Femtoscopic measurement of proton source in hadronic collisions with ALICE

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ALICE

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INFN Istituto Nazionale di Fisica Nucleare

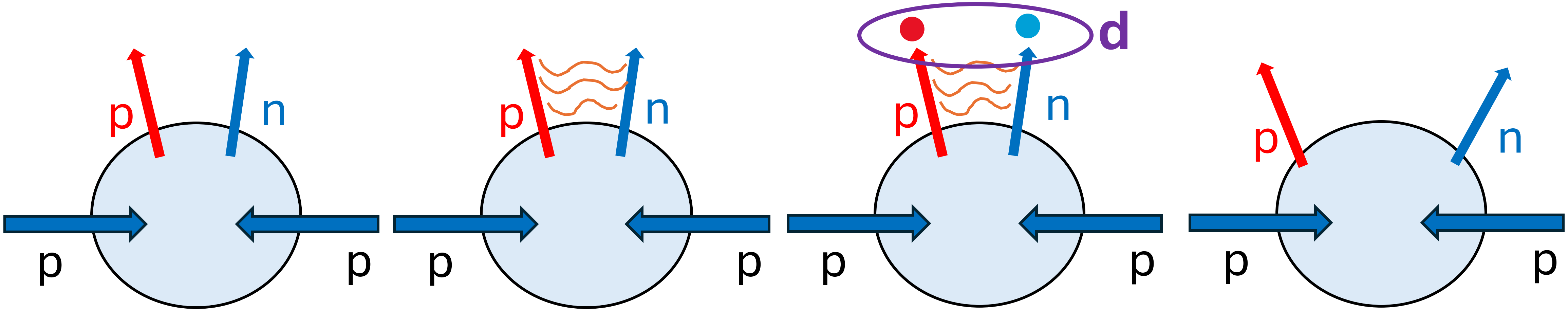
CosmicAntiNuclei

erc European Research Council Established by the European Commission

MOTIVATION: modelling formation of (anti)deuteron through coalescence

The formation mechanism of deuterons in high–energy collisions is still not well understood.
It can be constrained using data from hadronic collisions at the LHC.

In **coalescence** models, nucleons **close in phase space at the freeze–out can bind into nuclei due to the strong interaction in the final state.** [J. I. Kapusta Phys. Rev. C 21, 1301 (1980)]



The probability B_d of forming a deuteron (d) with momentum p by coalescence is:

$$B_d(p) \propto \int d^3\boldsymbol{r}^* |\varphi_d(\boldsymbol{r}^*)|^2 S(\boldsymbol{r}^*, R_{\text{inv}})$$

Nucleons relative distance $\boldsymbol{r}^*$
Source size R_{inv}

It depends on:

- the internal deuteron structure (known)
- the spatial distribution of nucleons in the source (unknown)

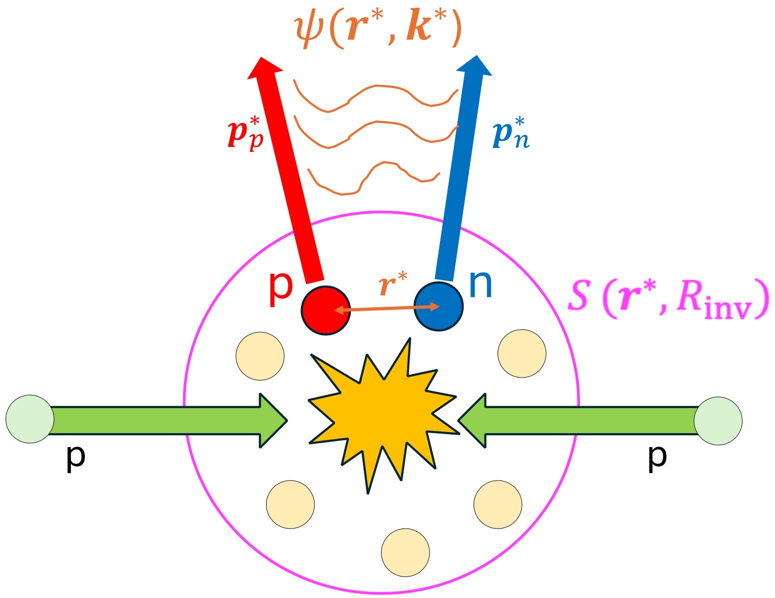
[Mahlein, M. et al., Eur. Phys. J. C 83, 804 (2023)]
[Bellini, F. et al., Phys. Rev. C 103, 014907 (2021)]

The femtoscopic technique

The femtoscopic technique is used to describe the particle–emitting source by measuring **correlations in momentum** among nucleon pairs. The **correlation function** C^{th} is defined as:

$$C^{th}(\boldsymbol{k}^*) = \int d^3\boldsymbol{r}^* \,|\,\psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2 S\,(\boldsymbol{r}^*, R_{\rm inv})$$

Relative distance $\boldsymbol{r^*} = \boldsymbol{r^*}_p - \boldsymbol{r^*}_n$
Relative momentum $\boldsymbol{k^*} = ½\,|\,\boldsymbol{p^*}_p - \boldsymbol{p^*}_n\,|$
measured in the pair rest frame.



Pair wave function, $\psi(\boldsymbol{r}^*, \boldsymbol{k}^*)$:
→ Solution of the Schrödinger equation for a given **interaction potential** for a particle pair.

Source function, $S(\boldsymbol{r}^*, R_{\rm inv})$:
→ Considering a Gaussian source profile, the p.d.f. of finding two nucleons at a relative distance $\boldsymbol{r^*}$ distributed with standard deviation $\boldsymbol{R_{\rm inv}}$.

$$C^{th}(\boldsymbol{k}^*) \begin{cases} < 1 \text{ if the interaction is repulsive} \\ = 1 \text{ if there is no correlation (for } \boldsymbol{k^*} \rightarrow +\infty) \\ > 1 \text{ if the interaction is attractive} \end{cases}$$

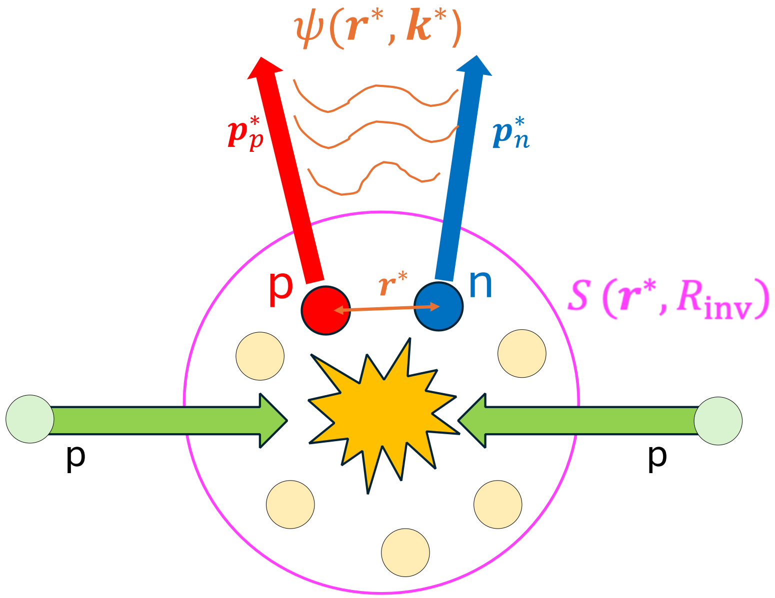
[L. Fabbietti, Ann. Rev. Nucl. Part. Sci. (2021) 71:377-402]

The femtoscopic technique

The experimental correlation function C^{exp} is measured from the distribution of nucleon pairs:

$$C^{exp}(\boldsymbol{k}^*) = N\frac{SE(\boldsymbol{k}^*)}{ME(\boldsymbol{k}^*)} = 1 + \lambda(C^{th}(\boldsymbol{k}^*) - 1)$$

Relative distance $\boldsymbol{r^*} = \boldsymbol{r^*_p} - \boldsymbol{r^*_n}$
Relative momentum $\boldsymbol{k^*} = \frac{1}{2}\,|\,\boldsymbol{p^*_p} - \boldsymbol{p^*_n}\,|$
measured in the pair rest frame.

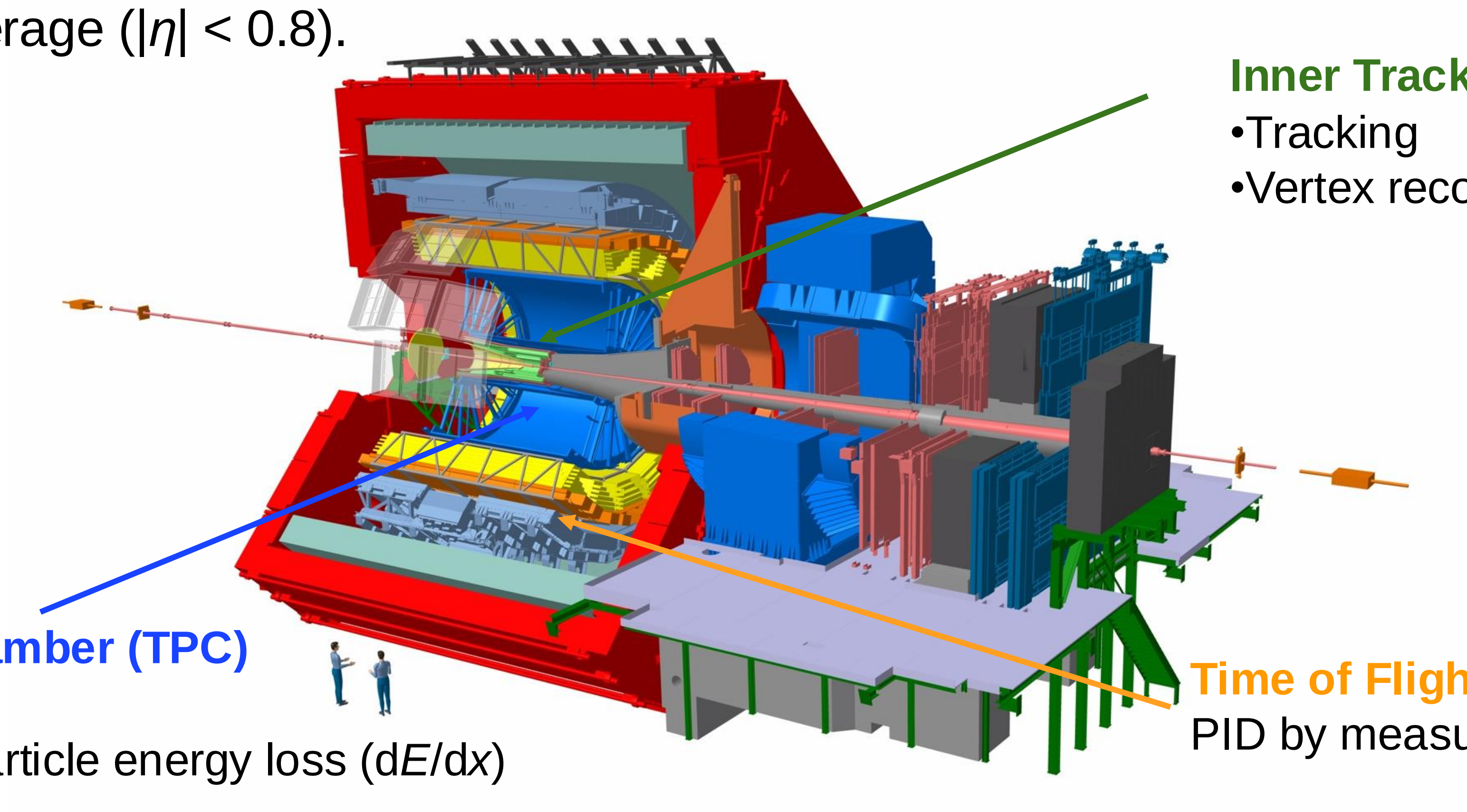


- SE: same event pairs
- ME: mixed event pairs (uncorrelated)
- $\boldsymbol{N}$: normalization factor calculated outside of the femtoscopic signal region
- λ : correlation strength, related to correlations from misidentified or non-primary proton pairs (non-genuine correlations) and to non–gaussianity of the source.

The ALICE detector in Run 3

A Large **I**on **C**ollider **E**xperiment detector has optimal characteristics for femtoscopic analysis:

- Optimal Particle Identification (PID) capabilities down to low momenta (≈ 150 MeV/c);
- Optimal track and vertex reconstruction;
- Mid-rapidity coverage ($|\eta| < 0.8$).



Inner Tracking System (ITS)
•Tracking
•Vertex reconstruction

Time Projection Chamber (TPC)
•Tracking
•PID by measuring particle energy loss (dE/dx)

Time of Flight (TOF)
PID by measuring the time of flight

[ALICE Coll., JINST 19 (2024) P05062]

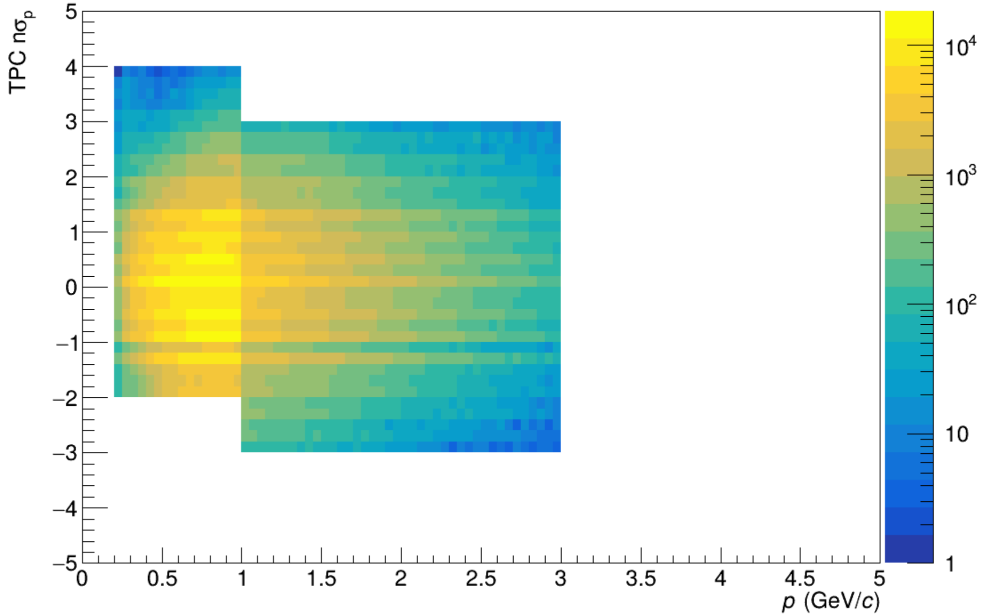
Analysis Details:

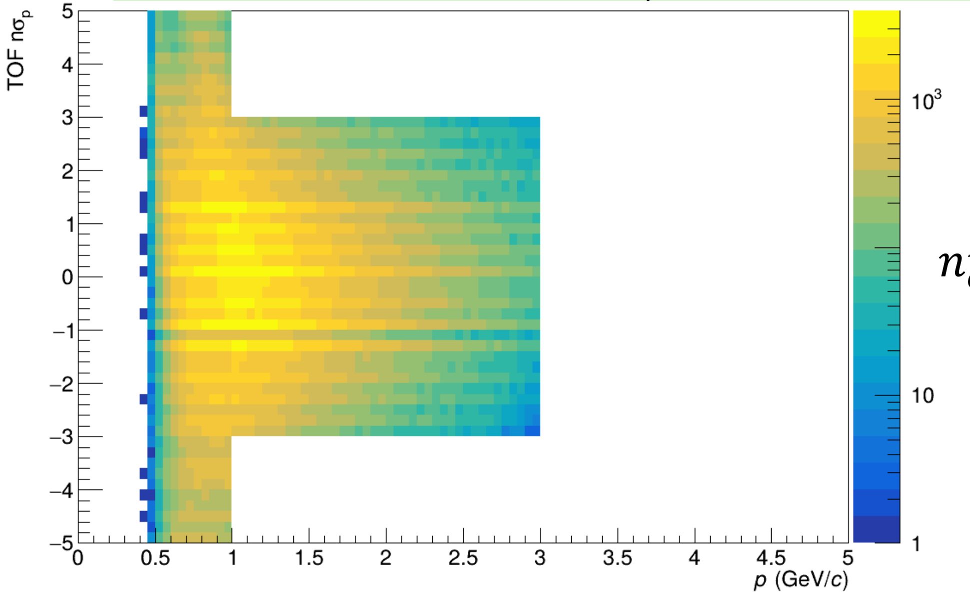
Event selection: Distance from primary vertex - $10 < V_z$ (cm) < 10
→ Selected 74 M (over 88 M in 2022 data sample)

Track Selection:
0.2 GeV/c < p < 3.0 GeV/c
$|\eta| < 0.8$
$|DCA_{xy}| < 0.004 + 0.013/pT$ (cm)
$|DCA_z| < 0.004 + 0.013/pT$ (cm)

Particle Identification:

p range	**TPC PID**	**TOF PID**
$0.2 \leq p$ (GeV/*c*) ≤ 1.0	$-2 < n_\sigma(p) < 4$	OFF
$1.0 \leq p$ (GeV/*c*) ≤ 3.0	$-3 < n_\sigma(p) < 3$	$-3 < n_\sigma(p) < 3$
full momentum region		reject track if $\|n_\sigma(\pi)\|<5.0$ || $\|n_\sigma(K)\|<5.0$





$$n_{\sigma,i}^{DET} = \frac{X_{meas}^{DET} - X_{exp,i}^{DET}}{\sigma^{DET}}$$

Pairing tracks:

Selected sample:
2.24M protons and 1.84M antiprotons

Selected tracks are paired to calculate the experimental CF

$$C^{exp}(\boldsymbol{k}^*) = N\frac{SE(\boldsymbol{k}^*)}{ME(\boldsymbol{k}^*)}$$

For SE tracks are paired within the same event

N calculated in k* = [0.24; 0.34] GeV/c

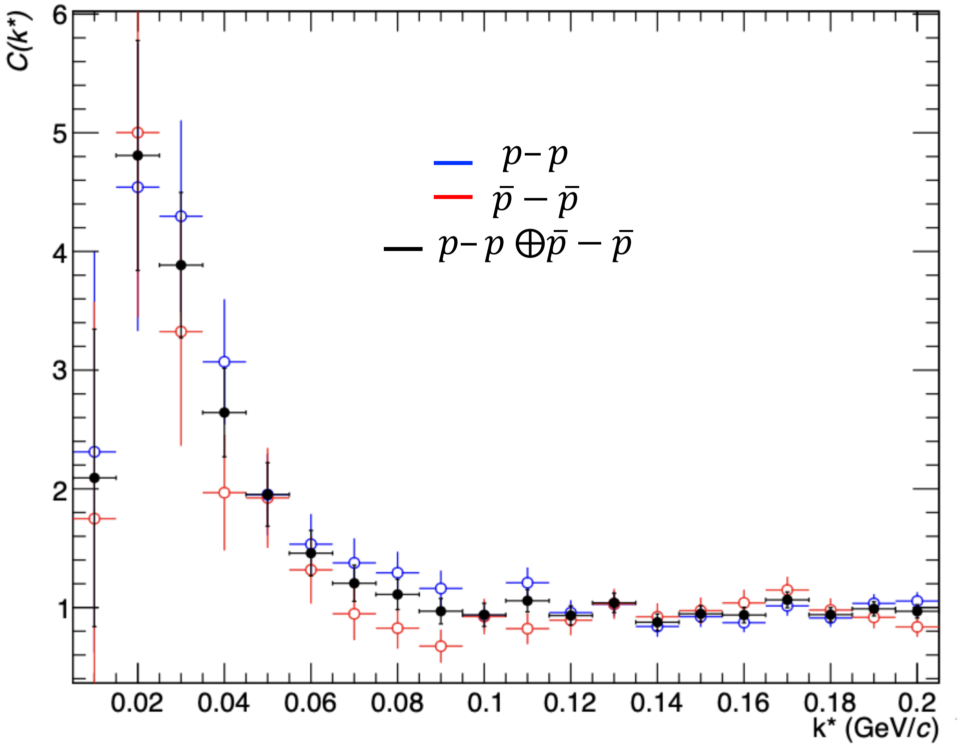
For ME Events are mixed using

- 10 equidistant bins within the full selected centrality/multiplicity percentile range
- 10 equidistant bins within the full selected Vz range [-10cm , 10 cm]

We require tracks in SE and ME to be separated more than 3 cm in TPC, to reduce merging and splitting effects

Number of pairs used

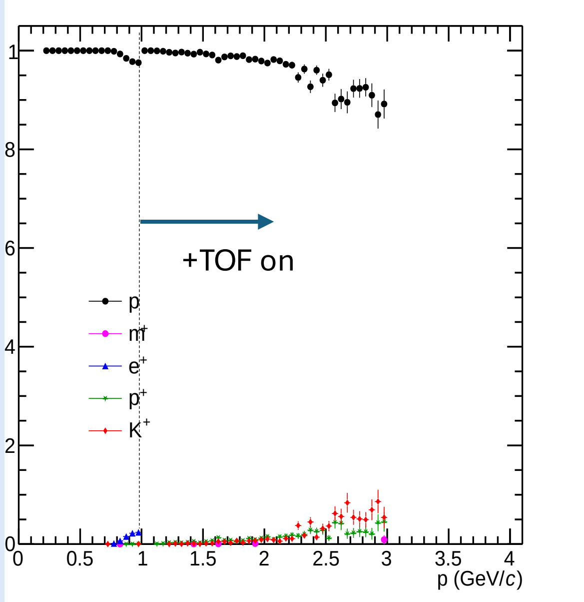
	same event	mixed event
p–p	34809	10^9
pbar–pbar	22311	10^9

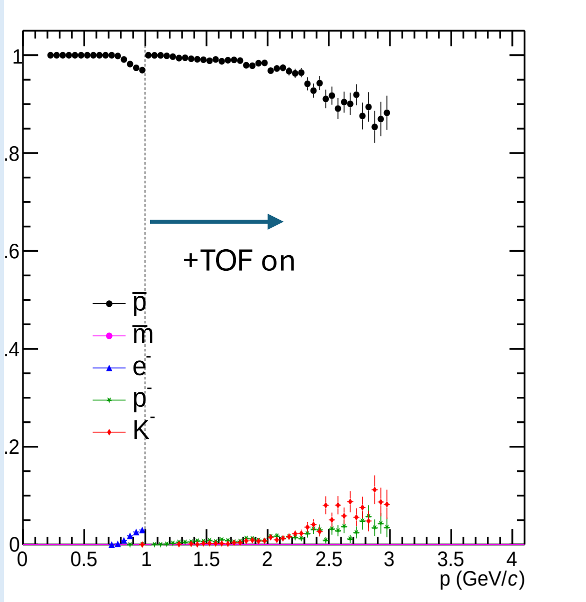


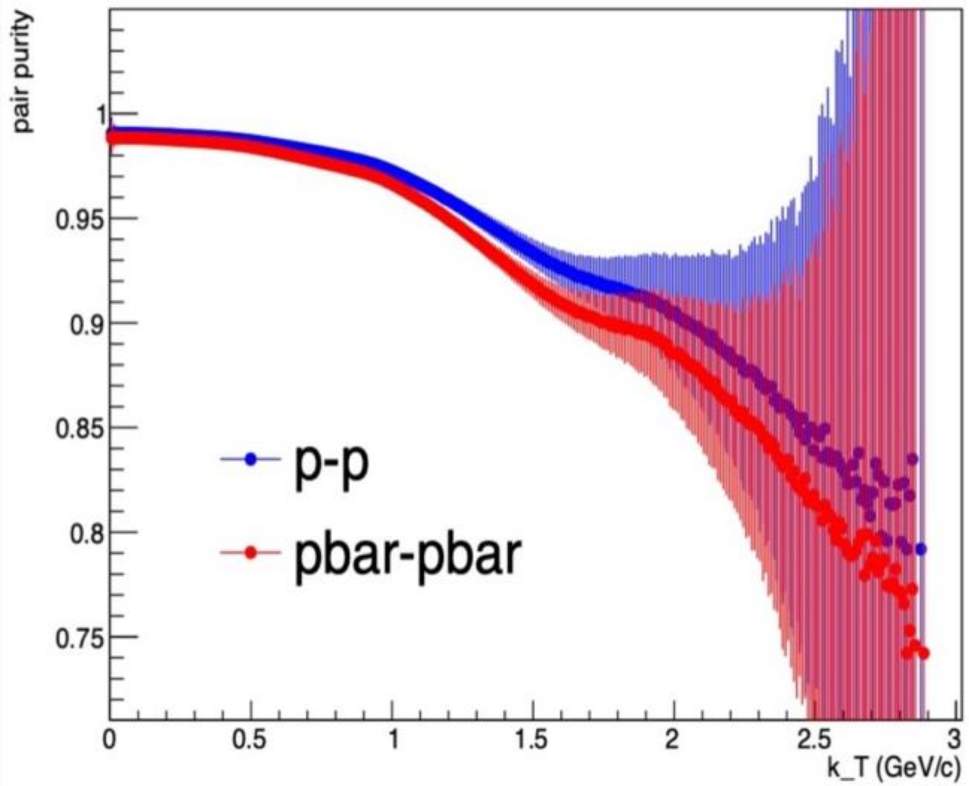
The total CF is the average of $p-p$ and $\bar{p}-\bar{p}$ CFs.

MonteCarlo: Purity

Single Particle Purity in MC sample
(applying all selections as in data)







Pair Purity = Purity$^{\text{particle 1}}(\mathbf{p}_1)$ x Purity$^{\text{particle 2}}(\mathbf{p}_2)$

$\mathbf{p}_1$ and $\mathbf{p}_2$ are three-momenta generated according to p-spectrum in data

Average values of kT weighted distributions:

PP ($p-p$)= 0.981

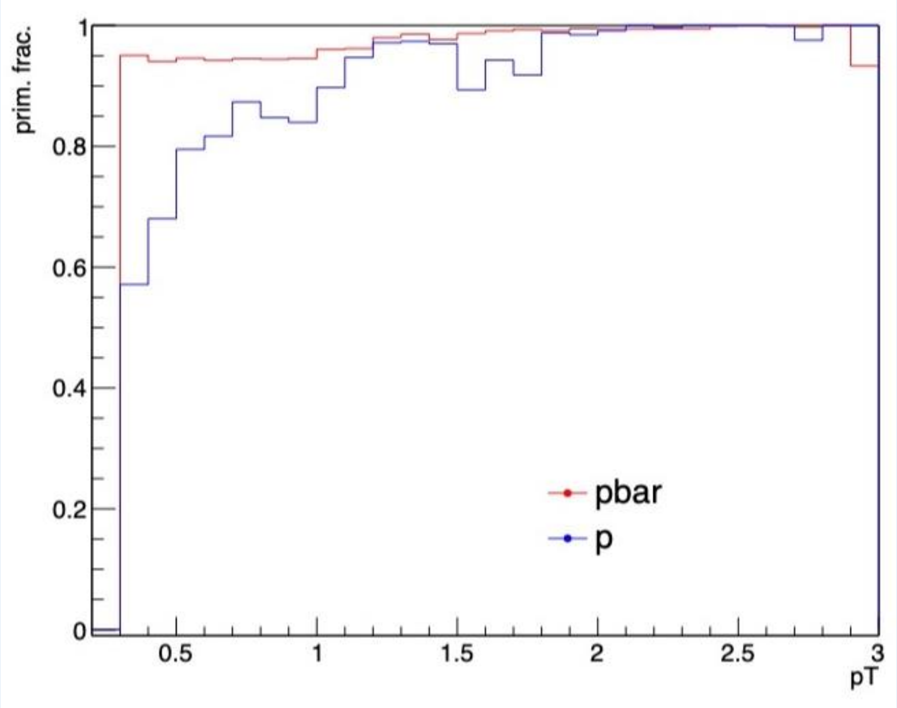
PP $(\bar{p}-\bar{p})$ = 0.976

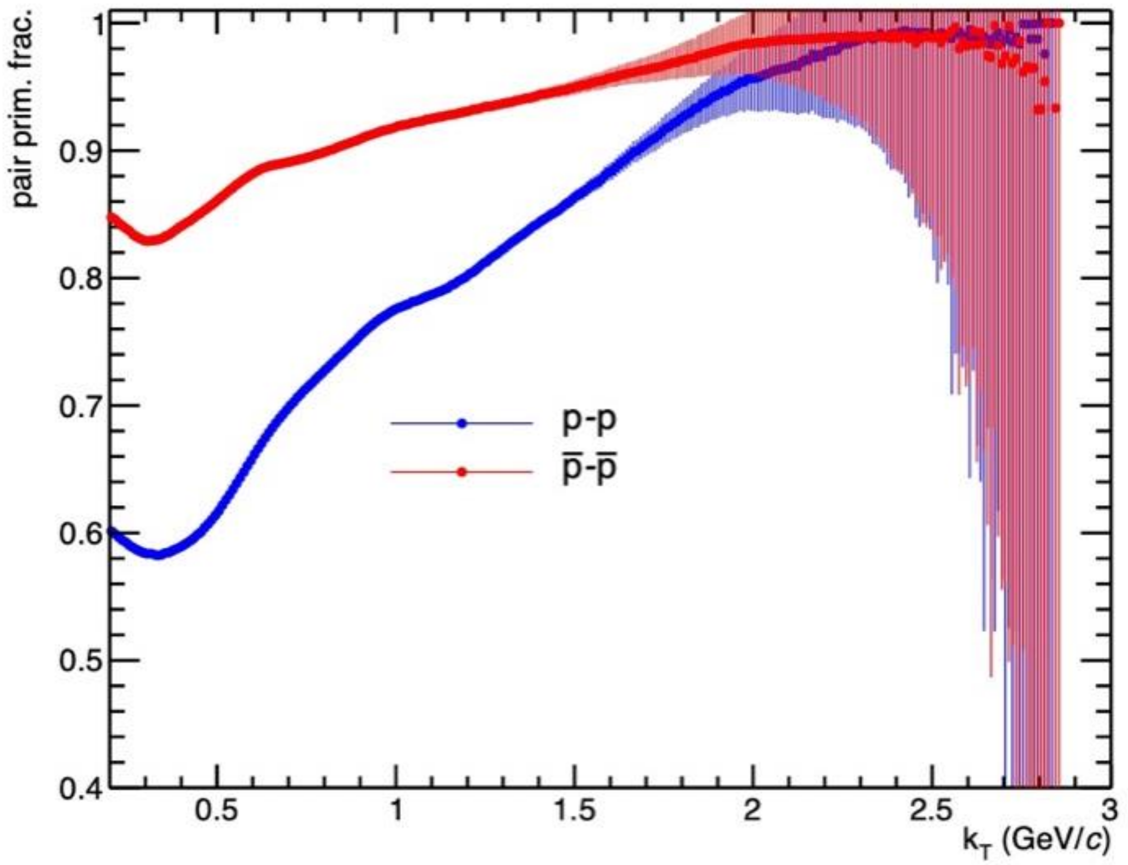
→ Weighted average of PP with number of pairs: **PP ($\mathbf{p-p} \oplus \bar{p}-\bar{p}$) = 0.98**

MonteCarlo: Primary Fraction

Single Particle Primary Fraction in MC sample

PF= Primaryes^{mc}/(weak^{mc}+material^{mc}+primaryes^{mc})





Average values of kT weighted distributions:

PPF $(p - p)$= 0.67

PPF $(\bar{p} - \bar{p}) = 0.88$

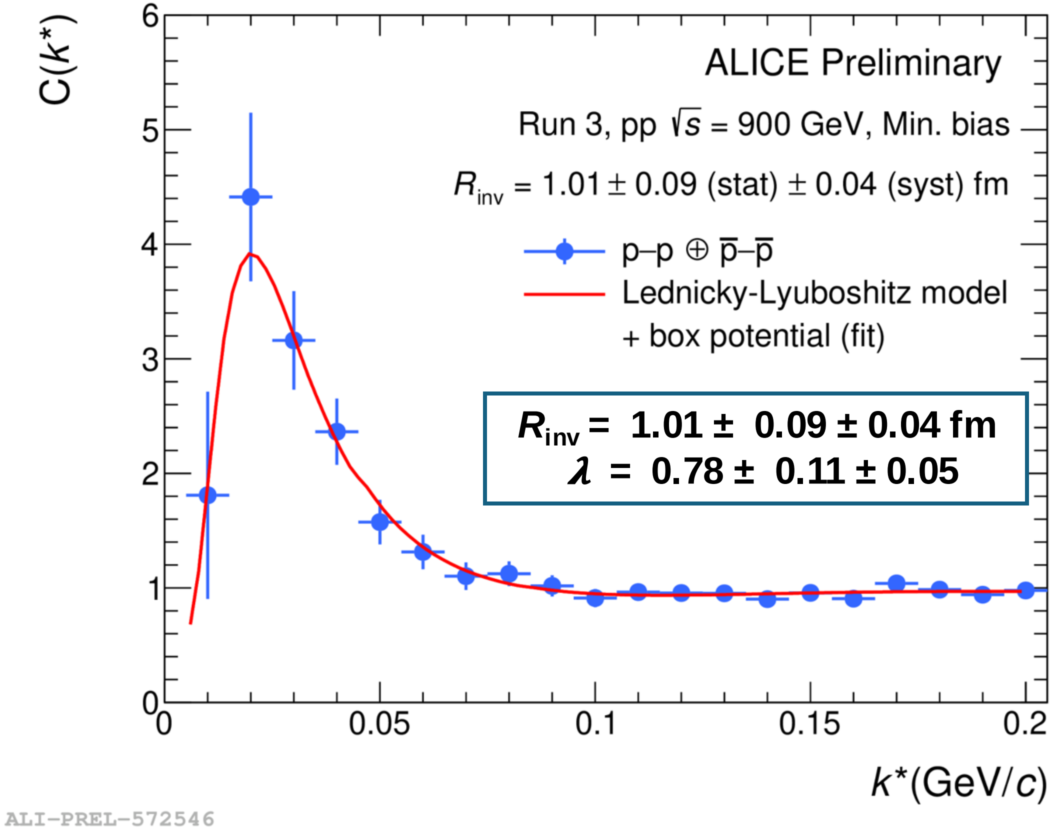
Pair PF = PF $^{particle\ 1}$(**pT**$_1$) x PF $^{particle\ 2}$(**pT**$_2$)

pT$_1$ and **pT**$_2$ are transverse momenta generated according to pT-spectrum in data

→ Weighted average of PPF with number of pairs: **PPF $(\mathbf{p - p} \oplus \bar{p} - \bar{p})$ = 0.75**

Fitting the Correlation Function

- CF is smeared to consider the finite momentum resolution of the detector, by folding the CF with resolution matrix
- The baseline is fitted using a third order polynomial for $0.2 < k^* \text{ (GeV/c)} < 2.0$
- The total CF is fitted $k^* < 200$ MeV/*c* with the **Lednický–Lyuboshitz model with a box potential approach** (considering both Coulomb and strong interactions) → Introduced in Gleb's presentation today!
- The **source size R_{inv}** and the **λ parameter** are **free fit parameters.**



$\lambda^{FIT} = 0.78 \pm 0.11$

$\lambda^{MC} = \lambda^{purity} \times \lambda^{primary} \approx 0.98 \times 0.75 = \mathbf{0.74}$

The **agreement** within statistical uncertainty of λ^{FIT} and λ^{MC} can be considered as an **indirect validation** of the theoretical model used for the fit

Proton source measurement in pp collisions at $\sqrt{s} = 0.9$ TeV

Comparison to published results in pp, p–Pb and Pb–Pb collisions with similar pair transverse mass $\langle m_T \rangle$:

$\langle \boldsymbol{m}_T \rangle = \sqrt{\boldsymbol{k}_T^2 + \boldsymbol{m}^2}$ pair transverse mass

$\boldsymbol{k}_T$ pair transverse momentum

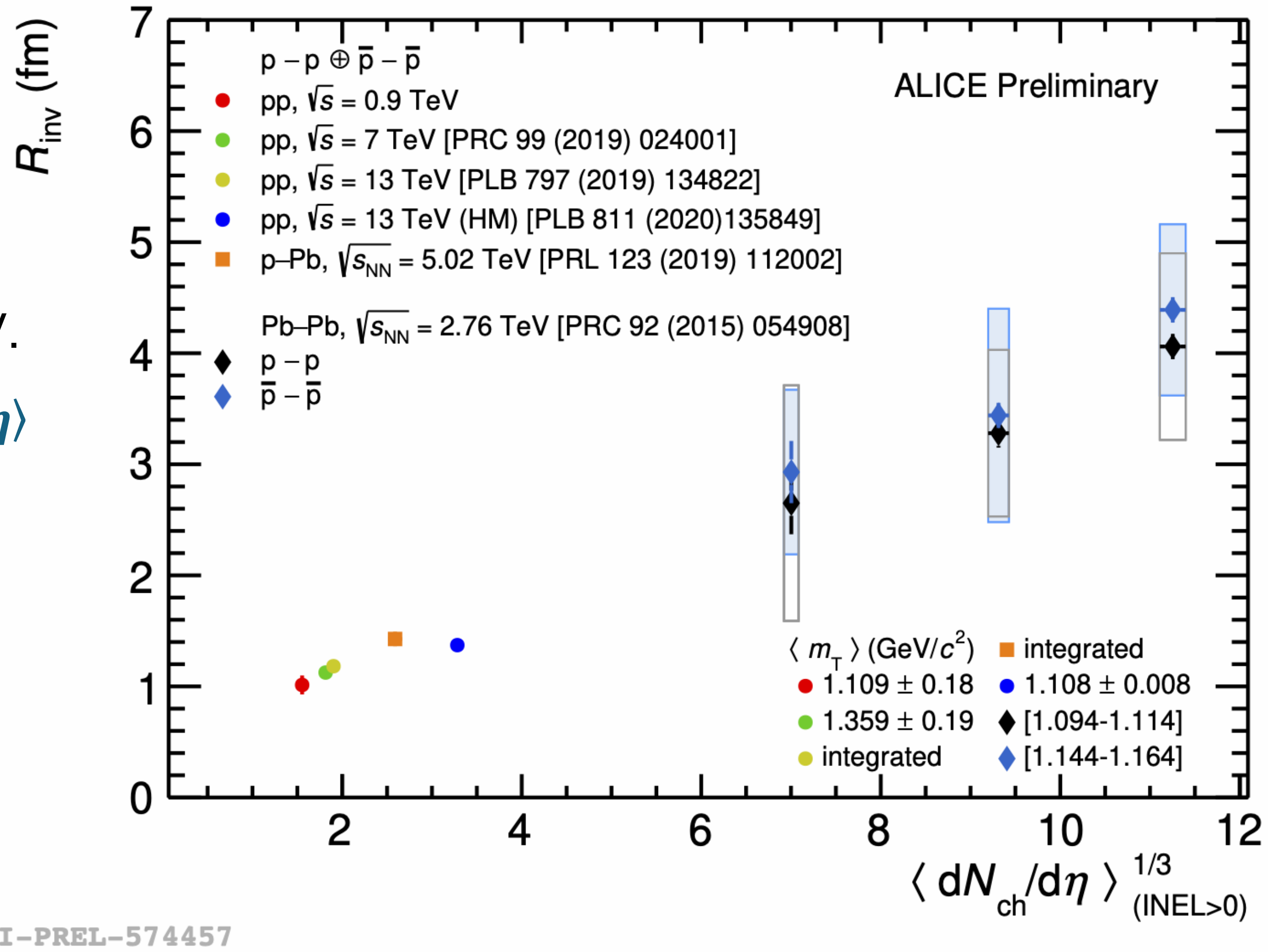
$\boldsymbol{m}$ proton mass

→ **Smallest source** in pp collisions at $\sqrt{s}$ = 0.9 TeV.

→ **A clear charged-particle multiplicity $\langle dN_{ch}/d\eta \rangle$ scaling is observed.**

R_{inv} = 1.01 ± 0.09 ± 0.04 fm

λ = 0.78 ± 0.11 ± 0.05



1D Proton source measurement in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV

In heavy ion collisions, we have evidence of the formation of a Quark–Gluon Plasma (QGP) and collective evolution of the particle source.
→ the femtoscopic correlation is a tool to investigate **collective dynamics.**

Physical quantity	Selection cut
Distance from Primary Vertex	$-10 < v_z(\text{cm}) < 10$
Pseudorapidity	eta < 0.8
Dca_xy	abs(dcaxy) < 0.004 + 0.013/pT
Dca_z	abs(dcaz) < 0.004 + 0.013/pT
Momentum	0.5 < p (GeV/c) < 4.0

p range	TPC selection	TOF selection
0.5 < p (GeV/c) < 4.0	$-2 < n_\sigma^{TPC} < 4$	$-3 < n_\sigma^{TOF} < 3$

+ rejection cuts for π/K in 5σ with TOF

Double track cuts:
$\Delta\eta < 0.02$ && $\Delta\phi^* < 0.03$ at R = 1.2 m

Centrality Bins:
- 0-10%
- 10-30%
- 30-50%
- 50-90%

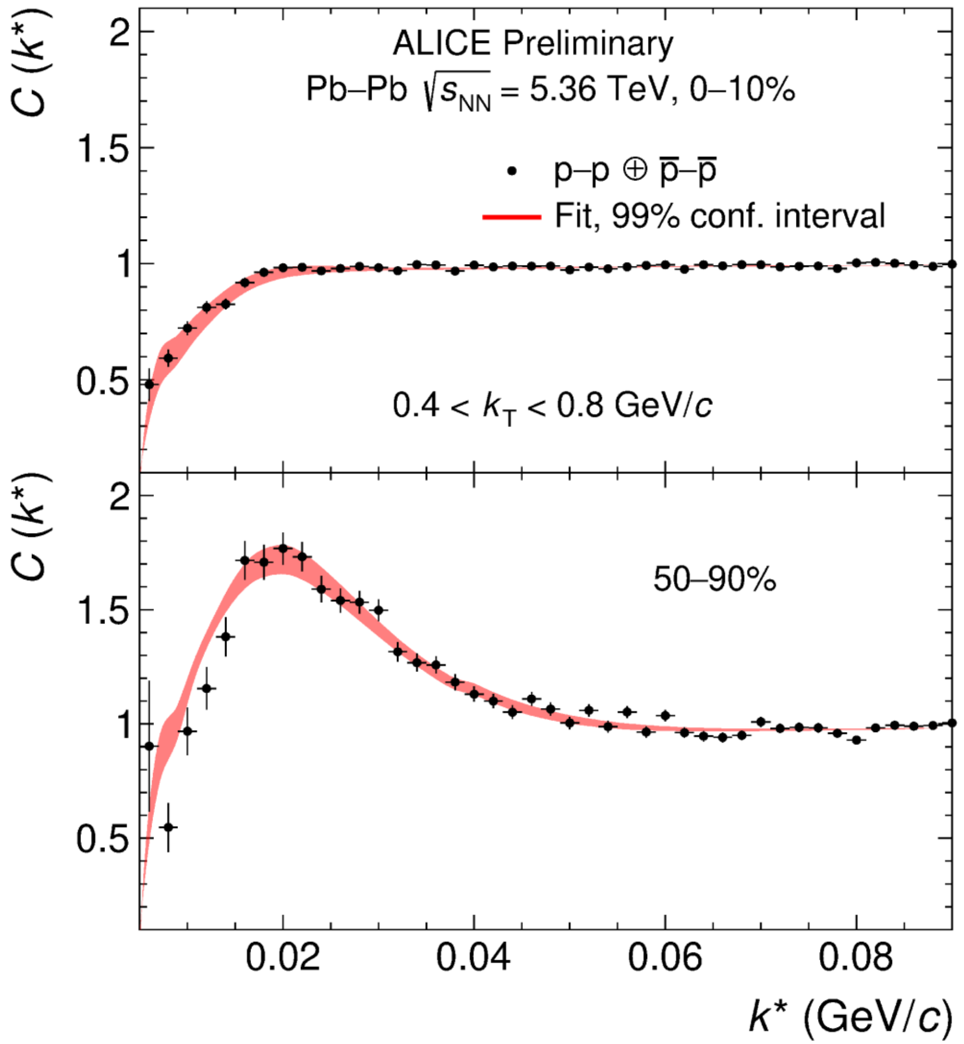
k_T bins (GeV/*c*):
- 0.4-0.8
- 0.8-1.0
- 1.0-1.2
- 1.2-1.6

1D Proton source measurement in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV

- Baseline correction with pol3 in k* (GeV/c)=[0.1-1.0]
- Resolution correction applied
- Fit the CF in k*(GeV/c)=[0-0.12] with LL model
  → more details in Gleb's presentation today

Bigger source for more central events (0–10%) means less pronounced peak than in peripheral events (50–90%).

First femtoscopic results in Pb–Pb Run 3!



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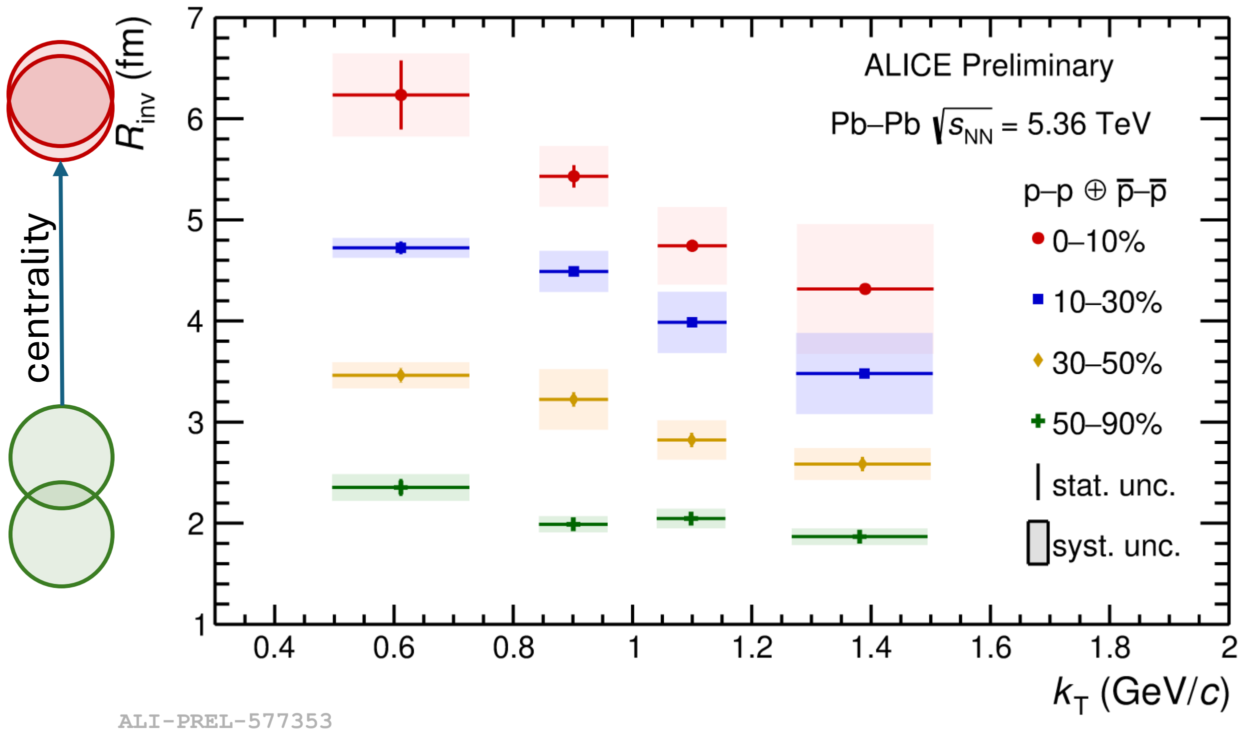
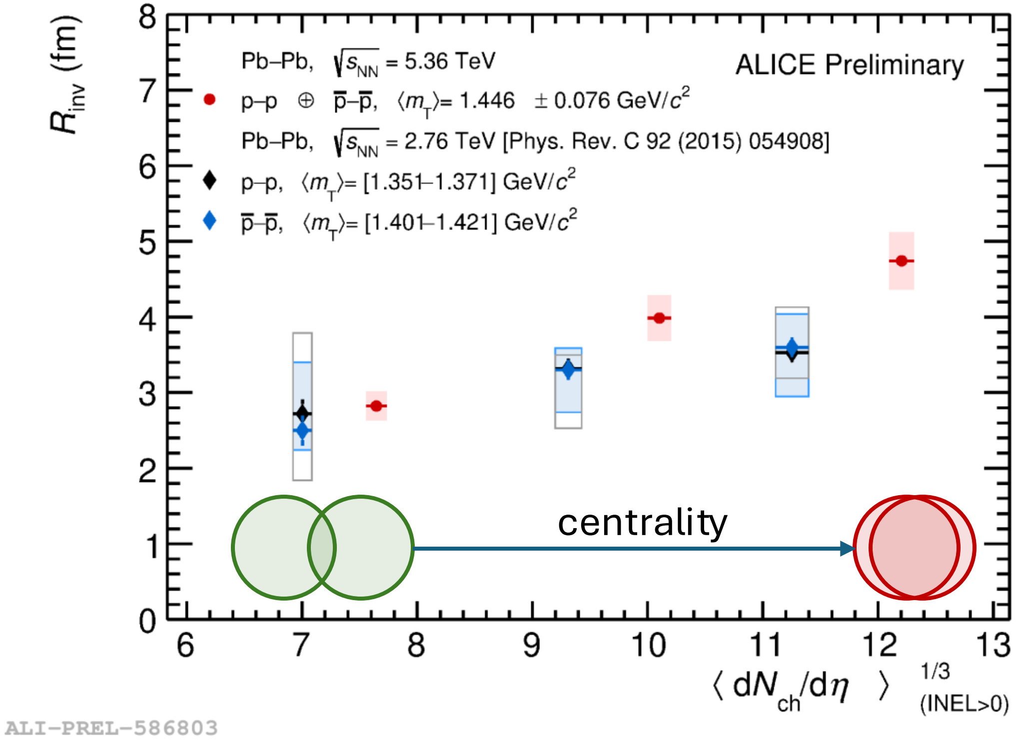
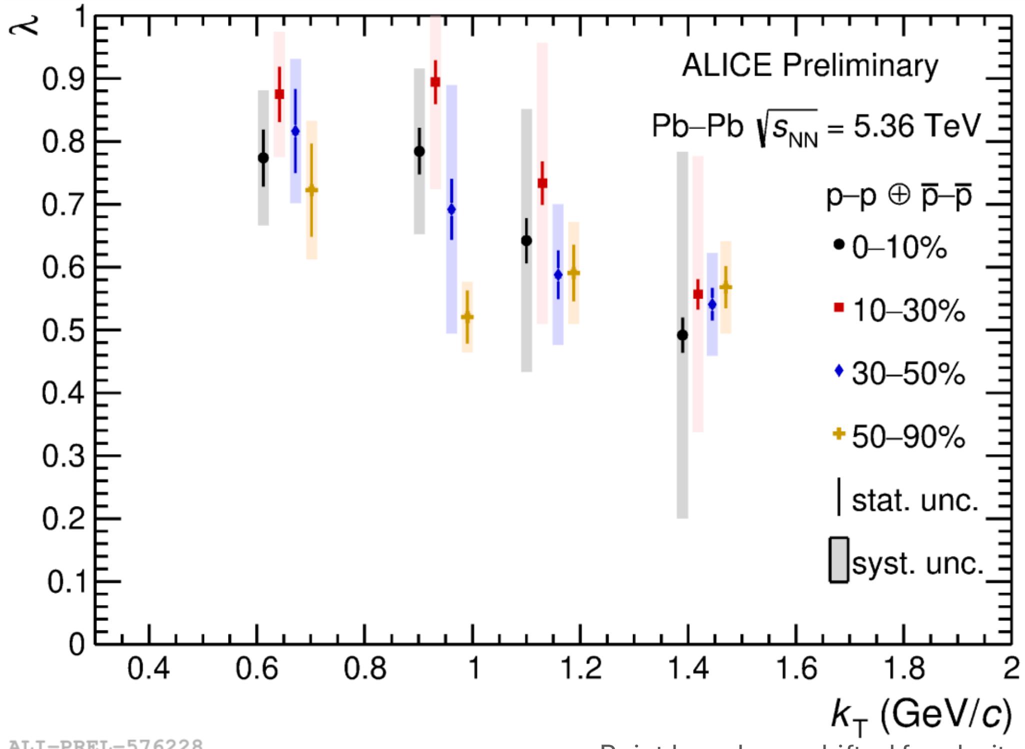
Proton source measurement in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV



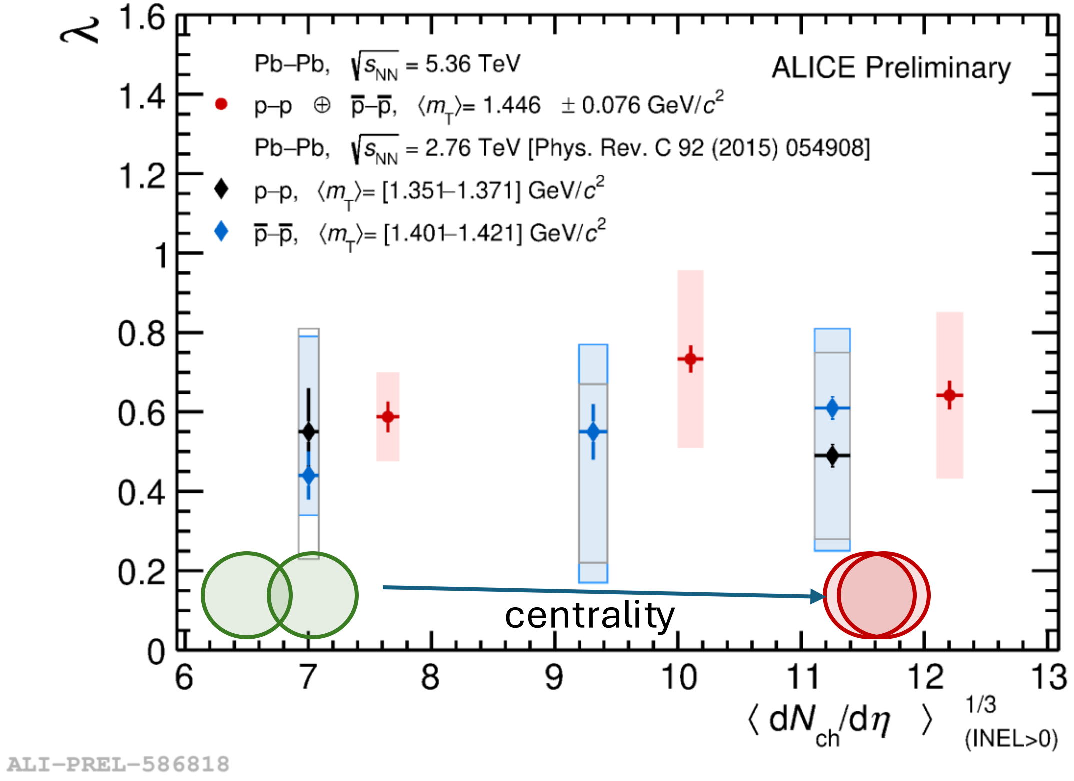


- **The source size decreases** from central towards peripheral events.
- R_{inv} decreases with increasing k_T → **presence of collective (radial) flow**.
- Radial flow weakens from central towards peripheral events.
- The new Run 3 are consistent with Run 1 results (at similar $\langle m_T \rangle$), but with much better precision.

λ parameters measurement in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV



Point have been shifted for clarity



- Extracted λ parameters are consistent in all centrality bins
- Decreasing trend with increasing the kT due to purity decrease
- λ parameters in Run3 are higher than the one from Run1 (with close mT)

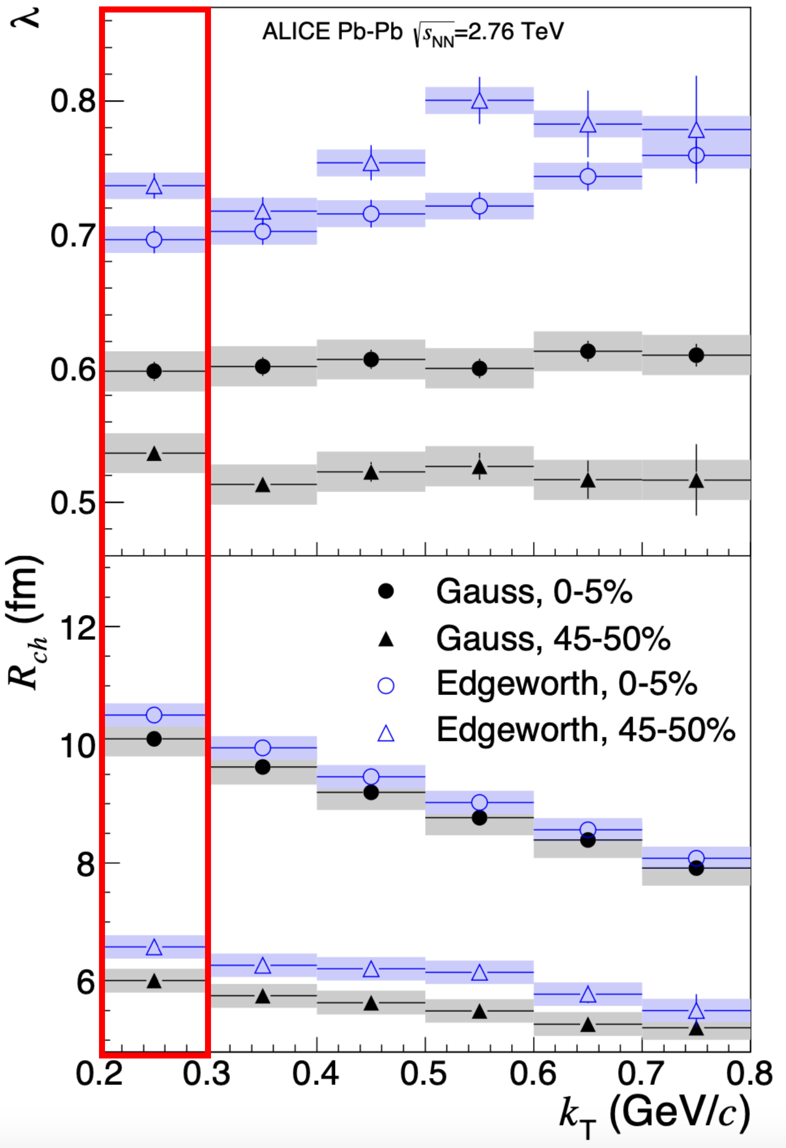
Summary

Femtoscopic measurements with ALICE's Run 3 data are performed:

In pp collisions:
- Smallest proton source ever measured at the LHC in pp collisions at $\sqrt{s}$ = 0.9 TeV
- Future application: use the measured proton source size for the coalescence modelling to estimate deuteron coalescence probability.

In Pb–Pb collisions:
- Proton radii exhibit the dynamics typical for heavy–ion collisions → collectivity
- New Run 3 results are in a good agreement with Run 1 ones increasing measurement precision
- Further improvement are expected (more statistics, better reconstruction, etc.)
  + We are working in 3D measurement of of proton source in PbPb

Re-fitting ALICE data with Levy Model



Trying to fit two-pion CF in Pb-Pb Collisions at sqrt(sNN)=2.76 TeV
https://inspirehep.net/literature/1262523
kT =[0.2-0.3] GeV
Using the novel method developed for Levy source calculation:

- Fit using ROOT
- Minimizer: ROOT::Minuit2::kMigrad for chi2 minimization
- ROOT::Math::Minimizer::SetStrategy → 2 (max level of reliability)

Results obtained with a **gaussian source**:

	Lambda	**Radius**
0-5%	0.5978± 0.007126	10.1±0.042
45-50%	0.5367±0.0049	6.007±0.0259

Re-fitting ALICE data with Levy Model

45-50% cent

FIRST ATTEMPT

N = 1.00215 +/- 0.00057061 (limited)

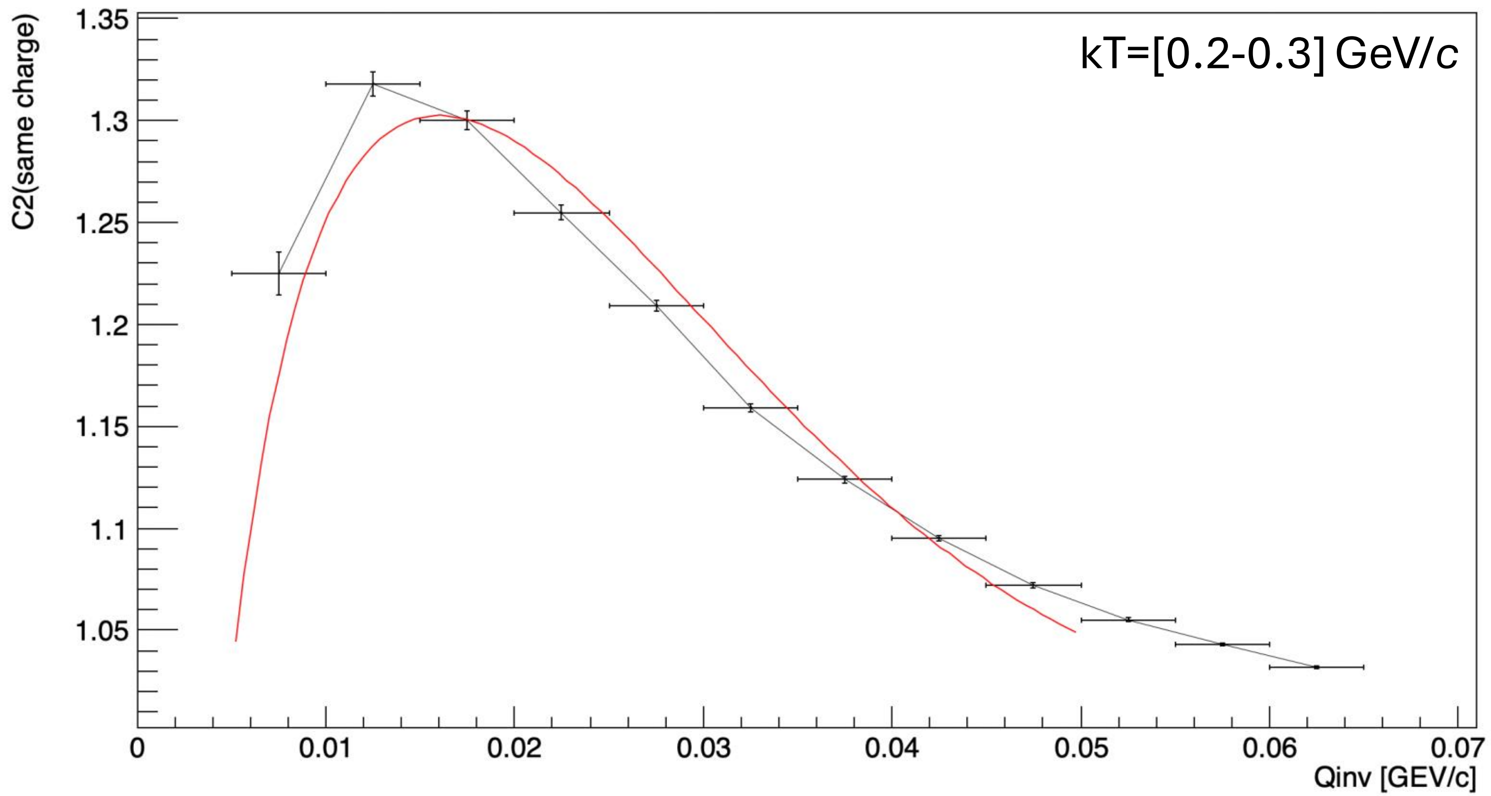
lambda = 0.5367 (fixed)

R = 6.007 (fixed)

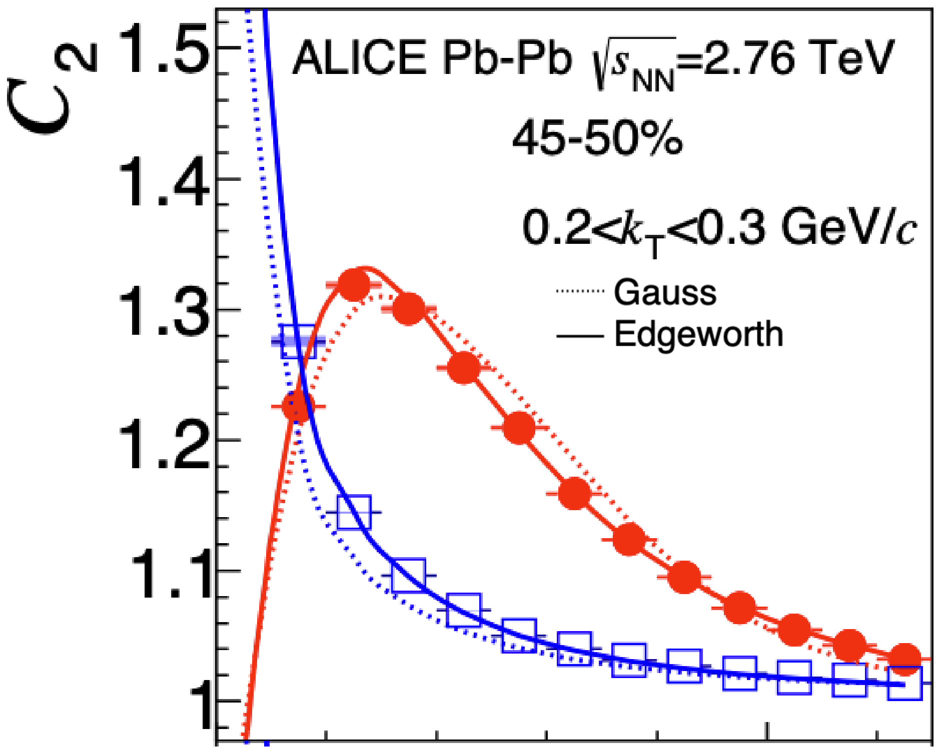
alpha = 2 (fixed)

Chi2/NDF: 343.5/4->85.875

All parameters are fixed to the value from the paper→ the fitting function reproduces *exactly* the red dotted curve



From publication:



Re-fitting ALICE data with Levy Model

45-50% cent

SECOND ATTEMPT – try to release some parameter

N = 0.996845 +/- 0.000690576 (limited)

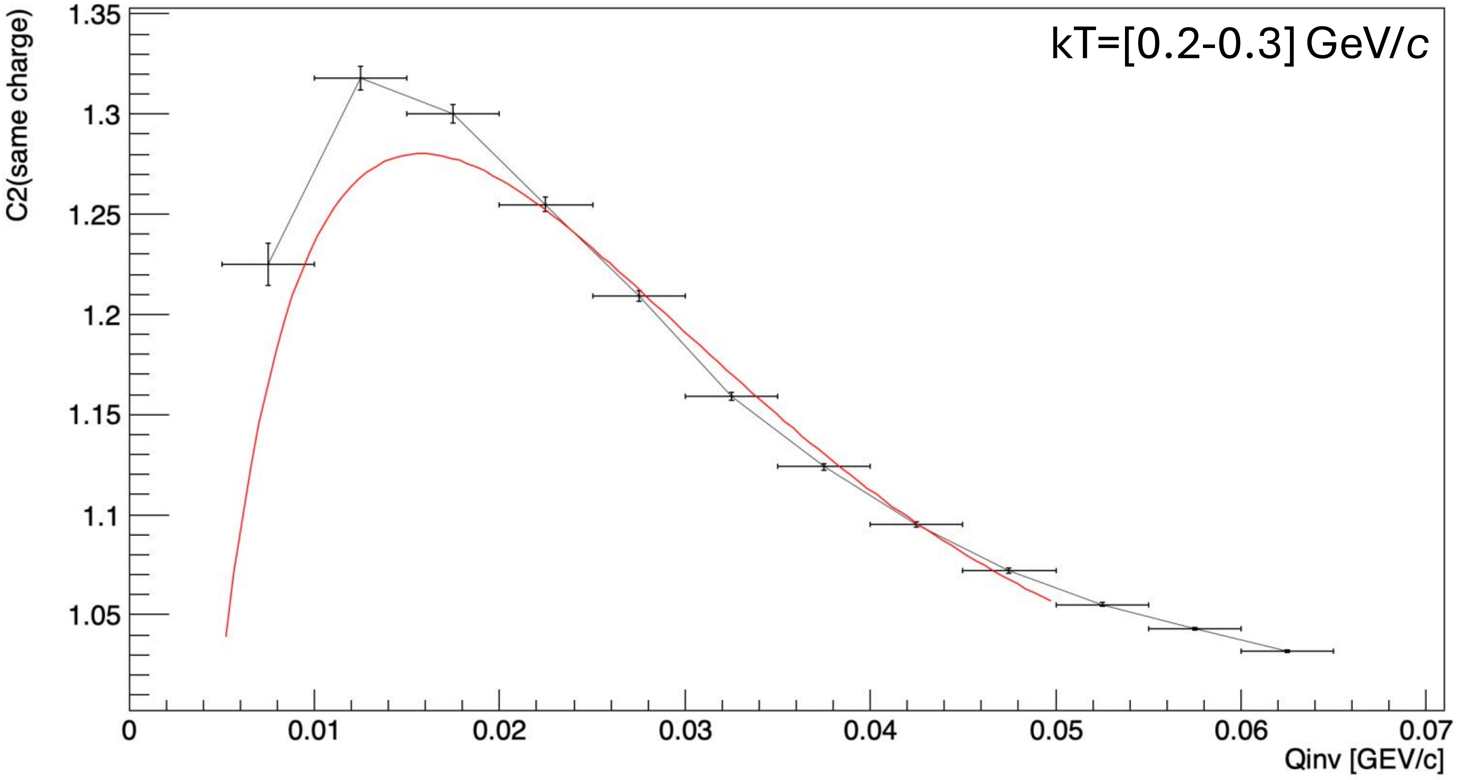
lambda = 0.5367 (fixed)

R = 6.007 (fixed)

alpha = 1.74102 +/- 0.0186333 (limited)

Chi2/NDF: 161.898/4->40.4745

Only lambda and R parameters are fixed to the value from the paper→ alpha differs from 2 (Gaussian case)

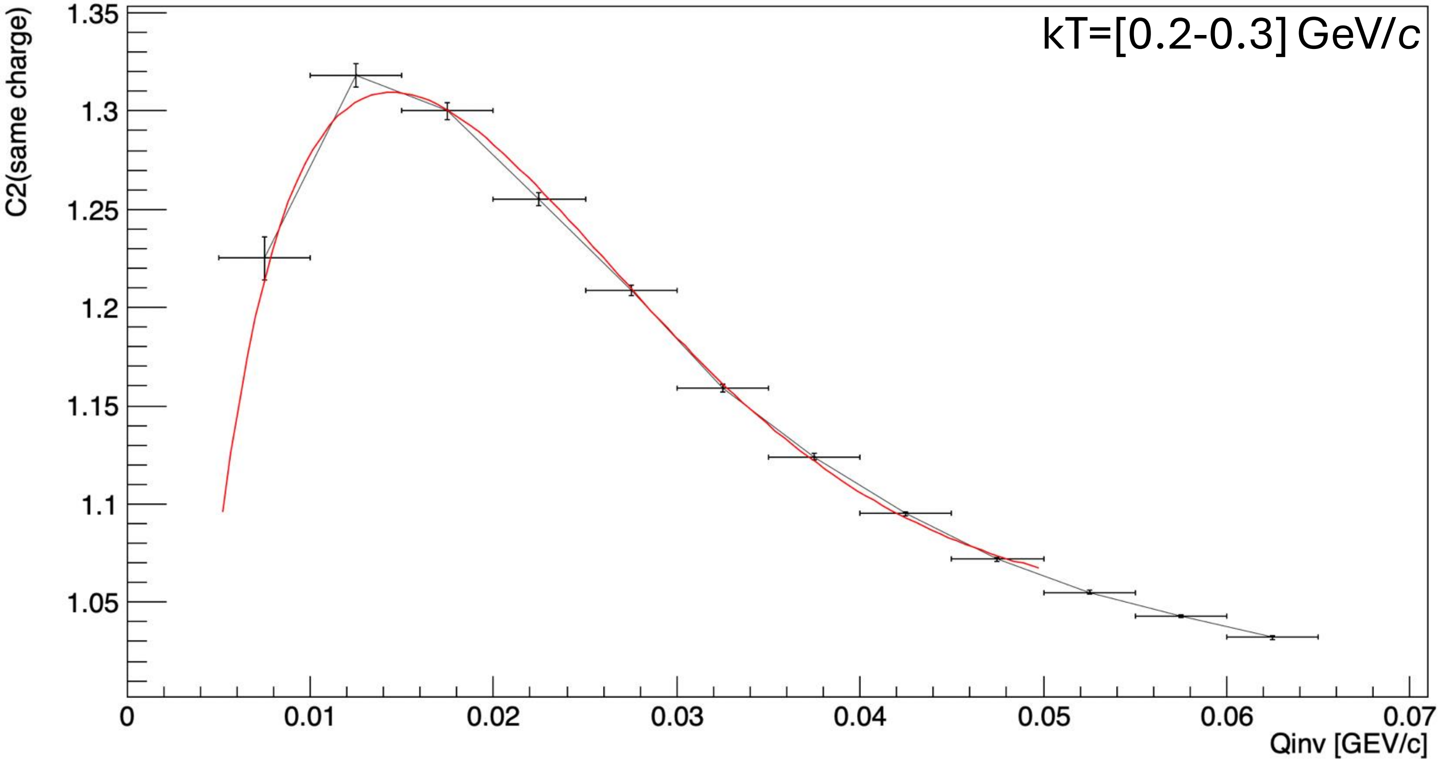


Re-fitting ALICE data with Levy Model

45-50% cent

THIRD ATTEMPT – try to release some parameter
N = 1.05303 +/- 0.00238809 (limited)
lambda = 0.468741 +/- 0.00602046 (limited)
R = 7.09842 +/- 0.087406 (limited)
alpha = 2 (fixed)
Chi2/NDF: 16.7324/4->4.18309

Only alpha parameters is fixed to 2→ Radius and lambda close to published values, fit is good

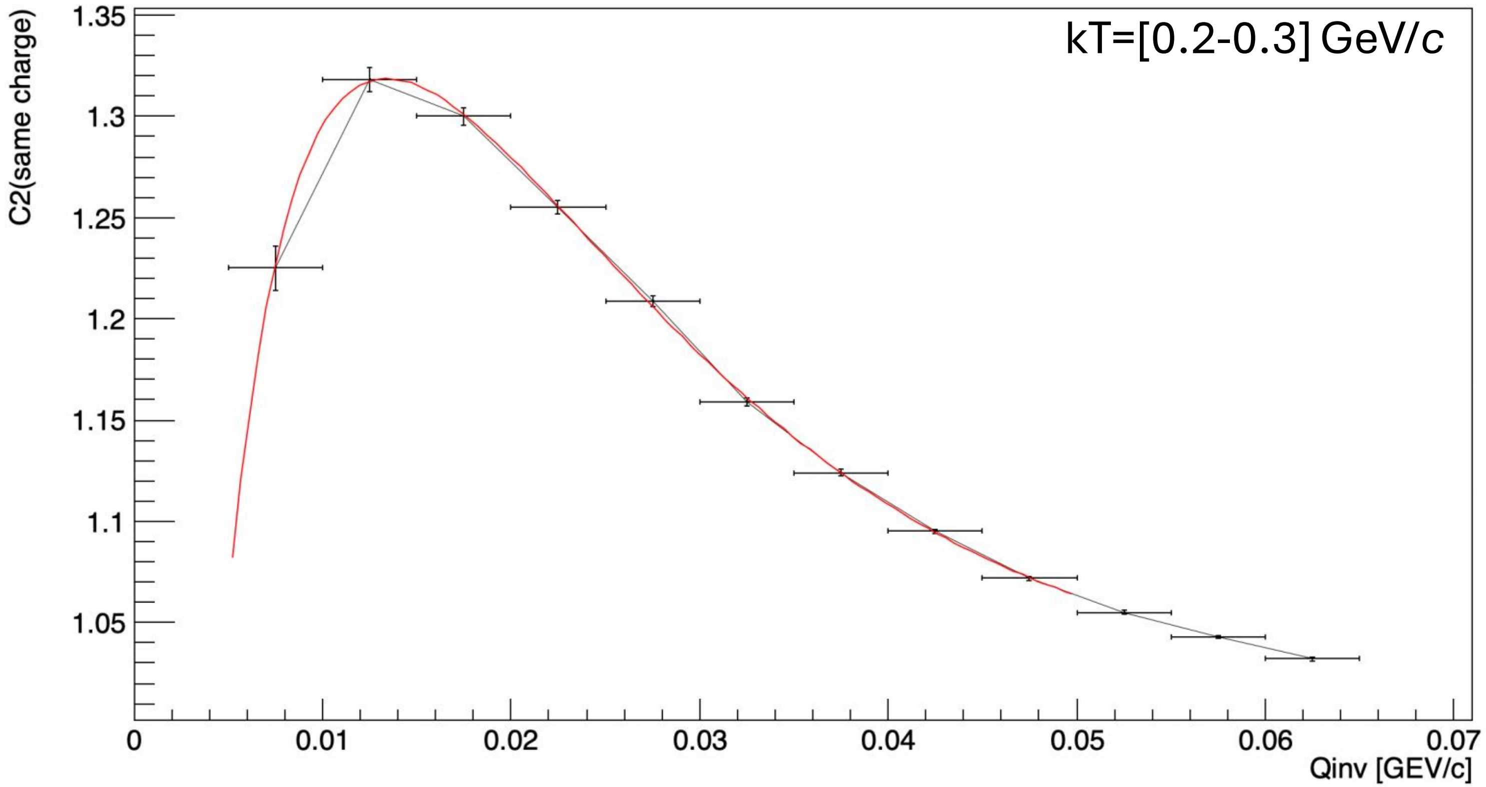


Re-fitting ALICE data with Levy Model

45-50% cent

FOURTH ATTEMPT – all parameters are free
N = 1.02238 +/- 0.0137683 (limited)
lambda = 0.682068 +/- 0.099733 (limited)
R = 7.91027 +/- 0.423126 (limited)
alpha = **1.40494** +/- 0.173238 (limited)
Chi2/NDF: 2.76297/4->0.690743

The fit correctly reproduce data points!
The shape is far from gaussianity

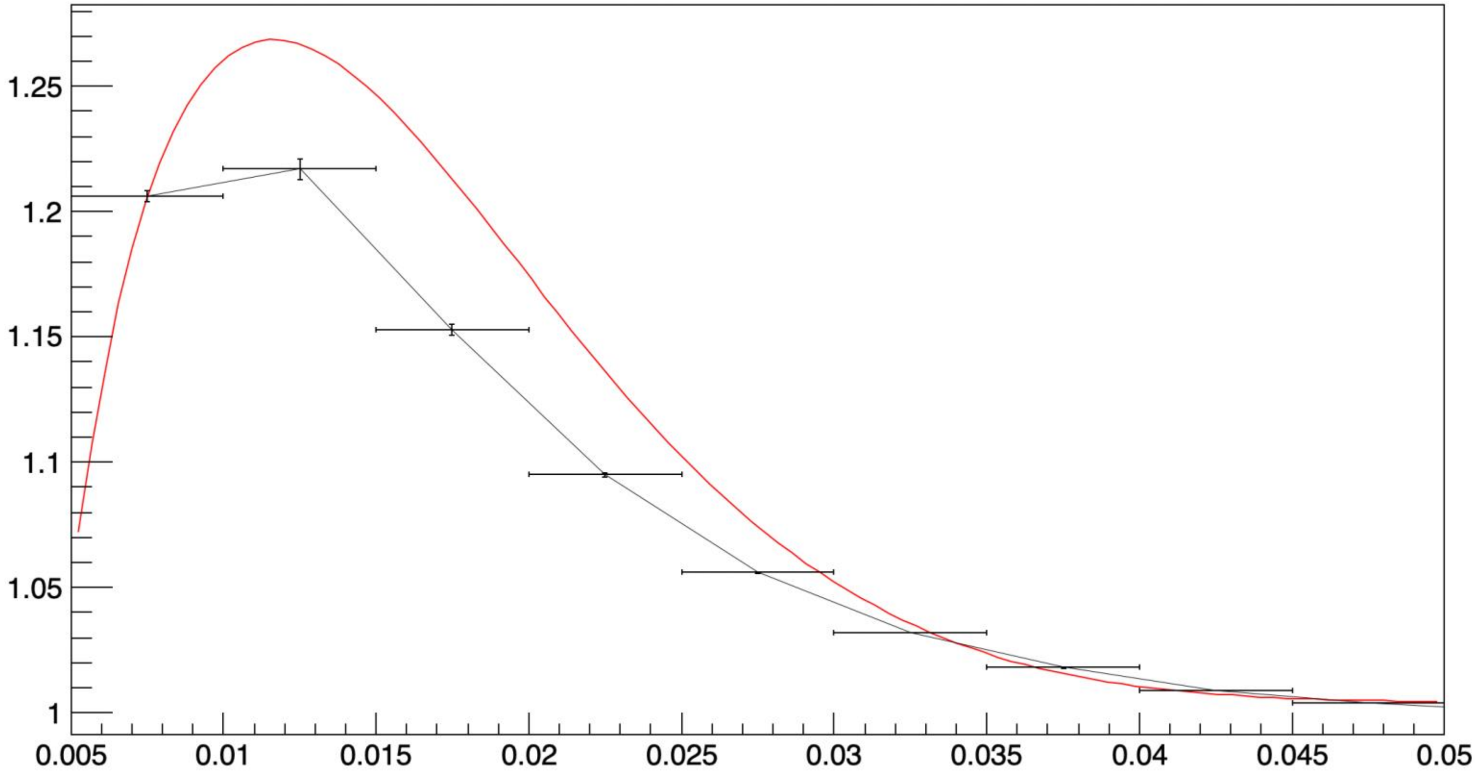


Re-fitting ALICE data with Levy Model

0-5% cent

N = 1.00871 +/- 5.58835e-05 (limited)
lambda = 0.5978 (fixed)
R = 10.1 (fixed)
alpha = 2 (fixed)
Chi2/NDF: 6768.93/4->1692.23

All parameters are fixed to the value from the paper→ the fitting function reproduces *more or less* the red dotted curve. Very high Chi2!



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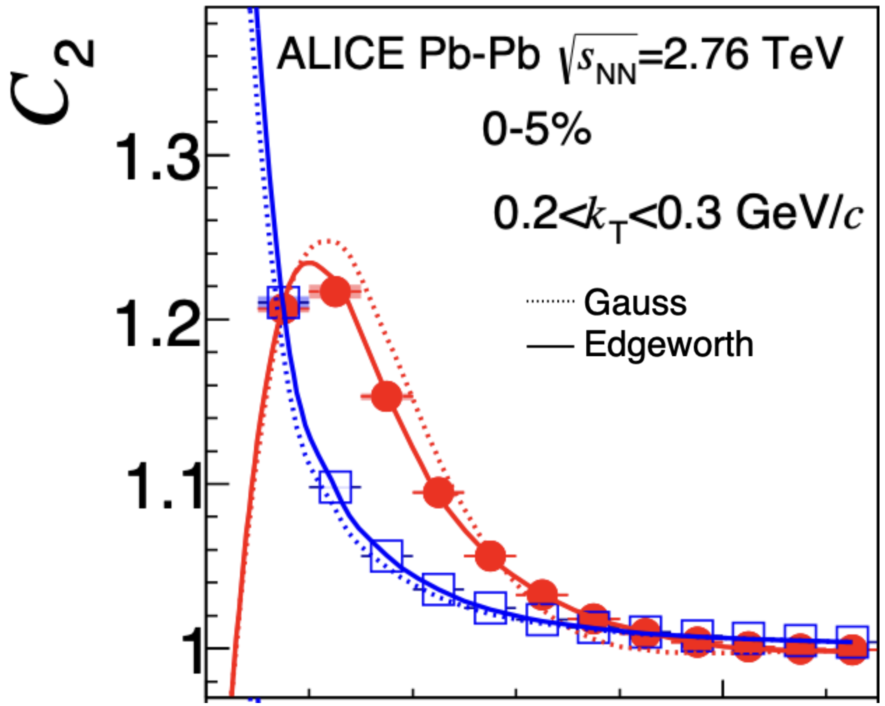
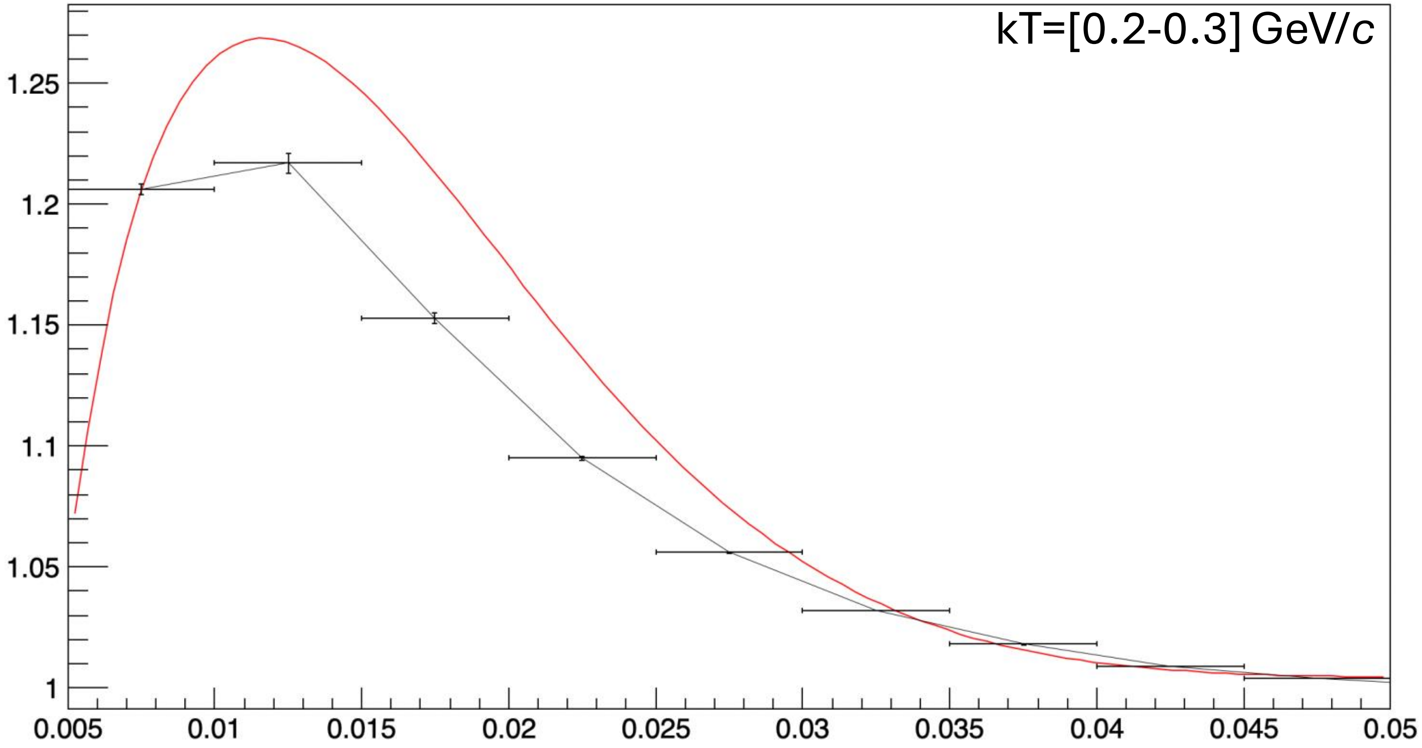


Re-fitting ALICE data with Levy Model

0-5% cent

N = 1.00871 +/- 5.58839e-05 (limited)
lambda = 0.5978 (fixed)
R = 10.1 (fixed)
alpha = 2 +/- 0.000199342 (limited)
Chi2/NDF: 6768.93/4->1692.23

Only lambda and R parameters are fixed to the value from the paper→ alpha is 2 (Gaussian case) but it basically reaches the limit

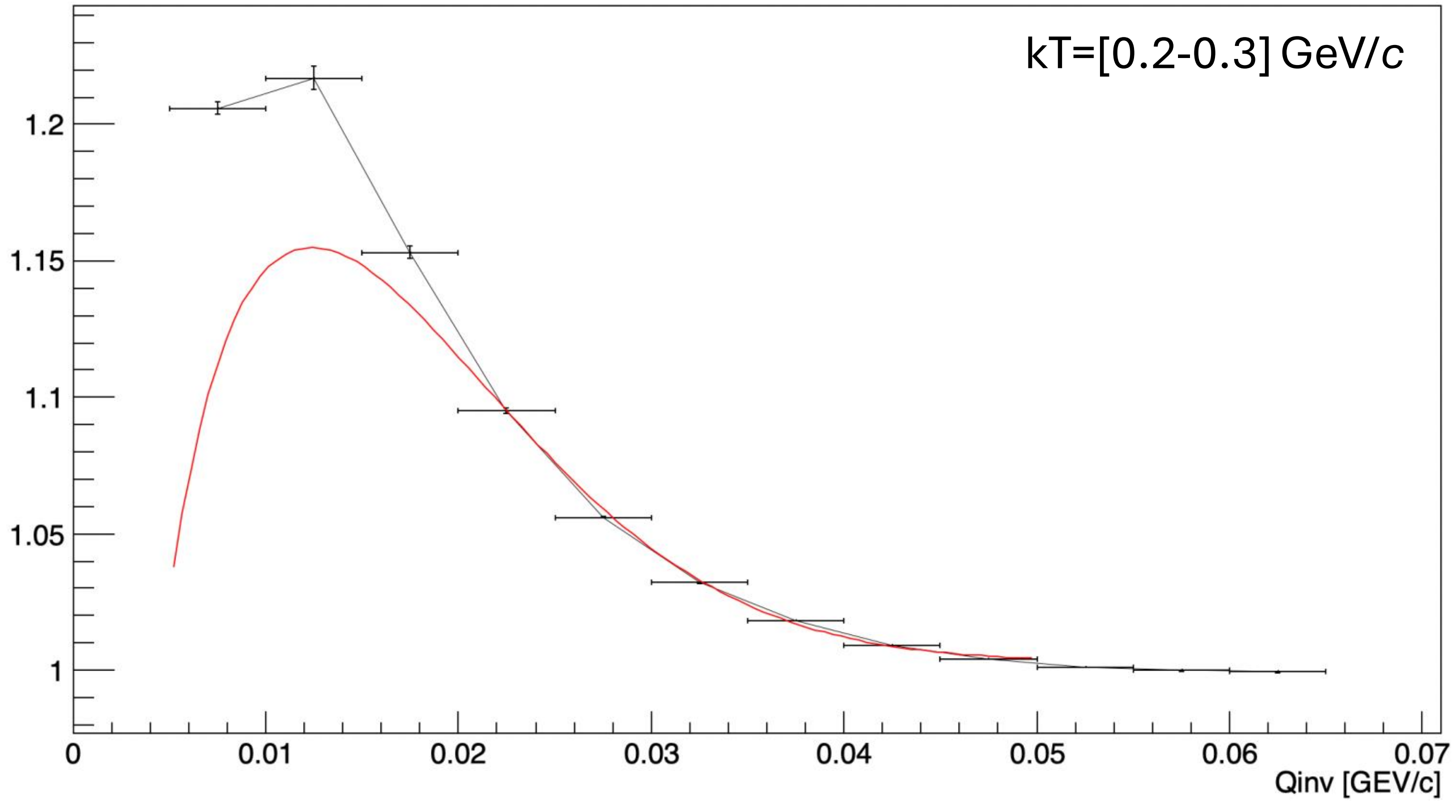


Re-fitting ALICE data with Levy Model

0-5% cent

N = 1.00561 +/- 0.000171627 (limited)
lambda = 0.323715 +/- 0.00365835 (limited)
R = 9.09976 +/- 0.0318721 (limited)
alpha = 2 (fixed)
Chi2/NDF: 581.761/4->145.44

Only alpha parameters is fixed to 2→ Radius and lambda close to published values, fit is not very good

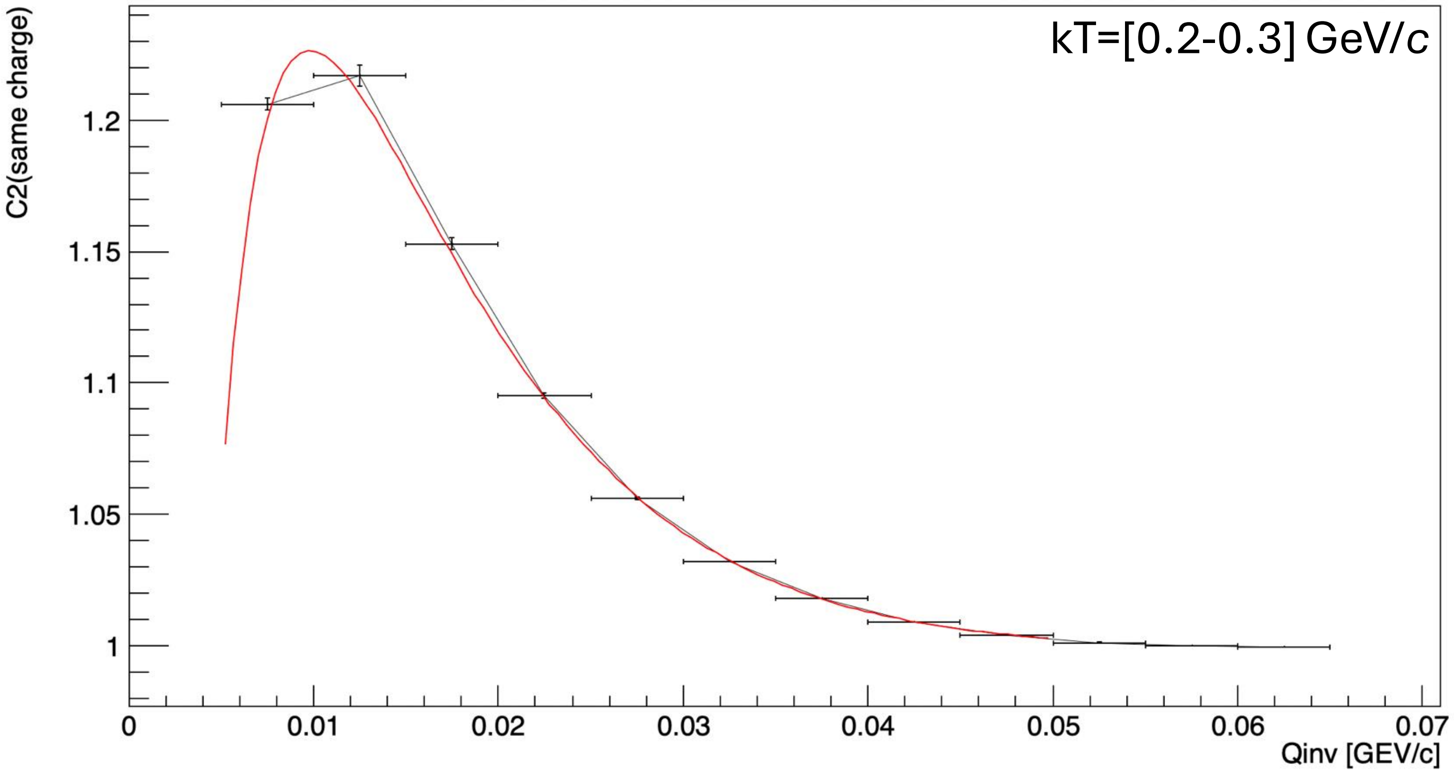


Re-fitting ALICE data with Levy Model

0-5% cent

N = 1.00148 +/- 0.000310684 (limited)
lambda = 1 +/- 0.0120328 (limited)
R = 16.8596 +/- 0.0900518 (limited)
alpha = 1.11063 +/- 0.00762877 (limited)
Chi2/NDF: 27.3769/4->6.84422

All parameters free: Lambda reaches the limit!→ working to improve fitting strategy



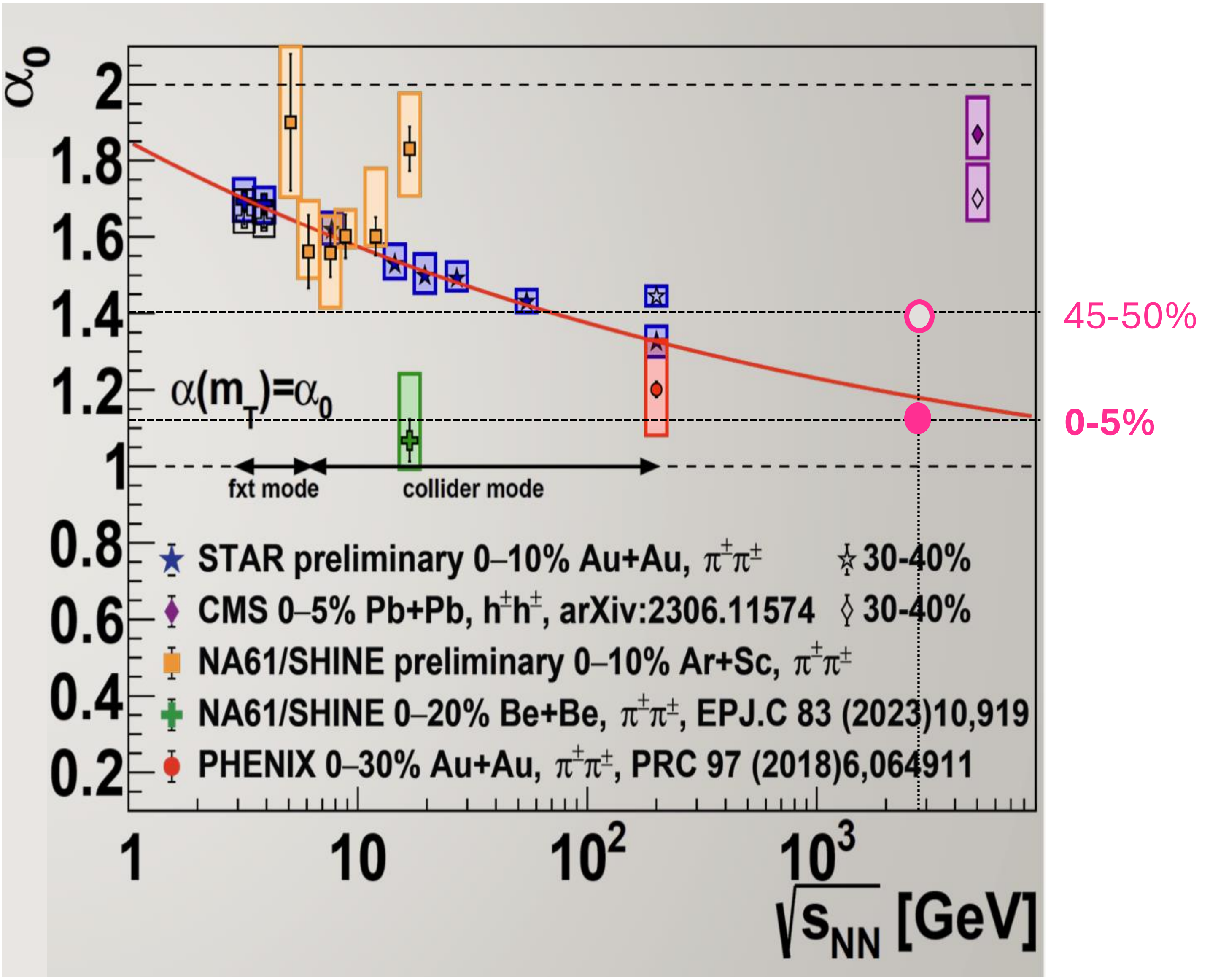
Comparison with other measurements

Very qualitative comparison with others measurements of the Levy parameter

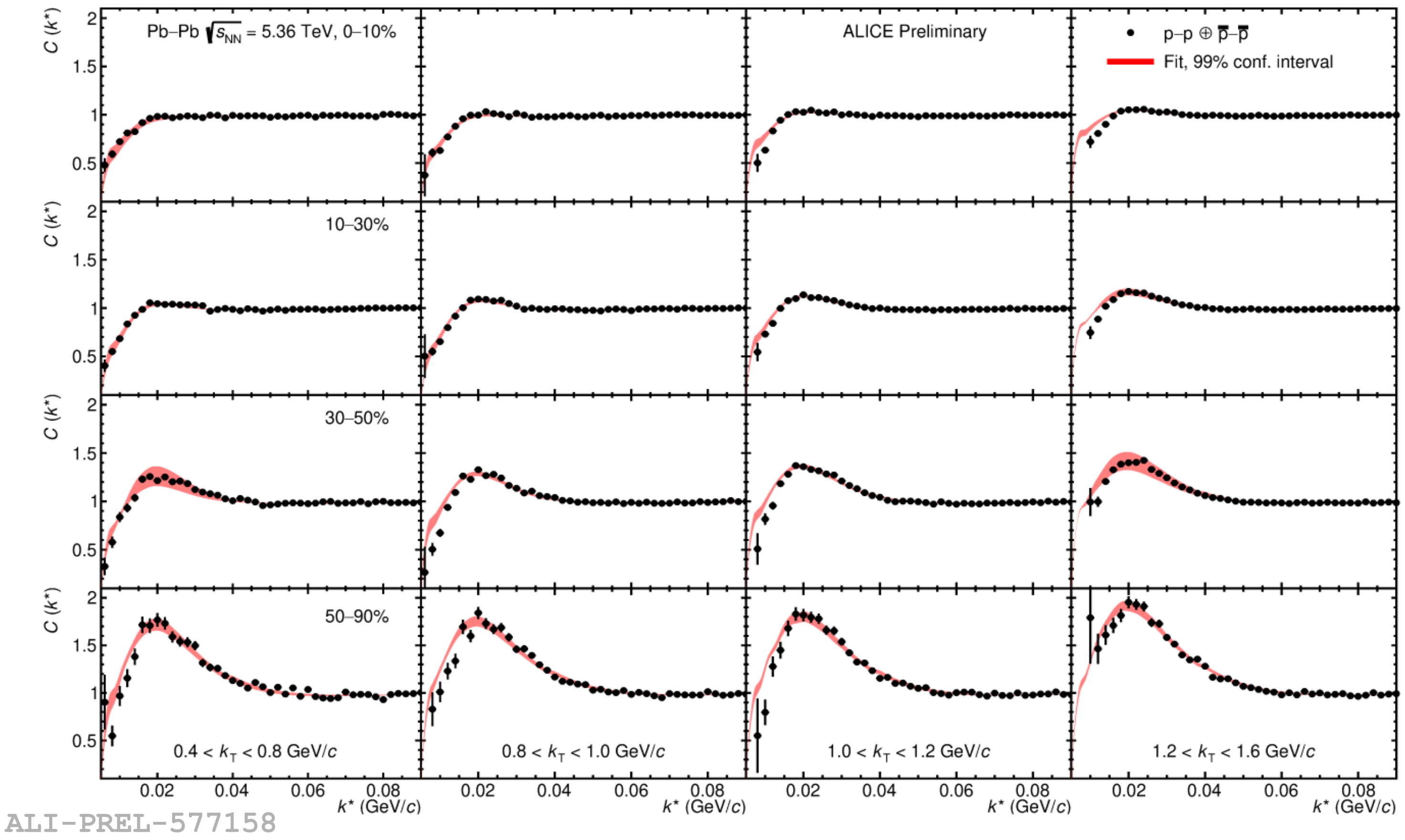
→ Comparison with CMS not easy:
α from most central and more peripheral collisions seem to be swapped

Calculation in 0-5% is not so stable..
Can we trust this first attempt??

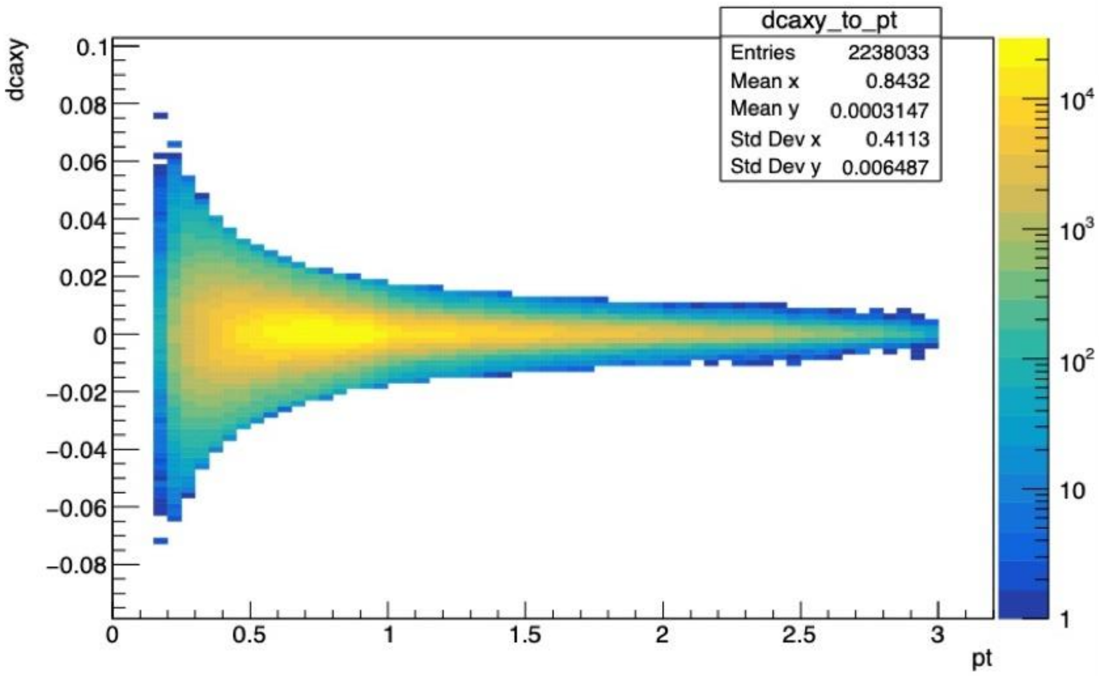
We are planning to fit ALICE two-Pion CF at 5.02 TeV, to have a better comparison

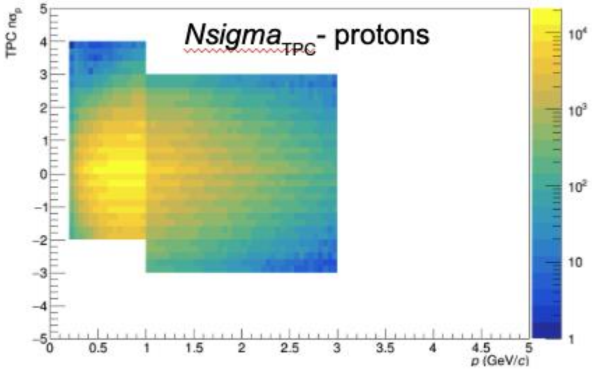


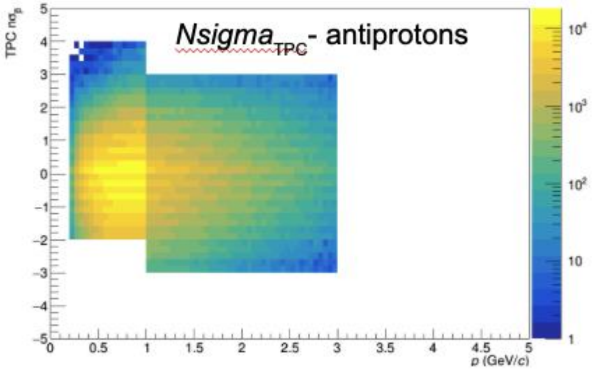
Backup

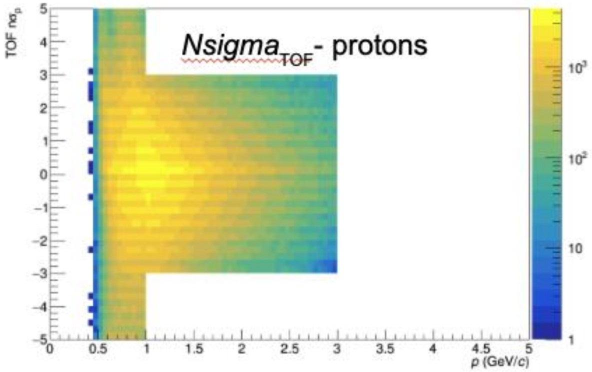

Pb–Pb $\sqrt{s_{NN}}$ = 5.36 TeV, 0–10%
ALICE Preliminary
p–p ⊕ $\bar{p}$–$\bar{p}$
Fit, 99% conf. interval
10–30%
30–50%
50–90%
0.4 < k_T < 0.8 GeV/c
0.8 < k_T < 1.0 GeV/c
1.0 < k_T < 1.2 GeV/c
1.2 < k_T < 1.6 GeV/c
$C(k^*)$
k^* (GeV/c)
ALI-PREL-577158

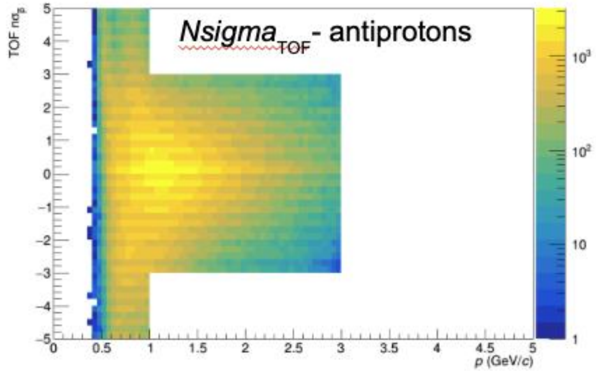
PID plots


dcaxy_to_pt
Entries 2238033
Mean x 0.8432
Mean y 0.0003147
Std Dev x 0.4113
Std Dev y 0.006487
dcaxy
pt


$Nsigma_{TPC}$- protons
TPC nσp
p (GeV/c)


$Nsigma_{TPC}$- antiprotons
TPC nσp̄
p (GeV/c)


$Nsigma_{TOF}$- protons
TOF nσp
p (GeV/c)


$Nsigma_{TOF}$- antiprotons
TOF nσp̄
p (GeV/c)