$\alpha(p) = 1 + \frac{\ln(R_{pA})}{\ln(A)} \approx 1 + \frac{\ln(R_{pA})}{A^{1/3}}$$

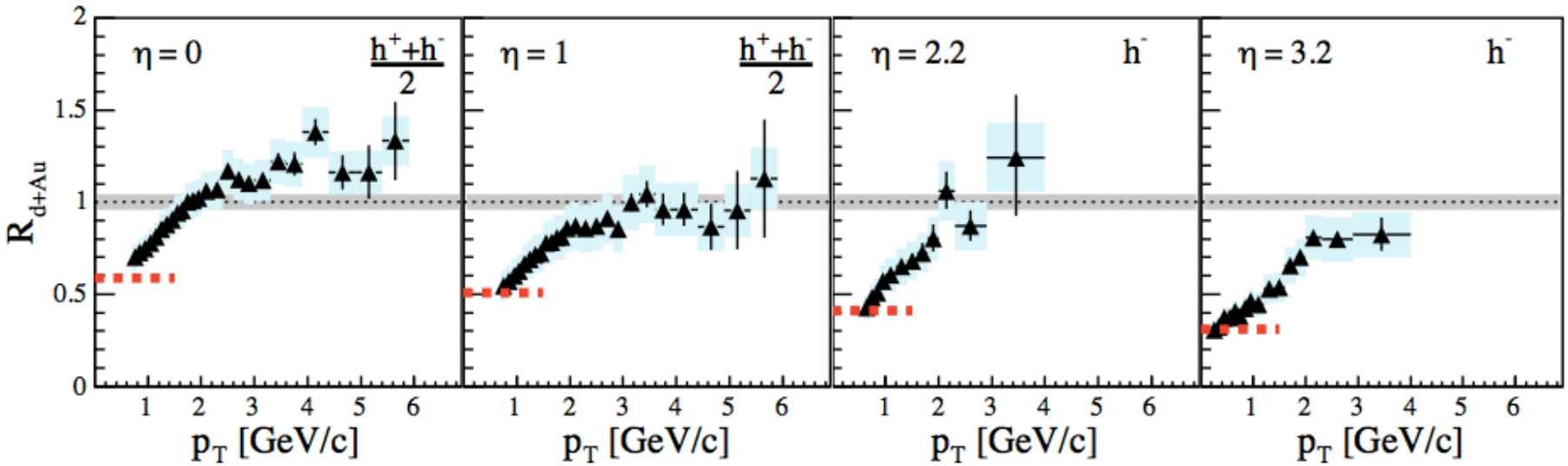


What do we know?

- **Jet quenching at RHIC:** X > 0.01

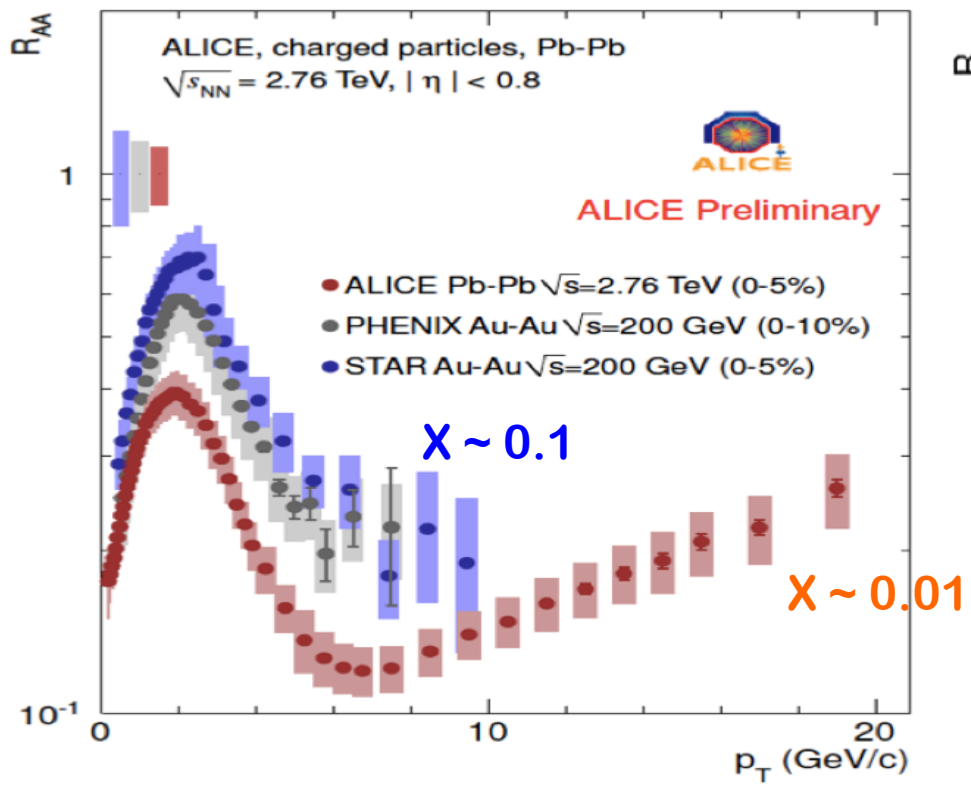


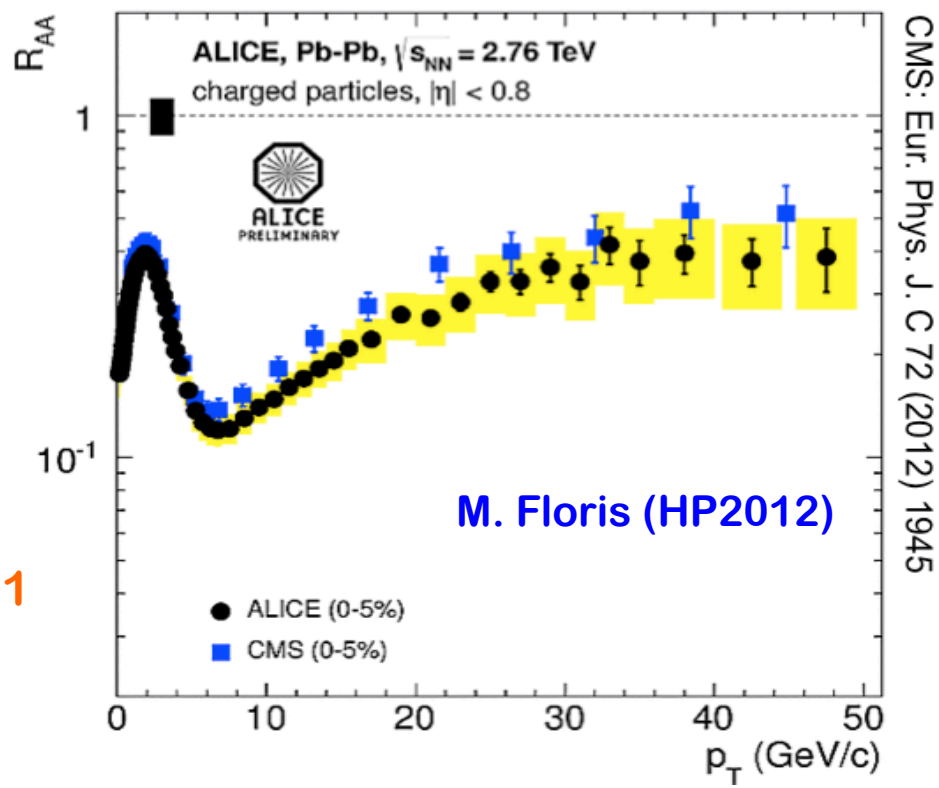




What do we know?

- **Jet quenching at LHC:** $A + A \rightarrow \mathrm{hadron(p)} + X$





- ✧ Stronger suppression than RHIC
- ✧ Change slope at large pT
- ✧ Any cold medium effect?

What we want to know?

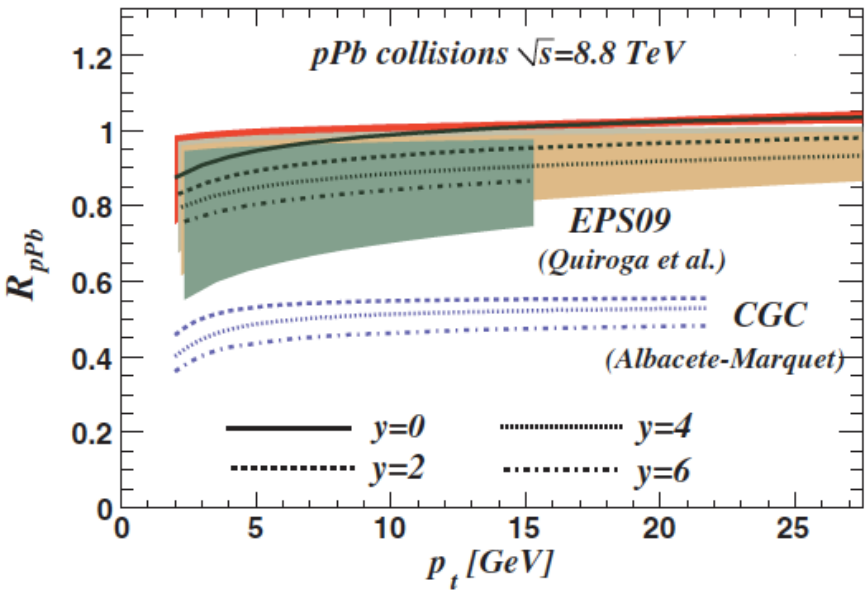
Salgado et al
J. Phys. G 2012

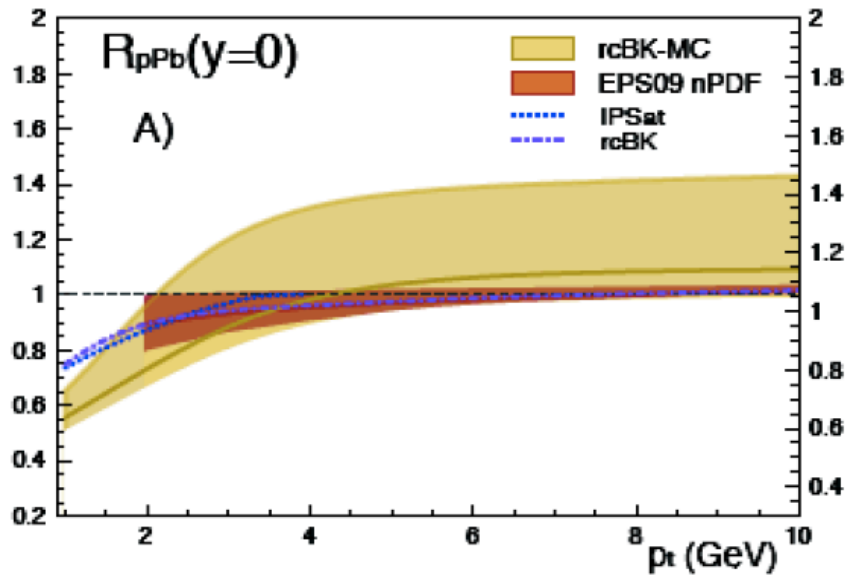
❑ p-Pb as a benchmark for Pb-Pb at LHC:

- ✧ Calibration of probes – hadronic vs electroweak (e.g. Z^0 in p-Pb)
- ✧ Initial condition for Pb-Pb collisions – influence on QGP formation?

❑ p-Pb as a laboratory for quark-gluon nuclear physics:

- ✧ Nuclear parton distribution functions?
- ✧ Coherent and incoherent QCD multiple scattering?
- ✧ Low x physics – saturation, CGC, …

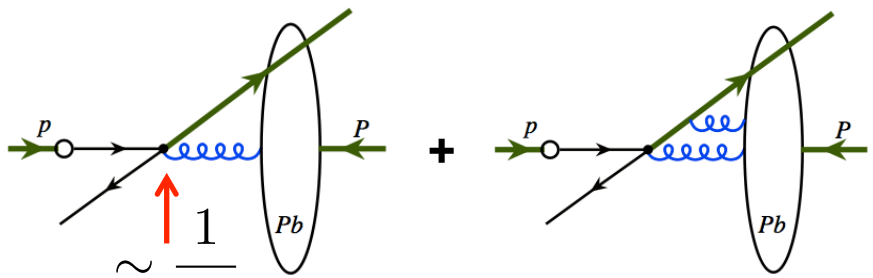




What we expect to see?

- **How is the high p_T single hadron produced in p-Pb?**
  - Every parton can participate in the hadronic collisions

$$d\sigma_{pPb} \propto \Bigg|$$



$$\sim \frac{1}{p_T} \Bigg|^2$$

$$\propto \hat{\sigma}^{\rm LP}_{ab\to c} \otimes f_{a/p} \otimes f_{b/Pb} (\otimes D_{h/c}) + \frac{Q_s^2}{p_T^2}\, \hat{\sigma}^{\rm NLP}_{ab\to c} \otimes f_{a/p} \otimes \mathcal{T}^{(4)}_{b/Pb} (\otimes D_{h/c})$$

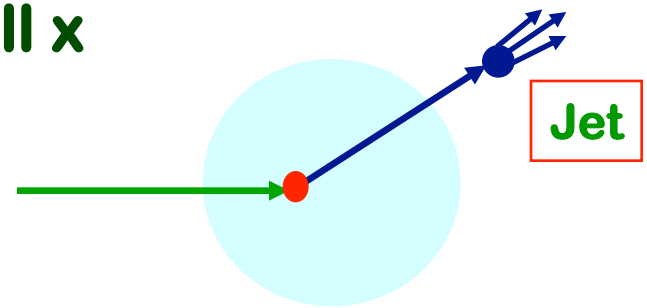
$$+ \frac{Q_s^2}{p_T^2}\, \hat{\sigma}^{\rm NLP(d)}_{ab\to c} \otimes f_{a/p} \otimes f_{b/Pb} (\otimes \mathcal{D}^{(4)}_{h/c}) + \ldots$$

  - Collinear factorization – power expansion if $Q_s \ll p_T$

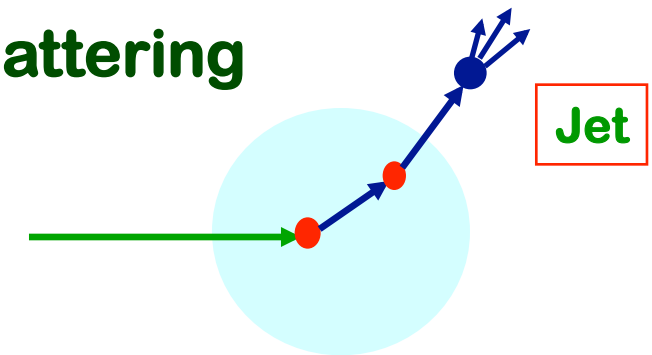
- **If $Q_s \sim p_T \gg \Lambda_{QCD}$, entering the saturation regime**
  - Every term is equally important!

What we expect to see?

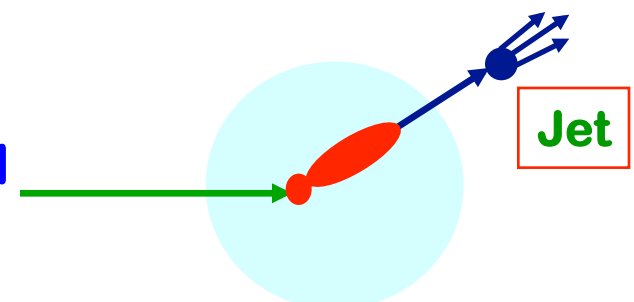
- **Single hard scattering – not too small x**
  - probes local parton densities
  - QCD dynamics – pQCD factorization
  - weak difference on target size



- **Independent/incoherent multiple scattering**
  - probes parton densities at different impact parameters
  - changes the distribution, not total rate



- **Coherent hard multiple scatterings**
  - changes production rate
  - no additional scale – power suppressed
  - probe multiparton correlations



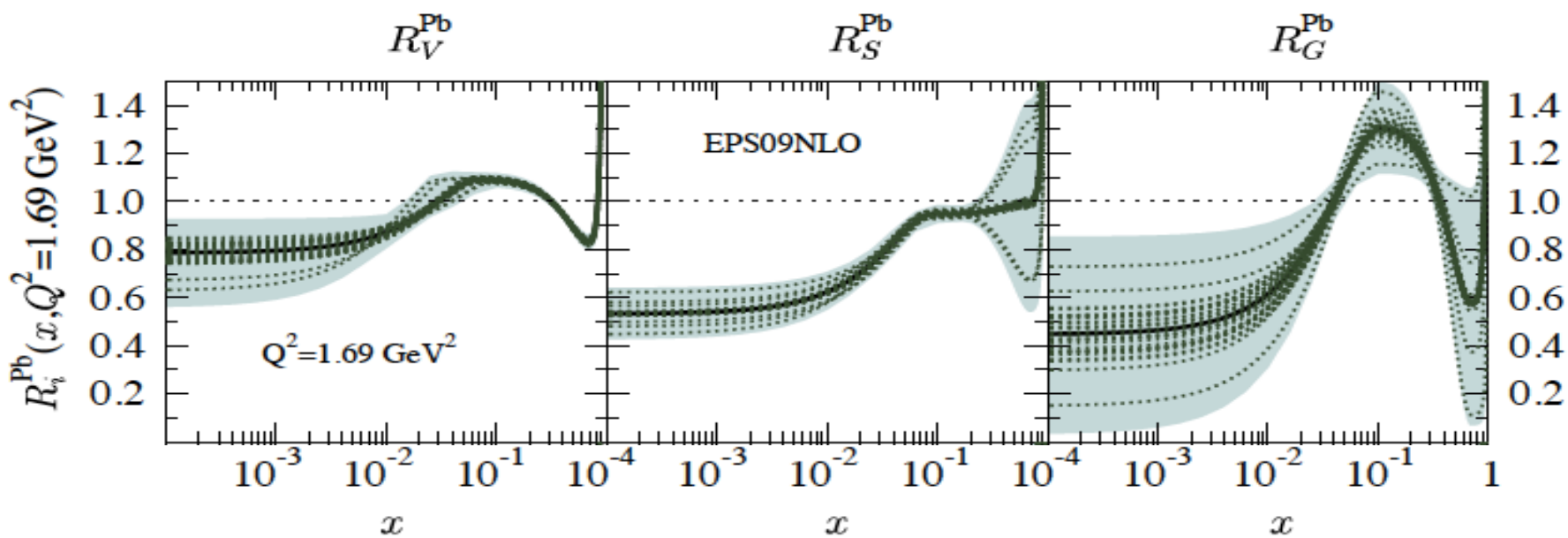
Nuclear parton distribution functions

- **Definition – same operators as proton PDFs:**

$$\phi_{q/h}(x,Q) = \int \frac{dy^-}{4\pi} e^{+ixp^+y^-} \langle p|\overline{\psi}_q(0)\gamma^+ \mathcal{U}_n(0,y^-)\psi_q(y^-)|p\rangle$$

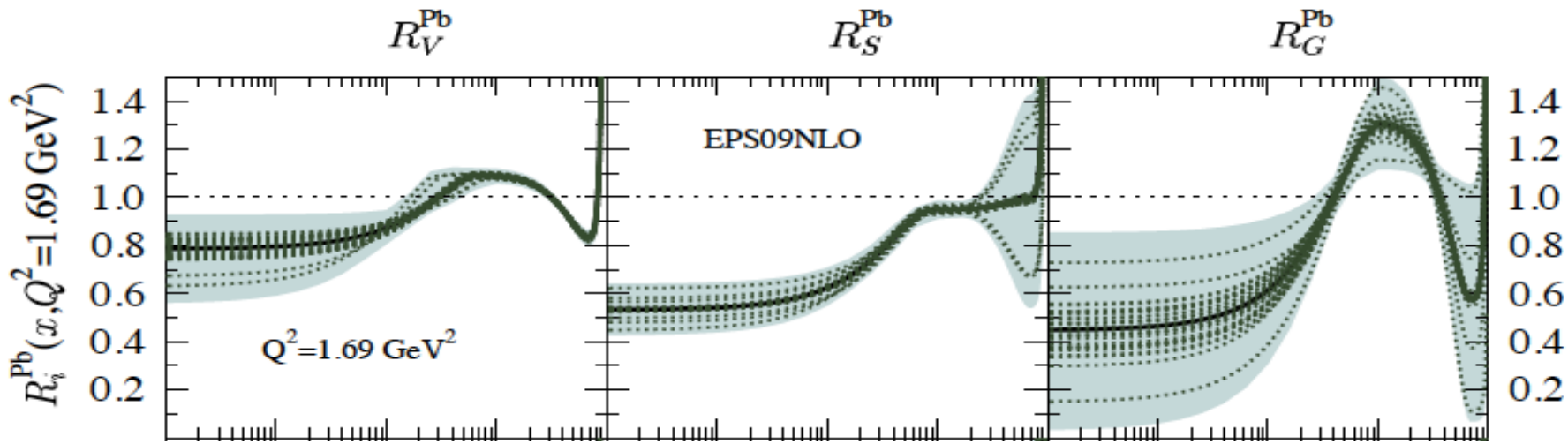
$$\phi_{q/A}(x,Q) = \int \frac{dy^-}{4\pi} e^{+ixp^+y^-} \langle P_A|\overline{\psi}_q(0)\gamma^+ \mathcal{U}_n(0,y^-)\psi_q(y^-)|P_A\rangle$$

- ✧ **Same operators ⇔ Same evolution equations**
- ✧ **DGLAP evolution for nPDFs at the leading power**
- ✧ **All nuclear A-dependence from the input distributions at Q_0**

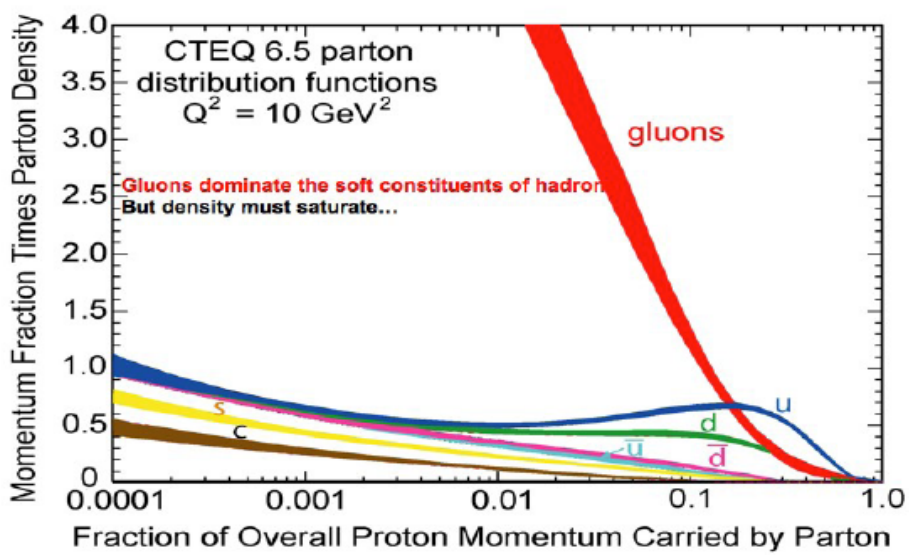


What DGLAP told us?

- No saturation:



Saturation of the ratio =\= saturation of PDFs!

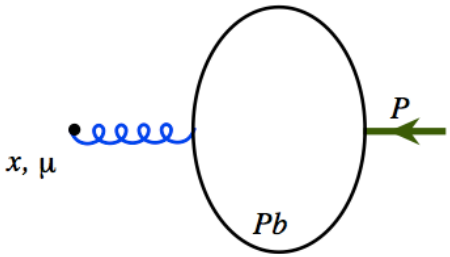


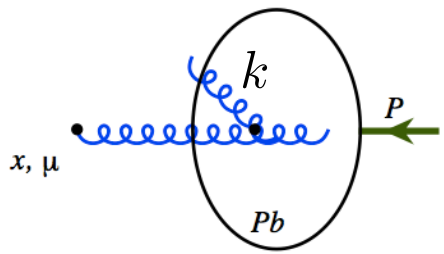
Nuclear gluon distributions and sea quark distributions grow as fast as that of proton at small x!

Need data at small-x!

Factorization and evolution

❑ DGLAP evolution:



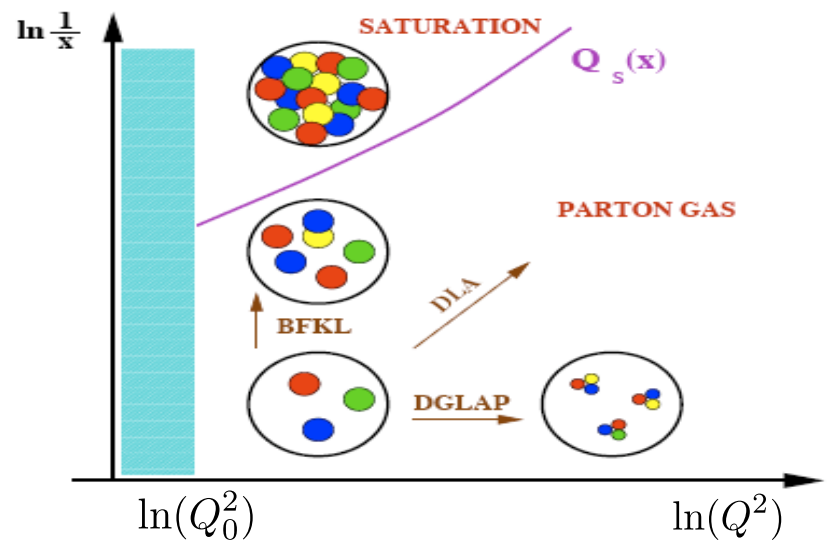


$$\alpha_s \frac{dx'}{x'} \frac{dk_\perp^2}{k_\perp^2}$$

- ✧ **Resum collinear (CO) logarithms:** $\ln^n(k_\perp^2) \Rightarrow \dfrac{\partial G(x,\mu)}{\partial \ln(\mu)}$
- ✧ **Evolution kernel:** $\propto \dfrac{dx'}{x'}$ **Responsible for the growth at small-x**
- ✧ **CO and UV are equivalent at leading power: DGLAP = RG**

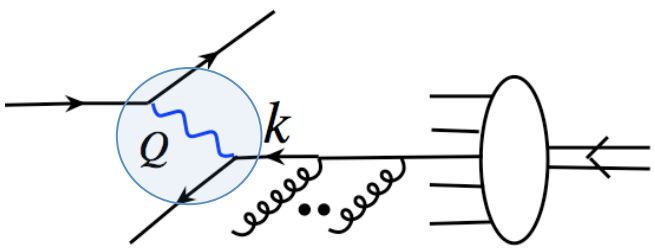
❑ BFKL evolution:

- ✧ **Resum:** $\ln(1/x)^n \Rightarrow \dfrac{\partial G(x,\mu)}{\partial \ln(1/x)}$
- ✧ **Evolution kernel:** $\propto \dfrac{dk_\perp^2}{k_\perp^2}$
- ✧ **BFKL is not a RG equation**



When leading power QCD fails?

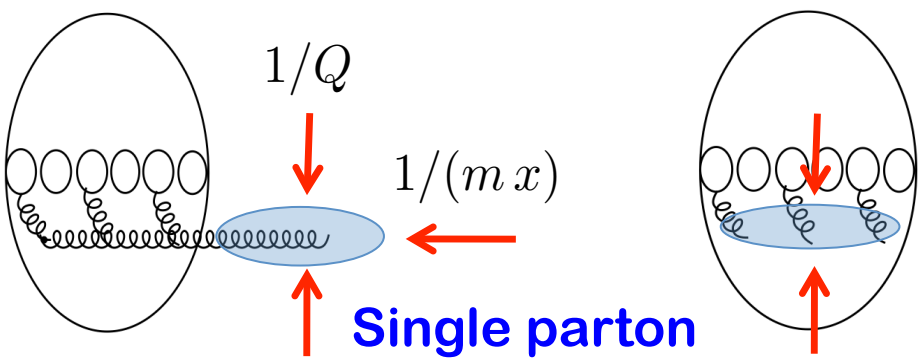
- **Parton's transverse momentum at the hard collision:**
  - ✧ is not equal to 1/fm – typical scale in hadron wave function
  - ✧ Gluon shower from both initial state and final-state partons, and soft interaction between them can all change the p_T



$$\langle k_T^2 \rangle \propto \Lambda_{\rm QCD}^2 \left[\ln(Q^2/\Lambda_{\rm QCD}^2)\right] \ln(S/Q^2)$$
$$\to 2\,\Lambda_{\rm QCD}^2 \left[\ln(Q^2/\Lambda_{\rm QCD}^2)\right] \ln(1/x) \propto 1/x^{1/3}$$

Leading power collinear factorization fails if $\langle k_T^2 \rangle \sim Q^2$

- **Parton recombination at the same impact parameter:**



$$\propto \left[\frac{Q_s(x)}{Q}\right]^n$$

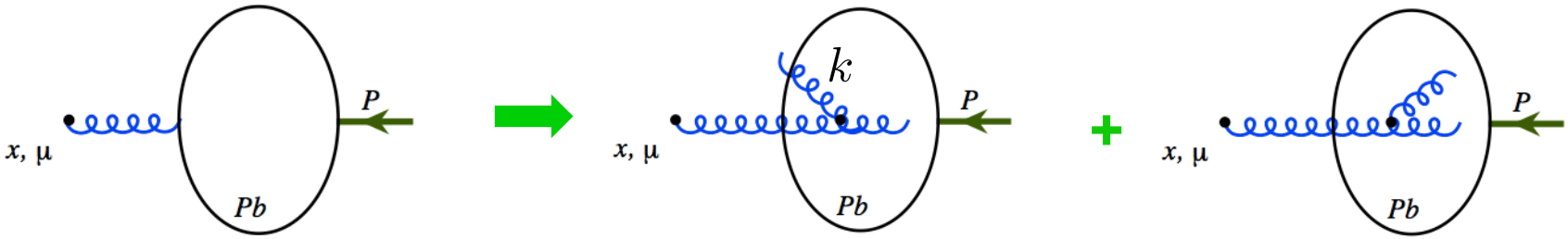
Multi-parton

Saturation scale:

$$Q_s(x) \propto A^{1/3}\, xG(x)$$
$$\propto \frac{A^{1/3}}{x^{\lambda}}$$

Recombination – nonlinear evolution

- **Recombination of gluon at the same impact parameter:**



- **Factorization of collinear divergences:** Gribov, Levin, Ryskin, 1983; Mueller, Qiu, 1986

$$\frac{\partial^2\, xG(x,Q^2)}{\partial \ln(1/x)\,\partial \ln(Q^2)} = \frac{3\alpha_s}{\pi}\, xG(x,Q^2) - \frac{3\alpha_s^2}{\pi^2 R^2 Q^2}\left[xG(x,Q^2)\right]^2$$

  - ✧ **A dynamical scale:** $Q_s(x)^2 = \frac{\alpha_s}{\pi R^2}\, xG(x,Q^2) \to 1/x^\lambda$
  - ✧ **Question: high order and high power?**

- **Recombination in dipole model – BK equation:**

$$\frac{\partial N(x,k^2)}{\partial \ln(1/x)} = \alpha_s\, \mathcal{K}_{\rm BFKL} \otimes N(x,k^2) - \alpha_s\left[N(x,k^2)\right]^2$$

Balitsky, 1996; Kovchegov, 1999

  - ✧ **Exact in the large N_c limit within dipole model**

Negative gluon density at low Q?

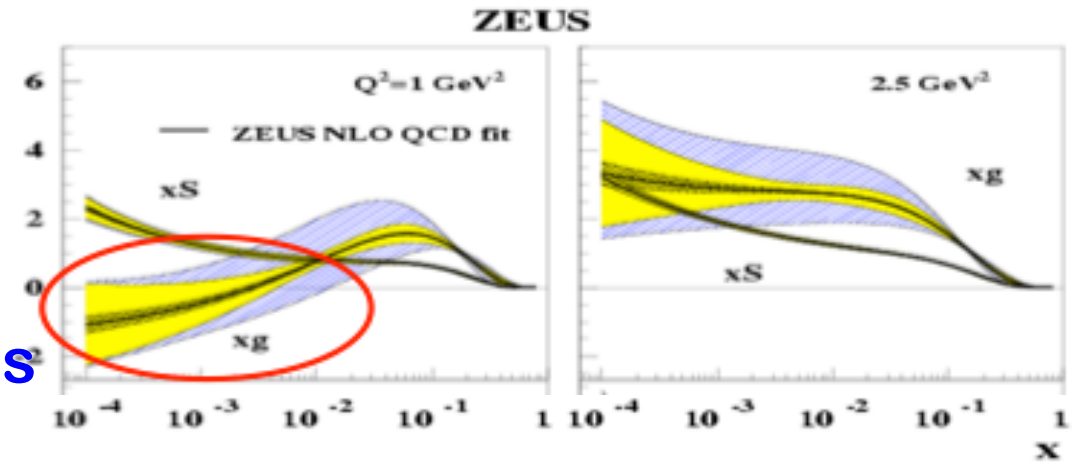
- DGLAP evolution lead to negative gluon density at low Q

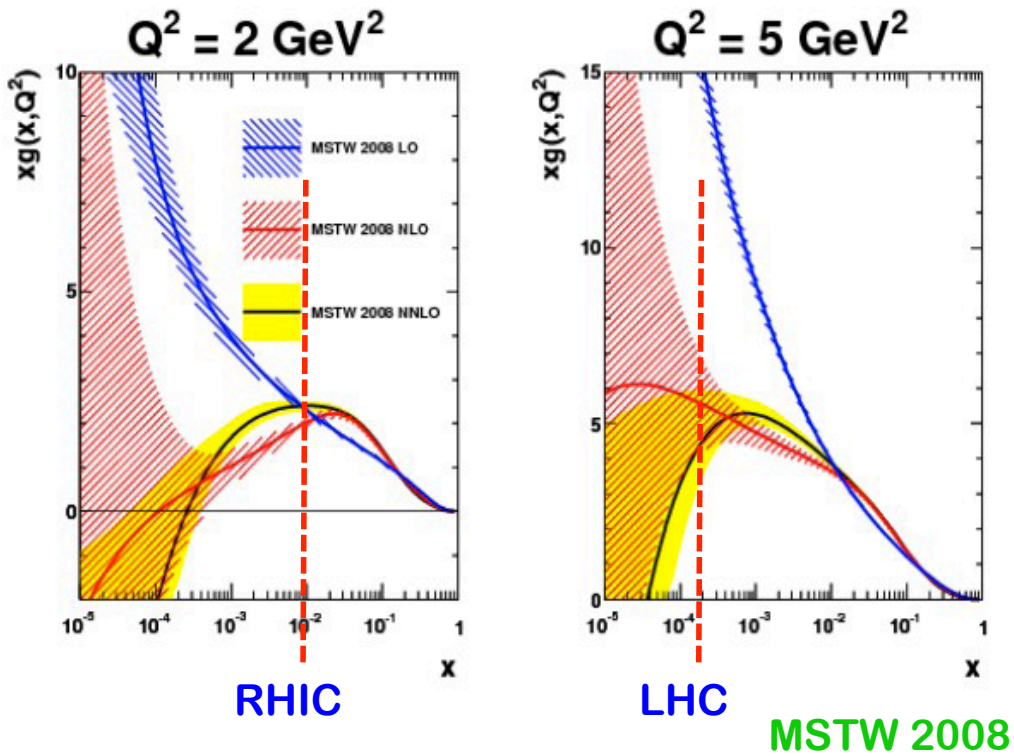
- QCD resummation leads to small gluon density at low Q

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

No!

Gluon recombination slows down small-x evolution





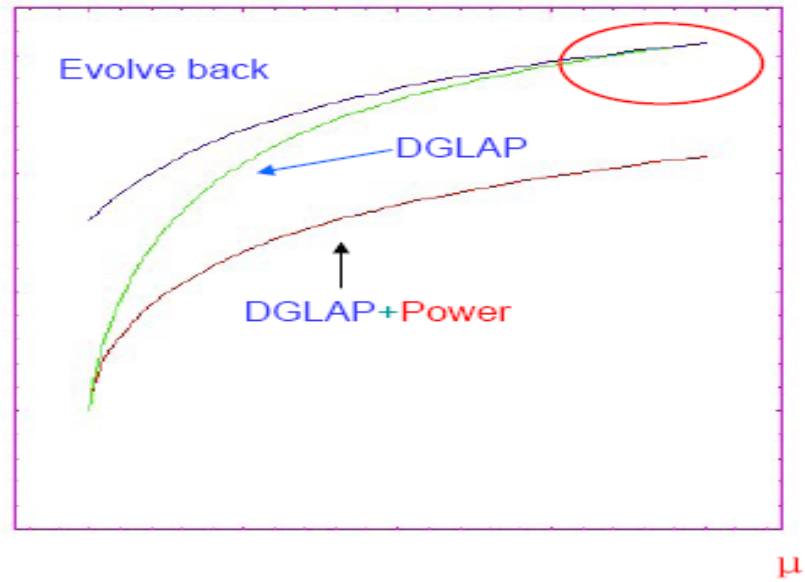
Role of recombination effect

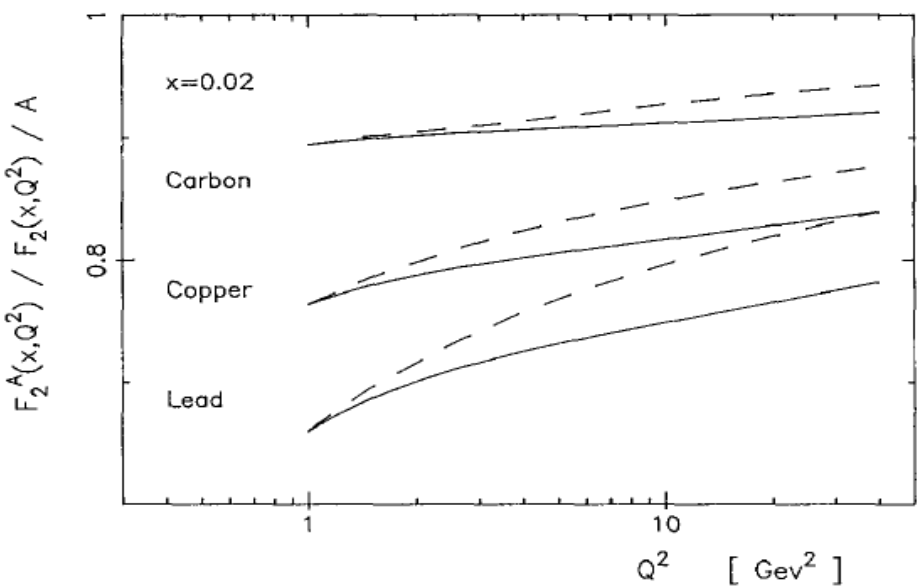
Leading order power correction

$$\frac{\partial \varphi(x,\mu^2)}{\partial \ln \mu^2} = P(x) \otimes \varphi(x,\mu^2) - \frac{1}{\mu^2}\rho(x,\mu^2)$$

$$\int_{\mu_0^2}^{\mu^2} \frac{d\ln\overline{\mu}^2}{\overline{\mu}^2} = \frac{1}{\mu_0^2} - \frac{1}{\mu^2} \rightarrow \frac{1}{\mu_0^2} \quad as\ \mu \rightarrow \infty$$

power correction can build up a big effect to low Q^2 distribution





✧ Corrections to nPDFs do not go away as $1/\mu^2$!

✧ What about higher power corrections?

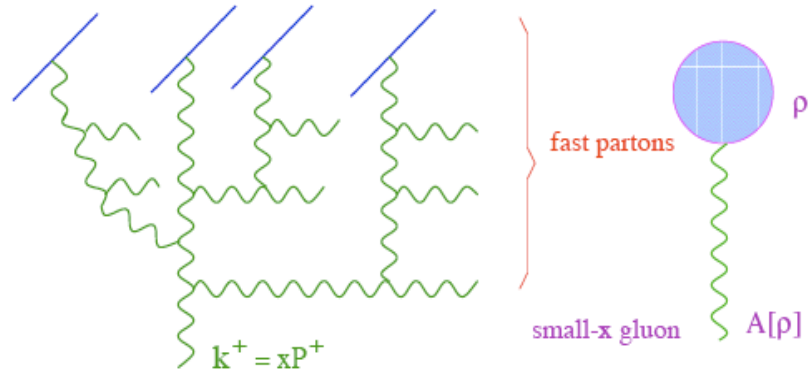
Qiu, 1987

Color glass condensate approach

- **An effective theory approach:**

  Integrate out large x partons into effective color density,

  McLerran-Venugopalan Model



- **Small-x gluons:**

  Effectively given by the classical field $A[\rho]$ that is radiated by fast partons $(x' > x)$ having a color charge density

- **Large-x partons – charge density ρ:**

  Effectively frozen (time dilation) in some random configurations and have the probability charge distribution, $W_Y[\rho]$.

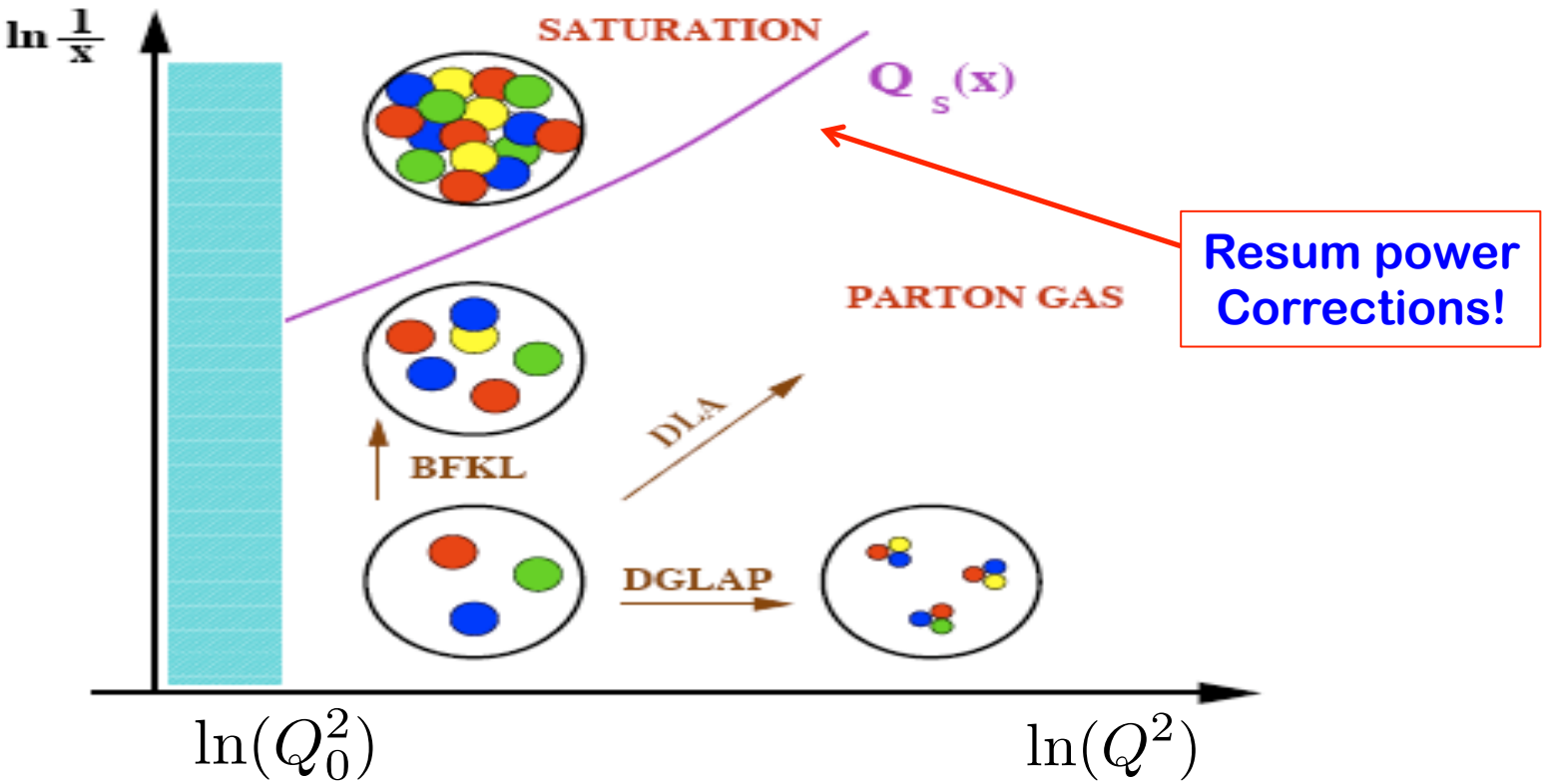
- **JIMWLK equation:**

$$\frac{\partial W_Y[\rho]}{\partial Y} = -H\left[\rho, \frac{\delta}{\delta\rho}\right] W_Y[\rho]$$

Lower x, more phase space for fast partons and their radiation

How to "see" the saturation?

- "Phase diagram" for the gluon "density":



Proton is dilute enough:

Use nuclear target - $A^{1/3}$ enhancement!

Medium size enhanced power corrections

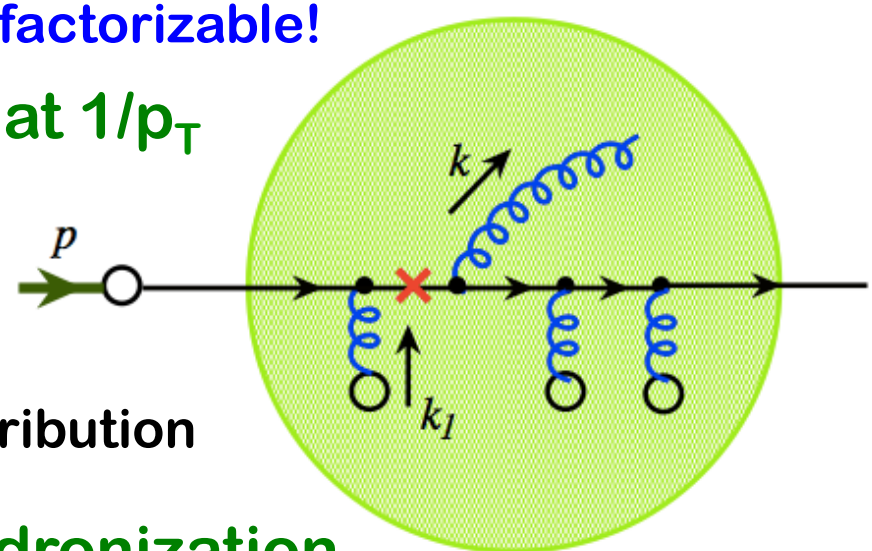
- **QCD collinear factorization:**

  $A^{1/3}$-enhanced power correction is factorizable!

- ✓ **Coherent multiple scattering at $1/p_T$**

  resummation of $\left(\alpha_s \frac{A^{1/3}}{p_T^2}\right)^n$

  – shift in x, small if $p_T >> Q_s$
  – important for steep falling distribution



- ✓ **Multiple scattering during hadronization**

  resummation of $\left(\alpha_s \frac{A^{1/3}}{Q_s^2}\right)^n$

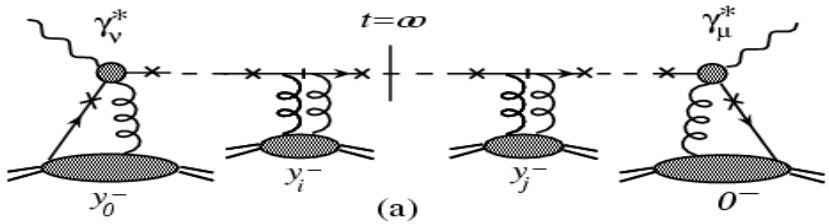
  – shift in z
  – effective energy loss – but, not relevant for jet production!

- ✓ **Initial-state shower (Sudakov type) – broadening**

  nPDFs entering the resummation formalsim – Thursday's talk on Z^0

“Shadowing” from power corrections

❑ Nuclear shadowing = nPDFs + power corrections:



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

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

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

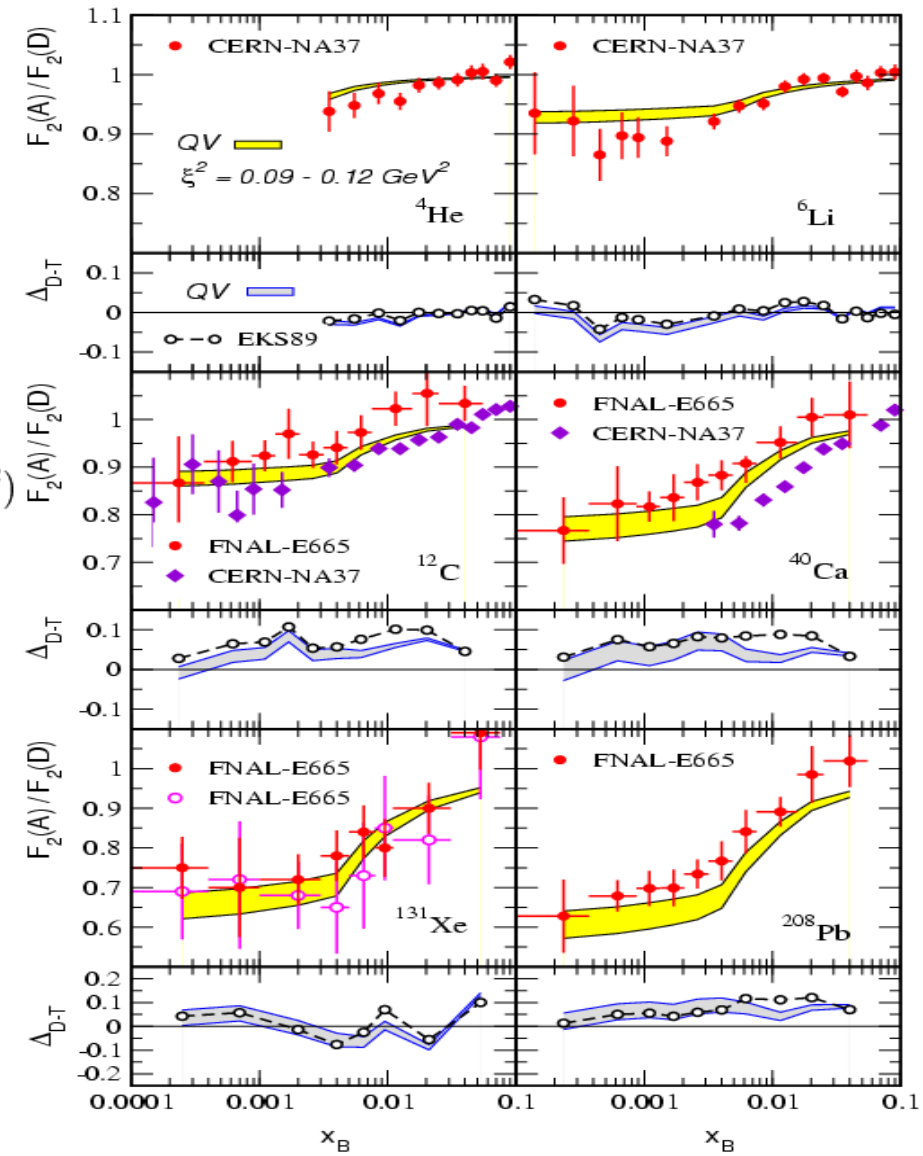
$$\Delta \equiv \frac{\xi^2}{Q^2} \left(A^{1/3} - 1 \right)$$

Only unknown!

$$\xi^2 = \frac{3\pi\alpha_s}{8R^2} \langle F^{+\alpha} F_\alpha{}^{+} \rangle \quad = 0.09 - 0.12 \text{ GeV}^2$$

Maximum power corrections

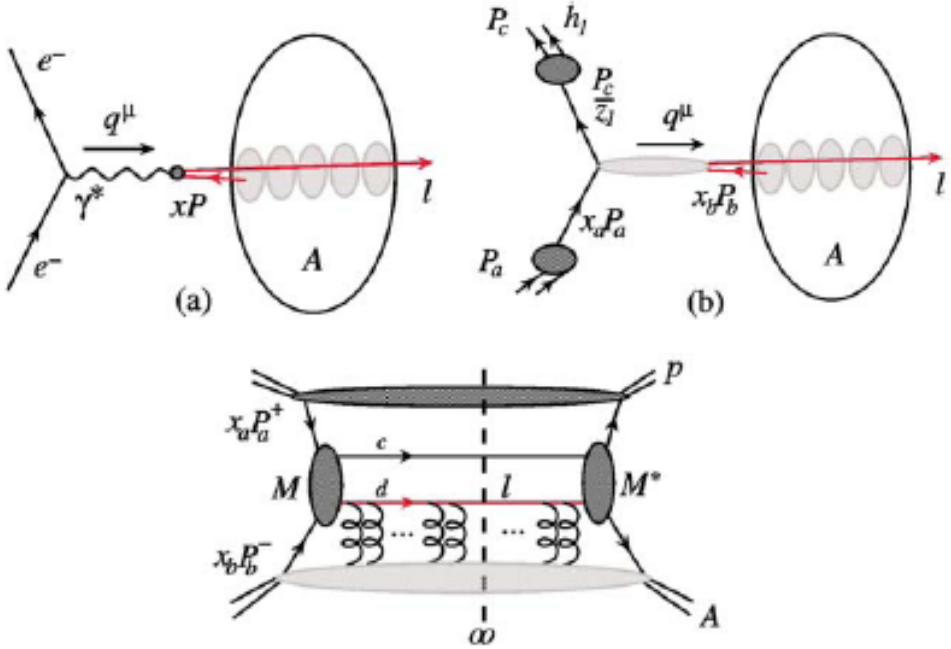
Neglect shadowing from nPDFs

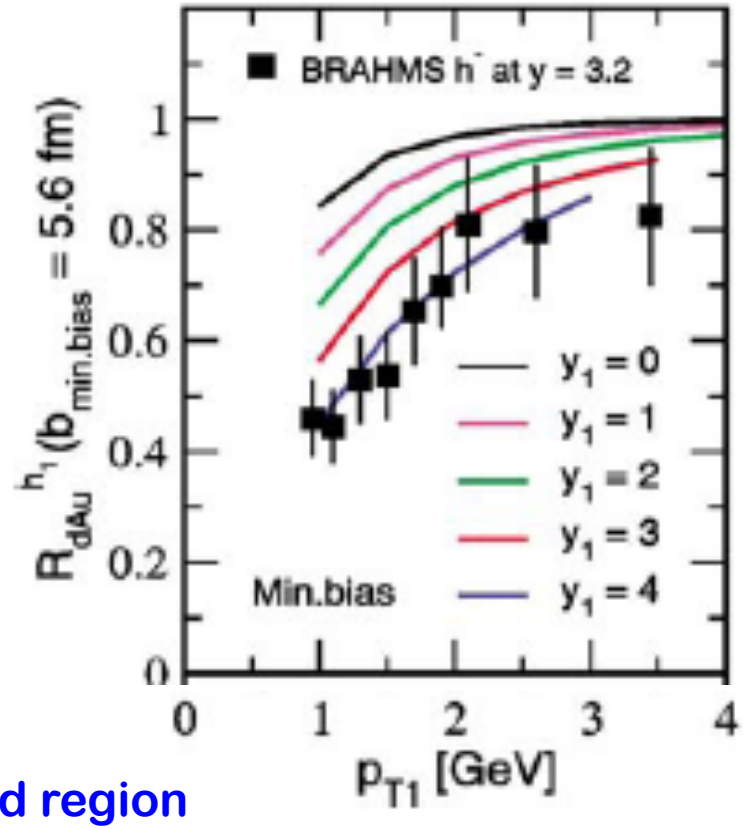


R_{pA} of single hadron production – RHIC

- **Power corrections to the hard part:**

Qiu, Vitev, 2006





- ✧ Keep t-channel only – dominates the forward region
- ✧ Same x-shift from inclusive DIS
- ✧ Large pT suppression from "energy loss" – important for RHIC energy
- ✧ Initial-state shower is less important at RHIC – edge of phase space

R_{pA} of single hadron production – LHC

- Numerical predictions are not quite ready yet

✓ Coherent multiple scattering at short-distance

resummation of $\left(\alpha_s \frac{A^{1/3}}{p_T^2}\right)^n$

– Smaller than RHIC – larger p_T

Also complication in S- and U-channels when y ~ 0

✓ Multiple scattering during hadronization

resummation of $\left(\alpha_s \frac{A^{1/3}}{Q_s^2}\right)^n$

Could have an enhancement for D-meson production peak in fragmentation function

– Smaller effect due to smaller effective z

✓ Initial-state shower (Sudakov type) – broadening

– Bigger effect due to a larger phase space for shower (at small p_T)

– Suppression from nPDFs at μ = 1/b, when b is sufficiently large

Should see more suppression in the forward region!

Summary

- pA @ LHC should have a rich physics program to explore QCD nonlinear dynamics and coherence
- Single hadron production in pA at LHC should be suppressed, but not as much as forward dAu at RHIC
- More suppression is expected for single hadron production in the forward region
- Suppression should be smaller for single jet production at the same parent parton energy
- What the data will tell us?

Thank you!