Probing Short-Range Correlations of Hadrons

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

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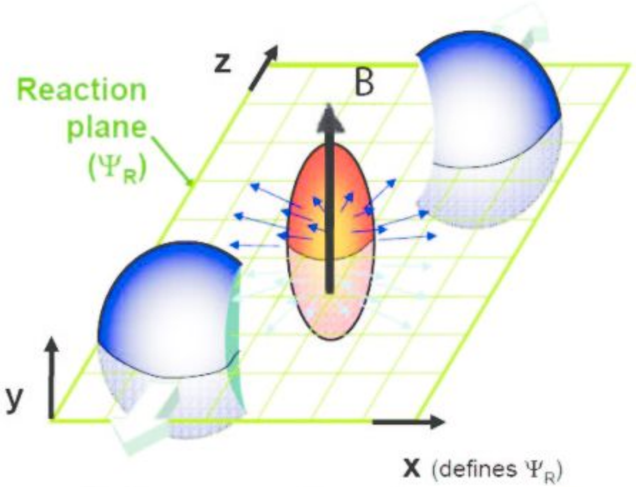
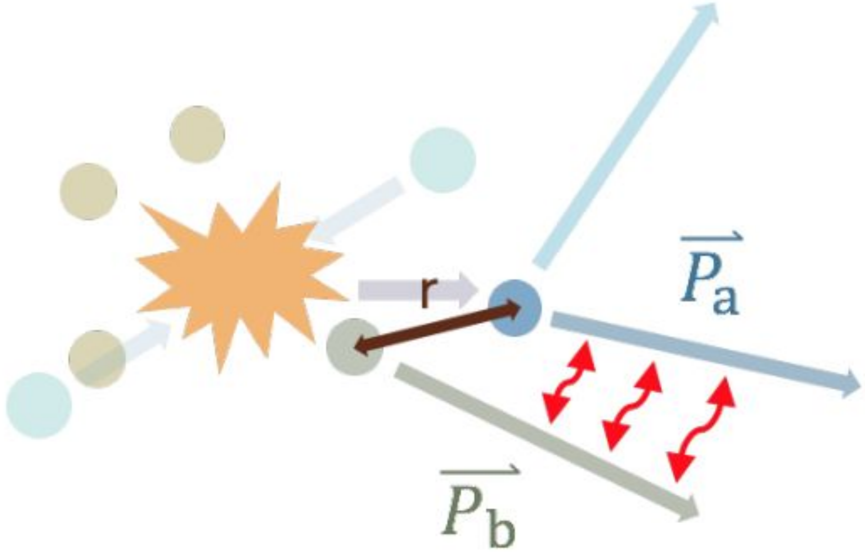
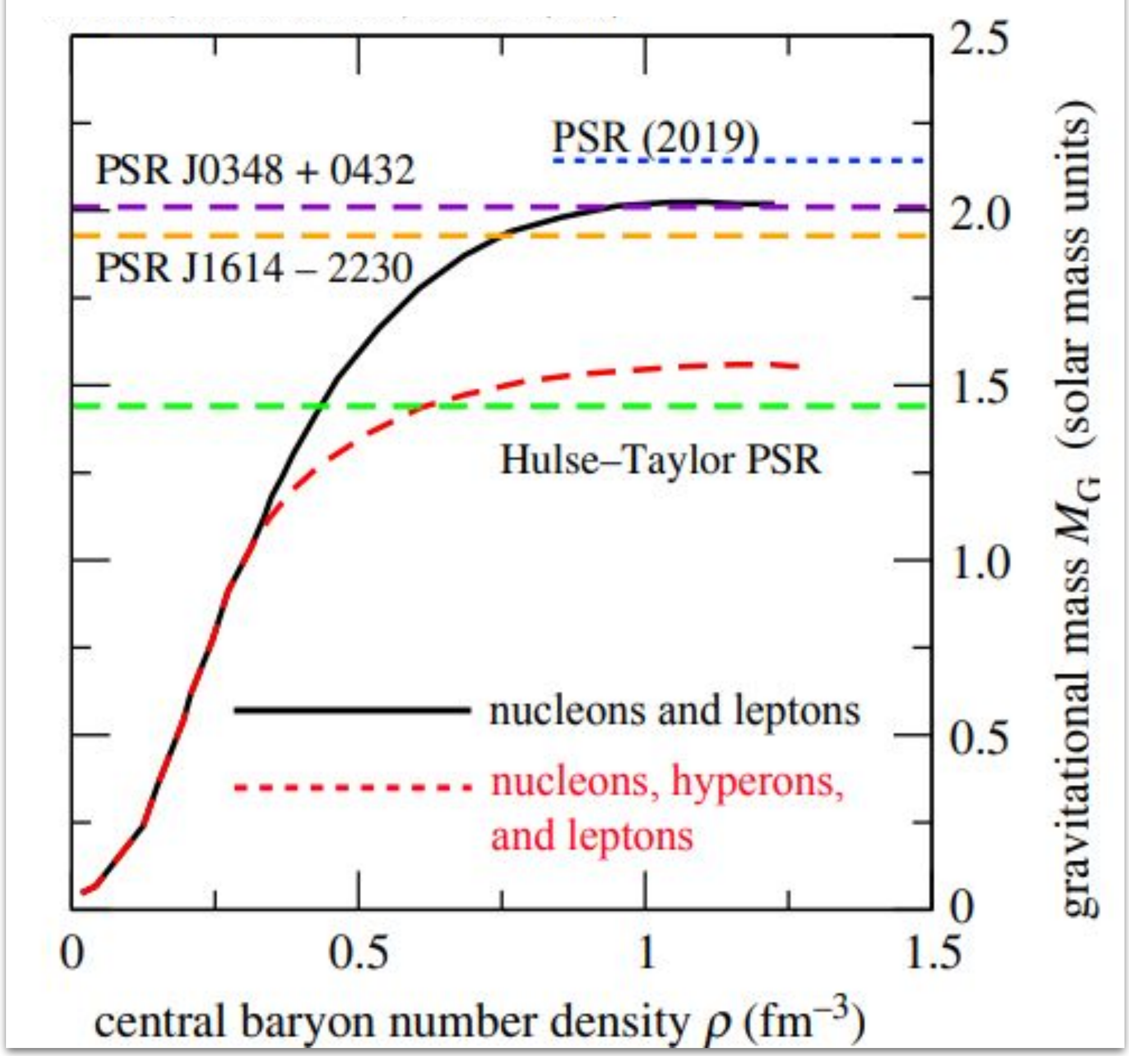




https://www.ph.nat.tum.de/denseandstrange/research/current-projects/yn-interaction-in-neutron-stars-from-alice-and-hades-data/

Neutron Star and hyperon puzzle ?

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

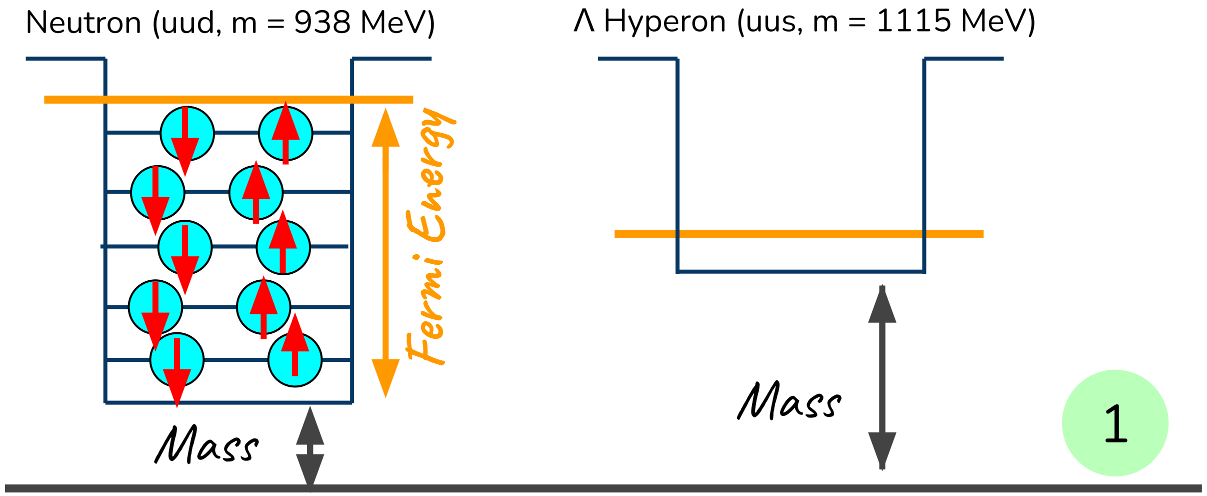


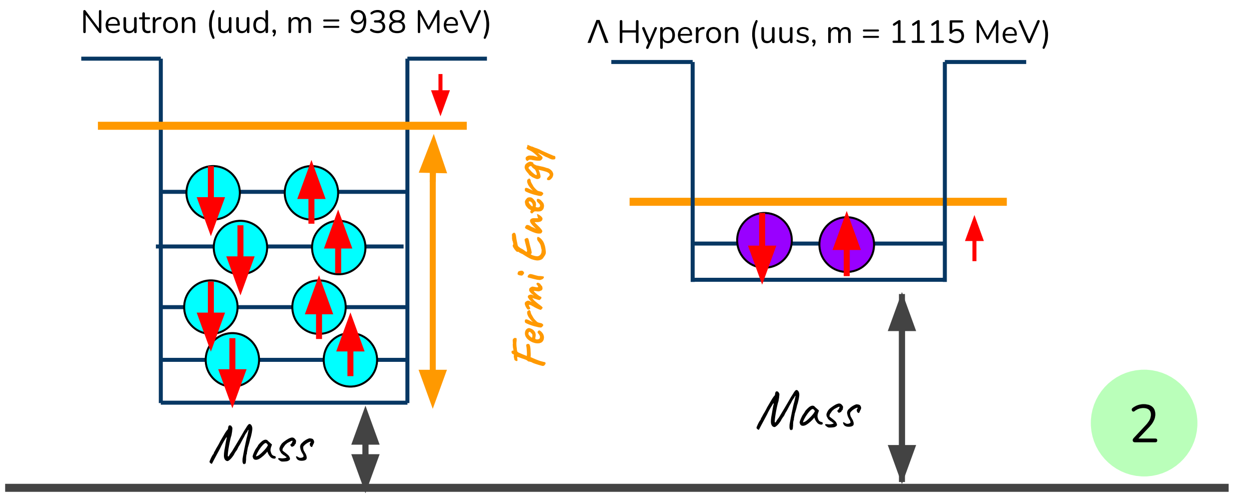
- Neutron stars (NS) are the remnants of the gravitational collapse of massive stars during supernova event.
- Their masses and radii are of the order of 1 – 2 $M_\odot$ and 10 – 12 km, respectively.
- Central densities in the range of 4 – 8 times the normal nuclear matter saturation density, ε_0 ~ 2.7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

Best suitable theory takes hyperons into account,

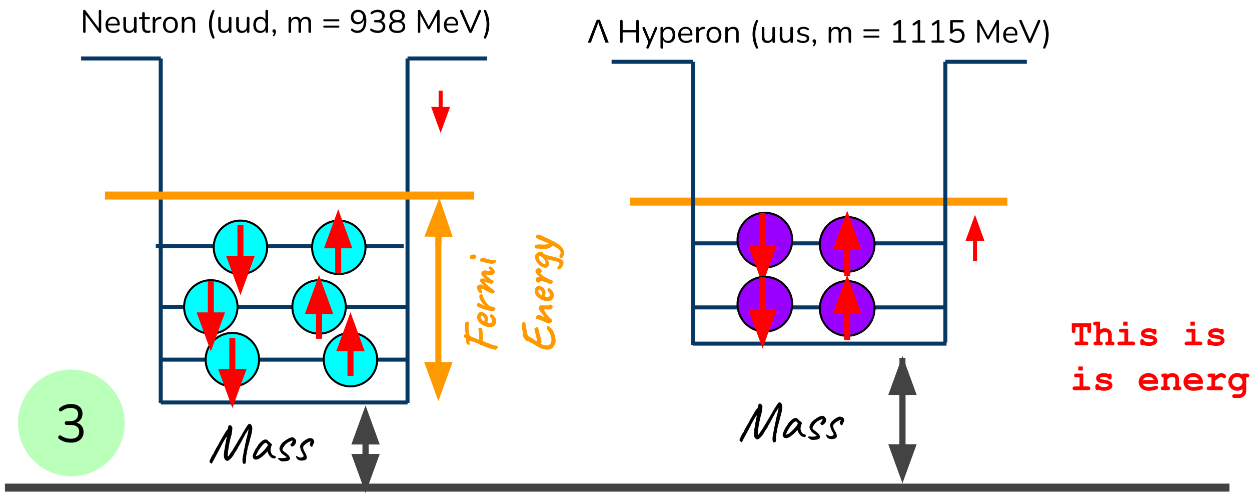
- Hyperons are expected to appear in the core of NS at $\rho \sim 2\text{-}3\ \rho_0$
- Hyperons softens the EoS —> Reduction on maximum NS mass
- Observation of the NS with $M_G > 2M_S$ is incompatible with such soft EoS
- Although the existence of hyperons is energetically favorable, their existence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

why hyperons are produced



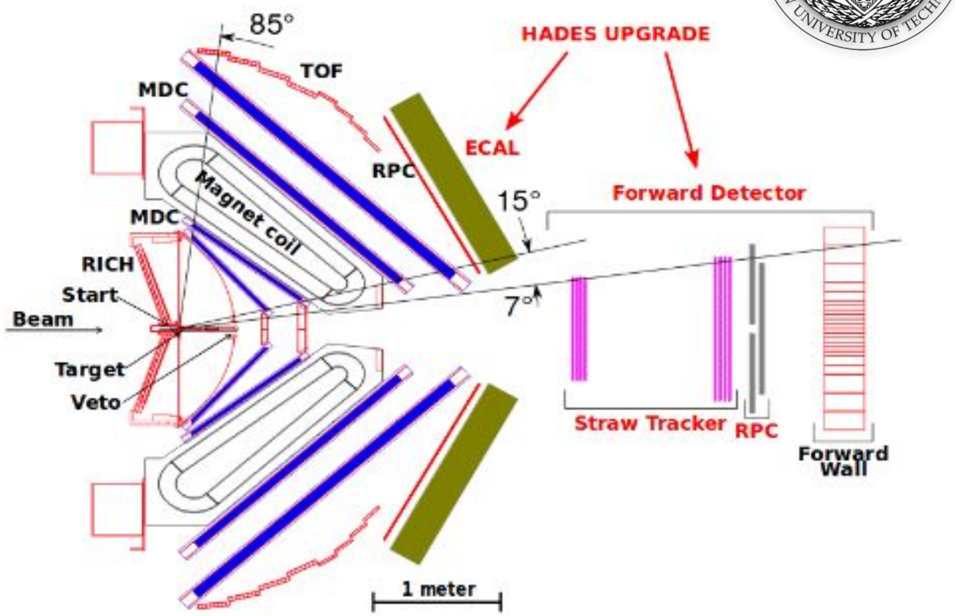


Expected evaluation in time



This is how existence of hyperons is energetically favorable.

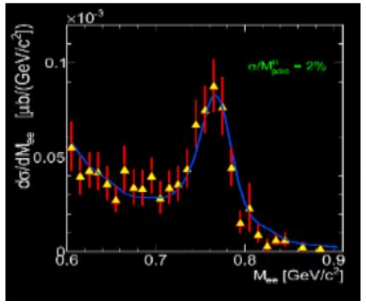
HADES Spectrometer

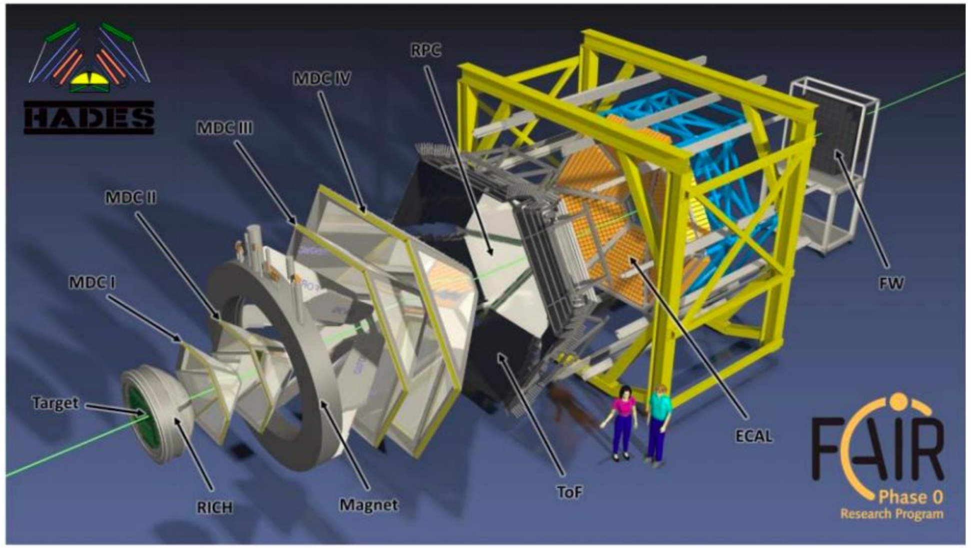


- SIS-18 beams: protons (1-4 GeV), nuclei (1-2 AGeV), pions (0.4-2 GeV/c) – secondary beam
- rare probes:(e^+, e^-), strangeness: $K^{+/-,0}$, Λ, Ξ^-, φ
- ΔM/M - 2% at ρ / ω
- PID : π/p/K – dE/dx (MDC) and TOF : σ_{tof} ~80 ps (RPC)
- electrons : RICH (hadron blind)
- neutral particles: ECAL

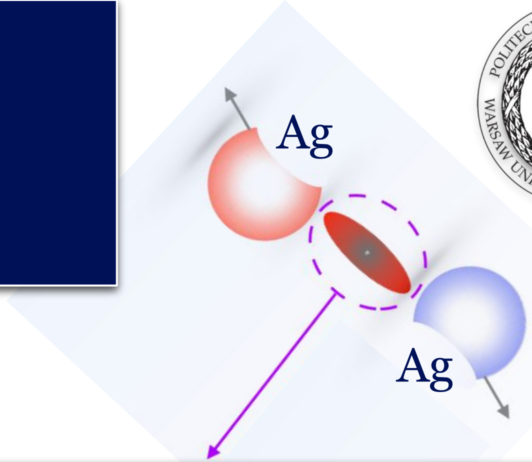
Geometry :

- full azimuthal, polar angles 18° - 85°

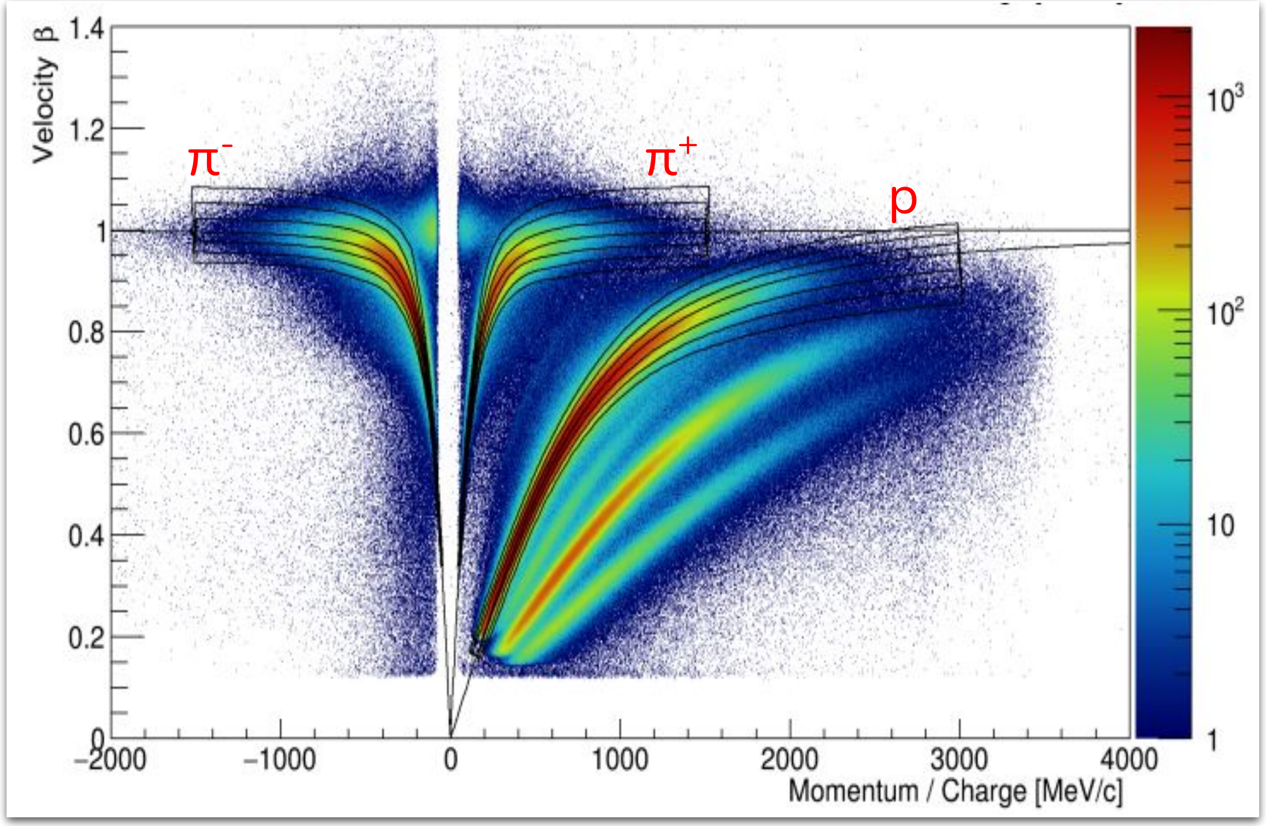




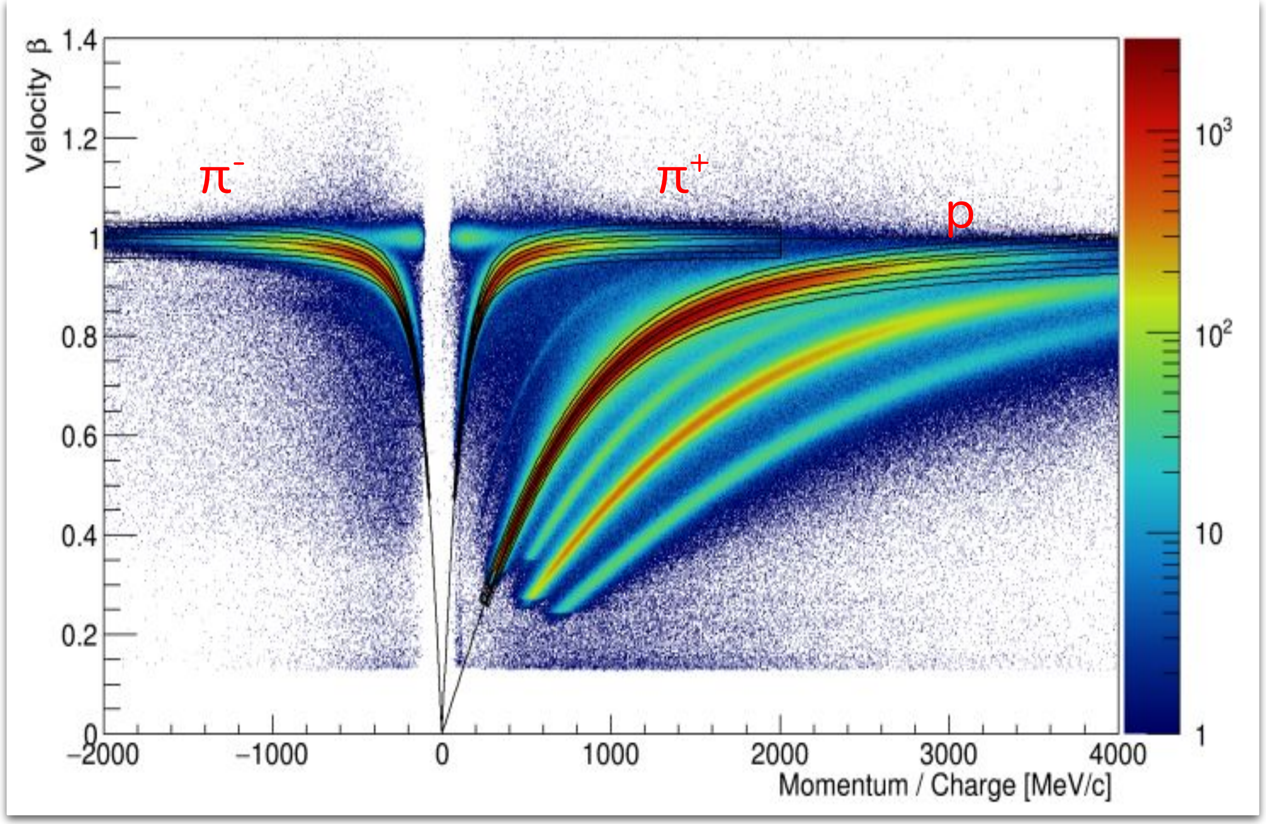
Particle identification



ToF

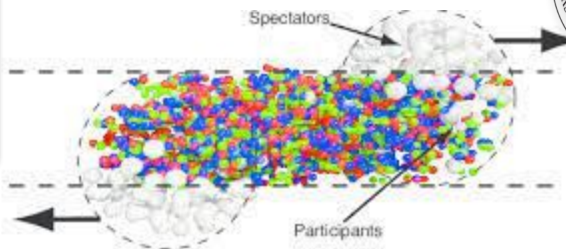


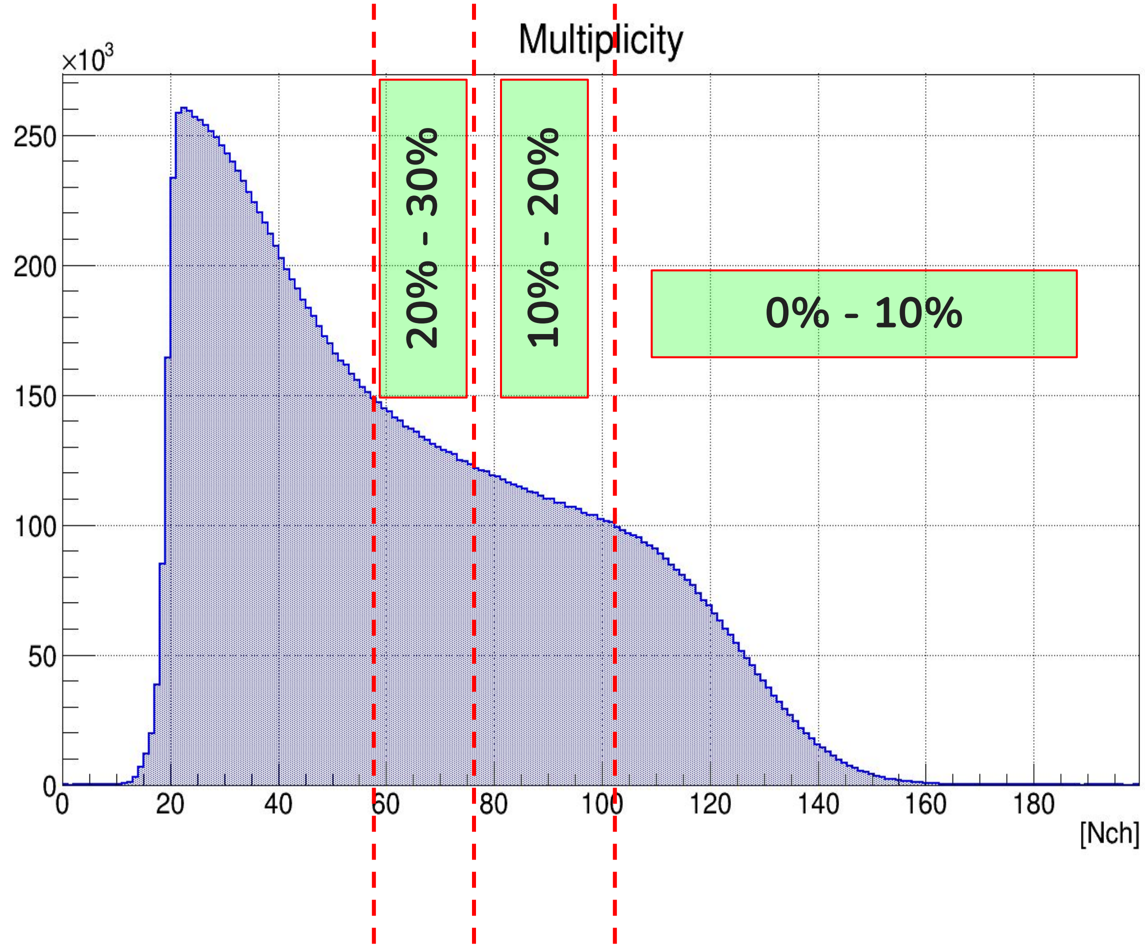
RPC

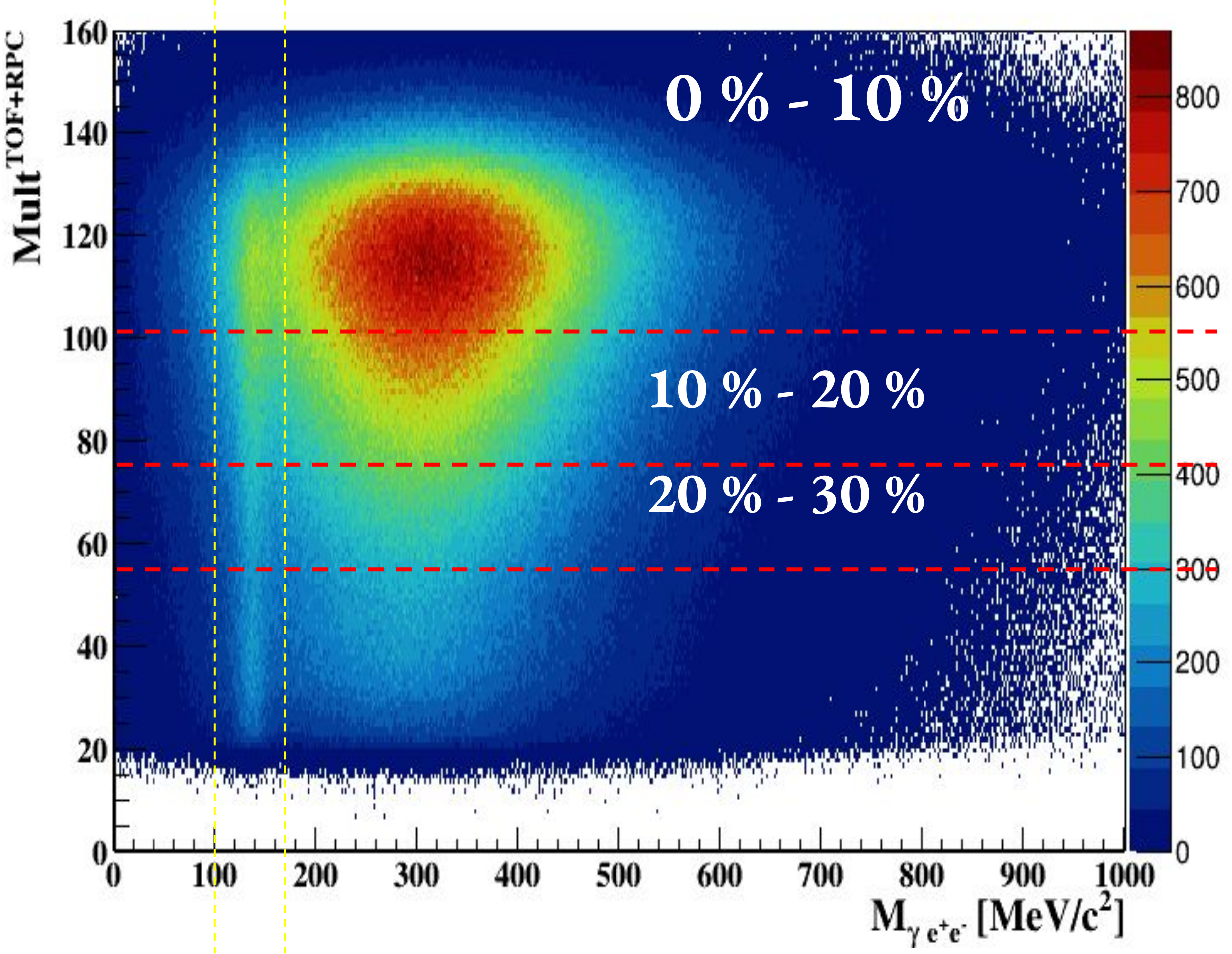


https://doi.org/10.21248/gups.68651

Selected events, Multiplicity

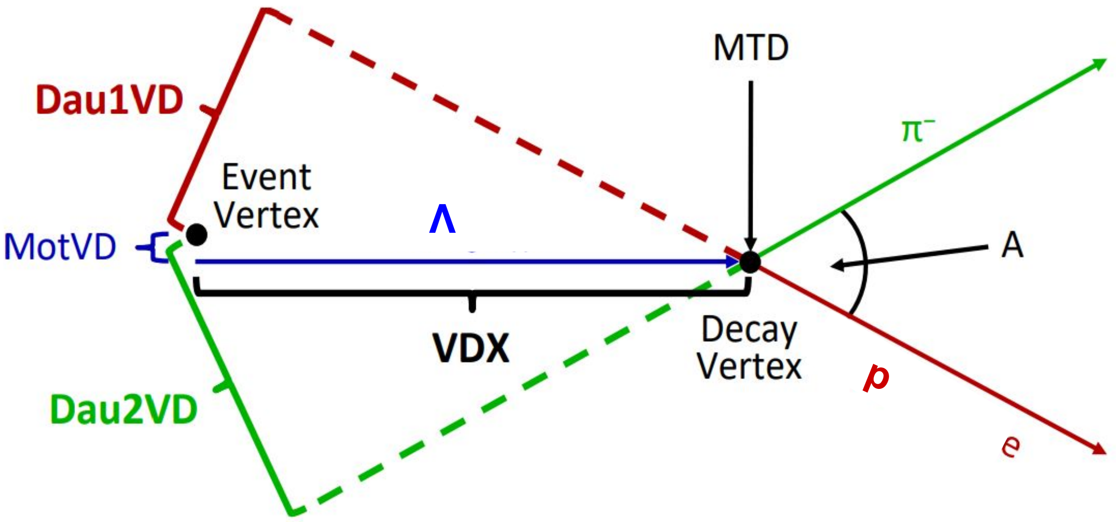






Signal Reconstruction

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**

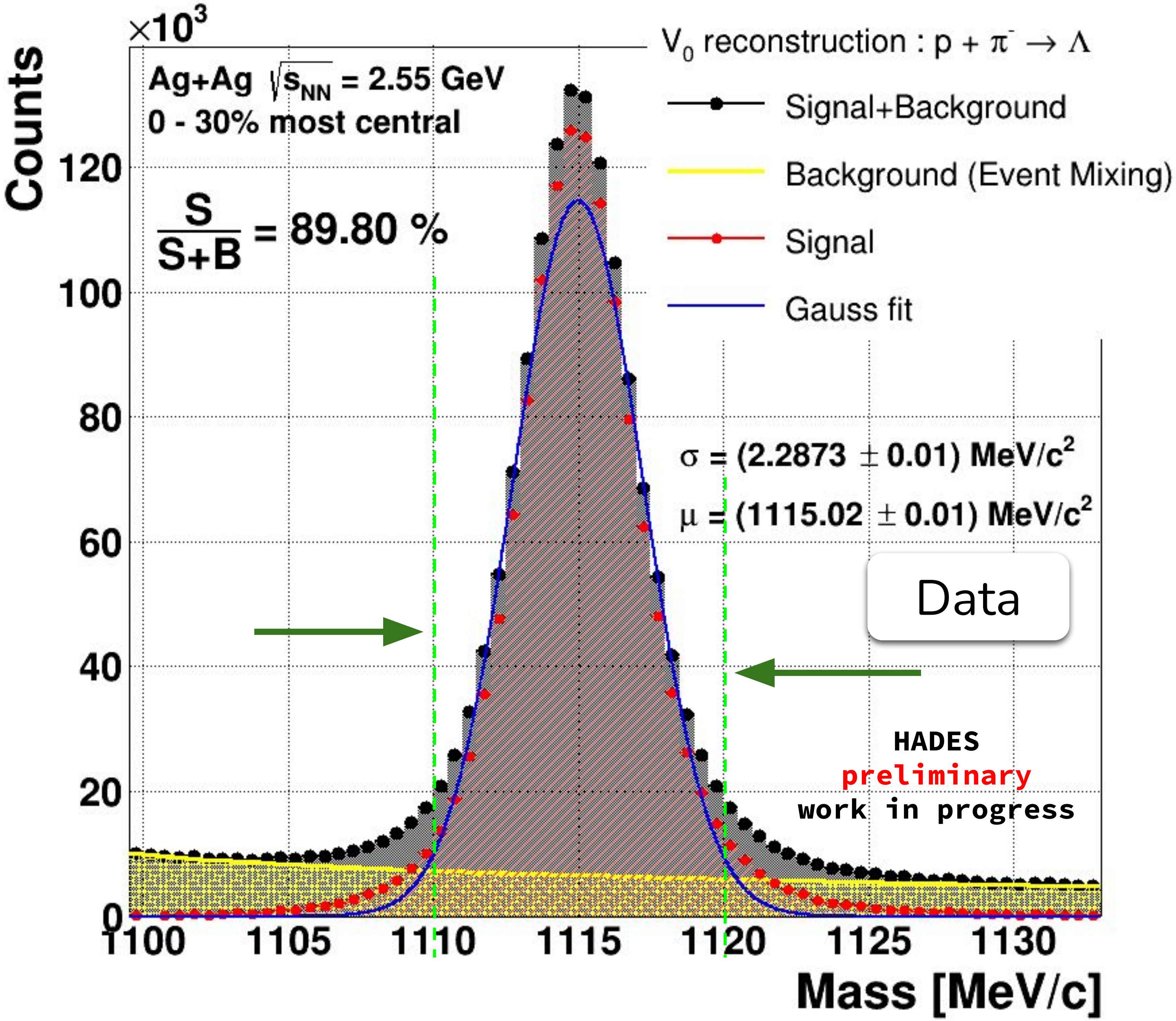
- DCA between the two daughter tracks (**MTD**) = **< 6 mm**

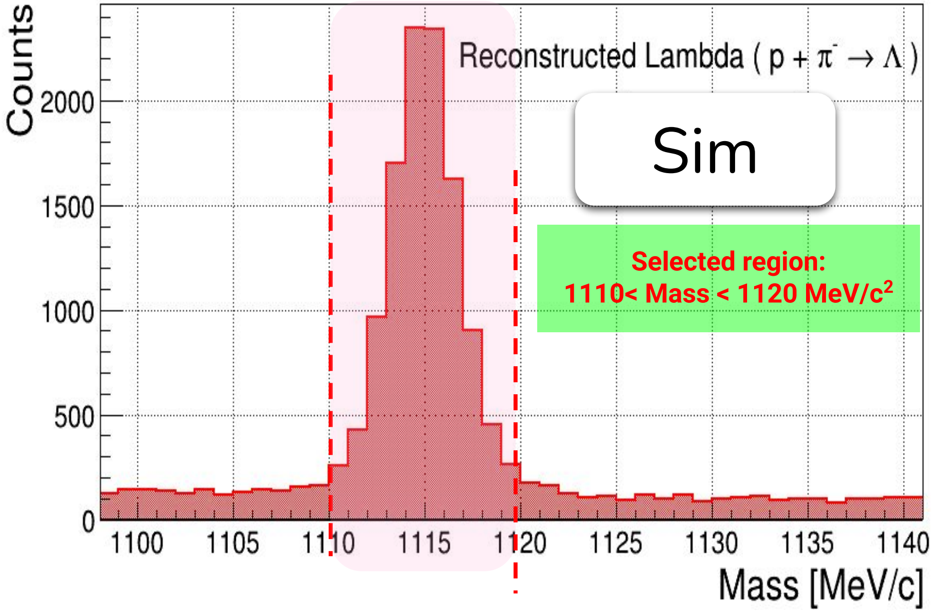
- Distance between the primary and secondary vertex (**VDX**) = **> 65 mm**

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

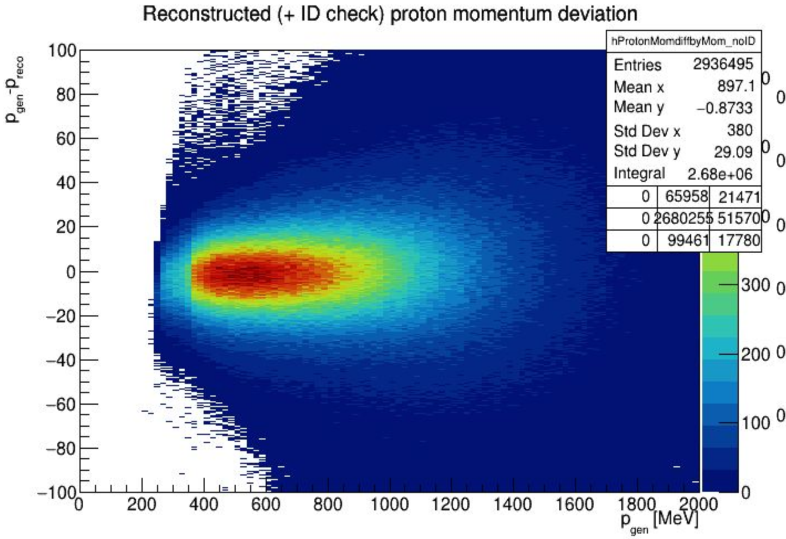
- Opening angle between the two daughter tracks (A) = **> 15^{o}**

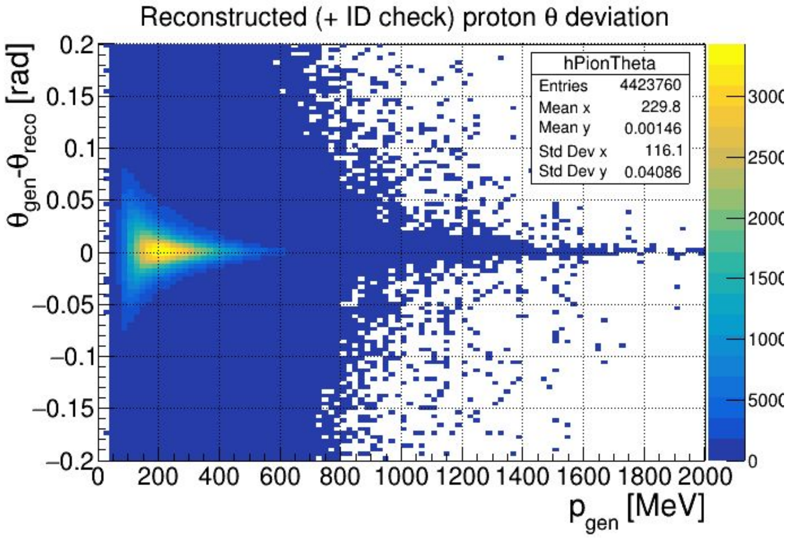
Reconstructed Λ signal ($\pi^- + p \rightarrow \Lambda$)

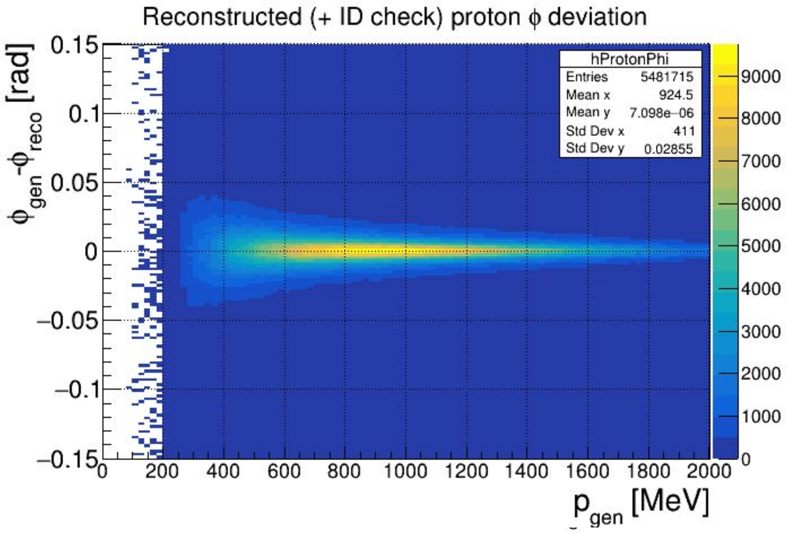


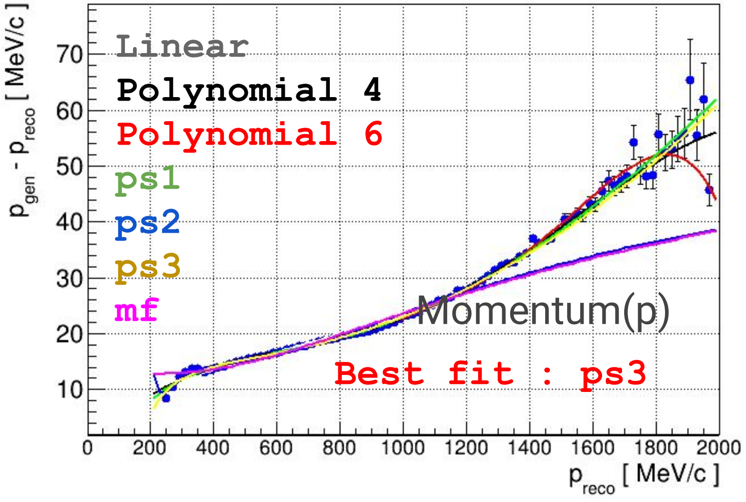


Proton resolution

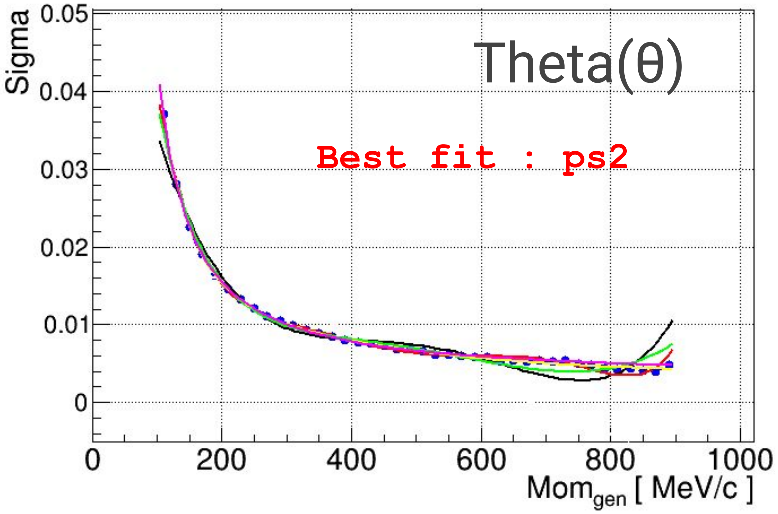

Reconstructed (+ ID check) proton momentum deviation


Reconstructed (+ ID check) proton θ deviation

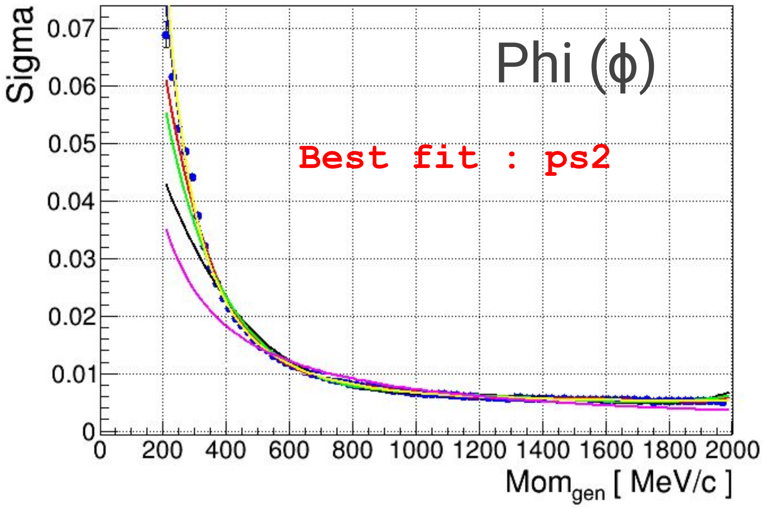

Reconstructed (+ ID check) proton ϕ deviation



Best fit : ps3

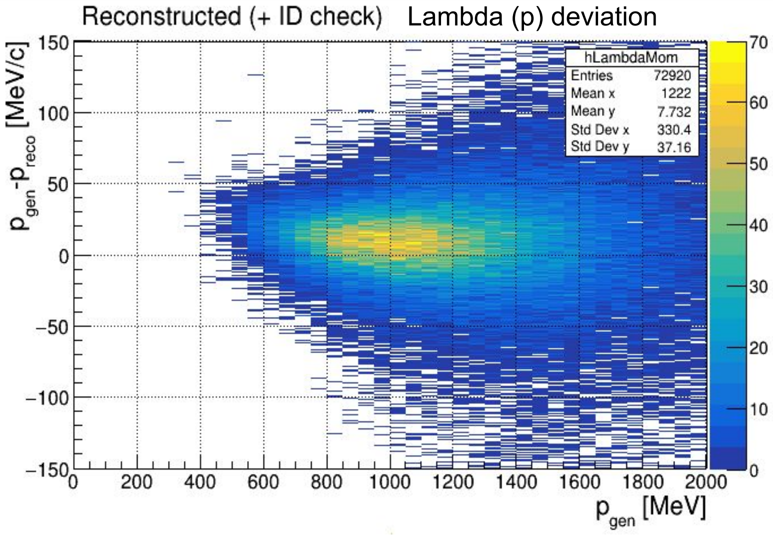


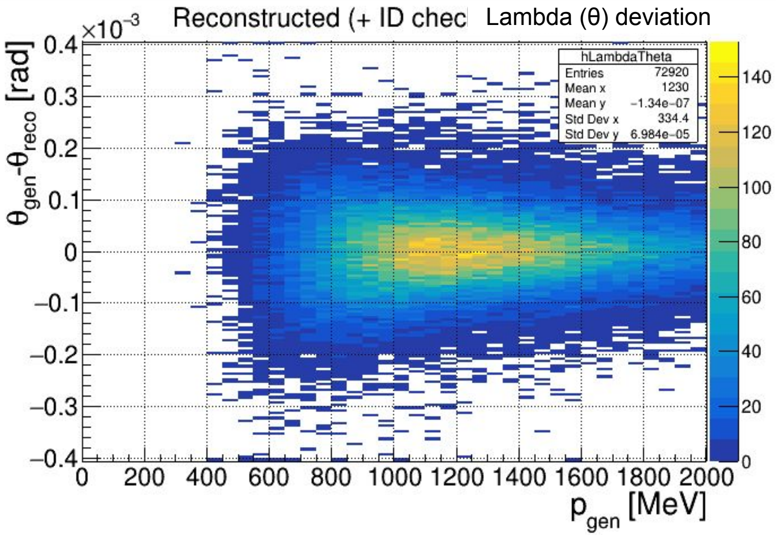
Best fit : ps2

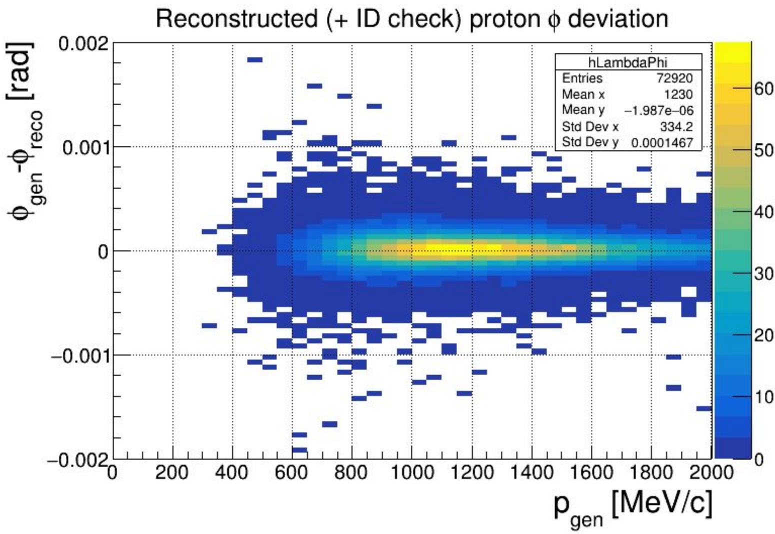


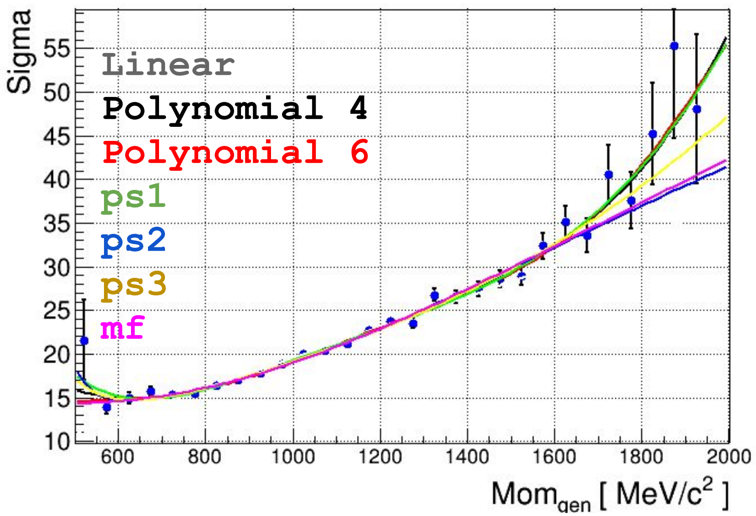
Best fit : ps2

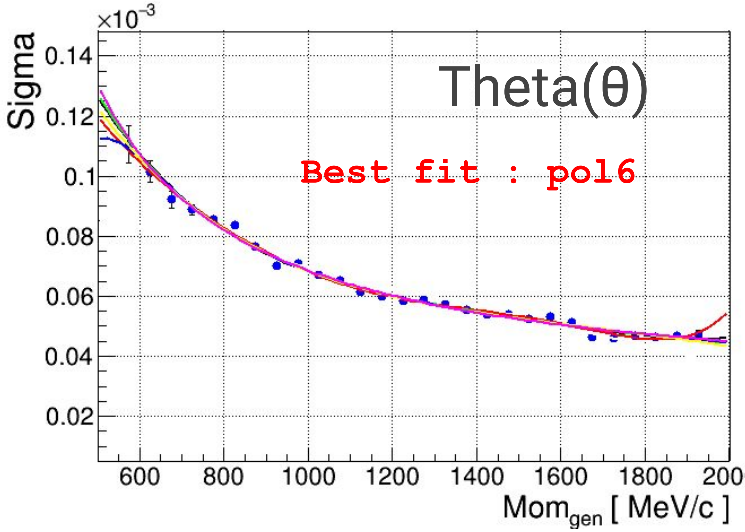
Lambda resolution


Reconstructed (+ ID check) Lambda (p) deviation

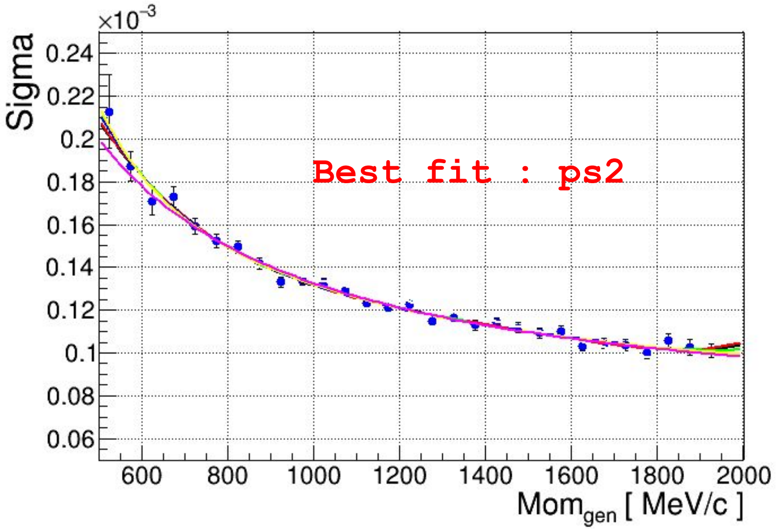

Reconstructed (+ ID chec Lambda (θ) deviation


Reconstructed (+ ID check) proton ϕ deviation

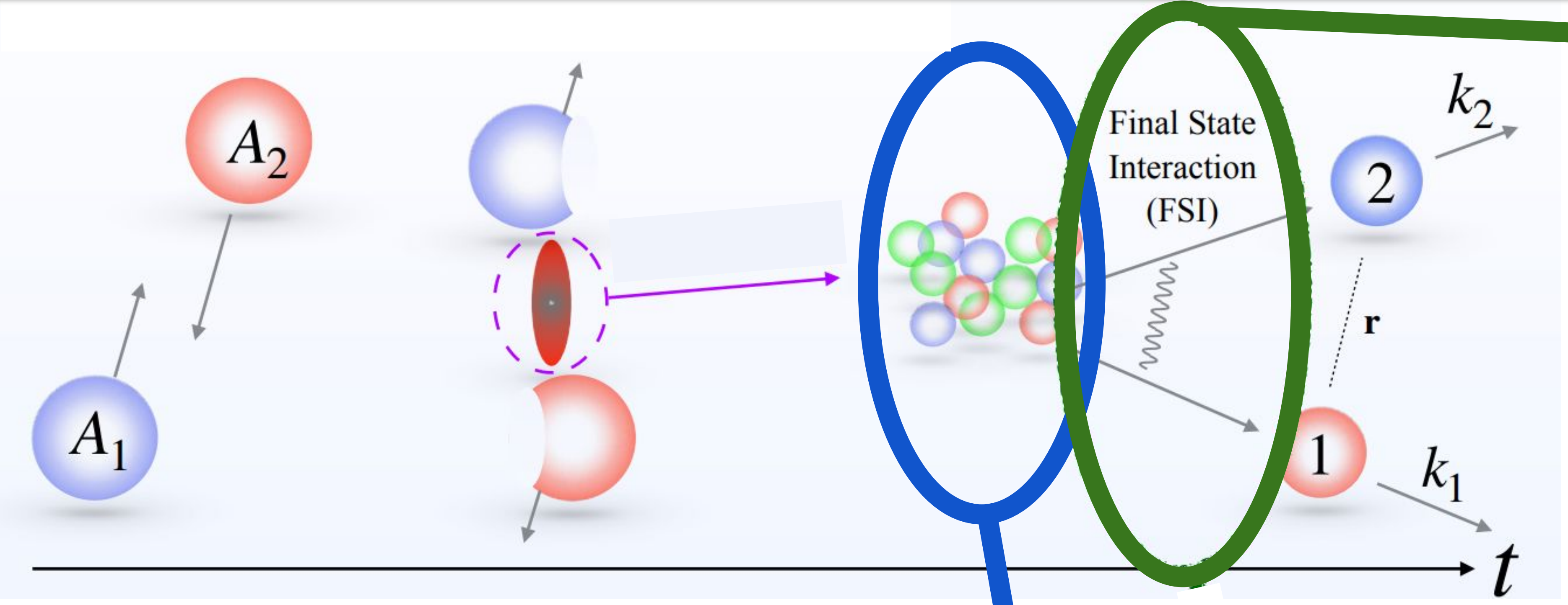



Theta(θ)

Best fit : pol6


Best fit : ps2

Hadron correlation in high energy nuclear collision



$\phi(q, r)$ relative wavefunction

Depends on ...

- Interaction (strong and Coulomb)
- quantum statistics (Fermions, bosons)

Use the information of particle 1 to 2 investigate interactions which are not well known

Hadron-hadron correlation

- Koonin-Pratt formula: S.E. Koonin, PLB 70 (1977)
  S. Pratt et. al. PRC 42 (1990)

$$C(q, r) = \int d^3r\, S(r)\, |\phi(q, r)|^2$$

$q = p_1 - p_2$: momentum difference

$S(r)$ source function

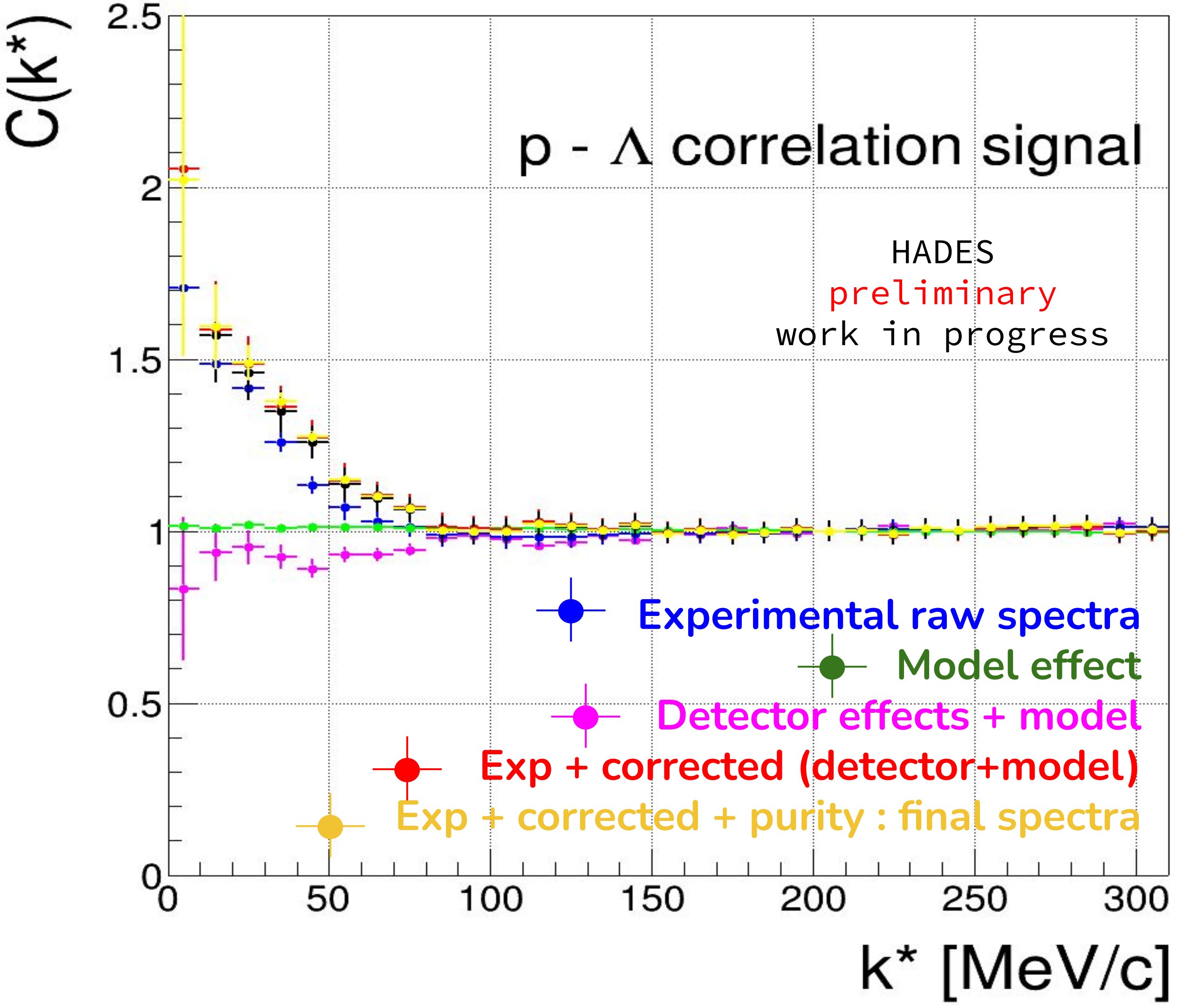
Depends on ...

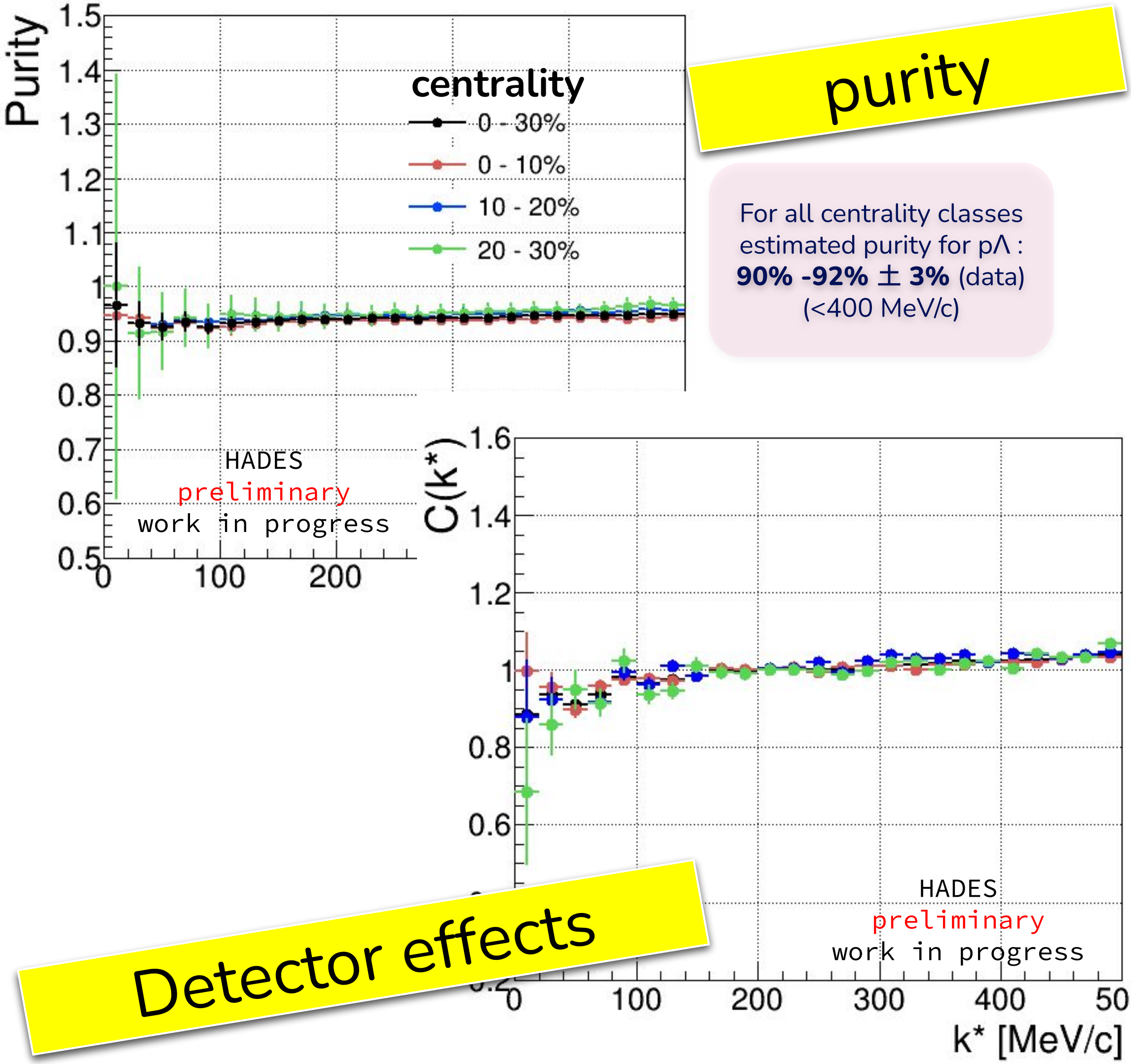
- Collision detail (**A**, energy, centrality, momentum)

Including information of...

- probe geometric properties .

p-Λ correlation in AgAg collision at 1.58 A GeV



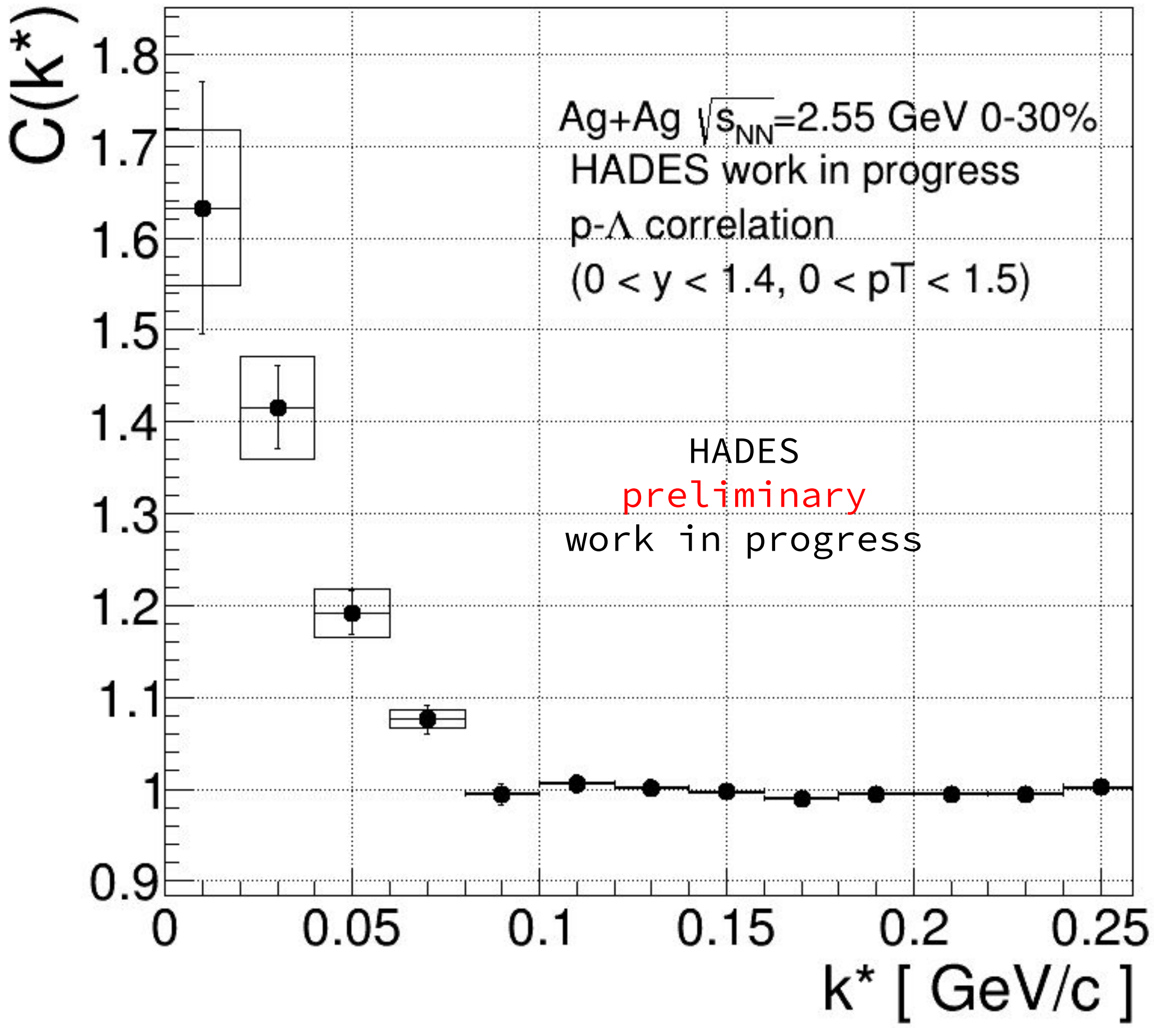


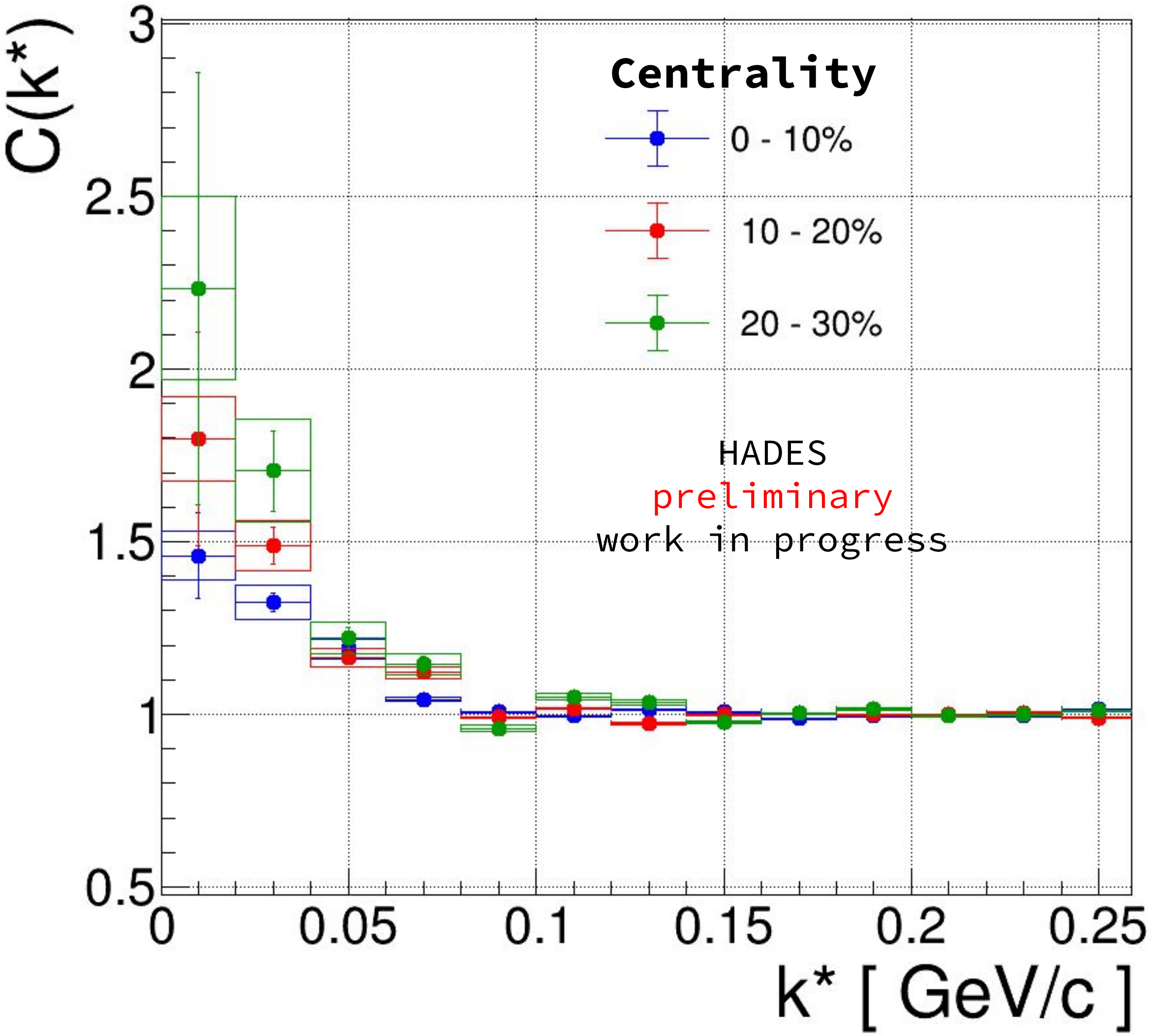
purity

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*)**

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

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

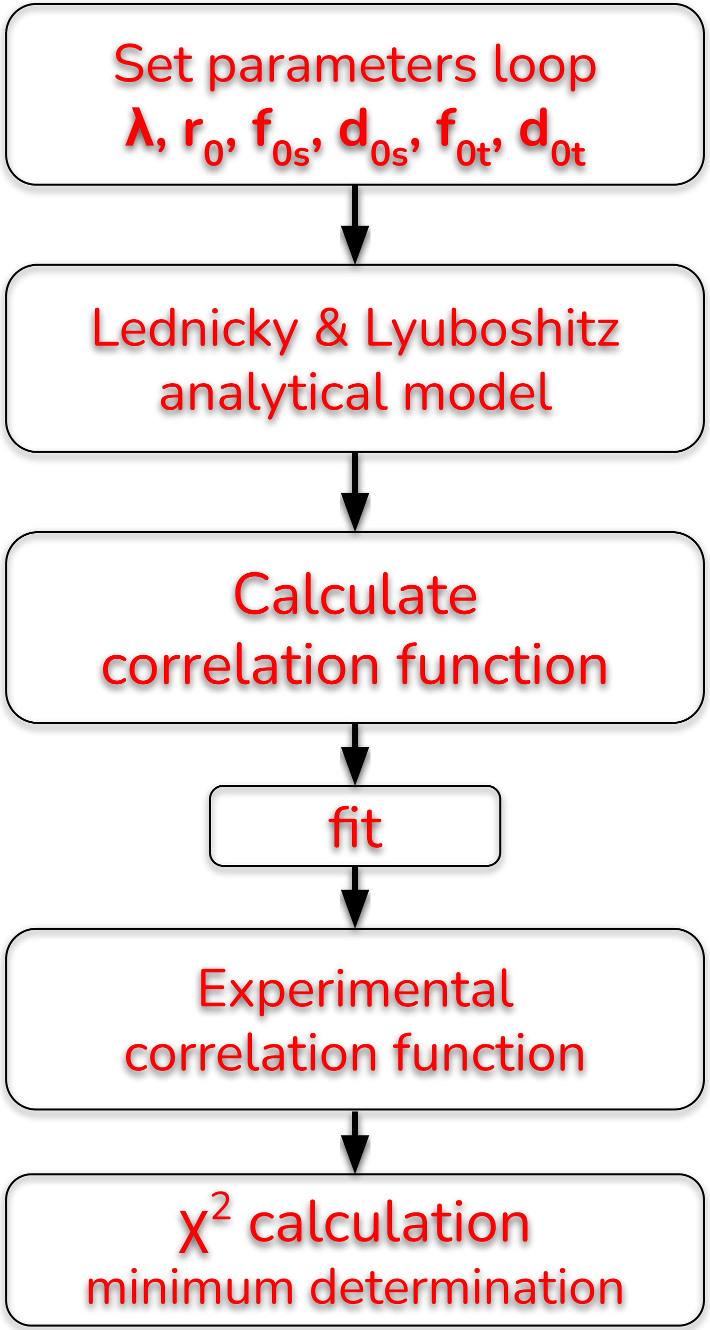
Decomposition for spin channels :

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

How do we formulate this model?

Principle ways of generate the theoretical correlation function.

HAL : Corrfit -Cumac : framework



Set parameters loop
λ, r_0, f_{0s}, d_{0s}, f_{0t}, d_{0t}

Lednicky & Lyuboshitz analytical model

Calculate correlation function

fit

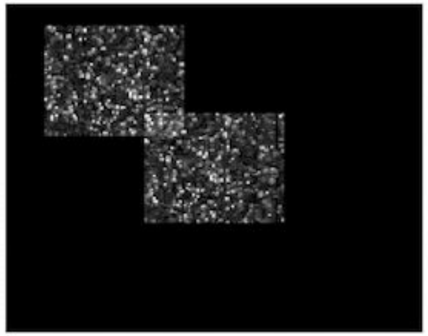
Experimental correlation function

χ^2 calculation
minimum determination

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.

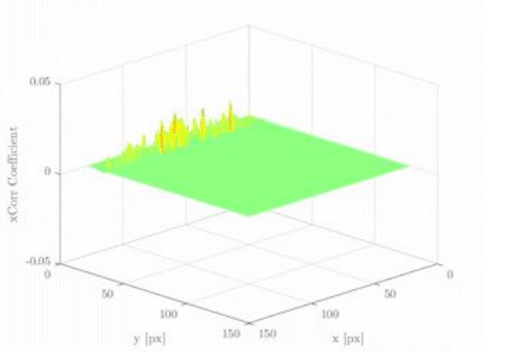
2. The first fitter employs ROOT minimizers, offering precise statistical uncertainty estimation, but it operates on "continuous" maps with limited control over parameter steps.

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

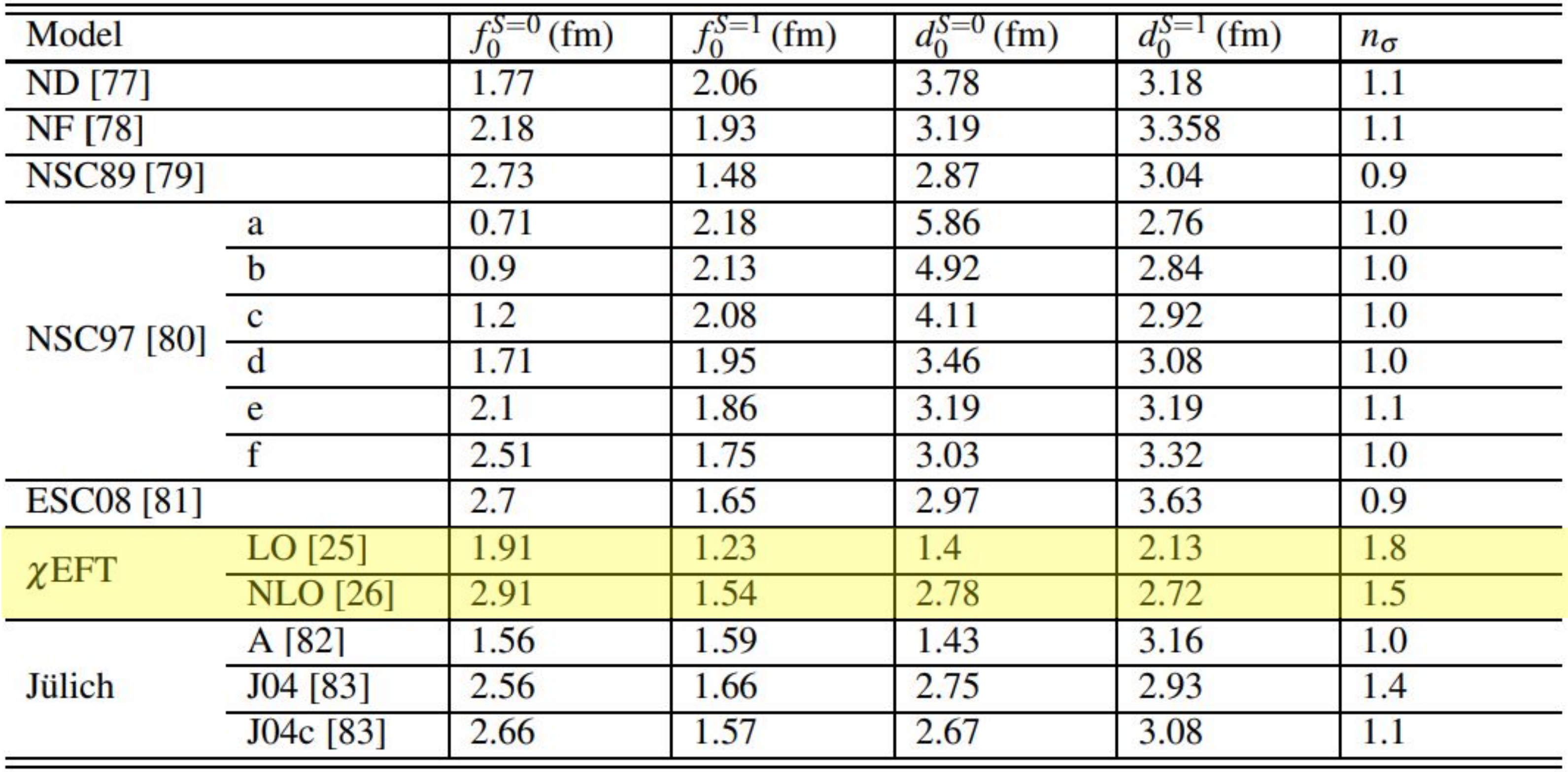


```
for( int λ = 0.6; λ < 0.8; λ+=0.1 )
    for( int r0 = 1.0; r0 < 4.0; r0+=0.1 )
        for( int f0 = 0.01; f0 < 5.0; f0+=0.1 )
            for( int d0 = 0.01; d0 <5.0; d0+=0.1)
                for( int ft = 0.01; ft < 5.0 ; ft += 0.1 )
                    for( int dt =0.01; dt < 5.0; dt+=0.1 )
 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

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



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



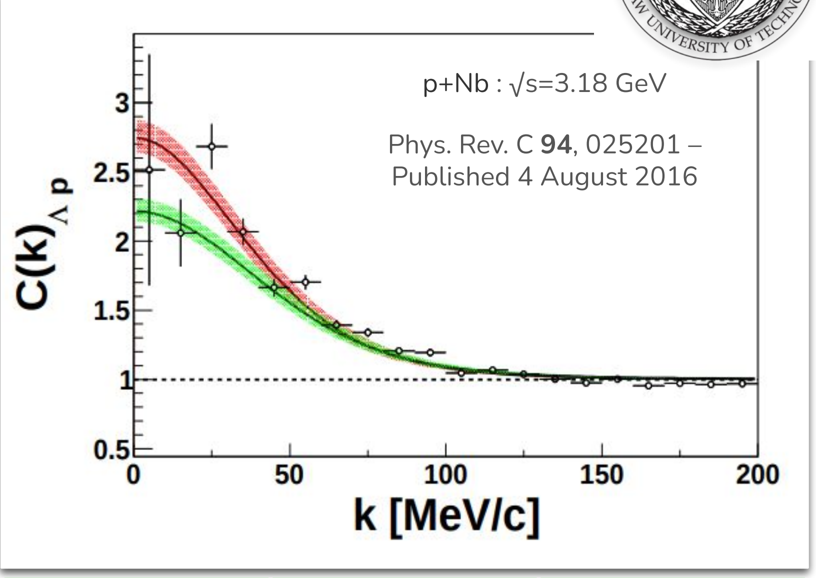
Model		$f_0^{S=0}$ (fm)	$f_0^{S=1}$ (fm)	$d_0^{S=0}$ (fm)	$d_0^{S=1}$ (fm)	n_σ
ND [77]		1.77	2.06	3.78	3.18	1.1
NF [78]		2.18	1.93	3.19	3.358	1.1
NSC89 [79]		2.73	1.48	2.87	3.04	0.9
NSC97 [80]	a	0.71	2.18	5.86	2.76	1.0
	b	0.9	2.13	4.92	2.84	1.0
	c	1.2	2.08	4.11	2.92	1.0
	d	1.71	1.95	3.46	3.08	1.0
	e	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



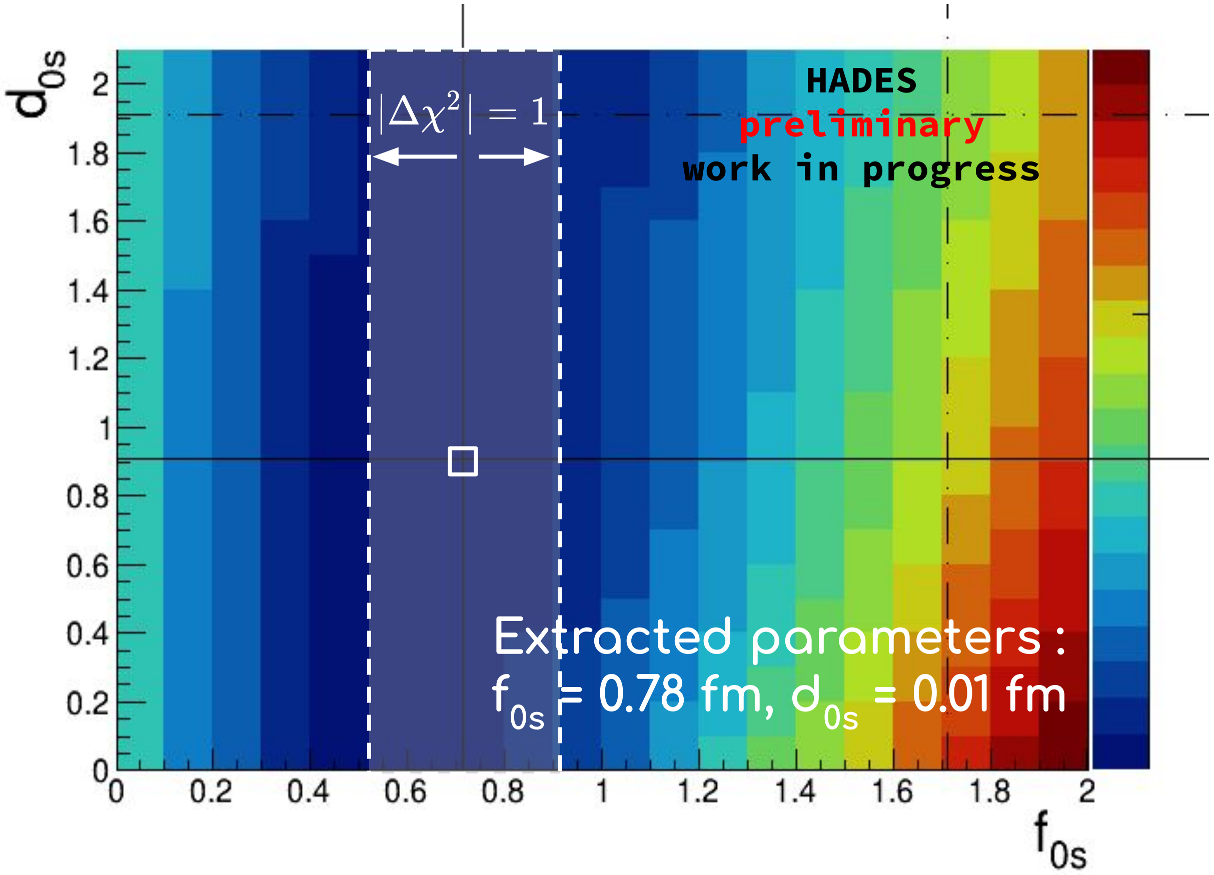
p+Nb : √s=3.18 GeV

Phys. Rev. C **94**, 025201 – Published 4 August 2016

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

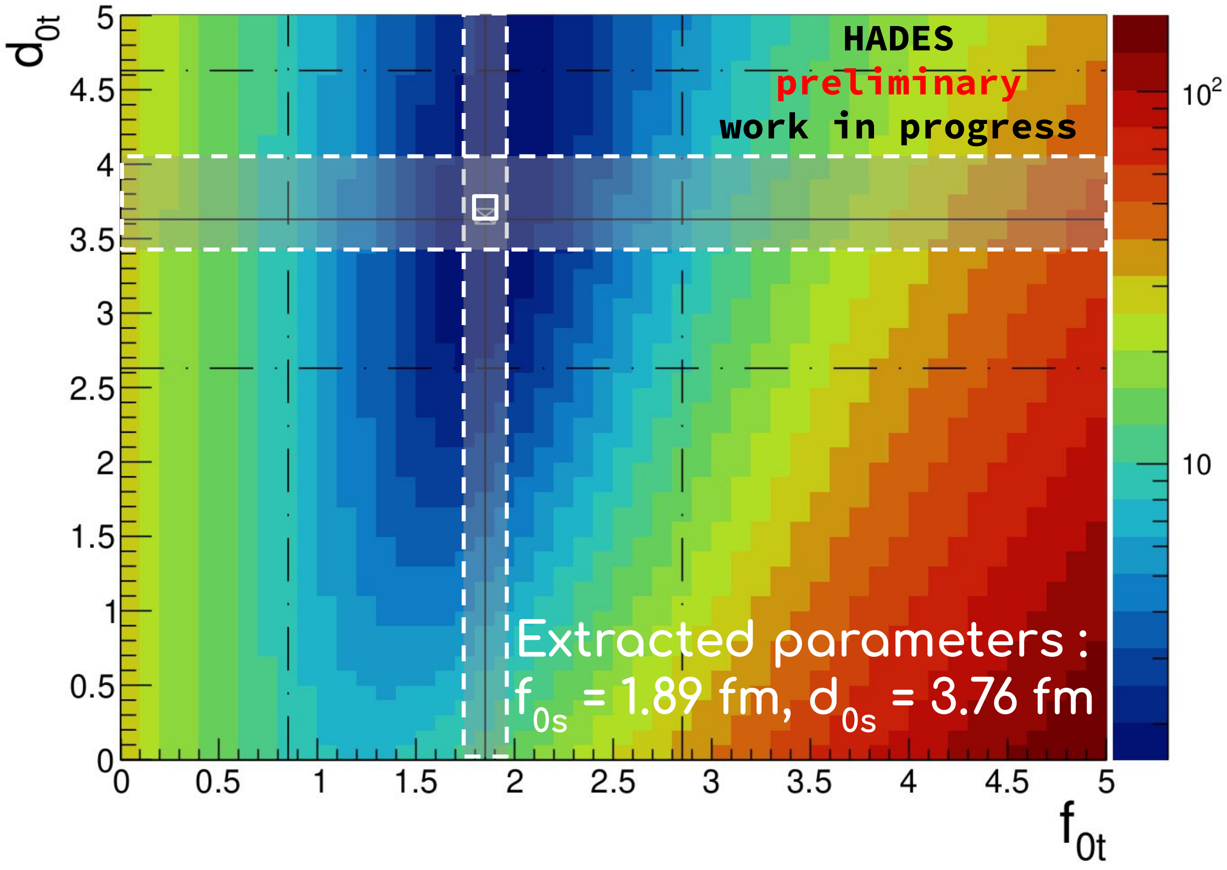
f_{0s}, d_{0s}, f_{0t} and d_{0t} parameters : χ^2 value

Singlet



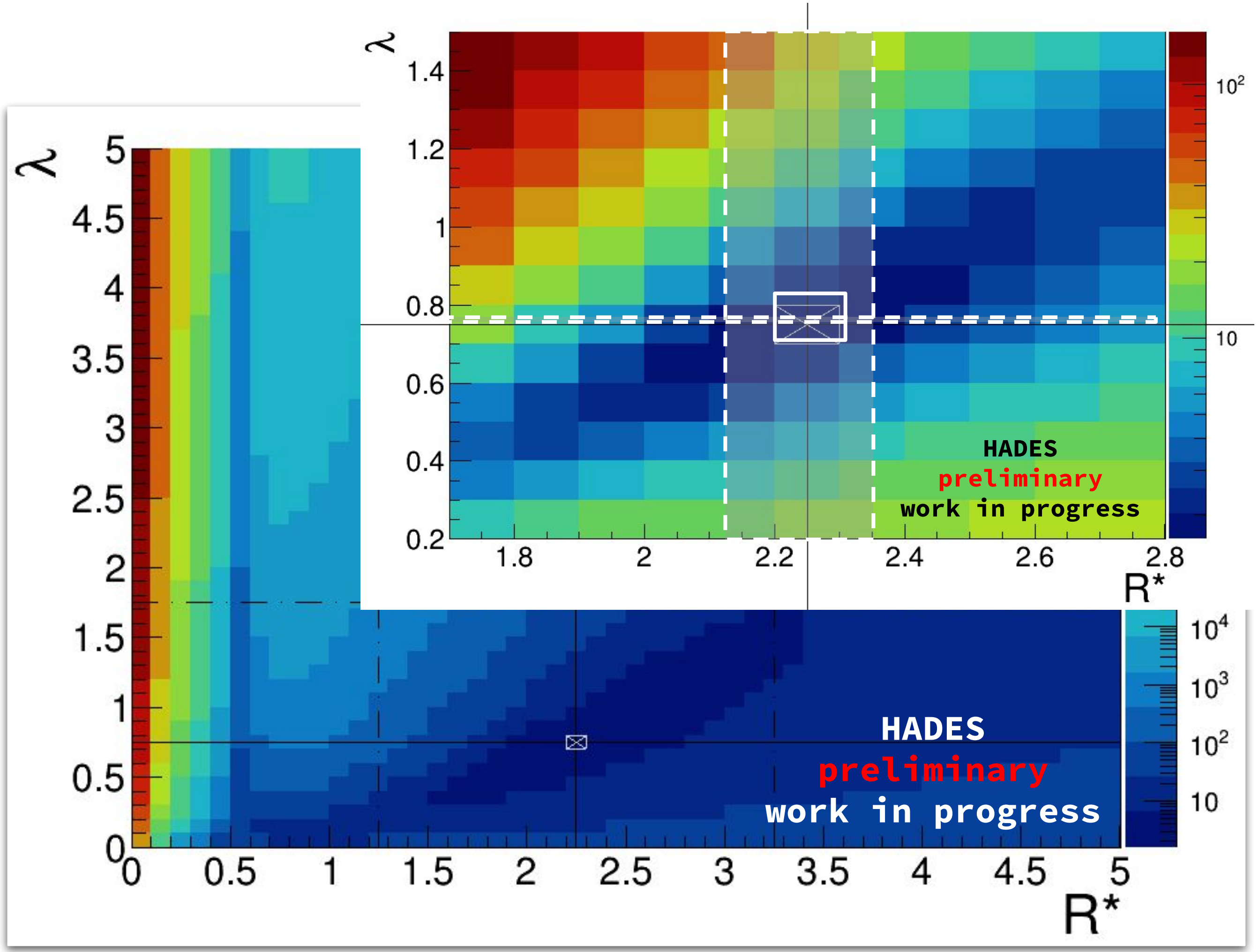
Extracted parameters :
f_{0s} = 0.78 fm, d_{0s} = 0.01 fm

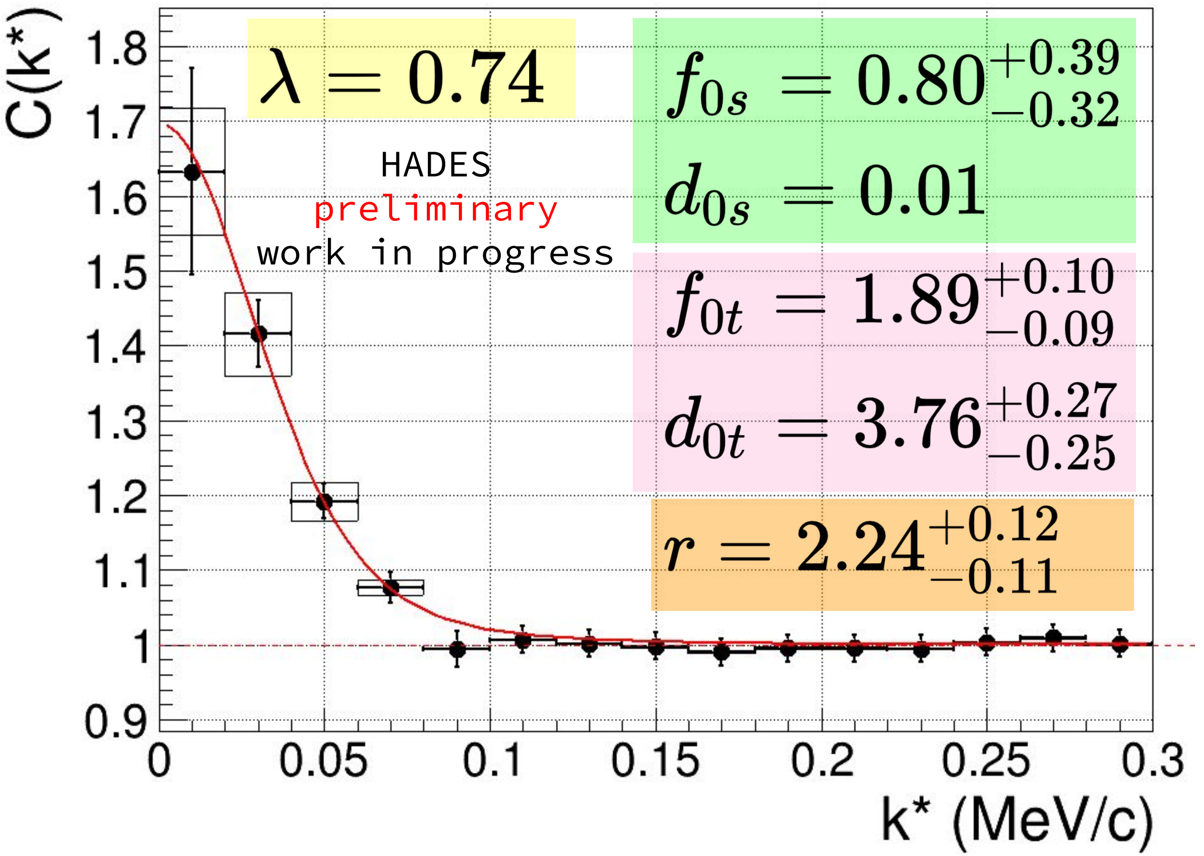
Triplet



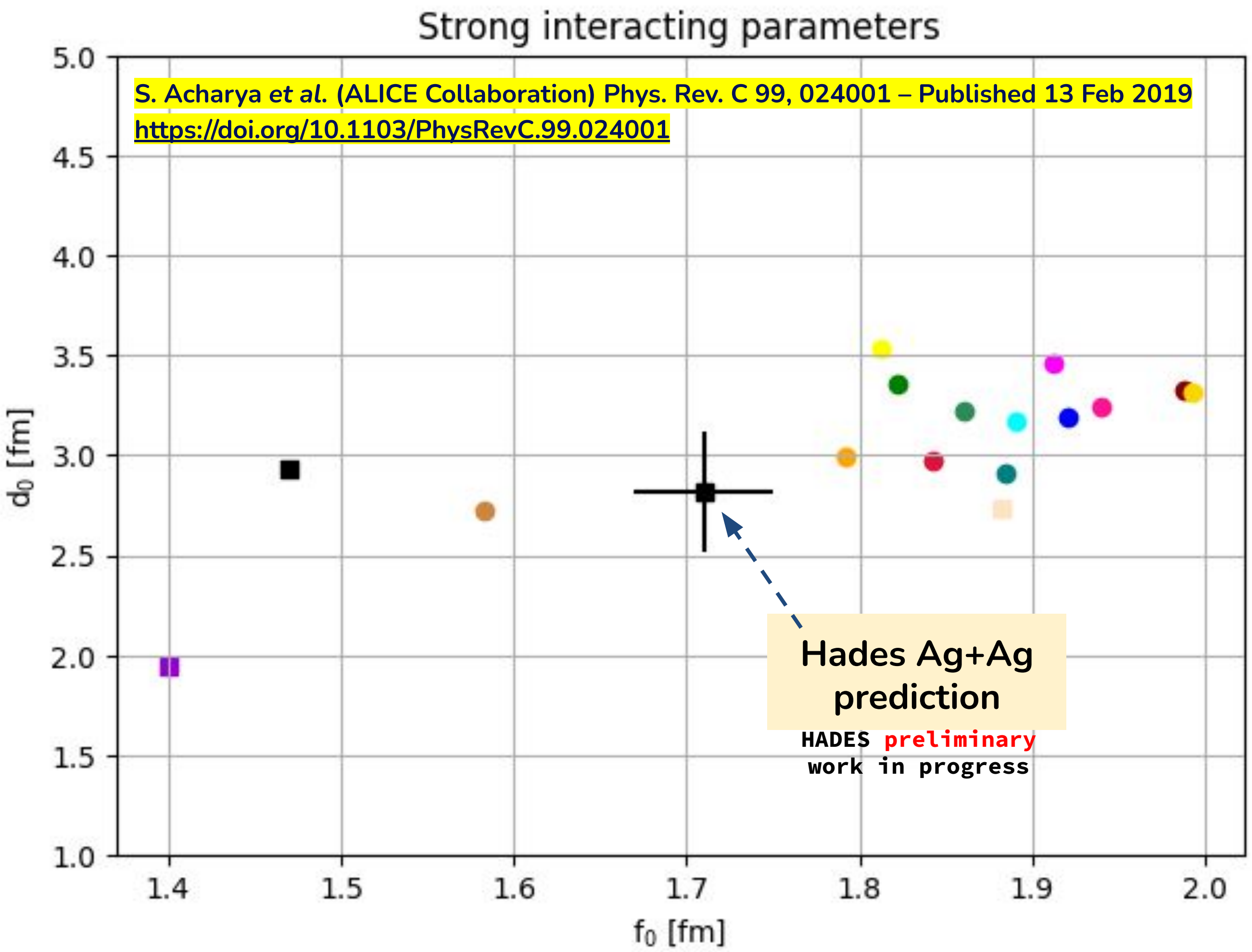
Extracted parameters :
f_{0s} = 1.89 fm, d_{0s} = 3.76 fm

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





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



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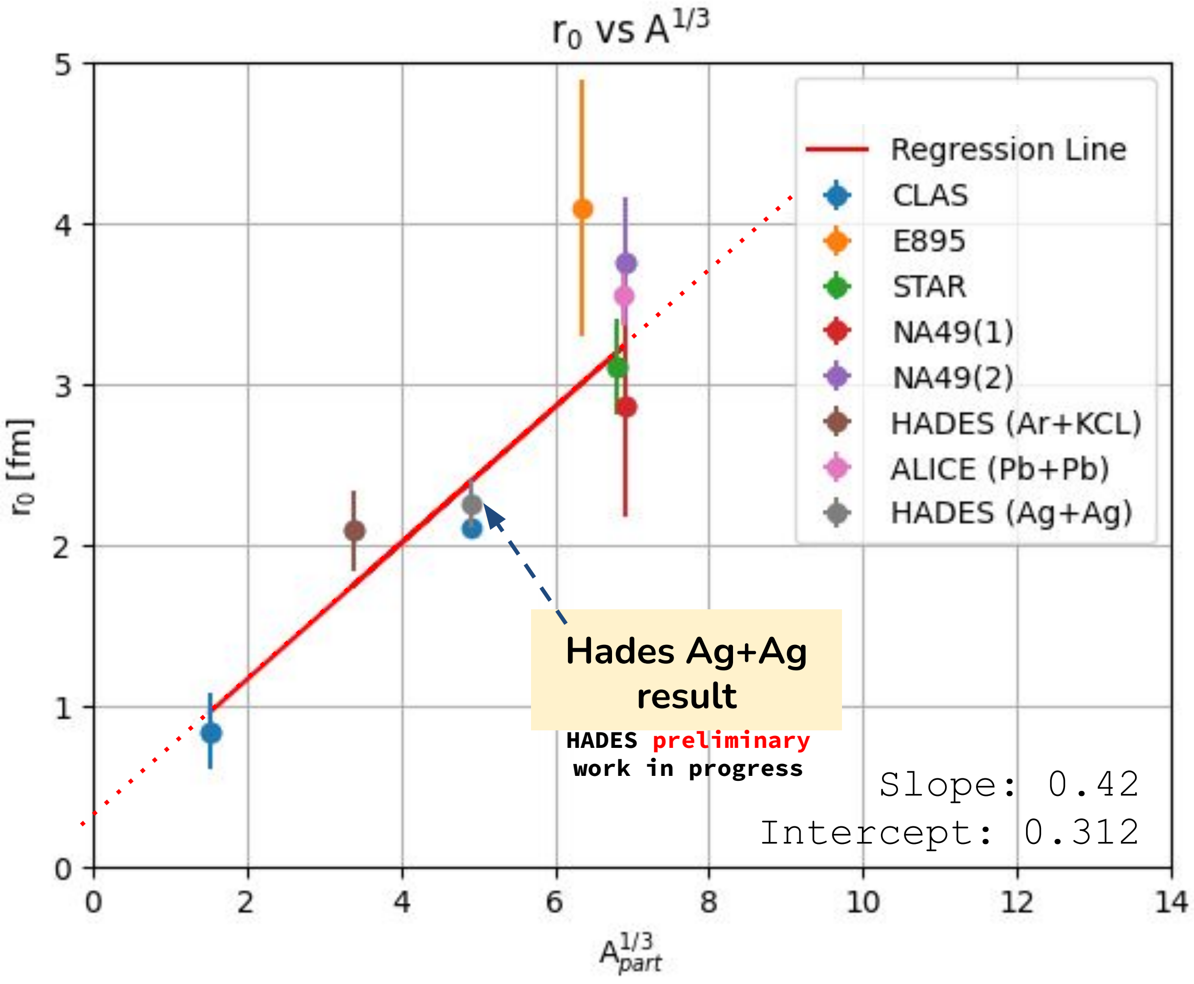
https://doi.org/10.1103/PhysRevC.99.024001

Hades Ag+Ag prediction

HADES preliminary
work in progress

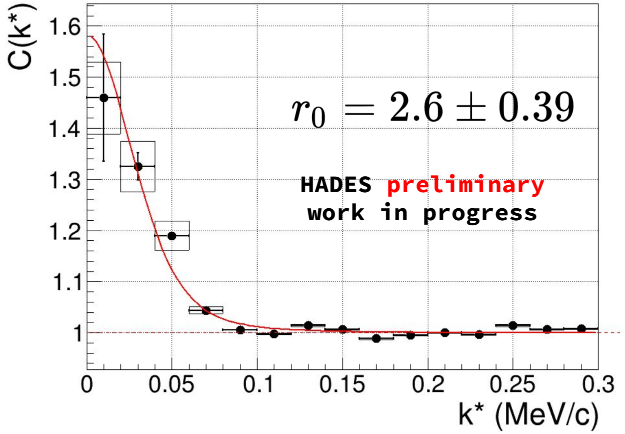


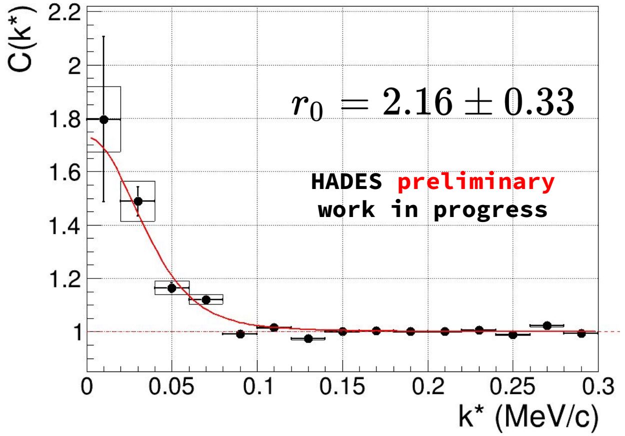
Hades Ag+Ag result

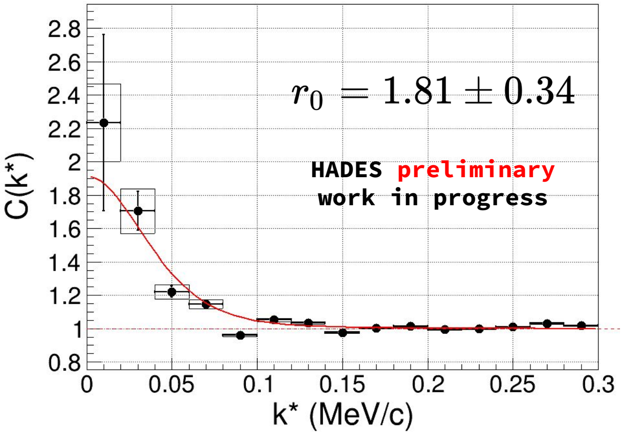
HADES preliminary
work in progress

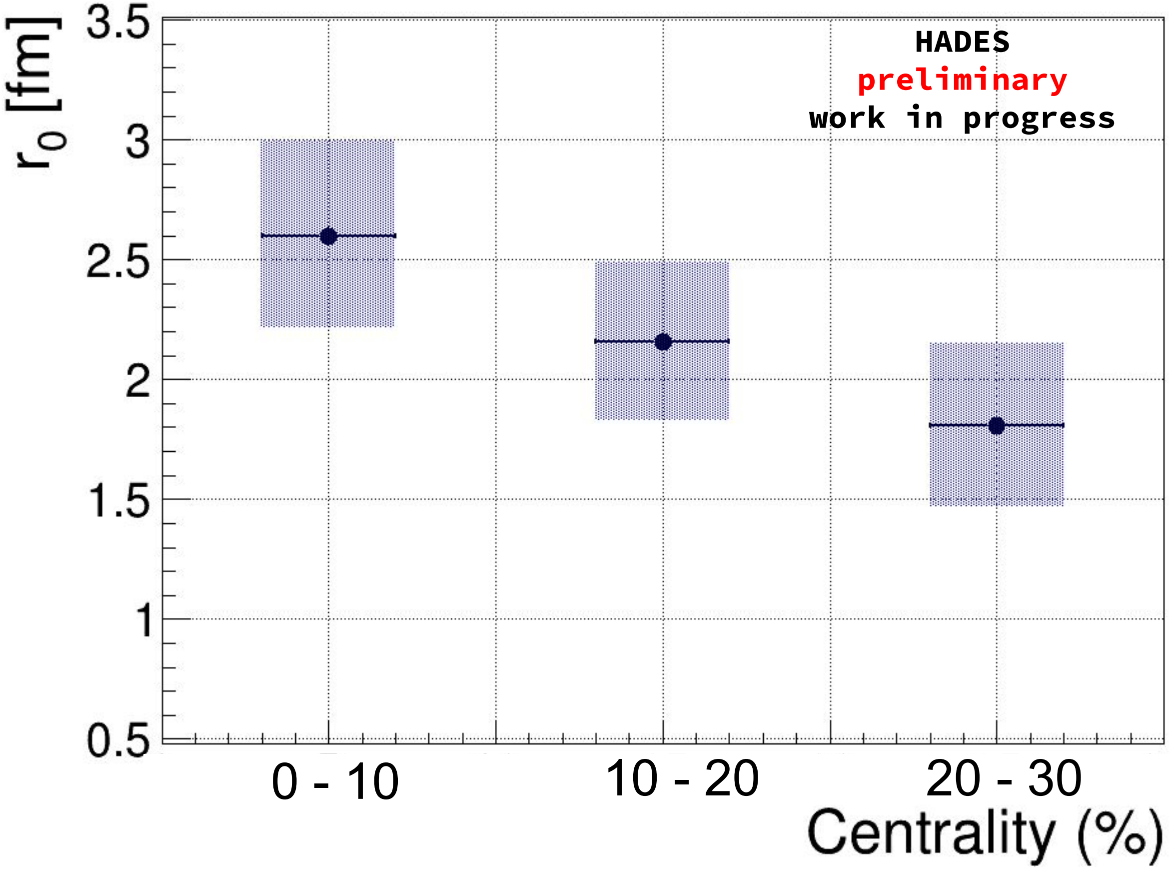
Slope: 0.42
Intercept: 0.312

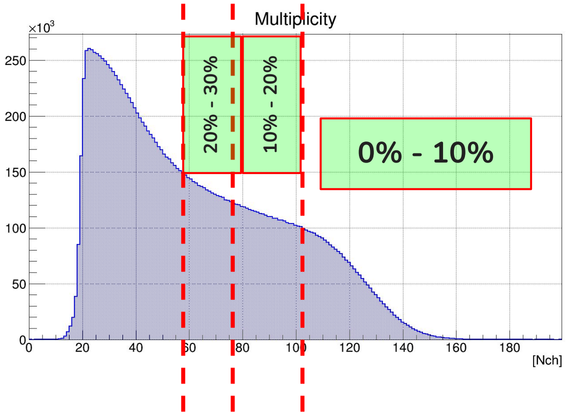
Result : p - Λ correlation :
centrality classes:
0-10%, 10-20%, 20-30%





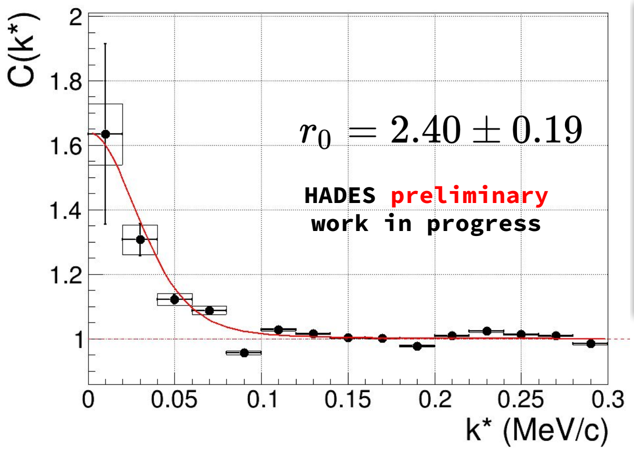


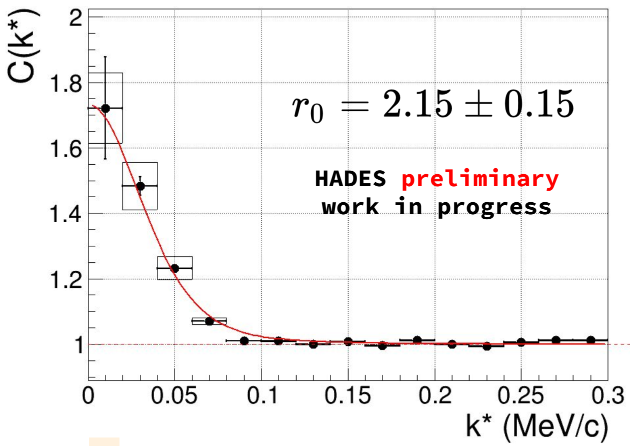


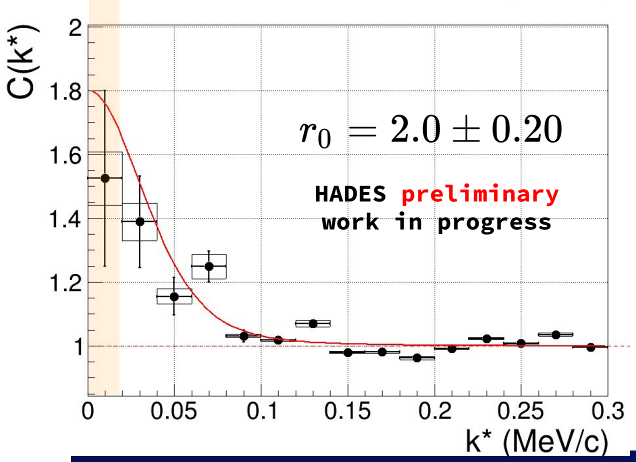


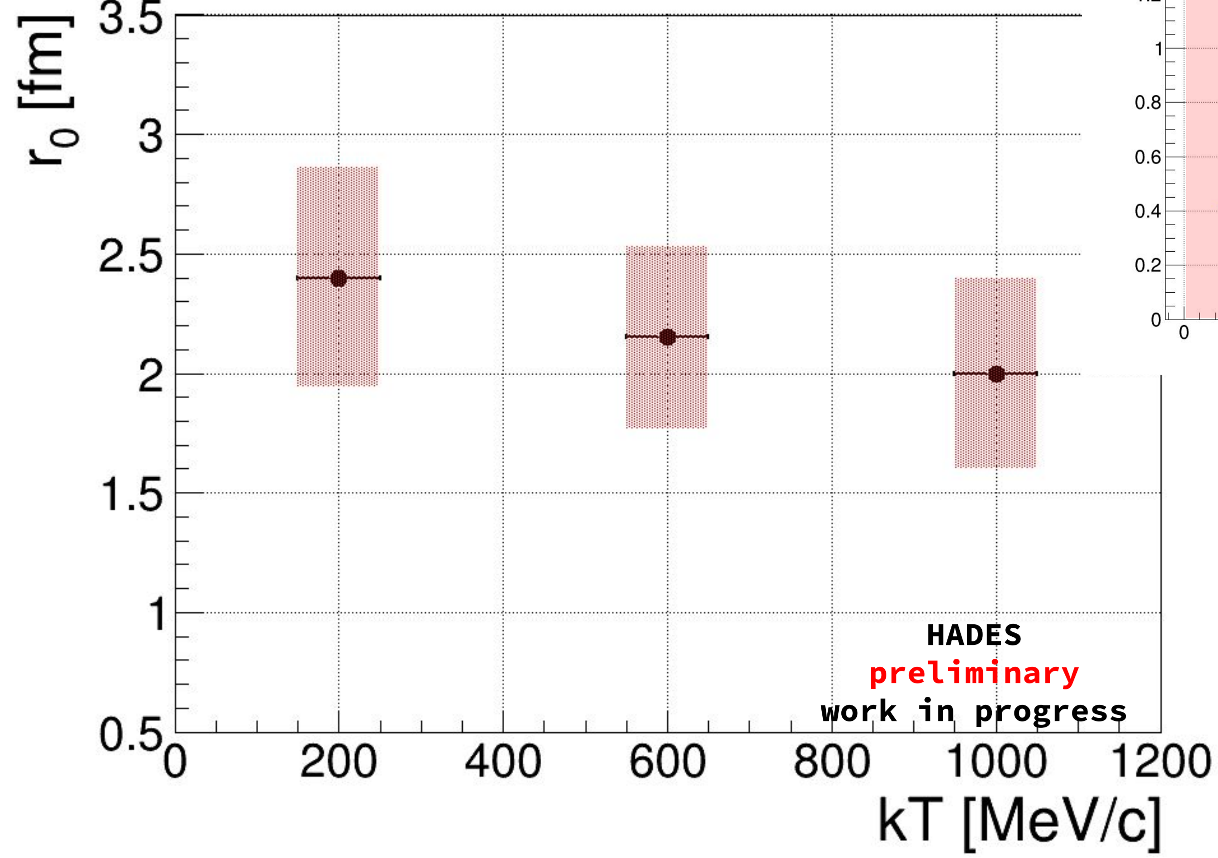
Centrality	Systematic Uncertainty
0 - 10 %	15.30 %
10 - 20 %	15.49 %
20 - 30 %	19.00 %

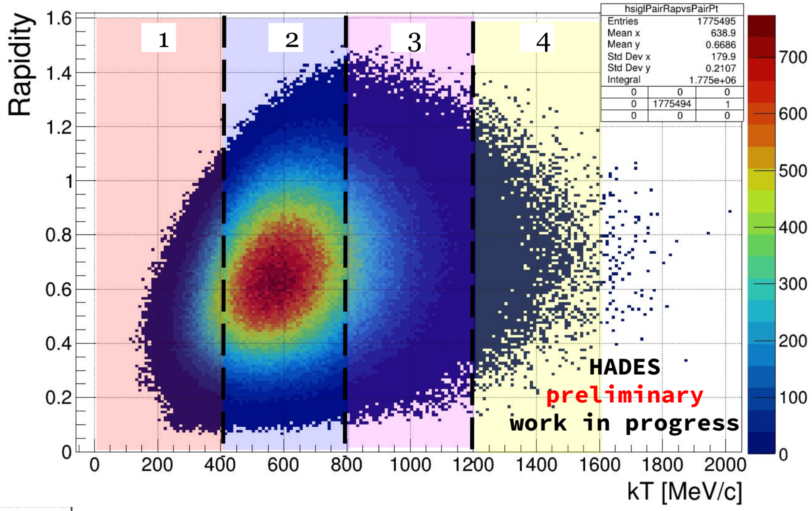
Result : p - Λ correlation :
kT bins : 0-400, 400-800, 800-1200 [MeV/c]





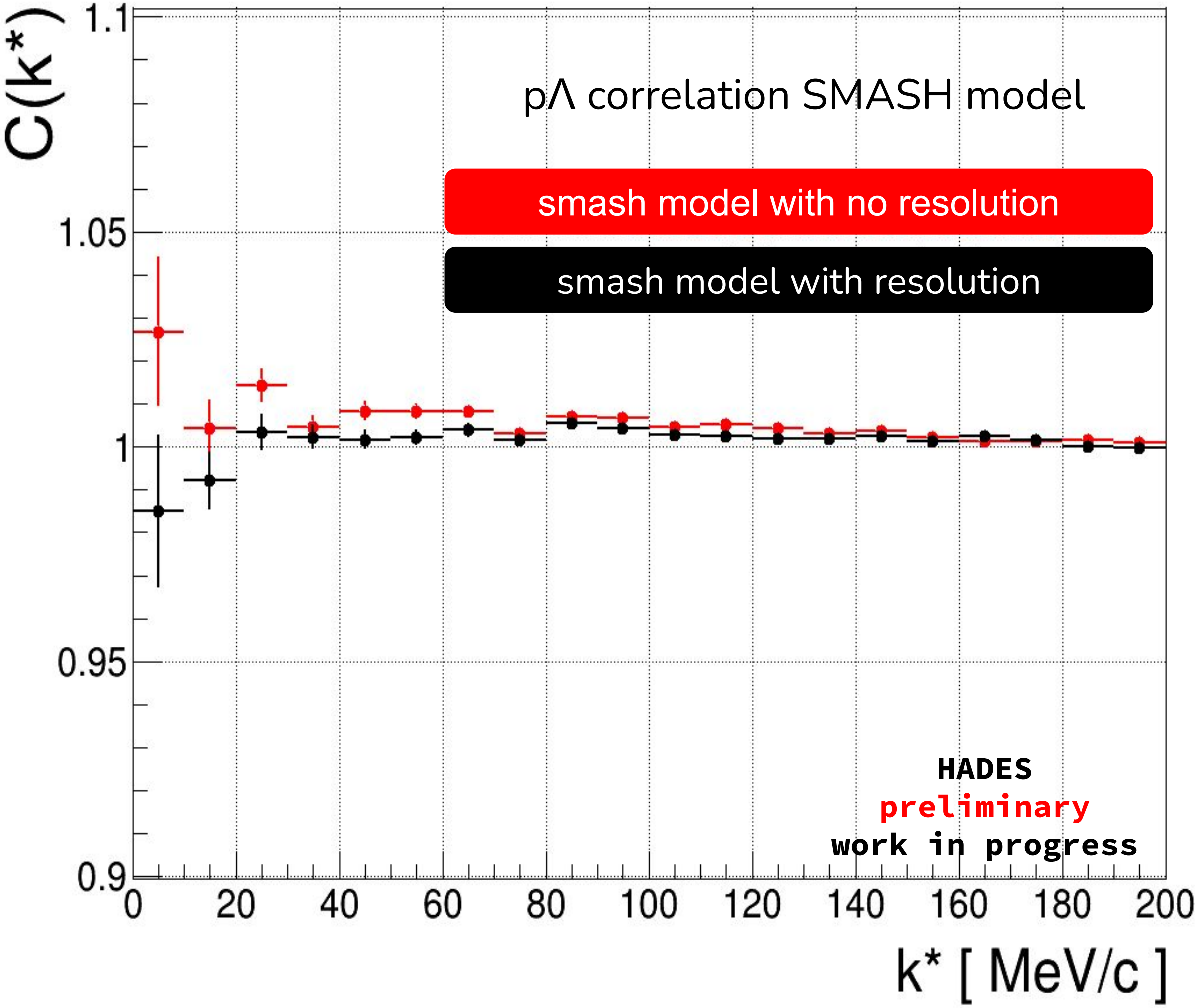


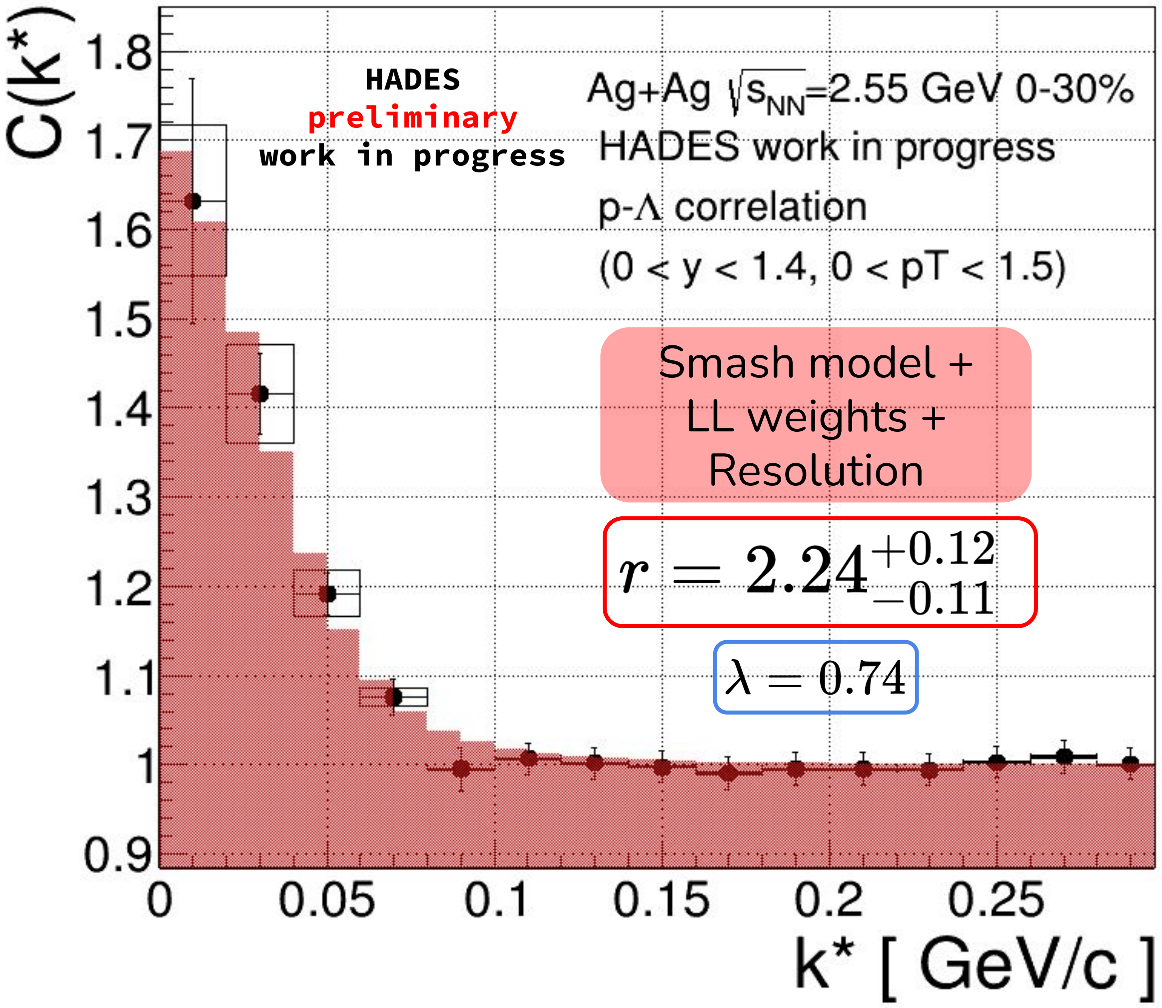




kT region	Systematic Uncertainty
0 - 400	19 %
400 - 800	15 %
800 - 1200	22 %

Resolution effects





Smash model +
LL weights +
Resolution

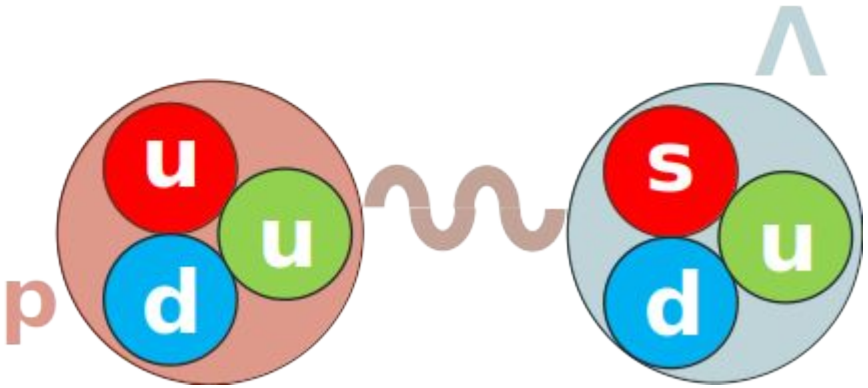
$$r = 2.24^{+0.12}_{-0.11}$$

$$\lambda = 0.74$$

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

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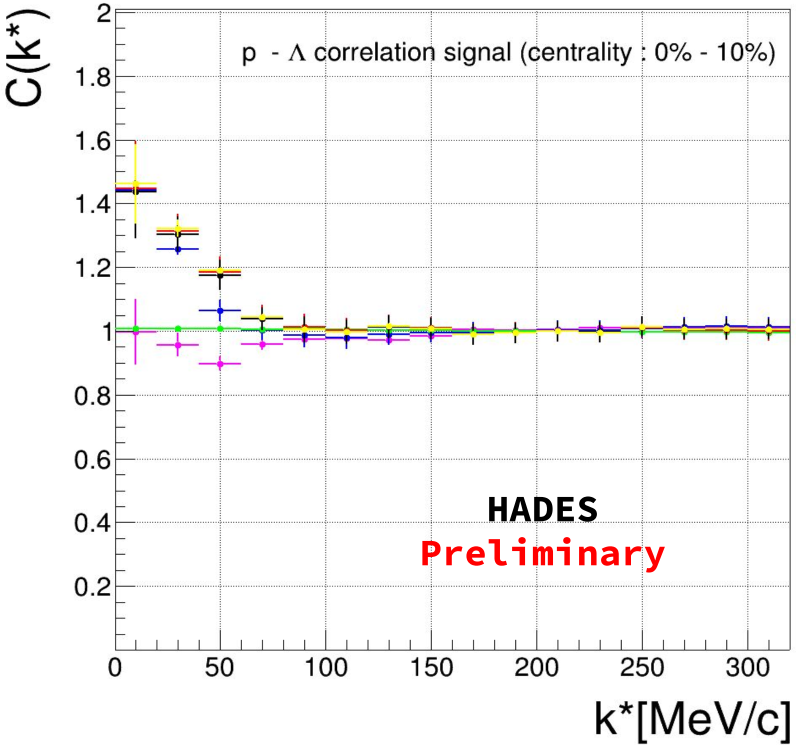
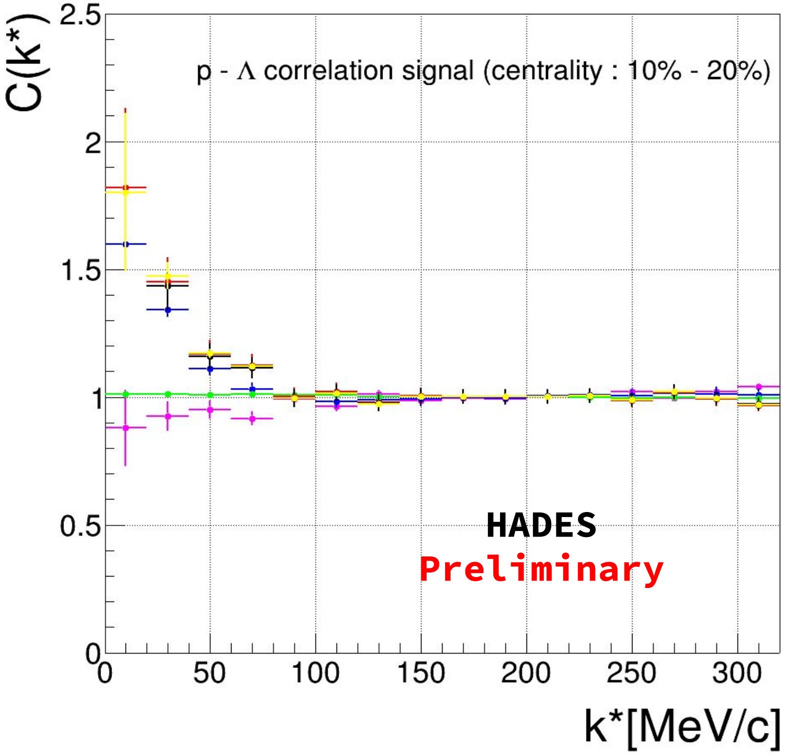
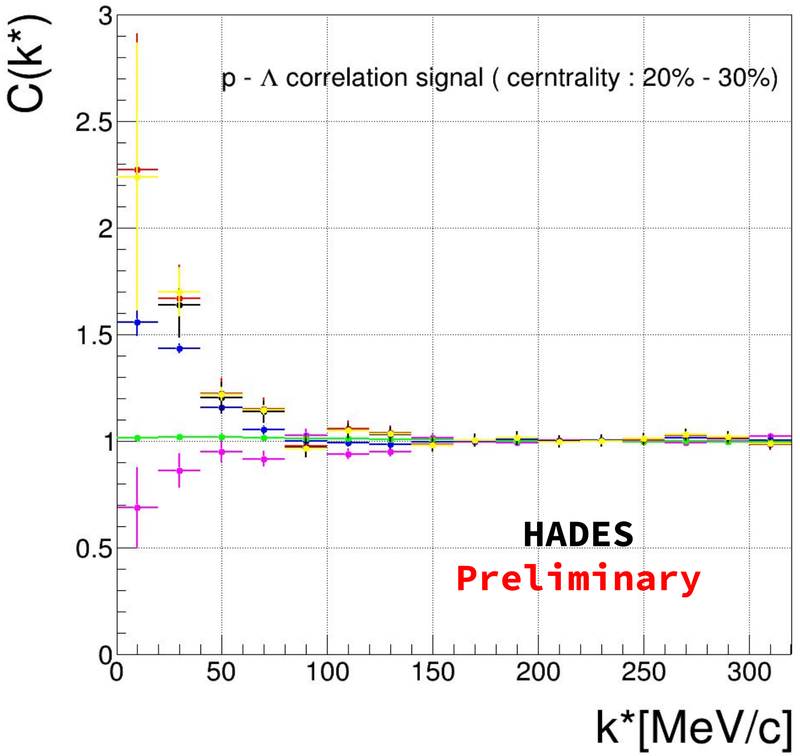
Result - II

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

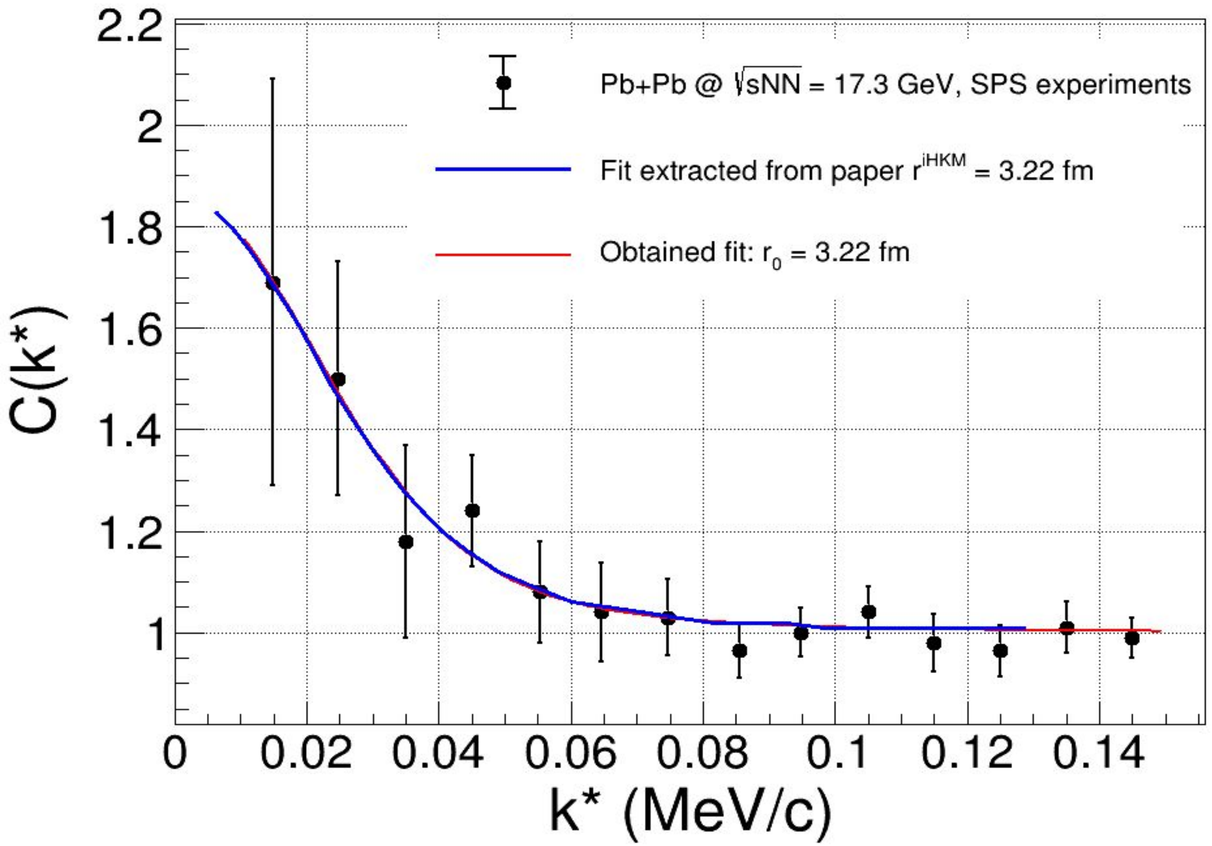


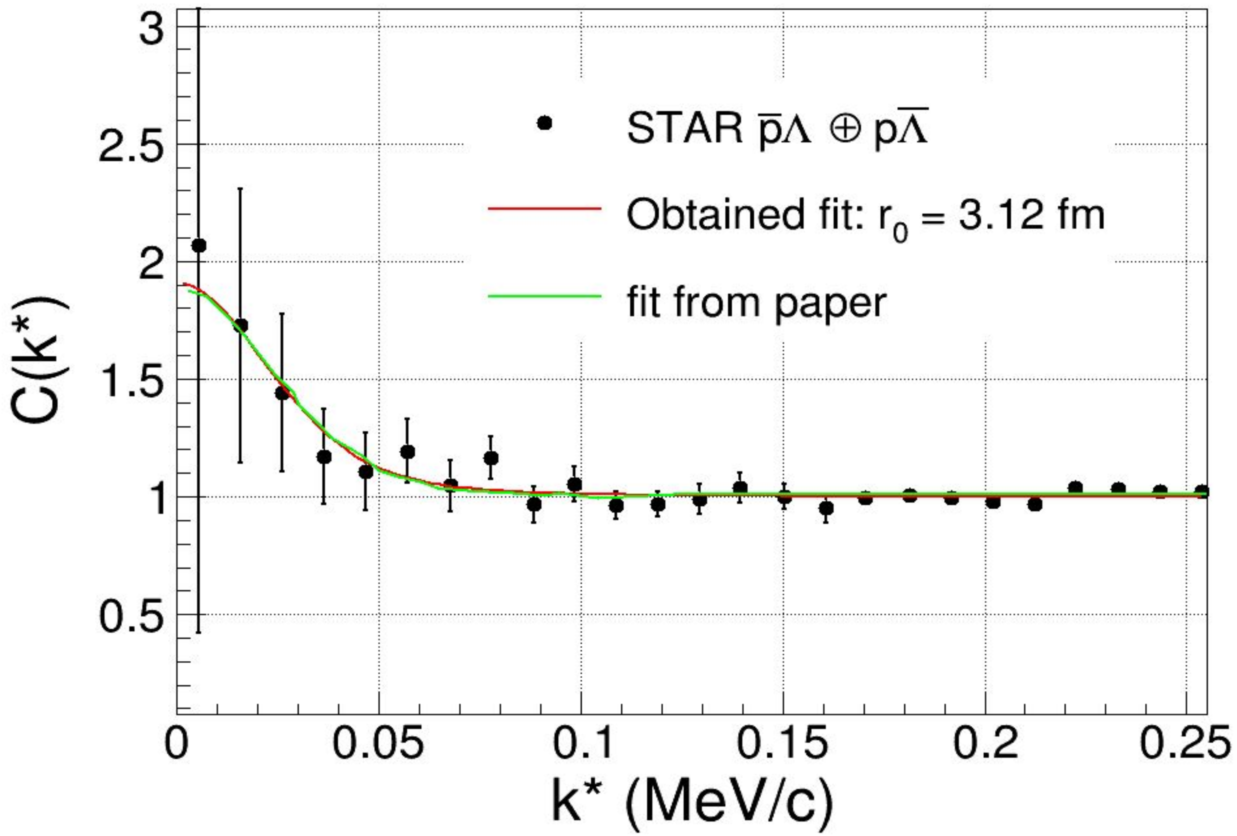




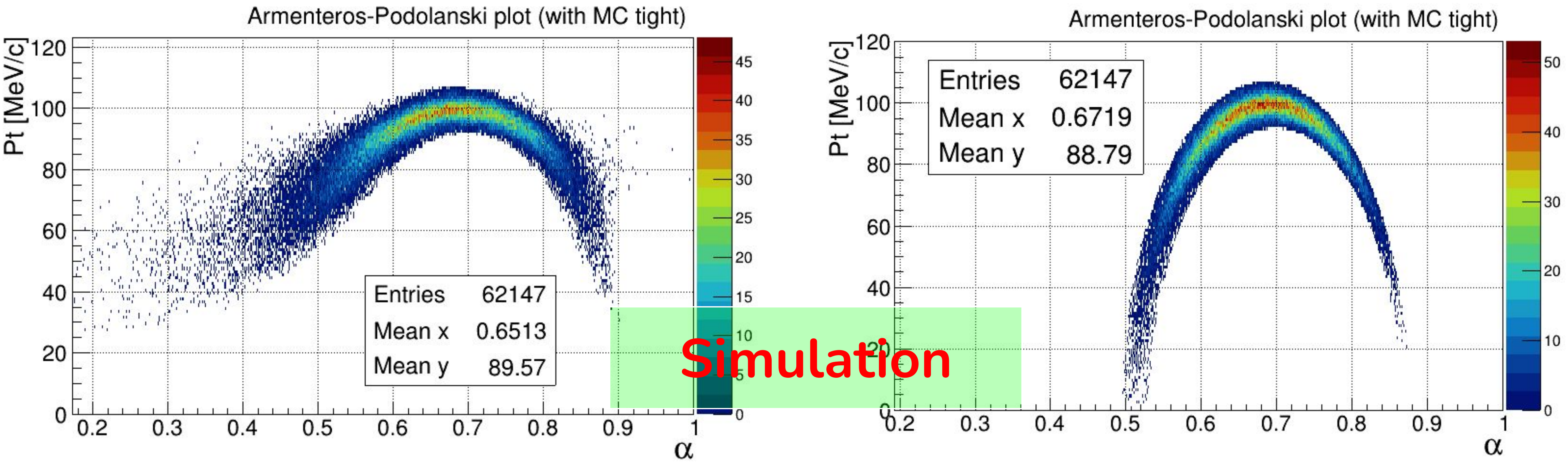
Result : STAR and LHC data

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





Armenteros-Podolanski plots



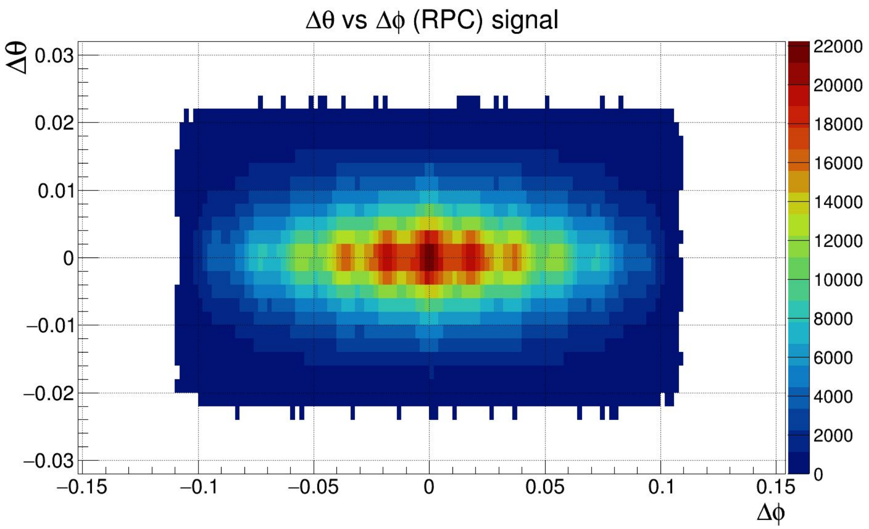
Simulation

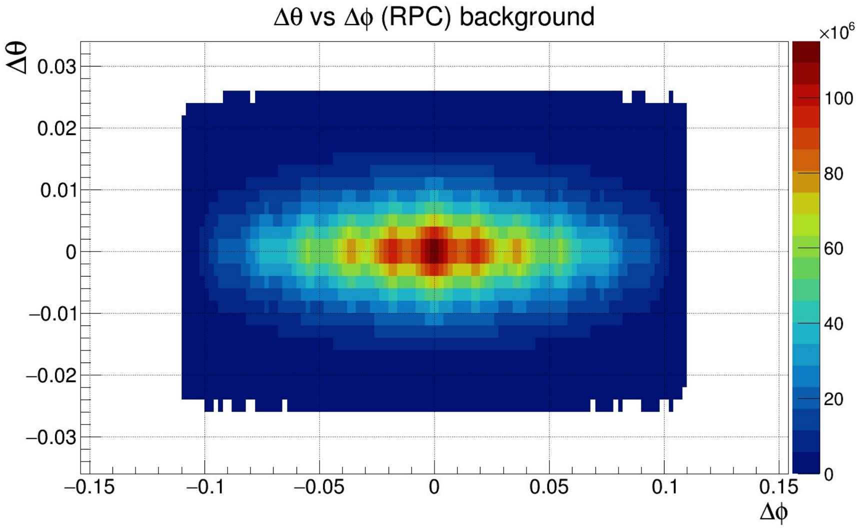
HADES :
Low energies

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

Corrected

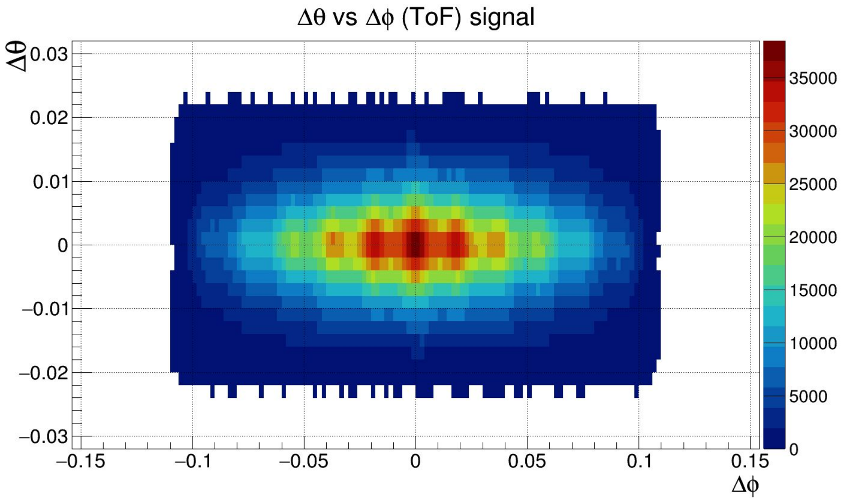
Δθ vs Δϕ distribution

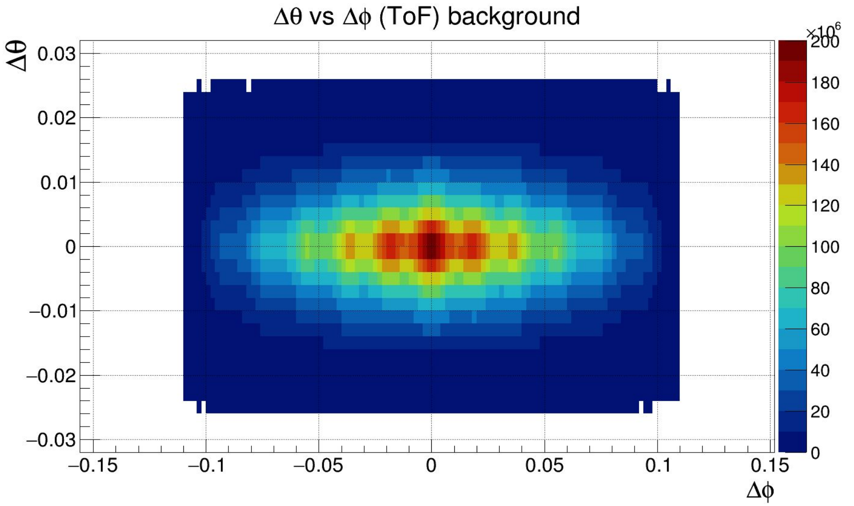




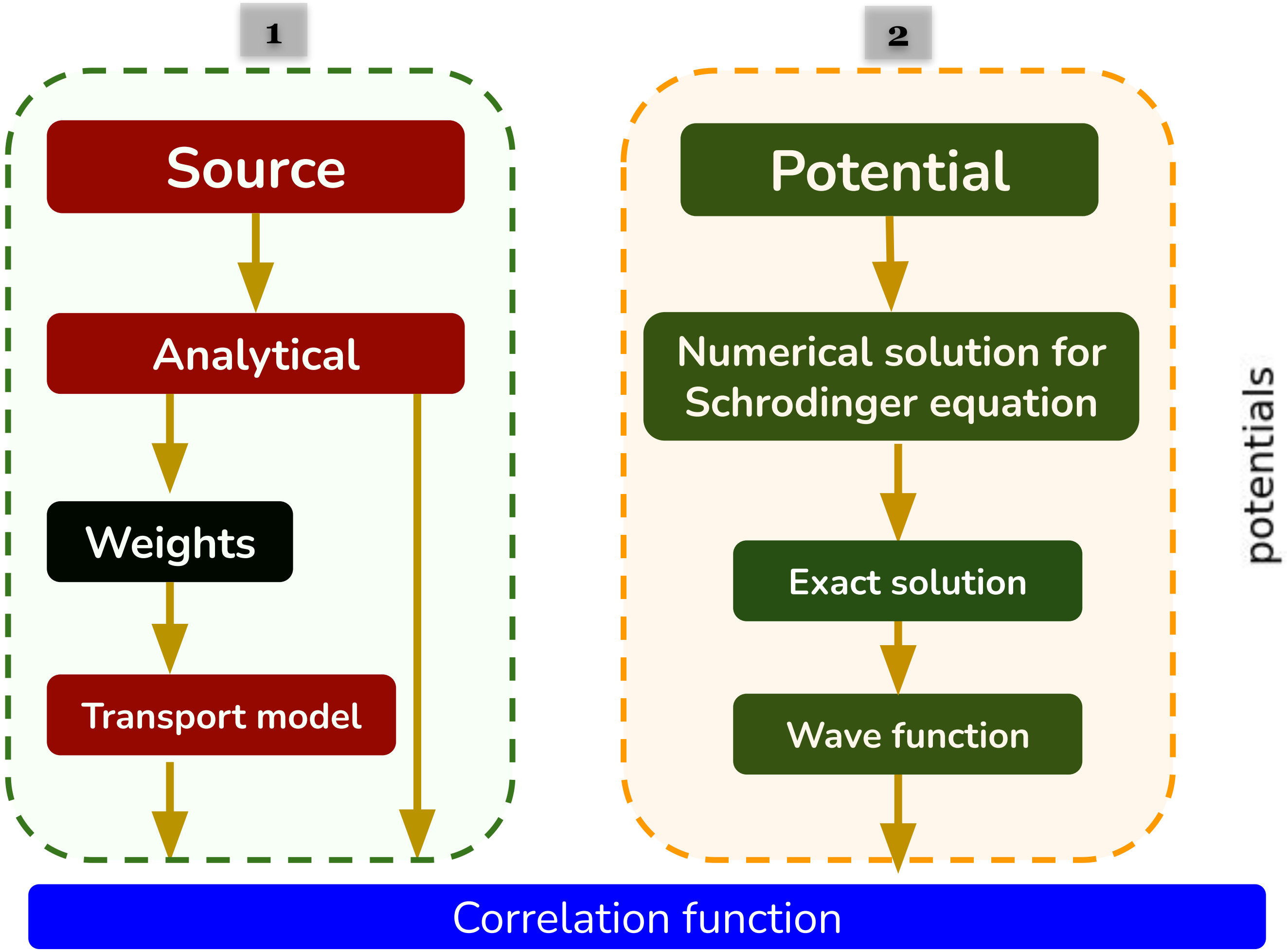
RPC results

ToF results





How correlations are obtain?



1

Source

Analytical

Weights

Transport model

2

Potential

Numerical solution for Schrodinger equation

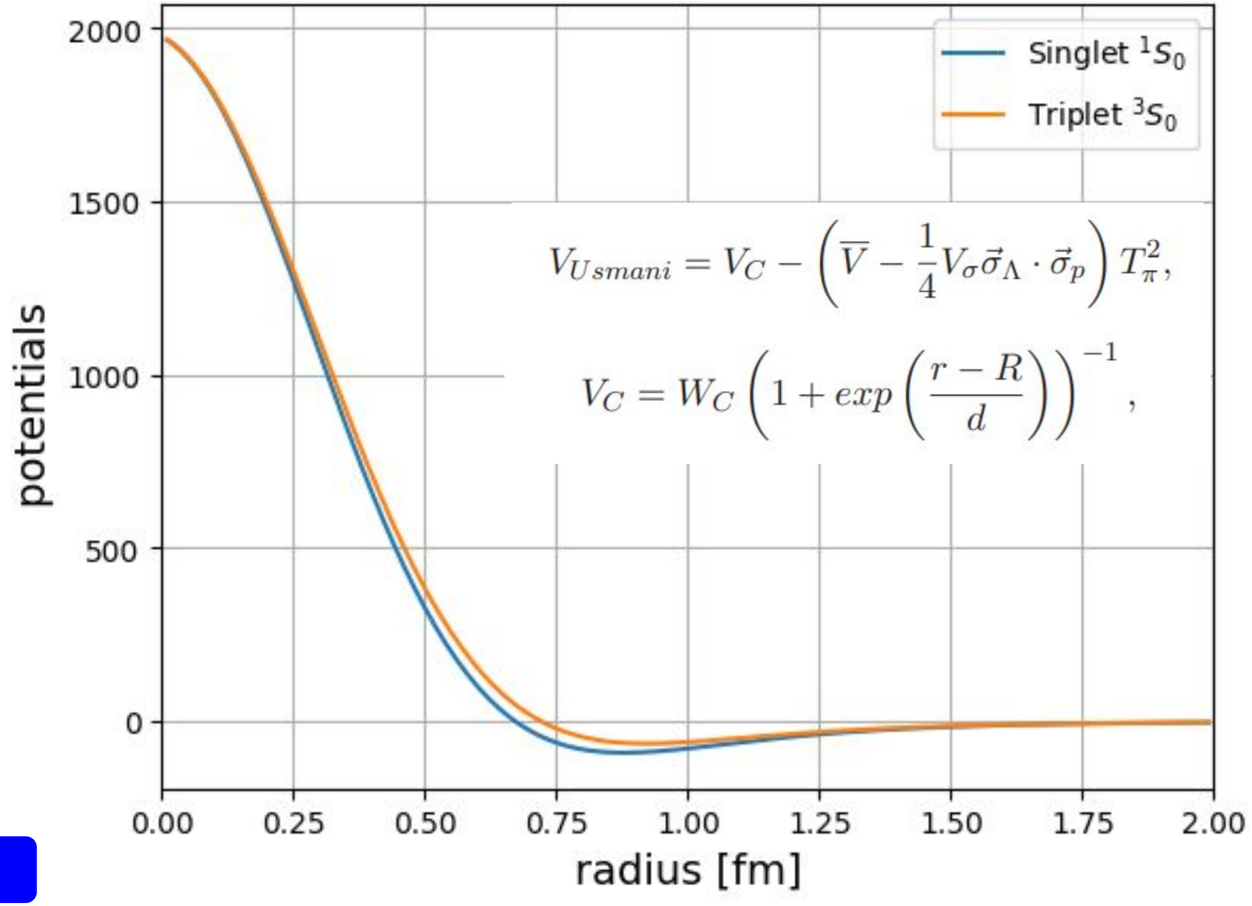
Exact solution

Wave function

Correlation function

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

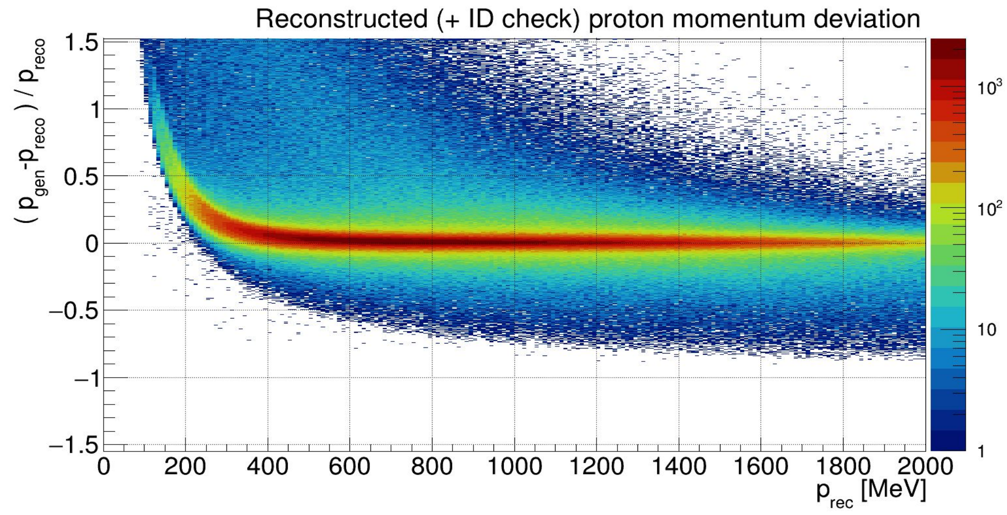
$$\Psi^S_{-\mathbf{k}^*}(\mathbf{r}^*) = e^{-i\mathbf{k}^* \cdot \mathbf{r}^*} + \frac{f^S(k^*)}{r^*} e^{ik^* \cdot r^*} .$$

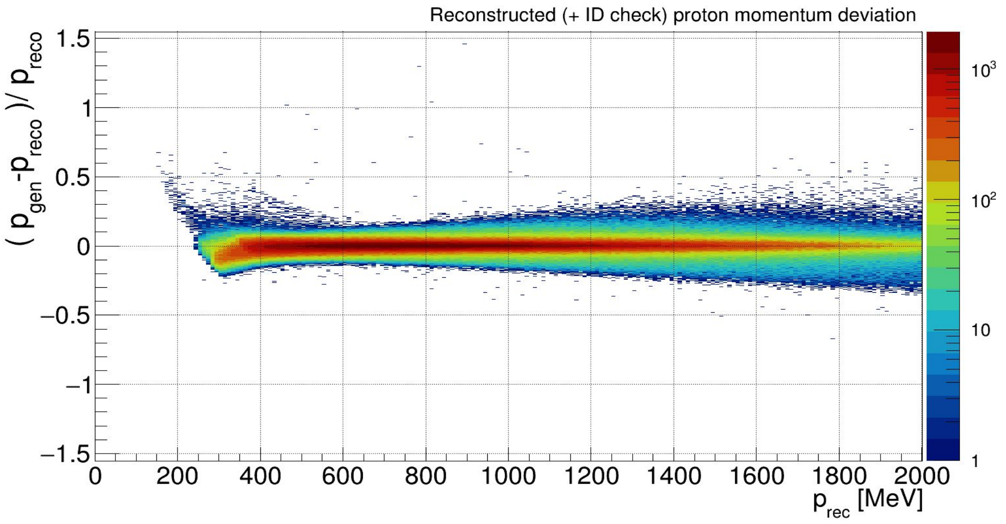
The effective range approximation for the scattering amplitude is

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

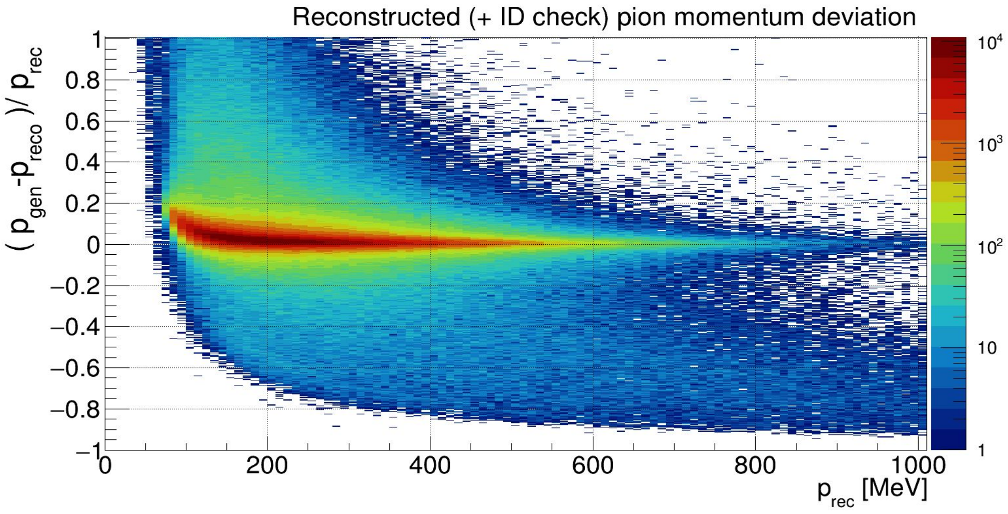
where $\boldsymbol{f_0^S}$ is the scattering length and $\boldsymbol{d_0^S}$ is the effective radius for a given total spin **S = 1** or **S = 0**.
The particle is assumed to be unpolarized (the polarization **P = 0**) :
singlet state **ρ_0 = ¼ (1 - P^2)** and triplet state **ρ_1 = ¾ (1 - P^2)**.

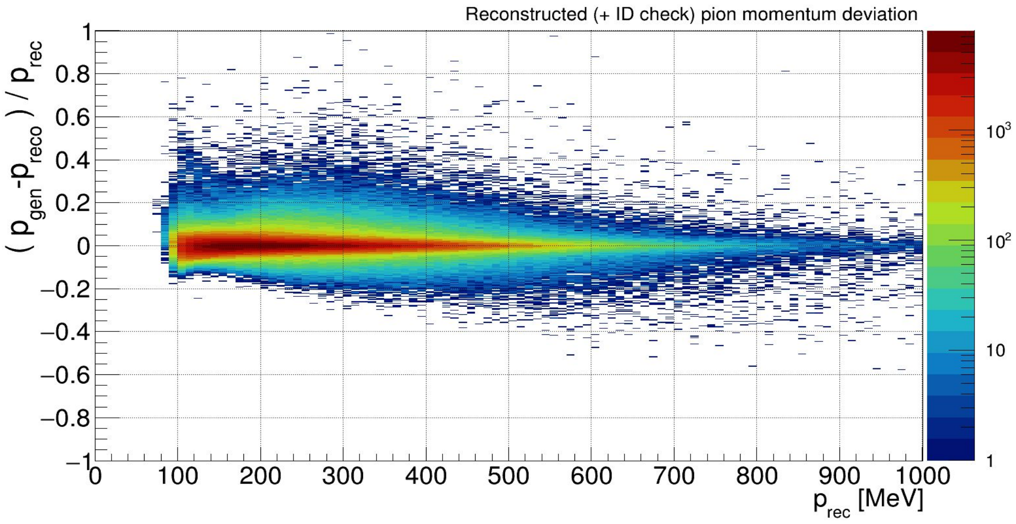
Energy-loss correction





Proton

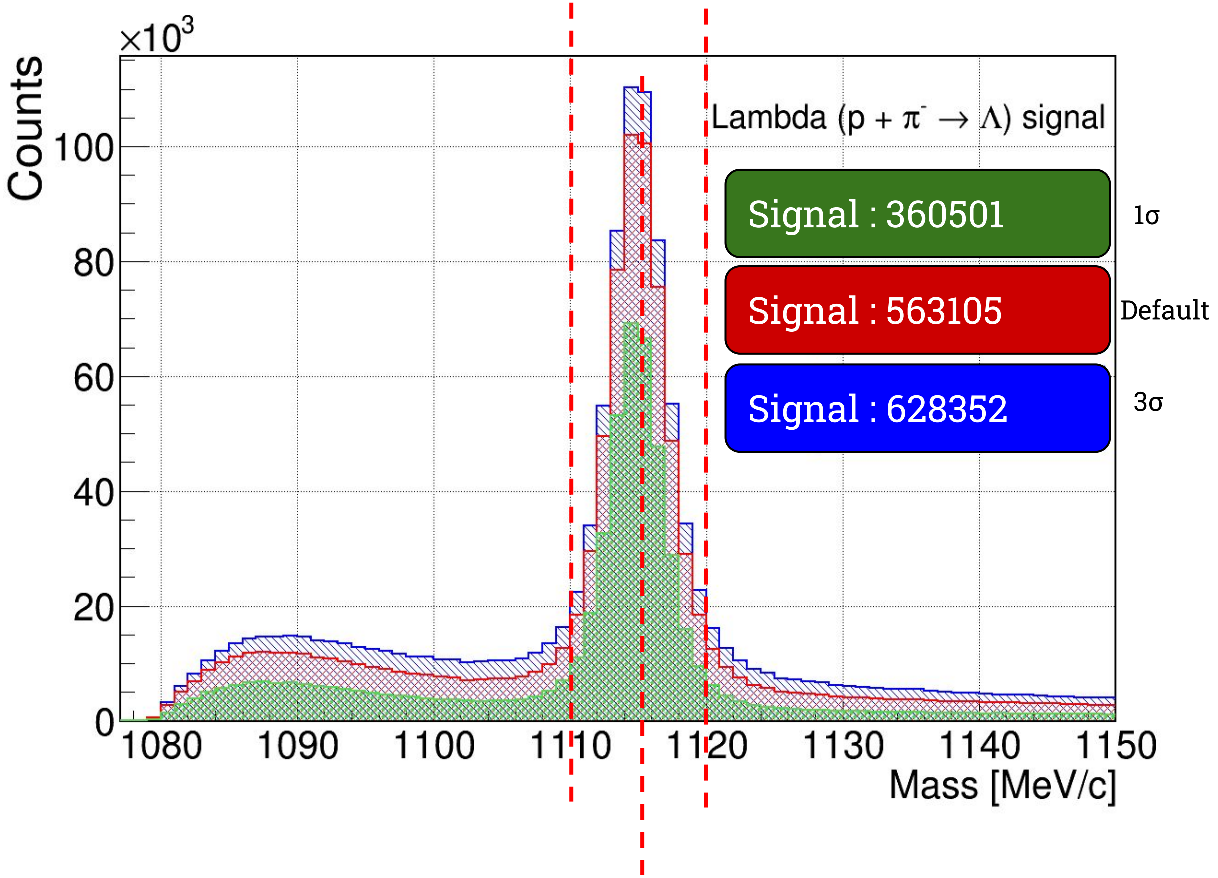




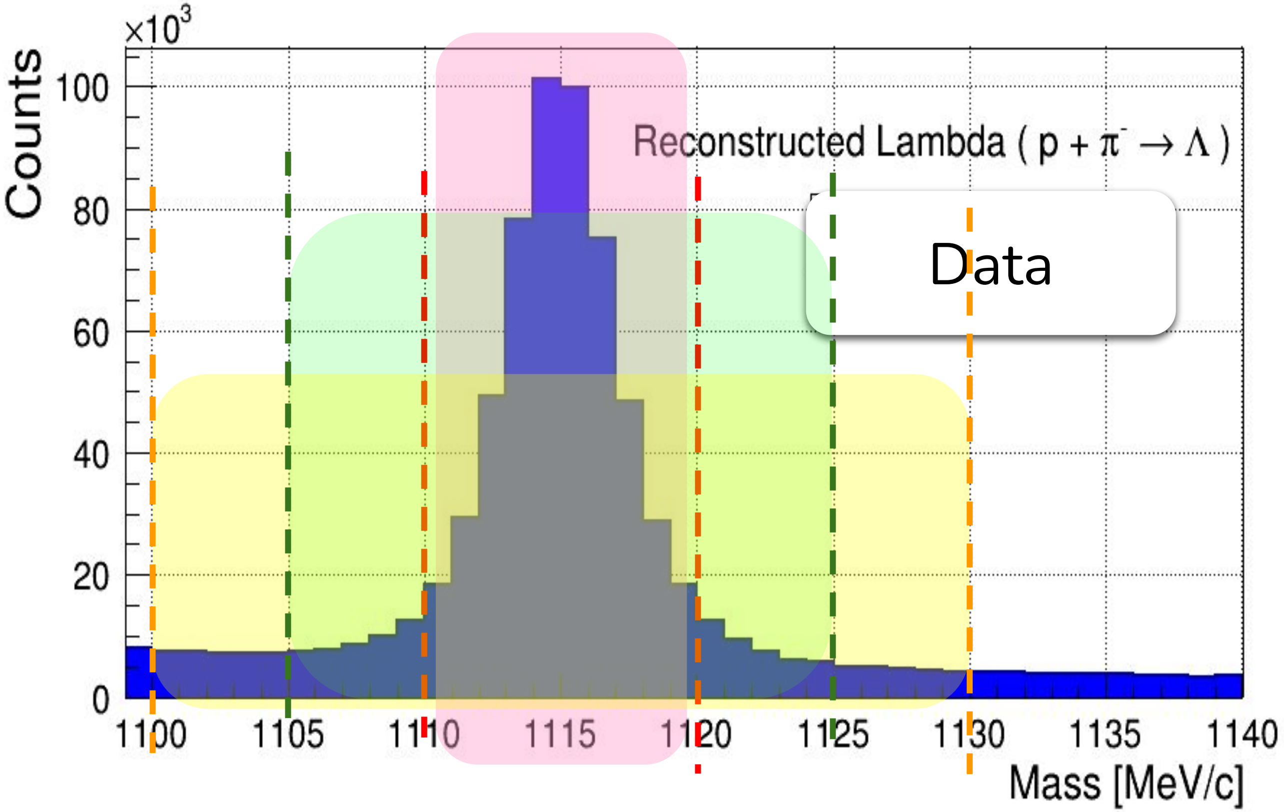
Pion

Systematics check (few of them)

PID variation



Mass cut variation



Thank you

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