PHYSICS OF RELATIVISTIC ION-ION COLLISIONS: SPD OPPORTUNITIES

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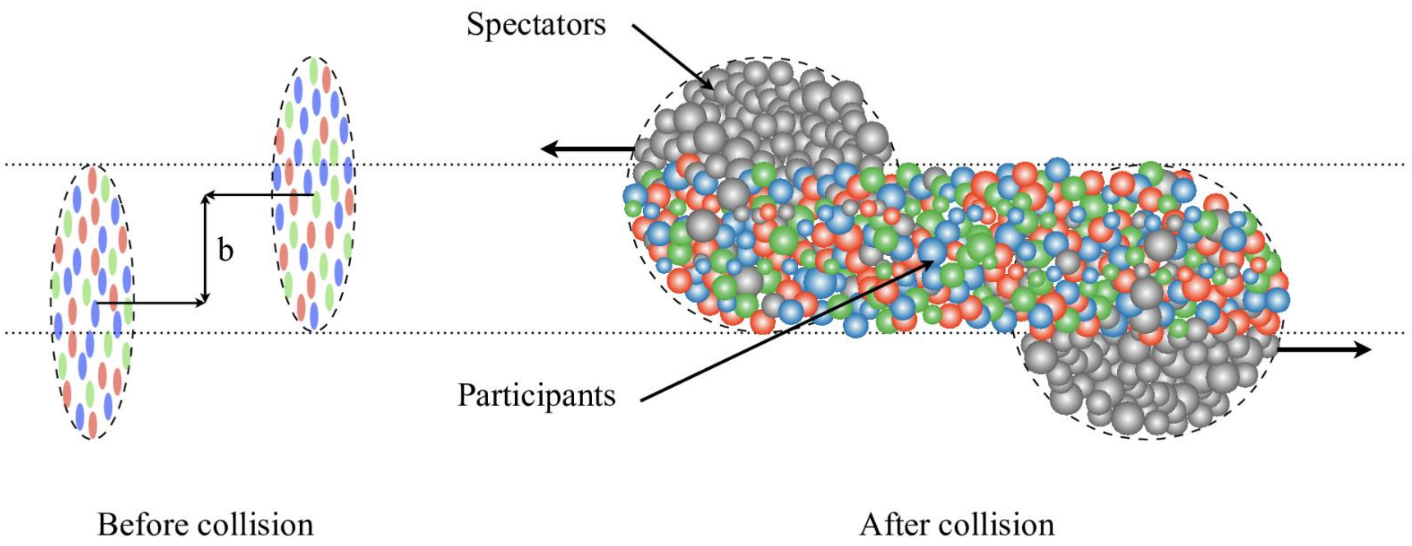
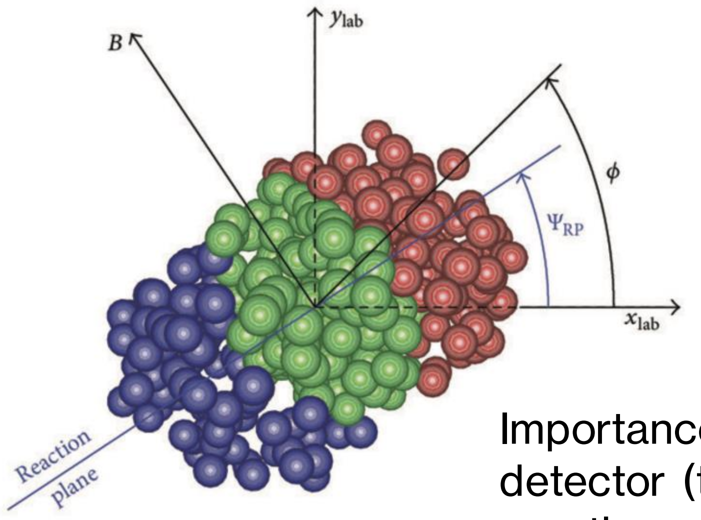
National Research Nuclear University MEPhI

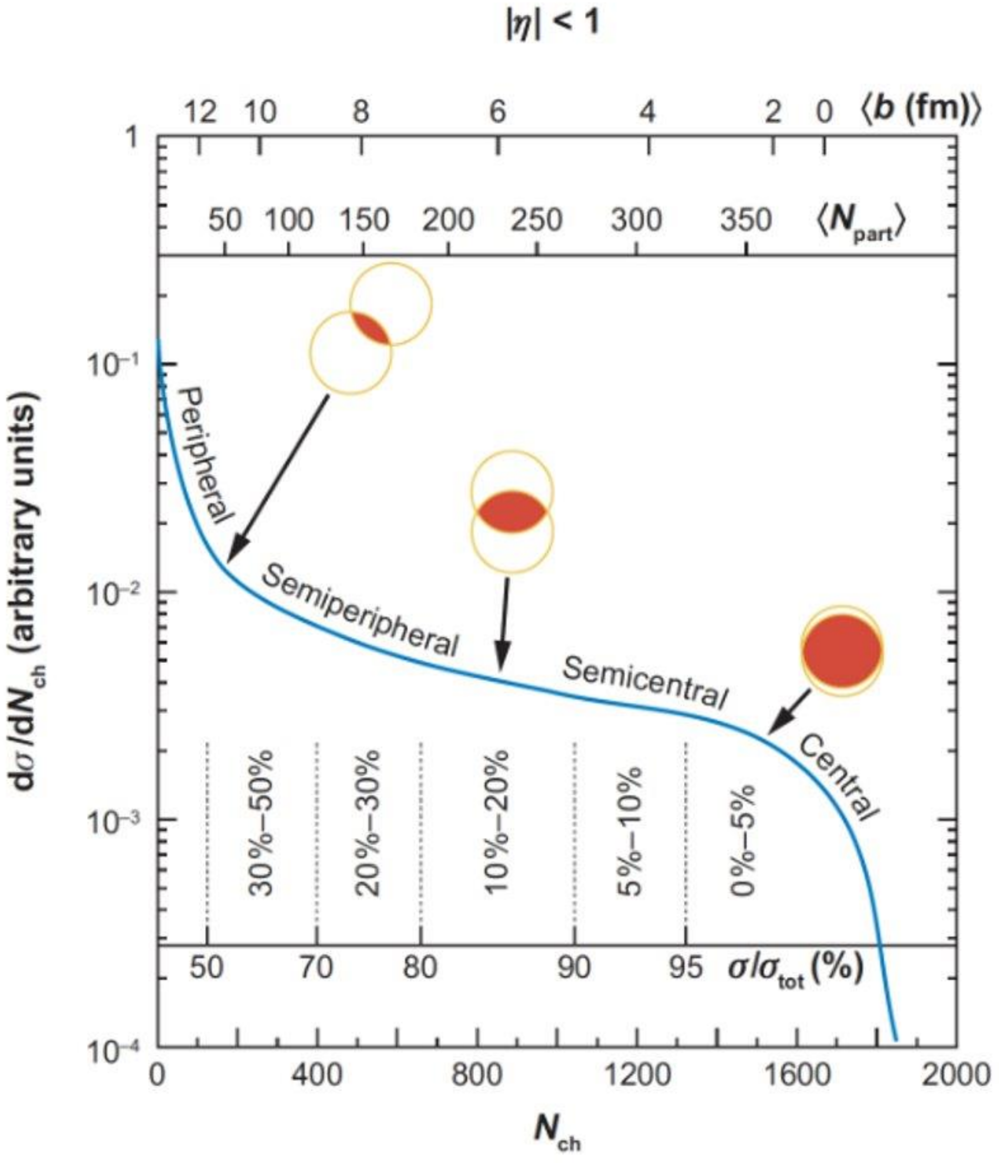
VI SPD Collaboration Meeting and Workshop on Information and Technology
Samara University, Samara, Russia
Oct. 23- 27, 2023

A Few Definitions...



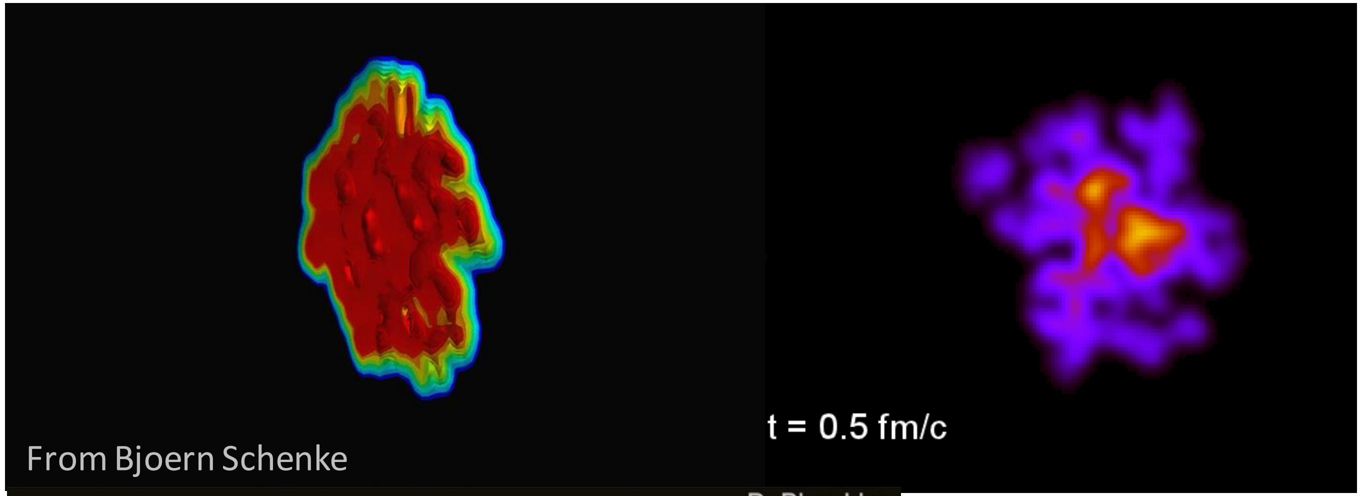


Importance of granular BBC detector (to reconstruct reaction plane angle)

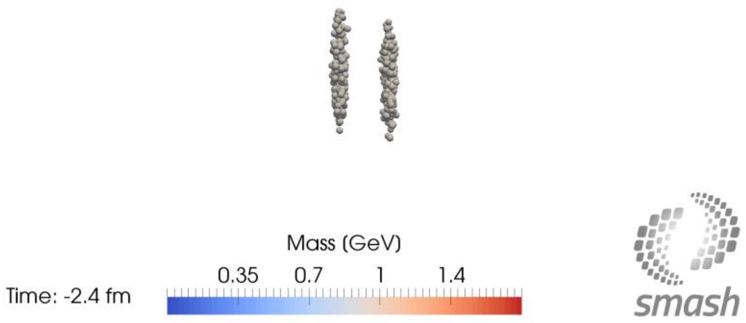


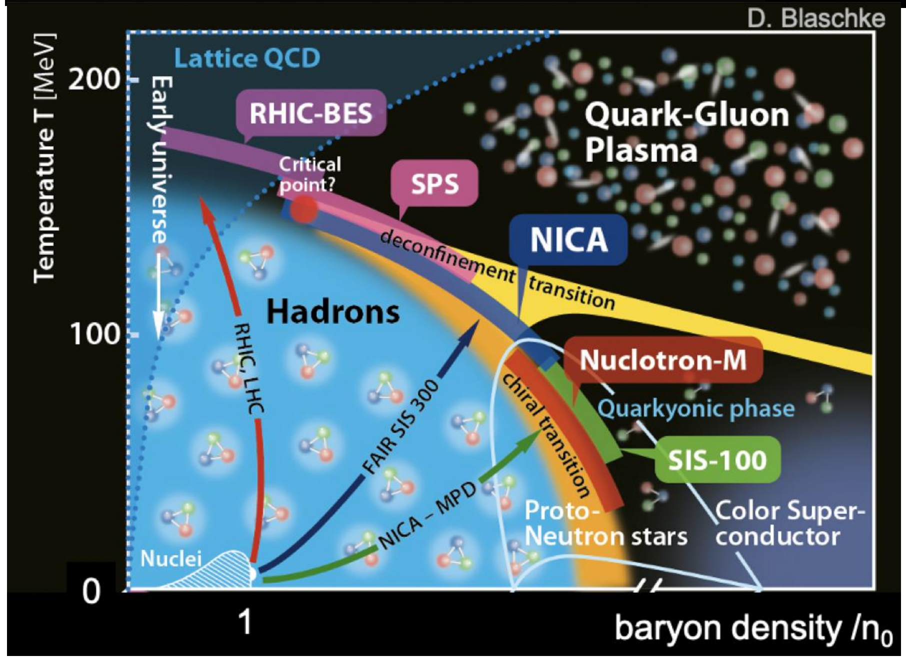
Picture of Relativistic Heavy Ion Collision

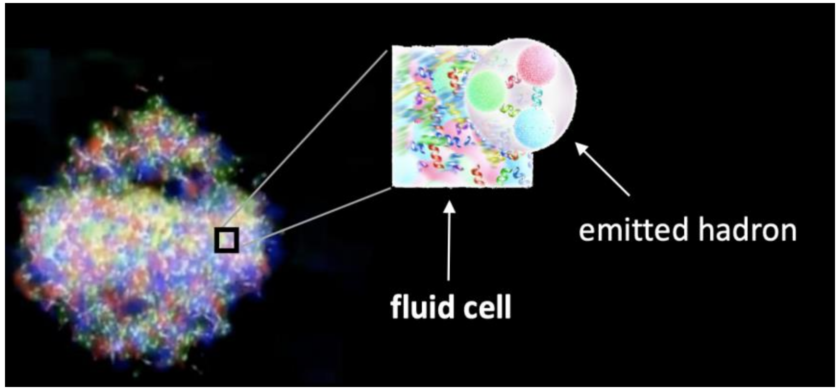
Hydrodynamic description of HIC
(high energies)



Hadronic transport description of HIC
(low energies)







Hadronization and Freeze-out

Emitted particles reflect properties of parent fluid cells

- chemical potentials
- temperatures
- collective velocities
- spin

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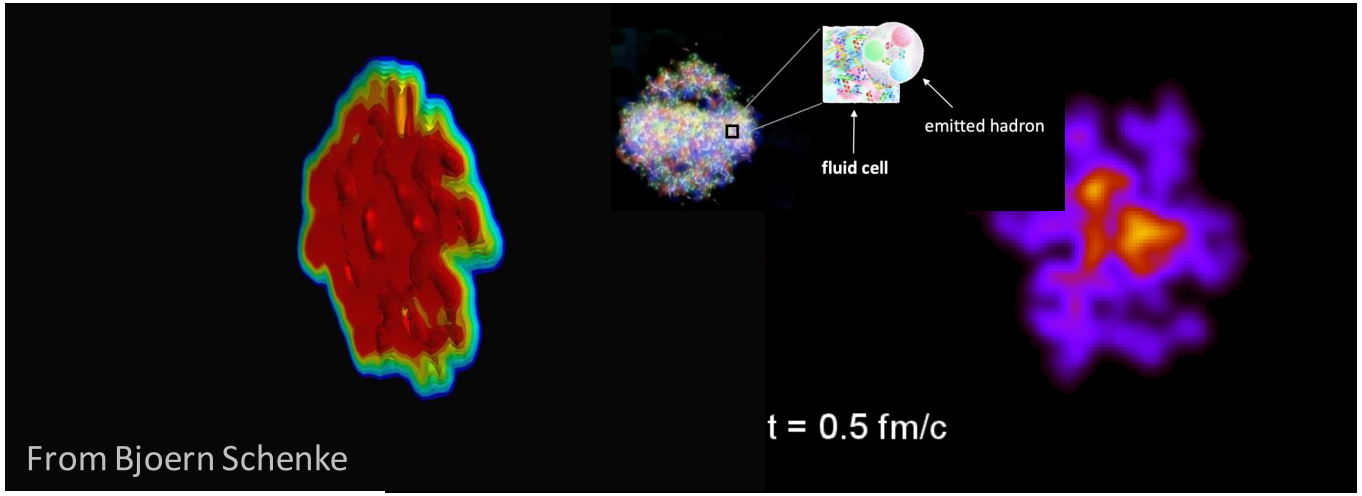

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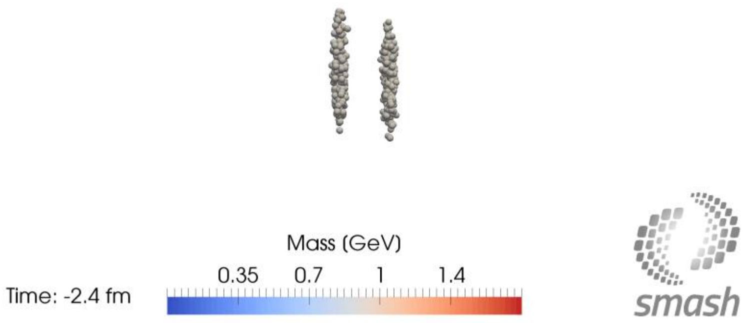
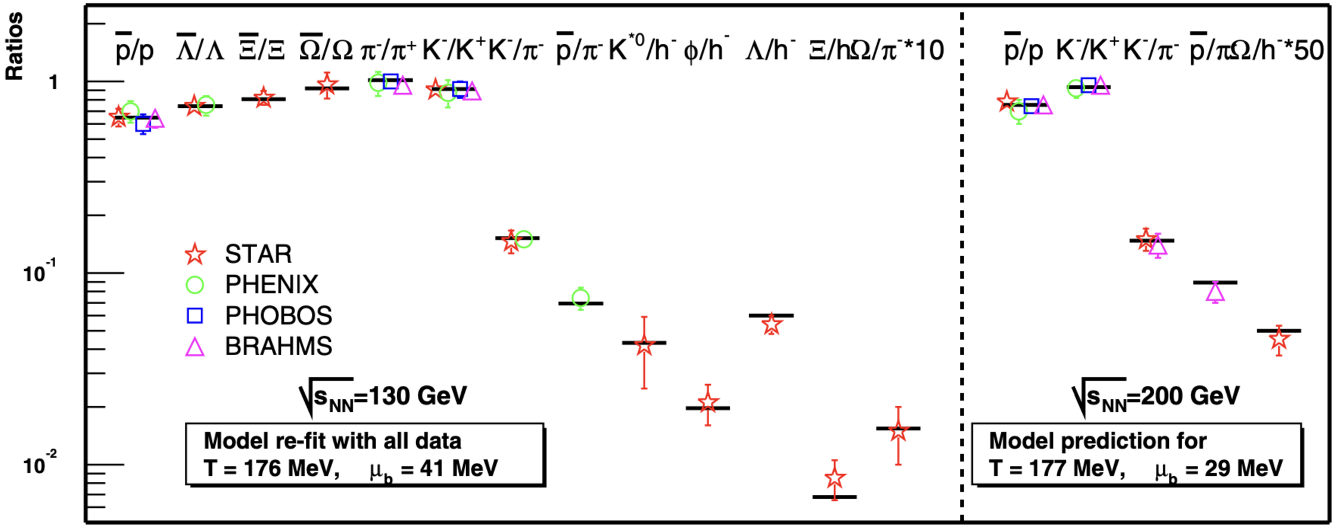


P. Braun-Munzinger et al. PLB 518 (2001) 41; D. Magestro. J. Phys. G 28 (2002) 1745



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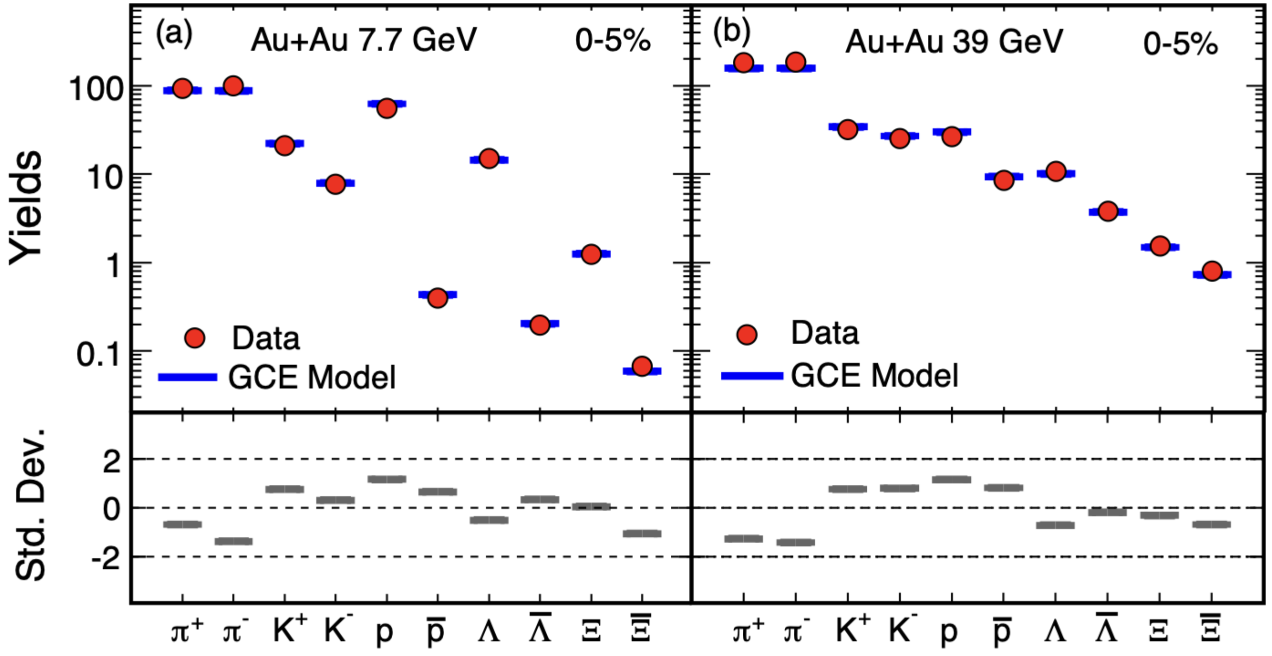
Mapping the QCD Phase Diagram



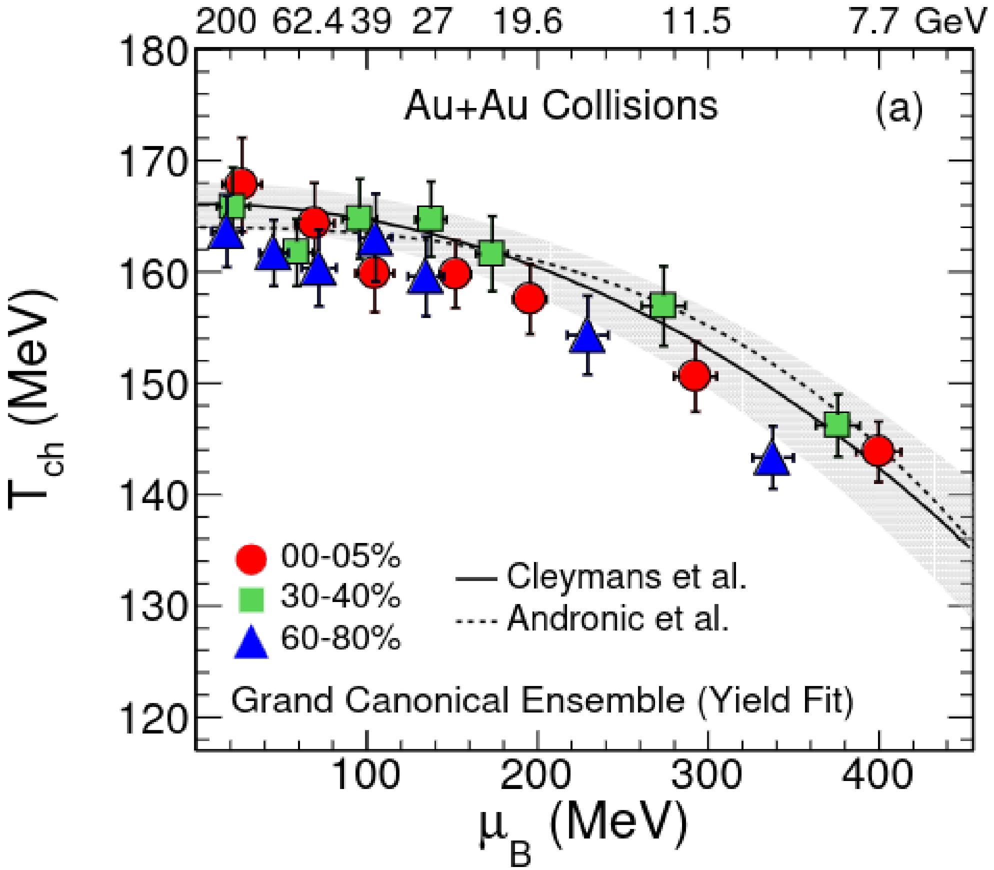
Grand Canonical Ensemble – B, Q and S are conserved on average

Canonical Ensemble – exact conservation of B, Q and S

Strangeness Canonical Ensemble – exact conservation of S

THERMUS model: S. Wheaton, J. Cleymans, and M. Hauer, Comput. Phys. Commun. 180, 84 (2009)

STAR. Phys. Rev. C 96 (2017) 44904



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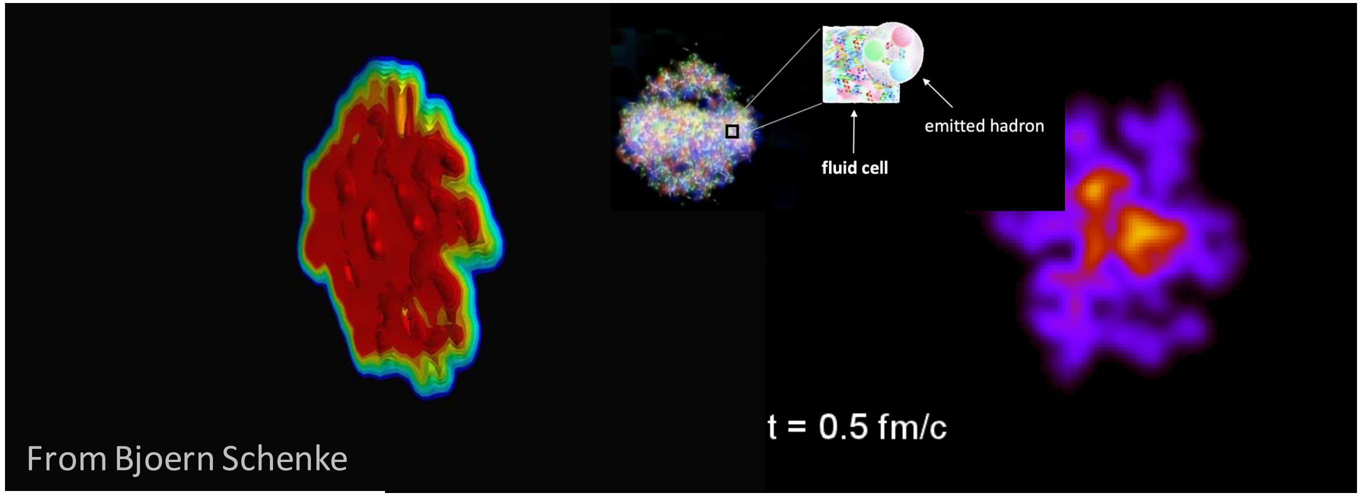

Hadronic transport description of HIC
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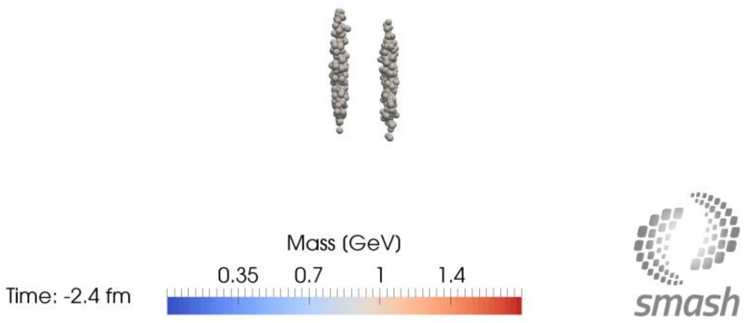
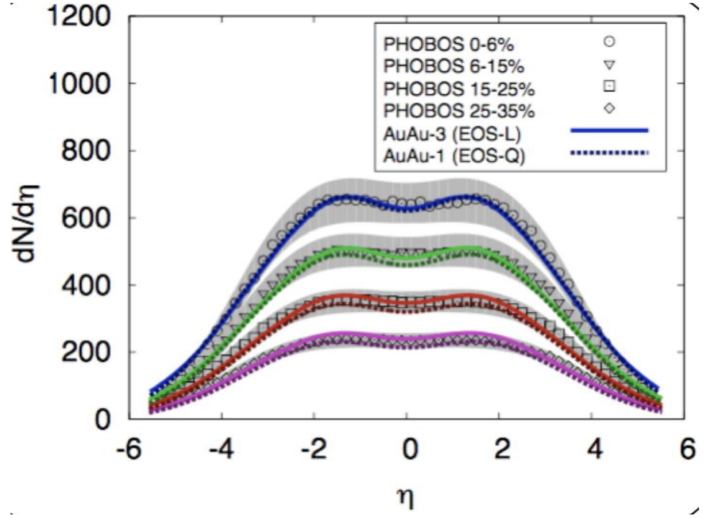
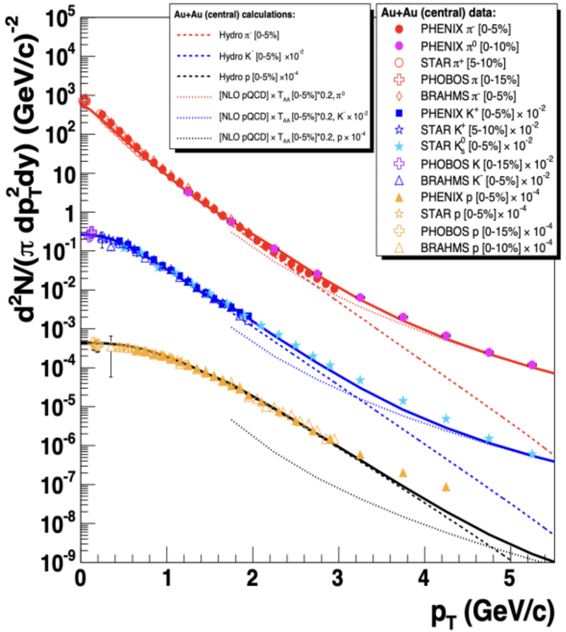


Longitudinal expansion



Transverse momentum



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Importance of Spectra Measurements

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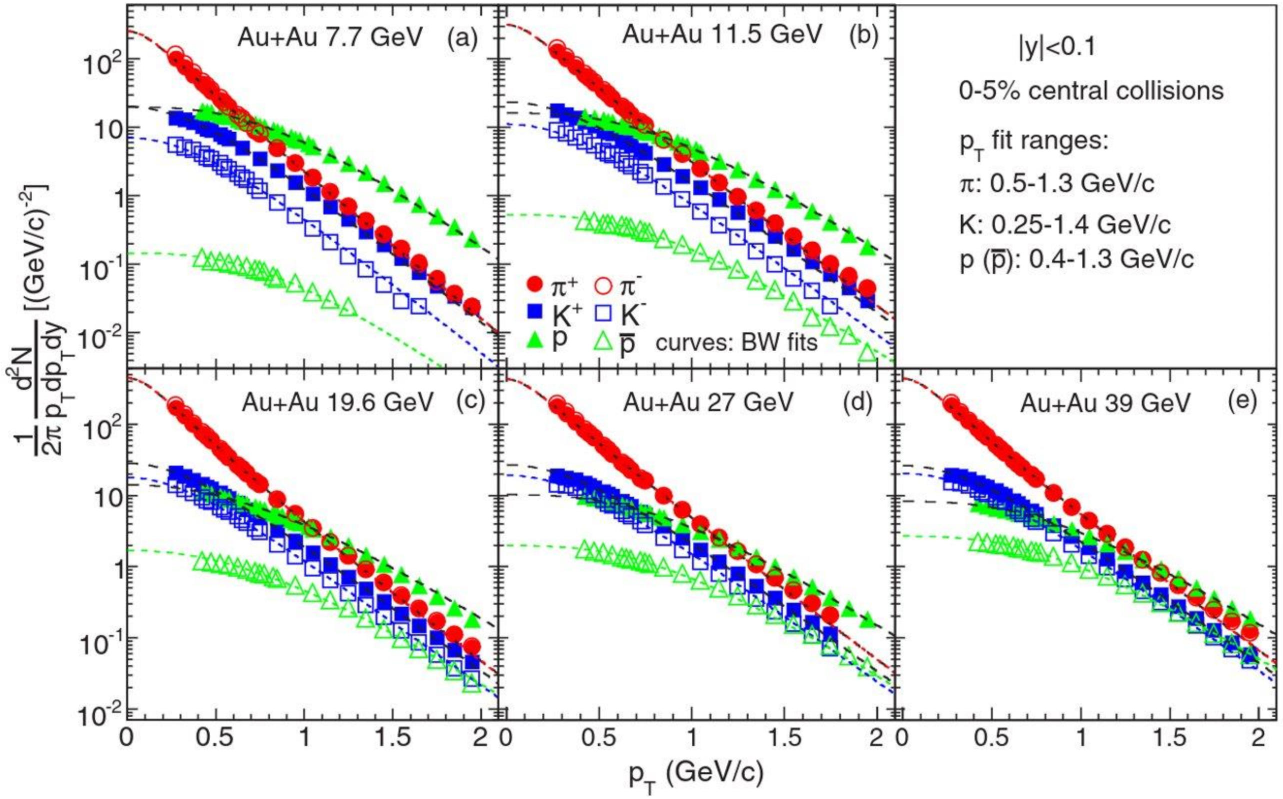
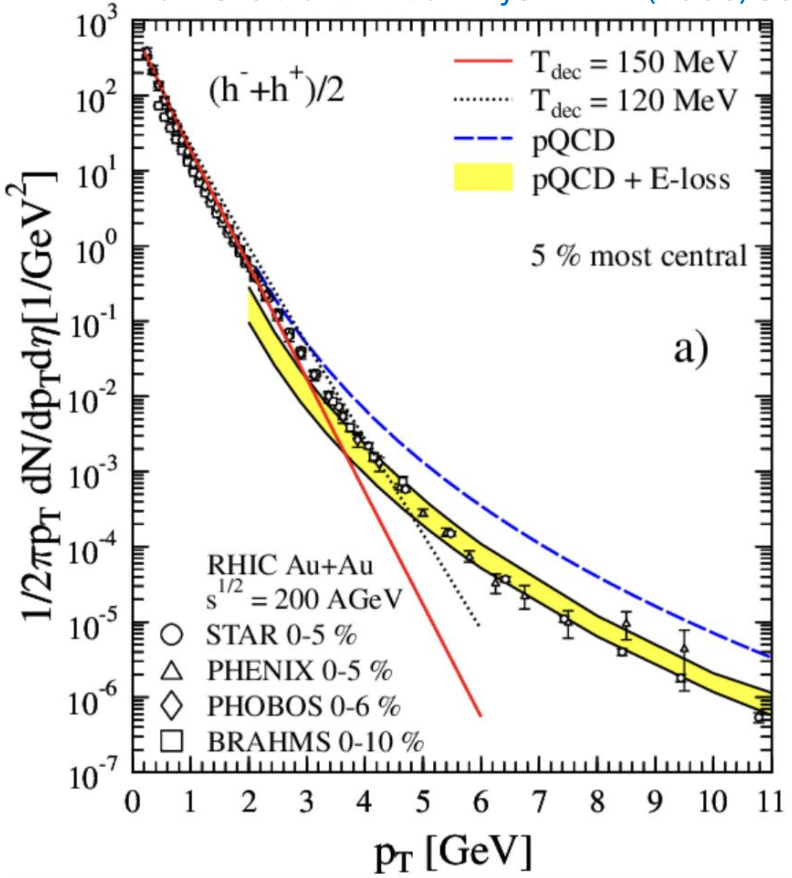


K.J. Eskola et al. Nucl. Phys. A 774 (2006) 805



Parameters: Temperature (T_{kin}) and transverse radial velocity (β) obtained by fitting the momentum distribution of particles

Blast-wave fits for particle spectra

$$\frac{d^2N}{2\pi p_T dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T}\right)$$

Study interplay between "soft" and "hard" physics:

- Perturbative and non-perturbative contribution
- Medium influence on heavy flavor production

QCD Phase Diagram

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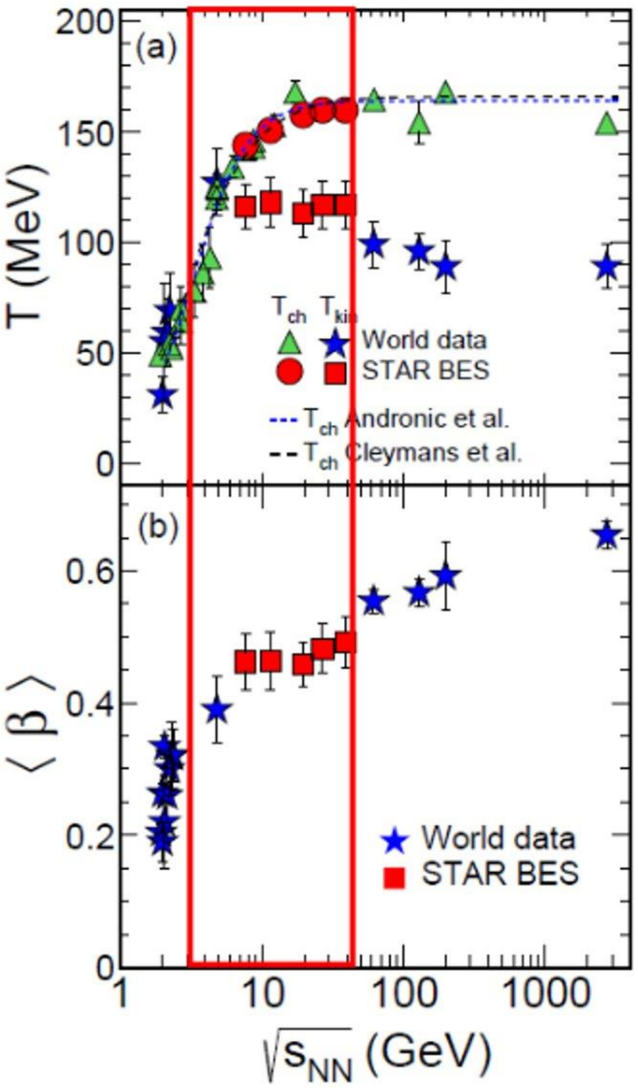
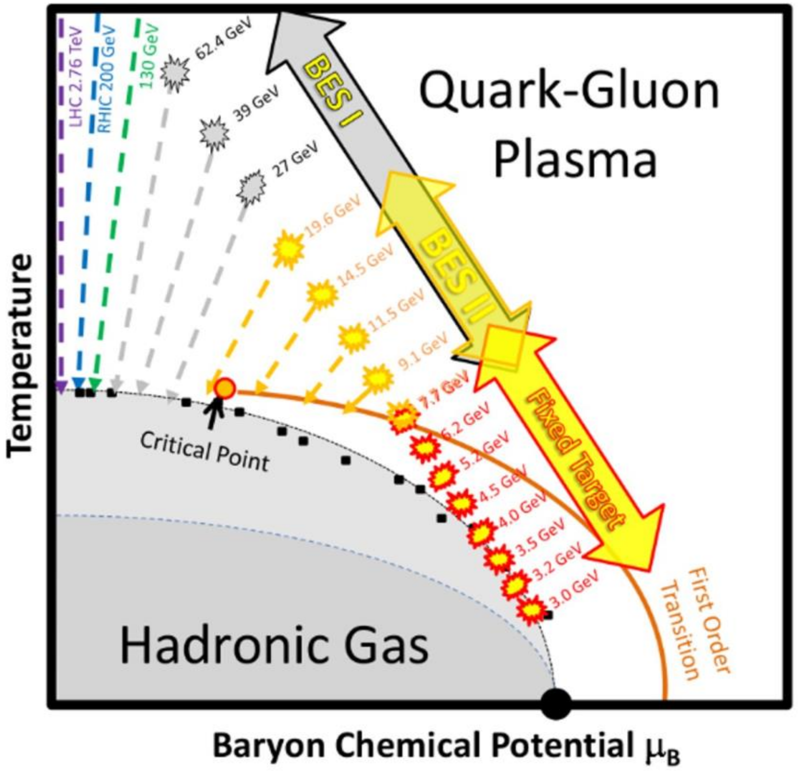
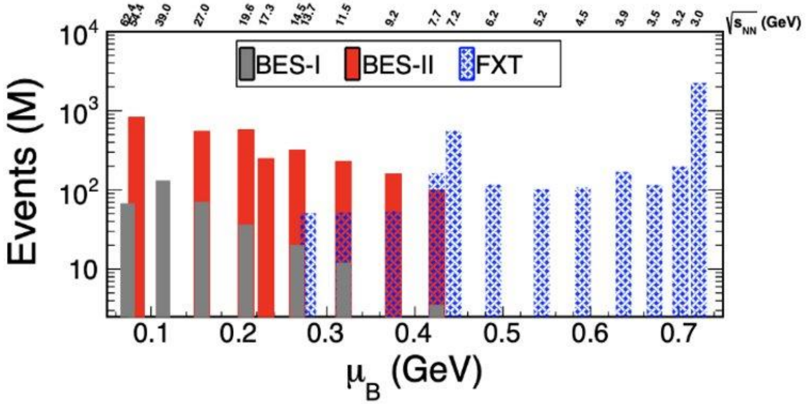


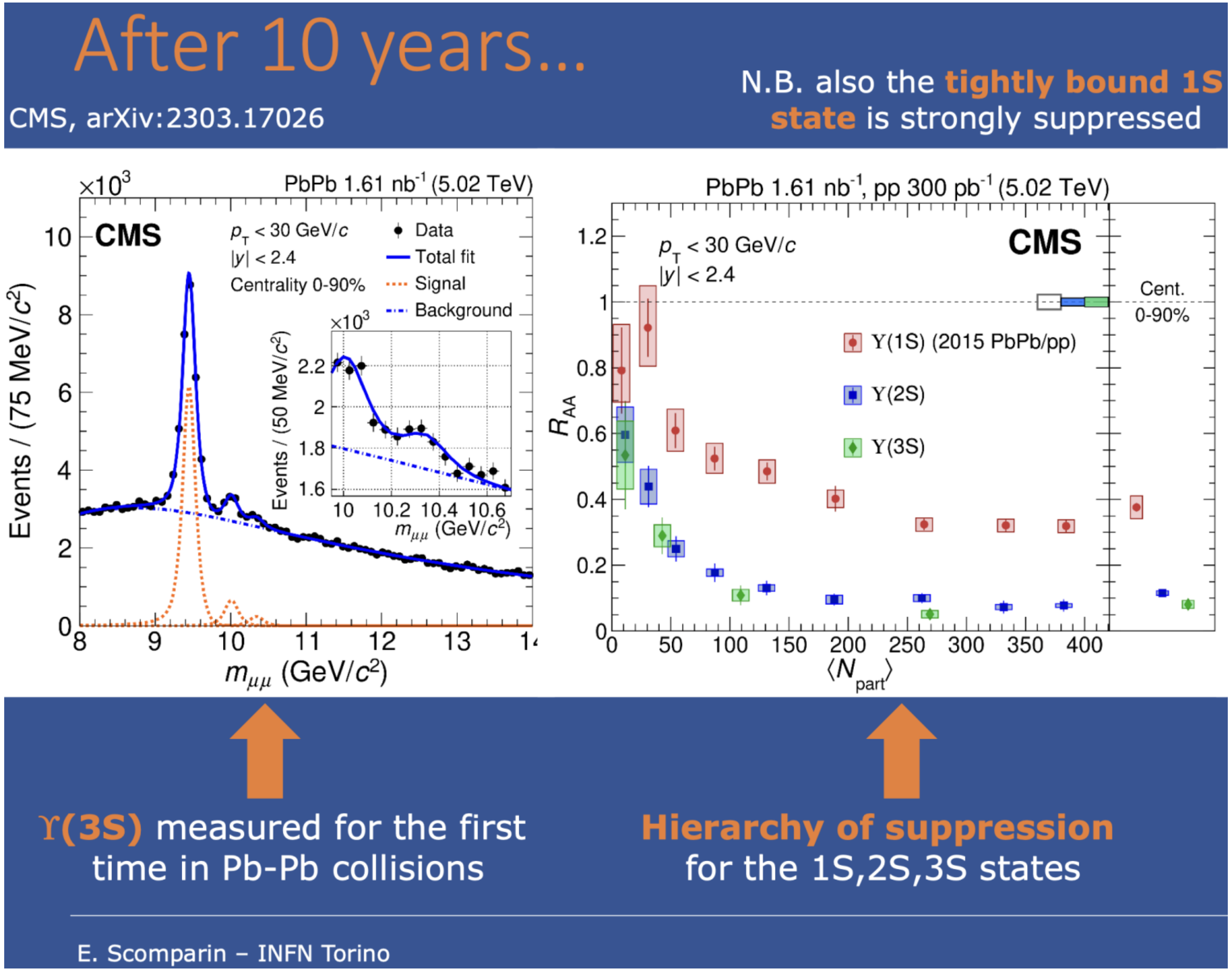




Lack of the light and medium A collision measurements:

- Probing different energy density regimes (different initial system sizes with at the same collision energy)
- Influence of initial state (quarks and gluons, nucleons, clusters, ...)

Heavy Flavor Measurements



From Quark Matter 2023

$$R_{AA} = \frac{d^2 N_{AA}/dy dp_T}{\langle T_{AA} \rangle \, d^2\sigma_{pp}^{INEL}/dy dp_T}$$

Study the mechanism of heavy flavor production in ion-ion collisions at low and intermediate energies

SPD has great opportunity to measure heavy flavor using dimuon channel as well as decays of D mesons with high-precision

Picture of Relativistic Heavy Ion Collision

Hydrodynamic description of HIC
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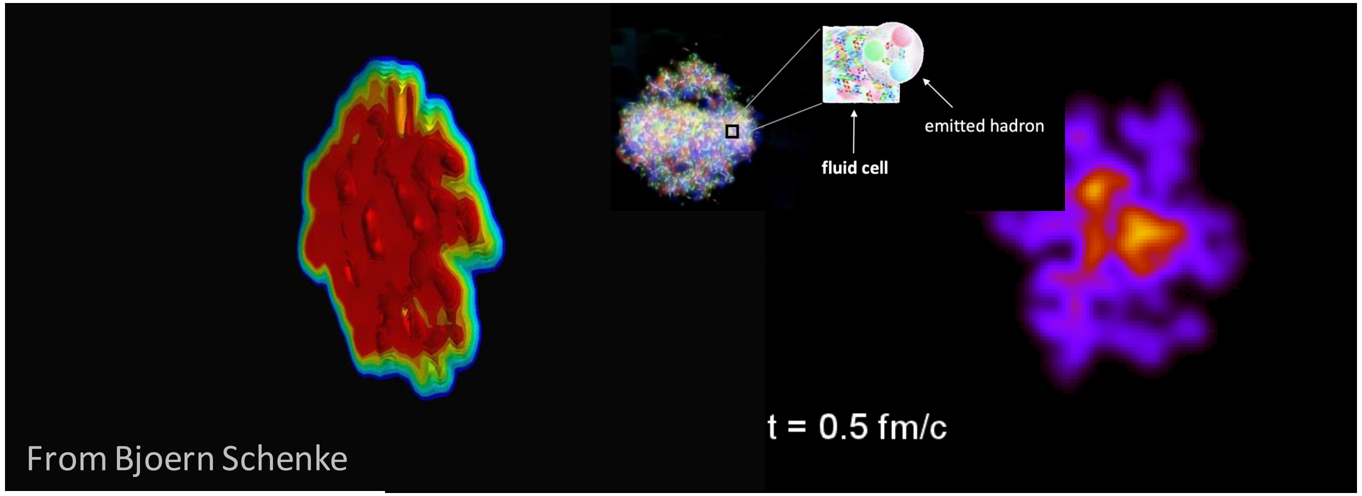

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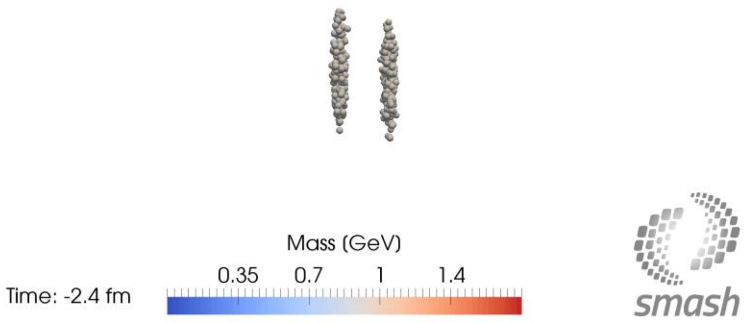

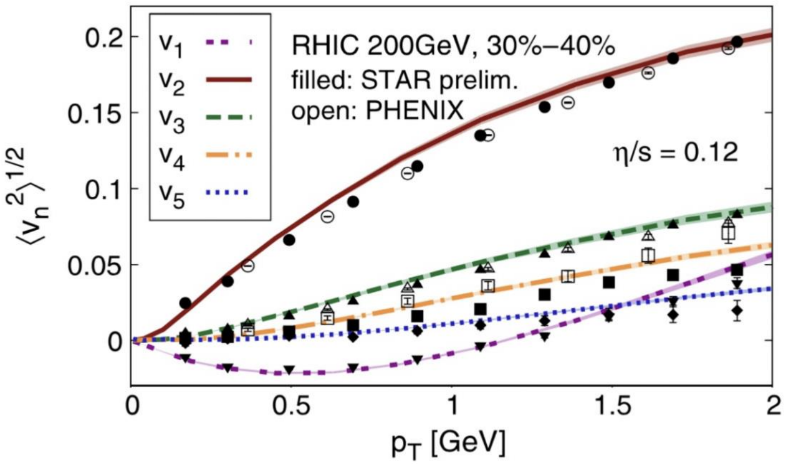

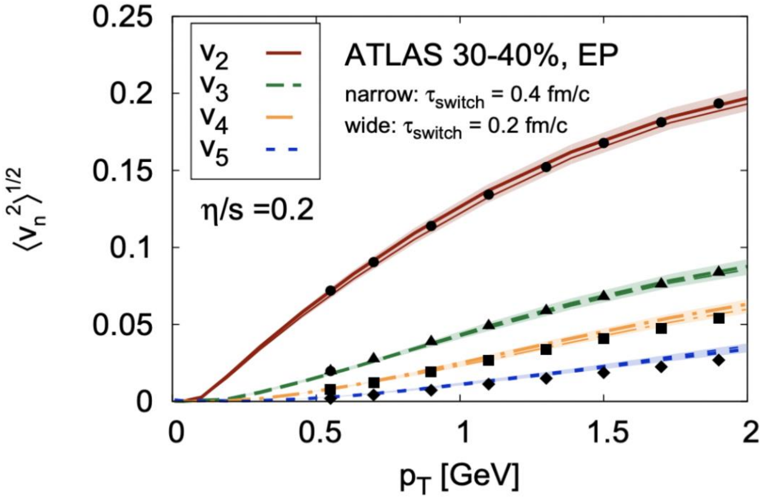

Hadronization and Freeze-out

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Evolution of A+A Collision

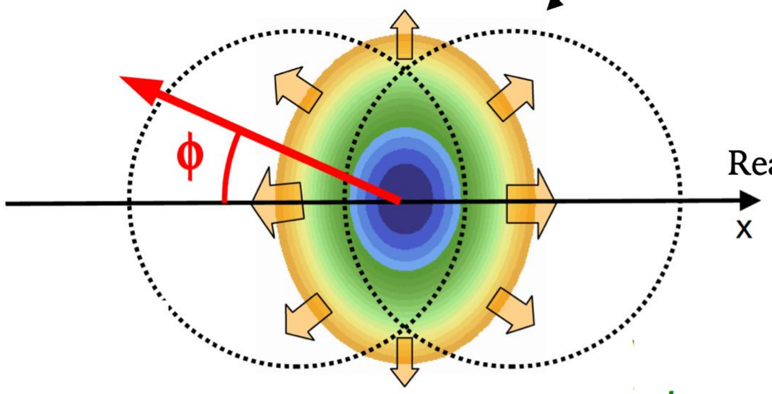
$$\frac{d^3\sigma}{dp^3/E} = \frac{d^3\sigma}{p_T dp_T dy d\phi} \rightarrow \int d\phi \frac{d\sigma}{2\pi p_T dp_T dy}$$ No anisotropy (central collisions)

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1 + 2\sum_{n=1}^{\infty} v_n cos[n(\phi - \Psi_{RP})])$$

Anisotropy present (non-central collisions)

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1 + 2v_1\cos(\phi - \Psi_R) + 2v_2\cos[2(\phi - \Psi_{RP})] + 2v_3\cos[3(\phi - \Psi_{RP})] + \dots)$$

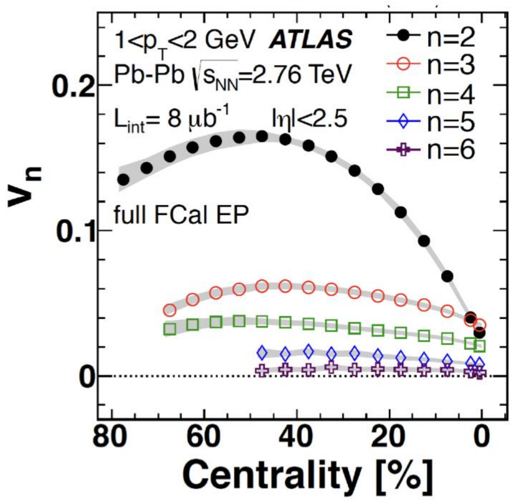
Radial flow Directed flow Elliptic flow Triangular flow



Courtesy of F. Retiere

Bigger pressure gradients *in-plane* that *out-plane*

PRC 86 (2012) 014907



Geometry response:

$v_n \sim \epsilon_n$

System size:

Less interactions develop less flow

- **Radial flow** continues to increase until thermal freeze-out (sensitive to **early** and **late stages** of collision);
- **Directed flow** is sideward motion of produced particles and nuclear fragments (sensitive to **early phase**);
- **Elliptic flow** built in **early phase** (saturates after spatial asymmetry and pressure gradients disappear);
- **Triangular** flow sensitive to **initial state** e-b-e fluctuations

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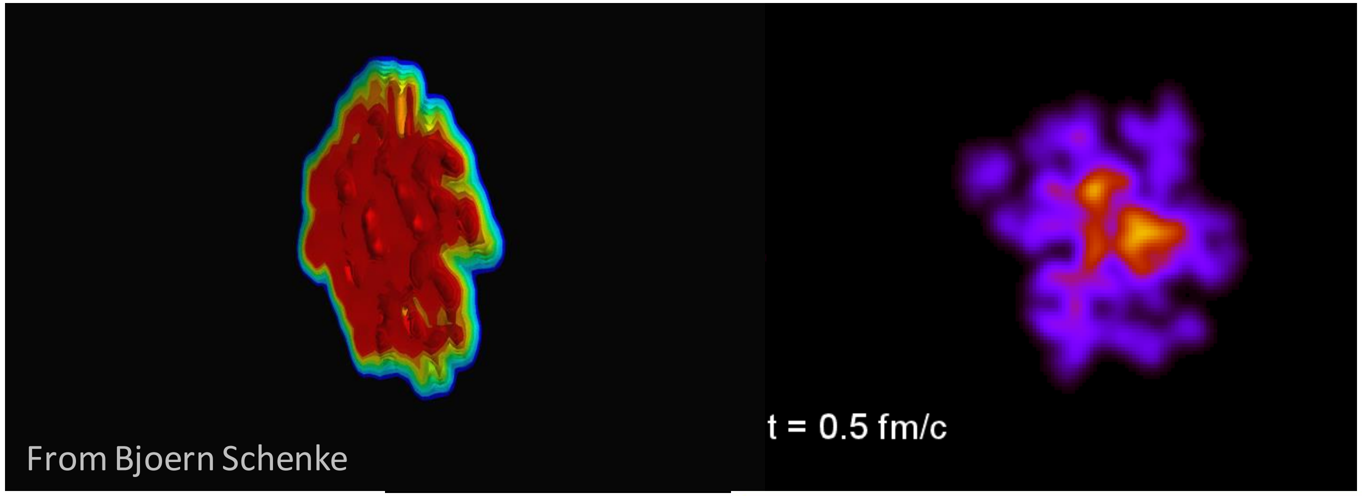

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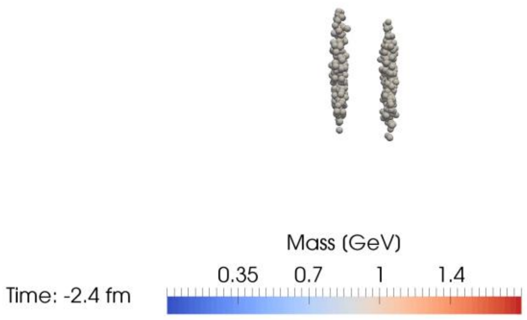
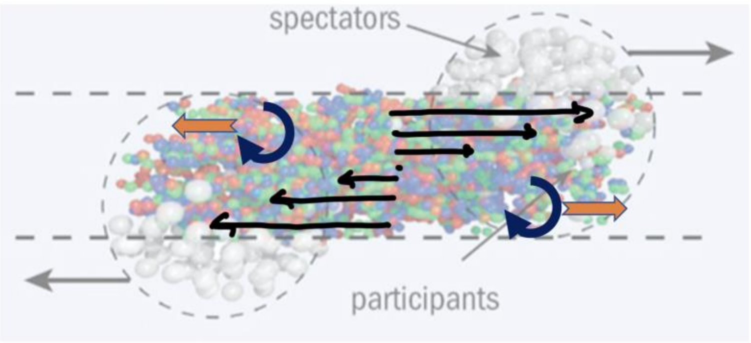
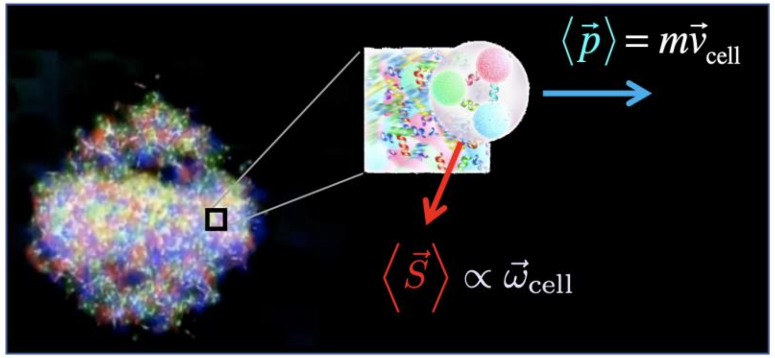


smash





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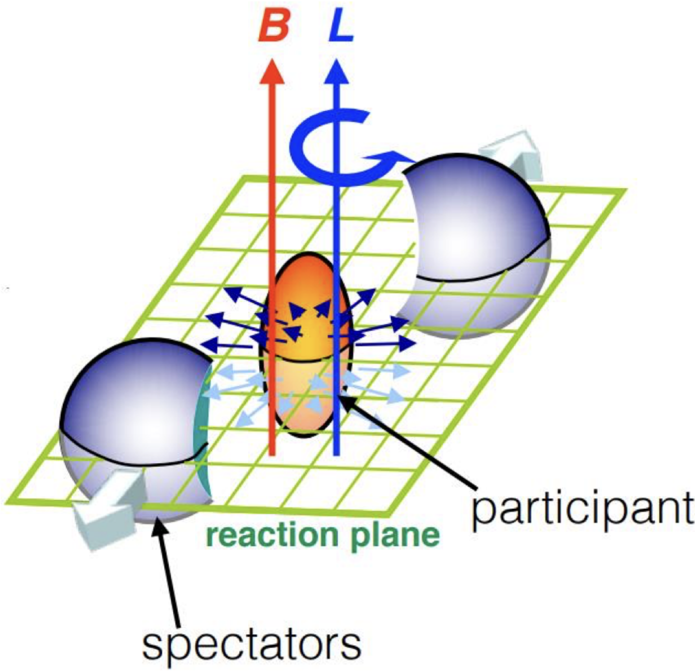
$$p(T, \mu_i, \mathbf{B}, \boldsymbol{\omega}) \propto \exp[(-E + \mu_i Q_i + \boldsymbol{\mu} \cdot \mathbf{B} + \boldsymbol{\omega} \cdot \mathbf{J})/T]$$

Polarization

$$\vec{P} \equiv \frac{\langle \vec{S} \rangle}{|\vec{S}|}$$

Vorticity in Heavy Ion Collision

- The Quark-Gluon Plasma (QGP) formed in non-central nucleus-nucleus collisions is associated with large angular momentum, that leads to vorticity in the medium
- Spin-orbit coupling aligns spin directions of produced particles along the direction of vorticity
  - Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)
  - S. A. Voloshin, arXiv:nucl-th/0410089
- Another possible source of particle polarization is magnetic field, created in non-central collisions in the initial stage
  - D. Kharzeev, L. McLerran, and H. Warringa, Nucl.Phys.A803, 227 (2008)
  - McLerran and Skokov, Nucl. Phys. A929, 184 (2014)



How to Measure?

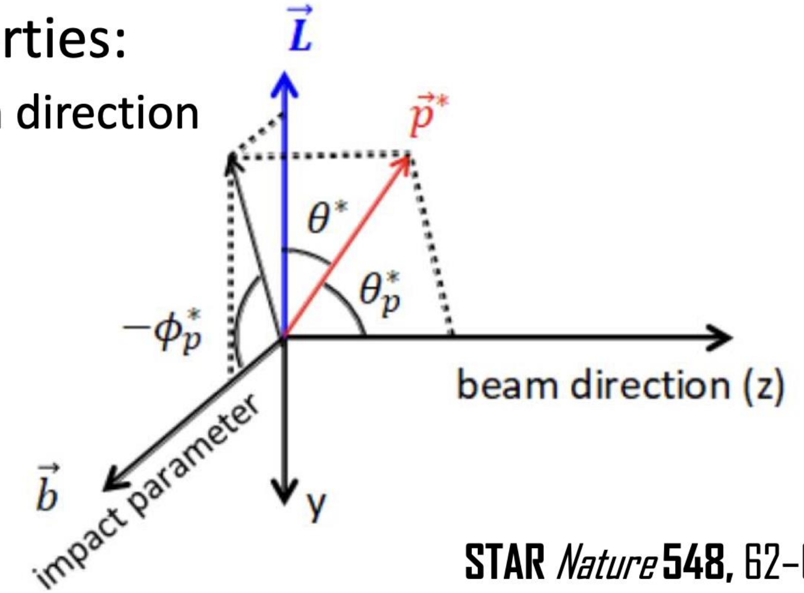
- Hyperons are “self-analyzing” due to weak decay properties:
  - Daughter baryons are preferentially emitted along parent spin direction
- Daughter baryons of hyperons with polarization ($\vec{P}$) follows the distribution:

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_H |\vec{P}| \cdot \widehat{p_b^*}\right) = \frac{1}{4\pi}\left(1 + \alpha_H P \cos\theta^*\right)$$

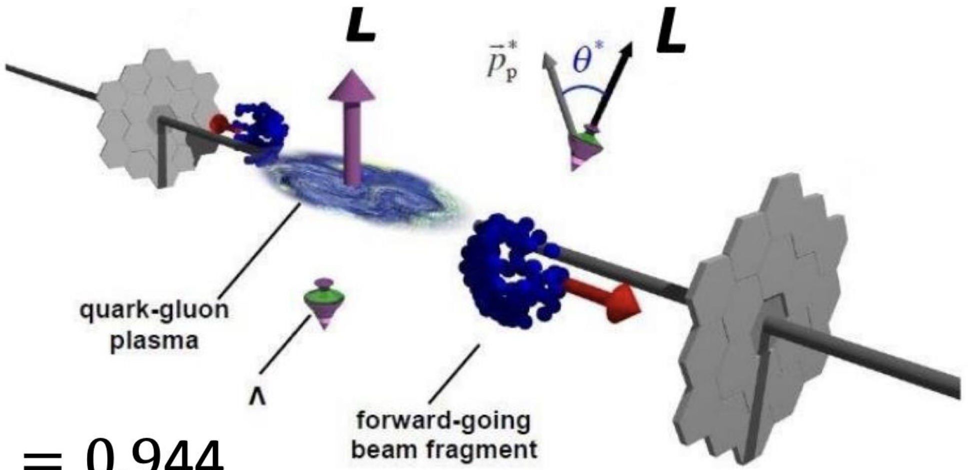
  - α_H - decay parameter, unique for each hyperon species
  - $\widehat{p_b^*}$ is the daughter baryon momentum in the parent frame
- Projection to the transverse plane can be measured:

$$P_H = \frac{8}{\pi\alpha_H}\frac{\langle sin(\psi_1 - \varphi_p^*)\rangle}{Res(\psi_1)}$$

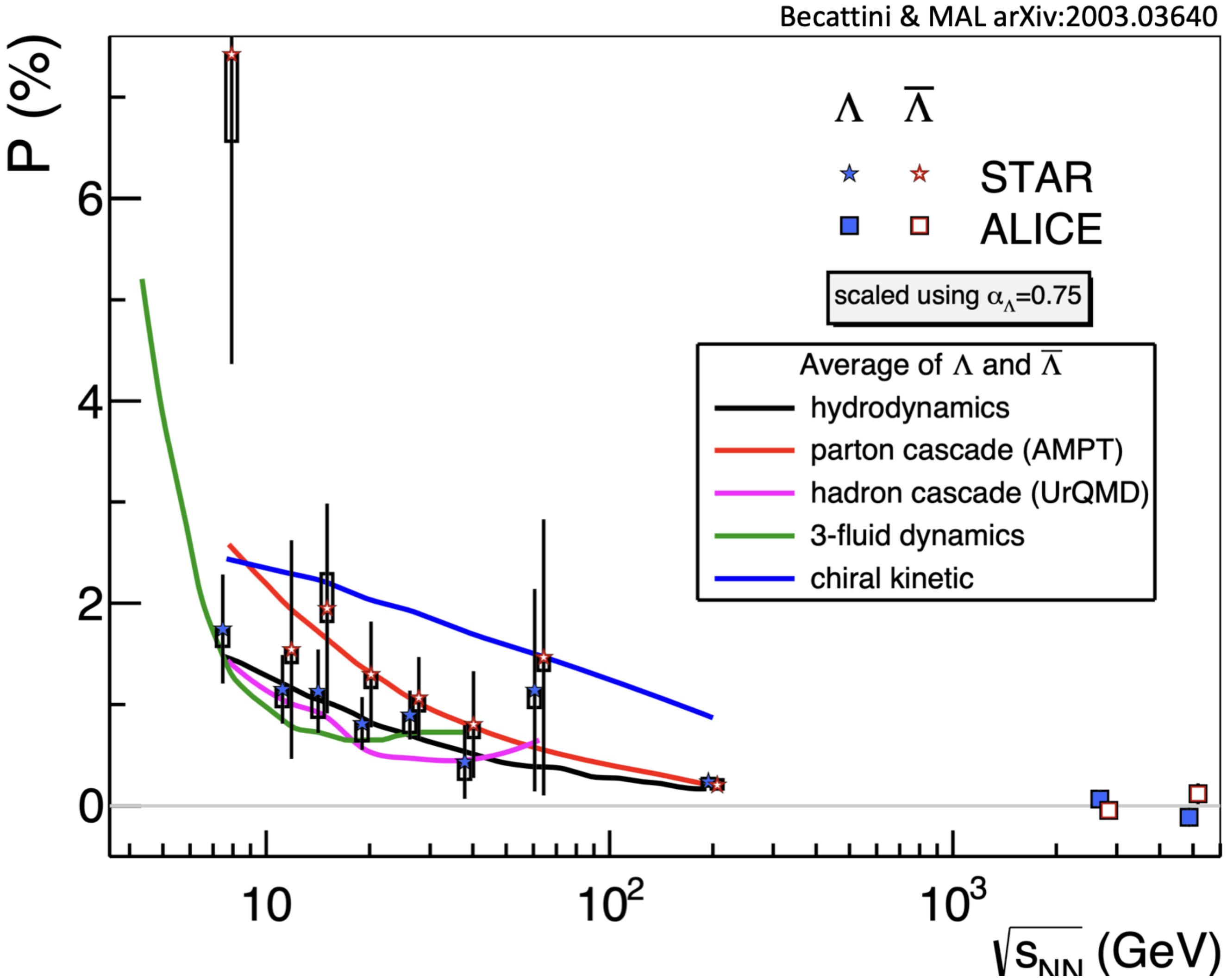
  - ψ_1 is first-order event plane angle (proxy for reaction plane)
  - ψ_1 and its resolution $Res(\psi_1)$ can be calculated with spectator’s signal.
- Ξ global polarization could also be measured via its daughter Λ polarization with transfer factor $C_{\Xi\Lambda} = 0.944$



STAR *Nature* **548**, 62–65 (2017)



Lambda Global Polarization



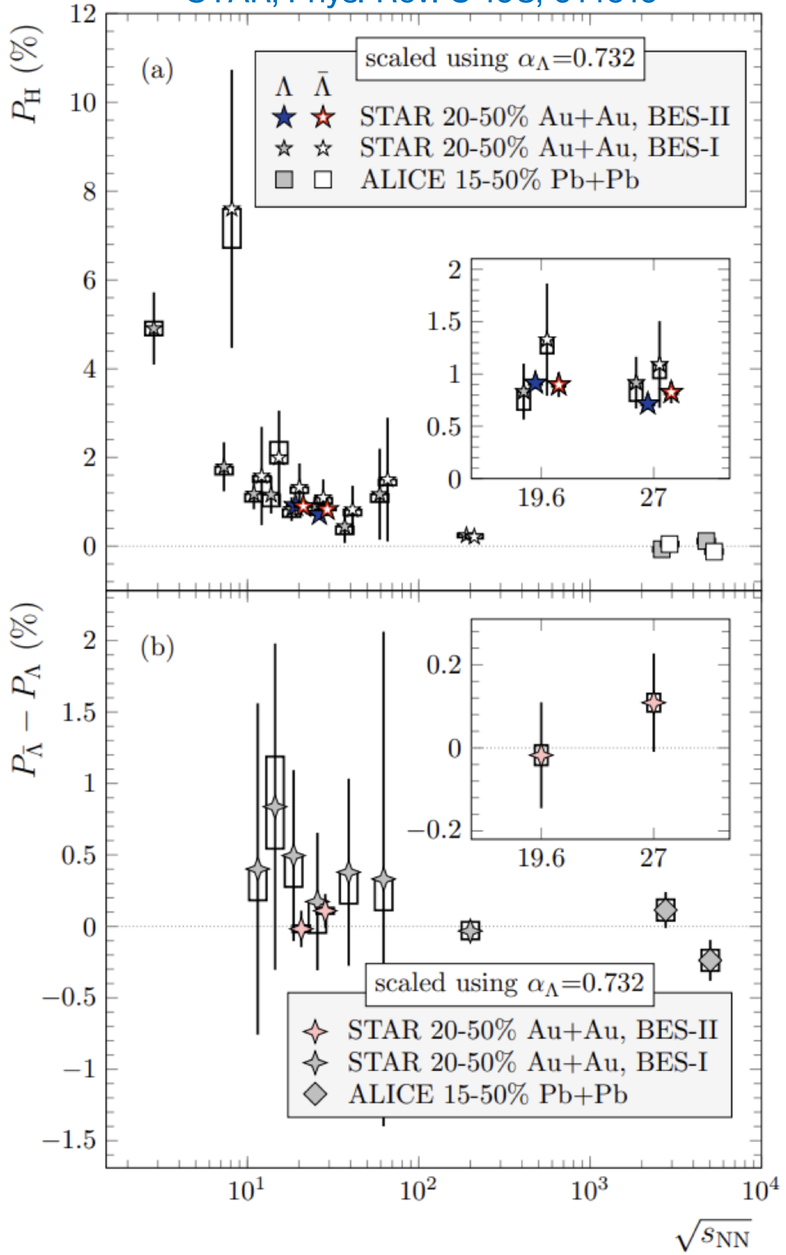
- Global polarization observed at RHIC in quantitative agreement with standard hydro ***pre***dictions [1]
- Three-fluid hydro, especially important at low root(s) [2]
- Transport calculations (coarse-graining to calculate vorticity) [3,4] & kinetic+coalescence [5]

[1] Karpenko I, Becattini F. Eur. Phys. J. C77:213 (2017)
[2] Ivanov YB, Toneev VD, Soldatov AA. Phys. Rev. C100:014908 (2019)
[3] Li H, Pang LG, Wang Q, Xia XL. Phys. Rev. C96:054908 (2017)
[4] Vitiuk O, Bravina LV, Zabrodin EE arXiv:1910.06292 [hep-ph] (2019)
[5] Sun Y, Ko CM. Phys. Rev. C96:024906 (2017)

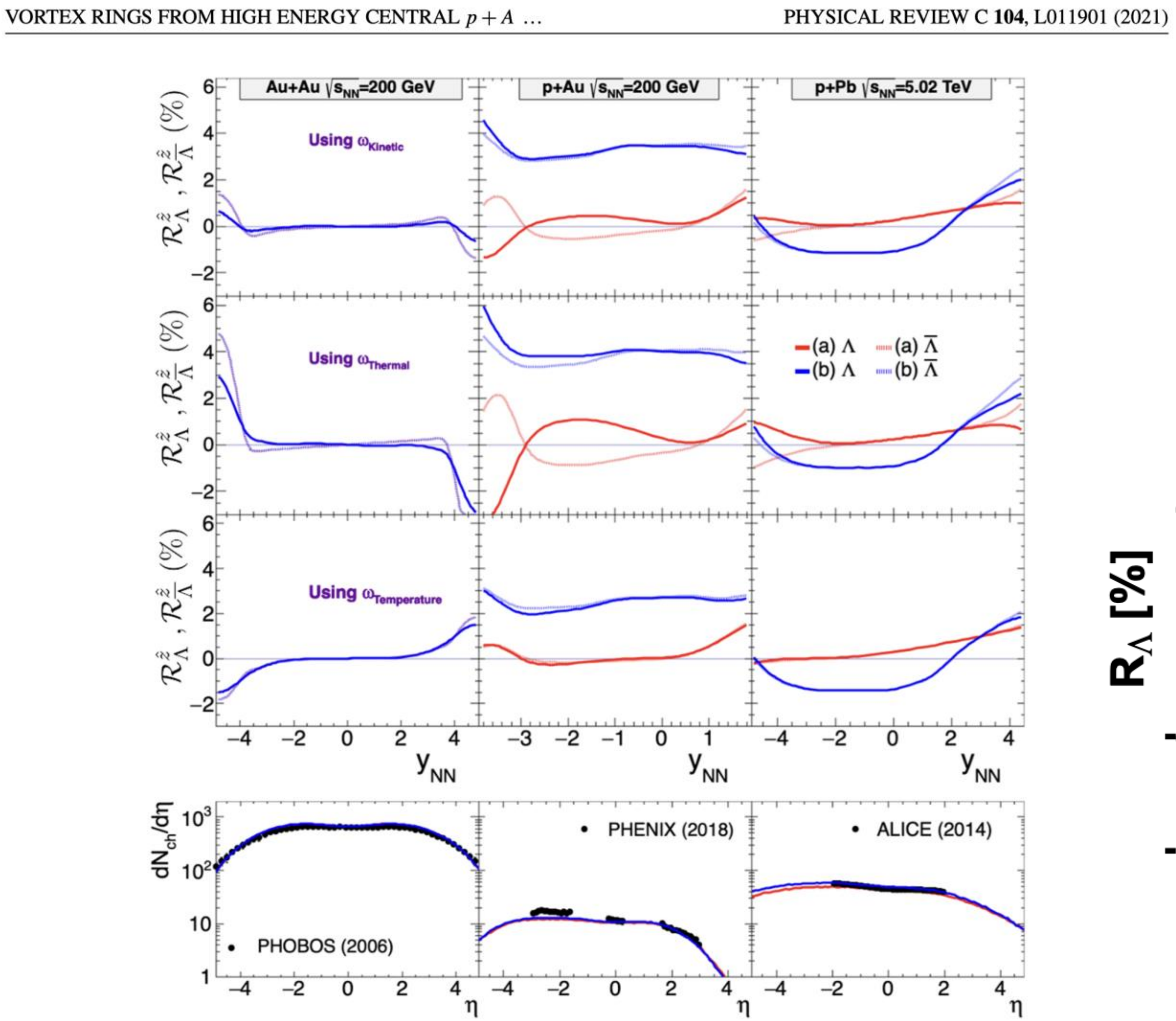
Lambda Global Polarization

- Global polarization of Λ hyperons was measured for $\sqrt{s_{NN}}$ = 3-200 GeV at STAR
- P_H decreases with increasing collision energy
- Theoretical calculations can quantitatively explain the energy dependence of the Λ polarization, but many of them fail to explain differential measurements
- Nowadays there is a growing interest to measure the global polarization of other hyperons such as Ξ.
- Ξ and Ω hyperons global polarization was measured in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
- <u>Ξ polarization may provide new input for global polarization and vorticity studies</u>

STAR, Phys. Rev. C 108, 014910



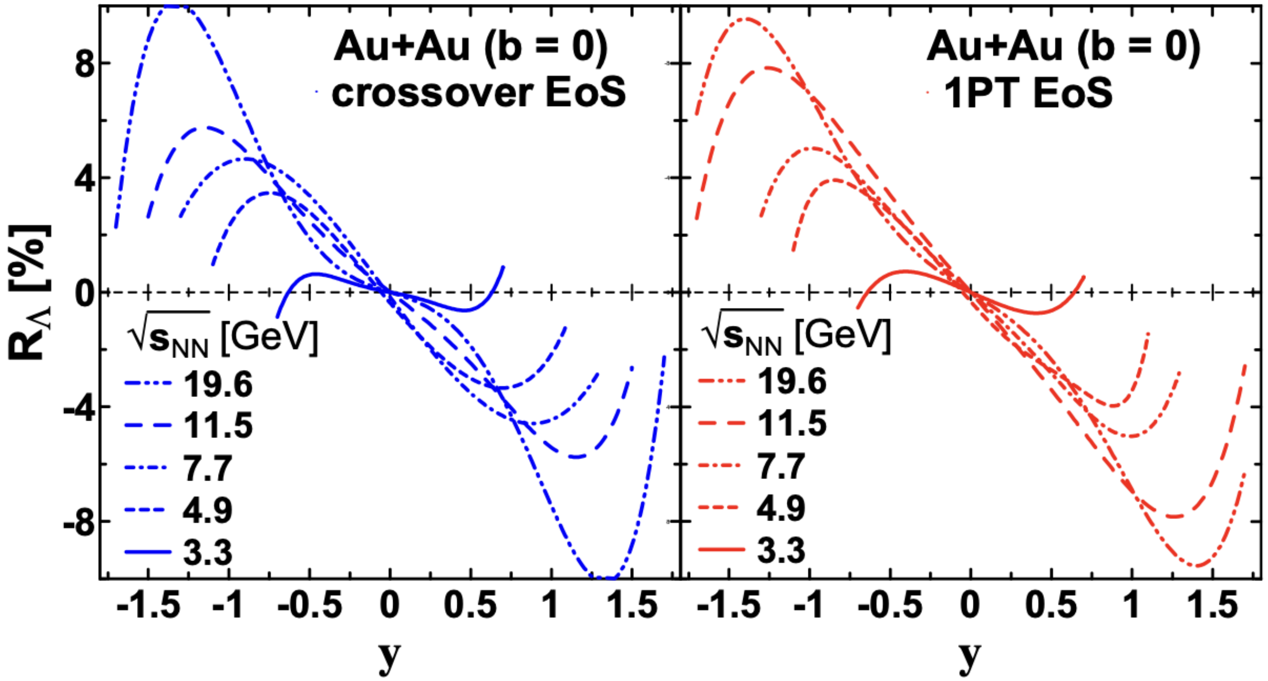
Rapidity Dependence of G.P.



Rapidity dependence of global hyperon polarization will provide important insights on the vorticity development in the medium

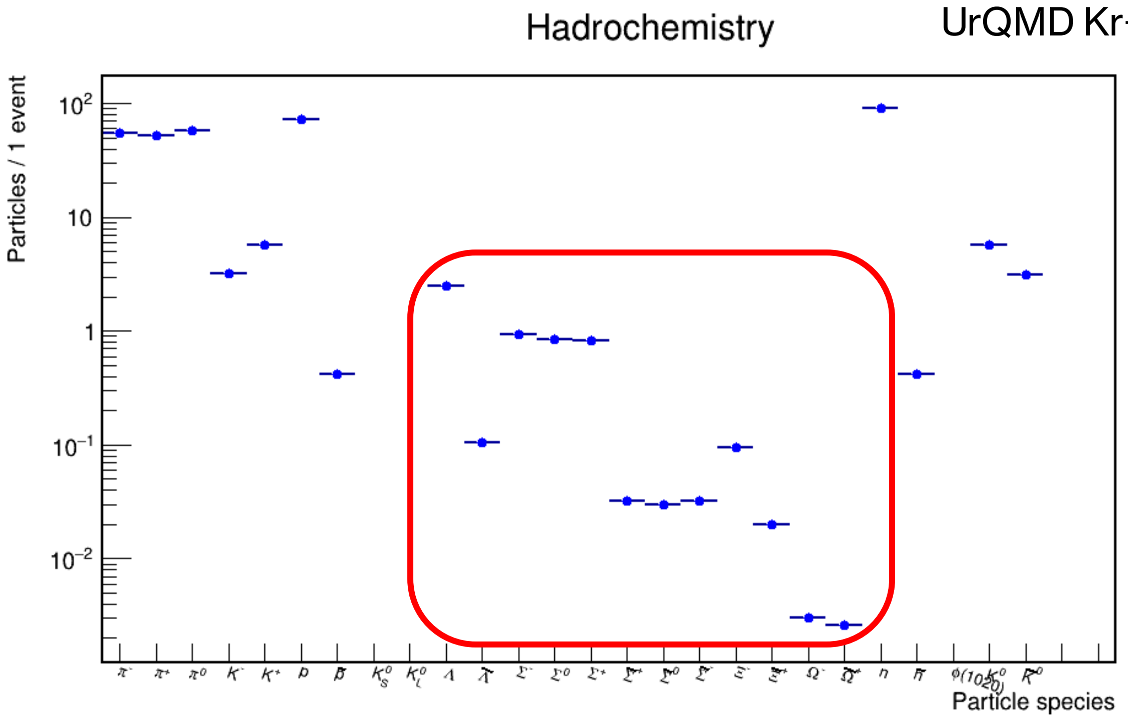
- Forward rapidity measurement is important

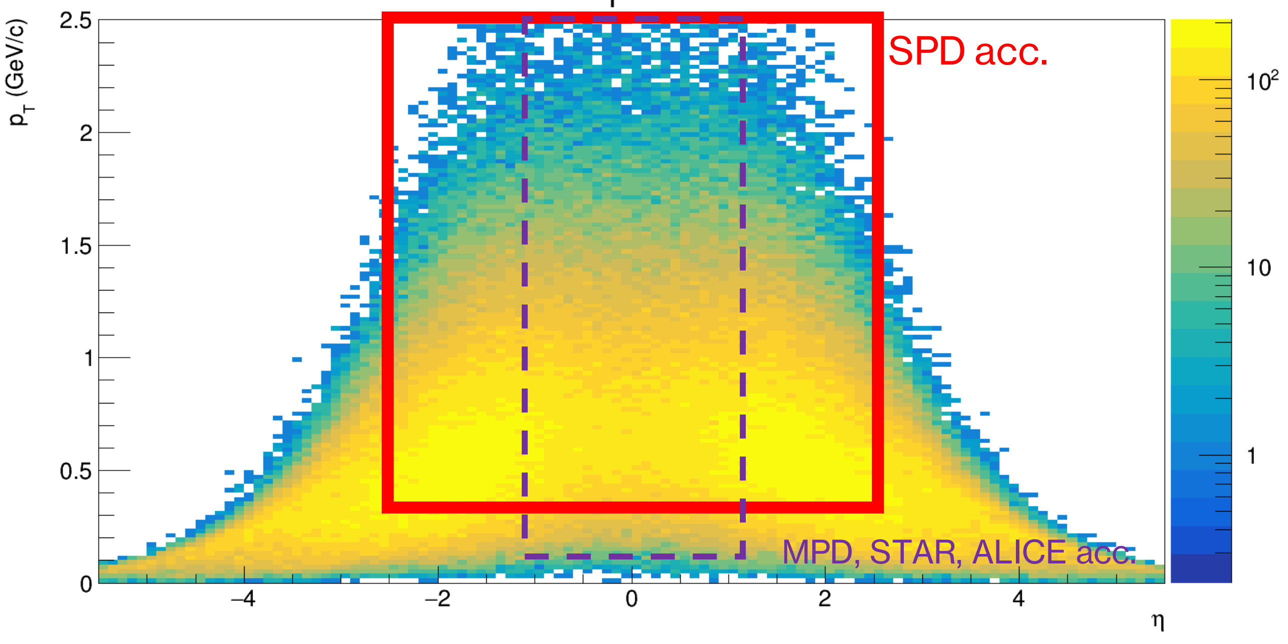
Yu.B. Ivanov. Phys. Rev. C 107 (2023) 2, L021902



Rapidity Dependence of Vorticity

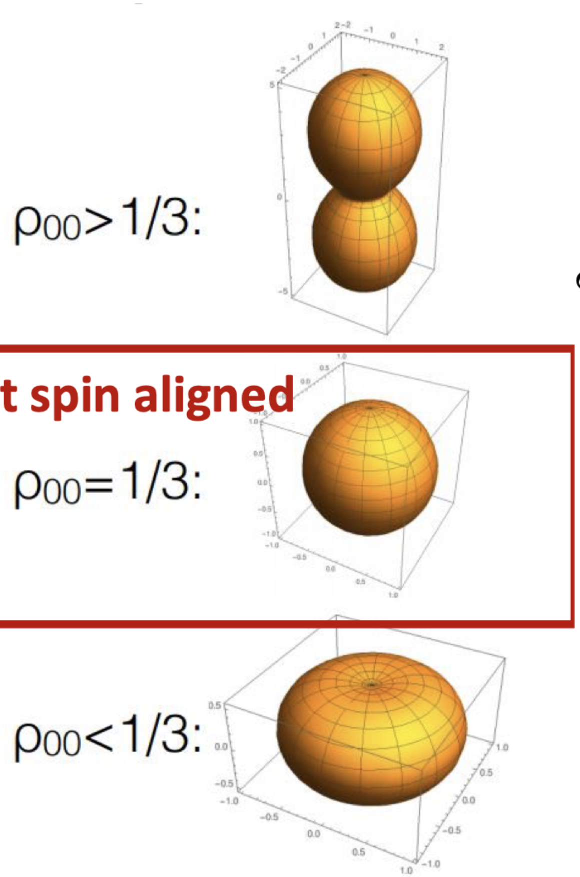
UrQMD Kr+Kr at $\sqrt{s_{NN}}$ = 12 GeV





- Simulation (without detector response) for Kr+Kr collisions at $\sqrt{s_{NN}}$ = 12 GeV
- Need to understand occupancy effects
- Many particles of interest in the SPD acceptance. Opportunity to pin down the spin transfer and provide high-accuracy measurements of the vortical structure of medium

Vector Meason Spin Alignment

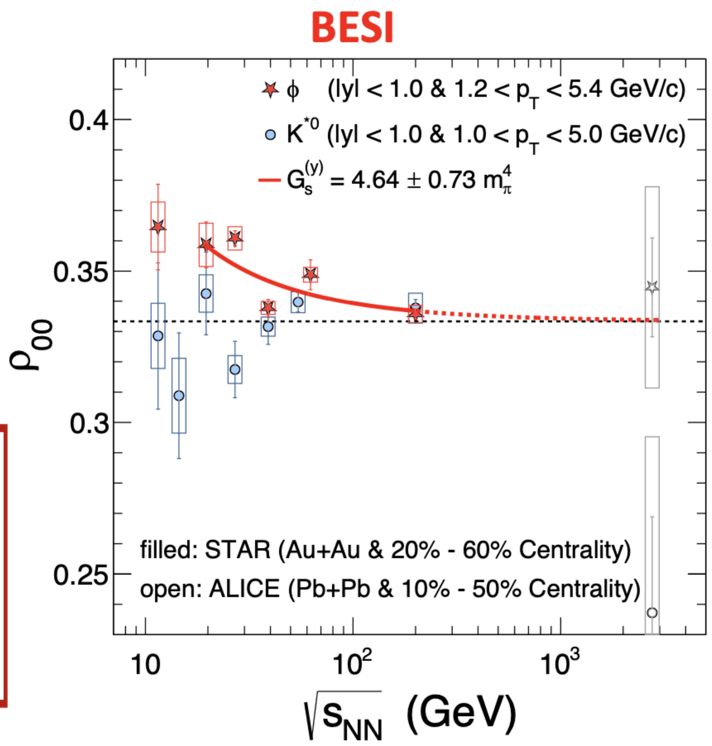


$K^{*0} \to \pi + K$

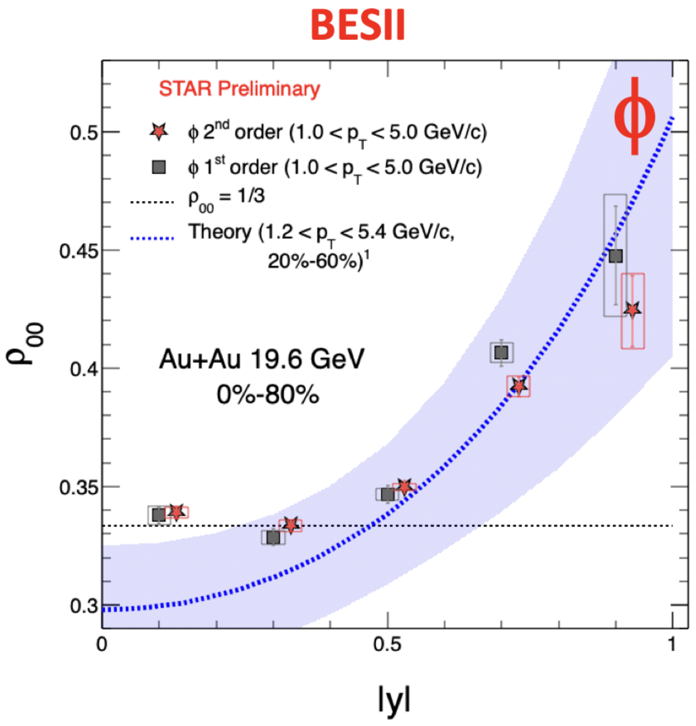
$\phi \to K^- + K^+$

$$\frac{dN}{d\cos\theta^*} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

$$\rho_{00} = \frac{1}{3} - \frac{4}{3}\langle\cos[2(\phi_p^* - \Psi_{RP})]\rangle$$



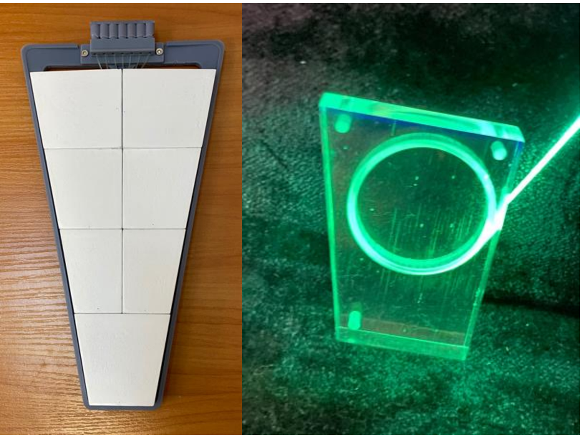
STAR, Nature 614 244 (2023)



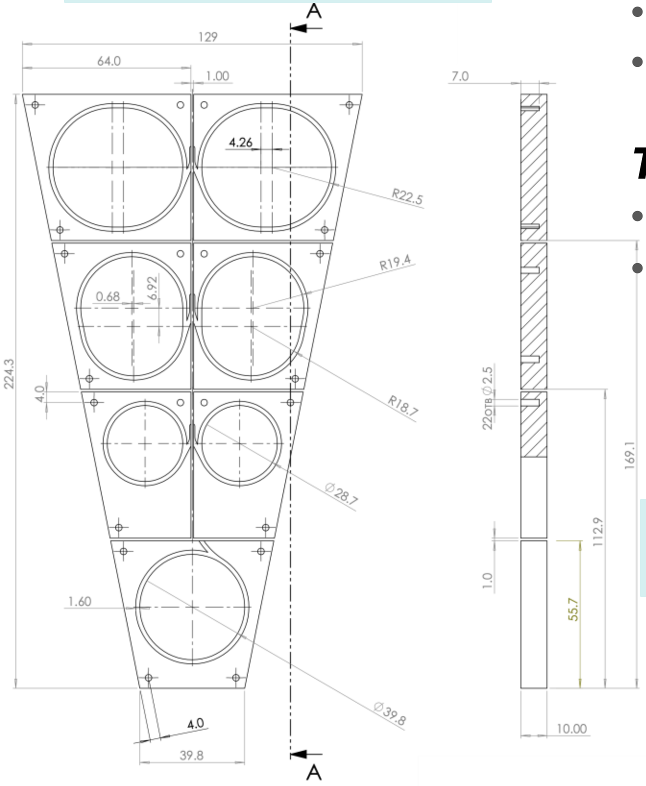
- **ϕ meson** ρ_{00} results indicate **spin alignment** → BESII results more significant.
- **Rapidity dependence roughly agrees** with theory invoking strong force field.

Rosi Reed - Quark Matter 2023

MEPhI Group Activities



7 tiles and test assembly



Hardware

- MEPhI group in collaboration with the LHEP JINR team is on the way to the 7-tile protype of BBC detector
- Materials selection
  - Chemically matted is preferred (not Tyvek)
  - Optical cement selection: still TBC
  - Kuraray Y-11 WLS is preferred

Physics and software

- Developing physics case for ion-ion physics with SPD
- Particle physics with polarized and unpolarized beams

Talks

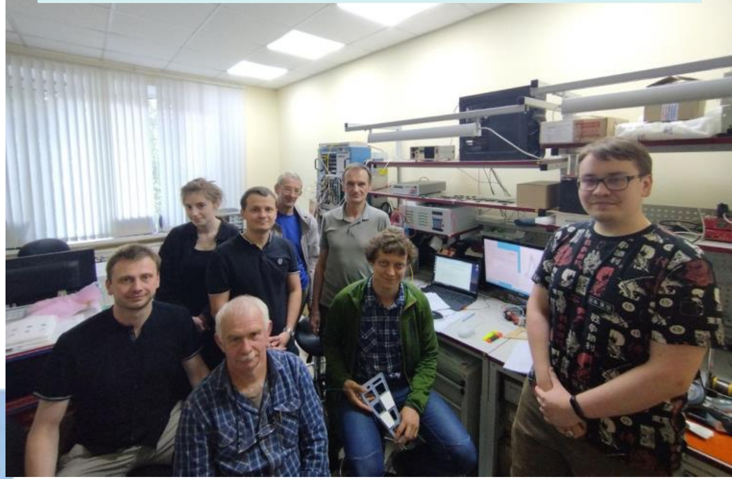
- Baldin Seminar (Arseniy Zakharov)
- AYSS (Arseniy Zakharov)

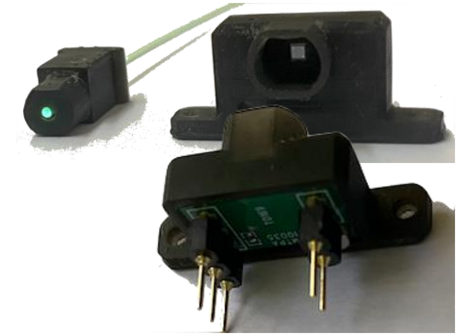
For details of the BBC design see Alexey Tishevsky's talk Tue. 1 pm

1-tile cosmic test setup in JINR

Tests in MEPhI (summer 2023)

Tests in JINR (summer 2023)





Summary

- Measurements of relativistic ion-ion collisions allow to test QCD in the laboratory
- Many interesting open questions that could be explored with SPD
  - Temperature and baryon chemical potentials at different energy densities
  - Effects of perturbative and non-perturbative regime on in-medium particle production
  - Viscosity and initial state influence on final-state particle production
  - Vortical structure of the QCD medium
- SPD has a unique capabilities to study medium properties in collisions of small (pp, pd, dd) and medium (Ar, O, Kr, Xe?) systems