Femtoscopy studies in Heavy Ion collisions experiment in HADES:

p-Λ correlation in AgAg collision at 1.58 A GeV

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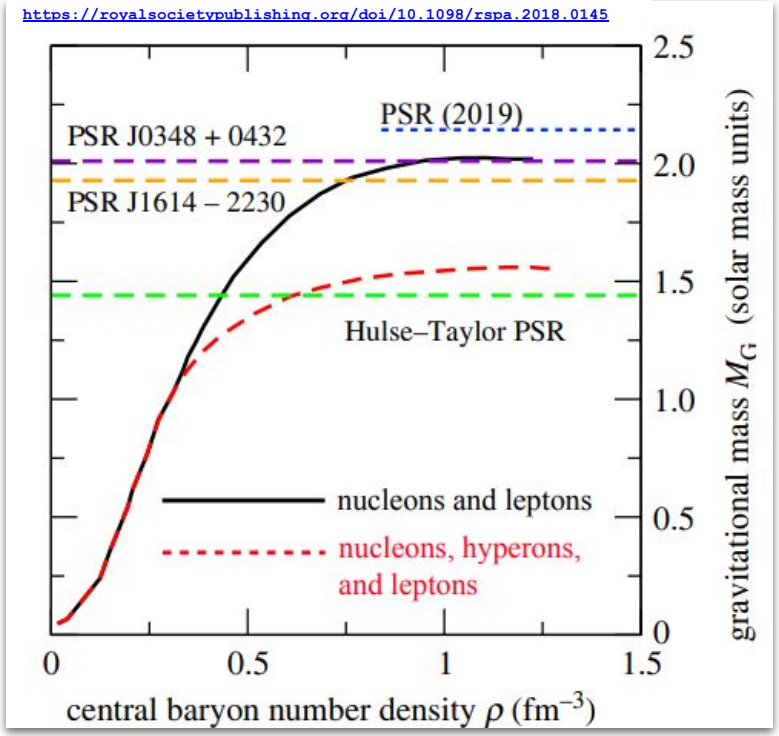
PLAN OF THE TALK

1. Introduction – motivation
2. HADES (GSI) detector system
3. RPC / ToF, particle identification
4. Weak Decay Recognition (Λ data / simulation)
5. Correlation theory
6. Femtoscopic correlation signal (p-Λ signal)
7. Correction using simulations / Purity estimation of identified pairs
8. Final results (I,II), systematics and simulation modeling
9. Summary .....

Neutron Star and hyperon puzzle ?

https://royalsocietypublishing.org/doi/10.1098/rspa.2018.0145



- Neutron stars (NS) are the remnants of the gravitational collapse of massive stars during supernova event.
- Their masses and radii are of the order of 1 – 2 $M_\odot$ and 10 – 12 km, respectively.
- Central densities in the range of 4 – 8 times the normal nuclear matter saturation density, $\varepsilon_0 \sim 2.7 \times 10^{14}$ g/cm^3 ($\rho_0 \sim 0.16$ fm^{-3})

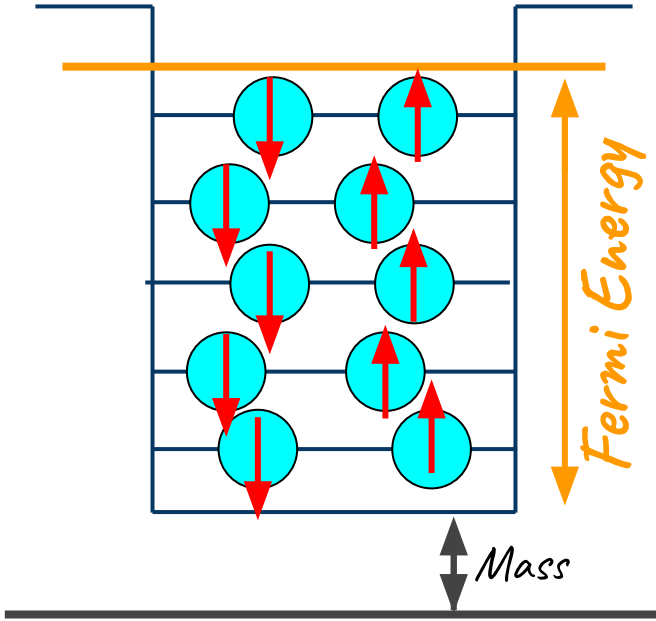
Best suitable theory takes hyperons into account,

- Hyperons are expected to appear in the core of NS at $\rho \sim 2\text{-}3\ \rho_0$
- Hyperons softens the EoS —> Reduction on maximum NS mass
- Observation of the NS with $M_G > 2M_S$ is incompatible with such soft EoS
- Although the existence of hyperons is energetically favorable, their existence makes the EoS softer and is not consistent with the experimental results. This is the essence of the **hyperon puzzle.**

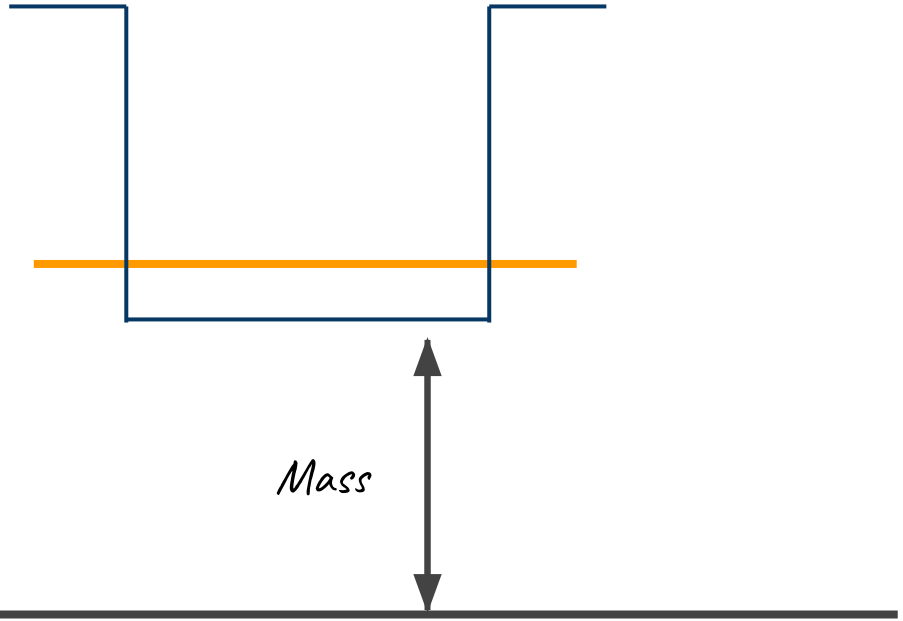
FOR MORE DETAIL : TALK : STRANGENESS IN NEUTRON STARS : DR. LAURA TOLOS

why hyperons are produced

Neutron (uud, m = 938 MeV)



Λ Hyperon (uus, m = 1115 MeV)



why hyperons are produced

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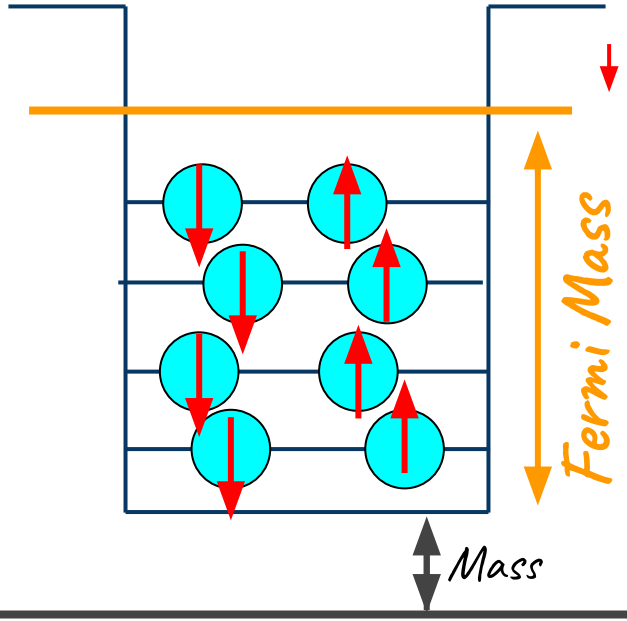

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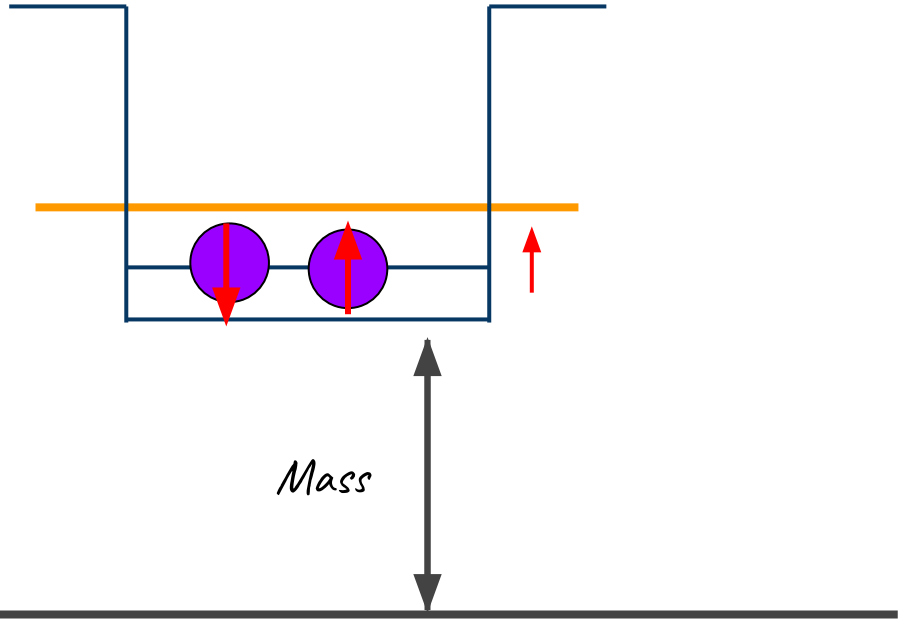

why hyperons are produced

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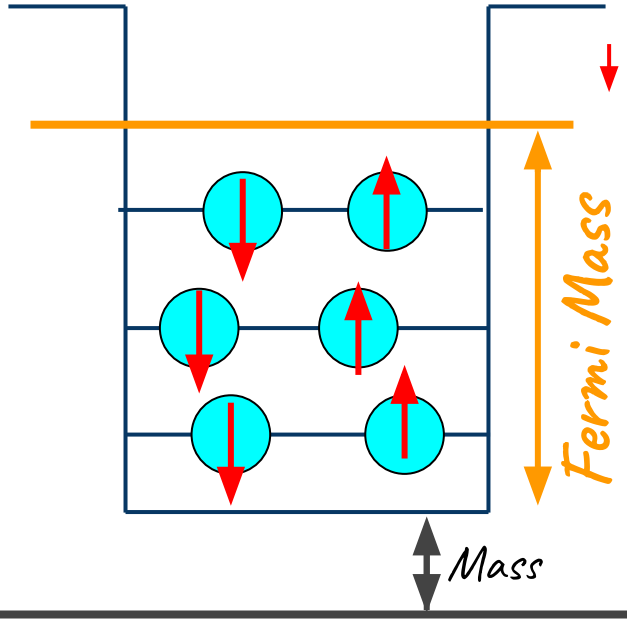

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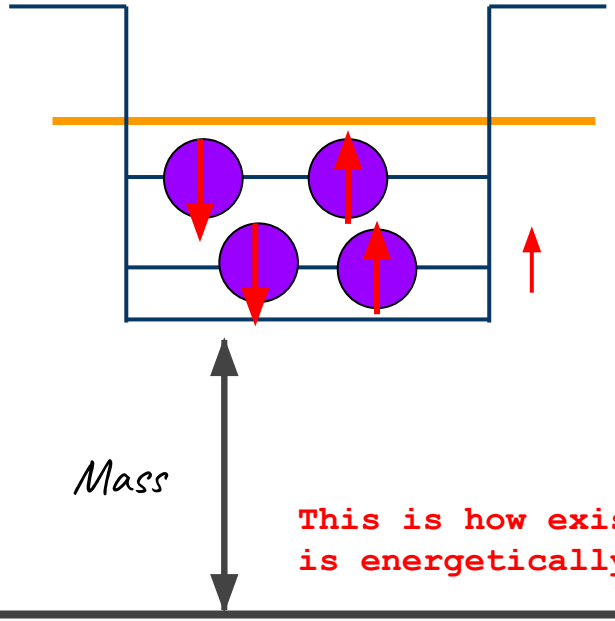
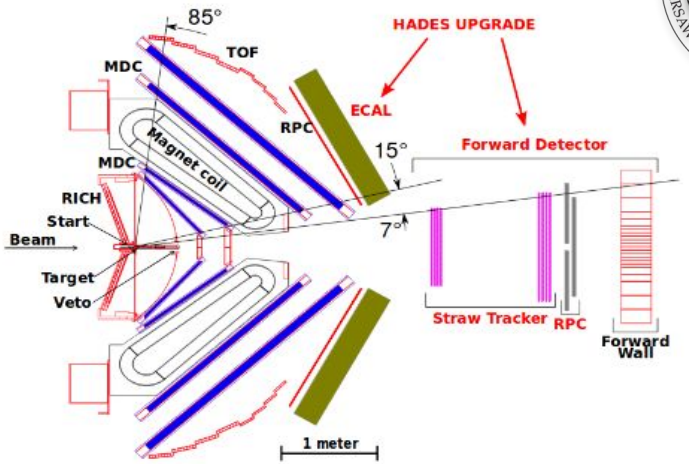
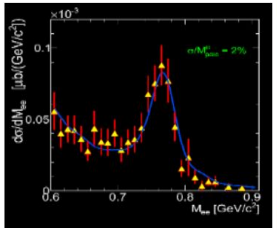


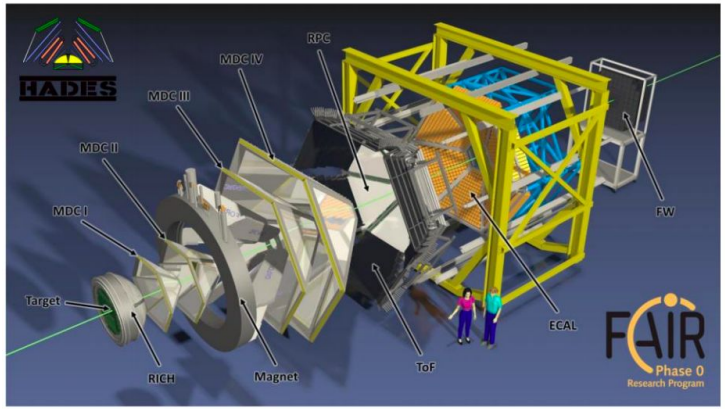
This is how existence of hyperons is energetically favorable.

HADES Spectrometer



- SIS18 beams: protons (1-4 GeV), nuclei (1-2 AGeV), pions (0.4-2 GeV/c) – secondary beam
- rare probes:(e^+, e^-), strangeness: $K^{+/-,0}$, Λ, Ξ^-, φ
- ΔM/M - 2% at ρ / ω
- PID : π/p/K – dE/dx (MDC) and TOF : σ_{tof} ~80 ps (RPC)
- electrons : RICH (hadron blind) TOF/Pre-Shower
- neutral particles: ECAL



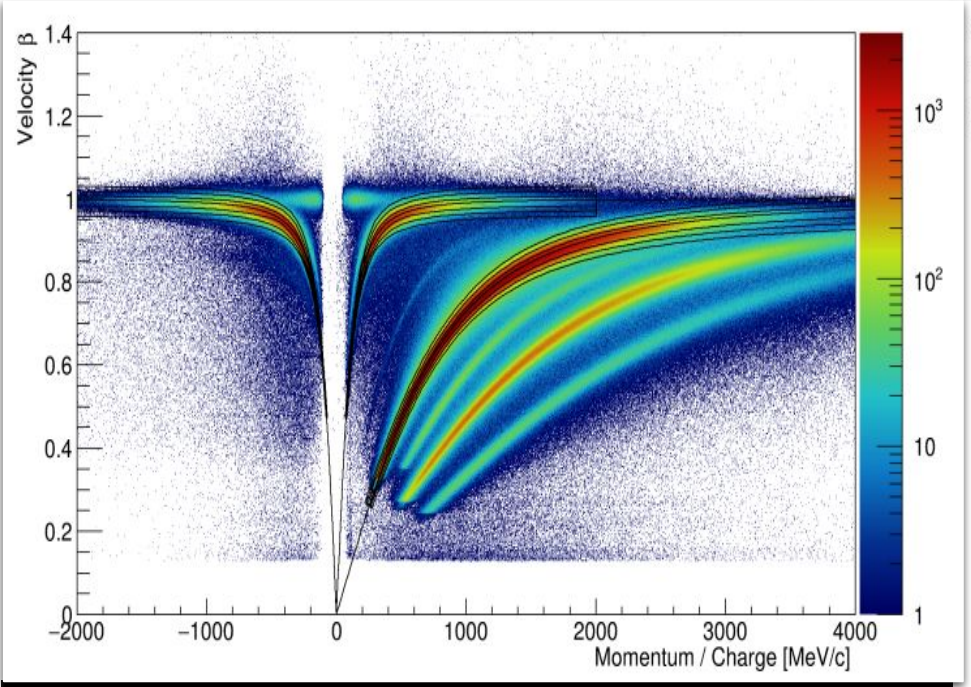


Geometry :

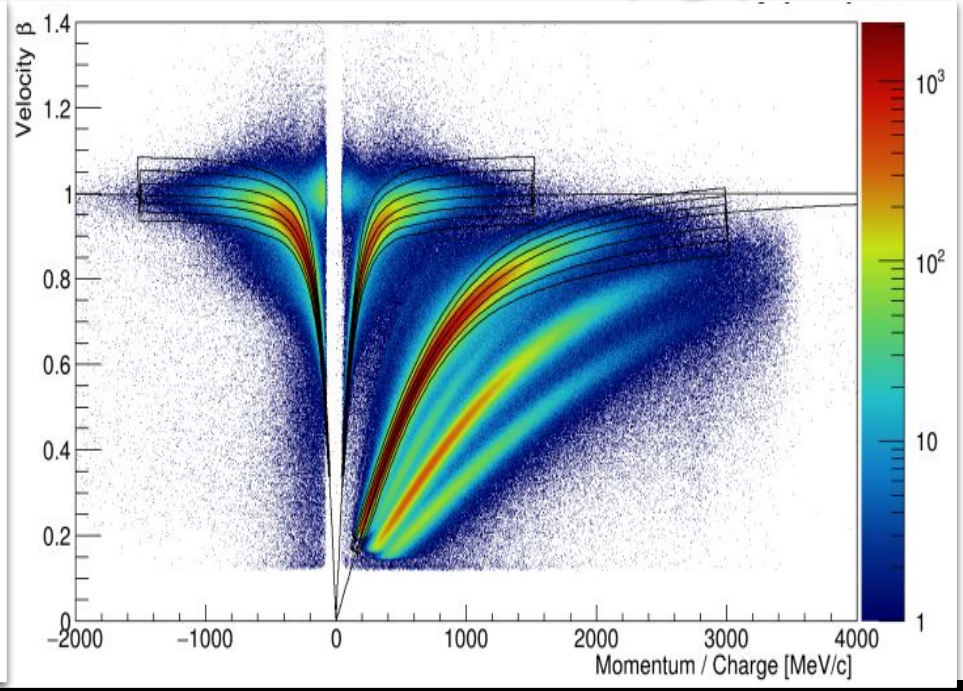
- full azimuthal, polar angles 18° - 85°

Particle identification using RPC

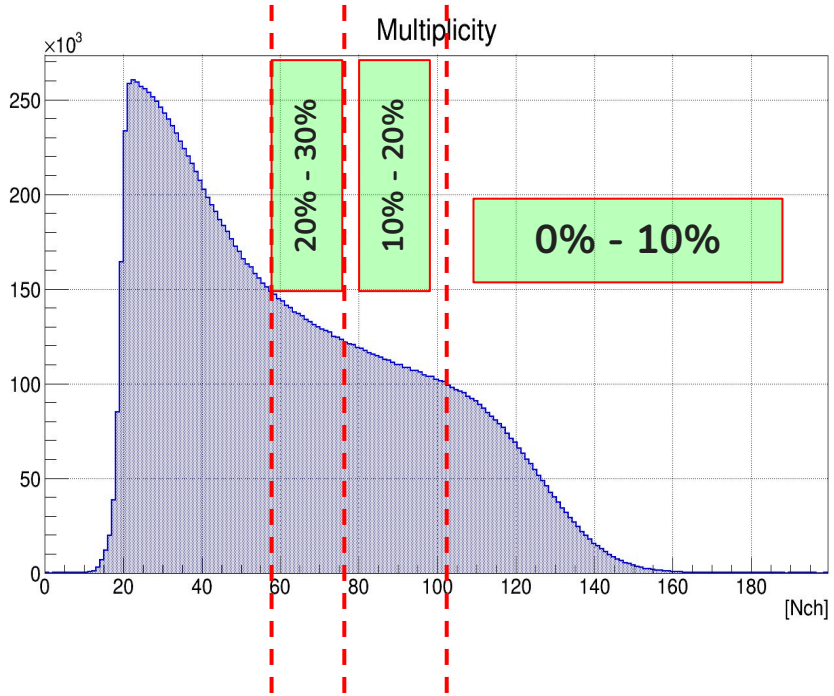
RPC

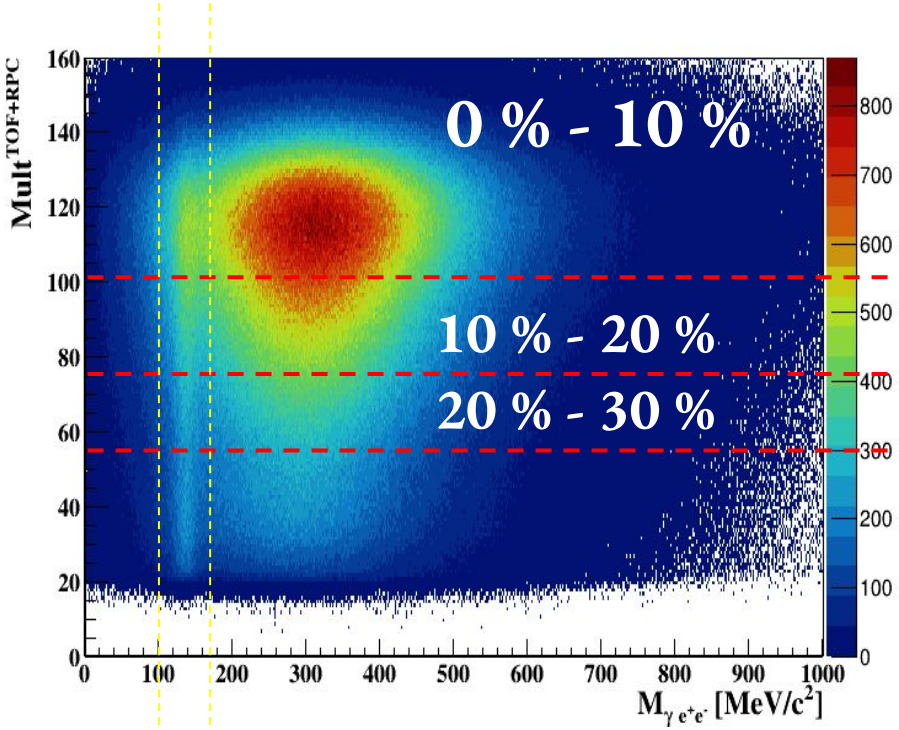


ToF



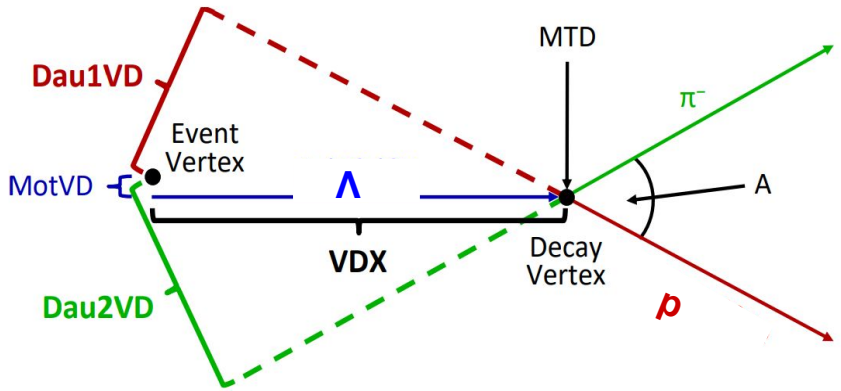
Selected events, Multiplicity





Signal Reconstruction

Weak Decay Recognition



Schematic depiction of the Off-Vertex-Decay-Topology of Λ decays.

- Distance between the primary and secondary vertex (**VDX**) = **> 65 mm**

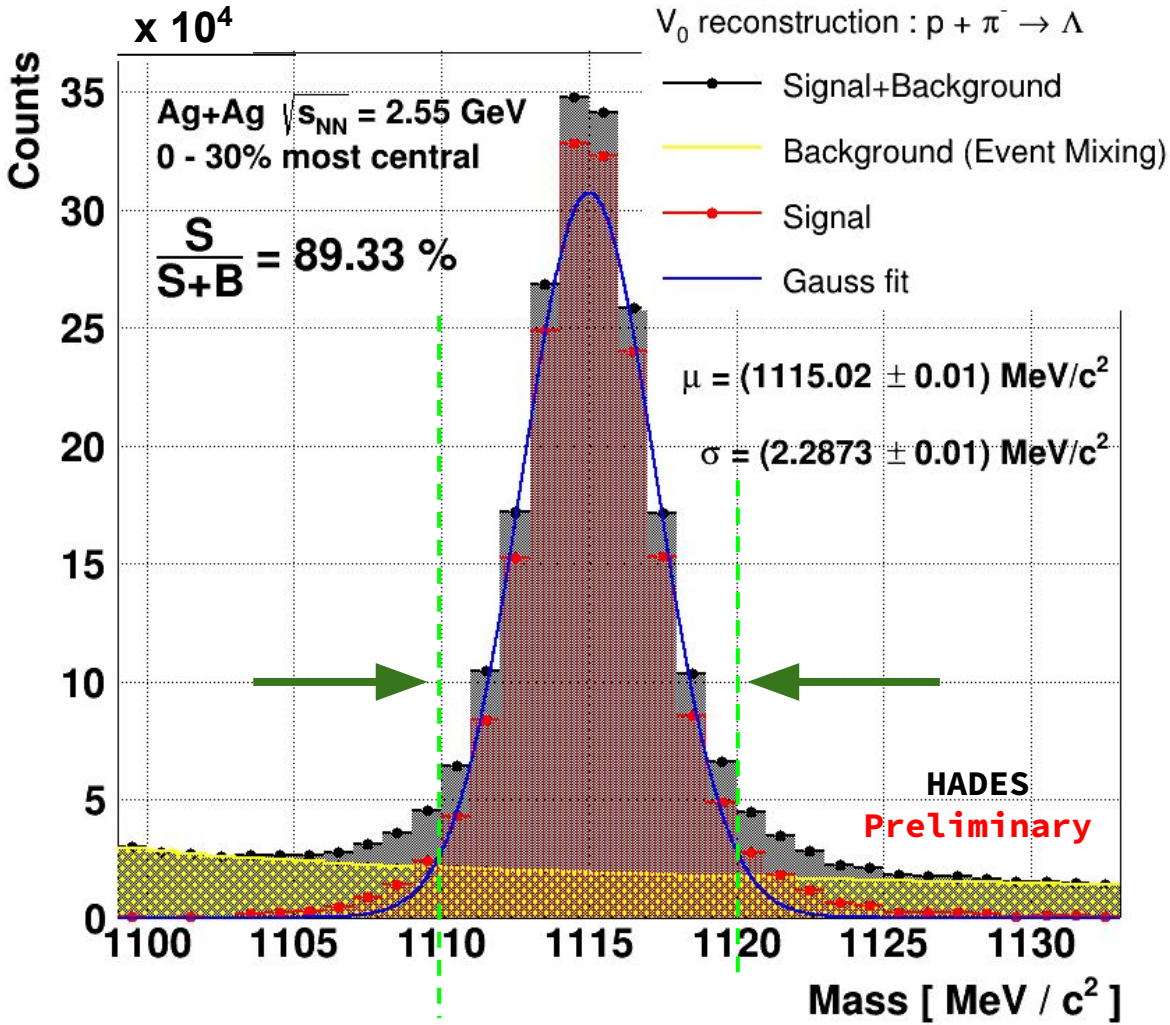
- Distance of closest approach (DCA) between the daughter tracks and the primary vertex,
  → **Dau1VD = > 8 mm**
  → **Dau2VD = > 24 mm**

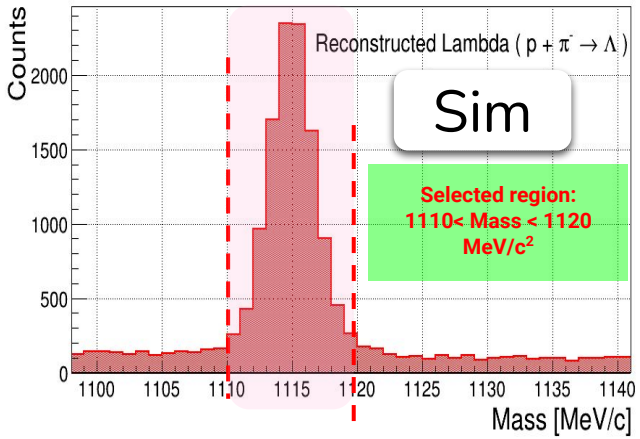
- DCA between reconstructed mother track and primary vertex (**MotVD**) = **< 5 mm**

- DCA between the two daughter tracks (**MTD**) = **< 6 mm**

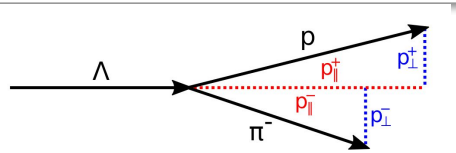
- Opening angle between the two daughter tracks (A) = **> 15 ^{o}**

Reconstructed Lambda Signal ($\pi^- + p \rightarrow \Lambda$)



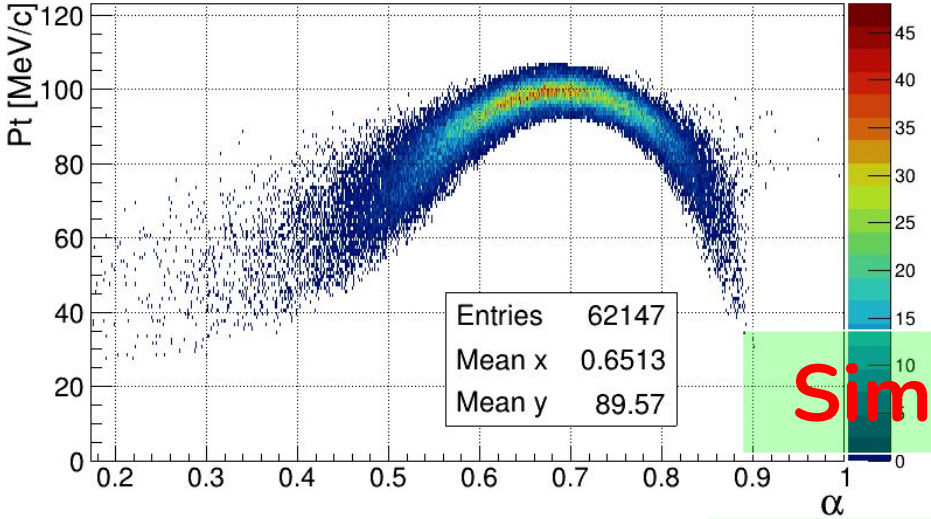


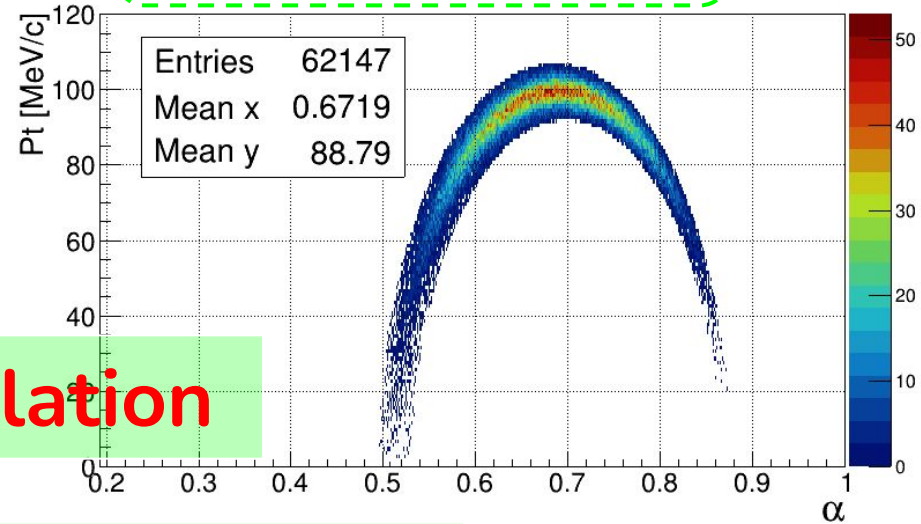
Armenteros-Podolanski plots



Geometrical definition of the Armenteros-Podolanski variables
Example : $\Lambda \rightarrow p + \pi^-$

$$p_T \quad vs \quad \alpha = \frac{p_{||}^{+} - p_{||}^{-}}{p_{||}^{+} + p_{||}^{-}}$$

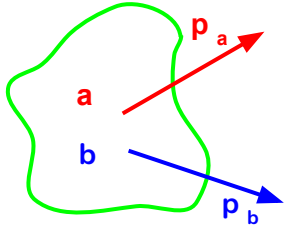




Simulation

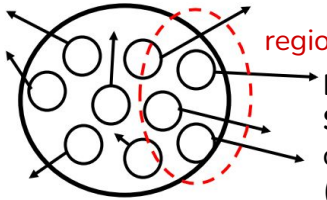
HADES : Low energies → **Additional boost to daughter particles TVector3 beta (0., 0., 0.99);** → **Corrected**

Strategy of analysis :



$$C^{ab}(P,q) = \frac{\mathbb{P}(\vec{p_a},\vec{p_b})}{\mathbb{P}(\vec{p_a})\mathbb{P}(\vec{p_b})} = \int d^3r' \, \underbrace{S_p(r')}_{1} \underbrace{|\phi(q,r')|^2}_{2}$$

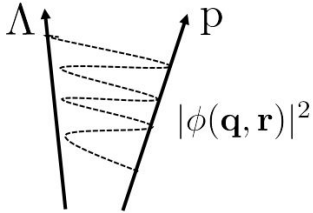
1



region of homogeneity == "Source" = $S_p(\mathbf{r'})$

Emission profile of the Ag-Ag system : **Source function :**Distribution of relative distance between the particle pairs (in CMS)

2



Use the information of point 1 to investigate particle interactions which are not well known

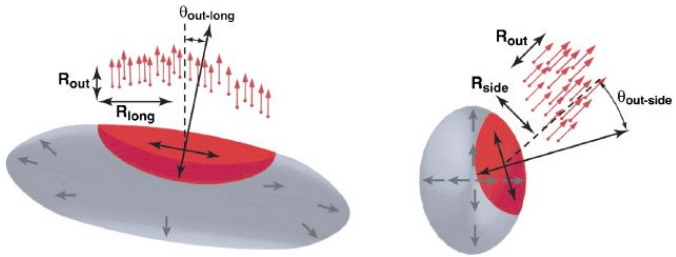
Method 1 :

- Lednicky Model : Correlation formula as a function of the Λp scattering length and source radii r_0.
- Scan and extract strong interacting parameters (f_0, d_0) and source radii (r_0).

Method 2 :

- SMASH simulation for particle correlation
- CRAB Afterburner to account for the Final State Interaction among the emitted particles.

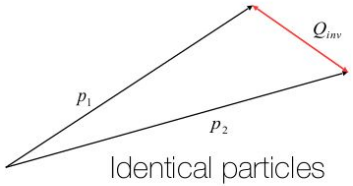
What does femtoscopy measure?



Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402

Q_{inv}

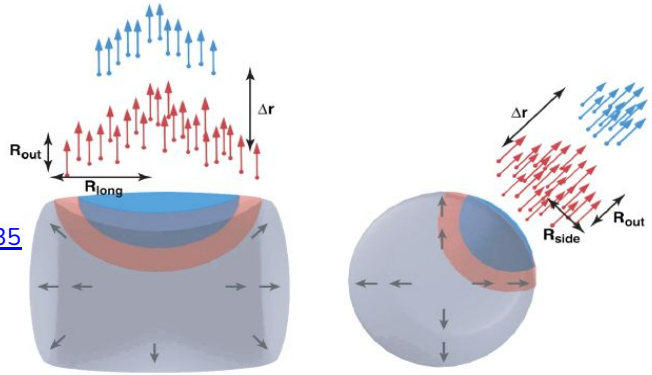
Longitudinal Co-Moving System - **LCMS**



Identical particles

Homogeneity region

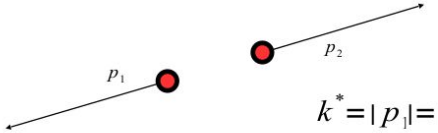
Y.M. Sinyukov, (1995),
https://doi.org/10.1007/978-1-4615-1945-4_35



Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402

k^*

Pair Rest Frame - **PRF**



$k^* = |p_1| = |p_2|$

Nonidentical particles

$Q_{inv} = 2k^*$ for $m_1 = m_2$

Lednicky & Lyuboshitz analytical model

$$C(k^*) = \left\langle \left| \Psi^S_{-\mathbf{k}^*}(\mathbf{r}^*) \right|^2 \right\rangle,$$

where the wave function Ψ^s represents the approximate stationary solution of the scattering problem

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

The effective range approximation for the scattering amplitude is

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

where f_0^S is the scattering length and d_0^S is the effective radius for a given total spin **S = 1** or **S = 0**.
The particle is assumed to be unpolarized (the polarization **P = 0**) :
singlet state $\rho_0 = \frac{1}{4}(1 - P^2)$ and triplet state $\rho_1 = \frac{3}{4}(1 - P^2)$.

Lednicky & Lyuboshitz analytical model

The normalized pair separation distribution (source function) **S(r*)** is assumed to be Gaussian,

$$S(\mathbf{r}^*) = (2\sqrt{\pi}r_0)^{-3} e^{-\frac{\mathbf{r}^{*2}}{4r_0^2}},$$

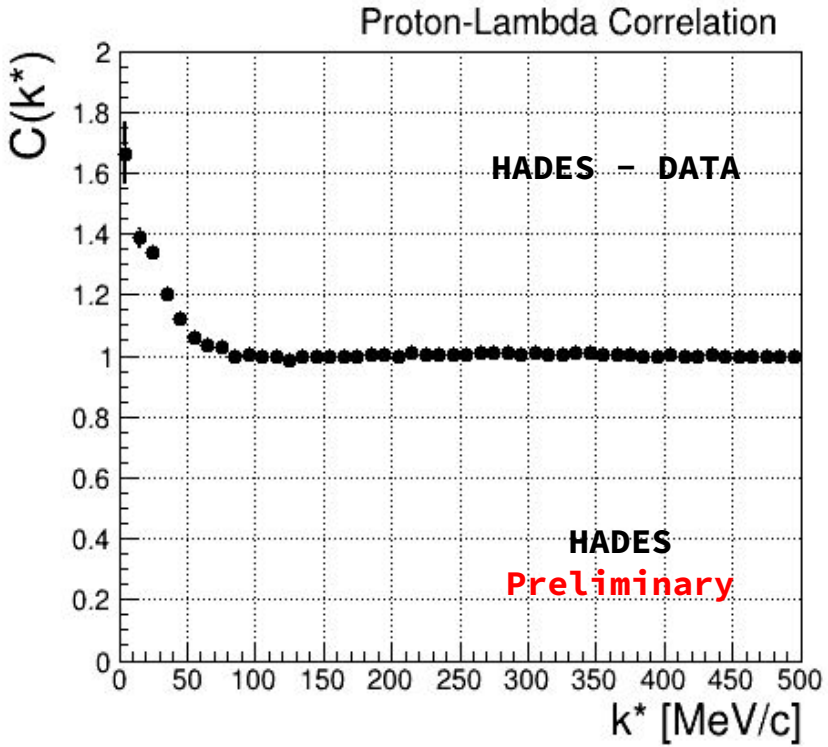
The correlated function can be calculated analytically by averaging Ψ^s over the total spin S and the distribution of the relative distances **S(r*)**

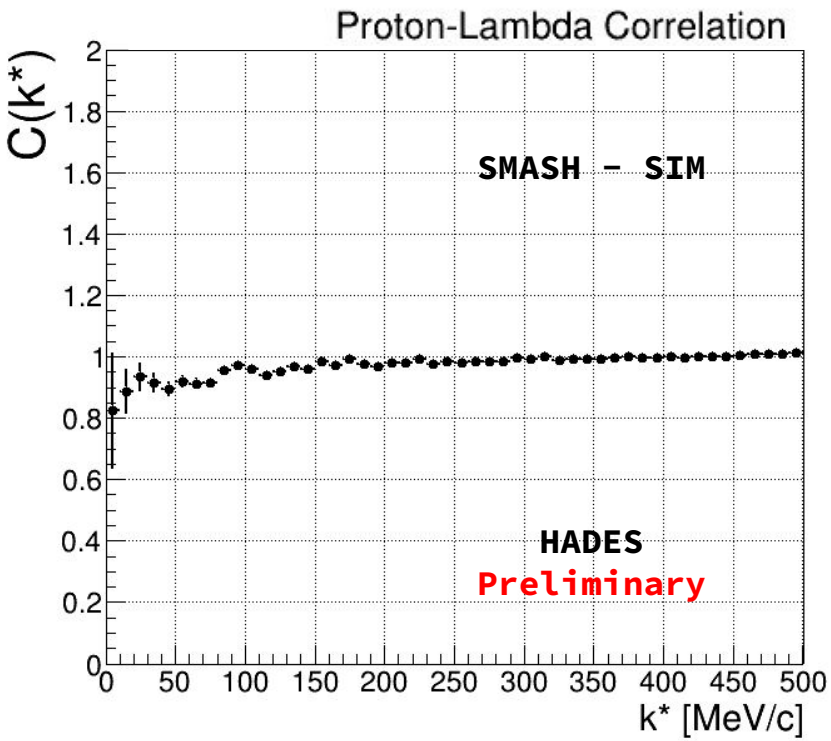
$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{r_0} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi}r_0} \right) + \frac{2\Re f^S(k^*)}{\sqrt{\pi}r_0} F_1(Qr_0) - \frac{\Im f^S(k^*)}{r_0} F_2(Qr_0) \right],$$

with $F_1(z) = \int_0^z dx e^{x^2 - z^2}/z$ and $F_2(z) = (1 - e^{-z^2})/z$.

L.L. papers: Sov.J.Nucl.Phys. 35 (1982) 770, Yad.Fiz. 35 (1981) 1316-1330
(also here: APH N.S., Heavy Ion Physics 3, 93–113 (1996). https://doi.org/10.1007/BF03053635)

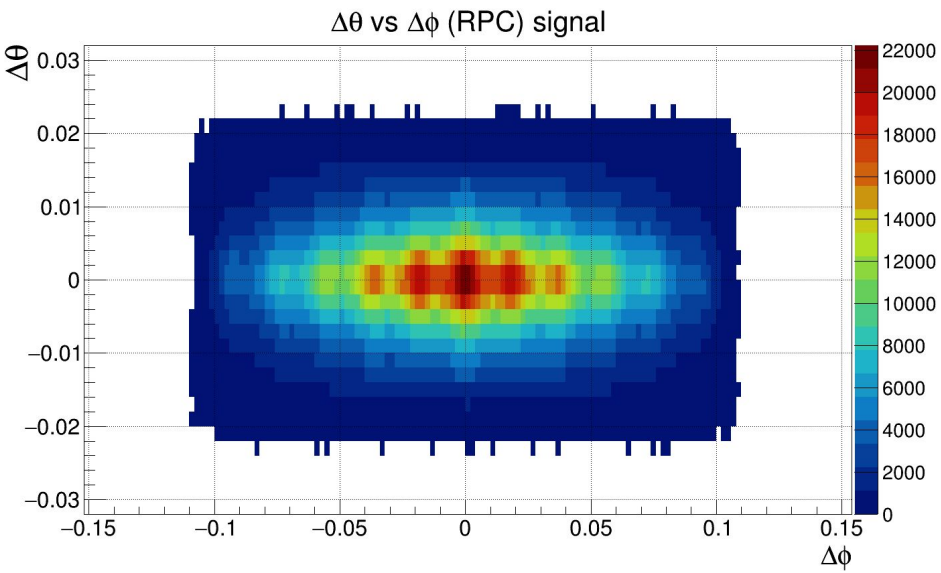
pΛ correlation – Data / Sim



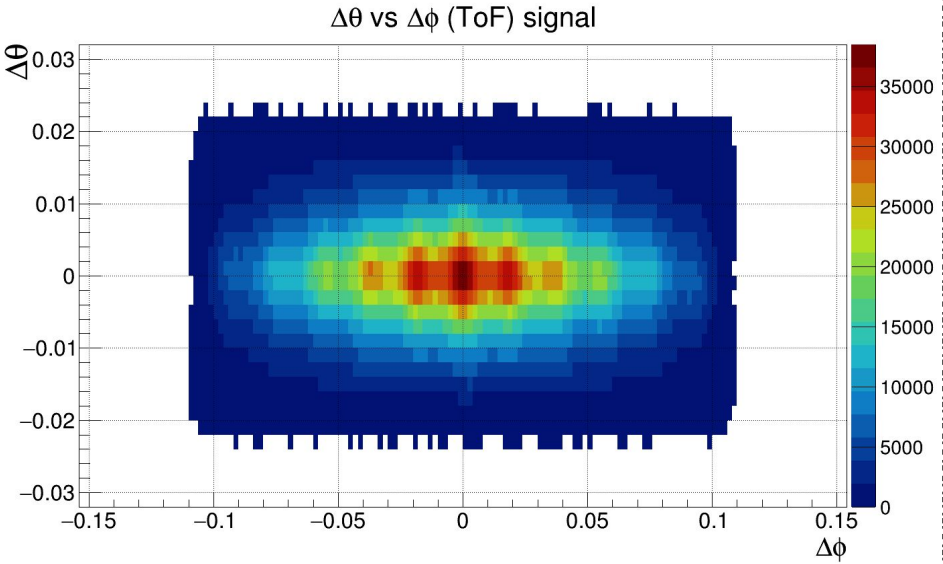


Δθ vs Δϕ distribution (Merging and Splitting)

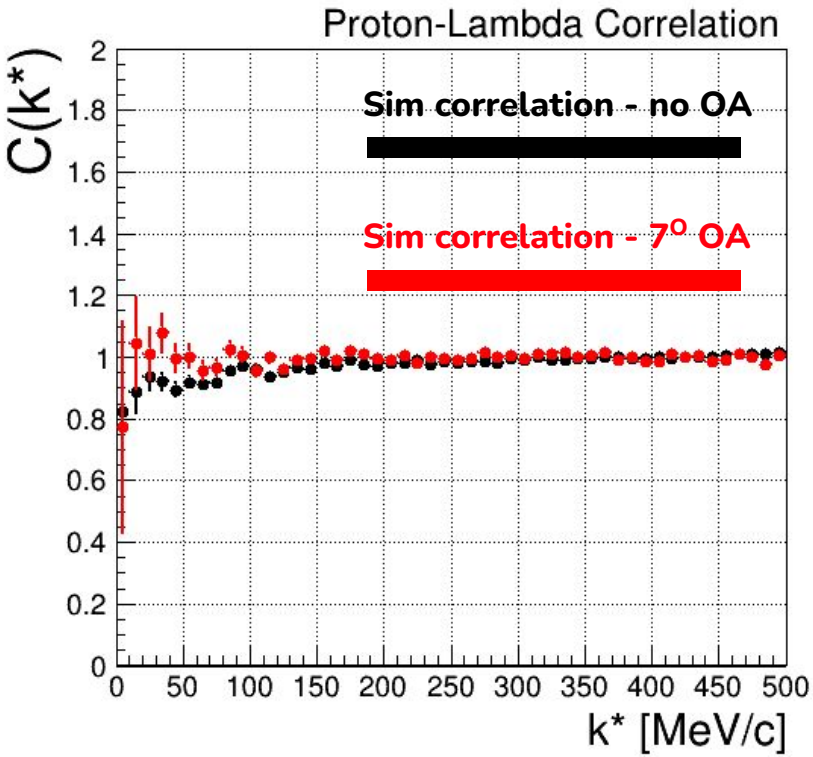
RPC results

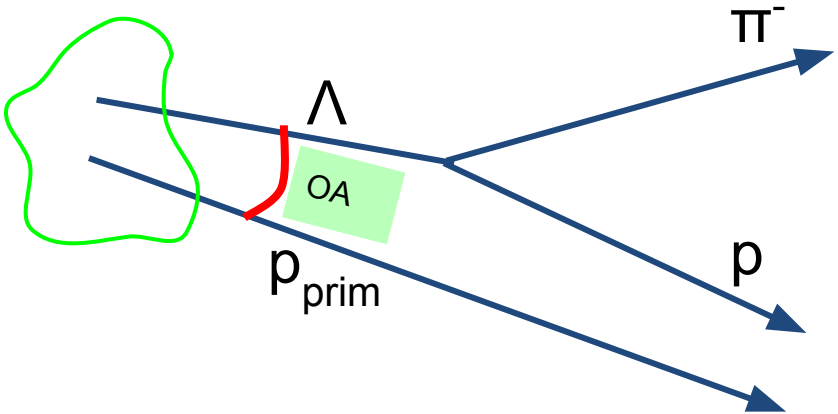


ToF results



pΛ correlation – Simulation

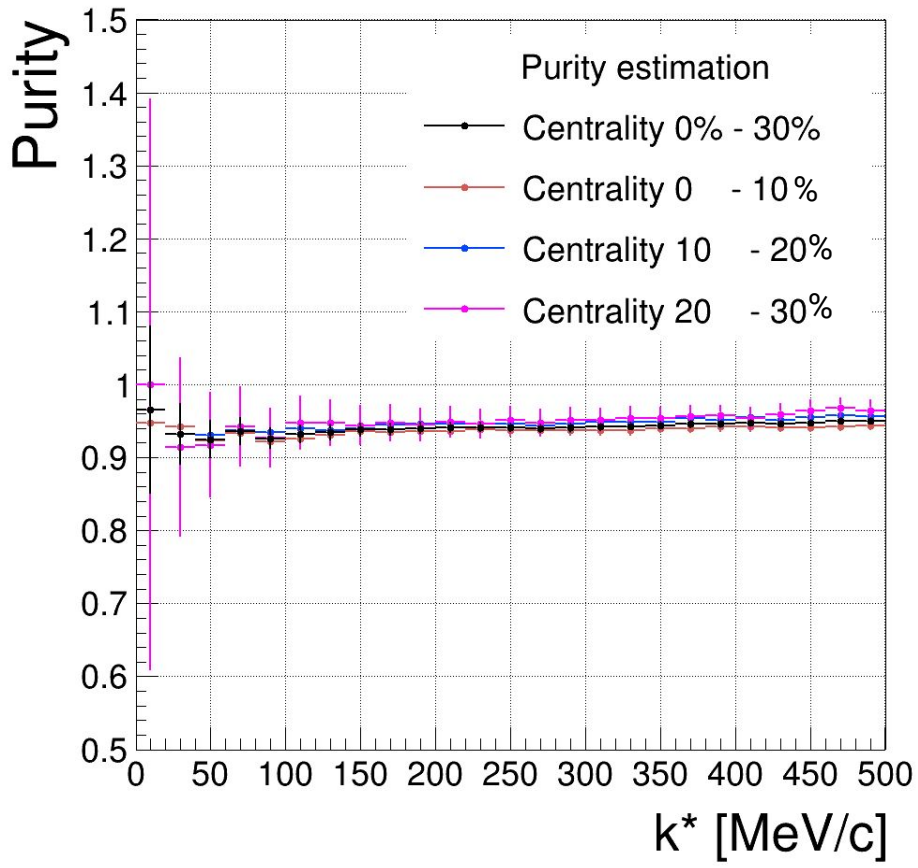




- Additional opening angle cut introduced between reconstructed Λ track and p track (primary)
- Solution is new problem : huge reduction in statistics is observed ~ 40%
- Double ratio correction is acceptable

Purity plot

$$C_{pur,corr}(k) = \frac{C_{pur,uncorr}(k)-1}{purity} + 1,$$



- Purity correction is included bin-by-bin

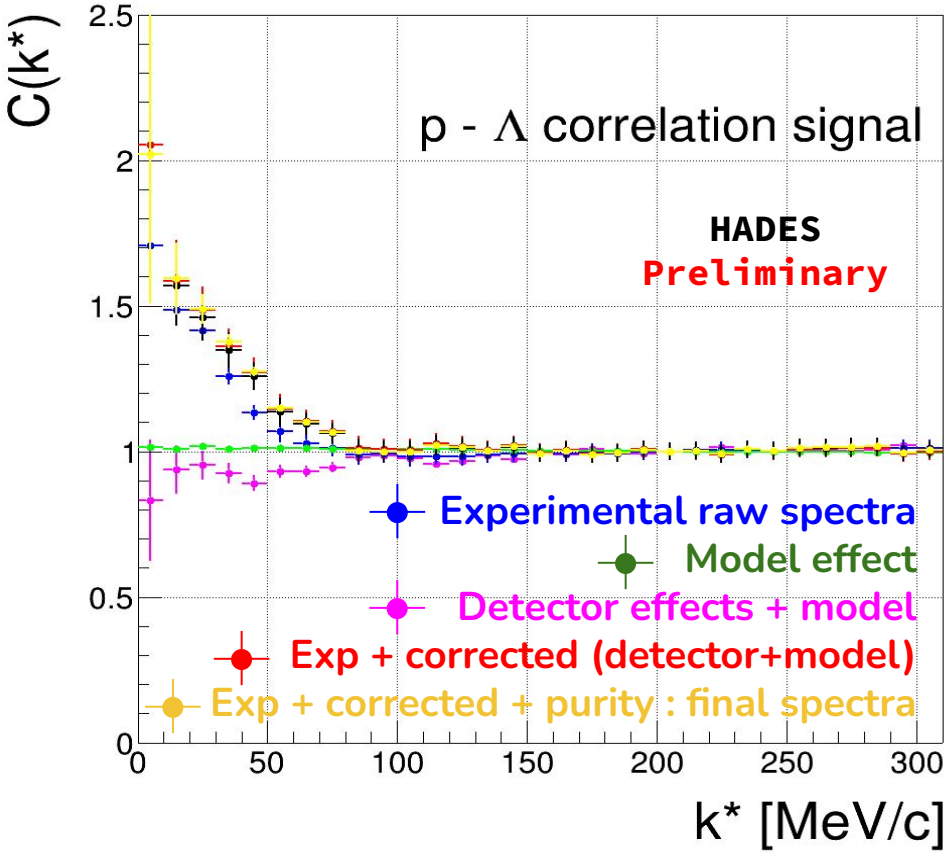
- performed on simulation
- Plotted with respect to k*
  – PID, DCA, Mass cuts

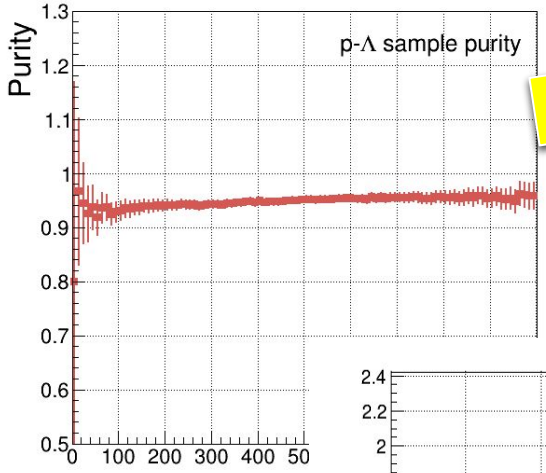
In addition :

- GeantPID (protons, pions)
- GeantParentTrackNum
- GeantParentPID (lambda)

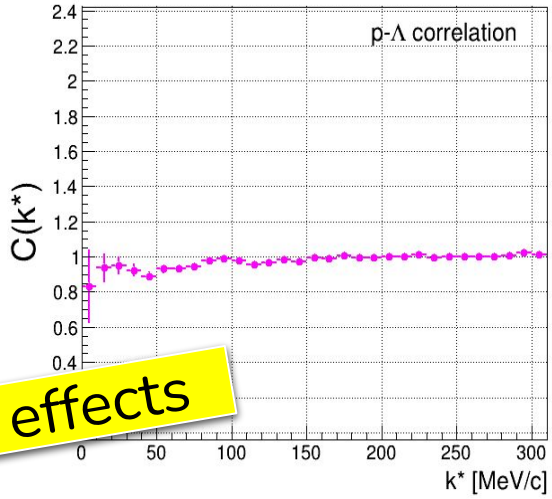
For all centrality classes estimated purity for pΛ :
90% -92% ± 3% (data) (<400 MeV/c)

p-Λ correlation in AgAg collision at 1.58 A GeV





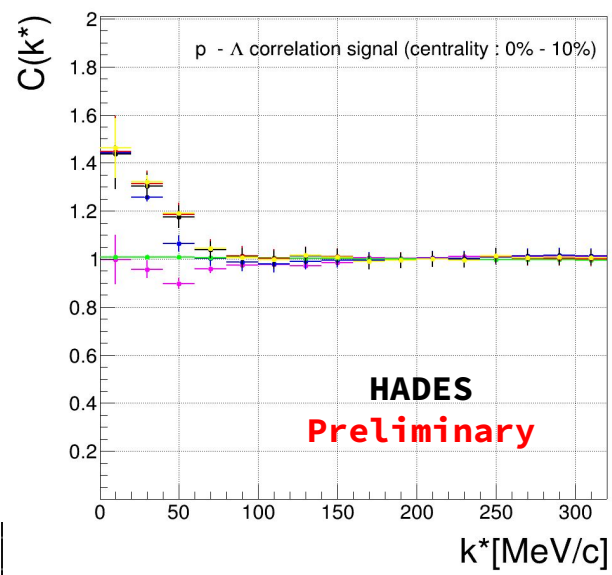
purity

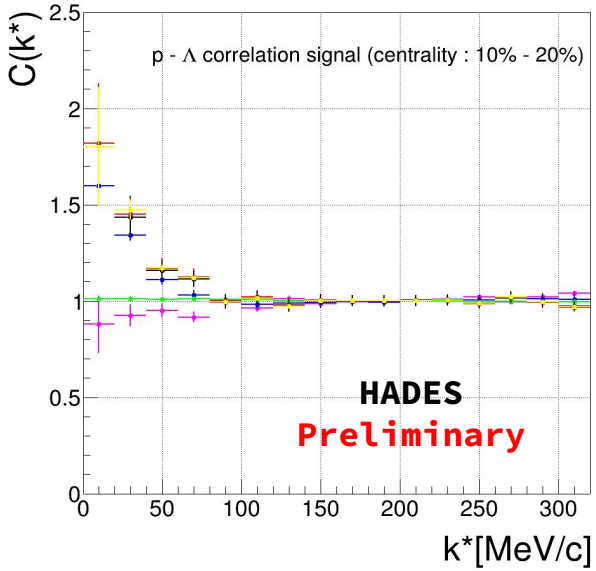


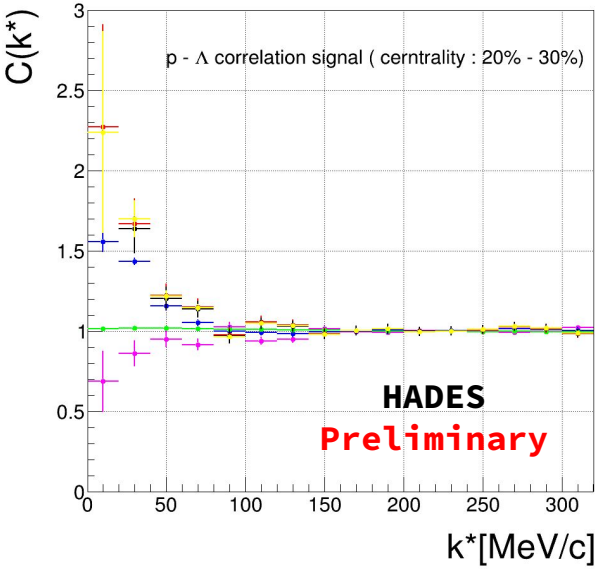
Detector effects

Result - II

- Experimental raw spectra
- Model effect
- Detector effects + model
- Exp + corrected (detector+model)
- Exp + corrected + purity : final spectra



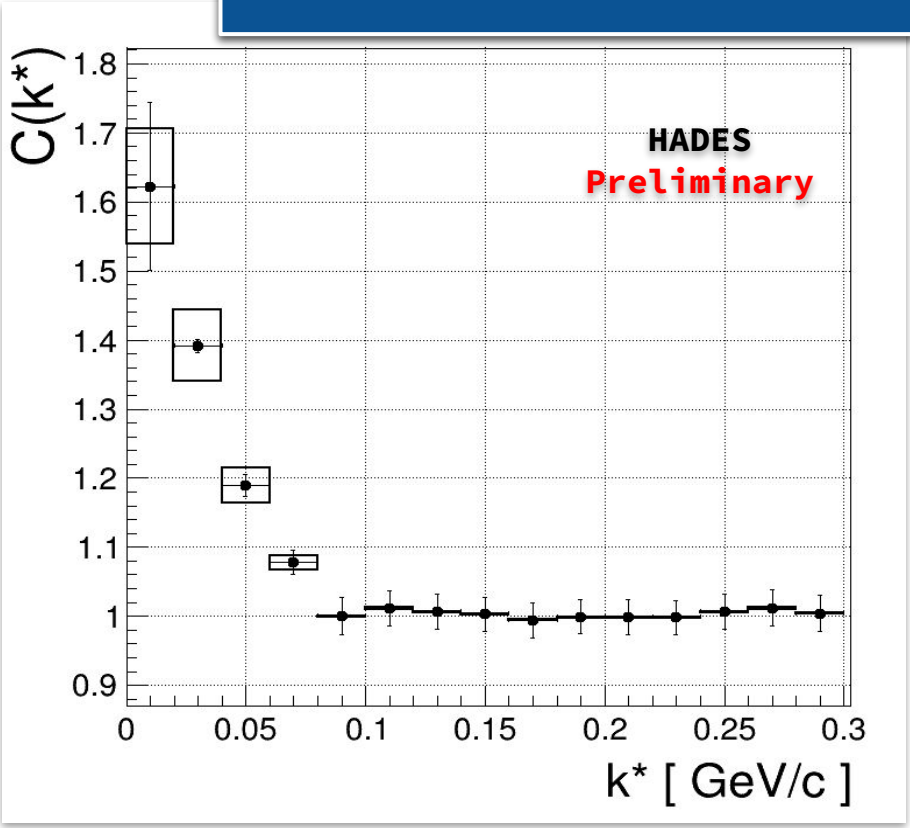




Systematic table

p - Λ correlation

PID cut		Done	8 %	Centrality 0 % - 30 %
DCA cuts	VDX	Done	1 %	
	Dau1VD	Done	1 %	
	Dau2VD	Done	2 %	
	MotVD	Done	1 %	
	MTD	Done	2 %	
	OA (Dau 1&2)	Done	2 %	
Mass cut		Done	10 %	
Total		13.4 %		



For other centralities work is under progress !

Summary :

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1. The correlation signals in Ag-Ag collision is extracted : **p–Λ**, (p–p correlation benchmark)
2. Detector effects and Purity corrections
3. Systematics studies are performed (final stage).
4. Resolution studies

2nd stage : (method1: work under progress)

3. Use Lednicky and Lyuboshitz (LL) analytical model
   - source radii (R),
   - extract strong interaction parameters,
   - Uncertainties determination

(Please stay tuned for the talk in QM/2023)

upcoming framework

```
for( int r0 = 0.5; r0 < 5.0; r0+=0.01 )
    for( int f0 = 0.5; f0 < 5.0; f0+=0.01 )
        for( int d0 =0.5; d0 <5.0; d0+=0.01)
            for( int ft = 0.5; ft < 5.0 ; ft += 0.01 )
                for( int dt =1.0; dt < 5.0; dt+=0.01 )
                    Calculate Lednicky-Luboshitz
                    correlation function : fit data
                    .    .    .    .    .
                    □2 : value is extracted : minimizer
```

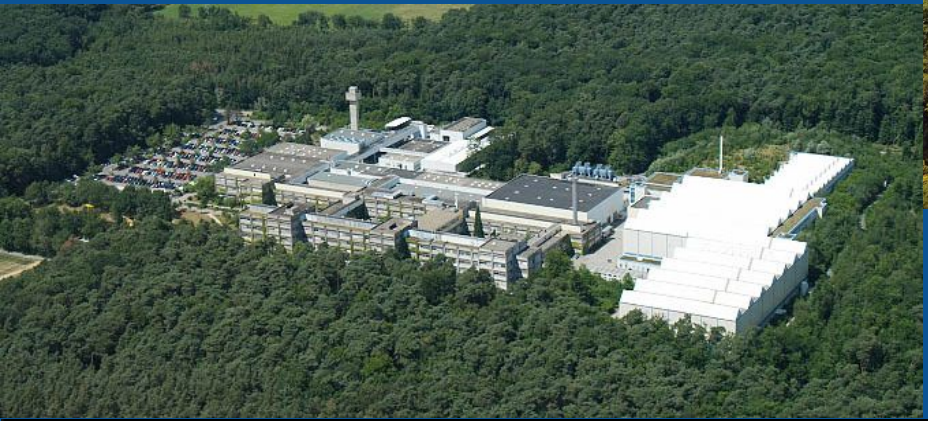
To characterize the interaction, LL model applies the approximated scattering theory, which uses the effective range of expansion and has two parameters: the scattering length f_0^S (which is directly linked with total cross-section of the process), and the effective range d_0^S .

2nd stage : (method2: work under progress)

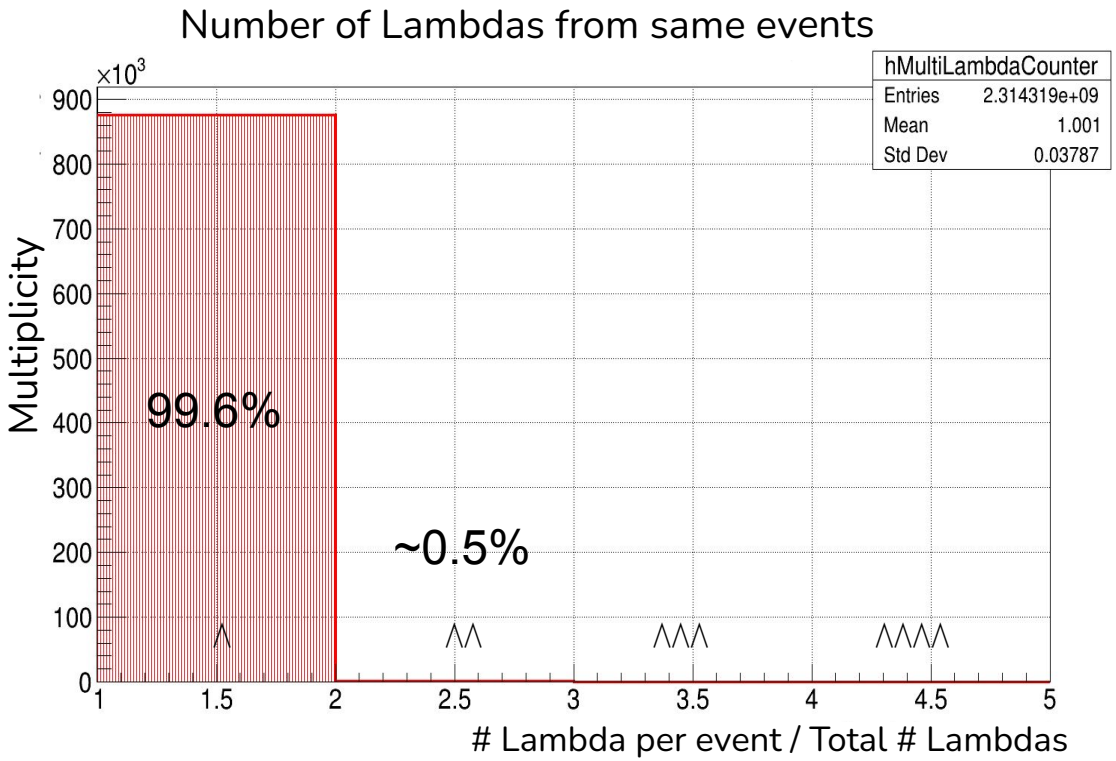
4. Extract source distribution from SMASH information for pp, pΛ, also check ΛΛ *(see talk : Mateusz Grunwald)*

source radii (**R**) [additional check - direct access to source radii] and use afterburner **CRAB**

Thank you

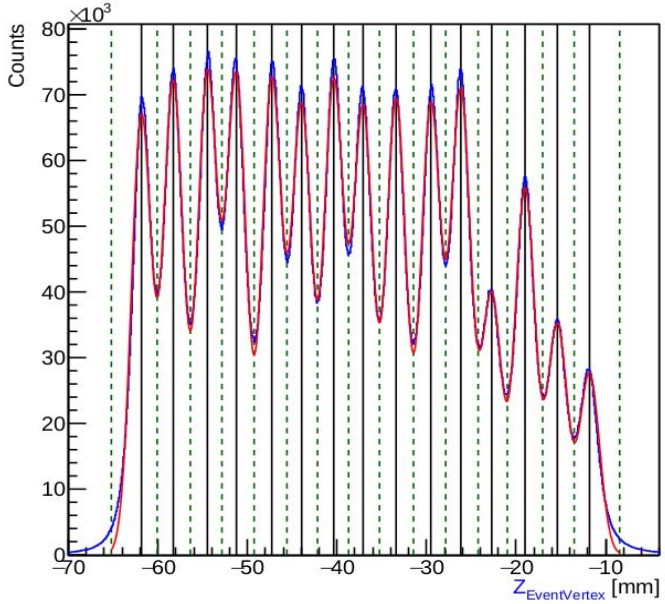


Lambda multiplicity



DCA parameters	
VDX	> 65 mm
Dau1VD	> 8 mm
Dau2VD	> 24 mm
MotVD	< 5 mm
MTD	< 6 mm
OA	> 15 ^{O}

Event Vertex determination

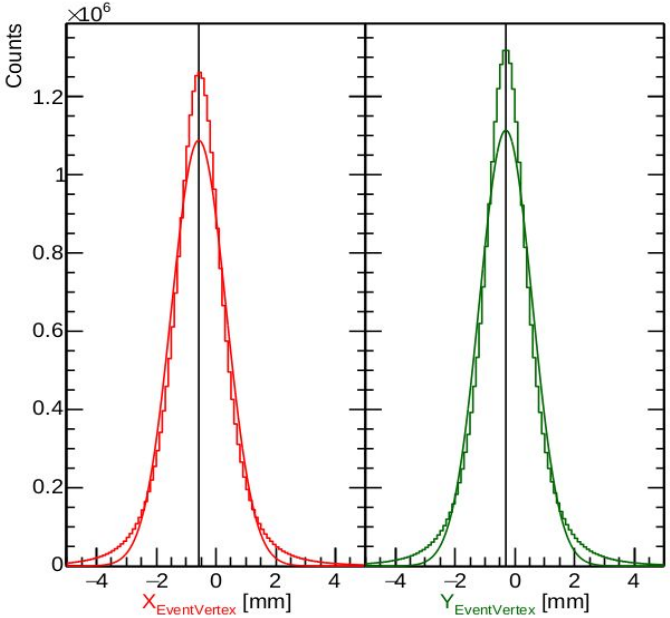


Obtained mean :

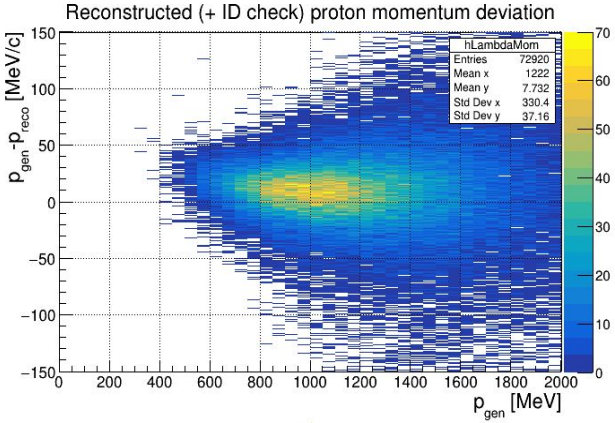
-0.578 mm : x-direction

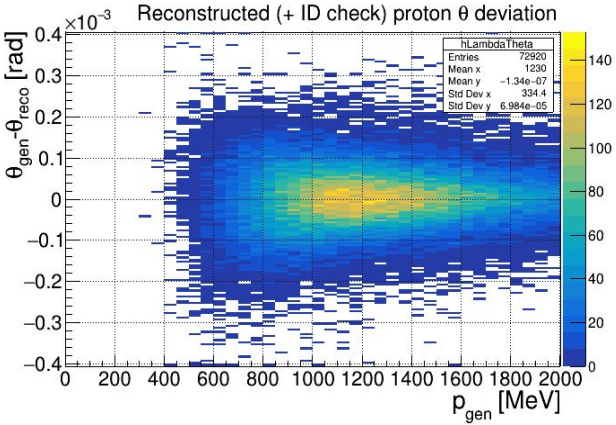
-0.299 mm : y-direction

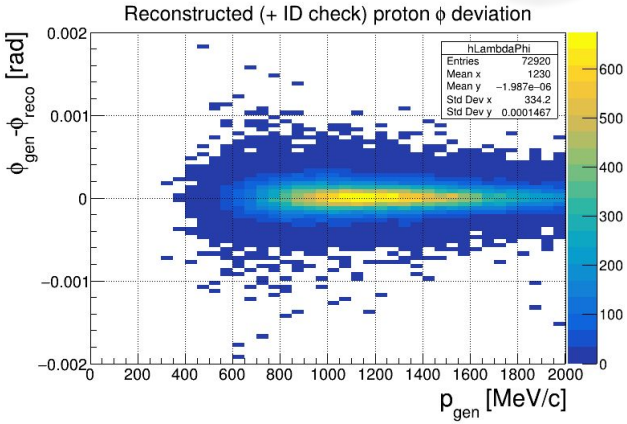
The 15 target segments are determined by a 15-fold Gaussian fit function with a common standard deviation (σ).

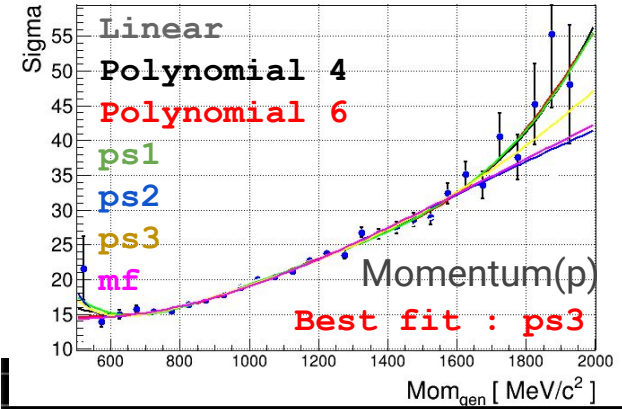


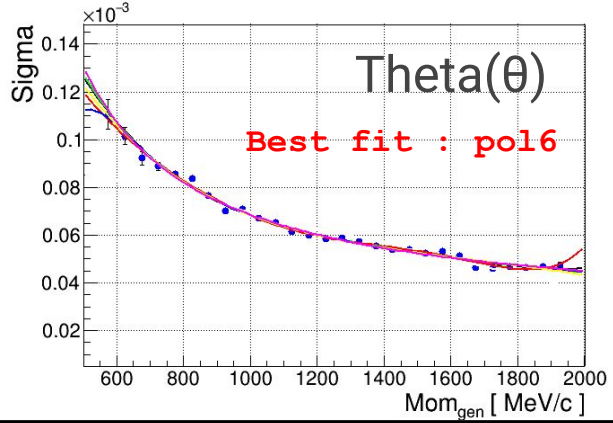
Lambda Resolution : Preparation for method II

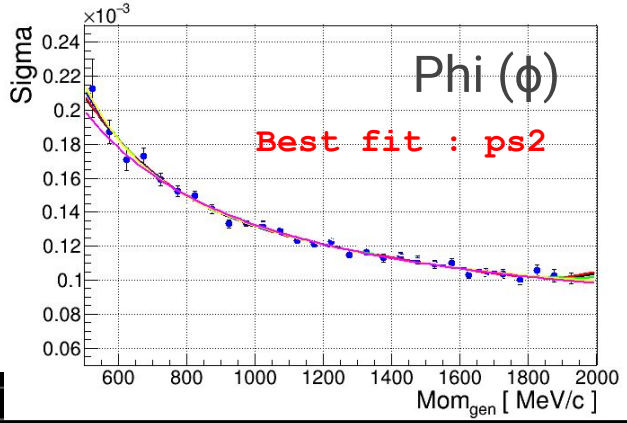


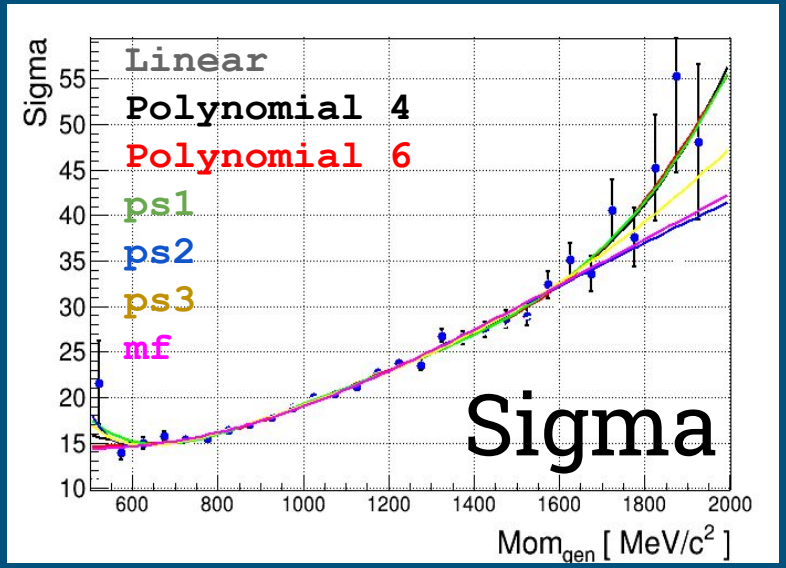












$$\text{ps1} = a + b\sqrt{x} + cx + dx^2 + fx^3$$

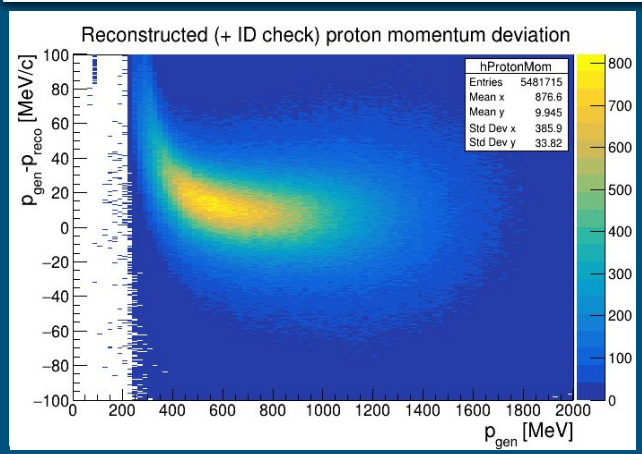
$$\text{ps2} = a + \frac{b}{x} + \frac{c}{x^2} + \frac{d}{x^3} + \frac{f}{x^4}$$

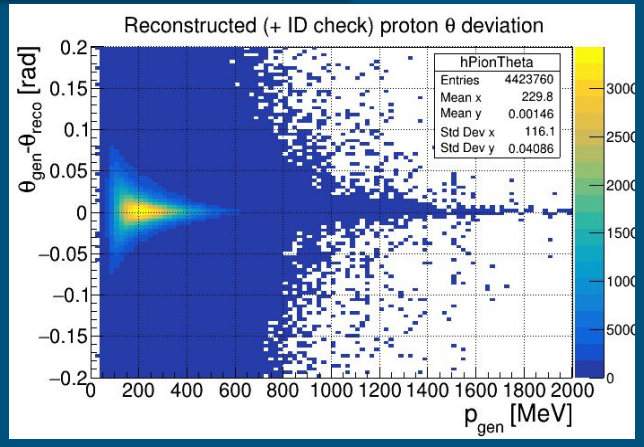
$$\text{ps3} = a + \frac{b}{x} + \frac{c}{x^2} + dx + fx^2$$

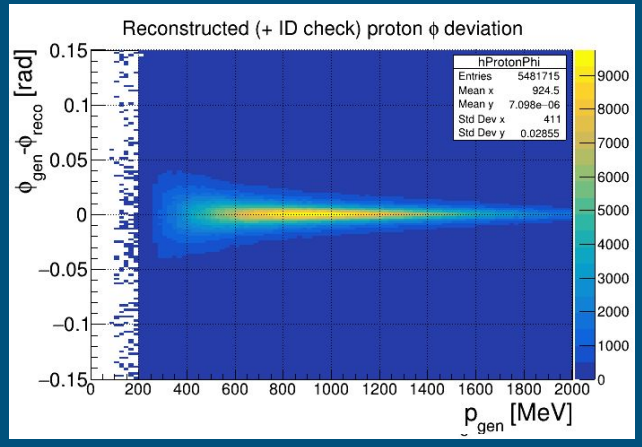
$$\text{mf} = a + b\,exp(\frac{c}{x})$$

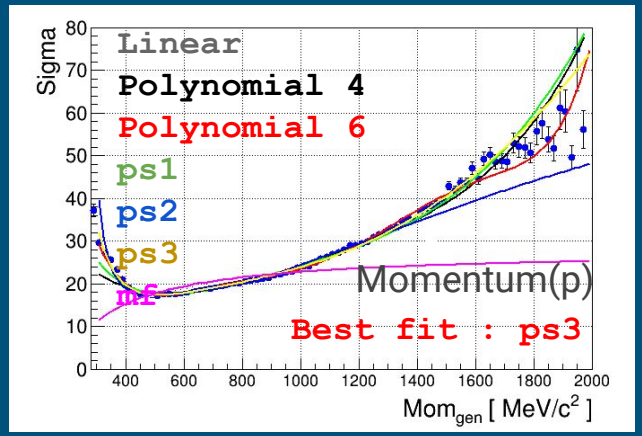
Formula	Linear	pol4	pol6	ps1	ps2	ps3	mf
χ^2	2.91	0.90	0.96	0.98	1.23	1.05	1.10

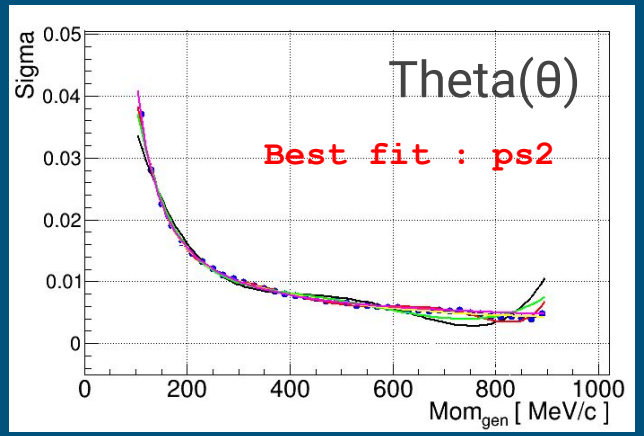
Proton Resolution

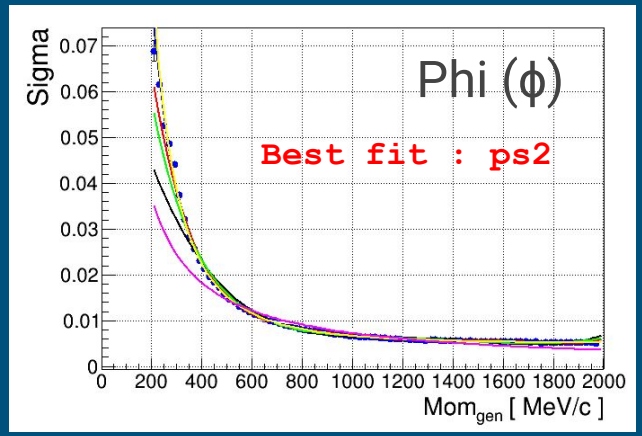




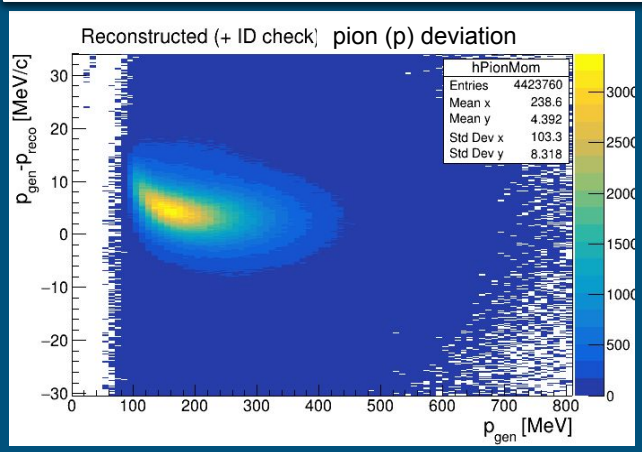


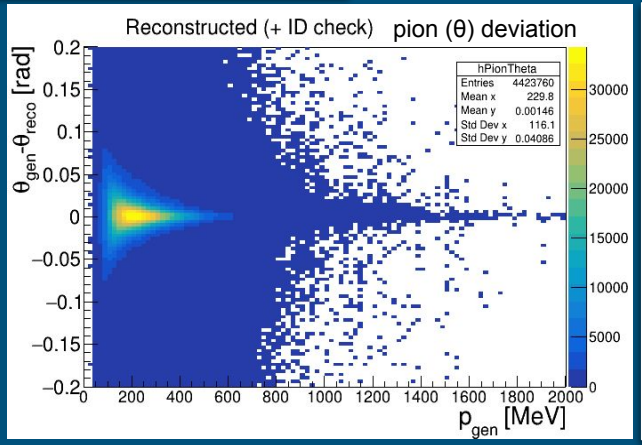


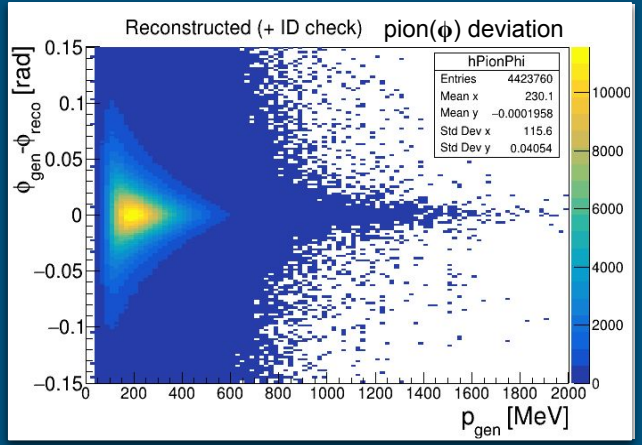


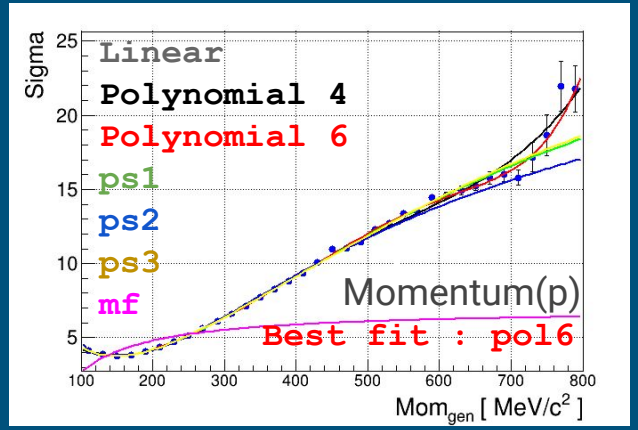


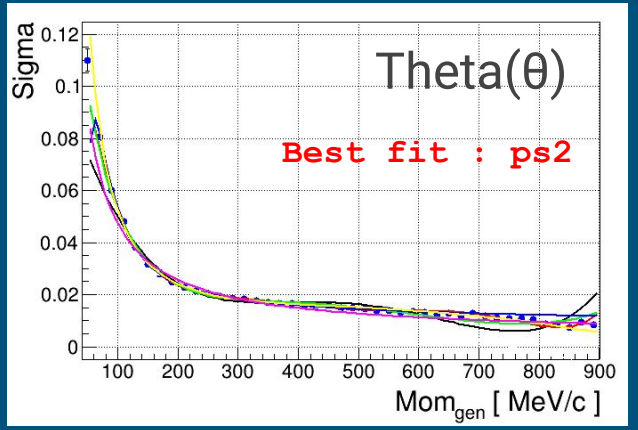
Pion Resolution

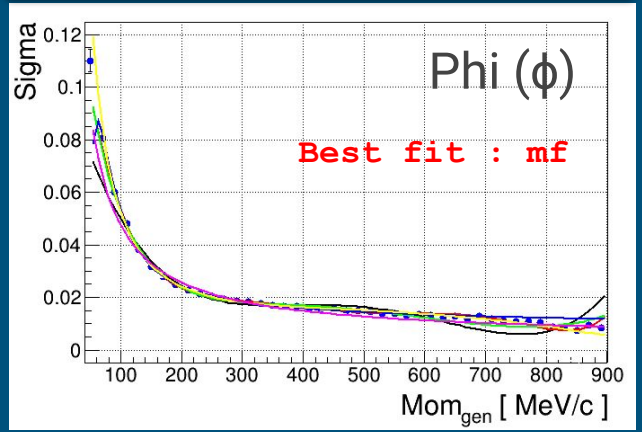






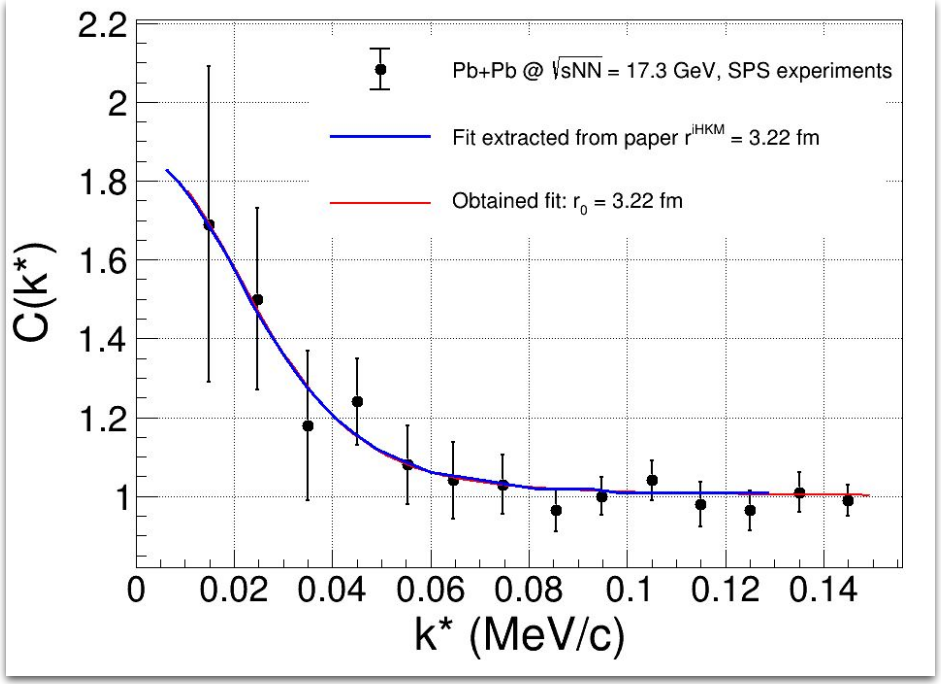


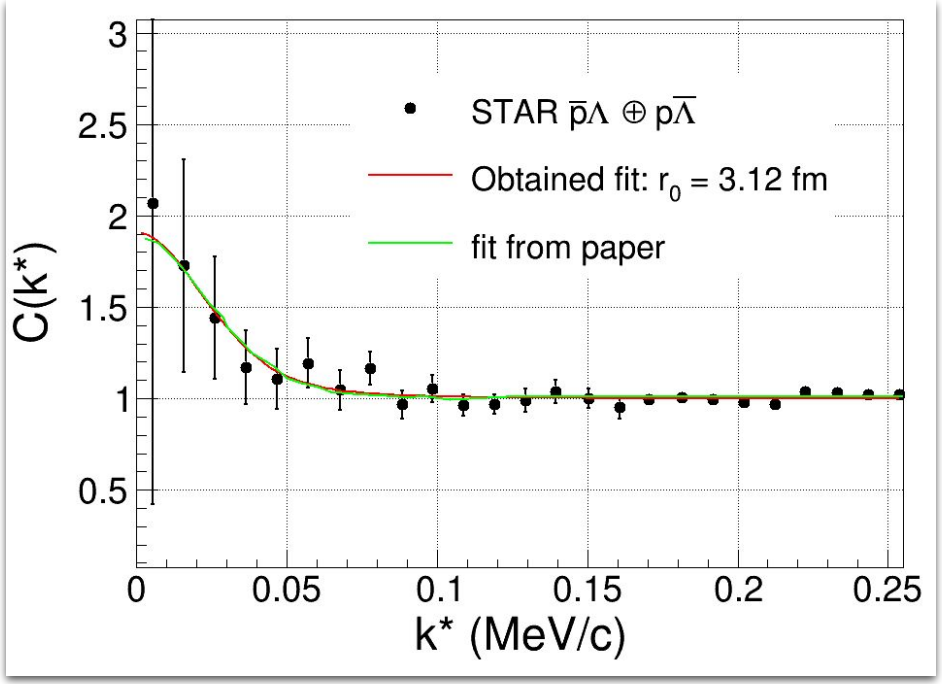




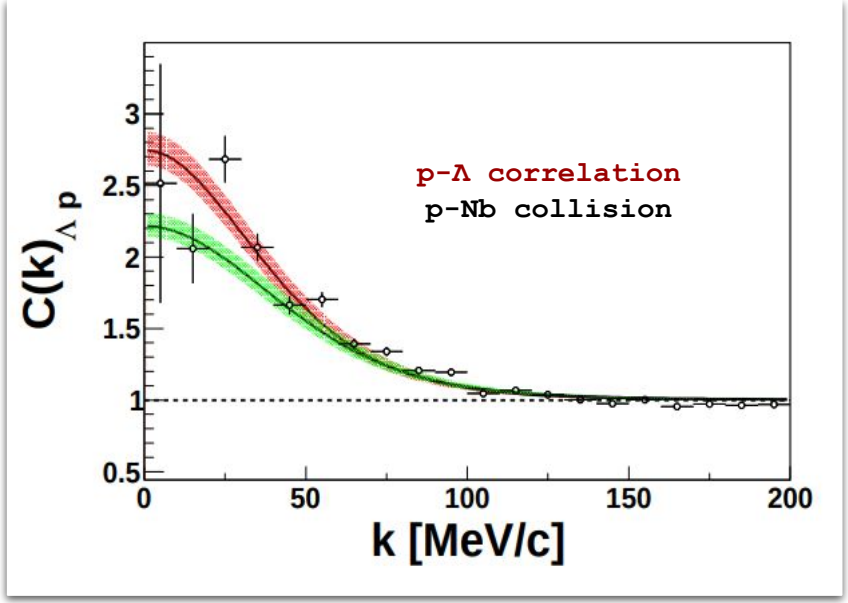
Result : STAR and SPS data : consistency check

RHIC : Au+Au @ 200 GeV and SPS : Pb+Pb @ 17.3 TeV





HADES results : p+Nb reaction



J. Adamczewski-Musch et al. (HADES Collaboration)
Phys. Rev. C 94, 025201 – Published 4 August 2016

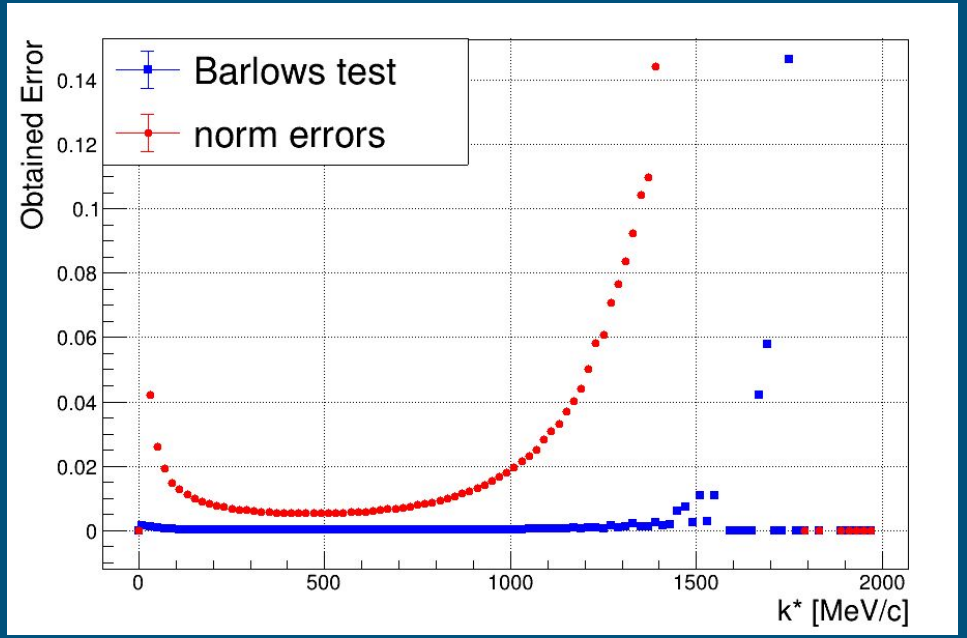
Parameters	LO	NLO
f_{0s}	1.91 fm	2.91 fm
d_{0s}	1.40 fm	2.78 fm
f_{0t}	1.23 fm	1.54 fm
d_{0t}	2.13 fm	2.72 fm
r_0	1.70±0.1	1.62±0.02

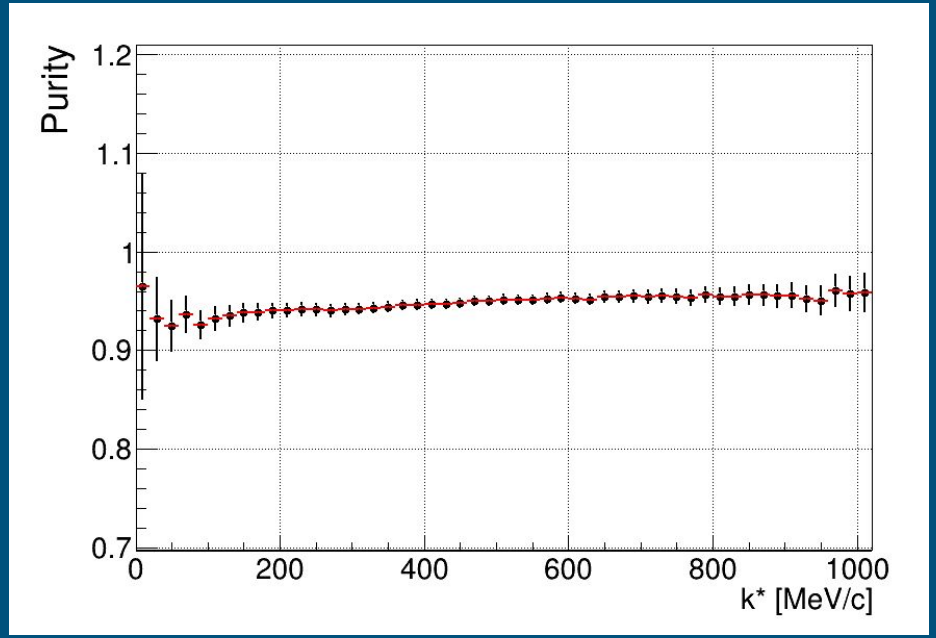
Barlow's test

$$f(n,d) = \frac{n(q)}{d(q)}, \textit{differentiation}: f(n,d)$$

Correlated factor

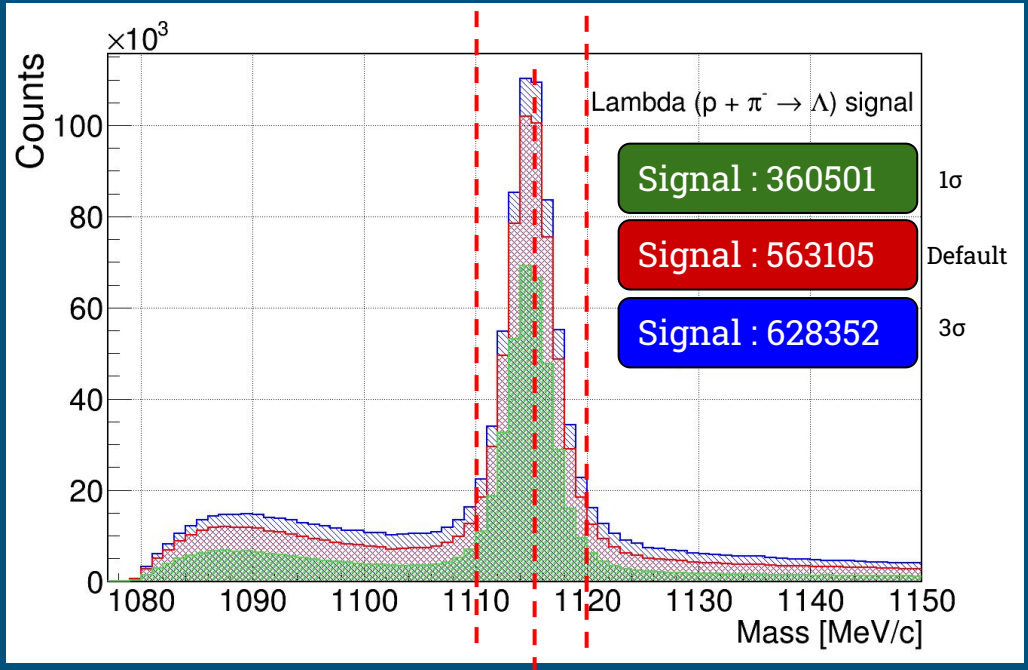
$$u(q) = \sqrt{((\frac{df(q)}{dn(q)}\sigma_{n(q)})^2 + (\frac{df(q)}{dd(q)}\sigma_{d(q)})^2 - z_\eta|\frac{df(q)}{dn(q)}\frac{df(q)}{dd(q)}|\sigma_{n(q)})^2\sigma_{d(q)})^2)}$$

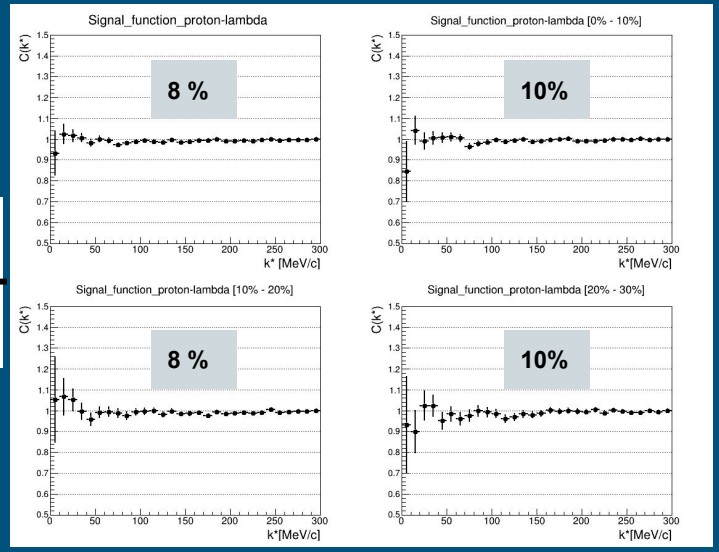


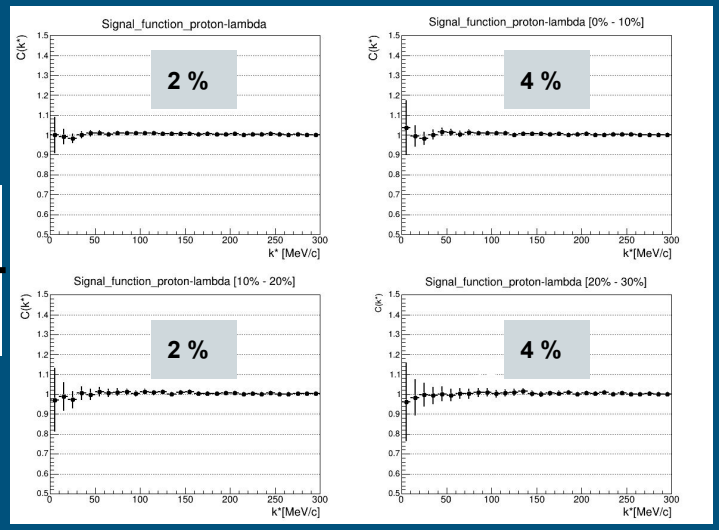


Systematics studies

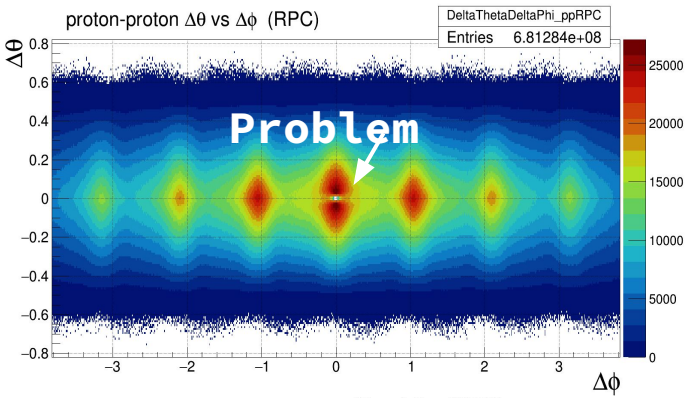
PID variation

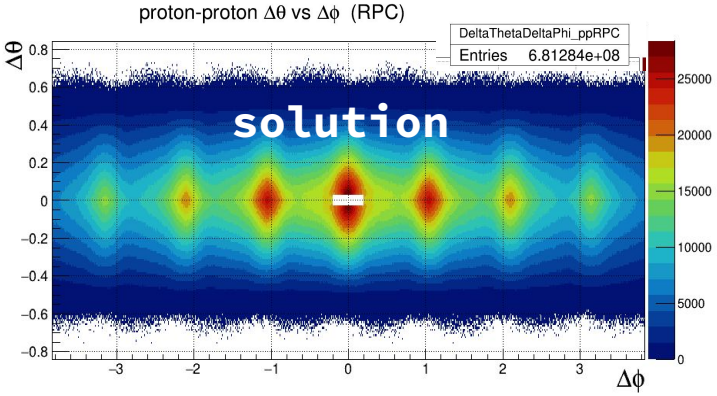






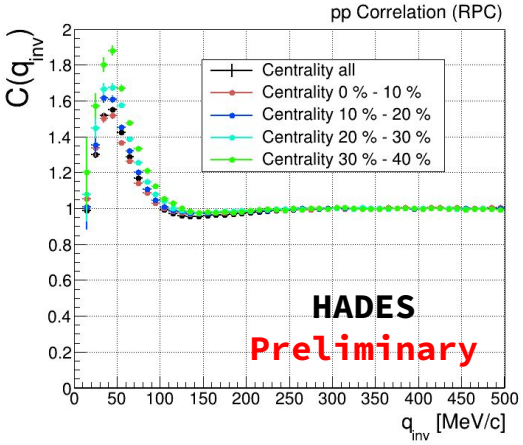
pp correlation – RPC / ToF

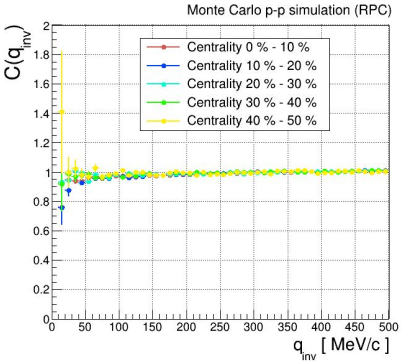


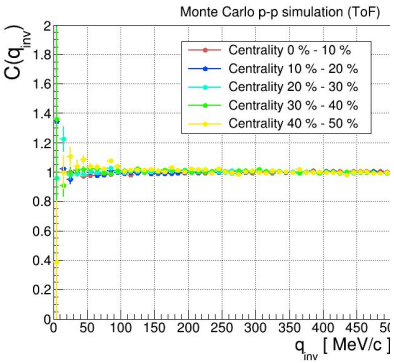


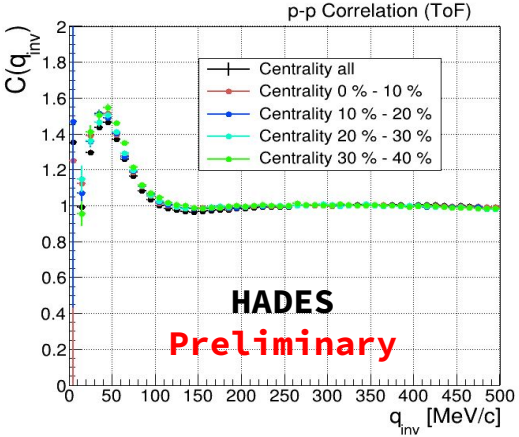
Conclusion :

Rejecting close pairs by applying angular cuts (ΔΘΔΦ cuts) ~ Double ratio correction









Thank you