Collective flow in small systems

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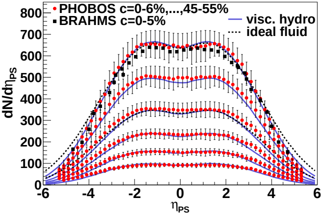
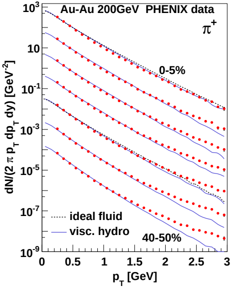
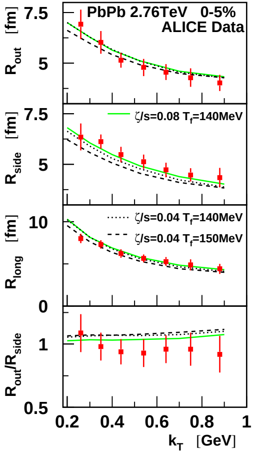
Collective expansion in A-A





HBT



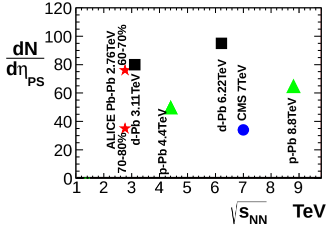
p-P@ LHC

p-Pb reference system - No FSI expected

but

Collective elliptic flow in p-Pb?

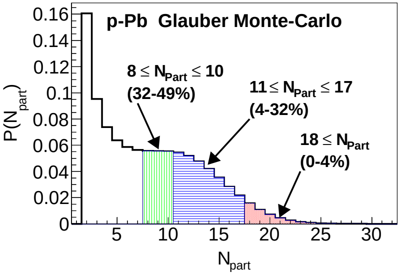
- Large enough density? yes
- Large enough eccentricity yes?
- Large enough size? (?)
  but should and can be tested
- Small enough gradients? no

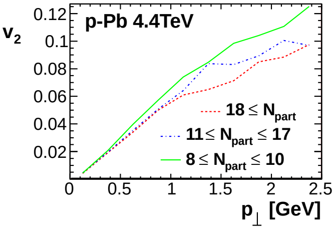


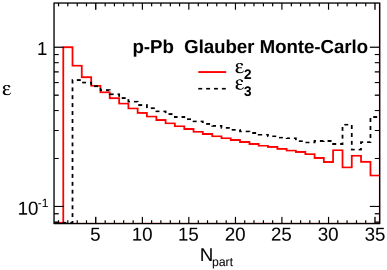
large multiplicity - large fireball - collective expansion?

$$l_{mf} = 0.2 - 0.3fm$$

Fireball in p-Pb



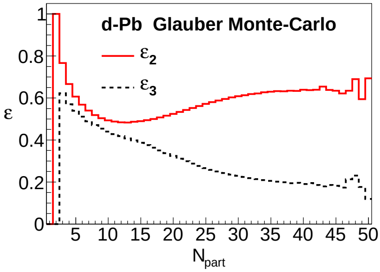


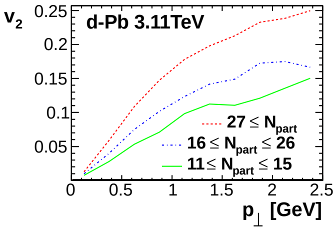


PB, arXiv:1112.0912

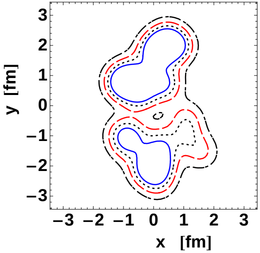
- collective flow effects $\simeq$ peripheral Pb-Pb
- can be observed
- p-A (d-A) is not p-p superposition

d-Pb





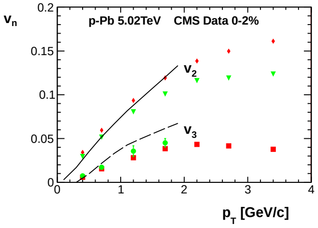
large elliptic flow

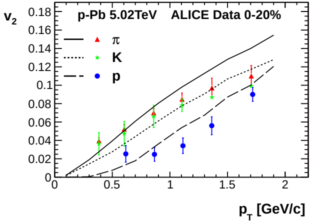


PB, arXiv:1112.0912

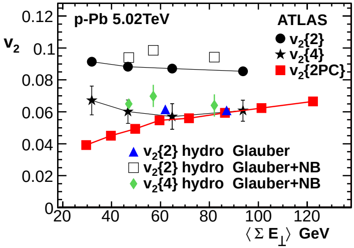
. . . it seems very interesting to look for collective effects in d-Au collisions at $\sqrt{s_N} = 200$GeV in RHIC experiments . . .

Elliptic and triangular flow





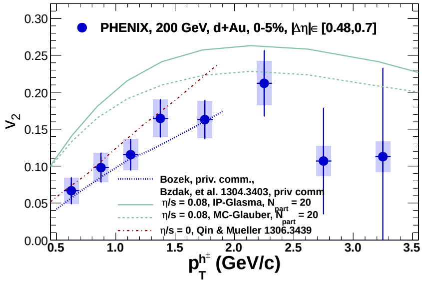
PB, Broniowski, Torrieri arXiv:1306.5442

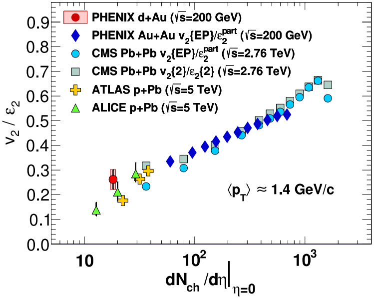


PB, Broniowski, arXiv:1304.3044

- elliptic and triangular flow
- mass hierarchy of v_2

d-Au at 200GeV

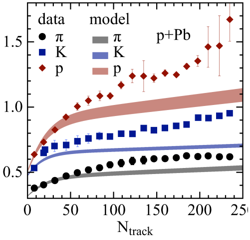




PHENIX, arXiv:1303.1794

large eccentricity - large elliptic flow

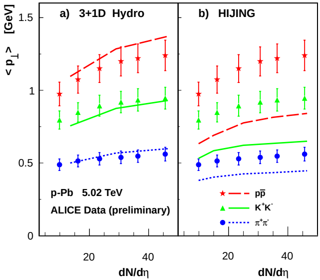
$< p_\perp >$ in small systems



Bzdak, Skokov, arXiv:1306.5442

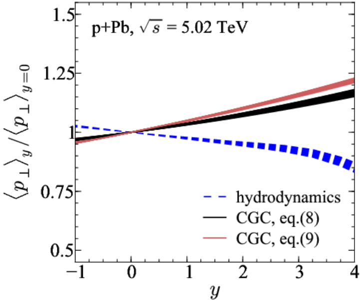
stronger transverse flow in p-Pb than in p-p

mass hierarchy of $< p_\perp >$



PB, Broniowski, Torrieri arXiv:1306.5442

$< p_\perp >$ rapidity dependence

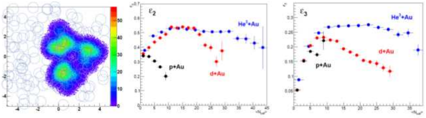


different prediction of CGC and hydro

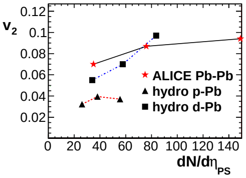
PB, Bzdak, Skokov, 1309.7358

ridge also from CGC, Dusling, Venugopalan, arXiv:1210.3890, 1211.3701, 1302.7018

small on big collisions



PHENIX proposal ⟶ v_3, Sickles et al. arXiv:1401.2432

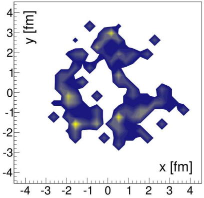


PB, arXiv:1112.0912

strong effect for d-A

intrinsic deformation dominates

over fluctuations

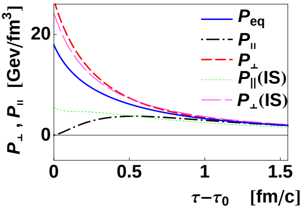


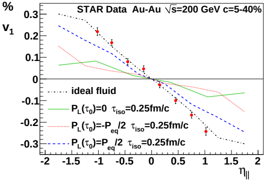
α clusters in ^{12}C Broniowski, Arriola arXiv:1312.0289

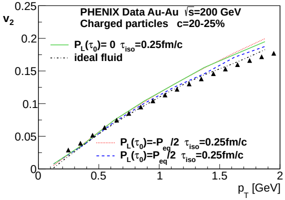
some effect for v_3 in ^3He-A,

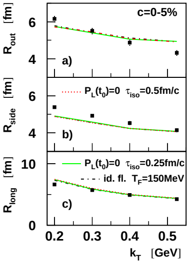
Nagle et al. arXiv:1312.4565

pressure anisotropy









PB, Wyskiel - arXiv:1009.0701

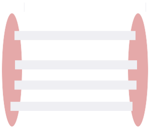
- early pressure anisotropy irrelevant!

hydrodynamics works effectively even at $P_L \simeq 0$

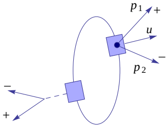
FSI scenarios

fields+thermalization

color fields

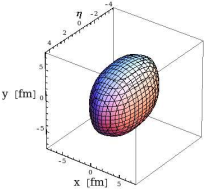


local thermalization → hadronization

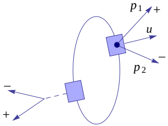


hydrodynamics

hydrodynamic expansion



hadronization, statistical emission



"thermalization" required

particles formed on small scales ⟶ local flow velocity

Summary

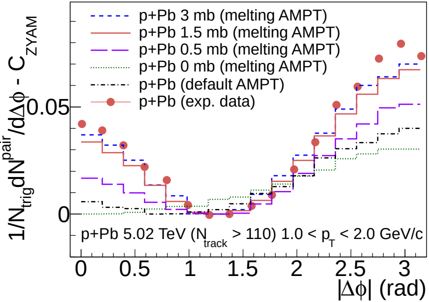
- Hydrodynamics works for Au-Au (RHIC) , Pb-Pb (LHC) does it in p-Pb, p-p ?
- Collectivity in pPb@LHC - explains v_2, v_3, ridge, $< p_\perp >$
- Experimental validation in small-on-big collisions?

Final State Interactions in p-Pb !

- particles produced locally $\longrightarrow$ momentum-position correlation

- Why hydrodynamics would work?
- **Effective theory for transverse expansion**
- We need observables for longitudinal pressure

flow from AMPT cascade in p-Pb



AMPT model, Ma, Bzdak, arXiv:1404.4129

energy-momentum tensor

$$T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p+\Pi & 0 & 0 \\ 0 & 0 & p+\Pi & 0 \\ 0 & 0 & 0 & p+\Pi \end{pmatrix} + \pi^{\mu\nu}$$

- shear viscosity

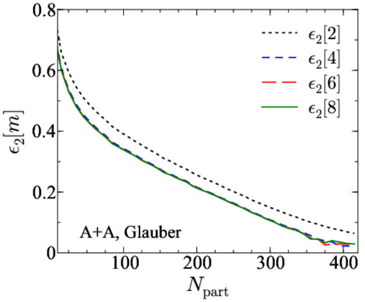
$$\Delta^{\mu\alpha}\Delta^{\nu\beta}u^\gamma\partial_\gamma\pi_{\alpha\beta} = \frac{2\eta\sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_\pi} - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_\pi}\partial_\alpha\left(\frac{\tau_\pi u^\alpha}{\eta T}\right)$$

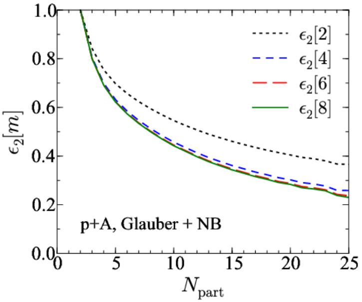
- bulk viscosity

$$u^\gamma\partial_\gamma\Pi = \frac{-\zeta\partial_\gamma u^\gamma - \Pi}{\tau_\Pi} - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\alpha\left(\frac{\tau_\Pi u^\alpha}{\zeta T}\right)$$

- viscosity corrections from velocity gradients
- **initial** stress tensor - pressure anisotropy
- equation of state

Higher cumulants



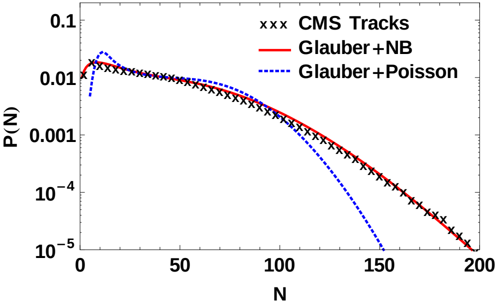


$v_2\{2\}^2 \simeq v_2^2 + \delta^2$ $v_2\{4\} = v_2\{6\} = v_2\{8\} \simeq v_2$
Bzdak,PB, McLerran

$v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\} < v_2\{2\}$

Glauber+NB

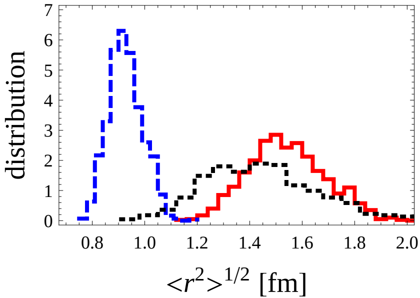
fluctuations from subnuclear dynamics



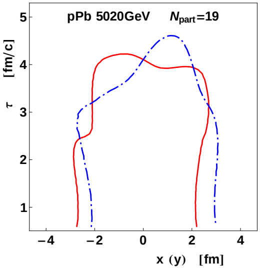
$$P(n) = \sum_i P_{part}(i) N p \lambda i, \kappa i(n)$$

Additional fluctuations of density (compared to Glauber)

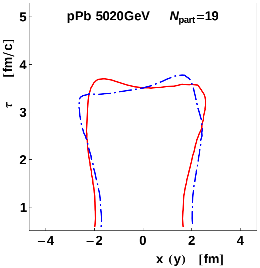
very different source sizes



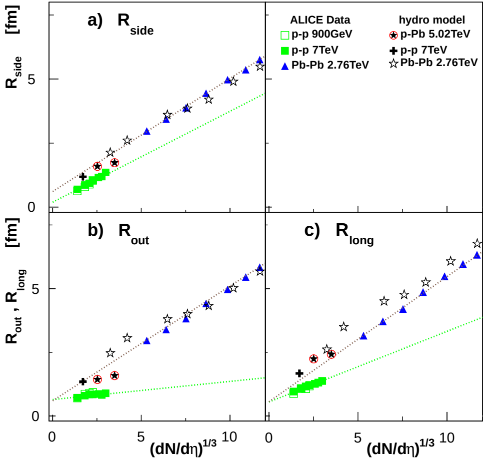
large source (standard)



compact source



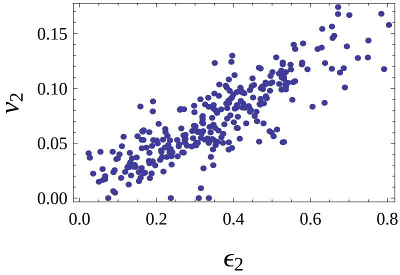
HBT systematics

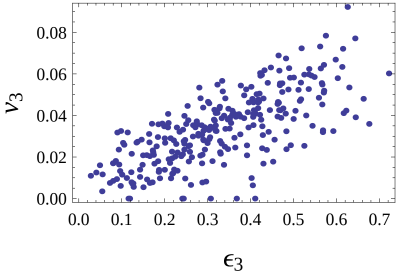


PB, Broniowski, arXiv:1301.3314

small system corrections!- Sinyukov, Shapoval - arXiv:1209.1747

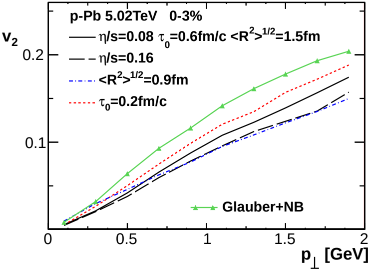
fireball asymmetry - flow asymmetry

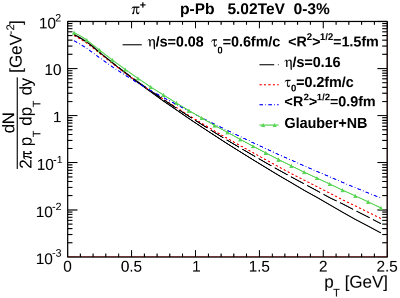




- Ev-by-Ev hydro response to geometry valid
- response strength depends on details

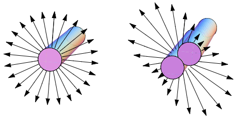
dependence on model details

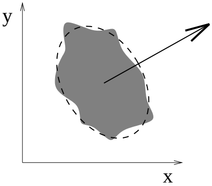


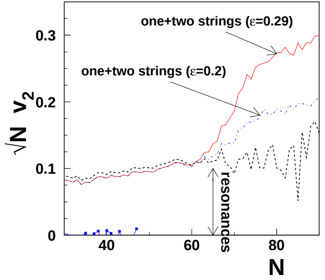


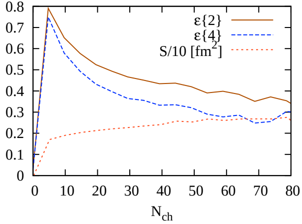
- response strength depends on details, initial eccentricity

Fireball shape in pp





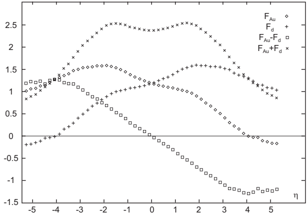




Bozek, 0911.2397

Asar et al., 1009.5643

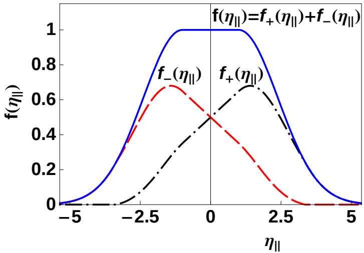
Casalderrey-Solana, Wiedemann, 0911.4400

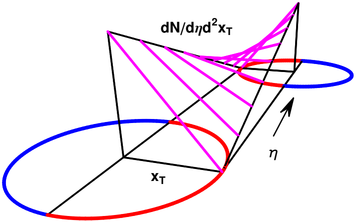


Asymmetric emission

(Białas, Czyż, Acta Phys.Polon.B36, 905 (2005))

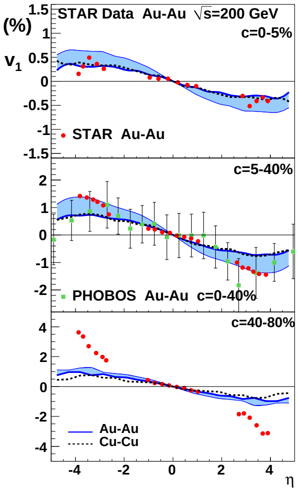
$$\rho(\eta, x, y) \quad \propto \quad f_+(\eta) N_+(x,y) + f_-(\eta) N_-(x,y)$$

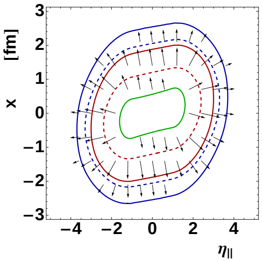




bremsstrahlung (Adil Gyulassy, Phys. Rev. C72, 034907 (2005))

Directed flow- tilted source





Bozek, Wyskiel, Phys. Rev. C81, 054902 (2010)

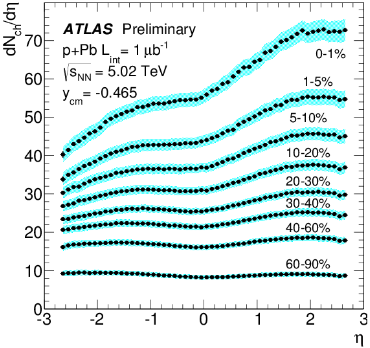
$$\partial_\tau u_x = -\frac{\partial_x p_\perp}{p+\epsilon}$$

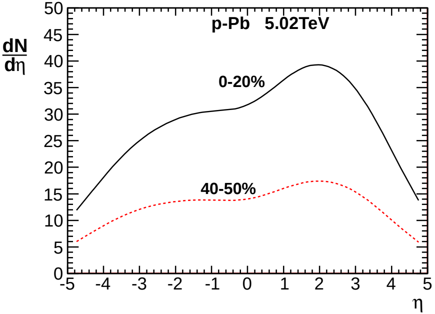
$$\partial_\tau Y = -\frac{\partial_\eta p_{||}}{\tau(p+\epsilon)}$$

tilted source $\rightarrow$ transverse pressure + longitudinal pressure

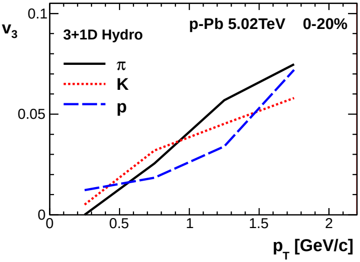
Glauber model

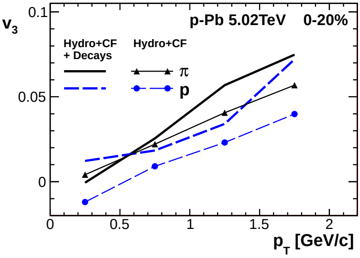
Asymmetric distributions





v_3 - small mass splitting





limited mass splitting

resonance decays spoil mass ordering

Early dynamics - far from equilibrium

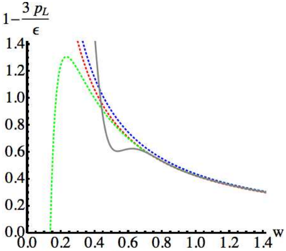
pressure asymmetry

$$T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p_{\|} & 0 & 0 \\ 0 & 0 & p_{\|} & 0 \\ 0 & 0 & 0 & p_{\|} \end{pmatrix}$$

Florkowski, Martinez, Ryblewski, Strikland

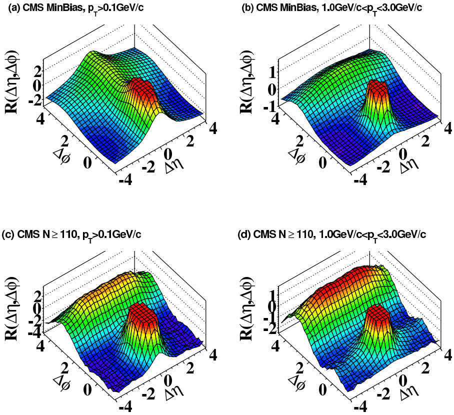
arXiv:1004.1594, 1007.0889

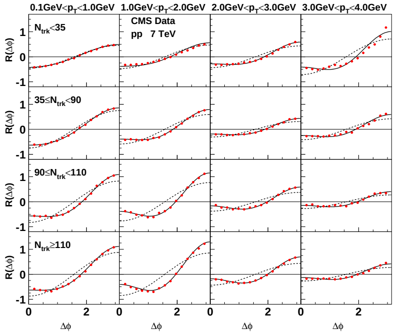
AdS/CFT



Heller, Janik, Witaszczyk, arXiv:1103.3452

Ridge in pp

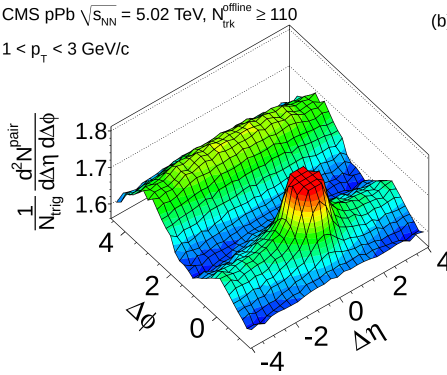


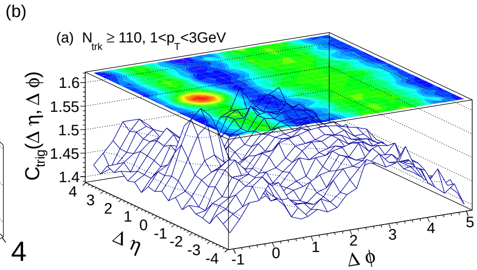


PB arXiv:1010.0405

can we measure (calculate) v_2

Ridge in p-Pb





PB, Broniowski, arXiv:1211.0845

ridge also from CGC, Dusling, Venugopalan, arXiv:1210.3890, 1211.3701, 1302.7018