# Coherent vortex states and experimental spin hydrodynamics

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In collaboration with Gabriel Rabelo-Soares,Gojko Vujanovic,Jun Takahashi

I gave to give a seminar on a totally unrelated topic, and only learned about the subject 2 days ago! So I thank Igor Ivanov for including me last minute, Nikolai Korchaging for references I quickly read and hope not to disappoint!

**The context** "the most vortical fluid". theory,experiment challenges

**How vortex states could help** "If I was an experimental magician
But you might make this happen!

**Connection to work in progress** wavefunction $\rightarrow$ hydro initial state!

(2004) Matter in heavy ion collisions seems to behave as a perfect fluid, characterized by a very rapid thermalization


## RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted — raising many new questions

April 18, 2005

TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory — say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

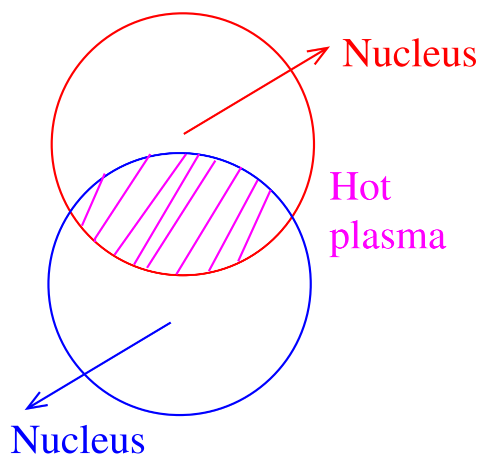
"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

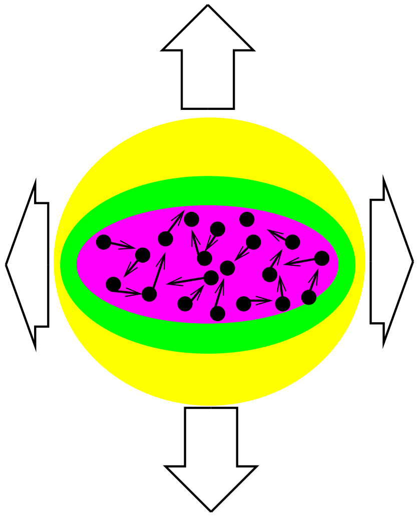
"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Initial azimuthal density gradients $\rightarrow$ pressure gradients $\rightarrow$ $p_T$ gradient

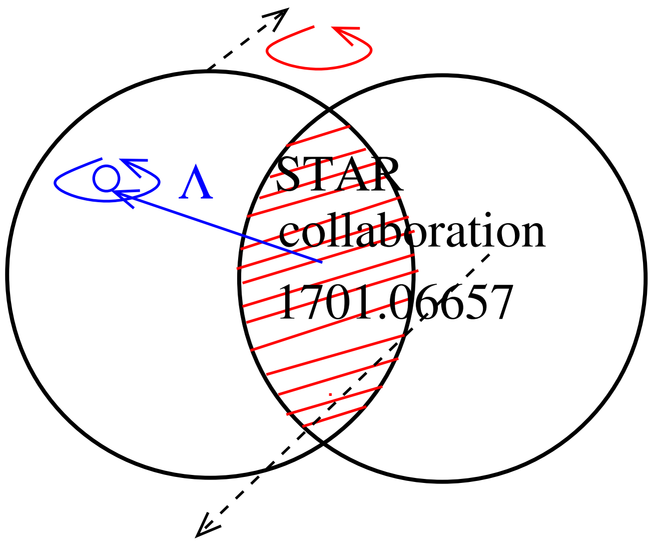
$$\frac{dN}{p_T dp_T dy d\phi} = \frac{dN}{p_T dp_T dy}\left[1 + 2v_n(p_T, y)\cos\left(n\left(\phi - \phi_0\left(n, p_T, y\right)\right)\right)\right]$$

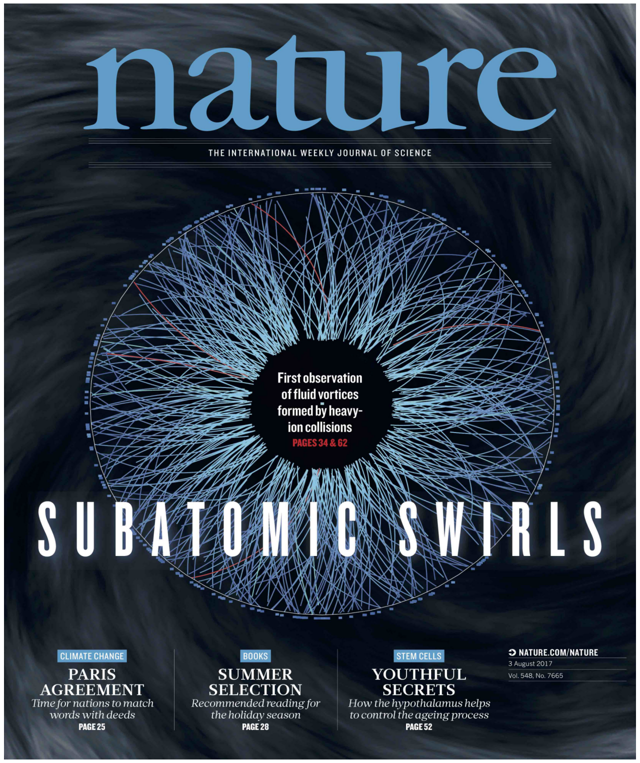
"trivial" effects ($\vec{p}$ conservation) also give you a $v_n$ . "Collectivity": Same $v_n$ from $\forall$ n-particle correlations , $\left\langle \frac{dN}{d\phi_1}\frac{dN}{d\phi_2}... \right\rangle$ , reaction plane dependence



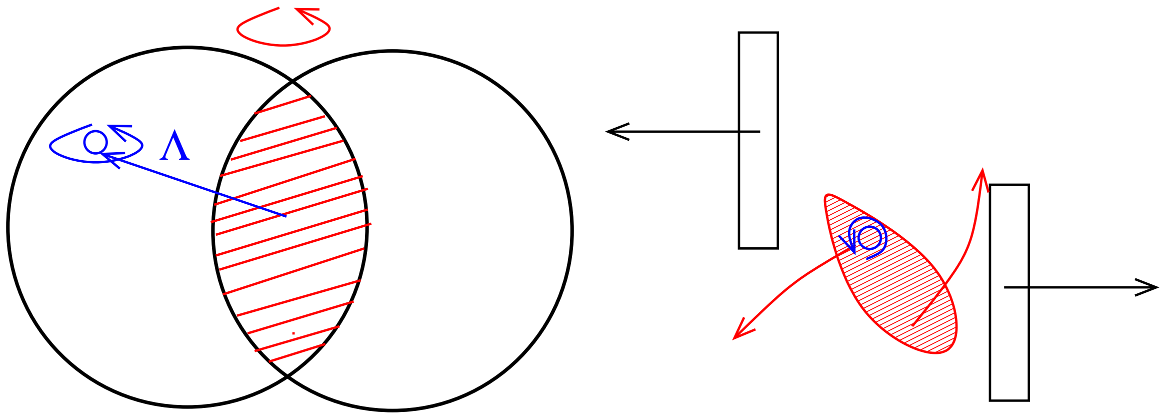



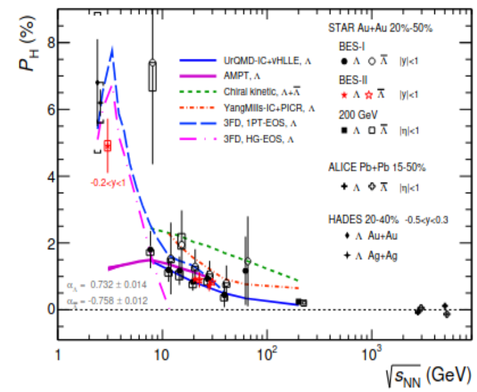
## 2016: Hydrodynamics with spin




A remarkable experimental discovery, which opened a fascinating field of theoretical investigation.



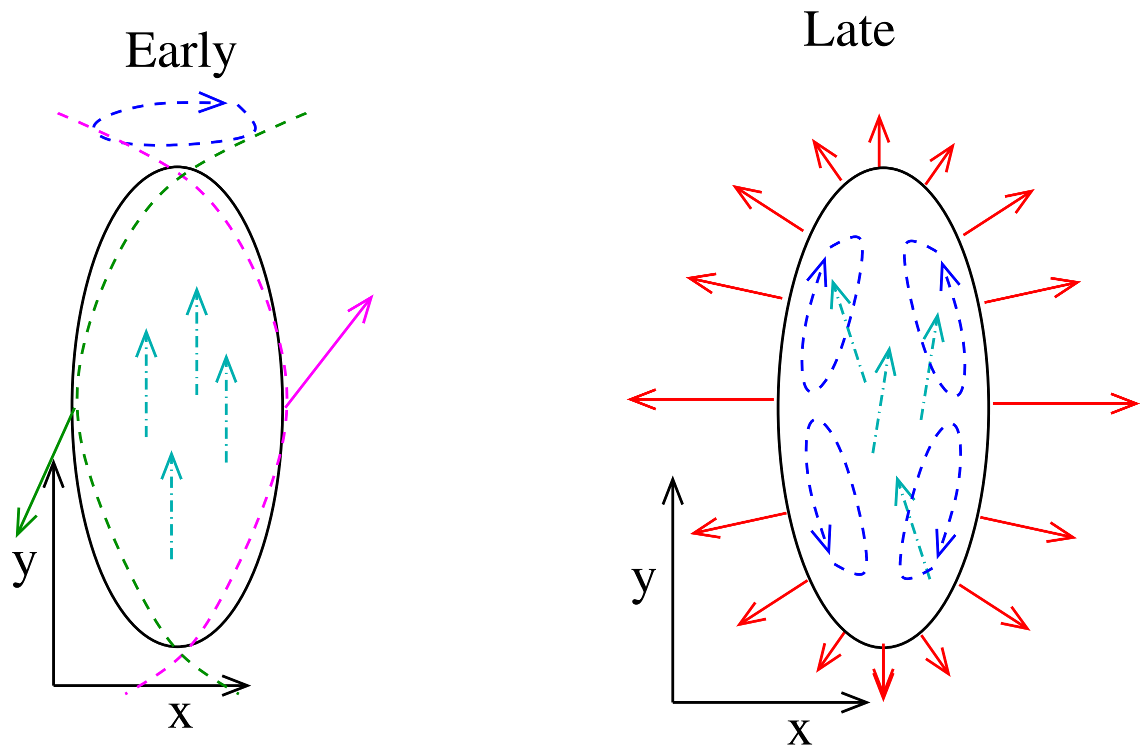




Unresolved statistical mechanics problem. Spin $\neq$ "small vortex".

**Spin** microstate, how angular momentum is shared determines entropy

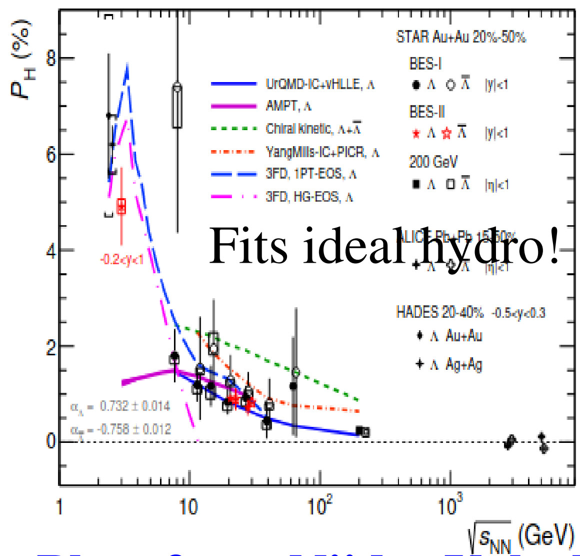
**Vorticity** A <u>classical</u> collective excitation carrying angular momentum

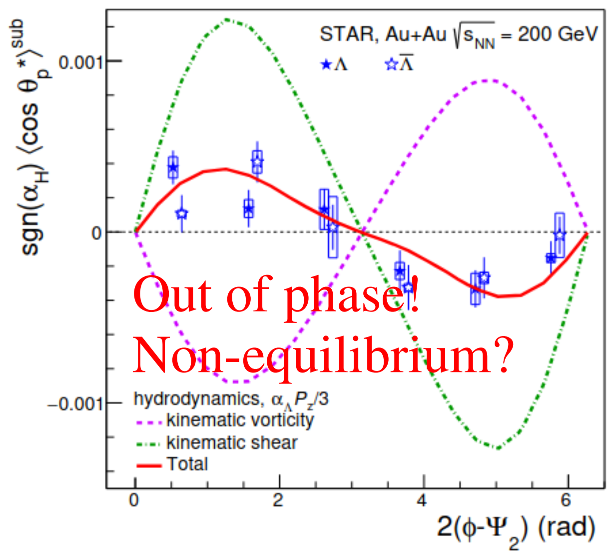
So spin hydrodynamics is <u>backreaction</u> of microscopic DoFs on macroscopic perturbations! EFT in development, conceptual issues (minimal dissipation, connection to transport, pseudogauges,non-locality...) not understood

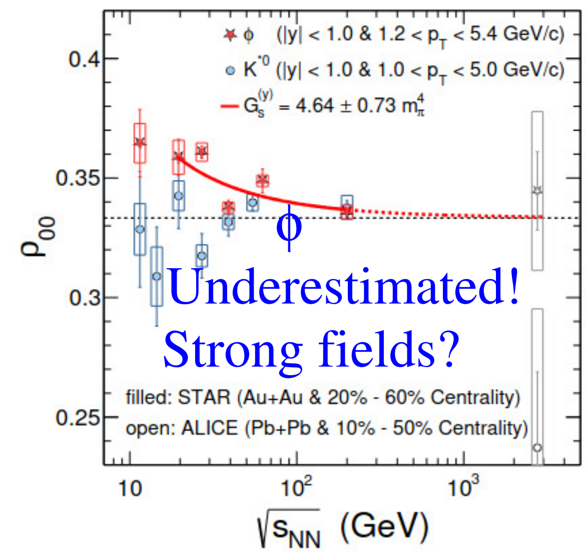



Global (transverse) vorticity formed as an initial state in non-transparent collisions (lower $\sqrt{s}$)
Local (longitudinal) vorticity initially 0, forms later on the time scale as $v_2$ by related dynamics (present at all energies)

THe phenomenology in a nutshell

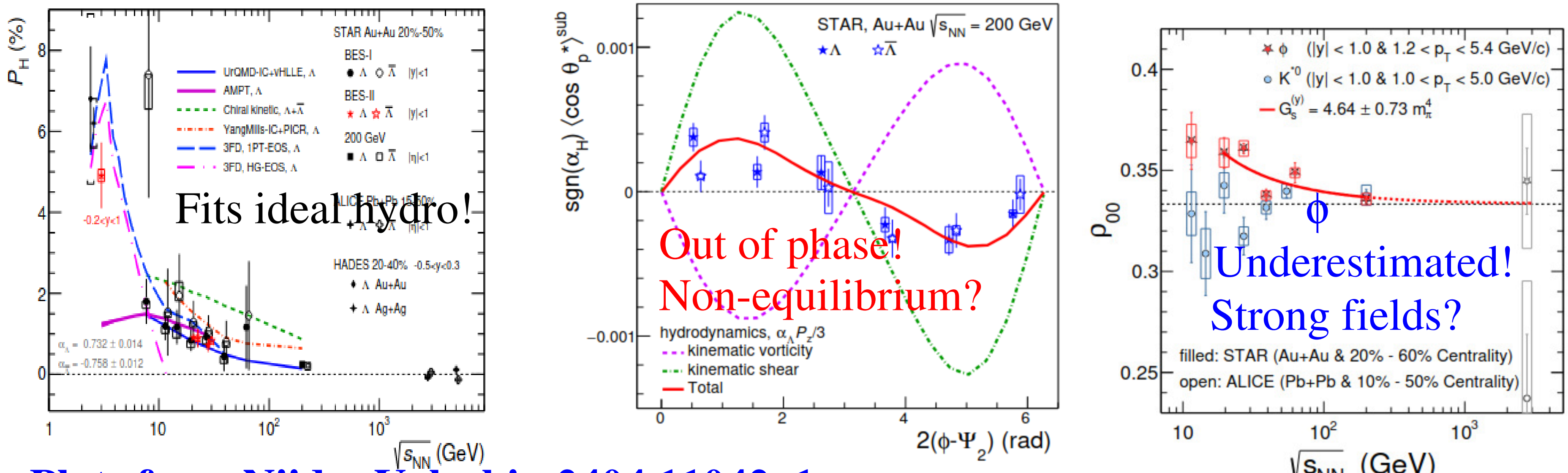



**Plots from Niida+Voloshin,2404.11042v1**

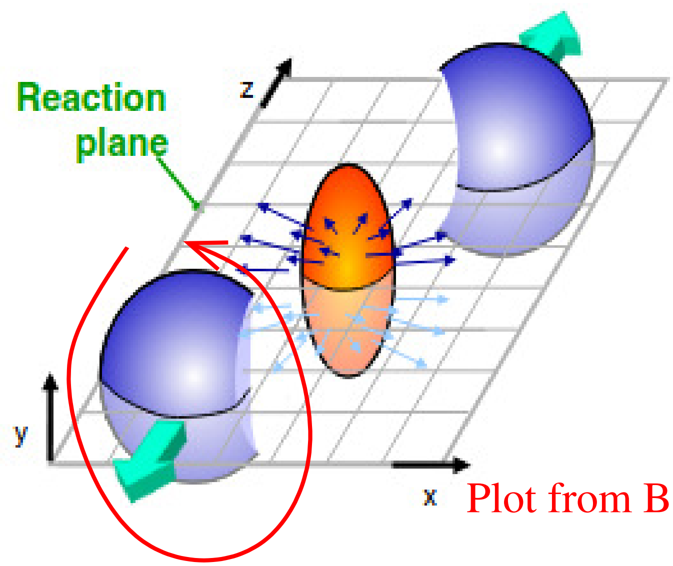
Ideal hydro Fits $\Lambda$ global (transverse) polarization out of phase for local (longitudinal) polarization (explanations around lack of equilibration) and underestimates $\phi$ but not $K^*$ spin alignment classical fields? Spin-orbit non-equilibrium? Coalescence?

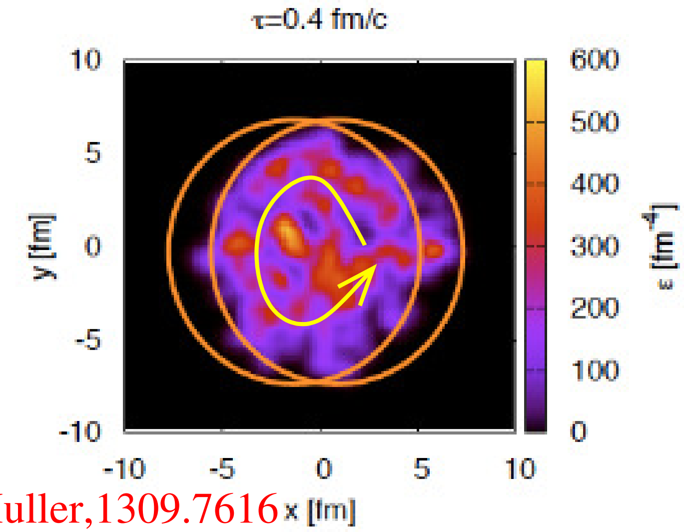



**Plots from Niida+Voloshin,2404.11042v1**

Global polarization tends to go down with energy, as expected (stopping ). Maximum within the range of fixed target experiments Local polarization nearly constant (as is time to develop)

What if I was an experimental magician ∀ problems were resolved?




Plot from B Muller,1309.7616

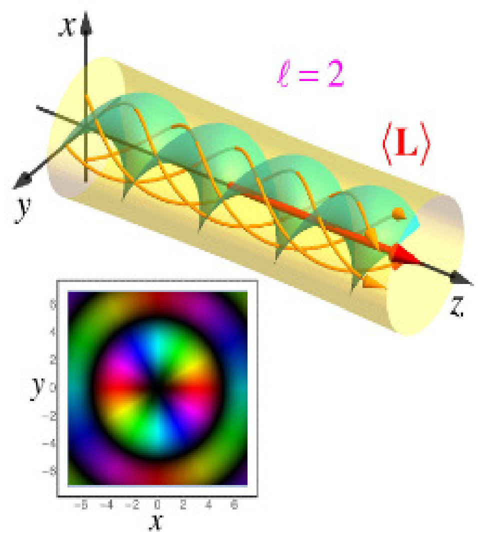
Put One nucleon in an initial vortical quantum state, collide with projectile that does not need to be in such a state, measure global and local polarization! Why worth doing? "tune" initial state contribution to local (longitudinal) spin by hand, sensitive probe to spin-vorticity non-equilibrium and interplay of global (transverse) and local vorticity.

Why (maybe) its feasible

- fixed target means vortical state nucleus can be a "target" (low energy)
- ions highly charged.
- At low $\sqrt{s}$/transparency only one vortex ion is enough!

If vortex $p\overline{p}$ scattering hadronic structure studies are possible, then so is rotating QGP!
Problem Need a lot of angular momentum $10^{3-4}\hbar$

But does it make sense?

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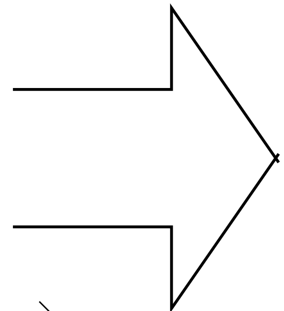
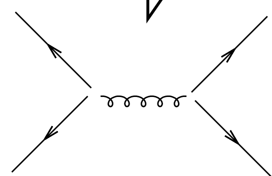




Initial state coherent, angular momentum carried by phase. will this? translate into hydro?

My current research! Briefly, is hydrodynamic initial state best described by A GPD $\sim \hat{T}_{\mu\nu}$ or A TMD $\sim \rho_{\perp gluons}$ ? Related to nature of thermalization

What is (ideal) hydrodynamics?

Conservation of momentum and Charge always gives us 5 Equations:

$$\underbrace{\partial_\mu \langle T^{\mu\nu} \rangle = 0}_{4} \quad , \quad \underbrace{\partial_\mu \langle j^\mu \rangle = 0}_{1}$$

Local equilibrium/isotropy, in some frame (at rest with $u^\mu$), reduces these 10+4 independent components

$$\langle T^{\mu\nu} \rangle = \underbrace{(e+p)u^\mu u^\nu - p g^{\mu\nu}}_{5 \quad e,p,u_{x,y,z}} \quad , \quad j^\mu = \underbrace{\langle \rho \rangle}_{1} u^\mu$$

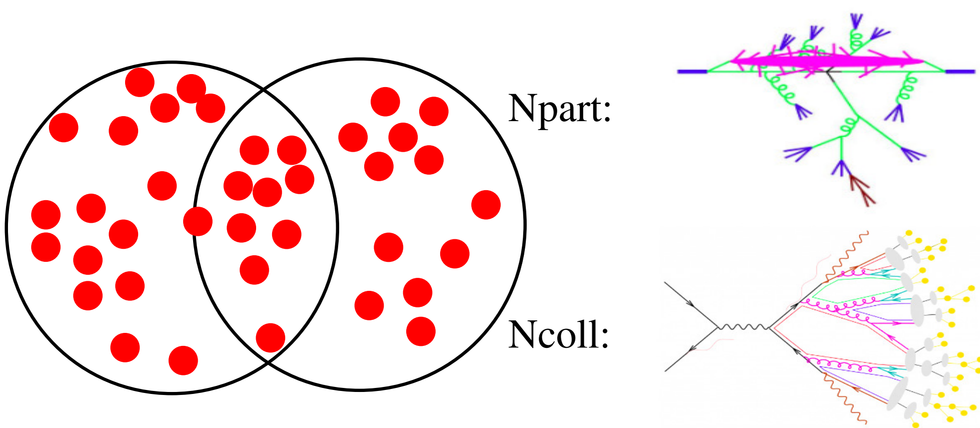
Together with the equation of state, system closed Viscosity gives more corrections equations, but still closed

$$p(e,\rho) \equiv \frac{\partial S}{\partial V} = T \ln \mathcal{Z} \quad , \quad e = -\frac{\partial \ln \mathcal{Z}}{\partial 1/T} \quad , \quad \rho = T \frac{\partial \ln \mathcal{Z}}{\partial \mu}$$

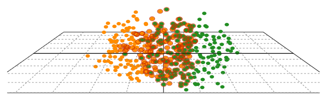
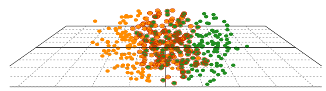
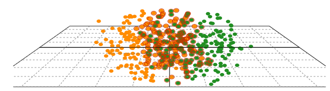
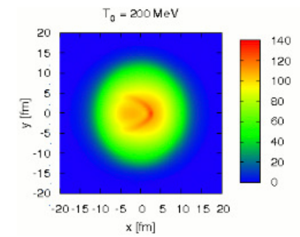
However,to solve we need non-hydrodynamic ingredients!

**“easy” EoS** at low chemical potential it is known from the lattice. Extending into $\mu$ is part of ongoing research

**“Hard” Initial conditions** (Energy/entropy density ) reasonable baseline: Incoherent superposition of nucleon-nucleon collision (Glauber model)+smearing. works as $R_{nucleus} \gg 1/Q^2 \gg 1/\sqrt{s}$

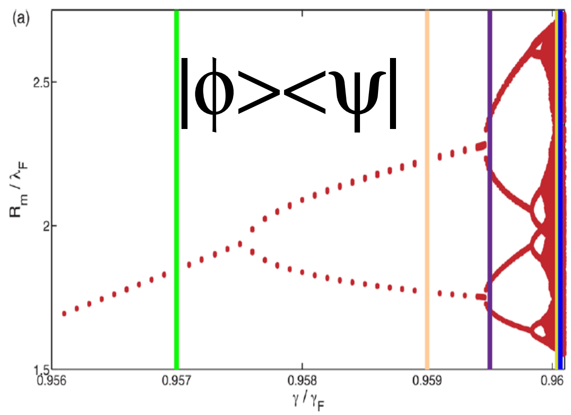


Complication: e-by-e correlations,subnucleonic structure

 ,  ,  ,....$\neq$ 

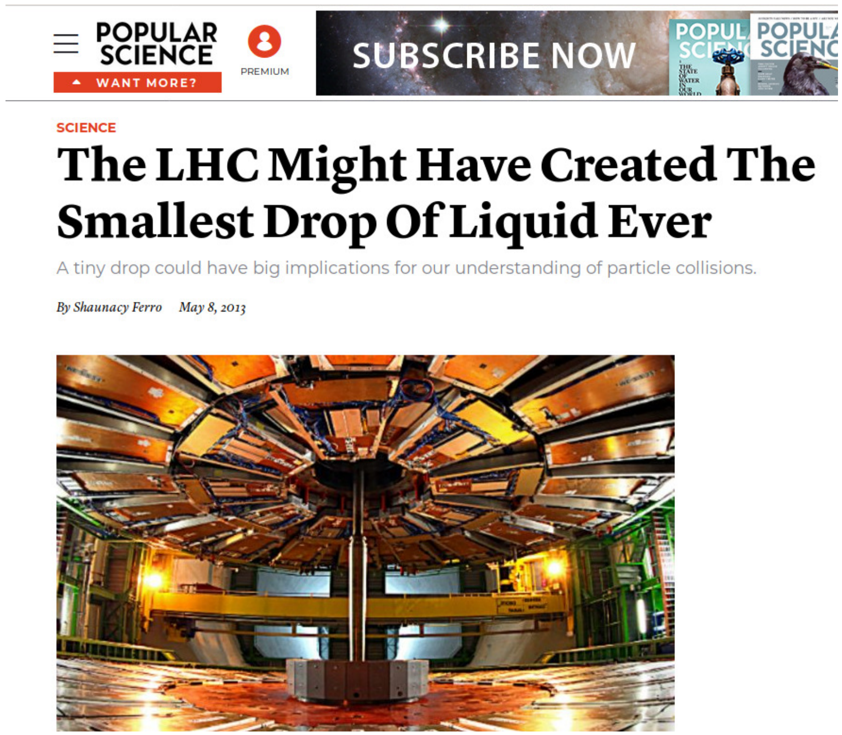

At most $<$ $+$ $+$ $+..>=$

e-by-e fluctuations and correlations complicated). For subnucleonic structure have estimates from color glass/saturation, but Need $\hat{T}^{\mu\nu}_{event} \simeq \left\langle \hat{T}^{\mu\nu} \right\rangle_{event}$ Hydro is a classical theory,need classical input all info in $\langle ... \rangle$




Microscopically this is a consequence of the initial state being maximally pure while every cell in hydrodynamics as maximally mixed DoFs. Sounds incoherent but if dynamics chaotic enough (Eigenstate thermalization ) it could actually make sense! quantum Fluctuations represented by multi-event classical ensemble

# However the LHC turned on and...



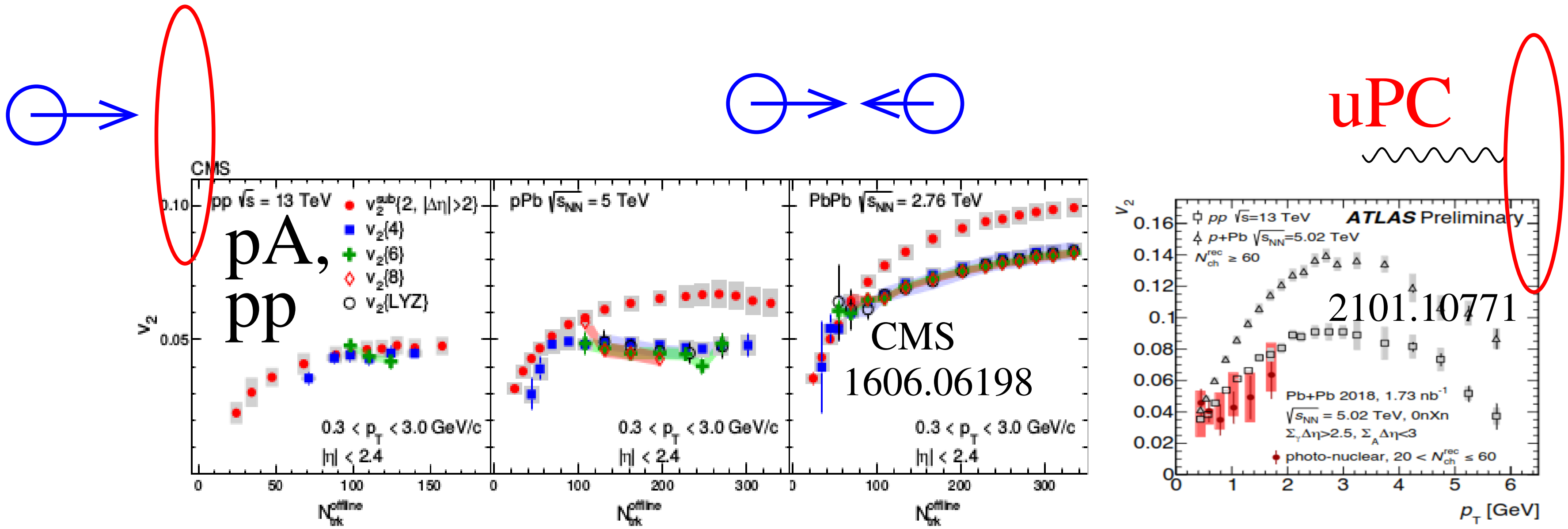


SCIENCE

## The LHC Might Have Created The Smallest Drop Of Liquid Ever

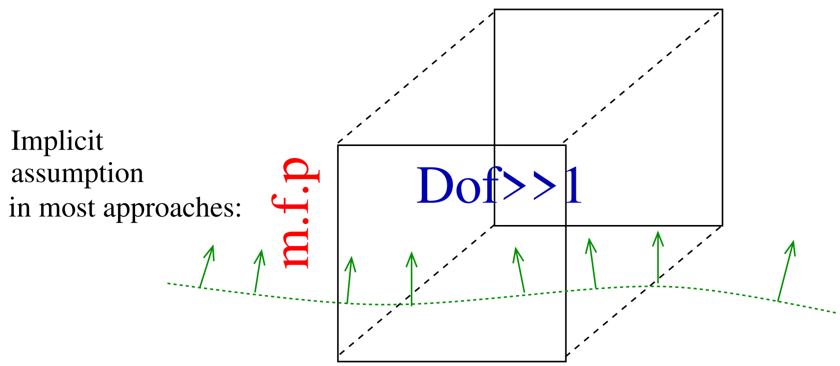
A tiny drop could have big implications for our understanding of particle collisions.

*By Shaunacy Ferro* *May 8, 2013*




1606.06198 (CMS) : When you consider geometry differences, hydro with $\mathcal{O}(20)$ particles "just as collective" as for 1000. Thermalization scale. 2101.10771 (ATLAS) also UPCs $\gamma^* A - \rho A$! It is clear that Subnucleonic degrees of freedom crucial

This raises conceptual problems



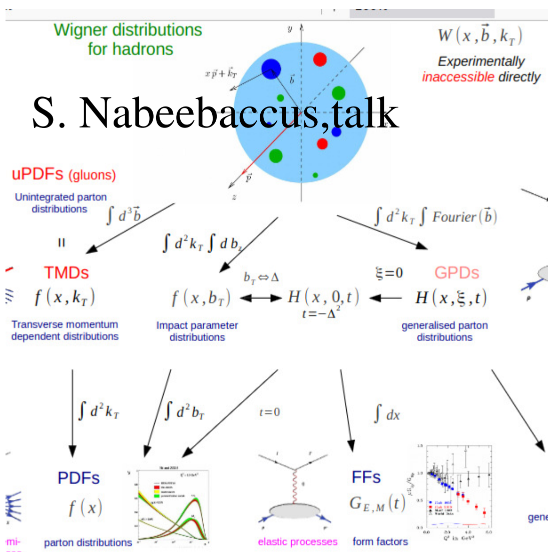

Hydrodynamics implicitly assumes a "thermodynamic limit in every cell", so $\langle e^2 \rangle - \langle e \rangle^2 \ll \langle e^2 \rangle$ ,thermodynamic fluctuations do not propagate. Need to study better connection to statistical mechanics . I work on this 2307.07021 , 2309.05154 2007.09224 ,2109.06389 ,But for this talk I will focus on an immediate "semi-technical" isse

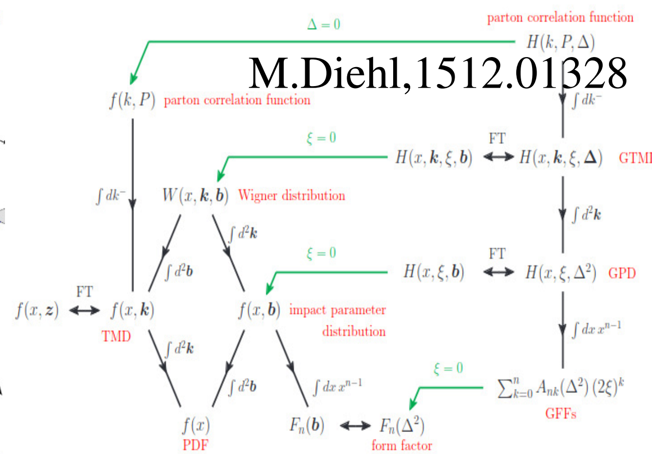
Qualitatively system seem equally collective as $v_n\{N\}$ independent of $N$ everywhere But what is the initial eccentricity of a nucleon-nucleon collision? no quantitative recipe that makes sense!

THe big issue: What are the initial conditions

**Hydro is a classical theory** initial conditions are <u>either</u> energy-momentum tensor $T_{\mu\nu}(x)$ or entropy density $s(x)$ Either works because one goes to the other via the EoS

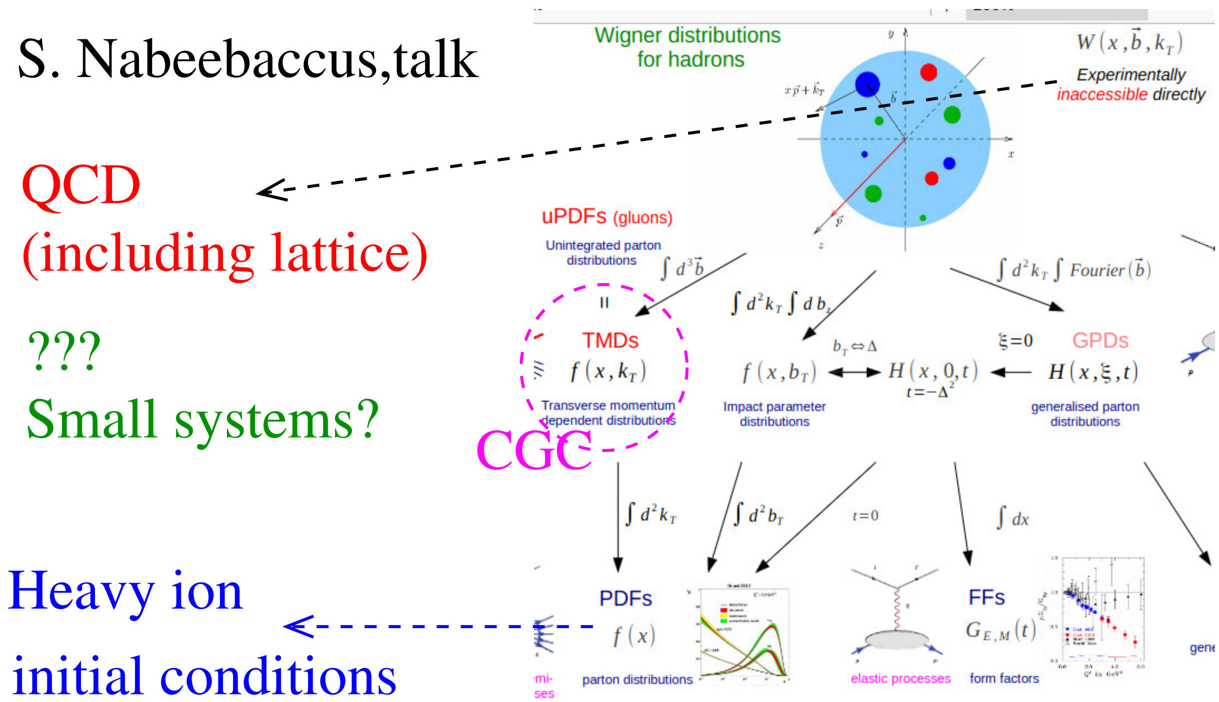
**The wave-function of the nucleon** ...



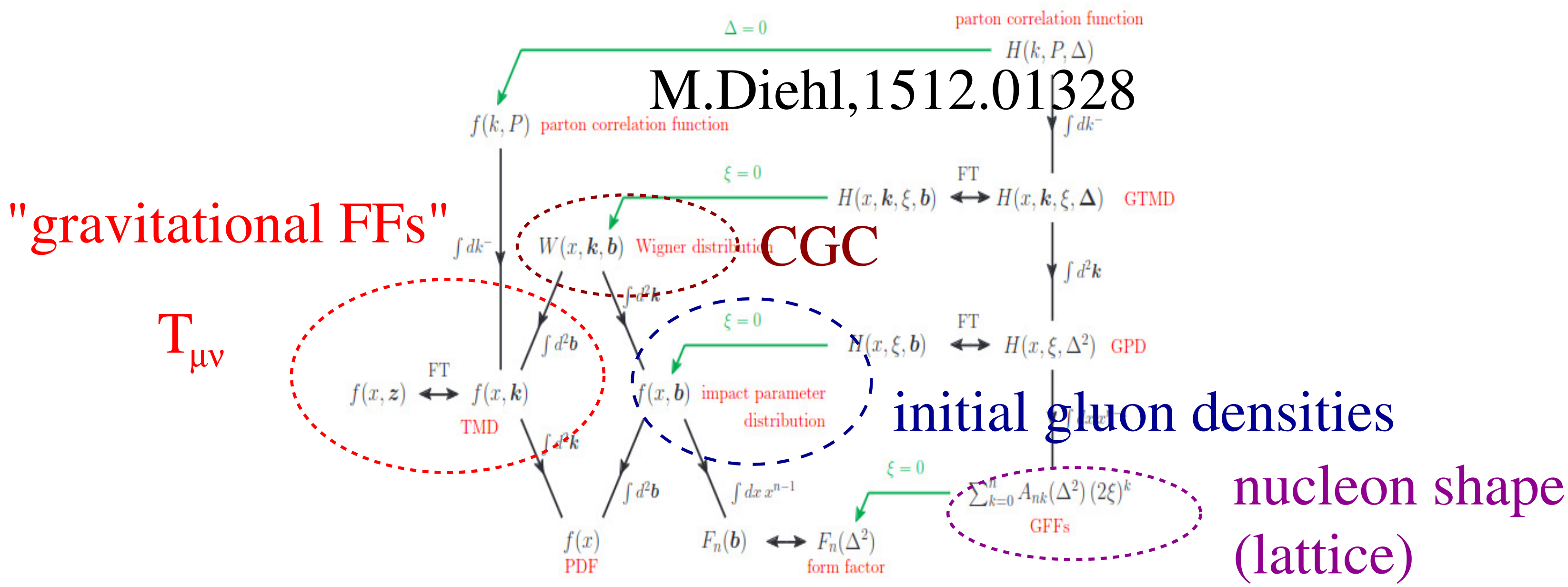
Big issue 1

Shape distributions are defineable in terms of Wigner functions and even calculable on the lattice, but relation to experimentally measureable processes (and HIC initial conditions) goes via transformations as well as limits and projections (non-invertible)



Big issue 2 (A huge one!)

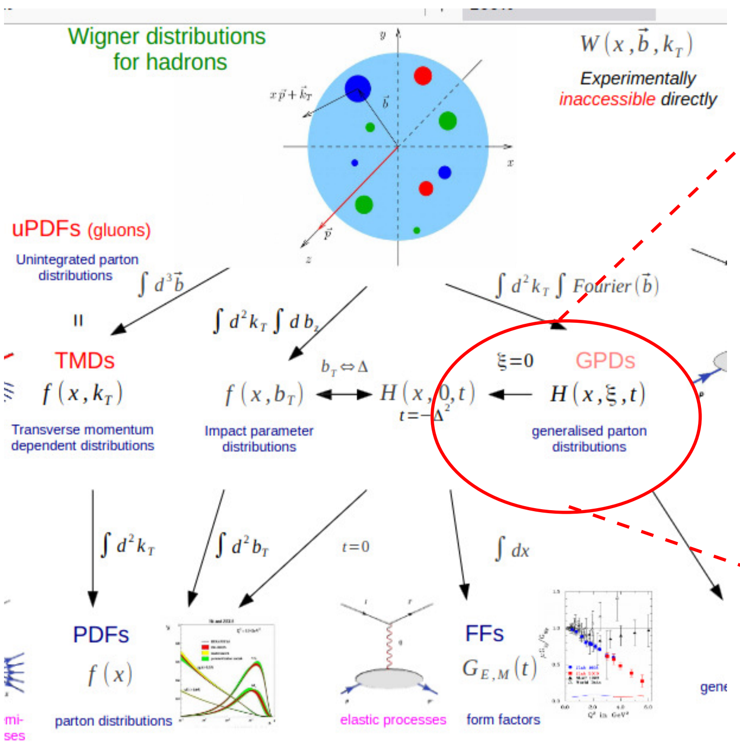
$T_{\mu\nu}(b_\perp, x_{bj})$ and $W_{partons}(b_\perp, x_{bj})$ characterized respectively by TMDs and GPDs . These are not transforms of each other, contain different information. What kind of "initial state" is it? CGC: TMD,Gaussians,thermalization not clear! (Kompost,free-flow etc)



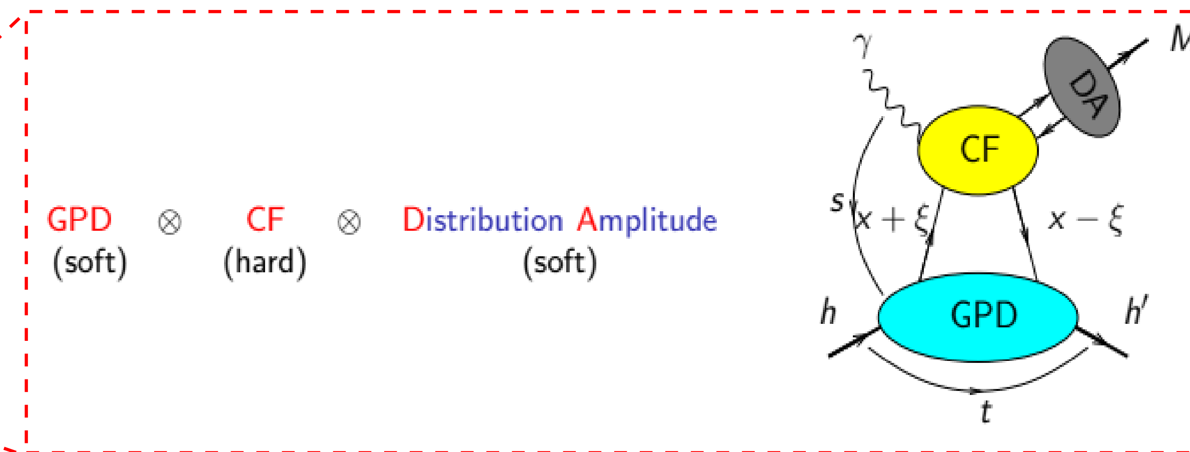
Beyond DiS structure process dependent! ,factorization less useful

transverse structure/motion of partons $\Rightarrow \underbrace{x_{structure}}_{z_{parton}/t_{parton} \sim p_z/E} \neq \underbrace{x_{kinematic}}_{p_z^{process}/E}$

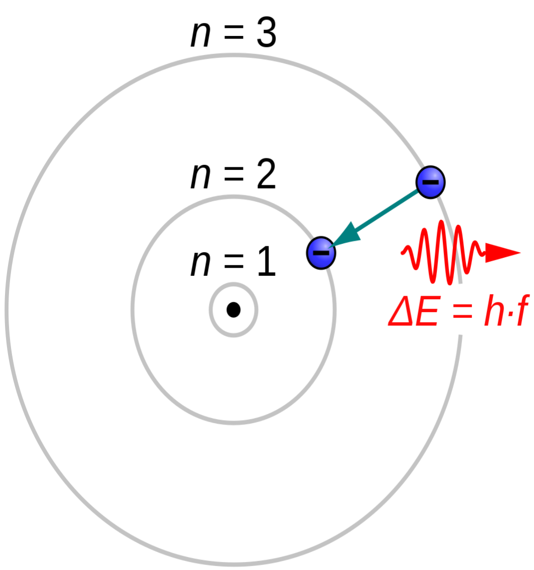
. How does one square this with universality of thermalization?




S. Nabeebaccus,talk



If you understand quantum mechanics this is not surprising We calculate wavefunctions... $\langle\psi|$ but measure process-dependent matrix elements $\left|\langle\psi_1|\,\hat{O}\,|\psi_2\rangle\right|^2$. Bohr picture works as $m_{electron} \gg r_{bohr}^{-1}$ so $\langle\psi_1|\,\hat{O}\,|\psi_2\rangle \simeq \int d^3x \,\langle\psi_{free}(x)|\,V(r)\,|\psi_{free}(x)\rangle$ but $r_{had}^{-1} \sim m_{had} \sim \Lambda_{QCD}$

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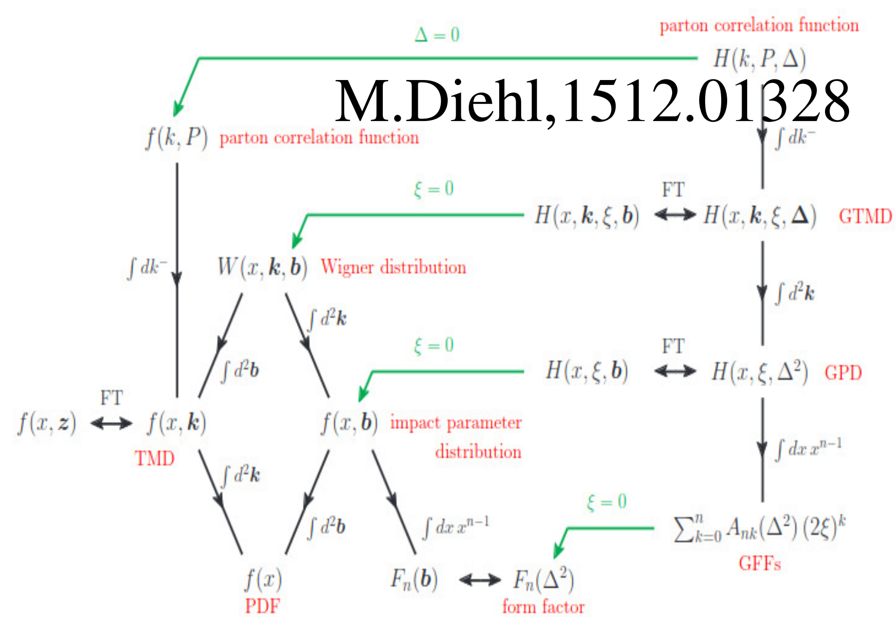
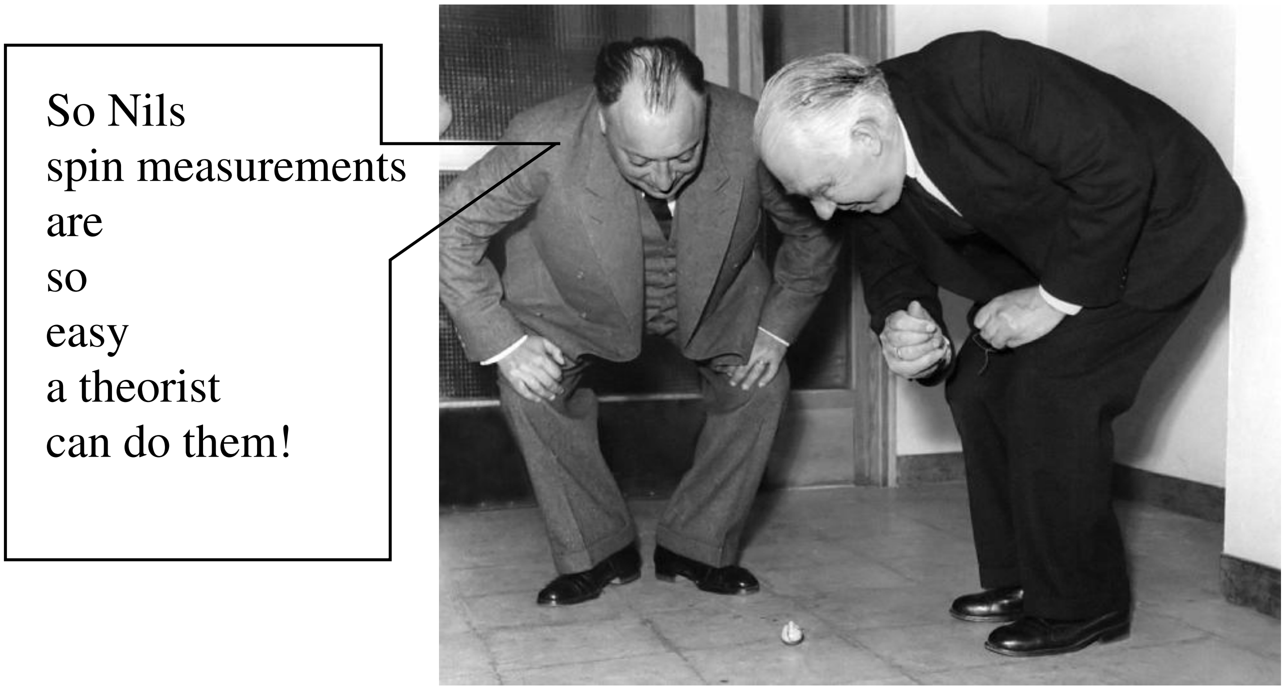



M.Diehl,1512.01328

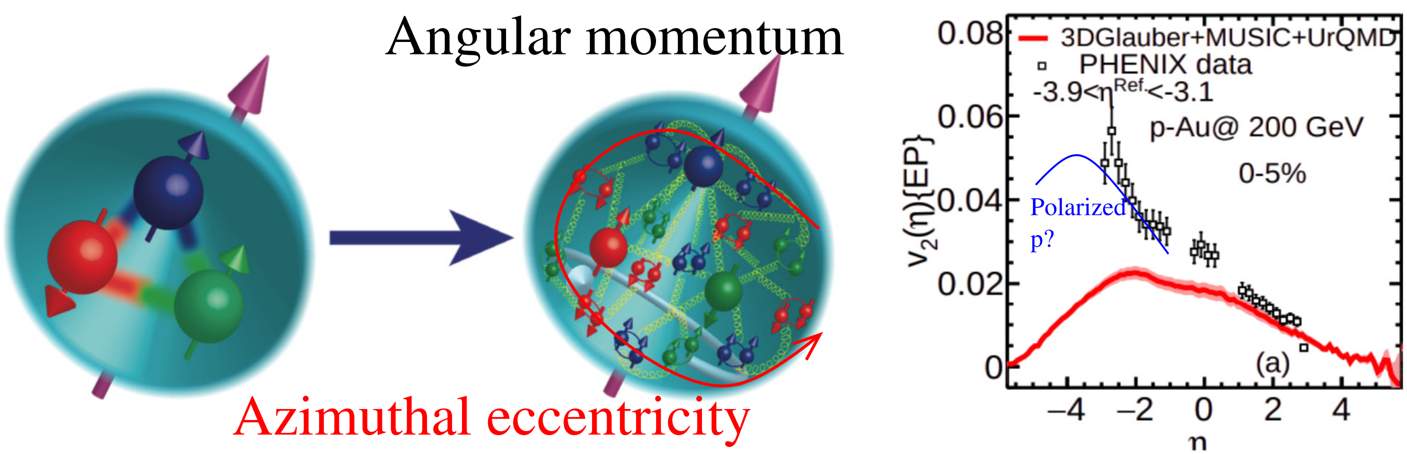
But how seriously can one take “initial states” in small systems as a “quantitative science”? What’s the hydro-relevant shape of a nucleon?




E.g., if Hydro “classicalizes” initial conditions. It means Hydro in small systems could lead to “classical spin measurement”

Remember $v_n$ sensitivity to eccentricity

$$v_n \sim A\mathcal{O}\left(\epsilon_n\right) + B\mathcal{O}\left(\langle T_{ini}\rangle \times R\right)\sum_m \mathcal{O}\left(\epsilon_n \epsilon_m\right) + C\mathcal{O}\left(\frac{\epsilon_n \eta}{sTR}\right) + \ldots$$

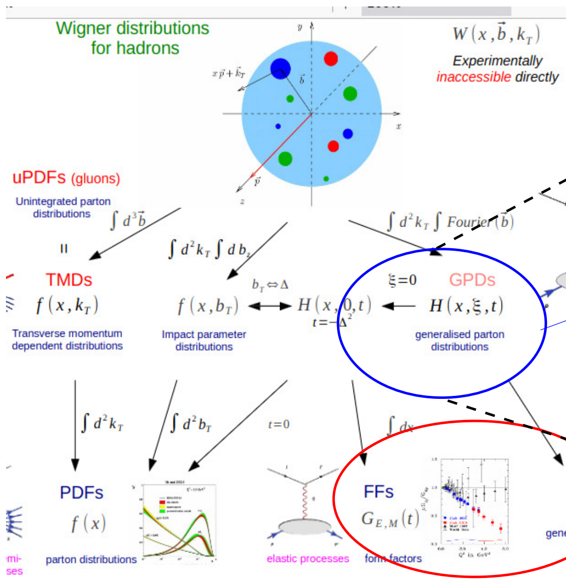



Spin dependent nucleon shape changes $v_2$ in polarized pA collisions. ultimate small system hydrodynamics? Experimentally feasible (data is there), But how does one get a theoretical estimate given the issues before?

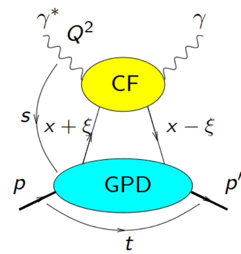
## Conclusion

- Hydrodynamics with spin experimentally confirmed, but theoretically non-understood
- Both initial state global vorticity and local vorticity generated by dynamics present. Equilibration uncertain.
- Spin vorticity interactions for arbitrary spin still not clear
- Scattering of vortical wavepackets a possible "handle" we can use to play with the above uncertainities.
- Conversion of a coherent ground state into a 'hot' initial condition for hydrodynamics an interesting problem

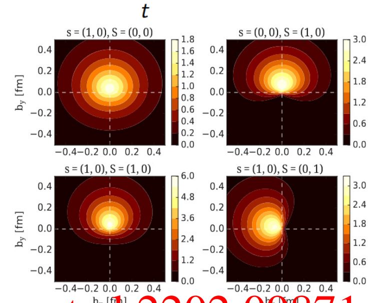
# SPARE SLIDES




S. Nabeebaccus,talk




lattice

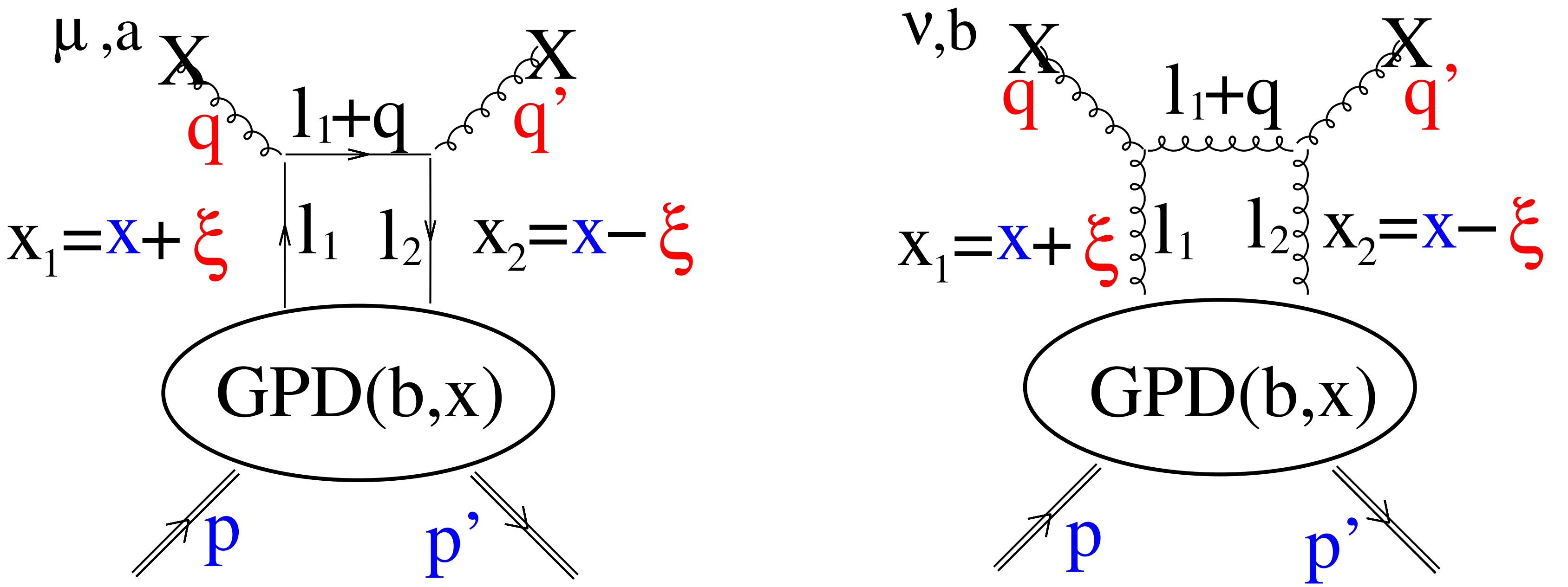



C.Alexandrou et al,2202.09871

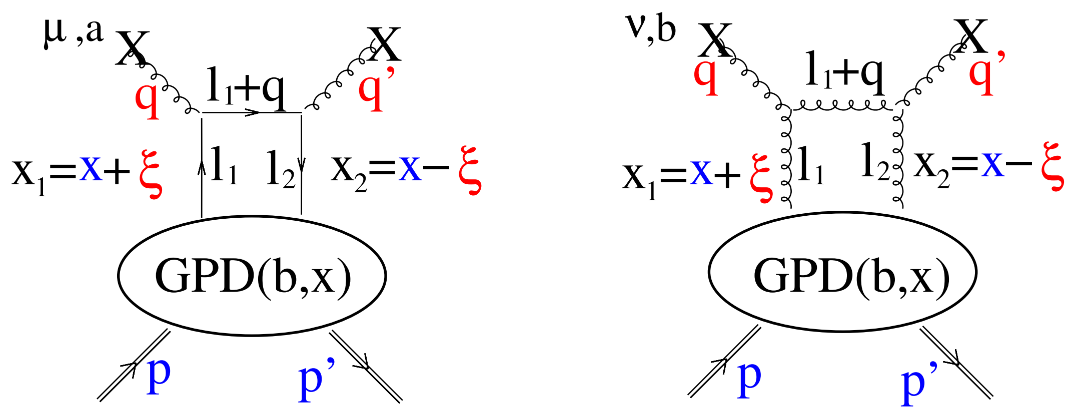
Lattice can measure azimuthally dependent Mellin moments

$$\int dx x^{n=0,1} \rho(b_x, b_y, x) \quad , \quad \rho \simeq g_0 + g_1 \cos(2\phi)$$

DVCS experimentally rare but conntects to $\lim_{\xi\to 0} \rho(b_x, b_y, x \pm \xi)$




Let us replace the virtual photon by an on-shell gluon from a thermal bath!
Same diagram up to $\alpha_s, tr[\lambda_{Gell-mann}]$ . A GPD talking to a heat-bath!




Simple but consistent: Instant thermalization+wounded nucleon picture

**Instant thermalization** The quanta coming in and out, photons in DVCS but gluons for hadronic collisions, are "in detailed balance with GPD"

**The Wounded nucleon picture** The longitudinal structure of the Nucleon is unchanged before and after, any energy transferred is transverse.

Detailed balance gives expression for $T(b_x, b_y, x_{bj})$ in terms of the GPD

$$\int d^3q d^3q' d^4 l_{1,2} \mathcal{H}\left(b_x, b_y, q, q', p, p', T(b_x, b_y, x)\right) = p', q' \leftrightarrow p, q$$

$$\mathcal{H}\left(...\right) = \rho_2\left(b_x, b_y, \zeta_1(q, q', p, p'), \zeta_2(q, q', p, p')\right) \left|M(p, p', q, q')\right|^2 \times$$

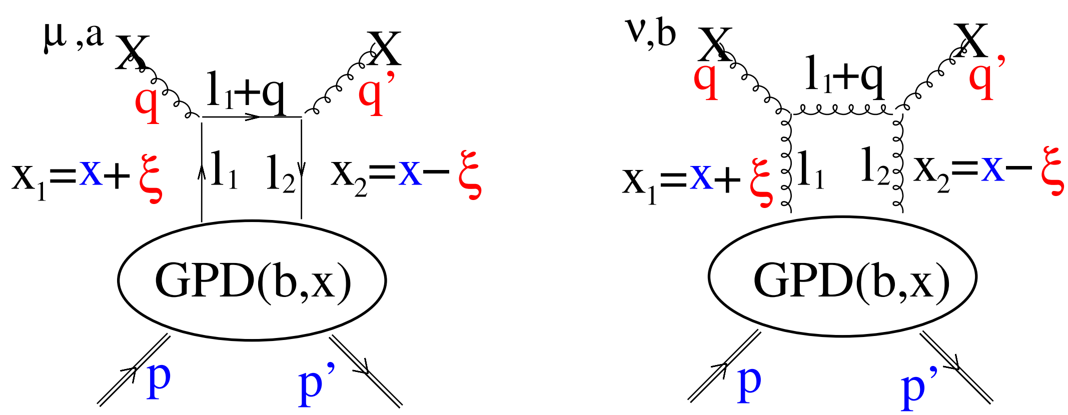
$$\times e^{-q_\mu \beta^\mu(b_x, b_y, x)} \left(1 + e^{-q'_\mu \beta^\mu(b_x, b_y, x)}\right) \delta^4\left(p + q - p' - q'\right)$$

$$\mathcal{H}\left(...\right) = \rho_2\left(b_x, b_y, x - \xi, x + \xi\right) \left|M(p, p', q, q')\right|^2 \times$$

$$\times e^{-q_\mu \beta^\mu(b_x, b_y, x)} \left(1 + e^{-q'_\mu \beta^\mu(b_x, b_y, x)}\right) \delta^4\left(p + q - p' - q'\right)$$

GPD enters via $\zeta_{1,2} = x_{bj} \pm \xi \; x_{bj}$ (observable),$\xi$ (integrated over)

$$\rho_2\left(b_x, b_y, \zeta_1(q, q', p, p'), \zeta_2(q, q', p, p')\right) = \rho(b_x, b_y, \zeta_1) \times \rho(b_x, b_y, \zeta_2)$$

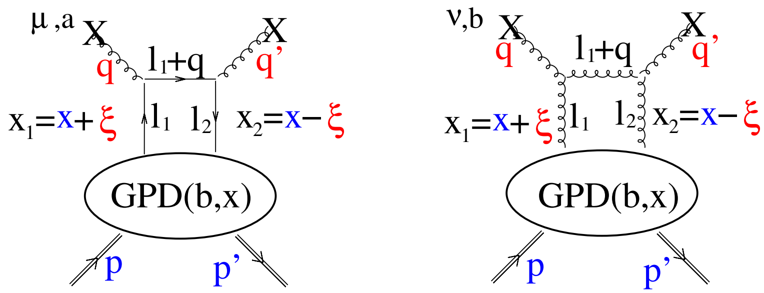



**Partons** co-move with $x \sim p_\perp e^{\pm y}$ ,in lightcone frame

$$p = \left(\frac{m}{2}\left(\cosh y \pm \sinh y\right), \mathbf{0}_\perp\right) \quad , \quad p' = \left(\frac{m_\perp}{2}\left(\cosh y \pm \sinh y\right), \mathbf{p}'_\perp \hat{\phi}_p\right)$$

$q, q'$ is thermal bath (integrated over),so

$$\int d^8 l_{1,2} 1 d^3 q d^3 q' \delta^4 \left(l_1 - l_2 + q - q'\right) \to \int d\xi d^2 \mathbf{\Delta}_\perp d\phi_{\mathbf{k}_\perp} |\mathbf{k}_\perp|^2 \frac{dq^+ d^2 \mathbf{q}_\perp}{2q^+} \frac{dq^{+'} d^2 \mathbf{q}'_\perp}{2q^{+'}}$$

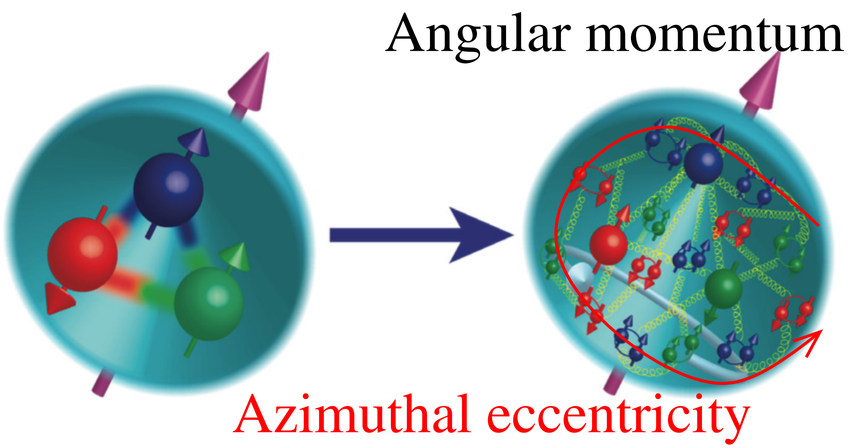


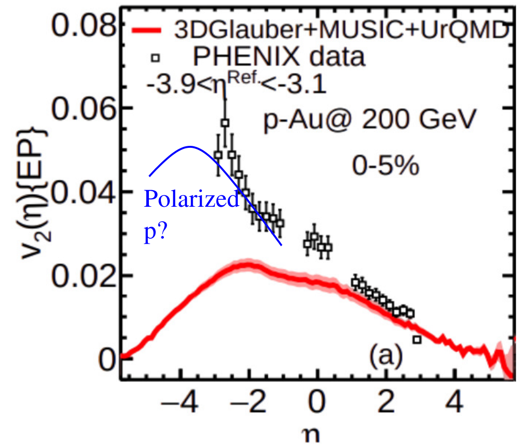

$$l_{2,1} = \left( P^+(x \pm \xi), \pm \frac{1}{8} \frac{\xi \mathbf{\Delta}_\perp^2 + 4\xi m^2}{(1-\xi^2)P^+}, \left[ k_\perp \pm \frac{1}{2} \mathbf{\Delta}_\perp \right] \hat{\phi} \right)$$

problem: GPD has no $k_\perp$ Diffractive limit fixes kinematics but is unrealistic ("all exchange in energy transverse", "wounded nucleon" has same mass as before impact $\mathbf{k}_\perp = -\frac{2x\xi p^{+2}}{\mathbf{\Delta}_\perp}$ Easy to go beyond this with saturation

$$\mathbf{k}_\perp = \sqrt{\left( \frac{2x\xi p^{+2}}{\mathbf{\Delta}_\perp} \right)^2 + Q^2} \quad , \quad f(Q)dQ \sim \exp\left[ -\left( \frac{Q}{Q_s} \right)^2 \right]$$

## Now we are getting somewhere!




Our approach is simplified but consistent, and gets a transverse spin-dependent $T(b_x, b_y, x_{bj})$ out of lattice data, including spin! $\epsilon_n(y) = \frac{c_n(y)}{c_0(y)}$

$$c_n(y) = \int db_x db_y \cos(n\phi) T^m(b_x, b_y, x) \delta\left(y + \ln\left(\frac{1}{x}\right)\right) \delta\left(\phi - \tan^{-1}\left(\frac{b_y}{b_x}\right)\right)$$

## Conclusions

- The observation of fluids in small systems throws a bunch of conceptual problems at us!
- Not clear how a classical fluid initial condition emerges out of deeply quantum configuration of a nucleon in small systems.
- Fast thermalization (detailed balance) and wounded nucleons (transverse energy exchange) could be a way forward,exciting prospect of linking lattice to hydro initial conditions
- EiC is coming and RHIC,LHC data is here , the symbiosis needs to be used to its fullest!
  Final frontier for quantitative hydro in small systems concurrent $v_2$ for $pA, p^{\Uparrow}A, \gamma^* A$ together with EiC 3D tomography!