

Two-Pion Intensity Interferometry in Collisions of Au+Au @ 1.23A GeV with HADES

Robert Greifenhagen for the HADES collaboration

Helmholtz-Zentrum Dresden-Rossendorf, Institute of Radiation Physics

r.greifenhagen@hzdr.de



DRESDEN
concept

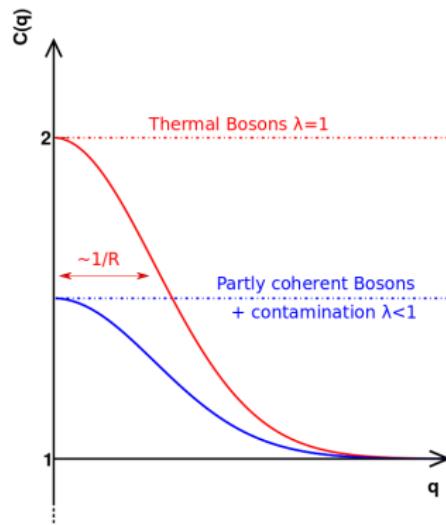


HZDR

 HELMHOLTZ
ZENTRUM DRESDEN
ROSSENDORF

Outline

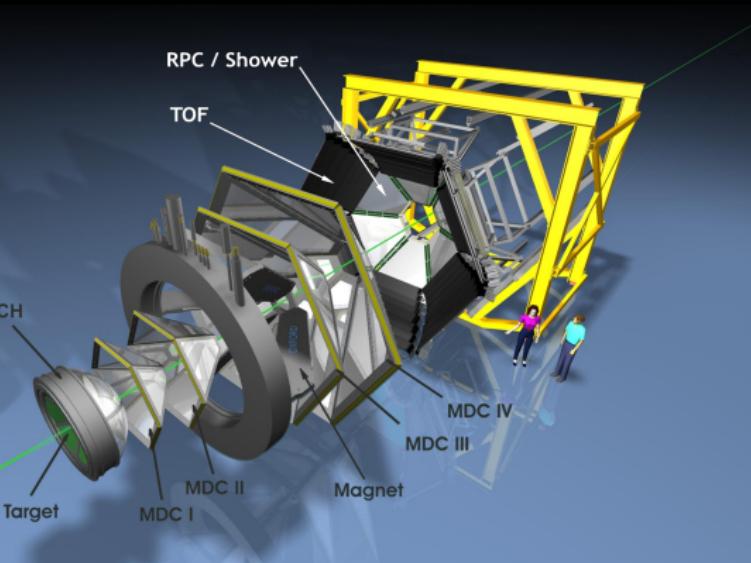
- HADES setup
- Method
 - extraction of source size from Bose-Einstein correlation signal
- Two-pion intensity-interferometry results
 - azimuthally integrated
 - azimuthal dependence
 - comparison with world data



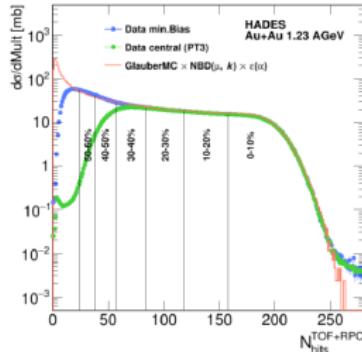
HADES @ SIS18

High Acceptance Di-Electron Spectrometer
at Heavy Ion Synchrotron SIS18 at GSI (Darmstadt, Germany)



- 
- fixed-target experiment,
 $16 < \theta < 88$ degrees
 - Au(1.23A GeV)+Au
 - $\sqrt{s_{NN}} = 2.4$ GeV
 - high performance
 - 557 beam hours with
 $(1.2 - 1.5) \times 10^6$ ions/s
 - trigger rate up to 8 kHz
 - ⇒ 2.1×10^9 events analysed
(0-40%)

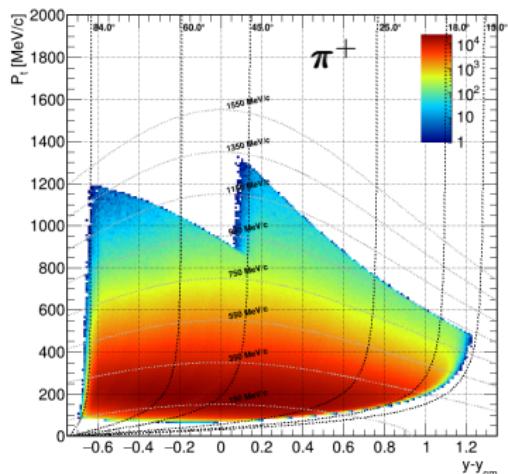
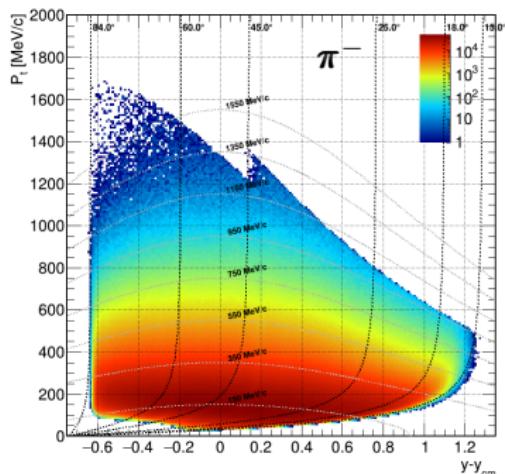
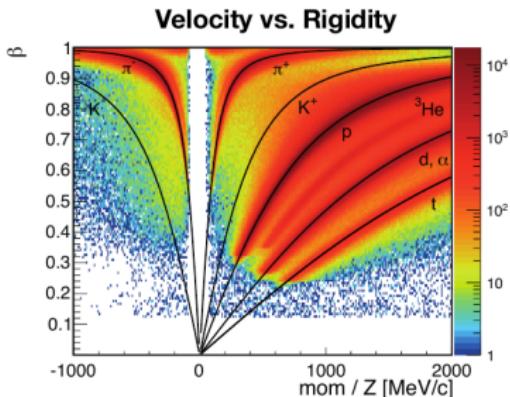
PID, phase space distribution



[EPJ A 54 (2018) 85]

- p/q via Runge-Kutta-procedure in known \vec{B} -field
- $\beta = \frac{s}{tc}$

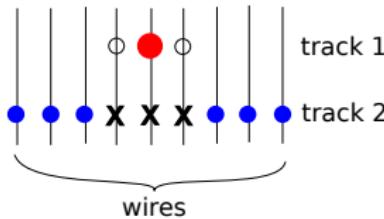
$$(t = t_{\text{TOF/RPC}} - t_{\text{START}})$$



Conditions

Two particle conditions

- binning in centrality + pair transverse momentum $p_{t12} = |\vec{p}_{t,1} + \vec{p}_{t,2}|$
(+ $(\phi - \phi_{EP})$ in azimuth. analysis)
- midrapidity $|y_{12} - y_{cm}| < 0.35$
- data-driven close-track pair cut
 - not same TOF/RPC cell
 - not same MDC wire ± 1

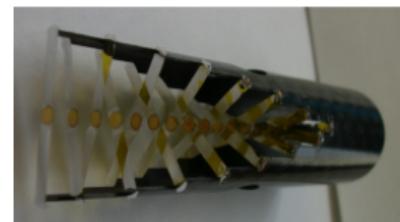


experimental C-function:

$$C(q) = N \frac{\sum Y_{12}(q)}{\sum Y_{12,mix}(q)}$$

Event mixing conditions

- same multiplicity:
 $|\text{mult}_i - \text{mult}_j| < 10$
- same event plane:
 $|\phi_i - \phi_j| < 10^\circ$
- same target slice:
 $|\text{VerZ}_i - \text{VerZ}_j| < 1.2 \text{ mm}$



- all other conditions:
as for true yield!

relative momentum
 $q = (p_1 - p_2)/2$ (!)

norm N : $C(q) \rightarrow 1$ for $q \rightarrow \infty$

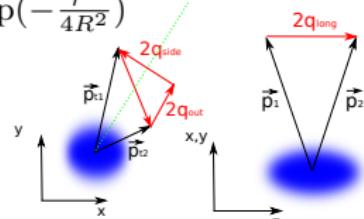
3-dim fit function

- including FSI → Coulomb (strong interaction neglected)

- assuming Gaussian source distribution $S(r) = \frac{\lambda}{(2\sqrt{\pi}R)^3} \exp(-\frac{r^2}{4R^2})$

Bertsch-Pratt parametrisation: $\vec{q} \rightarrow (q_o, q_s, q_l)$

boost into longitudinal co-moving system (LCMS), $p_{1z} = -p_{2z}$



Sinyukov-Bowler formula:

[Phys. Lett. B 432 (1998) 248]

$$C(\vec{q}) = C_0[(1 - \lambda) + \lambda \cdot K_{\text{Coul}}(\hat{q}, R_{\text{inv}}) \cdot \frac{(1 + e^{-\sum_{ij} 4q_i q_j R_{ij}^2})}{\text{Bose-Einstein(BE) part}}]$$

$$R_{ij}^2 = \begin{pmatrix} R_o^2 & R_{os}^2 & R_{ol}^2 \\ R_{os}^2 & R_s^2 & R_{sl}^2 \\ R_{ol}^2 & R_{sl}^2 & R_l^2 \end{pmatrix} \quad \Rightarrow 3 \text{ diagonal} + 3 \text{ nondiagonal geometrical variances}$$

$\lambda < 1 \rightarrow \text{incoherence} + \text{contamination}$

R_{inv} from 1-dim fit

$$\hat{q} = \langle q_{\text{inv}} \rangle(q_o, q_s, q_l, \hat{p}_{t12})$$

Gaussian momentum resolution correction → R increases by $\sim 2\%$

ϕ -dependent analysis

Fit formulas

$$(\beta_1 = 0)$$

[PLB 496 (2000) 1, PRC 57 (1998) 266]:

accounts for explicit ϕ dependence arising from the azimuthal rotation of (os) system relative to RP-fixed (xyz) system

$S_{\mu\nu}$ contains complete 3+1 dim. geom. info of elliptic region of homogeneity

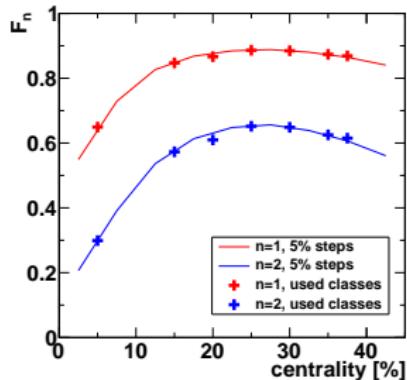
$$\begin{aligned} R_s^2 &= S_{11} \sin^2 \phi + S_{22} \cos^2 \phi - S_{12} \sin 2\phi, \\ R_o^2 &= S_{11} \cos^2 \phi + S_{22} \sin^2 \phi + S_{12} \sin 2\phi \\ &\quad - 2\beta_\perp S_{01} \cos \phi - 2\beta_\perp S_{02} \sin \phi + \beta_\perp^2 S_{00}, \\ R_l^2 &= S_{33} - 2\beta_l S_{03} + \beta_l^2 S_{00}, \\ R_{os}^2 &= S_{12} \cos 2\phi + \frac{1}{2} (S_{22} - S_{11}) \sin 2\phi \\ &\quad + \beta_\perp S_{01} \sin \phi - \beta_\perp S_{02} \cos \phi, \\ R_{ol}^2 &= (S_{13} - \beta_l S_{01}) \cos \phi - \beta_\perp S_{03} \\ &\quad + (S_{23} - \beta_l S_{02}) \sin \phi + \beta_l \beta_\perp S_{00}, \\ R_{sl}^2 &= (S_{23} - \beta_l S_{02}) \cos \phi - (S_{13} - \beta_l S_{01}) \sin \phi \end{aligned}$$

$$S_{\mu\nu}^{\text{true}} = S_{\mu\nu}^{\text{meas}} \cdot \frac{n \cdot \Delta/2}{\sin(n \cdot \Delta/2) \cdot F_n}$$

Δ : finite ϕ -bin width

$$F_n = \langle \cos(n \cdot [\phi_{\text{EP}} - \phi_{\text{RP}}]) \rangle$$

(method by J.-Y. Ollitrault, [nucl-ex/9711003])

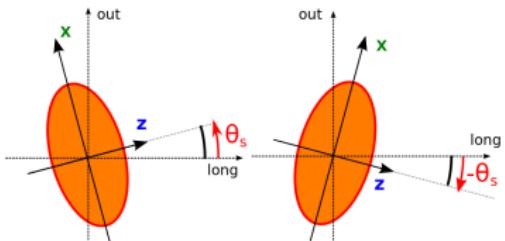


some details → backup, all details → [arxiv:1910.07885]

ϕ -dependent analysis II

spatial tilt in xz-plane:

$$\theta_s = \frac{1}{2} \tan^{-1} \left(\frac{2S_{13}}{S_{33} - S_{11}} \right)$$

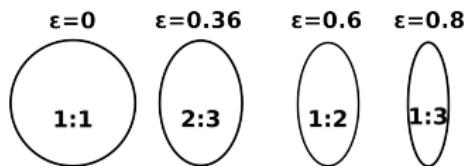


$$S^{\text{diag}} = R_y^T(\theta_s) \cdot S^{\text{true}} \cdot R_y(\theta_s)$$

→ diagonal elements of rotated S-matrix are geometrical variances $\sigma_t^2, \sigma_x^2, \sigma_y^2, \sigma_z^2$

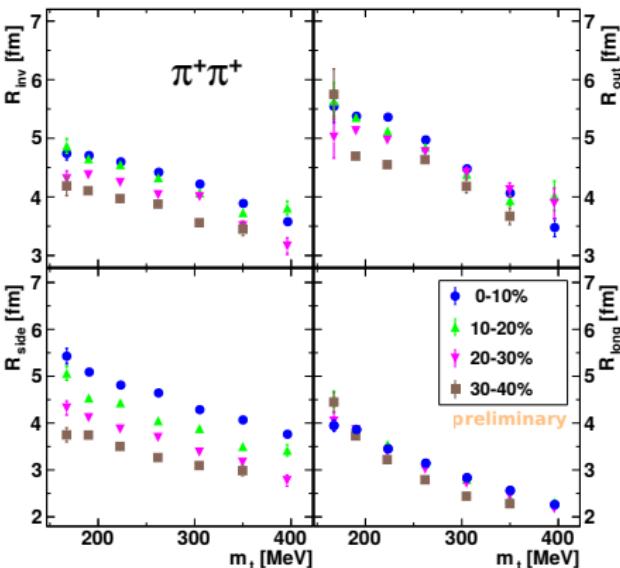
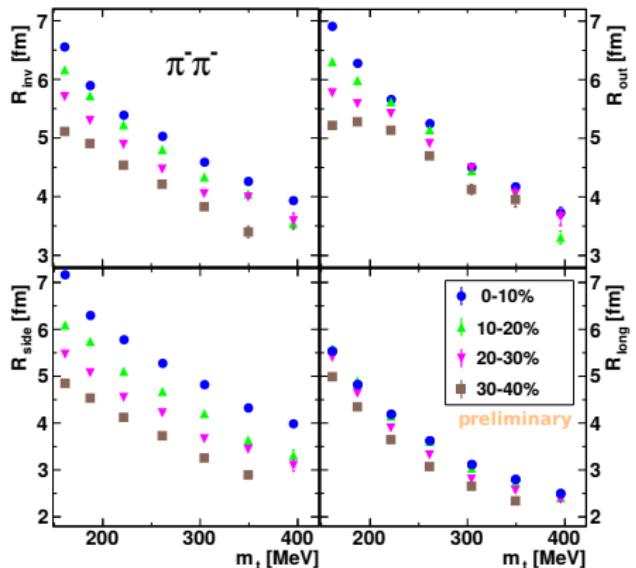
eccentricity in xy(zy)-plane:

$$\varepsilon_{xy(zy)} = \frac{\sigma_y^2 - \sigma_{x(z)}^2}{\sigma_y^2 + \sigma_{x(z)}^2}$$



initial nucleonic participant eccentricity $\varepsilon_{\text{initial}}$ → deduced from GlauberMC

HBT parameters, ϕ integrated

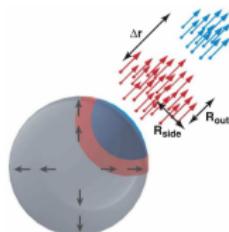


$$m_t = \sqrt{k_t^2 + m_\pi^2}$$

$$k_t = p_{t12}/2$$

decreasing R_i for increasing $m_t \rightarrow$ radial flow
+ resonance contributions
(mainly Δ 's)

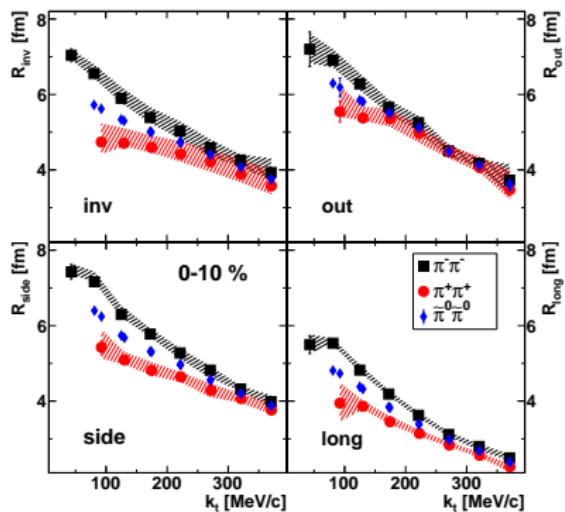
charge-sign differences clearly visible!



[nucl-ex/0505014]

Member of the Helmholtz Association

'Central' Coulomb pot.



First time observation of substantial charge-sign difference!

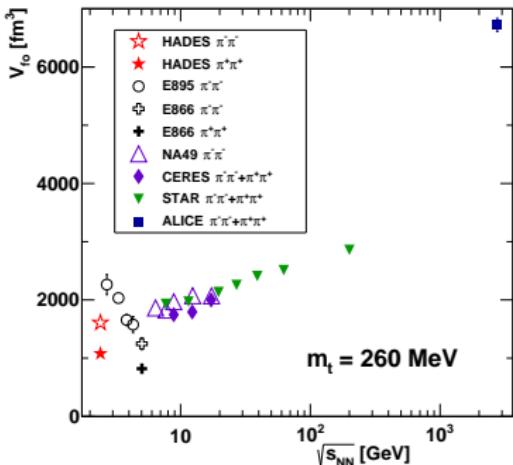
constructed $\tilde{\pi}^0\tilde{\pi}^0$ radii:

$$R_{\tilde{\pi}^0\tilde{\pi}^0}^2 = \frac{1}{2}(R_{\pi^+\pi^+}^2 + R_{\pi^-\pi^-}^2)$$

[PLB 795 (2019) 446]

excitation functs.

Au+Au, Au+Pb, Pb+Pb

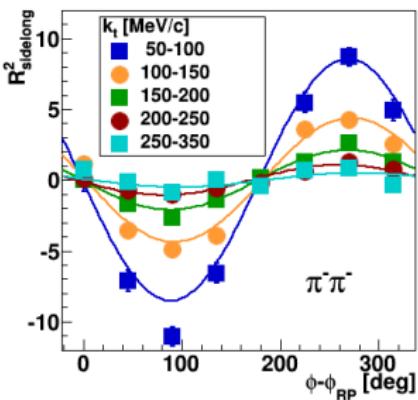
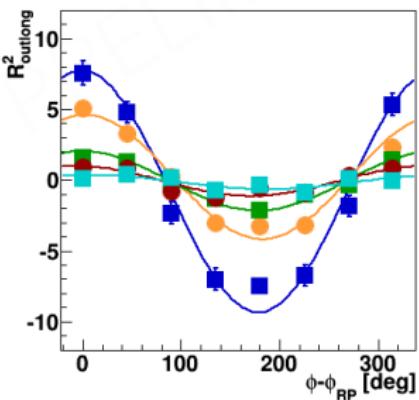
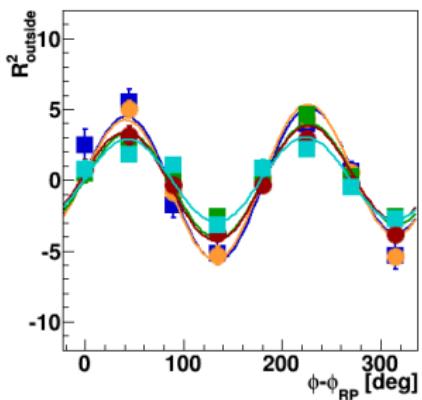
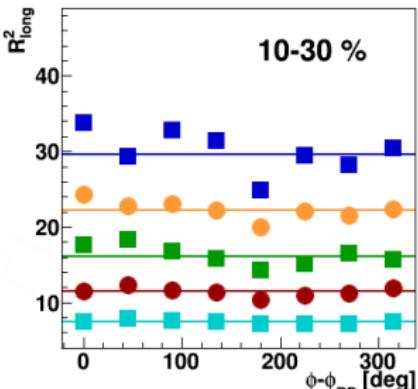
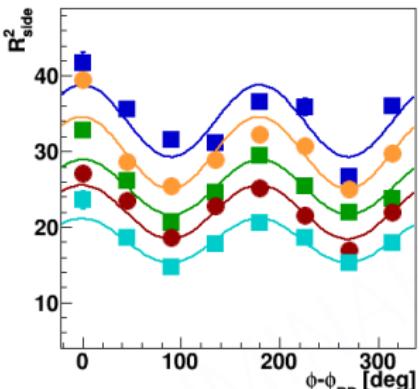
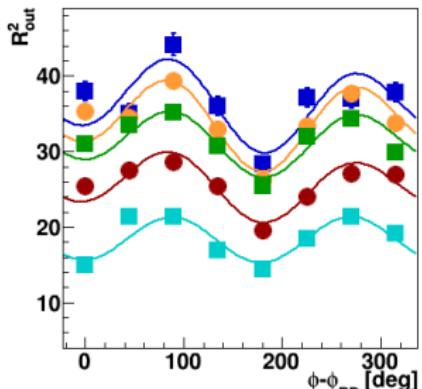


$$V_{\text{fo}} := (2\pi)^{\frac{3}{2}} R_{\text{side}}^2 R_{\text{long}}$$

HADES follows trend from STAR/NA49
more than trend from E895
→ room for structures?

$R_{\text{out}}, R_{\text{side}}, R_{\text{long}} \rightarrow$ backup

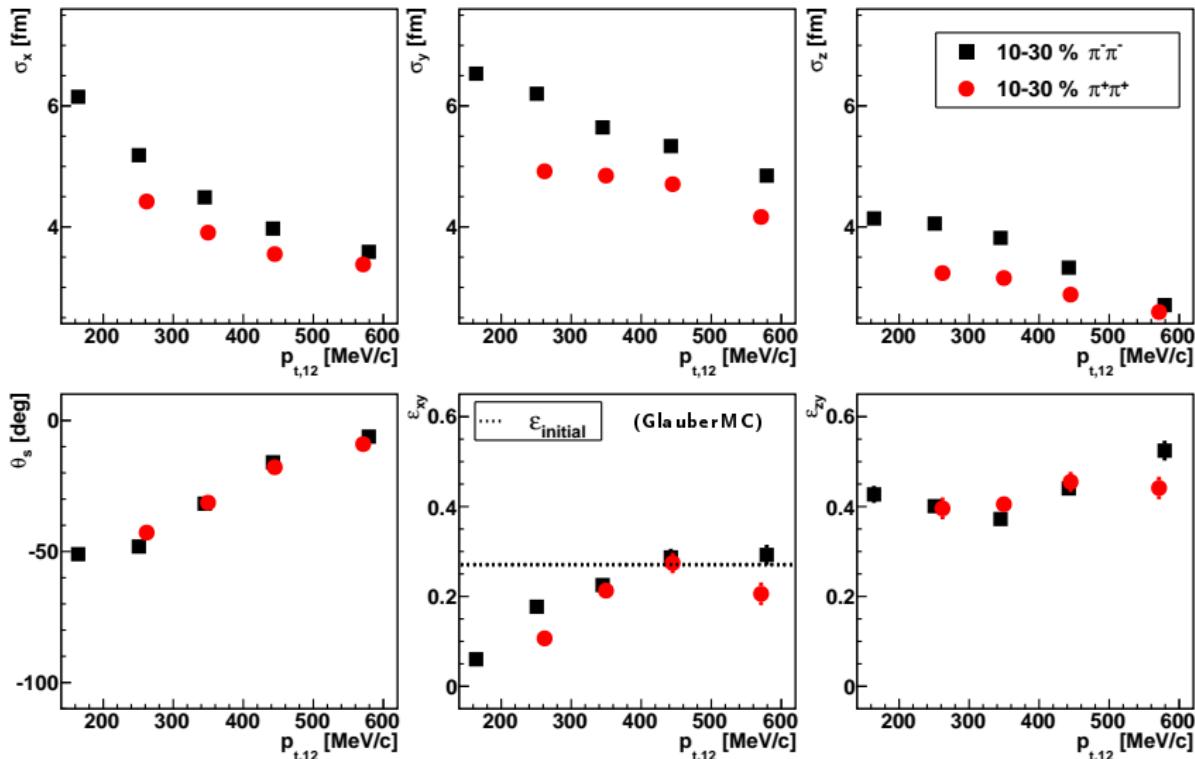
ϕ -dependent HBT parameters, $\pi^-\pi^-$



Geometrical results, 10-30%

[arxiv:1910.07885]

$\sigma_y > \sigma_x > \sigma_z \rightarrow$ "almond" shape

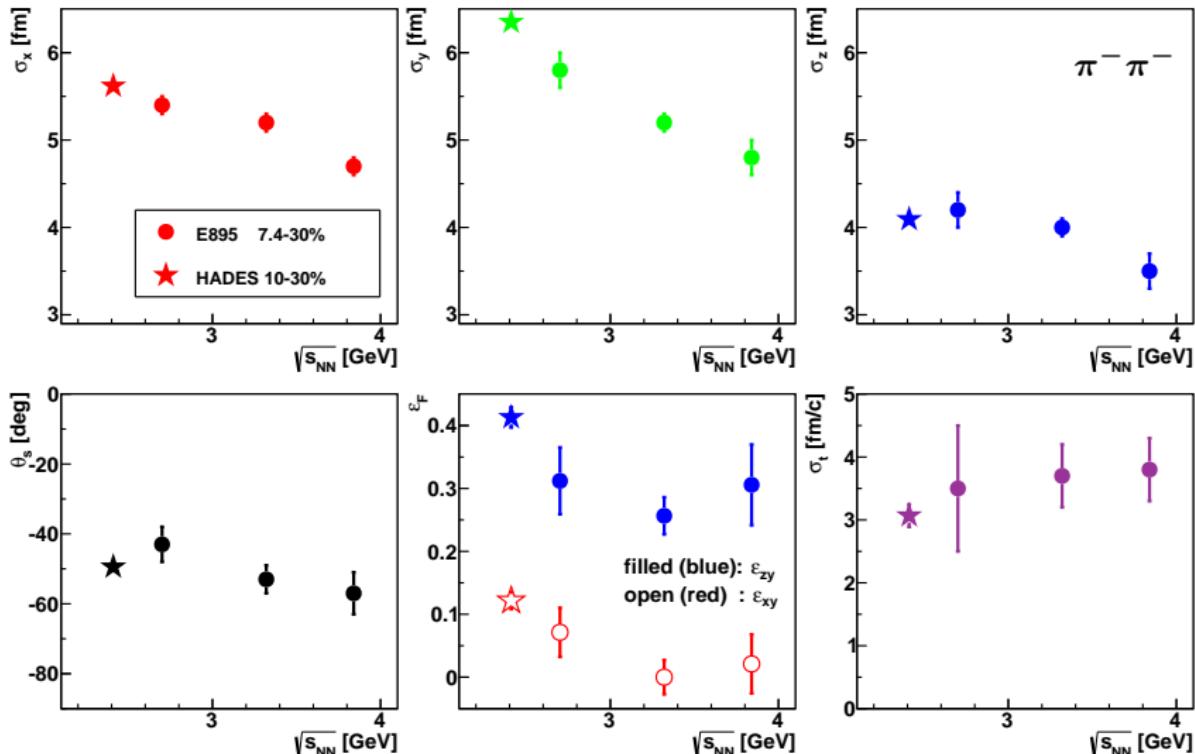


$\sigma_x, \sigma_y, \sigma_z$ clearly depend on pion charge, θ_s does not!

Excitation function, nearby energies (AGS)

[arxiv:1910.07885]

$$\theta_s \rightarrow \theta_s + 90^\circ \Rightarrow \sigma_x \leftrightarrow \sigma_z !$$



mean $k_t = 110 \text{ MeV}/c$ at low q

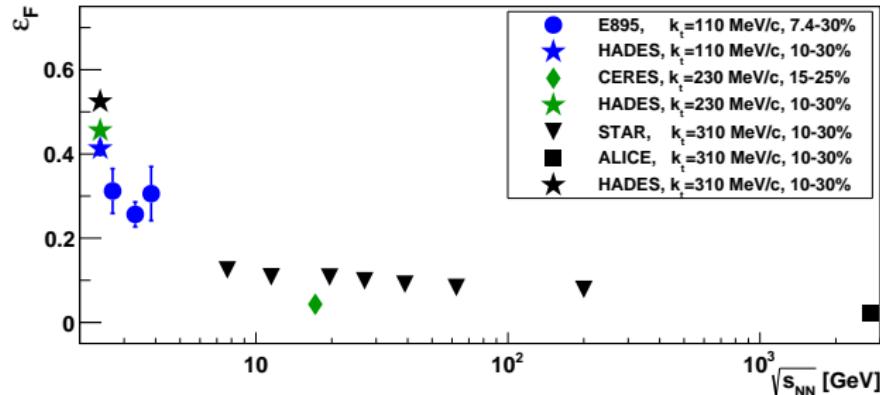
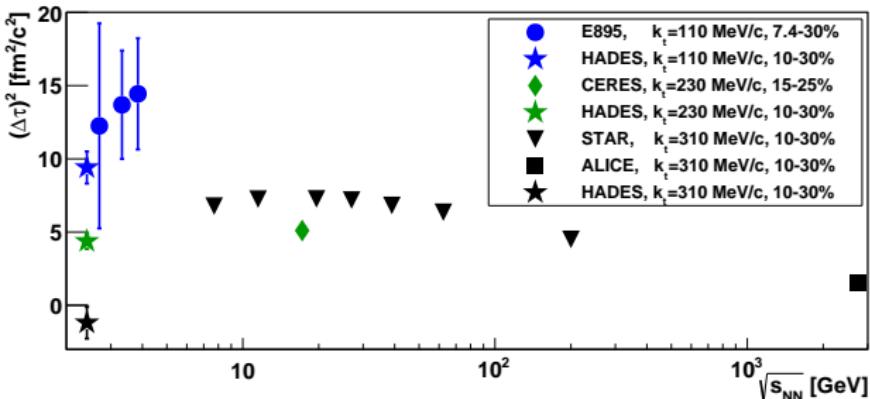
HADES@SIS18 follows trend from E895@AGS!

Excitation function on a larger scale

freeze-out duration:

$$(\Delta\tau)^2 = \sigma_t^2 \\ (\text{HADES/E895})$$

$$= (R_{\text{out}}^2 - R_{\text{side}}^2) / \beta_t^2 \\ (\text{CERES/STAR/ALICE})$$



[arxiv:1910.07885]

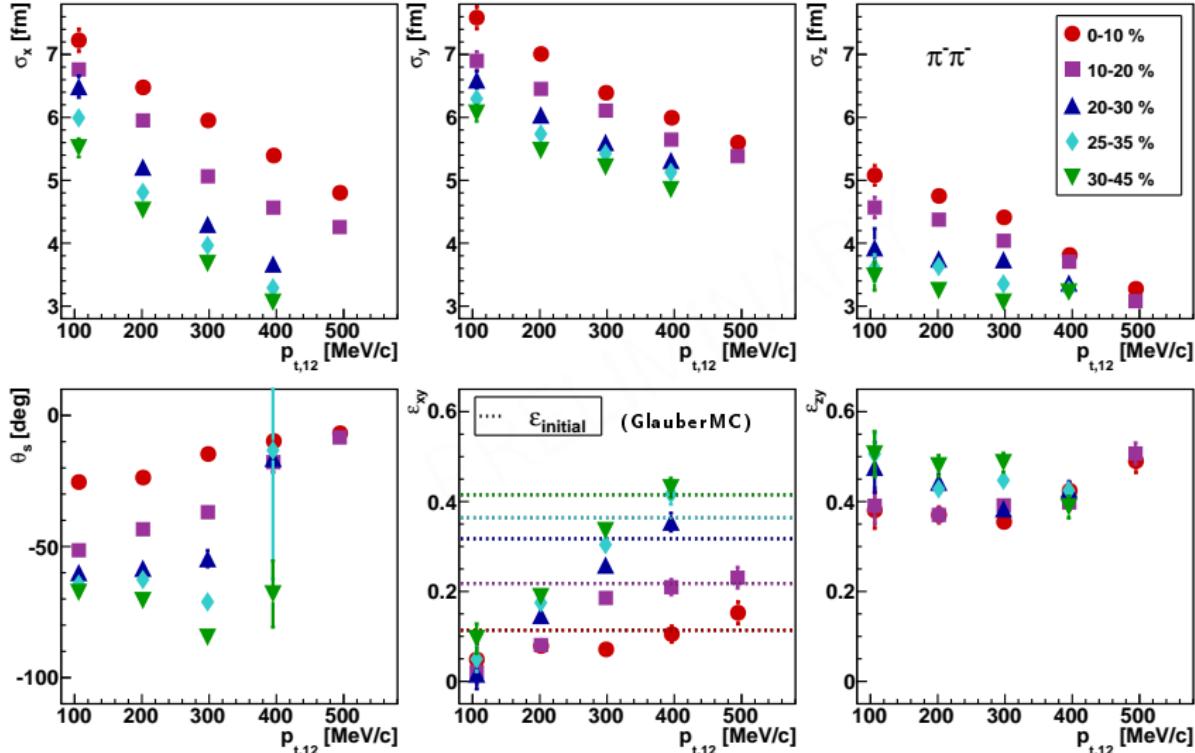
final eccentricity:

$$\varepsilon_F = \varepsilon_{zy} \\ (\text{HADES/E895}) \\ = 2 \cdot \frac{R_{s,2}^2}{R_{s,0}^2} \quad (\text{if } \theta_s \approx 0) \\ (\text{CERES/STAR/ALICE})$$

→ smooth trends

→ k_t matters!

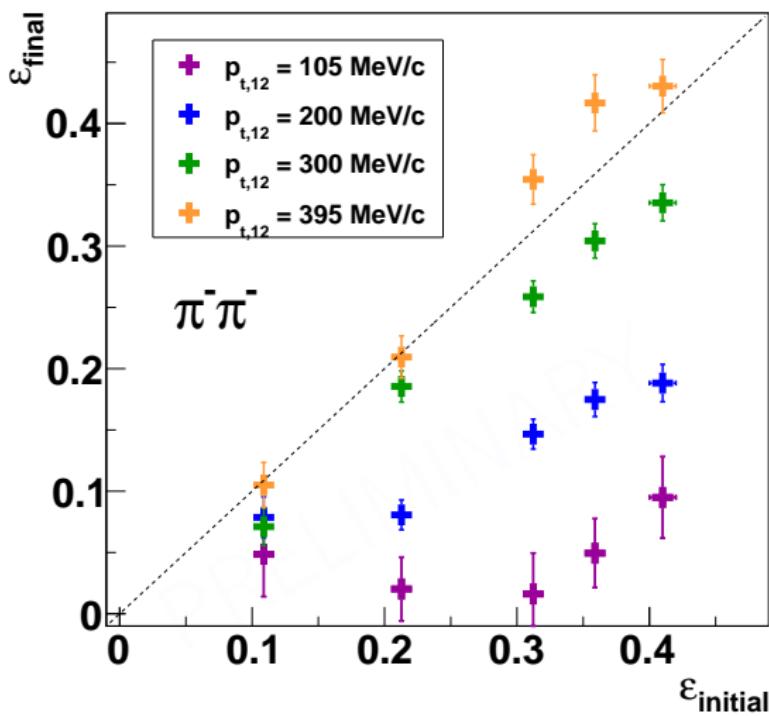
Geometrical results, all centralities, $\pi^-\pi^-$



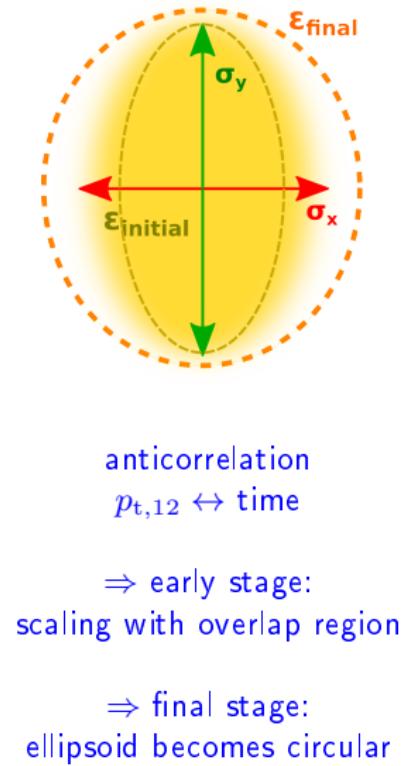
$\sigma_x, \sigma_y, \sigma_z$ increase with more central collisions and decreasing $p_{t,12}$!

$|\theta_s|$ decreases with more central collisions and increasing $p_{t,12}$!

$\varepsilon_{\text{final}}$ VS. $\varepsilon_{\text{initial}}$

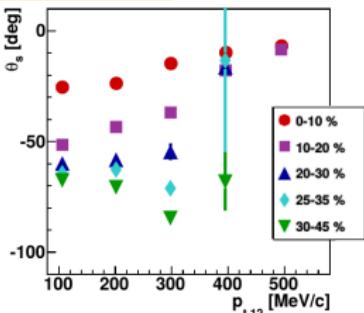
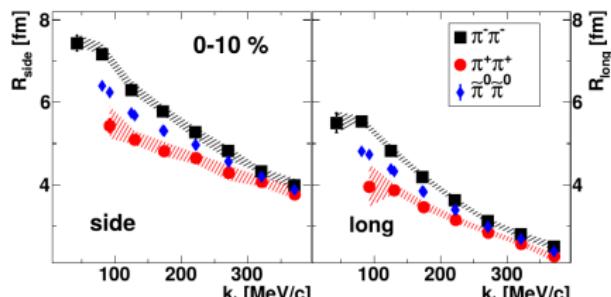


final ecc. recovers initial (nucleonic) ecc. at high p_t !



Summary

- multi-differential HBT analysis
 - $\pi^- \pi^-$ and $\pi^+ \pi^+$ separately
 - k_t and centrality dependent
 - ϕ -integrated and ϕ -dependent analysis
 - excitation functions including HADES data
 - HADES mostly confirms existing trends!
 - comparable only at same k_t !
- first time measured in HIC
 - substantial charge-sign difference of HBT radii
 - multi-differential analysis of tilt angle in xz plane



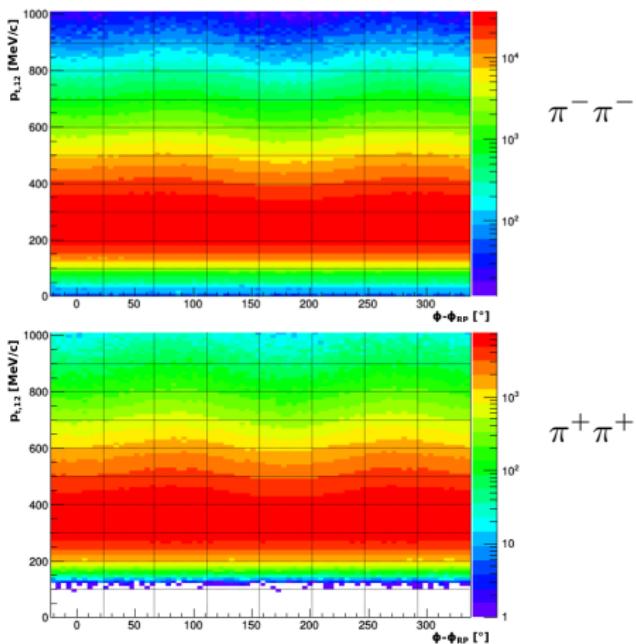
Thank you for your attention!



The HADES collaboration

Backup material

Phase space binning



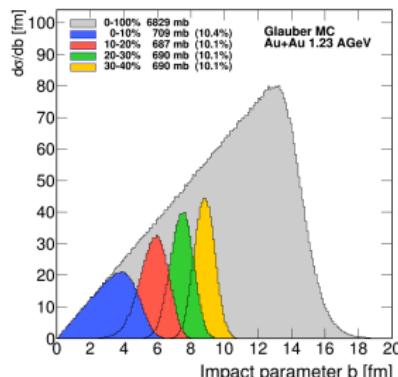
10-30% $q_{\text{inv}} < 50 \text{ MeV}/c$ $|y_{12} - y_{\text{cm}}| < 0.35$

$$p_{t,12} = |\vec{p}_{t,1} + \vec{p}_{t,2}|, \quad y_{12}: \text{pair rapidity}$$

aside: out-of-plane elliptic flow visible

Centrality

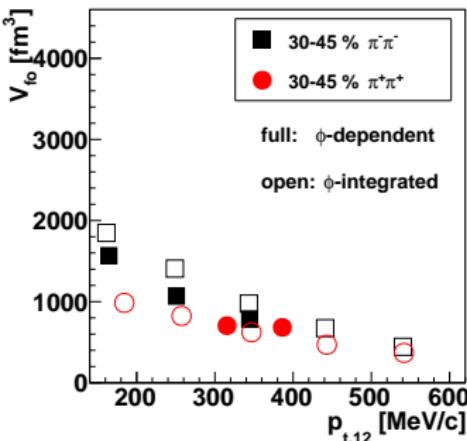
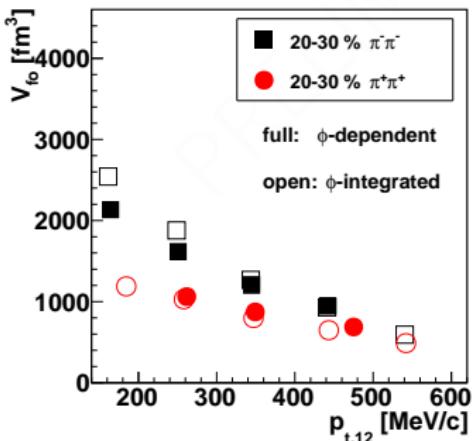
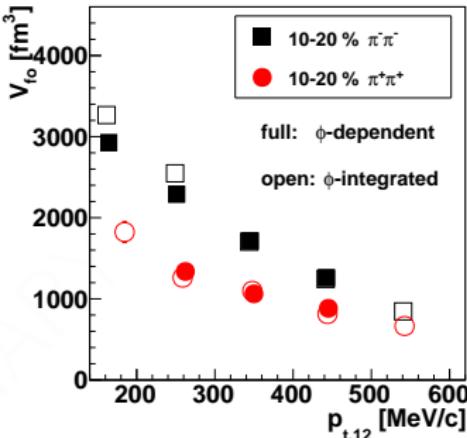
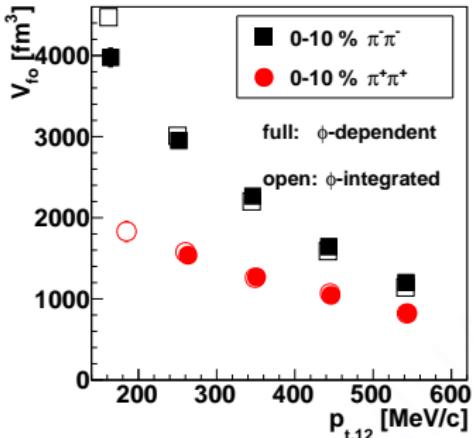
centr. determ. with GlauberMC



centr. (%)	$\langle b \rangle$ [fm]	$\langle A_{\text{part}} \rangle$
0-10	3.1	303
10-20	5.7	213
20-30	7.4	150
30-40	8.7	103
10-30	6.5	181
25-35	8.1	125
30-45	9.0	93

HADES [EPJ A 54 (2018) 85]

Freeze-out volume

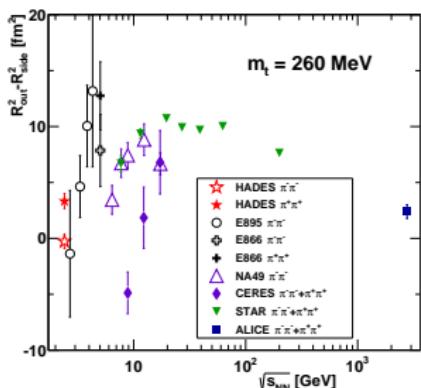
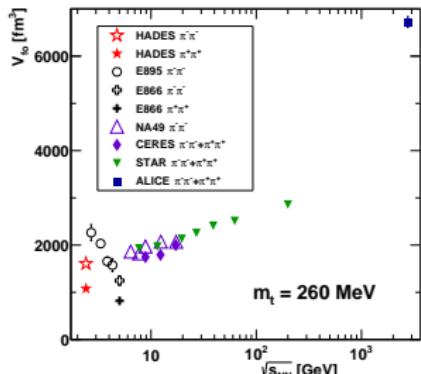
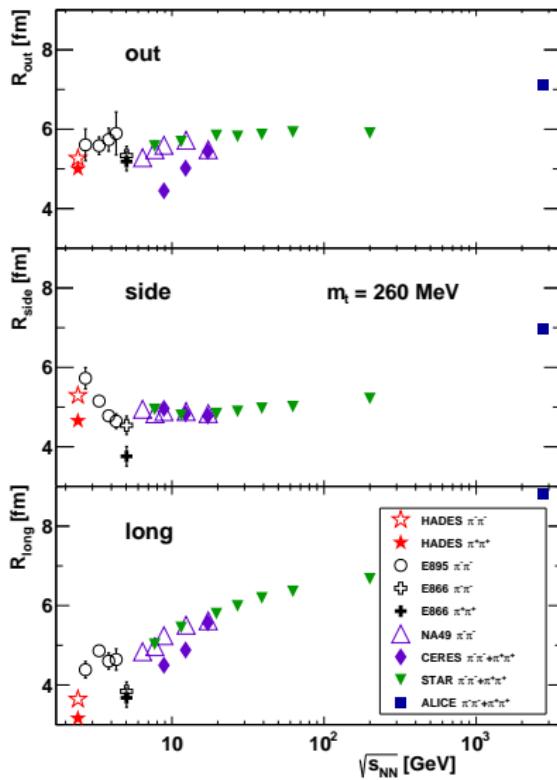


$$V_{fo} = (2\pi)^{3/2} \sigma_x \cdot \sigma_y \cdot \sigma_z \text{ (azimuthally dependent)}$$

$$(2\pi)^{3/2} R_{\text{side}}^2 \cdot R_{\text{long}} \text{ (azimuthally integrated)}$$

Excitation function, $m_t = 260 \text{ MeV}/c$, ϕ -integr.

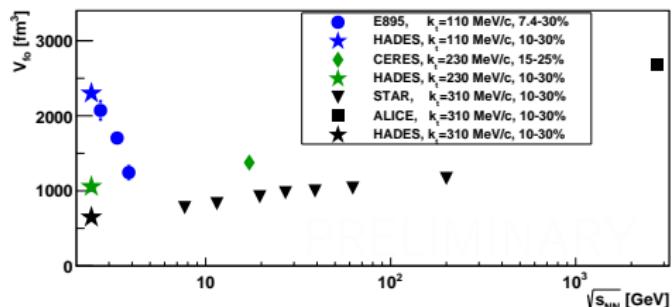
Au+Au, Au+Pb, Pb+Pb, most central



[arXiv:1811.06213]

Excitation function, ϕ -dependent

azimuthally dependent analysis only:

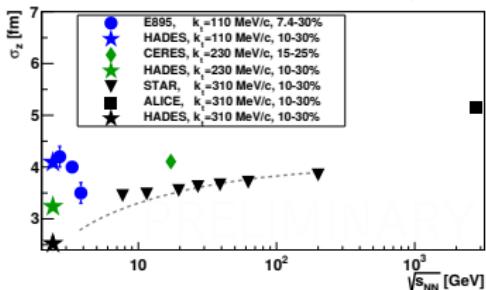
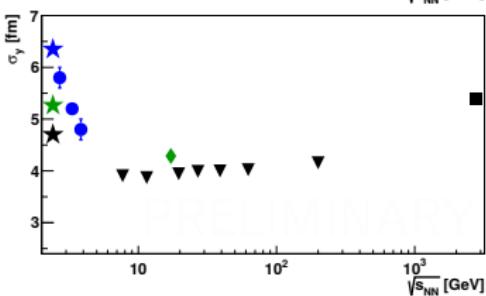
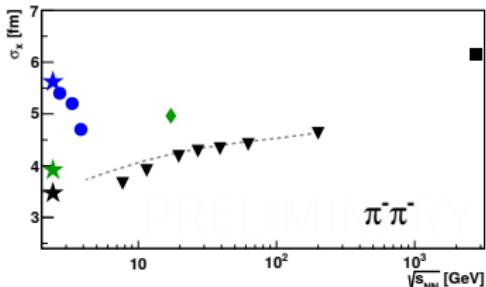


strong variation at low k_t !

at higher k_t :

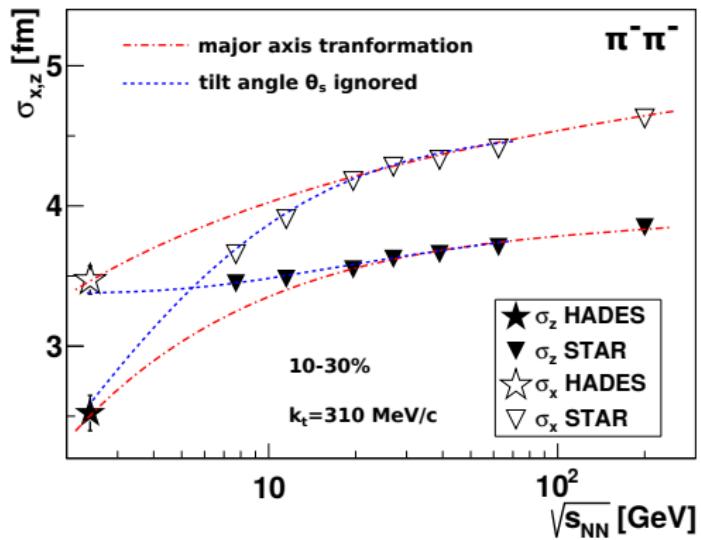
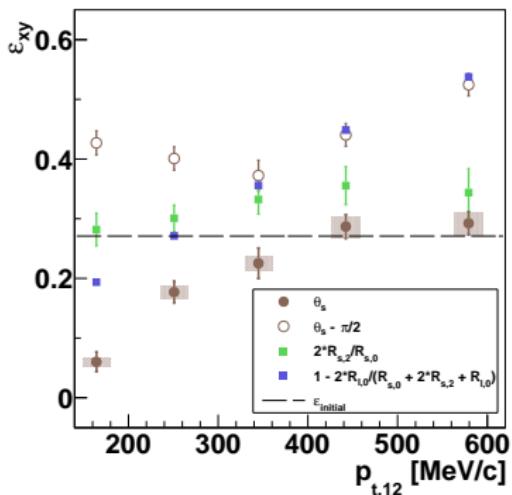
- volume increases smoothly with $\sqrt{s_{\text{NN}}}$
- σ_x, σ_z increase with energy, but σ_y decreases at low $\sqrt{s_{\text{NN}}}$

\Rightarrow similar observation as squeeze-out?



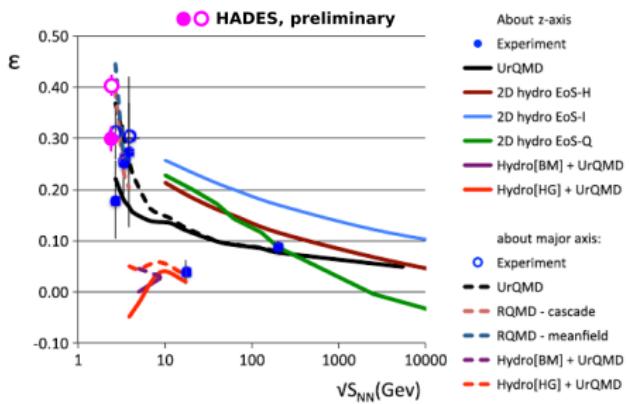
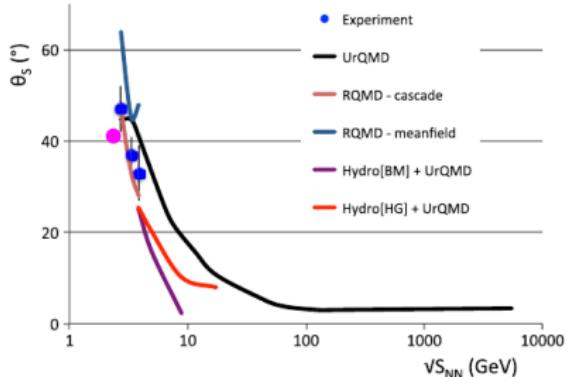
Excitation function, $\varepsilon_{\text{final}}$ II

Tilt angle has to be taken into account!



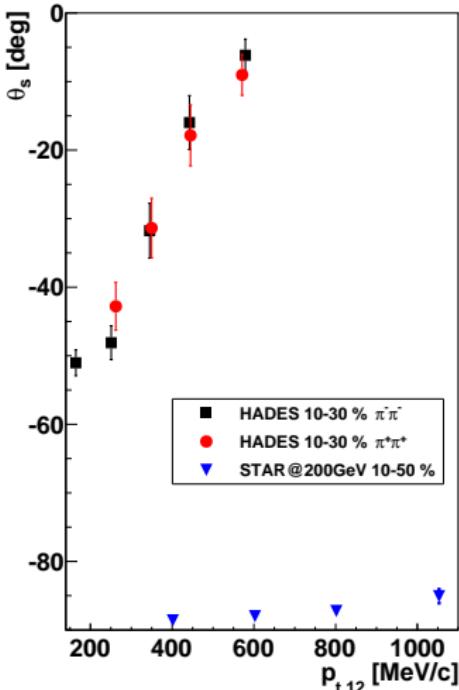
trends of blue and green data points (blue dashed lines) cross at tilt angle $\theta_s \approx 45^\circ$!

Excitation function θ_s (with model calculations)



[New J. Phys. 13 (2011) 065006]

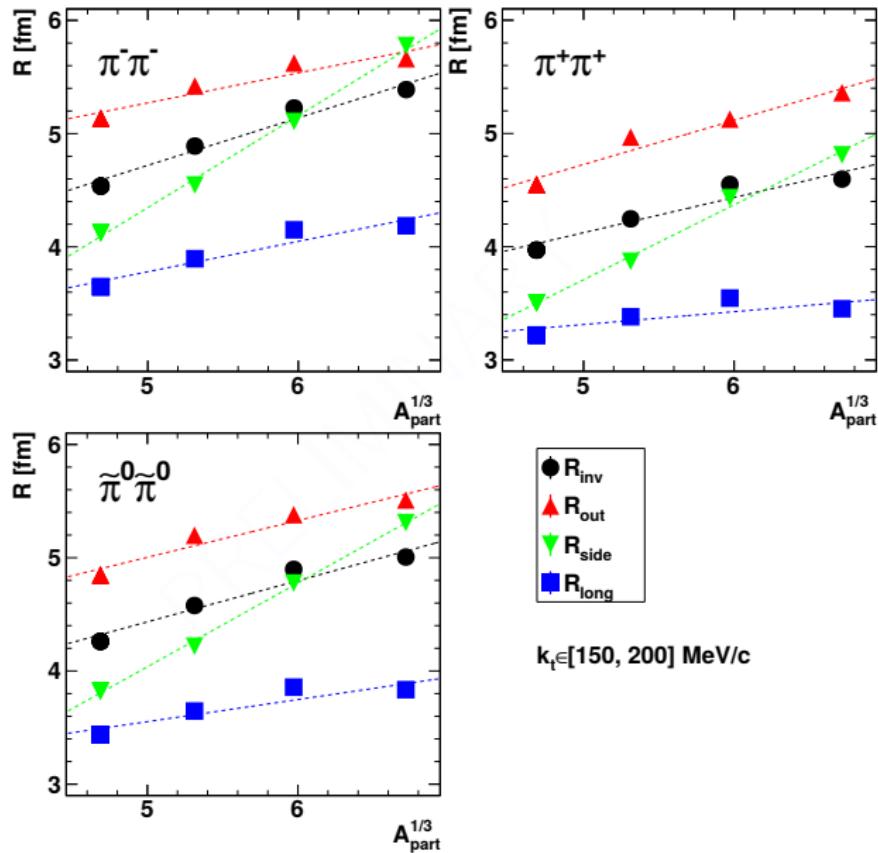
Y. Kawamura for STAR, WWND2019, prelim.



simulations predict smooth trend of
tilt angle

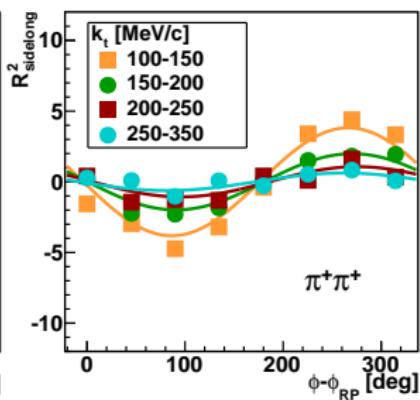
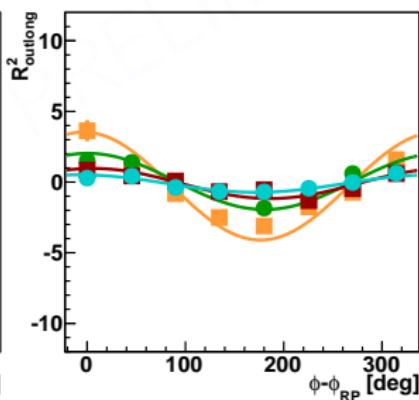
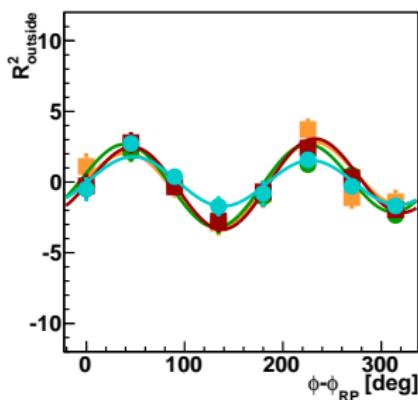
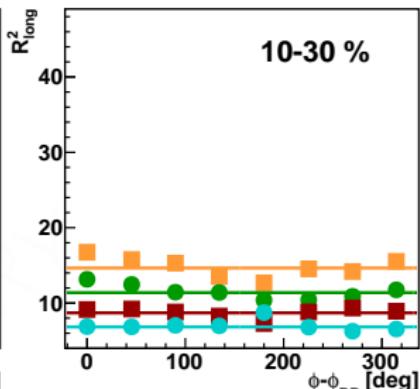
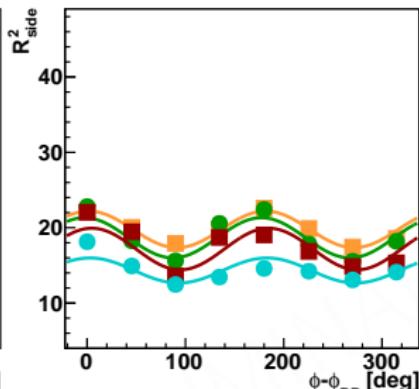
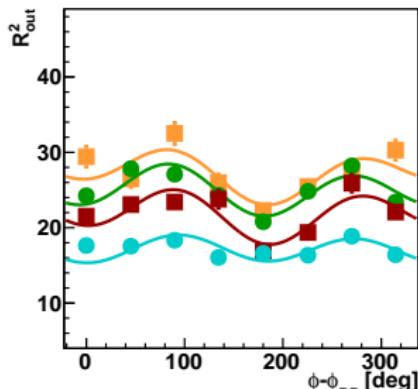
⇒ affirms that there is no crossing of
eccentricities!

A_{part} dependence, 0-10%

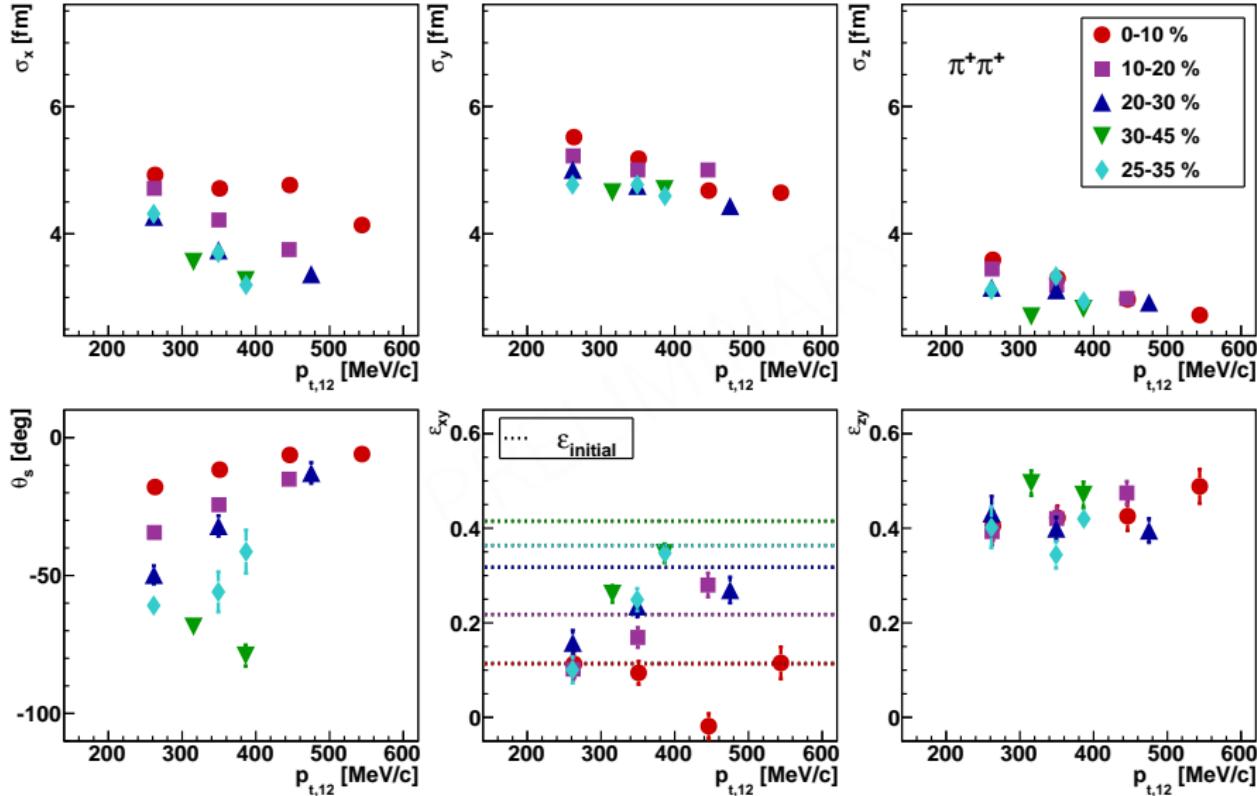


$k_t \in [150, 200]$ MeV/c

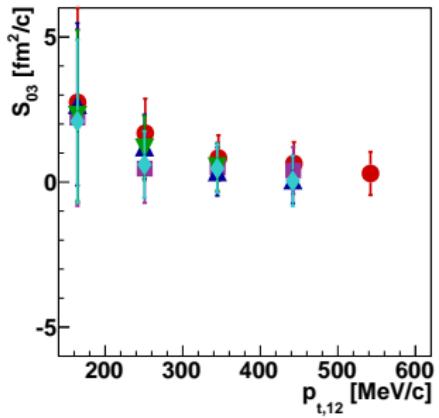
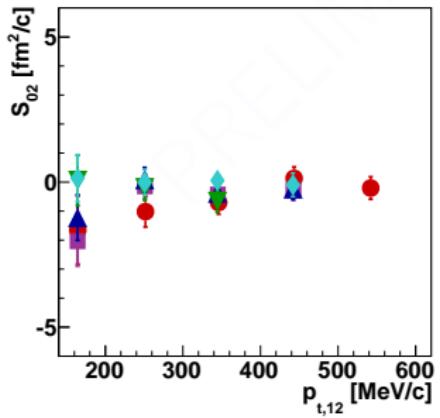
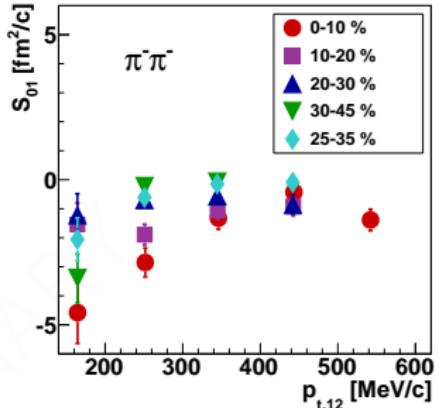
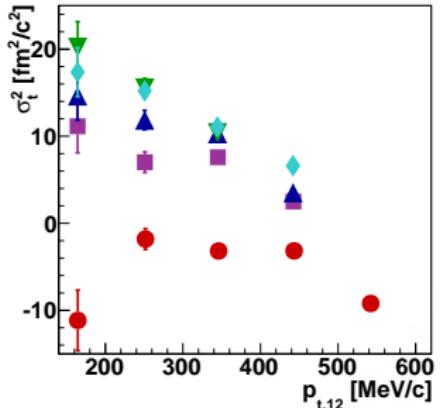
ϕ -dependent HBT parameters, $\pi^+\pi^+$, fit



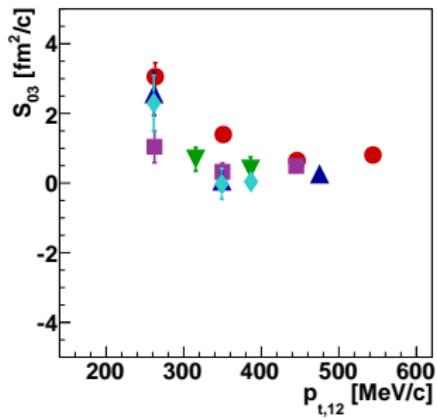
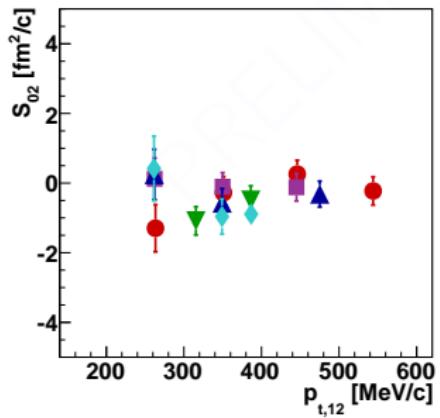
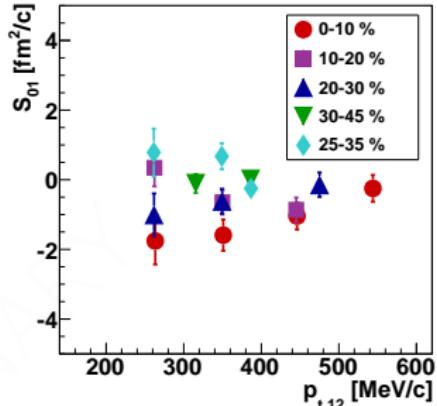
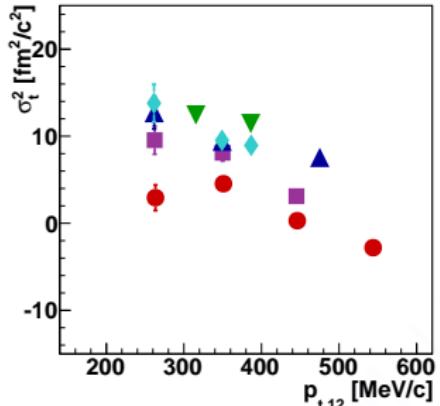
Geometrical results, all centralities, $\pi^+\pi^+$



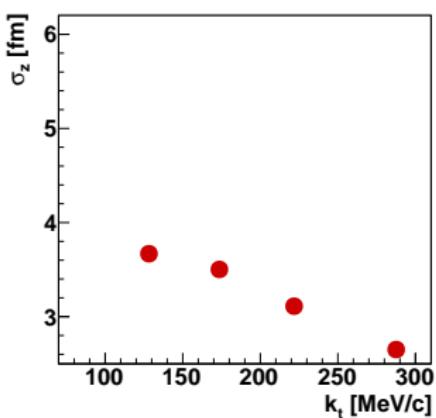
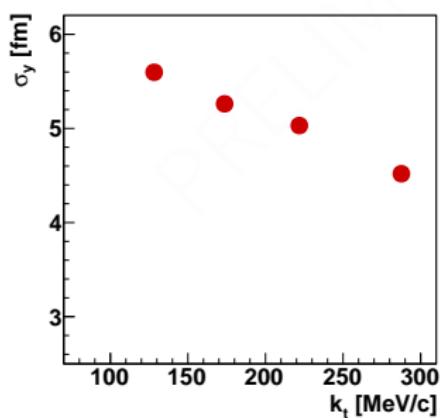
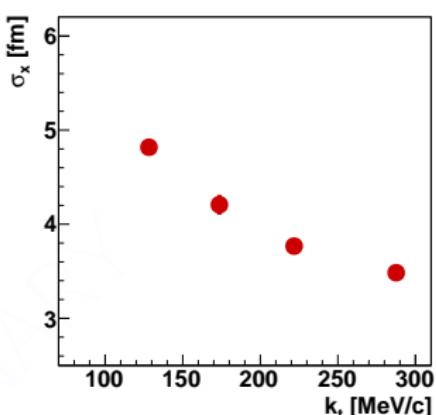
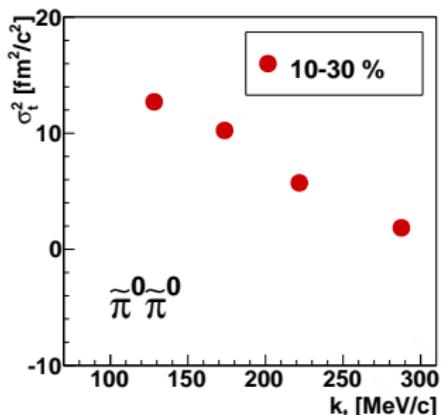
time components, $\pi^-\pi^-$



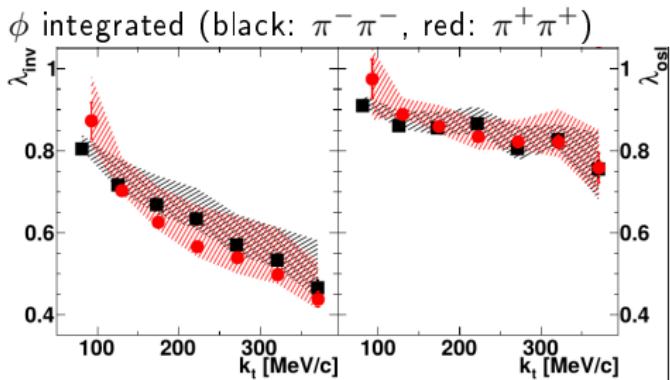
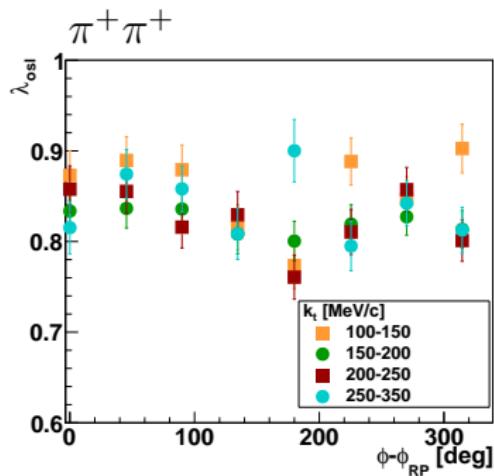
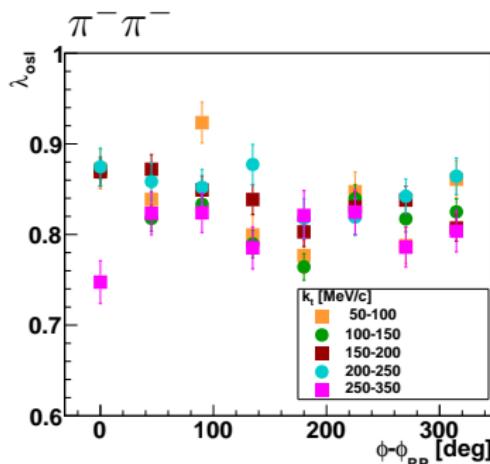
time components, $\pi^+\pi^+$



Constructed $\pi^0\pi^0$



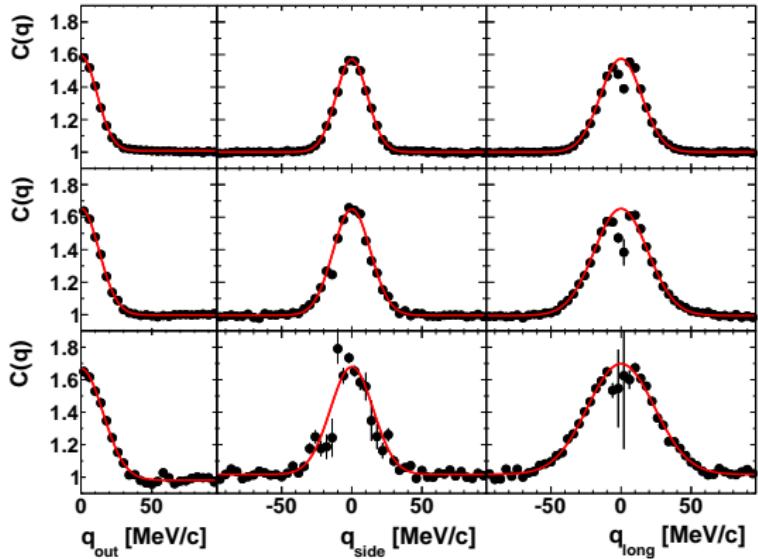
λ parameter



top: 10-30%

bottom: 0-10 %

1-dim projections, 0-10 % (φ -integrated)



top:

$$k_t = 100 - 150 \text{ MeV}/c$$

middle:

$$k_t = 200 - 250 \text{ MeV}/c$$

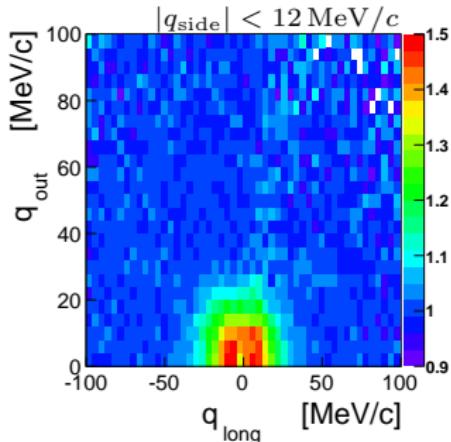
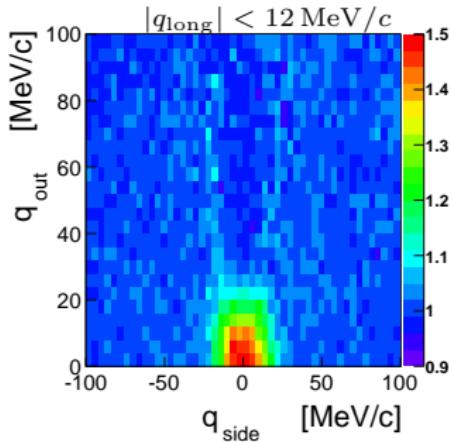
bottom:

$$k_t = 300 - 350 \text{ MeV}/c$$

project

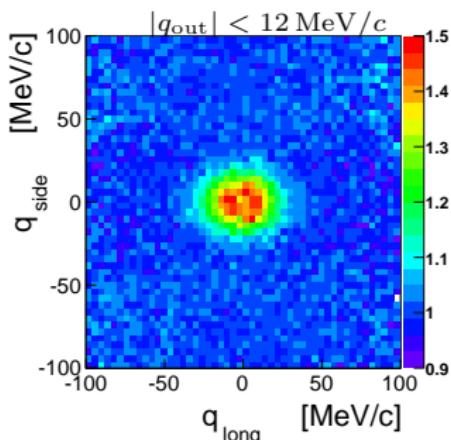
$$0 < q_{2,3} < 12 \text{ MeV}/c$$

example C-fct., projections

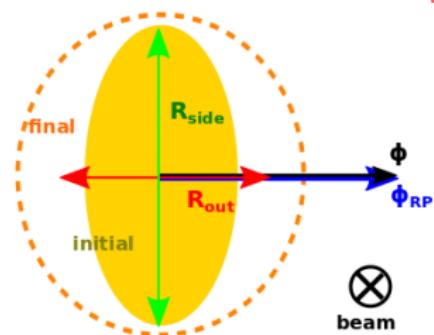


10 – 30%

$p_{t,12} \in [100, 400] \text{ MeV}/c$

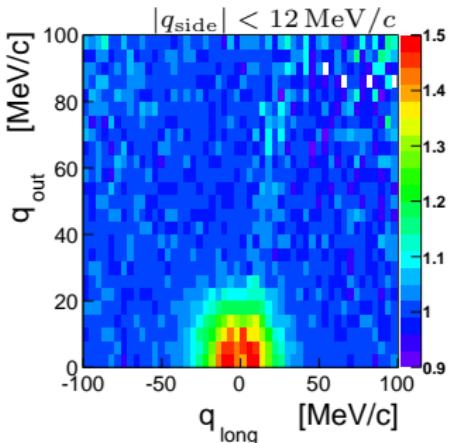
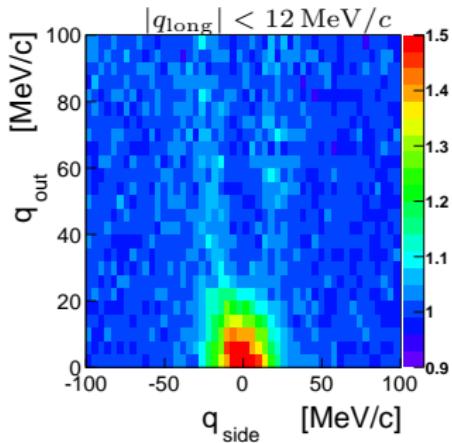


$[\phi - \phi_{\text{RP}}] = 0^\circ$



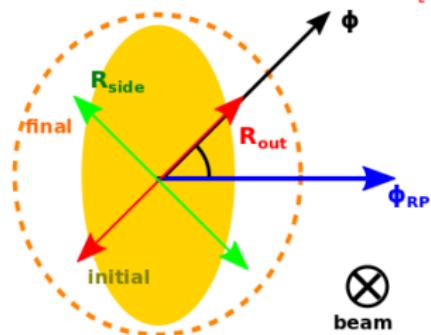
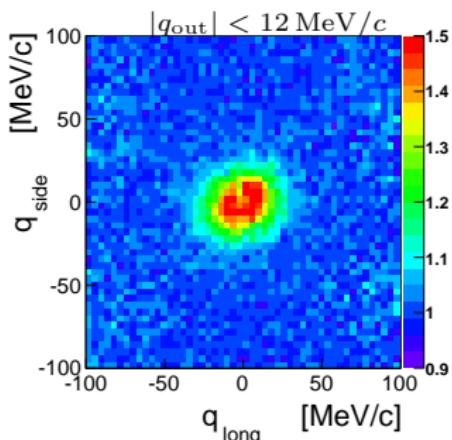
R_{out} at minimum
 R_{side} at maximum

example C-fct., projections



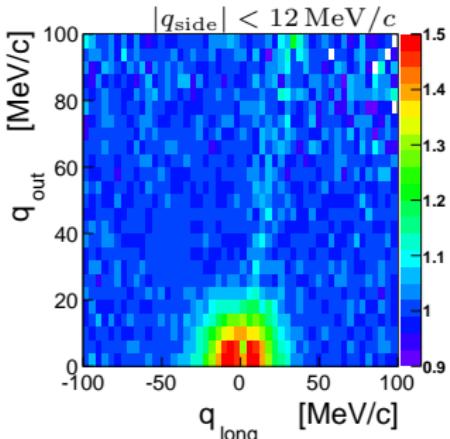
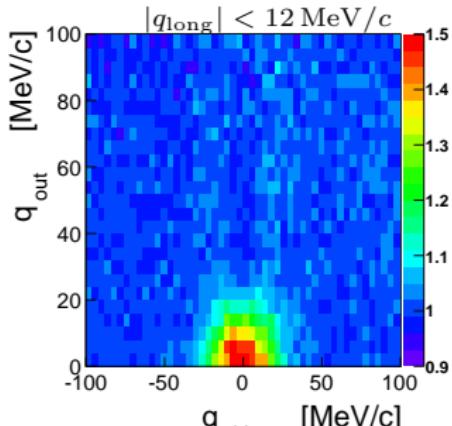
10 – 30%

$p_{t,12} \in [100, 400] \text{ MeV}/c$



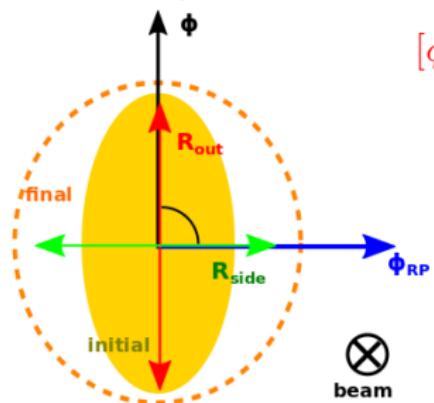
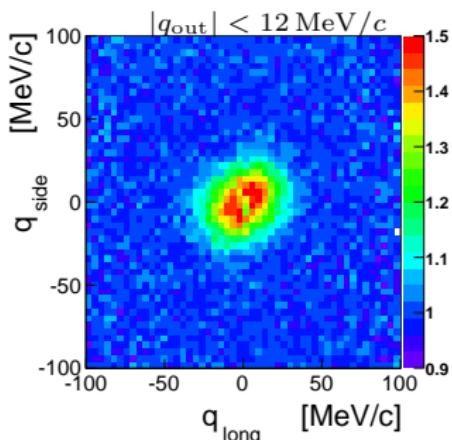
$$[\phi - \phi_{RP}] = 45^\circ$$

example C-fct., projections



10 – 30%

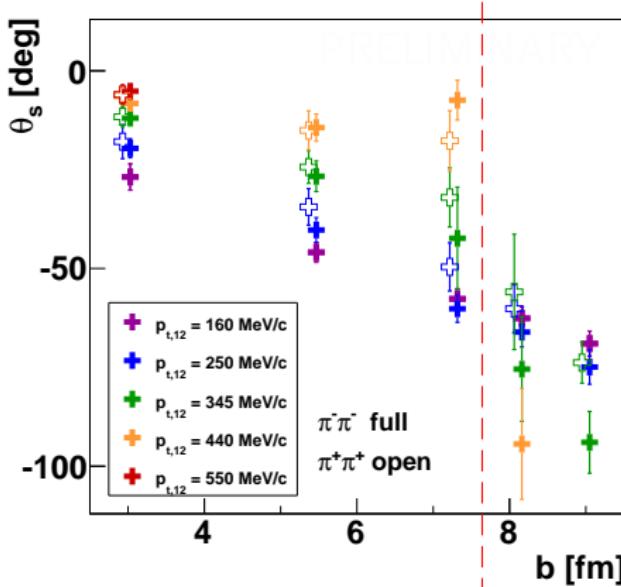
$p_{t,12} \in [100, 400] \text{ MeV}/c$



$$[\phi - \phi_{RP}] = 90^\circ$$

R_{out} at maximum
 R_{side} at minimum

Tilt $\theta_s(b)$

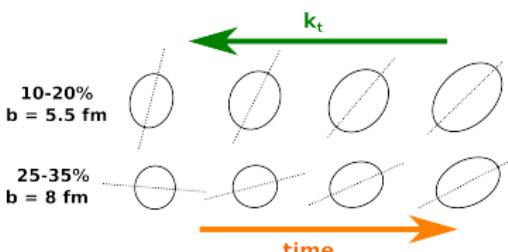


anticorrelation
 $p_{t,12} \leftrightarrow \text{time}$

⇒ early stage:
no tilt

⇒ final stage:
largest tilt magnitude

change in tilt orientation visible ?!



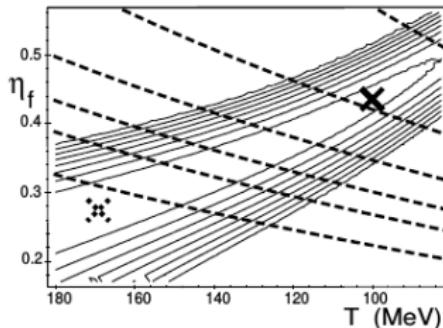
Interpretation of HBT results, 2 slopes

→ recipe from U. Wiedemann, U. Heinz, Phys. Rept. 319, 145 (1999)

$$E \frac{dN}{d^3 p} = P_1(p) = \int d^4 x S(x, p) \Leftrightarrow C_2(\vec{q}, \vec{K}) \approx 1 + \frac{|\int d^4 x S(x, K) e^{iqx}|^2}{|\int d^4 x S(x, K)|^2}$$

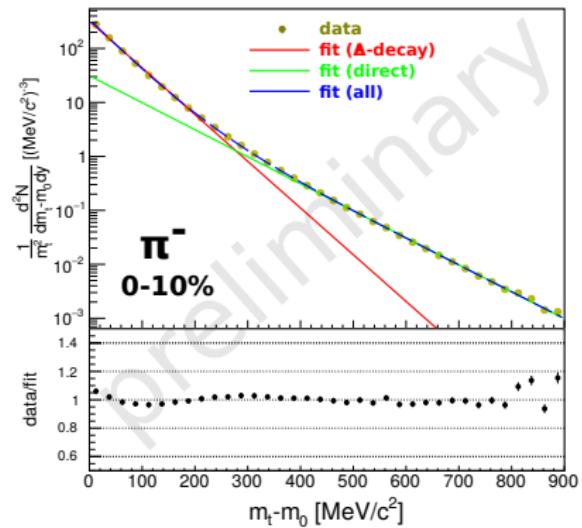
$$\Leftrightarrow R_i^2 = \langle \tilde{x}_i^2 \rangle = \frac{\int d^4 x \tilde{x}_i^2 S(x, K)}{\int d^4 x S(x, K)}$$

motivation: determ. flow velocity $\eta_t \leftrightarrow$
kin. freeze-out Temperature T_{fo}



$$\rightarrow S = S^\Delta + S^{\text{direct}}$$

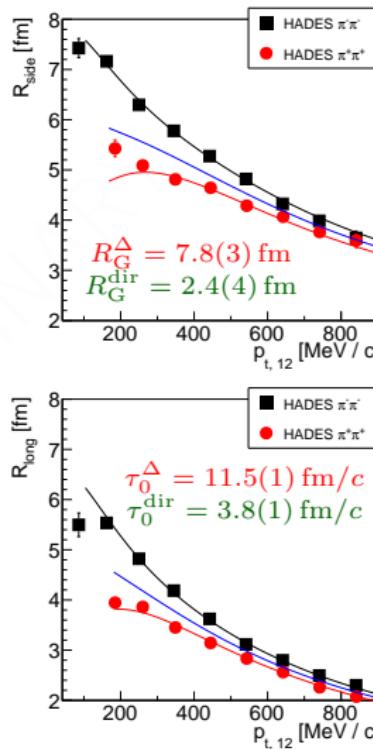
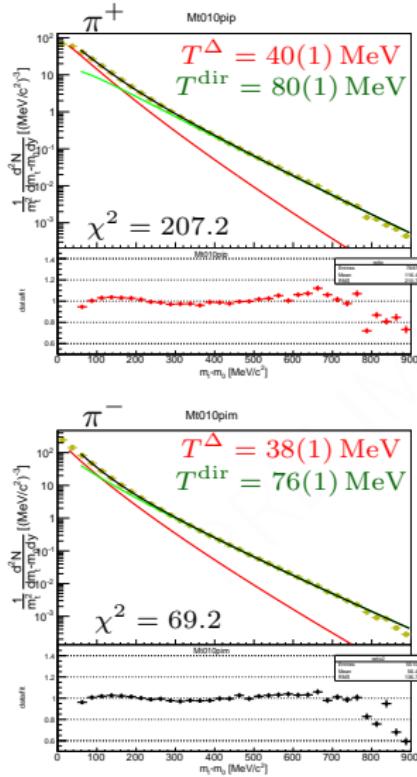
$$\Rightarrow R_i^2 = \frac{P_{1,\Delta} \cdot R_{i,\Delta}^2 + P_{1,\text{dir}} \cdot R_{i,\text{dir}}^2}{(P_{1,\Delta} + P_{1,\text{dir}})}$$



Single-part. spec. in SIS/AGS* energy regime best descr. by sum of **direct** + **(mainly)Δ decay** pions

* E895 [Phys. Rev. C 68 (2003) 054905]

Relativistic model, combined fit

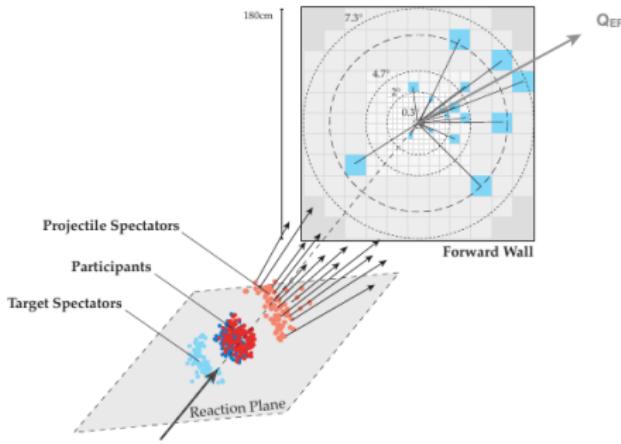


$$\begin{aligned} \Delta\tau^{\text{dir}} &= \Delta\tau^\Delta = 0 \\ v_r^{\text{dir}} &= 0.1 \\ v_r^\Delta &= 0.27(5) \\ V_C^{(1)} &= 8.4 \text{ MeV} \\ V_C^{(2)} &= 27(2)(1) \text{ MeV} \end{aligned}$$

2 Coulomb potentials V_C ,
2 flow velocities v_r ,
2 geom. radii R_G ,
2 freeze-out times τ_0 ,
2 freeze-out durations $\Delta\tau$

- too many parameters, w/o further constraints no meaningful param. determ. possible!
- + proof of principle: pion species chronology affects p_t dependence of HBT radii!

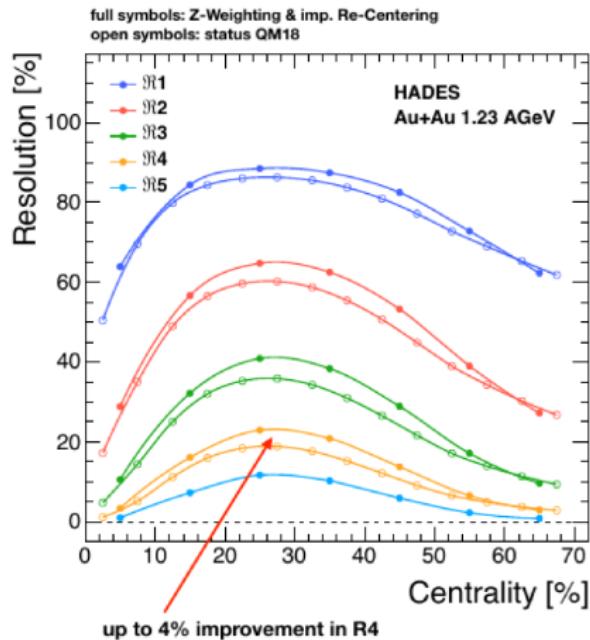
Event plane reconstruction and resolution



based on hits of projectile spectators in the Forward Wall (FW)

$$\vec{Q}_{EP} = \sum_{i=0}^N \vec{u}_i$$

Z-weighting up to charge 6 in FW



sub-event method

Excitation function, m_t -dep. of world data

