Saturation effects in forward-forward dijet production in p+Pb collisions

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A. van Hameren, P. Kotko, K. Kutak, CM and S. Sapeta, Phys.Rev. D89 (2014) 094014

Contents

- Parton saturation and non-linear evolution in QCD

  brief introduction

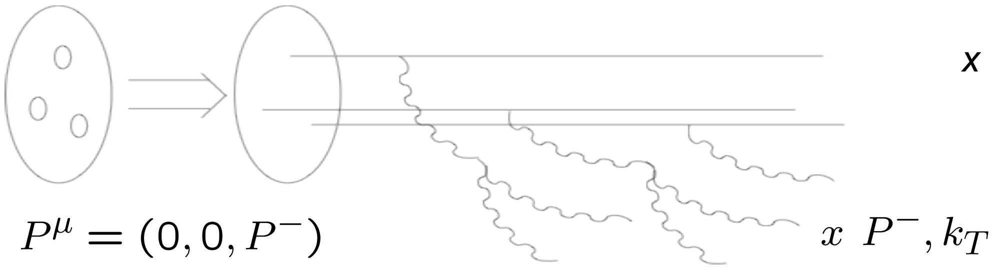
- Forward particle production in d+Au collisions

  reminder of saturation signals at RHIC: suppression of hadron production and di-hadron correlations in p+A vs p+p

- Forward di-jet production in p+Pb collisions

  extending the formalism to deal with high-p_T partons

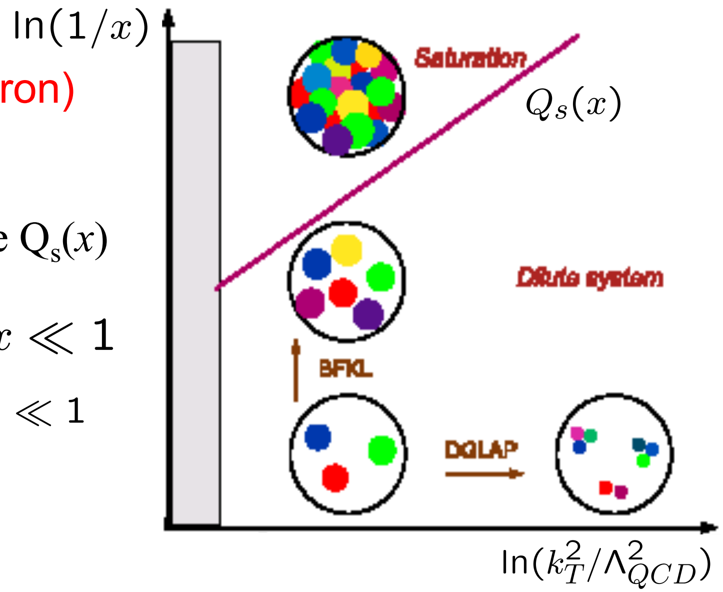
Map of parton evolution in QCD



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: $\alpha_s(Q_s^2) \ll 1$

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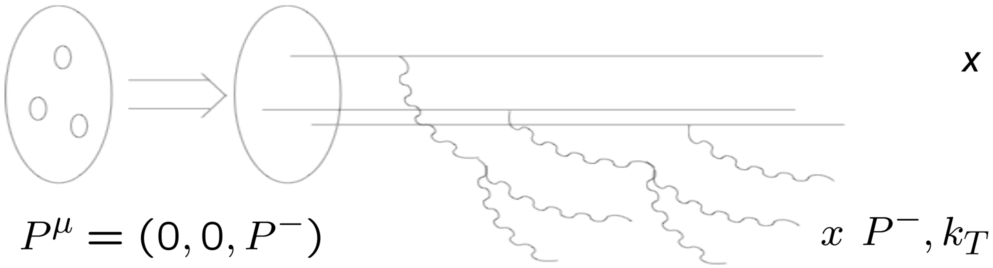

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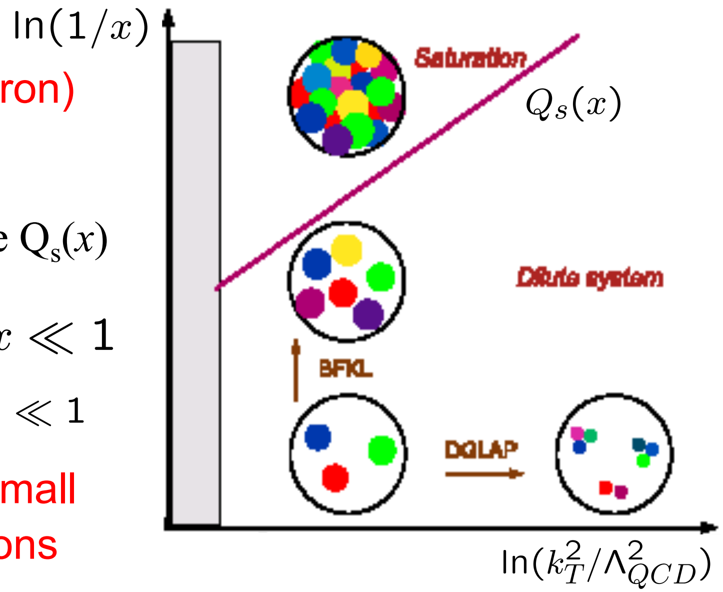

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collinear factorization does not apply when x is too small and the hadron has become a dense system of partons

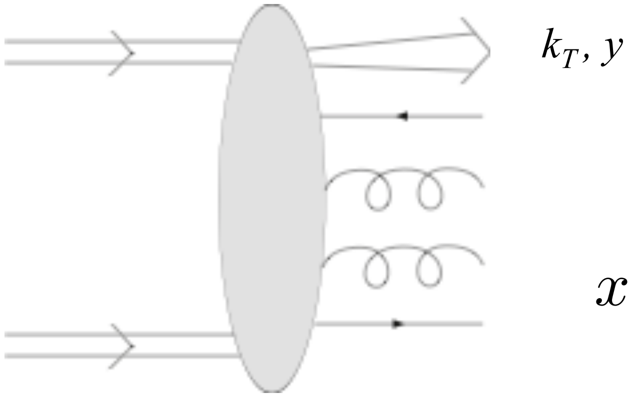
$$\sigma_{DIS}(x_{Bj}, Q^2) = \sum_{\text{partons } a} \int_{x_{Bj}}^{1} dx\ \underbrace{\varphi_{a/p}(x, Q^2)}_{\text{parton density}}\ \underbrace{\hat{\sigma}_a(x_{Bj}/x, Q^2)}_{\text{partonic cross-section}} + \underbrace{O\left(Q_0^2/Q^2\right)}_{\text{higher twist}}$$

higher twist $\rightarrow \dfrac{(A/x)^{1/3}}{Q^2}$

Forward particle production in d+Au collisions at RHIC

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:

$$x_1 = M_T\ e^{y}/\sqrt{s} \qquad x_2 = M_T\ e^{-y}/\sqrt{s}$$

$$M_T^2 = (k_T/z)^2 + m_h^2$$

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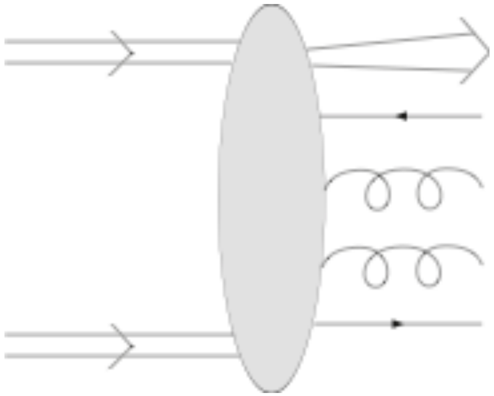

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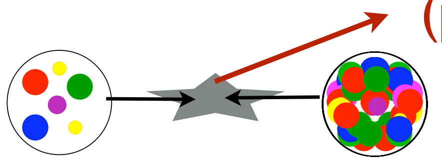

$(p_t, y_h >> 0)$

large-x parton from proj. (pdf)

small-x glue from target (CGC)

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

fragmentation

$$\left. + \, x_1 f_{g\,/\,p}(x_1, p_t^2) \, \tilde{N}_A \left(x_2, \frac{p_t}{z} \right) D_{h\,/\,g}(z, p_t^2) \right]$$

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

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

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

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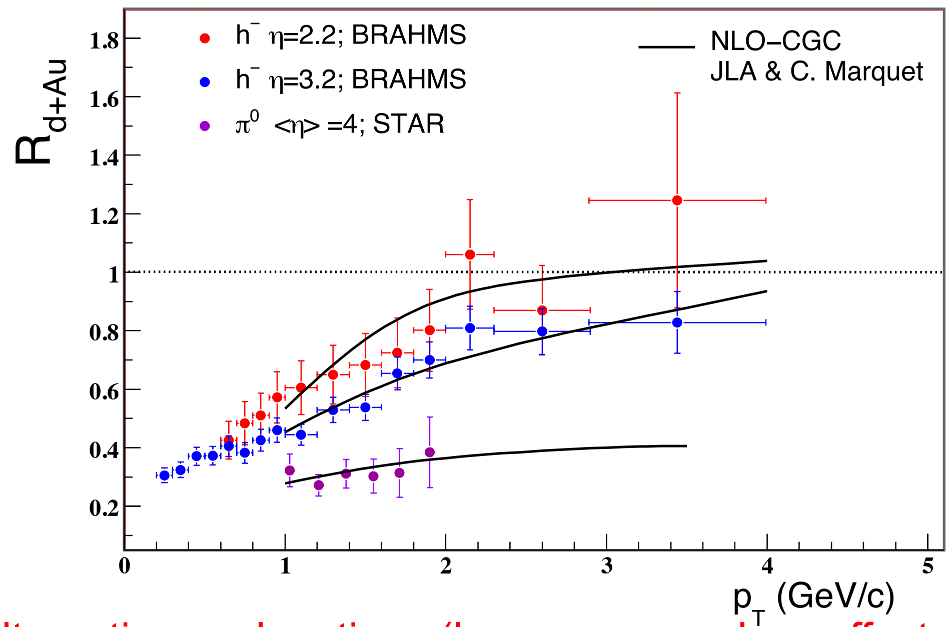


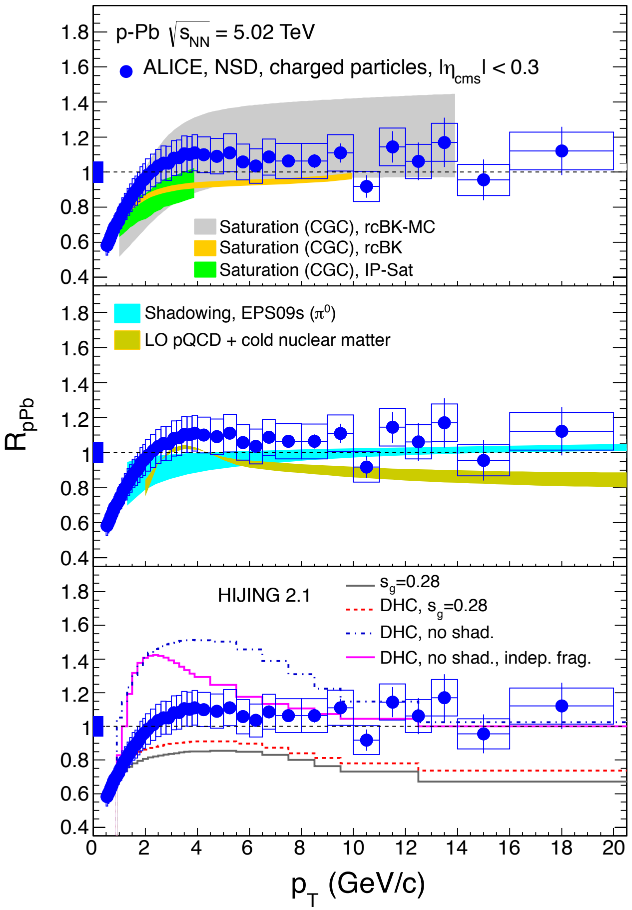
Albacete and CM (2010)

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

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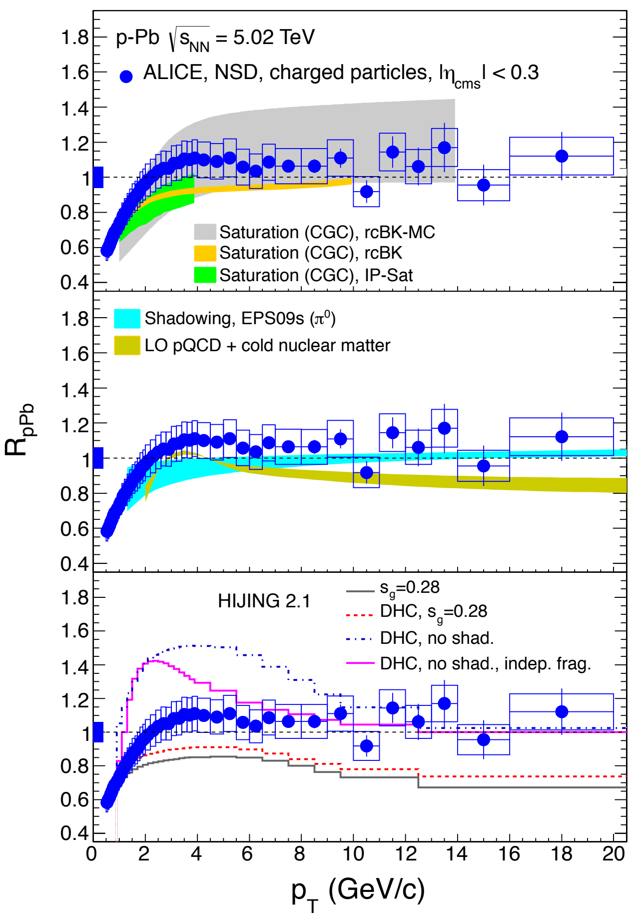

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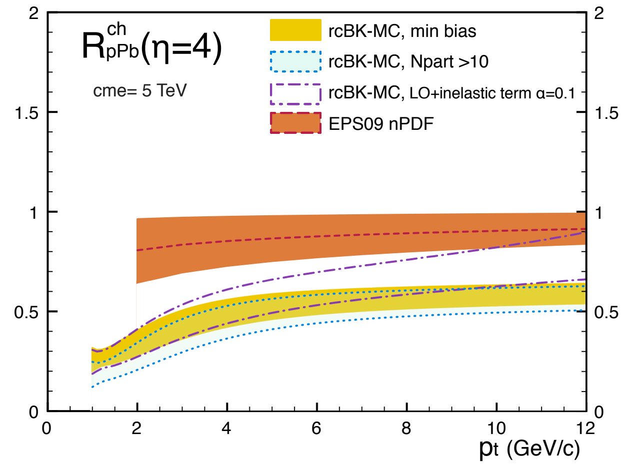
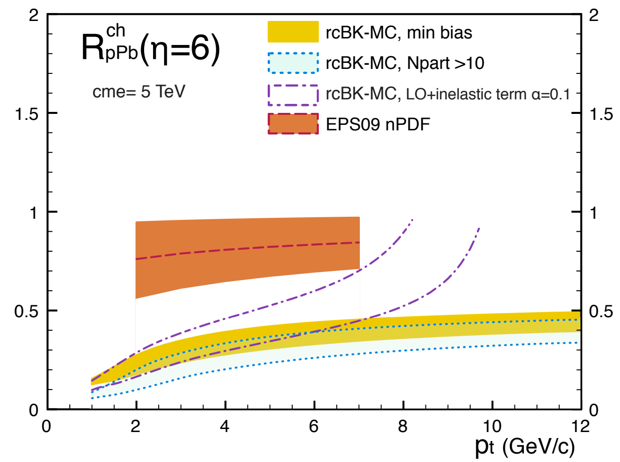
- predictions for forward rapidities





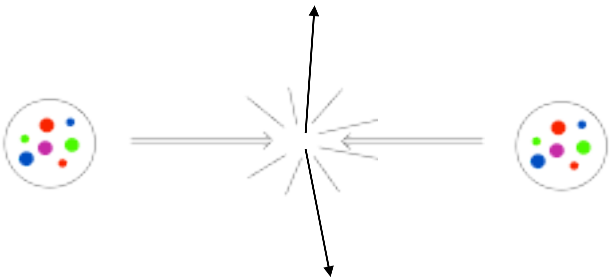
strong non-linear effects

Di-hadron final-state kinematics

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

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

scanning the wave functions:



$$x_p \sim x_A < 1$$

central rapidities probe moderate x

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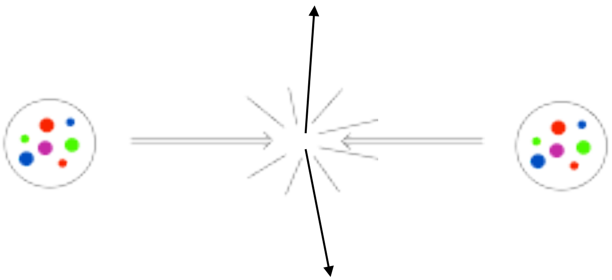

$$x_p \sim x_A < 1$$

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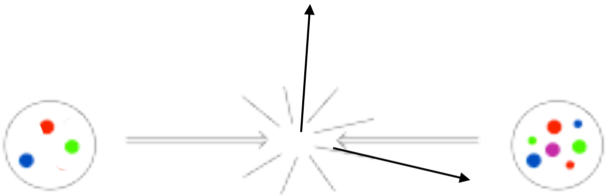
x_p increases | x_A ~ unchanged

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

forward/central doesn't probe much smaller x



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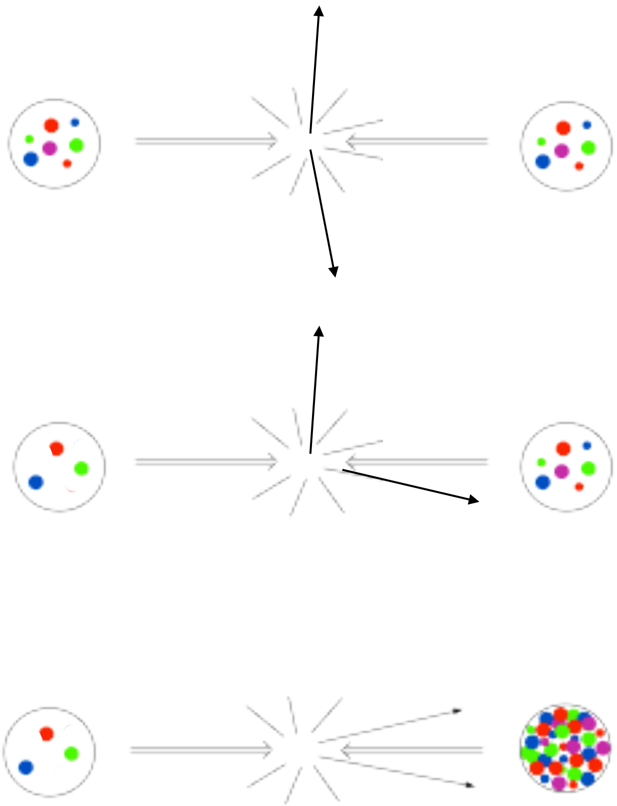

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forward/central doesn’t probe much smaller x

x_p ~ unchanged | x_A decreases

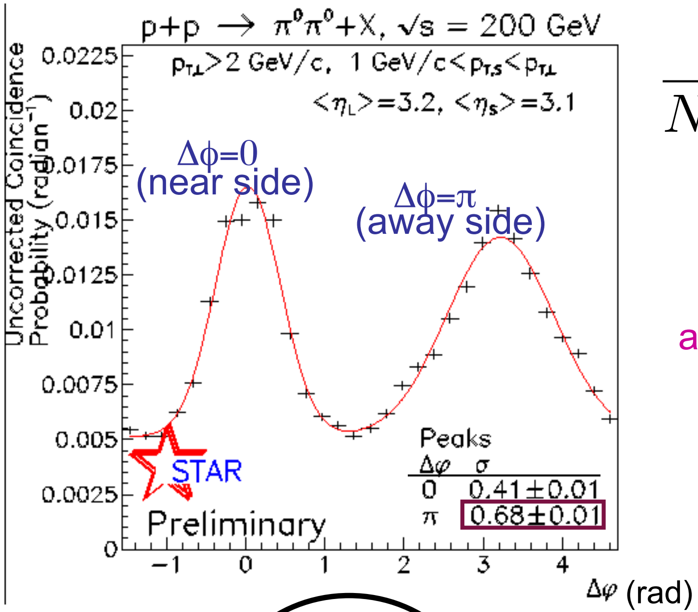
$$x_p \sim 1,\, x_A << 1$$

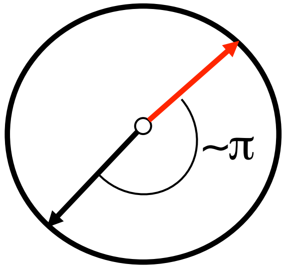
forward rapidities probe small x

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

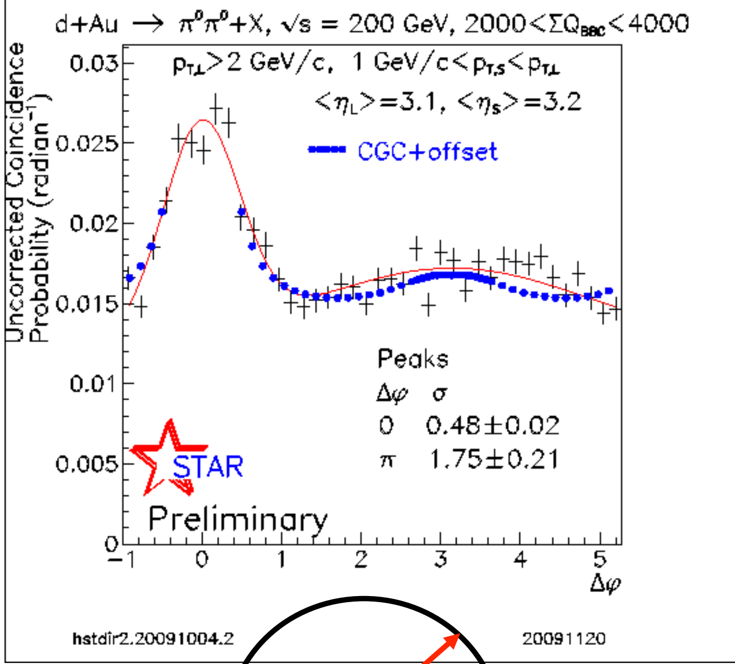


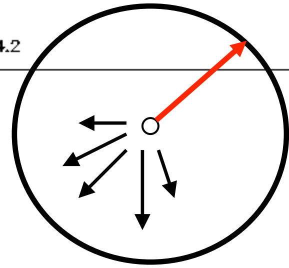


$$\frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\varphi}$$

Albacete
and CM (2010)

central d+Au collisions





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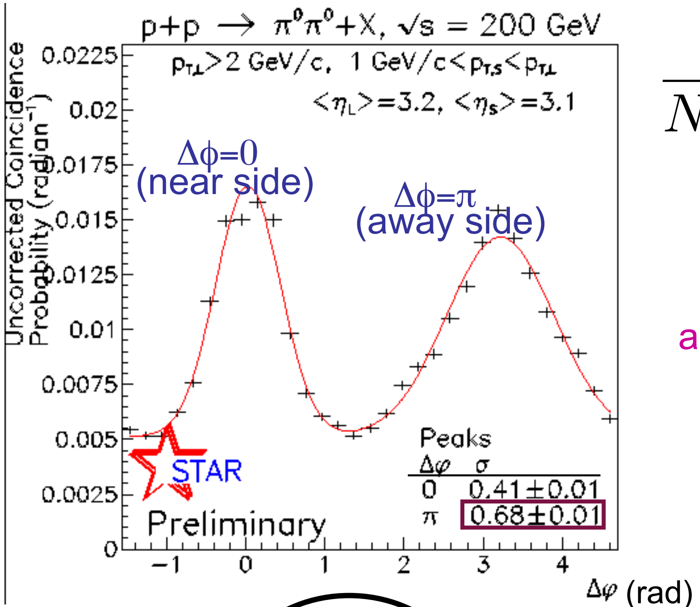

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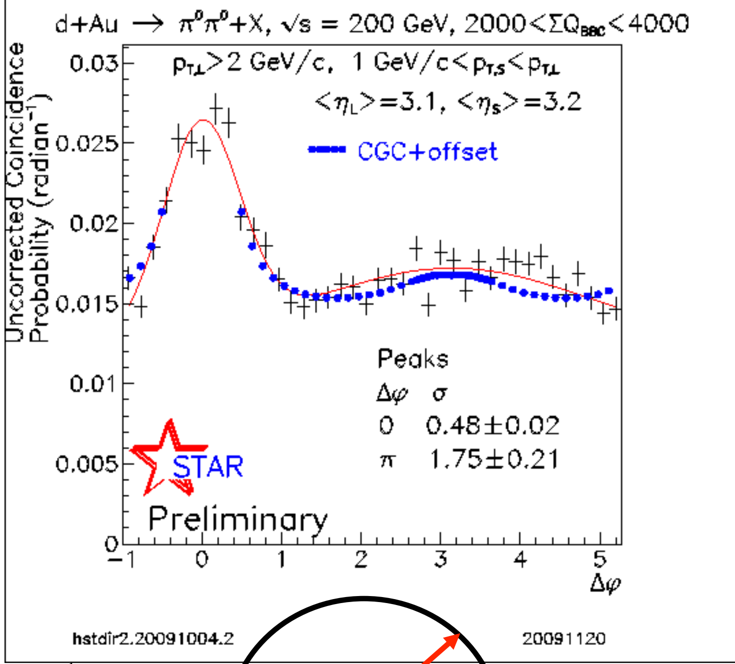
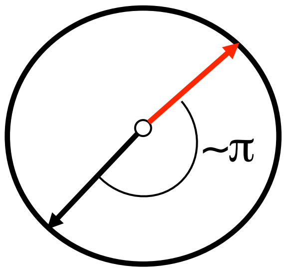
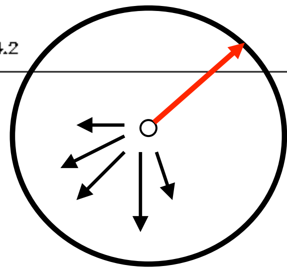




$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}} << 1$$



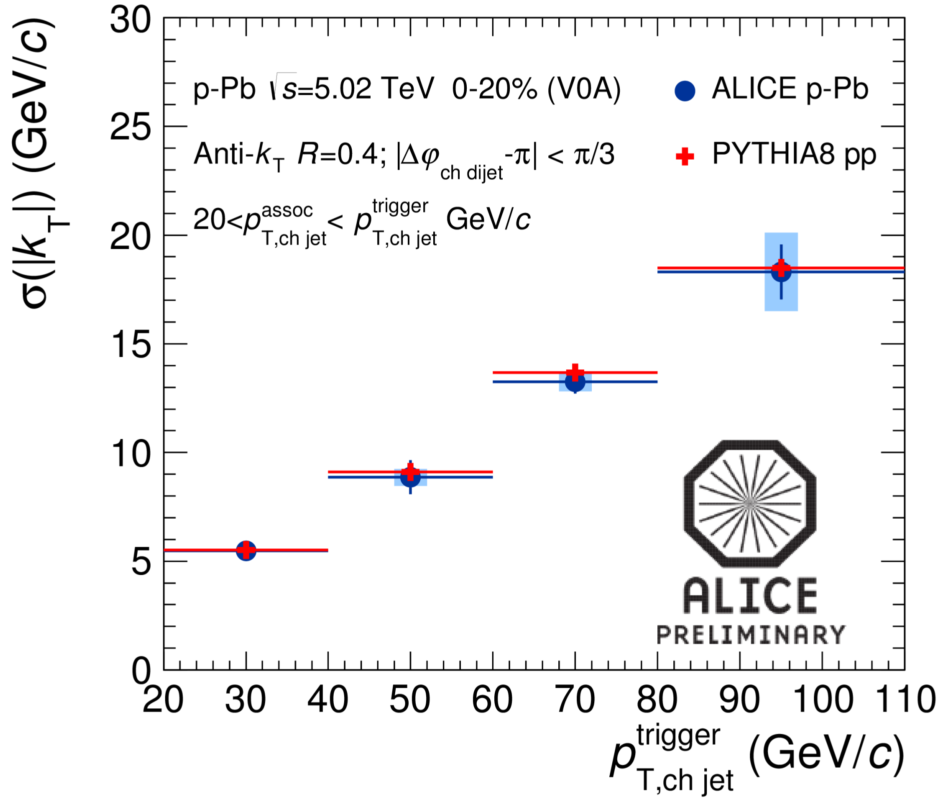
however, when $y_1 \sim y_2 \sim 0$ (and therefore $x_A \sim 0.03$),
the p+p and d+Au curves are almost identical

Forward di-jet production in p+Pb collisions at the LHC

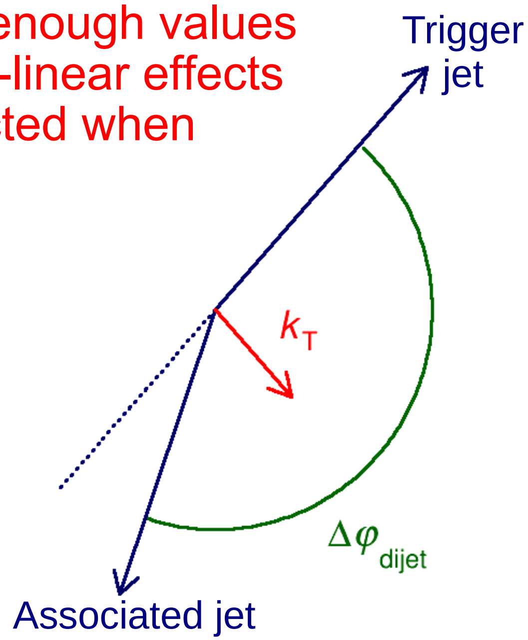
A. van Hameren, P. Kotko, K. Kutak, CM and S. Sapeta, 1402.5065

LHC di-jet mid-rapidity data

- no sign of nuclear effects on the di-jet imbalance



for small enough values of x_A, non-linear effects are expected when $k_T \sim Qs$



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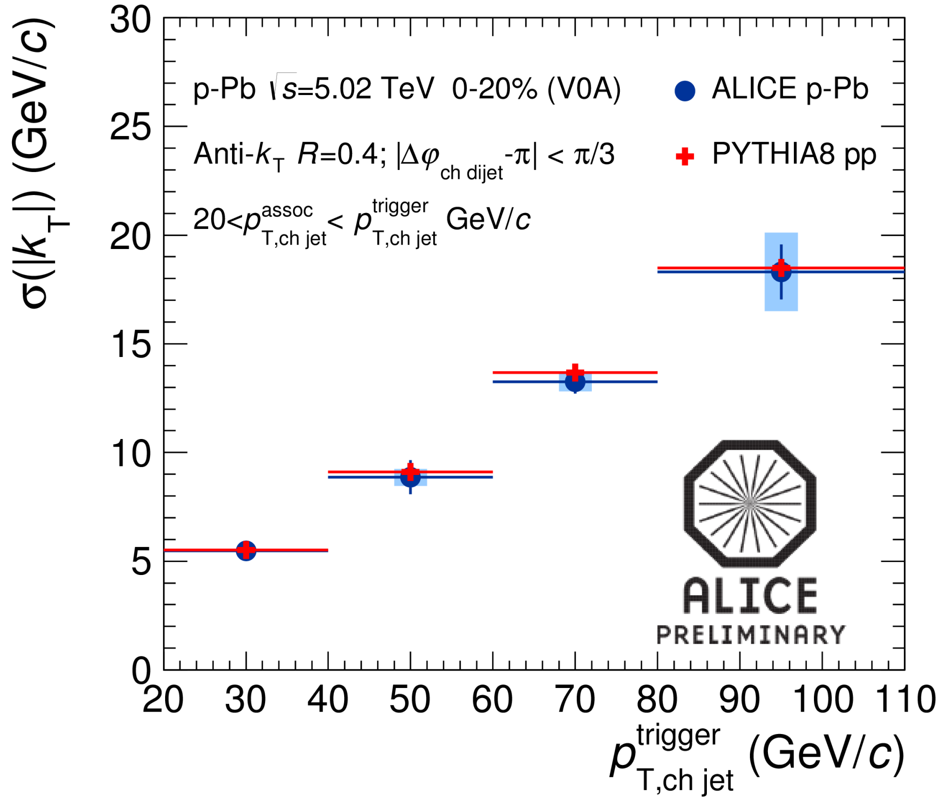

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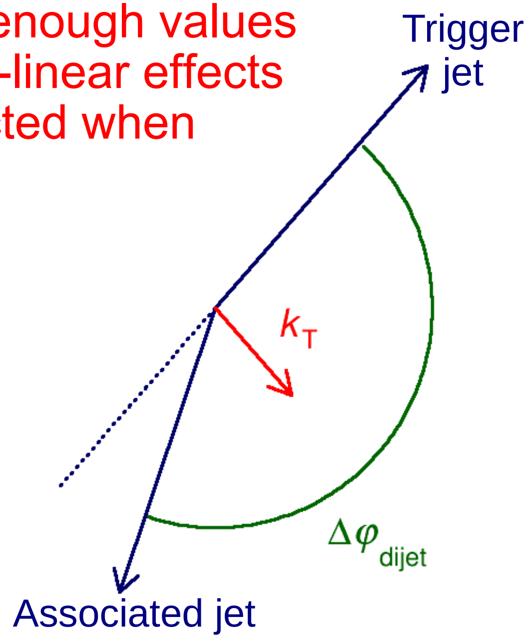

the di-jet imbalance is independent of A, and not related to Qs

all due to 3-jet final states, and perhaps some non-perturbative intrinsic k_T

one needs to look at forward di-jet systems to see non-linear effects

k_T factorization for forward di-jets

- a factorization can be established in the small *x* limit, for nearly back-to-back di-jets $Q_s,\ |\mathbf{p_{t1}}+\mathbf{p_{t2}}| \ll |\mathbf{p_{t1}}|,\ |\mathbf{p_{t2}}|$

$$\frac{d\sigma^{pA\to\mathrm{dijets}+X}}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \frac{\alpha_s^2}{(x_1x_2S)^2}\left[\sum_q x_1 f_{q/p}(x_1,\mu^2)\sum_i H_{qg}^{(i)}\mathcal{F}_{qg}^{(i)}(x_2,|\mathbf{p_{1t}}+\mathbf{p_{2t}}|)\right.$$

$$\left.+\frac{1}{2}x_1 f_{g/p}(x_1,\mu^2)\sum_i H_{gg}^{(i)}\mathcal{F}_{gg}^{(i)}(x_2,|\mathbf{p_{1t}}+\mathbf{p_{2t}}|)\right]$$

Dominguez, CM, Xiao and Yuan (2011)

with $x_1 = \frac{1}{\sqrt{S}}\left(p_{1t}e^{y_1}+p_{2t}e^{y_2}\right)\ ,\qquad x_2 = \frac{1}{\sqrt{S}}\left(p_{1t}e^{-y_1}+p_{2t}e^{-y_2}\right)$

but it involves several unintegrated gluon densities $\mathcal{F}_{qg}^{(i)}$ and $\mathcal{F}_{gg}^{(i)}$ and their associated hard matrix elements

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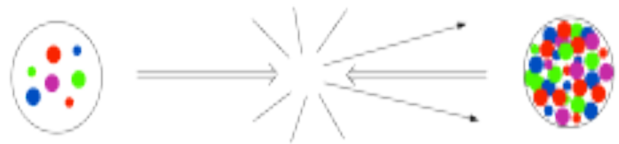
- only valid in asymmetric situations



Collins and Qiu (2007), Xiao and Yuan (2010)

does not apply with unintegrated parton densities for both colliding projectiles

Simplified factorization formula

- assuming in addition $Q_s \ll |\mathbf{p_{t1}} + \mathbf{p_{t2}}|$

one recovers the formula used in the high-energy factorization framework

$$\frac{d\sigma^{pA\to \text{dijets}+X}}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \sum_{a,c,d} \frac{1}{16\pi^3 (x_1 x_2 S)^2} |\overline{\mathcal{M}_{ag\to cd}}|^2 x_1 f_{a/p}(x_1,\mu^2)\, \mathcal{F}_A(x_2, |\mathbf{p_{1t}} + \mathbf{p_{2t}}|) \frac{1}{1+\delta_{cd}} \,.$$

involving only one unintegrated gluon density, the one also involved in F_2

Kutak and Sapeta (2012)

it is related to the dipole scattering amplitude $\mathcal{N}(x,r)$

$$\mathcal{F}_A(x,k) = \frac{N_c}{\alpha_s (2\pi)^3} \int d^2b \int d^2r\; e^{-i\mathbf{k}\cdot\mathbf{r}} \nabla_r^2\, \mathcal{N}(x,r)$$

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saturation effects are expected in the so-called geometric scaling window, when the incoming gluon momenta is not too large compared to Q_S

- we use two different unintegrated gluons, which both describe F_2

they are solutions of two small-x evolution equations, reflecting two proposed prescriptions to improve the LL Balitsky-Kovchegov equation

Running-coupling BK evolution

- the Balitsky-Kovchegov equation

Balitsky (1996), Kovchegov (1998)

$$\frac{\partial \mathcal{N}(x,r)}{\partial \ln(x_0/x)} = \bar{\alpha} \int \frac{d^2 r_1}{2\pi} \frac{r^2}{r_1^1 r_2^2} \left[\underbrace{\mathcal{N}(x,r_1) + \mathcal{N}(x,r_2) - \mathcal{N}(x,r)}_{\text{linear evolution : BFKL}} \underbrace{- \mathcal{N}(x,r_1)\mathcal{N}(x,r_2)}_{\text{saturation}} \right]$$

$$r_2 = |\mathbf{r} - \mathbf{r}_1|$$

Fourier Transform of dipole amplitude $\mathcal{N}(x,r)$ ≡ unintegrated gluon distribution

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saturation

$$r_2 = |\mathbf{r} - \mathbf{r}_1|$$

Fourier Transform of dipole amplitude $\mathcal{N}(x,r)$ ≡ unintegrated gluon distribution

- running-coupling (RC) corrections to the BK equation

$$\alpha_s(\mathbf{r}^2) = \left[-\frac{11N_c - 2N_f}{12\pi} \ln\left(\mathbf{r}^2 \Lambda_{QCD}^2\right) \right]^{-1}$$

taken into account by the substitution

$$\frac{\bar{\alpha}}{2\pi} \frac{(\mathbf{x}-\mathbf{y})^2}{(\mathbf{x}-\mathbf{z})^2(\mathbf{z}-\mathbf{y})^2} \xrightarrow[\text{Weigert}]{\text{Kovchegov}} \frac{N_c}{2\pi^2} \left[\frac{\alpha_s((\mathbf{x}-\mathbf{z})^2)}{(\mathbf{x}-\mathbf{z})^2} - 2\frac{\alpha_s((\mathbf{x}-\mathbf{z})^2)\alpha_s((\mathbf{z}-\mathbf{y})^2)}{\alpha_s((\mathbf{x}-\mathbf{y})^2)} + \frac{\alpha_s((\mathbf{z}-\mathbf{y})^2)}{(\mathbf{z}-\mathbf{y})^2} \right]$$

Balitsky

(2007)

$$\frac{N_c \alpha_s((\mathbf{x}-\mathbf{y})^2)}{2\pi^2} \left[\frac{(\mathbf{x}-\mathbf{y})^2}{(\mathbf{x}-\mathbf{z})^2(\mathbf{z}-\mathbf{y})^2} + \frac{1}{(\mathbf{x}-\mathbf{z})^2} \left(\frac{\alpha_s((\mathbf{x}-\mathbf{z})^2)}{\alpha_s((\mathbf{z}-\mathbf{y})^2)} - 1 \right) + \frac{1}{(\mathbf{z}-\mathbf{y})^2} \left(\frac{\alpha_s((\mathbf{z}-\mathbf{y})^2)}{\alpha_s((\mathbf{x}-\mathbf{z})^2)} - 1 \right) \right]$$

RC corrections represent most of the NLO contribution

Non-linear CCFM evolution

- a non-linear gluon cascade with coherence effects

  Kutak, Golec-Biernat, Jadach and Skrzypek (2012)

  solution compatible with F2 data not available yet

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  solution compatible with F2 data not available yet

- for now use simpler version Kutak and Stasto (2005)

$$\mathcal{F}_p(x,k^2) = \mathcal{F}_p^{(0)}(x,k^2) + \frac{\alpha_s(k^2)N_c}{\pi}\int_x^1 \frac{dz}{z}\int_{k_0^2}^{\infty}\frac{dl^2}{l^2}\left\{\frac{l^2\mathcal{F}_p(\frac{x}{z},l^2)\,\theta(\frac{k^2}{z}-l^2)\,-\,k^2\mathcal{F}_p(\frac{x}{z},k^2)}{|l^2-k^2|} + \frac{k^2\mathcal{F}_p(\frac{x}{z},k^2)}{|4l^4+k^4|^{\frac{1}{2}}}\right\}$$
$$+\frac{\alpha_s(k^2)}{2\pi k^2}\int_x^1 dz\left[\left(P_{gg}(z)-\frac{2N_c}{z}\right)\int_{k_0^2}^{k^2} dl^2\,\mathcal{F}_p\left(\frac{x}{z},l^2\right) + zP_{gq}(z)\Sigma\left(\frac{x}{z},k^2\right)\right]$$
$$-\frac{2\alpha_s^2(k^2)}{R^2}\left[\left(\int_{k^2}^{\infty}\frac{dl^2}{l^2}\mathcal{F}_p(x,l^2)\right)^2 + \mathcal{F}_p(x,k^2)\int_{k^2}^{\infty}\frac{dl^2}{l^2}\ln\left(\frac{l^2}{k^2}\right)\mathcal{F}_p(x,l^2)\right],$$

this is BK + running coupling + high-pt improvements
- kinematical constraints
- sea quark contributions
- non-singular pieces of the splitting functions

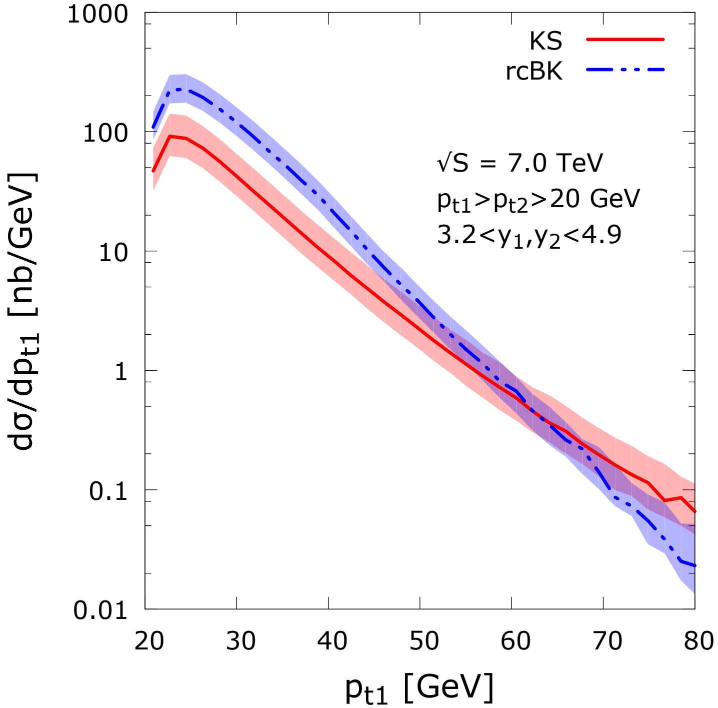
note: this is an equation for the impact-parameter integrated gluon density

Forward di-jet spectrum in p+p

- obtained with unintegrated gluons constrained from e+p low-x data

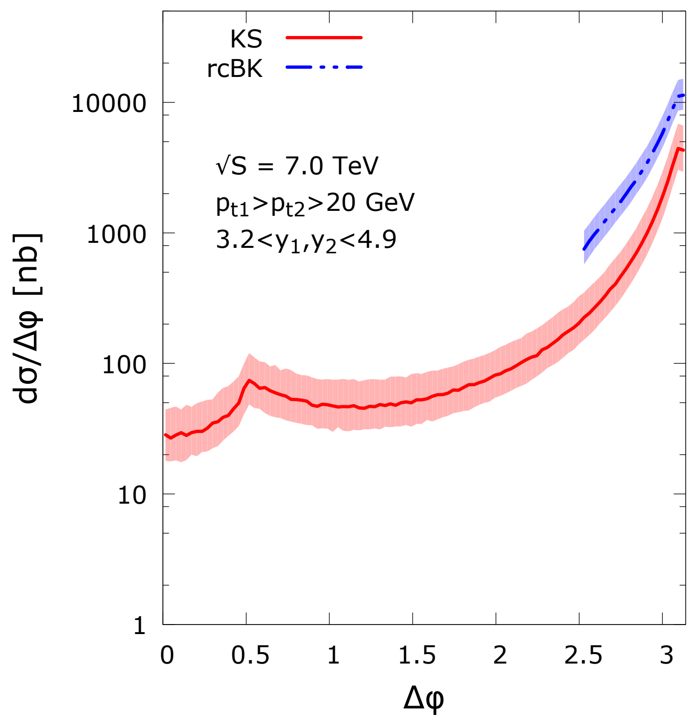
rcBK: normalization uncentainty due to impact parameter integration

p_{T1} dependence



- similar shape at low p_t
- KS better at large p_t

Δφ dependence



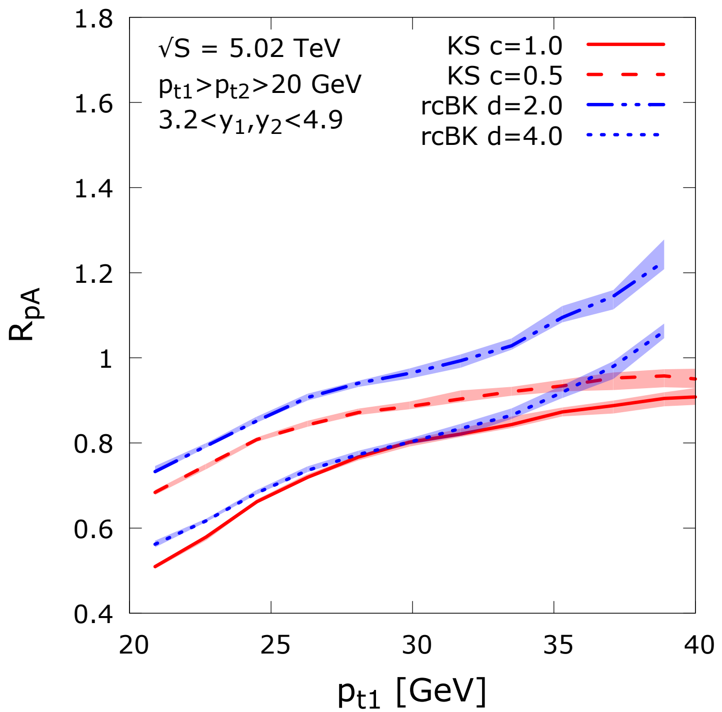
- rcBK not plotted away from $\Delta\varphi = \pi$
- kink due to cone radius of 0.5

Nuclear modification in p+Pb

- with a free parameter to vary the nuclear saturation scale

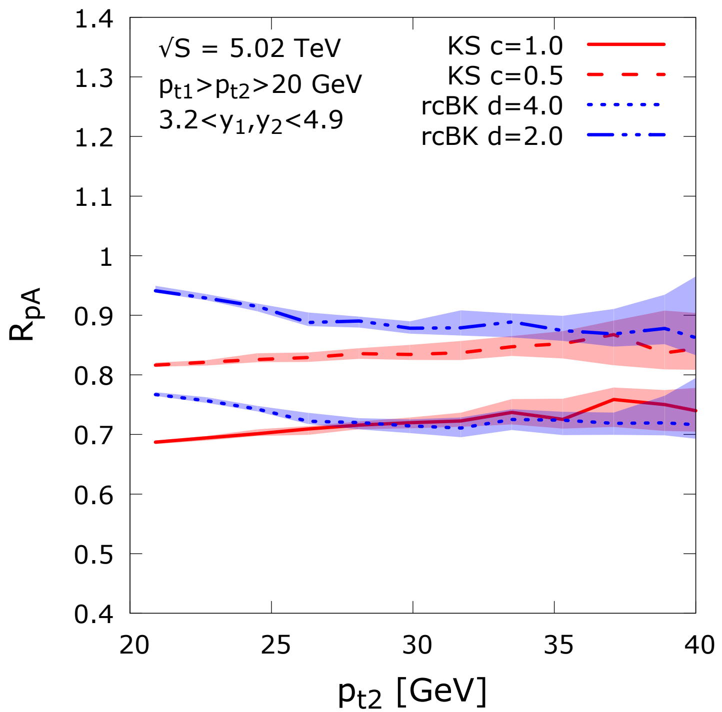
$Q^2_{sA} = d\ Q^2_{sp}$ (rcBK case) or $R^2 \to R^2_A = R^2\ A^{1/3}/c$ (KS case)

p_{T1} dependence



- rcBK: not correct at large pt
- KS: reaches unity at large pt

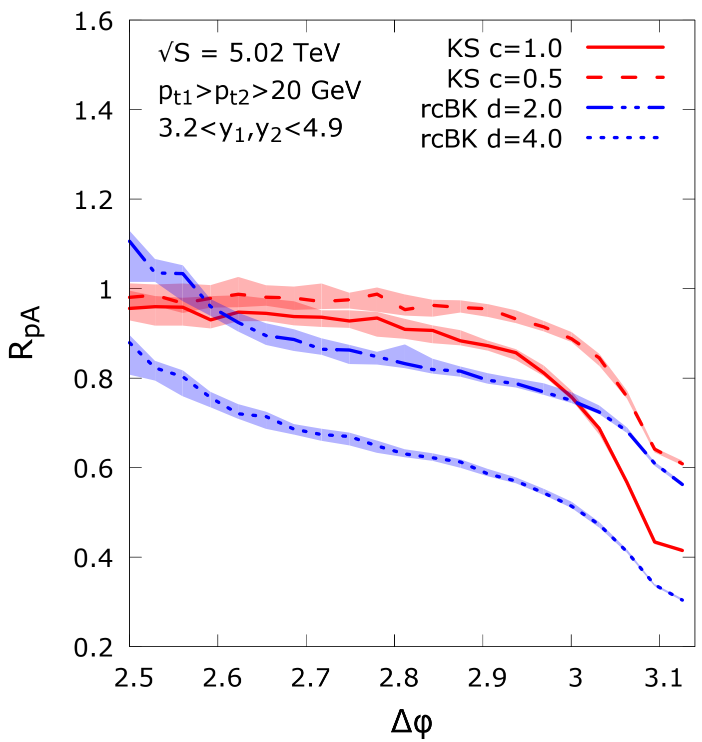
p_{T2} dependence



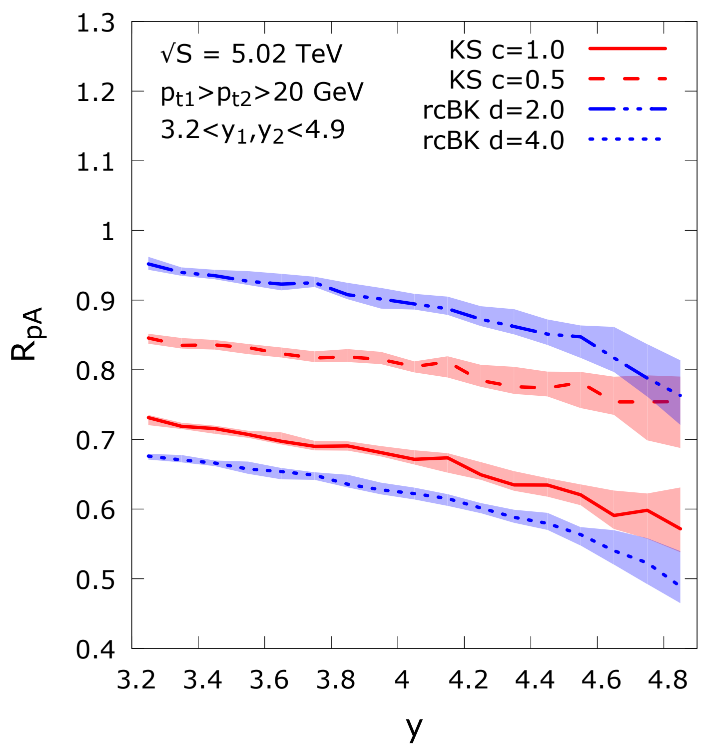
observable very sensitive to non-linear effects

Nuclear modification in p+Pb

Δφ dependence



y dependence

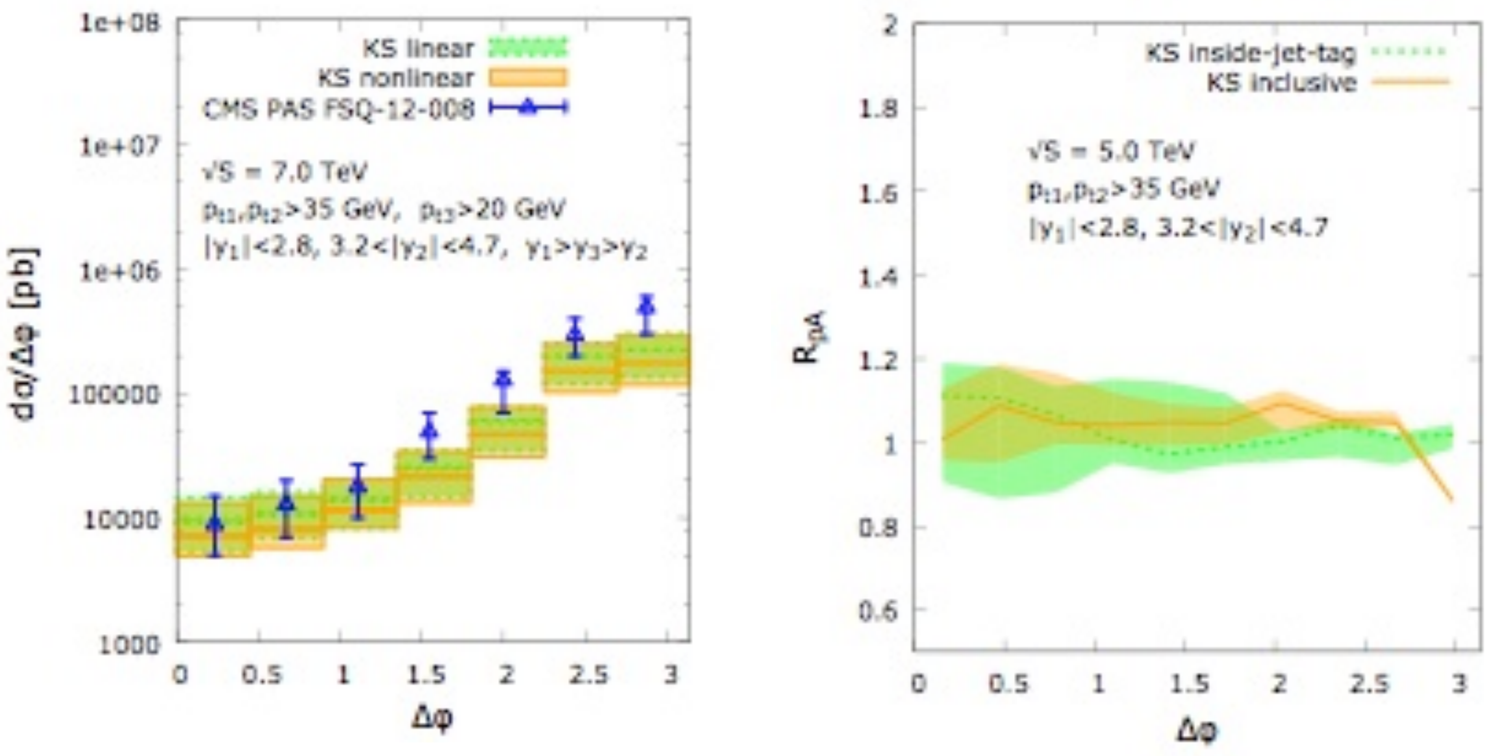


potentially big effects depending on the value of the nuclear saturation scale

caveat: near Δφ = π, our simplifying assumption $Q_s \ll |\mathbf{p_{t1}} + \mathbf{p_{t2}}|$ is not valid

CMS central-forward di-jet data

- non-linear effects are small, as expected



but this is a good test of the formalism,
which does a good job describing the data

van Hameren, Kotko, Kutak, and Sapeta (2014)

Conclusions

- Non-linear evolution of gluon density in Au nucleus 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

- Our goal: extend di-hadron calculation to di-jets, motivate LHC measurement

  - our preliminary results are encouraging

- Several improvements needed:

  - implement full factorization formula, to go beyond $Q_s \ll |\mathbf{p_{t1}} + \mathbf{p_{t2}}|$

  - use solution of non-linear CCFM equation when available

  - correct treatment of nuclear impact-parameter dependence

  - estimate effects of jet fragmentation