Studying the strong interaction with baryon-(anti)baryon femtoscopy in Pb-Pb collisions measured by ALICE

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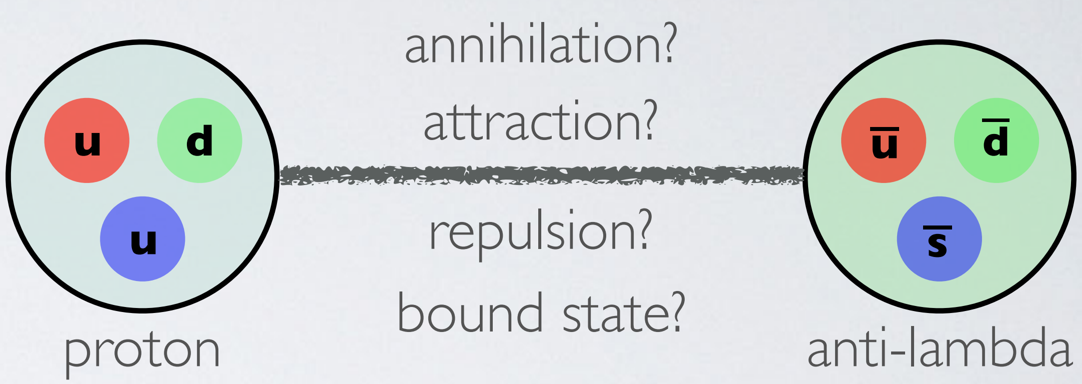
Outline

1) Motivation and introduction.
2) Fitting procedure and experimental correlation functions.
3) Measured strong interaction parameters.
4) Interpretation of the results.
5) Conclusions.

Motivation

The strong interaction between particles is an important problem in nuclear physics.

- What is the interaction cross section for baryon-antibaryon ($b\bar{b}$) pairs?
- Do baryons and antibaryons **attract or repel** with strong interaction?
- Can a pair of non-identical baryons (e.g. $p\bar{\Lambda}$) **annihilate**?
- Do $b\bar{b}$ **bound states** exist?



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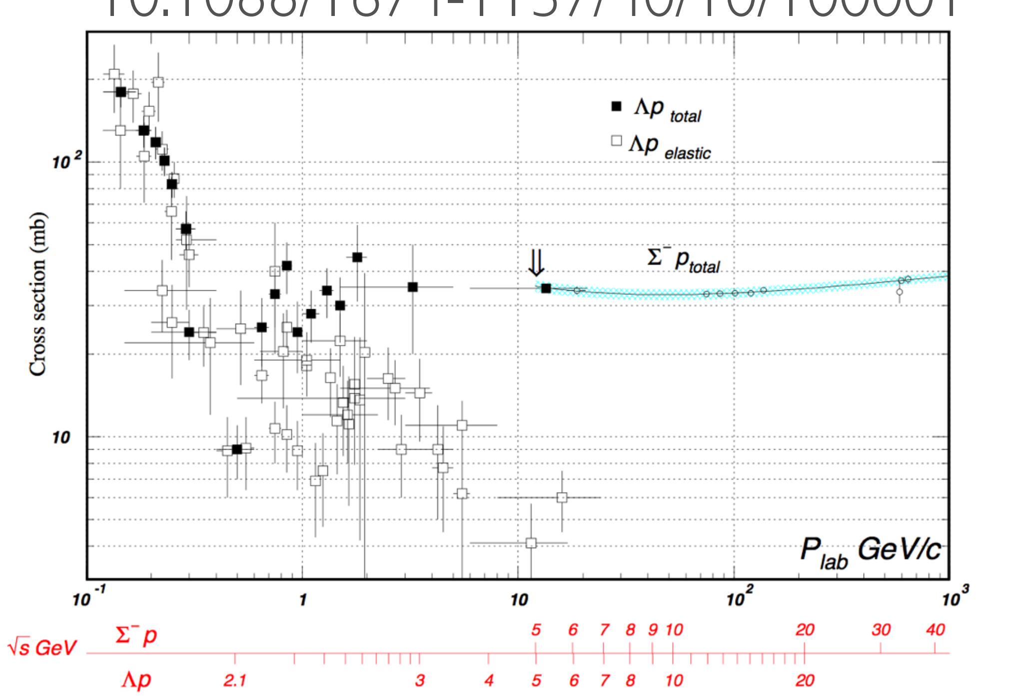


- baryon-baryon cross sections not well known,
- $b\bar{b}$ (baryon-antibaryon) parameters are practically unknown (except $p\bar{p}$, $n\bar{p}$, $d\bar{p}$),
- LHC is a baryon-antibaryon factory,
- ALICE can register and identify different (anti)baryons,
- **femtoscopy** provides a means for measuring $b\bar{b}$ interactions!

INTRODUCTION

Femtoscopy is a technique of measuring the distribution of relative momenta of pairs of particles.

This distribution depends on the shape and **size of the source** and **interactions** between those particles.

$$C(k^*) = \int S(\mathbf{r}) \left|\Psi(k^*, \mathbf{r})\right|^2 d^4\mathbf{r}$$

Correlation function

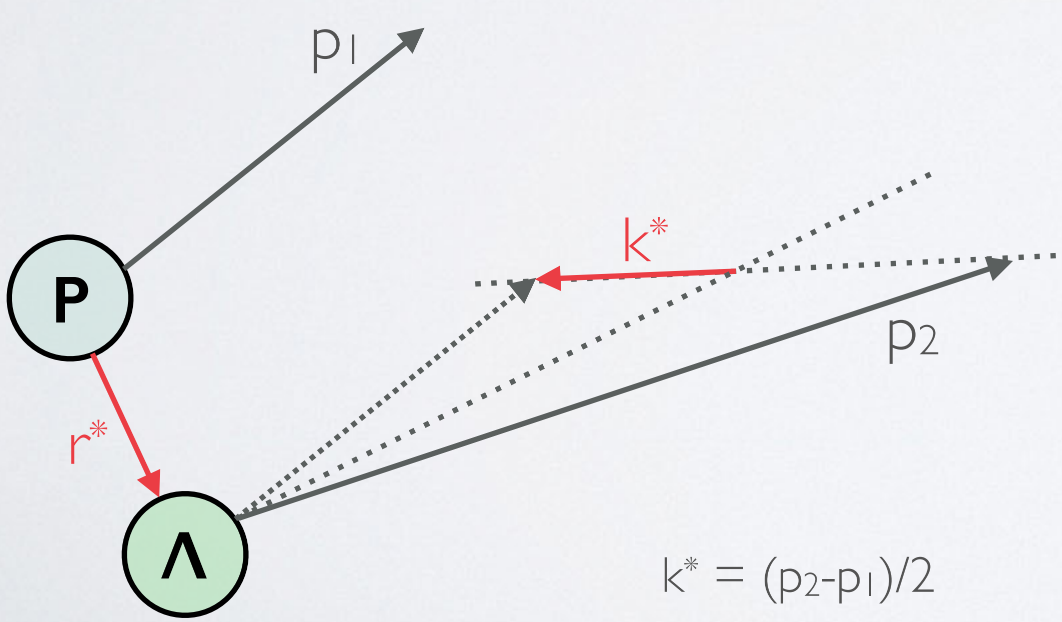
(can be measured in ALICE)

Source emission function

(spherically-symmetric gaussian)

Pair wave function

(describes interaction)



s-wave approximation:

$$\Psi(\mathbf{k}^*, \mathbf{r}^*) = e^{-i\mathbf{k}^*\mathbf{r}^*} + f(k^*)\frac{e^{ik^*r^*}}{r^*}$$

effective range approximation:

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

INTRODUCTION

We can use data collected by ALICE to extract strong interaction parameters.

$$C(k^*) = \int S(\mathbf{r}) \left| \Psi(k^*, \mathbf{r}) \right|^2 d^4\mathbf{r}$$

Let's measure this

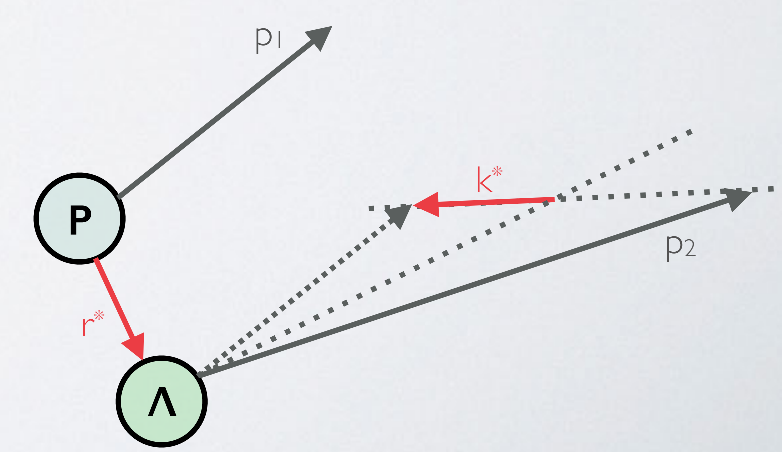
Make some assumptions about this

(based on previous measurements and studies)

$$\Psi(\mathbf{k}^*, \mathbf{r}^*) = e^{-i\mathbf{k}^*\mathbf{r}^*} + f(k^*) \frac{e^{ik^*r^*}}{r^*}$$

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

Finally, try to **extract** these parameters.



The correlation function is described by the following parameters:

- $\mathbf{r_0}$ - source size
- $\mathbf{f_0}$ - scattering length (complex number)
- $\mathbf{d_0}$ - effective range

At low relative momenta, cross section is described by scattering amplitude: $\sigma = 4\pi |f|^2$

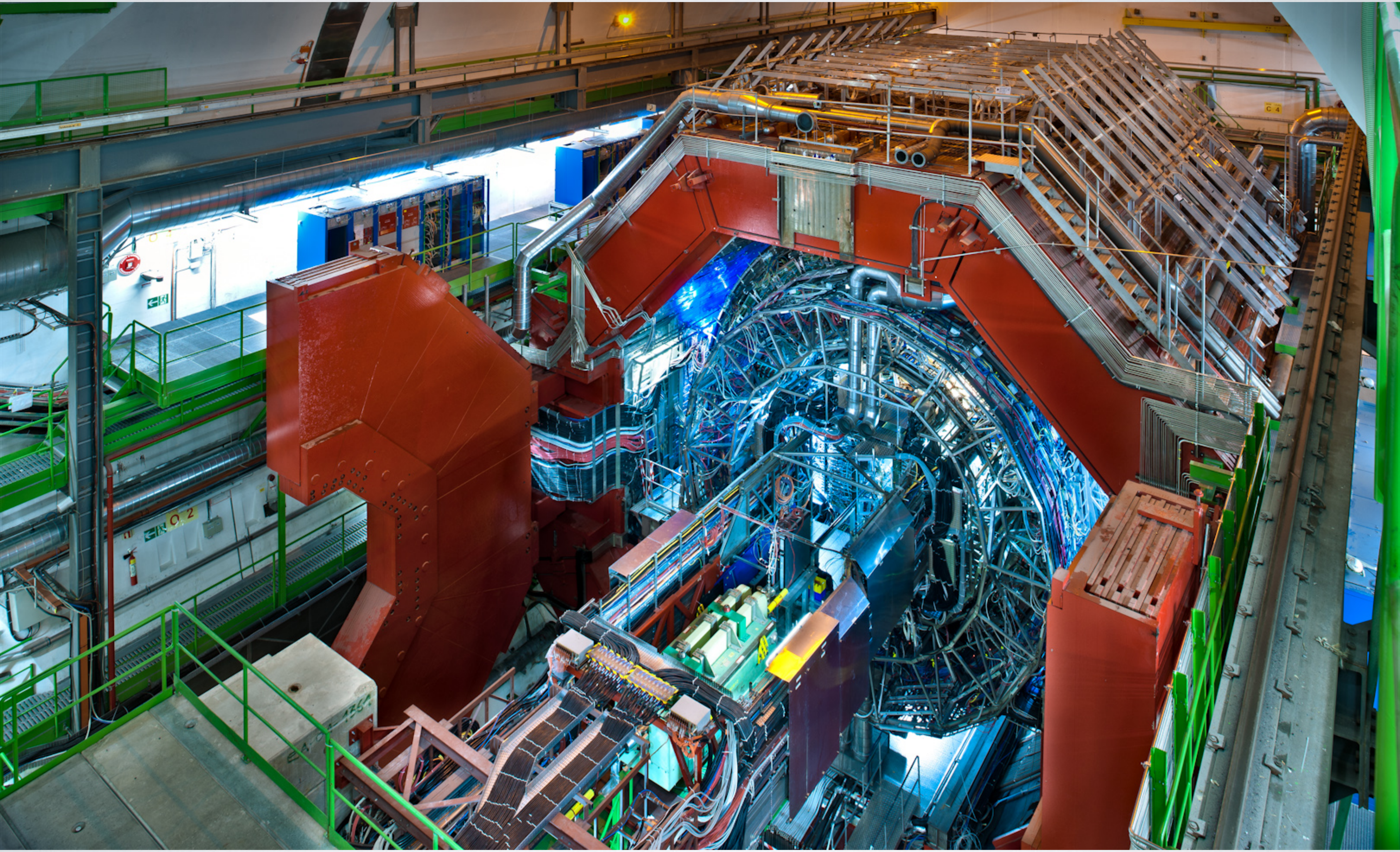
Measurement

LHC and ALICE

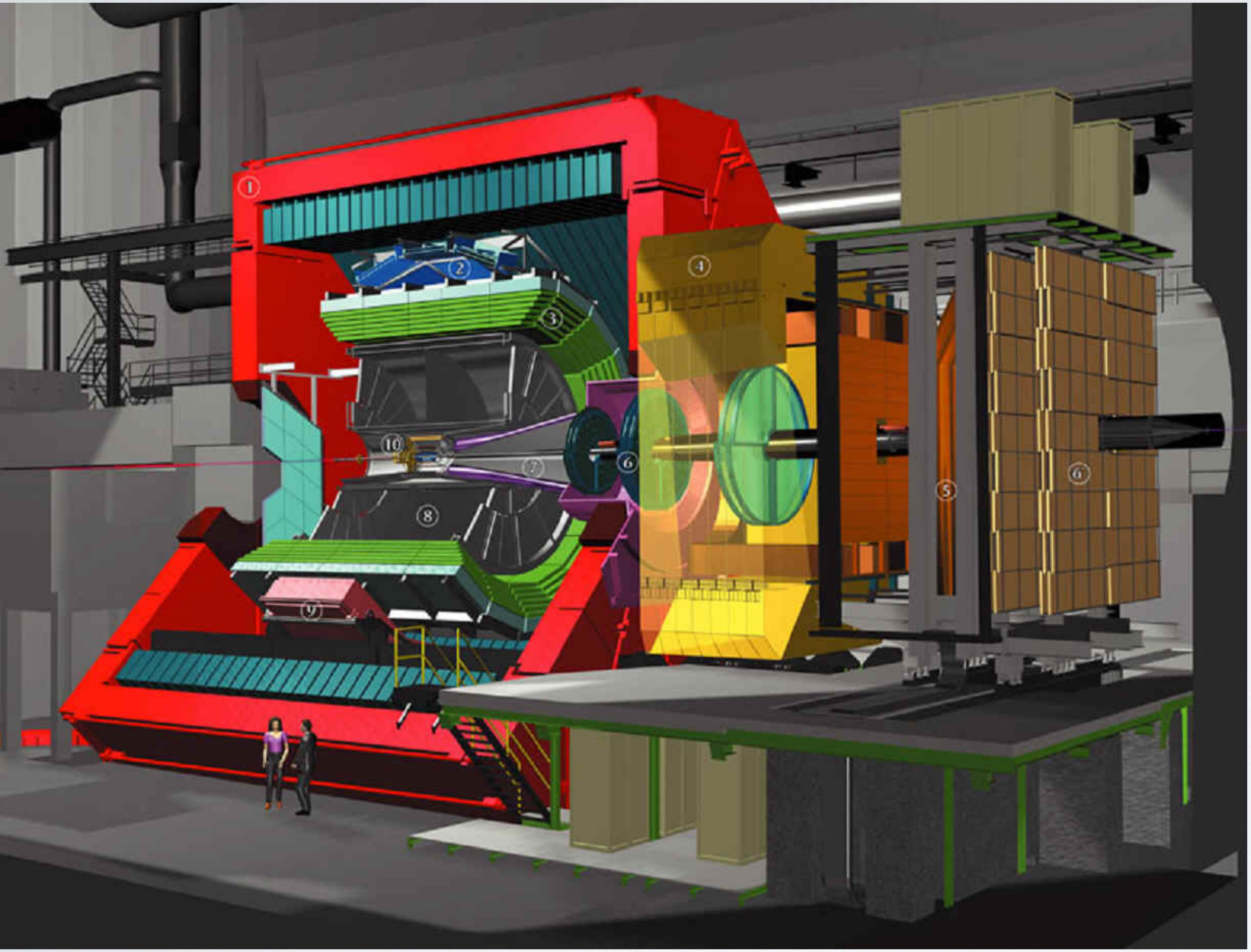
- LHC is a 27 km particle collider (pp, p-Pb, Pb-Pb),
- pp collisions up to 13 TeV center of mass energy, Pb-Pb up to 5.02 TeV per nucleon pair,
- four large experiments: ALICE, ATLAS, CMS, LHCb.

Measurement

LHC and ALICE



MEASUREMENT
LHC AND ALICE



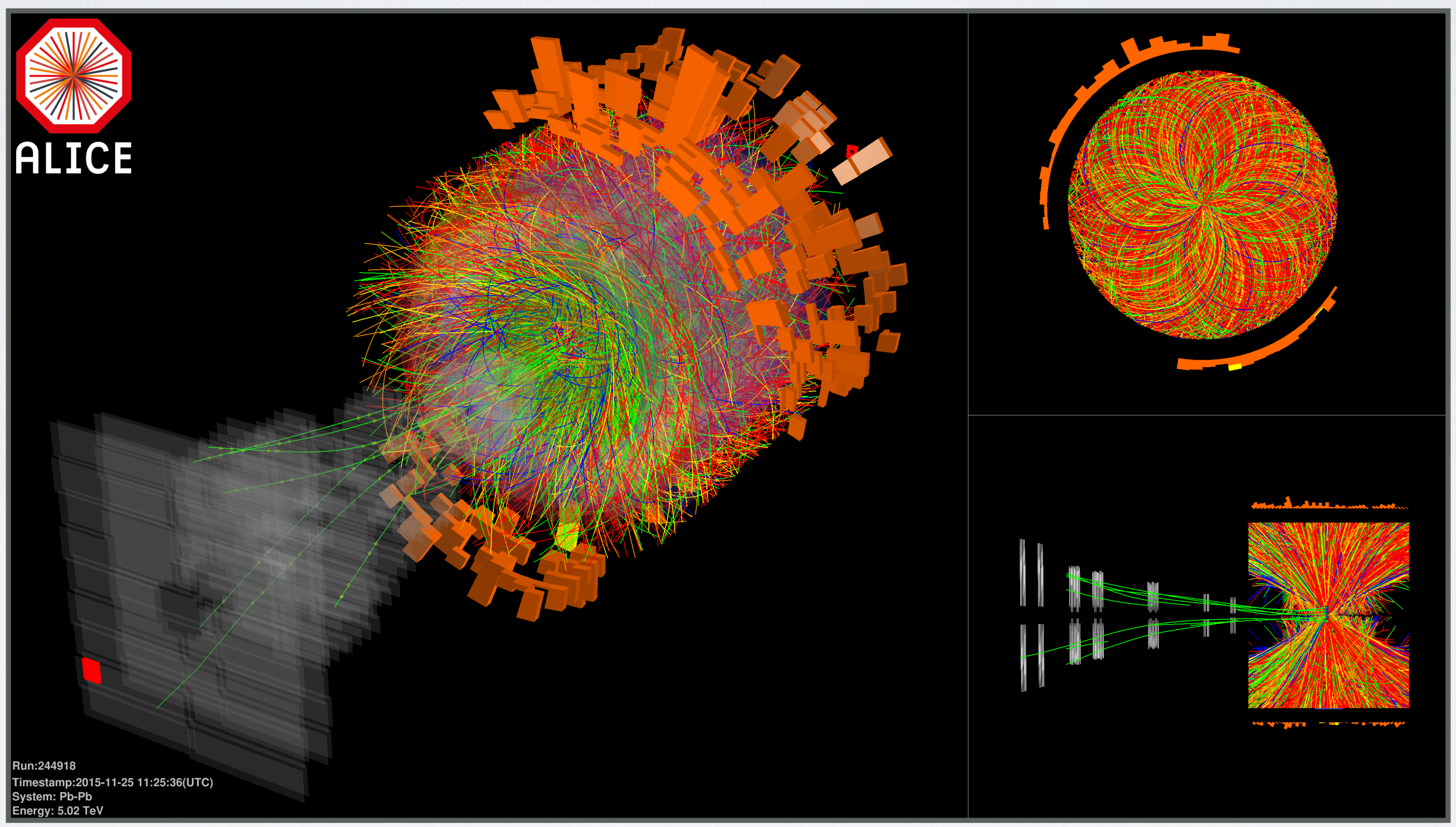
- ALICE (A Large Ion Collider Experiment) is designed mainly to register heavy-ion collisions,
- 19 sub-detectors,
- excellent PID at low-momenta.

MEASUREMENT

The experimental correlation function is defined as follows:

$$C(p_1,p_2)=\frac{P(p_1,p_2)}{P(p_1)\cdot P(p_2)}$$

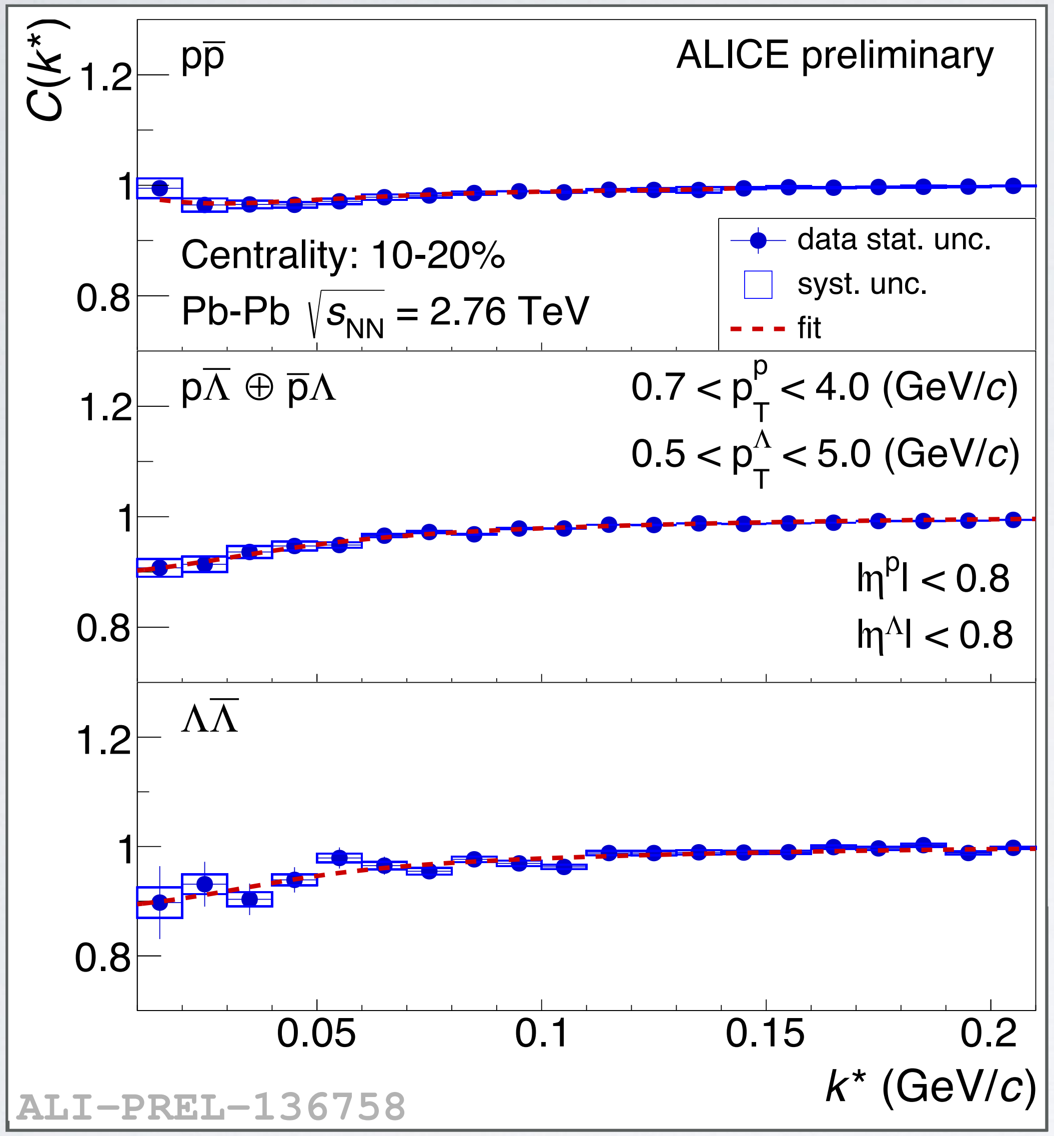
- $P(p_1,p_2)$ - probability of observing particles with momenta p_1 and p_2 simultaneously (in the same event),
- $P(p_1)$, $P(p_2)$ - probability of observing particles with momenta p_1 and p_2 independently (in two different events).

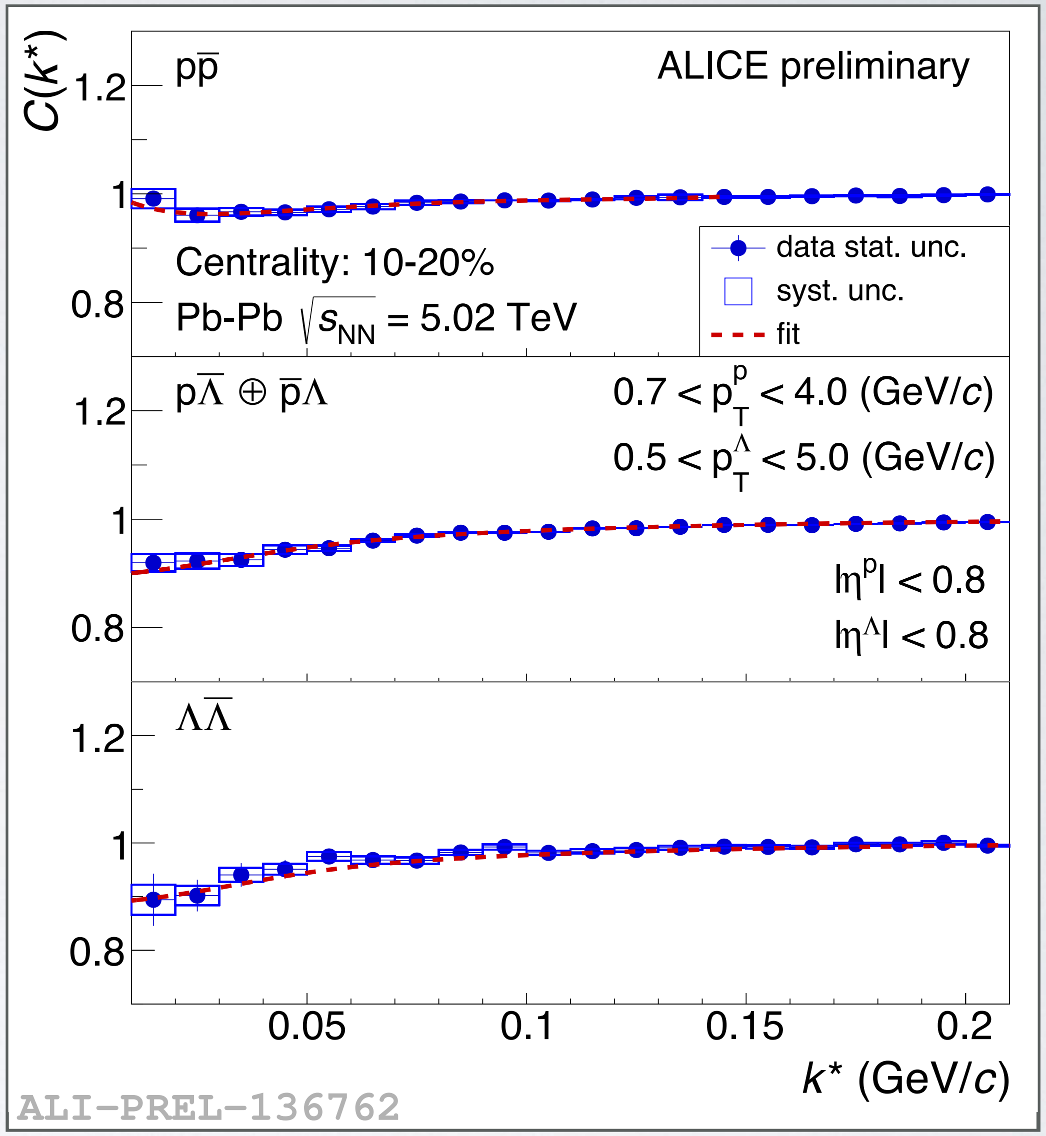


In ALICE we observe almost **the same number of particles and antiparticles**. ALICE allows identification of (anti)protons and (anti)lambdas with high precision, making femtoscopic studies possible.

Experimental correlation functions

A few examples of measured $b\bar{b}$ correlation functions:



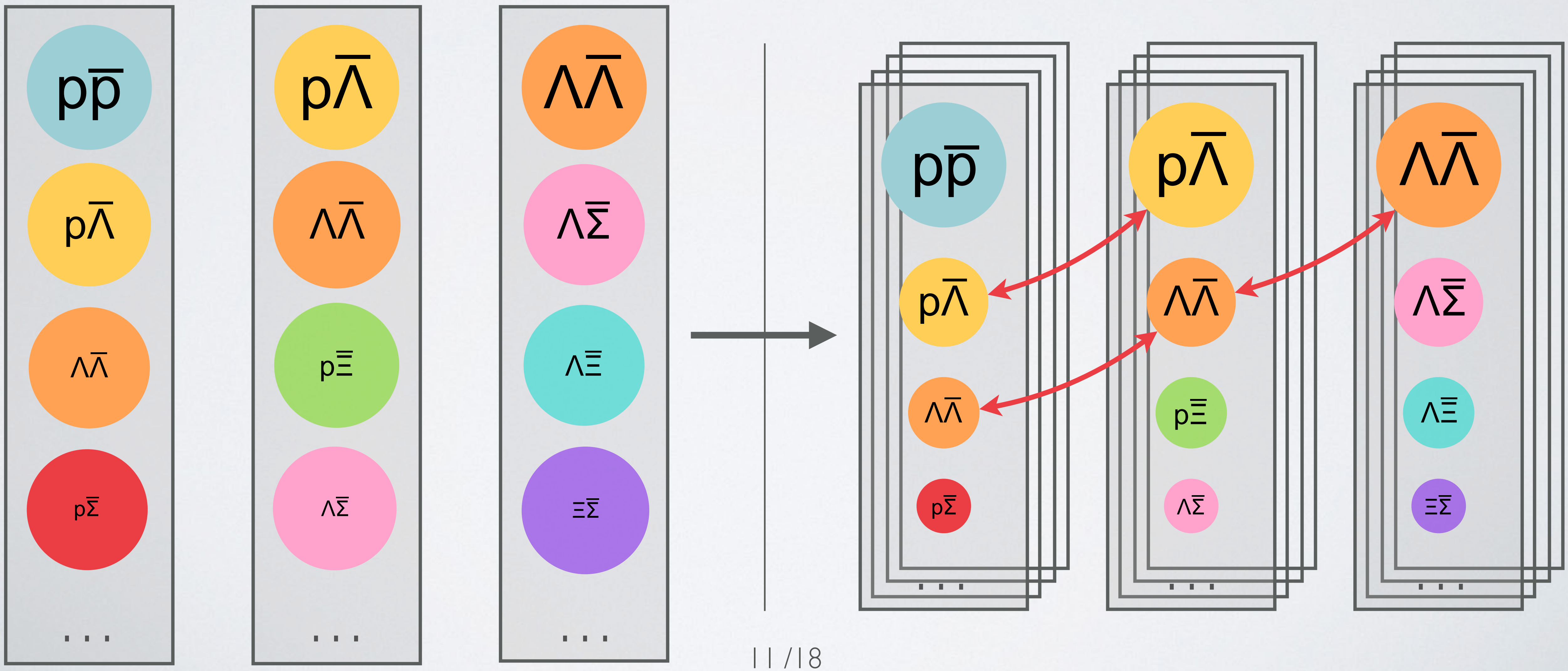


- **$\Lambda\bar{\Lambda}$ correlation function** measured for the first time in history.
- **$p\bar{p}$ correlation function** never published before.
- **$p\bar{\Lambda}$ analysed** for the first time together with other systems, in centrality bins and with full regard of residual correlations.

FITTING PROCEDURE

COMBINING DIFFERENT SYSTEMS

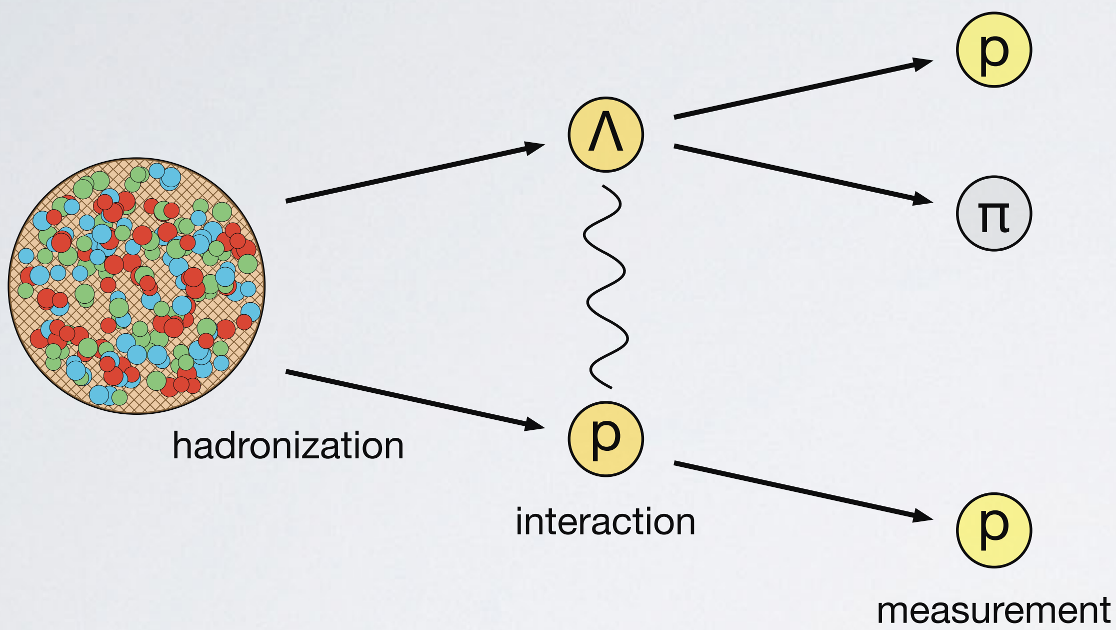
- χ^2 is calculated from all functional fits we have (**36 functions** in total):
  - 2.76 TeV + 5.02 TeV,
  - $p\bar{p}$, $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$,
  - 6 centrality bins.
- 3 sets of parameters: $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$ and the same parameters for heavier $b\bar{b}$ pairs,
- all parameters which are the same for different functions are **shared** between them.



FITTING PROCEDURE

RESIDUAL CORRELATIONS

The experimental correlation functions are indirectly influenced by **decays of heavier particles**.

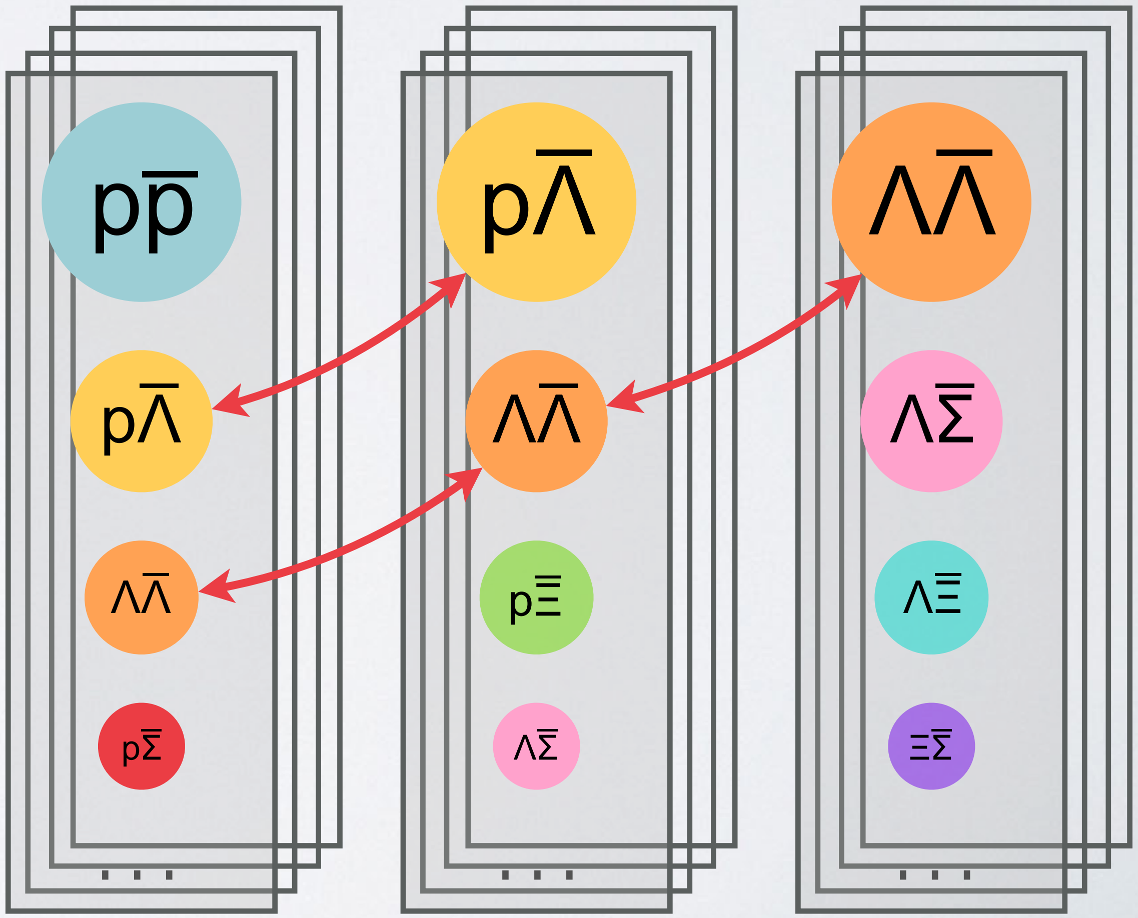


In this example, we plot proton-proton correlation function, but actually interaction was between proton and lambda…

The final correlation function is a weighted sum of correlation functions of all residual components:

$$C_{xy}(k^*) = 1 + \sum_i \lambda_i [C_i(k^*) - 1]$$

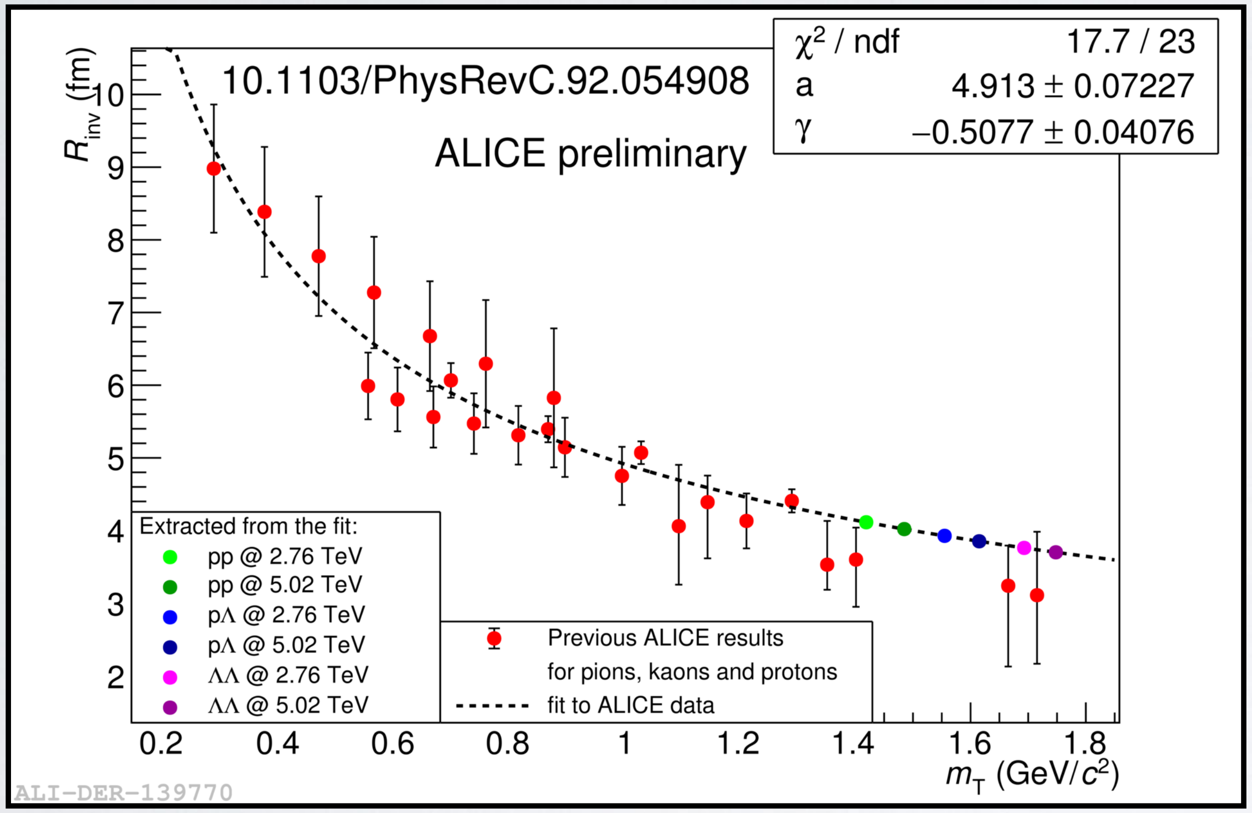
from Monte Carlo simulation (AMPT)



FITTING PROCEDURE

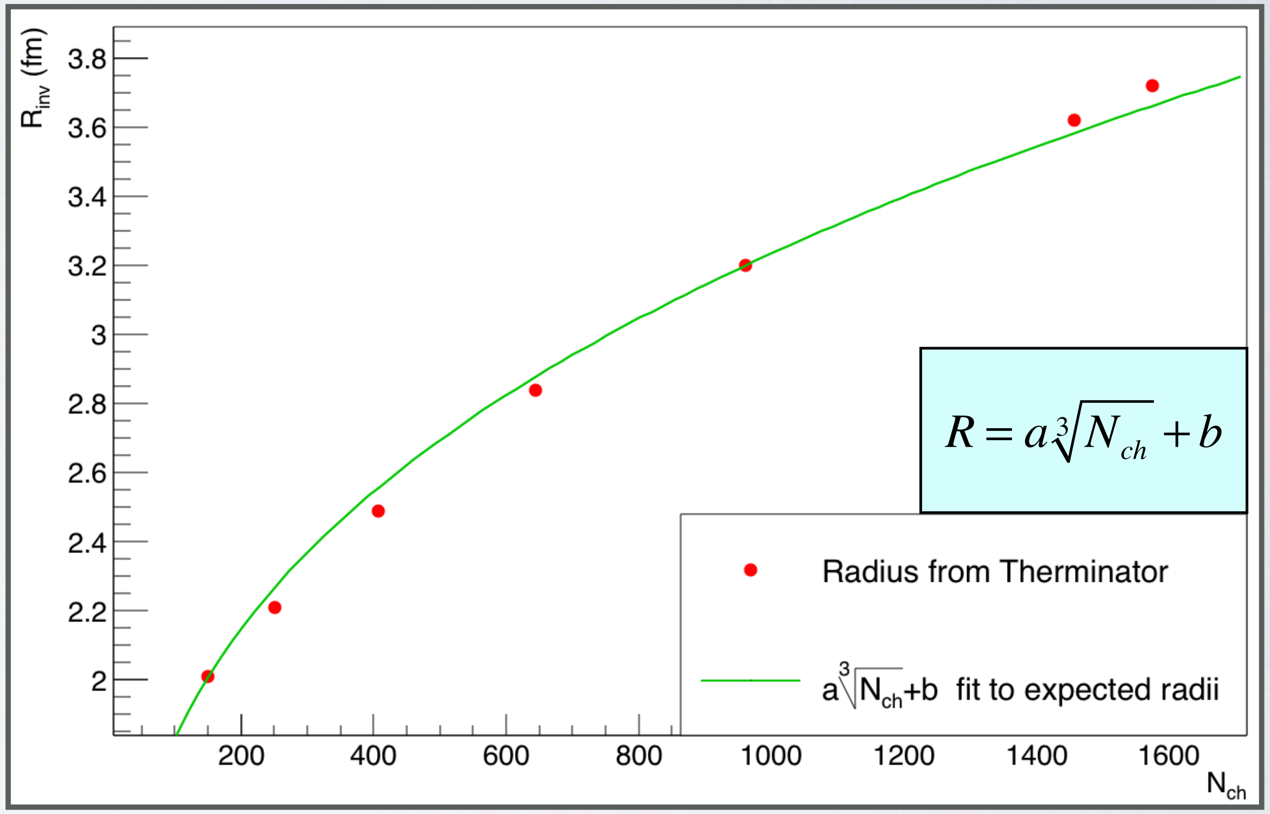
SOURCE SIZES

- For different particle pairs, we assume approximate **scaling with m_T** (transverse mass):



- Data for ππ, KK and pp come from previous ALICE measurements,
- Assume that $R_{b\bar{b}} = R_{bb}$.
- We extract $b\bar{b}$ radii from fit to the data.

- For different centralities, we assume that source sizes **scale with multiplicity**:

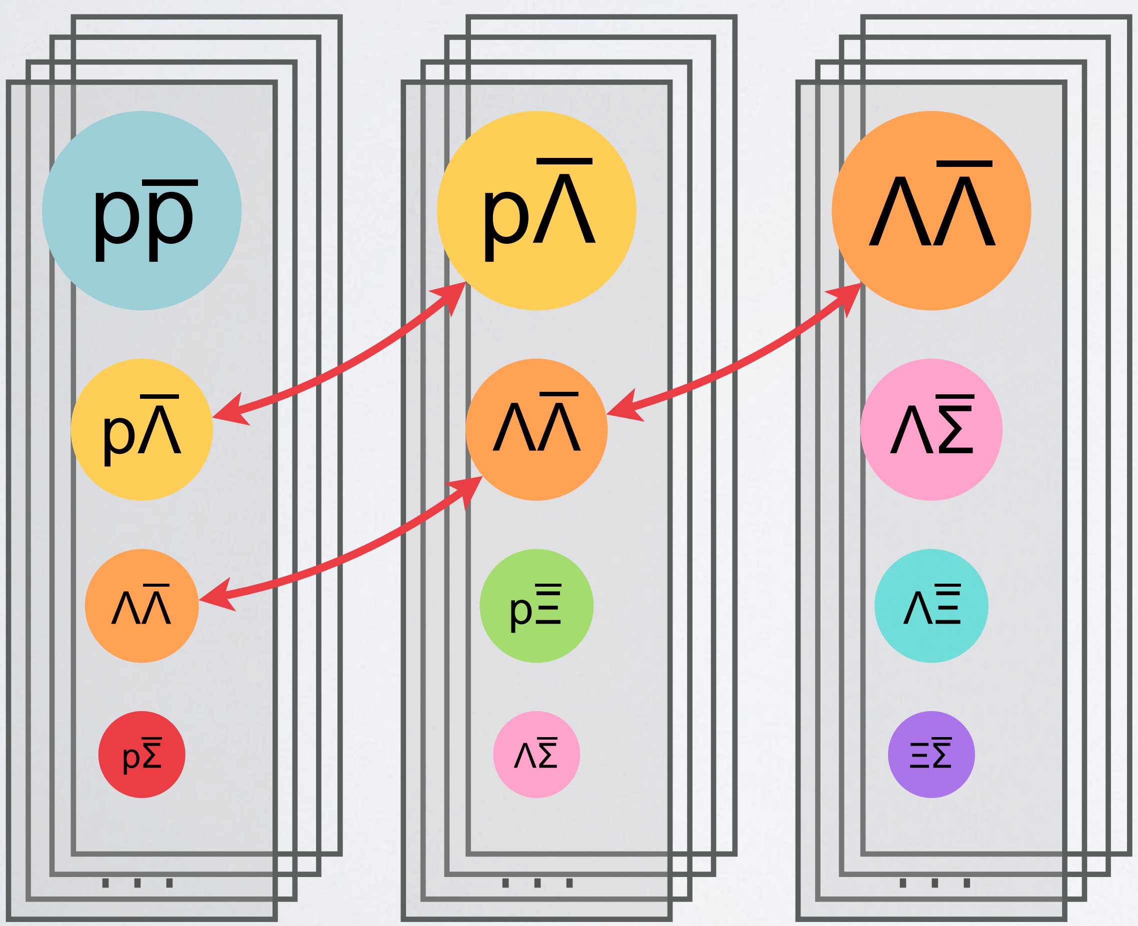


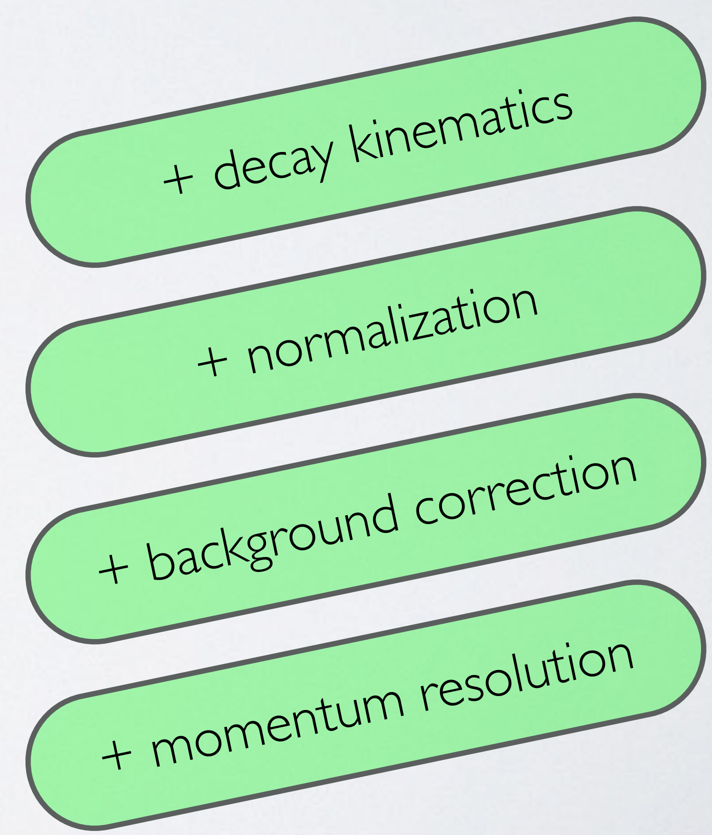
- Radius set for one centrality, then scaled for all others using calculated multiplicities for each centrality bin.

FITTING PROCEDURE

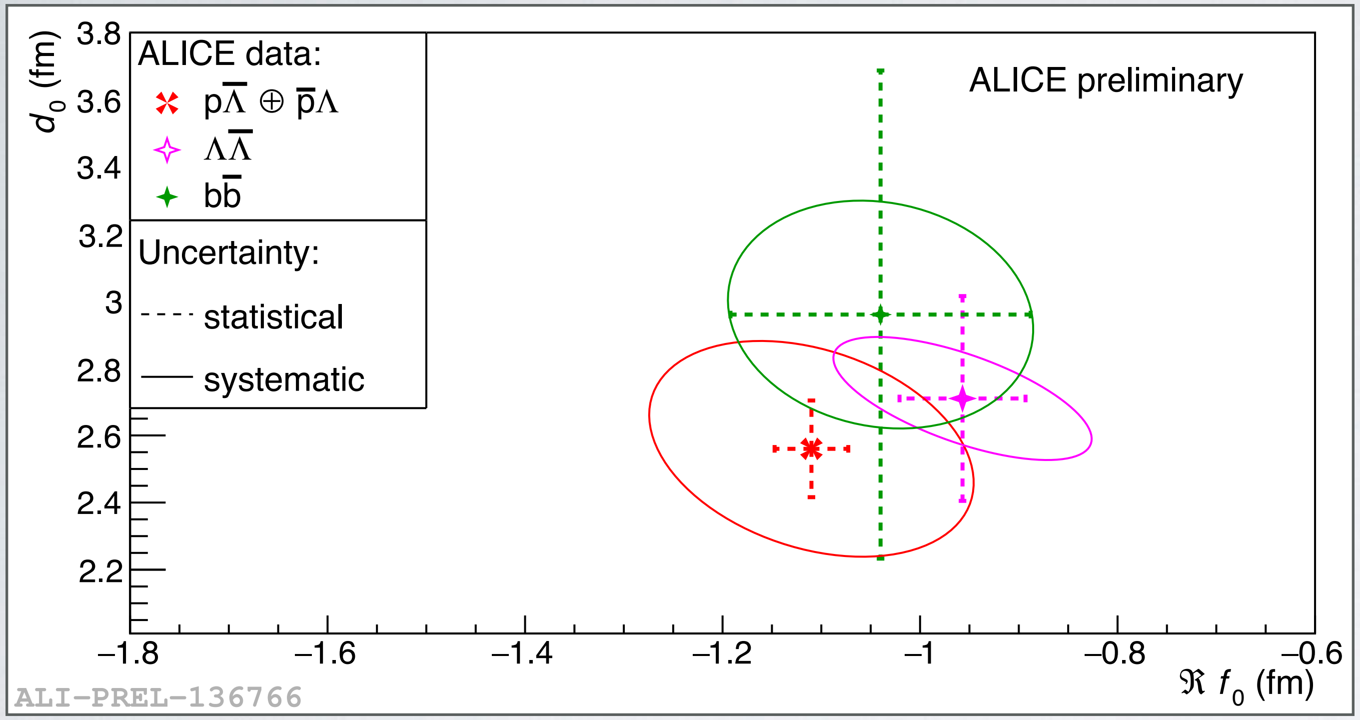
SUMMARY

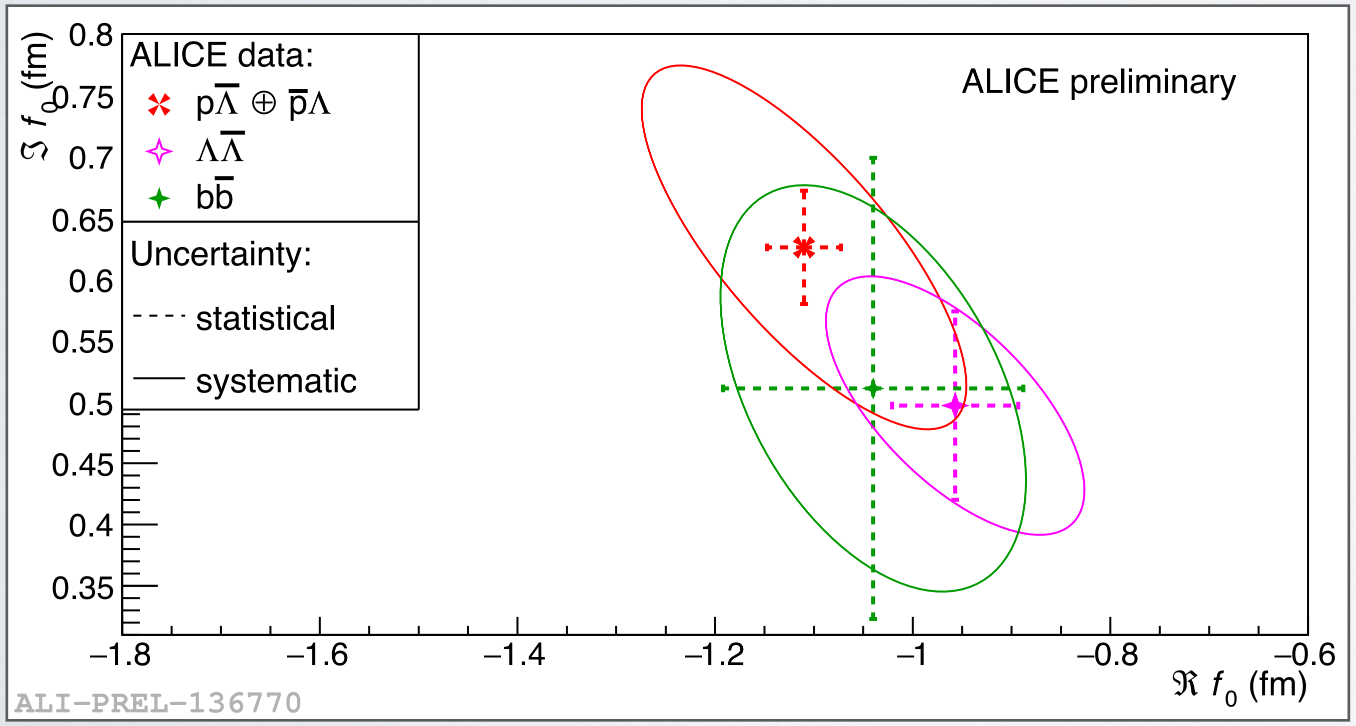
- χ^2 calculated for **36 functions**,
- **residual correlations** taken into account,
- radii **scaling with multiplicity** for different centrality bins,
- radii **scaling with m_T** for different pairs (including residual ones),
- **3 sets** of interaction parameters ($\Re f_0$, $\Im f_0$, d_0) for $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$ and heavier $b\bar{b}$ pairs,
- parameters **shared** between systems.





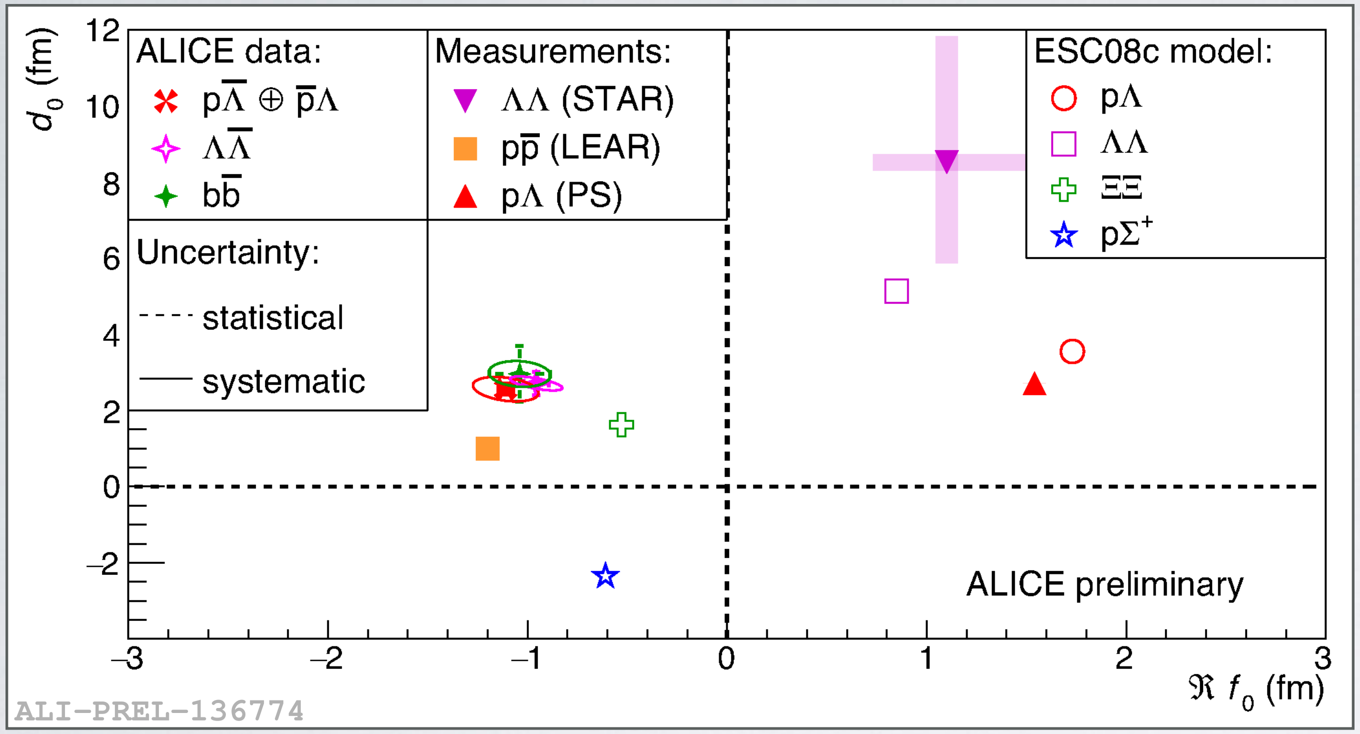
MEASURED INTERACTION PARAMETERS

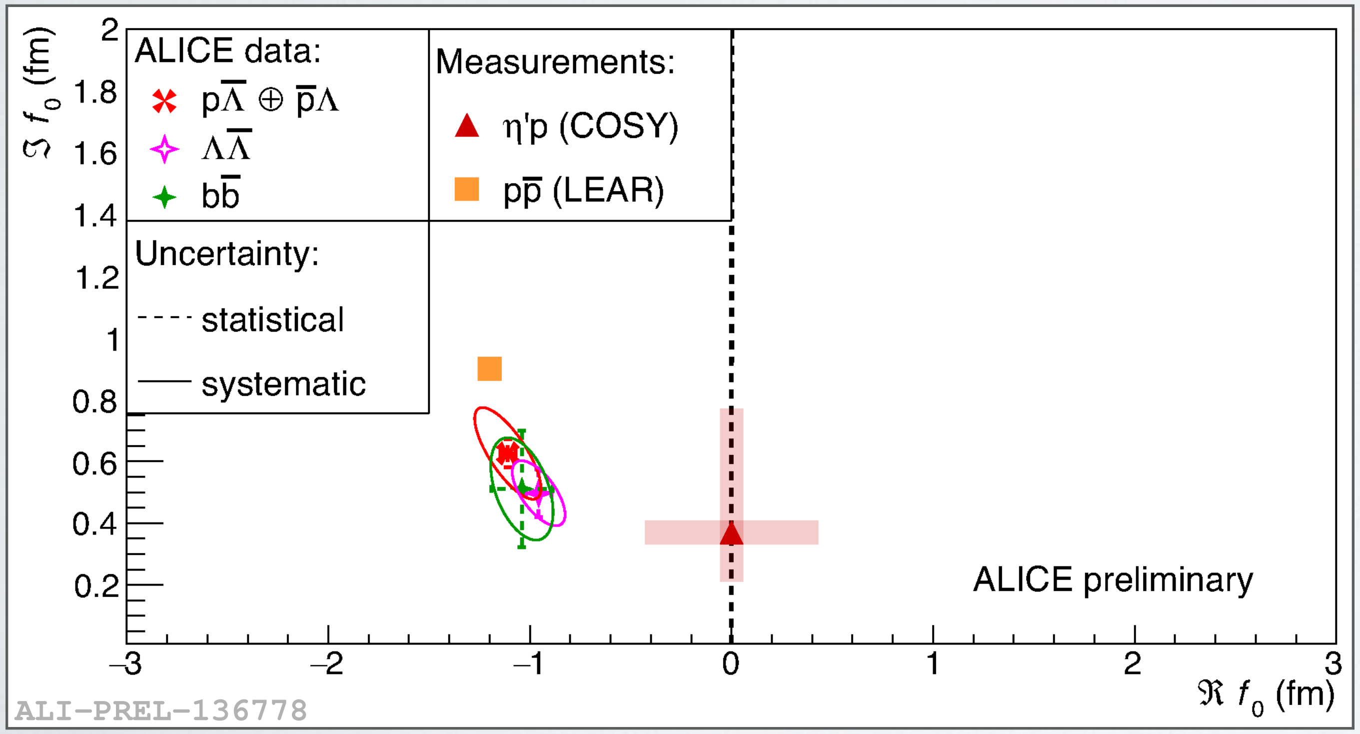




- **Combined fit** of $p\bar{p}$, $p\bar{\Lambda}$ and $\Lambda\bar{\Lambda}$ performed for the first time.
- we have measured 3 sets of parameters - for $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$ and effective parameters for heavier $b\bar{b}$.
- we have good **precision** relative to other measurements,
- values are similar for all measured pairs,
- results for $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$ and $b\bar{b}$ **similar to $p\bar{p}$**,
- $\Im$ **f_0 is non-zero** for all $b\bar{b}$ pairs,
- $\Re$ **f_0 is negative** for all $b\bar{b}$ pairs.

MEASURED INTERACTION PARAMETERS





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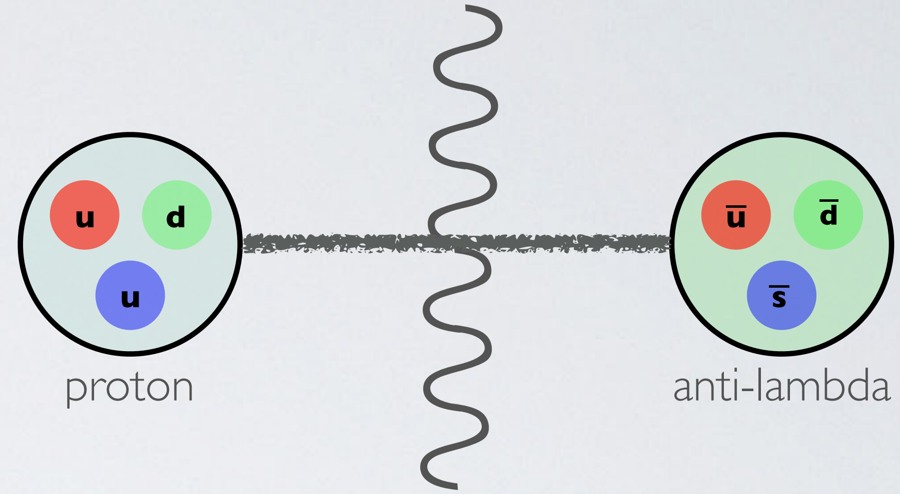
- $\Im$ **f_0 is non-zero** for all $b\bar{b}$ pairs,
- $\Re$ **f_0 is negative** for all $b\bar{b}$ pairs.

INTERPRETATION OF RESULTS

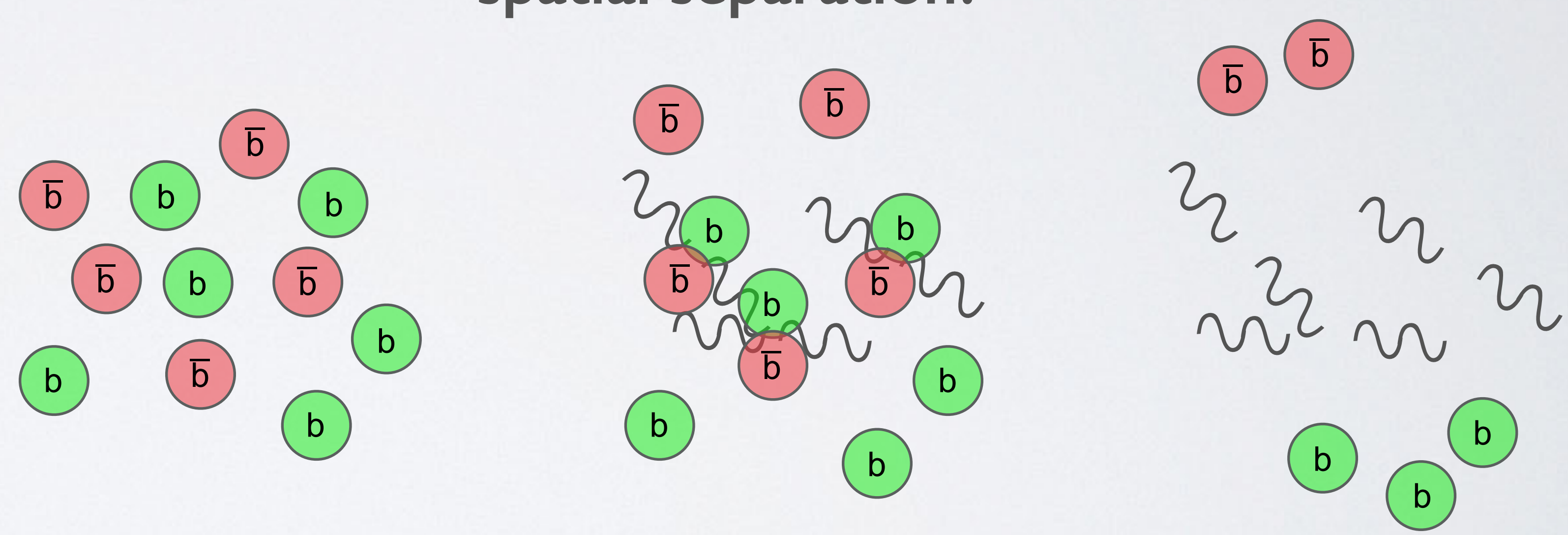
$\mathfrak{I}\, f_0$ non-zero → **annihilation**

(even for non-identical $b\bar{b}$ pairs, such as $p\bar{\Lambda}$!)

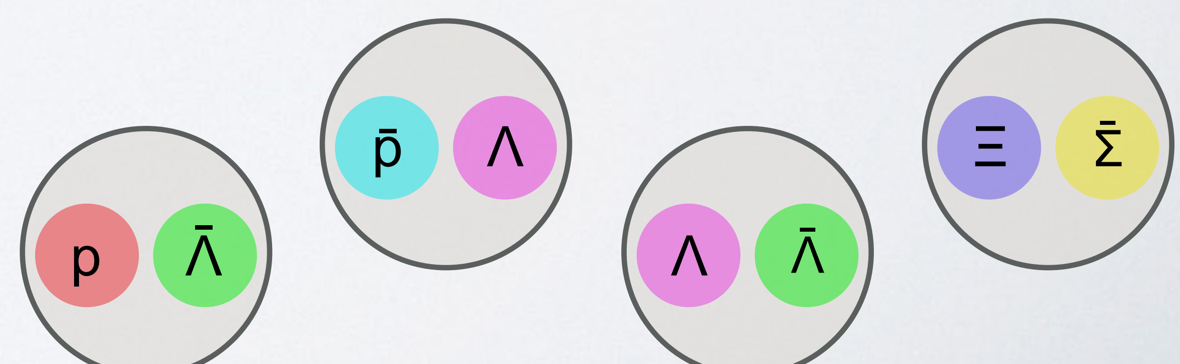


$\mathfrak{R}\, f_0$ negative

repulsion → **spatial separation?**

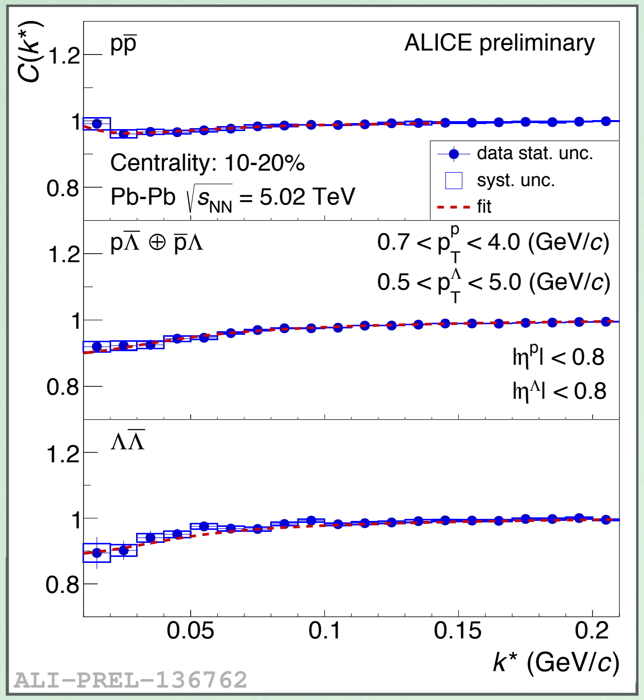


bound states?

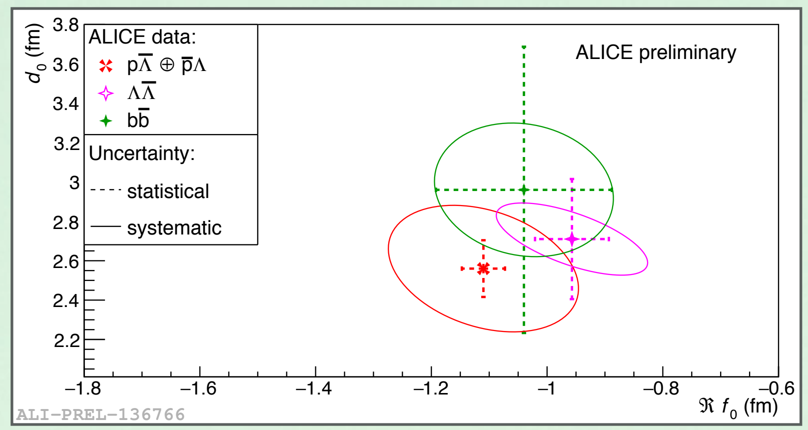


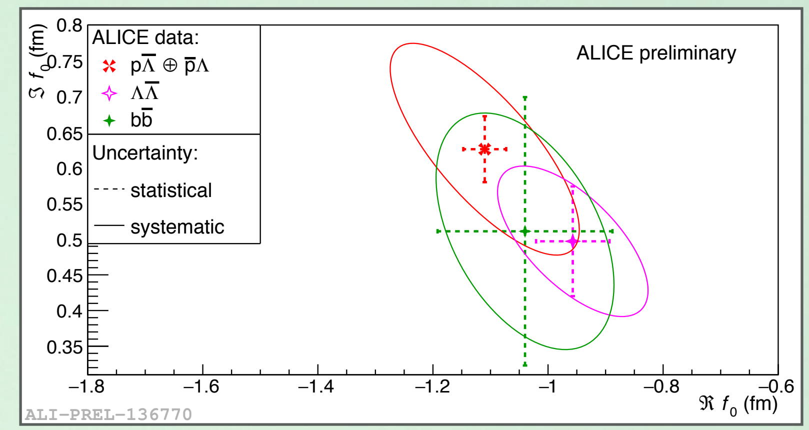
Conclusions

- femtoscopy is a powerful tool capable of measuring the strong interaction



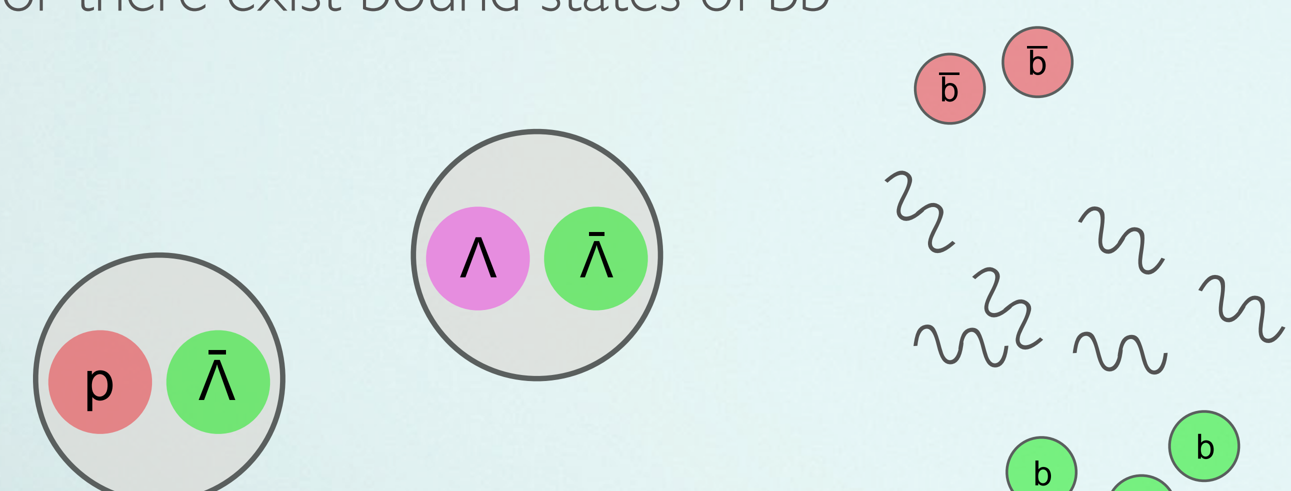
- pp, pp̄, pΛ, pΛ̄, ΛΛ, ΛΛ̄ correlations functions were measured by ALICE at 2.76 and 5.02 TeV
- this type of analysis was performed for the first time



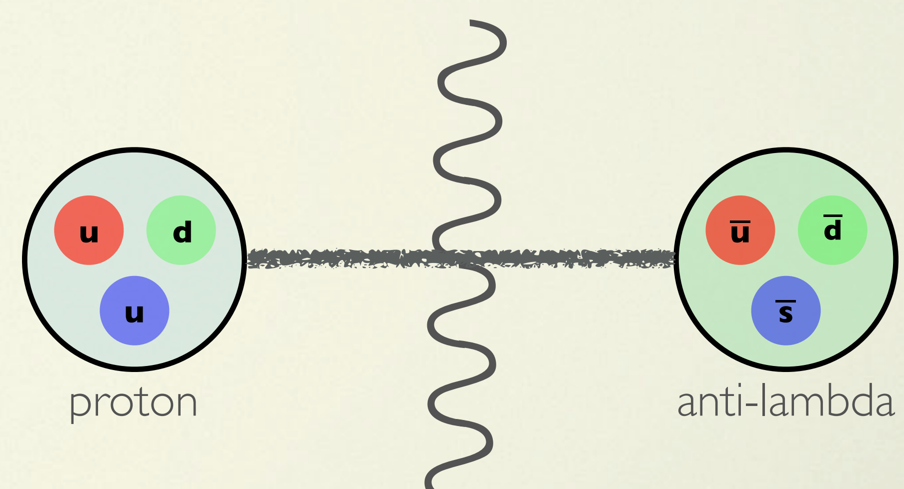


- scattering parameters ($\Re\, f_0$, $\Im\, f_0$ and d_0) were extracted for pΛ̄, ΛΛ̄ and heavier bb̄ pairs

- either strong interaction is repulsive for bb̄ pairs, or there exist bound states of bb̄



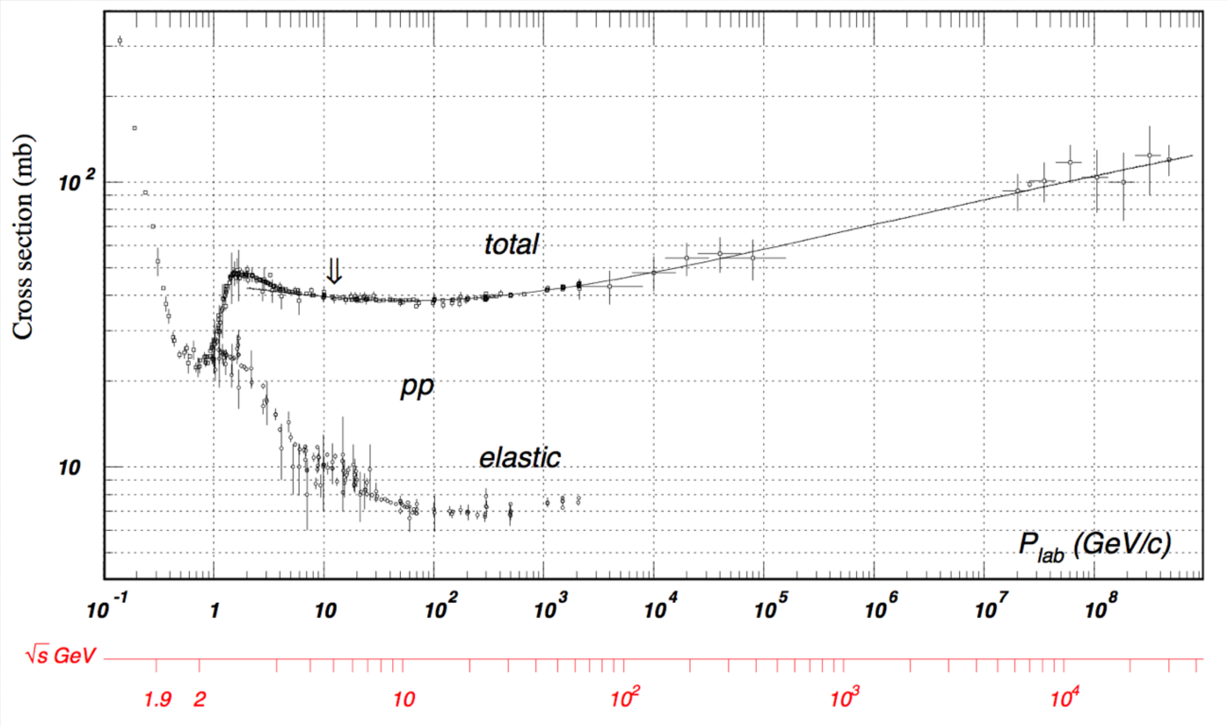
- annihilation is present and has similar magnitude for all bb̄ pairs

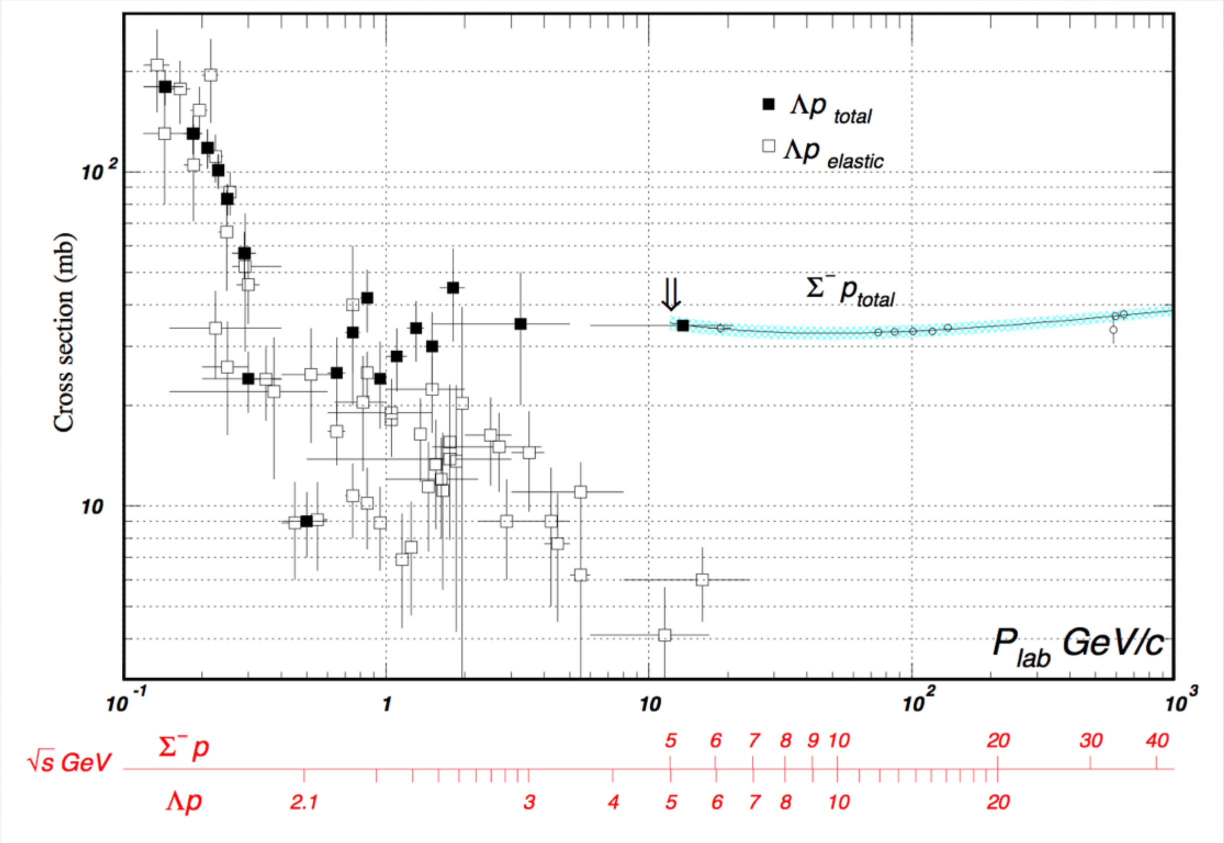


Backup

CUTS

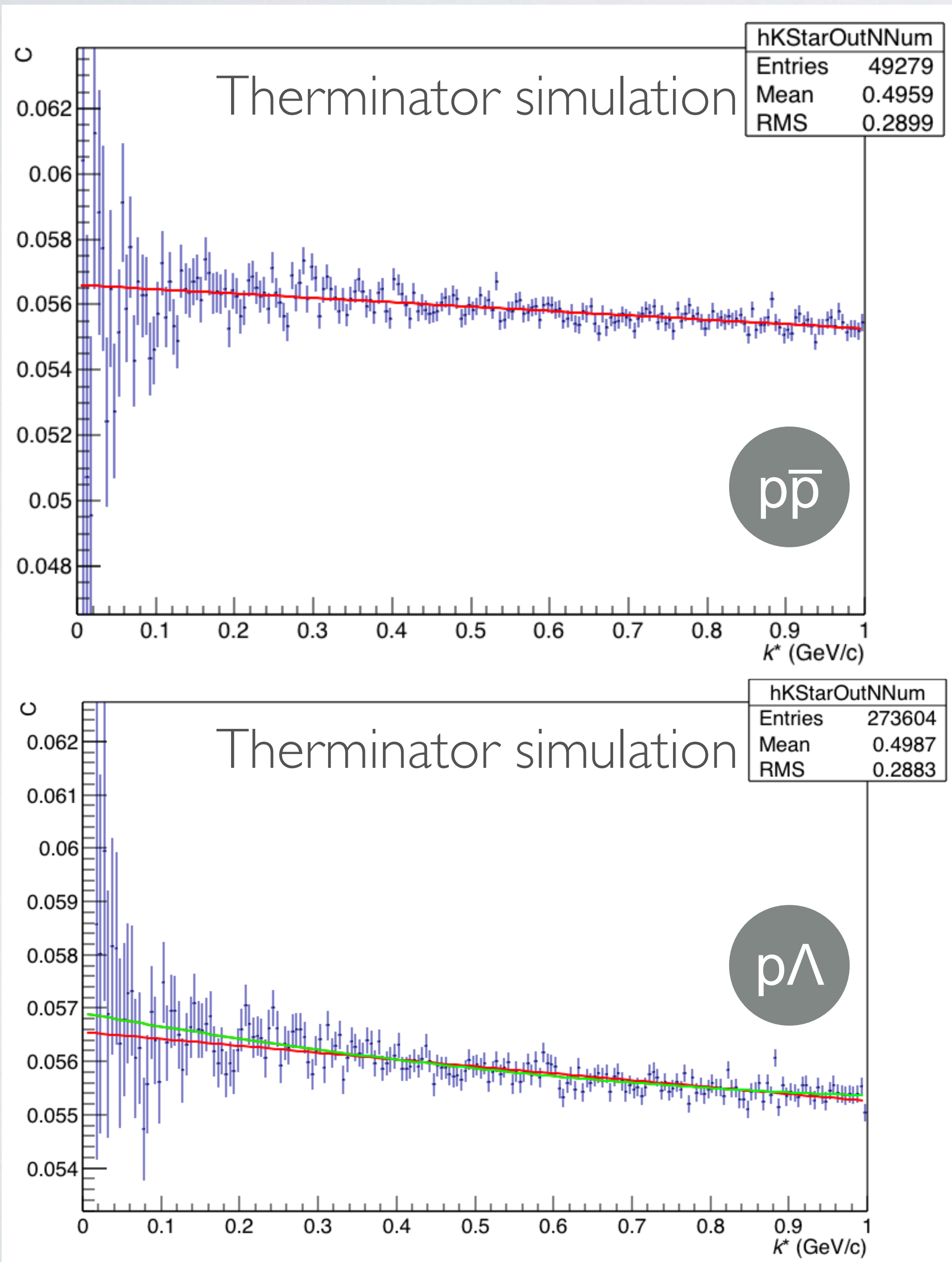
- Event, tracks and pair **cuts** were directly taken from previously approved analyses:
  - *Two-proton correlations in Pb-Pb collisions at* $\sqrt{s_{NN}}$*=2.76 TeV from the ALICE experiment at the LHC* (paper)
  - *Proton-lambda correlations in Pb-Pb collisions at* $\sqrt{s_{NN}}$*=2.76 TeV in the ALICE experiment* (preliminary, QM)
  - *Two-Lambda femtoscopy correlations in PbPb collisions at* $\sqrt{s_{NN}}$ *= 2.76 TeV from the ALICE experiment* (preliminary, QM)
  - One-dimensional pion, kaon, and proton femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV (arxiv.org/abs/1506.07884)





DESCRIPTION OF THE PROCEDURE

- **Background** removing procedure:



- Correlation functions were generated from Therminator, excluding all femtoscopic interactions,
- fits with different form of the background were performed (linear, quadratic, 3rd and 4th order polynomials),
- quadratic function was chosen and fitted to the experimental data for k^* from 0.15-0.30 to 0.80 GeV/c (depending on the system),
- fitted background was subtracted from the CF before fitting,
- influence of the choice of the background function is taken into account in systematic uncertainties studies.

Description of the procedure

Momentum resolution correction:

- for each pair and each centrality a matrix of q_{gen} vs. q_{rec} was generated,
- for each slice in q_{rec} a gaussian fit was done,
- dependance of σ_{mr} vs. q_{rec} was plotted,
- as it is almost constant, the average width was taken for fit function smearing.

Average σ_{mr} (k^* frame)		
Pair	2011 data (LHC12a17b)	2015 data (LHC16g1)
pp	0,010	0,010
$p\bar{p}$	0,010	0,010
$p\Lambda$	0,010	0,010
$p\bar{\Lambda}$	0,010	0,010
$\Lambda\Lambda$	0,009	0,009
$\Lambda\bar{\Lambda}$	0,009	0,009

Momentum resolution correction is crucial for proper analysis - it affects shape of the correlation function very significantly.

Description of the procedure

- Residual correlation **fractions** from AMPT or HIJING:

Pair	HIJING	AMPT
pp	0.35	0.25
pΛ	0.17	0.12
$\Lambda\Lambda$	0.02	0.02
pΣ^+	0.04	0.04
$\Lambda\Sigma^+$	0.01	0.01
$\Sigma^+\Sigma^+$	0.00	0.00

Pair	HIJING	AMPT
pΛ	0.36	0.29
$\Lambda\Lambda$	0.07	0.08
pΞ^-	0.04	0.02
pΞ^0	0.03	0.02
$\Lambda\Xi^-$	0.01	0.00
$\Lambda\Xi^0$	0.01	0.00
$\Lambda\Sigma^+$	0.02	0.03
$\Xi^0\Sigma^+$	0.00	0.00
$\Xi^-\Sigma^+$	0.00	0.00
$\Lambda\Sigma^0$	0.04	0.00
pΣ^0	0.19	0.00
$\Sigma^+\Sigma^0$	0.01	0.00

Pair	HIJING	AMPT
$\Lambda\Lambda$	0.21	0.37
$\Lambda\Xi^0$	0.04	0.03
$\Lambda\Xi^-$	0.05	0.04
$\Xi^0\Xi^0$	0.00	0.00
$\Xi^0\Xi^-$	0.00	0.00
$\Xi^-\Xi^-$	0.00	0.00
$\Lambda\Sigma^0$	0.22	0.00
$\Xi^0\Sigma^0$	0.02	0.00
$\Xi^-\Sigma^0$	0.03	0.00
$\Sigma^0\Sigma^0$	0.06	0.00

2011

Centrality	$dN_{ch}/d\eta$	$\langle N_{part} \rangle$	$(dN_{ch}/d\eta)/(\langle N_{part} \rangle/2)$
0–5%	1601 ± 60	382.8 ± 3.1	8.4 ± 0.3
5–10%	1294 ± 49	329.7 ± 4.6	7.9 ± 0.3
10–20%	966 ± 37	260.5 ± 4.4	7.4 ± 0.3
20–30%	649 ± 23	186.4 ± 3.9	7.0 ± 0.3
30–40%	426 ± 15	128.9 ± 3.3	6.6 ± 0.3
40–50%	261 ± 9	85.0 ± 2.6	6.1 ± 0.3
50–60%	149 ± 6	52.8 ± 2.0	5.7 ± 0.3
60–70%	76 ± 4	30.0 ± 1.3	5.1 ± 0.3
70–80%	35 ± 2	15.8 ± 0.6	4.4 ± 0.4

0-5%: 1601
5-10%: 1294
10-20%: 966
20-30%: 649
30-40%: 426
40-50%: 261

https://arxiv.org/pdf/1012.1657.pdf

2015

Centrality	$\langle dN_{ch}/d\eta \rangle$	$\langle N_{part} \rangle$	$\frac{2}{\langle N_{part} \rangle} \langle dN_{ch}/d\eta \rangle$
0–2.5%	2035 ± 52	398 ± 2	10.2 ± 0.3
2.5–5.0%	1850 ± 55	372 ± 3	9.9 ± 0.3
5.0–7.5%	1666 ± 48	346 ± 4	9.6 ± 0.3
7.5–10%	1505 ± 44	320 ± 4	9.4 ± 0.3
10–20%	1180 ± 31	263 ± 4	9.0 ± 0.3
20–30%	786 ± 20	188 ± 3	8.4 ± 0.3
30–40%	512 ± 15	131 ± 2	7.8 ± 0.3
40–50%	318 ± 12	86.3 ± 1.7	7.4 ± 0.3
50–60%	183 ± 8	53.6 ± 1.2	6.8 ± 0.3
60–70%	96.3 ± 5.8	30.4 ± 0.8	6.3 ± 0.4
70–80%	44.9 ± 3.4	15.6 ± 0.5	5.8 ± 0.5

0-5%: 1923
5-10%: 1586
10-20%: 1180
20-30%: 786
30-40%: 512
40-50%: 318

https://arxiv.org/pdf/1512.06104.pdf

- Baryon-baryon **scattering parameters** from ESC08c:

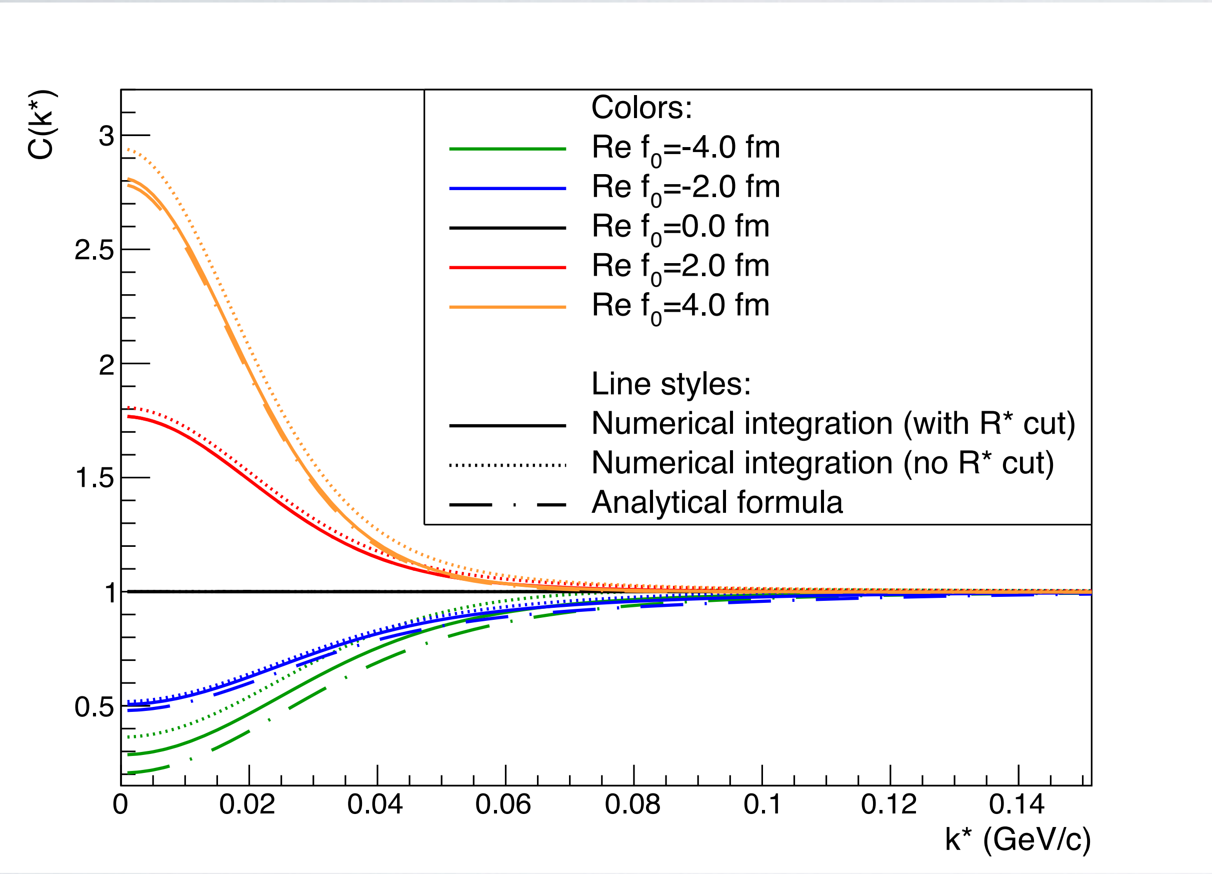
Pair	$f_0^s\ (fm)$	$d_0^s\ (fm)$	$f_0^t\ (fm)$	$d_0^t\ (fm)$
$p\Lambda$	2.46	3.14	1.73	3.55
$\Lambda\Lambda$	-	-	0.85	5.13
$p\Xi^{0/-}$	-0.56	-2.52	5.36	1.43
$\Lambda\Xi^{0/-}$	9.83	2.38	12.90	2.00
$\Xi^{0/-}\Xi^{0/-}$	7.25	2.00	-0.53	1.63
$p\Sigma^+$	3.91	3.41	-0.61	-2.35
$\Xi^{0/-}\Sigma^{+/0}$	2.80	2.46	10.90	1.92
$\Sigma^+\Sigma^+$	-	-	0.65	19.97
$\Lambda\Sigma^{+/0}$	from $\Lambda\Lambda$			
$\Sigma^0\Sigma^0$	from $\Lambda\Lambda$			
$p\Sigma^0$	from $p\Lambda$			
$\Sigma^0\Sigma^+$	from $\Lambda\Lambda$			

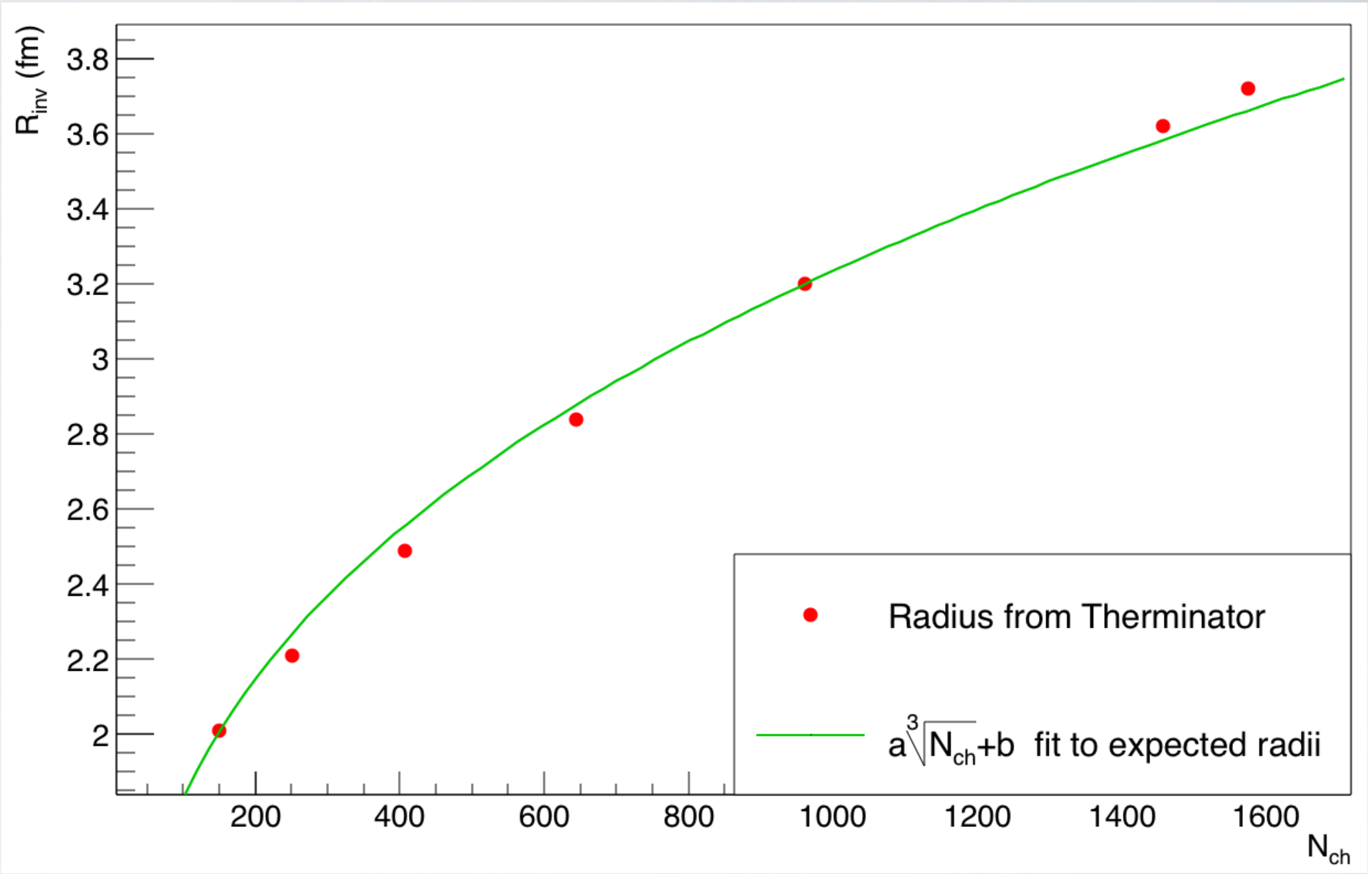
Extended-soft-core Baryon-Baryon Model ESC08 I. Nucleon-Nucleon Scattering
https://arxiv.org/abs/1408.4825

Extended-soft-core Baryon-Baryon Model Esc08 II. Hyperon-Nucleon Interactions
https://arxiv.org/abs/1501.06636

Extended-soft-core baryon-baryon model III: S=-2 hyperon-hyperon/nucleon interaction
https://arxiv.org/abs/1504.02634

Recent Nijmegen Extended-Soft-Core ESC08-models
http://www.phys.kyushu-u.ac.jp/fb20/PresentationFiles/Plenary/FB20_Rijken.pdf





Parameter	$b\bar{b}$	$\bar{p}\Lambda \oplus p\bar{\Lambda}$	$\Lambda\bar{\Lambda}$
$\Re f_0\ (fm)$	$-1.04^{\pm 0.24(syst)}_{\pm 0.15(stat)}$	$-1.11^{\pm 0.18(syst)}_{\pm 0.04(stat)}$	$-0.96^{\pm 0.16(syst)}_{\pm 0.06(stat)}$
$\Im f_0\ (fm)$	$0.51^{\pm 0.30(syst)}_{\pm 0.19(stat)}$	$0.63^{\pm 0.15(syst)}_{\pm 0.05(stat)}$	$0.50^{\pm 0.13(syst)}_{\pm 0.08(stat)}$
$d_0\ (fm)$	$2.96^{\pm 0.52(syst)}_{\pm 0.73(stat)}$	$2.56^{\pm 0.55(syst)}_{\pm 0.14(stat)}$	$2.71^{\pm 0.26(syst)}_{\pm 0.31(stat)}$