# Examination of heavy-ion collisions using EPOS model in the frame of the BES program at RHIC

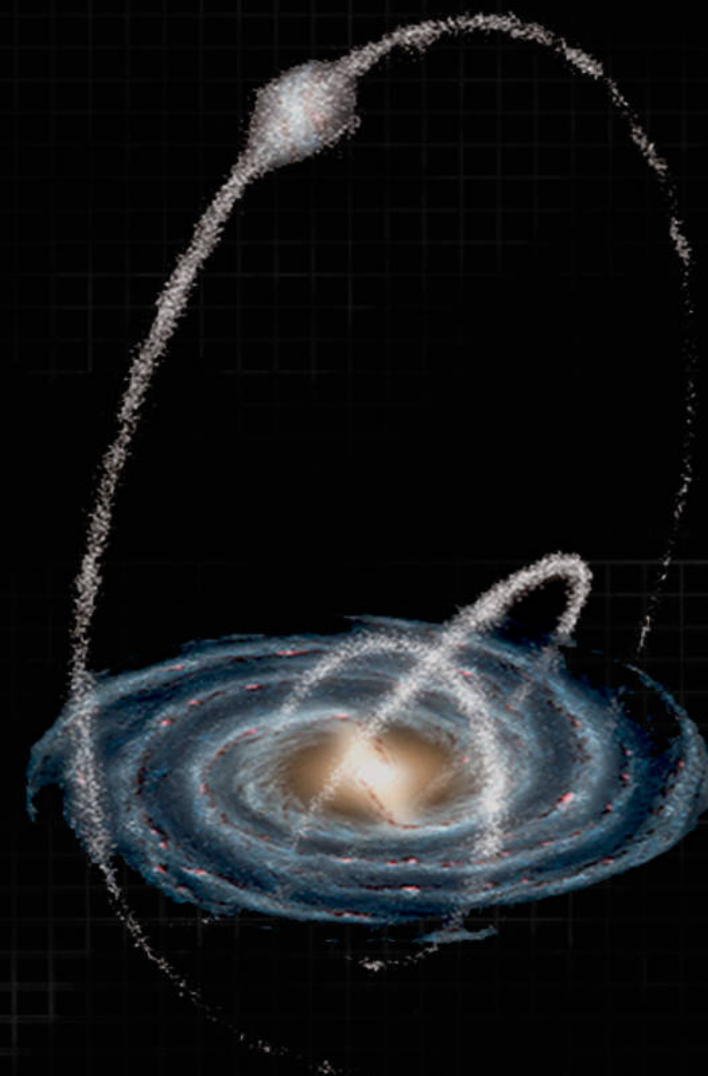
**Maria Stefaniak**

*Klaus Werner*
*Hanna Zbroszczyk*

in cooperation with

# Abstract

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



# Motivation

- EPOS - model for LHC & top RHIC energies
- What about lower energies?

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- EPOS - model for LHC & top RHIC energies
- What about lower energies?

↓

Studies of:

**EPOS simulations** ⟷ vs ⟷ **STAR experiment**

# EPOS generator

**E**nergy conserving quantum mechanical multiple scattering approach, based on **P**artons (parton ladders), **O**ff-shell remnants, and partons **S**aturation.

**Gribov - Regge theory**

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

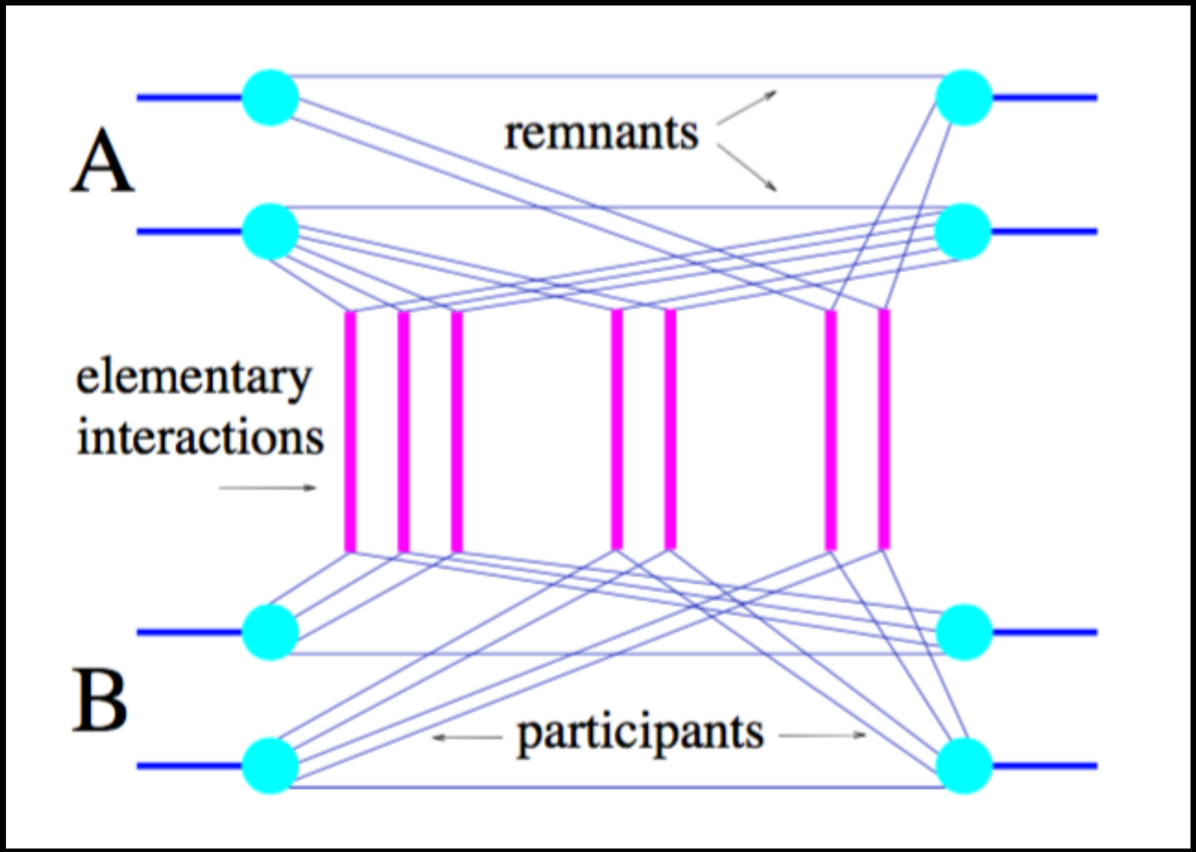
**Parton-based theory**

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

# EPOS generator

**Parton-based Gribov-Regge theory**

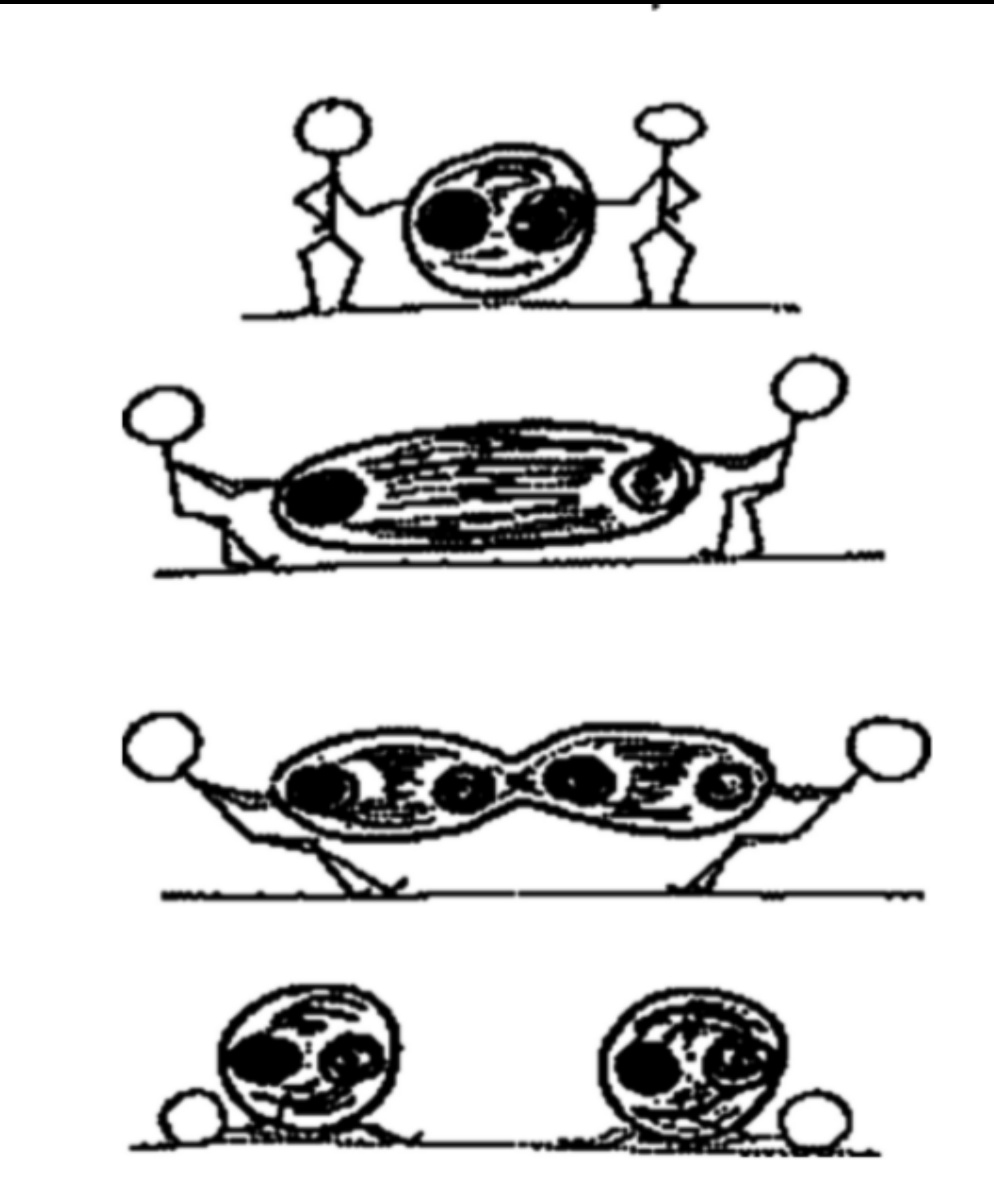
- Conservation of energy



# EPOS generator

**Parton-based Gribov-Regge theory**

- Conservation of energy
- Relativistic strings



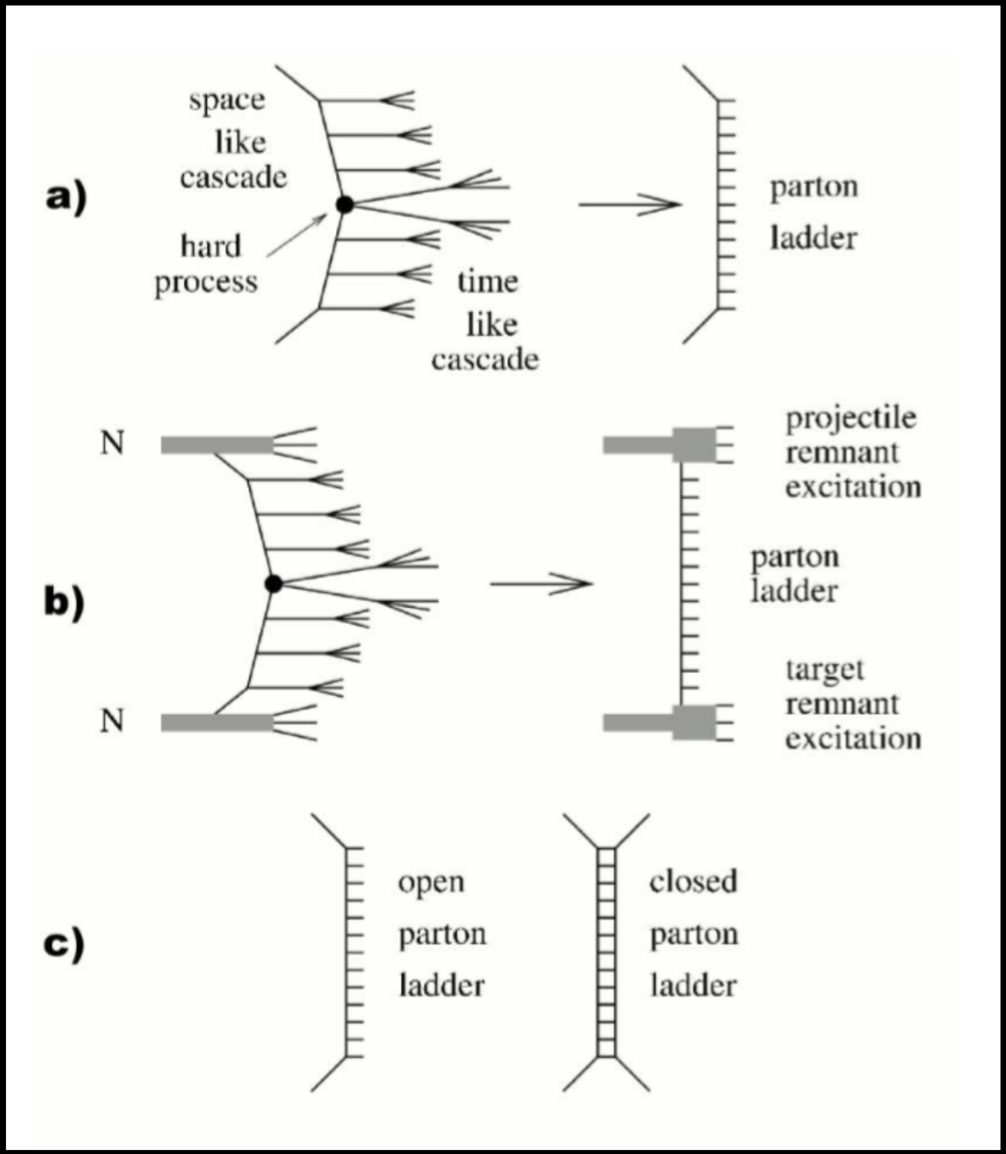
S. Mrówczyński

# EPOS generator

**Parton-based Gribov-Regge theory**

- Conservation of energy
- Relativistic strings
- Open and closed ladders

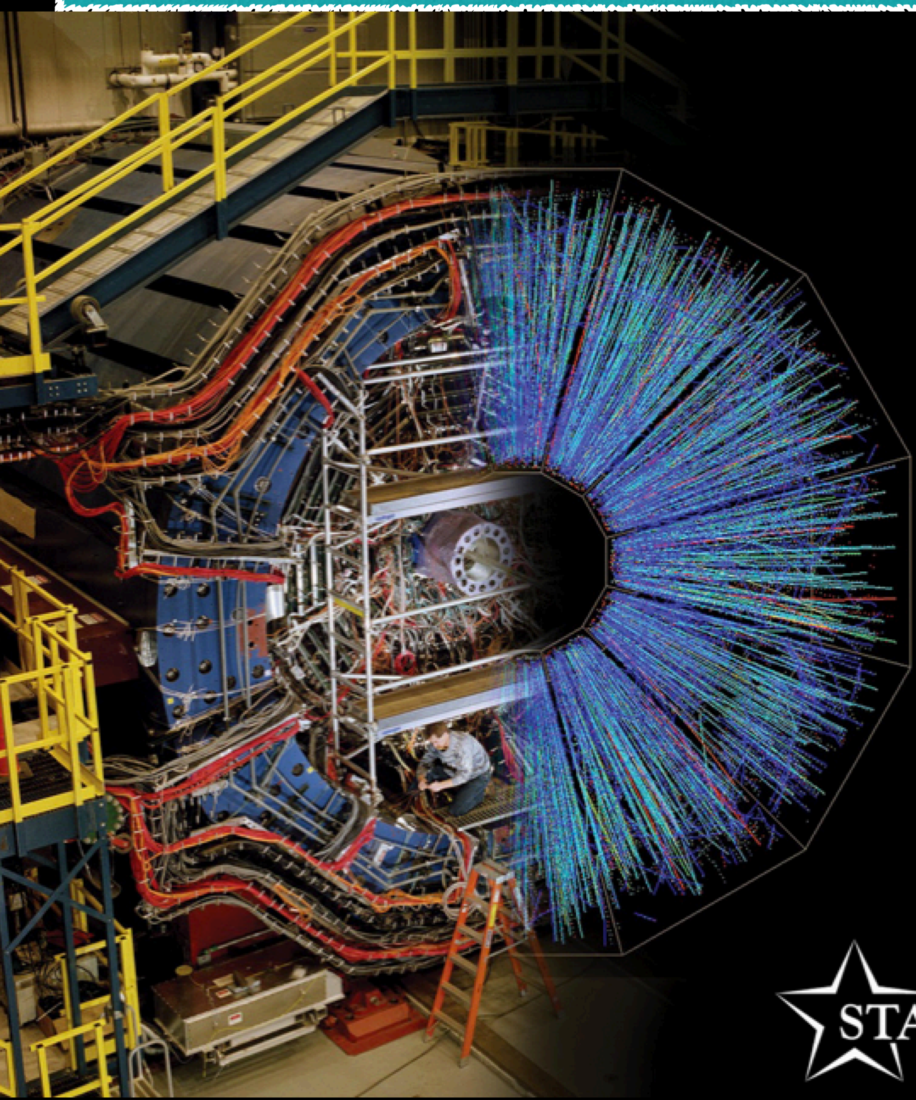
inelastic and elastic scattering

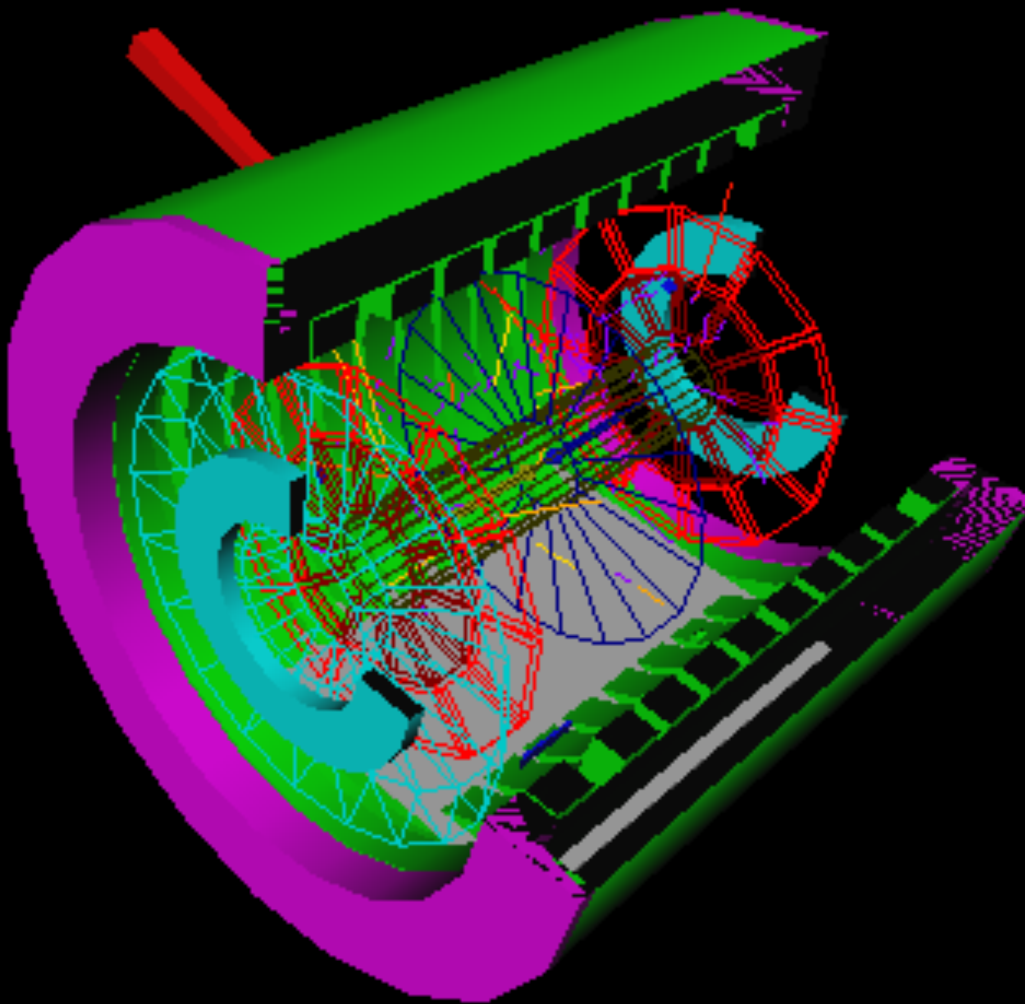


# Beam Energy Scan

**BES program:**

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





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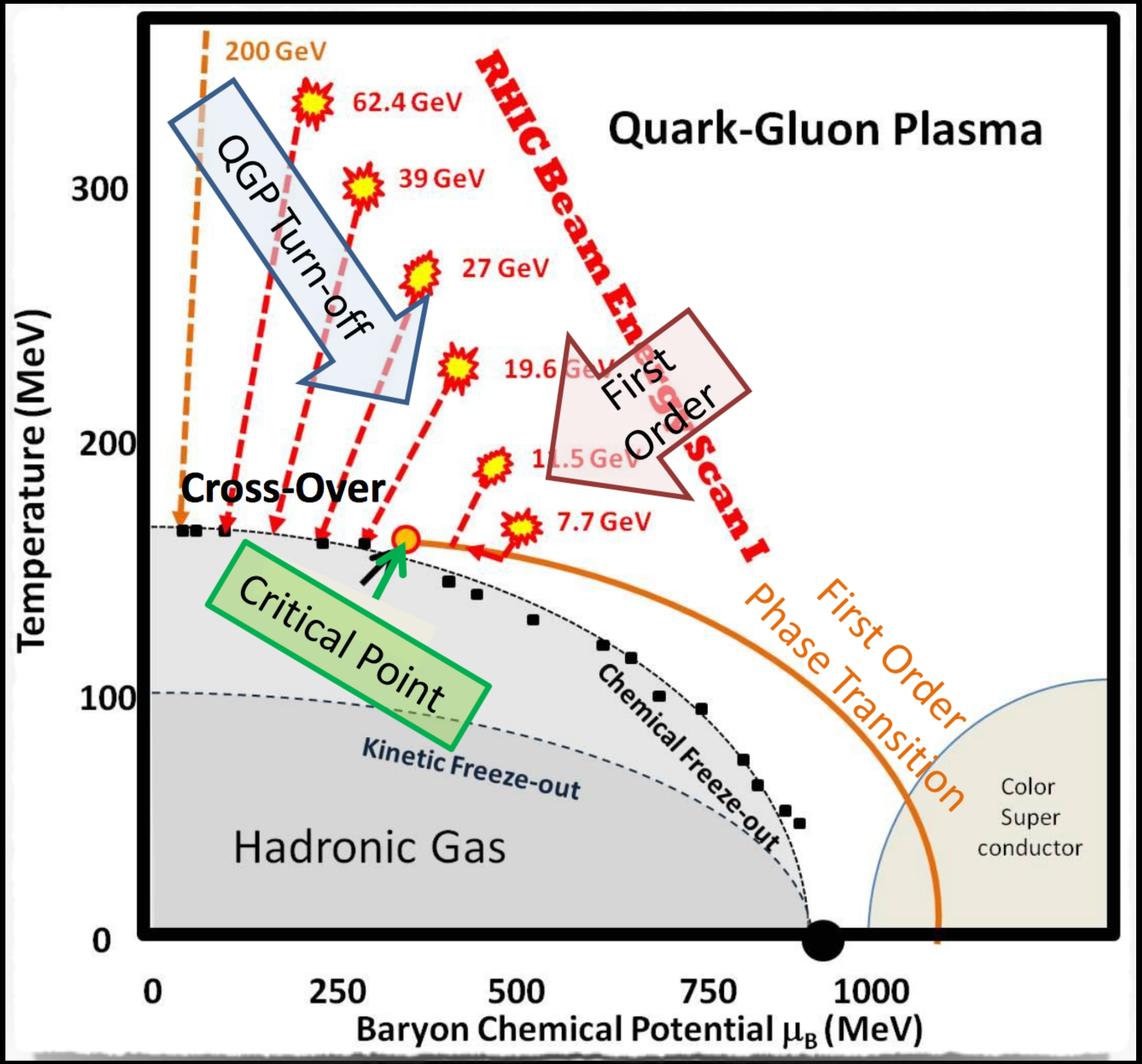
# Beam Energy Scan

**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



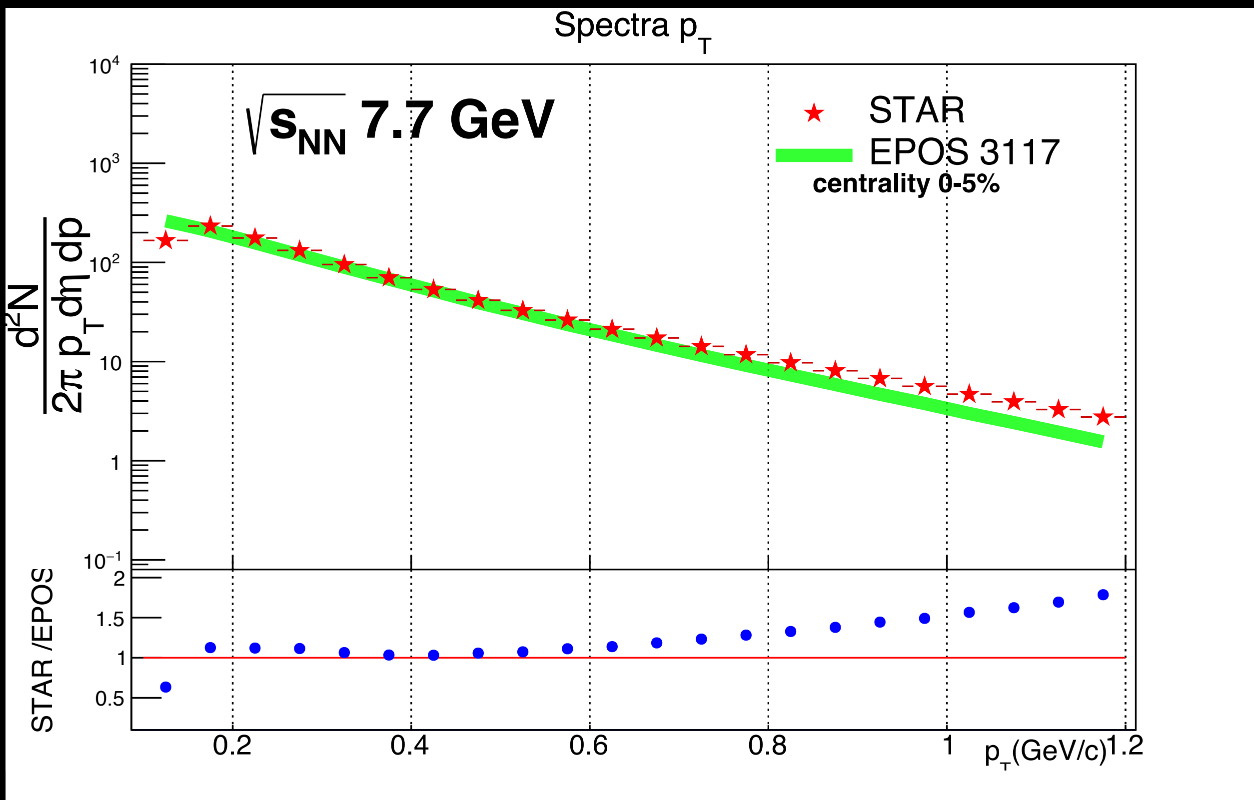
# Analysis & Results

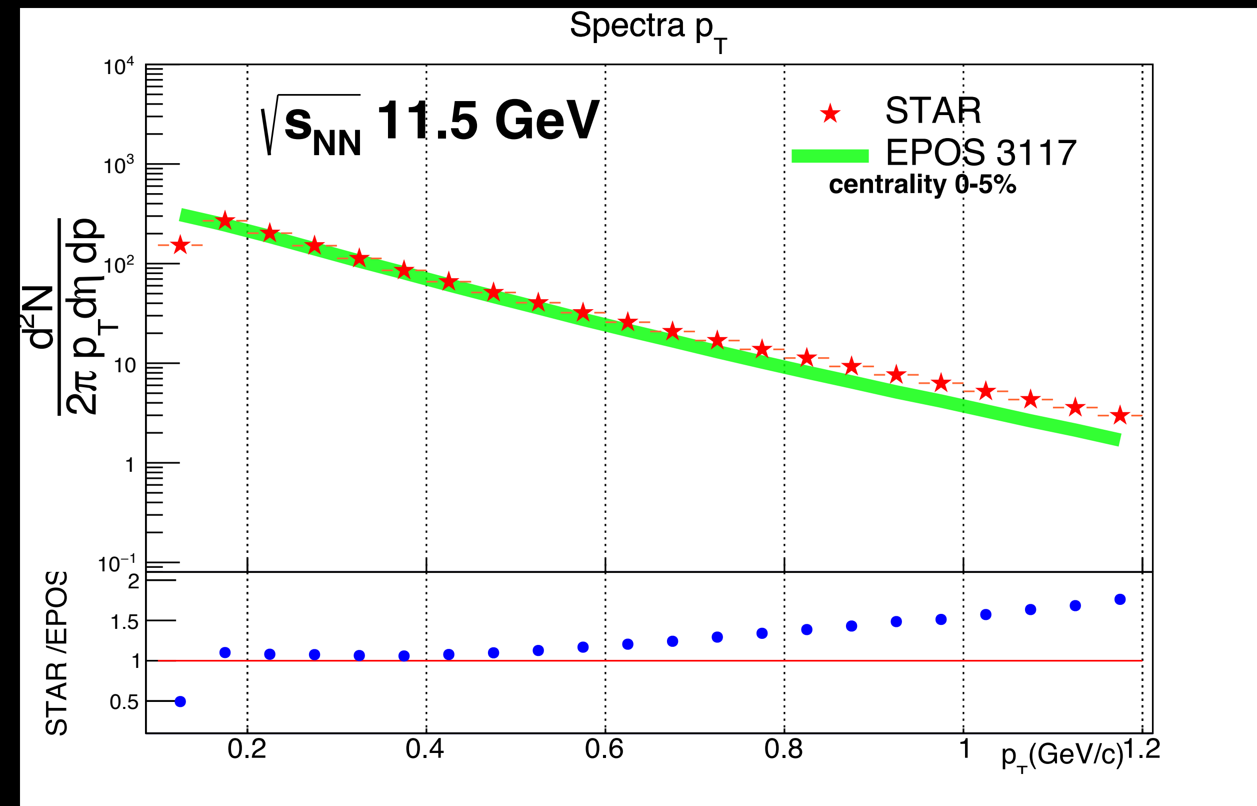
$$p_T = \sqrt{p_x^2 + p_y^2}$$

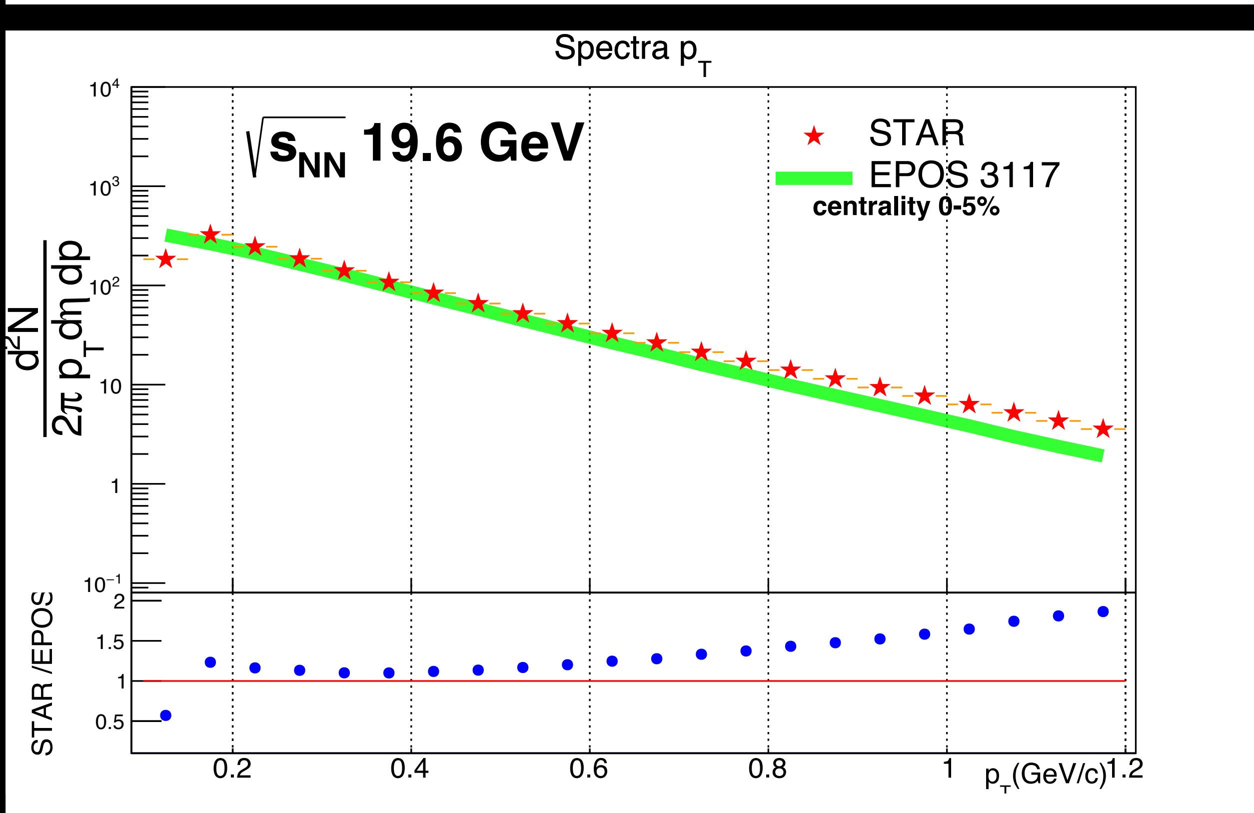
# Au+Au Analysis

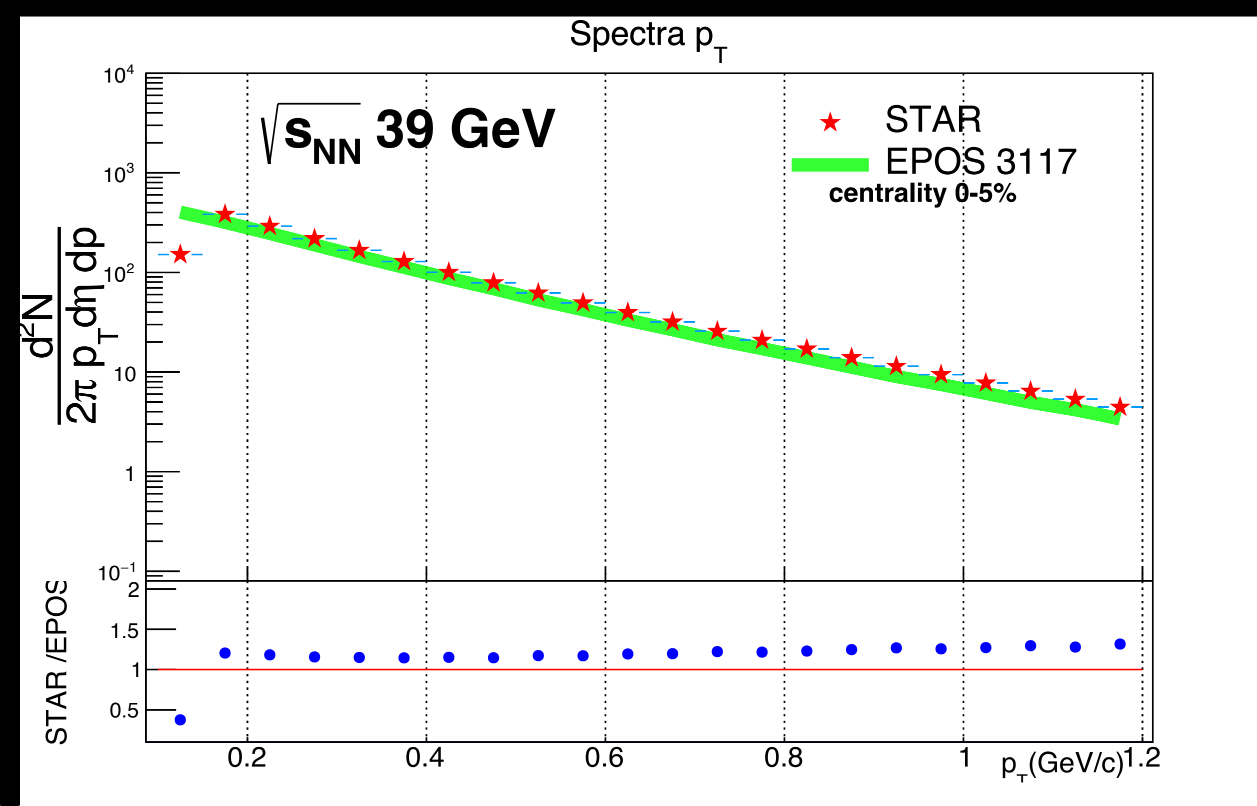
STAR data : J. Phys. Conf. Ser., 446:012017, 2013

## central 0-5%



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# Au+Au Analysis

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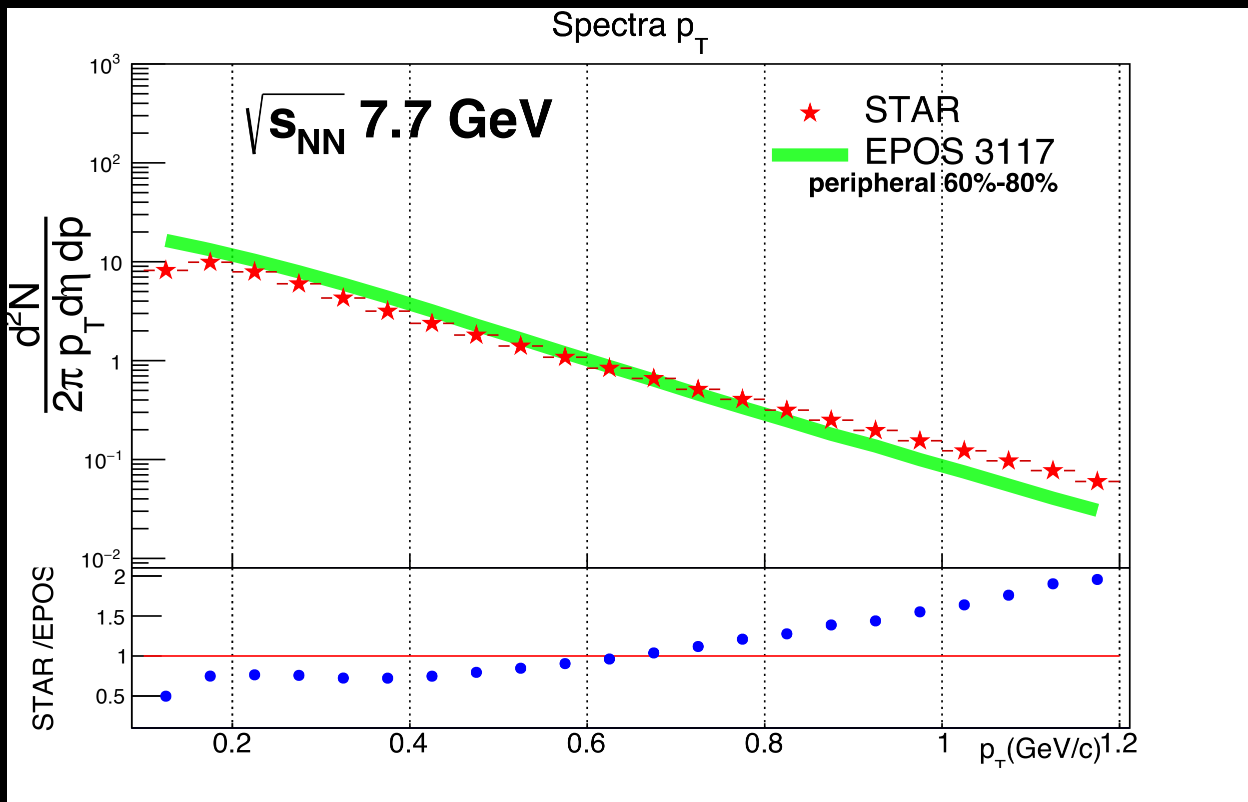
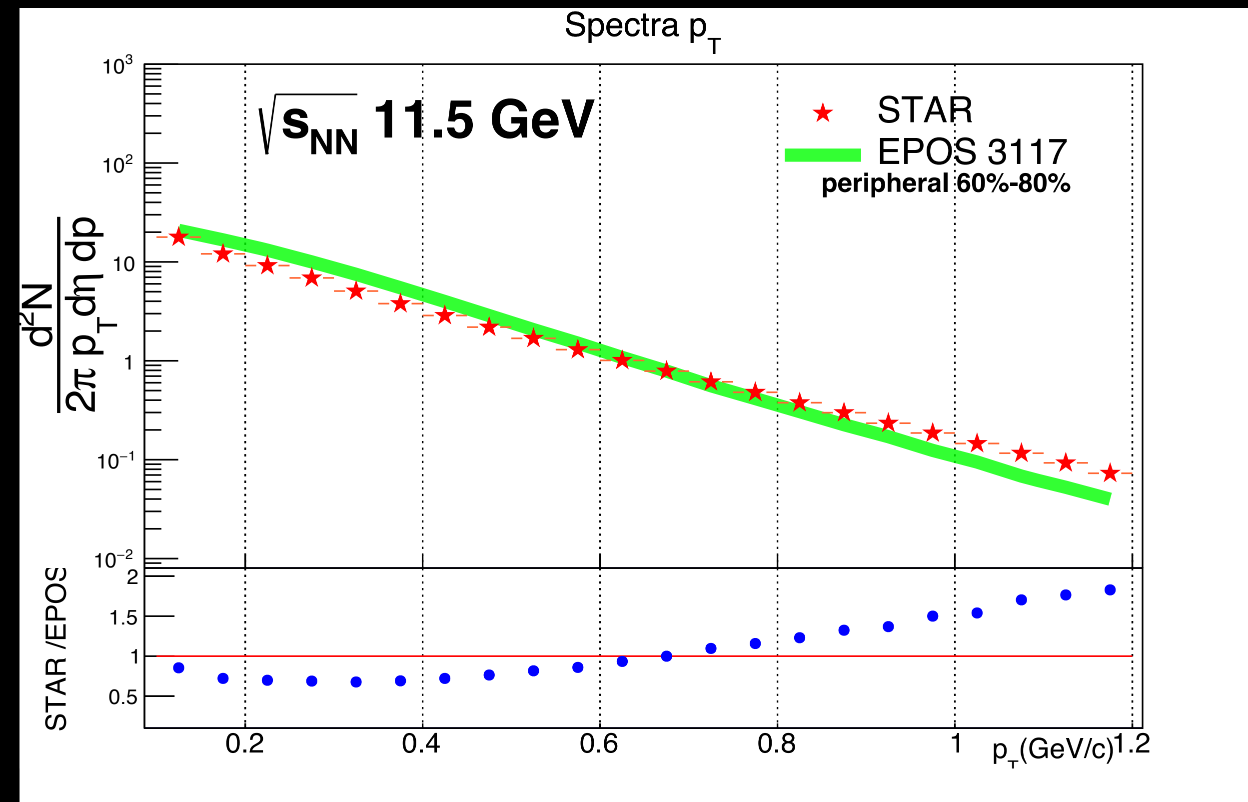
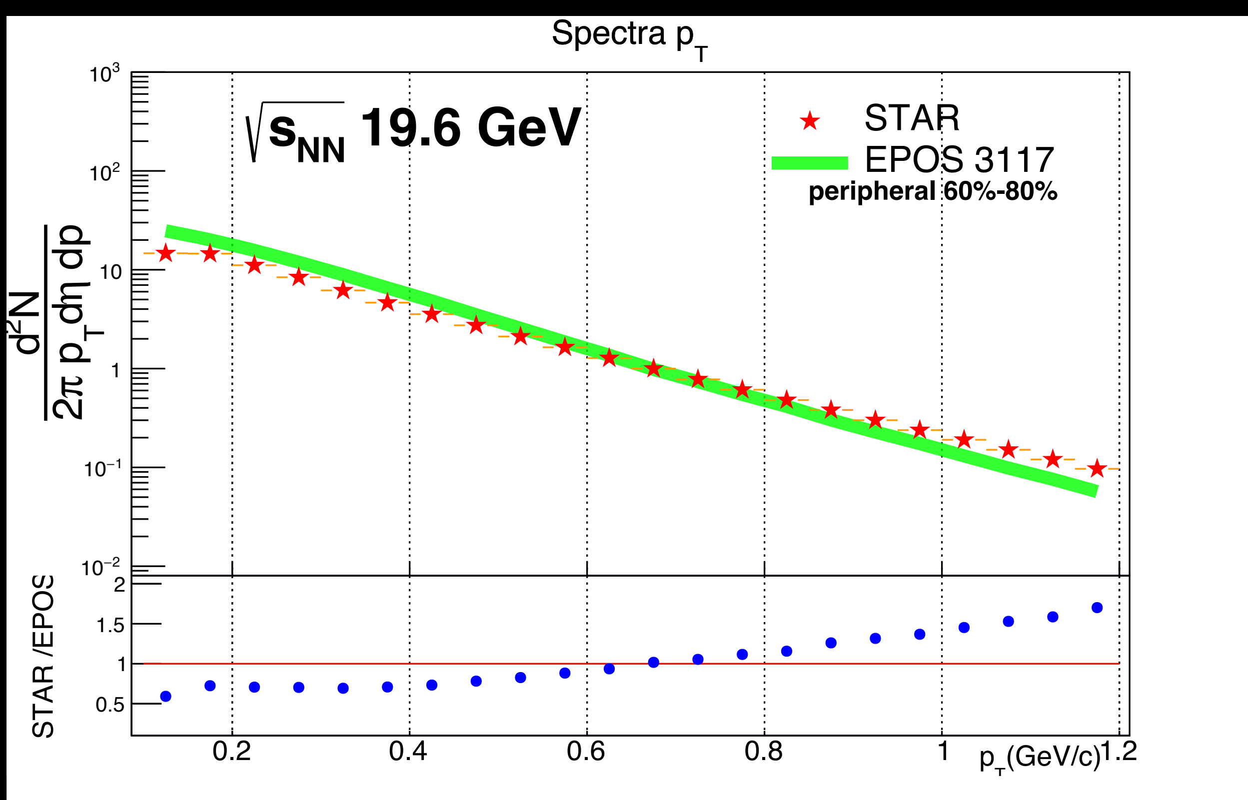
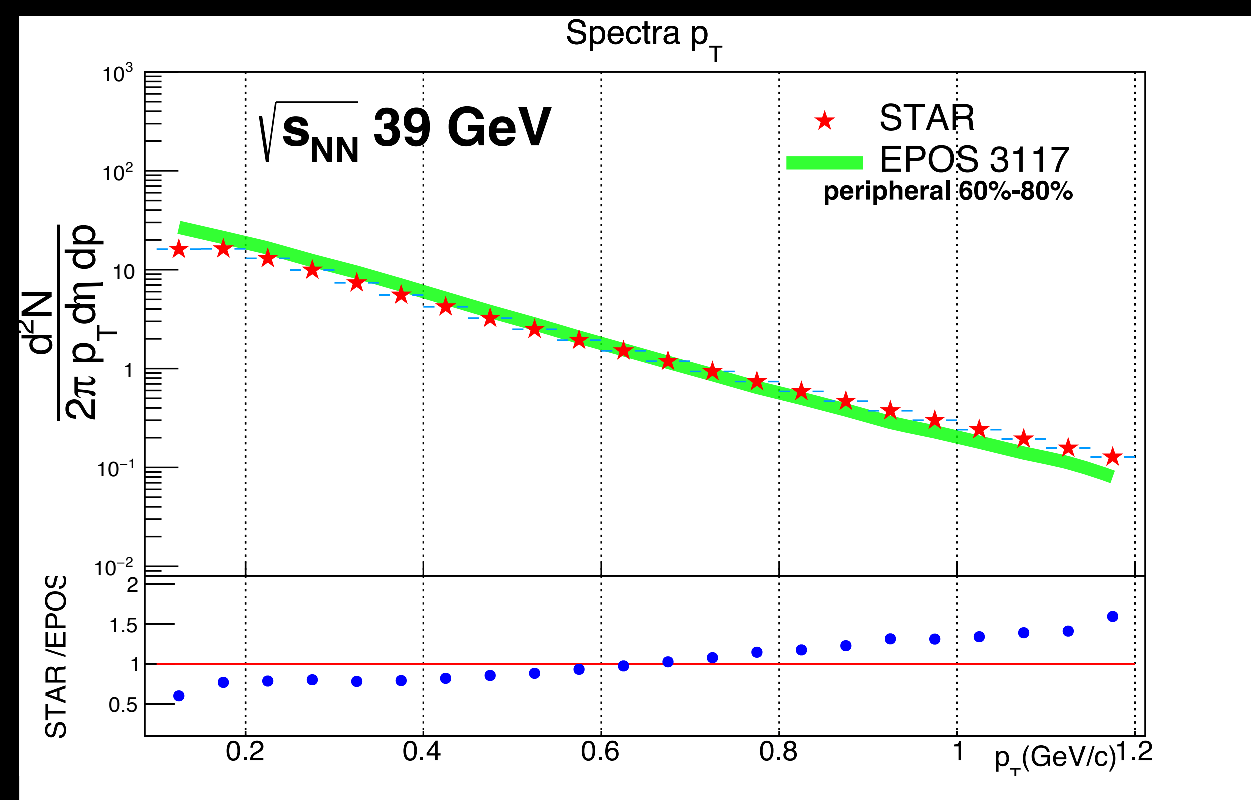
## peripheral 60%-80%



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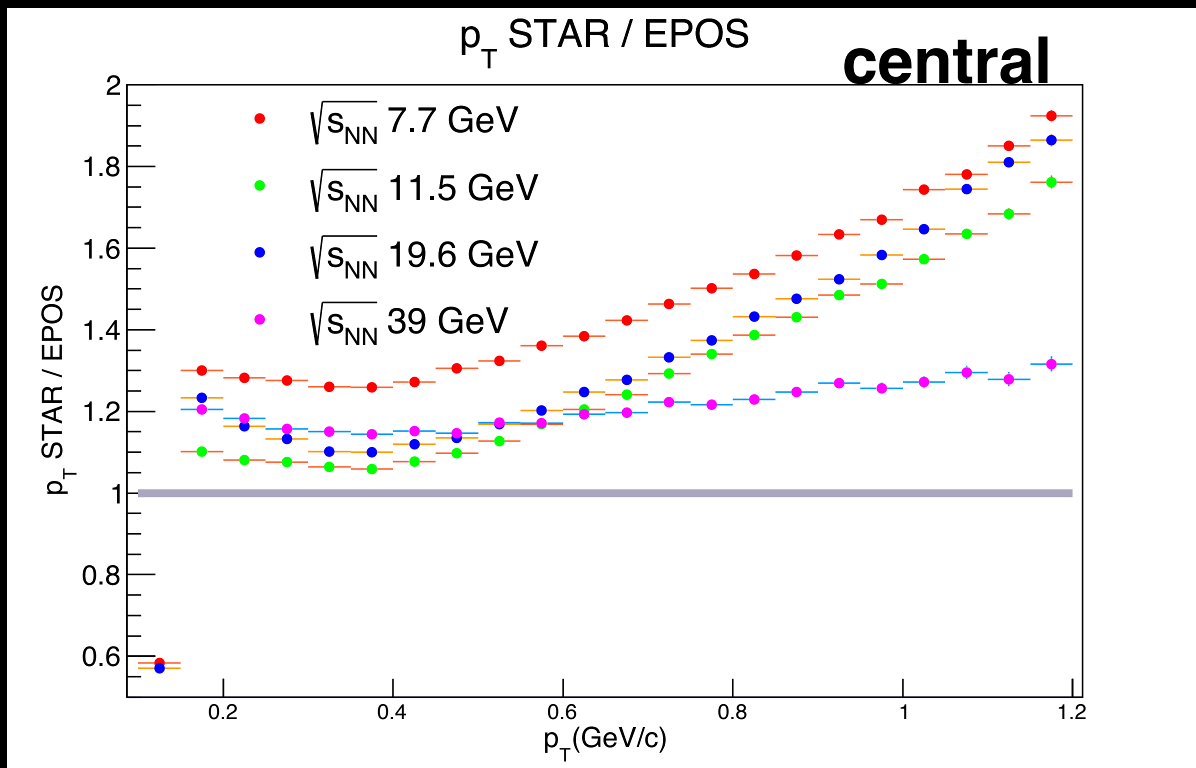
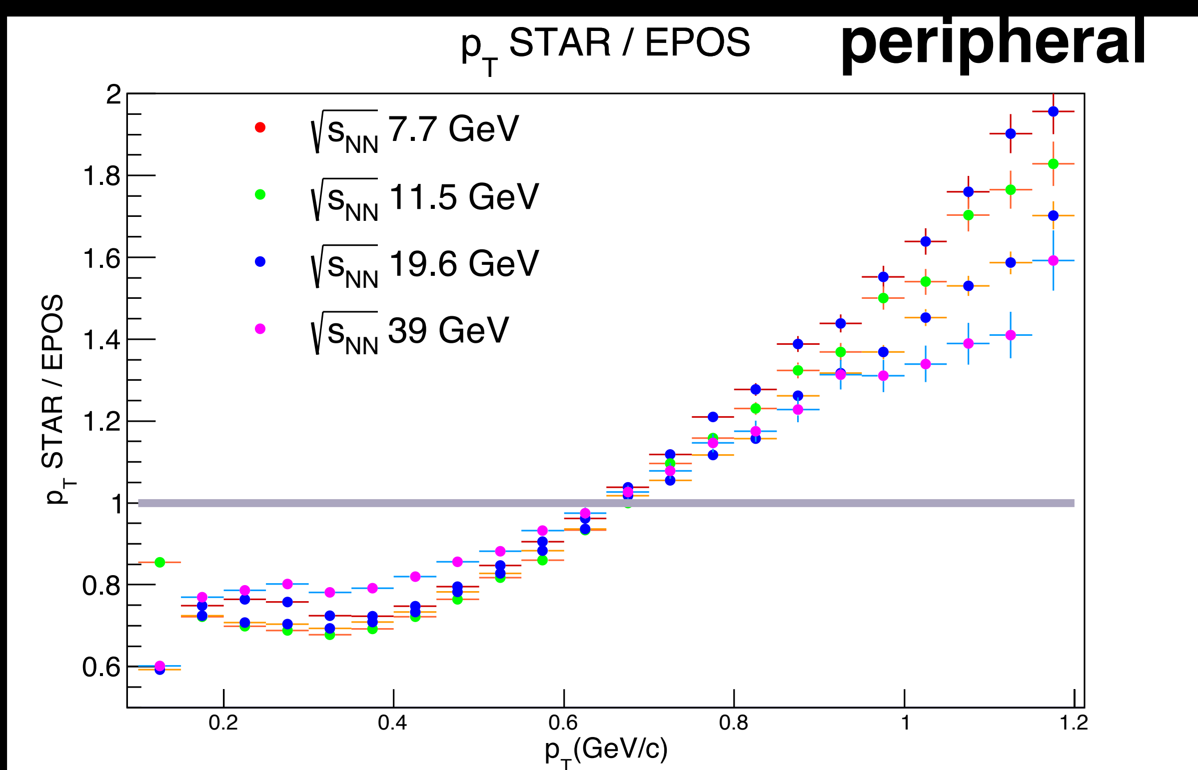
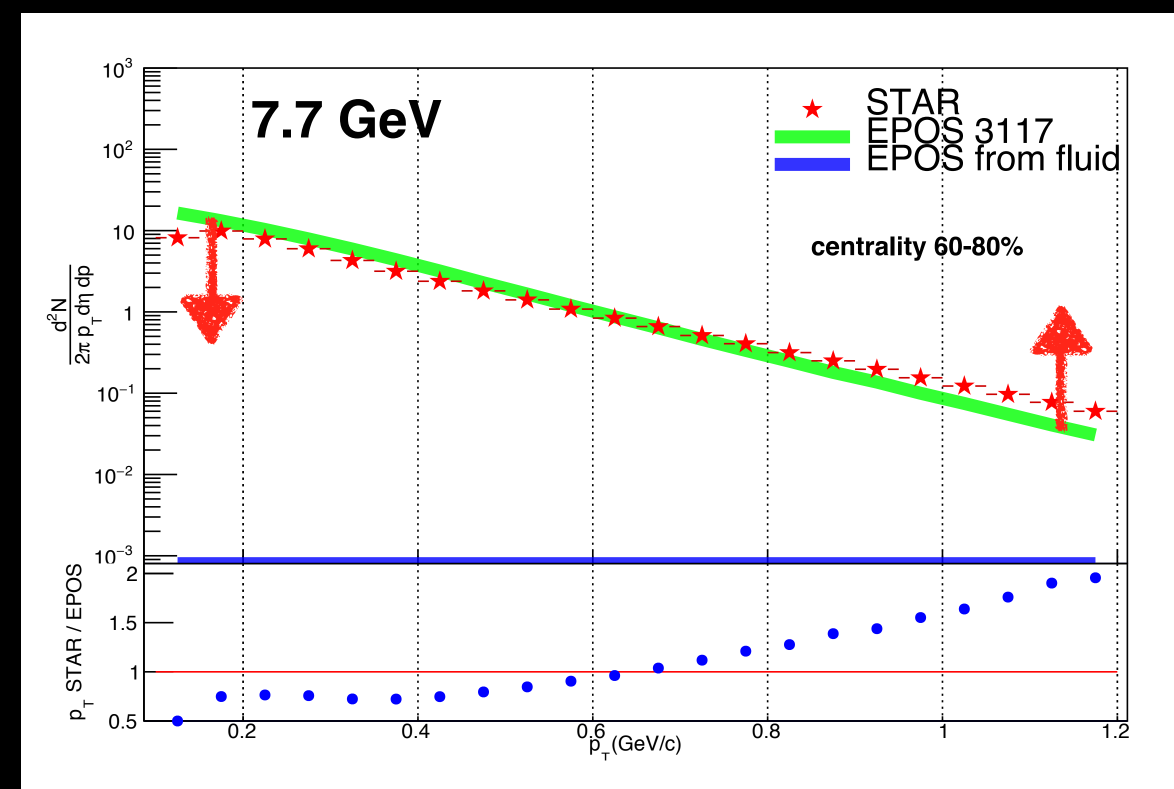



More particles derived from QGP



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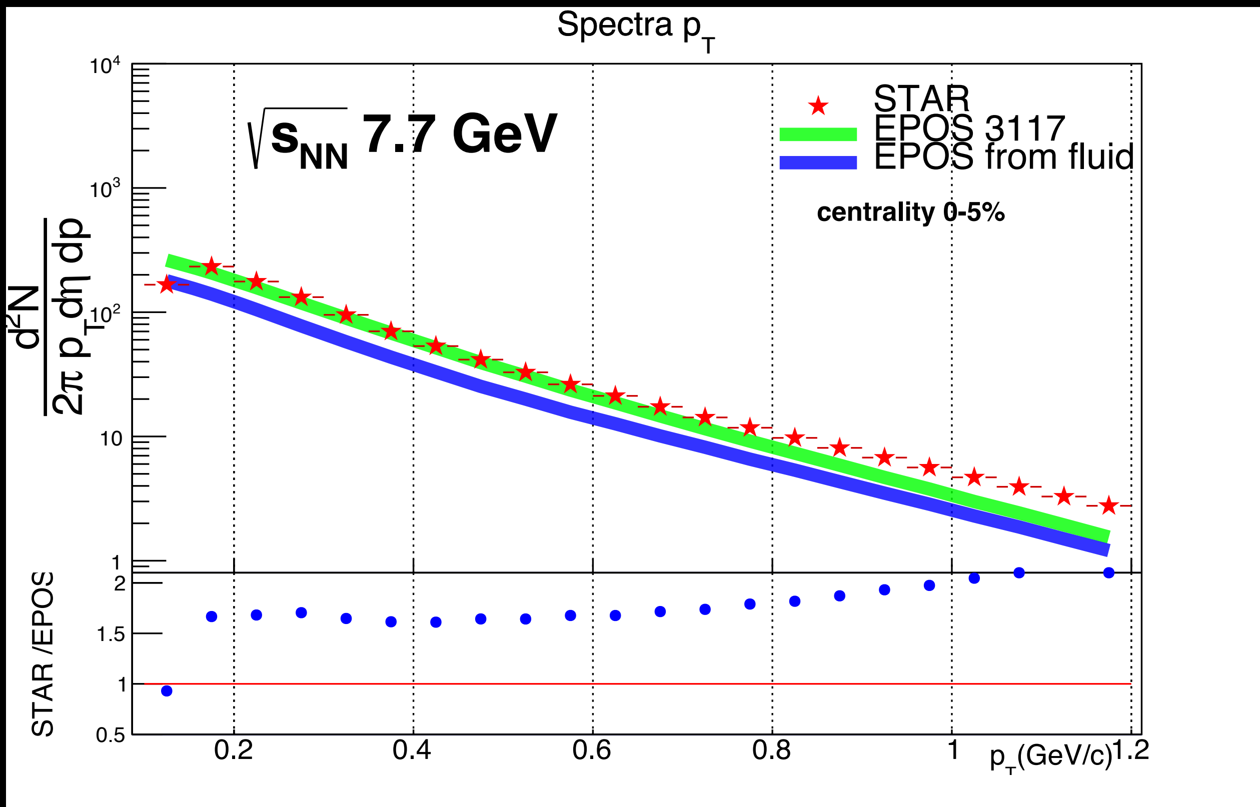


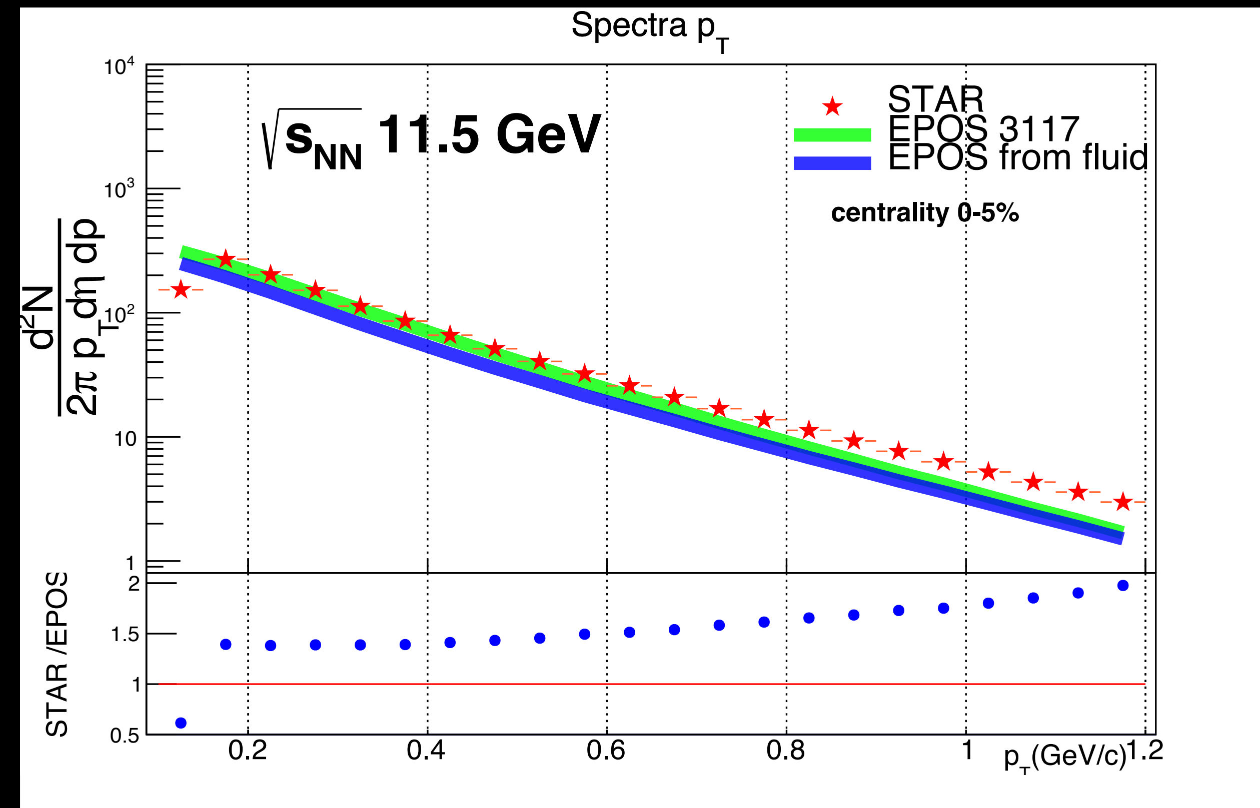


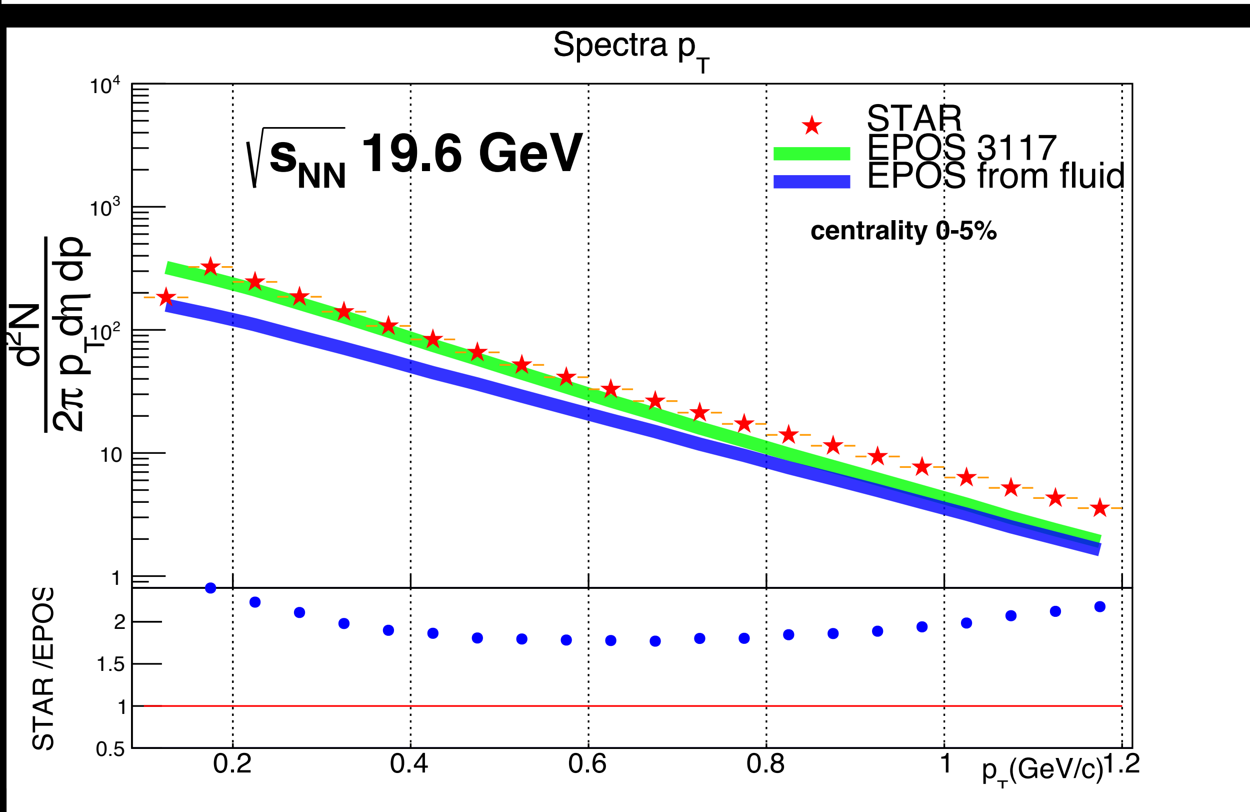


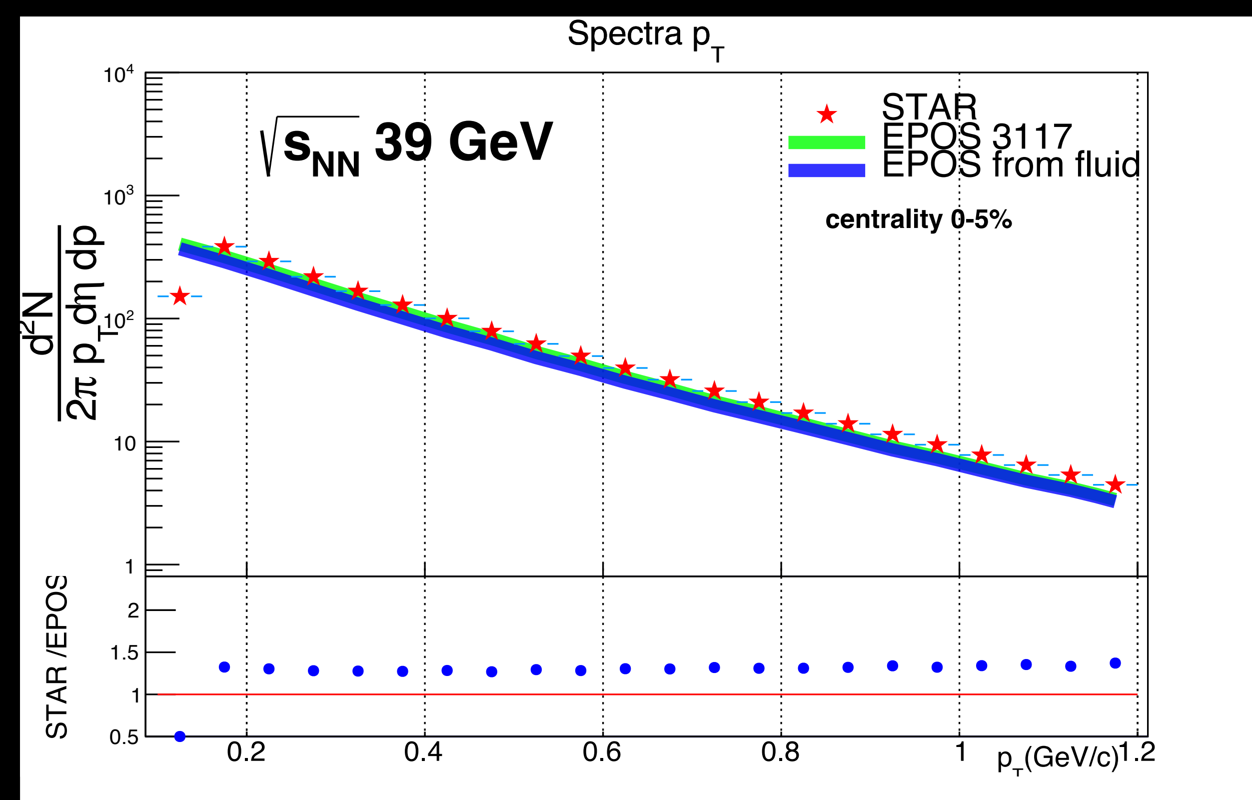

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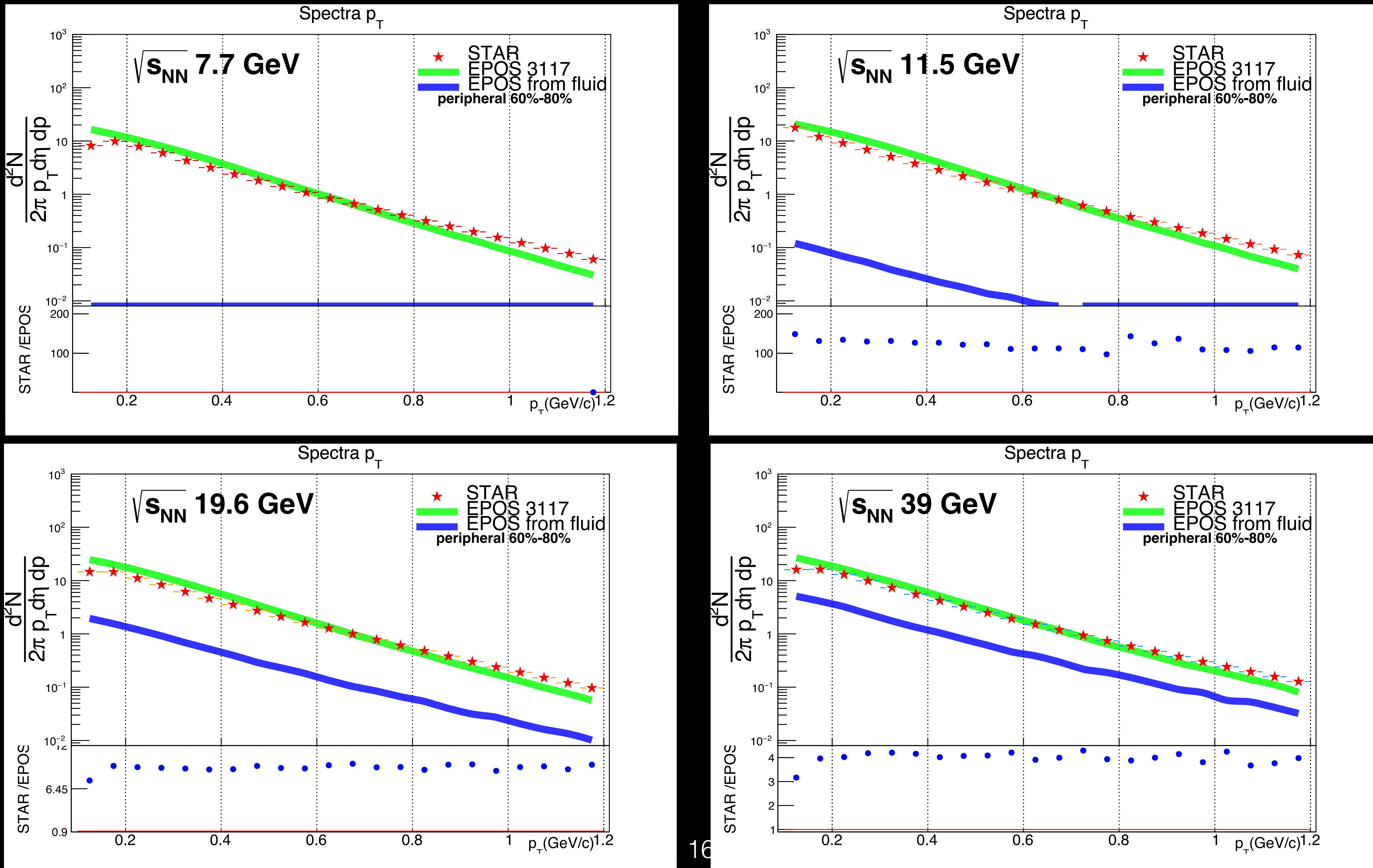

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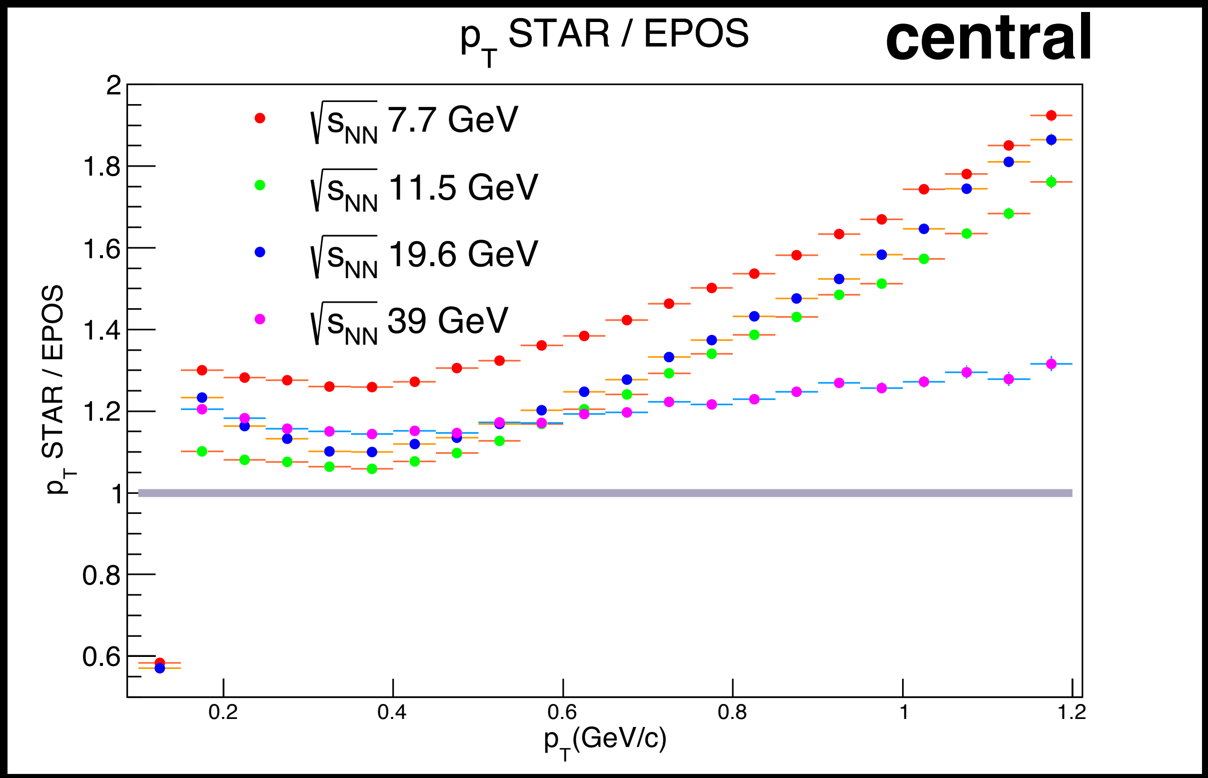


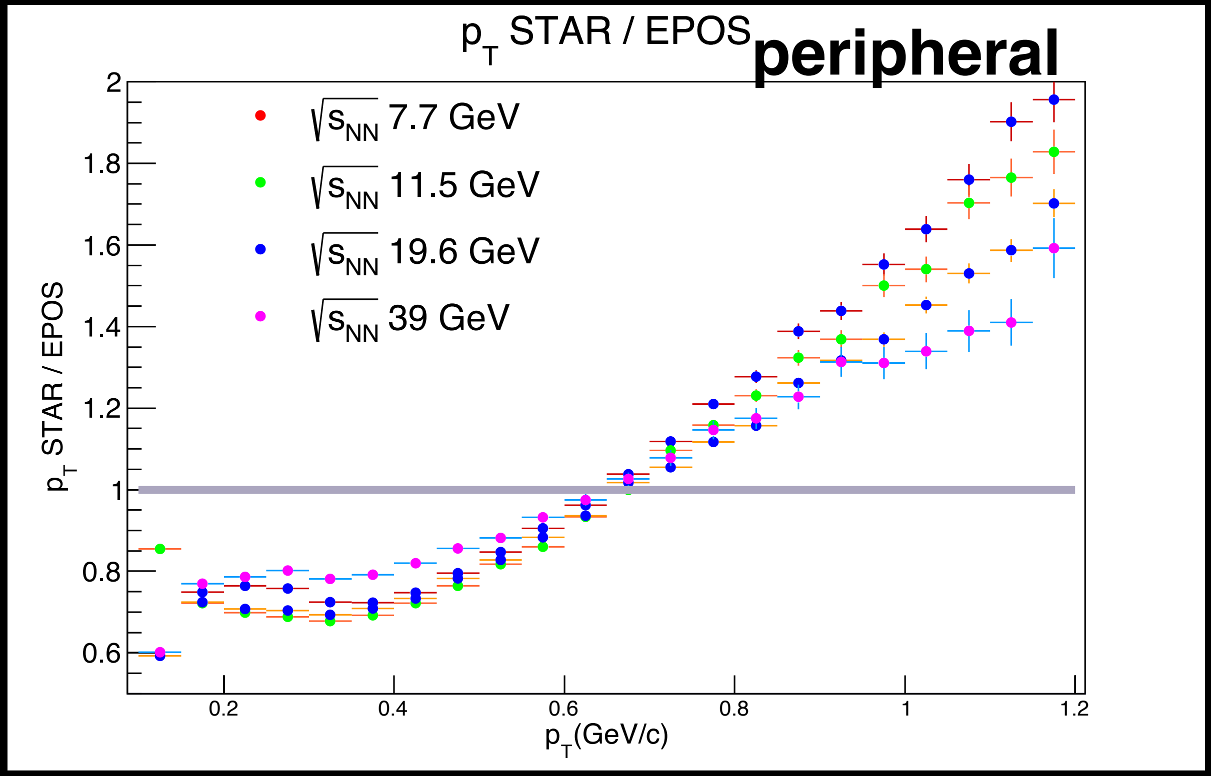

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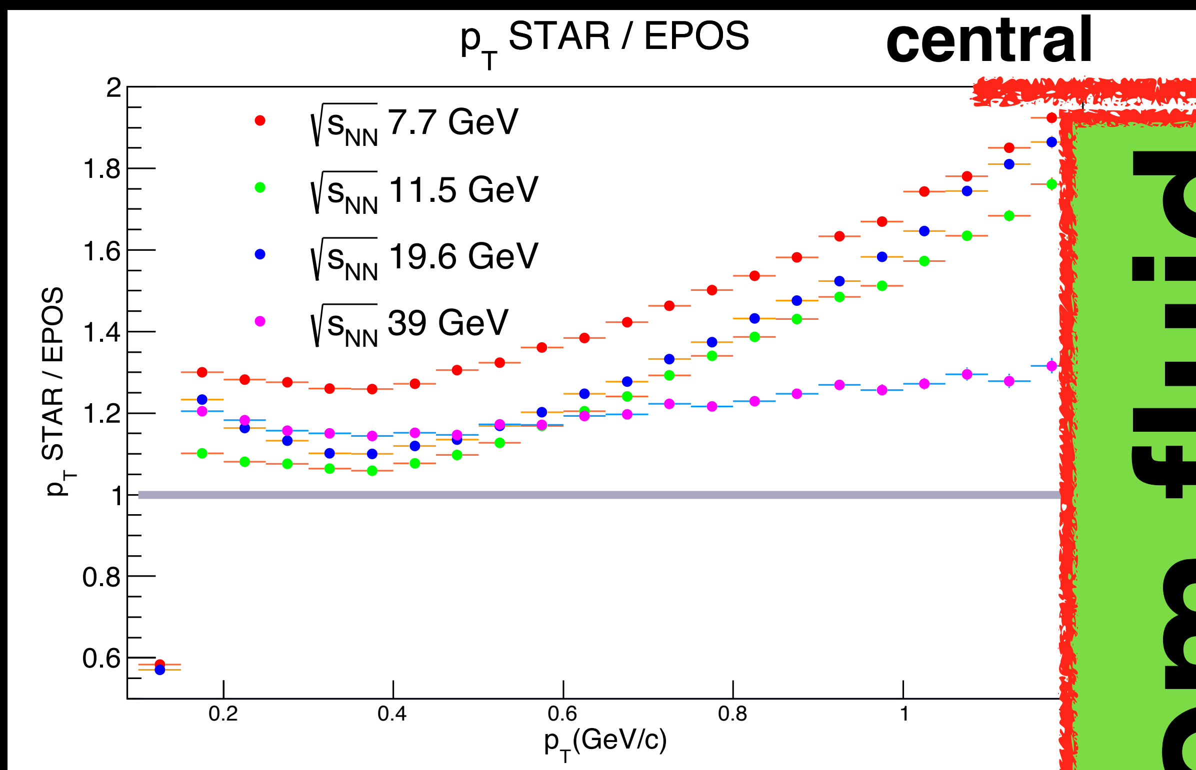
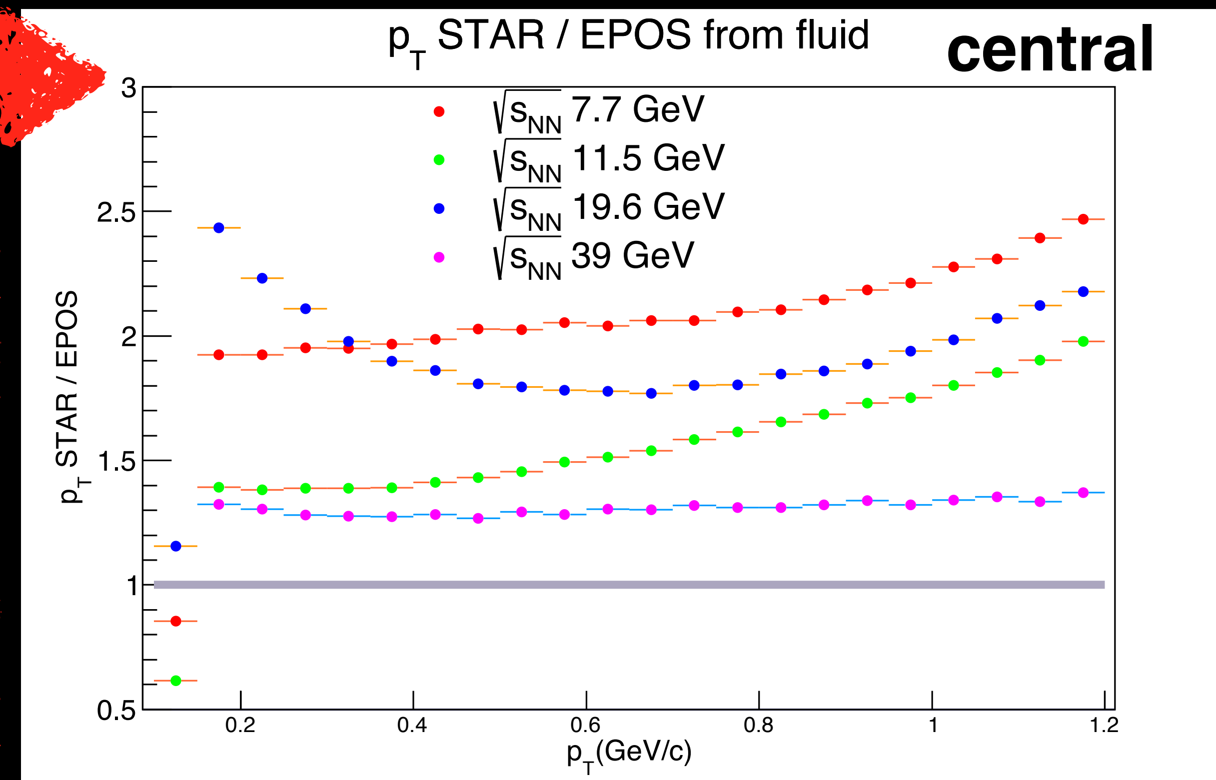
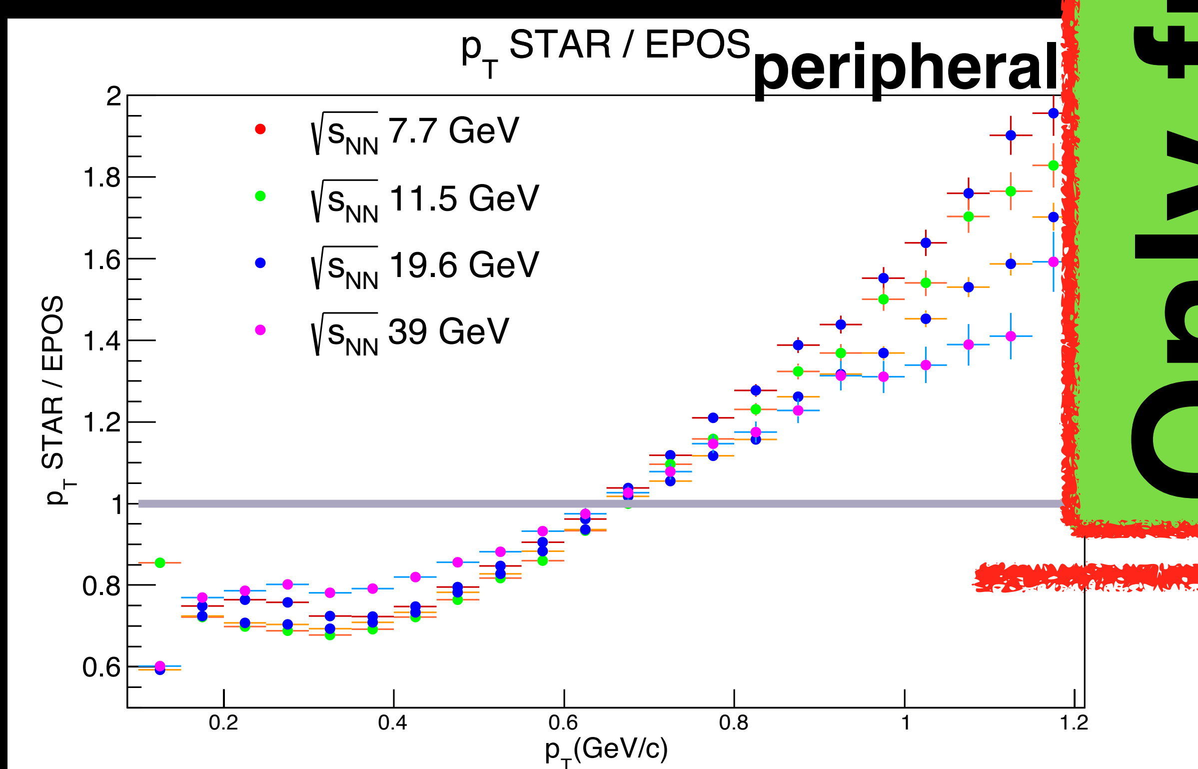
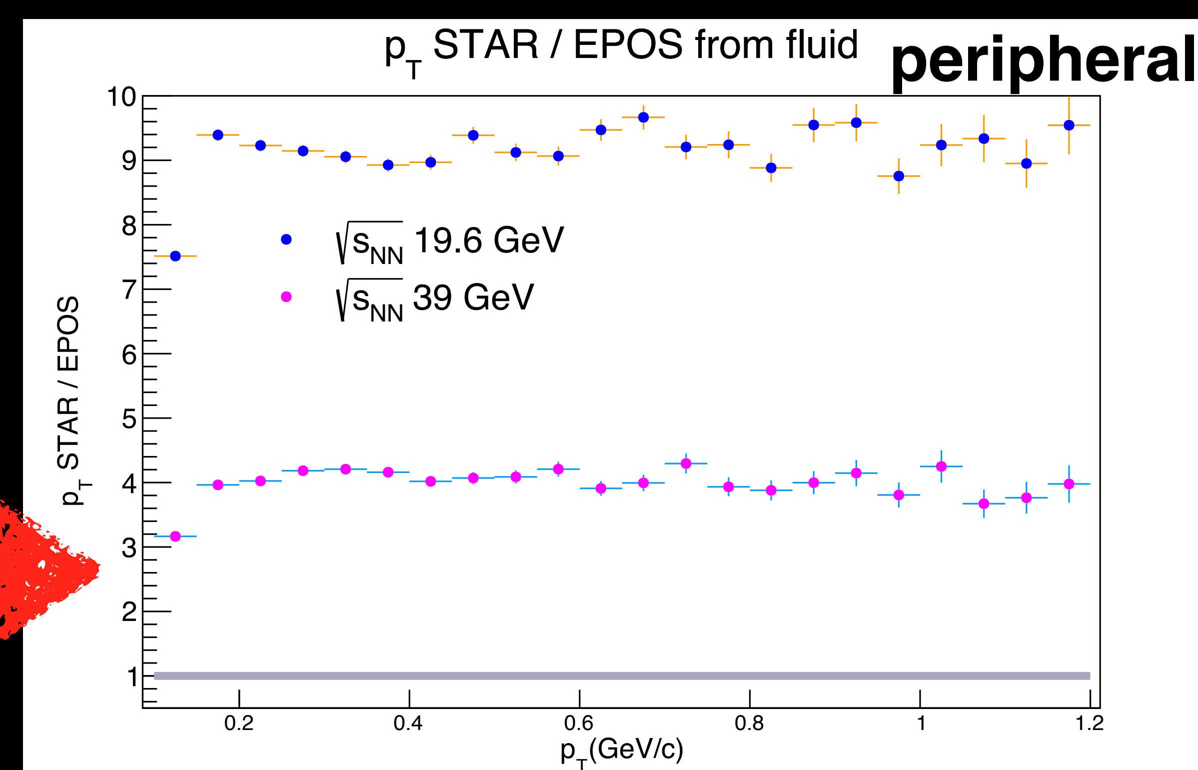



**Only from fluid**

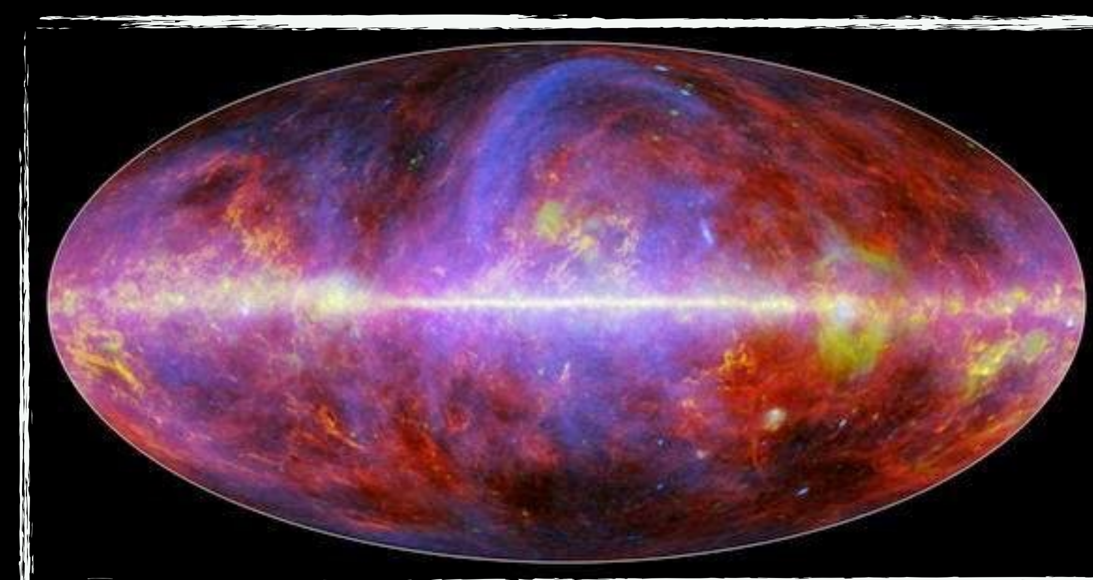


# Analysis

**HBT** method

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

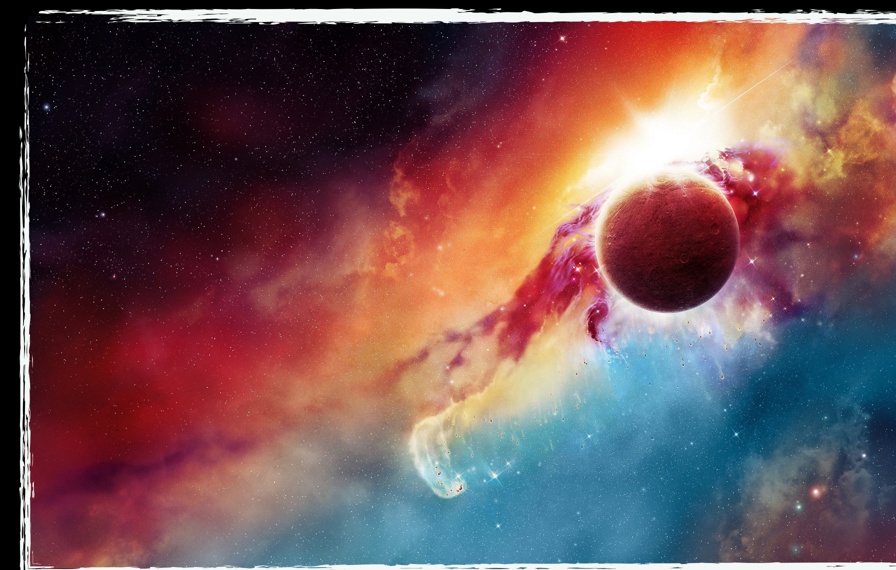


**HBT** method

# Analysis

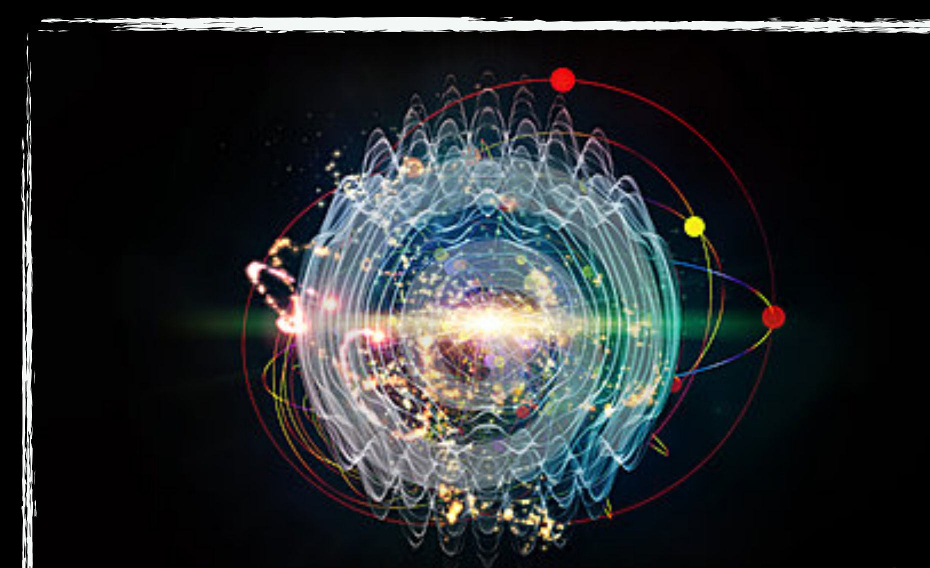
**HBT Method**

$\sim 10^{15}$ m



**Femtoscopy correlations**

$\sim 10^{-15}$ m

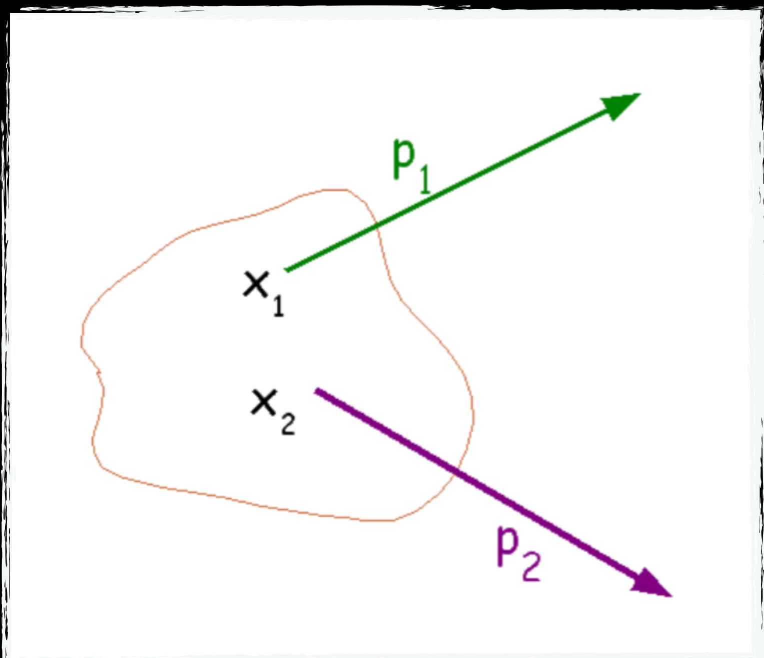


HBT method

# Analysis

**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

HBT method

# Analysis

In experiment:

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

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

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

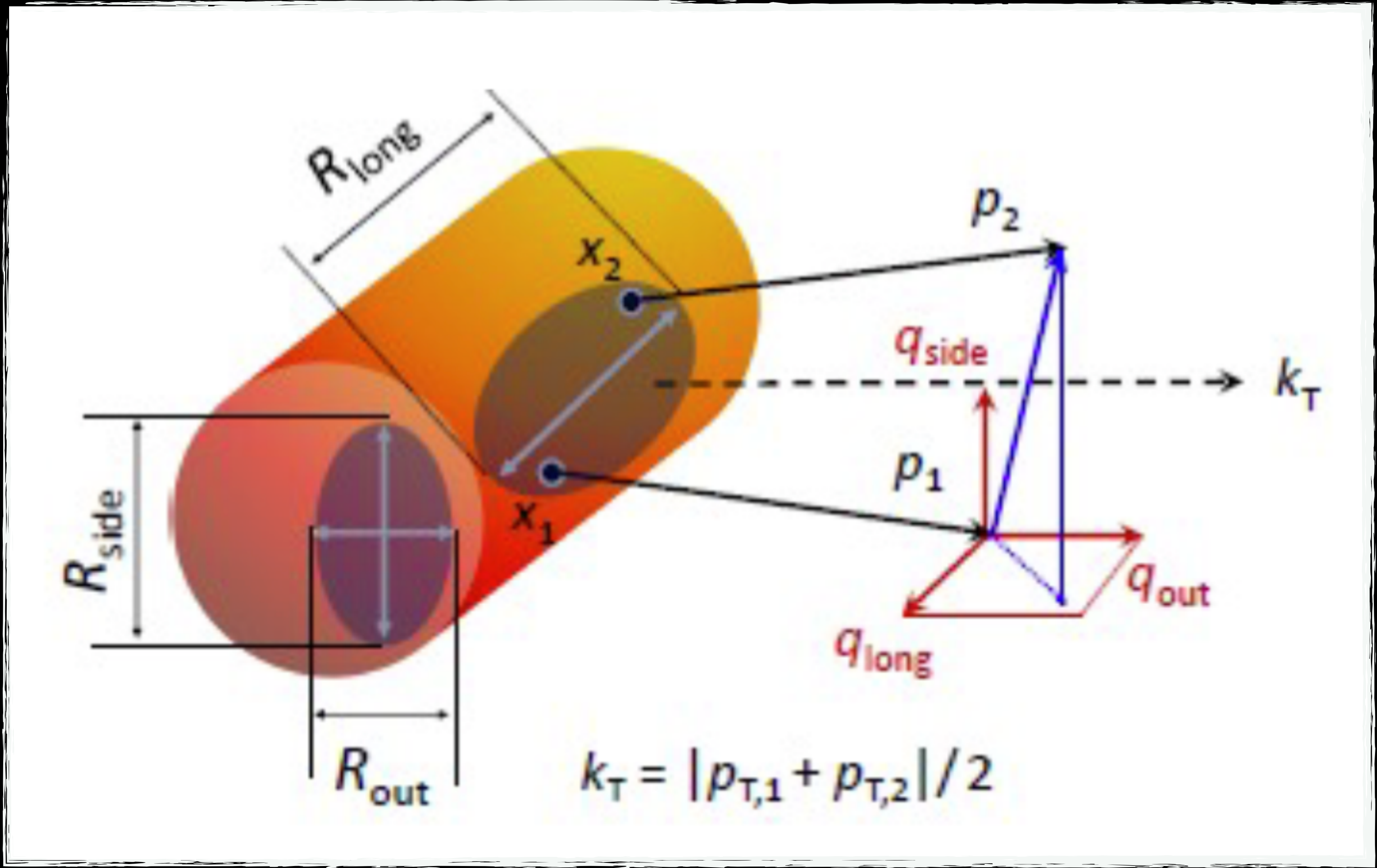
**Background, distribution of the difference of particles' momentums derived from DIFFERENT collisions**

HBT method

# Analysis

Parametrization:

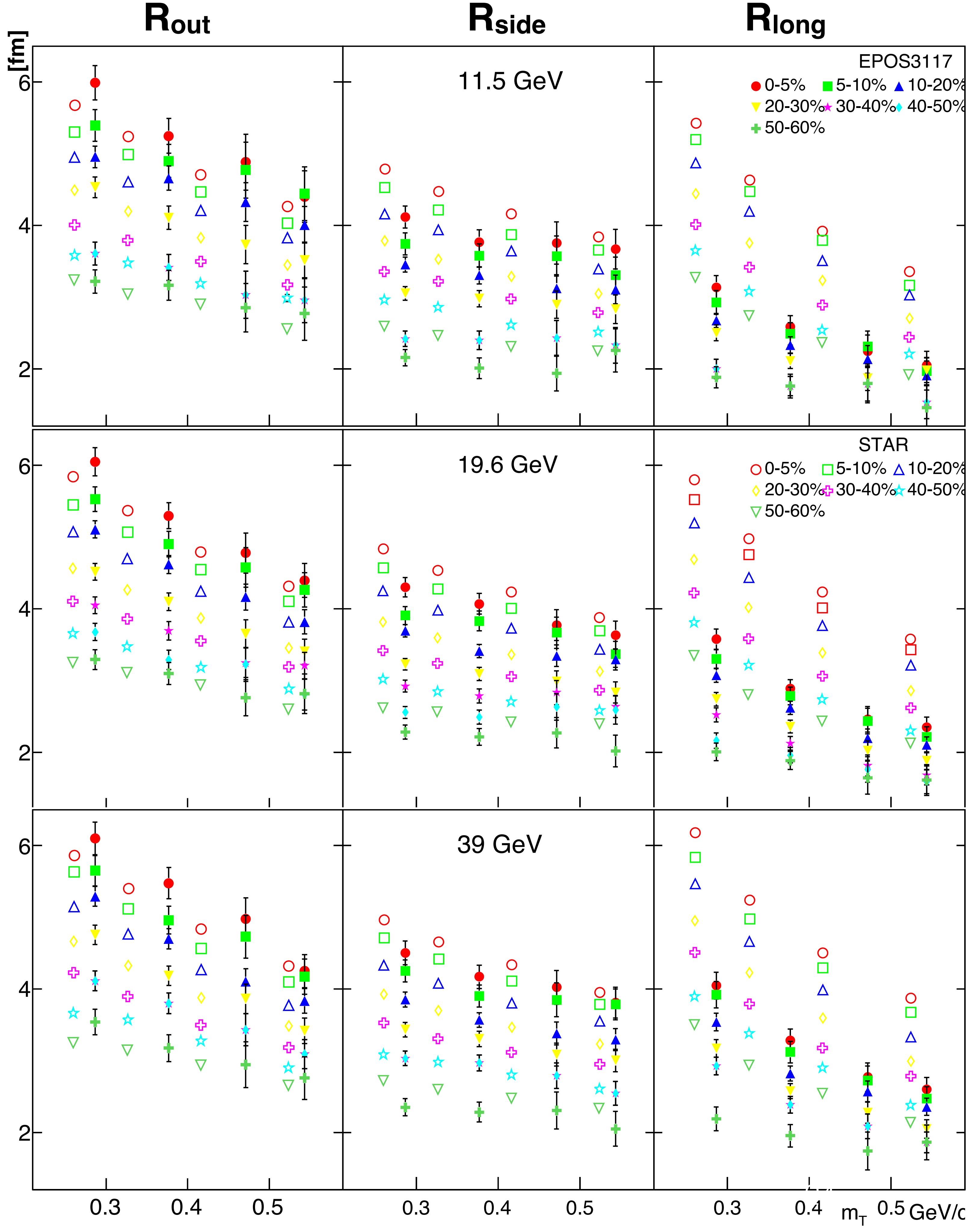
$$C(q_{out}, q_{side}, q_{long}, \lambda) = 1 + \lambda exp(-q_{out}^2 r_{out}^2 - q_{side}^2 r_{side}^2 - q_{long}^2 r_{long}^2)$$

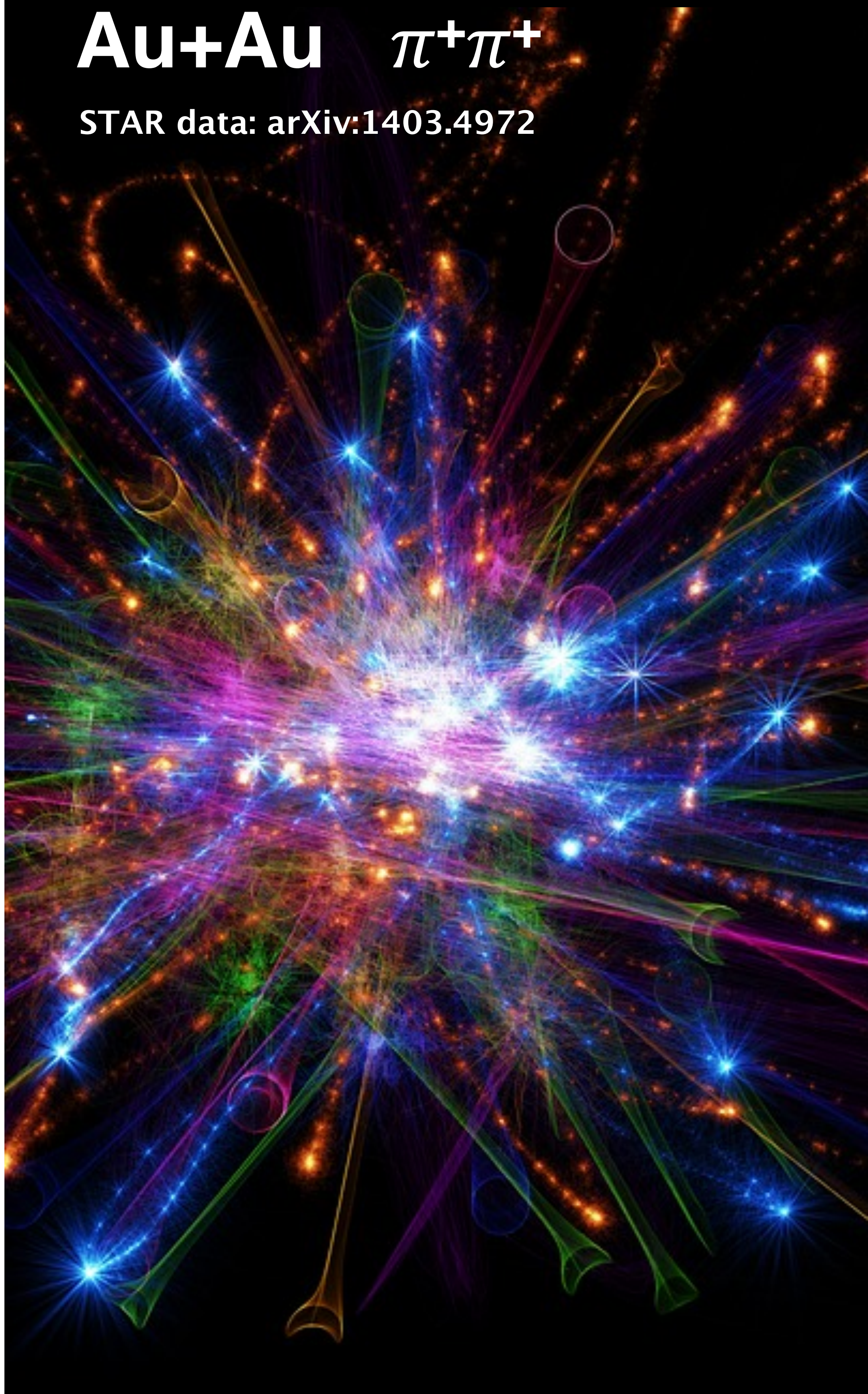


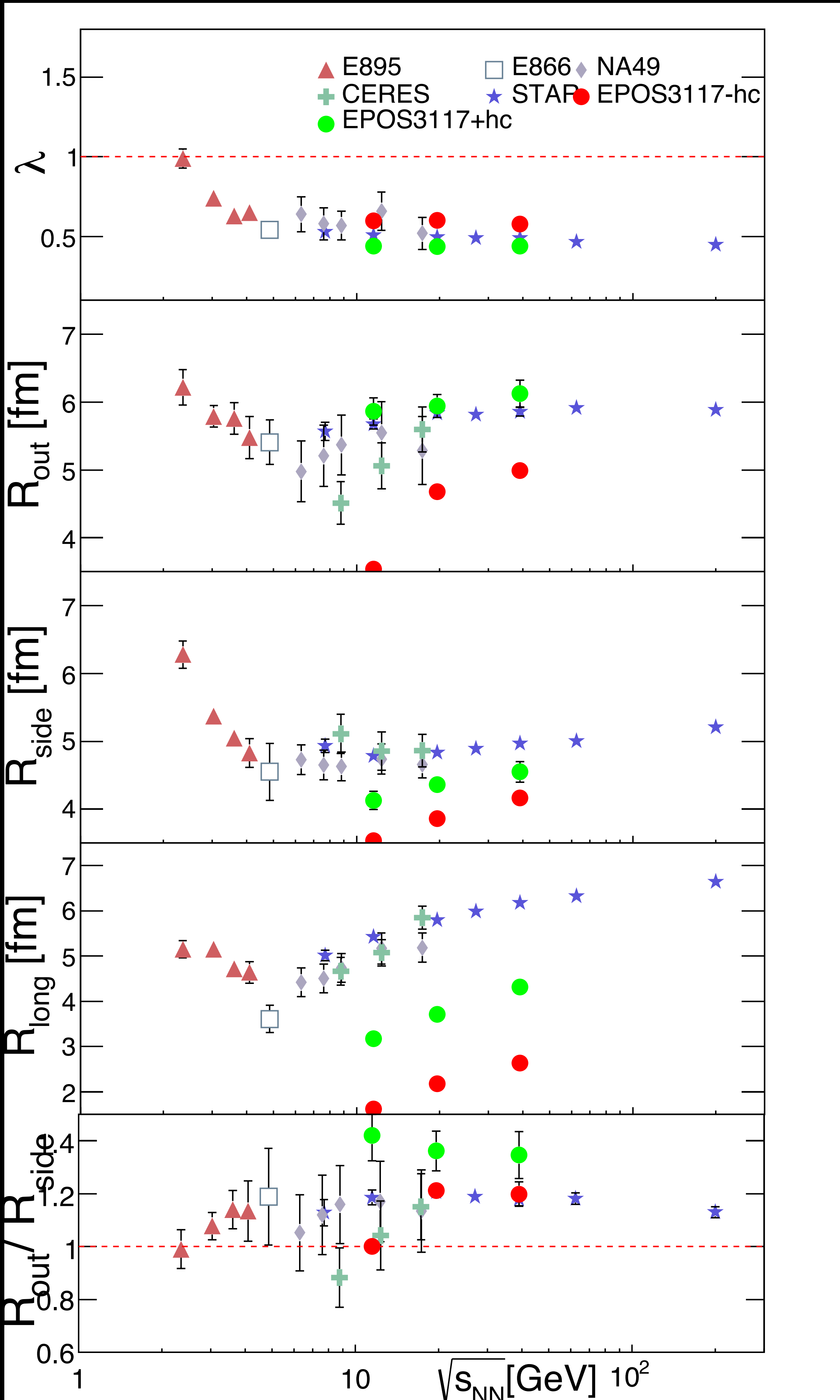
# **HBT** method

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

STAR data: arXiv:1403.4972






# Analysis

**HBT** method

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**

Elliptic flow

# Analysis

## - *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.

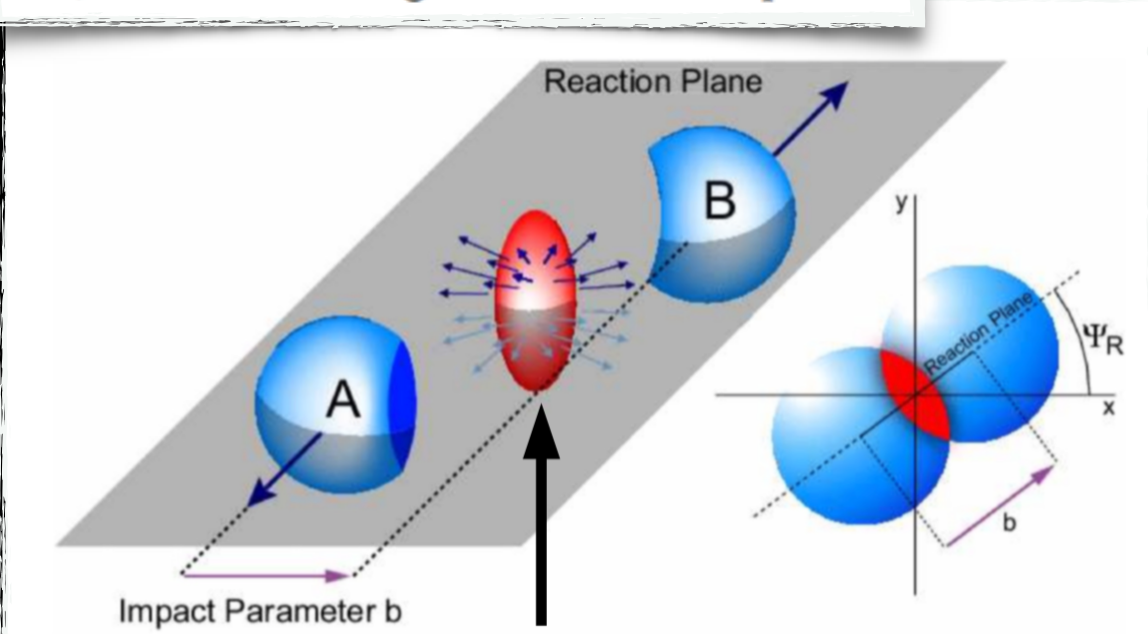
$$\frac{dN}{d(\phi - \Phi_{RP})} = \frac{N_0}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[(\phi - \Phi_{RP})]\right)$$

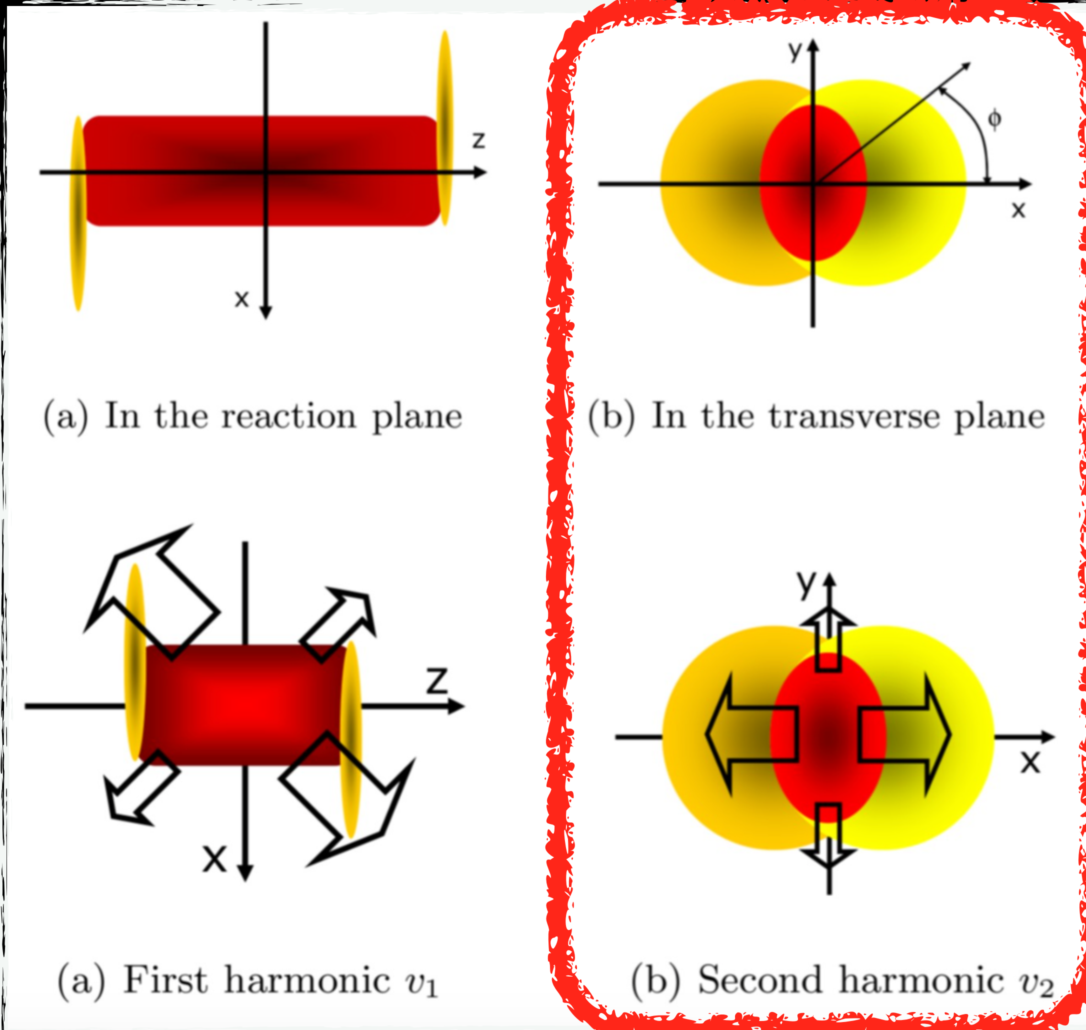
$N_0$ - number of particles

$v_n$ - n-th harmonic coefficient

$\phi$ - azimuthal angle of particles

$\Phi_{RP}$ - azimuthal angle of the reaction plane




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

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

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

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

Elliptic flow

# Analysis

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.

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

$\Phi_n^A$ - *event plane* calculated only using ”forward-pseudorapidity” particles while

$\Phi_n^B$ - with ”backward-pseudorapidity” ones.

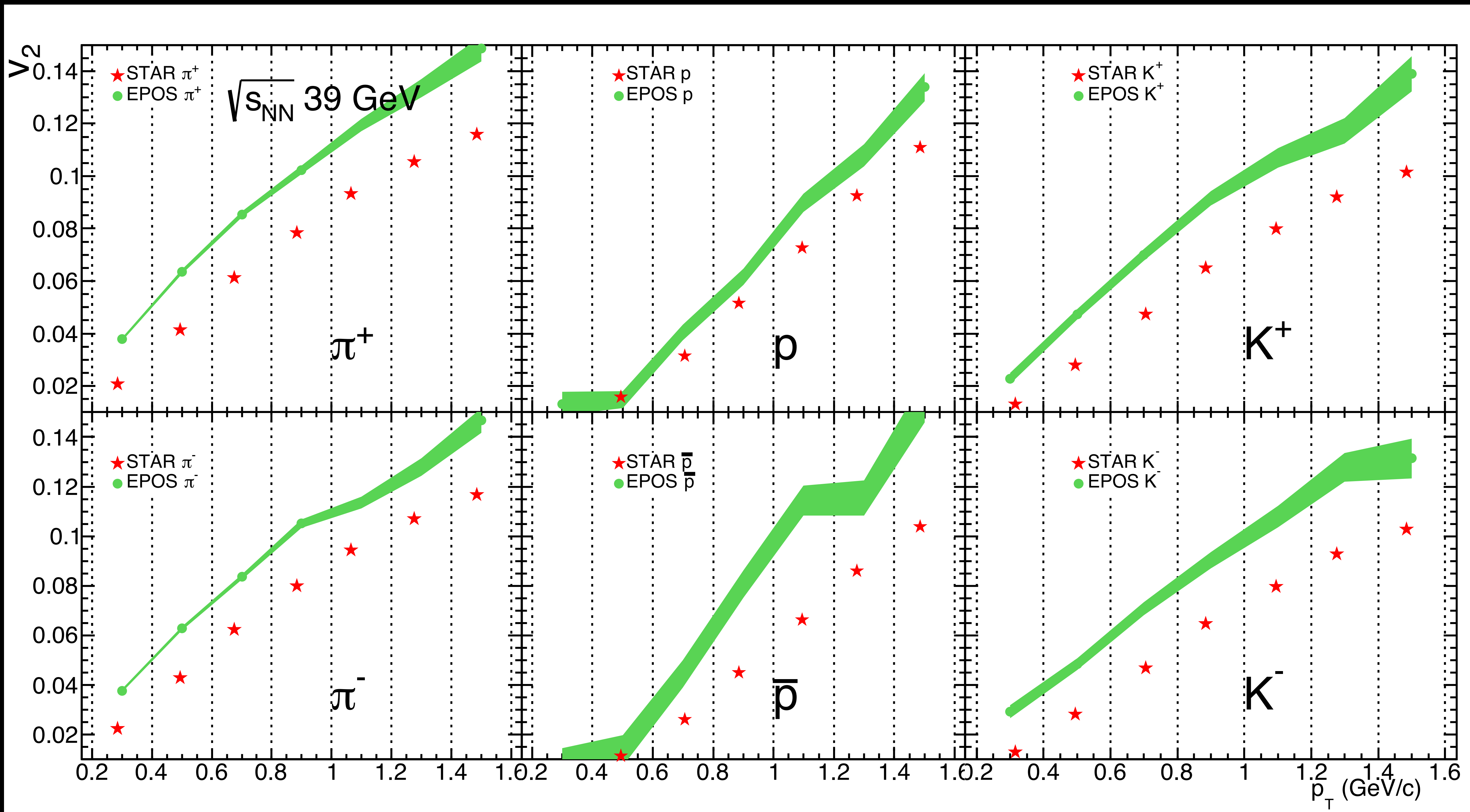
- Finally:

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

Elliptic flow

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

# Analysis



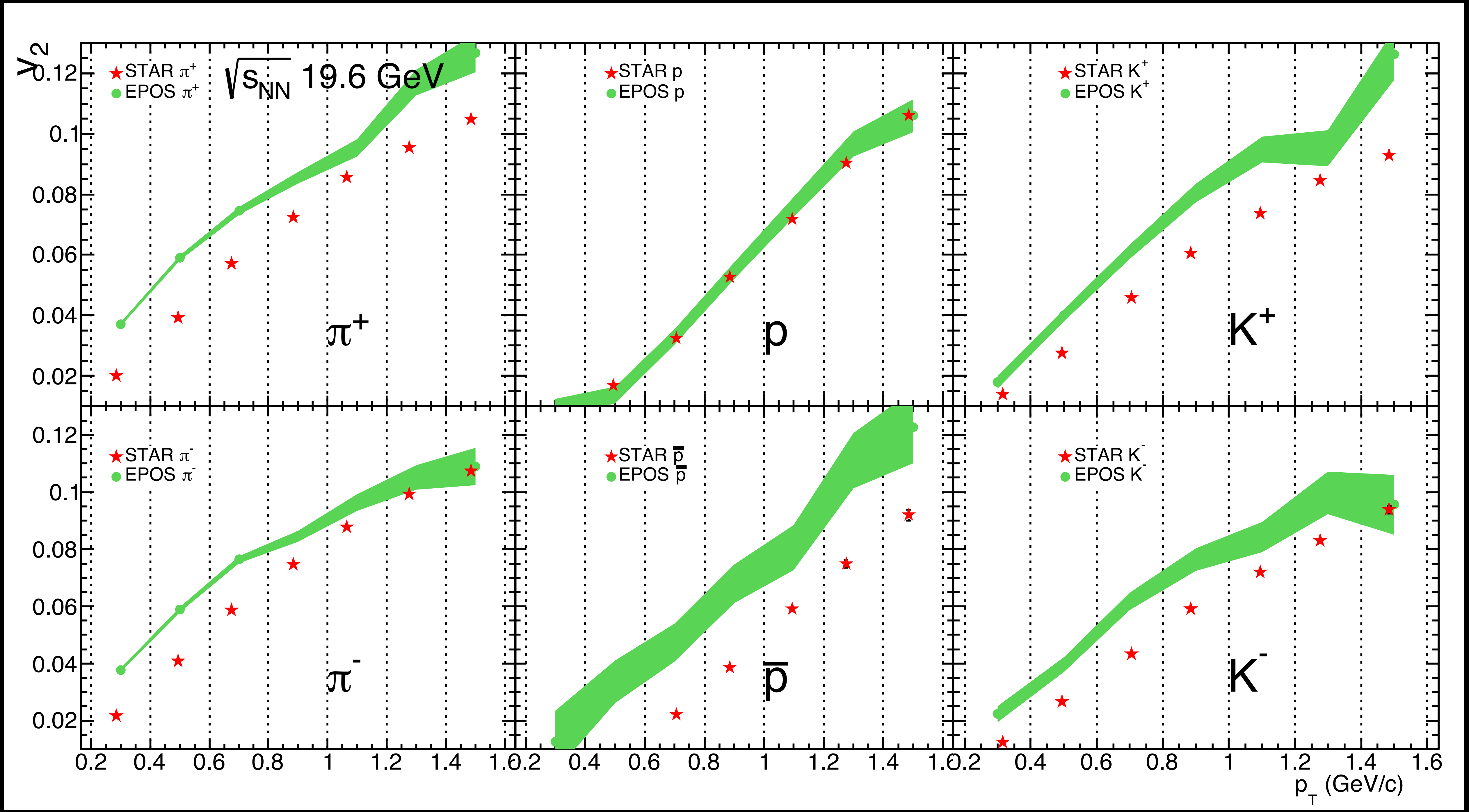

**Au+Au**

centrality: 0-80% p ∈ (0.15, 5 GeV/c) $|\eta| \in (0.05, 1)$

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

**Elliptic flow**

# Analysis

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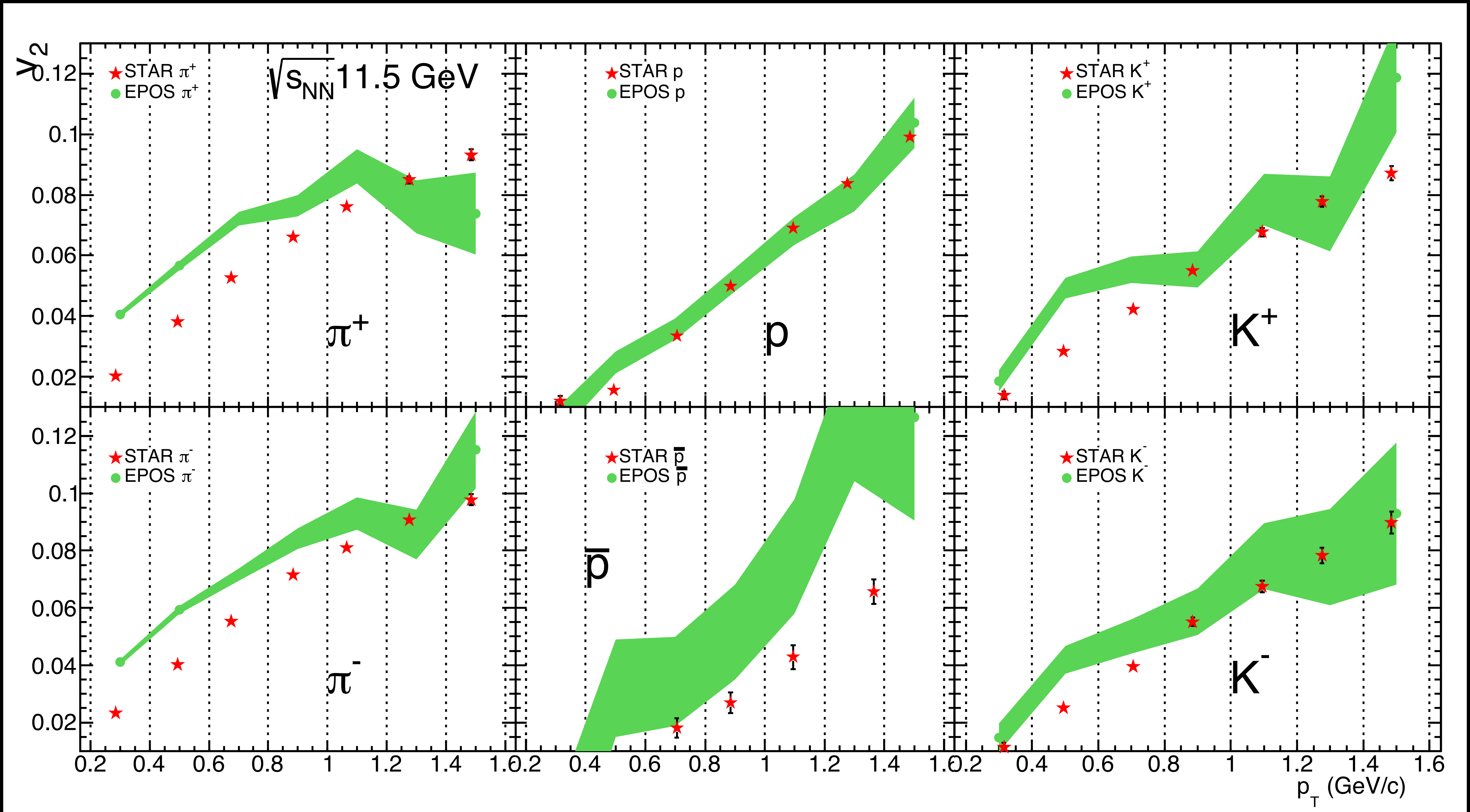


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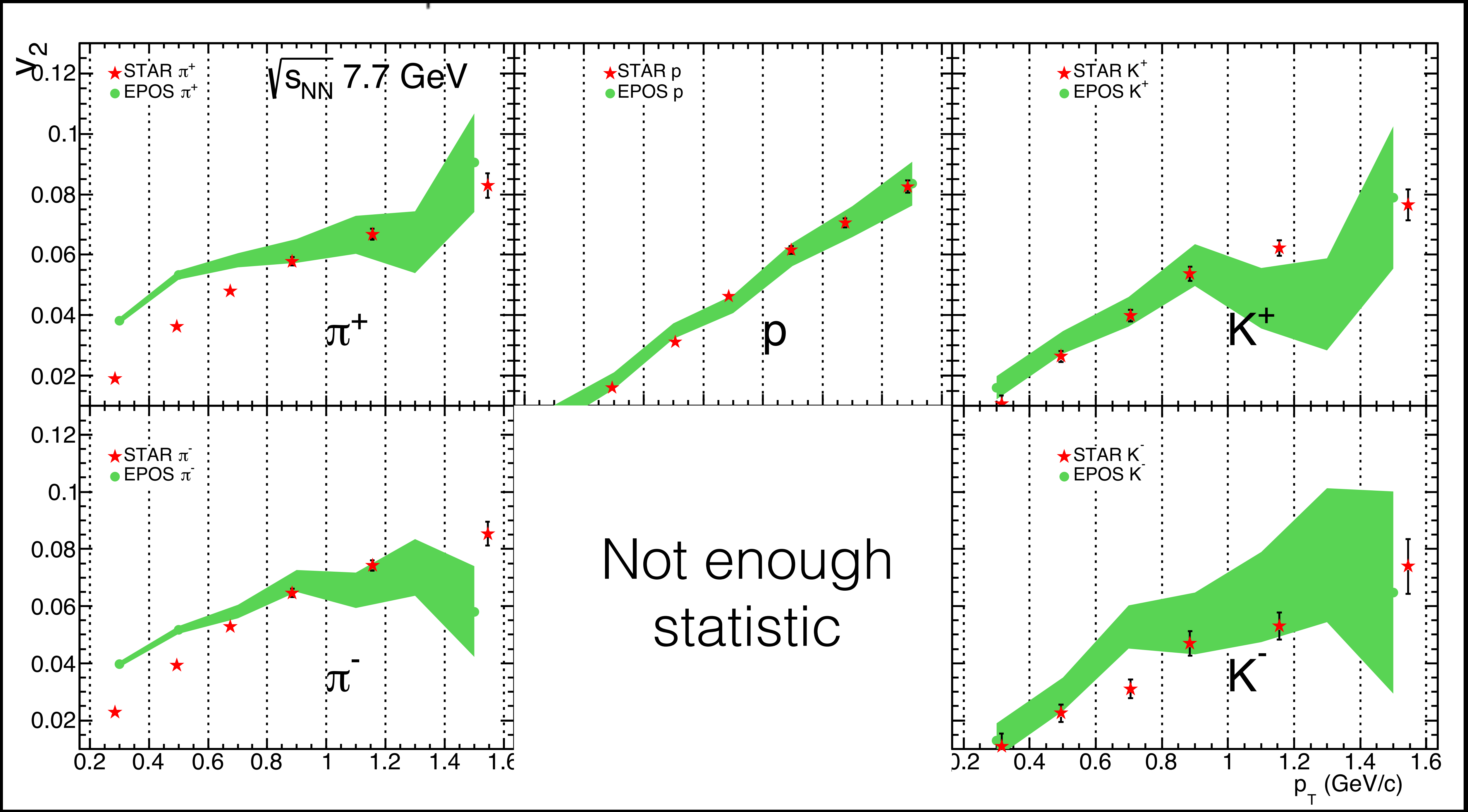


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# Conclusion

- 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

**ecliptic flow:**

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

# Plans

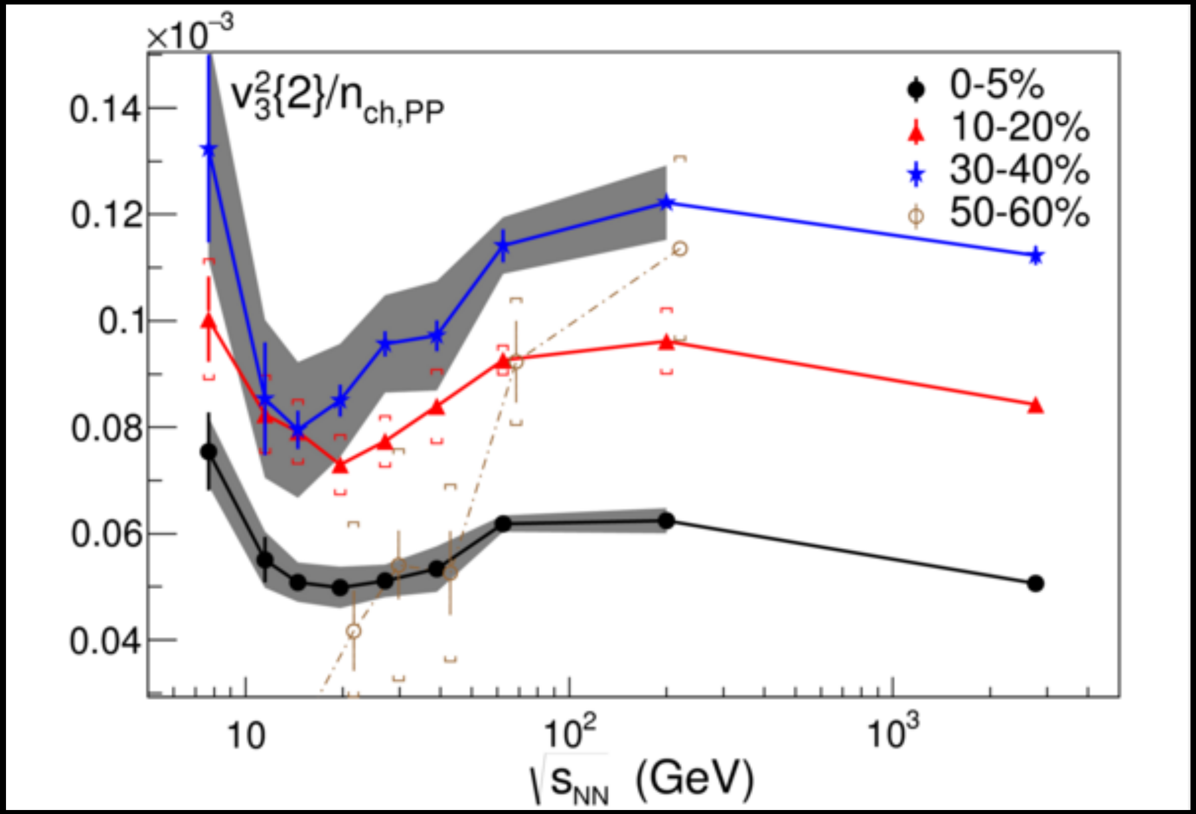
# Triangular flow

**Particularly sensitive to the presence of QGP phase**

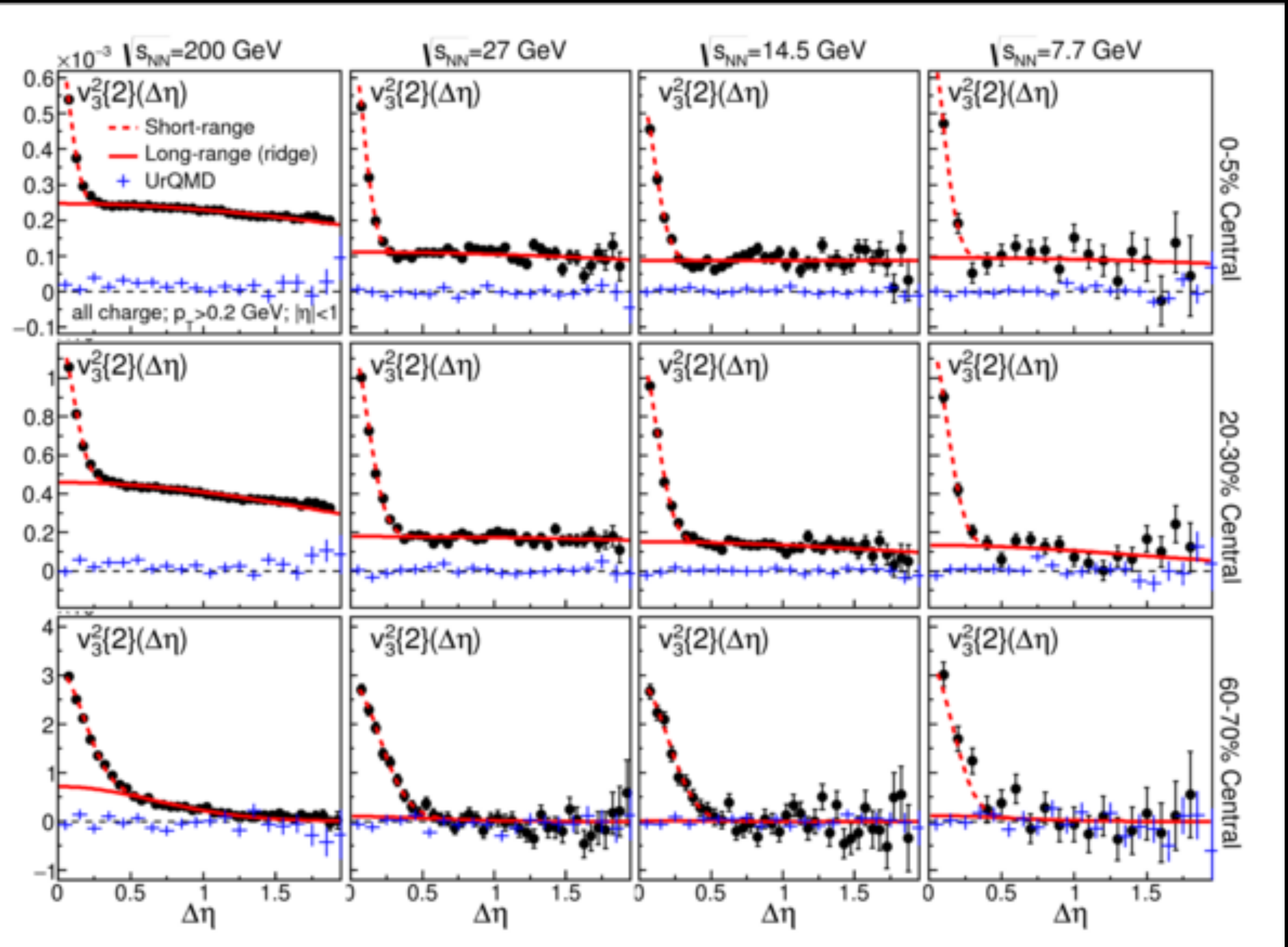
**The development of $v_3^2\{2\}$ relies strongly on the presence of a low viscosity QGP phase early in the collision**

arXiv:1601.01999v1 [nucl-ex] 8 Jan 2016

**Ideal observable to probe the formation of QGP**



# Triangular flow

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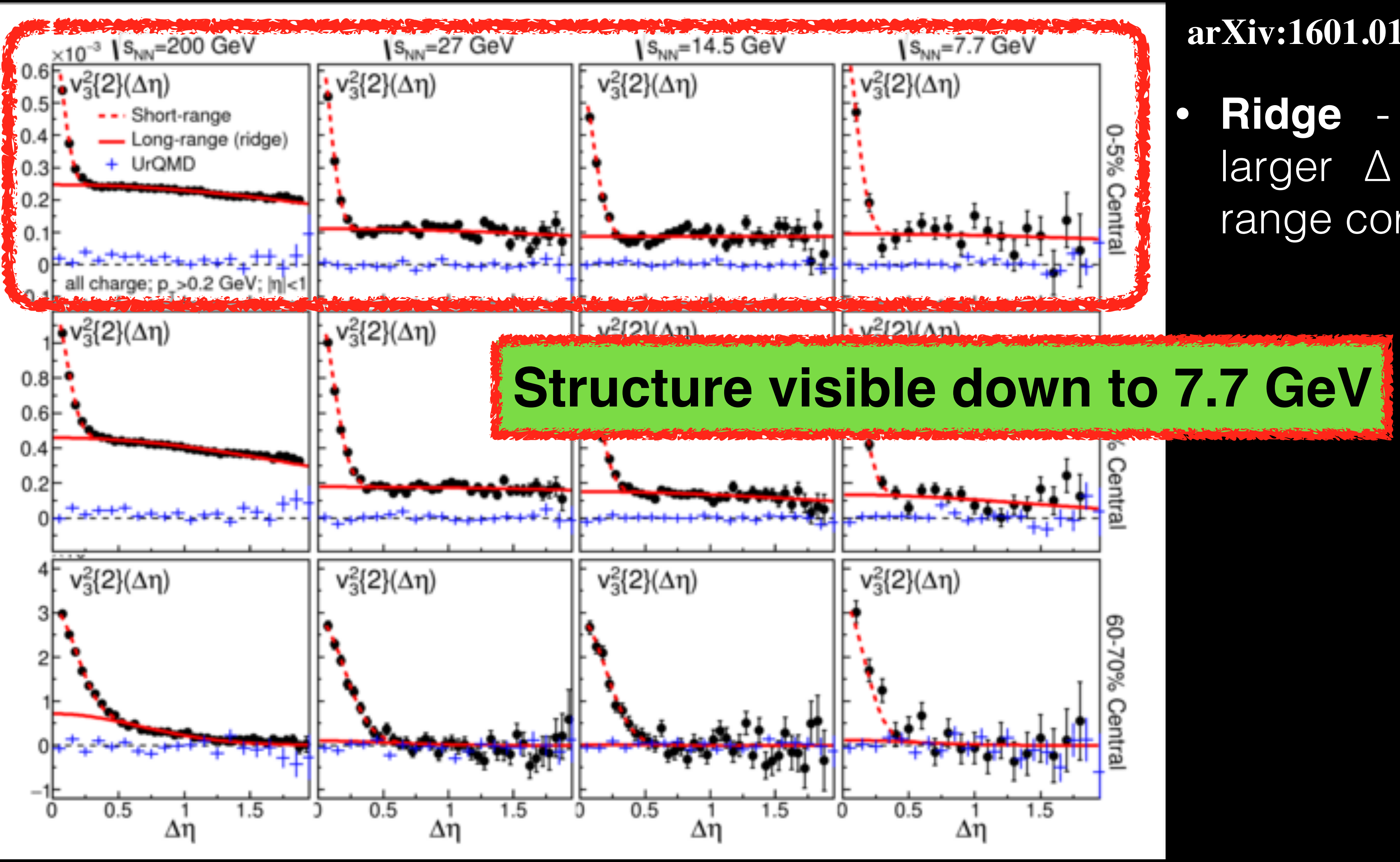


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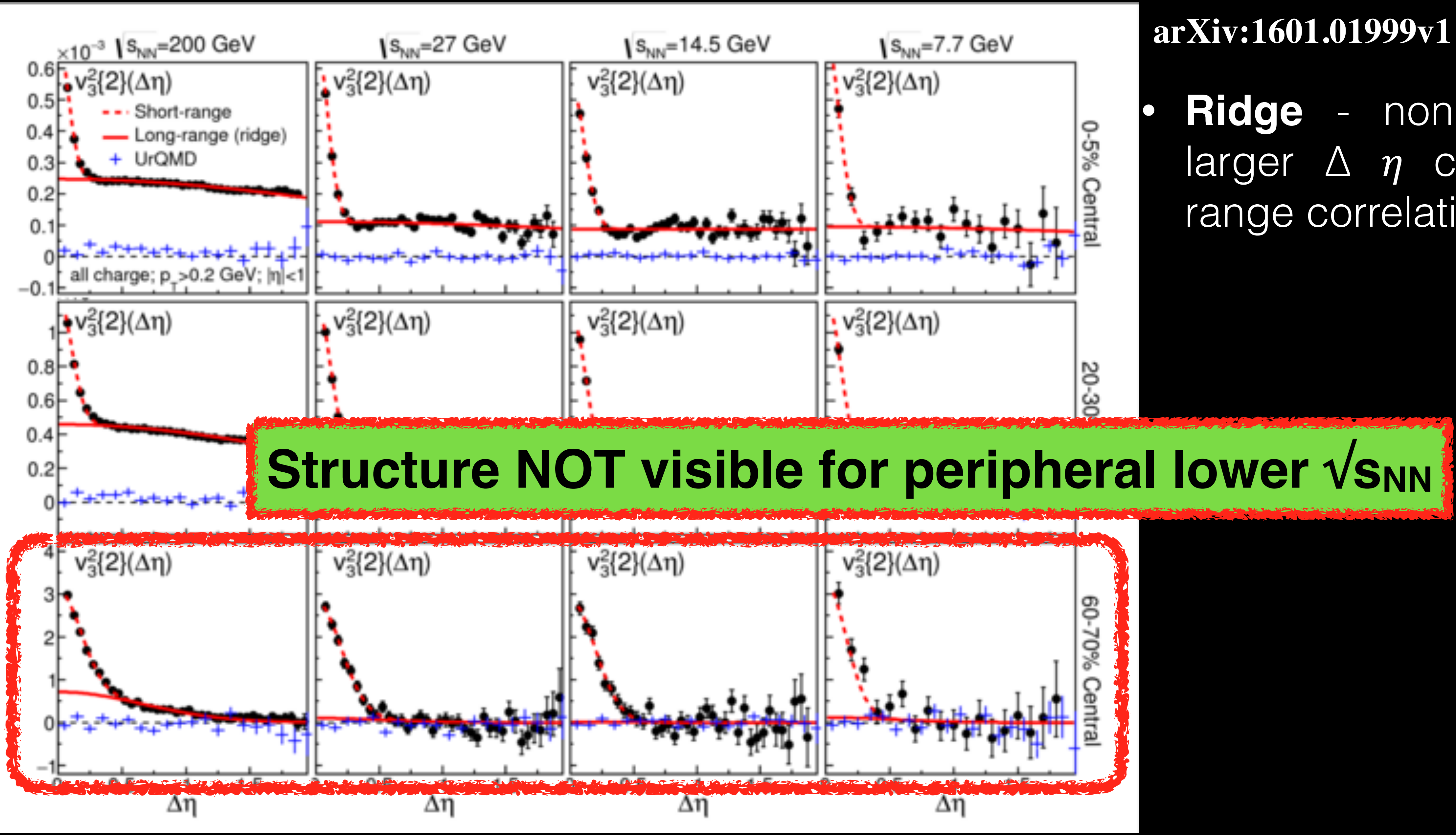
- **Ridge** - non-zero values at larger Δ $\eta$ caused by long-range correlations

# Triangular flow

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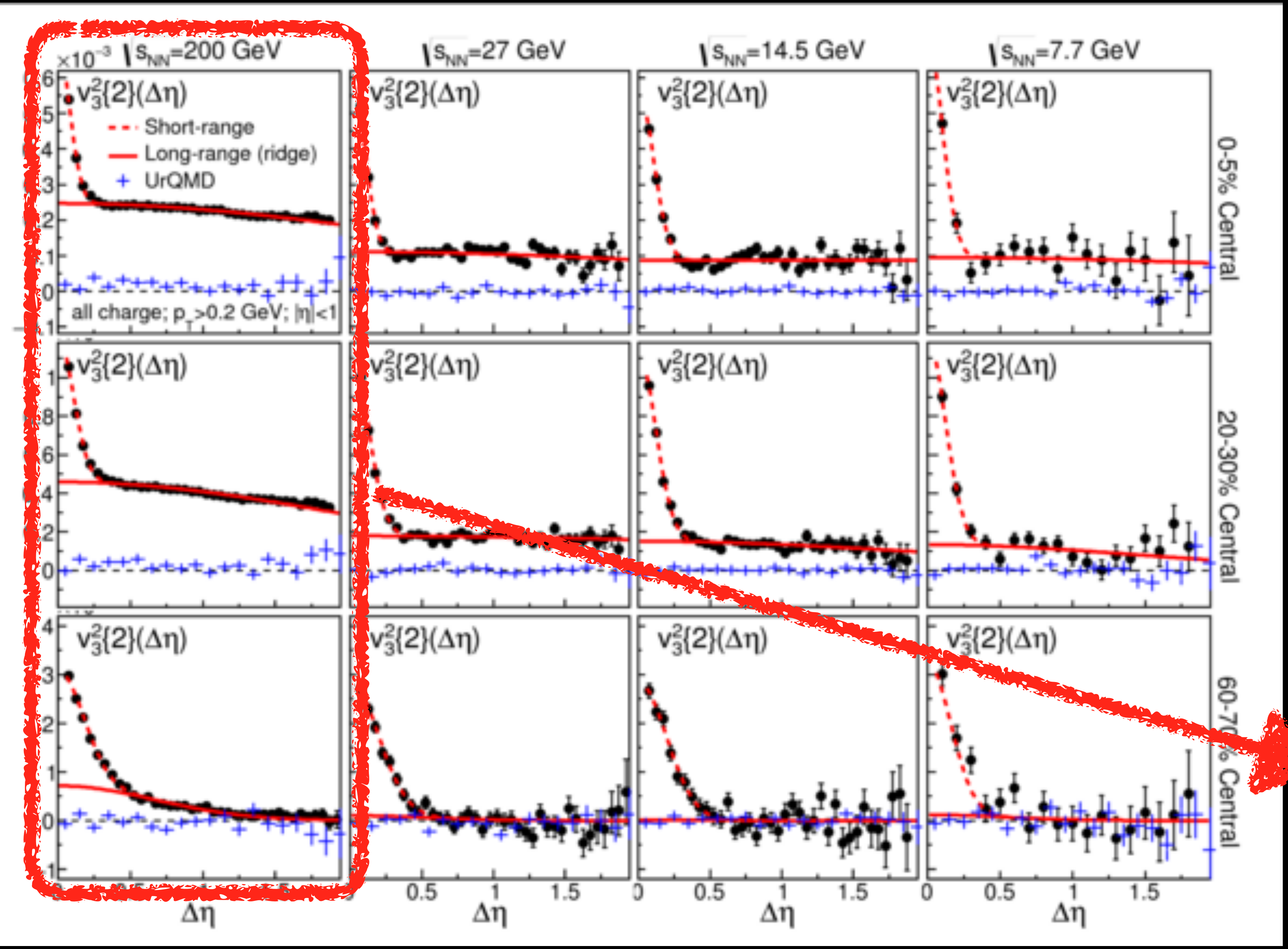


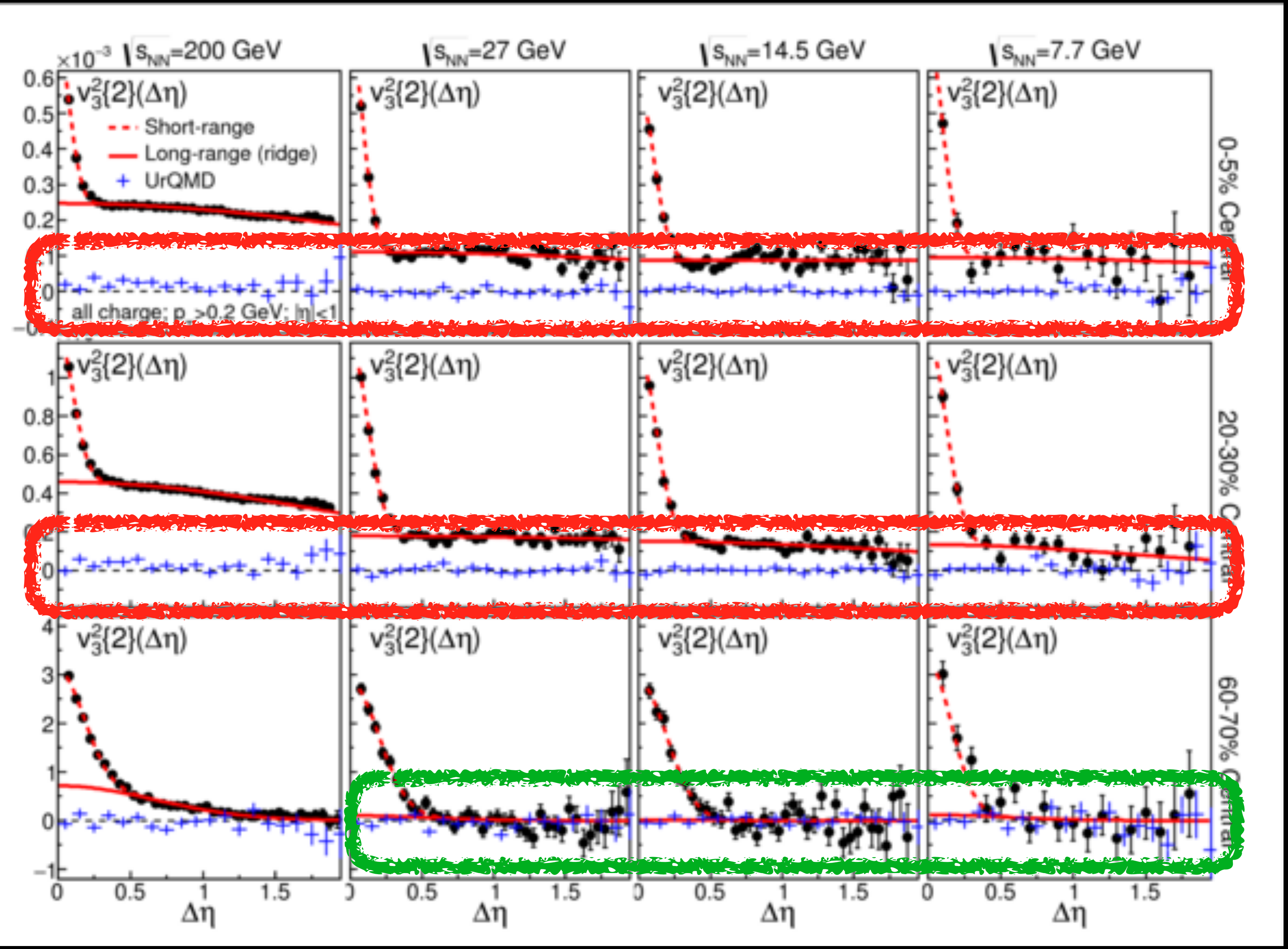

**arXiv:1601.01999v1 [nucl-ex] 8 Jan 2016**

- **Ridge** - non-zero values at larger $\Delta\ \eta$ caused by long-range correlations
- **Narrow peak -** caused by short-range correlations.

Can arise from several sources like:

- fragmentation of hard & semi-hard jets
- resonances
- HBT
- coulomb interference

# Triangular flow

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Can arise from several sources like:

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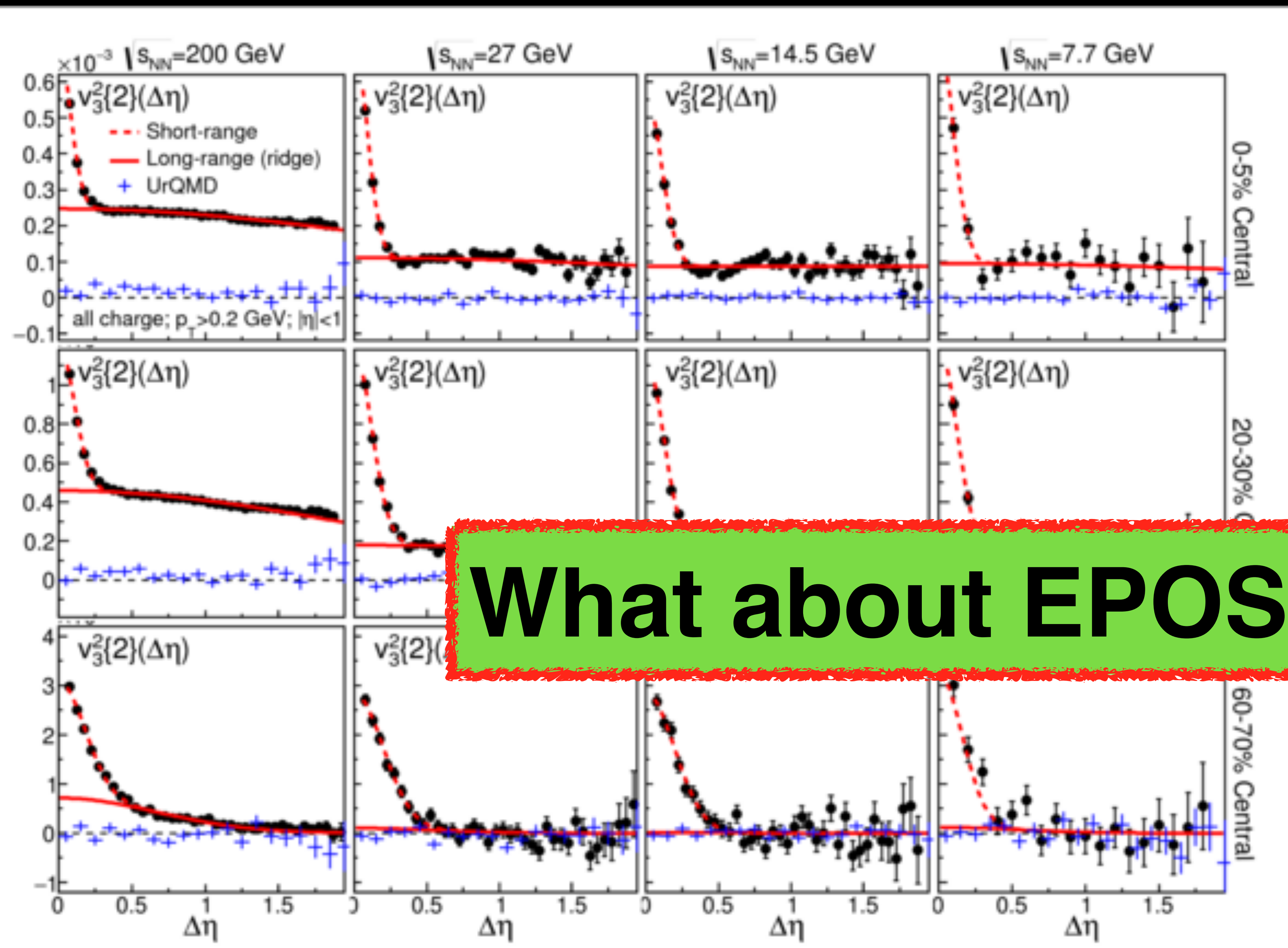
- **UrQMD** - non-QGP model in agreement with more peripheral, lower $\sqrt{s_{NN}}$.

# Triangular flow




**What about EPOS???**

arXiv:1601.01999v1 [nucl-ex] 8 Jan 2016

- **Ridge** - non-zero values at larger $\Delta\ \eta$ caused by long-range correlations
- **Narrow peak -** caused by short-range correlations.

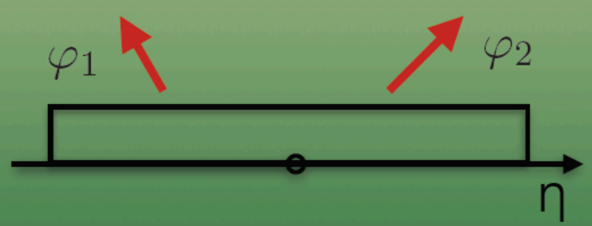
Can arise from several sources

- gmentation of hard & semi-hard jets
- resonances
- HBT
- coulomb interference

- **UrQMD** - non-QGP model in agreement with more peripheral, lower $\sqrt{s_{NN}}$.

# Triangular flow

Methods to exclude non-flow contributions:




**cumulant**

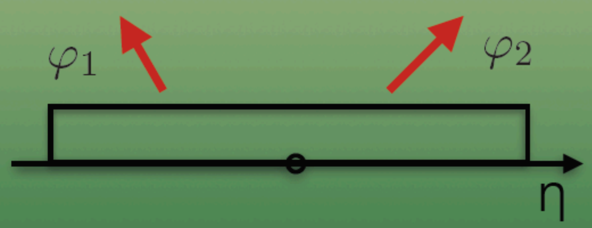
$$c_n\{2\} = \langle\langle 2 \rangle\rangle = \langle\langle \cos n(\varphi_1 - \varphi_2) \rangle\rangle$$

**flow coefficient**

$$v_n\{2\} = \sqrt{c_n\{2\}}$$

# Triangular flow

Methods to exclude non-flow contributions:

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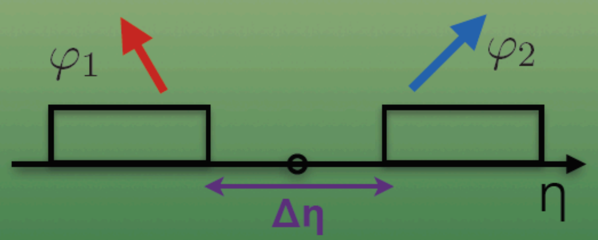


**cumulant**

$$c_n\{2, |\Delta\eta|\} = \langle\langle \cos n(\varphi_1 - \varphi_2) \rangle\rangle$$

**flow coefficient**

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# Triangular flow

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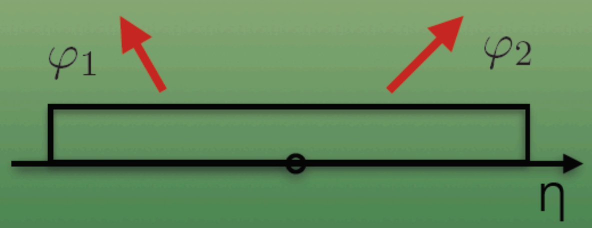


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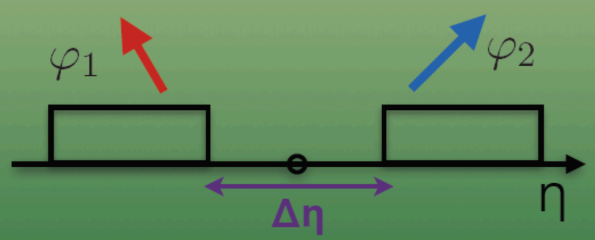


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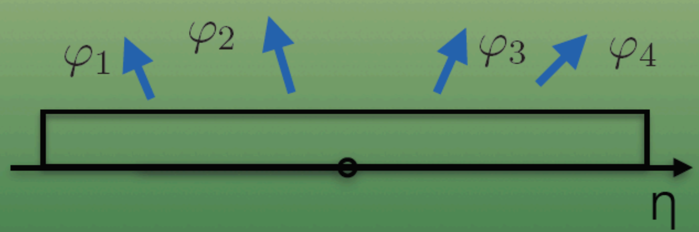
$$v_n\{2, |\Delta\eta|\} = \sqrt{c_n\{2, |\Delta\eta|\}}$$




**cumulant**

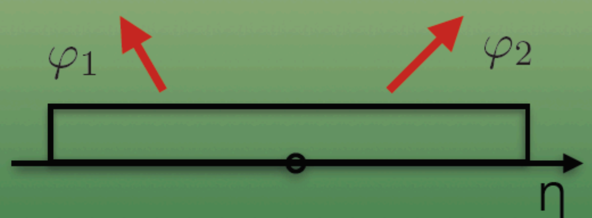
$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$

**flow coefficient**

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

# Triangular flow

Methods to exclude non-flow contributions:

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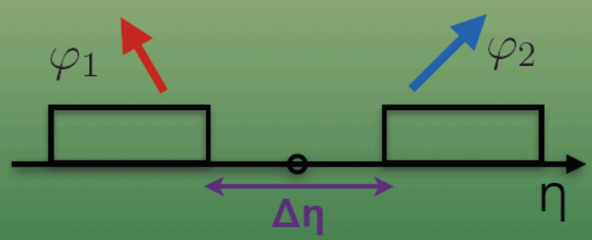
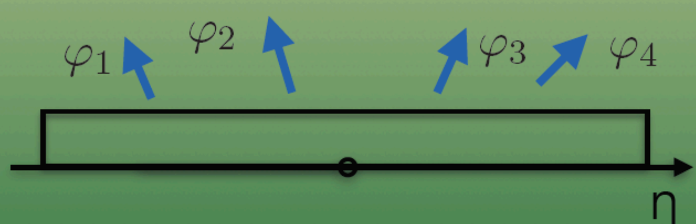



**cumulant**

$$c_n\{2, |\Delta\eta|\} = \langle\langle \cos n(\varphi_1 - \varphi_2) \rangle\rangle$$

**flow coefficient**

$$v_n\{2, |\Delta\eta|\} = \sqrt{c_n\{2, |\Delta\eta|\}}$$

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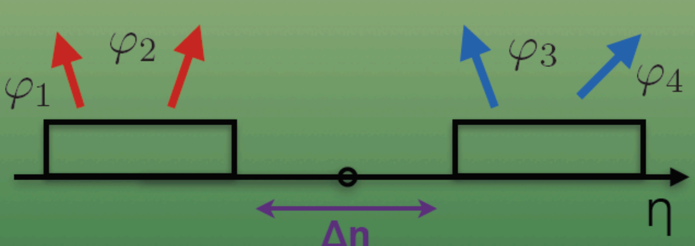



**cumulants**

$$c_n\{4, |\Delta\eta|\} = \langle\langle 4 \rangle\rangle_{|\Delta\eta|} - 2 \cdot \langle\langle 2 \rangle\rangle^2_{|\Delta\eta|}$$

**flow coefficient**

$$v_n\{4, |\Delta\eta|\} = \sqrt[4]{-c_n\{4, |\Delta\eta|\}}$$

# Triangular flow

**More detailed analysis**

**Identified Particles: proton, pion, kaon**

**Different types of calculation of triangular flow**

**EPOS analysis**

# EPOS

**Baseline for BES II?**

Thank you for your attention!

# Backup

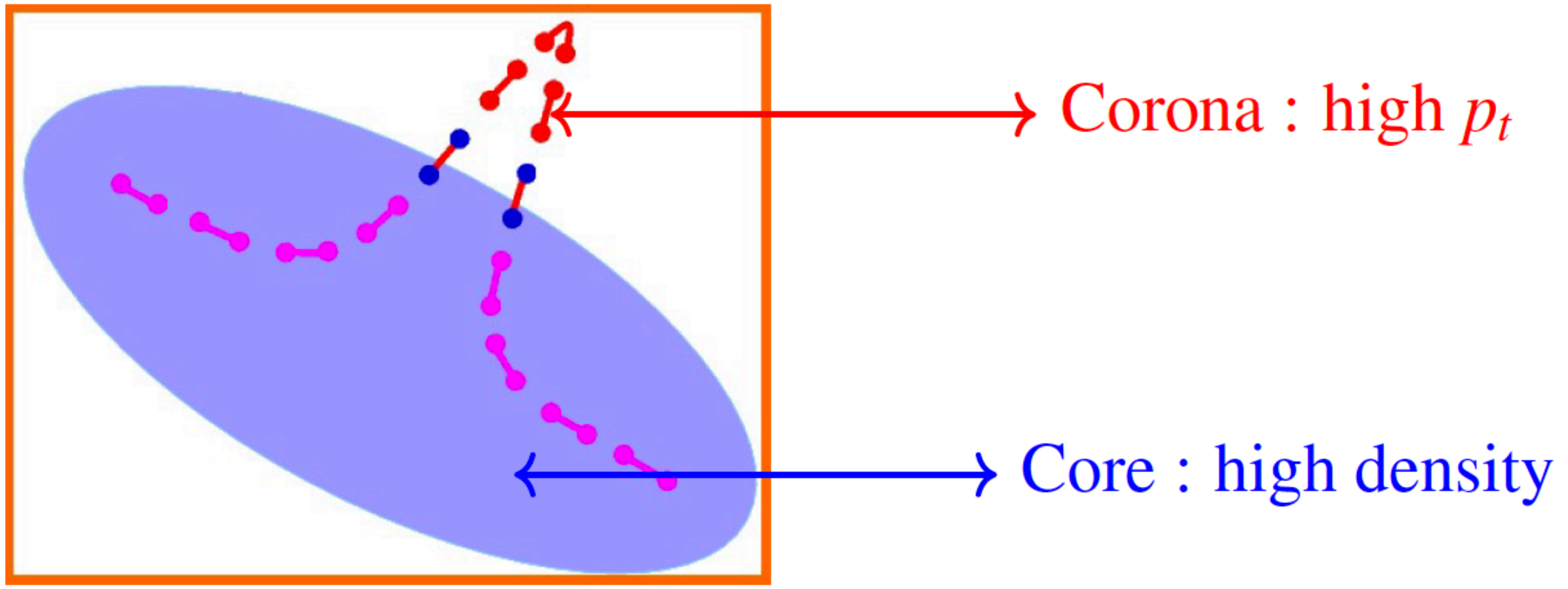
## Core-Corona Approach

• Statistical hadron

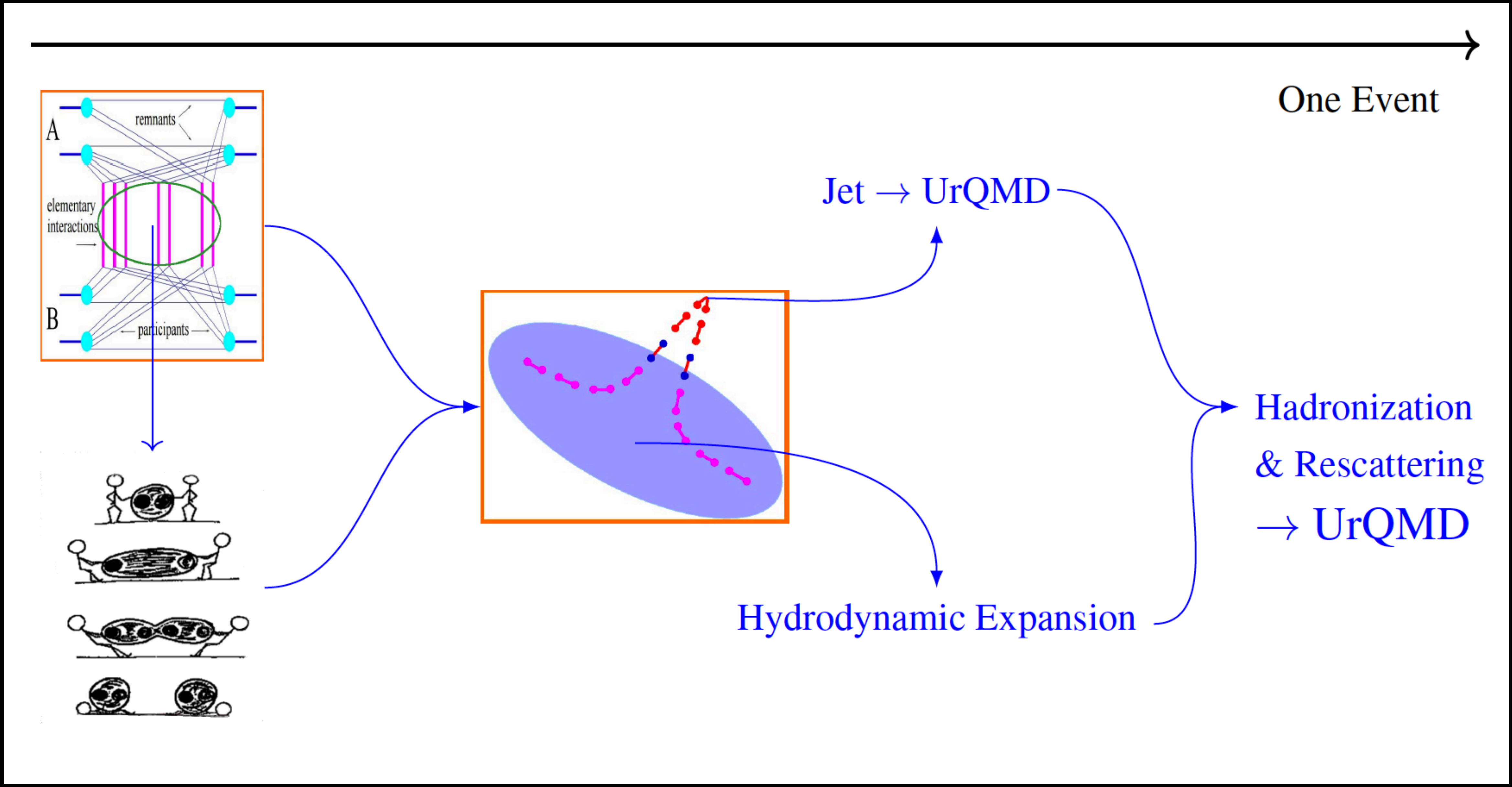
• Final state hadro

Using hydrodynamic $\rightarrow$ the Core is treated as a fluid

Corona becomes Jet $\Rightarrow$ Later Hadrons !




B. Guiot and K. Werner, J. Phys. Conf. Ser. **589** (2015) no.1


One Event
remnants
A
elementary
interactions
B
participants
Jet → UrQMD
Hadronization
& Rescattering
→ UrQMD
Hydrodynamic Expansion