Forward physics in p+A

(to probe non-linear QCD evolution)

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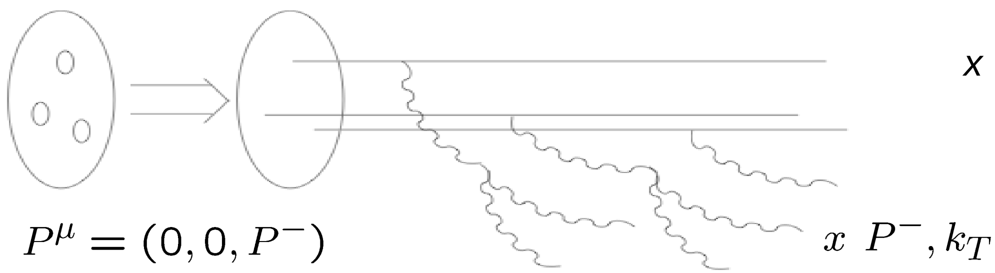
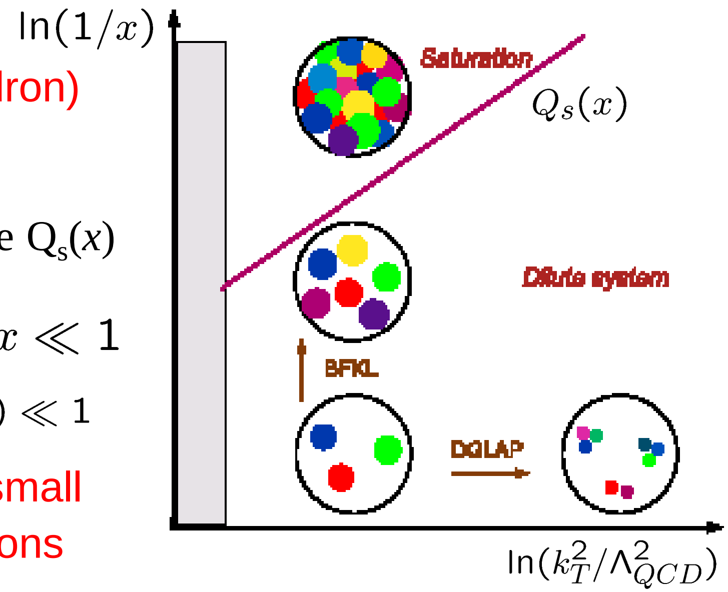
Map of parton evolution in QCD



x : parton longitudinal momentum fraction

k_T : parton transverse momentum

the distribution of partons as a function of x and k_T :



QCD linear evolutions: $k_T \gg Q_s$

DGLAP evolution to larger k_T (and a more dilute hadron)

BFKL evolution to smaller x (and denser hadron)

dilute/dense separation characterized by the saturation scale $Q_s(x)$

QCD non-linear evolution: $k_T \sim Q_s$ meaning $x \ll 1$

this regime is non-linear yet weakly coupled: $\alpha_s(Q_s^2) \ll 1$

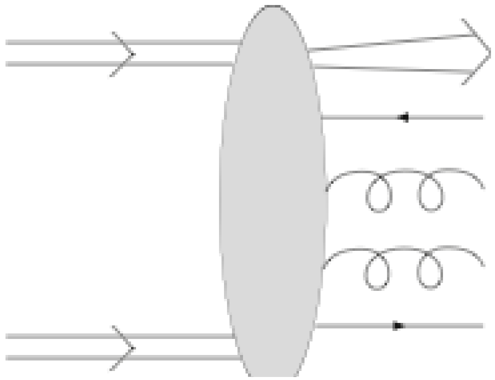
collinear factorization does not apply when x is too small and the hadron has become a dense system of partons

$$\sigma_{DIS}(x_{Bj}, Q^2) = \sum_{partons\ a} \int_{x_{Bj}}^{1} dx\, \varphi_{a/p}(x, Q^2)\, \hat{\sigma}_a(x_{Bj}/x, Q^2) + O\left(Q_0^2/Q^2\right)$$

parton density — partonic cross-section — higher twist → $\frac{(A/x)^{1/3}}{Q^2}$

Single inclusive hadron production

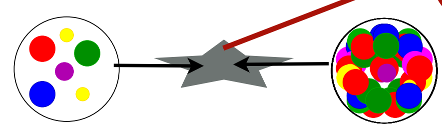
forward rapidities probe small values of *x*



transverse momentum k_T, rapidity $y > 0$

values of x probed in the process:

$$x_1 \sqrt{s} = k_T\, e^{y} \qquad x_2 \sqrt{s} = k_T\, e^{-y}$$



$$\frac{dN_h}{dy_h\, d^2p_t} = \frac{K}{(2\pi)^2} \sum_q \int_{x_F}^{1} \frac{dz}{z^2} \left[x_1 f_{q/p}(x_1, p_t^2)\, \tilde{N}_F\left(x_2, \frac{p_t}{z}\right) D_{h/q}(z, p_t^2) + x_1 f_{g/p}(x_1, p_t^2)\, \tilde{N}_A\left(x_2, \frac{p_t}{z}\right) D_{h/g}(z, p_t^2) \right]$$

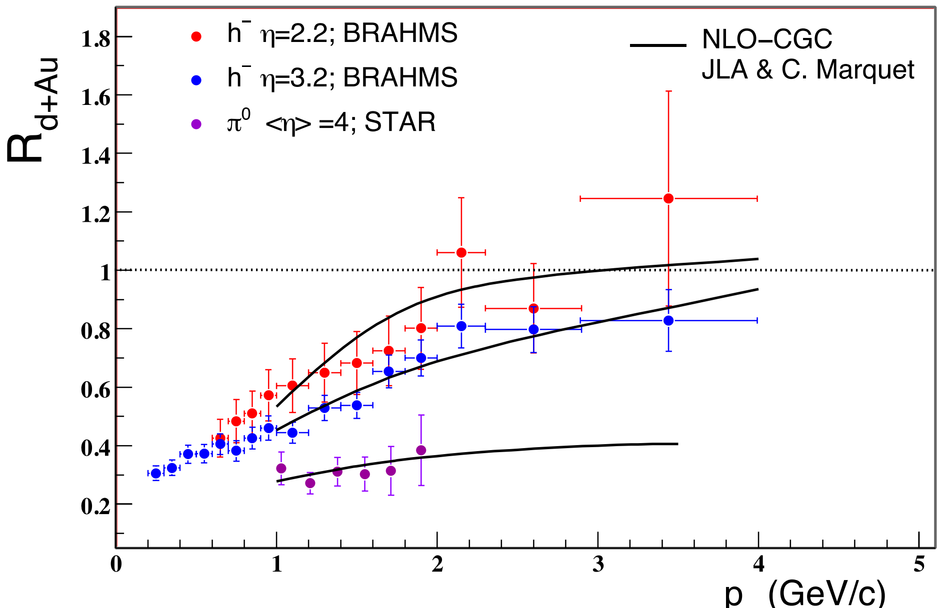
fragmentation

Nuclear modification factor

$R_{dA} = 1$ in the absence of nuclear effects, i.e. if the gluons in the nucleus interact incoherently as in A protons

$$R_{dA} = \frac{1}{N_{coll}} \frac{\frac{dN^{dA\to hX}}{d^2k dy}}{\frac{dN^{pp\to hX}}{d^2k dy}}$$

the suppressed production ($R_{dA} < 1$) was predicted in the Color Glass Condensate picture, along with the rapidity dependence



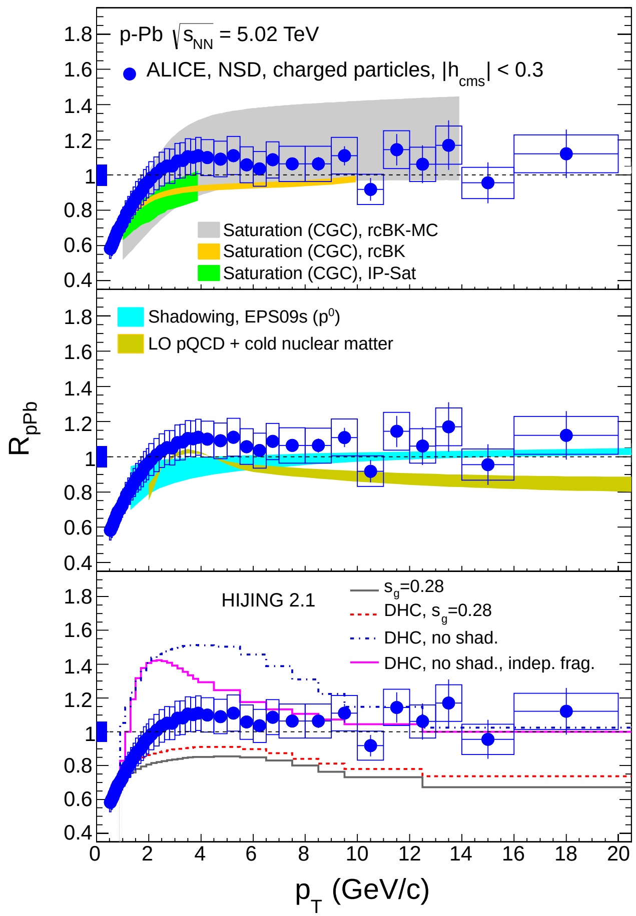
Albacete and CM (2010)

note: alternative explanations (large-x energy loss effects) have been proposed

Kopeliovich et al (2005), Frankfurt et al (2007)

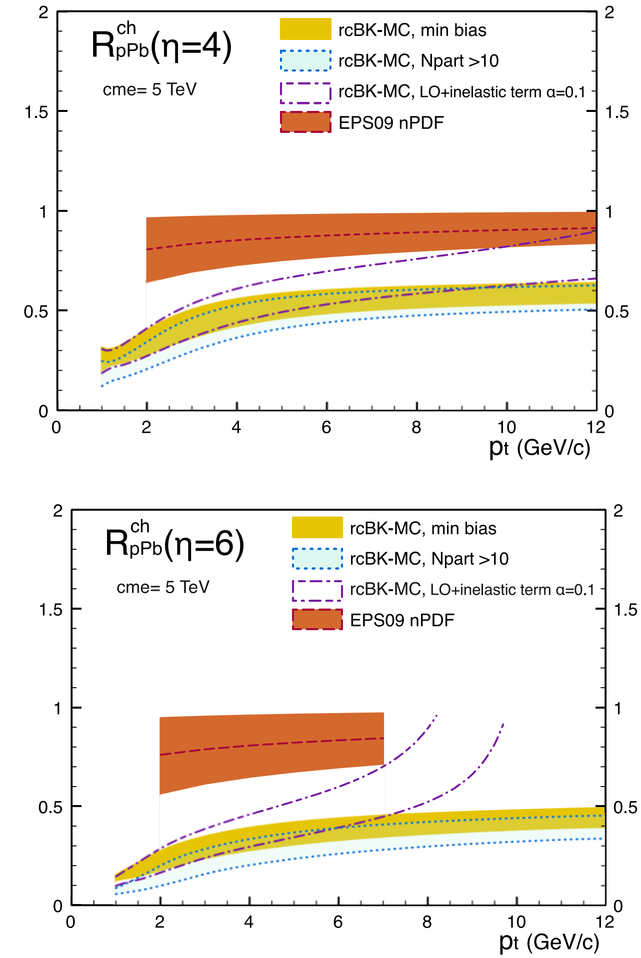
p+Pb @ the LHC

- mid-rapidity data



good description but not much non-linear effects

- predictions for forward rapidities



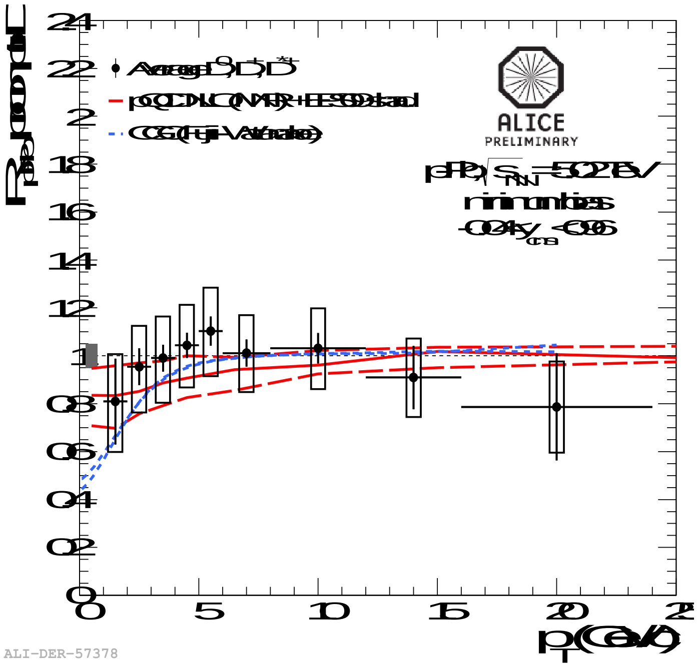
strong non-linear effects

Other recent LHC comparisons

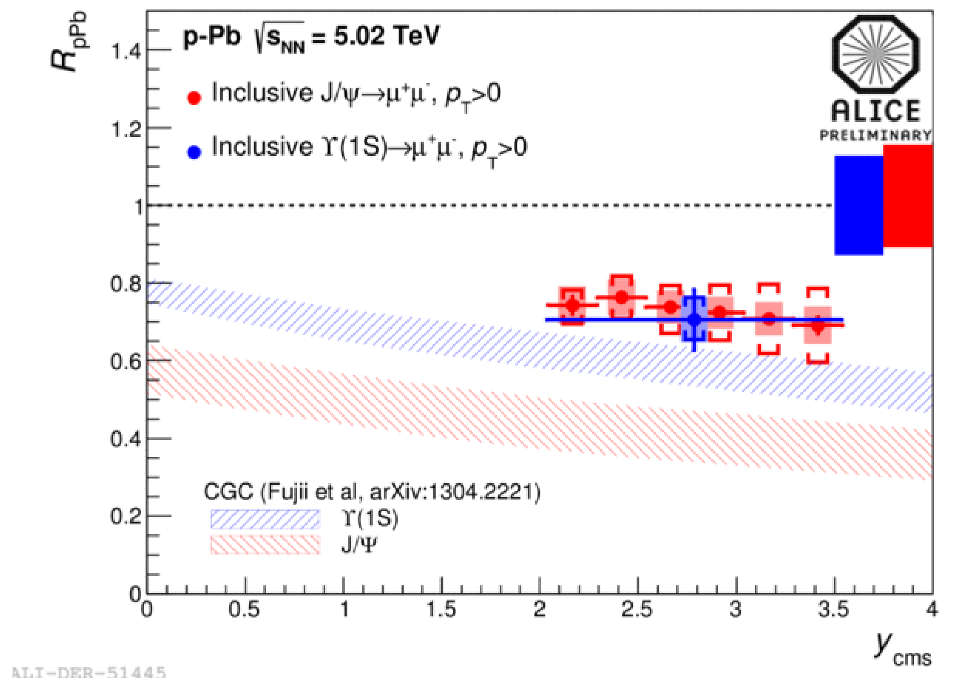
- open charm

Fujii and Watanabe (2013)

- quarkonia



mid-rapidity only
similar to the charged hadron data



CGC calculations are slighly below the data – saturation effects are perhaps not the most relevant in this case

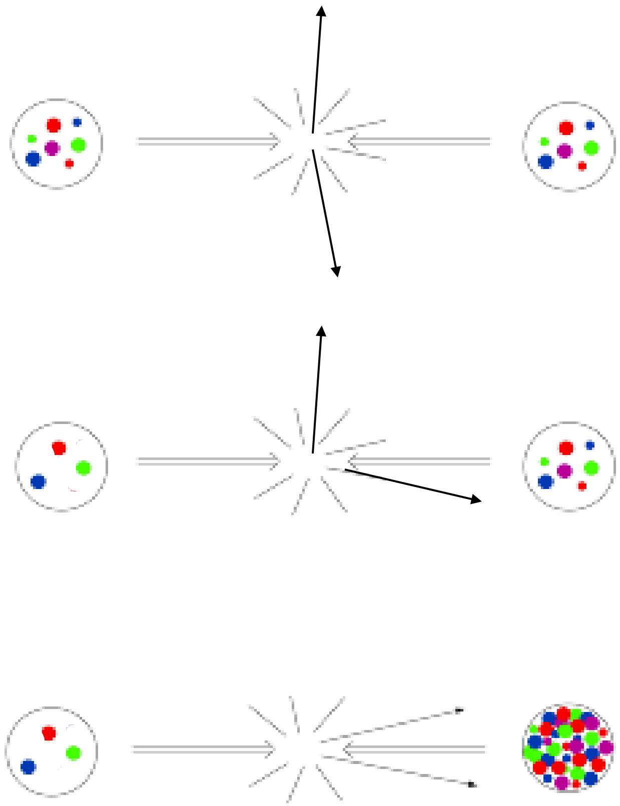
LHCb and ALICE (with planned upgrade) can measure charm at forward rapidities

Di-hadron final-state kinematics

final state : $k_1, y_1 \quad k_2, y_2$

$$x_p = \frac{k_1\, e^{y_1} + k_2\, e^{y_2}}{\sqrt{s}} \qquad x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}}$$

scanning the wave functions:



$$x_p \sim x_A < 1$$

central rapidities probe moderate x

x_p increases | x_A ~ unchanged

$$x_p \sim 1,\, x_A < 1$$

forward/central doesn't probe much smaller x

x_p ~ unchanged | x_A decreases

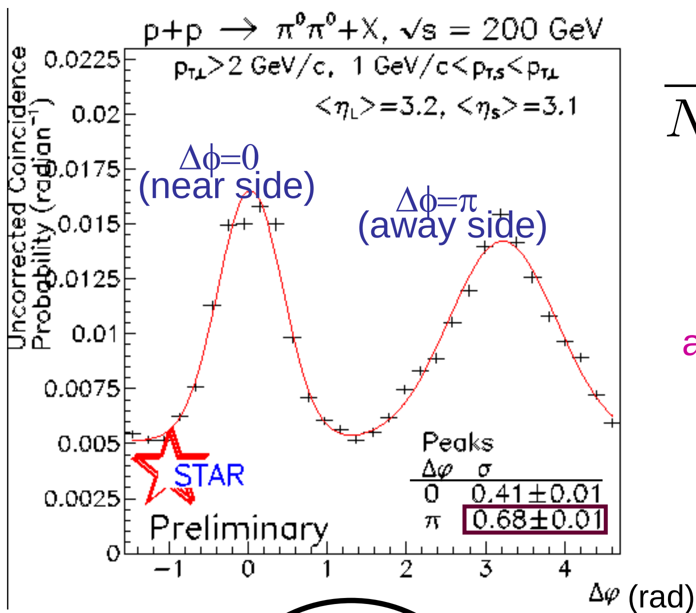
$$x_p \sim 1,\, x_A << 1$$

forward rapidities probe small x

Di-hadron angular correlations

comparisons between d+Au → $h_1\ h_2$ X (or p+Au → $h_1\ h_2$ X) and p+p → $h_1\ h_2$ X

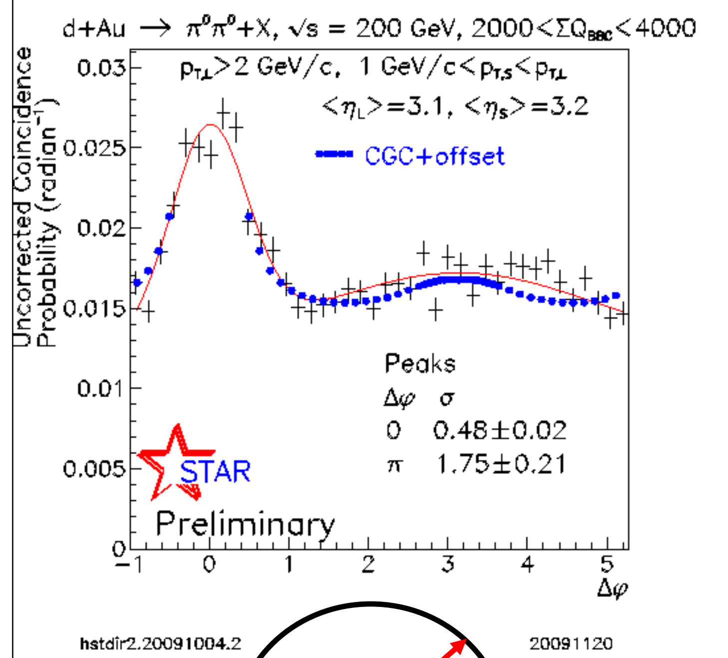
p+p collisions

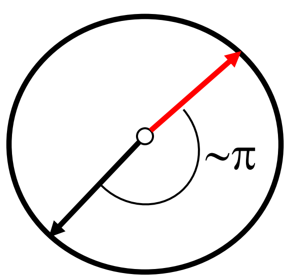


$$\frac{1}{N_{trig}}\frac{dN_{pair}}{d\Delta\varphi}$$

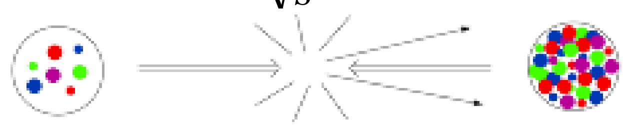
Albacete
and CM (2010)

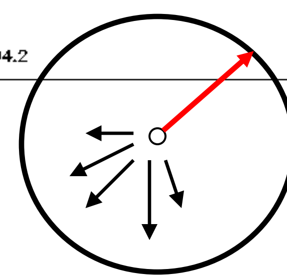
central d+Au collisions





$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}} << 1$$

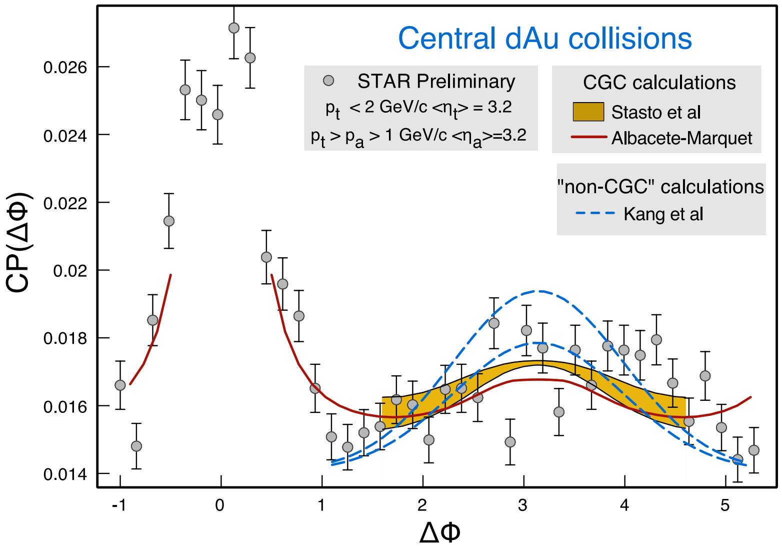


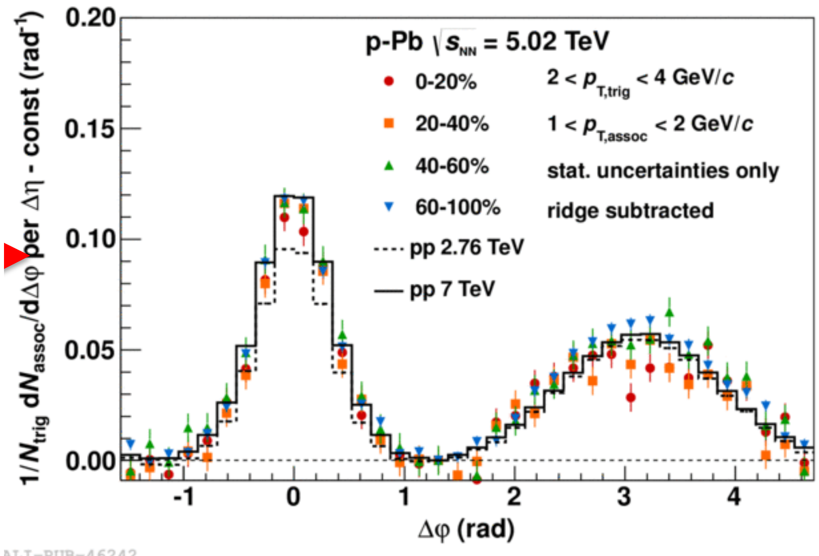


however, when $y_1 \sim y_2 \sim 0$ (and therefore $x_A \sim 0.03$),
the p+p and d+Au curves are almost identical

Recent progress and LHC data

- improved CGC calculations
  - Stasto, Xiao and Yuan (2012)
  - Lappi and Mantysaari (2013)
- first non-CGC description
  - Kang, Vitev and Xing (2012)
- recent ALICE mid-rapidity data





after subtracting from the data the so-called ridge, there is little away-side suppression with increasing centrality

forward rapidity data are needed here as well

Hard diffraction in p+A

single-hadron production in diffractive events $pA \to XhA$ Tuchin (2008)

could not be done at RHIC

- as a function of p_T of the hadron

the proportion of incoherent
diffraction decreases with A

- nuclear modifications

antishadowing of coherent diffraction

shadowing of incoherent diffraction

Conclusions

- Fundamental consequence of QCD dynamics:

  - at asymptotically small x/large A, QCD evolution becomes non-linear

- Non-linear evolution of gluon density in Au at RHIC:

  - suppression of single hadron production in d+Au vs p+p

  - suppression of back-to-back correlations of di-hadrons in d+Au vs p+p

- Awaiting more p+Pb forward rapidity data (so far only quarkonia)

- Diffraction ? $pA \to pX$ or/and $pA \to XA$ with AFP/TOTEM ?