Experimental Signals of Low-x Saturation

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Friday, April 12, 2019

Overview

1. What is Saturation?

2. Potential Signals of Saturation

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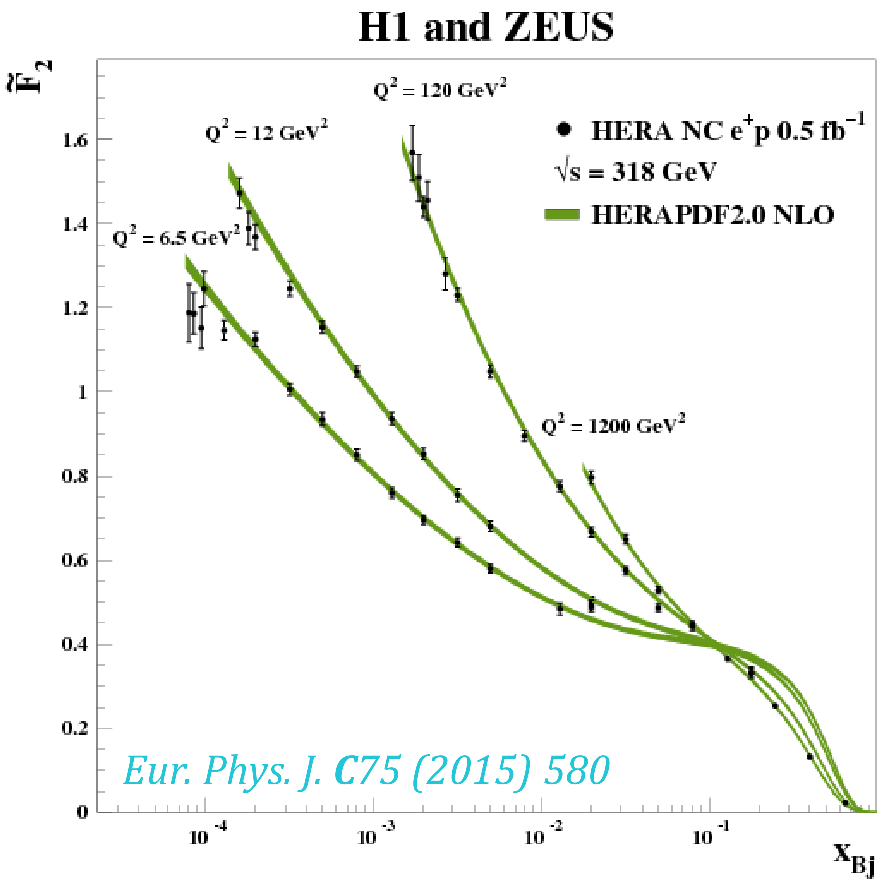
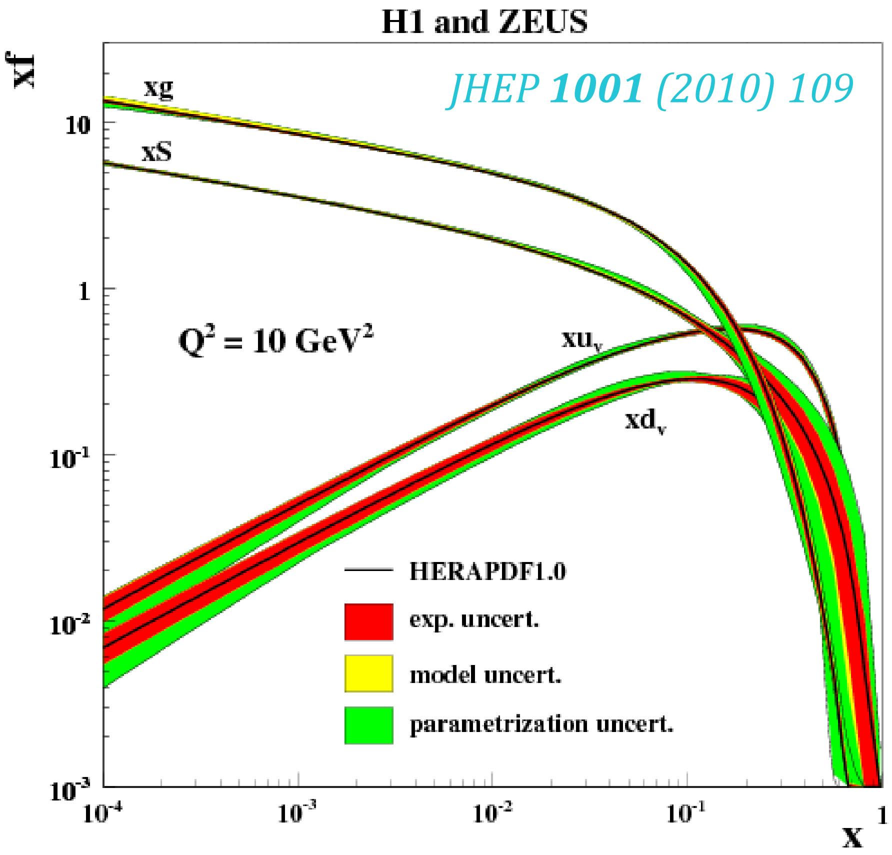
2. Potential Signals of Saturation

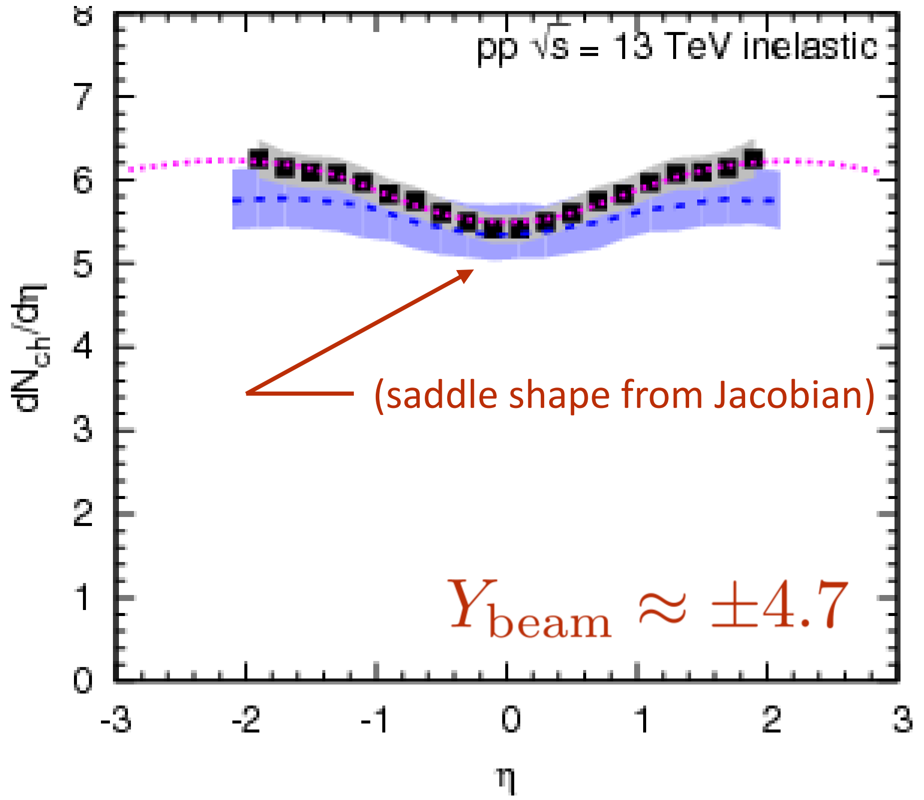




- At HERA, the proton structure functions **increase strongly at small x**
- Reflects a **power-law growth** of **gluon** and **sea quark densities**

Non-Abelian Bremsstrahlung at High Energies

*CMS Collaboration, Phys. Lett. **B**751 (2015) 143*



- At high energies, **QCD radiates soft gluons uniformly** around **mid-rapidity**

➢ Intrinsic feature of **non-Abelian** field theories

$$\frac{d\sigma^G}{dy} = \alpha_s \times (\text{const}) \qquad \frac{\sigma_{tot}^{(pp+G)}}{\sigma_{tot}^{(pp)}} \propto \alpha_s \, \Delta Y_{tot}$$

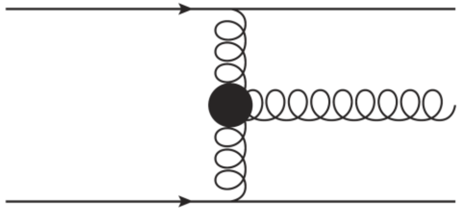
(small coupling) (large phase space)

$$\Delta Y \sim \ln \frac{s}{\Lambda^2} \sim \ln \frac{1}{x}$$

- Perturbation theory in pQCD relies on a **hierarchy of contributions**

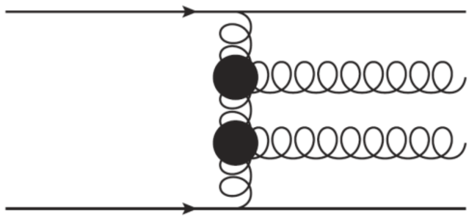
LO NLO

$$\alpha_s \gg \alpha_s^2 \gg \cdots$$



$\langle N_G \rangle_{LO} \sim \alpha_s \, \Delta Y$

$\gg$



$\langle N_G \rangle_{NLO} \sim (\alpha_s \, \Delta Y)^2$

$\gg$ …

$$\langle N_g \rangle \ll 1$$

- Perturbation theory in pQCD relies on a **hierarchy of contributions**

LO NLO

$$(\alpha_s \Delta Y) \sim (\alpha_s \Delta Y)^2 \sim \cdots$$

$\langle N_G \rangle_{LO} \sim \alpha_s \, \Delta Y$ $\sim$ $\langle N_G \rangle_{NLO} \sim (\alpha_s \, \Delta Y)^2$ $\sim$ ...

$$\langle N_g \rangle \gtrsim 1$$

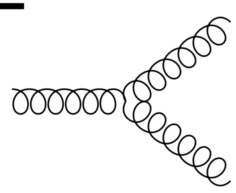
$$\Delta Y \sim \ln \frac{1}{x}$$

- At high energies (small x), the **large logarithmic phase space enhances** the probability of **soft gluon radiation**

$$\alpha_s \ln \frac{1}{x} \sim \mathcal{O}(1)$$

- Recast the systematic enhancement as a **differential equation**

$$\frac{d\langle N_G \rangle}{dY} = \langle N_G \rangle \times \left[\quad \right]$$

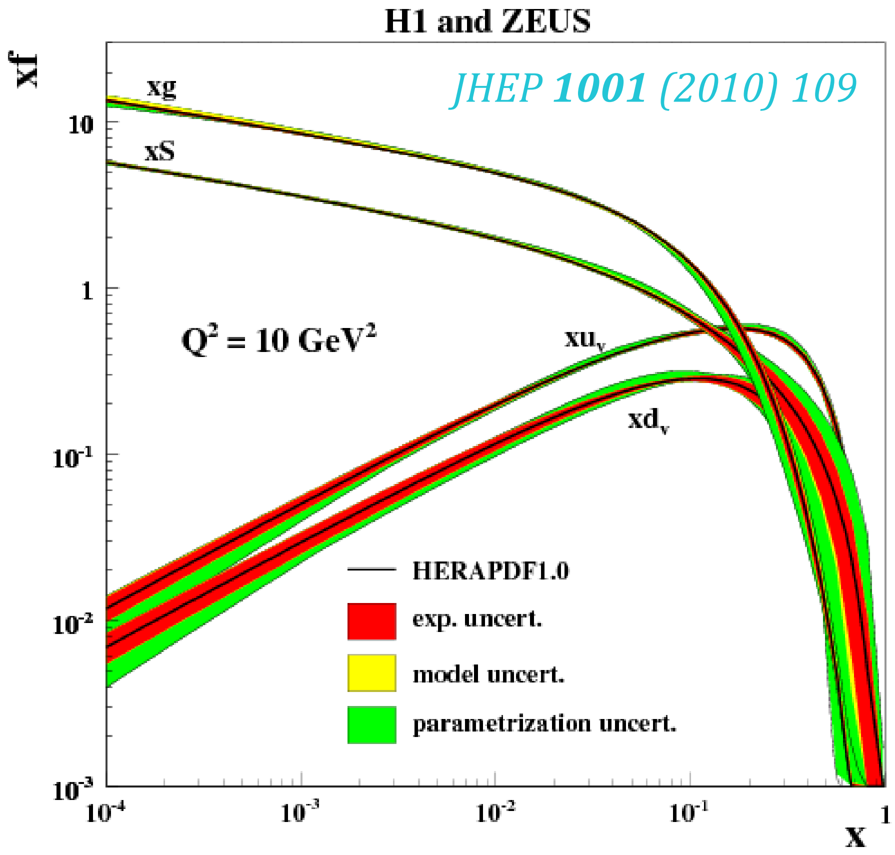


➢ **Power-law growth** of the **gluon density** at small x

Kuraev, Lipatov, and Fadin, Sov. Phys. JETP ***45*** *(1977) 199*
Balitsky and Lipatov, Sov. J. Nucl. Phys. ***28*** *(1978) 822*

$$\langle N_G \rangle \sim \left(\frac{1}{x}\right)^{(2.65\,\alpha_s)}$$

"Pomeron Intercept"



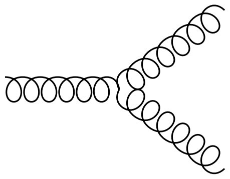
An Emergent Saturation Scale

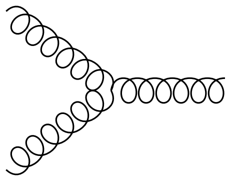
- At **high enough densities**, gluon **recombination** competes with bremsstrahlung

  - **Saturation** of the gluon density

L. V. Gribov, E. M. Levin, and M. G. Ryskin, Phys. Rept. ***100*** *(1983) 1*
A. H. Mueller and J. W. Qiu, Nucl. Phys. ***B268*** *(1986) 427*

$$\frac{d\langle N_G\rangle}{dY} = \langle N_G\rangle \times \Big[\quad \Big] - \langle N_G\rangle^2 \Big[\quad \Big]$$





$$\frac{d\rho_G}{dY\, dQ^2} = \left(\frac{\alpha_s N_c}{\pi}\right) \frac{\rho_G}{Q^2} - \left(\frac{\alpha_s^2 N_c \pi}{2 C_F}\right) \left(\frac{\rho_G}{Q^2}\right)^2$$

Equilibrium point: Q_s^2

- The **saturation momentum scale** **grows with the density**

$$Q_s^2(Y) \sim \alpha_s\, \rho(Y)$$

The Onset of the Nonlinear Regime

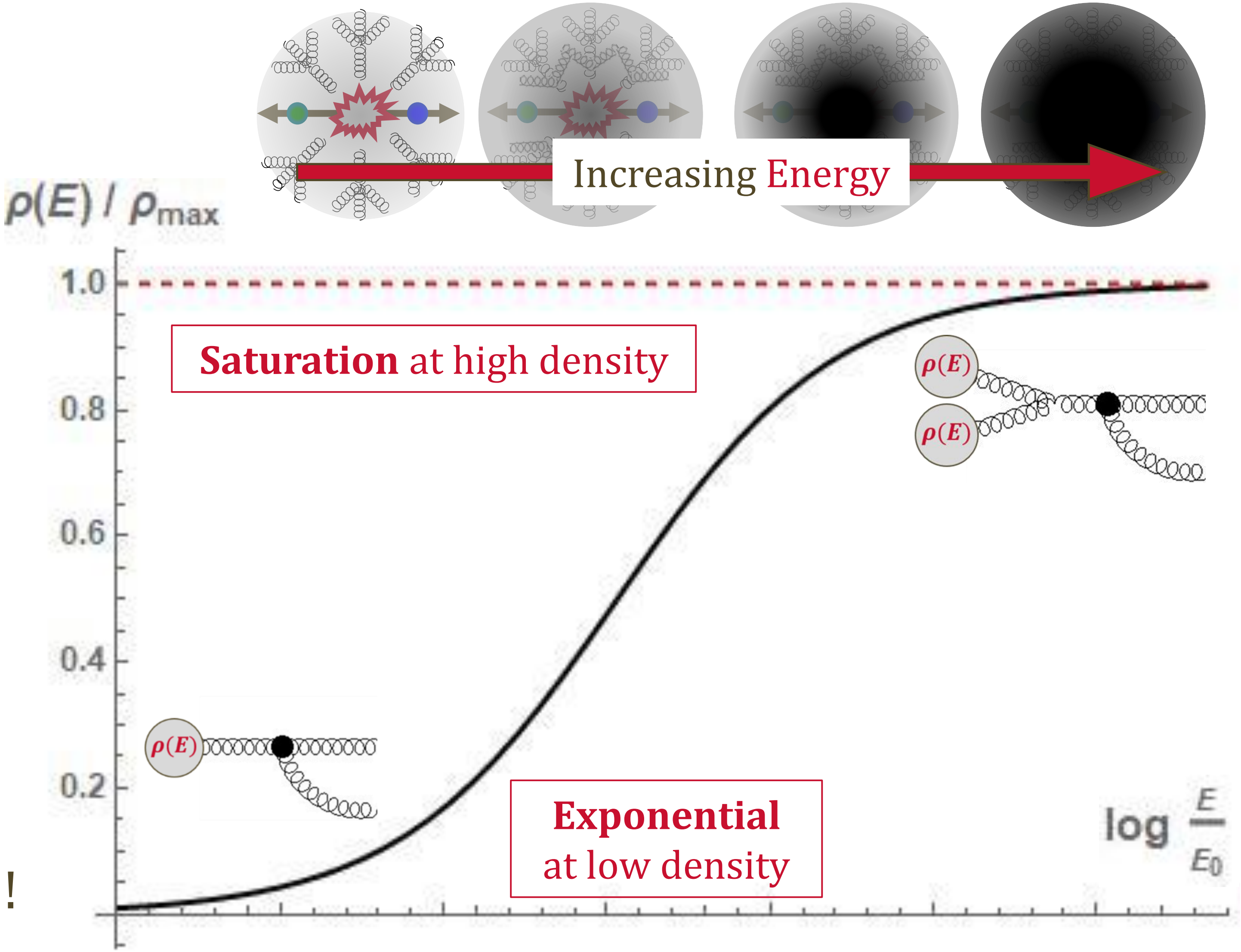
- Gluons have **nonlinear interactions**

➢ Naturally evolve toward a **maximum gluon density**

$$\rho_{max} = \frac{8\,Q_s^2}{3\,\pi^2\alpha_s}$$

$$\approx 20\ fm^{-2} \sim 10^{31}\ m^{-2}$$

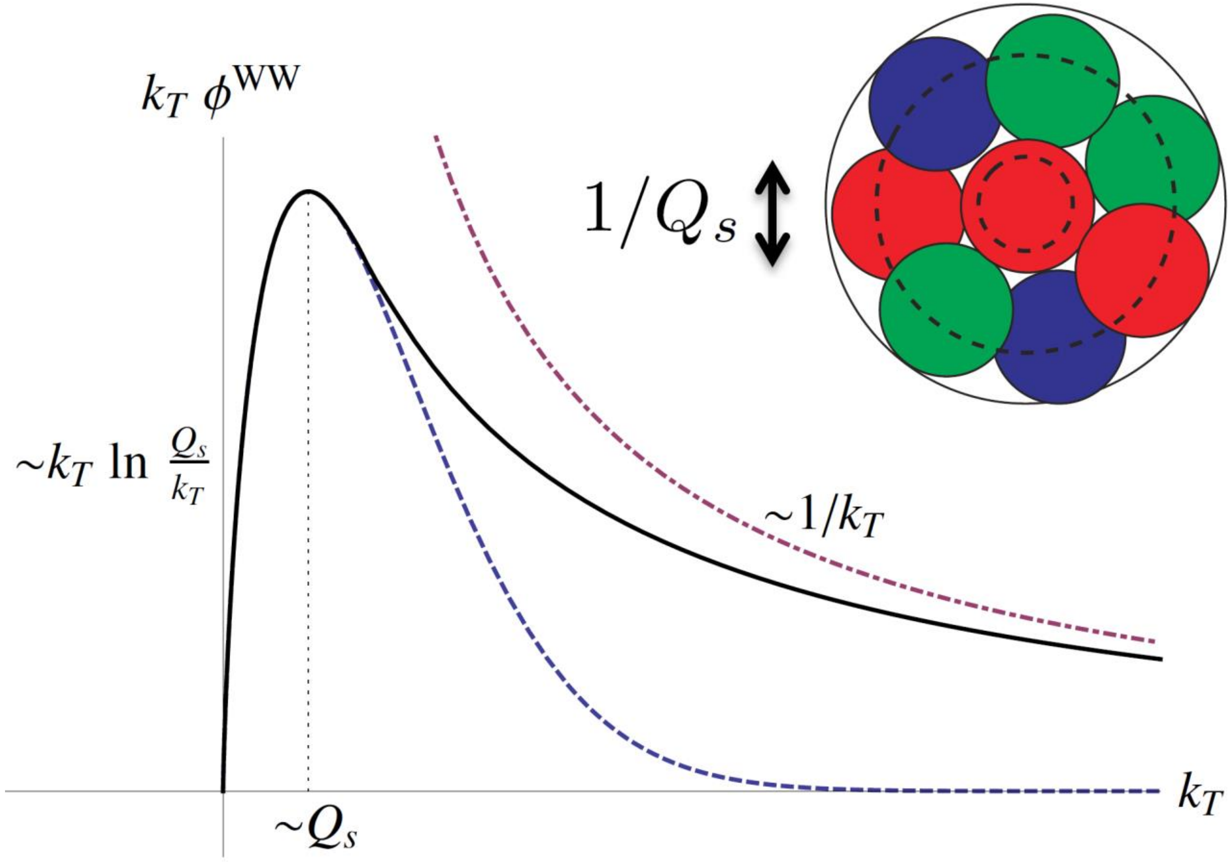
➢ Simplify to **classical** equations!



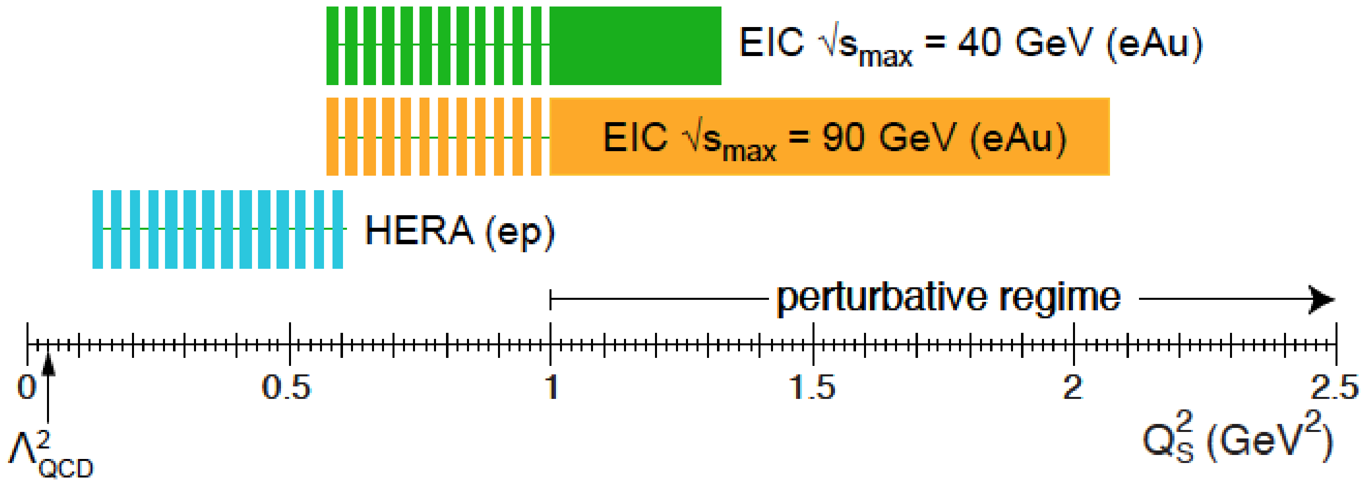
The Perturbative High-Density Limit

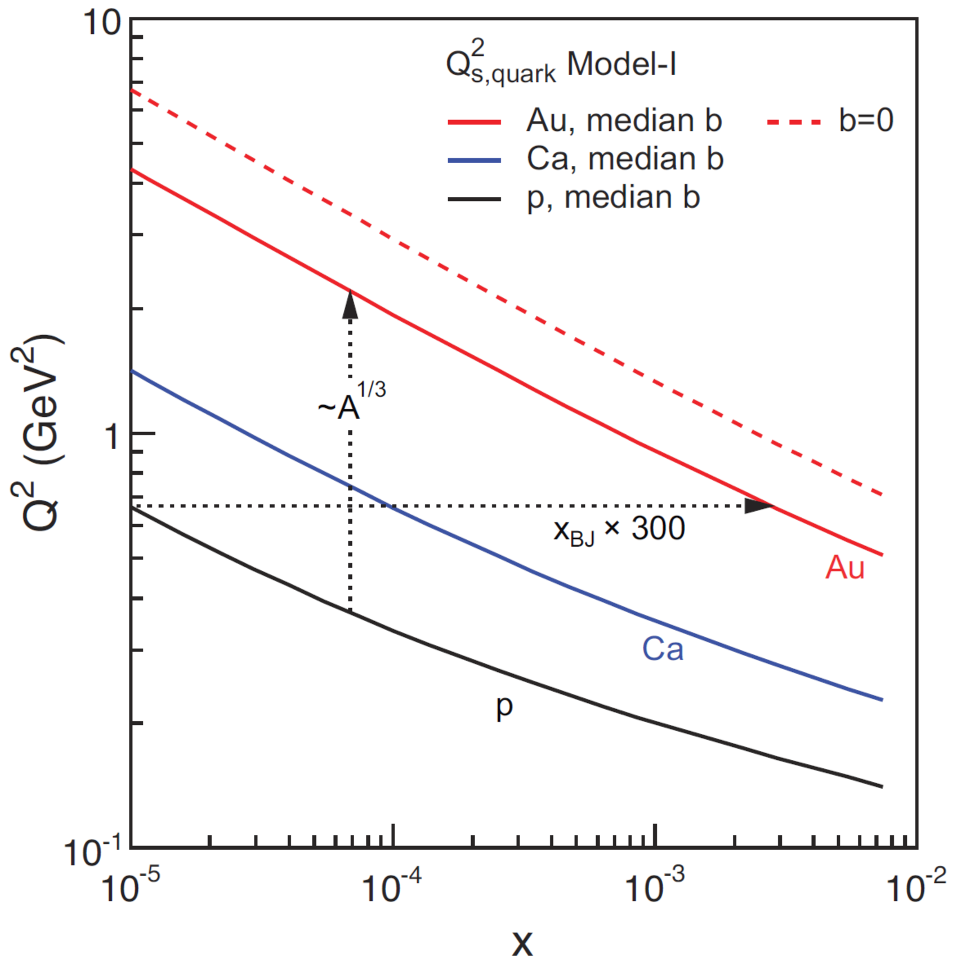
- Parton transverse momentum distributions are **dynamically screened below Q_s**

- If the **density is large enough** that Q_s becomes a (semi)hard scale, the dynamics become **perturbative**



- With high energies and heavy nuclei, a future **Electron-Ion Collider** may peek into this regime.



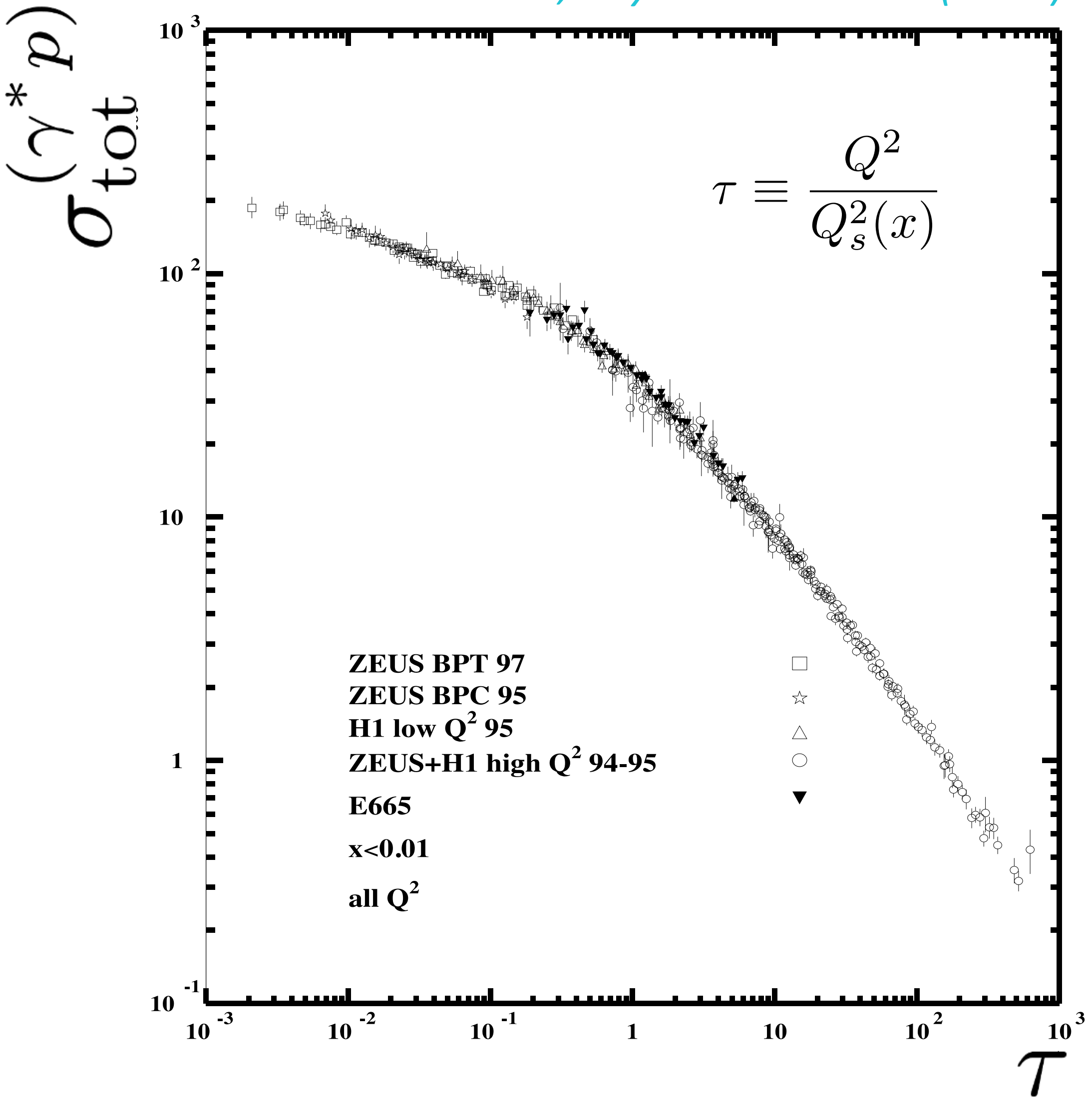


A. Accardi et al., Eur. Phys. J. ***A52*** *(2016)*

(Extended) Geometric Scaling

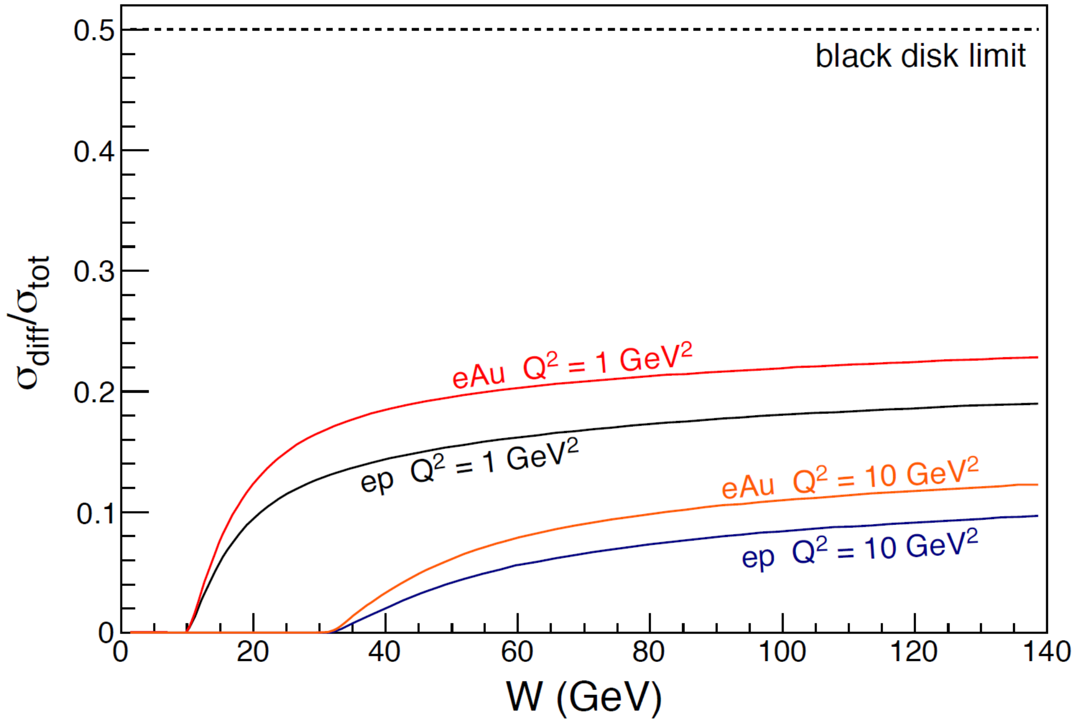
- **Geometric scaling**:
  - ➢ structure functions depend only on $\tau = Q/Q_s(x)$
  - ➢ Signal of "pre"-saturation
  - ➢ For $x < 0.01$, HERA data seems to exhibit geometric scaling

A. M. Stasto et al., Phys. Rev. Lett. ***86*** *(2001)*



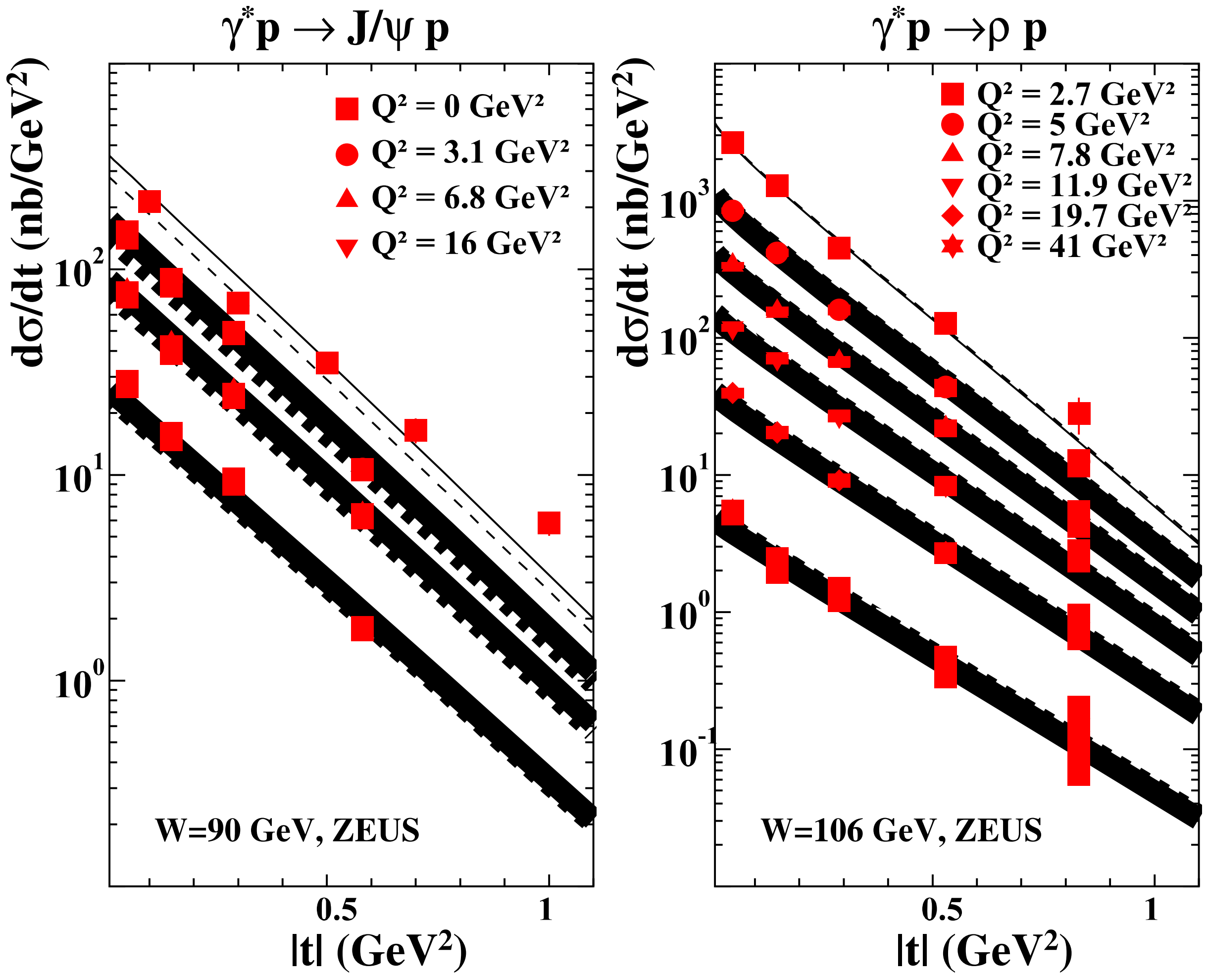
Diffraction in ep and eA

A. Accardi et al., Eur. Phys. J. ***A52*** *(2016)*

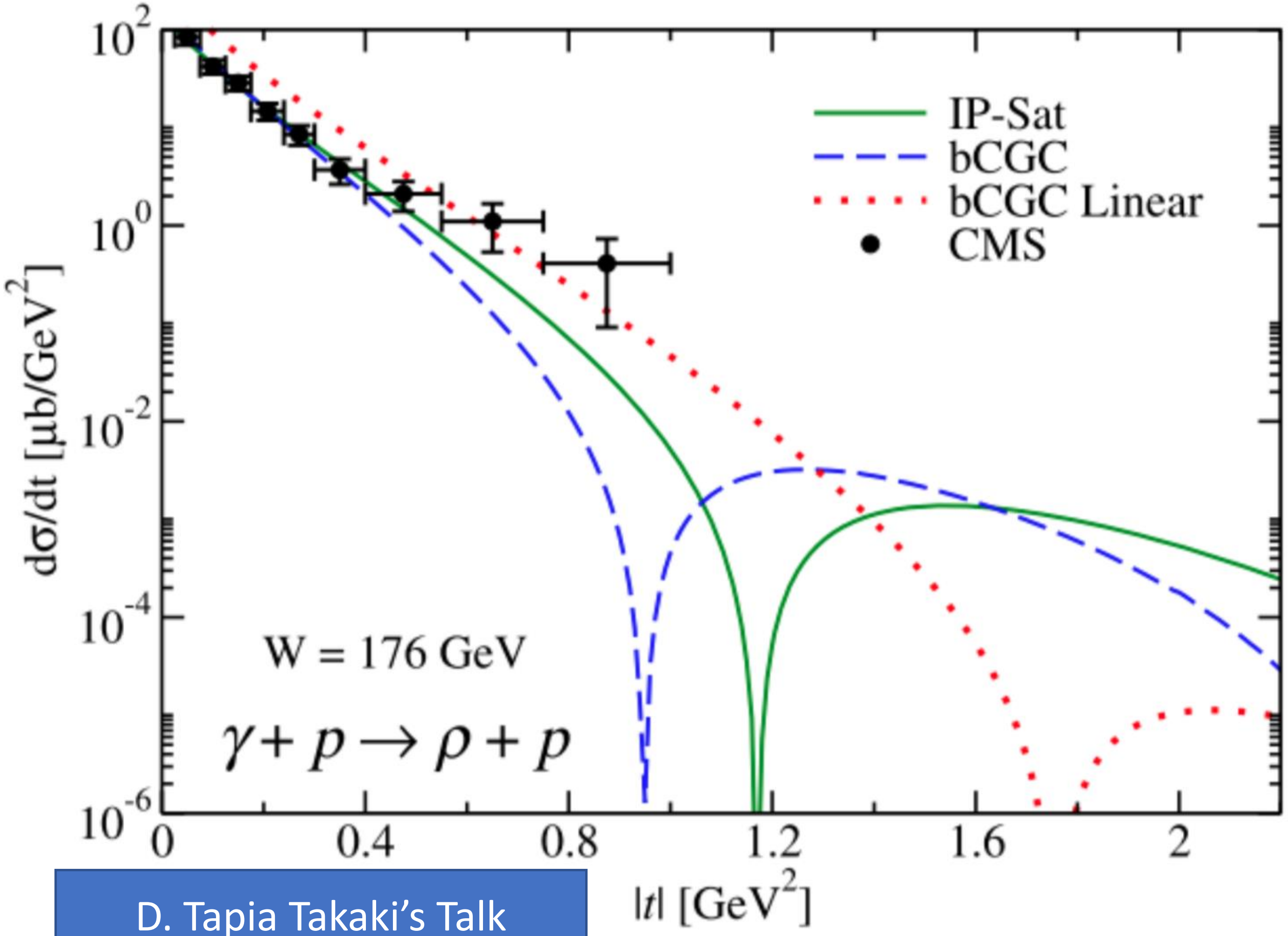


- Proportional to gluon density at amplitude level (GPD)

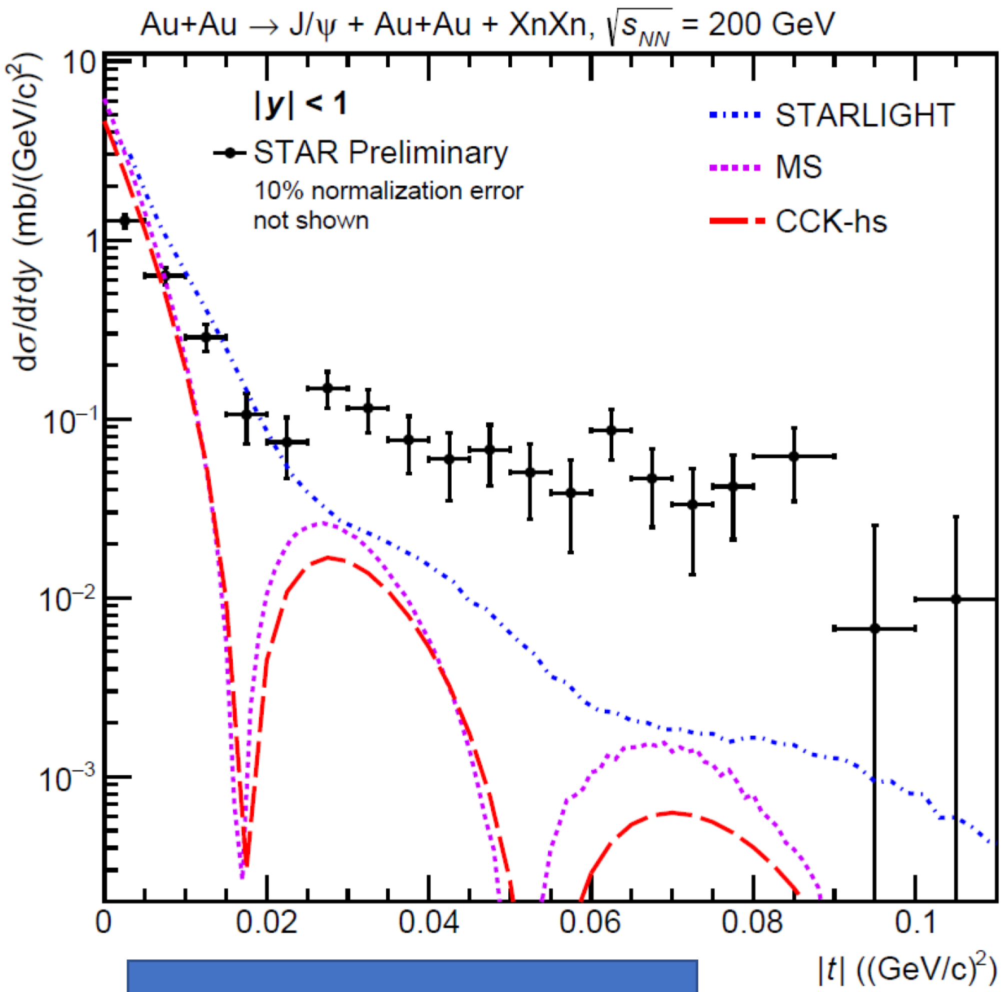
A. Rezaeian et al., Phys. Rev. ***D87*** *(2013)*



Diffraction in Ultraperipheral Collisions



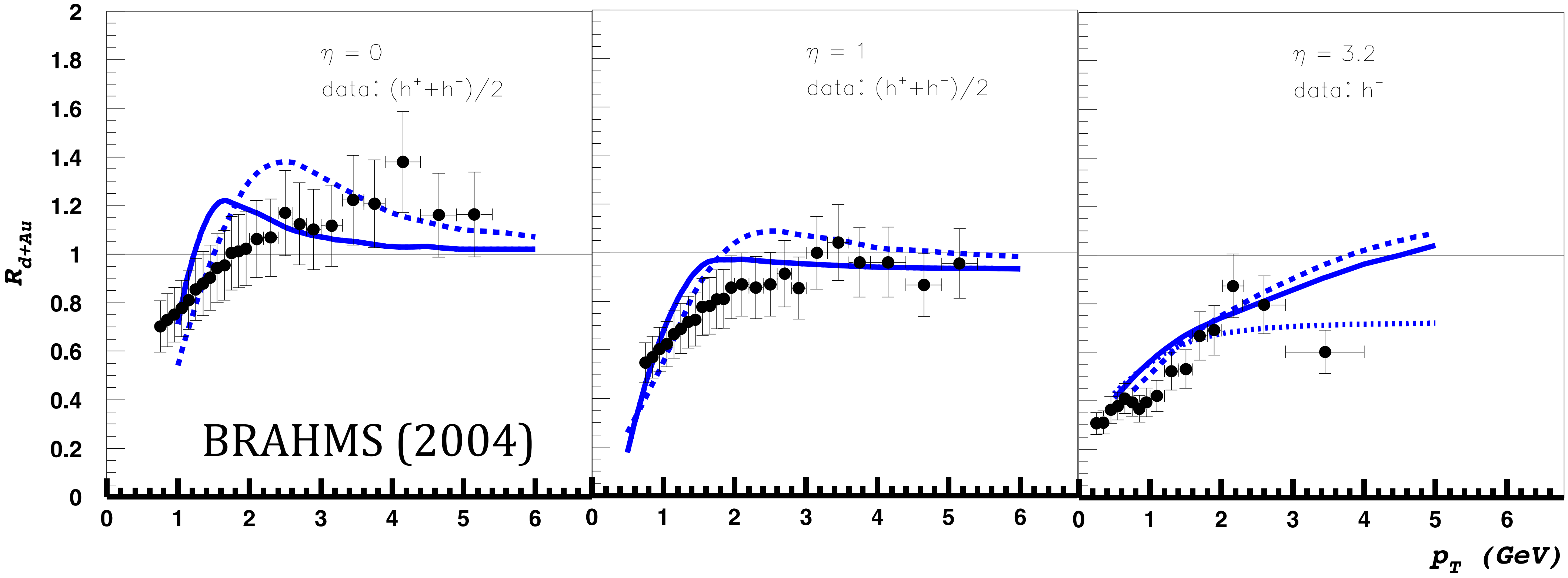
D. Tapia Takaki's Talk



J. Seger's Talk

The Cronin Peak in pA

D. Kharzeev et al., Phys. Lett. ***B599*** *(2004)*

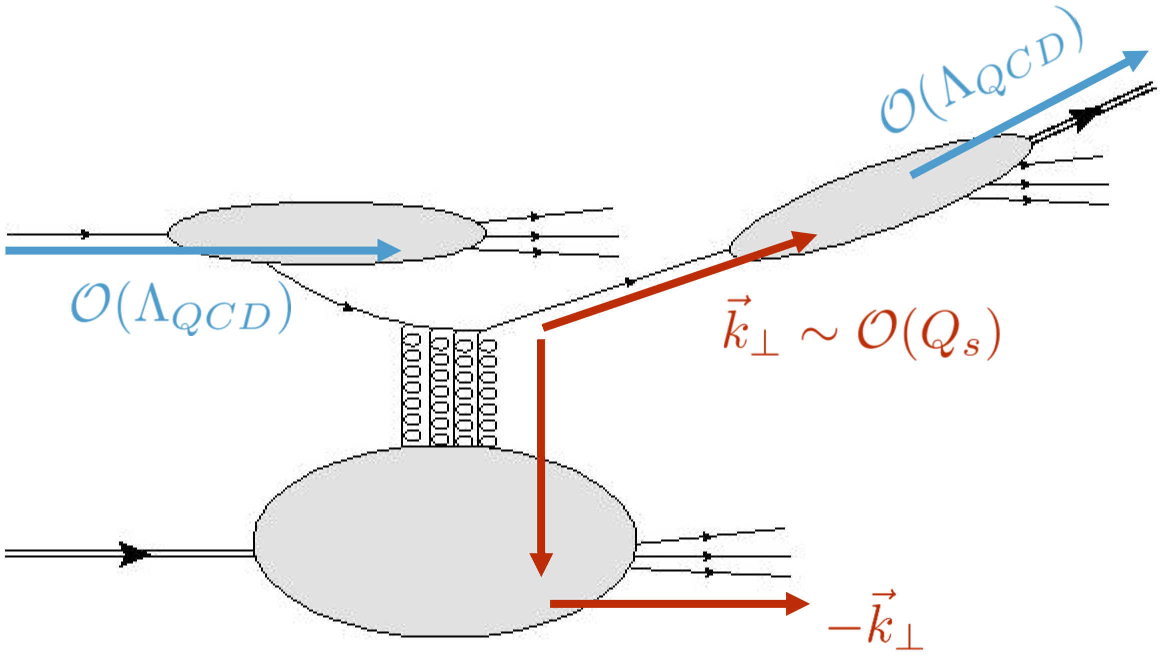


- Multiple scattering redistributes gluons to higher momenta: **Cronin enhancement**
  - ➢ **Nonlinear evolution destroys** the peak at forward rapidities

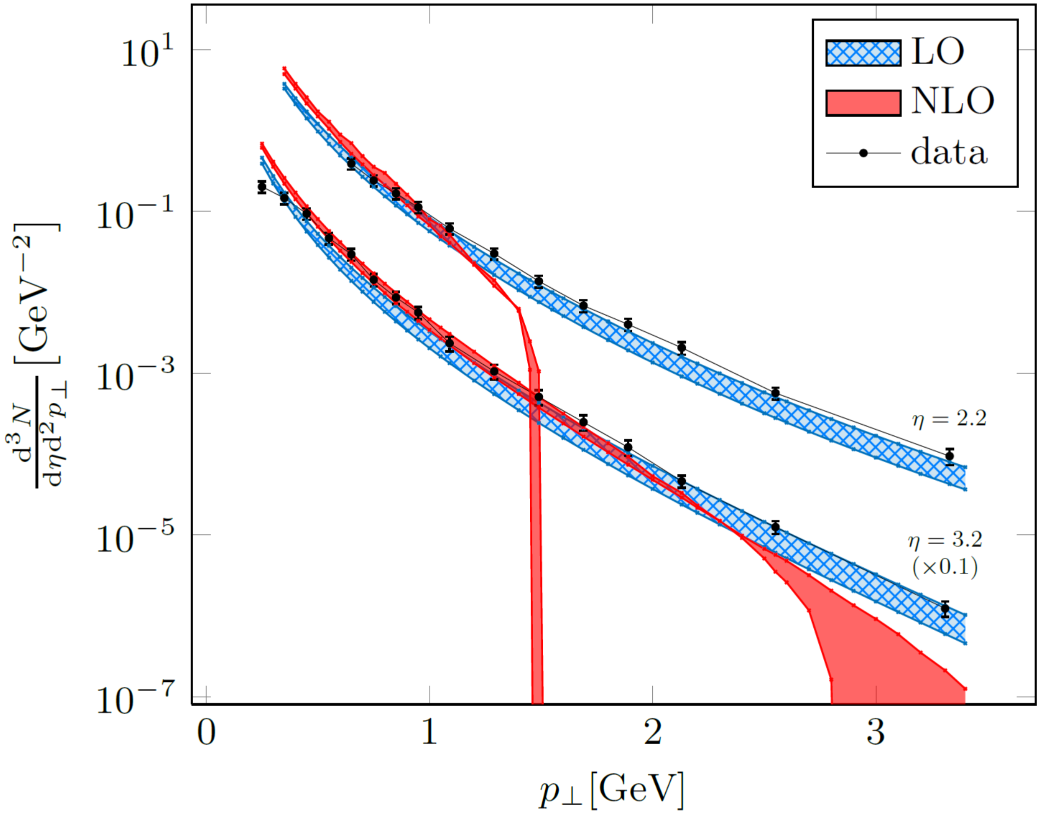
Hybrid Factorization in pA

$$\frac{d\sigma^{pA\to hX}_{\mathrm{LO}}}{d^2p_\perp dy_h} = \int_\tau^1 \frac{dz}{z^2}\left[\sum_f x_p q_f(x_p)\mathcal{F}(k_\perp)D_{h/q}(z) + x_p g(x_p)\tilde{\mathcal{F}}(k_\perp)D_{h/g}(z)\right]$$

G. Chirilli et al., Phys. Rev. ***D86*** *(2012)*



$k_T \sim \mathcal{O}(Q_s) \gg \Lambda_{QCD}$



A. Stasto et al., Phys. Rev. Lett ***112*** *(2014)*

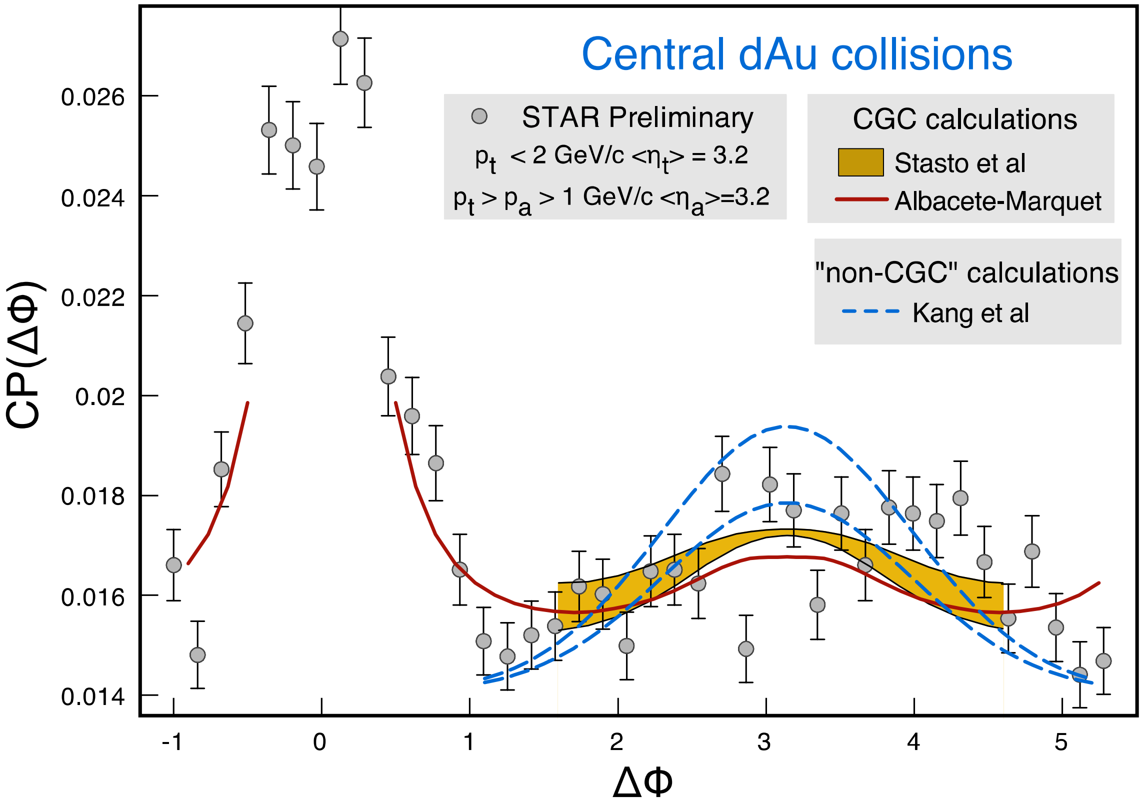
Back to Back Correlations in pA

- For **dihadron production in *pp***, there is a pronounced **back to back peak** at $\Delta\varphi \rightarrow \Delta\varphi + \pi$

➢ **Multiple scattering** from the medium **broadens and depletes** the back to back peak in ***pA***

➢ Natural in a saturation framework, but also **momentum broadening** in general

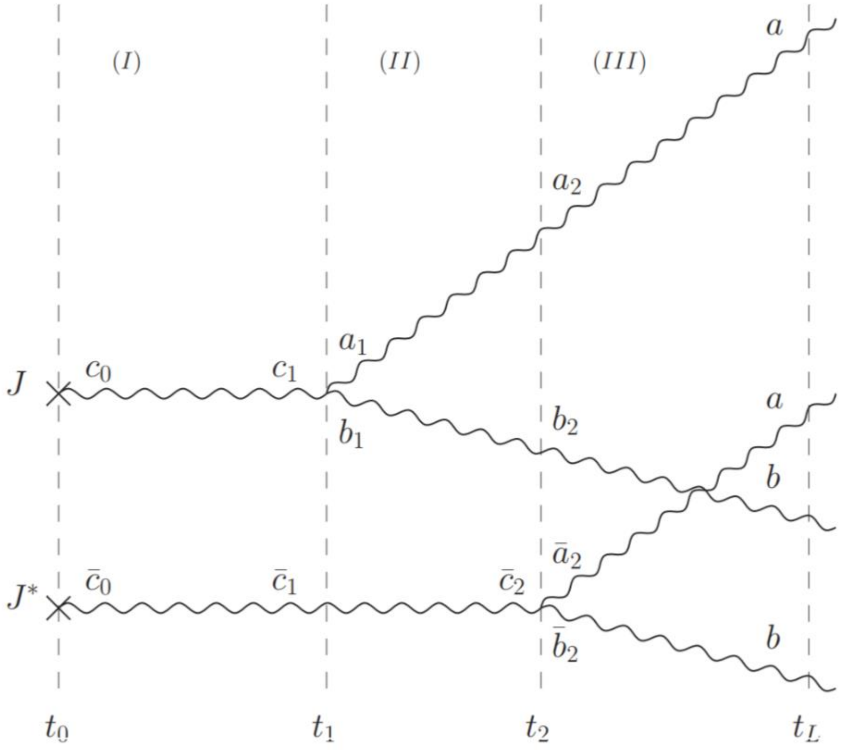
J. Albacete., Nucl. Phys. ***A910*** *(2013)*



$$S^{(2)}(Y,X|\omega) = \int \mathcal{D}\boldsymbol{u}\mathcal{D}\boldsymbol{v}\ \exp\left\{ i\omega \int_{x^+}^{y^+} \mathrm{d}t\ \dot{\boldsymbol{u}}\cdot\dot{\boldsymbol{v}} - \frac{N_c n}{2}\int_{x^+}^{y^+} \mathrm{d}t\,\sigma(\boldsymbol{u}) \right\}$$

$$S^{(3)}(Y,X|\boldsymbol{\omega}) = \int \mathcal{D}\boldsymbol{r}_2\mathcal{D}\boldsymbol{r}_1\mathcal{D}\boldsymbol{r}_0 \exp\left\{ \frac{i}{2}\int_{x^+}^{y^+} \mathrm{d}t\ (\omega_1\dot{\boldsymbol{r}}_1^2 + \omega_2\dot{\boldsymbol{r}}_2^2 - \omega_0\dot{\boldsymbol{r}}_0^2) \right\} \times \exp\left\{ -\frac{N_c n}{4}\int_{x^+}^{y^+} \mathrm{d}t\ [\sigma(\boldsymbol{r}_1-\boldsymbol{r}_0)+\sigma(\boldsymbol{r}_2-\boldsymbol{r}_0)+\sigma(\boldsymbol{r}_2-\boldsymbol{r}_1)] \right\}.$$

J.-P. Blaizot et al., JHEP ***1301*** *(2013)*

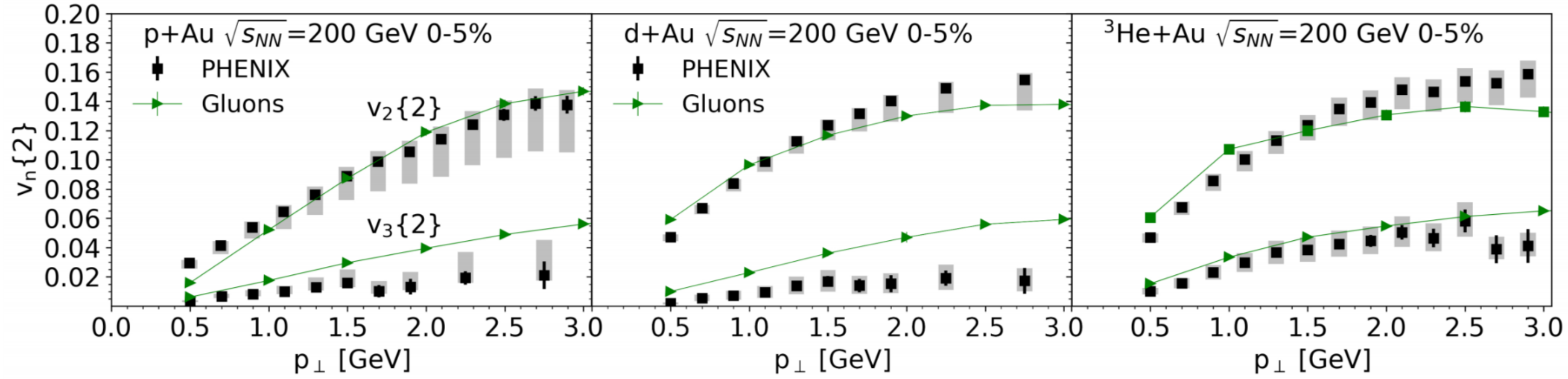


- **CGC Particle Production:**
  - Controlled by **dipole scattering cross sections**

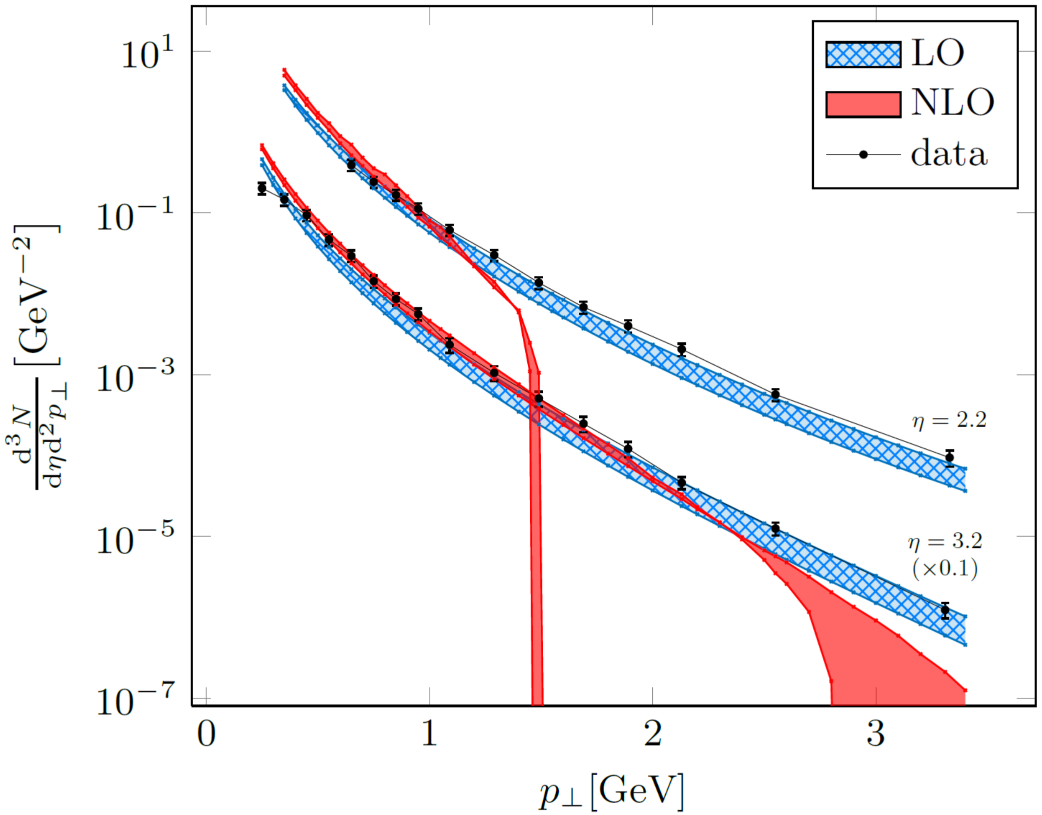
- The same amplitudes enter **jet quenching**
  - Stimulated **radiation** from multiple scattering

Multiparticle Correlations in pA / aA

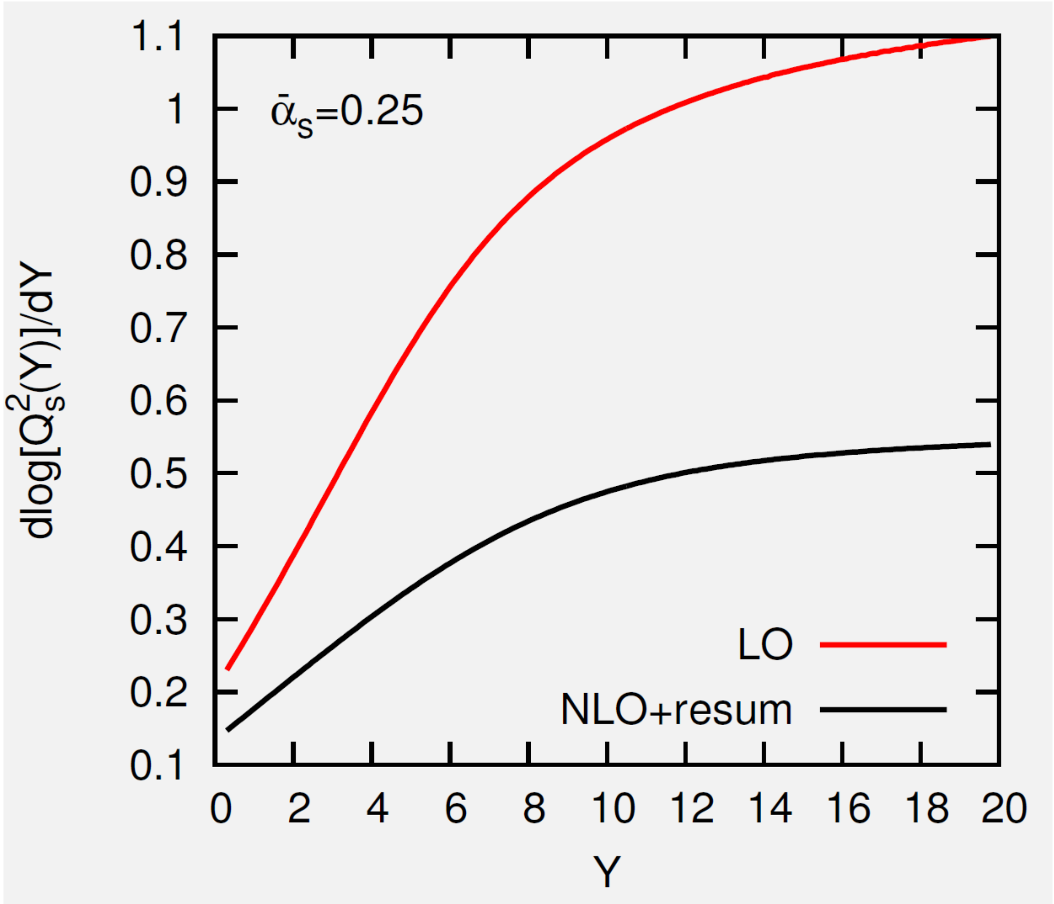
*Mace et al., Phys. Rev. Lett. **121** (2018), and arXiv:1901.10506*



- **Two-particle correlations** produced in small systems collisions
  - Correlations arise from scattering in **anisotropic color domains**



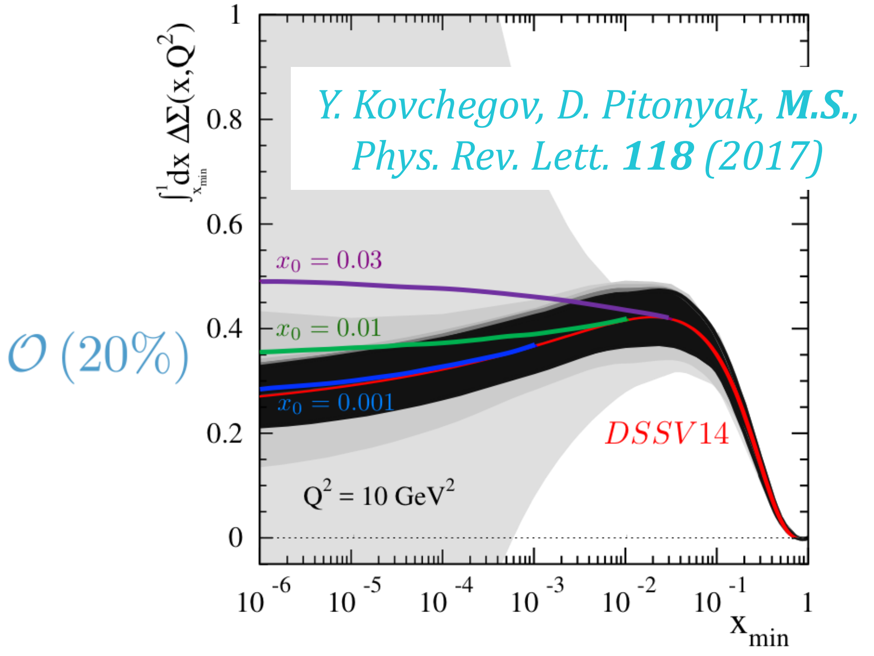
A. Stasto et al., Phys. Rev. Lett ***112*** *(2014)*



B. Ducloue et al., arXiv: 1902.06637

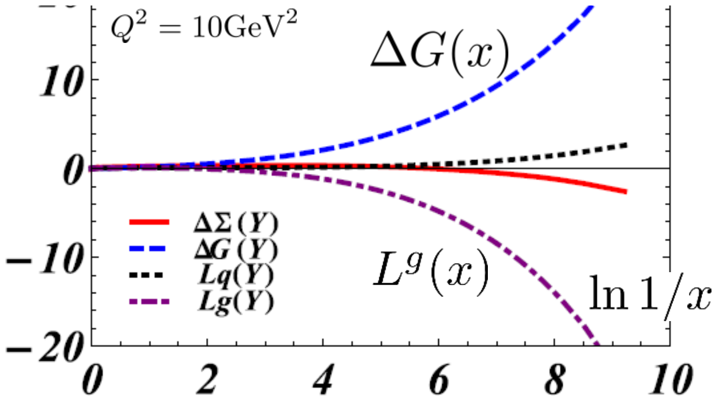
- Evolution equations at NLO introduce **double logarithms**
  - ➢ ***NLL′*** **Resummation**

- Small-x evolution of quark / gluon polarization
  - ➢ Also **double logarithmic**
  - ➢ Leads to enhancement of total spin contributions



- One approach: Light-Front Wave Functions
  - ➢ **Convergent** at small x
  - ➢ **O(20%)** enhancement

Y. Hatta, D.-J. Yang, Phys. Lett. **B781** (2018)



- Another approach: Infrared Evolution Equations
  - ➢ **Power-law growth** at small x
  - ➢ Total spin terms are apparently divergent
  - ➢ **Regulated** by nonlinear **saturation** corrections?

Overview

1. What is Saturation?

2. … ation

Concluding Perspective

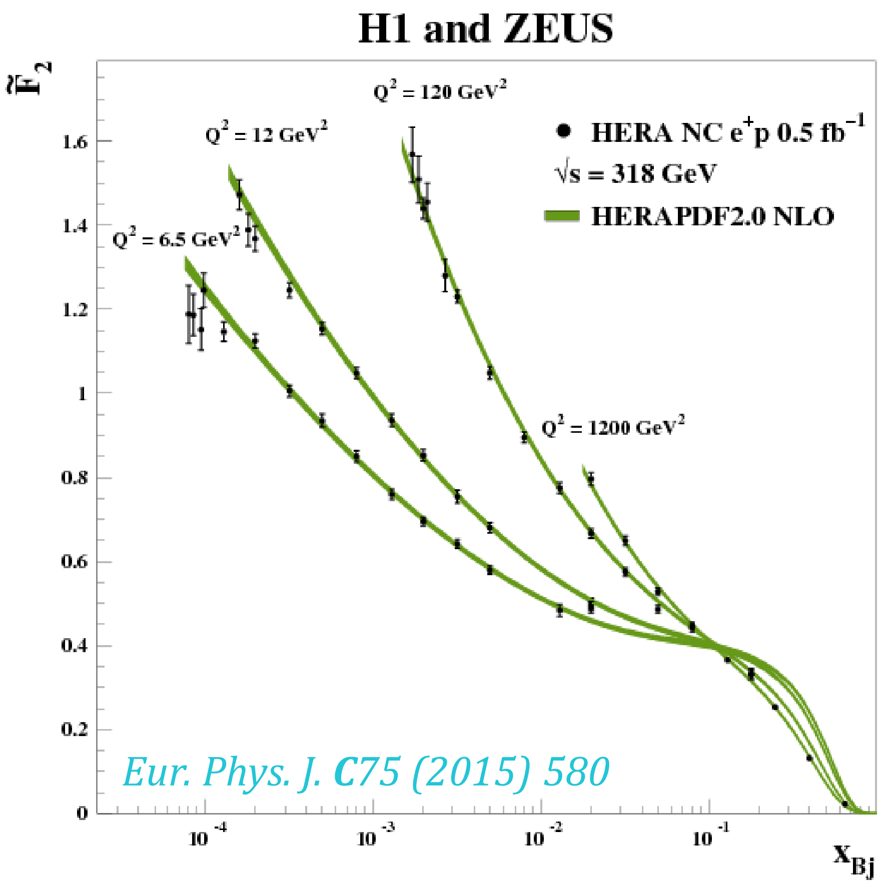
Saturation as a Fundamental Test of the Standard Model

- Power-law growth of the structure functions would **violate unitarity** if it continued

- **Saturation** is the mechanism by which **unitarity is restored** at high energies
  - ➢ QCD is a well-defined theory up to **infinite energies** and **infinite Q^2** (**UV complete**)

❖ *"Saturation is a non-negotiable property of QCD"*
– N. Armesto

- The same **non-Abelian** nature which gives **asymptotic freedom** also gives **saturation**
  - ➢ Fundamental test of quantum field theory



Eur. Phys. J. ***C*****75** *(2015) 580*