Di-jets at the EIC: probing gluons inside nuclei

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BROOKHAVEN NATIONAL LABORATORY

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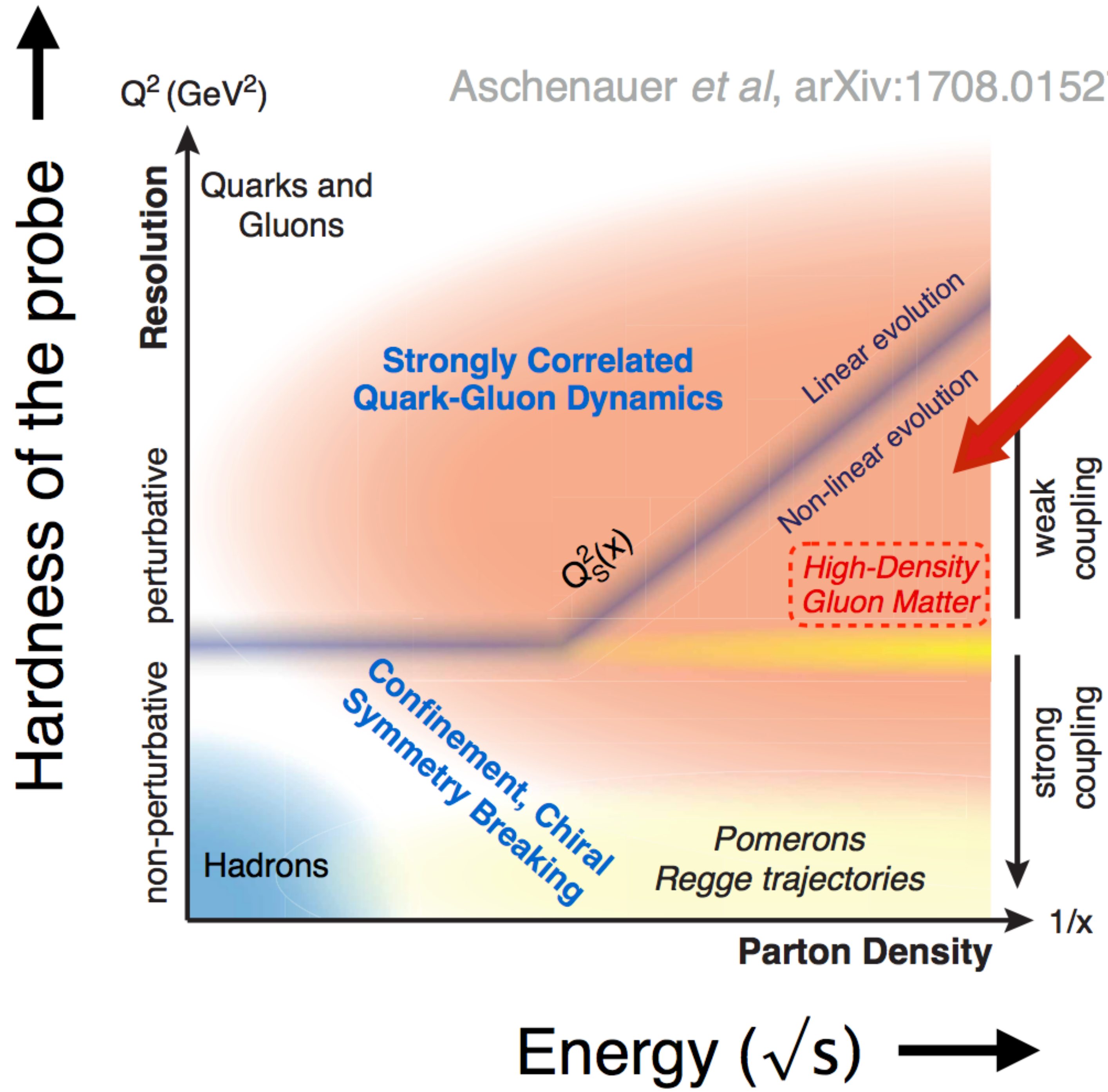
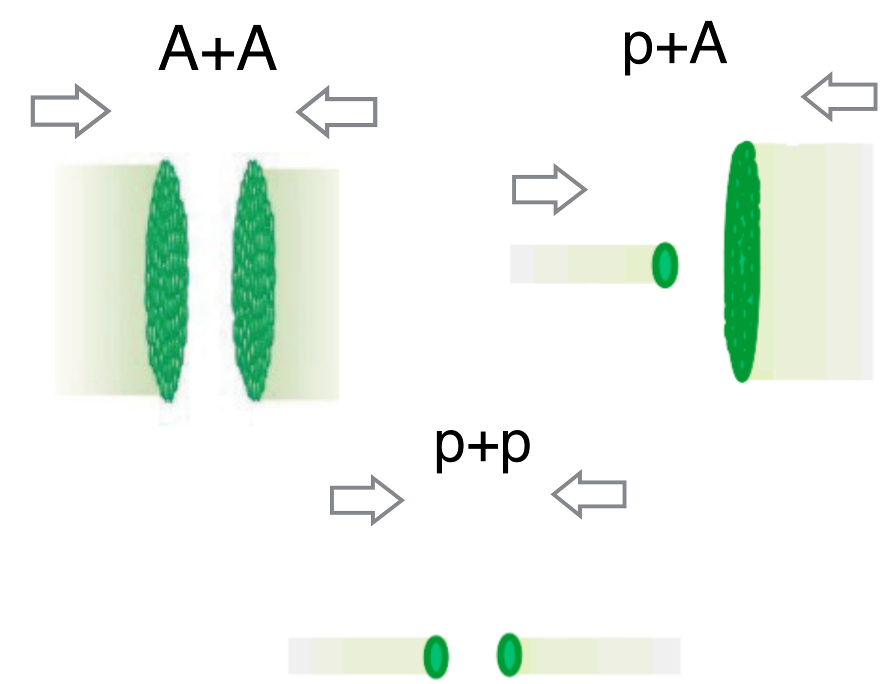
U.S. DEPARTMENT OF ENERGY | Office of Science

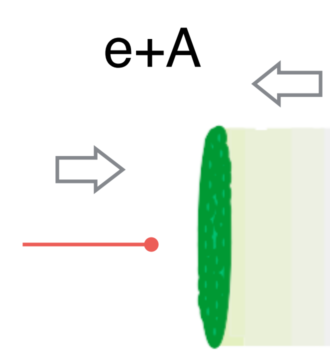
The landscape of QCD



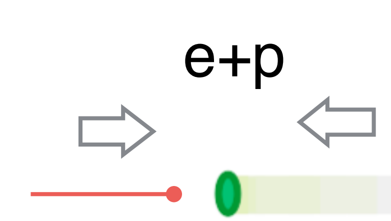
RHIC and LHC (present days)



Future (EIC)

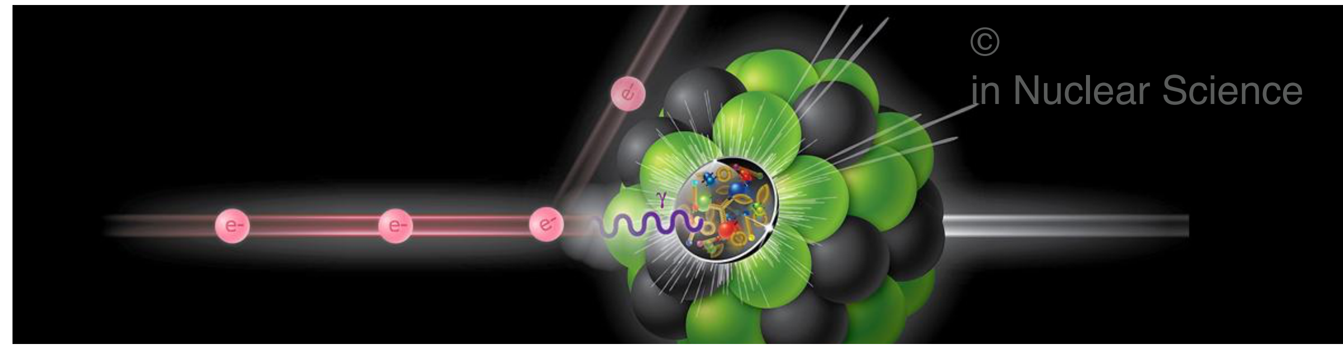


Past (HERA)



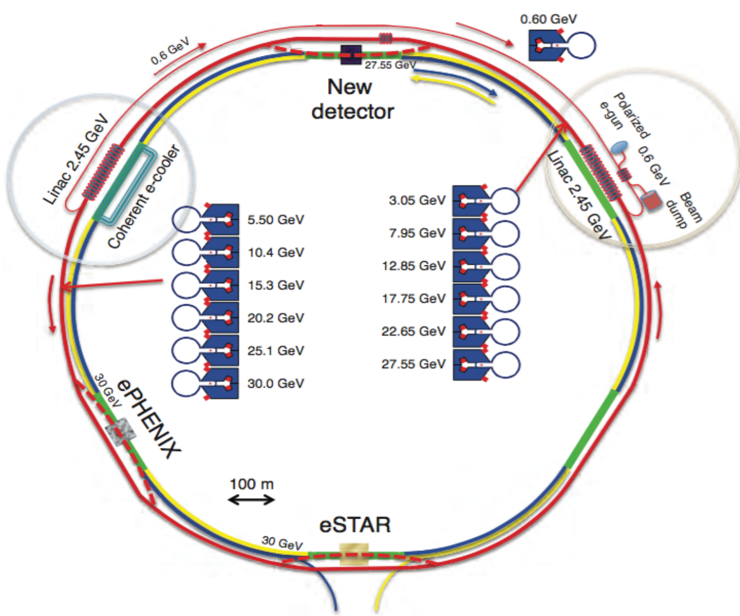
p+p,p/A+A probe the landscape but e+p, e+A do in most controlled way

The future Electron Ion Collider

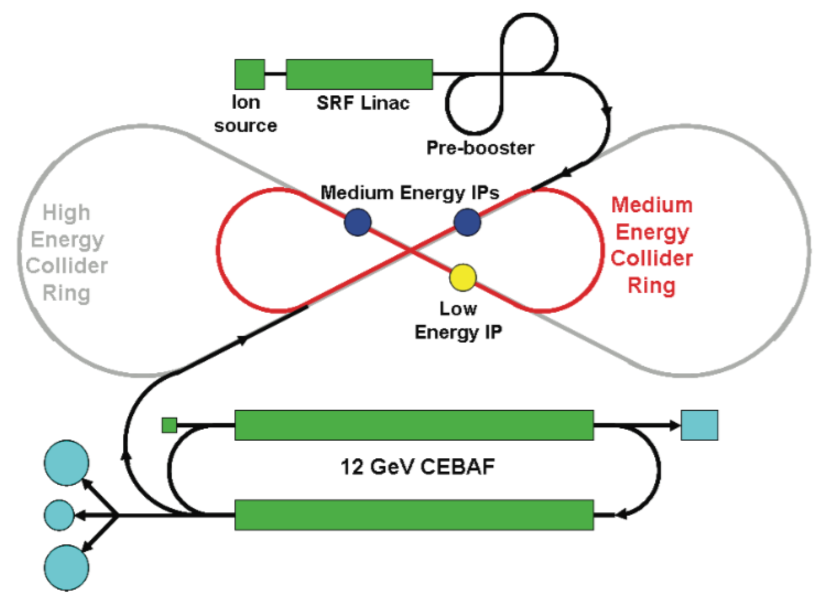


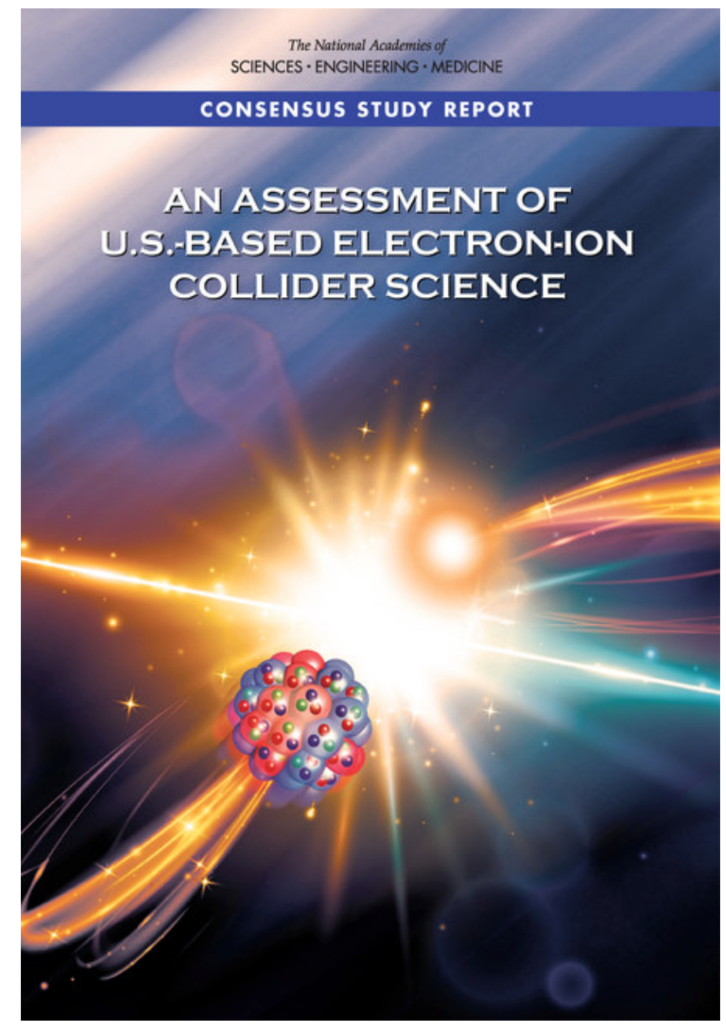
Two concepts have been proposed

eRHIC @ BNL



ELIC @ JLAB





Construction of a U.S.-based Electron Ion collider is a priority for the next decade — NAS review

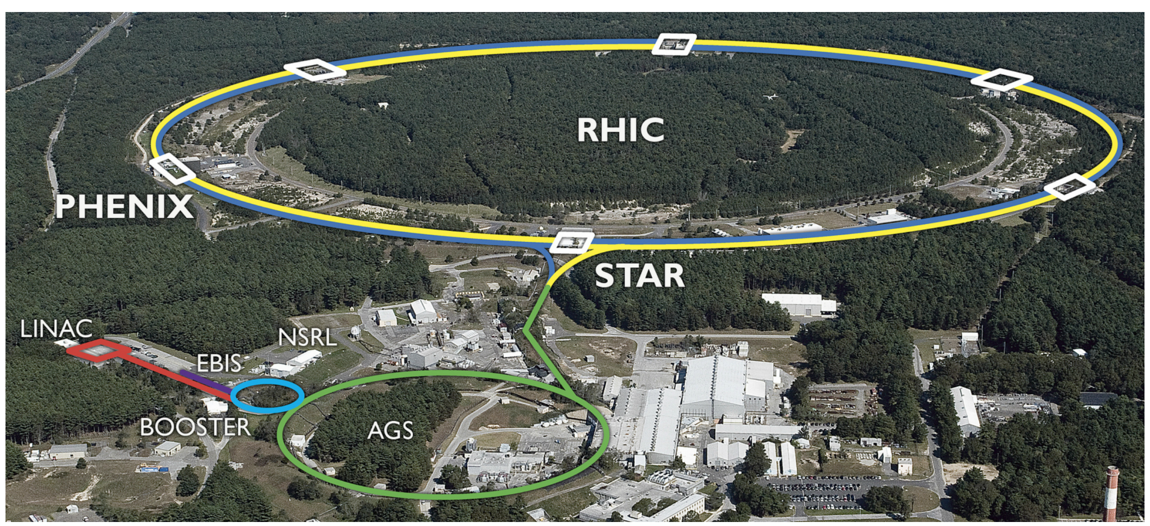
EIC white paper: Accardi

https://doi.org/10.17226/25171

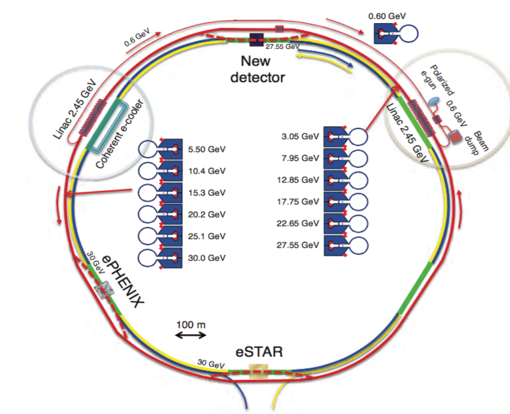
Transition to an EIC era

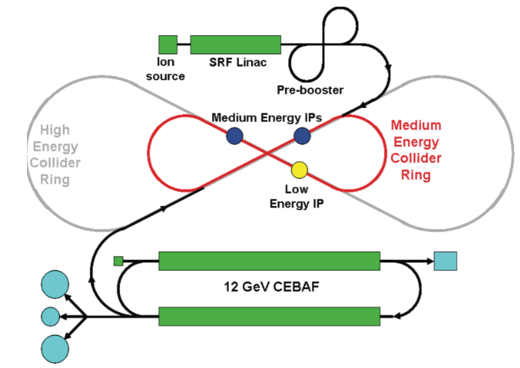
We are in the middle of a transition

RHIC-era



EIC-era





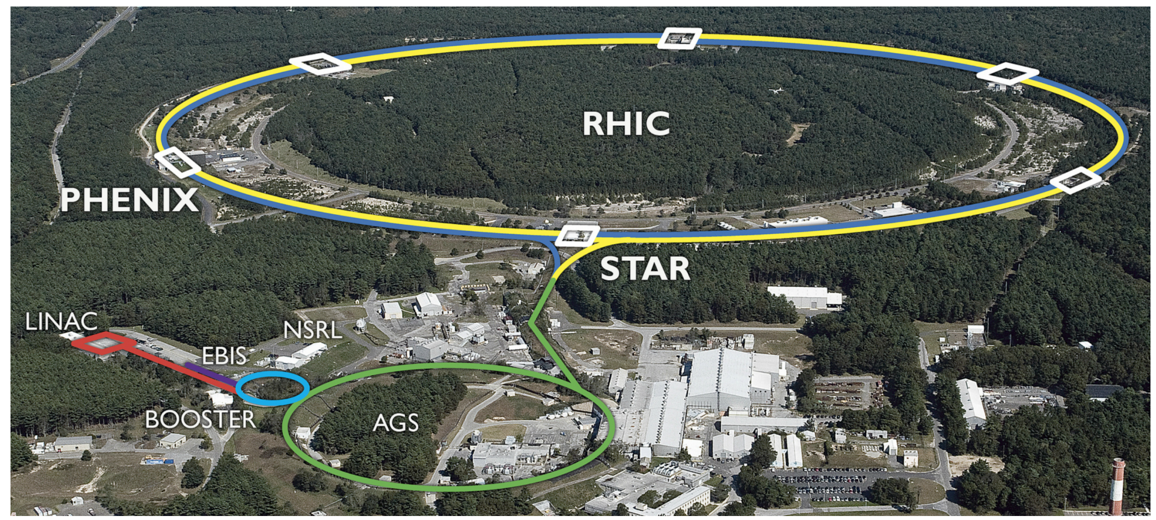
What insight do we heavy ion physicists bring in ?

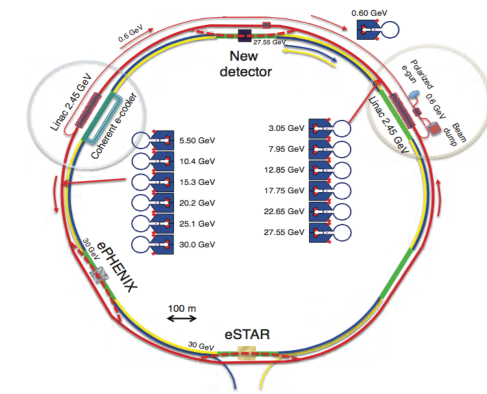
Transition to an EIC era

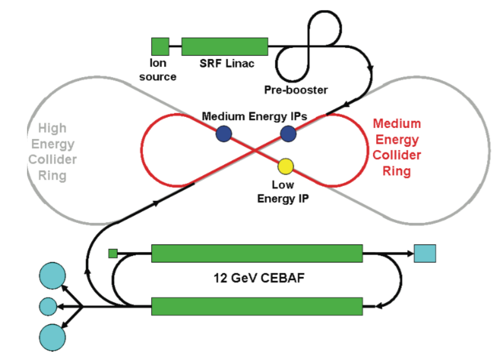
EIC

HERA

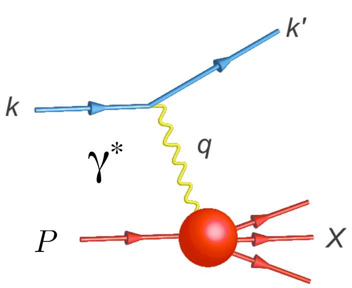
RHIC/LHC

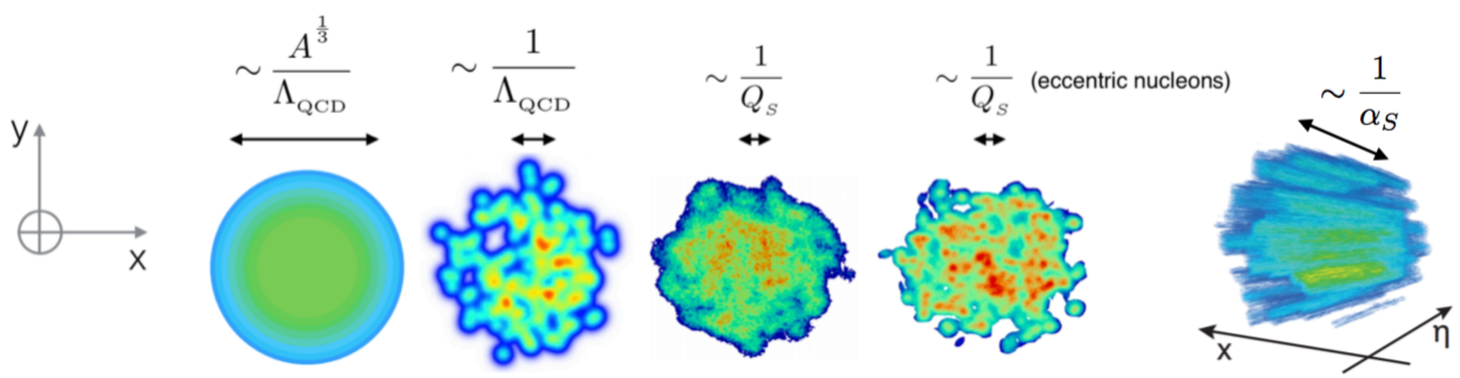


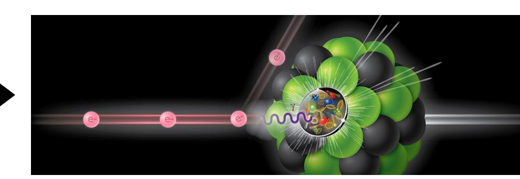




RHIC era changed our view of nuclei at high energies





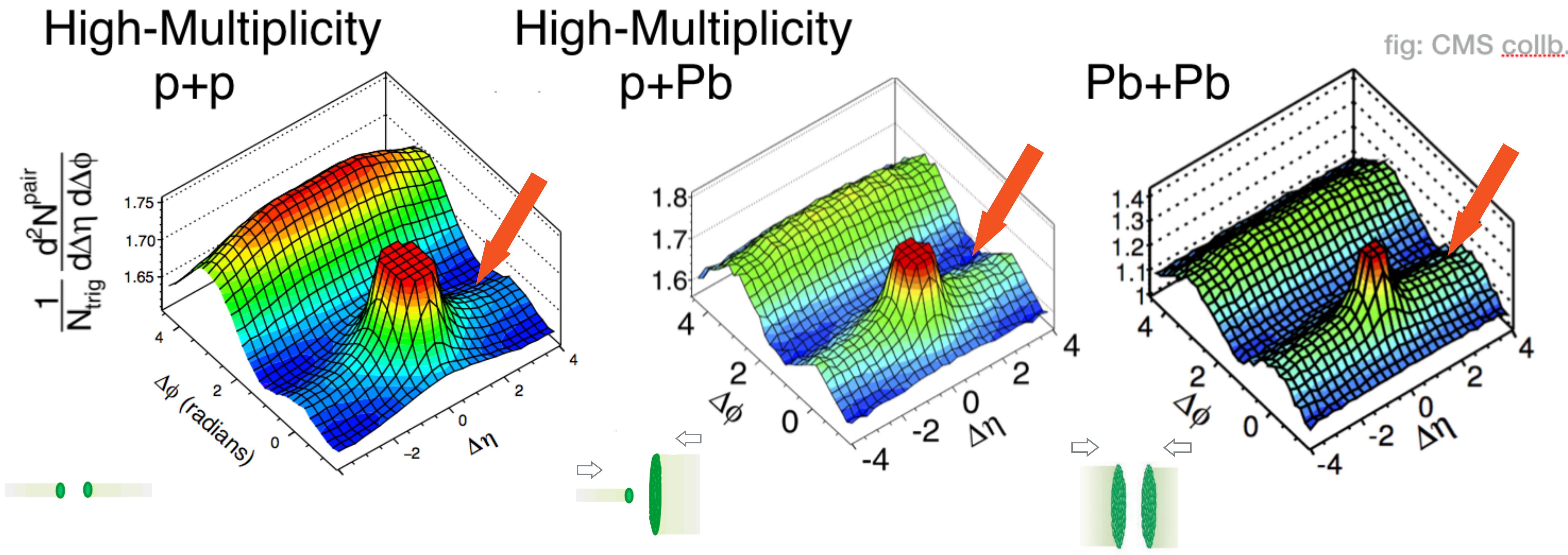


· · · · · **2007** · · · 2004 2008-10 2012-14 2016 · · · **2015-25** · · · · · **2029** · · · · ·

Can our knowledge of colliding nuclei make a difference to EIC physics?

Can our knowledge of correlation measurements make a difference ?

Di-hadron correlations : ridge + di-jets



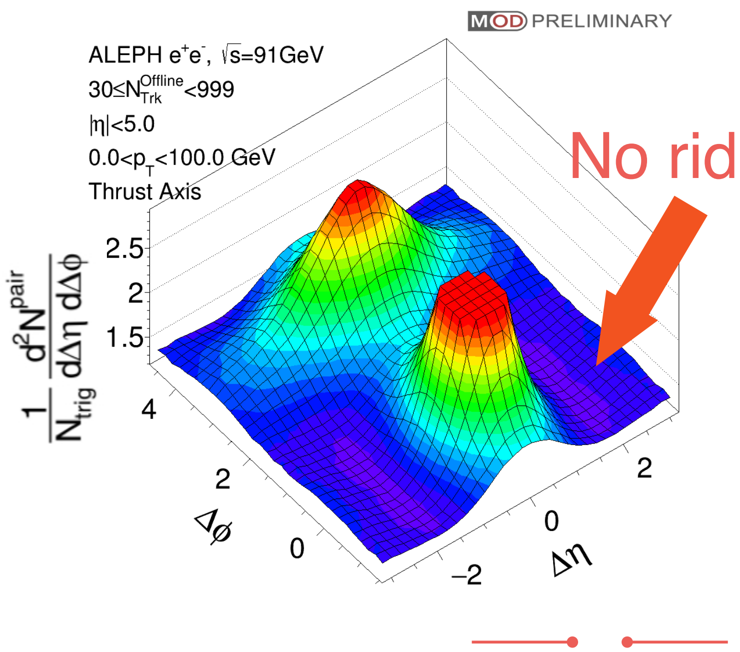
Di-hadron correlations is a very striking and widely studied phenomena :

Di-hadron correlations in relative pseudorapidity (Δη) & azimuth (Δφ)
High multiplicity p+p/A → strikingly similar to A+A

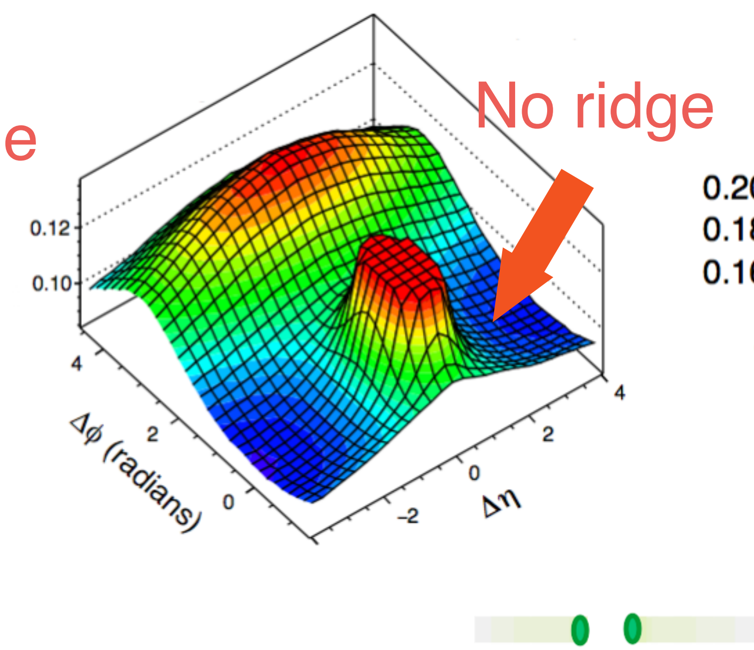
Di-hadron correlations across systems

Y-J. Lee, QM’18

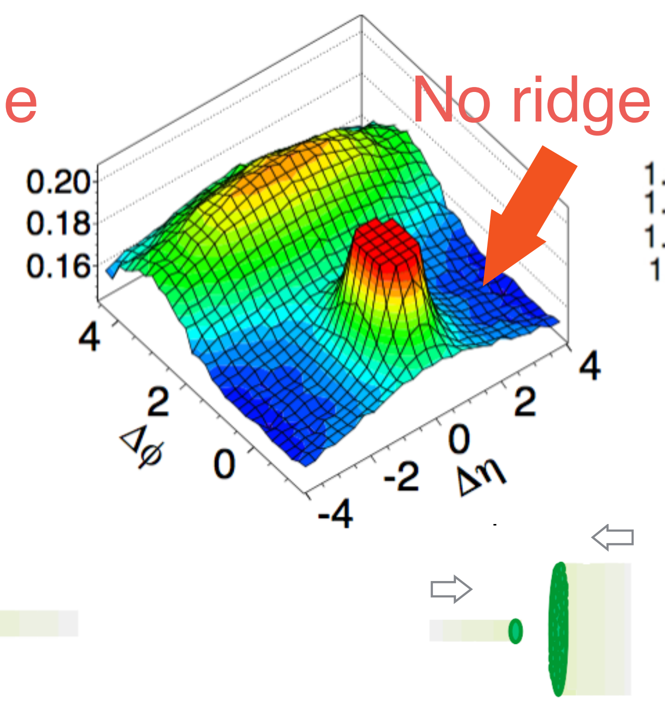
e^++e^-



Low multiplicity
p+p

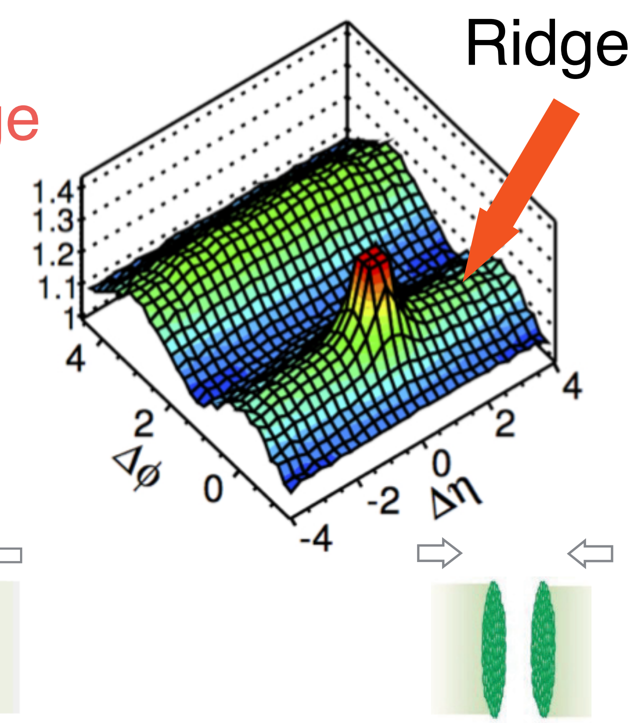


Low multiplicity
p+A



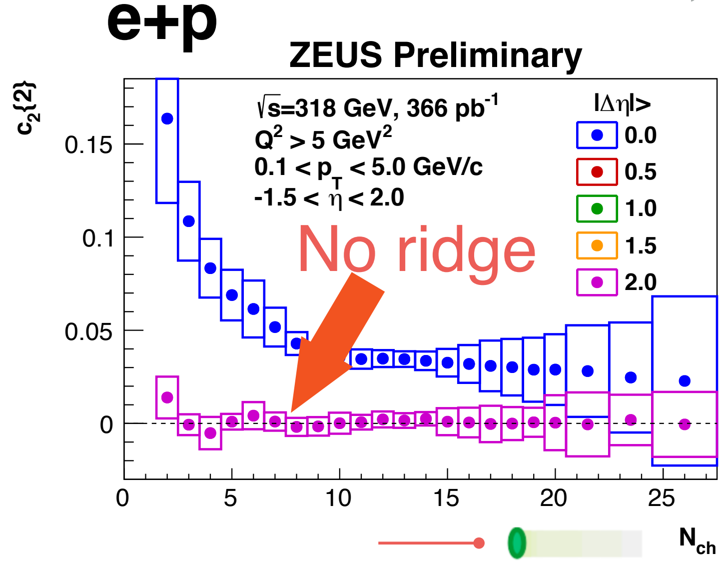
CMS collaboration

A+A



J. Onderwaater, QM’18

e+p



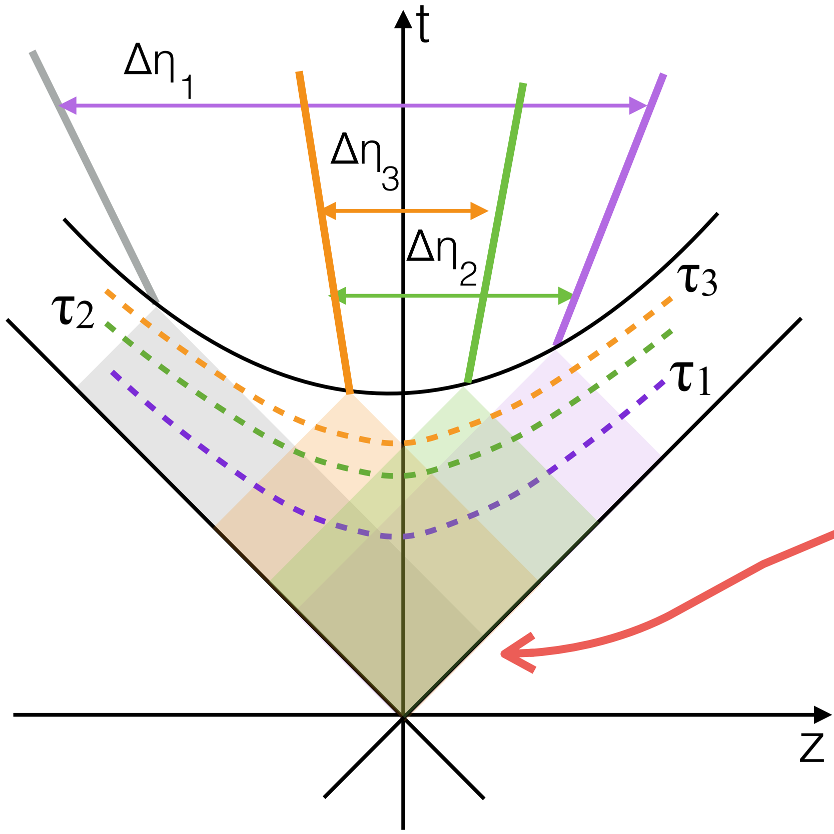
No ridge appears in e+e, e+p, similar to low multiplicity p+p/A collisions

Interesting systematics with collisions system (this also tell us a lot)

Di-hadron correlations : ridge + di-jets

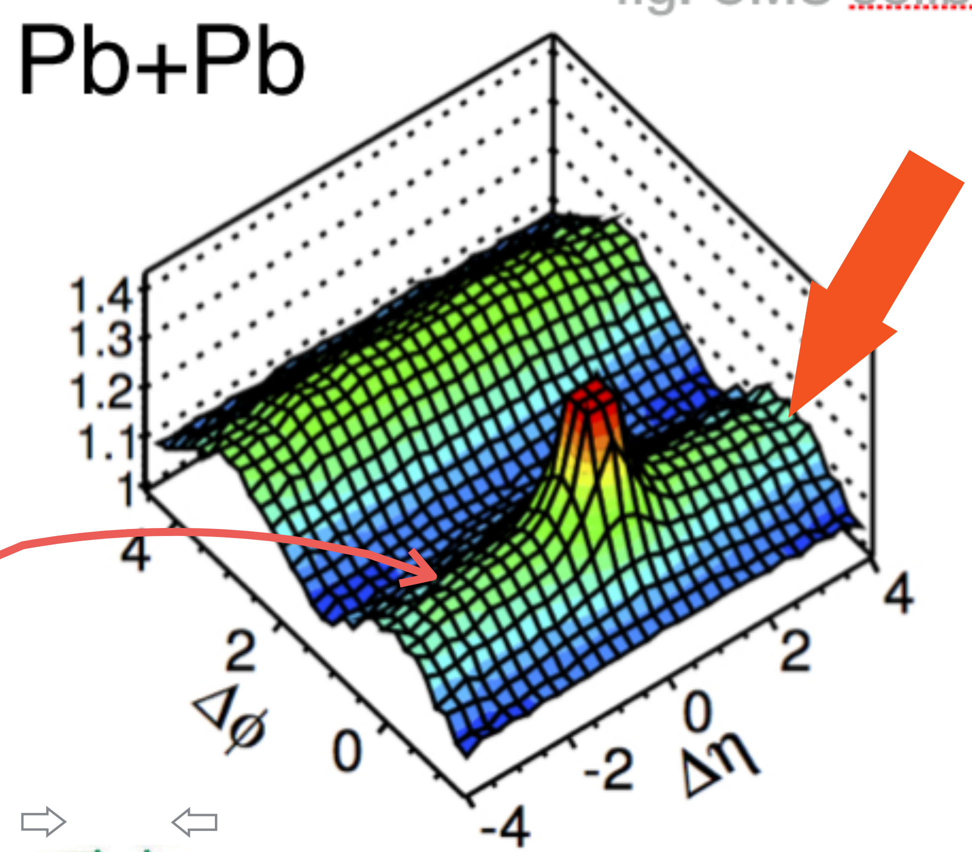
Most well understood are the measurements in A+A

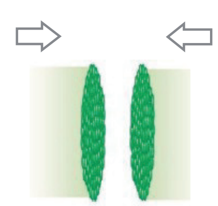
$$\tau_{\text{init.}} = \tau_{\text{f.o.}} \exp\left(-\frac{1}{2}\Delta y\right)$$



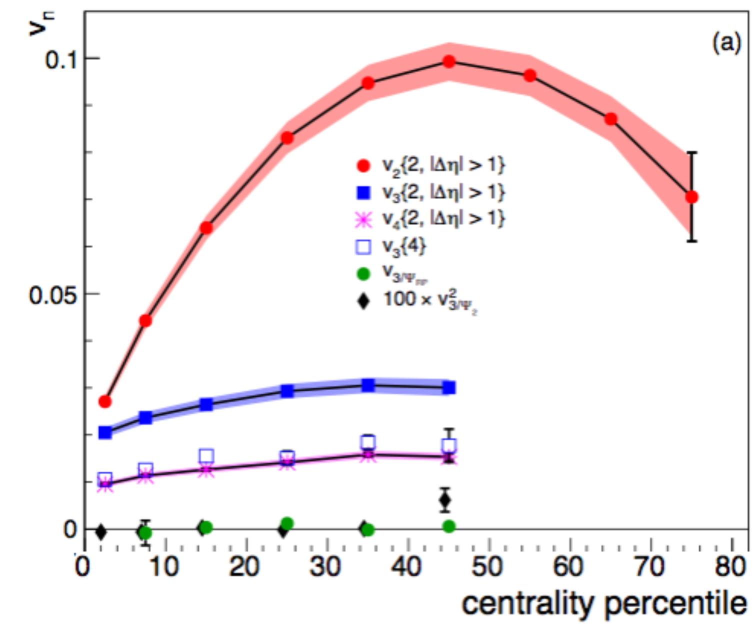
Dumitru et al, 1009.5295

fig: CMS collb.





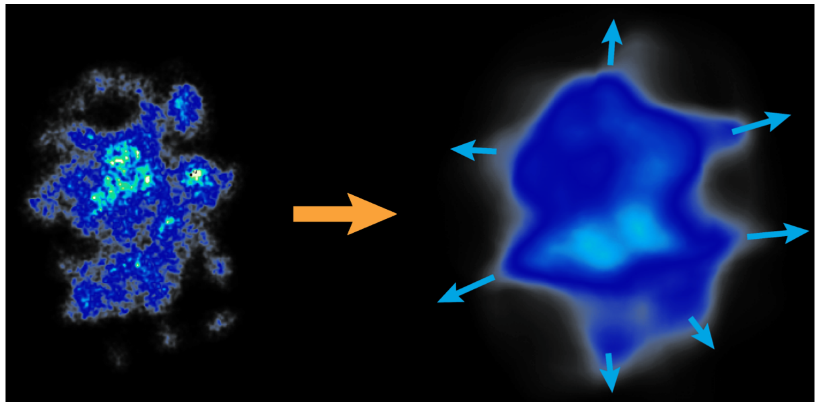
v_n @ RHIC/LHC



The long-range correlations probe early time correlations, the angular component is de-composed into harmonics, strongest is $v_2 = \langle\cos(2\phi)\rangle$

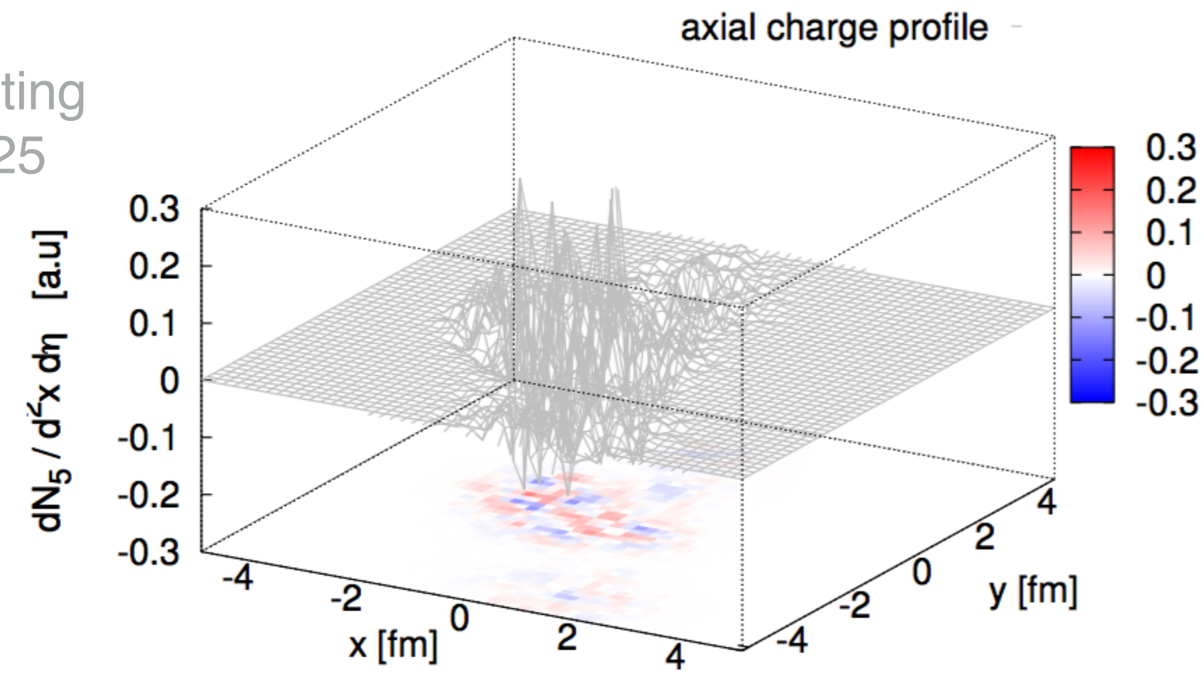
Advantage is that such correlations are easy to measure

What early time effects do we probe in A+A ?

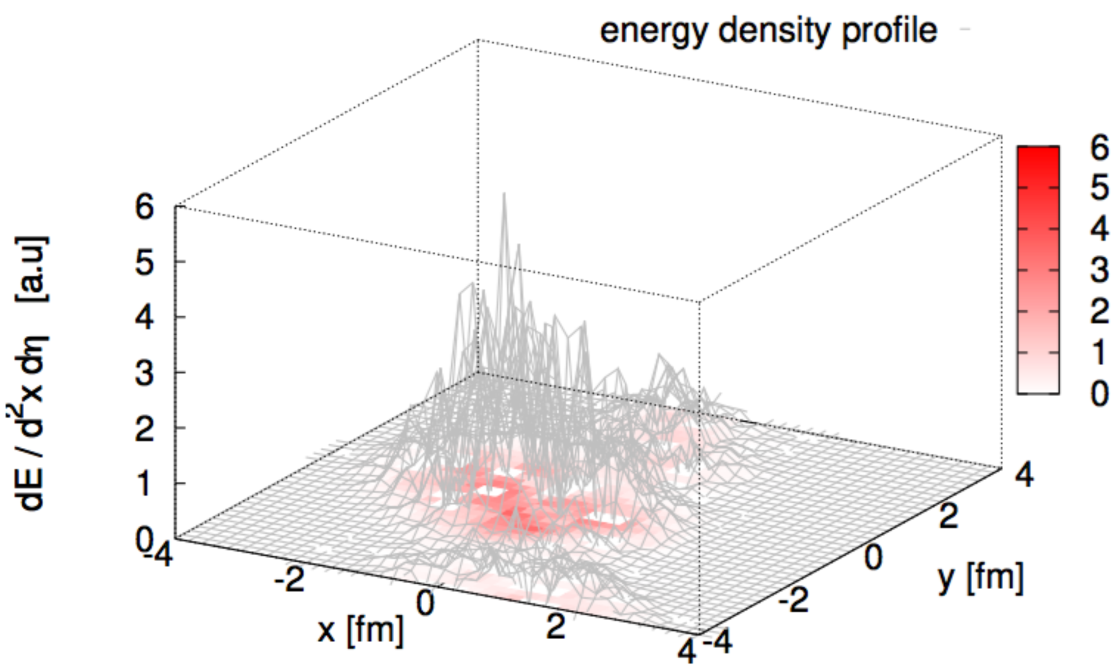


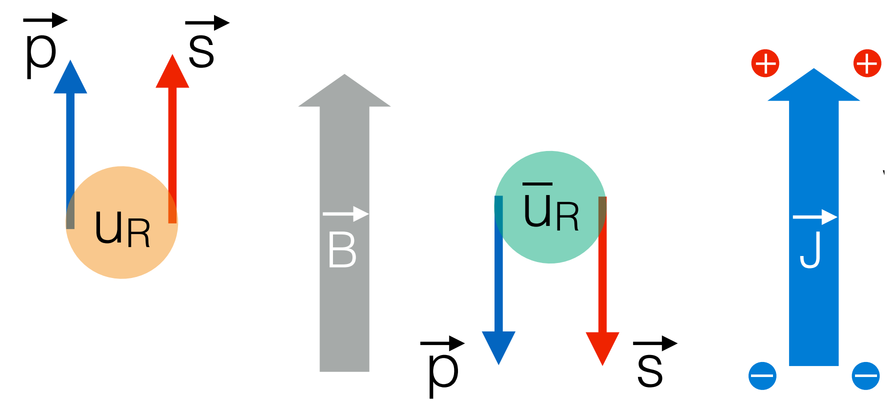
$$\langle \dot{\nu}(x)\dot{\nu}(y)\rangle$$
$$\propto \left[(G^{(1)}_{A1}(x,y))^2 (G^{(1)}_{A2}(x,y))^2 - (h^{(1)}_{\perp A1}(x,y))^2 (h^{(1)}_{\perp A2}(x,y))^2 \right]$$

Lappi, Schlichting
1708.08625



1. Hydrodynamics flow → initial state fluctuations of the energy density





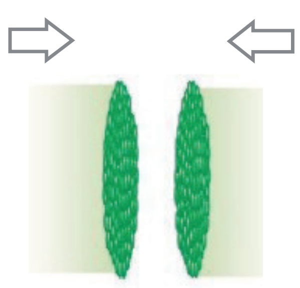
$$\langle \epsilon(x)\epsilon(y)\rangle$$
$$\propto G^{(1)}_{A1}(x,y) G^{(1)}_{A1}(x,y) \left[(G^{(1)}_{A2}(x,y))^2 + (h^{(1)}_{\perp A2}(x,y))^2 \right]$$
$$+ [A_1 \leftrightarrow A_2]$$

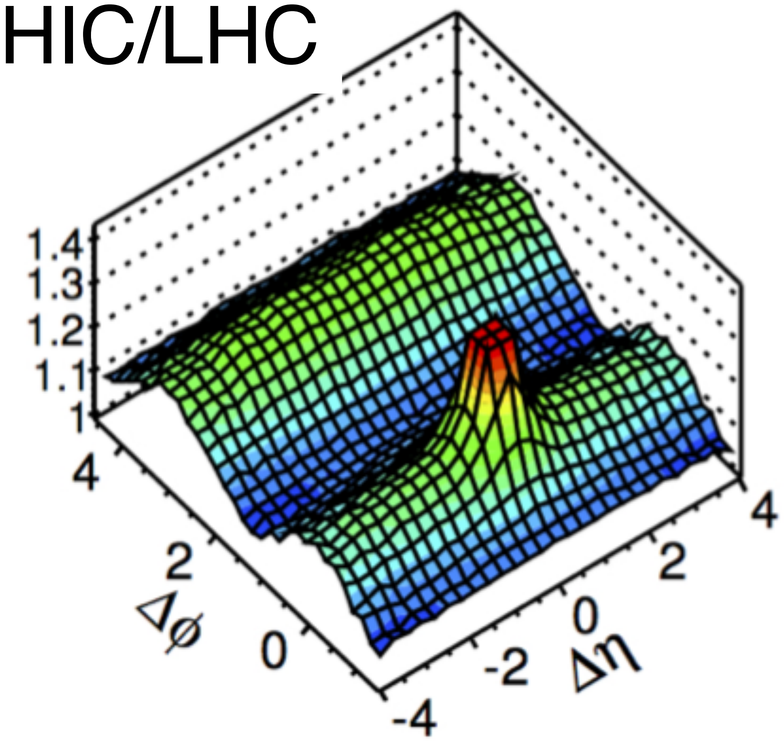
2. Chiral Effects → initial state fluctuations of the axial charge profile

Towards EIC observables

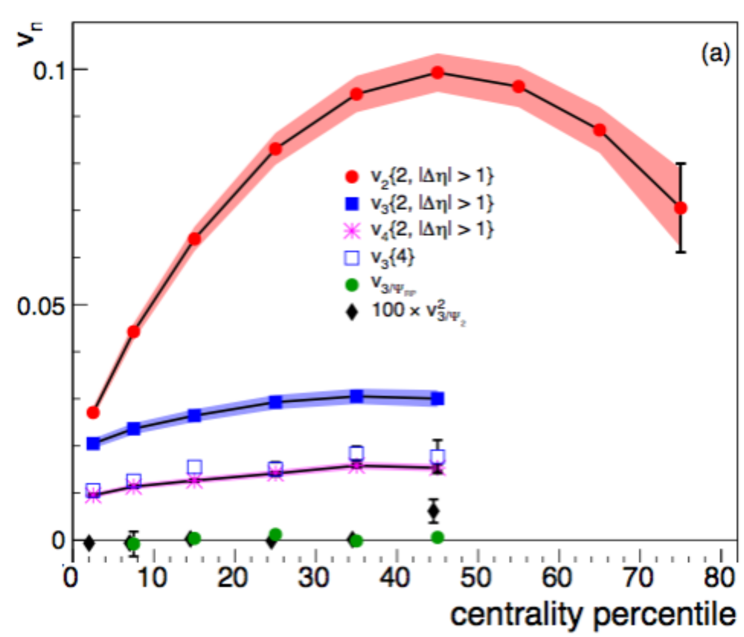
fig: CMS collb.

A+A @ RHIC/LHC

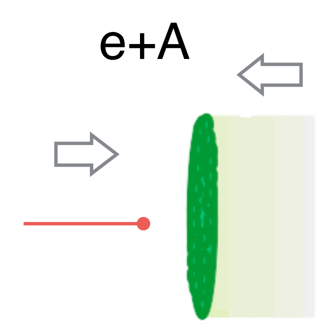


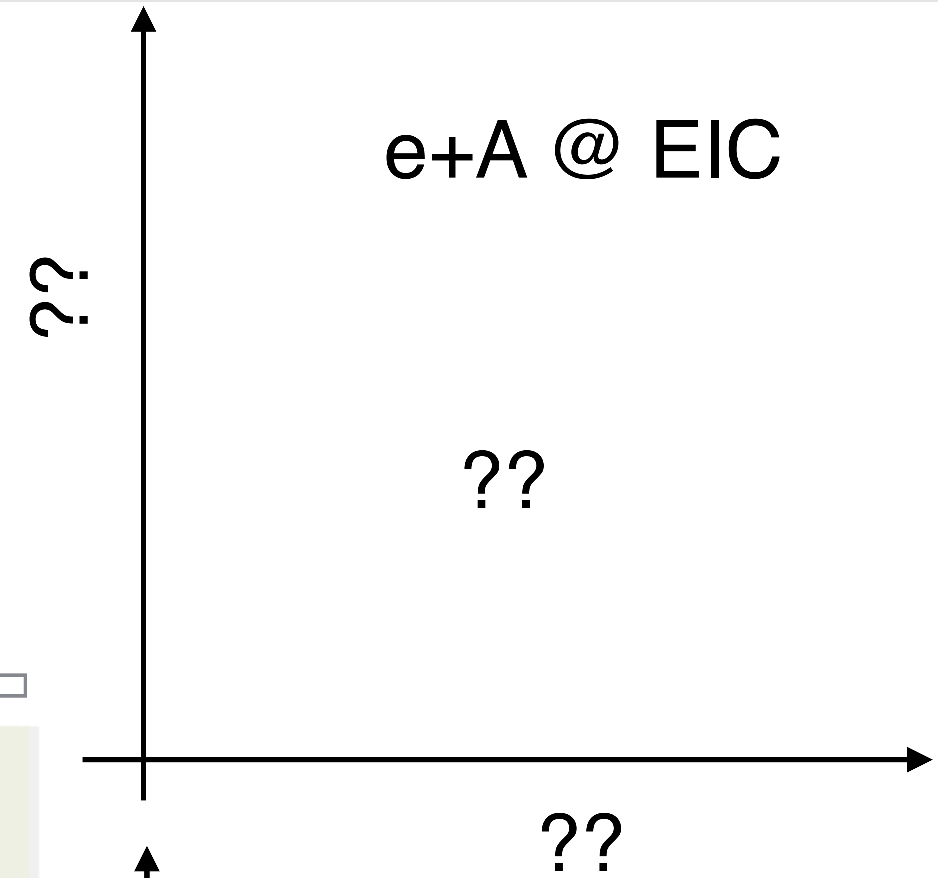


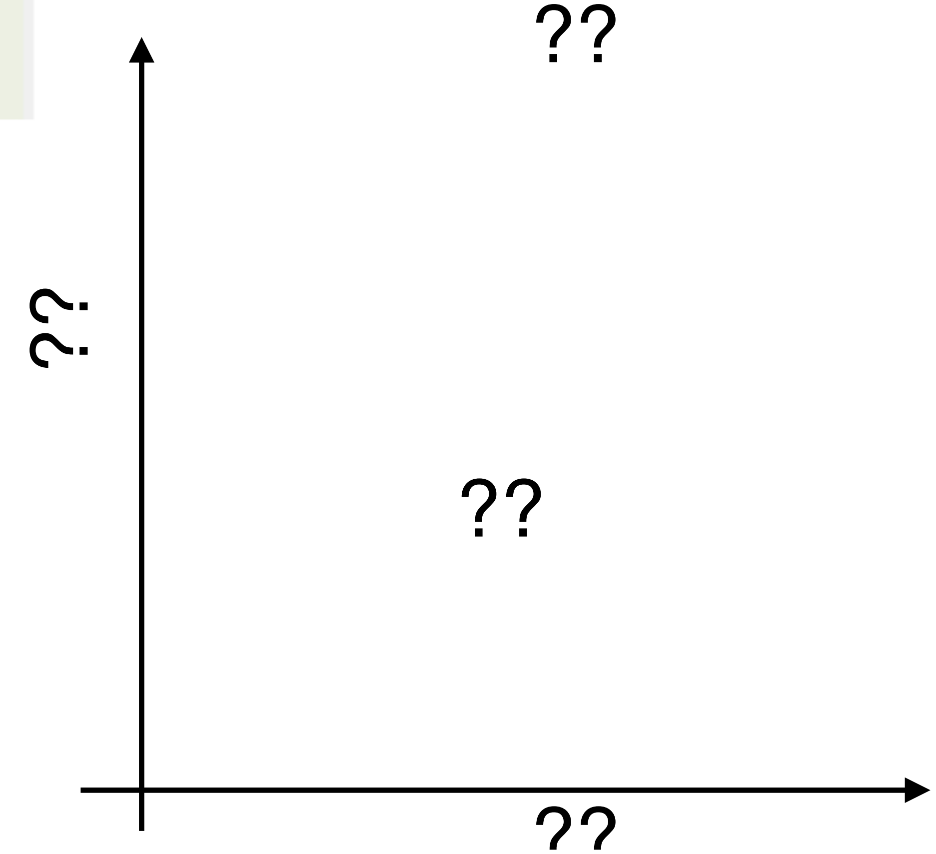
v_n @ RHIC/LHC



e+A @ EIC







Steps towards EIC observables

Small-x → two ways to represent the gluons inside hadrons/nuclei

Weizsacker-Williams (WW) : gluon distribution ($G^{(1)}$) + linearly polarized partner ($h^{(1)}$).

Dipole gluon distribution (DP) : ($G^{(2)}$) + linearly polarized partner ($h^{(2)}$).

Table: D. Boer 1611.06089, V. Skokov

	DIS	DY	SIDIS	$pA \to \gamma\, \text{jet}\, X$	$e\,p \to e'\, Q\bar{Q}\, X$ $e\,p \to e'\, j_1\, j_2\, X$	$pp \to \eta_{c,b}\, X$ $pp \to H\, X$	$pp \to J/\psi\, \gamma\, X$ $pp \to \Upsilon\, \gamma\, X$	$pA \to j_1 j_2 X$
$G^{(1)}$ (WW)	×	×	×	×	√	√	√	√
$G^{(2)}$ (DP)	√	√	√	√	×	×	×	√

	$pp \to \gamma\, \gamma\, X$	$pA \to \gamma^*\, \text{jet}\, X$	$e\,p \to e'\, Q\bar{Q}\, X$ $e\,p \to e'\, j_1\, j_2\, X$	$pp \to \eta_{c,b}\, X$ $pp \to H\, X$	$pp \to J/\psi\, \gamma\, X$ $pp \to \Upsilon\, \gamma\, X$
$h^{(1)}$ (WW)	√	×	√	√	√
$h^{(2)}$ (DP)	×	√	×	×	×

Mantysaari et al 1712.02508, Dumitru et al Phys. Rev. D 94, 014030 (2016), Dumitru et al Phys. Rev. Lett. 115 (2015) 25, 252301, Zheng et al Phys. Rev. D 89, 7, 074037 (2014),Toll et al, Phys. Rev. C 87, 024913 (2013), F. Dominguez et al Phys.Rev. D85 (2012) 045003, Metz et al Phys.Rev. D84 (2011) 051503, Dominguez et al Phys.Rev. D83 (2011) 105005, Boer et al Phys.Rev. D80 (2009) 094017, Mulders et al Phys.Rev. D63 (2001) 094021

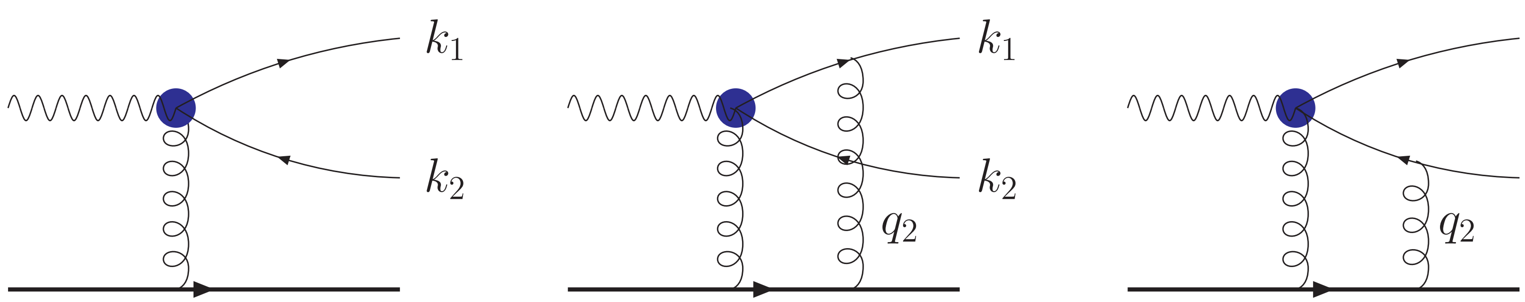
Inclusive di-jets at the EIC

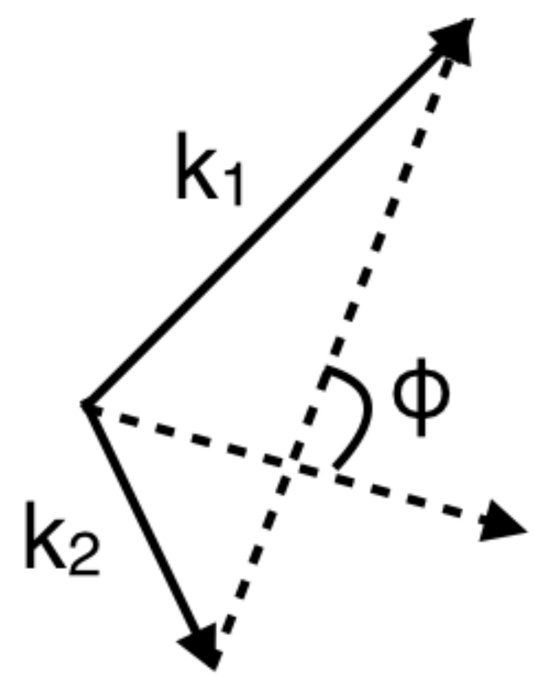
$$e\,A \to e'\,Q\,\overline{Q}\,X$$
$$e\,A \to e'\,j_1\,j_2\,X$$

Dumitru, Skokov Phys. Rev. D 94, 014030 (2016), Dumitru, Lappi, Skokov Phys. Rev. Lett. 115 (2015) 25, 252301, Dumitru, Skokov, Ullrch arXiv: 1809.02615v1

Dominguez, Xiao, Yuan 1009.2141,
Dominguez, Marquet, Xiao, Yuan 1101.0715

fig: 1101.0715



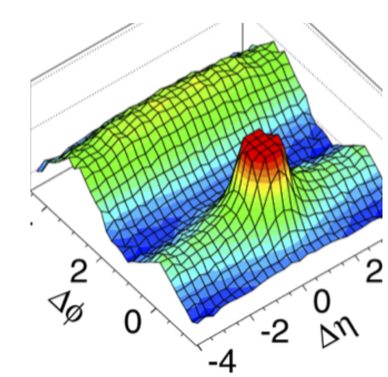


$$\vec{P}_\perp = (1-z)\vec{k}_1 - z\vec{k}_2 \quad , \quad \vec{q}_\perp = \vec{k}_1 + \vec{k}_2$$

Rapidity imbalance $\xi = \log \frac{1-z}{z}$

Relative azimuth $\phi = (\vec{P}_\perp \cdot \vec{q}_\perp)/(|\vec{P}_\perp||\vec{q}_\perp|)$

Analogy to Δη-Δϕ ridge

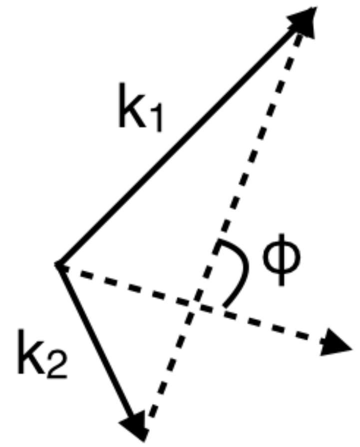


Inclusive di-jets at the EIC

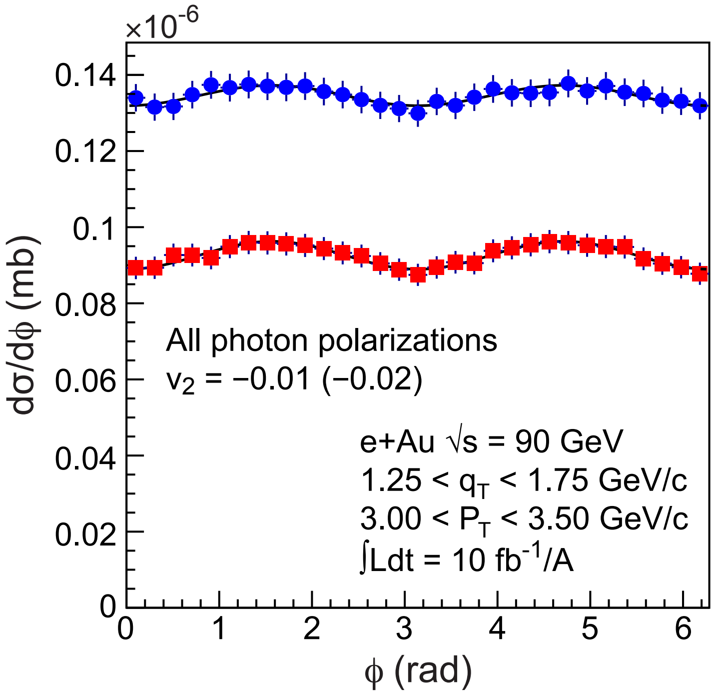
Dumitru, Skokov Phys. Rev. D 94, 014030 (2016), Dumitru, Lappi, Skokov Phys. Rev. Lett. 115 (2015) 25, 252301 Dumitru, Skokov, Ullrch arXiv: 1809.02615v1

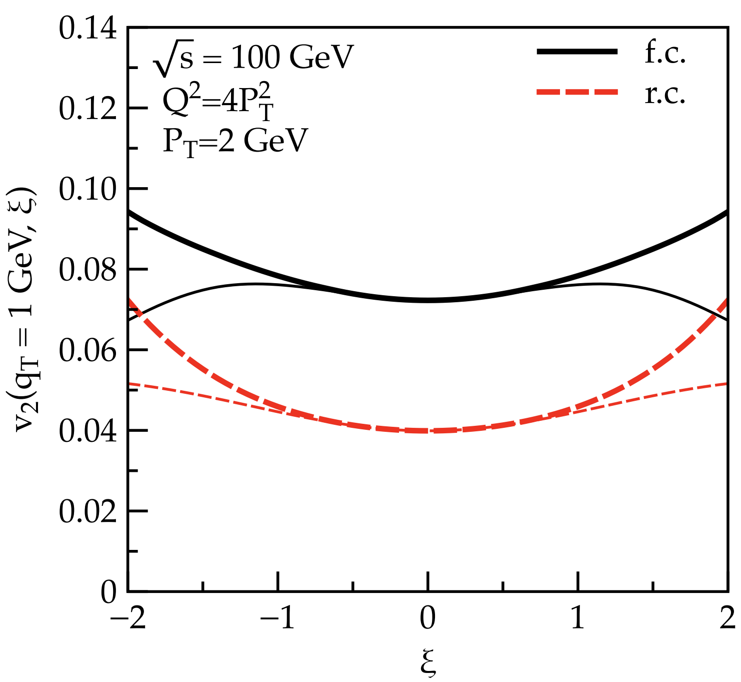
$$E_1 E_2 \frac{d\sigma^{\gamma_L^* A \to q\bar{q}X}}{d^3k_1 d^3k_2 d^2b} = \alpha_{em} e_q^2 \alpha_s \delta\left(x_{\gamma^*} - 1\right) z^2 (1-z)^2 \frac{8\epsilon_f^2 P_\perp^2}{(P_\perp^2 + \epsilon_f^2)^4}$$

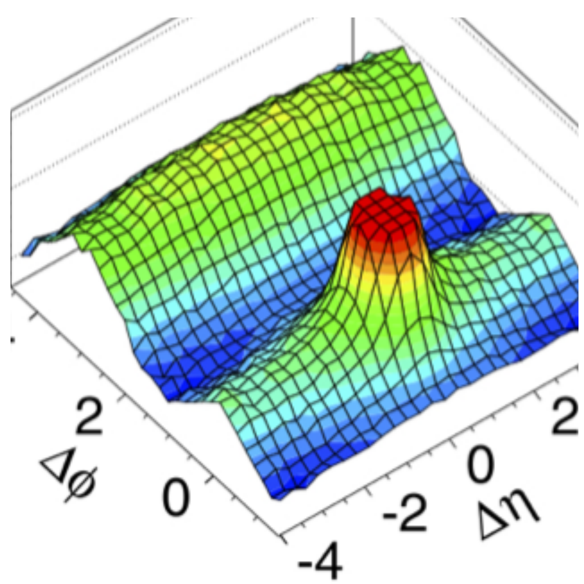
$$\times \left[xG^{(1)}(x, q_\perp) + \cos\left(2\phi\right) xh_\perp^{(1)}(x, q_\perp) \right]$$



WW gluon distribution ($G^{(1)}$) + linearly polarized partner ($h^{(1)}$)







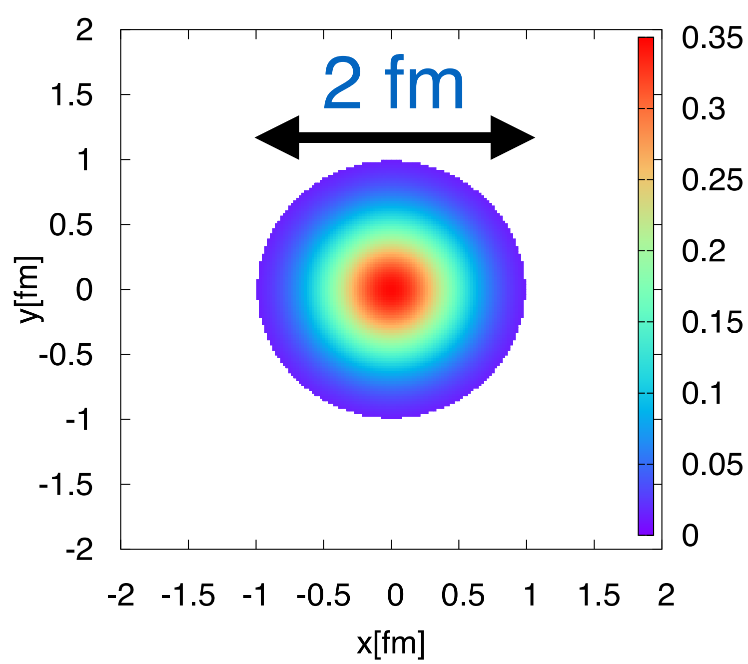
Computing it using an universal framework

IP-Sat : saturation models of DIS

Kowalski, Teaney hep-ph/0304189v3

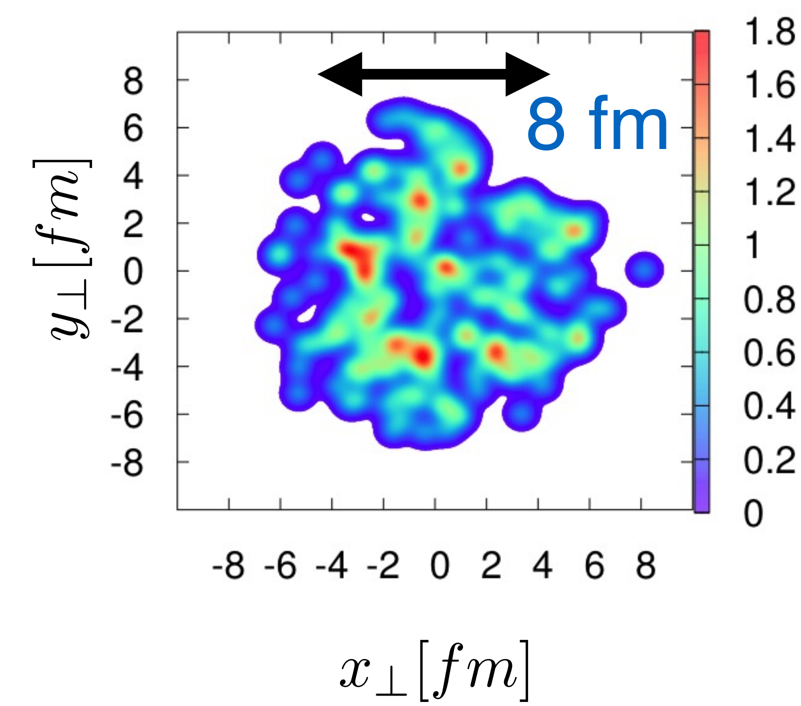
Round proton

$Q_s^2(\mathbf{x}_\perp, x{=}0.003, A{=}1)[\mathrm{GeV}^2]$



Lumpy Nucleus (single conf.)

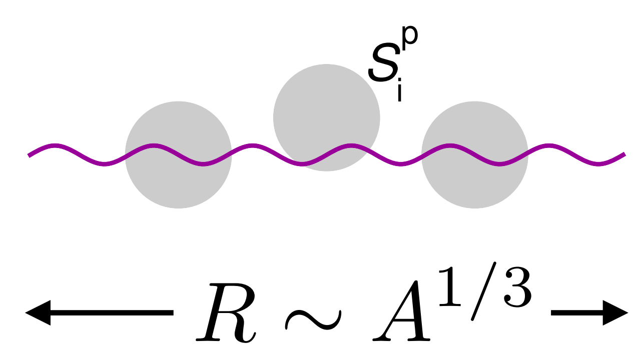
$Q_s^2(\mathbf{x}_\perp, Y{=}0.003, A{=}197)[\mathrm{GeV}^2]$



Less boost is needed to saturate a nucleus, larger A → larger Q_S

Nucleus → multiple scattering centers :

$$S^A_{\mathrm{dip}}(\mathbf{r}_\perp, x, \mathbf{b}_\perp) = \prod_{i=0}^{A} S^p_{\mathrm{dip}}(\mathbf{r}_\perp, x, \mathbf{b}_\perp)$$

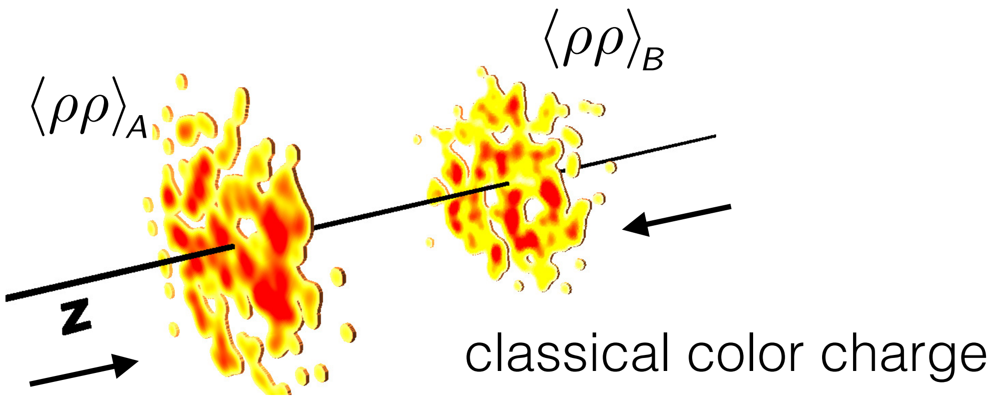


Color Glass Condensate, MV model,Glasma

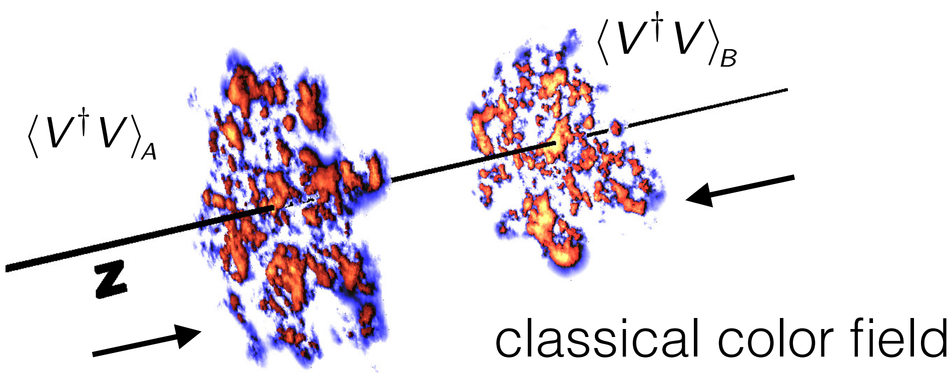
Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301

- Fundamental objects are Color Charge density matrices $\rho^a(x_\perp, Y)$, local Gaussian distribution $W[\rho]$ (MV-Model)

$$\langle \rho^a(\mathbf{x}_\perp)\rho^b(\mathbf{y}_\perp)\rangle \propto \delta^{ab}\delta^2(\mathbf{x}_\perp - \mathbf{y}_\perp) Q_s^2(\mathbf{x}_\perp)$$



- Color field before collisions : solving Yang Mills equations for each configuration of source $\rho(x_\perp)$ & current $J^\nu = \delta^\nu \rho(x_\perp)$



$$[D_\mu, F^{\mu\nu}] = J^\nu$$

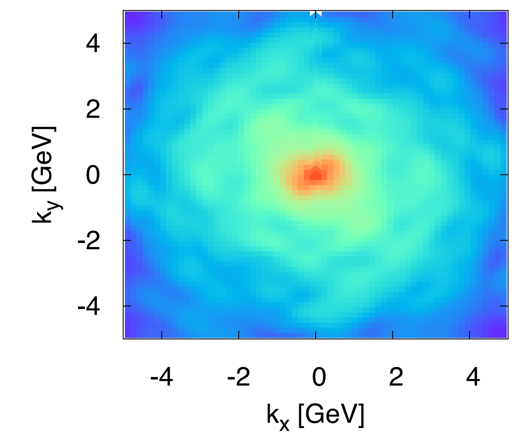
hep-ph/9809433, hep-ph/0303076,
arXiv:1206.6805,arXiv: 1202.6646

Computing it using an universal framework

Momentum space correlations : n-gluon distribution

$$\frac{dN_g}{dy} = \frac{2}{N^2}\int \frac{d^2k_T}{\tilde{k}_T}\left[\frac{g^2}{\tau}\mathrm{tr}\left(E_i(\mathbf{k}_\perp)E_i(-\mathbf{k}_\perp)\right)+\tau\,\mathrm{tr}\left(\pi(\mathbf{k}_\perp)\pi(-\mathbf{k}_\perp)\right)\right]$$

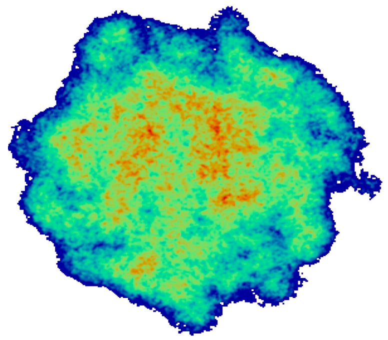
Input to PYTHIA, p+p/A collisions

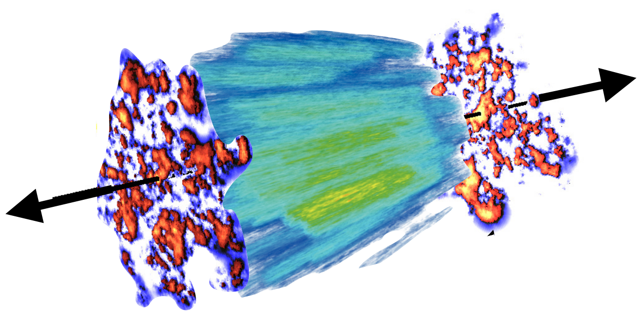


Position space correlations : Stress-Energy Tensor

$$T^{\mu\nu} = -g^{\gamma\delta}F^{\mu}_{\ \gamma}F^{\nu}_{\ \delta} + \frac{1}{4}g^{\mu\nu}F^{\gamma}_{\ \delta}F_{\gamma}^{\ \delta}$$

Input to hydro, transport,
p+A, A+A collisions





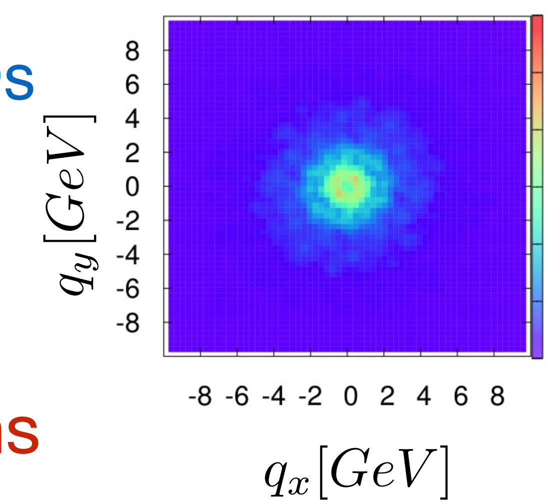
Light-cone gauge-fields

$$U(\mathbf{x}_T) = \mathbb{P}\exp\left\{ig\int dx^- A^+(x^-,\mathbf{x}_T)\right\}$$

Wave functions: Dipole-gluon & WWs TMDs

$$xG^{ij}_{\mathrm{WW}}(x,\vec{k}) = \frac{8\pi}{L^2}\int \frac{d^2\mathbf{x}_T}{(2\pi)^2}\frac{d^2\mathbf{y}_T}{(2\pi)^2}e^{-i\mathbf{k}_T\cdot(\mathbf{x}_T-\mathbf{y}_T)}\times\left\langle A^i_a(\mathbf{x}_T)A^j_a(\mathbf{y}_T)\right\rangle$$

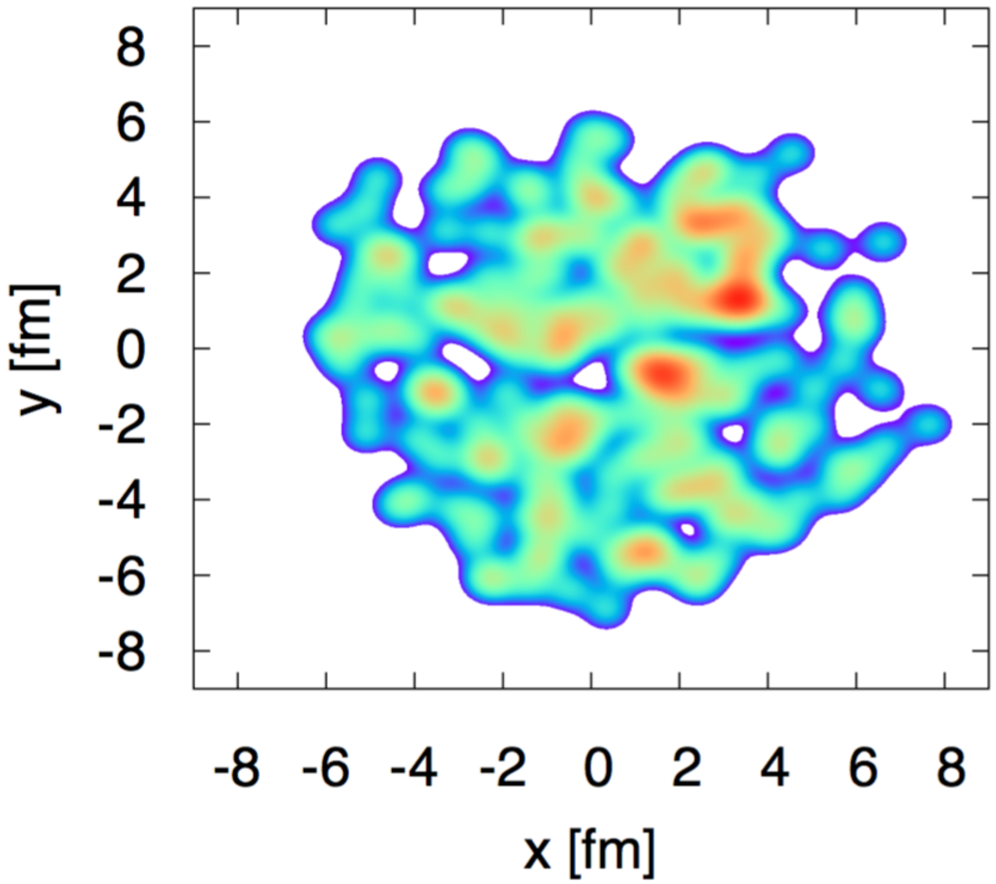
Input for EIC observables e+p/A collisions



Single configuration of an Au nucleus

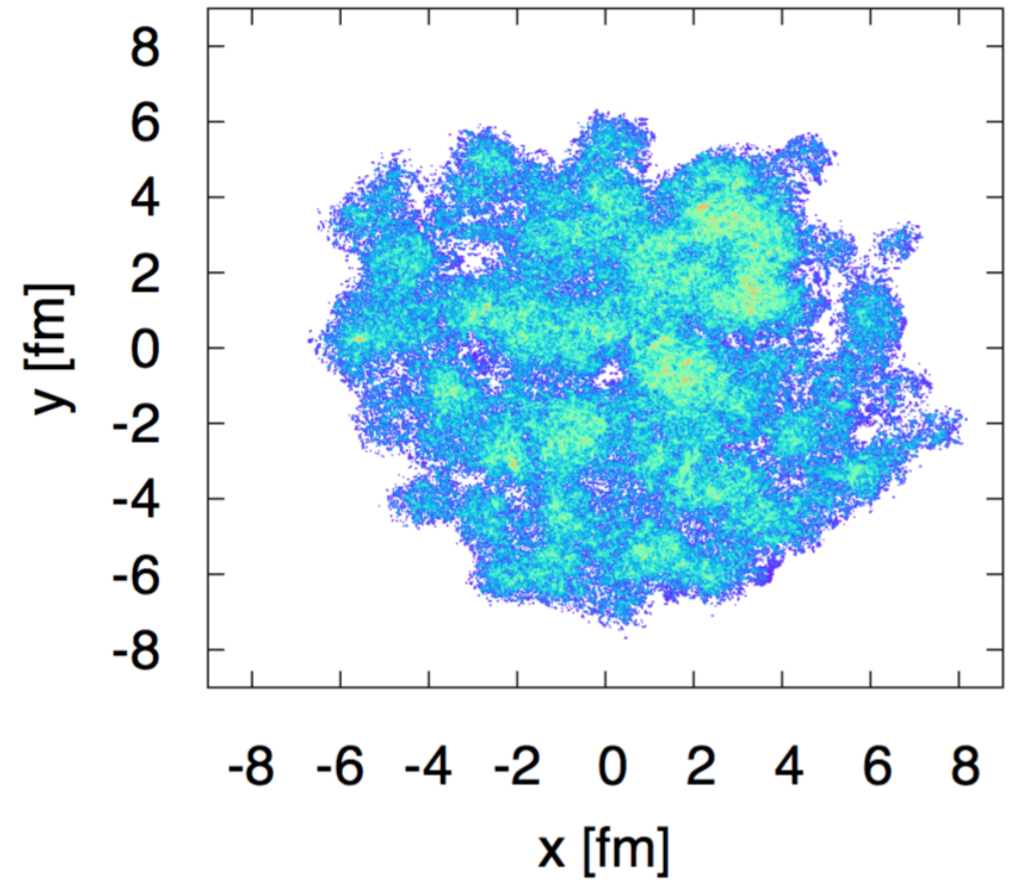
Single Color Charge configuration

$$\langle \rho(\mathbf{x_{1\perp}}) \rho(\mathbf{x_{2\perp}}) \rangle$$



Single Color field distribution

$$Tr(A_{\mathbf{x}\perp}(x, y))$$



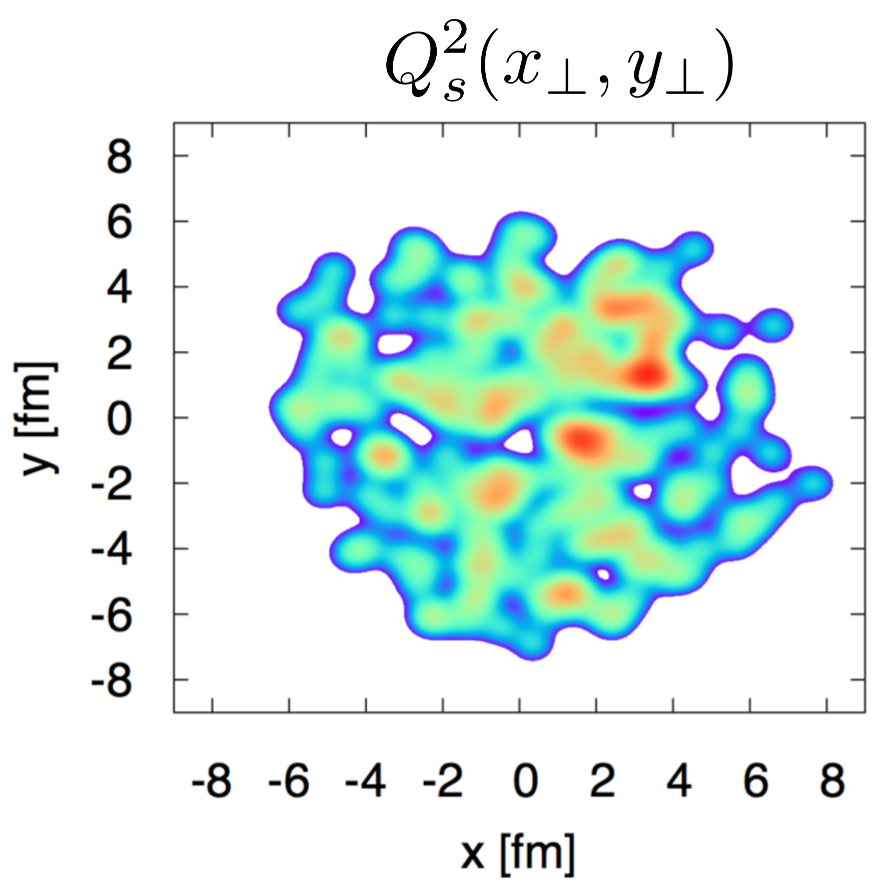
$$U(\mathbf{x}_T) = \mathbb{P} \exp \left\{ ig \int dx^- A^+(x^-, \mathbf{x}_T) \right\}$$

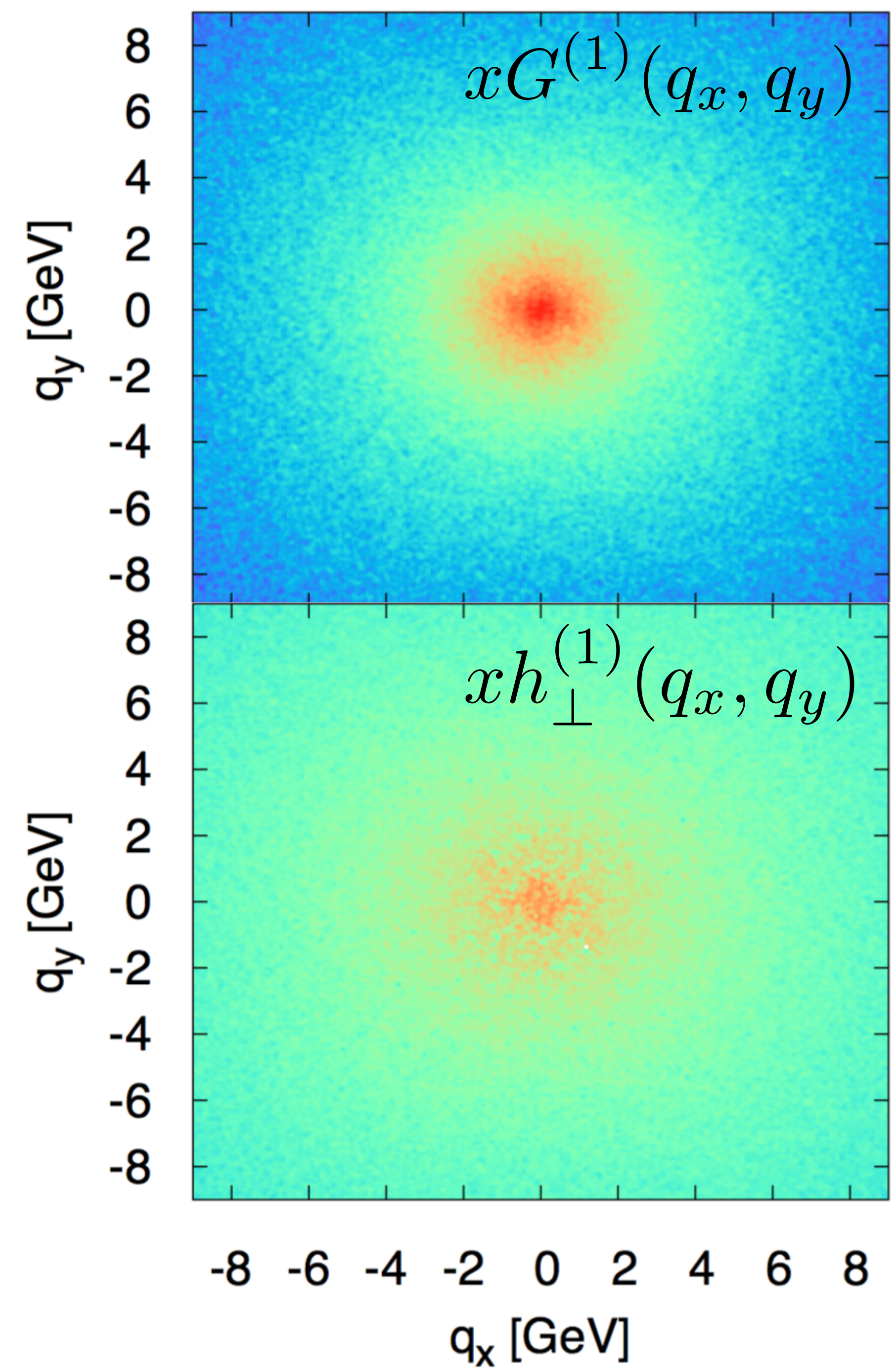
$$A^i(\mathbf{x}_T) = \frac{1}{ig} U^\dagger(\mathbf{x}_T)\, \partial_i U(\mathbf{x}_T)$$

Single configuration for Au nuclei at x=0.01, Y=1

Weizsacker-Williams gluon distributions

$$xG^{ij}_{\rm WW}(x,\vec{k}) = \frac{8\pi}{L^2}\int \frac{d^2\mathbf{x}_T}{(2\pi)^2}\frac{d^2\mathbf{y}_T}{(2\pi)^2} e^{-i\mathbf{k}_T\cdot(\mathbf{x}_T-\mathbf{y}_T)} \left\langle A^i_a(\mathbf{x}_T)A^j_a(\mathbf{y}_T)\right\rangle$$

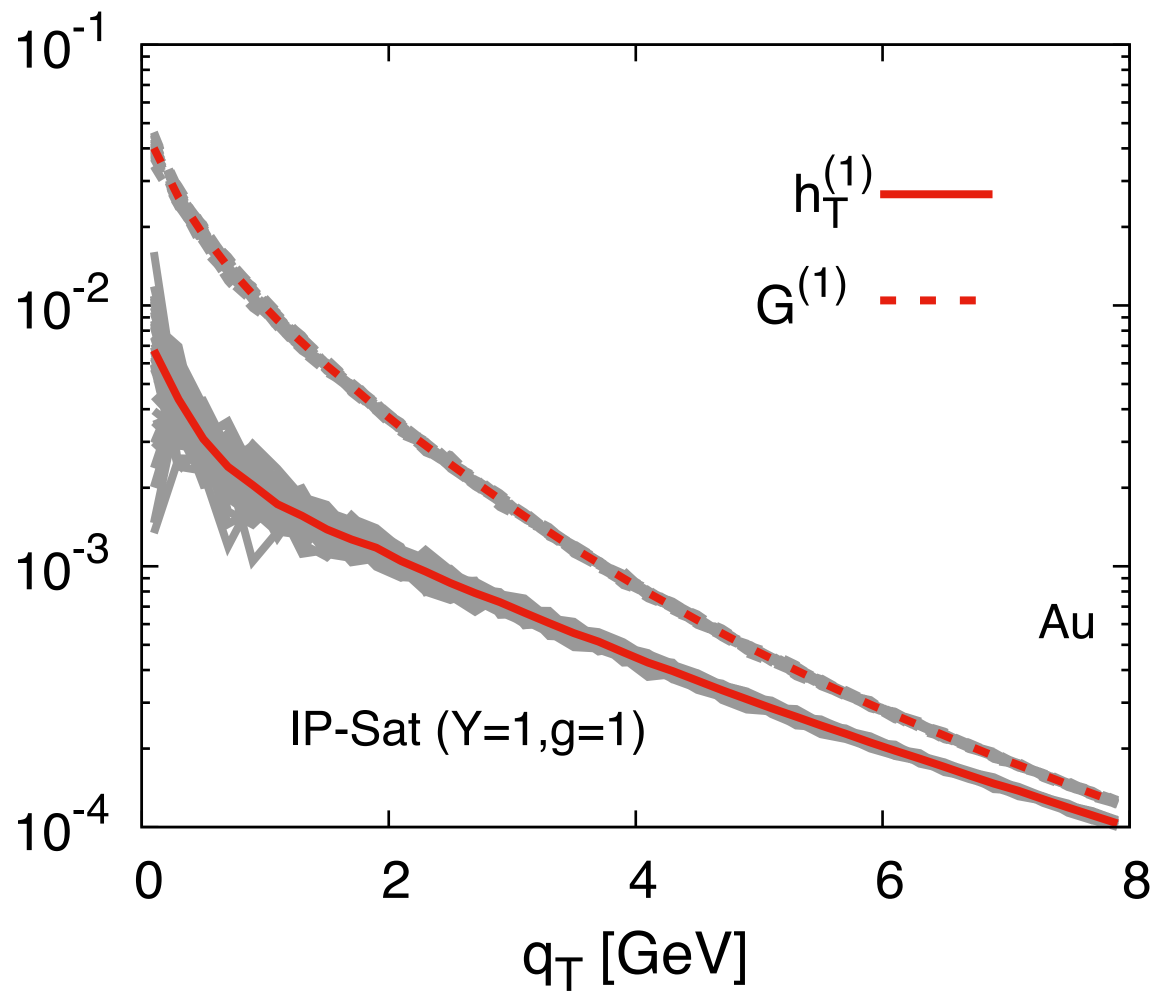


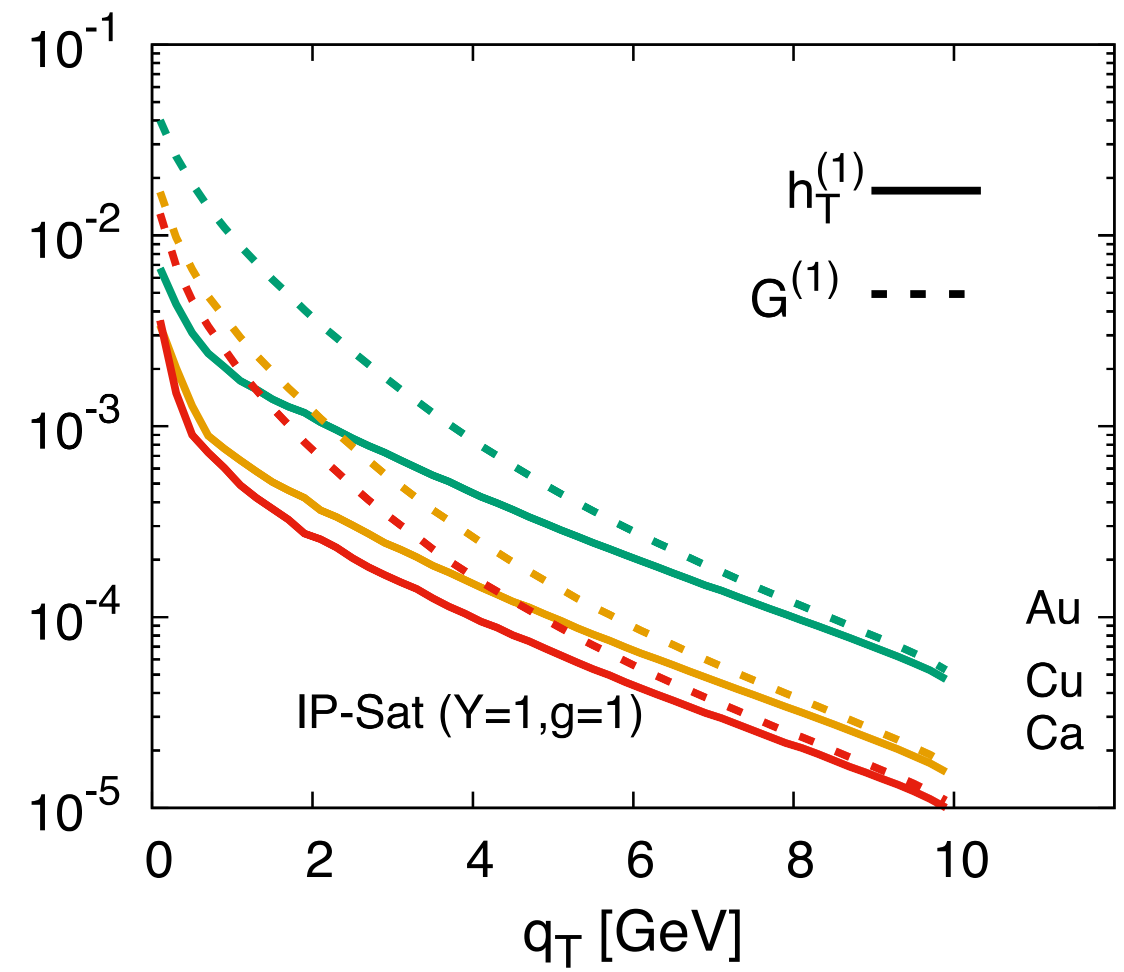


$$xG^{ij}_{\rm WW} = \frac{1}{2}\delta^{ij}xG^{(1)} - \frac{1}{2}\left(\delta^{ij} - 2\frac{k^ik^j}{k^2}\right)xh_\perp^{(1)}$$

Weizsacker-Williams gluon distributions

$$xG^{ij}_{\rm WW} = \frac{1}{2}\delta^{ij} xG^{(1)} - \frac{1}{2}\left(\delta^{ij} - 2\frac{k^i k^j}{k^2}\right) xh^{(1)}_{\perp}$$



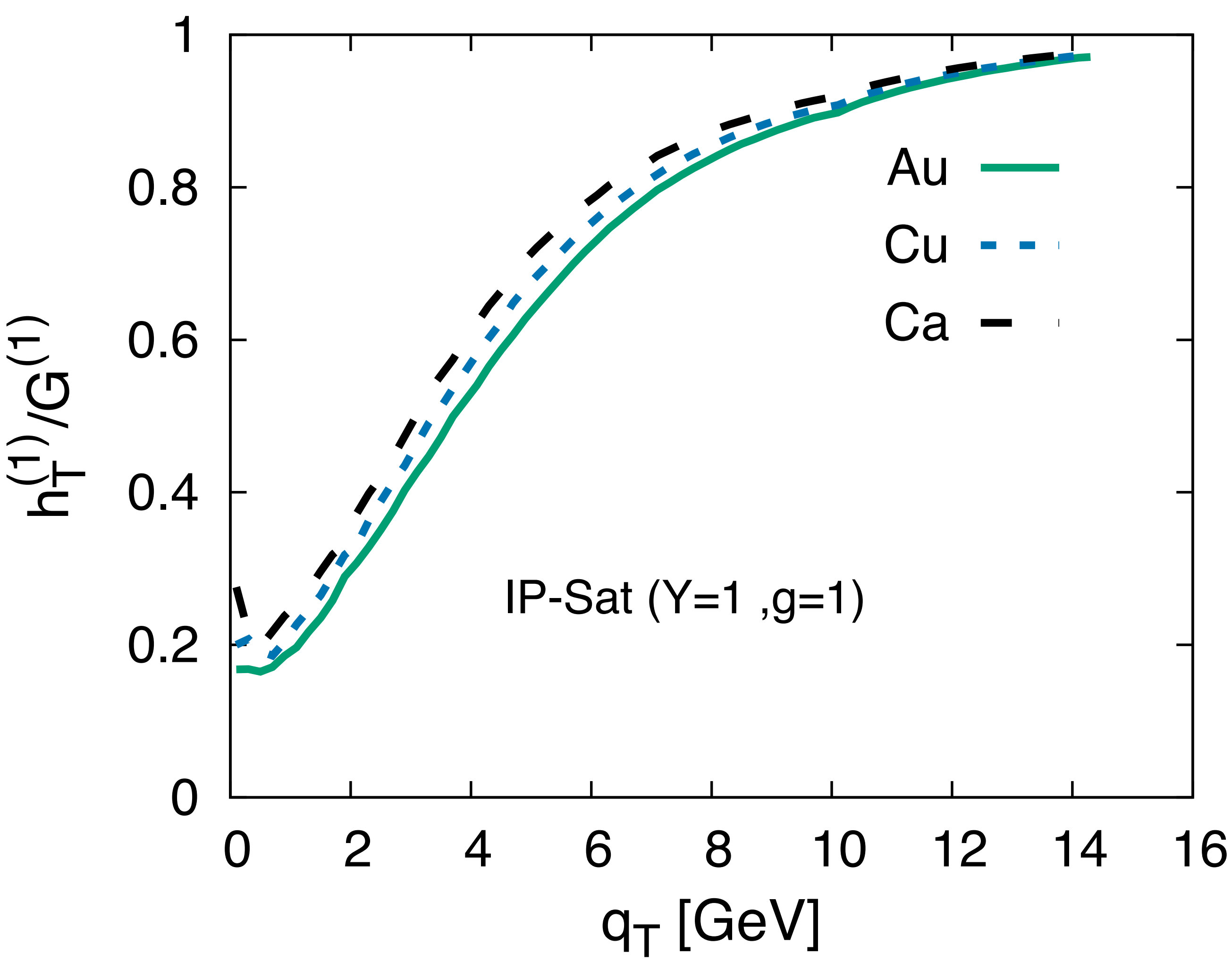


TMDs for different nuclei at fixed rapidity,
JIMWLK evolution left for future work

Estimates of the anisotropy for different systems

$$xG^{ij}_{\mathrm{WW}} = \frac{1}{2}\delta^{ij}xG^{(1)} - \frac{1}{2}\left(\delta^{ij} - 2\frac{k^i k^j}{k^2}\right)xh_\perp^{(1)}$$

$$E_1E_2\frac{d\sigma^{\gamma_L^* A\to q\bar{q}X}}{d^3k_1d^3k_2d^2b} = \alpha_{em}e_q^2\alpha_s\delta\left(x_{\gamma^*}-1\right)z^2(1-z)^2\frac{8\epsilon_f^2P_\perp^2}{(P_\perp^2+\epsilon_f^2)^4} \times\left[xG^{(1)}(x,q_\perp)+\cos\left(2\phi\right)xh_\perp^{(1)}(x,q_\perp)\right]$$



$$v_2^L = \frac{1}{2}\frac{xh_\perp^{(1)}(x,q_\perp)}{xG^{(1)}(x,q_\perp)}$$

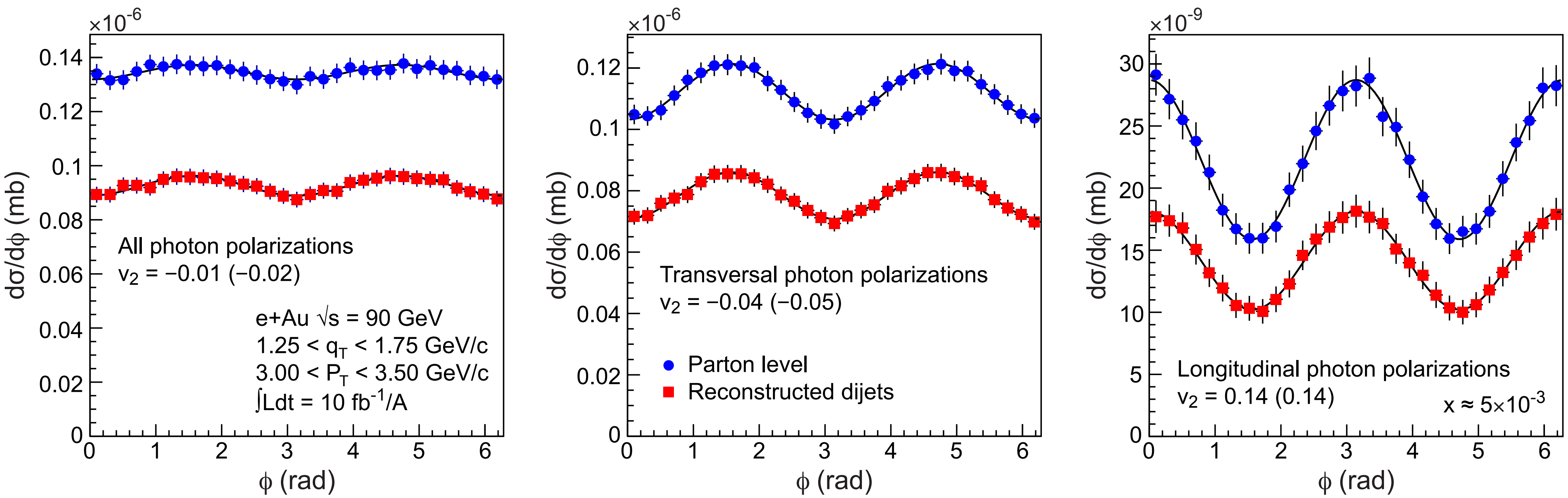
$$v_2^T = -\frac{\epsilon_f^2P_\perp^2}{\epsilon_f^4+P_\perp^4}\frac{xh_\perp^{(1)}(x,q_\perp)}{xG^{(1)}(x,q_\perp)}$$

Large long-range azimuthal correlations in DIS di-jets in different e+A collisions

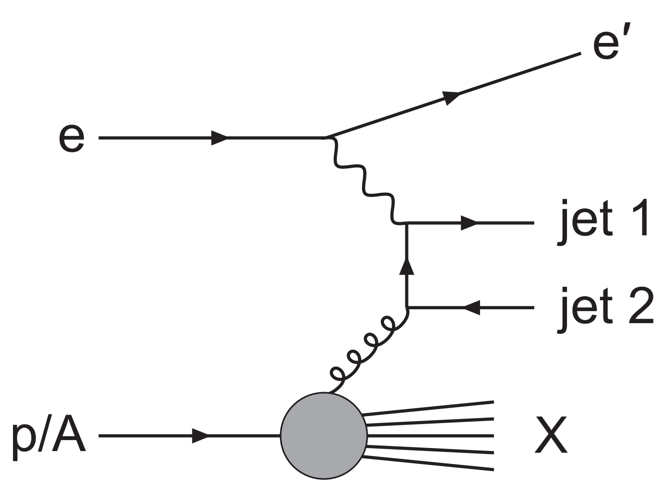
More studies & the un-correlated background

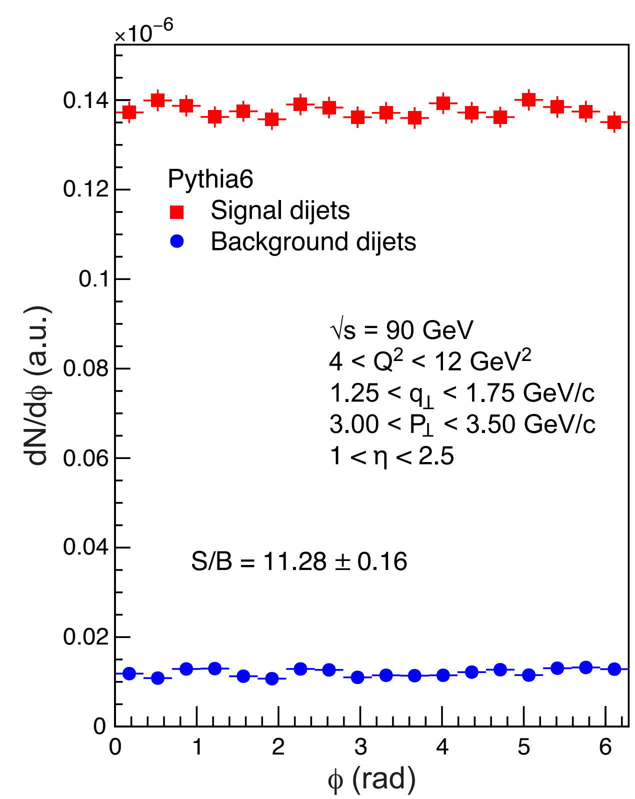
Dumitru, Skokov, Ullrch arXiv: 1809.02615v1

A phase shift between transverse & longitudinal photons (probe)



Photon-gluon fusion as a potential bkg.

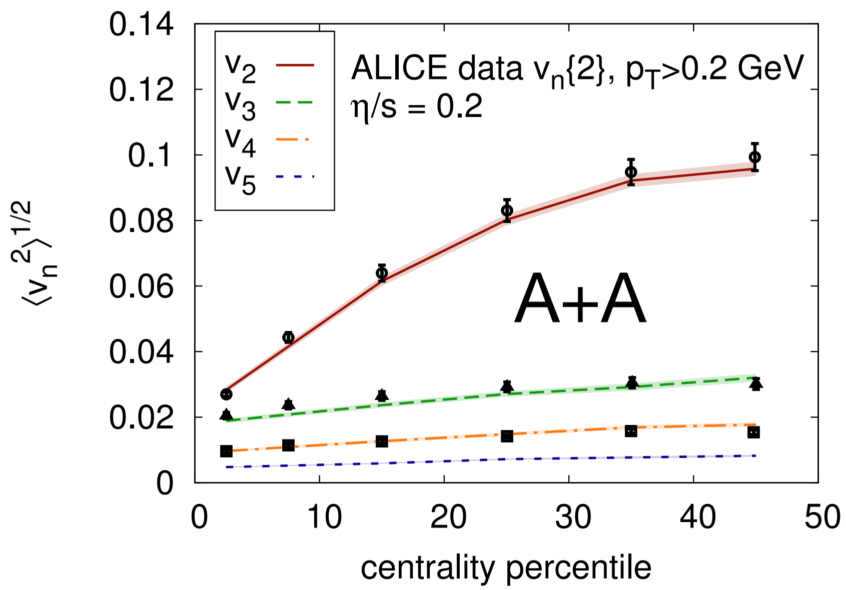


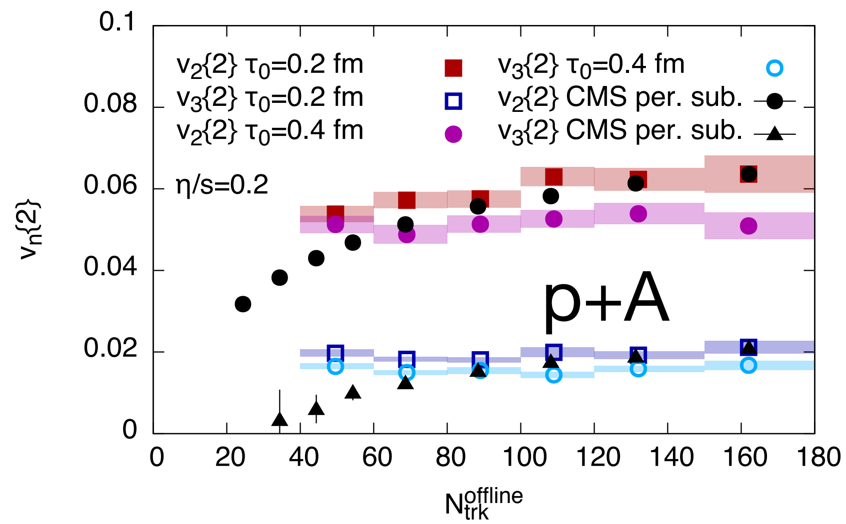


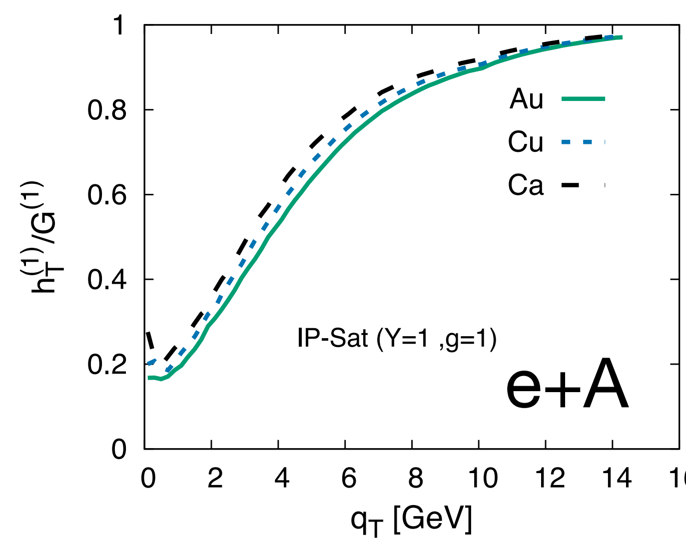
Summary and outlook

di-hadron correlations have been a key observable across different systems
They provide many information about the early stages of collisions

Quantities like v_2 are studied very widely at RHIC & LHC







It may be possible to measure similar correlations at the future EIC :

- Large long-range cos(2ϕ) anisotropy in DIS dijets is predicated to probe TMDs

Lessons from RHIC/LHC about modeling colliding nuclei will be helpful to further study such processes and may be implement in the Monte-Carlo generators for EIC

Thank you