Heavy-ion collisions and critical dynamics

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SEZIONE DI FIRENZE

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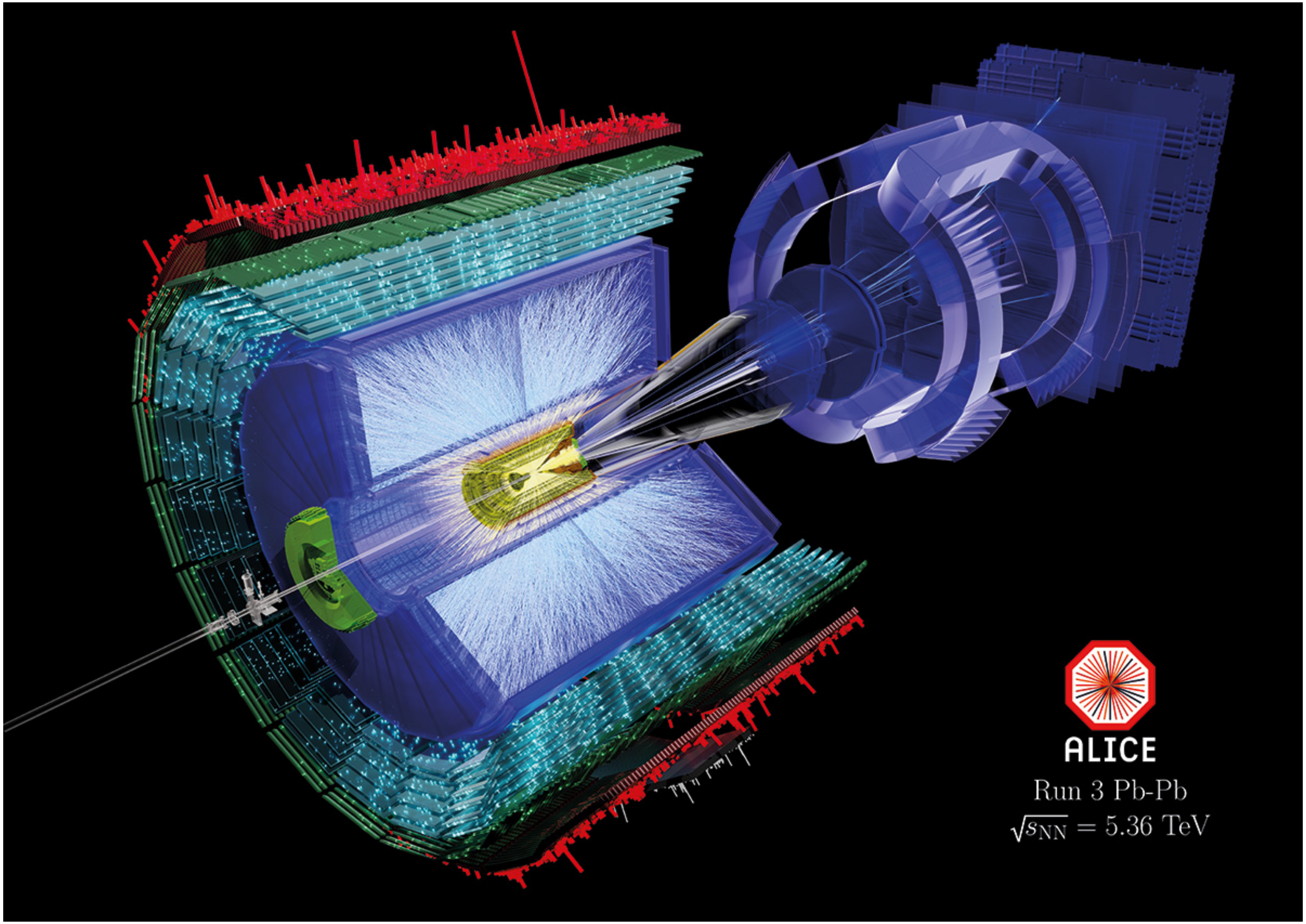
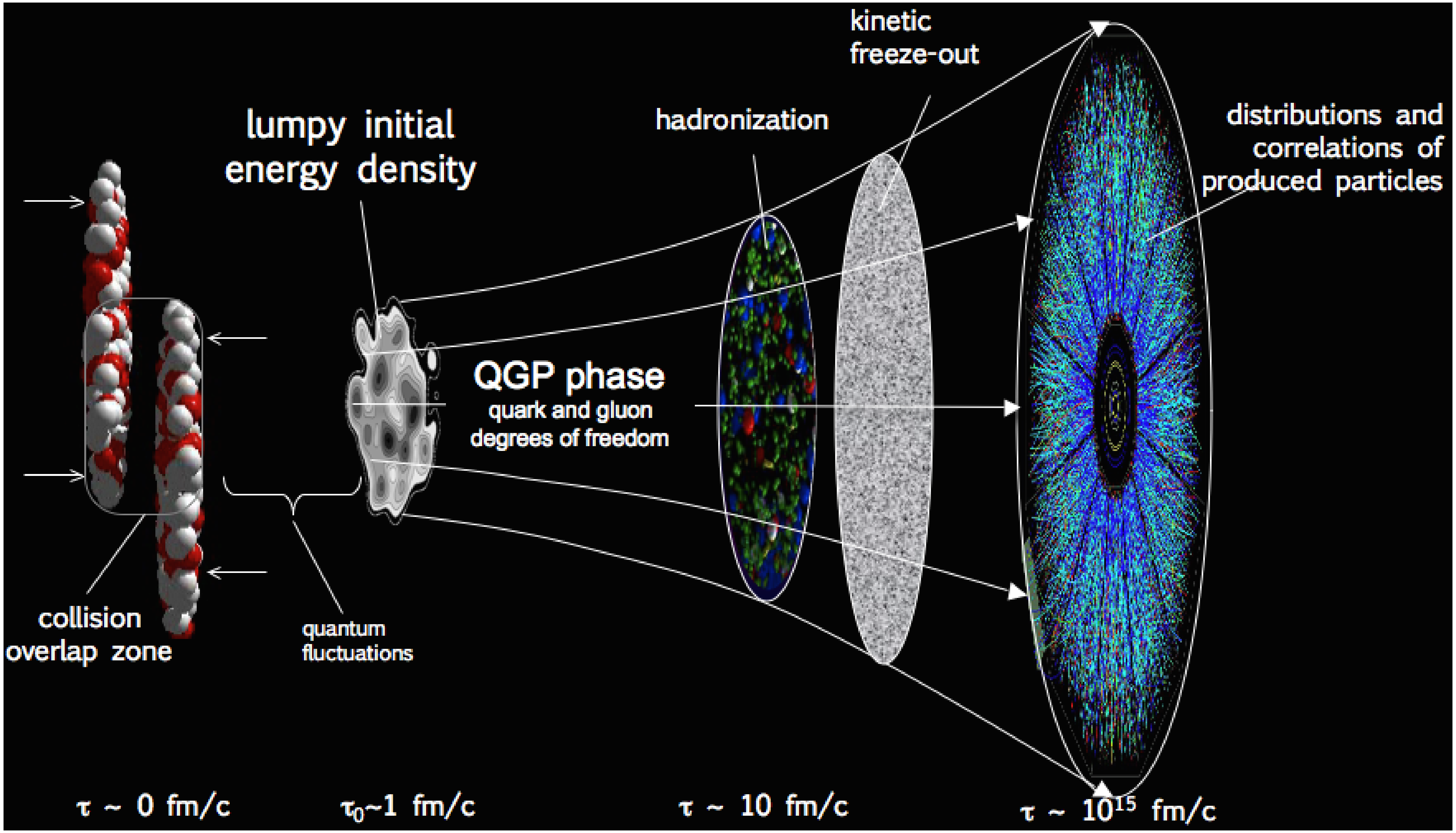
How a heavy ion collision looks like



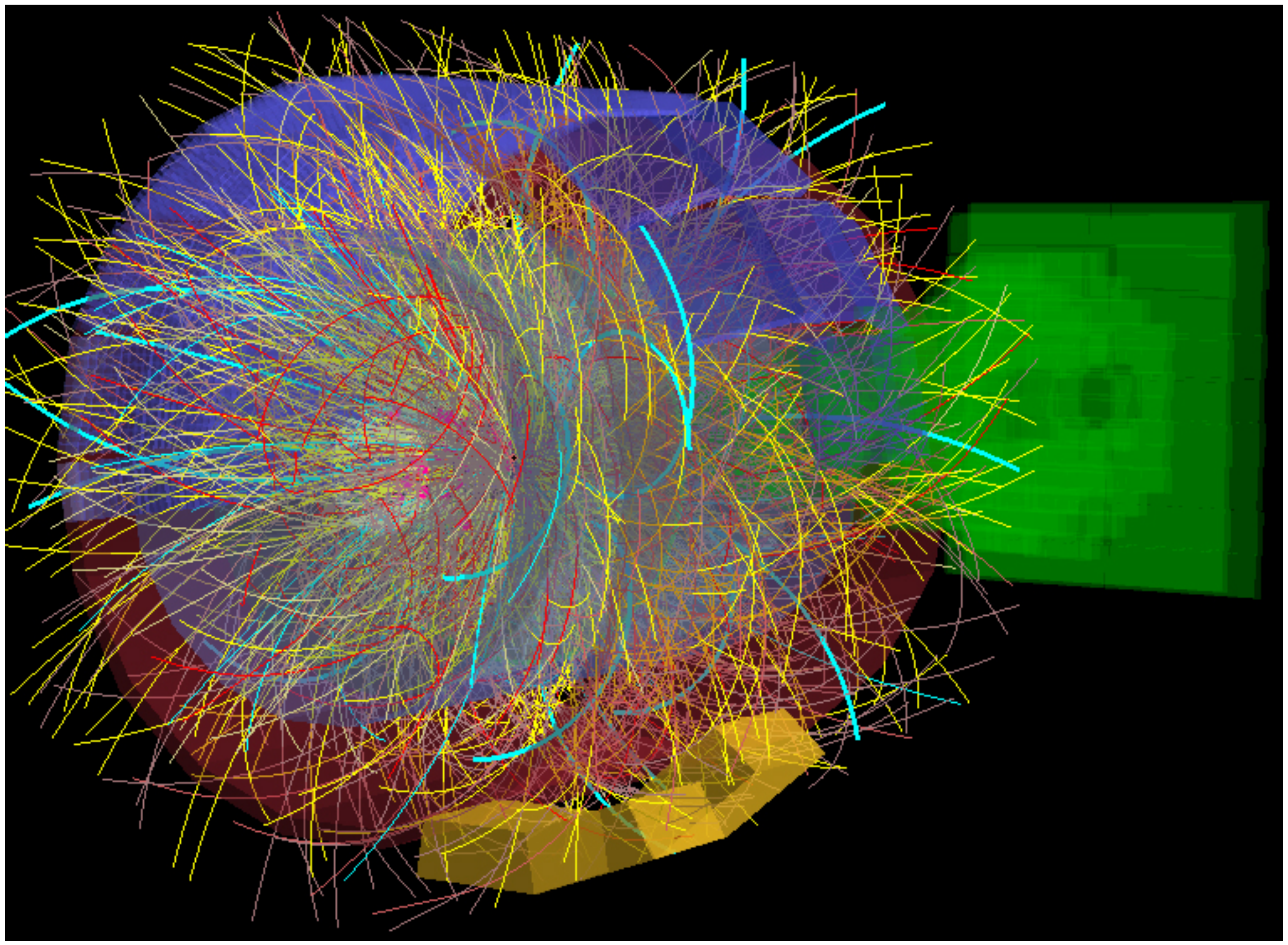
Event display run 3 ALICE@LHC

Heavy ion Collision

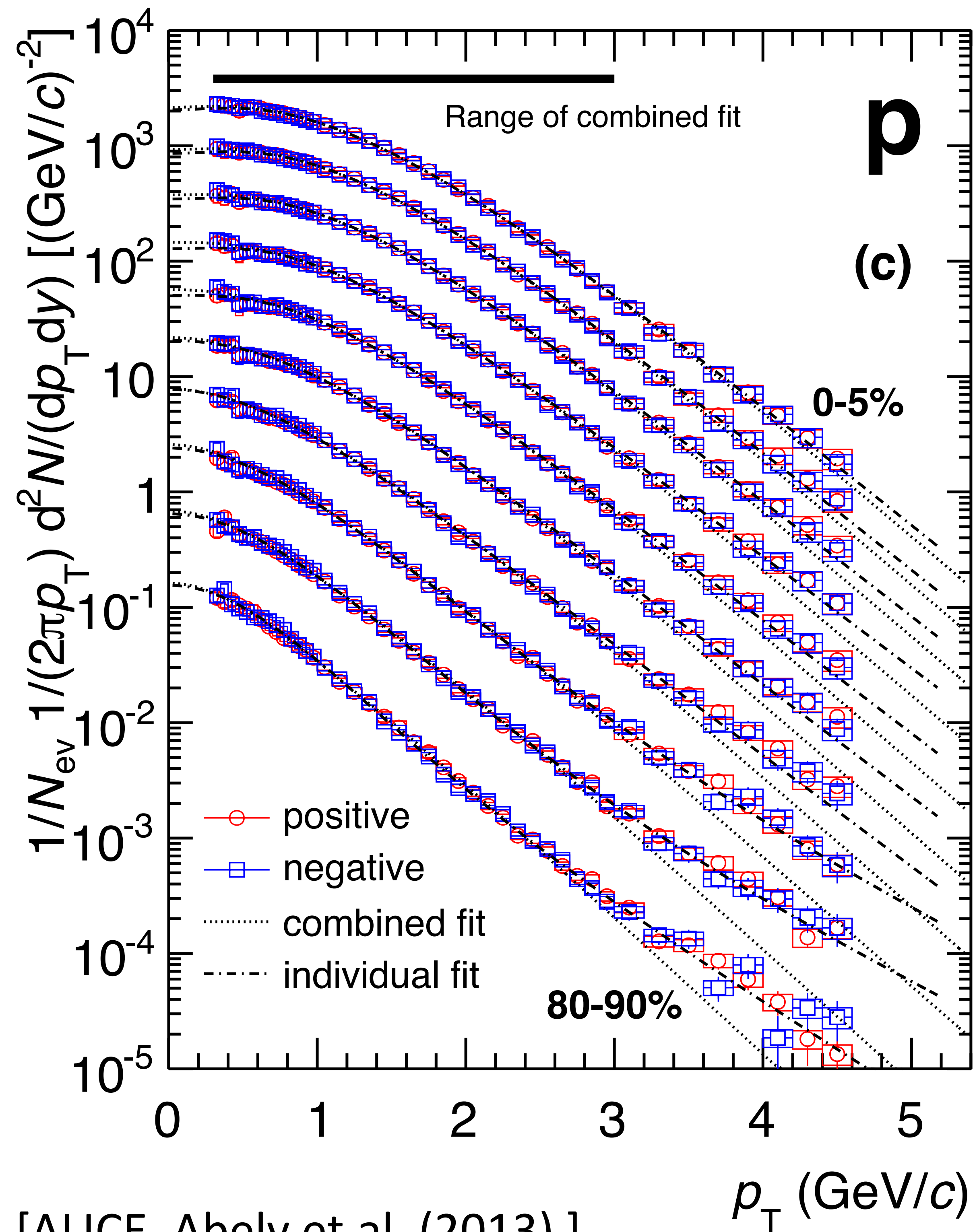


Intial condition Fluidynamic Freeze out

Spectra of identified particles



Events recorded by ALICE from the first lead ion collisions in 2011



Pt : Transverse momenta to the beam axis

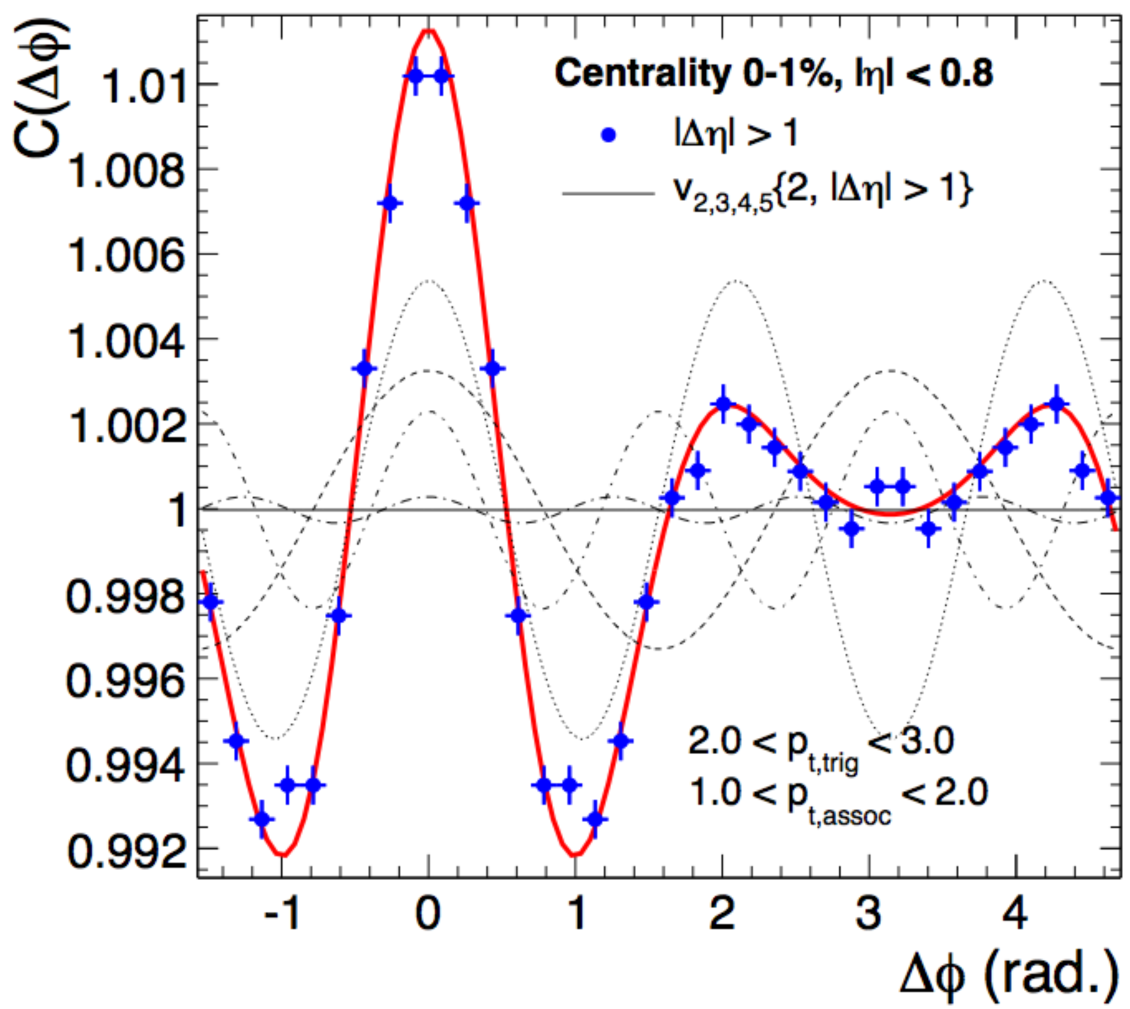
[ALICE, Abelv et.al. (2013)]

Two particle correlation function

- Normalized Correlation function

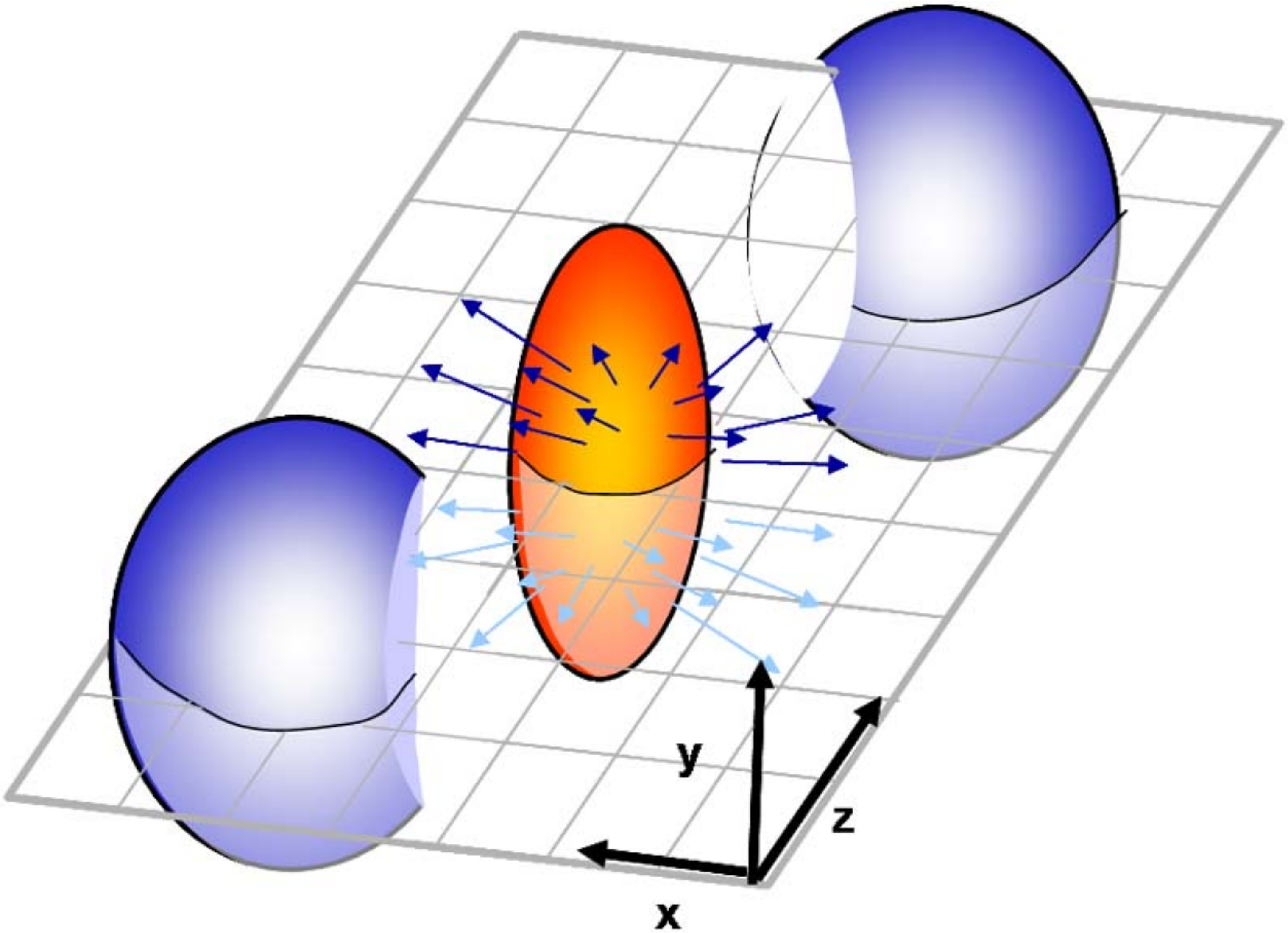
$$C(\phi_1,\phi_2) = \frac{\langle \frac{dN}{d\phi_1}\frac{dN}{d\phi_2}\rangle_{\text{events}}}{\langle \frac{dN}{d\phi_1}\rangle_{\text{events}}\langle \frac{dN}{d\phi_2}\rangle_{\text{events}}} = 1 + 2\sum_m v_m^2 \, \cos(m\,(\phi_1-\phi_2))$$

- The modulation in angles are signals of the initial state shape



[ALICE 2011, similar results from CMS, ATLAS, Phenix, Star]

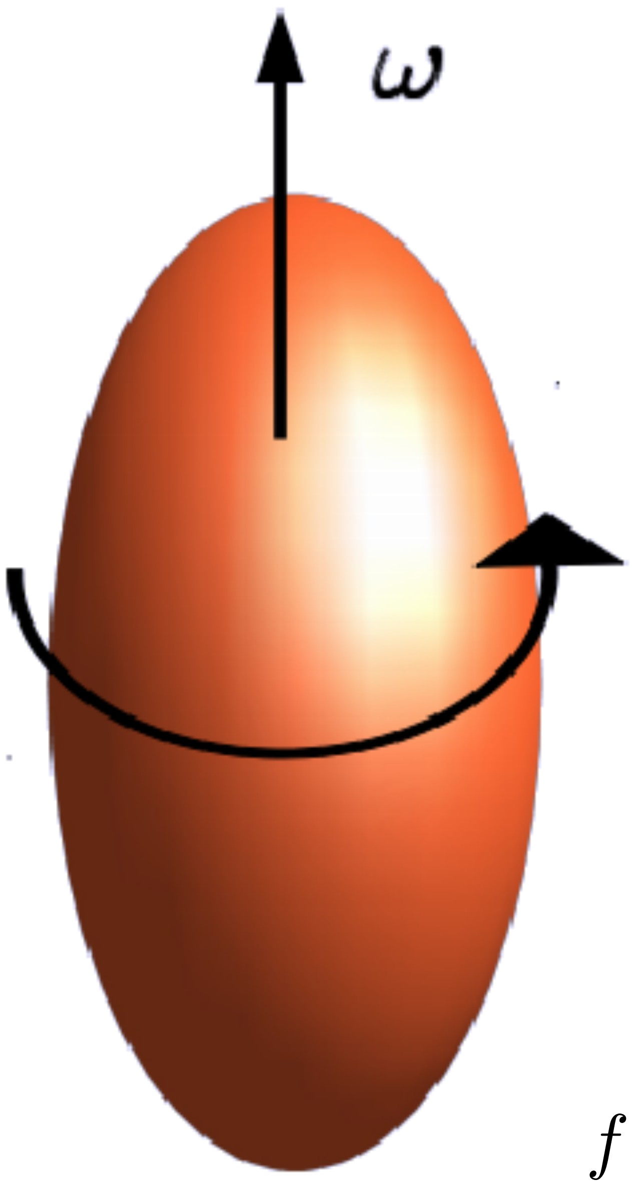
Polarization In HIC



In peripheral high energy heavy ion collisions the system has a large angular momentum and may manifest itself in the polarization of secondary produced particles

Rotating gas

F.Becattini, V.Chandra, L.Del Zanna and E.G (2013)



In rotating gas the particle, and antiparticle get polarized in the direction of the angular momentum.

For relativistic particle we propose an educated guess

$$f(x,p)_{rs} = \frac{1}{2m}\bar{u}_r(p)\Big(\exp[\beta\cdot p - \xi]\exp[\varpi^{\mu\nu}\Sigma_{\mu\nu}] + I\Big)^{-1} u_s(p)$$

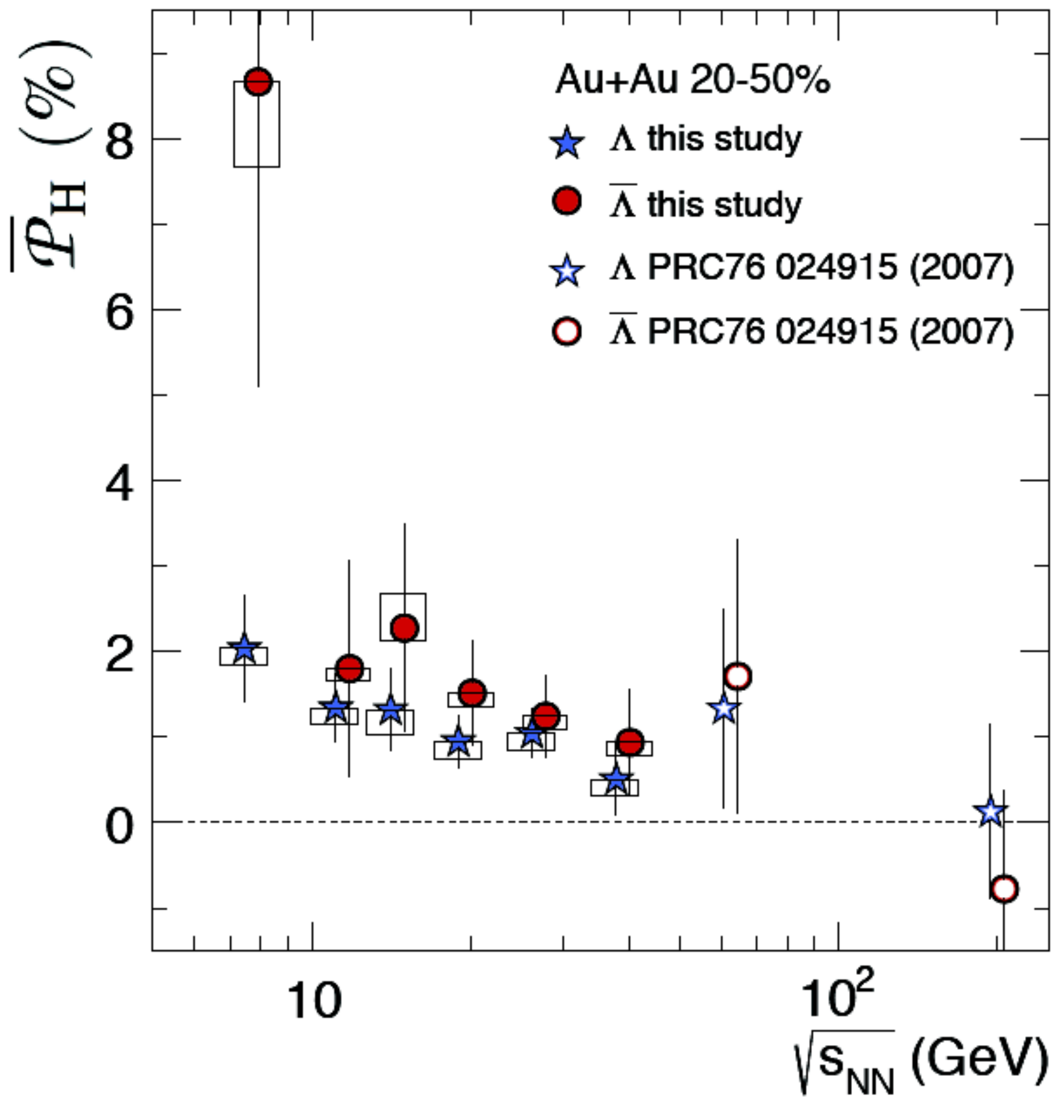
And similar for anti-particles

Only recently this formula as been proved a correct up to linear order

A.Palermo, F.Becattini EPJPlus (2023)

STAR measurement

STAR Collaboration, Global Lambda hyperon polarization in nuclear collisions, Nature 548 62-65, 2017



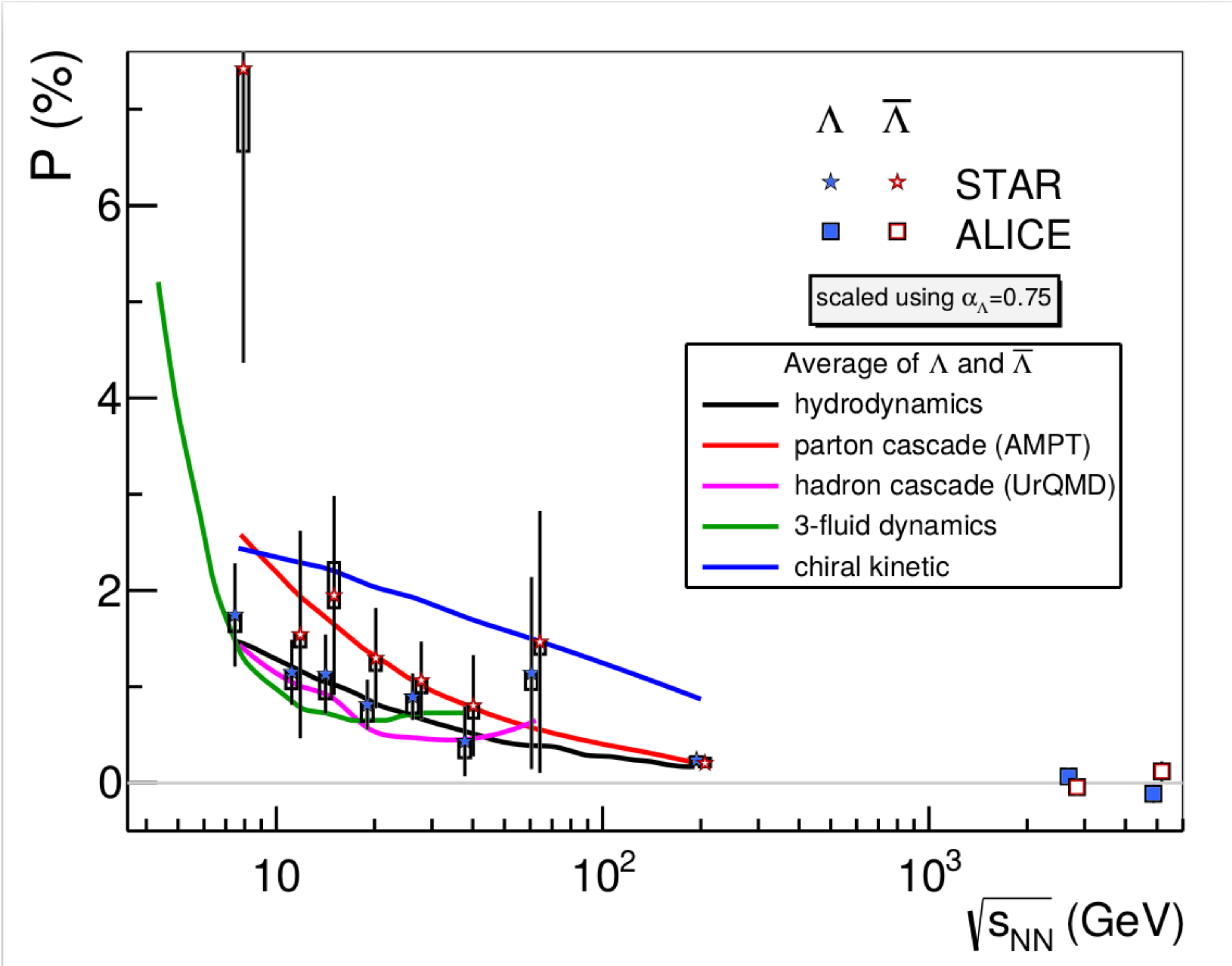
Particle and antiparticle have the same polarization sign.

Not driven by a EM field

Definitely favours the thermodynamic (equipartition) interpretation

Comparison with the data

Becattini, Lisa, Polarization and vorticity in the QGP, Ann. Rev. Part, Nucl. Sc. 70, 395 (2020)

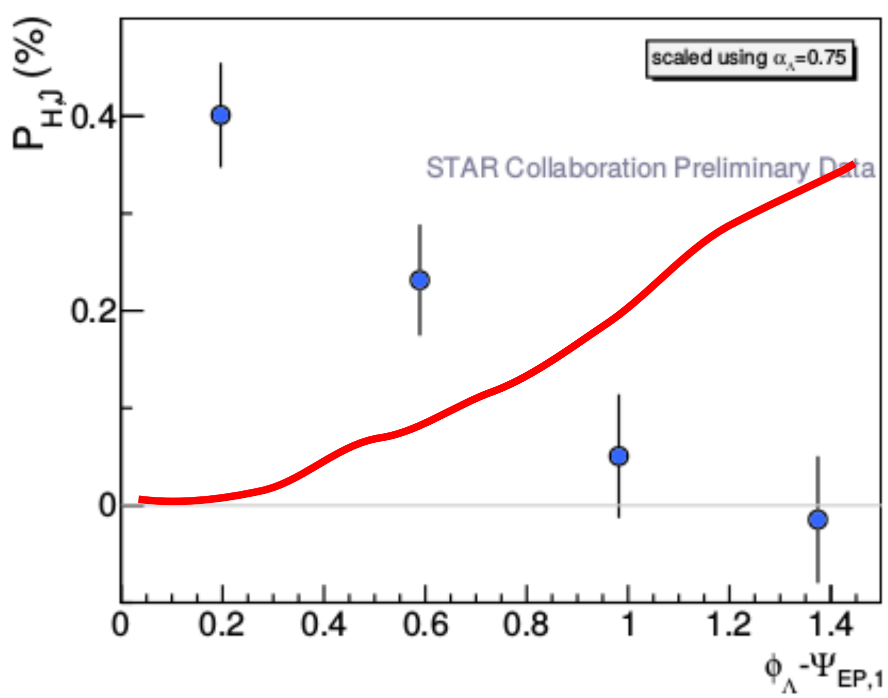


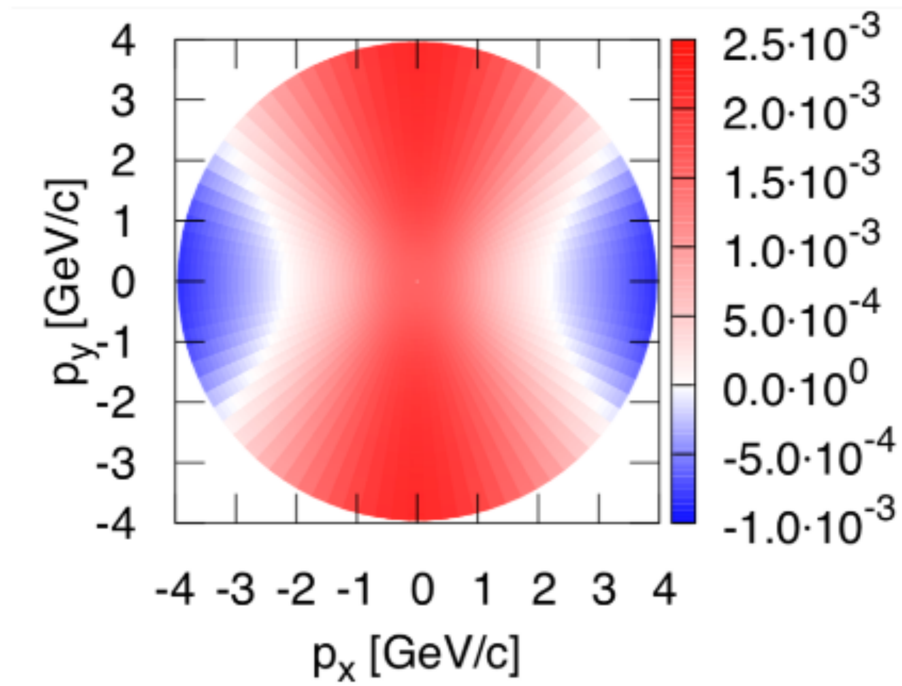
$$S^\mu(p) = \frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}p_\sigma \frac{\int_\Sigma \mathrm{d}\Sigma_\tau p^\tau n_F(1-n_F)\partial_\nu \beta_\rho}{\int_\Sigma \mathrm{d}\Sigma_\tau p^\tau \, n_F}$$

Different models of the collision, same formula for polarization

However

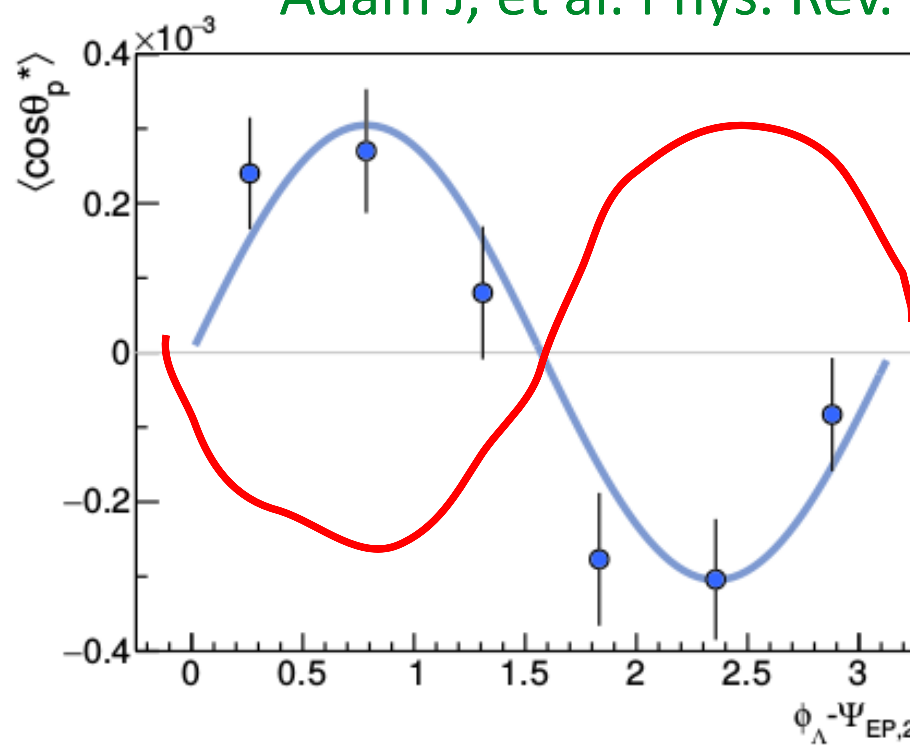
The dependence on the momentum (azimuthal angle) is the kind of the opposite !

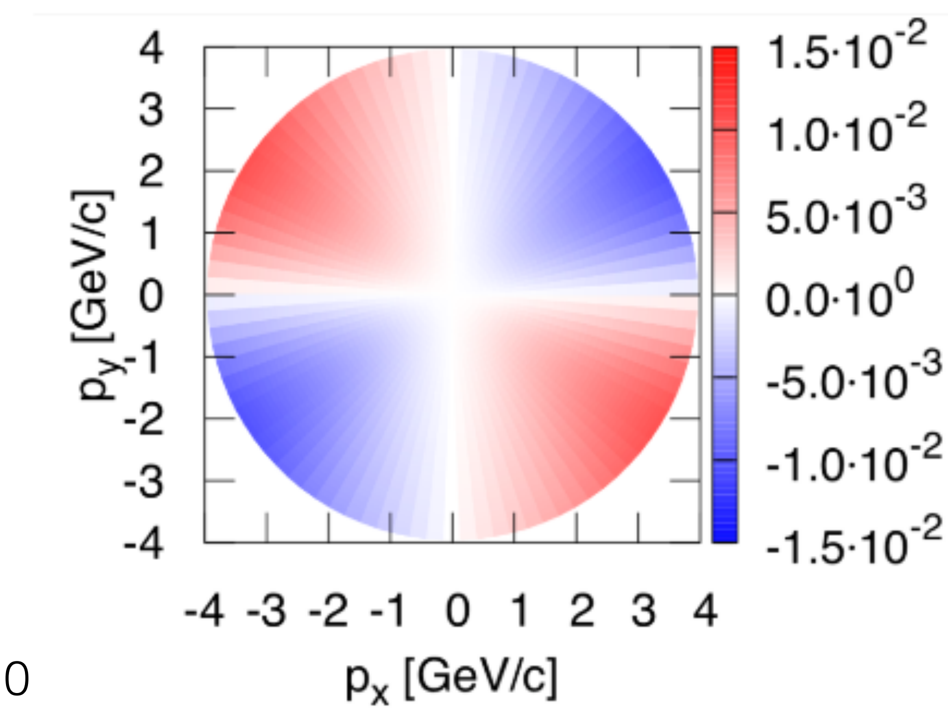




Niida T. Nucl. Phys. A982:511 (2019)

Adam J, et al. Phys. Rev. Lett. 123:132301 (2019)





Shear-Polarization

F. B., M. Buzzegoli, A. Palermo, Phys. Lett. B 820 (2021) 136519

The lambda get polarized also due to a symmetric gradient of the four-velocity too

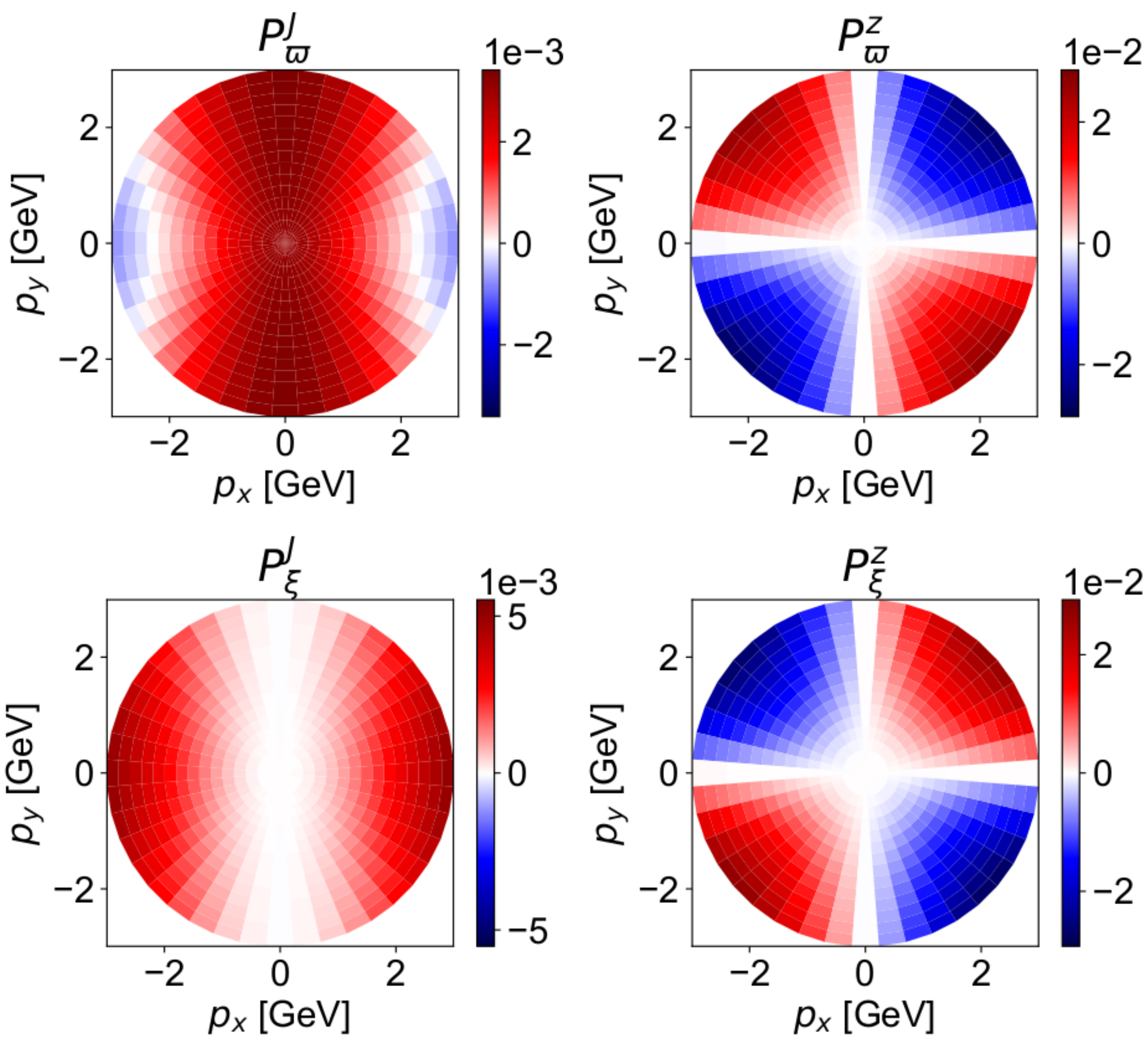
$$S^\mu_{\rm ILE}(p) = - \epsilon^{\mu\rho\sigma\tau} p_\tau \frac{\int_\Sigma {\rm d}\Sigma \cdot p \, n_F (1-n_F) \left[\omega_{\rho\sigma} + 2\, \hat{t}_\rho \frac{p^\lambda}{\varepsilon} \Xi_{\lambda\sigma} \right]}{8 m T_{\rm dec} \int_\Sigma {\rm d}\Sigma \cdot p \, n_F}$$

$$\Xi_{\rho\sigma} = \frac{1}{2} \left(\partial_\sigma u_\rho + \partial_\rho u_\sigma \right)$$

The same effect, but different formula was proposed by

S. Liu, Y. Yin, JHEP 07 (2021) 188

Numerical Result



Thermal-vorticity

Thermal-shear

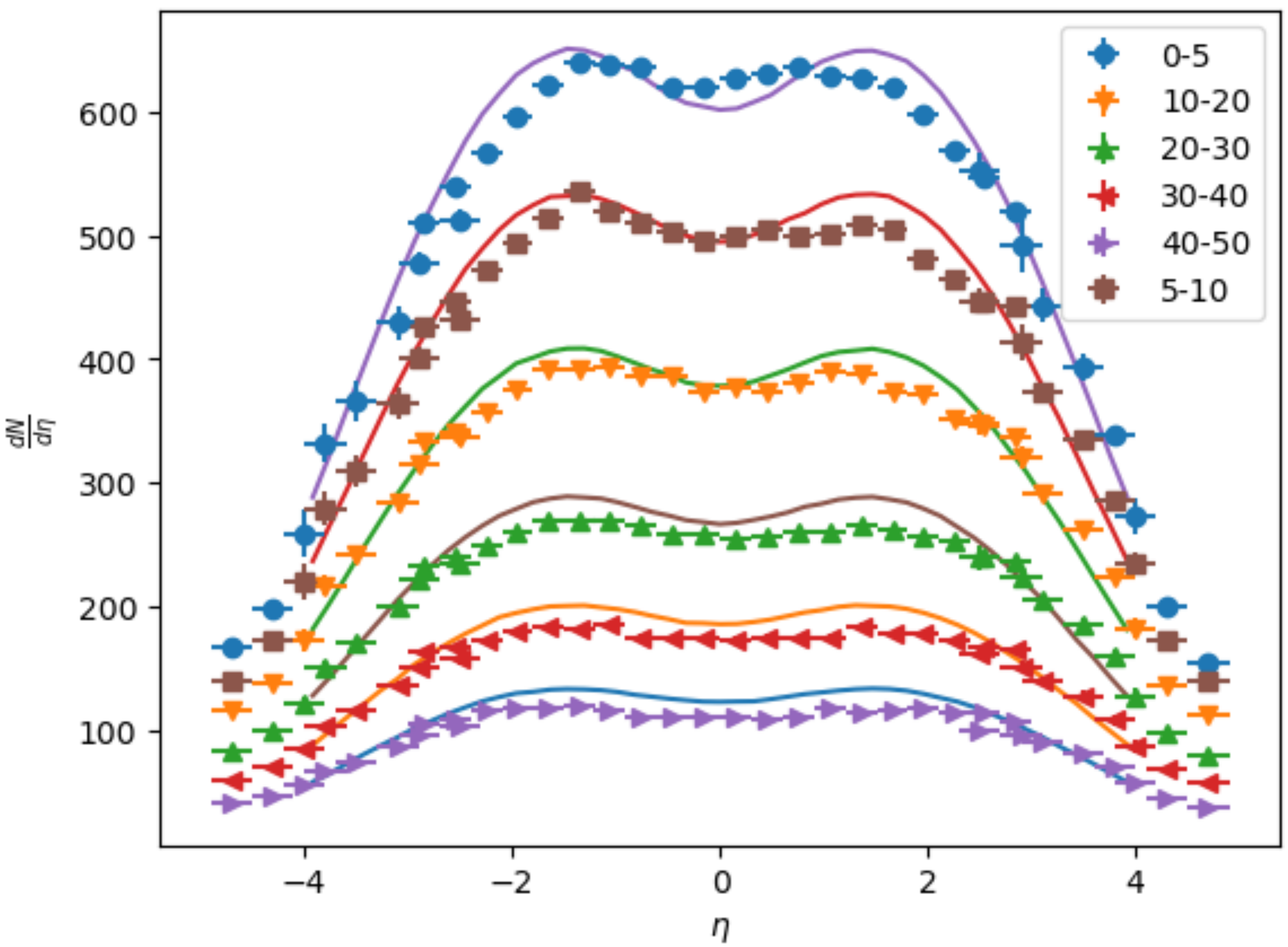
Based on the hydrodynamic code VHLLE (author I. Karpenko)
Similar output with ECHO-QGP (main author G. Inghirami).

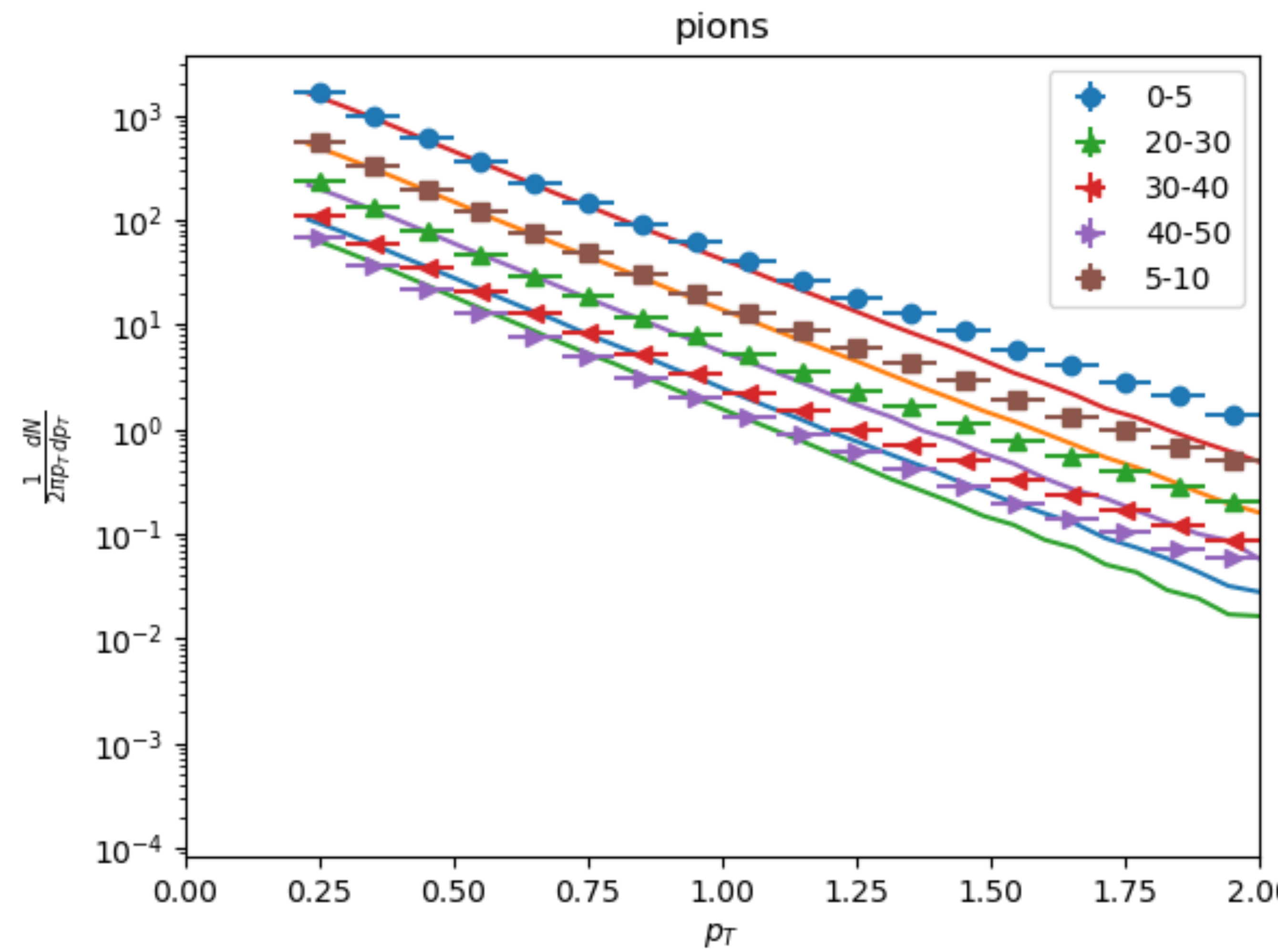
The opposite pattern as the previous calculations but still no precise comparison

Simulation at RHIC

We use the chain of code SuperMC+Vhlle+Smash to simulate the collision. The models have really many parameter.

200 Gev@RHIC



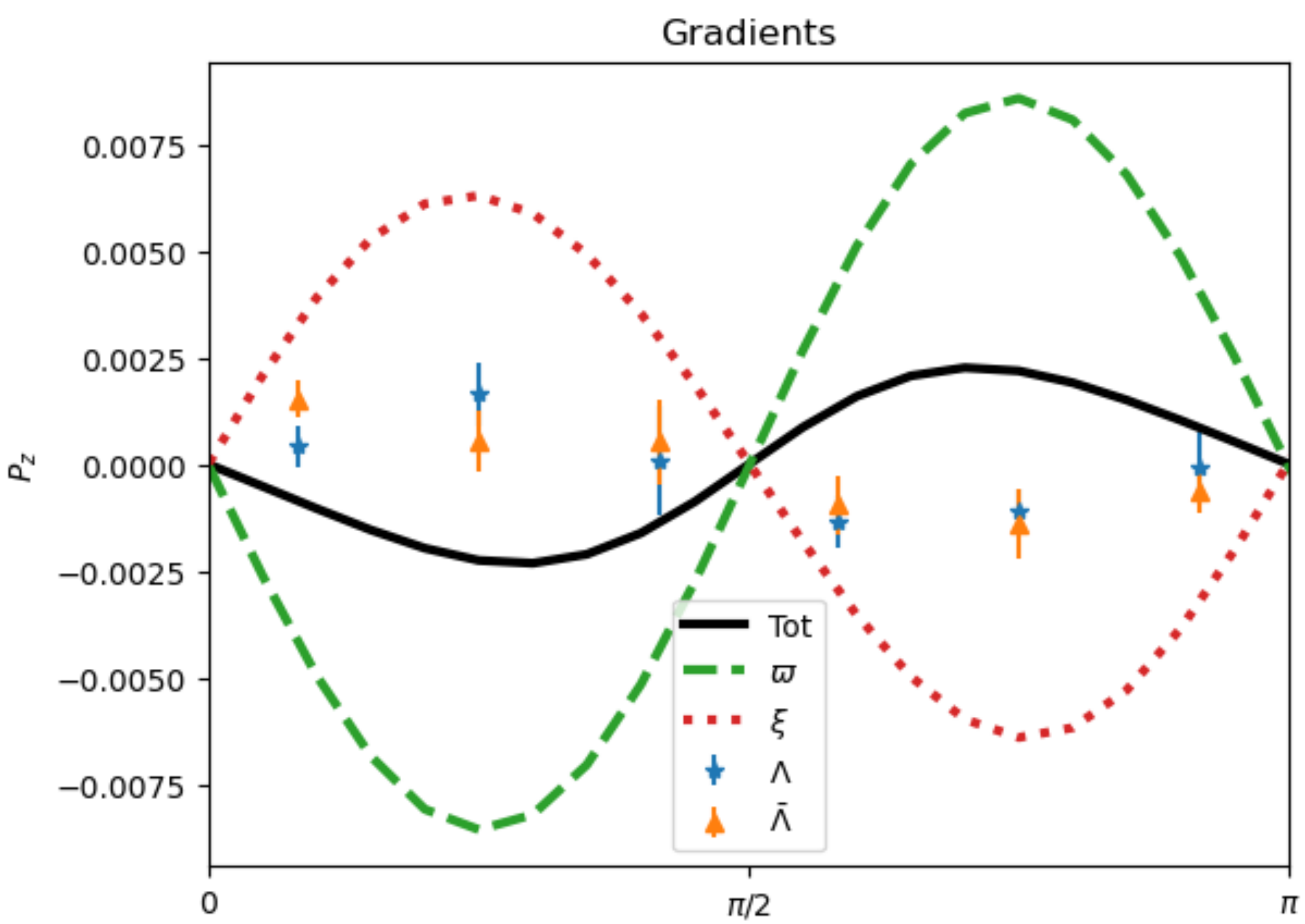


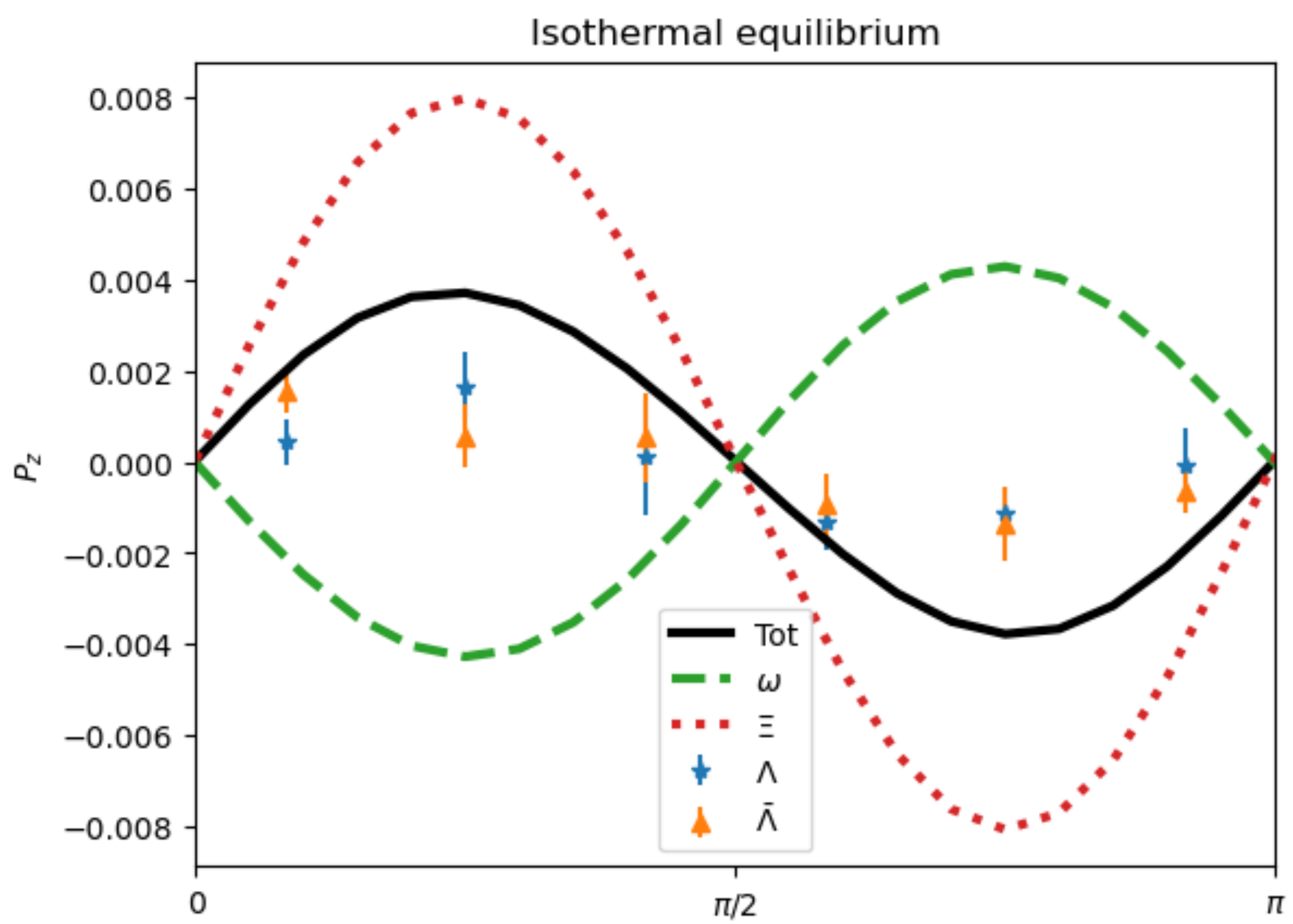
The multiplicity in rapidity and pt are fairly reproduce

Longitudinal polarization

We use the chain of code SuperMC+Vhlle+Smash to simulate the collision. The models have really many parameter.

200 Gev@RHIC



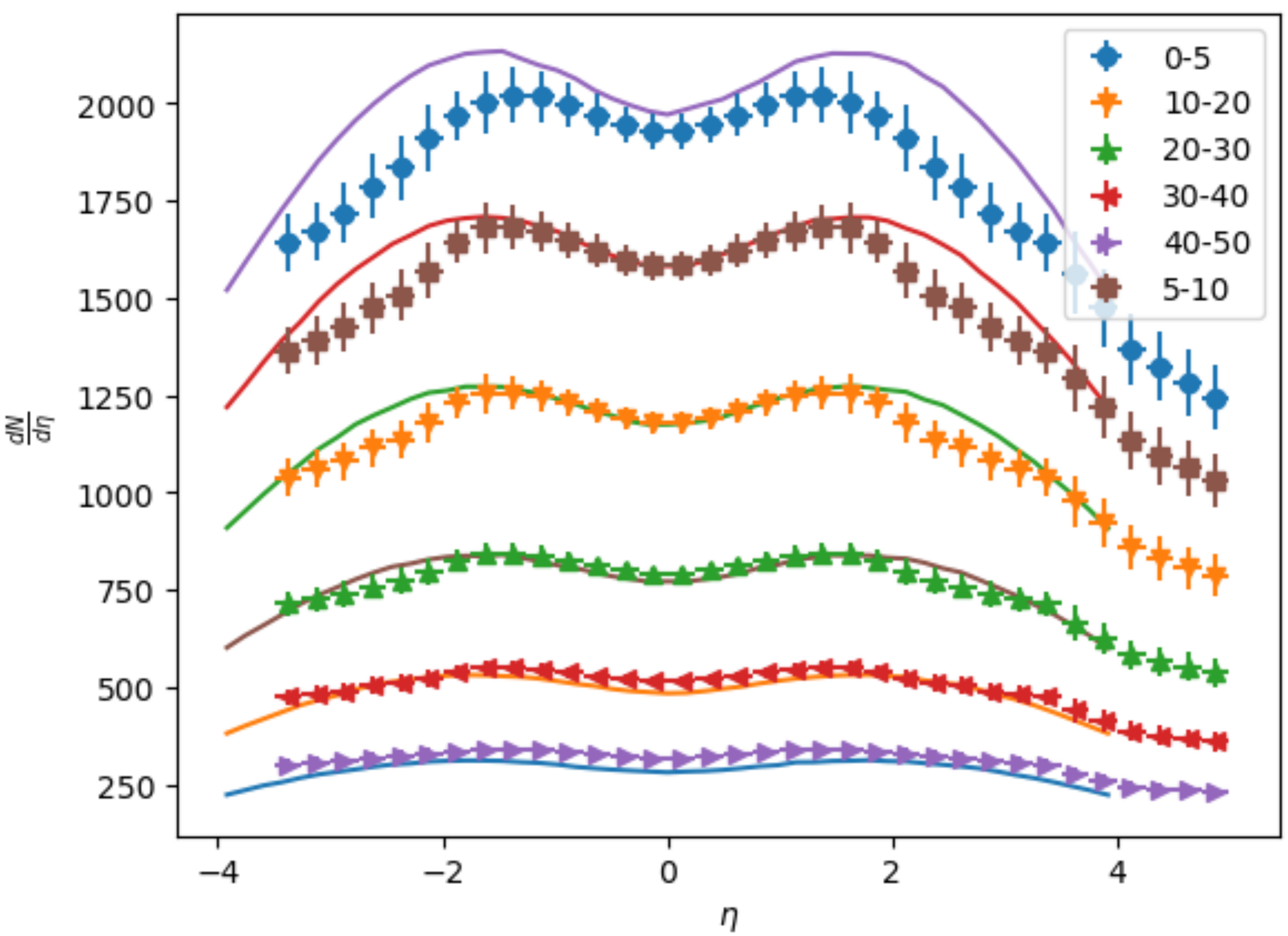


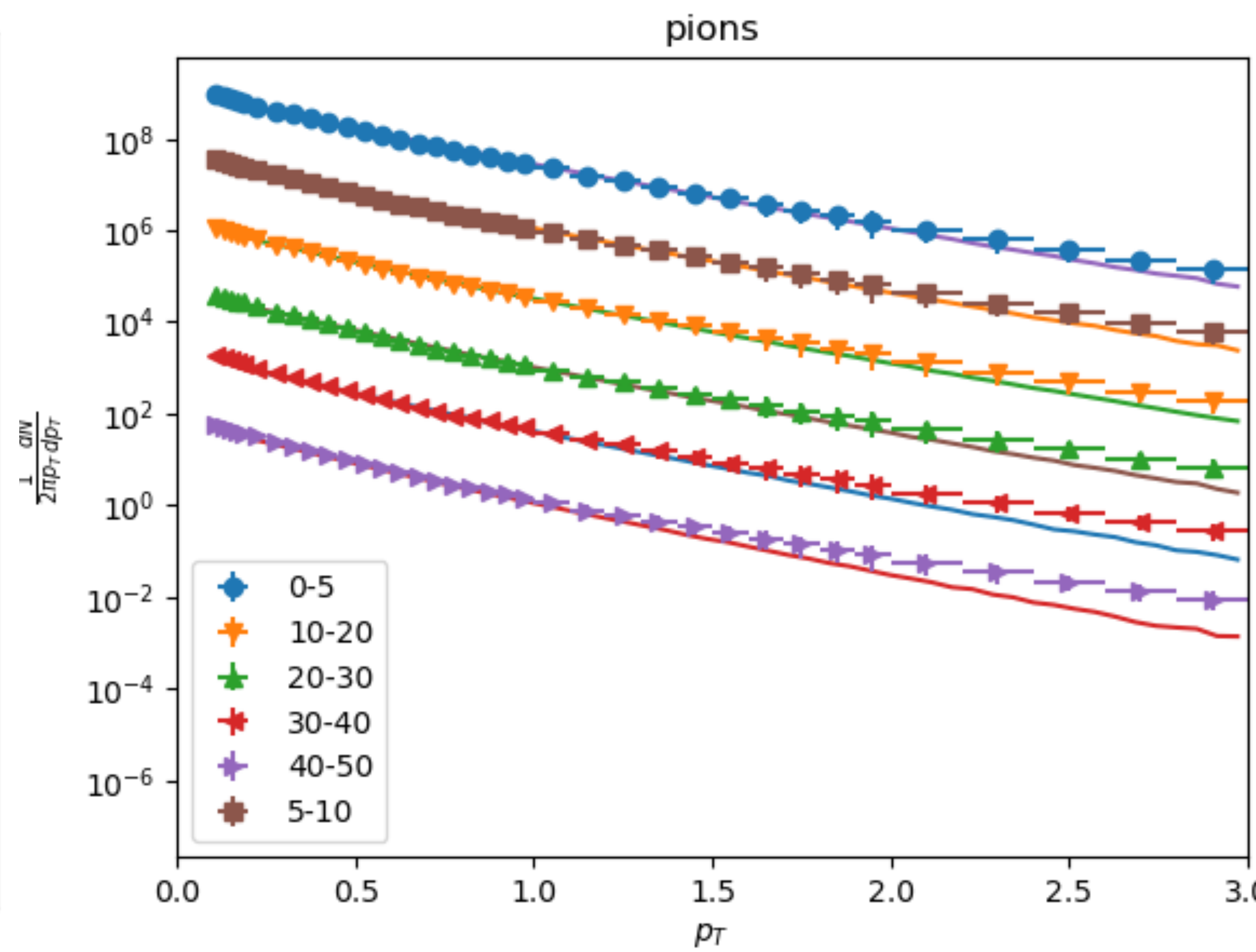
No decay included it will reduce the total signal

Simulation @LHC

We use the chain of code SuperMC+Vhlle+Smash to simulate the collision. The models have really many parameter.

5.02 Tev@LHC



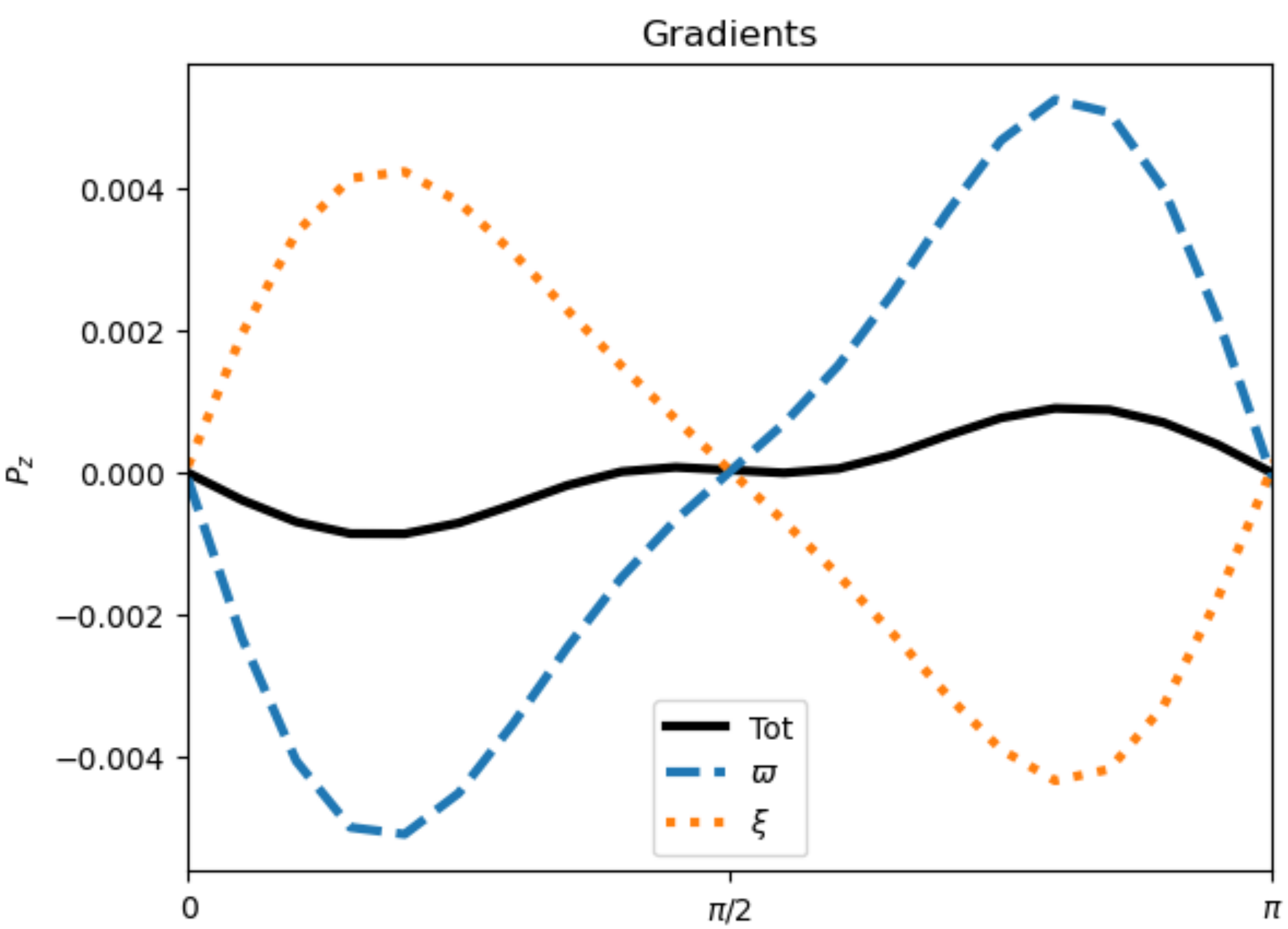


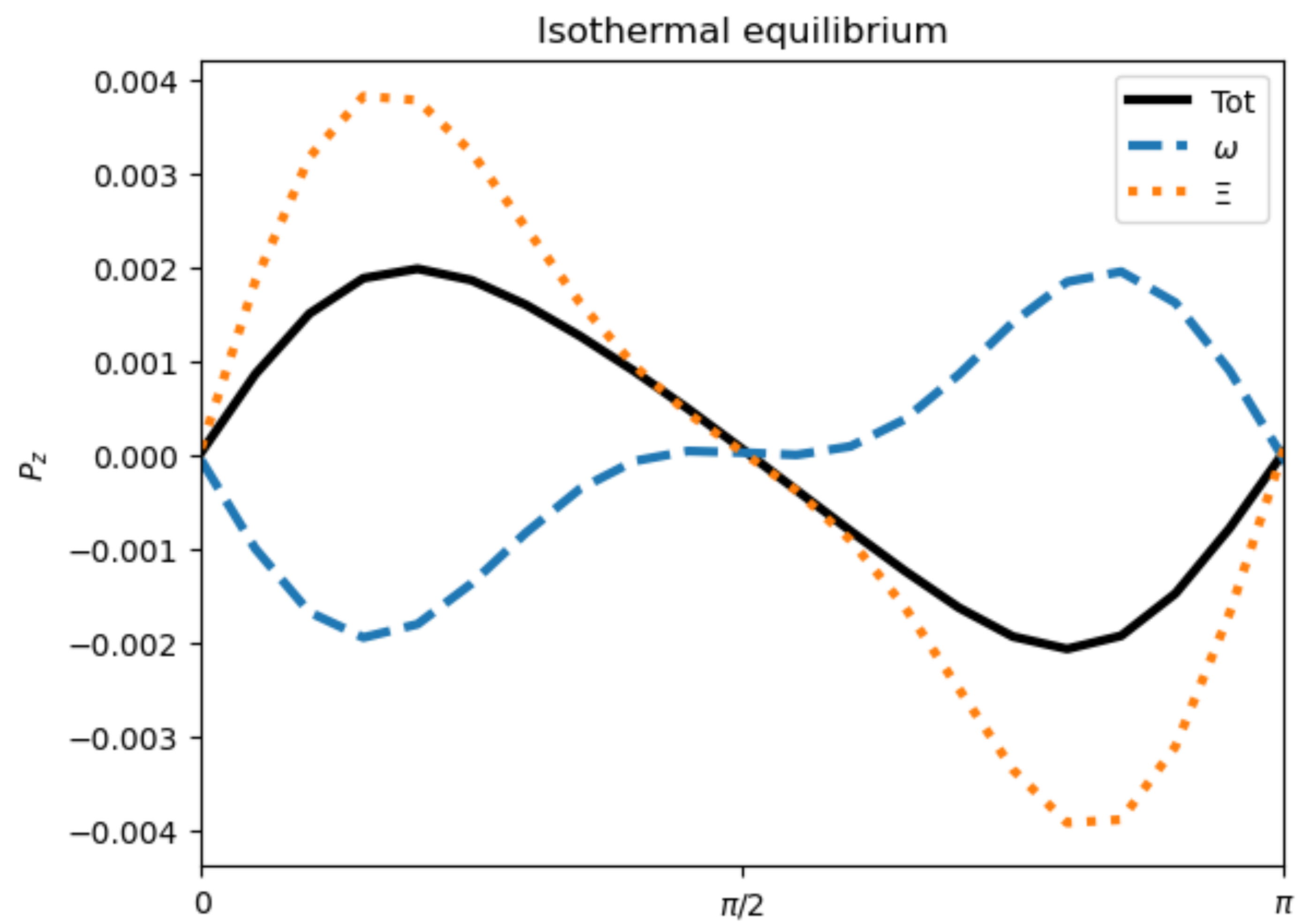
At LHC with sliglty different paramenter and bulk viscosity that is important

Longitudinal polarization @LHC

We use the chain of code SuperMC+Vhlle+Smash to simulate the collision. The models have really many parameter.

5.02 Tev@LHC



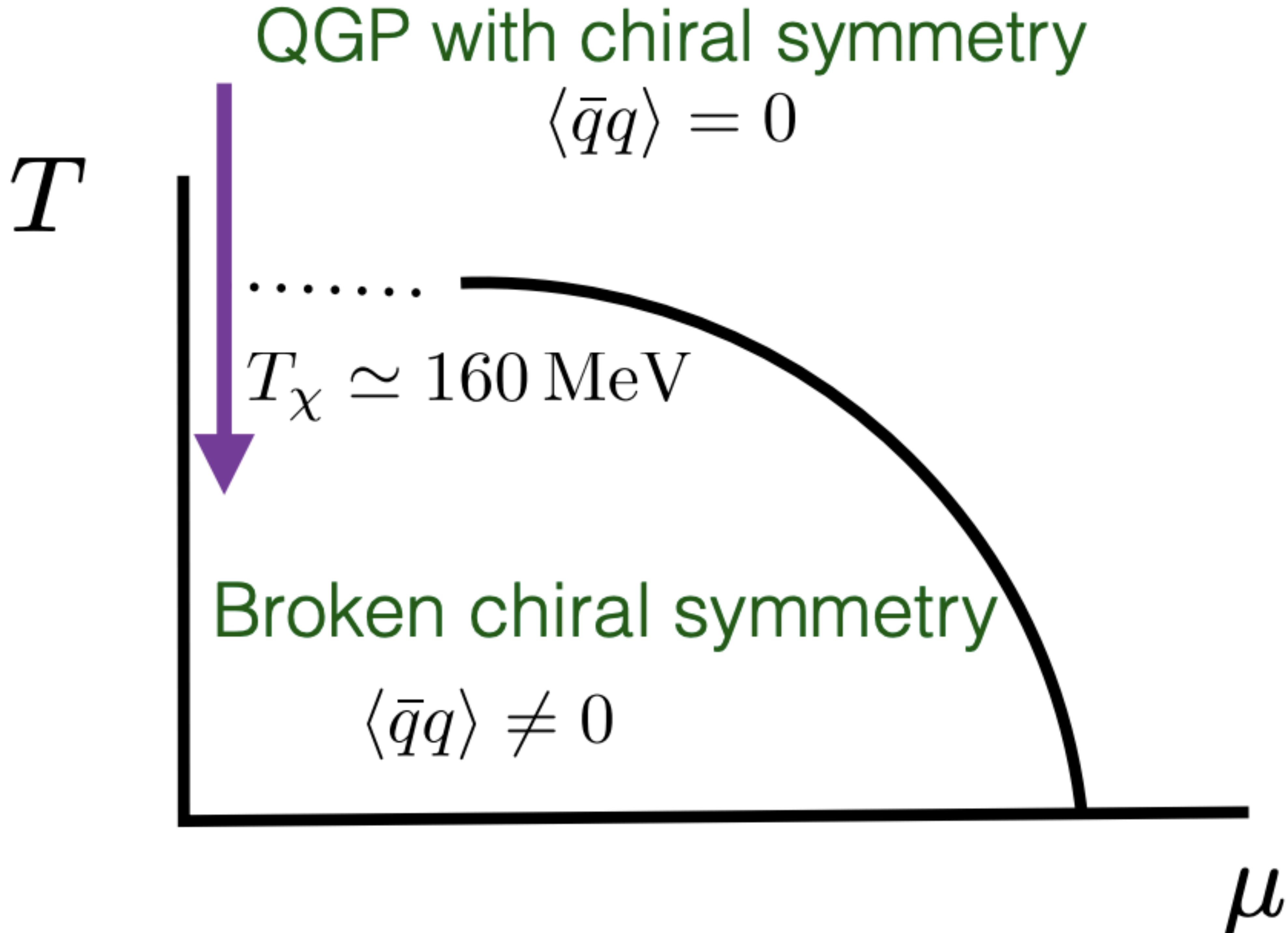


No decay included

The data are taken with a different centrality selection then RICH

Critical dynamics

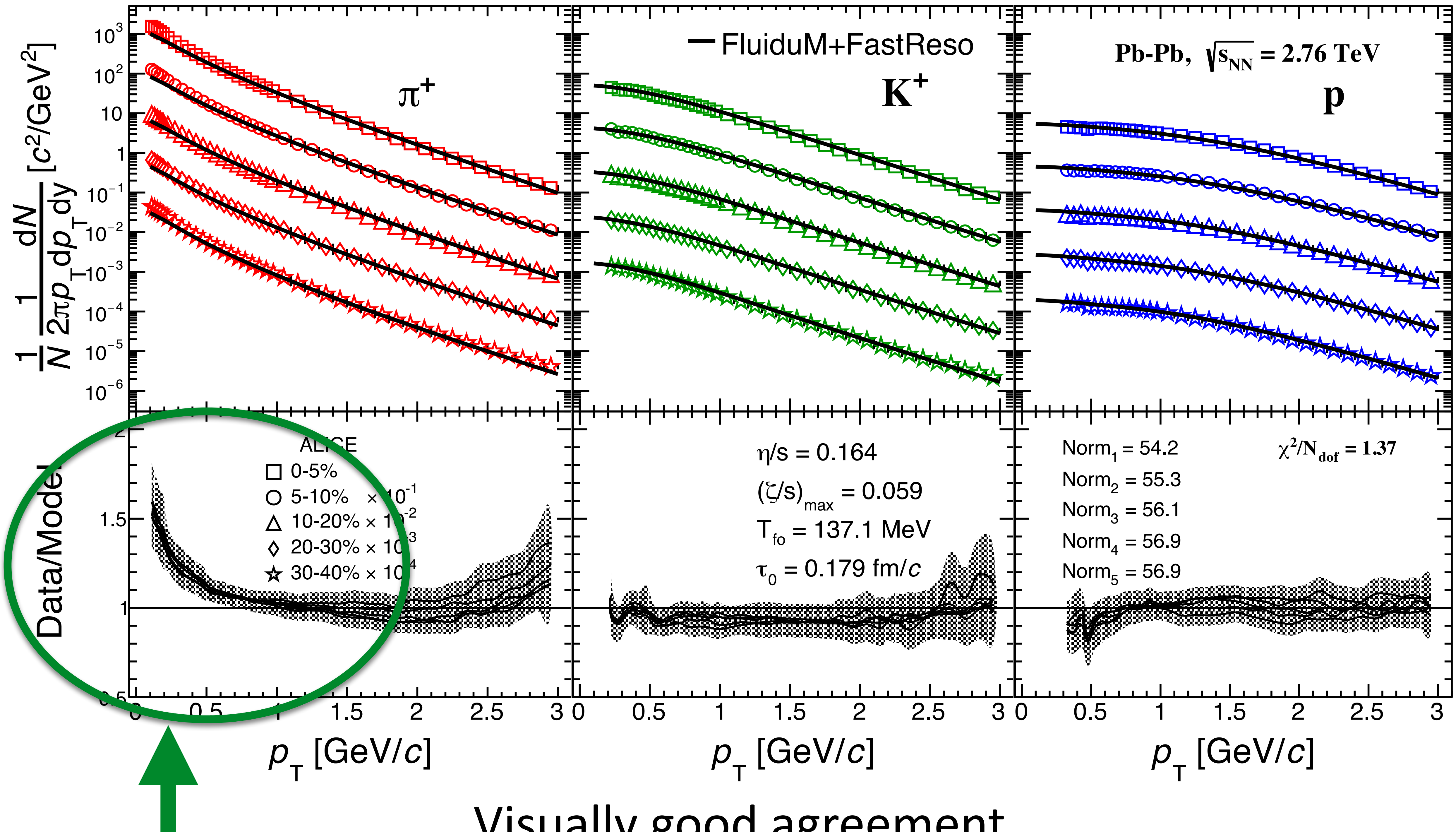
Motivation 1



We are neglecting any hydro-dynamics of the chiral condensate !

Maybe in the data ?

Fit the pt spectra of pions in the first five centralities



Visually good agreement,

but not amazing fit D. Devetak , et al JHEP (2019)

The main discrepancy is for pions at low pt

Equation of motion (Model G)

Rajagopal Wilczek (93)

Chiral condensate ϕ_a + Axial and Vector charge $n_{ab} = \chi_0 \mu_{ab}$

$$\partial_t \phi_a + g_0\, \mu_{ab}\phi_b = \Gamma_0 \nabla^2 \phi_a - \Gamma_0 (m_0^2 + \lambda\phi^2)\phi_a + \Gamma_0 H_a + \theta_a\,,$$

$$\partial_t n_{ab} + g_0\, \nabla \cdot (\nabla\phi_{[a}\phi_{b]}) + H_{[a}\phi_{b]} = D_0 \nabla^2 n_{ab} + \partial_i \Xi^i_{ab}\,.$$

Ideal part Dissipative part Gaussian Noise

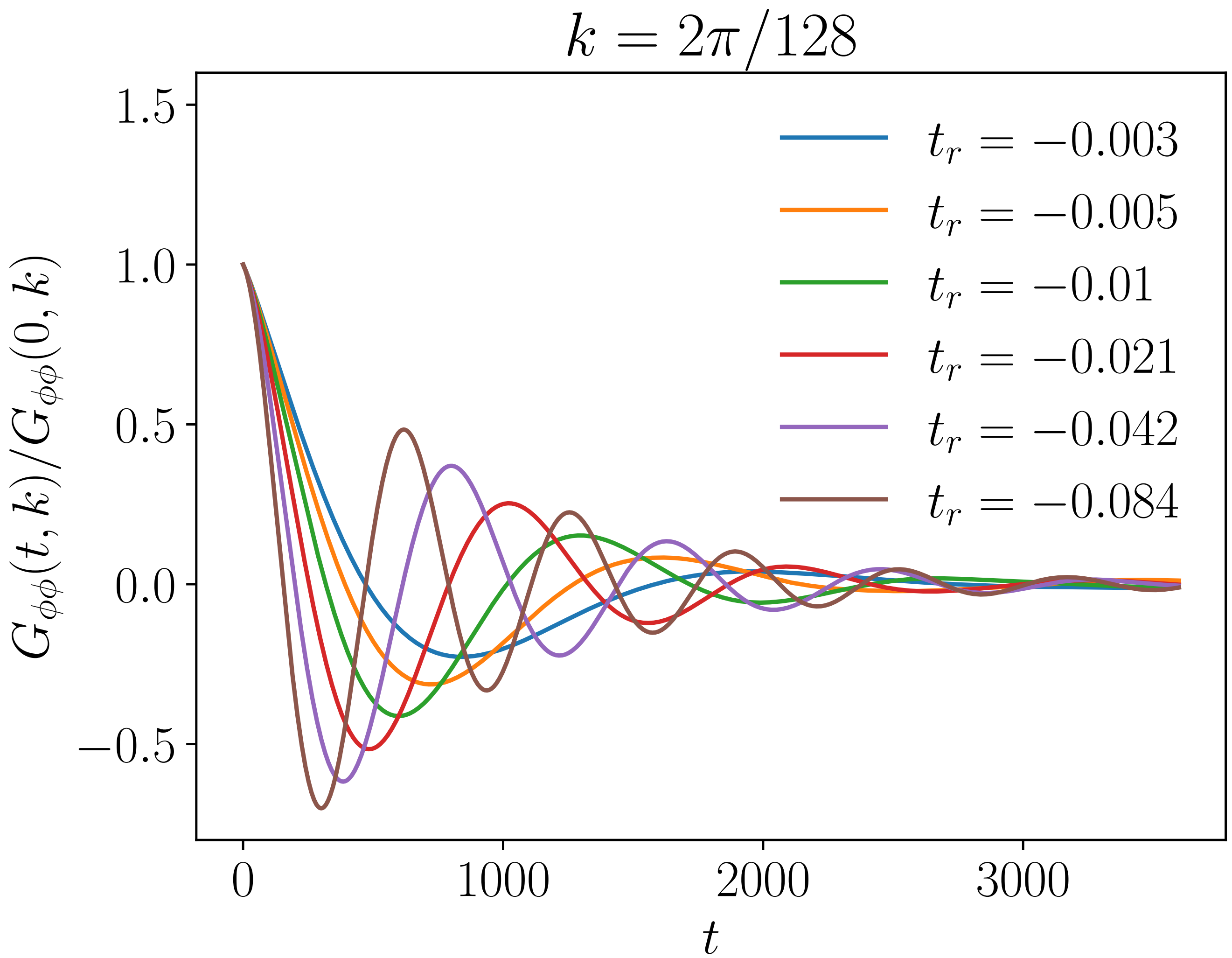
- The ideal part is charge conservation and Josephson constraint
- Two dissipative coefficient Γ_0 and D_0 and noise

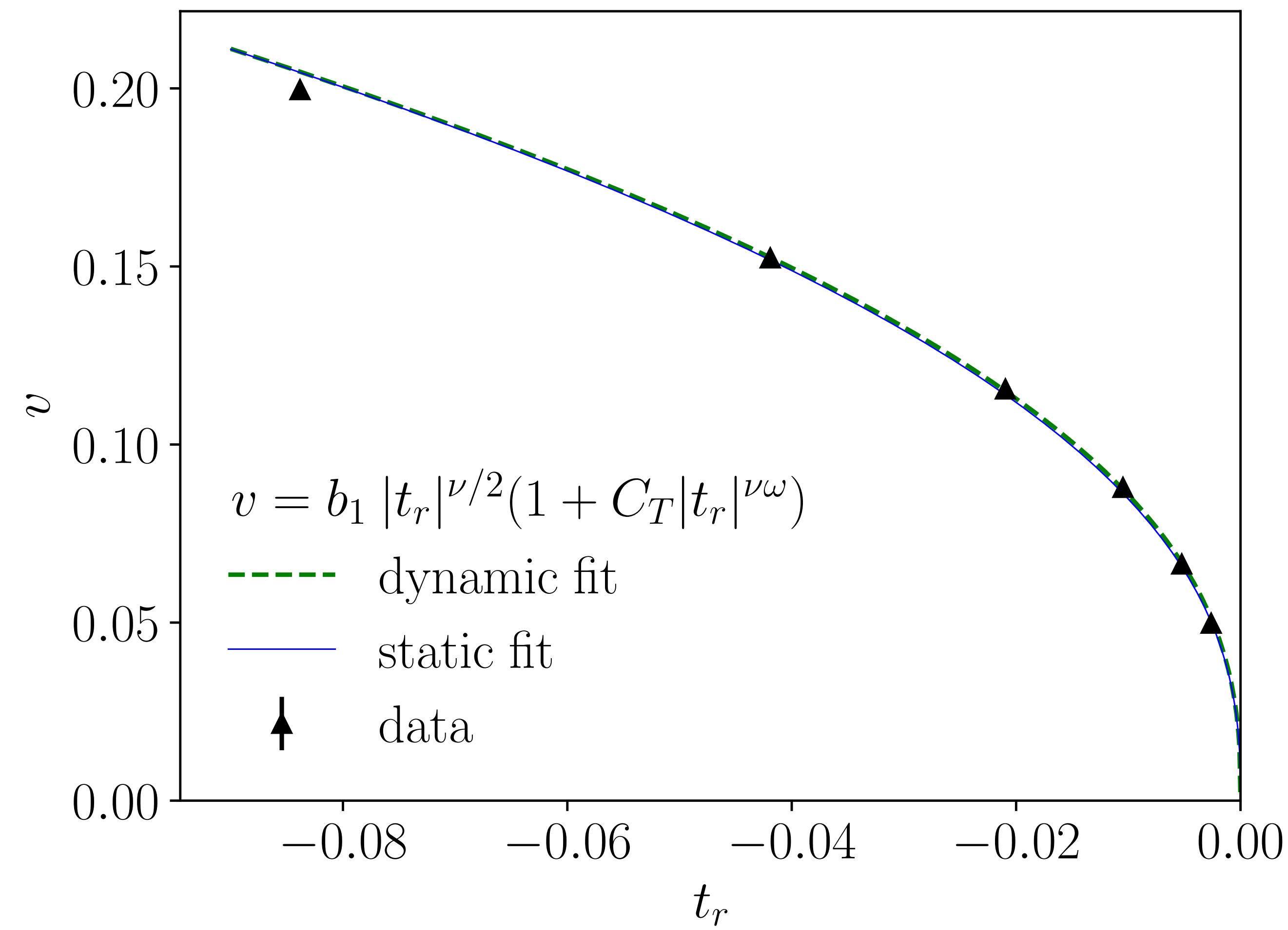
Diffusion at high temperature, pion propagation at low temperature as the vev develops

A. Florio, E.G., A. Soloviev, D, Teaney PRD (2022)
A. Florio, E.G., D, Teaney (2023)

Snap shoot of what is going on

In the broken phase one has pion waves





$$\omega(k) = vk + v_1 k^2.$$

The dispersion relation of the of the waves actually is determine by the GOR relation

$$v^2 \propto \langle \phi^2 \rangle$$

Thanks!!