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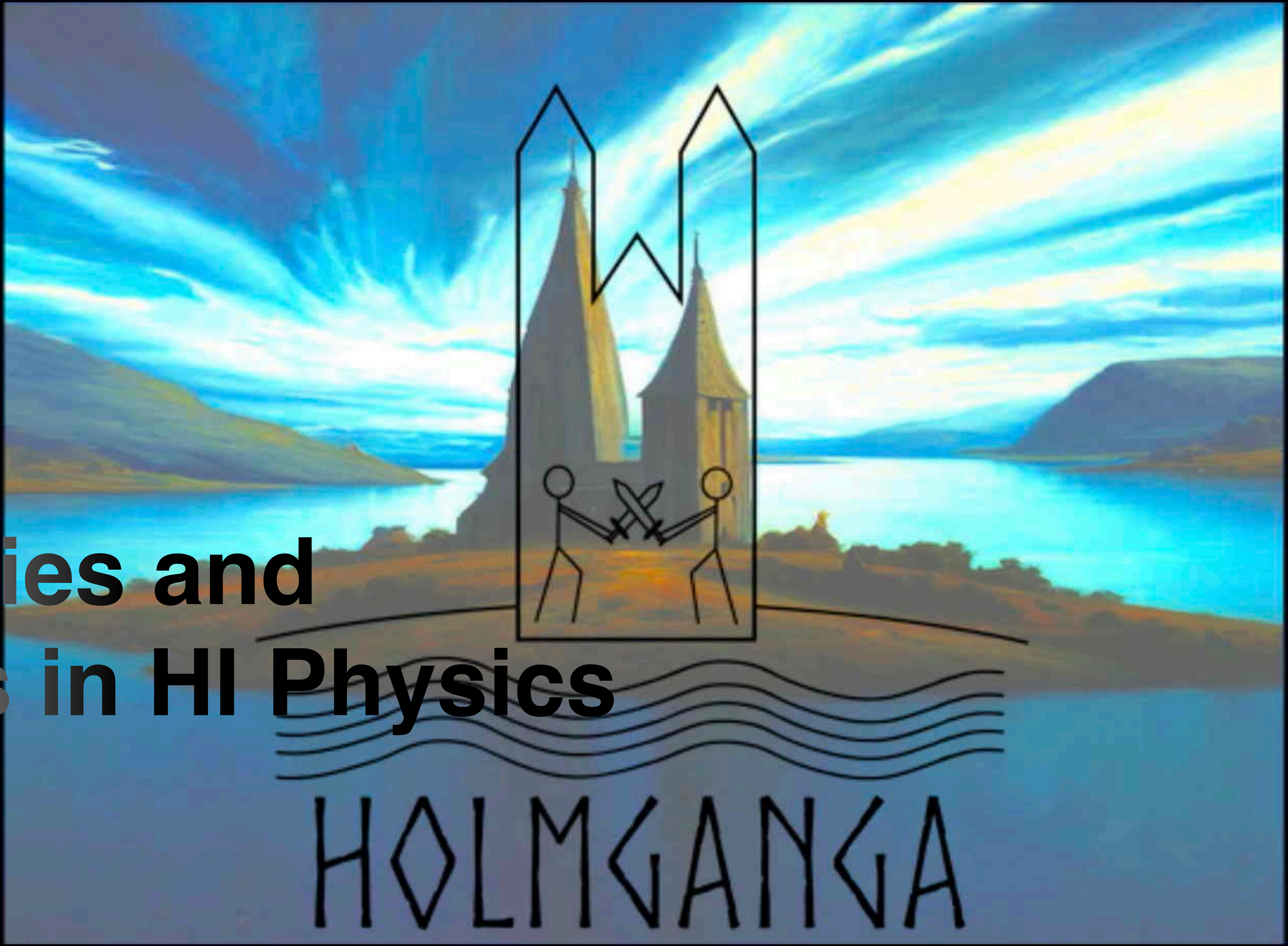
Opportunities and Challenges in HI Physics

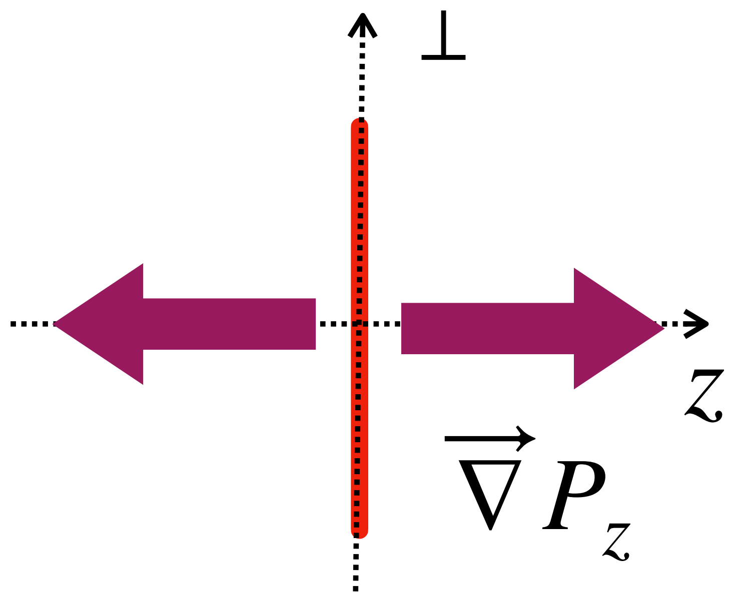


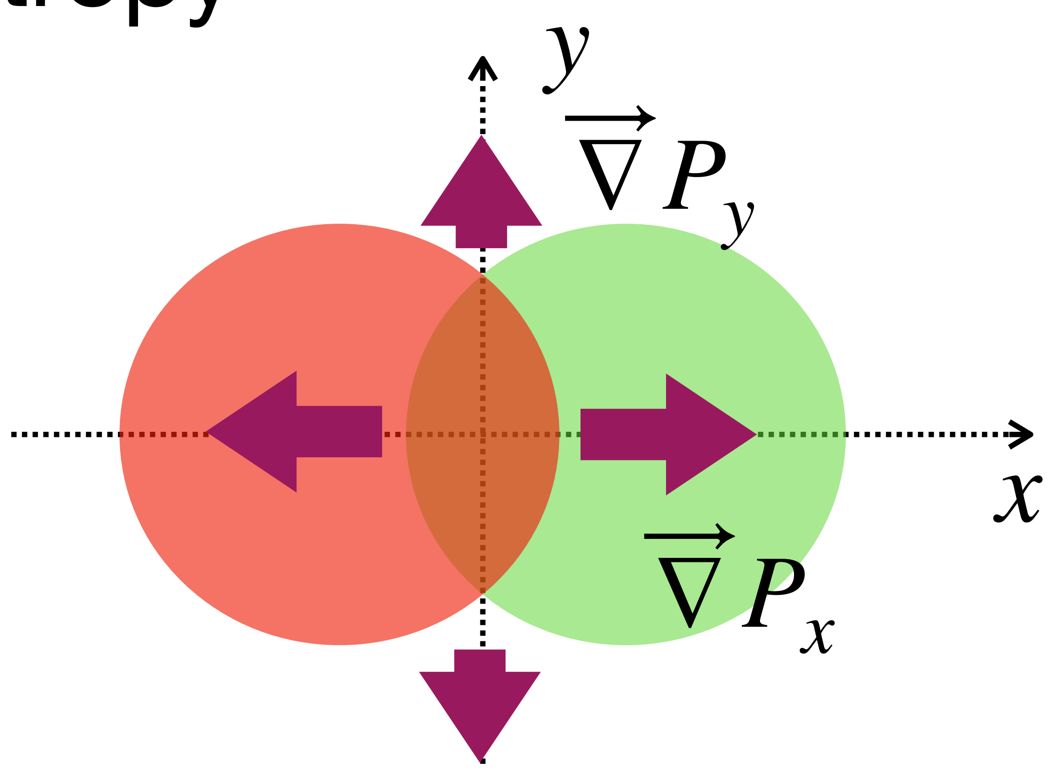
Holmganga: CLASH Workshop 2023

QGP Hypothesis

Fast Equilibration/Thermalization:

- Enormous Energy Density
- Large Spatial Anisotropy

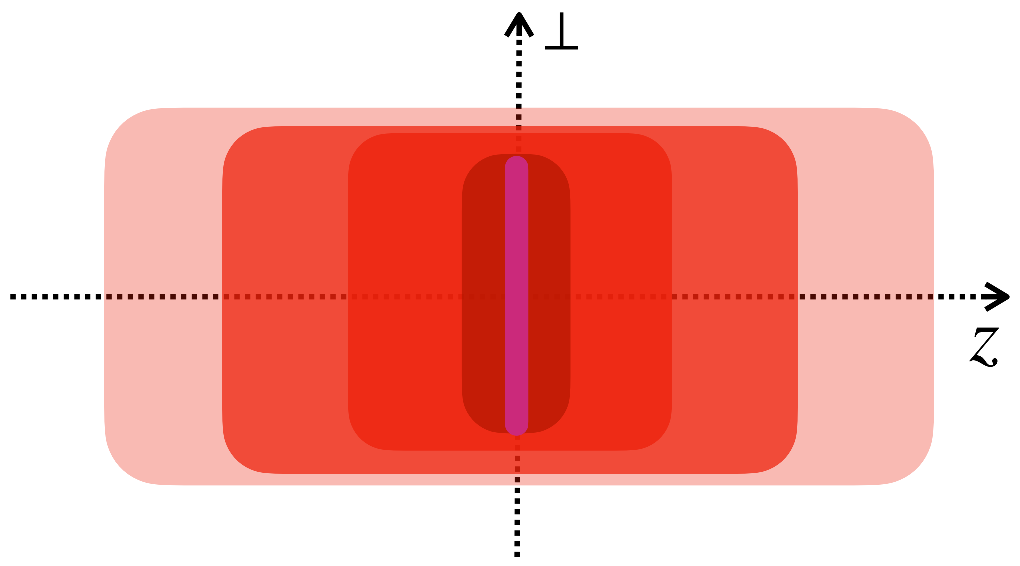


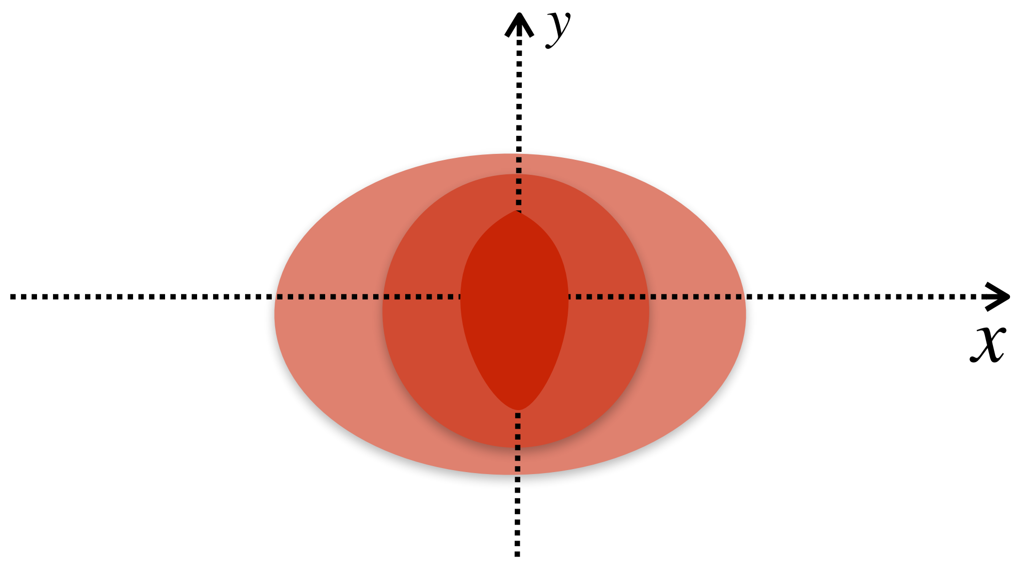


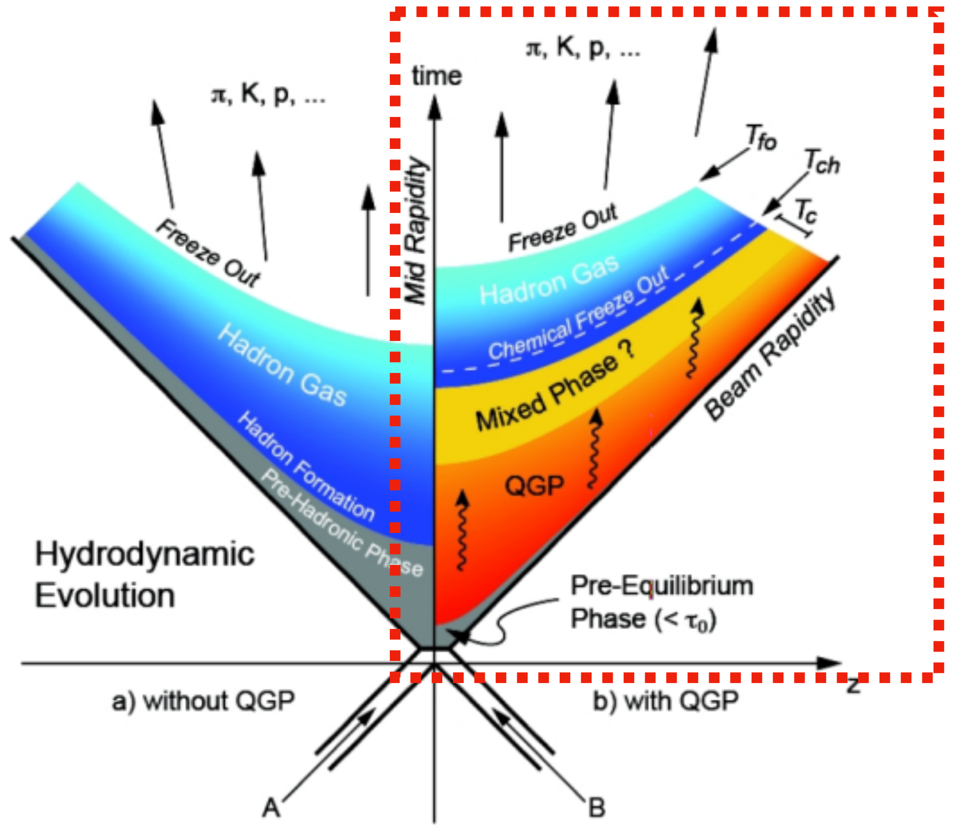
Anisotropic Pressure Gradients

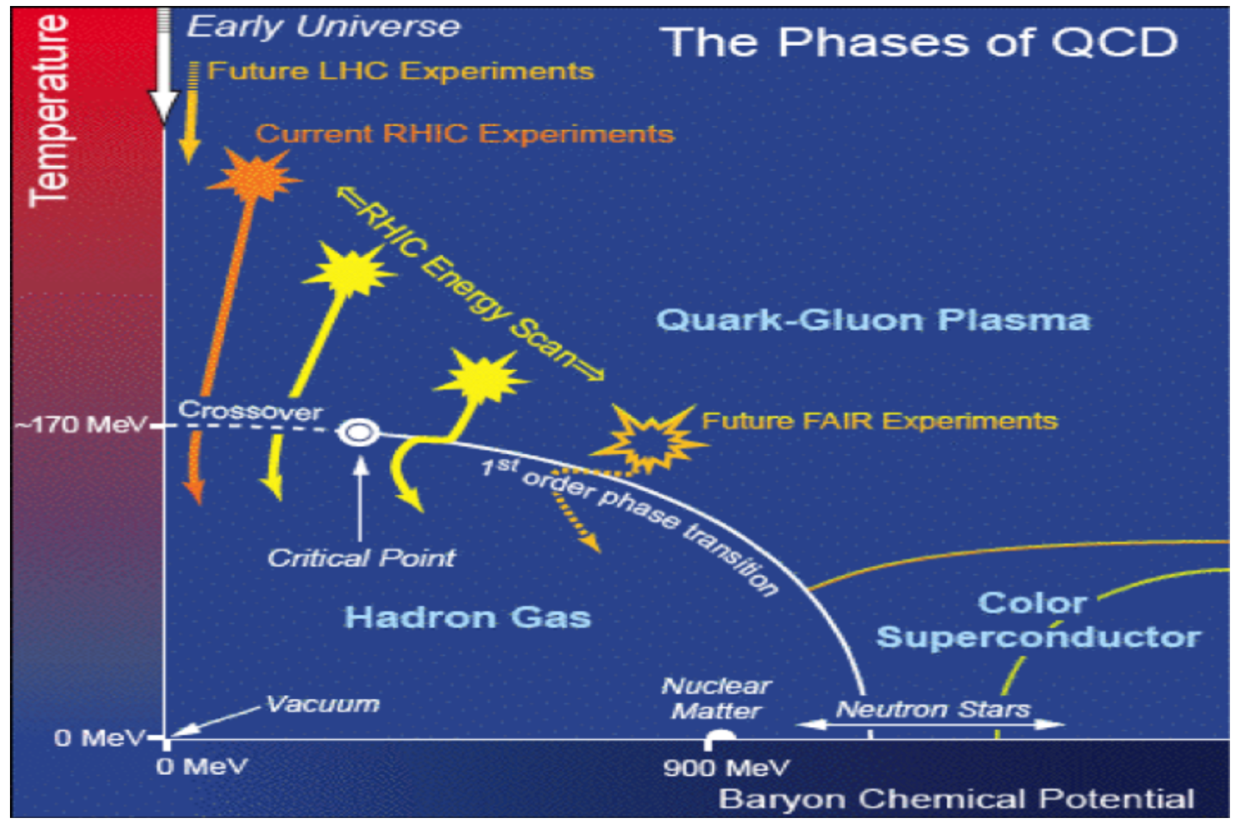
$$\vec{\nabla} P_z \gg \vec{\nabla} P_x \gg \vec{\nabla} P_y$$

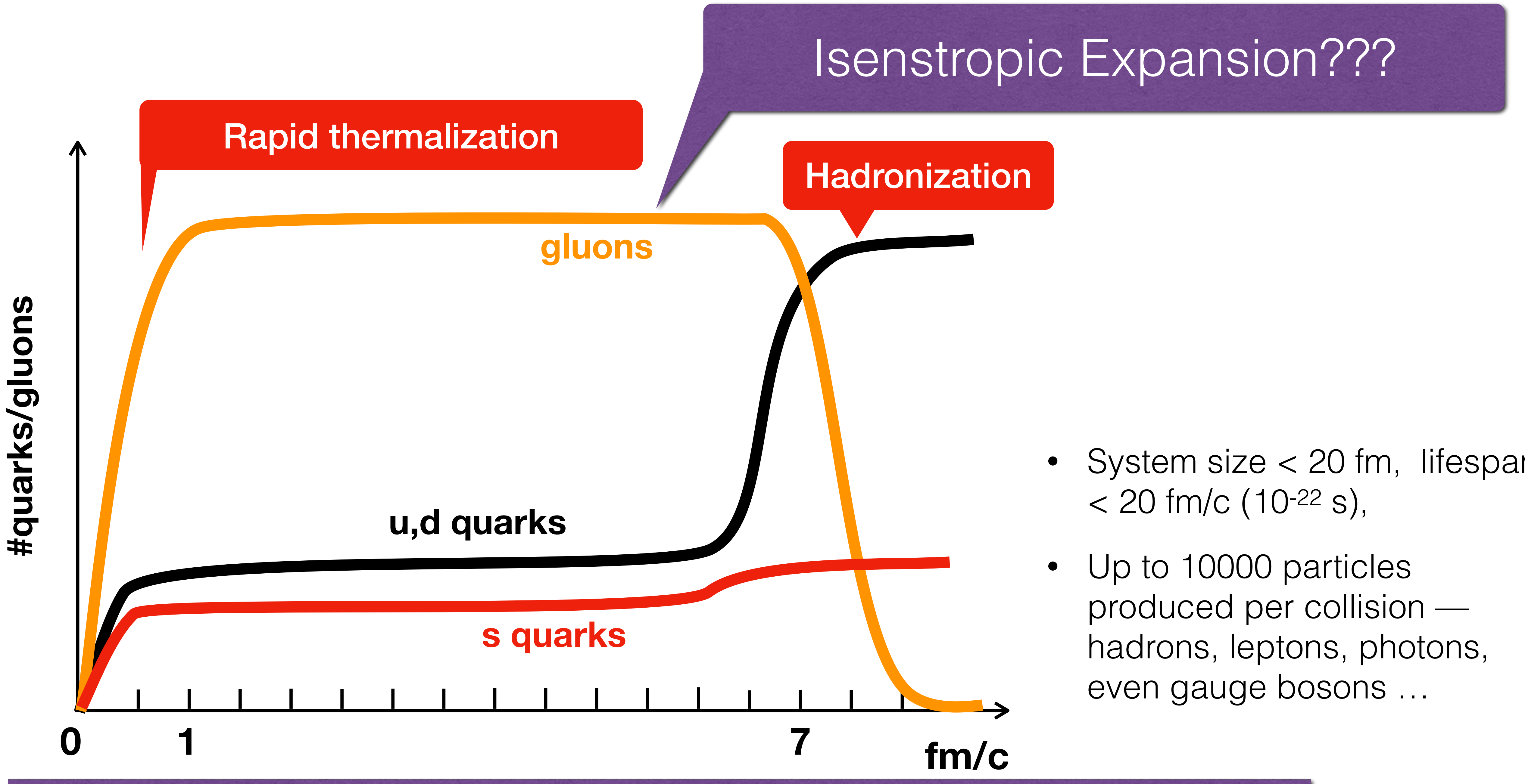
- Longitudinal/Isentropic Expansion
- Anisotropic Transverse Expansion











- System size < 20 fm, lifespan < 20 fm/c (10^{-22} s),
- Up to 10000 particles produced per collision — hadrons, leptons, photons, even gauge bosons …

Have we fully vetted this model?

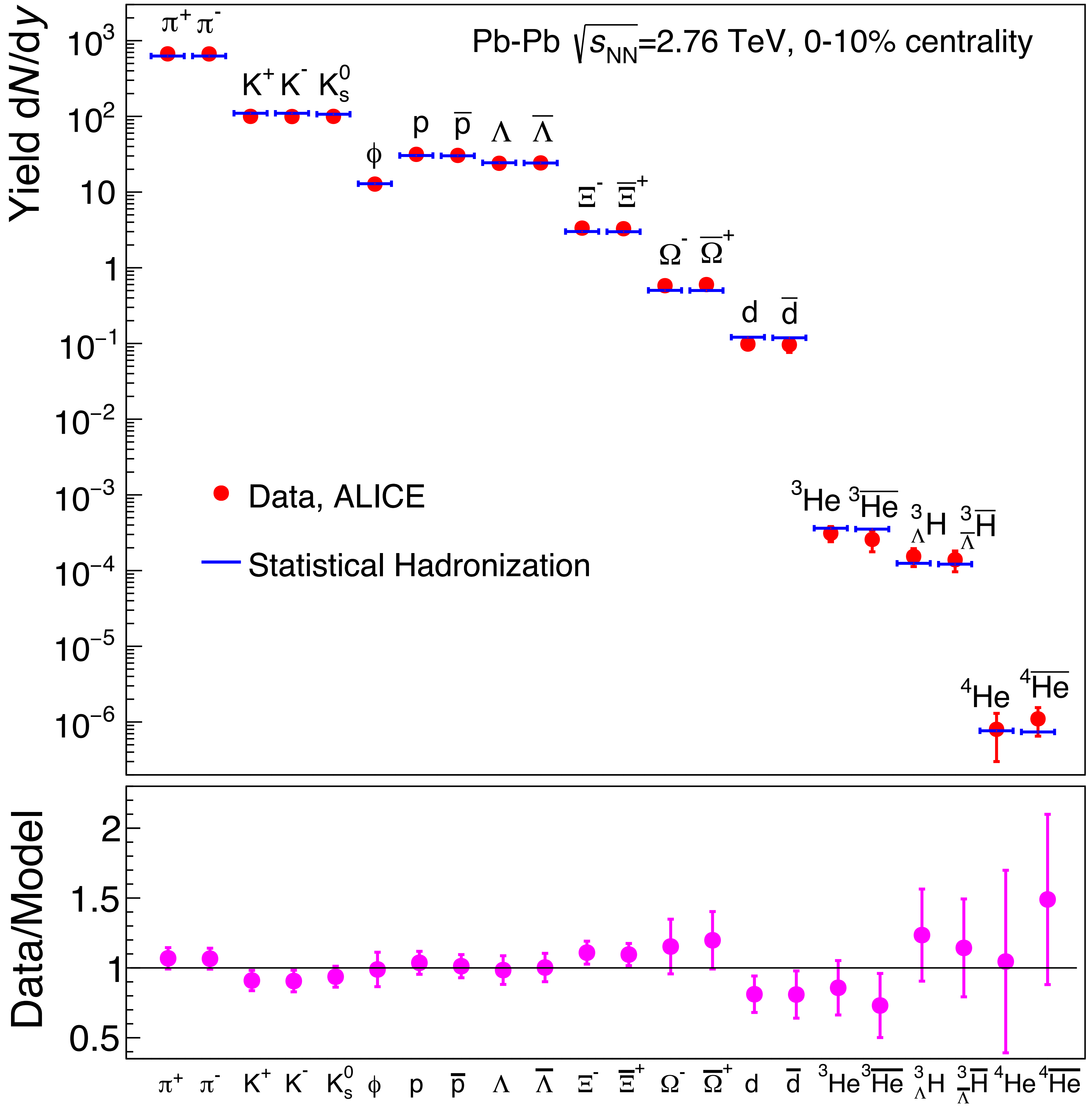
Thermalization !?!

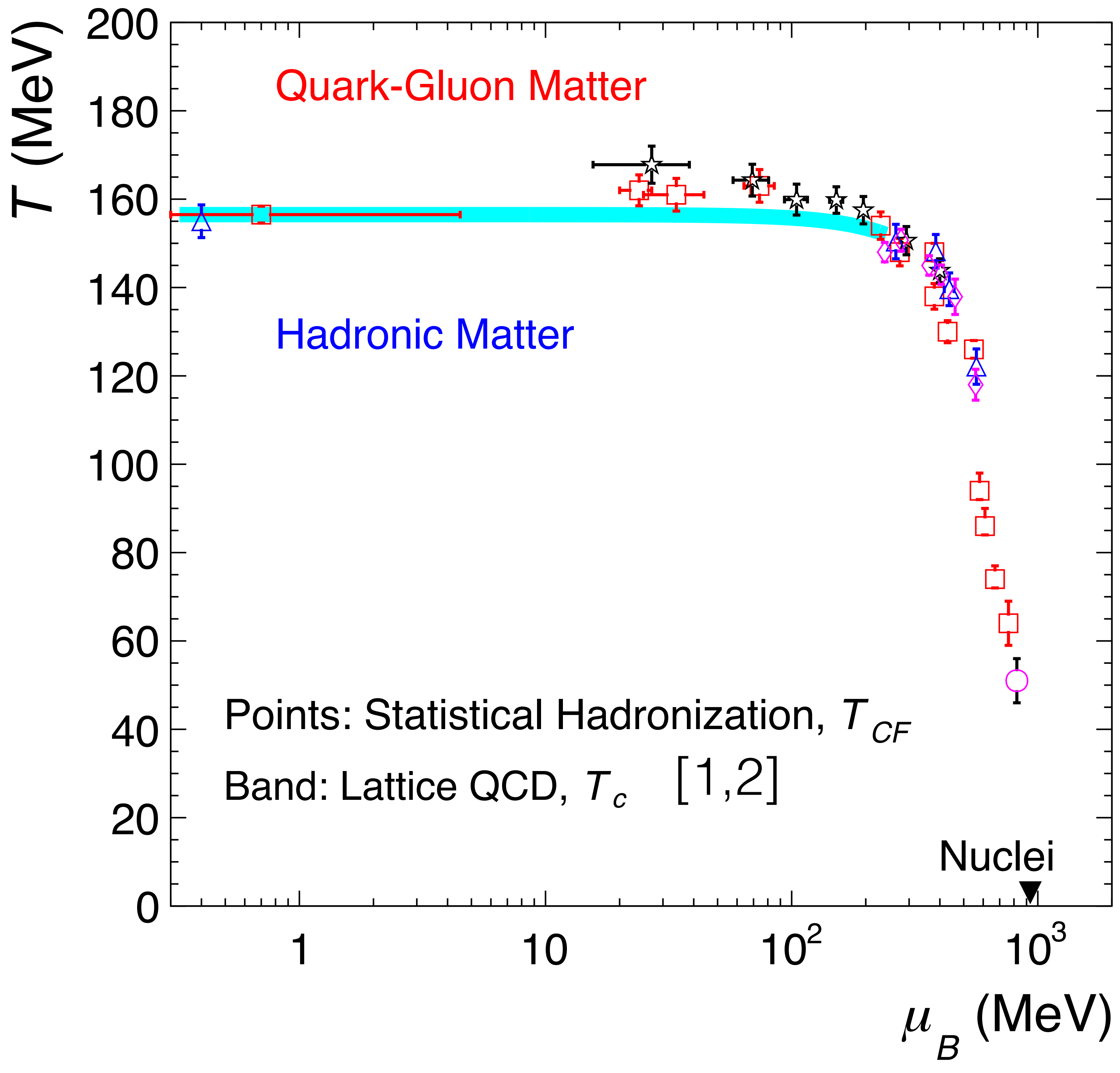
Hadron Resonance Gas Model(s)

$$N_i = -T\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i V}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(E_i-\mu_i)/T] \pm 1}$$

A. Andronic et al. Phys.Lett.B 792 (2019) 304; A. Andronic, et al., Nature, 561 (7723) (2018), p. 321

HRG Model w/ parameters T, μ_B, V; w/ "feed-downs": E&M, Strong Decays: e.g., $\Delta \to p(n) + \pi$, $\rho \to \pi + \pi$, …
Fit to ratios: Volume V cancels out





[1] A. Bazavov, et al. PLB 795 (2019) 15
[2] S. Borsanyi, et al., PRL 125 (2020) 052001

After chemical freeze-out
Elastic & Quasi-elastic scatterings
e.g., $\pi\pi \to \rho \to \pi\pi$
$p\pi \to \Delta \to p\pi$, etc

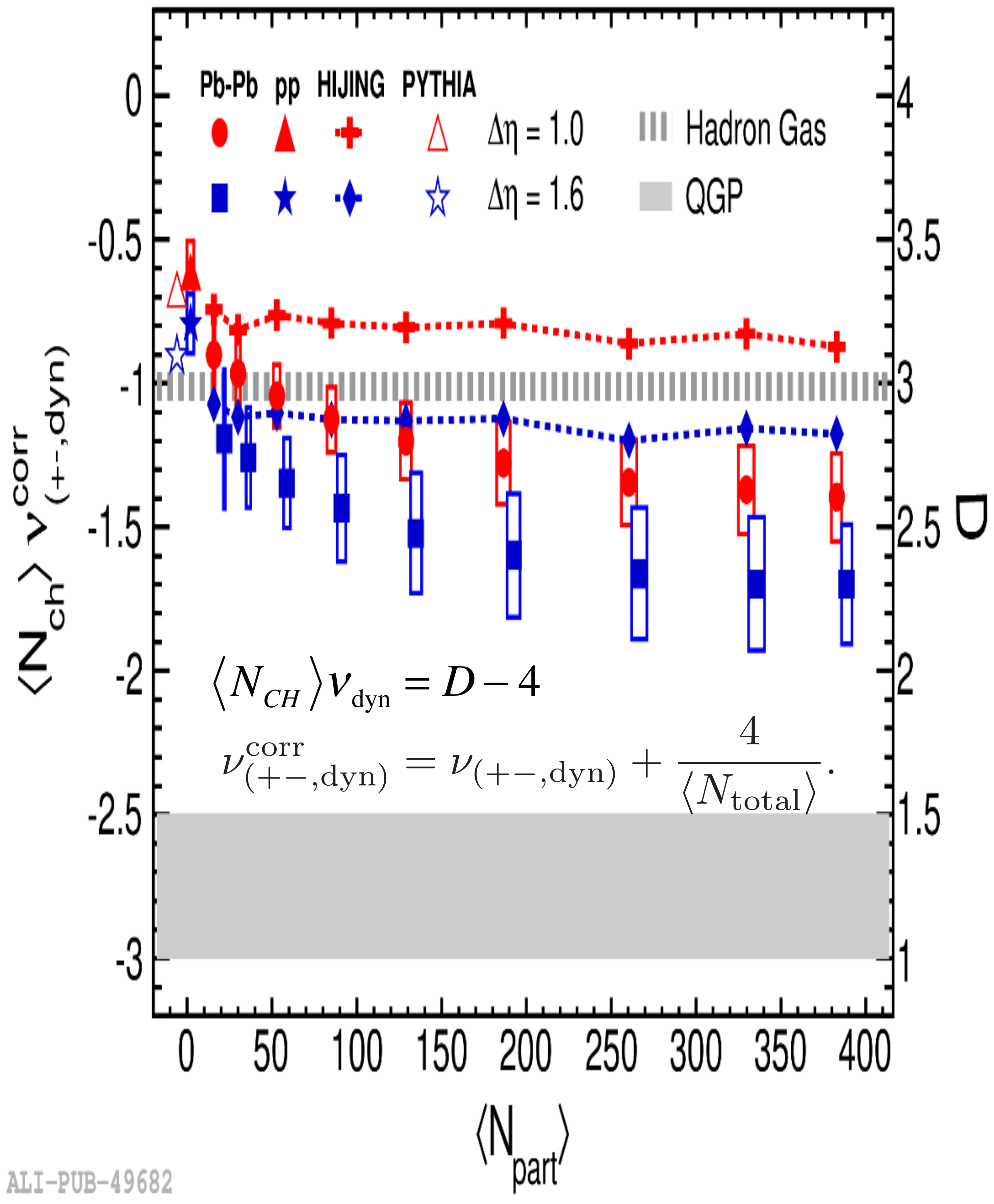
Thermal HG models predict observed abundances with spectacular precision!!

But do not account for …
- Quantum number conservation
- Long range longitudinal correlations
- Non vanishing balance functions
- Non vanishing integral correlations

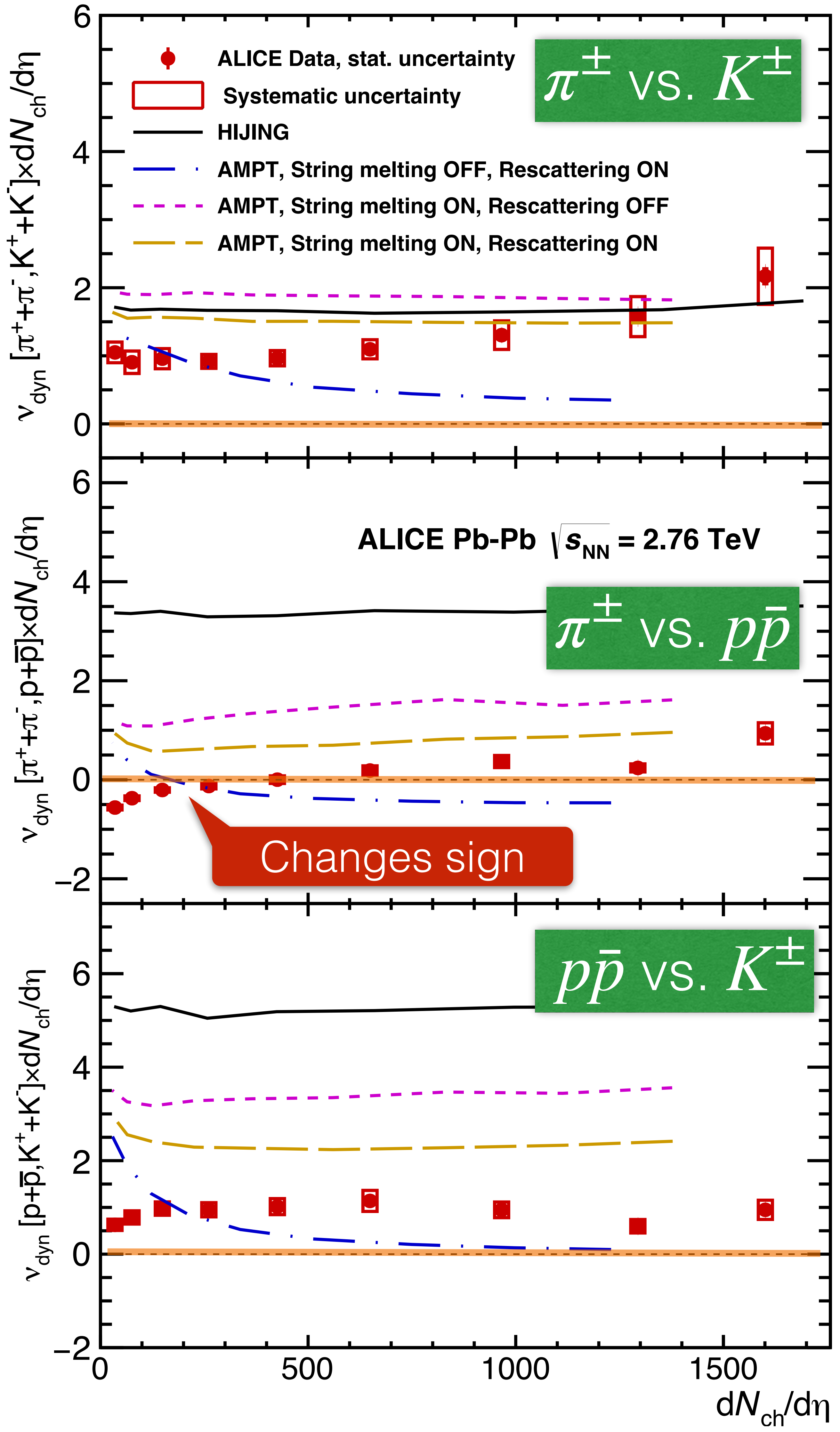
Why does it work so well?
What are we missing?

Measurements of ν_{dyn} and BF

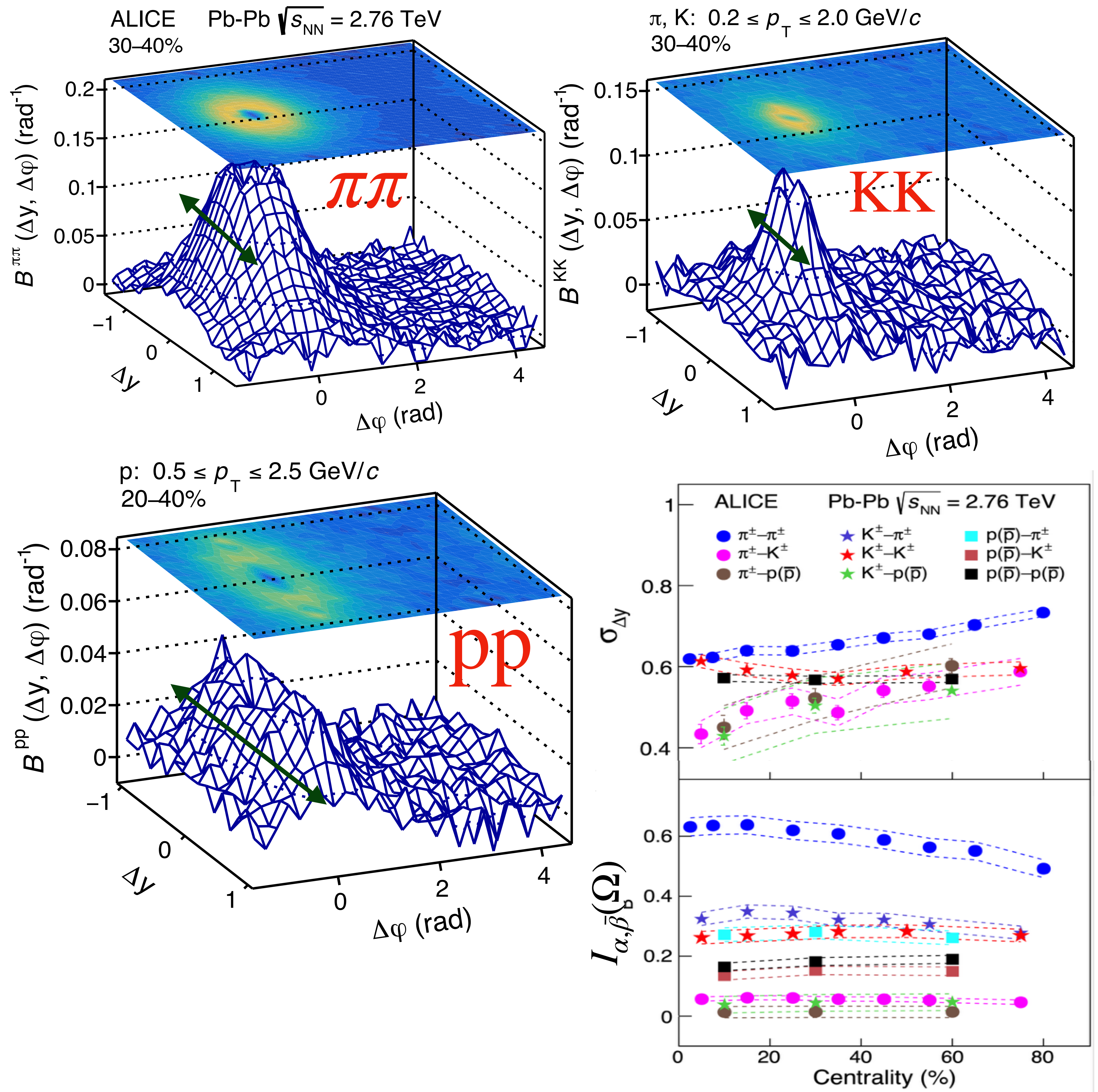
ALICE, PRL 110 (2013) 152301



ALICE, Eur.Phys.J.C 79 (2019) 3



ALICE, PLB 833 (2022) 137338



$$I_{\alpha,\bar{\beta}}(\Omega) = -\frac{1}{4}\frac{dN_T}{d\eta}\Delta\eta \times \nu_{\text{dyn}}^{\alpha,\bar{\beta}}(\Omega)$$

Can we really measure susceptibilities this way?

GCE Partition Function:

$$Z(V,T,\mu_B,\mu_Q,\mu_S) = \mathrm{Tr}\left[e^{-\beta\left(H-\sum_i \mu_i N_i\right)}\right]$$

$\beta = 1/T$, w/ T : System Temperature
H : Hamiltonian
μ_i: Chemical potentials
N_i: Conserved number operators

Dimensionless pressure___: $\frac{P}{T^4} = \frac{1}{VT^3}\ln\left[Z(V,T,\mu_B,\mu_Q,\mu_S)\right]$

Quark number density_____: $\langle n_q\rangle = \frac{T}{V}\frac{\partial \ln Z}{\partial \mu_q}$

Baryon densities_________: $\langle n_B\rangle = \frac{1}{3}\sum_q \langle n_u\rangle$:

Isospin density__________: $\langle n_I\rangle = \frac{1}{2}\left(\langle n_u\rangle - \langle n_d\rangle\right)$

Electric charge density__: $\langle n_Q\rangle = \frac{2}{3}\langle n_u\rangle - \frac{1}{3}\langle n_d\rangle - \frac{1}{3}\langle n_s\rangle$

Susceptibilities_________: $\chi^{BQS}_{ijk} = \frac{\partial^{i+j+k}[P/T^4]}{\partial\hat{\mu}^i_B\partial\hat{\mu}^j_Q\partial\hat{\mu}^k_S}$ w/ $\hat{\mu}_q \equiv \mu_q/T$, $q = B,Q,S$

Diagonal/Non-diagonal Cumulants..:

$$C^{BQS}_{ijk} = \frac{\partial^{i+j+k}}{\partial\hat{\mu}^i_B\partial\hat{\mu}^j_Q\partial\hat{\mu}^k_S}\ln\left[Z(V,T,\mu_B,\mu_Q,\mu_S)\right] = VT^3\chi^{BQS}_{ijk}(T,\mu_B,\mu_Q,\mu_S)$$

To avoid ambiguities associated with the unknown volume V, consider ratios of cumulants:

$$\frac{\sigma^q_2}{M_q} = \frac{C^q_2}{M_q} = \frac{\chi^q_2}{\chi^q_1} \qquad S_q\sigma^q_2 = \frac{C^q_3}{C^q_2} = \frac{\chi^q_3}{\chi^q_2}$$

$$\kappa_q\sigma^q_2 = \frac{C^q_4}{C^q_2} = \frac{\chi^q_4}{\chi^q_2} \qquad \frac{\kappa_q\sigma^q_2}{S_q} = \frac{C^q_4}{C^q_3} = \frac{\chi^q_4}{\chi^q_3}$$

But C^q_2 is entirely determine by charge conservation and the width of the acceptance…

C^q_n, n>2, only carries “new” information **if** $F_n \neq 0$ (factorial cumulants)
Make sure you check !!! [1]

Might be better to measure differential balance functions and their integrals…

$$B^{+,-} = \langle N_{-|+}\rangle - \langle N_{+|+}\rangle = \frac{\langle N_+N_-\rangle}{\langle N_+\rangle} - \frac{\langle N_+(N_+-1)\rangle}{\langle N_+\rangle}$$

$$I_{\alpha,\bar{\beta}}(\Omega) = -\frac{1}{4}\frac{dN_T}{d\eta}\Delta\eta\times\nu^{\alpha,\bar{\beta}}_{\mathrm{dyn}}(\Omega)$$

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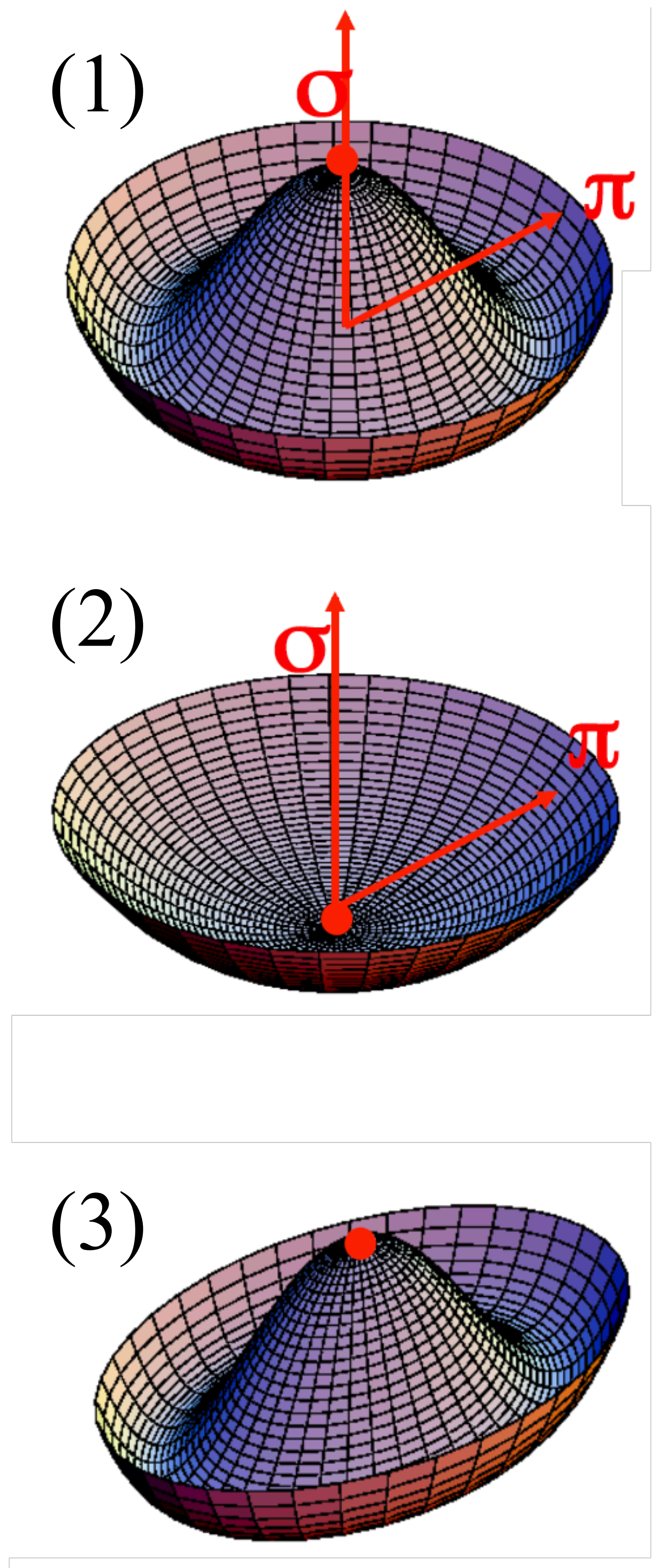
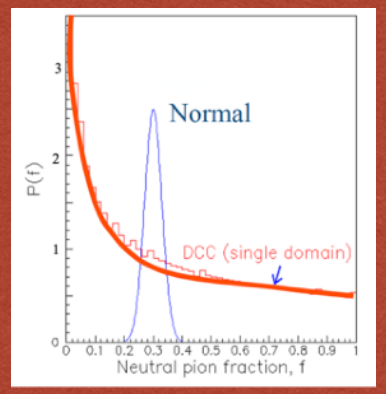
[1] C.P., Phys.Rev.C 100 (2019) 3, 034905

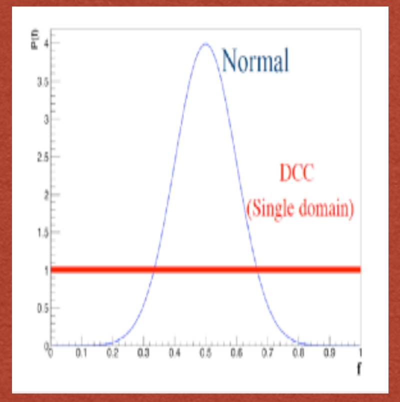
Remember Disoriented chiral condensate (DCCs)?



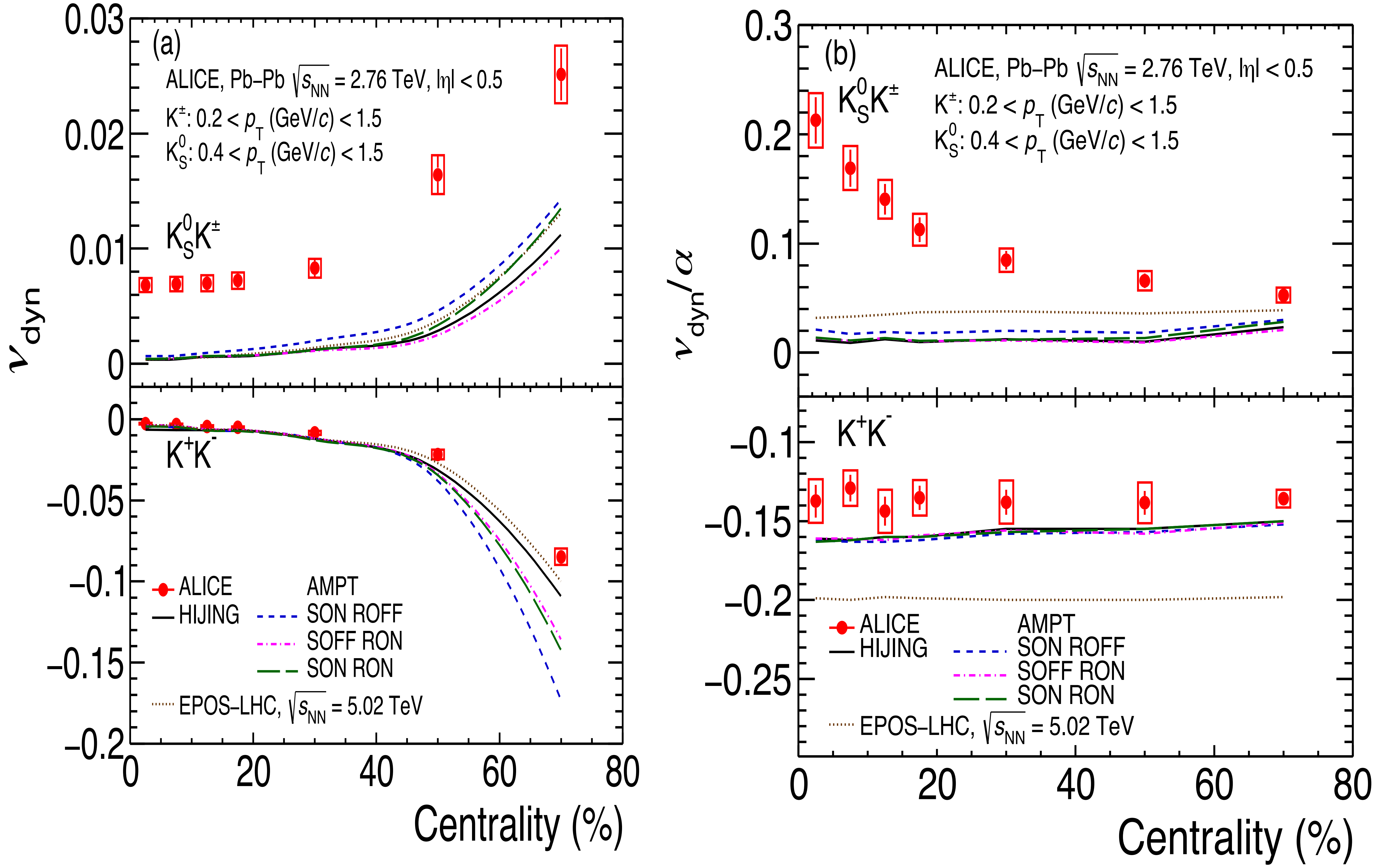
- **Pion sector**
  - Fluctuations of neutral vs. charge pions [1]
  - "Pulse" of low pT pions w/ neutral fraction
    $$f = \frac{N_{\pi^0}}{N_{\pi^0} + N_{\pi^-} + N_{\pi^+}}$$
  - Probability distribution:
    - $$P(f) = \frac{1}{2\sqrt{f}}$$



- **Kaon sector**
  - Fluctuations of neutral vs. charge kaons [2]
  - "Pulse" of low pT kaons w/ neutral fraction $f = \frac{N_{K^0} + N_{\bar{K}^0}}{N_{K^0} + N_{\bar{K}^0} + N_{K^-} + N_{K^+}}$
  - PDF:
    - $P(f) = 1$



ALICE, PLB 832 (2022) 137242



Very strong scaling violation of $\nu_{dyn}[K^0, K^{\pm}]$ vs. produced particle multiplicity.

[1] Randrup et al, PRC 59 (1999) 3329
[2] J. Kapusta, S.M.H. Wong PRL 86 (2001) 4251