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

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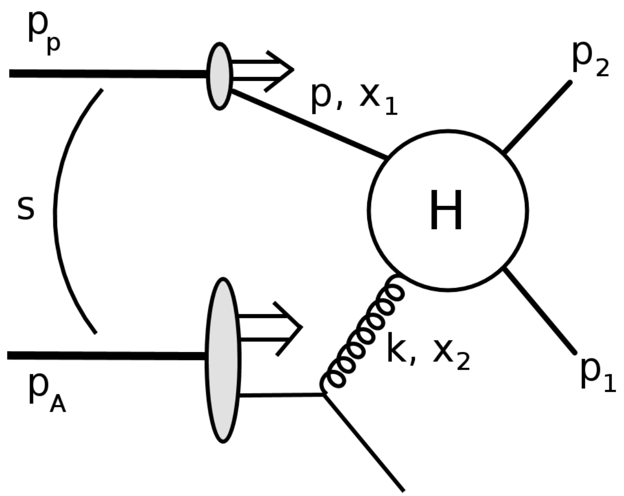
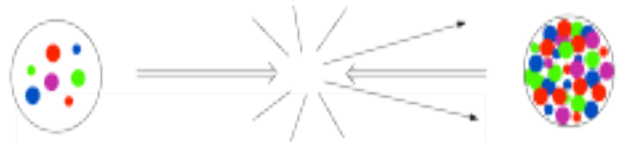
The context: forward di-hadrons

- 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):

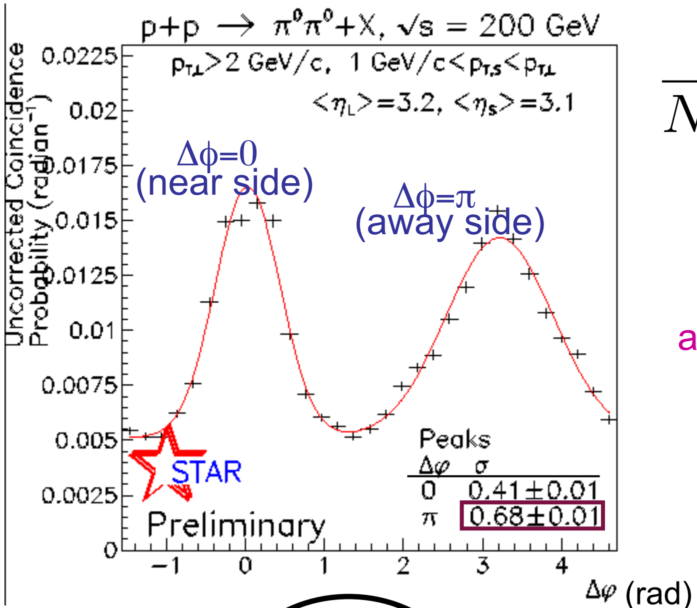
$$|k_t|^2 = |p_{1t} + p_{2t}|^2 = |p_{1t}|^2 + |p_{2t}|^2 + 2|p_{1t}||p_{2t}|\cos\Delta\phi \qquad |p_{1t}|, |p_{2t}| \gg |k_t|, Q_s$$

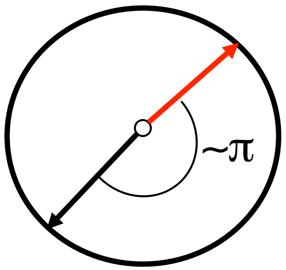
prediction: modification of the k_t distribution in p+Pb vs p+p collisions

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

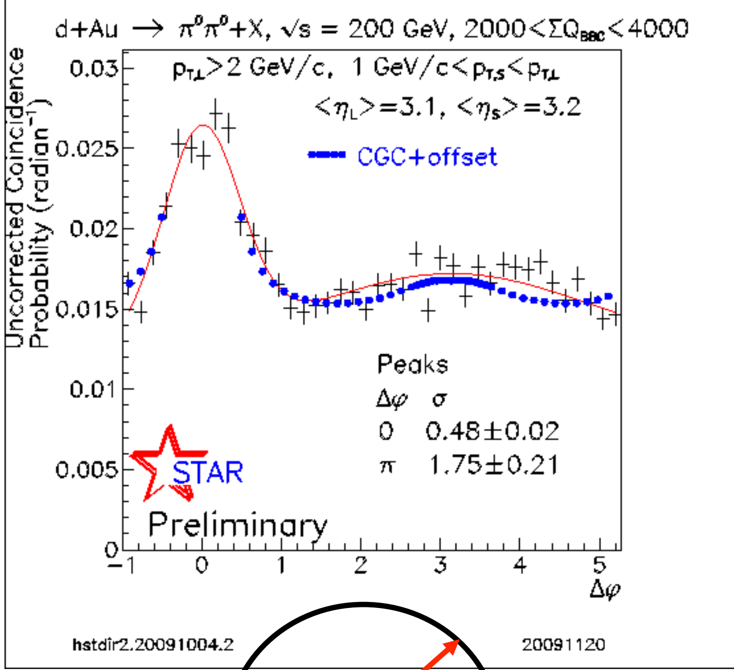


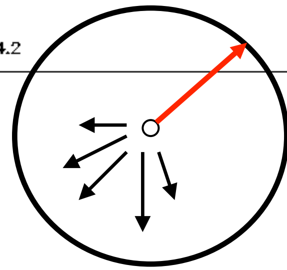


$$\frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\varphi}$$

Albacete
and CM (2010)

central d+Au collisions





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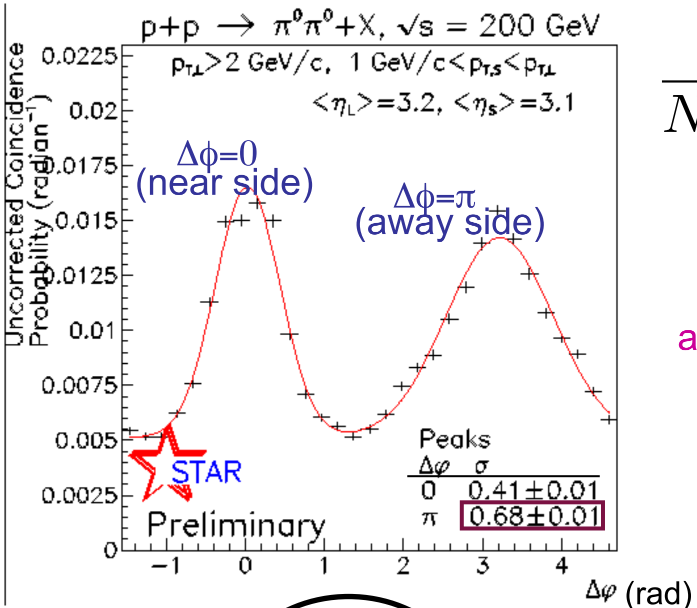

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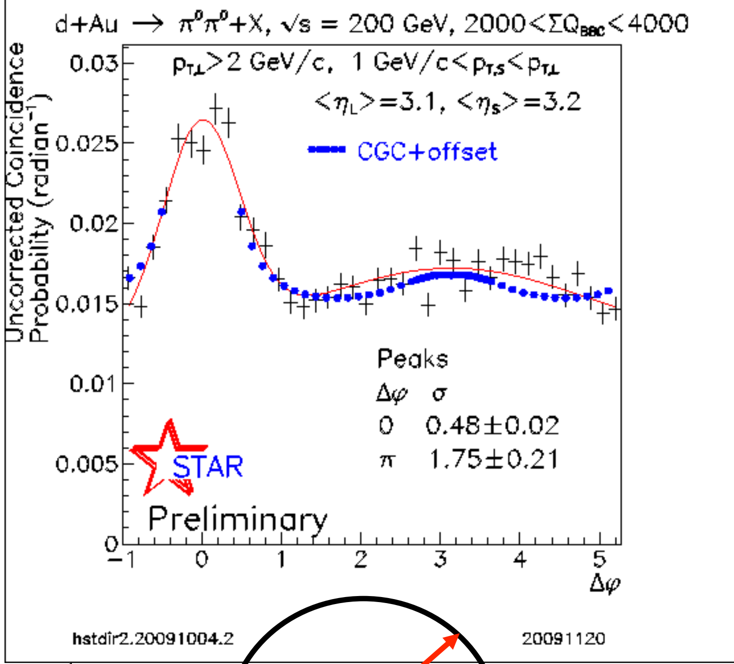
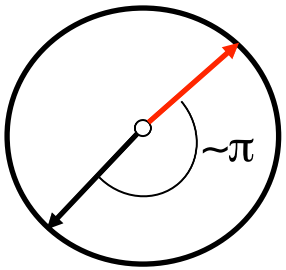
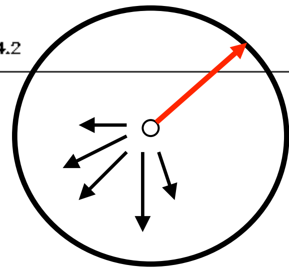




$$x_A = \frac{k_1\,e^{-y_1} + k_2\,e^{-y_2}}{\sqrt{s}} << 1$$



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-jets in the back-to-back regime

TMD factorization

$$|p_{1t}|, |p_{2t}| \gg |k_t|, Q_s$$

- a factorization can be established in the small *x* limit, for nearly back-to-back di-jets

Dominguez, CM, Xiao and Yuan (2011)

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

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

this is the so-called Transverse Momentum Dependent (TMD) factorization formula

e.g. Bomhof, Mulders and Pijlman (2006)

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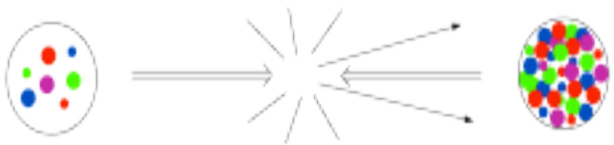
- only valid in asymmetric situations

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



does not apply with unintegrated parton densities for both colliding projectiles

TMD factorization

- 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)

from the CGC framework (valid at small-x): by extracting the leading power

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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 $|p_{1t}|, |p_{2t}| \gg |k_t|, Q_s$

Evaluating the gluon TMDs at small-x

The other TMDs at small-x

- involved in the $gg^* \to q\bar{q}$ and $gg^* \to gg$ channels

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

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

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

$$\mathcal{F}_{gg}^{(5)}(x_2,k_t) = -\frac{4}{g^2}\int\frac{d^2\mathbf{x}d^2\mathbf{y}}{(2\pi)^3}\, e^{-ik_t\cdot(\mathbf{x}-\mathbf{y})}\left\langle \mathrm{Tr}\left[(\partial_i U_{\mathbf{x}})U_{\mathbf{y}}^\dagger U_{\mathbf{x}}U_{\mathbf{y}}^\dagger(\partial_i U_{\mathbf{y}})U_{\mathbf{x}}^\dagger U_{\mathbf{y}}U_{\mathbf{x}}^\dagger\right]\right\rangle_{x_2} ,$$

$$\mathcal{F}_{gg}^{(6)}(x_2,k_t) = -\frac{4}{g^2}\int\frac{d^2\mathbf{x}d^2\mathbf{y}}{(2\pi)^3}\, e^{-ik_t\cdot(\mathbf{x}-\mathbf{y})}\,\frac{1}{N_c^2}\left\langle \mathrm{Tr}\left[(\partial_i U_{\mathbf{x}})U_{\mathbf{y}}^\dagger(\partial_i U_{\mathbf{y}})U_{\mathbf{x}}^\dagger\right]\mathrm{Tr}\left[U_{\mathbf{x}}U_{\mathbf{y}}^\dagger\right]\mathrm{Tr}\left[U_{\mathbf{y}}U_{\mathbf{x}}^\dagger\right]\right\rangle_{x_2} .$$

with a special one singled out: the Weizsäcker-Williams TMD

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

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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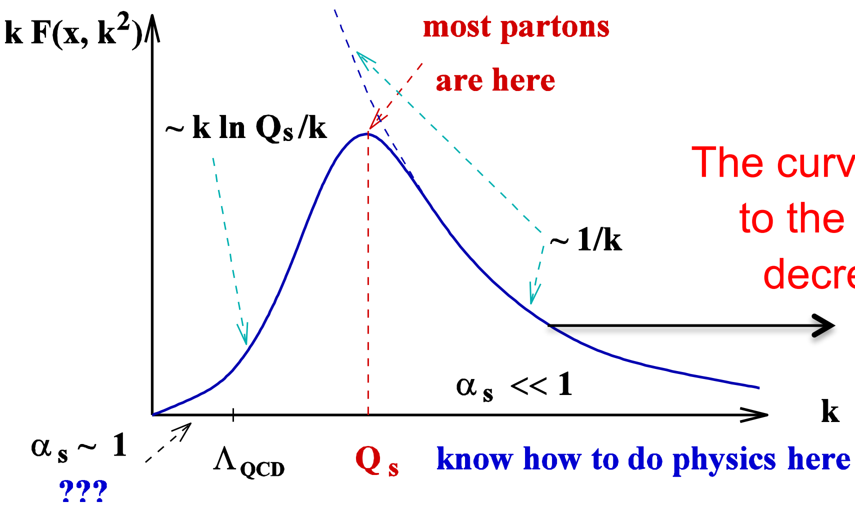
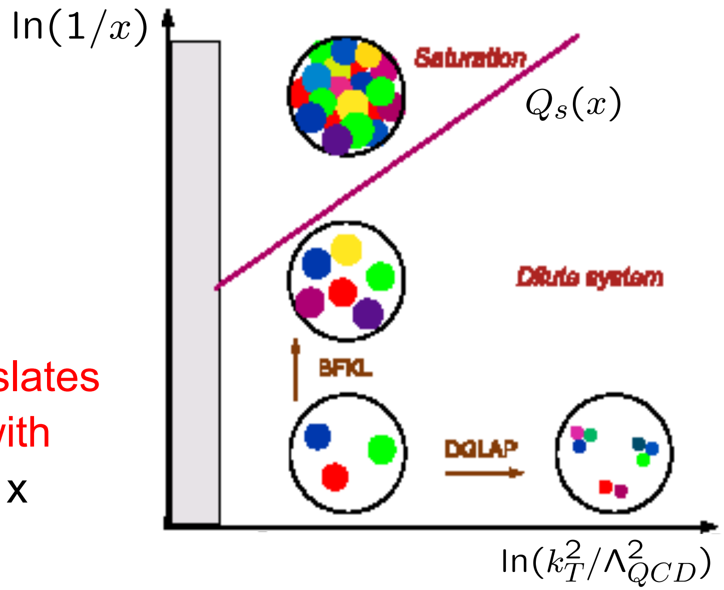
- qualitative solutions for the gluon TMDs:



The curve translates to the right with decreasing x



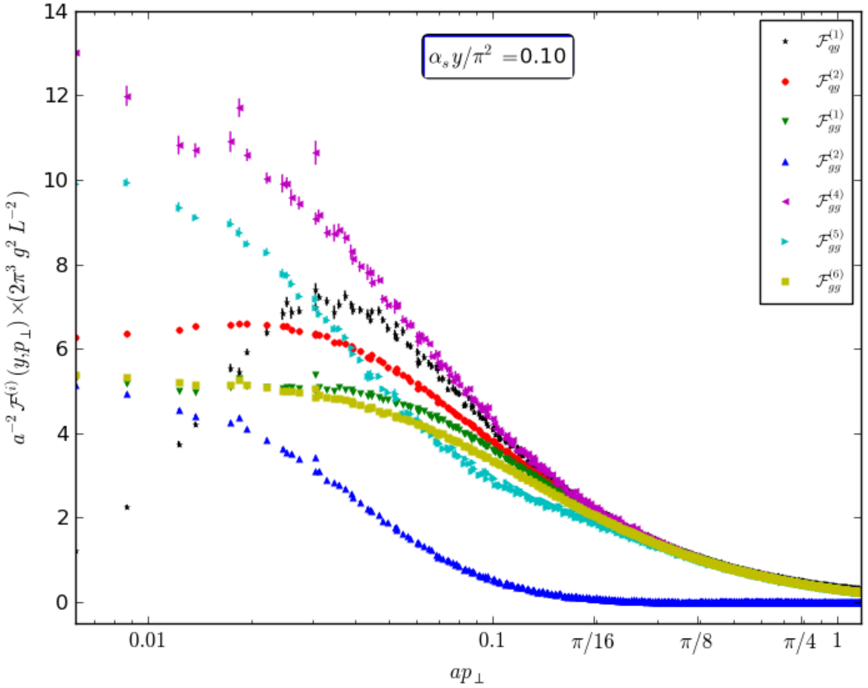
the distribution of partons as a function of x and k_T

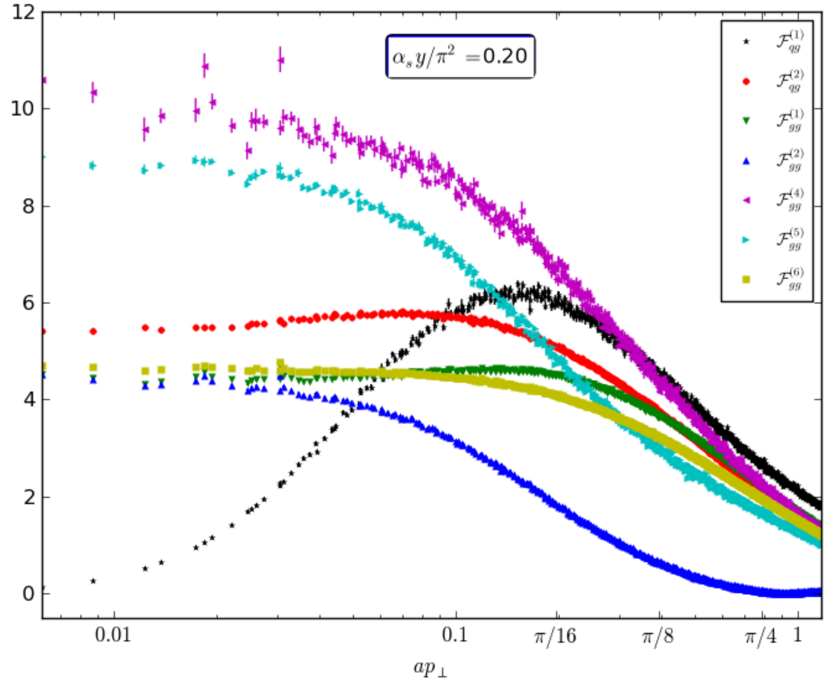
JIMWLK numerical results

using a code written by Claude Roiesnel

initial condition at y=0 : MV model
evolution: JIMWLK at leading log

CM, Petreska, Roiesnel (2016)

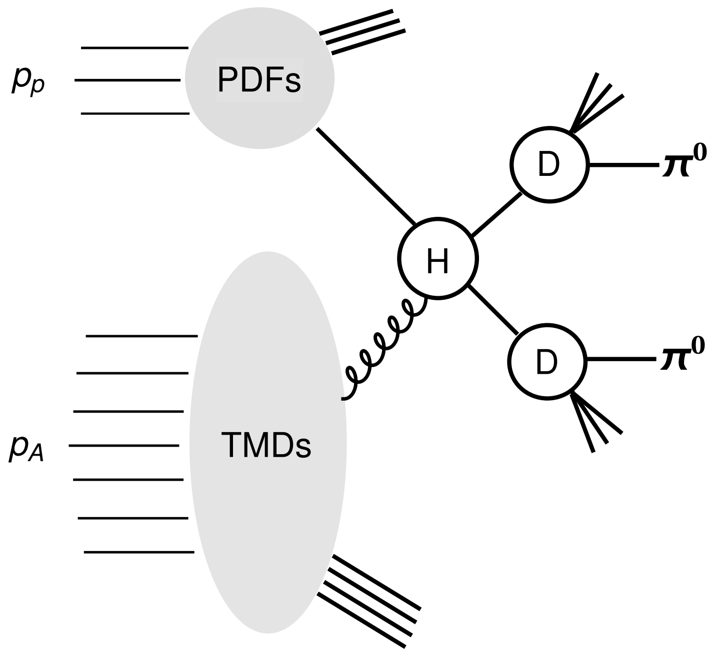




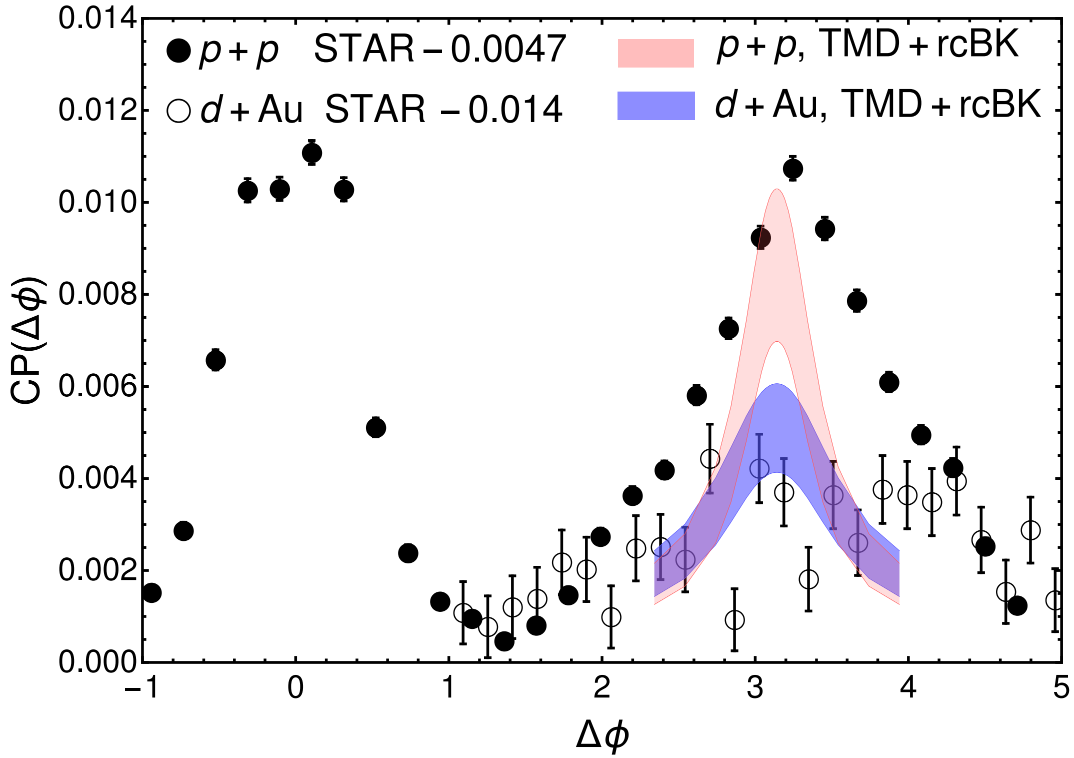
saturation effects impact the various gluon TMDs in very different ways

Back to experiments

STAR forward di-hadrons



Albacete, Giacalone, CM and Matas, in preparation



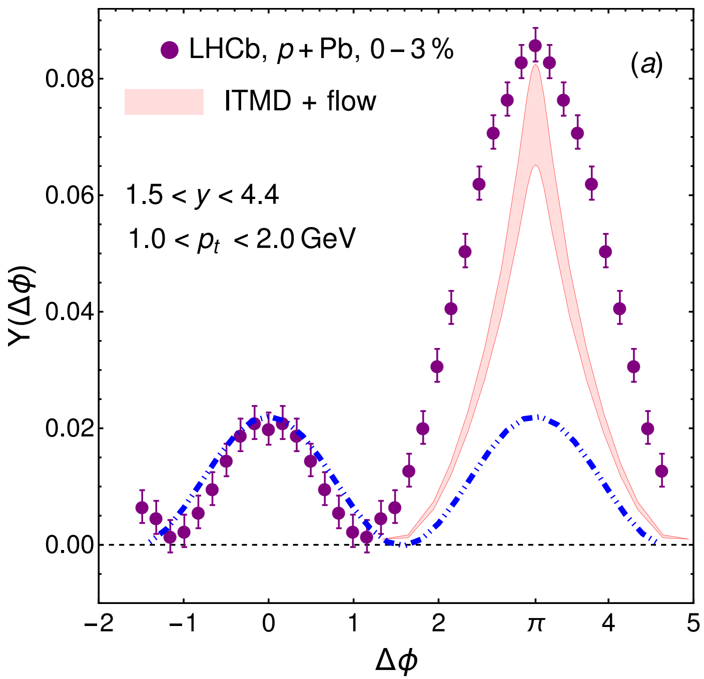
new description of the away-side peak suppression

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



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Giacalone and CM, in progress

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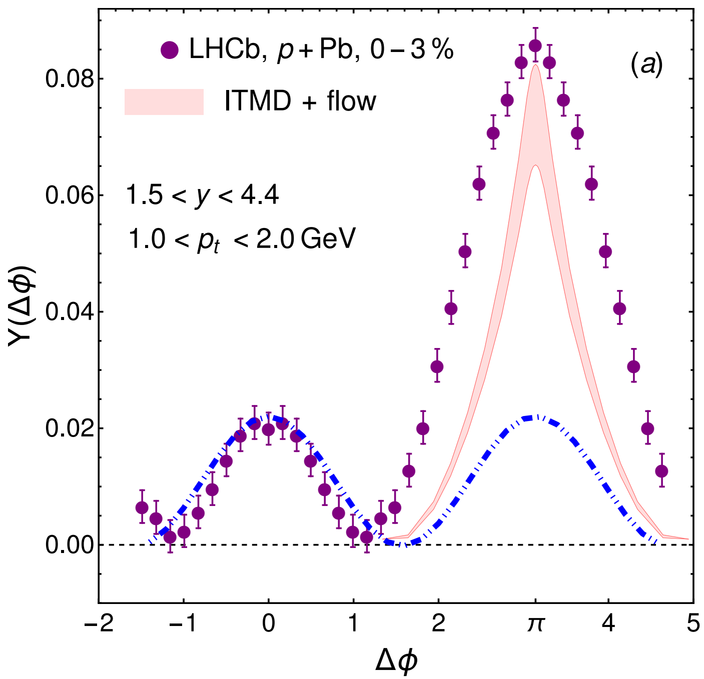

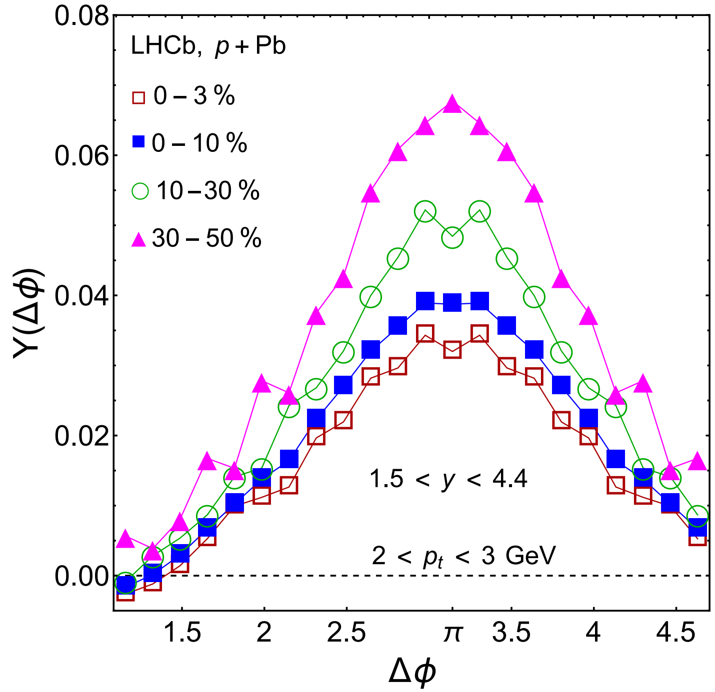

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Giacalone and CM, in progress

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

Conclusions I

- for forward di-hadron production, TMD factorization and CGC calculations are consistent with each other in the overlapping domain of validity

  small *x* and leading power of the hard scale $|p_{1t}|, |p_{2t}| \gg |k_t|, Q_s$

- saturation physics is relevant if the di-hadron transverse momentum imbalance $|k_t|$ is of the order of the saturation scale Qs

- the cross-section involves several gluon TMDs, with different operator definitions

Conclusions II

- given an initial condition, the gluon TMDs can all be obtained at smaller values of x, from the JIMWLK equation
- as expected, the various gluon TMDs coincide at large transverse momentum, in the linear regime
- however, they differ significantly from one another at low transverse momentum, in the non-linear saturation regime
- we hope to see at the LHC, a confirmation of the saturation signal seen at RHIC