Probing Short-Range Correlations of Hadrons

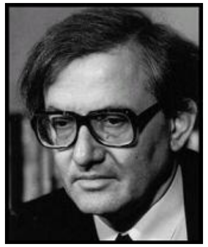
Femtoscopy Analysis of p-Λ pairs in Ag-Ag collisions at 1.58 A GeV with HADES

Narendra Rathod
for the HADES Collaboration.

Faculty of Physics, Nuclear Physics Division,
Warsaw University of Technology, Warsaw, Poland.

talk@

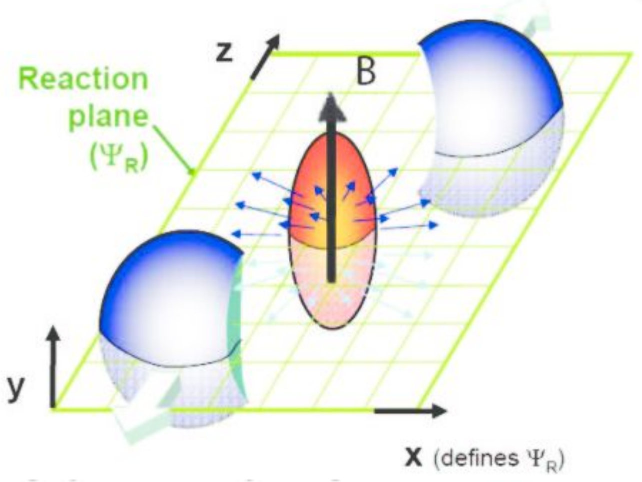
ZIMÁNYI SCHOOL 2023

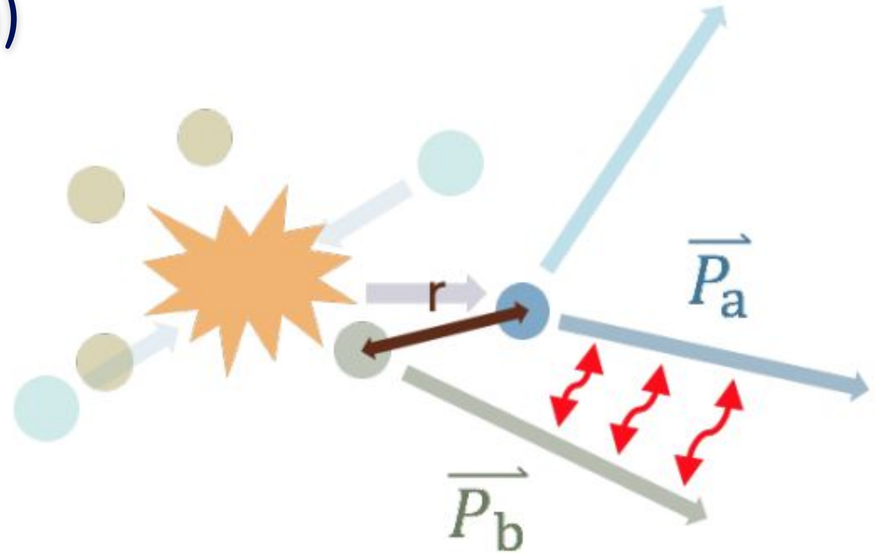


Organizers

Content

1. Introduction – motivation
2. HADES (GSI) detector system
3. RPC / ToF, particle identification / centrality
4. Weak Decay Recognition (Λ data / simulation)
5. Correlation theory / Experimental results
6. Lednicky & Lyuboshitz (LL) analytical model
7. global result comparison
8. Final results minimum bias
9. Summary …..

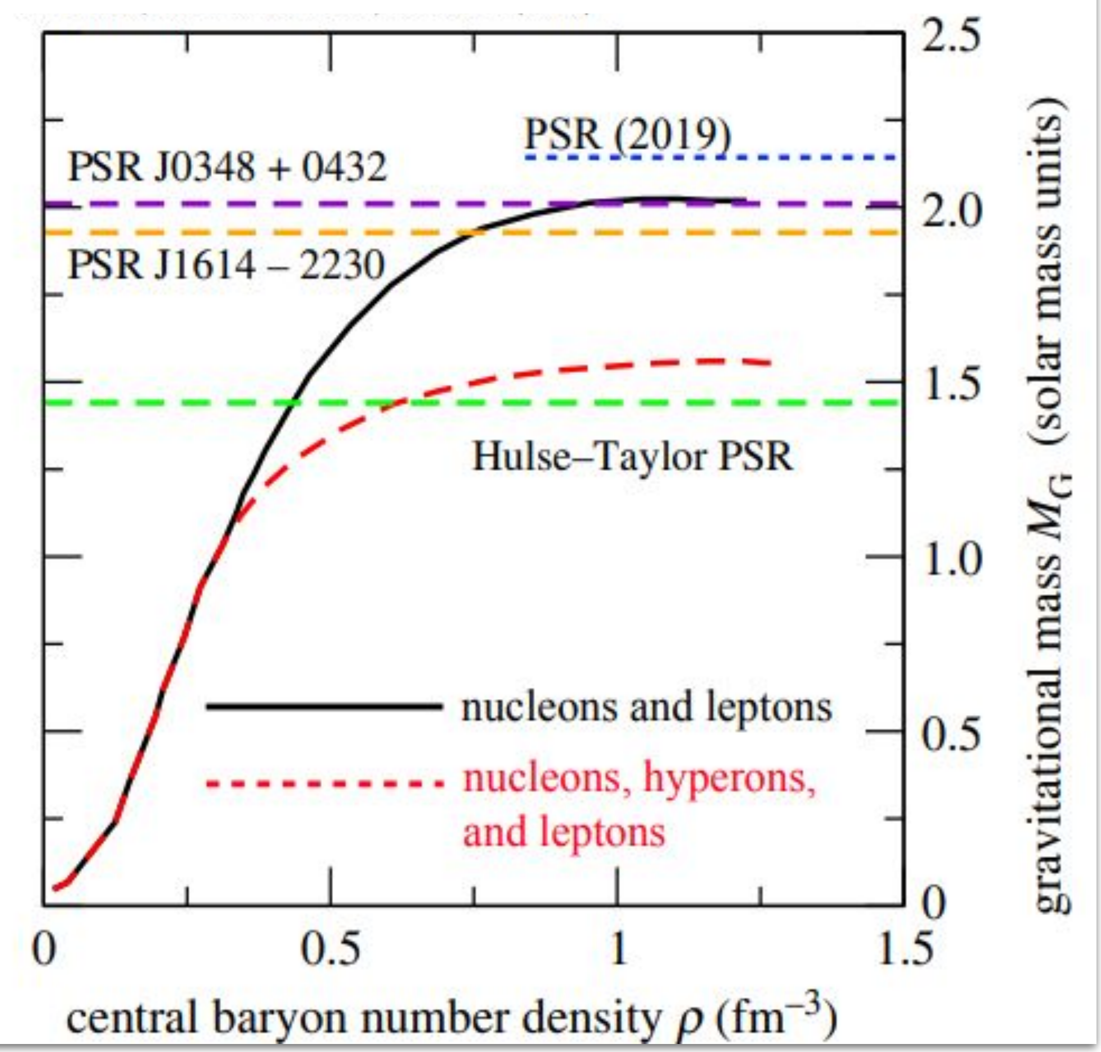




https://www.ph.nat.tum.de/denseandstrange/research/current-projects/yn-interaction-in-neutron-stars-from-alice-and-hades-data/

Neutron Star and hyperon puzzle ?

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

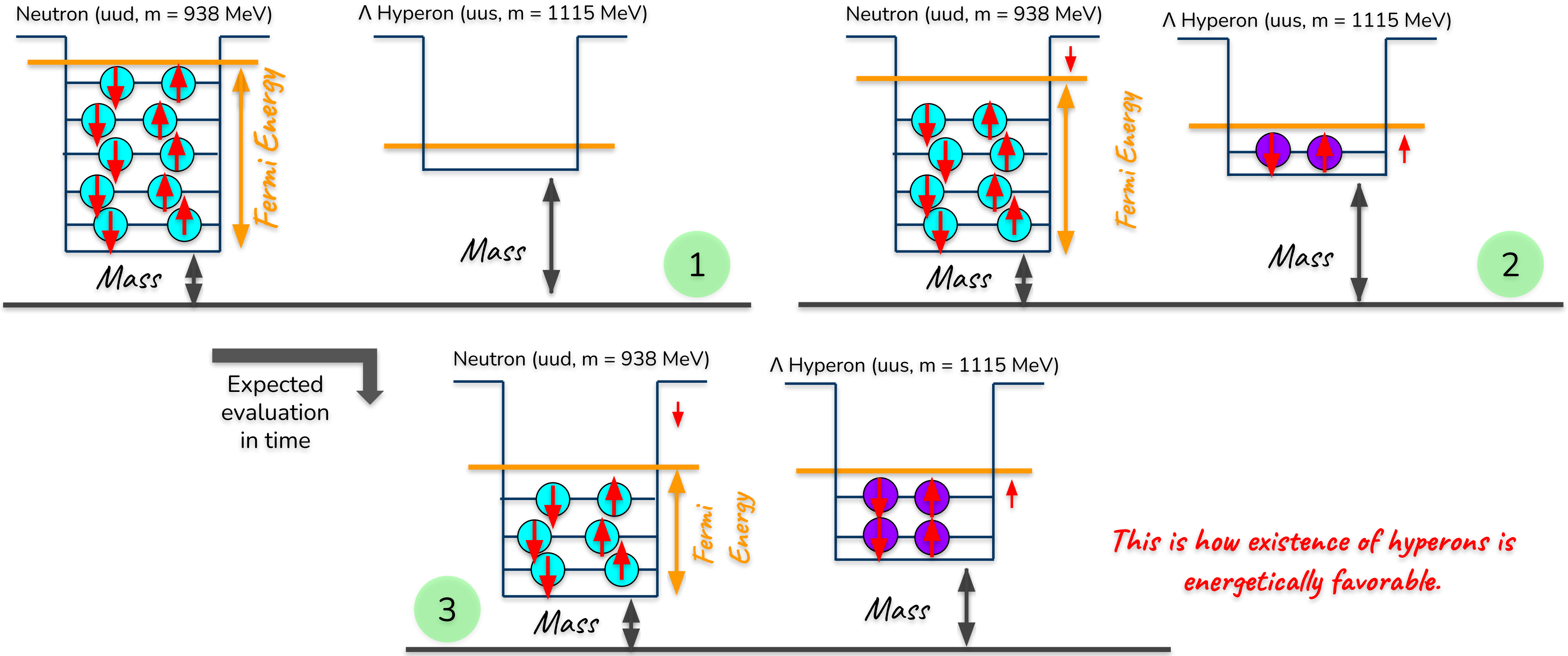


- Neutron stars (NS) are the remnants of the gravitational collapse of massive stars during supernova event.
- Their masses and radii are of the order of 1 – 2 $M_{\odot}$ and 10 – 12 km, respectively.
- Central densities in the range of 4 – 8 times the normal nuclear matter saturation density, ε_0 ~ 2.7 × 10^{14} g/cm^3 (ρ_0 ~ 0.16 fm^{-3})

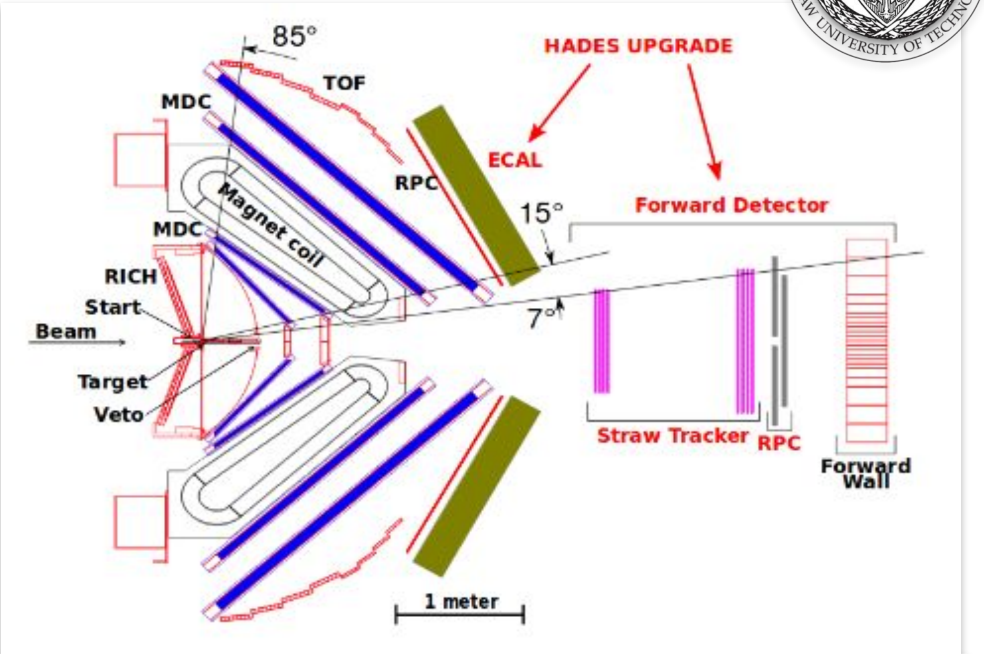
Best suitable theory takes hyperons into account,

- Hyperons are expected to appear in the core of NS at ρ ~ 2- 3 ρ_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.**

why hyperons are produced



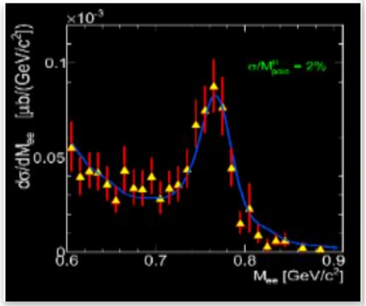
HADES Spectrometer

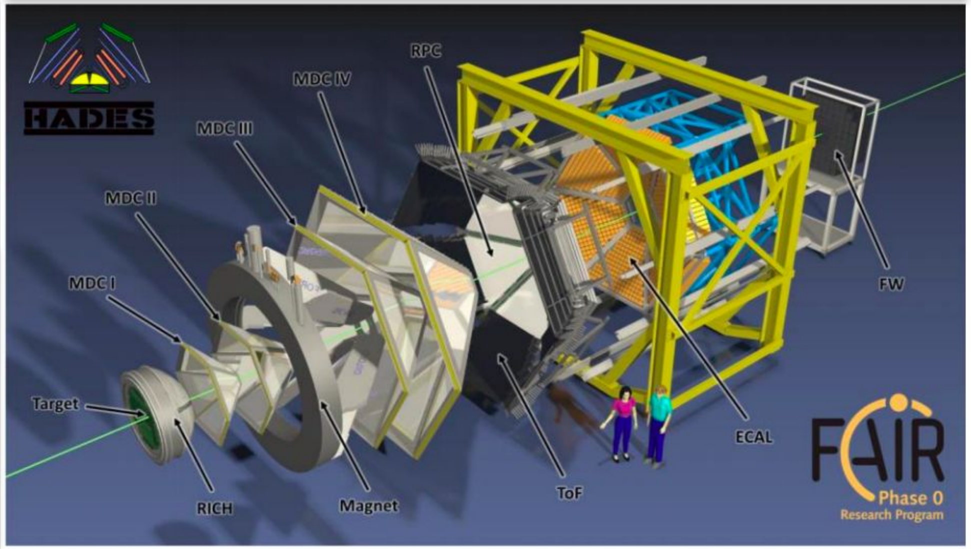


- SIS-18 beams: protons (1-4 GeV), nuclei (1-2 AGeV), pions (0.4-2 GeV/c) – secondary beam
- rare probes:(e^+, e^-), strangeness: $K^{+/-,0}$, Λ, Ξ^-, φ
- $\Delta M/M$ - 2% at ρ / ω
- PID : π/p/K – dE/dx (MDC) and TOF : σ_{tof} ~80 ps (RPC)
- electrons : RICH (hadron blind)
- neutral particles: ECAL

Geometry :

- full azimuthal, polar angles 18° - 85°

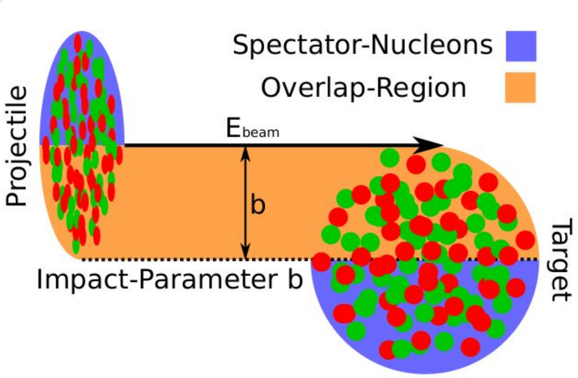


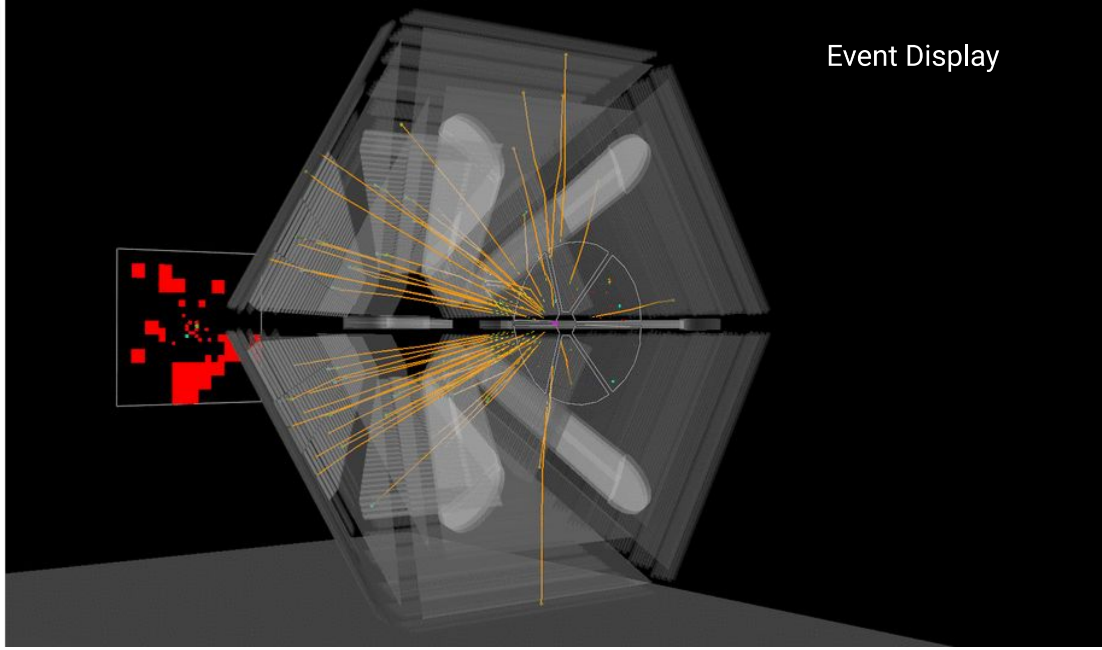


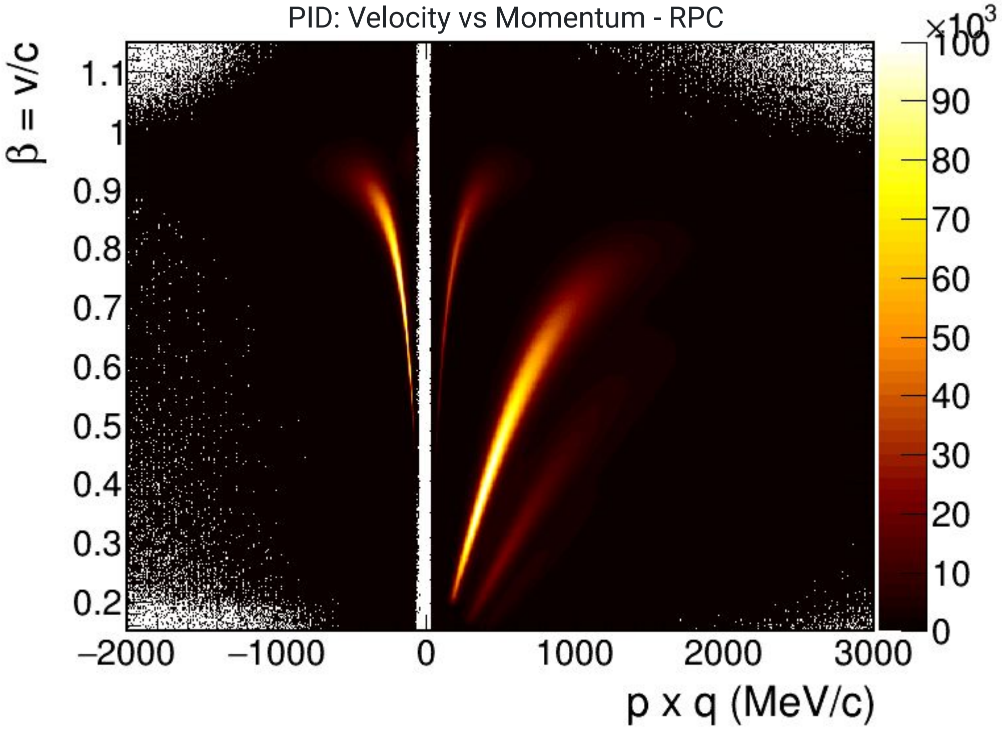
HADES Ag-Ag collision

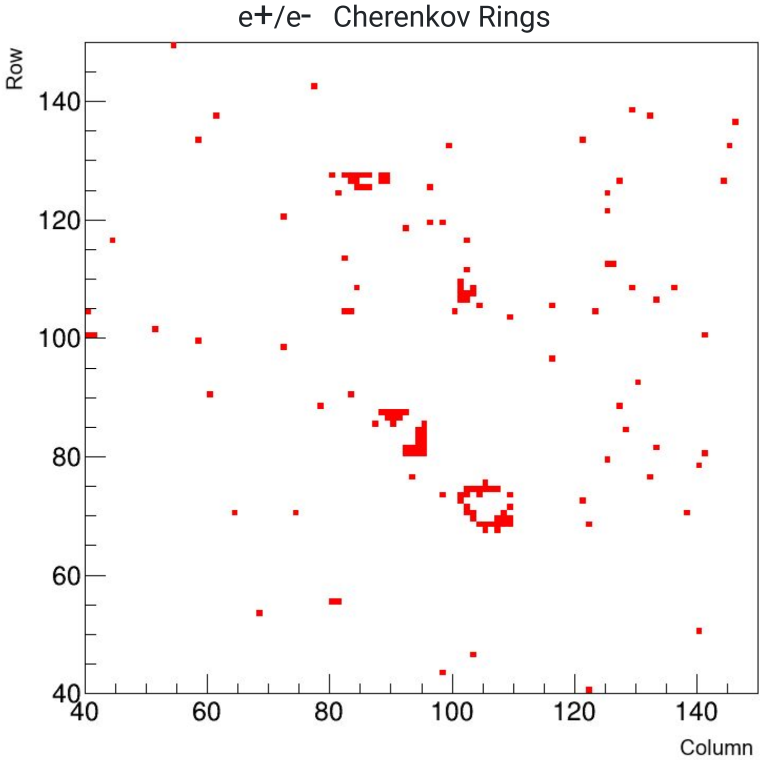
Ag-Ag @ 1.58 A GeV
(march-19 data)

Duration : 430.9 h
Events recorded : 13.64×10^{9}
Mean event rate : 8.8 kHz
Data recorded : 333.6 TB

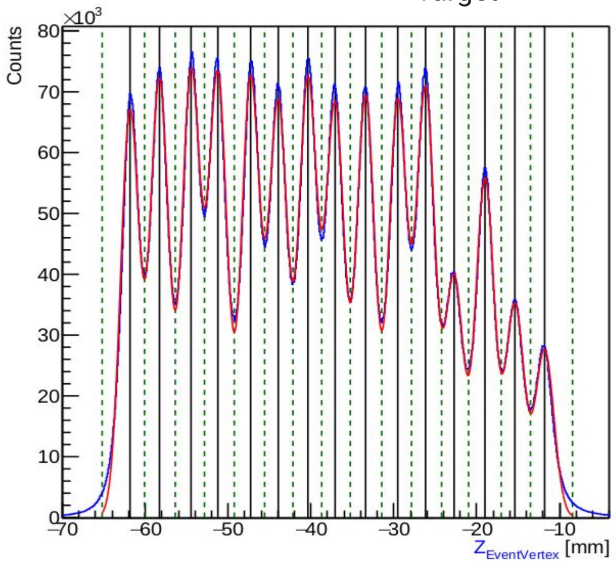




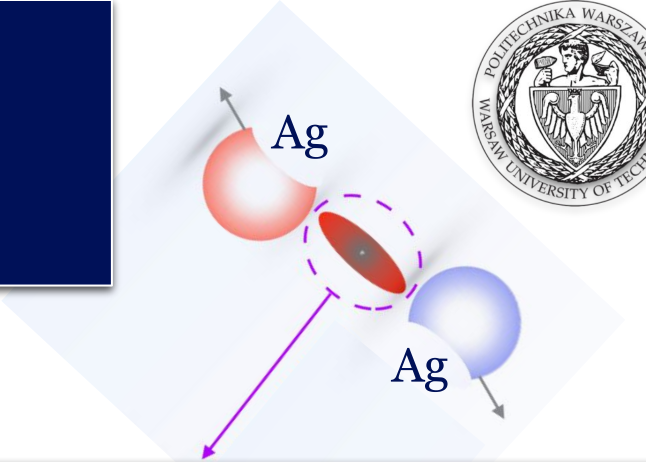




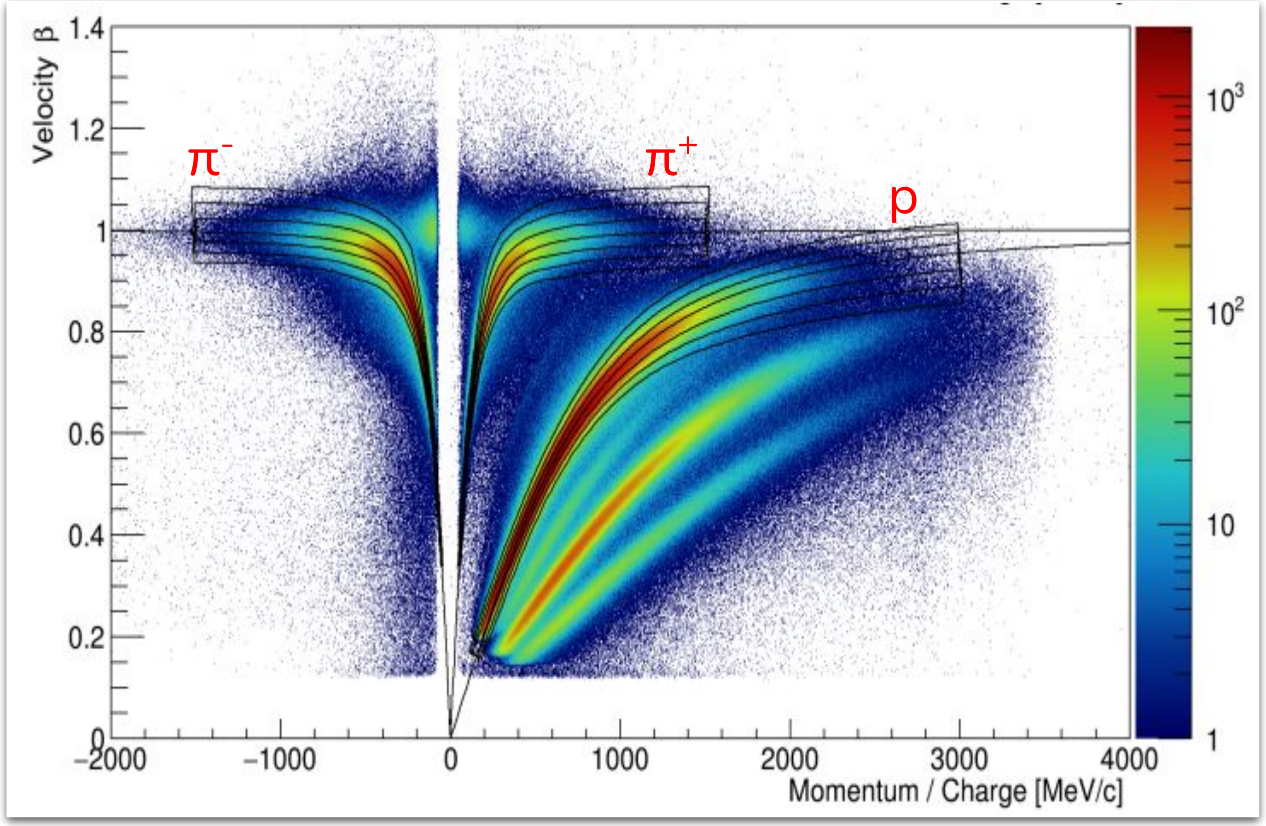
The 15 target segments are determined by a 15-fold Gaussian fit function with a common standard deviation (σ).



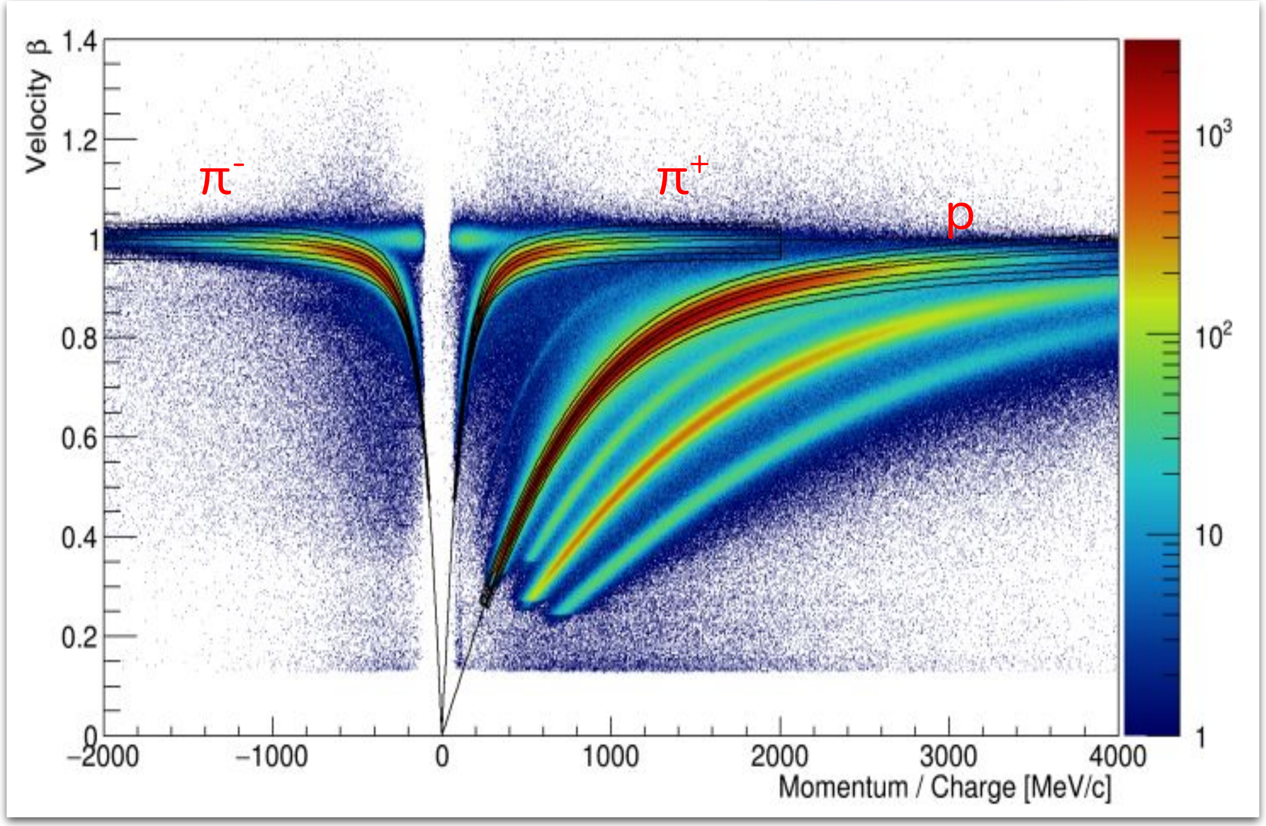
Particle identification



ToF

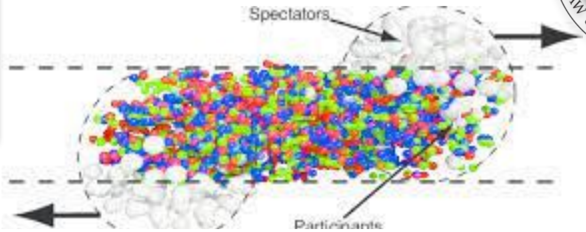


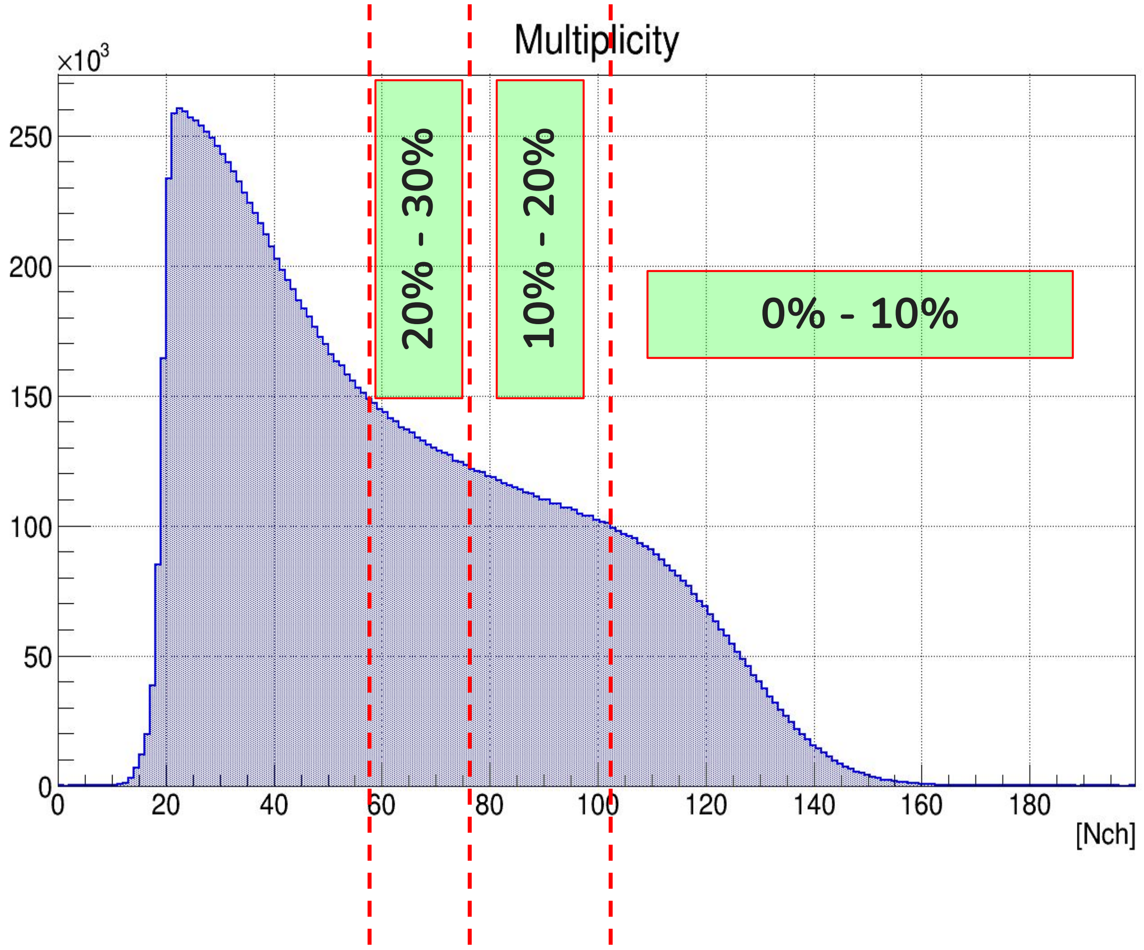
RPC

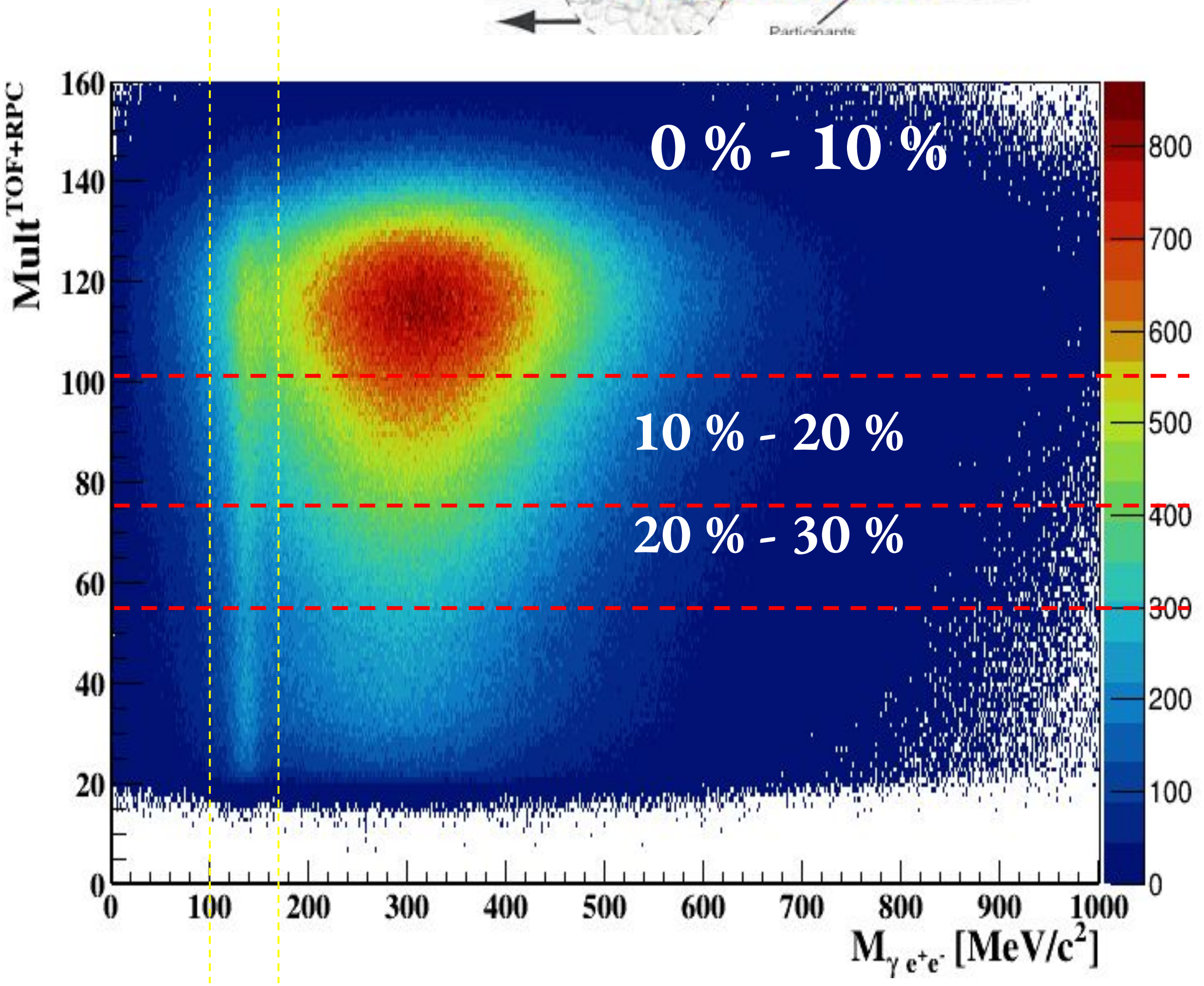


https://doi.org/10.21248/gups.68651

Selected events, Multiplicity

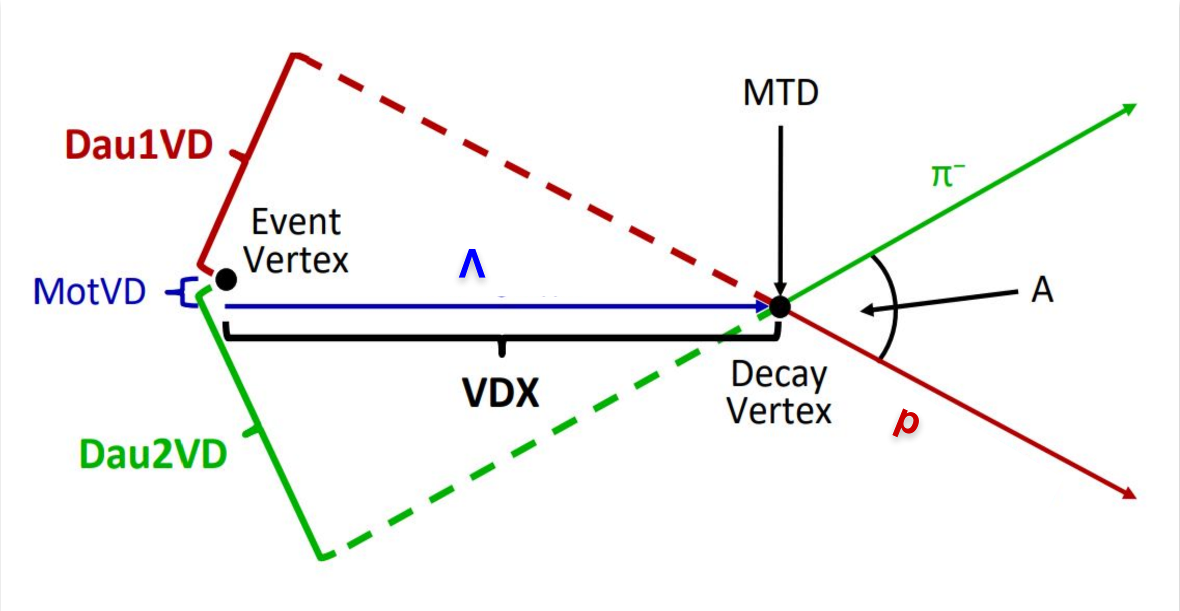






Signal Reconstruction

Weak Decay Recognition



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

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

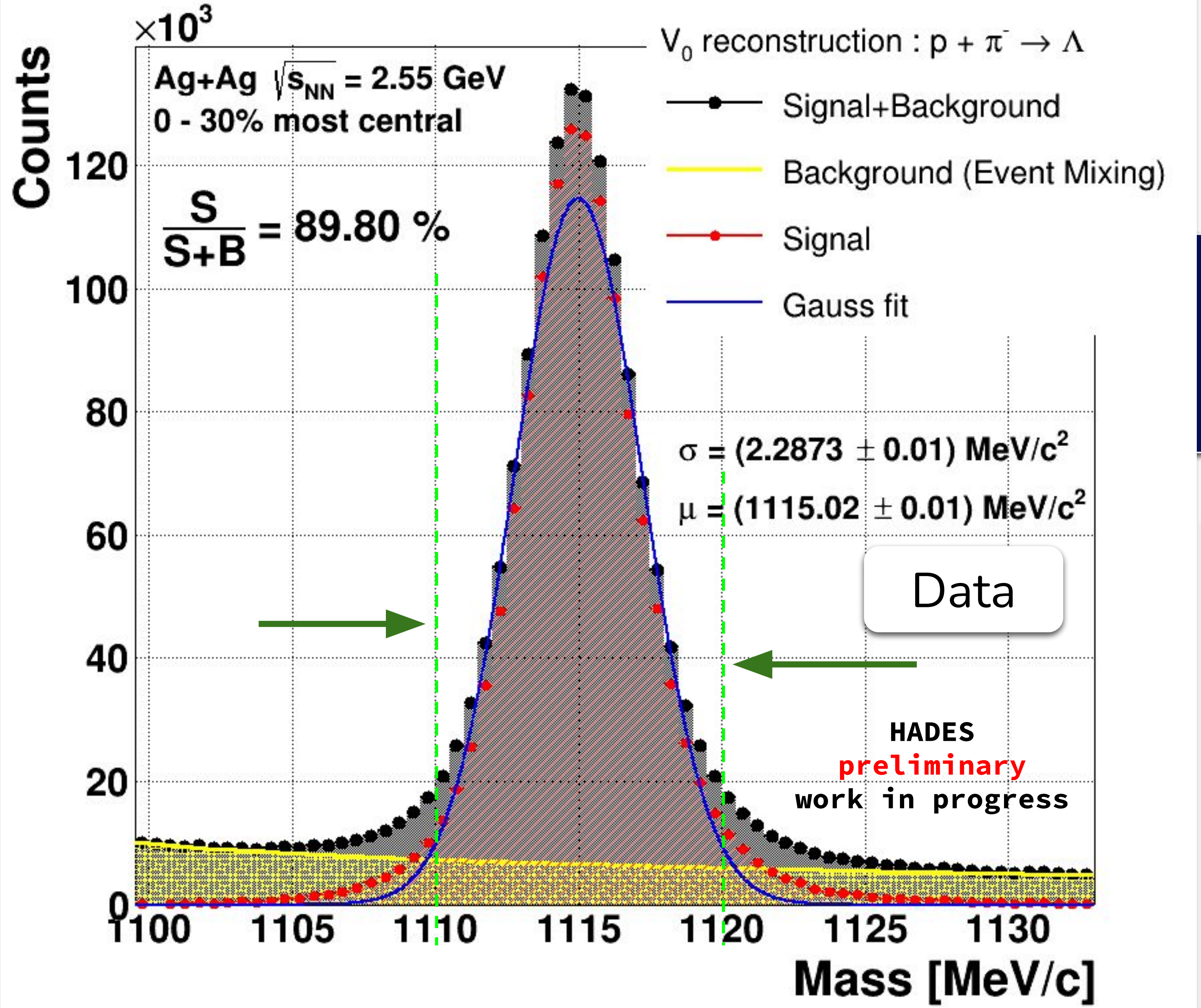
- DCA between reconstructed mother track and primary vertex (**Mot-VD**) = **< 5 mm**

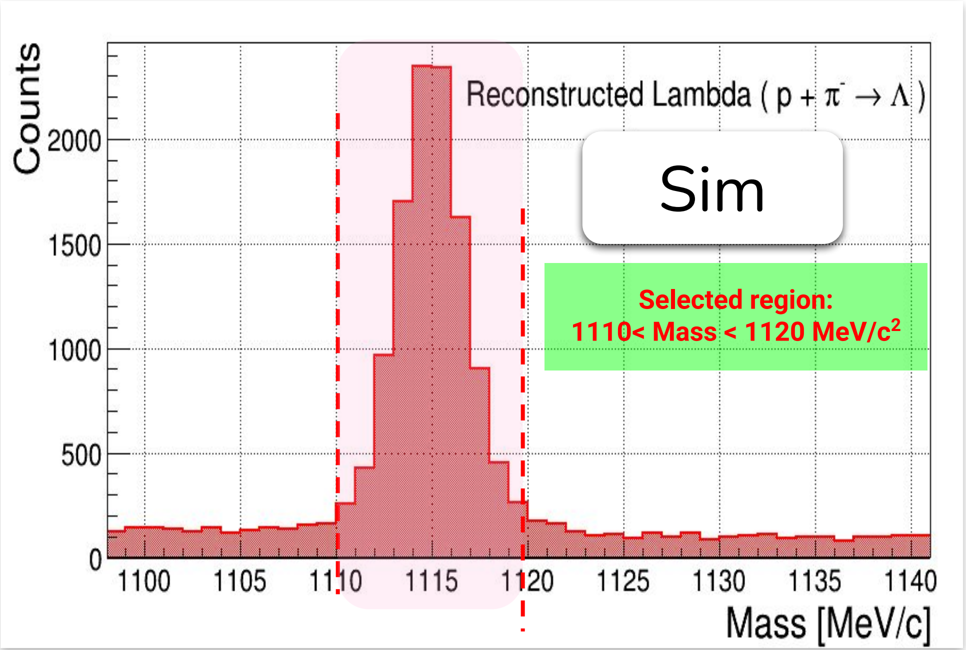
- Distance between the primary and secondary vertex (**VDX**) = **> 65 mm**

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

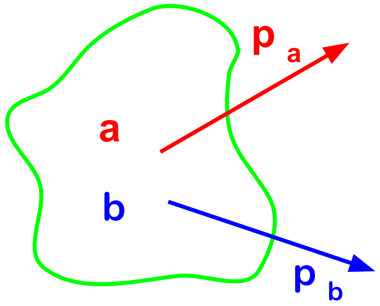
- Opening angle between the two daughter tracks (A) = **> 15 °**

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





Strategy of analysis

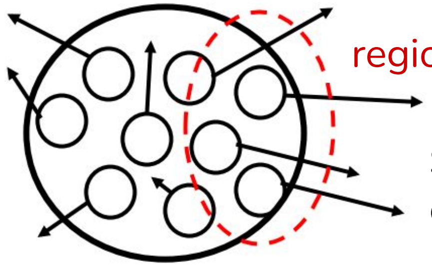


$$C^{ab}(P,q) = \frac{\mathbb{P}(\vec{p_a},\vec{p_b})}{\mathbb{P}(\vec{p_a})\mathbb{P}(\vec{p_b})} = \int d^3r' \, S_p(r')|\phi(q,r')|^2$$

1 — $S_p(r')$

2 — $|\phi(q,r')|^2$

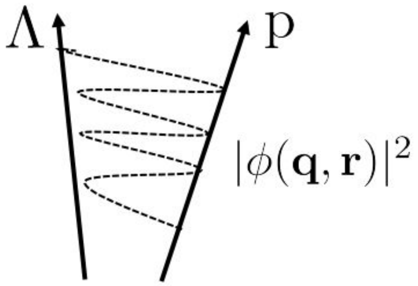
1



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

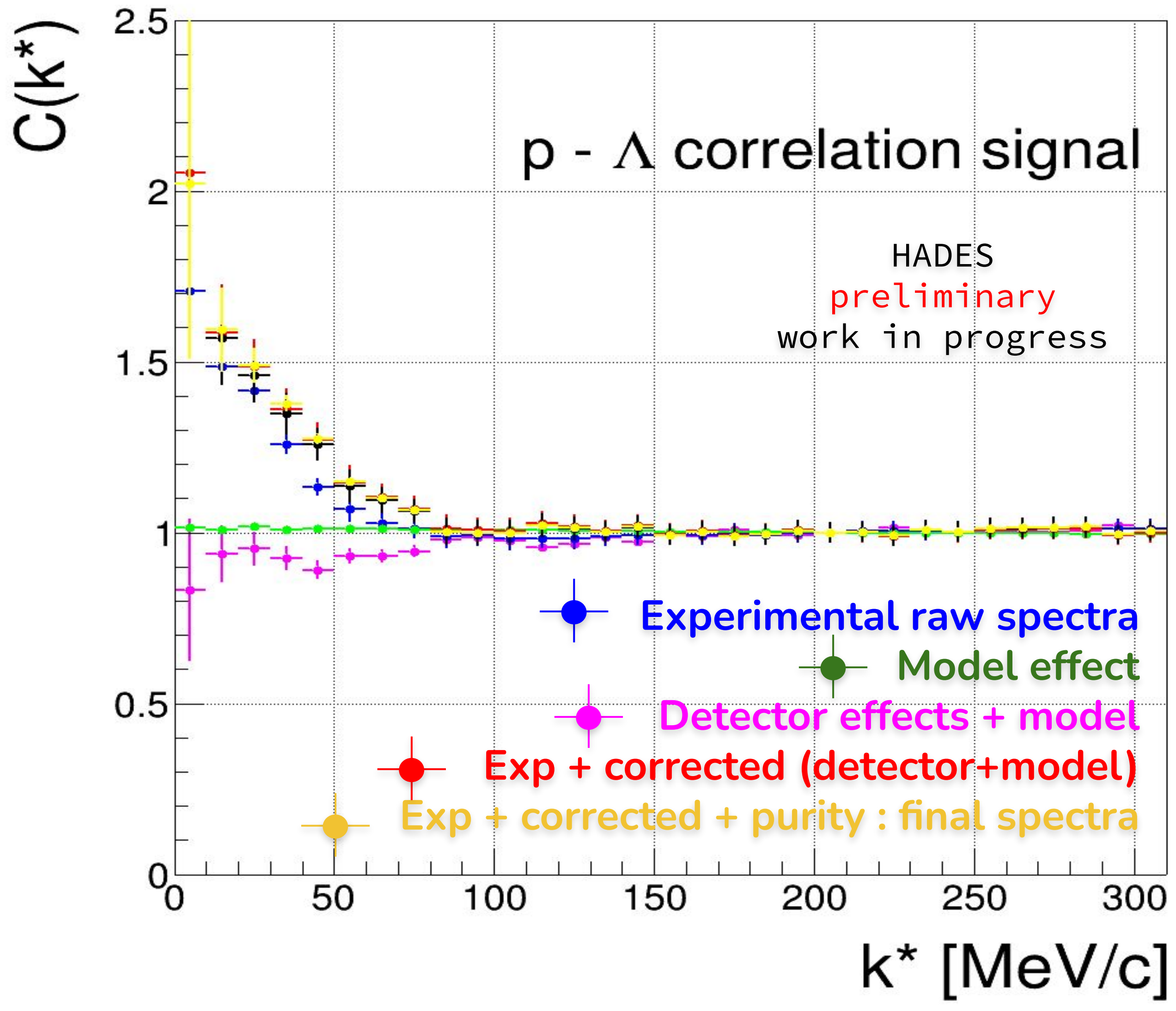
Method 1 :

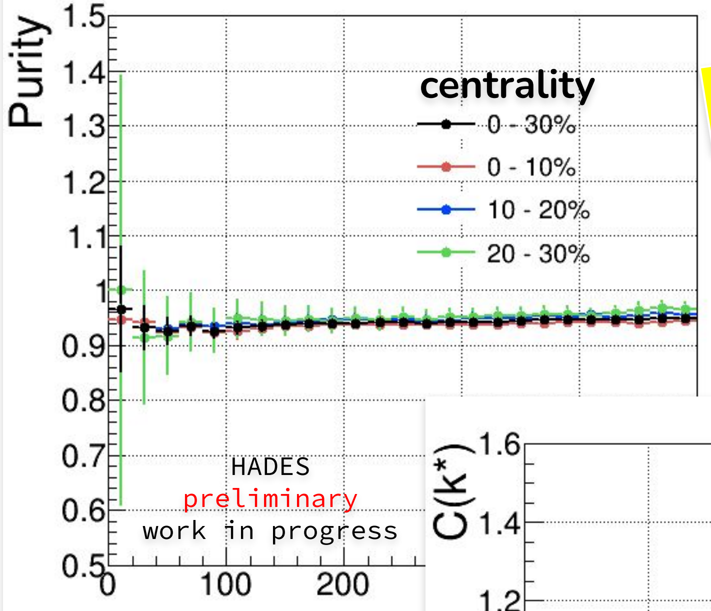
- Lednicky Model : Correlation formula as a function of the Λp scattering length and source radii r_0.
- Scan and extract strong interacting parameters (f_0, d_0) and source radii (r_0).

Method 2 :

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

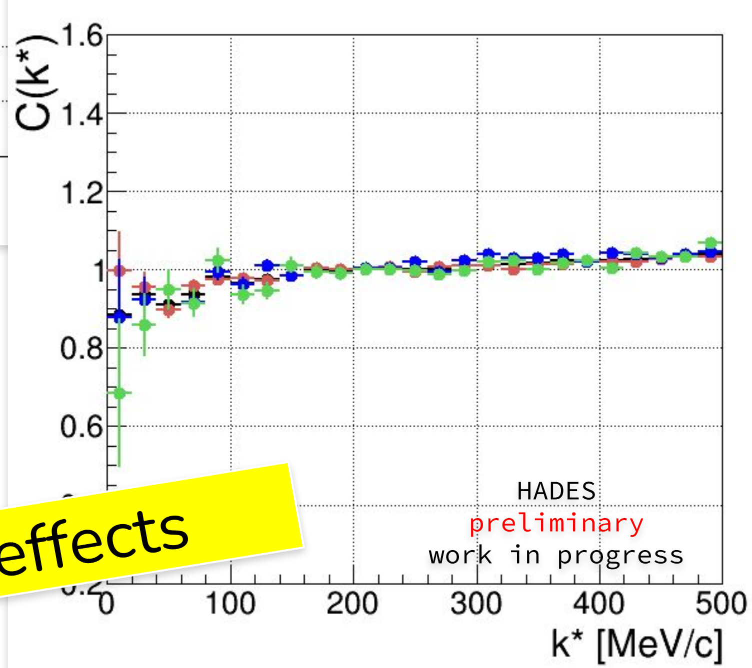
p-Λ correlation in AgAg collision at 1.58 A GeV





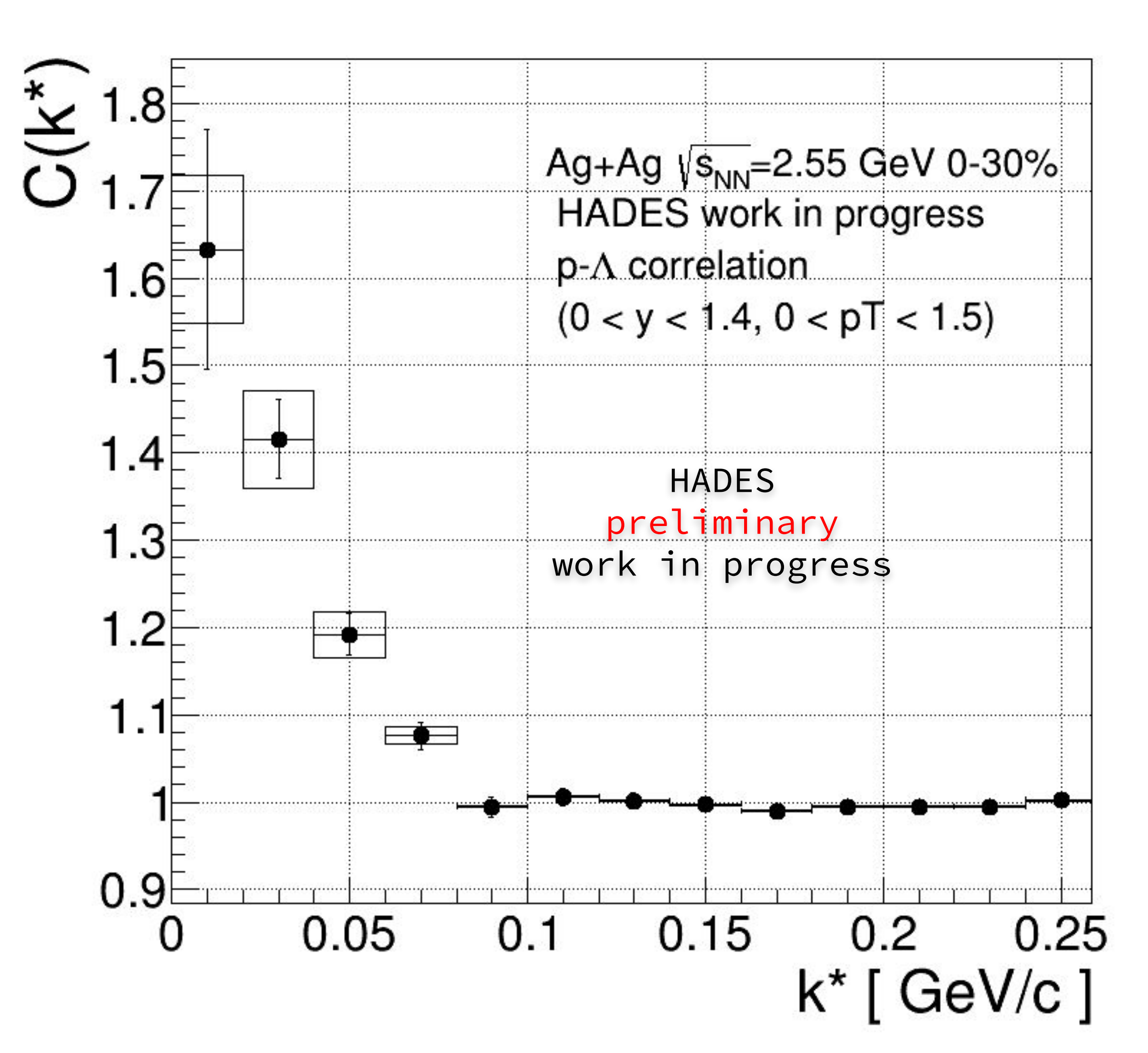
purity

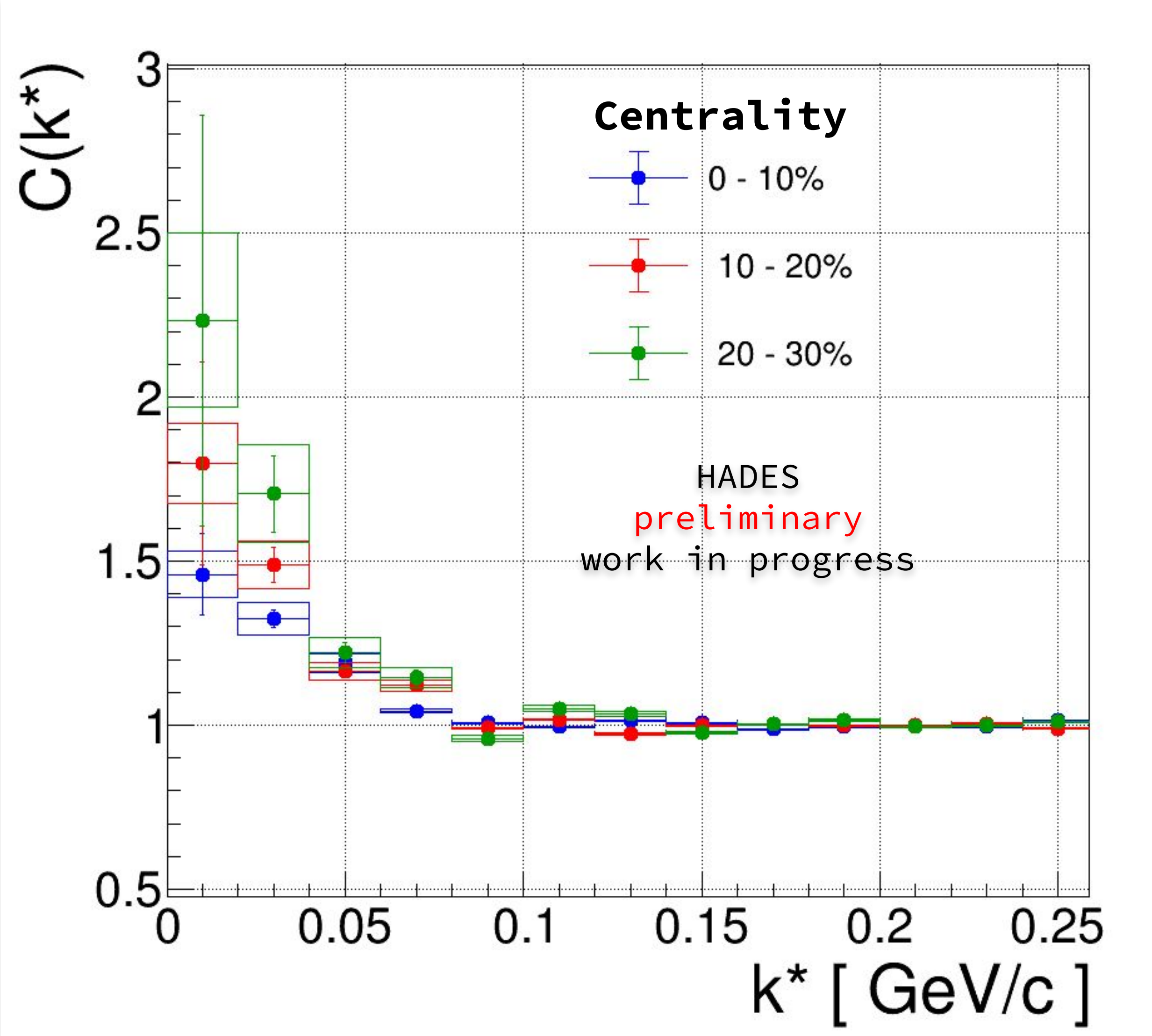
For all centrality classes estimated purity for pΛ : **90% -92% ± 3%** (data) (<400 MeV/c)



Detector effects

Result : p - Λ correlation





Lednicky & Lyuboshitz (LL) analytical model

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

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

Ref : Lednicky, Richard & Lyuboshits, V.L.. (1982). Effect of the final-state interaction on pairing correlations of particles with small relative momenta. Sov. J. Nucl. Phys. (Engl. Transl.); (United States). 35:5.

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*)**

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

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

Decomposition for spin channels :

$$C(k^*) = \frac{1}{4}(1 + \lambda C(k^*, s = 0)) + \frac{3}{4}(1 + \lambda C(k^*, s = 1))$$

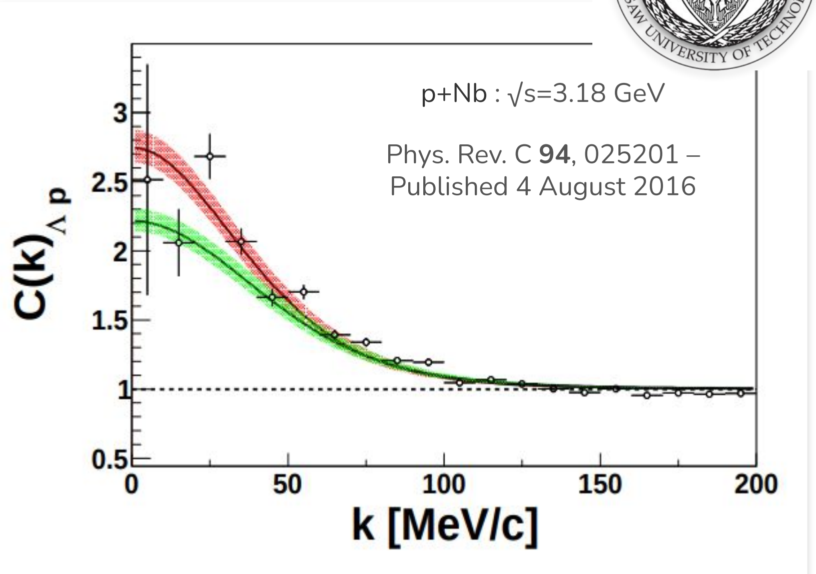
Parameters : $f_{0s}, d_{0s}, f_{0t}, d_{0t}$

Model		$f_0^{S=0}$ (fm)	$f_0^{S=1}$ (fm)	$d_0^{S=0}$ (fm)	$d_0^{S=1}$ (fm)	n_σ
ND [77]		1.77	2.06	3.78	3.18	1.1
NF [78]		2.18	1.93	3.19	3.358	1.1
NSC89 [79]		2.73	1.48	2.87	3.04	0.9
NSC97 [80]	a	0.71	2.18	5.86	2.76	1.0
	b	0.9	2.13	4.92	2.84	1.0
	c	1.2	2.08	4.11	2.92	1.0
	d	1.71	1.95	3.46	3.08	1.0
	e	2.1	1.86	3.19	3.19	1.1
	f	2.51	1.75	3.03	3.32	1.0
ESC08 [81]		2.7	1.65	2.97	3.63	0.9
χEFT	LO [25]	1.91	1.23	1.4	2.13	1.8
	NLO [26]	2.91	1.54	2.78	2.72	1.5
Jülich	A [82]	1.56	1.59	1.43	3.16	1.0
	J04 [83]	2.56	1.66	2.75	2.93	1.4
	J04c [83]	2.66	1.57	2.67	3.08	1.1

S. Acharya *et al.* (ALICE Collaboration) Phys. Rev. C 99, 024001 – Published 13 Feb 2019
https://doi.org/10.1103/PhysRevC.99.024001

parameter scan boundaries : f_0 [0.01, 5.0], d_{0s} [0.01, 2.0] and d_{0t} [0.01, 5.0]

HADES results



Parameters	p-Nb (LO)	p-Nb (NLO)
f_{0s}	1.91 fm	2.91 fm
d_{0s}	1.40 fm	2.78 fm
f_{0t}	1.23 fm	1.54fm
d_{0t}	2.13 fm	2.72fm
r_0	1.71±0.10	1.62±0.02

HAL : Corrfit -Cumac : framework

Set parameters loop
$\lambda, r_0, f_{0s}, d_{0s}, f_{0t}, d_{0t}$

↓

Lednicky & Lyuboshitz analytical model

↓

Calculate correlation function

↓

fit

↓

Experimental correlation function

↓

χ^2 calculation minimum determination

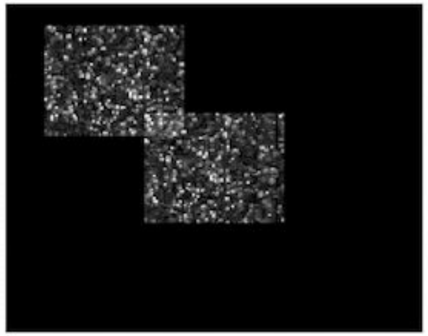
How do we formulate this model?

Principle ways of generate the theoretical correlation function.

1. The Lednicky-Luboshitz semi-analytical model (utilized in CorrfitCumac codes) provides an immediate correlation function value but may be computationally intensive due to integral calculations.

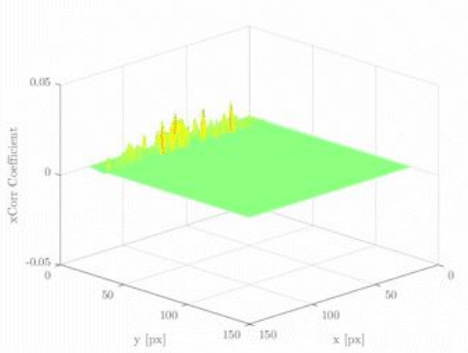
2. The first fitter employs ROOT minimizers, offering precise statistical uncertainty estimation, but it operates on "continuous" maps with limited control over parameter steps.

3. The second fitter, Hal:Minimizer, accommodates "non-continuous" functions, allowing parameters to change in discrete steps. However, it provides only approximate uncertainty estimates.



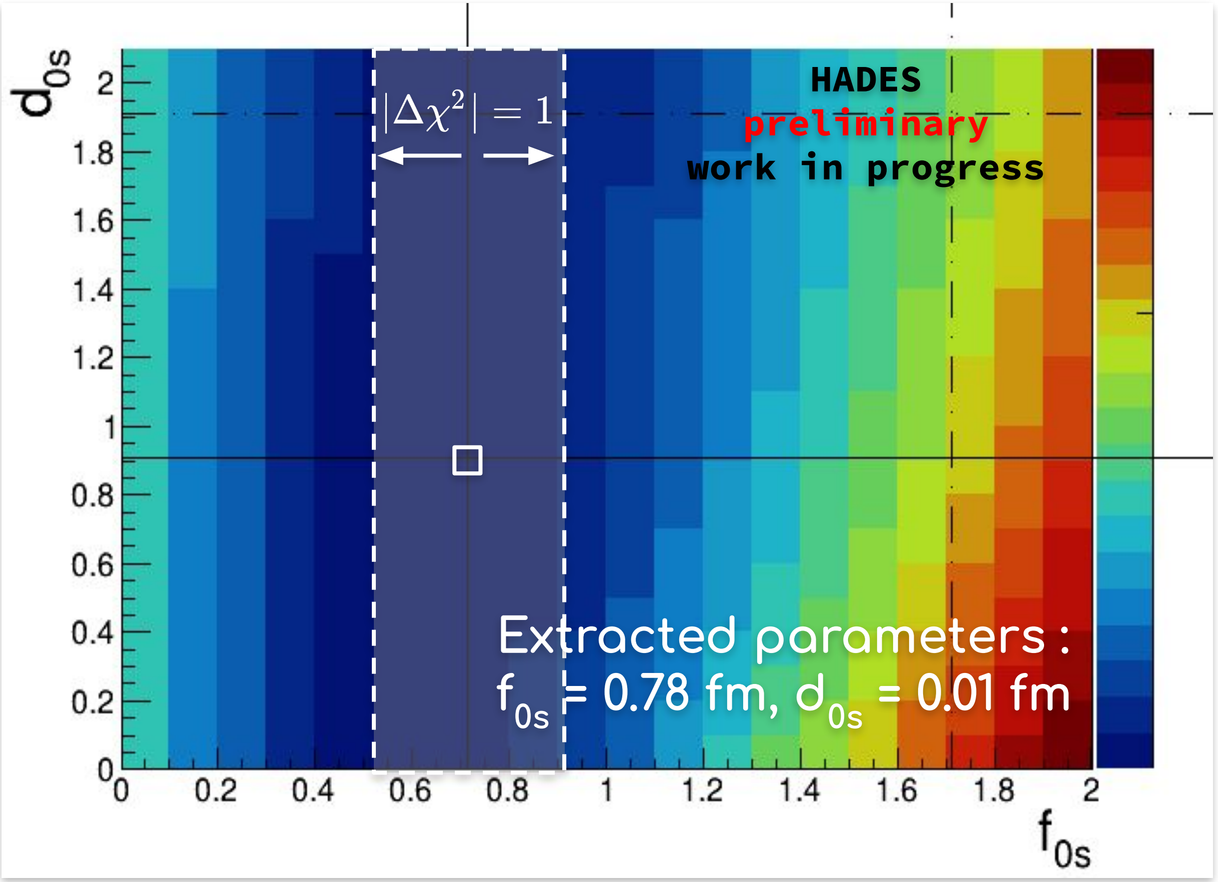
```
for( int λ = 0.6; λ < 0.8; λ+=0.1 )
    for( int r0 = 1.0; r0 < 4.0; r0+=0.1 )
        for( int f0 = 0.01; f0 < 5.0; f0+=0.1 )
            for( int d0 = 0.01; d0 <5.0; d0+=0.1)
                for( int ft = 0.01; ft < 5.0 ; ft += 0.1 )
                    for( int dt =0.01; dt < 5.0; dt+=0.1 )
                        Calculate Lednicky-Luboshitz
                        correlation function : fit data
                        χ2 : value is extracted : minimizer
```

Special Thanks to Dr. Daniel Wilanek and Prof. Yuri Sinyukov

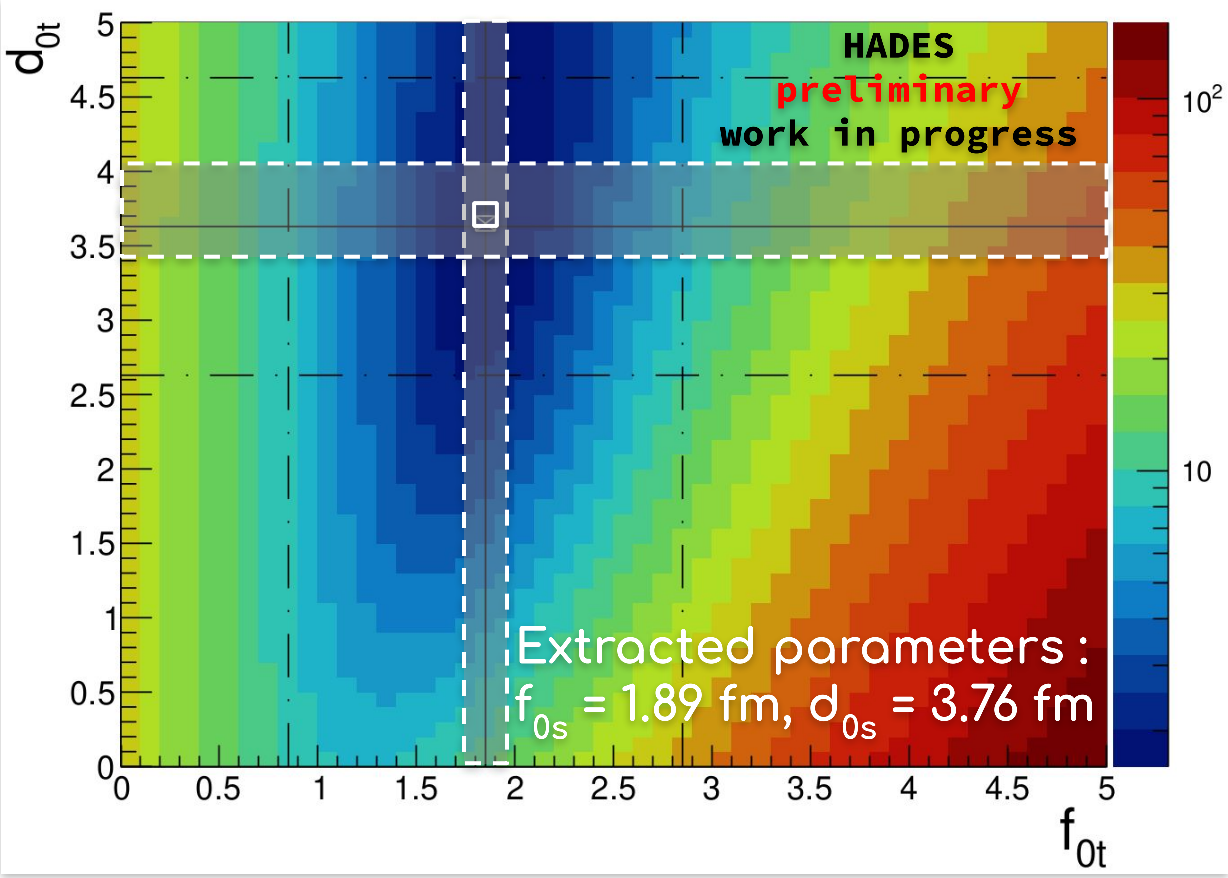


f_{0s}, d_{0s}, f_{0t} and d_{0t} parameters : χ^2 value

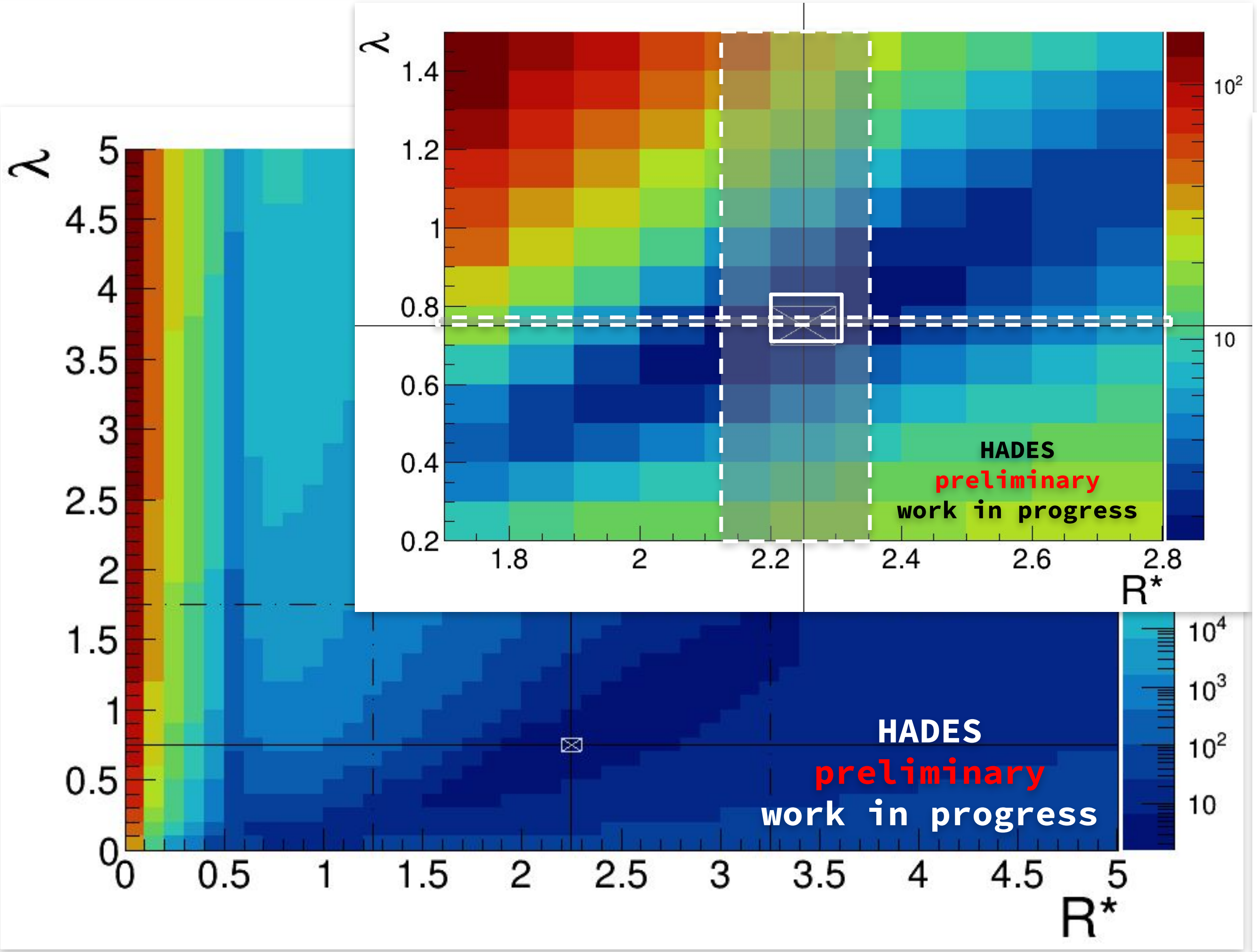
Singlet

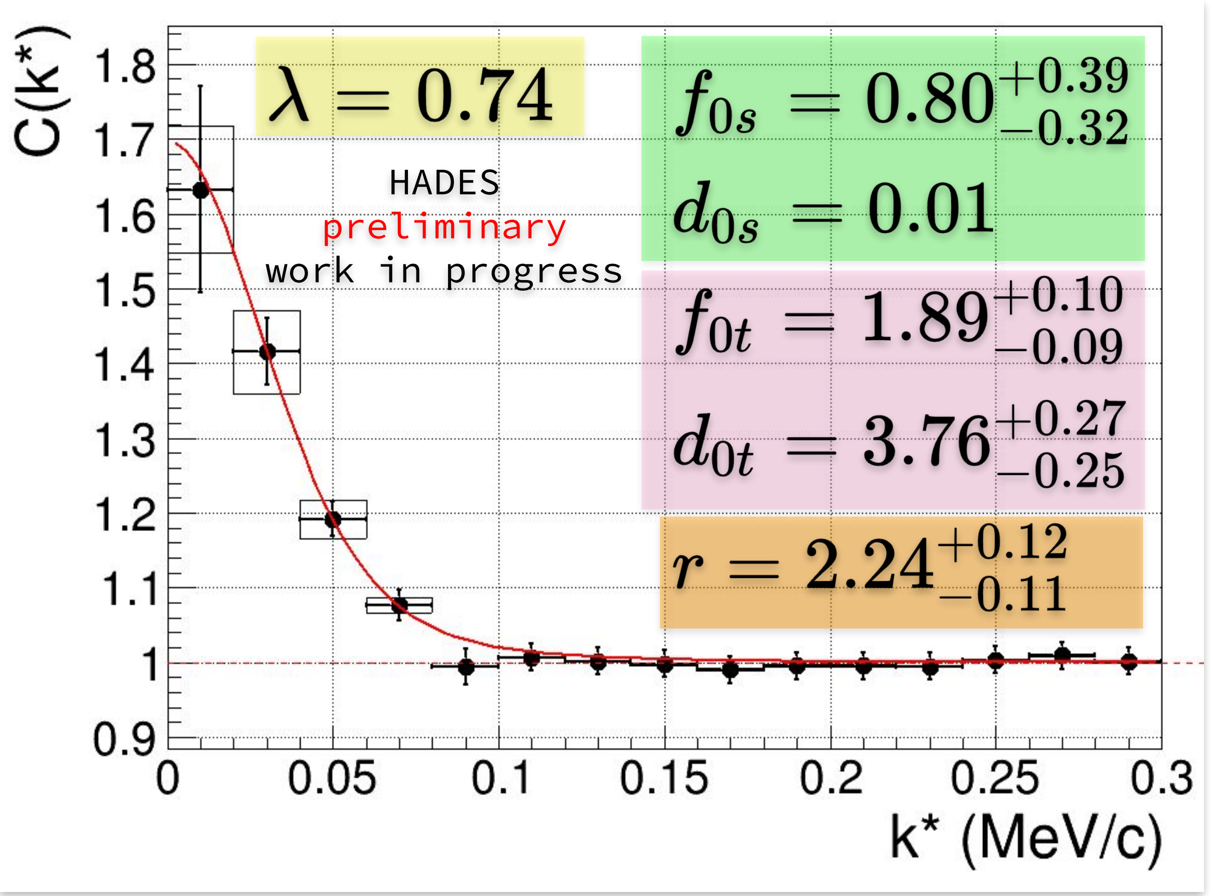


Triplet

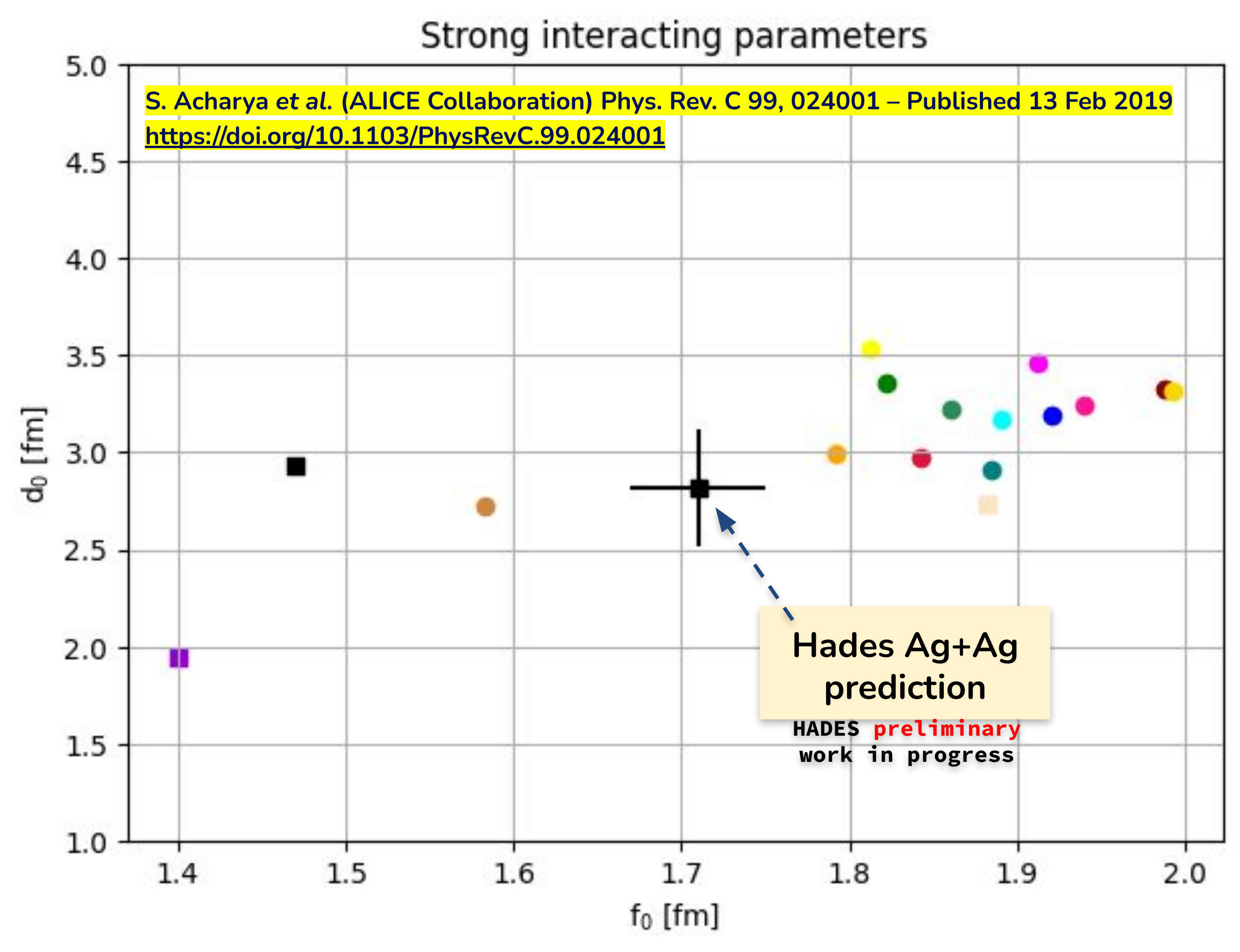


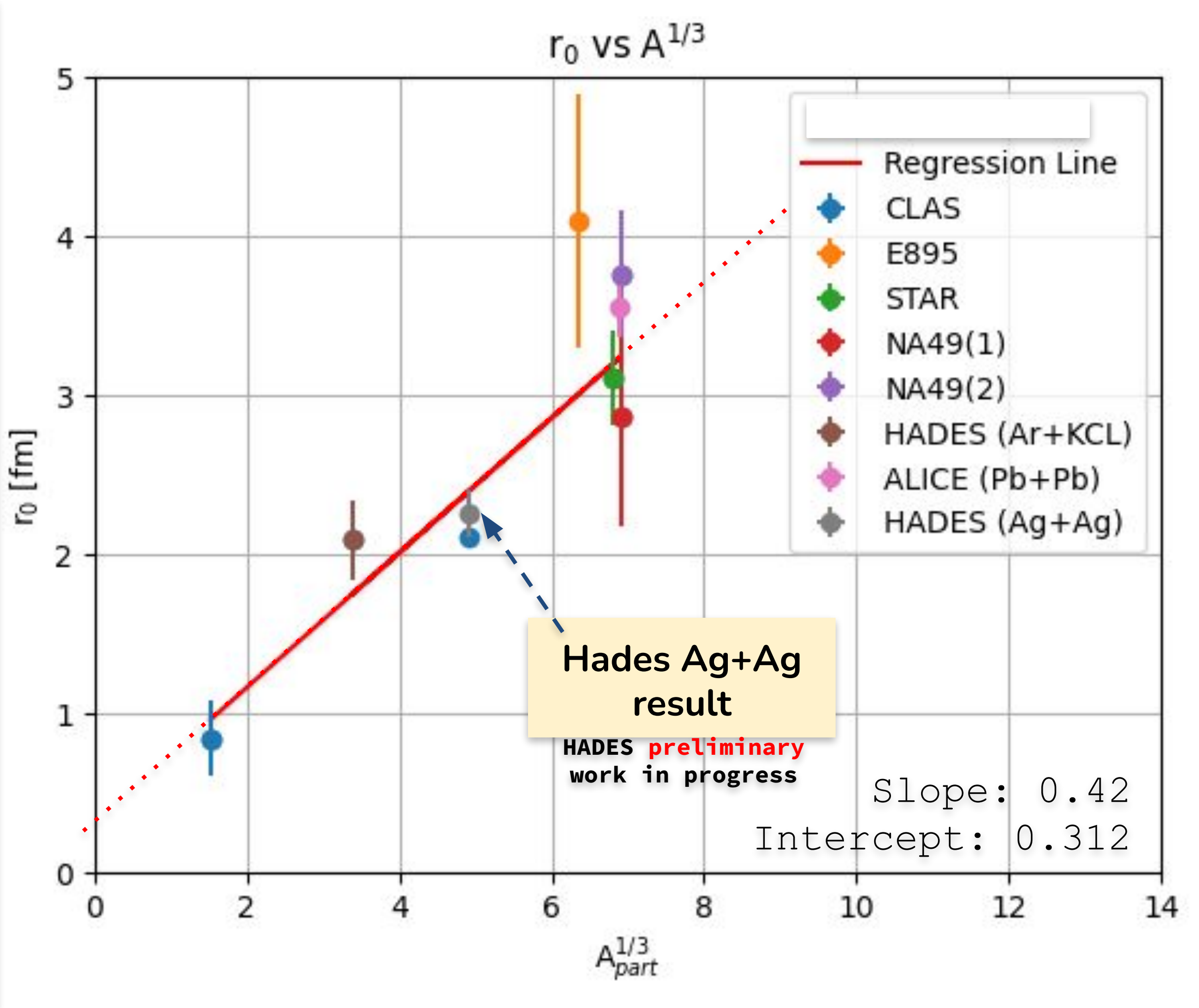
1. λ and R [fm] parameters : χ^2 value
2. Fitted spectra with extracted parameters



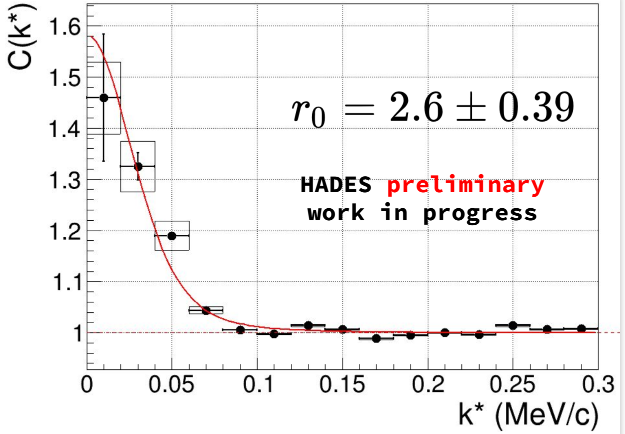


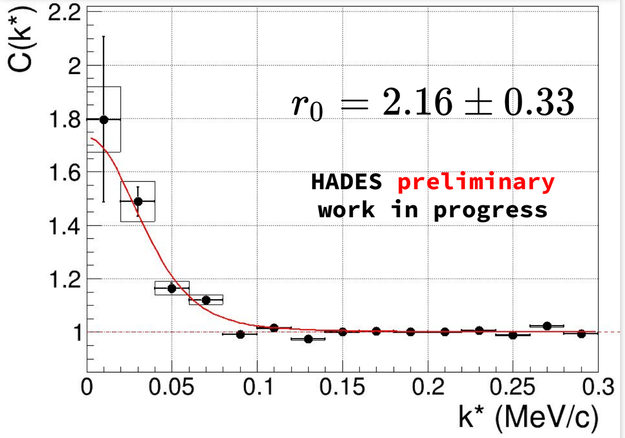
Parameters scan and Plot : r_0 vs $A_{part}^{1/3}$

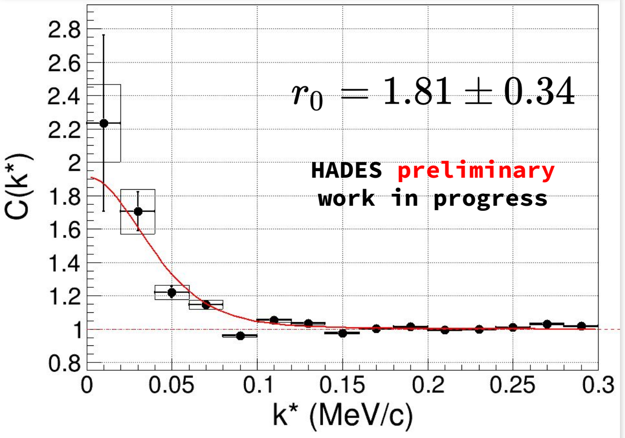


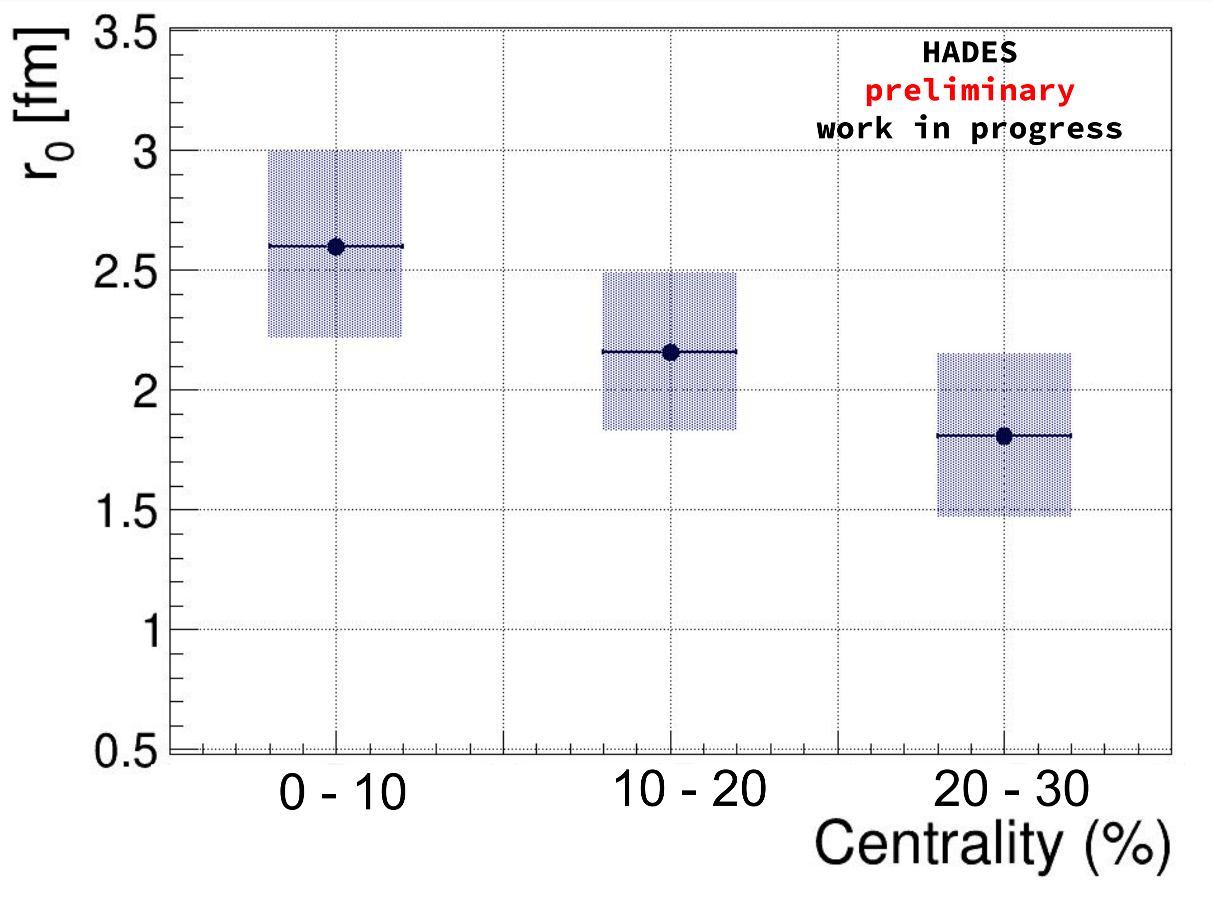


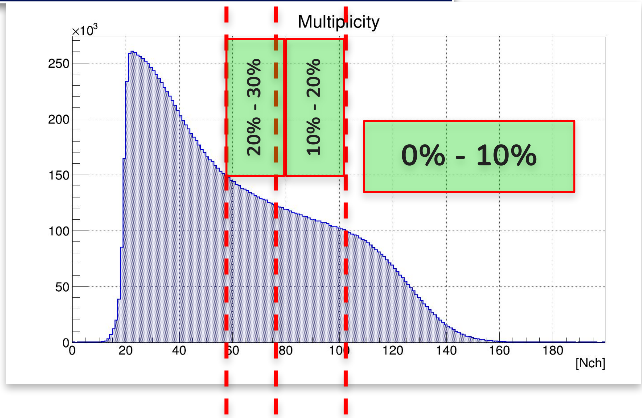
Result : p - Λ correlation : centrality classes: 0-10%, 10-20%, 20-30%





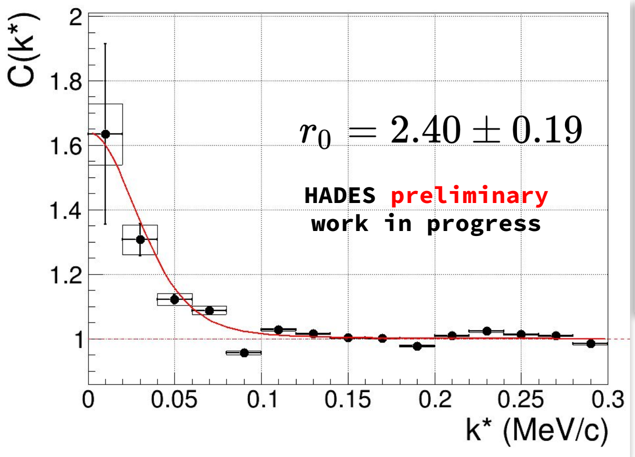


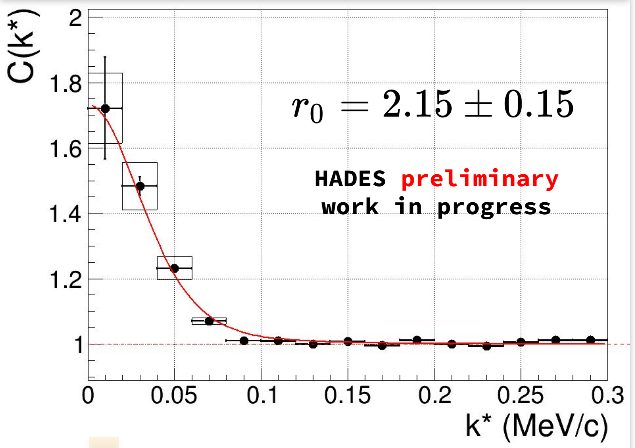


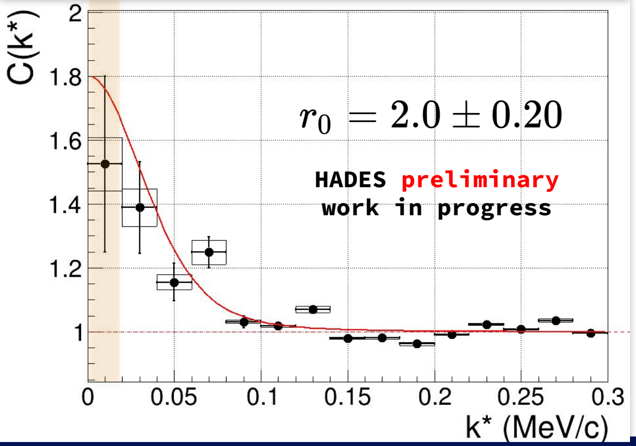


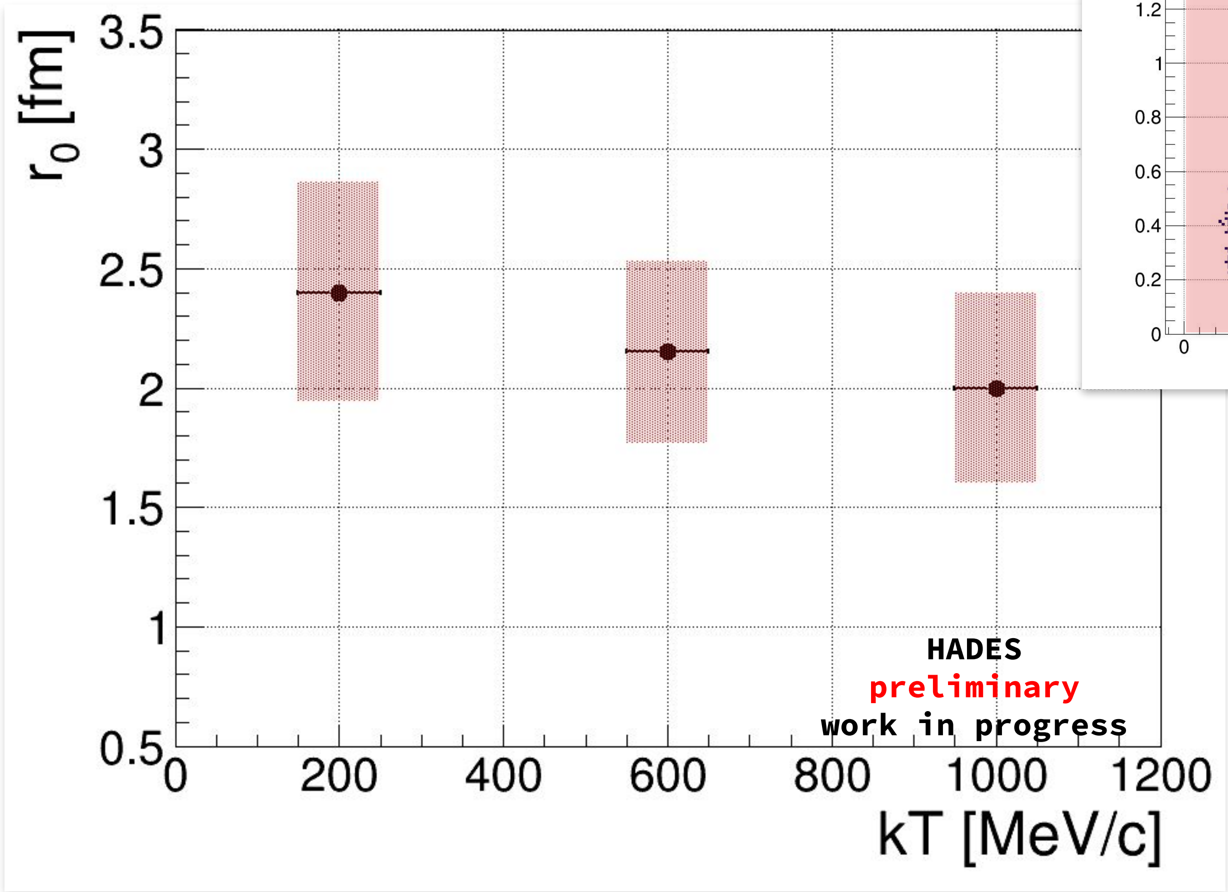
Centrality	Systematic Uncertainty
0 - 10 %	15.30 %
10 - 20 %	15.49 %
20 - 30 %	19.00 %

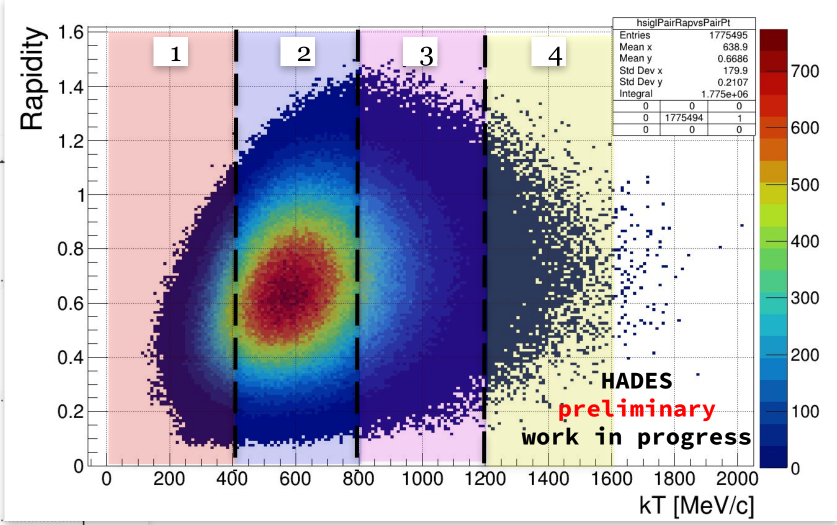
Result : p - Λ correlation :
kT bins : 0-400, 400-800, 800-1200 [MeV/c]





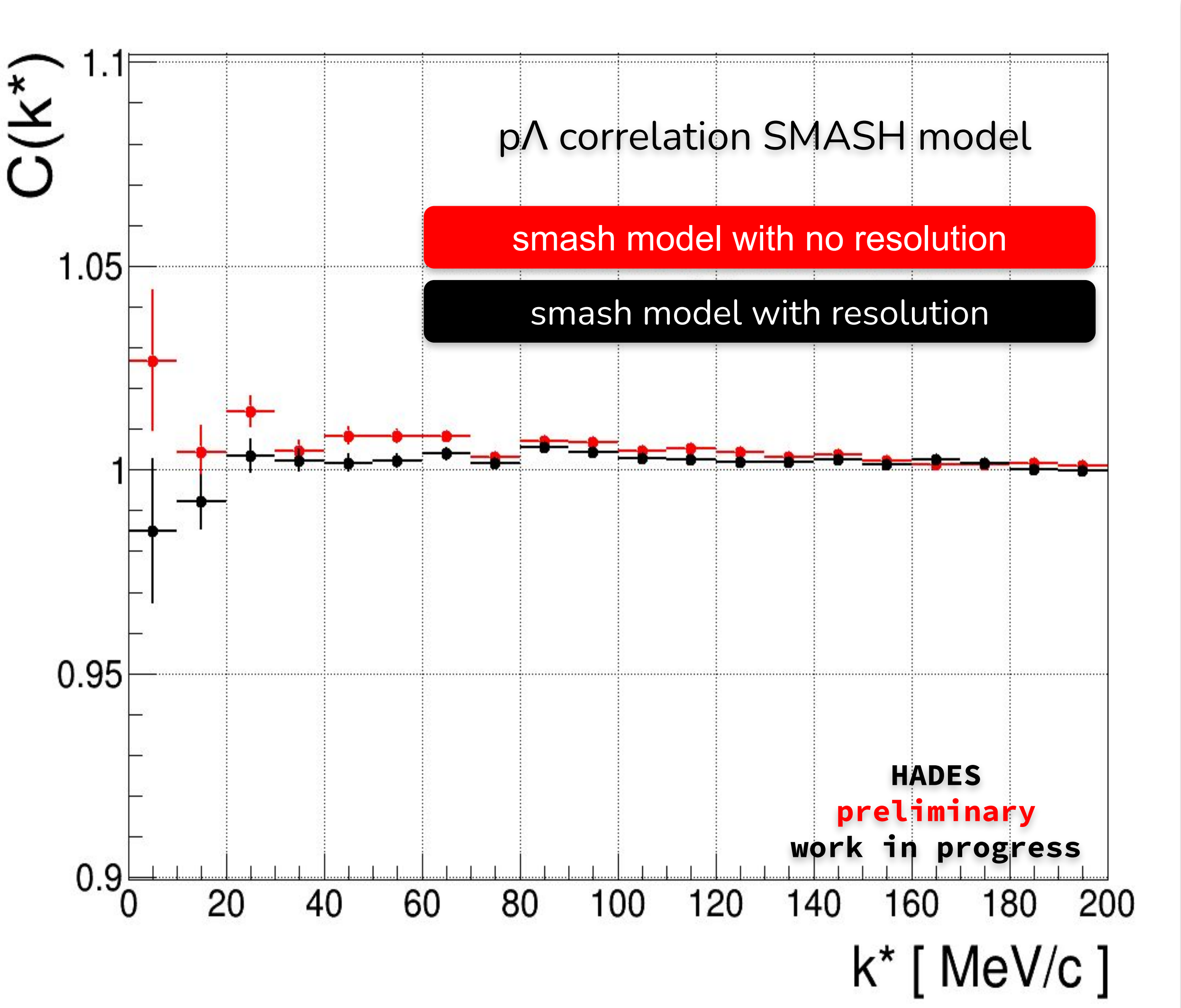


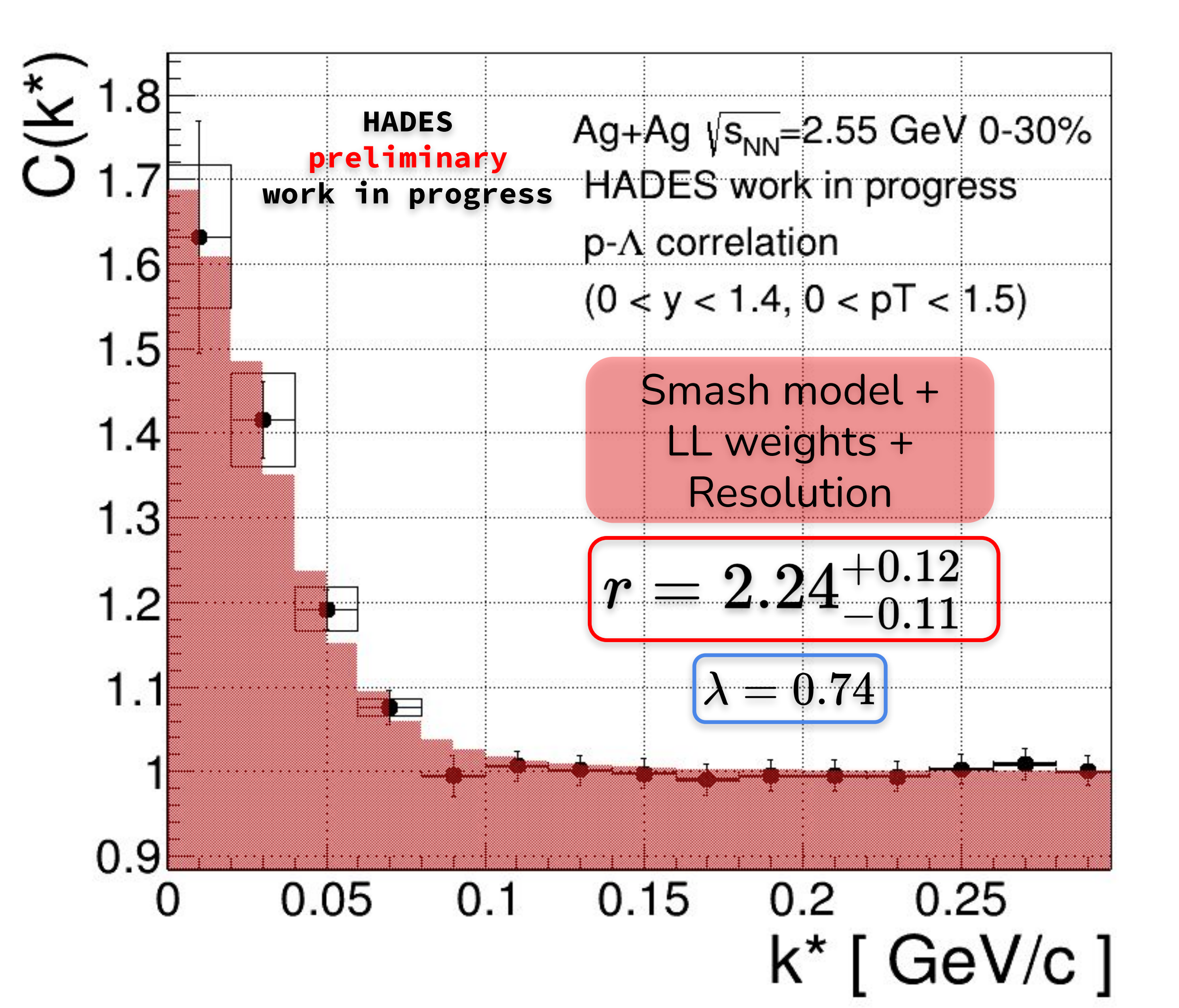




kT region	Systematic Uncertainty
0 - 400	19 %
400 - 800	15 %
800 - 1200	22 %

Resolution effects

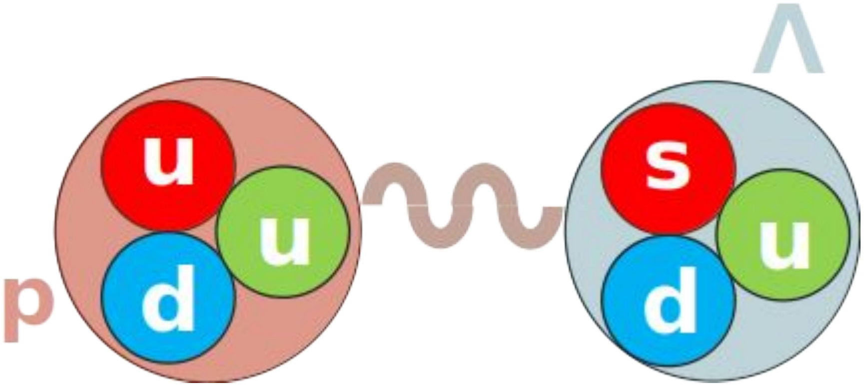




Summary

1. The correlation signals in Ag-Ag collision is extracted : **p–Λ**, ✔
2. Resolution effects (θ, ϕ, p) studies are performed, fits are available for MC ✔
3. Systematics studies are performed✔
4. Detector effects, purity determination and model interference are studied✔

2nd stage : (towards strong parameters)



5. Use Lednicky and Lyuboshitz (LL) analytical model
   - source radii (R), ✔
   - extract strong interaction parameters✔
   - Uncertainties ✔ (χ^2 method done✔, ALICE bootstrap technique under progress .....)

6. adding proton and lambda resolution resolution to smash model with LL weights✔
7. Few cross-checks needed to lock obtain parameters : resolution✔, check mT / pT ✔ scaling, rechecks centrality results, acceptance check.

Results will be ready for publication (Stay tuned)

What's next ? (new ideas to explore)

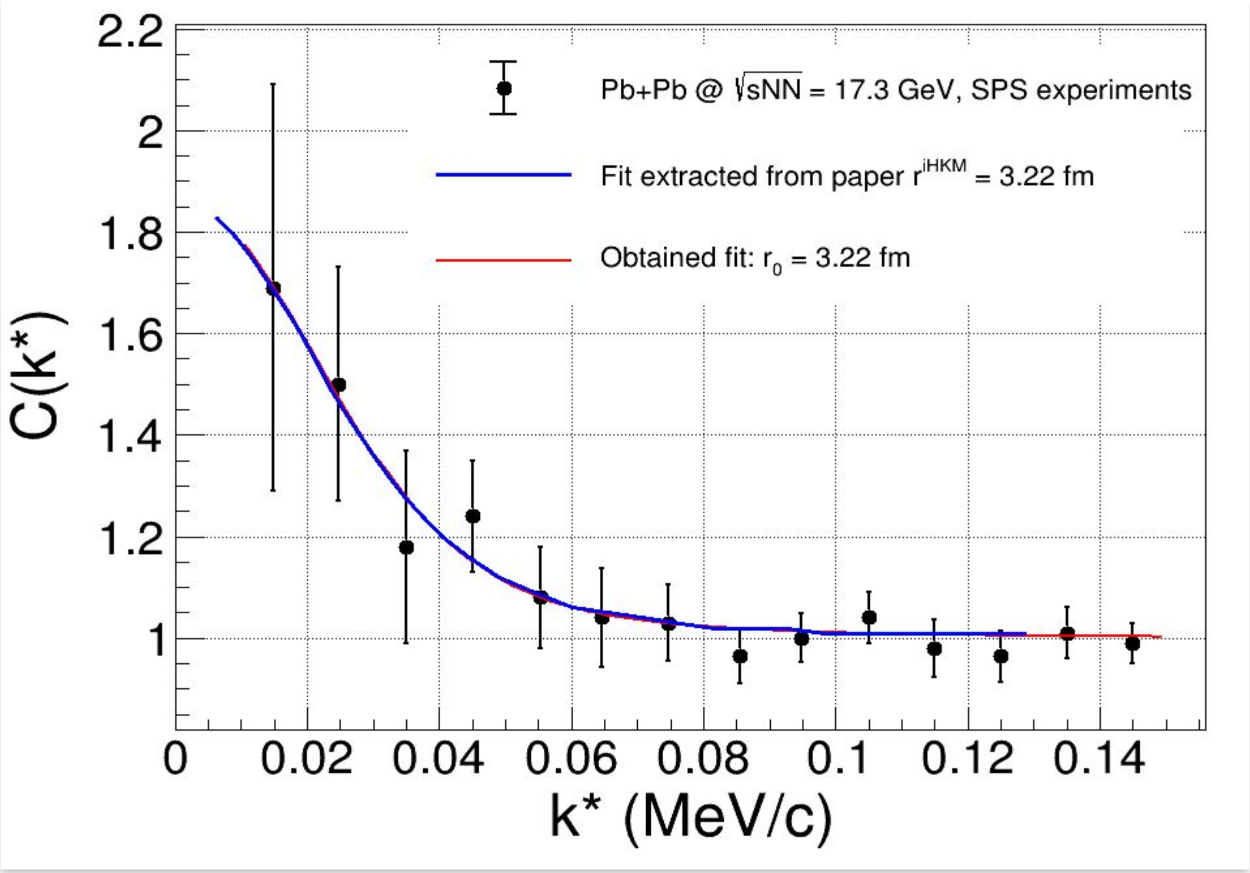
8. physics behind heavier hydrogen (deuteron) interaction with lambda (**d–Λ**) will be interesting.
9. also opportunity to work with new HADES (p-p collision)- data for femtoscopy studies………

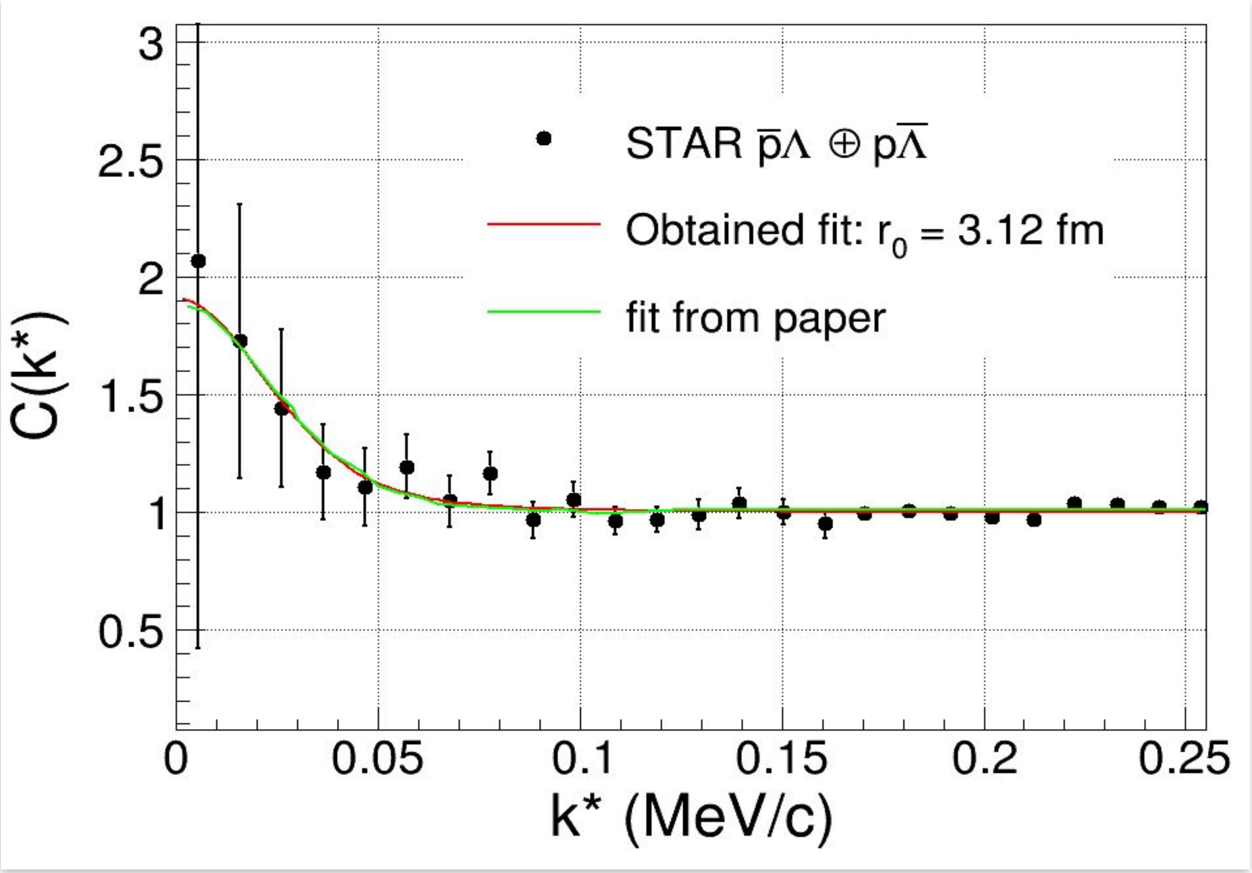
Thank you

for any specific detail please mail : narendra.rathod@pw.edu.pl

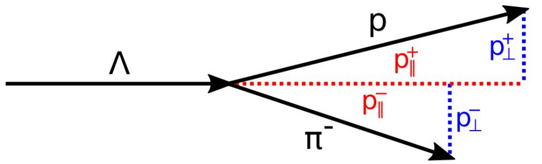
Result : STAR and LHC data

RHIC : Au+Au @ 200 GeV and STAR : LHC Pb+Pb @ 2.76 TeV : Testing fitting procedure



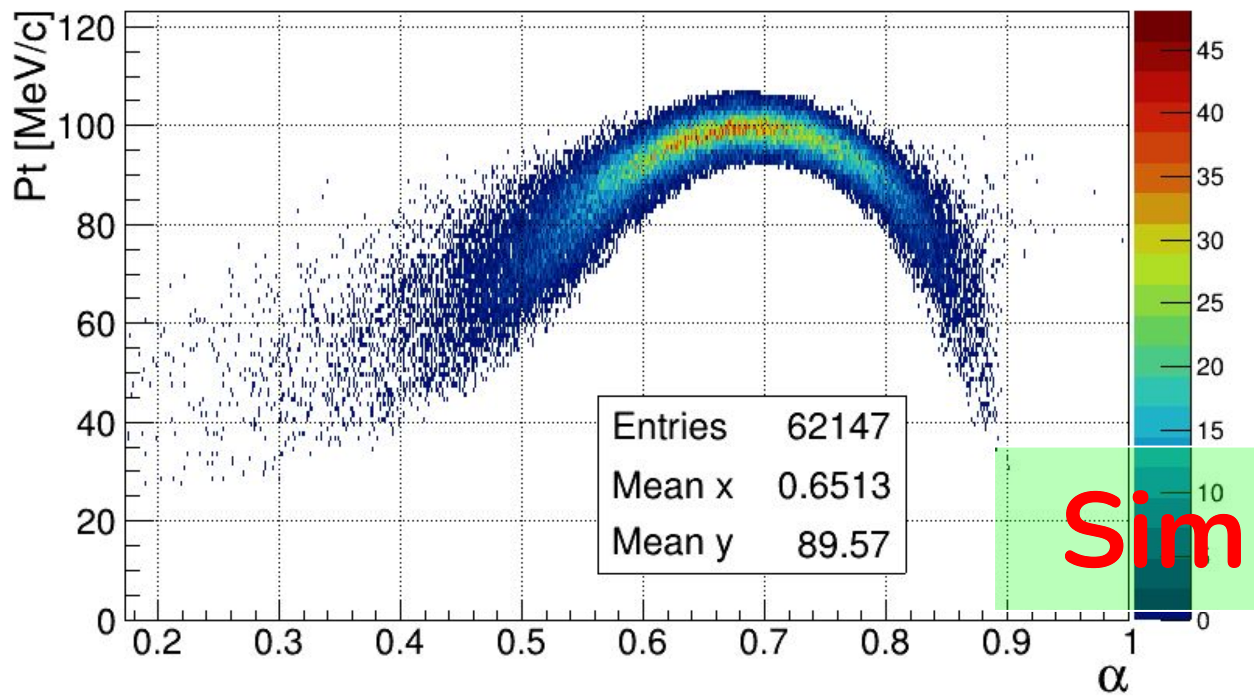


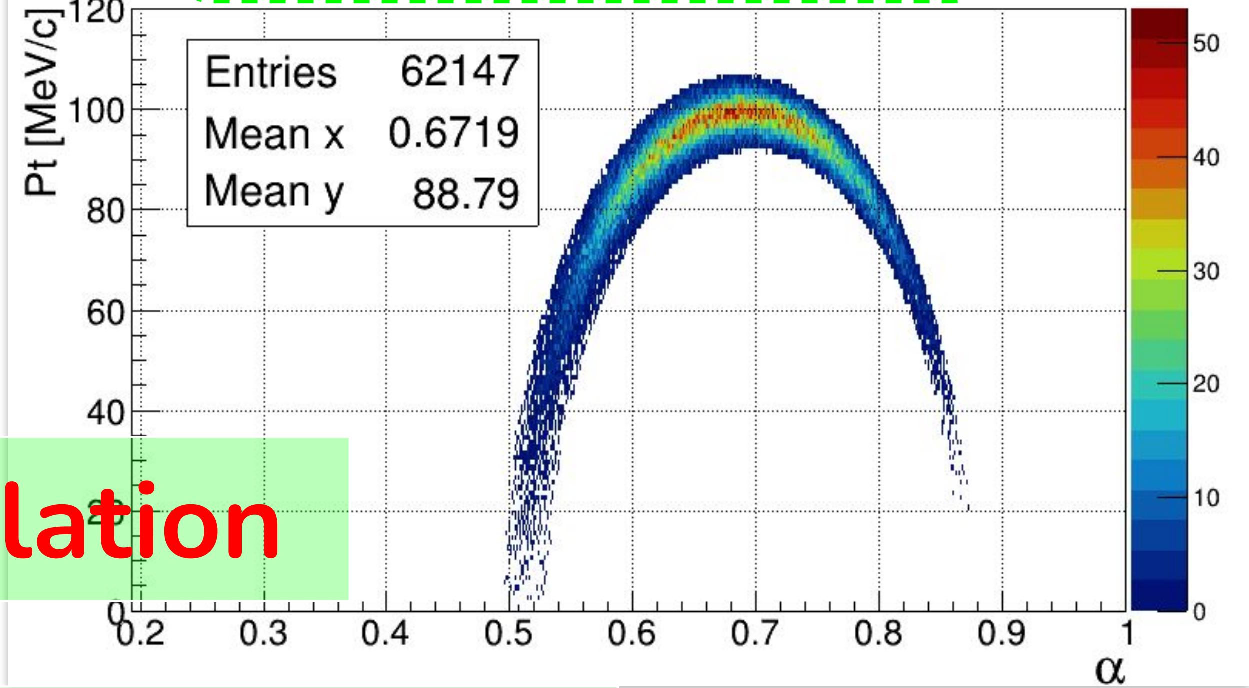
Armenteros-Podolanski plots



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

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

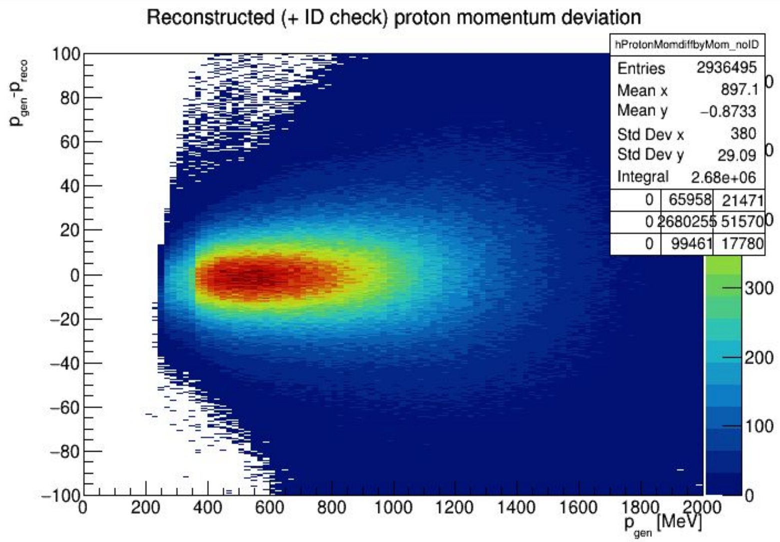


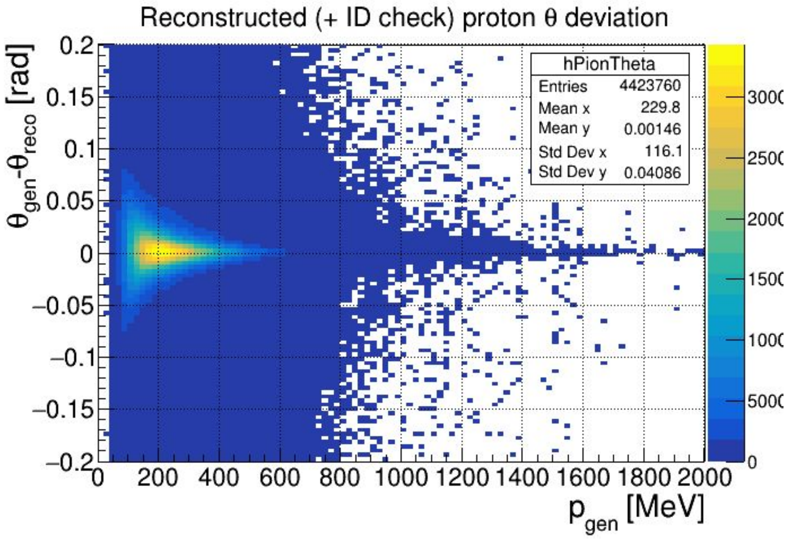


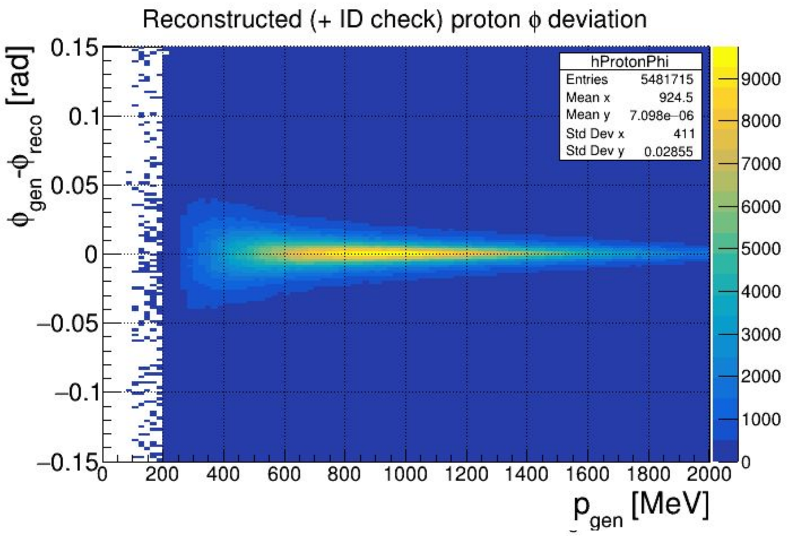
Simulation

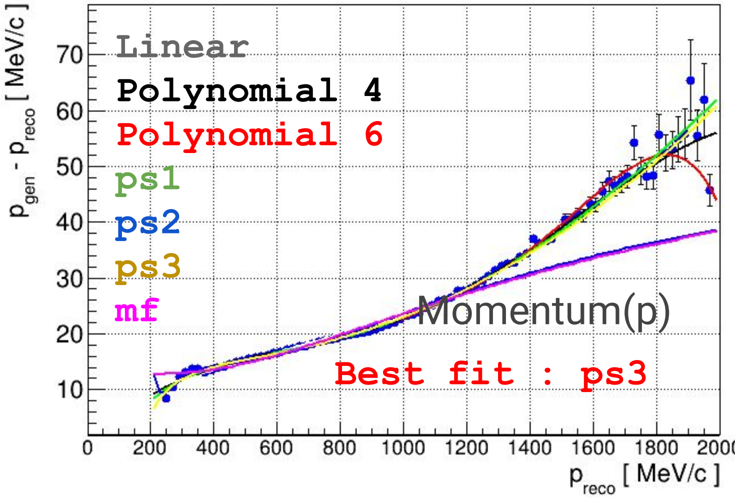
HADES : Low energies → **Additional boost to daughter particles TVector3 beta (0., 0., 0.99);** → **Corrected**

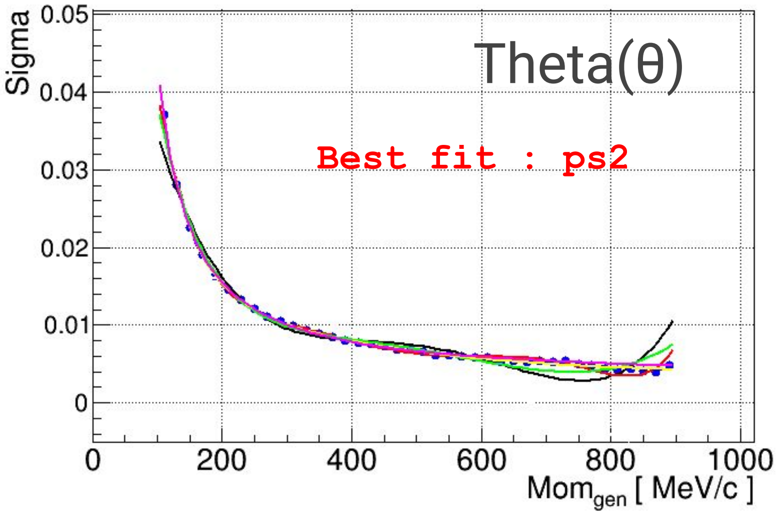
Proton resolution

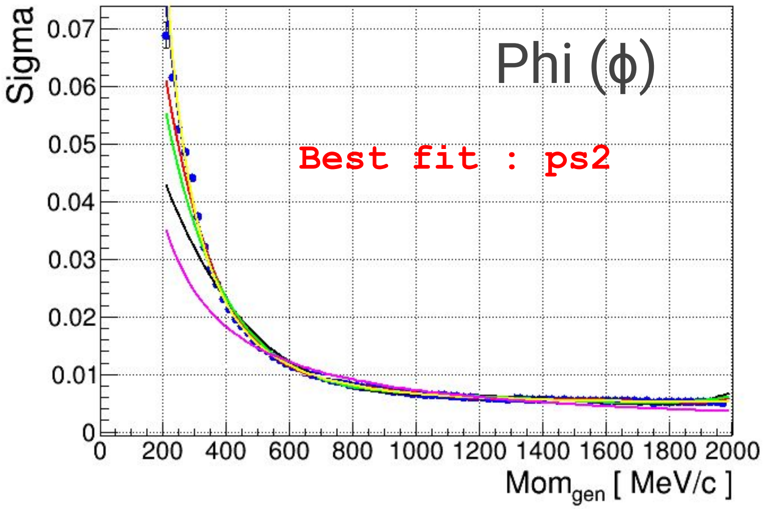




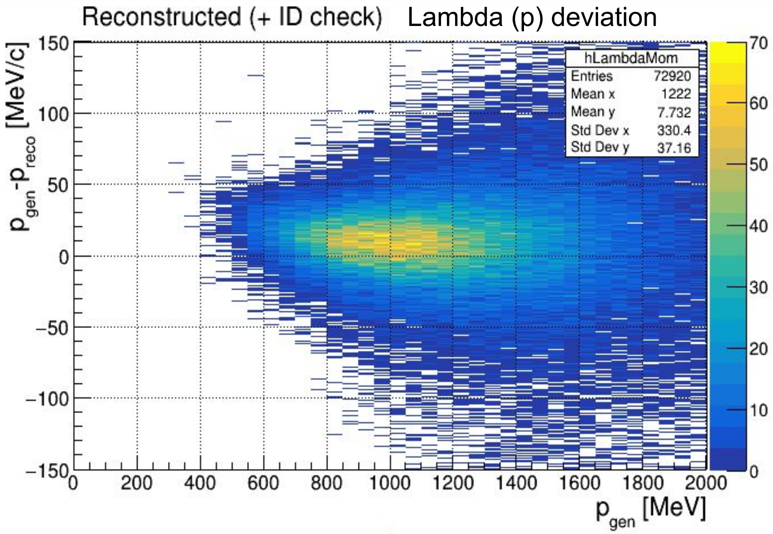


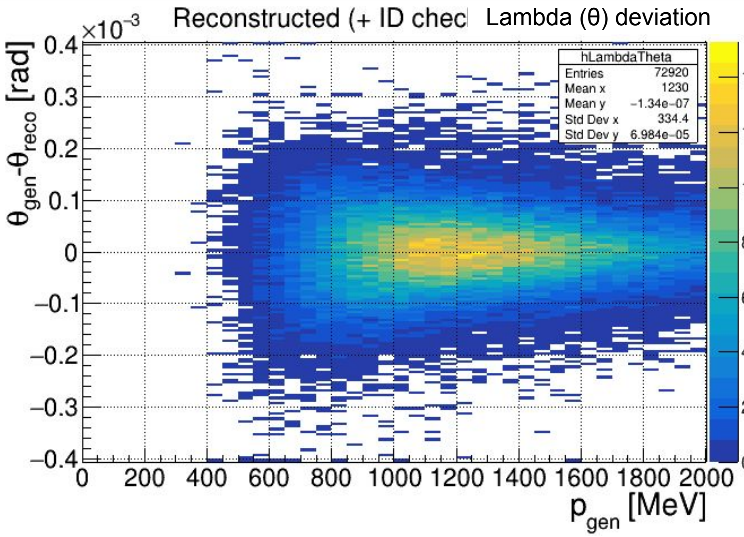


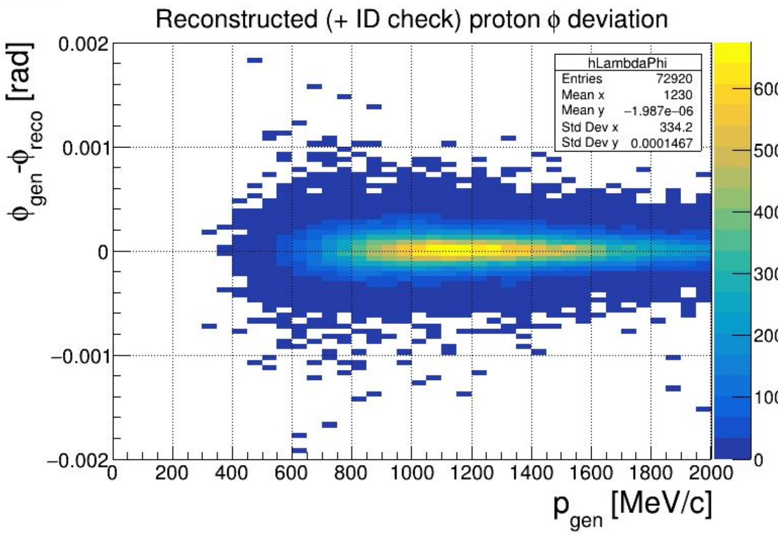


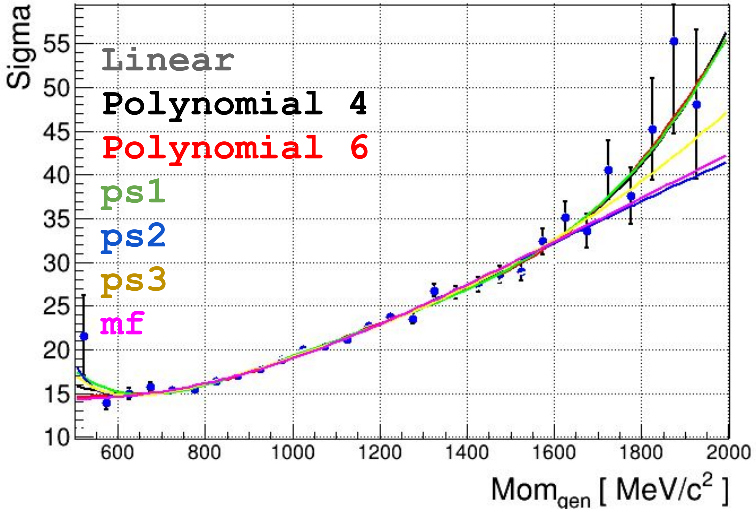


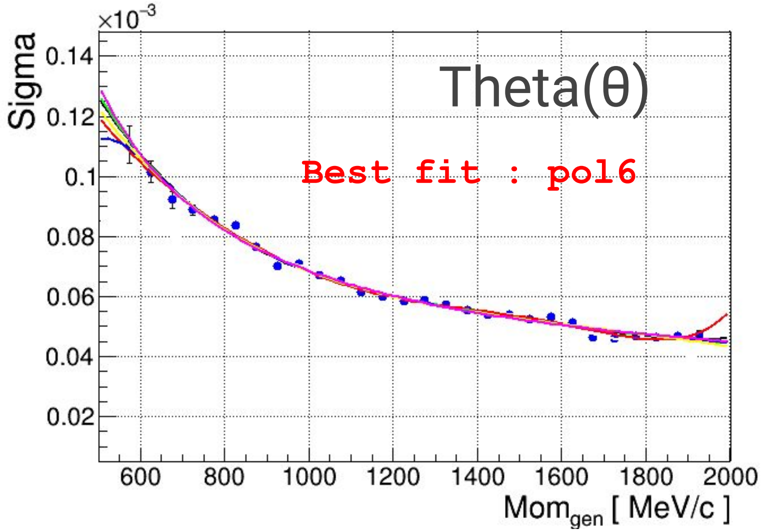
Lambda resolution

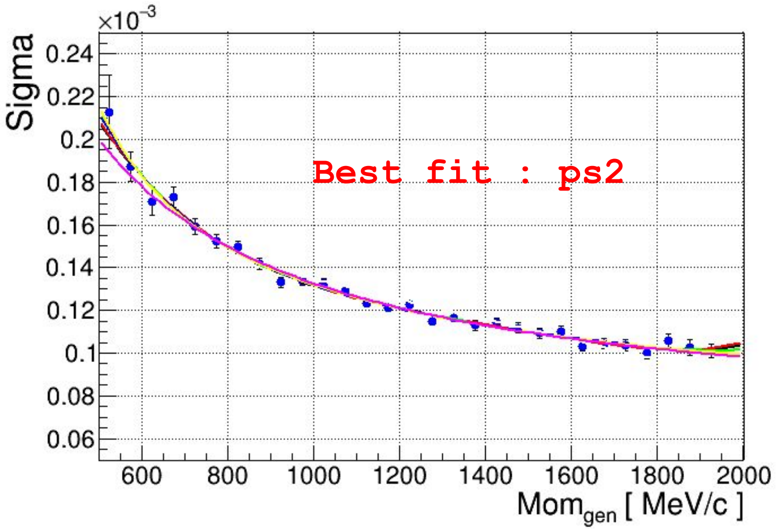






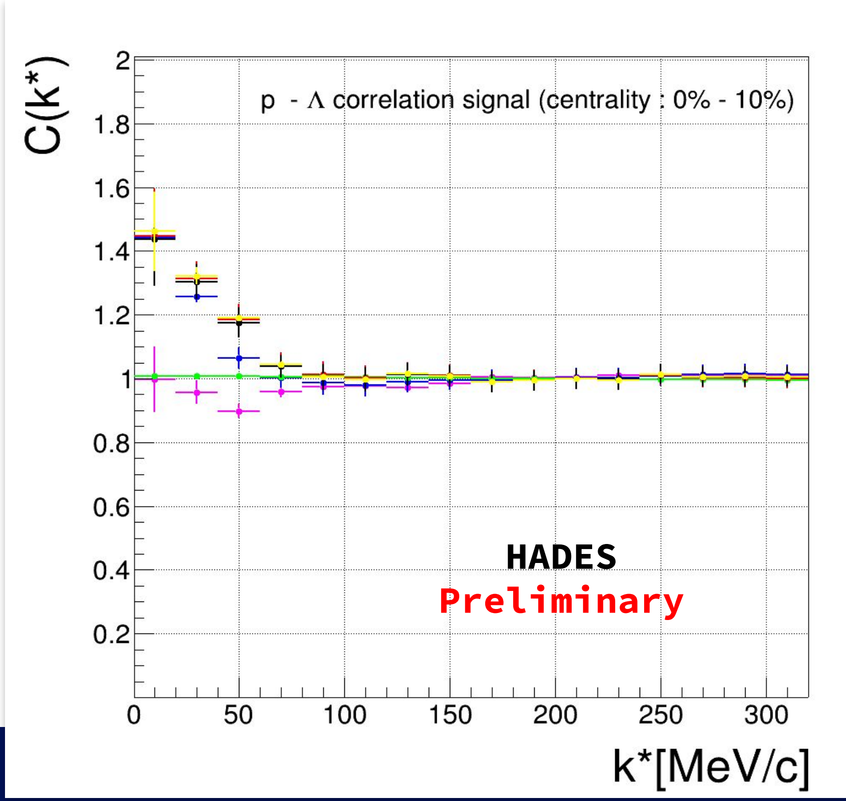


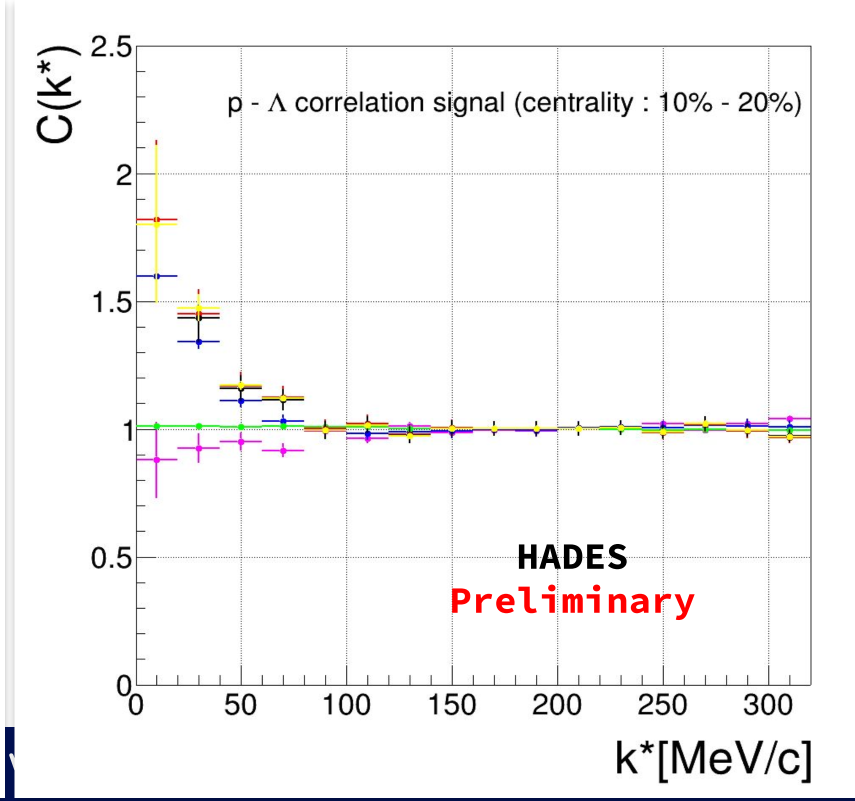


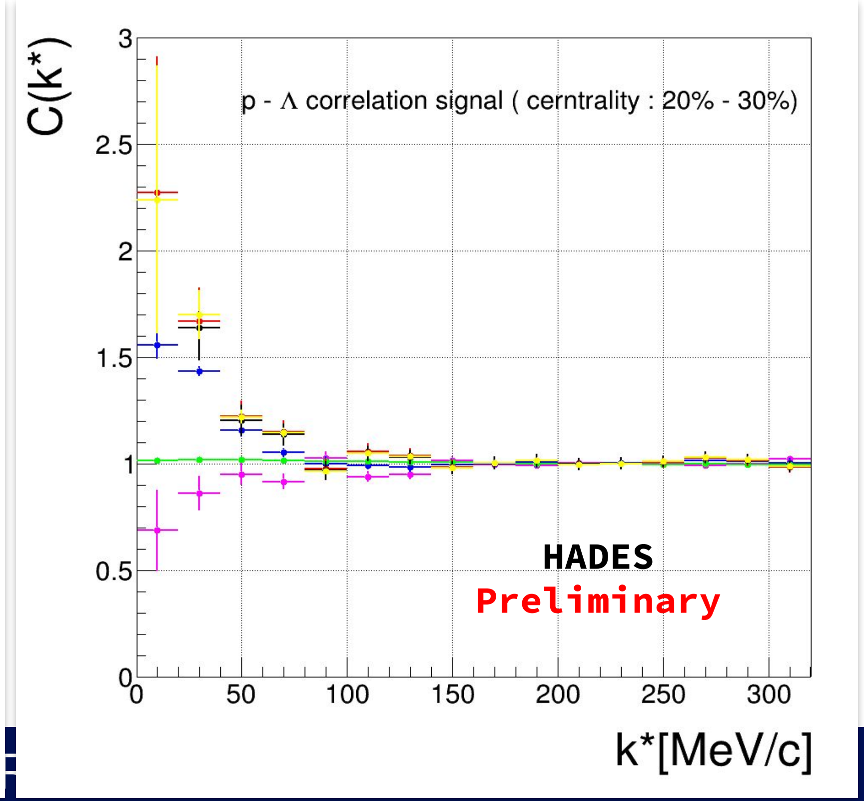


Result - II

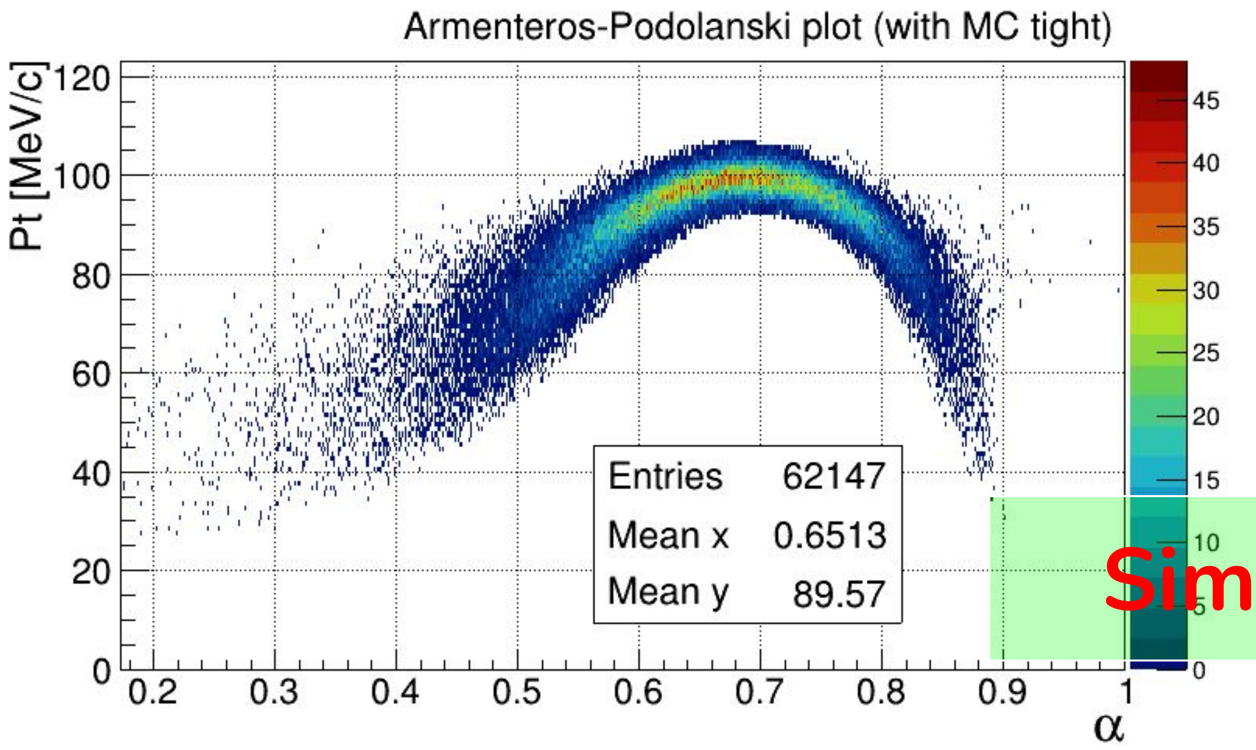
- Experimental raw spectra
- Model effect
- Detector effects + model
- Exp + corrected (detector+model)
- Exp + corrected + purity : final spectra

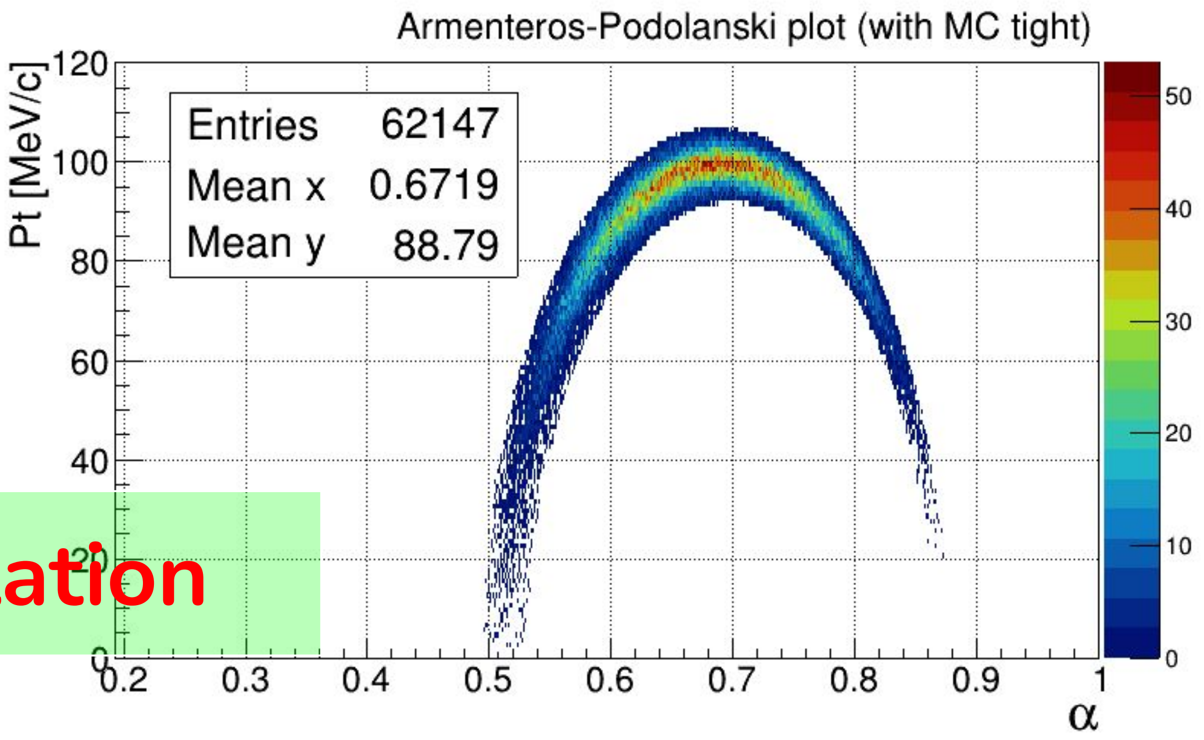






Armenteros-Podolanski plots





Simulation

HADES :
Low energies

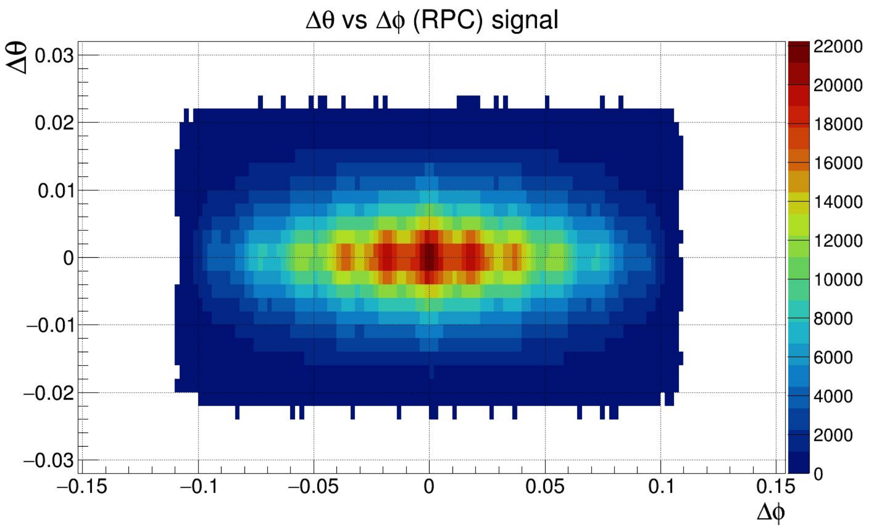
→

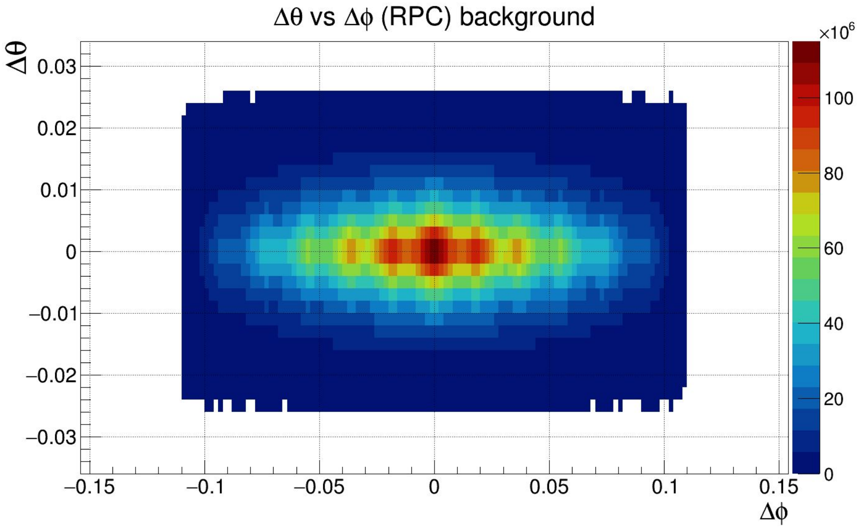
Additional boost to daughter particles
TVector3 beta (0., 0., 0.99);

→

Corrected

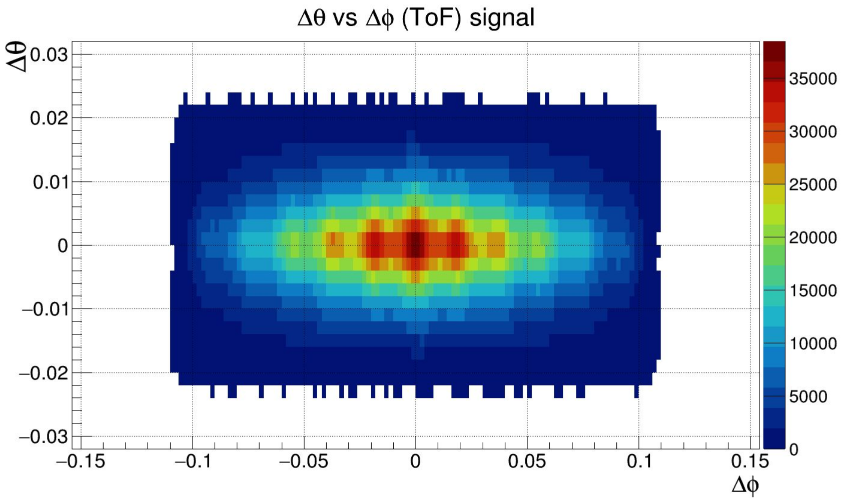
Δθ vs Δϕ distribution

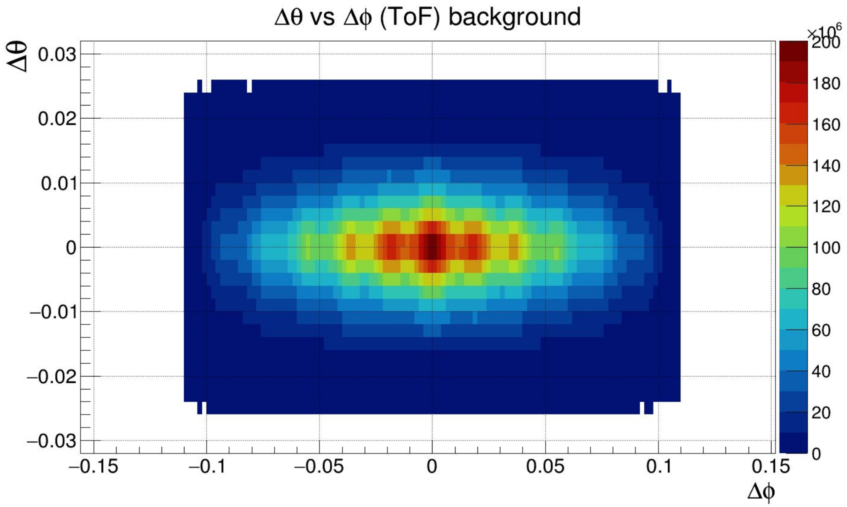




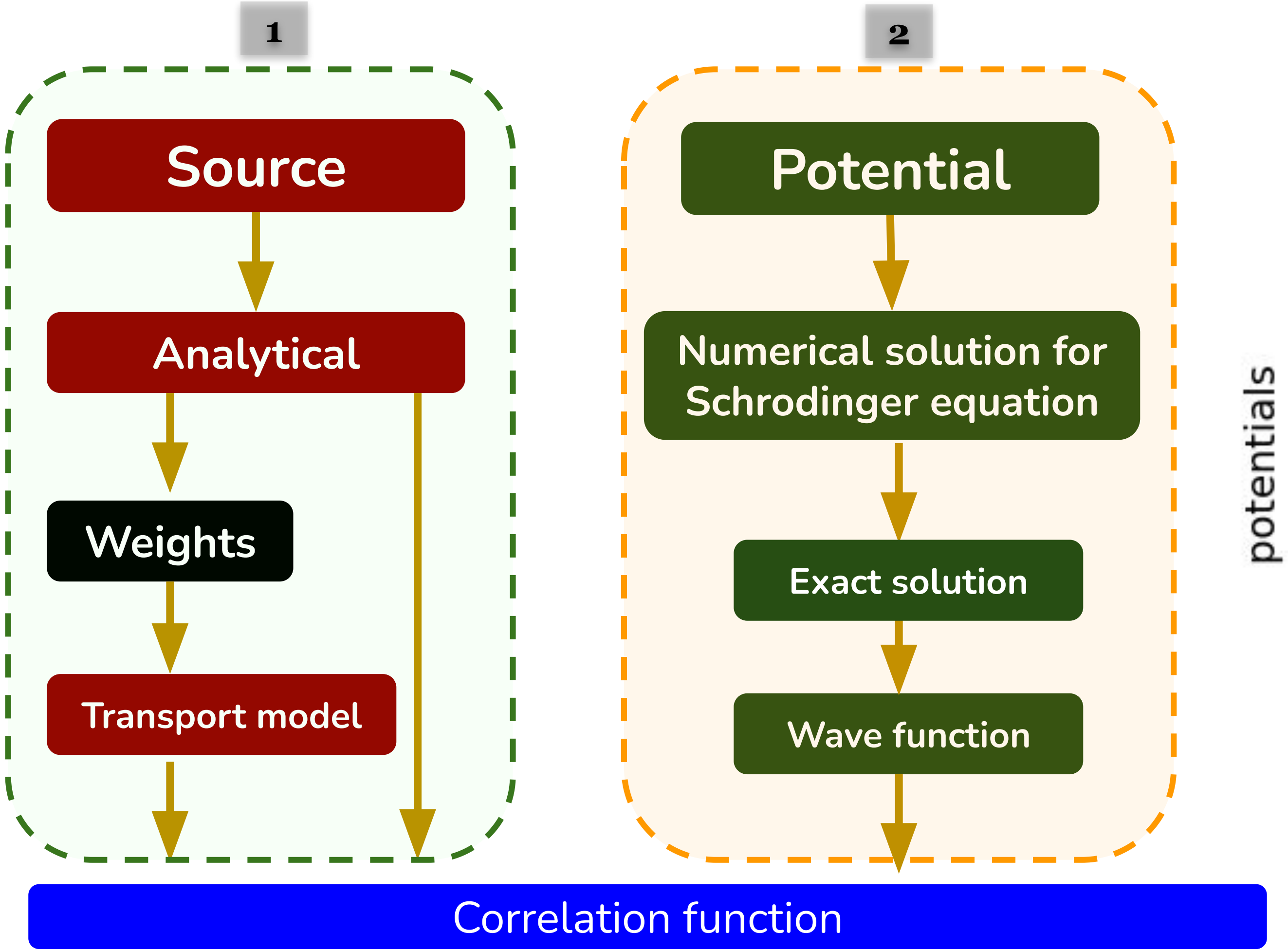
RPC results

ToF results



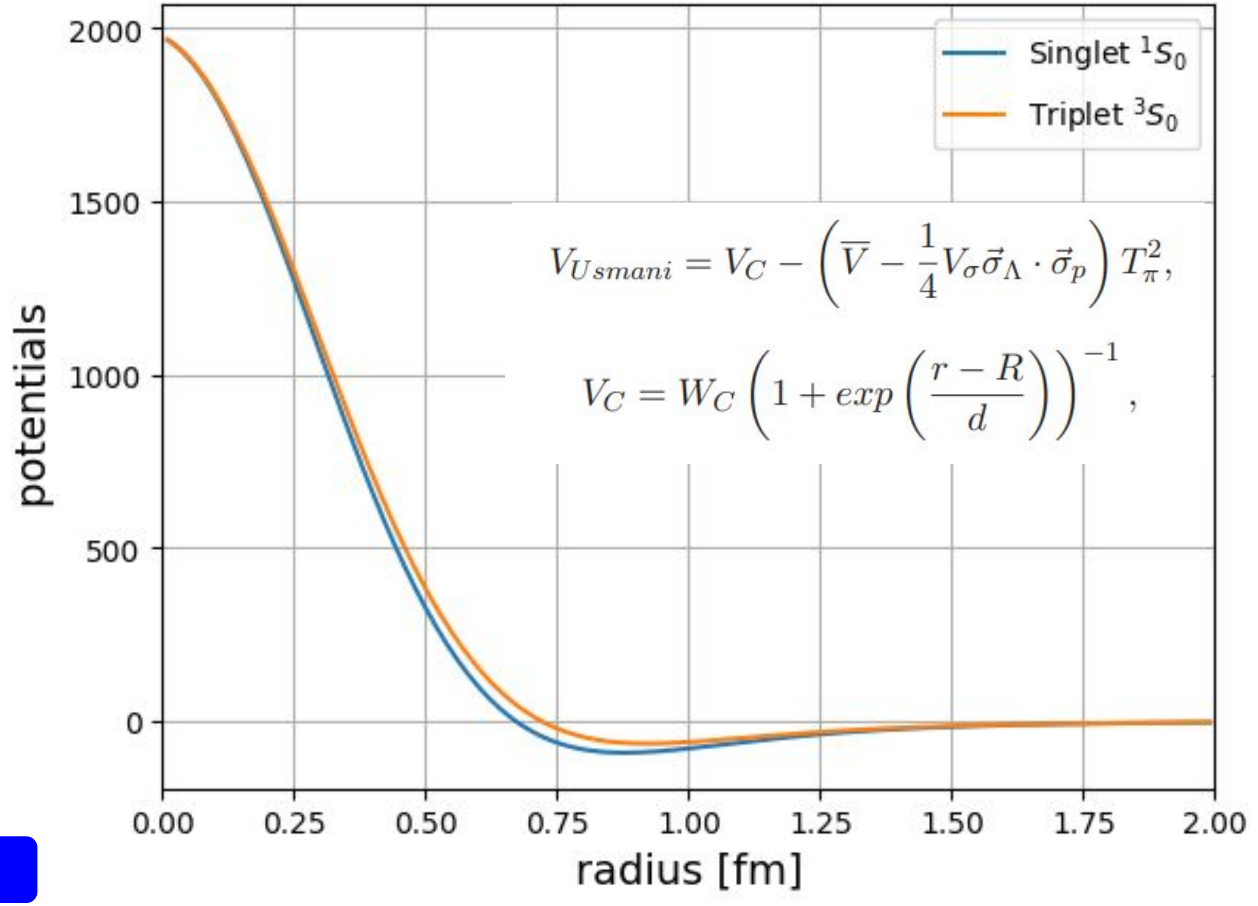


How correlations are obtain?



https://indico.mitp.uni-mainz.de/event/191/contributions/3148/attachments/2450/2649/VMS_BORMIO2020_final.pdf

https://doi.org/10.1103/PhysRevLett.83.3138



$$V_{Usmani} = V_C - \left(\overline{V} - \frac{1}{4} V_\sigma \vec{\sigma}_\Lambda \cdot \vec{\sigma}_p\right) T_\pi^2,$$

$$V_C = W_C \left(1 + exp\left(\frac{r-R}{d}\right)\right)^{-1},$$

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

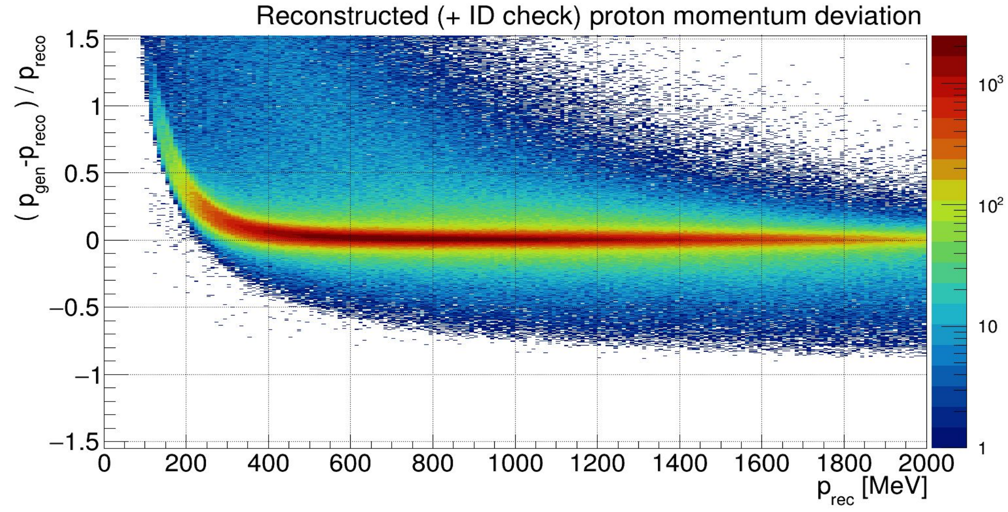
$$\Psi^S_{-\mathbf{k}^*}(\mathbf{r}^*) = e^{-i\mathbf{k}^*\cdot\mathbf{r}^*} + \frac{f^S(k^*)}{r^*} e^{ik^*\cdot r^*}.$$

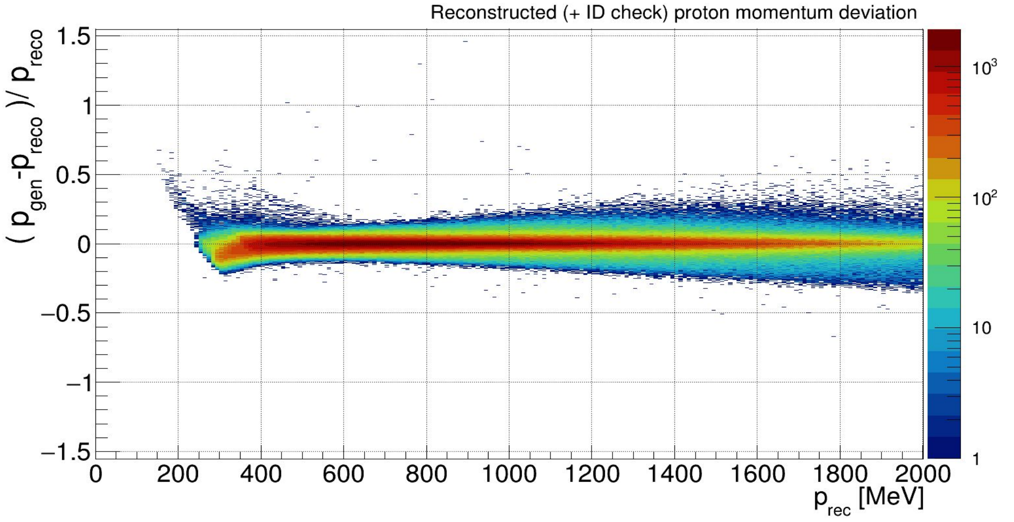
The effective range approximation for the scattering amplitude is

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

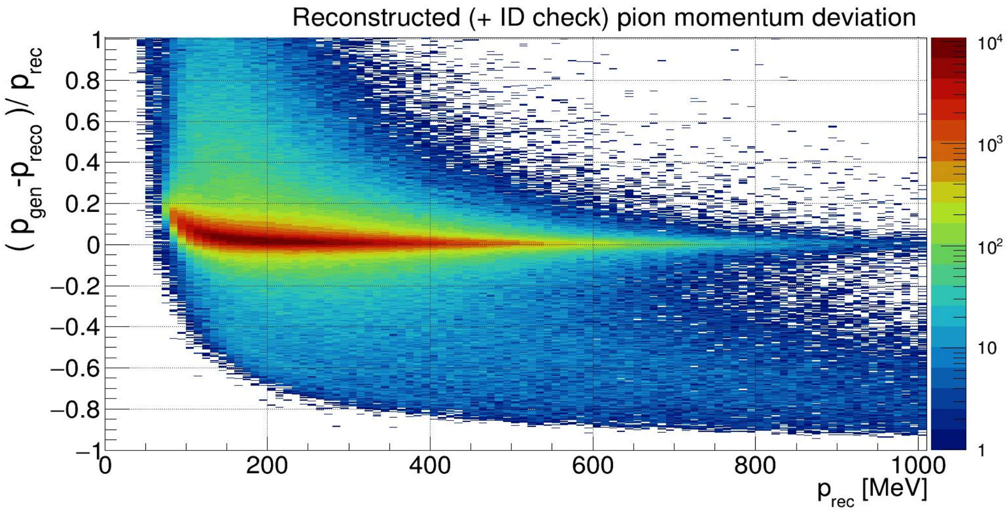
where $\boldsymbol{f_0^S}$ is the scattering length and $\boldsymbol{d_0^S}$ is the effective radius for a given total spin **S = 1** or **S = 0**.
The particle is assumed to be unpolarized (the polarization **P = 0**) :
singlet state $\boldsymbol{\rho_0 = ¼ (1 - P^2)}$ and triplet state $\boldsymbol{\rho_1 = ¾ (1 - P^2)}$.

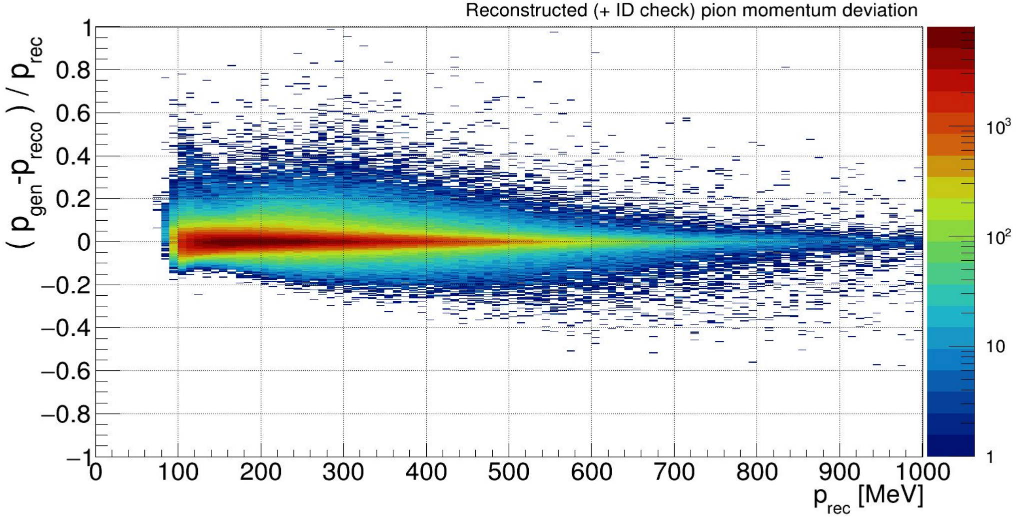
Energy-loss correction





Proton

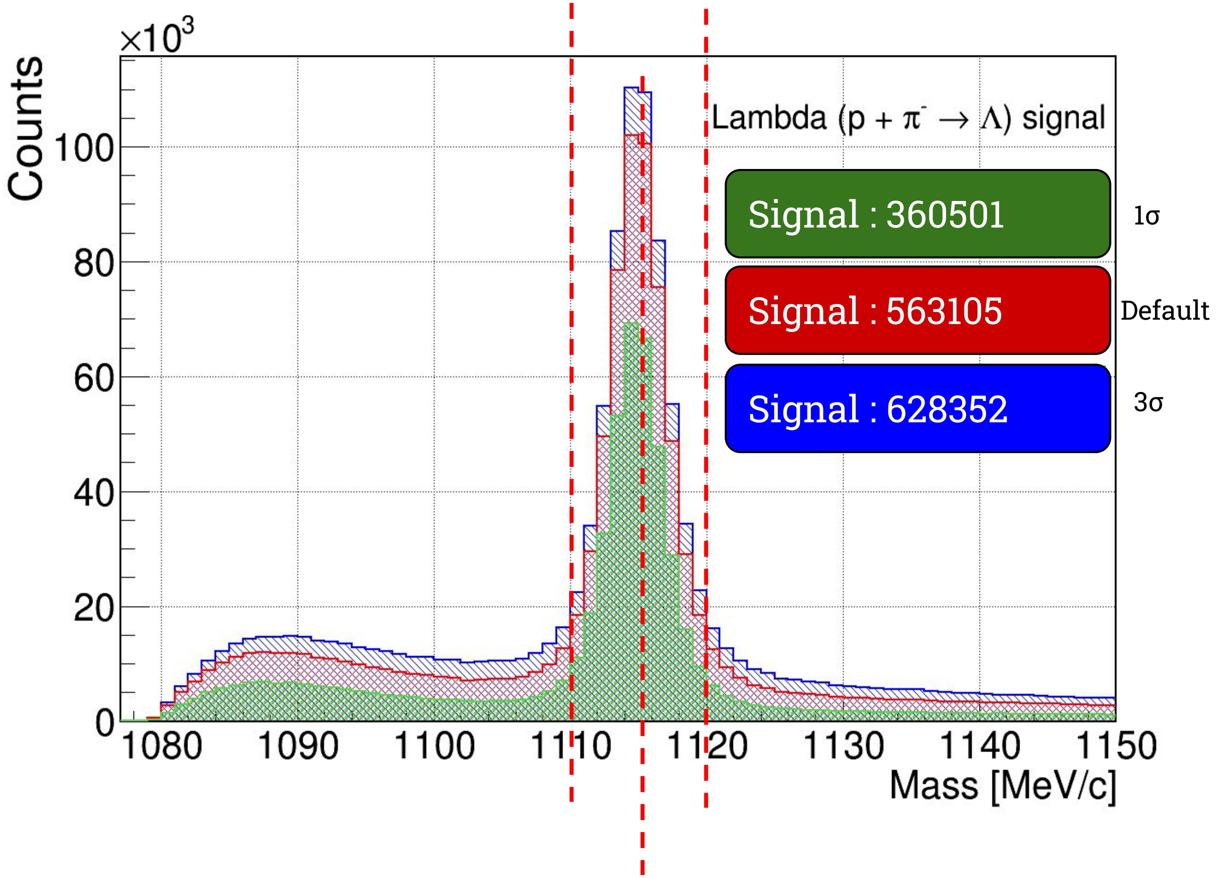




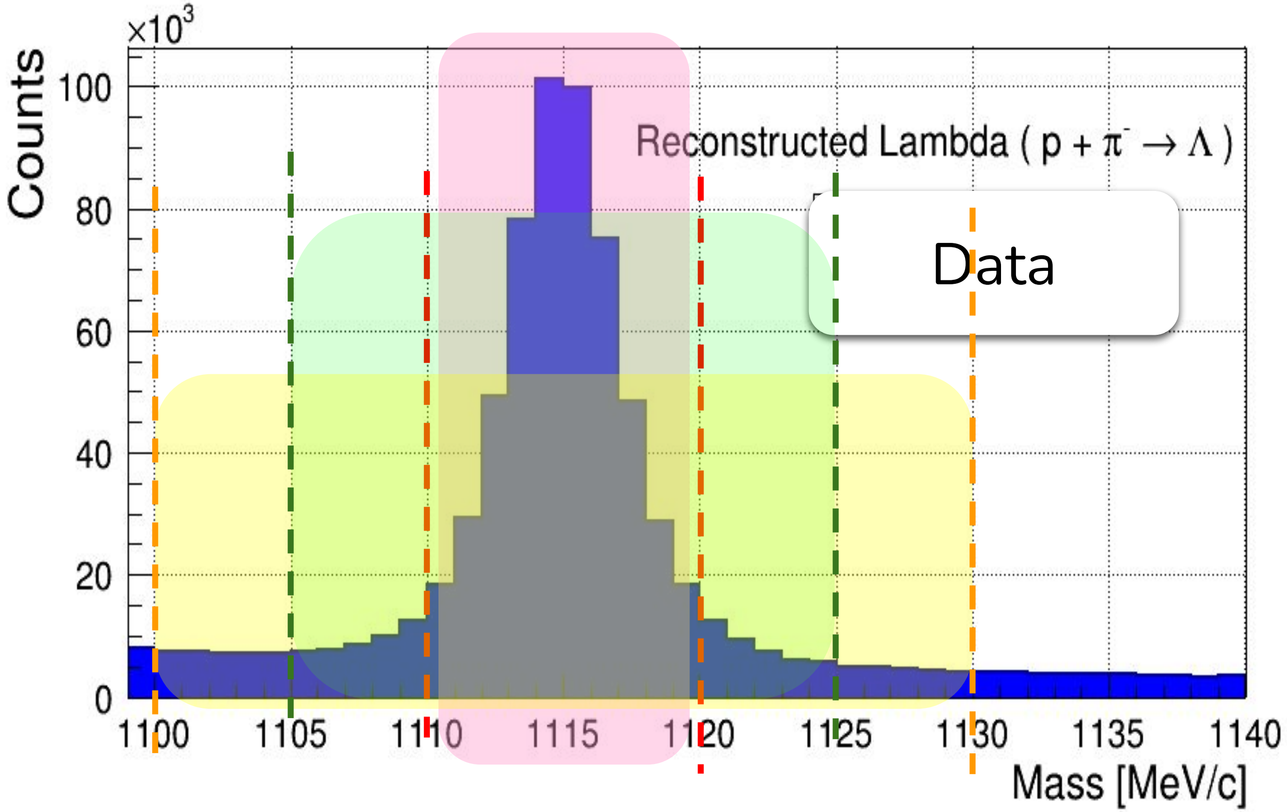
Pion

Systematics check (few of them)

PID variation



Mass cut variation



Thank you

POLITECHNIKA WARSZAWSKA
WARSAW UNIVERSITY OF TECHNOLOGY

HADES

GSI