IGFAE
Instituto Galego de Física de Altas Enerxías

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UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

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Initial stages in heavy-ion collisions - from small to large systems

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Unión Europea
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"

EXCELENCIA MARÍA DE MAEZTU

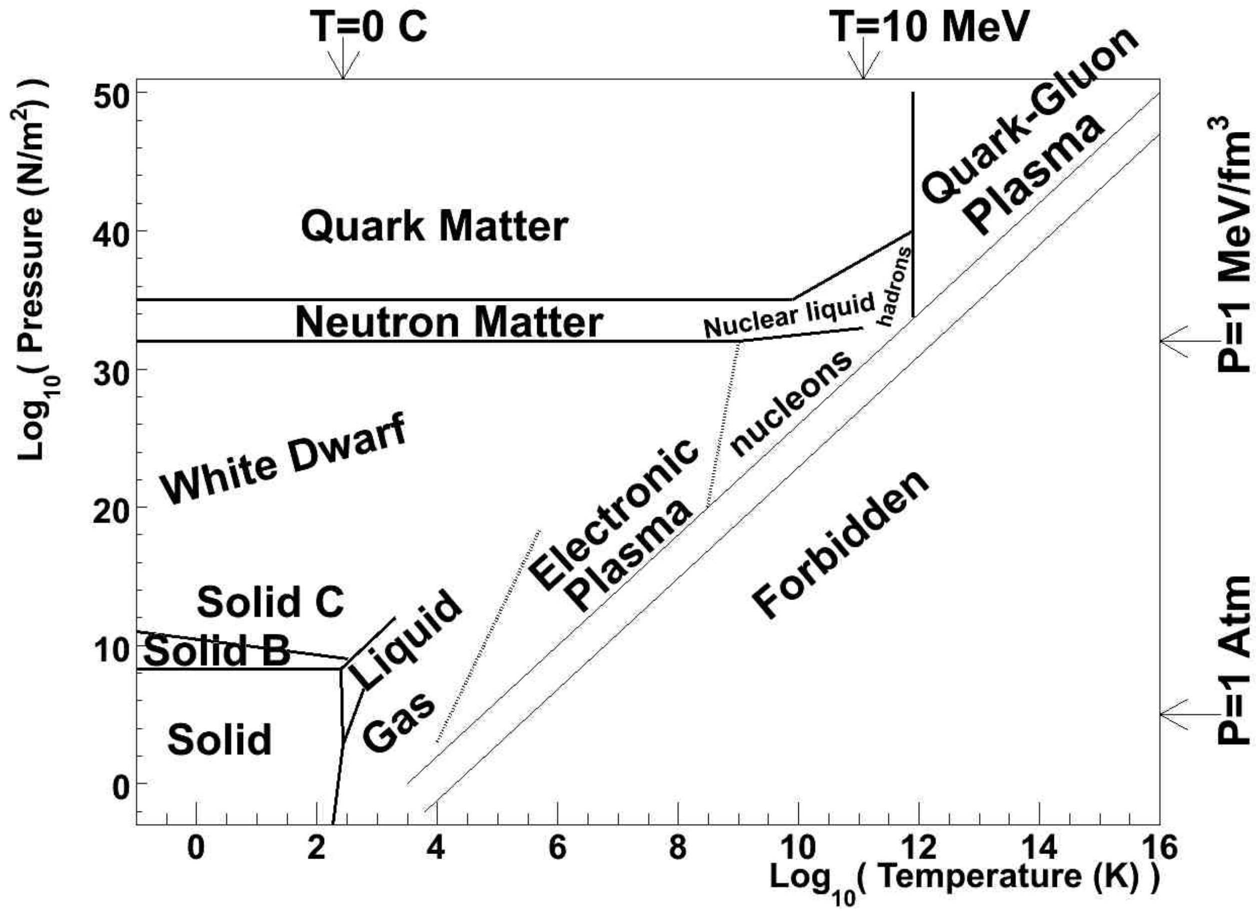
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMIA Y COMPETITIVIDAD

XUNTA DE GALICIA

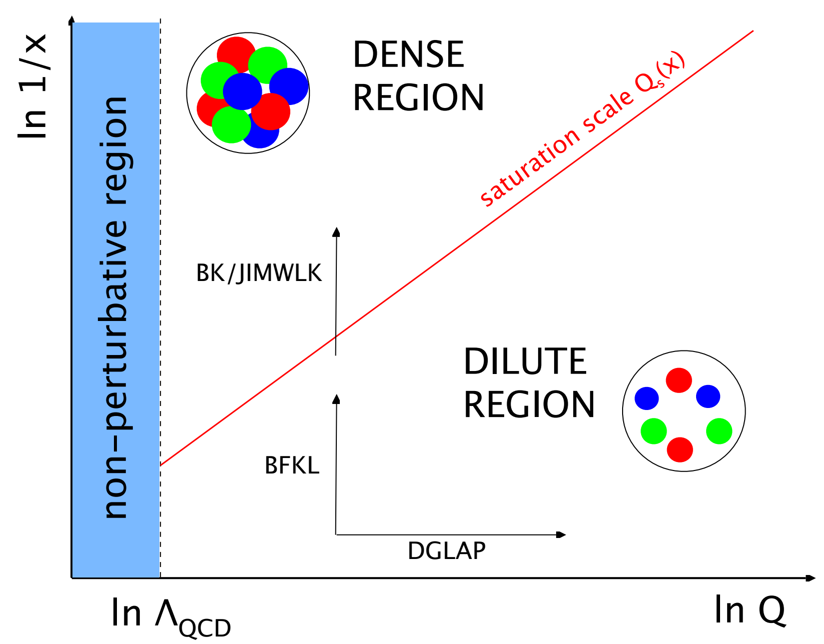
Contents:

Heavy-ion collisions:

- Behaviour of matter at high temperature and baryon number: confinement and chiral symmetry breaking.



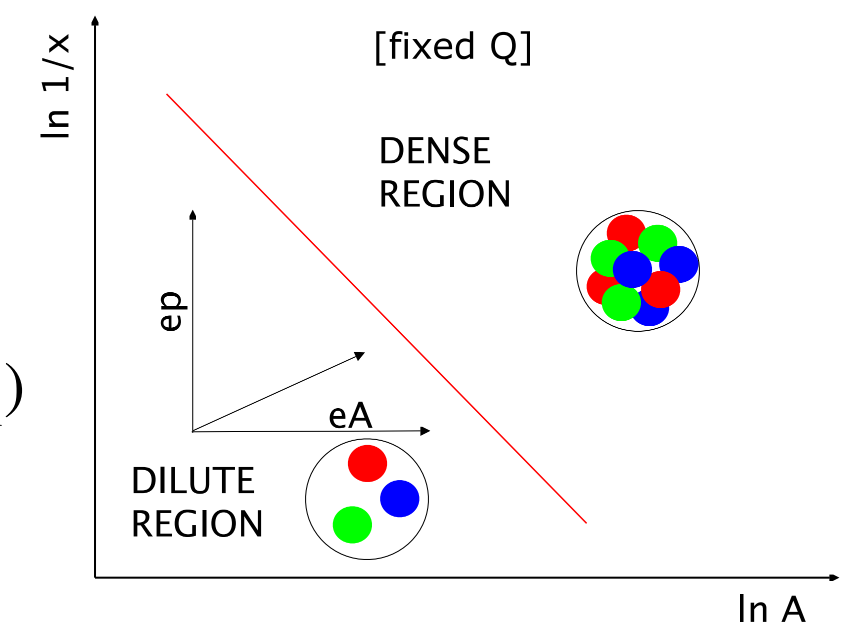
- Behaviour of QCD at high energies/A ≡ high partonic densities.



$$\frac{xG_A(x,Q^2_{s,A})}{\pi R_A^2 Q^2_{s,A}} \sim 1$$

$$\Longrightarrow Q^2_{s,A} \propto A^{1/3} xG_p(x,Q^2_{s,A})$$

$$\propto A^{1/3}\frac{1}{x^{1/3}}$$



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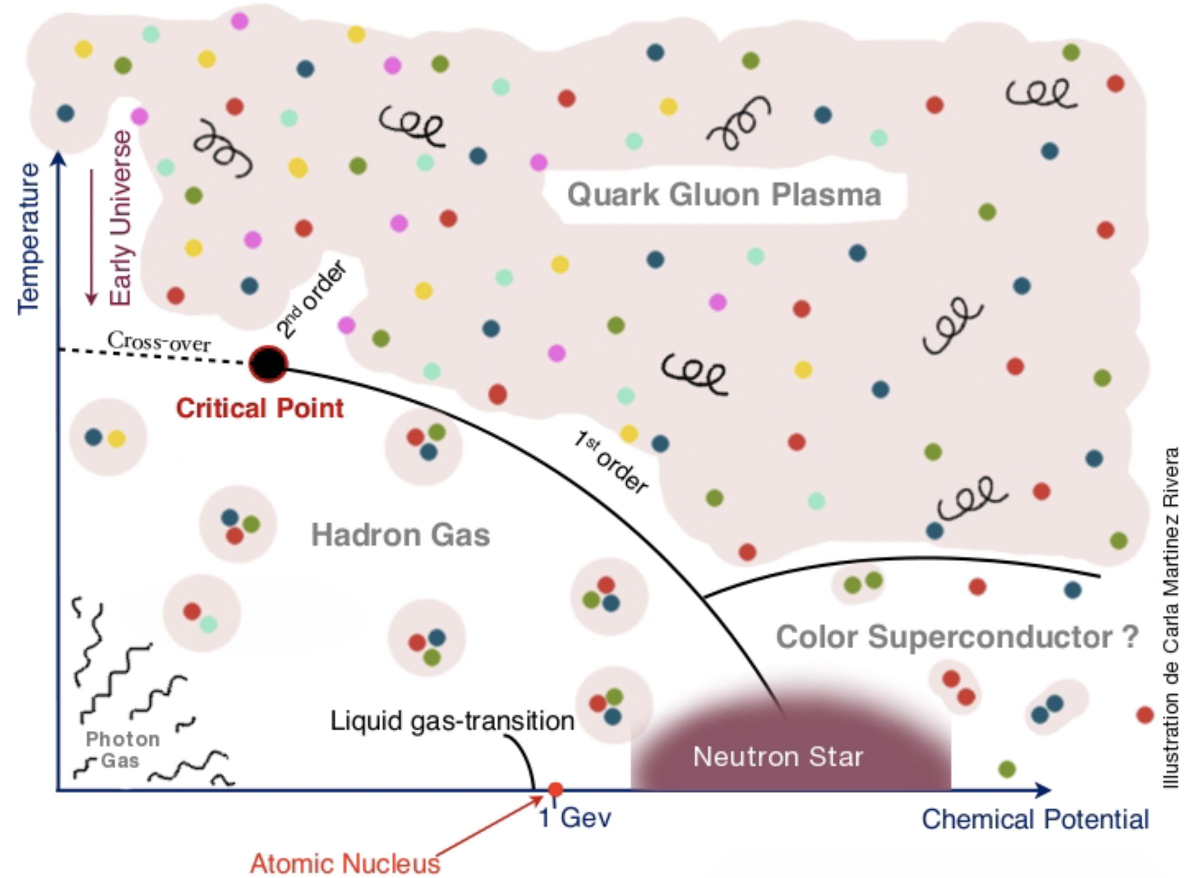

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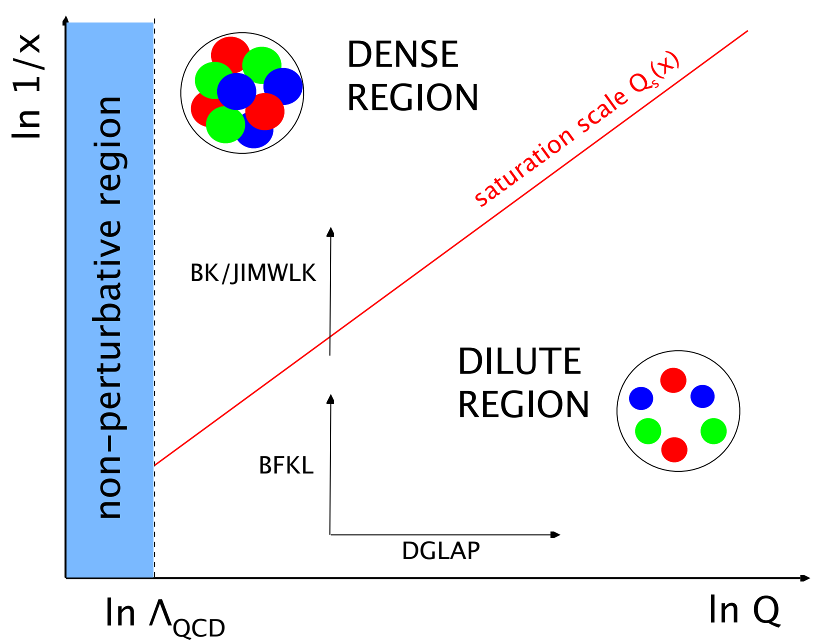

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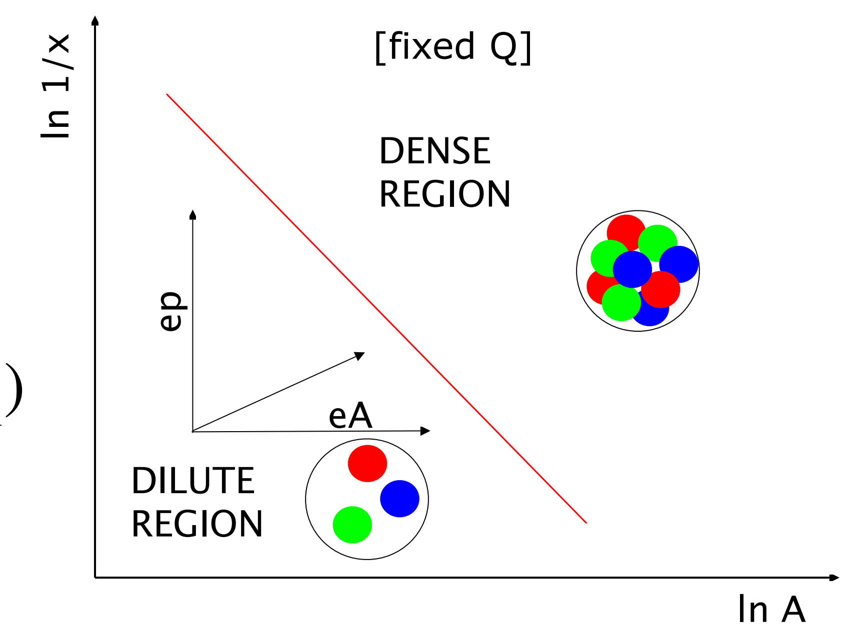


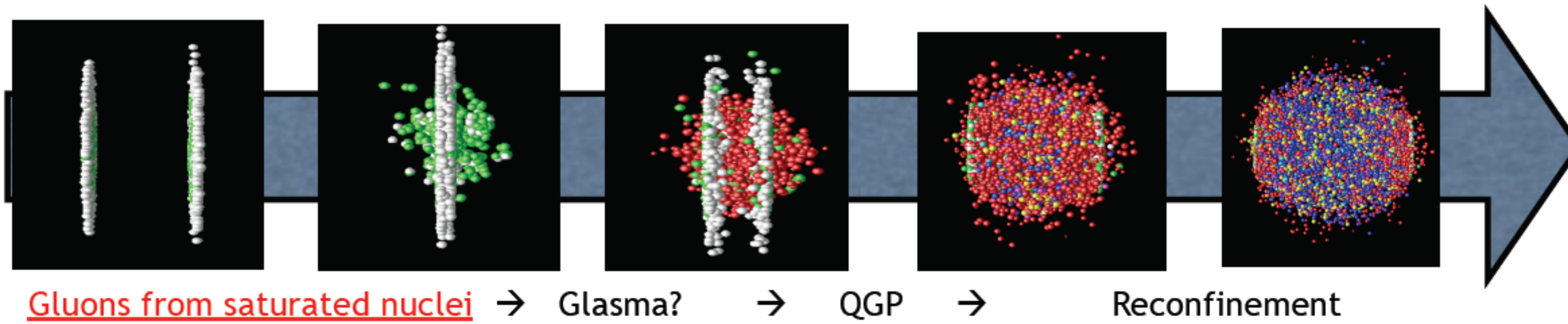
The yet unsolved questions:

• Nucleus ≠ Zp+(A-Z)n.
• Particle production at large scales similar to pp (dilute regime).

• Medium behaves very early like a low viscosity liquid: macroscopic description.

• Medium is very opaque to colour.

[B.Cole]



• Lack of information about small-x partons, correlations and transverse structure.
• We do not understand the dense regime.

• How isotropised the system becomes?
• Why is hydro effective so fast, which dynamics?
• Why does this happen in pp/pA?

• What are the dynamical mechanisms for such opacity? Weak or strong coupling?
• How to extract accurately medium parameters?

The yet unsolved questions:

- Nucleus ≠ Zp+(A-Z)n.
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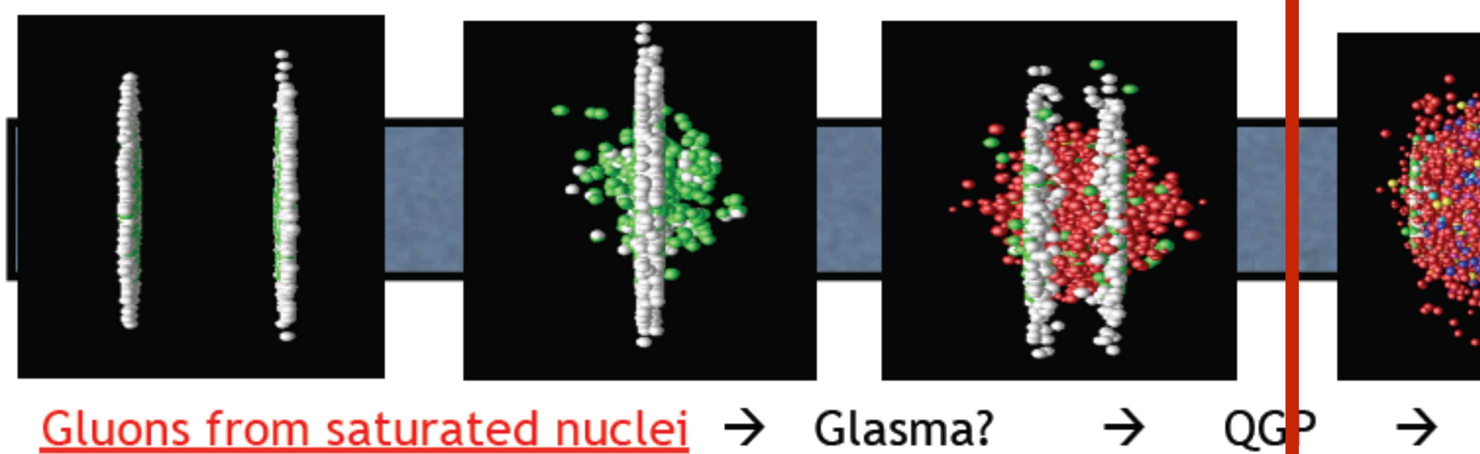
- Medium behaves very early like a low viscosity liquid: macroscopic description.

- I will focus on the physics that, observed in both small (pp, pA) and in large (AA) systems, seems to originate in the initial stages of the collisions.

- I will concentrate on non-hydrodymanical approaches, taking for granted that everybody knows hydro…

[B. Cole]



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parameters?

The context:

- Macroscopic techniques to describe nuclear matter and nuclear collisions can be traced back to the first studies of nuclear structure.
- 60's - Glauber model, Regge-Gribov theory: pre-QCD microscopic approaches to hadronic and nuclear collisions, unified approach.
- Right after QCD proposal: Collins-Perry, Cabbibo-Parisi, Bear Mountain proceedings,… deconfined matter could be created in heavy-ion collisions, later called QGP, formed by free partons (gas).
- 2001: azimuthal asymmetries as a signature of collective behaviour describable by relativistic hydrodynamics, later found at RHIC with little viscosity: perfect liquid in heavy-ion collisions, macroscopic description.
- 2008-2009: ridge discovered in AuA collisions at RHIC.
- 2010: ridge discovered in high multiplicity pp collisions at the LHC, later in pPb, hydrodynamic description working.
- Note: that pp could be described like AA was predicted both from the hydro and from the microscopic point of view (~2008).

The context:

• Macroscopic techniques to describe nuclear matter and nuclear collisions can be traced back to the first studies of nuclear structure.

From an old paradigm to a new one?

Old: QGP produced in AA, pp as reference (vacuum), pA to separate (uninteresting) “cold nuclear matter” effects.

New: Smooth transition from pp to AA whose implications are still under debate:

➜ QGP is formed in small systems?

➜ Hydro-like collective behaviour, strangeness enhancement,… are general features of high energy hadronic collisions?

later in pPb, hydrodynamic description working.

• Note: that pp could be described like AA was predicted both from the hydro and from the microscopic point of view (~2008).

Contents:

1. Introduction.

2. Experimental findings.

3. Non-hydrodynamical approaches to collectivity.

4. Summary.

Summary:

Collective hadronisation

Collective expansion (hydro-like)

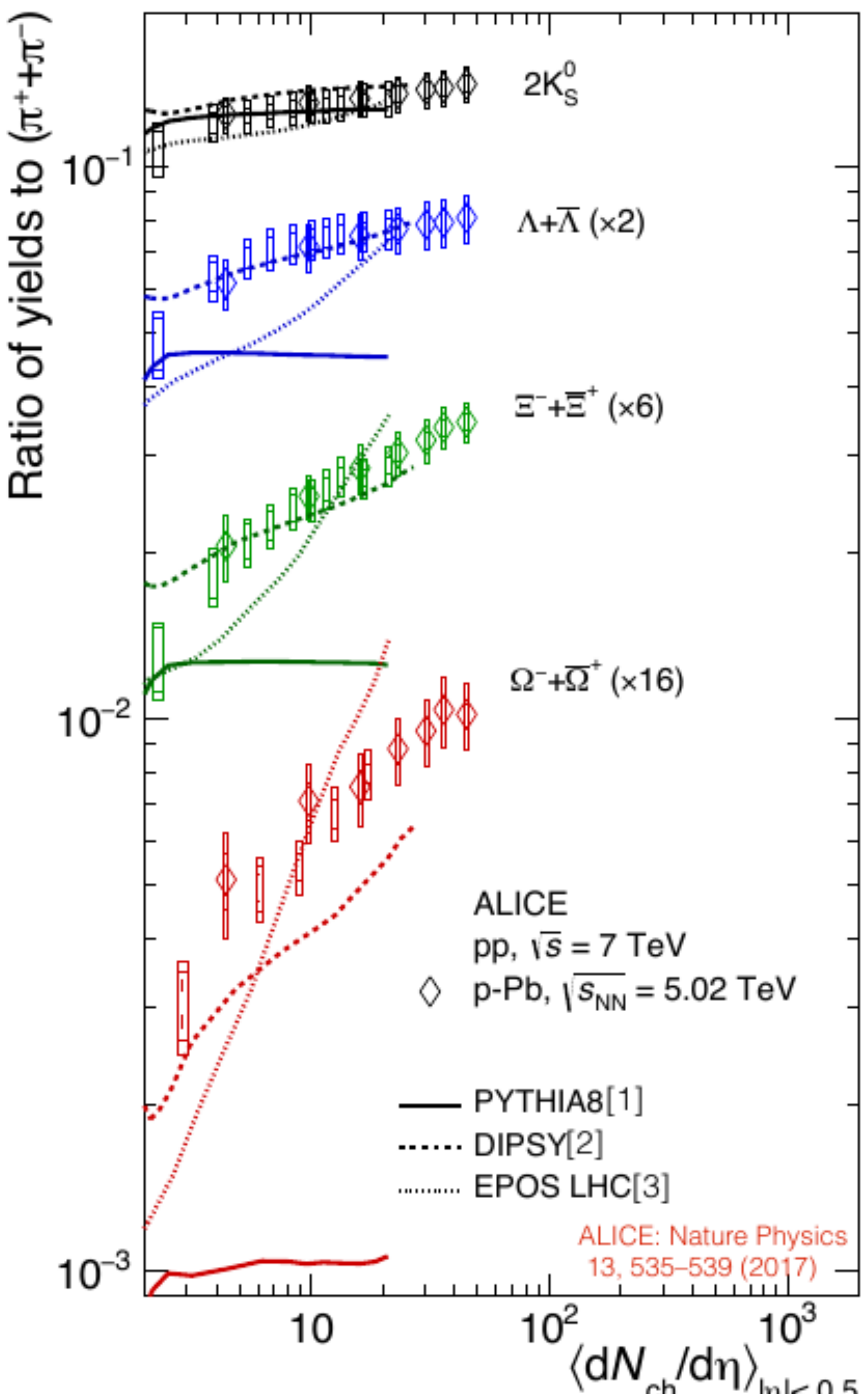
Direct photons

Final state interactions (non-hydro)

Observable or effect	PbPb	pPb (high mult.)	pp (high mult.)	Refs.
Low p_T spectra ("radial flow")	yes	yes	yes	[1–10]
Intermed. p_T ("recombination")	yes	yes	yes	[5, 6, 10–15]
Particle ratios	GC level	GC level except Ω	GC level except Ω	[8, 9, 16, 17]
Statistical model	$\gamma_s^{GC} = 1$, 10–30%	$\gamma_s^{GC} \approx 1$, 20–40%	$\gamma_s^{C} < 1$, 20–40%	[9, 18, 19]
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$	[20–28]
Azimuthal anisotropy (v_n) (from two part. correlations)	$v_1 - v_7$	$v_1 - v_5$	v_2, v_3	[29–31] [32–39, 39–43]
Characteristic mass dependence	$v_2 - v_5$	v_2, v_3	v_2	[39, 42–48]
Directed flow (from spectators)	yes	no	no	[49]
Charge dependent flow (CME, CMW)	yes	yes	not observed	[50–54]
Higher order cumulants (mainly $v_2\{n\}$, $n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ"	[39, 55–64, 64–69]
Weak η dependence	yes	yes	not measured	[41, 65, 67, 70–76]
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured	[40, 77, 78]
Event-by-event v_n distributions	$n = 2 - 4$	not measured	not measured	[79, 80]
Event plane and v_n correlations	yes	yes	yes	[81–84]
Direct photons at low p_T	yes	not measured	yes	[85, 86]
Jet quenching	yes	not observed	not observed	[87–107]
Heavy flavor anisotropy	yes	yes [108]	not measured	[108–118]
Quarkonia	J/$\psi\uparrow$, $\Upsilon\downarrow$	suppressed	not measured	[108, 118–125, 125–138]

HL/HE-LHC workshops, preliminary, to be published

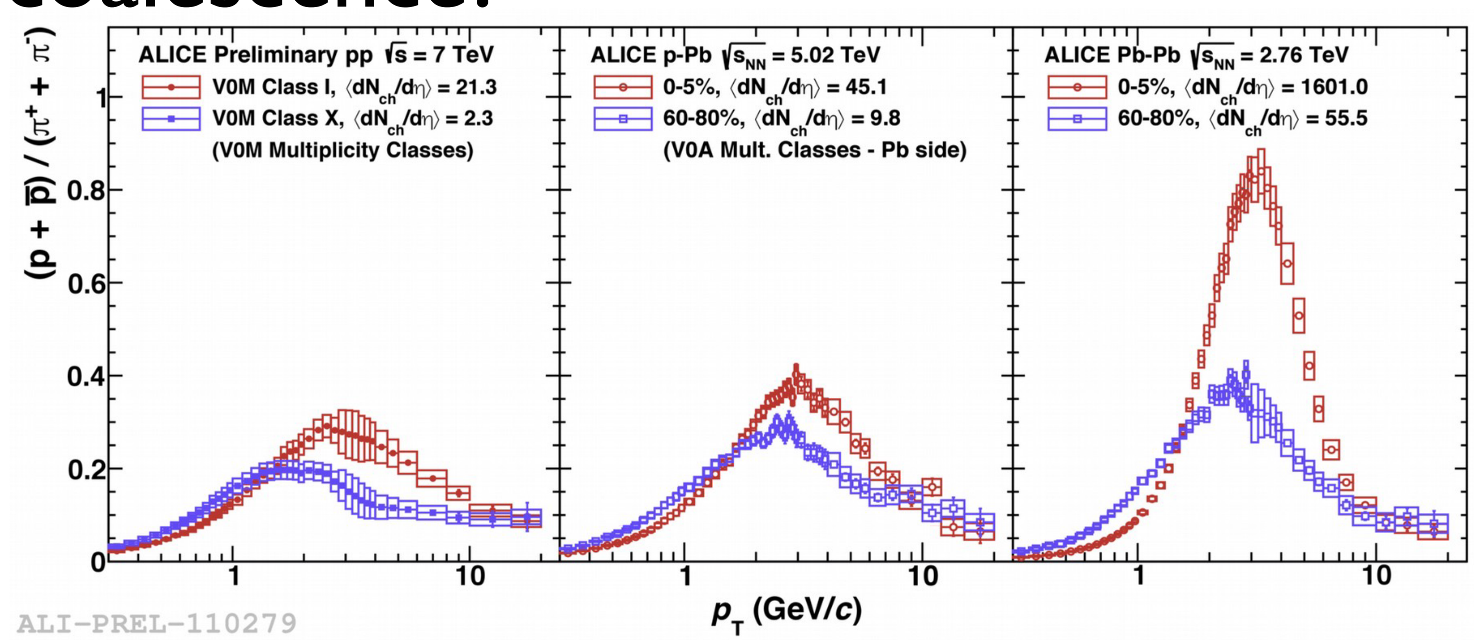
Collective hadronisation:



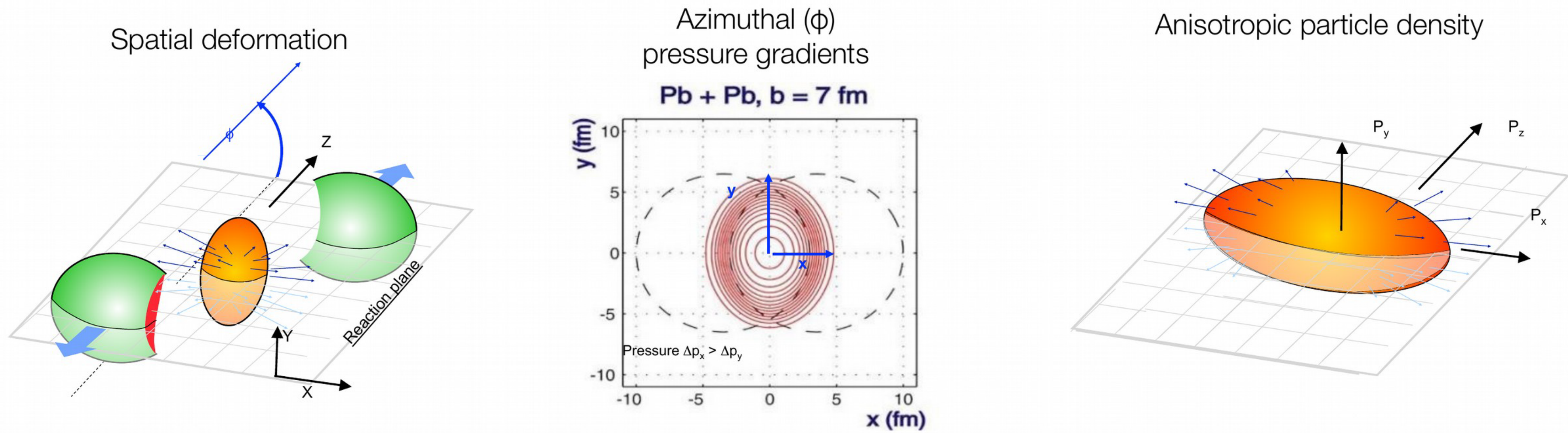
- Smooth increase of strange particles with respect to pions from pp to PbPb, when plotted as a function of multiplicity.
- Baryon/meson enhancement at intermediate p_T, from pp to PbPb.

⇒

Non-perturbative fragmentation: statistical, recombination, coalescence?



Collective expansion:



$$\frac{dN}{d\varphi} \propto 1 + 2\boxed{v_1}\cos[\varphi - \Psi_1] + 2\boxed{v_2}\cos[2(\varphi - \Psi_2)] + 2\boxed{v_3}\cos[3(\varphi - \Psi_3)] + ..$$

- Fourier coefficients now measured via n-particle correlations:

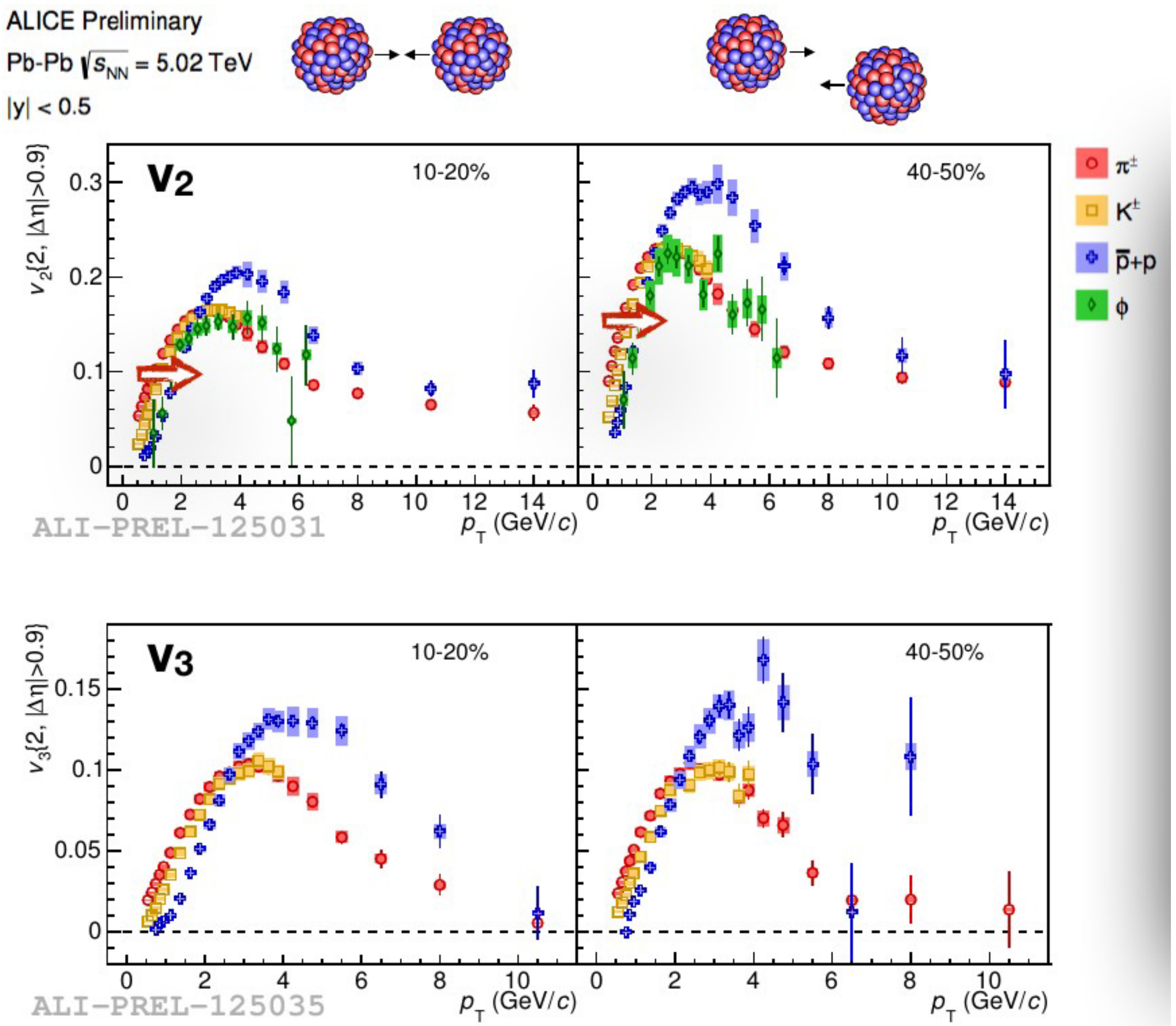
$$\left\langle\!\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \right\rangle\!\right\rangle \equiv \left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \right\rangle - \left\langle e^{in(\phi_1-\phi_3)} \right\rangle \left\langle e^{in(\phi_2-\phi_4)} \right\rangle - \left\langle e^{in(\phi_1-\phi_4)} \right\rangle \left\langle e^{in(\phi_2-\phi_3)} \right\rangle$$

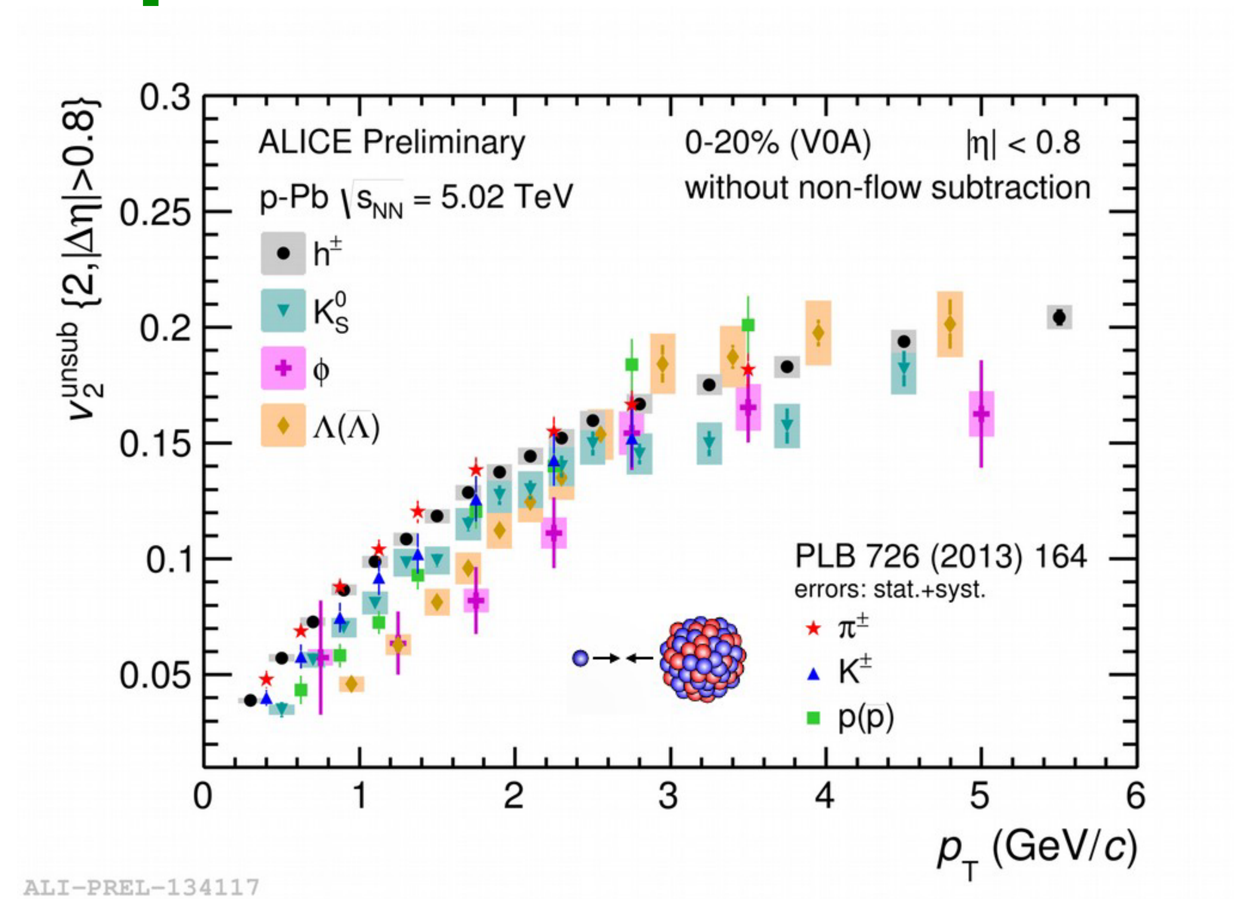
$$c_2\{4\} = \left\langle\!\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \right\rangle\!\right\rangle = -v_n^4 + O\left(\frac{1}{N^3} + \frac{v_{2n}^2}{N^2}\right)$$

$$V_{n\Delta}(p_T^a, p_T^b) \equiv \langle \cos n(\phi^a - \phi^b) \rangle \stackrel{?}{=} v_n(p_T^a) \times v_n(p_T^b)$$

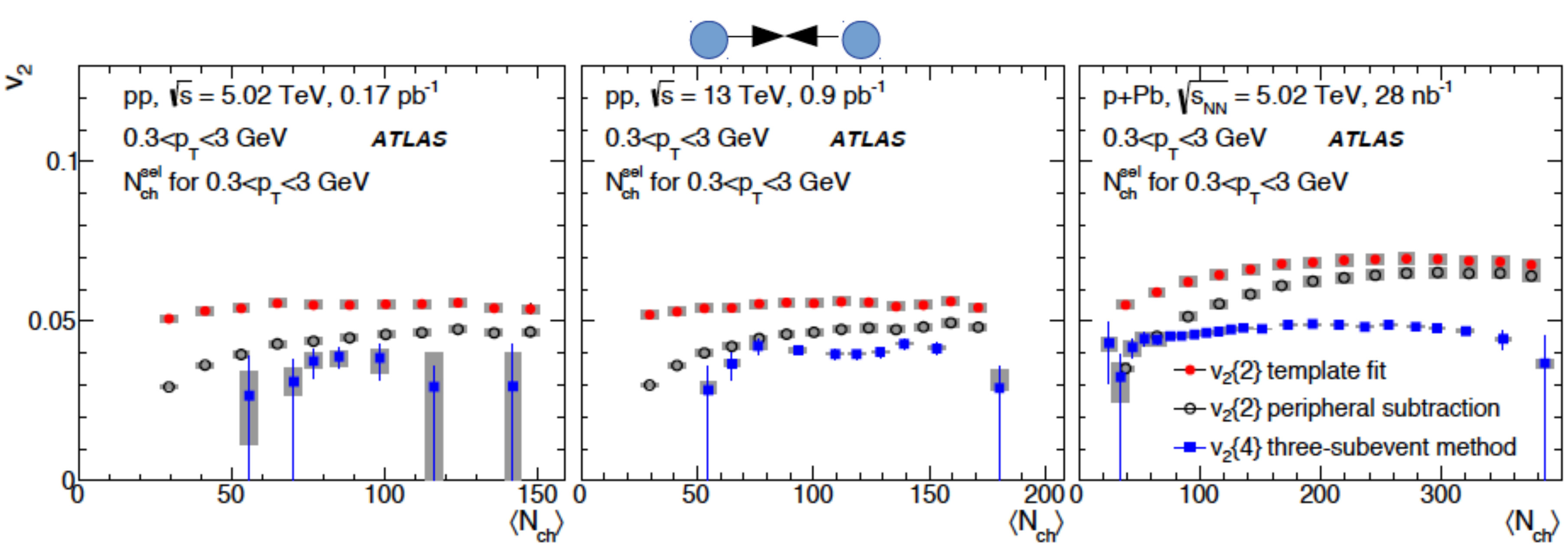
- Factorisation in ideal hydro, broken by ebe fluctuations (damped by viscosity).

Collective expansion:





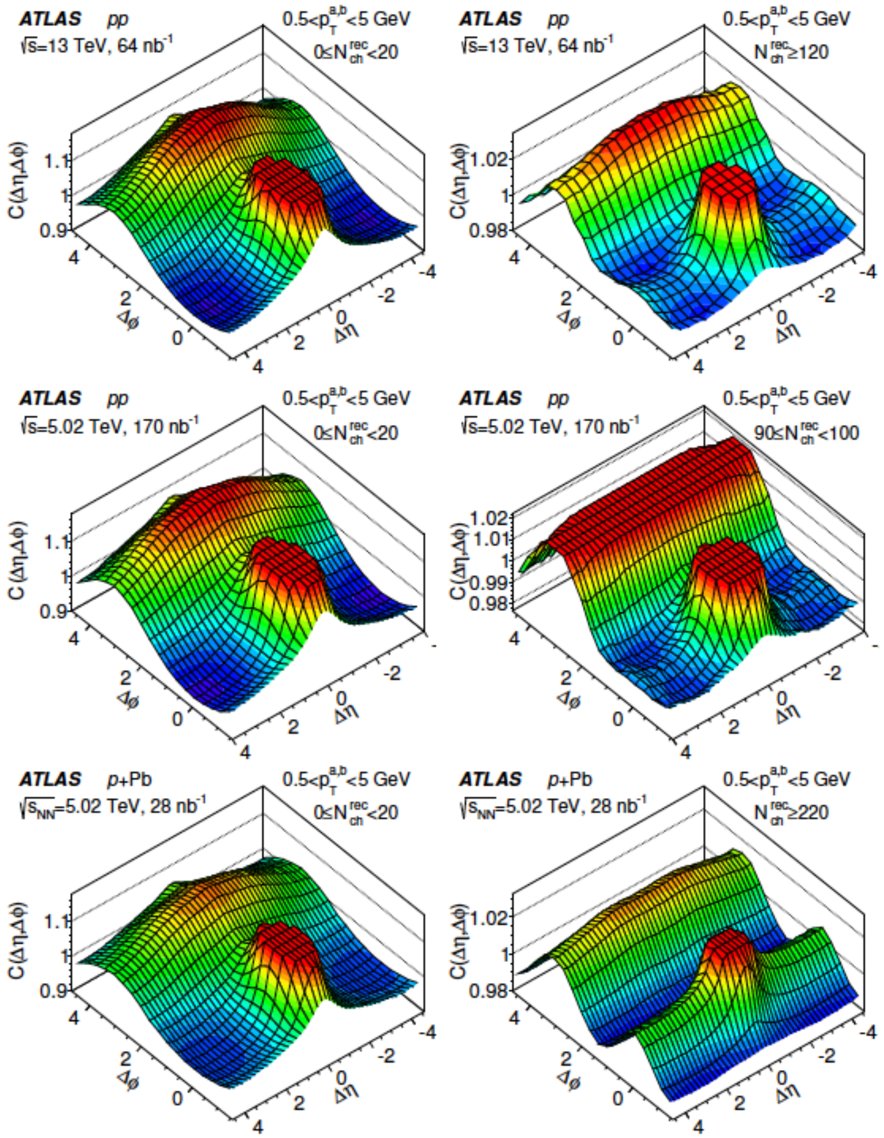
- Mass ordering for Fourier coefficients, characteristic of hydro.

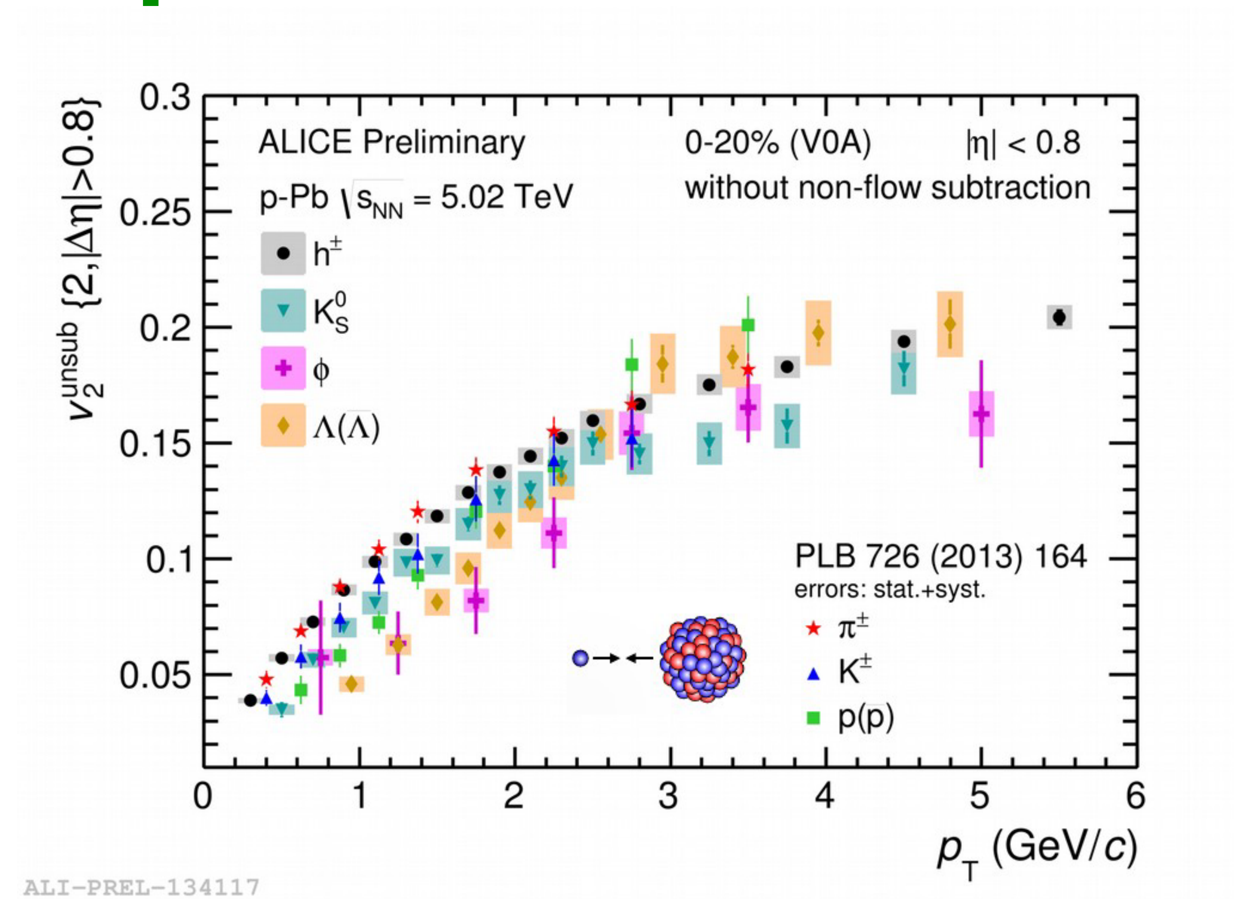


1708.03559

Collective expansion:

1609.06521





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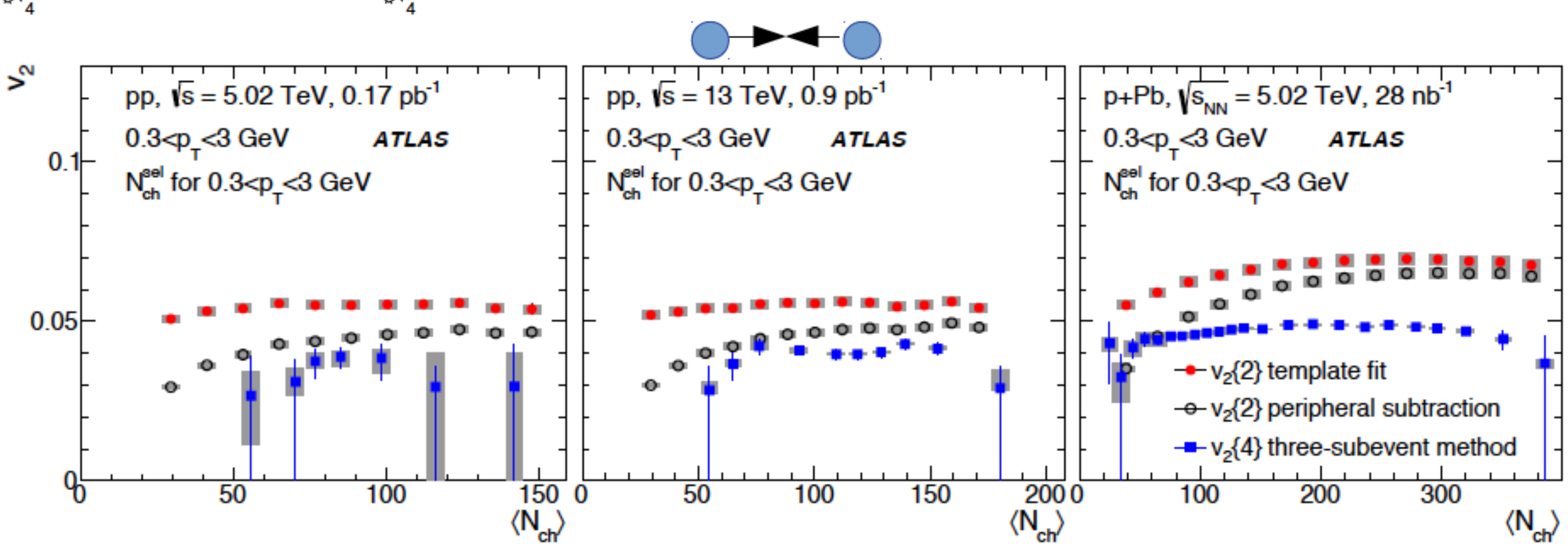

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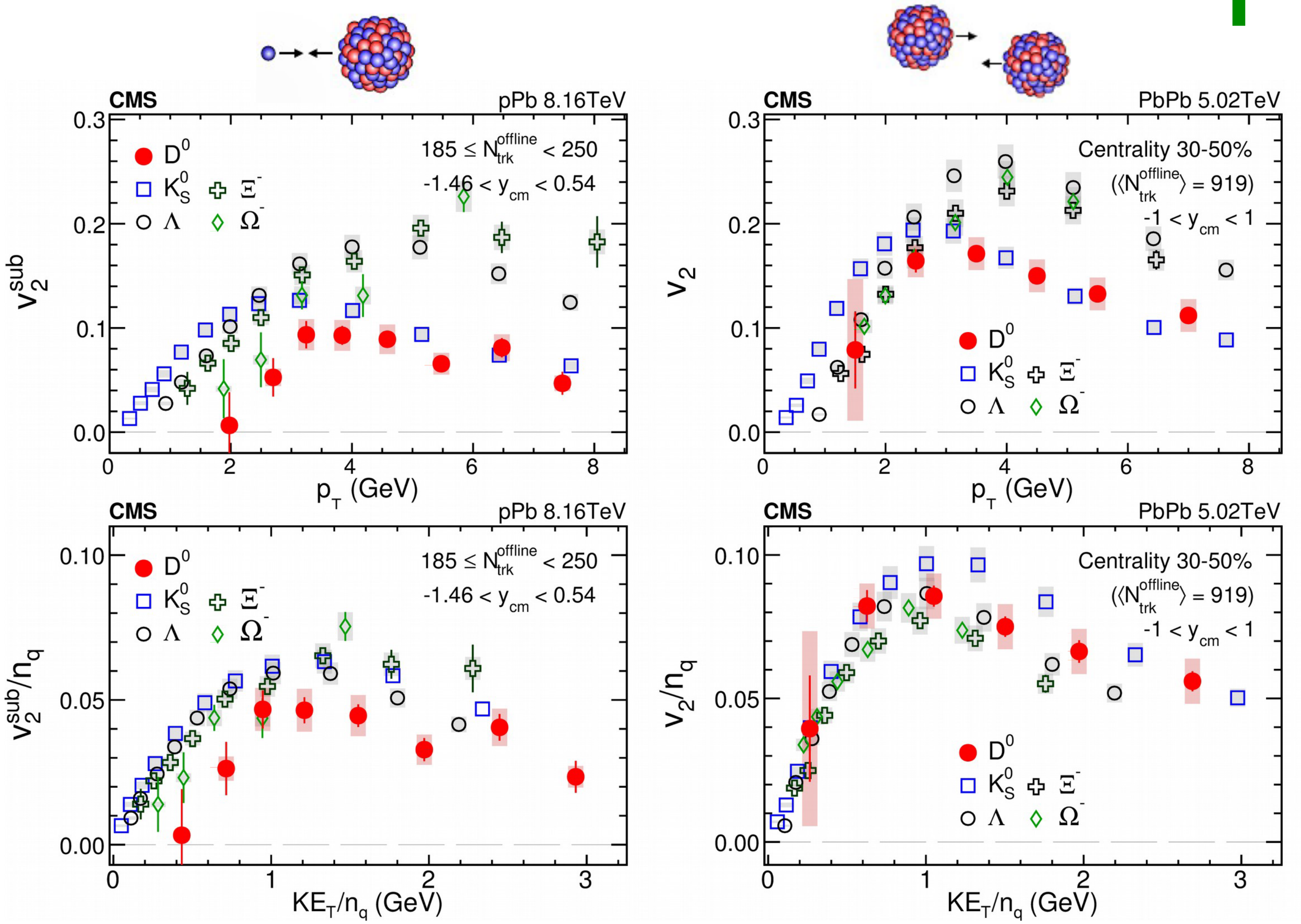
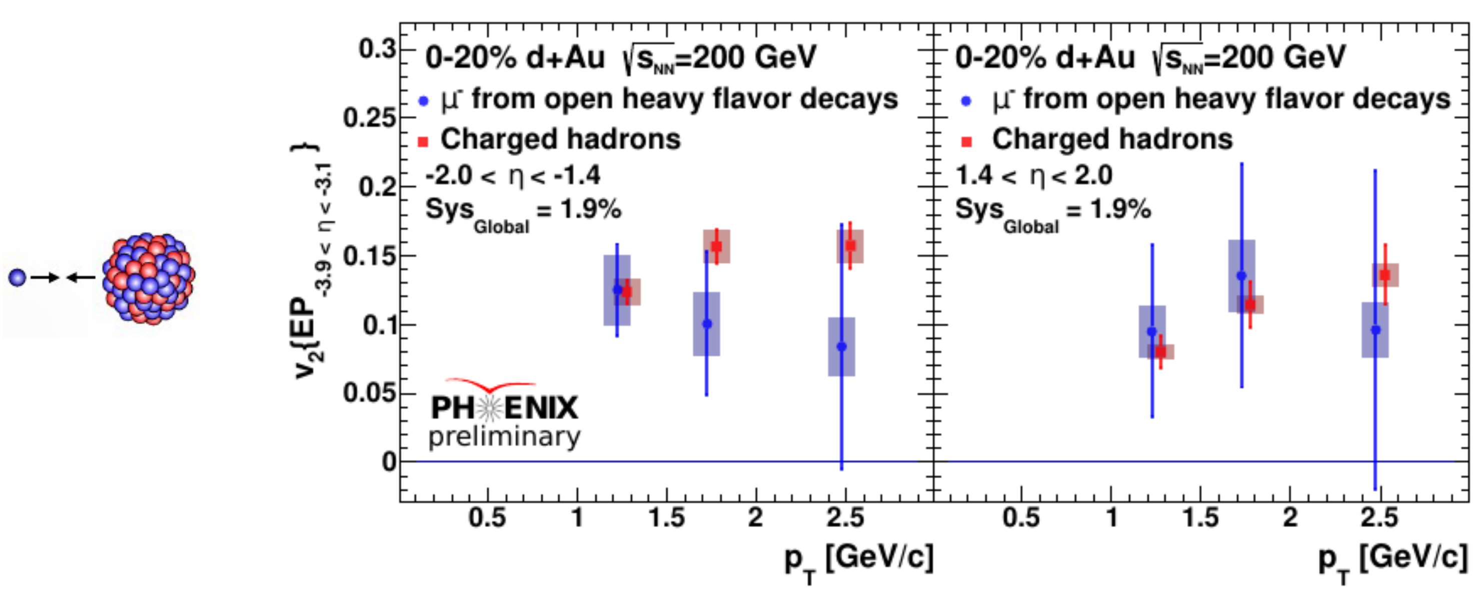
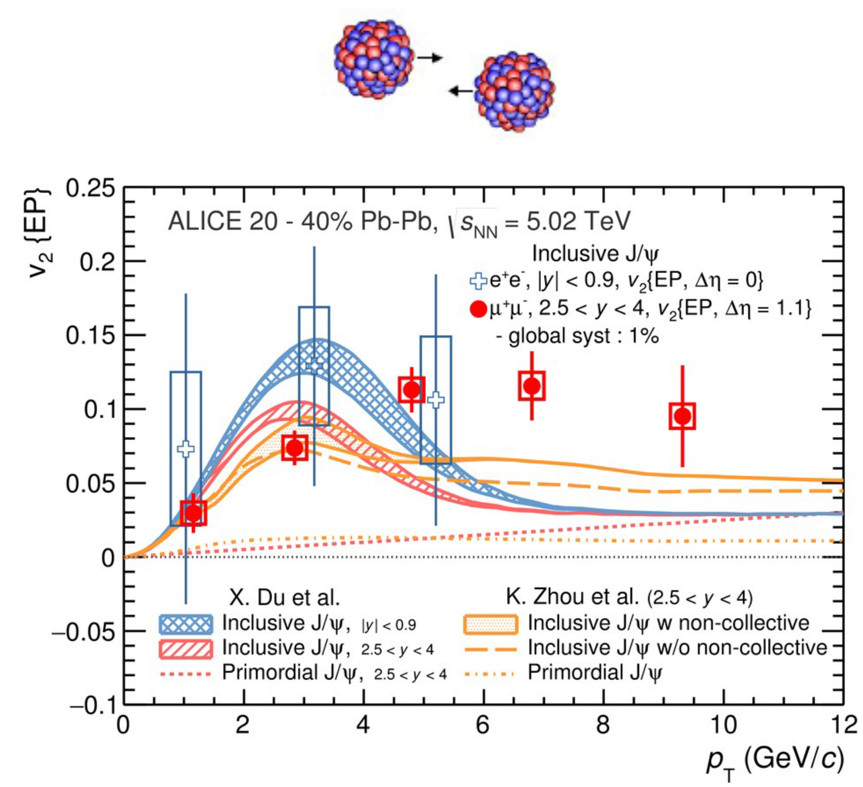
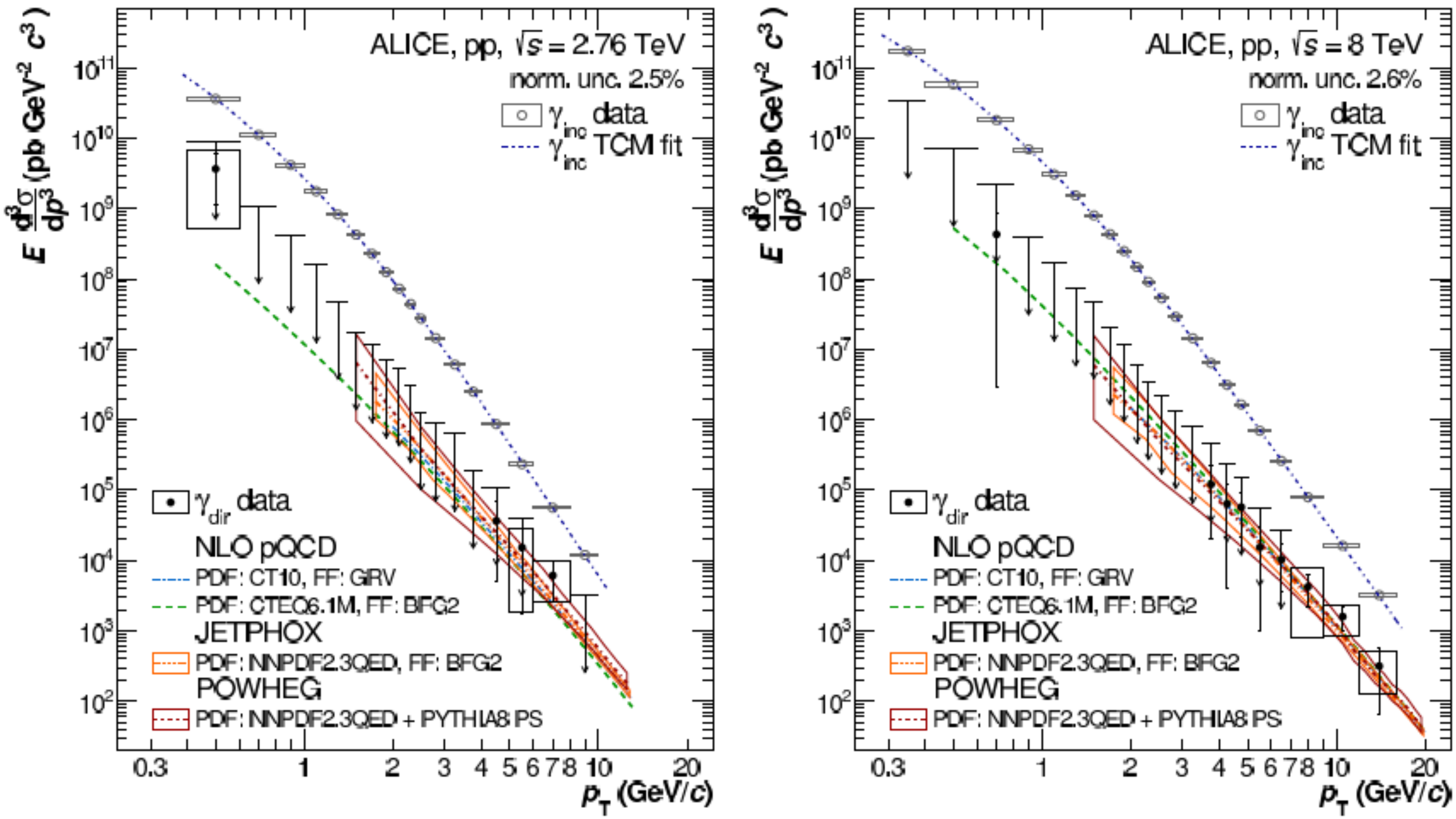


- Charm “flow” is used to extract the diffusion coefficient of heavy quarks in the QGP, is sizeable in pPb.



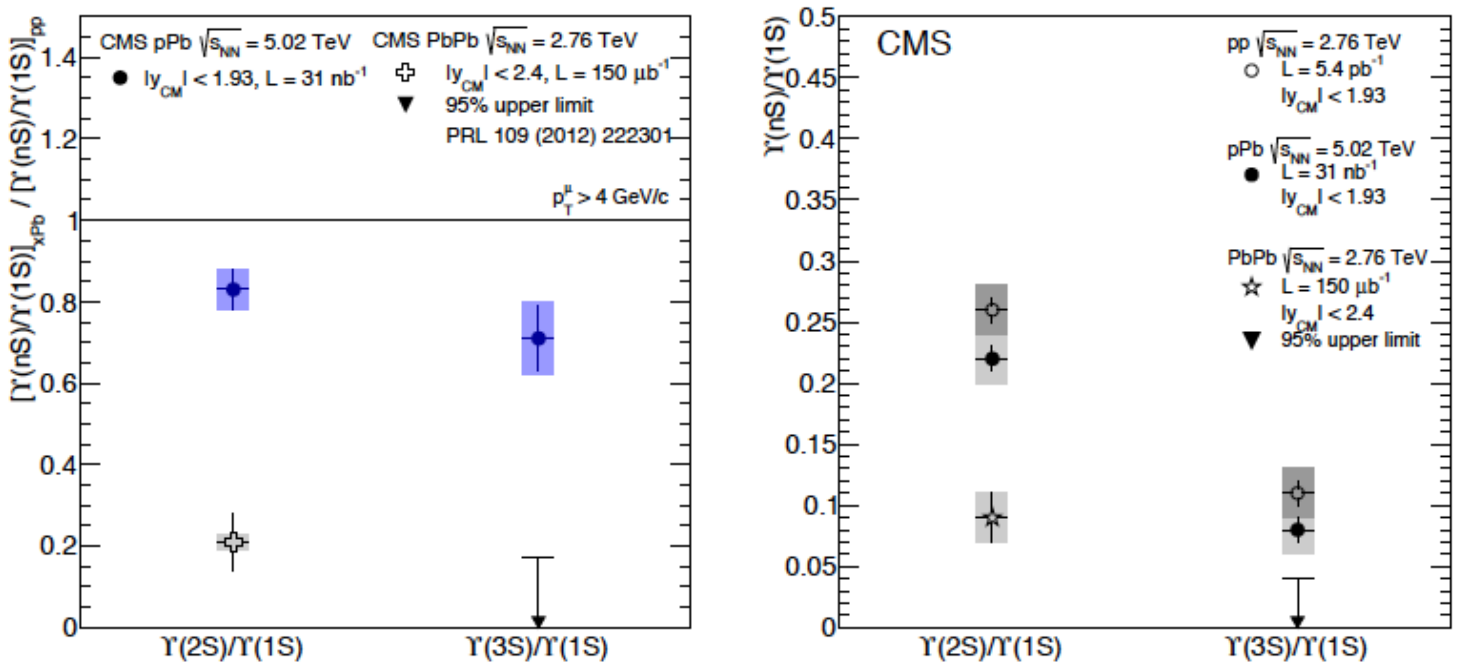


Direct photons:

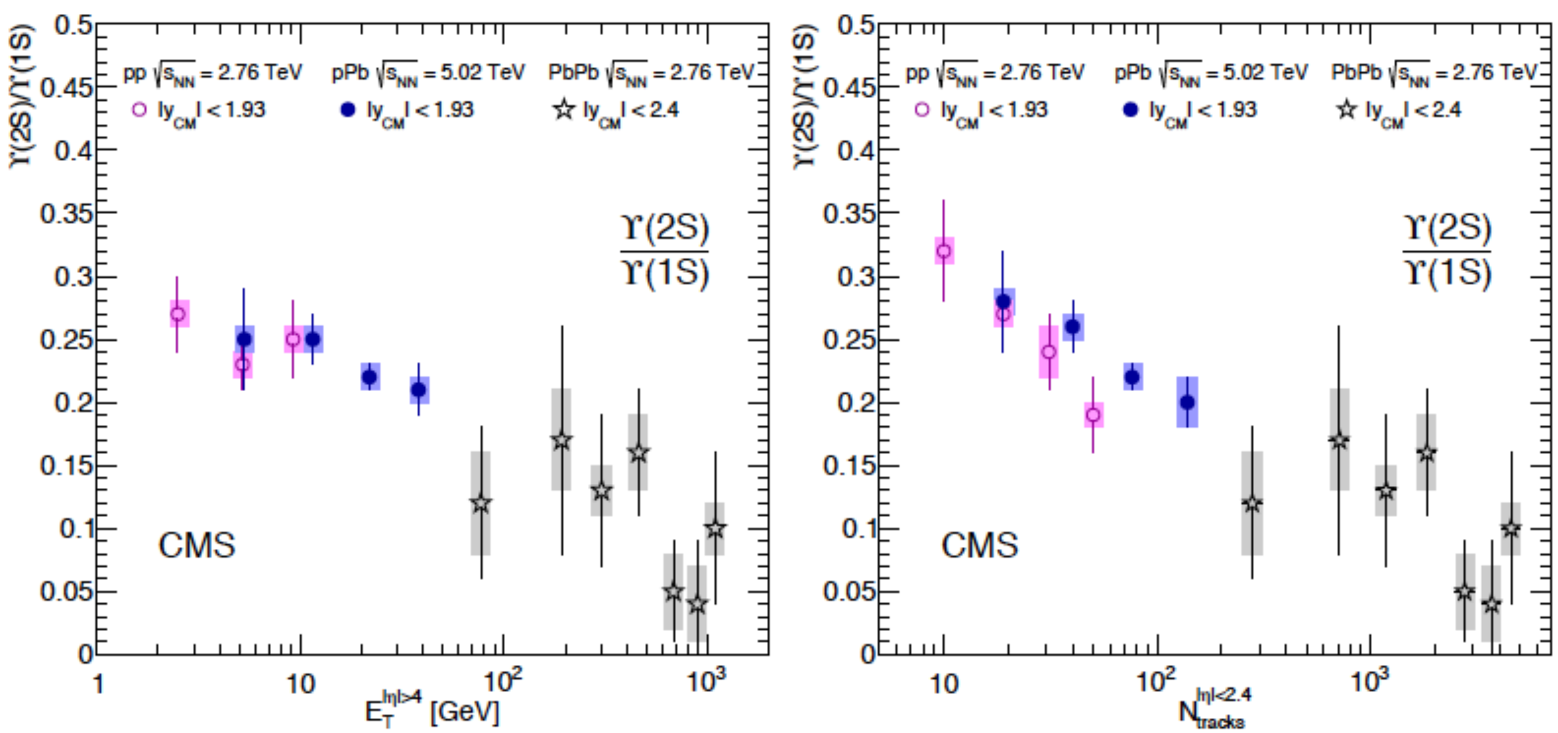


• Direct photon production in pp compatible with pQCD expectations, though room for other origins (evident in PbPb).

Final state effects:



1312.6300

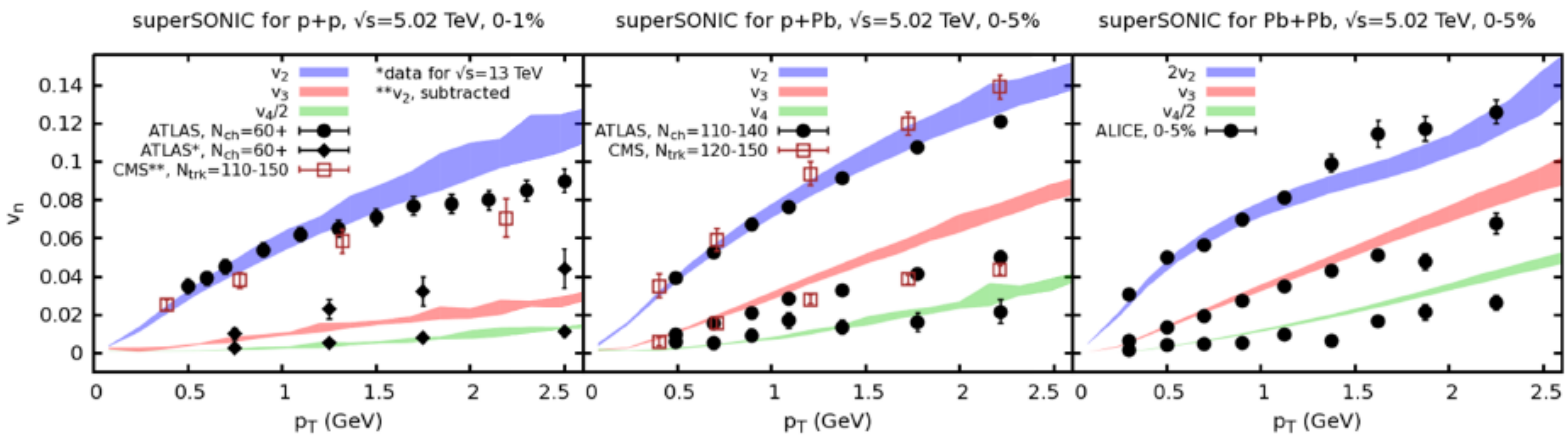


- The relative suppression of bottomonium states in PbPb was interpreted as due to Debye screening in the plasma: thermometer.

- The same effect has been observed in pPb to be smooth with increasing hadronic activity.

The amazing hydro:

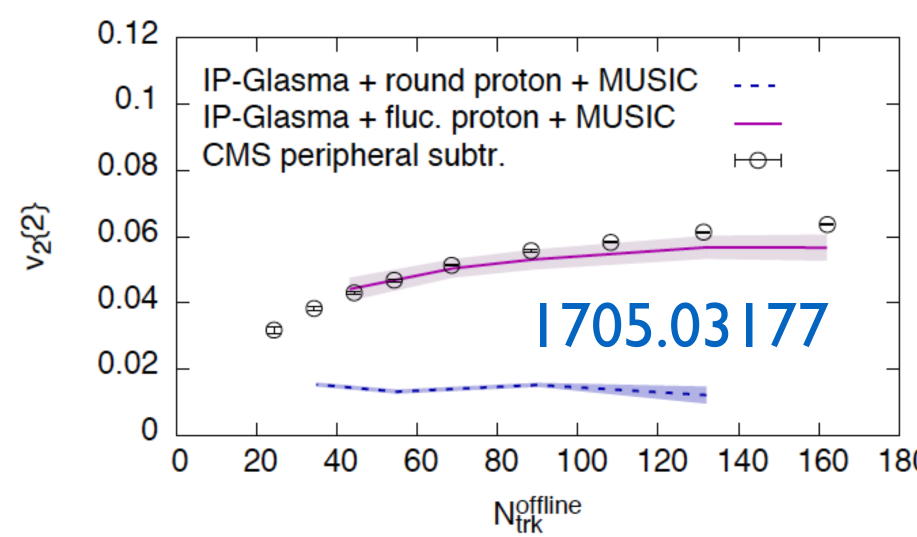
- Viscous hydro works in all three systems: pp to pPb to PbPb.



1701.07145, proton as 3 hot spots

FIG. 2. Elliptic (v_2), triangular (v_3) and quadrupolar (v_4) flow coefficients from superSONIC simulations (bands) compared to experimental data from ATLAS, CMS and ALICE (symbols) for p+p (left panel), p+Pb (center panel) and Pb+Pb (right panel) collisions at $\sqrt{s} = 5.02$ TeV [58–62]. Simulation parameters used were $\frac{\eta}{s} = 0.08$ and $\frac{\zeta}{s} = 0.01$ for all systems. Note that ATLAS results for v_3, v_4 are only available for $\sqrt{s} = 13$ TeV, while all simulation results are for $\sqrt{s} = 5.02$ TeV.

- But this is non trivial: subnucleon dof's in the proton (hot spots).



Contents:

See the talk by François Gelis.

CGC:

- Several explanations for the ridge proposed in the CGC:

  ➜ Assume that the final state carries the imprint of initial-state correlations;

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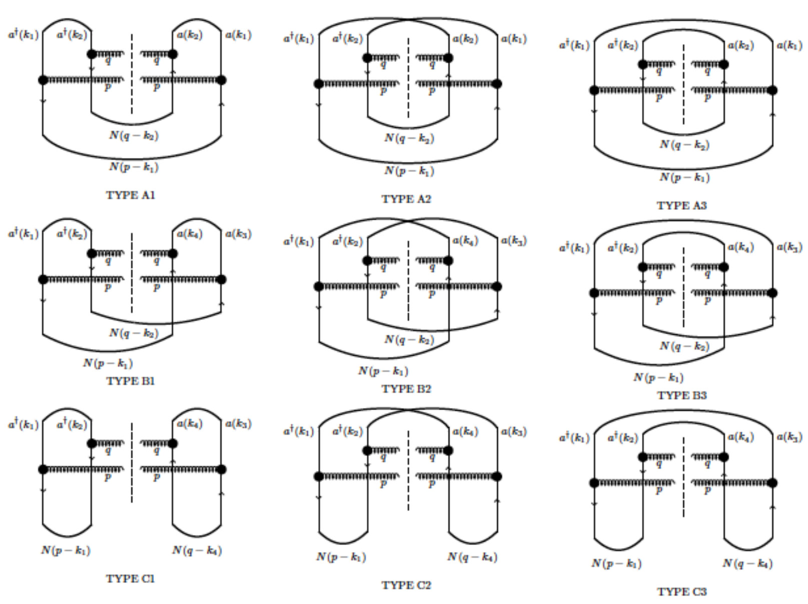

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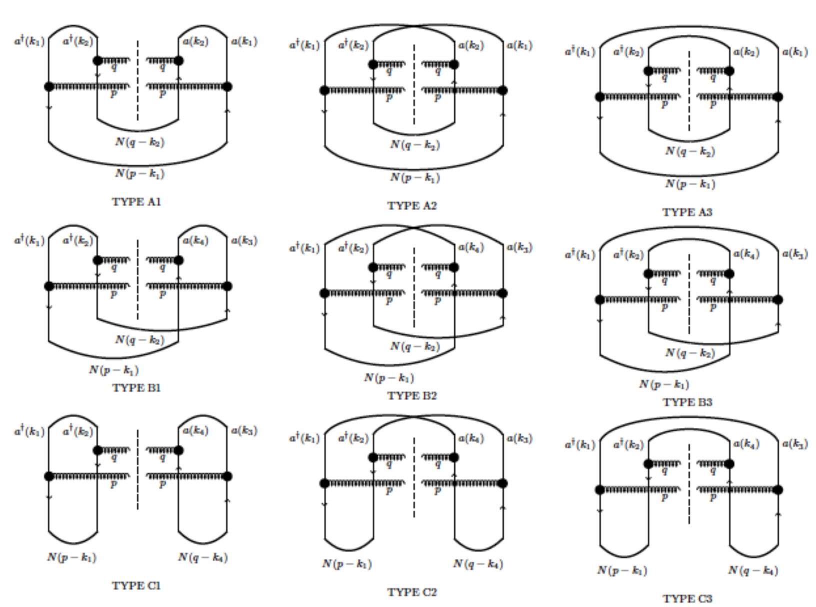
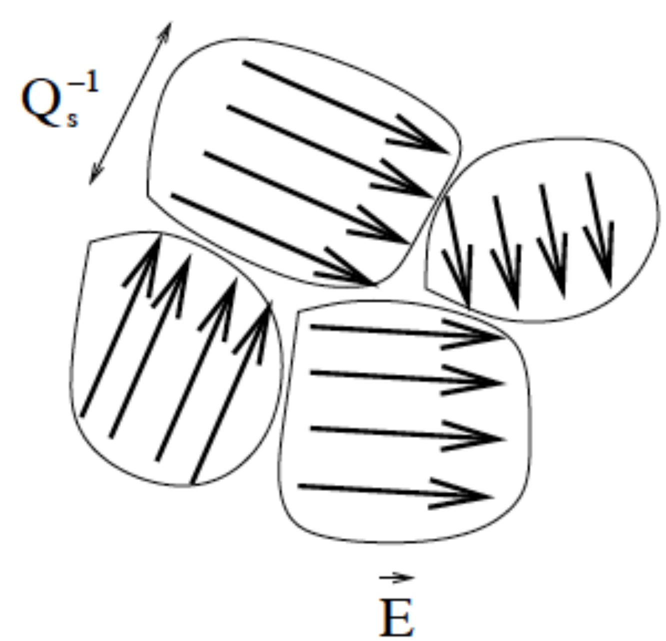


- Local anisotropy of target fields (Kovner-Lublinsky, Dumitru-McLerran-Skokov).



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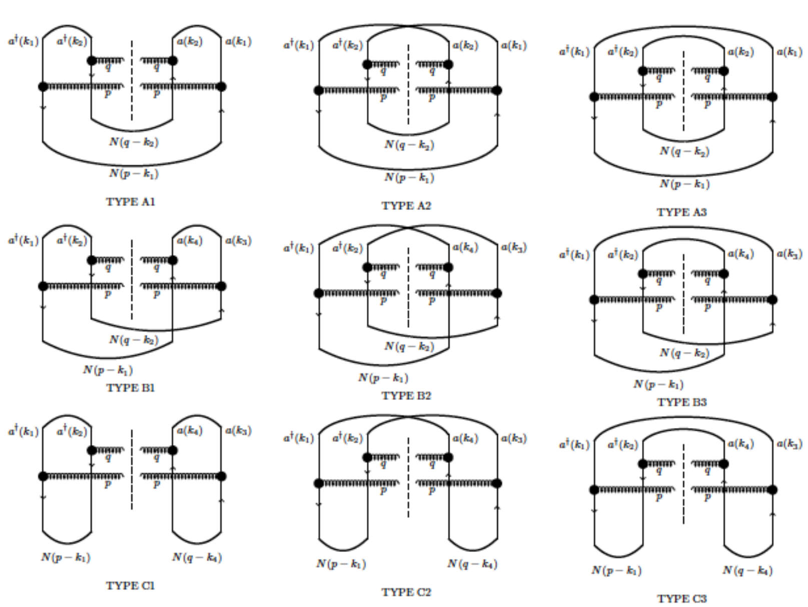

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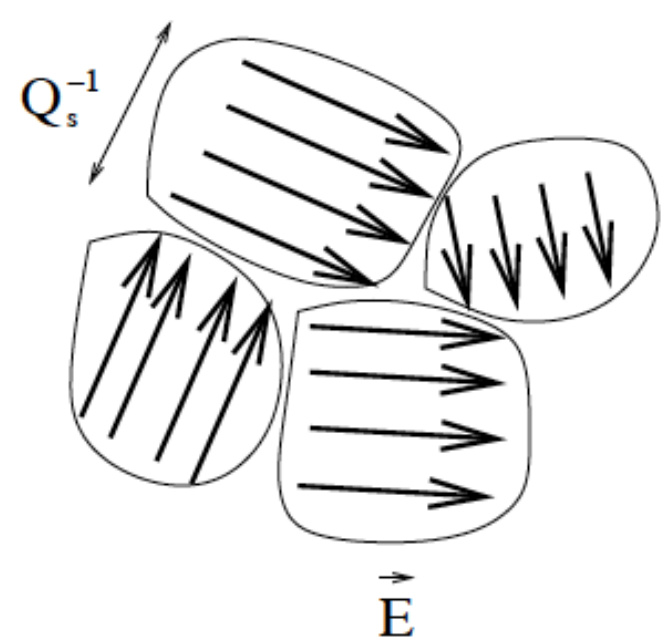
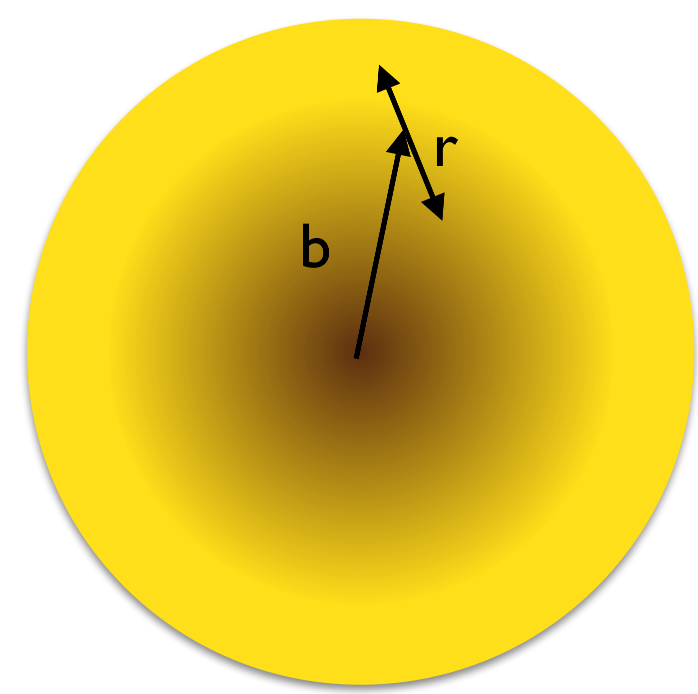


- Spatial variation of partonic density (Levin-Rezaeian-Gotsman).



An example: two quarks

- The two-particle inclusive cross section reads:

$$\frac{d\sigma}{dp^+d^2pdq^+d^2q} = \frac{1}{(2\pi)^6} \langle v|\Omega\, \hat{S}^\dagger\, \Omega^\dagger\ \ [\,d^\dagger_{\alpha,s_1}(p^+,p)\, d^\dagger_{\beta,s_2}(q^+,q) d_{\beta,s_2}(q^+,q)\, d_{\alpha,s_1}(p^+,p)]\ \Omega\, \hat{S}\, \Omega^\dagger|v\rangle$$

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operator that diagonalises perturbatively
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$$\{d^\omega_{s_1}(k^+,k),d^{\dagger\zeta}_{s_2}(q^+,q)\} = (2\pi)^3\delta^{\omega\zeta}\delta_{s_1s_2}\delta(k^+-q^+)\delta^{(2)}(k-q)$$ quark cre/anni. operator

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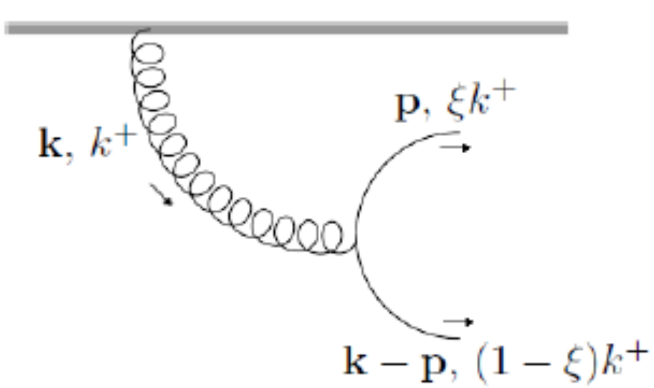
- Dressed valence state of interest here from the LCH (1610.03453):

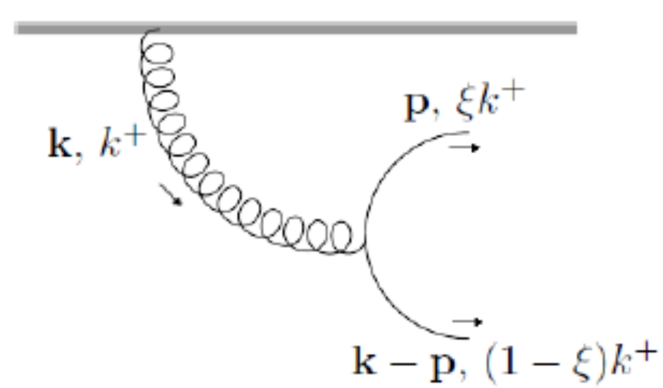
$$|v\rangle^D_4 = \text{virtual} + \frac{g^4}{2}\int\frac{dk^+d\alpha\,d^2p'\,d^2\bar{p}'}{(2\,\pi)^3}\frac{d\bar{k}^+d\beta\,d^2q'\,d^2\bar{q}'}{(2\,\pi)^3}$$

$$\times\left[\zeta^{\epsilon\iota}_{s_1's_2'}(k^+,p',\bar{p}';\alpha)\zeta^{\gamma\delta}_{r_1r_2}(\bar{k}^+,q',\bar{q}';\beta)\ d^{\dagger\epsilon}_{s_1'}(\bar{\alpha}k^+,p')\,\bar{d}^{\dagger\iota}_{s_2'}(\alpha k^+,\bar{p}')\ d^{\dagger\gamma}_{r_1}(\bar{\beta}\bar{k}^+,q')\,\bar{d}^{\dagger\delta}_{r_2}(\beta\bar{k}^+,\bar{q}')\right]|v\rangle$$

ρ_1



ρ_2



An example: two quarks

- The two-particle inclusive cross section reads:

valence state

$$\frac{d\sigma}{dp^+ d^2p\, dq^+ d^2q} = \frac{1}{(2\pi)^6} \langle v | \Omega\, \hat{S}^\dagger\, \Omega^\dagger \; [\, d^\dagger_{\alpha,s_1}(p^+,p)\, d^\dagger_{\beta,s_2}(q^+,q)\, d_{\beta,s_2}(q^+,q)\, d_{\alpha,s_1}(p^+,p)\,]\; \Omega\, \hat{S}\, \Omega^\dagger | v \rangle$$

operator that diagonalises perturbatively the Light Cone QCD Hamiltonian

eikonal S-matrix

$$\{ d^\omega_{s_1}(k^+,k), d^{\dagger\zeta}_{s_2}(q^+,q) \} = (2\pi)^3 \delta^{\omega\zeta} \delta_{s_1 s_2} \delta(k^+ - q^+) \delta^{(2)}(k-q)$$ quark cre/anni. operator

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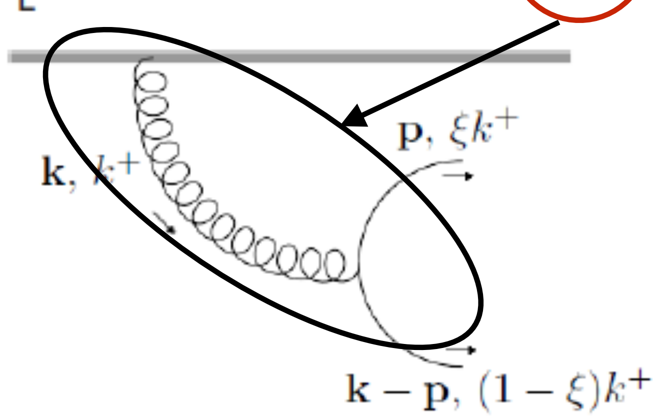
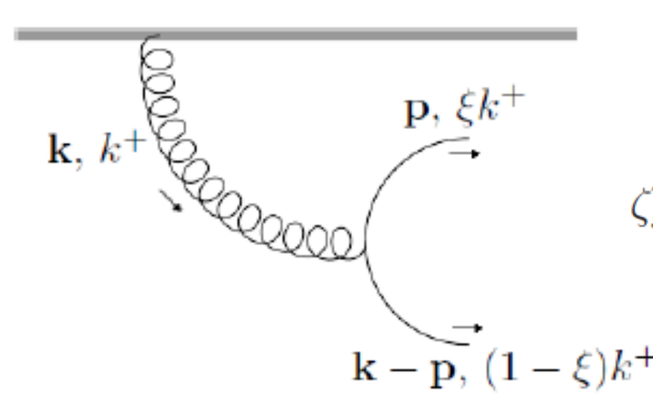
$$\times \left[\zeta^{\epsilon\iota}_{s'_1 s'_2}(k^+,p',\bar{p}';\alpha)\, \zeta^{\gamma\delta}_{r_1 r_2}(\bar{k}^+,q',\bar{q}';\beta)\; d^{\dagger\epsilon}_{s'_1}(\bar{\alpha}k^+,p')\, \bar{d}^{\dagger\iota}_{s'_2}(\alpha k^+,\bar{p}')\; d^{\dagger\gamma}_{r_1}(\bar{\beta}\bar{k}^+,q')\, \bar{d}^{\dagger\delta}_{r_2}(\beta\bar{k}^+,\bar{q}') \right] |v\rangle$$

ρ1



ρ2



$$\zeta^{\gamma\delta}_{s_1 s_2}(k^+,p,q,\alpha) = \tau^a_{\gamma\delta} \int \frac{d^2k}{(2\pi)^2}\, \rho^a(k)\, \phi_{s_1 s_2}(k,p,q;\alpha)$$

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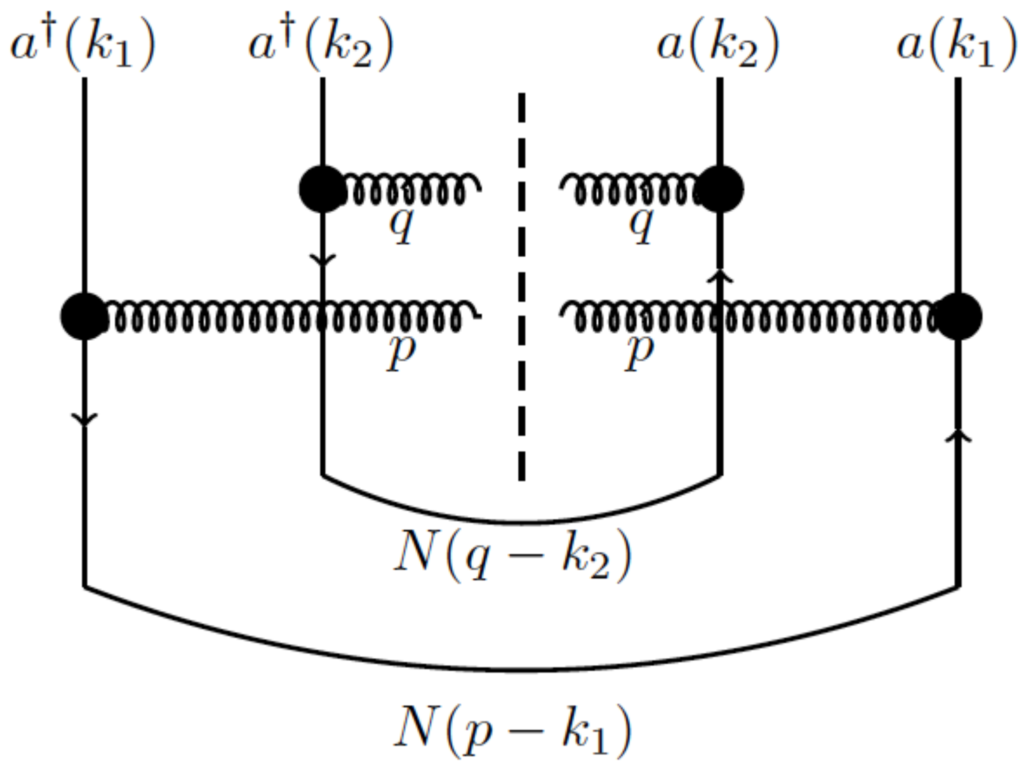
- ρg~1, so only density-enhanced contributions are taken i.e. NOT

ρ

Glasma graphs for gluons (I):

• The appearance of the ridge in the final state, within the glasma graph approach, can be traced to the Bose enhancement of gluons in the (rapidity invariant) wave function:

1503.07126, 1509.03223



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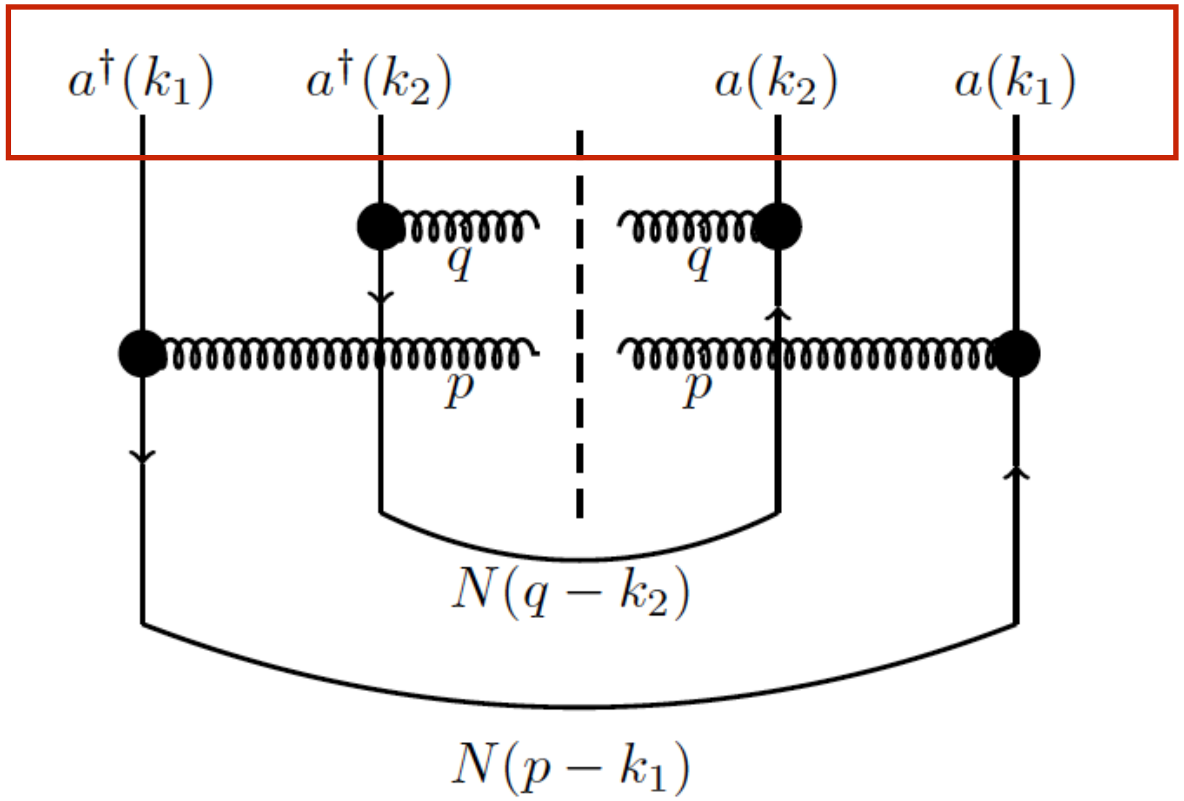

gluons in the WF

1503.07126, 1509.03223

$$[a_a^i(k), a_b^{\dagger j}(p)] = (2\pi)^2 \delta_{ab}\delta^{ij}\delta^{(2)}(k-p)$$

$$a_a^i(k) \equiv \frac{1}{\sqrt{Y}} \int_{|\eta<Y/2|} \frac{d\eta}{2\pi}\, a_a^i(\eta, k)$$

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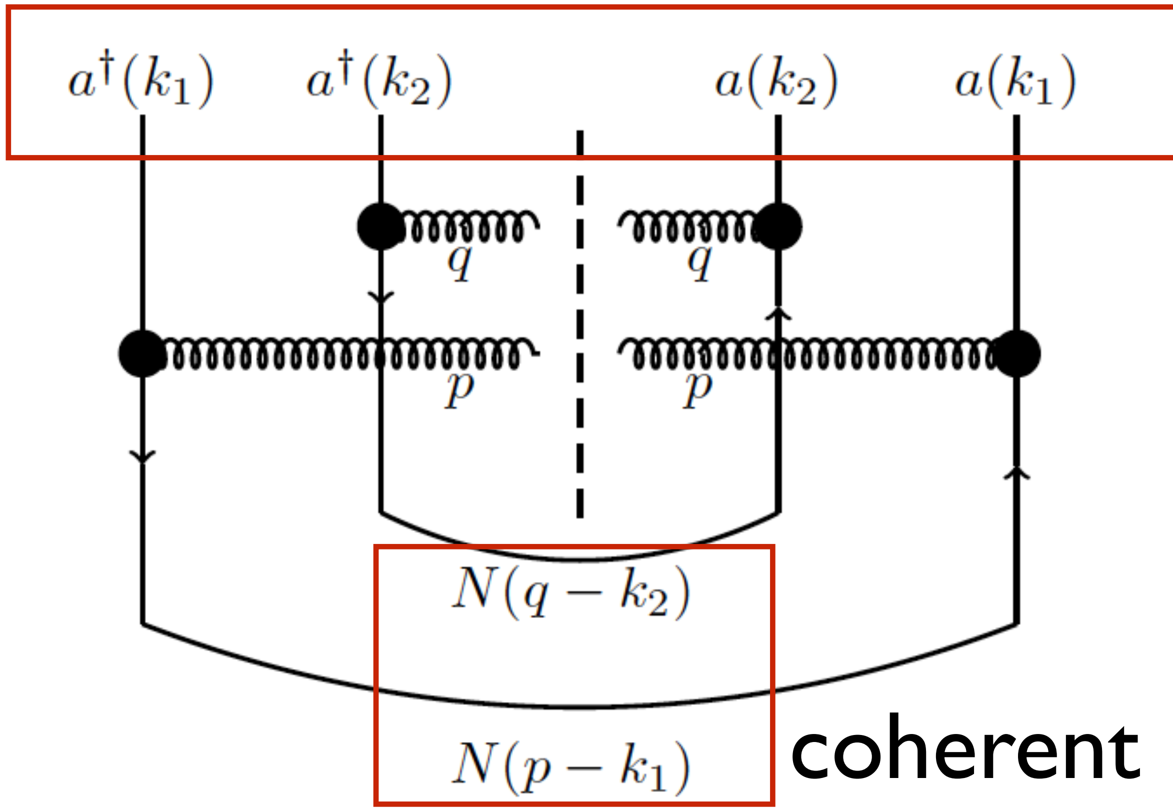

gluons in the WF

coherent rescattering on the target - S-matrix

1503.07126, 1509.03223

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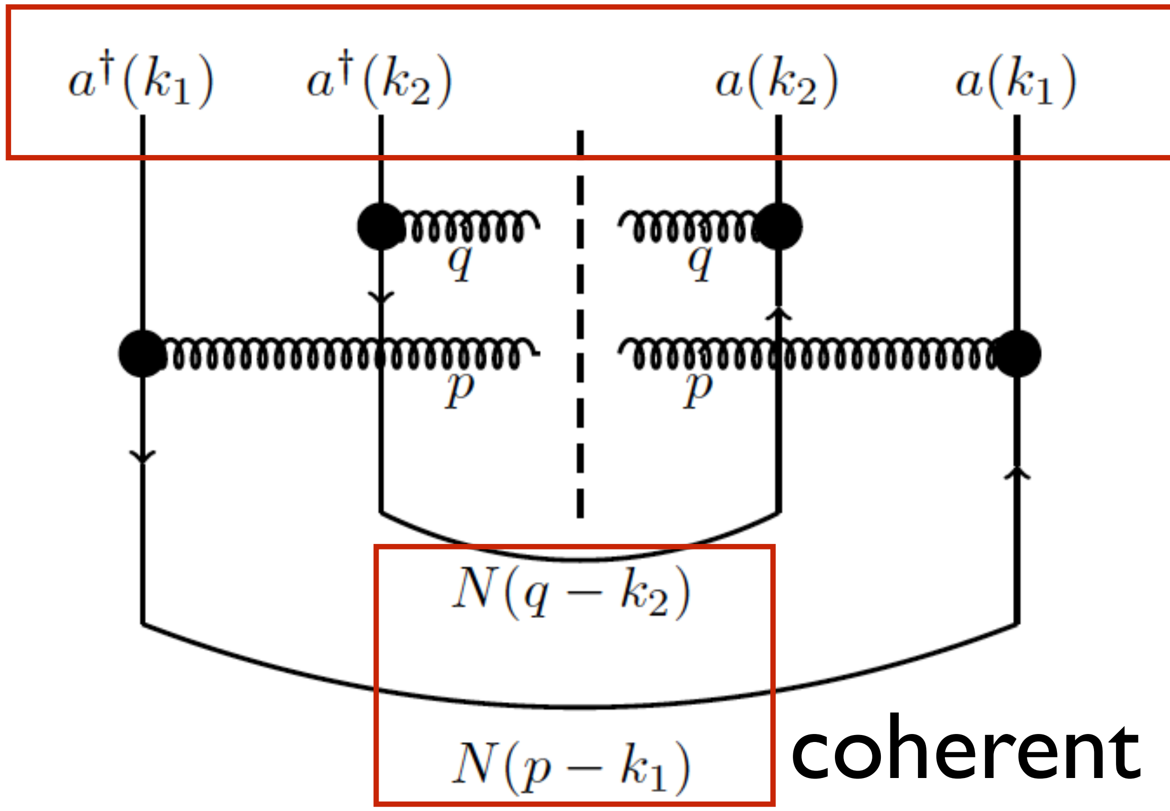

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coherent rescattering on the target - S-matrix

$$C \int_{k_1,k_2} \langle in|a^{\dagger i}_a(k_1) a^{\dagger j}_b(k_2) a^k_a(k_1) a^l_b(k_2)|in\rangle \left[\delta^{ik} - \frac{k_1^i k_1^k}{p^2}\right] \left[\delta^{jl} - \frac{k_2^j k_2^l}{q^2}\right] N(p-k_1) N(q-k_2)$$

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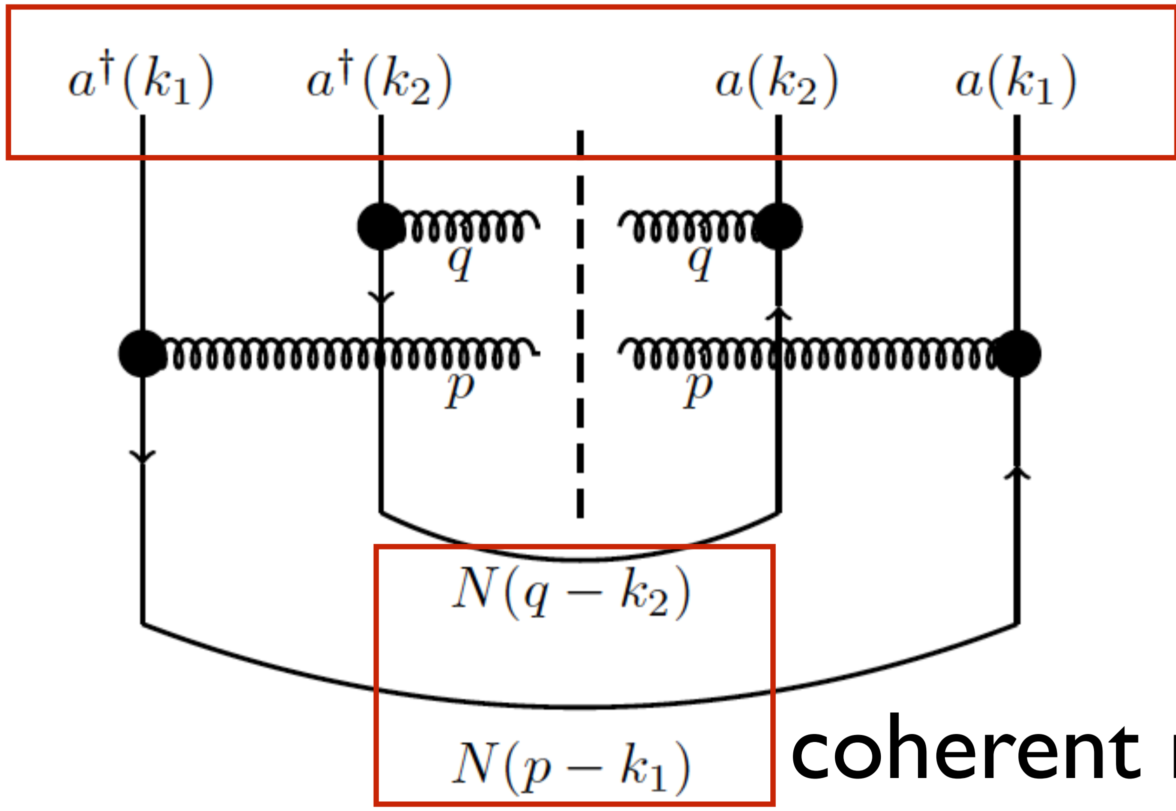

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1503.07126, 1509.03223

$$[a_a^i(k), a_b^{\dagger j}(p)] = (2\pi)^2 \delta_{ab}\delta^{ij}\delta^{(2)}(k-p)$$

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coherent rescattering on the target - S-matrix

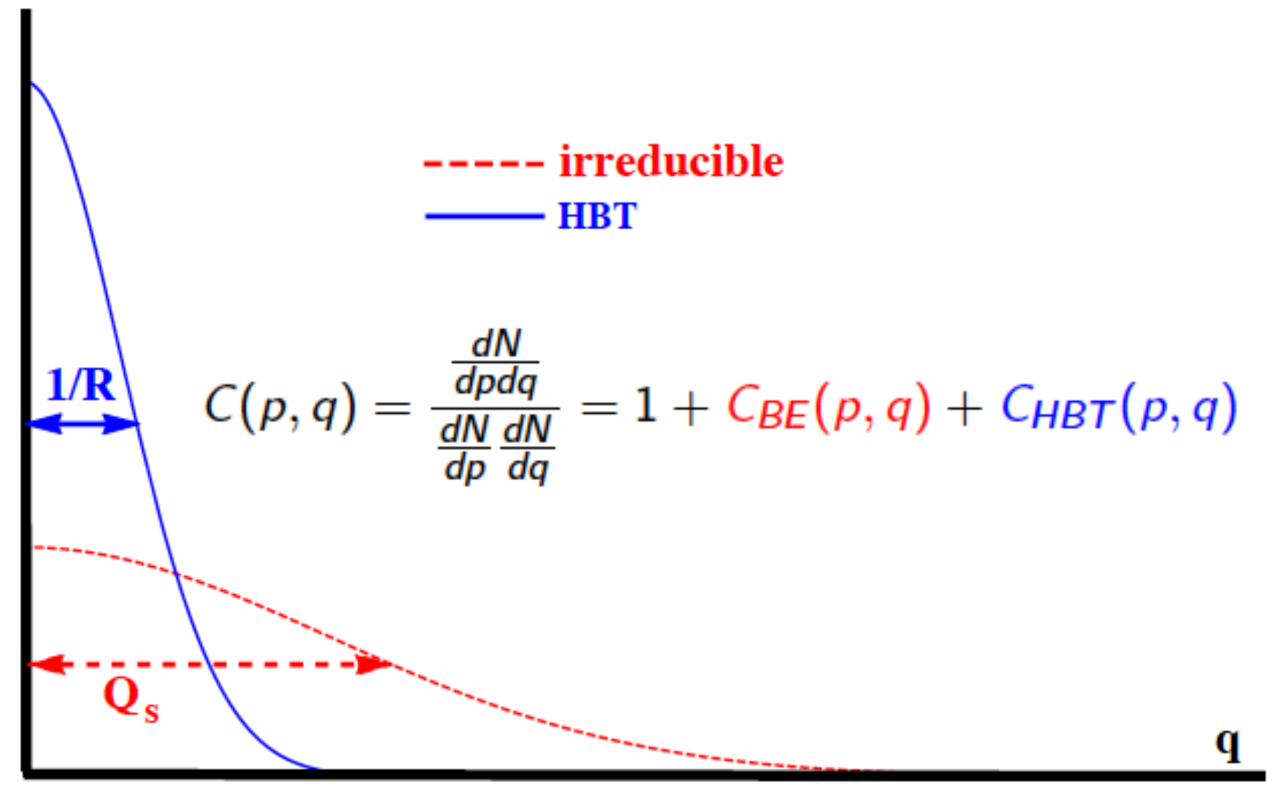
$$C\int_{k_1,k_2} \boxed{\langle in|a_a^{\dagger i}(k_1)a_b^{\dagger j}(k_2)a_a^k(k_1)a_b^l(k_2)|in\rangle} \left[\delta^{ik} - \frac{k_1^i k_1^k}{p^2}\right]\left[\delta^{jl} - \frac{k_2^j k_2^l}{q^2}\right] N(p-k_1)N(q-k_2)$$

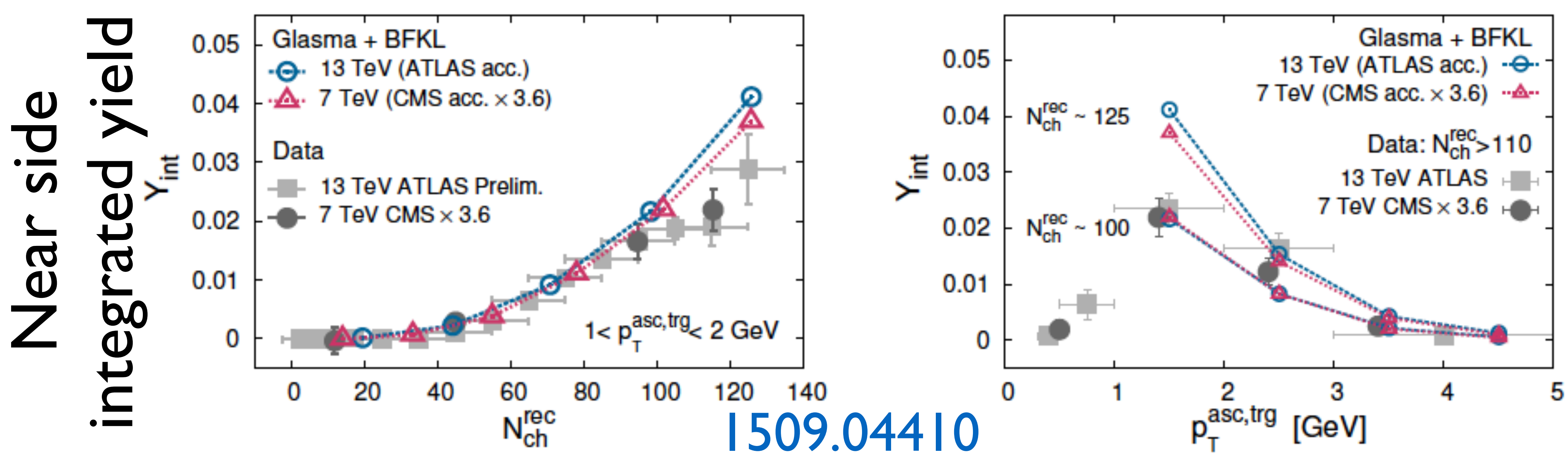
$$D(k_1,k_2) = S^2(N_c^2-1)^2 \frac{k_1^i k_1^k k_2^j k_2^l}{k_1^2 k_2^2} \frac{g^4\mu^2(k_1)\mu^2(k_2)}{k_1^2 k_2^2} \left\{1 + \frac{1}{S(N_c^2-1)}\left[\delta^{(2)}(k_1-k_2) + \delta^{(2)}(k_1+k_2)\right]\right\}$$

$$a^*(k) = a(-k)$$

Glasma graphs for gluons (II):

- It can be extended for quarks giving Pauli blocking (1610.03020): short range anticorrelation in the near side ridge.
- It contains information both on the 'source' size $1/Q_s$ (BE, suppressed by the number of sources), and on the size of the distribution of 'sources' R (HBT).





1509.04410

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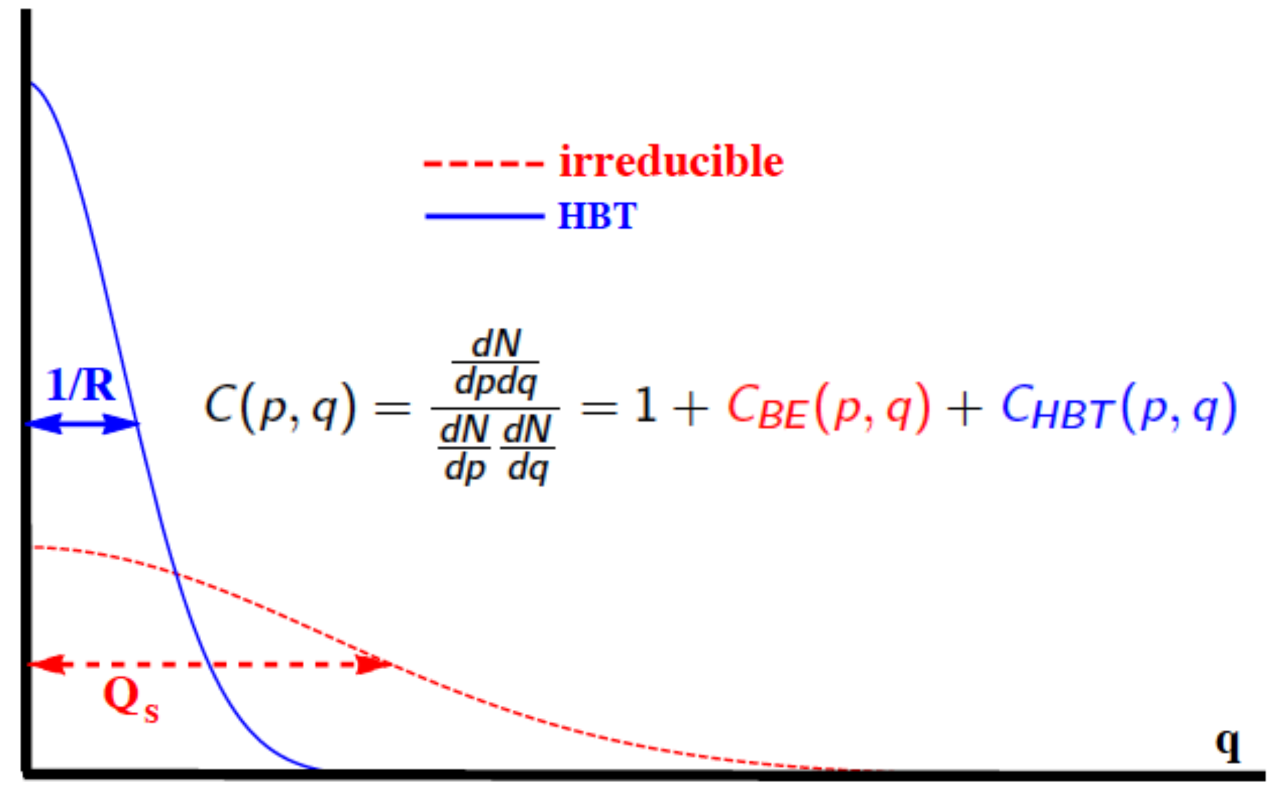


- Limitations:

  ➜ S-matrices for rescattering of partons with the target are expanded in colour fields ⇒ low density approximation.

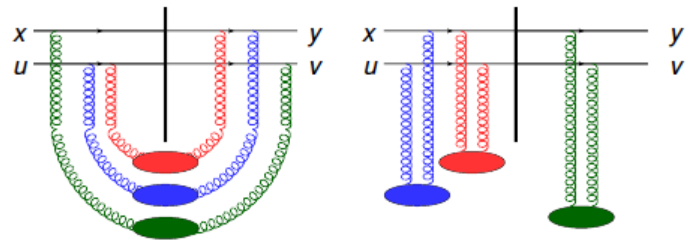
  ➜ Gaussian (MV) isotropic colour correlations taken ⇒

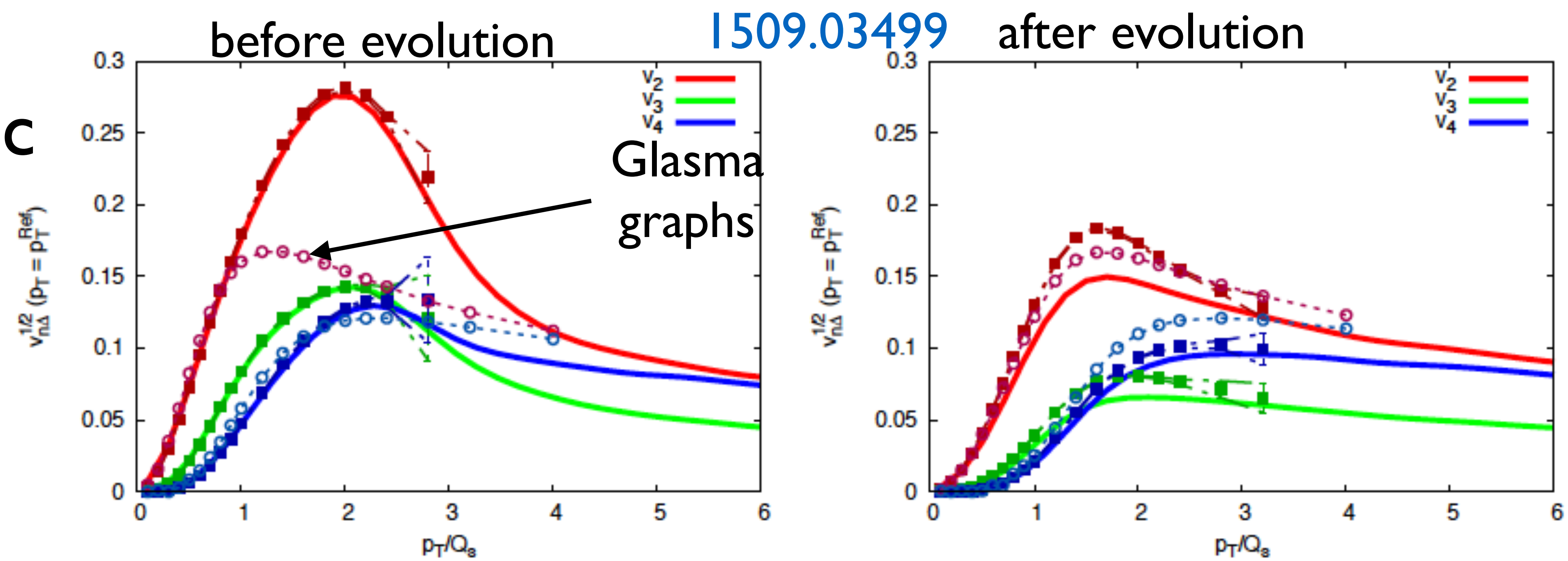
  correlations subleading in N_c, no odd harmonics, $c_2\{4\}>0$.

$$\langle \rho_T^a(k)\rho_T^b(p)\rangle_T = (2\pi)^2\lambda^2(k)\delta^{ab}\delta^{(2)}(k+p)$$

Beyond glasma graphs (I):

- Density corrections: numeric and analytic work (1612.07790; 1802.08166).





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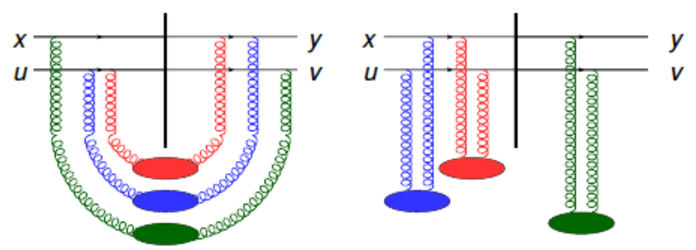

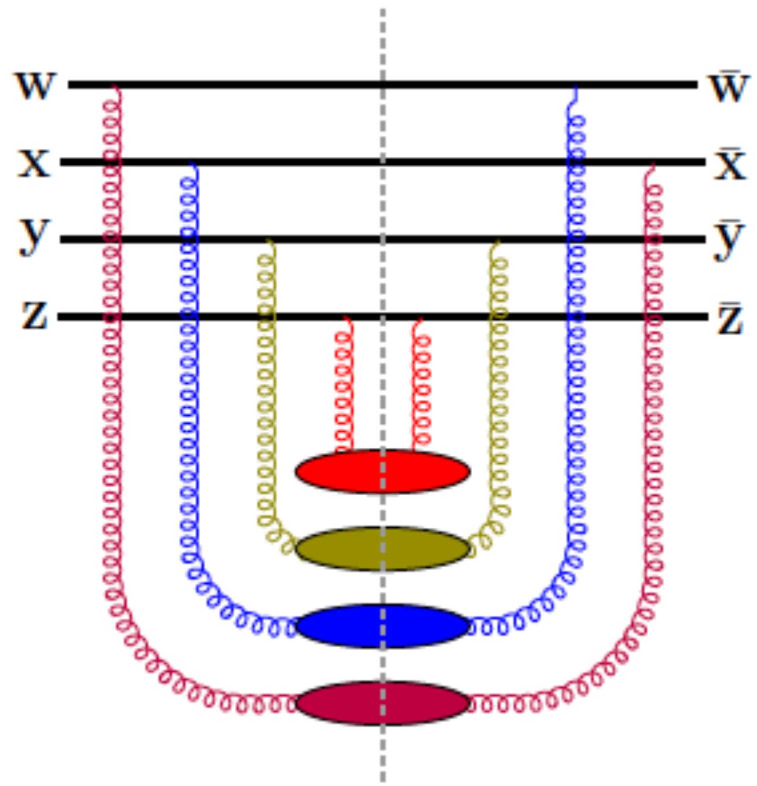

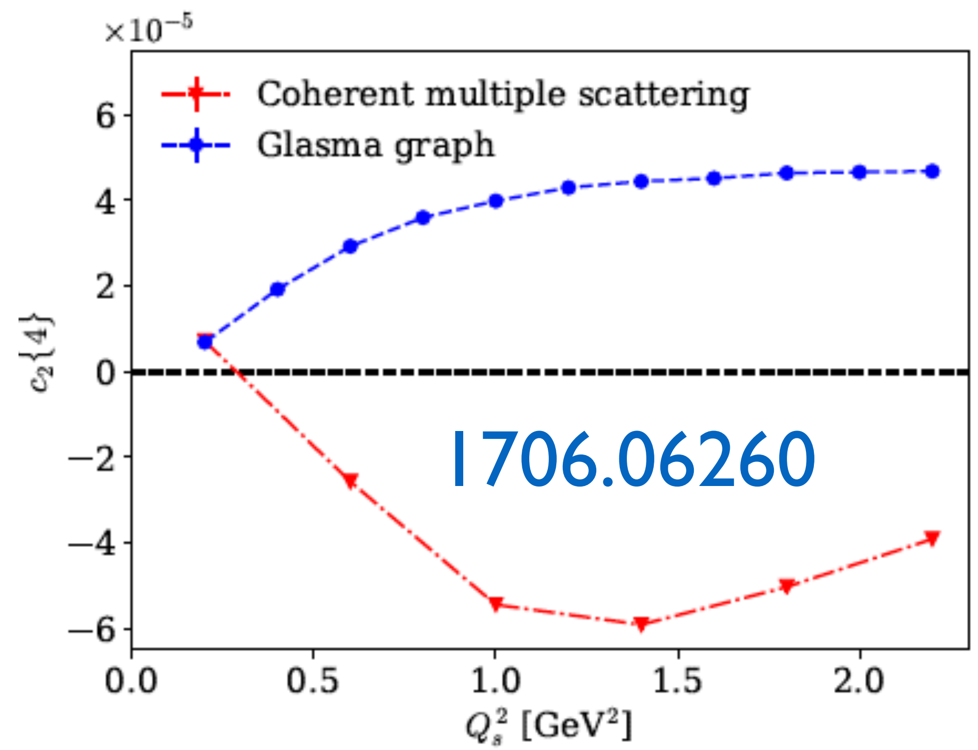

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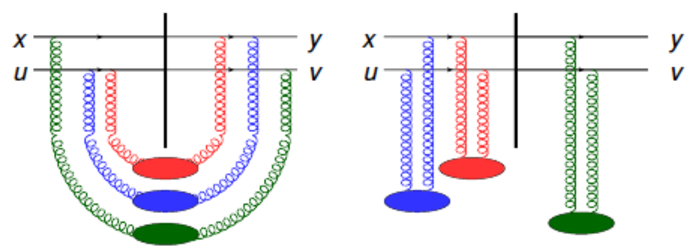
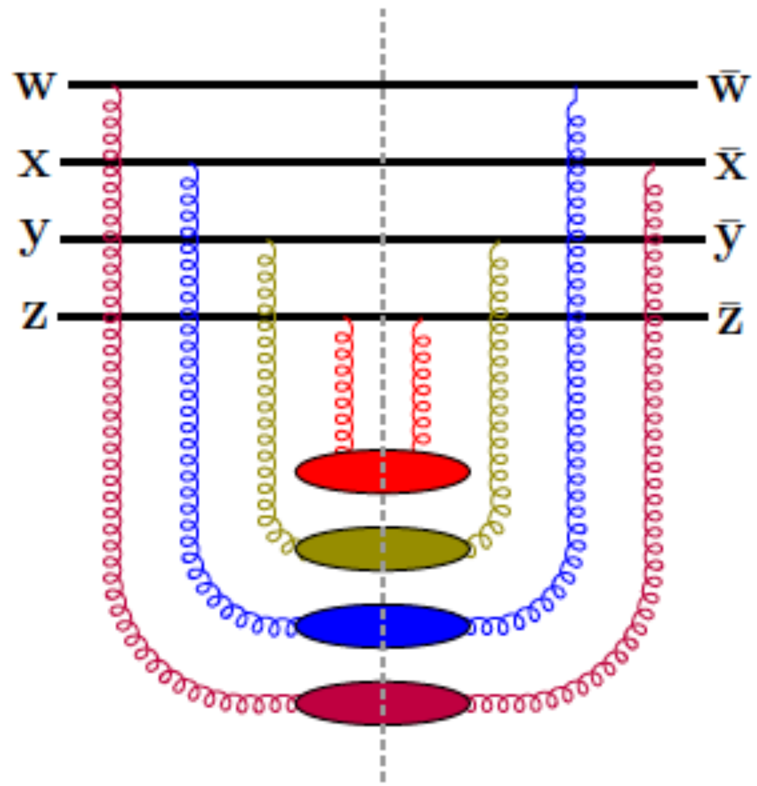
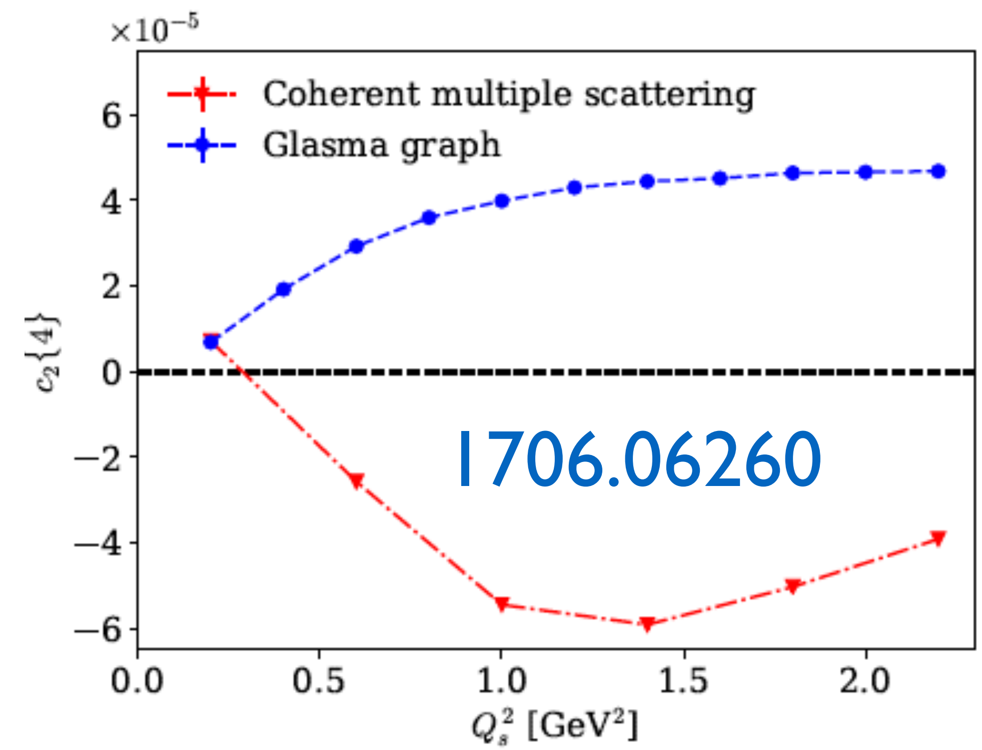






- Anisotropic domains (1503.03897):

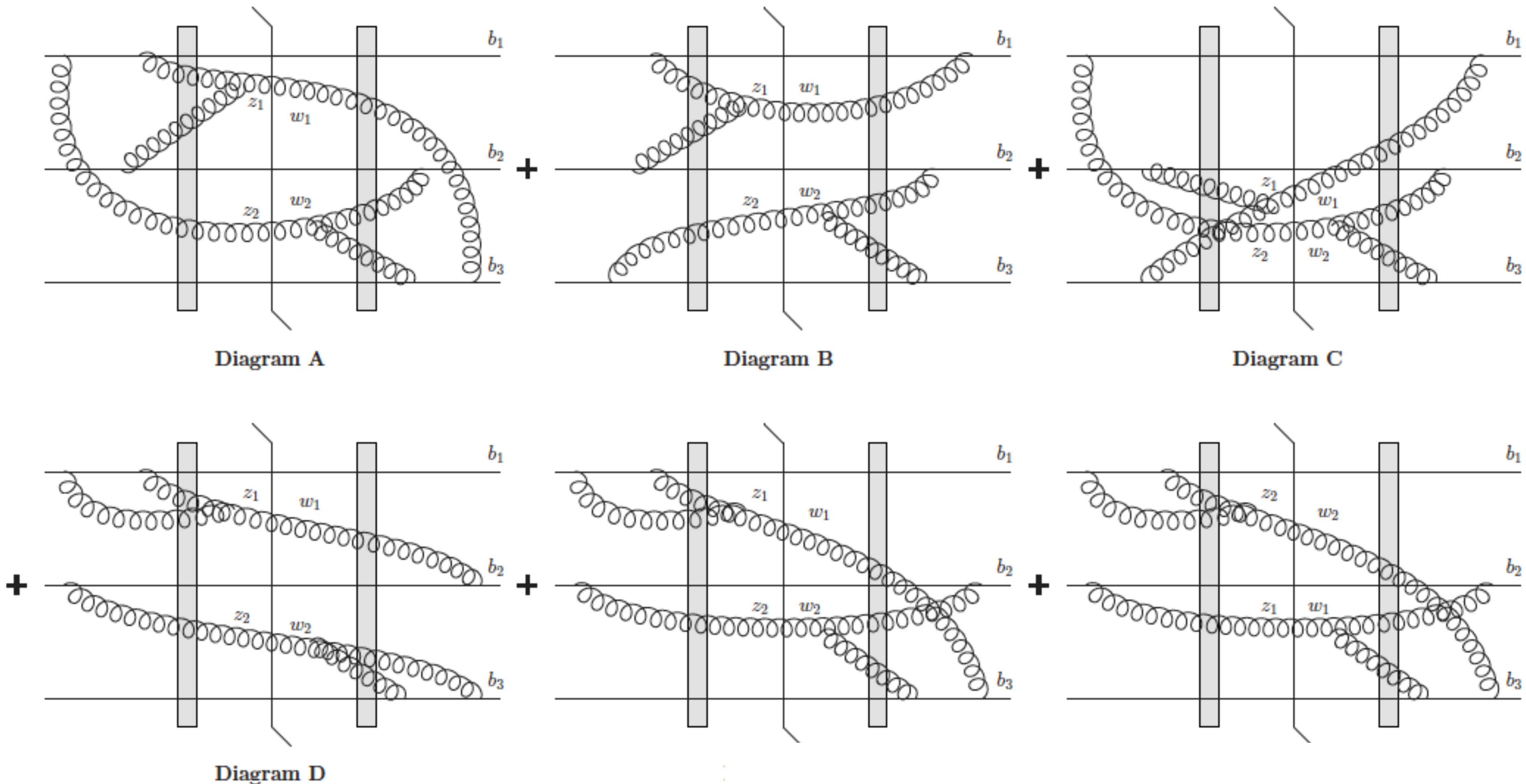
$$\frac{g^2}{N_c}\langle E_i^a(\mathbf{b}_1)E_j^b(\mathbf{b}_2)\rangle = \frac{1}{N_c^2-1}\delta^{ab}\delta_{ij}\,Q_s^2\,\Delta(\mathbf{b}_1-\mathbf{b}_2)$$

$$\frac{g^2}{N_c}\langle E_i^a(\mathbf{b}_1)E_j^b(\mathbf{b}_2)\rangle_{\hat a} = \frac{1}{N_c^2-1}\delta^{ab}\,Q_s^2\,\Delta(\mathbf{b}_1-\mathbf{b}_2)\left(\delta_{ij}+\boxed{2\mathcal{A}\left[\hat a_i\hat a_j-\frac{1}{2}\delta_{ij}\right]}\right)$$

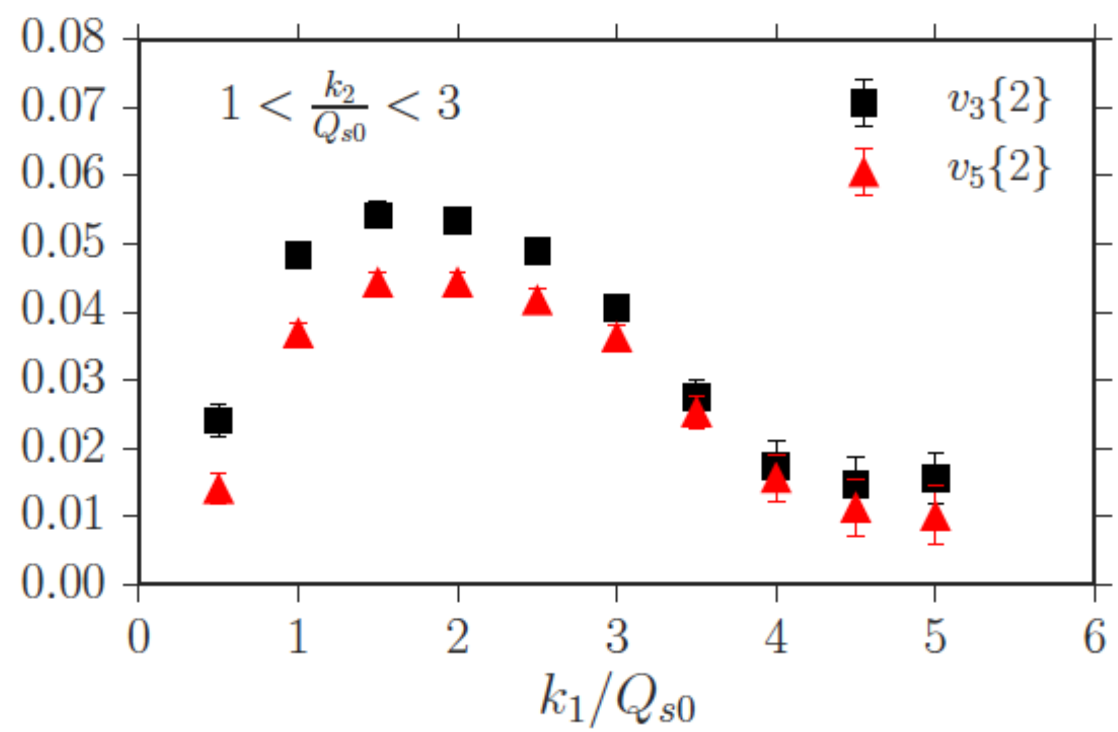
number of domains

$$-c_2\{4\} = -\frac{1}{4}\left[\frac{1}{N_D(N_c^2-1)}\right]^3 < 0 \quad\longrightarrow\quad c_2\{4\} \equiv -(v_2\{4\})^4 = -\frac{1}{N_D^3}\left(\mathcal{A}^4-\frac{1}{4(N_c^2-1)^3}\right)$$

Beyond glasma graphs (II):



- Three scatterings for odd harmonics: higher orders in the projectile wave function (1612.07790; 1802.08166).



Beyond glasma graphs (III):

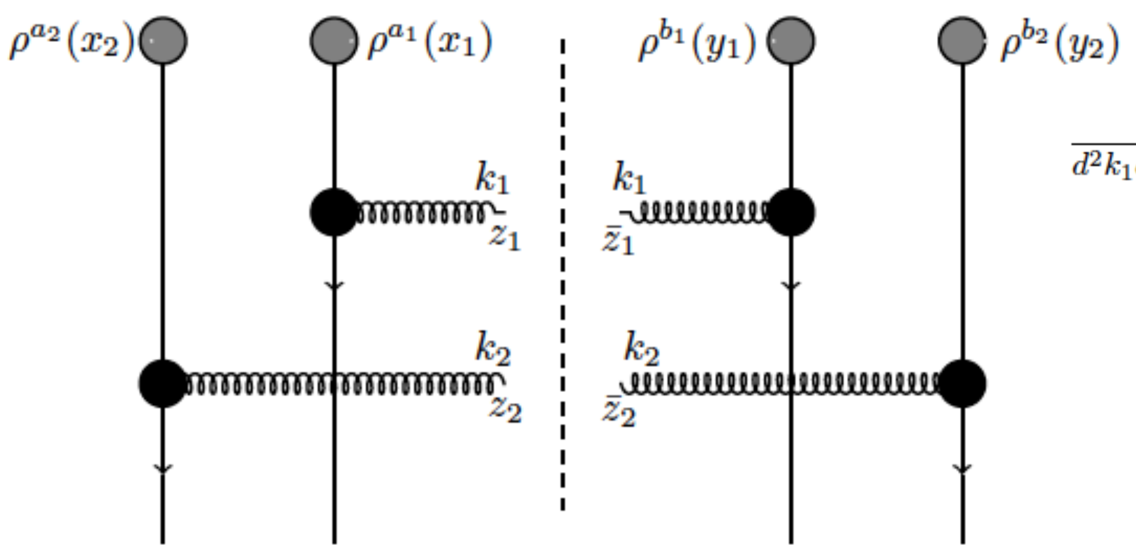
- Density corrections in the target calculated (1804.02910; 1805.07739):

➜ Full two-gluon correlation, large N_c part of the three-gluon inclusive and of the 4-gluon cumulant computed.

➜ Factorisation of the target averages assumed: colour neutralisation at scale $1/Q_s$ imply pair configurations.

➜ Only the highest order target correlated provides the fully correlated piece: quadrupole for two, sextuple for three, octupole for four.

➜ All BE/HBT contributions, even BE from the target $1/N_c$ suppressed.



$$\begin{aligned}\frac{d\sigma}{d^2k_1 d\eta_1 d^2k_2 d\eta_2} &= \alpha_s^2(4\pi)^2 \int_{z_1\bar{z}_1 z_2\bar{z}_2} e^{ik_1\cdot(z_1-\bar{z}_1)+ik_2\cdot(z_2-\bar{z}_2)} \\ &\times \int_{x_1x_2y_1y_2} A^i(x_1-z_1)A^i(\bar{z}_1-y_1)A^j(x_2-z_2)A^j(\bar{z}_2-y_2)\left\langle \rho^{a_1}(x_1)\rho^{a_2}(x_2)\rho^{b_1}(y_1)\rho^{b_2}(y_2)\right\rangle_P \\ &\times \left\langle [U(z_1)-U(x_1)]^{a_1c}[U^\dagger(\bar{z}_1)-U^\dagger(y_1)]^{cb_1}[U(z_2)-U(x_2)]^{a_2d}[U^\dagger(\bar{z}_2)-U^\dagger(y_2)]^{db_2}\right\rangle_T .\end{aligned}$$

$$\left\langle U^{ab}(x)U^{cd}(y)\right\rangle_T = \delta^{ac}\delta^{bd}\frac{1}{(N_c^2-1)^2}\left\langle \mathrm{tr}\left[U(x)U^\dagger(y)\right]\right\rangle_T = \delta^{ac}\delta^{bd}\frac{1}{N_c^2-1}d(x,y),$$

$$\begin{aligned}\langle Q(x,y,z,v)\rangle_T &= d(x,y)d(z,v)+d(x,v)d(z,y)+\frac{1}{N_c^2-1}d(x,z)d(y,v), \\ \langle D(x,y)D(z,v)\rangle_T &= d(x,y)d(z,v)+\frac{1}{(N_c^2-1)^2}\left[d(x,v)d(y,z)+d(x,z)d(v,y)\right].\end{aligned}$$

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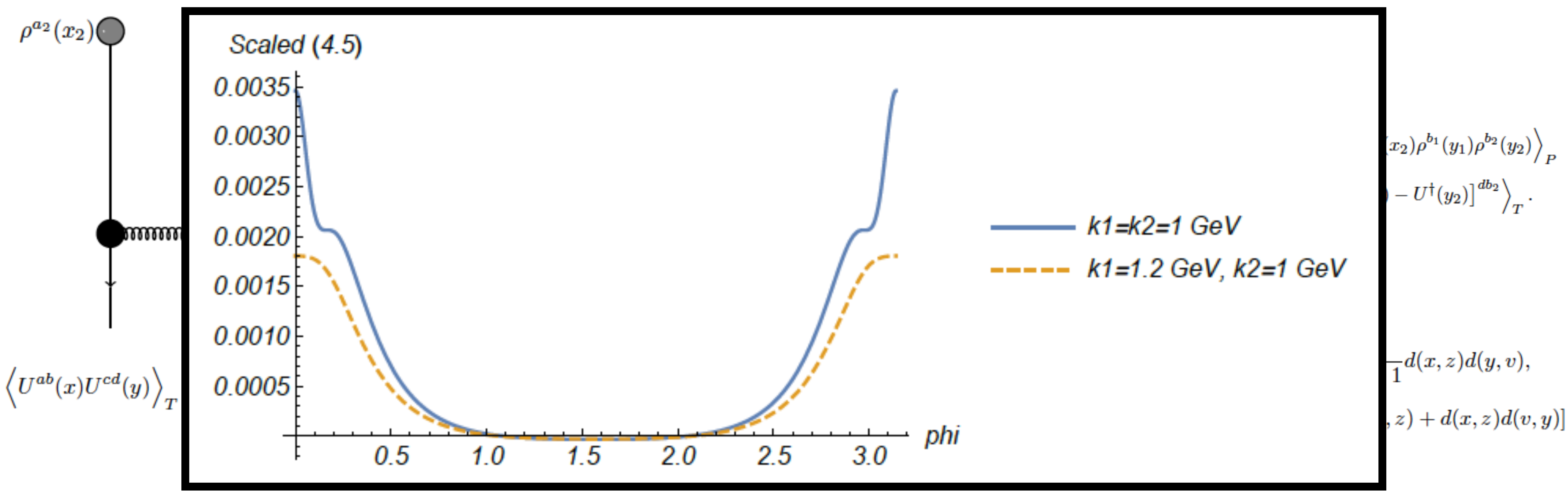

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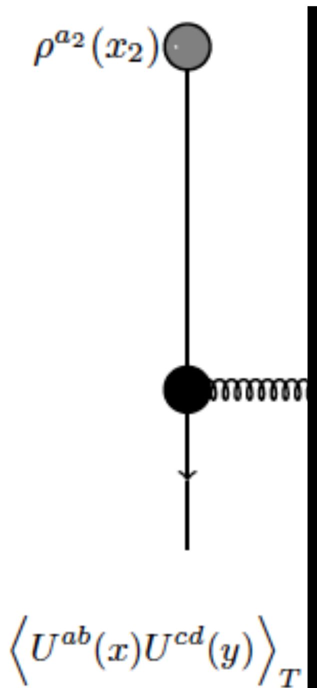
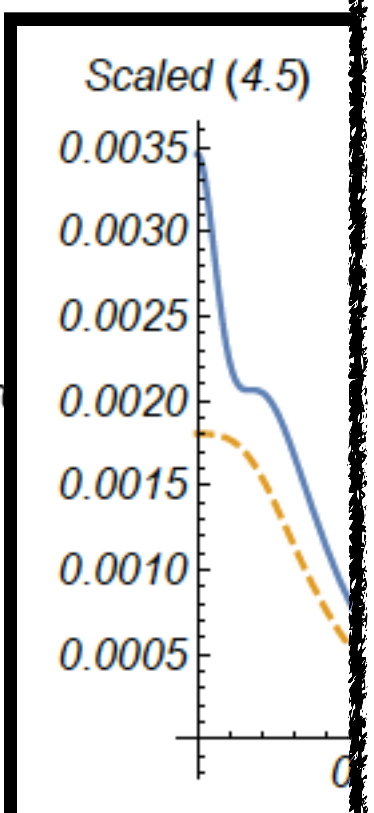


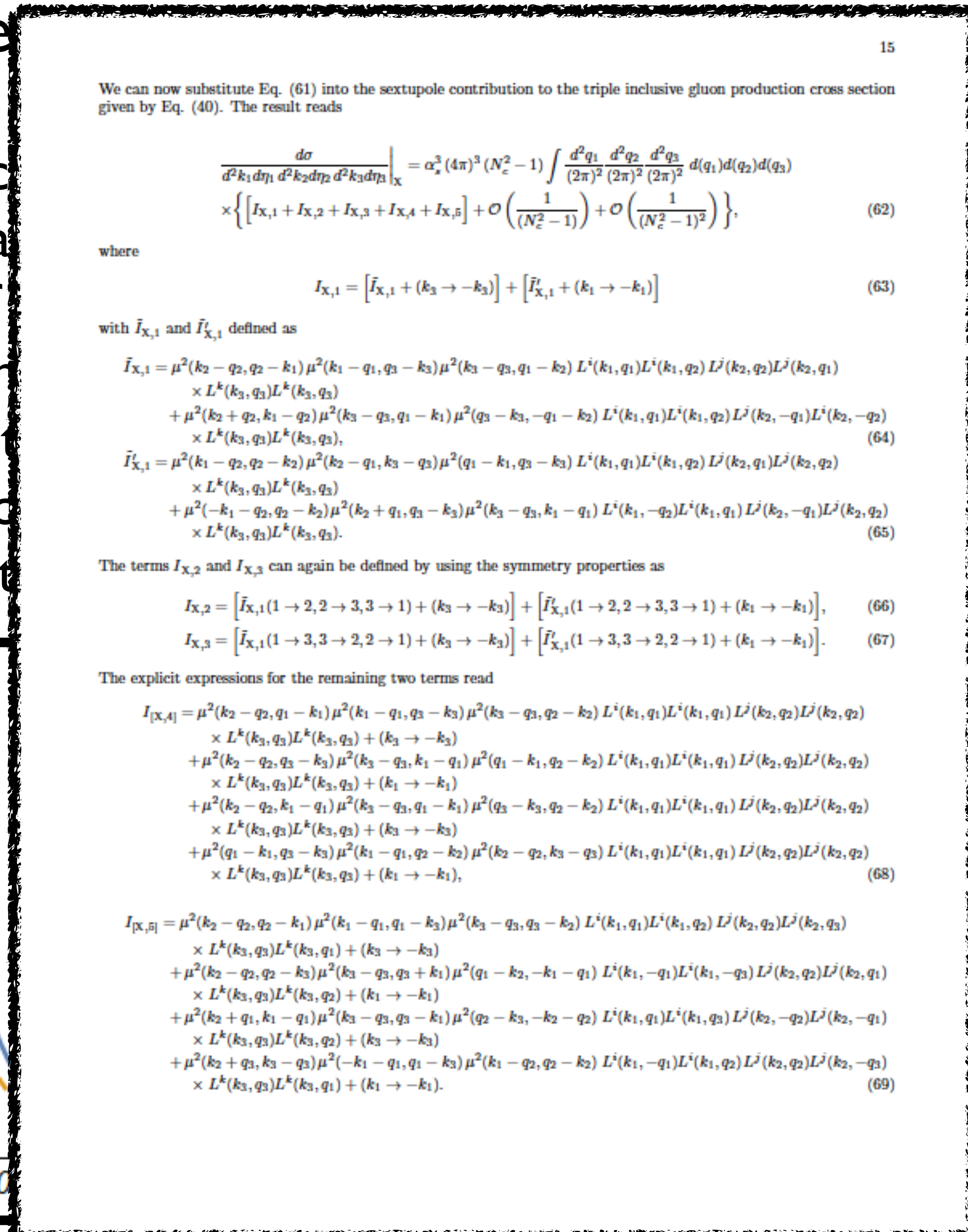


$x_2)\rho^{b_1}(y_1)\rho^{b_2}(y_2)\rangle_P$

$-U^\dagger(y_2)]^{db_2}\rangle_T$.

$\frac{}{1}d(x,z)d(y,v)$,

$,z)+d(x,z)d(v,y)]$.



15

We can now substitute Eq. (61) into the sextupole contribution to the triple inclusive gluon production cross section given by Eq. (40). The result reads

$$\left.\frac{d\sigma}{d^2k_1d\eta_1\,d^2k_2d\eta_2\,d^2k_3d\eta_3}\right|_{\rm X}=\alpha_s^3\,(4\pi)^3\,(N_c^2-1)\int\frac{d^2q_1}{(2\pi)^2}\frac{d^2q_2}{(2\pi)^2}\frac{d^2q_3}{(2\pi)^2}\,d(q_1)d(q_2)d(q_3)$$
$$\times\left\{\left[I_{\rm X,1}+I_{\rm X,2}+I_{\rm X,3}+I_{\rm X,4}+I_{\rm X,5}\right]+\mathcal{O}\left(\frac{1}{(N_c^2-1)}\right)+\mathcal{O}\left(\frac{1}{(N_c^2-1)^2}\right)\right\}, \quad (62)$$

where

$$I_{\rm X,1}=\left[\bar I_{\rm X,1}+(k_3\to -k_3)\right]+\left[\bar I'_{\rm X,1}+(k_1\to -k_1)\right] \quad (63)$$

with $\bar I_{\rm X,1}$ and $\bar I'_{\rm X,1}$ defined as

$$\begin{aligned}\bar I_{\rm X,1}=&\,\mu^2(k_2-q_2,q_2-k_1)\,\mu^2(k_1-q_1,q_3-k_3)\,\mu^2(k_3-q_3,q_1-k_2)\,L^i(k_1,q_1)L^i(k_1,q_2)\,L^j(k_2,q_2)L^j(k_2,q_1)\\&\times L^k(k_3,q_3)L^k(k_3,q_3)\\&+\mu^2(k_2+q_2,k_1-q_2)\,\mu^2(k_3-q_3,q_1-k_1)\,\mu^2(q_3-k_3,-q_1-k_2)\,L^i(k_1,q_1)L^i(k_1,q_2)\,L^j(k_2,-q_1)L^i(k_2,-q_2)\\&\times L^k(k_3,q_3)L^k(k_3,q_3), \quad (64)\\ \bar I'_{\rm X,1}=&\,\mu^2(k_1-q_2,q_2-k_2)\,\mu^2(k_2-q_1,k_3-q_3)\,\mu^2(q_1-k_1,q_3-k_3)\,L^i(k_1,q_1)L^i(k_1,q_2)\,L^j(k_2,q_1)L^j(k_2,q_2)\\&\times L^k(k_3,q_3)L^k(k_3,q_3)\\&+\mu^2(-k_1-q_2,q_2-k_2)\,\mu^2(k_2+q_1,q_3-k_3)\,\mu^2(k_3-q_3,k_1-q_1)\,L^i(k_1,-q_2)L^i(k_1,q_1)\,L^j(k_2,-q_1)L^j(k_2,q_2)\\&\times L^k(k_3,q_3)L^k(k_3,q_3). \quad (65)\end{aligned}$$

The terms $I_{\rm X,2}$ and $I_{\rm X,3}$ can again be defined by using the symmetry properties as

$$I_{\rm X,2}=\left[\bar I_{\rm X,1}(1\to 2,2\to 3,3\to 1)+(k_3\to -k_3)\right]+\left[\bar I'_{\rm X,1}(1\to 2,2\to 3,3\to 1)+(k_1\to -k_1)\right], \quad (66)$$
$$I_{\rm X,3}=\left[\bar I_{\rm X,1}(1\to 3,3\to 2,2\to 1)+(k_3\to -k_3)\right]+\left[\bar I'_{\rm X,1}(1\to 3,3\to 2,2\to 1)+(k_1\to -k_1)\right]. \quad (67)$$

The explicit expressions for the remaining two terms read

$$\begin{aligned}I_{\rm [X,4]}=&\,\mu^2(k_2-q_2,q_1-k_1)\,\mu^2(k_1-q_1,q_3-k_3)\,\mu^2(k_3-q_3,q_2-k_2)\,L^i(k_1,q_1)L^i(k_1,q_1)\,L^j(k_2,q_2)L^j(k_2,q_2)\\&\times L^k(k_3,q_3)L^k(k_3,q_3)+(k_3\to -k_3)\\&+\mu^2(k_2-q_2,q_3-k_3)\,\mu^2(k_3-q_3,k_1-q_1)\,\mu^2(q_1-k_1,q_2-k_2)\,L^i(k_1,q_1)L^i(k_1,q_1)\,L^j(k_2,q_2)L^j(k_2,q_2)\\&\times L^k(k_3,q_3)L^k(k_3,q_3)+(k_1\to -k_1)\\&+\mu^2(k_2-q_2,k_1-q_1)\,\mu^2(k_3-q_3,q_1-k_1)\,\mu^2(q_3-k_3,q_2-k_2)\,L^i(k_1,q_1)L^i(k_1,q_1)\,L^j(k_2,q_2)L^j(k_2,q_2)\\&\times L^k(k_3,q_3)L^k(k_3,q_3)+(k_3\to -k_3)\\&+\mu^2(q_1-k_1,q_3-k_3)\,\mu^2(k_1-q_1,q_2-k_2)\,\mu^2(k_2-q_2,k_3-q_3)\,L^i(k_1,q_1)L^i(k_1,q_1)\,L^j(k_2,q_2)L^j(k_2,q_2)\\&\times L^k(k_3,q_3)L^k(k_3,q_3)+(k_1\to -k_1), \quad (68)\end{aligned}$$

$$\begin{aligned}I_{\rm [X,5]}=&\,\mu^2(k_2-q_2,q_2-k_1)\,\mu^2(k_1-q_1,q_1-k_3)\,\mu^2(k_3-q_3,q_3-k_2)\,L^i(k_1,q_1)L^i(k_1,q_2)\,L^j(k_2,q_2)L^j(k_2,q_3)\\&\times L^k(k_3,q_3)L^k(k_3,q_1)+(k_3\to -k_3)\\&+\mu^2(k_2-q_2,q_2-k_3)\,\mu^2(k_3-q_3,q_3+k_1)\,\mu^2(q_1-k_2,-k_1-q_1)\,L^i(k_1,-q_1)L^i(k_1,-q_3)\,L^j(k_2,q_2)L^j(k_2,q_1)\\&\times L^k(k_3,q_3)L^k(k_3,q_2)+(k_1\to -k_1)\\&+\mu^2(k_2+q_1,k_1-q_1)\,\mu^2(k_3-q_3,q_3-k_1)\,\mu^2(q_2-k_3,-k_2-q_2)\,L^i(k_1,q_1)L^i(k_1,q_3)\,L^j(k_2,-q_2)L^j(k_2,-q_1)\\&\times L^k(k_3,q_3)L^k(k_3,q_2)+(k_3\to -k_3)\\&+\mu^2(k_2+q_3,k_3-q_3)\,\mu^2(-k_1-q_1,q_1-k_3)\,\mu^2(k_1-q_2,q_2-k_2)\,L^i(k_1,-q_1)L^i(k_1,q_2)\,L^j(k_2,q_2)L^j(k_2,-q_3)\\&\times L^k(k_3,q_3)L^k(k_3,q_1)+(k_1\to -k_1). \quad (69)\end{aligned}$$

Other approaches: MPIs

- Multiple (partonic) interactions were known to create rapidity correlations since the 70's (Capella et al., Levin et al.).
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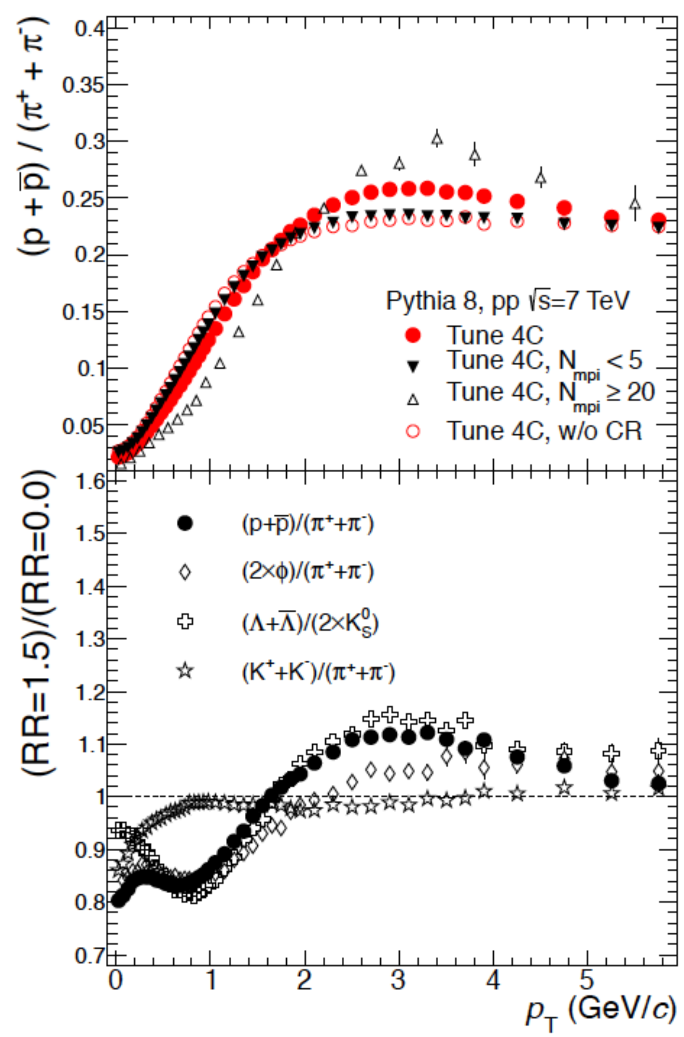
1303.6326



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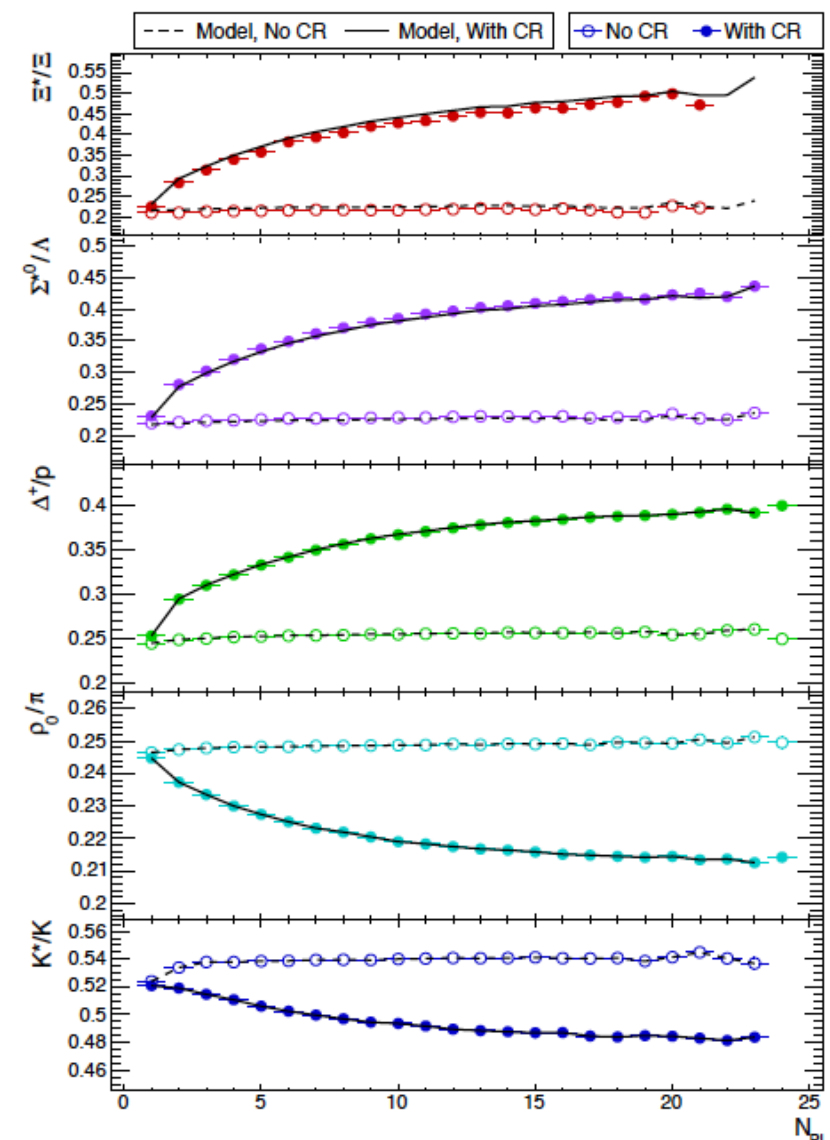

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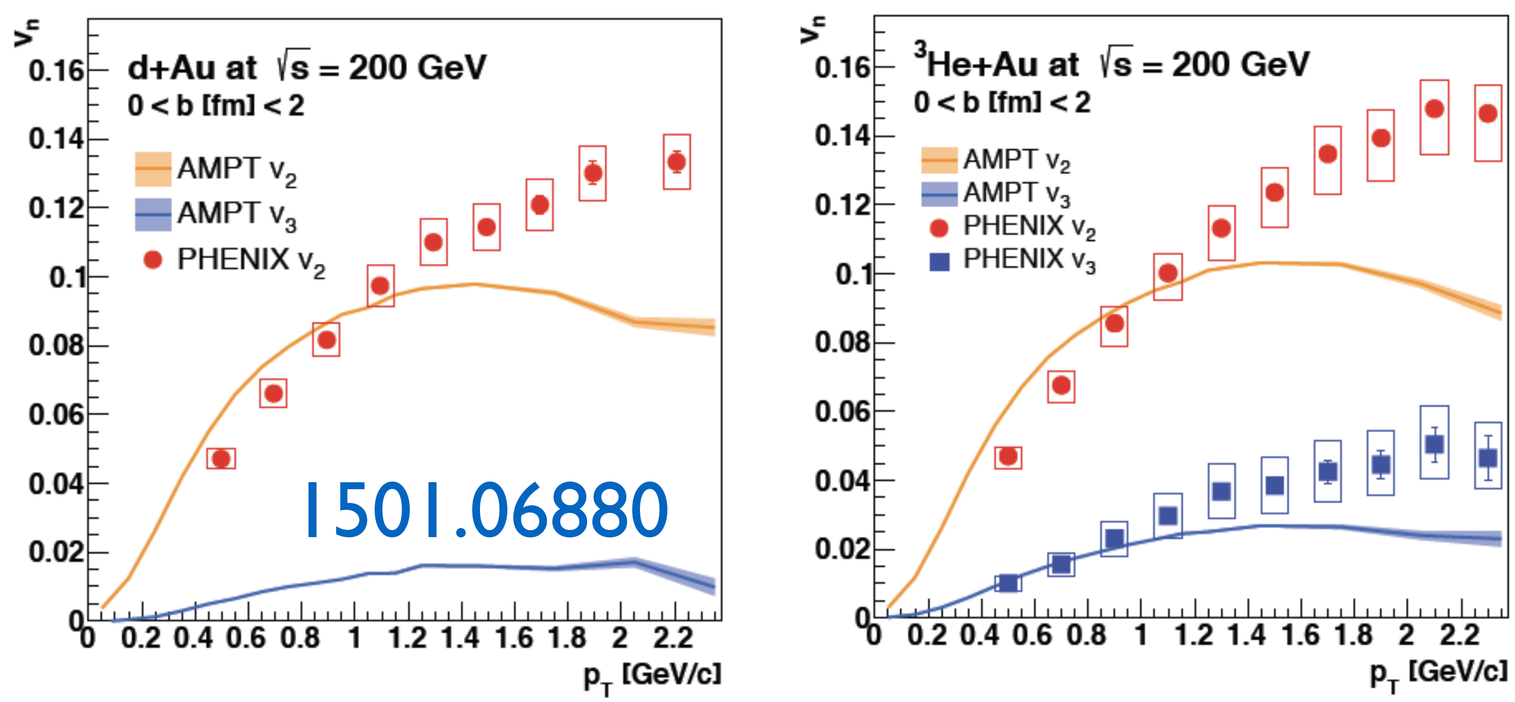

Other approaches: MPIs

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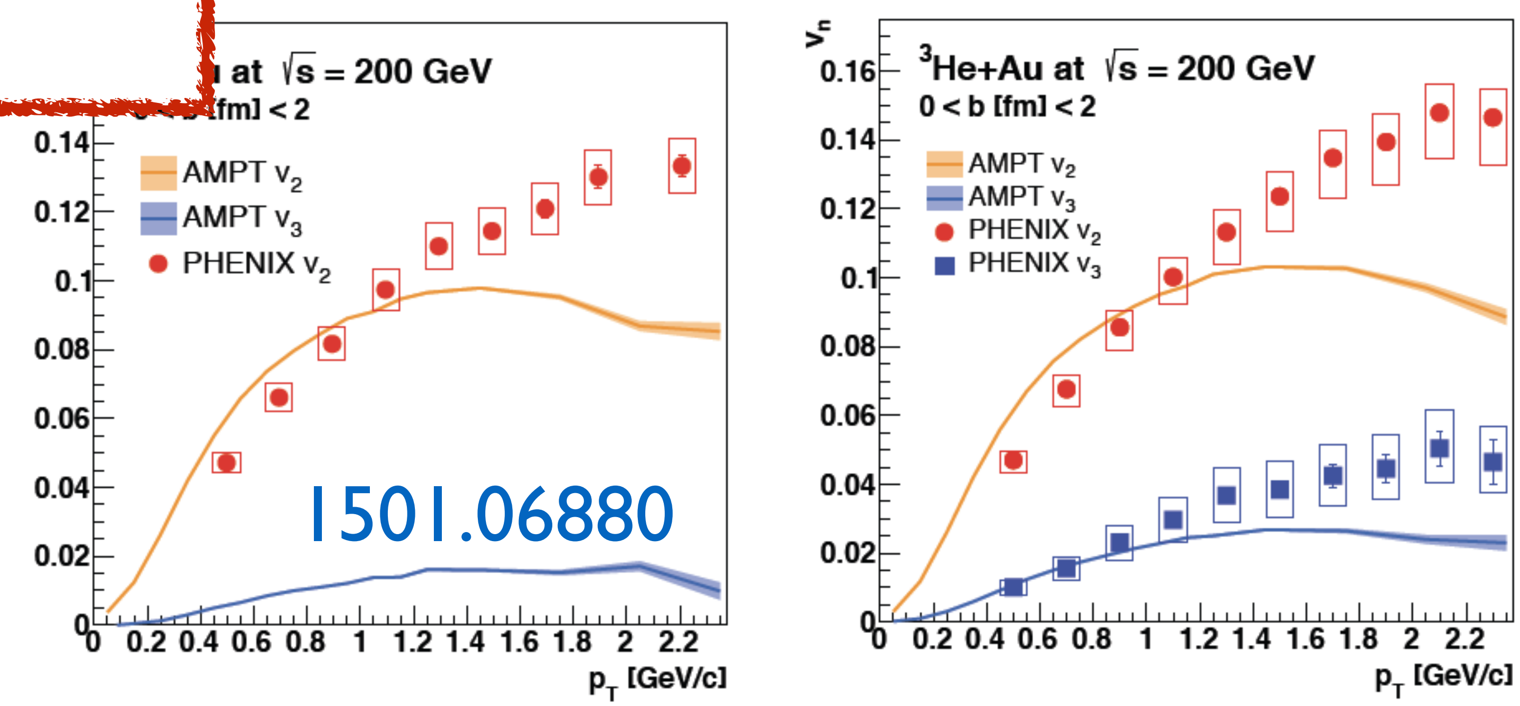
all, AA MC models: DPMJET,

Note: multiple scattering is contained in the CGC but, usually, when we talk about MPIs we refer to a collinear framework where a knowledge of multiple parton densities is required: hybrid model (1701.00494).

enhancement.

- Other formulations: string percolation (Pajares et al.), colour ropes (RQMD, AMPT), dipole swing (in DIPSY), string effect (Brodsky et al.),…



The onset of collectivity:

- A most crucial question is when a collective behaviour appears i.e. how small a system may be while still showing collective behaviour.
- Smaller than pp: eA/ep and e^+e^- (remember CR in WW events).

- 1707.02307:
one string / two (0.5 fm apart) in AMPT, azimuthal asymmetries led by rescatterings, as in pp/AA.

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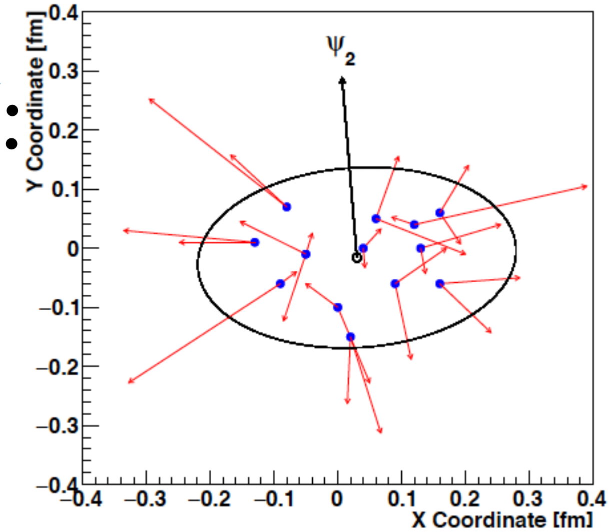
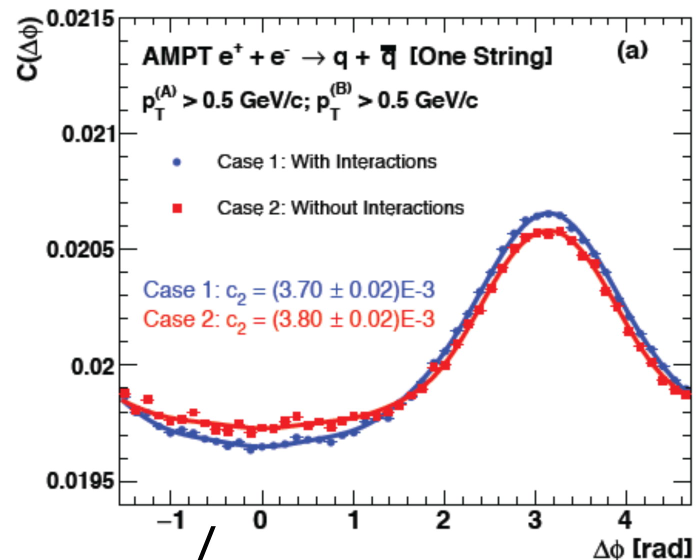
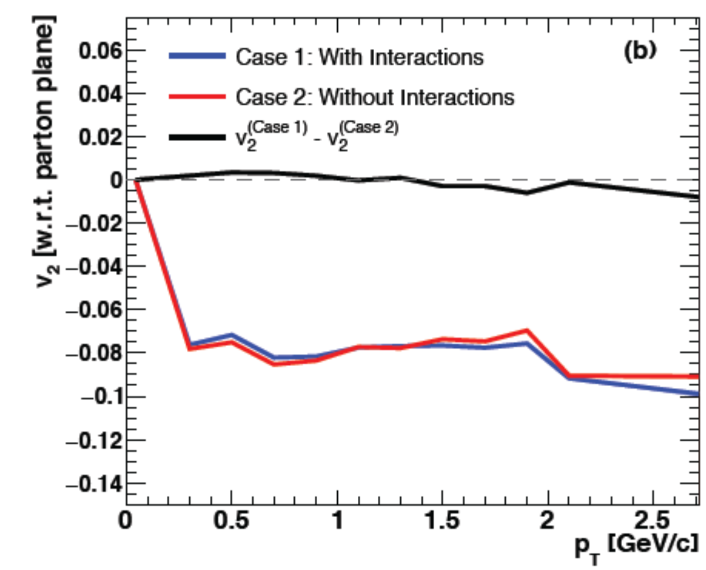
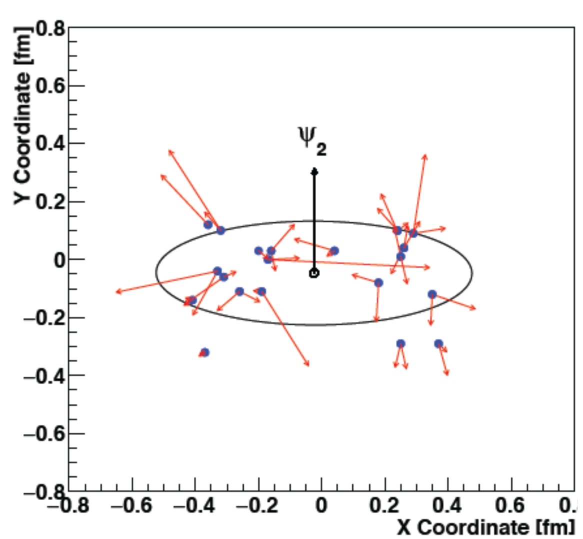
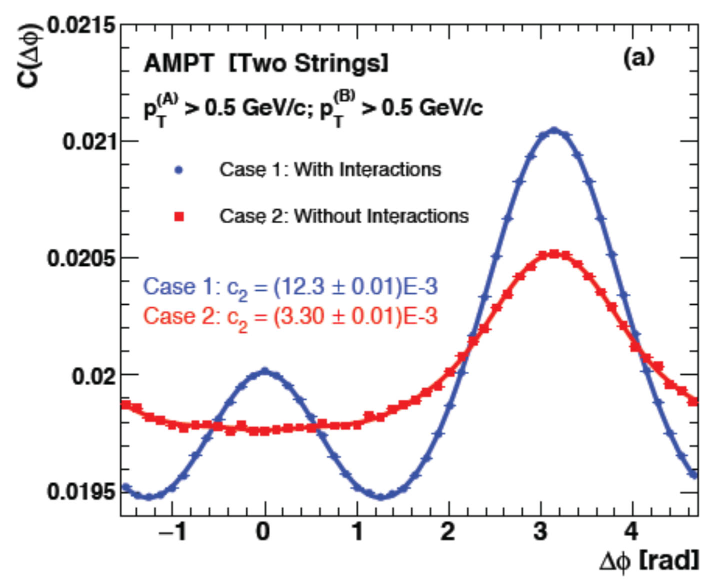


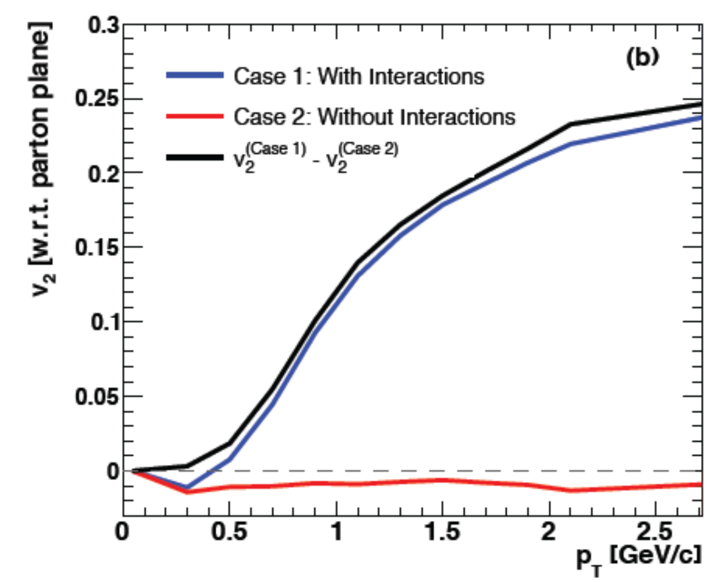




$\sqrt{s}=m_Z$







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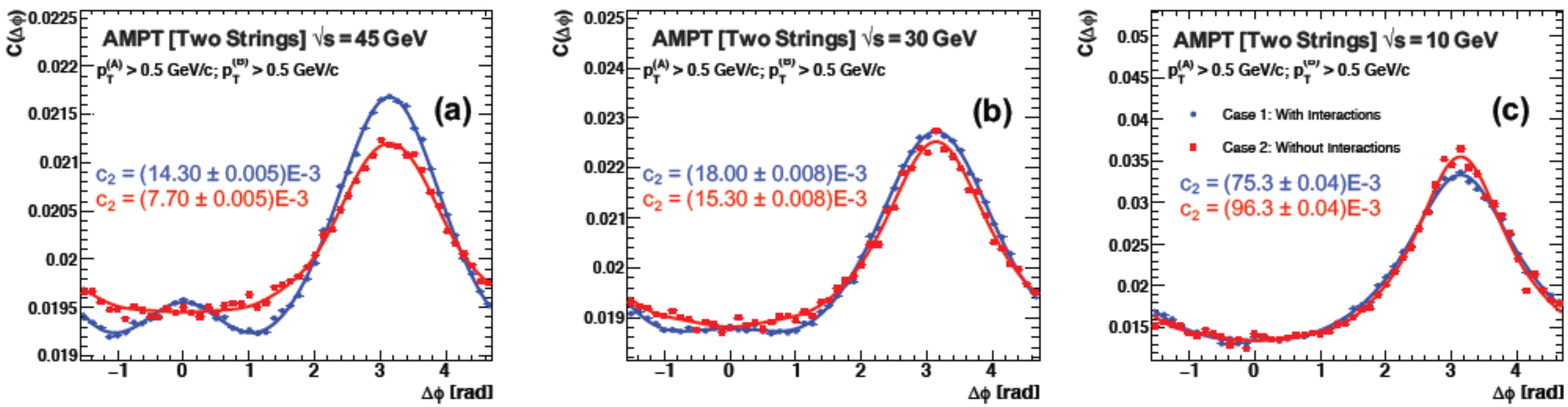

Energy (GeV)	$N_{partons}$ -	$dN_{ch}/d\eta$ ($\|\eta\| < 2$)	% of Partons w/ $N_{scatter} > 0$
184	95	11.6	40.4%
91	75	11.2	40.3%
60	63	10.5	39.2%
45	55	9.7	38.7%
30	44	8.3	37.6%
10	19	6.5	24.6%
4.5	9	3.7	11.3%

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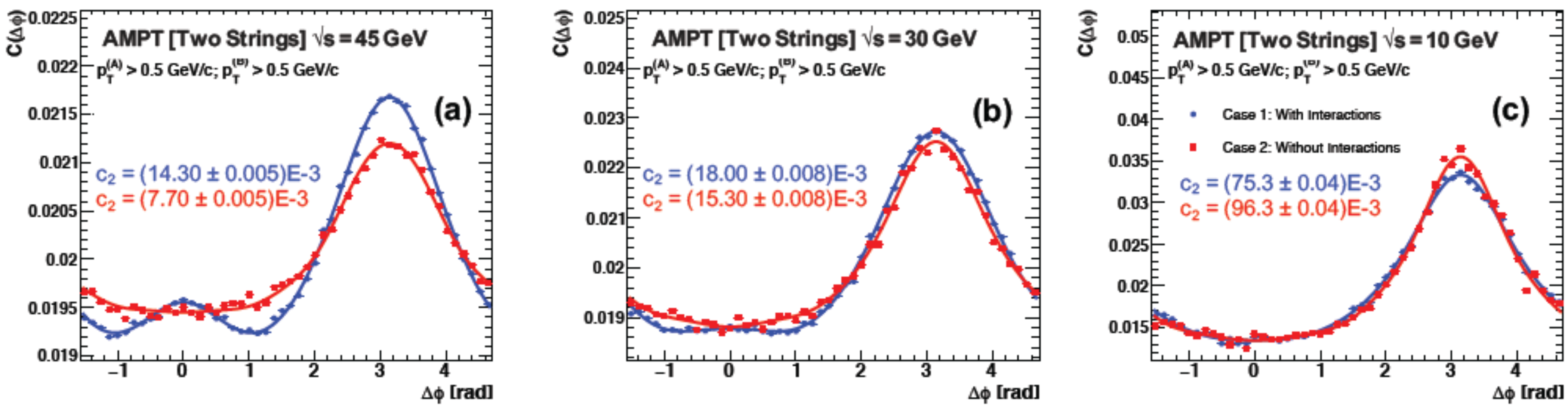

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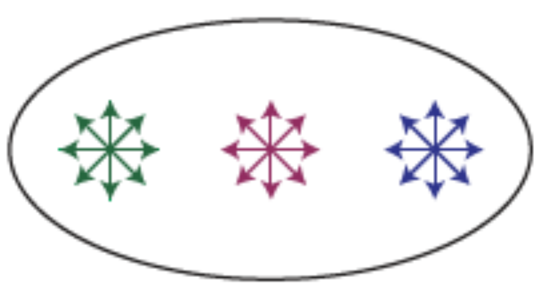
- It seems to be the combination of large enough # of partons/ particles + more than one source that works.

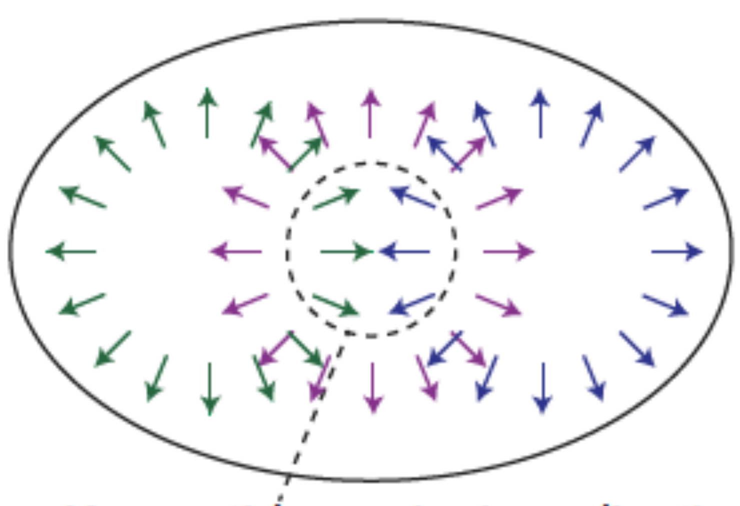
Transport theory versus hydro:

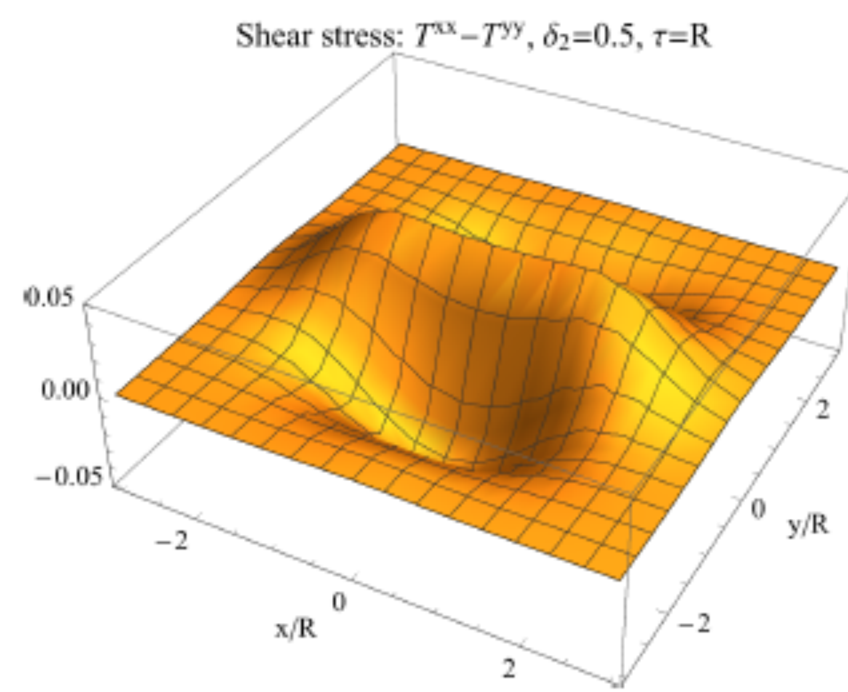
• Recently proposed that in small systems, kinetic theory looks more sensible that hydro: one-hit dynamics to produce anisotropies (linear and non linear response), milder dependence on initial conditions,… relevant to determine η/s. [1803.02072, 1805.04081]

$$\hat{\gamma} = R/l_{mfp}, \quad l_{mfp} = (\gamma \epsilon^{1/4})^{-1} = \tau_\pi$$

$$F(\vec{x}_\perp, \phi, \tau_0) = 2\varepsilon_0\, \delta(v_z)\, \exp\left[-\frac{r^2}{R^2}\right] \left(1 + \delta_2 \frac{r^2}{R^2} \cos 2\theta\right)$$







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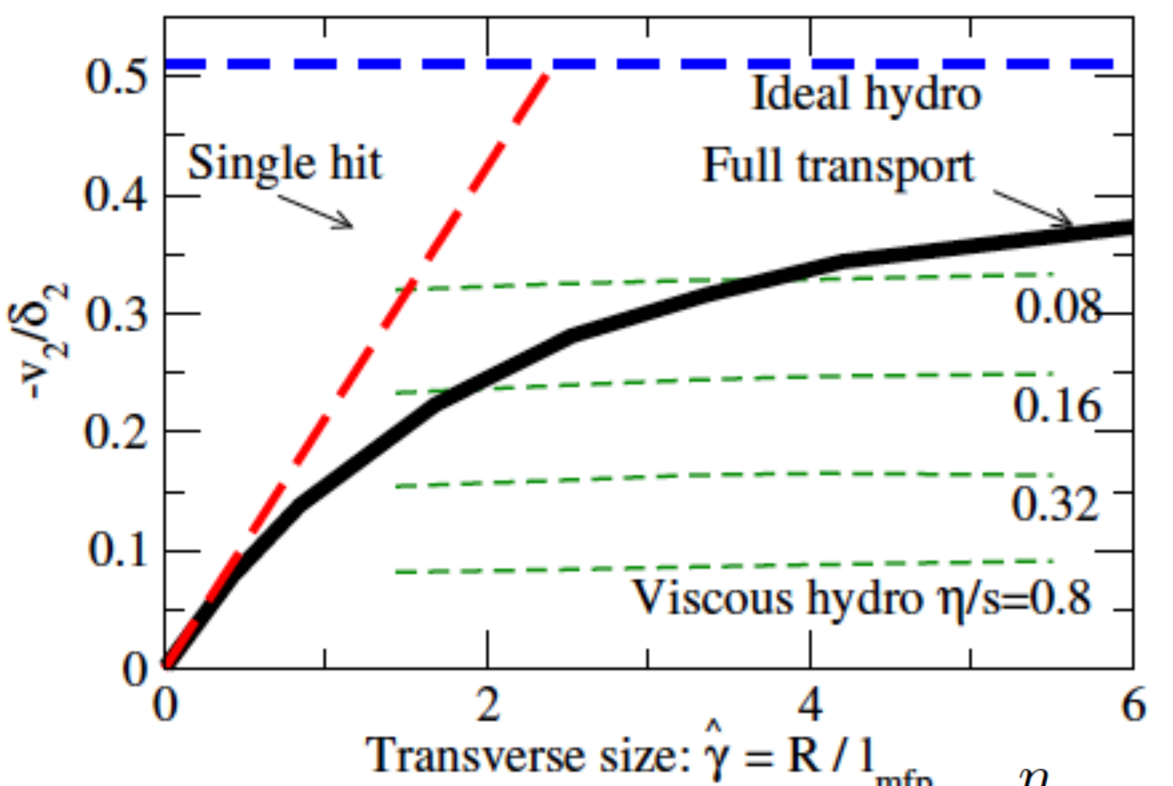
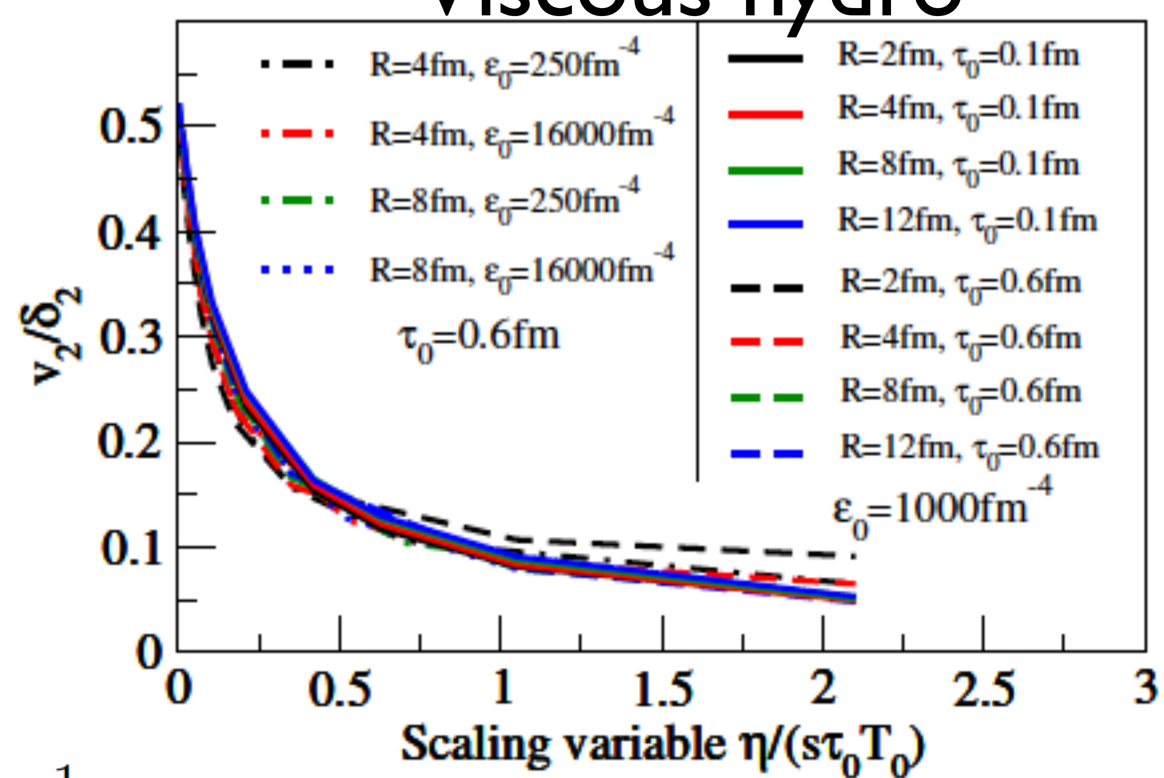


Viscous hydro



$$\frac{\eta}{sT} = \frac{1}{\gamma\epsilon^{1/4}}\frac{1}{5}$$

- Kinetic theory, free for these ambiguities ⇒ larger values of η/s.

Summary:

• Initial stages contain nowadays several of the most striking uncertainties in the field: onset of collectivity? → macroscopic description versus microscopic dynamics.

• The continuity of the physics between small and large systems is motivating a change of paradigm in heavy-ion physics.

• Hydro provides a good description but fine tuning is required (dependence on initial conditions, subnucleon structure).

• Alternatives exist: microscopic calculations in CGC, kinetic theory, in the weak coupling domain.

Is there a relation between both? How emergence works in QCD?

Summary:

Thanks a lot to the organisers for the invitation and you all for your attention!

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