XII Polish Workshop on Relativistic Heavy-Ion Collisions
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Examination of the heavy-ion collisions using EPOS model* in the frame of BES program at RHIC

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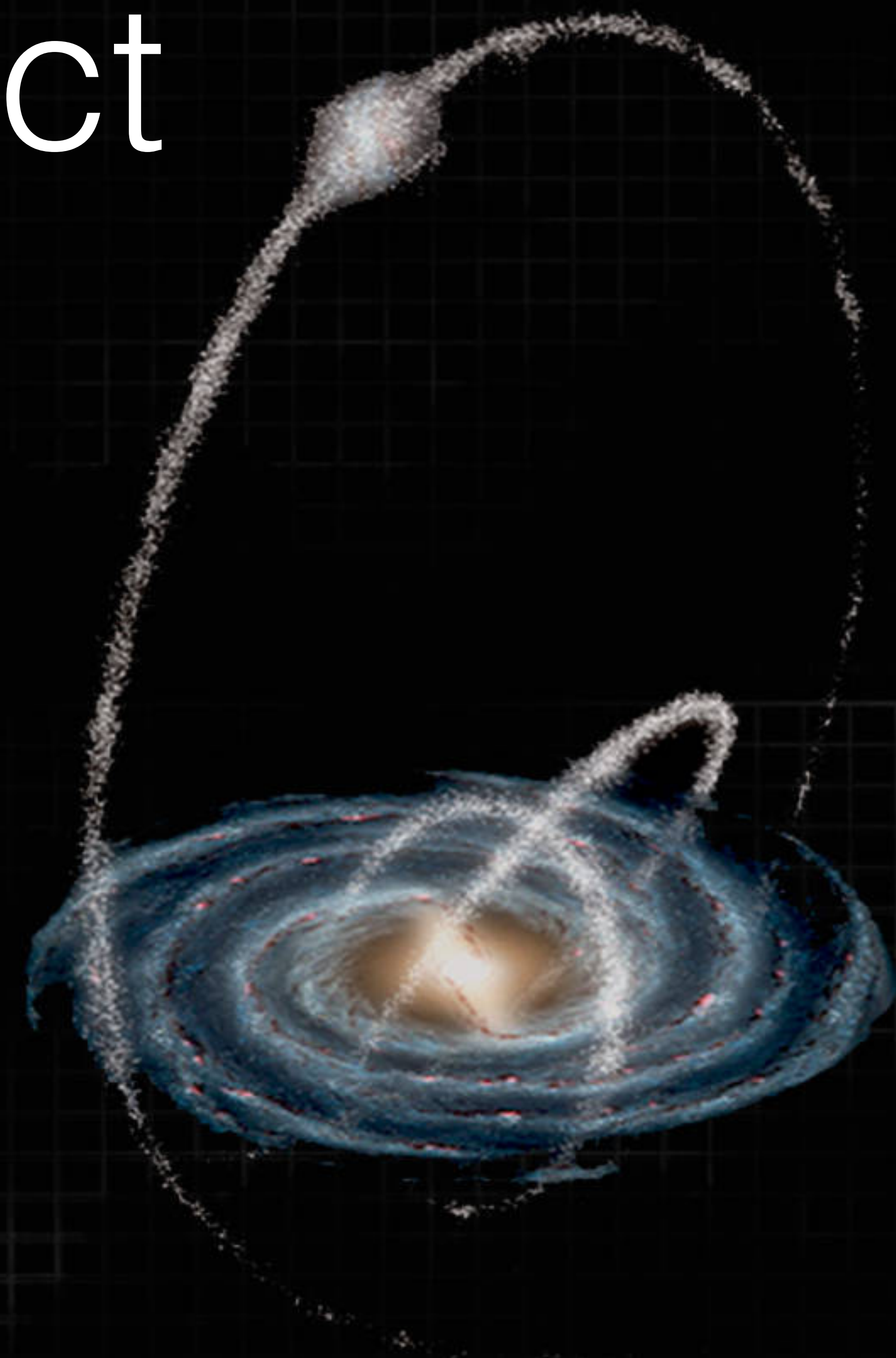
*Progress report

Abstract

- Motivation
- EPOS generator
- Beam Energy Scan program
- Methods of analysis and results
  - p_T spectra
  - Femtoscopy correlations
  - Azimuthal Anisotropy
- Conclusion



Motivation

- Adaptation of the EPOS model to work with lower energies
- study discrepancies between theoretical description of processes present immediately after heavy-ion collisions and STAR data
- visualize the impact of hadron cascades on the size of particle-emitting source

$\sqrt{s_{NN}}$ **: 7.7 GeV, 11.5 GeV, 19.6 GeV, 27 GeV, 39 GeV** and **62.4 GeV**

EPOS generator

Energy conserving quantum mechanical multiple scattering approach, based on **P**artons (parton ladders), **O**ff-shell remnants, and **S**plitting of parton ladders.

Gribov - Regge theory

- Soft aspects of particle collisions
- Multiple scattering
- Interactions described with Pomerons
- …

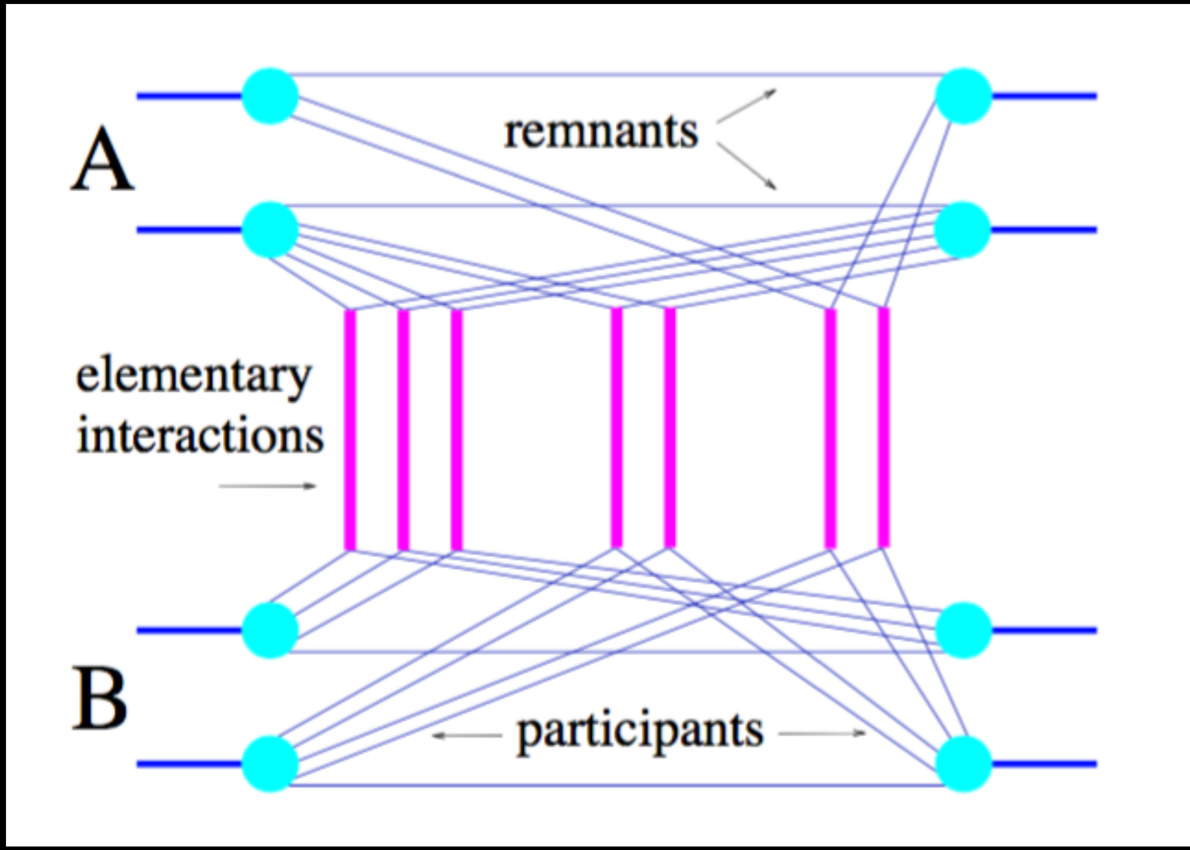
Parton-based theory

- Partons: quarks & gluons
- Calculation of parton jets
- QCD & QED
- …

EPOS generator

Parton-based Gribov-Regge theory

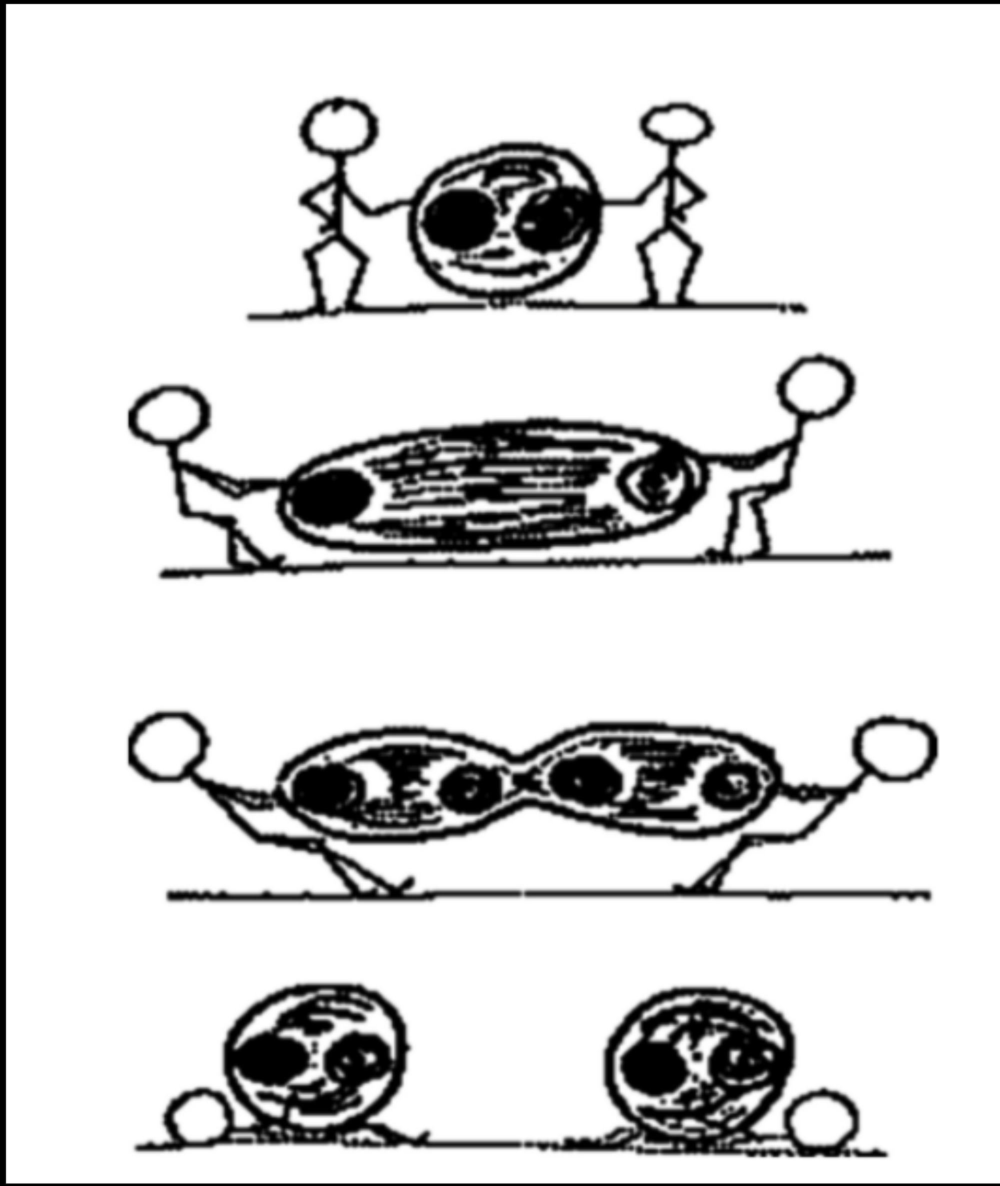
- Conservation of energy



EPOS generator

Parton-based Gribov-Regge theory

- Conservation of energy
- Lund string model

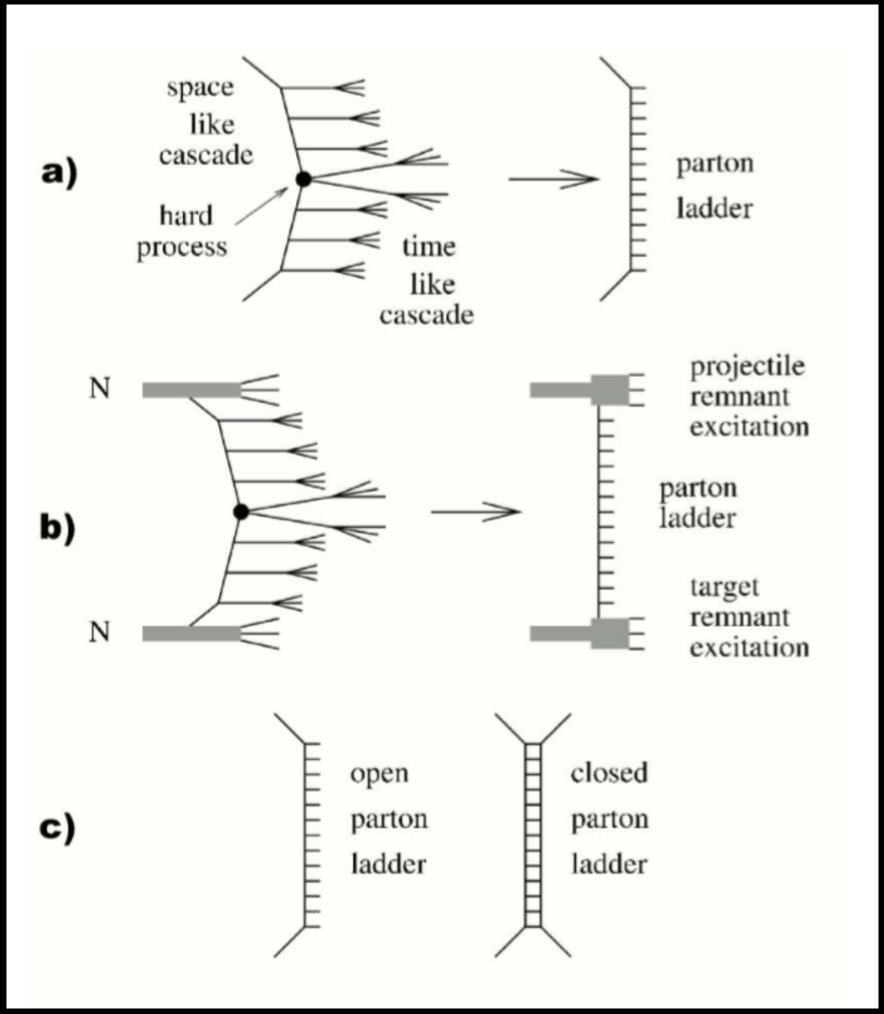


EPOS generator

Parton-based Gribov-Regge theory

- Conservation of energy
- Lund string model
- Open and closed ladders

inelastic and elastic scattering



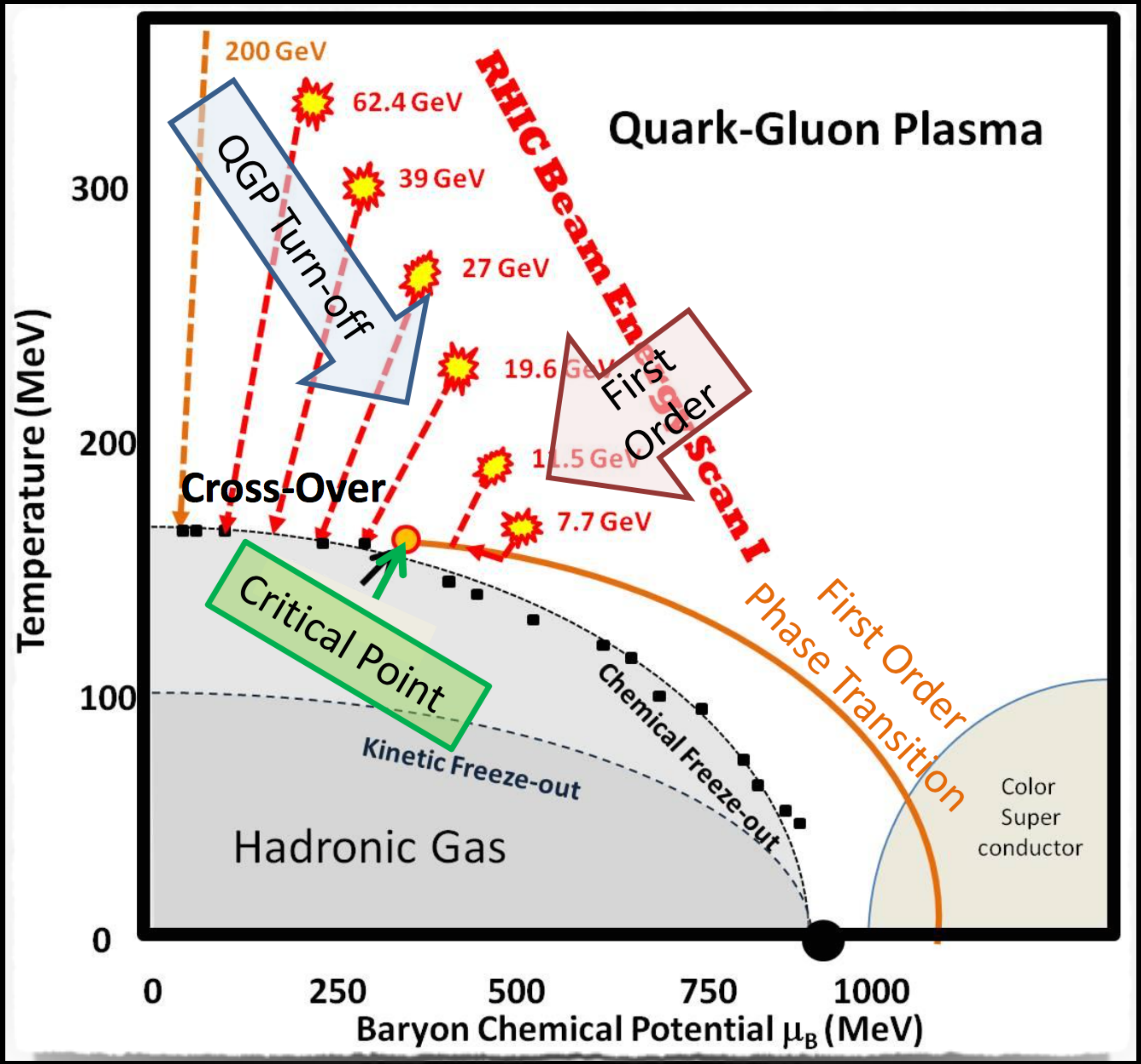
Beam Energy Scan

BES program:

- Run at RHIC in Brookhaven National Laboratory
- Collisions of: Au + Au

Three Goals:

- Turn-off QGP signatures
- Find critical point
- Examine First order phase transition



Beam Energy Scan

BES

$\sqrt{s_{NN}}$: 7.7 GeV, 11.5 GeV, 19.6 GeV, 27 GeV, 39 GeV and 62.4 GeV

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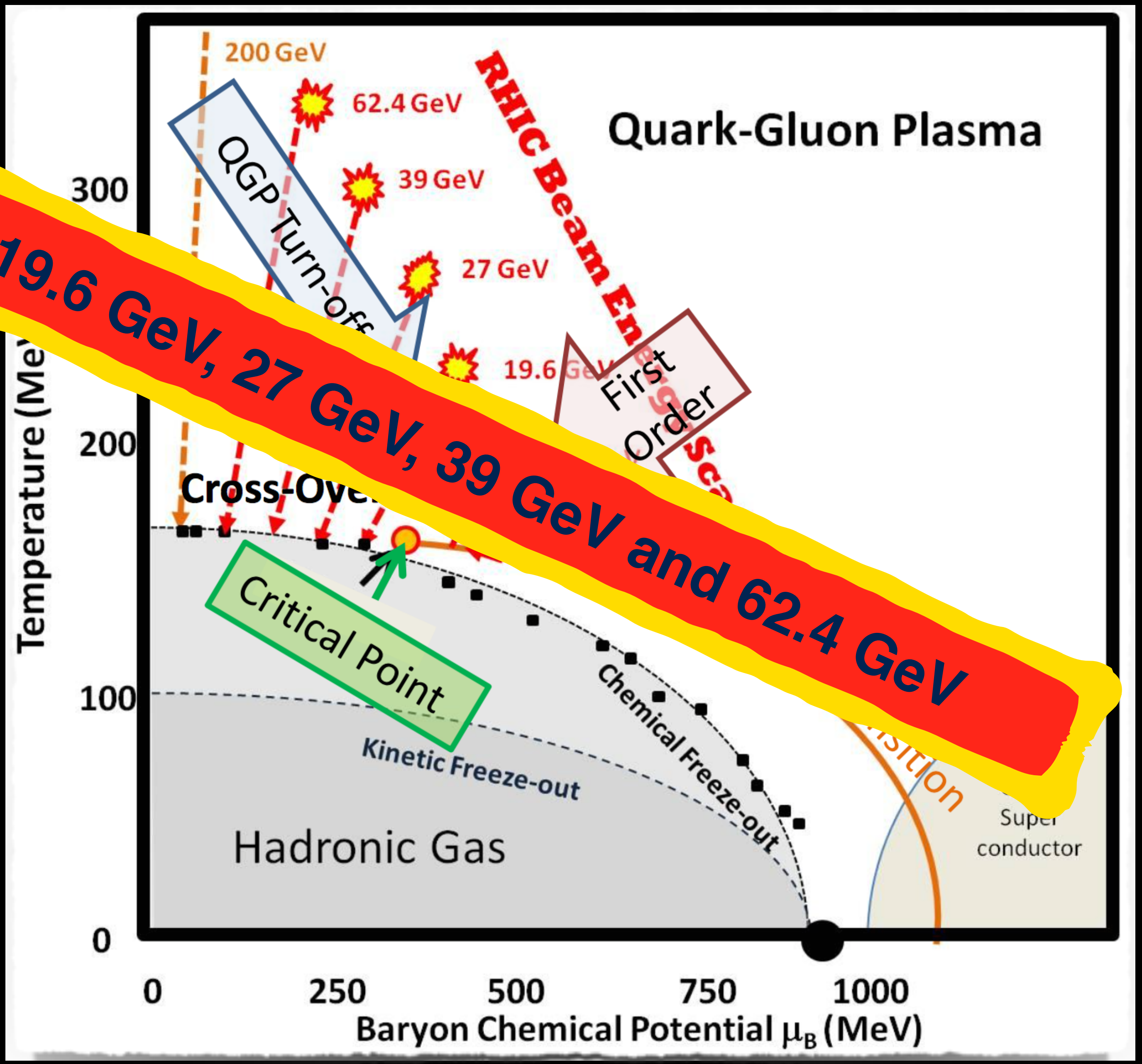
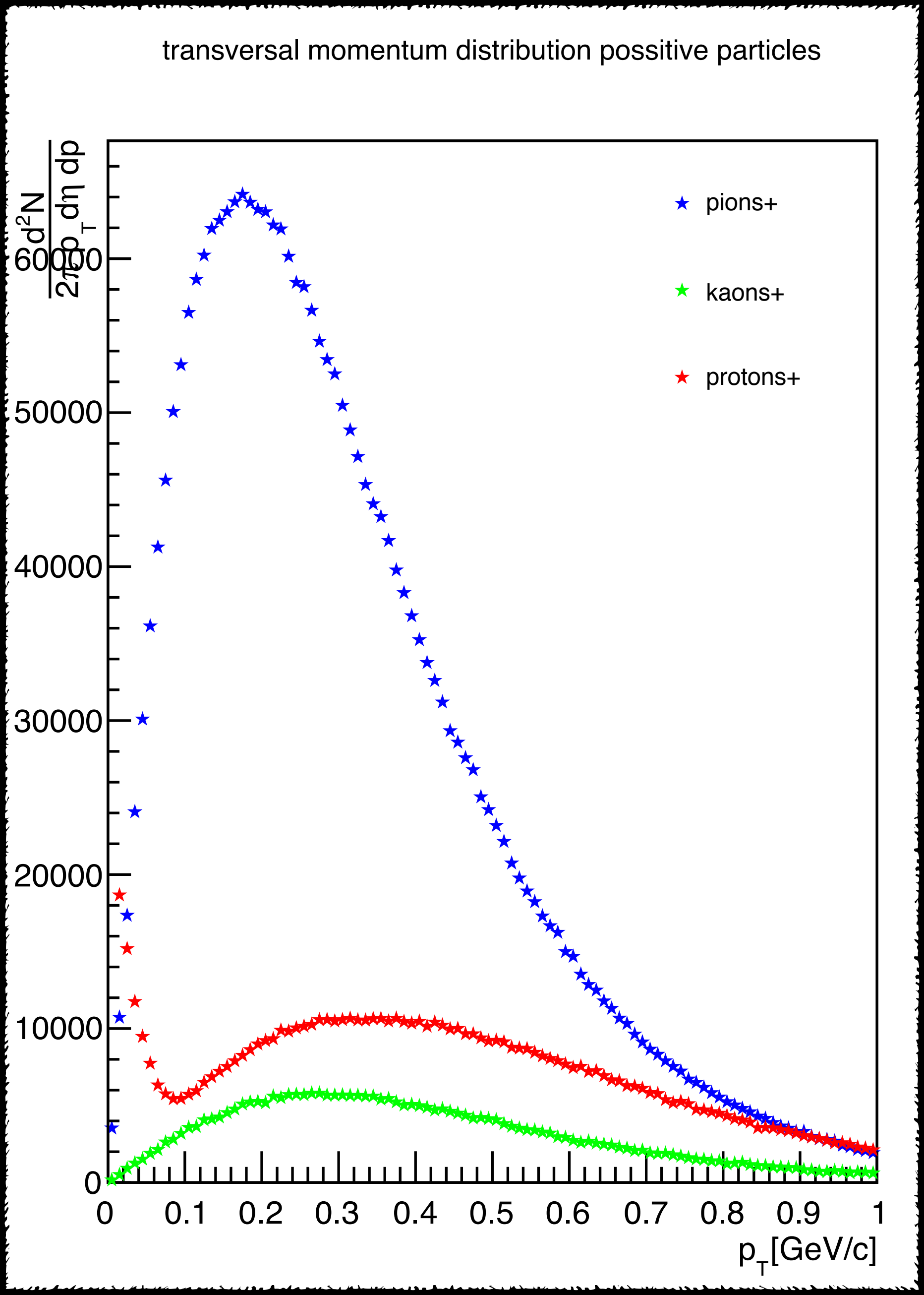


Methods of analysis

- **p_T spectra**
- Femtoscopy correlations
- Azimuthal Anisotropy



p_T - transverse momentum

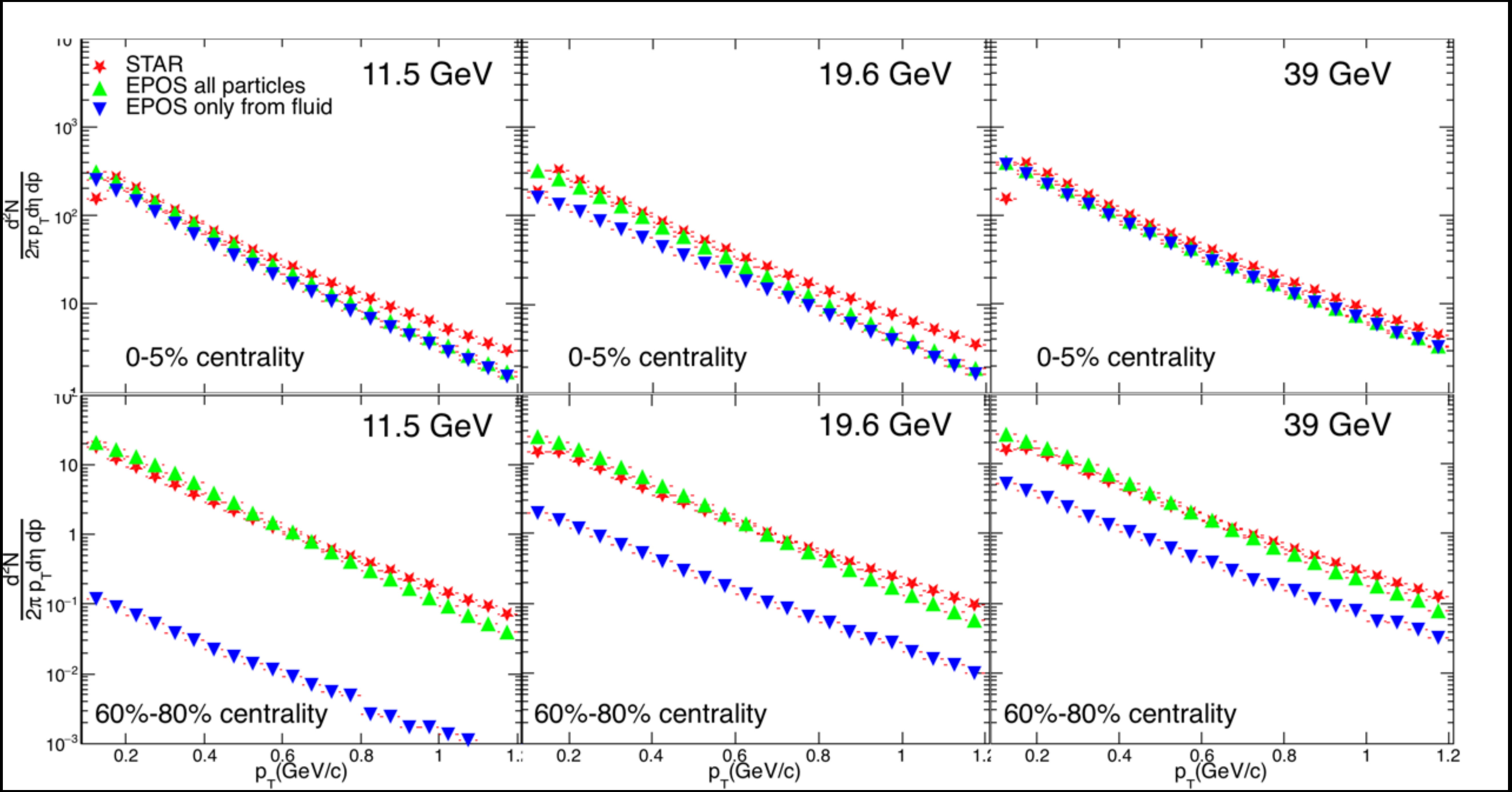
$$p_T = \sqrt{p_x^2 + p_y^2}$$

How many particles do have given transverse momentum?

p_T spectra results

STAR data : J. Phys. Conf. Ser., 446:012017, 2013

Au+Au |y|<0.5



p_T spectra results

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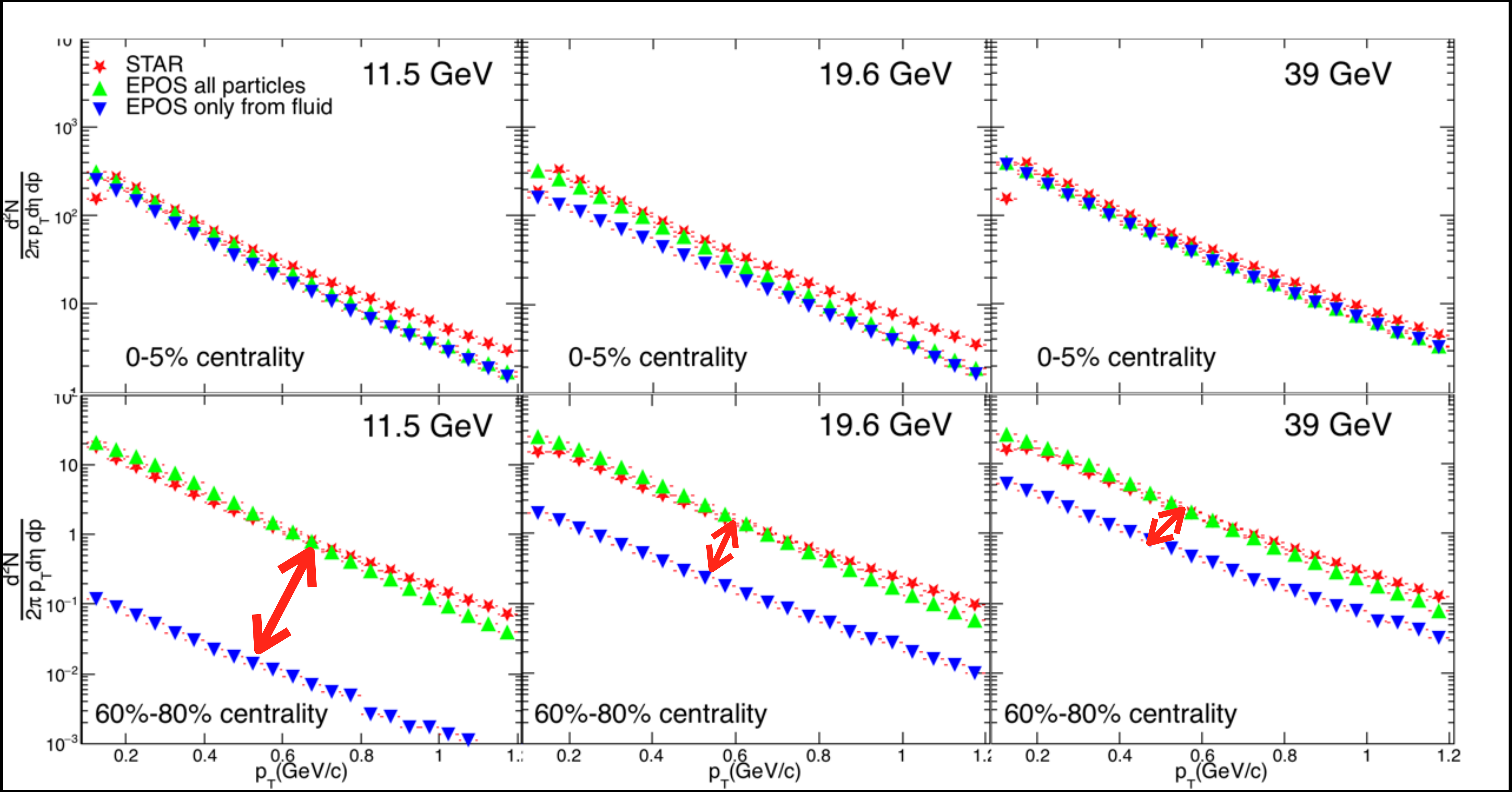
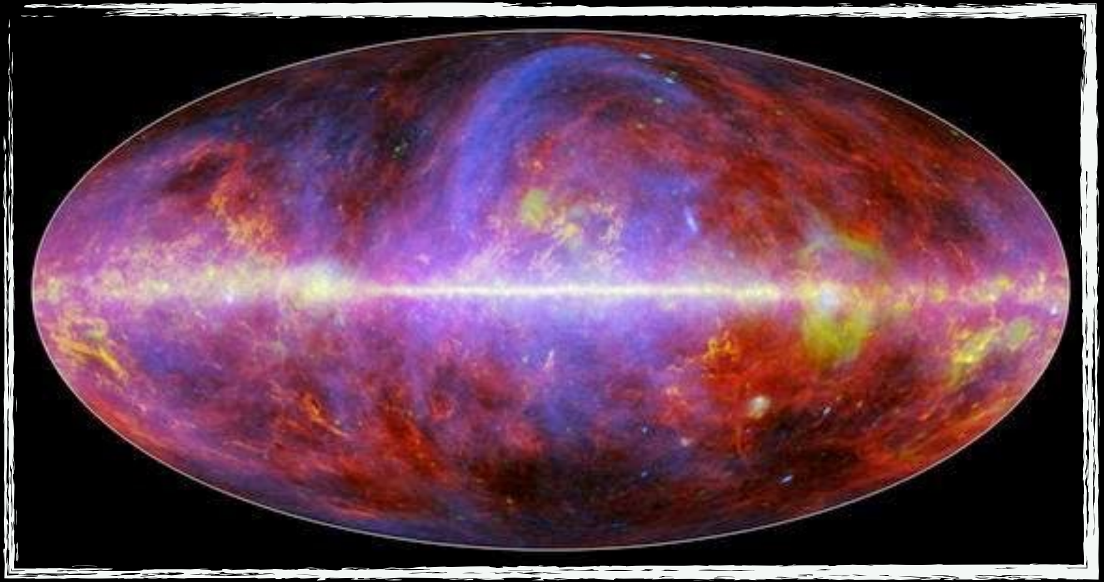


Methods of analysis

- p_T spectra
- **Femtoscopy correlations**
- Azimuthal Anisotropy

HBT method

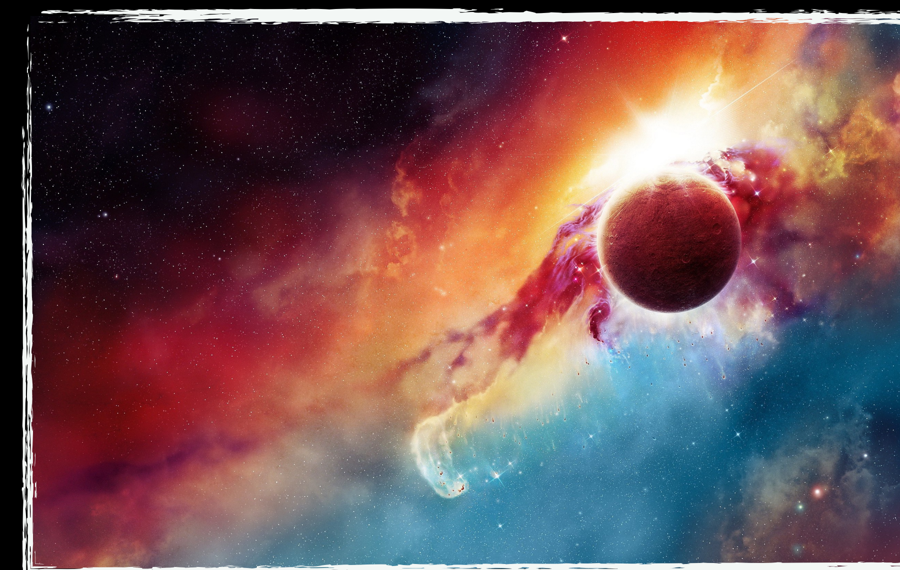
R.**H**anbury **B**rown and R.Q.**T**wiss



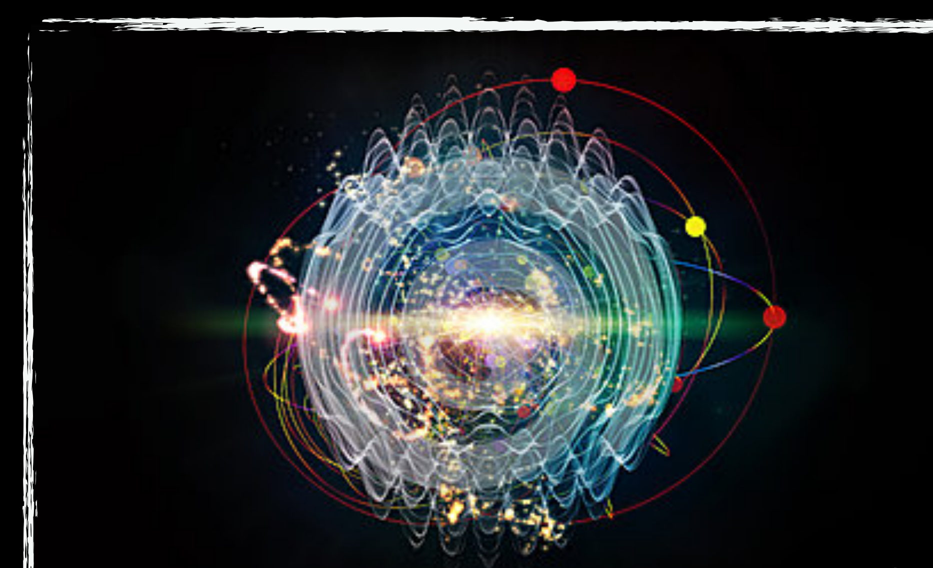
Methods of analysis

- p_T spectra
- **Femtoscopy correlations**
- Azimuthal Anisotropy

HBT Method — $\sim 10^{15}$ m



Femtoscopy correlations — $\sim 10^{-15}$ m

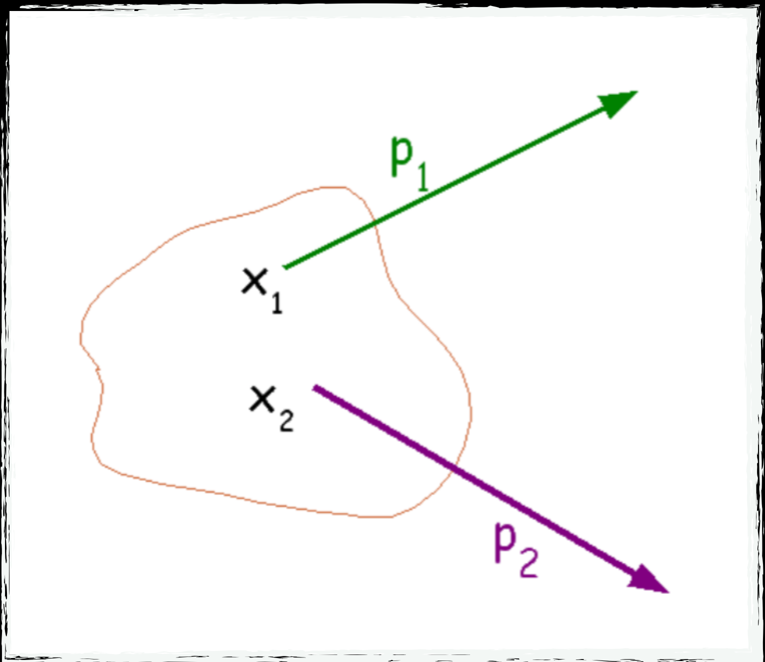


Methods of analysis

- **Femtoscopy correlations - correlation function**

Two-particle distribution

$$P_2(p_1, p_2) = E_1 E_2 \frac{dN}{d^3 p_1 d^3 p_2} = \int d^4 x_1 S(x_1, p_1) d^4 x_2 S(x_2, p_2) \Phi(x_2, p_2 | x_1, p_1)$$



$$C(p_1, p_2) = \frac{P_2(p_1, p_2)}{P_1(p_1) P_1(p_2)}$$

One-particle distribution

$$P_1(p) = E \frac{dN}{d^3 p} = \int d^4 x S(x, p)$$

S(x,p) – emission function: the distribution of source density probability of finding particle with x and p

Methods of analysis

- **Femtoscopy correlations - in experiment**

Signal, distribution of the difference of particles' momentums derived from the SAME collision

$$C_2(\vec{q}) = \frac{A(\vec{q})}{B(\vec{q})}$$

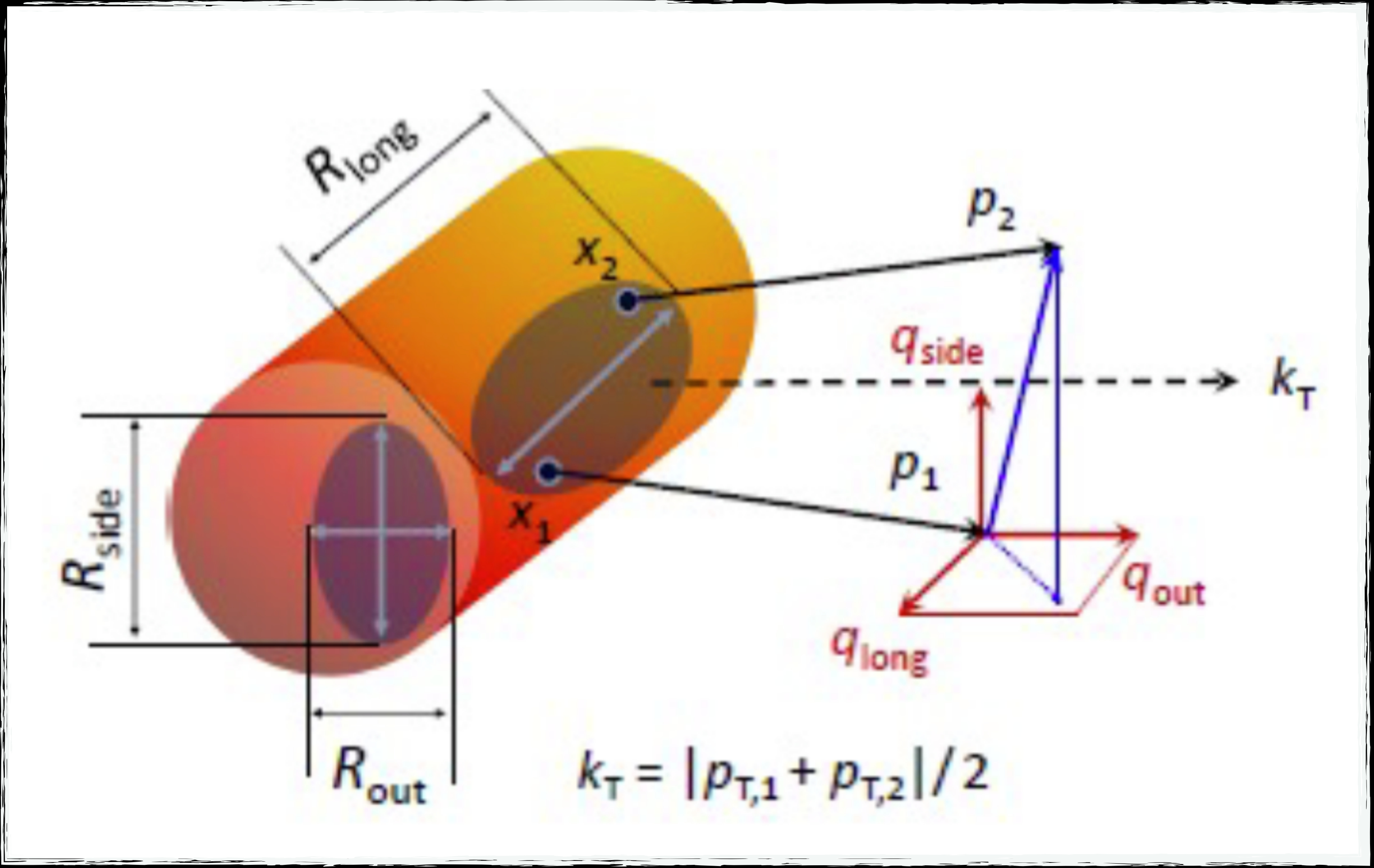
$$\vec{q} = \overrightarrow{p_1} - \overrightarrow{p_2}$$

Background, distribution of the difference of particles' momentums derived from DIFFERENT collisions

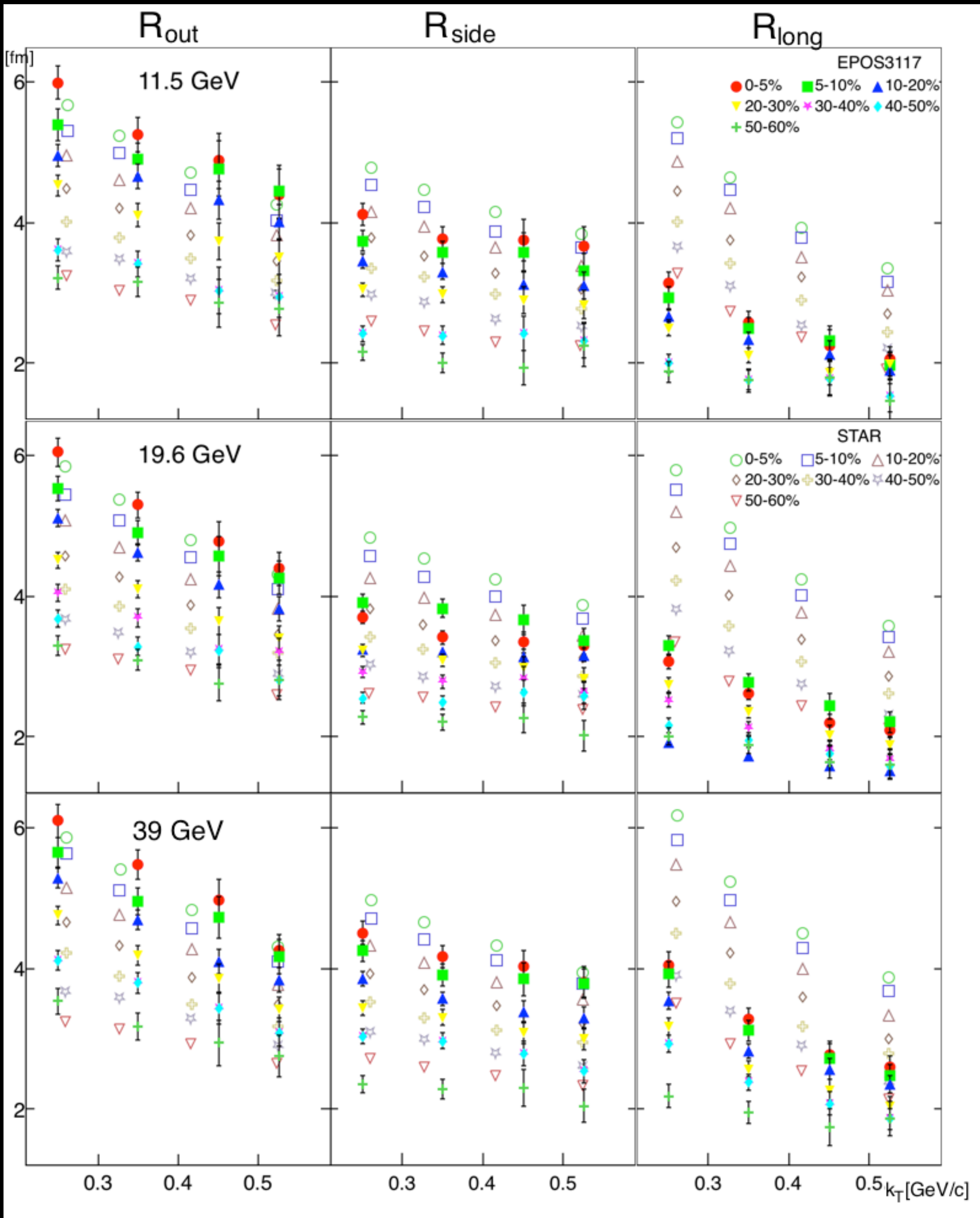
Methods of analysis

- **Femtoscopy correlations - parametrization**

$$C(q_{out}, q_{side}, q_{long}, \lambda) = 1 + \lambda exp(-q_{out}^2 r_{out}^2 - q_{side}^2 r_{side}^2 - q_{long}^2 r_{long}^2)$$

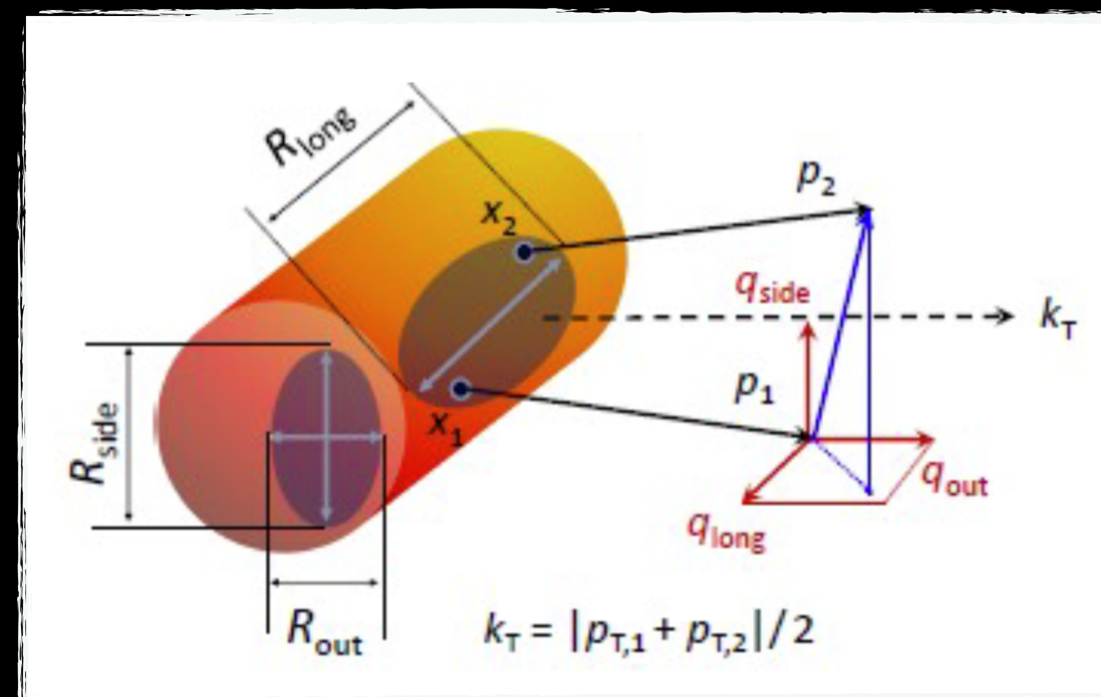


Sizes of the source



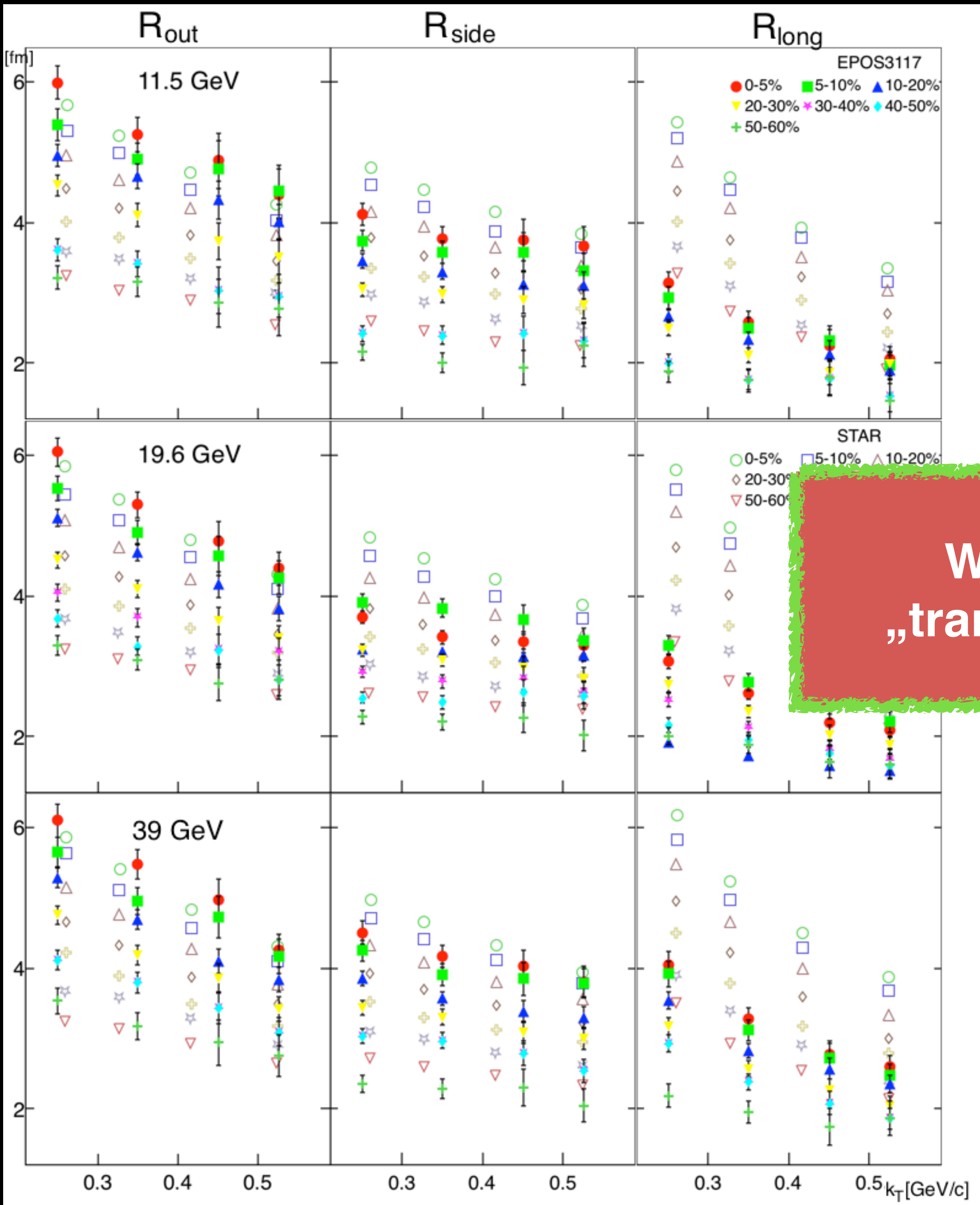
Au+Au $\pi^+\pi^+$

STAR data: arXiv:1403.4972



- R_{out} - bigger then STAR
- R_{side} - lower then STAR
- R_{long} - huge discrepancies!

Sizes of the source



Au+Au $\pi^+\pi^+$

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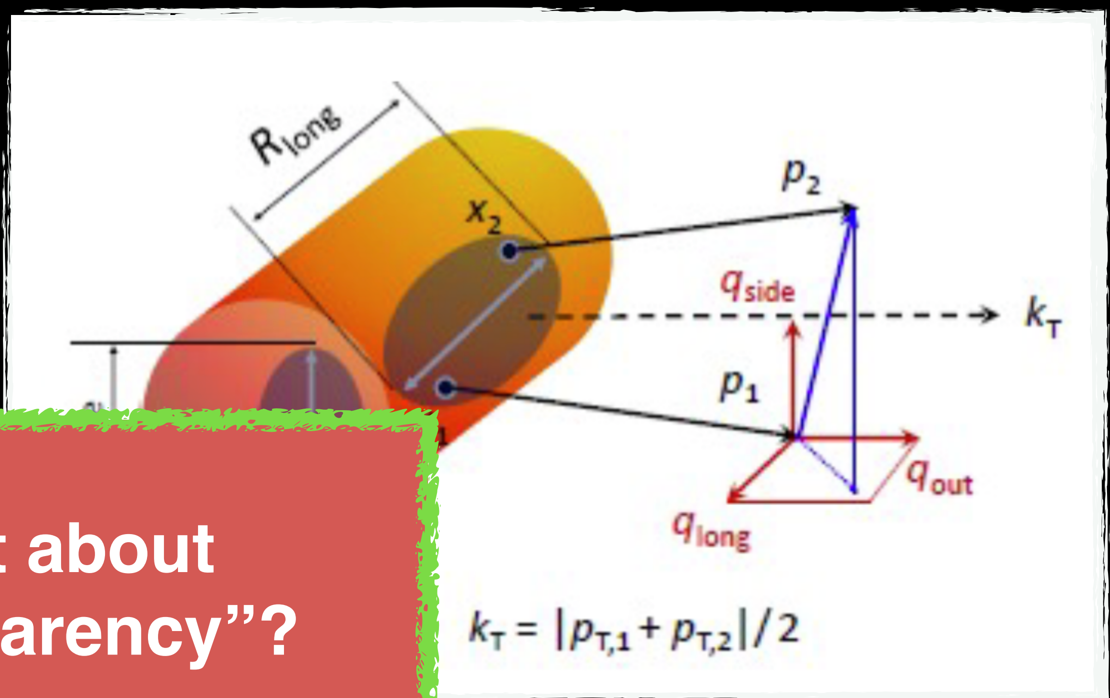
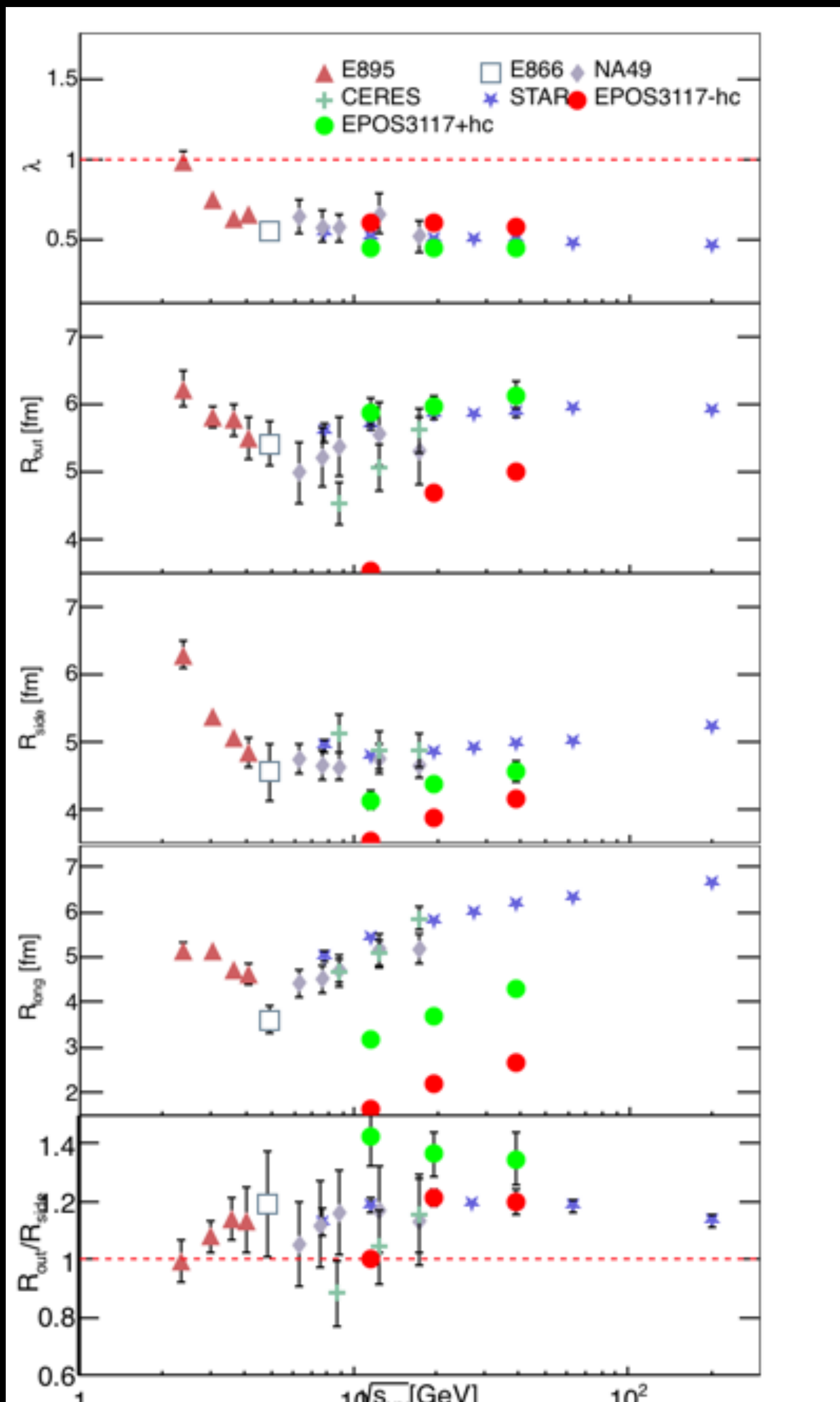


What about „transparency"?

- R_{out} - bigger then STAR
- R_{side} - lower then STAR
- R_{long} - huge discrepancies!

Sizes of the source

arXiv:1403.4972



Lambda comparable!

R_{out} comparable!

R_{side} slightly lower

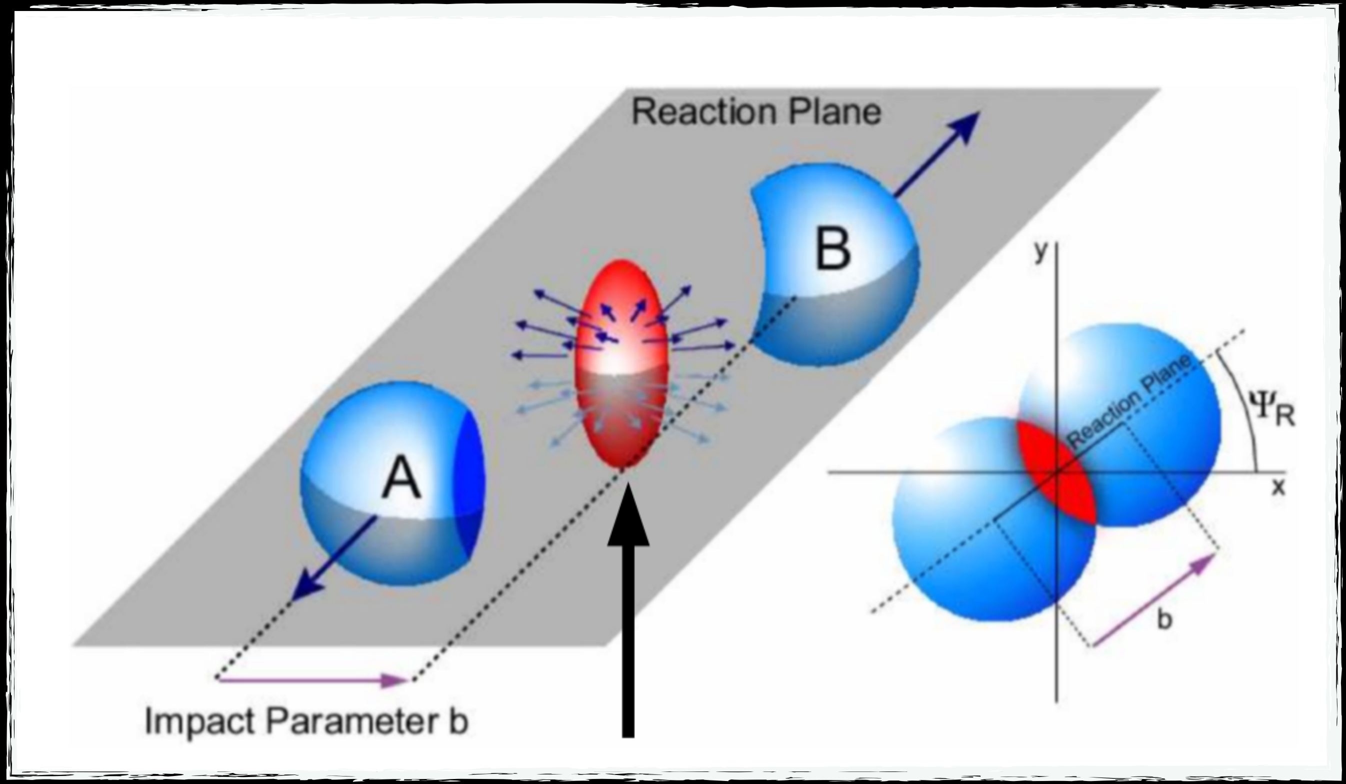
R_{long} relevantly lower

Impact of the *hadron cascades*

Au+Au $\pi^+\pi^+$ $k_T \approx 0.225$ GeV/c

Methods of analysis

- p_T spectra
- Femtoscopy correlations
- **Azimuthal Anisotropy**
  - *event plane* method



One way of studying the azimuthal anisotropy is the Fourier decomposition, where each of coefficients reports to the shape of matter flow.

$$\frac{dN}{d(\phi - \Phi_{RP})} = \frac{N_0}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[(\phi - \Phi_{RP})]\right)$$

N_0 - number of particles

v_n - n-th harmonic coefficient

ϕ - azimuthal angle of particles

Φ_{RP} - azimuthal angle of the reaction plane

Methods of analysis

- p_T spectra
- Femtoscopy correlations
- **Azimuthal Anisotropy**
  - event plane

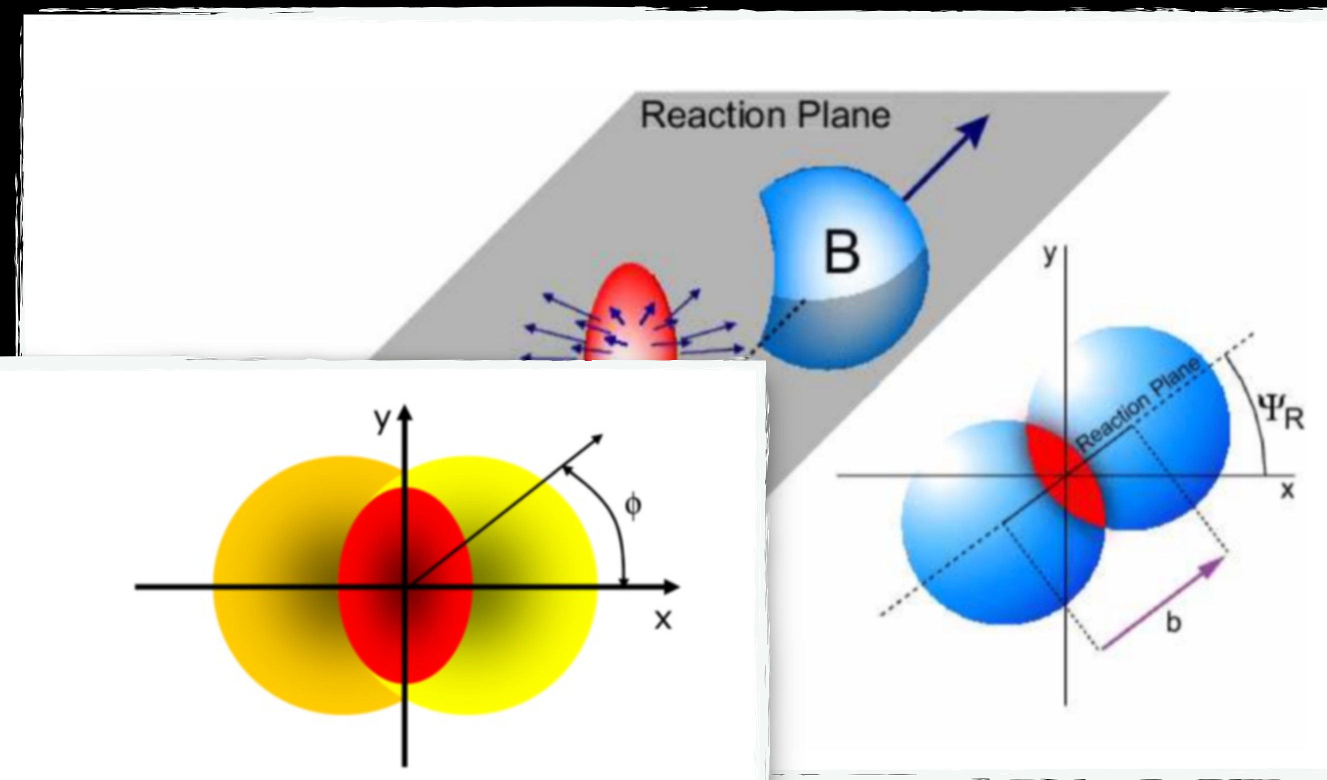
One way of studyi… anisotropy is the Fou… where each of coeffic… shape of matter flow.

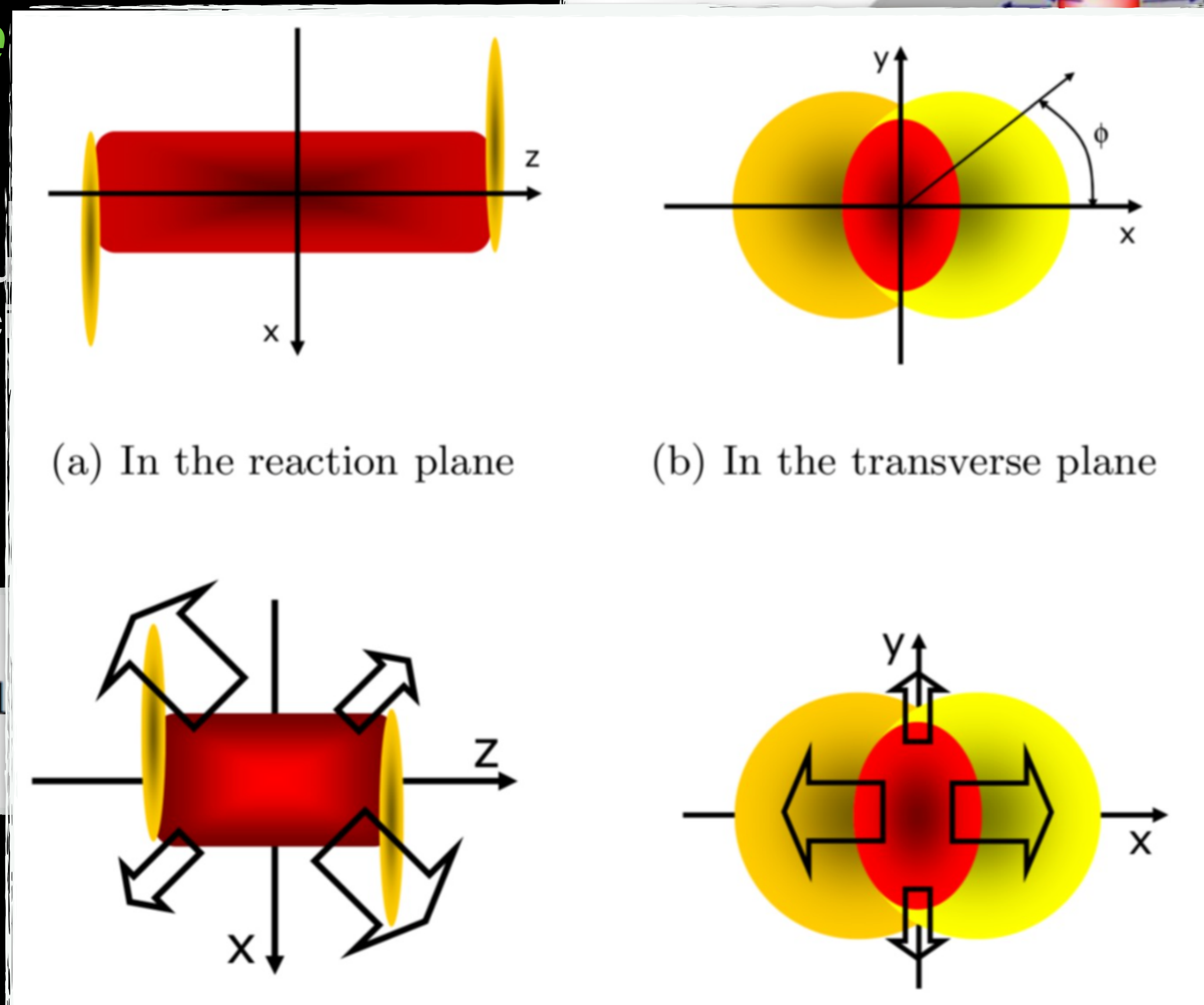
$$\frac{dN}{d(\phi - \Phi_{RP})} = \frac{N_0}{2\pi}\left(1 \ldots\right.$$

…ient

…ticles

…the reaction plane





(a) In the reaction plane (b) In the transverse plane

(a) First harmonic v_1 (b) Second harmonic v_2

Methods of analysis

- p_T spectra
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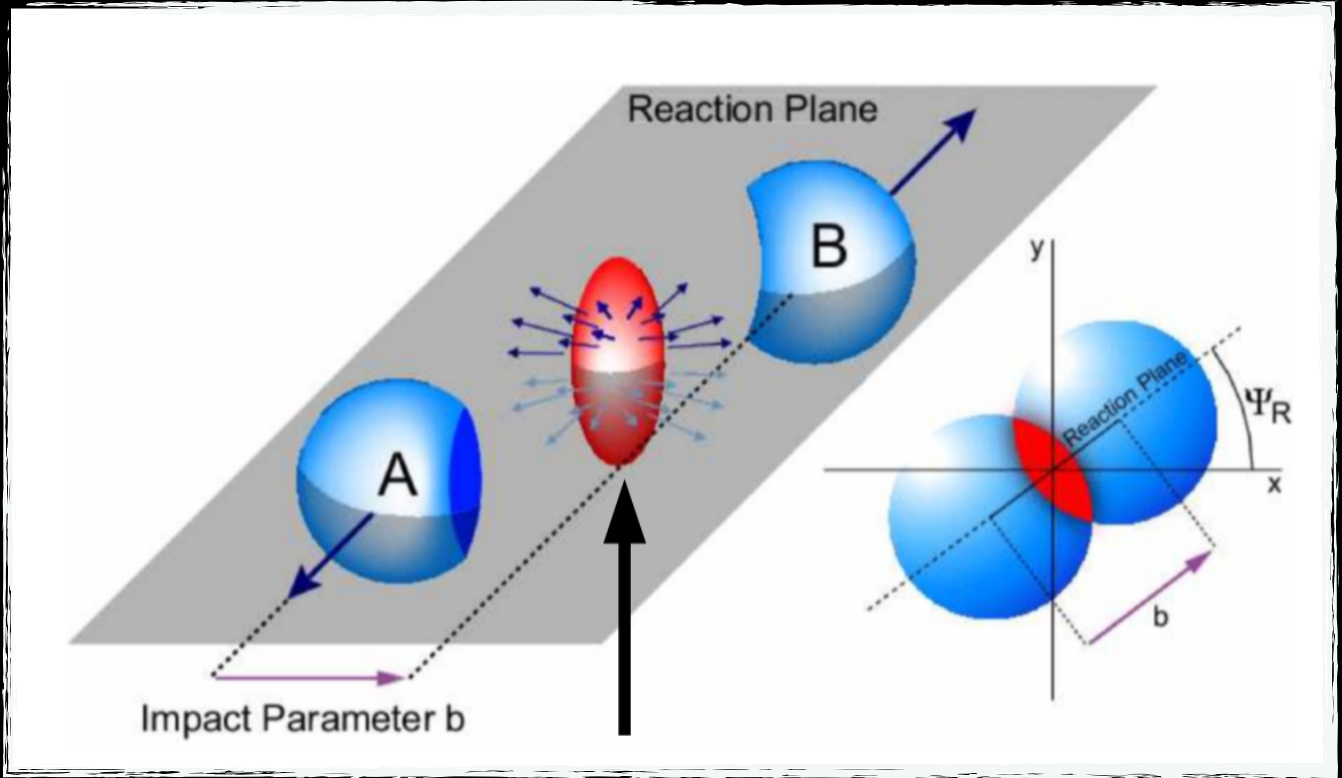
  - *event plane* method



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Methods of analysis

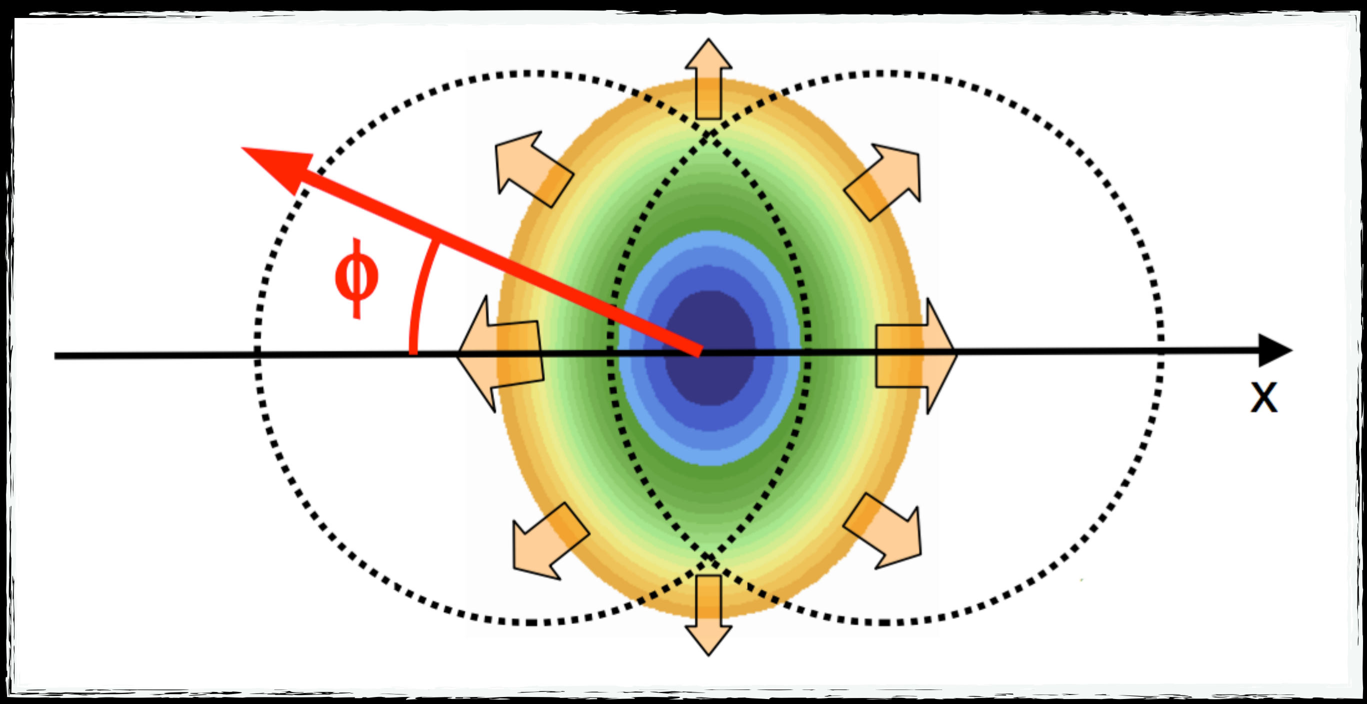
- p_T spectra
- Femtoscopy correlations
- **Azimuthal Anisotropy**
  - *event plane* method

- **Estimate *event plane* with equation (Fourier coefficient n = 2, elliptic flow)**

$$\Phi_2 = \tan^{-1}\left(\frac{\sum_i w_i sin(2\phi_i)}{\sum_i w_i cos(2\phi_i)}\right)/2$$

w_i -weight of i particle

ϕ_i - azimuthal angle of particles



Methods of analysis

- **Azimuthal Anisotropy - *event plane* method**

In analyze of elliptic flow were used η−sub method:

- from all measured particles there are selected two groups with ”forward” and ”backward” pseudorapidity with a gap between them.
- To express the observed v_2 of particles with respect to already investigated event plane one uses:

$$v_2^{obs}(p_T, y) = \langle \cos[2(\phi_i - \Phi_2)] \rangle$$

- As a consequence of the final multiplicity limitation in the investigation of the angle of the reaction plane, the correction of v_2 with event plane resolution have to be done.

$$R_2 = \sqrt{\langle \cos[2(\Phi_2^A - \Phi_2^B)] \rangle}$$

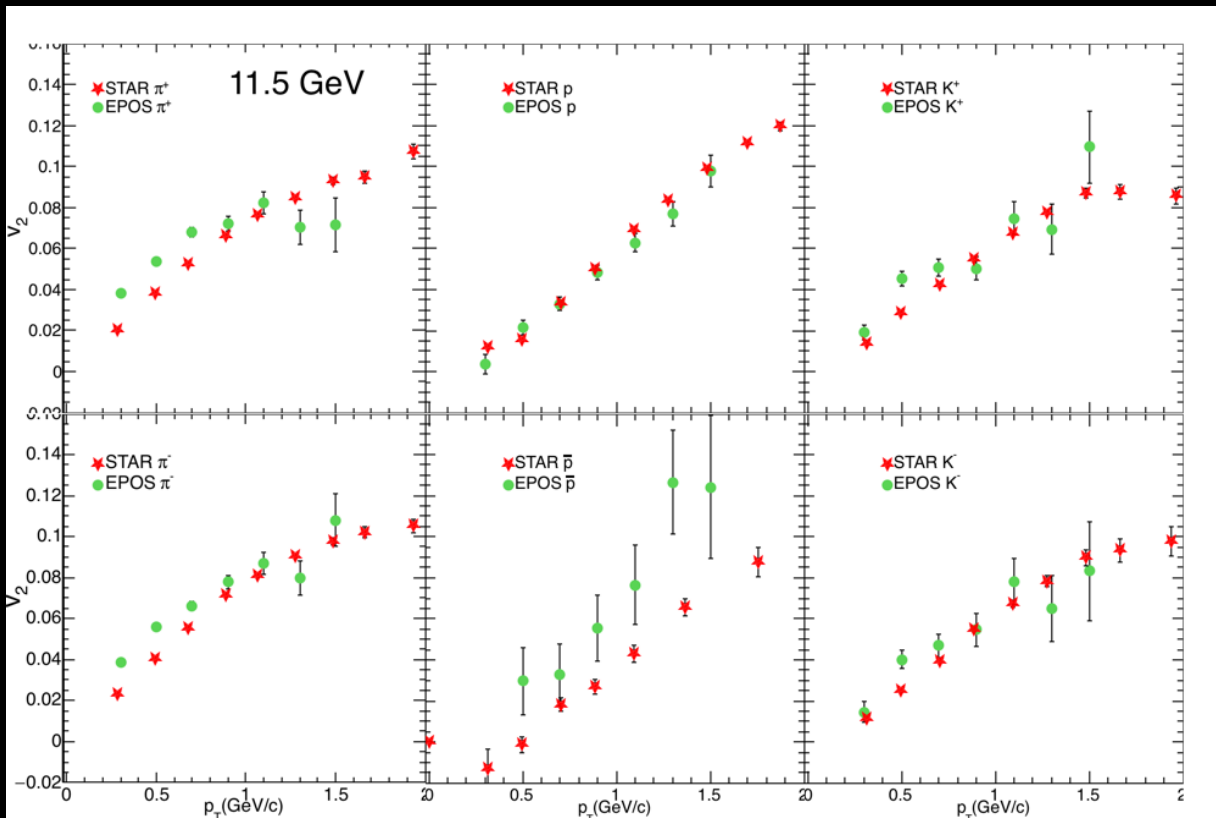
Φ_n^A - *event plane* calculated only using ”forward-pseudorapidity” particles while
Φ_n^B - with ”backward-pseudorapidity” ones.

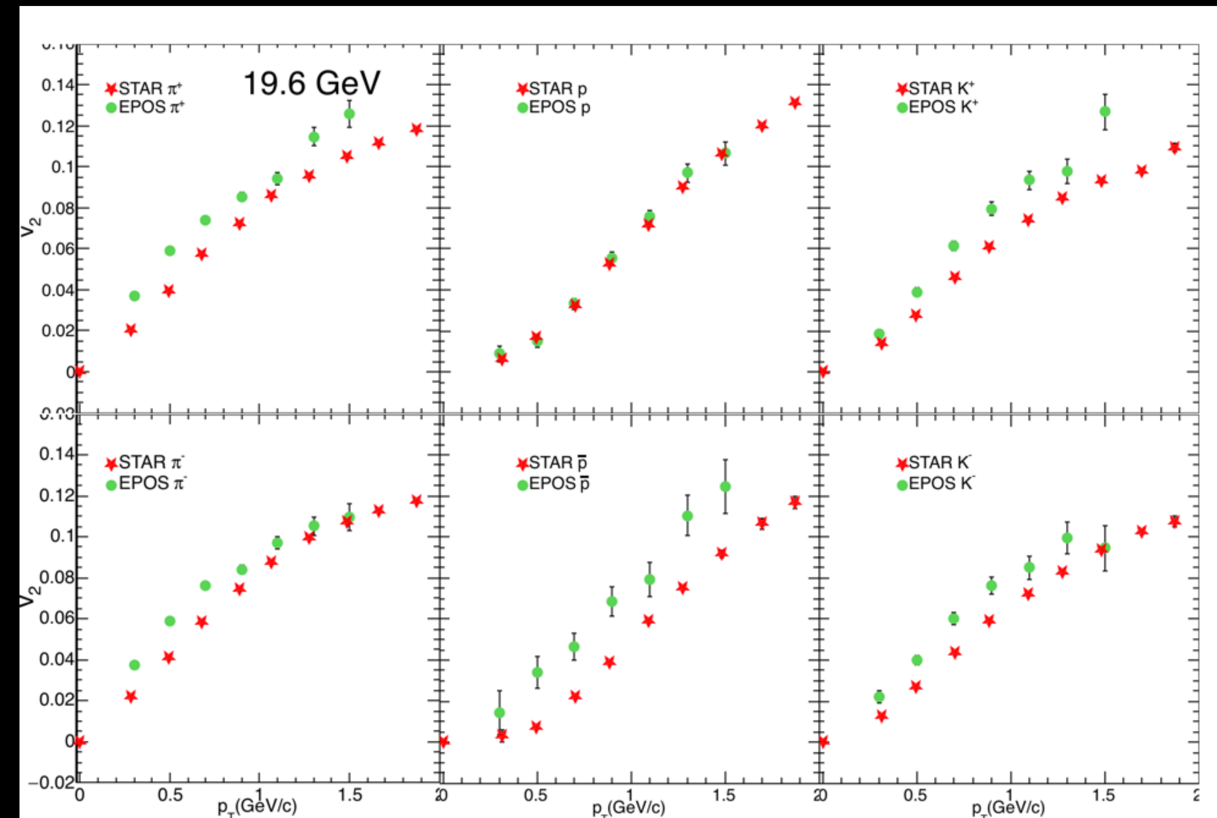
- Finally:

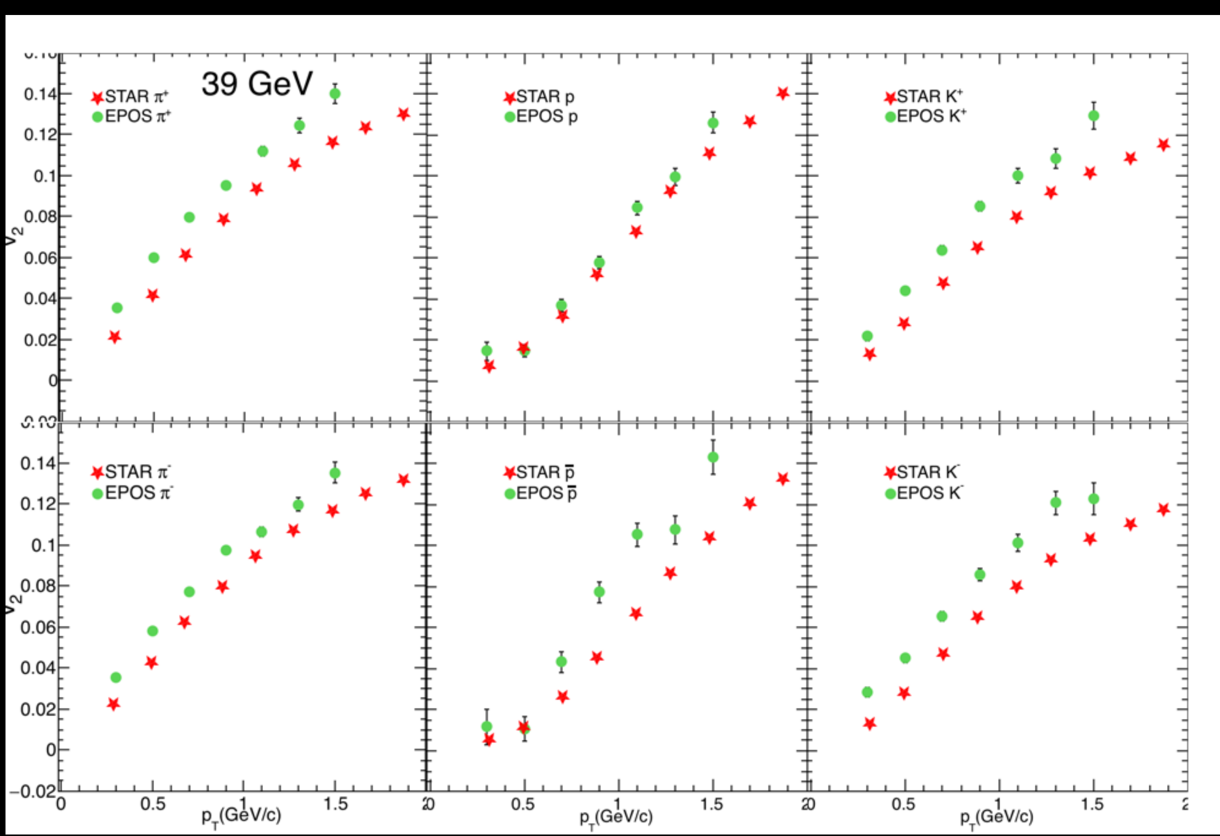
$$v_2 = \frac{v_2^{obs}}{R_2}$$

v_2

STAR data published in Phys. Rev., C88:014902, 2013







Lighter particles too high v_2

Protons comparable

Anti-protons not enough statistic

Au+Au

$|\eta| \in (0.05, 1)$

$p \in (0.15, 5\ \mathrm{GeV/c})$

centrality: 0-80%

Conclusion & future plans

- Three different methods were used:
    - transverse momentum spectra
    - elliptic flow
    - femtoscopy correlations
- Decreasing energy of collision results in more relevant differences between simulated and STAR data

p_T spectra: Not enough particles created in fluid in case of the peripheral collisions

femtoscopy:

- Relevant discrepancy in R_{long} between the simulated and experimental data
- Huge impact of the hadron cascades on the homogeneity length

elliptic flow:

- too high values for the lighter particles
- protons in range of expectation

Conclusion & future plans

about 100 hours to Diploma exam

Conclusion & future plans

- $\sqrt{s_{\mathrm{NN}}}$ 7.7, 27, 62.4 GeV have to be studied
- Model's parameters for BES program are still under way
- Hydrodynamical evolution of the system is studied

Thank you for your attention!

References

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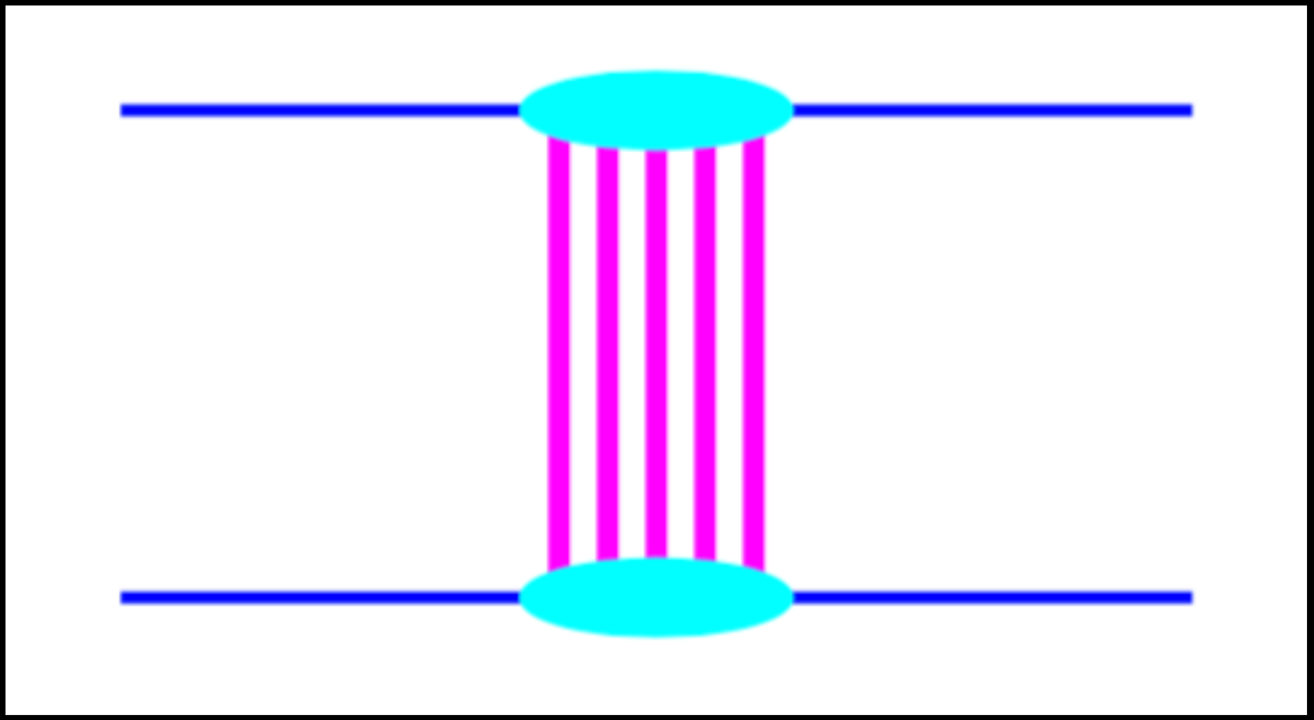
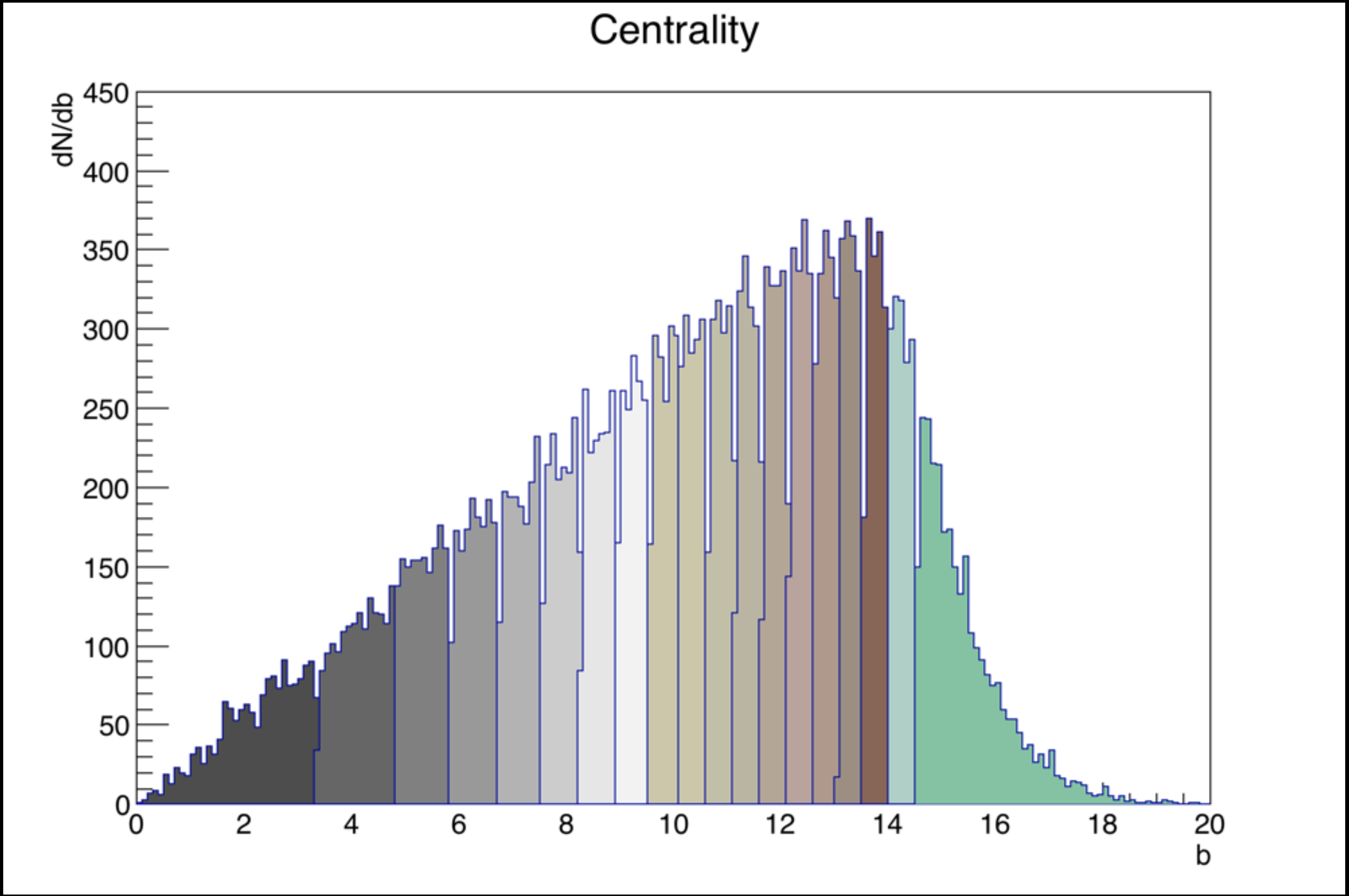
- [9] Stephen P. Horvat. Measurement of beam energy dependent nuclear modification factors at STAR. J. Phys. Conf. Ser., 446:012017, 2013.

Pomerons:

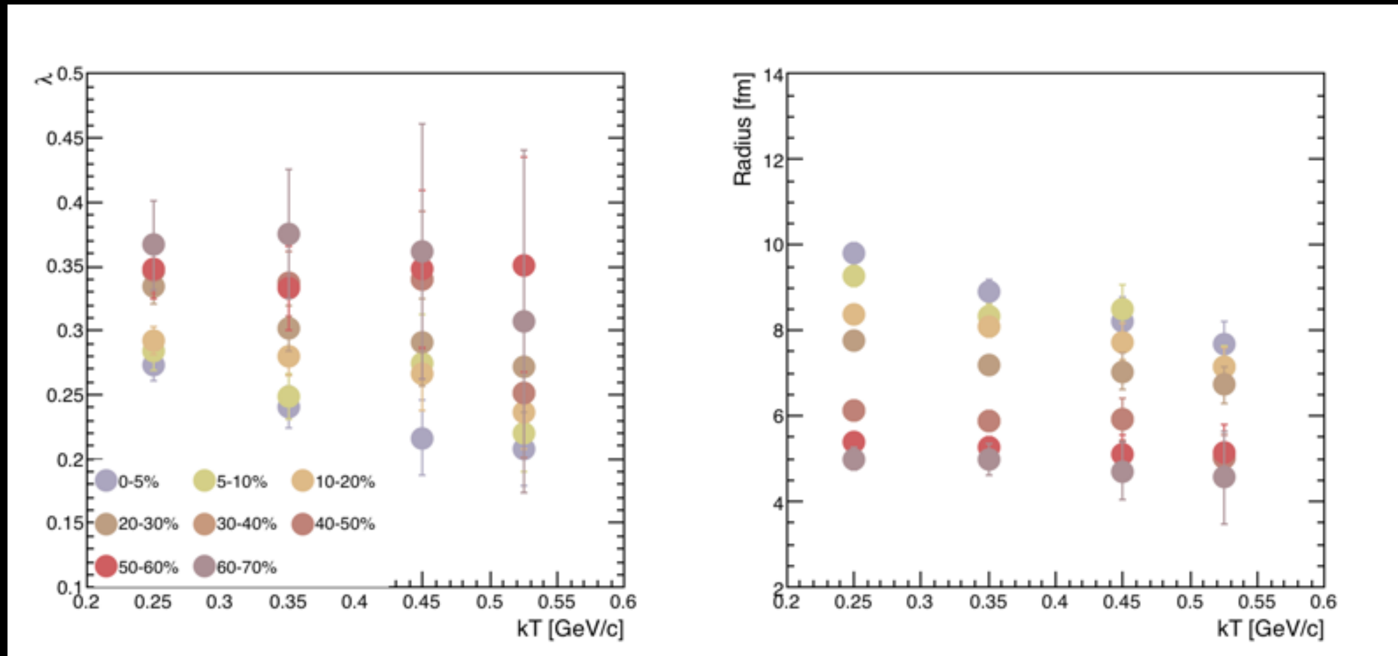
- theoretical objects
- parametrized by elastic amplitude
- considered identical but treated differently up to the order
- no partons, no QCD & QED



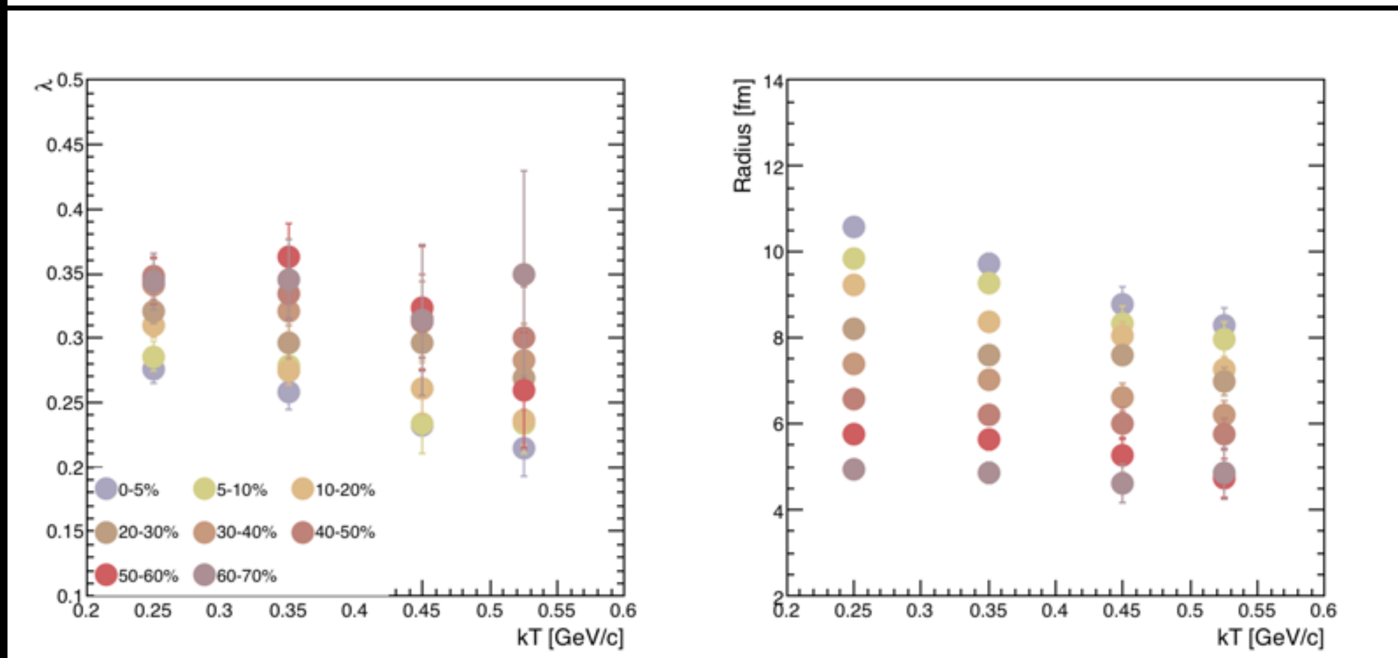
Centrality:



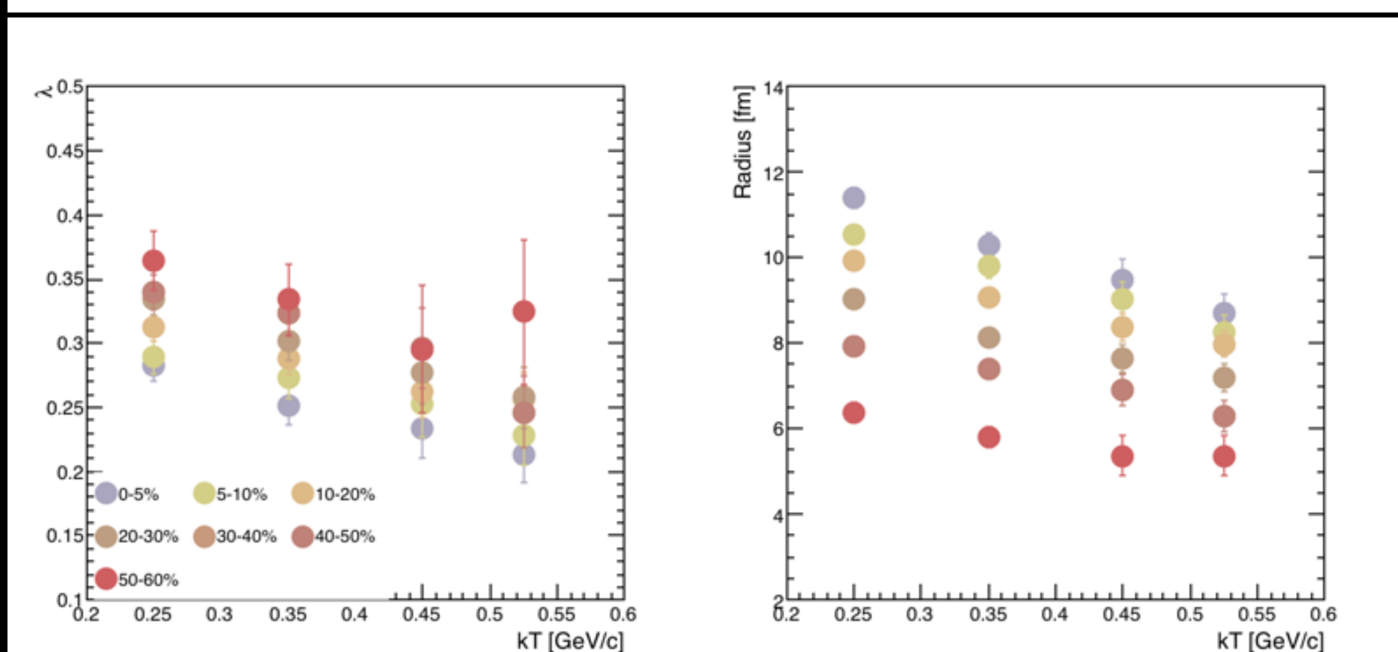
Centrality
dN/db
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
18
20
b



11.5 GeV



19.6 GeV



39 GeV