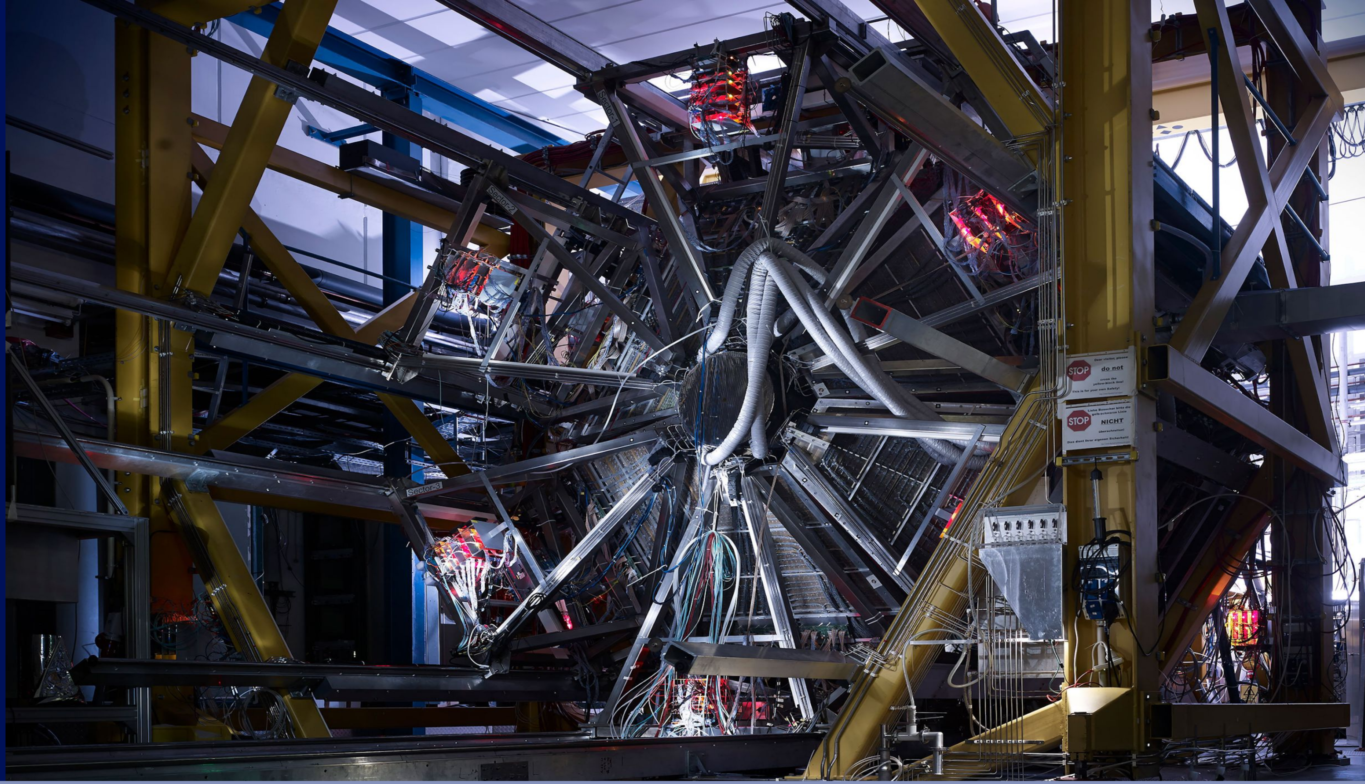
The study of short-range interactions using femtoscopic correlation

Current status in HADES



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   b. Weak Decay Recognition (Λ data / simulation)
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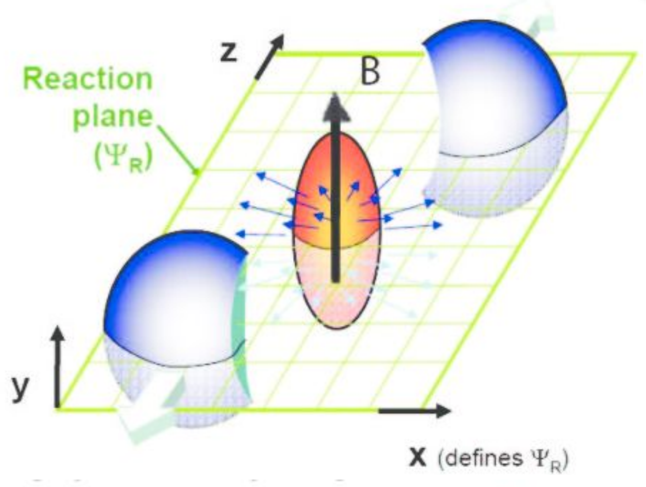
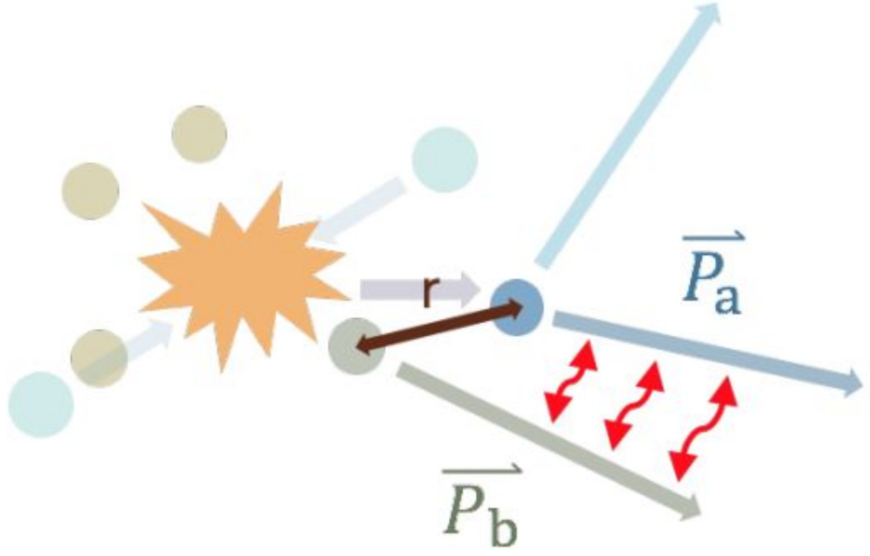




https://www.ph.nat.tum.de/denseandstrange/research/current-projects/yn-interaction-in-neutron-stars-from-alice-and-hades-data/

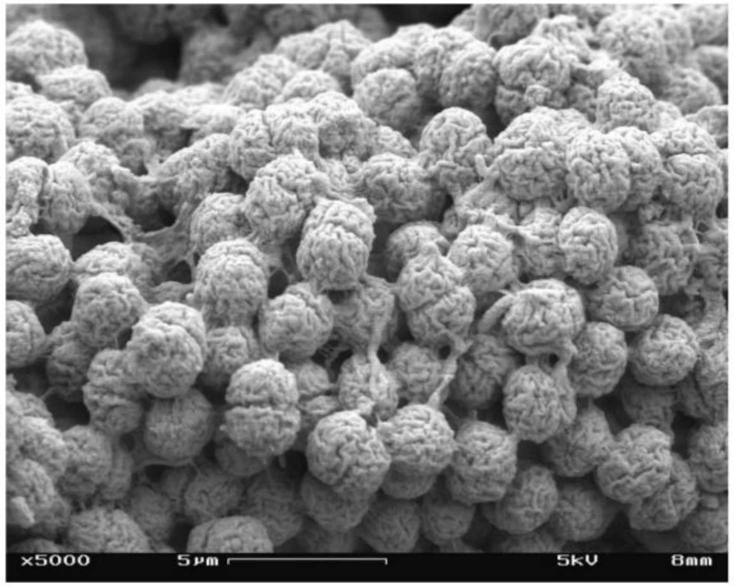
Microscopy and Wavelength

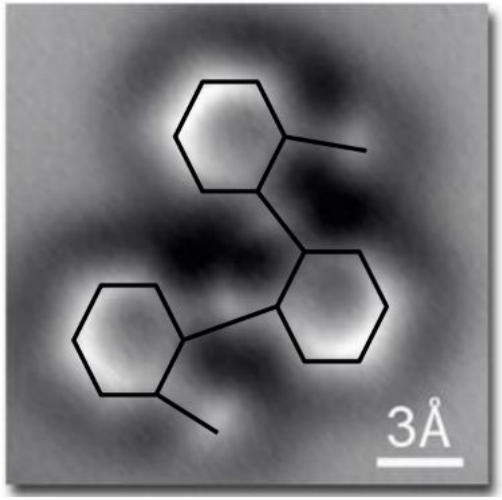
- Wave + object = interference, if $\lambda \lesssim$ length scale
- Wavelength of light 3-600 nm: smaller objects not
    - resolvable due to interference
      (1µm = 10^{-6} m, microscope)

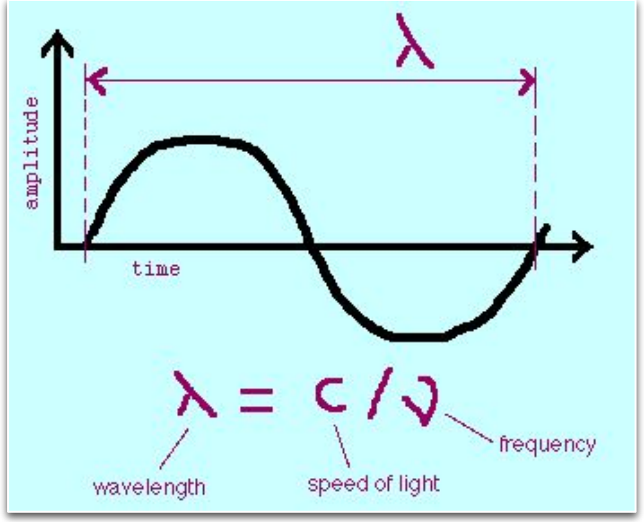
- Electron microscope: nanoscope
    - 1 nm = 10^{-9} m = 10 Å resolution
    - Visible biological nanostructures

- Size of atoms: approx. 10^{-10} m
    - Atomic force microscope!

- Atomic nucleus:
    - 1 fm = 10^{-15} m
  ➔ Femtoscope?

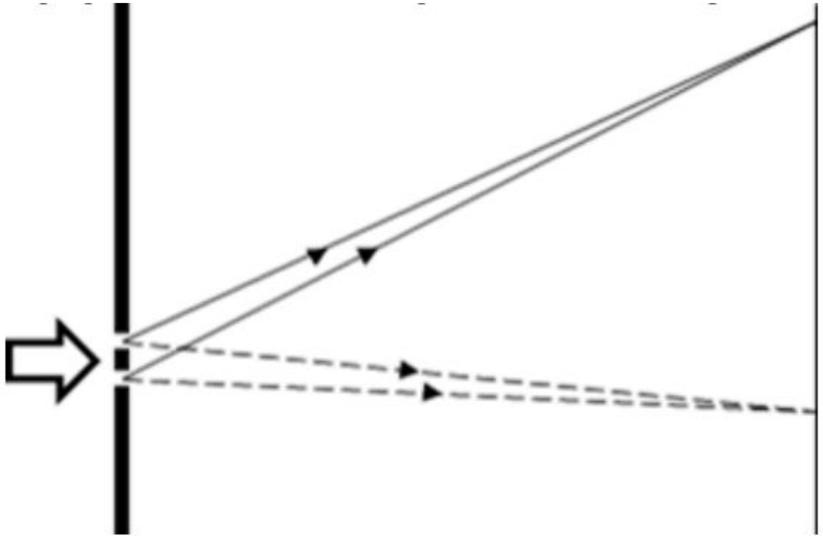


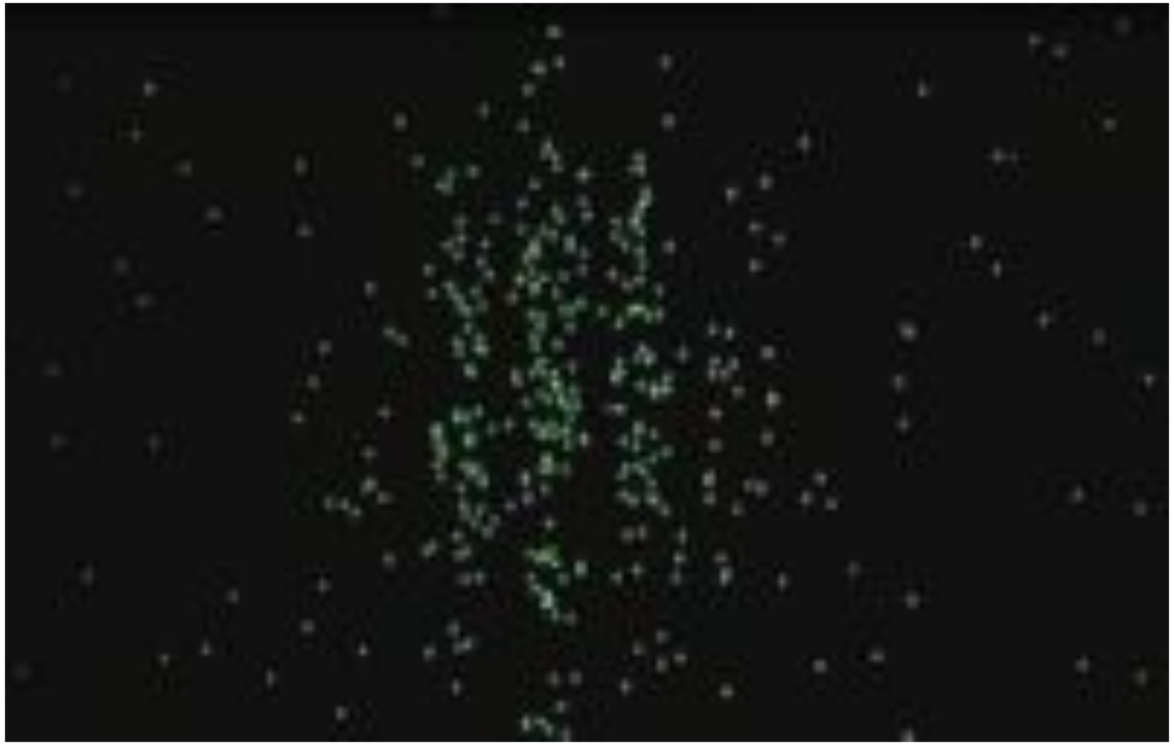




Single photon interference

- What happens in double slit experiment with weak source?
- Only a single photon arrives at a time
- Smallest possible energy packet, cannot split!
- Will there be interference?
- Yes, but appears sequentially

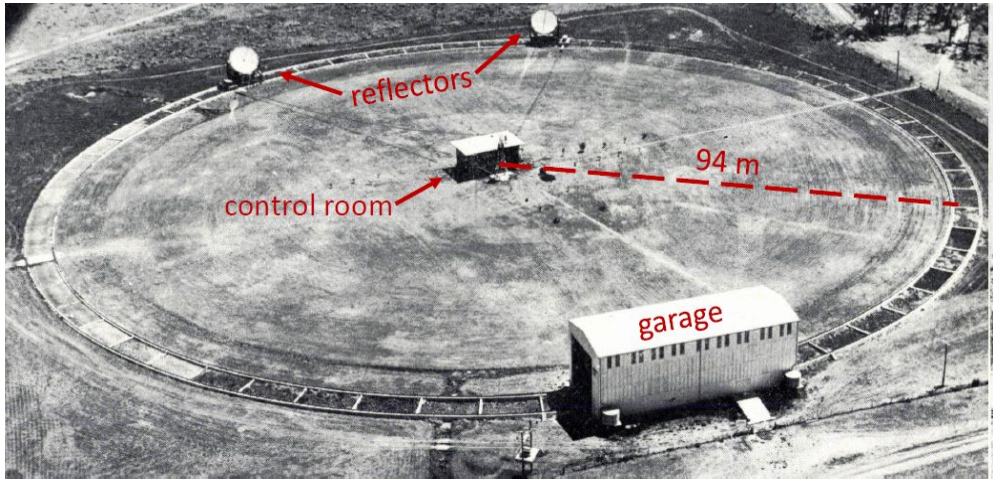


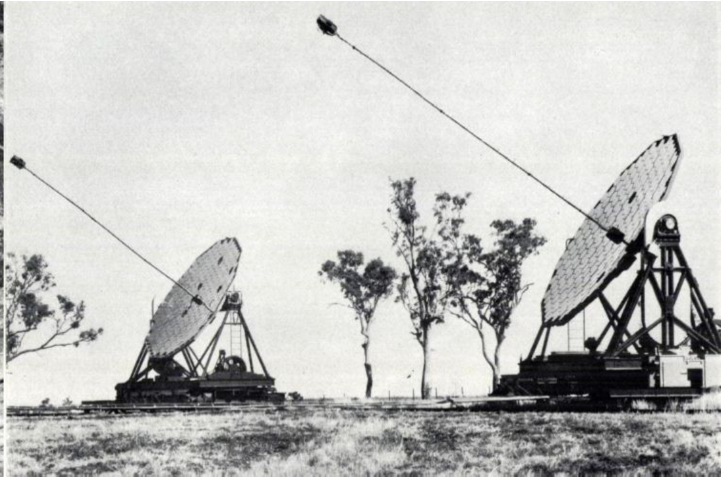


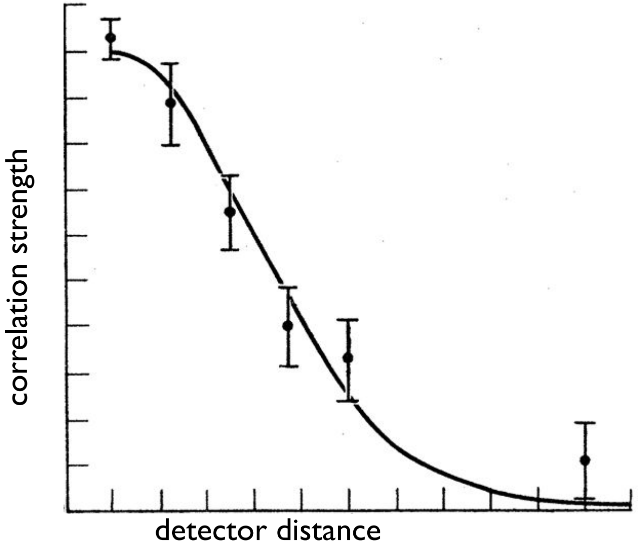
- Photon interferes with itself?
- The two possibilities interfere!

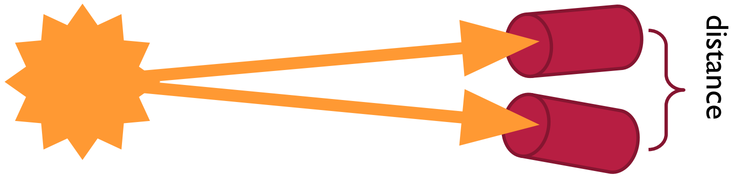
A SURPRISING DISCOVERY: HBT CORRELATIONS

- Radio astronomy: Jansky, 1933, weird 24h oscillation; stars also emit EM radiation in the radio domain!
- R. **H**. **B**rown: investigated radio waves from stars
  - Jordell Bank (optical and radio telescopes), tabletop experiment (optics), Narrabri (stellar interferometer)
- R. Q. **T**wiss helped to understand results mathematically
- Weird correlation in all experiments: joint intensity ”too frequent”, interference?
- „Interference between two different photons never occurs”
  P. A. M. Dirac, Quantum Mechanics (Oxford UP, London, 1958)







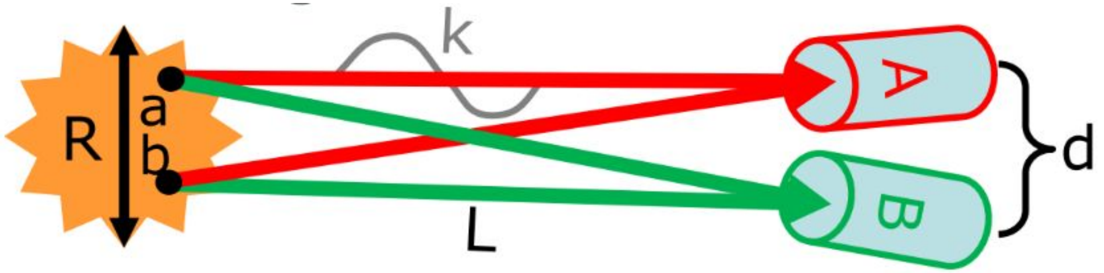


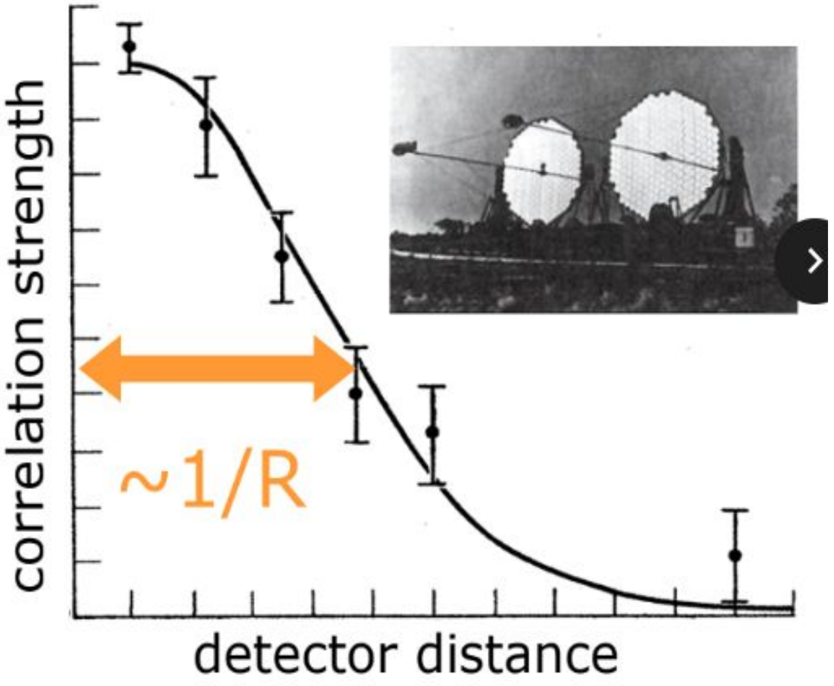
A classical description of the HBT effect

- Detector A: average intensity $< I_A >$ from sources a and b
- Detector B: intensity $< I_B >$
- Depending on source size, many geometries possible
- Average joint intensity: $< I_A I_B >$
- Very simple treatment, but works approximately
- Brown's measurement : $C(\Delta) = \frac{<I_A I_B>}{<I_A><I_B>} = 1 + \frac{1}{2} cos(\Delta)$

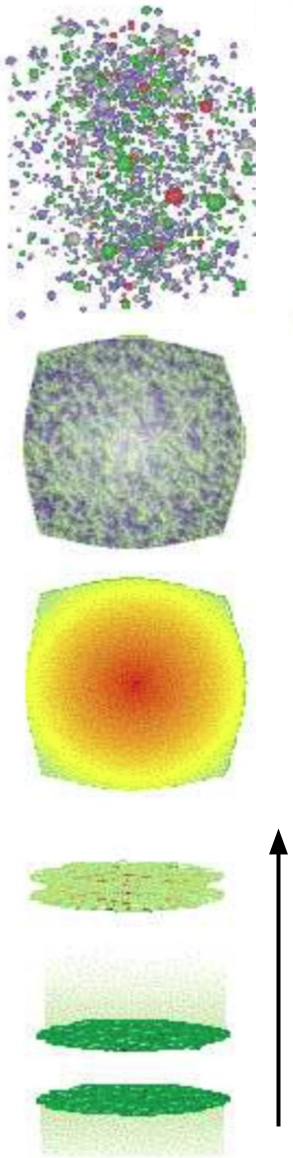
$\Delta = \frac{kRd}{L}, if\, d << R << L,$ measures : $\frac{C(\Delta)-1}{C(0)-1} = cos(\Delta)$

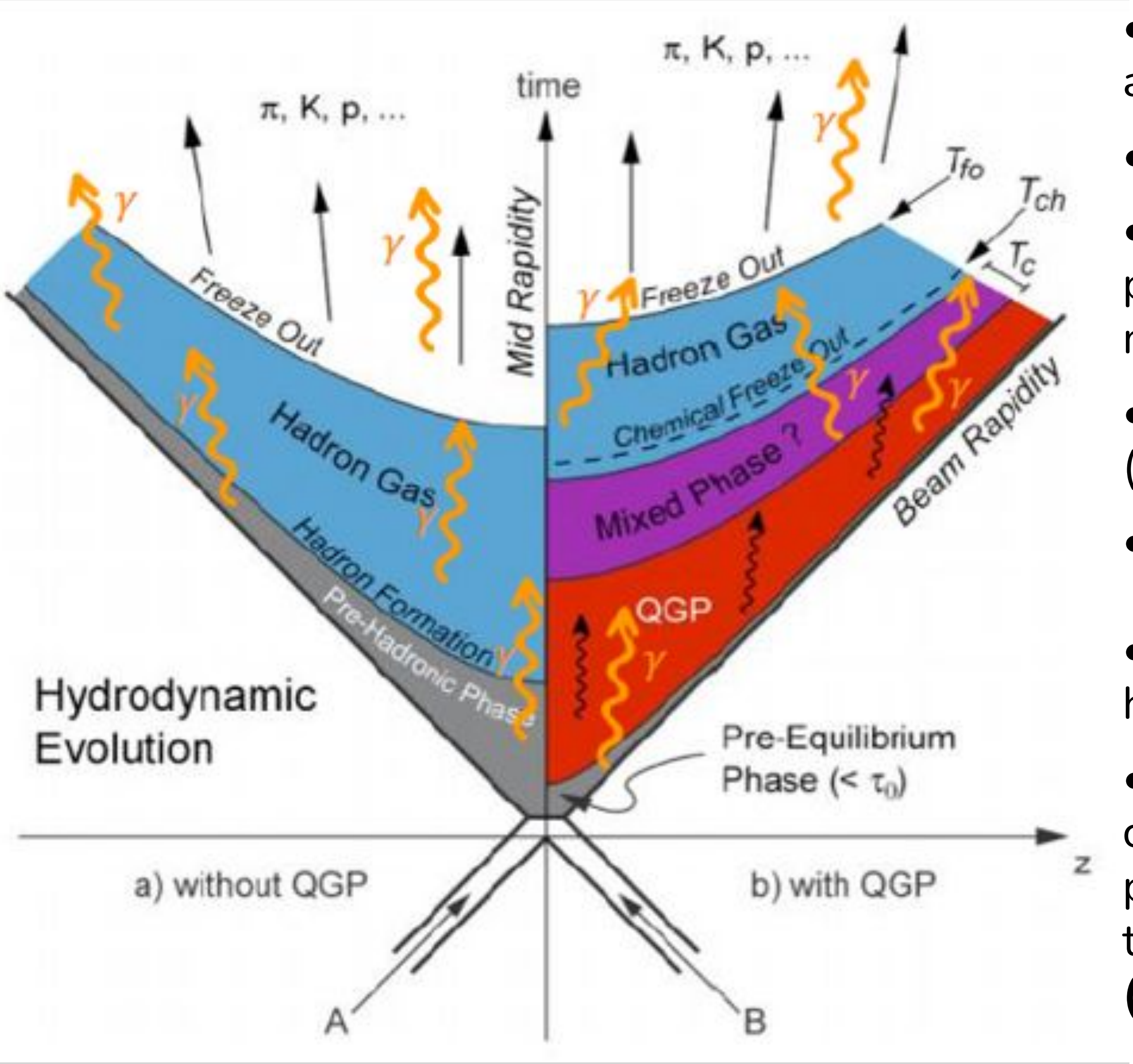
- Size of pointlike source (star) measurable : 30 nano radians (Sirius)
- Nanoscope (in radians) here comes first measurement





Evolution of matter in HI collisions



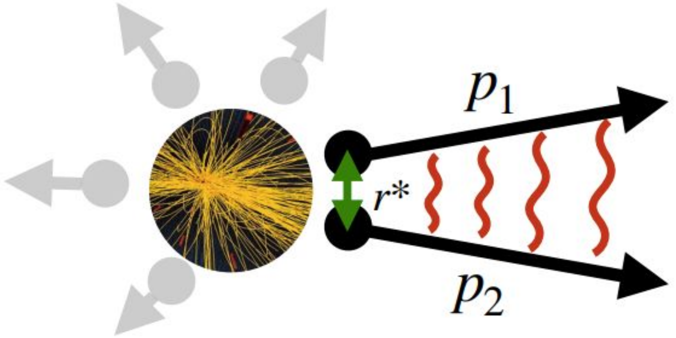


- ”Little bangs” in huge particle accelerators
- Deconfined matter created
- One of the main goals of high energy physics: investigate and understand this matter
- Matter freezes out extremely quickly (~10 fm/c), then free streams
- How to access the spacetime geometry?

- Via HBT correlations of frozen out hadrons!
- measurement of space-time characteristics **R**, **cτ** **~fm** of particle production using particle correlations due to the effects of **QS** and **FSI.**
(short range)

Femtoscopy : two particle correlation

Femtoscopy (originating from HBT):
the method to probe geometric and dynamic properties of the source



Space-time properties ($10^{-15}m$, $10^{-23}s$) can be determined due to two-particle correlations that arise due to:

Quantum Statistics (Fermi-Dirac, Bose-Einstein);

Final State Interactions (Coulomb, strong)

determined | assumed | measured

$$C(k^*, r^*) = \int S(r^*)\,|\Psi(k^*, r^*)|^2 d^3r^* = \frac{Sgnl(k^*)}{Bckg(k^*)}$$

$Sgnl(k^*)$ → Pairs from the same collision

$Bckg(k^*)$ → Pairs from different collisions

$S(r^*)$ - source function

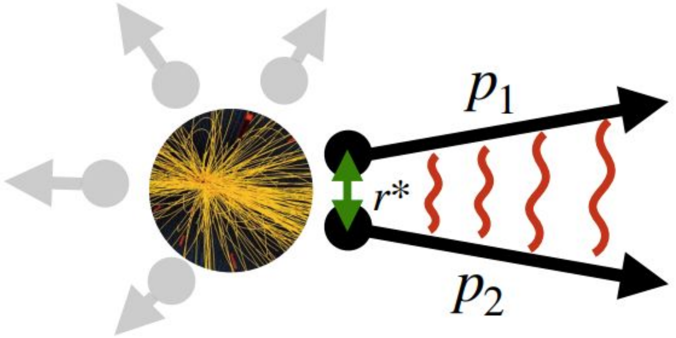
$\Psi(k^*, r^*)$ - two-particle wave function (includes e.g. FSI interactions)

$\frac{Sgnl(k^*)}{Bckg(k^*)}$ - correlation function

q, q_{inv}, k^* →pair-momentum component (depending of the reference frame)

Femtoscopy : two particle correlation

If we assume we know the emission/source function, measured correlation function used to determine parameters of Final State Interactions



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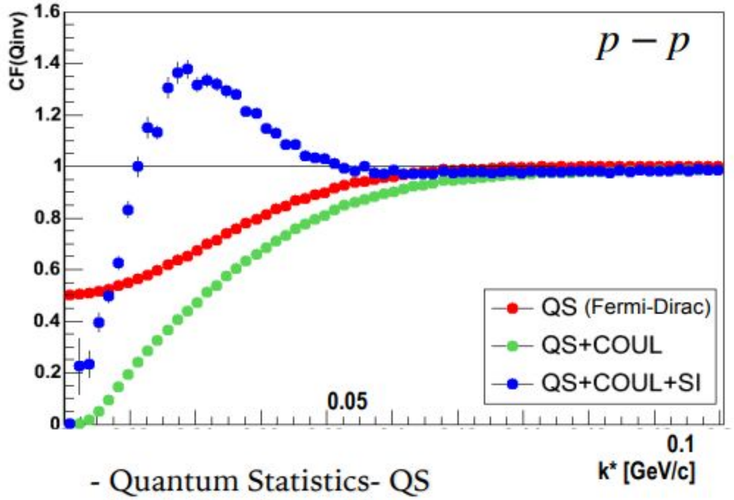
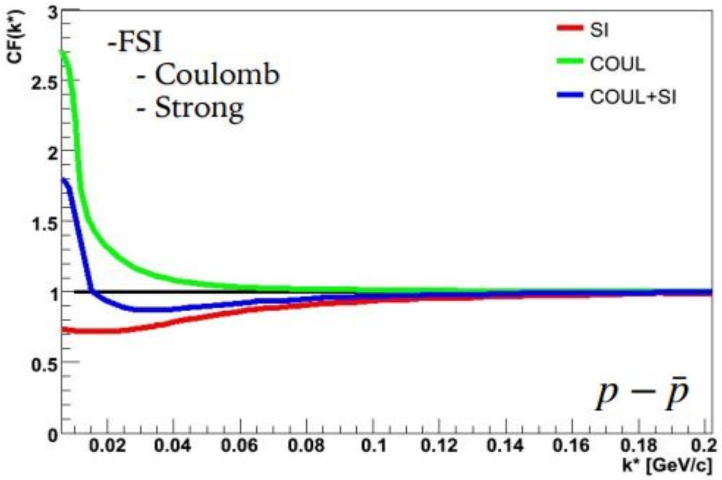
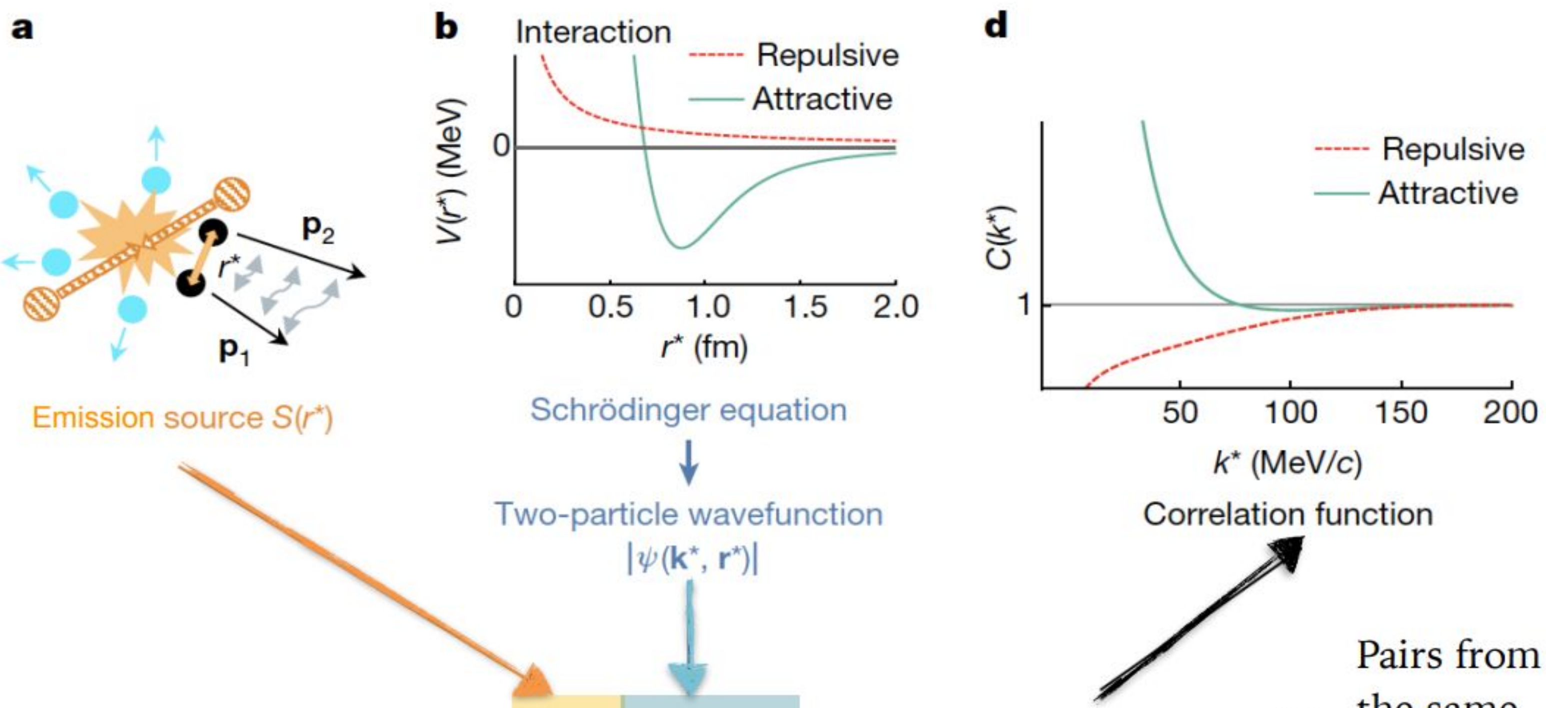
Femtoscopy : two particle correlation



- Quantum Statistics- QS
- Final State Interactions
    - Coulomb
    - Strong





c

$$C(k^*, r^*) = \int S(r^*)\,|\Psi(k^*, r^*)|^2 d^3r^* = \frac{Sgnl(k^*)}{Bckg(k^*)}$$

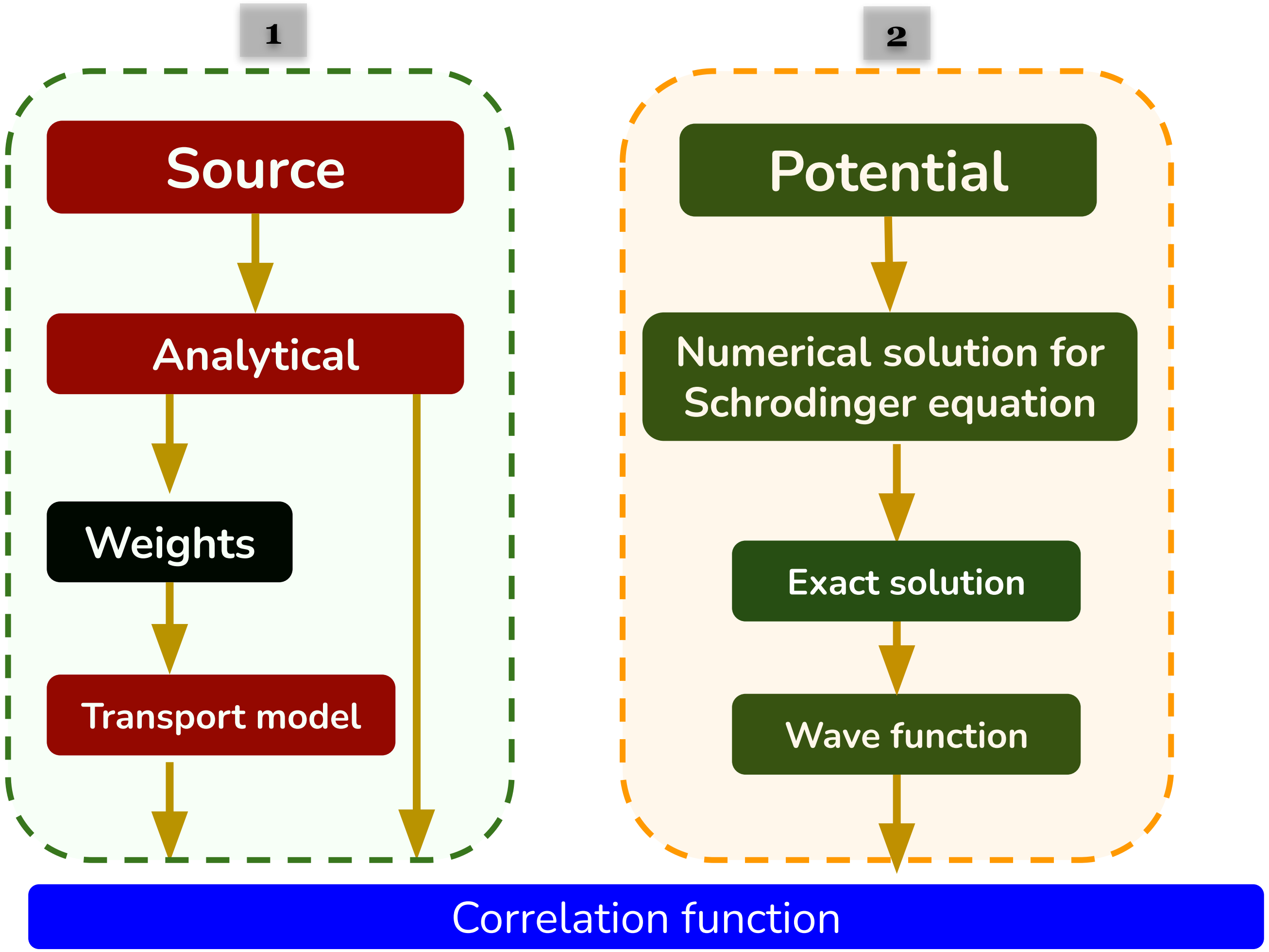
Pairs from the same collision

Pairs from different collisions

Object of study of Traditional femtoscopy

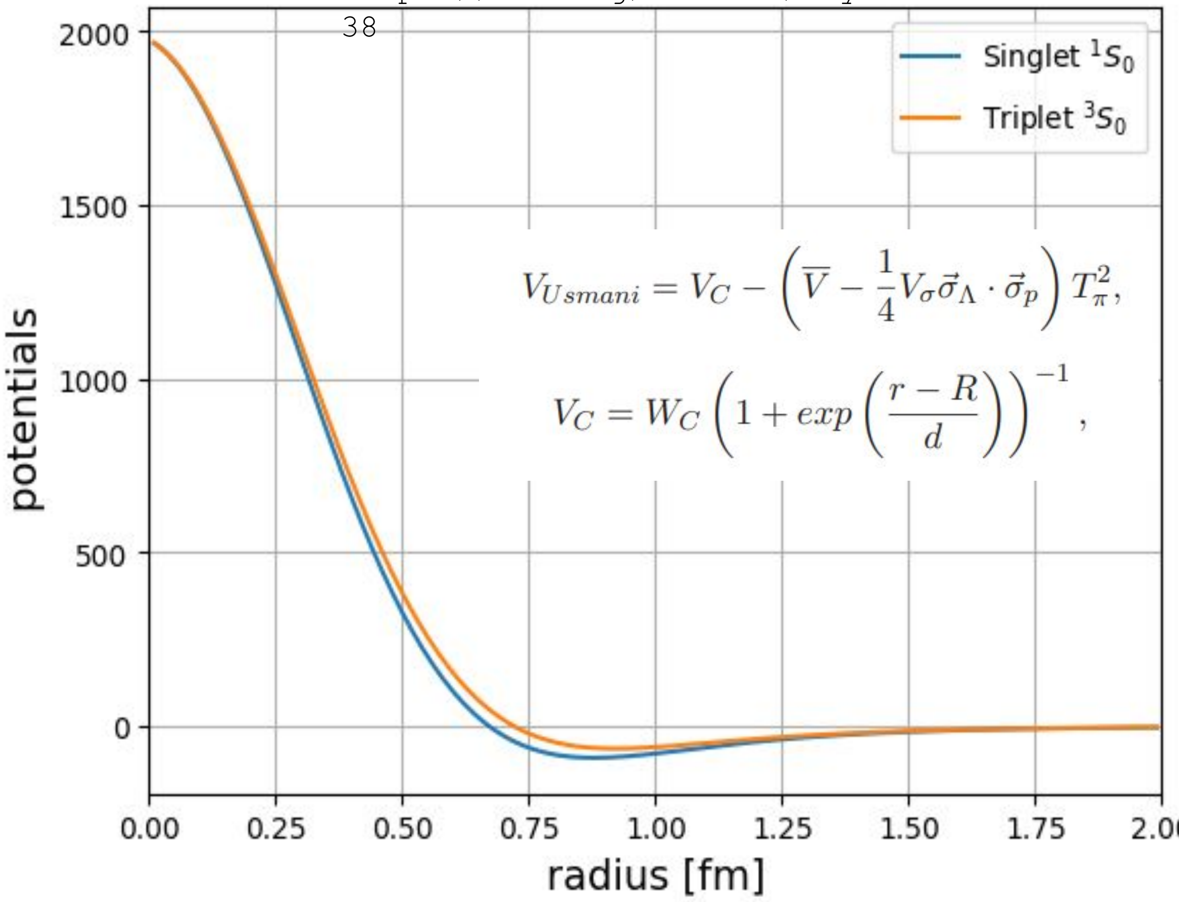
Object of study of non-traditional femtoscopy

How correlations are obtain?



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

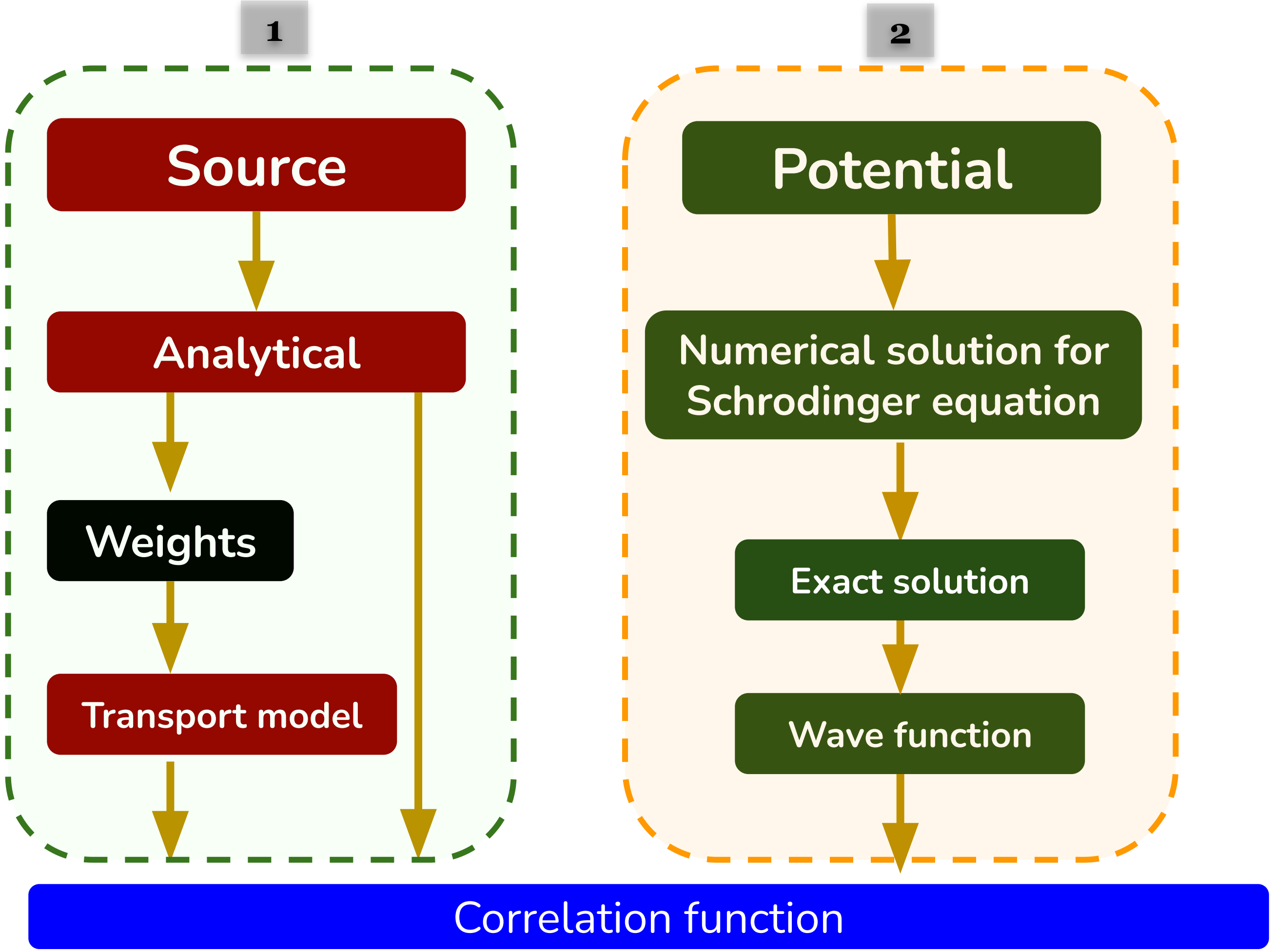
https://doi.org/10.1103/PhysRevLett.83.3138



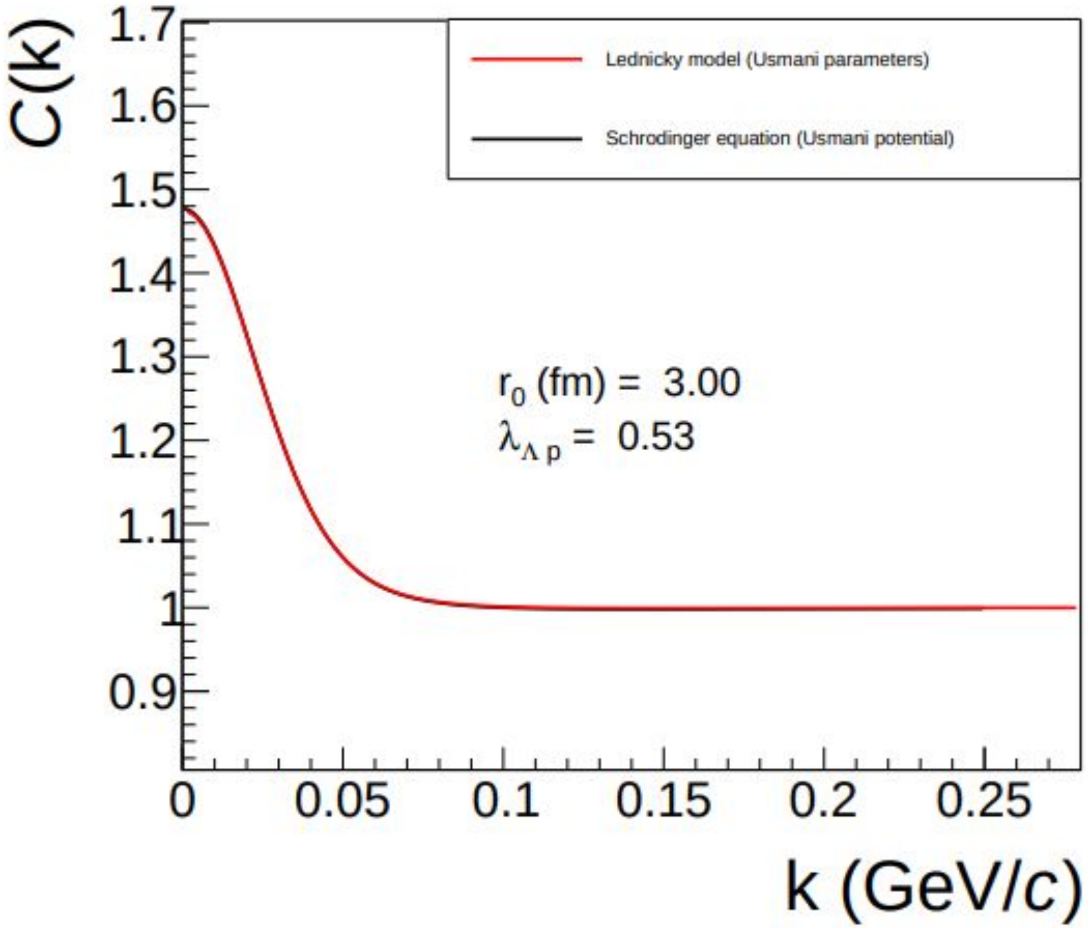
$$V_{Usmani} = V_C - \left(\overline{V} - \frac{1}{4}V_\sigma \vec{\sigma}_\Lambda \cdot \vec{\sigma}_p\right) T_\pi^2,$$

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

How correlations are obtain?



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

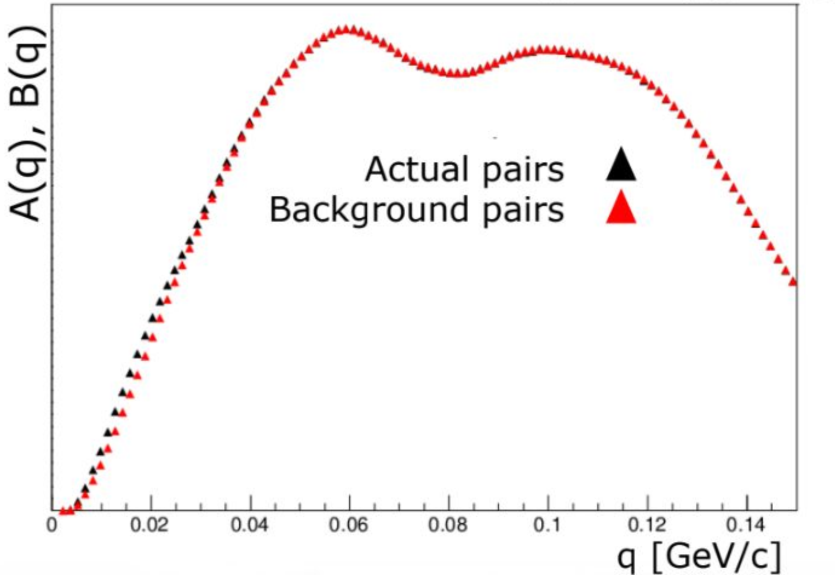


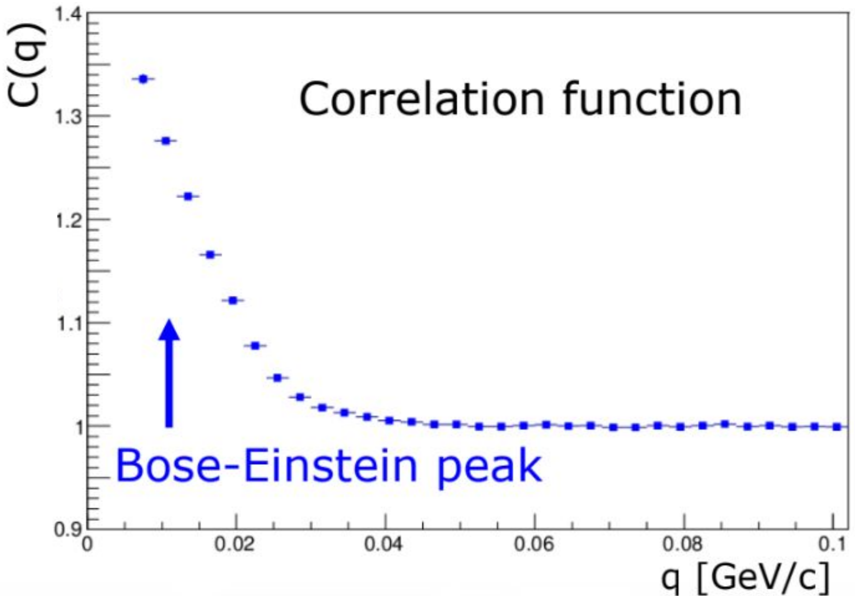
https://www.das.ktas.ph.tum.de/DasDocs/Public/PhD_Theses/arnold-oliver_thesis.pdf

Please follow Robert Oliver Phd thesis (HADES : GSI)

How to measure correlation function : Exp ?

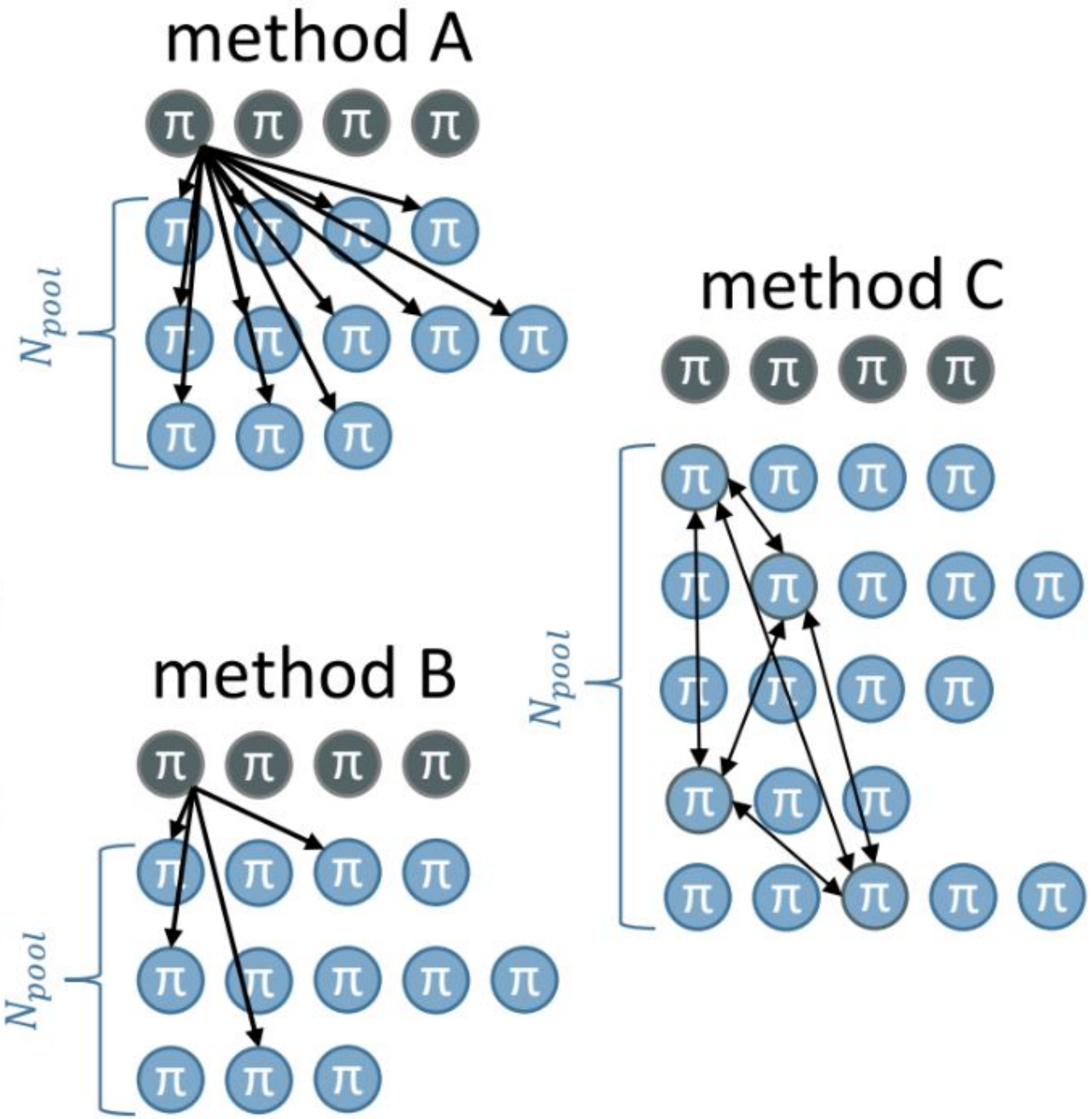
- Momentum distribution of pairs: many effects
- Detector acceptance and efficiency
- Kinematics (momentum distributions)
- Event mixing, distribution of actual & background pairs: A q , B(q)
- Background via pairs from different events: no quantum statistics
- Correlation: ratio C q = A(q)/B(q)





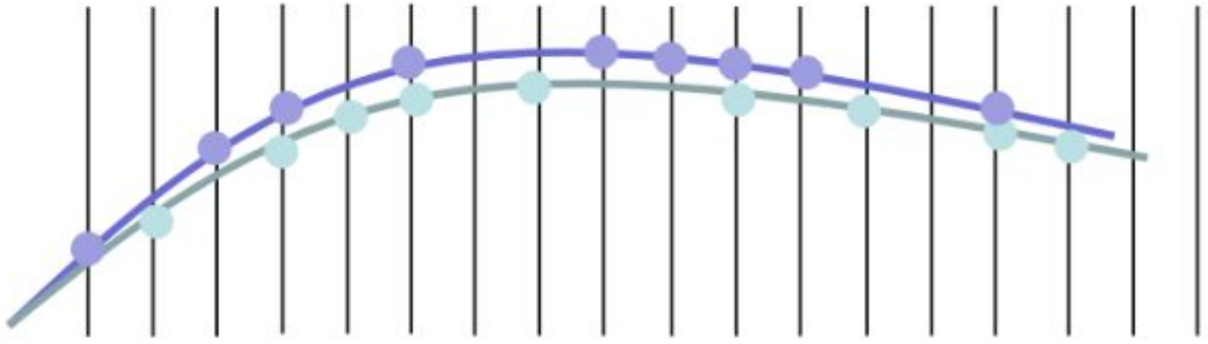
Experimental technique : mixed events

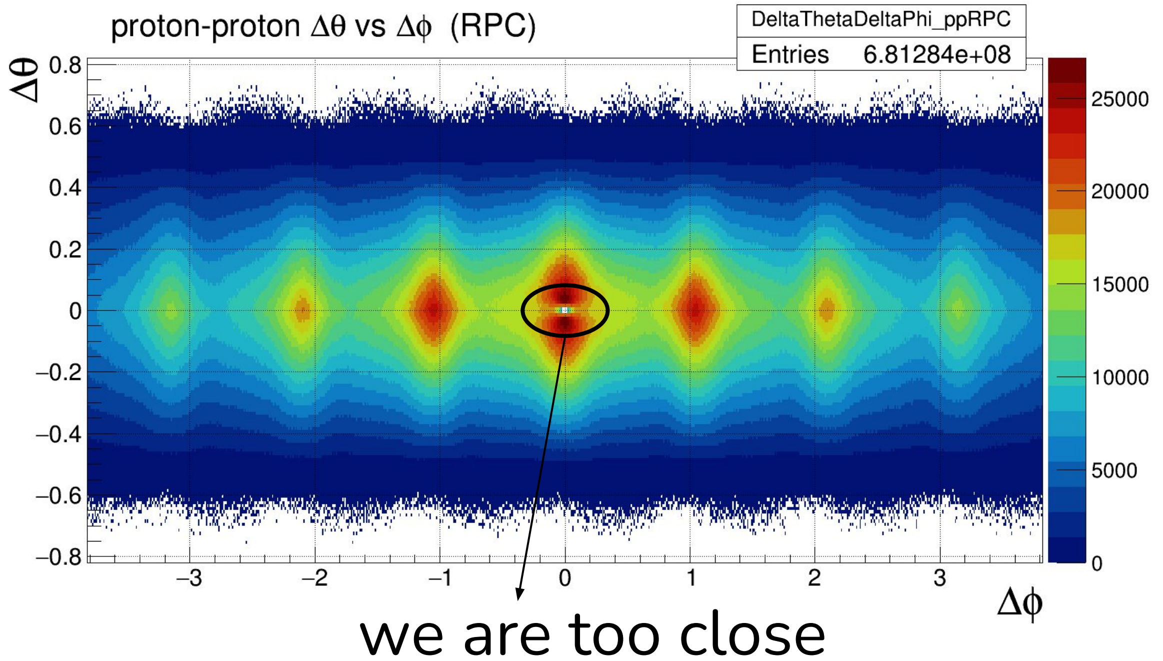
- Basic idea: take N_{pool} separate (but similar) events (i.e., in centrality or vertex location)
- Take an event with N pions
- **Method A**: pair all pions of the pool to all actual pions
- **Method B**: pair all actual pions to a random selection of N background pions
- **Method C**: create a randomly selected mixed event, pair internally
- Other possibilities exist...

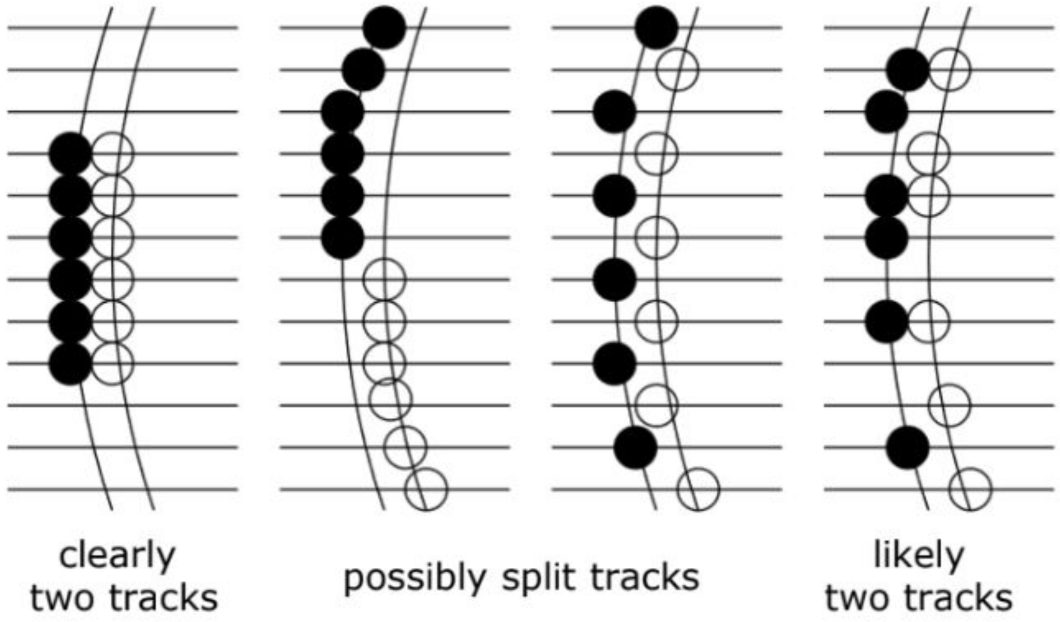


Experimental challenges : merging/splitting

- **Tracking**: detector hits used to reconstruct particle tracks
- **Merging**: hits by close particles reconstructed as one track
- **Splitting**: hits by one particle reconstructed as two tracks
- Need to cut this:





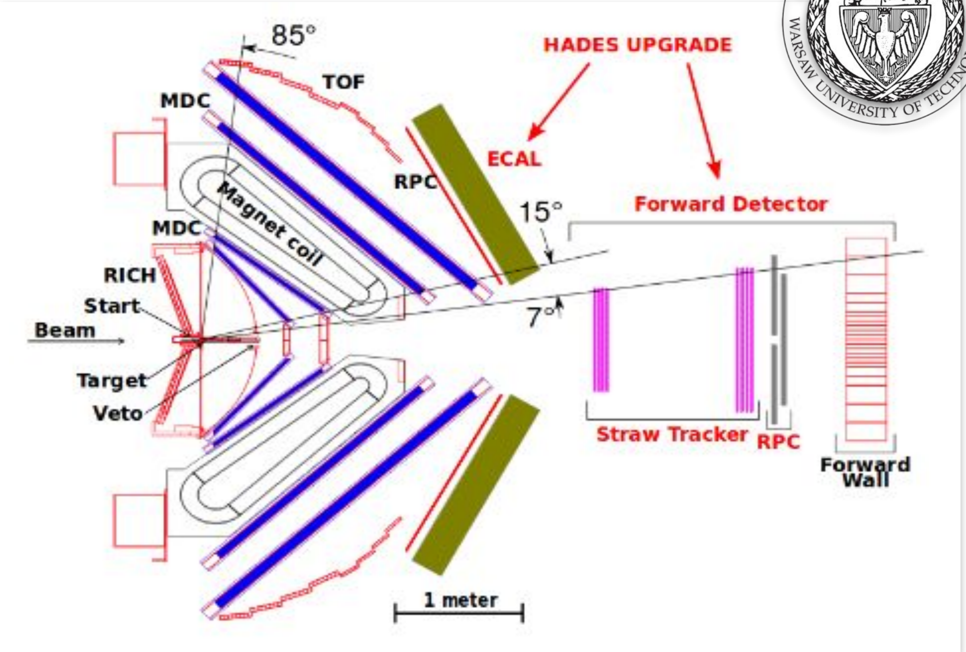


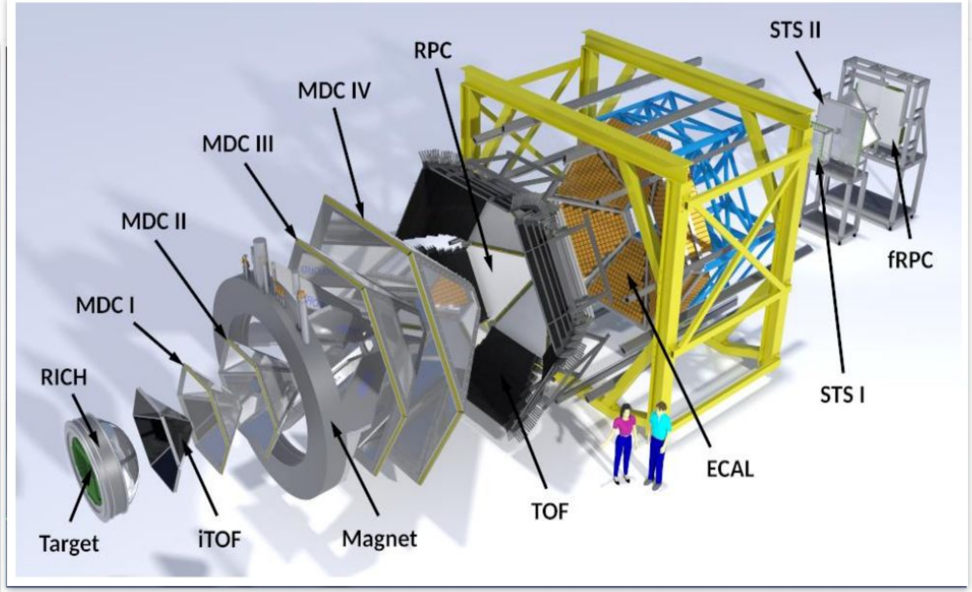
HADES Spectrometer

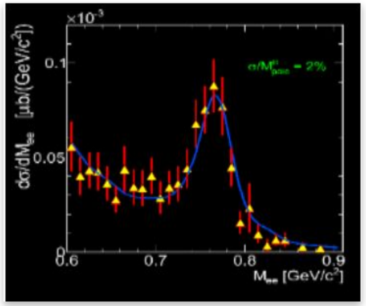
- SIS-18 beams: protons (1-4 GeV), nuclei (1-2 AGeV), pions (0.4-2 GeV/c) – secondary beam
- rare probes:(e^+, e^-), strangeness: $K^{+/-,0}$, Λ, Ξ^-, φ
- $\Delta M/M$ - 2% at ρ / ω
- PID : π/p/K – dE/dx (MDC) and TOF : σ_{tof} ~80 ps (RPC)
- electrons : RICH (hadron blind)
- neutral particles: ECAL

Geometry :

- full azimuthal, polar angles 18º - 85º



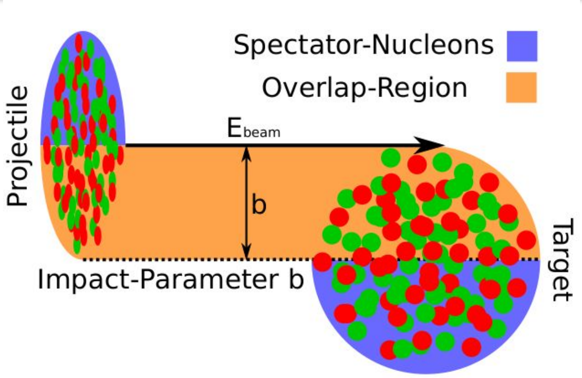


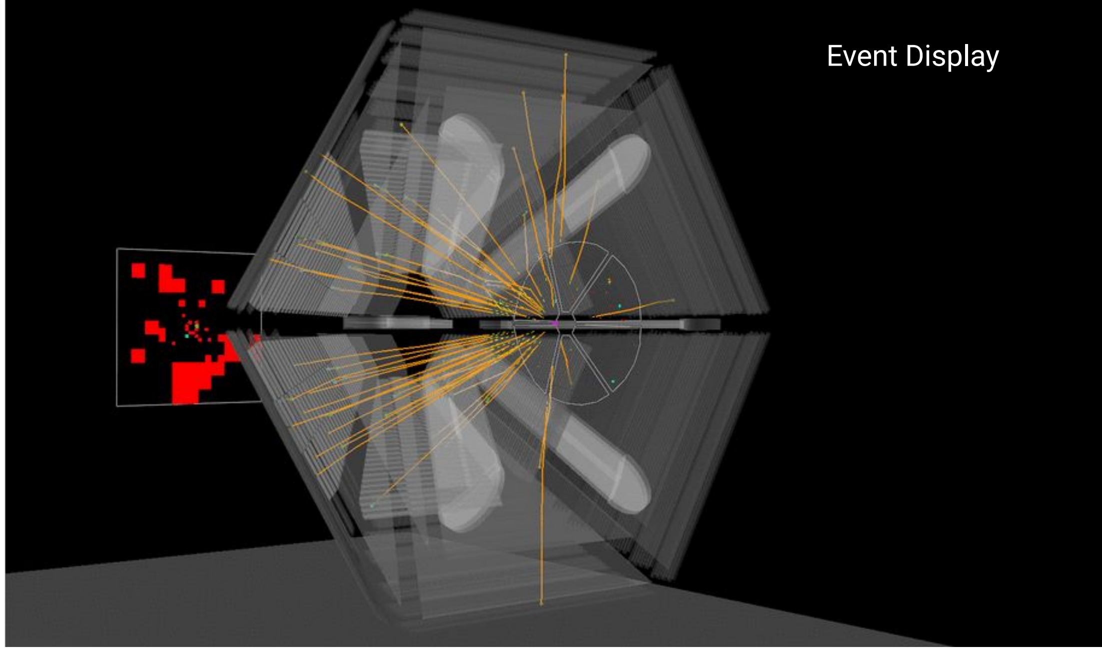


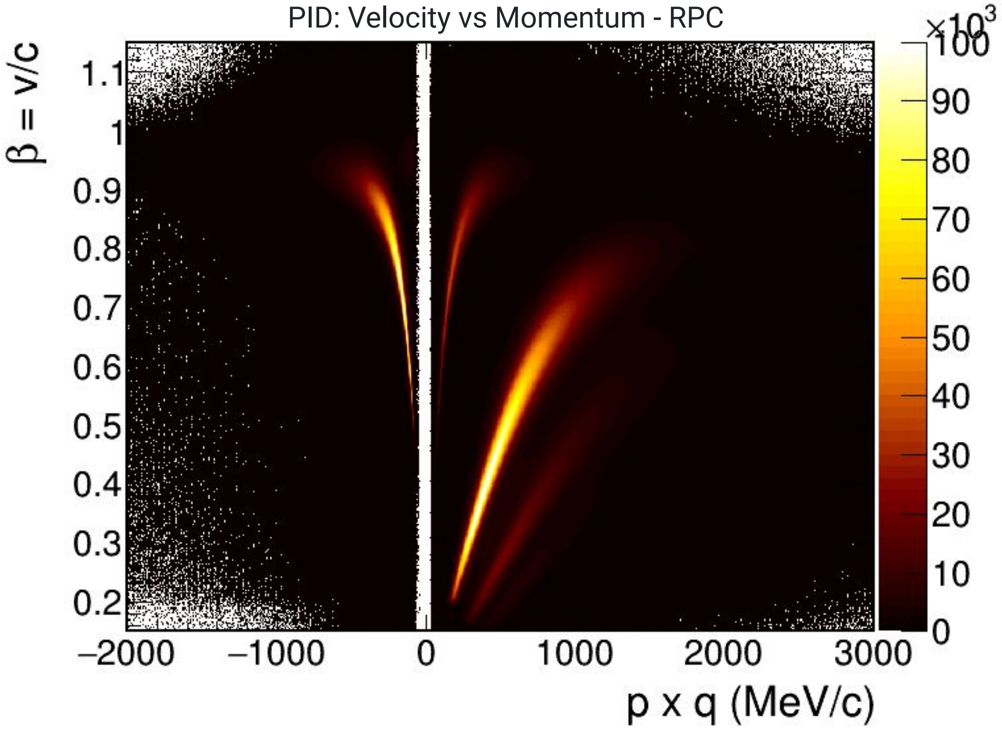
HADES Ag-Ag collision

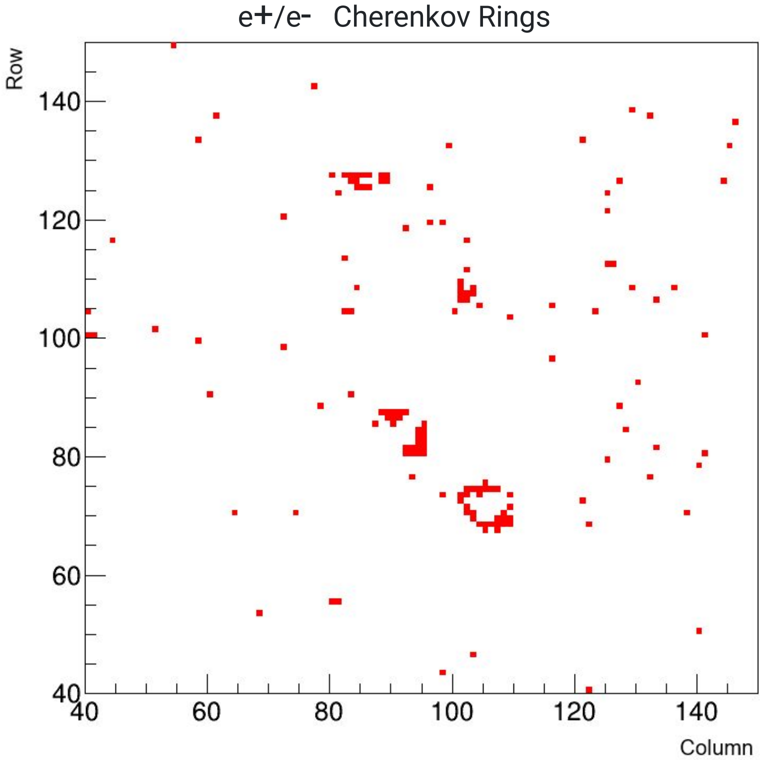
Ag-Ag @ 1.58 A GeV
(march-19 data)

Duration : 430.9 h
Events recorded : 13.64 × 10 [9]
Mean event rate : 8.8 kHz
Data recorded : 333.6 TB

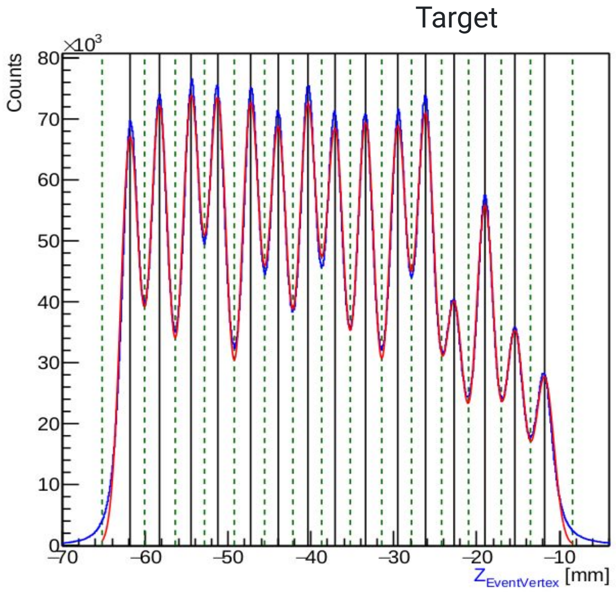








The 15 target segments are determined by a 15-fold Gaussian fit function with a common standard deviation (σ).

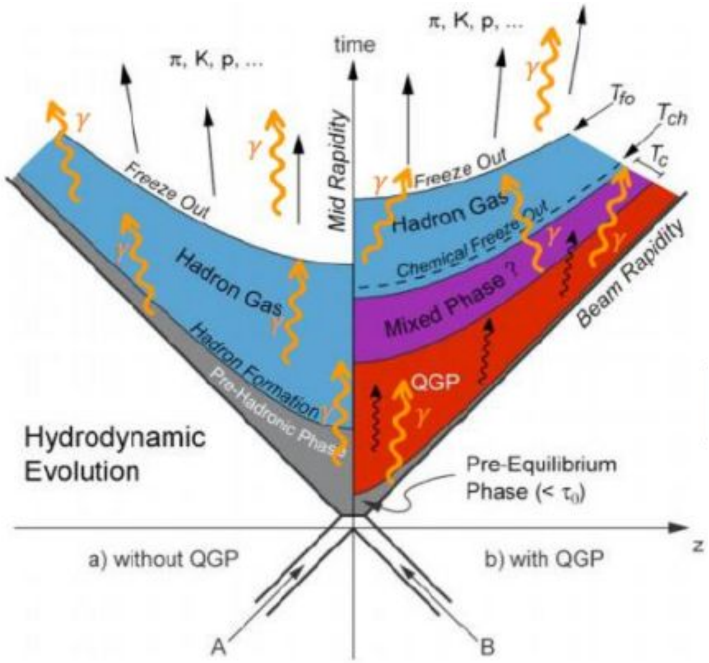


photon-photon femtoscopy

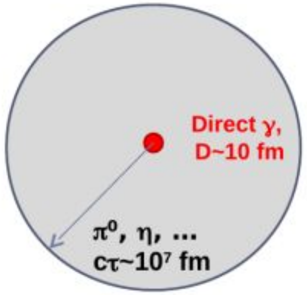
for more detail contact :
mateusz.grunwald.dokt@pw.edu.pl

Measure source properties at early stages -> inaccessible for hadrons

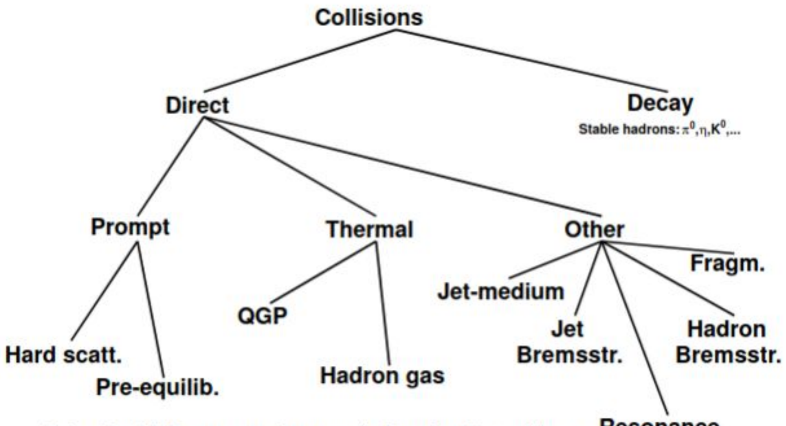
- Estimate direct photon yield via femtoscopy
- Experimentally challenging



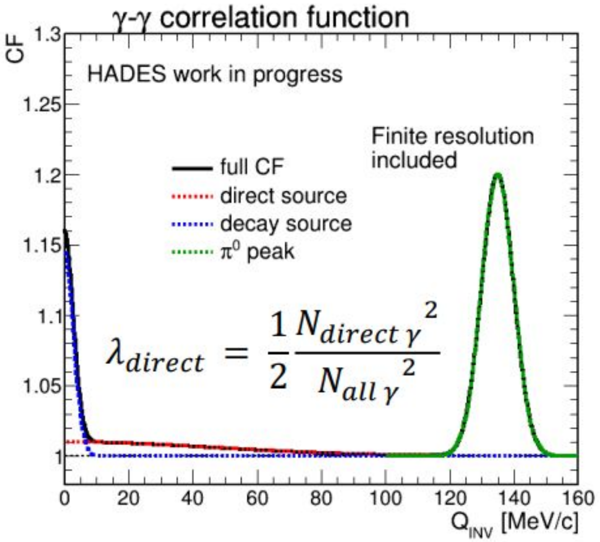
J. Stachel. K. Reygers, QGP physics SS2015 6., „Space-time evolution of the QGP"



$$Q_{INV} = m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos(\alpha_{\gamma\gamma}))}$$



Gabor David, Reports on Progress in Physics 83.4, „Direct real photons in relativistic heavy ion collisions"



photon-photon femtoscopy

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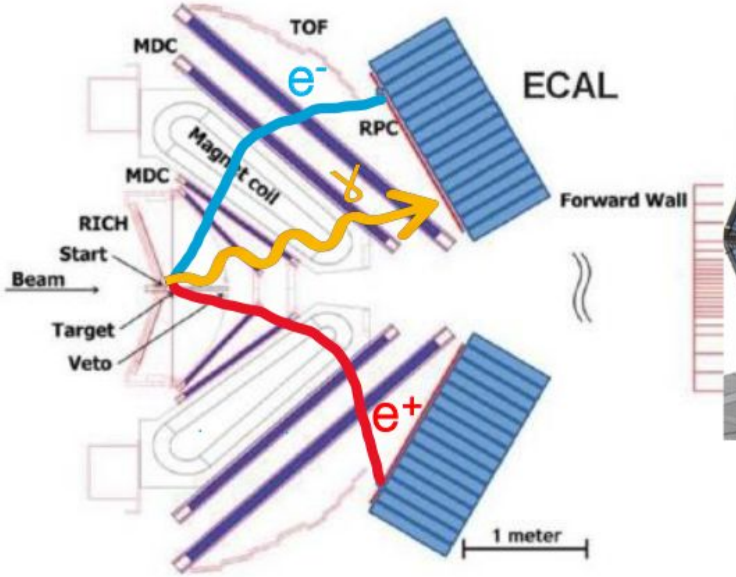
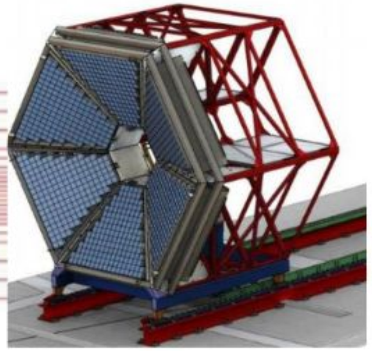
Electromagnetic calorimeters (ECAL)



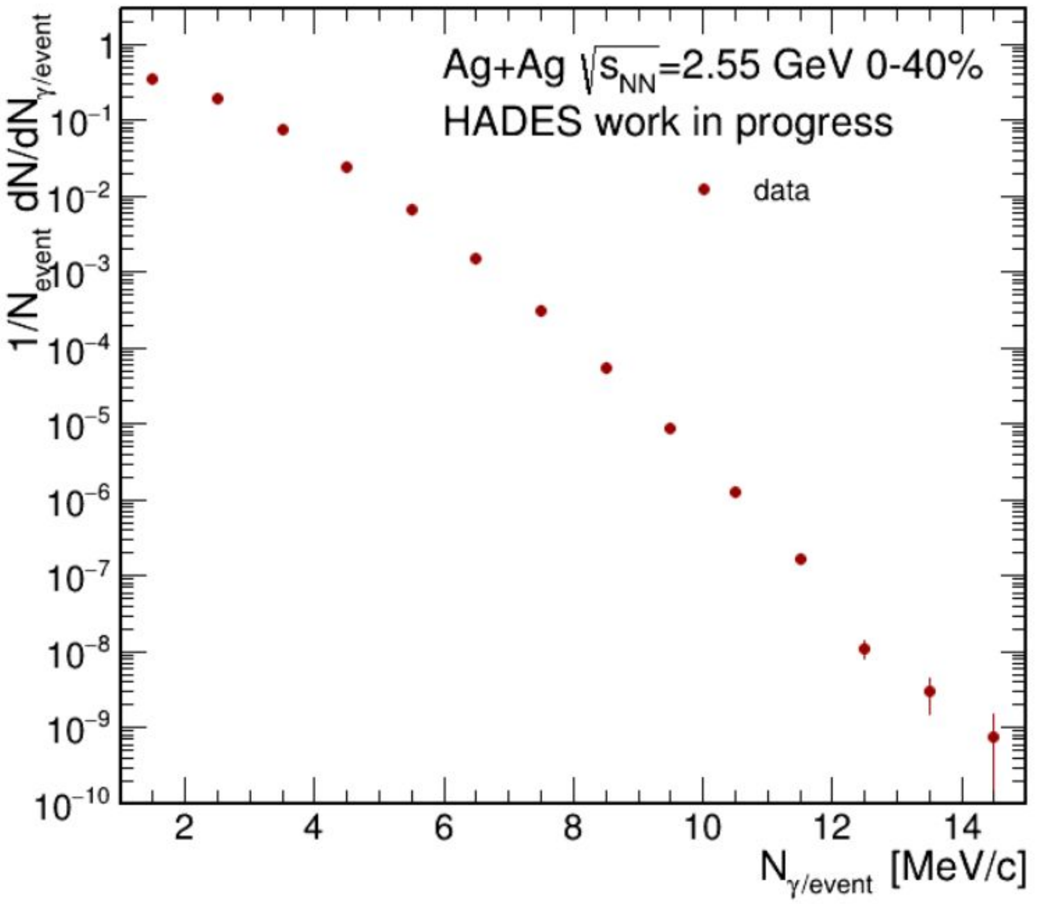


Resolution
(Energy, time, angular):

$$\frac{\sigma_E}{E} = \frac{6\%}{\sqrt{E}(GeV)}$$

$$\sigma_t < 300\ ps$$

$$\sigma_{\theta,\phi} = 2°$$



- **Photon definition:**
  - No matching with charged tracks or hits in ToF detectors
  - Energy > 100 MeV
  - β within 2σ from expected photon peak (β=1), adjusted for each module (and time of beamtime)

photon-photon femtoscopy

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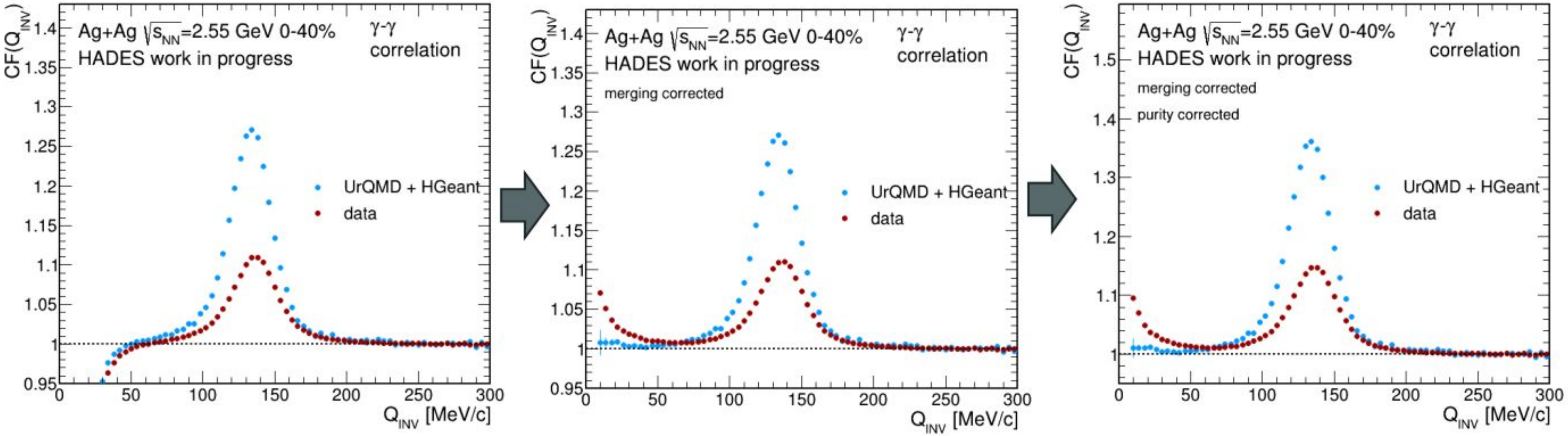
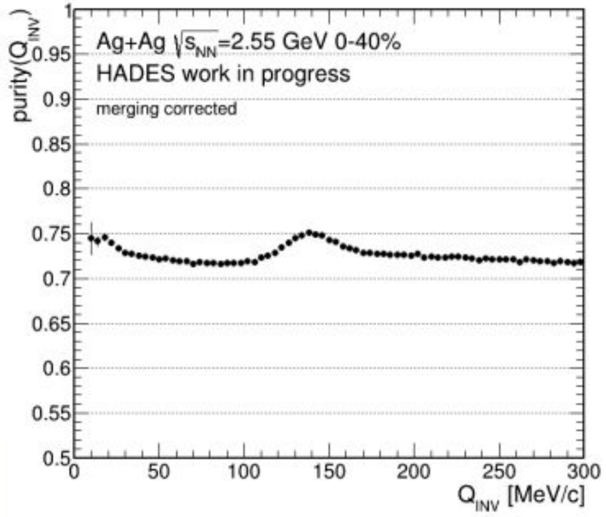


$$purity_{sim}(Q_{INV}) = \frac{N_{\gamma\gamma\ pair}(Q_{INV})}{N_{any\ pair}(Q_{INV})}$$

$$CF_{pur\ corr}(Q_{INV}) = \frac{CF(Q_{INV}) - 1}{purity\ (Q_{INV})} + 1$$

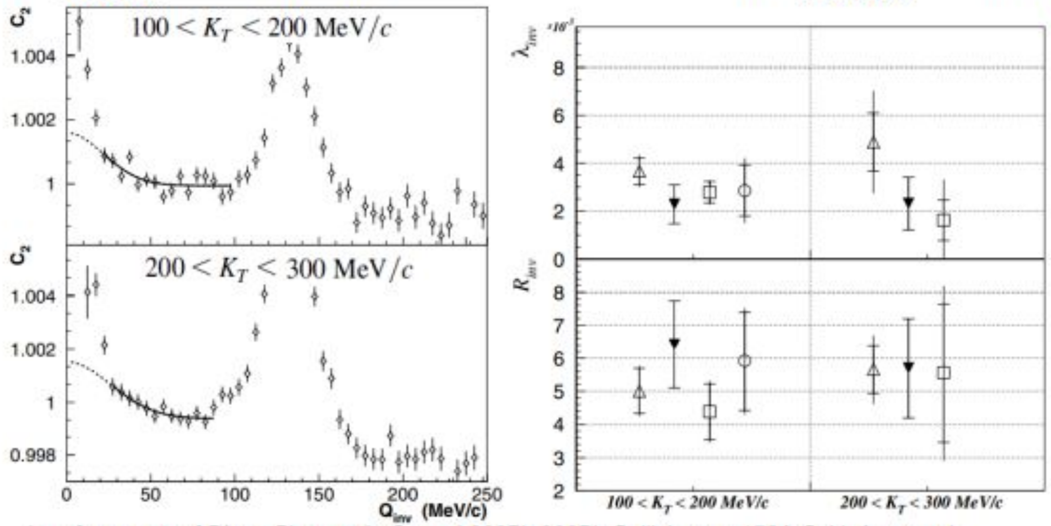
$$Q_{INV} = \sqrt{(\vec{p_1} - \vec{p_2})^2 - (E_1 - E_2)^2}$$



statistical uncertainties only

photon-photon femtoscopy

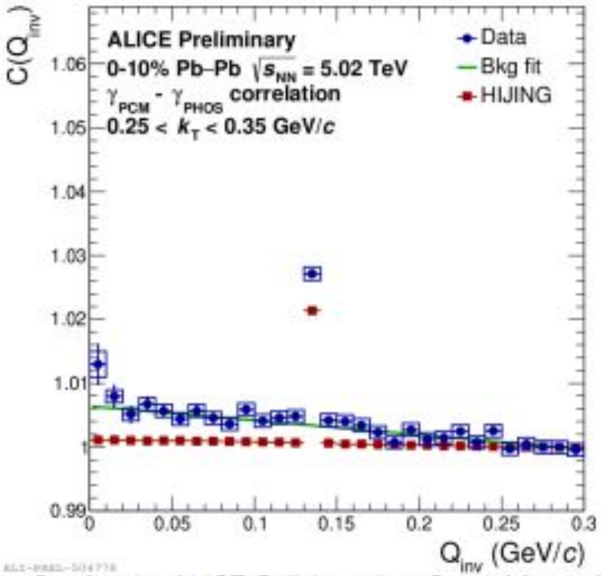
Phenix outcome



Interferometry of Direct Photons in Central 208Pb 208Pb Collisions at 158A GeV, Aggarwal, M. M., Physical Review Letters, 93(2). doi:10.1103/physrevlett.93.022301

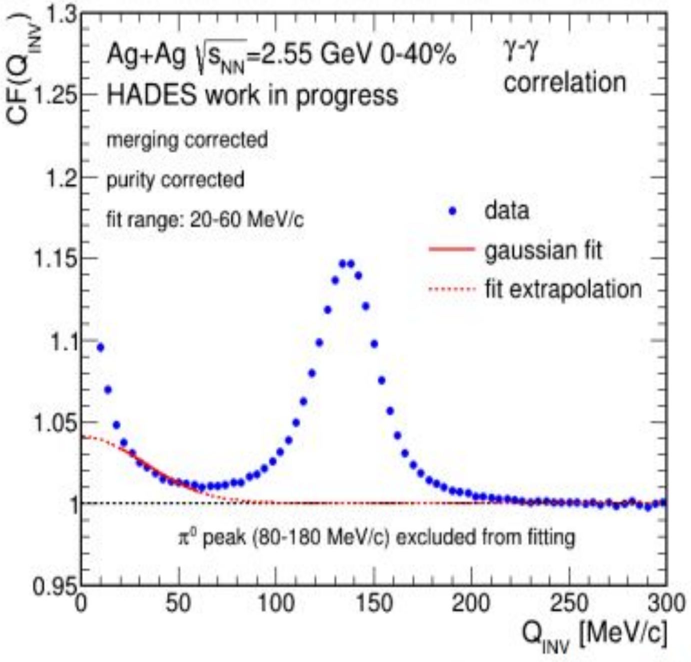
fitting contain only quantum statistics and background

Alice outcome

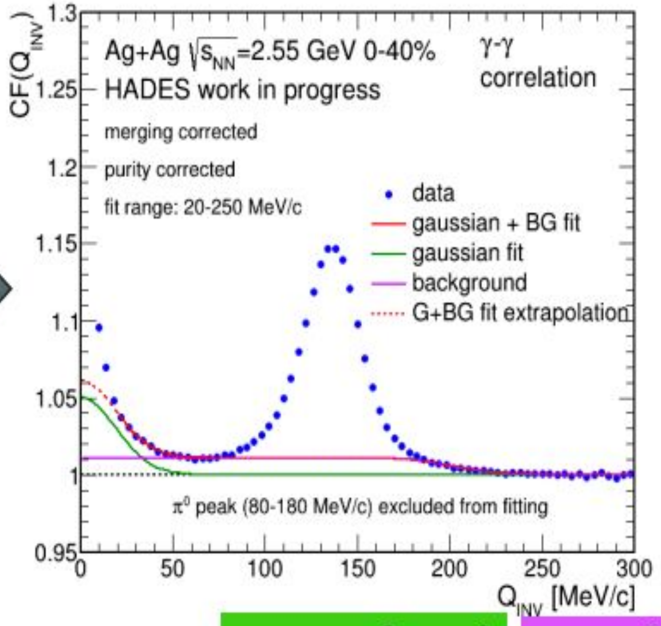


Mike Sas for the ALICE Collaboration, Quark Matter 2022

HADES outcome



$$CF(Q_{INV}) = 1 + \lambda e^{(-Q_{INV}{}^2 \cdot R_{INV}{}^2)}$$



$$CF(Q_{INV}) = 1 + \lambda e^{(-Q_{INV}{}^2 \cdot R_{INV}{}^2)} + \frac{a_0}{1+(a_1 \cdot Q_{INV})^{a_2}}$$

for more detail contact :
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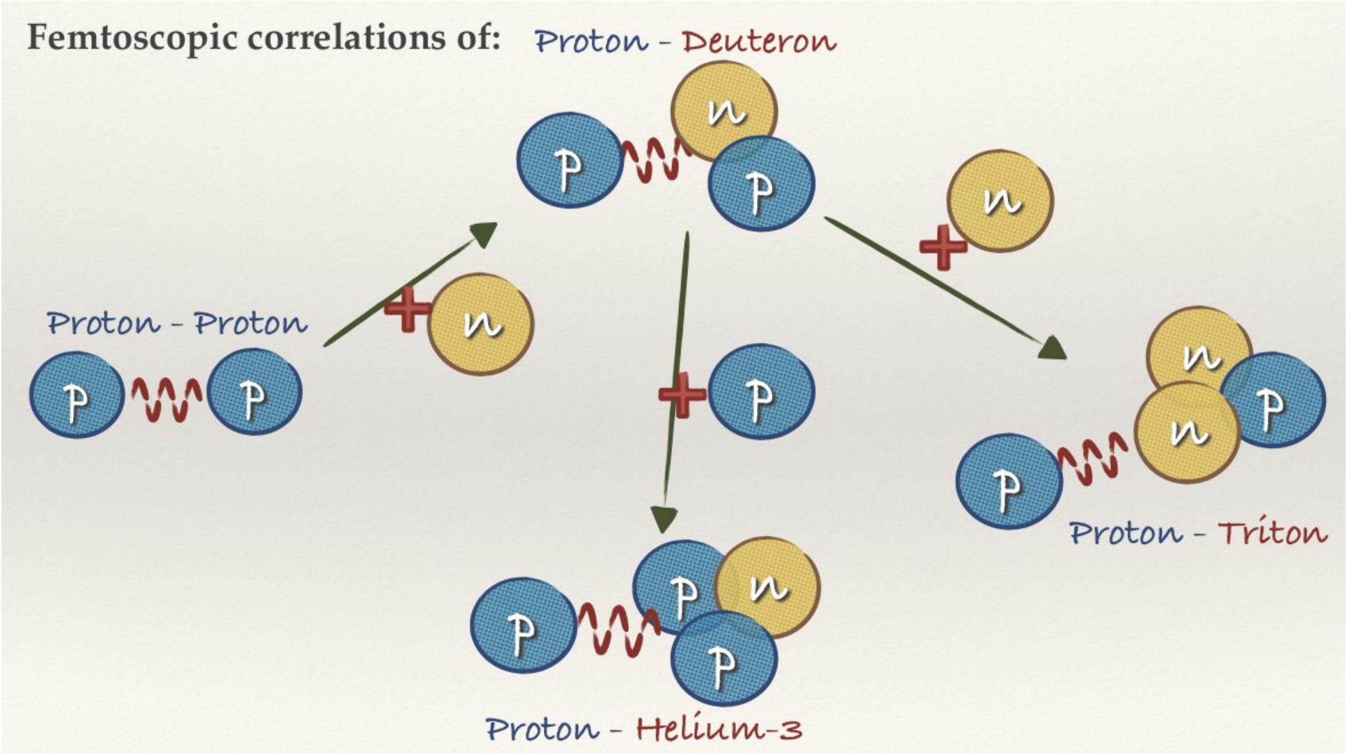
proton-proton and proton cluster femtoscopy

- Studies of excited / bound states
- From two nucleons to many nucleons system, relevant reference for neutron star studies

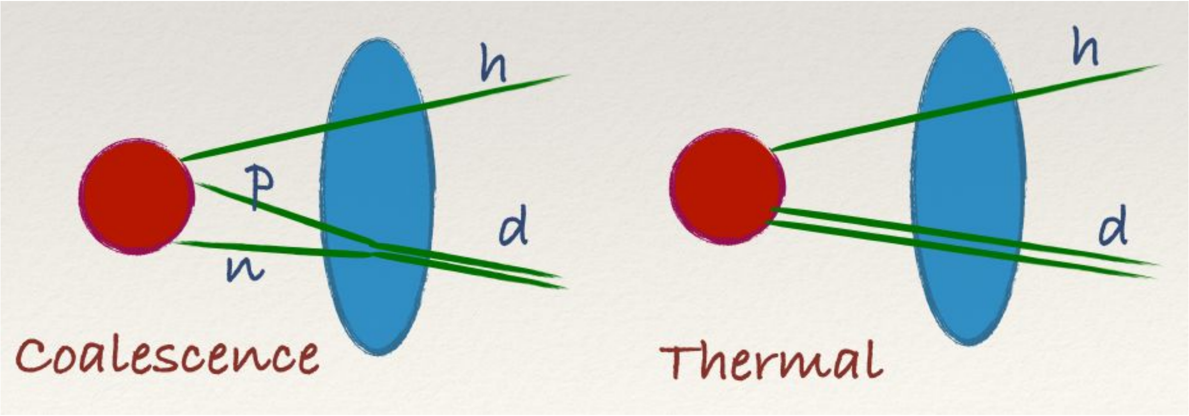
Studies of decaying nuclear state presence,

Some of them impossible to see in traditional "**mass invariant**" distributions

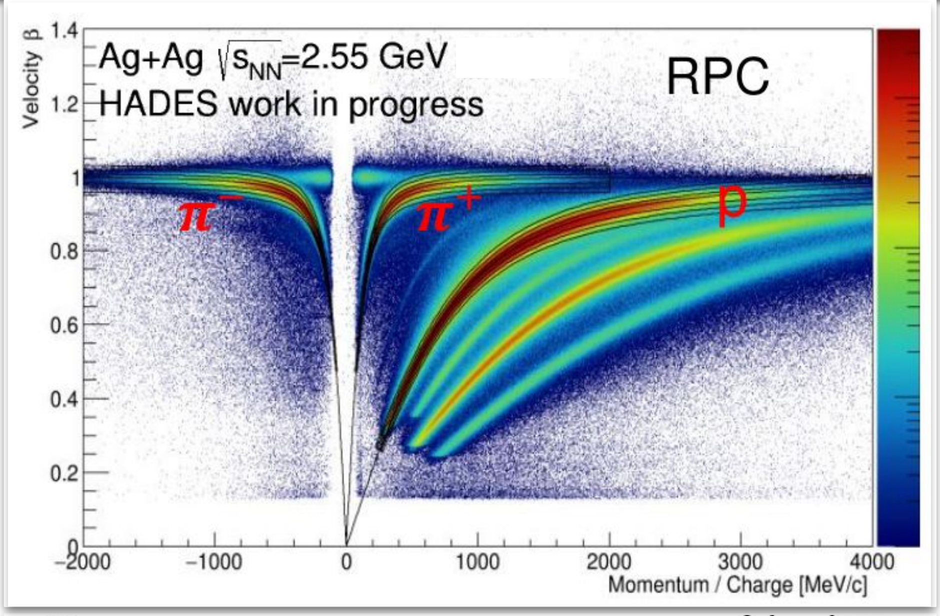


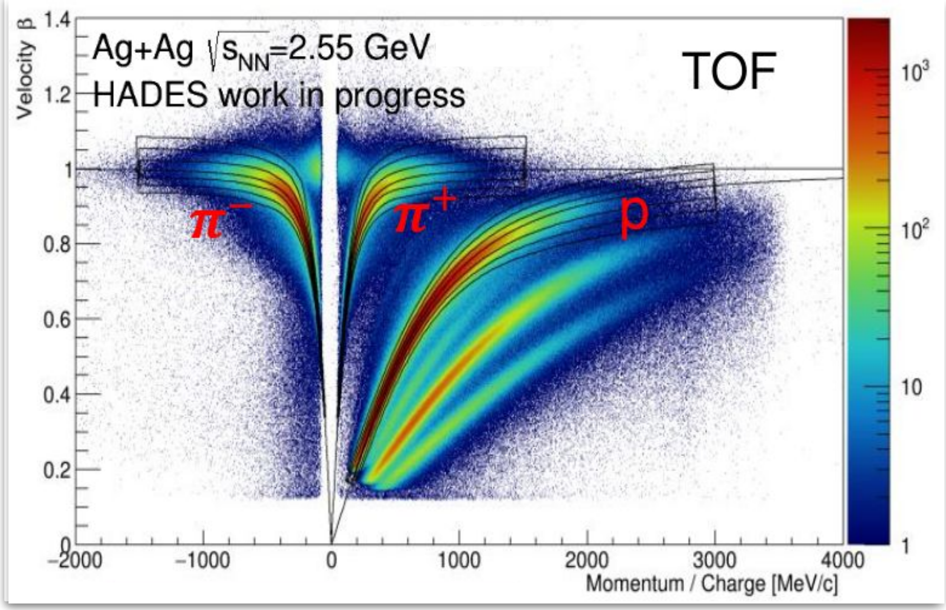
Femtoscopic correlations provide the access to these studies

Possible validation of the production mechanism



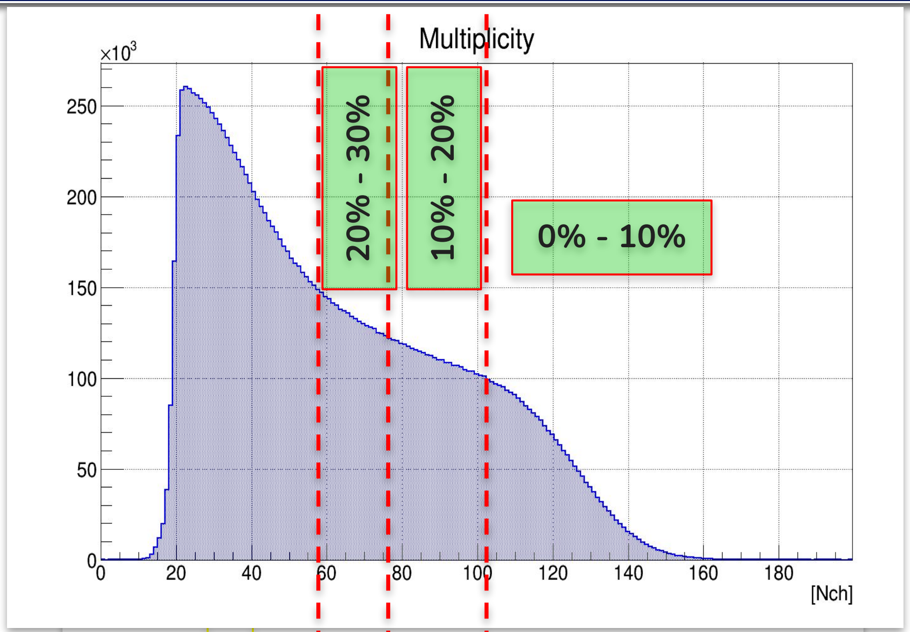
Particle identification

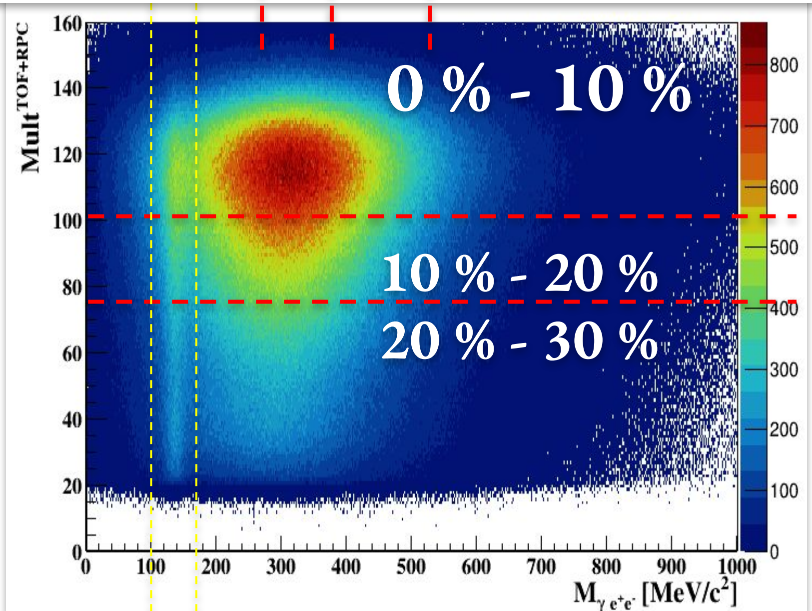




https://doi.org/10.21248/gups.68651

Selected events, Multiplicity



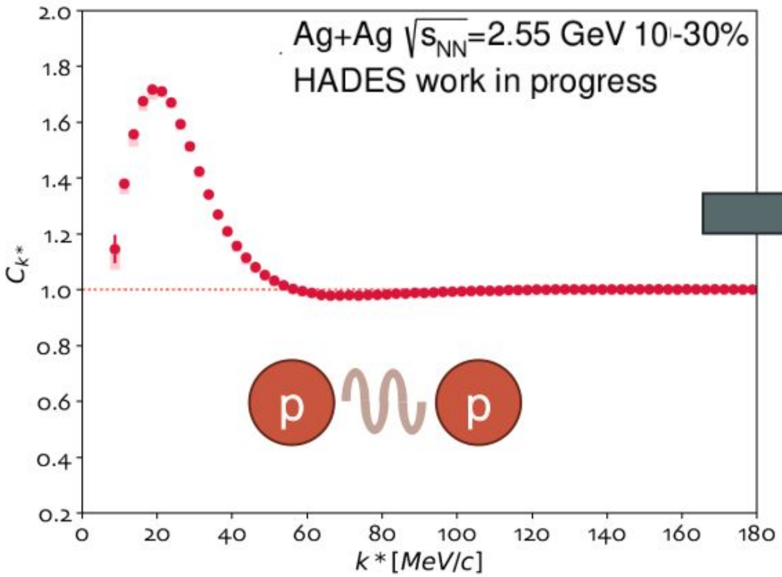


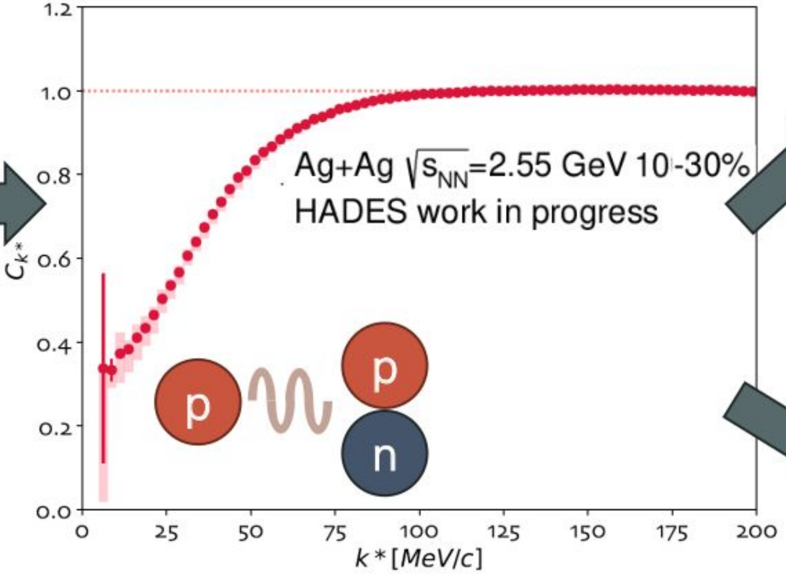
TOF+RPC vs ECal

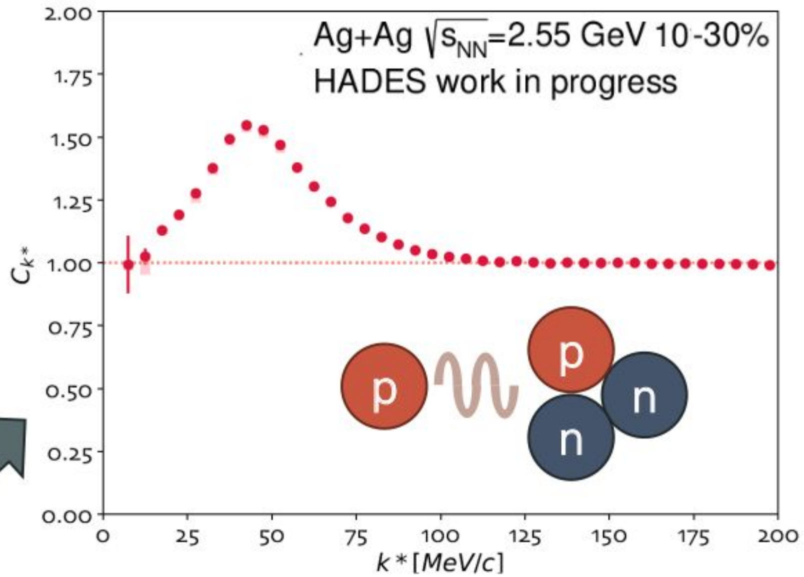
proton-proton and proton cluster femtoscopy

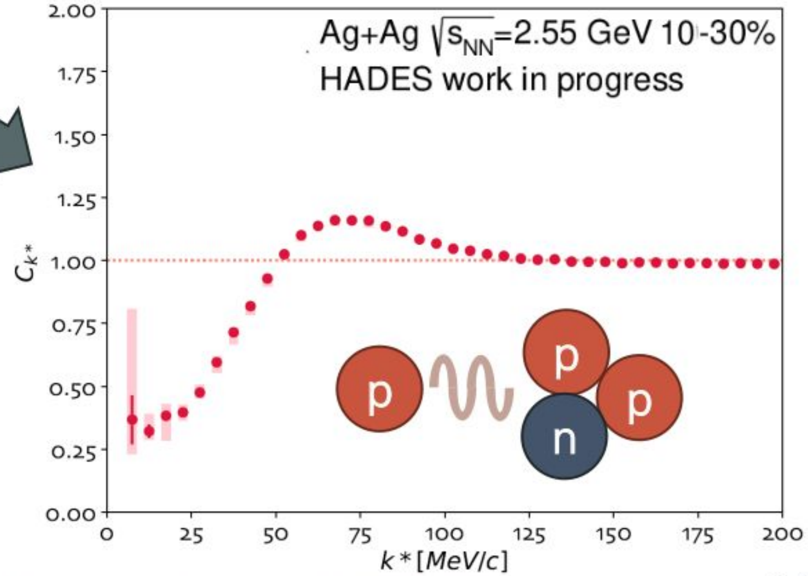
From proton proton (**2 nucleons**) to proton – cluster (**many nucleons**)

k_T: (350,500) MeV/c









Systematic uncertainties:

- Variation of Δθ and Δϕ
- Variation of nσ for PID

for more detail contact : stefaniak.9@osu.edu

proton-proton and proton cluster femtoscopy

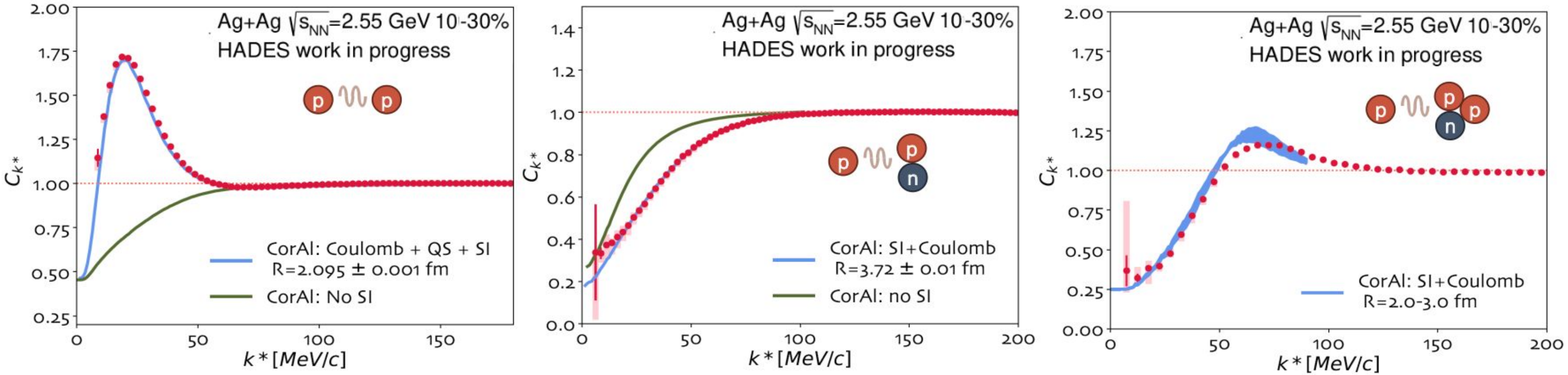
$$CF(k^*) = \int \boldsymbol{S(r^*)} |\Psi(r^*, k^*)|^2 \, dr^*$$

Gaussian source with a given radius

Calculated with potentials:

p+p: V.G.J. Stoks et al., Phys. Rev. C 49, 2950 (1994)
p+d: T.C. Black at al: Phys.Lett.B 471 (1999) 103-107
p+3He: T. V. Daniels at al. PRC 82, 034002 (2010)

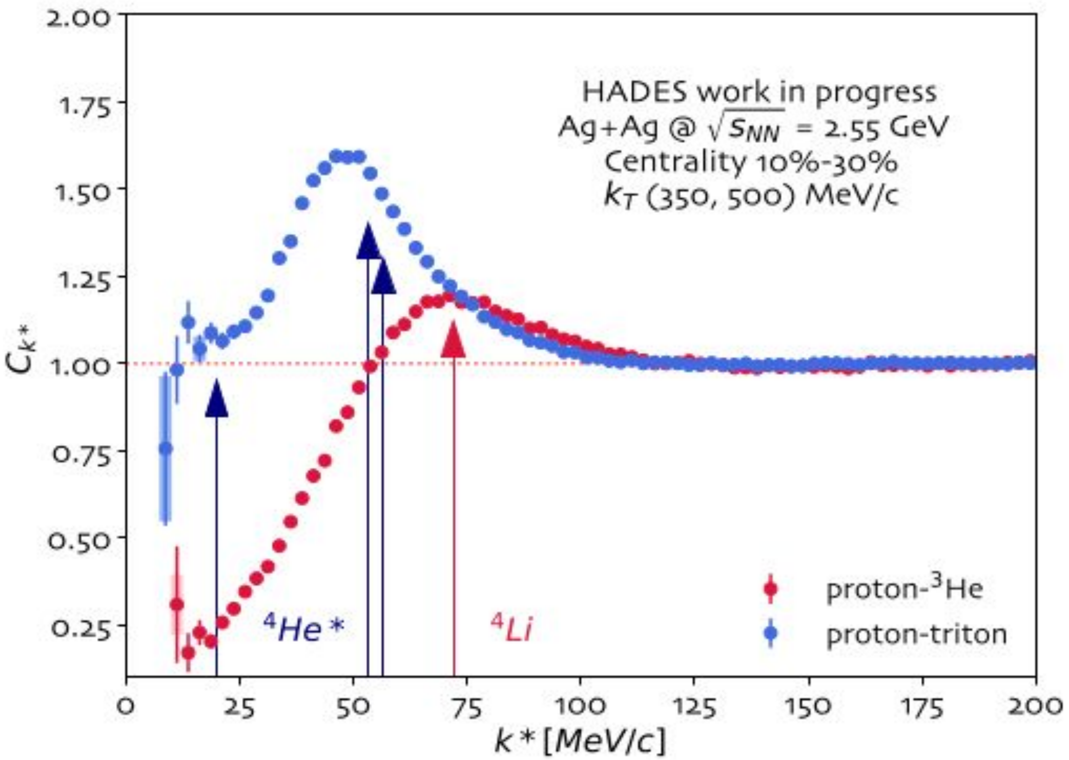
k_T: (350,500) MeV/c



Good description of p-cluster CFs

for more detail contact : stefaniak.9@osu.edu

proton-proton and proton cluster femtoscopy



Proton - ^{3}He and proton - triton comparison

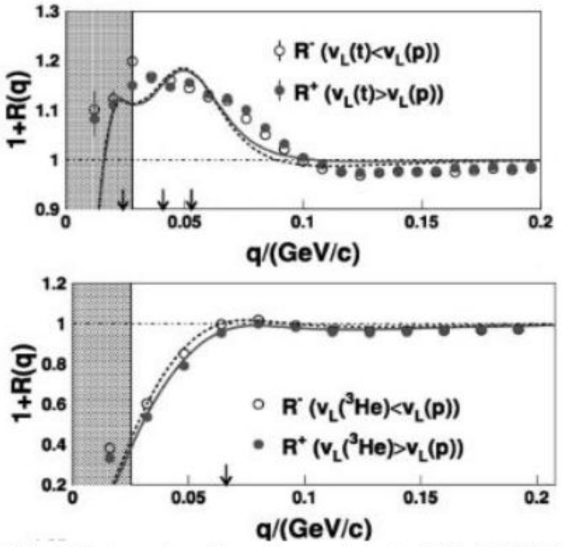
- Similar masses
- Same baryon number

- Different charges -> different strength of coulomb interactions
- Different stability

Decay sources

$$^4_2He^* \longrightarrow t + p$$

$$^4_3Li \longrightarrow {}^3_2He + p$$



FOPI Collaboration:Eur. Phys. J. A 6, 185–195 (1999)

Excited states of ^{4}He*:

- E = 20.21 MeV, $J^\pi = 0^+$, Γ = 0.5 MeV, Γ_p/Γ = 1, k^*_1 = 20 MeV/c
- E = 21.01 MeV, $J^\pi = 0^-$, Γ = 0.84 MeV, Γ_p/Γ = 0.76, k^*_2 =53.3 MeV/c
- E = 21.84 MeV, $J^\pi = 2^-$, Γ =2.01 MeV, Γ_p/Γ = 0.63, k^*_3 = 56.6 MeV/c

Unbound ground state of ^{4}Li:

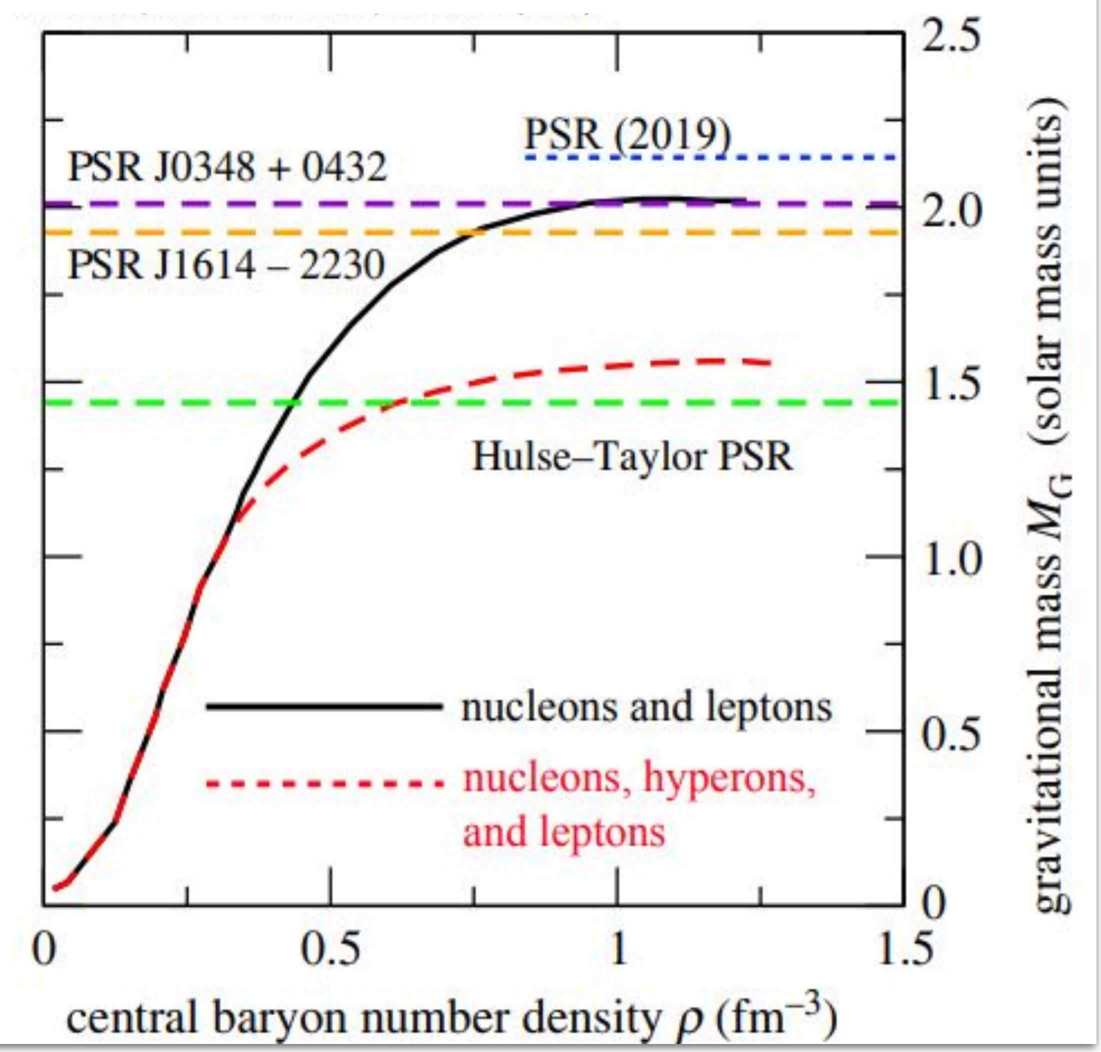
- J^π = 2-, Γ = 6.0 MeV, Γ_p/Γ = 1, $k^*_0 \approx$ 72 MeV/c

for more detail contact : stefaniak.9@osu.edu

Effect of (possible) resonances might be visible

Neutron Star and hyperon puzzle ?

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

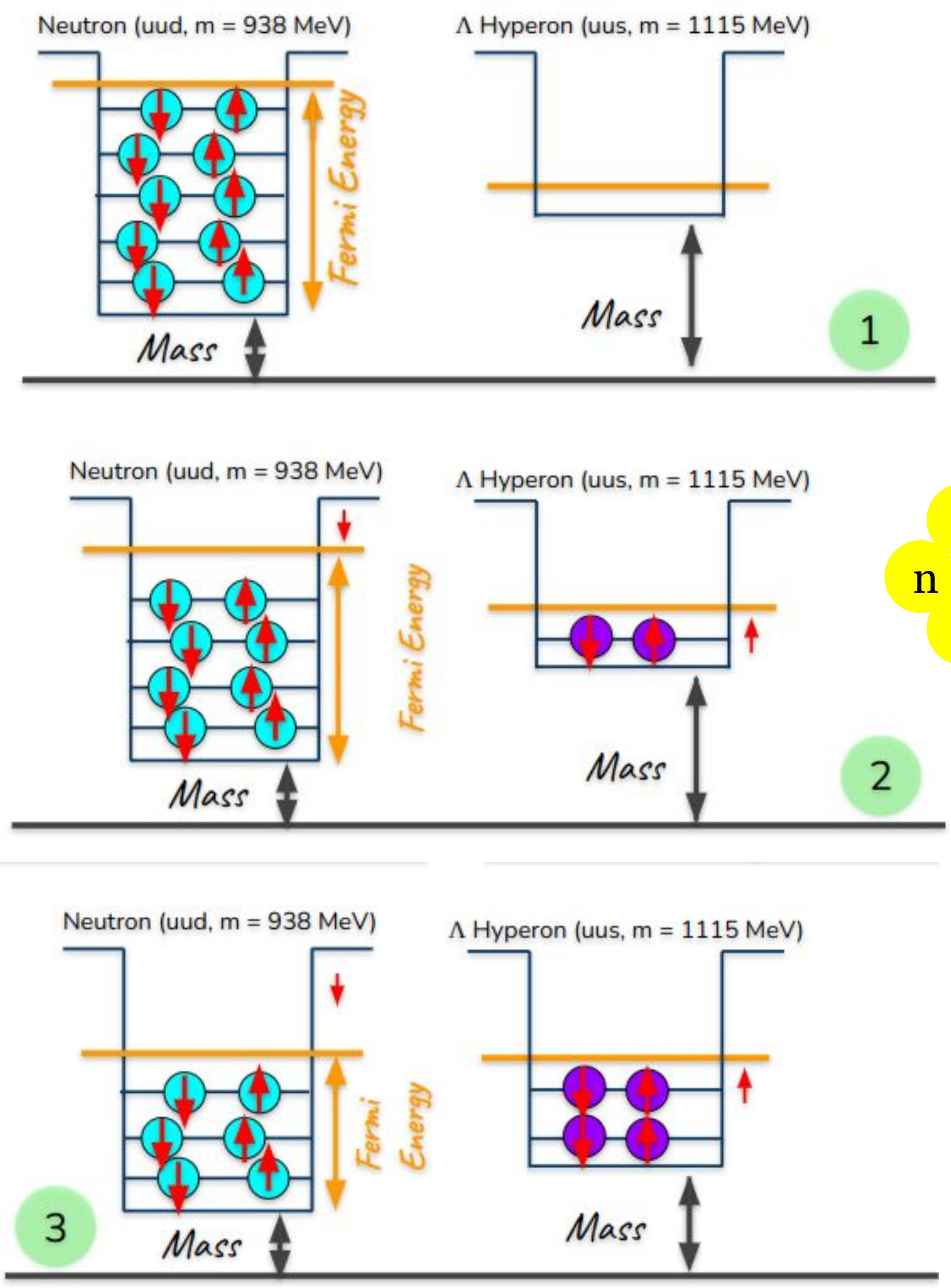


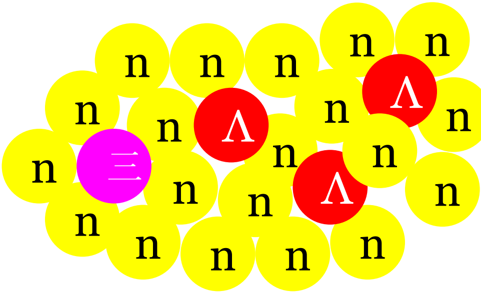
- Neutron stars (NS) are the remnants of the gravitational collapse of massive stars during supernova event.
- Their masses and radii are of the order of 1 – 2 $M_\odot$ and 10 – 12 km, respectively.
- Central densities in the range of 4 – 8 times the normal nuclear matter saturation density, ε_0 ~ 2.7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

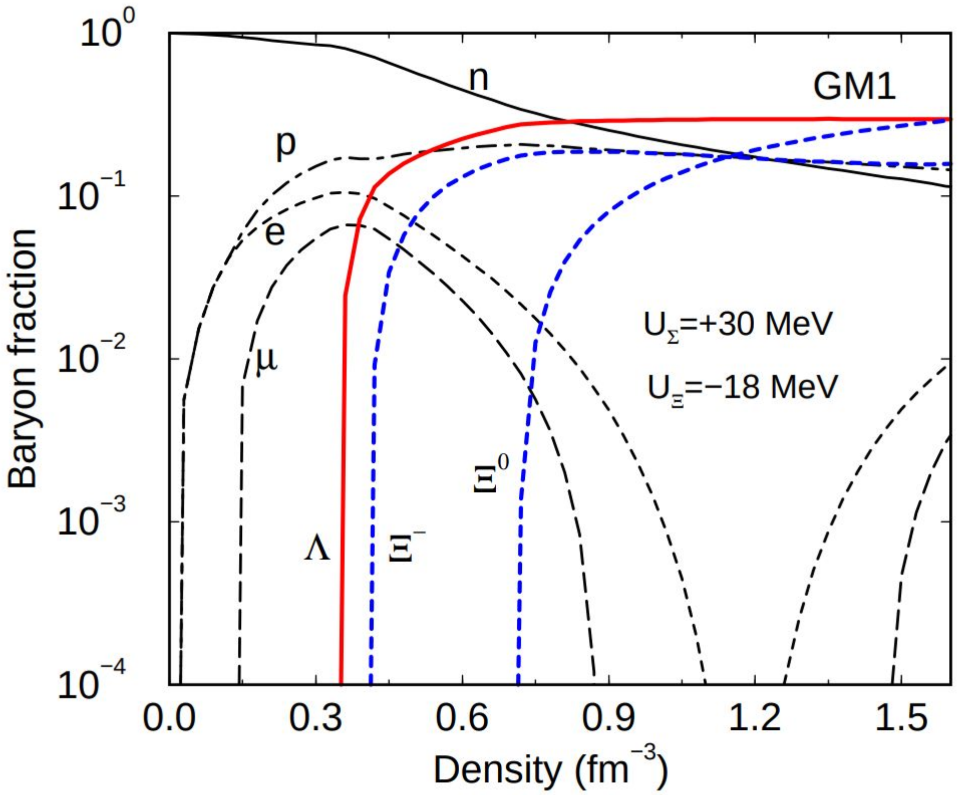
Best suitable theory takes hyperons into account,

- Hyperons are expected to appear in the core of NS at $\rho \sim 2$- 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.**

hyperons appearance in NS







J. Schaffner-Bielich
Nucl.Phys.A804:309-321,2008

- With increasing baryonic densities hyperons production becomes energetically favorable
- Exact composition strongly depends on constituent interaction and couplings

Signal Reconstruction

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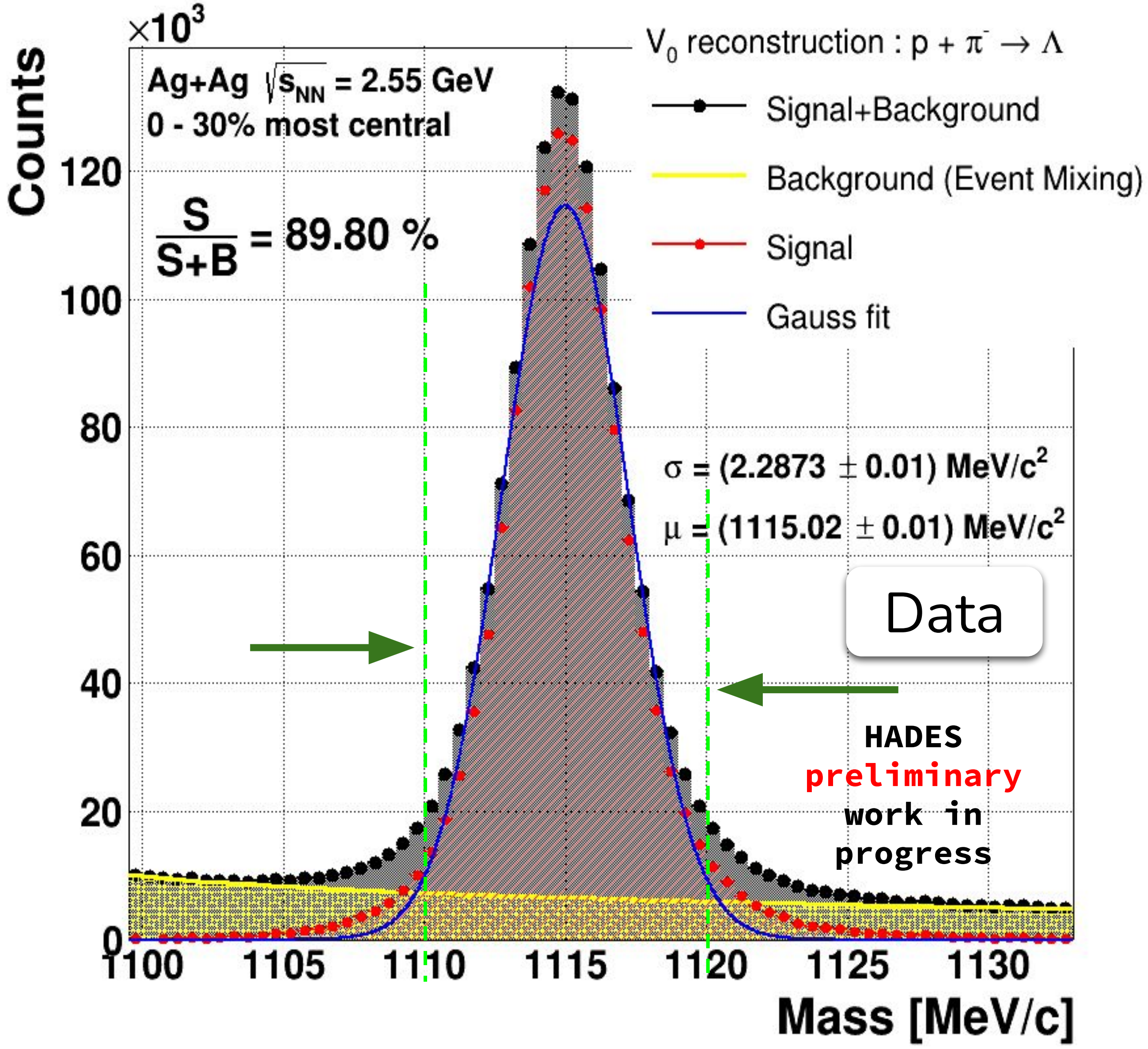
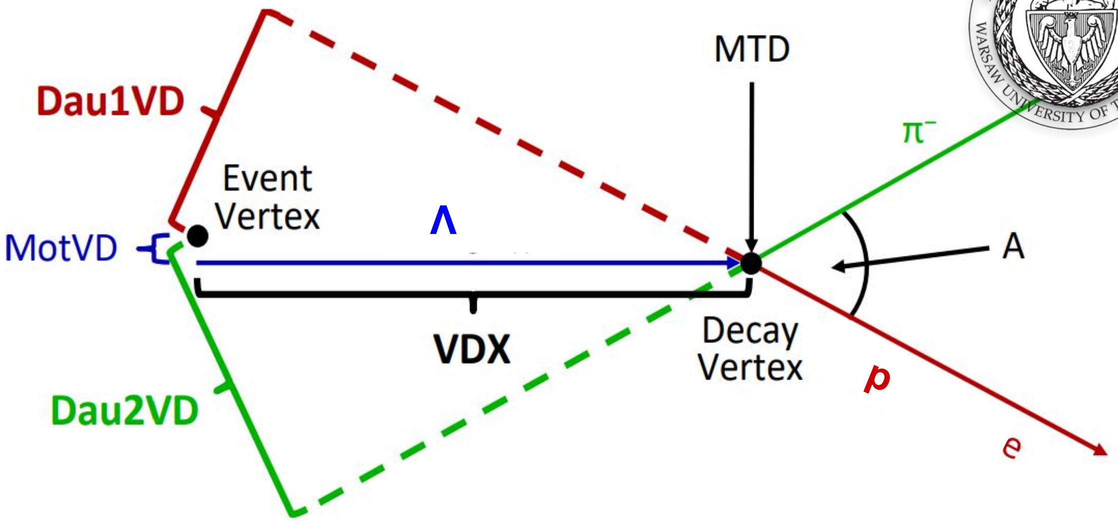
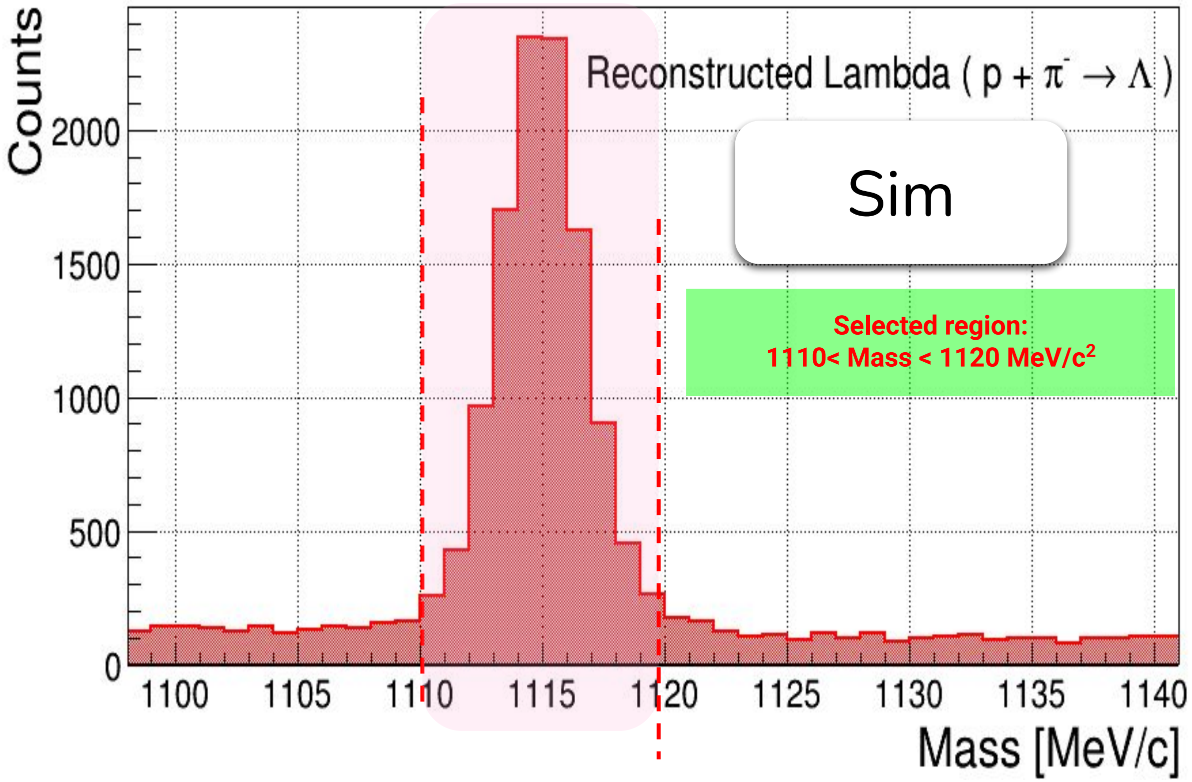
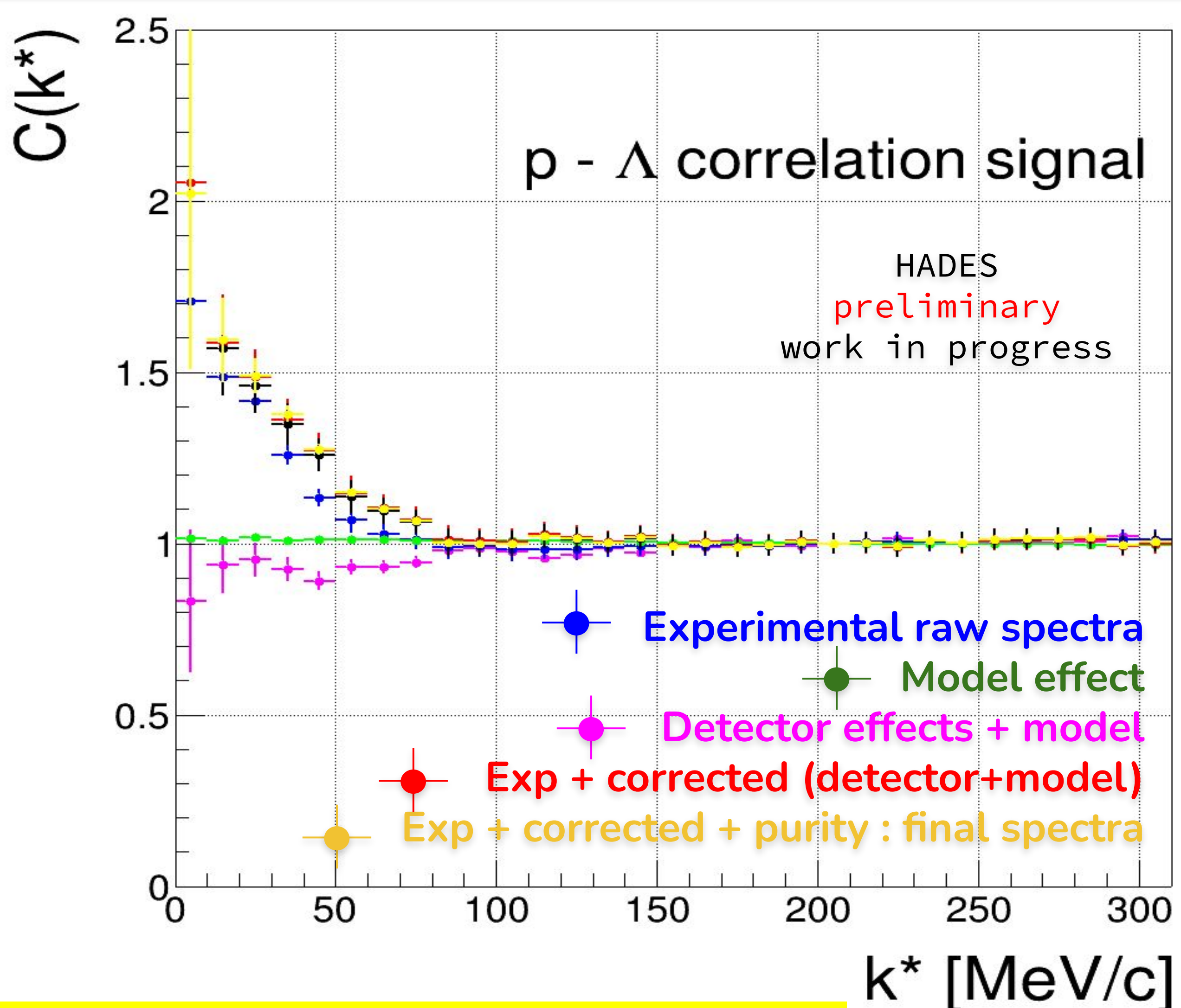


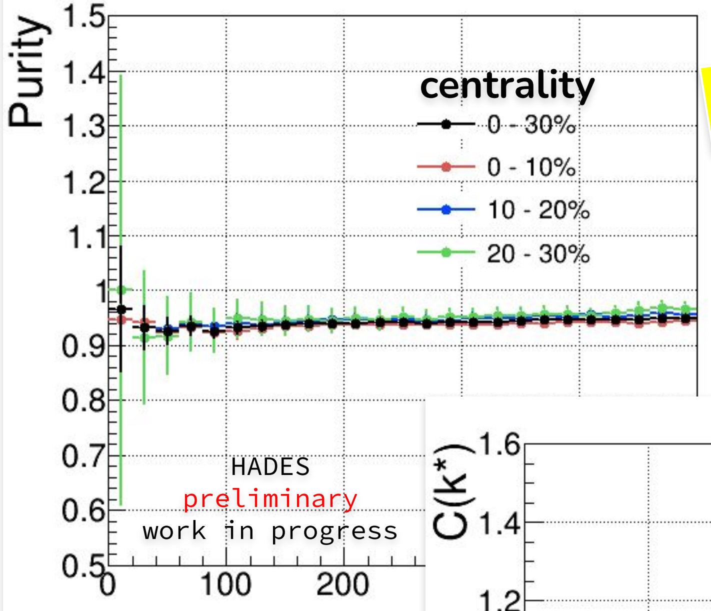




p-Λ correlation in AgAg collision at 1.58 A GeV

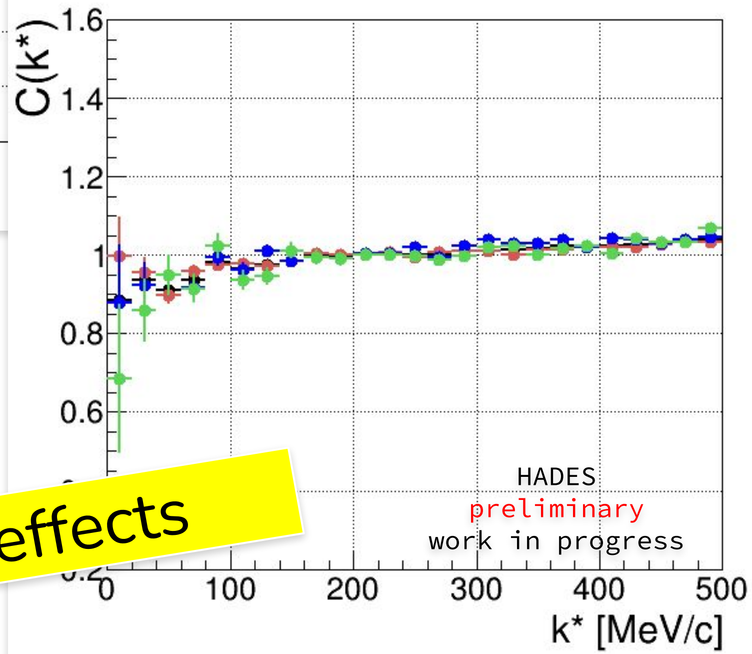


for more detail contact : nsrathore.rajput@gmail.com



purity

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



Detector effects

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 :

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

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

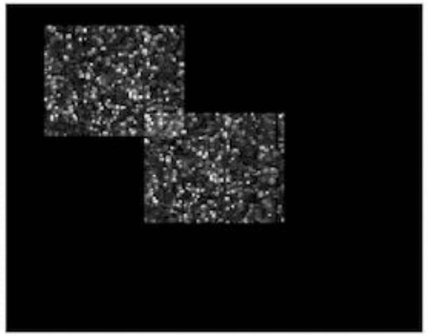
↓

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.

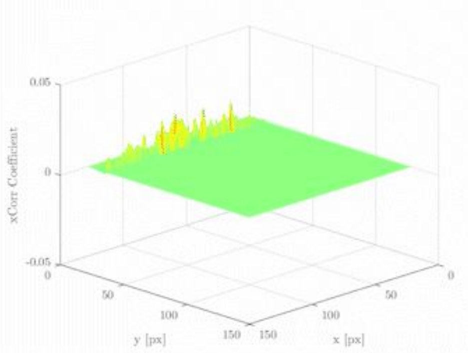
2. The first fitter employs ROOT minimizers, offering precise statistical uncertainty estimation, but it operates on "continuous" maps with limited control over parameter steps.

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



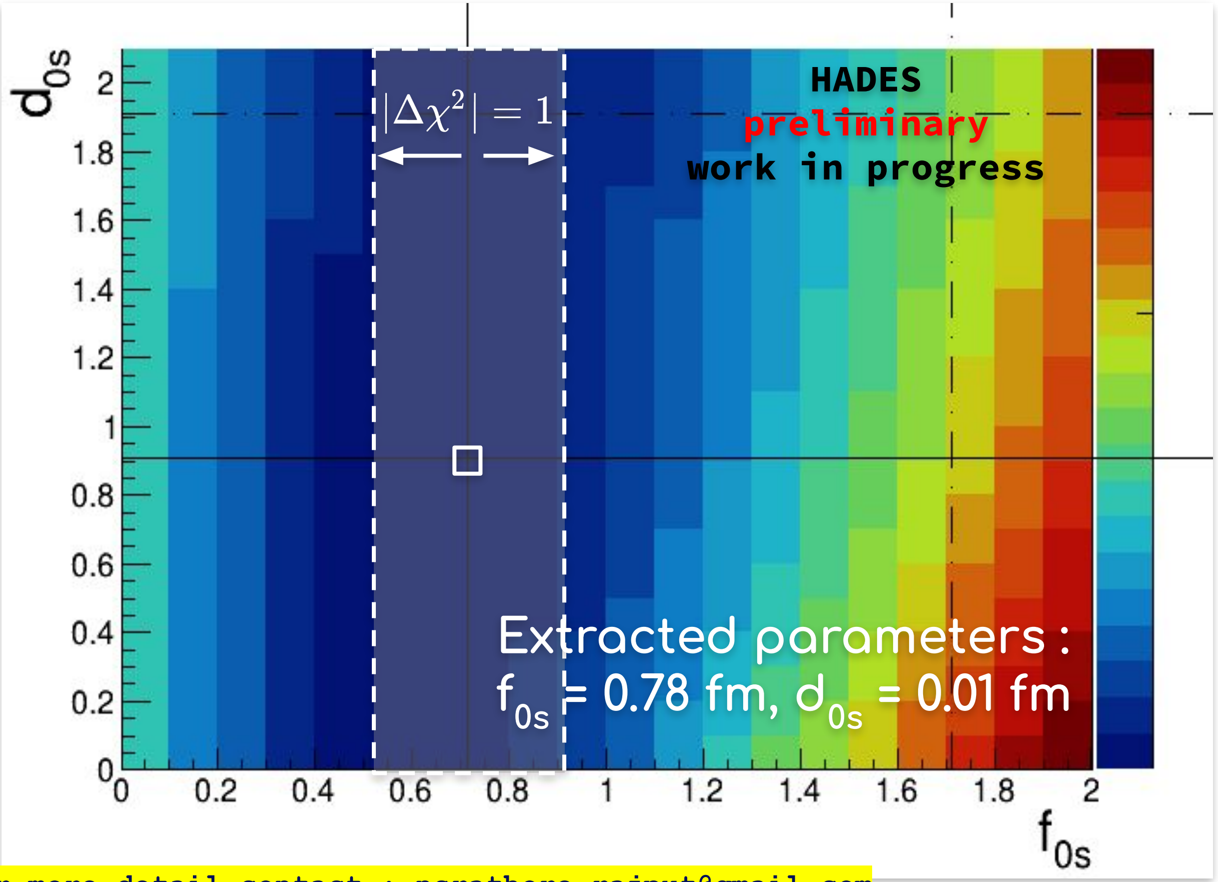
```
for( int λ = 0.6; λ < 0.8; λ+=0.1 )
    for( int r0 = 1.0; r0 < 4.0; r0+=0.1 )
        for( int f0 = 0.01; f0 < 5.0; f0+=0.1 )
            for( int d0 = 0.01; d0 <5.0; d0+=0.1)
                for( int ft = 0.01; ft < 5.0 ; ft += 0.1 )
                    for( int dt =0.01; dt < 5.0; dt+=0.1 )
 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

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

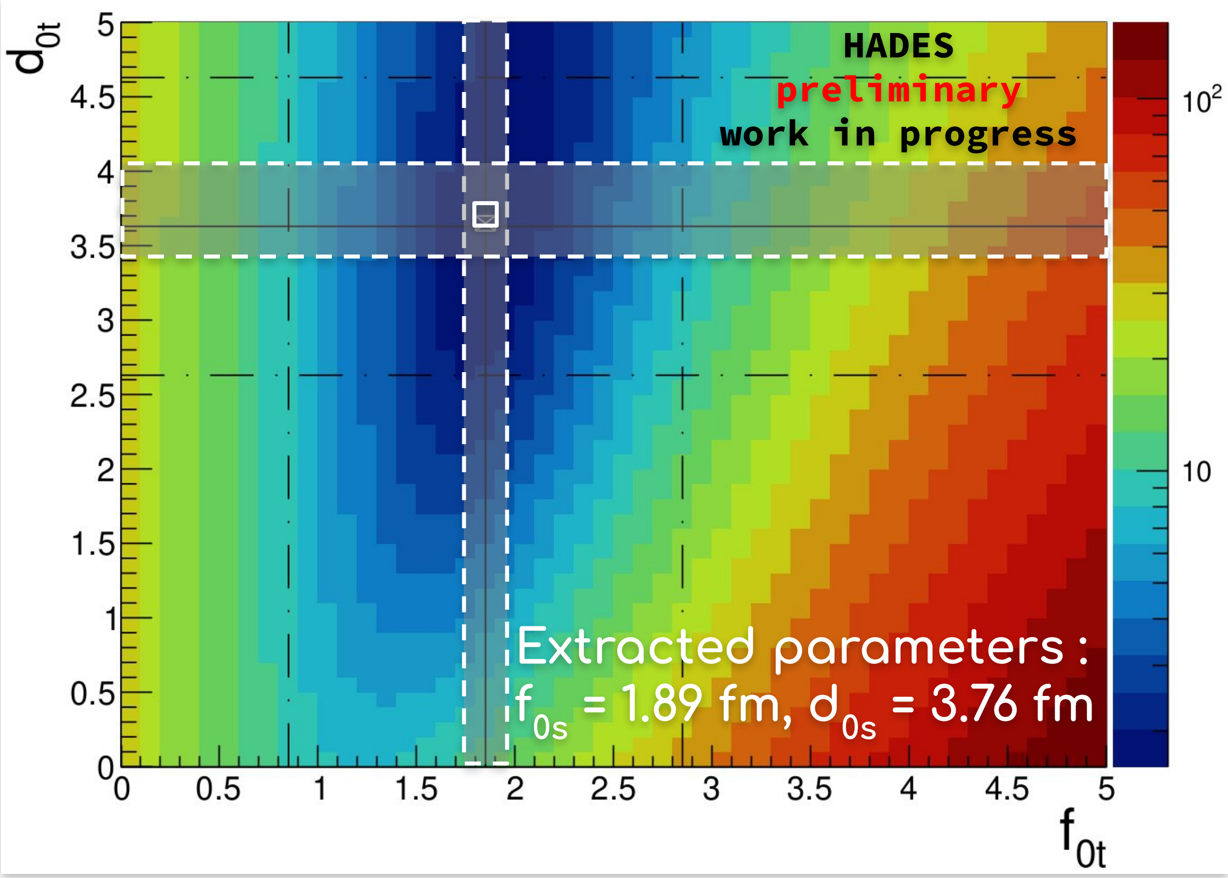


f_{0s}, d_{0s}, f_{0t} and d_{0t} parameters : χ^2 value

Singlet

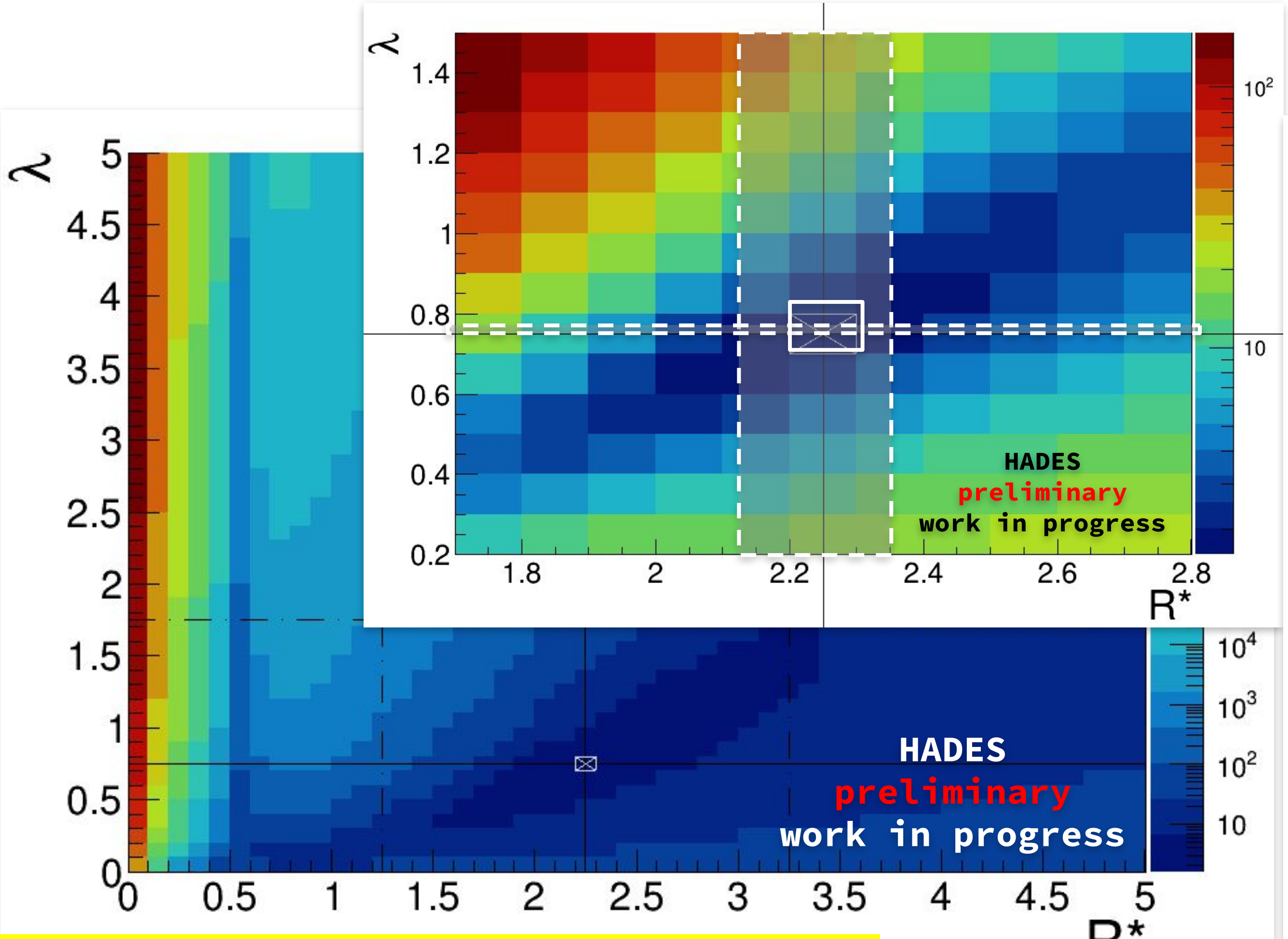


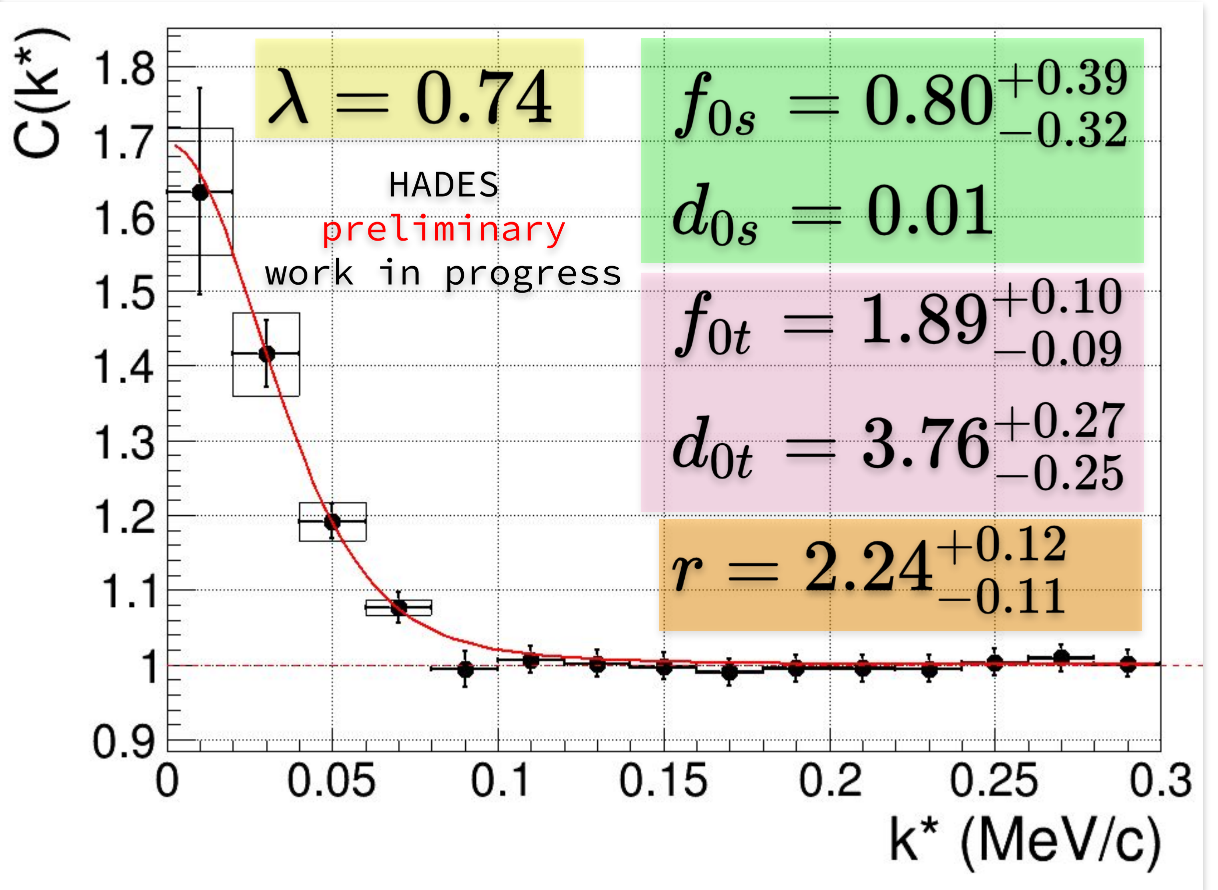
Triplet



for more detail contact : nsrathore.rajput@gmail.com

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





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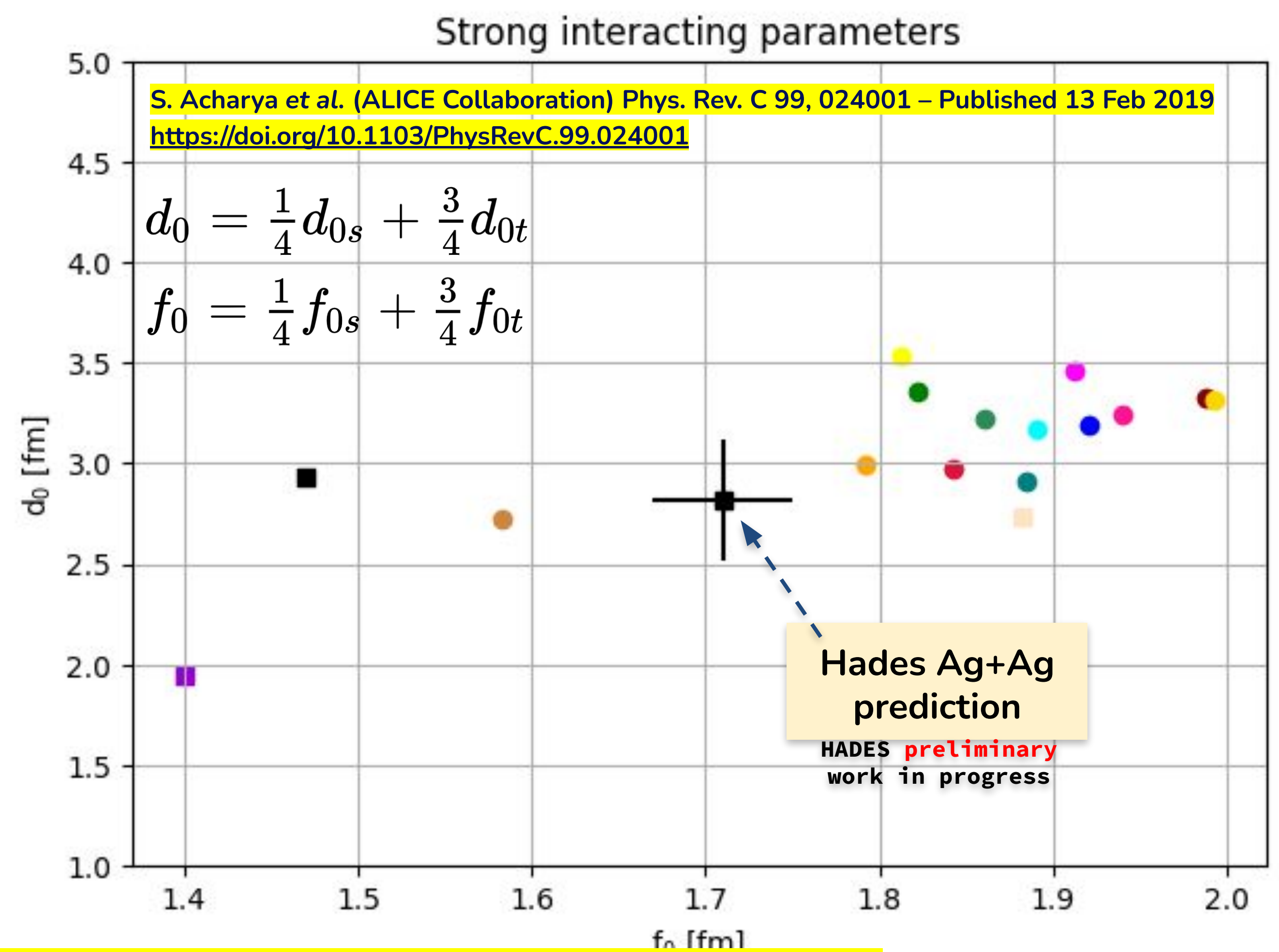
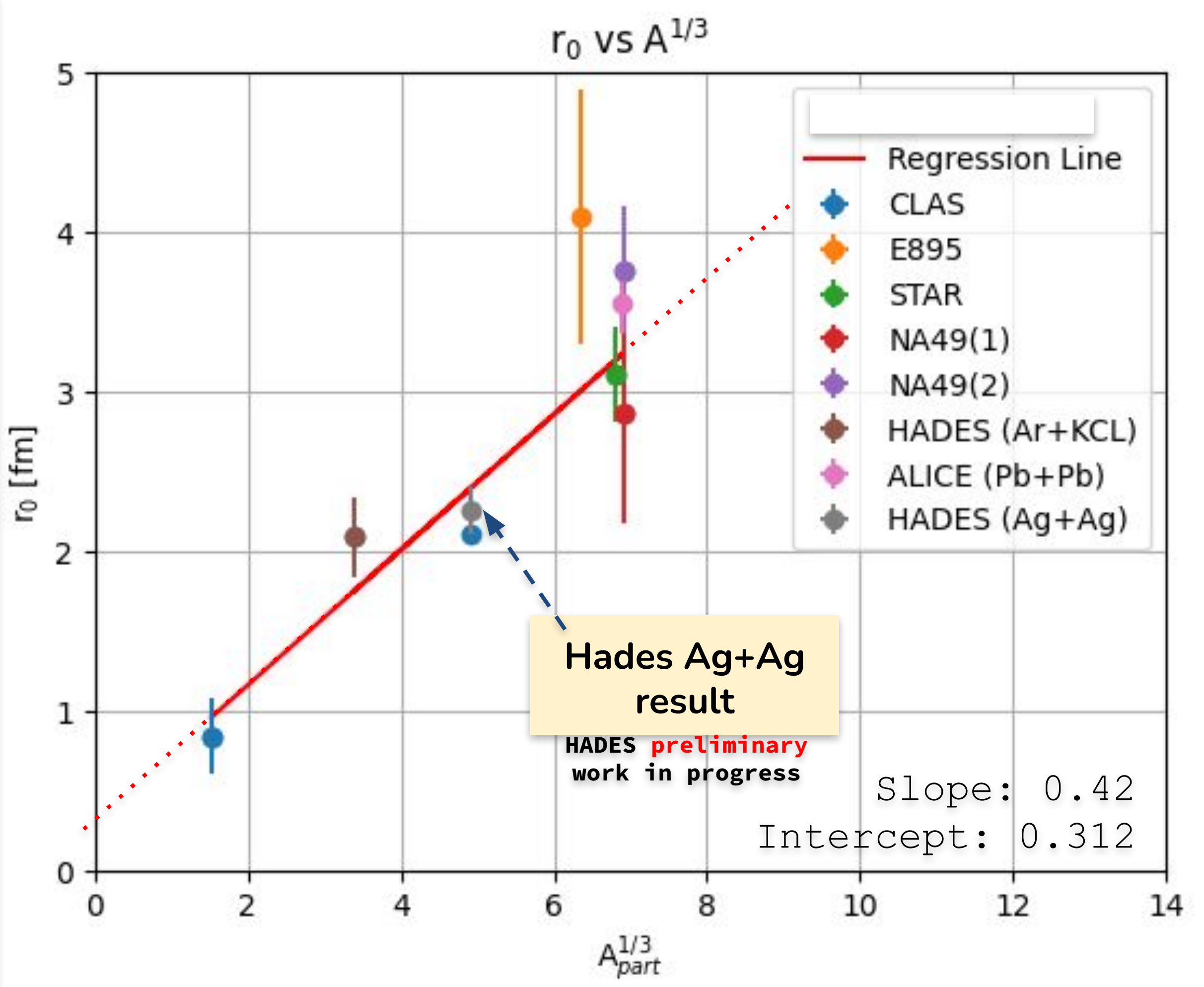
Parameters scan and Plot : r_0 vs $A_{part}^{1/3}$





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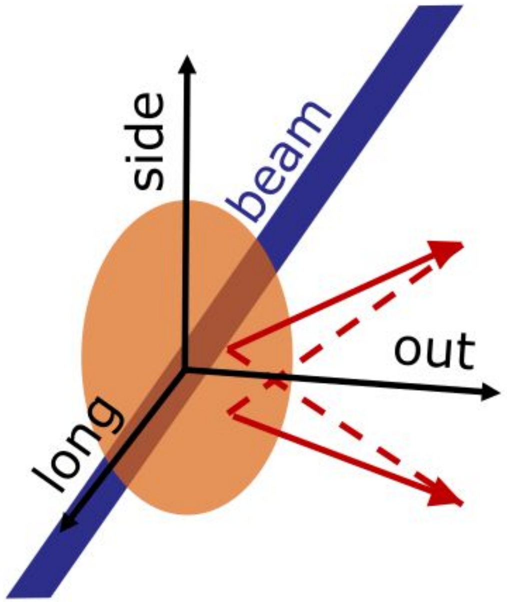
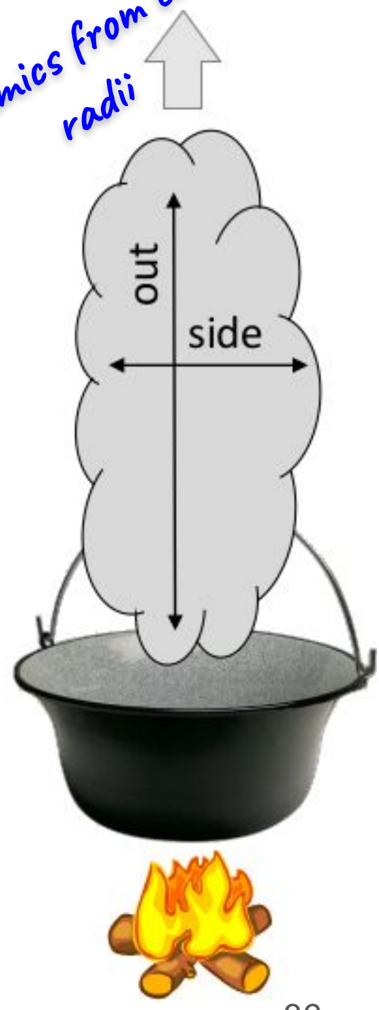
The Bertsch-Pratt coordinates, HBT radii

- A choice for an 1D variable : $q_{inv} = \sqrt{-(k_1 - k_2)^2}$
- Shape : Gaussian (diffusion, central limit theorem)
- In general: $C(q_{inv}) = 1 + \lambda e^{-R_{\mu\nu} q^\mu q^\nu}$
- Pair coordinate system :
    - **Out**: pair transverse ($\perp$ to beam) momentum
    - **Long**: beam direction
    - **Side**: perpendicular to both



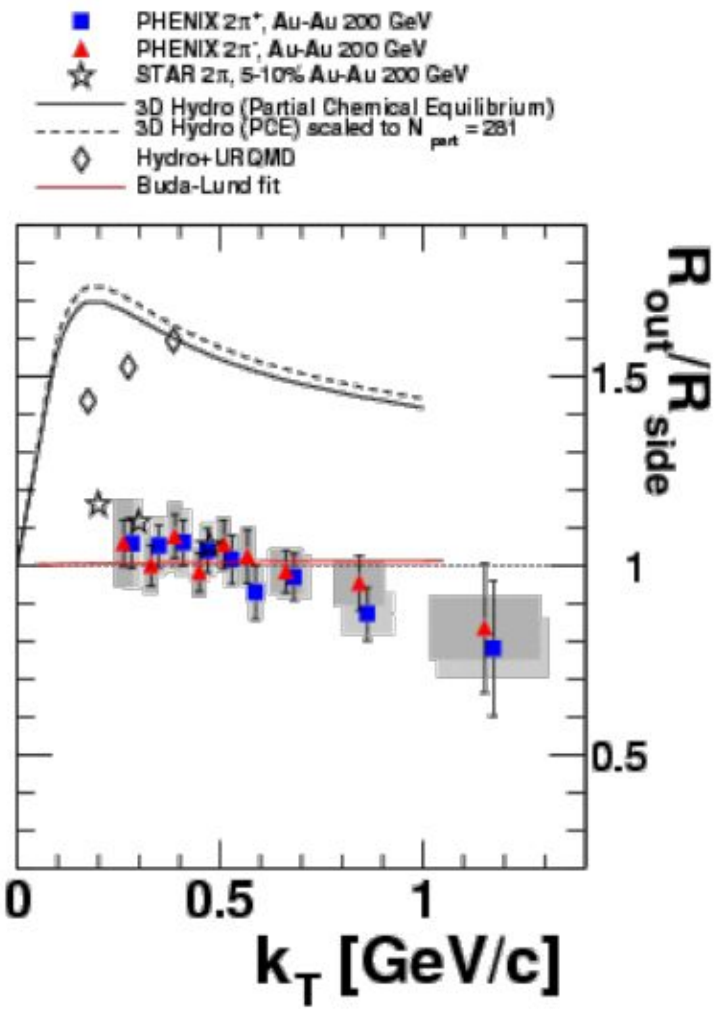
- Typically in LCMS (longitudinally comoving system)
    - Zero pair longitudinal momentum, i.e. $K^\mu = (M_t, K_t, 0, 0)$
    - Then: $q_0 = \frac{m_{1t}^2 - m_{2t}^2}{2M_t}$ $q_{out} = \frac{p_{1t}^2 - p_{2t}^2}{2K_t}$ $q_{side} = \frac{p_{2x}p_{1y} - p_{1x}p_{2y}}{K_t}$ $q_{long} = \frac{E_2 p_{1z} - E_1 p_{2z}}{M_t}$
    - Mass shell condition: $q^\mu K_\mu = 0 \Rightarrow q^0 = \frac{K_t}{M_t} q_{out} = \beta_t q_{out}$
- From $\mathbf{R}^2_{\mu\nu}$ matrix usually $\mathbf{R}_{out}$, $\mathbf{R}_{side}$, $\mathbf{R}_{long}$ nonzero: HBT radii
- Angular dependence appears ($\mathbf{R}_{os}$) as well

QGP dynamics from the HBT radii



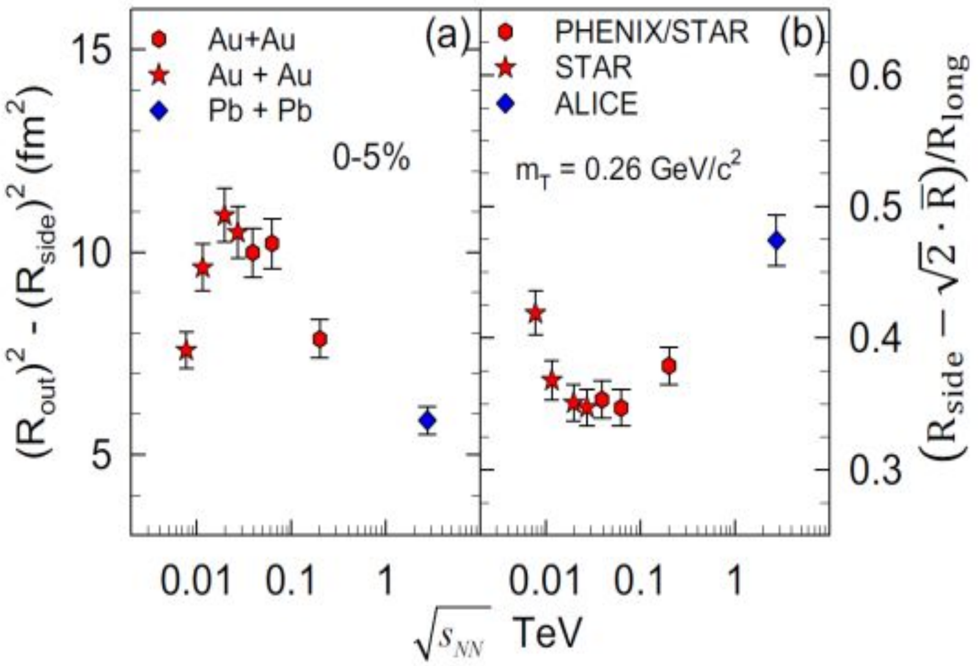
Outcome : essence of hot dense matter

First order phase transition excluded



Non-monotonicities may signal the Critical End Point (CEP)

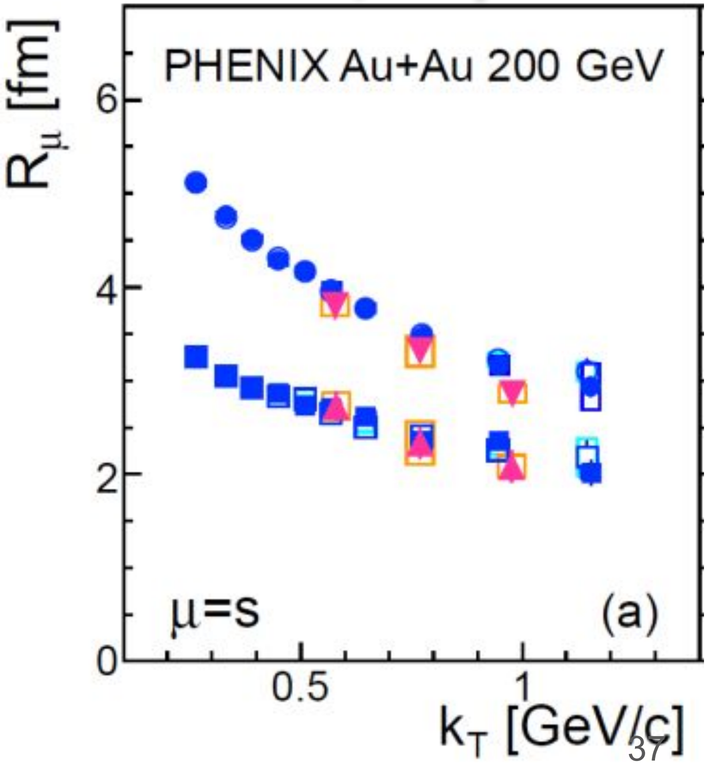
- Out-side difference or side-average, versus coll. energy



Transverse mass scaling observable

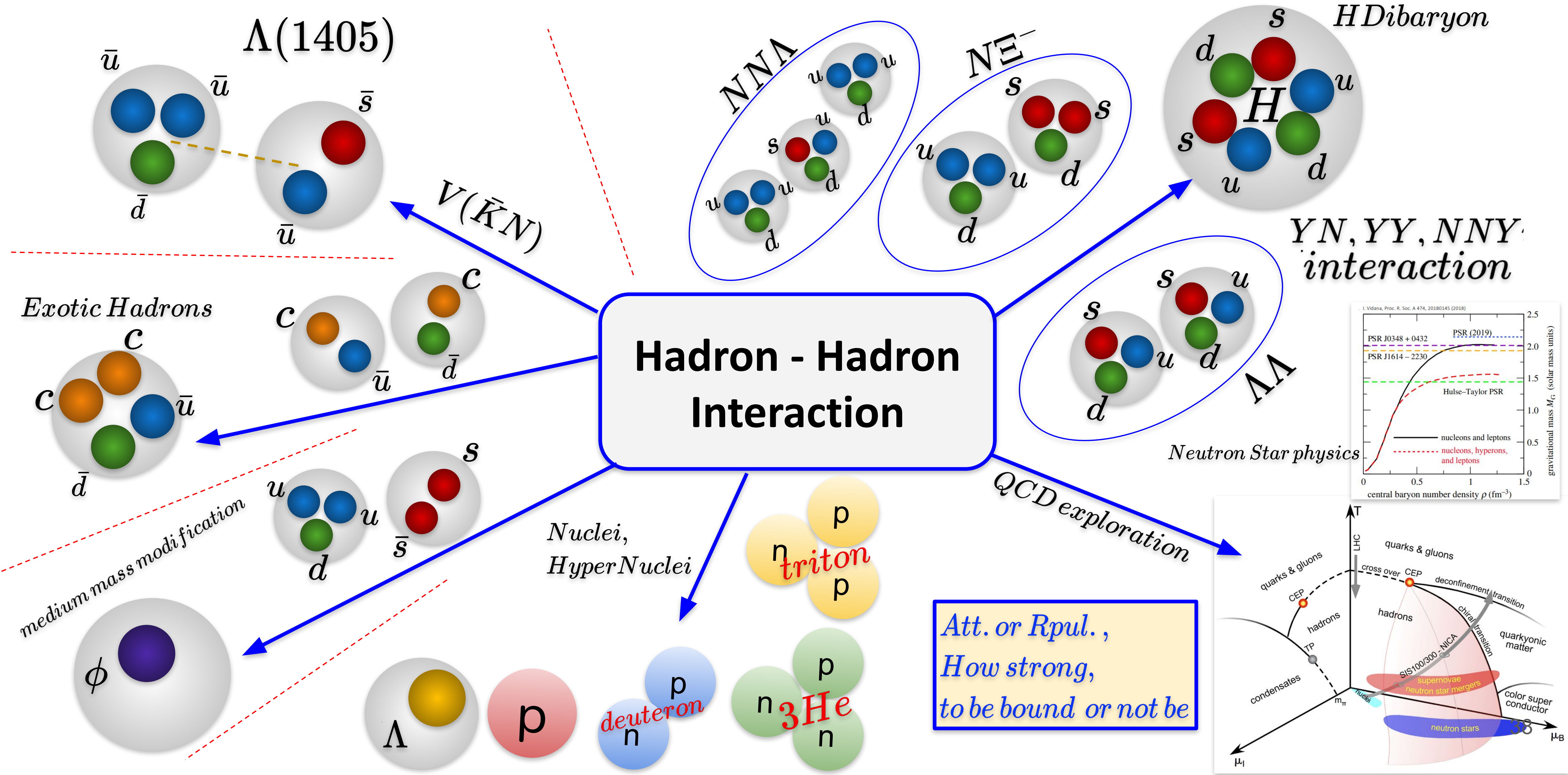
⇒ transverse flow

- Slight difference between kaon and pion pairs



PHENIX, Phys.Rev. C92 (2015) no.3, 034914

Hadron - Hadron Interaction



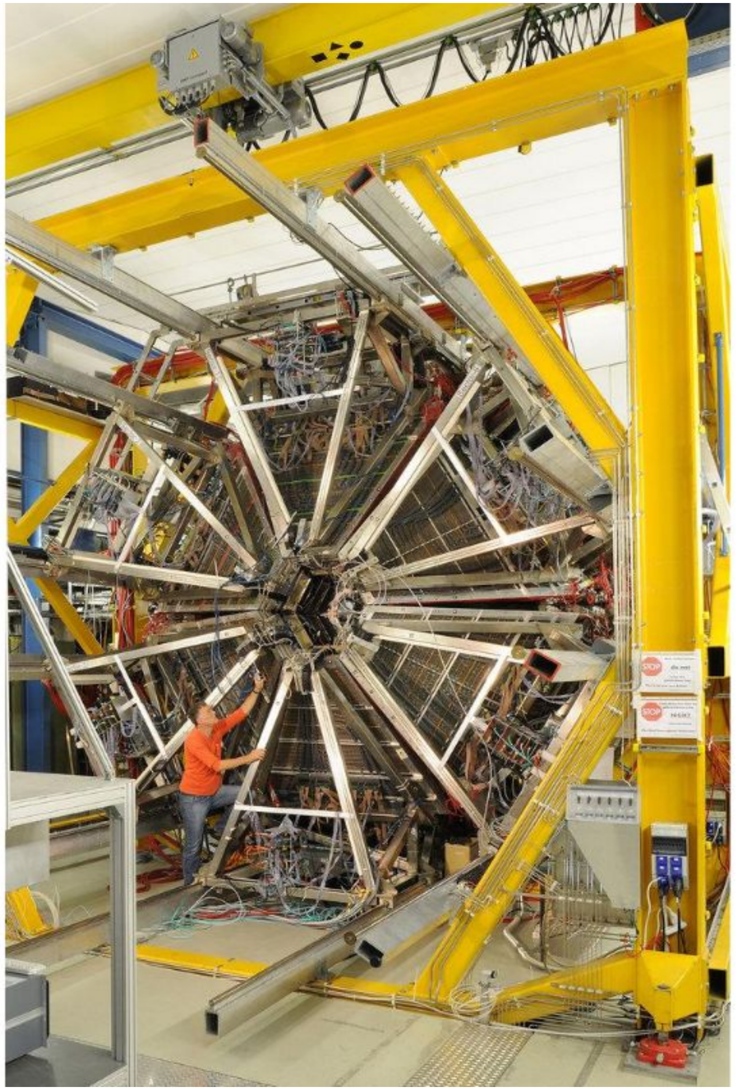
Summary

- **Photon-photon** correlation **exhibits an enhancement** at low Q_{inv}. Additional, unknown background contribution was observed. Complementary study with photons reconstructed via conversion method is ongoing.

- **Strong interaction parameters** have been **determined** from **proton-lambda** correlations. Estimated source radius is consistent with proton-proton correlation.

- **Proton-proton** and **proton-deuteron** correlation functions show **good match with theory**. Signatures from $^{4}_{2}\boldsymbol{He}^{*}$ and $^{4}_{3}\boldsymbol{Li}$ **decays** of were observed.

- The same analyses will be performed new HADES data from p-p at $\sqrt{s_{NN}}$ = 3.46 GeV.



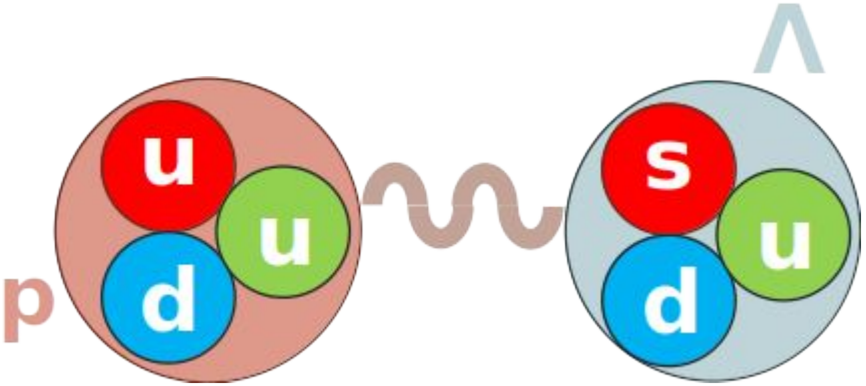
Thank you

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

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.

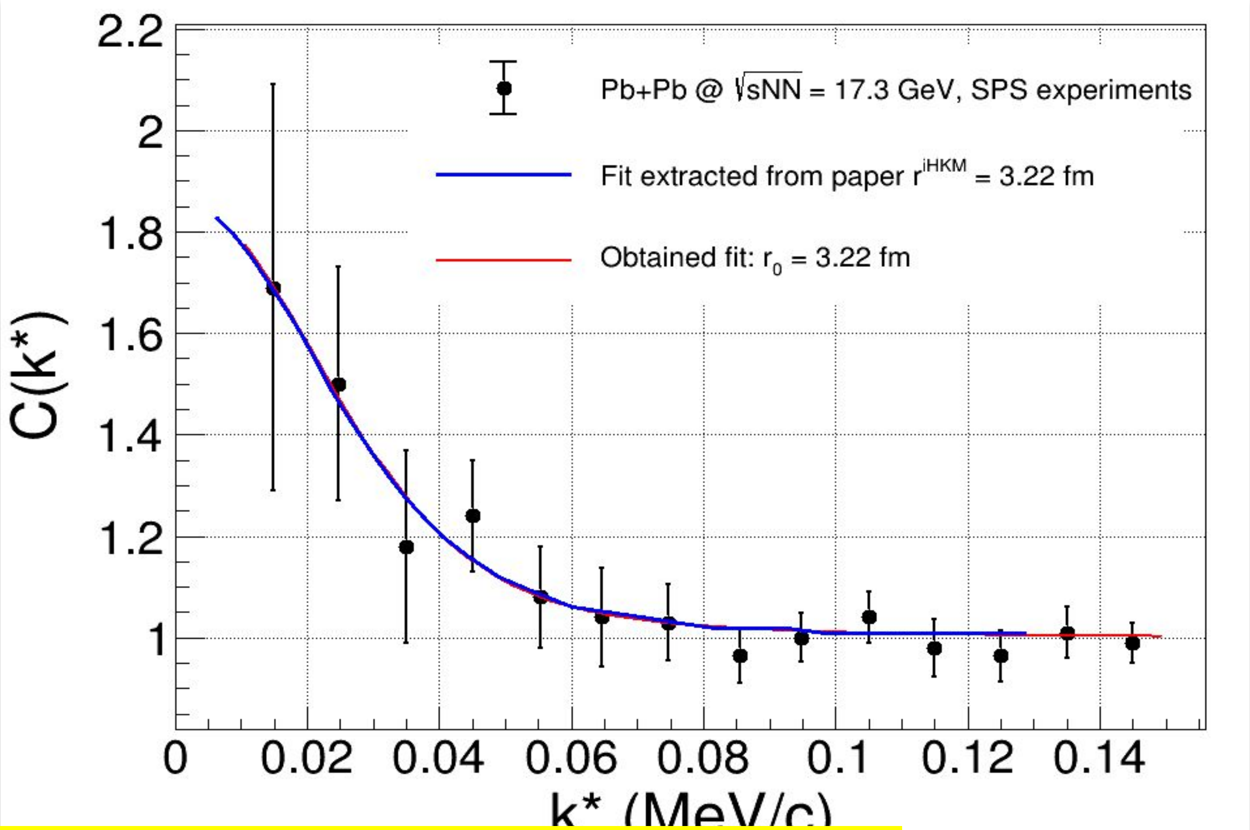
Results will be ready for publication (Stay tuned)

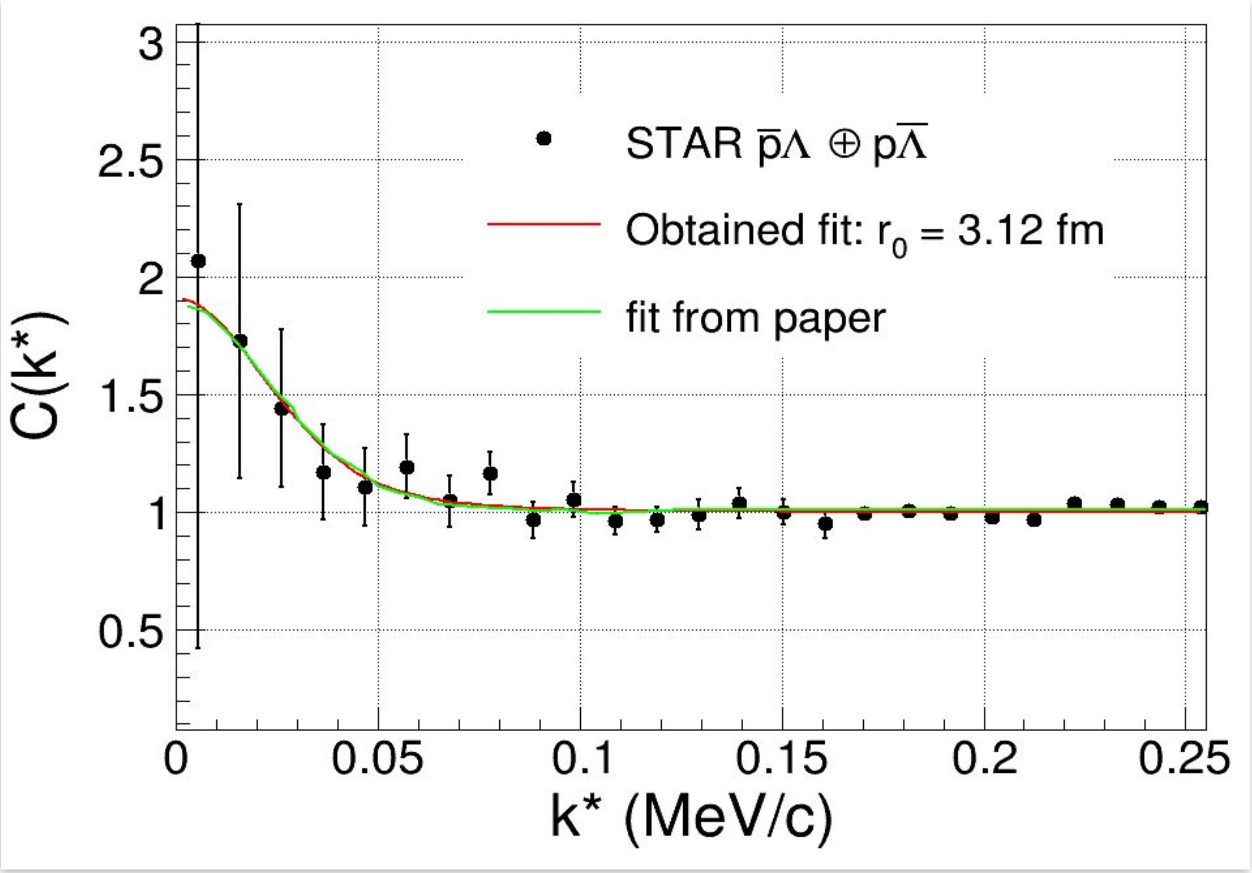
What's next ? (new ideas to explore)

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.........

Result : STAR and LHC data

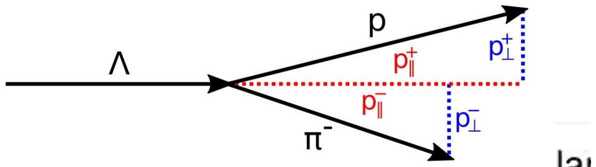
RHIC : Au+Au @ 200 GeV and STAR : LHC Pb+Pb @ 2.76 TeV : Testing fitting procedure





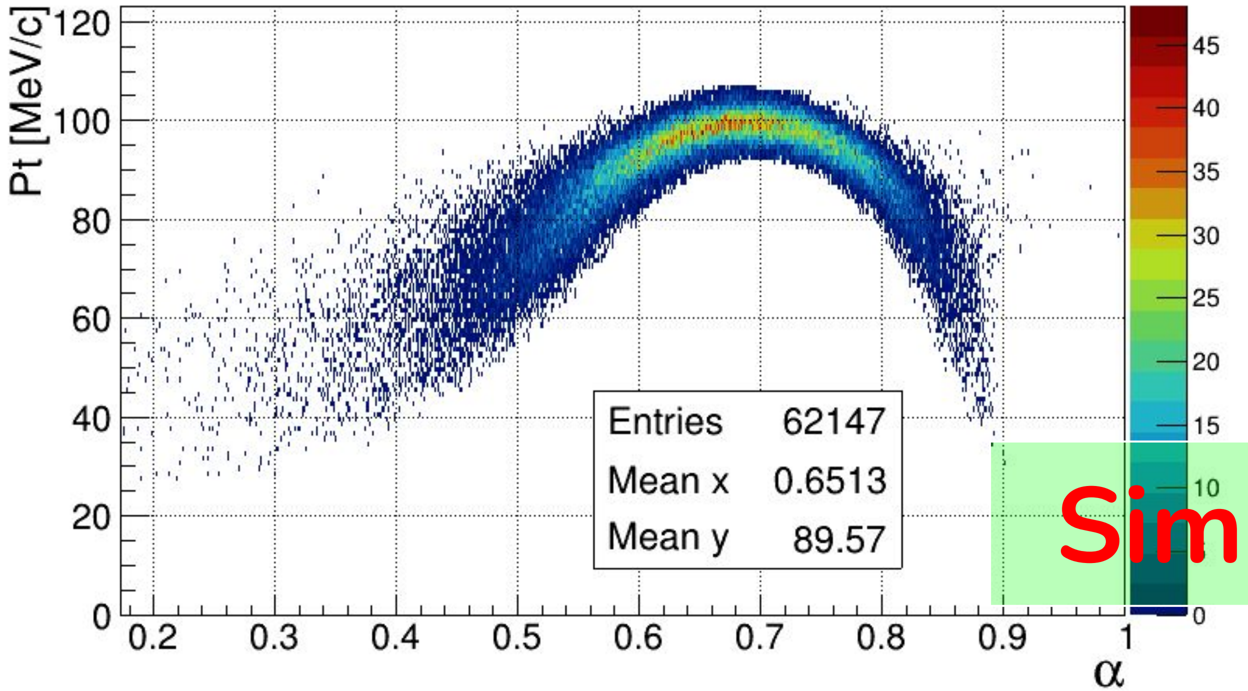
for more detail contact : nsrathore.rajput@gmail.com

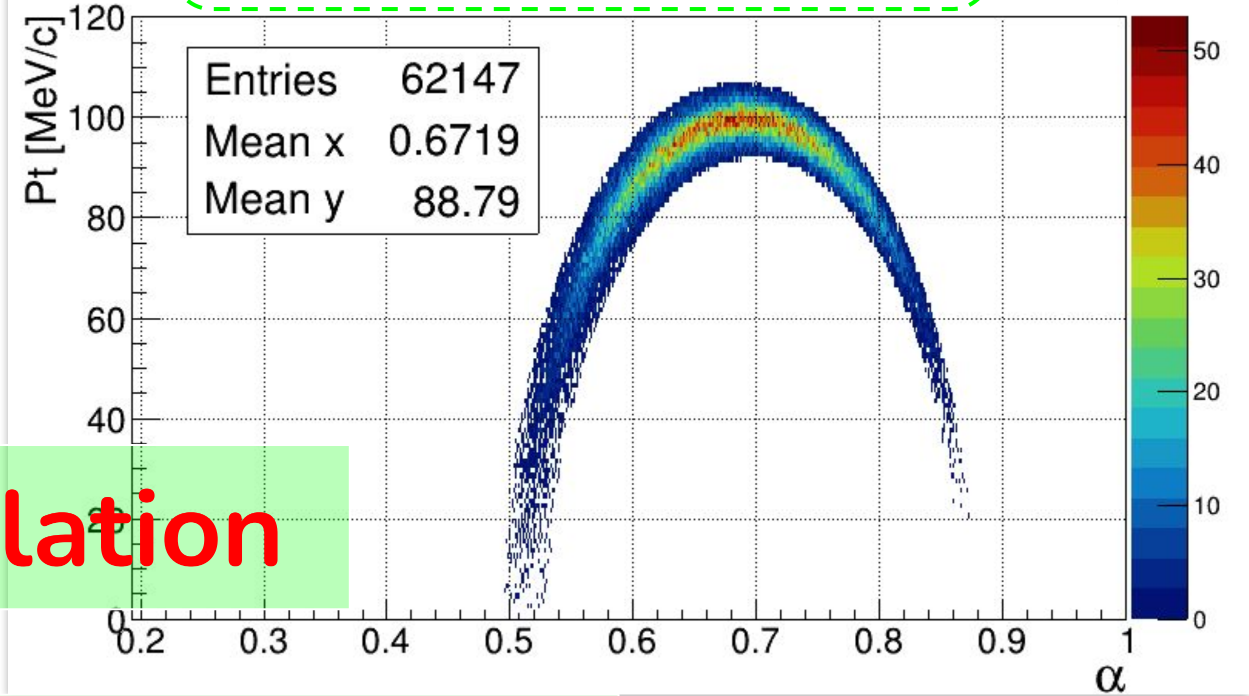
Armenteros-Podolanski plots



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

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



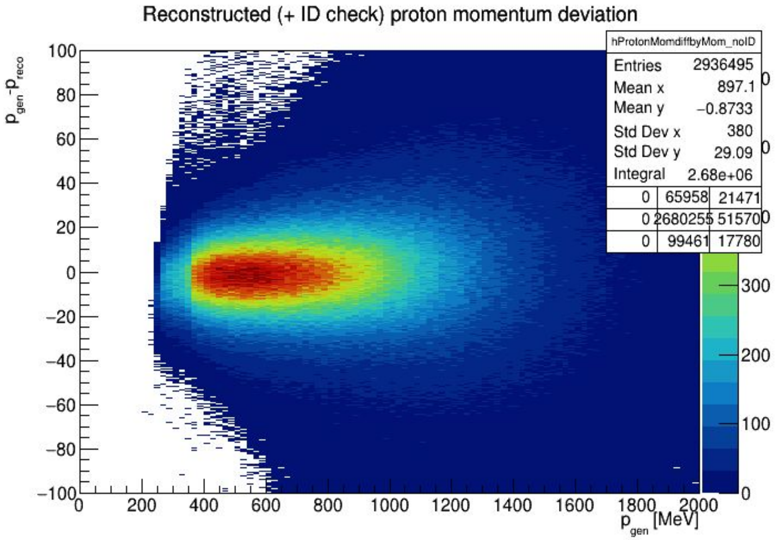


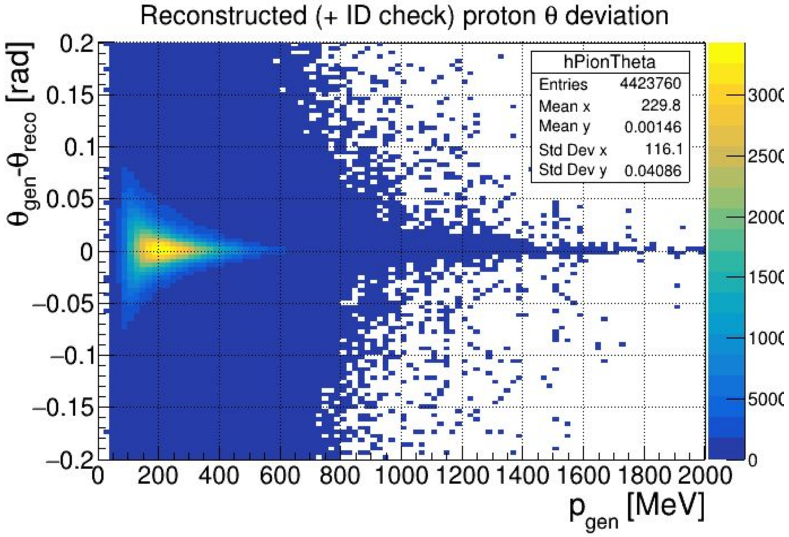
Simulation

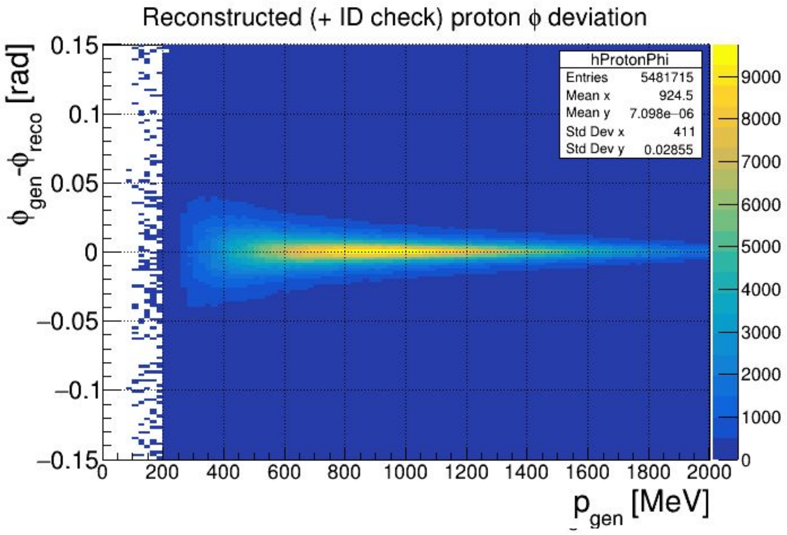
HADES : Low energies → **Additional boost to daughter particles TVector3 beta (0., 0., 0.99);** → **Corrected**

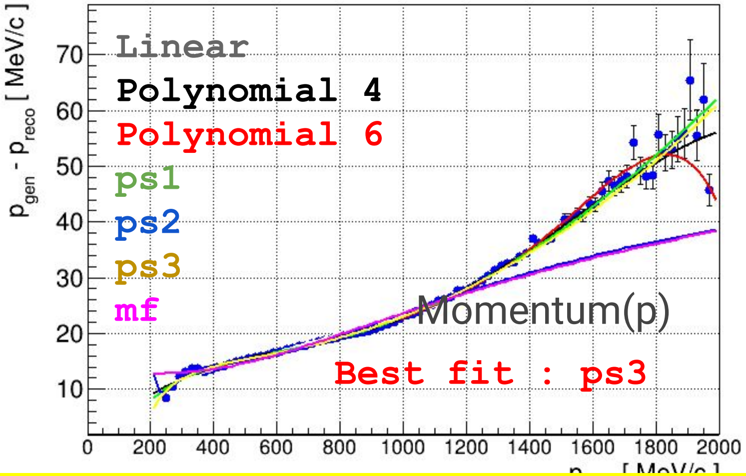
for more detail contact : nsrathore.rajput@gmail.com

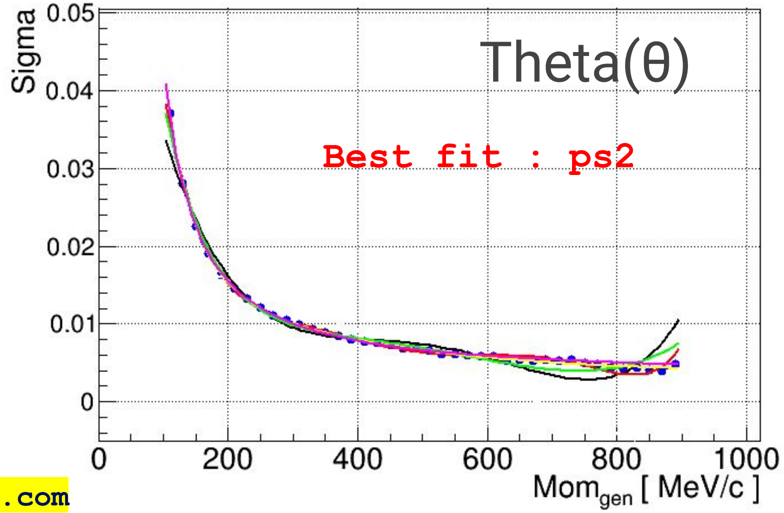
Proton resolution

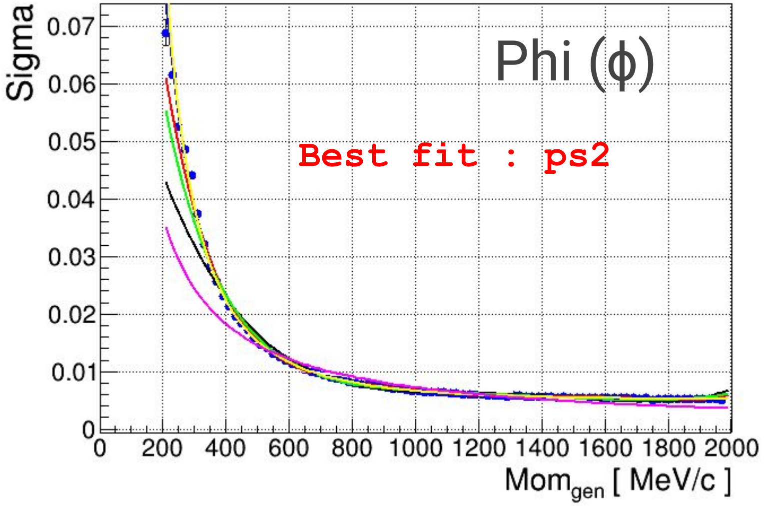












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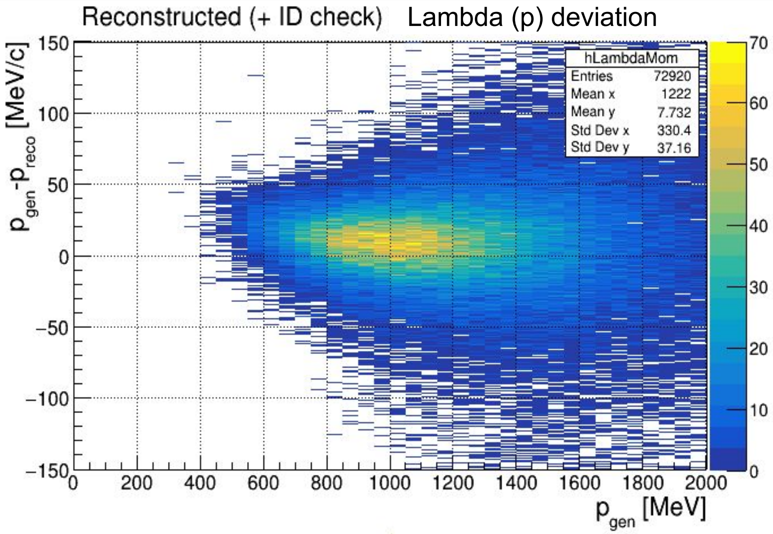
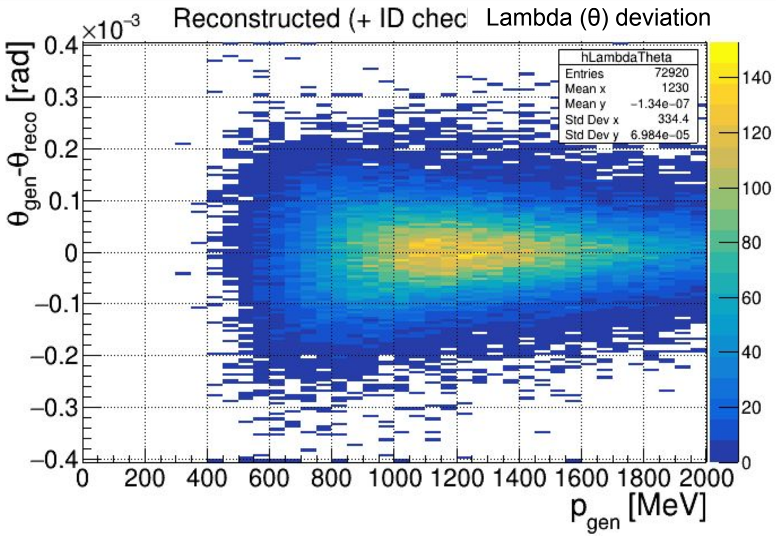
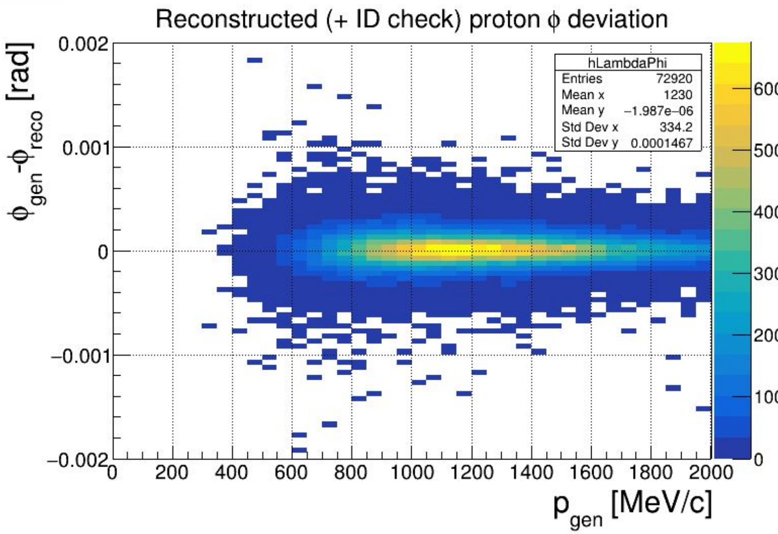
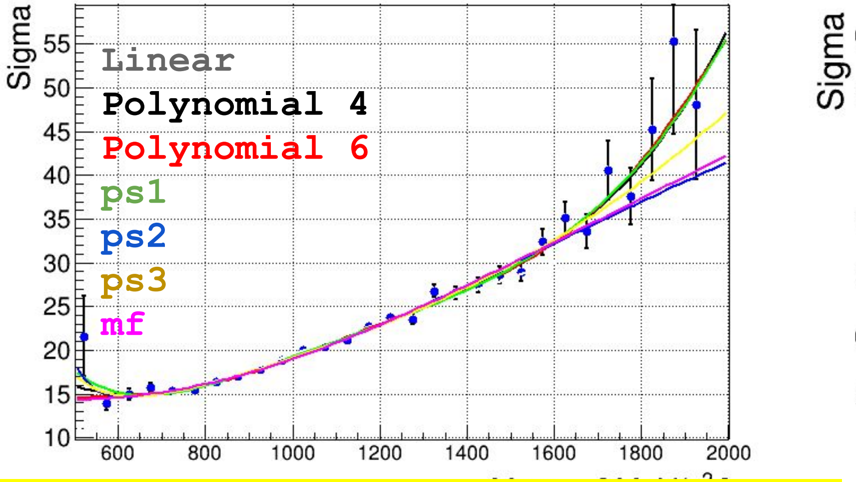
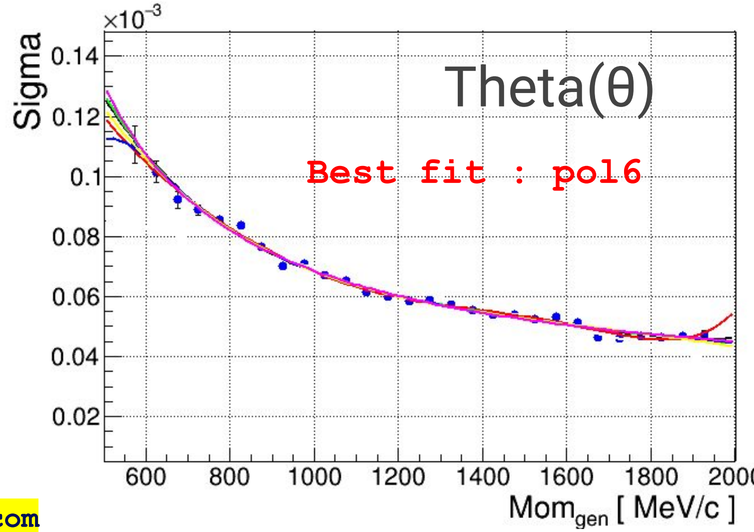
Lambda resolution

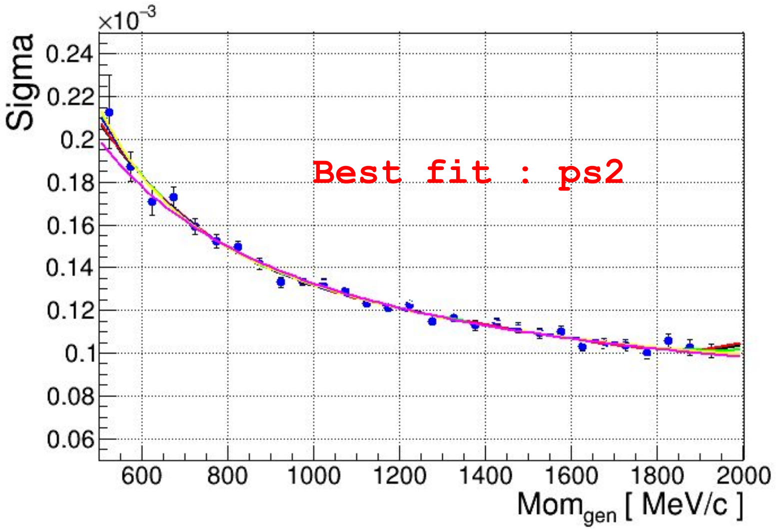












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Result - II

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

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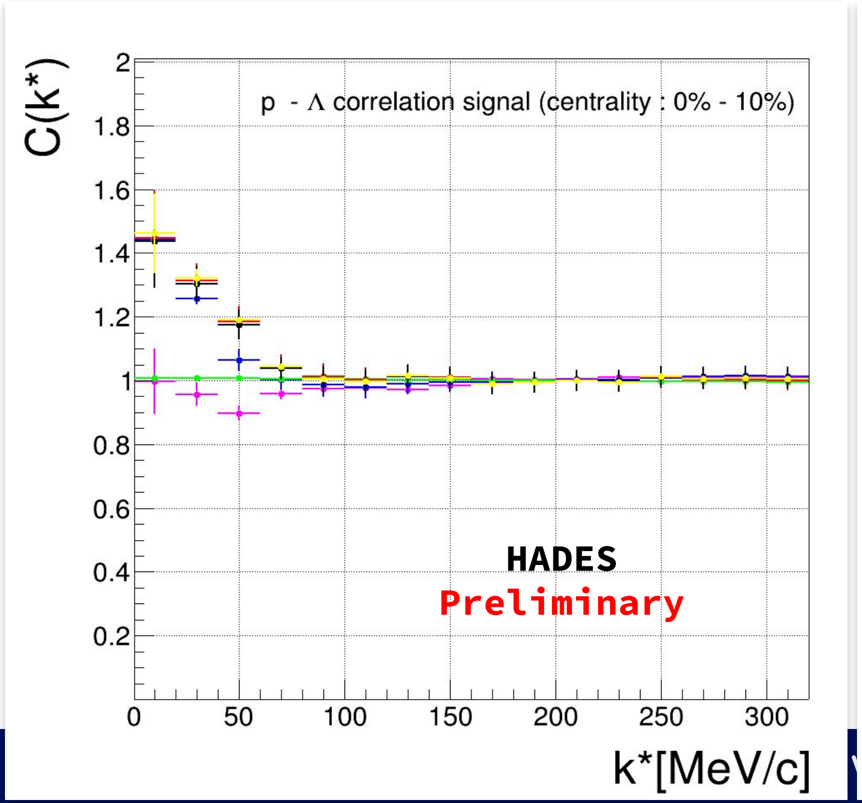
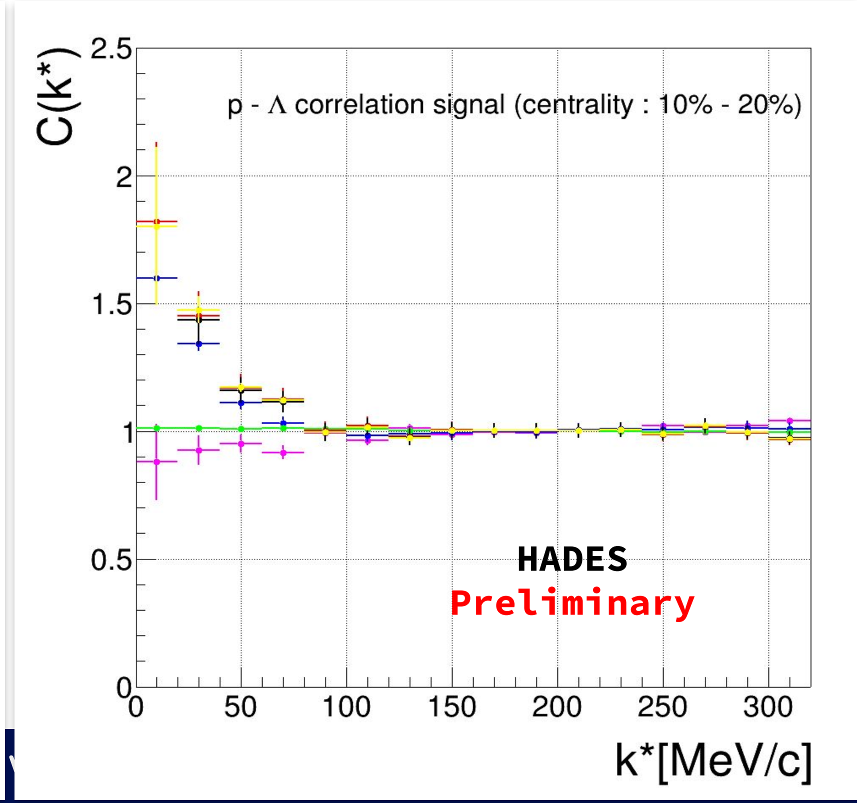
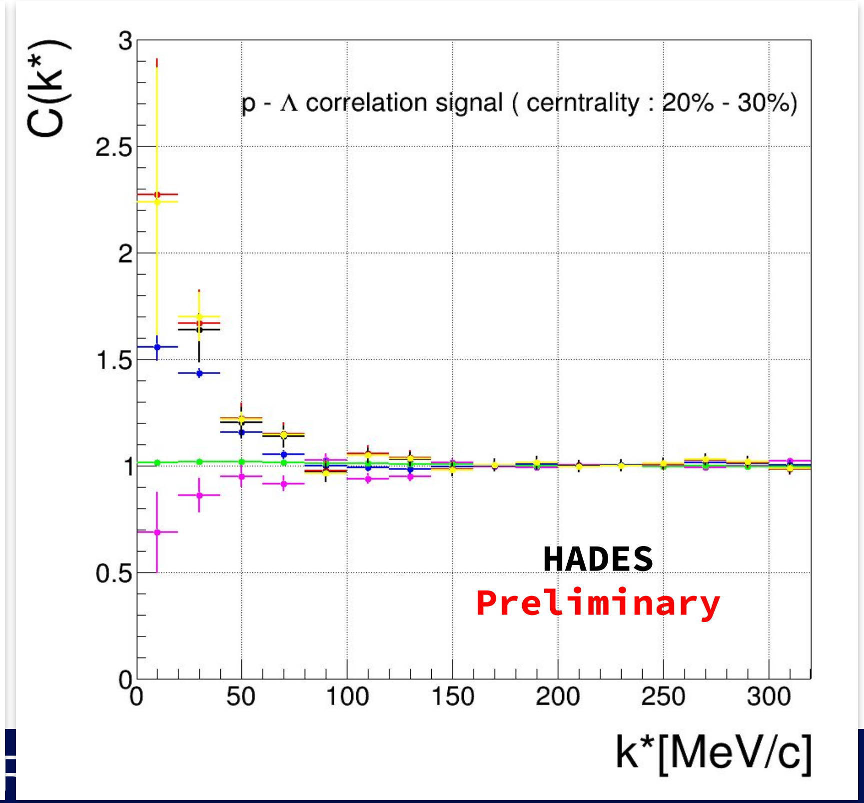
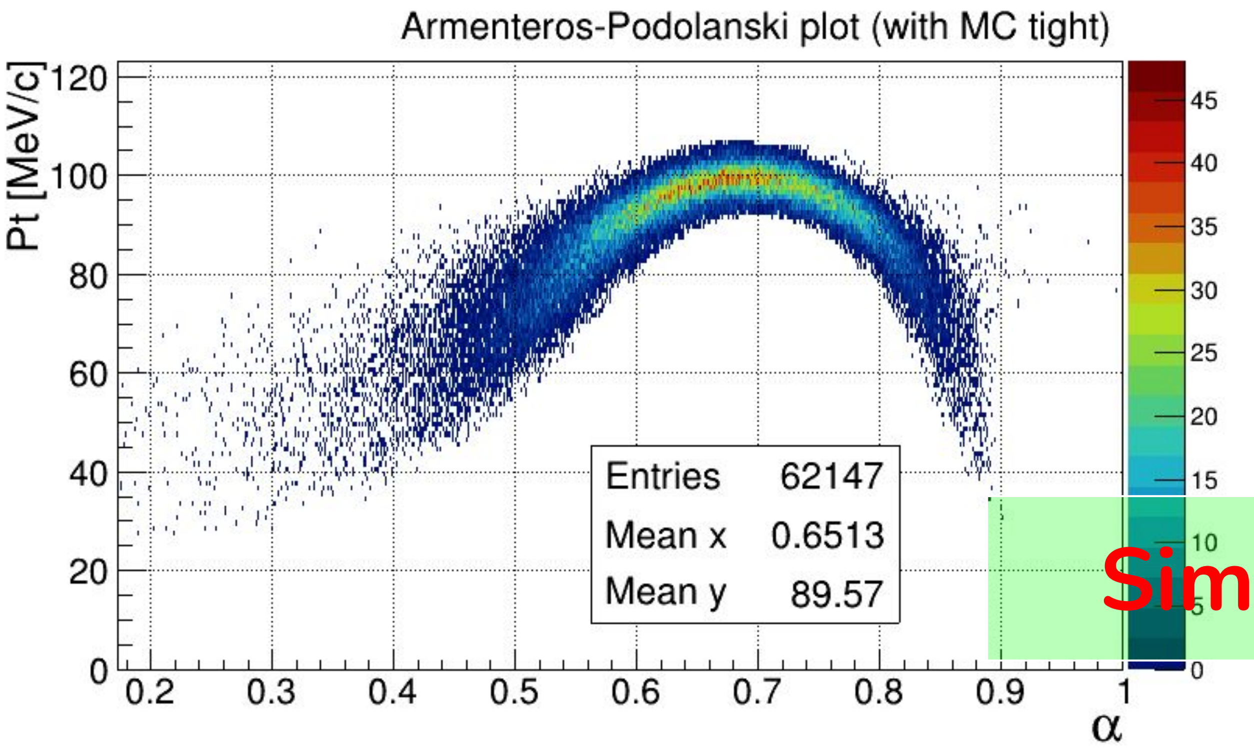
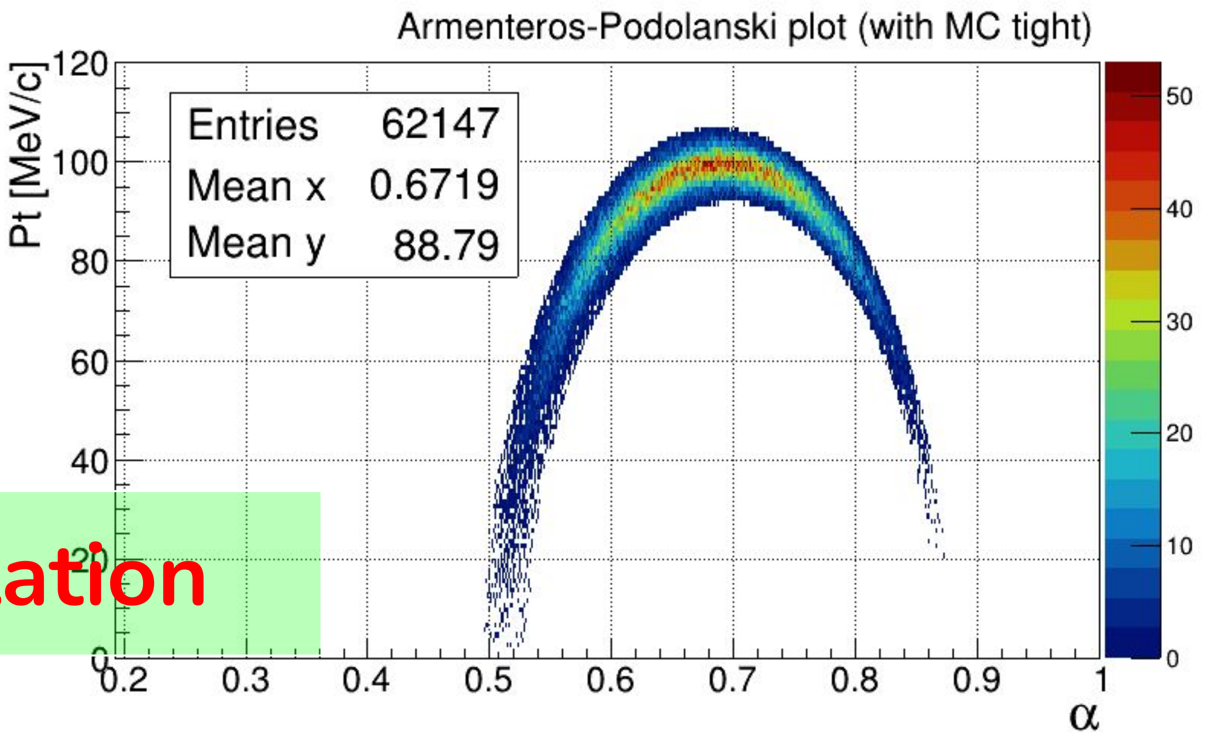






Armenteros-Podolanski plots





Simulation

HADES :
Low energies

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

→ **Corrected**

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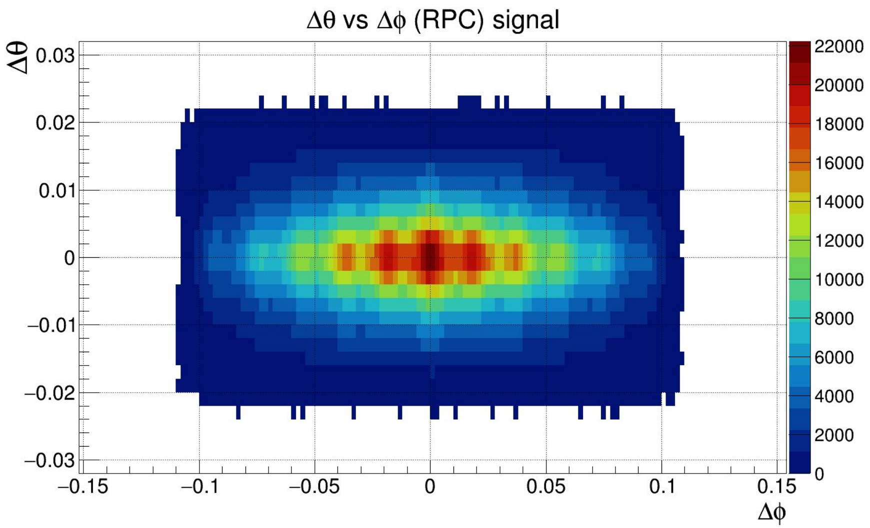
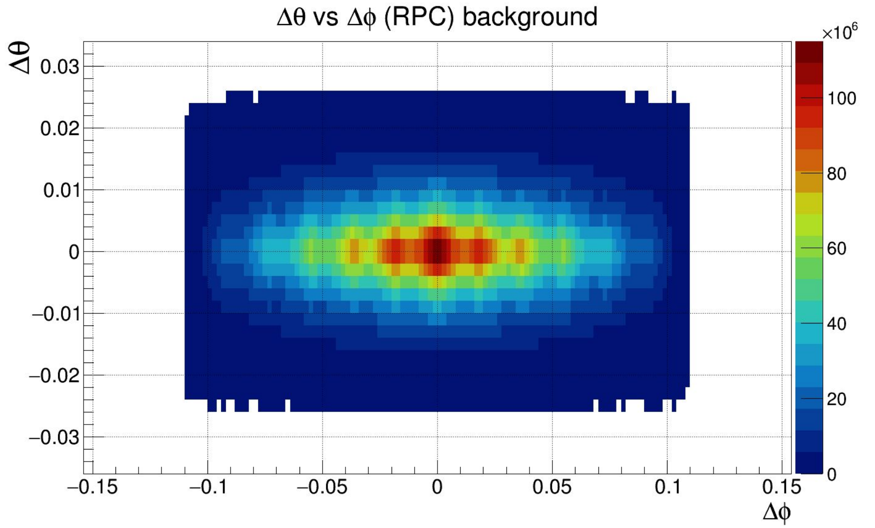
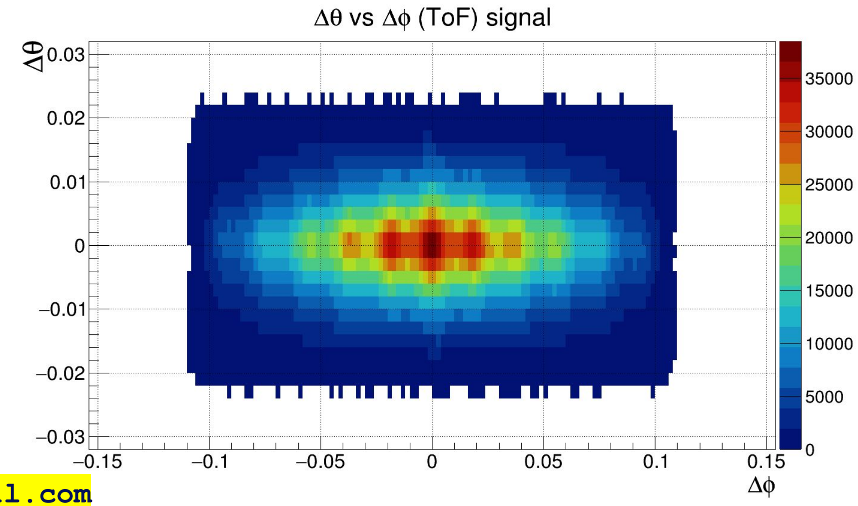
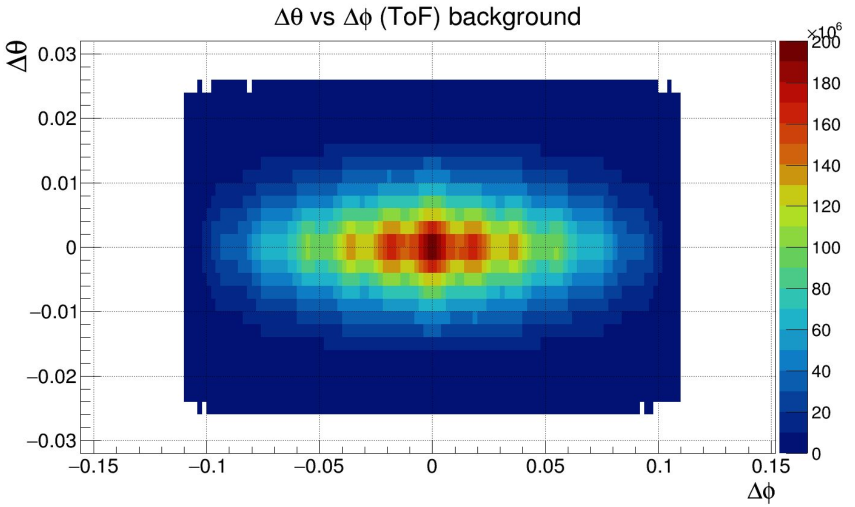
Δθ vs Δϕ distribution





RPC results





ToF results

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Lednicky & Lyuboshitz analytical model

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

where the wave function $\mathbf{\Psi^s}$ represents the approximate stationary solution of the scattering problem

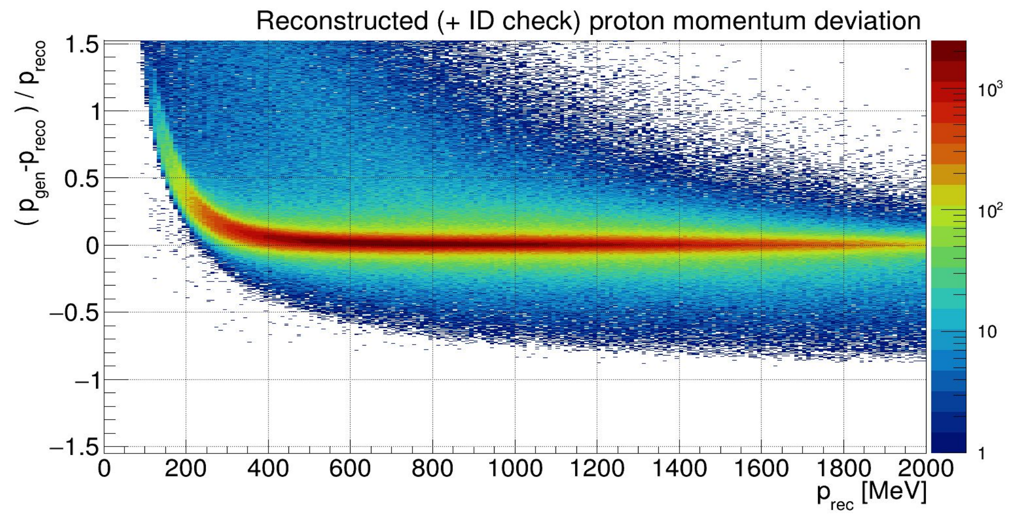
$$\Psi^S_{-\mathbf{k}^*}(\mathbf{r}^*) = e^{-i\mathbf{k}^* \cdot \mathbf{r}^*} + \frac{f^S(k^*)}{r^*} e^{ik^* \cdot r^*}.$$

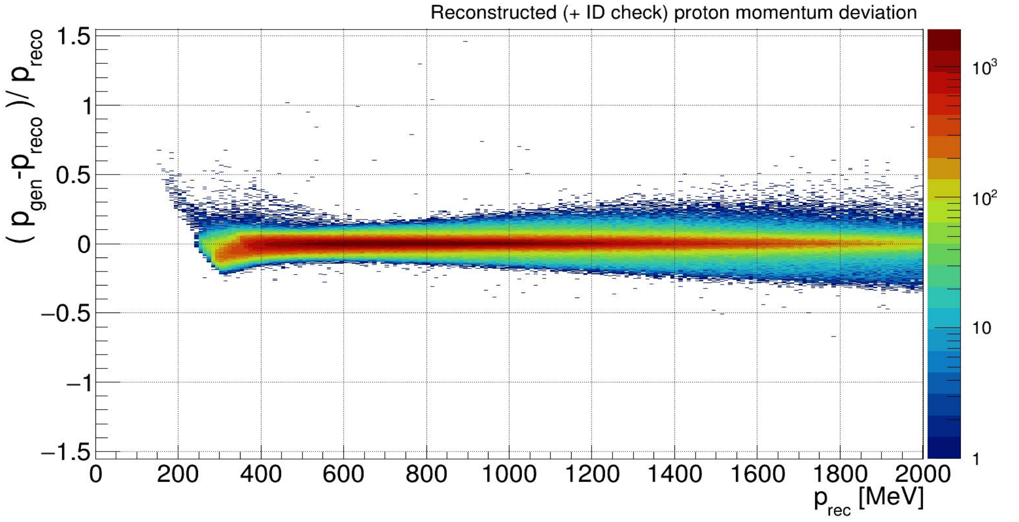
The effective range approximation for the scattering amplitude is

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

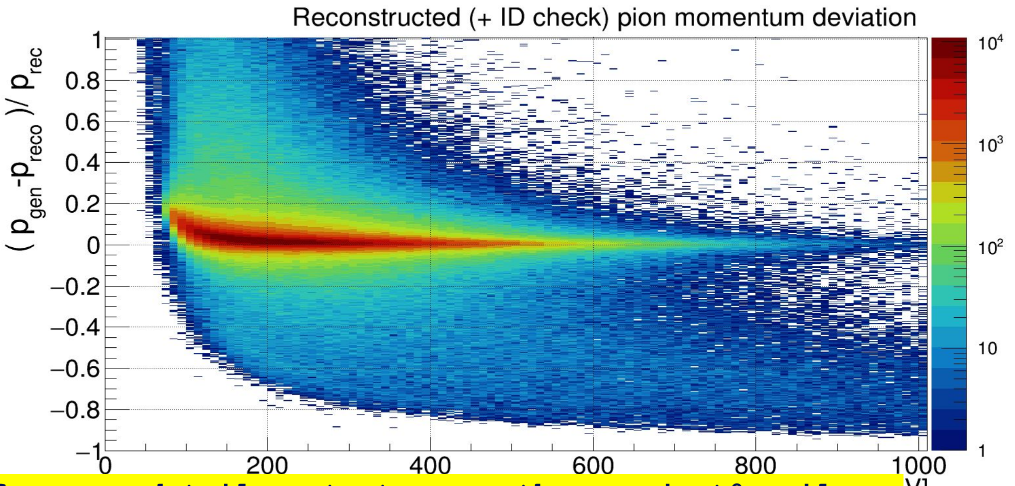
where $\boldsymbol{f_0^S}$ is the scattering length and $\boldsymbol{d_0^S}$ is the effective radius for a given total spin **S = 1** or **S = 0**.
The particle is assumed to be unpolarized (the polarization **P = 0**) :
singlet state $\boldsymbol{\rho_0 = \frac{1}{4} (1 - P^2)}$ and triplet state $\boldsymbol{\rho_1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

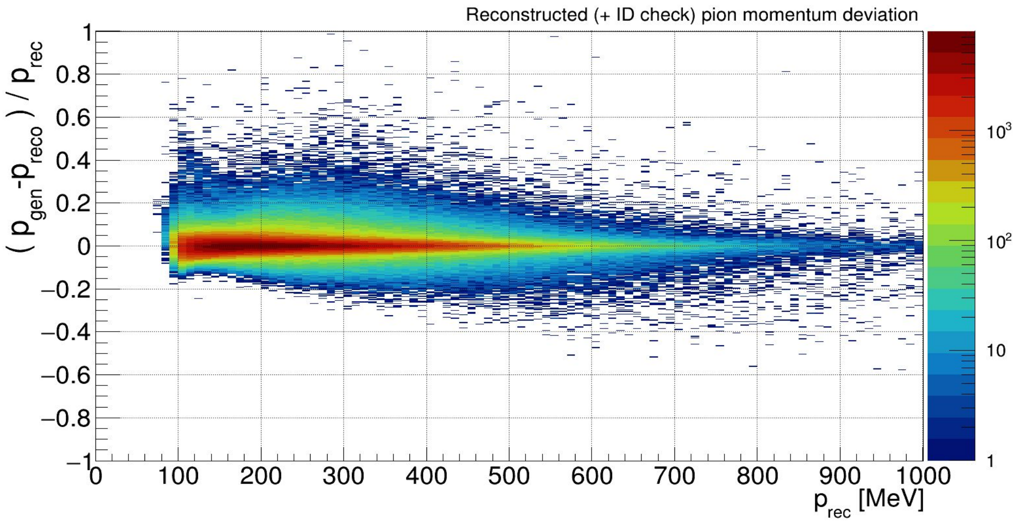
Energy-loss correction





Proton





Pion

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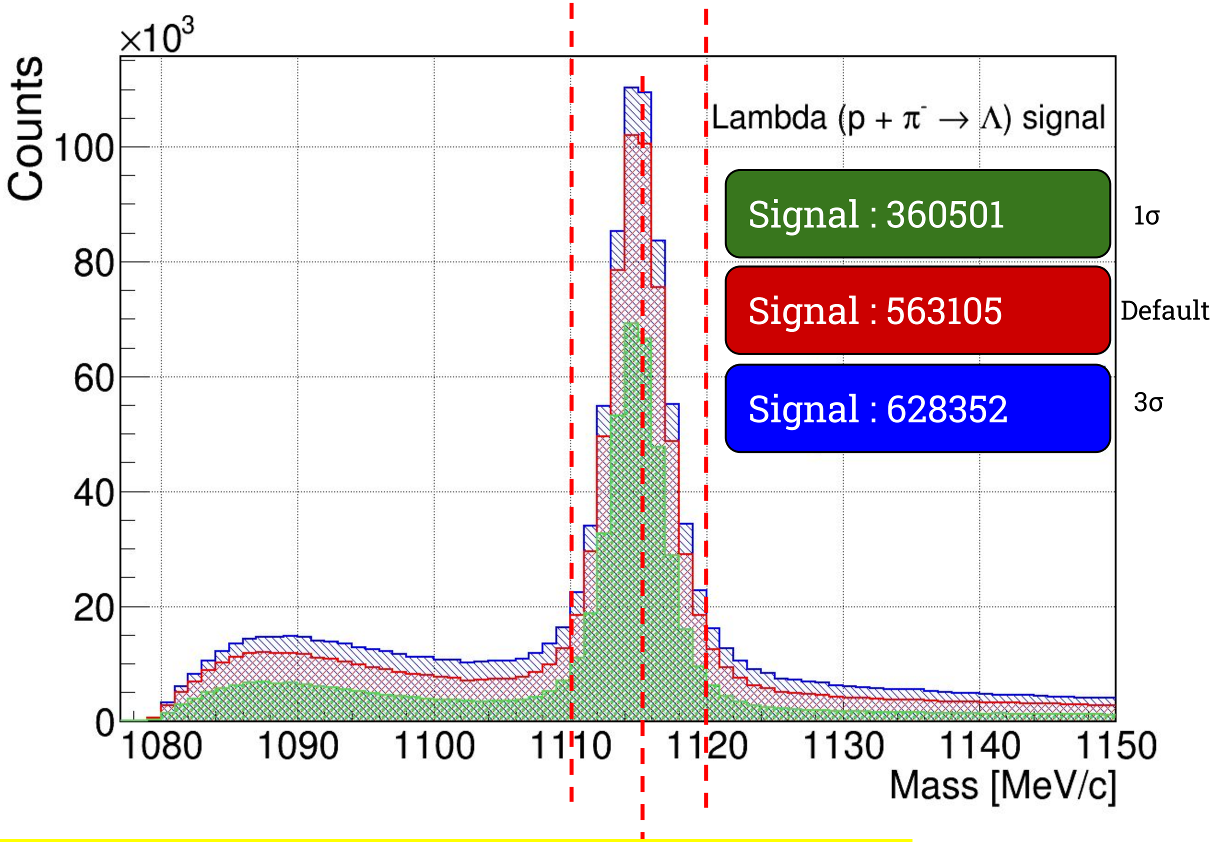
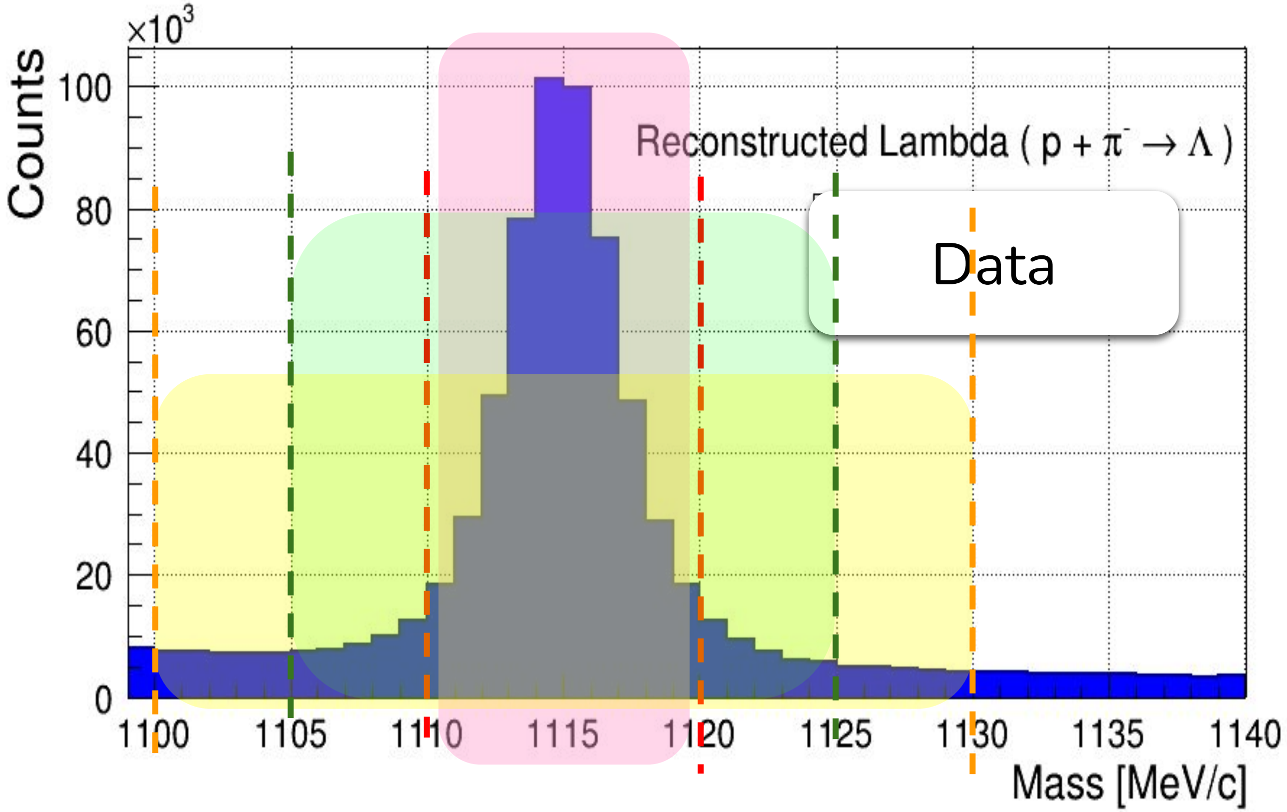
Systematics check (few of them)

PID variation



Mass cut variation



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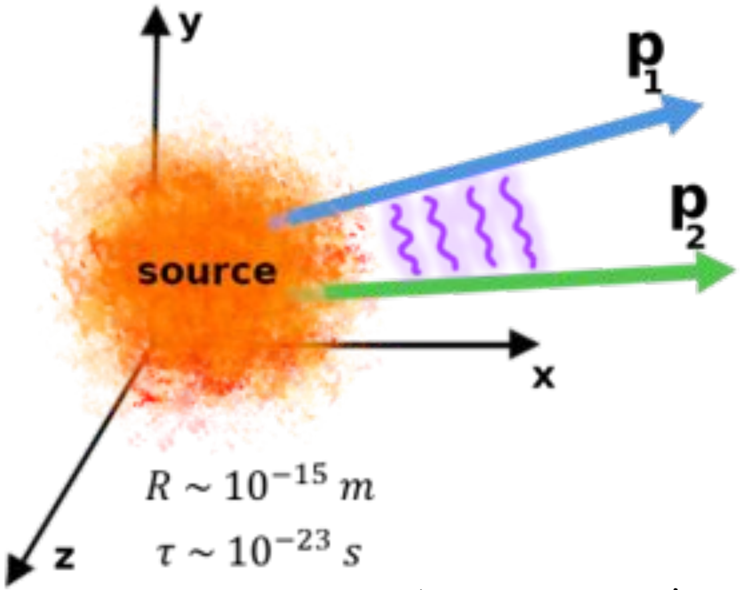
Femtoscopy : two particle correlation

Goal - measure source's space-time characteristics and interactions between particles through low relative momentum correlations.



Theory

Single particle emission function :

$$P(\vec{p}) = \int S(\vec{x},\vec{p})d^3x$$

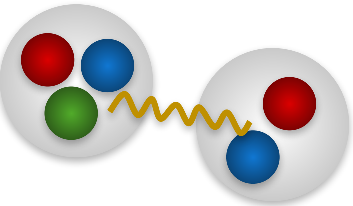
Two particle emission function :

$$P(\vec{p_1},\vec{p_1}) = \int S(\vec{x_1},\vec{p_1};\vec{x_2},\vec{p_2})|\Psi(\vec{x_1},\vec{p_1};\vec{x_2},\vec{p_2})|^2 d^3x_1 d^3x_2$$

Correlation function :

$$C(\vec{p_1},\vec{p_2}) = \frac{P(\vec{p_1},\vec{p_2})}{P(\vec{p_1})P(\vec{p_2})}$$

$$\vec{x} = particle's\, position$$
$$\vec{p} = particle's\, momentum$$
$$\Psi(\vec{x_1},\vec{p_1};\vec{x_2},\vec{p_2}) = two\, particle's\, wave\, function$$
$$S(\vec{x},\vec{p}) = source\, function$$
$$q = |\vec{p_1} - \vec{p_2}| = momentum\, difference$$
$$N_{same}(q_{inv}) = same\, event\, distribution$$
$$N_{mixed}(q_{inv}) = mixed\, event\, distribution$$

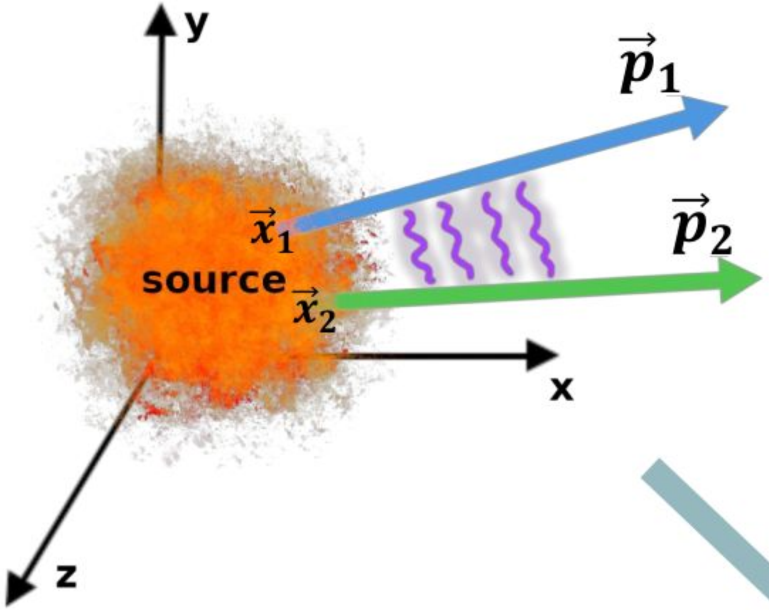


Experiment

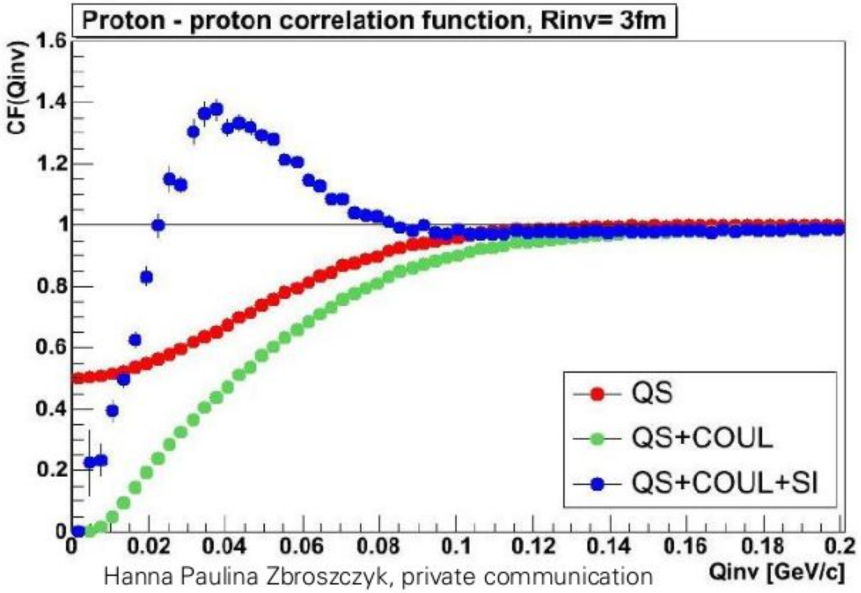
Correlation function :

$$C(q_{inv}) = \frac{N_{same}(q_{inv})}{N_{mixed}(q_{inv})}$$

Femtoscopy : two particle correlation



$q = |\vec{p}_1 - \vec{p}_2|$: momentum difference
$r = |\vec{x}_1 - \vec{x}_2|$: relative distance



$$CF(r,q) = \int S(r)|\Psi(r,q)|^2 d^3r$$

Determine the geometry and dynamic properties (traditional femtoscopy)

Determine the interactions (non-traditional femtoscopy)

Effects and interactions :

- **QS** – quantum statistics (Bose-Einstein or Fermi-Dirac), identical particles
- **Coul** – Coulomb interactions, charged particles
- **SI** – strong interactions, hadrons

***CF* < 1** : repulsion
***CF* = 1**: no correlation
***CF* > 1** : attraction

Thank you