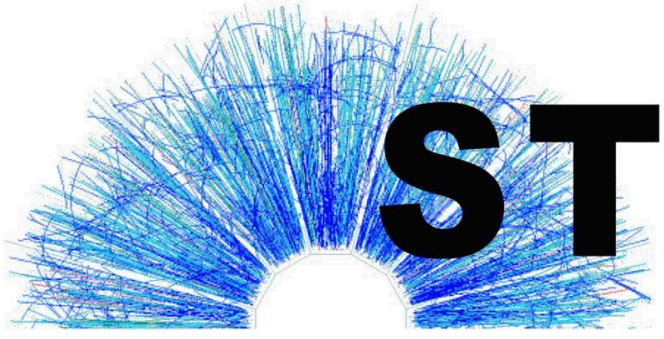
WARSAW UNIVERSITY OF TECHNOLOGY

# Proton femtoscopy


Sebastian Siejka

*For the STAR collaboration*

Warsaw University of Technology
Faculty of Physics



**NICA Days 2017**
Warsaw, Poland
9th November 2017

# Outline and motivation

1) Motivation and basics of proton femtoscopy

2) Cuts used for Au+Au collisions at $\sqrt{s_{NN}}$ = 39 GeV

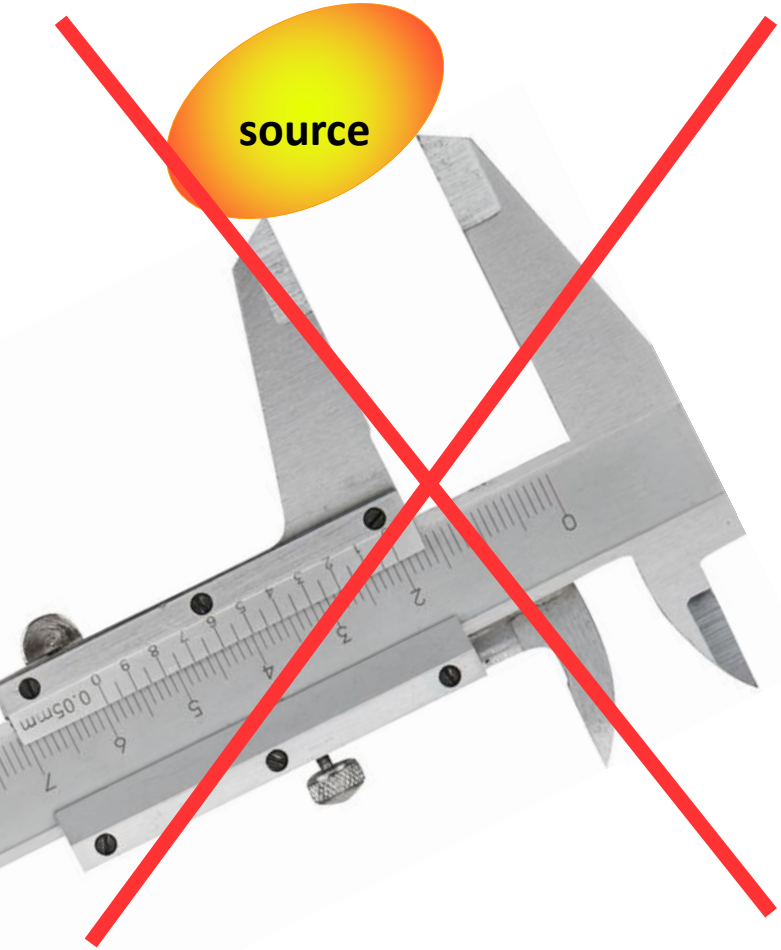
3) Results from Beam Energy Scan:

Au+Au collisions at $\sqrt{s_{NN}}$ = 39, 11.5 and 7.7 GeV

4) Summary and conclusions

**if we extract the source radii from baryon-baryon correlations we will be able to compare those with the radii already obtained from meson-meson and meson-baryon correlations - such comparison will provide us complementary information about the source characteristics**

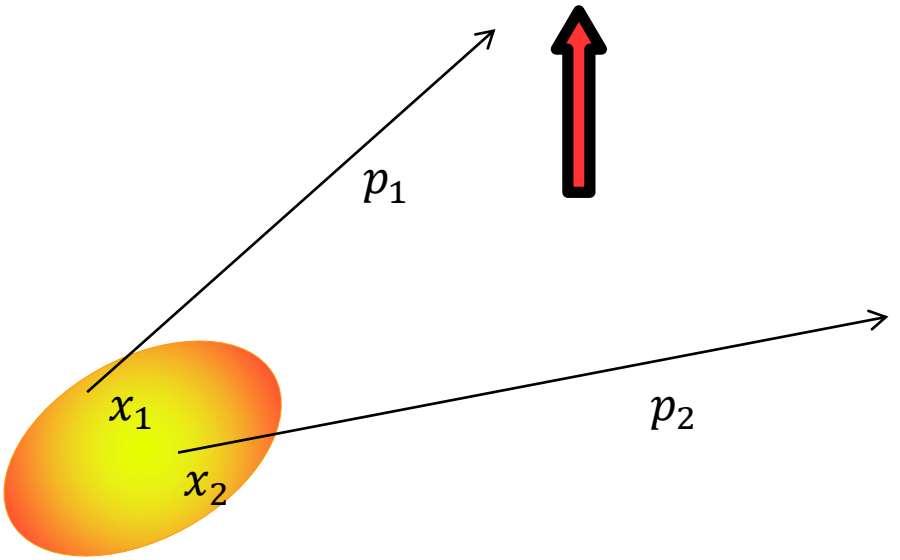
# Few words about femtoscopy



# Few words about femtoscopy


**The correlation function**

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



# Few words about femtoscopy

**Two-particle distribution**

$$P_2(p_1,p_2) = E_1E_2\frac{dN}{d^3p_1d^3p_2} = \int d^4x_1 S(x_1,p_1) d^4x_2 S(x_2,p_2)\Phi(x_2,p_2 \mid x_1,p_1)$$

**The correlation function**

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

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

**Single-particle distribution**

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

# Proton correlations

**Identical baryon-baryon**

- Quantum Statistics (QS)
- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)

**Nonidentical baryon-antibaryon**

- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)

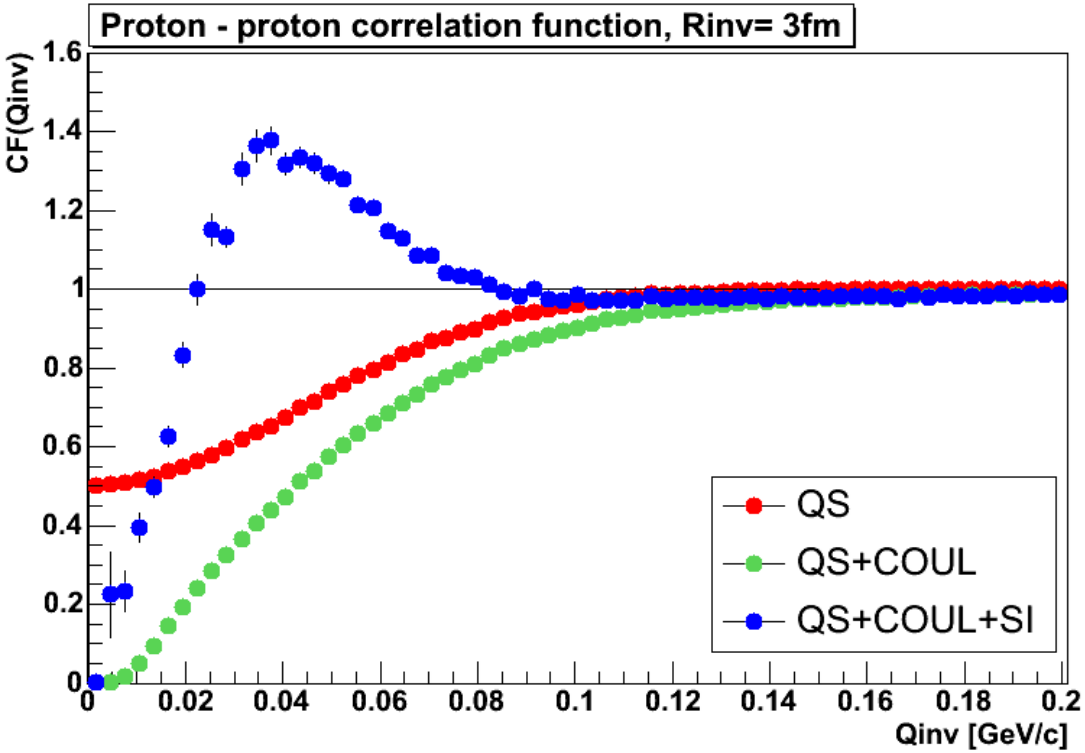
# Proton correlations

**Identical baryon-baryon**

- Quantum Statistics (QS)
- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)

**Nonidentical baryon-antibaryon**

- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)




UrQMD *Au+Au;*$R_{inv} = 3fm$

Relativistic Hadron-Hadron Collisions in the Ultra-Relativistic Quantum M
J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859-1896

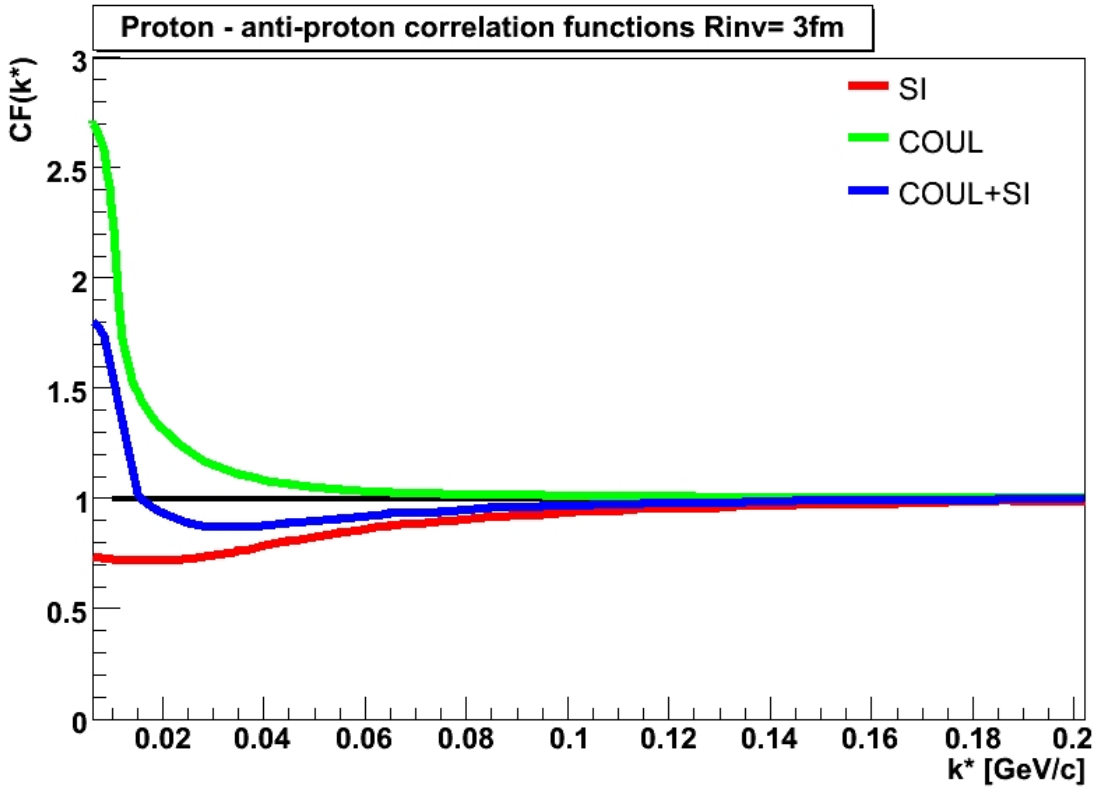
# Proton correlations

**Identical baryon-baryon**

- Quantum Statistics (QS)
- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)

**Nonidentical baryon-antibaryon**

- Final State Interactions:
  - Coulomb Interaction (COUL)
  - Strong Interaction (SI)

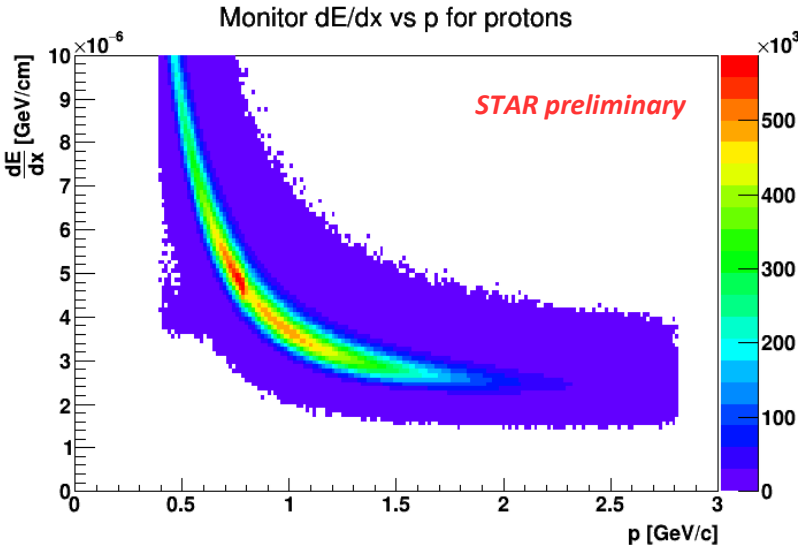



UrQMD *Au+Au;*$R_{inv} = 3fm$

Relativistic Hadron-Hadron Collisions in the Ultra-Relativistic Quantum M
J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859-1896

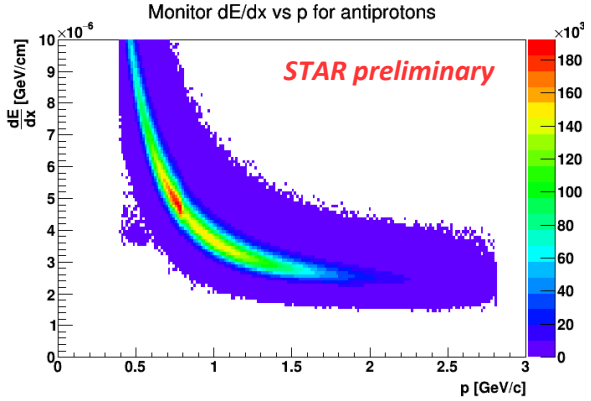
# Data selection

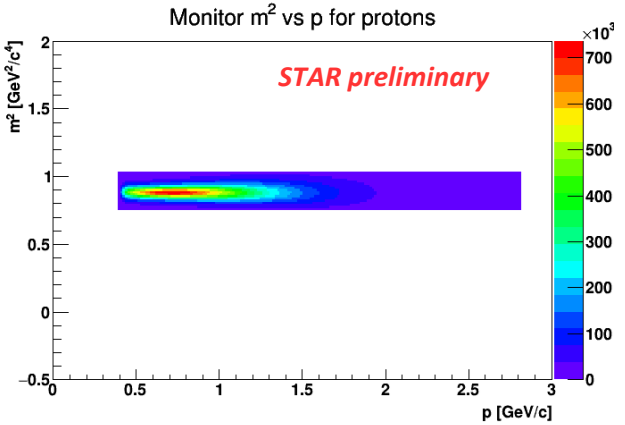
## Example plots showing data that passed selection criteria for Au+Au collisions at $\sqrt{s_{NN}}$ = 39 GeV



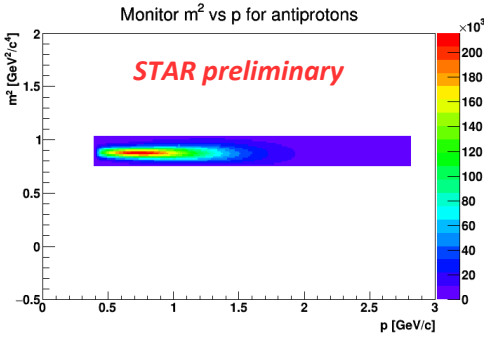

| Cut | Range/value |
|---|---|
| Momentum ( p ) | 0.4 < p < 3.0 [GeV/c] |
| Mass window | 0.76 < m < 1.03 [GeV/c^2] |
| N σ | -3.0 < N < 3.0 |
| Z vertex:<br>- 7.7 GeV<br>- 11.5 GeV<br>- 39 GeV | [cm]<br>-70 < z < 70<br>-50 < z < 50<br>-30 < z < 30 |

below p=0.8 GeV/c information from TPC is sufficient for particle identification

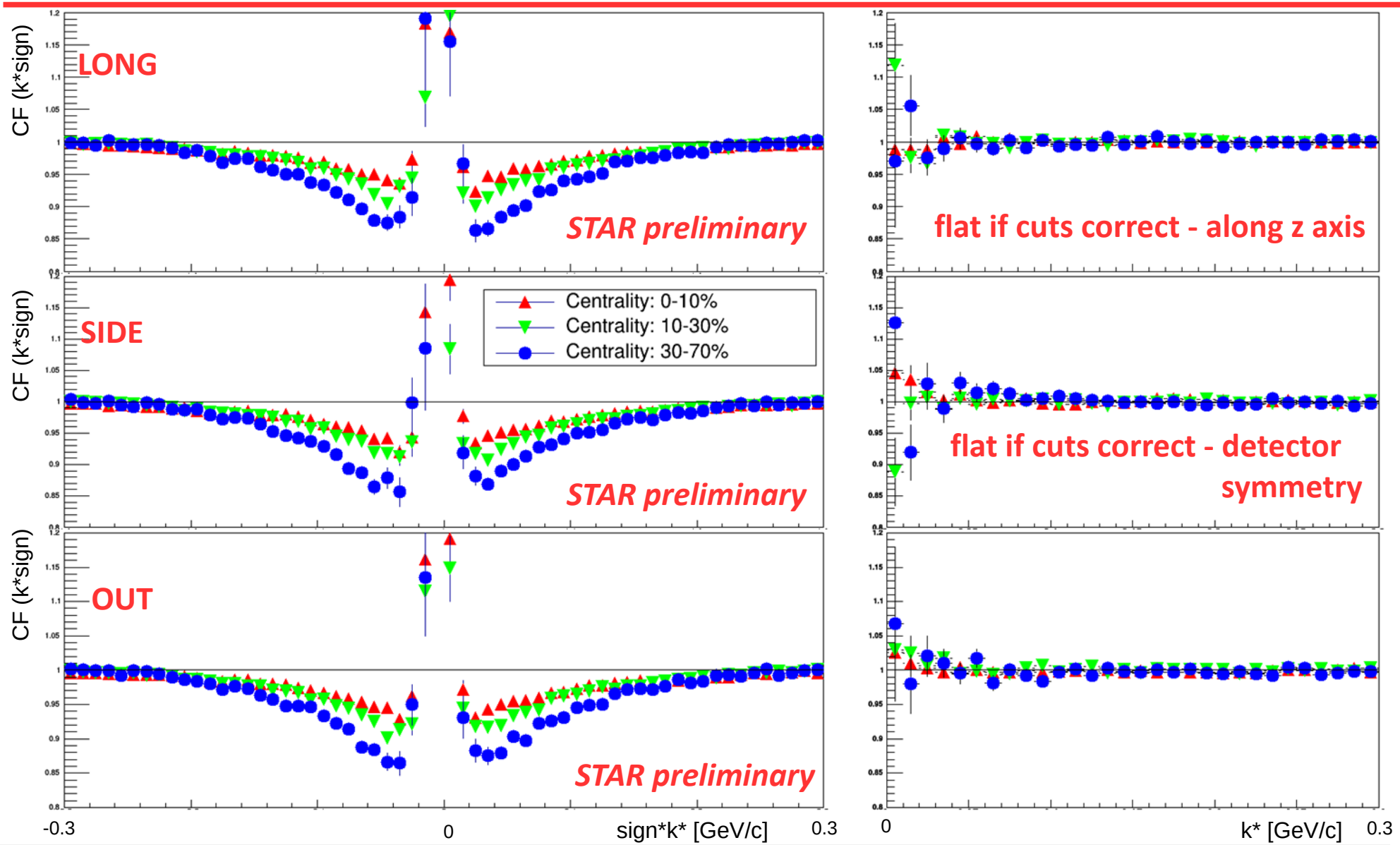



above p=0.8 GeV/c we need combined information from TPC and ToF in order to properly identify particles



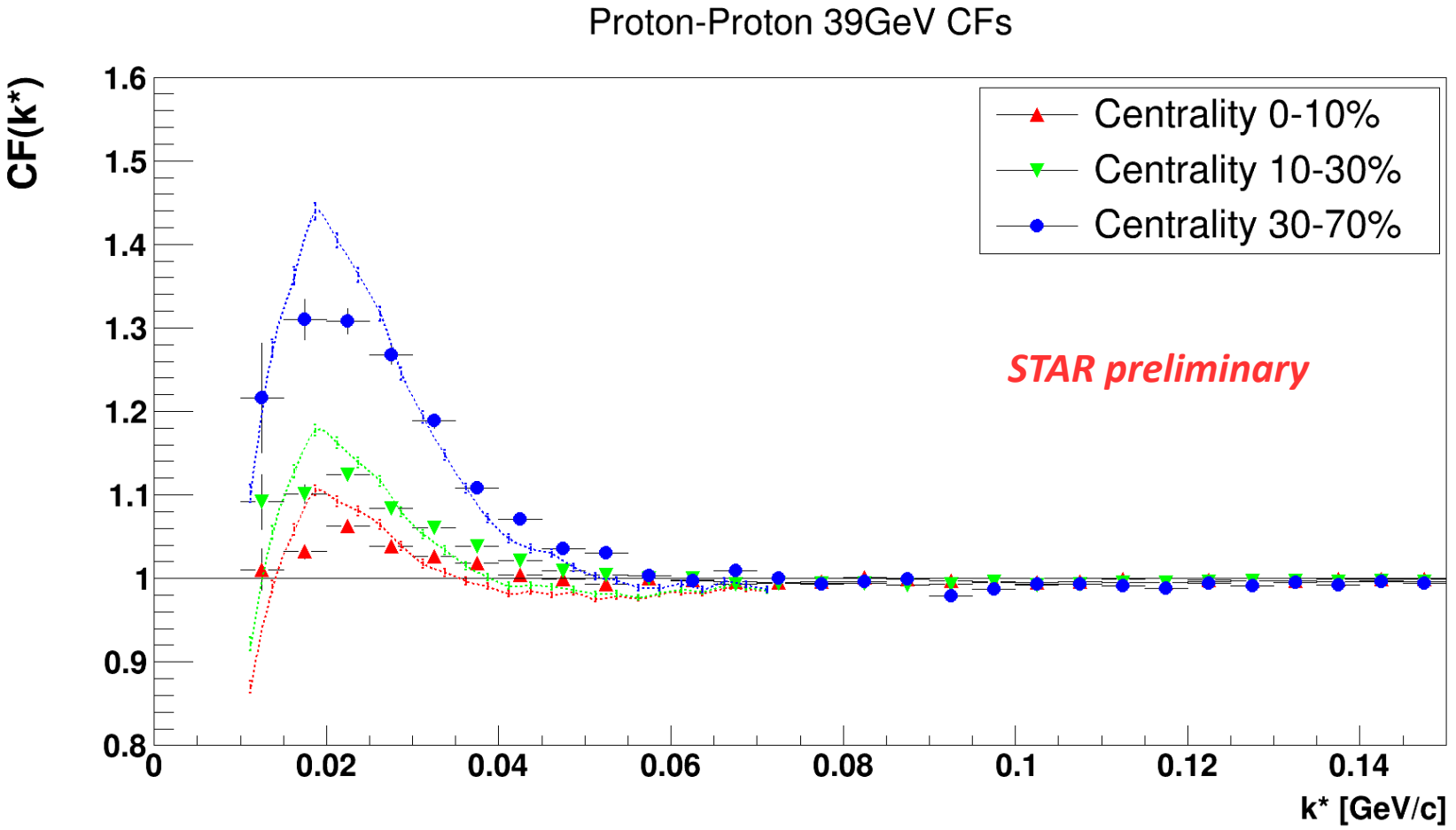
# Double Ratio



# Analysis of Au+Au collisions @ 39 GeV

**Measured correlation functions are shown** **Clear centrality dependence**

$$R_{p-p}(0-10\,\%) > R_{p-p}(10-30\,\%) > R_{p-p}(30-70\,\%)$$




0-10%
Rinv = 4.03
± 0.14 fm

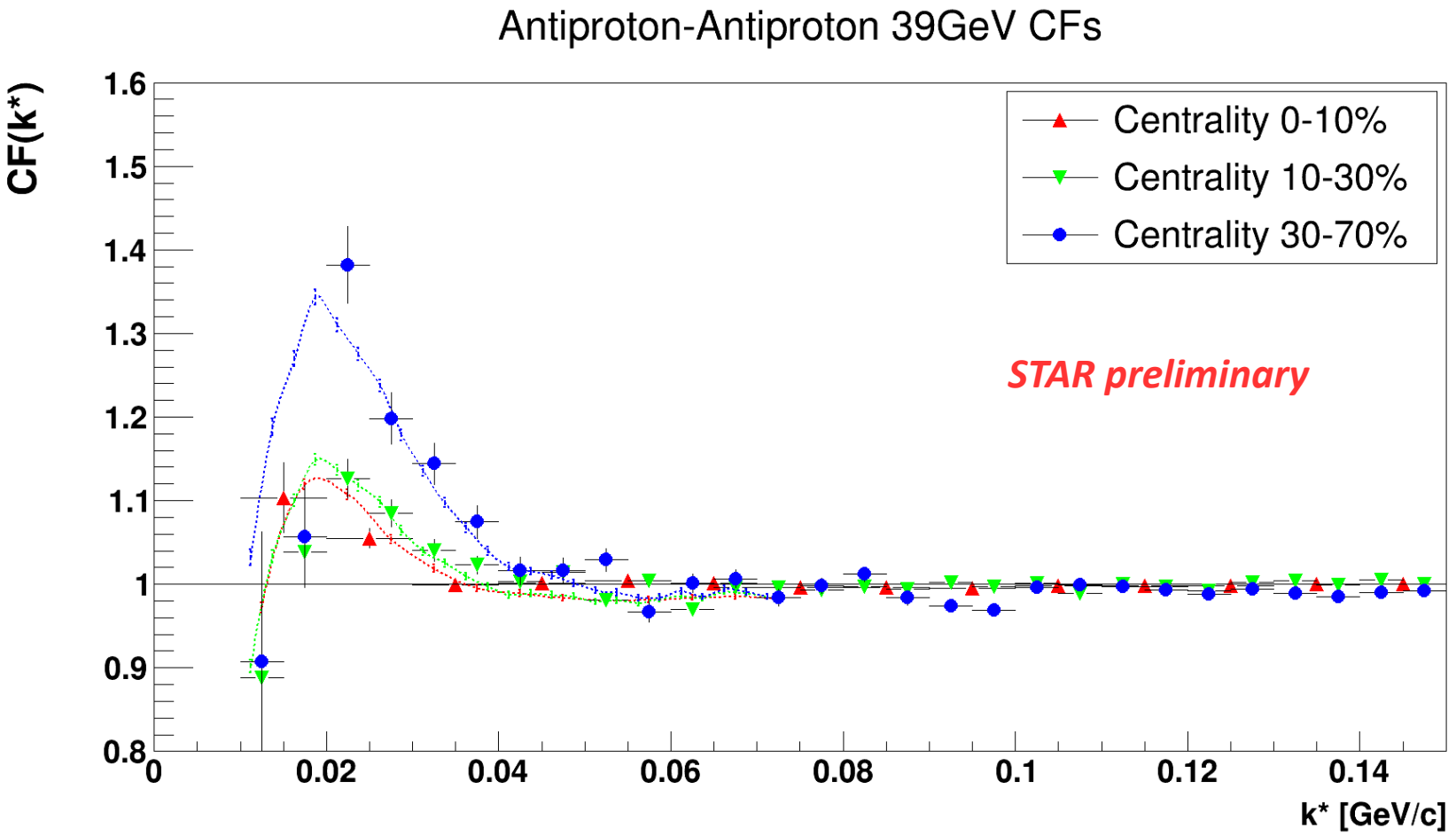
10-30%
Rinv = 3.60
± 0.14 fm

30-70%
Rinv = 2.77
± 0.14 fm

# Analysis of Au+Au collisions @ 39 GeV

**Measured correlation functions are shown** **Clear centrality dependence**

$$R_{p-p}(0-10\,\%) > R_{p-p}(10-30\,\%) > R_{p-p}(30-70\,\%)$$




0-10%
Rinv = 3.95
± 0.14 fm

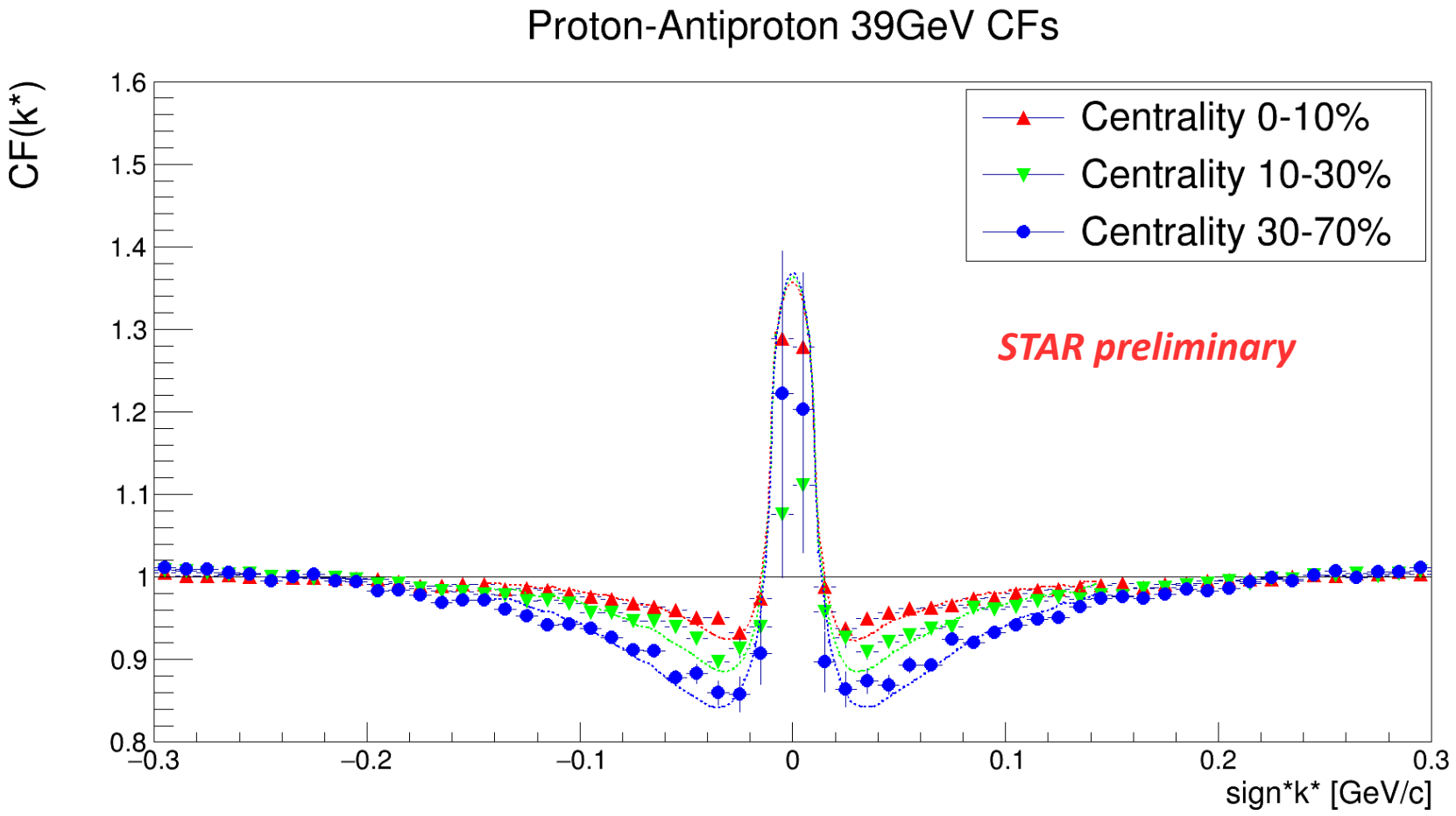
10-30%
Rinv = 3.79
± 0.21 fm

30-70%
Rinv = 3.05
± 0.14 fm

# Analysis of Au+Au collisions @ 39 GeV

**Measured correlation functions are shown** **Clear centrality dependence**

$$R_{p-p}(0-10\,\%) > R_{p-p}(10-30\,\%) > R_{p-p}(30-70\,\%)$$




0-10%
Rinv = 3.56
± 0.14 fm

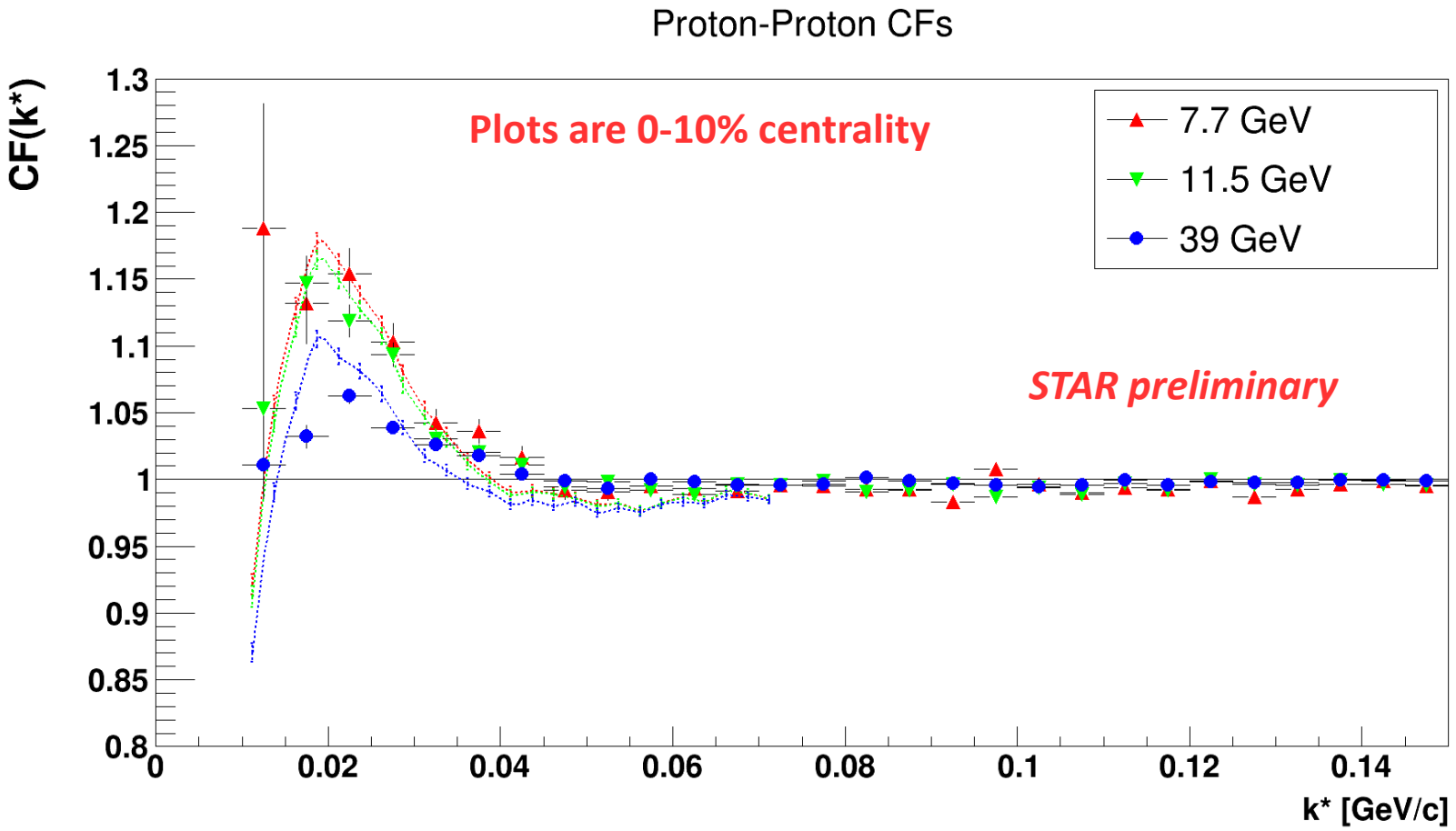
10-30%
Rinv = 2.88
± 0.14 fm

30-70%
Rinv = 2.30
± 0.14 fm

# Analysis of Au+Au collisions - comparison of plots for different energies

**Measured correlation functions are shown** **Clear energy dependence**

$$R_{p-p}(39\,GeV) > R_{p-p}(11.5\,GeV) > R_{p-p}(7.7\,GeV)$$

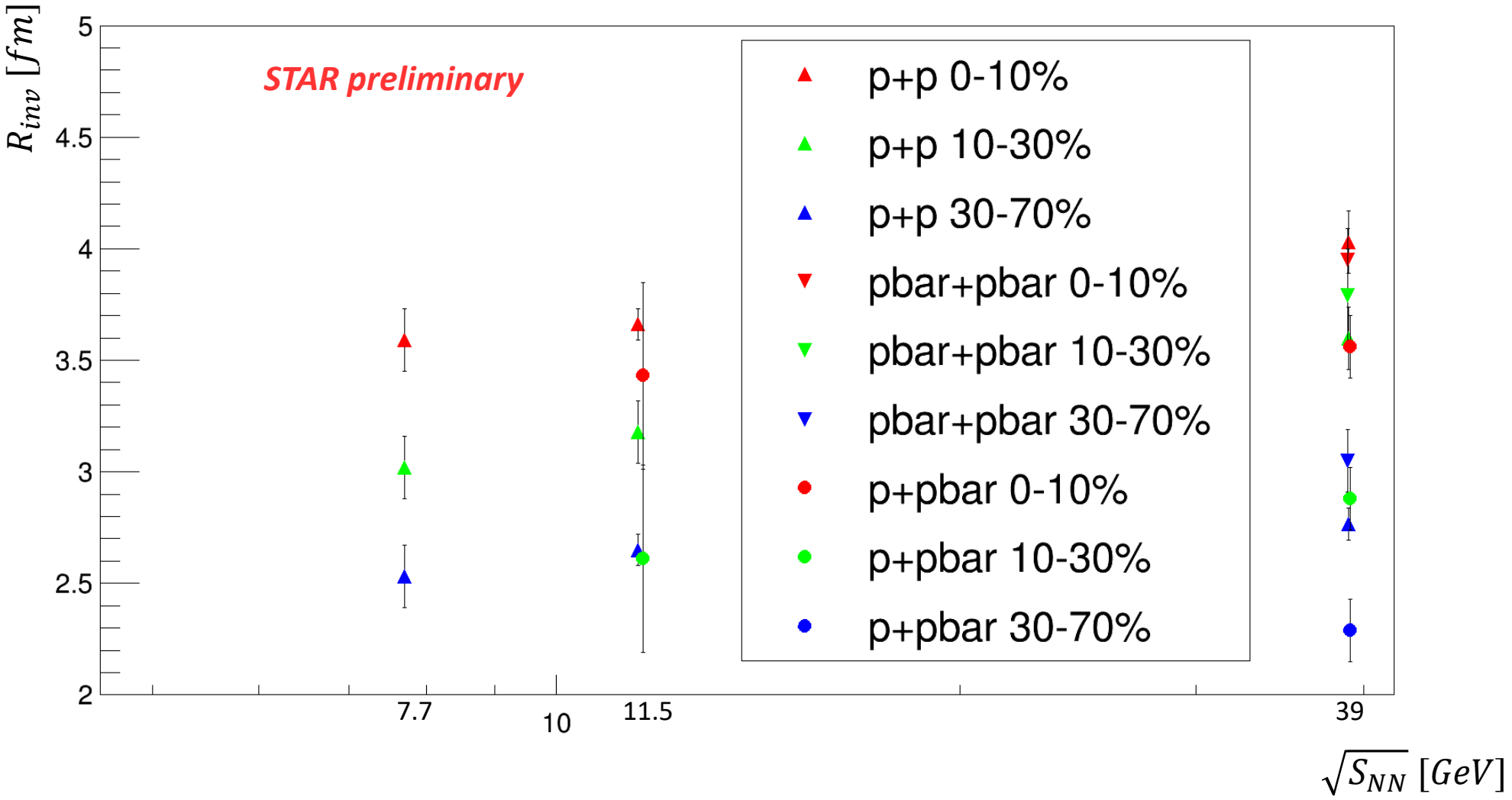



7 GeV 0-10%
Rinv = 3.59
± 0.14 fm

11 GeV 0-10%
Rinv = 3.661
± 0.071 fm

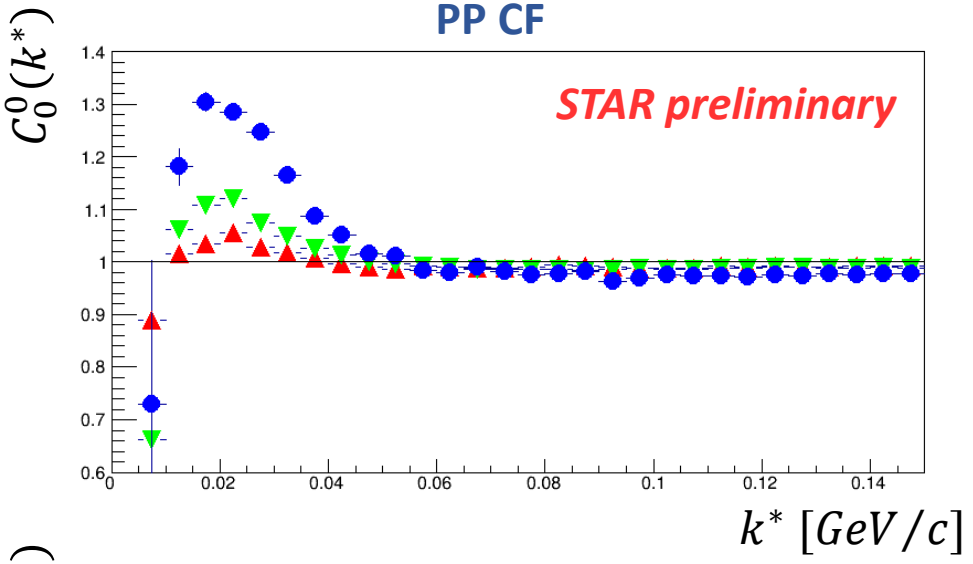
39 GeV 0-10%
Rinv = 4.03
± 0.14 fm

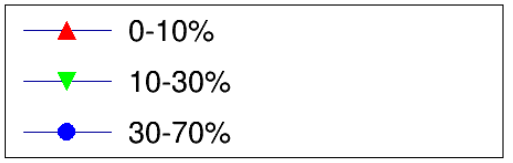
# Analysis of Au+Au collisions - comparison



# Analysis of Au+Au collisions @ 39 GeV – Spherical Harmonics

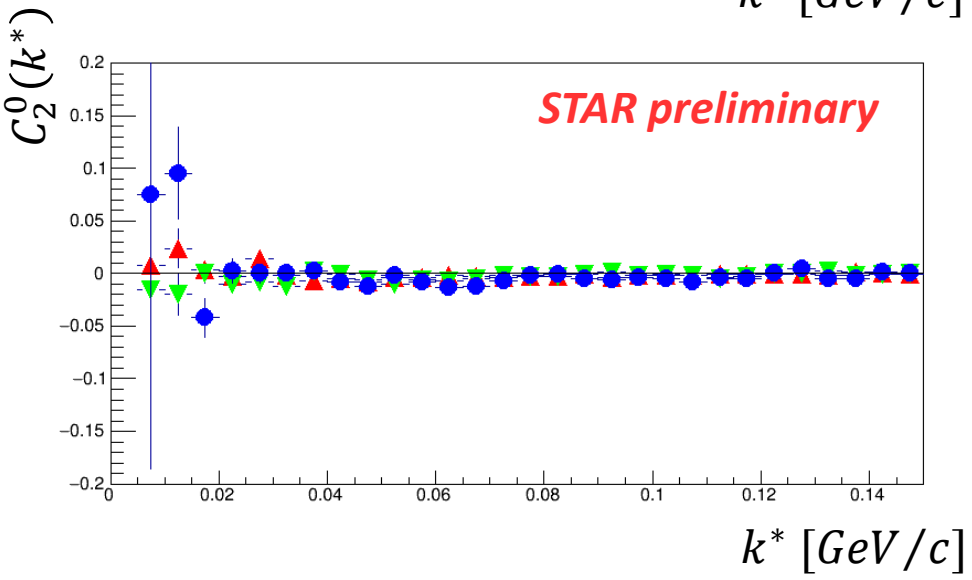
PP CF



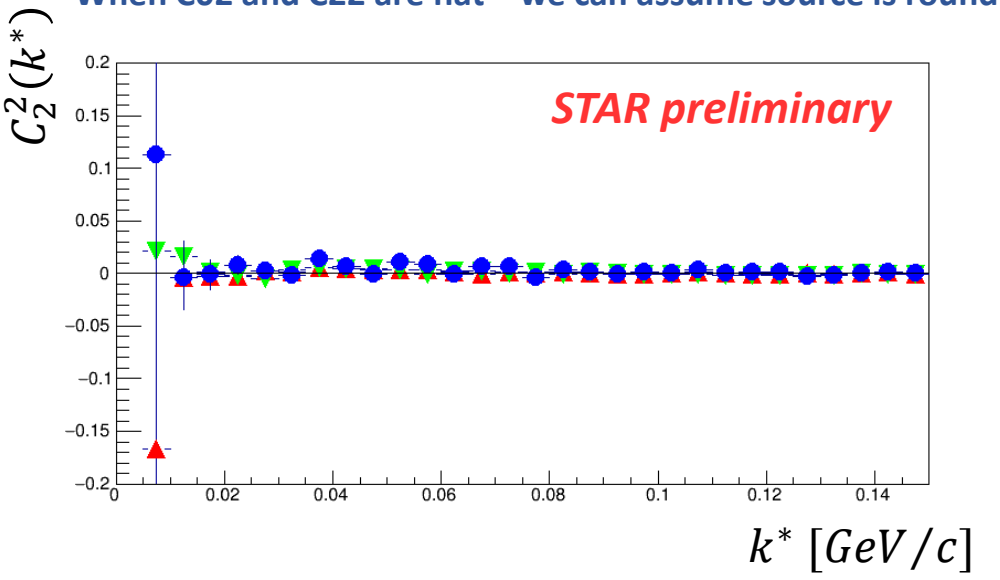




**Spherical Harmonics – one of the most advanced representations of the correlation function**

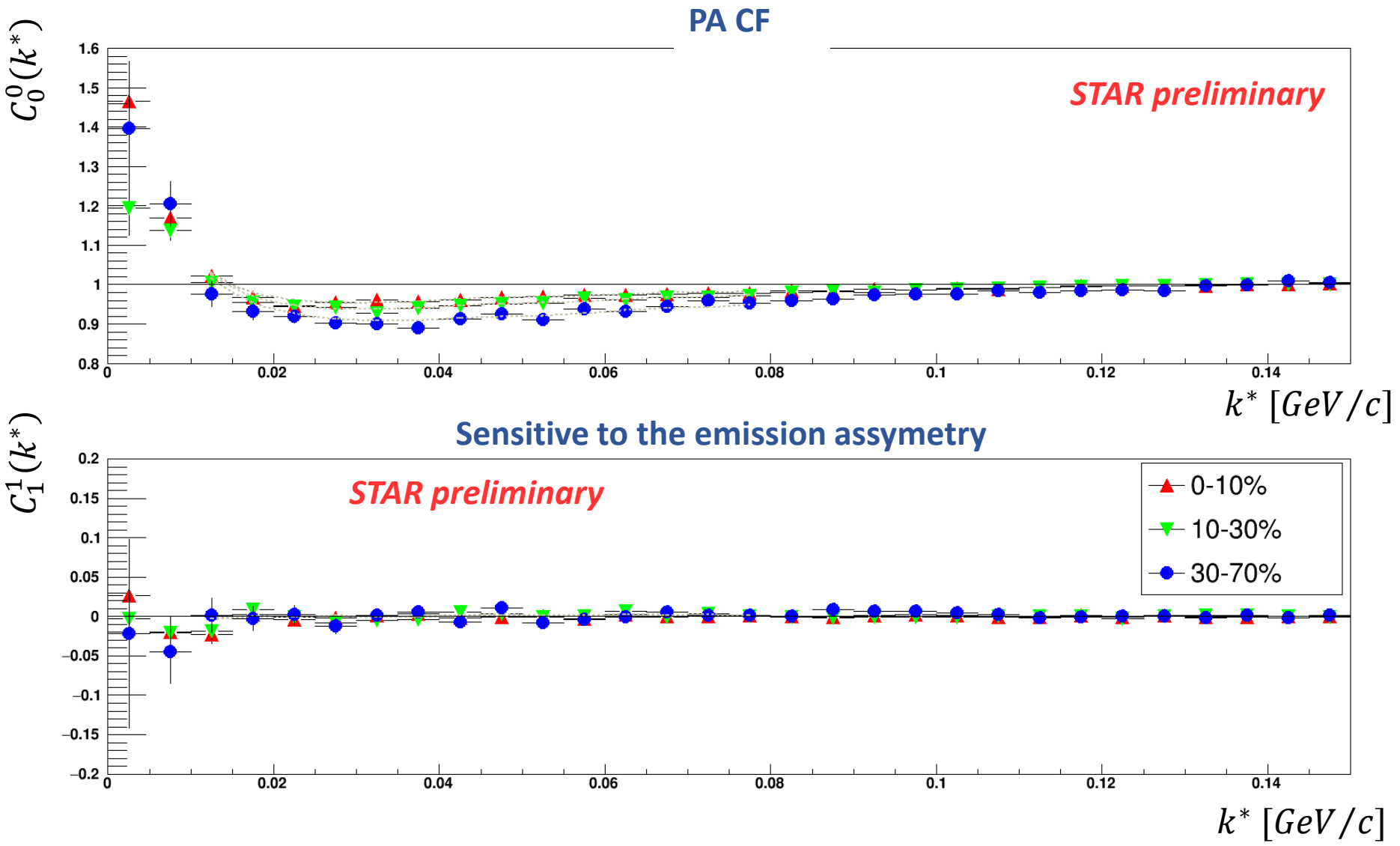
*P. Danielewicz and S. Pratt. Phys. Lett. B618: 60 2005*
*P. Danielewicz and S. Pratt. Phys. Rev. C75: 034907 2007*




When C02 and C22 are flat – we can assume source is round



# Analysis of Au+Au collisions @ 39 GeV – Spherical Harmonics



# Summary

- **Data analysed: 7.7 GeV, 11.5 GeV, 39 GeV**
- **Improved selection criteria provide better particle identification.**
- **proton - proton, antiproton - antiproton and proton - antiproton systems checked**

  => the range of correlations different for identical and non-identical particle combinations
- **(anti)proton femtoscopy sensitive to Quantum Statistic Effects and Final State Interactions**

  => Baryon-baryon and baryon-antibaryon CFs are differently affected by the strong interaction (due to the annihilation process)
- **the results allow for source sizes observation:**

  **radii increase with centrality at fixed $\sqrt{s_{NN}}$**

$$\mathbf{R_{p-p}(0-10\%) > R_{p-p}(10-30\%) > R_{p-p}(30-70\%)}$$

  **radii increase with $\sqrt{s_{NN}}$ at fixed centrality**

$$\boldsymbol{R_{p-p}(39\ \mathrm{GeV}) > R_{p-p}(11.5\ \mathrm{GeV}) > R_{p-p}(7.7\ \mathrm{GeV})}$$

# Thank you for your attention

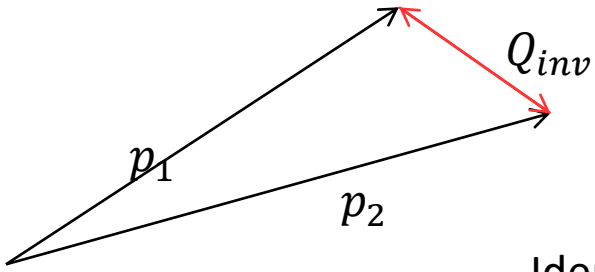
# Few words about femtoscopy

**The correlation function**

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

$Q_{inv}$

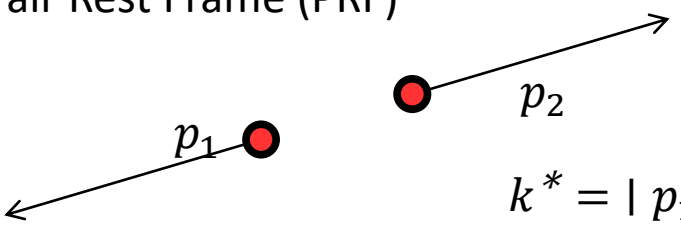
In Longitudinal Co-Moving System (LCMS)




Identical baryons

$k^*$

In Pair Rest Frame (PRF)




$k^* = | p_1 | = | p_2 |$

Non-identical baryons

$Q_{inv} = 2\mathrm{k}^*$

for $m_1 = m_2$

# Proton correlations

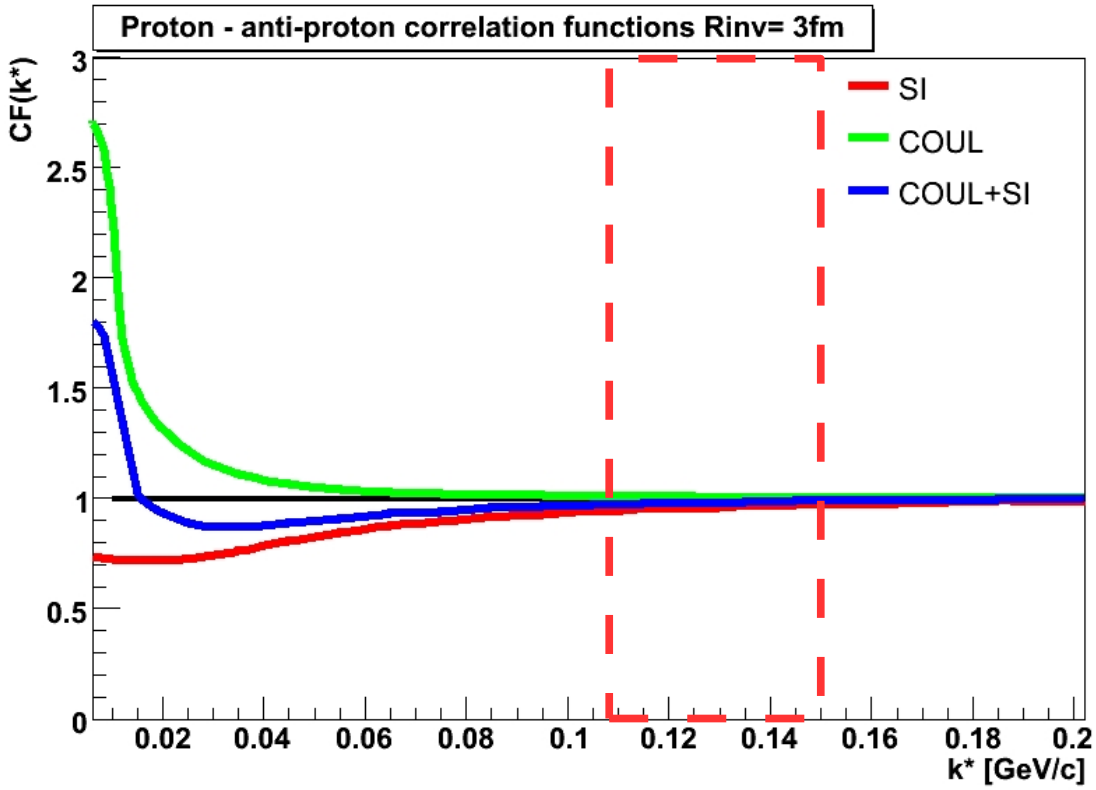
**Identical baryon-baryon**

- Quantum Statistics (QS)
- Final State Interactions:
  - Coulomb Interactions (COUL)
  - Strong Interactions (SI)

**Non-identical baryon-antibaryon**

- Final State Interactions:
  - Coulomb Interactions (COUL)
  - Strong Interactions (SI)

$k^* \approx 130\ MeV/c$




UrQMD *Au+Au;*$R_{inv} = 3fm$

# Proton correlations

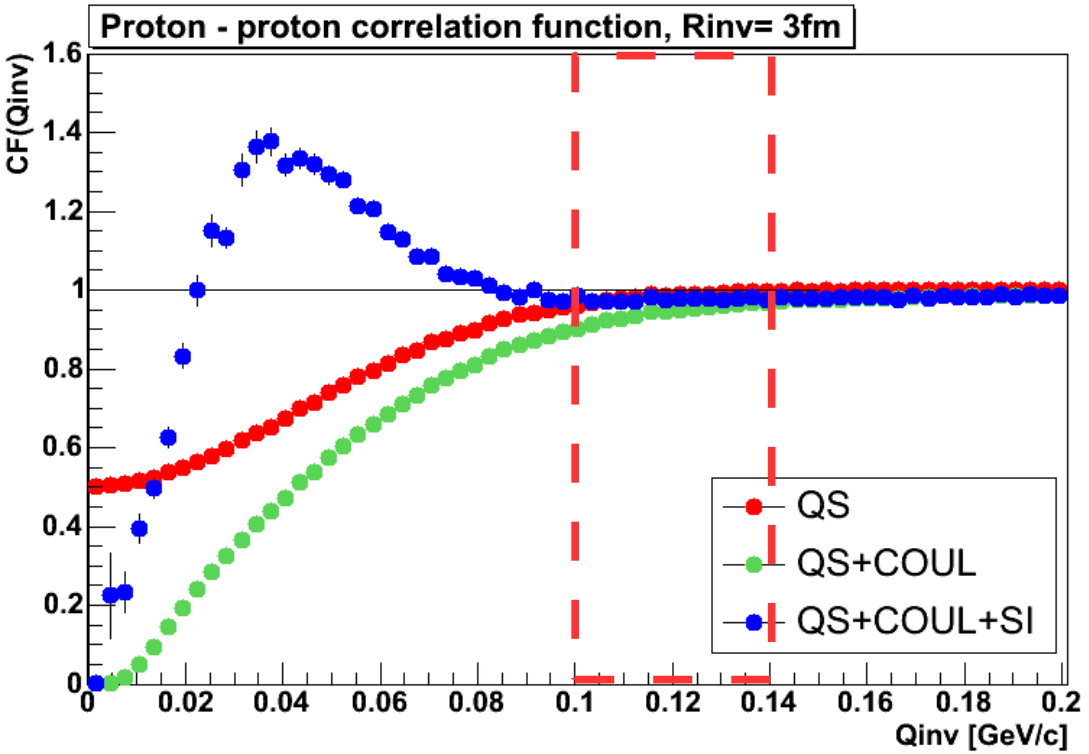
**Identical baryon-baryon**

- Quantum Statistics (QS)
- Final State Interactions:
  - Coulomb Interactions (COUL)
  - Strong Interactions (SI)

**Non-identical baryon-antibaryon**

- Final State Interactions:
  - Coulomb Interactions (COUL)
  - Strong Interactions (SI)

$k^* \approx 60\ MeV/c$




UrQMD *Au+Au;*$R_{inv} = 3fm$

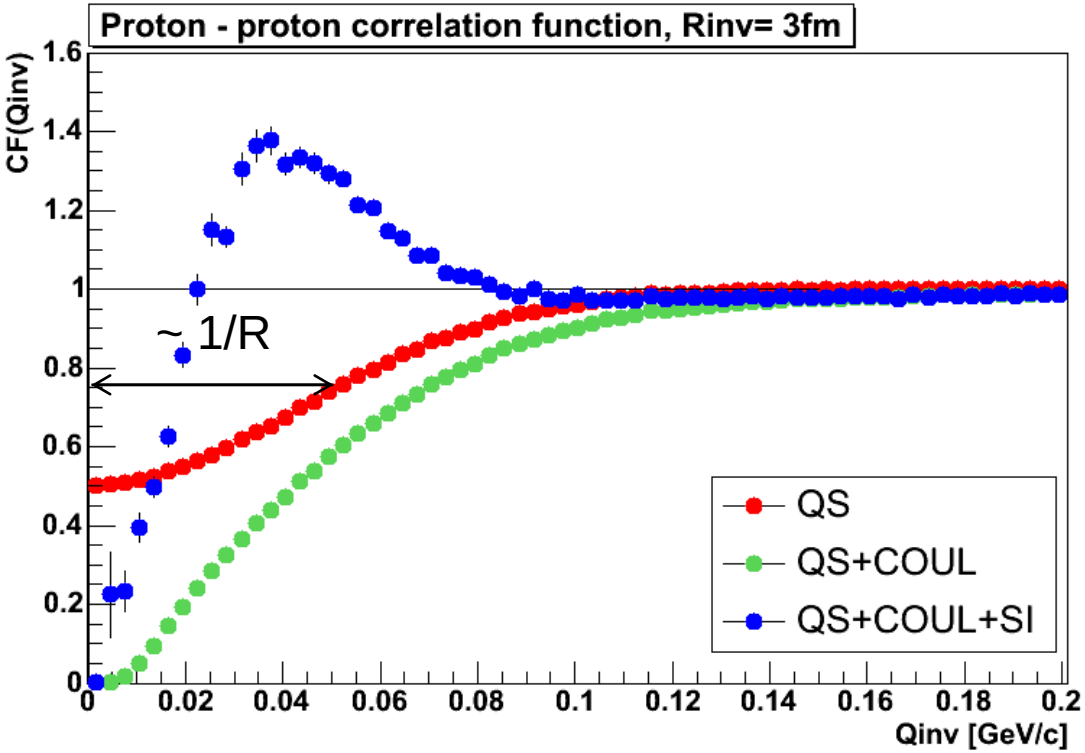
# Proton correlations

**Why to do this?**

We can calculate radii using the correlation functions.

The width of the Quantum Statistics part in correlation functions is inversely proportional to the radius of the source size.

The radii can be qualitatively compared using the height and the width of the pike in identical baryon-baryon correlation functions.



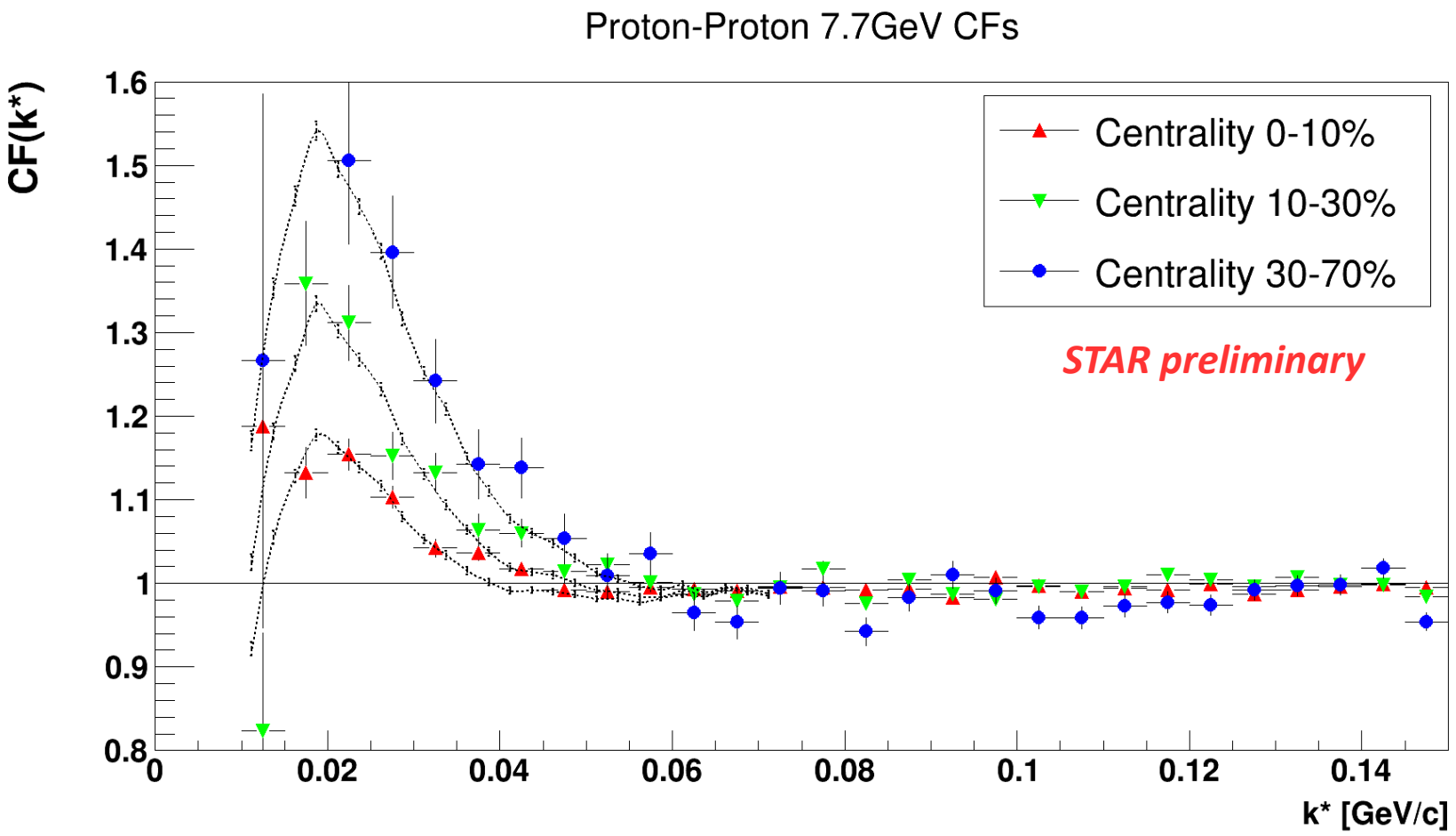

UrQMD *Au+Au;*$R_{inv} = 3fm$

Relativistic Hadron-Hadron Collisions in the Ultra-Relativistic Quantum M
J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859-1896

# Analysis Au+Au collisions @ 7.7 GeV

**Measured correlation functions are shown** **Clear centrality dependence**

$$R_{p-p}(0-10\,\%) > R_{p-p}(10-30\,\%) > R_{p-p}(30-70\,\%)$$




0-10%
Rinv = 3.59 fm
± 0.14

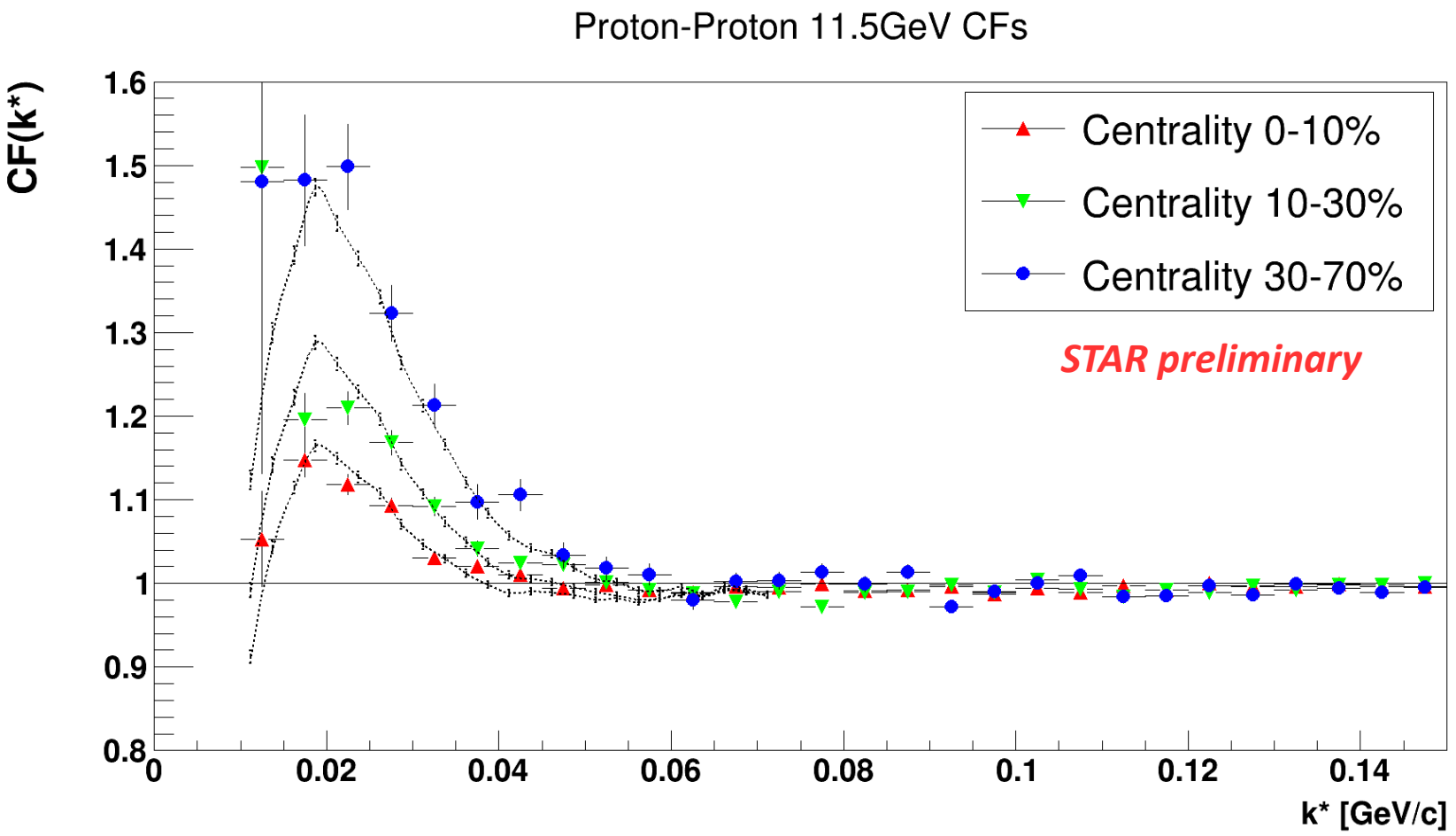
10-30%
Rinv = 3.02 fm
± 0.14

30-70%
Rinv = 2.53 fm
± 0.14

# Analysis Au+Au collisions @ 11.5 GeV

**Measured correlation functions are shown** **Clear centrality dependence**

$$R_{p-p}(0-10\,\%) > R_{p-p}(10-30\,\%) > R_{p-p}(30-70\,\%)$$




0-10%
Rinv = 3.661 fm
± 0.071

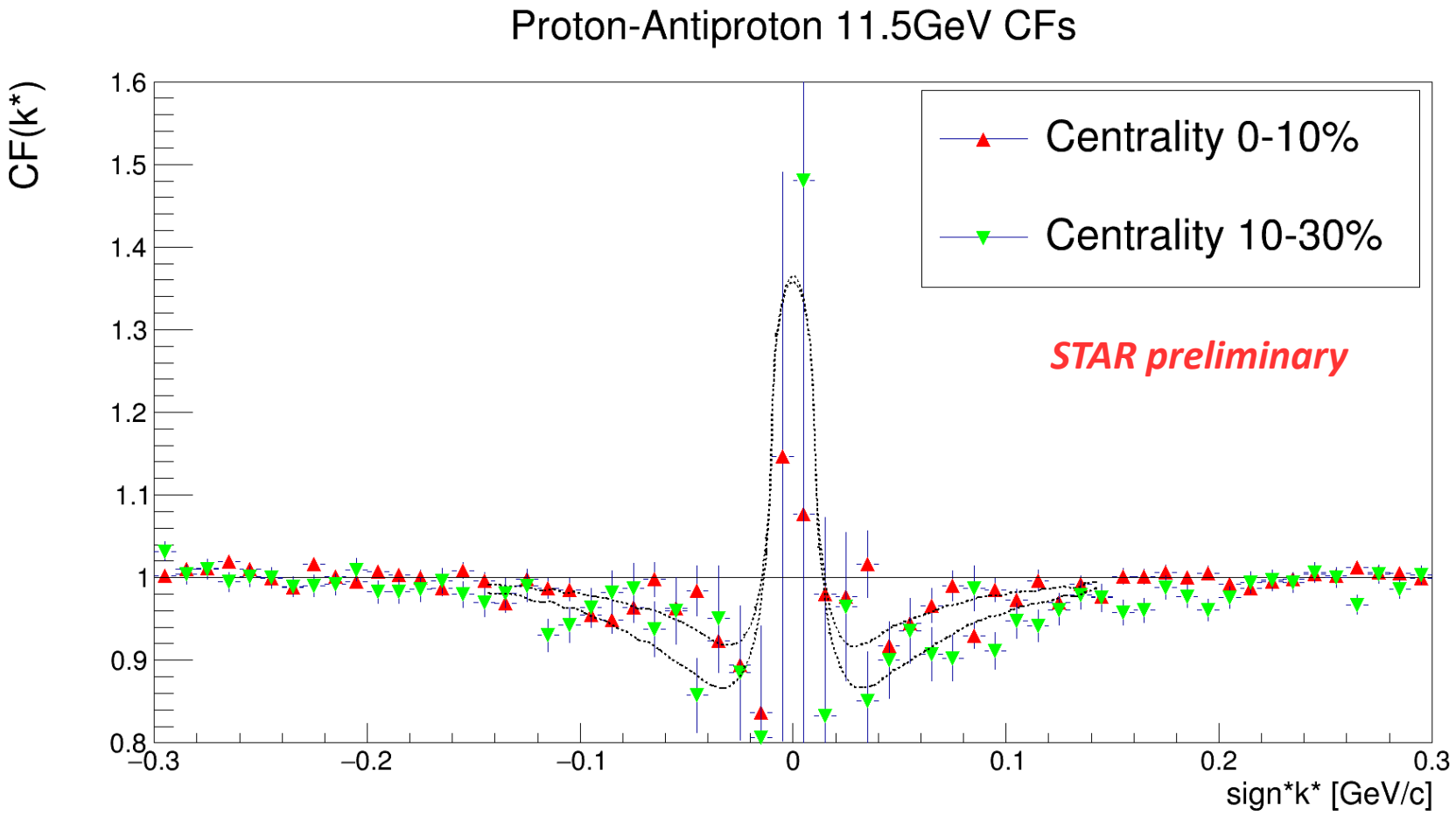
10-30%
Rinv = 3.18 fm
± 0.14

30-70%
Rinv = 2.65 fm
± 0.14

# Analysis Au+Au collisions @ 11.5 GeV

**Measured correlation functions are shown** **Clear centrality dependence**

$$R_{p-p}(0-10\,\%) > R_{p-p}(10-30\,\%) > R_{p-p}(30-70\,\%)$$




0-10%
Rinv = 3.43 fm
± 0.42

10-30%
Rinv = 2.61 fm
± 0.42