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EXCELENCIA MARÍA DE MAEZTU 04/2025-03/2031

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Relativistic Heavy-Ion Collisions: from the initial to the final state

Juan Torres-Rincon. Universitat de Barcelona & ICCUB

Hadron and Nuclear Physics group workshop

Barcelona, 01/26/2025

Project ID: PID2023-147112NB-C21

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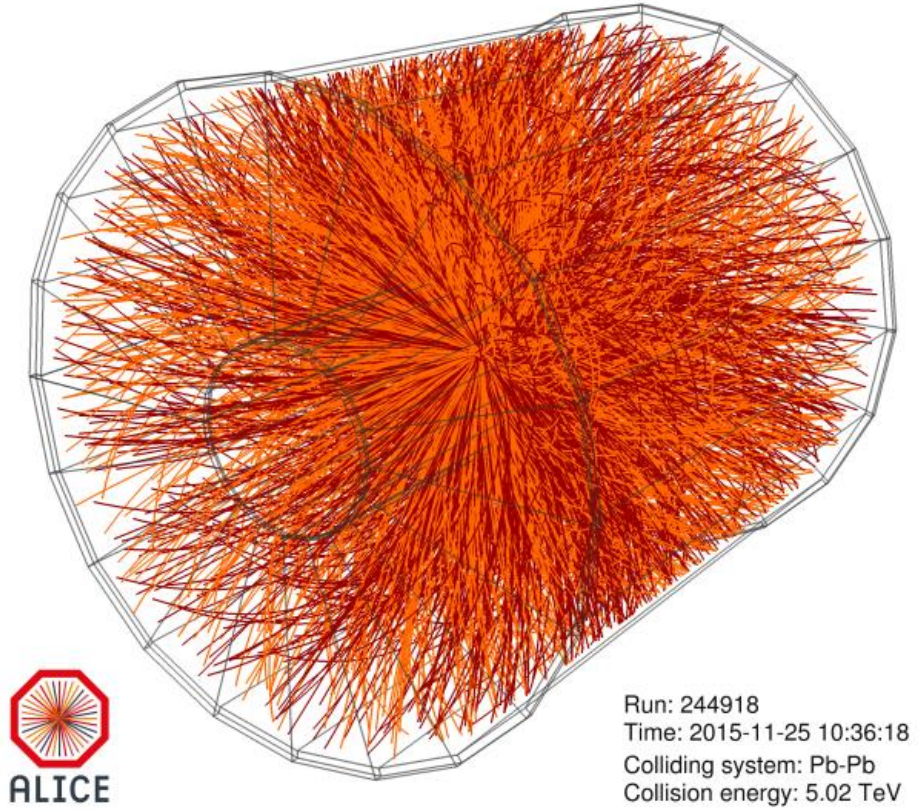

Relativistic heavy-ion collisions: from the initial to the final state

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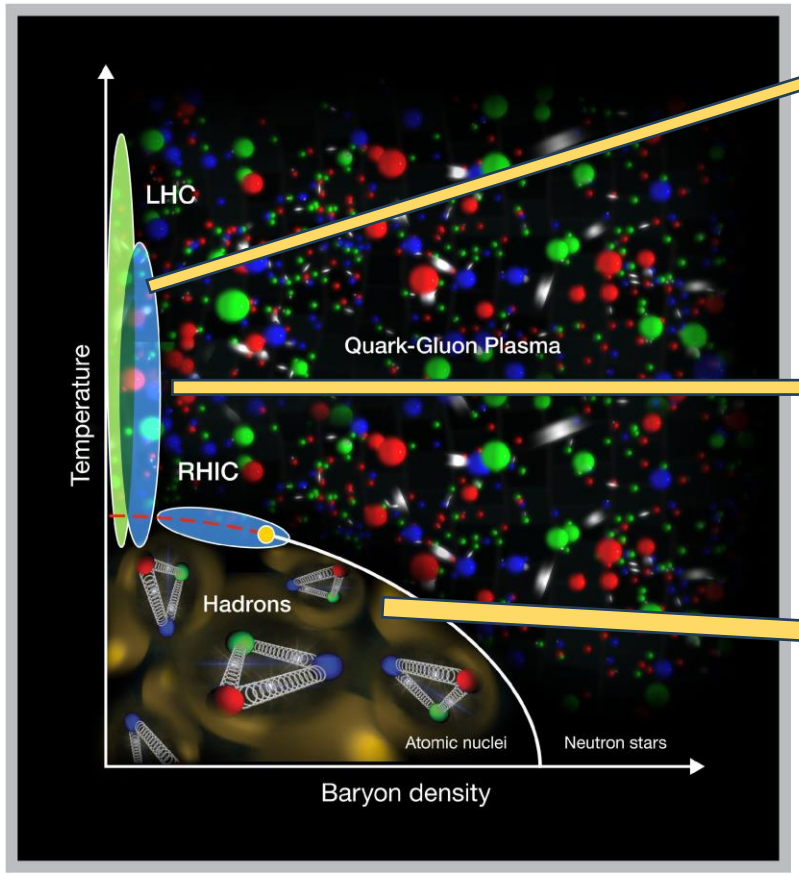
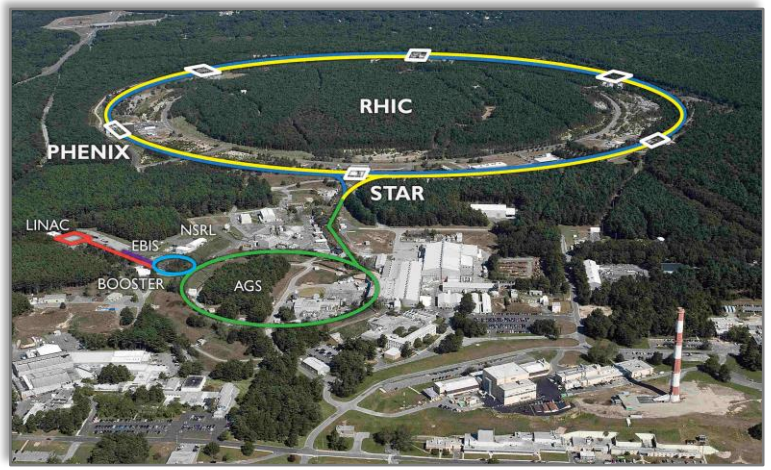
Phase Diagram of QCD



SPS/LHC, Genève (Switzerland)

GSI/FAIR, Darmstadt (Germany)



RHIC, Brookhaven (USA)

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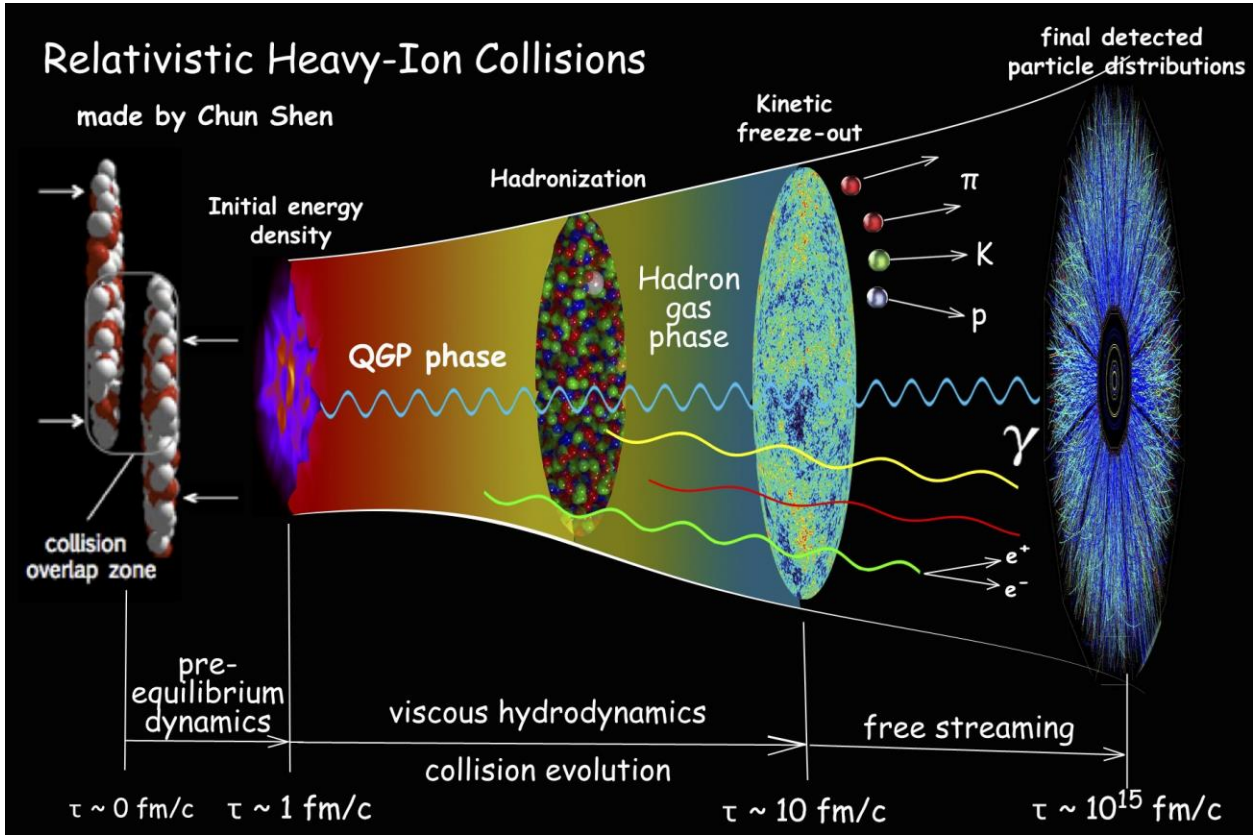
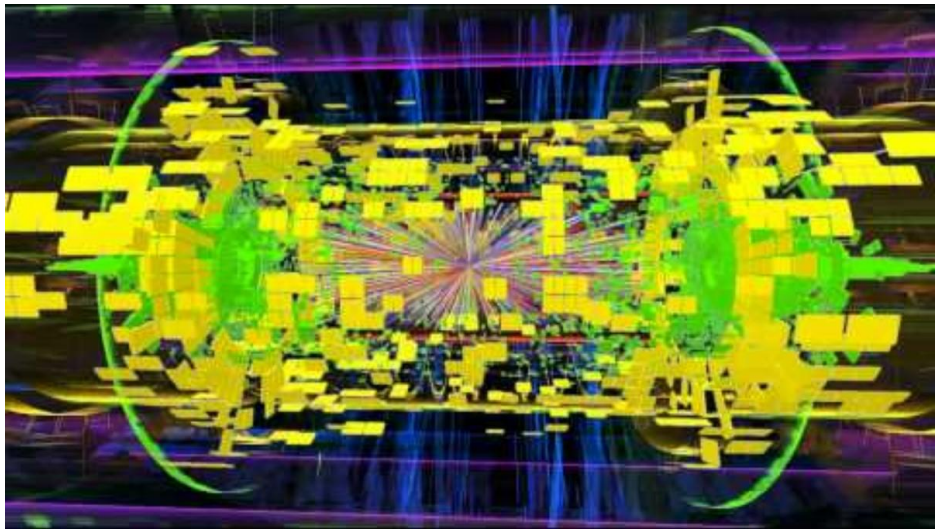
Stages of a RHIC



C. Shen



ATLAS @ LHC

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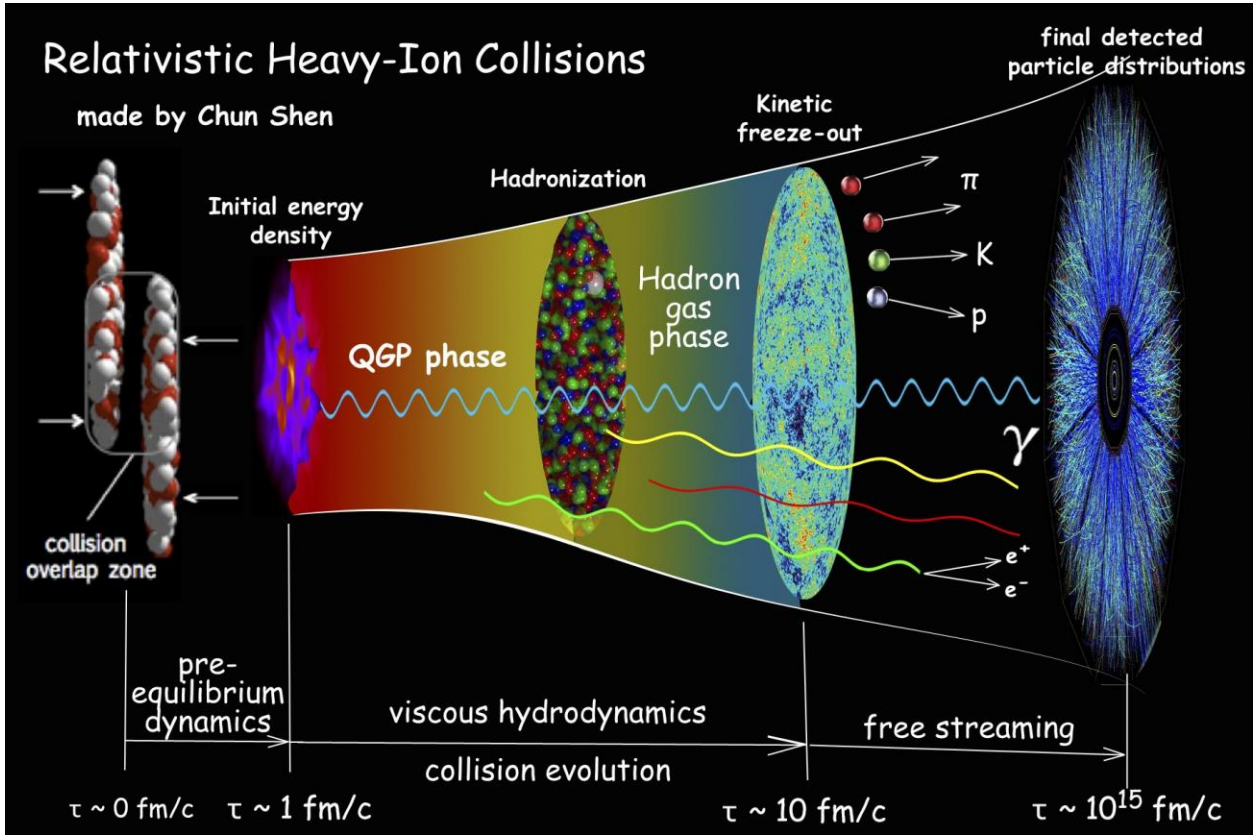
Stages of a RHIC



C. Shen

- **Initial state**
  - First collisions and nuclear deformation: V. Magas, A. Reina (SMASH), J. Menéndez, D. Frycz and JMTR
- **Quark-Gluon Plasma**
  - Charm flavor in QGP: JMTR w/ N. Oei and M. Nair
  - Hydrodynamics, vorticity: V. Magas, A. Reina
- **Hadron gas phase**
  - D-meson propagation: À. Ramos, G. Montaña and JMTR
  - Hadron interactions and femtoscopy: A. Parreño, À. Ramos, M. Piquer, V. Magas, V. Mathieu and JMTR

Initial state:
Nuclear Deformation
(talks by Ángel Reina and Dorian Frycz)

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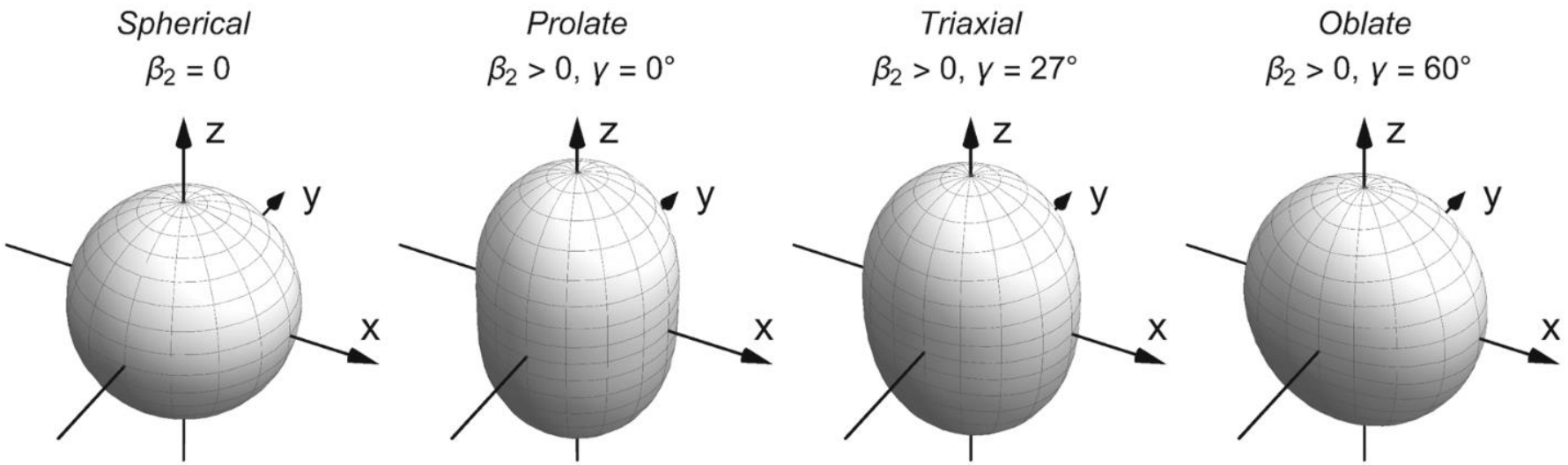
Initial state: Nuclear Deformation

talks by Ángel and Dorian



Y. Zhou, NBI
Eur. Phys. J. A (2024) 60:38

$$R(\theta,\phi) = R_0\left(1 + \beta_2\left[\cos\gamma Y_2^0(\theta,\phi) + \sin\gamma Y_2^2(\theta,\phi)\right] + \beta_3 Y_3^0(\theta,\phi) + \cdots\right)$$

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{[r - R(\theta,\phi)]/a}}$$

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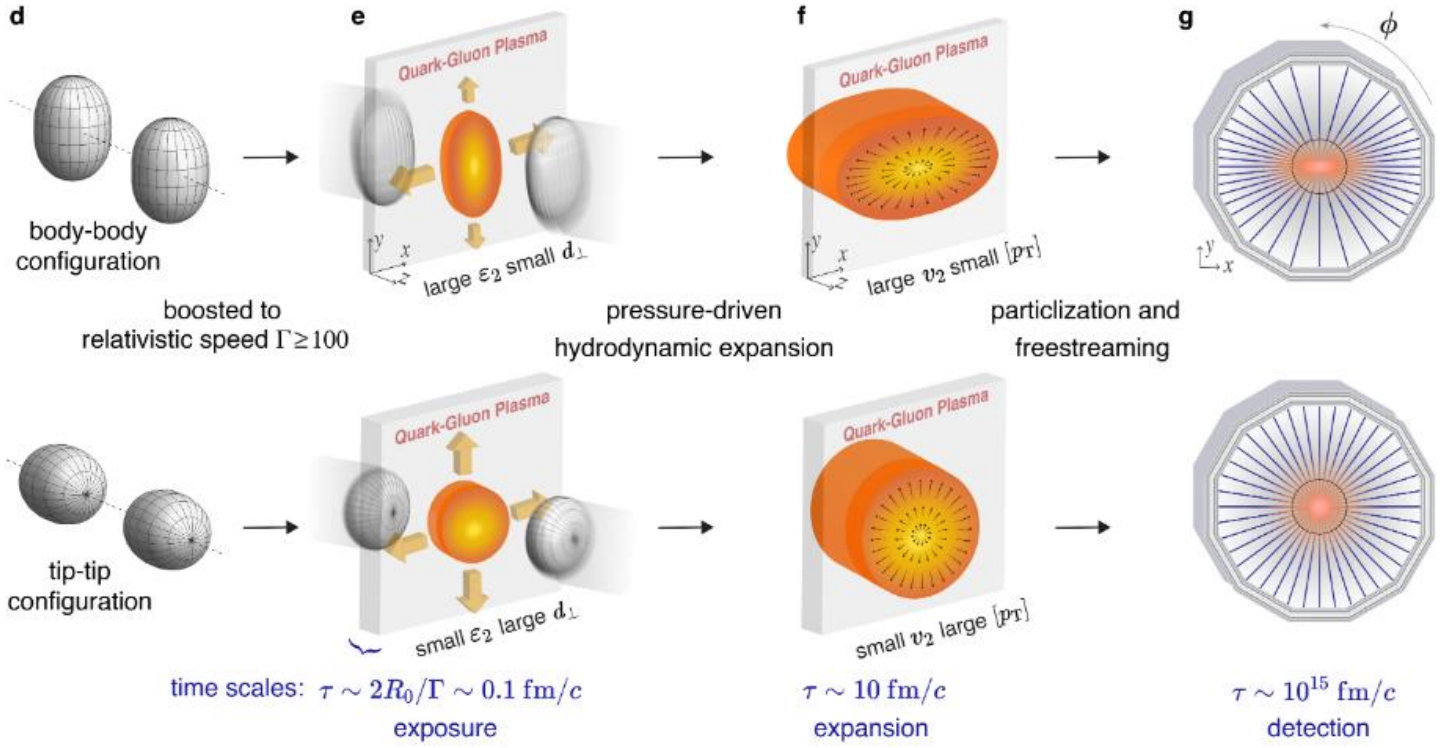
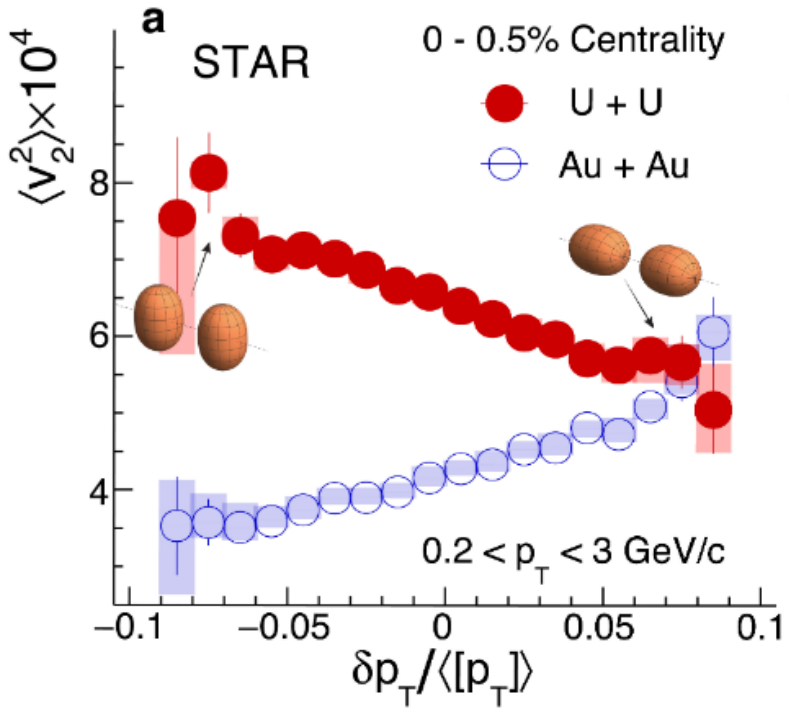
Initial stage: Nuclear Deformation

talks by Ángel and Dorian

G. Giacalone, *Phys. Rev. Lett.* 124, 202301 (2020)





STAR Coll., *Nature* 635 (2024) 8037, 67-72

Final state:

Hadron Femtoscopy

(talk by Marc Piquer)

Relativistic heavy-ion collisions: from the initial to the final state

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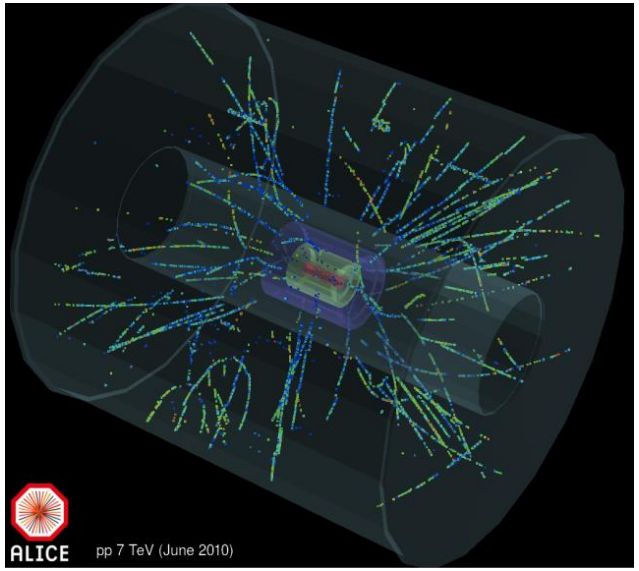
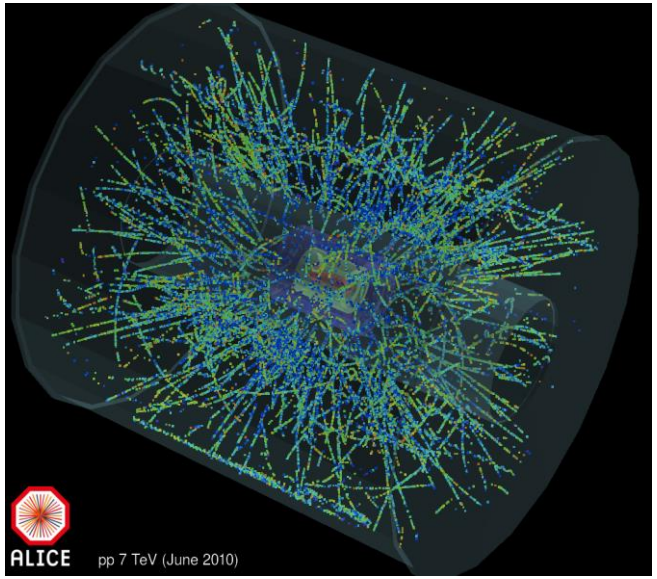
Final state

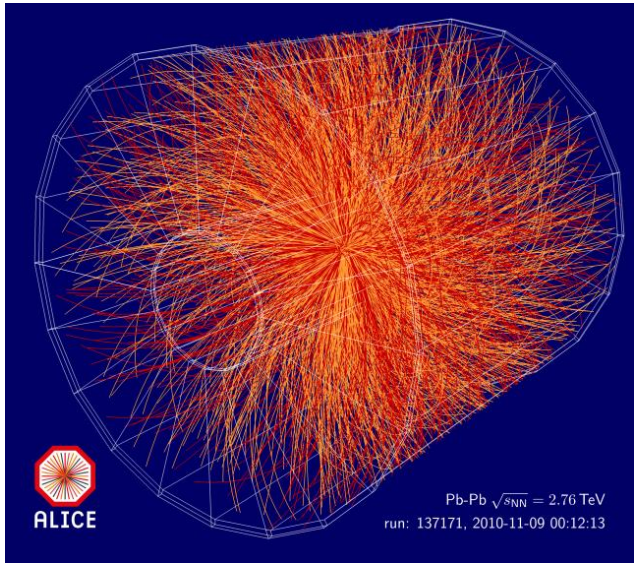
pp @ $\sqrt{s} = 7$ TeV
(low mult.)

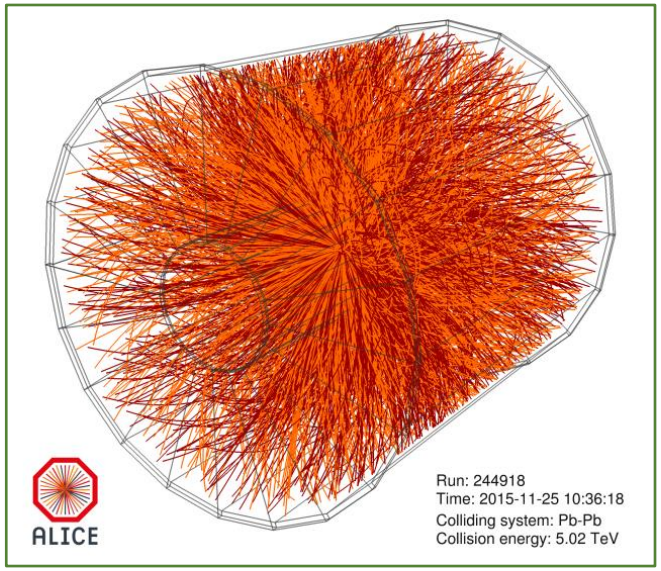




pp @ $\sqrt{s} = 7$ TeV
(high mult.)

PbPb @
$\sqrt{s_{NN}} = 2.76$ TeV





PbPb @
$\sqrt{s_{NN}} = 5.02$ TeV

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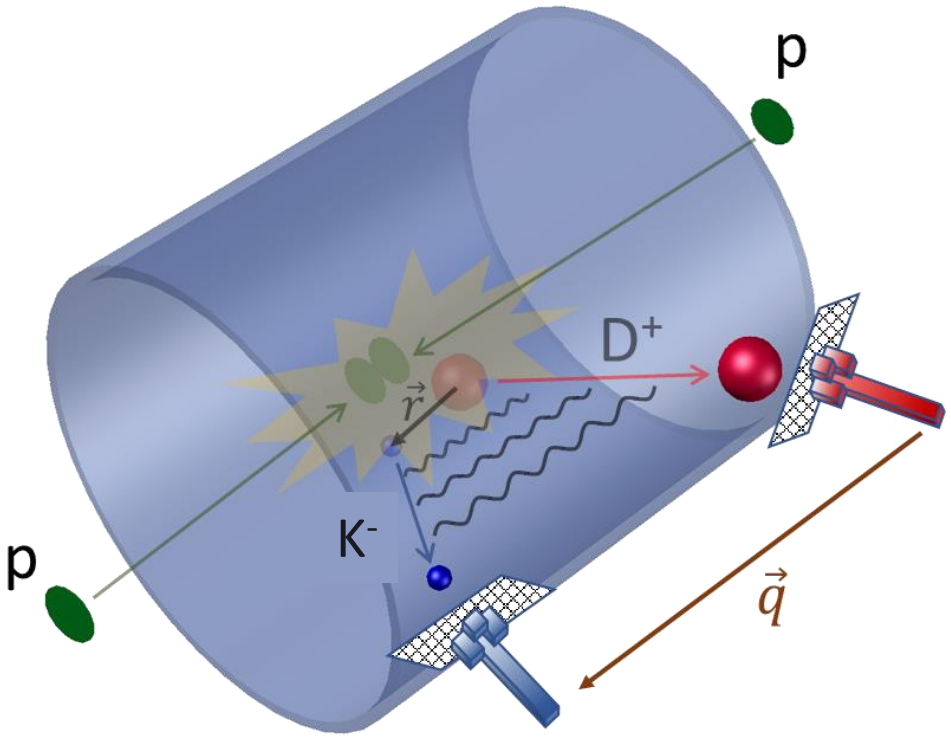
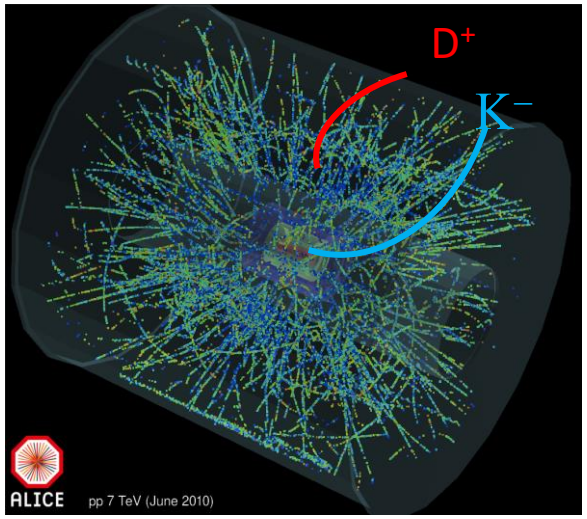
Femtoscopy in RHICs

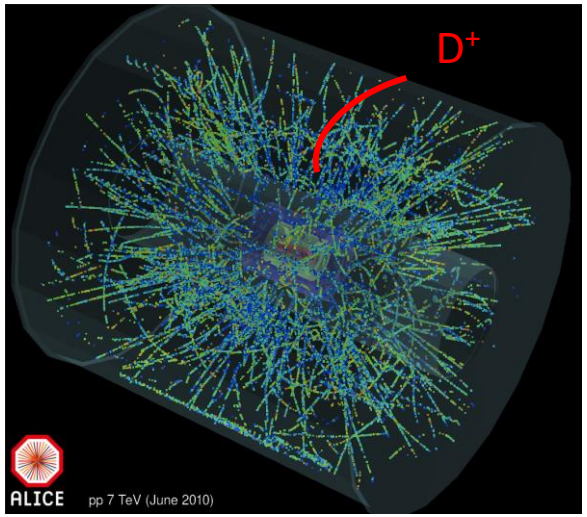


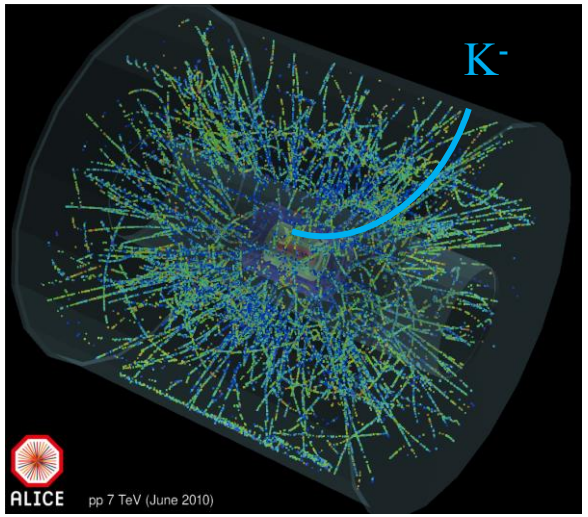
Pair Correlation Function

$$C(\boldsymbol{q}) = \mathcal{N}\,\frac{N_{\text{same}}(\boldsymbol{q})}{N_{\text{mixed}}(\boldsymbol{q})}$$

'Event mixing' technique,
10^6-10^7 events







U. Heinz, B. Jacak, *Ann.Rev.Nucl.Part.Sci.* 49 (1999) 529-579
M. Lisa, S. Pratt, U.Wiedemann,
Ann.Rev.Nucl.Part.Sci. 55 (2005) 357

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Koonin-Pratt formula

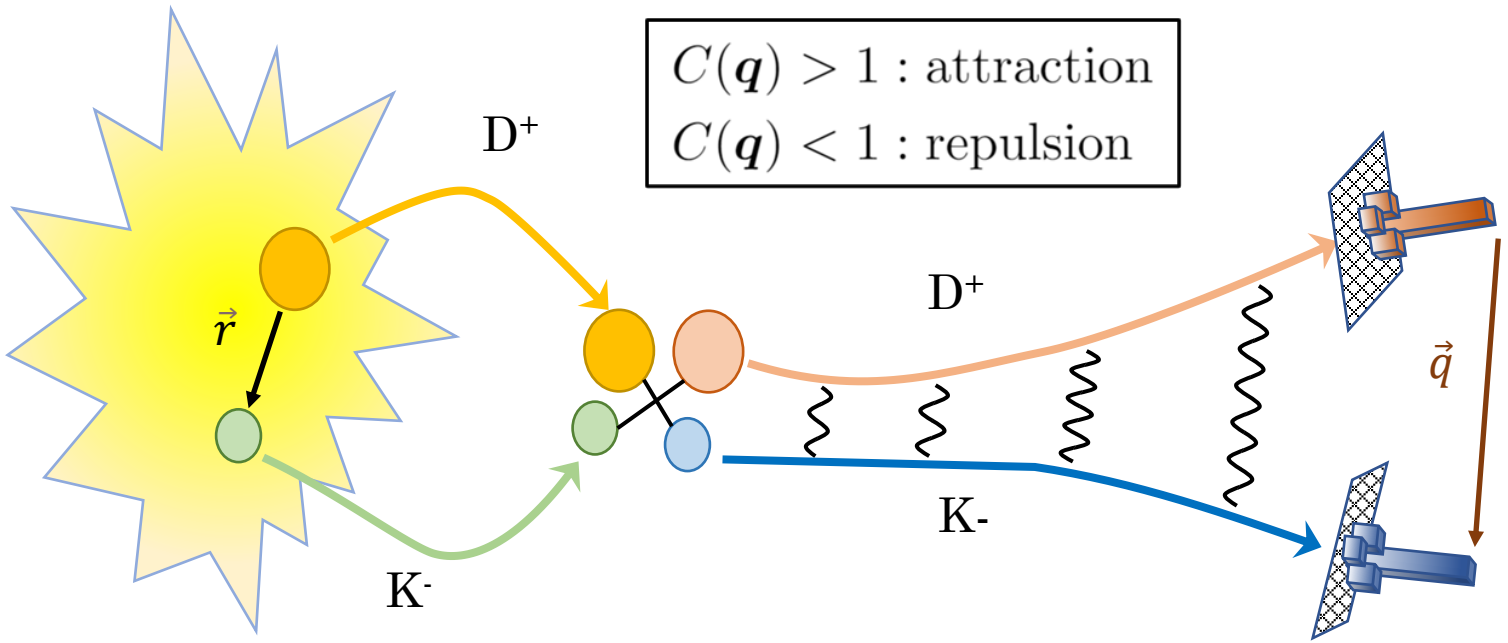
Koonin, *Phys.Lett.B*, 70, 43 (1977)
Pratt, Csorgo, Zimanyi, *Phys.Rev.C*, 42, 2646 (1990)

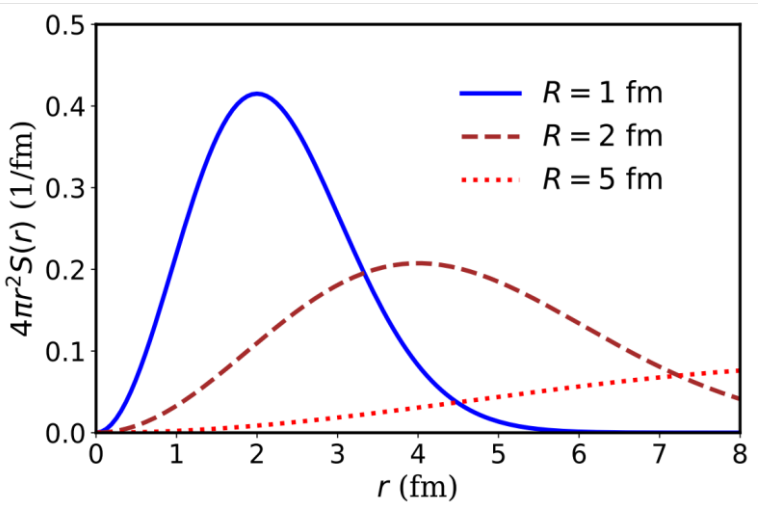
$$C(\boldsymbol{q}) = \int d^3r\ S(\boldsymbol{r})|\Psi(\boldsymbol{q};\boldsymbol{r})|^2$$

→ Pair wave function with CM momentum $\boldsymbol{q}$

→ Source function

$C(\boldsymbol{q}) > 1$: attraction
$C(\boldsymbol{q}) < 1$: repulsion

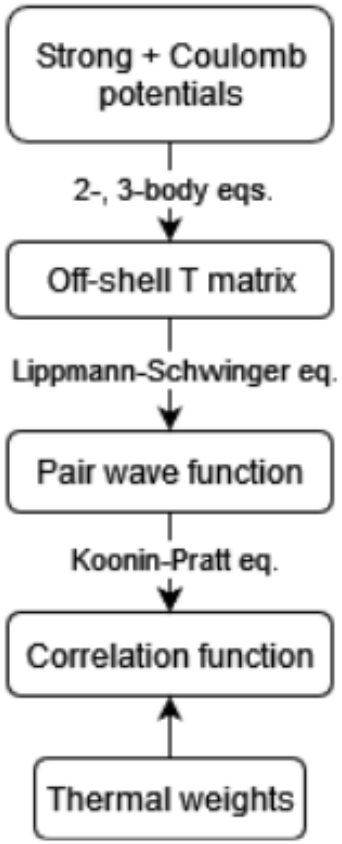


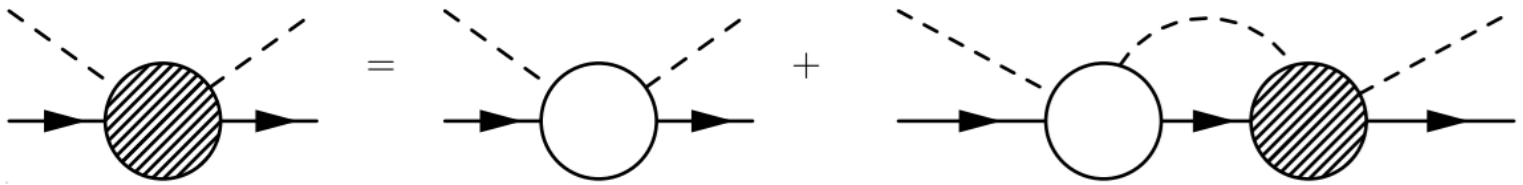


$$S(r) = \frac{1}{(2\sqrt{\pi}R)^3}\exp\left(-\frac{r^2}{4R^2}\right)$$

Methodology 1: T-matrix-based Routine for hadrOn femtoscopY

TROY





$$T_{if}(q',q;\sqrt{s}) = V_{if}(q',q;\sqrt{s}) + \sum_l \int_0^\infty \frac{4\pi k^2 dk}{(2\pi)^3} \frac{V_{il}(q',k;\sqrt{s})\, T_{lf}(k,q;\sqrt{s})}{2\omega_{H,l}\, 2\omega_{\phi,l}\, (\sqrt{s} - \omega_{H,l} - \omega_{\phi,l} + \mathrm{i}\eta)}$$

Lippmann-Schwinger equation

$$|\Psi\rangle = |\Phi\rangle + \frac{1}{E - \hat{H}_0 + \mathrm{i}\eta} T\,|\Phi\rangle$$

Koonin-Pratt equation

$$C(\boldsymbol{q}) = \int d^3r\; S(\boldsymbol{r}) |\Psi(\boldsymbol{q};\boldsymbol{r})|^2$$

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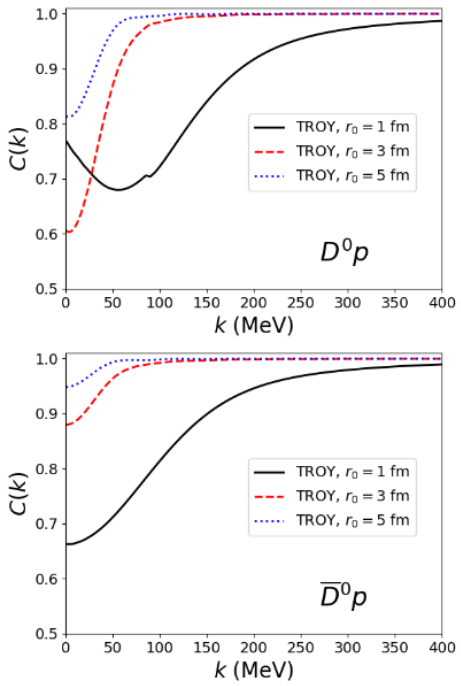
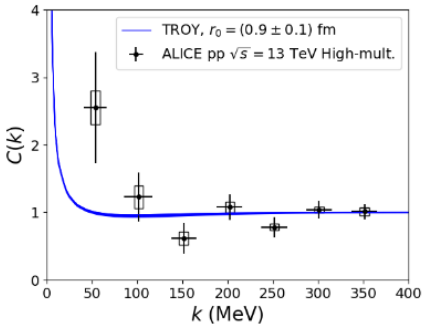
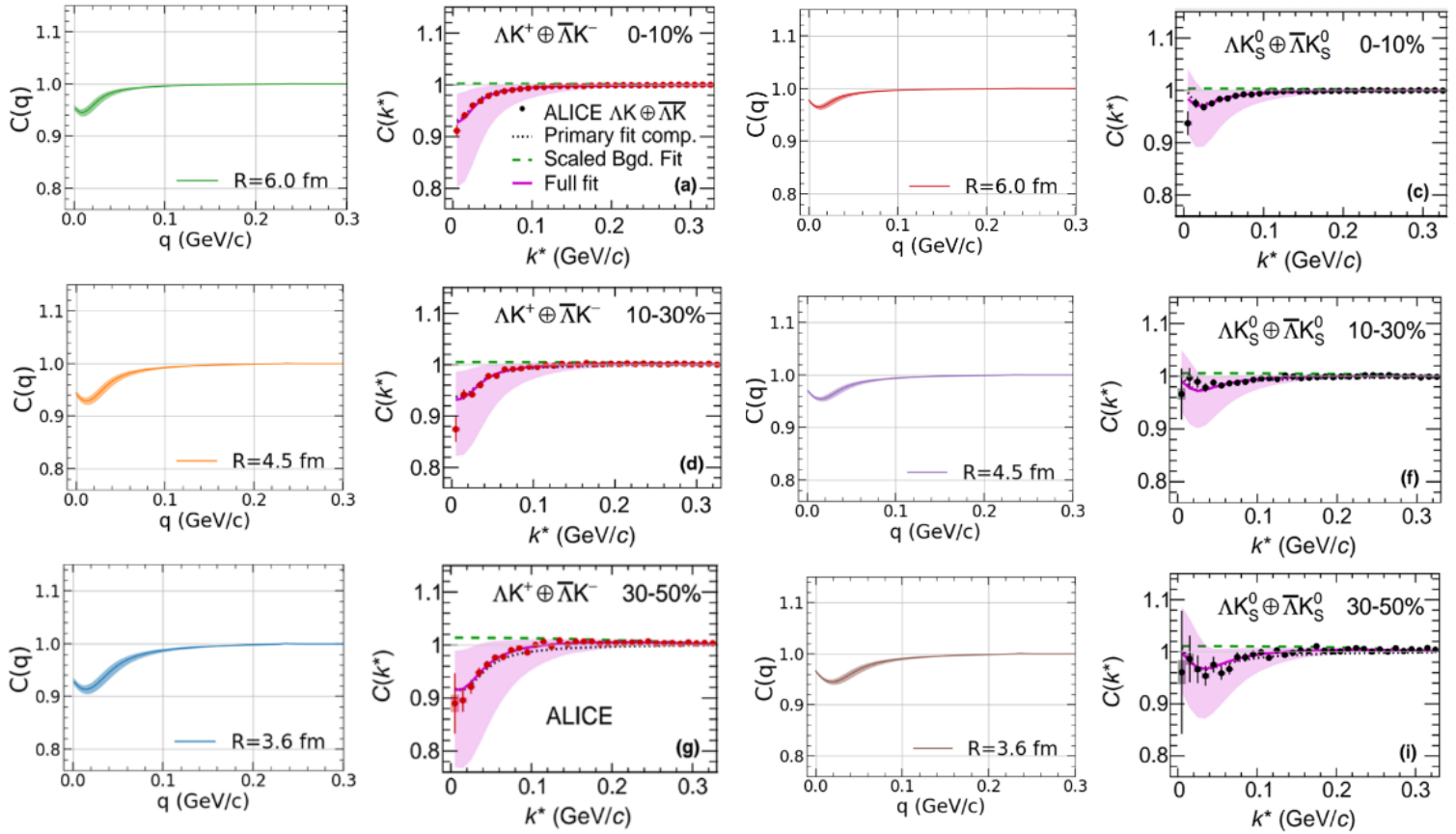
Results with TROY in meson-baryon systems



D^+p





Barbat *et al*. [JMTR] 2507.07864

MSc thesis, Álvaro Peña Almazán. UB. 07/12/2024

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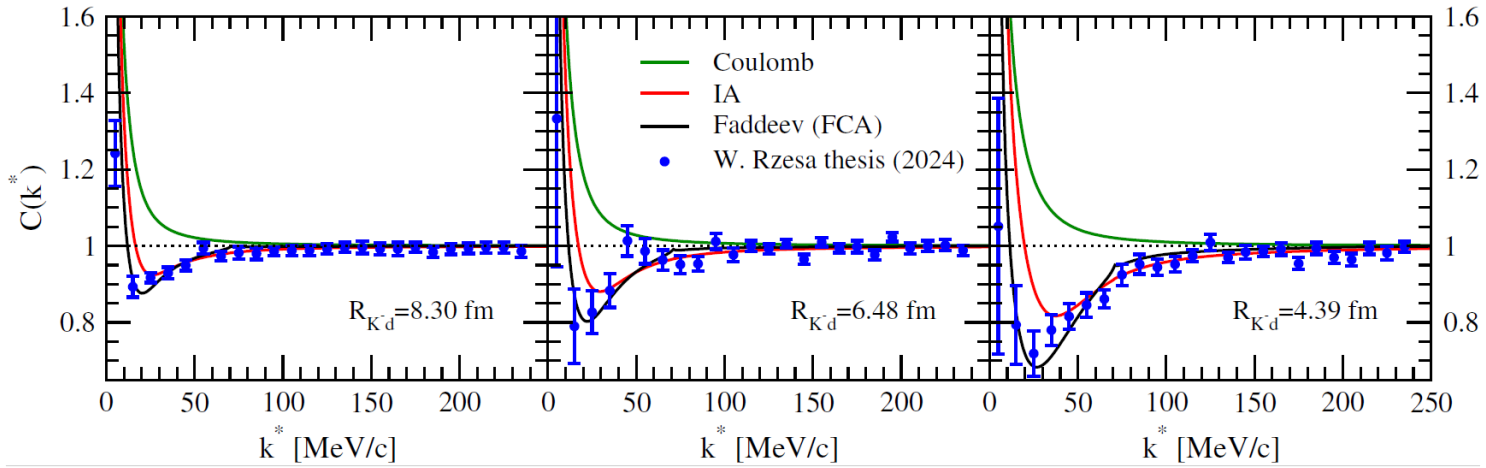
Kaon-Deuteron system

À. Ramos, JMTR, A. De Fagoaga, E. Cabré, 2507.22593 [hep-ph]

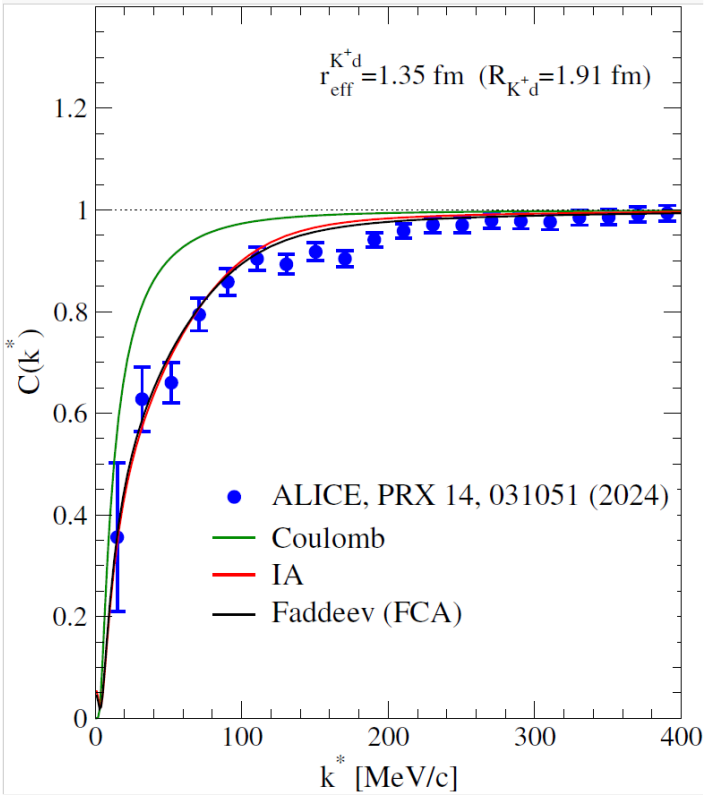
Centrality: 0-10% 10-30% 30-50%



Pb-Pb collisions @ $s^{1/2}_{NN}$=5.02 TeV

W. Rzesa, Ph.D. thesis, Warsaw U. of Tech. (2024) (ALICE Coll.)

High multiplicity p-p collisions @ $s^{1/2}_{NN}$=13 TeV data from ALICE



Source radii only indicative number from experimental fits

Signal enhanced in small systems.

Methodology 2: Schrödinger Equation

Effective theory

Fit the parameters

Effective potential

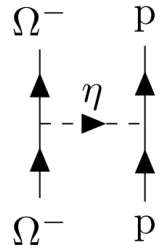
Schrödinger equation

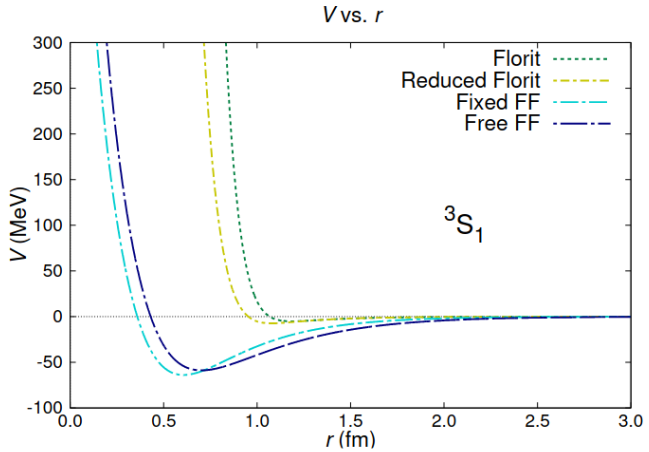
Scattering wave functions

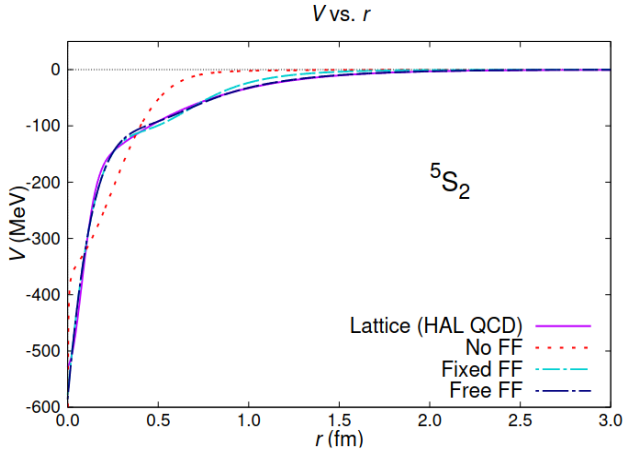
Koonin-Pratt formula

Correlation function

$$\hat{V}_\eta^{\rm el} = C_{{\rm p}\eta\bar{\rm p}} C_{\Omega\eta\bar{\Omega}} \frac{{m_\eta}^2}{3} \left(\frac{{\Lambda_\eta}^2}{{\Lambda_\eta}^2 - {m_\eta}^2} \right)^2 \left[\frac{e^{-m_\eta r}}{4\pi r} - \frac{e^{-\Lambda_\eta r}}{4\pi r} + \frac{({m_\eta}^2 - {\Lambda_\eta}^2)\Lambda_\eta}{8\pi {m_\eta}^2} e^{-\Lambda_\eta r} \right] \vec{\mathbb{S}} \cdot \vec{\sigma}$$







$$\left[\frac{{\rm d}^2}{{\rm d}r^2} + k^2 - \frac{2\mu Z_1 Z_2 \alpha}{r} - 2\mu \hat{V}(r) - \frac{l(l+1)}{r^2} \right] u_l(r) = 0$$

Koonin-Pratt equation

$$C(\boldsymbol{q}) = \int d^3r \; S(\boldsymbol{r}) |\Psi(\boldsymbol{q};\boldsymbol{r})|^2$$

see talk by Marc

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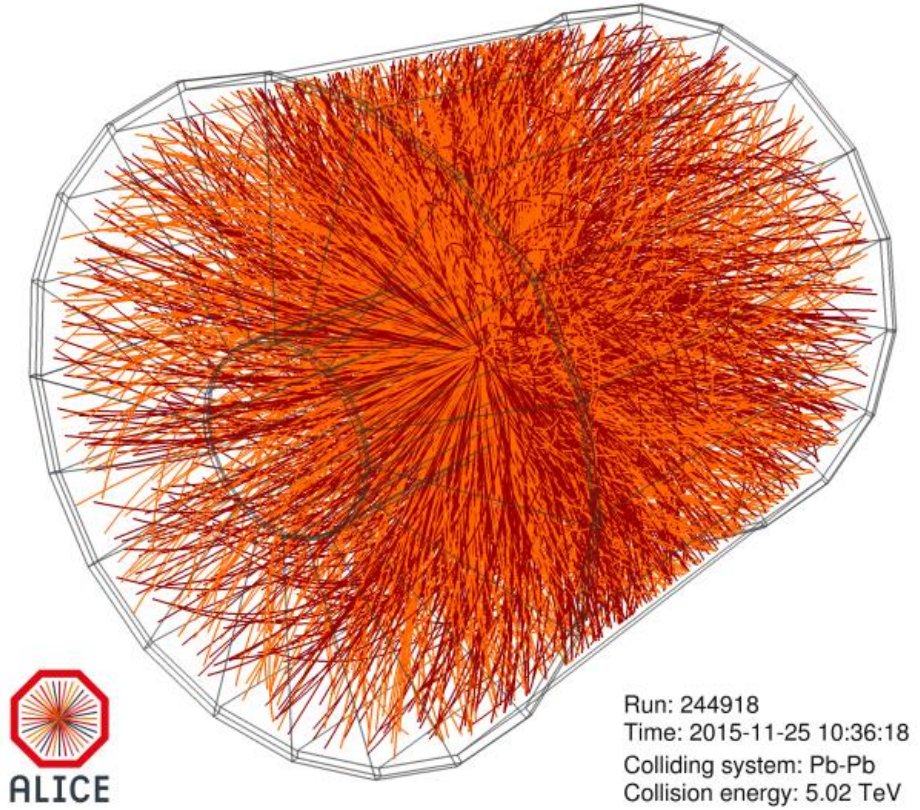

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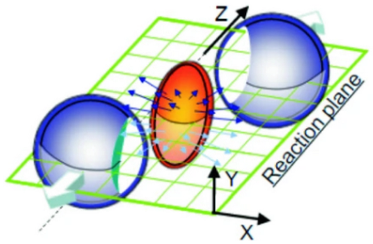
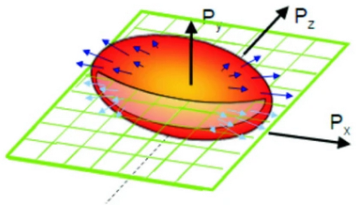
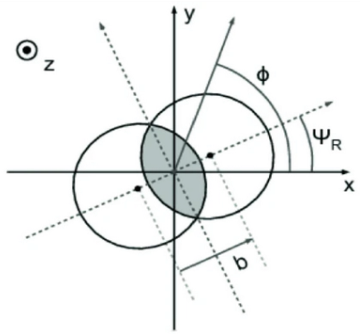
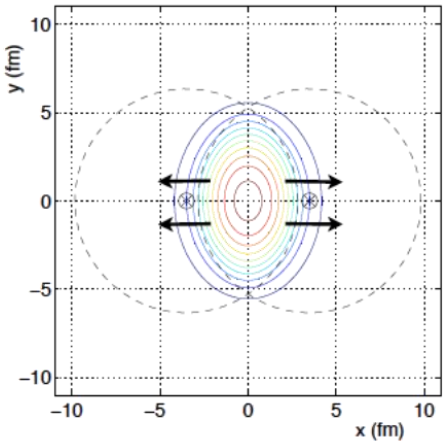
Anisotropic flow

- Peripheral collisions generate spatial asymmetry
- Pressure gradients transform into momentum anisotropy via collective response of the system

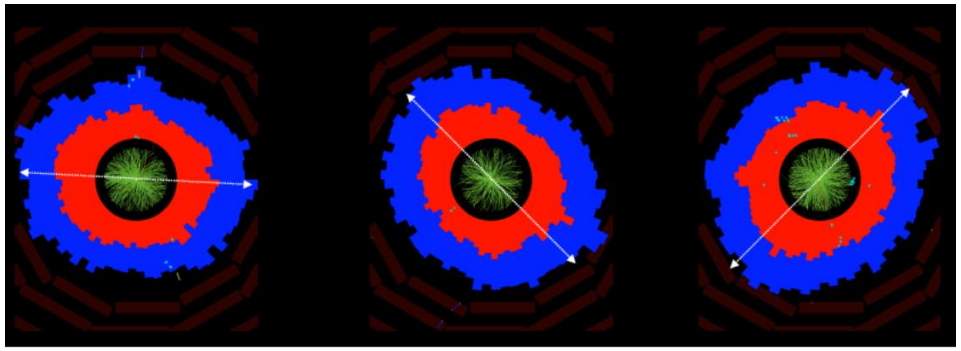








- Anisotropy in (p_x, p_y) momenta (dependence on ϕ)

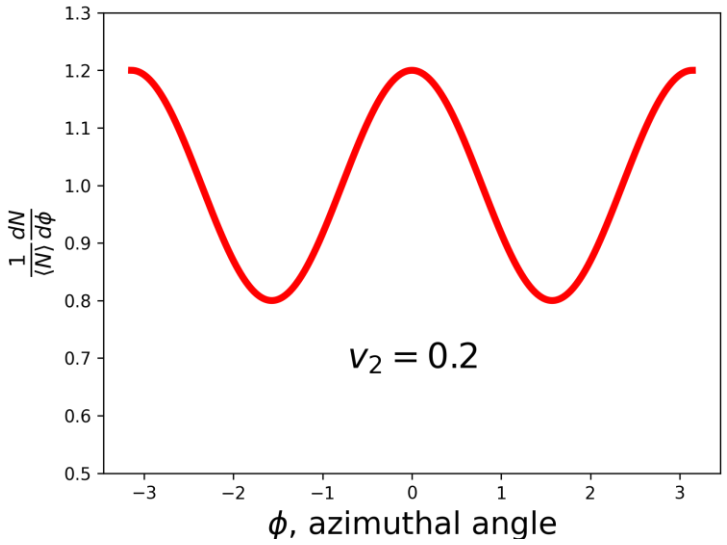


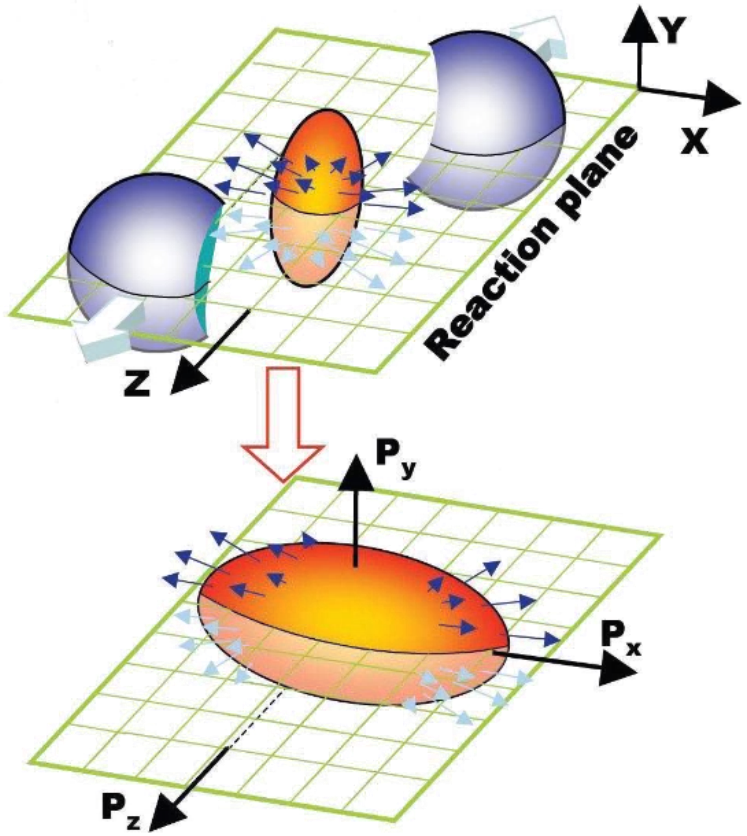
Energy in CMS calorimeter
(from B. Wyslouch)

Anisotropic flow

- Anisotropic flow is measured by Fourier coefficients v_n of the azimuthal momentum distribution.
- The most relevant one is the elliptic flow v_2

$$E_p \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left(v_2(p_T) \cos[2(\phi - \psi_R)] + \cdots\right)$$





Hiroshi Masui (2008)

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