Femtoscopic measurement of proton source in pp collisions at $\sqrt{s} = 900\ GeV$ with ALICE

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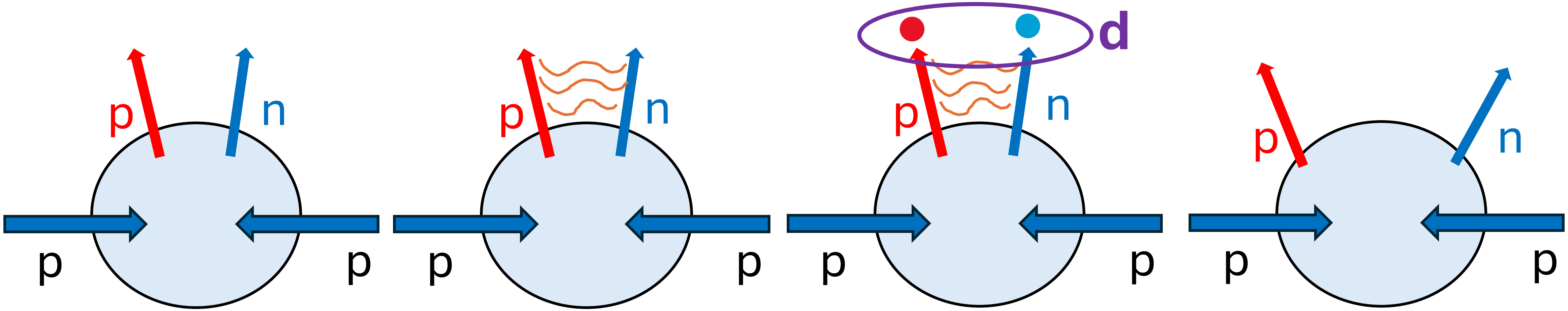
MOTIVATION: modelling formation of (anti)deuteron through coalescence

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:

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

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)

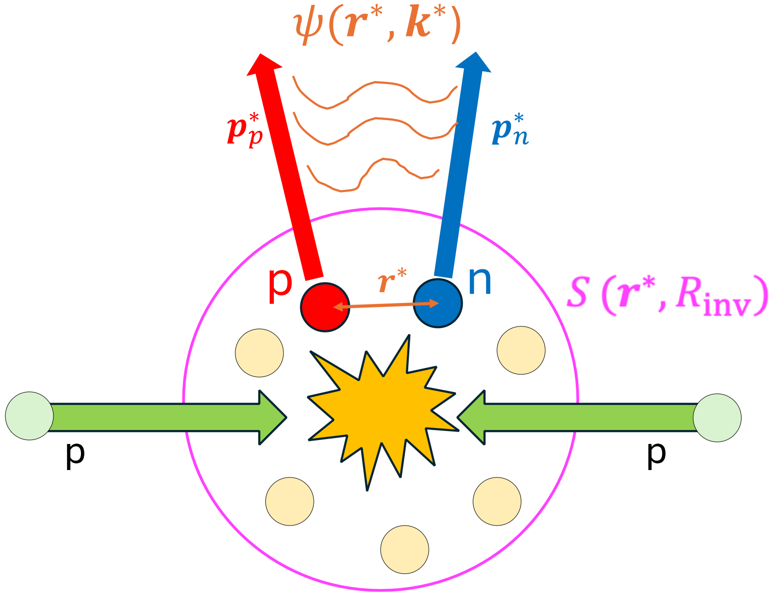
[Mahlein, M. et al., Eur. Phys. J. C 83, 804 (2023)]
[Bellini, F. et al., Phys. Rev. C 103, 014907 (2021)]

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:

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

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.



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

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

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

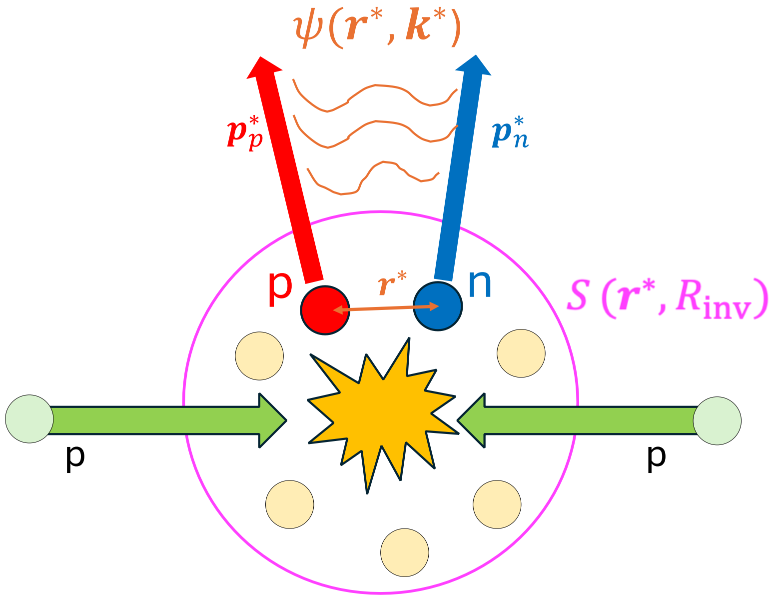
[L. Fabbietti, Ann. Rev. Nucl. Part. Sci. (2021) 71:377-402]

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 ***r* = r****$_p$***– r****$_n$
Relative momentum ***k* = ½ | p****$_p$***– p****$_n$ **|**
measured in the pair rest frame.

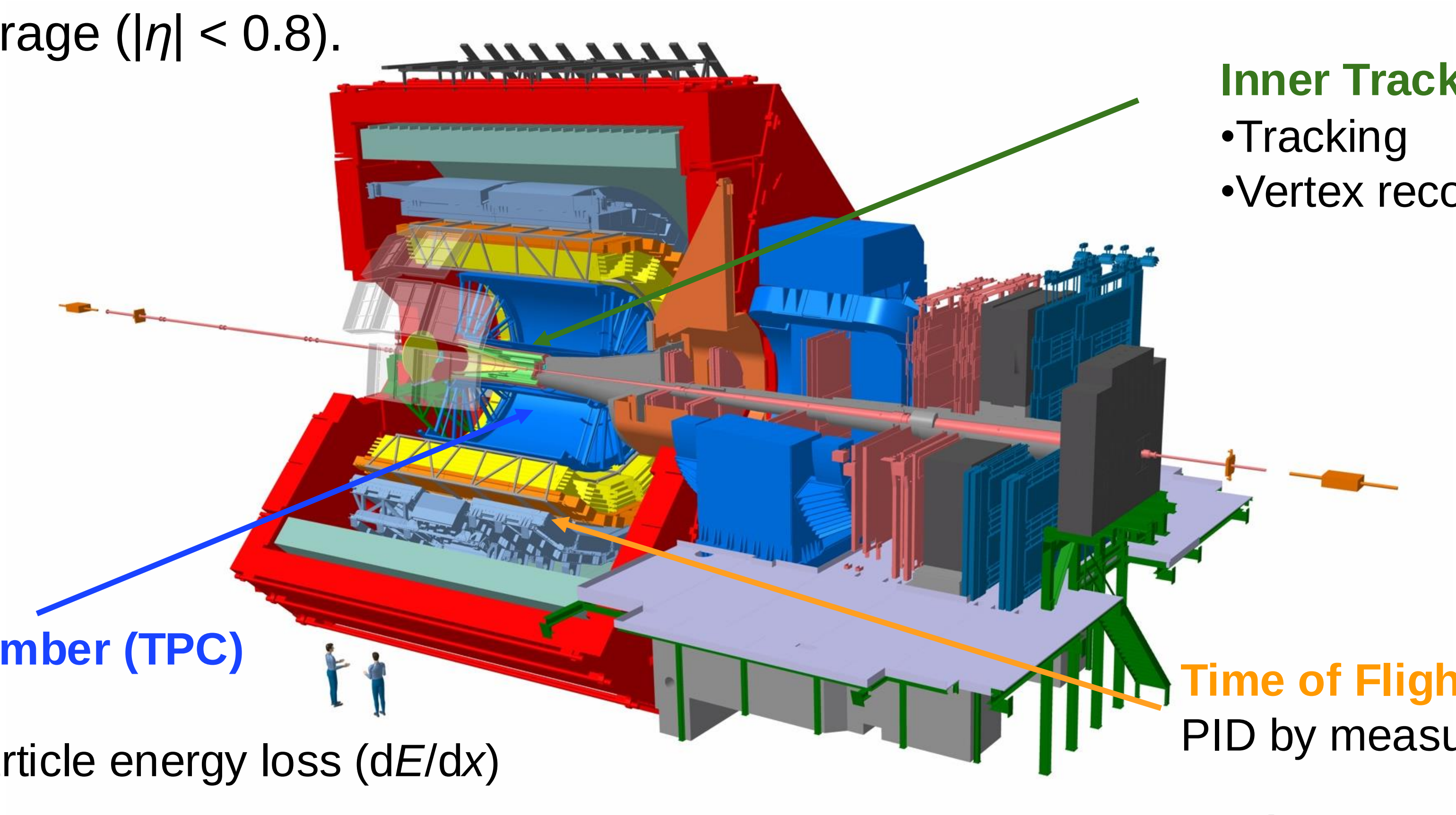


- SE: same event pairs
- ME: mixed event pairs (uncorrelated)
- $\boldsymbol{N}$: normalization factor calculated outside of the femtoscopic signal region
- λ : correlation strength, related to correlations from misidentified or non-primary proton pairs (non-genuine correlations) and to non–gaussianity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

Time of Flight (TOF)

PID by measuring the time of flight

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

Analysis Details:

Event selection: events accepted only with small FT0C-FT0A time difference at trigger level
+ 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
$|\eta| < 0.8$
Number of clusers found in TPC ≥ 100
TPC Crossed-rows over findable Cls ≥ 0.9
TPC Fraction of Shared Cls < 0.05
Number of clusers in ITS ≥ 6
TPC $\chi^2 < 4$
ITS $\chi^2 < 5$
$|DCA_{xy}| < 0.004 + 0.013/pT$ (cm)
$|DCA_z| < 0.004 + 0.013/pT$ (cm)

New cut

Particle Identification:

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

Selected sample:
2.24M protons and 1.84M antiprotons

Pairing tracks:

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

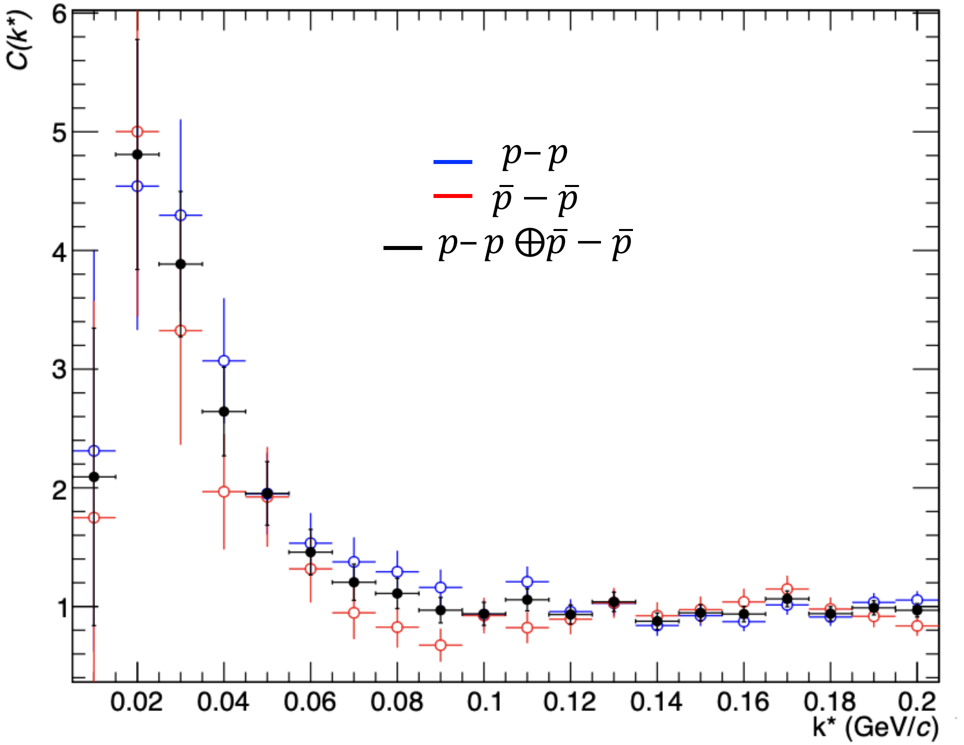
For ME Events are mixed using

- 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

Numeber of pairs used

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



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

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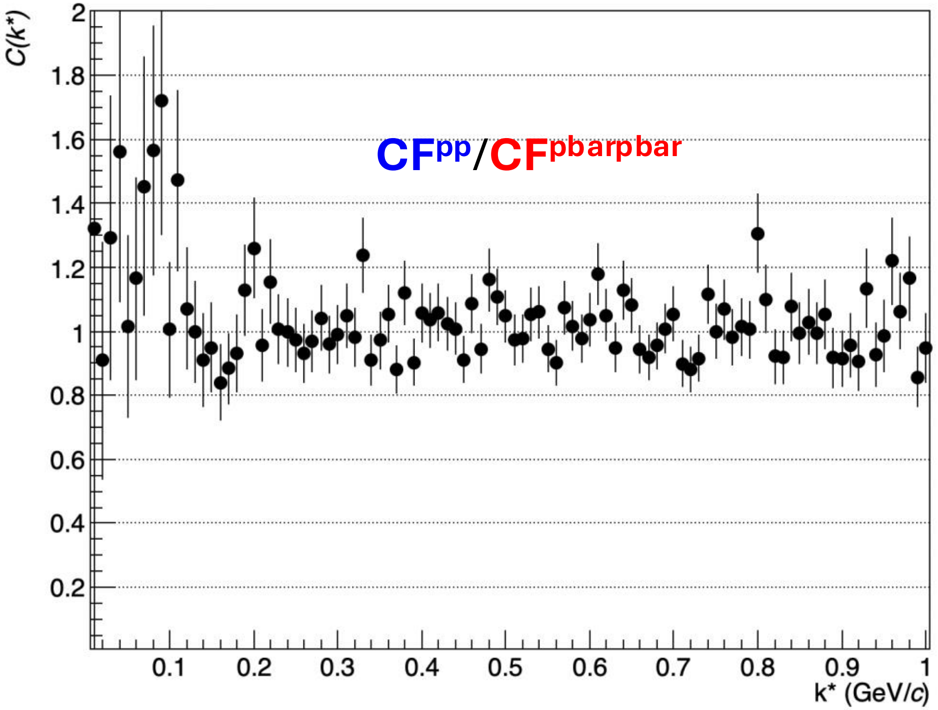
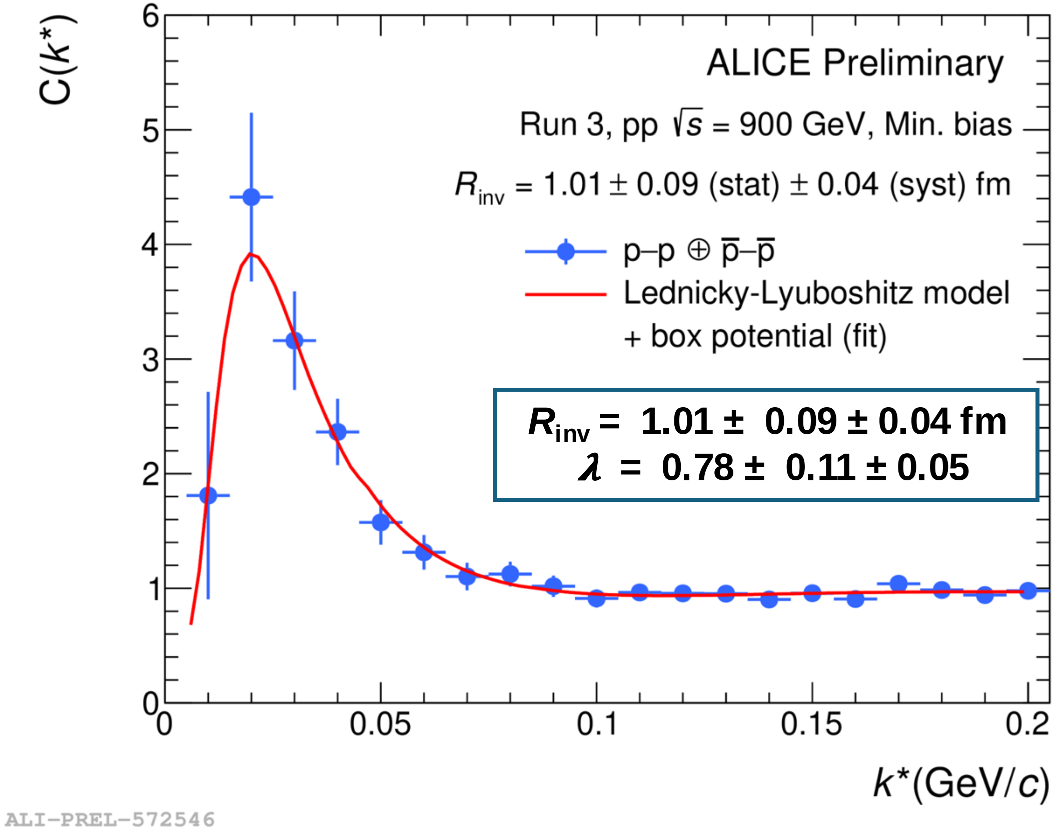


The total CF is the average of $\mathrm{p}-\mathrm{p}$ and $\bar{p}-\bar{p}$ CFs.

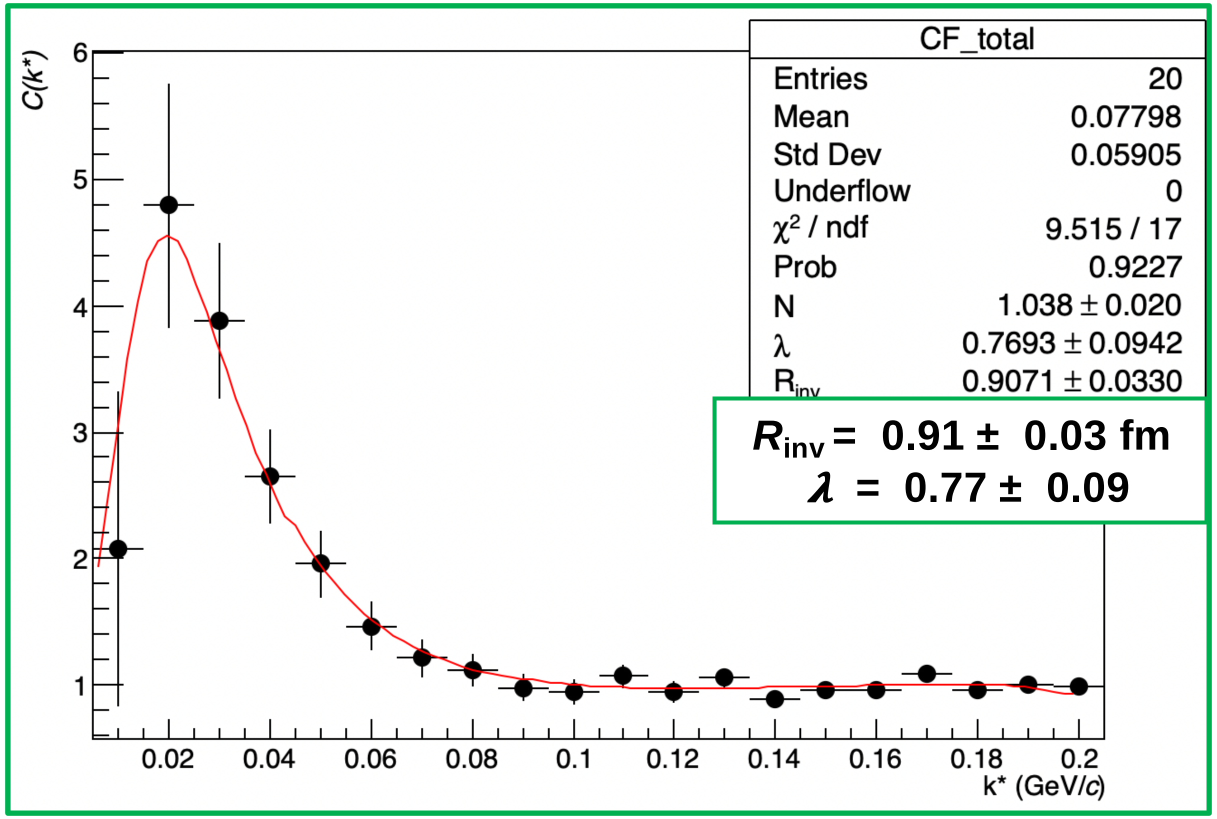
Proton source measurement in pp collisions at $\sqrt{s} = 0.9$ TeV

- CF is smeared to take into account the finite momentum resolution of the detector, by folding the CF with resolution matrix
- The total CF is fitted with the **Lednický–Lyuboshitz model with a box potential approach** (considering both Coulomb and strong interactions).
- The **source size R_{inv}** and the **λ parameter** are **free fit parameters.**

[Lednický, R. et al., Sov.J.Nucl.Phys. 35 (1982) 770]
[Lednický, R., Phys.Part.Nucl. 40 (2009) 307-352]



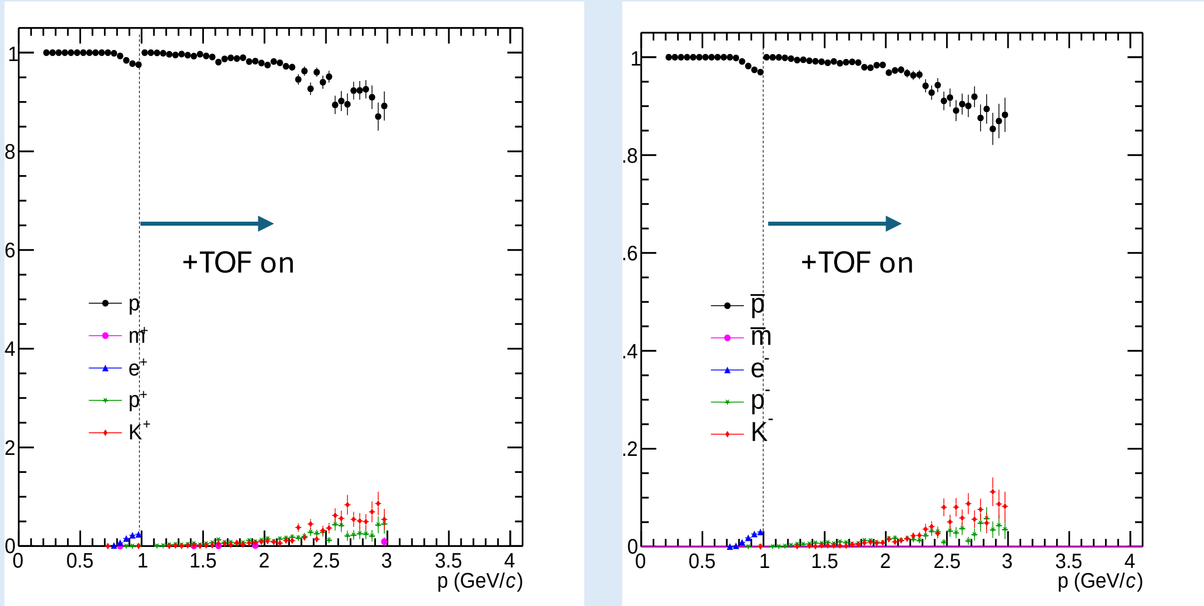
$R_{\mathrm{inv}} = 1.01 \pm 0.09 \pm 0.04$ fm
$\lambda = 0.78 \pm 0.11 \pm 0.05$

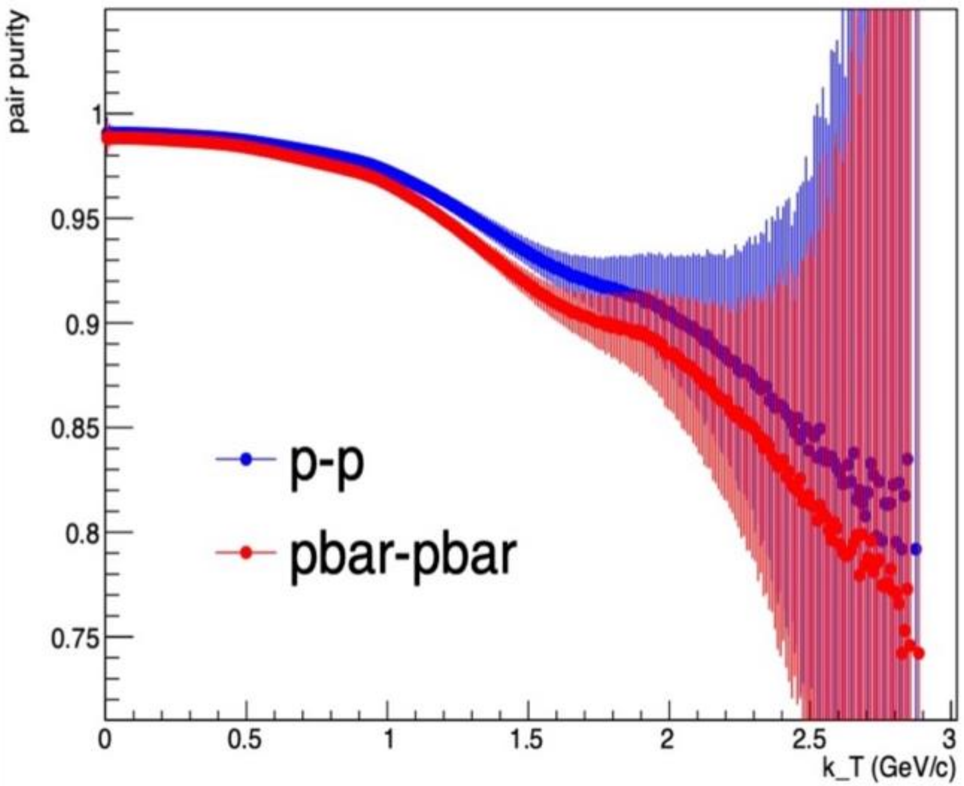


$R_{\mathrm{inv}} = 0.91 \pm 0.03$ fm
$\lambda = 0.77 \pm 0.09$

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

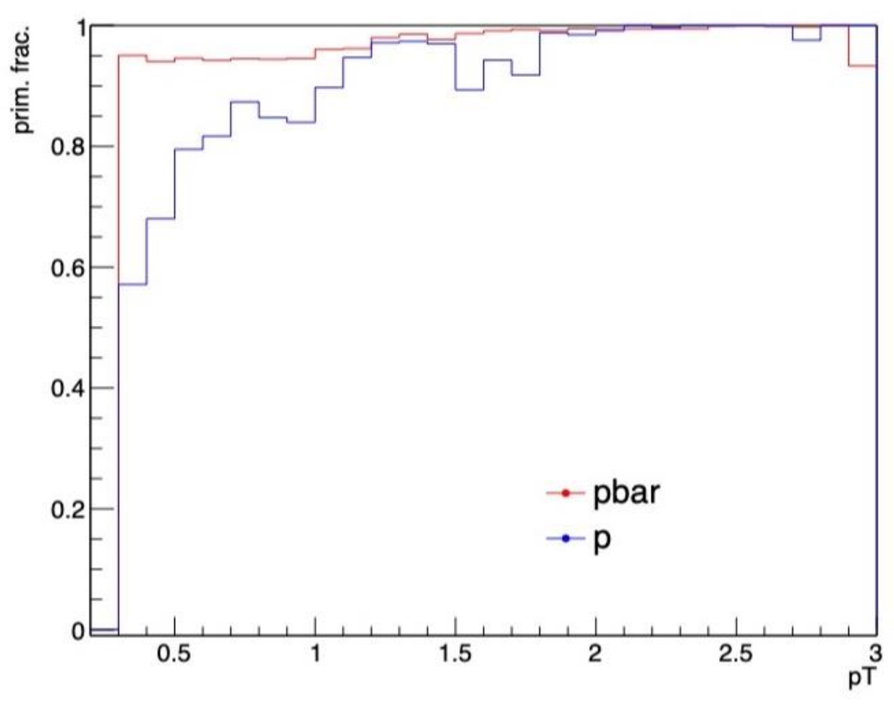
PP $(\bar{p} - \bar{p}) = 0.976$

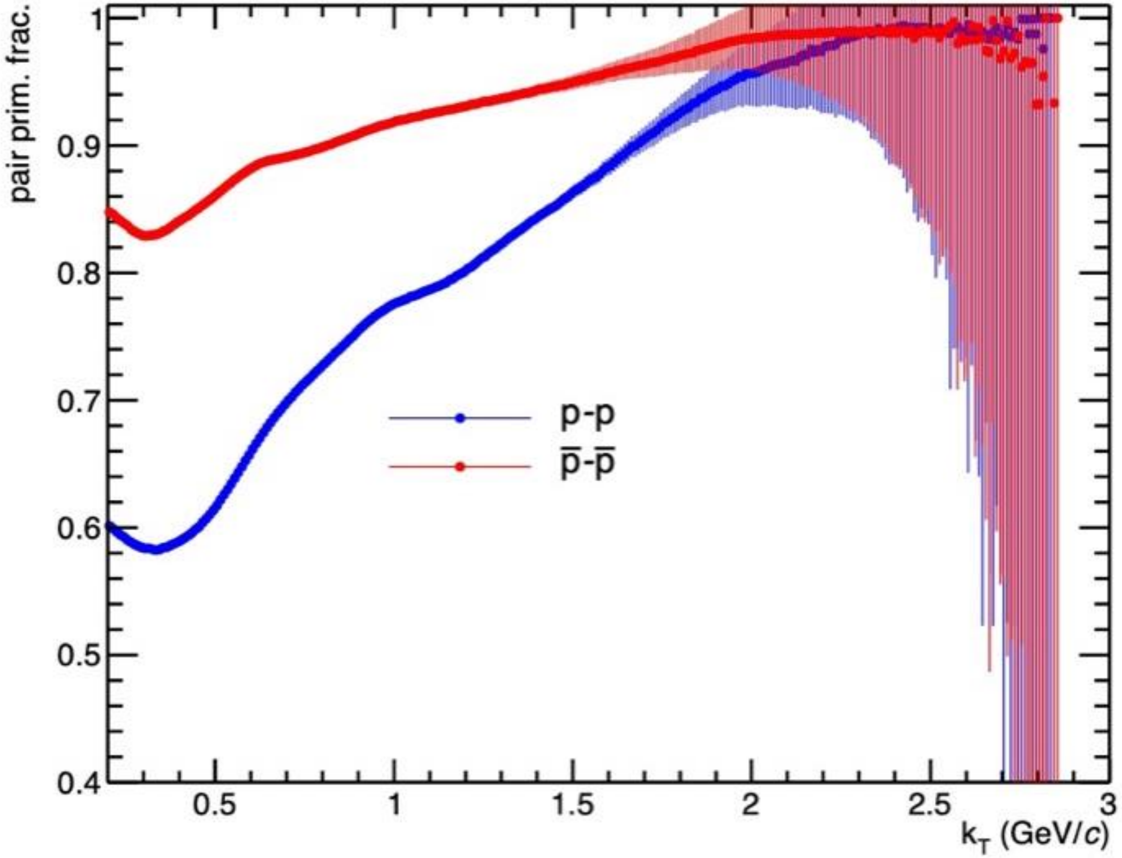
→ Weighted average of PP with number of pairs: **PP $(\mathbf{p} - \mathbf{p} \oplus \bar{p} - \bar{p})$ = 0.98**

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

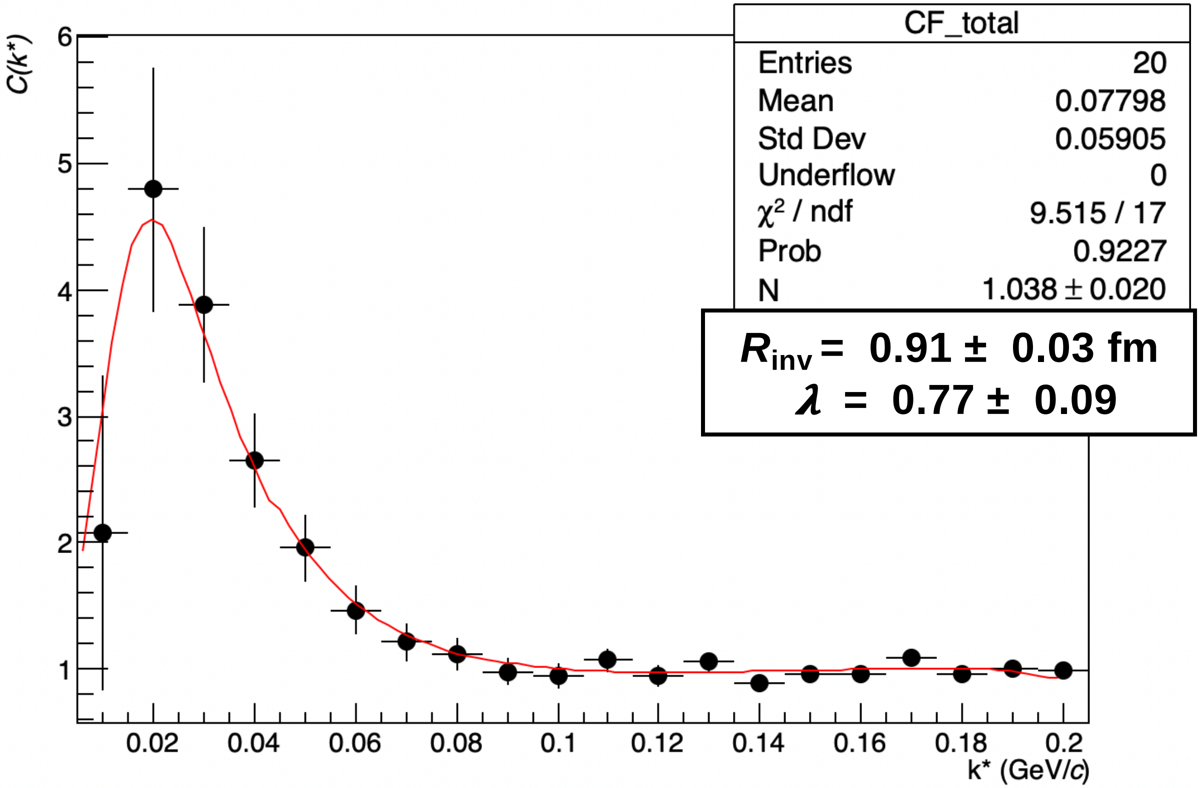
Pair PF = PF $^{\text{particle 1}}$($\mathbf{pT}_1$) x PF $^{\text{particle 2}}$($\mathbf{pT}_2$)

$\mathbf{pT}_1$ and $\mathbf{pT}_2$ 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**

λ parameter : Crosscheck with MC

- The source size R_{inv} and the λ parameter are **free** fit parameters**.**



$$R_{\text{inv}} = 0.91 \pm 0.03 \text{ fm}$$
$$\lambda = 0.77 \pm 0.09$$

$$\lambda^{\text{FIT}} = 0.77 \pm 0.09$$

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

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 $\langle m_\mathrm{T} \rangle$:

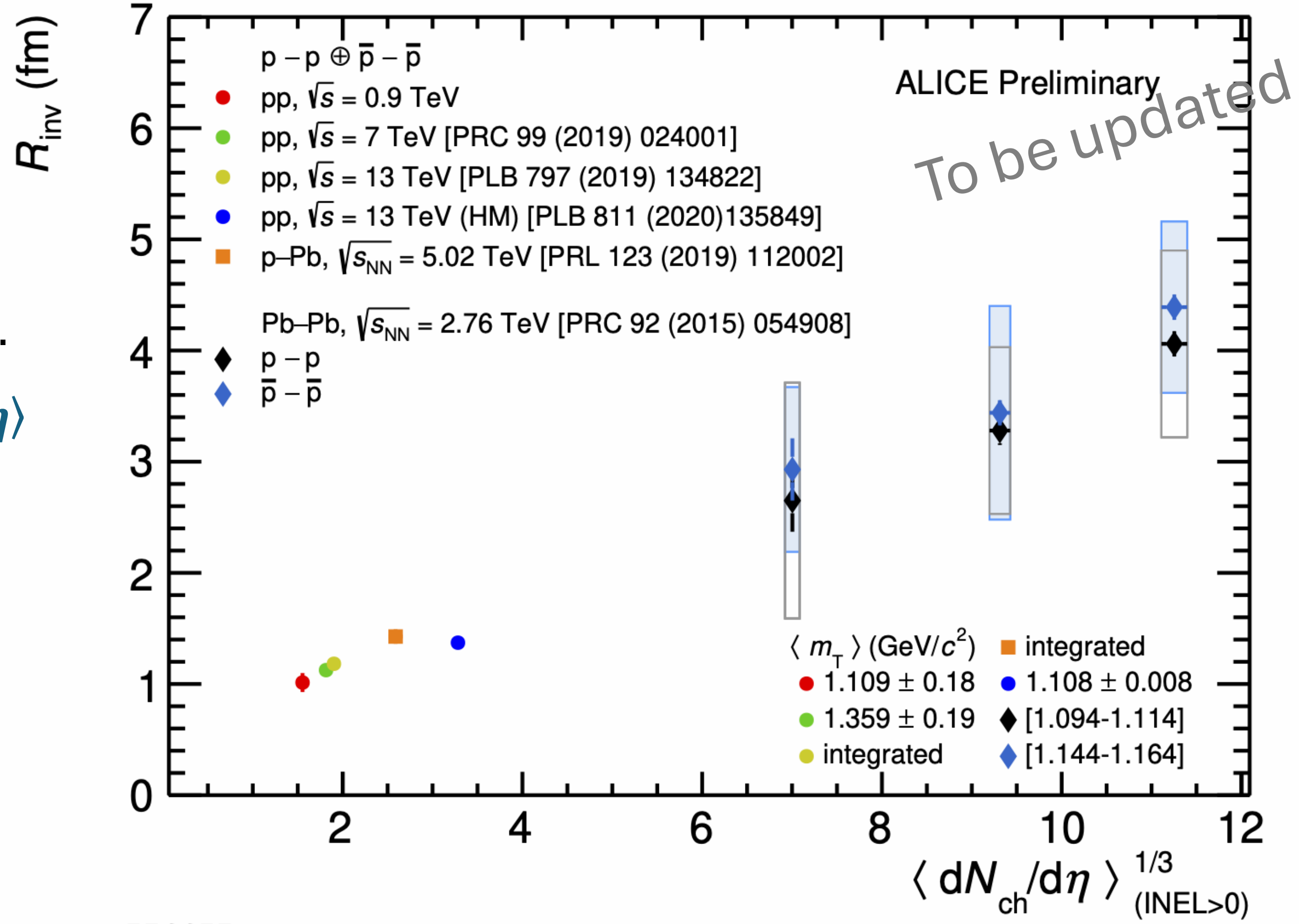
$\langle m_\mathrm{T} \rangle = \sqrt{k_\mathrm{T}^2 + m^2}$ pair transverse mass

k_T pair transverse momentum
m proton mass

→ **Smallest source** in pp collisions at √s = 0.9 TeV.

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

$$R_\mathrm{inv} = 1.01 \pm 0.09 \pm 0.04 \text{ fm}$$
$$\lambda = 0.78 \pm 0.11 \pm 0.05$$



ALI-PREL-574457

Summary

- First ever measurement in pp collisions at $\sqrt{s}$ = 0.9 TeV of the p–p correlation function (CF).
- Smallest proton source ever measured at the LHC
- Future application: use the measured proton source size for the coalescence modelling to estimate deuteron coalescence probability.

Improvements wrt approved results:

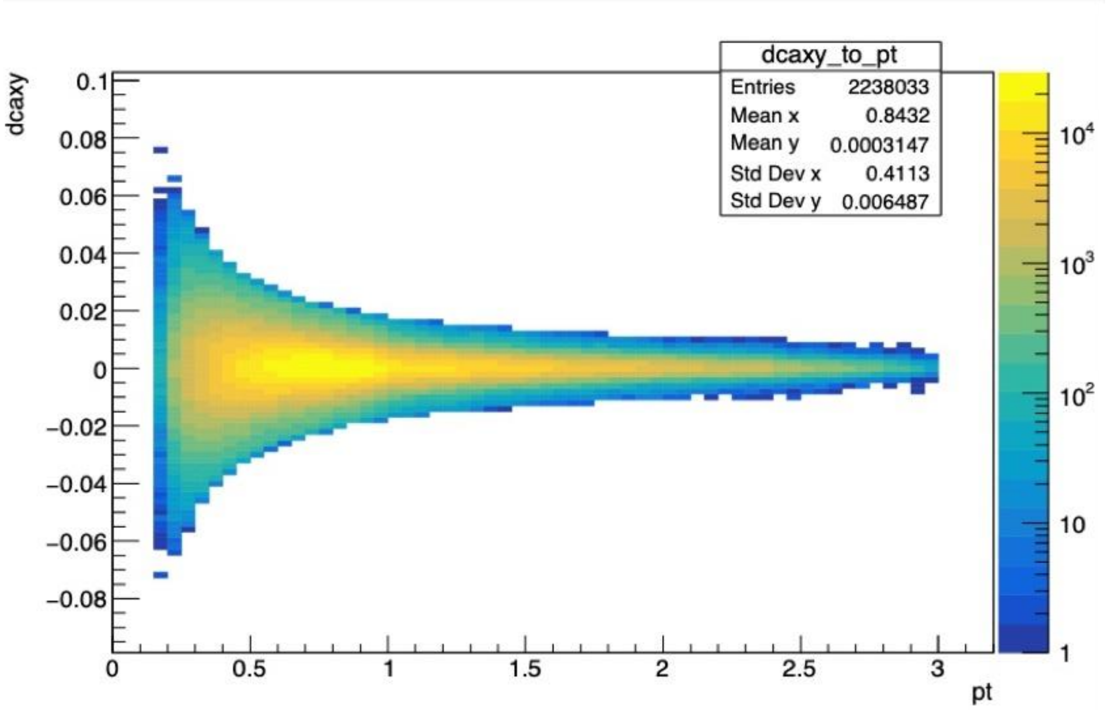
- Implemented pT dependent DCA cut
- Introduced average separation cut
- Stronger consistency of p—p and pbar—pbar CFs
- Statistical uncertainty reduced in fit parameters
- Pair Purity and Primary Fraction from MC have been recalculated and in better agreement with fit results

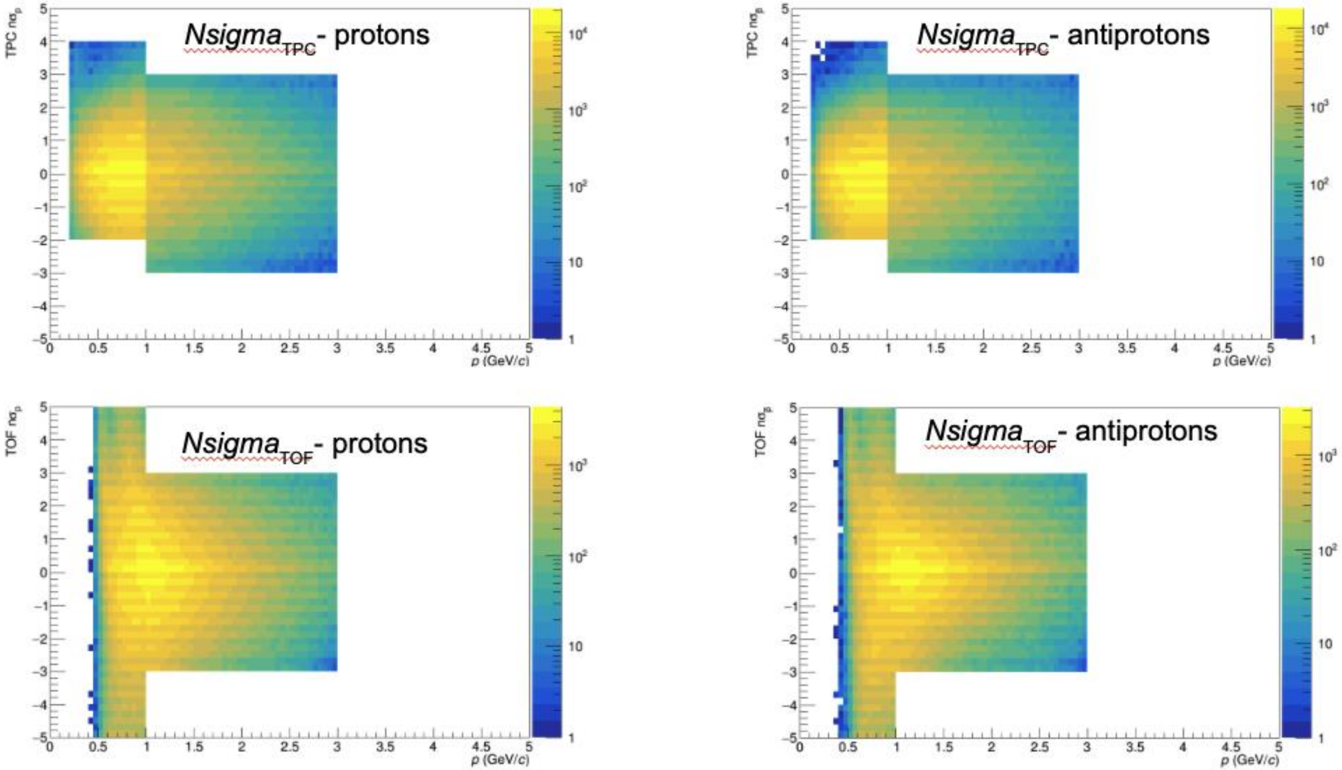
Last Check to be done: → finalize systematic uncertainty

Future perspectives:

- ○ Request from physics coordination to analyze the data sample from 2024 (expected x2 statistics):
  - →waiting for reconstruction
- ○ We are planning to propose this analysis for a publication

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
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
0
0.5
1
1.5
2
2.5
3
pt
10^4
10^3
10^2
10
1


$Nsigma_{TPC}$ - protons
$Nsigma_{TPC}$ - antiprotons
$Nsigma_{TOF}$ - protons
$Nsigma_{TOF}$ - antiprotons
TPC $n\sigma_p$
TPC $n\sigma_{\bar{p}}$
TOF $n\sigma_p$
TOF $n\sigma_{\bar{p}}$
p (GeV/c)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
−5
−4
−3
−2
−1
0
1
2
3
4
5
10^4
10^3
10^2
10
1