High energy scattering in QCD and gluon saturation

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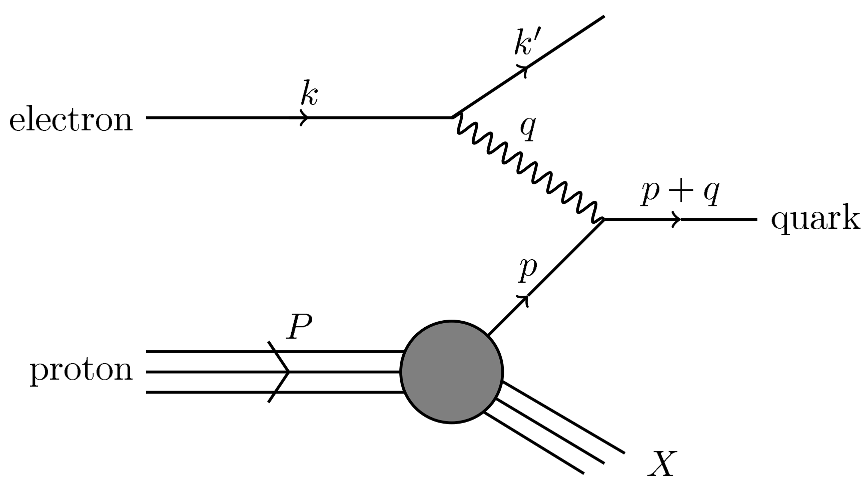
High energy scattering in QCD

"hard scattering"
- large momentum exchange
- weakly coupled system
- perturbative

"soft scattering"
- small momentum exchange
- strongly coupled system
- non-perturbative

DIS in QCD:



Three Lorentz invariant quantities:

(i) $q^2 = -Q^2$ (virtuality of the incoming photon)

(ii) $x = \dfrac{Q^2}{2P\cdot Q}$ (longitudinal momentum fraction carried by the parton)

(iii) $s \simeq 2P\cdot Q$ (energy of the colliding $\gamma - p$ system)

Increasing the energy ($s = Q^2/x$) of the system

Bjorken limit: fixed $x, Q^2 \to \infty$
- density of partons decreases
- system becomes more dilute
- evolution wrt Q^2 is given by the DGLAP

Regge-Gribov limit: fixed $Q^2, x \to 0$
- density of partons increases
- system becomes dense
- causes **saturation**

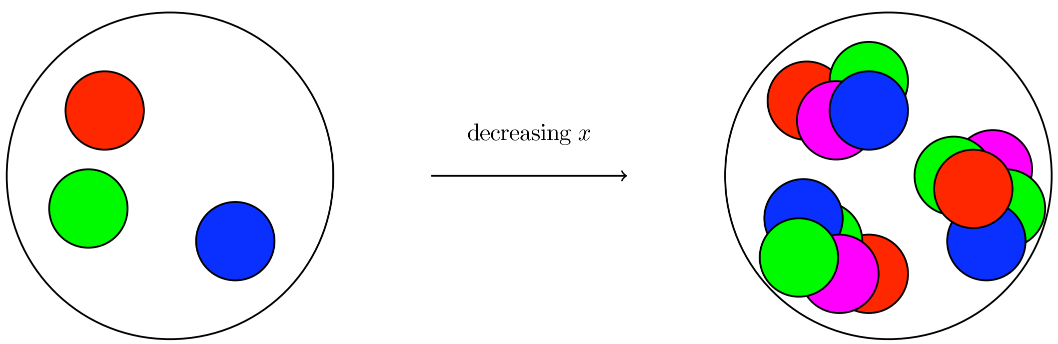
Regge-Gribov limit and gluon saturation

In the infinite momentum frame:

- transverse size of the photon $\sim 1/Q$ (very small probe)
- can scatter off a quark with size of $\sim 1/Q$

$\Rightarrow$ **Q is the transverse resolution scale**

decreasing x at fixed Q^2 $\Rightarrow$ evolution wrt rapidity $Y = \ln(1/x)$



- # of gluons increase due to splitting
- transverse scale doesn't change (fixed Q^2)
- mother and daughter partons have the same size

$\Downarrow$

density of partons increases and causes saturation

High energy scattering in QCD:

- Regge-Gribov limit: $x \to 0$ (*gluon saturation*)
  - Q_s : saturation scale $\equiv \alpha_s \times$ (gluon density per unit area)
  - measure of the strength of gluon interactions at high density
  - $Q_s \gg \Lambda_{\mathrm{QCD}} \Rightarrow$ weak coupling methods can still be applied!

in the saturation regime, scattering prescription:

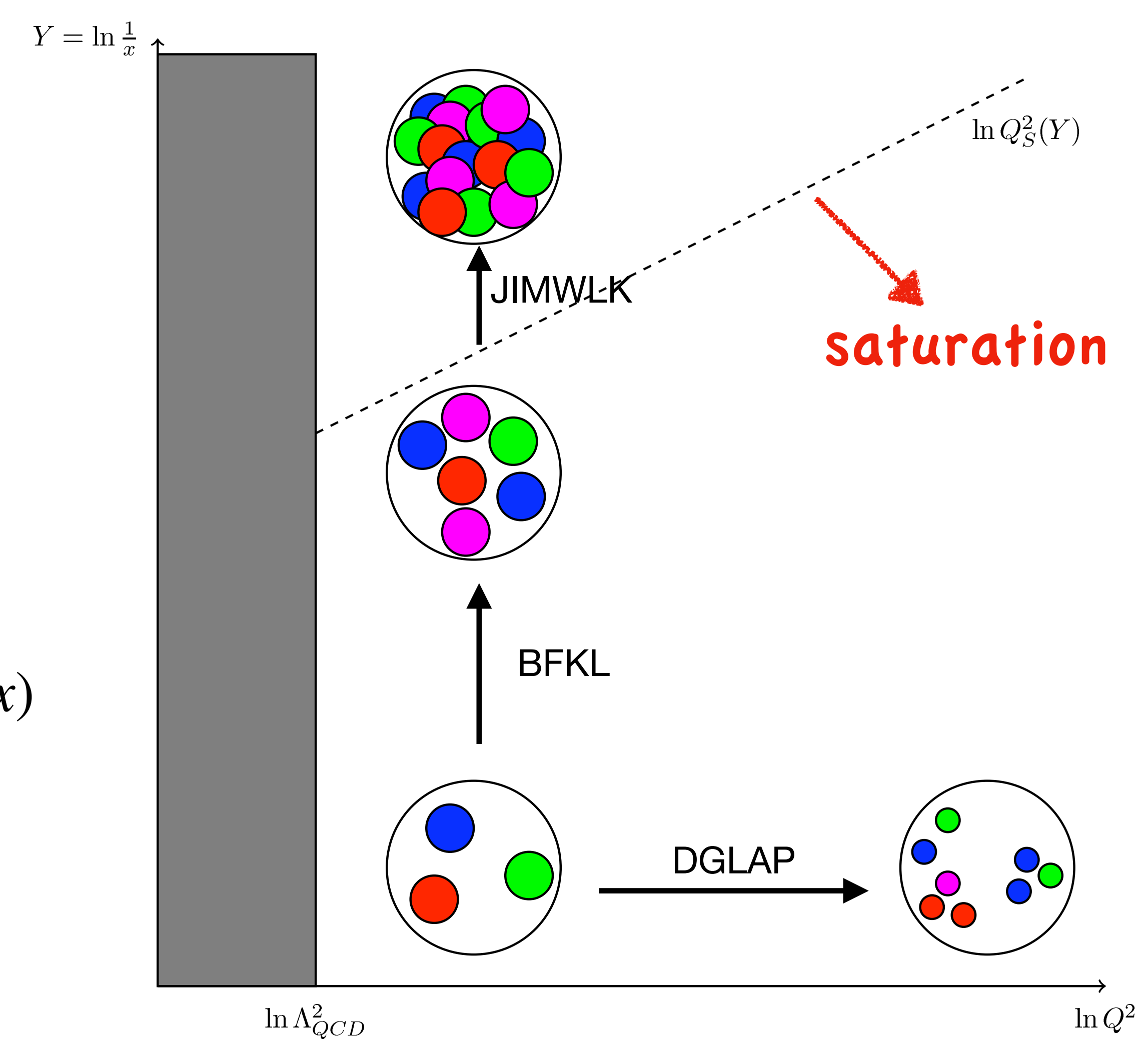
Color Glass Condensate (CGC)

"effective degrees of freedom" wrt a cut-off λ^+

- fast partons: $k^+ > \lambda^+$: described by color sources $J^\mu(x)$
- slow partons: $k^+ < \lambda^+$: described by color fields $A^\mu(x)$

interaction between fast and slow partons :

$$\int d^4x J^\mu(x) A_\mu(x)$$



Within the CGC framework: *expectation value of an observable* $\mathcal{O}$ $\Rightarrow$ $\langle \mathcal{O} \rangle \equiv \int [D\rho]\, W[\rho]\, \mathcal{O}[\rho]$

distribution function for the color sources ρ^a

Rapidity, $Y = \ln(1/x)$, *evolution of the distribution function is governed by JIMWLK equation.*

Eikonal interaction between the projectile and the target:

each parton picks up a Wilson line during the interaction with the target $\longmapsto$ $U_{\mathcal{R}} = \mathcal{P}_+ \exp\left[ig \int dx^+ T^a_{\mathcal{R}} A^-_a(x^+, x) \right]$

at the level of the background field of the target eikonal approximation amounts to:

- $A^\mu_a(x) \simeq \delta^{\mu -} A^-_a(x)$
- $A^\mu_a(x) \simeq A^\mu_a(x^+, x_\perp)$
- $A^\mu_a(x) \propto \delta(x^+)$

possible applications in the gluon saturation regime:

- *dilute-dilute scattering* : *no* saturation effects / BFKL formalism
  can be applied to: $\gamma^* - \gamma^*$, DIS on p, pp at moderate energies
- *dilute-dense scattering* : saturated target / CGC formalism
  can be applied to: DIS on A, **pA collisions**, forward pp
- *dense-dense scattering*: saturated projectile and target / nonlinear dynamics of Yang-Mills fields
  can be applied to: pp at very high energies, heavy ion collisions

saturation sensitive observables in pA collisions :

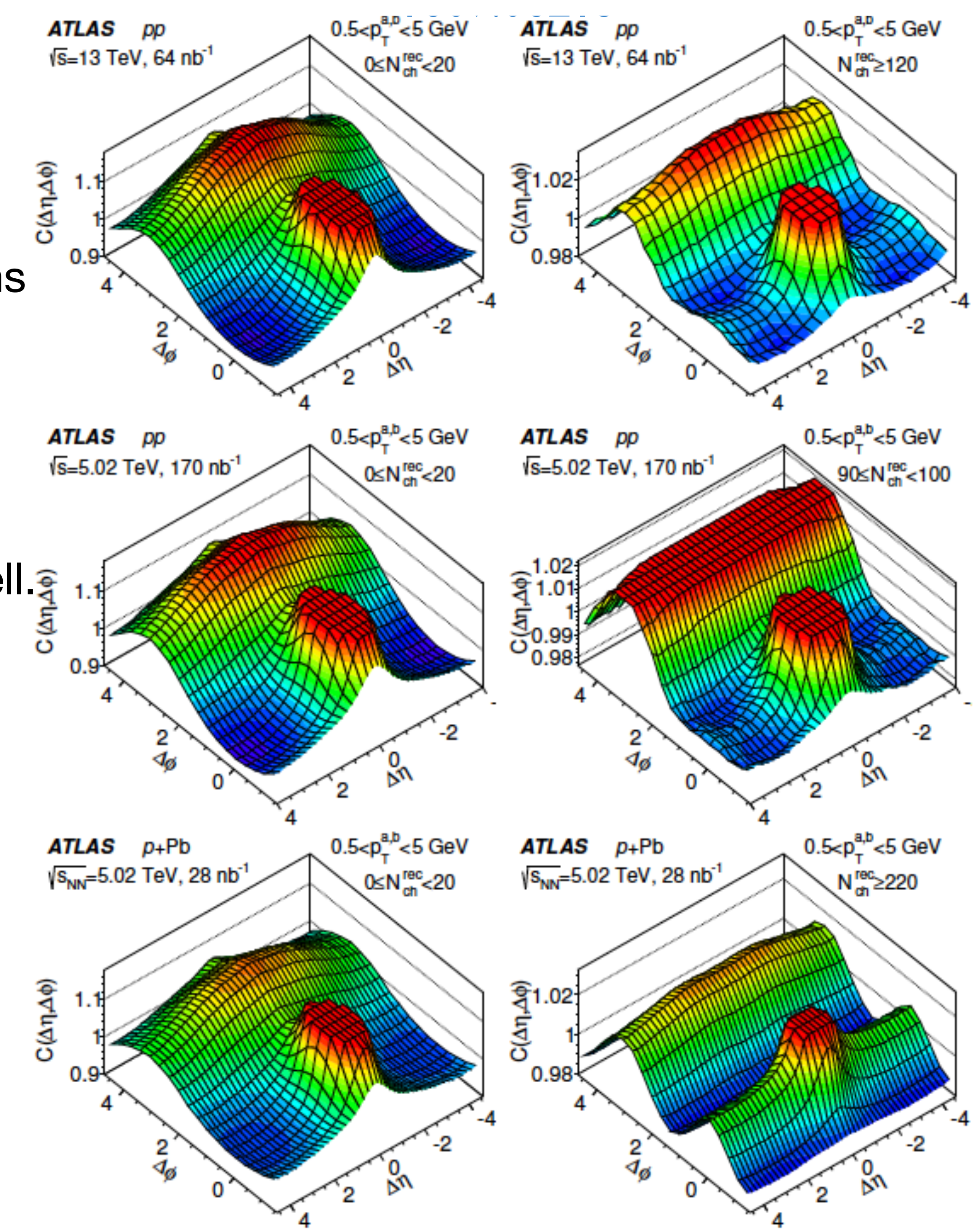
- forward particle/jet production
- two particle correlations

Particle correlations and the Ridge

The ridge structure :

- *correlations between particles over large intervals of rapidity peaking at zero and π azimuthal angle.*
- *observed first at RHIC in Au-Au collisions.*
- *observed at LHC for high multiplicity pp and pA collisions.*

[ATLAS Collaboration - arXiv:1609.06213]



Ridge in HICs ⟷ collective flow due to strong final state interactions

- good description of the data in the framework of relativistic viscous hydrodynamics

Ridge in small systems :

- similar reasoning looks tenuous but hydro describes the data very well.

Can it be initial state effect ?

idea: *final state particles carry the imprint of the partonic correlations that exit in the state*.

✱ several mechanisms have been suggested to explain the Ridge correlations in the CGC framework.

✱ *double inclusive gluon production cross section:*

$$\frac{d\sigma}{d^3k_1 d^3k_2} \propto \int_{q_1 q_2} \left[I_0 + \frac{1}{N_c^2 - 1} I_1 + \frac{1}{(N_c^2-1)^2} I_2 \right] + \left(k_2 \to -k_2 \right)$$

symmetry under $\left(k_2 \to -k_2\right)$: *"accidental symmetry of the CGC"*

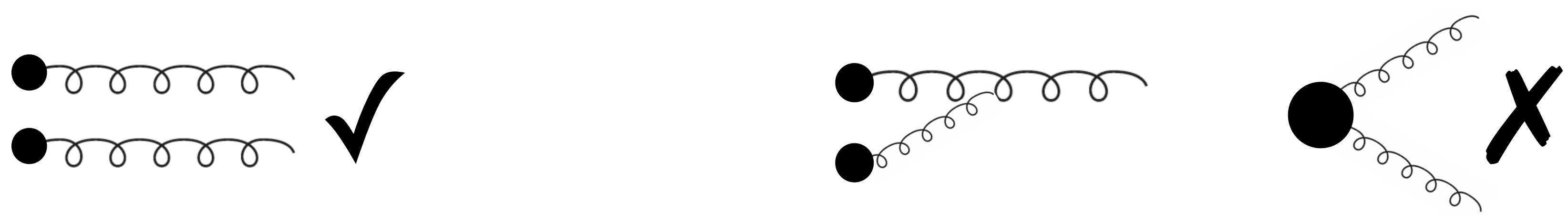
Tools to study the ridge correlations: *Flow coefficients* $\mapsto$ $v_n(p_T) = \dfrac{V_{n\Delta}(p_T, p_T^{ref})}{\sqrt{V_{n\Delta}(p_T^{ref}, p_T^{ref})}}$ $V_{n\Delta}(k_1, k_2) = \dfrac{\int_0^\pi N(k_1, k_2, \Delta\phi)\,\cos(n\Delta\phi)\,d\Delta\phi}{\int_0^\pi N(k_1, k_2, \Delta\phi)\,d\Delta\phi}$

Challenge: "accidental symmetry in CGC" $\Rightarrow$ **vanishing odd flow coefficients!**

Breaking the accidental symmetry :

- density corrections to the projectile wave function

[Kovner, Lublinsky, Skokov - arXiv:1612.07790] / [Kovchegov, Skokov - arXiv:1802.08166]



$$\frac{dN^{\text{even, odd}}(\mathbf{k}_\perp)}{d^2k dy} = \frac{1}{2}\left(\frac{dN(\mathbf{k}_\perp)}{d^2k dy}\Big[\rho_p, \rho_t\Big] \pm \frac{dN(-\mathbf{k}_\perp)}{d^2k dy}\Big[\rho_p, \rho_t\Big]\right)$$ $\Rightarrow$ non-vanishing odd harmonics.

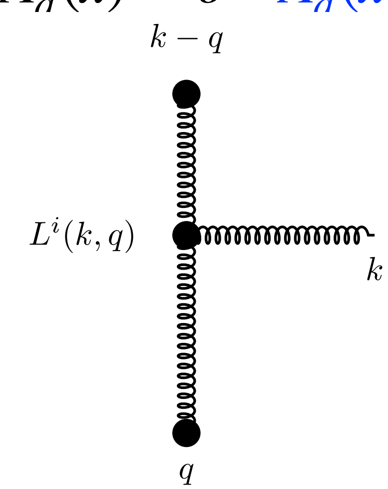
- subeikonal corrections due to finite longitudinal width of the target

[Agostini, T.A., Armesto - arXiv:1902.044830] / [Agostini, T.A., Armesto - arXiv:1907.03668]

relax the eikonal approximation by considering a finite width target: $A_a^\mu(x) = \delta^{\mu-}\delta(x^+)A_a^\mu(x_T) \rightarrow A_a^\mu(x) = \delta^{\mu-}A_a^\mu(x^+, x_T)$

In the weak field limit (pp collisions):

Production amplitude $\mathscr{M} \propto L^i_{\text{NonEik}}(\underline{k}, q; x^+) = \left[\dfrac{(k_T - q_T)^i}{(k_T - q_T)^2} - \dfrac{k_T^i}{k_T^2}\right] e^{ik^- x^+}$



$O(1)$ terms: eikonal Lipatov vertex

[Agostini, T.A., Armesto - arXiv:1902.044830] / [Agostini, T.A., Armesto - arXiv:1907.03668]

Double inclusive gluon production cross section with non-eikonal Lipatov vertex:

$$\underline{k} \equiv (k^+, k_T) \qquad k^- = \frac{k_T^2}{2k^+}$$

$$\frac{d\sigma}{d^3k_1 d^3k_2}\bigg|_{\text{NonEik}} \propto \int_{q_1 q_2} \left\{ f(k_1, q_1; k_2, q_2) + \mathcal{G}_2^{\text{NonEik}}(k_1^-, k_2^-; L^+) g(k_1, q_1; k_2, q_2) \right] + (\underline{k}_2 \to -\underline{k}_2) \right\}$$

all non-eikonal effects are encoded in $\mathcal{G}_2^{\text{NonEik}}(k_1^-, k_2^-; L^+) = \left\{ \frac{2}{(k_1^- - k_2^-)L^+} \sin\left[\frac{(k_1^- - k_2^-)}{2} L^+ \right] \right\}^2$

$\mathcal{G}_2^{\text{NonEik}}(k_1^-, k_2^-; L^+)$ is not symmetric under $(\underline{k}_2 \to -\underline{k}_2)$

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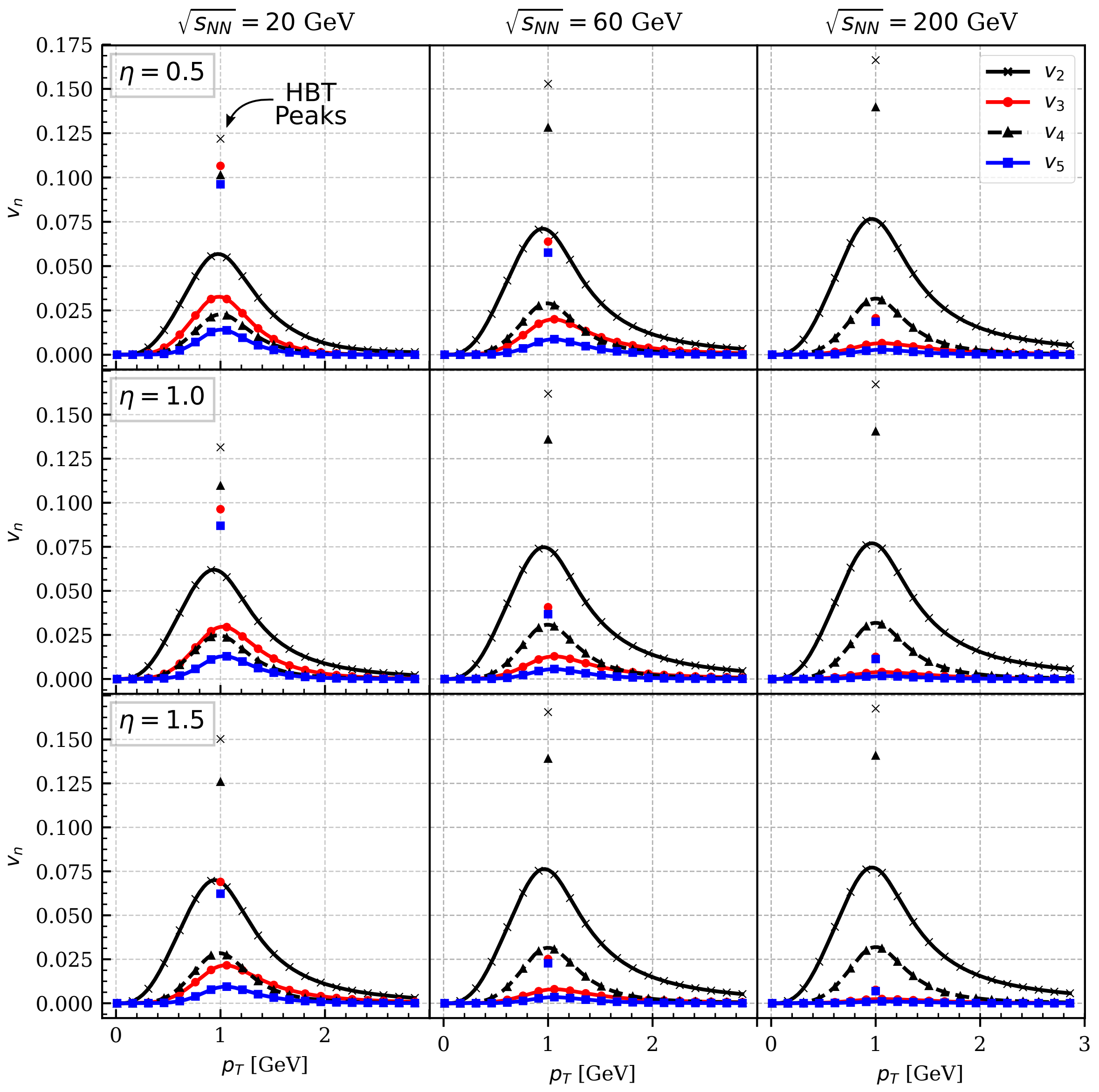
Non-eikonal corrections are breaking the accidental symmetry!

Non-zero odd flow coefficients with non-eikonal corrections:



Disclaimer: Non-eikonal effects alone can not describe the odd-harmonics HOWEVER there is a contribution originating from these effects for certain kinematic region.

✱Due to the accidental symmetry of CGC, odd flow coefficients vanish.

✱The accidental symmetry can be broken in different ways.

✱Non-eikonal corrections break the symmetry ⟶ non-zero odd flow coefficients.

What's next?

✱ Single and double inclusive gluon production with non-eikonal corrections.

Agostini, T.A., Armesto - under preparation (January 2020)

✱ Breaking the accidental symmetry with quantum color flow effects.

T.A., Marquet - under preparation (January 2020)