Forward di-hadron back-to-back correlations in p+A collisions at RHIC and the LHC

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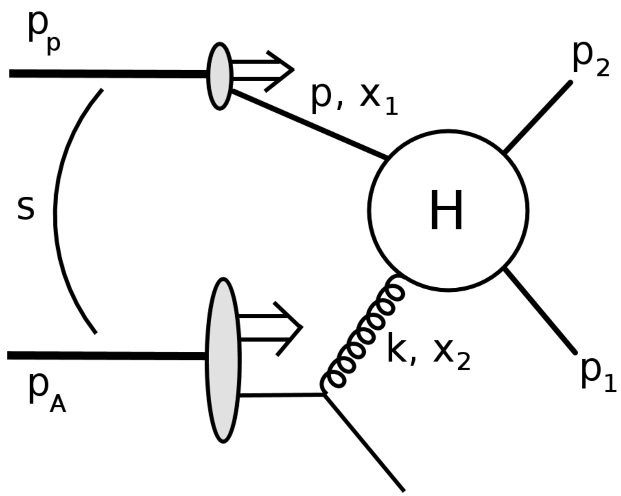
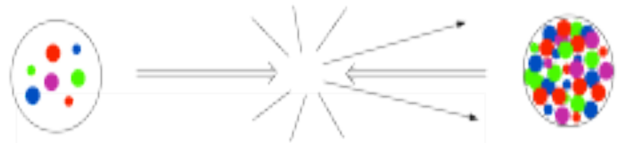
based on Albacete, Giacalone, CM and Matas, arXiv:1805.05711

The context: forward di-hadrons

- large-x projectile (proton) on small-x target (proton or nucleus)





$$\langle k_{1t}\rangle \sim \Lambda_{QCD} \qquad \langle k_{2t}\rangle \sim Q_s(x_2)$$

$$Q_s(x_2) \gg \Lambda_{QCD}$$

so-called “dilute-dense” kinematics

Incoming partons’ energy fractions:

$$x_1 = \frac{1}{\sqrt{s}}\left(|p_{1t}|e^{y_1} + |p_{2t}|e^{y_2}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(|p_{1t}|e^{-y_1} + |p_{2t}|e^{-y_2}\right)$$

$$\xrightarrow{y_1,y_2 \gg 0} \qquad x_1 \sim 1, \qquad x_2 \ll 1$$

CM (2007)

Gluon’s transverse momentum (p_{1t}, p_{2t} imbalance):

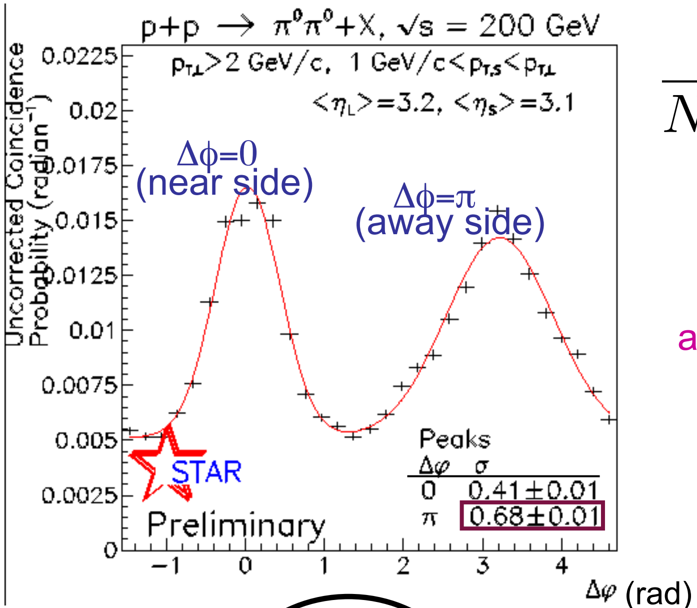
$$|k_t|^2 = |p_{1t} + p_{2t}|^2 = |p_{1t}|^2 + |p_{2t}|^2 + 2|p_{1t}||p_{2t}|\cos\Delta\phi$$

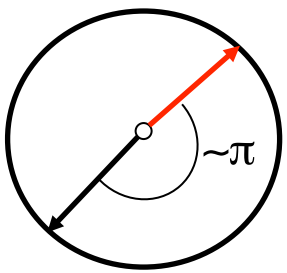
prediction: modification of the k_t distribution in p+Pb vs p+p collisions

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

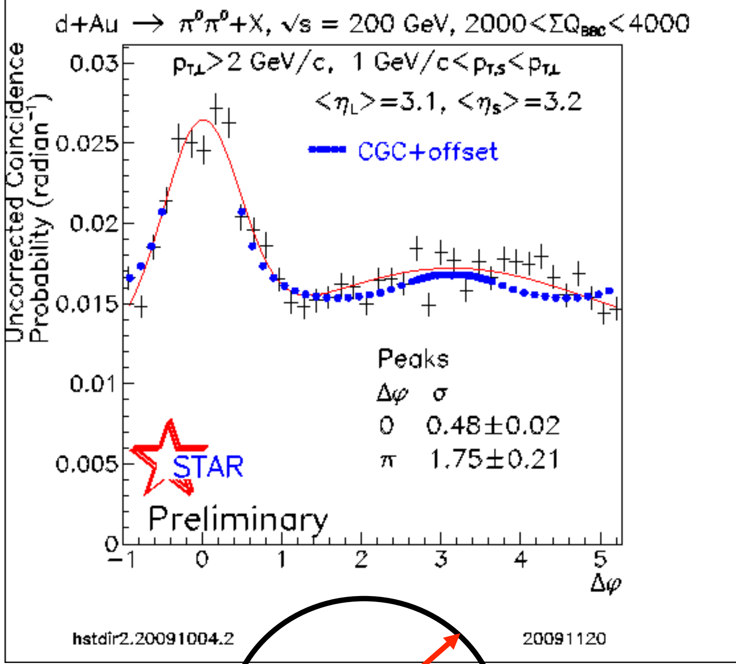


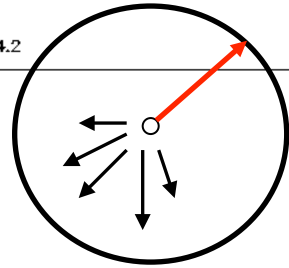


$$\frac{1}{N_{trig}}\frac{dN_{pair}}{d\Delta\varphi}$$

Albacete
and CM (2010)

central d+Au collisions





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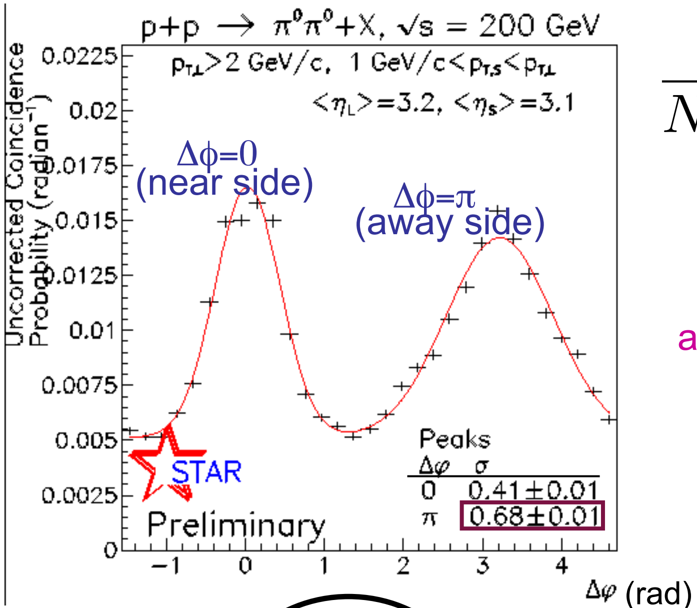

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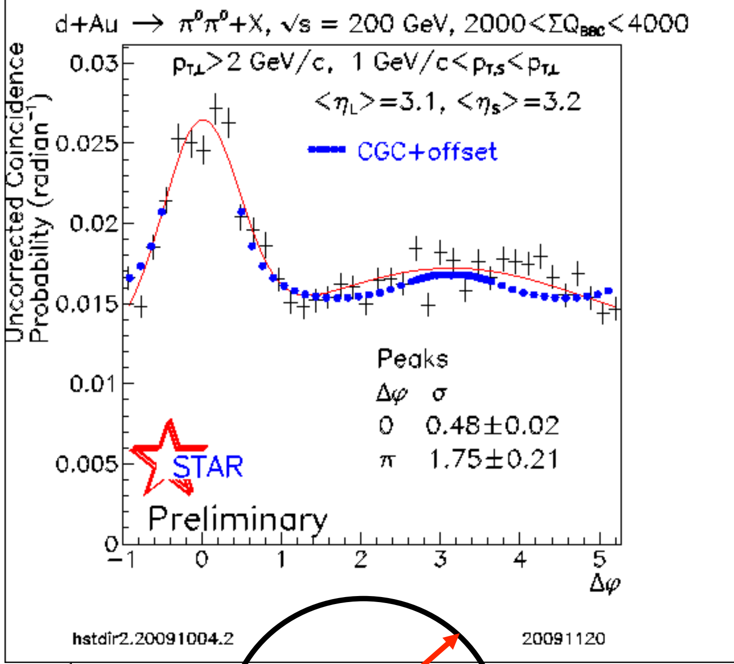
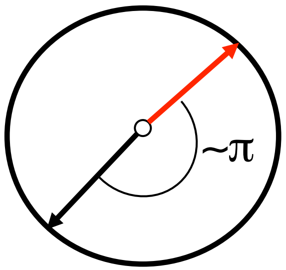
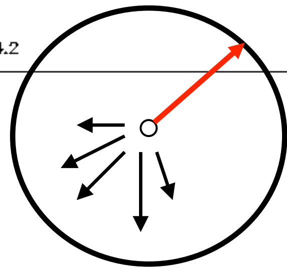




$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}} << 1$$



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

Color Glass Condensate (CGC) calculation of forward di-hadrons

Nearly back-to-back di-hadrons

- The full CGC formula is notoriously difficult to deal with CM (2007)

presented at Quark Matter 10 years ago, no complete implementation, but several approximations studied

Albacete, CM (2010) Stasto, Xiao and Yuan (2012) Lappi and Mantysaari (2013)

- instead, we shall focus on a restricted kinematic window where saturation effects are most important: the vicinity of $\Delta\Phi = \pi$

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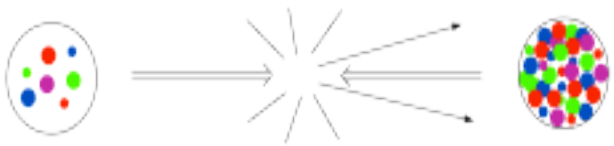
- there, one can take the limit $|p_{1t}|, |p_{2t}| \gg |k_t|, Q_s$ and simplify the full formula

in practice, we keep only the leading $1/|p_{ti}|$ power, but we still have all orders in $(Q_s/k_t)^n$

the result is a Transverse Momentum Dependent (TMD) factorization formula

- only valid in asymmetric situations

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



does not apply with TMD parton densities for both colliding projectiles

TMD factorization

- the following factorization formula can be established in the small-x_2 limit, for nearly back-to-back di-jets:

Dominguez, CM, Xiao and Yuan (2011)

$$\frac{d\sigma^{pA\to\pi^0\pi^0X}}{dy_1\, dy_2\, d^2p_{1t}\, d^2p_{2t}} = \frac{\alpha_s^2}{2C_F}\int_{p_{t1}\frac{e^{y_1}}{\sqrt{s}}/(1-p_{t2}\frac{e^{y_2}}{\sqrt{s}})}^{1}\frac{dz_1}{z_1^2}\int_{p_{t2}\frac{e^{y_2}}{\sqrt{s}}/(1-\frac{p_{t1}}{z_1}\frac{e^{y_1}}{\sqrt{s}})}^{1}\frac{dz_2}{z_2^2}\,\frac{z(1-z)}{P_t^4}$$

$$\Big\{D_{\pi^0/g}(z_1,\mu^2)\big[x_1u(x_1,\mu^2)\ D_{\pi^0/u}(z_2,\mu^2)+x_1d(x_1,\mu^2)\ D_{\pi^0/d}(z_2,\mu^2)\big]P_{gq}(z)\ \times$$
$$\times\ \Big[(1-z)^2\mathcal{F}_{qg}^{(1)}(x_2,k_t)+\mathcal{F}_{qg}^{(2)}(x_2,k_t)\Big]+$$
$$+\ D_{\pi^0/g}(z_2,\mu^2)\big[x_1u(x_1,\mu^2)\ D_{\pi^0/u}(z_1,\mu^2)+x_1d(x_1,\mu^2)\ D_{\pi^0/d}(z_1,\mu^2)\big]P_{gq}(1-z)\ \times$$
$$\times\ \Big[z^2\mathcal{F}_{qg}^{(1)}(x_2,k_t)+\mathcal{F}_{qg}^{(2)}(x_2,k_t)\Big]+$$

$qg^* \to qg$ channel

$$+\ 2\big[D_{\pi^0/u}(z_1,\mu^2)\ D_{\pi^0/u}(z_2,\mu^2)+D_{\pi^0/d}(z_1,\mu^2)\ D_{\pi^0/d}(z_2,\mu^2)\big]\ x_1g(x_1,\mu^2)\ P_{qg}(z)\ \times$$
$$\times\ \Big[\mathcal{F}_{gg}^{(1)}(x_2,k_t)-2z(1-z)\big(\mathcal{F}_{gg}^{(1)}(x_2,k_t)-\mathcal{F}_{gg}^{(2)}(x_2,k_t)\big)\Big]+$$

$gg^* \to q\bar{q}$ channel

$$+\ D_{\pi^0/g}(z_1,\mu^2)D_{\pi^0/g}(z_2,\mu^2)\ x_1g(x_1,\mu^2)\ P_{gg}(z)\ \times$$
$$\times\ \Big[\mathcal{F}_{gg}^{(1)}(x_2,k_t)-2z(1-z)\big(\mathcal{F}_{gg}^{(1)}(x_2,k_t)-\mathcal{F}_{gg}^{(2)}(x_2,k_t)\big)+\mathcal{F}_{gg}^{(6)}(x_2,k_t)\Big]\Big\},$$

$gg^* \to gg$ channel

it involves *several* transverse-momentum-dependent (TMD) gluon distributions for the target nucleus: $\mathcal{F}_{qg}^{(i)}$ $\mathcal{F}_{gg}^{(i)}$

The back-to-back regime

- this TMD factorization formula for $x_2 \ll x_1 \sim 1$ can be derived in two ways:

from the generic TMD factorization framework (valid up to power corrections): by taking the small-x limit

Bomhof, Mulders and Pijlman (2006)

Kotko, Kutak, CM, Petreska, Sapeta and van Hameren (2015)

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- at small x, the TMD gluon distributions can be written as:

(showing here the $qg^* \to qg$ channel TMDs only)

$$U_{\mathbf{x}} = \mathcal{P}\exp\left[ig\int_{-\infty}^{\infty} dx^+ A_a^-(x^+,\mathbf{x})t^a\right]$$

$$\mathcal{F}_{qg}^{(1)}(x_2,|k_t|) = \frac{4}{g^2}\int\frac{d^2x d^2y}{(2\pi)^3}\; e^{-ik_t\cdot(\mathbf{x}-\mathbf{y})}\left\langle \mathrm{Tr}\left[(\partial_i U_{\mathbf{y}})(\partial_i U_{\mathbf{x}}^\dagger)\right]\right\rangle_{x_2}$$

$$\mathcal{F}_{qg}^{(2)}(x_2,|k_t|) = -\frac{4}{g^2}\int\frac{d^2x d^2y}{(2\pi)^3}\; e^{-ik_t\cdot(\mathbf{x}-\mathbf{y})}\frac{1}{N_c}\left\langle \mathrm{Tr}\left[(\partial_i U_{\mathbf{x}})U_{\mathbf{y}}^\dagger(\partial_i U_{\mathbf{y}})U_{\mathbf{x}}^\dagger\right]\mathrm{Tr}\left[U_{\mathbf{y}}U_{\mathbf{x}}^\dagger\right]\right\rangle_{x_2}$$

these Wilson line correlators also emerge directly in CGC calculations when $|p_{1t}|,|p_{2t}| \gg |k_t|, Q_s$

x evolution of the gluon TMDs

the evolution of Wilson line correlators with decreasing x can be computed from the so-called JIMWLK equation

$$\frac{d}{d\ln(1/x_2)}\left\langle O\right\rangle_{x_2} = \left\langle H_{JIMWLK}\; O\right\rangle_{x_2}$$

Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner

a functional RG equation that resums the leading logarithms in $y = \ln(1/x_2)$

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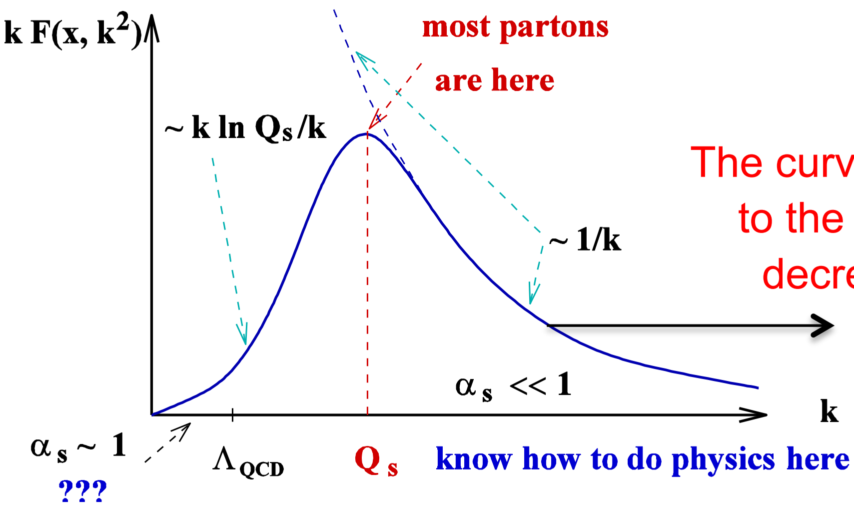
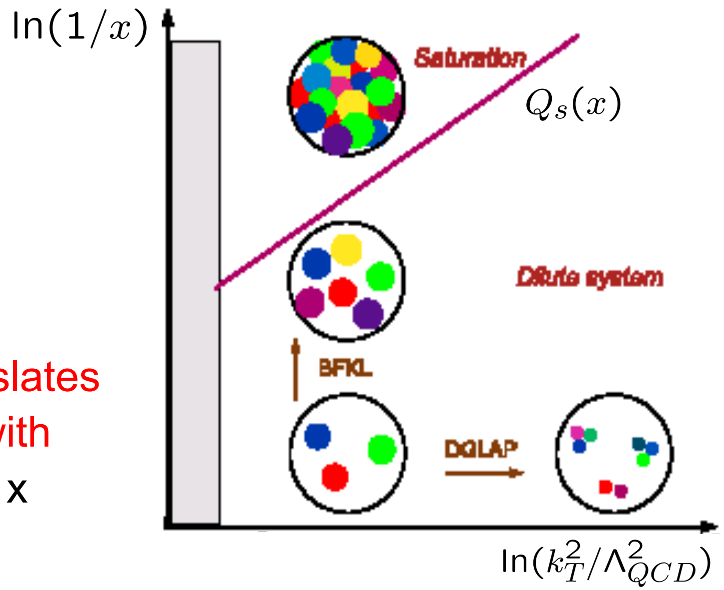
- qualitative solutions for the gluon TMDs:



The curve translates to the right with decreasing x



the distribution of partons as a function of x and k_T

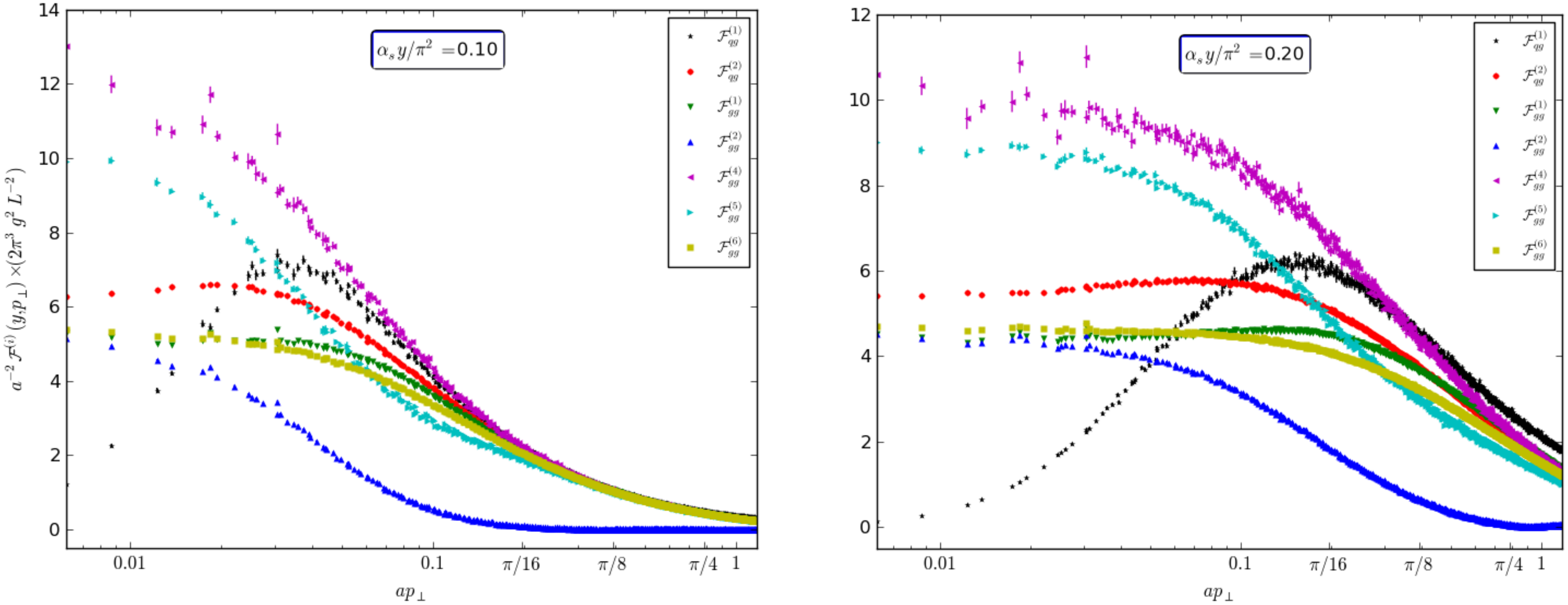
JIMWLK numerical results

using a code written by Claude Roiesnel

initial condition at y=0 : McLerran-Venugopalan model

evolution: JIMWLK at leading log

CM, Petreska, Roiesnel (2016)



saturation effects impact the various gluon TMDs in very different ways

The Gaussian truncation

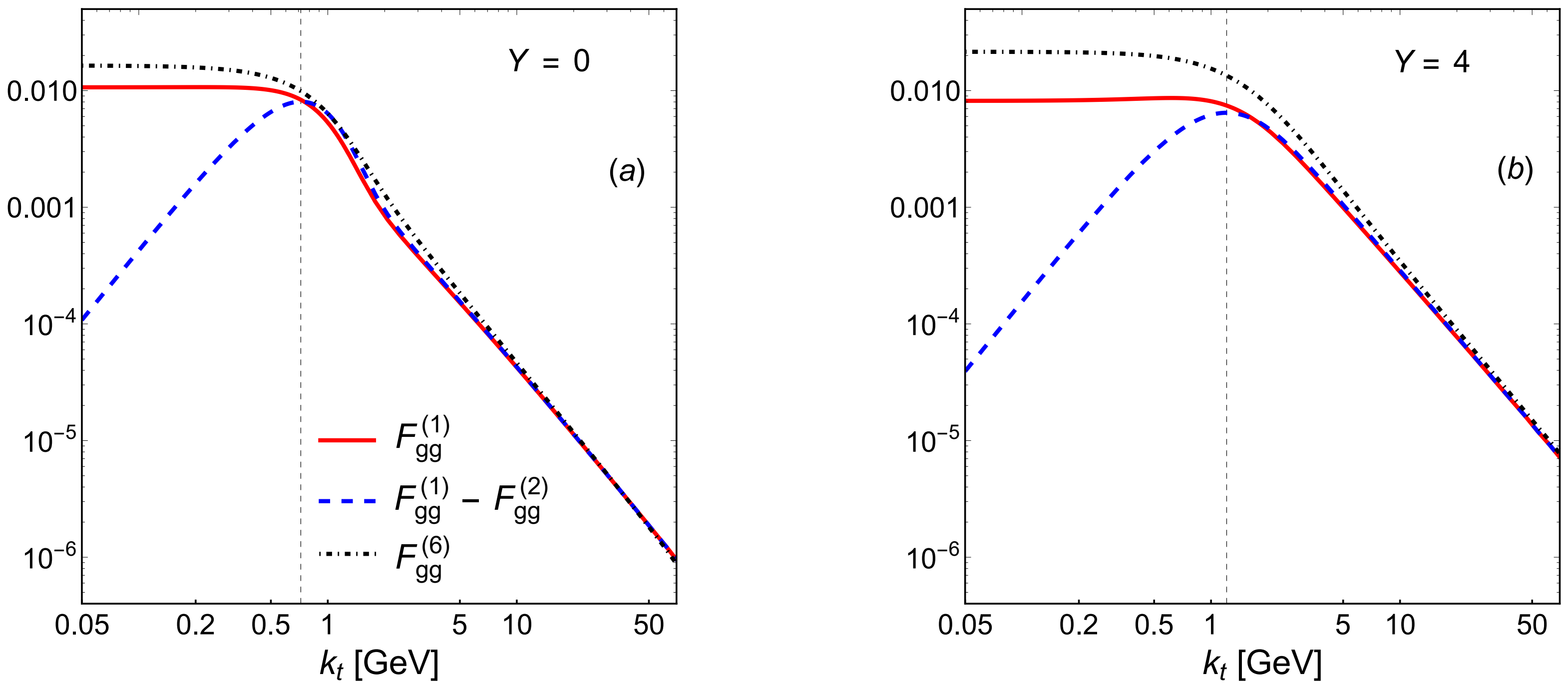
- this approximation allows to express any Wilson-line correlator in terms of the solution to a simpler equation: the Balitsky-Kovchegov equation

in addition, running-coupling corrections can be implemented

- some numerical results:

McLerran-Venugopalan initial condition

after some evolution: $Y=\ln(1/x_2)$



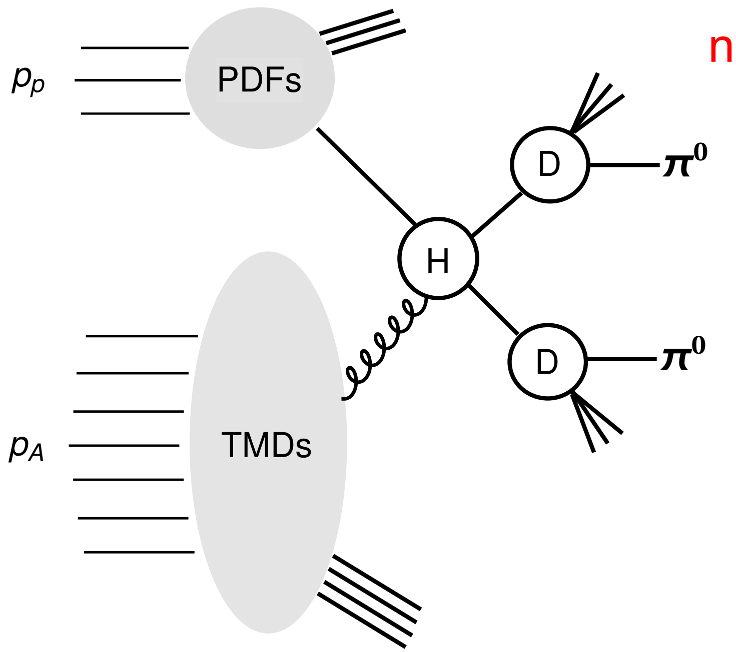
we use those gluon distributions to compute the forward di-hadron cross section

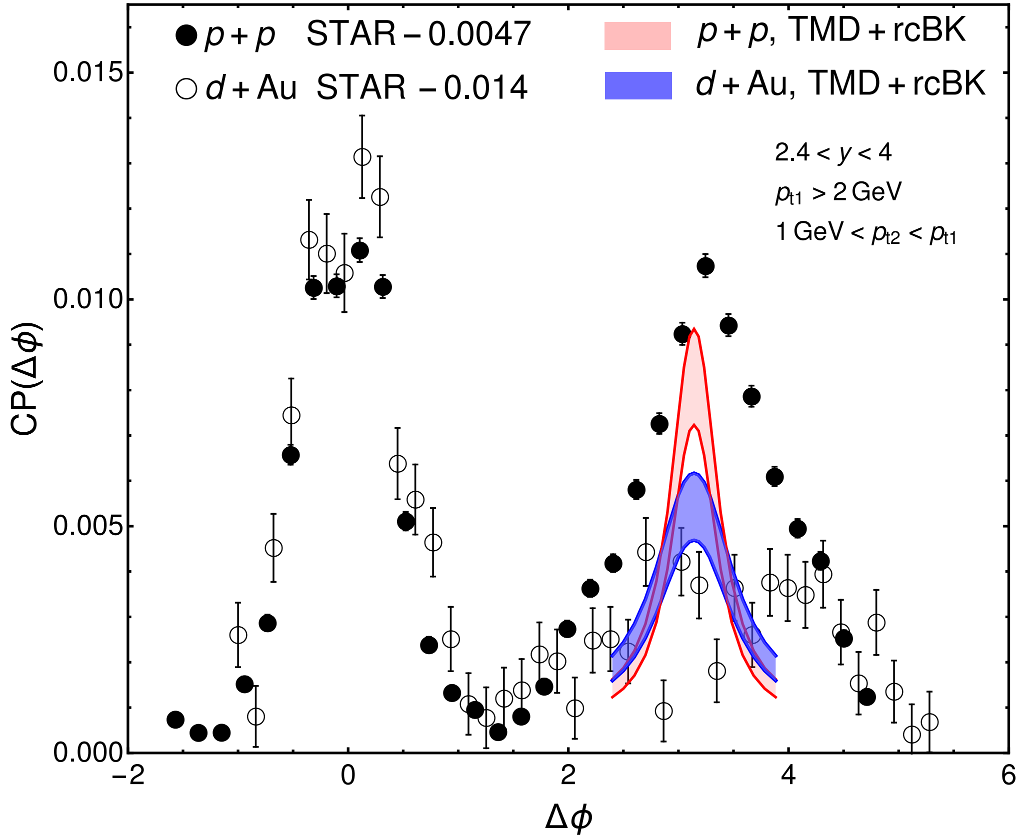
Back to experiments

STAR forward di-hadrons

Albacete, Giacalone, CM and Matas, arXiv:1805.05711

new description of the away-side peak suppression





p+Au predictions ready:
a rapidity binning would
provide a strong test

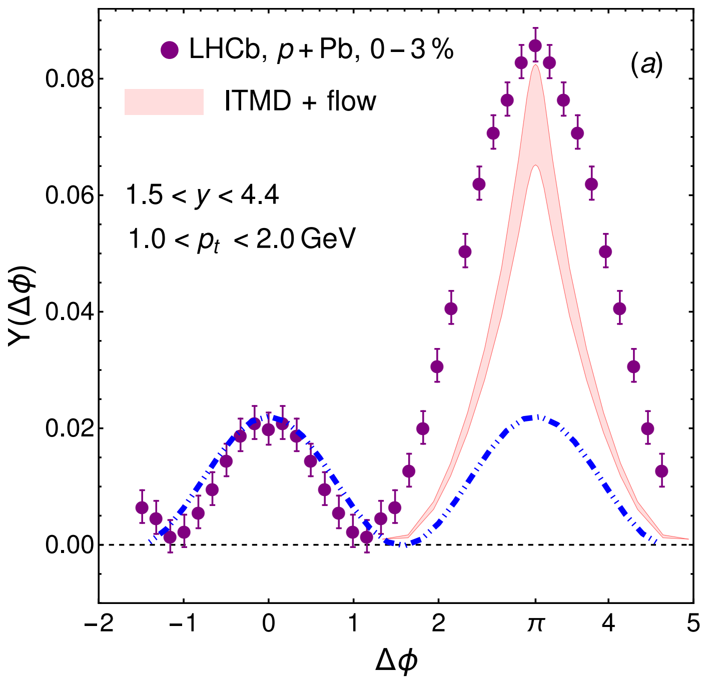
cannot be applied to the overall $\Delta\Phi$ range, but improves the previous approximations near $\Delta\Phi = \pi$ (also gluon initiated process are included)

LHCb forward di-hadrons

- LHCb measured the di-hadron correlation function at forward rapidities

the delta phi distribution shows:

- a ridge contribution (could be flow, Glasma graphs or something else)
- the remainder of the away-side peak can be qualitatively described in the CGC



- need p+p baseline to be conclusive

Giacalone and CM, in progress

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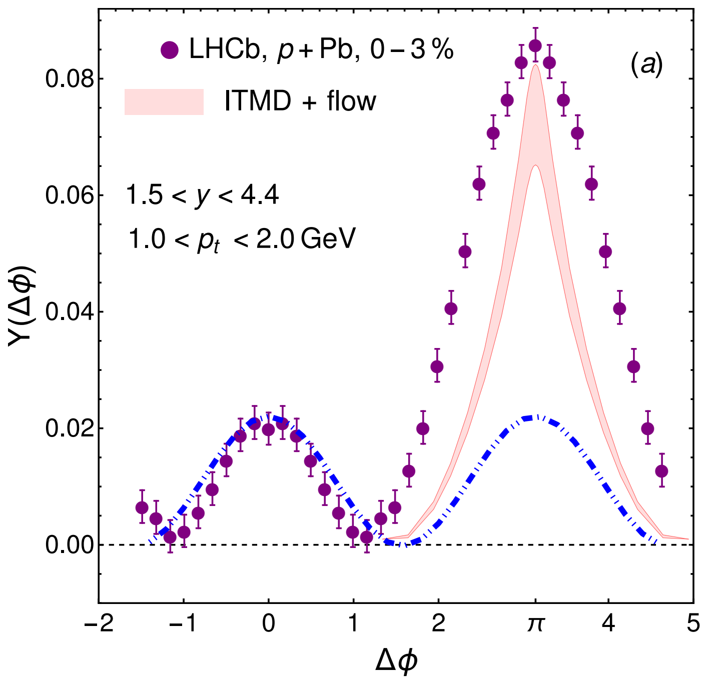

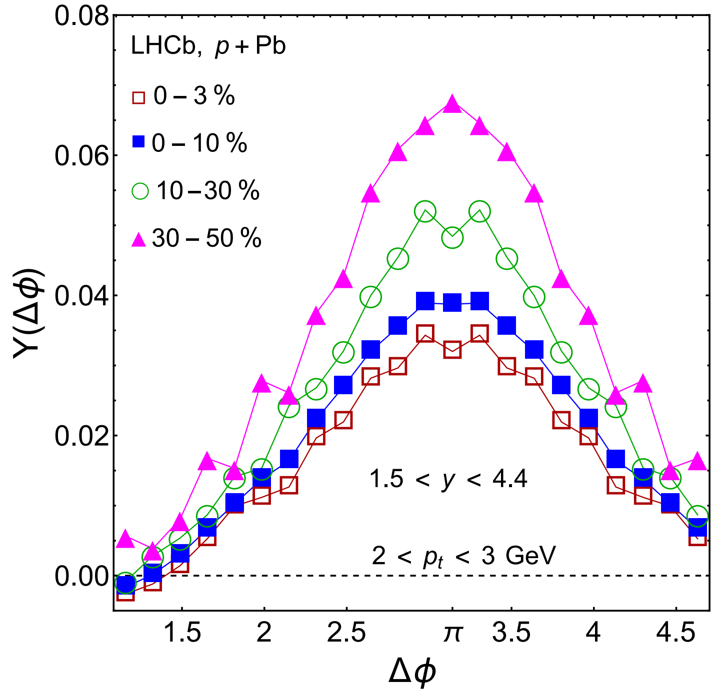

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Giacalone and CM, in progress

suppression of the away-side peak with increasing centrality seen in the data

Conclusions

- we revisited forward di-hadron production in the CGC framework, focusing on nearly back-to-back hadrons
- there, saturation effects are most relevant, as the di-hadron transverse momentum imbalance $|k_t|$ is of the order of the saturation scale Qs, or smaller
- the cross-section involves several gluon TMDs, with different operator definitions, which we obtain from rcBK evolution
- this TMD formulation is well adapted to implement the soft-gluon resummation needed to get the correct width of the away-side peak
- we hope to see at the LHC, a confirmation of the saturation signal seen at RHIC