What can we learn from femtoscopic and angular correlations of identified particles in ALICE?

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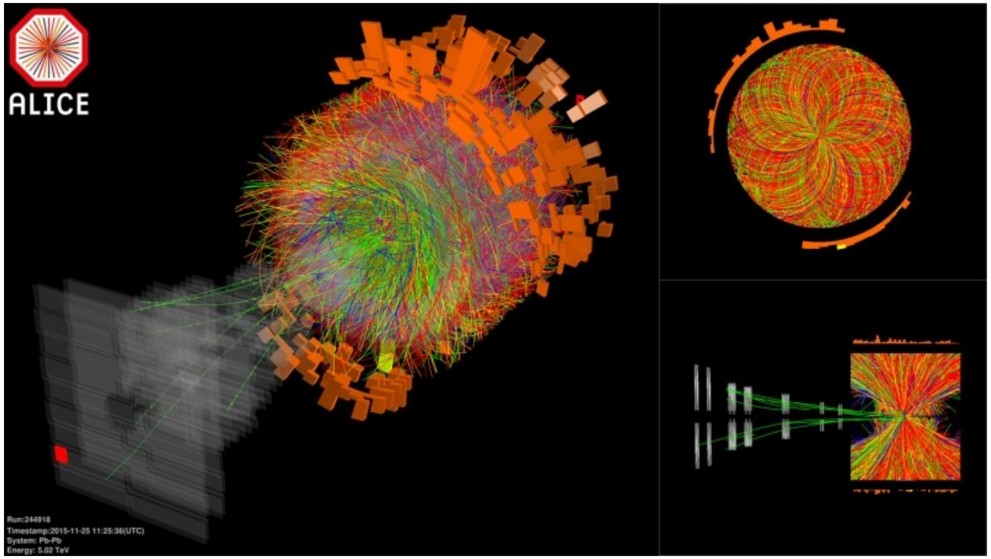
Femtoscopy – going beyond the system size

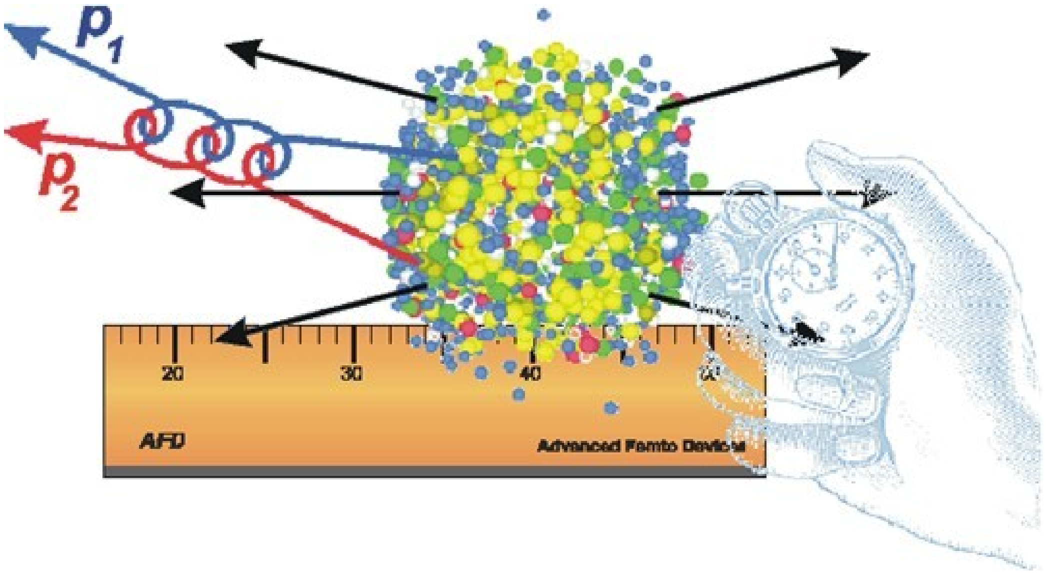
Correlations of baryons

$K^0_s K^{\pm}$ **correlations**

Femtoscopy technique



from M. Lisa and S. Pratt



- **Femtoscopy** – measures space-time characteristics of the source using particle correlations in <u>momentum space</u>
- Main sources of correlations:
  - Quantum statistics (QS)
    - bosons (i.e. pions) – Bose-Einstein QS
    - fermions (i.e. protons) – Fermi-Dirac QS
  - Final-state interactions (FSI)
    - strong interaction
    - Coulomb repulsion or attraction

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

In the experiment:

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

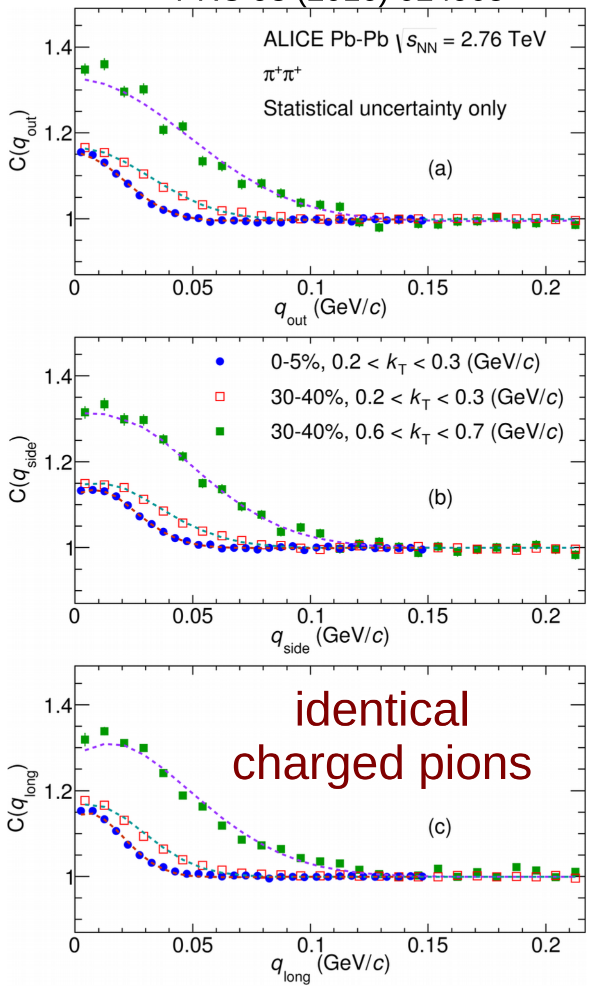
$A(\vec{q})$ - signal distribution (“same” events)

$B(\vec{q})$ - background distribution (“mixed” events)

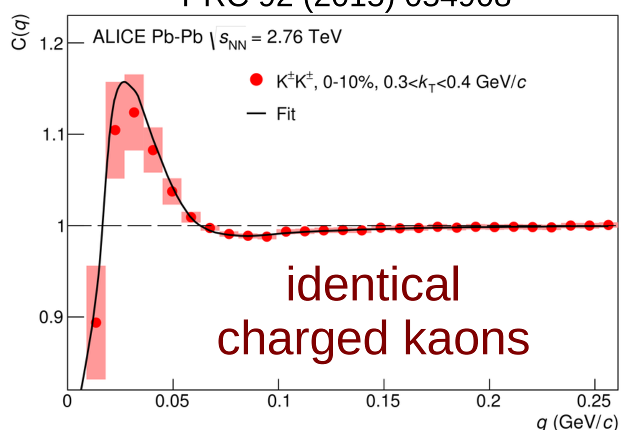
How does it look like?

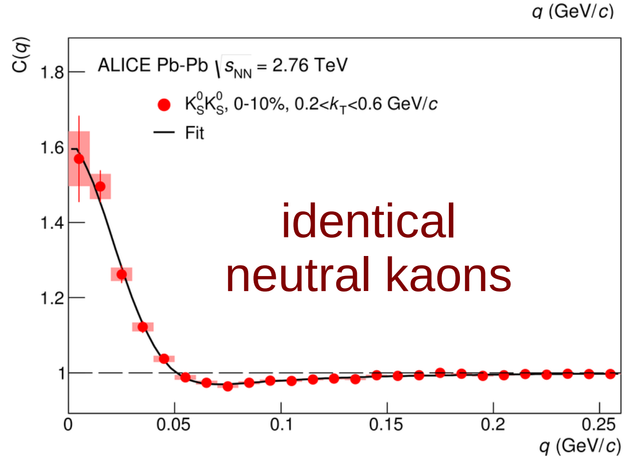
The correlation functions have various shapes, depending on the pair type (interactions involved), collision system and energy, pair transverse momentum, etc.

PRC 93 (2016) 024905



PRC 92 (2015) 054908





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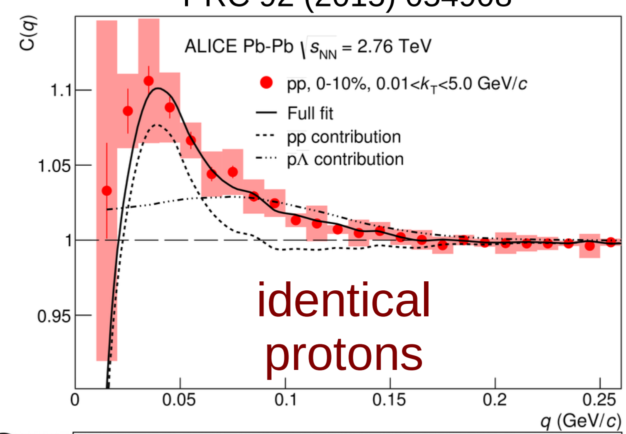
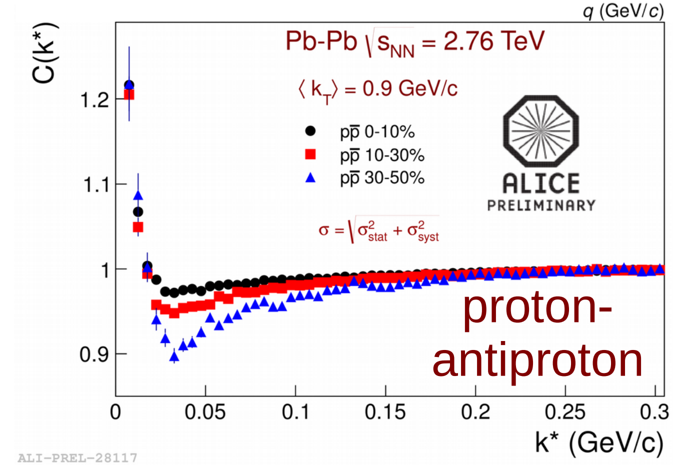




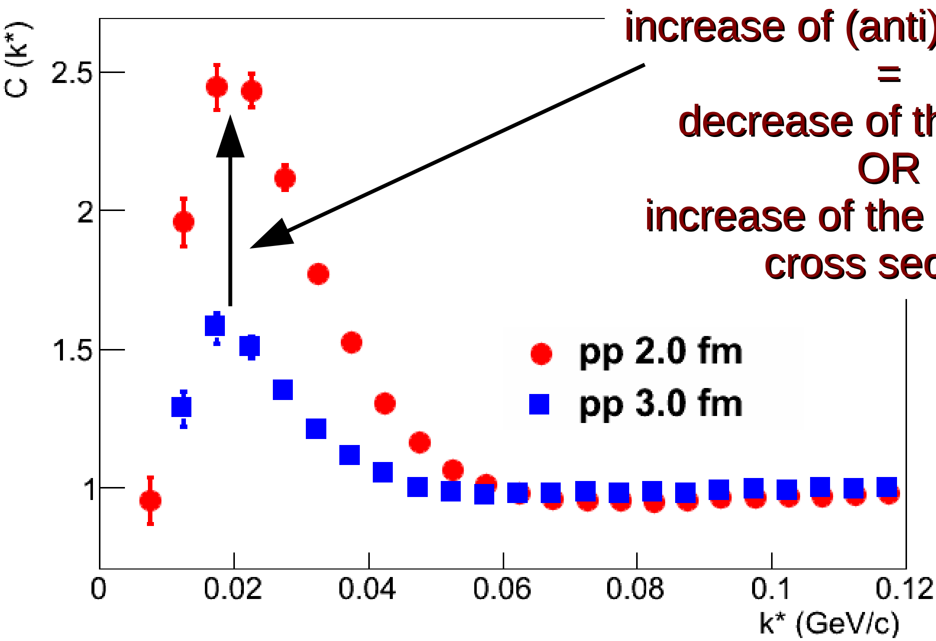
Going beyond the system size

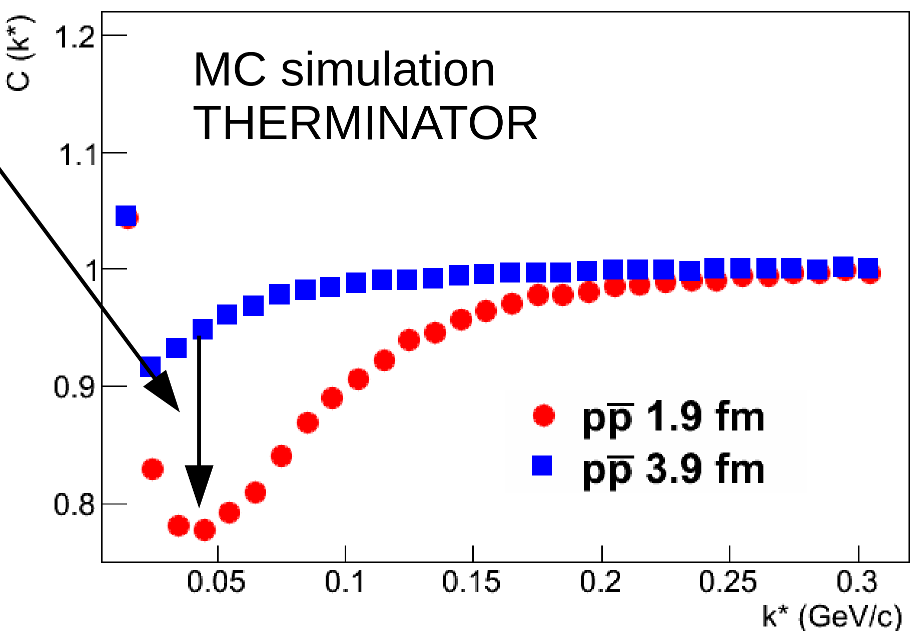
$$C(q)=\int S(r)|\Psi(q,r)|^2 d^4 r$$

measured correlation

emission function (source size/shape)

pair wave function (includes cross section)





Correlation from Strong Interaction

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

measured correlation — emission function (source size/shape) — **pair wave function (includes cross section)**

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

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

- If only Strong Final State Interaction (FSI) the result of integration:

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

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

where ρ_S are the spin fractions

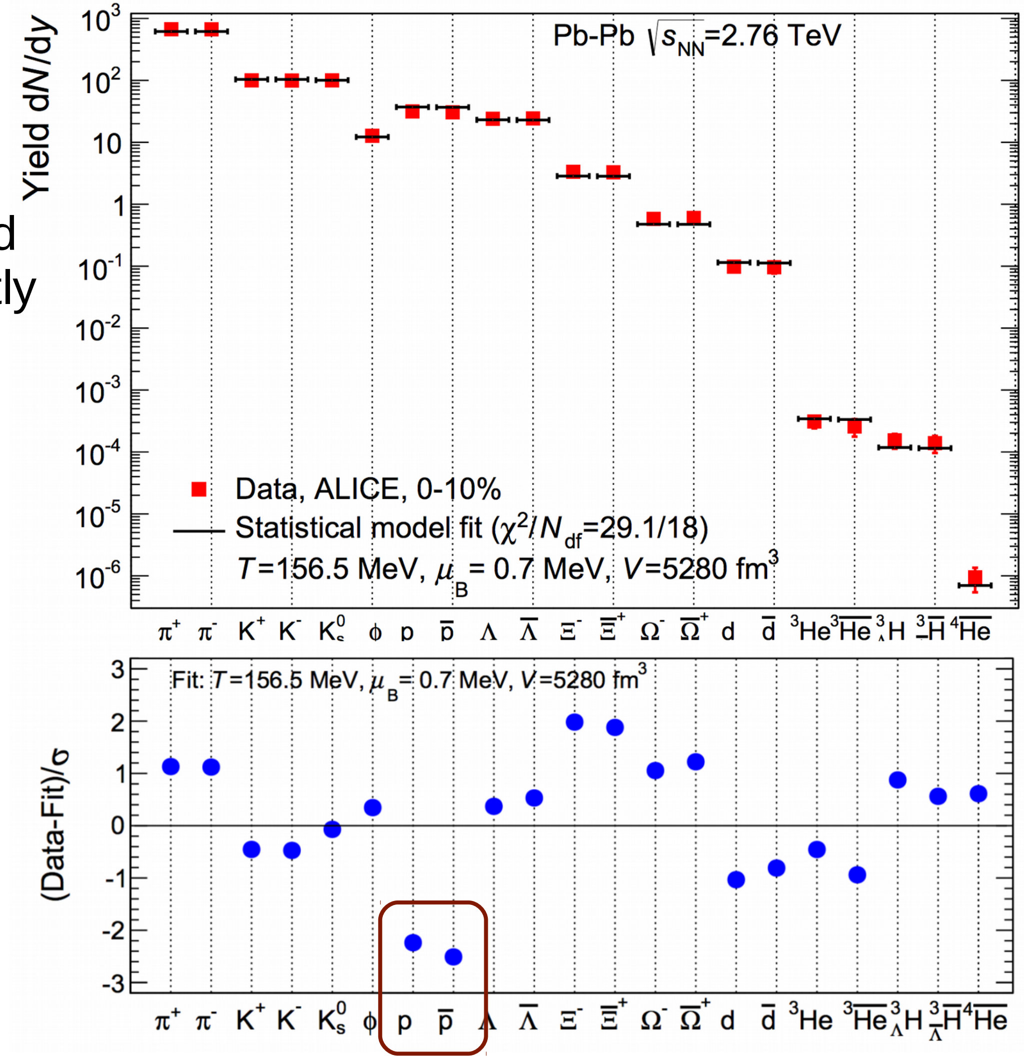
- The correlation function is finally characterized by **three parameters**:
  - **radius** R, **scattering length** f_0, and **effective radius** d_0
  - **Cross section** σ (at low k^*) **is simply:** $\sigma=4\pi|f|^2$

$$F_1(z)=\int_0^z x e^{x^2-z^2}/z\, dx$$

$$F_2(z)=(1-e^{-z})/z$$

What are the potential applications?

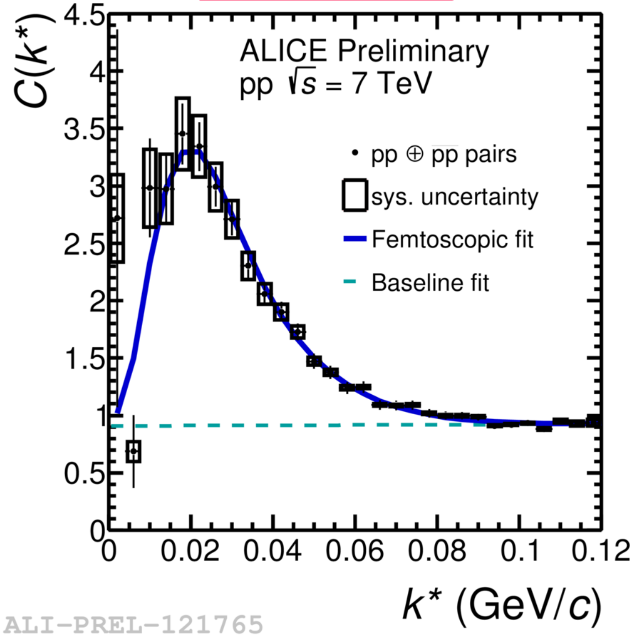
- Input to models with re-scattering phase (eg. UrQMD):
  PRC 89 (2014) 054916
  - annihilation cross sections only measured for $p\bar{p}$, $\bar{p}n$, and $\bar{p}d$ pairs – UrQMD currently **guesses it for other systems** from $p\bar{p}$ pairs
  - should help us to answer the question on deviations of baryon yields from thermal model expectations
- 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



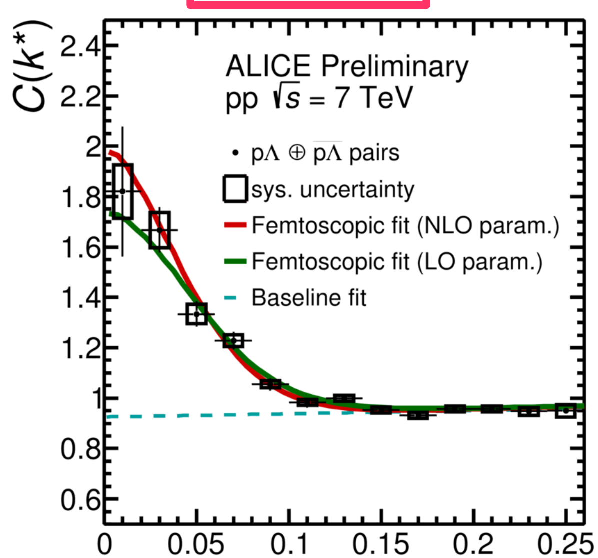
A. Andronic, SQM 2016

Baryon-baryon correlations

pp+$\overline{\text{pp}}$



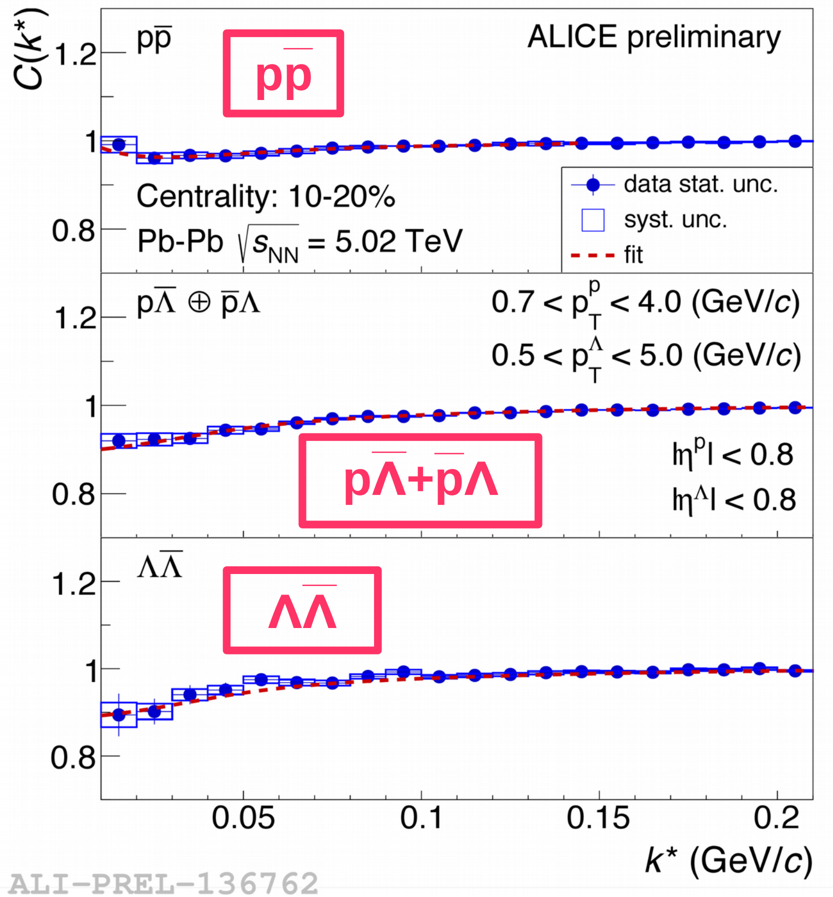
pΛ+$\overline{\text{p}\Lambda}$

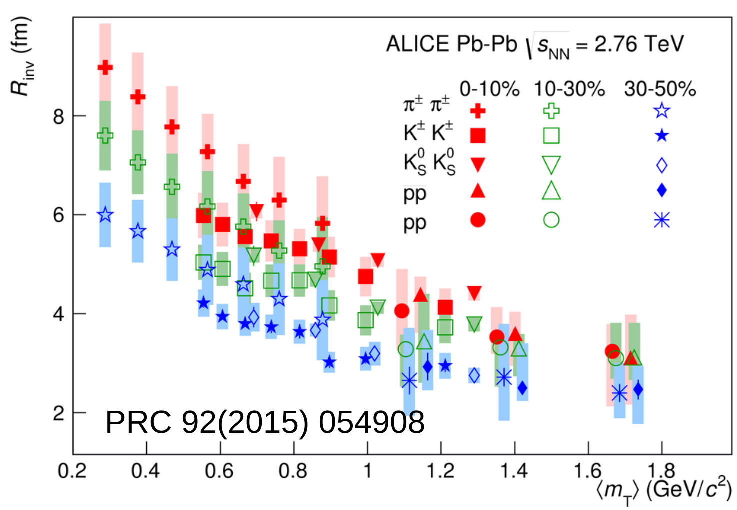


Oliver Arnold
QM 2017 poster
http://cern.ch/go/bTS8

- ALICE particle identification capabilities allow us to measure correlations of different baryons
- Except for pairs like proton-proton or proton-neutron, cross sections for other baryons practically not known
  - eg. only ~30 points for proton-lambda interaction measurements exist
- ALICE can constrain cross sections for these systems at low relative momentum *k**
- Assuming LO and NLO scattering parameter predictions in the fit (from Nucl. Phys. A915, 24-58)
- Preliminary results of simultaneous fit to proton-proton and proton-lambda correlation functions:
  - extracted source size: $R = 1.31 \pm 0.02 \ fm$
  - NLO predictions seems to be slightly more accurate, however we still lack statistics
  - we hope to have more accurate results after analysing 13 TeV LHC Run2 data

Baryon-antibaryon correlations



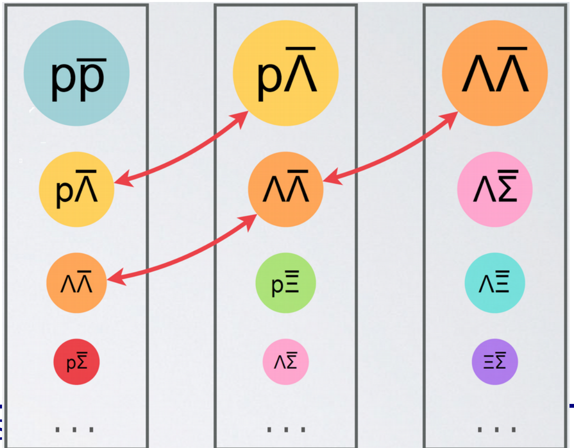


Explanation of the fitting procedure:

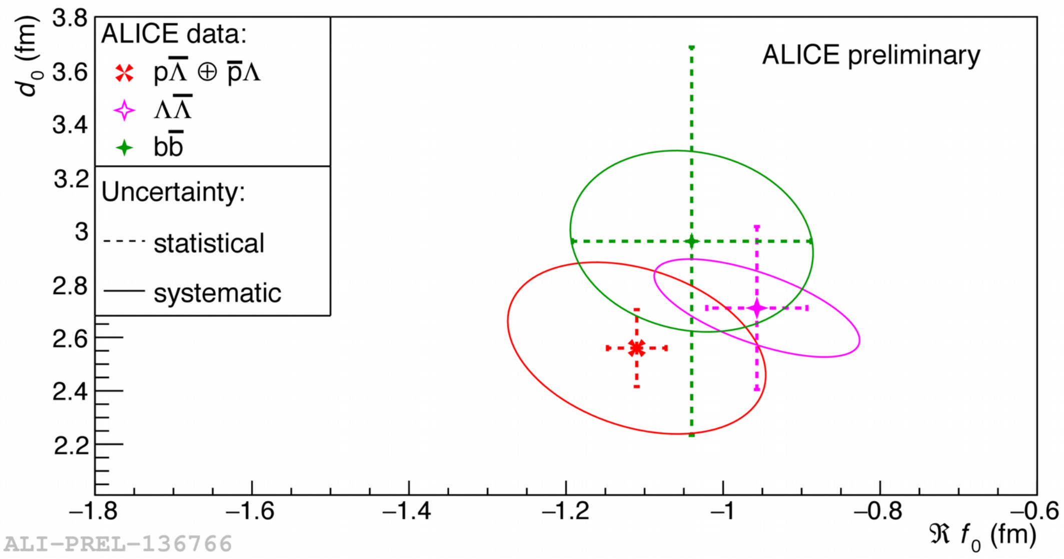
- χ^2 is calculated from a "global" fit to all functions: 2 data sets, 3 pair combinations, 6 centrality bins (**total 36 functions**)
- simultaneous fit accounts for parameters **shared** between different systems (such as ΛΛ̄ scattering length)
- **radii scale with multiplicity** for a given system

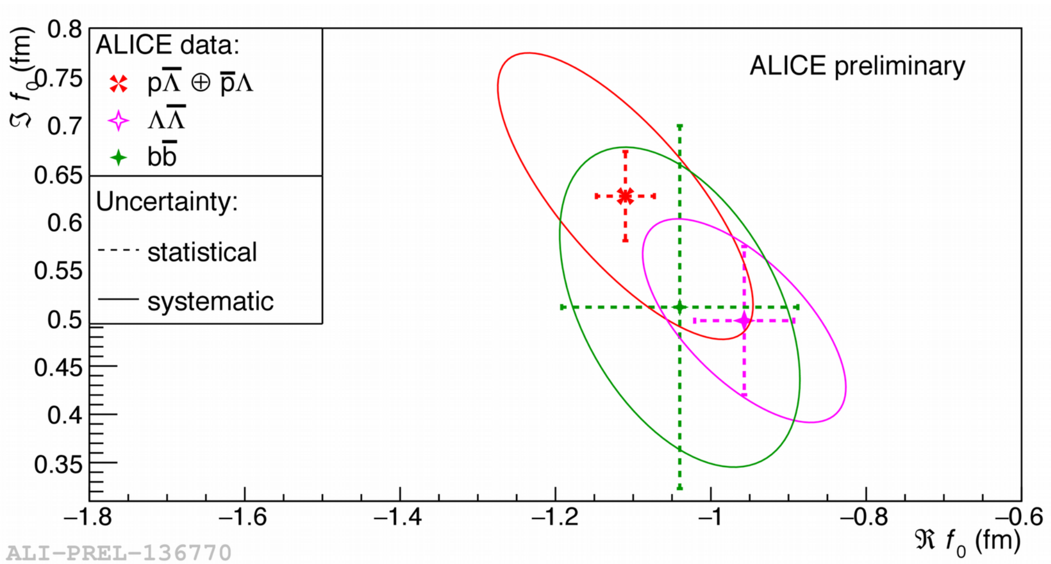
$$R_{inv} = a \cdot \sqrt[3]{N_{ch}} + b$$

- for different system we assume **radii scaling with** $\boldsymbol{m_T}$
- Fractions of **residual pairs** taken from AMPT



Baryon-antibaryon correlations





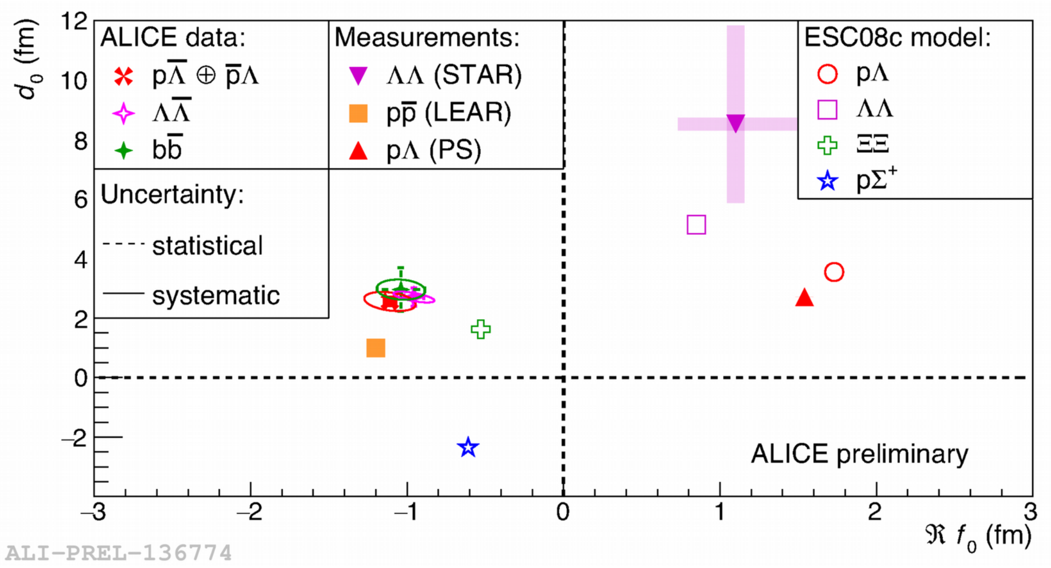
Conclusions from fitting:

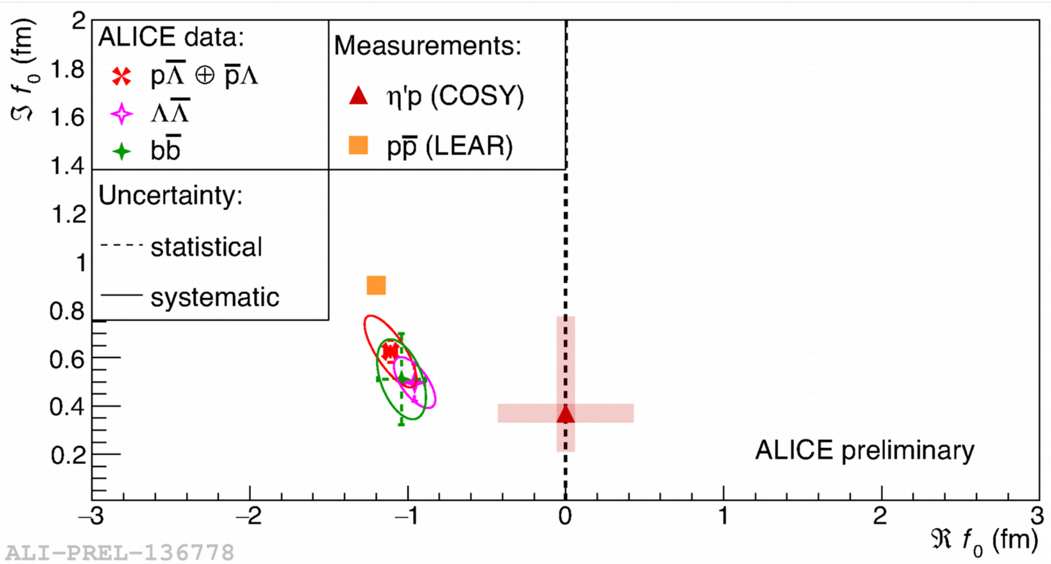
- Interaction parameters are measurable
- Scattering parameters for **all baryon-antibaryon pairs are similar to each other** (UrQMD assumption is valid)
- We observe a **negative real part of scattering length** → repulsive strong interaction or creation of a bound state (existence of baryon-antibaryon 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





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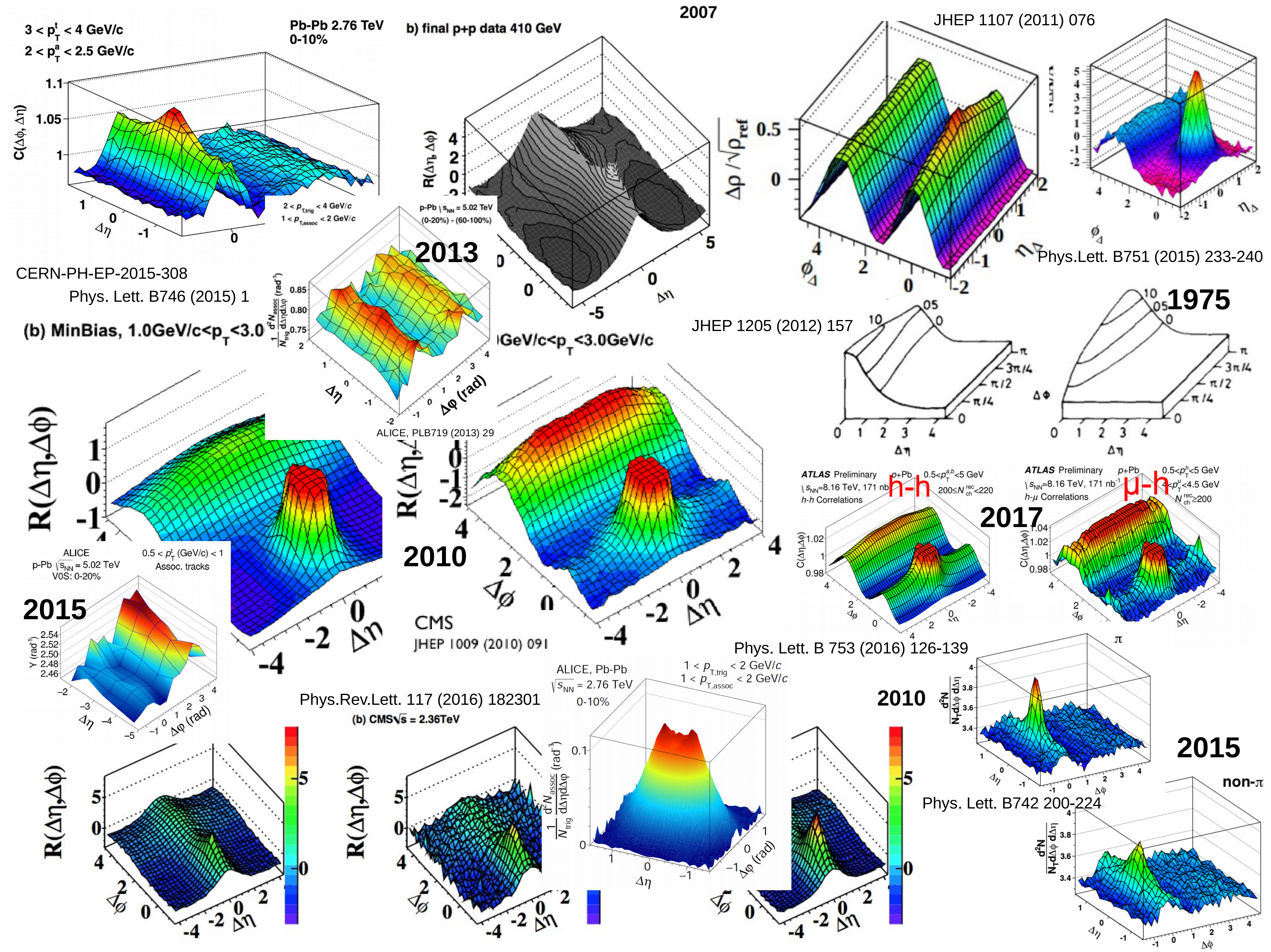
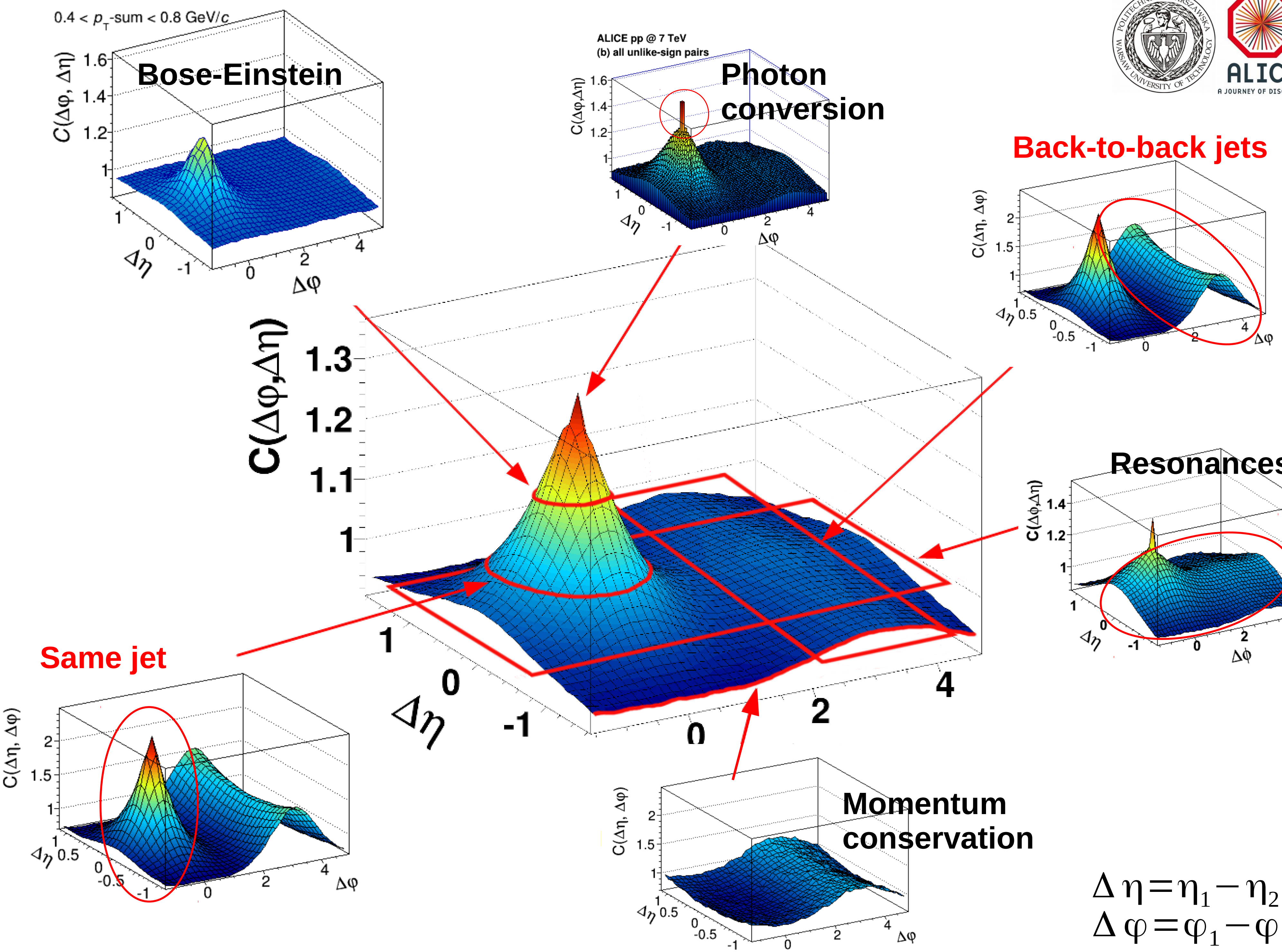
Are baryons interesting?

Let’s look at correlations in angular space



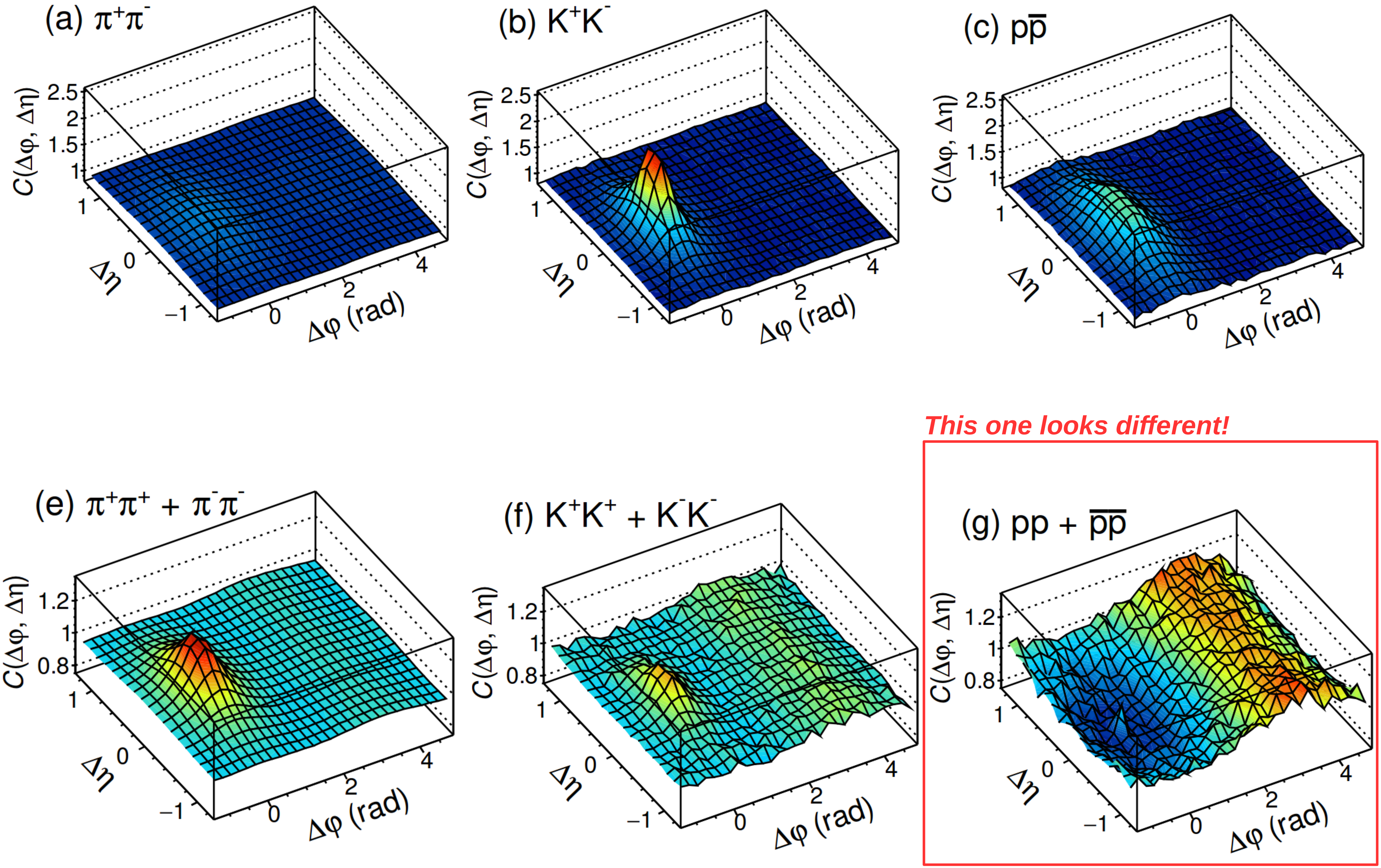
2007
JHEP 1107 (2011) 076
Pb-Pb 2.76 TeV
0-10%
b) final p+p data 410 GeV
CERN-PH-EP-2015-308
Phys. Lett. B746 (2015) 1
2013
ALICE, PLB719 (2013) 29
Phys.Lett. B751 (2015) 233-240
1975
JHEP 1205 (2012) 157
(b) MinBias, 1.0GeV/c<p_T<3.0
2010
CMS
JHEP 1009 (2010) 091
ATLAS Preliminary
h-h
μ-h
2017
2015
Phys. Lett. B 753 (2016) 126-139
Phys.Rev.Lett. 117 (2016) 182301
(b) CMS√s = 2.36TeV
ALICE, Pb-Pb
2010
Phys. Lett. B742 200-224
2015
non-π



$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$

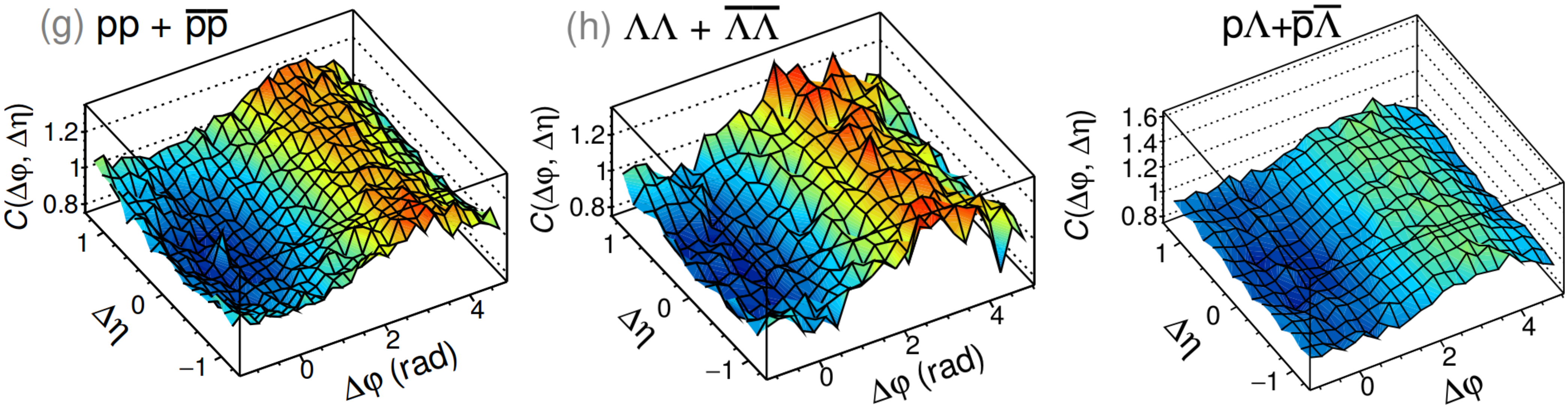
ΔηΔφ of identified particles

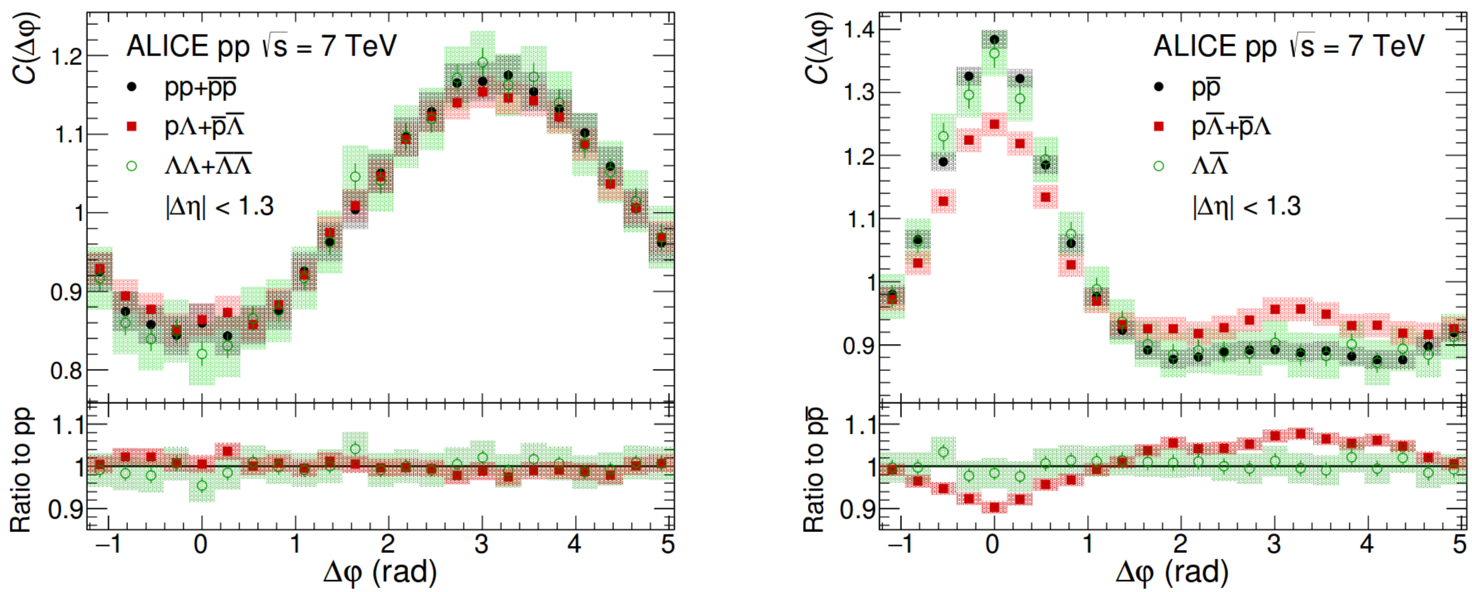
Eur.Phys.J. C77 (2017) no.8, 569



ΔηΔφ of identified particles

Eur.Phys.J. C77 (2017) no.8, 569

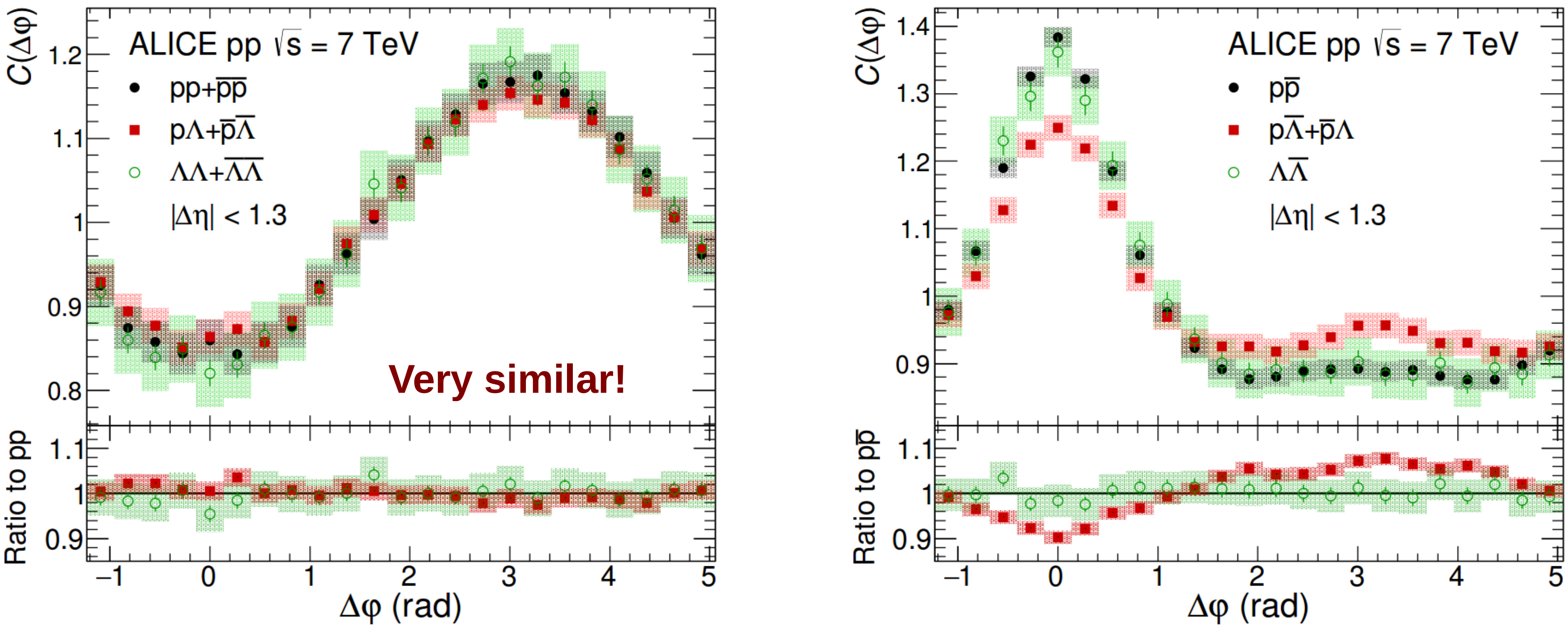




- Similar depletion is observed for lambda-lambda and proton-lambda pairs as well
- Projections – baryon-baryon pairs consistent within uncertainties
- Similarity, but to a lesser extent, is observed also in the baryon-antibaryon case

Δφ correlation of baryons

Eur.Phys.J. C77 (2017) no.8, 569



- Projections show how similar baryon-baryons pairs are – consistent within uncertainties
- Similarity between pairs, but to a lesser extent, is also observed in the baryon-antibaryon case

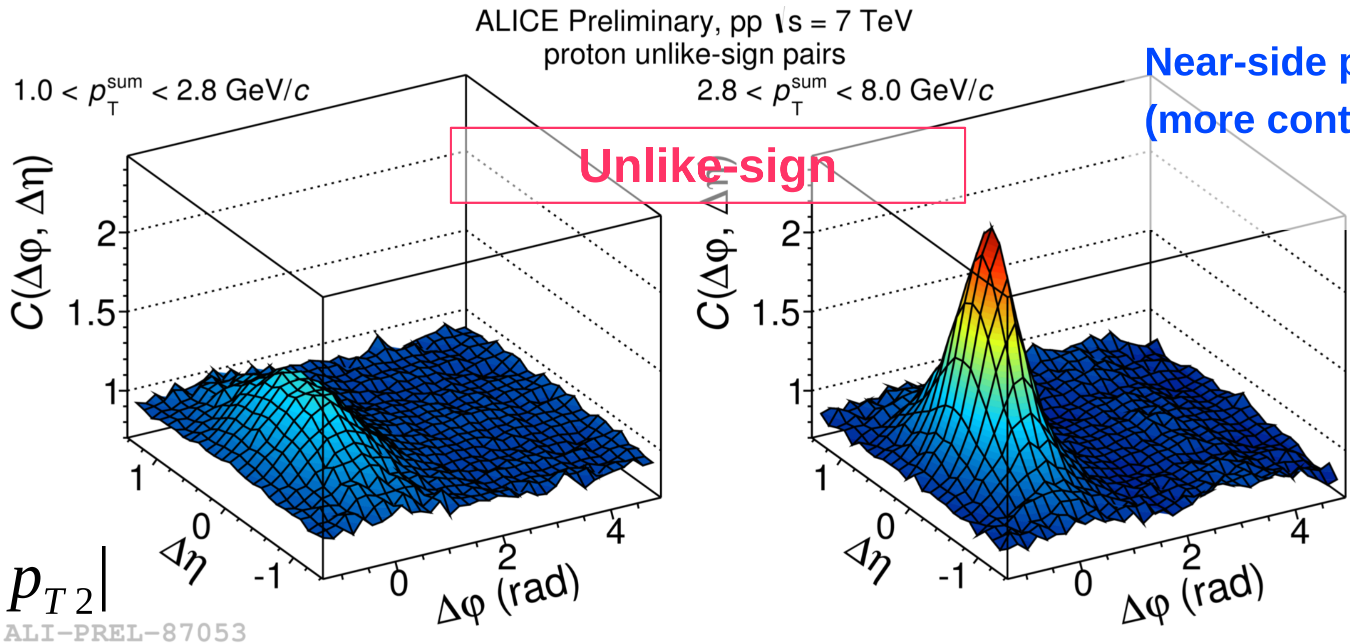
Possible explanations:

- Fermi-Dirac Quantum Statistics? NO (non-identical particles)
- Coulomb repulsion? NO (uncharged particles)
- Strong Final-State Interactions? NO (small peak visible for proton-proton pairs)

- **How does it change with p_T?**

Δφ correlation of baryons

Eur.Phys.J. C77 (2017) no.8, 569

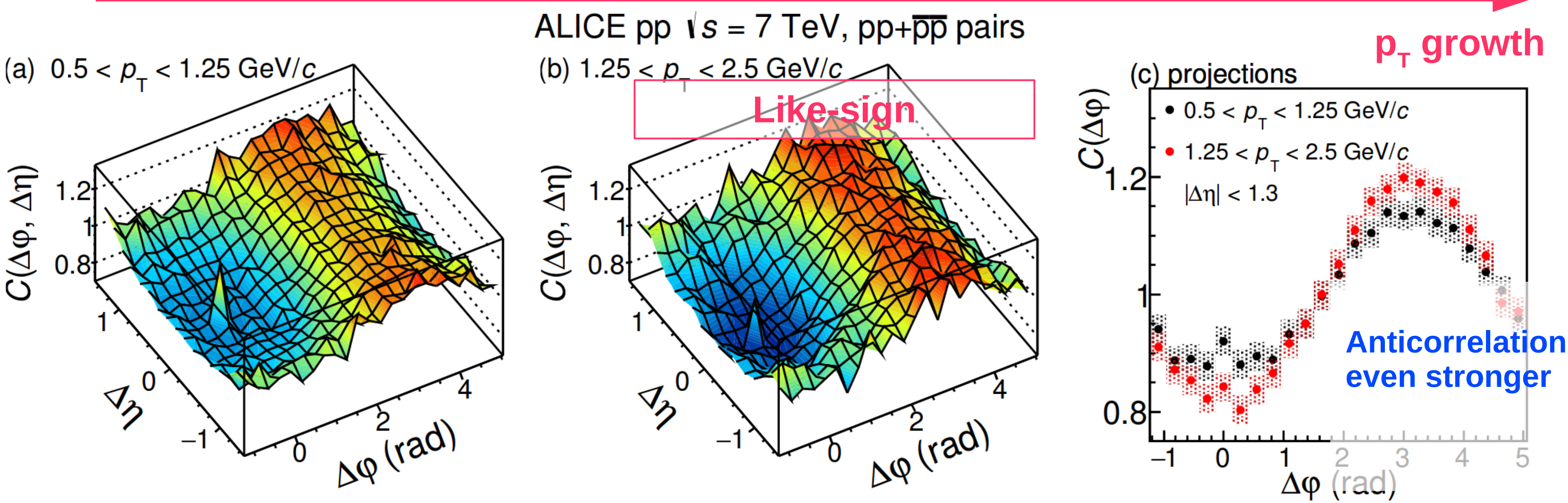


Unlike-sign

Near-side peak grows with p_T (more contribution from jets)

$$p_T^{sum} = |p_{T1}| + |p_{T2}|$$

p_T growth

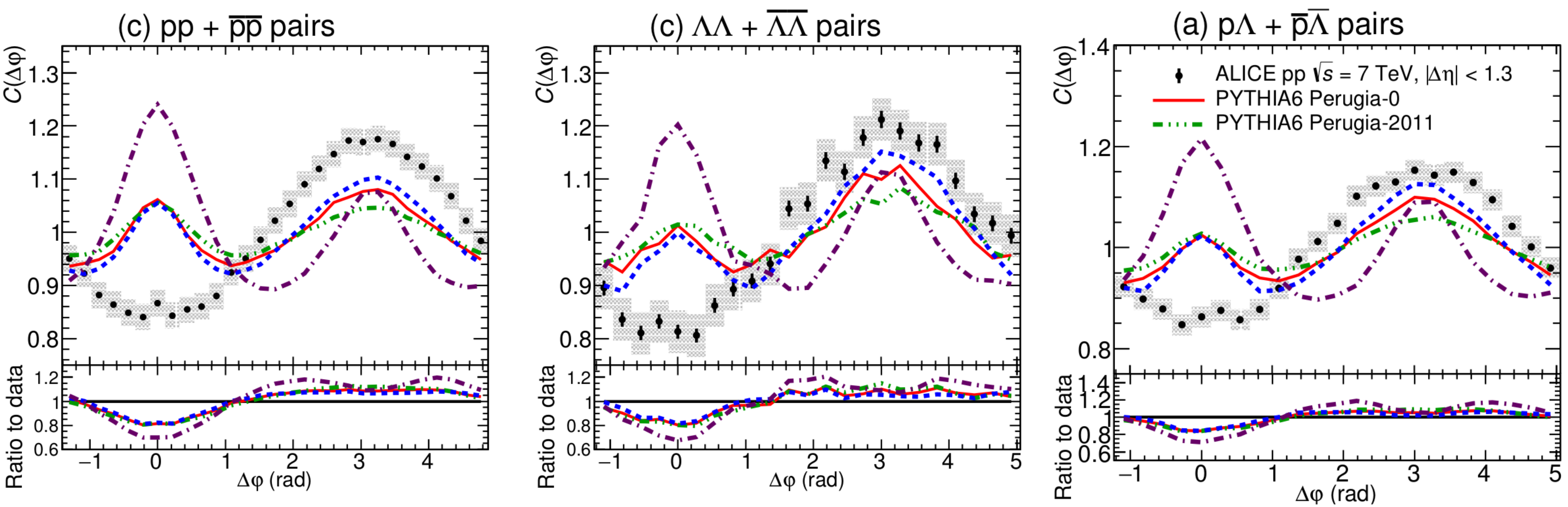


Like-sign

Anticorrelation even stronger

Δφ correlation of baryons

Eur.Phys.J. C77 (2017) no.8, 569



- None of studied current MC models agree 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

Rapidity correlations in e^+e^- collisions

A Parametrization of the Properties of Quark Jets
R.D. Field, R.P. Feynman (Caltech). Nov 1977. 131 pp.
Published in Nucl.Phys. B136 (1978) 1

<u>From mechanism of jet production</u>:
Two primary hadrons with the same **baryon number** (or **charge** or **strangeness**) **are separated** by at least two steps in rank ("rapidity").

R. Feynman "Quark Jets" 8th ISMD 1977

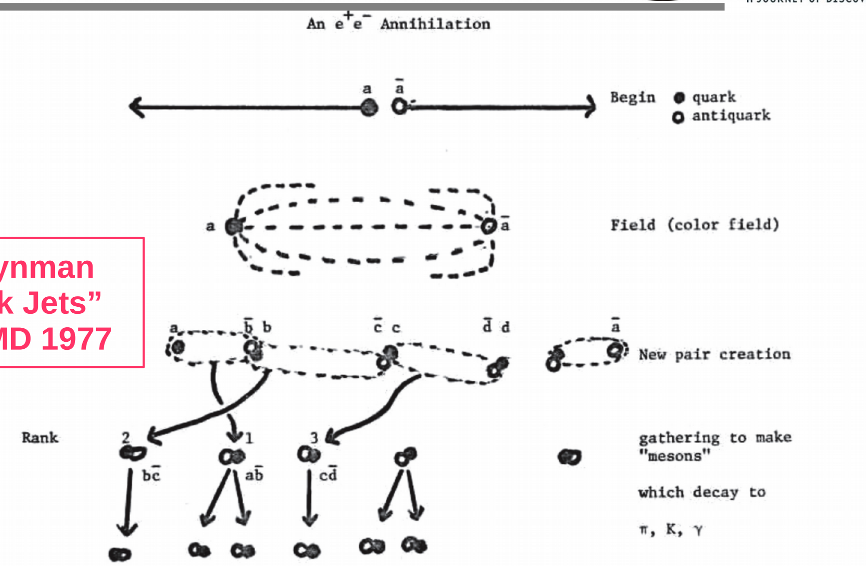
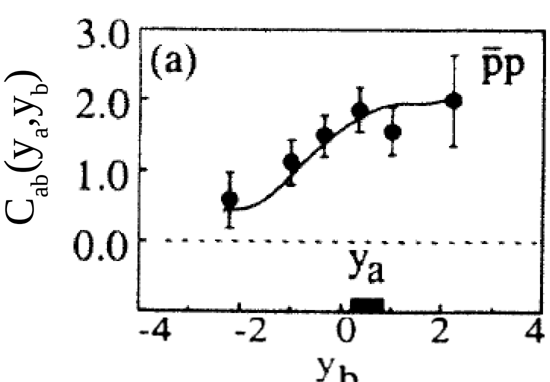


Fig. 10. Transparency from a talk Feynmen gave on our model for how quarks fragment into hadrons at the International Symposium on Multiparticle Dynamics (ISMD), Kaysersberg, France, June 12, 1977.

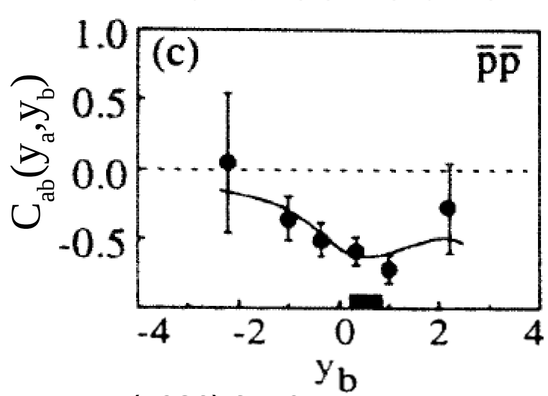
We are not likely to find two baryons or two antibaryons at the same rapidity

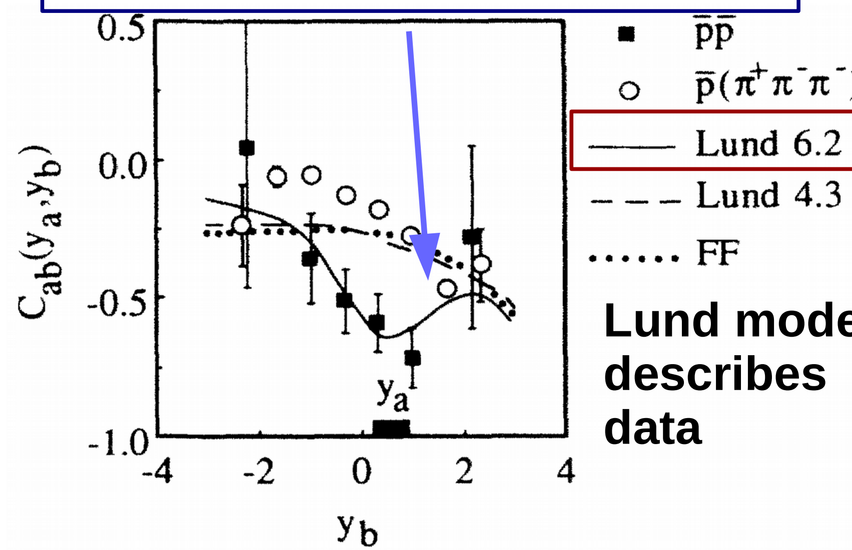
- **Models for e^+e^- agree** with observations seen in data.

correlation



anti-correlation





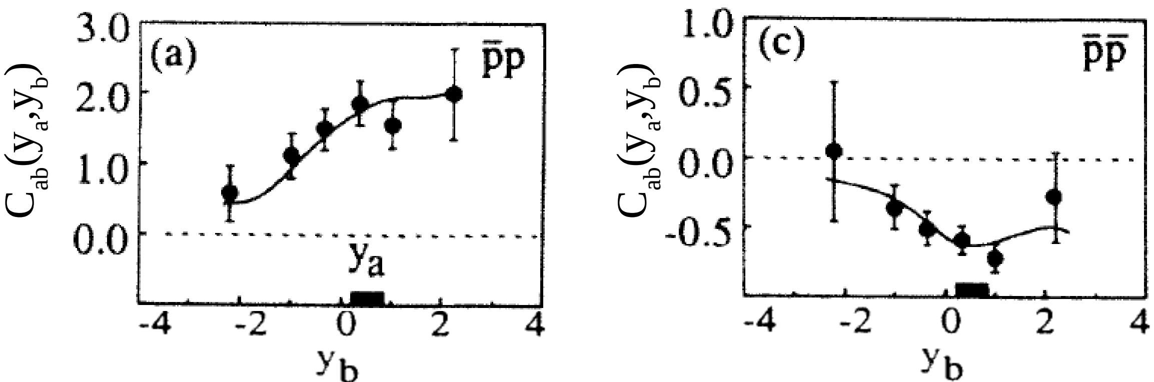
Lund model describes data

TPC/Two Gamma Collaboration, Phys.Rev.Lett. 57 (**1986**) 3140

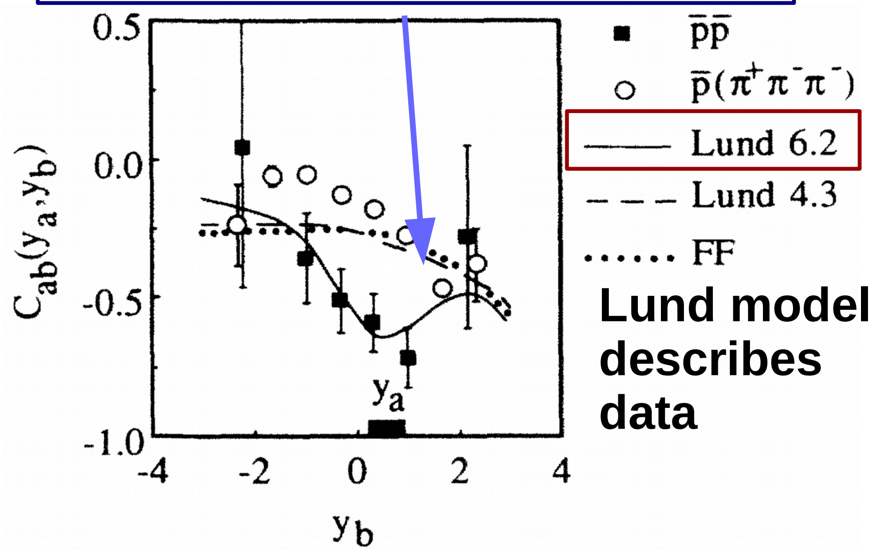
Rapidity correlations in e^+e^- collisions

- **Models for e^+e^- agree** with observations seen in data.

correlation **anti-correlation**



TPC/Two Gamma Collaboration (H. Aihara et al.), Phys.Rev.Lett. 57 (**1986**) 3140



Lund model describes data

Hypothesis from e^+e^- studies at $\sqrt{s}$ = 29 GeV (SLAC-PEP):

- Depletion is a manifestation of **"local" baryon number conservation**

- Production of 2 baryons in a single jet would be suppressed if the initial parton energy is small when compared to the energy required to produce 4 baryons in total (2 in the same mini-jet + 2 anti-particles) – fine explanation at 29 GeV collision energy, **but why at 7 TeV?!**

Femtoscopy – beyond the system size

Correlations of baryons

$K^0_s K^{\pm}$ correlations

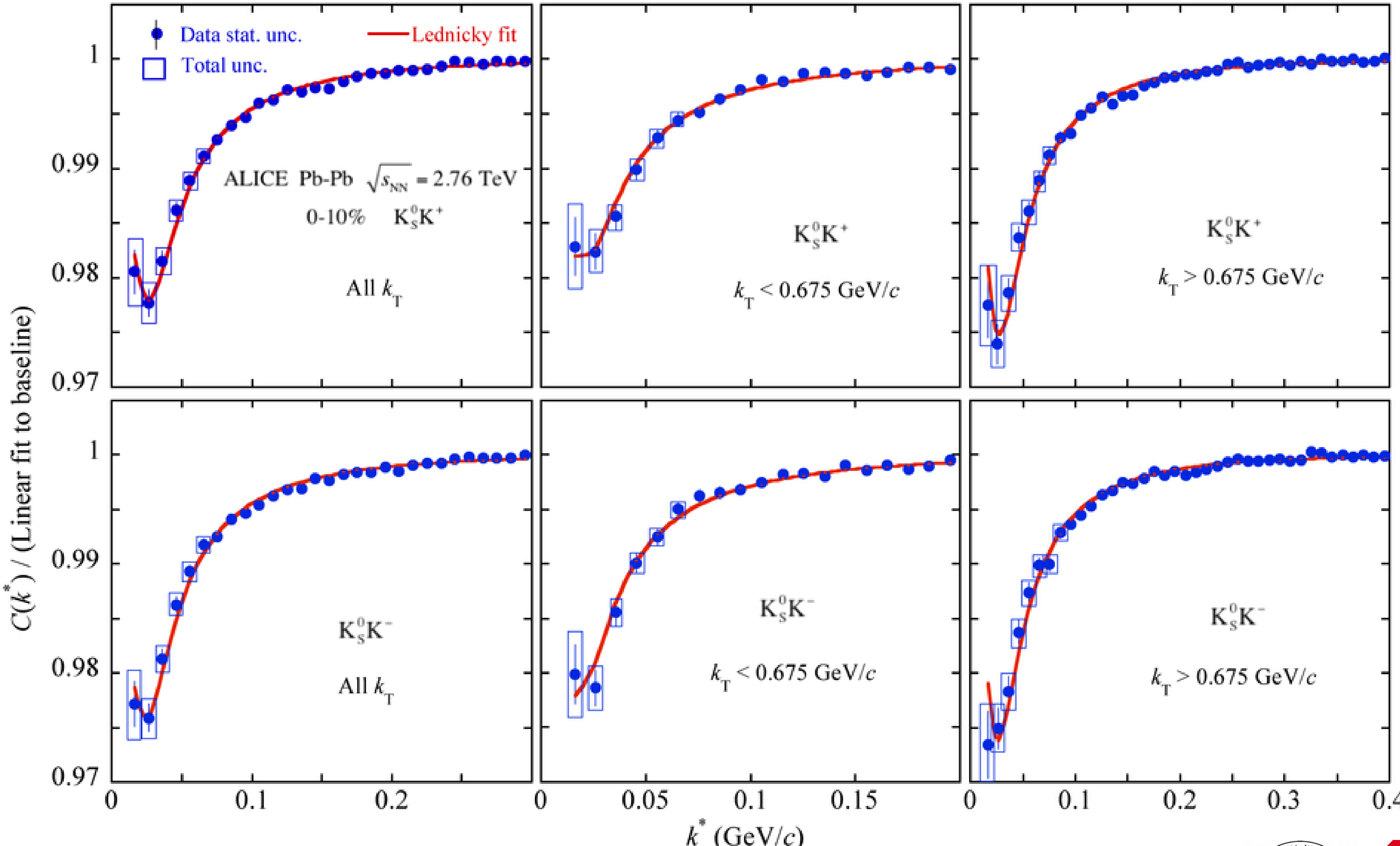
Motivation for $K^0_s K^{\pm}$ analysis

- **Which sources of correlations are present in kaon systems?**
  - Quantum Statistics (QS) – both $K^0_s K^0_s$ and $K^{\pm}K^{\pm}$
  - Coulomb FSI – $K^{\pm}K^{\pm}$
  - **Strong FSI –** $K^0_s K^0_s$ **(via** $f_0(980)/a_0(980)$ **resonances)**
- **Why are** $K^0_s K^{\pm}$ **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**
- **We can study the properties of the** $a_0(980)$ **resonance, which is a proposed tetraquark state** (PRC 75 (2007) 045206)
- $a_0(980)$ mass and coupling parameters (in GeV) extracted from model fits to ϕ decay experiments:

$$f(k^*) = \frac{\gamma_{a_0 \to K\bar{K}}}{m_{a_0}^2 - s - i\gamma_{a_0 \to K\bar{K}} k^* - i\gamma_{a_0 - \pi\eta} k_{\pi\eta}}$$

	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)

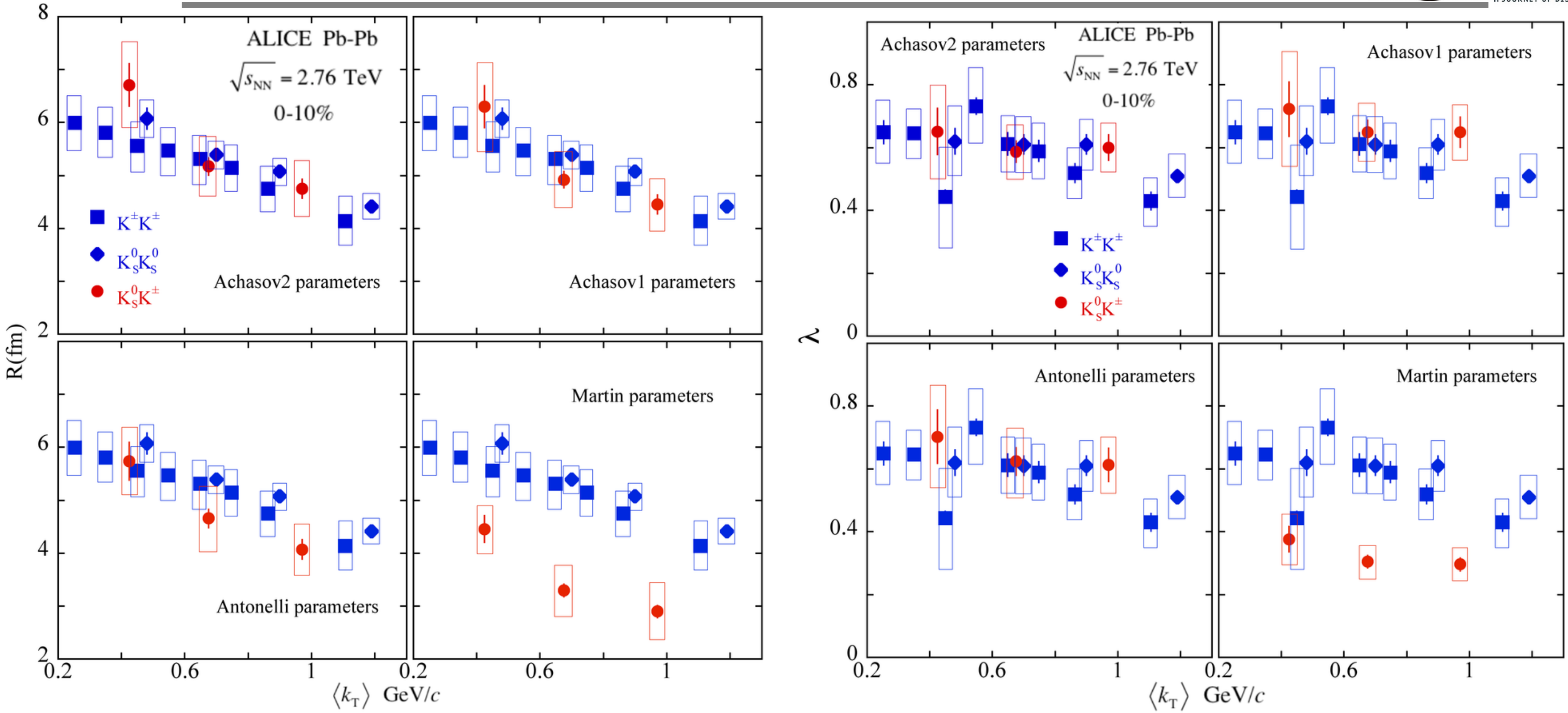
Measured correlation functions $C_{raw}(k^*)$/(linear fit)



- The a_0(980) final state interaction gives **excellent** fits to data!

arXiv:1705.04929, accepted by PLB, DOI: 10.1016/j.physletb.2017.09.009

Results of the fits

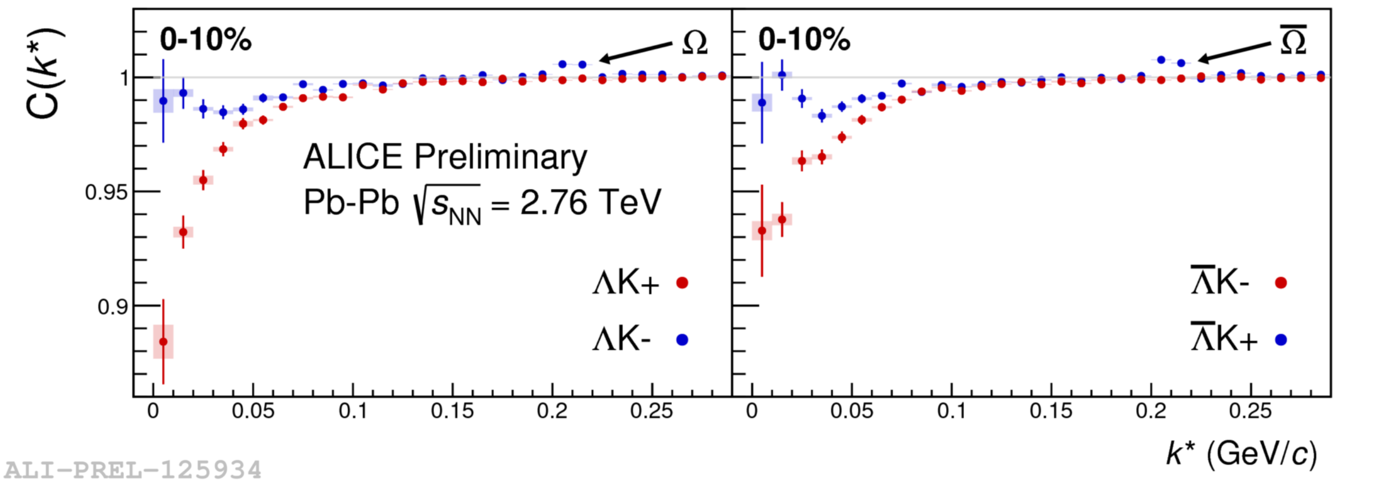


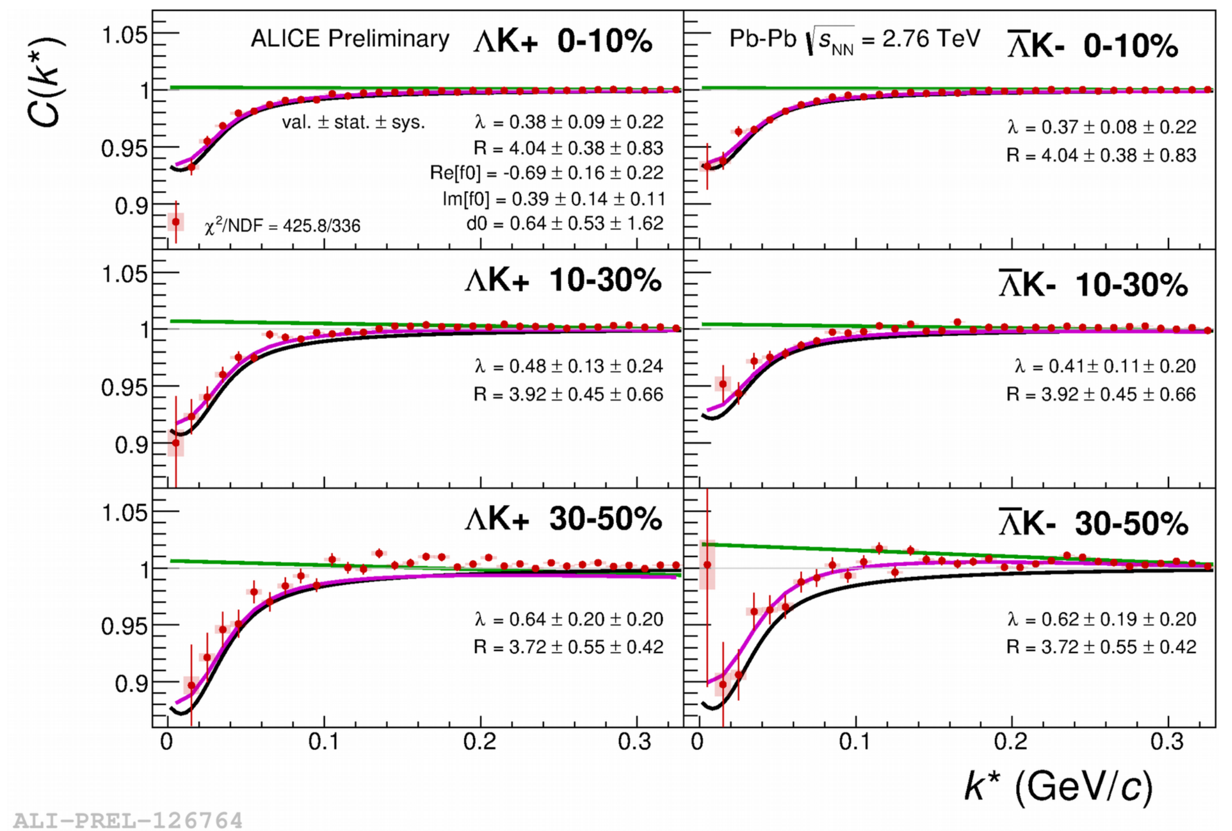
- "Achasov" parameter fits give best agreements with $K^0_sK^0_s$ and $K^{\pm}K^{\pm}$ results
- "Antonelli" parameter fits are somewhat lower
- "Martin" parameter fits much lower
- **Present results favor higher** $a_0(980)$ **parameters**

arXiv:1705.04929, accepted by PLB, DOI: 10.1016/j.physletb.2017.09.009

Other interesting correlations

- Many other interesting correlations not covered in this talk
- 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^{-}?
- For details see Quark Matter 2017 poster by J. Buxton http://cern.ch/go/qwF7





Summary

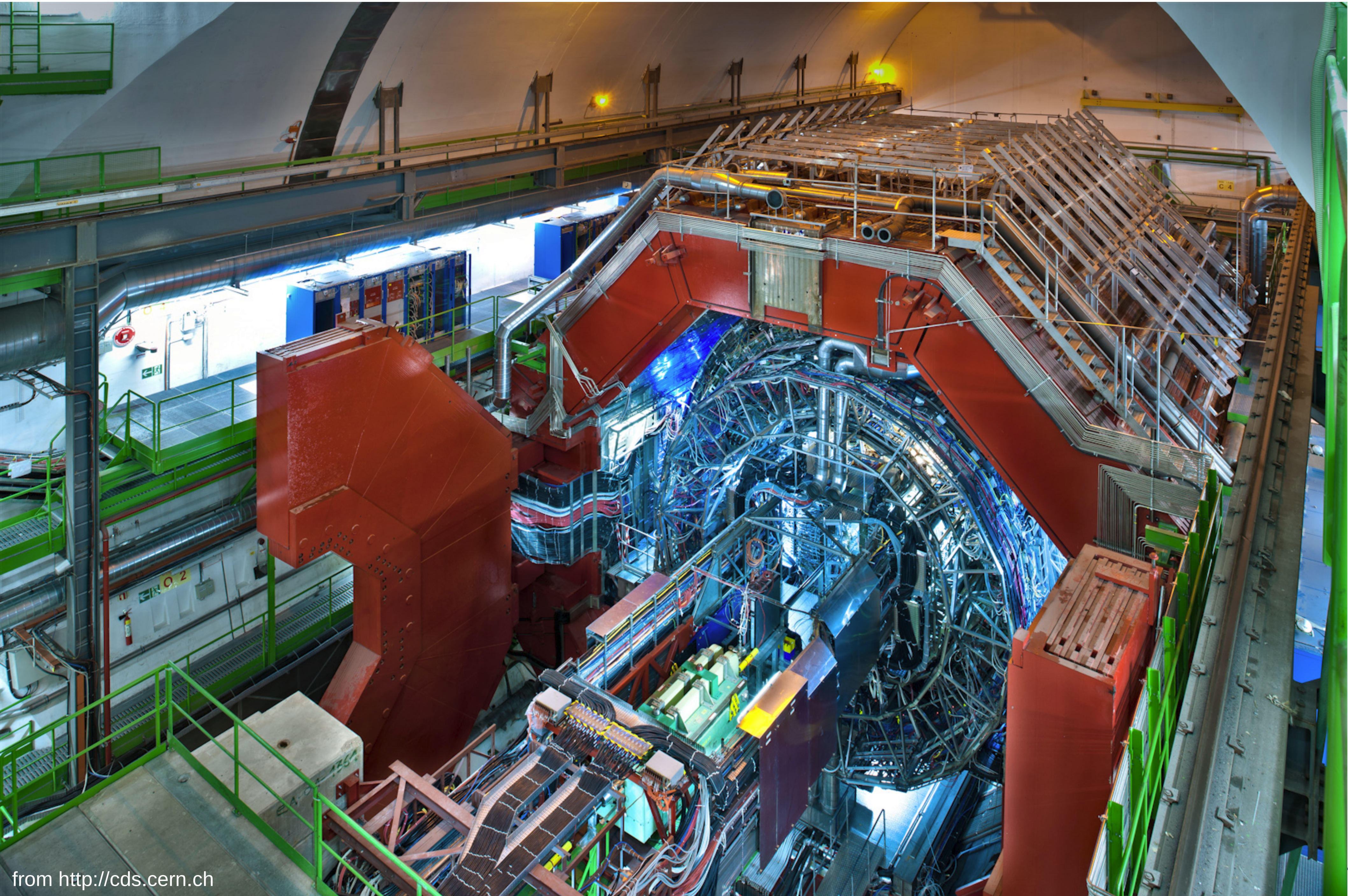
- **ALICE can probe strong interaction cross sections with femtoscopy**
- **Correlations of baryons reveal interesting features** and baryons in general seem to be of great importance:
  - Unique experimental environment at RHIC and LHC → "baryon-antibaryon pair factories"
  - Femtoscopic correlation functions sensitive to strong interaction potential, including annihilation, possible $b\bar{b}$ bound states?
  - Angular correlations reveal unexpected behavior – no two or more baryons in a single (mini-)jet?
- **$K^0_sK^{\pm}$ femtoscopic correlations measured for the first time:**
  - a_0(980) FSI gives excellent description of the signal
  - No difference wrt identical kaons if larger mass and coupling a_0(980) parameters used ("Achasov1" and "Achasov2") - e.g. "a_0(1000)" favored over "a_0(980)"

THANK YOU!

The author would like to acknowledge the support of

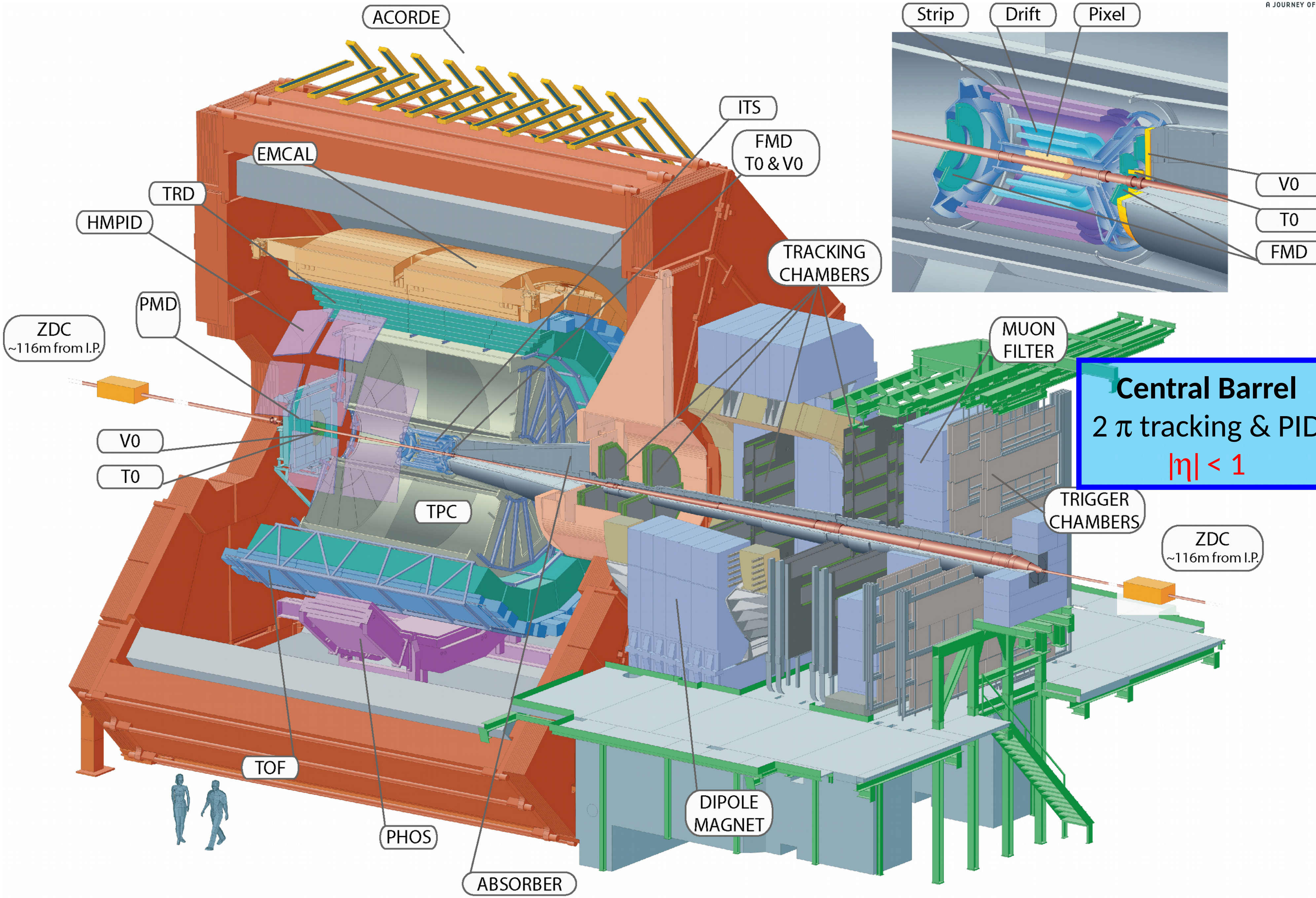
National Science Centre
Poland

ALICE experiment



from http://cds.cern.ch

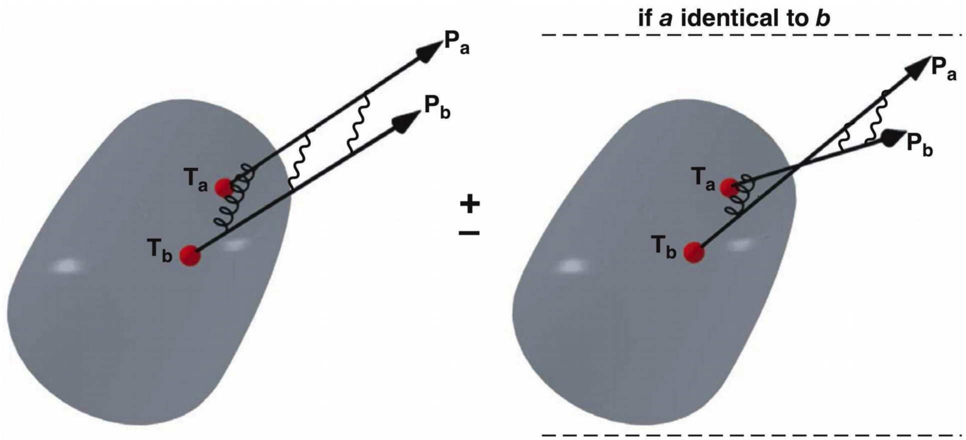
ALICE experiment



Central Barrel
2 π tracking & PID
$|\eta| < 1$

Identical bosons – typical scenario

M.Lisa *et al*, Annu. Rev. Nucl. Part. Sci. 55 (2005), 357



$$q = p_a - p_b, \quad q = 2 \cdot k^*$$

$$r = T_a - T_b$$

- Quantum interference of indistinguishable scenarios:
  - we detect a pair of particles with momenta p_{a} and p_{b} knowing that they have been emitted somewhere from the source T_a and T_b.

$$\Psi = \frac{1}{\sqrt{2}}\left[\exp\left(-i\,p_a T_a - i\,p_b T_b\right) + \exp\left(-i\,p_a T_b - i\,p_b T_a\right)\right]$$

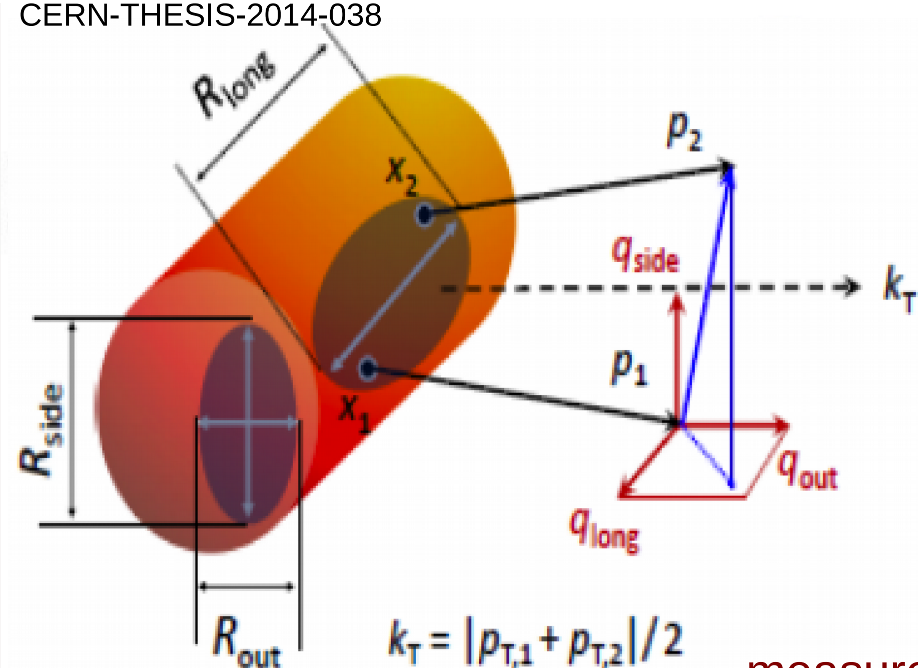
$$|\Psi|^2 = 1 + \frac{1}{2}\left[\exp\left(-i\,p_a T_a - i\,p_b T_b + i\,p_a T_b + i\,p_b T_a\right) + \exp\left(-i\,p_a T_b - i\,p_b T_a + i\,p_a T_a + i\,p_b T_b\right)\right]$$

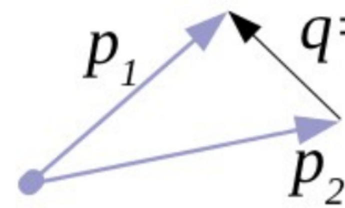
$$= 1 + \frac{1}{2}\left\{\exp\left[-i\left(T_a - T_b\right)\left(p_a - p_b\right)\right] + \exp\left[i\left(T_a - T_b\right)\left(p_a - p_b\right)\right]\right\}$$

$$= 1 + \cos\left(q\,r\right)$$

Reference frame

CERN-THESIS-2014-038





The Koonin-Pratt formula
(S.E. Koonin, PLB70 (1977) 43; S.Pratt et al., PRC42 (1990) 2646)

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

measured correlation — emission function — pair wave function

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

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

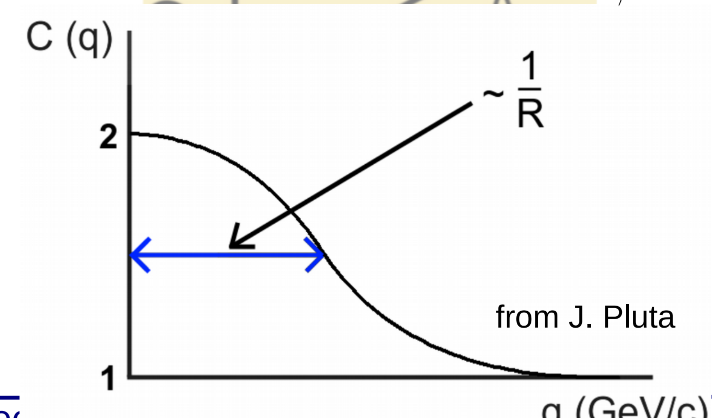
$$C = 1 + \lambda \exp\left(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2\right)$$

with Coulomb – Bowler-Sinyukov formula:

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

- The size *R* is a referred to as the **“HBT radius”**.
- The width of the correlation function is inversely proportional to *R*.

- The correlation function is obtained from the source function and pair interaction. Inverting the relation one can learn about the source characteristics (e.g. HBT radii).

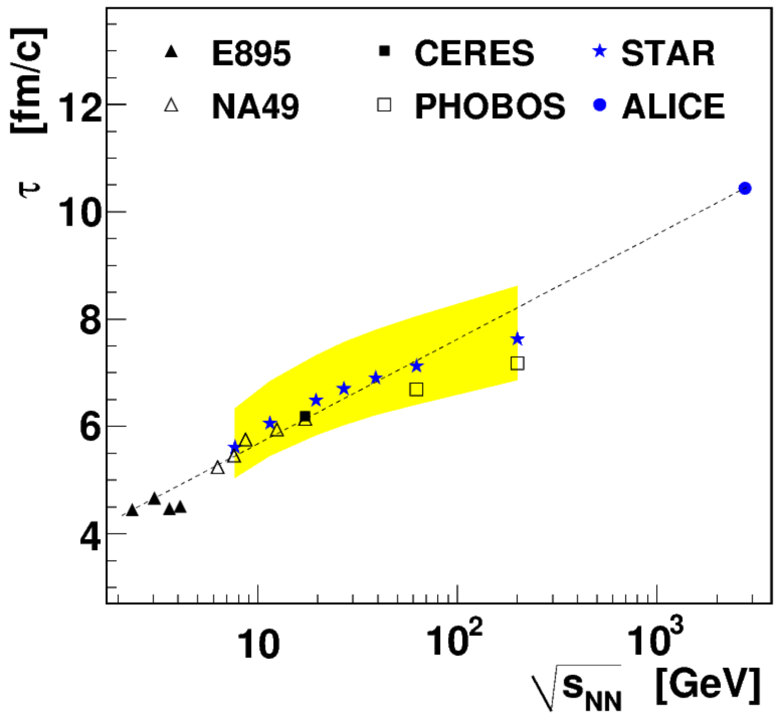


Measuring system lifetime and volume

- Lifetime can be estimated from the longitudinal radius
- Clear increase of 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)
- **BUT… This talk is not about the traditional femtoscopy**

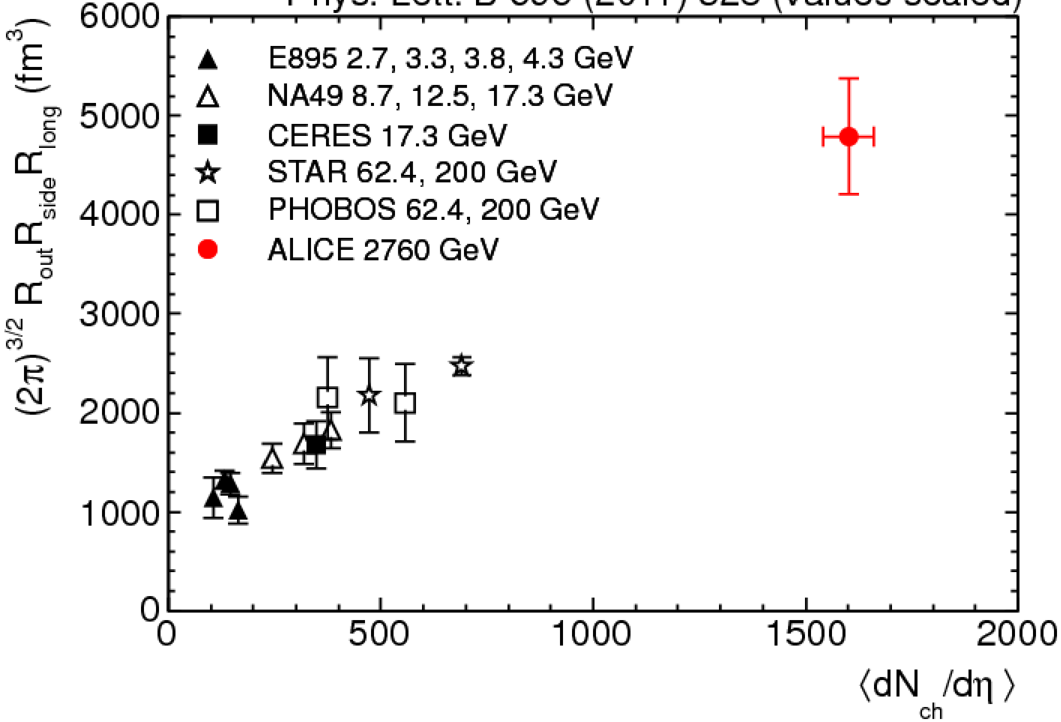
lifetime

STAR, PRC 92 (2015) 014904



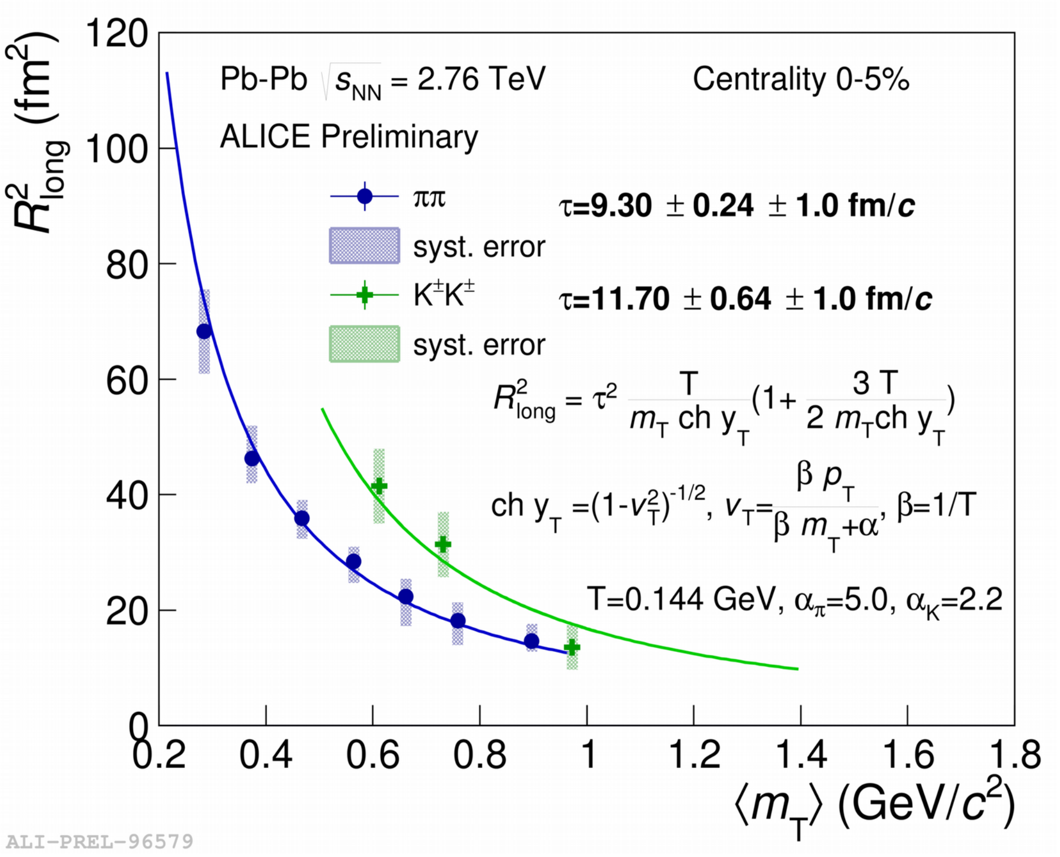
volume

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

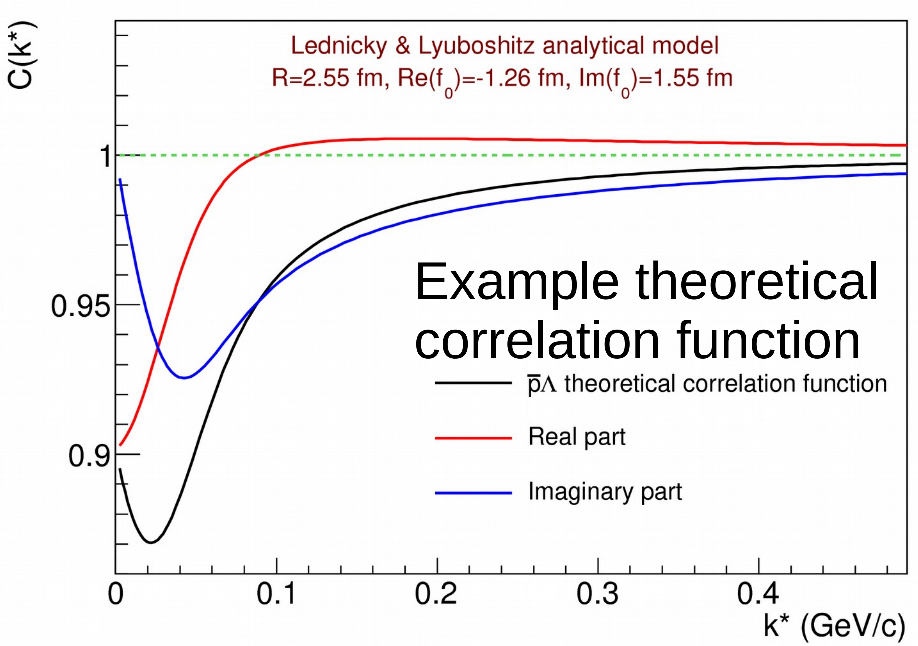


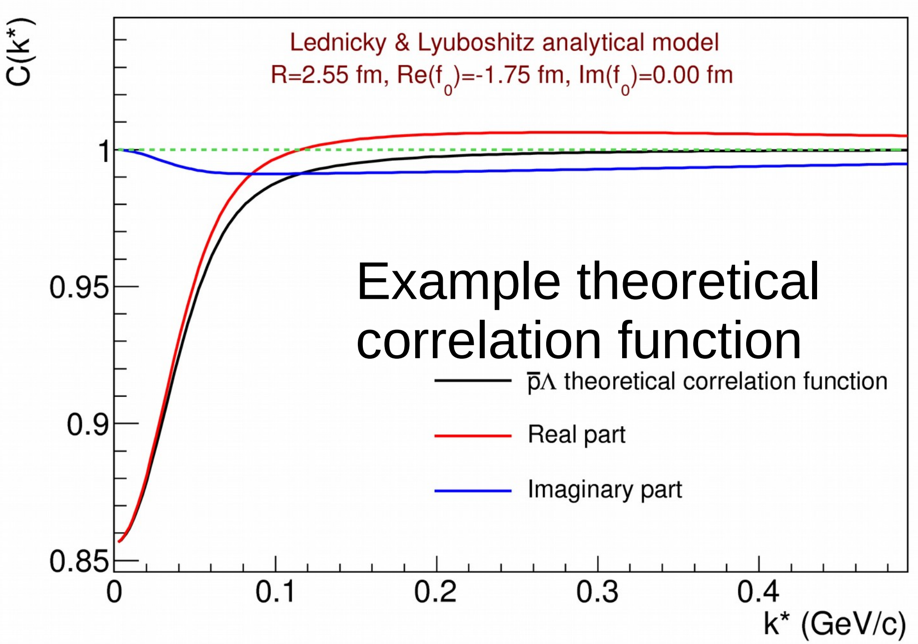
Measuring system lifetime and volume

- Lifetime can be estimated from the longitudinal radius
- Longer time for kaons, when compared to pions: model interpretation – influence on kaon evolution time from rescattering via K* resonance



Correlation from Strong Interaction – $\bar{p}\Lambda$ example





- 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**

Annihilation vs. yields and femtoscopy

Strong interaction parametrized by scattering length f_0 and effective range d_0

Point-like, large momentum transfer interaction (rescattering)

Infinite time interaction at low relative momentum (Final State Interaction)

Fold in with density and dynamics, e.g. via UrQMD

Fold in with source function

Decrease of single particle yield (important for thermal model)

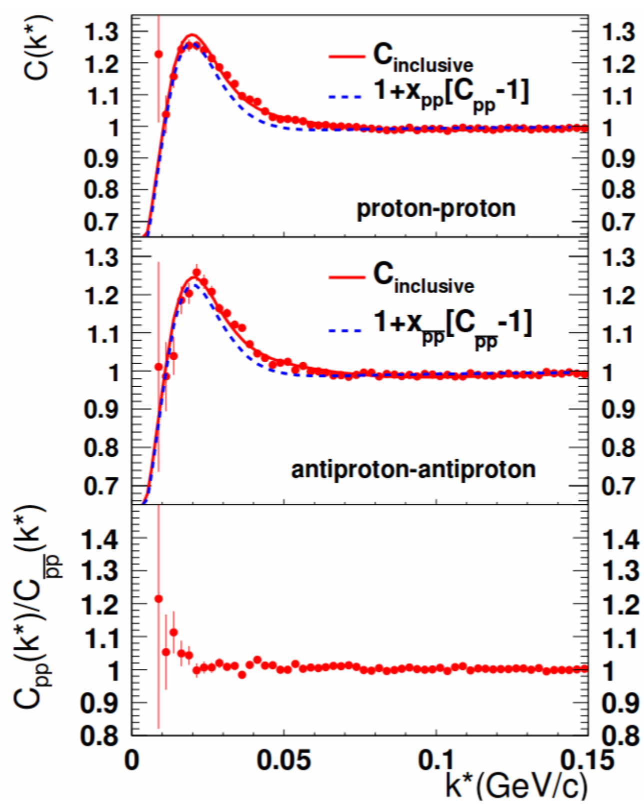
Specific shape of the femtoscopic two-particle correlation function with wide annihilation effect

- Measured cross-sections (f_0 and d_0 parameters) can be supplied to UrQMD for a realistic calculation of the decrease of baryon yield
- **Currently UrQMD uses theory guesses for most baryon-antibaryon potentials!**

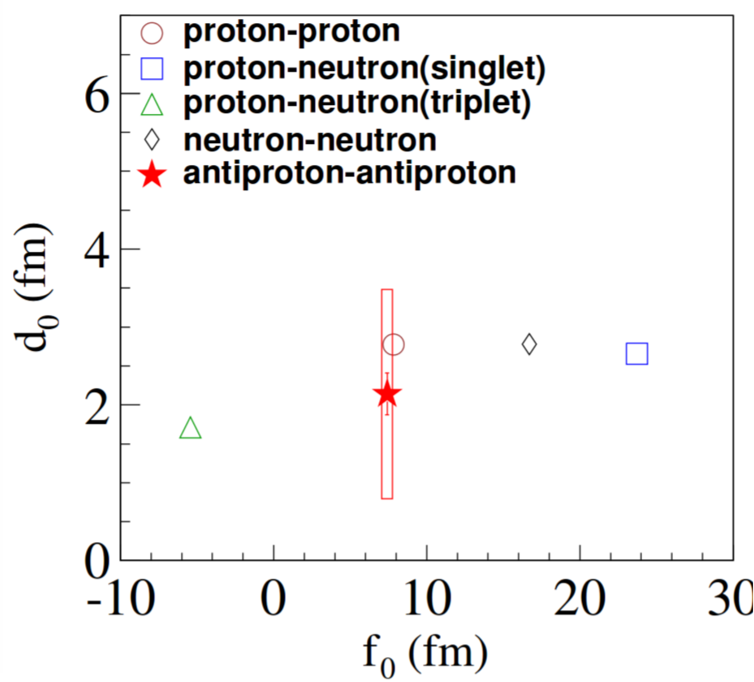
Au-Au: pp and $\overline{p}\overline{p}$ correlations @ STAR

Figure 4 presents the first measurement of the antiproton-antiproton interaction, together with prior measurements for nucleon-nucleon interactions. Within errors, the f_0 and d_0 for the antiproton-antiproton interaction are consistent with their antiparticle counterparts – the ones for the proton-proton interaction. Our measurements provide parameterization input for describing the

- Exactly the same methodology was used by STAR to measure $\overline{p}\overline{p}$ interaction (Nature paper)
- **Conclusions:**
  - LHC and RHIC are “baryon-antibaryon pair factories” - unique opportunities
  - Both ALICE and STAR, with their perfect PID, are the only experiments where such measurements are possible



STAR Collaboration
Nature 527,345-348 (2015)



Residual correlations in pp

- The excess about 50 MeV/c in k* is explained by residual correlations, from main decay channel leading to protons:

$$\Lambda \rightarrow p + \pi^-$$

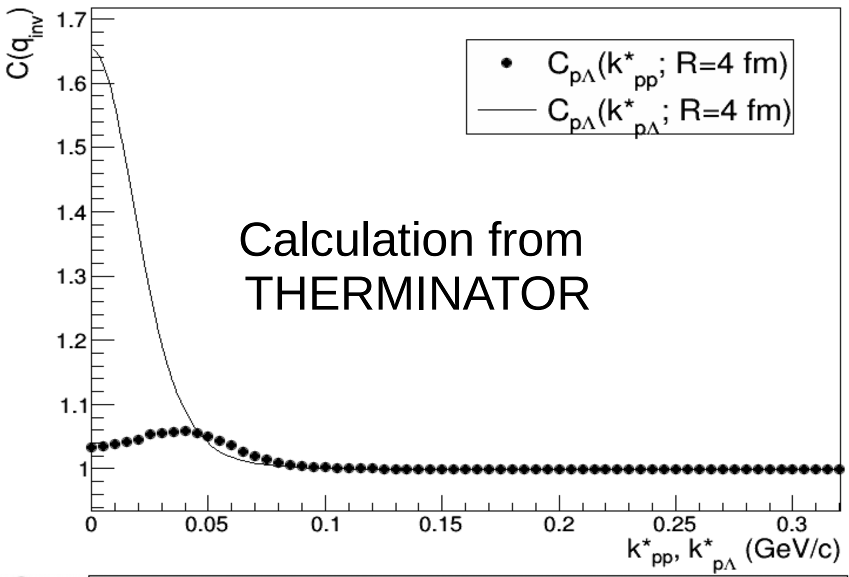
- Fitting function is a combination of theoretical pp and pΛ functions:

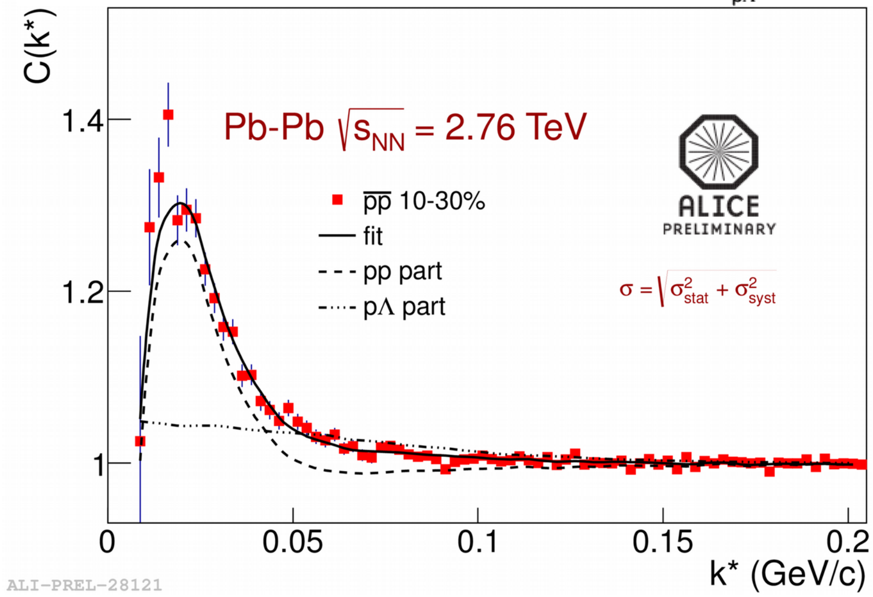
$$C_{meas}(k^*) = 1 + \lambda_{pp}(C_{pp}(k_{pp};R) - 1) +$$
$$\lambda_{p\Lambda}\left(\int C_{p\Lambda}(k_{p\lambda};R)\,T(k_{p\lambda},k_{pp}) - 1\right)$$

- Assume Gaussian source, $R_{pp}/R_{p\Lambda}$ ratio, decay kinematics taken into account.

- Results with RC effect taken into account published in:

Phys. Rev. C 92, 054908 (2015)

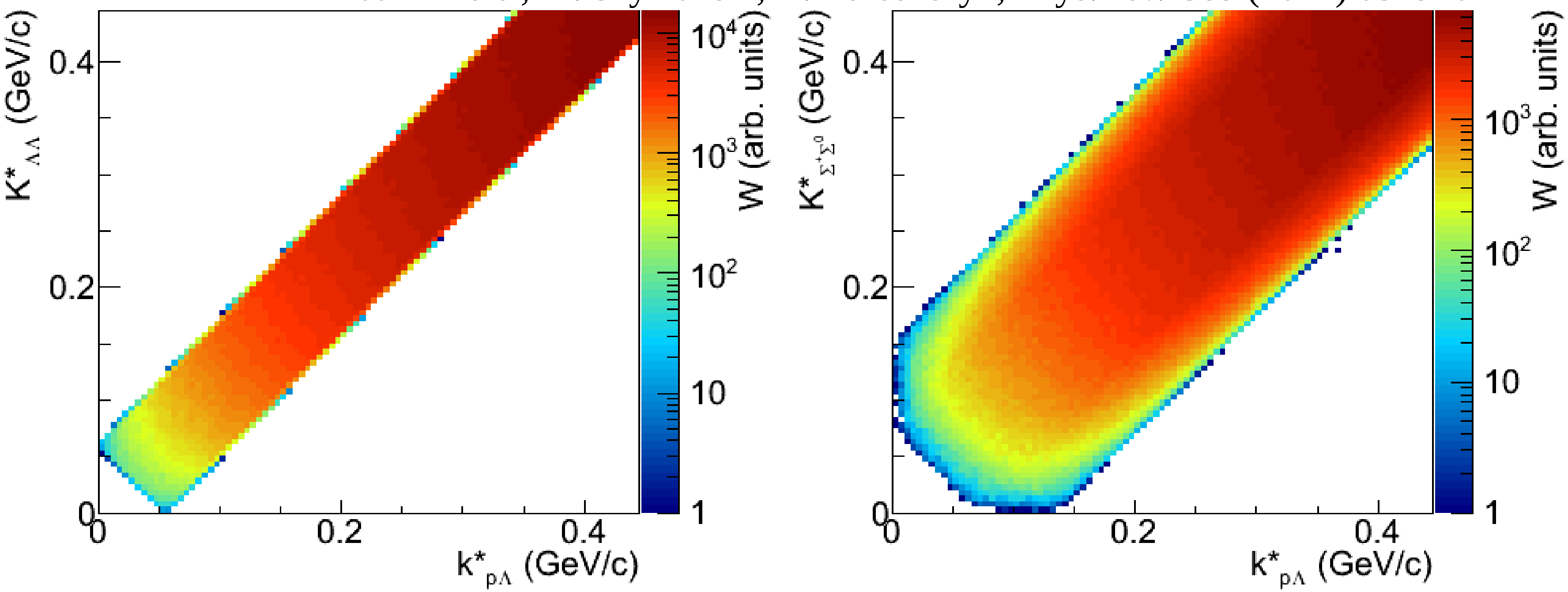




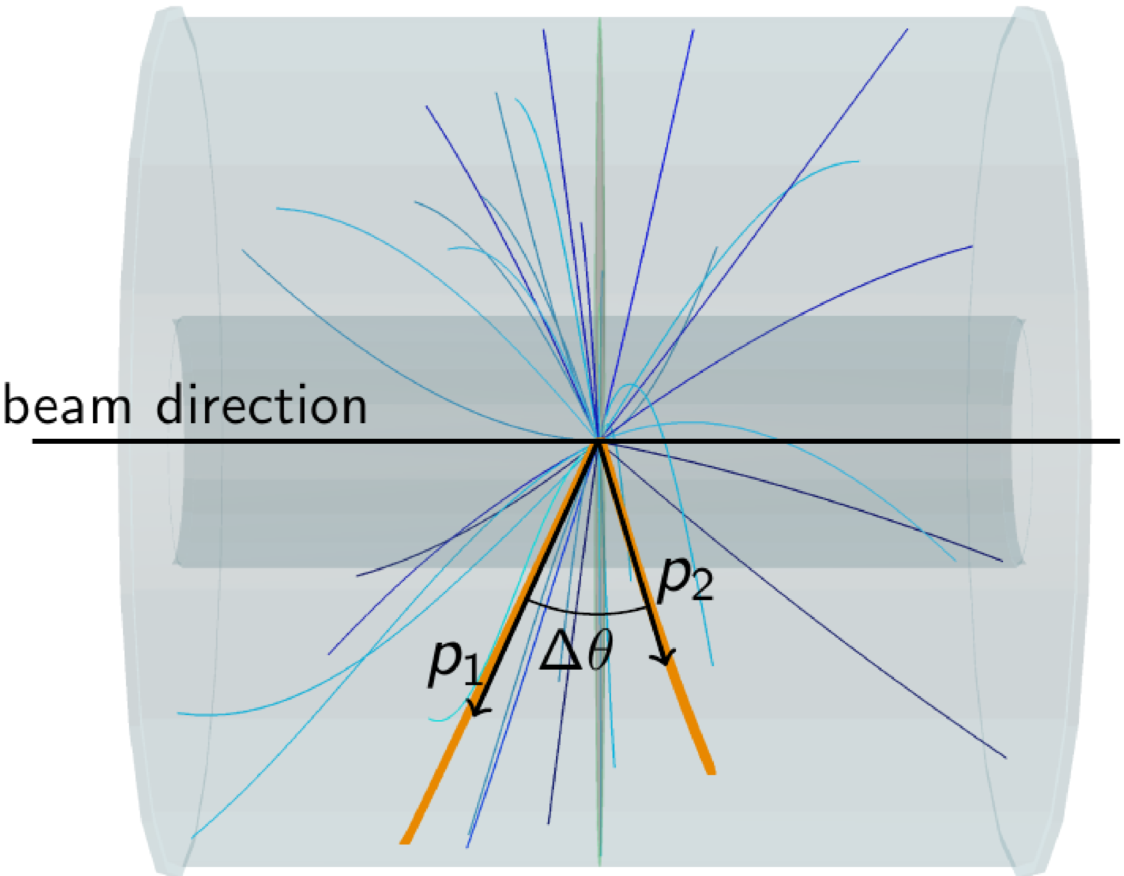
Residual correlations in pp – transformation matrix

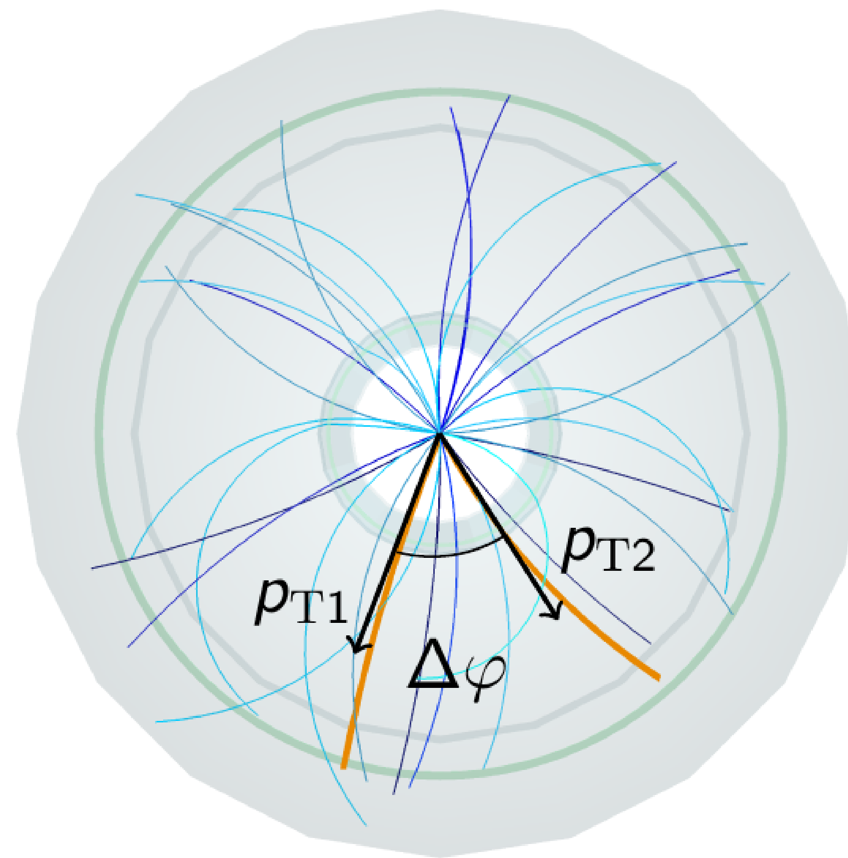
- The transformation matrix T from parent pair $k*$ to the daughter pair $k*$ determined by random decay, bound by decay momenta
- When only one particle decays, it has a rectangular shape, for pairs when both particles decay it is smeared more

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



Two-particle ΔηΔφ angular correlations





p - particle momentum;

θ - polar angle;

η - pseudorapidity:

$$\eta = -\ln\left|\mathrm{tg}\frac{\theta}{2}\right|$$

$$\eta = -\ln\left|\tan\frac{\theta}{2}\right|$$

p_T - transverse momentum;

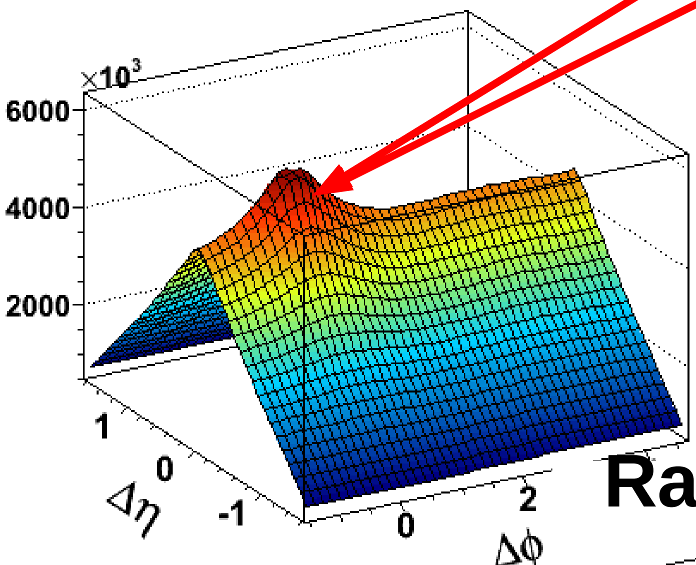
φ - azimuthal angle;

Fig. A. Zaborowska

ΔηΔφ correlation function in experiment

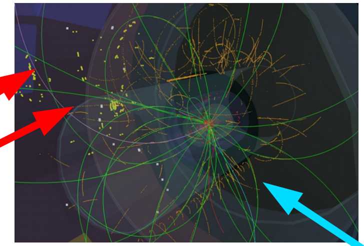
Signal distribution

$$S(\Delta\eta,\Delta\phi)=\frac{d^2N^{signal}}{d\Delta\eta\Delta\phi}$$



Same event pairs

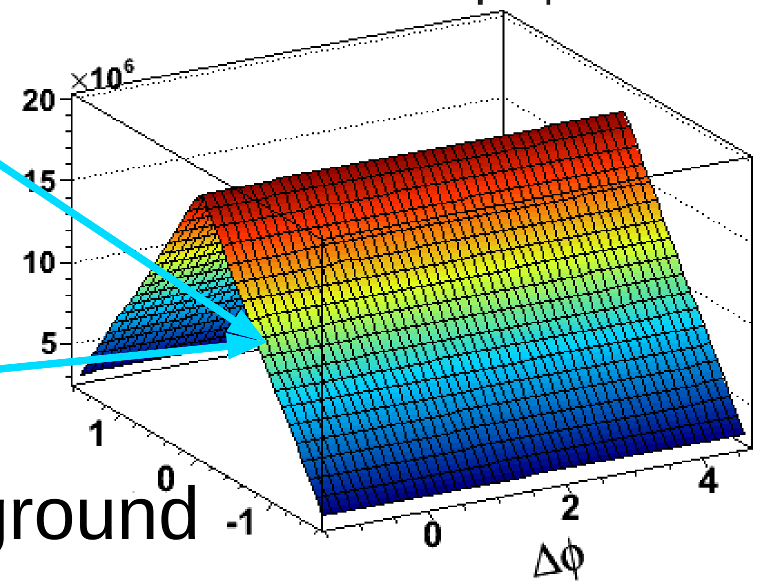
Event 1



Event 2

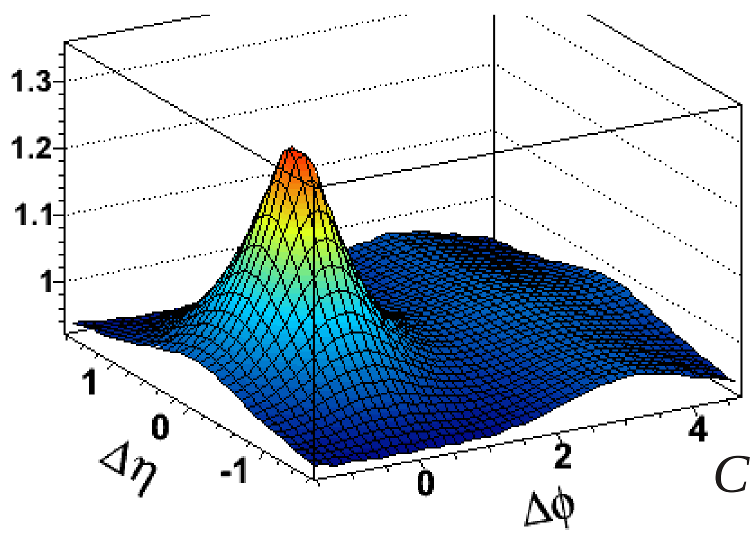
Background distribution

$$B(\Delta\eta,\Delta\phi)=\frac{d^2N^{mixed}}{d\Delta\eta\Delta\phi}$$



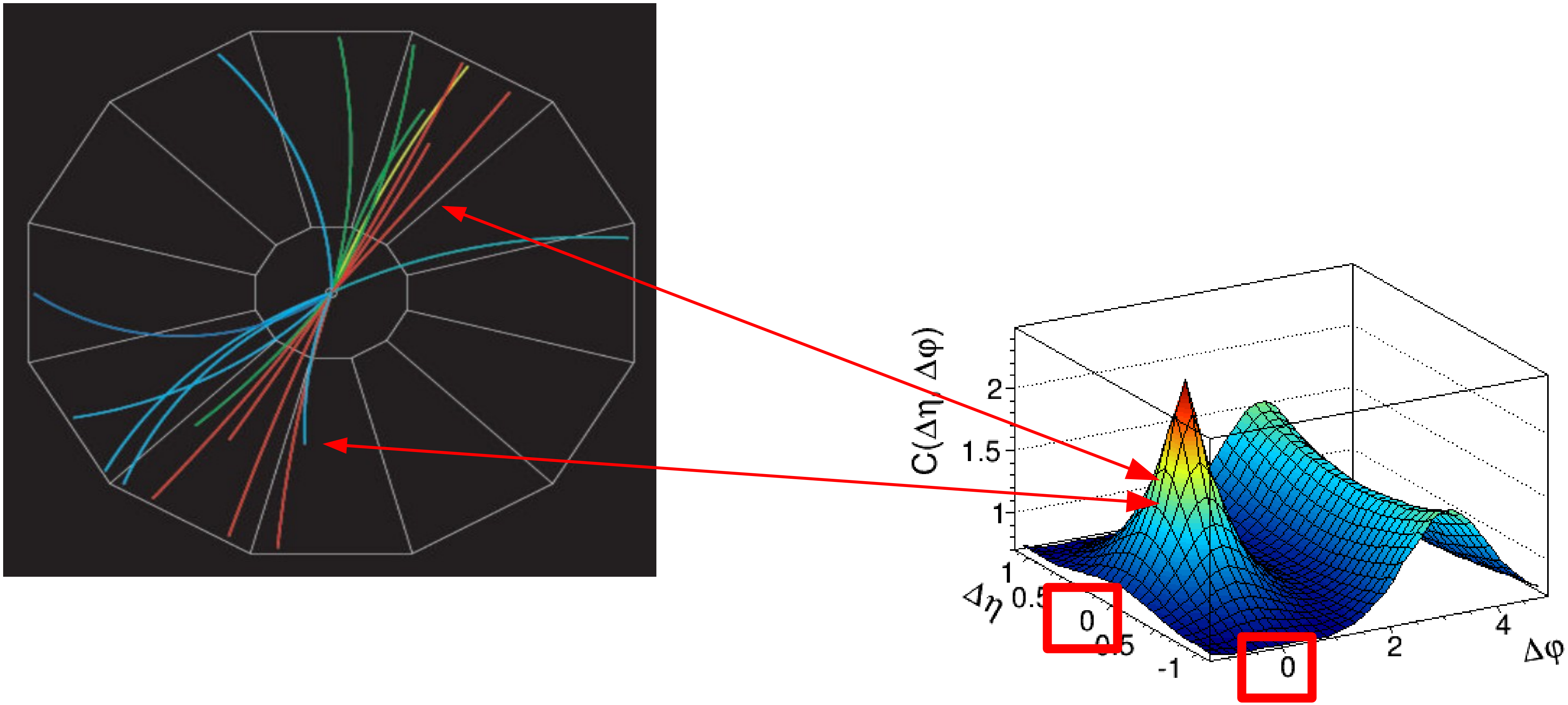
Mixed event pairs

Ratio signal/background



$$C(\Delta\eta,\Delta\phi)=\frac{N_{pairs}^{mixed}}{N_{pairs}^{signal}}\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

How does it work?



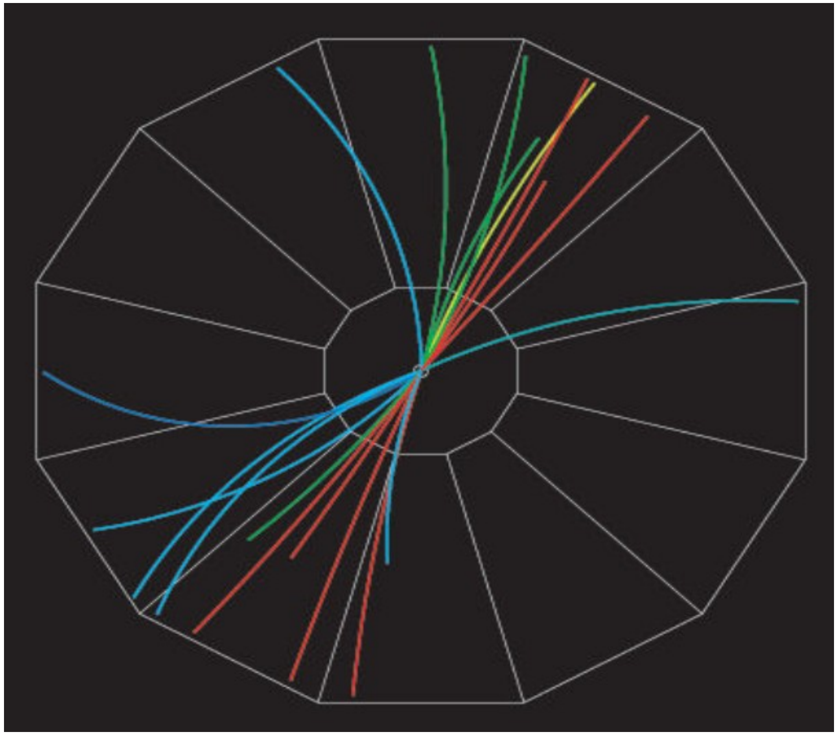
Near-side peak

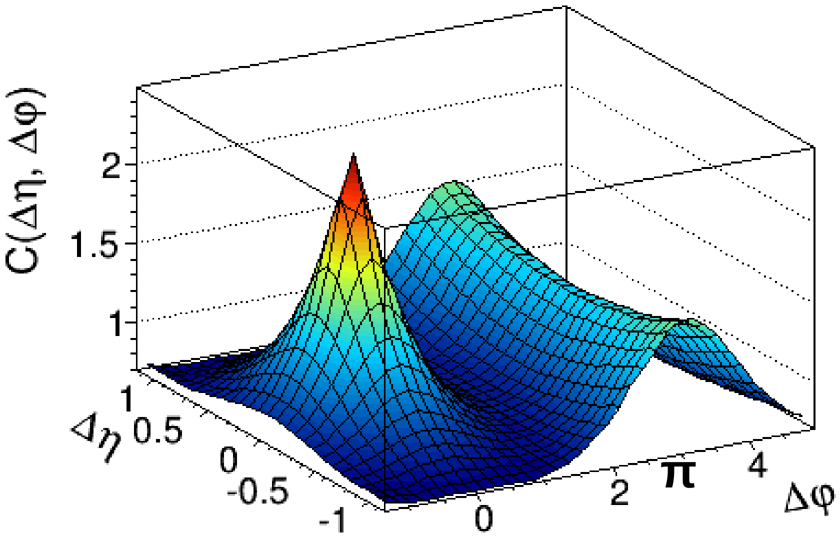
For particles from the same jet (red):

- $\Delta\varphi \sim 0$

- $\Delta\eta \sim 0$

How does it work?





For particles from from back-to-back jets (blue): *Away-side ridge*

- **Δφ ~ π**
- **Δη ~ const distribution, if avaraged over many events**

Properties of quark jets

Two primary hadrons with the same
- baryon number
- (or) charge
- (or) strangeness

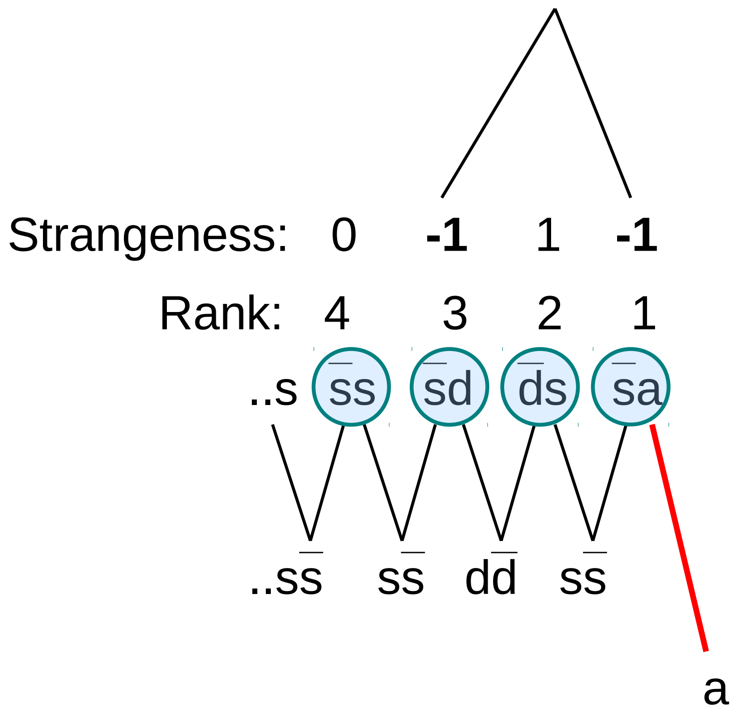
are **separated** by at least two steps is rank.

We are not likely to find two baryons/strange particles or two antibaryons/anti-strange particles at the same rapidity*.

Modern models (like Lund string mode used in PYTHIA) are derived from FF model.

Example

The same strangeness:
3 – 1 = 2 steps in rank



*) Provided that the order of particles in rapidity closely reflects their order in rank (Phys. Rev. Lett. 57 (1987) 3140)

PYTHIA anno 1978

(then called JETSET)

LU TP 78-18
November, 1978

A Monte Carlo Program for Quark Jet Generation

T. Sjöstrand, B. Söderberg

A Monte Carlo computer program is presented, that simulates the fragmentation of a fast parton into a jet of mesons. It uses an iterative scaling scheme and is compatible with the jet model of Field and Feynman.

Note:
Field-Feynman was an early fragmentation model
Now superseded by the String (in PYTHIA) and Cluster (in HERWIG & SHERPA) models.

```
      SUBROUTINE JETGEN(N)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /PAR/ PUD, PS1, SIGMA, CX2, EBEG, WFIN, IFLBEG
      COMMON /DATA1/ MESO(9,2), CMIX(6,2), PMAS(19)
      IFLSGN=(10-IFLBEG)/5
      W=2.*EBEG
      I=0
      IPD=0
C 1 FLAVOUR AND PT FOR FIRST QUARK
      IFL1=IABS(IFLBEG)
      PT1=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI1=6.2832*RANF(0)
      PX1=PT1*COS(PHI1)
      PY1=PT1*SIN(PHI1)
  100 I=I+1
C 2 FLAVOUR AND PT FOR NEXT ANTIQUARK
      IFL2=1+INT(RANF(0)/PUD)
      PT2=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI2=6.2832*RANF(0)
      PX2=PT2*COS(PHI2)
      PY2=PT2*SIN(PHI2)
C 3 MESON FORMED, SPIN ADDED AND FLAVOUR MIXED
      K(I,1)=MESO(3*(IFL1-1)+IFL2,IFLSGN)
      ISPIN=INT(PS1+RANF(0))
      K(I,2)=1+9*ISPIN+K(I,1)
      IF(K(I,1).LE.6) GOTO 110
      TMIX=RANF(0)
      KM=K(I,1)-6+3*ISPIN
      K(I,2)=8+9*ISPIN+INT(TMIX+CMIX(KM,1))+INT(TMIX+CMIX(KM,2))
C 4 MESON MASS FROM TABLE, PT FROM CONSTITUENTS
  110 P(I,5)=PMAS(K(I,2))
      P(I,1)=PX1+PX2
      P(I,2)=PY1+PY2
      PMTS=P(I,1)**2+P(I,2)**2+P(I,5)**2
C 5 RANDOM CHOICE OF X=(E+PZ)MESON/(E+PZ)AVAILABLE GIVES E AND PZ
      X=RANF(0)
      IF(RANF(0).LT.CX2) X=1.-X**(1./3.)
      P(I,3)=(X*W-PMTS/(X*W))/2.
      P(I,4)=(X*W+PMTS/(X*W))/2.
C 6 IF UNSTABLE, DECAY CHAIN INTO STABLE PARTICLES
  120 IPD=IPD+1
      IF(K(IPD,2).GE.8) CALL DECAY(IPD,I)
      IF(IPD.LT.I.AND.I.LE.96) GOTO 120
C 7 FLAVOUR AND PT OF QUARK FORMED IN PAIR WITH ANTIQUARK ABOVE
      IFL1=IFL2
      PX1=-PX2
      PY1=-PY2
C 8 IF ENOUGH E+PZ LEFT, GO TO 2
      W=(1.-X)*W
      IF(W.GT.WFIN.AND.I.LE.95) GOTO 100
      N=I
      RETURN
      END
```

Rapidity correlations in e^+e^- collisions

Study of baryon correlations in e+e− annihilation at 29 GeV
TPC/Two Gamma Collaboration (H. Aihara et al.), Phys.Rev.Lett. 57 (**1986**) 3140

Measured (anti)protons and (anti)lambdas!

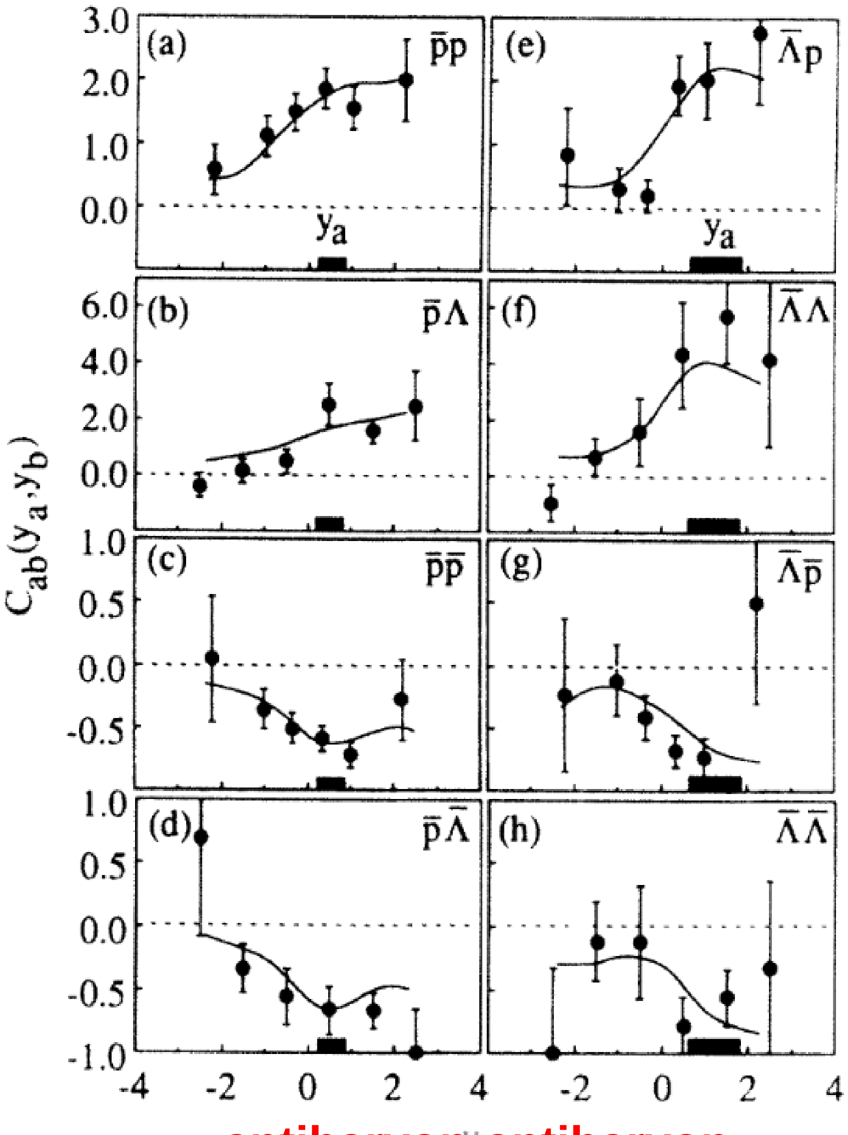
Particles with the opposite baryon number create positive correlation, regardless of their type (i.e. we see correlation for proton-lambda systems).

Particles with the same baryon number create anticorrelation, regardless of their type.

We are not likely to find two baryons or two antibaryons at the same rapidity (anticorrelation).

Is it similar for **hadron-hadron collisions**?
Do models reproduce these features?

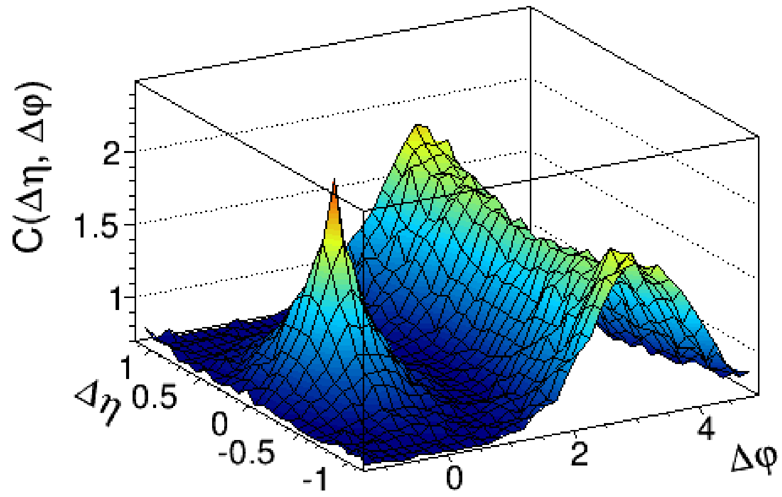
baryon-antibaryon
no anticorrelation



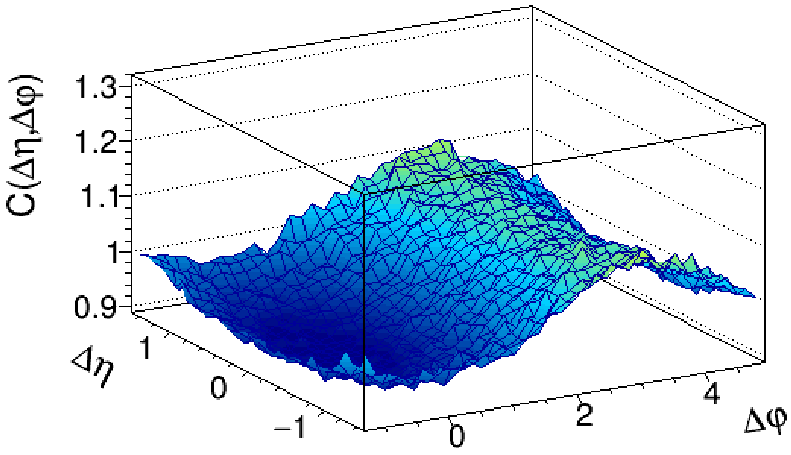
antibaryon-antibaryon
anticorrelation!

Conservation Laws Model (CALM): Simple MC

Jet correlations dominate the correlation function shape



Anti-correlation shape can be easily reproduced with a toy Monte Carlo with conservation laws included (no other physics)



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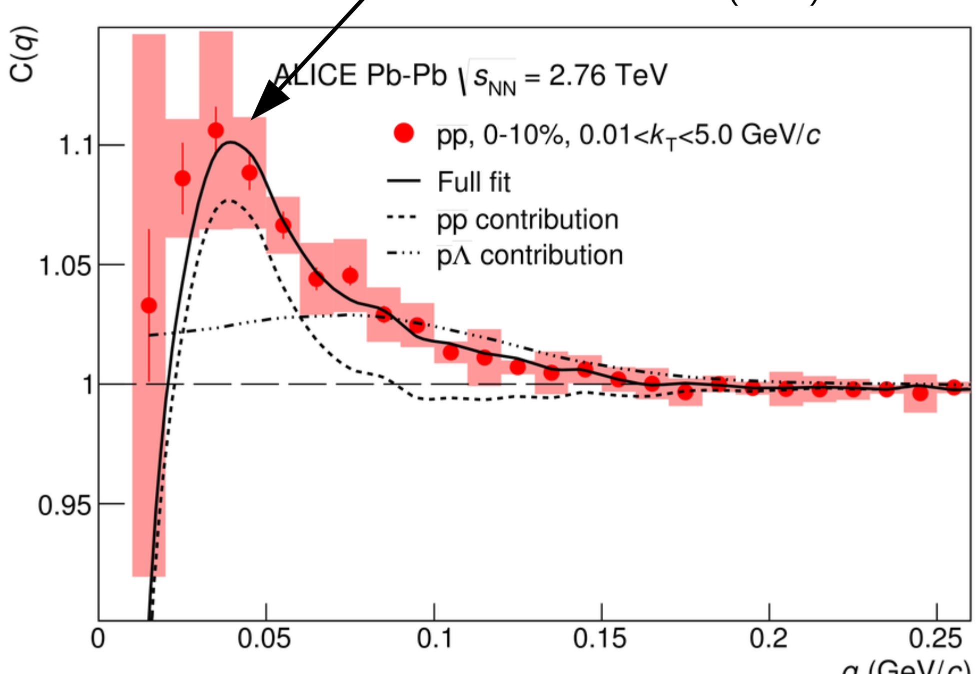
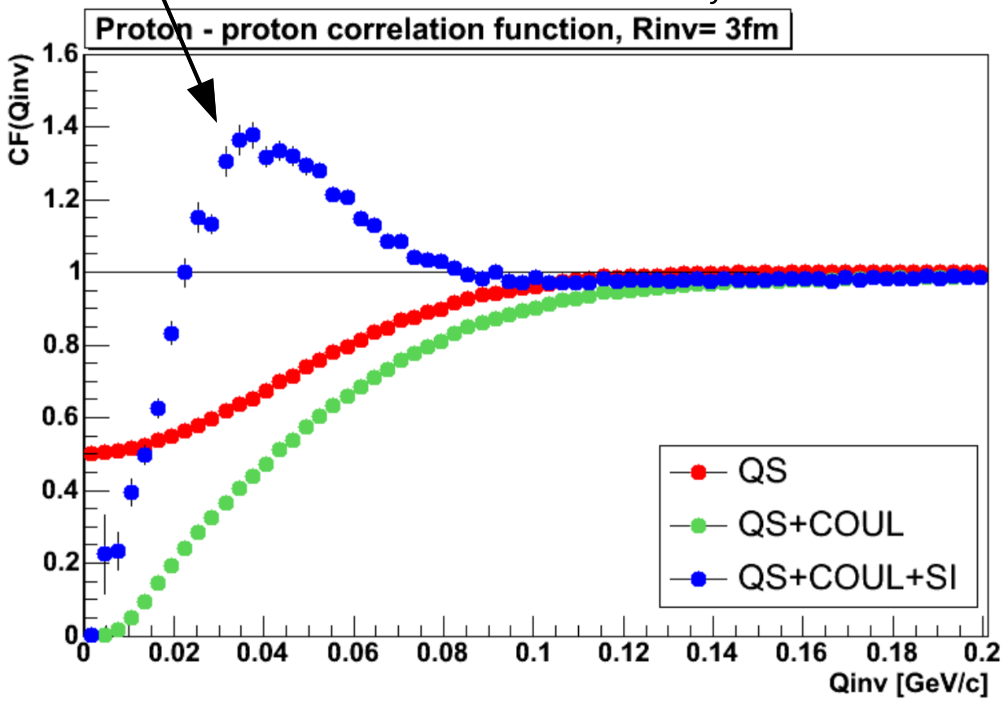
Femtoscopic measurements: protons

- How does strong interaction manifest in these correlations?
- Example – proton correlations:
  - **Fermi-Dirac QS + Coulomb + strong interaction**
  - Dominant effect around q_{inv} = 0.04 GeV/c
  - Strong interaction the only source of positive correlation for baryons

PRC 92 (2015) 054908



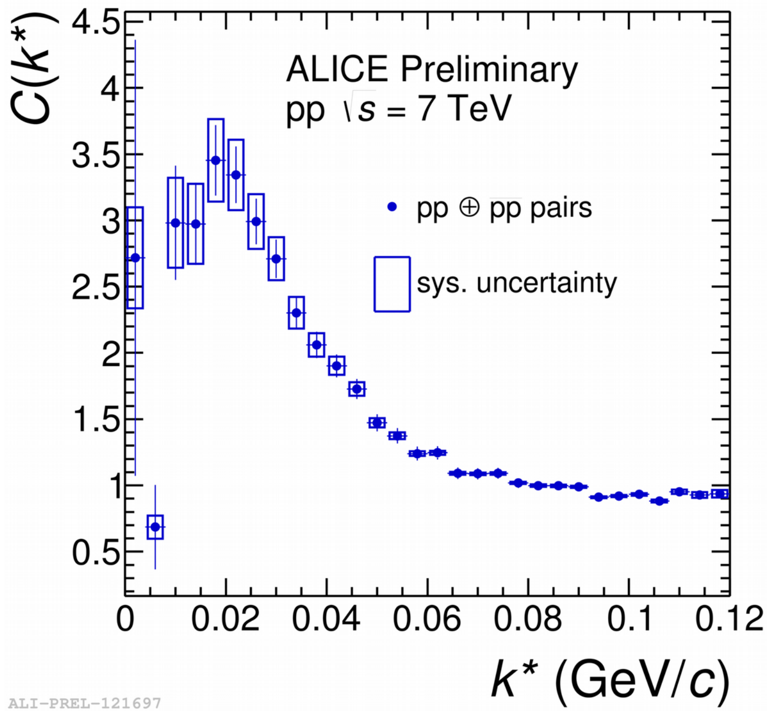
PhD thesis of H. Zbroszczyk



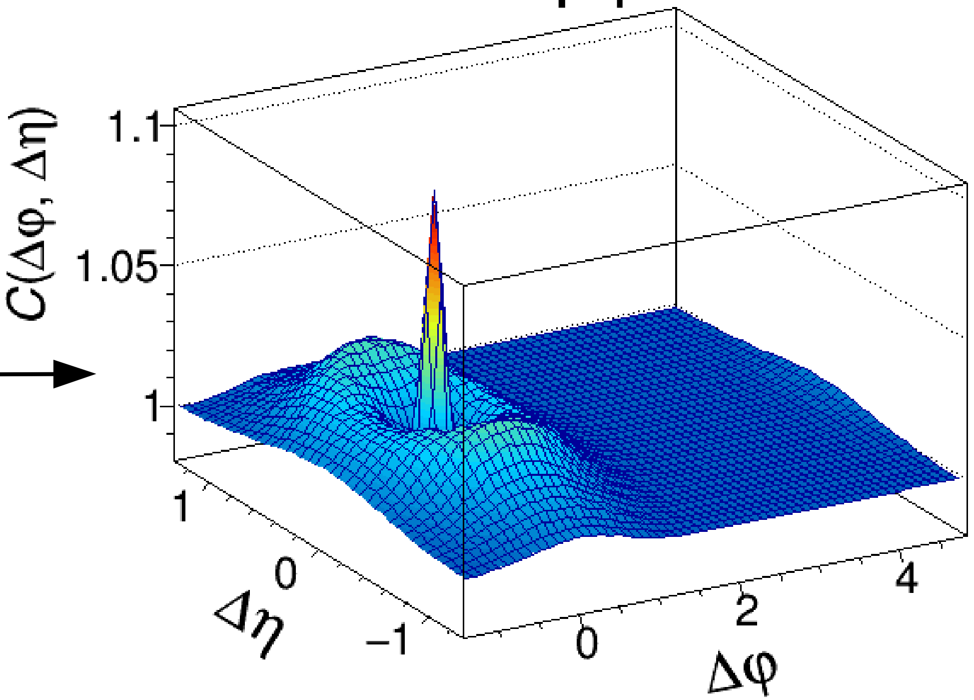
Proton correlations – transformation

- Direct transformation from $C(q_{inv})$ to $C(\Delta\eta\Delta\varphi)$ **not possible**
- One can employ a simple **Monte Carlo procedure:**
  - generate random η and φ from uniform distributions (for 2 particles: η_1, η_2, φ_1, φ_2)
  - generate random p_T from measured p_T distribution (for 2 particles: p_{T1}, p_{T2})
  - calculate k* from generated η_1, η_2, φ_1, φ_2, p_{T1} and p_{T2}
  - take the value of measured femtoscopic correlation function at given k* and apply it as weight while filling the numerator of ΔηΔφ

pp femto corr. fun



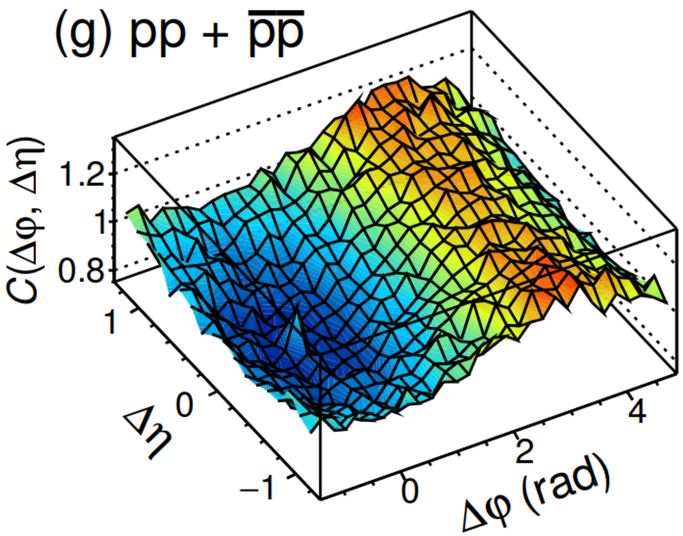
transformed ΔηΔφ corr. fun.



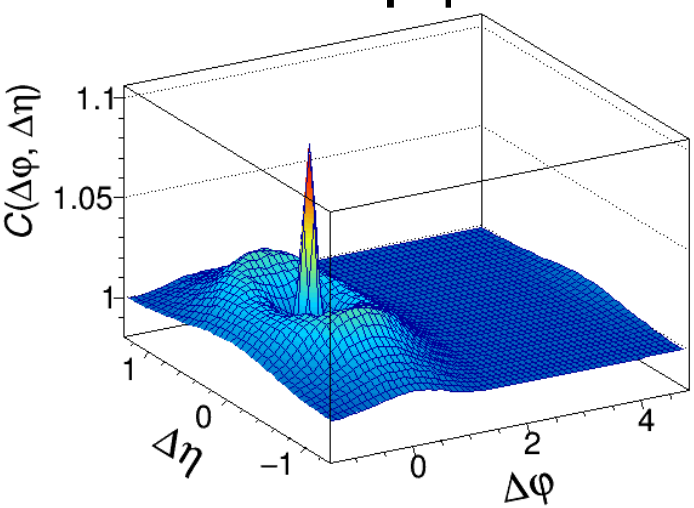
Protons – femtoscopic correlations

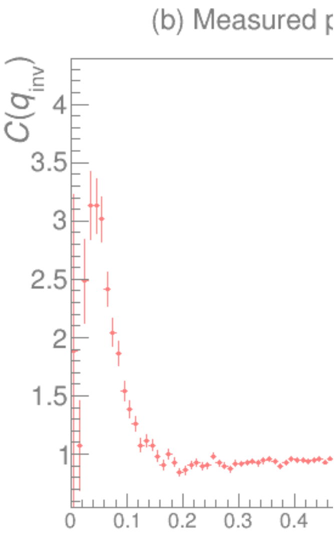
Results:

- Femto correlation produces spike at (Δη,Δφ)=(0,0)
- Both the height and the width of two peaks comparable
- FSI cannot produce observed anti-correlation
- **Unsolved question: why are baryons so different?**



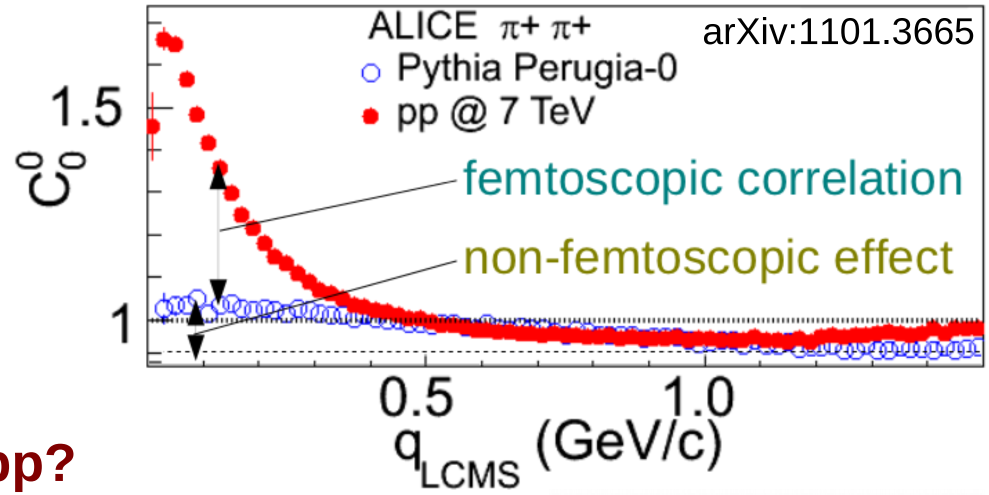
transformed ΔηΔφ corr. fun.



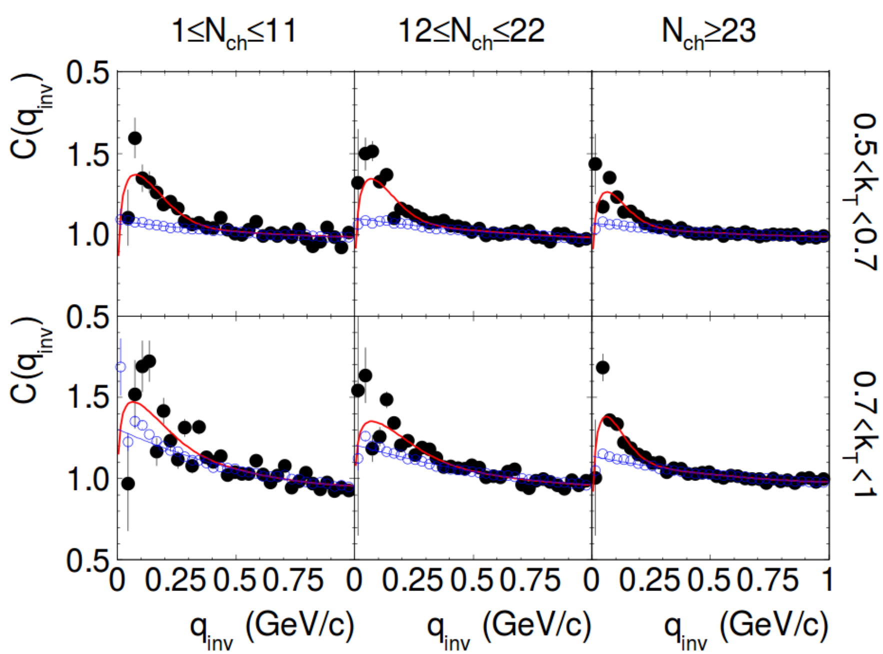


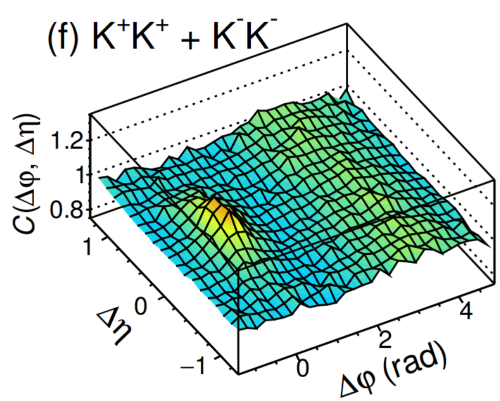
Non-femtoscopic correlations

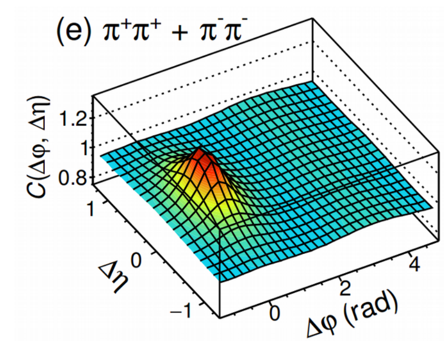
- Non-femtoscopic correlations visible in small systems for **pions** and **kaons**:
  - Grow with increasing k_T
  - Grow with decreasing multiplicity
  - **Significant problem in the fitting procedure**
- So far **<u>hypothesis</u> of minijet/jet origin**
- **How do baryon correlations look like in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



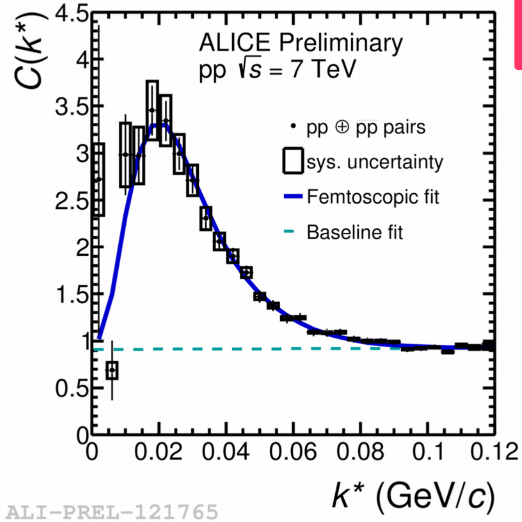
arXiv:1212.5958

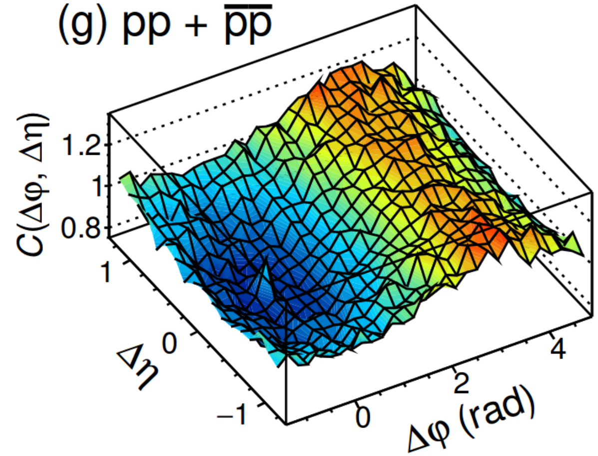




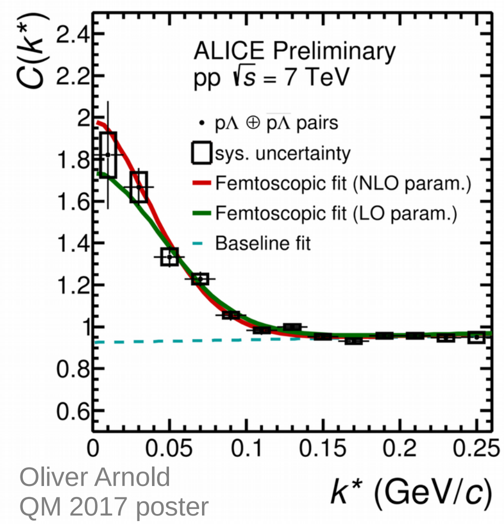


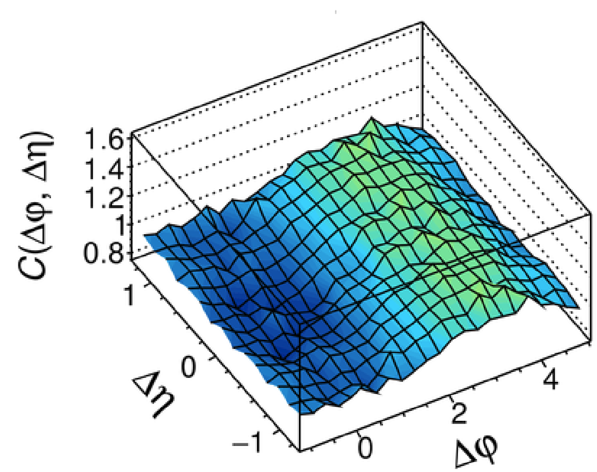
pp+$\overline{\mathrm{pp}}$



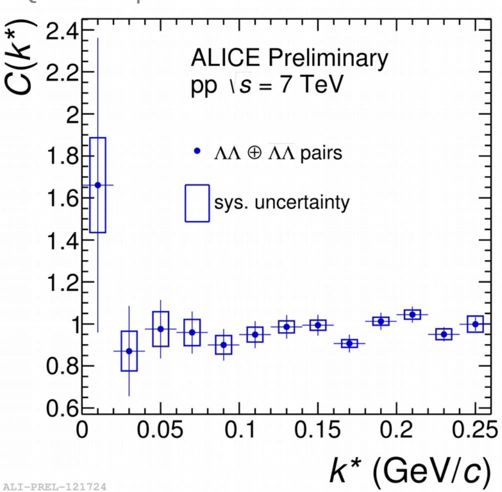


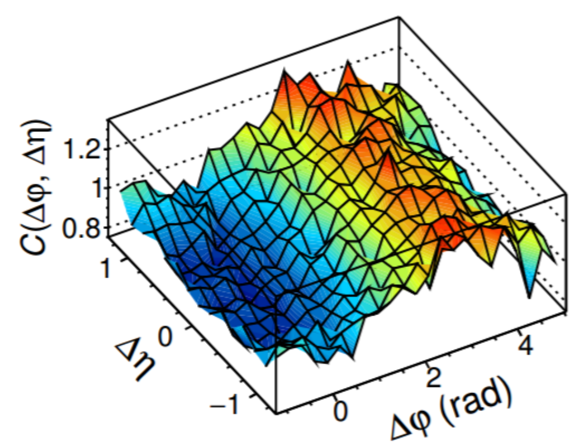
pΛ+$\overline{\mathrm{p\Lambda}}$





ΛΛ+$\overline{\Lambda\Lambda}$





Flat baseline for all baryon-baryon pair measurements.

Consistent picture from femtoscopic measurements and ΔηΔφ!