Physics Opportunities at an Electron-Ion Collider 2023

EXTREME Collaboration: a full hybrid model to simulate High Energy Heavy Ion Nuclear Collisions

Jun Takahashi for the EXTREME Collaboration

UNICAMP

The Extreme Collaboration

The The **EX**periment and **T**heo**R**y in **E**xtreme **M**att**E**r collaboration is a group of researchers focused on phenomenology of High Energy Heavy Ion Collisions, with special interest in connecting theory with experiments.

FAPESP
SÃO PAULO RESEARCH FOUNDATION

Projeto temático 2017/05685-2

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UNICAMP: J. T.; D.D. Chinellato; G. Torrieri, A.V. Giannini; M. N. Ferreira

USP: M. Luzum

UFF: G.S. Denicol

UFSC: T. Nunes da Silva

UIUC: J. Noronha; M. Hippert

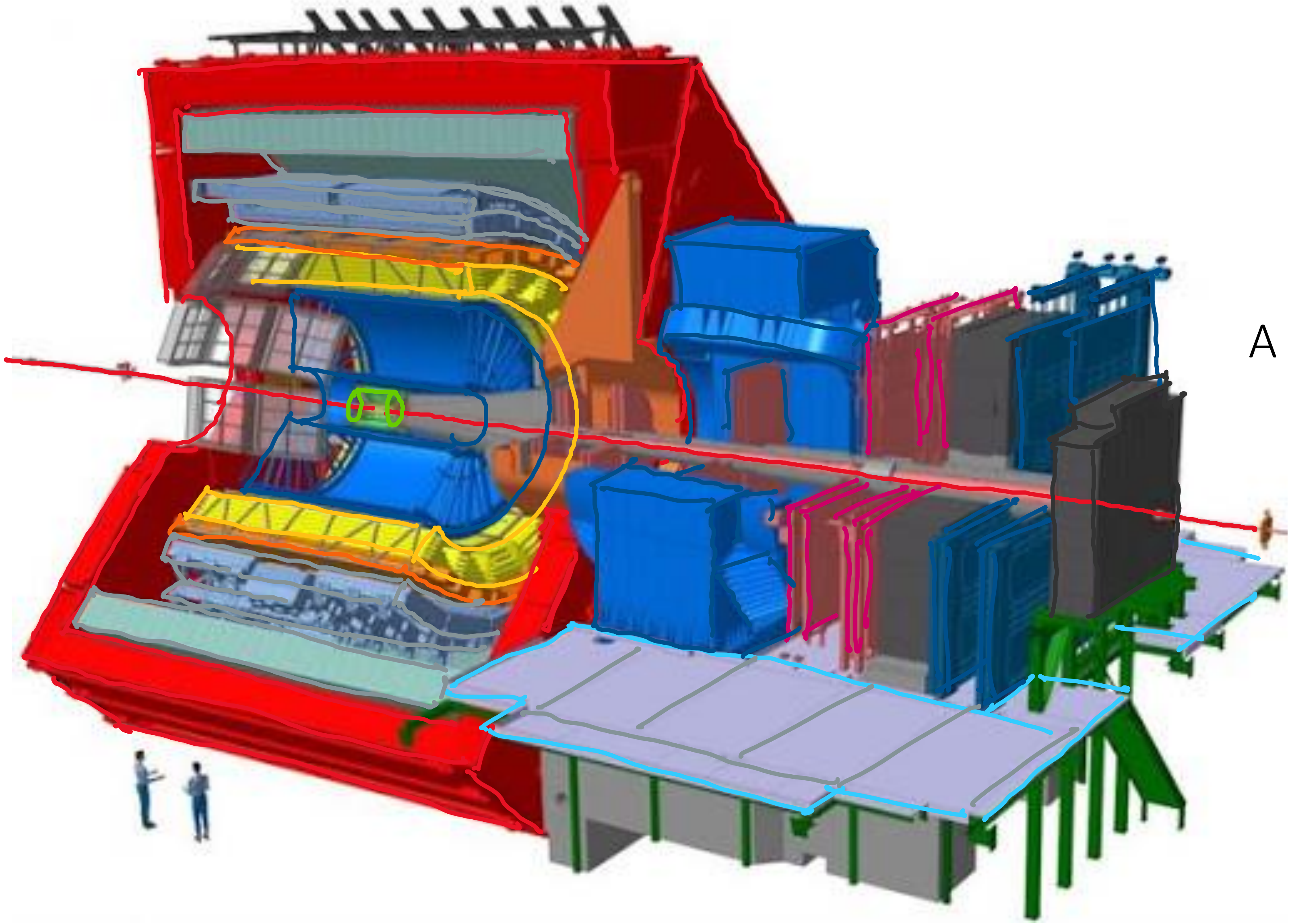
3C Collaboration

UNICAMP: J. T.; D.D. Chinellato; G. Torrieri, J.G.P. Barbon; W. M. Serenone; V. H. Ribeiro

OSU: M. Lisa

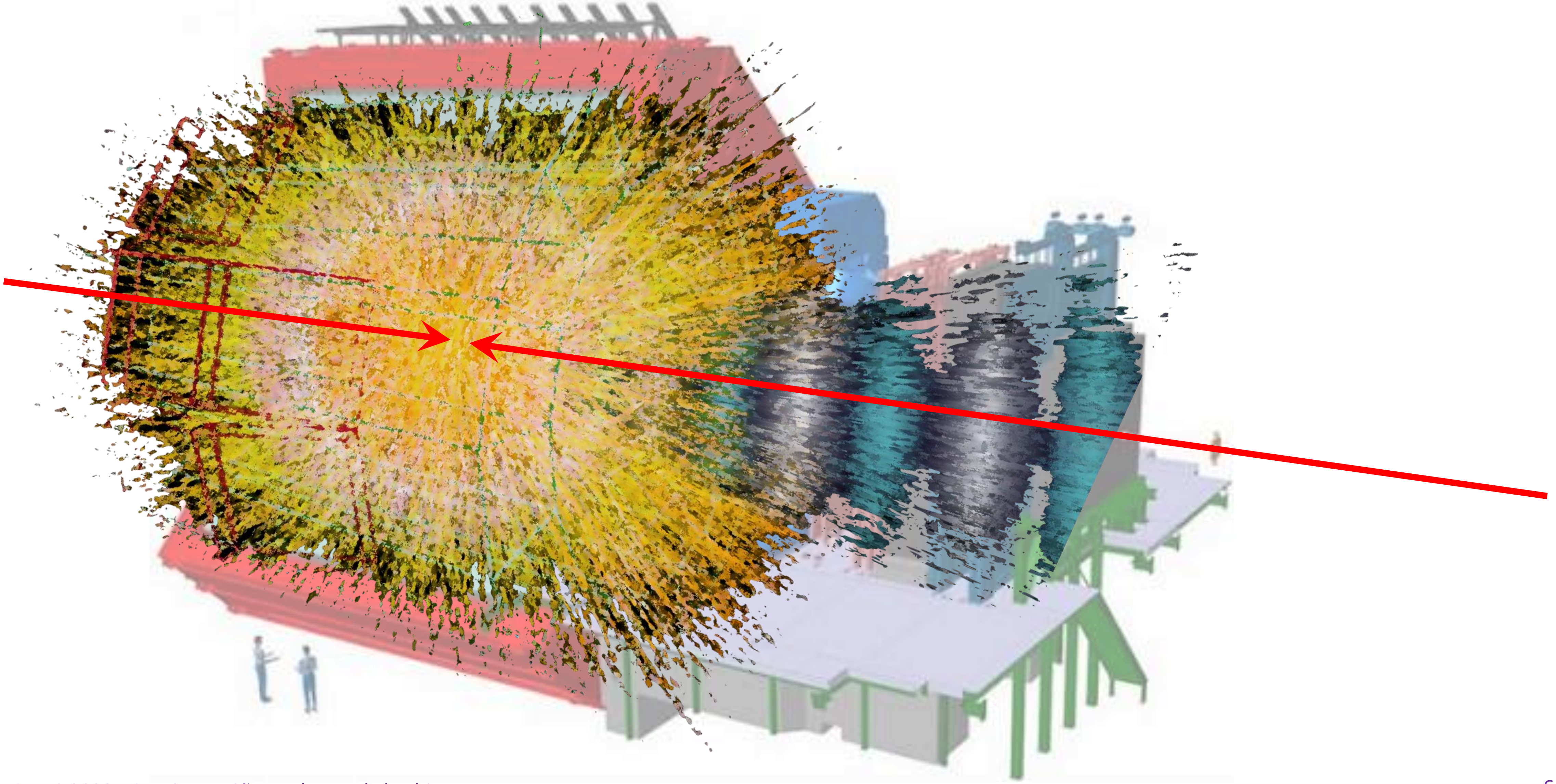
WSU: C. Shen

The Experiment

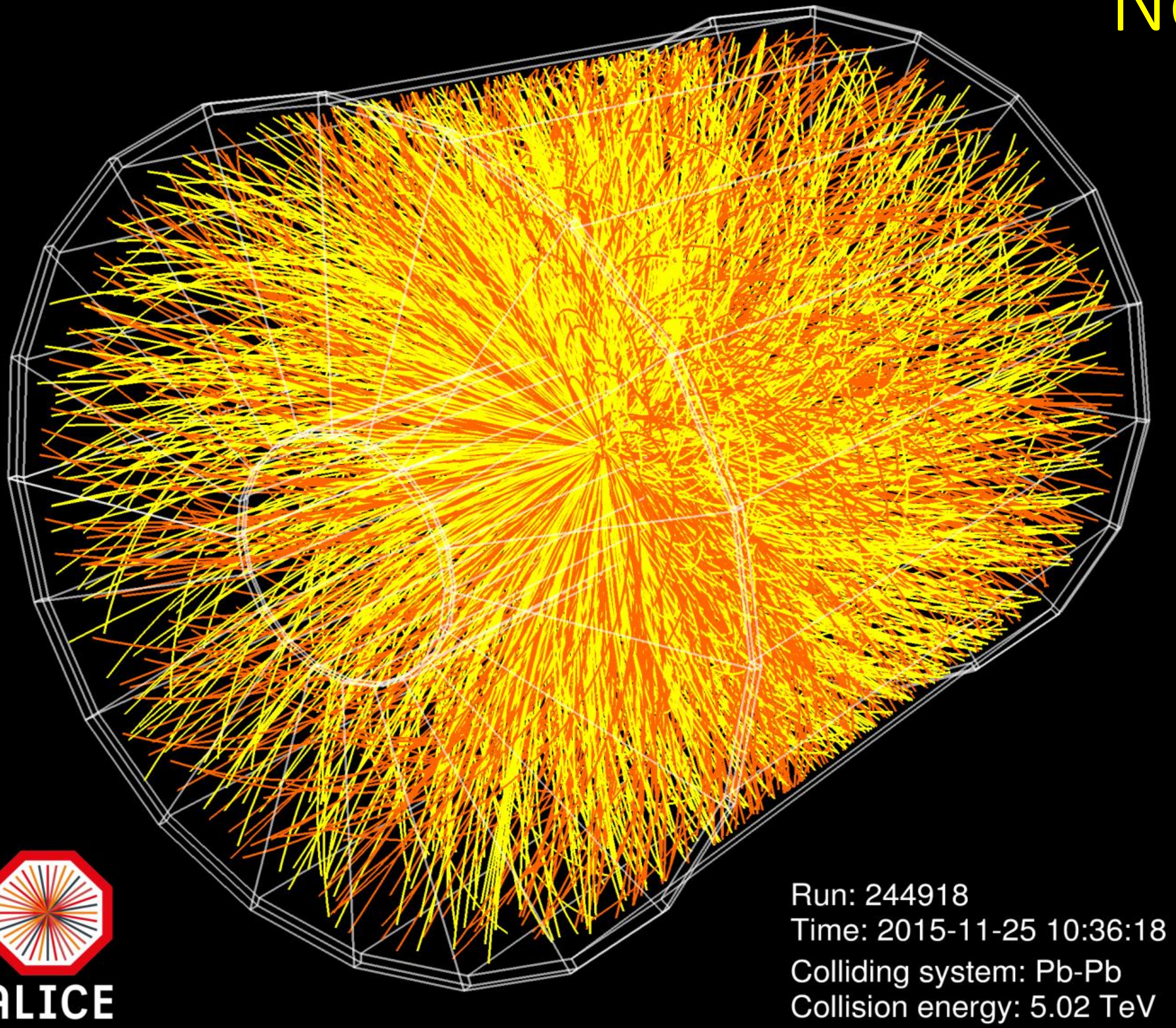


A Large Ion Collider Experiment

The Data



Need to connect theory to data



ALICE

Evolution of a Heavy Ion Collision

Early Stage

Hydrodynamic evolution

Particlization

Hadron Gas

Hybrid model simulation

Early Stage	EbE initial condition generator.
Pre-equilibrium	Pre-equilibrium dynamics (free-streaming or EKT)
Hydrodynamic evolution	3+1 hydrodynamic evolution, $\partial_\mu T^{\mu\nu} = 0$ + transport coeffic. + EOS
Particlization	Thermal production of hadrons from freezeout hypersurface + out of equilibrium corrections
Hadron Gas	Hadronic cascade simulator, scattering and decays.
Experimental observables	EbE final particles, just like in the experiments.

Hybrid model simulation

Early Stage

Pre-equilibrium

Hydrodynamic evolution

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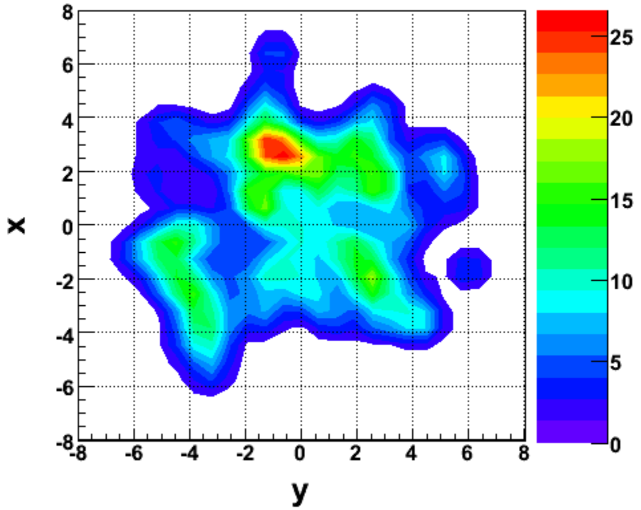
Hadron Gas

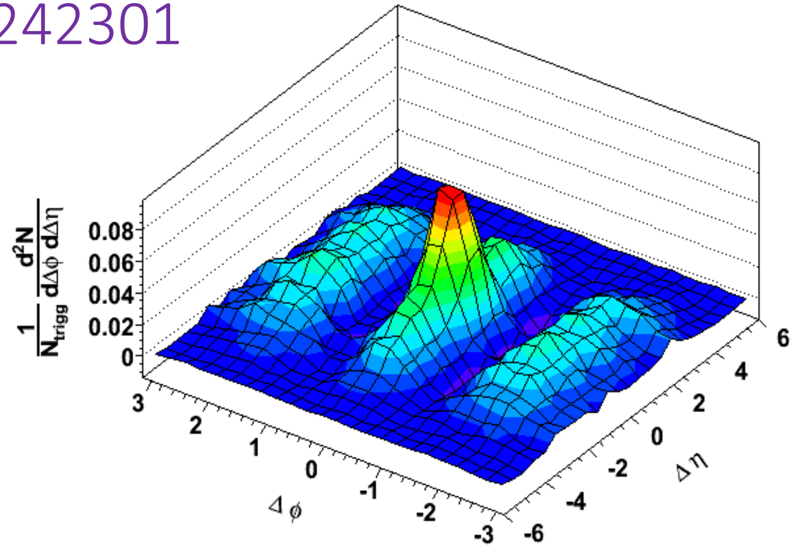
Experimental observables

Do we really need all this to understand data?

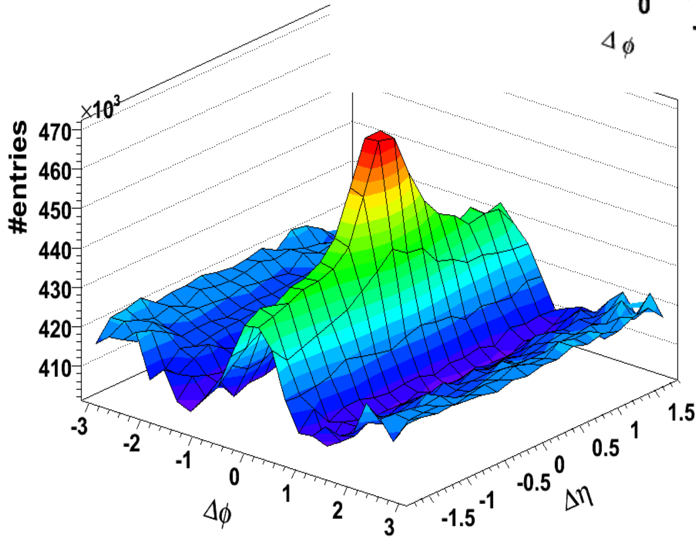
NexSPheRIO collab. PRL 103 (2009) 242301



Fluctuating EbE initial condition



NexSPheRIO



STAR @ RHIC

Hybrid model simulation

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Do we really need all this to understand data?

Since RHIC:

- Large amount of data
- Different collision systems and energies
- New experimental observables
- Higher order observables (v_n)
- Better precision in measurements
- Extreme events: ultracentral collisions, small systems, high multiplicity pp ….

Hybrid model simulation

Early Stage	EbE initial condition generator.
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Hybrid model simulation

Early Stage	TRENTo [1] or IP-Glasma
Pre-equilibrium	Kompost [2]
Hydrodynamic evolution	MUSIC [3]
Particlization	iSS sampler [4]
Hadron Gas	UrQMD [5]
Experimental observables	HadrEx format in ROOT [6]

The entire chain must be connected in a consistent way and requires state of the art computational resources.

[1] http://qcd.phy.duke.edu/trento/
[2] A. Kurkela, et al. PRL 122(12):122302, 2019.
[3] http://www.physics.mcgill.ca/music/
[4] https://github.com/chunshen1987/iSS
[5] https://urqmd.org/
[6] https://sites.ifi.unicamp.br/hadrex/

Configuring the simulation chain

Early Stage

Pre-equilibrium

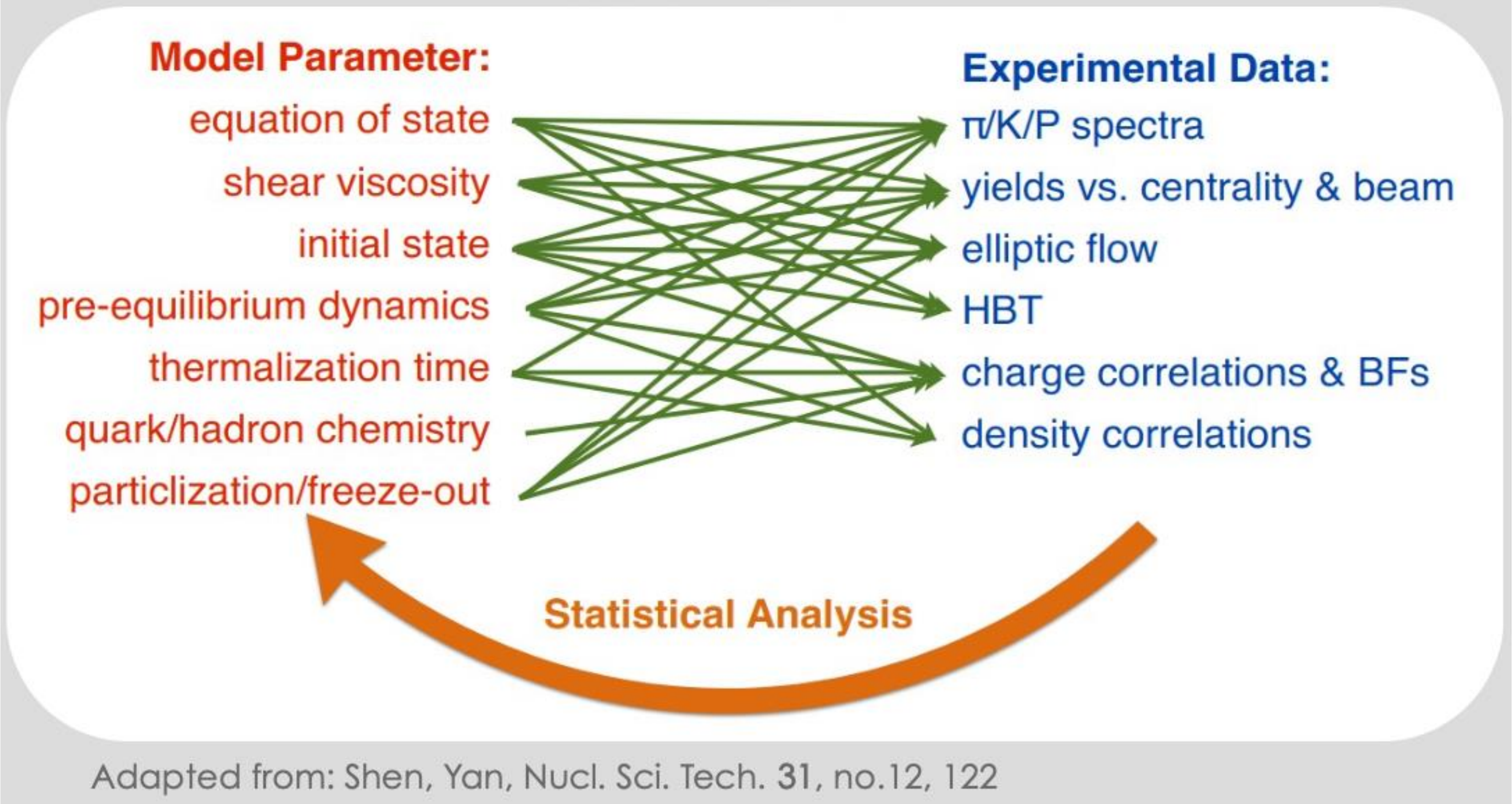
Hydrodynamic evolution

Particlization

Hadron Gas

Experimental observables

Every and each piece of simulation step has parameters (physical and empirical) that needs to be set.



Early Stage

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Experimental observables

Configuring the simulation chain

Every and each piece of simulation step has parameters (physical and empirical) that needs to be set.

To start, we use a set of parameters from similar chains:.

- Duke group [1]
- JETSCAPE [2]
- Trajectum [3]

All chains provide a set of parameters from Bayesian analysis considering some experimental observables N_{ch}, $\langle p_T \rangle$ and v_n.

All chains have some differences between them and to ours but show a good overall agreement with the fitted data.

[1] Moreland, Bernhard, Bass, PRC 101, 024911 (2020)
[2] Everett et. al. [JETSCAPE] PRL 126, 242301 (2021)
[3] Nijis et. al. PRC 103, 054909 (2021); PRL 126, 202301 (2021)

Configuring the simulation chain

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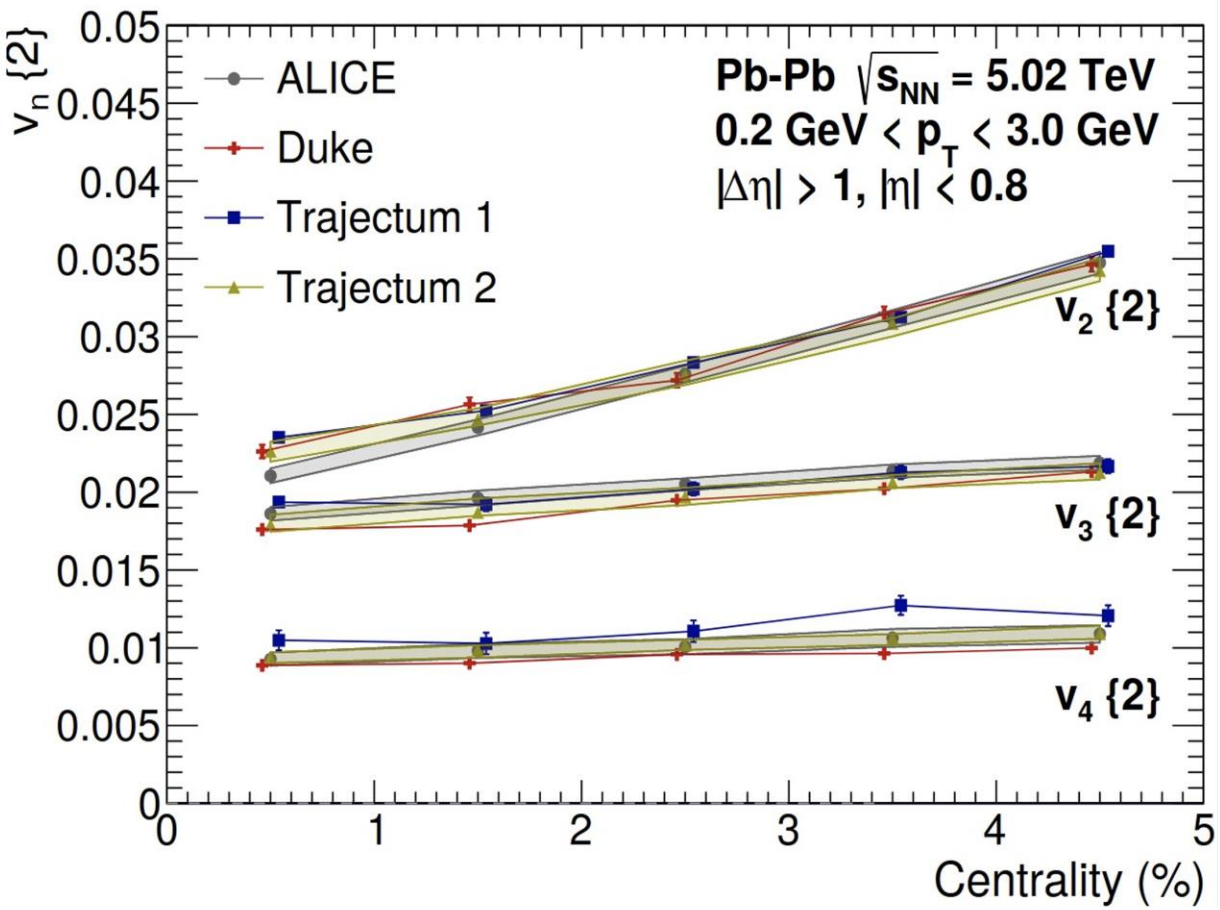

Configuring the simulation chain

Early Stage

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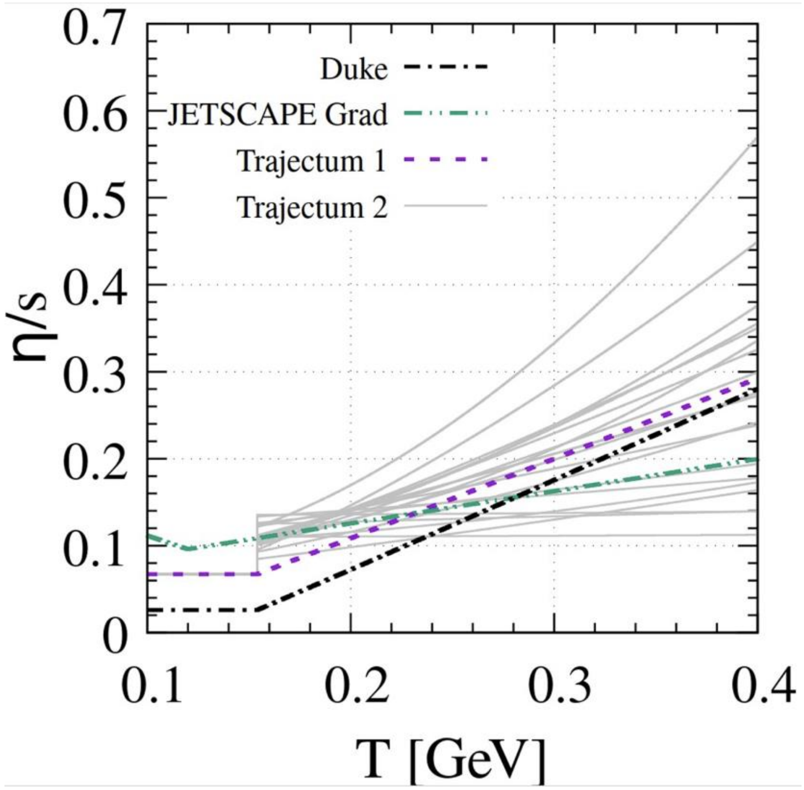
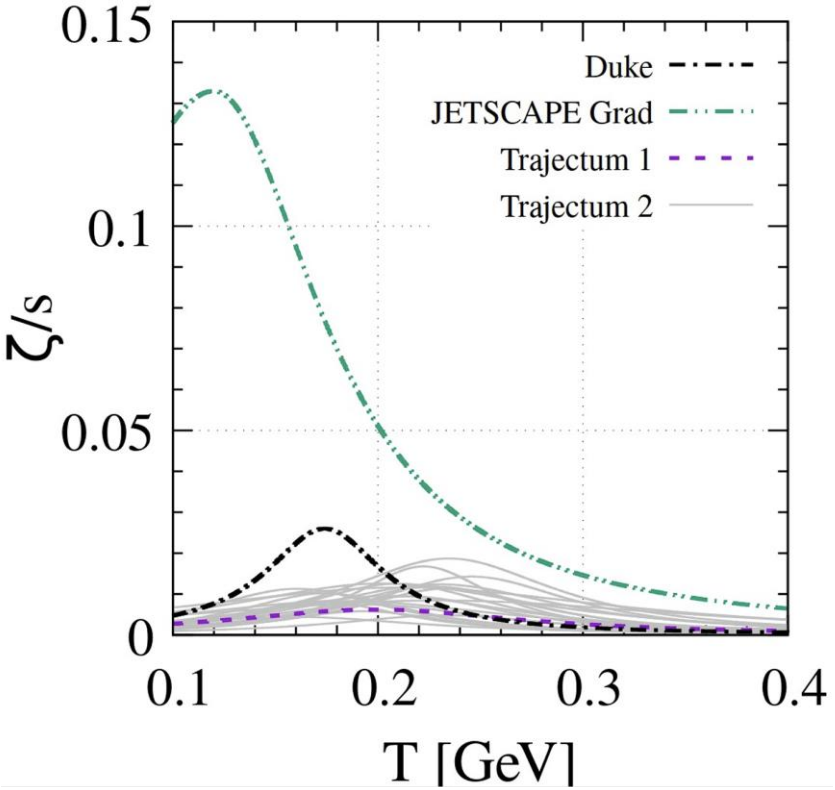
Experimental observables

Though they all "fit" the data, the physical parameters used can vary considerably.





EXTREME Collab. PRC 107, 044907 (2023)

Configuring the simulation chain

Early Stage

Pre-equilibrium

Hydrodynamic evolution

Particlization

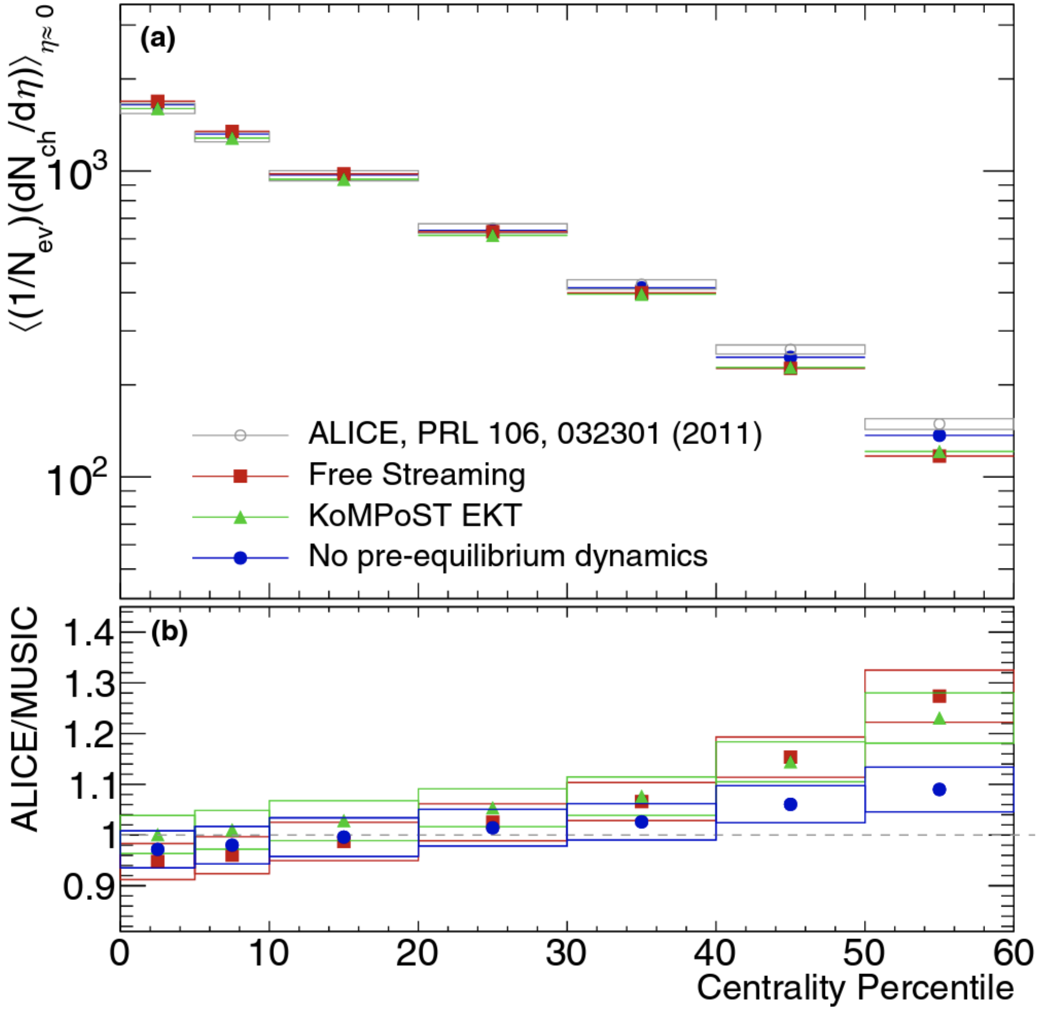
Hadron Gas

Experimental observables

An overall normalization is done comparing total number of charged particles N_{ch} from experimental data.

Once chain configuration is done, we start getting events to analyze with same tools as the experiments.

- p_T spectra
- Flow Observables V_n
- Polarization.



Configuring the simulation chain

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Experimental observables

Once chain configuration is done, we start getting events to analyze with same tools as the experiments.

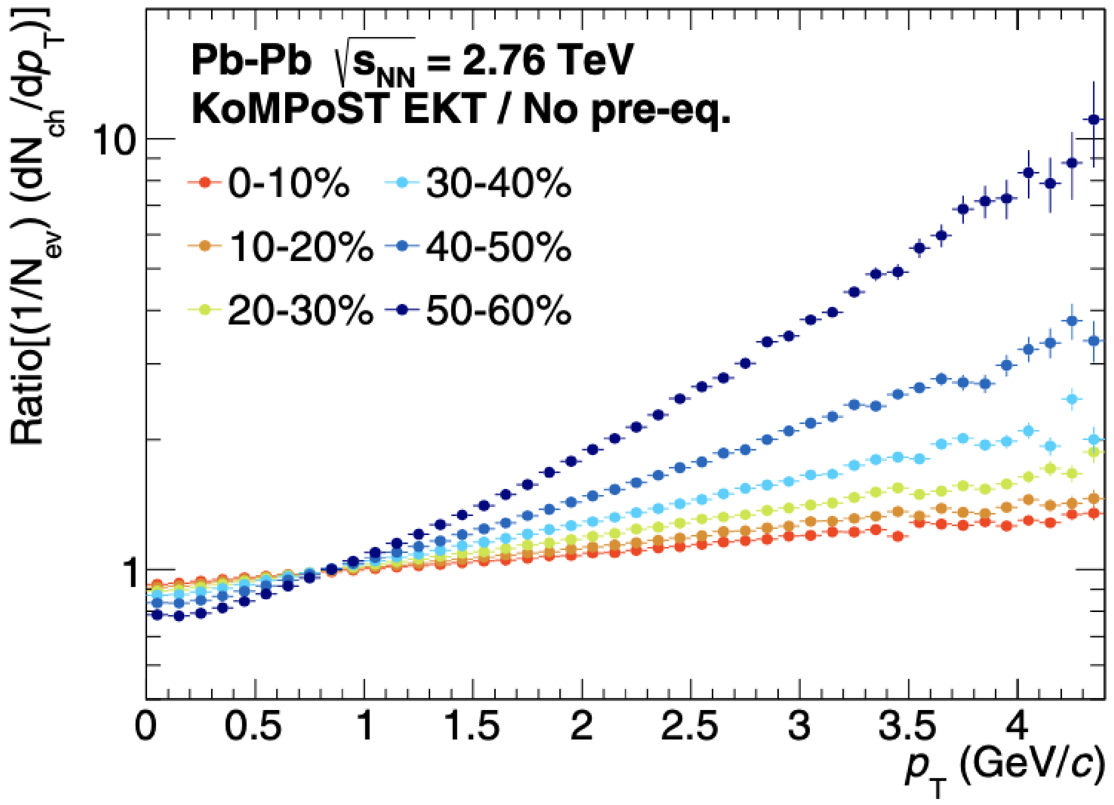
- p_T spectra
- Flow Observables V_n
- Polarization.

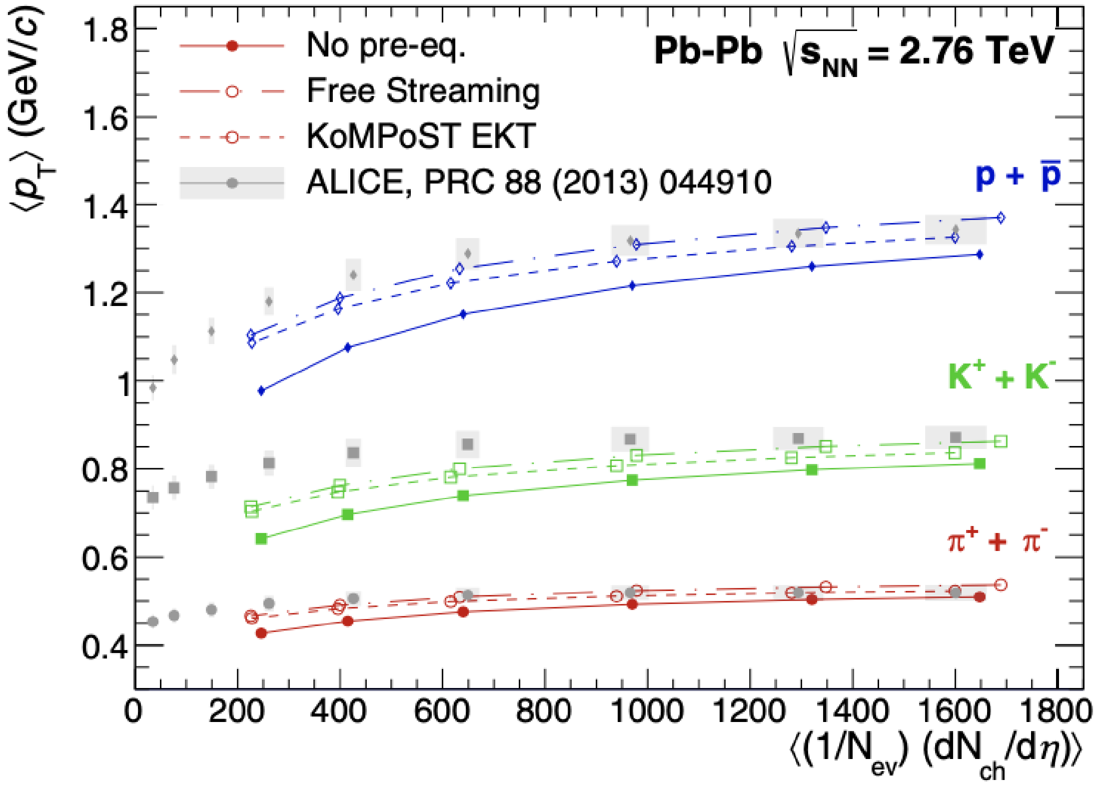
We can now perform a systematic study,

- checking the effects of each chain component.
- correlate IC with final observable
- test sensitivity and limitation of observables
- test the extreme, small and ultracentral.
- look for new ideas.

Effects of each chain component

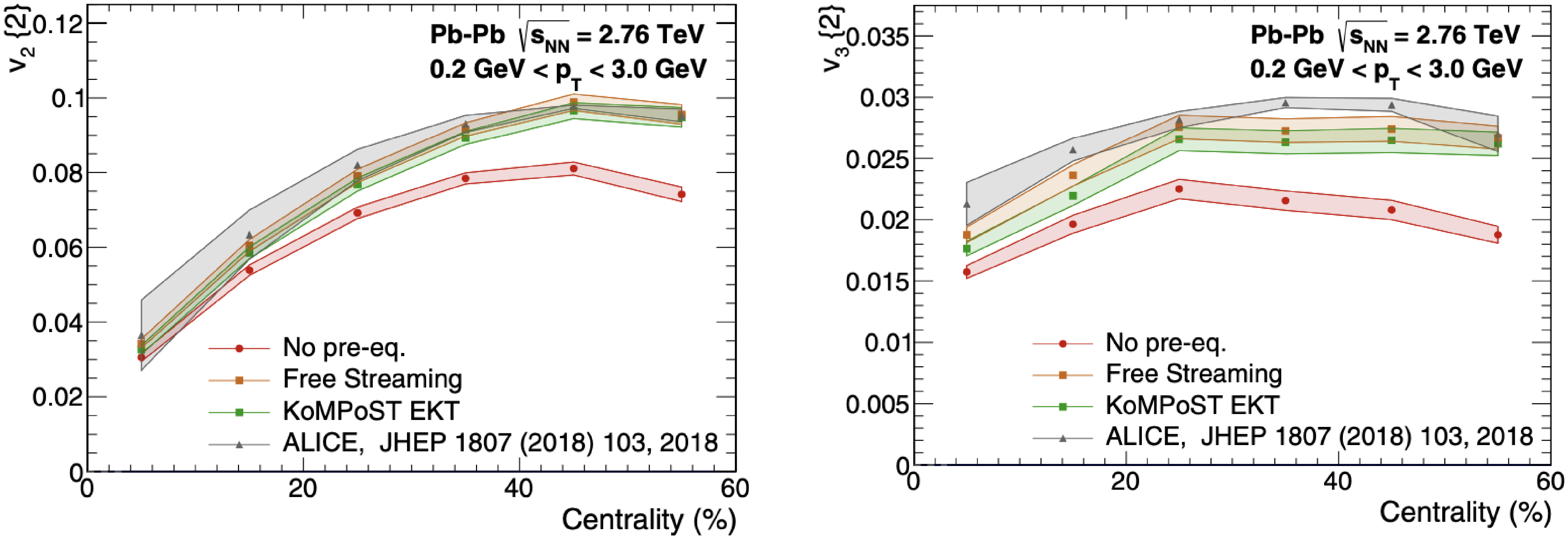
EXTREME Collab. PRC 103, 054906 (2021)





Effects of each chain component

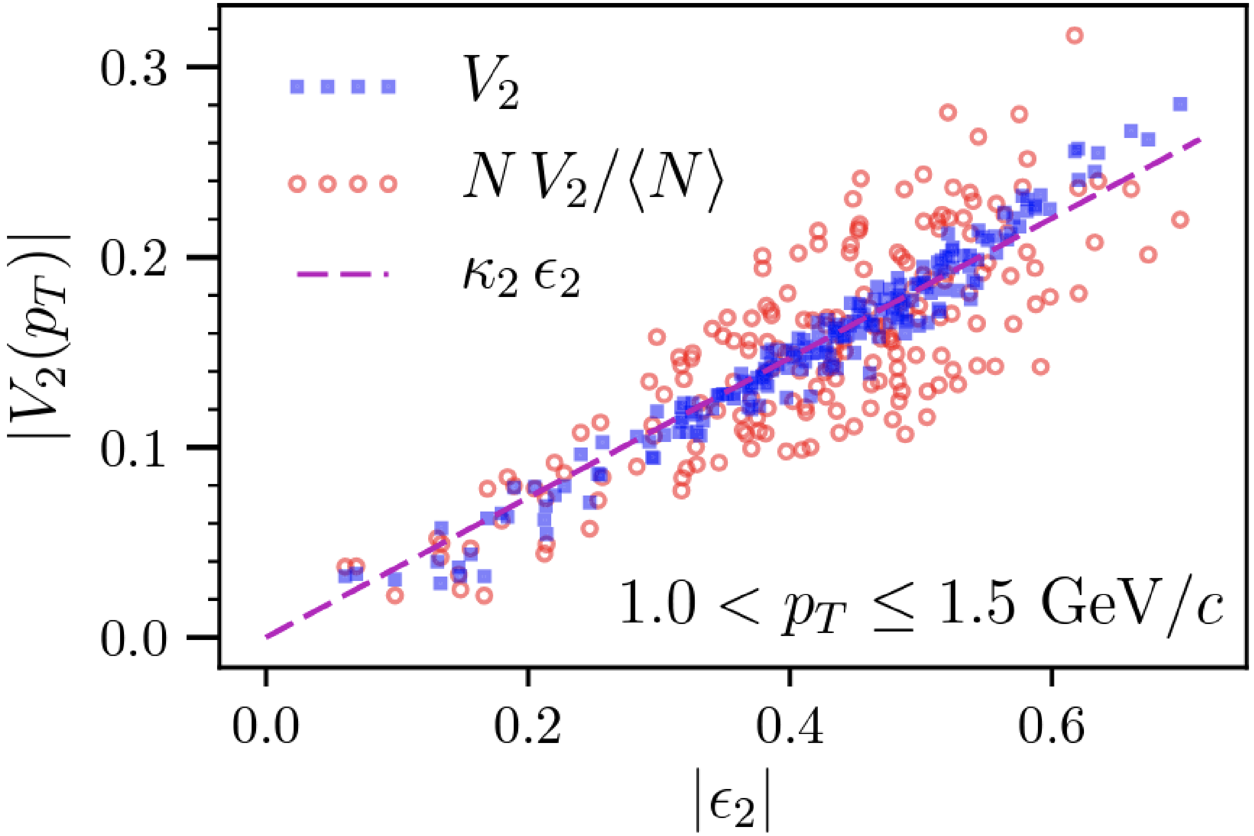
EXTREME Collab. PRC 103, 054906 (2021)



Increase of integrated v_n due to pre-equilibrium dynamics.

Allows to correlate IC with final observables

EXTREME Collab. PRC 102, 064909 (2020)



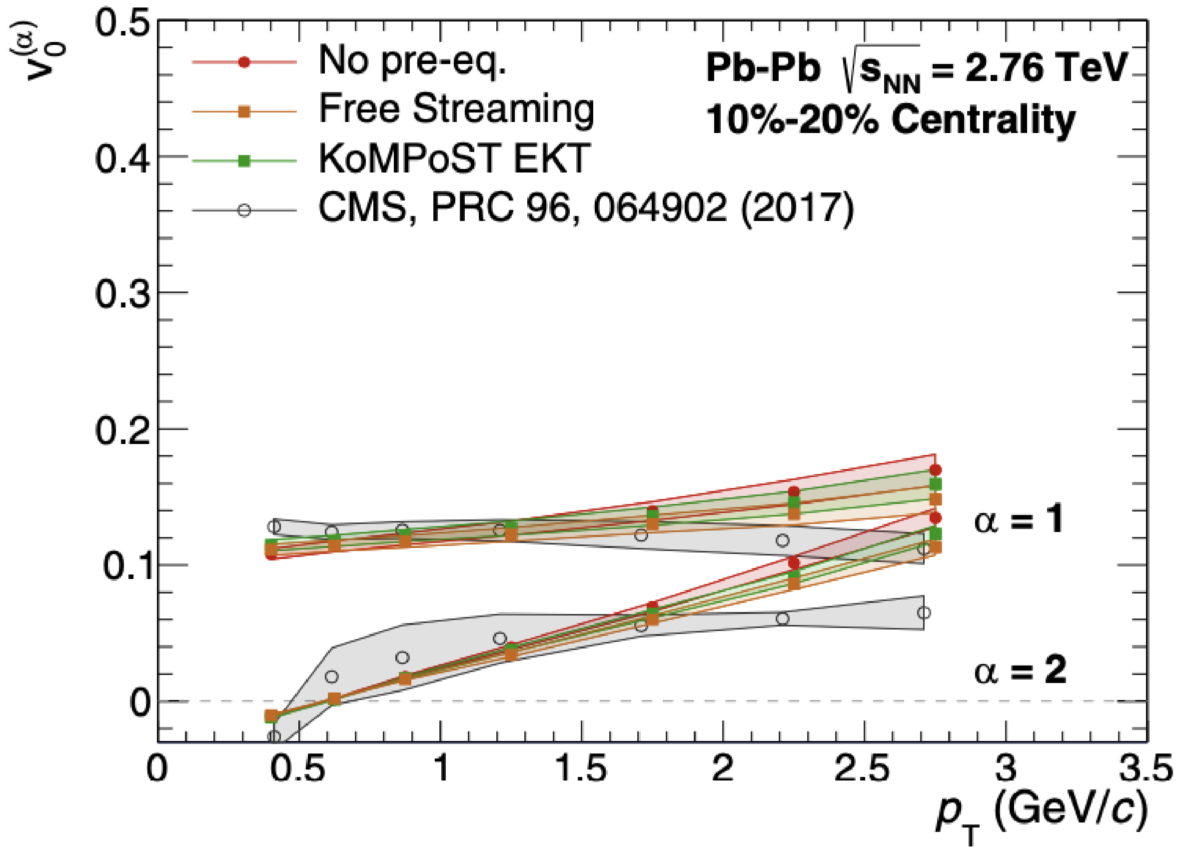
Blue: flow per particle

$$\frac{dN}{dy\,p_T\,dp_T\,d\varphi} = \frac{1}{2\pi} N(p_T, y) \sum_{n=-\infty}^{\infty} V_n(p_T, y)\, e^{-in\varphi},$$

Red: inclusion of multiplicity fluctuations.

Test sensitivity/limitation of observables

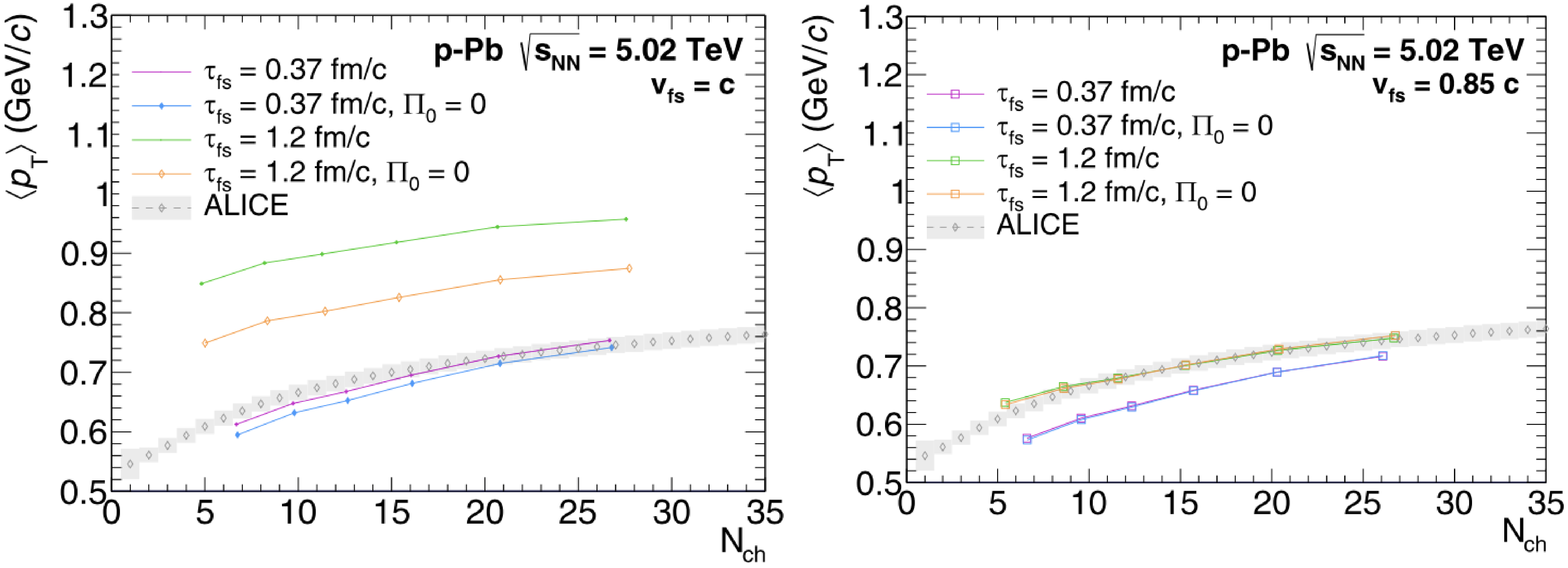
EXTREME Collab. PRC 101, 034903 (2020)



PCA of two particle correlation matrix.

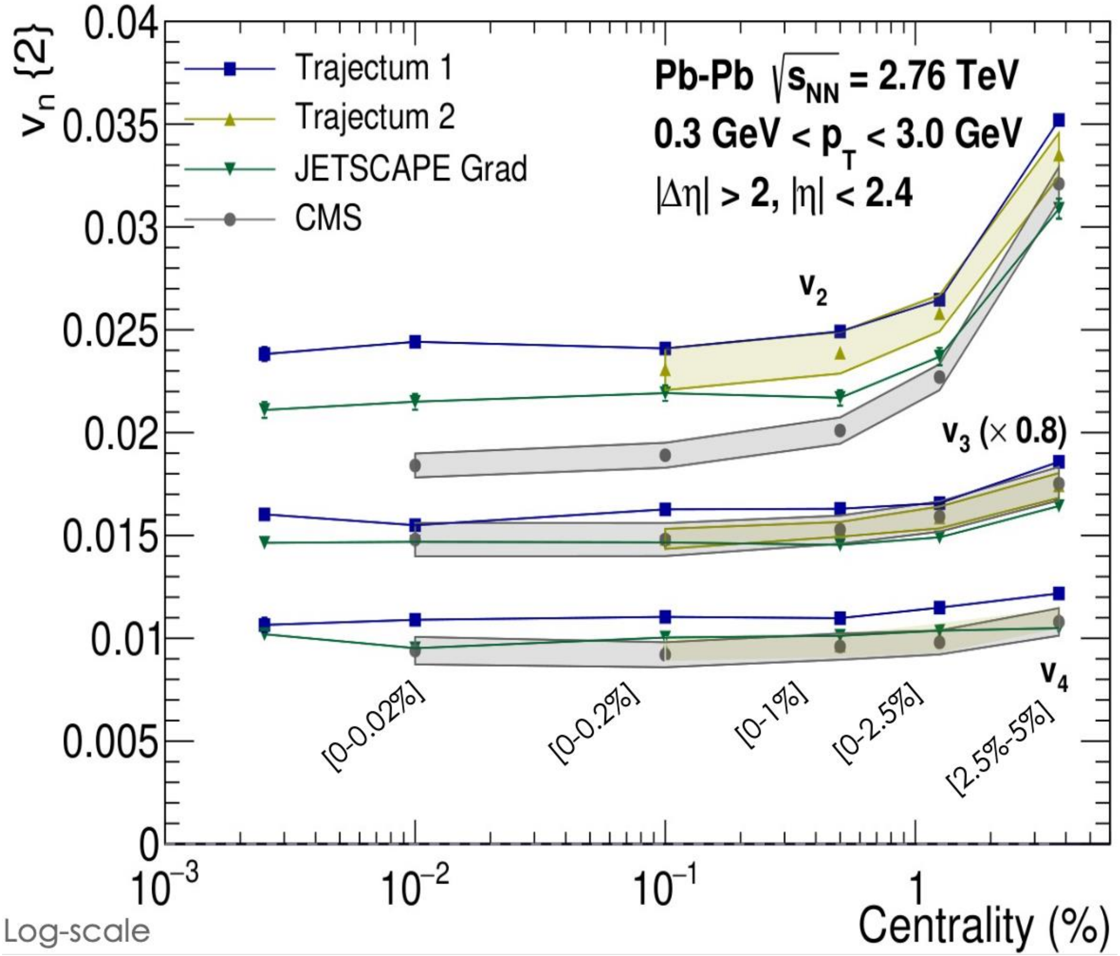
Test small systems (p-Pb)

EXTREME Collab. PRC 107, 044901 (2023)



Test ultracentral Pb-Pb

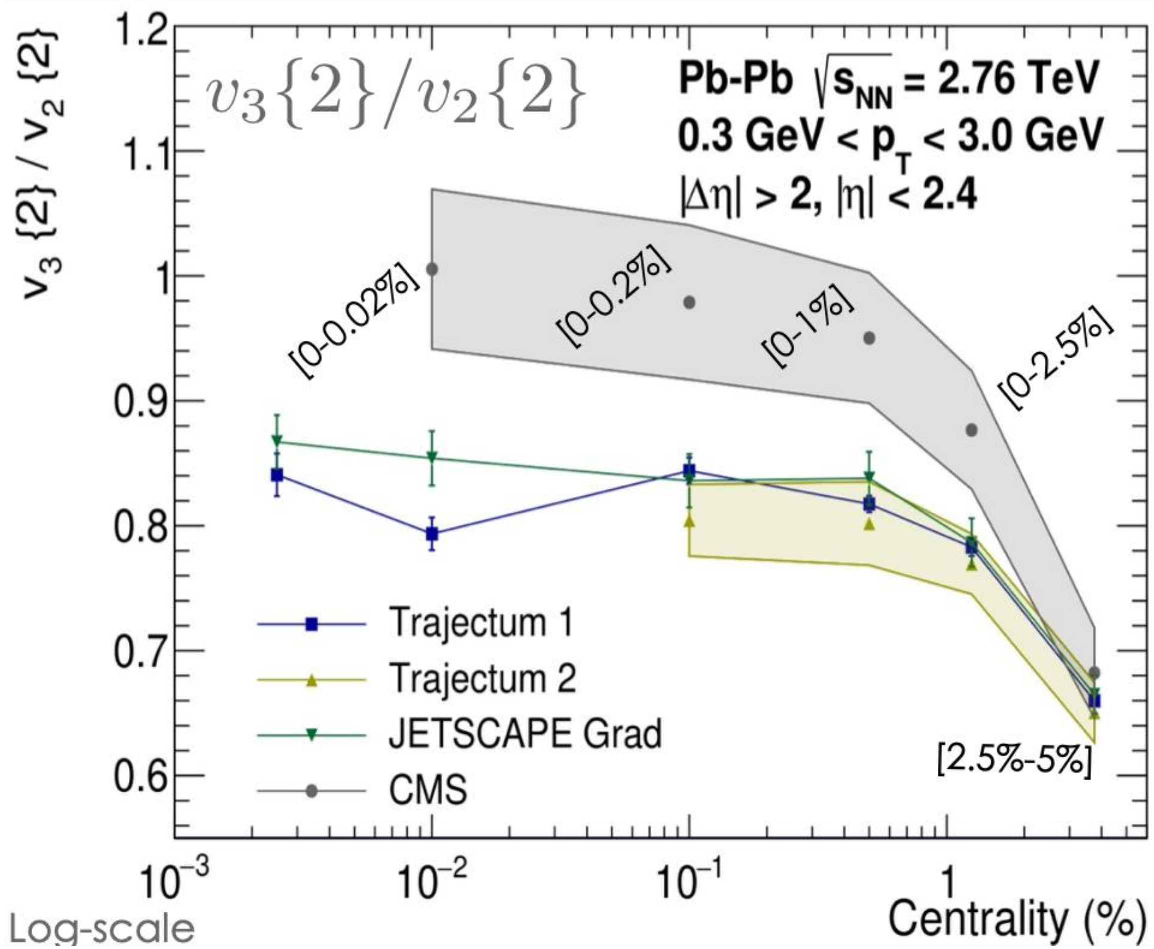
EXTREME Collab. PRC 107, 044907 (2023)



Models were fitted to describe data from central to peripheral collisions, but ultracentral data were not included in the fits.

Test ultracentral Pb-Pb

EXTREME Collab. PRC 107, 044907 (2023)

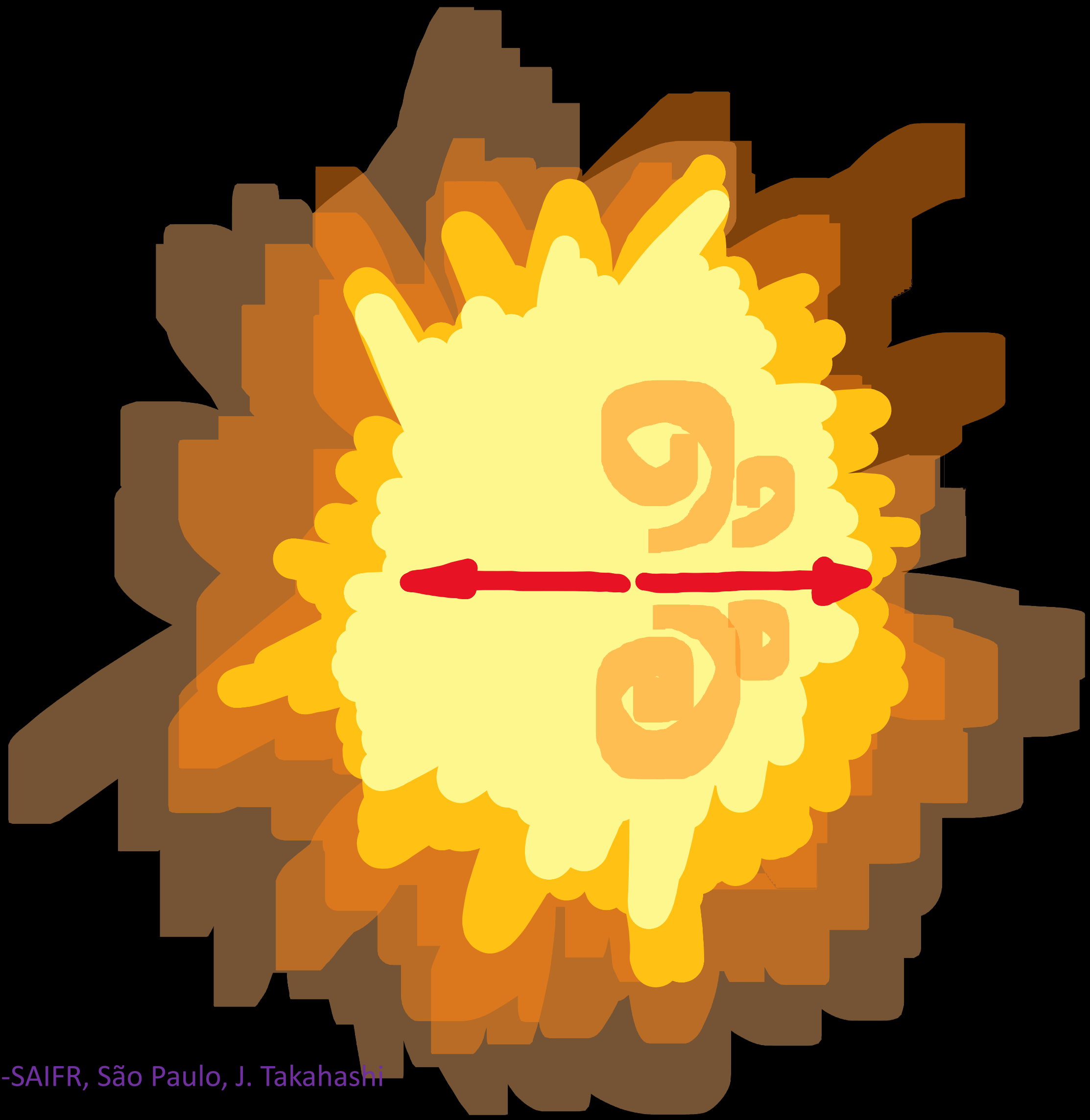


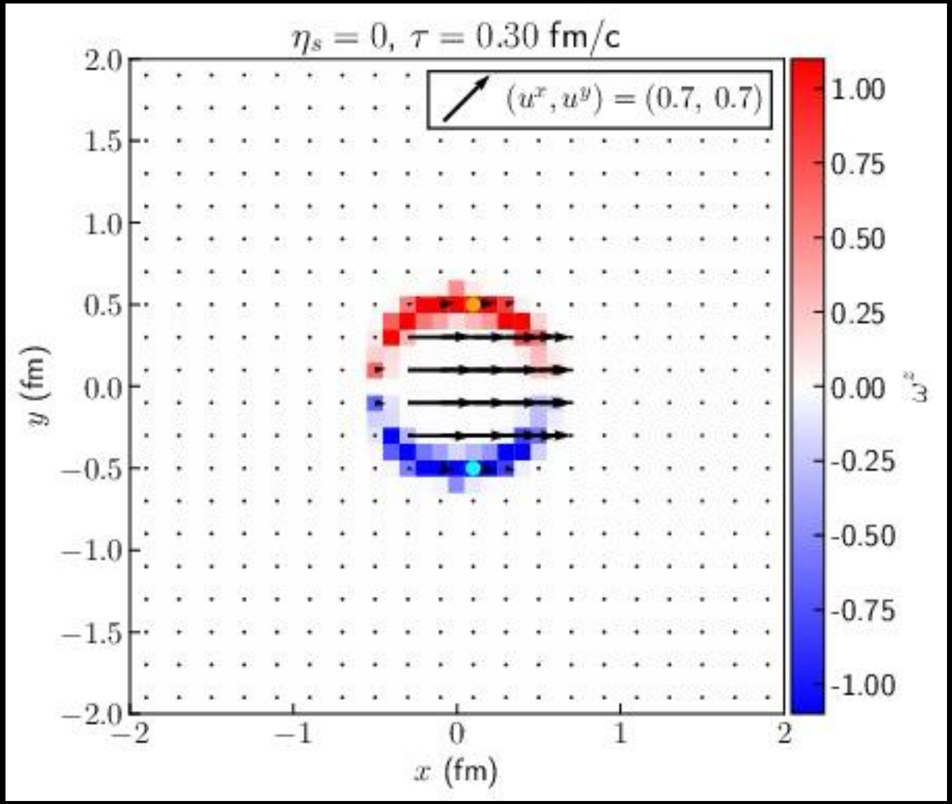
Models were fitted to describe data from central to peripheral collisions, but ultracentral data were not included in the fits.

All models fail to describe ultracentral data, where hydrodynamics should be most applicable.

Something seems to be still missing.

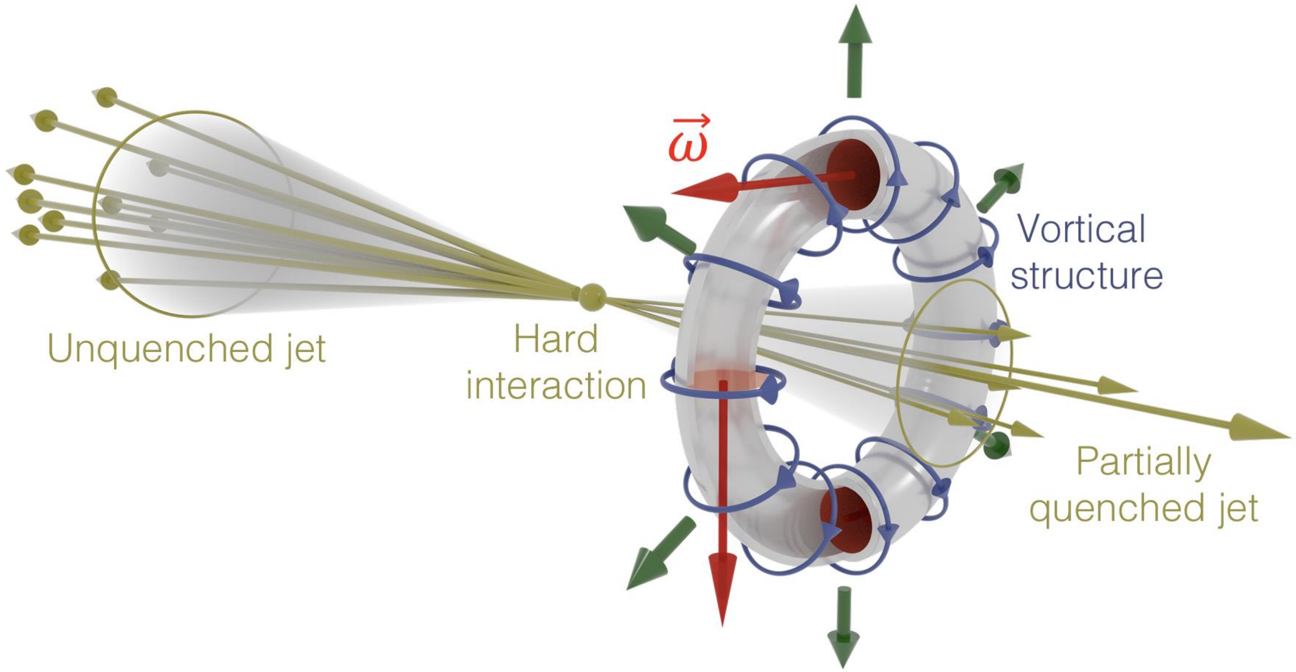
Cool idea: Vorticity in the QGP

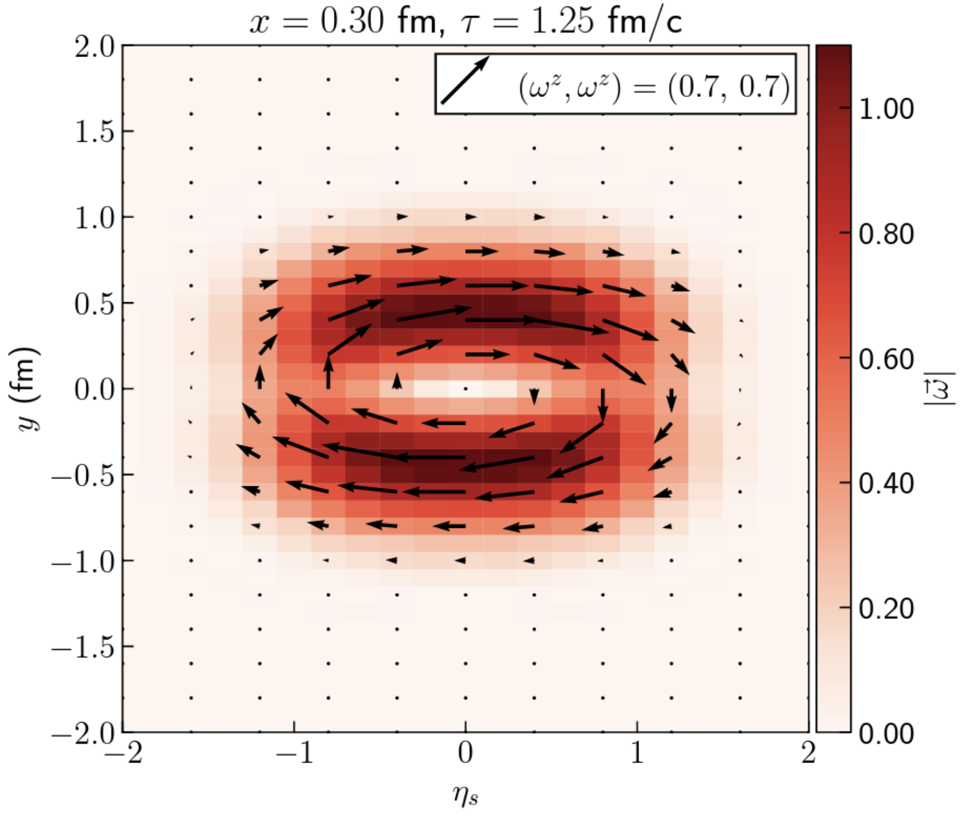




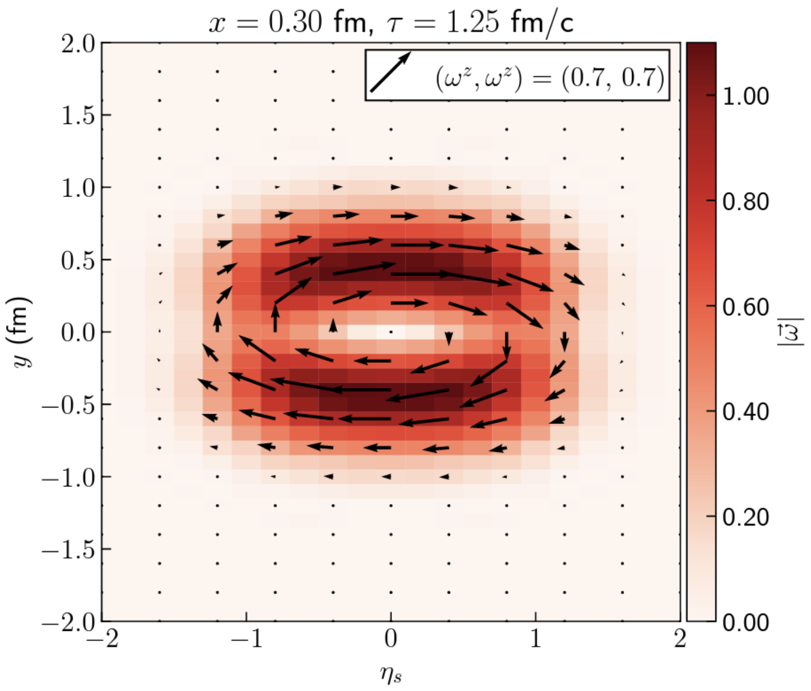
Test a very cool idea

3C Collab. PLB 820 (2021) 136500



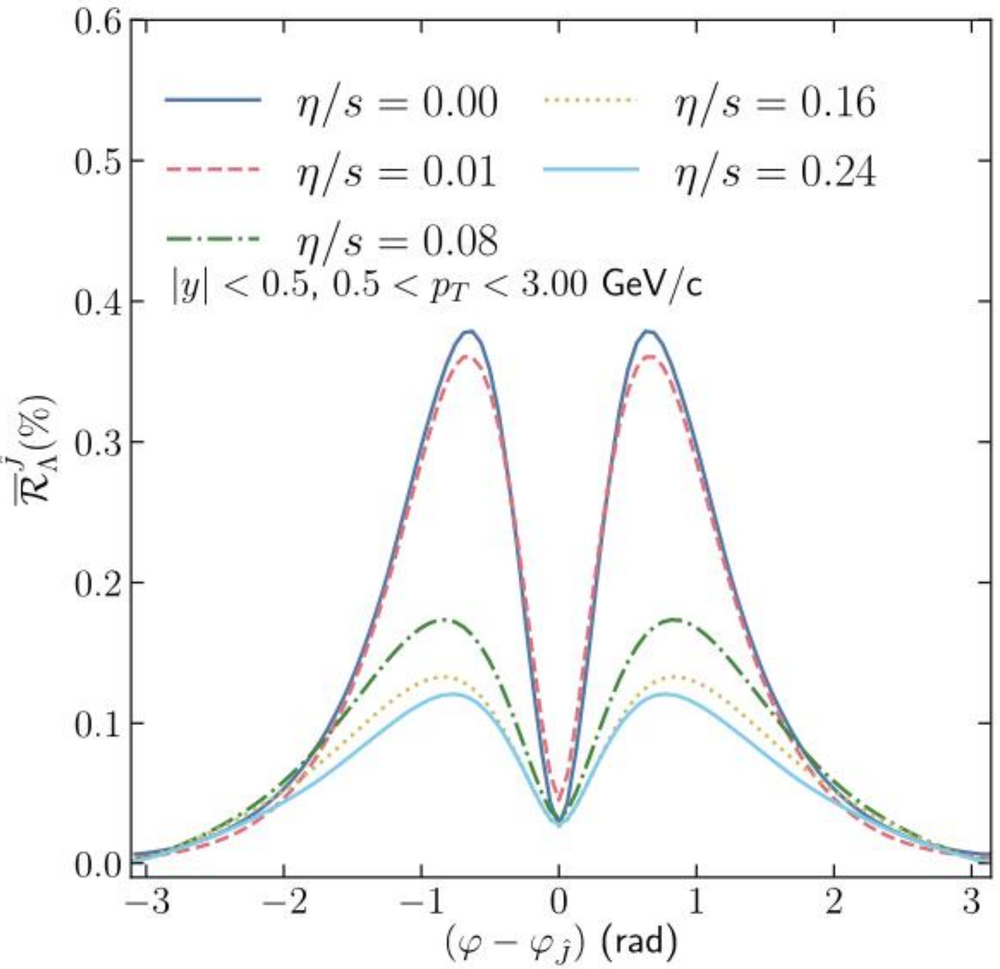


Propose a new observable



$$\overline{\mathcal{R}}_{\Lambda}^{\hat{t}} \equiv \left\langle \frac{\vec{P}_{\Lambda} \cdot (\hat{t} \times \vec{p}_{\Lambda})}{|\hat{t} \times \vec{p}_{\Lambda}|} \right\rangle_{p_T, y}$$

3C Collab. PLB 820 (2021) 136500



Propose a new observable

3C Collab. just submitted to arXiv.

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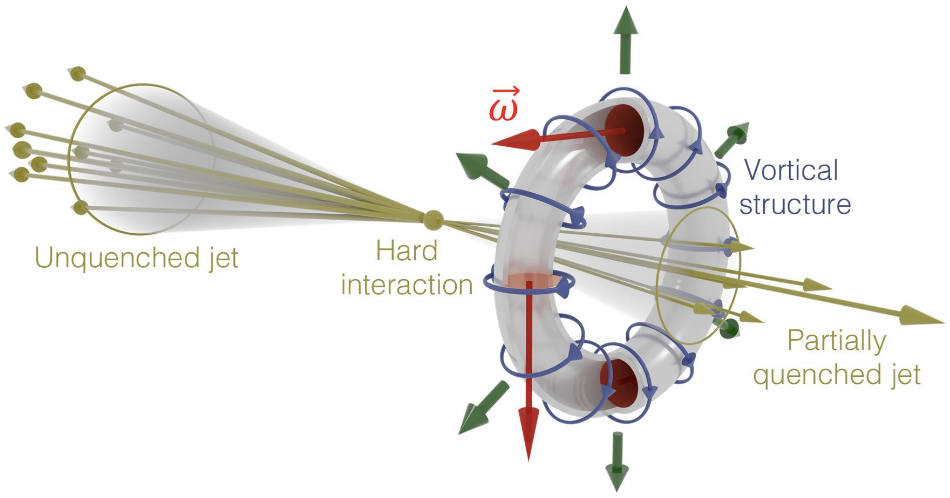
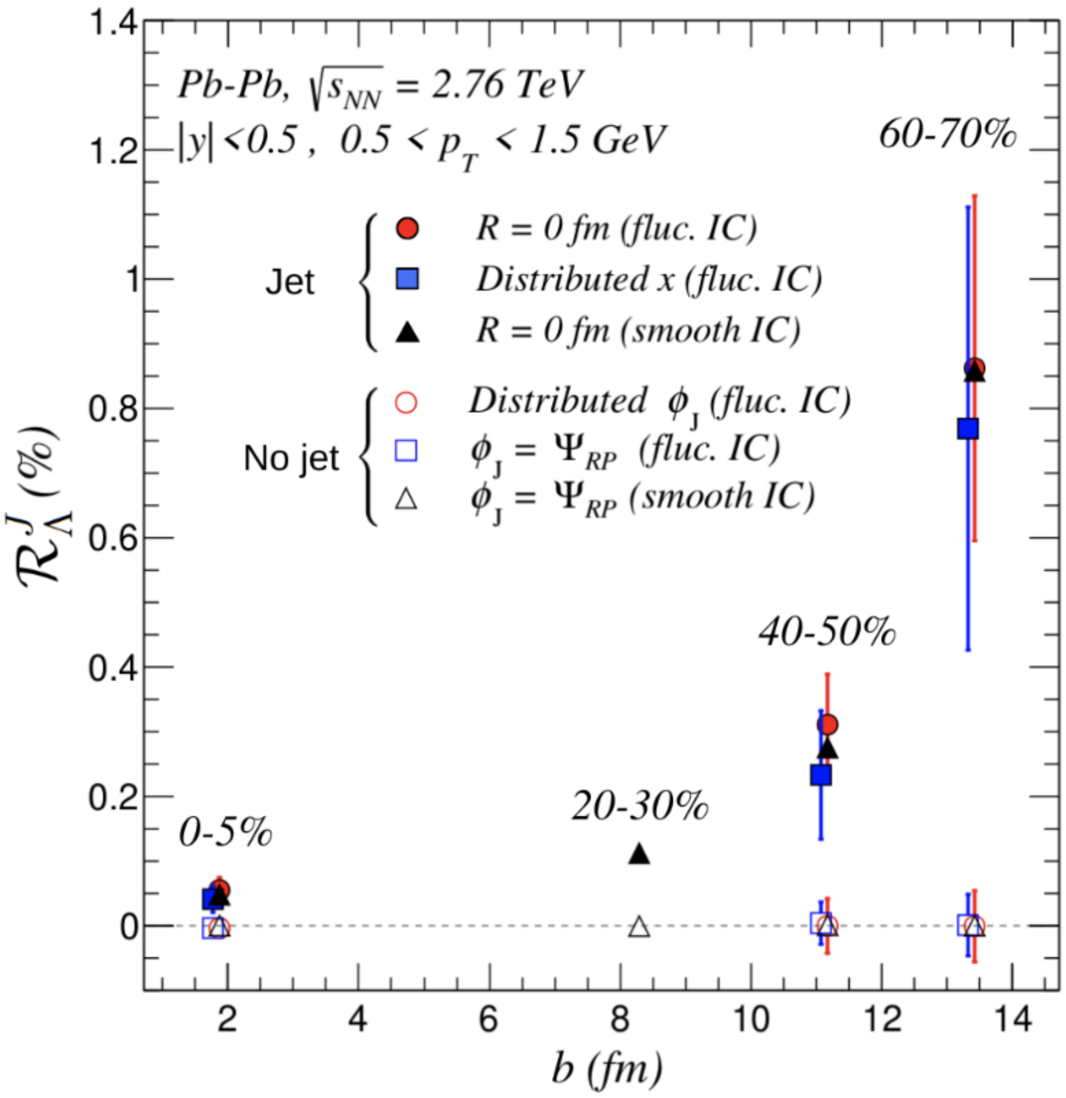
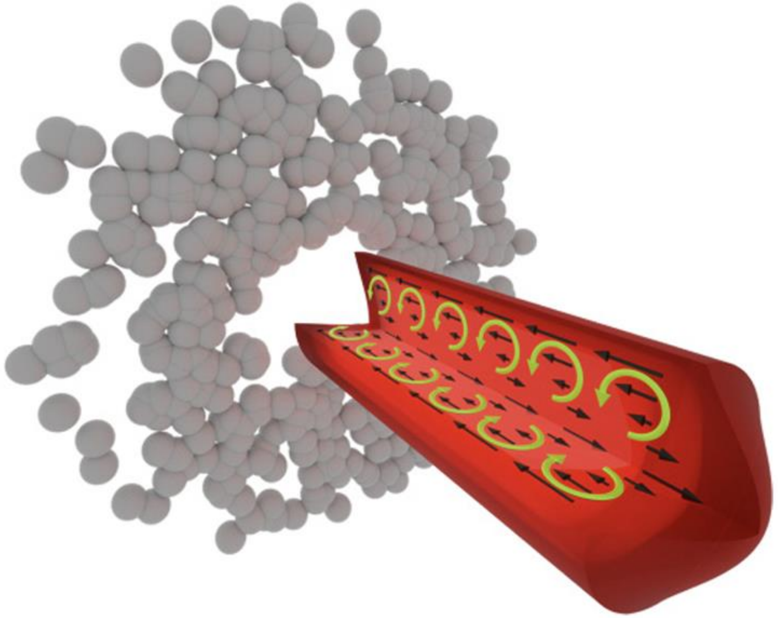


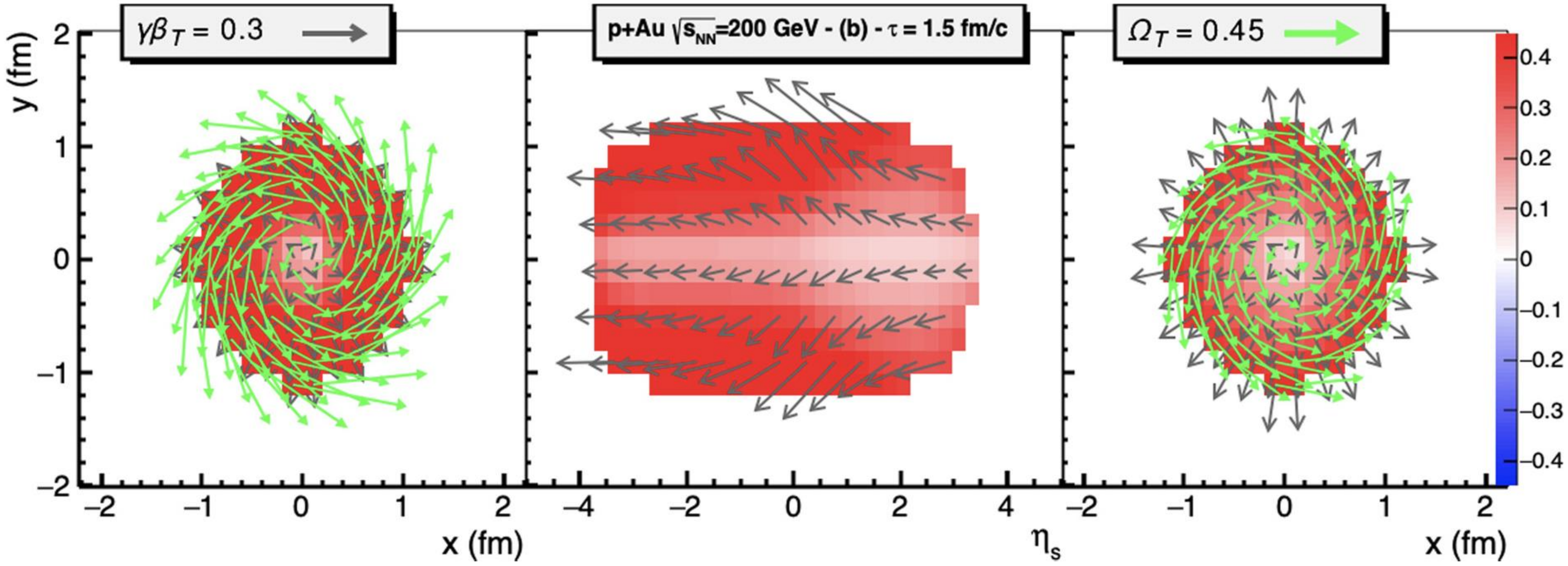


Vortex rings in p+A collisions

3C collaboration, PRC 104, L011901 (2001)



$$\overline{\mathcal{R}}_{\Lambda}^{\hat{t}} = 2\left\langle \frac{\vec{S}'_{\Lambda} \cdot (\hat{t}' \times \vec{p}'_{\Lambda})}{|\hat{t}' \times \vec{p}'_{\Lambda}|} \right\rangle_{\phi},$$



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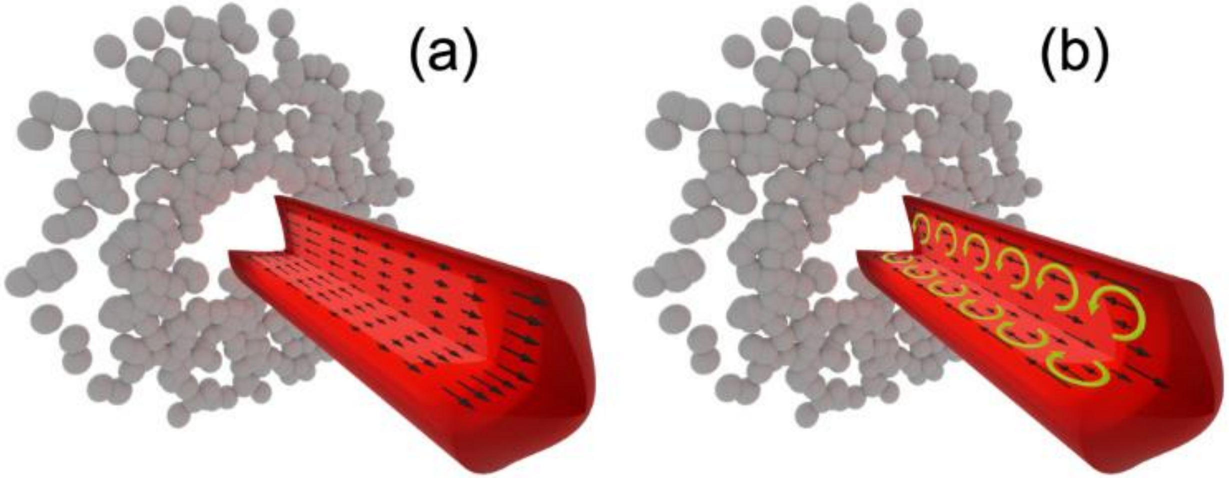
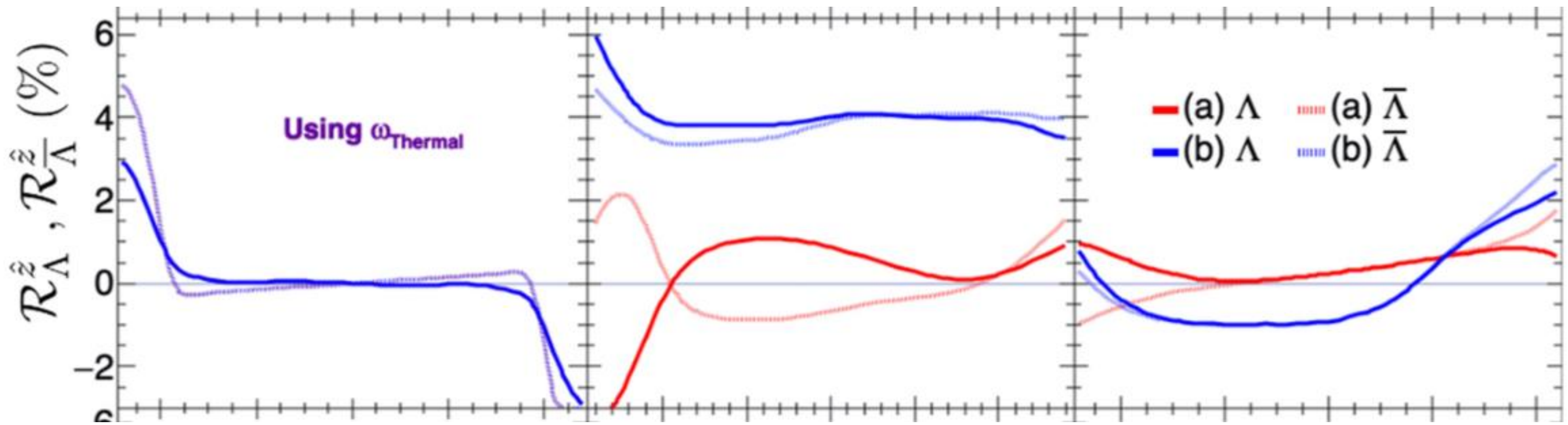




In Summary

- We put together a complex hybrid EbE simulation code for Heavy-Ion Collisions.
- We put together a complex hybrid group of researchers with common topics of interest.

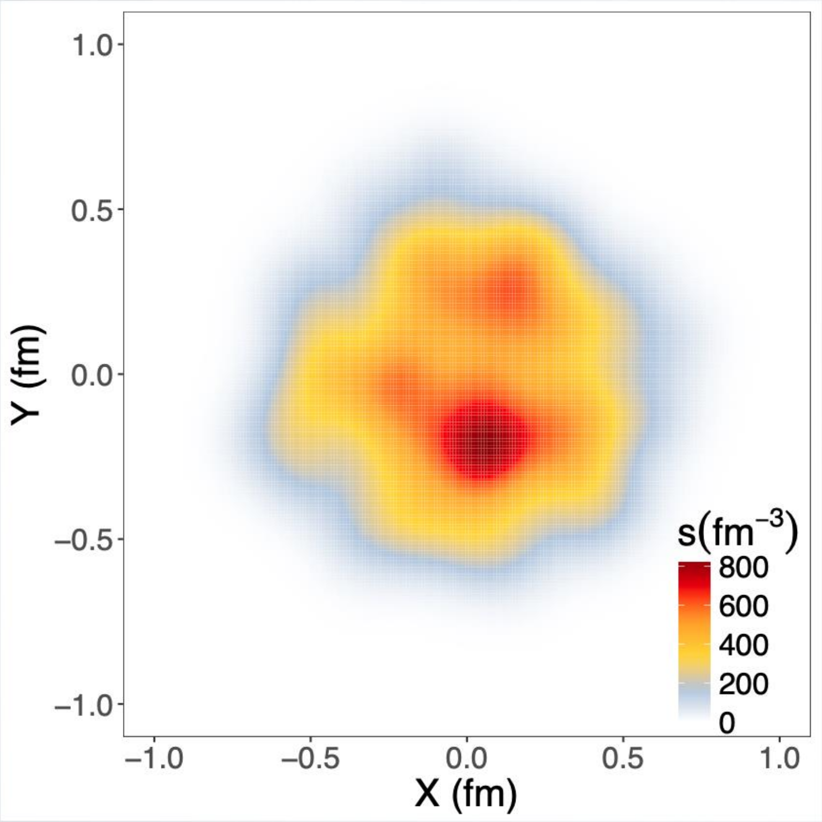
Many results:

- Comparison to experimental data
- Constrain to models
- Precision tests
- New ideas and observables.
- New collaborations.

Thank you

Back-up

INITIAL CONDITIONS WITH TRENTO



- TRENTo is a parametric wounded nucleon IC model;

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

$$\frac{dS}{dy} \propto \left(\frac{T_A^p + T_B^p}{2} \right)^{1/p}$$

Back-up

HYDRODYNAMICS

Ideal Hydro

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

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

Energy and momentum conservation

Other conserved quantities (B, S, Q)

Back-up

HYDRODYNAMICS

Second-order viscous Hydro (Israel-Stewart type)

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

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

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

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

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

See Denicol et al., PRC90:024912 (2014)

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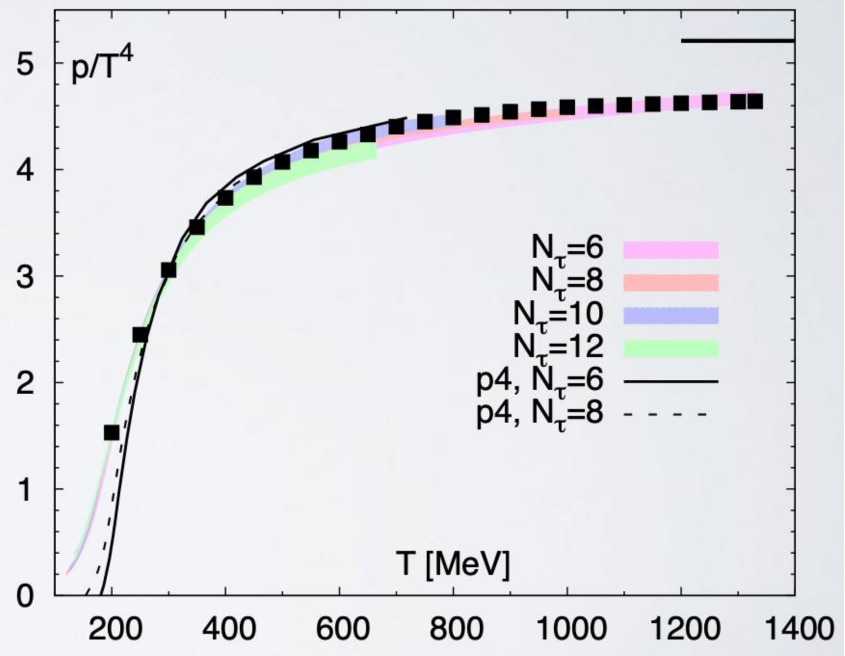
Back-up

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)

Back-up

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/)

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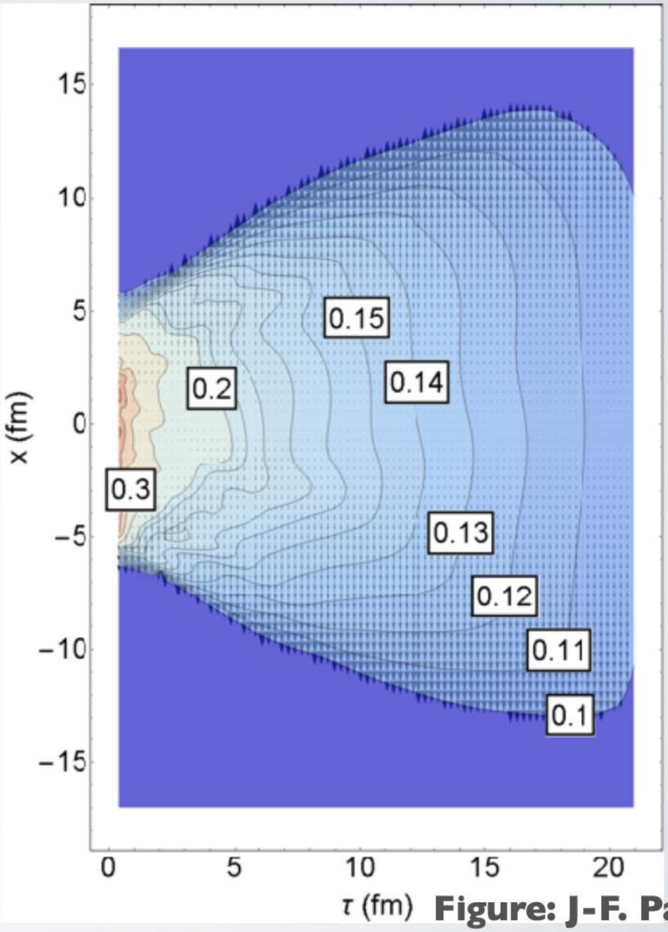
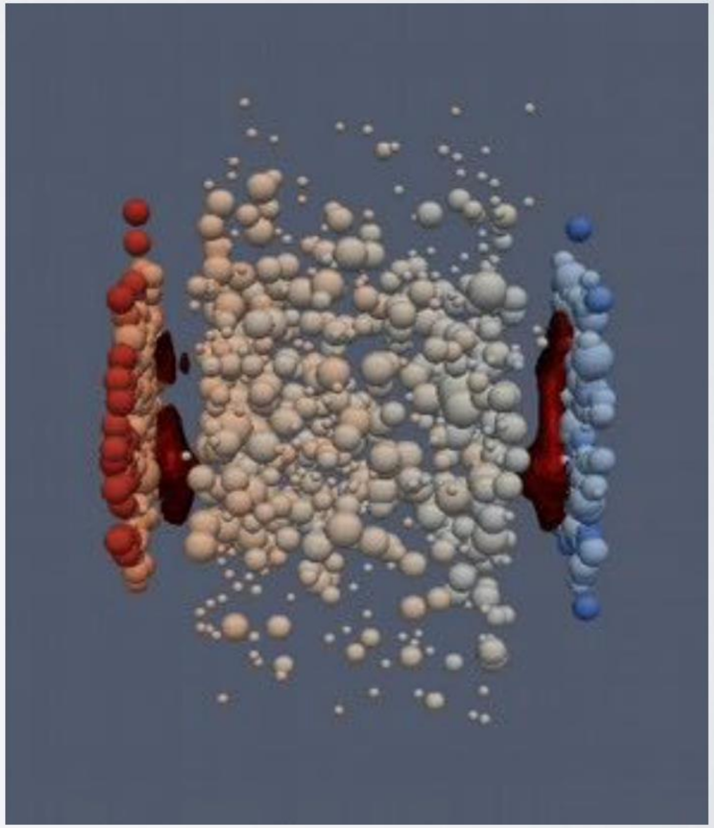


Figure: J-F. Paquet

Back-up

PARTICLIZATION

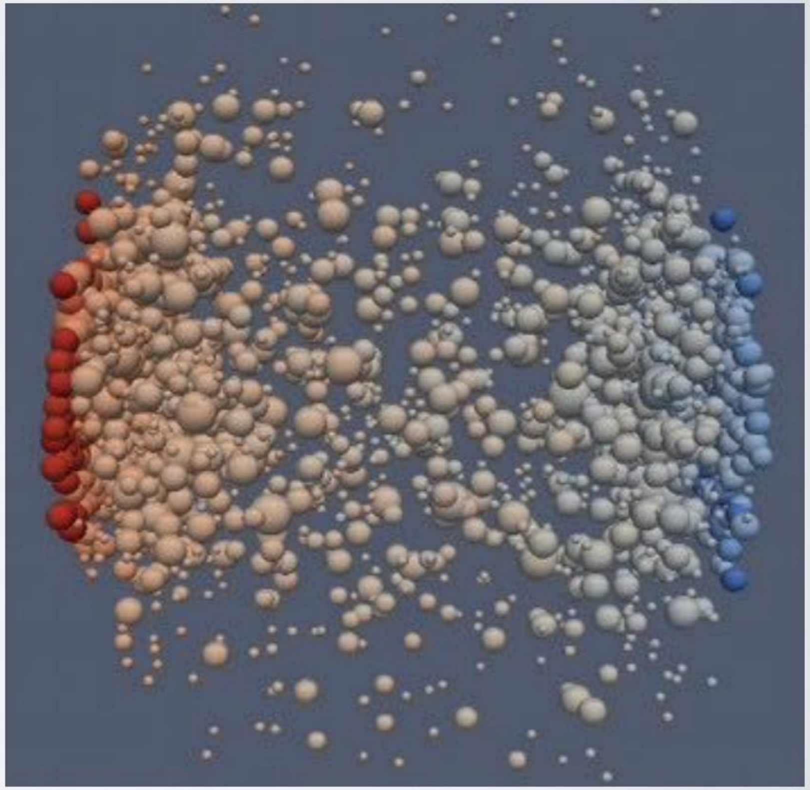
- The fluid description is matched to a kinetic one, by sampling discrete particles;
- Sampling is carried over the freeze-out hypersurface obtained at the end of hydro;
- iSS code is a publicly available sampler (github.com/chunshen1987/iSS)



Back-up

URQMD

- Most widely used microscopic transport model that simulates dynamics of the hadronic system;
- Simulates binary collisions, resonance formation and decays;
- Code is publicly available with restrictions (urqmd.org)



Back-up

Particle distribution in azimuth

Single particle distribution in a single event:

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

Pair distribution:

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

Back-up

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

Back-up

Principal Component Analysis

We approximate the correlation matrix:

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

And diagonalize it:

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

And ordering λ from largest to smallest:

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

Back-up

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