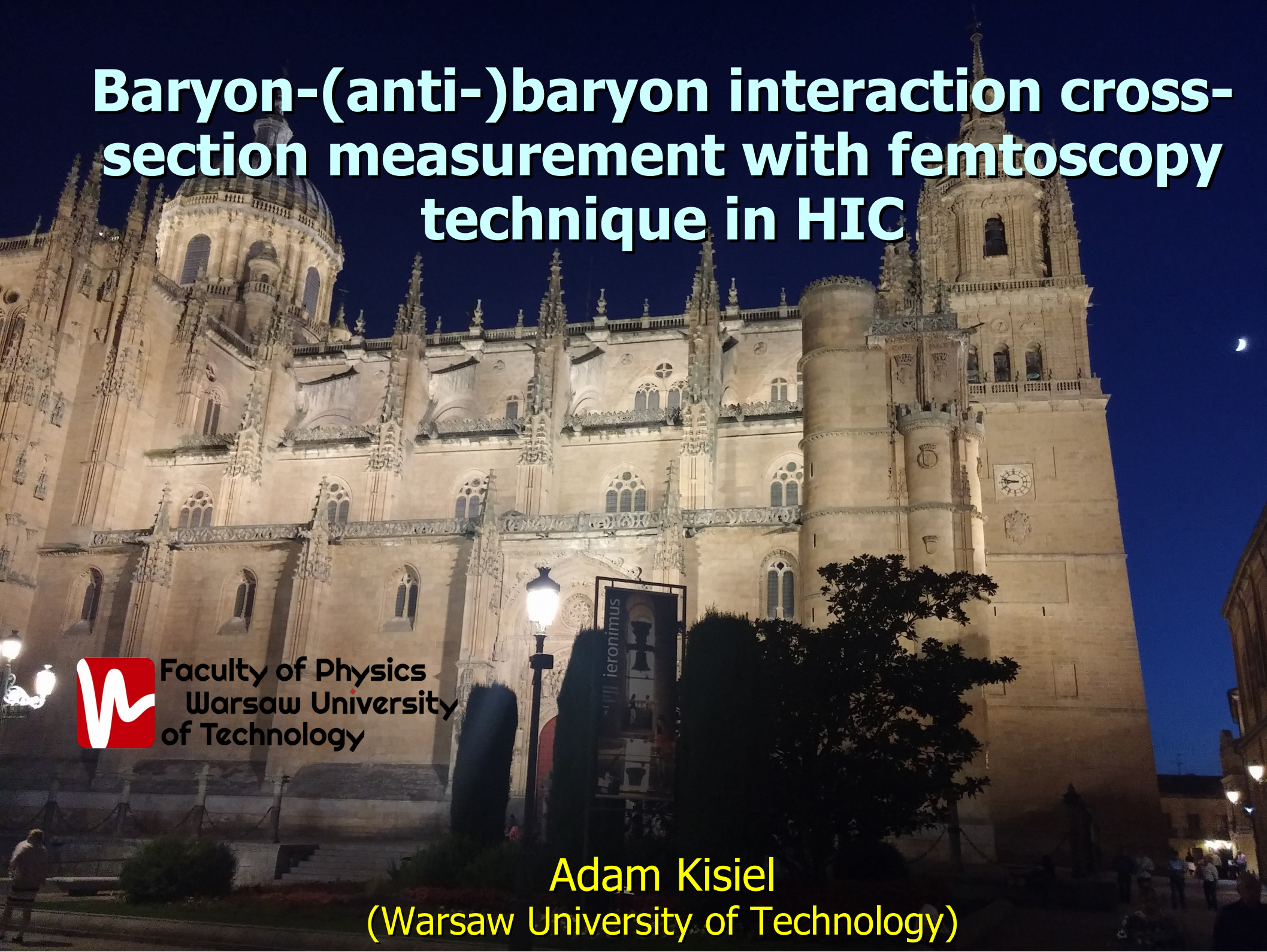
Baryon-(anti-)baryon interaction cross-section measurement with femtoscopy technique in HIC



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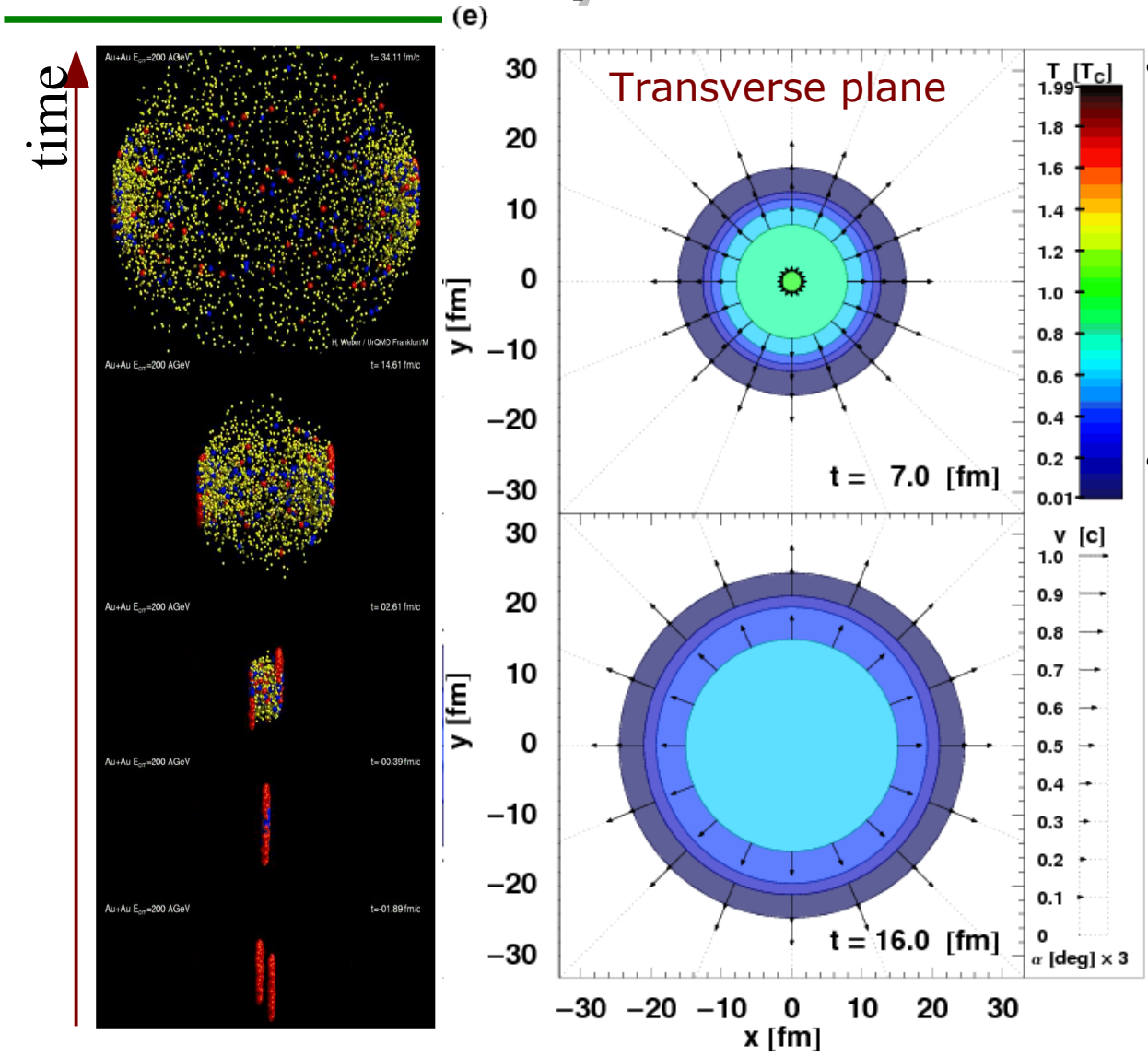
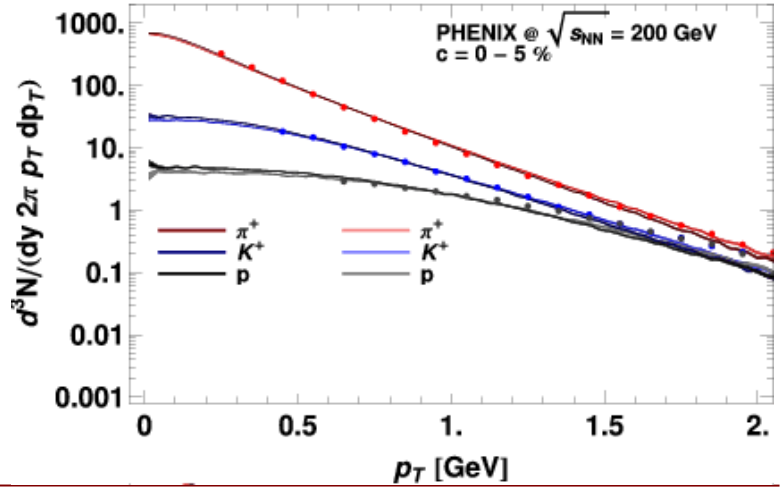
Heavy-ion collision evolution

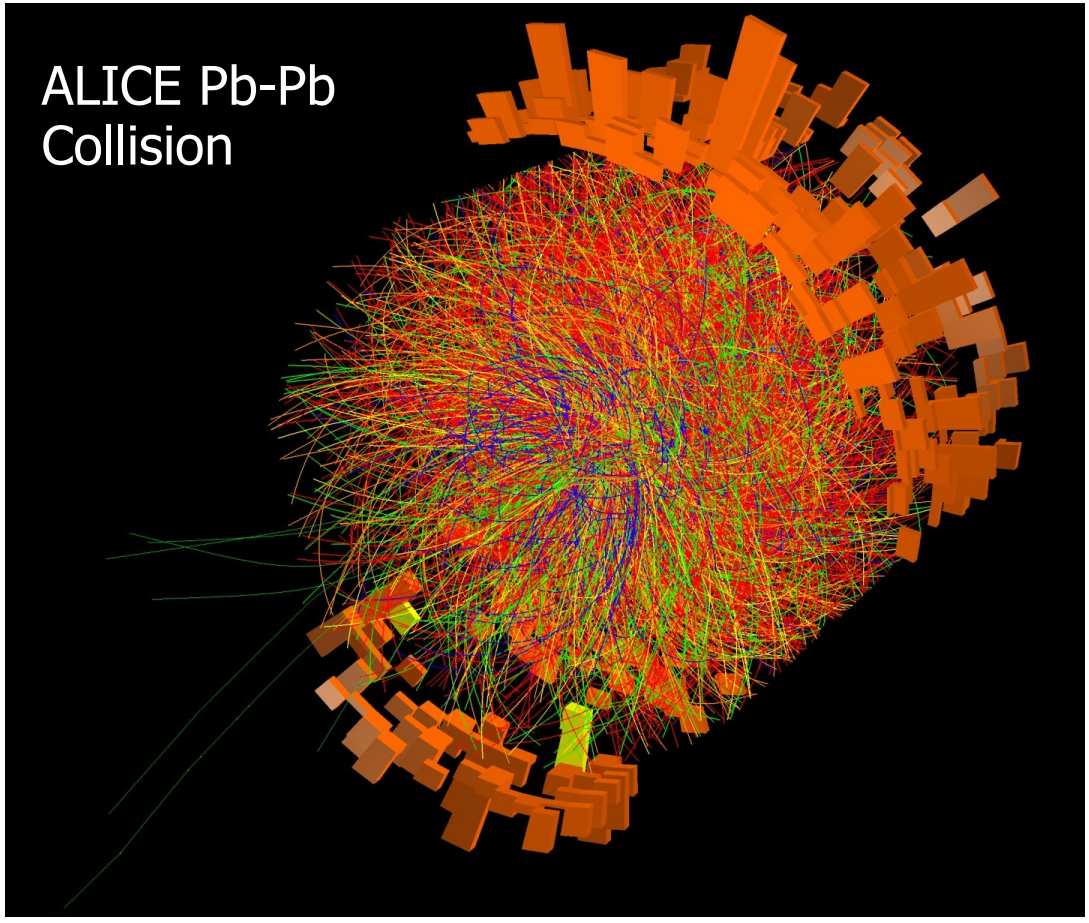


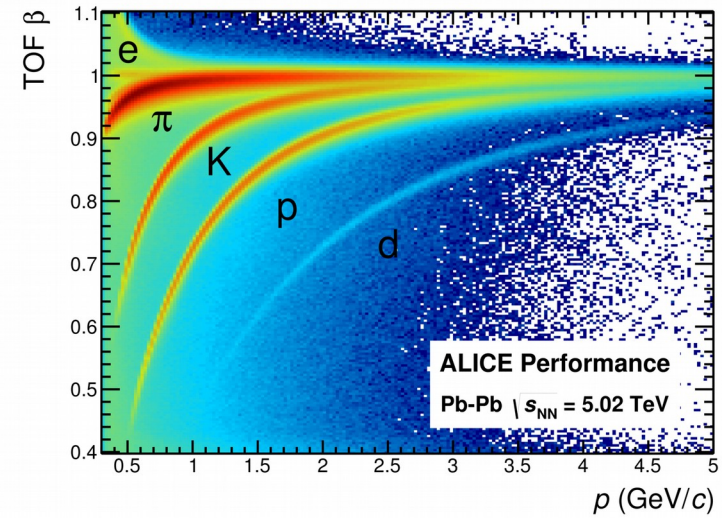
M. Chojnacki, W. Florkowski, PRC 74 (2006) 034905

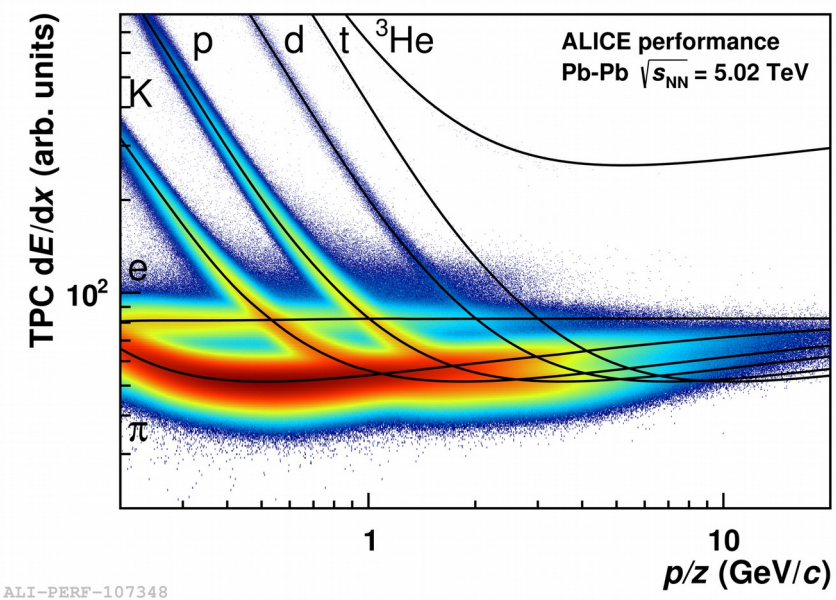
- HIC is expected to go through a QGP phase, from which particles are produced (freeze-out) thermally
- Matter moves collectively in explosive manner (radial flow)



Particle production in HIC



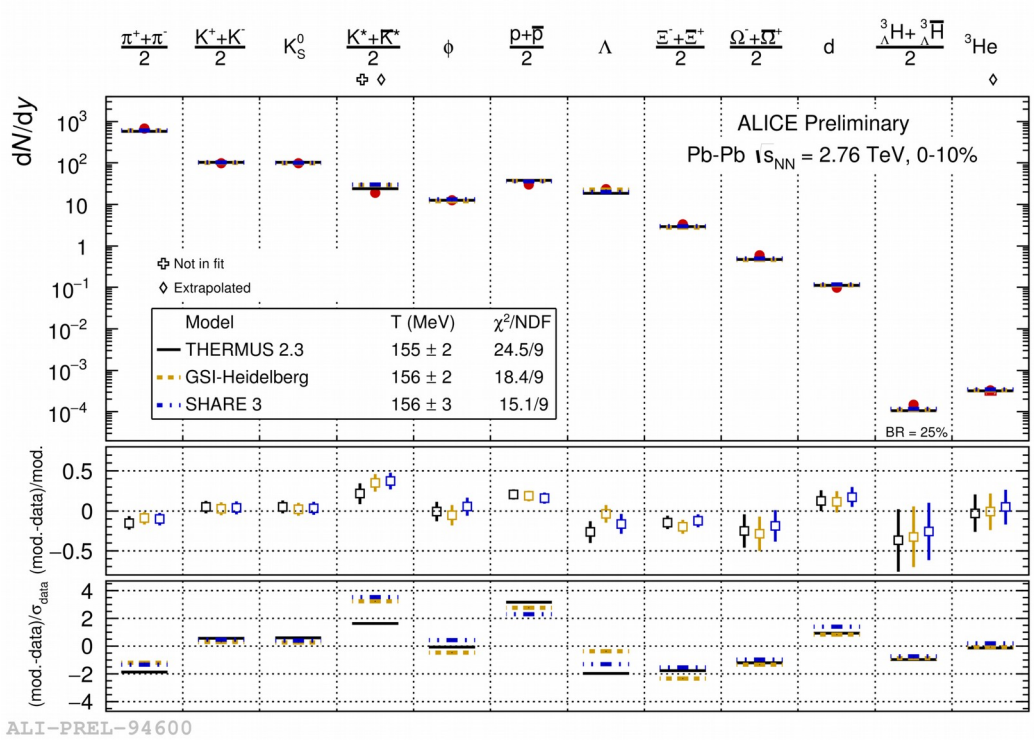


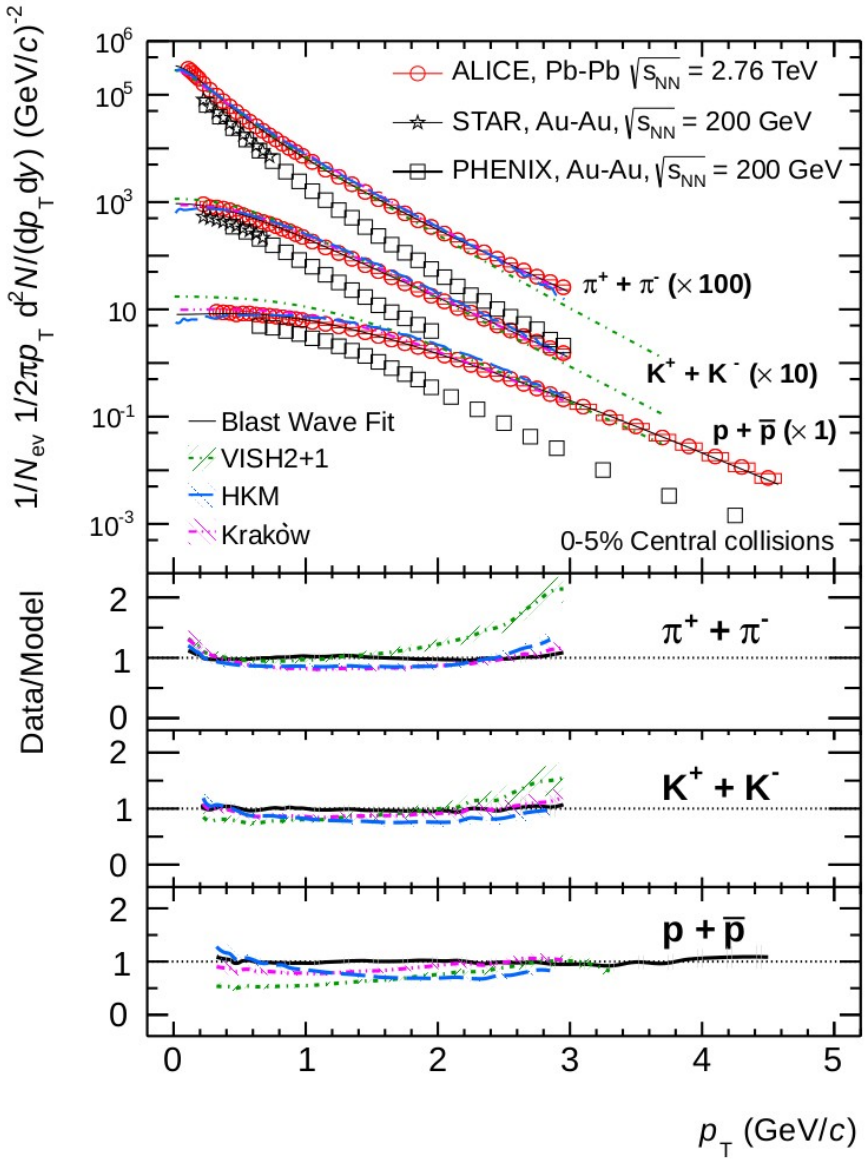


- At RHIC and LHC – several thousand particles per event
- STAR, ALICE – excellent PID at low p_T

(Anti-)Baryon production in HIC

- Similar no. of baryons and anti-baryons produced at RHIC and LHC, at low-p_T, PID needed (STAR, ALICE)
- HIC are matter-antimatter pair factories (p, Λ, Ξ, Ω, ...)





Baryon femtoscopy

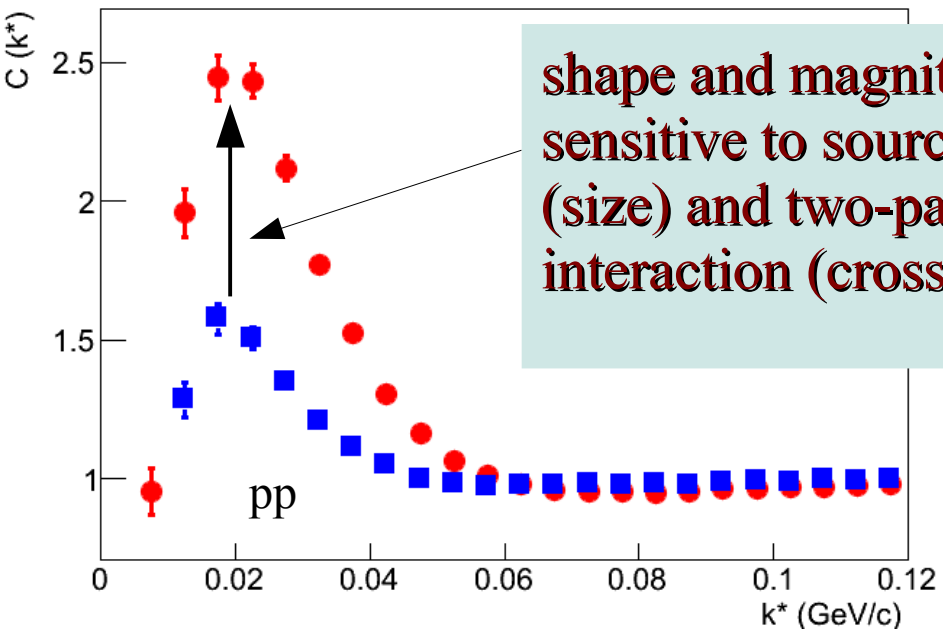
- Femtoscopy: use two-particle correlation function C and known interaction Ψ to extract information on the source emission function S

$$C(\vec{q}) = \int S(\vec{r}) |\Psi(\vec{q}, \vec{r})|^2 d^4 r \quad \text{(Koonin-Pratt equation)}$$

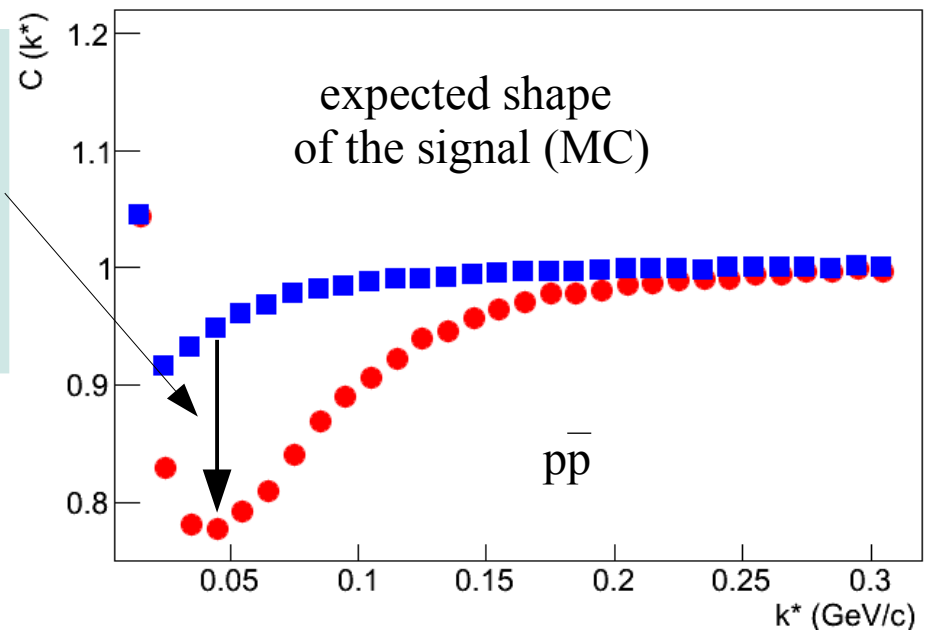
measured correlation

emission function (radius)

cross-section

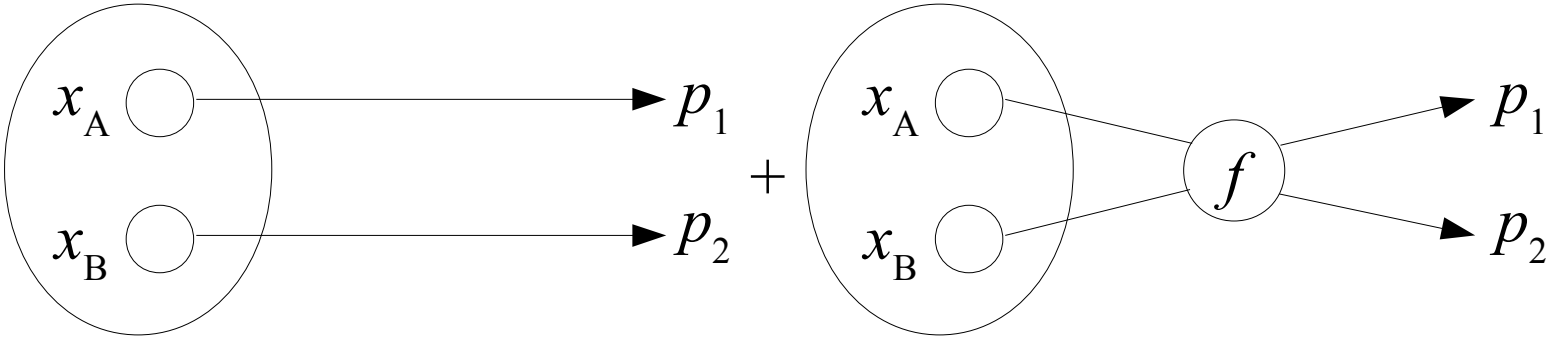


shape and magnitude sensitive to source shape (size) and two-particle interaction (cross-section)



- The procedure can be reversed: study Ψ with known S

Correlation from Strong interaction



$q = 2k^* = p_1 - p_2$

$r = x_A - x_B$

- Femtoscopy: correlation C connects interaction Ψ and source S

$$C(\vec{q}) = \int S(\vec{r}) |\Psi(\vec{q}, \vec{r})|^2 d^4 r$$

- Strong interaction after hadrons' last scattering (freeze-out)
  - Ψ is the Bethe-Salpeter amplitude, (solution of the quantum scattering problem, taken with the inverse time direction)

$$\Psi = \exp(-i \vec{k}^* \vec{r}) + f \frac{\exp(ik^* r)}{r} \qquad \text{(s-wave approximation)}$$

$$f^{-1} = \frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - ik^* \qquad \text{(effective range approximation)}$$

  - Cross-section σ (at low relative momentum k^*) is simply:

$$\sigma = 4\pi |f|^2$$

Lednicky&Lyuboshitz formula

- For the case of pure strong interaction, the integral equation for C performed analytically for a Gaussian source S:

$$C(k^*)=1+\sum_S \rho_S\left[\frac{1}{2}\left|\frac{f^S(k^*)}{R}\right|^2\left(1-\frac{d_0^S}{2\sqrt{\pi}R}\right)+\frac{2\Re f^S(k^*)}{\sqrt{\pi}R}F_1(2k^*R)-\frac{\Im f^S(k^*)}{R}F_2(2k^*R)\right]$$

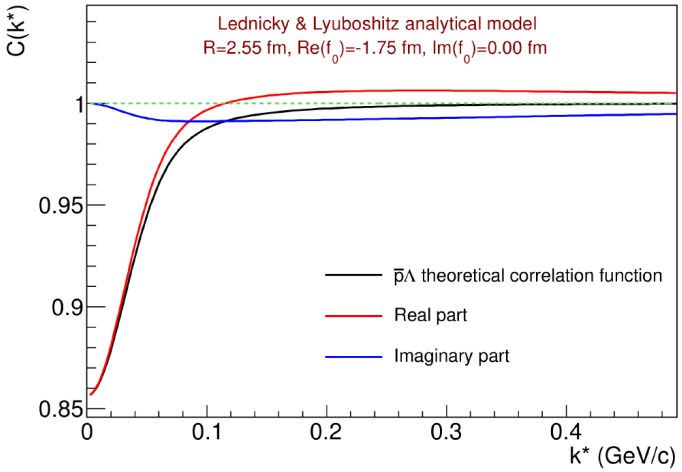
  where ρ_S are the pair spin fractions, F_1 and F_2 are known functions, R is the Gaussian source width (variance)

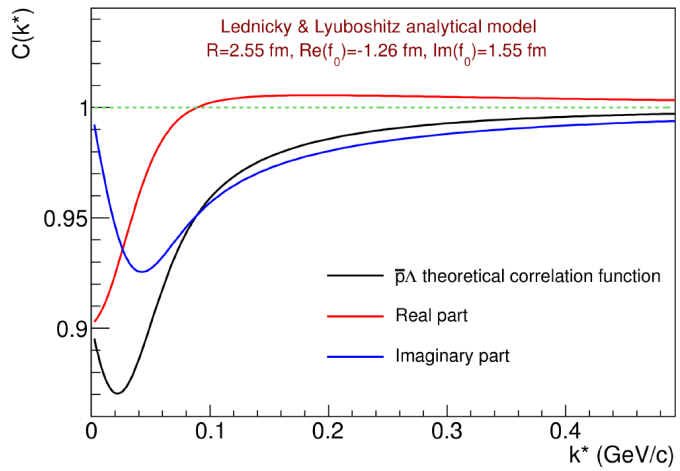
- Scattering length f_0 and effective range d_0 appear directly in the correlation function form, real and imaginary part of f have distinctly different contributions

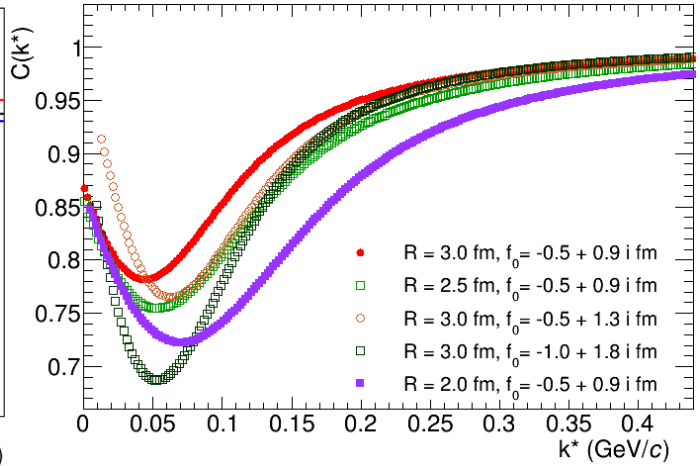
- Not realistic to fit R and interaction parameters (f_0, d_0) simultaneously, at least one must be fixed

Lednicky, Lyuboshitz, Sov. J. Nucl. Phys., 35, 770 (1982)

Real and imaginary part of f

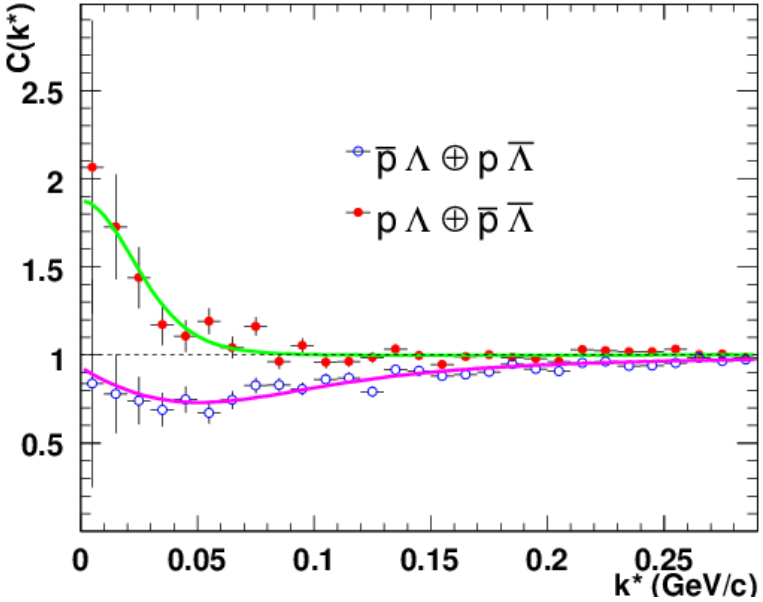




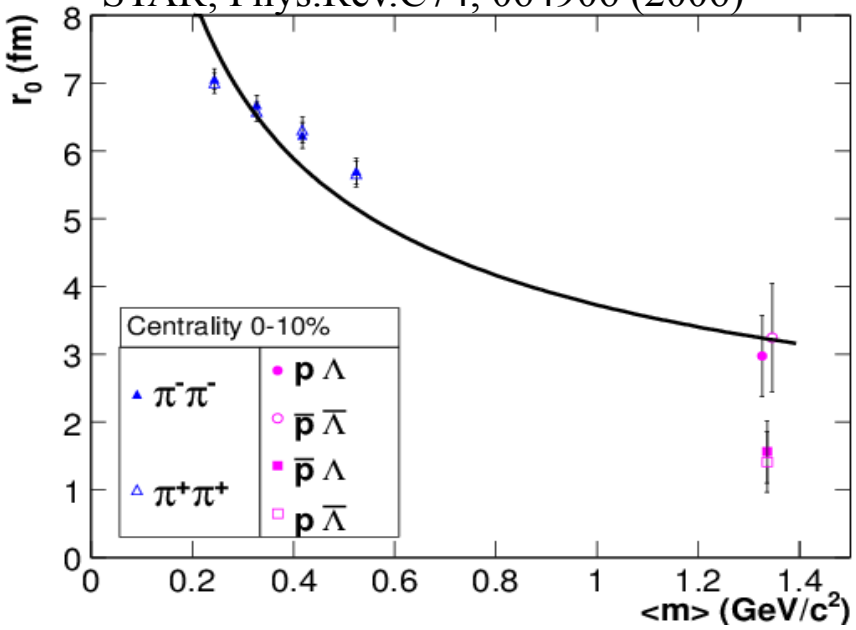


- A sharp peak (depression) at low k^*, for positive (negative) value of Re(f_0) (width – up to 100 MeV/c)
- A broad depression at larger k* for non-zero values of Im(f_0) (baryon annihilation) (width – several hundred MeV/c)
- Dependence of the CF on the system size and scattering length non-trivial, may be difficult to distinguish

Has it been done? $p\Lambda$ and $p\bar{\Lambda}$ in STAR



STAR; Phys.Rev.C74, 064906 (2006)

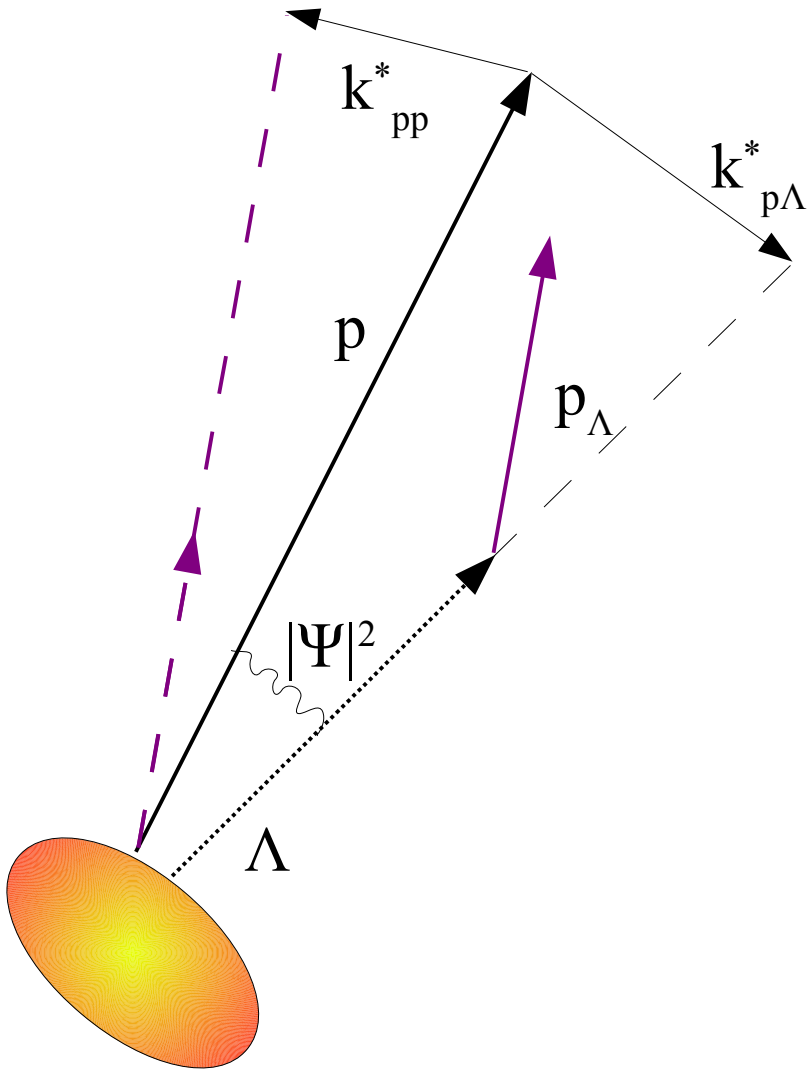


- Data fitted with Lednicky&Lyuboshitz formula
- $p\Lambda$ radius is 3.09 fm, predictions from hydrodynamics (m_T or k_T scaling) also give a "large" radius

  AK, M. Gałażyn, P. Bożek, Phys.Rev. C90 (2014) 6, 064914
  Yu.Sinyukov, V. Shapoval, V. Naboka, arXiv:1508.01812
- Unrealistically low radius obtained for $p\bar{\Lambda}$ from the fit (should be similar)

  R=1.50 +/- 0.05 +/- 0.3 fm
- Effective range fixed to 0
- Residual correlations explicitly not taken into account

Residual correlations

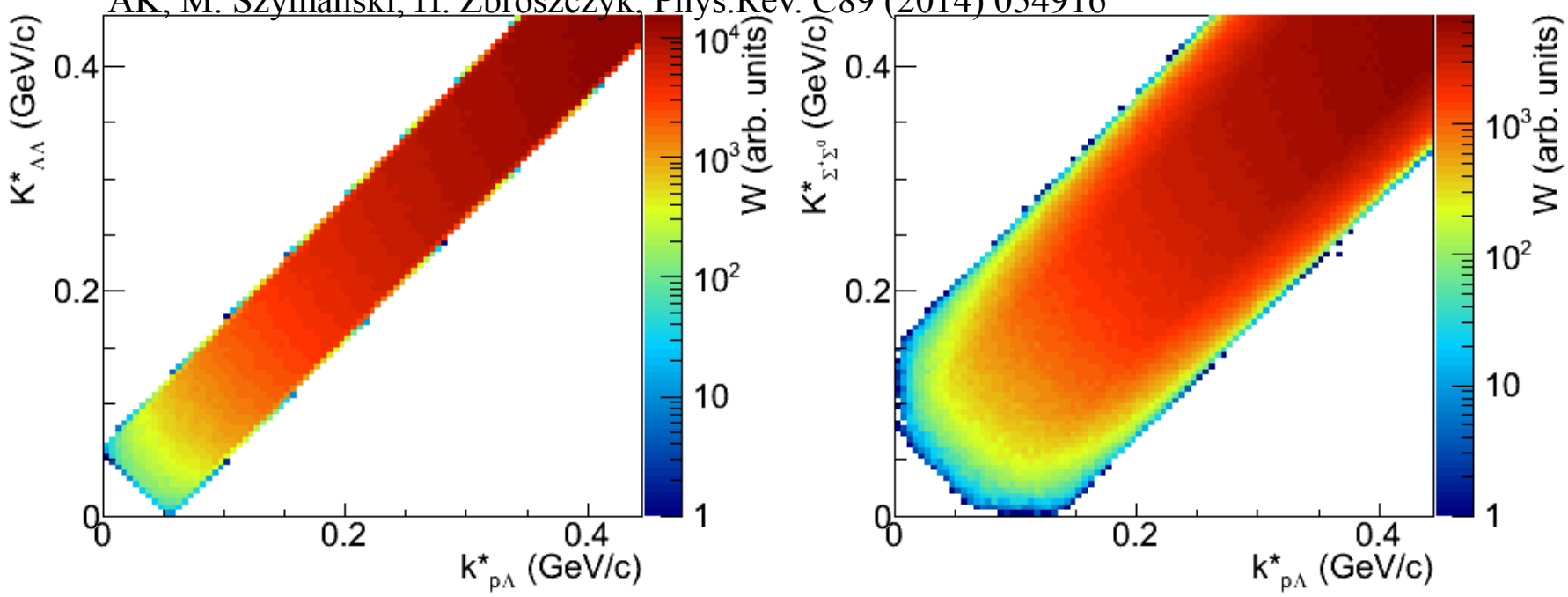


- For colliders weak decay baryons with momentum in similar direction as parent – decay momentum is small with respect to the baryon mass (e.g. Λ → p: 101 MeV/c)
- The femtoscopic correlation of the parent pair is smeared by the decay, but can still be significant – if:
  - (A) Parent correlation is strong (large cross-section)
  - (B) Secondaries are numerous with respect to primordial baryons
  - (C) Decay momentum is small

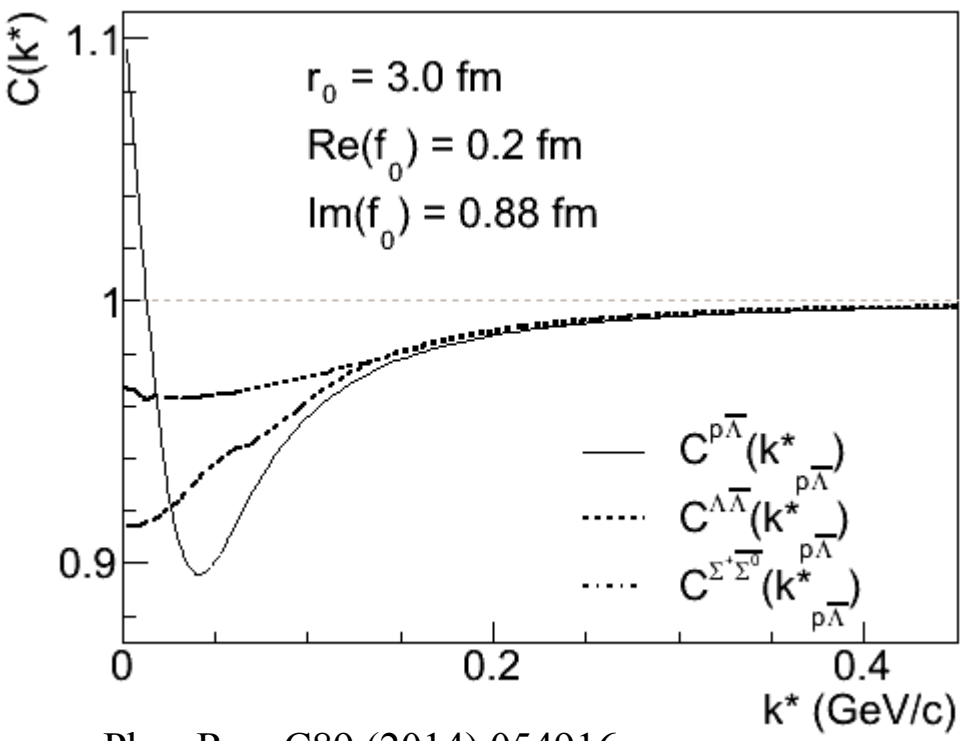
The transformation matrix

- The transformation matrix T from parent pair k* to the daughter pair k* determined by random decay, bound by decay momenta
- When only one particle decays, it has a rectangular shape, for pairs when both particles decay it is smeared more

F. Wang, S. Pratt; Phys. Rev. Lett. 83, 3138 (1999)
AK, M. Szymański, H. Zbroszczyk, Phys.Rev. C89 (2014) 054916



Smearing by decay



Phys.Rev. C89 (2014) 054916

- By how much is the correlation smeared in the decay?
- At low momentum the shape changes significantly and is smoothed out, but is not trivial
- At large momentum the contribution is very similar to the original one

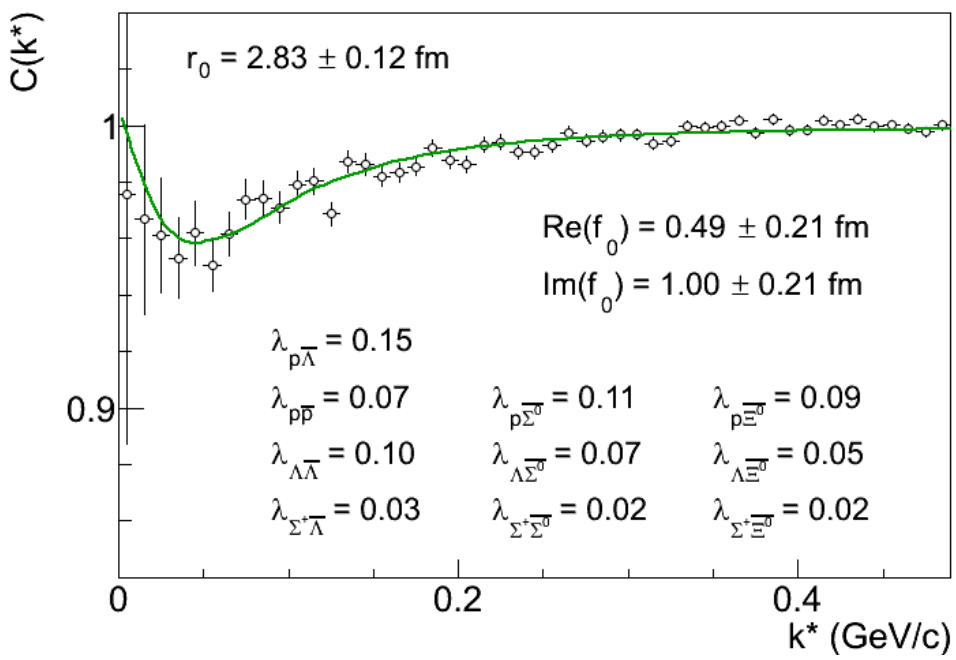
$$C^{\bar{X}Y\to\bar{p}\Lambda}(k^*_{\bar{p}\Lambda})=\frac{\int C^{\bar{X}Y}(k^*_{\bar{X}Y})\,W(k^*_{\bar{p}\Lambda},k^*_{\bar{X}Y})\,dk^*_{\bar{X}Y}}{\int W(k^*_{\bar{p}\Lambda},k^*_{\bar{X}Y})\,dk^*_{\bar{X}Y}}$$

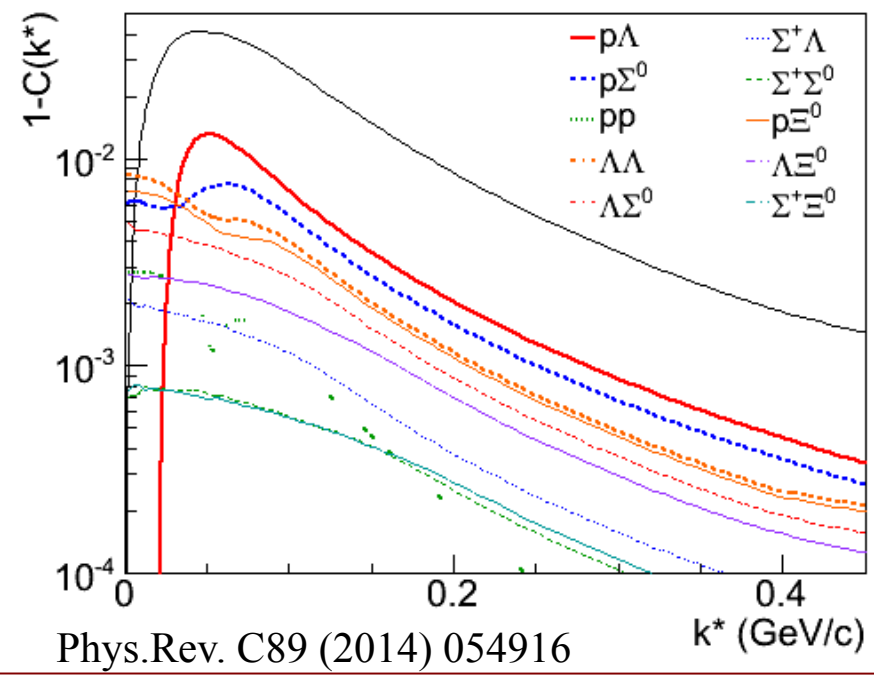
Correcting STAR $p\bar{\Lambda}$ for residual corr.

- The correlation is fitted with:

$$C^{\bar{X}Y\to\bar{p}\Lambda}(k^*_{\bar{p}\Lambda})=1+\lambda_{p\Lambda}\left(C^{\bar{p}\Lambda}(k^*_{\bar{p}\Lambda})-1\right)+\sum_{\bar{X}Y}\lambda_{\bar{X}Y}\left(C^{\bar{X}Y}(k^*_{\bar{p}\Lambda})-1\right)$$

- Radius comparable to the expectations is obtained
- All pairs provide a significant contribution to the correlation
- Im(f_0) asumed the same for all pairs – consistent with $p\bar{p}$





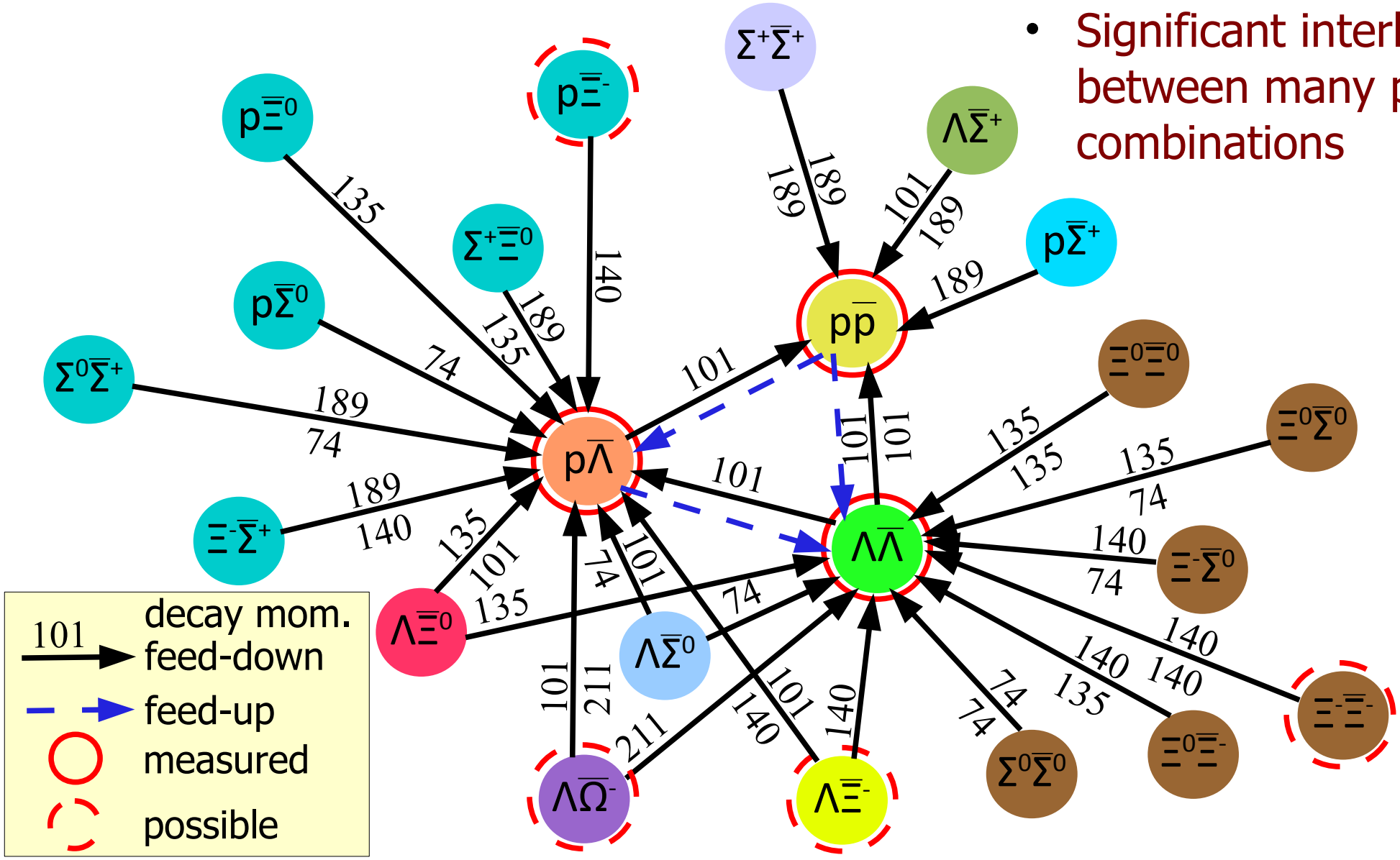
Phys.Rev. C89 (2014) 054916

Measuring $B\overline{B}$ in ALICE

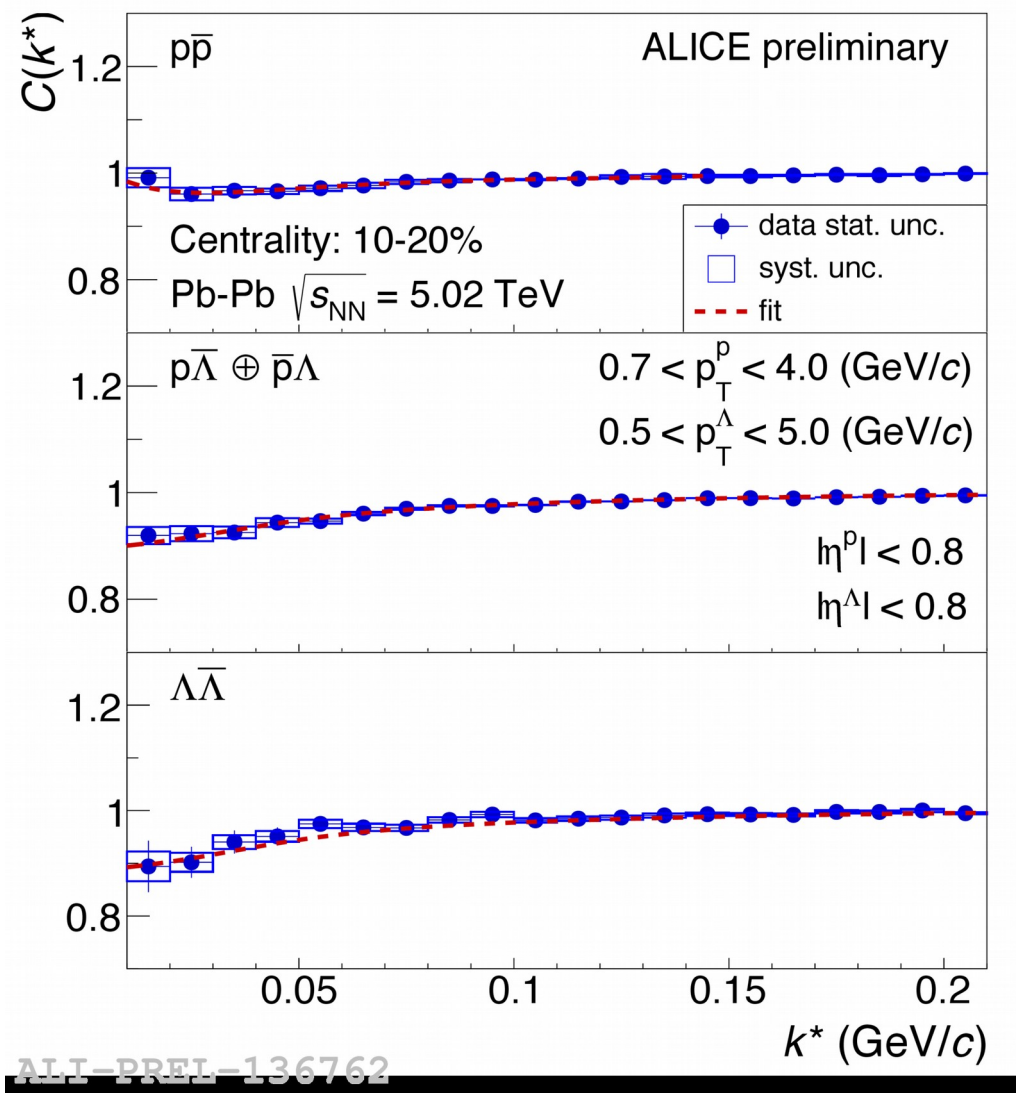
- Recent ALICE measurement of baryon-(anti-)baryon correlations
  - 6 centralities, 2 collision energies, 3 baryon-antibaryon systems (+3 baryon-baryon as well, not shown here)
- Employed dedicated PID procedures of ALICE
  - Protons measured directly in TPC, also used TOF for PID
  - Lambdas measured via V0 decay topology with TPC, PID enhanced by TOF as well
- Complete set of $p\overline{p}$, $p\overline{\Lambda}$, $\Lambda\overline{\Lambda}$ correlation functions
  - In fitting – used spin-averaged (f_0, d_0), separate sets for $p\overline{\Lambda}$, $\Lambda\overline{\Lambda}$ and a separate set for all higher-mass residual pairs

Residual correlation web

- Significant interlinks between many pair combinations



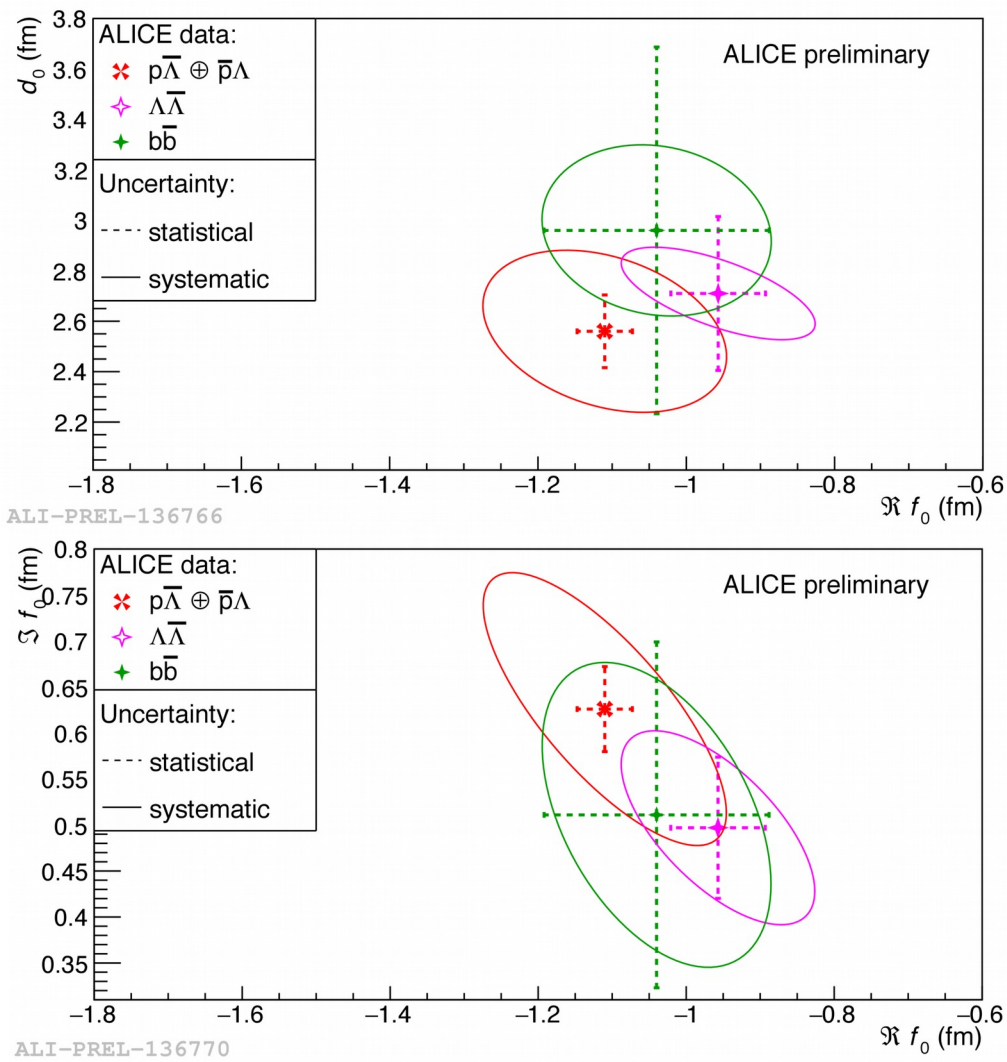
Baryon-Antibaryon in ALICE



L. Barnby (ALICE), EXA 2017
Ł. Graczykowski (ALICE), ISMD 2017

- All combinations of baryon-antibaryon correlation functions with pairs containing protons and lambdas
- Fit fully including the web of residual correlations
- Combined fit to 6 centralities x 2 collision energies x 3 systems
- Interaction parameters free in the fit (3 sets)
- Sizes constrained to m_T scaling predictions

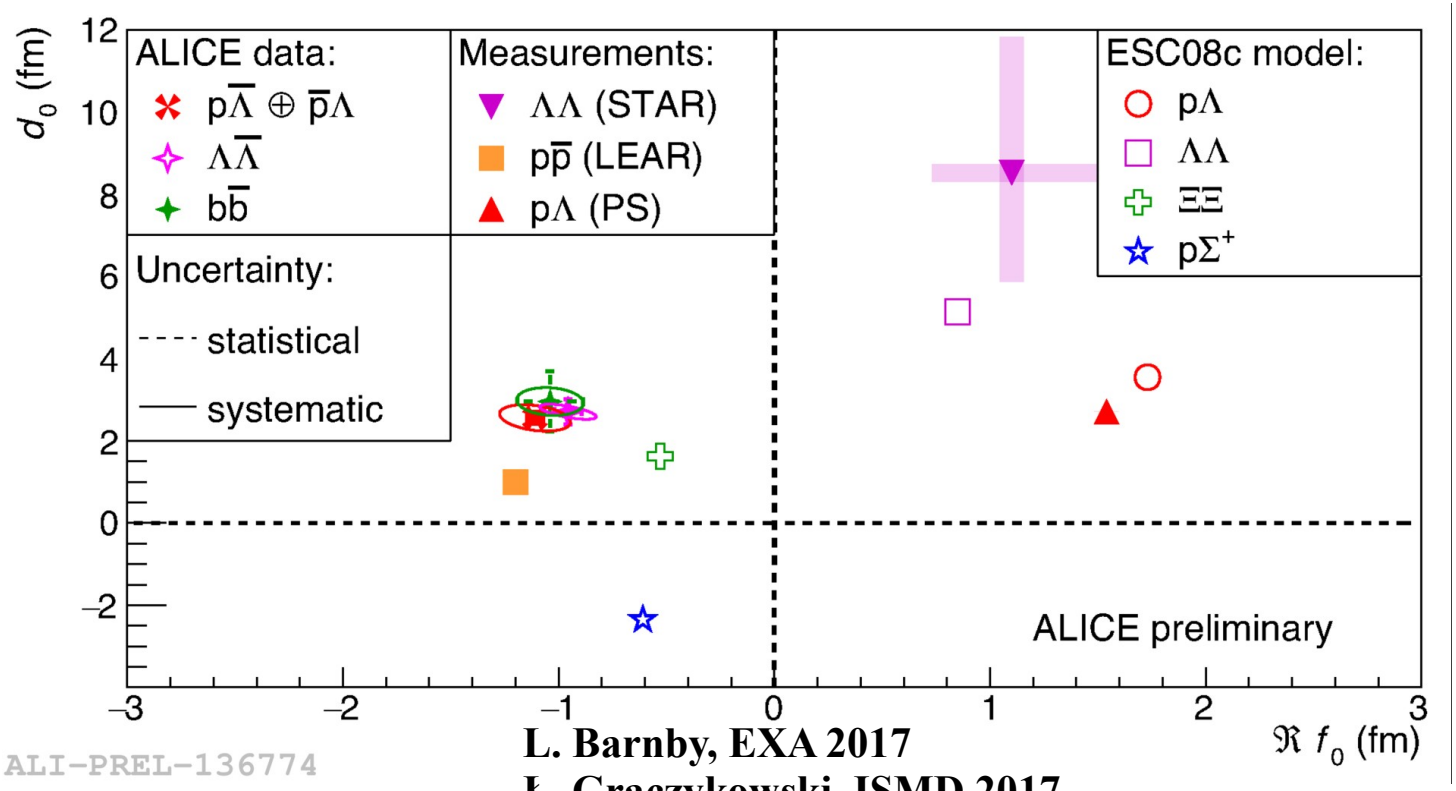
Measurement of strong $B\bar{B}$ interaction



L. Barnby (ALICE), EXA 2017
Ł. Graczykowski (ALICE), ISMD 2017

- Estimation of the scattering length and effective range
- Assumption of d_0=0 not necessary
- Non-zero negative value of the real part of f_0
- Non-zero value of imaginary part of f_0 (annihilation), comparable for all pair types

Comparison to other measurements



L. Barnby, EXA 2017
Ł. Graczykowski, ISMD 2017

- ALICE measurement competitive in accuracy to world data on baryon-antibaryon interaction
- Real part of f_0 for baryon-antibaryon – comparable value but opposite sign to baryon-baryon

Conclusions

- RHIC and LHC are baryon-antibaryon pair factories, provide unique measurement opportunities
- The correlations are sensitive to the strong interaction potential parameters, including the annihilation
- Residual correlations are especially relevant for baryon pairs due to the ratio of decay momenta to particle momenta
- Residual correlations are particularly important for annihilation due to the large k^*-width of the effect
- STAR data on proton-antilambda correlations is reanalyzed taking into account residual correlations, giving realistic results
- Combined fit for 3 pair types done for the first time in ALICE
- ALICE provides world-class data on all parameters of the baryon-antibaryon strong scattering parameters, with more potentially in the future, also for baryon-baryon, including (multi-)strange baryons