Highlights Chapter 7: Matter

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Introduction and motivation

Heavy-ion collisions in a nutshell

p ($\boldsymbol{\pi}$) + p (n) reactions

Reference measurements for Heavy-ion collisions

The FAIR energy range

p ($\boldsymbol{\pi}$) + A reactions

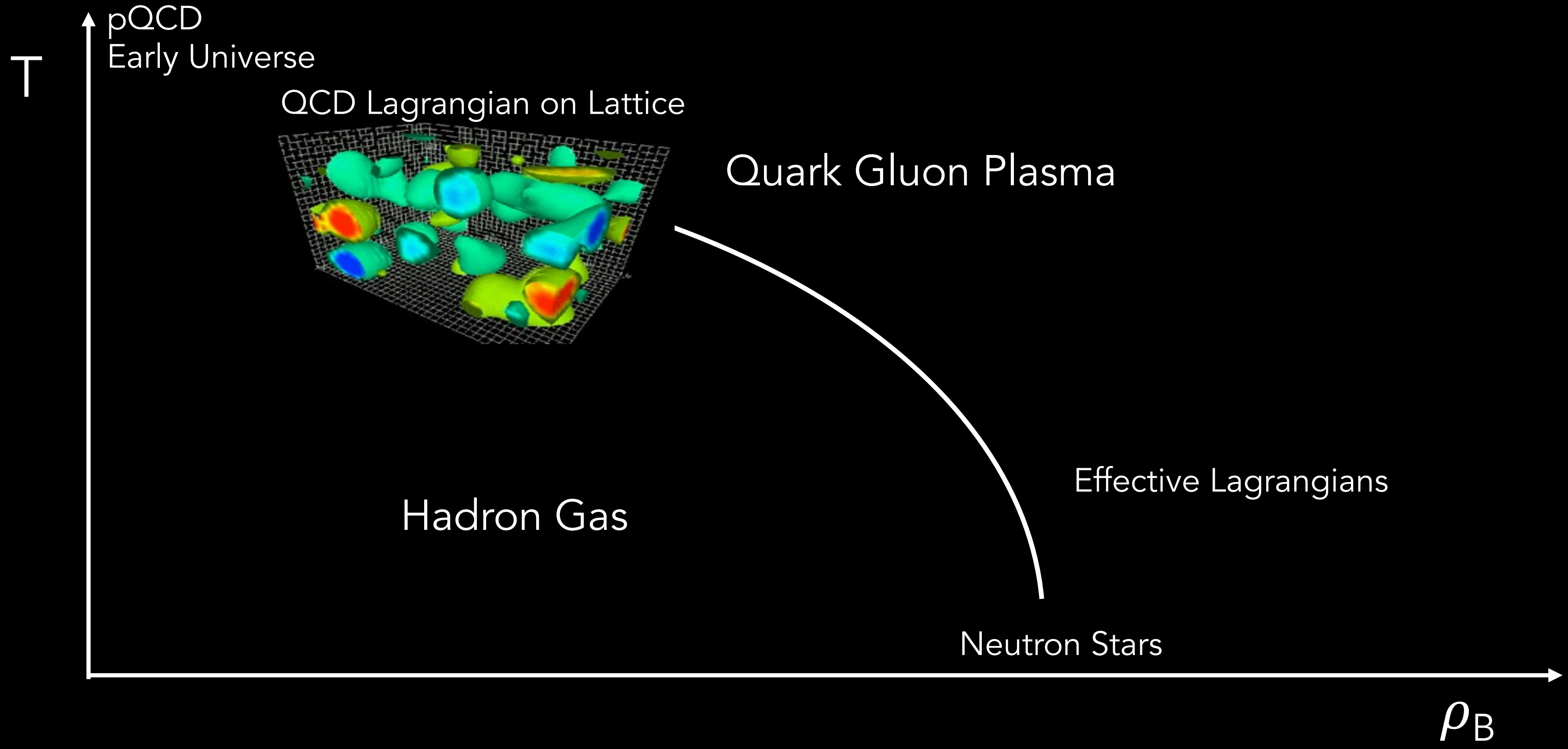
In-medium hadron properties

Hypernuclei formation

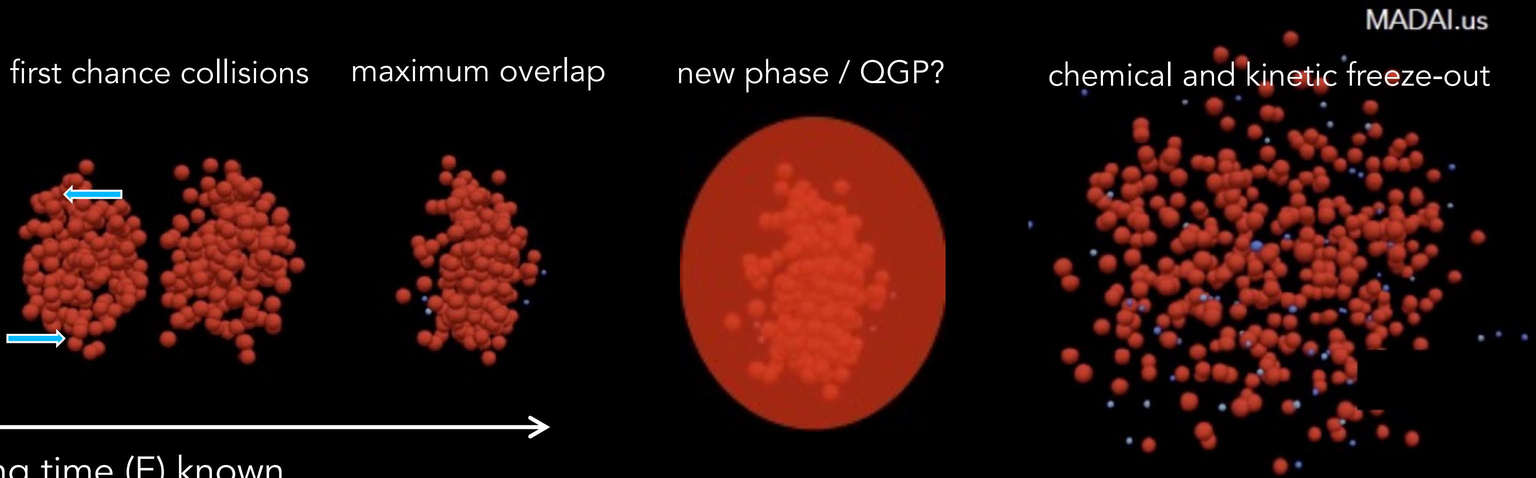
Charmonium in cold nuclear matter

Summary

The phase diagram of strongly interacting matter



Creating Extreme QCD Matter in the Laboratory: HICs



Passing time (E) known

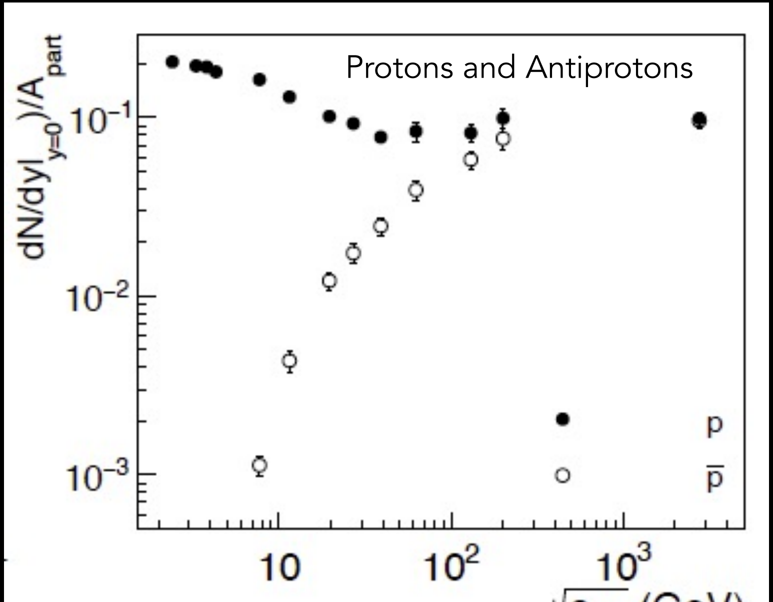
Lifetime of the system: Extract from comparison of observables with models ≈ 10^{-22}s (10 fm/c).

Directly controllable quantities:

- number of baryons in the colliding nuclei → The more the better: reproduce matter properties.
- center of mass energy $\sqrt{s_{NN}}$

→ Current accelerator facilities cover 3 orders of magnitude from a few GeV to TeV

Energy Dependence of hadron emission:



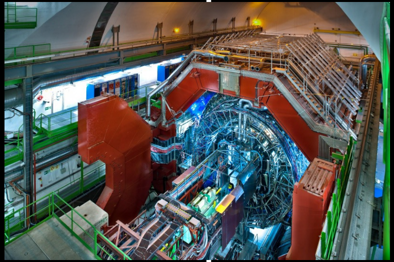
Data compilation M. Lorenz, HS, 2022

Similar amount of matter and antimatter at LHC at mid-rapidity

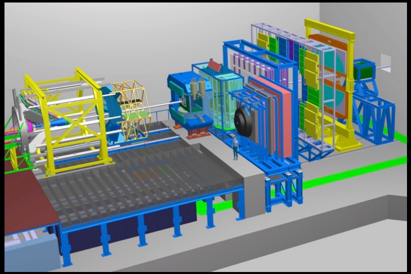
T

pQCD
Early Universe

Quark Gluon Plasma



Hadron Gas

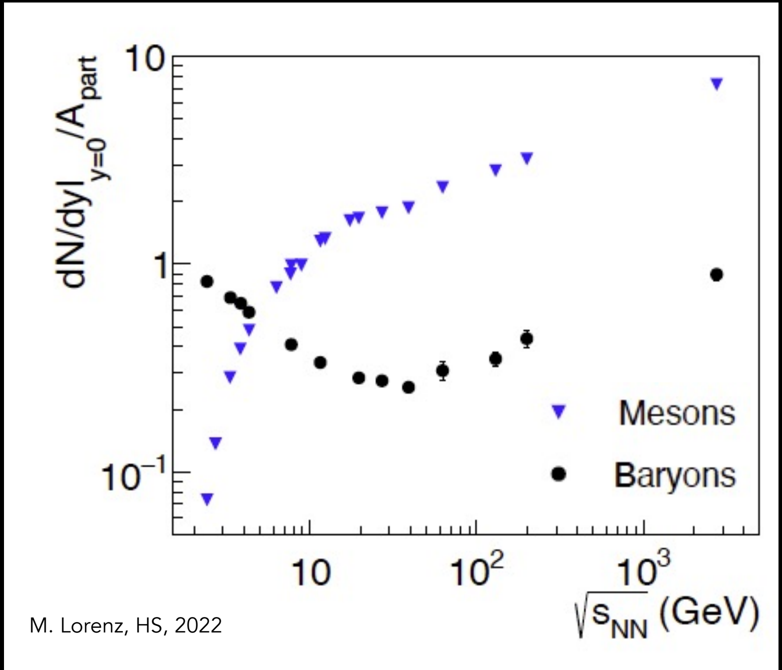


Neutron Stars

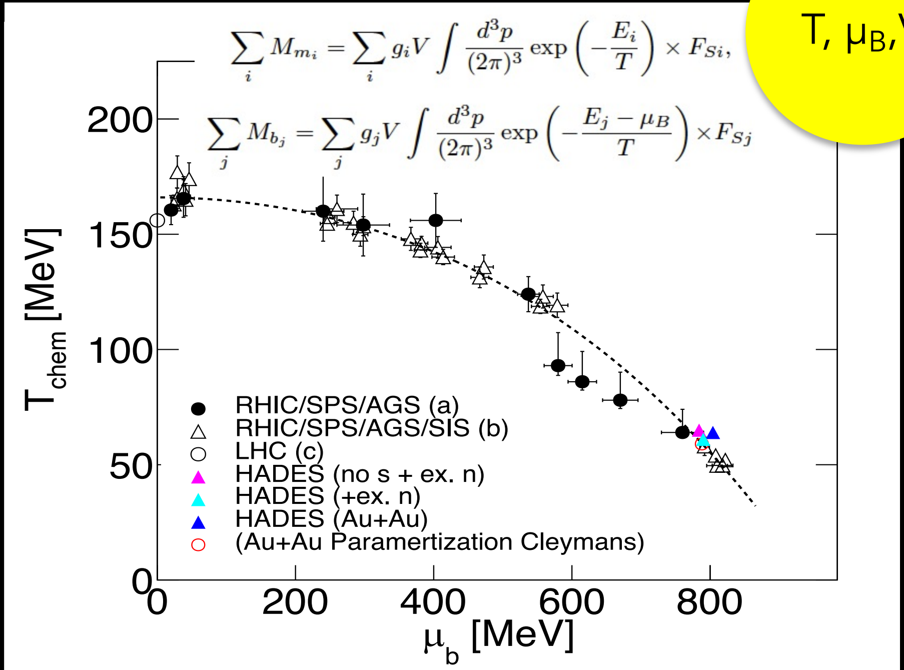
ρ_B

Energy Dependence of hadron emission:

T, μ_B,V



Switch from a baryon to meson dominated system at 4 GeV



Measurements at different $\sqrt{s}$ line up on a common curve

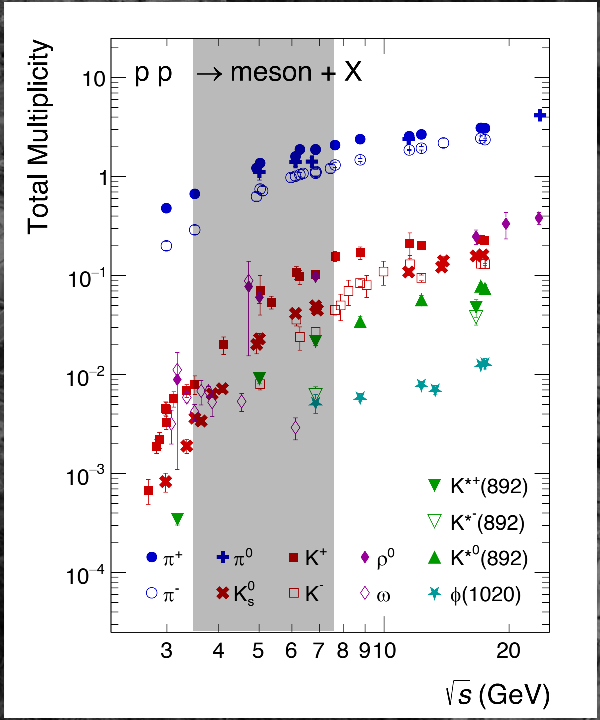
→ HIC allow to probe systematically the phase diagram.

→ $\sqrt{s}$ changes from GeV to TeV, T_{chem} changes by factor 3. Hadronic interactions important at all energies.

The FAIR energy range

Theory situation:
complicated region for phenomenological models:

- transition from resonance production mechanisms (2 → 2, 2 → 3) to multiparticle production (2 → n)
- transition from nuclear resonance models (3d phase space) to string formation and decay (longitudinal phase space) is not well known



Experimental situation:

- poor data on (light and strange) hadron multiplicities in p+p reactions
- practically NO data on hadron production in p+n reactions
- little information on differential spectra, correlations etc.
- no elastic scattering data for p_{Lab} > 1GeV (urgently needed for transport approaches)
- little information about multi-step processes

Reference measurements are basis for solid interpretation of heavy-ion data!

Reference measurements: highlights

Cross section measurements:

- high interaction rates, allow for reconstruction of rare hadrons
- large geometrical acceptance allows for study of large fraction of final state hadron
- dilepton capability for reconstruction of e.m. decay channels

π-beam

- systematic excitation of baryon and hyperon resonances, due to more selective excitation and larger cross-sections.

Nuclear targets

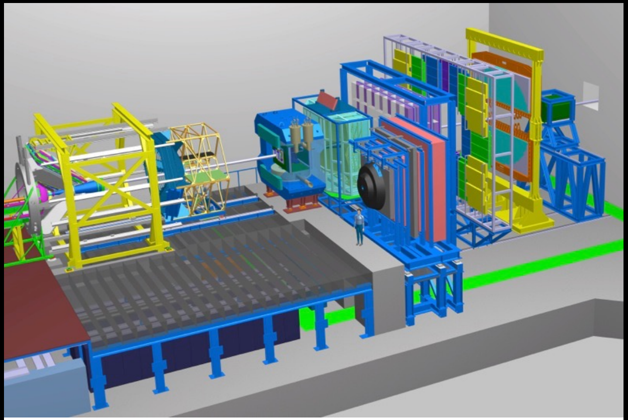
- intermediate step between p+p and π+p collisions, addressing re-scattering, multi-step processes ..

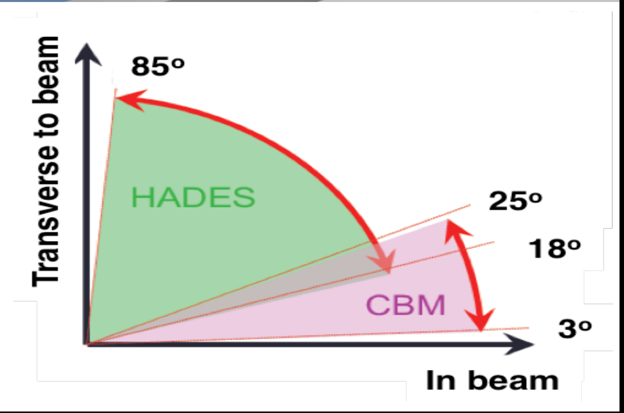
Isospin effects

- different nuclear targets

Phase-space distributions (isotropic vs. longitudinal elongated)

- Map out the transition from hadron to quark and gluon dominated hadron production.





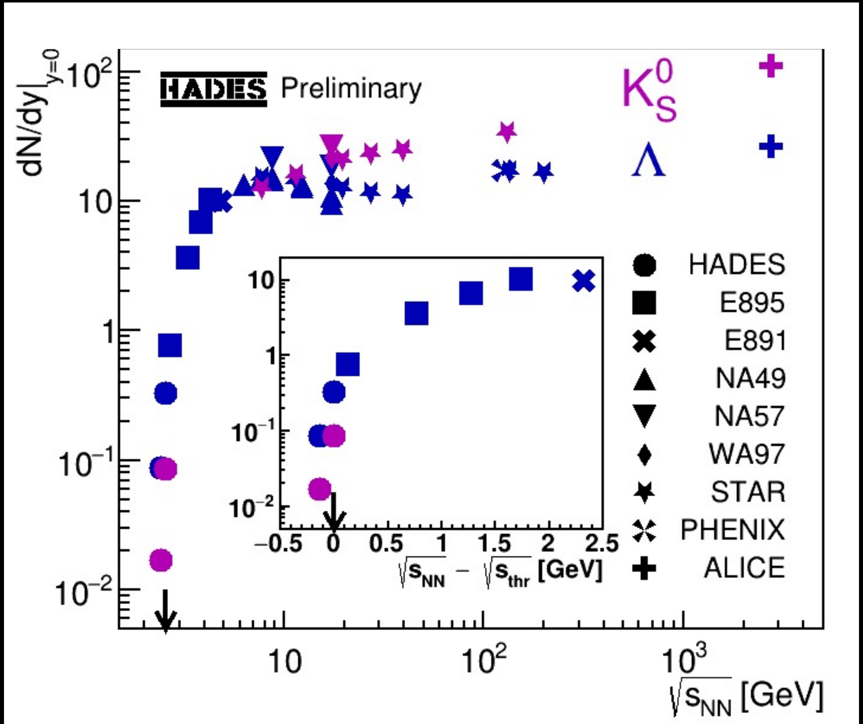
Sub-threshold strangeness production

Unique observable:
Not produced in binary NN collisions below $\sqrt{s_{NN}}$= 2.55 GeV

NN→NYK$^+$: $\sqrt{s_{NN}}$= 2.55 GeV,
NN→NNK$^+$K$^-$: $\sqrt{s_{NN}}$= 2.86 GeV
(strong K$^-$ suppression).

Energy must be provided from the system.

Steep excitation function
→ high sensitivity to properties of matter in the collision zone (Equation of State)



However, several effects influence sub-threshold strangeness production in the medium:

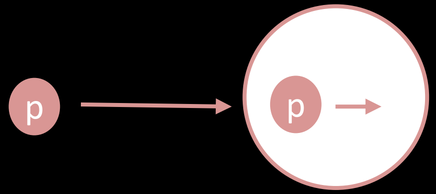
1. Multistep and multiparticle reactions. C.Hartnack, Phys. Rept. 510 (2012), 119-200
   Isolated N+N or more coherent process? Hadron formation time relative to the in-medium propagation time.

2. Role of resonances as energy reservoir. J. Steinheimer, J. Phys. G 43 (2016) no.1, 015104

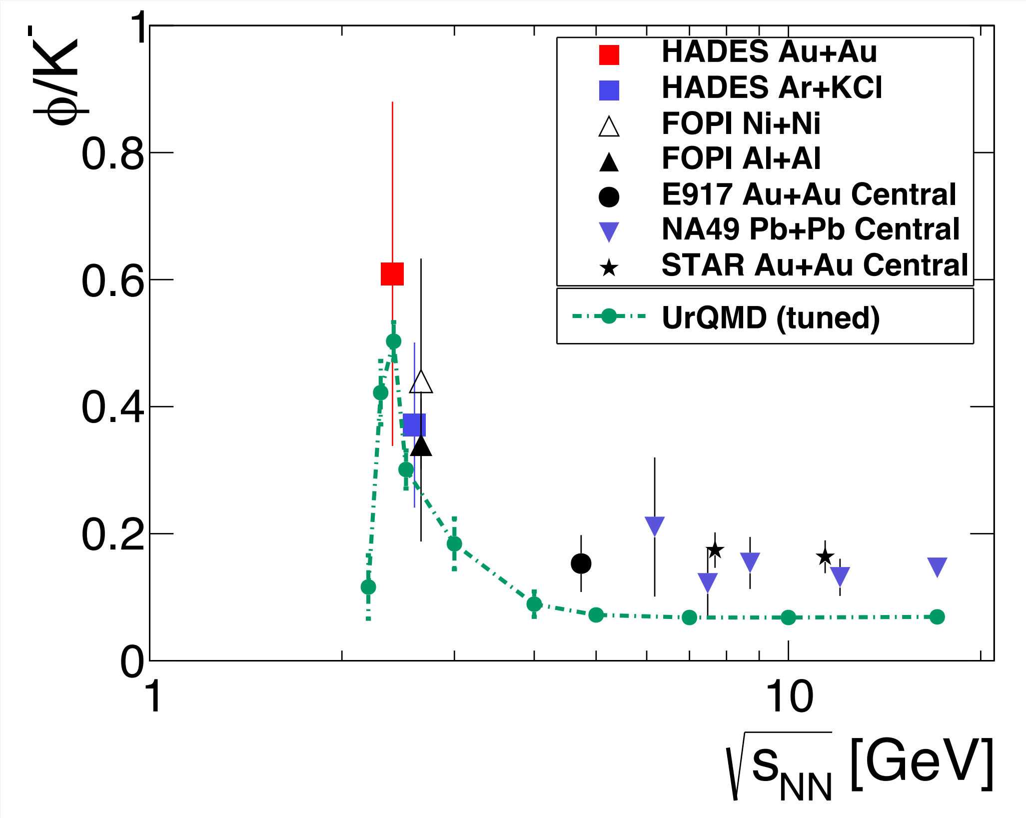
3. In-medium modifications lowering/enhancing the production thresholds due to the mass reduction/enhancement, e.g. G-matrix approach T. Song, Phys. Rev. C 103 (2021) no.4, 044901

→ Excitation function of strange and multi-strange hadrons in p+p, p+A and A+A.

4. Fermi-motion and short-range correlation of p+n pairs.
   → Quasi p+p elastic scattering have a strong preference for interacting with forward going high momentum nuclear protons, "Selective Attention".
   4.5 GeV kinetic energy optimal,
   e.g. possible with HADES+NeuLand



Sub-threshold production: ϕ/K^-



UrQMD:

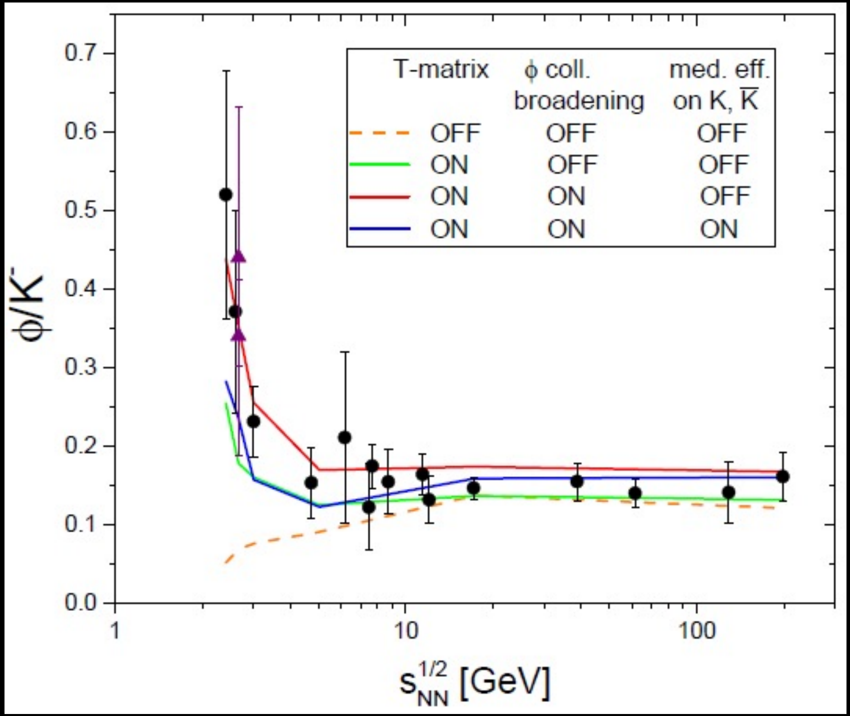
Tuned to match elementary data by increased branching ratios of N* (needed in the tails of the resonances, consistent with OZI rule)

Fixed to p+p data from Anke

First transport model to explain Φ/K^-

J. Steinheimer, J. Phys. G 43 (2016) no.1, 015104

Sub-threshold production of multi-strange hadrons



Orange: without T-matrix & broadening

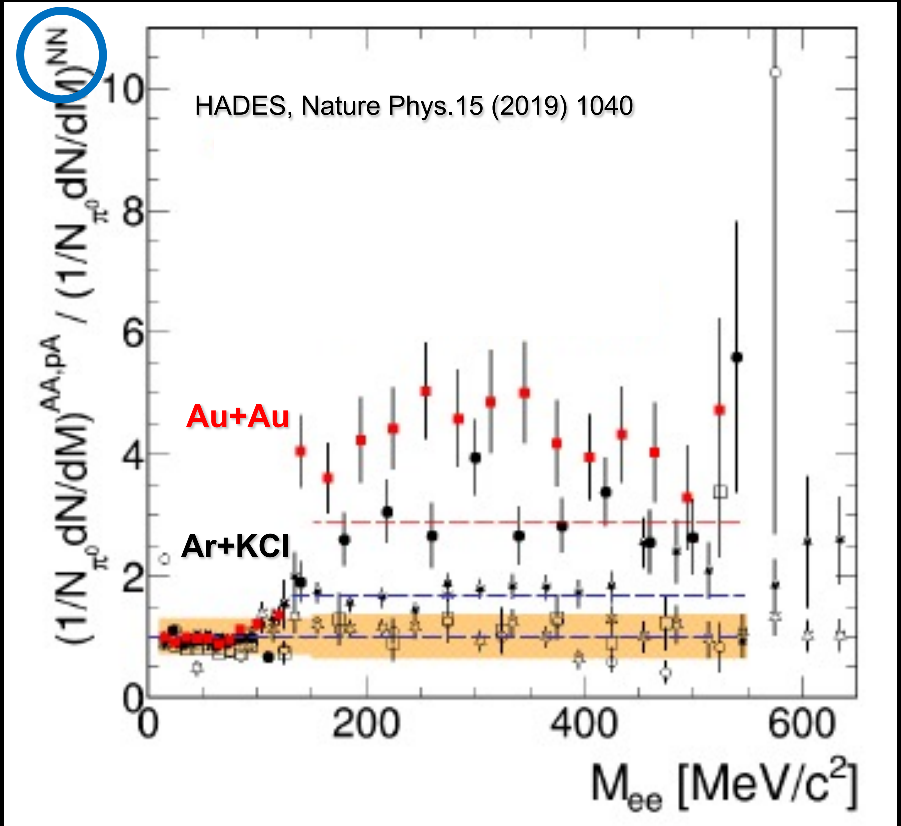
➔ underestimate the ratio at low energies

T-matrix (green), T-matrix & broadening (red) enhance the ratio

However, medium effects on K, Kbar (blue) suppress it due to the enhanced K^- production at low energy

T. Song et al., PRC 106, 24903 (2022)

Dilepton-radiation



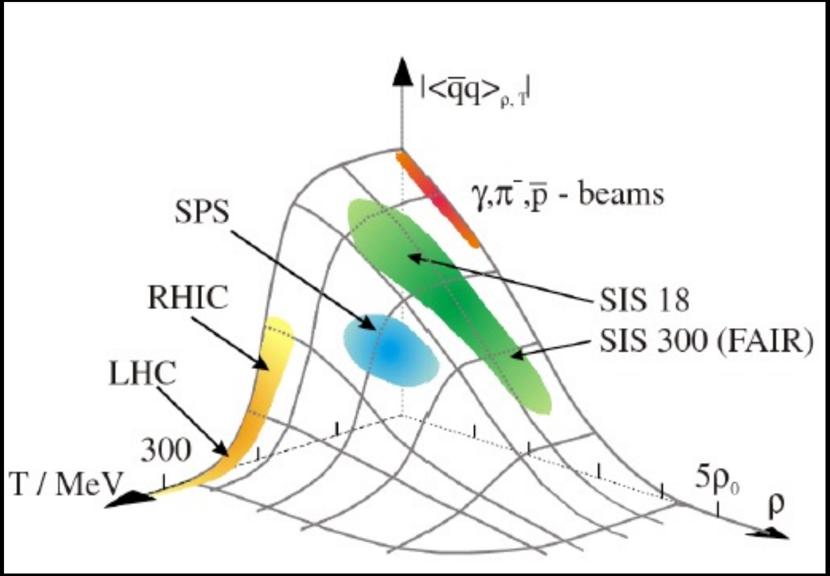
Strong in-medium excess of dilepton radiation in Au+Au vs. NN, increases with the system size.

→ p+p and n+p references needed

In-medium hadron properties in cold nuclear matter

“Observed hadron masses are nature's compromise between distortion of the vacuum and localization!” F. Wilczek

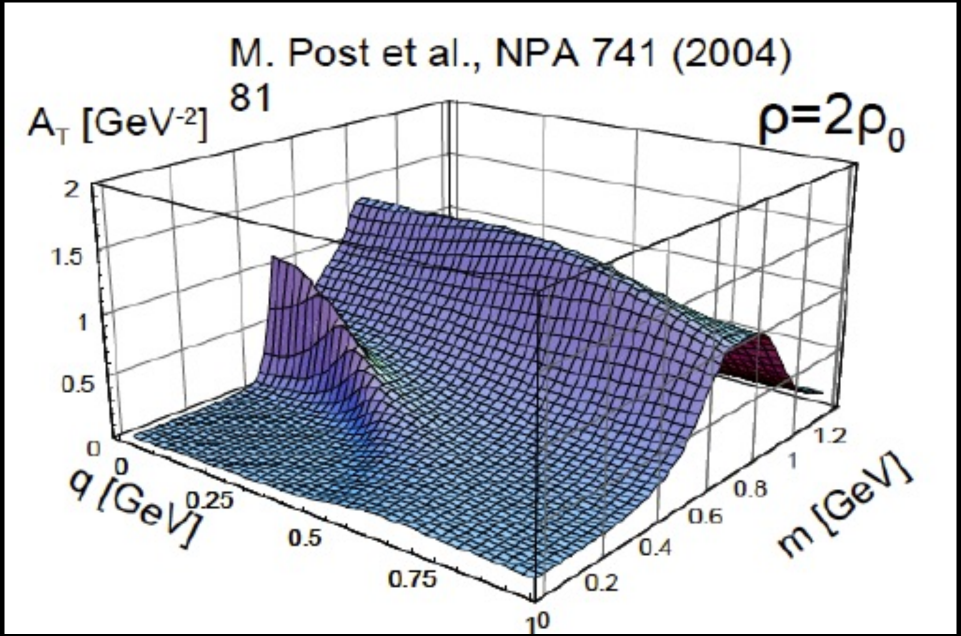
→ *Change vacuum, change hadron properties!*



Heavy-ion collisions:
Larger effects compared compared to cold matter.

Cold nuclear matter:
The easiest way to distort the QCD vacuum, controlled conditions (static medium).

In-medium hadron properties



Medium effects restricted to low momenta!
→ ensure acceptance

Geometrical Acceptance at low momenta

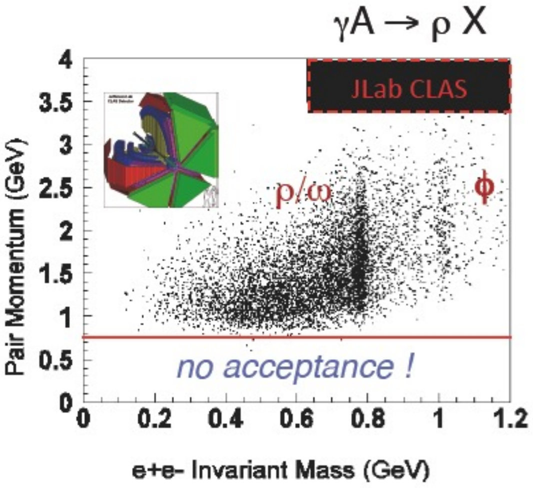
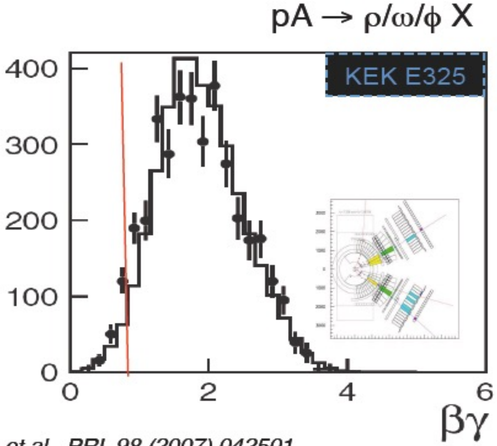
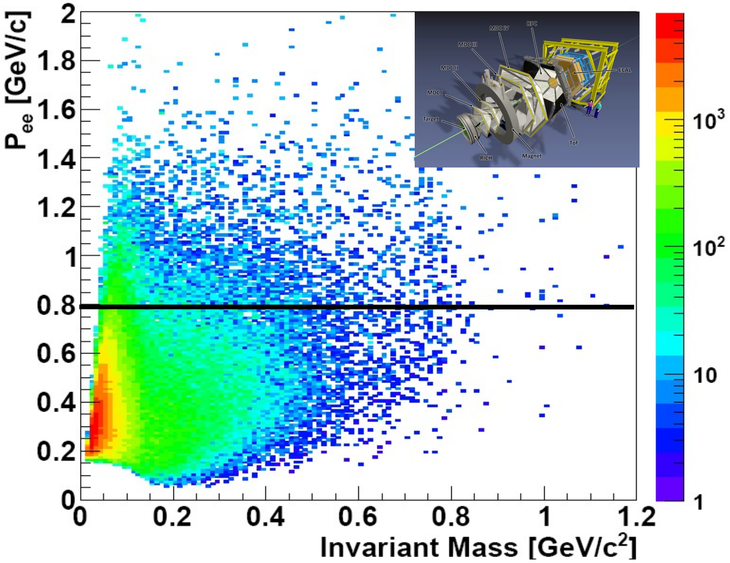


Fig. from S.Leupold et al., nucl-th 0907.2388

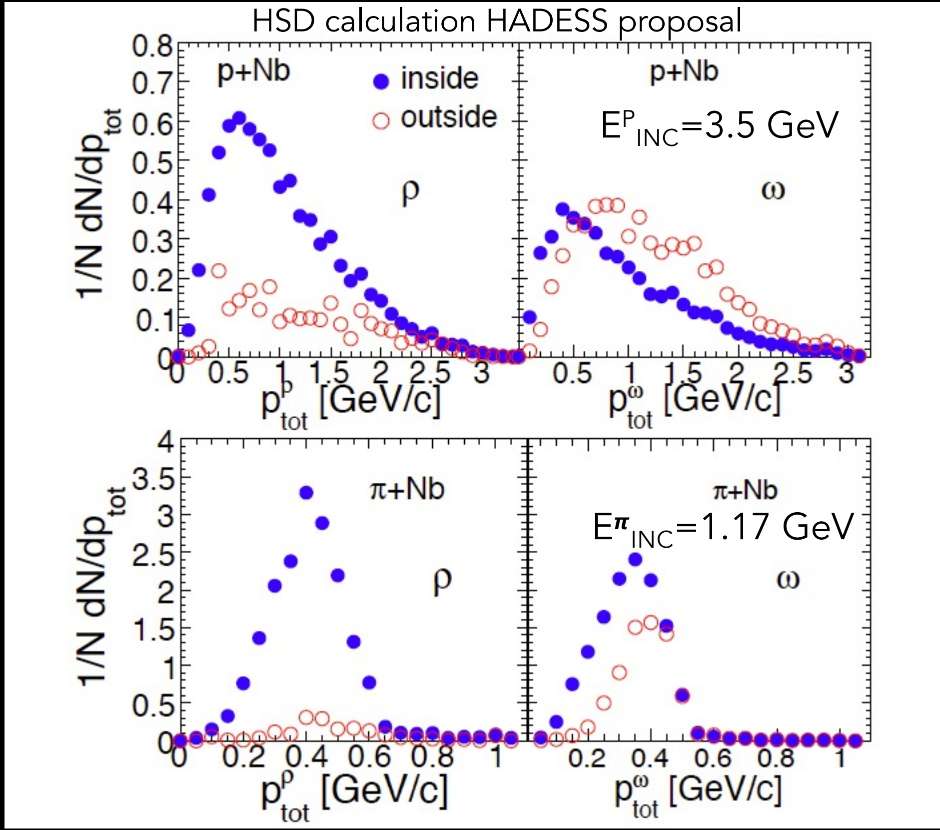


Muto et al., PRL 98 (2007) 042501

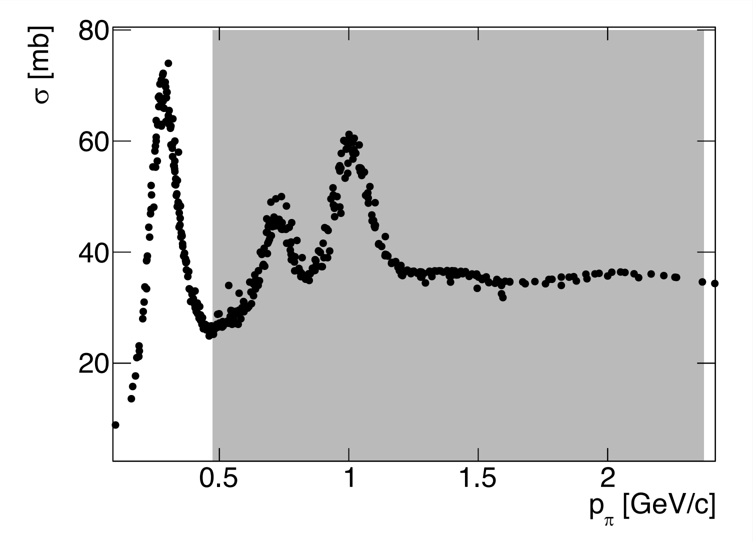


Low momentum coverage: worldwide unique feature of HADES

π induced reactions: small recoil momenta of secondaries



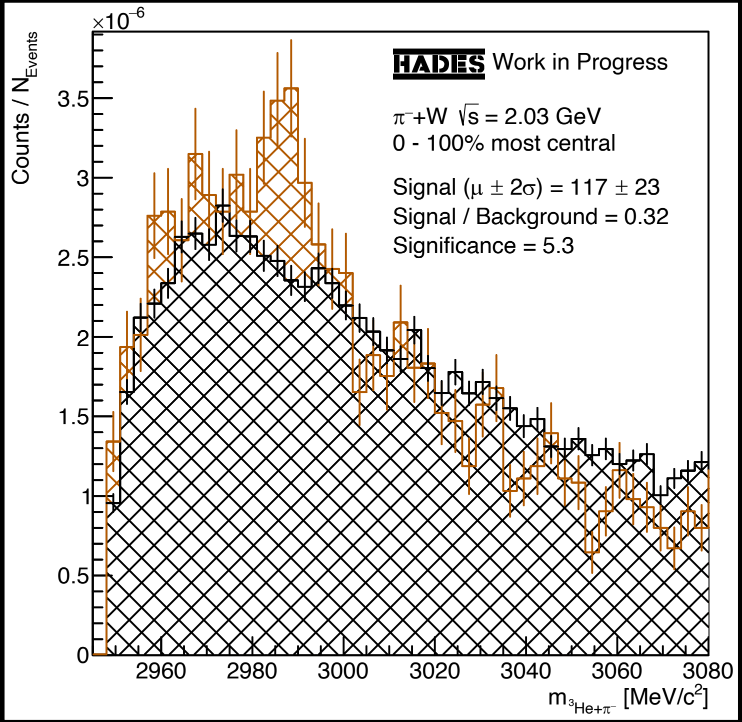
Optimal population of low momentum region



- Line shape and line strength of vector mesons via e.m. decays
- Strangeness production and propagation
- Hypernuclei formation

A. Kittiratpattana et. al. Phys.Rev.C 109 (2024) 4, 044913

Hypernuclei count rate estimates for 2026



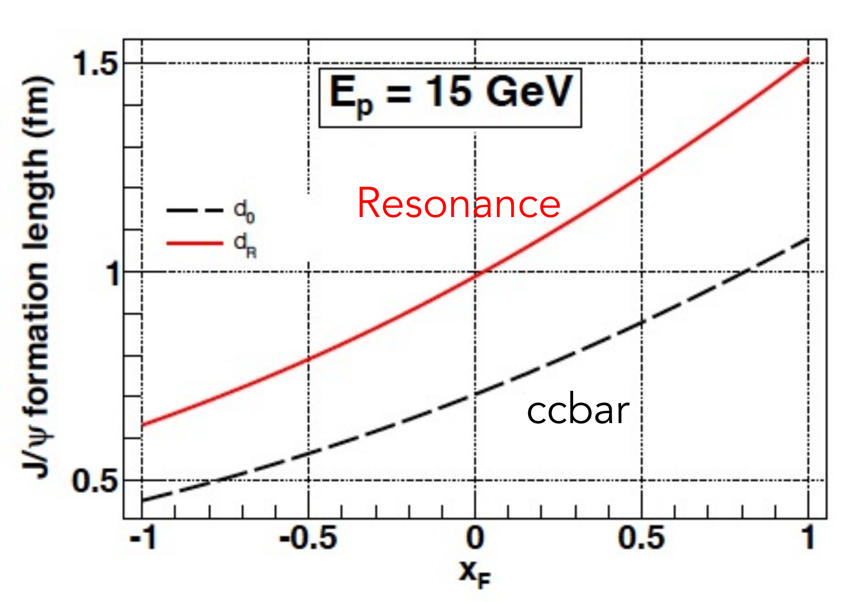
Analysis based on
1.7 x 10^8 π+W events at $\sqrt{s}_{\pi N}$= 2 GeV

2014: 21 shifts, DAQ_{rate}: 1kHZ
Expected for 2026: 42 shifts, DAQ_{rate}: 45 kHz
→ gain factor: f_{shift} 2 · f_{DAQ} 45 = 90!

→ ~ 10000 hypertritons

π beam experiments offer excellent opportunity for studying hypernuclei

Charm at CBM



P. P. Bhaduri et. al. J. Phys. G 45 (2018)

- Perturbative probe at low energies.
- Cross section and production mechanism unknown at SIS100 energies $\sqrt{s_{NN}} < 8$ GeV.
- Gluon fusion vs. gluon exchange. ω to $^{J}/_{\psi}$ should be suppressed by the OZI rule if gluon exchange is the dominant process.
- $^{J}/_{\psi}$ multiplicities key observable for QGP
  A. Andronic et. Al. Eur.Phys.J.C 76 (2016) 3, 107
- Important reference measurement of $^{J}/_{\psi}$ absorption in cold nuclear matter possible at CBM

Summary

- heavy-ion collisions allow to probe systematically the phase diagram.
- reference measurements mandatory solid interpretation of heavy-ion data.
- in particular needed in the FAIR energy range.
- CBM/HADES are well suited for this.

- small recoil momenta and low momentum coverage optimal conditions for line shape and line strength measurements of vector mesons
- excellent opportunity for studying hypernuclei
- important reference measurement of $^{J}/_{\psi}$ in cold nuclear matter possible at CBM

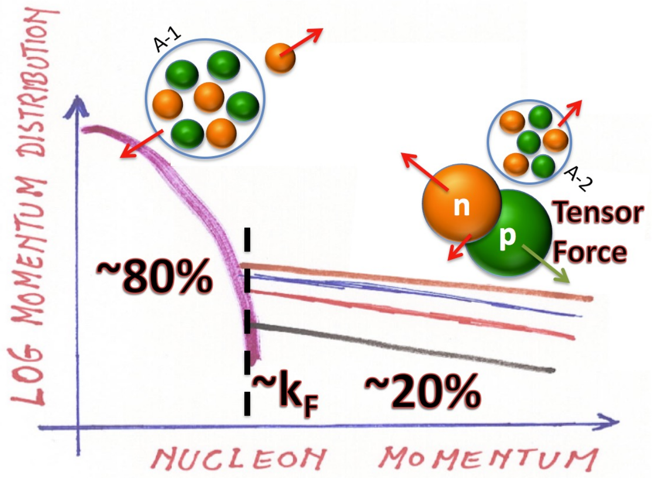
Timeline

2025 → : π - induced reactions at HADES
→ Cold matter studies: vector-mesons, strangeness and hypernuclei

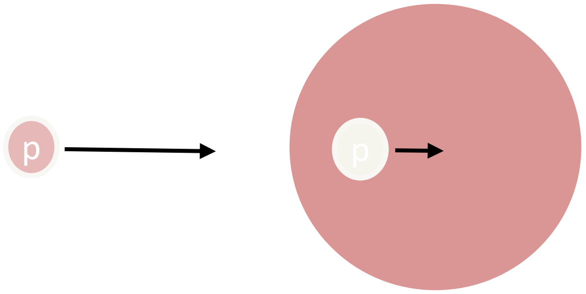
2029 →: p - induced reactions at CBM/HADES
→ Reference measurements for HICs
→ $^{J}/_{\psi}$ in cold nuclear matter

203X → ($\overline{\text{p}}$) – induced reactions

Short Range Correlations (SRC)



Quasi p+p elastic scattering have a strong preference for interacting with forward going high momentum nuclear protons, "**Selective Attention**".



Map out the the transition (Migdal jump) in the nucleonic momentum distribution from a mean-field part to the high-momentum tail dominated by SRC.

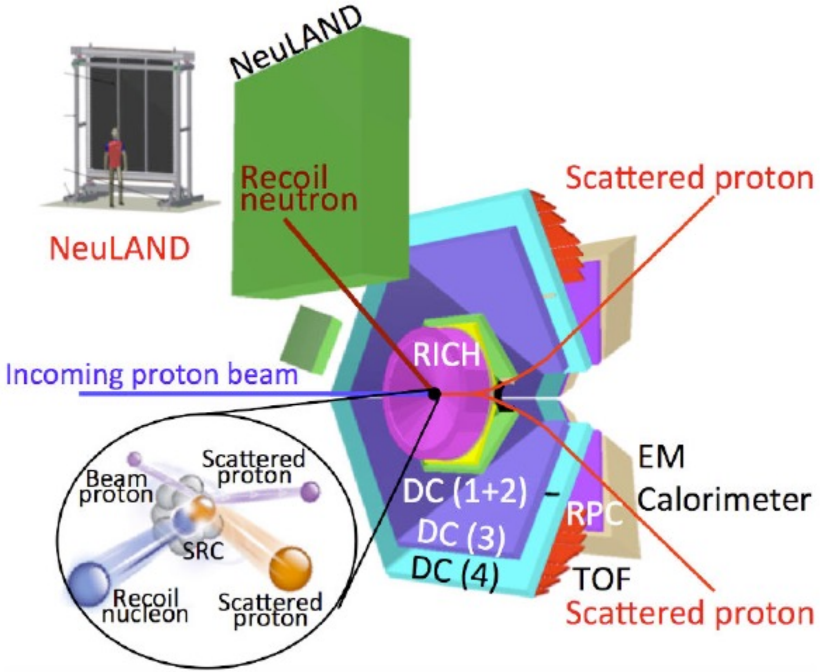
Study the factorization of the reaction mechanisms at low energies (important test for studies of SRC in inverse kinematics at FAIR).

4.5 GeV is ideal!

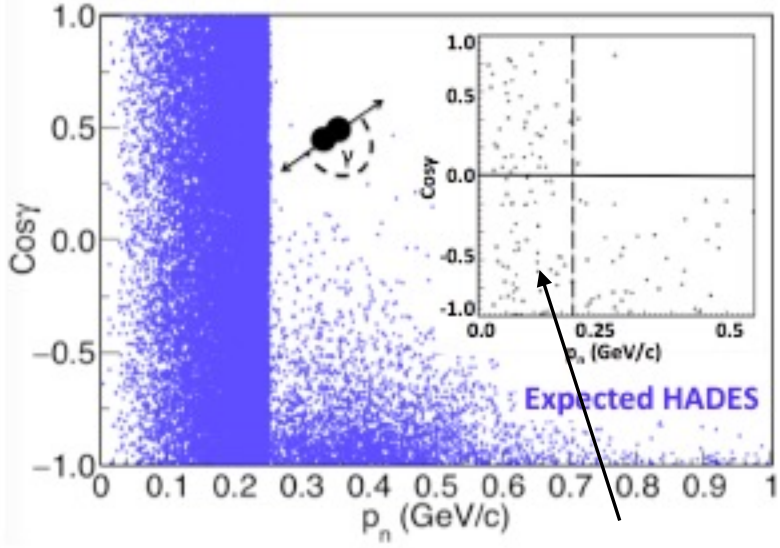
Short Range Correlations (SRC)

Experimental Setup:

- HADES as detector for the 2 forward p
- NeuLAND technology for the recoil neutron



The **Migdal jump** mapped with the anticipated HADES+NeuLAND technology events (factor 50 compared to BNL data).



np-SRC	pp-SRC
4×10^3	2.5×10^3