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Identical Pion Interferometry from Au+Au Collisions at $\sqrt{s_{\mathrm{NN}}}$ = 3.2, 3.5, 3.9 GeV in the STAR Experiment at RHIC

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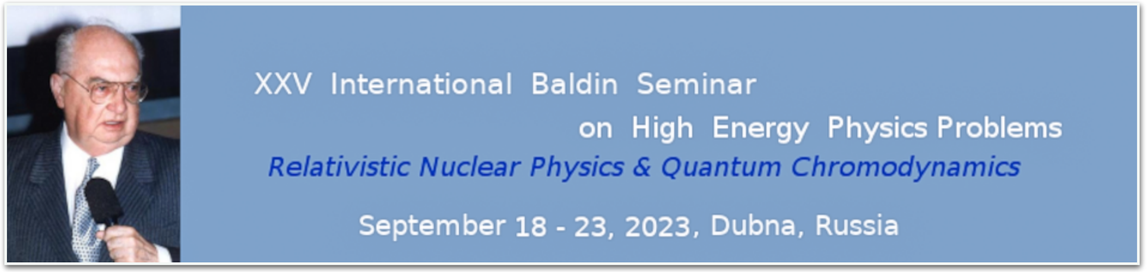
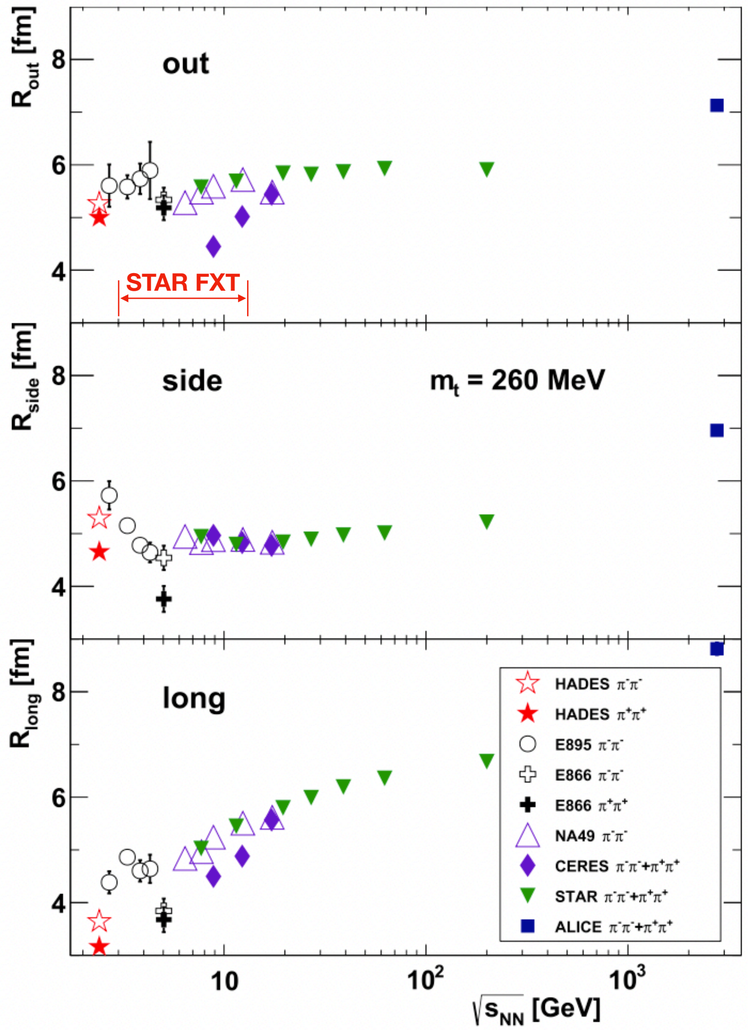


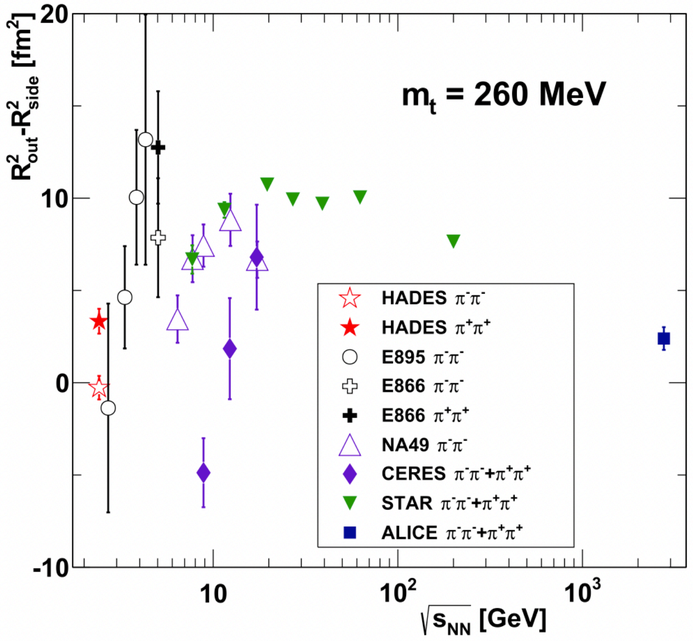
Outline

- The STAR experiment and the Fixed-Target (FXT) Program at RHIC
- Correlation femtoscopy
- Extracted femtoscopic parameters from pion correlation functions in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 3.2, 3.5, 3.9 GeV:
  - Pair transverse momentum (k_{T}) dependence
  - Collision energy dependence
  - Pair rapidity (y_{pair}) dependence

Motivation

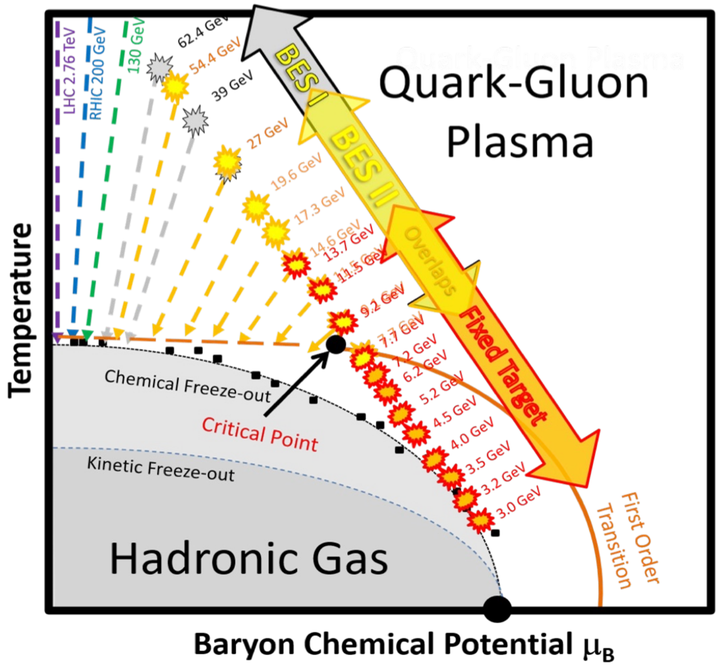
HADES, PLB **795**, 446 (2019)

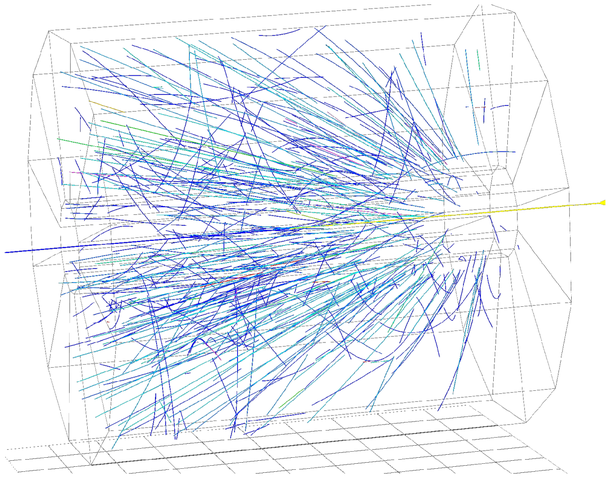


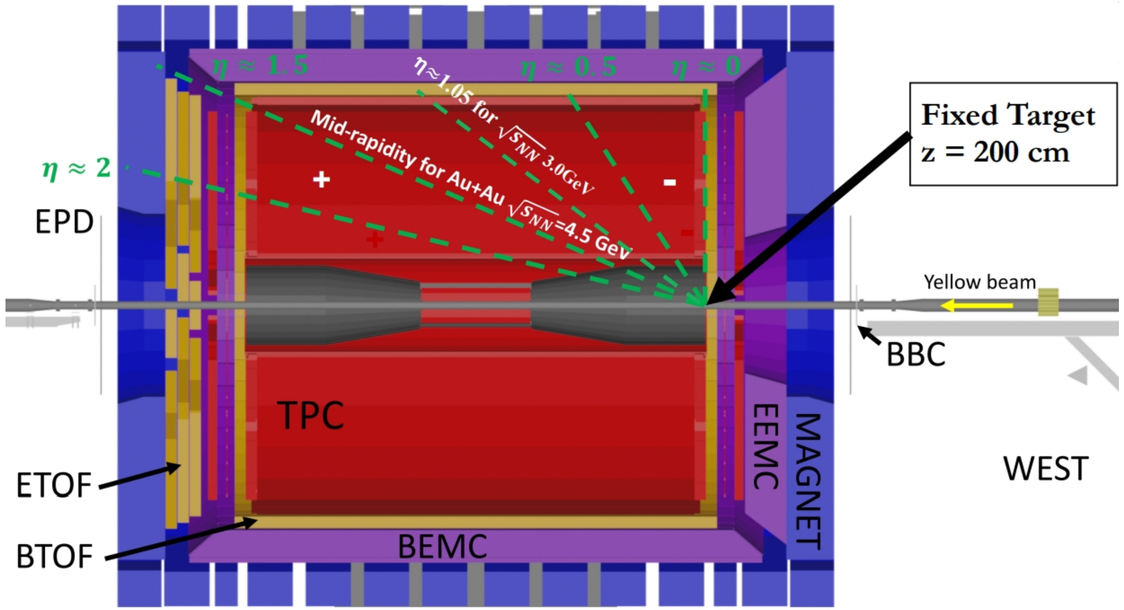


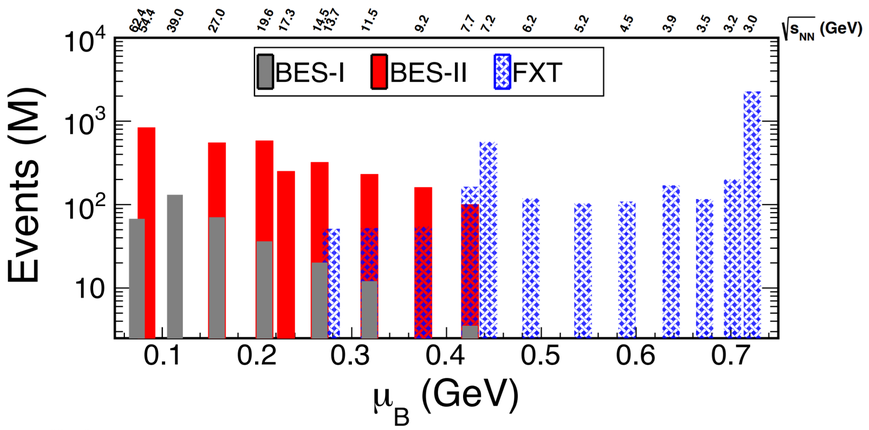
- The correlation femtoscopy is a useful tool to study the spatial and temporal charateristics of systems of femtometer scale
- $R^2_{\mathrm{out}} - R^2_{\mathrm{side}}$ sensitive to emission duration has a peculiar energy dependence
- Large uncertainties of existing measurements in the high net-baryon density region

The STAR detector & Fixed-Target Program



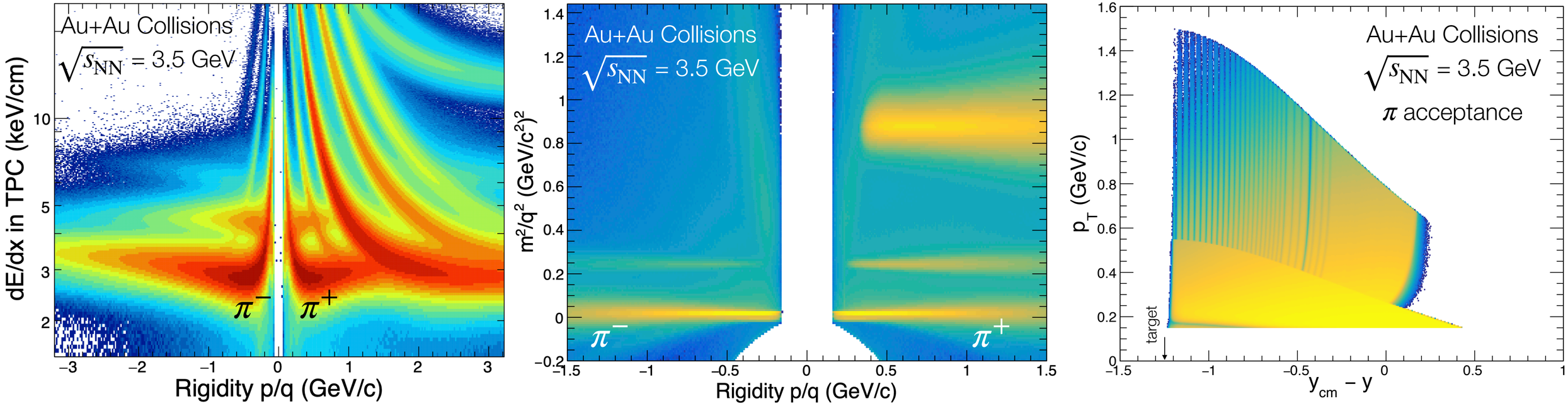






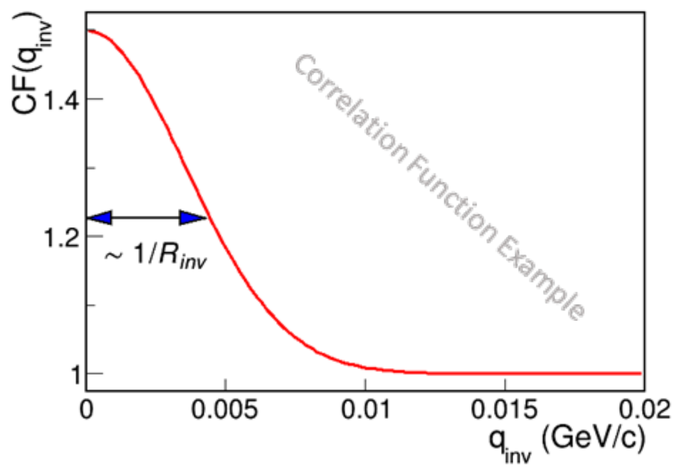
- Gold target was installed on the west end of STAR TPC
- Fixed-target (FXT) program gives access to energies $\sqrt{s_{NN}} < 7.7$ GeV at RHIC

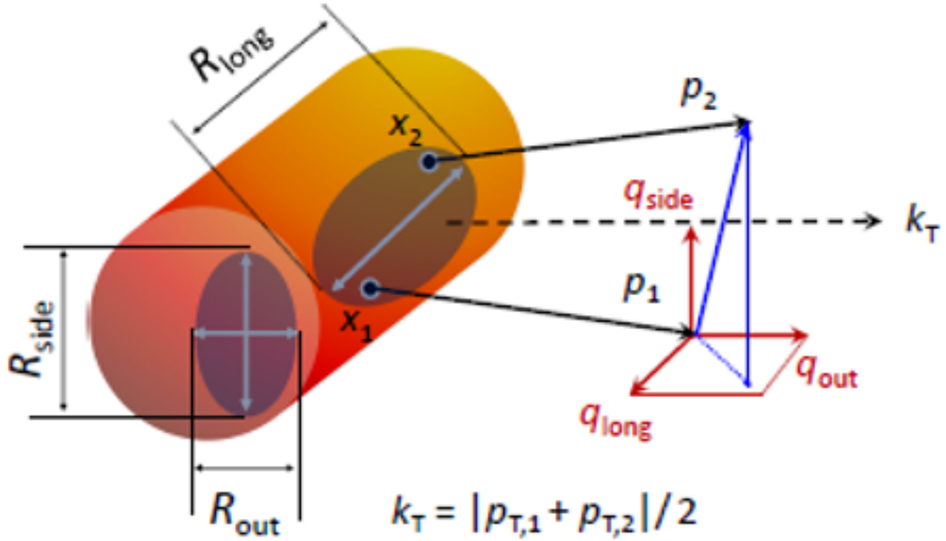
Pion identification



- $0.15 < p < 0.55$ GeV/c: TPC identification
- $0.55 < p < 1.5$ GeV/c: TPC+TOF identification
- Good particle identification capability based on TPC and TOF

Measuring two-particle correlation function





- Experimentally, correlation function: $C(\vec{q}) = A(\vec{q})/B(\vec{q})$
  - Relative momentum $\vec{q} = \vec{p_1} - \vec{p_2}$
  - $A(\vec{q})$ — measured distribution of $\vec{q}$ within the same event, containing quantum statistic correlation and final state interactions
  - $B(\vec{q})$ — background distribution of $\vec{q}$ of two tracks from different events, where physical correlations are absent
- Projection of $\vec{q}$ onto Bertsch-Pratt longitudinal co-moving system (LCMS):
  - $q_{\rm out}$ — along pair transverse momentum ($k_{\rm T}$)
  - $q_{\rm long}$ — along beam direction
  - $q_{\rm side}$ — perpendicular to the other two axes

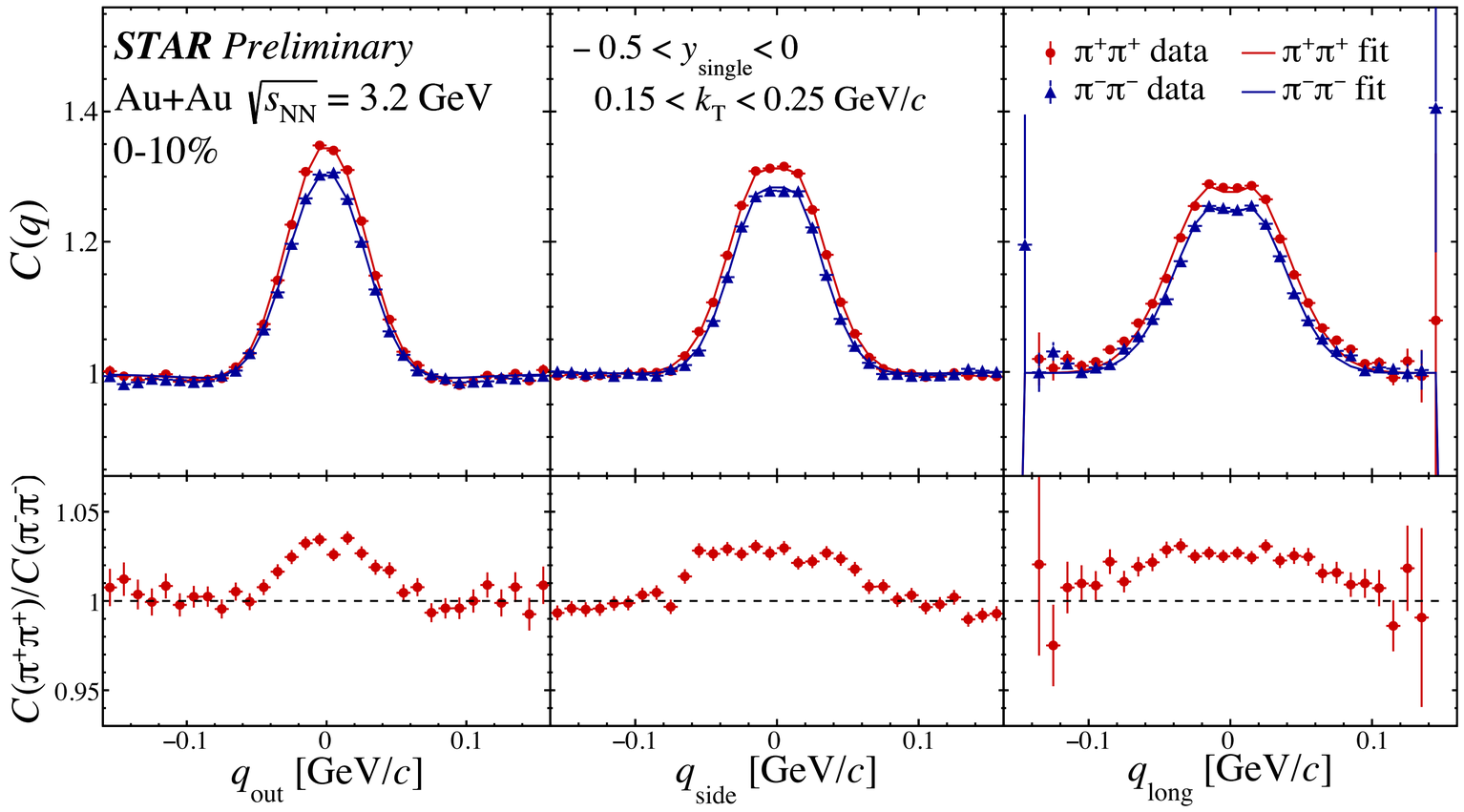
S. Pratt, PRD 33, 1314 (1986)
G. Bertsch, M. Gong, M. Tohyama, PRC 37, 1896 (1988)

Fitting the correlation function

- Bowler—Sinyukov procedure: $C(\vec{q}) = N\left[(1-\lambda) + \lambda K_{\mathrm{Coul}}(q_{\mathrm{inv}})(1+G(\vec{q}))\right]$,
  $G(\vec{q}) = \exp(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - 2 q_o^2 q_l^2 R_{ol}^2)$
  - N — normalization factor, λ — correlation strength factor, K_{Coul} — Coulomb correction
  - $R_{\mathrm{out}} \sim$ geometrical size + emission duration
  - $R_{\mathrm{side}} \sim$ geometrical size
  - $R_{\mathrm{long}} \sim$ source lifetime
  - $R^2_{\mathrm{out-long}} \sim$ tilt of the CF in the $(q_{\mathrm{out}}, q_{\mathrm{long}})$ plane, depending on the degree of asymmetry of the rapidity acceptance w.r.t. midrapidity
  - Fit using Log-likelihood method:
    $$\chi^2 = -2\left[A \ln\left(\frac{C(A+B)}{A(C+1)}\right) + B \ln\left(\frac{A+B}{B(C+1)}\right)\right],\ C = A/B$$

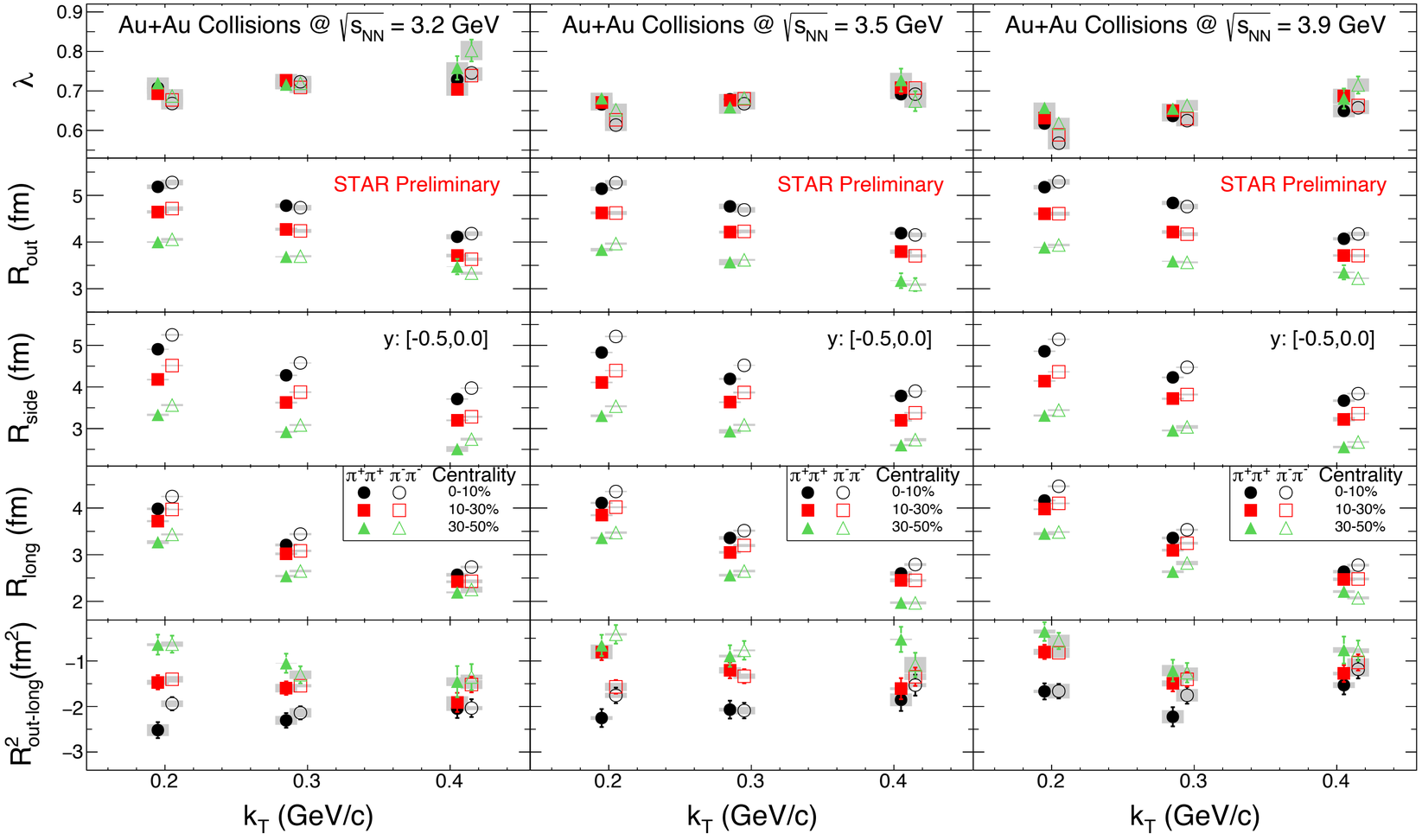
M.G. Bowler, PLB 270, 69 (1991)
Yu.M. Sinyukov, et. al., PLB 432, 248 (1998)
E802, PRC 66, 054906 (2002)

Measured identical pion correlation function



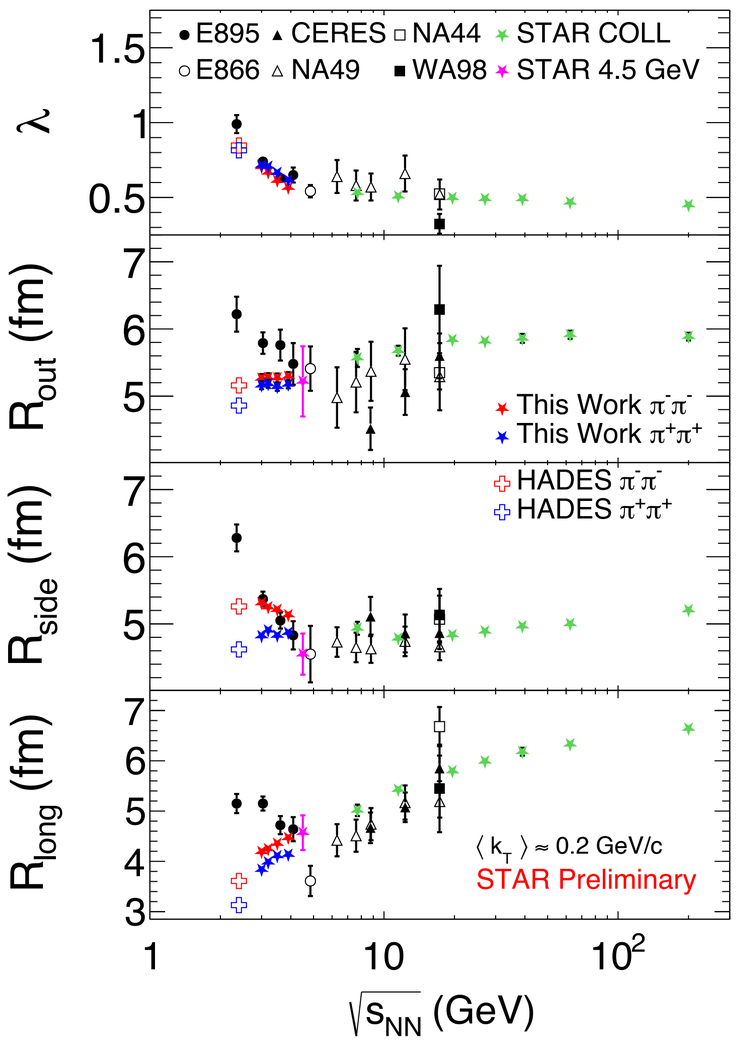
- Slight difference (<5%) between measured correlation functions of positively and negatively charged pions for $0.15 < k_T < 0.25$ GeV/c in 0-10% most central collisions
  - May be attributed to residual electric charge

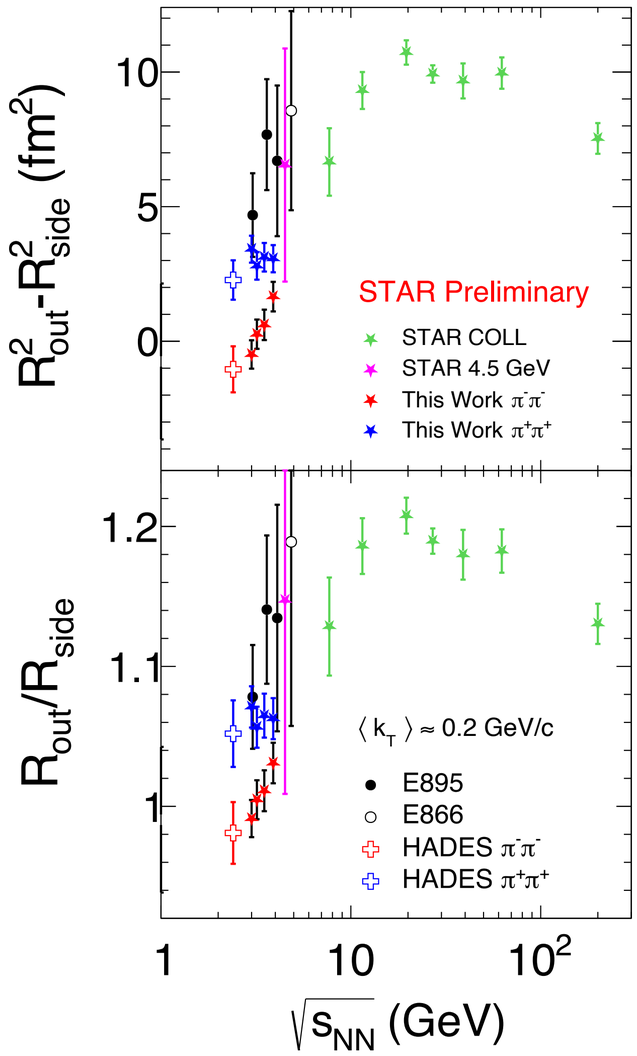
k_{T}-dependence of femtoscopic parameters



- λ increases with increasing k_{T}
- Femtoscopic radii: R_{out}, R_{side}, R_{long}
  - decrease with increasing k_{T} due to transverse flow
  - decrease from central to peripheral collisions due to geometry of overlapping region
- Non-zero $R^2{}_{\text{out-long}}$ due to asymmetric acceptance w.r.t. midrapidity

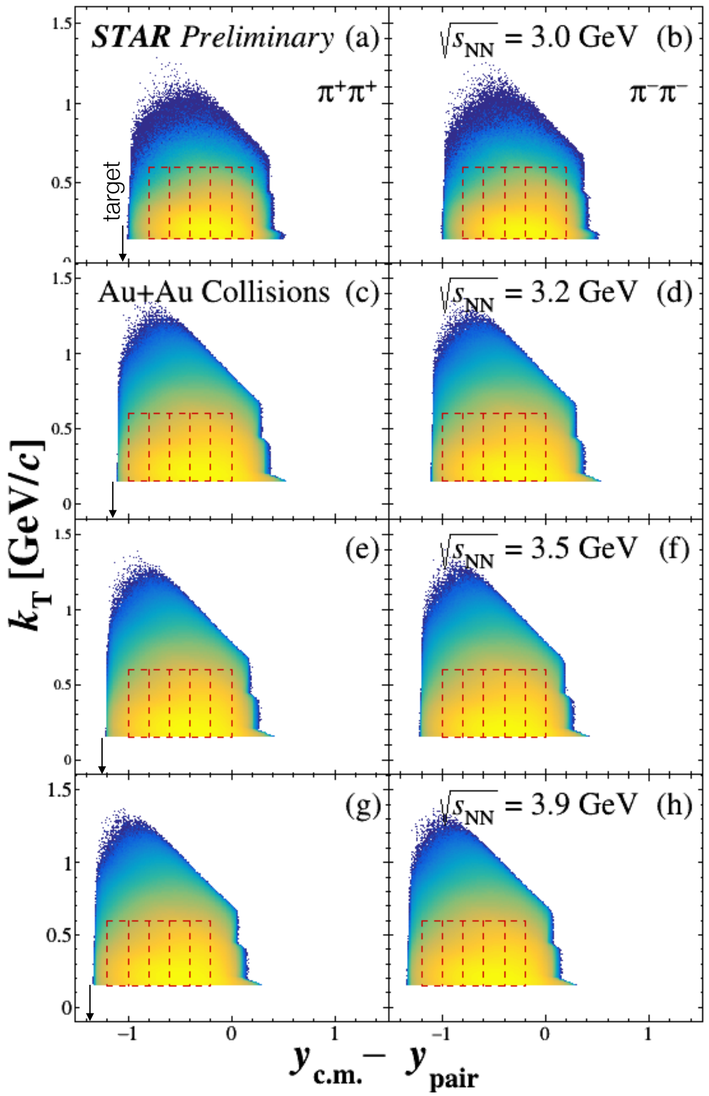
Collision energy dependence of parameters





- Extracted parameters and $R^2_{\mathrm{out}}-R^2_{\mathrm{side}}$, $R_{\mathrm{out}}/R_{\mathrm{side}}$ ratios at $\sqrt{s_{\mathrm{NN}}}$ = 3.0-3.9 GeV follow the trend of HADES and STAR's collider mode results, rather than E895 results

Rapidity differential analysis

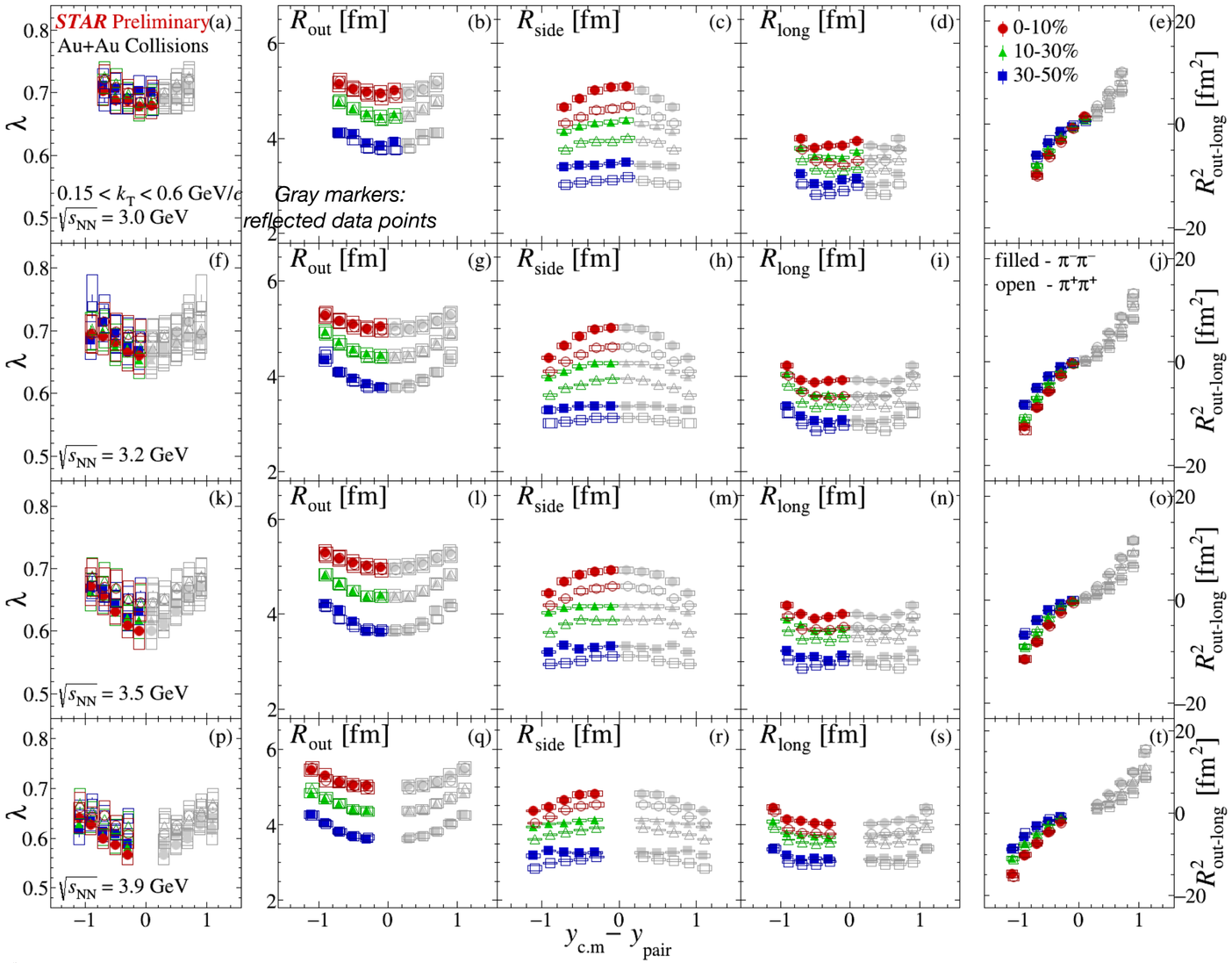


- Pion pair acceptance is divided into 6 windows:
  - Pair transverse momentum k_T: [0.15, 0.6] GeV/*c*
  - Pair rapidity bin width Δy_{pair} = 0.2
- Rapidity coverage in center-of-mass system:

$\sqrt{s_{NN}}$, GeV	3.0	3.2	3.5	3.9
y_{pair} (CMS)	[−0.8, 0.2]	[−1, 0]	[−1, 0]	[−1.2, −0.2]

- Expectations for the pair rapidity dependence at low energies:
  - $R^2_{out-long}(y^{CMS}_{pair})$: sign change w.r.t midrapidity (y^{CMS}_{pair} = 0)
  - $R_{long}(y^{CMS}_{pair})$: parabolic dependence
  - $R_{side}(y^{CMS}_{pair})$: decreases with increasing $|y^{CMS}_{pair}|$ → boost-invariance breaking

Rapidity dependence of femtoscopic parameters



- The difference of R_{side} and R_{long} between positive and negative pion is observed
- R_{side} decreases when moving away from midrapidity
  - Hint on boost-invariance breaking
- $|R^2{}_{\text{out-long}}|$ is larger for larger $|y^{\mathrm{CMS}}_{\mathrm{pair}}|$

Summary

- We reported two-pion femtoscopy measurements in Au+Au collisions for 0-10%, 10-30%, 30-50% centrality classes at $\sqrt{s_{\mathrm{NN}}}$ = 3.2, 3.5, 3.9 GeV
- Difference between CF($\pi^+\pi^+$) and CF($\pi^-\pi^-$) is observed, which may be attributed to residual electric charge
- **k_{T}-dependence:** R_{out}, R_{side}, R_{long} decrease with increasing k_{T} due to transverse flow
- **Centrality dependence:** R_{out}, R_{side}, R_{long} decrease from central to peripheral collisions due to geometry of overlapping region
- **Energy dependence:** extracted femtoscopic parameters and $R^2{}_{\mathrm{out}}-R^2{}_{\mathrm{side}}$, $R_{\mathrm{out}}/R_{\mathrm{side}}$ ratios favour the trend of HADES and STAR's collider results
- **y_{pair}-dependence:** R_{side} decreases when moving away from midrapidity giving a hint on boost-invariance breaking

Back-up

Slides from Richard Lednicky (1)

Longitudinal boost-invariant expansion

Sources (fluid elements) of lifetime τ are produced at t=z=0 in NN CMS, move in longitudinal z-direction uniformly in rapidity η and decay according to thermal law $\exp(-E^*/T)$:

$$t = \tau \cosh(\eta) \quad z = \tau \sinh(\eta) \quad \xrightarrow{\text{LCMS}} \quad t = \tau \cosh(\eta^L) \quad z = \tau \sinh(\eta^L)$$
$$E = m_t \cosh(y) \quad p_z = m_t \sinh(y) \qquad\qquad E = m_t \quad p_z = 0$$

$Q \to 0$, so LCMS source rapidity $\boxed{\eta^L \approx \eta - y}$

$$\exp(-E^*/T) = \exp[-m_t \cosh(-\eta^L)/T] \approx \exp(-m_t/T)\, \exp[-\eta^{L2}/2(T/m_t)]$$

& a wide η "plateau" $\Rightarrow$ $\boxed{\langle\eta^L\rangle \approx 0,\ \langle\eta^{L2}\rangle \approx T/m_t}$

LCMS radii:

$$R_z^2 = \langle(z-\langle z\rangle)^2\rangle \equiv \langle z'^2\rangle \quad R_y^2 = \langle y'^2\rangle \quad R_x^2 = \langle(x'-v_t t')^2\rangle \quad R_{xz}^2 = \langle(x'-v_t t')z'\rangle$$

$$R_z^2 = \langle[\tau \sinh(\eta^L)]^2\rangle - \langle\tau \sinh(\eta^L)\rangle^2 \approx \tau_0^2 T/m_t \quad R_{xz}^2 \approx 0$$
$$R_x^2 = \langle x'^2\rangle - 2v_t\langle x't'\rangle + v_t^2\langle t'^2\rangle \quad \langle t'^2\rangle \approx (\Delta\tau)^2(1+T/m_t)$$

$v_t = p_t/m_t$

$\tau_0^2 \equiv \langle\tau^2\rangle = \langle\tau\rangle^2 + (\Delta\tau)^2$

$R_z \to \tau_0$ = evolution time **$R_x \to \Delta\tau$ = emission duration if $\langle x't'\rangle = 0$ & $\langle x'^2\rangle = \langle y'^2\rangle$**

Slides from Richard Lednicky (2)

Transverse expansion

Thermal law $\exp(-E^*/T)$ & gaussian tr. density profile $\exp(-r^2/2r_0^2)$

& linear tr. radial flow rapidity profile $\vec{\rho}(\vec{r}) = \rho_0 \vec{r}/r_0$

LCMS: $x = r\cos\varphi$ (out), $y = r\sin\varphi$ (side), $z = \tau\sinh(\eta^L)$ (long)

LCMS tr. velocity (nonrel. ρ, v^*, η^L): $\vec{v}_t \approx \vec{\rho} + \vec{v}^* + \eta^L\hat{z}$

v^* = velocity (thermal) in SRF, $v^{*2} \approx \eta^{L2} + \rho^2 + v_t^2 - 2\rho v_t\cos\varphi$

$E^* = m_t[\cosh\rho\cosh(\eta^L) - \sinh\rho v_t\, x/r] \approx m_t(1+v^{*2}/2)$

Emiss. f-n $dG(p,x)/d\eta d^2\vec{r} \sim \exp(-E^*/T)\exp(-r^2/2r_0^2)$

$\approx \exp\{-m_t/T - [\eta^{L2} + (\rho_0 r/r_0)^2 - 2v_t(\rho_0 x/r_0)]m_t/2T - r^2/2r_0^2\}$

$$\Rightarrow \boxed{\begin{array}{l} \langle y\rangle = 0 \quad \langle x\rangle = r_0 v_t \rho_0 / [\rho_0^2 + T/m_t] \\ R_y^2 = \langle y'^2\rangle = \langle x'^2\rangle = r_0^2 / [1 + \rho_0^2 m_t/T] \end{array}}$$

$\boxed{x' = x - \langle x\rangle}$

Note: for a box-like profile $(r < R) \rightarrow \langle x'^2\rangle < \langle y'^2\rangle$

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Slides from Richard Lednicky (3)

Lowing energy → narrowing rapidity "plateau"

⇒ NN CMS rapidity (y) dependence of LCMS radii

in NN CMS: const $d\eta$ → $\exp(-\eta^2/2\sigma^2)\, d\eta$

$\langle\eta^{L2}\rangle \approx (T/m_t)$ → $\langle\eta^{L2}\rangle \approx (T/m_t) / [1+T/(m_t\,\sigma^2)] + y^2 / [1+m_t\,\sigma^2/T]^2$

$\langle\eta^{L}\rangle \approx 0$ → $\langle\eta^{L}\rangle \approx -y / [1+m_t\,\sigma^2/T]$

$R_z^2 \approx \tau_0^2(T/m_t)$ → $\tau_0^2\{ (T/m_t) / [1+T/(m_t\,\sigma^2)] + y^2[(\Delta\tau/\tau_0) / (1+m_t\,\sigma^2/T)]^2 \}$

$\langle t'^2\rangle \approx (\Delta\tau)^2[1+ (T/m_t)]$ → $(\Delta\tau)^2[1+ (T/m_t) / [1+T/(m_t\,\sigma^2)] + y^2/[1+m_t\,\sigma^2/T]^2]$

$R_{xz}^2 \approx 0$ → $-v_t\langle\eta^{L}\rangle\{(\Delta\tau)^2[(1+ \langle\eta^{L2}\rangle/2)] + \tau_0^2(T/m_t) / [1+T/(m_t\,\sigma^2)]\}$

With the increasing energy the "plateau" width σ increases, recovering the infinite plateau result: $\langle\eta^{L2}\rangle \approx (T/m_t)$, $\langle\eta^{L}\rangle \approx 0$

Other parameters τ_0, $\Delta\tau$, T, r_0, ρ_0 also increase with energy

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