# Bose-Einstein correlations of charged kaons produced by 200 GeV Au+Au collisions in STAR at RHIC

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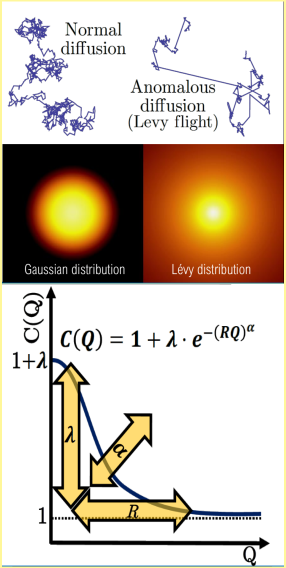
# Outline

# Introduction: Charged-kaon femtoscopy




- Mapping geometry of source → momentum correlations of like-sign kaon-pairs: $C(q) = 1 + \tilde{D}(q)$; $\tilde{D}(q)$: FT of pair-source $D(r)$
- Usually assumed shape for $D(r)$: Gaussian
- Generalization – Lévy distribution: $\mathcal{L}(r; \lambda, R) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-(RQ)^\alpha} e^{iQr} dQ$
- $R$: Lévy-scale, $\lambda$: correlation-strength, $\alpha$: Lévy-exponent, $Q$: integration variable
- $\alpha = 2$: Gauss; $\alpha < 2$: power-law; $\alpha = 1$: Cauchy (or, exponential)
- **Possible reasons for non-Gaussian sources:**
  - Proximity to CEP: irrelevant at 200 GeV
  - Jet fragmentation: not relevant in A+A collisions at any energy
  - Anomalous diffusion: possible in A+A collisions at 200 GeV
    [T. Csörgő, S. Hegyi, T. Novák, W.A. Zajc, AIP Conf.Proc. 828 (2006) 1, 525-532; T. Csörgő, S. Hegyi, T. Novák, W.A. Zajc, Acta Phys.Polon.B 36 (2005) 329-337; M. Csanád, T. Csörgő, M. Nagy, Braz.J.Phys. 37 (2007) 1002-1013]

# Introduction: Anomalous diffusion:- Hadronic re-scattering

- Evidence of non-Gaussian source-distribution for pions found in Au+Au collisions at PHENIX & STAR
- Extracted coordinate-space distributions show heavy tail
- Hydro.-calculations assume idealised freeze-out: sudden jump in mean-free-path from 0 to $\infty$
- **More realistic scenario – hadronic re-scattering:**
  - System cools & dilutes with expanding hadron-gas
  - Mean-free-path gradually diverges to $\infty$, in finite time-interval
  - Re-scattering occurs in time-dependent mean-free-path-system
  - Anomalous diffusion – experimentally observed as power-law-shaped tails in coordinate-space distributions
  - In contrast to Gaussian, strongly-decaying tails observed in normal diffusion (Brownian motion)

# Introduction: Anomalous diffusion:- Lévy-distribution

- **Normal diffusion:**
  - Momentum-space diffusion equation:

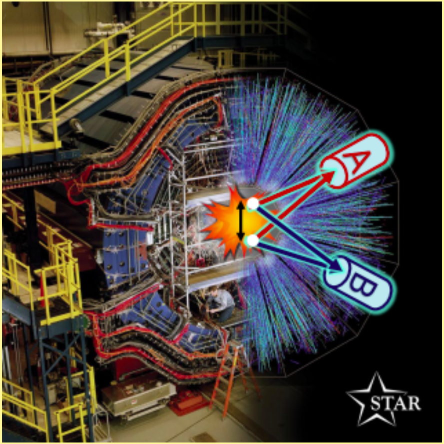
$$\frac{\partial W}{\partial t} = -K_n Q^2 W(Q,t) \ ;$$

    where $K_n$: normal diffusion constant, $Q$: momentum, $t$: time & $W(Q,t)$: momentum-space probability distribution
  - Coordinate-space solution: $W(r,t) = \frac{1}{\sqrt{4\pi K_n t}} e^{-\frac{r^2}{4K_n t}} \rightarrow$ Gaussian
- **Anomalous diffusion:**
  [T. Csörgő, S. Hegyi, T. Novák, W.A. Zajc, AIP Conf.Proc. 828 (2006) 1, 525-532]
  - Coordinate-space diffusion (generalised Fokker-Planck) equation:

$$\frac{\partial W}{\partial t} + v\frac{\partial W}{\partial r} + \frac{F(r)}{m}\frac{\partial W}{\partial v} = \eta_{\alpha' 0} D_t^{1-\alpha'} L_{\mathrm{FP}} W(r,v,t)$$

  - Momentum-space solution: $W(Q,t) = e^{-tK^\alpha |Q|^\alpha}$
    $\rightarrow$ characteristic function (FT) of Lévy-stable source-distributions, with $\alpha$: Lévy-exponent & $K$: anomalous diffusion constant

# Introduction: The STAR experiment at RHIC




- **S**olenoidal **T**racker **A**t **R**HIC
- Colliding $^{238}$U, $^{197}$Au, $^{63}$Cu, $^{96}$Zr, $^{96}$Ru, $^{27}$Al, $^{3}$He, d & p
- Multiple centre-of-mass energies ($\sqrt{s_{\mathrm{NN}}}$) for BES-I & BES-II
- Measurement: RHIC BES (2016) with Au+Au collisions at 200 GeV
- PID: $dE/dx$ for $K^+$, $K^-$

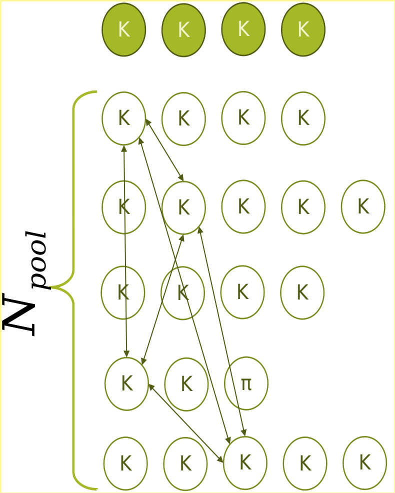
# Methodology: Event & track processing

- **Event processing:**
  - 3.06 billion events from 2016 RHIC beam-energy scan (BES) at 200 GeV in STAR's PicoDST file-storage
  - Trigger cuts (VPD, TPC, etc.) bring no. of events down to 2.59B
  - 0-30% centrality cut further reduces no. of events to 776 million
  - 52.8% of 776M events processed to get particle-tracks for analysis
- **Track processing:**
  - Tracks read in & cut (PID, $N_{\mathrm{Hits}}$, etc.); $A(q)$ obtained
  - Pair cuts (FMH, SL & $\Delta z - \Delta u$) applied
  - Particles from current event stored in pool; events mixed
  - Over-weighting of events avoided $\rightarrow$ only one particle selected from one event; $B(q)$ & $C(q)$ obtained
  - $C(q)$ fit with Coulomb-corrected Lévy-function
  - Fit parameters extracted & plotted with systematic uncertainties.

# Methodology: Summary of analysis cuts

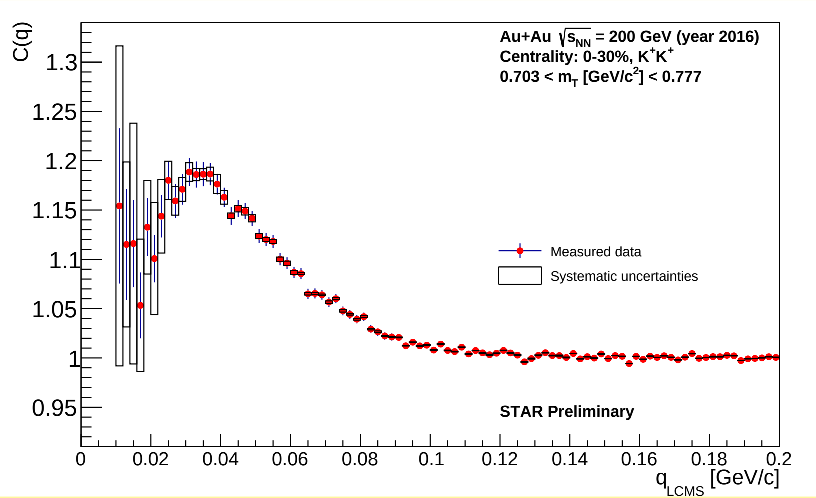
- **Event cuts:**
  - Trigger cuts
  - Vertex cuts
  - TOF-multiplicity vs. reference-multiplicity cuts
  - Centrality cut
- **Single-track cuts:**
  - PID cut
  - $N_{\mathrm{Hits}}$ cut
  - $p_{\mathrm{T}}$ cut
  - DCA cut
- **Pair cuts:**
  - Splitting-level cut
  - Fraction-of-merged-hits cut
  - $\Delta z - \Delta u$ cuts

# Methodology: Measurement details




- Momentum ($q$) measured in **L**ongitudinally **C**o-**M**oving **S**ystem: $q_{\mathrm{LCMS}} = |\vec{p}_1 - \vec{p}_2|_{\mathrm{LCMS}}$
- Spherical symmetry in $q_{\mathrm{LCMS}}$ ideal for 1D analysis of 3D system
- $A(q)$ - kaon pairs from same event
- $B(q)$ - kaon pairs from mixed event
- Mixed event created by randomly selecting kaon-pairs from pool
- Correlation-function: $C(q) = A(q)/B(q)$
- 3 $m_{\mathrm{T}}$ bins used; $m_{\mathrm{T}} = \sqrt{m^2 + (k_{\mathrm{T}}/c)^2}$
- Lévy-type corr. func.: $C(q) = 1 + \lambda \cdot e^{-(Rq)^{\alpha}}$

# Correlation-function: $C(q)$




- Correlation-function shows Bose-Einstein-peak & Coulomb-hole

# Lévy-fitting: Lévy-function & Coulomb-correction

- **Bowler-Sinyukov formula with Coulomb-repulsion:**
  [Y. Sinyukov *et al*; Phys.Lett.B 432 (1998) 248-257]

$$C(q) = \left[1 - \lambda + \lambda \cdot K(q) \cdot \left(1 + e^{-(Rq)^{\alpha}}\right)\right] \cdot N \cdot (1 + \varepsilon q) \ ,$$

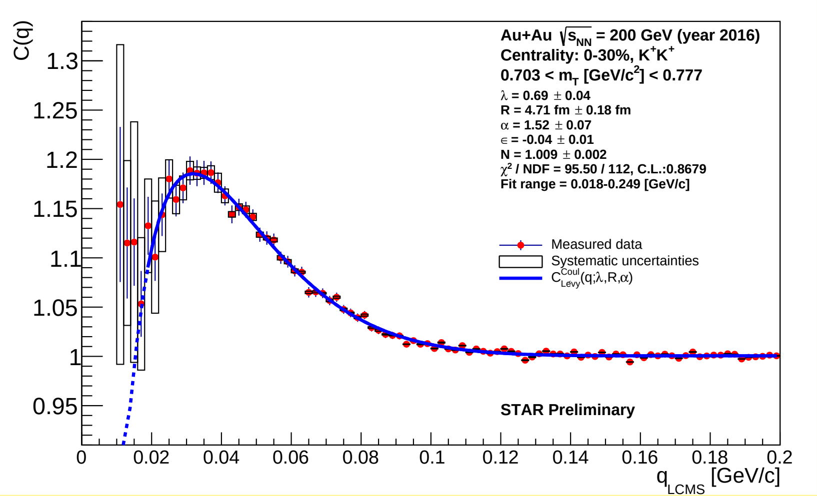
  - $N \cdot (1 + \varepsilon q)$: assumed linear background

- **Coulomb-correction:**
  [M. Csanád, S. Lökös, M. Nagy; Phys.Part.Nucl. 51 (2020) 3, 238-242]

$$K(q; \alpha, R) = \frac{\int D(r) |\psi^{\mathrm{Coul}}(r)|^2 dr}{\int D(r) |\psi^0(r)|^2 dr} \ ,$$

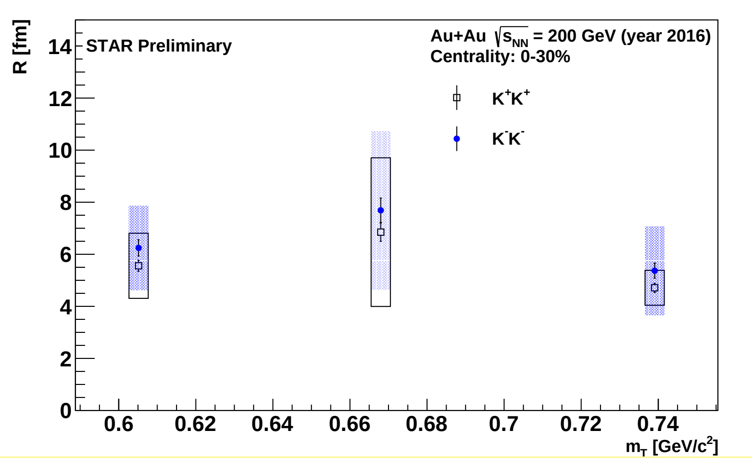
  - $D(r)$: spatial pair-distribution
  - $\psi^0$: 2-particle; plane-wave
  - $\psi^{\mathrm{Coul}}$: Coulomb-wave
  - $K(q; \alpha, R)$ modified for kaons & calculated numerically

# Lévy-fitting: Sample fit



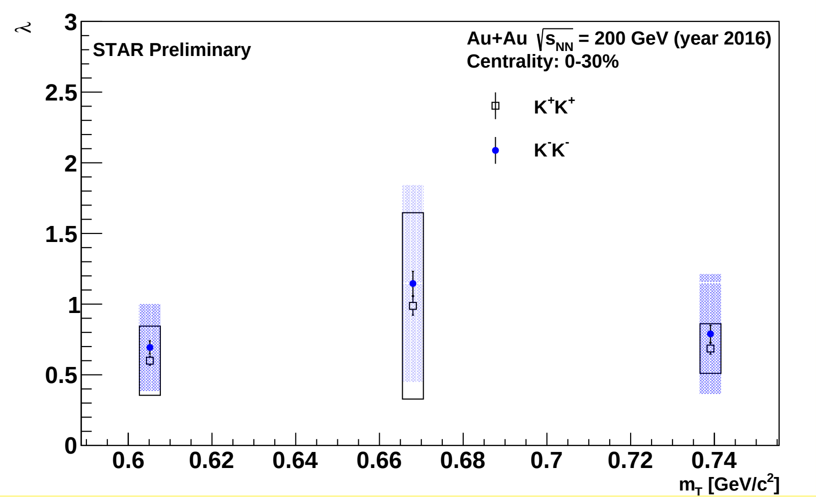

- Measured $C(q)$ agrees quantitatively with best fit over entire q-range
- $N \approx 1$ & $\varepsilon \approx 0$ from fitting → linear contribution negligible

# Fit-parameters: Lévy-scale $R$



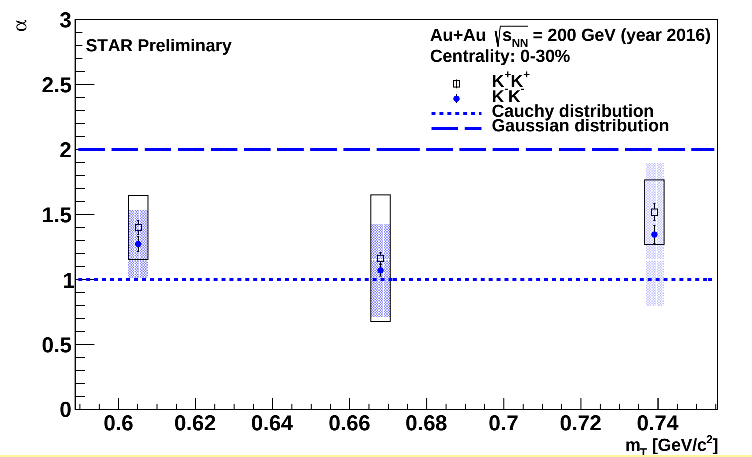

- Kaon-homogeneity length: very weak dependence on $m_{\mathrm{T}}$; large unc.'s
- Possible slight decrease; not contradicting hydro.-predictions
- Similar to PHENIX pion data: $R_\pi(m_{\mathrm{T}}=0.6-0.7\ \mathrm{GeV}/c^2) \approx 5-7$ fm
  [PHENIX Collaboration; Phys.Rev.C 97 (2018) 6, 064911]

# Fit-parameters: Correlation-strength $\lambda$




- Intercept of corr.-func. $\rightarrow$ Core-Halo model: $\lambda = N_{\rm C}/(N_{\rm C} + N_{\rm H})$
  [T. Csörgő, B. Lorstad, J. Zimányi; Z.Phys.C 71 (1996) 491-497]
- Close to unity; in line with expected, small fraction of decay-kaons

# Fit-parameters: Lévy-exponent $\alpha$




- May describe extent of anomalous diffusion
- $\alpha \approx 1.0 - 1.5$ for kaons, similar to PHENIX pion results: $\alpha_\pi \approx 1.2$
  [PHENIX Collaboration; Phys.Rev.C 97 (2018) 6, 064911]
- Suggesting non-Gaussian source for charged kaons, similar to pions

# Summary

## Conclusions

- Preliminary analysis suggests a non-Gaussian source-shape for pairs of charged kaons produced in heavy-ion collisions.
- Lévy-stability-exponent $\alpha$ is comparable to that of pions.
- Anomalous diffusion not solely responsible for the heavy tails, since $\alpha_K \approx \alpha_\pi$; $\alpha_K \nless \alpha_\pi$.
- A full systematic-uncertainty-analysis is required to achieve definitive conclusions about source-geometry.
- Similar measurements at lower centre-of-mass energies would be interesting as probes for CEP.

# NTN XVIII

**Thank you for your attention!**