Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

ALICE

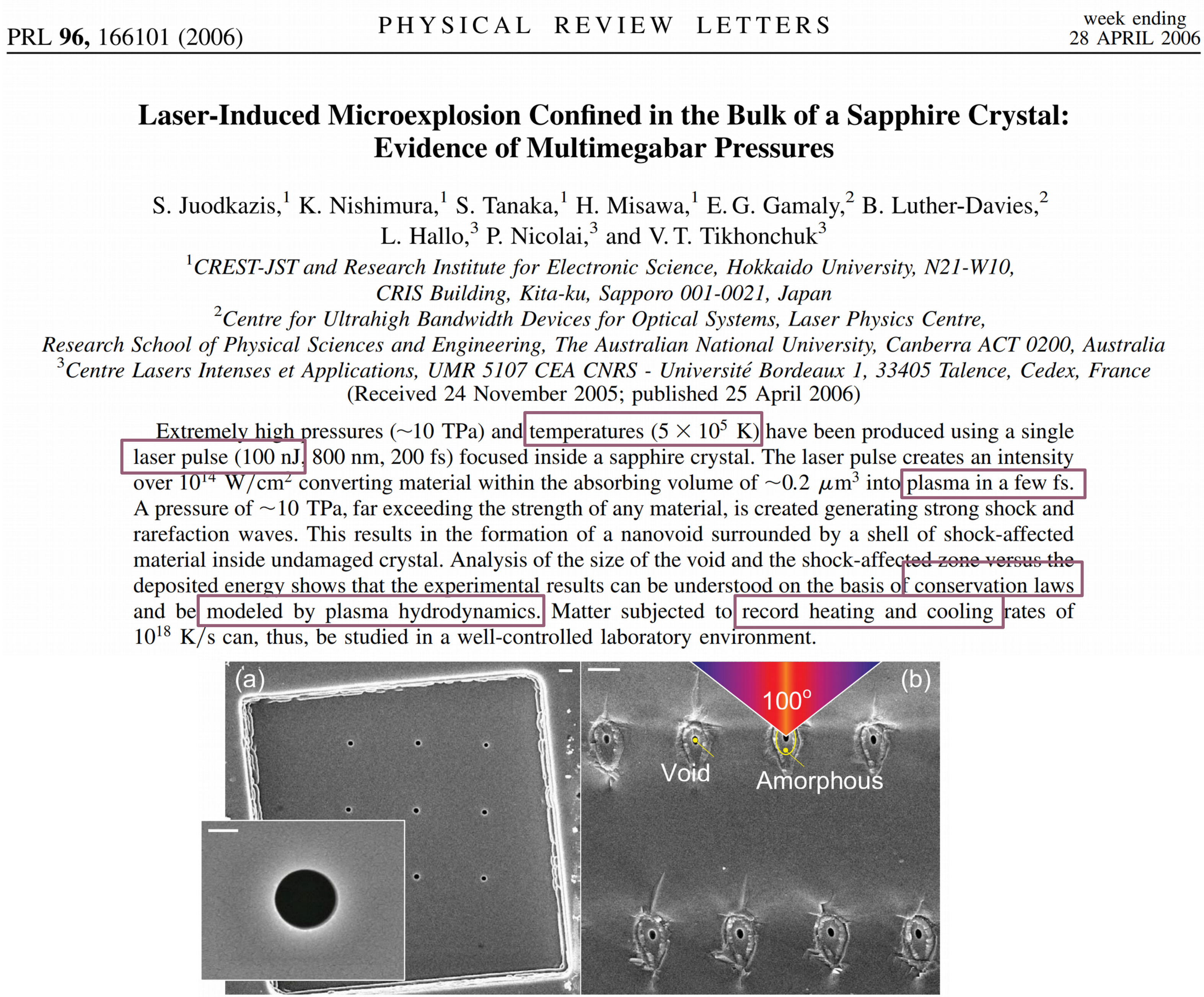
Probing space-time evolution at the femtometer scale in pp and Pb-Pb collisions with ALICE

Łukasz Graczykowski
for the ALICE Collaboration

CERN-LHC Seminar
CERN
5 March 2019

Idea borrowed from Mike Lisa

Femtoscopy technique



PRL **96,** 166101 (2006) PHYSICAL REVIEW LETTERS week ending 28 APRIL 2006

Laser-Induced Microexplosion Confined in the Bulk of a Sapphire Crystal: Evidence of Multimegabar Pressures

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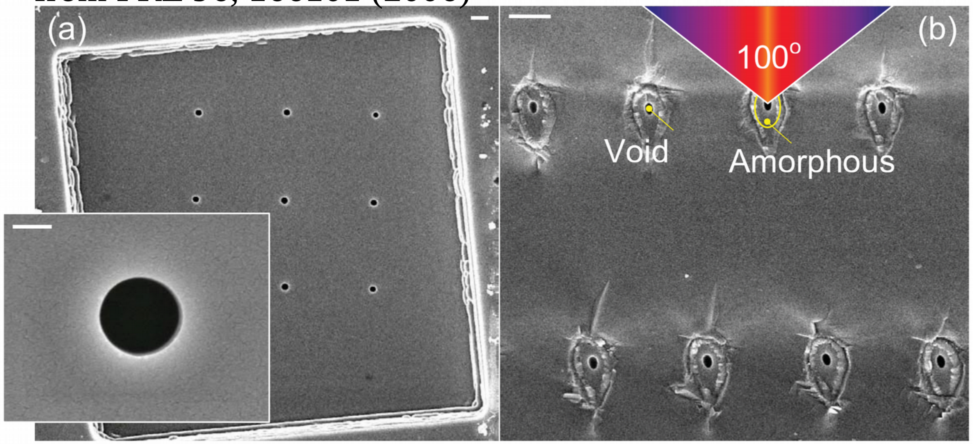
(Received 24 November 2005; published 25 April 2006)

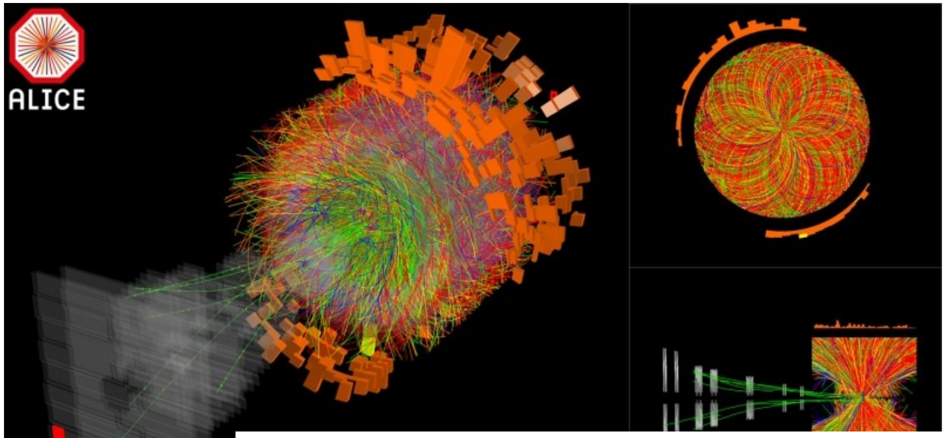
Extremely high pressures (~10 TPa) and temperatures (5×10^5 K) have been produced using a single laser pulse (100 nJ, 800 nm, 200 fs) focused inside a sapphire crystal. The laser pulse creates an intensity over 10^{14} W/cm^2 converting material within the absorbing volume of ~0.2 μm^3 into plasma in a few fs. A pressure of ~10 TPa, far exceeding the strength of any material, is created generating strong shock and rarefaction waves. This results in the formation of a nanovoid surrounded by a shell of shock-affected material inside undamaged crystal. Analysis of the size of the void and the shock-affected zone versus the deposited energy shows that the experimental results can be understood on the basis of conservation laws and be modeled by plasma hydrodynamics. Matter subjected to record heating and cooling rates of 10^{18} K/s can, thus, be studied in a well-controlled laboratory environment.

Idea borrowed from Mike Lisa

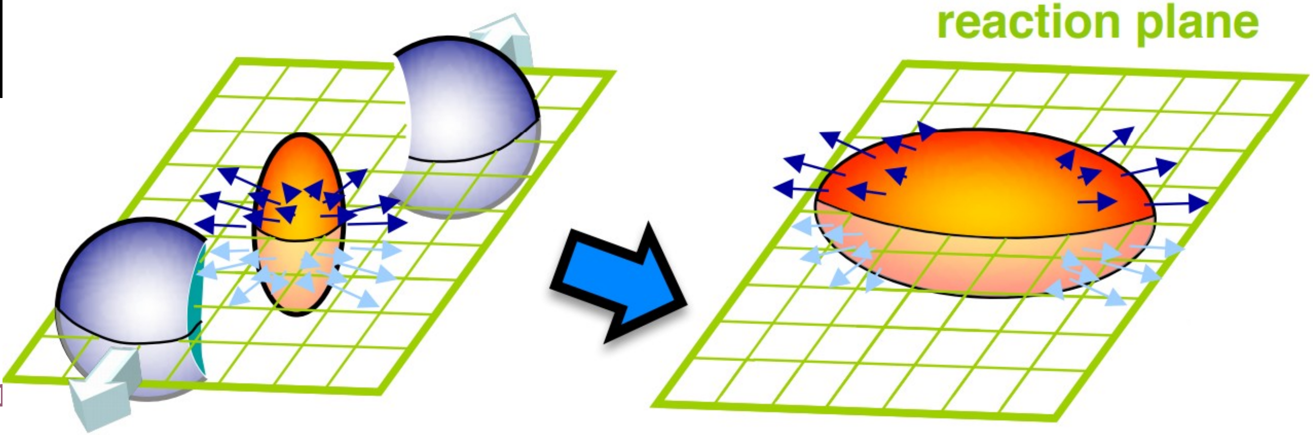
Femtoscopy technique

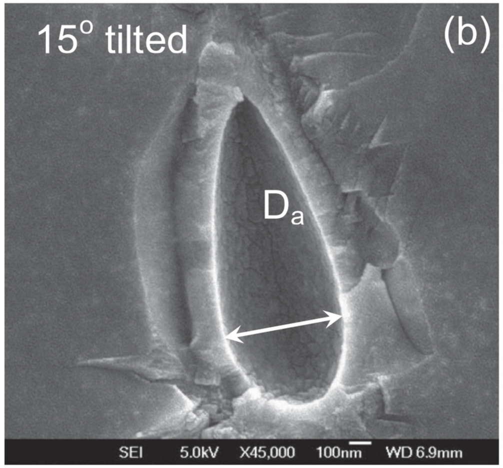
from PRL 96, 166101 (2006)



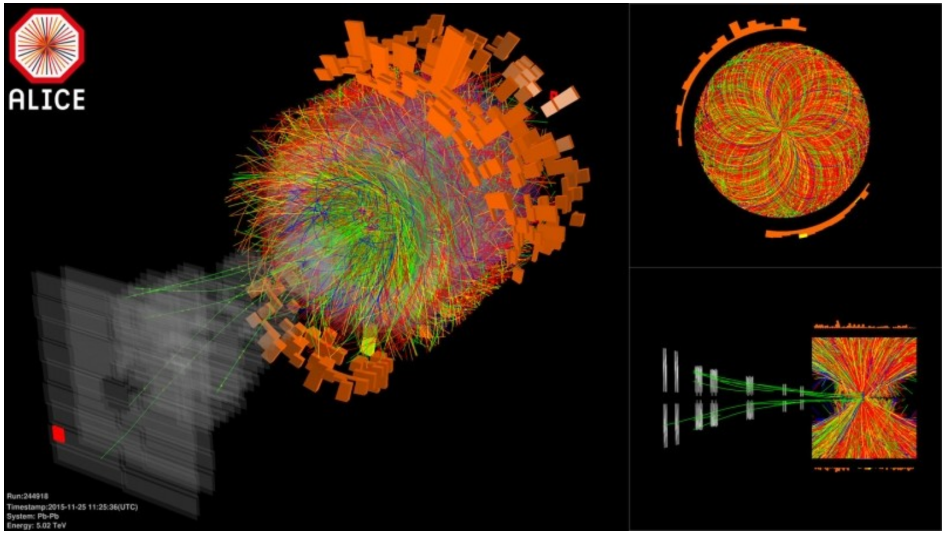


- Does it look similar?
- Let’s see:
  - energy quickly deposited
  - enter plasma phase
  - expand hydrodynamically
- We can do a “post mortem” analysis to investigate i.e. the source geometry

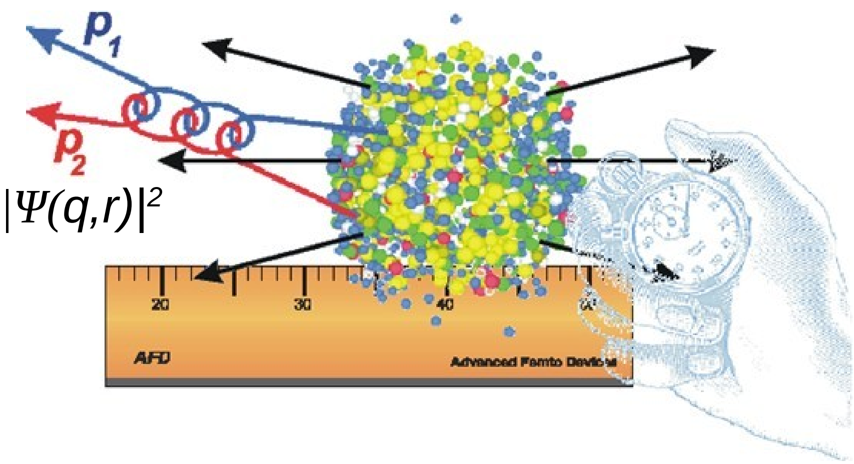




Femtoscopy technique



from M. Lisa and S. Pratt



- **Femtoscopy – measures space-time characteristics of the source using particle correlations in momentum space**

$$C(\vec{p}_1,\vec{p}_2)=\frac{P_{12}(\vec{p}_1,\vec{p}_2)}{P_1(\vec{p}_1)P_2(\vec{p}_2)}$$

$$\vec{q}=\vec{p}_1-\vec{p}_2$$
$$\vec{r}=\vec{x}_1-\vec{x}_2$$

experiment

$$C(\vec{q})=\frac{A(\vec{q})}{B(\vec{q})}$$

$A(\vec{q})$ - correlated pairs (“same events”)

$B(\vec{q})$ - uncorrelated pairs (“mixed events”)

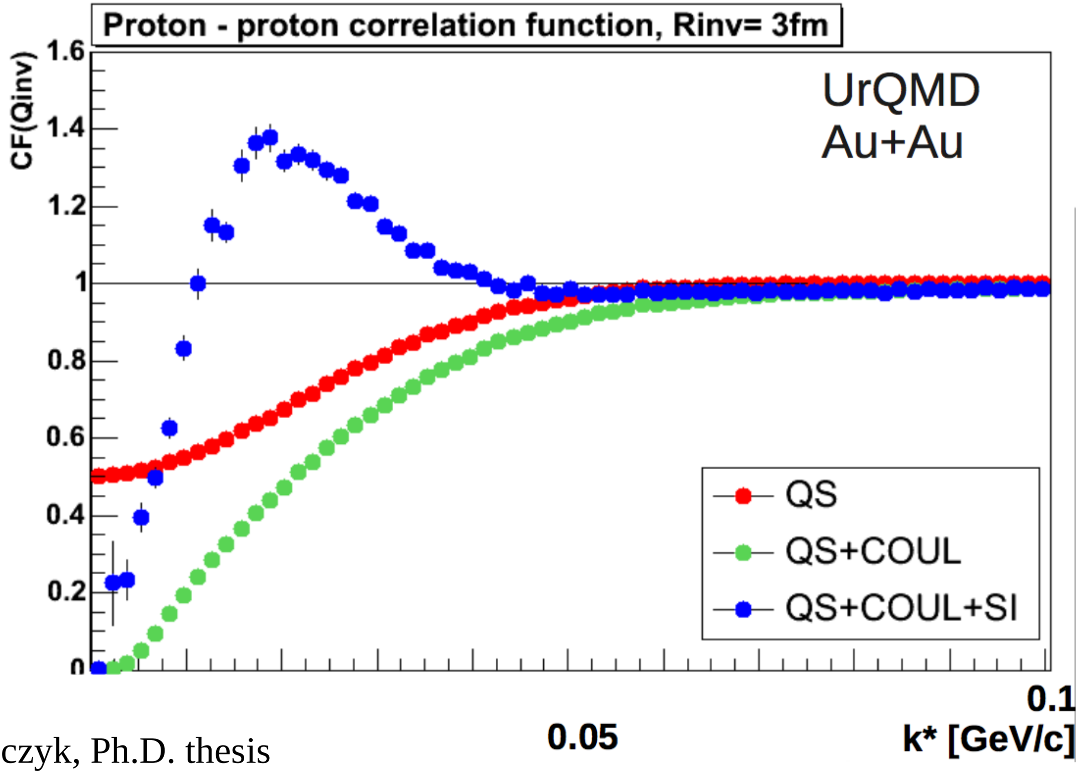
theory (models)

$$C(\vec{q})=\frac{\int d^3r\,S_{12}(\vec{q},\vec{r})|\Psi(\vec{q},\vec{r})|}{\int d^3x_1\,S_1(\vec{x}_1,\vec{p}_1)\int d^3x_2\,S_2(\vec{x}_2,\vec{p}_2)}$$

$$C(\vec{q})=\int d^3r\,S(\vec{q},\vec{r})|\Psi(\vec{q},\vec{r})|$$

Why are particles correlated?

- Main sources of correlations:
  - Quantum statistics (QS)
    - pairs of identical bosons (i.e. pions) – Bose-Einstein QS
    - pairs of identical fermions (i.e. protons) – Fermi-Dirac QS
  - Final-state interactions (FSI)
    - strong interaction
    - Coulomb interaction

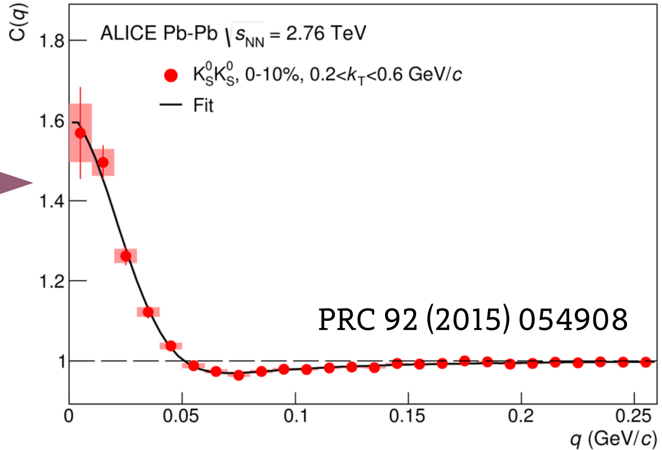


H. Zbroszczyk, Ph.D. thesis

How does it look in data?

Quantum Statistics

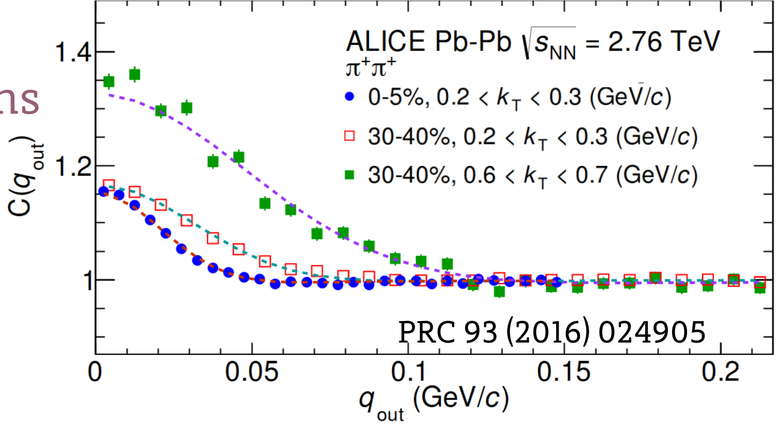
identical neutral kaons



PRC 92 (2015) 054908

Quantum Statistics + Coulomb FSI

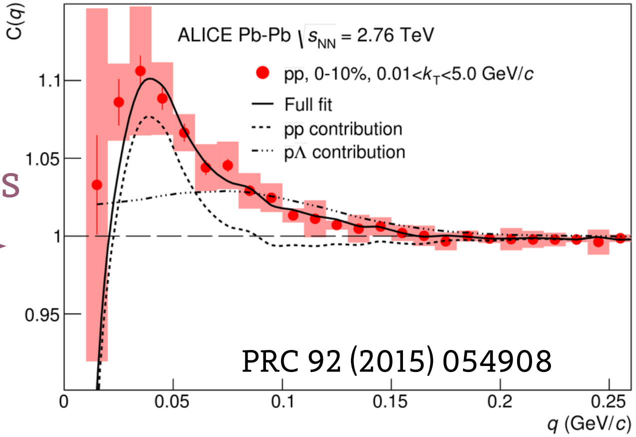
identical charged pions



PRC 93 (2016) 024905

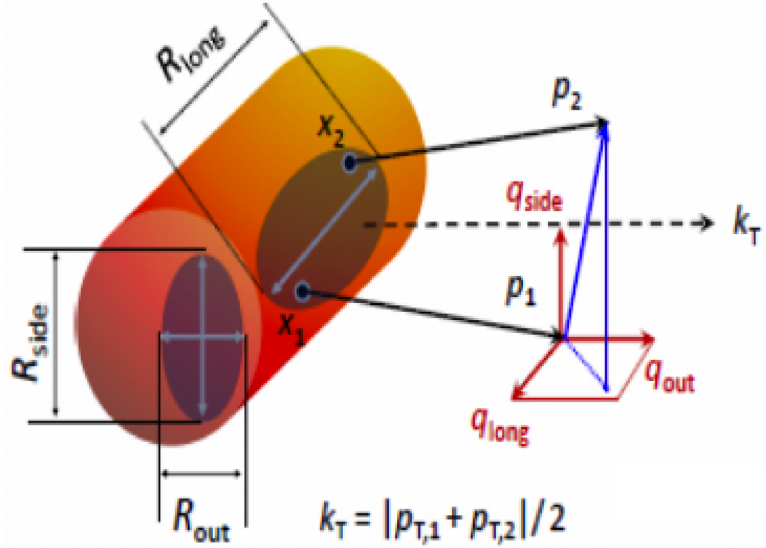
Quantum Statistics + Coulomb FSI + strong FSI

identical protons



PRC 92 (2015) 054908

Know your reference frame



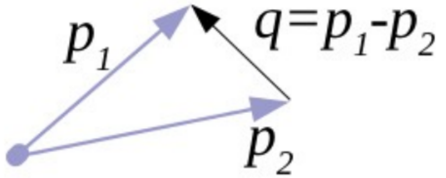
- 3-dimensional **Longitudinally Co-Moving System (LCMS)**
- Decomposition of q:
  - ***Long* along the beam:** sensitive to longitudinal dynamics and evolution time
  - ***Out* along k_T:** sensitive to geometrical size, emission time and space-time correlation
  - ***Side* perpendicular to *Long* and *Out*:** sensitive to geometrical size
- For statistically challenged analyses, measurement in one dimension (giving only one size) in **Pair Rest Frame (PRF)**

$$m_T = \sqrt{k_T^2 + m_\pi^2}$$

LCMS frame:

$$p_{1,long} = -p_{2,long}$$

PRF frame:



$$k^* = \frac{1}{2} q$$

“Traditional” femtoscopy

Measuring the system size

$$C(\vec{q}) = \int \boxed{S(\vec{r})} |\Psi(\vec{q},\vec{r})|^2 d^3 r$$

measured correlation

Obtained by experiment

emission function
(source size/shape)

Unknown

Two-particle
wave function

Interaction known
(e.g. analytical formula)

- **Two main topics in this part:**
  - collectivity and spatial geometry of the system
  - temporal particle emission from QGP

HBT radius

In case of identical bosons, CF is a Fourier transformation of WF

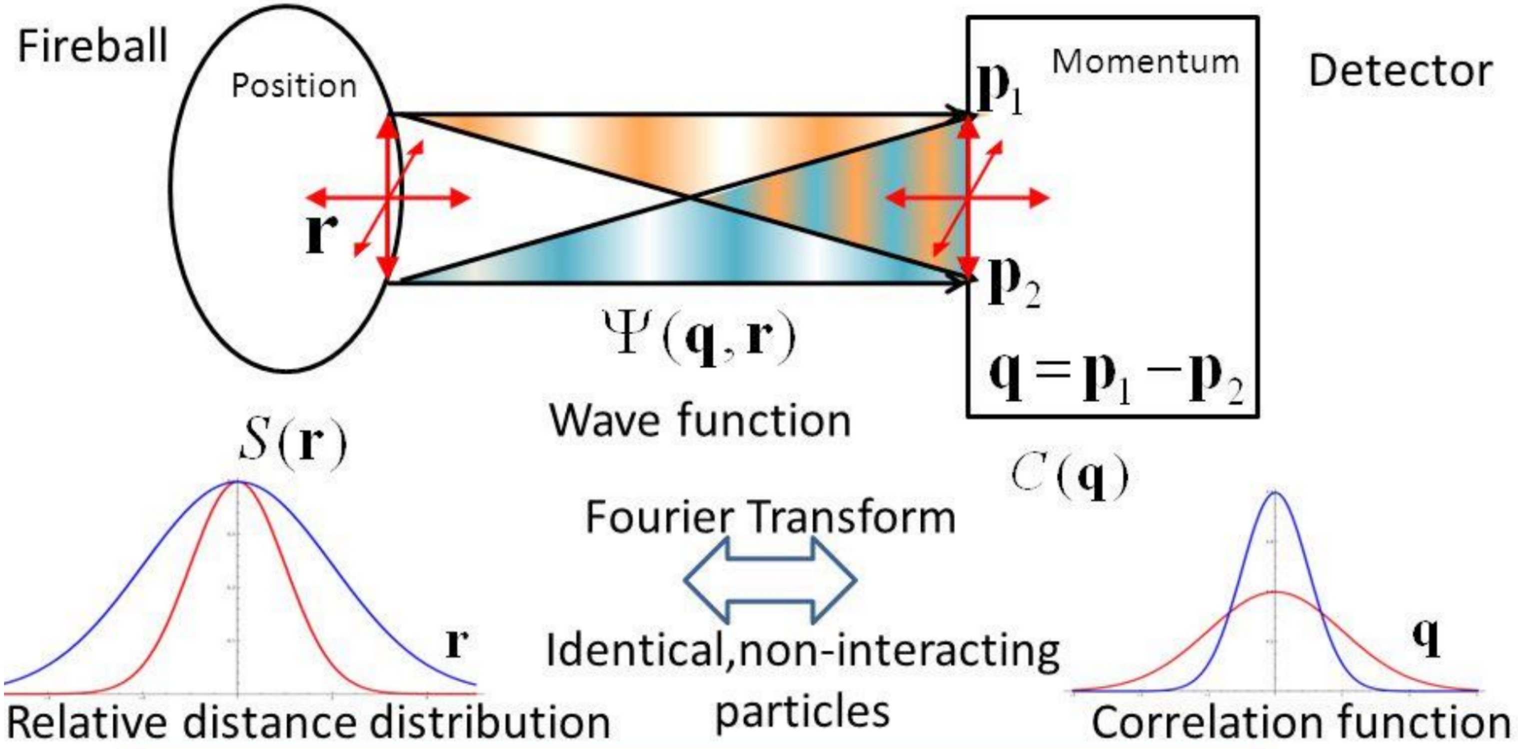
Gaussian source

$$S(\vec{r}) \sim \exp\left(-\frac{r_{out}^2}{4R_o^2} - \frac{r_{side}^2}{4R_s^2} - \frac{r_{long}^2}{4R_l^2}\right)$$

$$|\Psi(\vec{q},\vec{r})|^2 = 1 + \cos(\vec{q}\,\vec{r})$$

Bose-Einstein QS

$$C = 1 + \lambda \exp\left(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2\right)$$



from Michiel de Kock

HBT radius

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Bose-Einstein QS

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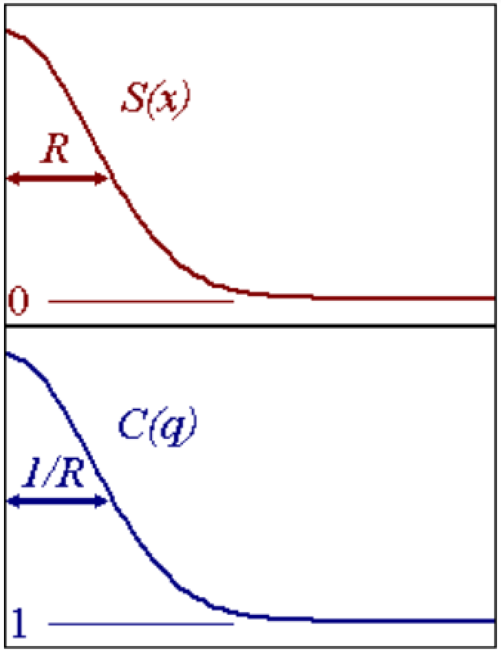
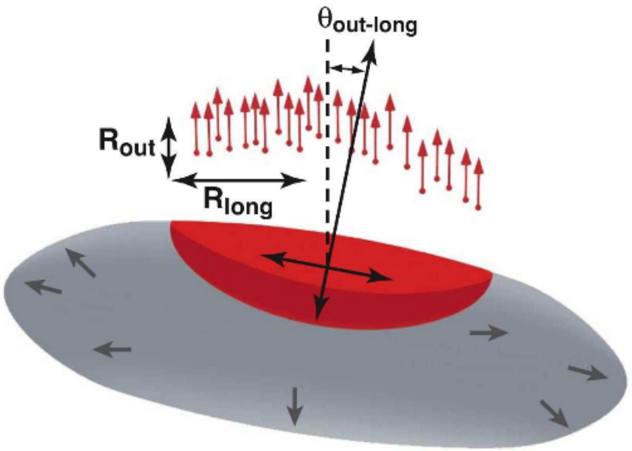
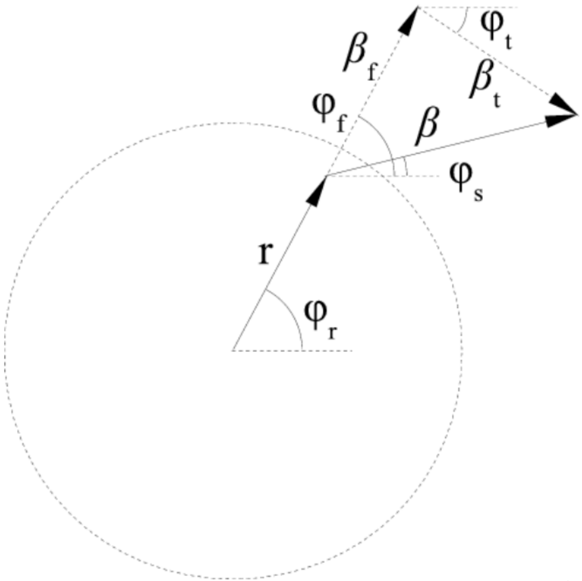




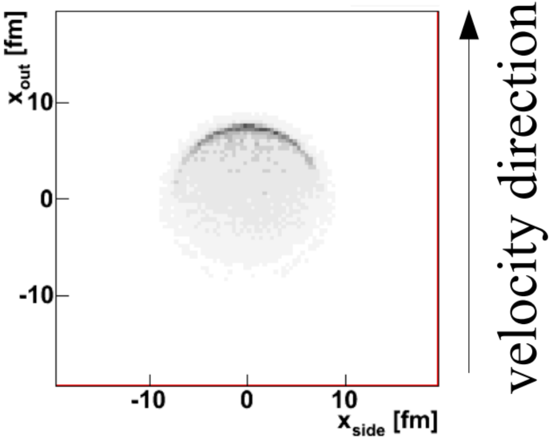
from Ann.Rev.Nucl.Part.Sci.55:357-402,2005

- The size (or sizes in 3D) R is referred to as the **“HBT radius”**
  → size of the **“region of homogeneity”**
  region from which particles are emitted with similar velocity

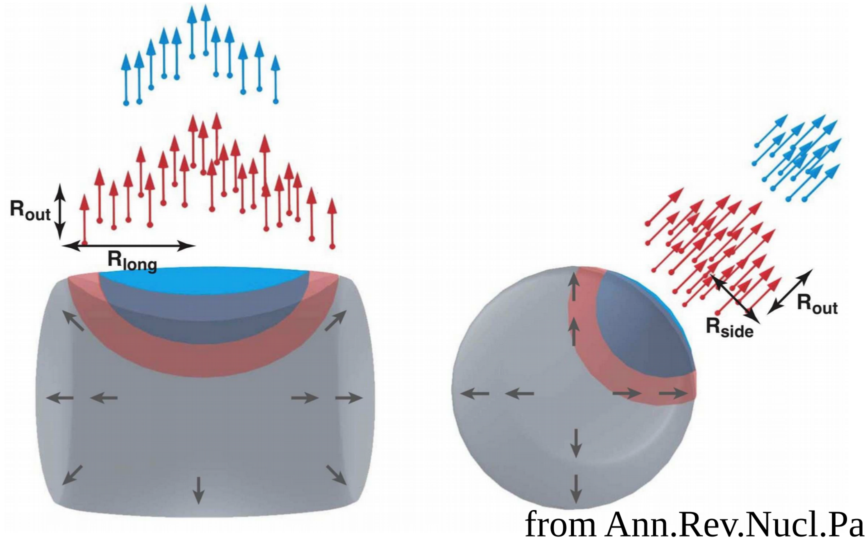
Probing collectivity



- Particle emitted from the medium will have a collective (flow) velocity β_f and thermal (random) velocity β_t
- While m_T (transverse momentum or particle mass) grows, $\beta_t \sim 1/\sqrt{m_T}$ decreases, the region from where particles are emitted gets smaller and shifted towards the outside of the source



from PRC 81, 064906 (2010)



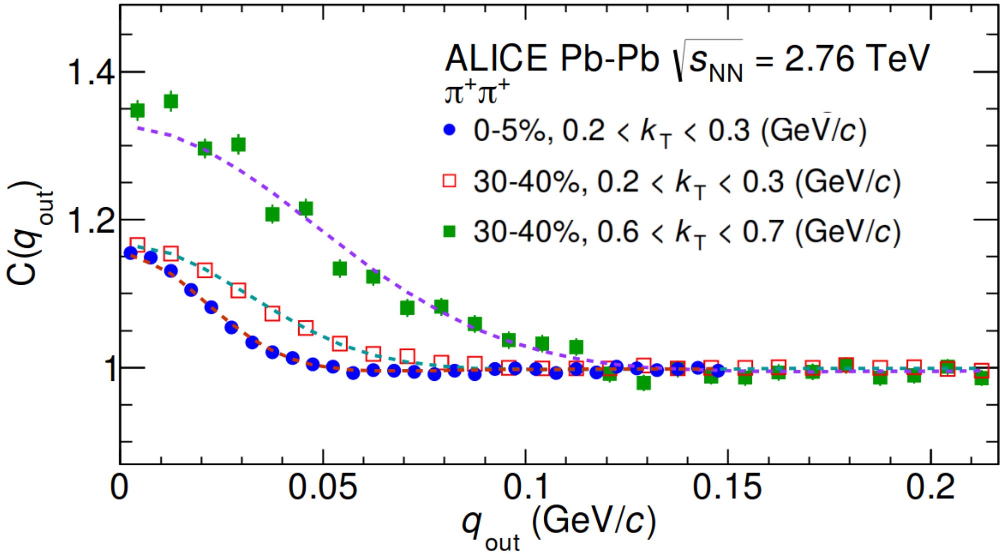
blue – heavier (or higher p_T)

red – lighter (or lower p_T)

from Ann.Rev.Nucl.Part.Sci.55:357-402,2005

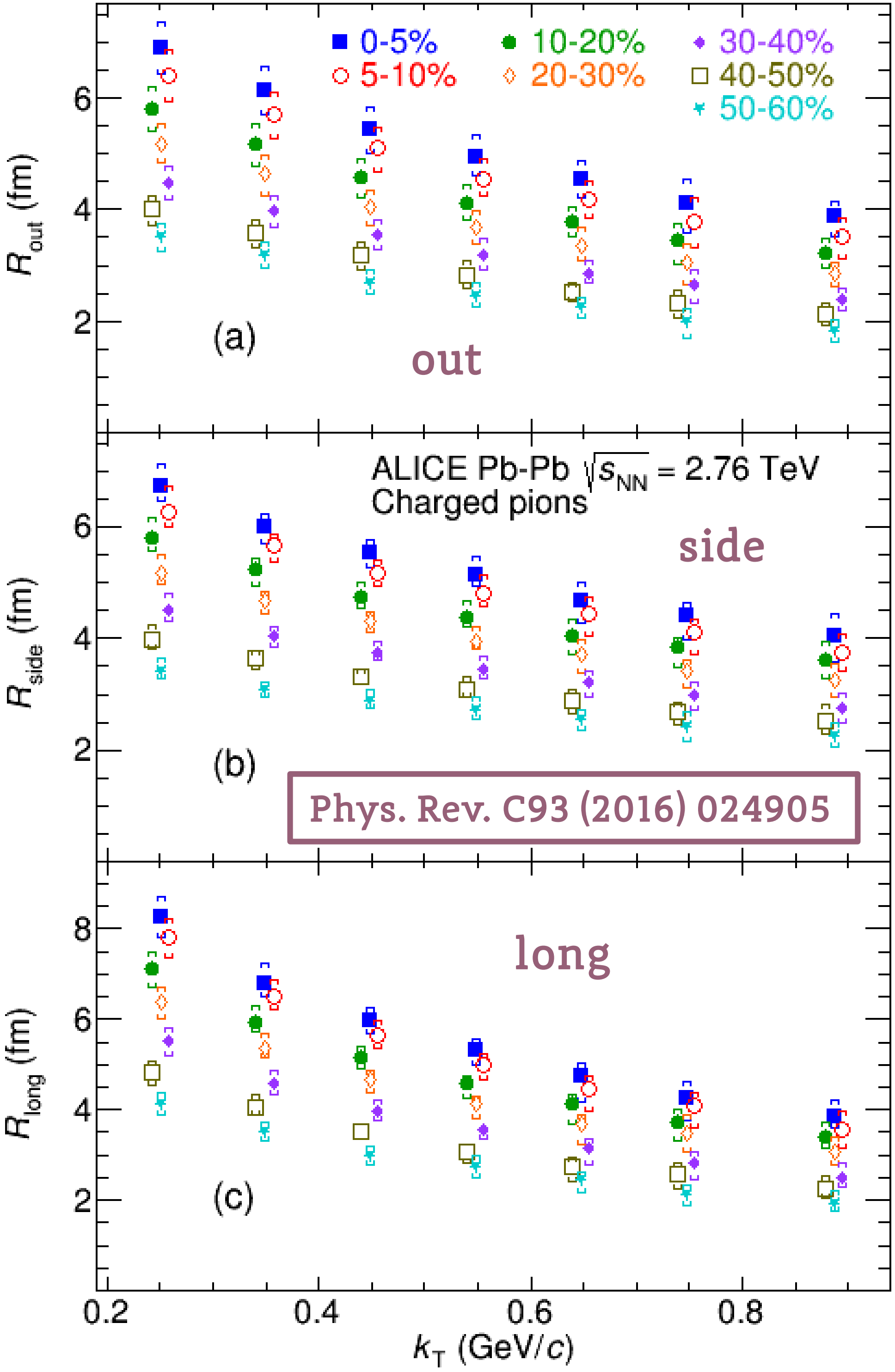
- **<u>Conclusion:</u> HBT radii should get smaller with increasing k_T or m_T**

Pion femtoscopy



- Very **good description** of the measured correlation function with the **Gaussian source**

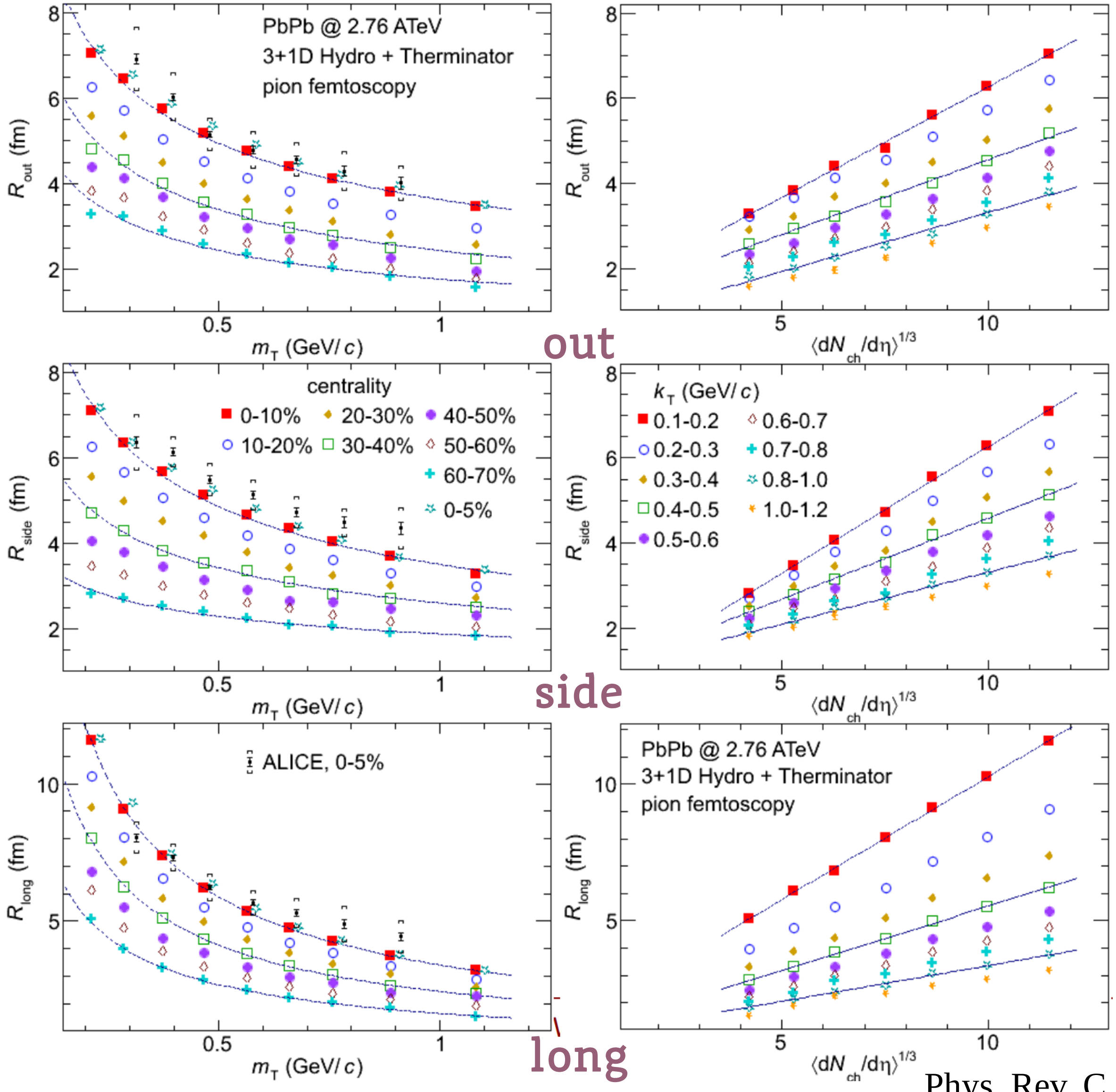
- Radii **universally grow with event multiplicity** and **fall with pair transverse momentum k_T**



Phys. Rev. C93 (2016) 024905

Pion femtoscopy

m_T scaling multiplicity scaling

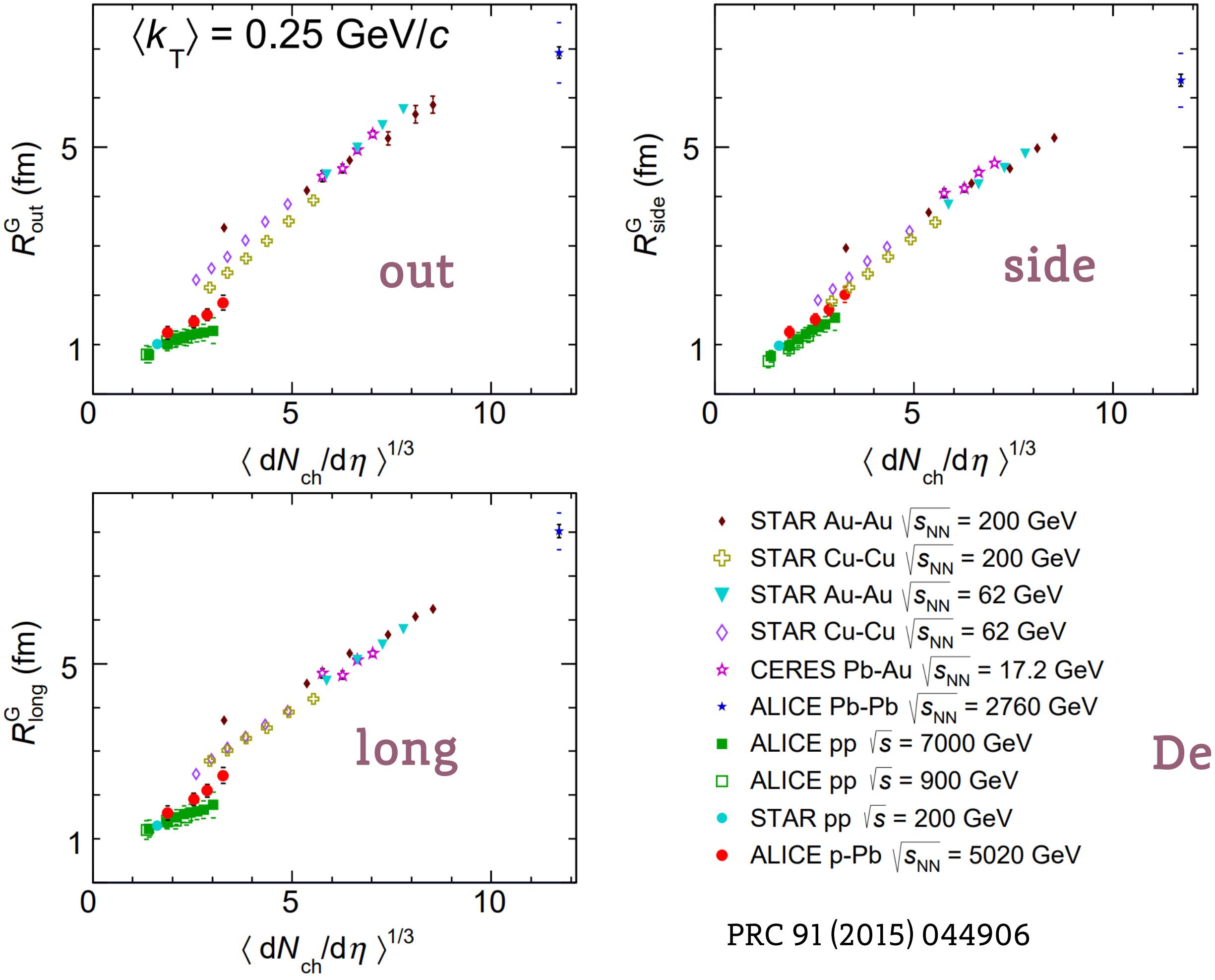


- Both scalings **in agreement with calculations from collective (hydrodynamic) models** – qualitatively and quantitatively

Phys. Rev. C 90, 064914 (2014)

Pion femtoscopy – small systems

- **Remarkable agreement** between many different experiments and energies
- Linearity extends to pp and p-Pb collisions – although slopes are different
- Initial collision geometry does influence the final measured radii



PRC 91 (2015) 044906

$$R \propto N^{1/3}$$

$$R^3 \propto V \propto \mathrm{N}$$

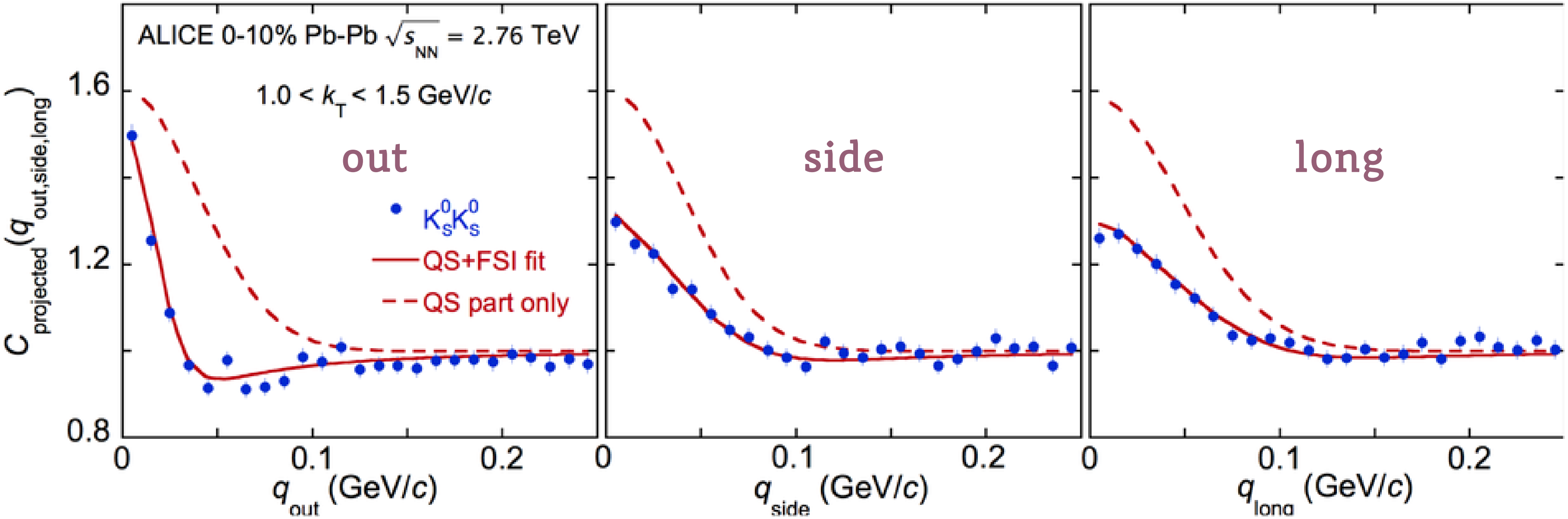
$$\frac{N}{V} = \rho = \text{constant}$$

Density is a function of the measured slope

Kaon femtoscopy

- **Cleaner signal than pions** (less affected by resonance decays)
- **Consistency check**
  - charged and neutral kaons
  - different detection techniques

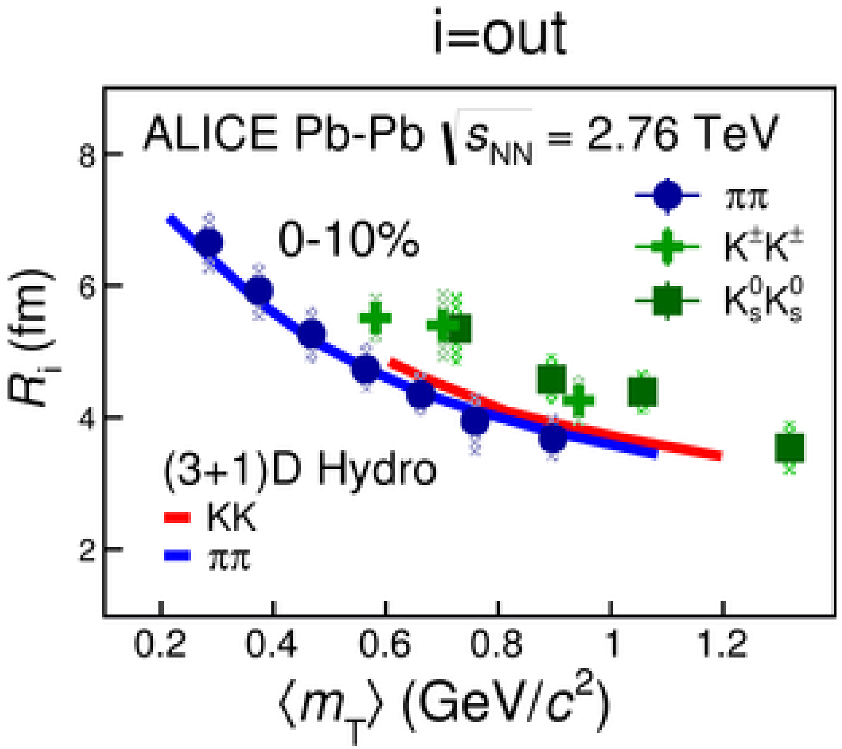
Phys. Rev. C96 (2017) 064613



Kaon femtoscopy

- Results:
  - **broken m_T-scaling** → radii larger than for pions (possibly due to rescattering **through K* resonance**)
  - comparison to hydro **without rescattering phase** → **scaling present**

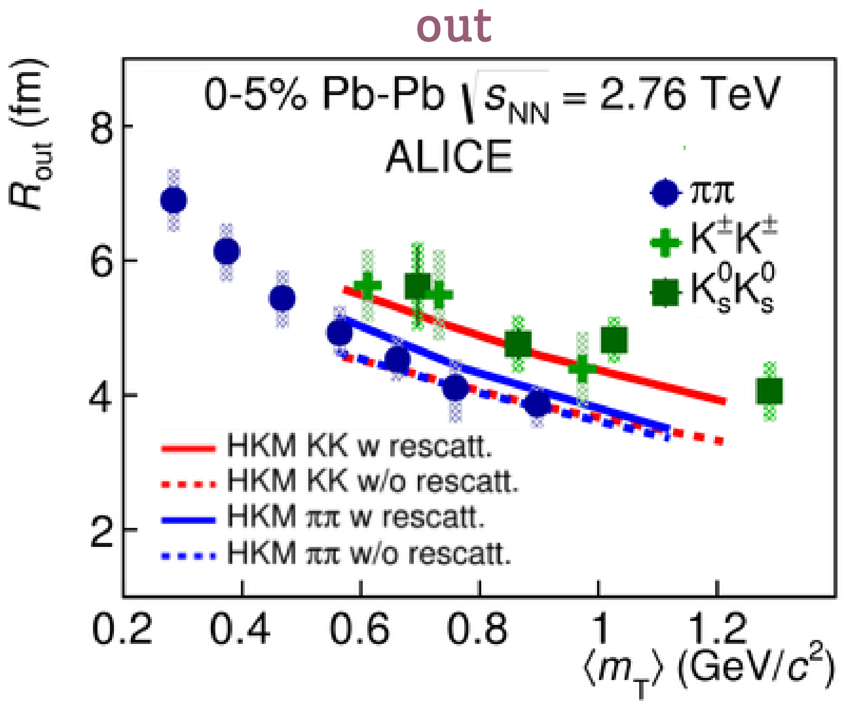
Phys. Rev. C96 (2017) 064613



Kaon femtoscopy

- Results:
  - **broken m_T-scaling** → radii larger than for pions (possibly due to rescattering **through K* resonance**)
  - comparison to hydro **<u>with</u> rescattering phase → scaling broken**
  - model does describe the data

Phys. Rev. C96 (2017) 064613


out

- From m_T scaling of R_{long} we can extract times for pions and kaons:
  - $$R^2_{long} = \tau^2_{max} \frac{T_{max}}{m_T \cosh y_T}\left(1 + \frac{3T_{max}}{2m_T \cosh y_T}\right)$$

    Y. Sinyukov, *et al* Nucl. Phys. A946 (2016) 227–239
  - **emission time of kaons is <u>larger</u> than that of pions by 2.1 fm**

method	T (GeV)	τ_π (fm/c)	τ_K (fm/c)
fit with Eq. (9)	0.144	9.5 ± 0.2	11.6 ± 0.1

Pion-kaon femtoscopy

$$C(\vec{q})=\int |\Psi(\vec{q},\vec{r})|^2 \boxed{S(\vec{r})} d^3 r$$

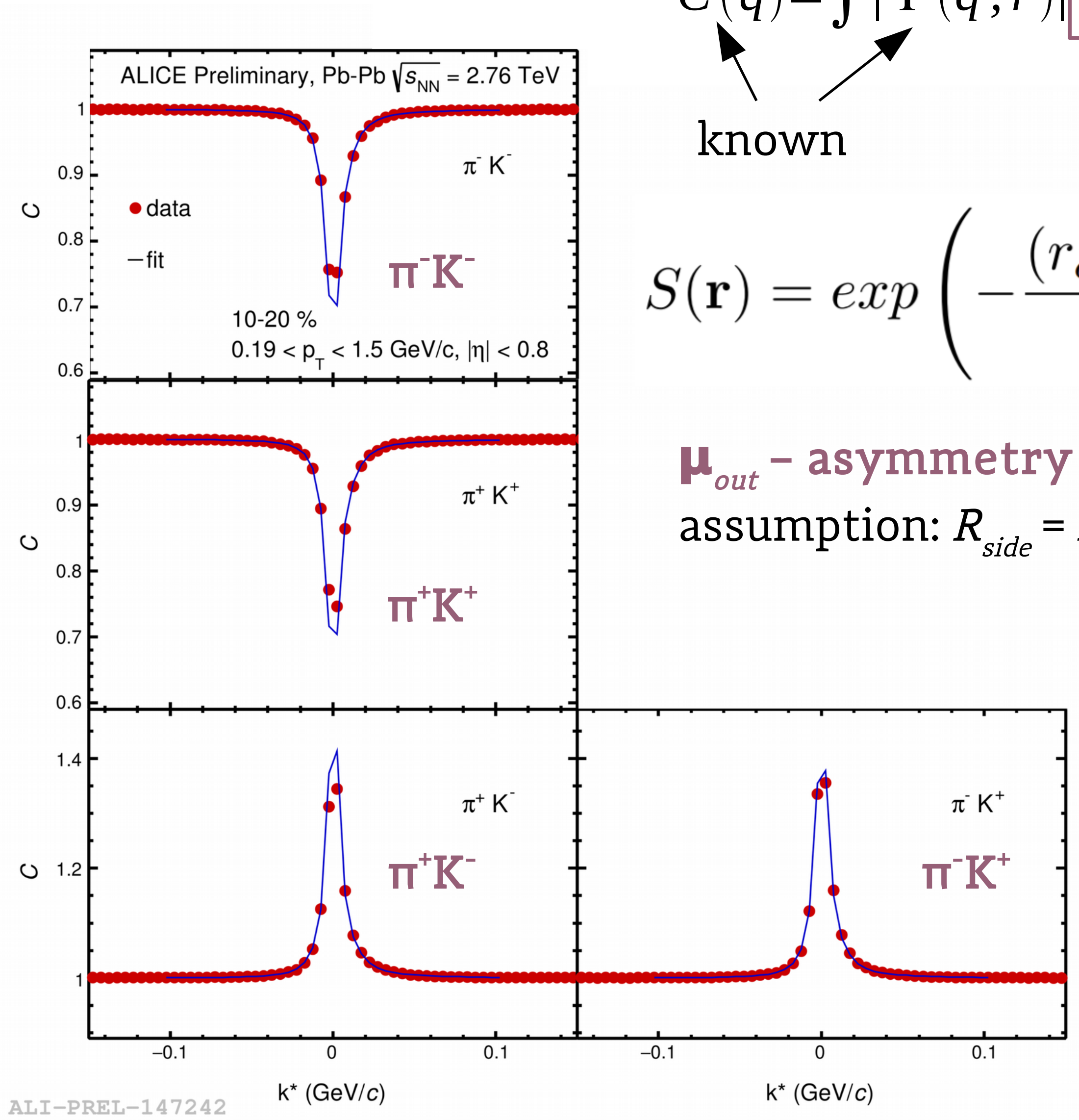
known

unknown

$$S(\mathbf{r}) = exp\left(-\frac{(r_{out}-\boxed{\mu_{out}})^2}{R_{out}^2} - \frac{r_{side}^2}{R_{side}^2} - \frac{r_{long}^2}{R_{long}^2}\right)$$

μ_{out} – asymmetry in out direction

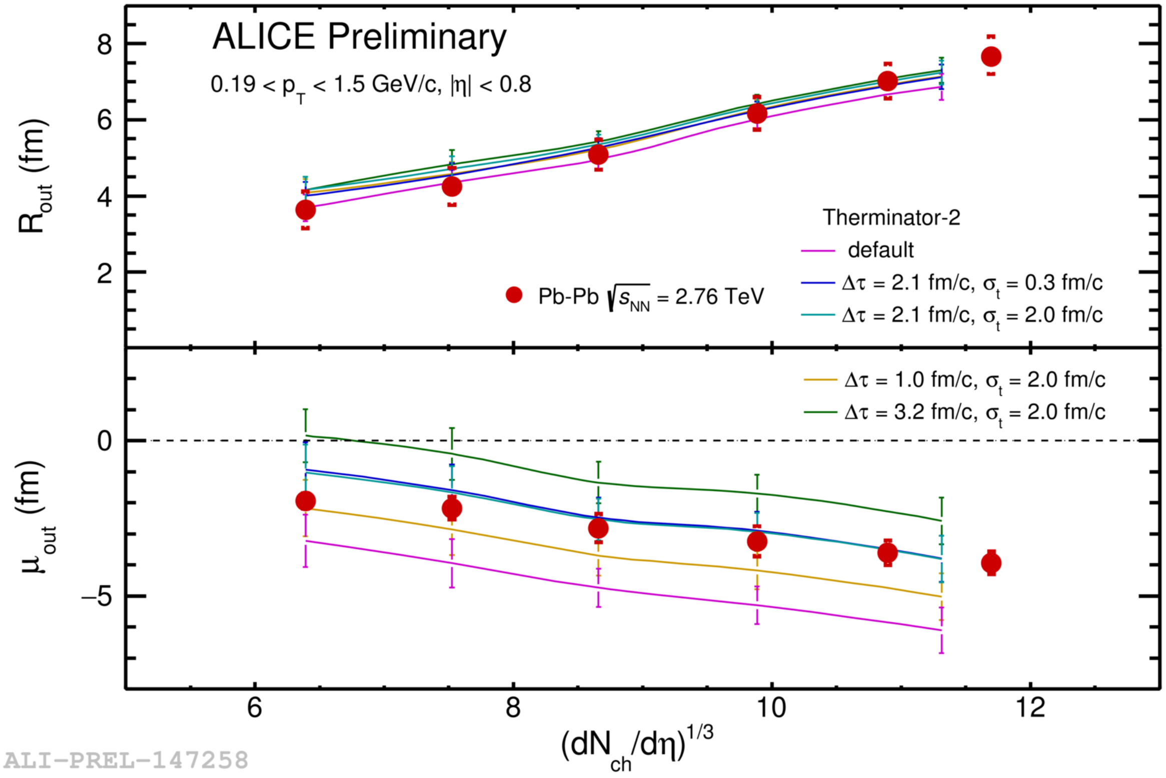
assumption: $R_{side} = R_{out}$, $R_{long} = 1.3 R_{out}$



ALI-PREL-147242

- **4 different pair combinations**
- **Independent check of rescattering phase** (emission asymmetry)

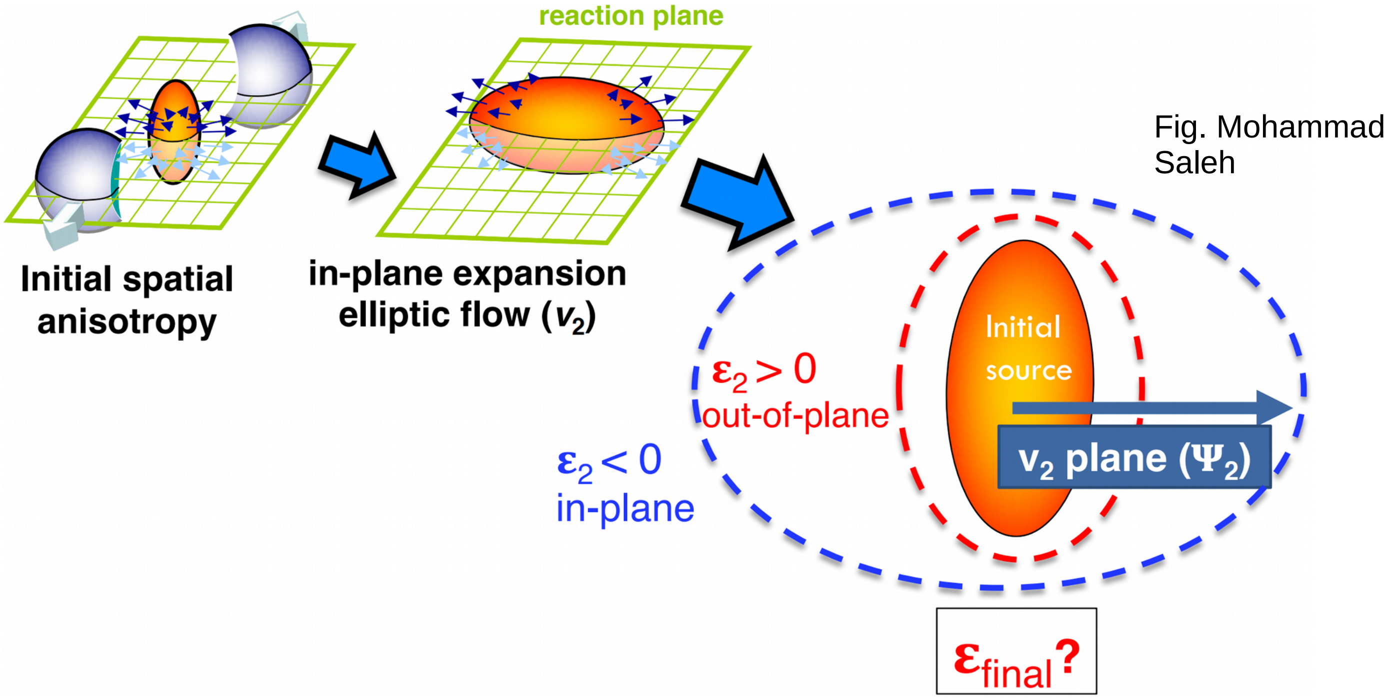
Pion-kaon femtoscopy



- **ALICE data (points):** significant negative pion-kaon emission asymmetry is observed which increases with centrality
- **Model (lines):** kaon emission **delay of 2.1 fm/c introduced in Therminator 2** model **predicts** the measured asymmetry

→ **different particle species freeze out at different times**

Azimuthally differential pion femtoscopy



- Can we measure the final source eccentricity and how does it relate to anisotropy in initial stage?
- We expect the source to be more spherical at freeze-out wrt initial state due to stronger in-plane expansion

Azimuthally differential pion femtoscopy

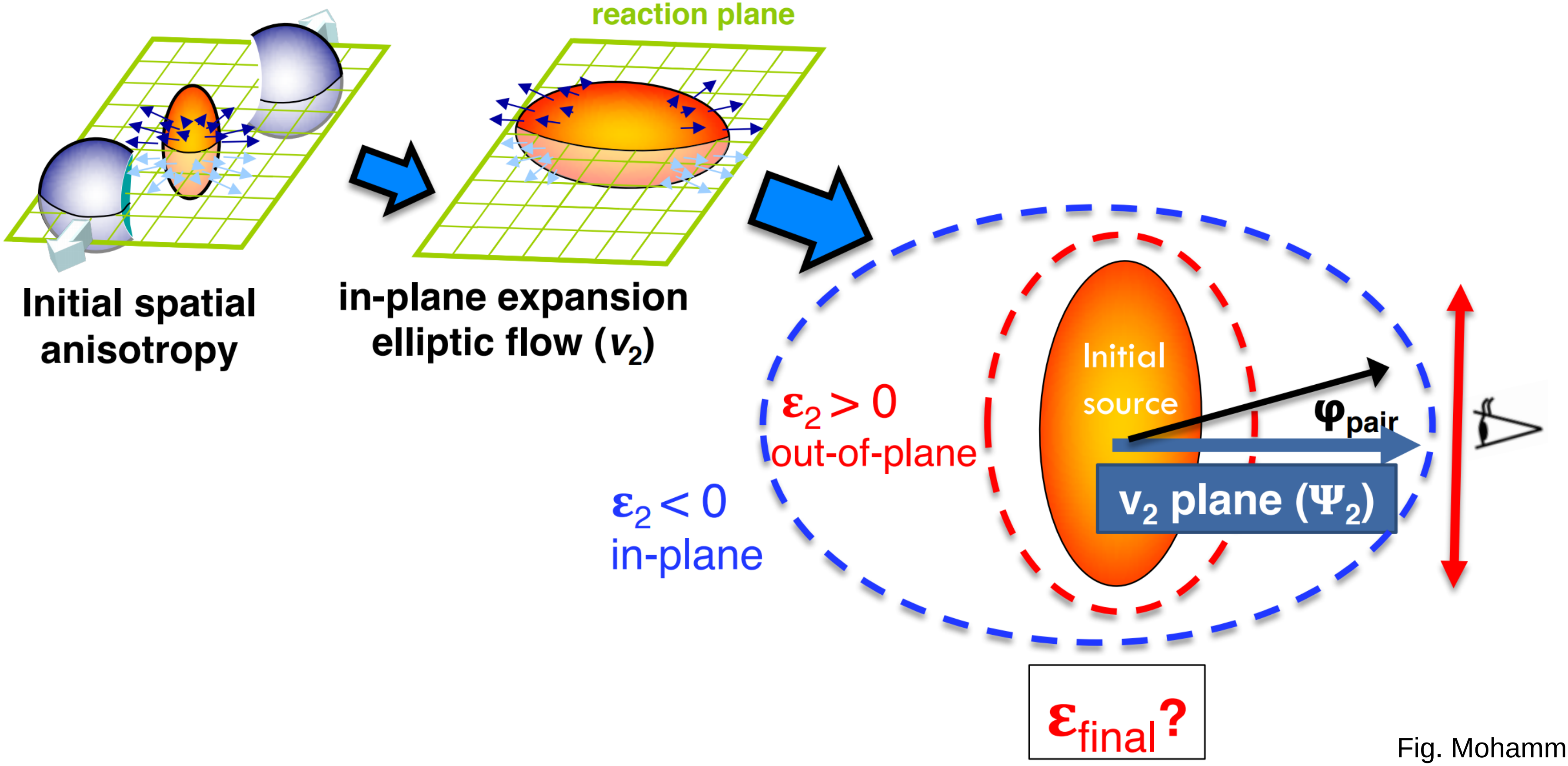
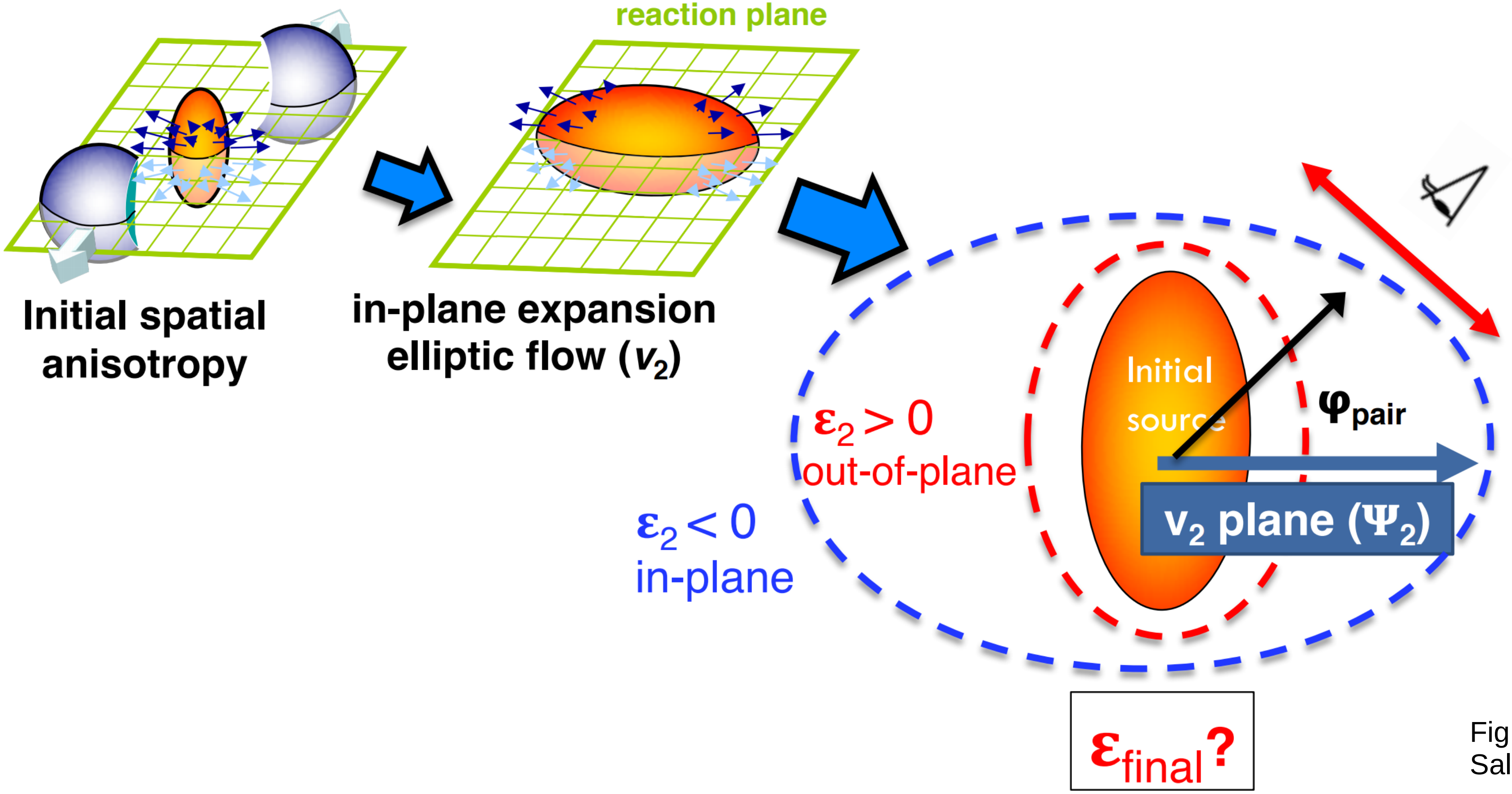


Fig. Mohammad Saleh

- We can use femtoscopy and look at the source size from different angles!

Azimuthally differential pion femtoscopy


reaction plane

Initial spatial anisotropy

in-plane expansion elliptic flow (v_2)

$\varepsilon_2 > 0$ out-of-plane

$\varepsilon_2 < 0$ in-plane

Initial source

φ_{pair}

v_2 plane (Ψ_2)

ε_{final}?

Fig. Mohammad Saleh

- We can use femtoscopy and look at the source size from different angles!

Azimuthally differential pion femtoscopy

Fig. Mohammad Saleh

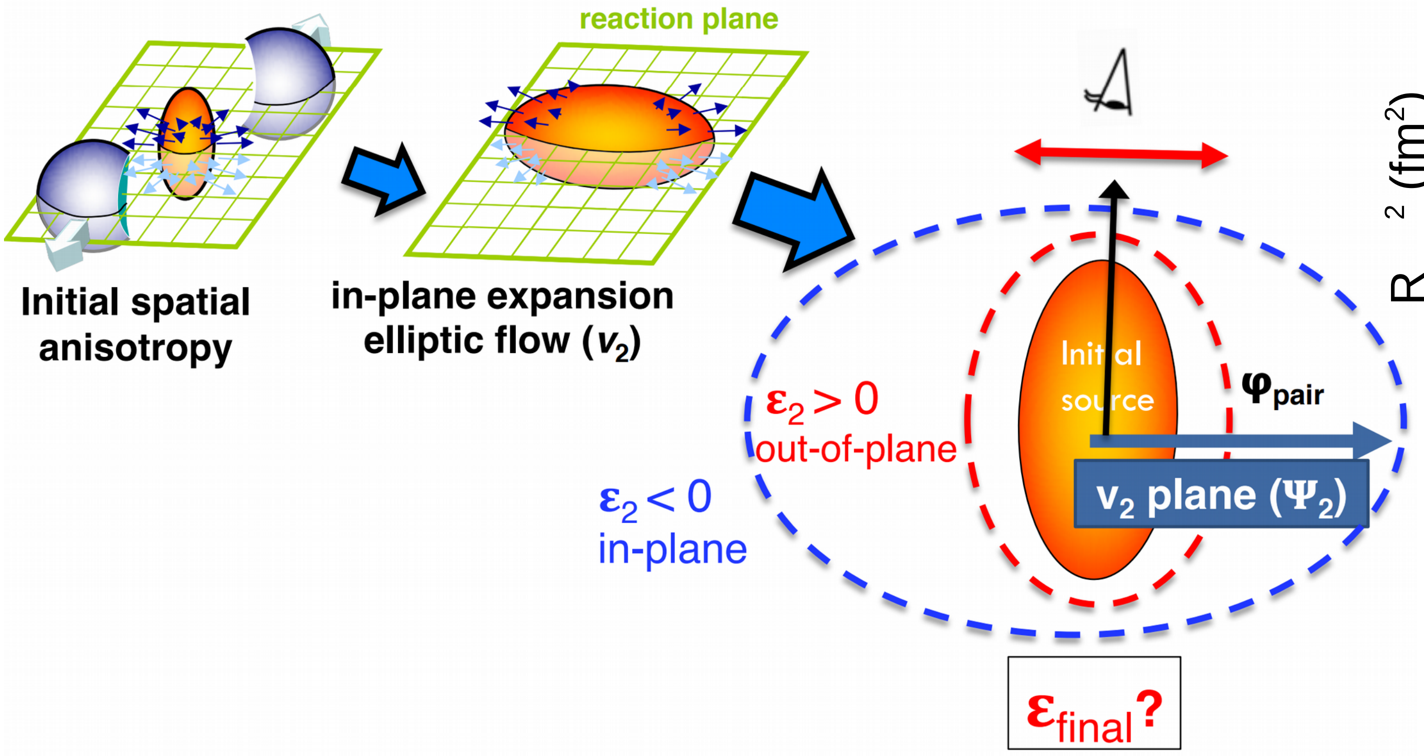
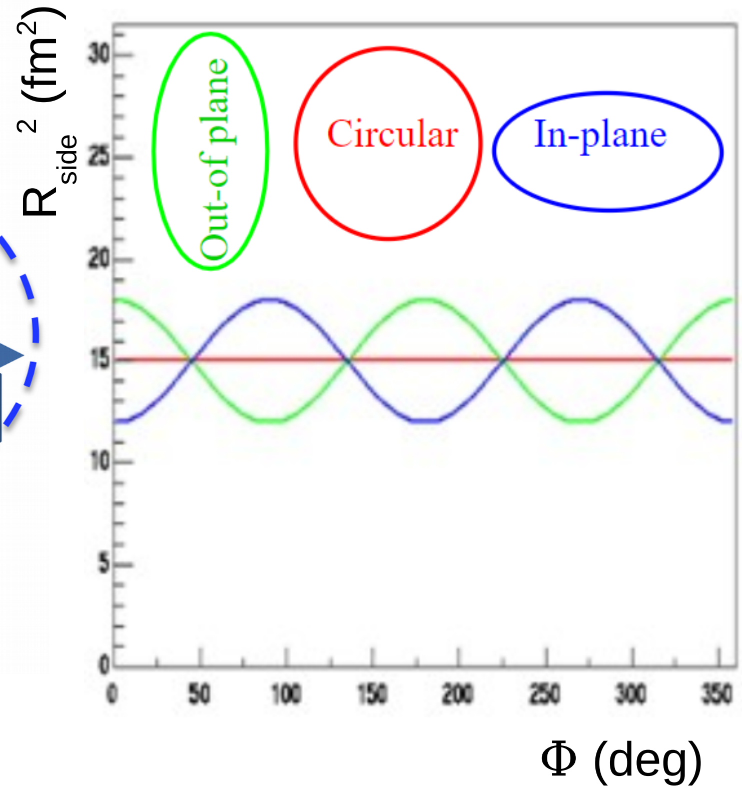


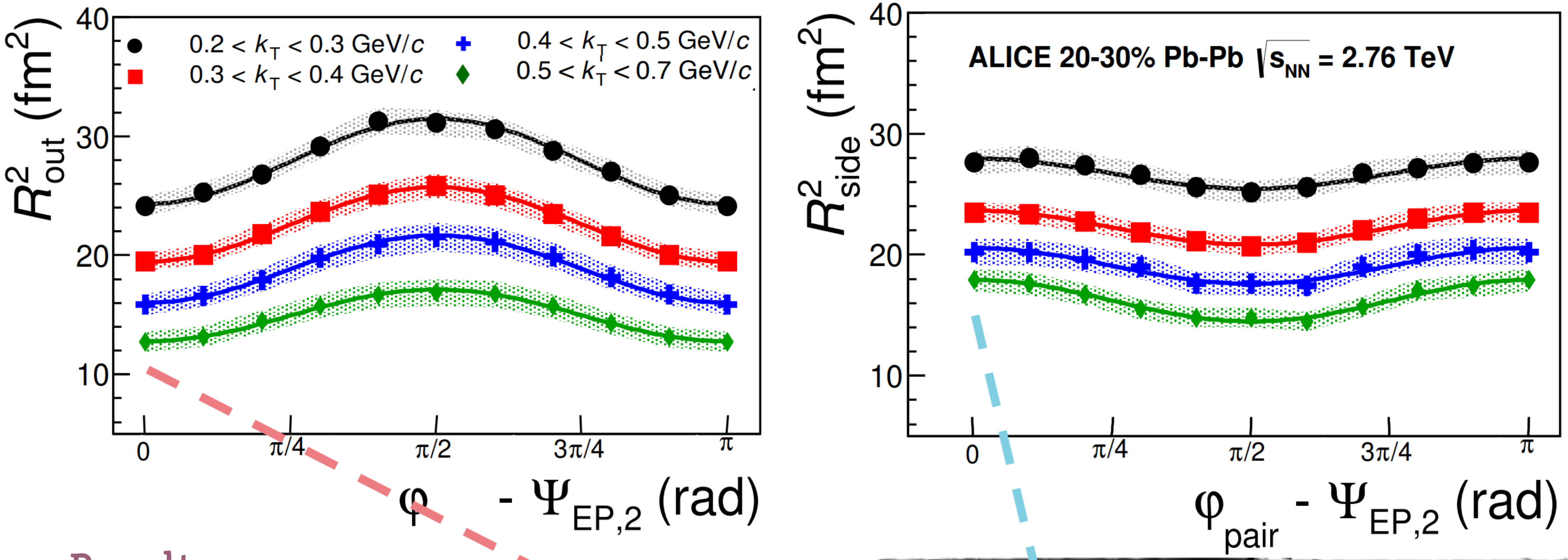
Fig. Richard Lednicky



- **We can use femtoscopy and look at the source size from different angles!**
- We expect **radii oscillations**, depending on the final anisotropy of the source

Azimuthally differential pion femtoscopy

PRL 118 (2017), 222301



Results:

- out and side radii **oscillate out-of-phase**, as it should be!
- Pion source at the freeze-out is **elongated in the out-of-plane direction**

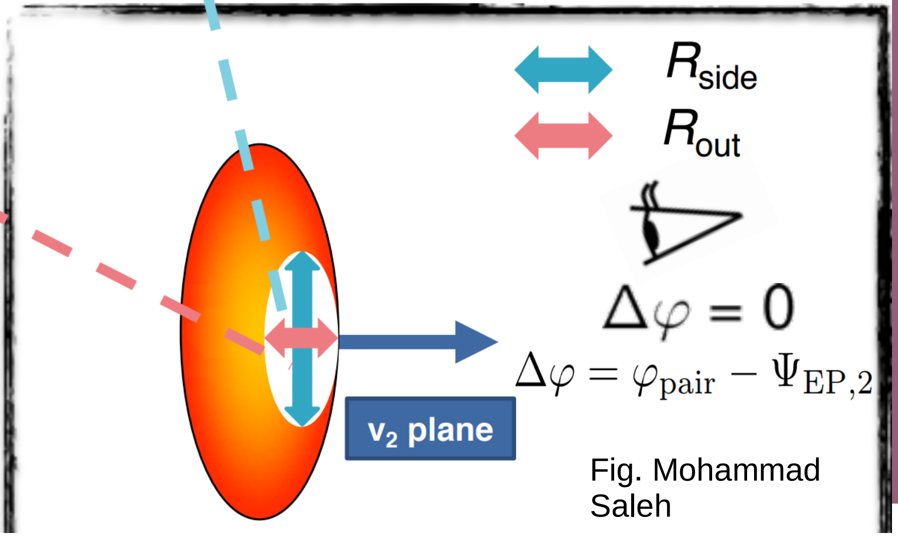
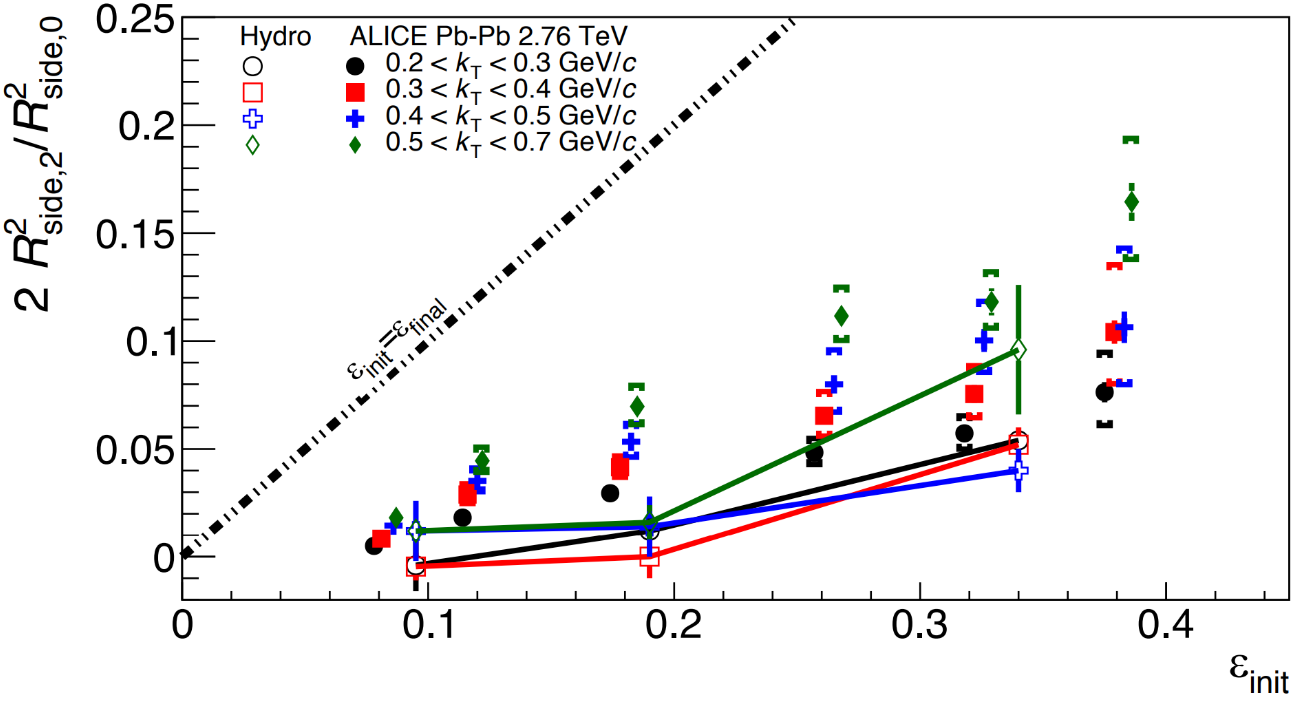


Fig. Mohammad Saleh

Azimuthally differential pion femtoscopy

PRL 118 (2017), 222301



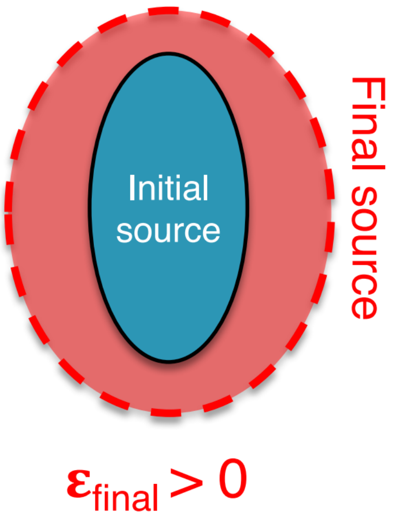


Fig. Mohammad Saleh

Results:

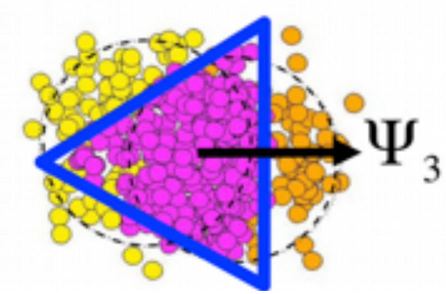
- The final source eccentricity is **smaller than initial anisotropy, but still exhibits an out-of-plane elongated source**, even after stronger in-plane expansion
- Hydrodynamic **models agree qualitatively** but predict **more isotropic source**

- **BUT, can we do more?**

Azimuthally differential pion femtoscopy

PLB 785 (2018) 320

Initial geometry



Final source shape

??

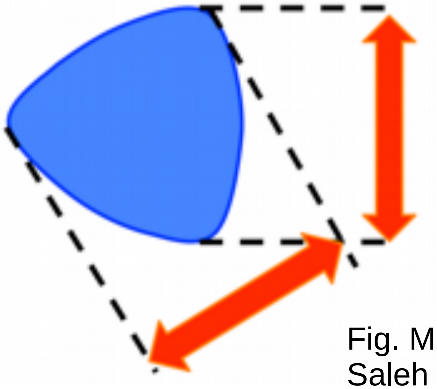
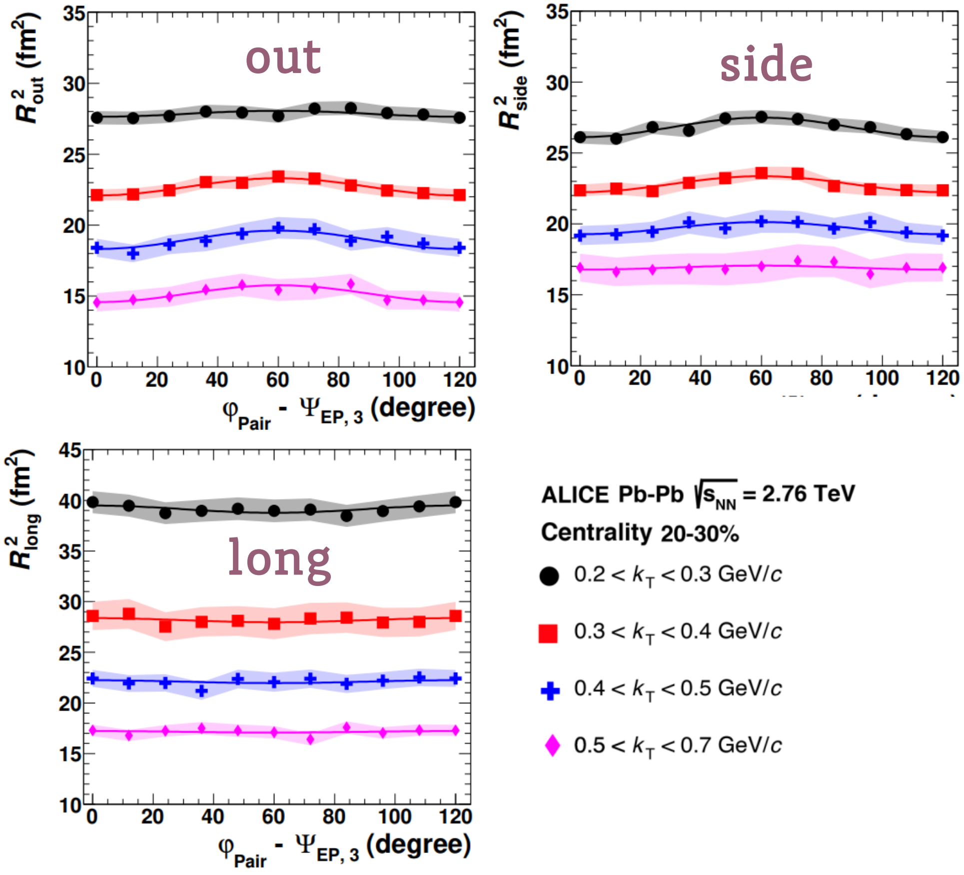


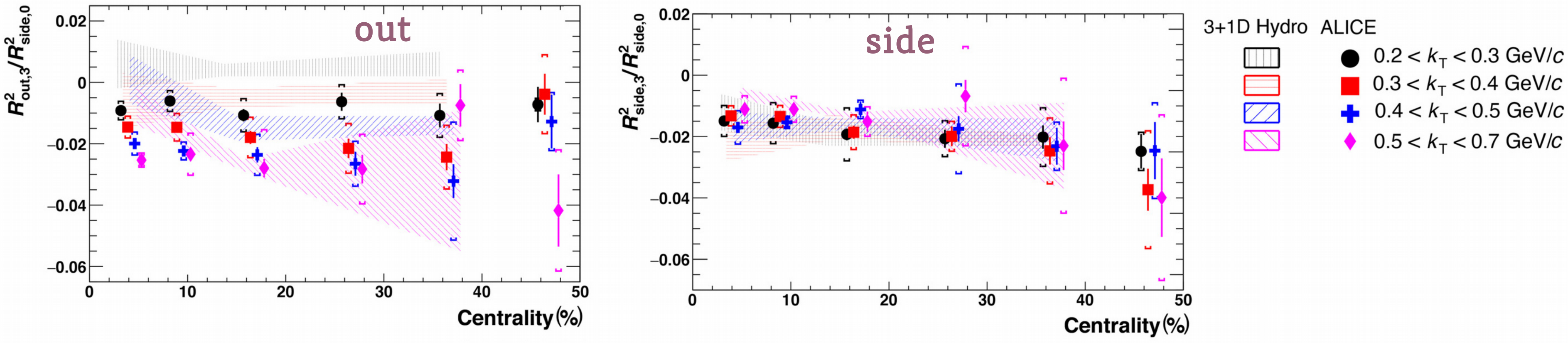
Fig. Mohammad Saleh

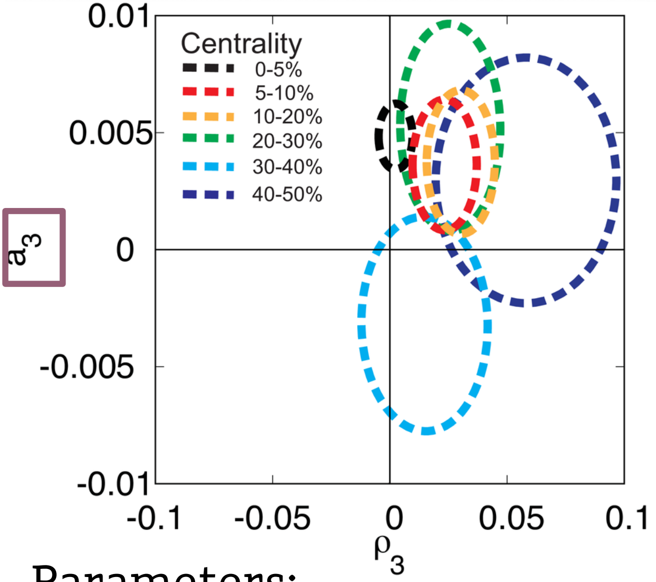


- Pion source size relative to the **3rd harmonic event plane** in Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV
- Out and side radii **oscillate in-phase**
- No oscillations for long radius
- Such **oscillations** are consistent if the **radial expansion includes third harmonic modulation**
- For triangular but **static** source **no oscillations are expected**

Azimuthally differential pion femtoscopy

PLB 785 (2018) 320





Parameters:

a_3 – final source anisotropy

ρ_3 – transverse flow

- **Side radii oscillations agree well with hydrodynamic models,** others only qualitatively
- We can also calculate the final anisotropy:

$$R(\phi) = R_0 \left(1 - \sum_{n=2}^{\infty} a_n \cos(n(\phi - \Psi_n))\right)$$

- a_3 is close to zero, which is significantly smaller than the initial triangular eccentricities which are on the order of 0.2-0.3
- **Conclusion: initial state triangularity is washed out at freeze-out** due to triangular flow

What about pp and p-Pb frontier?

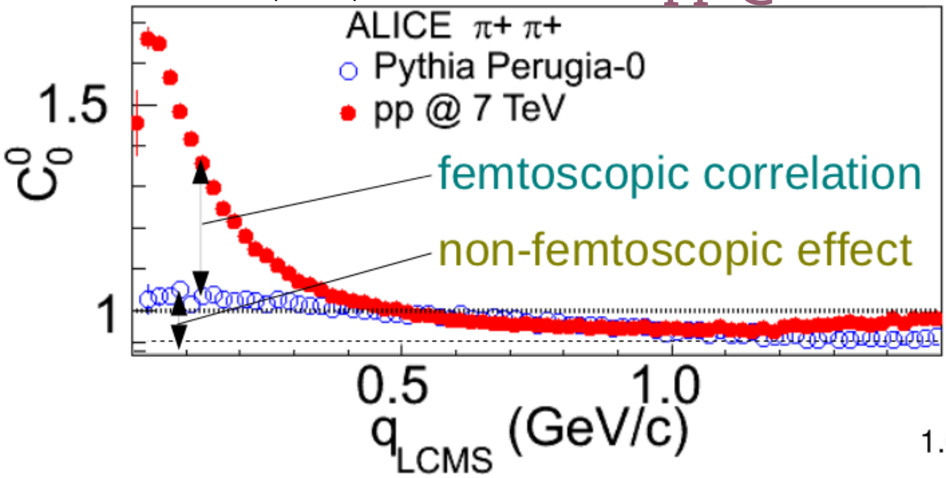
New developments in small systems

Non-femtoscopic correlations

- In small systems we are looking for **signs of collectivity**
- In pp and p-Pb significant non-femtoscopic correlations are present – **hypothesis of (mini-)jet origin**

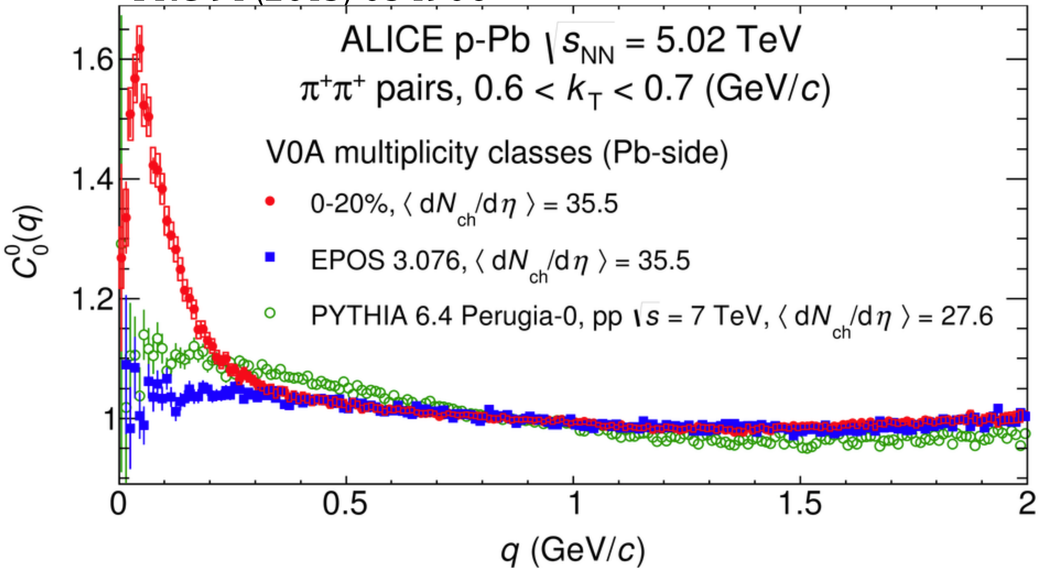
pions
pp @ 7 TeV

PRD 84 (2011) 112004



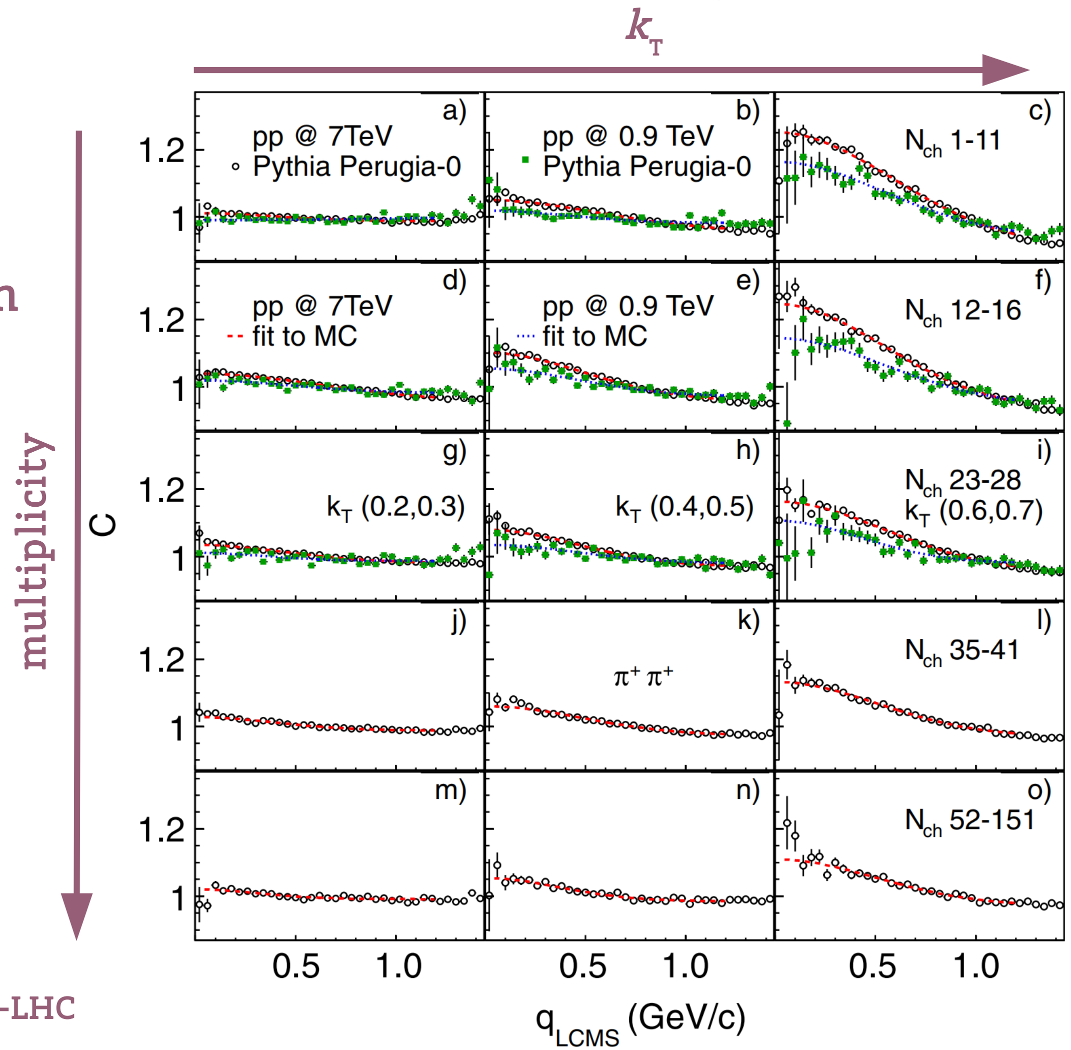
pions
p-Pb @ 5.02 TeV

PRC 91 (2015) 034906



Non-femtoscopic correlations

- In small systems we're looking for signs of collectivity
- In pp and p-Pb significant non-femtoscopic correlations are present – **<u>hypothesis</u> of (mini-)jet origin**
- Non-femtoscopic background **significantly limits** the accessible range in k_T

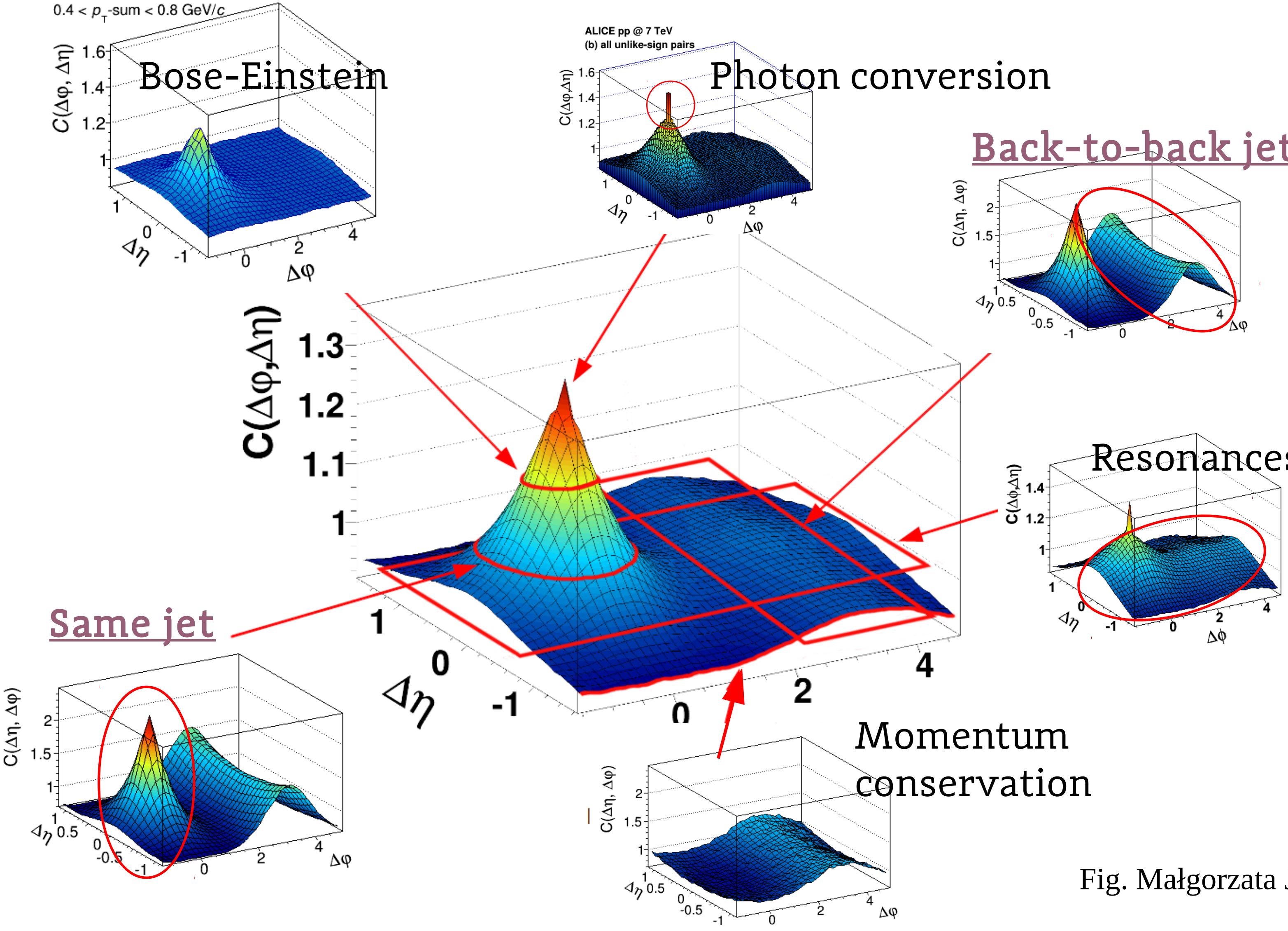


pions
Pythia simulation

PRD 84 (2011) 112004

How do (mini-)jets look like?

Let’s look at angular space



Bose-Einstein

Photon conversion

Back-to-back jets

Resonances

Same jet

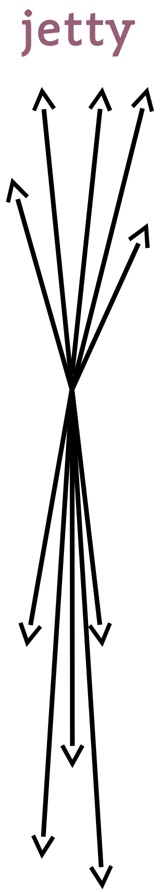
Momentum conservation

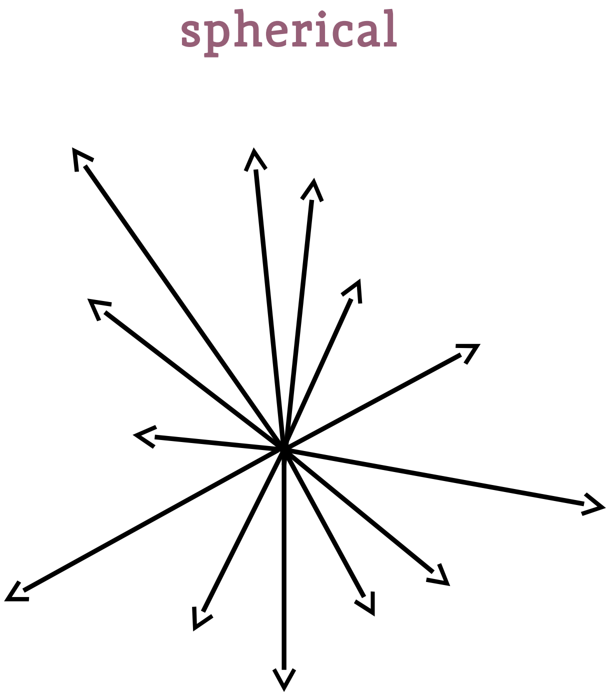
Fig. Małgorzata Janik

Jets produce streams of particles close to each other – like femto correlations!

Sphericity

- How about selecting events which do have (mini-)jets or not?





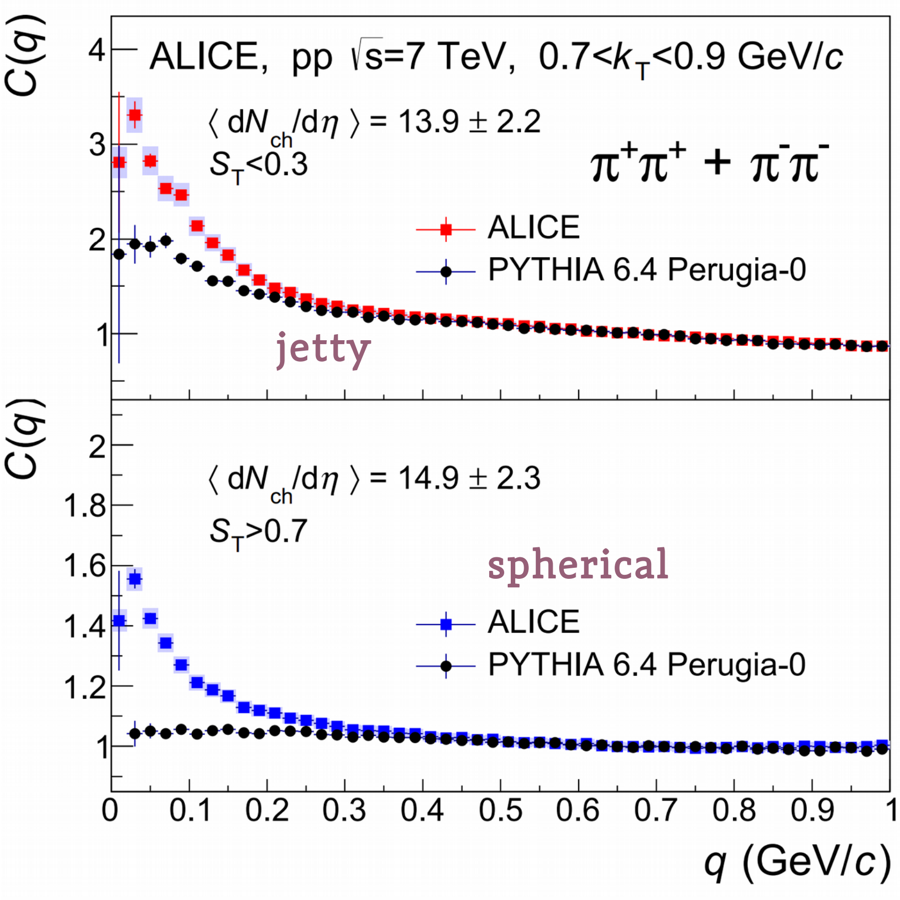
$$S^{L}_{xy} = \frac{1}{\sum_i p_{T\,i}} \sum_i \frac{1}{p_{T\,i}} \begin{pmatrix} p^2_{x\,i} & p_{x_i} p_{y_i} \\ p_{y_i} p_{x\,i} & p^2_{y_i} \end{pmatrix}$$

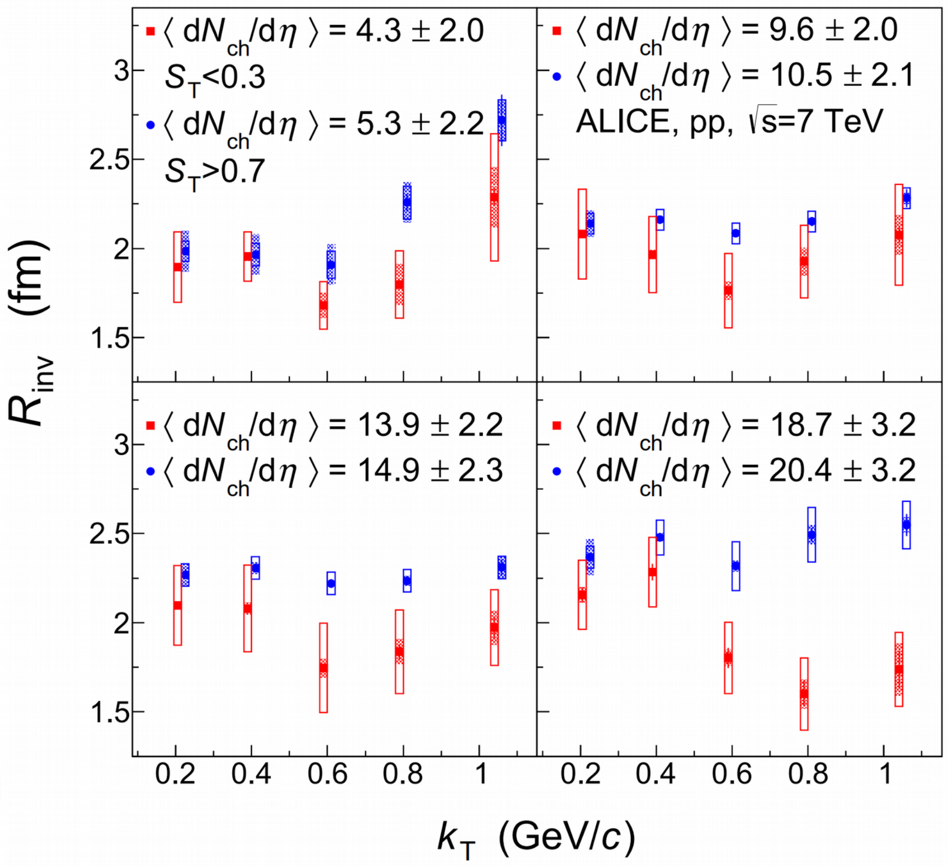
$$S_T = \frac{2\lambda_2}{\lambda_1 + \lambda_2} \Rightarrow S_T = \begin{cases} \approx 0 & \text{Jet-like} \\ \approx 1 & \text{Spherical} \end{cases}$$

Sphericity

- (Mini-)jet contribution is the main source of underlying correlation
- Sphericity analysis allows to extend the studied k_T range
- k_T dependece of 1D radii in PRF not well explored
- **Next step:** 3D analysis in LCMS to check for the k_T scaling

arXiv:1901.05518





Going beyond the system size

Beyond the system size

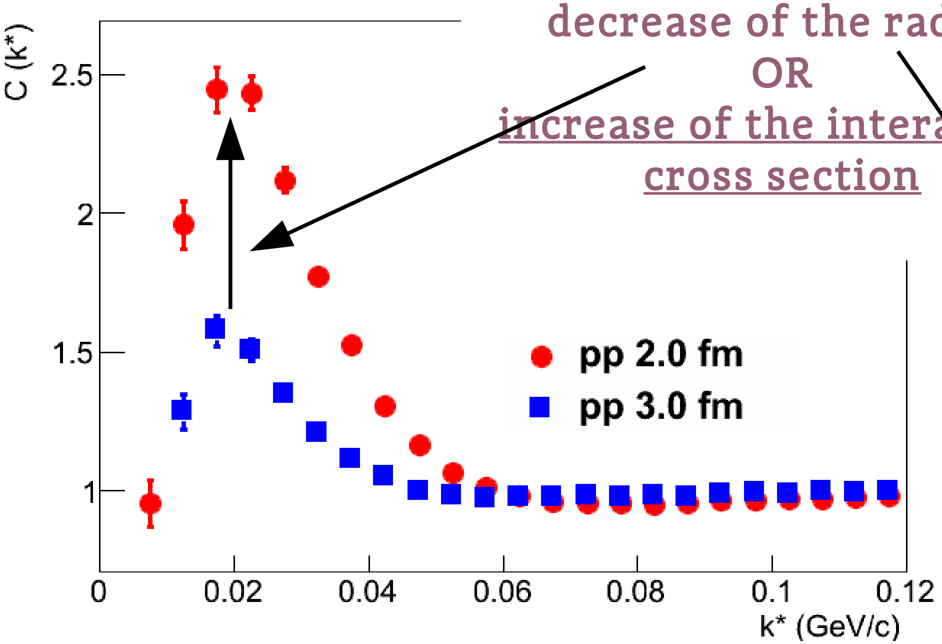
$$C(q)=\int S(r)|\Psi(q,r)|^2 d^4 r \qquad q=2\cdot k^{*}=p_1-p_2$$

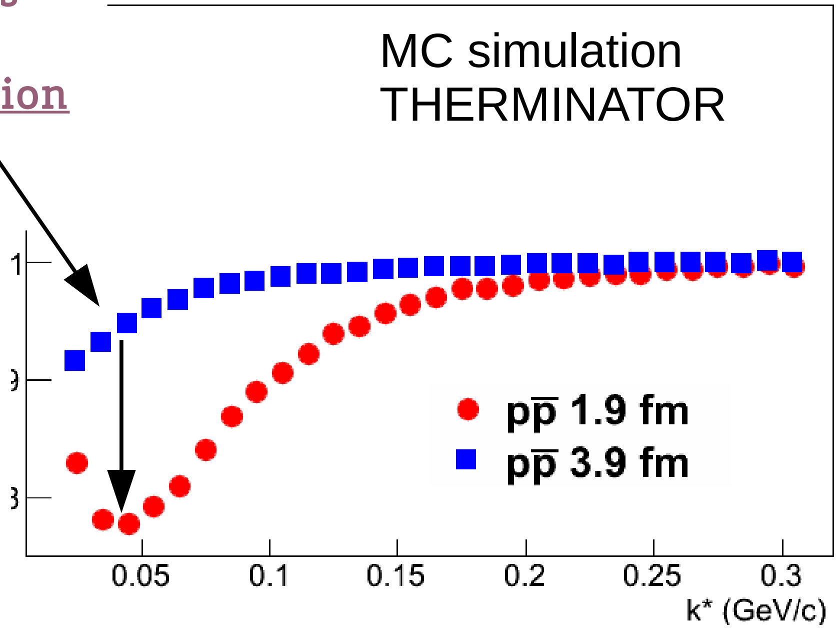
measured correlation

emission function
(source size/shape)

pair wave function
(includes cross section)

increase of (anti)correlation
=
decrease of the radius
OR
increase of the interaction
cross section





- One can use femtoscopy to measure interactions for those pairs where it is poorly known or not known at all!
- Powerful tool when scattering experiments are not possible

Beyond the system size

$$C(q)=\int S(r)\boxed{|\Psi(q,r)|^2}d^4r \qquad q=2\cdot k^*=p_1-p_2$$

measured correlation

emission function
(source size/shape)

pair wave function
(includes cross section)

pair wave function → $\Psi=\exp(-ik^*r)+f\frac{\exp(ik^*r)}{r}$ s-wave scattering approximation

scattering amplitude → $f^{-1}(k^*)=\frac{1}{f_0}+\frac{1}{2}d_0k^{*2}-ik^*$ effective range approximation

- If only Strong FSI is present:

Lednicky equation

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

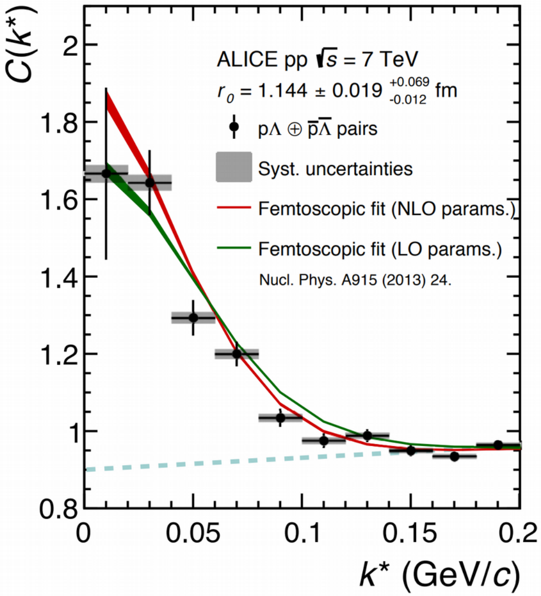
Sov. J. Nucl. Phys., 35, 770 (1982)

where ρ_S are the spin fractions

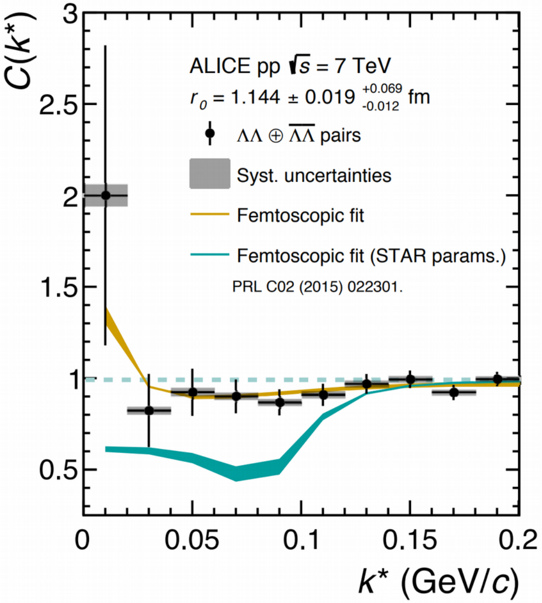
- The correlation function is characterized by **three parameters**:
  - **radius** R, **scattering length** f_0, and **effective radius** d_0
  - **cross section** σ **(at low** k^*) is simply: $\sigma=4\pi|f|^2$

Baryon-baryon correlations

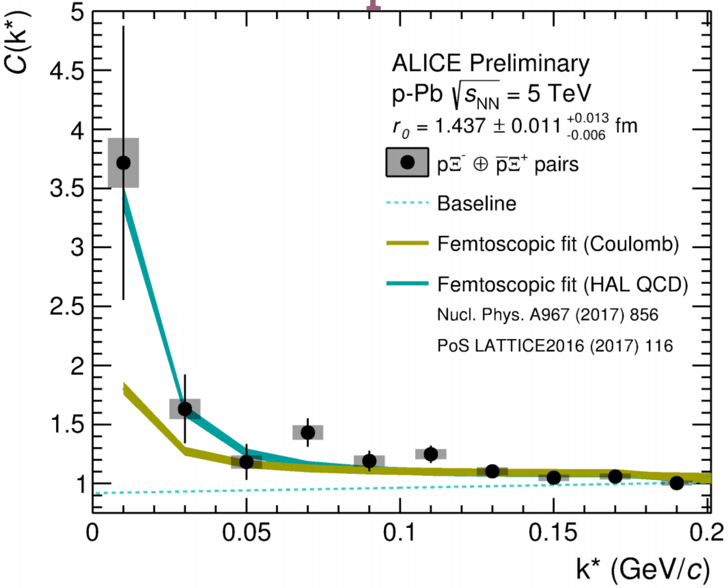
pΛ



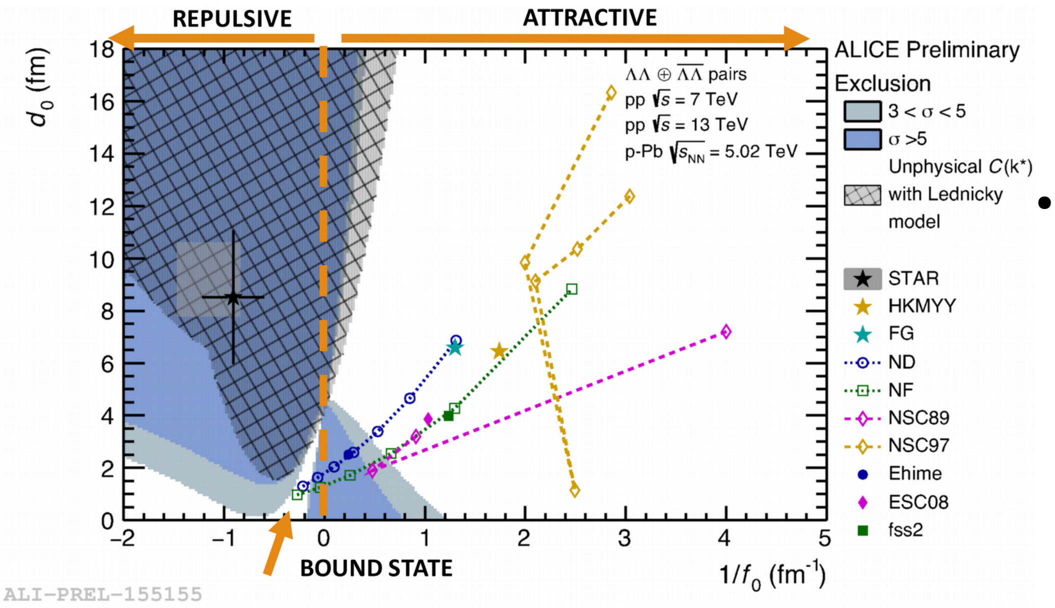
ΛΛ



pΞ



ALI-PREL-144825



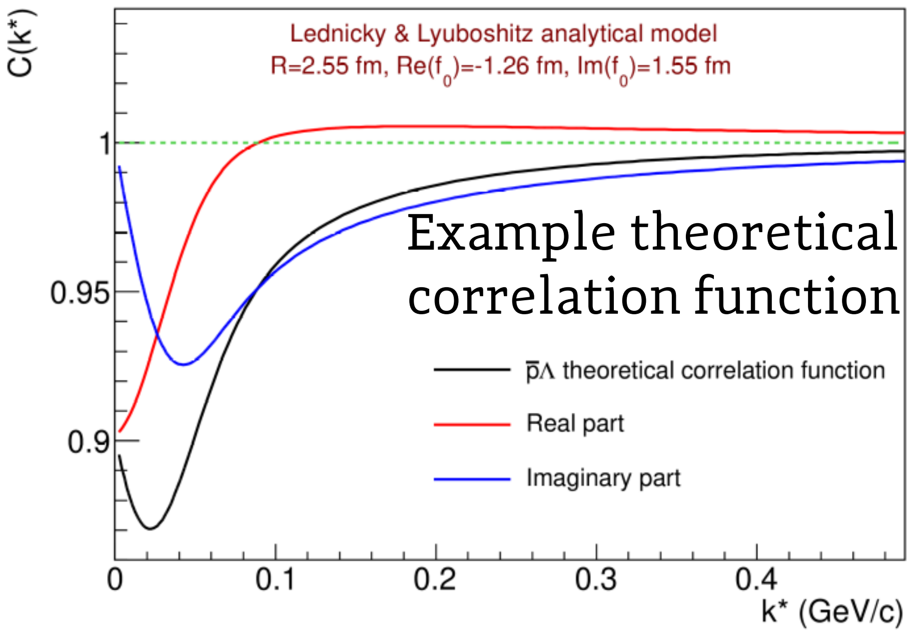
ALI-PREL-155155

- Constraining lambda-lambda scattering parameters and bound states (H-dibaryon)
- First measurement of attractive proton-Ξ potential

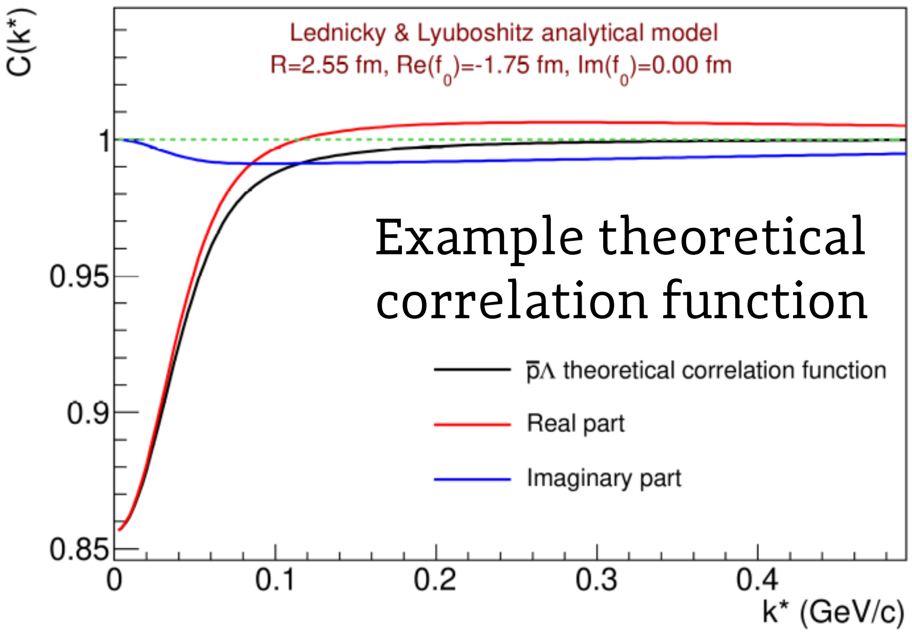
For details see CERN-LHC Seminar 25 Sep 2018
https://indico.cern.ch/event/749074/

PRC 99 (2019) 024001

Baryon-antibaryon correlations



Example theoretical correlation function



Example theoretical correlation function

- Real and imaginary part of scattering length have **distinctively different contributions**
- Contribution from Re(f_0) is either positive or negative but **very narrow** (up to 100 MeV/c) in k^*
- The Im(f_0) accounts for baryon-antibaryon annihilation and produces a **wide** (hundreds of MeV) **negative correlation**

Baryon-antibaryon correlations

- Correlation functions measured for <u>two collision energies</u>
- $\Lambda\bar{\Lambda}$ correlations measured for the <u>first time</u>
- Wide negative correlation seen for all pairs

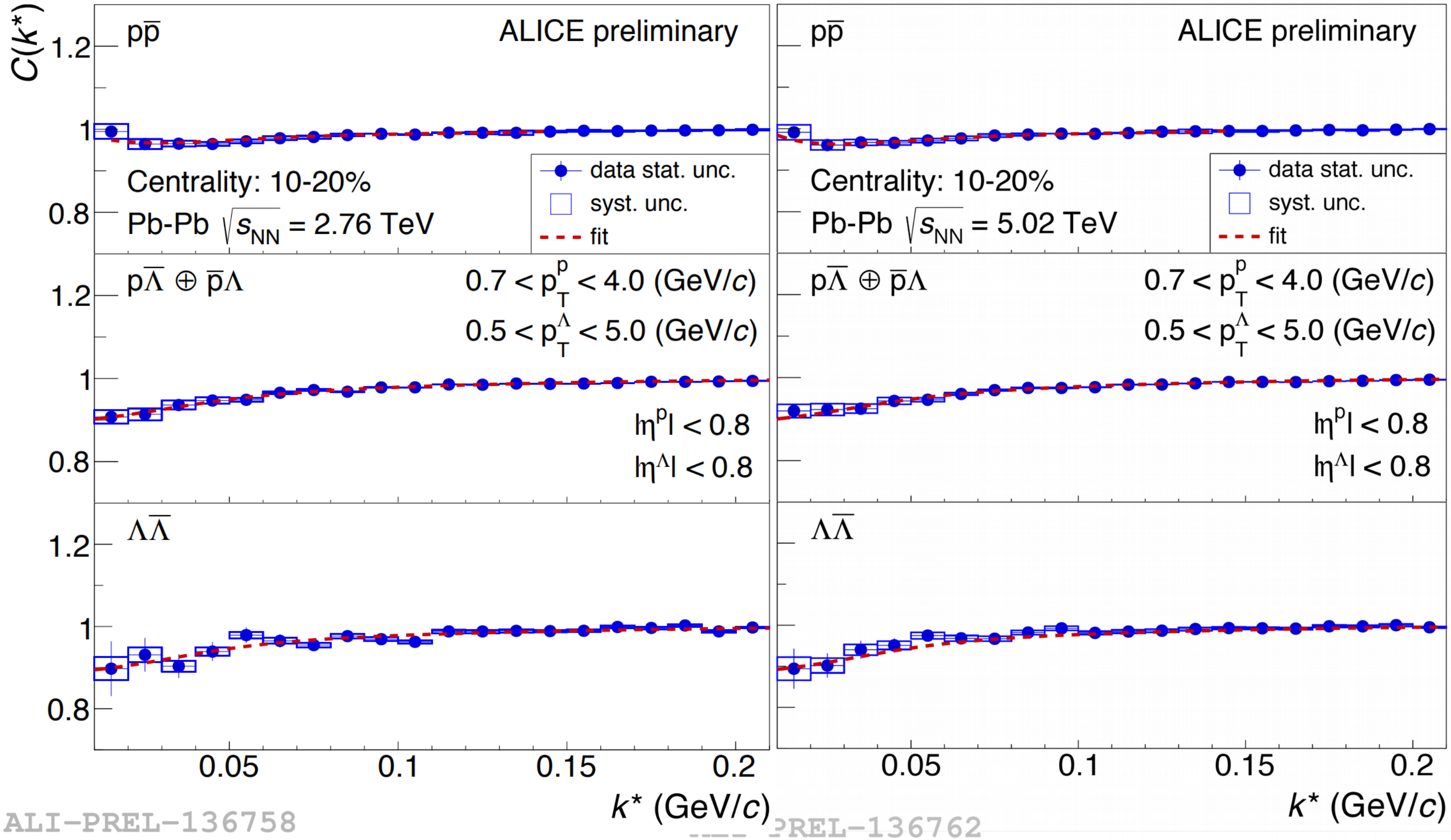
Pb-Pb @ 2.76 TeV

Pb-Pb @ 5.02 TeV

$p\bar{p}$

$p\bar{\Lambda}+\bar{p}\Lambda$

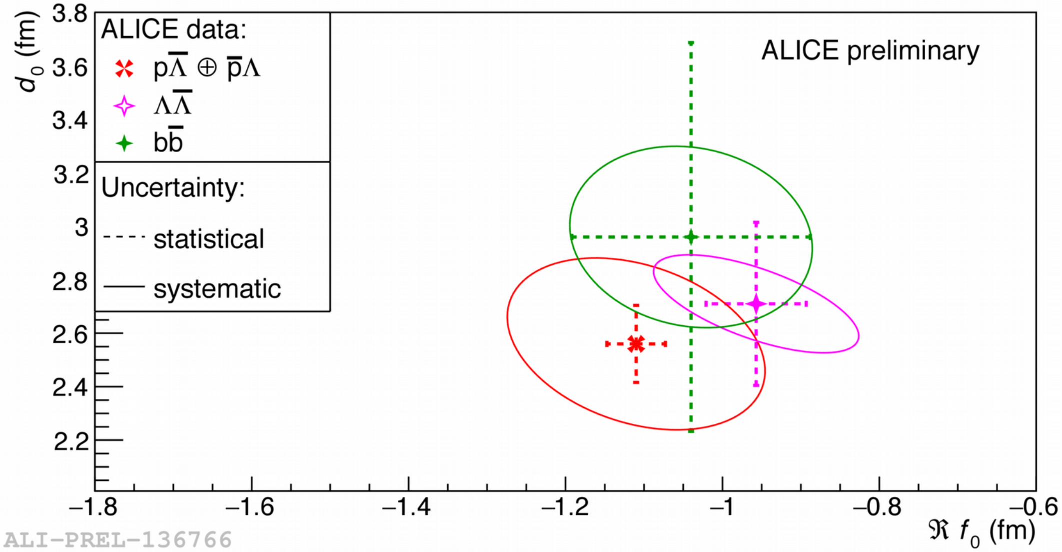
$\Lambda\bar{\Lambda}$



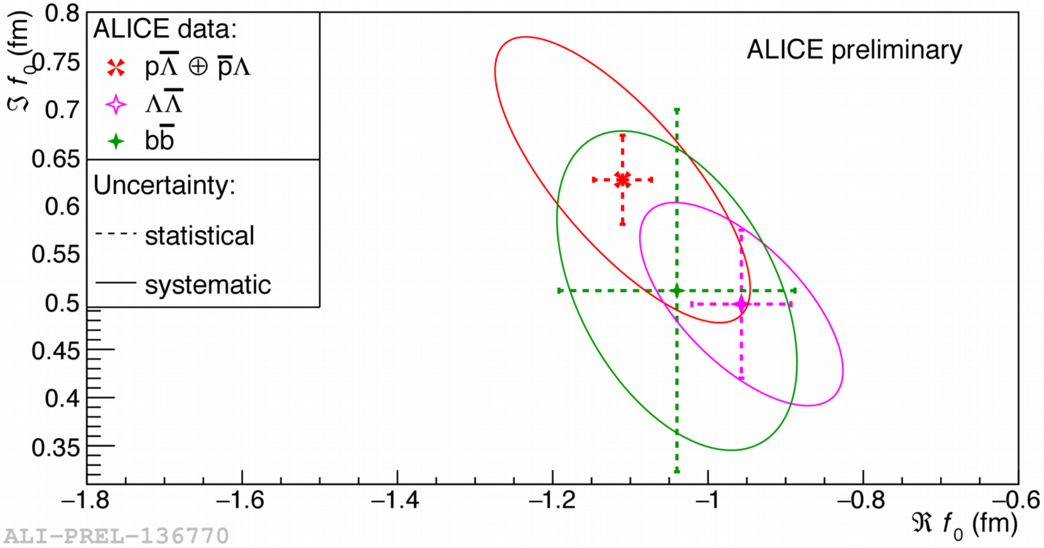
ALI-PREL-136758

ALI-PREL-136762

Baryon-antibaryon correlations



ALI-PREL-136766

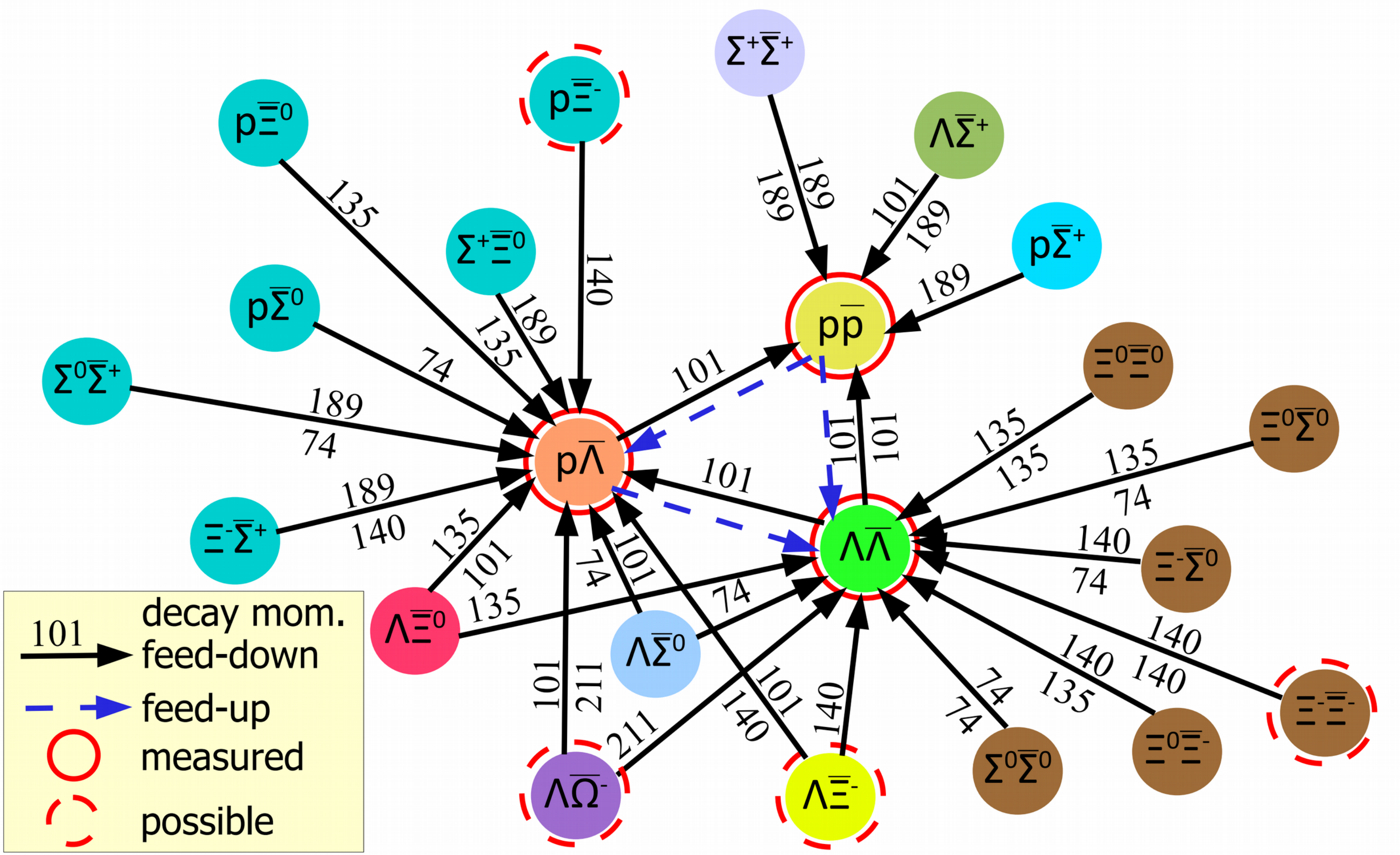


ALI-PREL-136770

Conclusions from fitting:

- Interaction parameters are measurable
- Scattering parameters for **all baryon-antibaryon pairs are similar to each other**
- We observe a **negative real part of scattering length →** repulsive strong interaction or creation of a bound state (existence of baryon-antibaryon bound states?)
- Significant **positive imaginary part of scattering length** – presence of a non-elastic channel – annihilation

Residual correlations and other possibilites

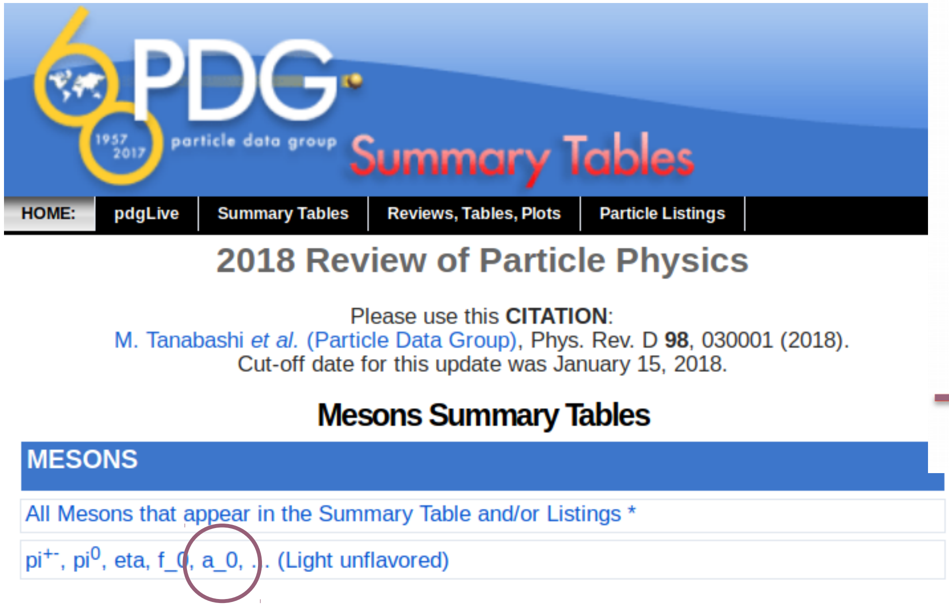


Motivation for $K^0_sK^\pm$ analysis

- Which sources of correlations are present in kaon systems?
  - Quantum Statistics (QS) – both $K^0_sK^0_s$ and $K^\pm K^\pm$
  - Coulomb FSI – $K^\pm K^\pm$
  - **Strong FSI –** $K^0_sK^0_s$ **(via** $f_0(980)/a_0(980)$ **resonances)**
- Why are $K^0_sK^\pm$ pairs interesting?
  - only Strong FSI:
    - $f_0(980)$ resonance is isospin = 0 → no $f_0(980)$ strong interaction
    - $a_0(980)$ **resonance is isospin = 1 as is the kaon pair → only** $a_0(980)$ **strong interaction present**
- $a_0(980)$ resonance is a proposed tetraquark state (PRC 75 (2007) 045206)
- $a_0(980)$ mass and coupling par. (in GeV) from fits to ϕ decay experiments

	m_{a0}	$\gamma_{a0\to K\bar{K}}$	$\gamma_{a0\to\pi\eta}$	Reference
"Martin"	0.974	0.3330	0.2220	Nucl. Phys. B 121, 514 (1977)
"Antonelli"	0.985	0.4038	0.3711	arXiv: hep/ex-0209069 (2002)
"Achasov1"	0.992	0.5555	0.4401	Phys. Rev. D 68, 014006 (2003)
"Achasov2"	1.003	0.8365	0.4580	Phys. Rev. D 68, 014006 (2003)

Motivation for $K^0_sK^{\pm}$ analysis



2018 Review of Particle Physics

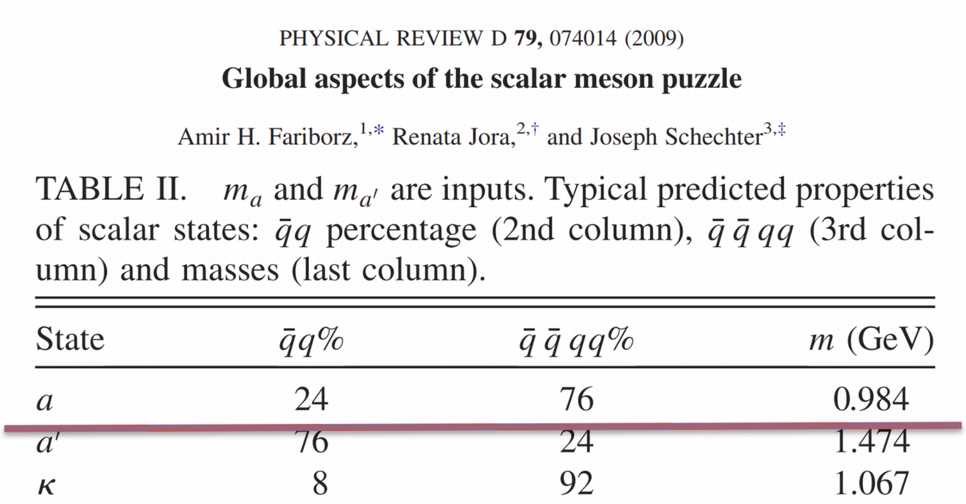
Please use this **CITATION**:
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).
Cut-off date for this update was January 15, 2018.

Mesons Summary Tables

MESONS

All Mesons that appear in the Summary Table and/or Listings *

pi^{+-}, pi^0, eta, f_0, a_0, . . (Light unflavored)



PHYSICAL REVIEW D **79,** 074014 (2009)

Global aspects of the scalar meson puzzle

Amir H. Fariborz,[1,*] Renata Jora,[2,†] and Joseph Schechter[3,‡]

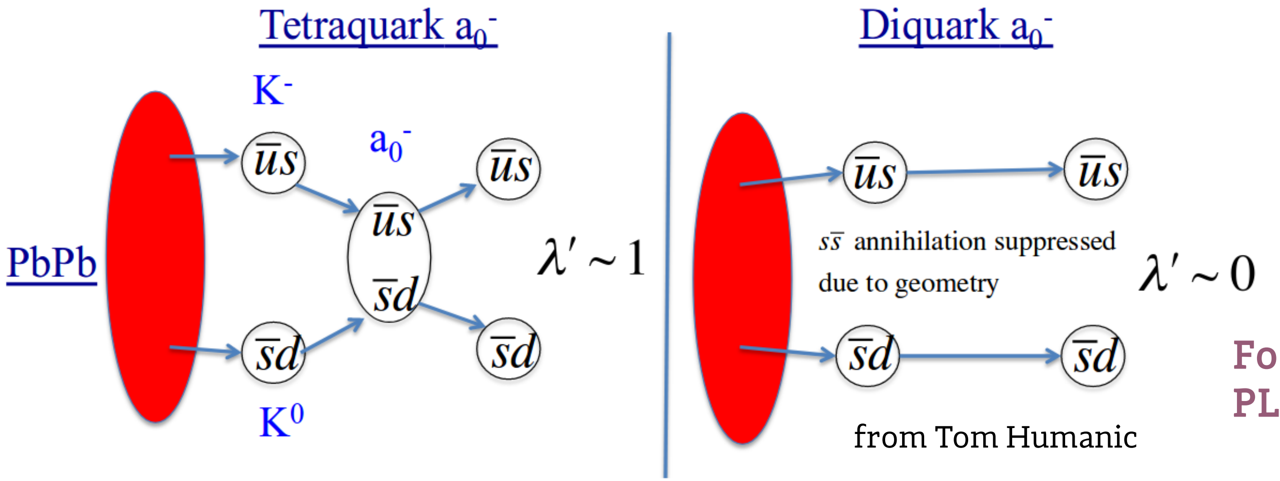
TABLE II. m_a and $m_{a'}$ are inputs. Typical predicted properties of scalar states: $\bar{q}q$ percentage (2nd column), $\bar{q}\,\bar{q}\,qq$ (3rd column) and masses (last column).

State	$\bar{q}q\%$	$\bar{q}\,\bar{q}\,qq\%$	m (GeV)
a	24	76	0.984
a'	76	24	1.474
κ	8	92	1.067

a_0 predicted to be **76% tetraquark**
PDG still lists it as a **light meson**

- **How femtoscopy can help to determine which state it is?**

$\boxed{\lambda' \equiv \lambda_{K^0K^-}/\lambda_{KK}}$ for $\bar{u}s\bar{s}d$ vs. $\bar{u}d$ a_0^- expected from geometry



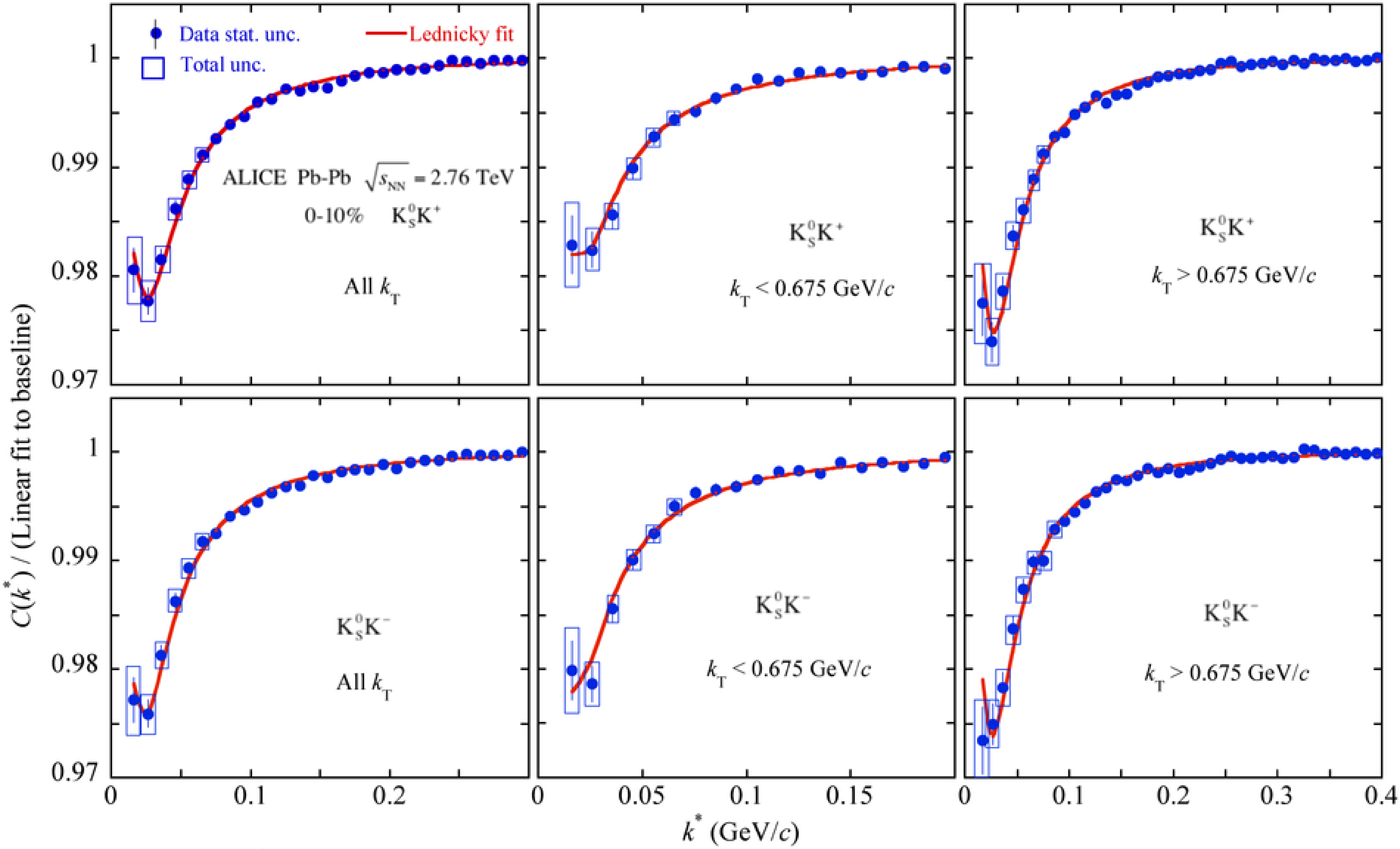
from Tom Humanic

For details:
PLB 774 (2017) 64-77

Measured correlation functions

$C_{raw}(k^*)/(\text{linear fit})$

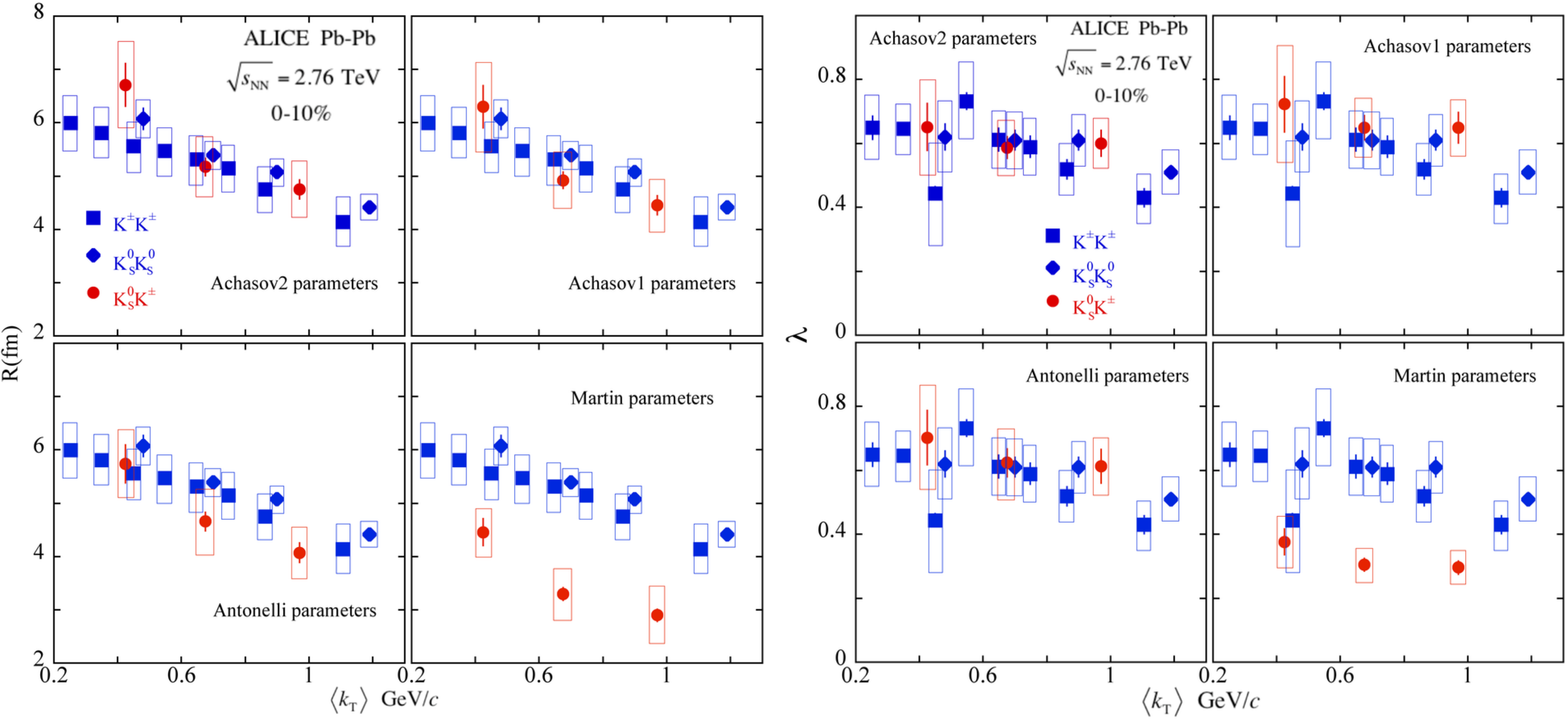
PLB 774 (2017) 64-77



The $a_0(980)$ final interaction gives an excellent fit to the data!

Results of the fit

PLB 774 (2017) 64-77

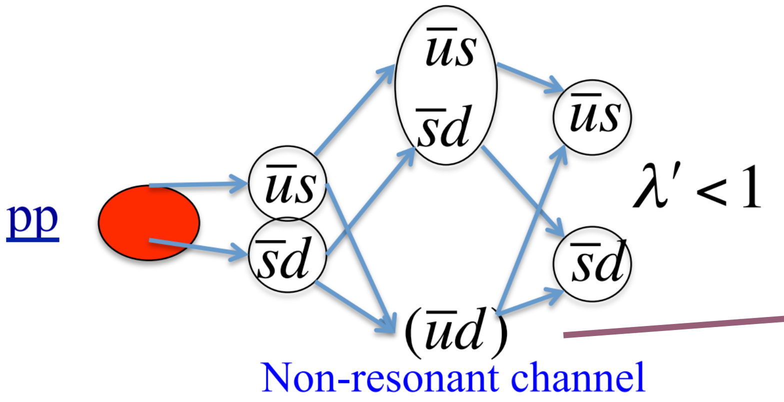


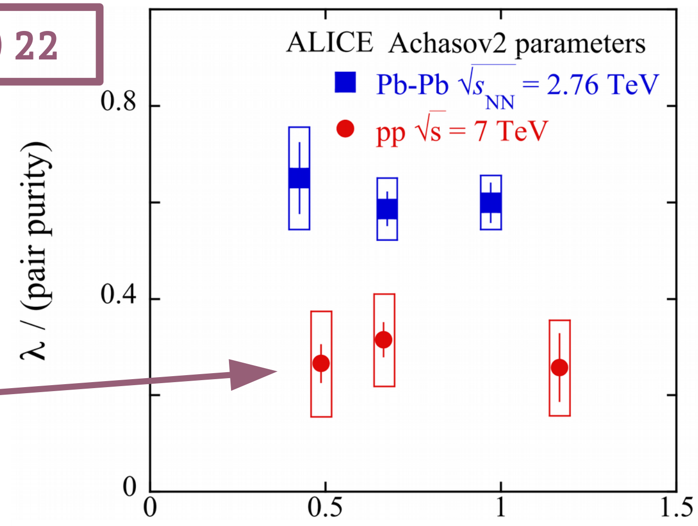
- **"Achasov" parameter fits give best agreements with** $K^0_sK^0_s$ **and** $K^{\pm}K^{\pm}$
- "Antonelli" parameter fits are somewhat lower
- "Martin" parameter fits much lower
- **Present results favor higher** $a_0(980)$ **parameters →** $a_0(1000)$

Can pp collisions tell us more?

PLB 790 (2019) 22

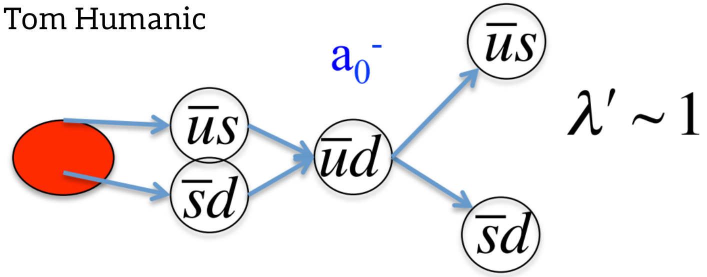
Tetraquark a_0^-

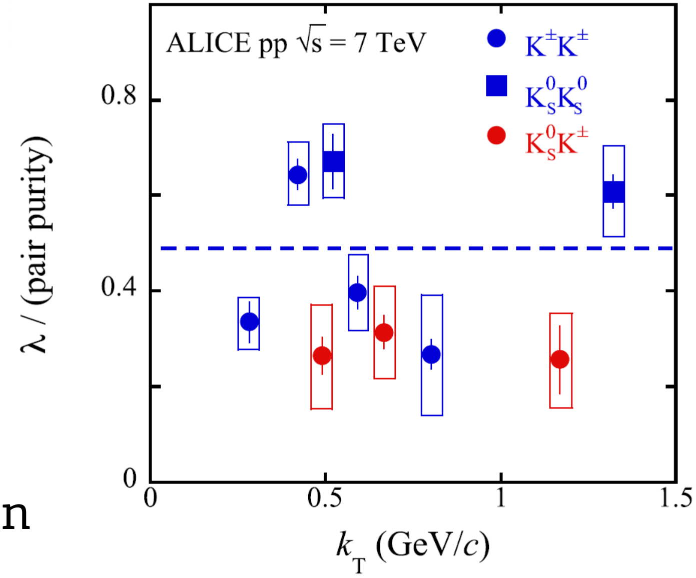




Diquark a_0^-

from Tom Humanic





- λ parameters from pp are significantly lower than Pb-Pb (non-resonant channel also present)
- They also tend to be lower than for identical-kaon analysis
- **Results from both pp and Pb-Pb favor a_0 to be a tetraquark**

Status of femtoscopy in ALICE

- Two-pion Bose-Einstein correlations in pp collisions at $\sqrt{s}$=900 GeV, Phys. Rev. D 82 (2010) 052001
- Two-pion Bose-Einstein correlations in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Lett. B 696 (2011) 328-337
- Femtoscopy in pp a 0.9 and 7 TeV, Phys. Rev. D 84 (2011) 112004
- K0sK0s correlations in pp collisions at $\sqrt{s}$=7 TeV from the LHC ALICE experiment, Phys. Lett. B 717 (2012) 151-161
- Charged kaon femtoscopic correlations in pp collisions at $\sqrt{s}$=7 TeV, Phys. Rev. D 87 (2013) 052016
- Two and Three-Pion Quantum Statistics Correlations in Pb-Pb Collisions at $\sqrt{s_{NN}}$=2.76 TeV at the LHC Phys. Rev. C 89 (2014) 024911
- Freeze-out radii extracted from three-pion cumulants in pp, p-Pb and Pb-Pb collisions at the LHC, Phys. Lett. B 739 (2014) 139-151
- Pion femtoscopy in p-Pb Phys. Rev. C 91 (2015) 034906
- Multipion Bose-Einstein correlations in pp, p-Pb, and Pb-Pb collisions at the LHC, Phys. Rev. C 93 (2016) 054908
- Centrality dependence of pion freeze-out radii in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV Phys. Rev. C 93 (2016) 024905
- 1D pion, kaon , proton femtoscopy in Pb-Pb Phys. Rev. C 92 (2015) 054908
- Azimuthally differential pion femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV, Phys. Rev. Lett. 118 (2017) 222301
- Kaon femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Rev. C96 (2017) 064613
- Measuring K0sK± interactions using Pb-Pb collisions at $\sqrt{s_{NN}}$ =2.76 TeV, Phys. Lett. B 774 (2017) 64
- Azimuthally-differential pion femtoscopy relative to the third harmonic event plane in Pb-Pb collisions at $\sqrt{s_{NN}}$ =2.76 TeV, Phys. Lett. B 785 (2018) 320-331
- Measuring K0sK± interactions using pp collisions at $\sqrt{s}$ =7 TeV, Phys. Lett. B 790 (2019) 22
- p-p, p-Λ and Λ-Λ correlations studied via femtoscopy in pp reactions at $\sqrt{s}$=7 TeV, Phys. Rev. C 99 (2019) 024001
- Event-shape and multiplicity dependence of freeze-out radii in pp collisions at $\sqrt{s}$=7 TeV, arXiv:1901.05518

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- Event-shape and multiplicity dependence of freeze-out radii in pp collisions at √s=7 TeV, arXiv:1901.05518

18 papers in total
~7.5% of all ALICE papers
(241, 3 March 2019)

3 more coming soon

Summary

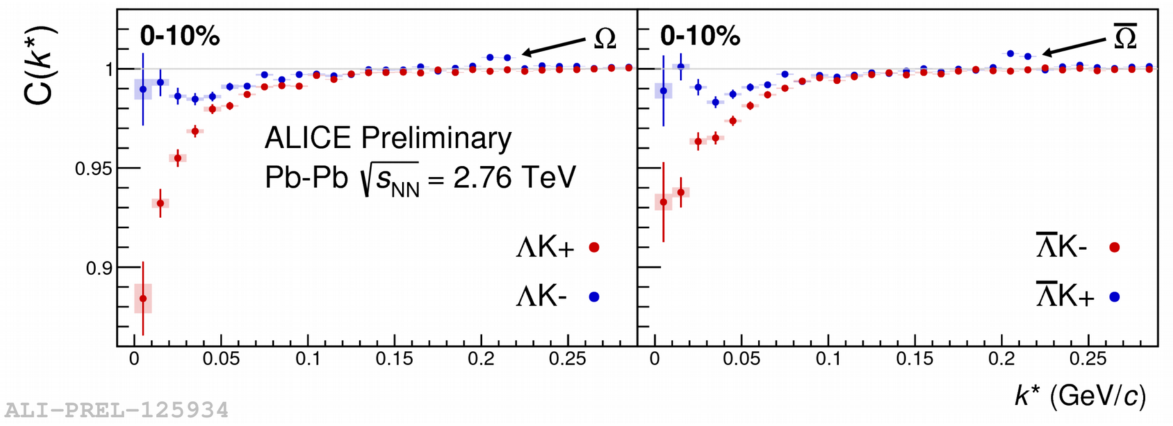
- Femtoscopy in ALICE has produced a rich set of results
  - Remarkable scaling of radii from various experiments is kept also at LHC energies
- More differential and complex analysis are being carried out right now
  - Kaon-kaon and pion-kaon femtoscopy suggest that **kaons are emitted later than pions**. Data show **2.1 fm/c delay** between pion and kaon average emission time
  - Pion source at the freeze-out is **elongated in the out-of-plane direction**. Initial state **triangularity is washed-out at freeze out**
  - In small systems – sphericity allows for better handle of underlying non-femtoscopic correlations
- Femtoscopy has also become a powerful tool for hadron physics
  - Unique experimental environment at LHC → **“matter-antimatter pair factory”**
  - Possibility to study exotic states such as **tetraquarks**
- More new and exciting analyses are on the way – stay tuned!

Thank you!

Backup

Other interesting pairs

- Many other interesting correlations are currently studied by ALICE
- Lambda-kaon (both charged and neutral) pairs
  - scattering parameters measured for the first time
- ΛK^+ shows greater suppression at low k* compared to: ΛK^-:
  - effect arising from $s\bar{s}$ annihilation compared to $u\bar{u}$?
  - or S=0 ΛK^+ system has more interaction channels than S=-2 ΛK^-?

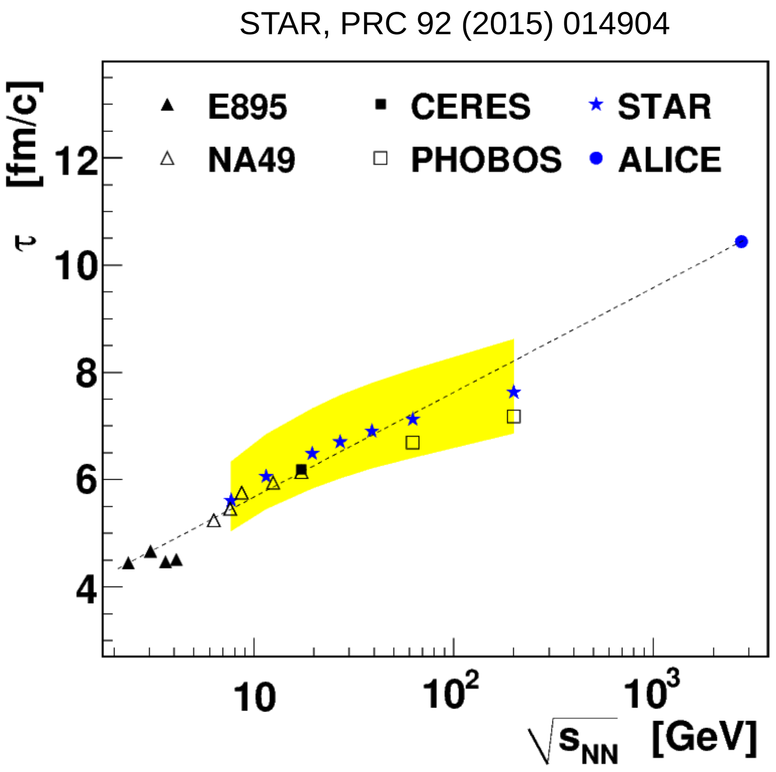


ALI-PREL-125934

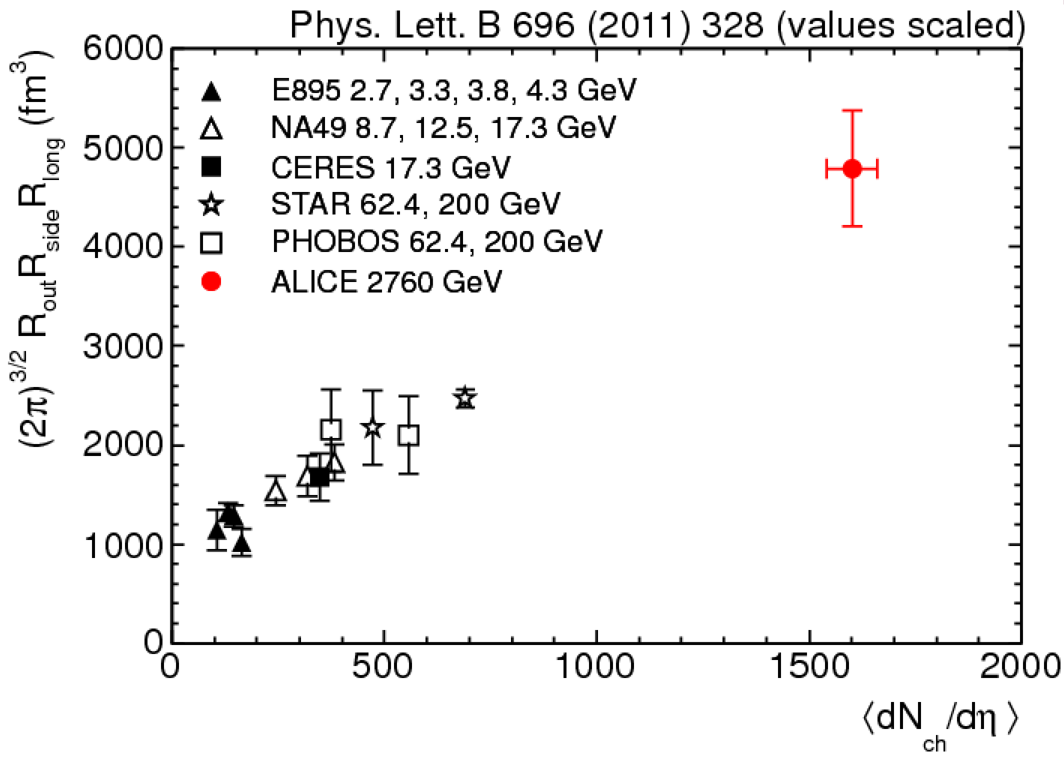
Pion femtoscopy

- Lifetime can be estimated from the longitudinal radius
- Clear increase of the system volume and lifetime with collision energy, at LHC system **twice as large** and **living 30% longer** than at top RHIC energy (good conditions for QGP studies)

Lifetime


STAR, PRC 92 (2015) 014904

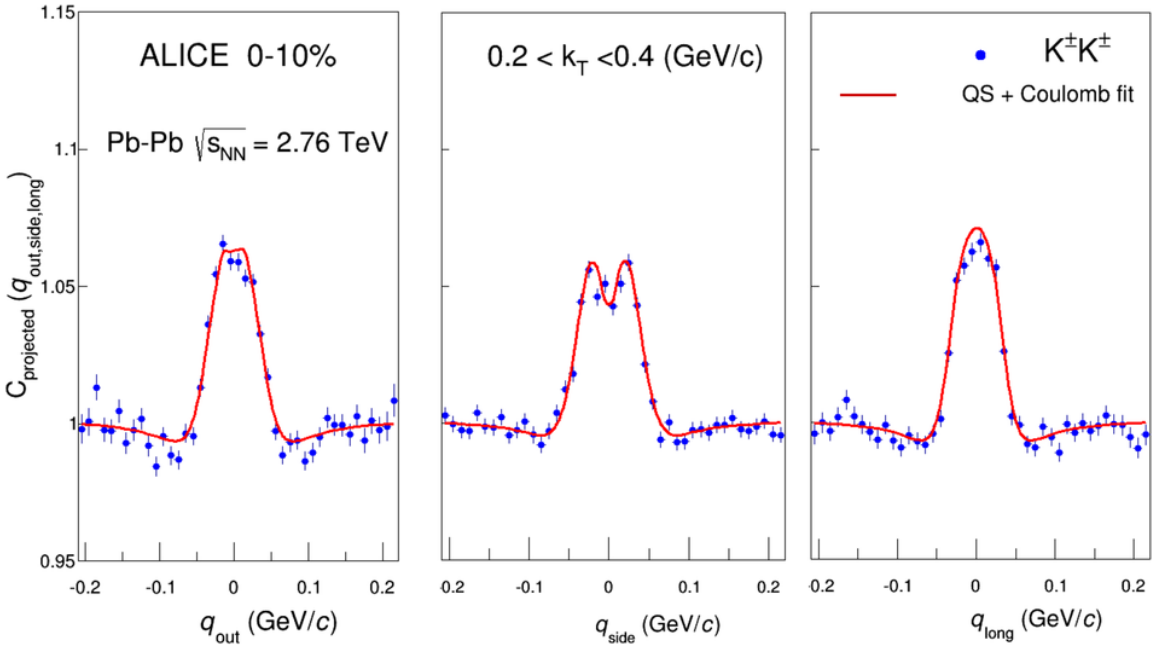
Volume

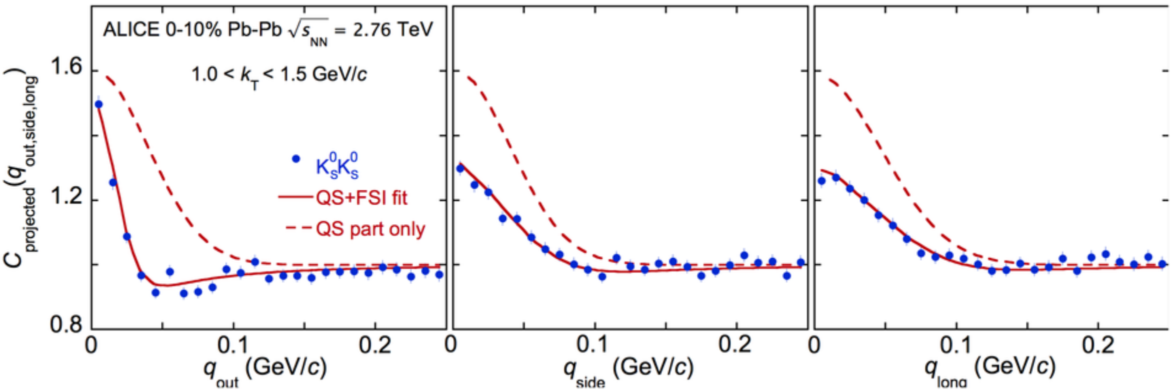

Phys. Lett. B 696 (2011) 328 (values scaled)

Kaon femtoscopy

Phys. Rev. C96 (2017) 064613

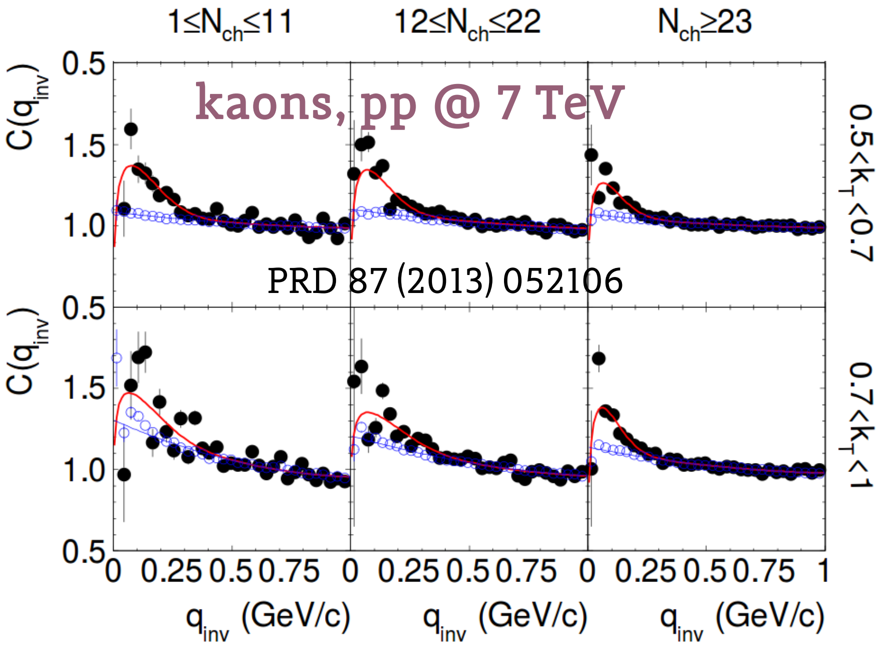
- **Cleaner signal** compared to pions (less affected by resonances)
- Studying **neutral and charged kaons** together provides a convenient **consistency check** (different experimental techniques)
  - Charged Kaons: QS + Strong and Coulomb FSI
  - Neutral Kaons: QS + Strong FSI (including resonances)
- Models which describe pions well, should describe kaons with **equal precision**
- **Rescattering phase has different influence on pions and kaons:**
  → can lead to broken m_T-scaling
  → good probe of the rescattering phase effects





Non-femtoscopic correlations

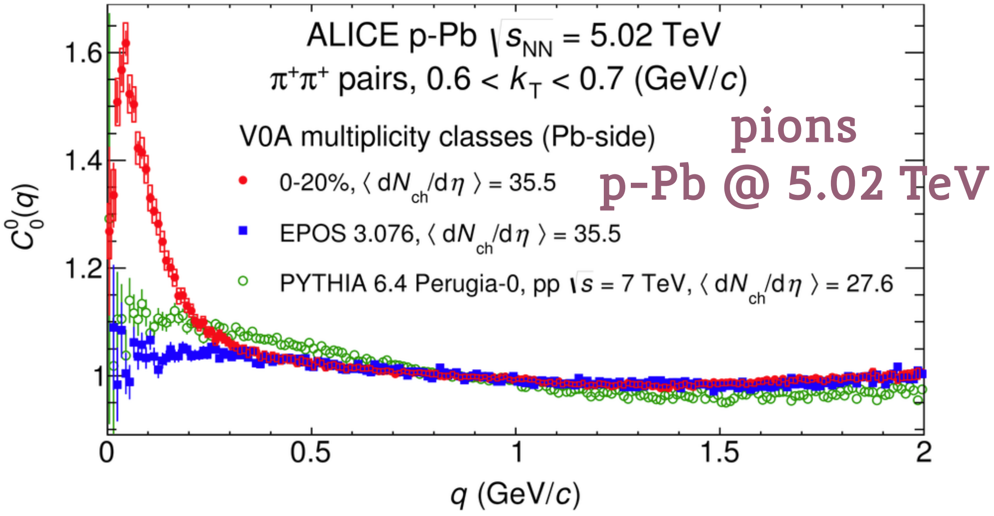
- Non-femtoscopic correlations visible in small systems for pions and kaons:
    - Grow with increasing k_T
    - Grow with decreasing multiplicity
    - **Significant source of systematics in the fitting procedure**
- So far hypothesis of (mini-)jet origin
- How can we test it?



kaons, pp @ 7 TeV

PRD 87 (2013) 052106

PRC 91 (2015) 034906



pions p-Pb @ 5.02 TeV

Beyond the system size

$$C(q)=\int S(r)|\Psi(q,r)|^2 d^4 r \qquad q=2\cdot k^*=p_1-p_2$$

measured correlation

emission function
(source size/shape)

pair wave function
(includes cross section)

- Pair wave function Ψ can be parametrized with **scattering length** f_0, and **effective radius** d_0 parameters.

The correlation function is characterized by **three parameters**:

- **radius** R, **scattering length** f_0, and **effective radius** d_0
- **cross section** σ **(at low** k^***)** is simply: $\sigma=4\pi|f|^2$

Potential applications

- Input to models with re-scattering phase (eg. UrQMD):
  - annihilation cross sections only measured for $p\bar{p}$, $\bar{p}n$, and $\bar{p}d$ pairs – UrQMD currently **guesses it for other systems** from pp pairs

- Structure of baryons/search for CPT violation

  STAR, Nature 527, 345-348 (2015)

- Search for H-dibaryon

  ALICE, PLB 752 (2016) 267-277

- Hypernuclear structure theory

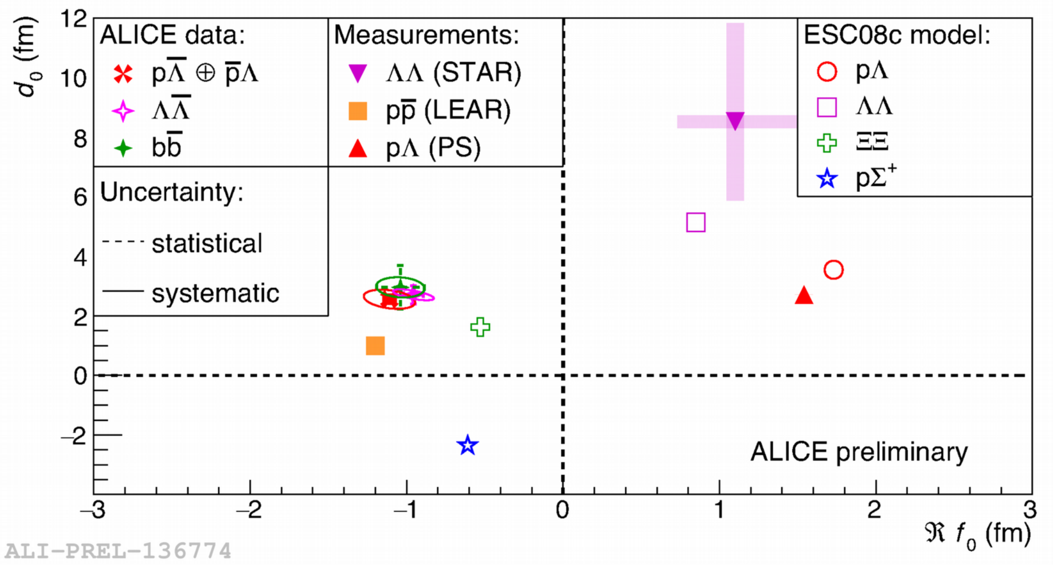
  Nucl.Phys. A914 (2013) 377-386

- Neutron star equation of state

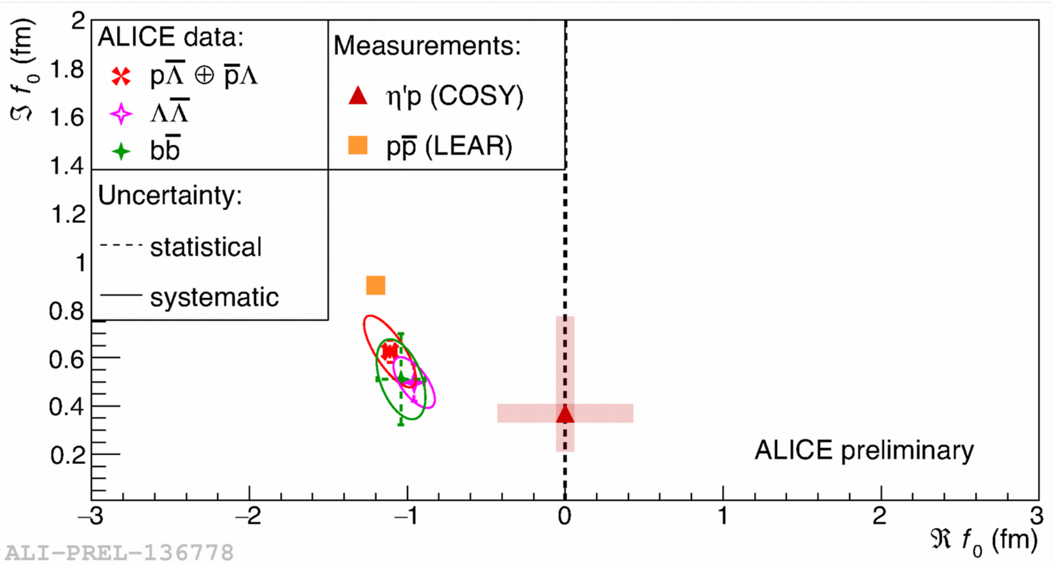
  Nucl.Phys. A804 (2008) 309-321

- Relativistic heavy-ion collisions at LHC or RHIC produce very similar number of baryons and antibaryons, "matter-antimatter pair factories"

Baryon-antibaryon correlations



ALI-PREL-136774



ALI-PREL-136778

Jeremi Niedziela, PhD thesis

Conclusions from fitting:

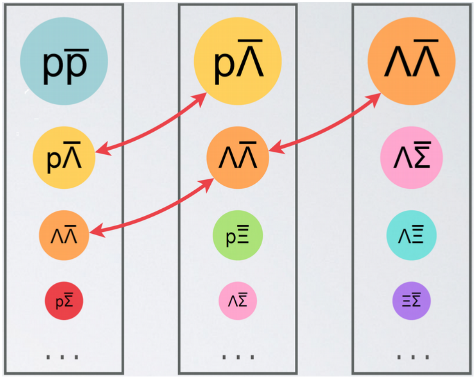
- Interaction parameters are measurable
- Scattering parameters for **all baryon-antibaryon pairs are similar to each other** (UrQMD assumption is valid)
- We observe a **negative real part of scattering length** → repulsive strong interaction or creation of a bound state (existence of baryon-antibaryon bound states?)
- Significant **positive imaginary part of scattering length** – presence of a non-elastic channel – annihilation

Next steps: try to look for baryon-antibaryon bound states

Baryon-antibaryon correlations

Explanation of the fitting procedure:

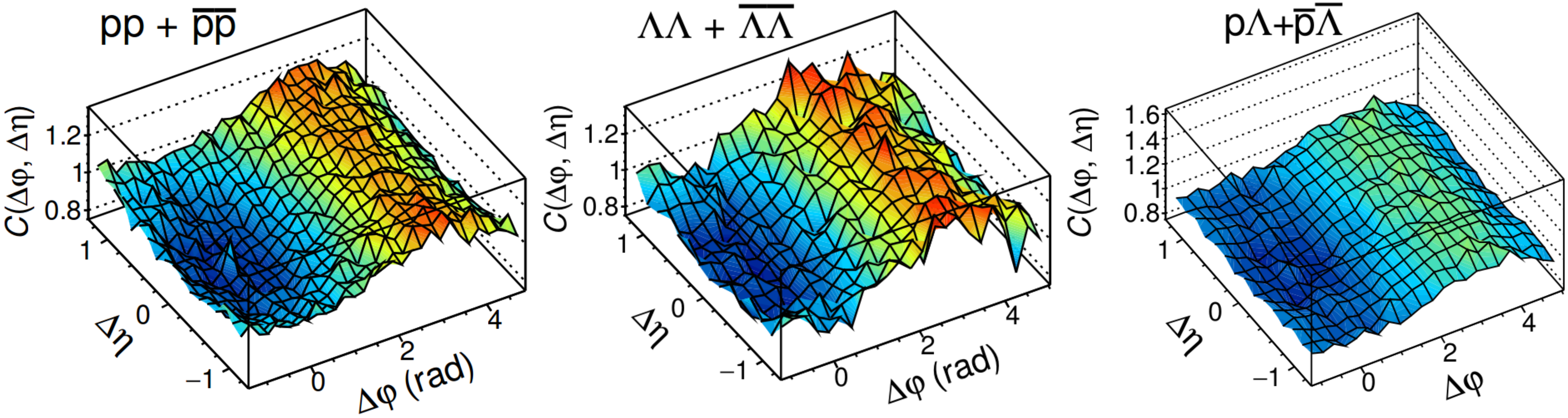
- **χ^2** is calculated from a “global” fit to all functions:
  2 data sets, 3 pair combinations, 6 centrality bins (**total 36 functions**)
- simultaneous fit accounts for parameters **shared** between different systems (such as $\Lambda\bar{\Lambda}$ scattering length)
- **radii scale with multiplicity** for a given system $R_{inv} = a \cdot \sqrt[3]{N_{ch}} + b$
- for different systems we assume **radii scaling with** m_T
- Fractions of **residual pairs** taken from AMPT



ΔηΔφ of baryons

Eur.Phys.J. C77 (2017) 8, 569

Małgorzata Janik, ŁG

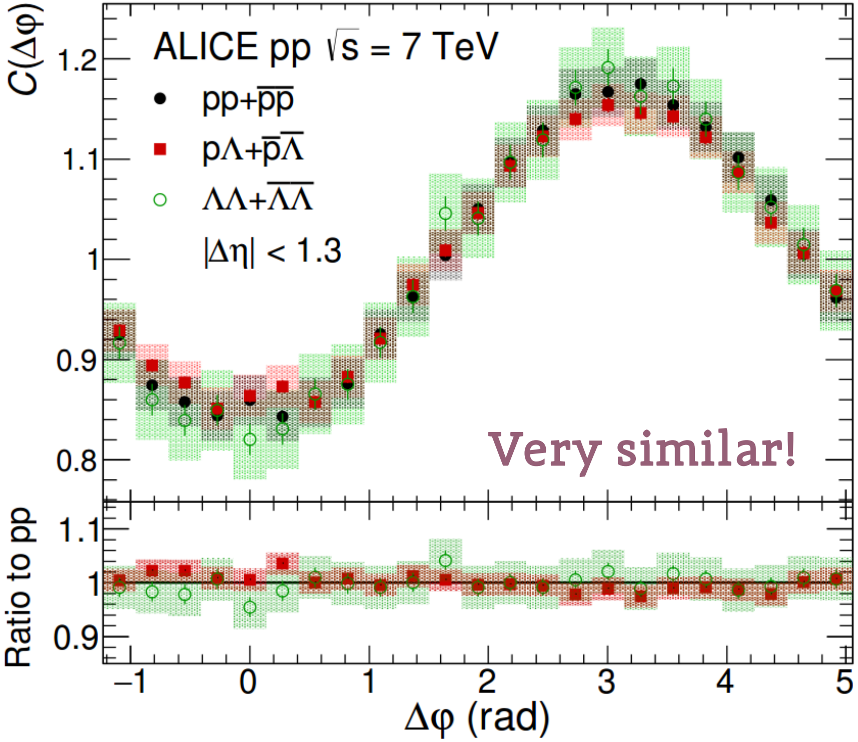


- We found that all baryon-baryon pairs show a **depression** instead of a typical near-side peak

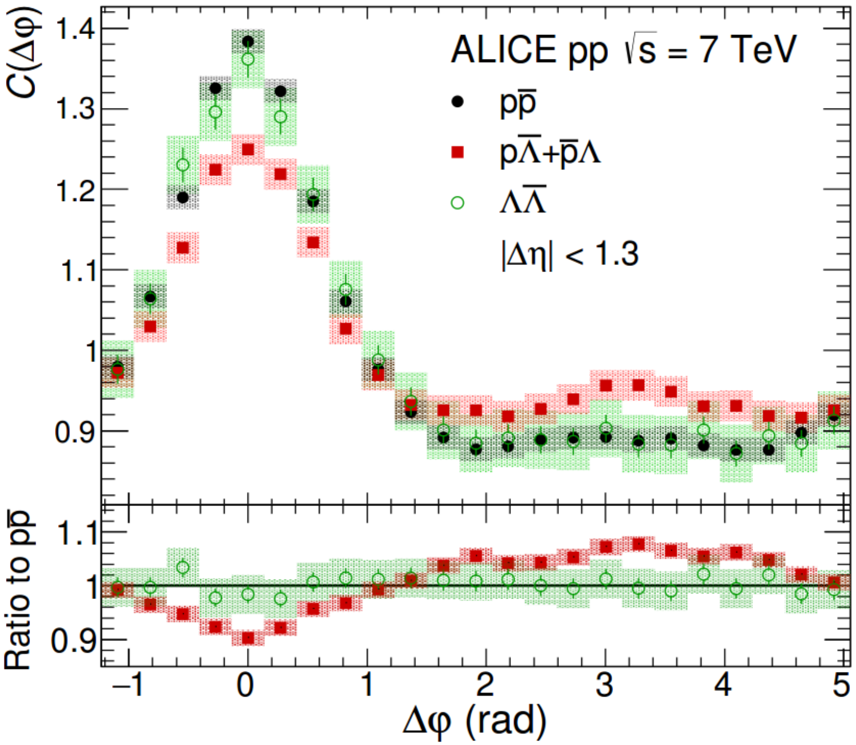
ΔηΔφ of baryons

Małgorzata Janik, ŁG

Eur.Phys.J. C77 (2017) 8, 569



Very similar!



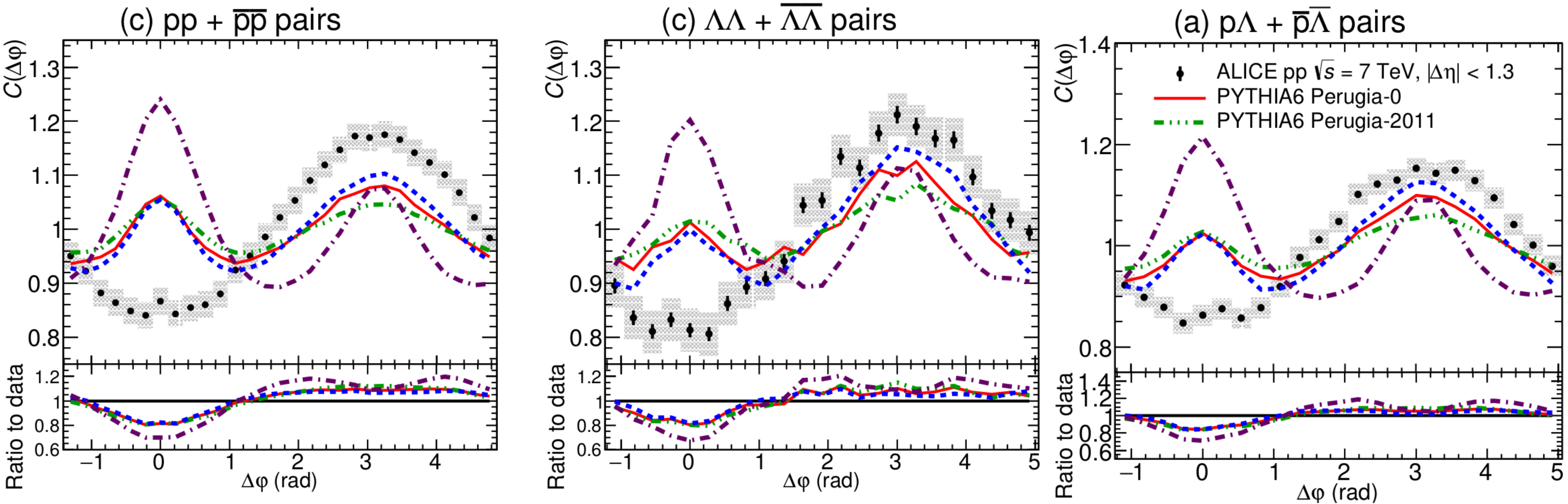
- Projections show how similar are baryon-baryons pairs to each other
- Similarity between pairs, to a lesser extent, is also observed in the baryon-antibaryon case

Possible explanations:

- Fermi-Dirac Quantum Statistics? **NO (non-identical particles)**
- Coulomb repulsion? **NO (uncharged particles)**
- **Strong Final-State Interactions?** (see next slides)

Are baryons interesting?

Eur.Phys.J. C77 (2017) 8, 569



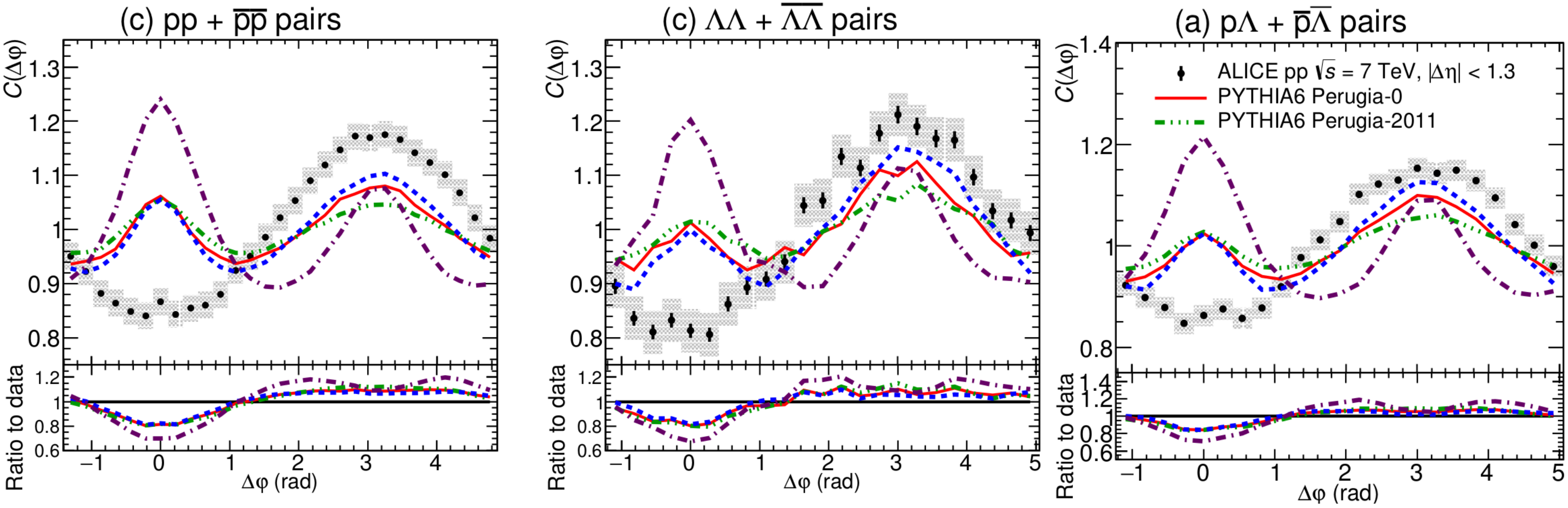
- **Azimuthal correlations: depletion** instead of a near-side peak visible for **baryon-baryon pairs** in pp collisions @ 7 TV
- **New baryon production mechanism needed** (T. Sjöstrand, QM 2018)
- It seems we do not understand some fundamental properties of baryons

For details see CERN-LHC seminar by
Małgorzata Janik
30 May 2017
https://indico.cern.ch/event/632396/

ΔηΔφ of baryons

Eur.Phys.J. C77 (2017) 8, 569

Małgorzata Janik, ŁG



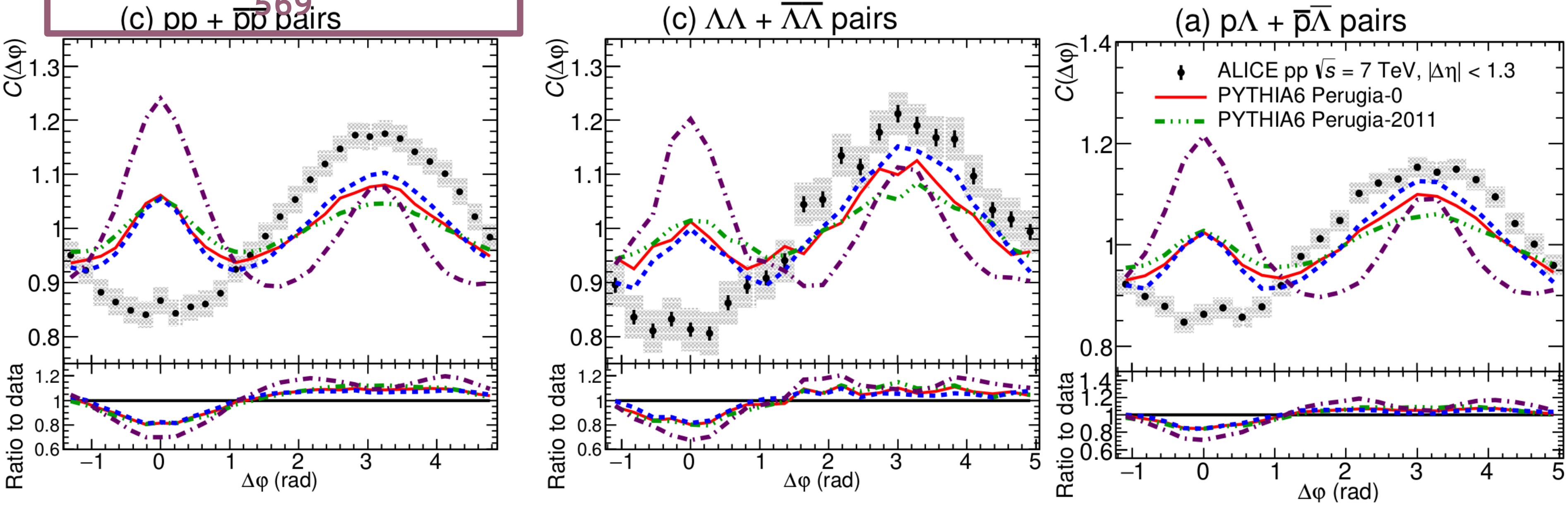
- None of studied MC models (PYTHIA, PHOJET, EPOS, HERWIG) agrees with the data even qualitatively

- What can be the explanation of this effect?

Let's look at similar studies in e^+e^- collisions at √s = 29 GeV (SLAC-PEP) from late 80's

ΔηΔφ of baryons

Eur.Phys.J. C77 (2017) 8, 569



- **Depletion** instead of a near-side peak visible for **baryon-baryon pairs** in azimuthal correlations
- None of studied Monte Carlo models (PYTHIA, PHOJET, EPOS, HERWIG) agrees with the data even qualitatively
- Results challenge current hadronization models
- **Possible explanation → AMPT with string melting and new coalescence model describes qualitatively our data**

ΔηΔφ of baryons

arXiv:
1808.10641
31 Aug 2018

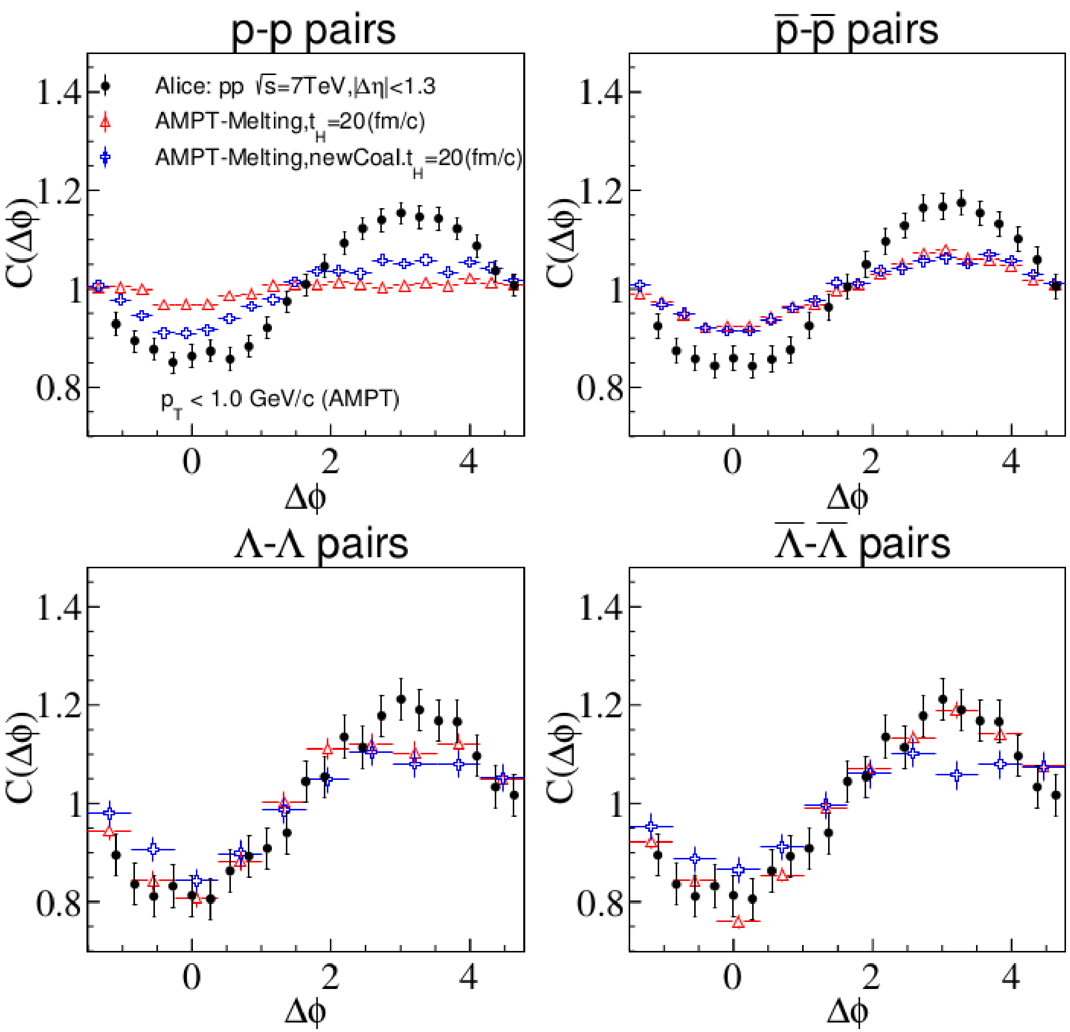


FIG. 6: One-dimensional $\Delta\phi$ correlation functions of p-p, $\bar{p}$-$\bar{p}$, Λ-Λ and $\bar{\Lambda}$-$\bar{\Lambda}$ for $p_T < 1.0$ GeV/c from the AMPT model. Open symbols represent AMPT calculations with different configurations as illustrated in the figure. Solid points are experiment data [14].

- **Possible explanation → AMPT with string melting and new coalescence model describes qualitatively ALICE data**

Summary and outlook

T. Sjostrand, QM 2018

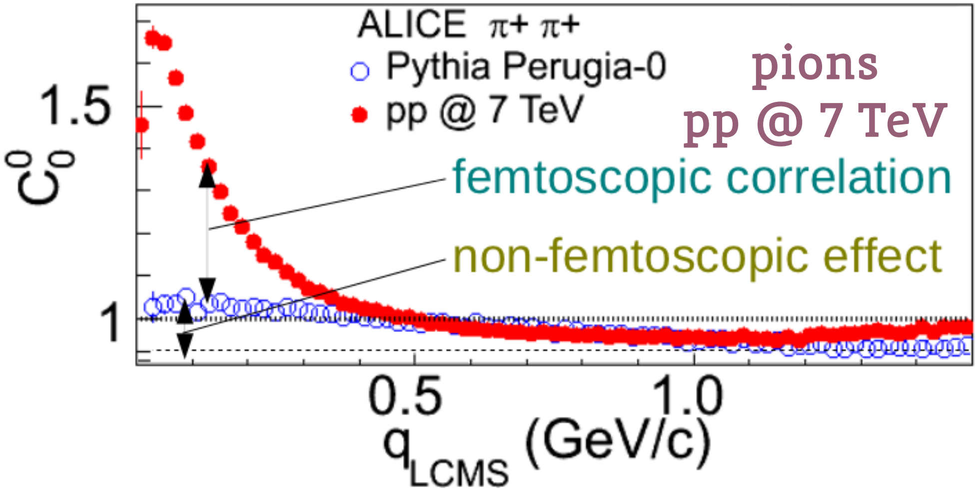
- Conventional pp generators successful, with MPI + CR generating some collectivity, but now cracks.
- Need new framework for baryon production.
- String close-packing likely to influence hadronization, before (shoving), during (ropes) and after (rescattering).
- Currently no known unique solution, so free to explore.
- Several recent & ongoing studies look promising, but much work and few active with pp generator outlook.
- Further experimental input crucial!

Whole new field of study opening up!

Non-femtoscopic correlations

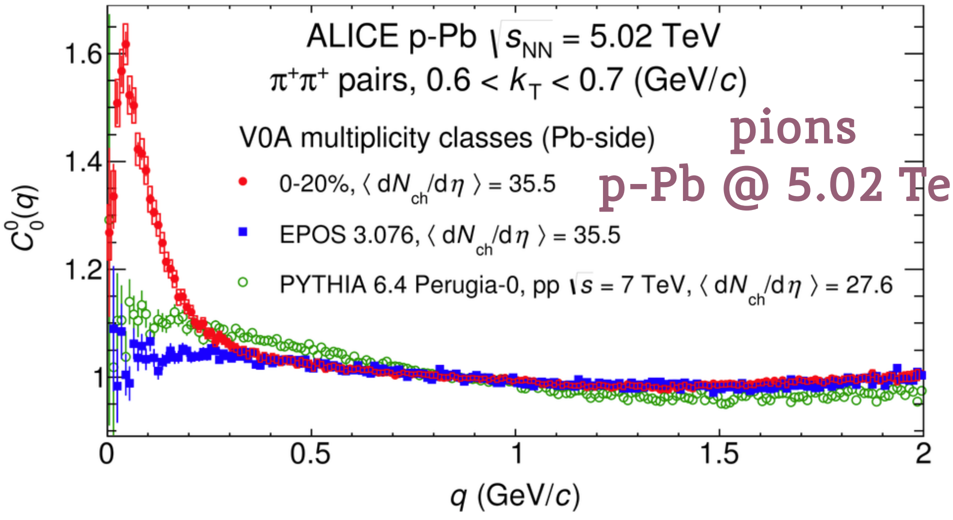
- Non-femtoscopic correlations visible in small systems for pions and kaons:
  - Grow with increasing k_T
  - Grow with decreasing multiplicity
  - **Significant source of systematics in the fitting procedure**
- So far only <u>hypothesis</u> of (mini-)jet origin
- How do baryon correlations look like in pp?

PRD 84 (2011) 112004

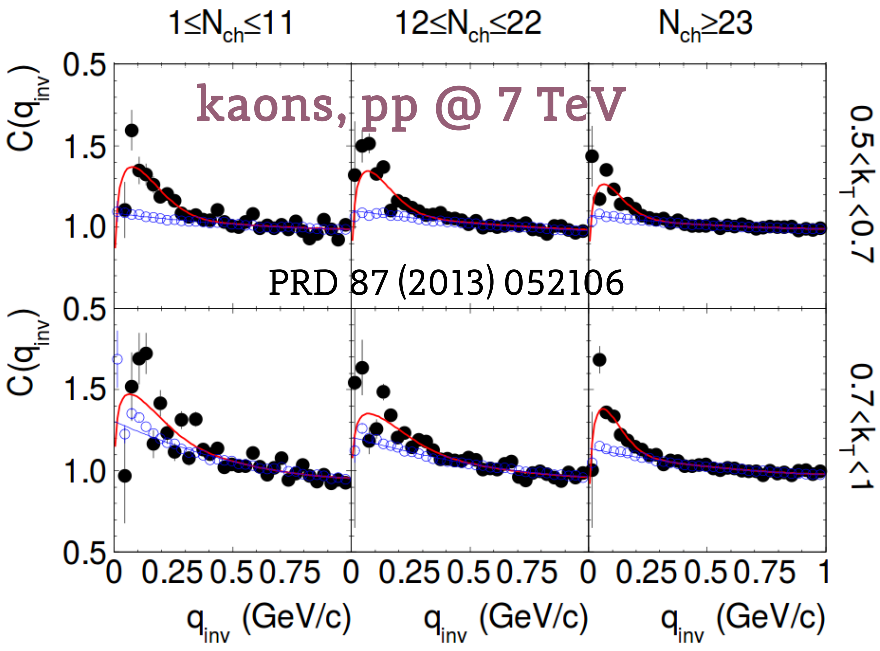


pions
pp @ 7 TeV

PRC 91 (2015) 034906



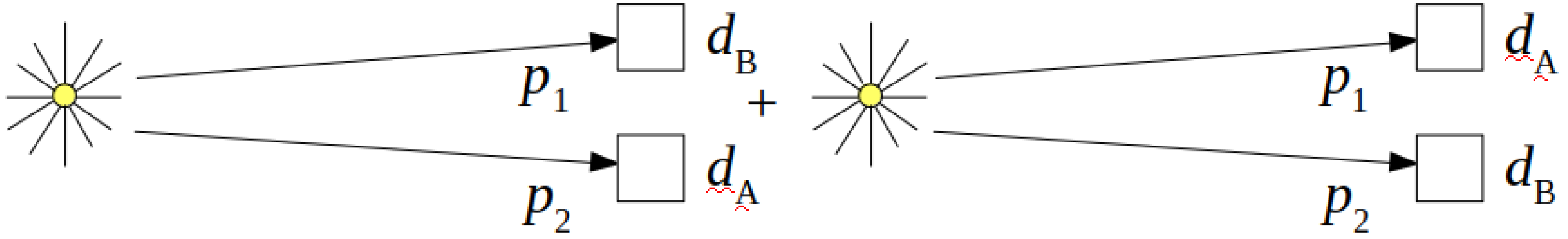
pions
p-Pb @ 5.02 TeV



kaons, pp @ 7 TeV

PRD 87 (2013) 052106

Long history of HBT



$q = p_1 - p_2$

$d = d_A - d_B$

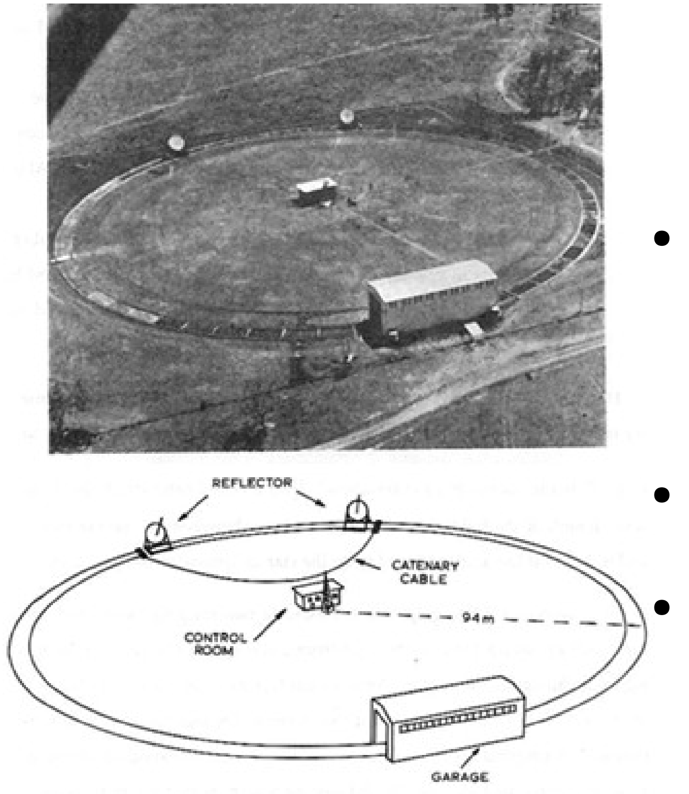
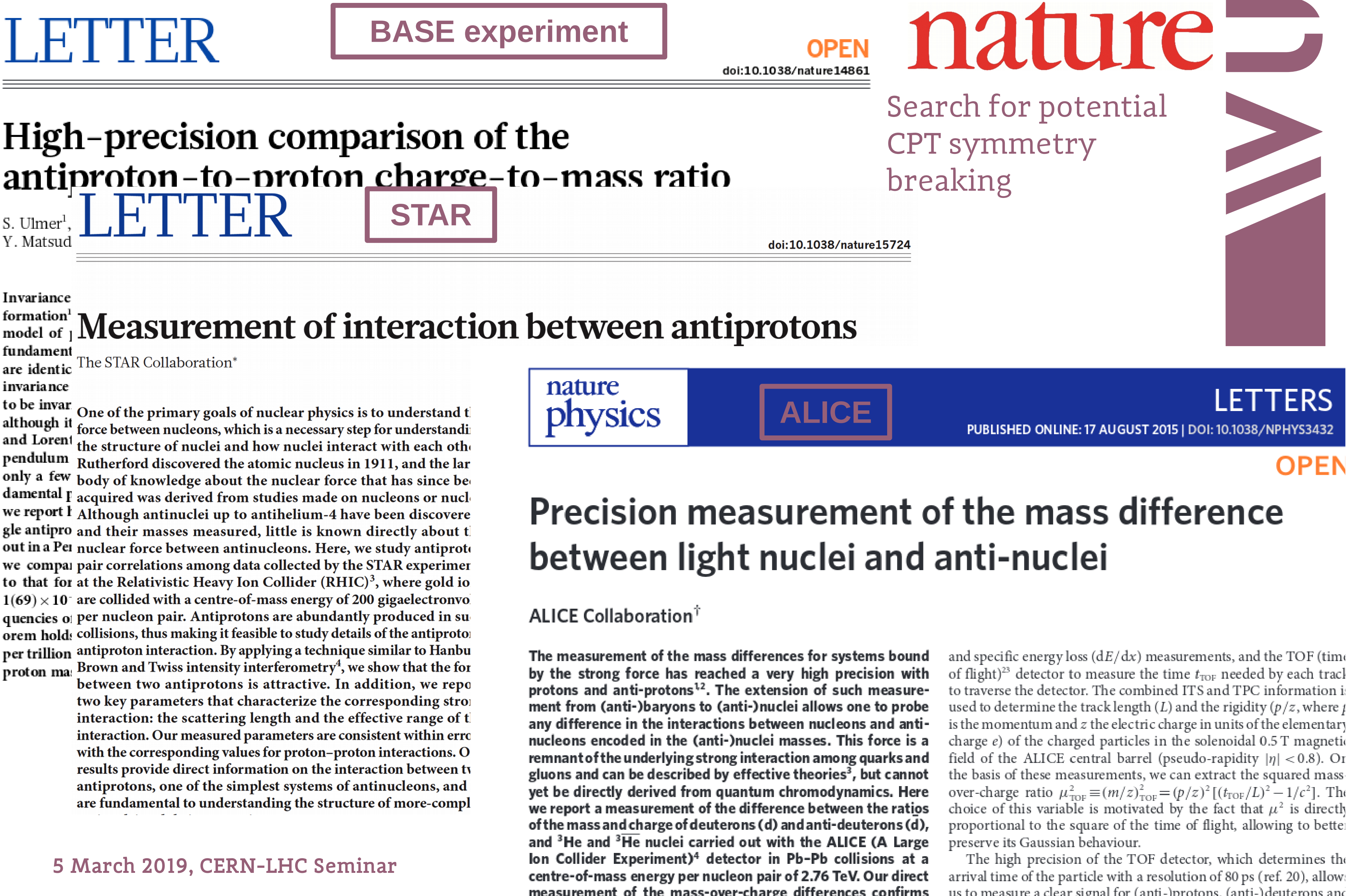


Figure 1. Aerial photo and illustration of the original HBT apparatus. They have been extracted from Ref.[1].

- In astronomy angular size of the star is measured via photon correlation vs. spatial separation of detectors
- The momentum spread can be inferred, which is transformed into angular size of the star
- The mathematical formalism is similar
- The first measurement was done by Hanbury-Brown and Twiss – HBT !

Are baryons interesting?



LETTER

BASE experiment

OPEN

doi:10.1038/nature14861

High-precision comparison of the antiproton-to-proton charge-to-mass ratio

S. Ulmer[1],
Y. Matsud

Invariance
formation[1]
model of
fundament
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LETTER

STAR

doi:10.1038/nature15724

Measurement of interaction between antiprotons

The STAR Collaboration*

One of the primary goals of nuclear physics is to understand t
force between nucleons, which is a necessary step for understandi
the structure of nuclei and how nuclei interact with each oth
Rutherford discovered the atomic nucleus in 1911, and the lar
body of knowledge about the nuclear force that has since be
acquired was derived from studies made on nucleons or nucl
Although antinuclei up to antihelium-4 have been discovere
and their masses measured, little is known directly about t
nuclear force between antinucleons. Here, we study antiprot
pair correlations among data collected by the STAR experimer
at the Relativistic Heavy Ion Collider (RHIC)[3], where gold io
are collided with a centre-of-mass energy of 200 gigaelectronvo
per nucleon pair. Antiprotons are abundantly produced in su
collisions, thus making it feasible to study details of the antiproto
antiproton interaction. By applying a technique similar to Hanbu
Brown and Twiss intensity interferometry[4], we show that the for
between two antiprotons is attractive. In addition, we repo
two key parameters that characterize the corresponding stro
interaction: the scattering length and the effective range of t
interaction. Our measured parameters are consistent within erro
with the corresponding values for proton–proton interactions. O
results provide direct information on the interaction between tv
antiprotons, one of the simplest systems of antinucleons, and
are fundamental to understanding the structure of more-compl

nature

Search for potential CPT symmetry breaking

nature physics

ALICE

LETTERS

PUBLISHED ONLINE: 17 AUGUST 2015 | DOI: 10.1038/NPHYS3432

OPEN

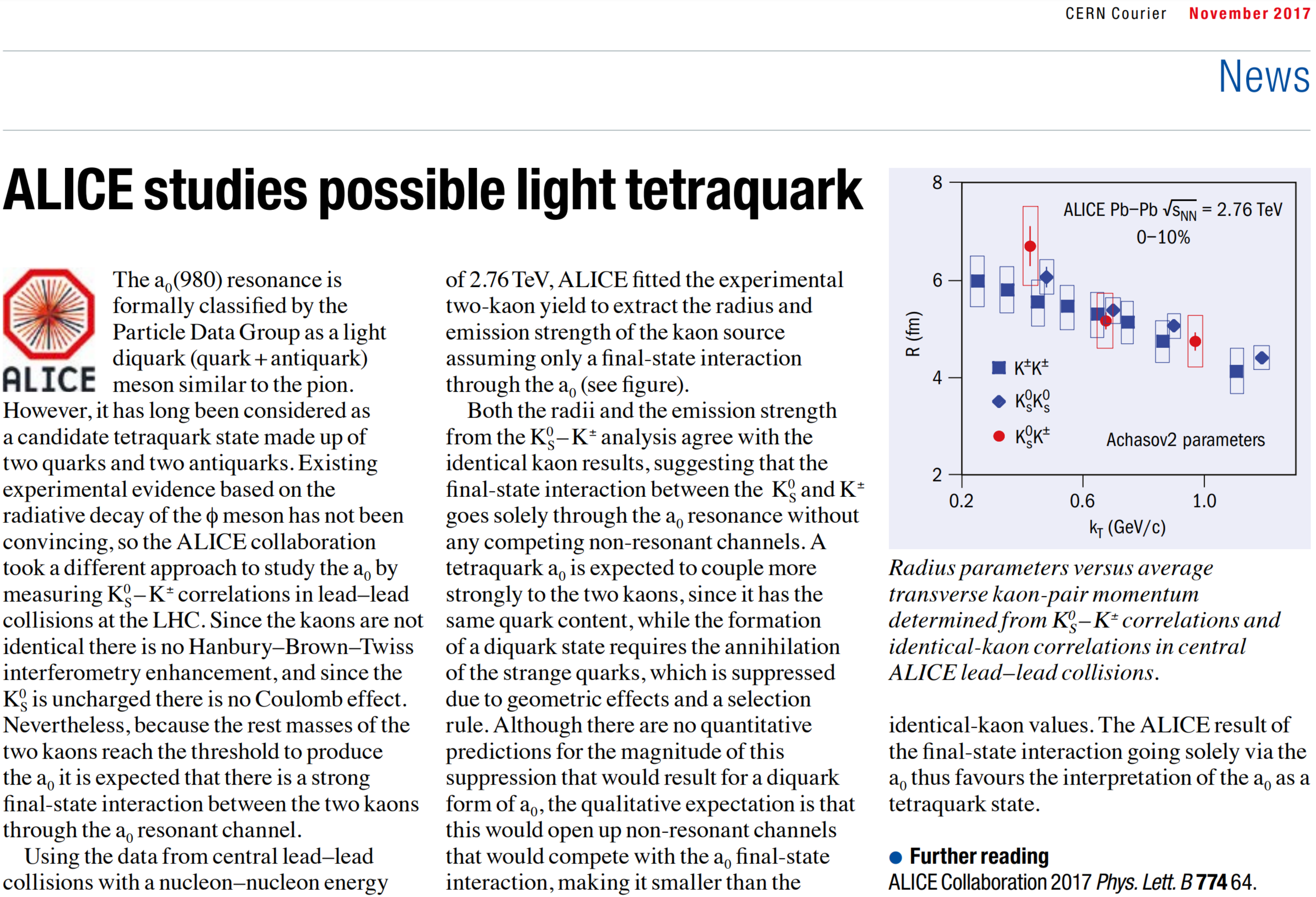
Precision measurement of the mass difference between light nuclei and anti-nuclei

ALICE Collaboration†

The measurement of the mass differences for systems bound by the strong force has reached a very high precision with protons and anti-protons[1,2]. The extension of such measurement from (anti-)baryons to (anti-)nuclei allows one to probe any difference in the interactions between nucleons and anti-nucleons encoded in the (anti-)nuclei masses. This force is a remnant of the underlying strong interaction among quarks and gluons and can be described by effective theories[3], but cannot yet be directly derived from quantum chromodynamics. Here we report a measurement of the difference between the ratios of the mass and charge of deuterons (d) and anti-deuterons ($\overline{d}$), and ^{3}He and $^3\overline{He}$ nuclei carried out with the ALICE (A Large Ion Collider Experiment)[4] detector in Pb-Pb collisions at a centre-of-mass energy per nucleon pair of 2.76 TeV. Our direct measurement of the mass-over-charge differences confirms

and specific energy loss (dE/dx) measurements, and the TOF (tim
of flight)[23] detector to measure the time t_{TOF} needed by each trac
to traverse the detector. The combined ITS and TPC information i
used to determine the track length (L) and the rigidity (p/z, where
is the momentum and z the electric charge in units of the elementar
charge e) of the charged particles in the solenoidal 0.5 T magneti
field of the ALICE central barrel (pseudo-rapidity $|\eta| < 0.8$). Or
the basis of these measurements, we can extract the squared mass
over-charge ratio $\mu^2_{TOF} \equiv (m/z)^2_{TOF} = (p/z)^2[(t_{TOF}/L)^2 - 1/c^2]$. The
choice of this variable is motivated by the fact that μ^2 is directl
proportional to the square of the time of flight, allowing to bette
preserve its Gaussian behaviour.

The high precision of the TOF detector, which determines th
arrival time of the particle with a resolution of 80 ps (ref. 20), allow
us to measure a clear signal for (anti-)protons, (anti-)deuterons and



ALICE studies possible light tetraquark

The a$_0$(980) resonance is formally classified by the Particle Data Group as a light diquark (quark + antiquark) meson similar to the pion. However, it has long been considered as a candidate tetraquark state made up of two quarks and two antiquarks. Existing experimental evidence based on the radiative decay of the ϕ meson has not been convincing, so the ALICE collaboration took a different approach to study the a$_0$ by measuring K^0_S–$K^\pm$ correlations in lead–lead collisions at the LHC. Since the kaons are not identical there is no Hanbury–Brown–Twiss interferometry enhancement, and since the K^0_S is uncharged there is no Coulomb effect. Nevertheless, because the rest masses of the two kaons reach the threshold to produce the a$_0$ it is expected that there is a strong final-state interaction between the two kaons through the a$_0$ resonant channel.

Using the data from central lead–lead collisions with a nucleon–nucleon energy of 2.76 TeV, ALICE fitted the experimental two-kaon yield to extract the radius and emission strength of the kaon source assuming only a final-state interaction through the a$_0$ (see figure).

Both the radii and the emission strength from the K^0_S–$K^\pm$ analysis agree with the identical kaon results, suggesting that the final-state interaction between the K^0_S and $K^\pm$ goes solely through the a$_0$ resonance without any competing non-resonant channels. A tetraquark a$_0$ is expected to couple more strongly to the two kaons, since it has the same quark content, while the formation of a diquark state requires the annihilation of the strange quarks, which is suppressed due to geometric effects and a selection rule. Although there are no quantitative predictions for the magnitude of this suppression that would result for a diquark form of a$_0$, the qualitative expectation is that this would open up non-resonant channels that would compete with the a$_0$ final-state interaction, making it smaller than the identical-kaon values. The ALICE result of the final-state interaction going solely via the a$_0$ thus favours the interpretation of the a$_0$ as a tetraquark state.

Radius parameters versus average transverse kaon-pair momentum determined from K^0_S–$K^\pm$ correlations and identical-kaon correlations in central ALICE lead–lead collisions.

● Further reading

ALICE Collaboration 2017 *Phys. Lett. B* **774** 64.

Status of femtoscopy in ALICE

- **Previous results**
  - Multipion Bose-Einstein correlations in pp, p-Pb, and Pb-Pb collisions at the LHC, Phys. Rev. C 93 (2016) 054908
  - Centrality dependence of pion freeze-out radii in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV Phys. Rev. C 93 (2016) 024905
  - 1D pion, kaon , proton femtoscopy in Pb-Pb Phys. Rev. C 92 (2015) 054908
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  - Freeze-out radii extracted from three-pion cumulants in pp, p-Pb and Pb-Pb collisions at the LHC, Phys. Lett. B 739 (2014) 139-151
  - Two and Three-Pion Quantum Statistics Correlations in Pb-Pb Collisions at $\sqrt{s_{NN}}$=2.76 TeV at the LHC Phys. Rev. C 89 (2014) 024911
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  - K0sK0s correlations in pp collisions at $\sqrt{s}$=7 TeV from the LHC ALICE experiment Phys. Lett. B 717 (2012) 151-161
  - Femtoscopy in pp a 0.9 and 7 TeV: Phys. Rev. D 84 (2011) 112004,
  - Two-pion Bose-Einstein correlations in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV Phys. Lett. B 696 (2011) 328-337
  - Two-pion Bose-Einstein correlations in pp collisions at $\sqrt{s}$=900 GeV, Phys. Rev. D 82 (2010) 052001
- **Newly published papers:**
  - Azimuthally-differential pion femtoscopy relative to the third harmonic event plane in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, arxiv: 1803.10594
  - Azimuthally differential pion femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV, Phys. Rev. Lett. 118 (2017) 222301
  - Kaon femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Rev. C96 (2017) 064613
  - Measuring K0SK± interactions using Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV, Phys. Lett. B 774 (2017) 64
- **Preliminary results:**
  - Baryon results:
    - $p\bar{p}$, $\overline{pp}$, pp from Run2
    - Baryon-baryon correlations ($p\Lambda$, $\bar{p}\bar{\Lambda}$, $\Lambda\Lambda$, and $\overline{\Lambda\Lambda}$) from Run1 and Run2
    - Baryon-antibaryon correlations ($p\bar{p}$, and $p\bar{\Lambda}$, $\bar{p}\Lambda$, and $\Lambda\bar{\Lambda}$) from Run1 and Run2
    - Analysis of heavier baryons (eg. $p\Xi$, $\bar{p}\Xi$)
  - Lambda-K+, Lambda-K-, and Lambda-K0s
  - Kaon-proton

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  - Lambda-K+, Lambda-K-, and Lambda-K0s
  - Kaon-proton

New since last WPCF