Material for the discussion session:
- Coulomb effect
- Collectivity at 2-3 GeV

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Szymon Harabasz for the **HADES** Collaboration

Analysis of charged pions

HADES Collaboration, EPJA 56 (2020) 10, 259
https://www.hepdata.net/record/ins1796710

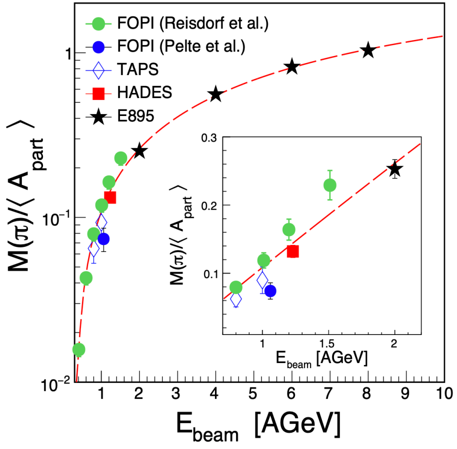

Fig. 8 Pion multiplicity $M(\pi)$ per mean number of participating nucleon $\langle A_{part} \rangle$ as a function of the kinetic beam energy E_{beam}. The dashed curve is a fit to the data points except for the one labeled "FOPI (Pelte et al.)", as suggested in [4]. The inset magnifies the energy region around the HADES point.

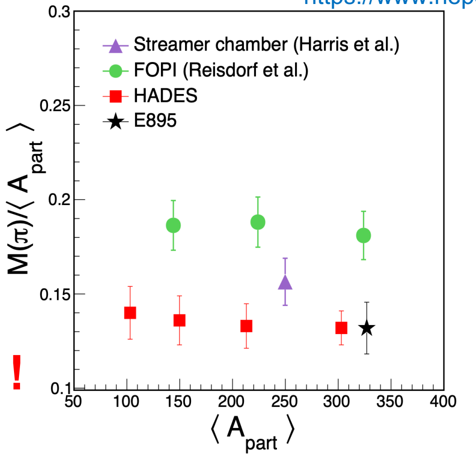

Fig. 9 Comparison of the centrality dependence of $M(\pi)/\langle A_{part} \rangle$ in Au+Au collisions to earlier measurements at similar energies. The results from FOPI, E895, and from the BEVALAC Streamer Chamber group (the latter for $La + La$ collisions) have been scaled to 1.23 A GeV; note the suppressed zero on the ordinate.

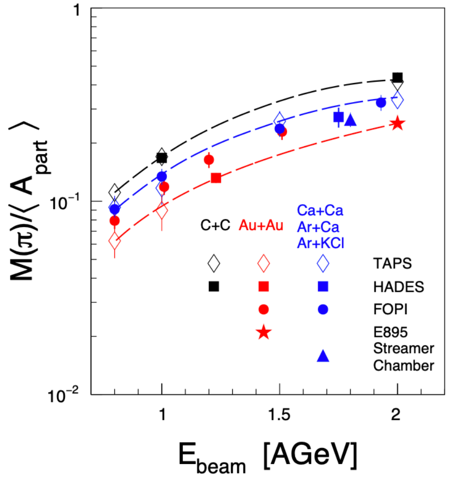

Fig. 10 Pion multiplicity per participating nucleon as a function of beam energy for three different systems: C+C (black) [7, 22, 39], Ar+KCl (blue) [4, 7–9, 40] and Au+Au (red) [4, 6, 7, 11]. The curves are polynomial fits to these data used to interpolate the multiplicities as a function of bombarding energy for corresponding systems.

More data needed

Not Everything is Known Yet About Few-GeV HIC

Example for π^-, same holds for π^+

HADES Collaboration, EPJA 56 (2020) 10, 259
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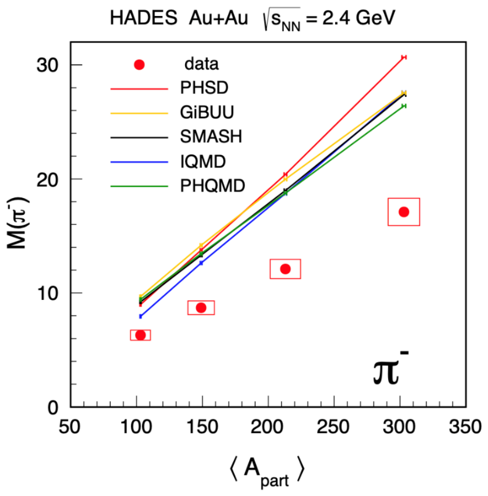

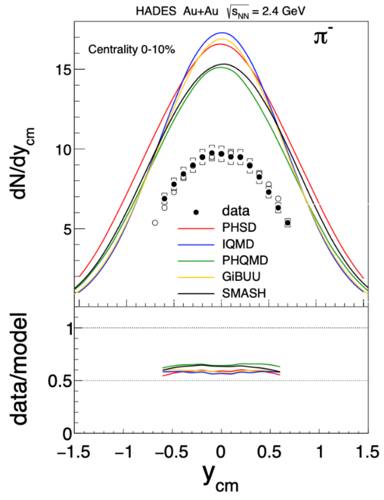

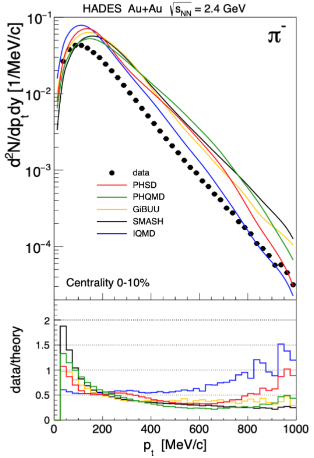

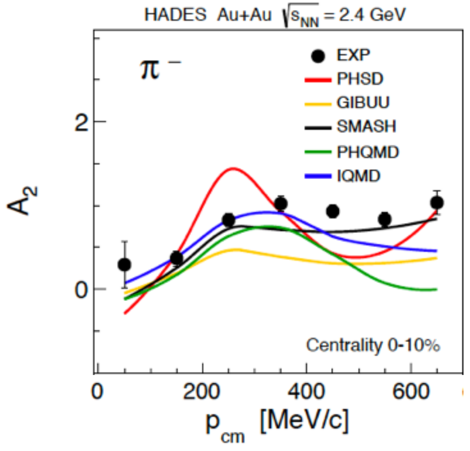

$$\frac{dN}{d(cos\theta_{cm})} = C(1 + A_2 cos^2\theta_{cm})$$

Pion and Proton "Temperatures" in HIC
R. Brockmann *et al.*, PRL 1984

- Only width of the rapidity distributiion is correctly described by the models
- Is there something fundamentally missing?

Trasnsport works well for C+C collisions

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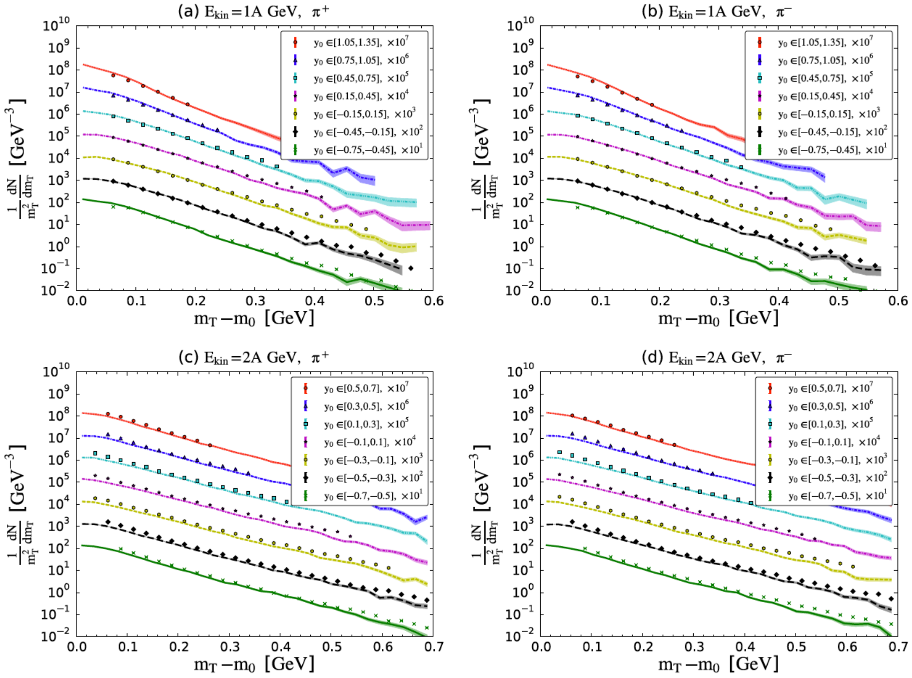
J. Weil *et al.* (SMASH), PRC 94 (2016) 054905



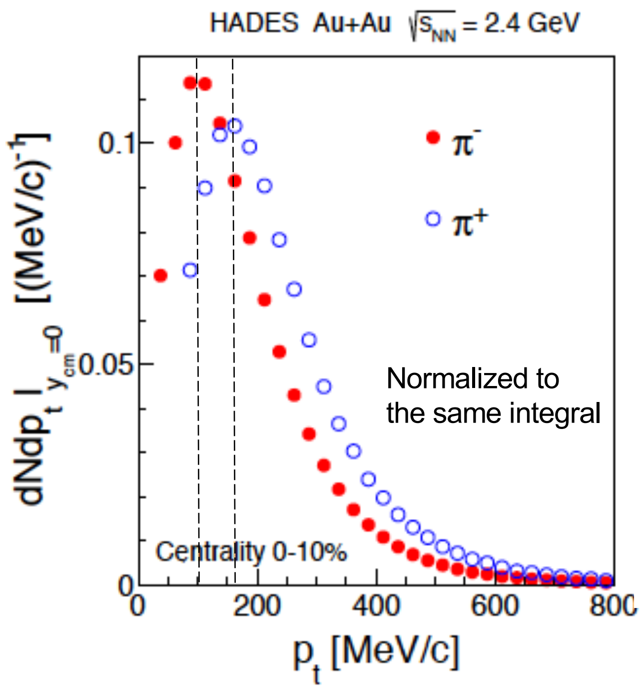
A. Larionov *et al.* (GiBUU), 2009.11702v3

TABLE I. Pseudo neutral π^0 multiplicities N_{π^0} as defined by Eq. (62) from GiBUU for various colliding systems. The results for Au+Au and Ag+Ag are geometrically weighted in the impact parameter ranges that corresponds to 0 − 40% centrality which are $b < 9.3$ fm and $b < 7.7$ fm, respectively. For the other systems the impact parameter distributions reproducing the HADES trigger were used.

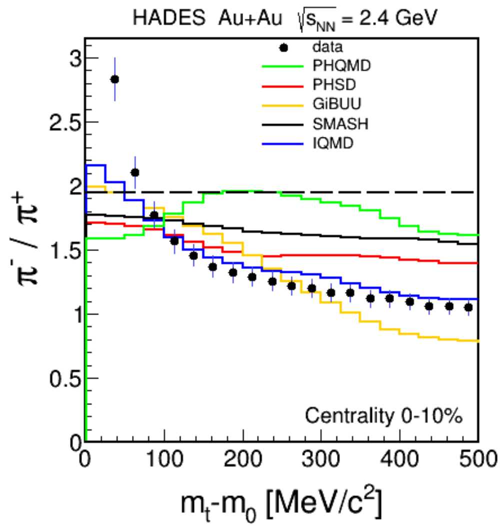
system	N_{π^0}	exp.	Ref.
Au+Au, 1.23*A* GeV	12.8	8.65 ± 0.52	[25]
C+C, 1*A* GeV	0.53	0.52 ± 0.08	[23]
C+C, 2*A* GeV	1.00	1.16 ± 0.16	[84]
Ar+KCl, 1.76*A* GeV	4.1	3.50 ± 0.25	[24]
Ag+Ag, 1.58*A* GeV	9.8		

Coulomb Potential of the Fireball

HADES Collaboration, MS. in preparation



- Split of peak positions:
  → 100 MeV/c for π^-
  → 160 MeV/c for π^+
- Attributed to the "Coulomb" interaction of pions with the positive charge of the fireball



- Only GiBUU and IQMD implement the final state EM interaction
- Second-to-best approach: fit to the data

Coulomb Potential of the Fireball

HADES Collaboration, MS. in preparation

Shift in the total pion energy

$$E_f(p_f) = E_i(p_i) \pm V_C$$

D. Cebra *et al.*, arXiv:1408.1369
A. Wagner *et al.*, PLB 420 (1998) 20

Damping factor to account for fireball expansion

H.W. Barz, et al. PRC 57 (1998) 2536

$$V_{eff} = \begin{cases} V_C\left(1 - e^{-x^2}\right) & \text{for boost-invariant expansion} \\ V_C\left(\mathrm{erf}(x) - (2/\sqrt{\pi})xe^{-x^2}\right) & \text{for spherical expansion} \end{cases}$$

$$x = (E_\pi/m_\pi - 1)\, m_p/T_p$$

Lower beam energies

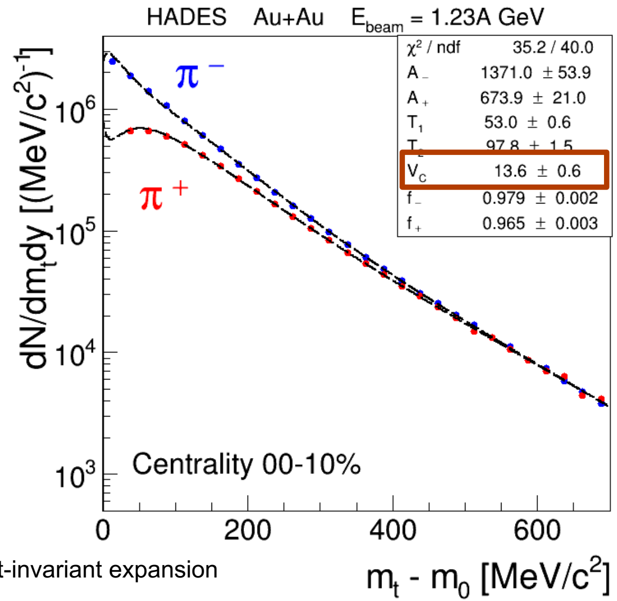
Modified double-Boltzmann fit function

$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = A\left(f\, e^{-E_i/T_1} + (1-f)\, e^{-E_i/T_2}\right) \cdot Jac \cdot Jac_{\mathrm{damp}}$$

$$Jac = \frac{E_i p_i}{E_f p_f}$$

G. Baym, P. Braun-Munziger, NPA 610 (1996) 286c

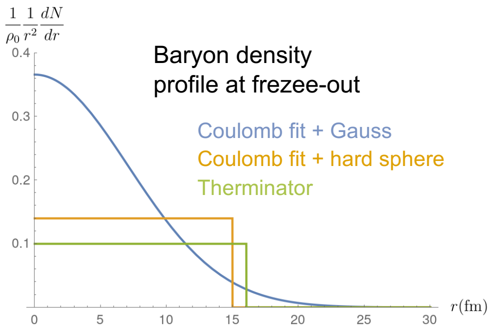
$$Jac_{\mathrm{damp}} = \begin{cases} 1 \mp \dfrac{V_C m_p}{m_\pi T_p} e^{-x^2} & \text{for boost-invariant expansion} \\ 1 \mp \dfrac{2}{\sqrt{\pi}} \dfrac{V_C m_p}{m_\pi T_p} x e^{-x^2} & \text{for spherical expansion} \end{cases}$$



Method of Extracting Freeze-out Parameters

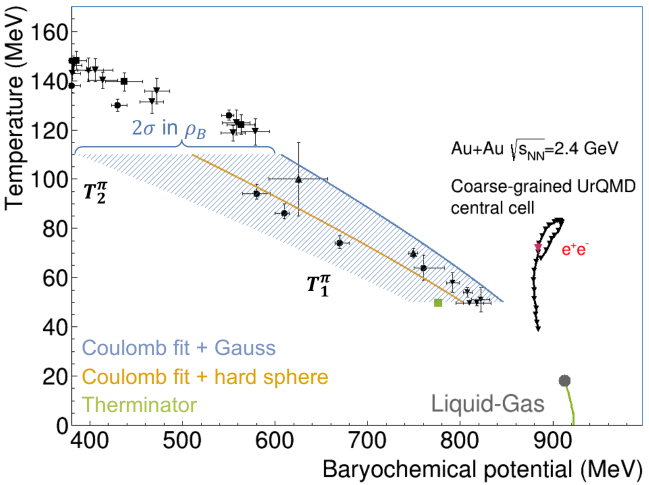
HADES Collaboration, MS. in preparation

V_c → charge radius → Baryon density distribution
assuming charge radius = matter radius



First shot with a few simplifications:

$$\mu_B = m_N + T\ln\left(\frac{\rho_B}{g}\left(\frac{m_N T}{2\pi}\right)^{-3/2}(\hbar c)^3\right)$$



Hatched area: extends from density at the center to the one at 2σ.

- Independent way of estimating freeze-out point/region in phase diagram
- Result consistent with fits to particle yields

Protons and Light Nuclei $v_n, n = 1 - 6$

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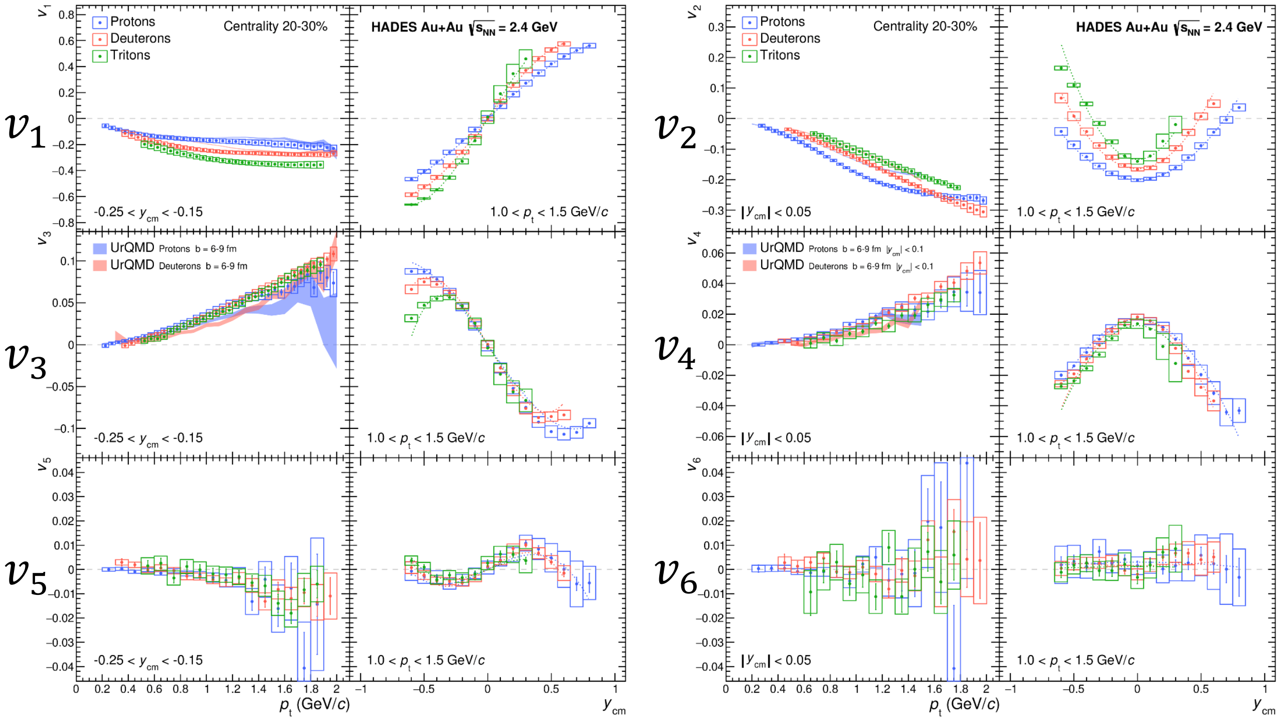


HADES Collaboration, PRL 125 (2020) 262301,
https://www.hepdata.net/record/ins1797626

Sensitivity to the EoS: $\boldsymbol{p, d\ v_{2,3,4}\{\psi_{RP}\}}$

$$V_{sk} = -124\left(\frac{\rho_{int}}{\rho_0}\right) + 71\left(\frac{\rho_{int}}{\rho_0}\right)^2$$

UrQMD: P. Hillmann *et al.*, J. Phys. G47 (2020) 055101

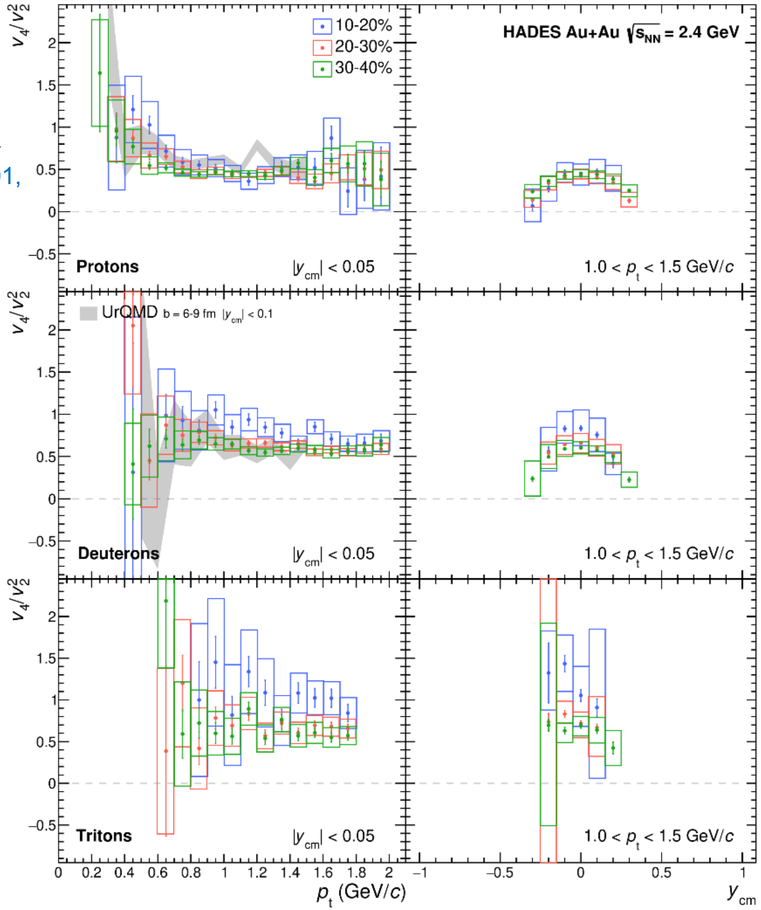
Rapidity dependense paramerized with

$$v_{1,3,5}(y_{cm}) = a y_{cm} + b y_{cm}^3$$

$$v_{2,4,6}(y_{cm}) = c + d y_{cm}^2$$

"Ideal fluid scaling" ?
of Protons and Light Nuclei

HADES Collaboration, PRL 125 (2020) 262301,
https://www.hepdata.net/record/ins1797626

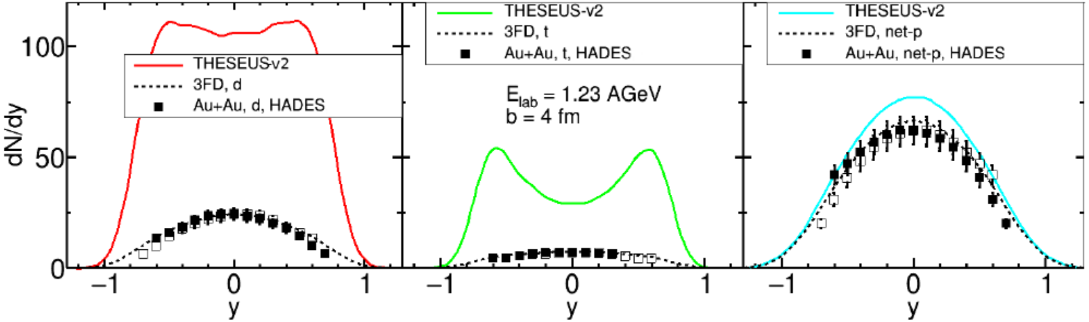


Ideal fluid dynamics predicts contribution to v_4 from v_2 at large p_t by $v_4 = 0.5\ {v_2}^2$

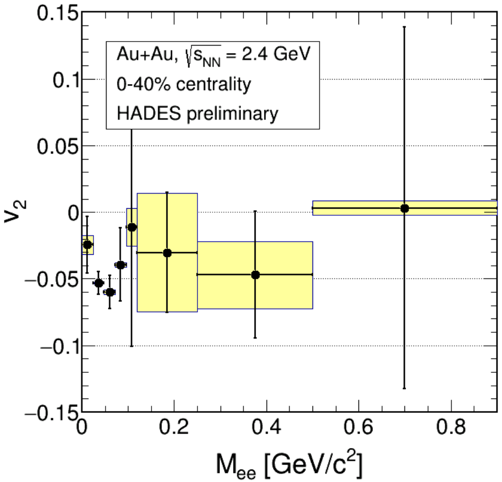
N. Borghini and J.-Y. Ollitrault, PLB 642 (2006) 227-231

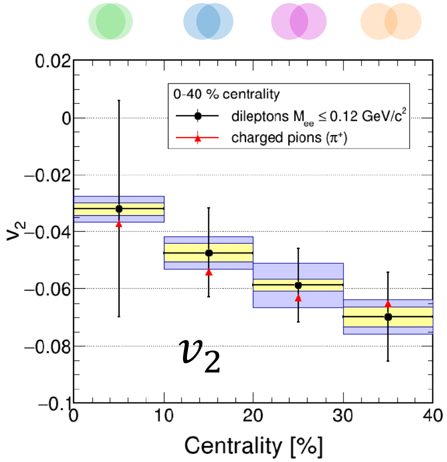
Hydro calculation at RHIC predict $v_4/{v_2}^2 \sim 0.63$

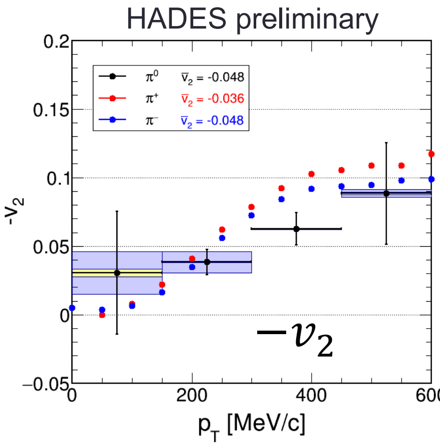
D. Blaschke et al., arXiv:2004.01159

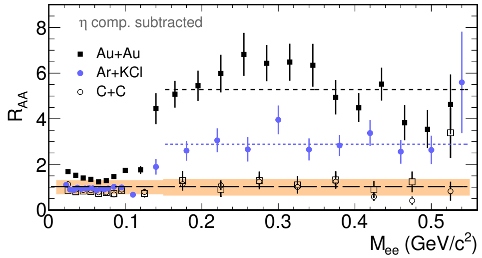


Azimuthal anisotropy of virtual photons









- v_2 in π^0 Dalitz range:
  - Stronger in peripheral collisions
  - Consistent with v_2 of charged pions
- Reflects the R_{AA} vs. M_{ee} behavior – relative contribution of the "in-medium" radiation