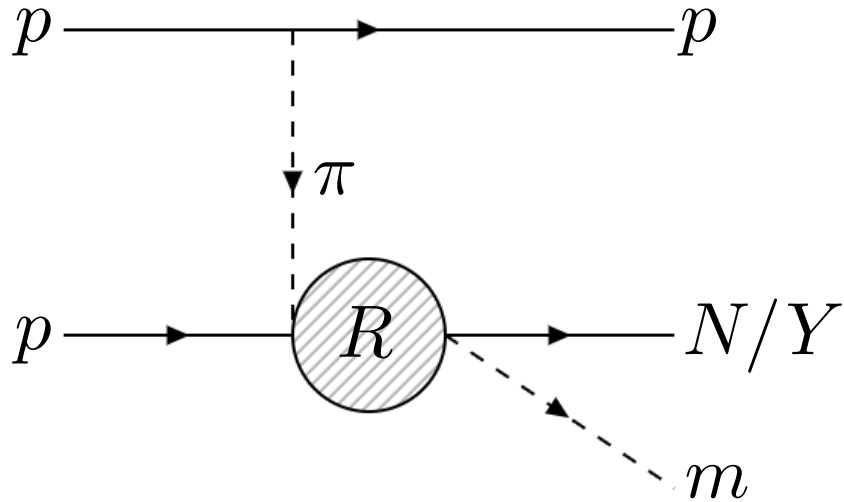


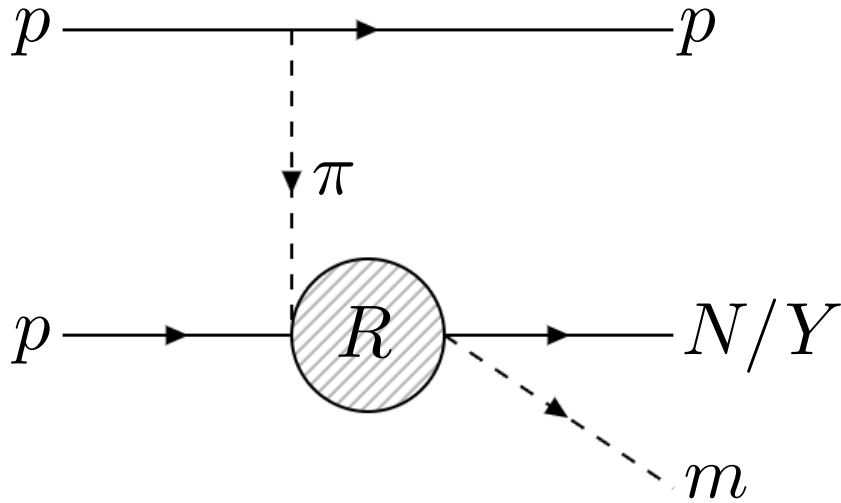
# $\pi$ -Beam @ HADES

Systematic Simulation Studies



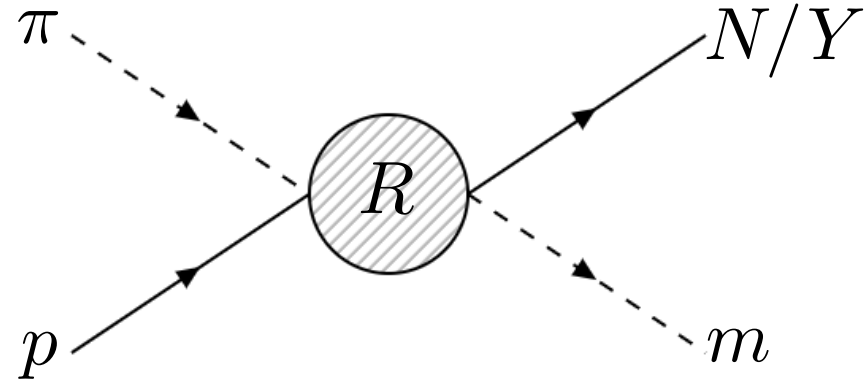


- Primary beam ( $8 \times 10^7$  p/bunch)  
Resonance excitation in subsystem leads to higher radial excitations
- Tool for small statistical uncertainties



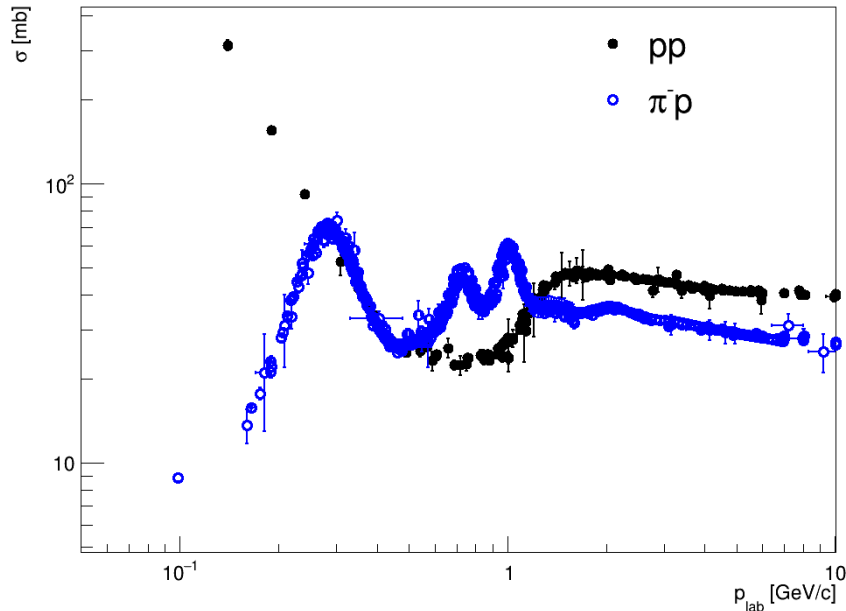
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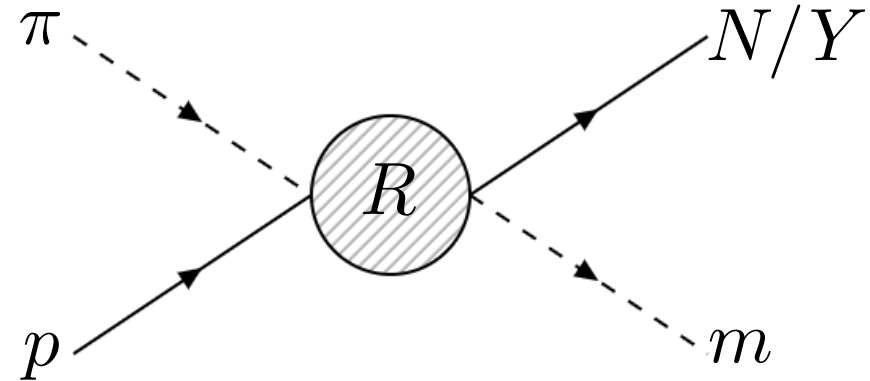


Secondary beam ( $8 \times 10^5$   $\pi$ /bunch)  
 S-channel resonance excitation with minimal reaction energy spread

- Tool for small systematic uncertainties

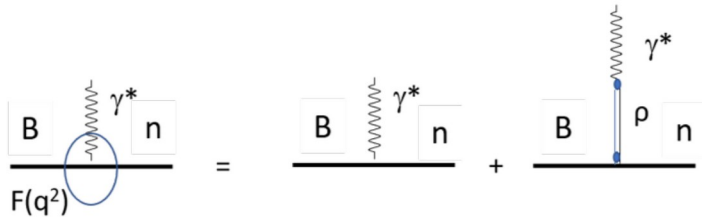
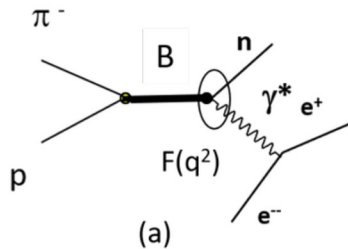


DOI: [10.1103/PhysRevD.110.030001](https://doi.org/10.1103/PhysRevD.110.030001)



Secondary beam ( $8 \times 10^5 \pi/\text{bunch}$ )  
 S-channel resonance excitation with  
 minimal reaction energy spread  
 > Tool for small systematic uncertainties

## emTFF measurements



The transition rate for a reaction is given by the product of the absolute square of the amplitude and a phase space factor

### Fermis Golden Rule

- Can be measured via differential decay rate
  - $d\Gamma / dM_{e^+e^-} \propto |G_T(q^2)|^2 \times \text{phase space}$
  - $|G_T(q^2)|^2$ : combination of squared electric, magnetic and coulomb form factors (model-dependent)
- and via the differential cross section
  - $d\sigma / dM_{e^+e^-} \propto (d\sigma / dM_{e^+e^-})_{\text{QED}} \times (|G_T(q^2)|^2 / |G_T(0)|^2)$
  - $(d\sigma / dM_{e^+e^-})_{\text{QED}}$ : point-like Baryon
  - $|G_T(q^2)|^2 / |G_T(0)|^2$ : Form factor correction
- as well as the spin-density-matrix via polarisation/PWA
  - $\rho_{ij} \propto G_T(q^2)$
  - $\rho_{11} = 0.5$ : real photons,  $\rho_{11} > 0.5$ : virtual photons

- Studying in-medium modifications (here e.g. „ $\rho$ -melting“)

## Vacuum spectral function

$$\mathcal{A}_\rho(M) \propto \frac{M^2 \Gamma_\rho}{(M^2 - M_\rho^2)^2 + M^2 \Gamma_\rho^2}$$

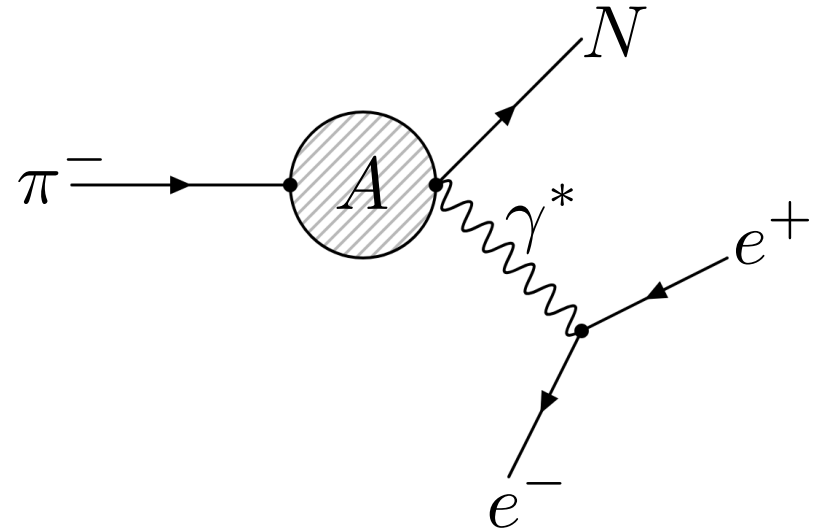
## In-medium spectral function (widening)

$$\mathcal{A}_\rho^*(M) \propto \frac{M^2 \Gamma_\rho^*}{(M^2 - (M_\rho^*)^2)^2 + M^2 (\Gamma_\rho^*)^2}$$

With  $\Gamma_\rho^* = \Gamma_{\rho, \text{vacuum}} + \Gamma_{\rho, \text{coll}} + \Gamma_{\rho, \text{pion cloud}}$

## Dalitz decay with modified $\rho$

$$\frac{d\Gamma^{N^* \rightarrow Ne^+e^-}}{dM_{e^+e^-}} \propto |G_T(q^2)|^2 \cdot \mathcal{A}_\rho^*(M_{e^+e^-})$$



# Main Goals of the Program

- Studying in-medium modifications (here e.g. „ $\rho$ -melting“)

## Vacuum spectral function

$$A_\rho(M) \propto \frac{M^2 \Gamma_\rho}{(M^2 - M_\rho^2)^2 + M^2 \Gamma_\rho^2}$$

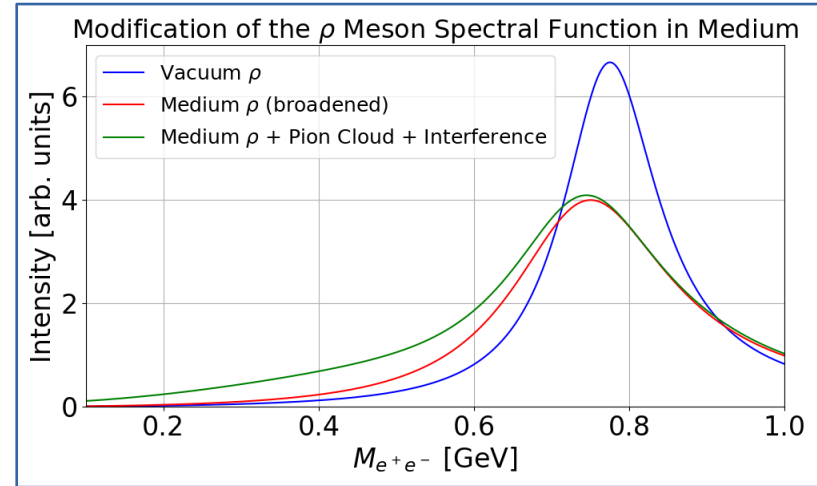
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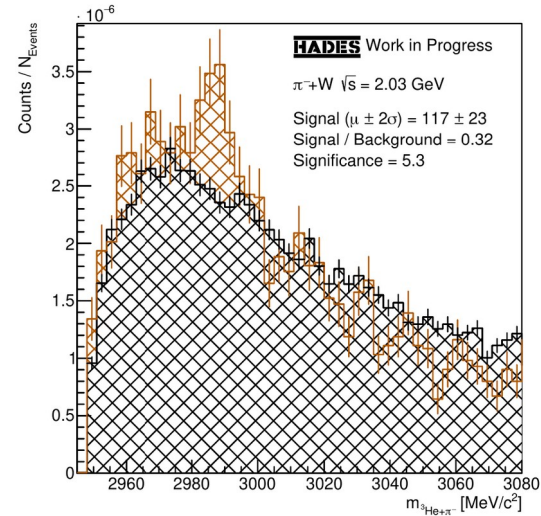
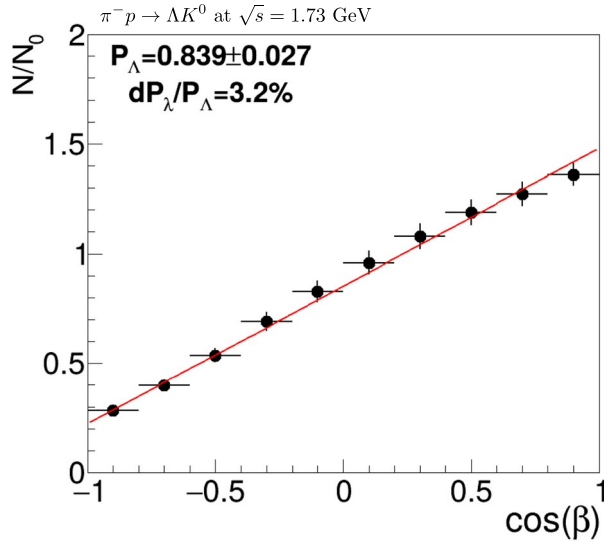
$$\frac{d\Gamma^{N^* \rightarrow Ne^+e^-}}{dM_{e^+e^-}} \propto |G_T(q^2)|^2 \cdot A_\rho^*(M_{e^+e^-})$$



“effective-model”:  $A = \text{Breit-Wigner}(M) + \text{Pion Cloud}(M) + \text{Interference}(M)$   
broadening: fixing  $\Gamma = 250 \text{ MeV}/c^2$   
pion cloud and interference: additive exponential terms

# Main Goals of the Program

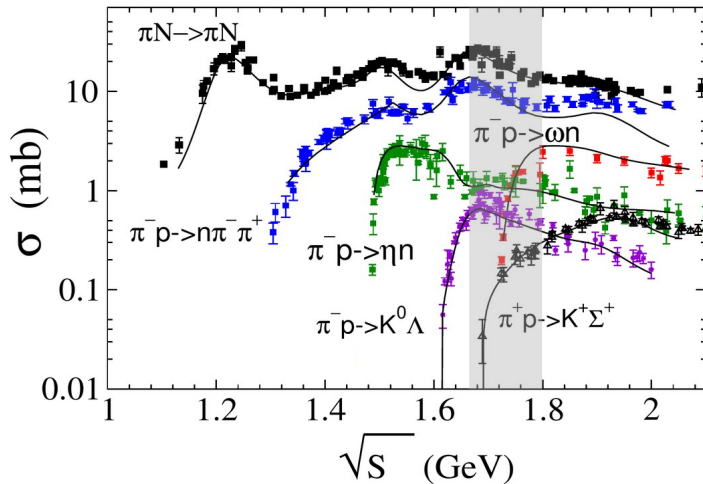
- Studying strange quark dynamics



$\pi$ -QCD Whitepaper

# Energy Scan (Approved)

- Scan from  $p_\pi = 1.007$  to  $1.228$  GeV/c
- Target strategy: Polyethylene (CH<sub>2</sub>), carbon
- Physics case: Hadronic spectroscopy, „probing the landscape“



- Baryonic resonances
- Strangeness production
- Vector meson studies

Expected statistics ( $p_\pi = 1.115$  GeV/c, 7 shifts (2 days, 8 hours), Polyethylene target):

$\pi^+ \pi^- n$	$\pi^0 \pi^- p$	$\pi^0 \pi^0 n$	$K^0 \Lambda$	$\Sigma^0 K^0$	$\Sigma^- K^+$	$\eta n$	$\omega n$
$24 \times 10^6$	$10 \times 10^6$	$3.4 \times 10^5$	$1.3 \times 10^5$	$5.6 \times 10^4$	$5.0 \times 10^5$	$8.4 \times 10^4$	$3.4 \times 10^5$

DOI: [10.1103/PhysRevC.93.045206](https://doi.org/10.1103/PhysRevC.93.045206)

- Systematic study of setup parameters based on key physics channels
  - Magnetic field
  - Trigger
  - RICH & iTOF
  - Forward tracking
  - Target geometry and START
- Prepared for and handed to CB and TB
- [Github Repo](#) for transparency
- Baseline: Feb22 Setup

## Towards an Optimised HADES Setup for Pion Beam

I. Ciepał, M. Kohls, P. Tlustý, M. Zielinski  
*For the HADES Beamtime Coordination*

### Abstract

This report is endorsed by the HADES beamtime coordinators for proton- and pion-induced reactions. The goal is to formulate a recommendation regarding the ideal setup to achieve the physics goals described for the beam energy scan in proposal G-122-00141. For the form factor measurements described in the other half of proposal G-22-00141, the belows' discussion on the necessity for RICH is unambiguous. While arguments from the technical coordination side are not primarily discussed in this study, we find evidence that the advantages for keeping RICH in place outweigh the disadvantages. Furthermore, the Forward Tracking stations (FTS-iRPC) are recommended to be set up for the reconstruction of specific physics channels and iTOF is not necessarily needed for triggering and  $t_0$  reconstruction, while worsening the quality of the obtained data.

### Contents

<b>1</b>	<b>Magnetic Field Studies</b>	<b>1</b>
1.1	$\pi^- (1 \text{ GeV}/c) + p \text{ INCL } ++$ Cascade Simulations . . . . .	1
1.2	$\pi^- (1.16 \text{ GeV}/c) + p \rightarrow K_S^0 + A$ (DT 1777)	3

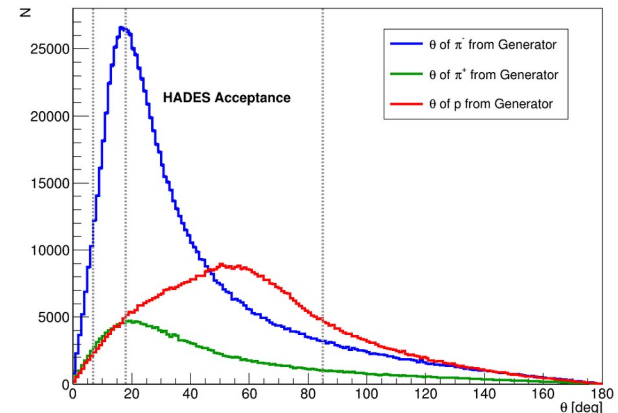
### 1 Magnetic Field Studies

The goal of the beam energy scan focuses on hadronic decay channels of resonances (in particular such containing strangeness). Previous settings for the magnetic field during beamtimes often focused on an optimised accep-

- Using INCL, we see a weak magnetic field dependence for the overall single pion and proton final state acceptance x efficiency

FPOL(current)	$\pi^-$	$\pi^+$	$p$
<b>0.92 (3200A)</b>	42.7 %	36.2 %	25.4 %
<b>0.72 (2500A)</b>	42.9 %	37.5 %	26.0 %
<b>0.47 (1600A)</b>	43.0 %	39.1 %	26.4 %

Table 1: Acceptance  $\times$  Efficiency values for the different particle species at the three magnetic-field settings derived from INCL simulations with  $p_{\pi^-, \text{Beam}} = 1 \text{ GeV}/c$  and HGeant+HADES tracking. All statistical uncertainties are below 0.1 %



- Using INCL, we see a weak magnetic field dependence for the overall single pion and proton final state acceptance x efficiency
- When reconstructing  $\pi^- p \rightarrow \Lambda [p \pi^-] K_S^0 [\pi^+ \pi^-]$ , difference becomes more pronounced

FPOL(current)	$\pi^-$	$\pi^+$	$p$
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<b>0.47 (1600A)</b>	38.4 %	35.8 %	43.5 %

Table 3: Acceptance  $\times$  Efficiency values for the different particle species at the three magnetic-field settings derived from PLUTO simulations for the  $\pi^- + p \rightarrow K_S^0(\rightarrow \pi^+ \pi^-) + \Lambda(\rightarrow p \pi^-)$  channel at  $p_{\pi^-, \text{Beam}} = 1.16 \text{ GeV}/c$  and HGeant+HADES tracking.

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FPOL(current)	Acc $\times$ Eff	$\sigma$ [MeV/c <sup>2</sup> ]
<b>0.92 (3200A)</b>	7.8 %	2.82
<b>0.72 (2500A)</b>	8.8 %	2.95
<b>0.47 (1600A)</b>	9.4 %	3.19

Table 4: Acceptance  $\times$  Efficiency values for the number of reconstructed  $\Lambda$ s and width of the invariant mass signal peaks as function of magnetic field setting, derived from PLUTO simulations for the  $\pi^- + p \rightarrow K_S^0(\rightarrow \pi^+ \pi^-) + \Lambda(\rightarrow p \pi^-)$  channel at  $p_{\pi^-, \text{Beam}} = 1.16$  GeV/c and HGeant+HADES tracking.

# Magnetic Field Settings

- Using INCL, we see a weak magnetic field dependence for the overall single pion and proton final state acceptance x efficiency
- When reconstructing  $\pi^- p \rightarrow \Lambda [p \pi^-] K_S^0 [\pi^+ \pi^-]$ , difference becomes more pronounced, especially when looking at the reconstructed Lambdas
  - A magnet current setting of 2500 A appears to deliver the best trade-off between precision and raw yield

FPOL(current)	$\pi^-$	$\pi^+$	$p$
0.92 (3200A)	36.4 %	33.3 %	31.3 %
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- Iza & Pavel compiled possible set of triggers

Set of the trigger conditions which can be applied during the 2027 run:

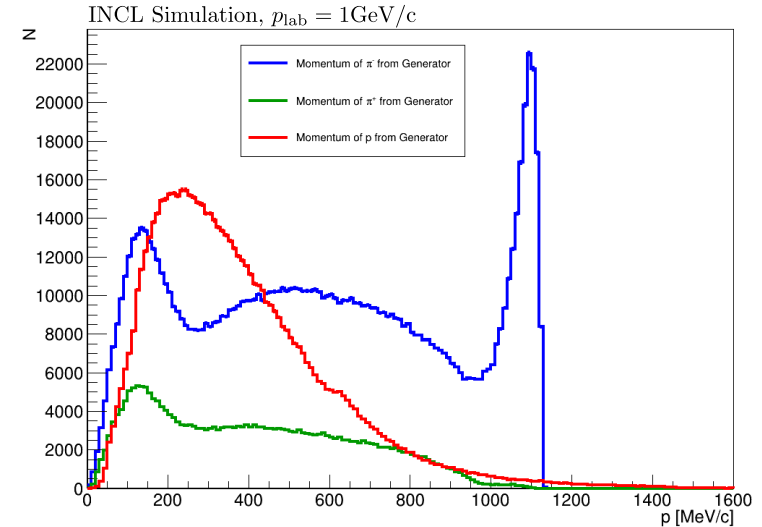
1.  $M1 = (\text{TOF} \parallel \text{RPC})_{\text{hitMult}} \geq 1$  (min. bias)
2.  $M2 = (\text{TOF} \parallel \text{RPC})_{\text{hitMult}} \geq 2$
3.  $(\text{TOF} \parallel \text{RPC})_{\text{secMult}} \geq 1$  (min. bias)
4.  $(\text{TOF} \parallel \text{RPC})_{\text{secMult}} \geq 2$
5.  $\text{fullSector\_Mult} \geq 1$  (min. bias)
6.  $\text{fullSector\_Mult} \geq 2$
7.  $(\text{TOF} \parallel \text{RPC})_{\text{subsecMult}} \geq 1$  (min. bias)
8.  $(\text{TOF} \parallel \text{RPC})_{\text{subsecMult}} \geq 2$

- Iza & Pavel compiled possible set of triggers
- One of the main issues:
  - iTOF presence causes **additional multiple scattering** (later more)
  - **With iTOF**, main trigger could be **HADES multiplicity  $\geq 1$**  with high purity (negligible accidental coincidences)
    - No numbers here, due to uncertain beam conditions
    - Based on current estimates we still expect  $\sim 1$  kHz of rate for each setting with about 30% chance coincidences

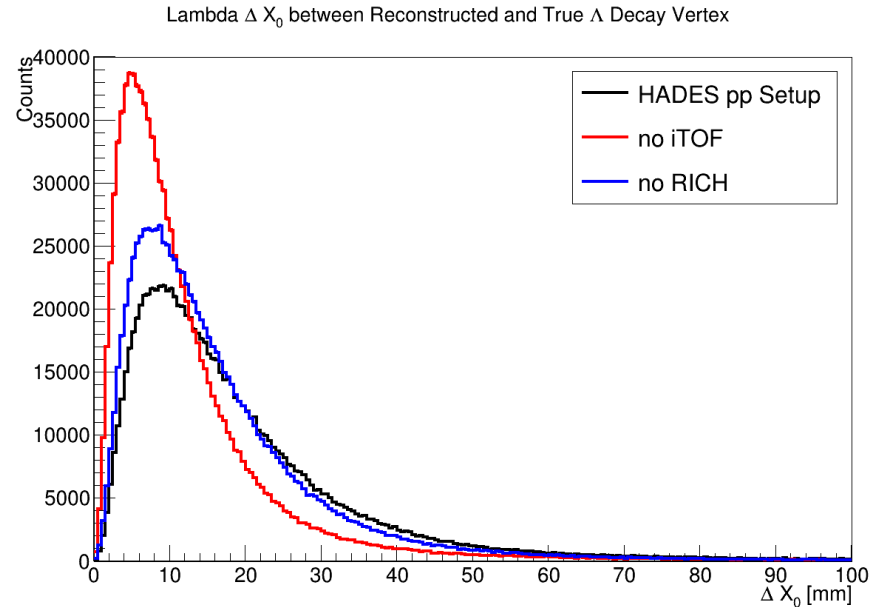
Set of the trigger conditions which can be applied during the 2027 run:

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7.  $(TOF \parallel RPC)_{subsecMult} \geq 1$  (min. bias)
8.  $(TOF \parallel RPC)_{subsecMult} \geq 2$

- Problem: more than 90% of charged pions and more than 50% of protons have momenta  $< 800$  MeV/c, with charged pions peaking at around 200 MeV/c ( $p_{\pi^-} = 1$  GeV/c)
  - In p+p,  $p < 200$  MeV/c was problematic!
- Idea: iteratively replace RICH and iTOF with volumes of air, comparing it to full setup

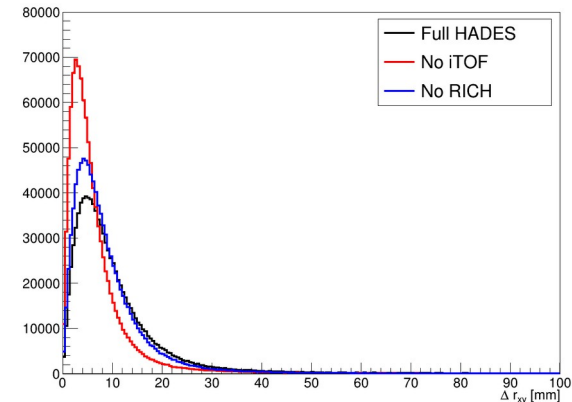
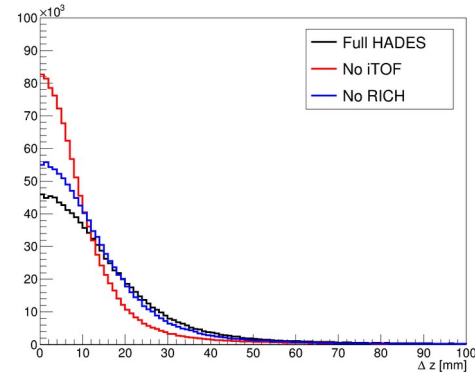


- PLUTO Simulation  $\pi^- p \rightarrow \Lambda [p \pi^-] K_S^0$   
 $[\pi^+ \pi^-]$
- $p_{\pi^-} = 1.16 \text{ GeV}/c$
- Using Lambda reconstruction as proxy for influence of multiple scattering for pointing precision
  - $\Delta X_0$ : residual for reconstructed Lambda decay vertex vs generator ground truth

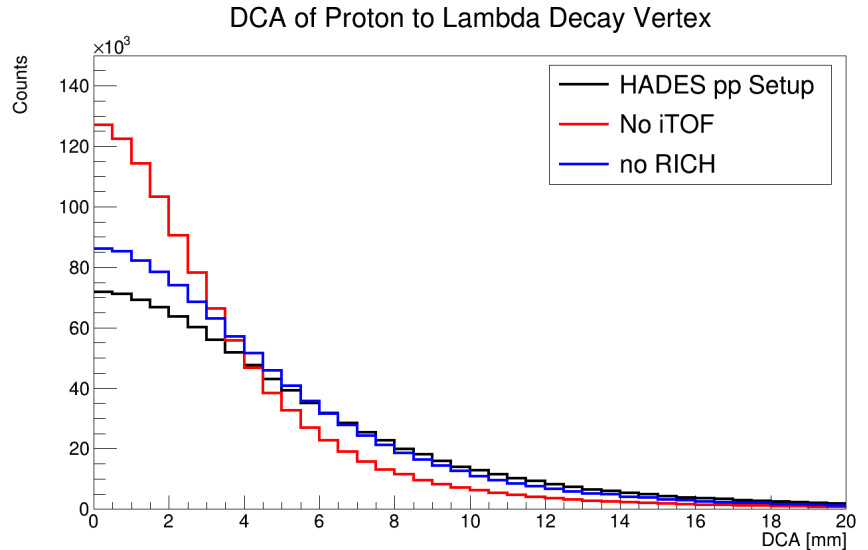


# Multiple Scattering in RICH and iTOF

- PLUTO Simulation  $\pi^- p \rightarrow \Lambda [p \pi^-] K_S^0$   
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- Using Lambda reconstruction as proxy for influence of multiple scattering for pointing precision
  - $\Delta X_0$ : residual for reconstructed Lambda decay vertex vs generator ground truth
  - Separated in longitudinal and transverse component
  - DCA between proton and pion from Lambda
- iTOF significantly worsens quality

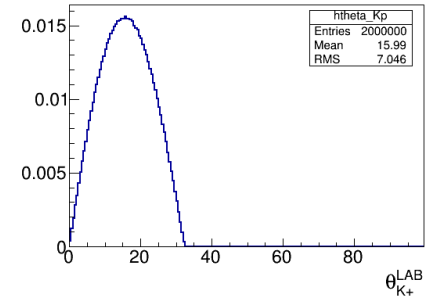
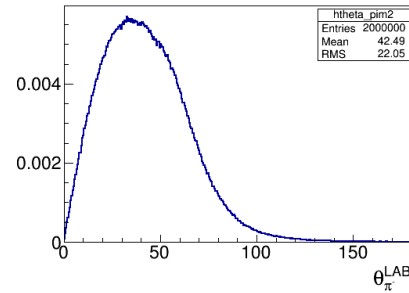
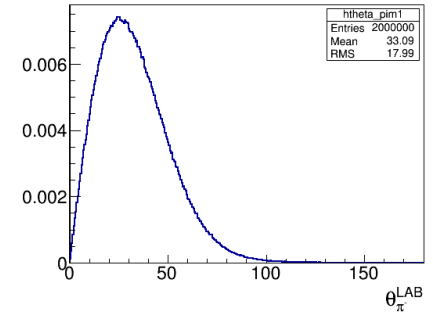
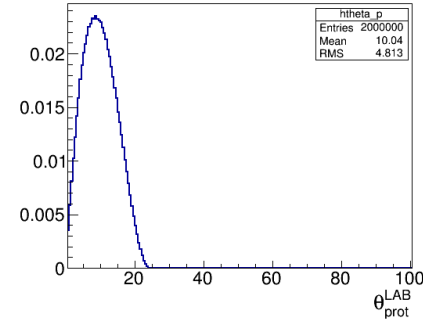
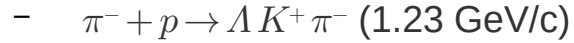
Setup	MPV [mm]	$\sigma$ [mm]
<b>Full</b>	$9.95 \pm 0.01$	$3.64 \pm 0.01$
<b>No RICH</b>	$8.56 \pm 0.01$	$3.11 \pm 0.01$
<b>No iTOF</b>	$5.95 \pm 0.01$	$2.24 \pm 0.01$

Table 9: Resulting Landau Fit Parameters for  $\Delta X$  distributions between reconstructed and true  $\Lambda$  decay vertex for different material budget setups.

Setup	Acc $\times$ Eff	$\sigma$ [MeV/c <sup>2</sup> ]
<b>Full</b>	$7.8 \pm 0.1 \%$	$2.82 \pm 0.01$
<b>No RICH</b>	$8.6 \pm 0.1 \%$	$2.47 \pm 0.01$
<b>No iTOF</b>	$8.8 \pm 0.1 \%$	$2.44 \pm 0.01$

Table 10: Acceptance  $\times$  Efficiency values for the number of reconstructed  $\Lambda$ s and width of the invariant mass signal peaks for different HADES setups, derived from PLUTO simulations for the  $\pi^- + p \rightarrow K_S^0(\rightarrow \pi^+ \pi^-) + \Lambda(\rightarrow p \pi^-)$  channel at  $p_{\pi^-, \text{Beam}} = 1.16 \text{ GeV}/c$  and HGeant+HADES tracking.

- Essential for channels at energetic threshold



- Important for channels at energetic threshold
  - $\pi^- + p \rightarrow \Lambda K^+ \pi^-$  (1.23 GeV/c)
  - $\pi^- + p \rightarrow K_S^0 + \Sigma^0 [\Lambda + \gamma]$  (1.16 GeV/c)

reaction	$N_{reco}^{HADES}$	$N_{reco}^{FT}$
$\pi^- + p \rightarrow K_S^0 + \Lambda$	296500	230
$\pi^- + p \rightarrow K_S^0 + \Sigma^0$	85500	29000

Table 11: Number of reconstructed  $\Lambda$ 's and  $\Sigma^0$ 's in the exclusive analysis with the decayed proton registered in HADES and FT.

reaction	$\epsilon_{reco}^{HADES}$ [%]	$\epsilon_{reco}^{FT}$ [%]
$\pi^- + p \rightarrow K_S^0 + \Lambda$	6	$\leq 1\%$
$\pi^- + p \rightarrow K_S^0 + \Sigma^0$	1	0.4

Table 12: Reconstruction efficiency for  $\Lambda$  and  $\Sigma^0$  in the exclusive analysis with the decayed proton registered in HADES and FT.

- Pion beam program essential to enhance understanding of structure and dynamics of baryonic resonances
- Report produced to deliver recommendations on the basis of physics considerations
  - Many more details in the report
  - Now that we have some time: in-beam detector for beam momentum measurement?

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- Report produced to deliver recommendations on the basis of physics considerations
  - Many more details in the report
  - Now that we have some time: in-beam detector for beam momentum measurement?
- Paper in preparation regarding upcoming beam energy scan (systematic performance studies and baseline estimation)
  - Official simulations currently in preparation by Jochen

# BACKUP

- Density matrix in QM is projection operator on state  $|\psi\rangle$ 
  - $\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i|$
  - $\sum_i p_i = 1$  probability for state
  - for pure states  $i = 1$  (and  $p = 1$ )
  - Spin orientation, phase relations, etc encoded
- For a spin-s-system  $\rho$  is a  $(2s+1) \times (2s+1)$  matrix
  - Diagonal elements show probabilities for spin states
  - Non-diagonal elements show phase relations between spin states
  - Example Spin  $\frac{1}{2}$ : 
$$\rho = \begin{pmatrix} \rho_{\uparrow\uparrow} & \rho_{\uparrow\downarrow} \\ \rho_{\downarrow\uparrow} & \rho_{\downarrow\downarrow} \end{pmatrix}$$

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- Example Spin  $\frac{1}{2}$ : 
$$\rho = \begin{pmatrix} \rho_{\uparrow\uparrow} & \rho_{\uparrow\downarrow} \\ \rho_{\downarrow\uparrow} & \rho_{\downarrow\downarrow} \end{pmatrix}$$

- To measure it one can use polarisation measurements

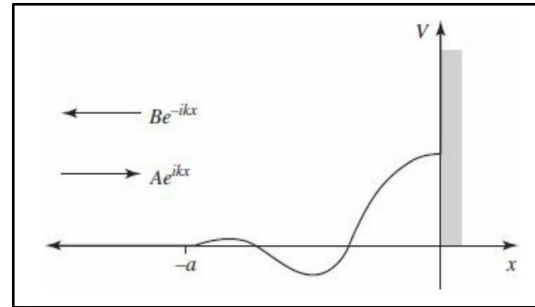
- For a spin  $\frac{1}{2}$  particle decaying spin density matrix is then 
$$\rho = \frac{1}{2}(1 + \vec{P} \cdot \vec{\sigma})$$
- With vector  $P$  polarisation vector
- And vector  $\sigma$  the pauli matrices

- In PWA: comes from amplitude and Clebsch-Gordan-Coefficients

- Low-momentum-transfer reactions (e.g.,  $\pi^-p \rightarrow K^0\Lambda$ ) offer high sensitivity to hyperon polarization
- Why is it important?

- PWA separates scattering wave functions into their components defined by the quantum numbers

- Orbital angular momentum ( $\ell$ )
- Parity (P)
- Isospin (I)
- Spin (S)

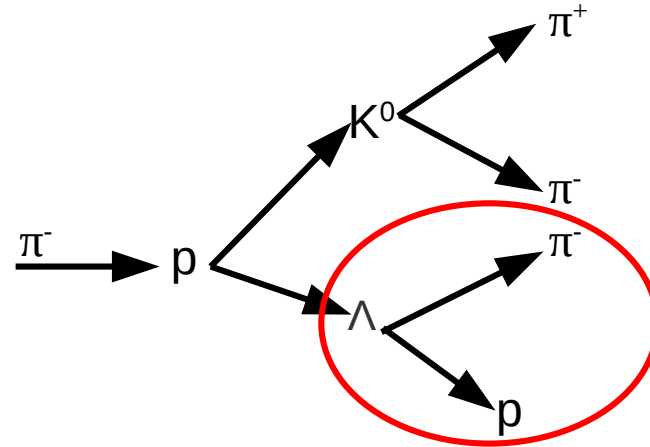
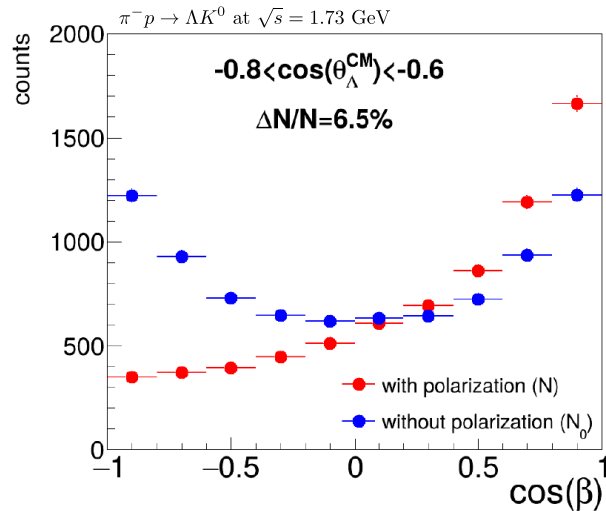


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- Polarisation indicates which partial wave dominates and helps to discern resonances with similar mass but different spin/parity (resolving ambiguities)

- S-wave (L=0) has no polarisation
- P-wave (L=1) would show an angular dependence

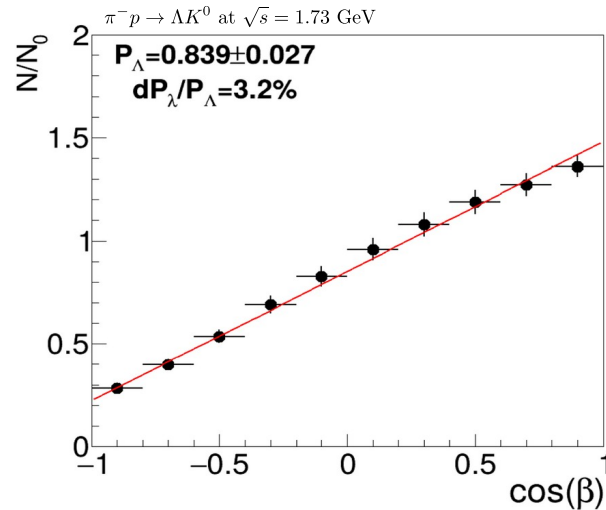
- Low-momentum-transfer reactions (e.g.,  $\pi^- p \rightarrow K^0 \Lambda$ ) offer high sensitivity to hyperon polarization



$\theta$ :  $\Lambda$  emission angle in the reaction system c.m. frame

[π-QCD Whitepaper](#)

- Low-momentum-transfer reactions (e.g.,  $\pi^- p \rightarrow \Lambda K^0$ ) offer high sensitivity to hyperon polarization



In the Lambda c.m. frame:

$$\frac{dN}{d \cos \beta} = N_0 (1 + \alpha P_\Lambda \cos \beta) \cdot f(\cos \beta)$$

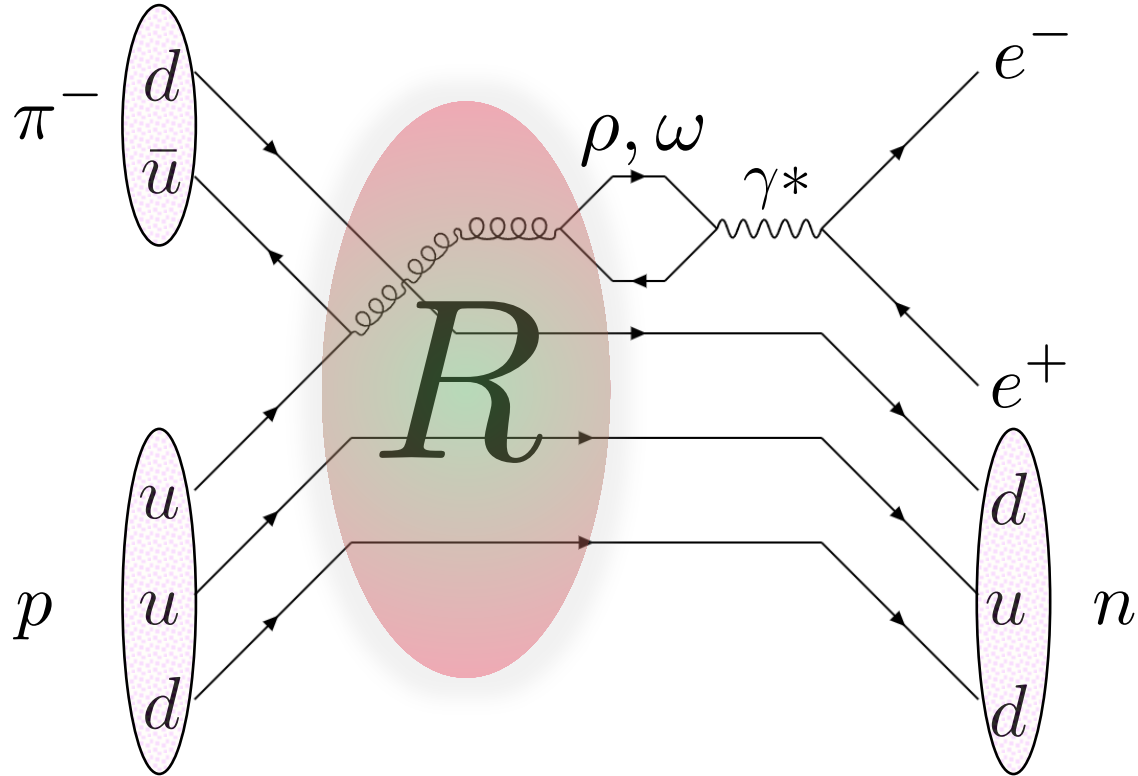
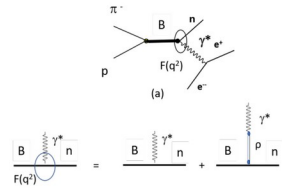
Polarisation term    phase-space term

$\beta$ : angle between p vector and polarisation axis

$P_\Lambda$ : polarisation (inclination/ $\alpha$ )

$\alpha \approx 0.750$ : asymmetry parameter of  $\Lambda$ -decay

$\pi$ -QCD Whitepaper



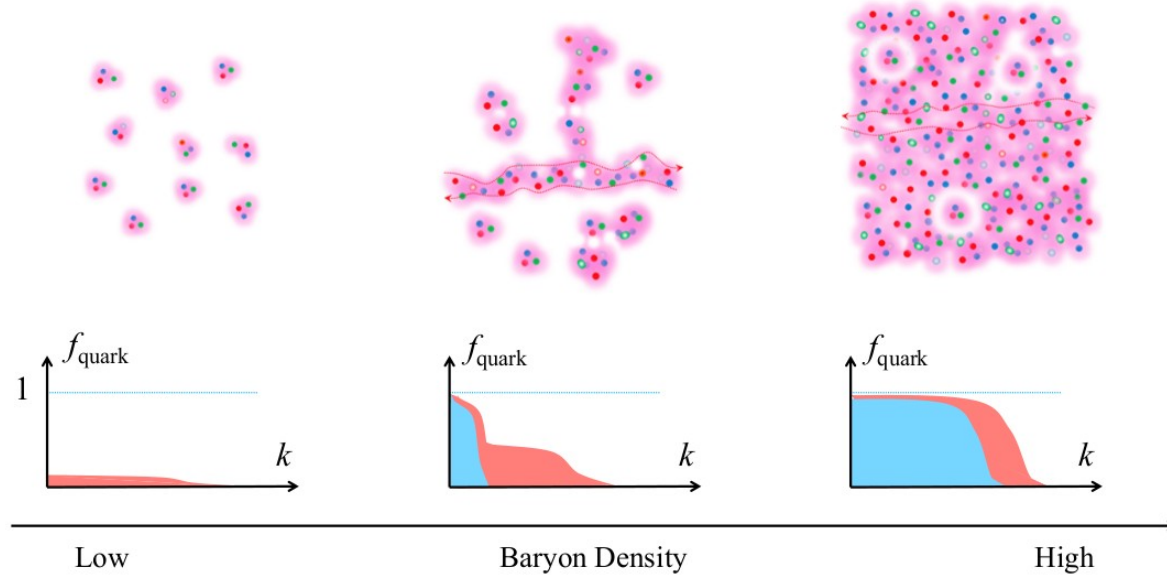


FIG. 12. Graphical representation of Soft and Hard Deconfinement based on the percolation picture. The occupation function,  $f_{\text{quark}}(k)$ , for quarks with momenta  $k$  is also schematically illustrated. The red (blue) area in  $f_{\text{quark}}(k)$  indicates the contributions from localized (delocalized) modes.

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