3D pion HBT correlations and their Lévy parameters in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at STAR

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ZIMÁNYI SCHOOL 2024

L. Kassák: Image architecture

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ON HEAVY ION PHYSICS

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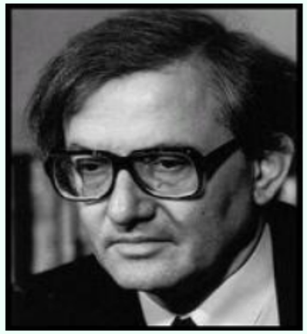

József Zimányi (1931 - 2006)

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03/12/2024

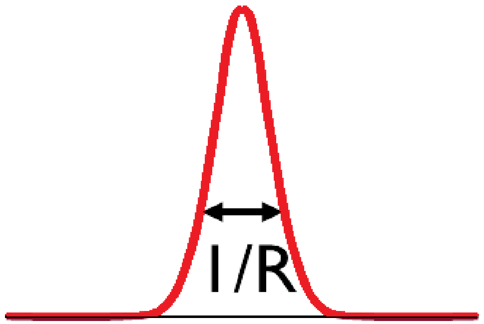
Outline:

- Introduction
- Motivation
- Analysis
- Results
- Summary and conclusions

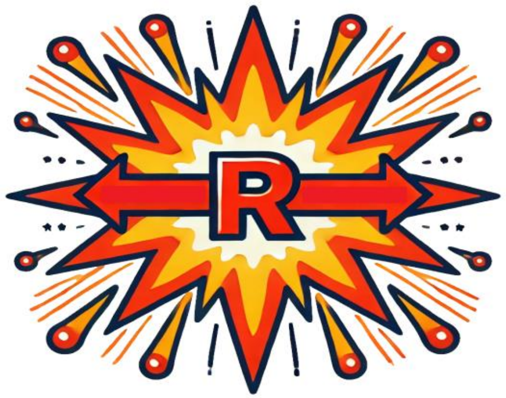
Lévy-stable distribution: could provide a more accurate source description, incorporates a power-law tail, deviates from standard Gaussian framework

Introduction:

- Technique used to study the space-time evolution of particle-emitting sources in heavy-ion collisions
    - R. Hanbury Brown and R. Q. Twiss Nature 178 (1956)
- Intensity correlations as a function of detector distance
- Measuring size of otherwise apparently point-like sources
- Goldhaber, Goldhaber, Lee and Pais: applicable in high energy physics
    - Goldhaber, Goldhaber, Lee and Pais Phys.Rev.Lett.3 (1959) 181
- Resolving the femtometer scale size and structure of particle emission from QGP



Corr. funct. $\mathbf{C(q) = 1 + |\tilde{S}(Q)|^2}$



Momentum correlation $C(q)$, $q = |p_1 - p_2|$, is related to the source $S(r) \rightarrow C(q) = 1 + |\tilde{S}(\mathrm{Q})|^2$

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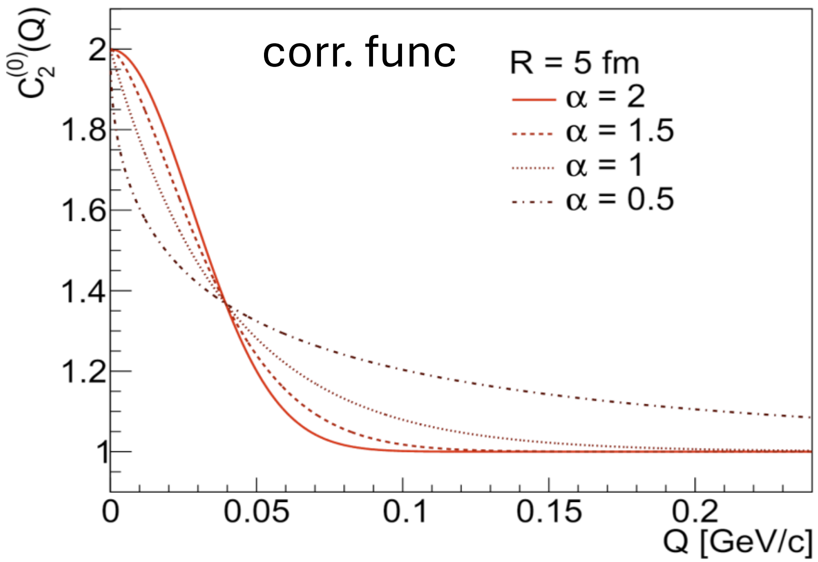
HBT analyses with Lévy sources have been done in 1D so far, developing this to 3D is important:

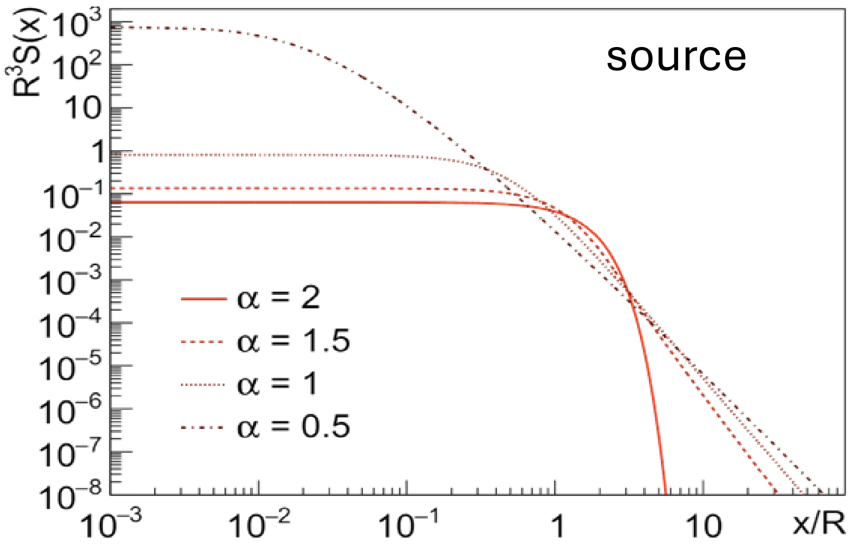
→ check if deviation from Gaussian in 1D is because of directional avg.
→ provides a more complete picture of the source geometry
→ allows for comparison with 1D results to check its consistency

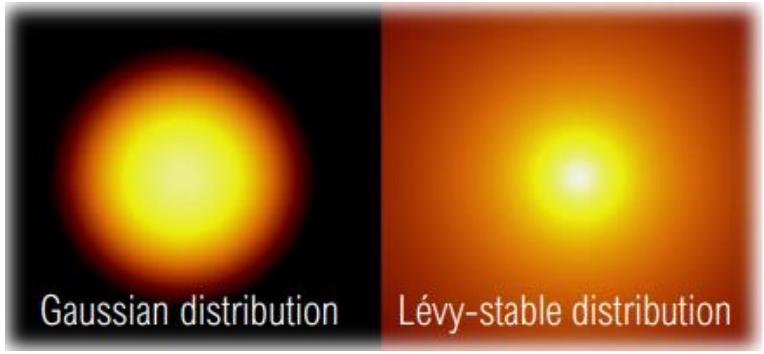
Lévy distributions in femtoscopy:

- Femtoscopic correlation functions often assume Gaussian sources
- Lévy-stable distributions: more flexible approach to characterize shape and size

Csörgő,Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67-78







- Lévy seen in both data (correlation functions and imaging) and simulations (EPOS, UrQMD)
  - See talks by D. Kincses, E. Árpási, L. Kovács
- Lévy-exponent α extracted from SPS through RHIC to LHC in 1D analyses
  - See talks by B. Pórfy and S. Lökös

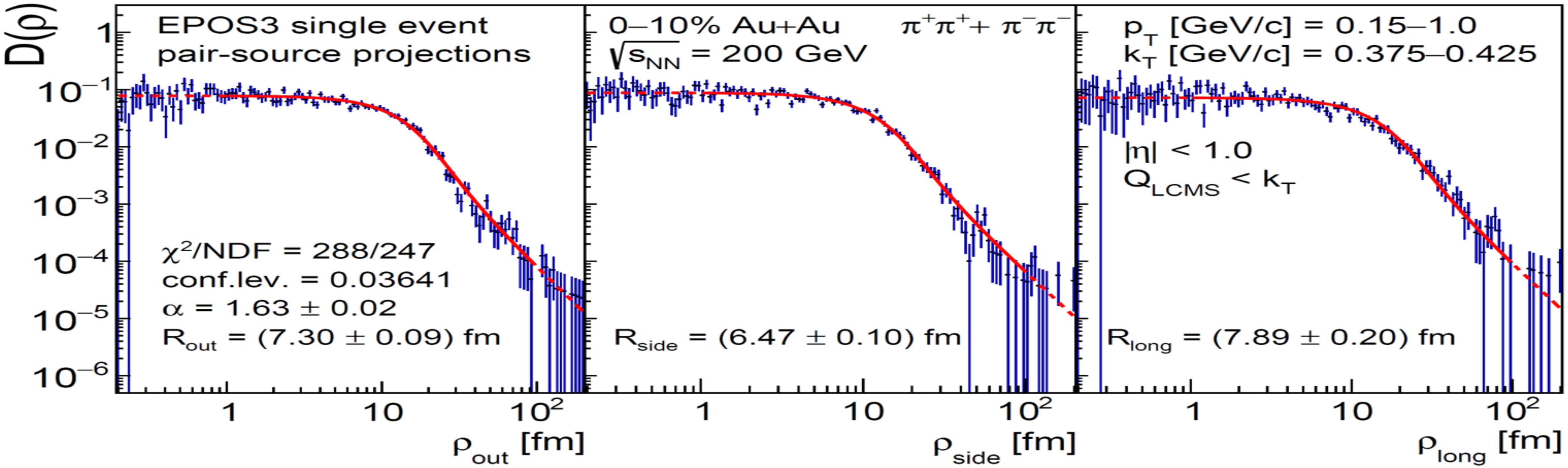
Motivation and interpretation:

- **Possible interpretations of the non-Gaussian, $\alpha < 2$ Lévy exponent:**
  - Jet fragmentation *Csörgő, Hegyi, Novák, Zajc, Acta Phys.Polon. B36*
  - Critical behavior *Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc. 828*
  - Event averaging *Cimerman, Tomasik, Plumberg, Phys.Part.Nucl. 51 (2020) 3, 282*
  - **Resonance decays** *Kórodi, Kincses, Csanád, Phys.Lett.B 847 (2023) 138295*
  - **Hadronic scattering** *Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002 & arXiv:2409.10373*

Hadronic scattering (see talk by D. Kincses)

Important at 200 GeV, EPOS+UrQMD includes these, source function investigated in 3D

arXiv:2409.10373



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- Analysis — Experimental selection criteria detailed, same as previous 1D analysis
- Results
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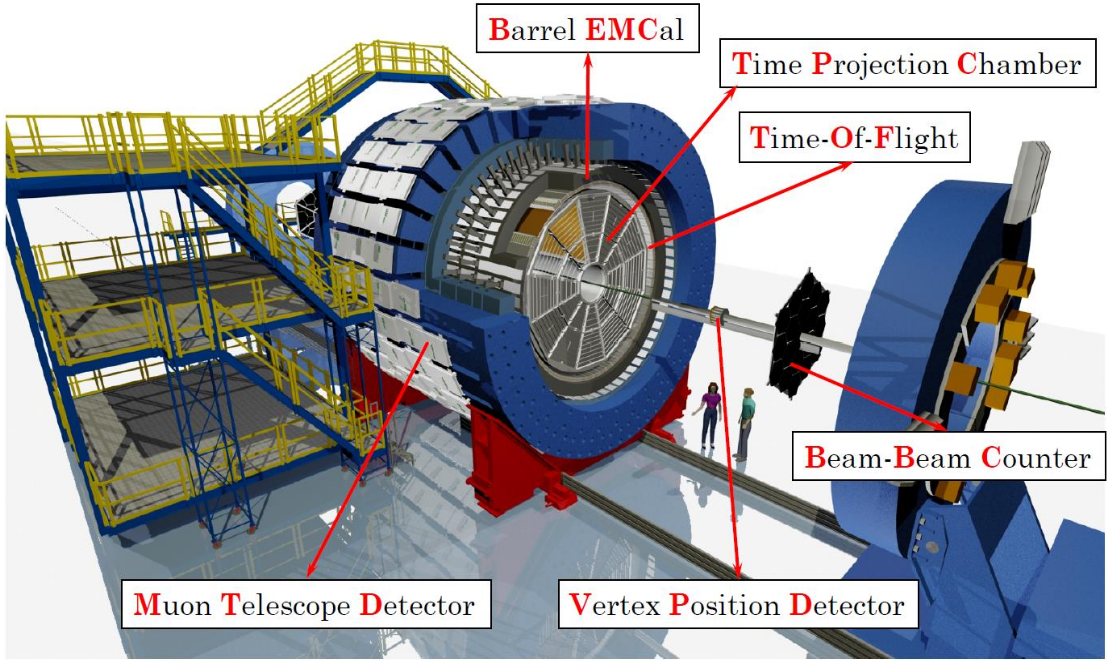
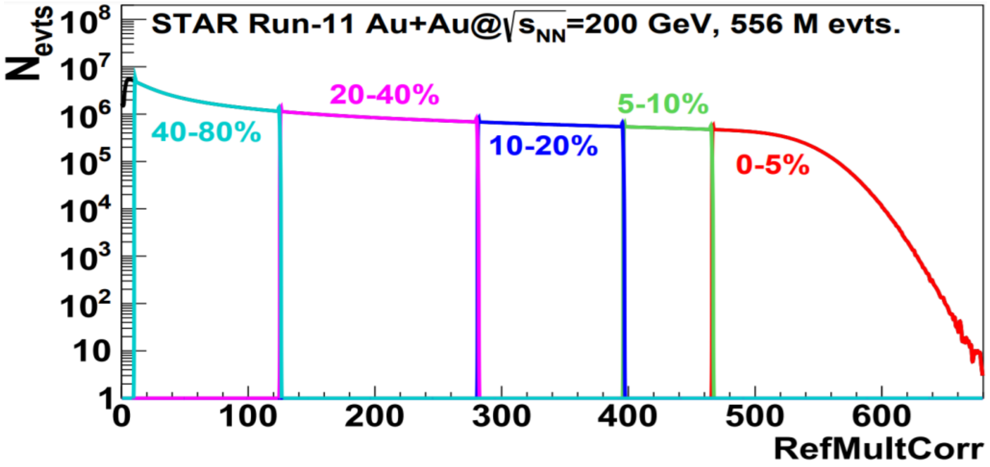
Lévy HBT analysis at STAR, Au+Au @ 200 GeV:

- **STAR Run-11 data analyzed**
  After trigger cuts and bad run cuts: **556M events**
- **Detectors used for the analysis:**
  - **BBC, TPC, VPD**: centrality, vertex position
  - **TPC**: tracking, dE/dx Particle Identification (PID)
  - **TOF**: time-of-flight PID
- **Event selection:**
  - Vertex cuts: $|v_z^{TPC} - v_z^{vpd}| < 3\ cm$; $|v_r^{TPC}| < 2\ cm$; $|v_z^{TPC}| < 25$; $|v_z^{vpd}| < 25$
  - **Pile-up removal using TOF vs. TPC multiplicity**
  - **Centrality selection:** 0-10%





Lévy HBT analysis at STAR, Au+Au @ 200 GeV:

- **Track selection criteria:**
  - Combined PID using TPC $N\sigma$ (based on dE/dx) and TOF $N\sigma$ (based on time-of-flight)

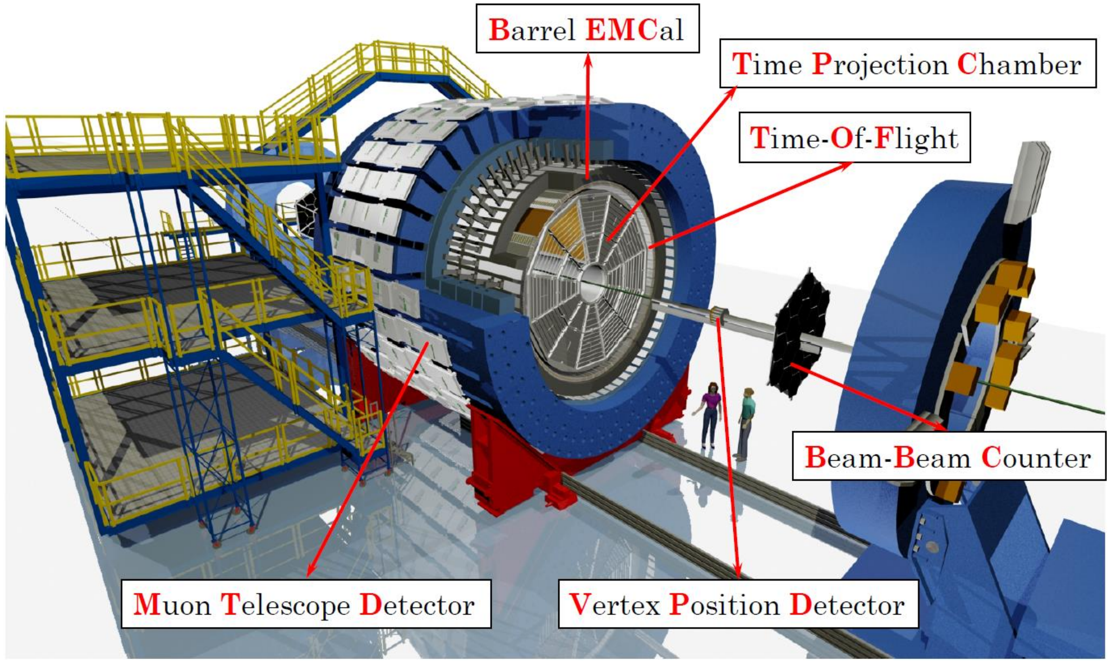
    combined PID: $\sqrt{N\sigma^2_{TOF,\pi} + N\sigma^2_{TPC,\pi}} < 2.5$

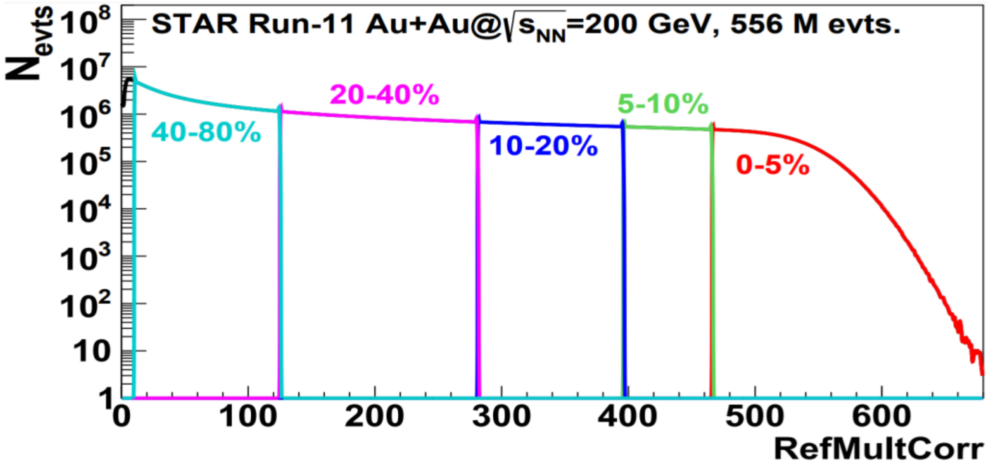
    If no TOF info, TPC PID: $N\sigma_{TPC,\pi} < 2$

    $N\sigma_{TPC,K,p,e} > 2$

  - Momentum selection : $0.15 < p_T$ [GeV/c] < 1.0
  - Rapidity selection : $|\eta| < 0.75$
  - TPC number of hits selection: Nhitsfit > 20
    Nhitsfit/Nhitsposs > 0.55
  - Distance of Closest Approach selection : DCA < 2 cm

- **Pair selection criteria :** J. Adams et al. (STAR Coll.), Phys. Rev. C 71, 044906 (2005)
  - Splitting level (SL) < 0.6
  - Fraction of Merged Hits (FMH) < 5%
  - Average pair-separation (on TPC pad rows) $\Delta r > 3$ cm



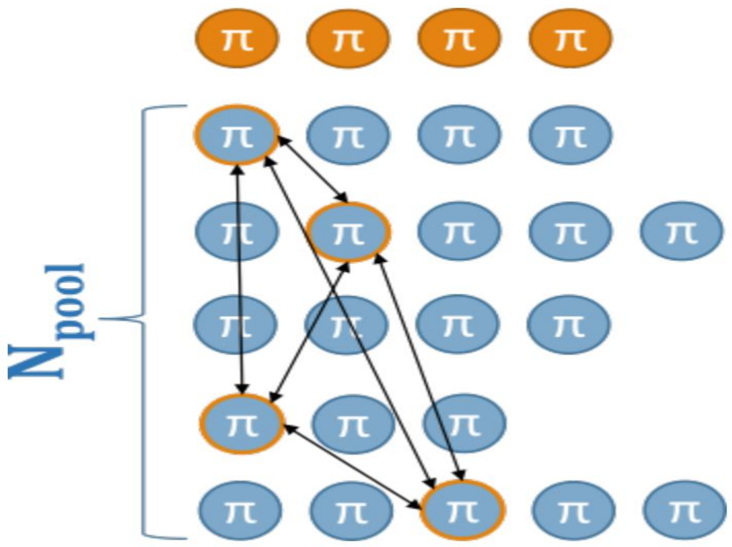


Fitting process:

A(q) - Pairs from same event

B(q) - Pairs from mixed events

C(q) - Correlation function, C(q) = A(q)/B(q)



→ Event mixing with 2 cm wide zvtx

→ Pair average momentum selection:

19 average transverse momentum k_T bins,
from (0.175 - 0.65) GeV/c

3D correlation function

Possible background

Correlation strength

Levy exponent

$$C_2(q_{out}, q_{side}, q_{long}) = N(1 + \varepsilon_o|q_o| + \varepsilon_s|q_s| + \varepsilon_L|q_L|)\left(1 - \lambda + \lambda \cdot K(q_{inv}, R_{inv}, \alpha) \cdot \left(1 + e^{-|q_i R_{ij}{}^2 q_j|^{\alpha/2}}\right)\right)$$

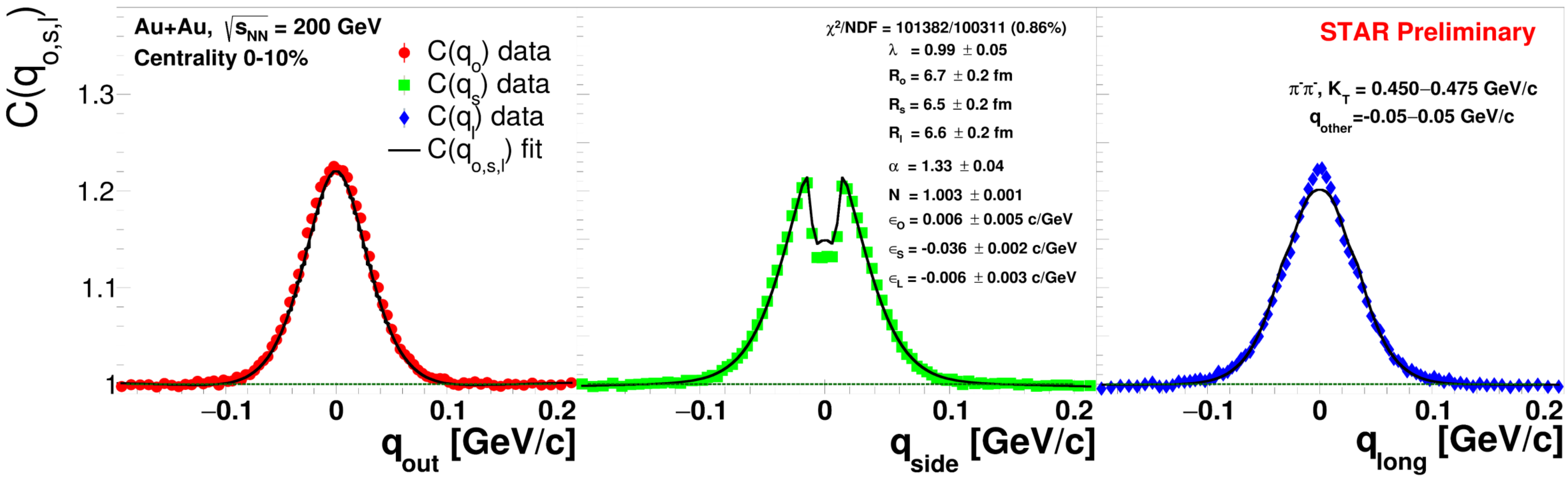
Coulomb correction with
$R_{inv}(R_{out}, R_{side}, R_{long})$

→ Used fitting method, **Coulomb FSI** + **Lévy-source**

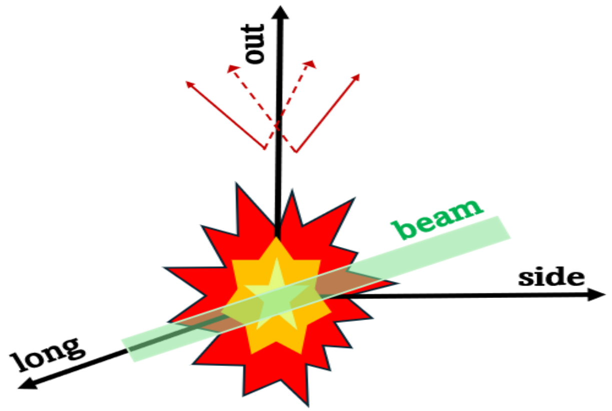
→ $\mathbf{R_{inv}}$ calculated from $\mathbf{R_{out}}$, $\mathbf{R_{side}}$, $\mathbf{R_{long}}$; iterative fitting, all parameters have to converge

→ $\varepsilon_o, \varepsilon_s, \varepsilon_L$: residual non-femtoscopic background; en-mom. conservation, resonance decays, bulk flow, minijets, etc

3D fit projections:



- **3D two-pion corr. functions**
- **Iterative self-consistent fitting method**, Coulomb FSI + Lévy-source
  - Non−femtoscopic background ($\varepsilon_{out}, \varepsilon_{side}, \varepsilon_{long}$): bulk flow, minijets, etc
- Fits converged and have conf.level acceptable in all cases
- Fit range studies included in systematic checks



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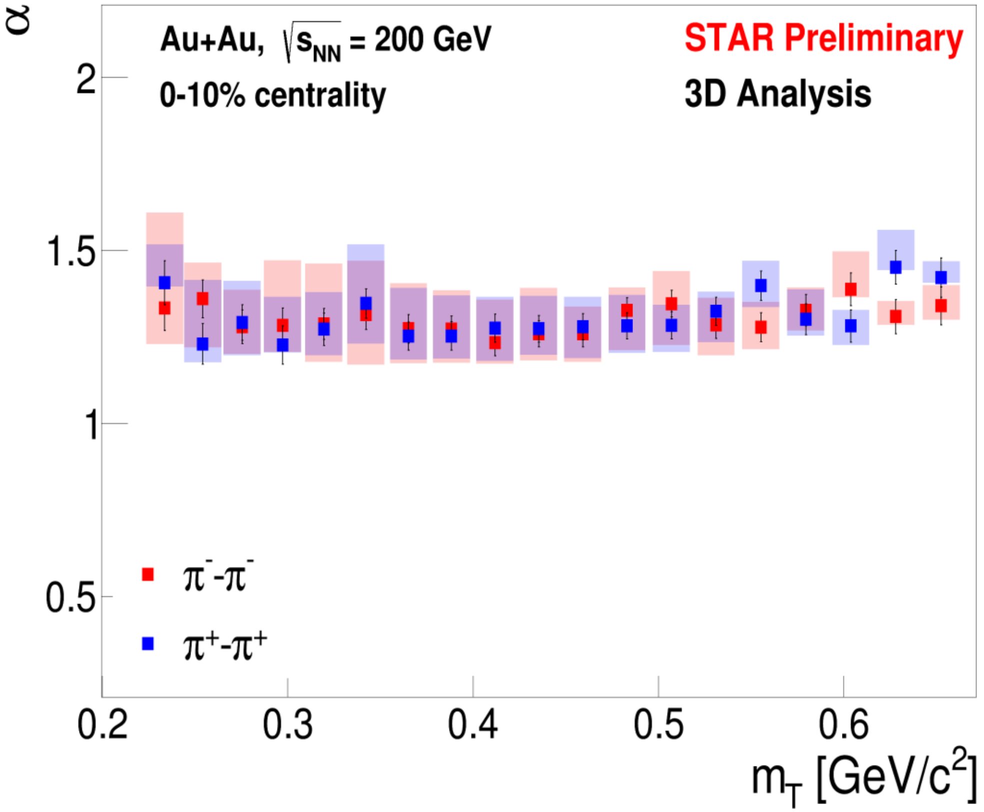
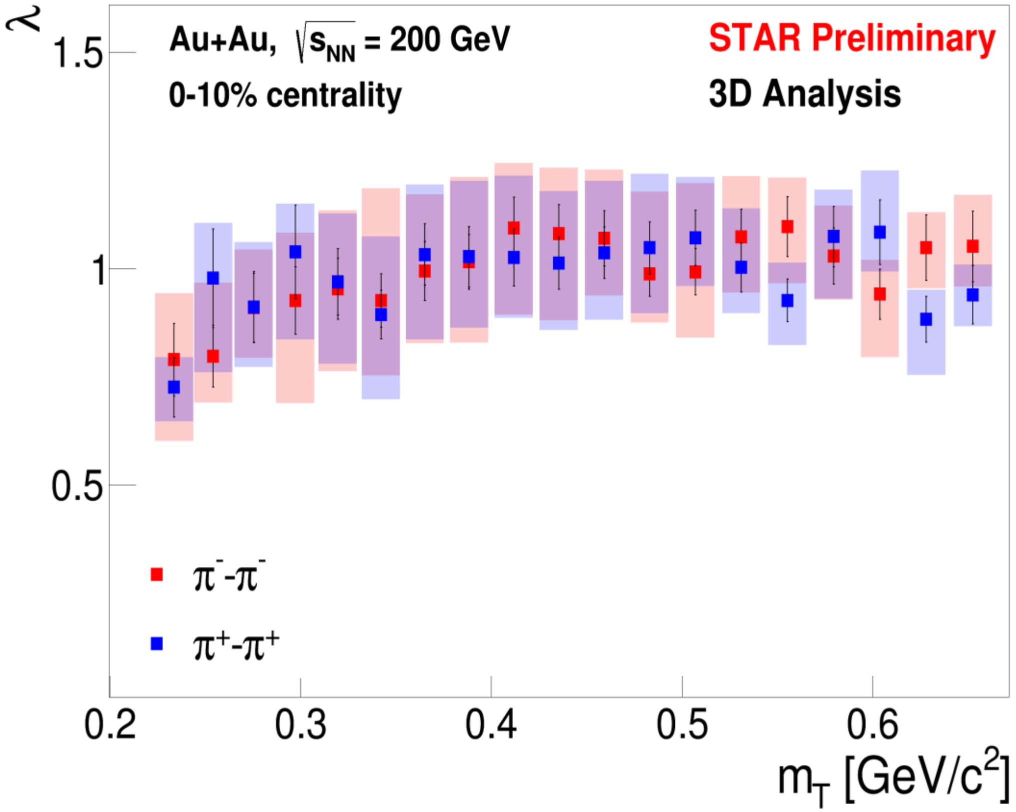
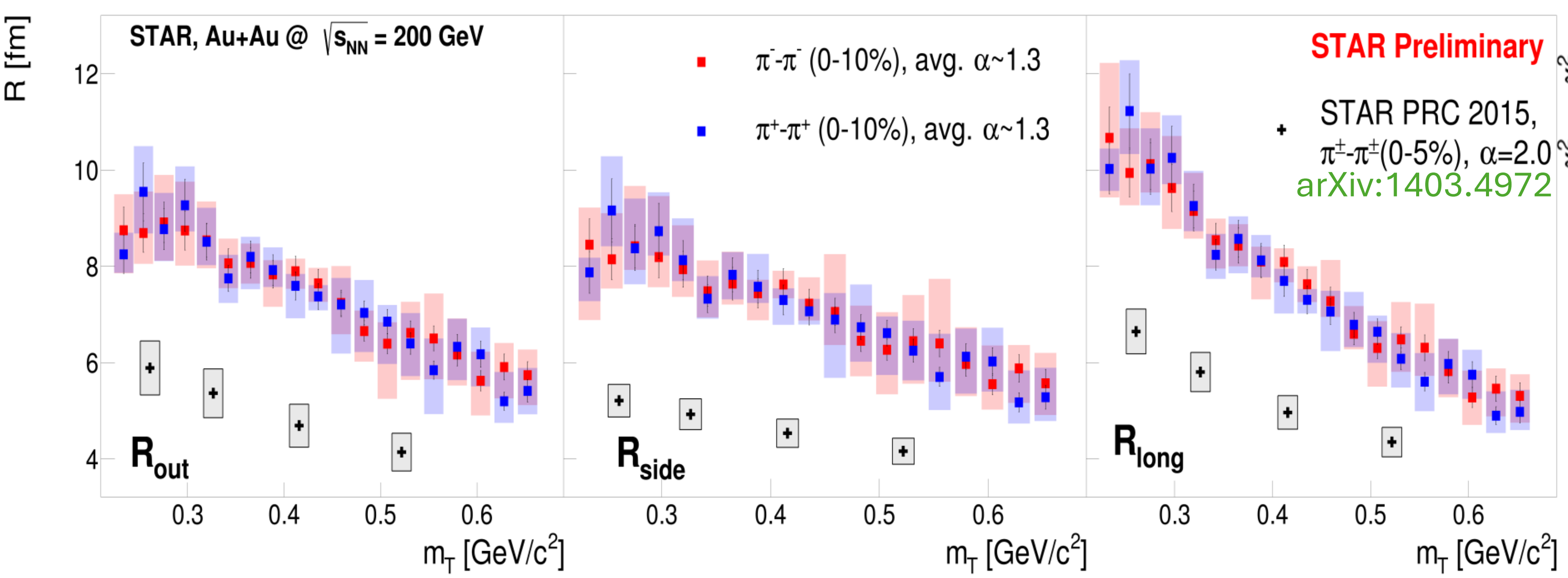
m_T dependence of α and λ:



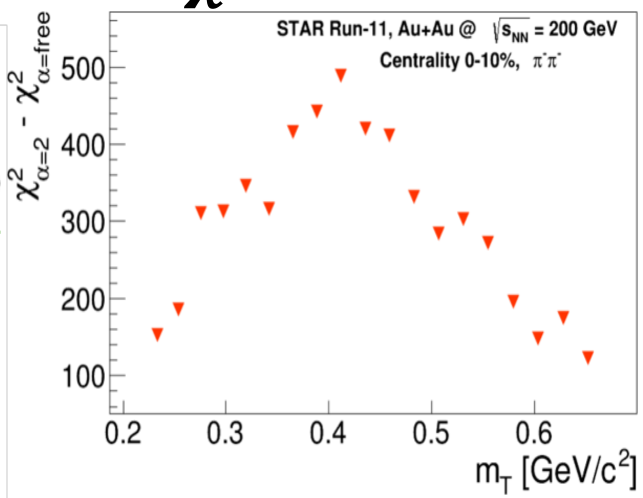


- **Lévy exponent α**: negligible dependence on m_T , average value ~ 1.3; far from critical value (0.5), Cauchy (1.0) and Gauss (2.0).
- **Correlation strength λ:** small increase from low to high m_T.

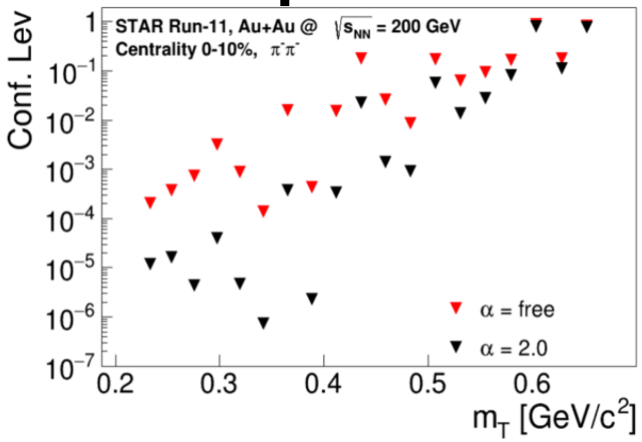
m_T dependence of the source radii:



χ^2 Difference

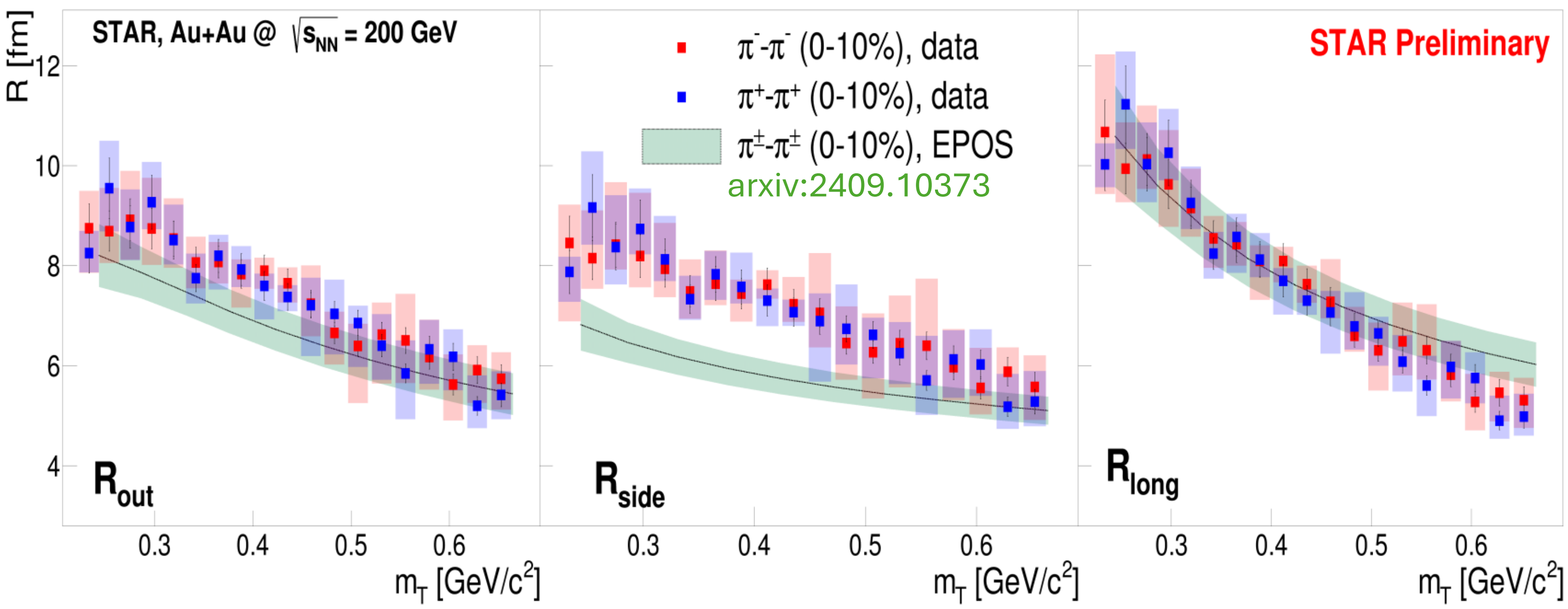


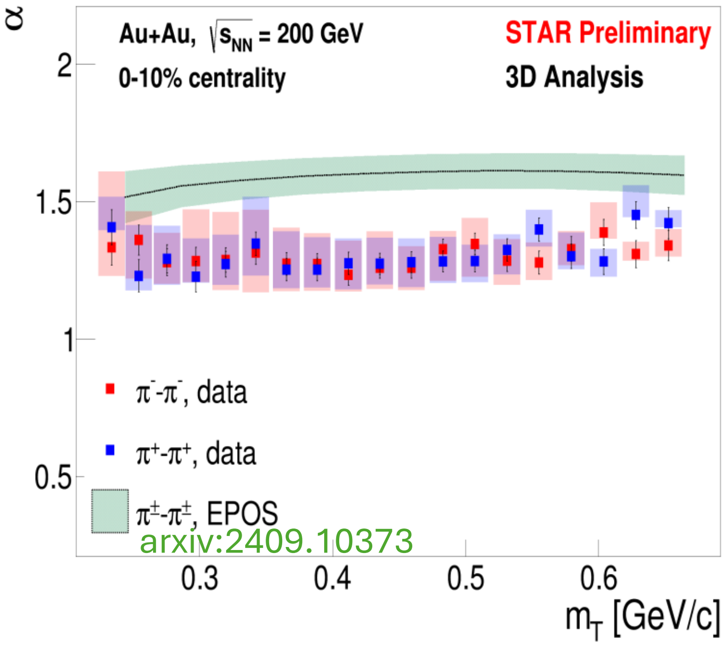
Fit p-values



- **Lévy-scale R:** usual decreasing trend with m_T
- Free $\boldsymbol{\alpha}$ fits reduce $\boldsymbol{\chi^2}$ by 200-500 units compared to Gaussian fits
- χ^2/NDF values within 1-1.04 for all fits
- Confidence levels (p-values) improve by 1-3 orders of magnitude with free $\boldsymbol{\alpha}$

Comparison to EPOS:





- **EPOS and data** (both from 3D analysis) comparison shows good agreement
- Small difference in side direction and in α.

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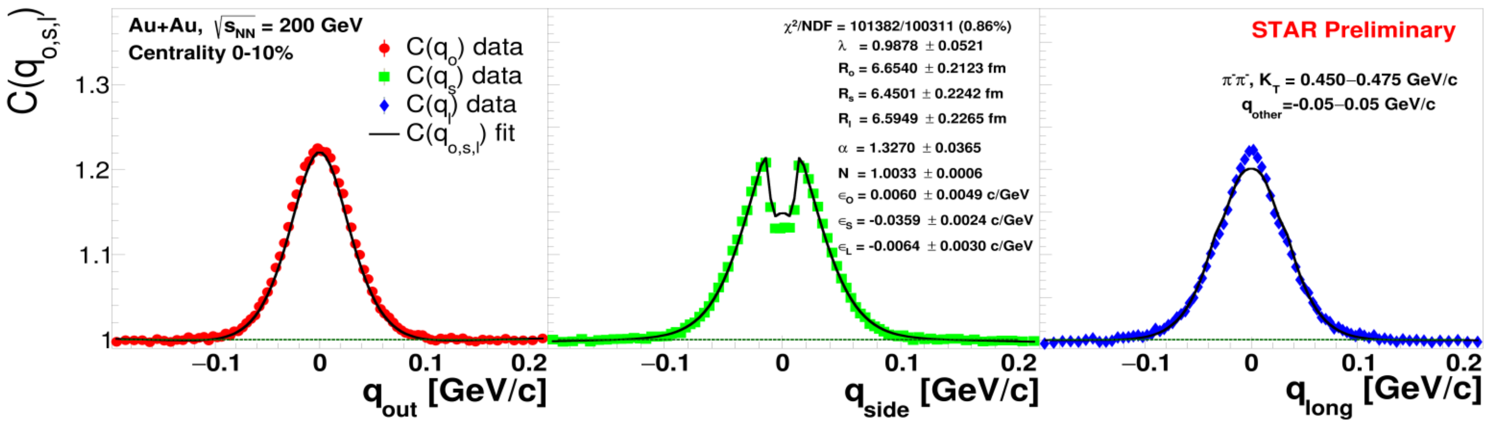
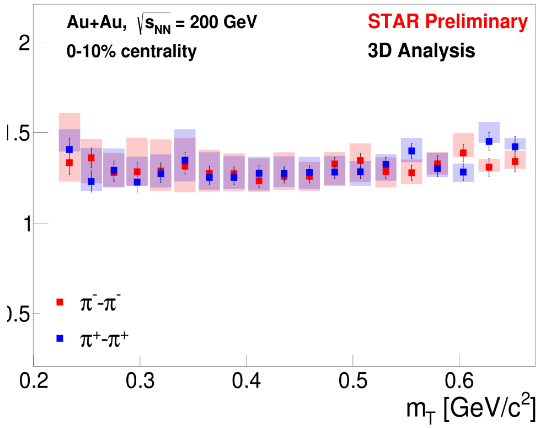
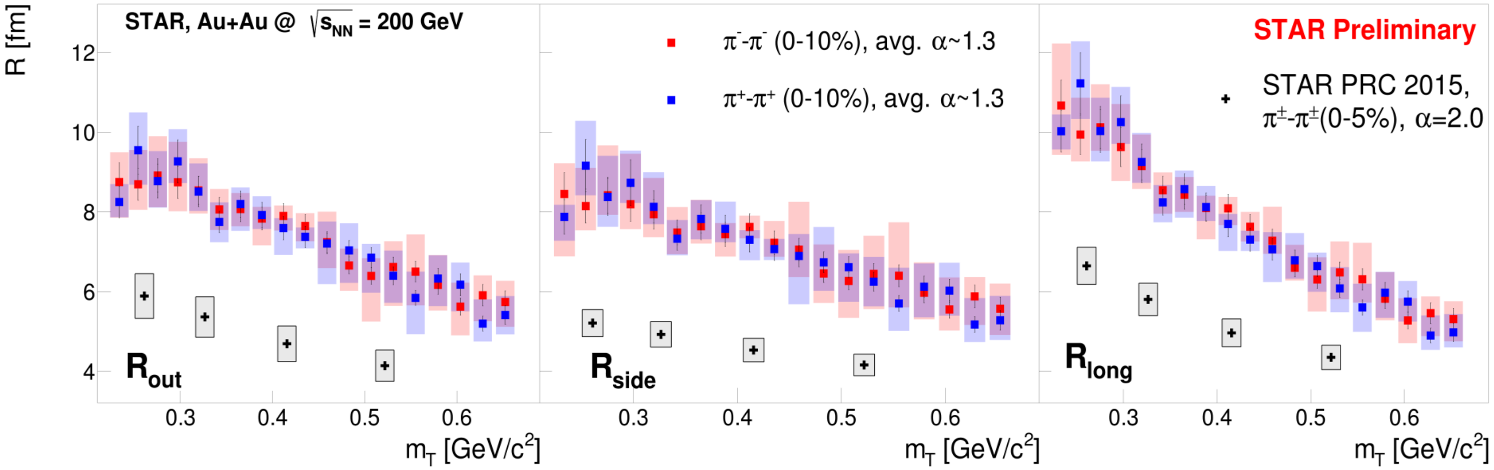
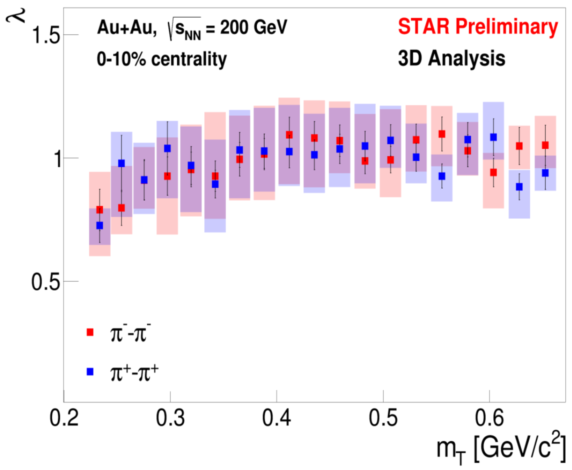
Summary and conclusions:

- Three-dimensional two-pion correlation functions investigated
- Fits with Lévy-source assumption + Coulomb FSI provide good description



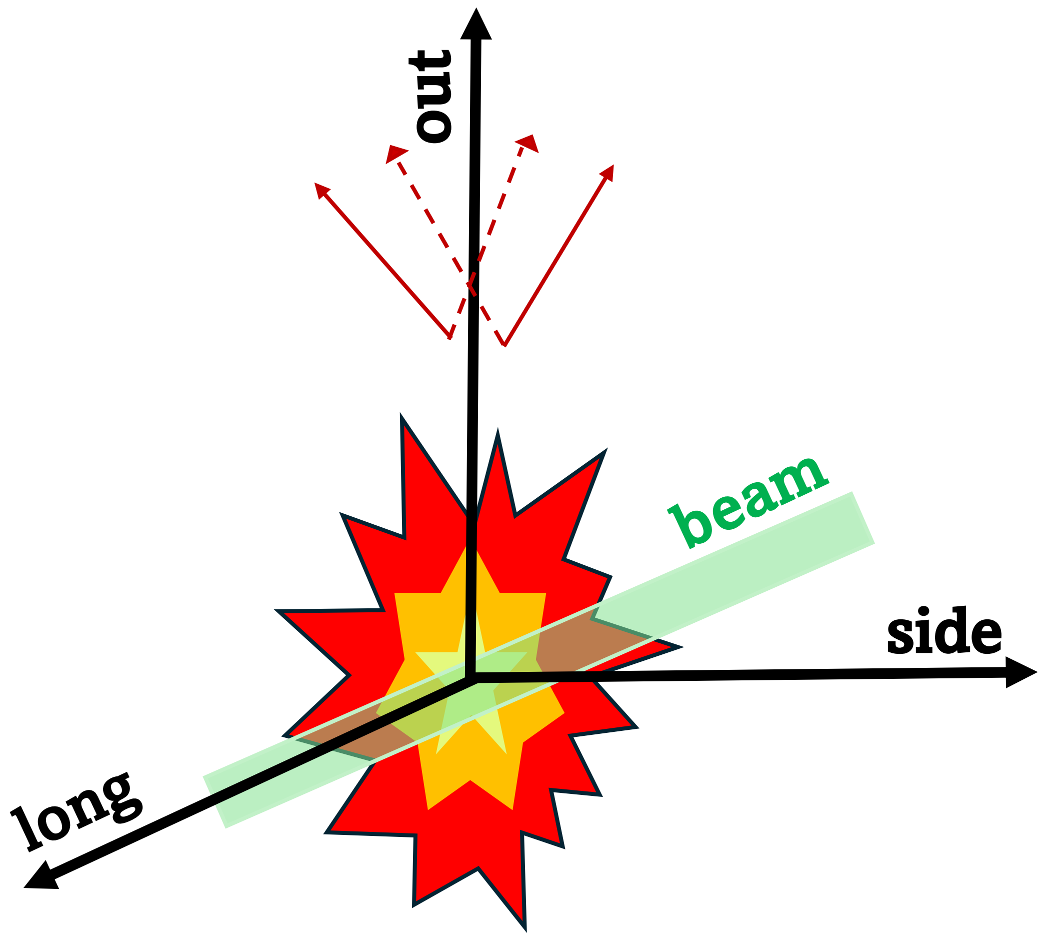




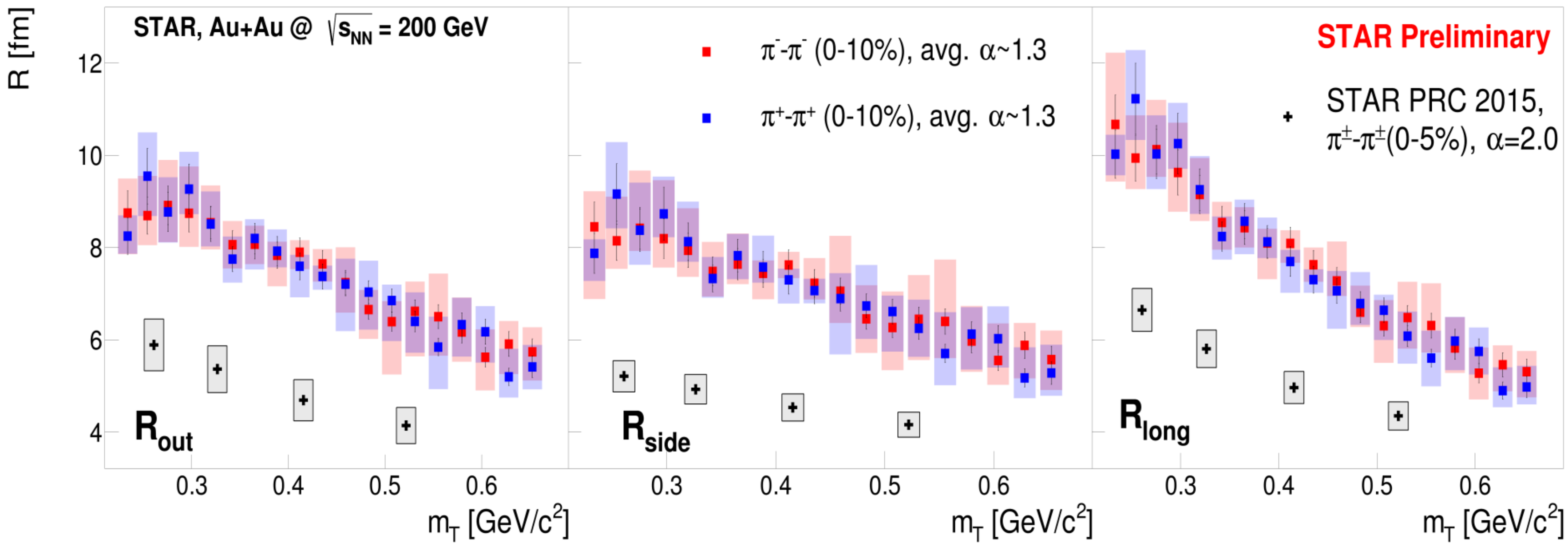


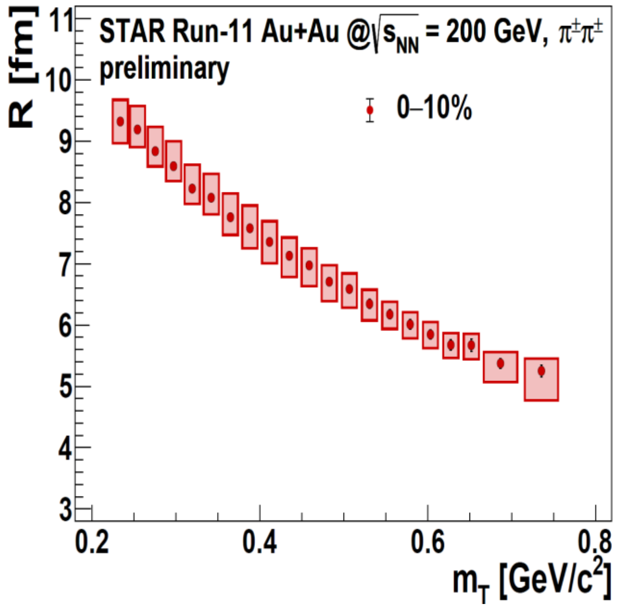

Thank you!

Backup



m_T dependence of the source parameters:





- **Lévy-scale R:** usual decreasing trend with m_T, both 1D and 3D confirms that.
- Free α fits reduce **χ^2** by 200-500 units compared to Gaussian fits.
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m_T dependence of the source parameters:

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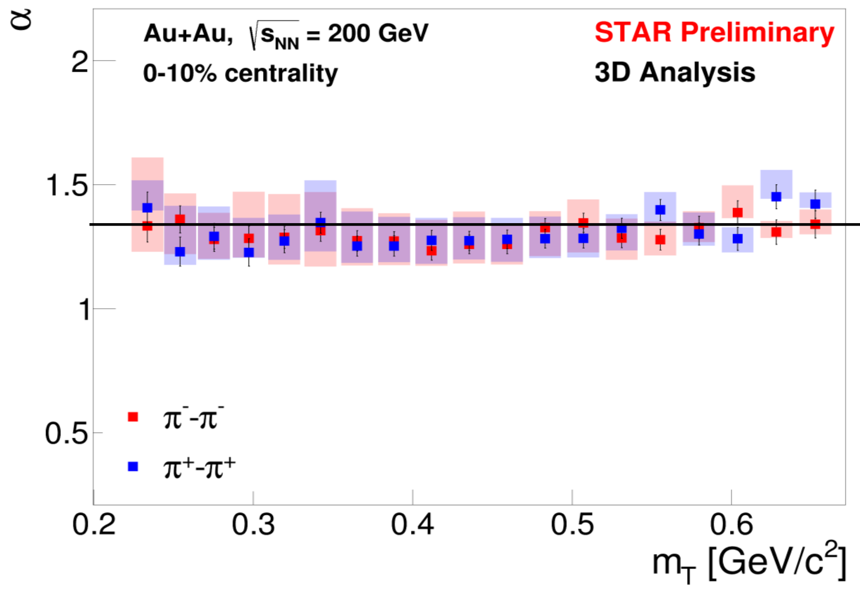
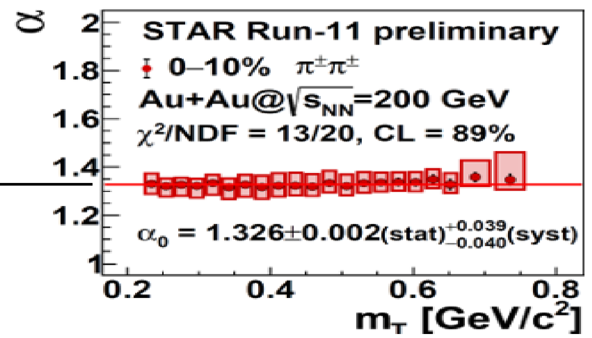
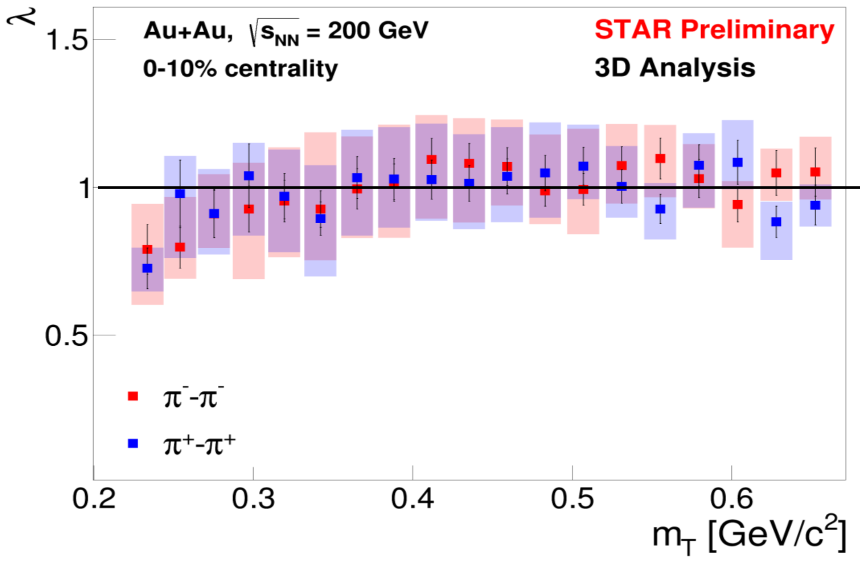
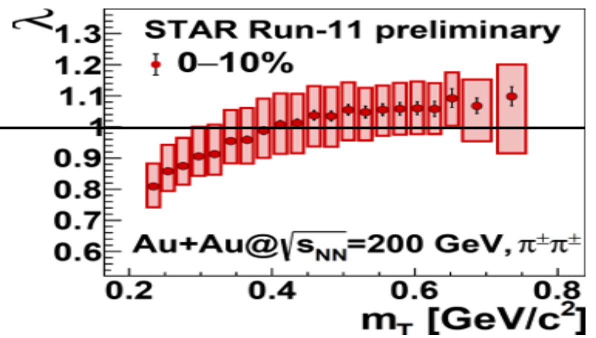
  → far from critical value (0.5), Cauchy (1.0) and Gauss (2.0)





- **Correlation strength $\boldsymbol{\lambda}$:** small increase from low to high m_T.





Coulomb correction:

3D correlation function

Possible background

Correlation strength

Levy exponent

$$C_2(q_{out}, q_{side}, q_{long}) = N(1 + \varepsilon_o|q_o| + \varepsilon_s|q_s| + \varepsilon_L|q_L|)\left(1 - \lambda + \lambda \cdot K(q_{inv}, R_{inv}, \alpha) \cdot \left(1 + e^{-|q_i {R_{ij}}^2 q_j|^{\alpha/2}}\right)\right)$$

Coulomb correction with $R_{inv}(R_{out}, R_{side}, R_{long})$

$$q_{inv} = \sqrt{(1 - {\beta_T}^2) qO^2 + {q_S}^2 + {q_L}^2}$$

$$R_{inv} = \sqrt{\frac{(1 - {\beta_T}^2){R_O}^2 + RS^2 + {R_L}^2}{3}}$$