Non-flow studies with D-Dbar correlations at the EIC

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- Non-flow in high-multiplicity p+A collisions from the CGC perspective
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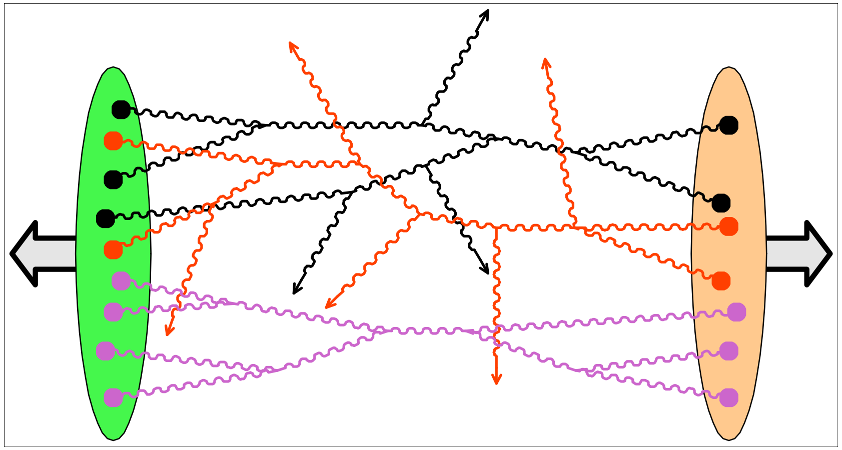
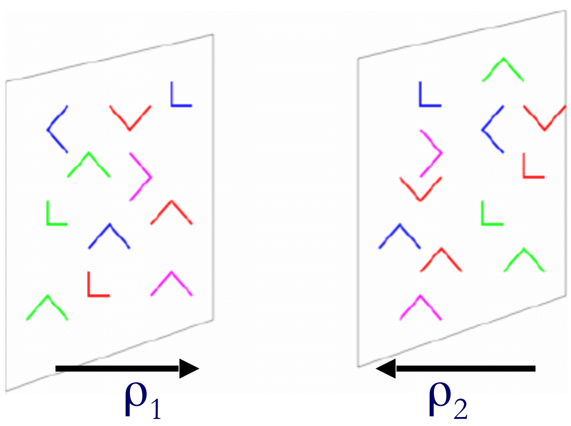
- Further experimental tests in UPC and at the EIC using heavy-quark pairs

Non-flow in high-multiplicity p+A collisions: CGC perspective



Collision of two CGCs

- the initial condition for the time evolution in heavy-ion collisions, and high-multiplicity p+p and p+A



before the collision:

$$J^\mu = \delta^{\mu +}\delta(x^-)\rho_1(x_\perp) + \delta^{\mu -}\delta(x^+)\rho_2(x_\perp)$$

$$\rho_1 \sim 1/g \qquad \rho_2 \sim 1/g$$

the distributions of ρ contain the small-x evolution of the nuclear wave functions

$$|\Phi_{x_1}[\rho_1]|^2 \qquad |\Phi_{x_2}[\rho_2]|^2$$

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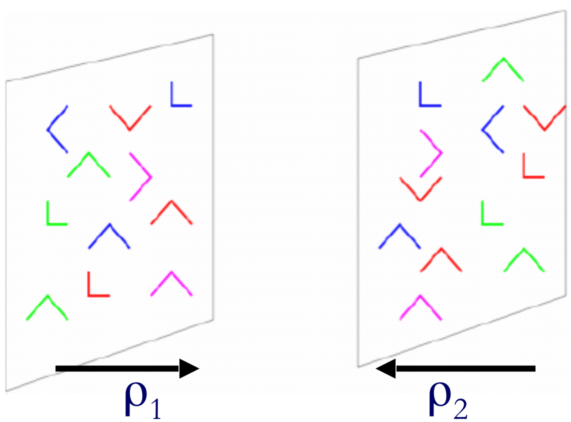

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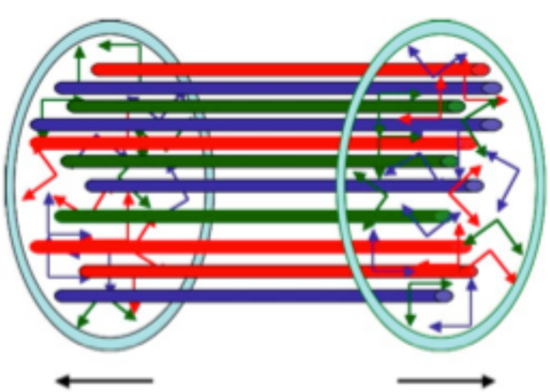
these wave functions are mainly non-perturbative, but their evolution is known



$$\frac{d}{d\ln(1/x)}\left|\Phi_x[\alpha]\right|^2 = H^{JIMWLK} \otimes \left|\Phi_x[\alpha]\right|^2$$

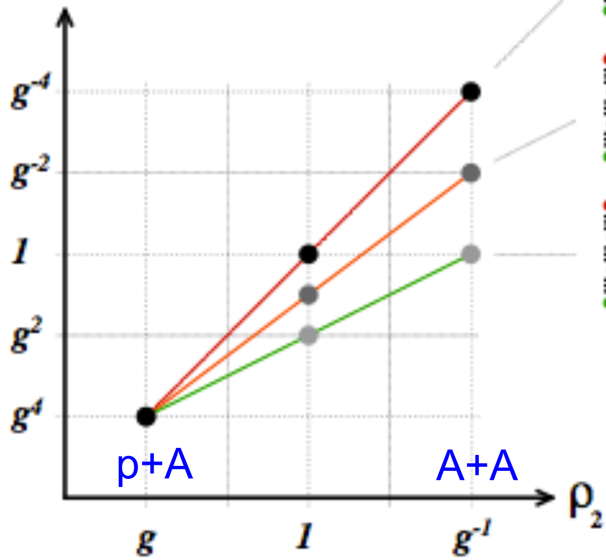
- after the collision: the Glasma phase

the gluon field is a complicated function of the two classical color sources

Two-particle production in the CGC

Gelis, Lappi and Venugopalan (2008)

strength of the diagrams
(power-counting)



leads to so-called Glasma graphs, produces double ridge, dominates in A+A collisions

usually neglected (vanishes with Gaussian averaging)

back-to-back jets, dominate in dilute-dilute/low-multiplicity collisions

strength of the color charge of the projectile

the target is always dense $\rho_1 \sim 1/g$

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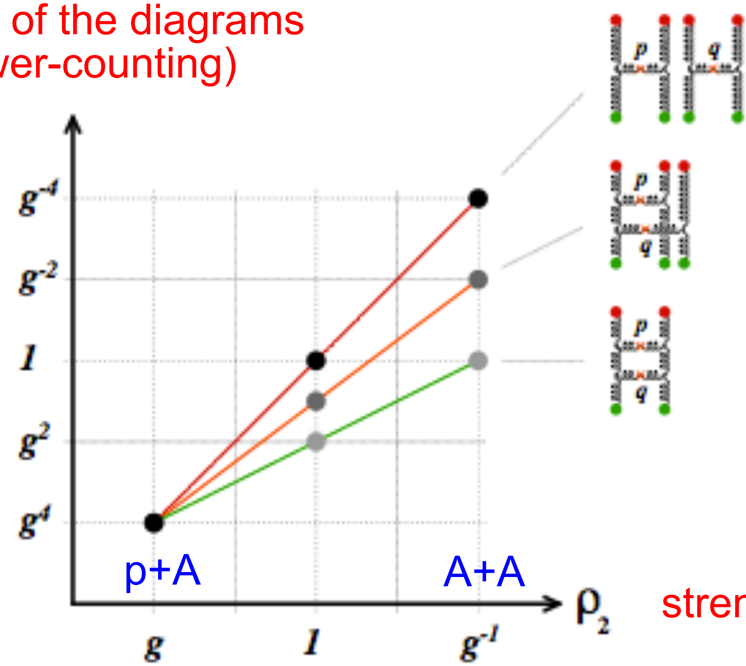

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those diagrams yield initial QCD momentum correlations which contribute to “non-flow”
(as opposed to “flow” which is a hydro response to initial spatial anisotropies)

as the system later becomes a perfect fluid,
one expects most of those initial correlations to become negligible

in small-systems (p+p, p+A), they may still have a sizeable contribution

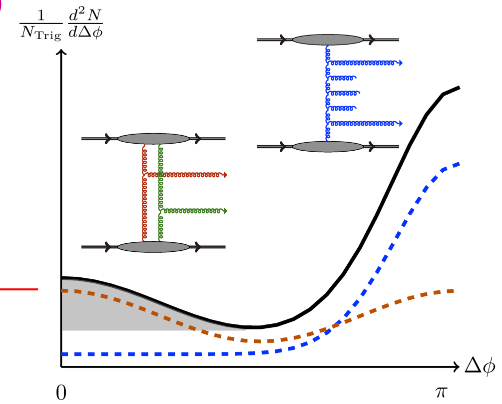
The ridge from initial state physics

Dumitru, Dusling, Gélis, Jalilian-Marian, Lappi and Venugopalan (2011)

Kovner and Lublinsky (2011)

- CGC calculation after Gaussian averaging

additionnal double ridge in the correlation function compared to standard QCD di-jets



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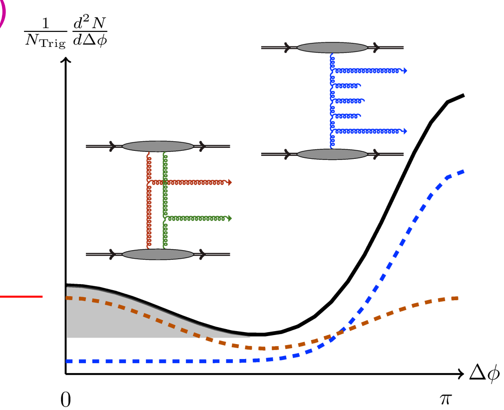
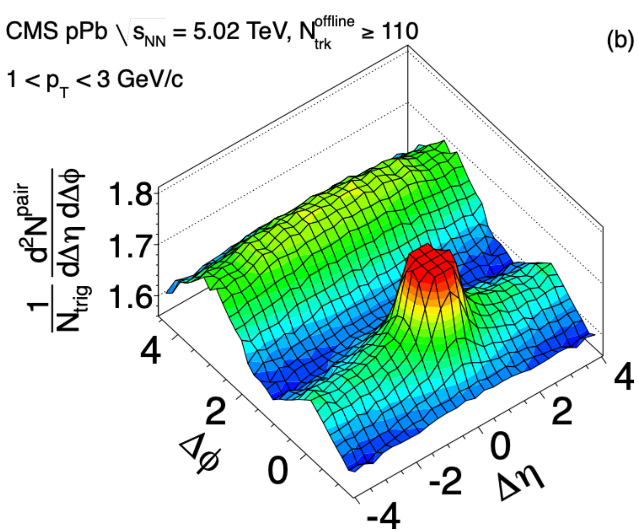
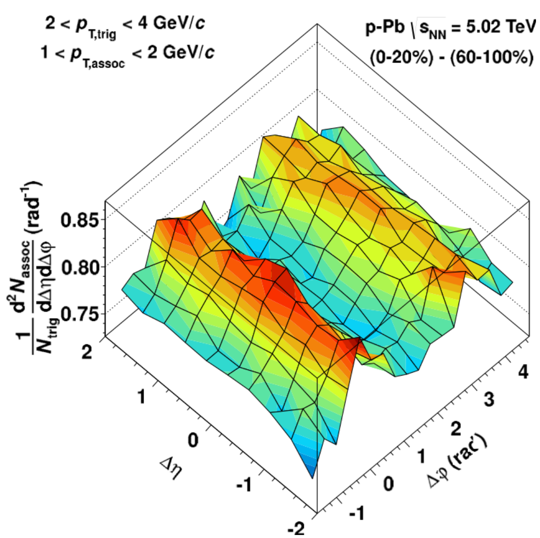


- non-flow subtraction typically only remove the jet component





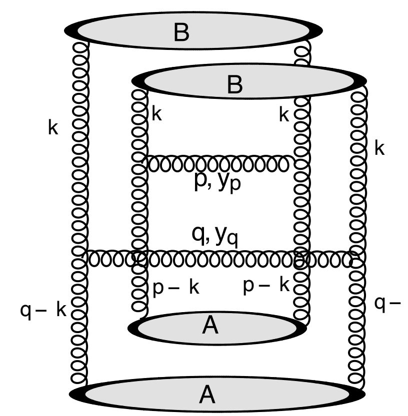
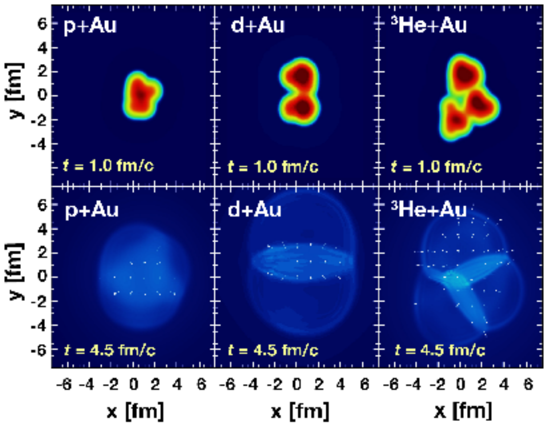


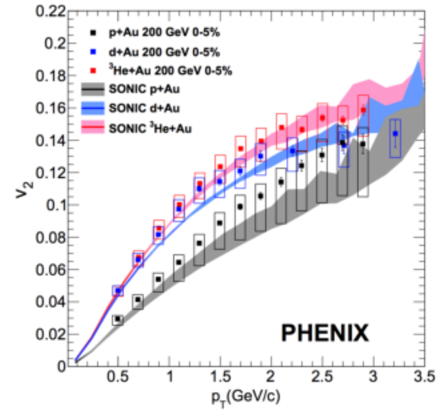
diagram which gives the $\Delta\phi$ dependence

most of the ridge comes from flow, but a non-flow contribution could remain especially in p+p, p+A collisions

Example of leftover non-flow after di-jet peak subtraction

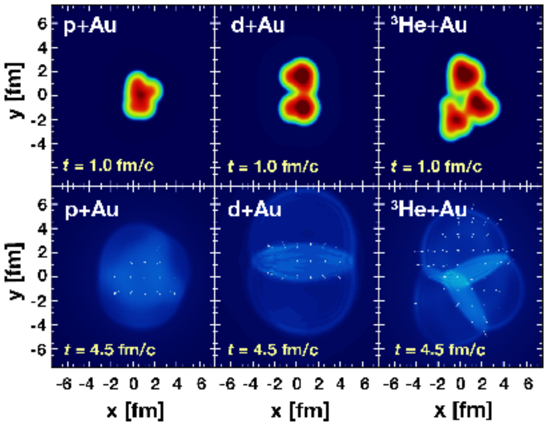
Response-to-geometry v_n …

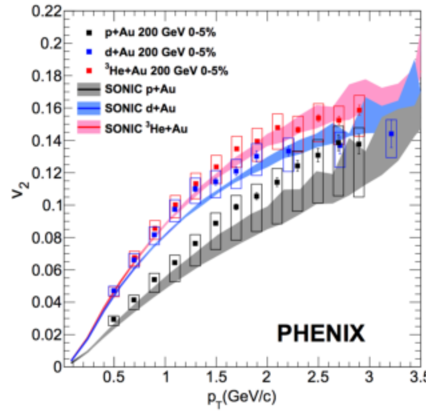


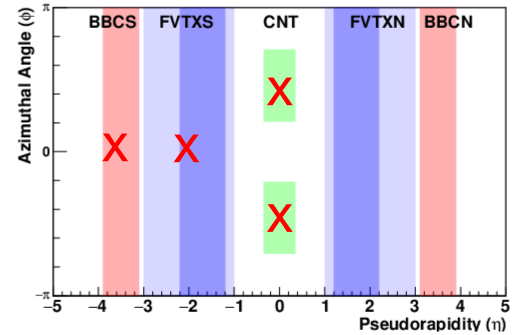


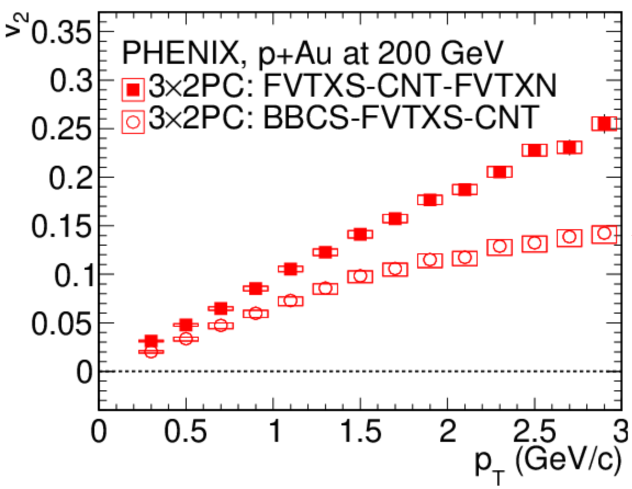
$$v_2(\mathrm{p{+}Au}) < v_2(\mathrm{d{+}Au})$$

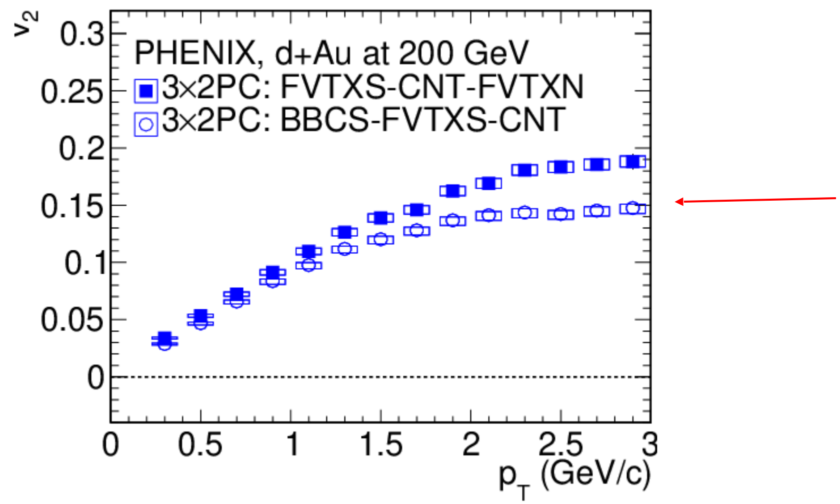
Response-to-geometry v_n …







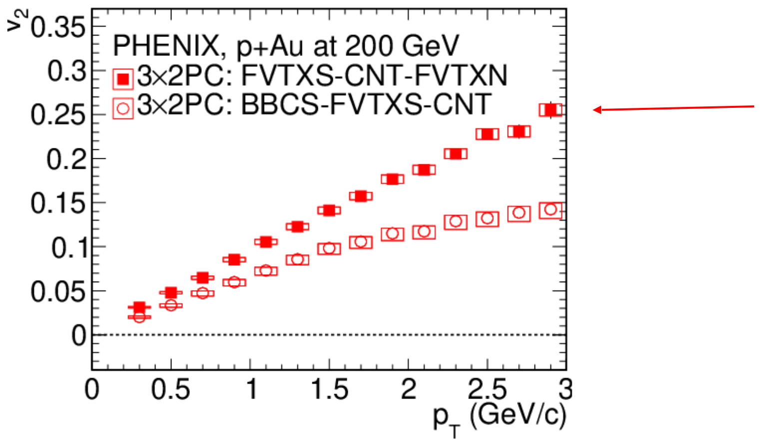


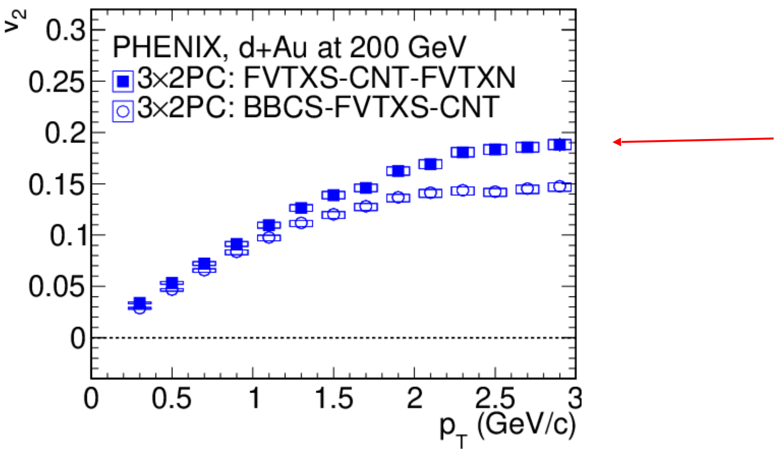


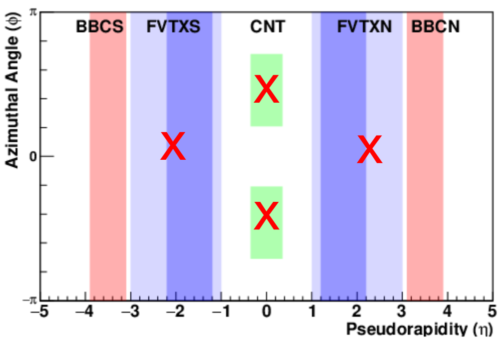
$$v_2(\mathrm{p+Au}) < v_2(\mathrm{d+Au})$$

…vs non-flow v_n at forward rapidities

Reverse ordering for v_2 $v_2(\mathrm{p+Au}) > v_2(\mathrm{d+Au})$







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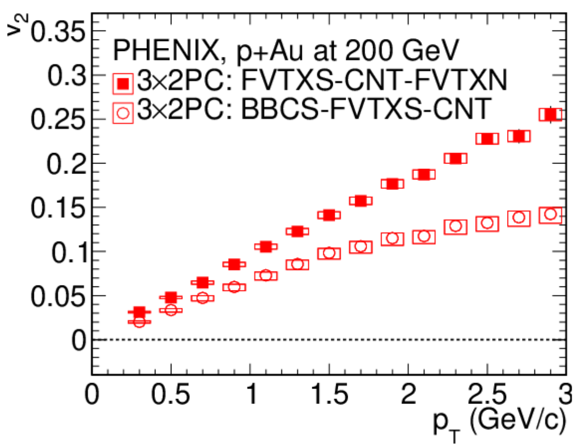
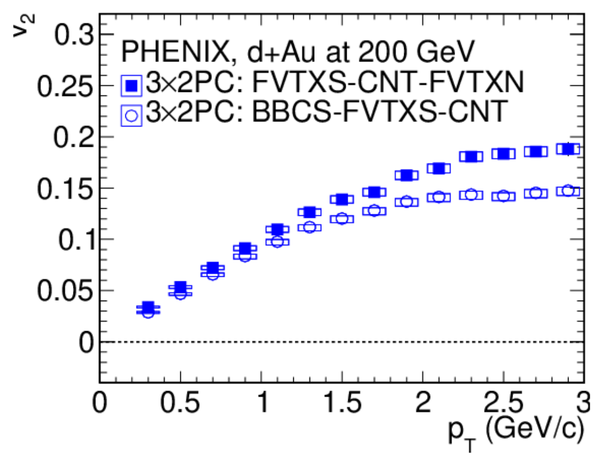
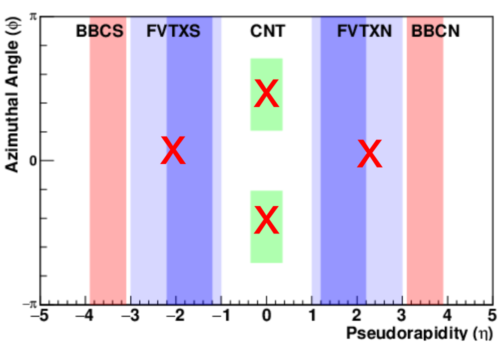
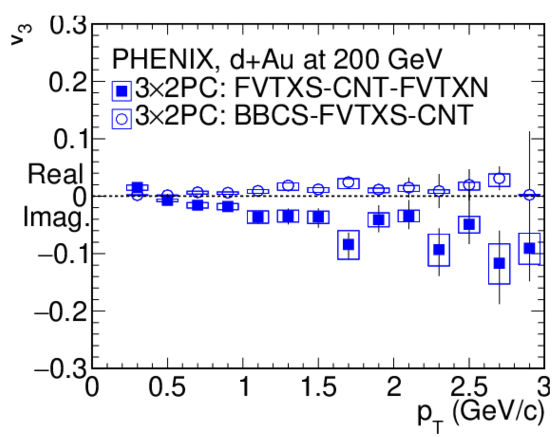


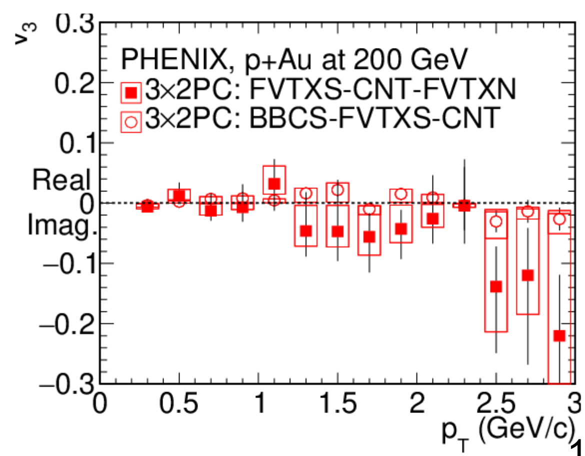


Negative v_3

not consistent with hydro/final-state effect





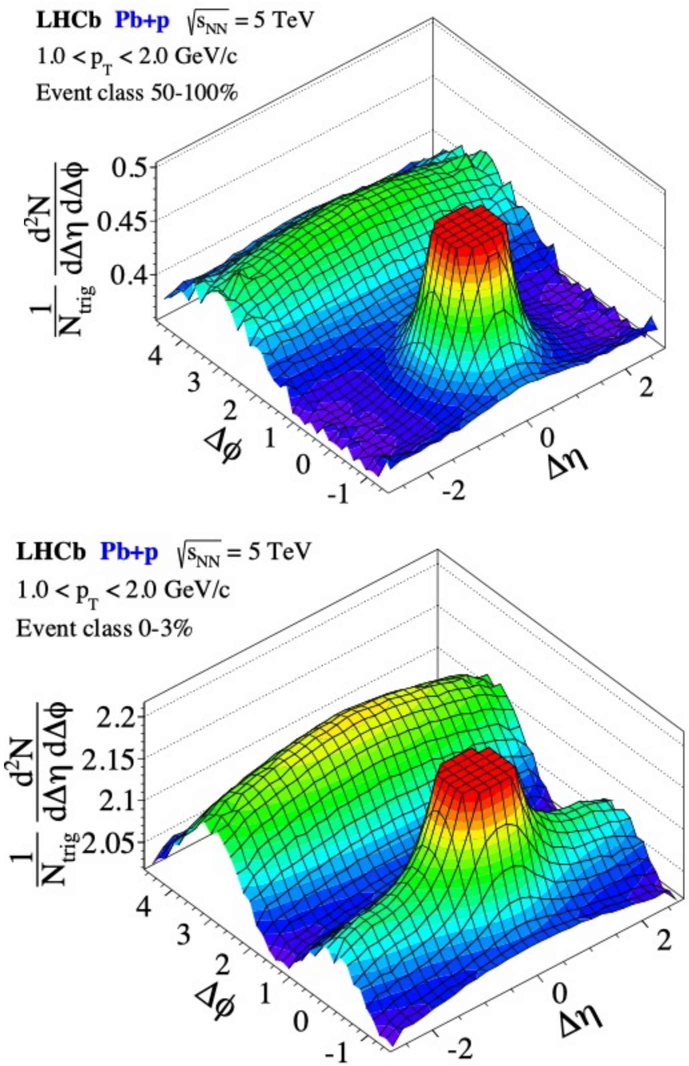


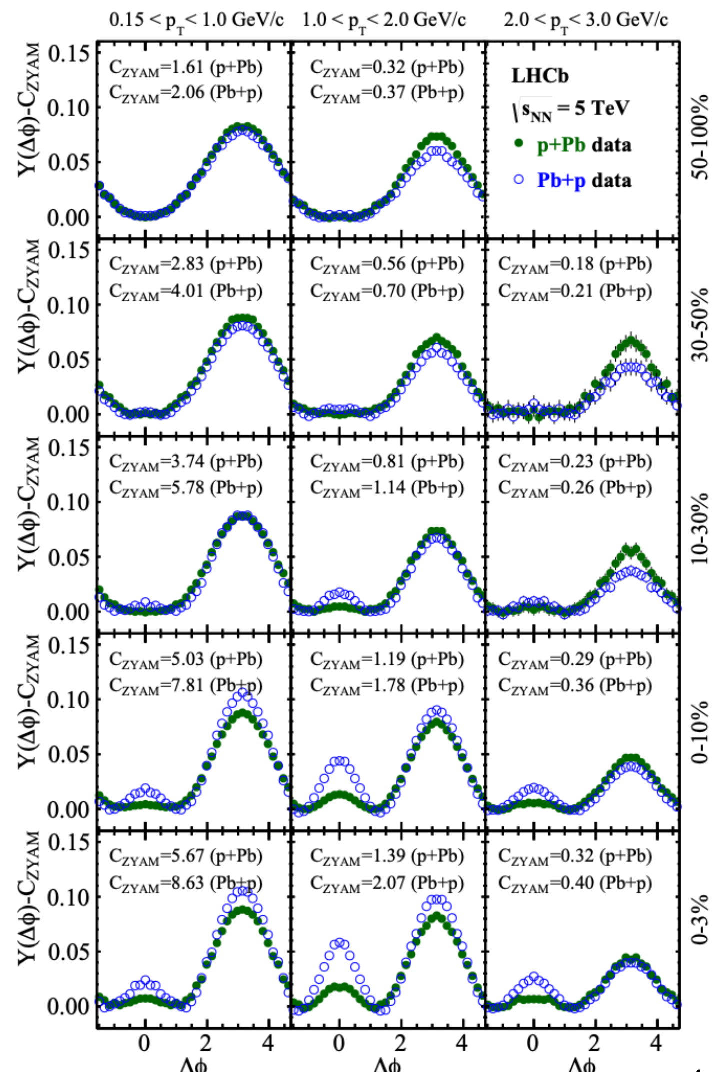
can be reproduced with CGC calculation

Kohara, CM and Vila (2023)

Example of centrality-dependent non-flow in jet component

This happens at forward rapidities





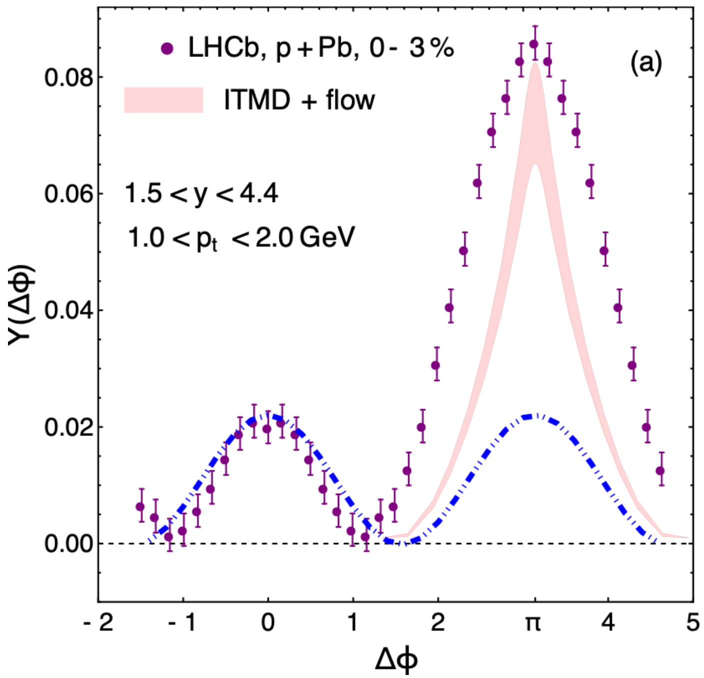
initially v_n was not extracted from those correlation functions

LHCb forward di-hadrons

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

Giacalone and CM (2019)

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



without a soft gluon resummation,
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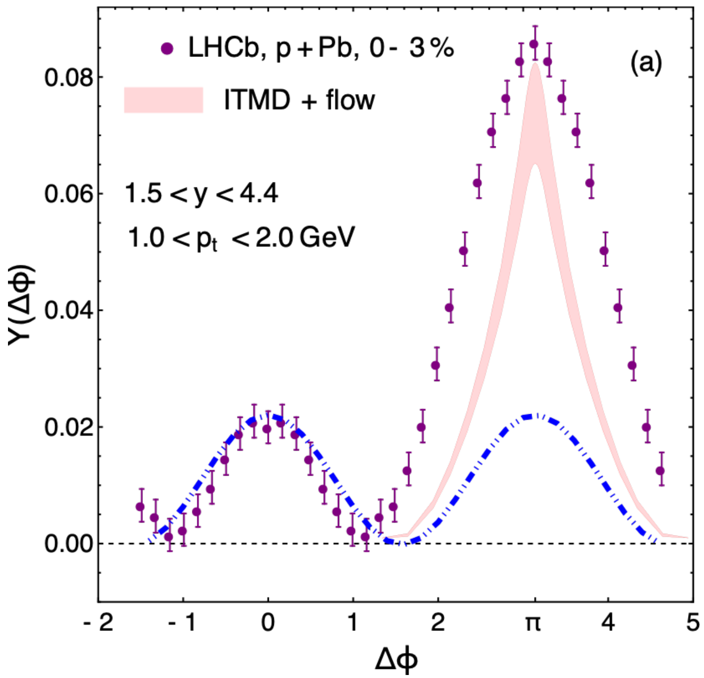

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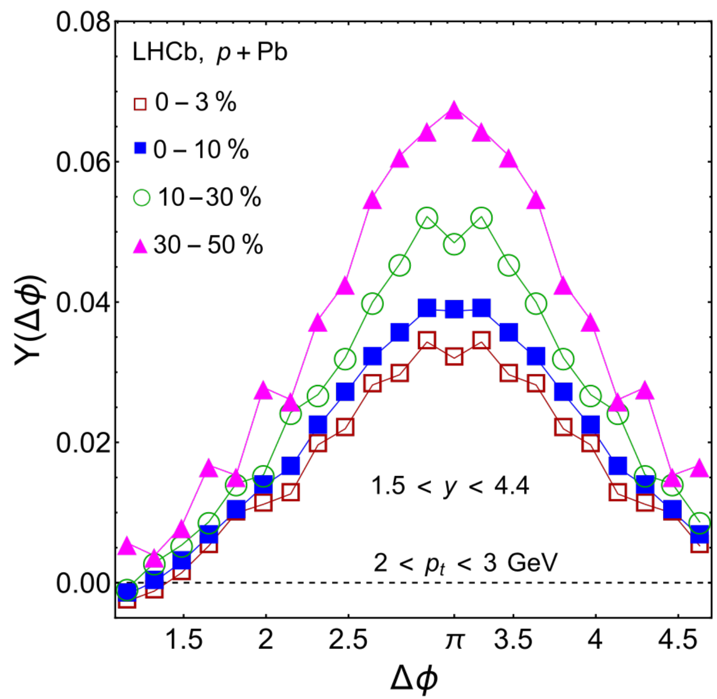


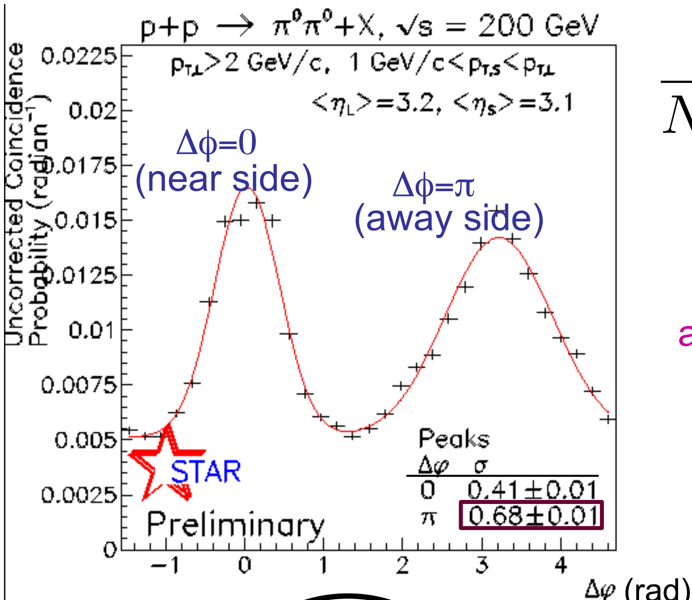
suppression of the away-side peak
with increasing centrality seen in the data

Away-side peak suppression: saturation signal

Original STAR data

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

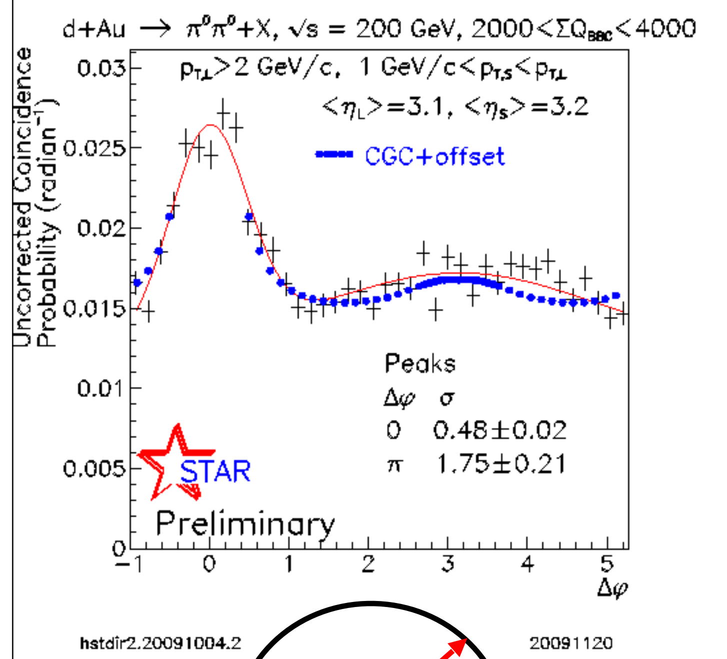
p+p collisions

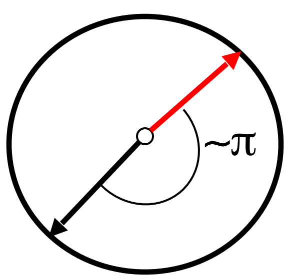


$$\frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\varphi}$$

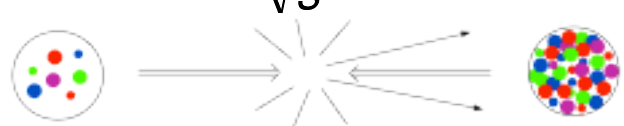
Albacete
and CM (2010)

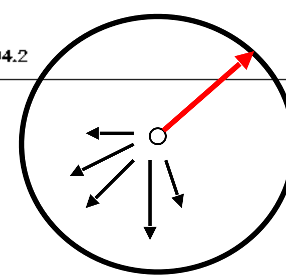
central d+Au collisions





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





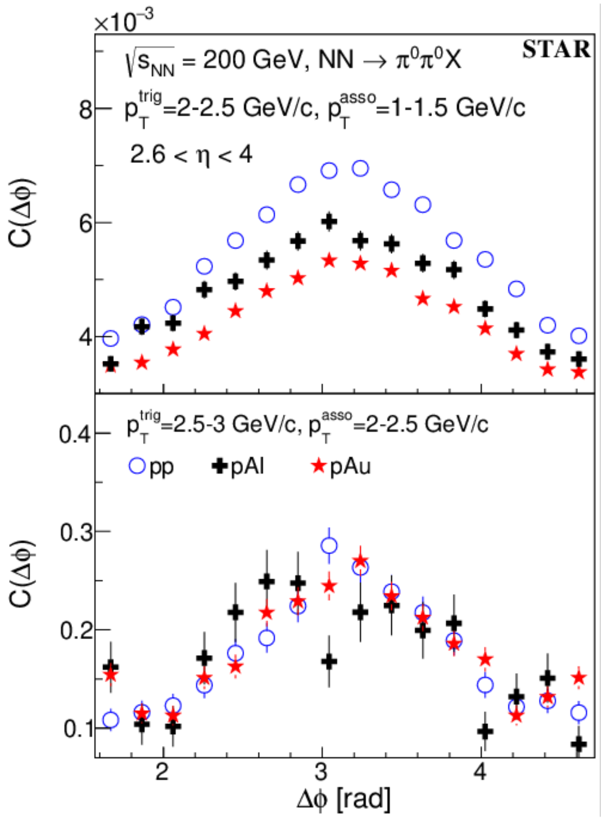
however, when $y_1 \sim y_2 \sim 0$ (and therefore $x_A \sim 0.03$),
the p+p and d+Au curves are almost identical

New STAR data

- forward di-hadron correlation function in p+Au, p+Al and p+p collisions

low pt: away-side peak suppression with increasing A

STAR Collaboration (2022)



high pt: correlation unchanged

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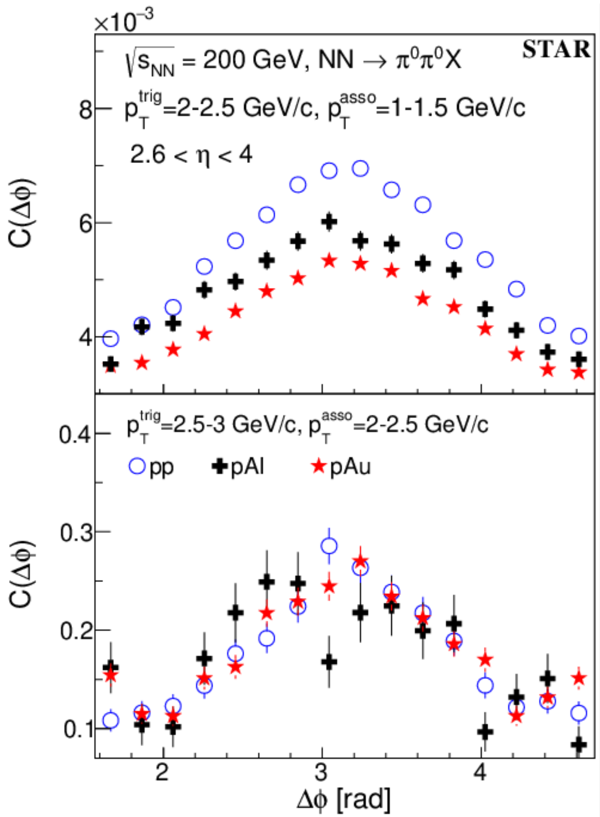
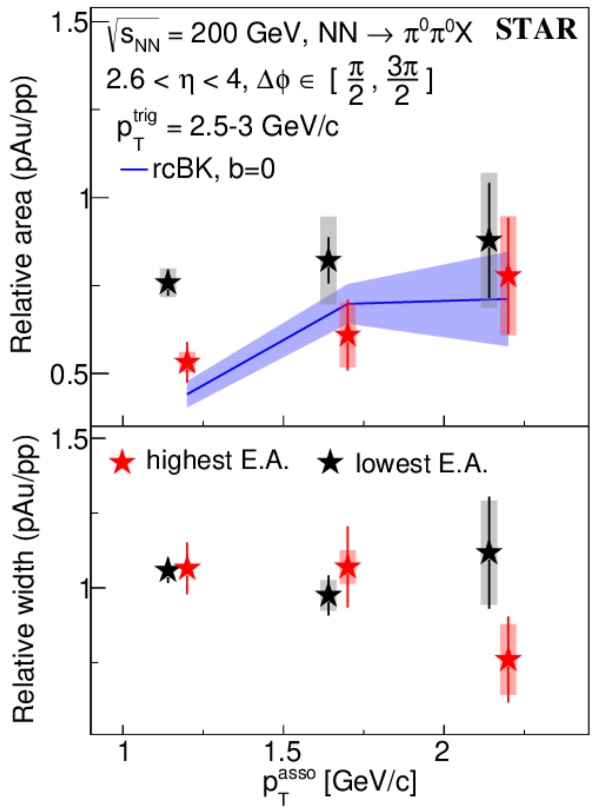




area suppressed

width unchanged

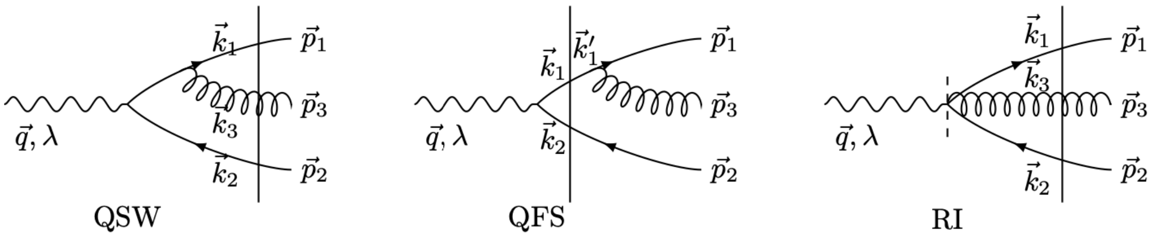
high pt: correlation unchanged

CGC calculation from
Albacete, Giacalone, CM and Matas, (2019)

Soft gluon emissions in di-hadron / di-jet production

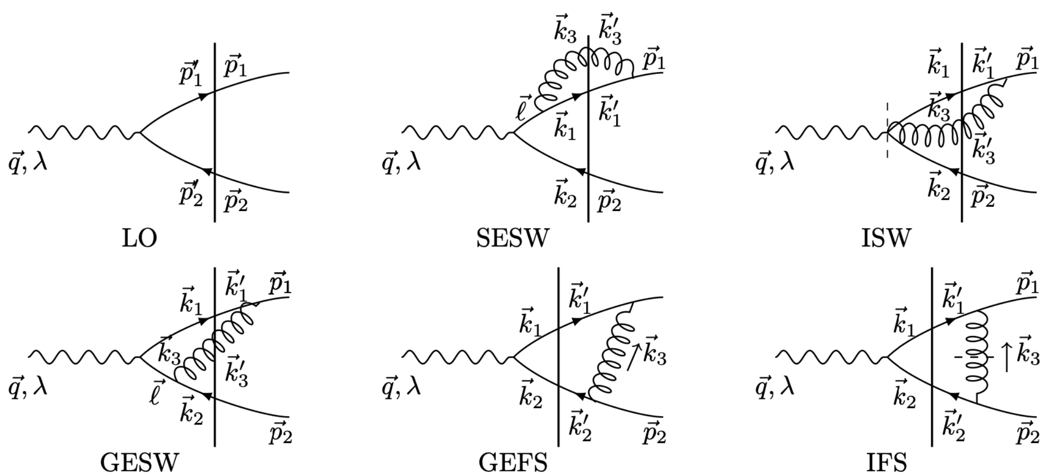
NLO corrections

- real emission diagrams



Altinoluk, Boussarie, CM and Taels (2020)
Caucal, Salazar and Venugopalan (2021)
Bergabo and Jalilian-Marian (2022)
Taels, Altinoluk, Beuf and CM (2022)
Iancu and Mulian (2023)

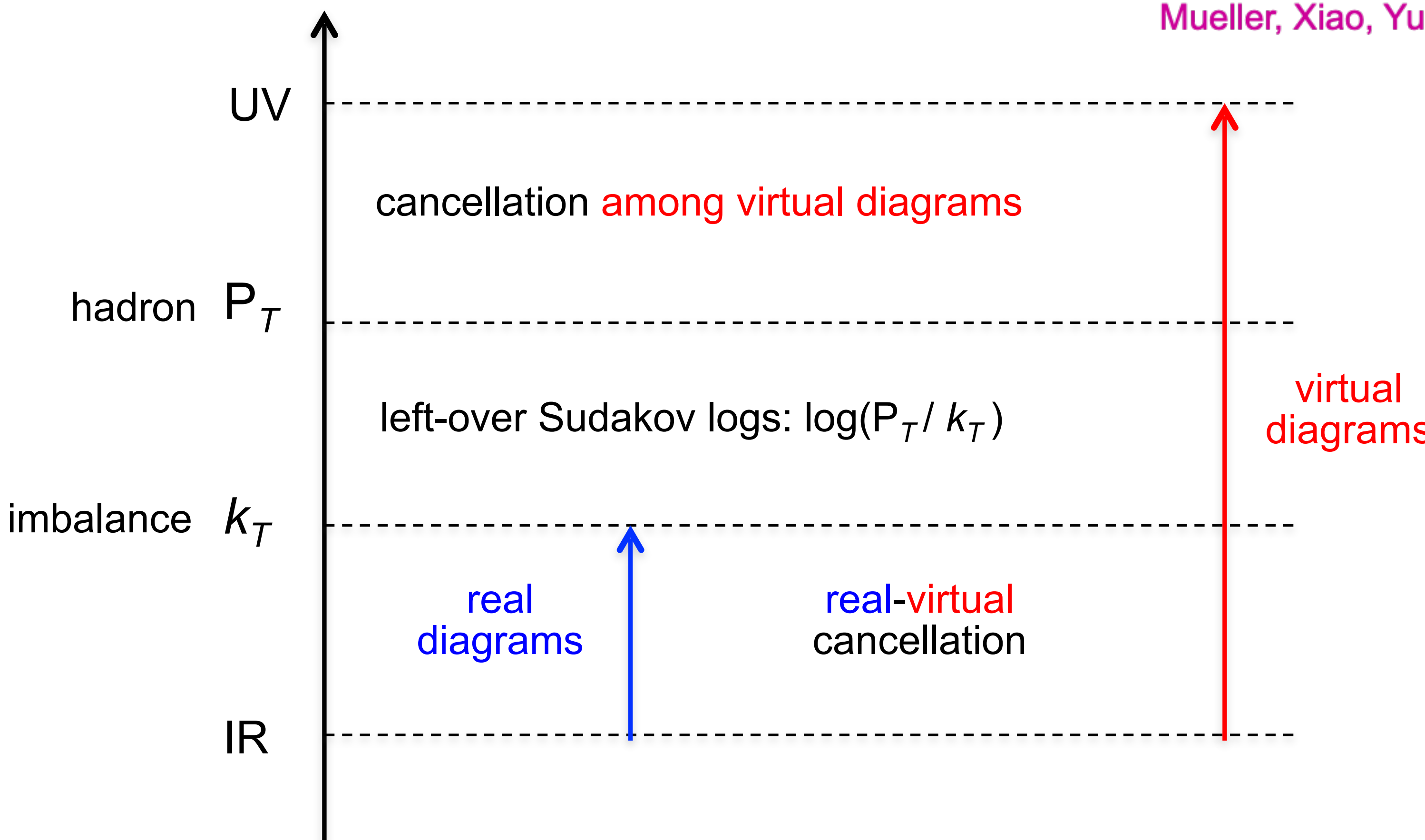
- virtual diagrams



Sudakov logarithms

- they arise from "incomplete" cancellation of IR divergences

Mueller, Xiao, Yuan (2013)

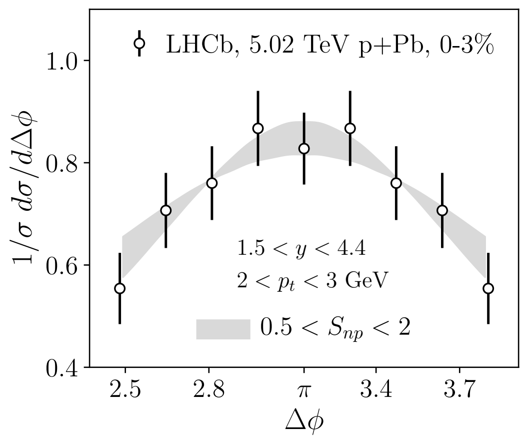


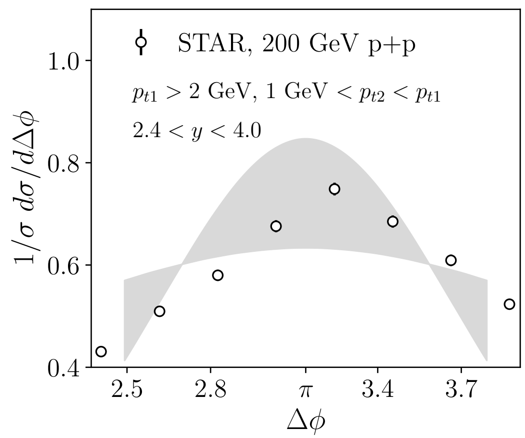
just as saturation effects, Sudakov logs are important in the back-to-back regime $k_T \ll P_T$

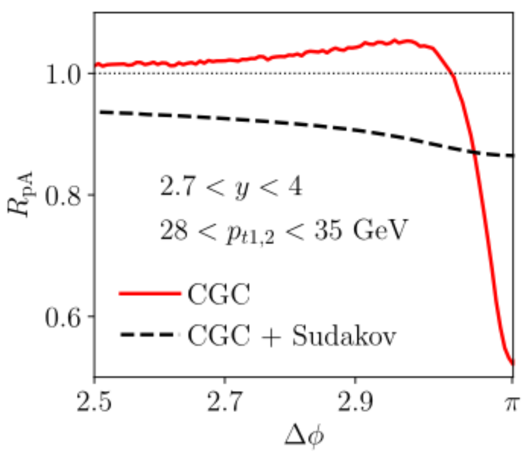
Back to phenomenology

the width of the away-side peak is well described
however, we lose control on the normalization

this is because we are very sensitive to non-perturbative physics
this was to be expected since the Sudakov logarithms are not really large







Forward di-hadrons correlations

forward di-hadron correlations has been the prime observable
to look for saturation effects in p+Pb vs p+p collisions CM (2007)

however, there is a competition between saturation effects and soft-gluon emissions: e.g. STAR sees suppression of the away-side peak (dominated by saturation) but no broadening (dominated by Sudakov)

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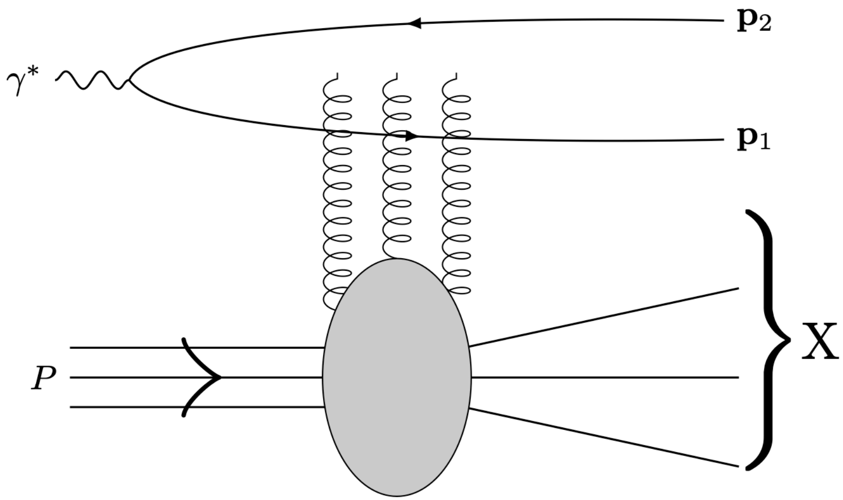
- one should consider observables less sensitive to soft radiation, which will leave more room for saturation signals
- transverse EECs are a popular option, which at small x are straightforward to obtain from already-known double-inclusive cross-sections
- alternatively, one may use heavy quarks, in which case soft gluon radiation is also suppressed (dead cone)

those studies are important if one wants to build a robust model for the non-flow component in two-particle correlations

Heavy-quark pair production

$Q\bar{Q}$ photo-production at small x



$$\langle k_t \rangle \sim Q_s$$

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

(*) the photon may also be virtual, but a large Q^2 value is not needed

The hard scale is: $|p_{1t}|,\ |p_{2t}| \sim \mathbf{P} \gg Q_s$

The semi-hard scale is:

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

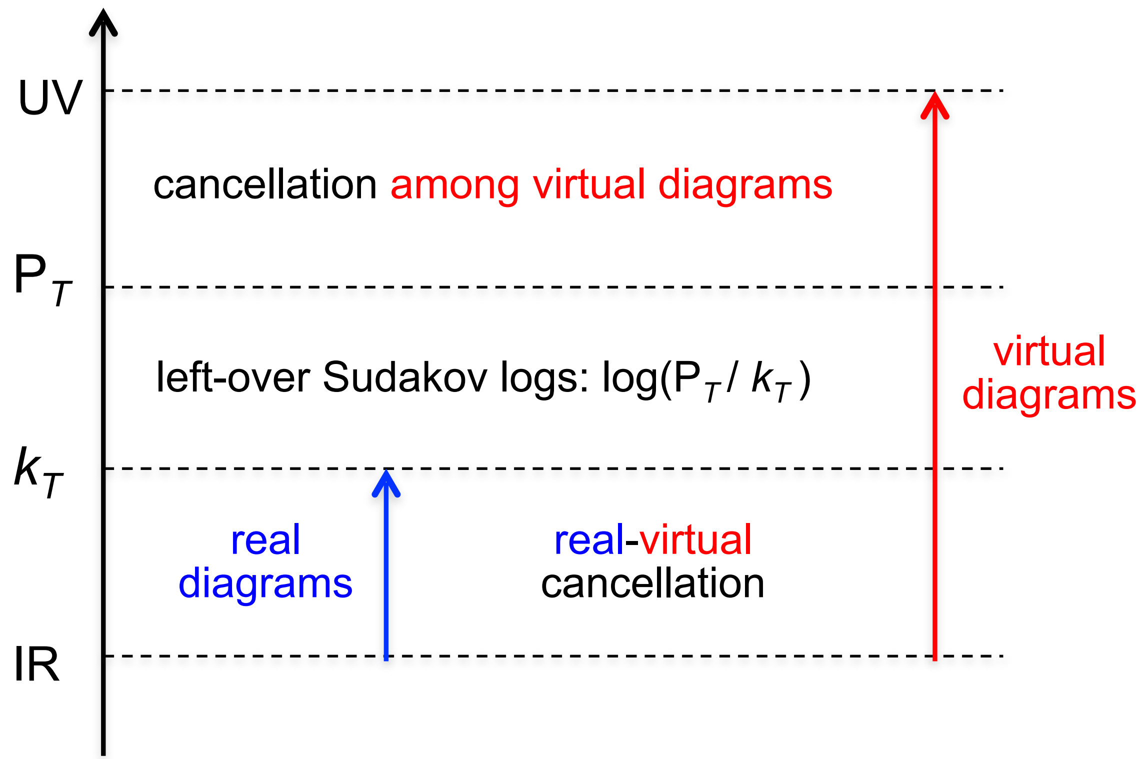
→ the small-x gluon's transverse momentum (di-jet imbalance)

Using heavy quarks

- we computed the Sudakov factor for heavy quark production

following the method in Hatta, Xiao, Yuan, Zhou (2021)

we considered this regime for the heavy quark mass, unifying the massive calculation and the massless limit

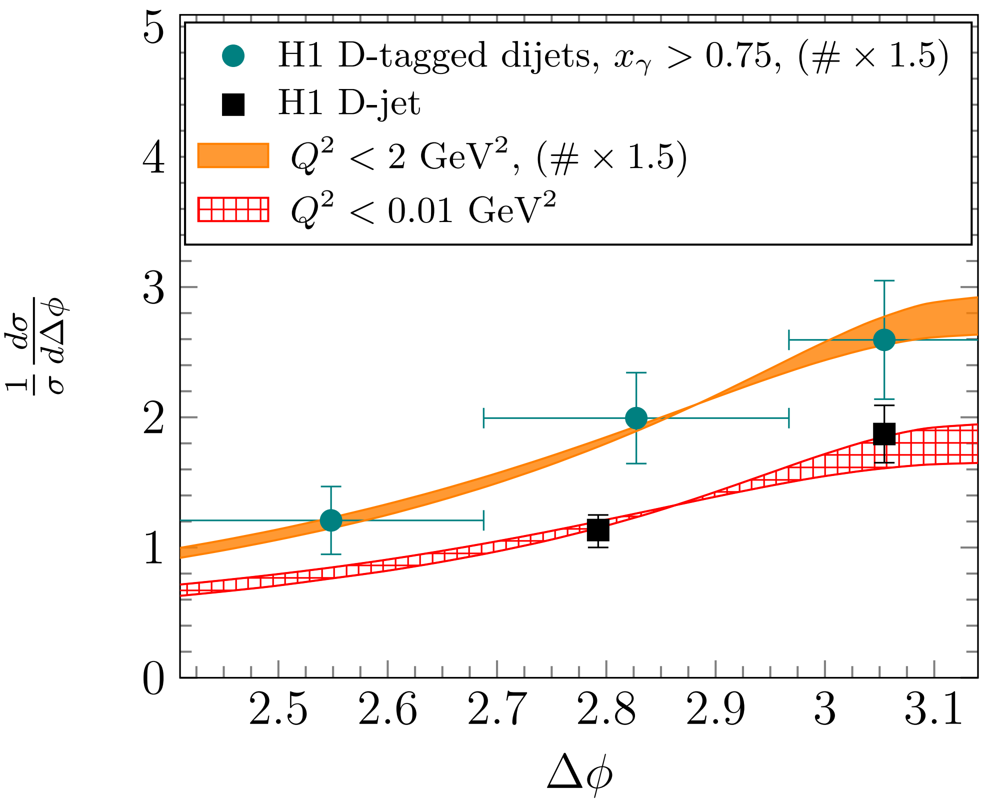


CM, Y. Shi and B.-W. Xiao, arXiv:2510.18949

Comparison with HERA e+p data

CM, Y. Shi and B.-W. Xiao, arXiv:2510.18949

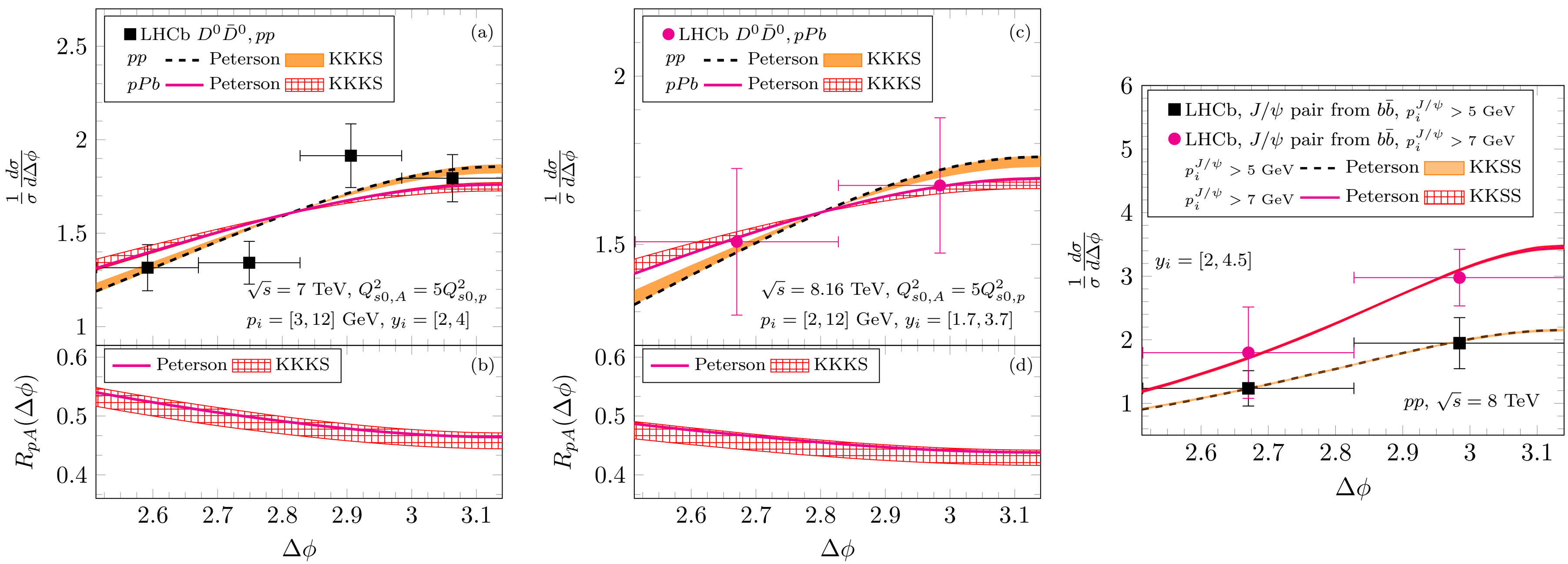
first description of HERA data



Comparison with LHC p+A data

Z. Gao, CM, Y. Shi and B.-W. Xiao, arXiv:2605.01527

we also compare to p+Pb data in order to further validate our massive Sudakov resummation

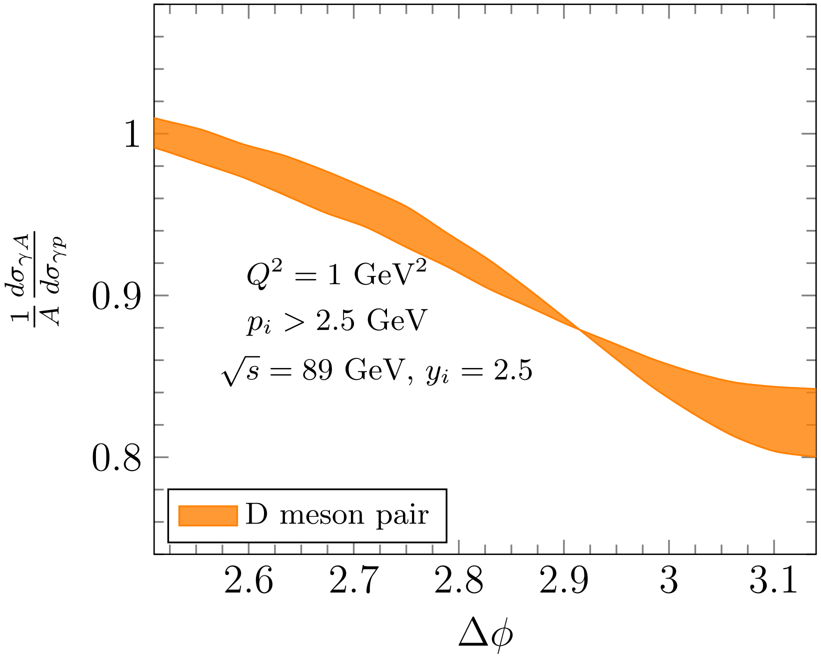


Predictions for EIC and LHC (in UPCs)

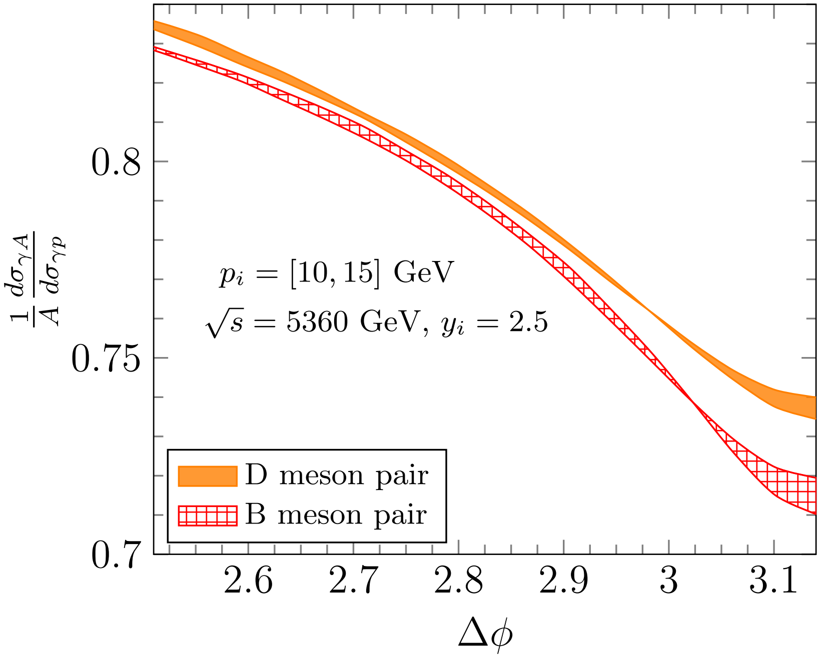
$\Delta\Phi$ distribution

the γ+A / γ+p suppression survives after the Sudakov factor is included

EIC γ+A / γ+p



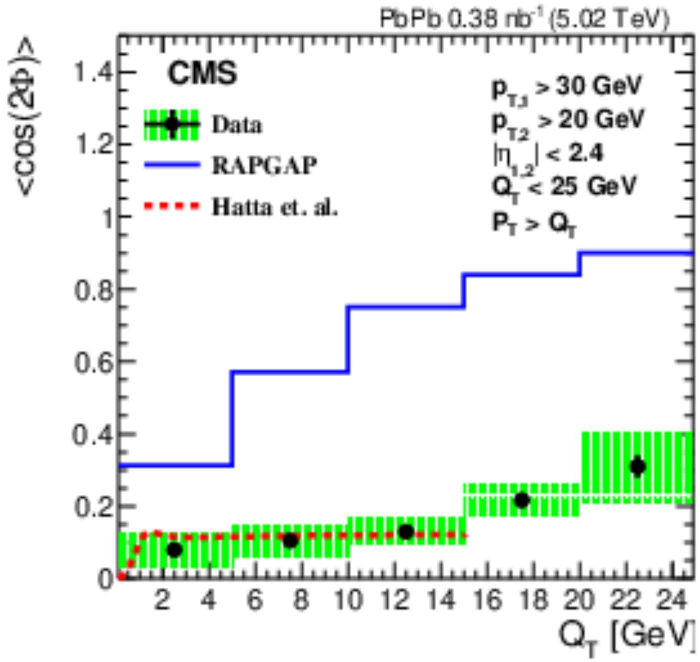
UPC γ+A / γ+p



inverse mass ordering due to suppression of soft gluon emission

The "asymmetry" observables $\langle \cos(n\phi) \rangle$

- measurement previously performed in exclusive UPCs

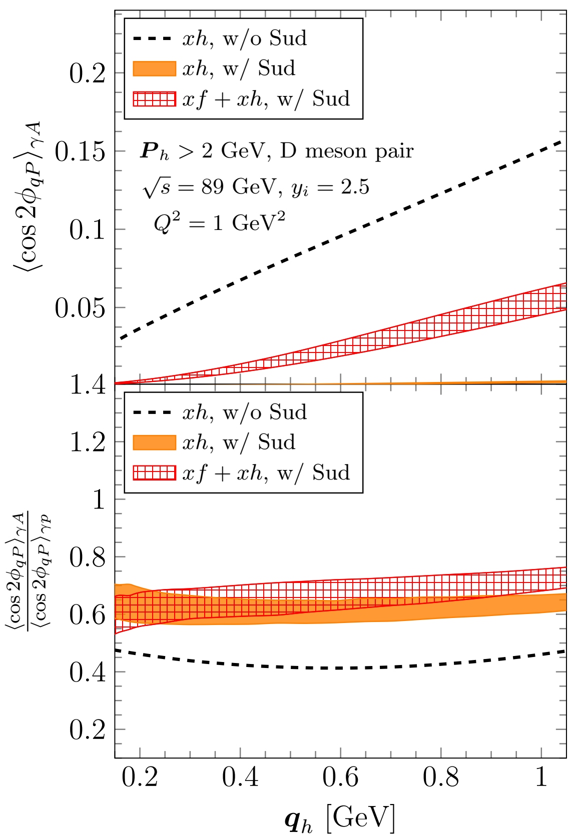


CMS collaboration (2023)

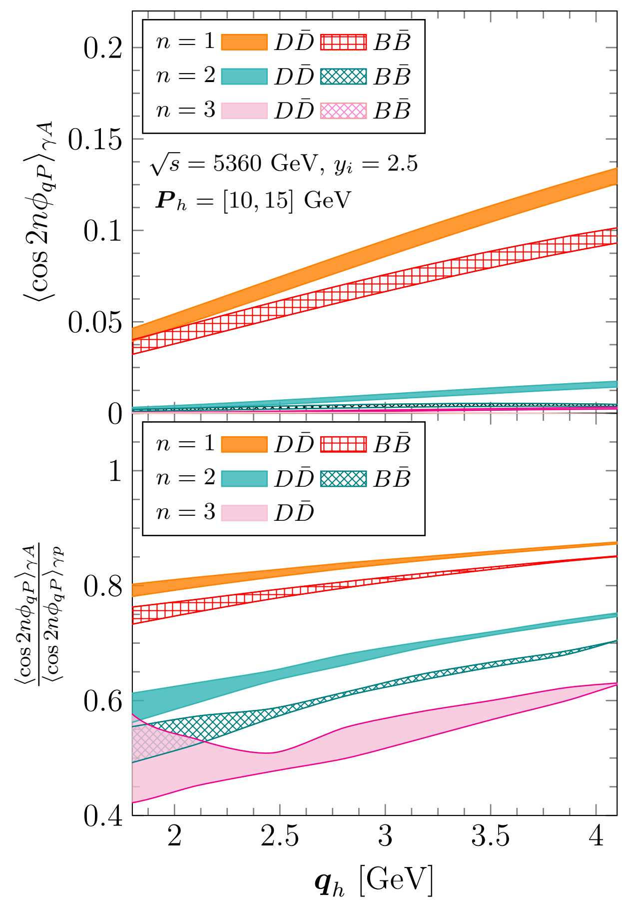
we advocate doing the same with inclusive UPCs

Asymmetry with heavy $Q\bar{Q}$ pair

EIC γ+A & γ+p



UPC γ+A & γ+p



higher harmonics are even more sensitive to non-linear effects

Conclusions

- steady progress is made in order to understand non-flow effects, in particular in situation where it can be done from first principles, this is the case at small-x/forward rapidities
- the centrality dependence of non-flow effects, due to saturation, must be accounted for when extracting the flow components
- soft gluon emission can mask saturation effects
- the simultaneous resummation of leading small-x and CSS logs was recently achieved
- the description of non-flow contributions in two-particle correlations can be further constrained, recent development focus on using heavy-quarks