Studying heavy-ion collisions using a hybrid model

FAPESP
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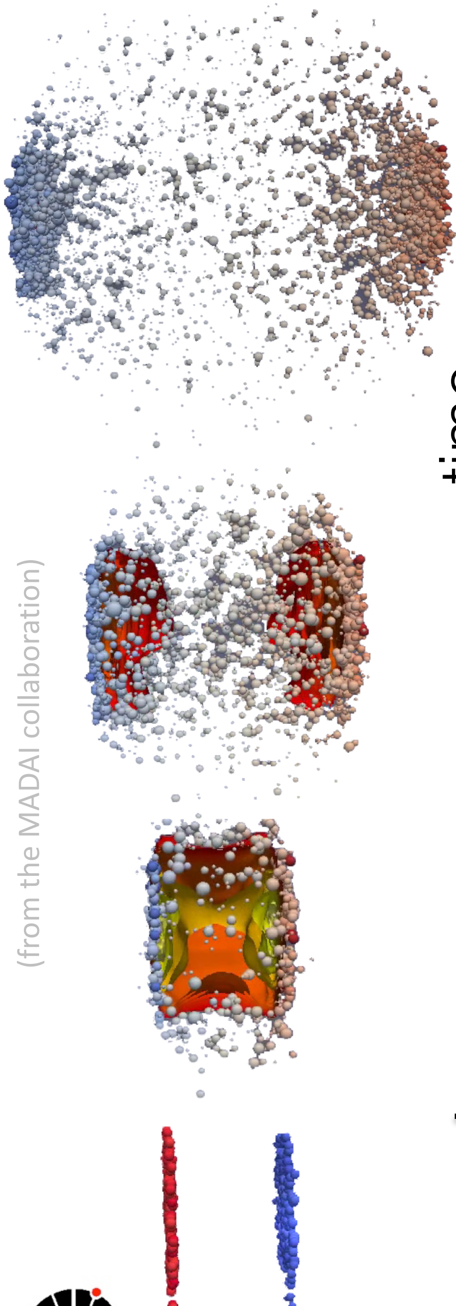
T. Nunes da Silva[1], M. Hippert[2], **D. D. Chinellato[1]**, M. Luzum[2], J. Noronha[2], J. Takahashi[1]

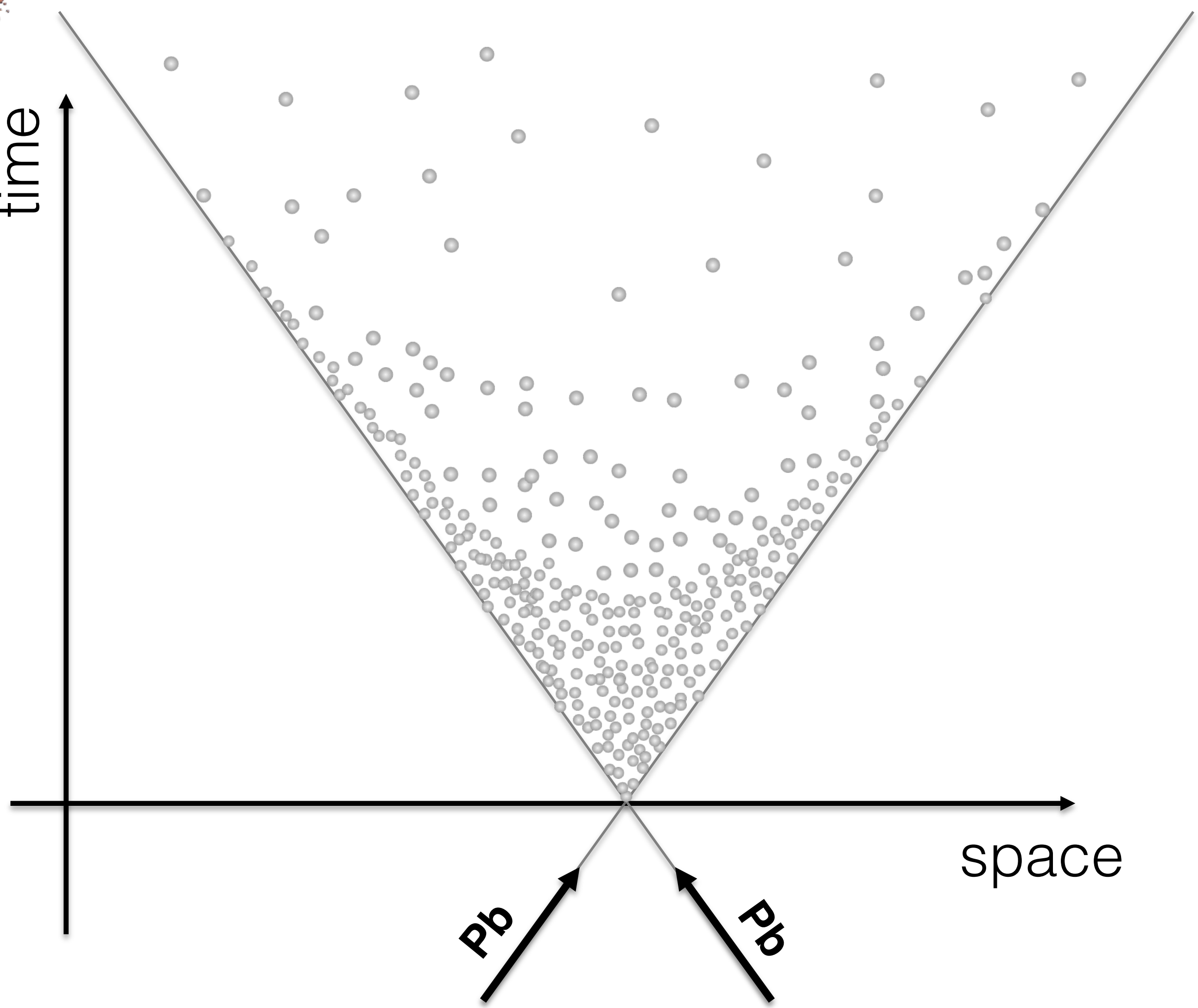
[1] - Universidade Estadual de Campinas, Campinas, Brazil
[2] – Universidade de São Paulo, São Paulo, Brazil

(Schematic representation of)

A heavy ion collision



(from the MADAI collaboration)



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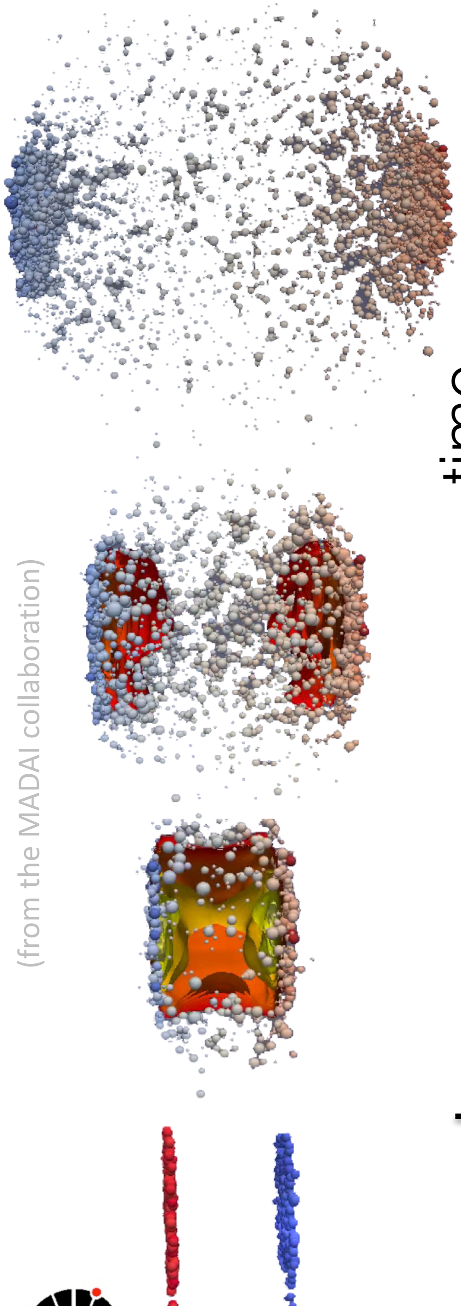

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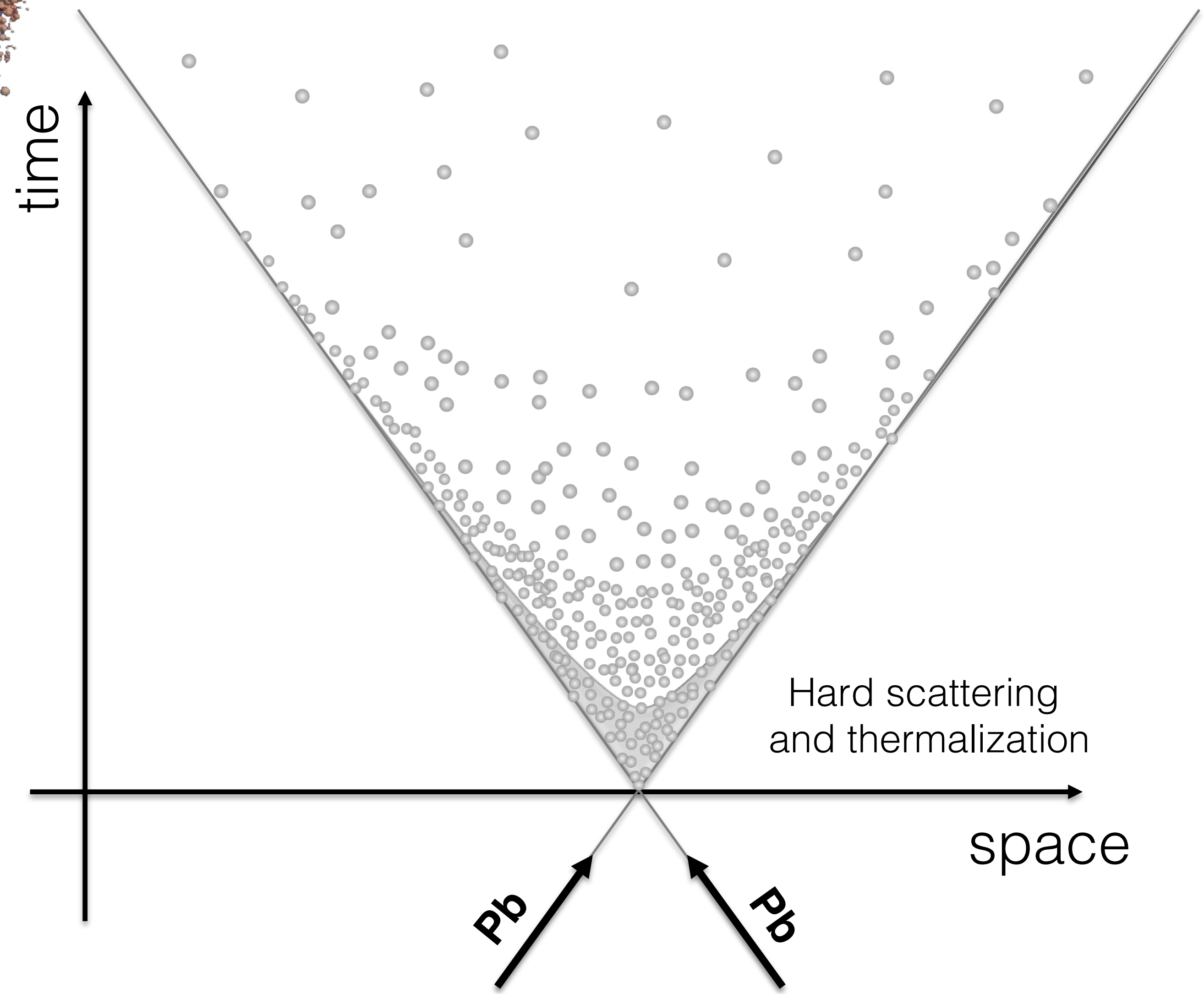

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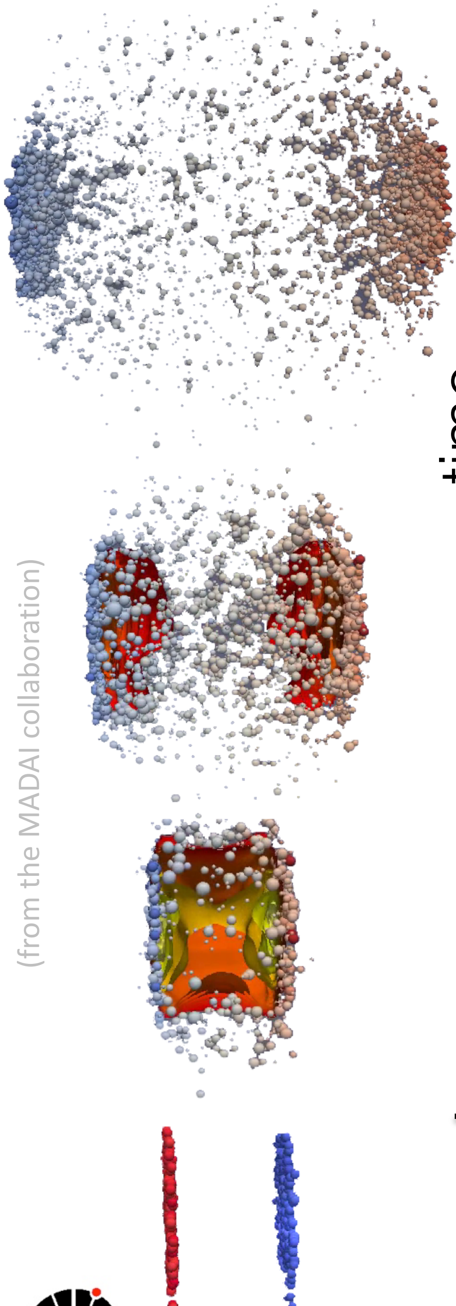
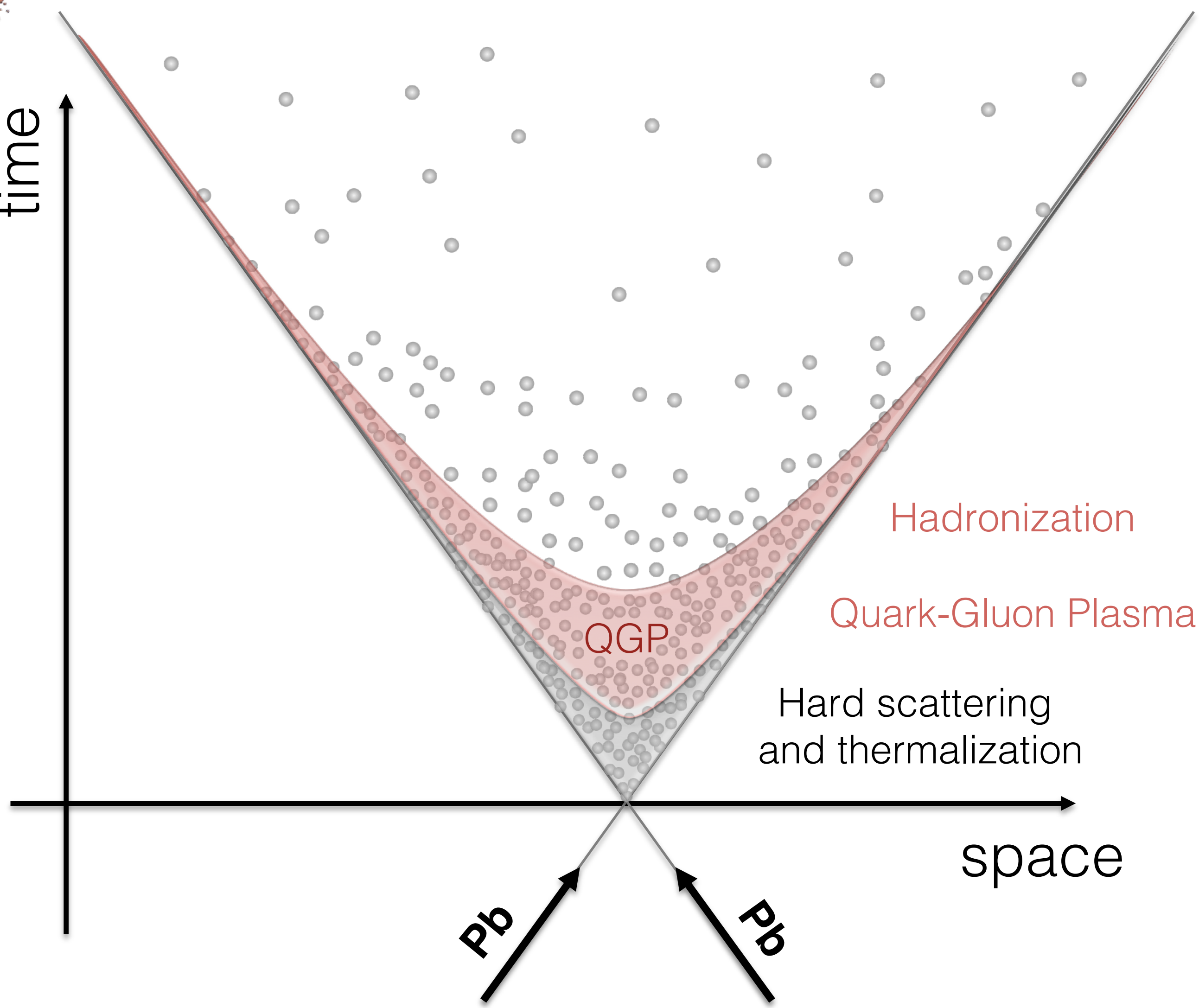
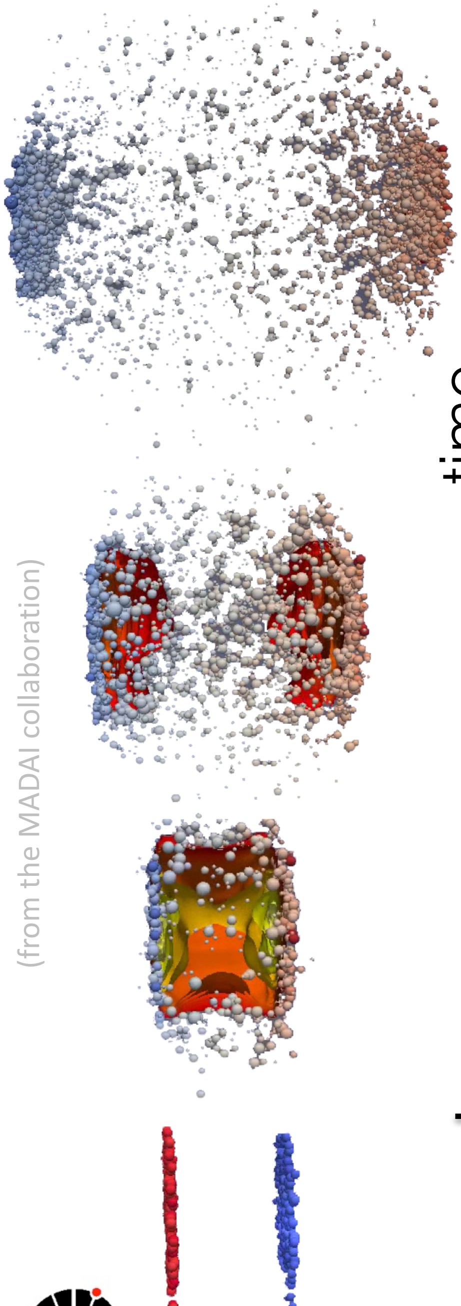
A heavy ion collision





(Schematic representation of)

A heavy ion collision



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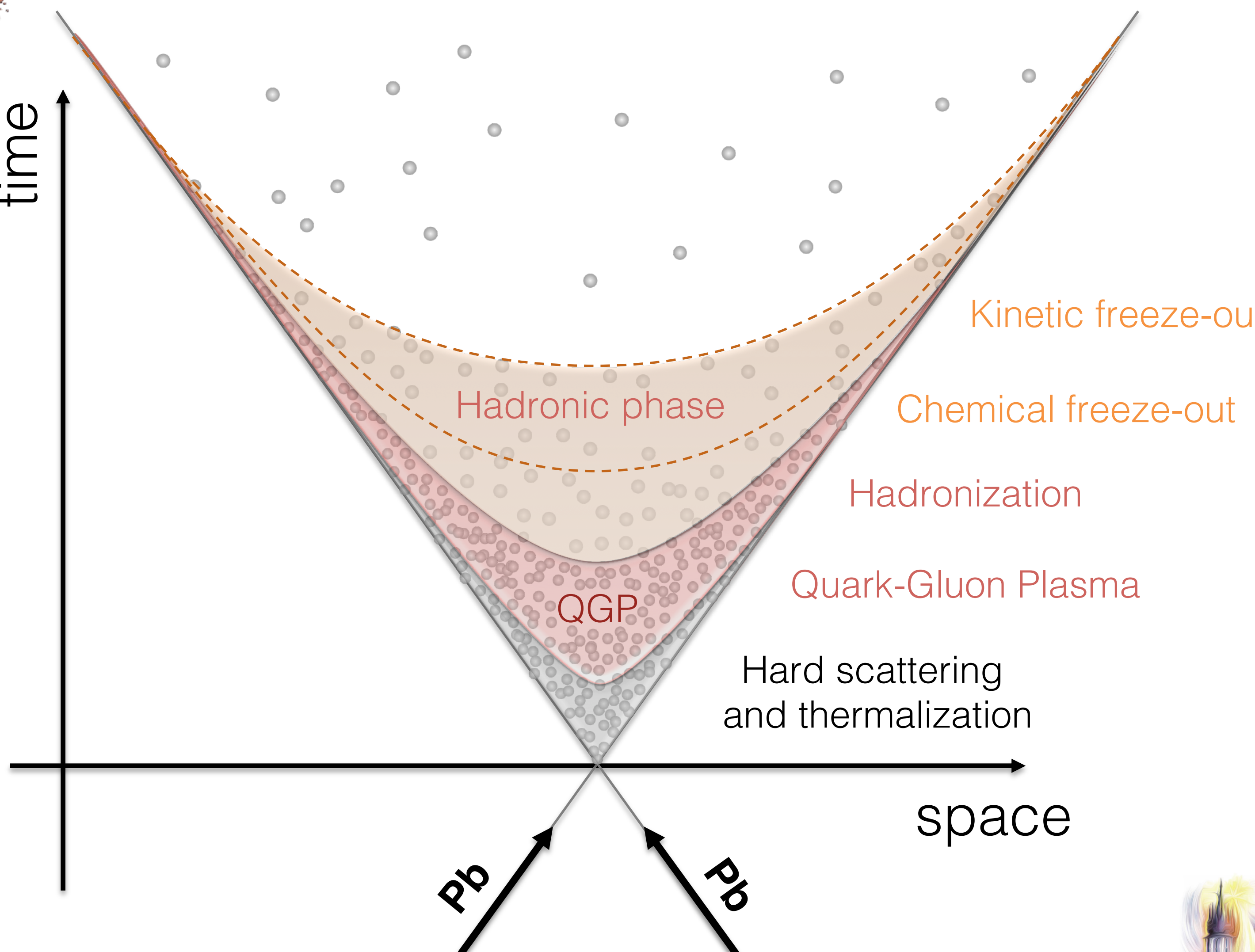

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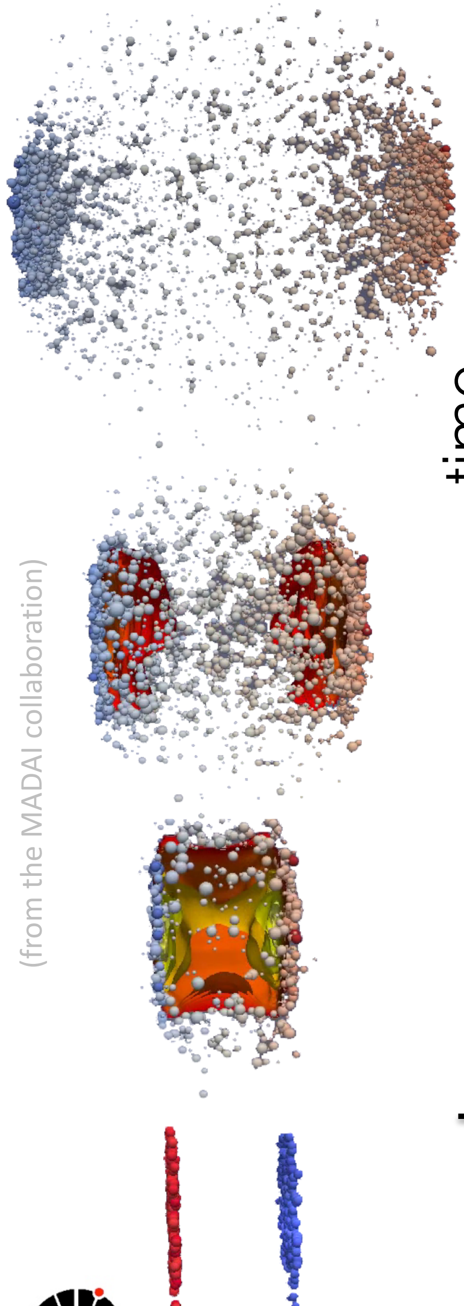
(Schematic representation of)

A heavy ion collision



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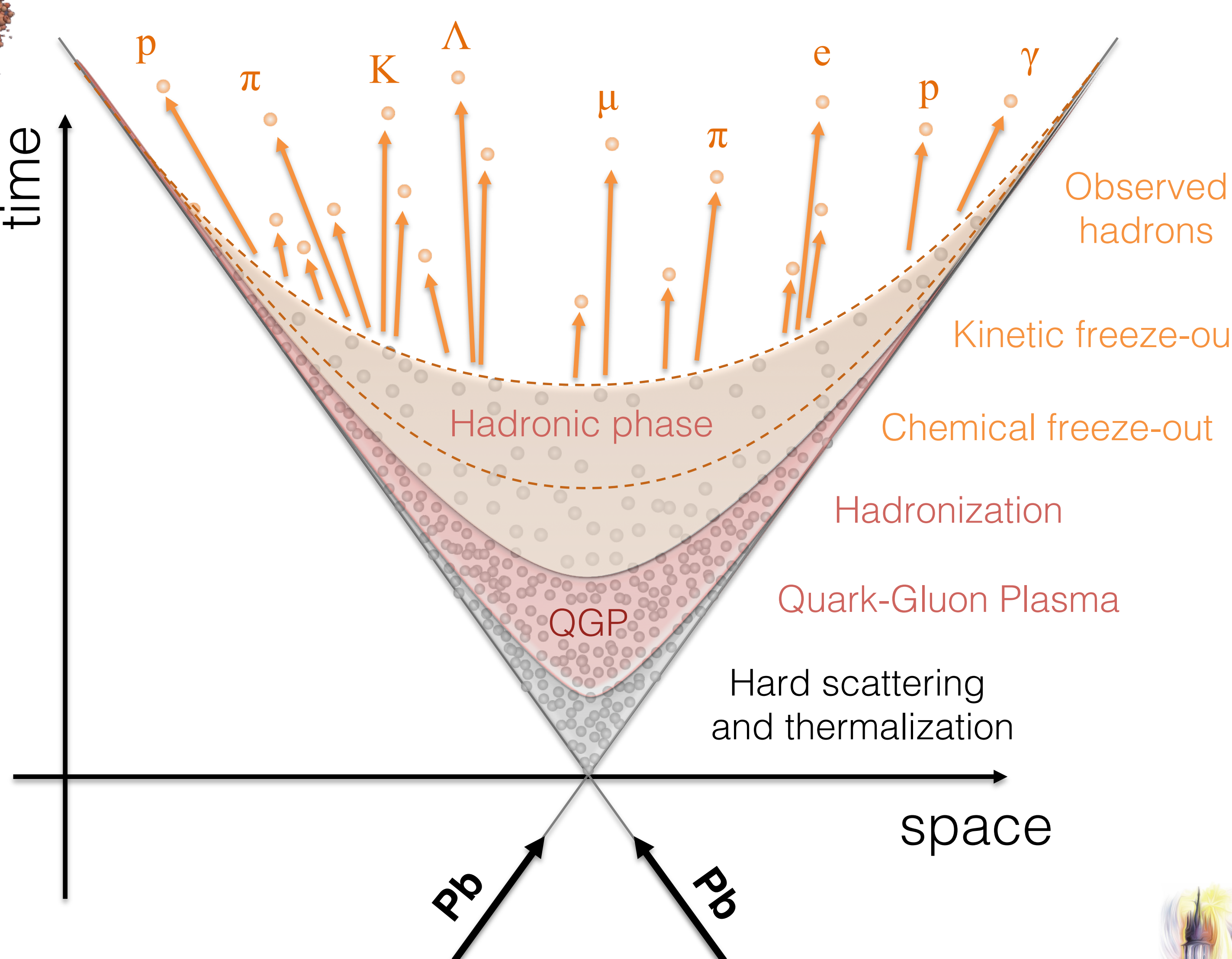

Simulating a heavy ion collision: hybrid model

Early stage model

QGP
- Initial condition
- Particlization hypersurface

hadrons
- Discrete particles
- Final particles
- Observables

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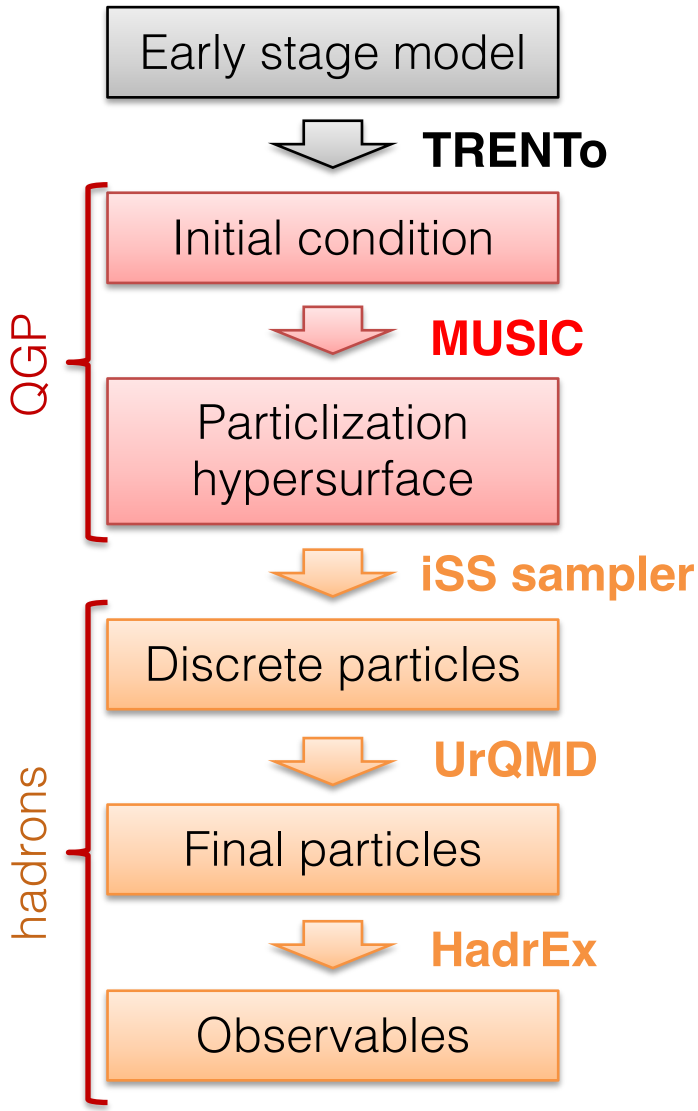
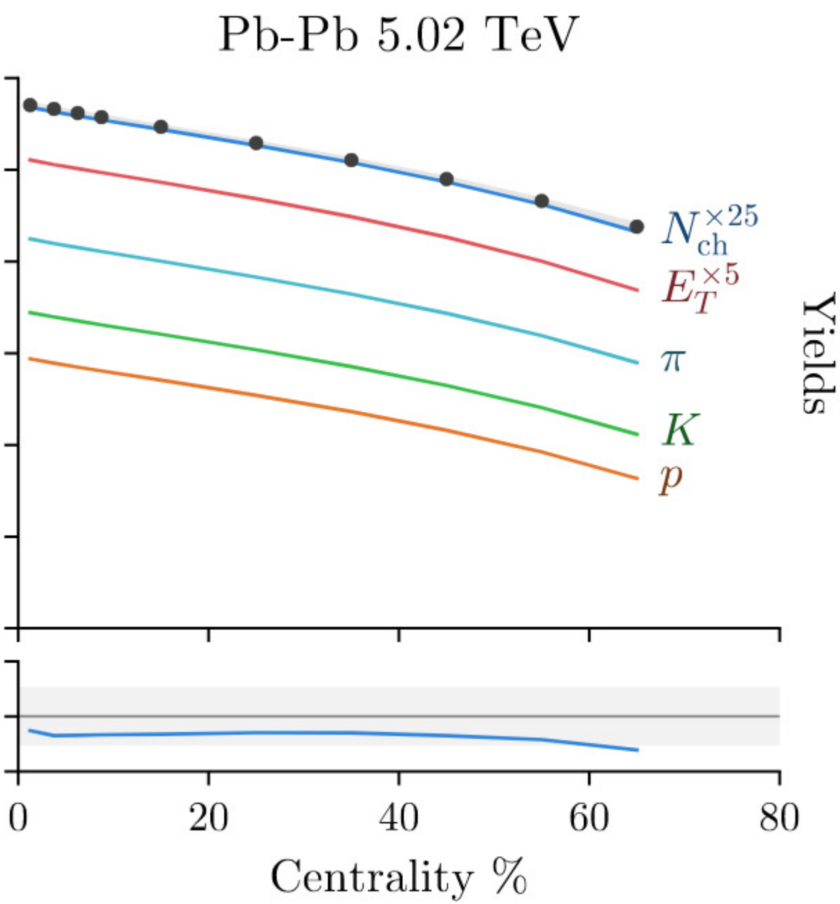
Simulating a heavy ion collision: hybrid model



- ← **TRENTo** [1]: initial condition generator
- ← **MUSIC** [2]: 3+1 hydrodynamics for the evolution of the QGP phase
- ← **iSS sampler** [3]: thermal production of hadrons from freezeout hypersurface
- ← **UrQMD** [4]: hadronic cascade simulator: scattering and resonance decays
- ← **HadrEx**: a convenient general-purpose analysis framework

[1] http://qcd.phy.duke.edu/trento/
[2] http://www.physics.mcgill.ca/music/
[3] https://github.com/chunshen1987/iSS
[4] https://urqmd.org/

Configuring the chain

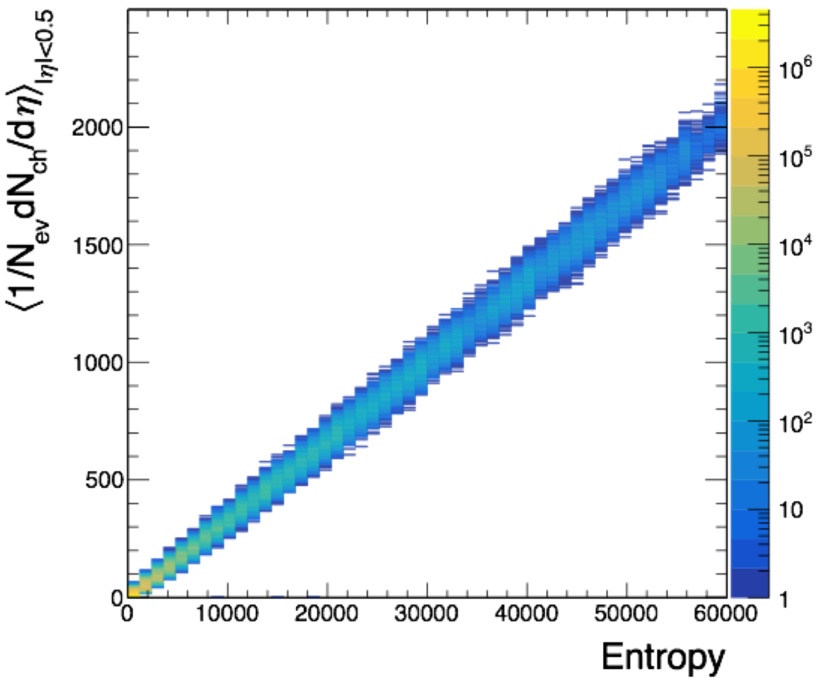


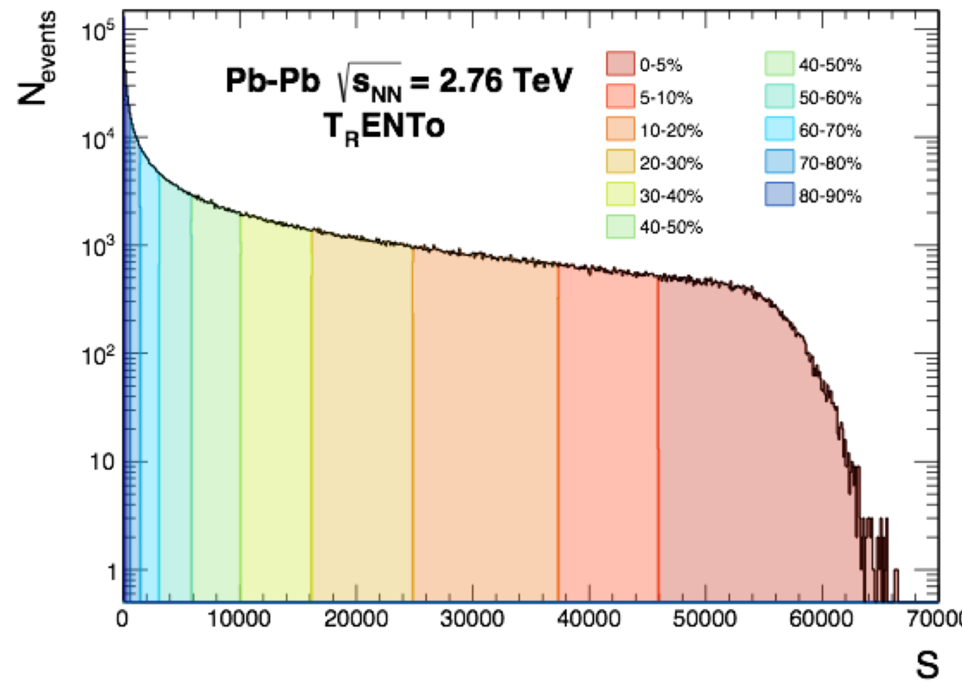
[1] Nuc.Phys.A, 967 (67-73)

← TRENTo + Free Streaming + VISH2+1 + FRZOUT + UrQMD (by the Duke group [1]): obtained optimal a posteriori parameters

- We utilize these parameters but with a different overall normalization
- Minor differences in the two approaches under study

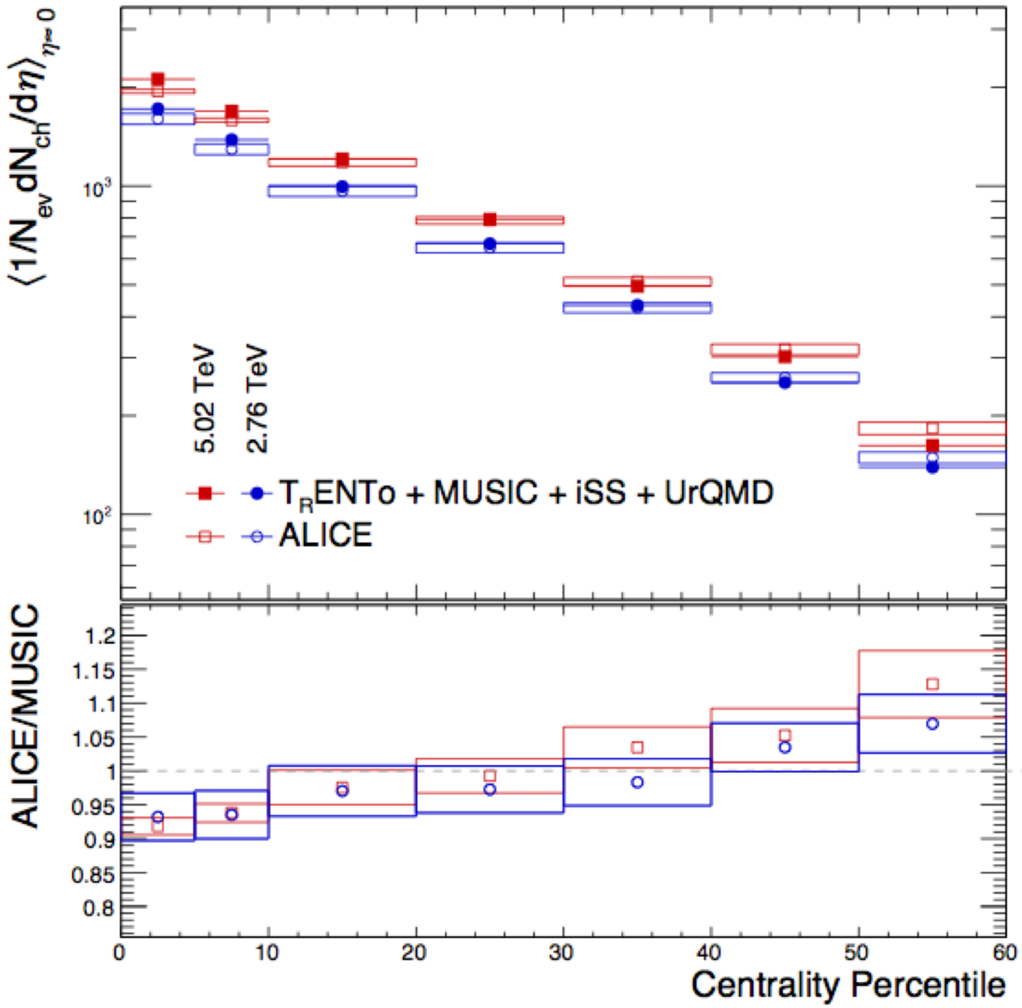
Centrality determination





- Strongly correlated: Initial entropy S and final charged-particle multiplicity
- Centrality calibration based on a sample of 10^6 TRENTo initial conditions and entropy classification

Charged-particle multiplicity density



← Description acceptable within uncertainties (~10%) within 0-60%

- Centrality dependence similar for both energies

Particle distribution in azimuth

Single particle distribution in a single event:

$$\frac{dN}{d\vec{p}} = \sum_{n=-\infty}^{+\infty} V_n(p)\, e^{in\varphi} \qquad V_n(p) \equiv \frac{1}{2\pi \Delta p_T \Delta\eta} \sum_{j=1}^{M(p)} \exp(in\varphi_j)$$

Pair distribution:

$$\left\langle \frac{d^2 N_{pairs}}{dp_a dp_b} \right\rangle = \underbrace{\left\langle \frac{dN}{dp_a} \frac{dN}{dp_b} \right\rangle}_{\text{Leading term}} + \underbrace{\mathcal{O}(N)}_{\text{Non-flow}}$$

Studying how particle pairs are correlated:

The pair correlation matrix

Fourier expansion of the pair distribution:

$$\left\langle \frac{d^2 N_{pairs}}{dp_a dp_b} \right\rangle = \sum_{n=-\infty}^{+\infty} V_{n\Delta}\left(p_a, p_b\right) e^{in(\varphi_a - \varphi_b)}$$

With:

$$V_{n\Delta}\left(p_a, p_b\right) = \begin{pmatrix} \langle V_n\left(p_1\right) V_n^*\left(p_1\right)\rangle & \langle V_n\left(p_1\right) V_n^*\left(p_2\right)\rangle & (\ldots) \\ \langle V_n\left(p_2\right) V_n^*\left(p_1\right)\rangle & \langle V_n\left(p_2\right) V_n^*\left(p_2\right)\rangle & (\ldots) \\ (\ldots) & (\ldots) & (\ldots) \end{pmatrix}$$

and 1, 2, 3… refers to the various momentum intervals used for analysis

Principal **C**omponent **A**nalysis

We approximate the correlation matrix:

$$V_{n\Delta}\left(p_a, p_b\right) \approx \sum_{\alpha=1}^{k} V_n^{(\alpha)}\left(p\right) V_n^{(\alpha)*}\left(p_b\right)$$

And diagonalize it:

$$V_{n\Delta}\left(p_a, p_b\right) = \sum_{\alpha} \lambda^{(\alpha)} \psi^{(\alpha)}\left(p_a\right) \psi^{(\alpha)*}\left(p_b\right)$$

And ordering λ from largest to smallest:

$$V_n^{(\alpha)} \equiv \sqrt{\lambda^{(\alpha)}} \psi^{(\alpha)}$$

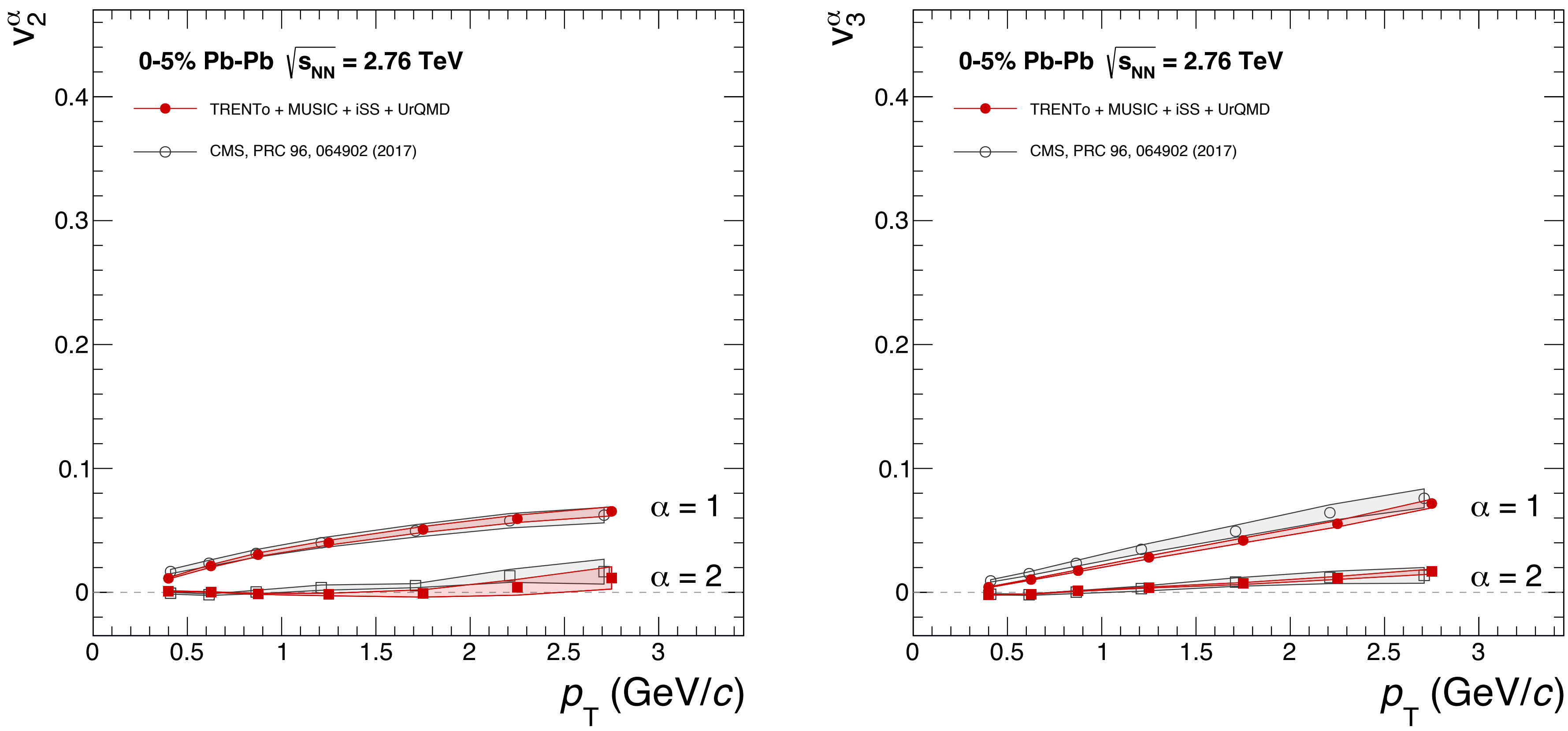
How is this related to the usual flow coefficients?

For compatibility with the usual flow picture:

$$v_n^{(\alpha)}(p) \equiv \frac{V_n^{(\alpha)}(p)}{V_0(p)}$$

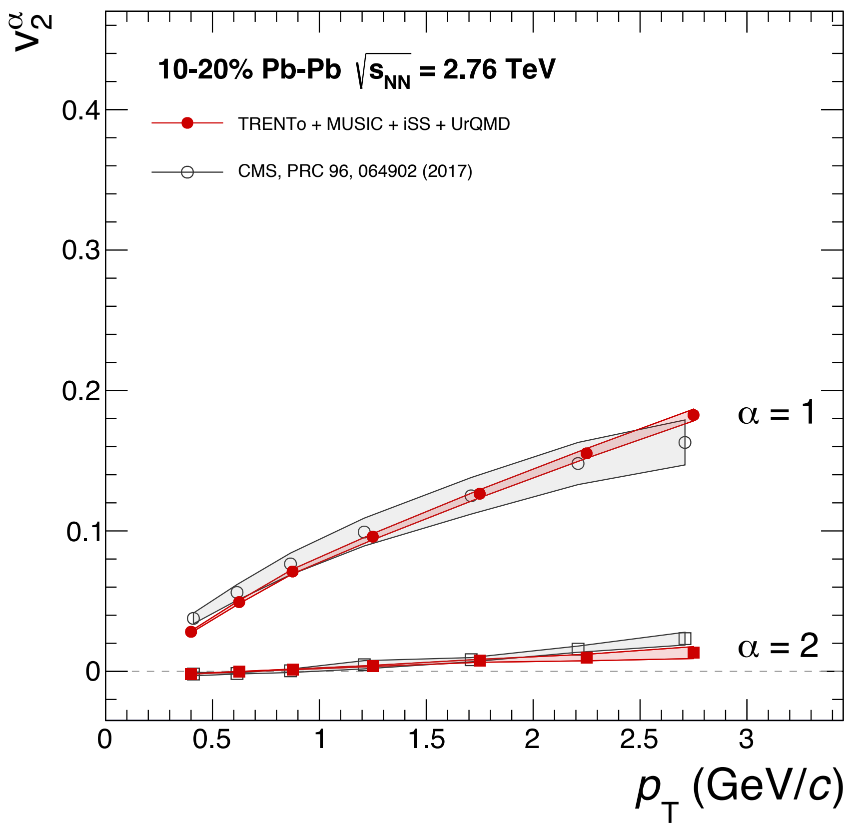
- This way, the $\alpha = 1$ term will be equivalent to v_n measured via the usual two-particle correlation techniques...
- …and the subleading ($\alpha = 2$) term quantifies factorization breaking in different momentum bins
- More information by exploiting the correlation matrix

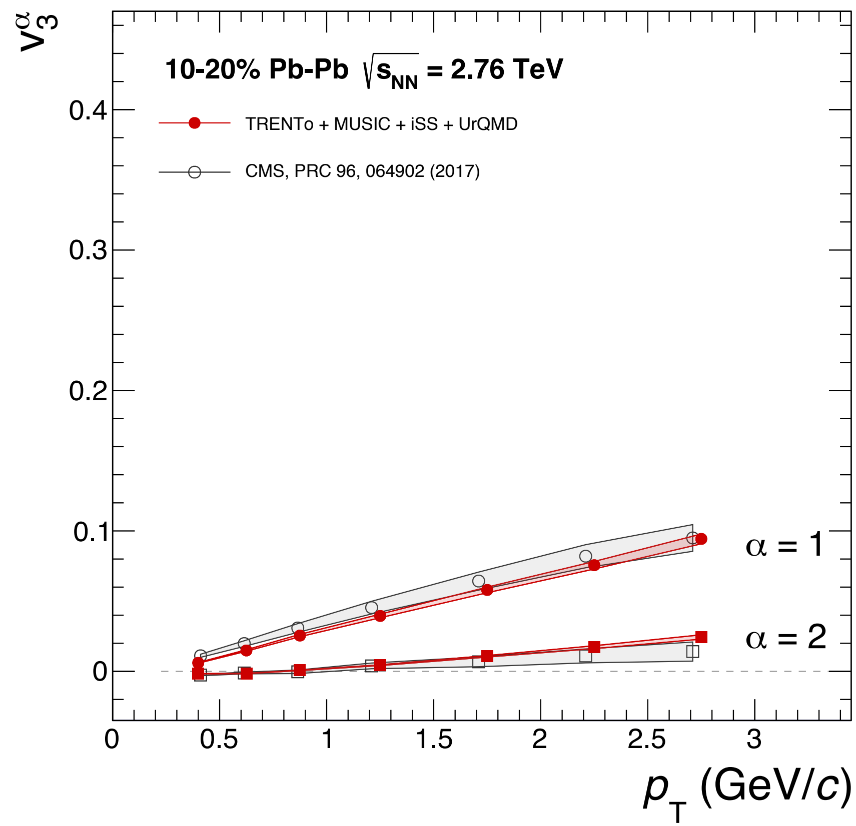
Pb-Pb 2.76 TeV: PCA as a function of p_T, 0-5%



- Model describes data within uncertainties for α = 1, 2

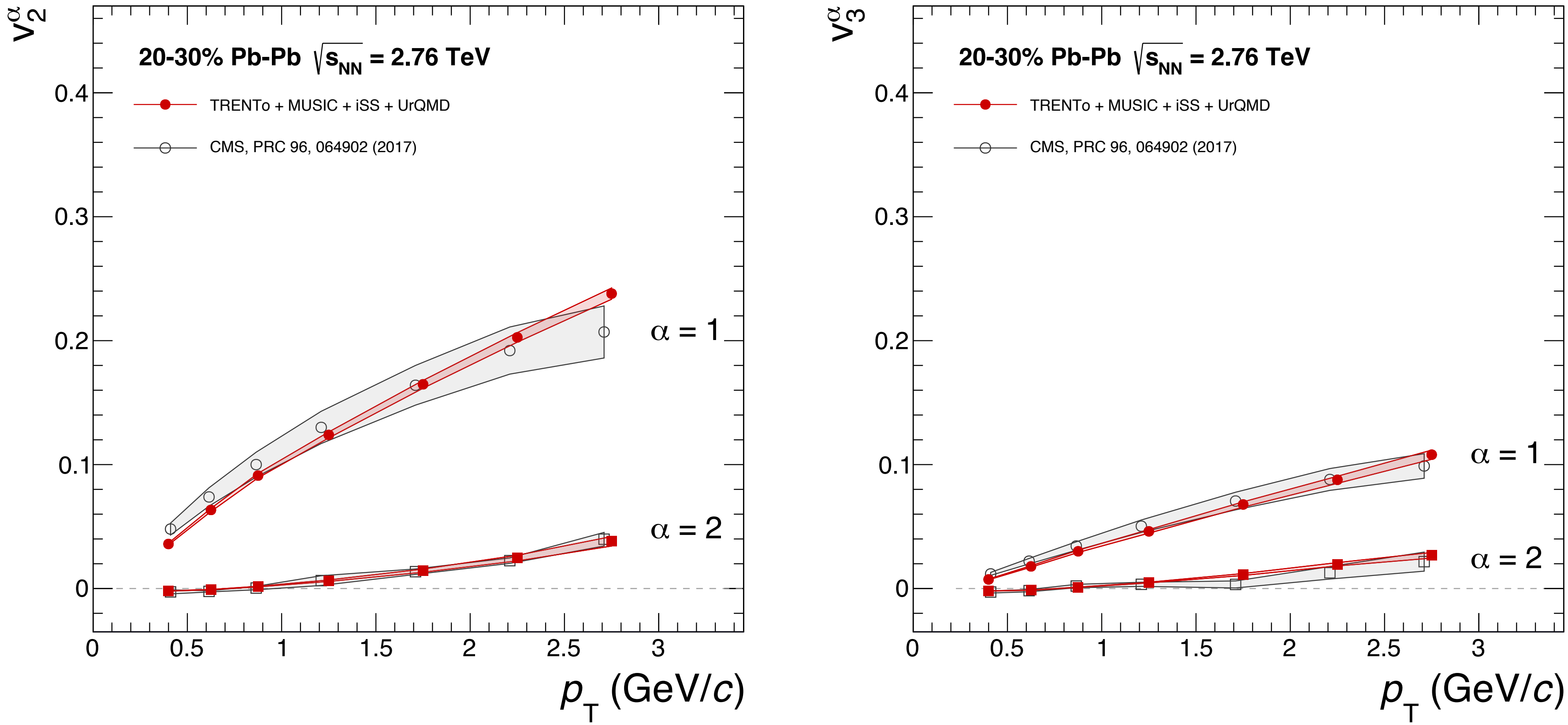
Pb-Pb 2.76 TeV: PCA as a function of p_T, 10-20%





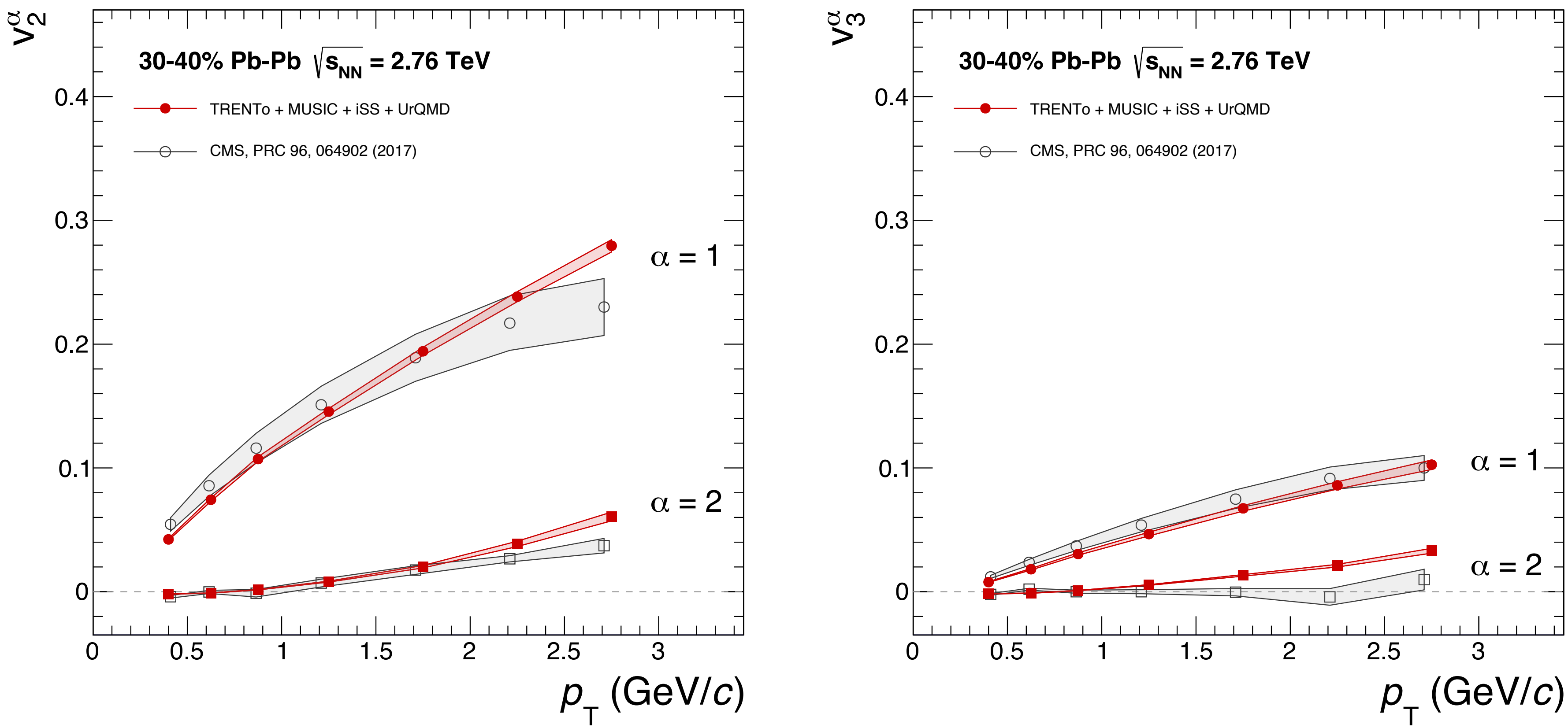
- Model describes data within uncertainties for α = 1, 2

Pb-Pb 2.76 TeV: PCA as a function of p_T, 20-30%



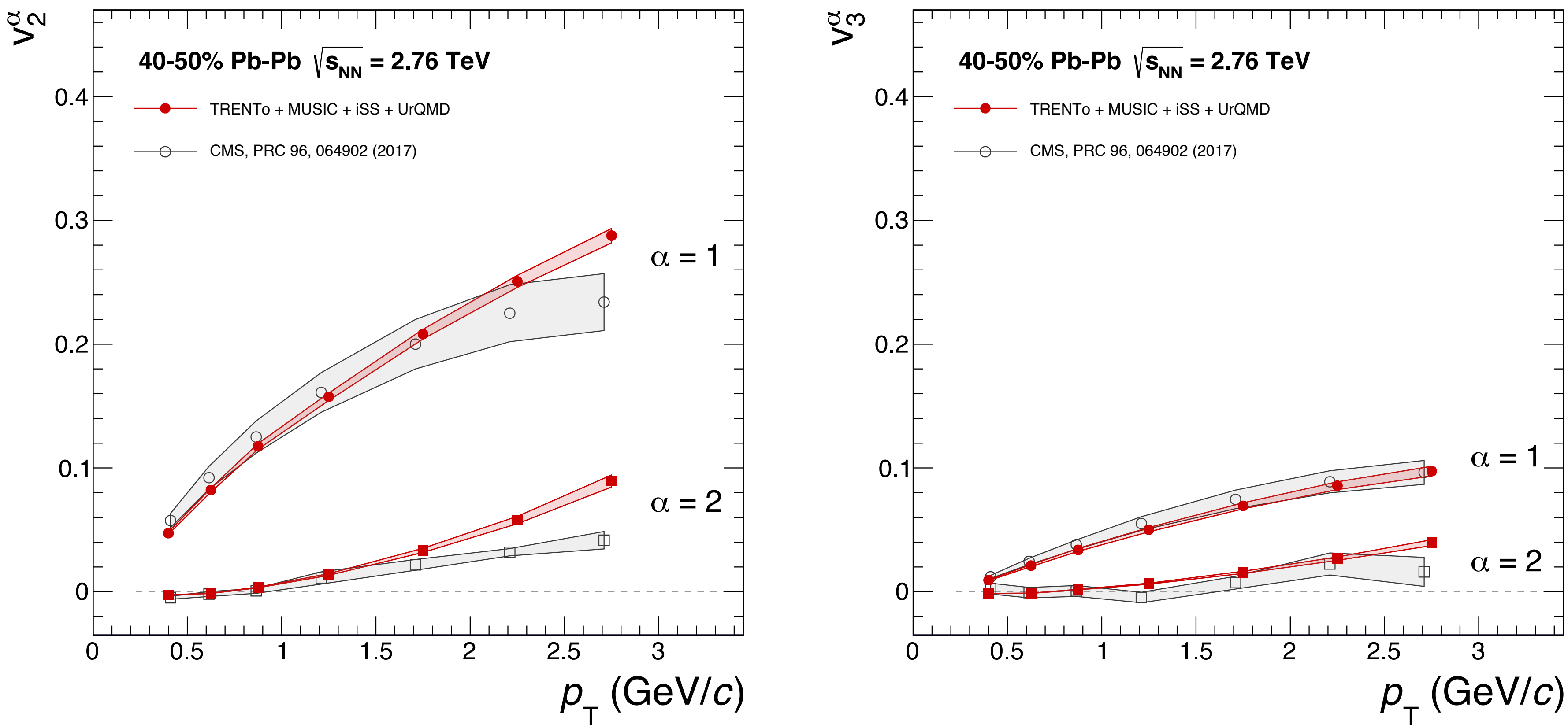
- Model describes data within uncertainties for α = 1, 2

Pb-Pb 2.76 TeV: PCA as a function of p_T, 30-40%



- Model describes data within uncertainties for α = 1, 2
- …but deviations appear for semi-central collisions at high p_T

Pb-Pb 2.76 TeV: PCA as a function of p_T, 40-50%



- Model describes data within uncertainties for α = 1, 2
- …but deviations appear for semi-central collisions at high p_T

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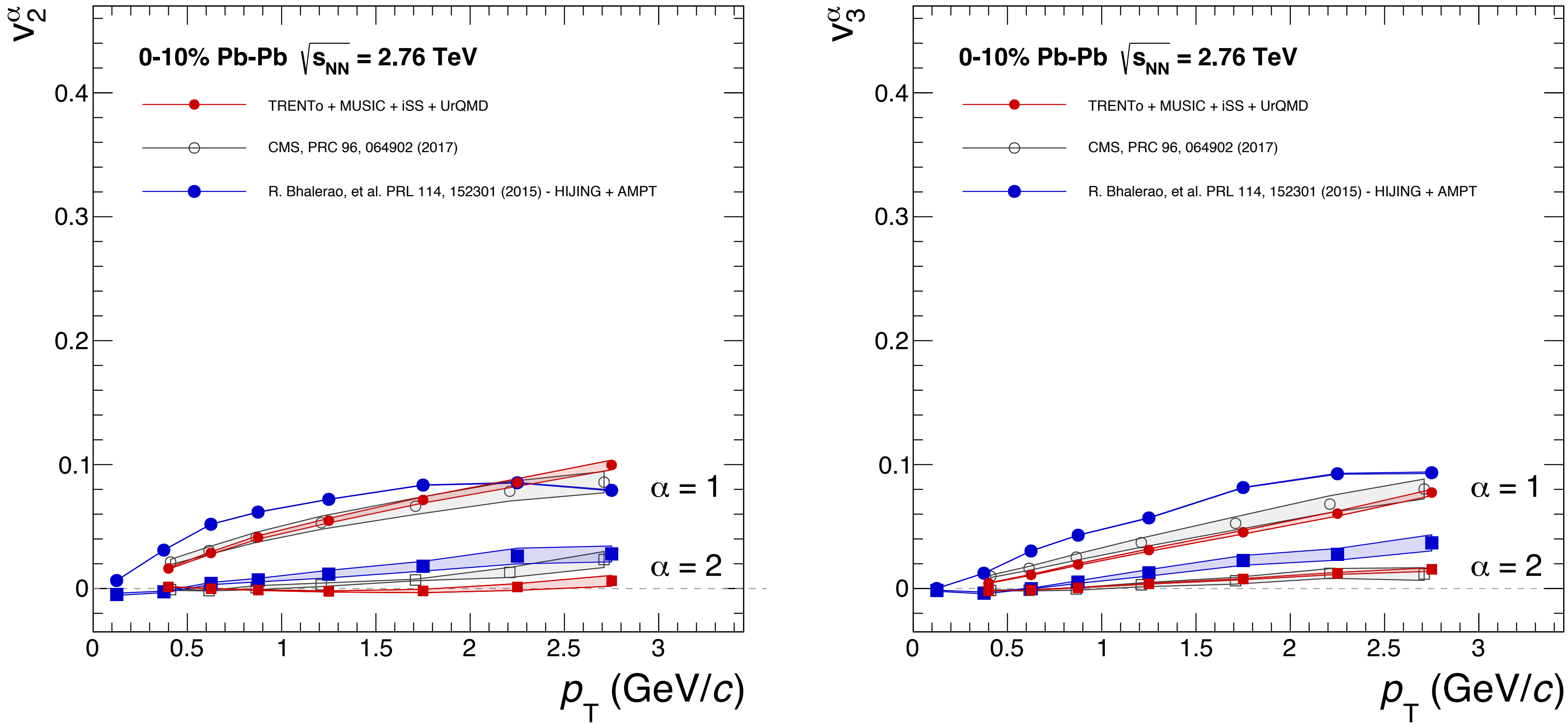
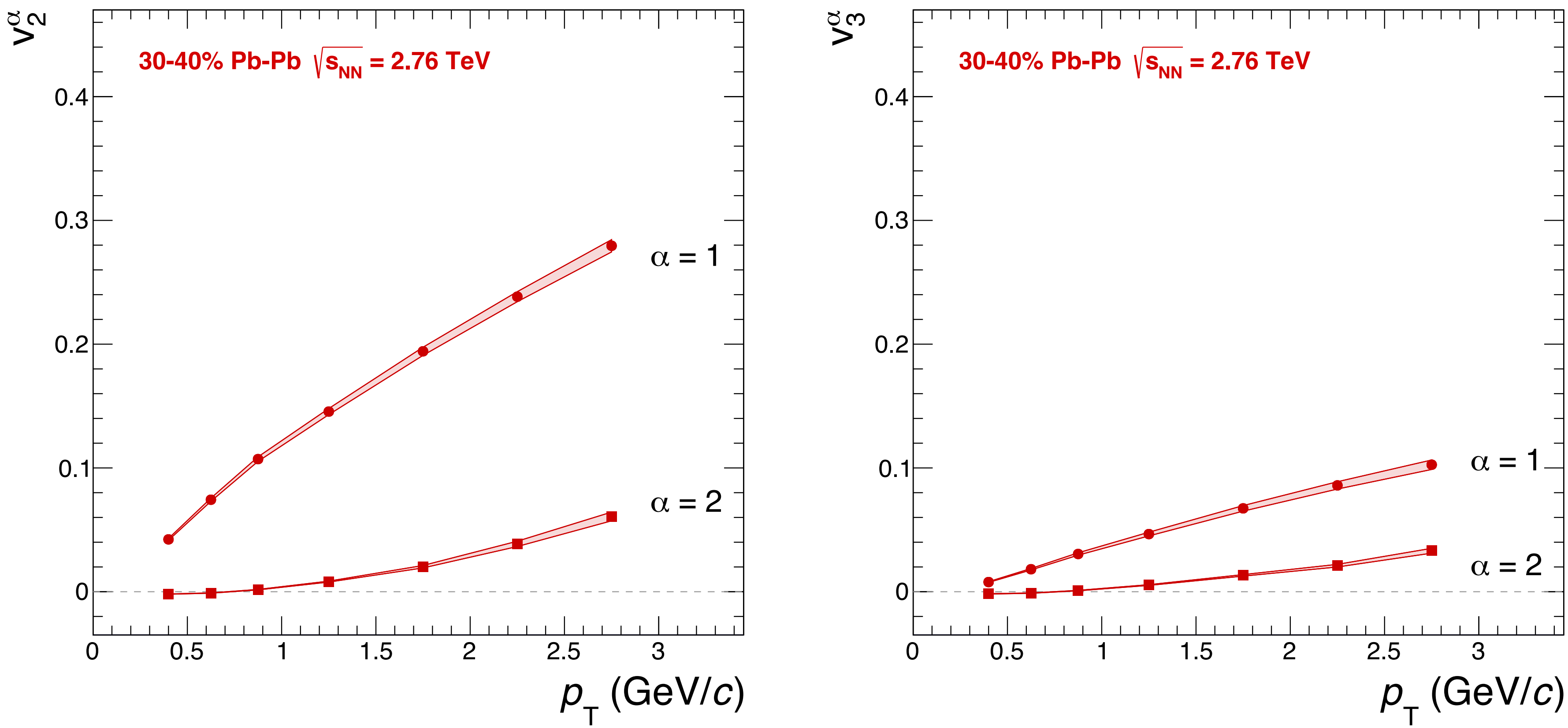
Comparison to Bhalerao et al: 0-10%



- HIJING+AMPT (Bhalerao et al, no hydrodynamics) fails to accurately predict the data

The energy dependence of PCA results



- Do results change significantly with energy?

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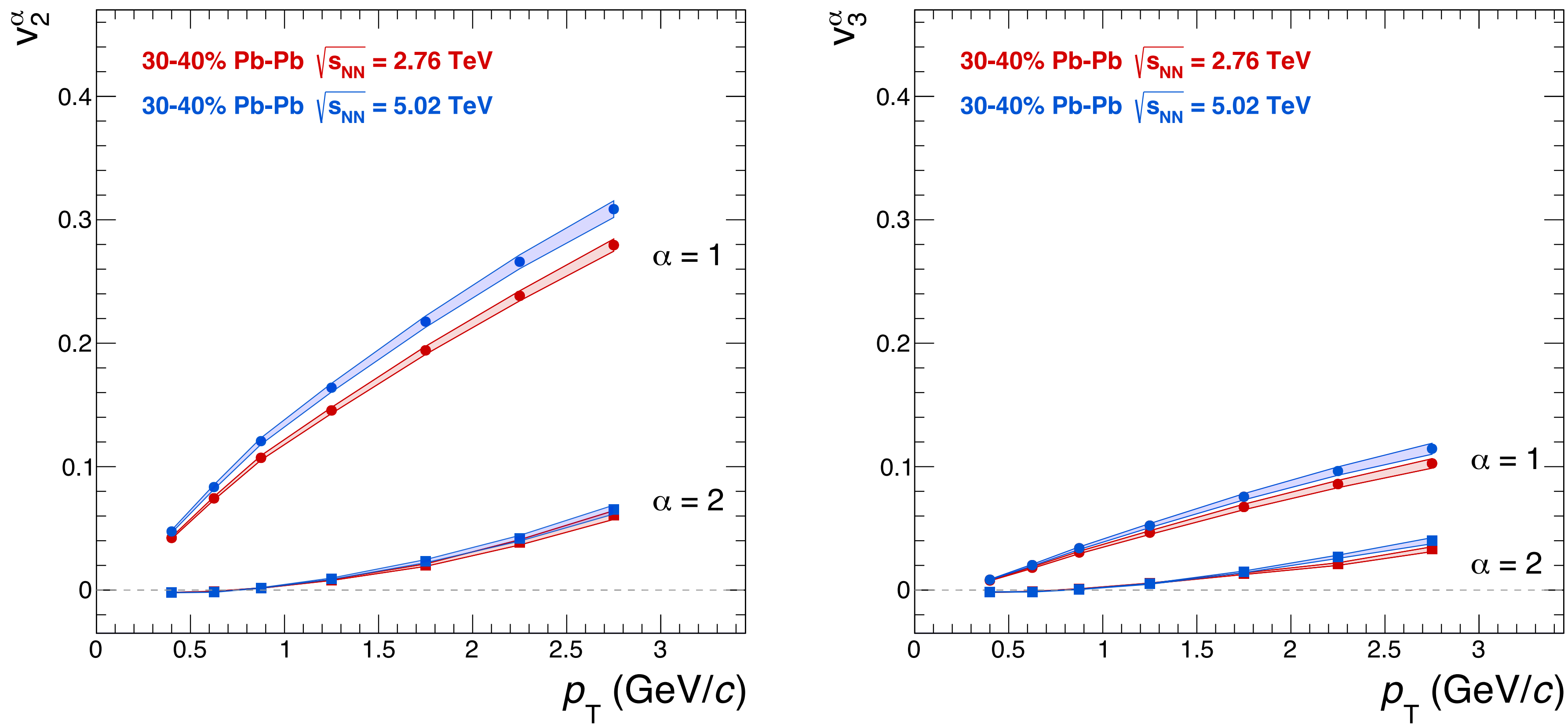
The energy dependence of PCA results



- Do results change significantly with energy?
- Weak energy dependence: $v_n^{(\alpha)}$ at most 10% larger

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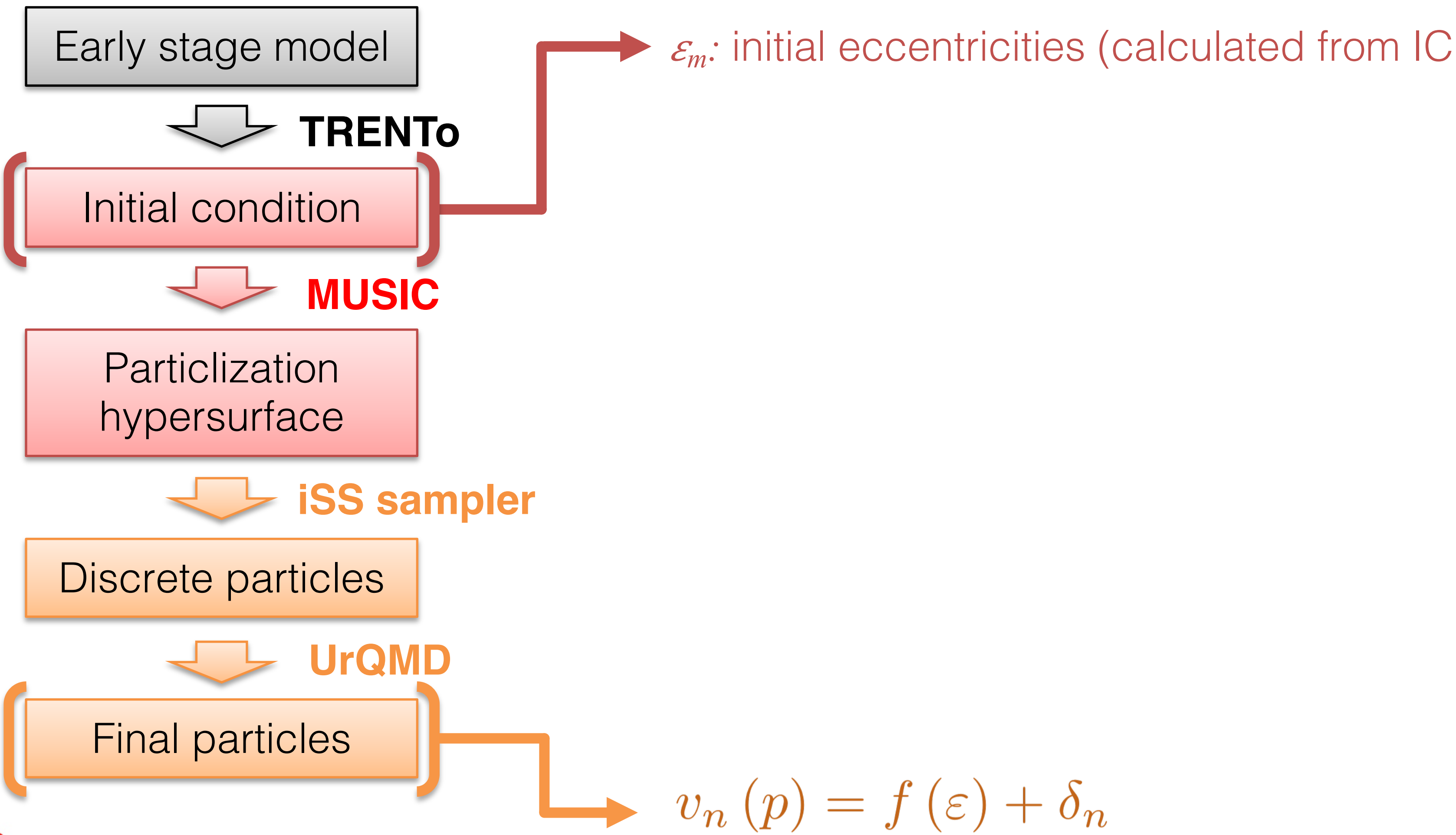
Work in progress:
Studying hydrodynamic response



Work in progress:
Studying hydrodynamic response

Early stage model

↓ **TRENTo**

Initial condition → ε_m: initial eccentricities (calculated from IC)

↓ **MUSIC**

Particlization hypersurface

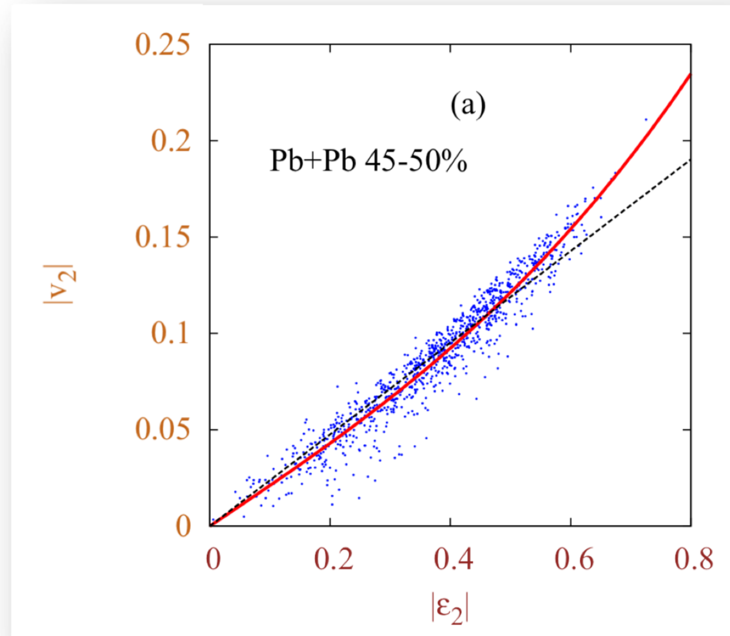
↓ **iSS sampler**

Discrete particles

↓ **UrQMD**

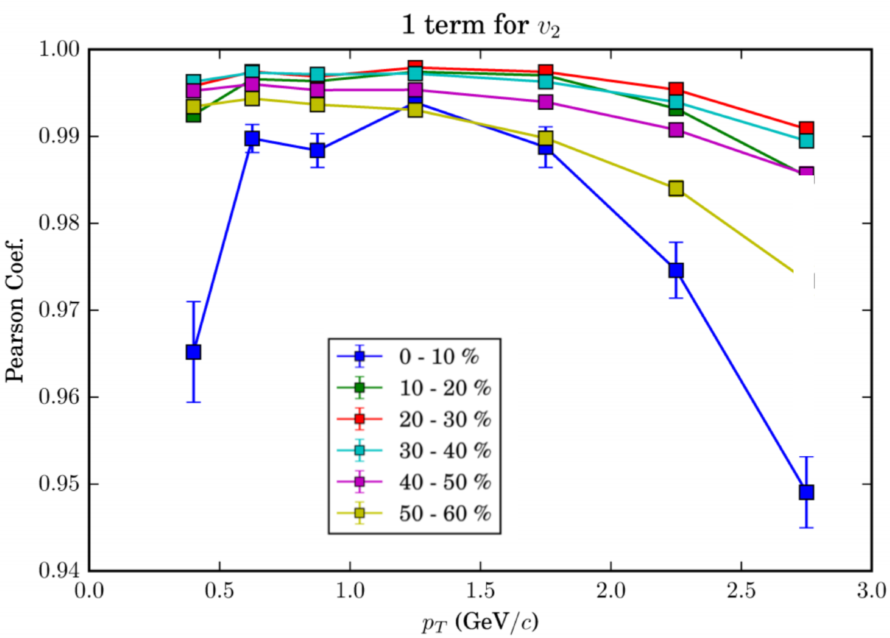
Final particles →

$$v_n(p) = f(\varepsilon) + \delta_n \approx \underbrace{k_2 \varepsilon_2}_{n=2}$$



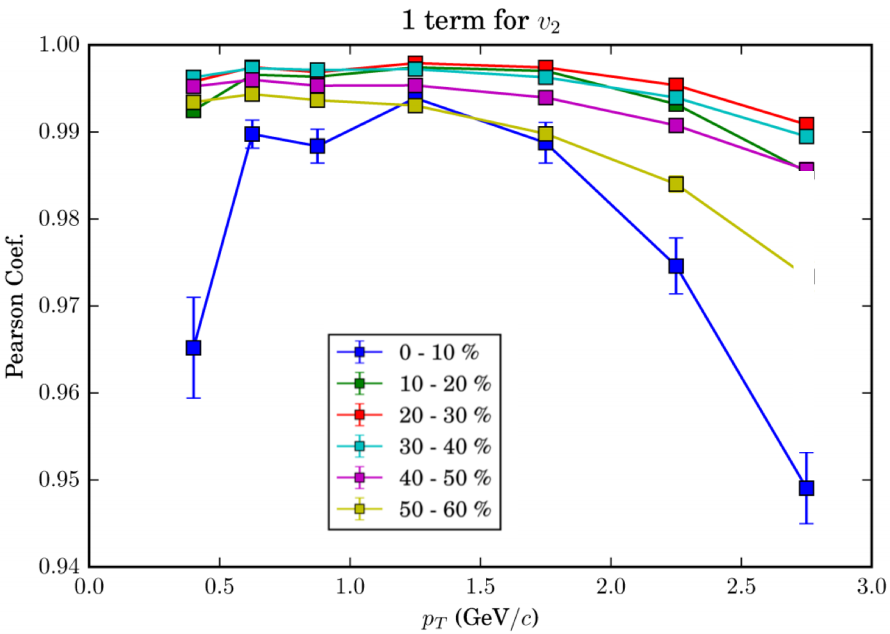
PRC **93**, 014909 (2016)

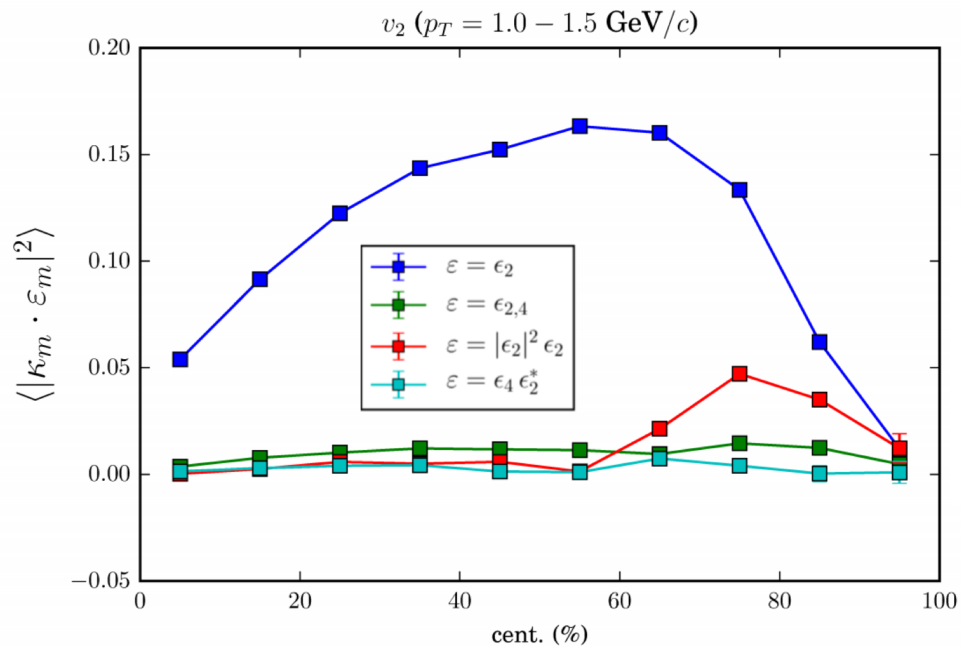
Work in progress:
Studying hydrodynamic response: a first look



- Very successful description: initial and final flow well correlated across large momentum range

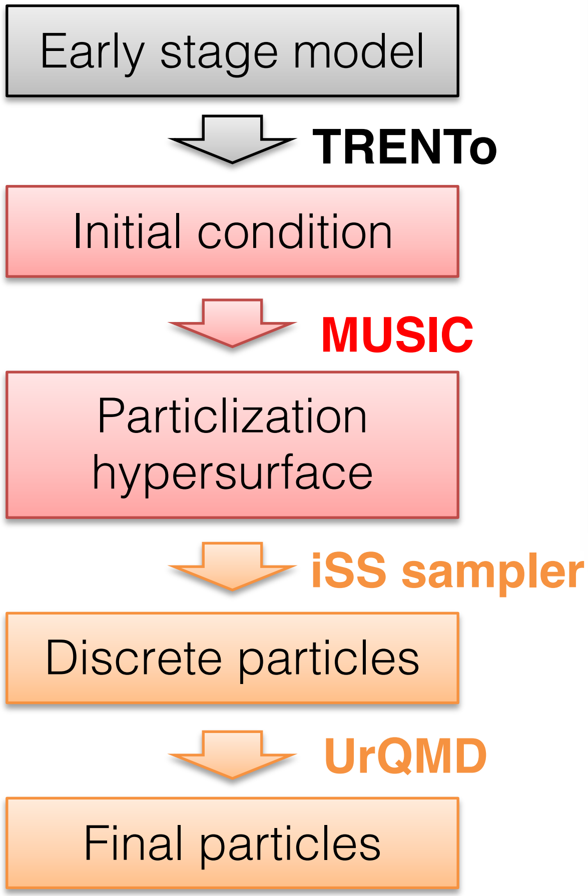
Work in progress: Studying hydrodynamic response: a first look

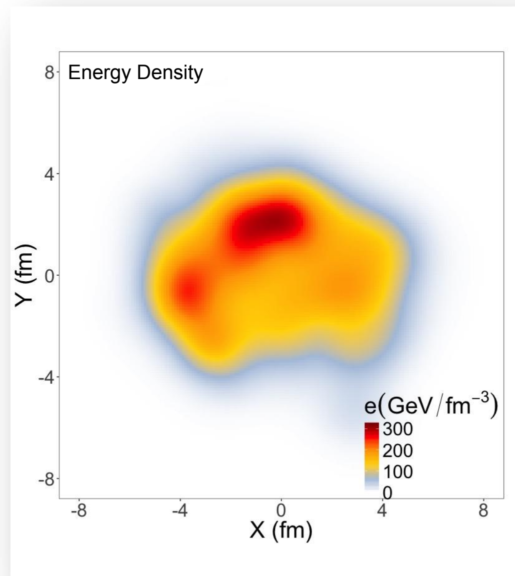




- Very successful description: initial and final flow well correlated across large momentum range
- Where do higher order corrections matter? Peripheral events
  - p_T-differential study pending

A more realistic IC: TRENTo + KoMPost





- Standard initial conditions: only energy terms of energy-momentum tensor populated → unrealistic

A more realistic IC: TRENTo + KoMPost

Early stage model

↓ **TRENTo + KoMPost**

Initial condition

↓ **MUSIC**

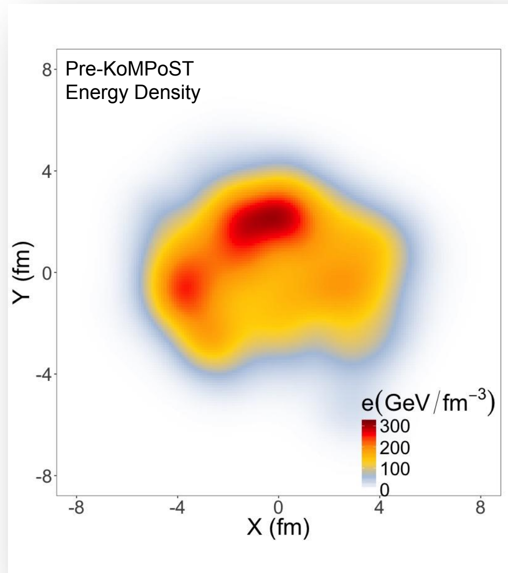
Particlization hypersurface

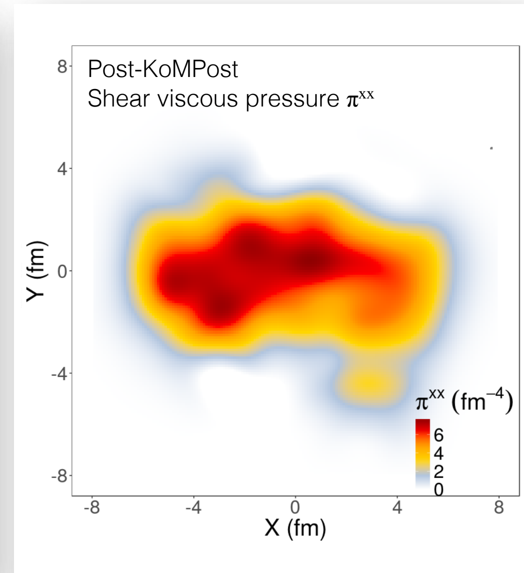
↓ **iSS sampler**

Discrete particles

↓ **UrQMD**

Final particles





- Standard initial conditions: only energy terms of energy-momentum tensor populated → unrealistic
- Pre-equilibrium dynamics can be simulated with kinetic theory: KoMPost [1]

[1] https://arxiv.org/abs/1805.00961

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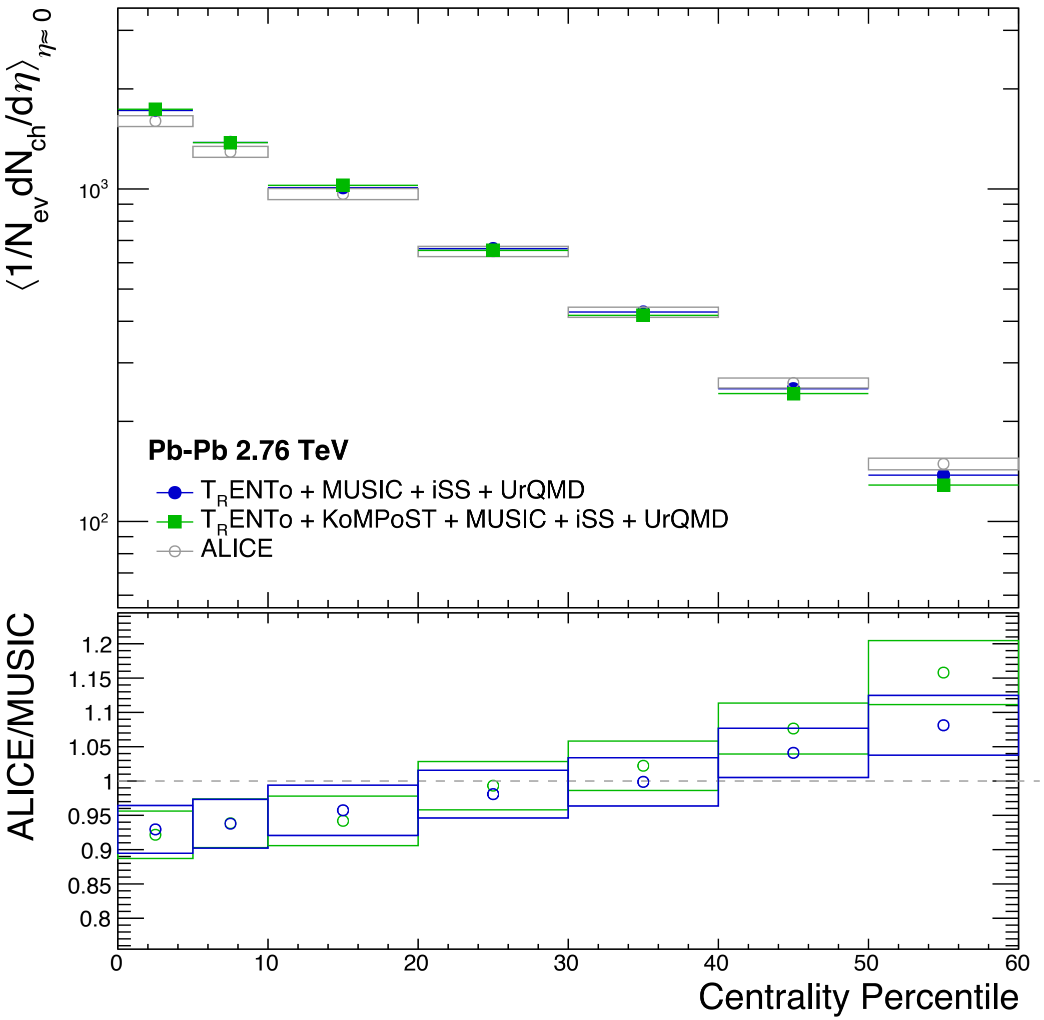
Work in progress:

The KoMPost pre-equilibrium model

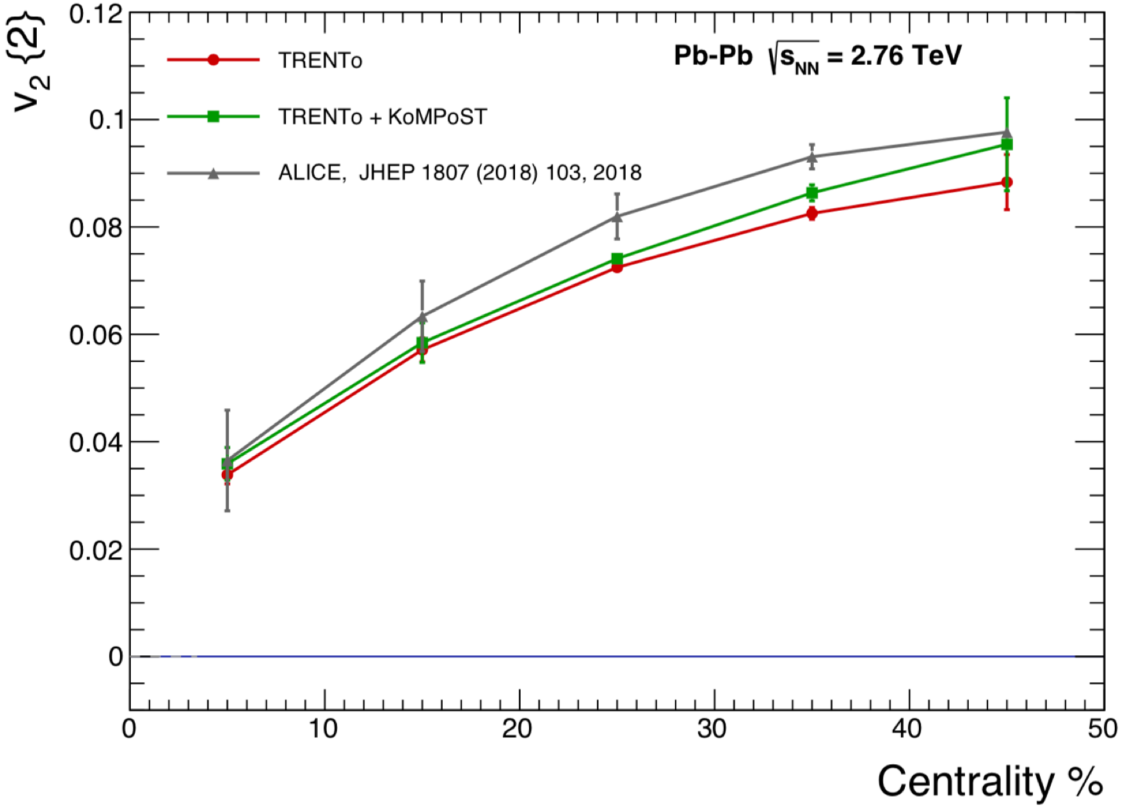


← No dramatic effect on multiplicities in central collisions

- Slight worsening in peripheral events?

Work in progress:

KoMPost: first results



- Slight increase in integrated flow with pre-equilibrium dynamics?
- Possibly due to energy-momentum tensor being populated by additional terms

Summary and outlook

- Our hybrid model describes CMS data for the PCA of flow well in central Pb-Pb events at 2.76 TeV
- We predict a small (~10%) increase in the PCA results for 5.02 TeV
- A lot of work being done:
  - Hydrodynamic response, effect of pre-equilibrium dynamics and rescattering (UrQMD), …
  - Extension to RHIC BES-II energies and to small systems

Thank you!

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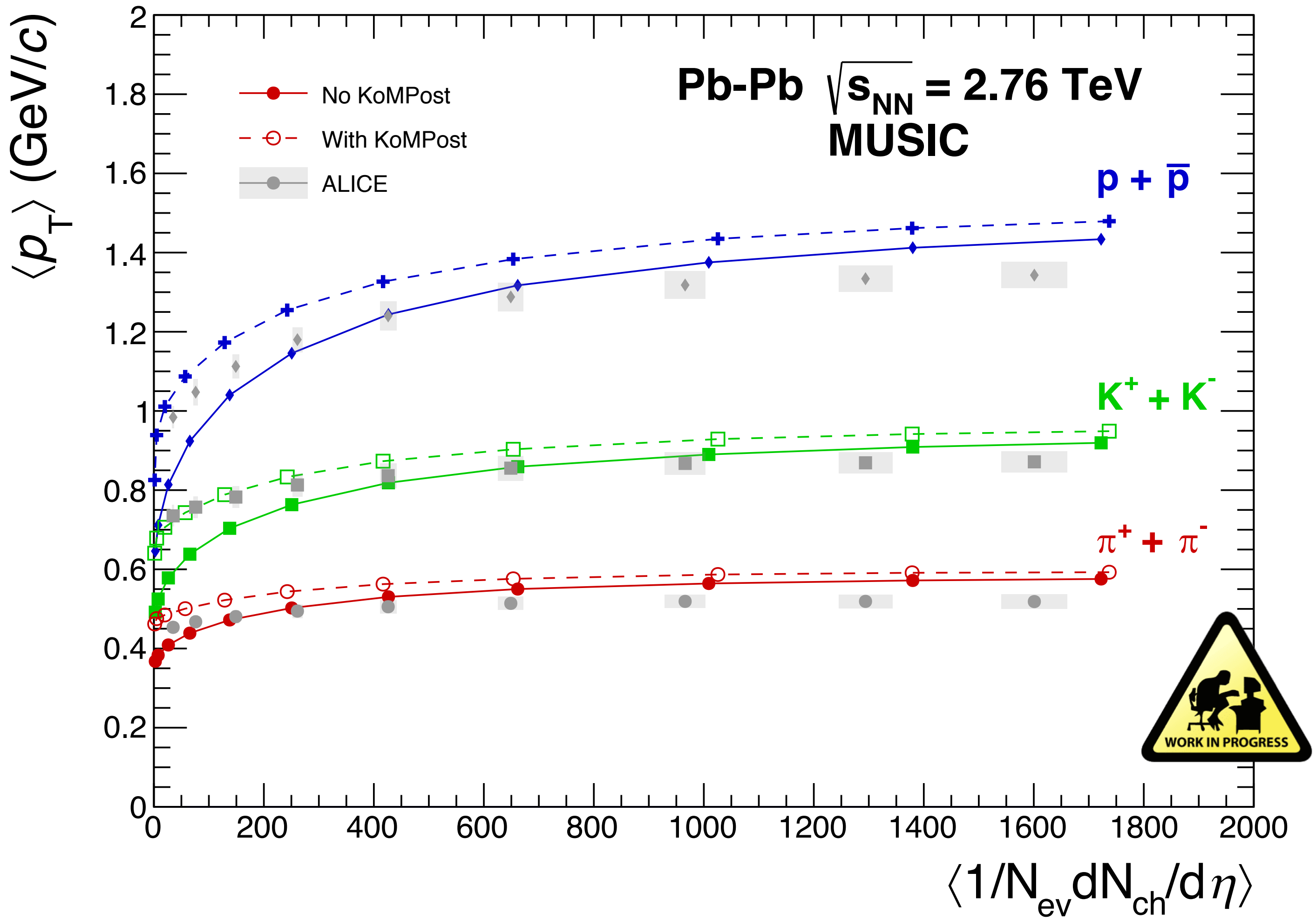
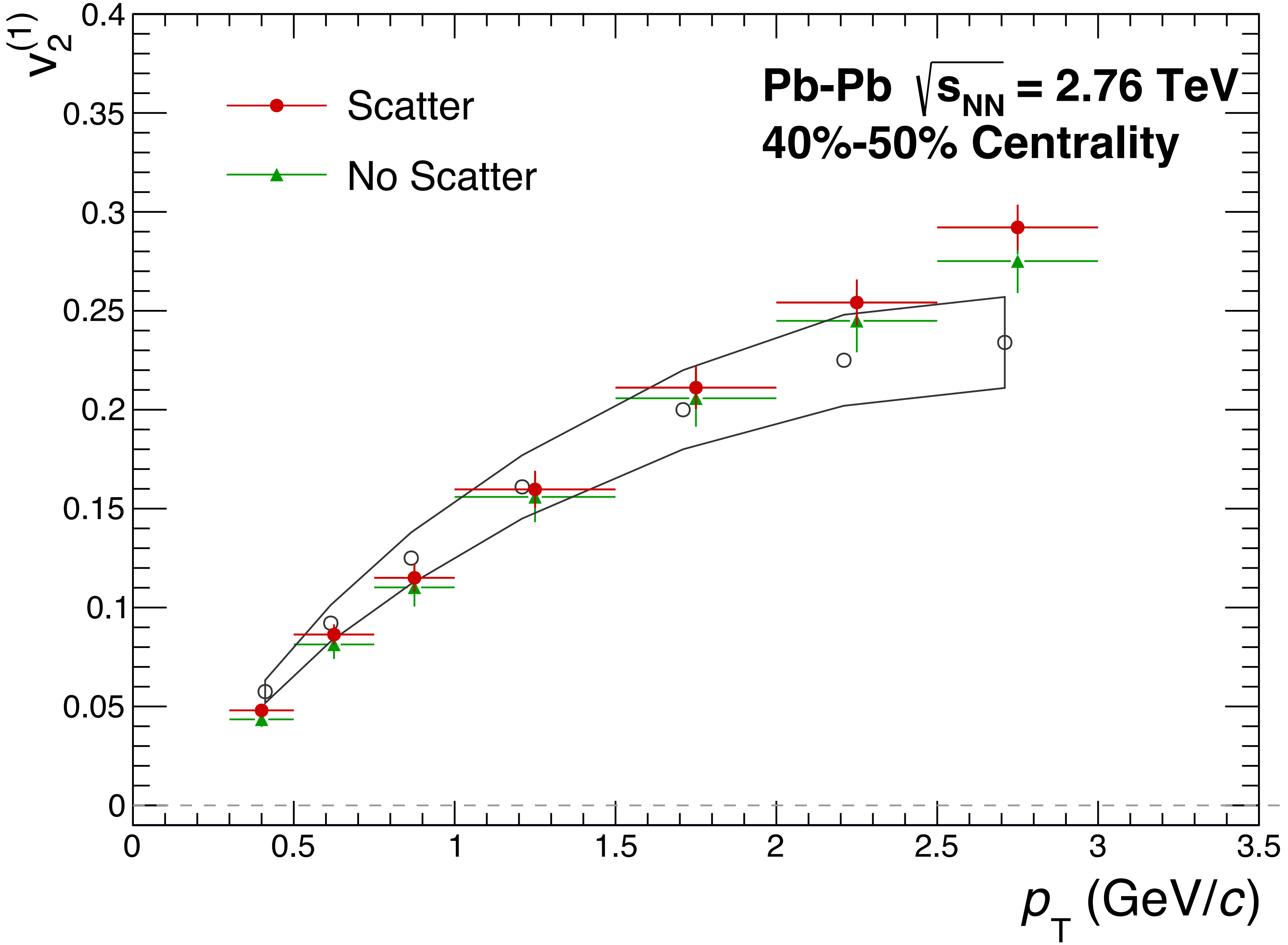
Backup

Average momentum



A very first look at…

Effects of rescattering



Parameters from Bayesian analysis

(from https://arxiv.org/abs/1704.07671)

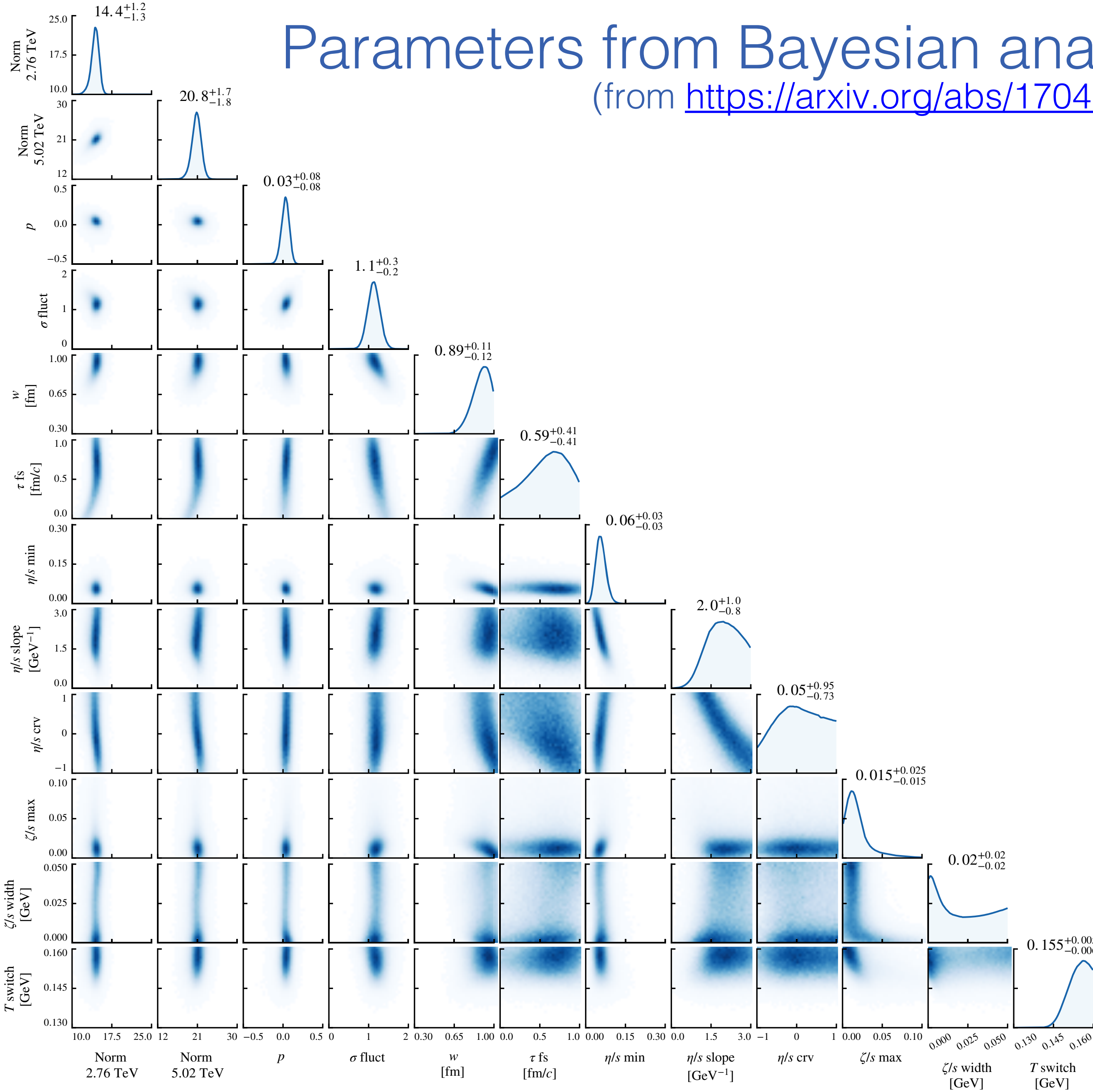
Initial condition parameters

Hydrodynamization time

Shear viscosity

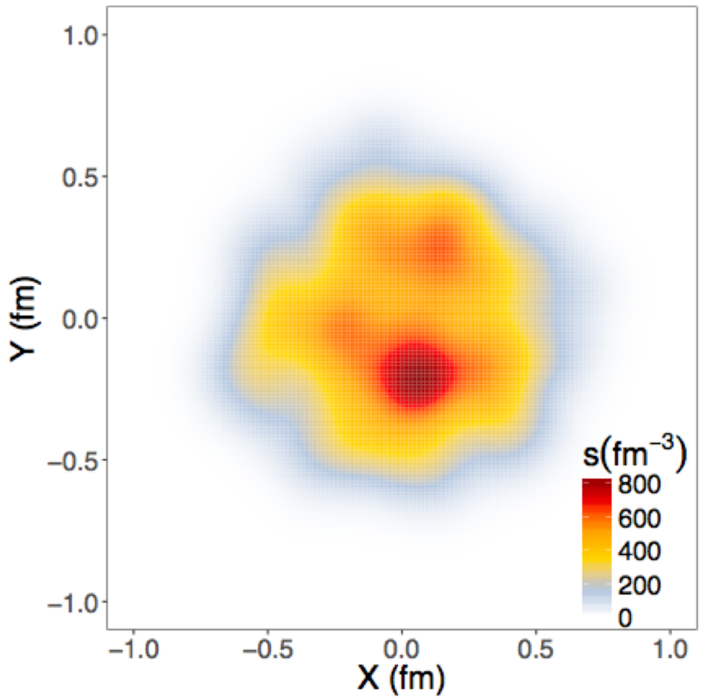
Bulk viscosity

Freezeout temp.



TRENTo

arXiv:1412.4708v2 [nucl-th]



- A parametric initial condition generator based on eikonal entropy deposition via a "reduced thickness" function

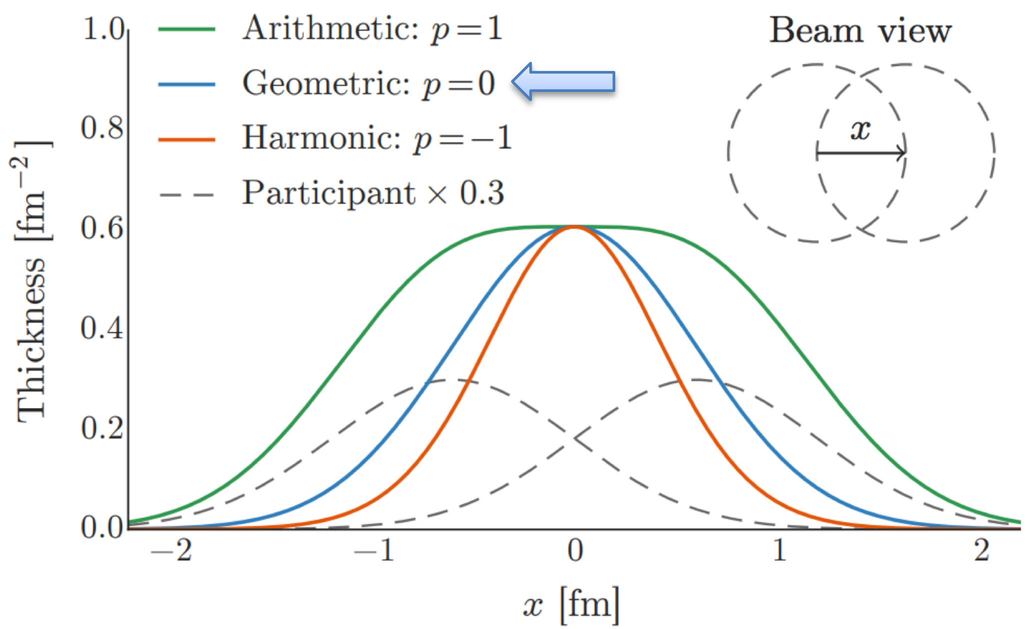
$$T_{A,B}(x,y) = \int dz \rho^{part}_{A,B}(x,y,z)$$

$$\frac{dS}{dy}\Big|_{\tau=\tau_0} \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$$

TRENTo

arXiv:1412.4708v2 [nucl-th]

$$T_R = \begin{cases} \max(T_A, T_B) & p \to +\infty, \\ (T_A + T_B)/2 & p = +1, \ \text{(arithmetic)} \\ \sqrt{T_A T_B} & p = 0, \quad \text{(geometric)} \\ 2\,T_A T_B/(T_A + T_B) & p = -1, \quad \text{(harmonic)} \\ \min(T_A, T_B) & p \to -\infty. \end{cases}$$



Hydrodynamics with MUSIC

- Eulerian 3D+1 relativistic second-order viscous hydrodynamics code for event by event (EBE) HIC simulations;
- Evolution is solved through the Kurganov-Tadmor method; (J.Comp.Phys 160, 214 - 2000)
- Code is written in C++ and supports parallelization;
- Code is publicly available (physics.mcgill.ca/music/)

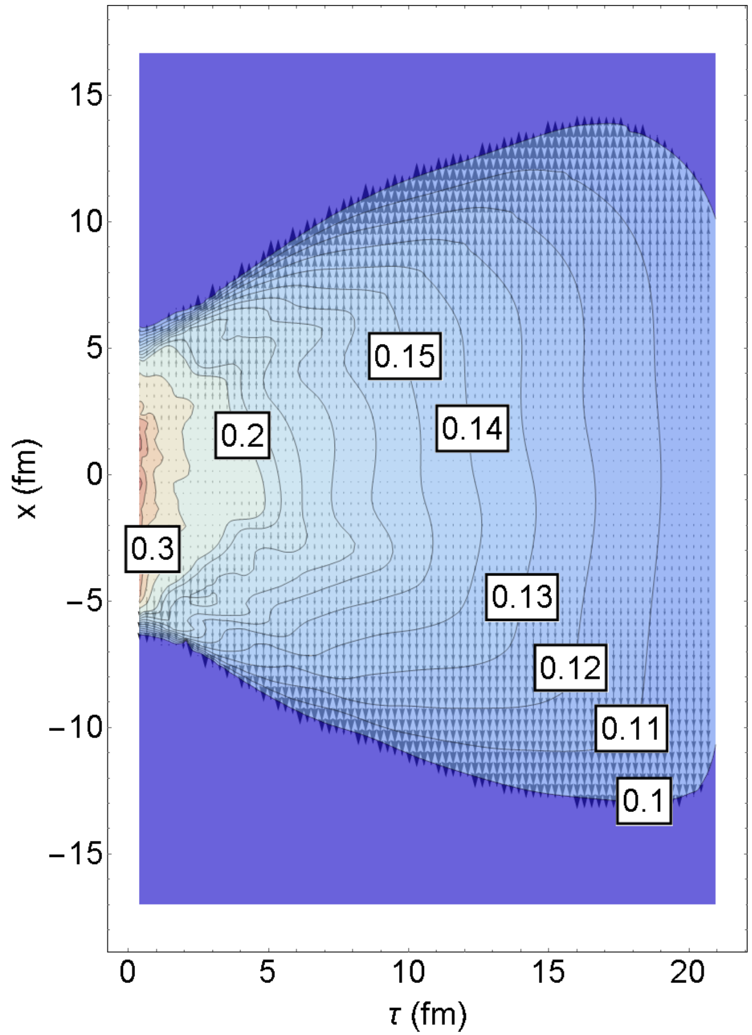
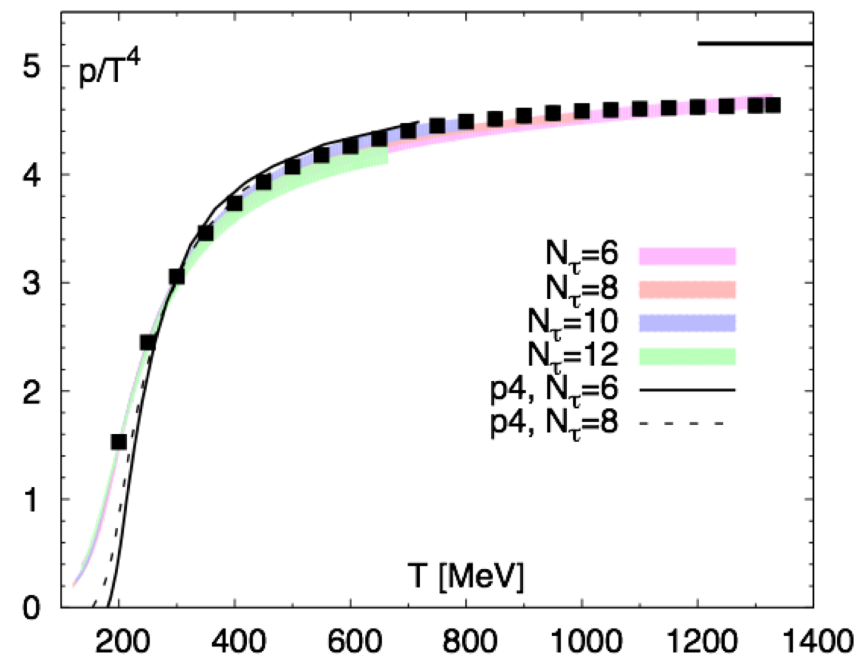


Figure: J-F. Paquet

The equation of state

- External input necessary to close the evolution system of equations;
- Calculated from first principles (e.g. Lattice QCD);
- Details of EOS can influence the extraction of transport coefficients.



A. Bazavov et al.,
Phys. Rev. D 95, 054504 (2017)

Simulation parameters
TRENTo

$$p = 0.007, \sigma_{fluc} = 0.918, w = 0.956, d_{min} = 1.27$$

$$n_{2.76} = 286.23, n_{5.02} = 343.48$$

$$x_{2.76} = 6.28, x_{5.02} = 7.0$$

p: Reduced Thickness
w: Nucleon Width
d: Nucleon minimum distance

σ_{fluc} : Standard deviation of nucleon mutiplicity fluctuations
n: normalization
x: Inelastic nucleon-nucleon cross-section

Simulation parameters
Hydro

$$T_{fo} = 151 MeV, \tau_0 = 0.2 fm$$

$$x_{max} = y_{max} = 14 fm, N_x = N_y = 280$$

Lattice EOS s95p-v1.2 w/ UrQMD species
(Huovinen and Petrescky, Nucl.Phys.A837:26-53,2010)

Simulation parameters
Hydro: viscosity

Shear viscosity

$$(\eta/s)(T) = (\eta/s)_{min} + (\eta/s)_{slope} \cdot (T - T_C) \cdot (T/T_c)^{(\eta/s)crv}$$

$$(\eta/s)_{min} = 0.081, (\eta/s)_{slope} = 1.11 GeV^{-1}$$

$$(\eta/s)_{crv} = -0.48, T_C = 154 MeV$$

Bulk viscosity

$$(\zeta/s)(T) = \frac{(\zeta/s)_{max}}{1 + \frac{T - (\zeta/s)_{T_0}}{(\zeta/s)_{width}}}$$

$$(\zeta/s)_{max} = 0.052, (\zeta/s)_{width} = 0.022 GeV. T_0 = 183 MeV$$

Ideal hydro

Energy density

Pressure

Flow velocity

$$T^{\mu\nu}_{ideal} = (\epsilon + \mathcal{P})u^{\mu}u^{\nu} - \mathcal{P}g^{\mu\nu}$$

$$\partial_{\mu}T^{\mu\nu} = 0 \quad + \quad \partial_{\mu}j^{\mu}_{i} = 0$$

Energy and momentum conservation

Other conserved quantities (B, S, Q)

Hydro with viscosity: Israel-Stewart

shear viscous Pressure (tensor)

bulk viscous Pressure (scalar)

$$T^{\mu\nu} = T^{\mu\nu}_{ideal} + \pi^{\mu\nu} - (g^{\mu\nu} - u^{\mu}u^{\nu})\Pi$$

$$\partial_{\mu} T^{\mu\nu} = 0 \qquad \partial_{\mu} j_i^{\mu} = 0$$

+ complicated equations of motion for $\pi^{\mu\nu}, \Pi$

Total of 14 non-linear coupled PDEs, with 13 transport coefficients:

$$\eta(T,\mu), \zeta(T,\mu), \tau_{\pi}(T,\mu), \delta_{\pi\pi}(T,\mu), \ldots$$

Hydro with viscosity: Israel-Stewart

$$T^{\mu\nu} = T^{\mu\nu}_{ideal} + \boxed{\pi^{\mu\nu}} - (g^{\mu\nu} - u^{\mu}u^{\nu})\boxed{\Pi}$$

$$\partial_{\mu}T^{\mu\nu} = 0 \qquad \partial_{\mu}j^{\mu}_{i} = 0$$

$$\tau_{\pi}\dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = \boxed{2\eta}\sigma^{\mu\nu} + 2\tau_{\pi}\pi^{\langle\mu}_{\alpha}\omega^{\nu\rangle\alpha} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_{7}\pi^{\langle\mu}_{\alpha}\pi^{\nu\rangle\alpha}$$
$$- \tau_{\pi\pi}\pi^{\langle\mu}_{\alpha}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} + \varphi_{6}\Pi\pi^{\mu\nu}$$

Shear PDE

$$\tau_{\Pi}\dot{\Pi} + \Pi = \boxed{-\zeta\theta} - \delta_{\Pi\Pi}\Pi\theta + \varphi_{1}\Pi^{2} + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} + \varphi_{3}\pi^{\mu\nu}\pi_{\mu\nu}$$

Bulk PDE

A heavy ion collision