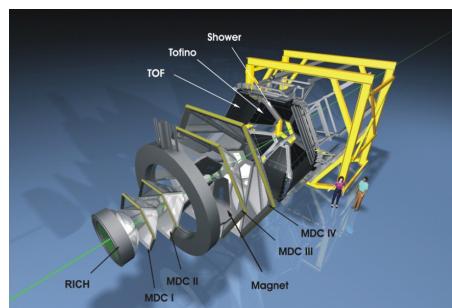


French contribution to the HADES experiment at GSI

B. Ramstein, IJCLab
*Journée Toulousaine d'études en Physique
Astro-Nucléaire, 30 November 2021*



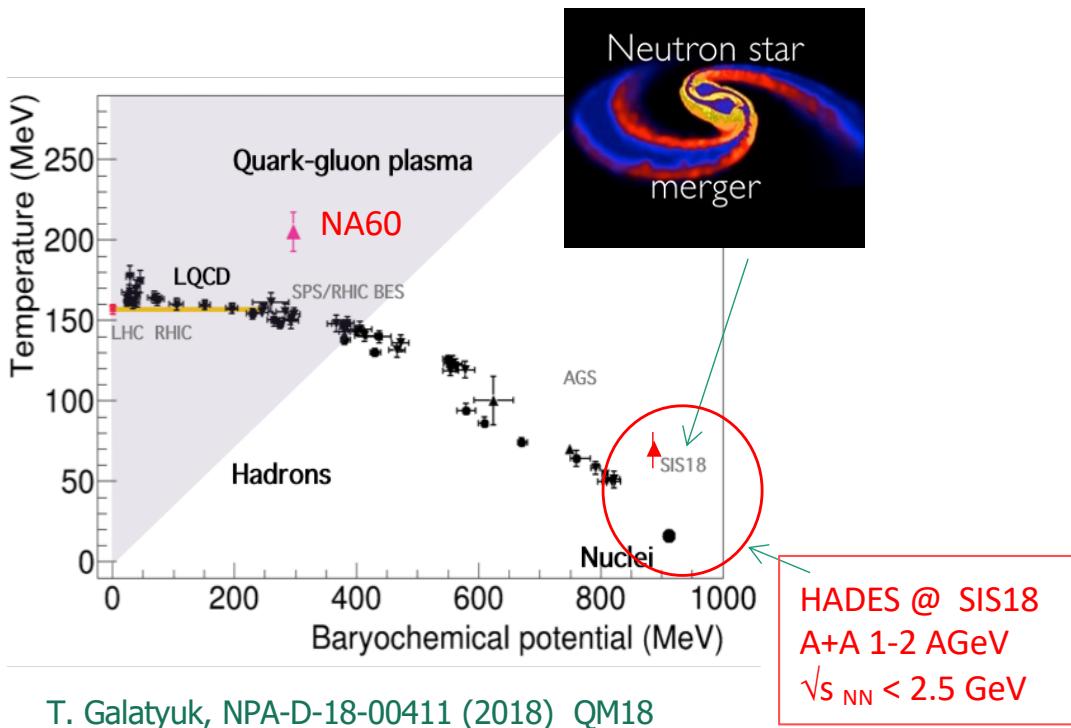
Outline

- General motivations of HADES experiments
 - The HADES detector
 - Results from the elementary reaction program
 - Baryon resonance studies
 - Complementarity with heavy-ion reactions
 - Perspectives
- cf Joachim's talk for more about dense matter studies*

QCD phase diagram: open questions

High T, low μ_B

- ❑ Lattice QCD calculations
- ❑ 2nd order transition between hadronic and quark-gluon phase = cross-over
- ❑ Chiral symmetry restoration



T. Galatyuk, NPA-D-18-00411 (2018) QM18

observables

- ✓ Correlations and fluctuations
- ✓ Collective effects (flow,...)
- for all possible particle species*
- ✓ Strangeness
- ✓ Dileptons

Low T, high μ_B

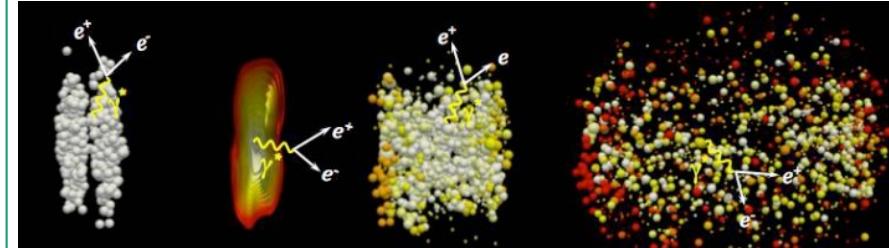
- ❑ Effective models are needed
- ❑ First order transition ?
Search for a critical point
- ❑ Chiral symmetry restoration ?
- ❑ Microscopic structure of baryon rich matter.
Baryonic resonances, hyperons
Medium effects on hadron properties

Dilepton probe and vector mesons

Ideal probe of the dense and hot phase:

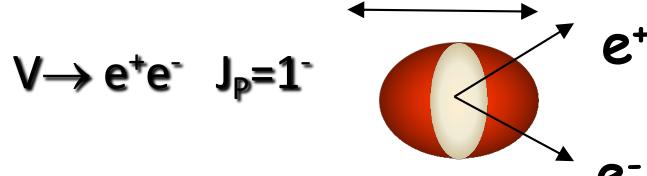
- No strong final state interaction
- Reflects the **whole history** of the collision
 - ✓ temperature
 - ✓ time evolution
 - ✓ criticality
 - ✓ **vector meson spectral function**

Expected to be modified in-medium by Chiral Symmetry Restoration and/or by hadronic interactions



$$R(A=100) \approx 5.5 \text{ fm}$$

$$m_{e^+e^-} = \sqrt{(\tilde{p}_{e^+} + \tilde{p}_{e^-})^2} \approx 2\sqrt{p_{e^+}p_{e^-}} \sin \frac{\theta_{e^+e^-}}{2}$$



Meson	Mass (MeV/c ²)	Γ (MeV/c ²)	$c\tau$ (fm)	Main decay	e ⁺ e ⁻ BR
ρ	768	152	1.3	$\pi^+\pi^-$	4.4×10^{-5}
ω	782	8.43	23.4	$\pi^+\pi^-\pi^0$	7.2×10^{-5}
ϕ	1019	4.43	44.4	K^+K^-	3.1×10^{-4}

HADES in the GSI and FAIR context



French contribution to FAIR : 27.5 M€

SIS100 beams : 2026

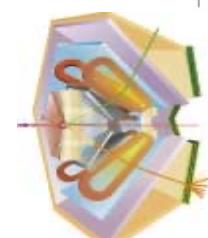
HADES@GSI

p, d, π , HI beams

p : $E_{\max} = 4.5 \text{ GeV}$

Au: $E_{\max}/A \sim 1.25 \text{ GeV}$

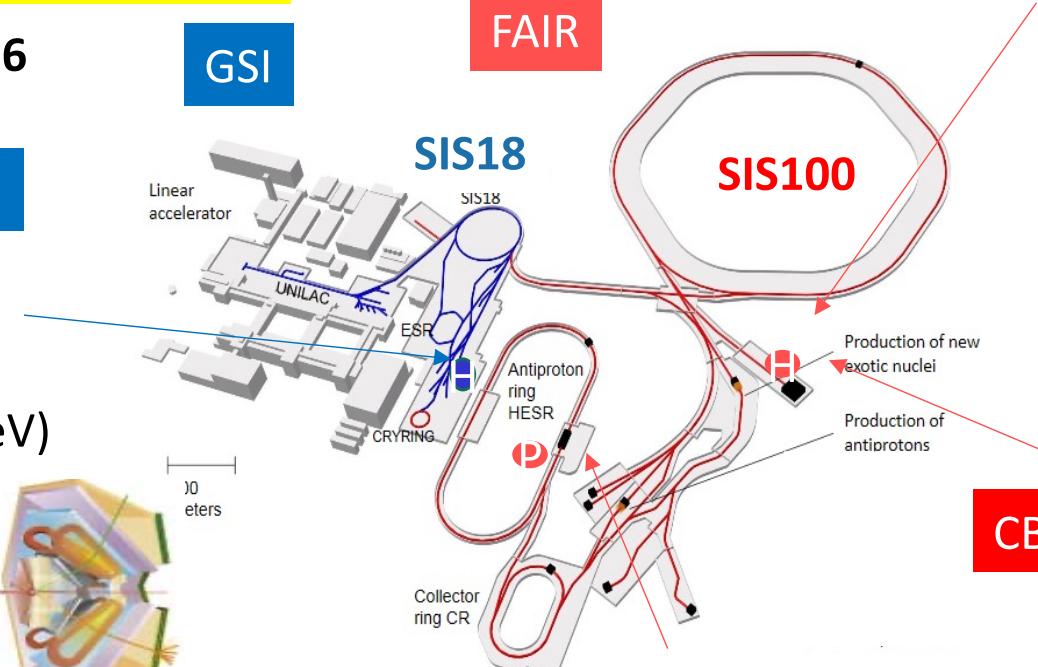
only hadronic
phys. exp. at GSI



FAIR (Facility for Antiproton and Ion Research) 4 pillars:
APPA (Atomic Physics, Plasma and Applied sciences)
NUSTAR (Nuclear STructure, Astrophysics and Reactions)
CBM (Compressed Baryonic Matter: HADES and CBM exp.)
PaNDa (AntiProton ANnihilation at DArmstadt)

GSI

FAIR



B. Ramstein, Toulouse,

PANDA

\bar{p} : 1.5-15 GeV/c

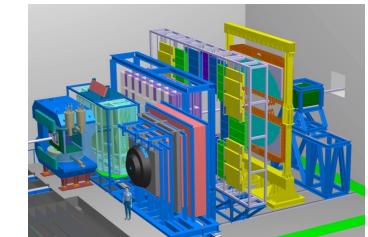
HADES@FAIR

p, d, HI beams

Au: $E_{\max}/A \sim 4 \text{ GeV}$

p: $E_{\max} = 29 \text{ GeV}$

up to 200 kHz



CBM@FAIR

HI beams

Au: $E_{\max}/A \sim 11 \text{ GeV}$

A/Z=2: $E_{\max}/A \sim 14 \text{ GeV}$

up to 10 MHz

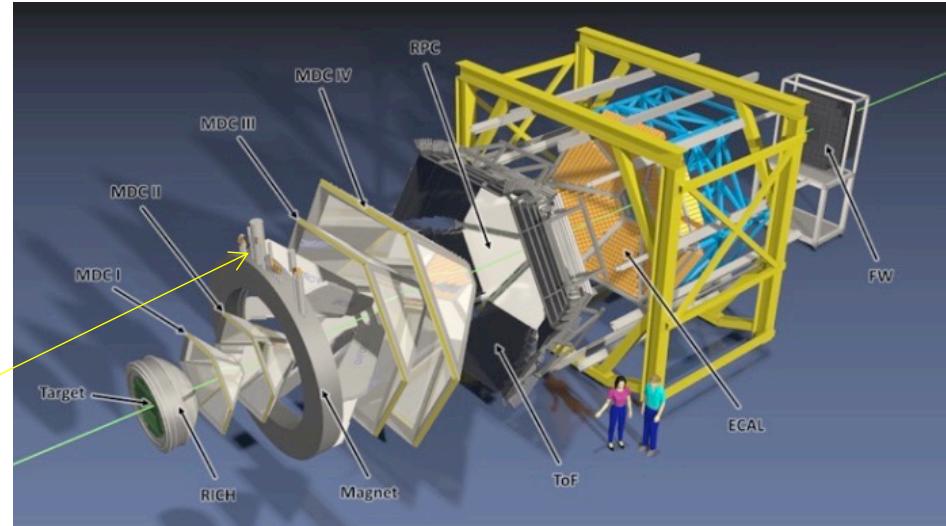
The HADES spectrometer



4th plan of tracking built by IPNO
6 drift chambers (2000-2006)
Drift cell ($14 \times 10 \text{ mm}^2$)
Active surface 21 m^2
7200 sensitive wires



LH₂ target (built by the IPN0
Cryogeny group)



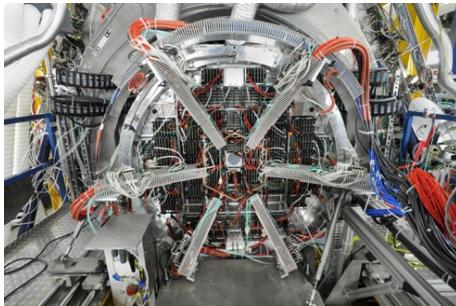
Acceptance: Full azimuth, polar angles $18^\circ - 85^\circ$
Momentum measurement

Magnet: $\int B dl = 0.1 - 0.34 \text{ Tm}$

MDC: 24 Mini Drift Chambers

Leptons: $\Delta x \sim 140 \mu$ per cell, $\Delta p/p \sim 1-2 \%$

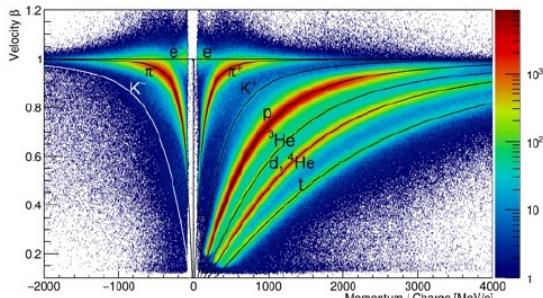
HADES upgrade: FAIR-Phase0



New RICH photon detector & read-out
(coll. with CBM@FAIR)
Gain in e^+e^- efficiency x5

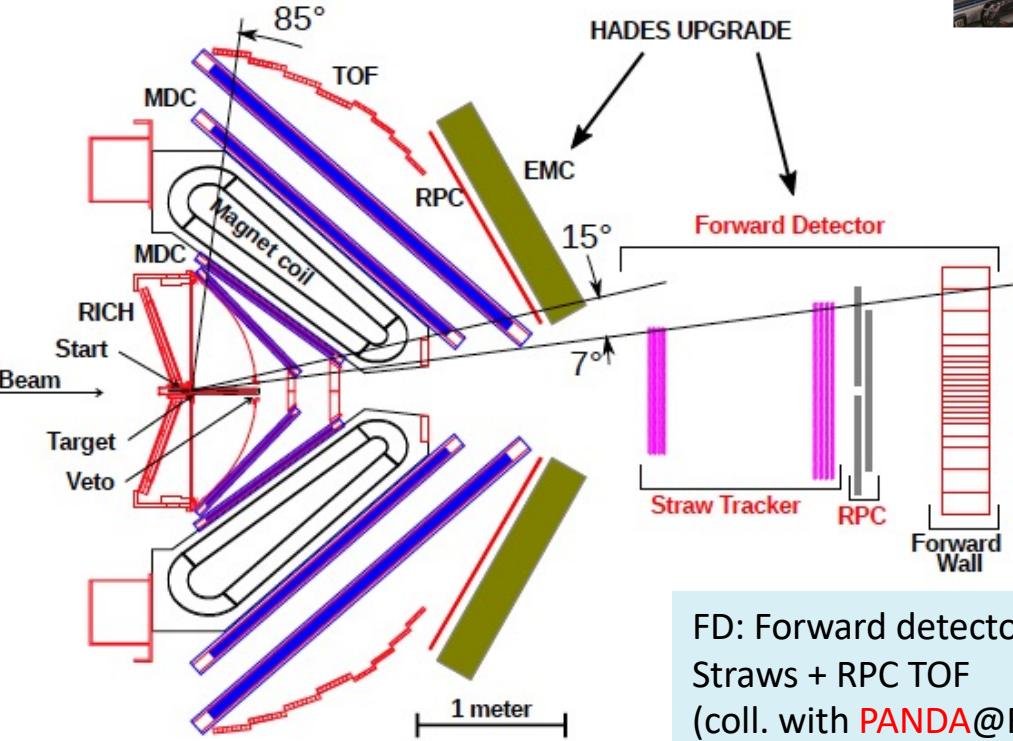
used in Au+Au exp. March 2019

Particle identification by means of:
velocity, momentum, dE/dx , RICH information \sim all combined in a multivariate analysis (neural network)



New ECAL (lead glass), $\Delta E/E \sim 5\%$
 $\gamma \rightarrow$ neutral mesons and e^+e^- detection

used in Au+Au exp. March 2019



FD: Forward detector ($0.5-6.5^\circ$)
Straws + RPC TOF
(coll. with PANDA@FAIR)
 $\sigma(x) \sim 150 \mu m$ $\sigma(TOF) \sim 70 ps$

Commissioned in p+p beam test Feb. 2021

IPNO contribution to the FD : mechanics constructed in Orsay and financial contribution (2017-2018) to straw tube construction in Krakow



HADES physics programme

Very broad physics programme including

- High statistics multidifferential analysis of hadron production
- Rare probes (e+e- and strangeness)

Experiments (2004-2021)

Hadronic matter studies :

C+C 1 and 2A GeV, Ar+ KCl 1.75A GeV, Au+Au 1.25 AGeV, Ag+Ag 1.65A GeV

Cold matter: (« normal density » nuclear matter)

p+Nb 3.5 GeV, π^- +C/W 1.7 GeV/c , π^- +CH₂ 0.7 GeV/c (**1 on-going PhD at IJCLab**)

Elementary reactions: 5 PhD at IPNO/IJCLab + 1 on-going

Reference spectra + selective channels

p+ p 1.25, 2.2 , 3.5 GeV, d+p 1.25 GeV/nucléon, π^- +CH₂ 0.7 GeV/c

HADES collaboration :

about 130 physicists,

20 institutes, Czech Republic, France, Germany, Poland, Portugal, Russia

recent new membership: Uppsala, Warsaw.

nucleon-nucleon reactions

Main dilepton sources for pp collisions

Long-lived sources:

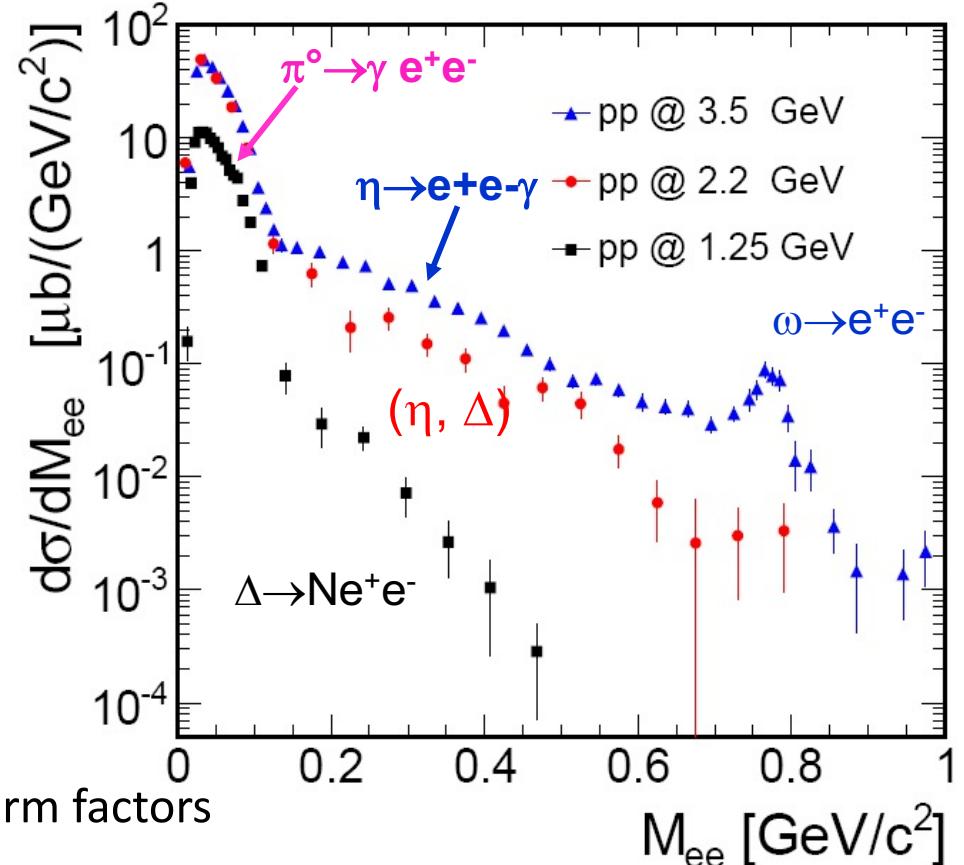
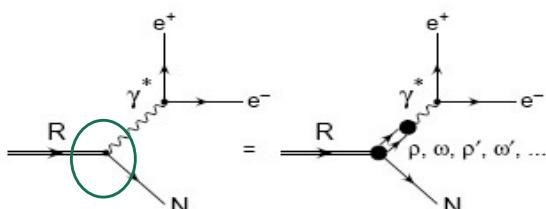
- π^0 Dalitz : $\pi^0 \rightarrow \gamma e^+ e^-$ (BR $\sim 1.2\%$)
 $\Delta(1232) \rightarrow N\pi^0, N(1520) \rightarrow N\pi^0\pi, \dots$
- η Dalitz : $\eta \rightarrow \gamma e^+ e^-$ (BR $\sim 0.6\%$)
 $N(1535) \rightarrow N\eta, \dots$

Short-lived sources:

- ω Dalitz: $\omega \rightarrow \pi^0 e^+ e^-$ (BR $\sim 7.7 \cdot 10^{-4}$)
- ρ/ω direct: $\rho \rightarrow e^+ e^-$ (BR $\sim 4-7 \cdot 10^{-5}$)
- Baryon Dalitz decays $\Delta/N^* \rightarrow Ne^+e^-$

Vector Meson Dominance

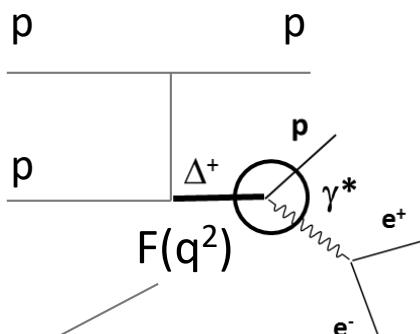
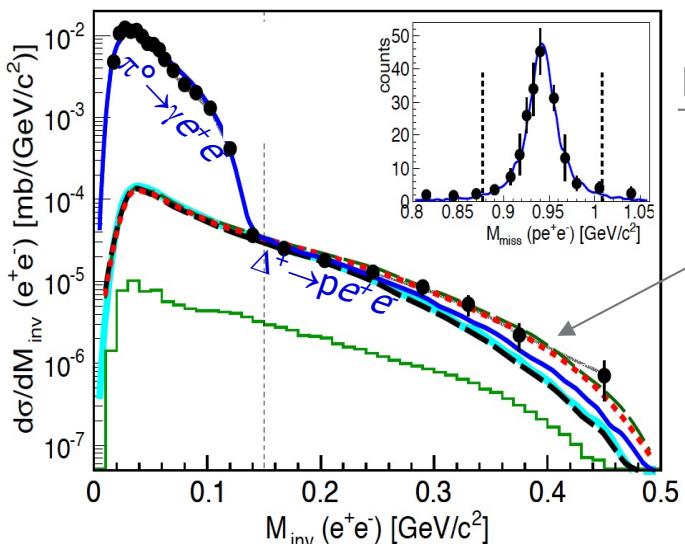
Time-like electromagnetic baryon transition form factors



G. Agakishiev et al., PRC85 054005 (2012);
Eur.Phys.J. A50 (2014) 8

$\Delta(1232)$ Dalitz decay studies with HADES

E=1.25 GeV pp \rightarrow pp e^+e^-
HADES PRC95, 065205 (2017)



- Δ Production amplitudes from PWA of $\text{pp} \rightarrow \text{pp}\pi^\circ$ and $\text{pp} \rightarrow \text{pn}\pi^+$
- Analysis of helicity angle distributions

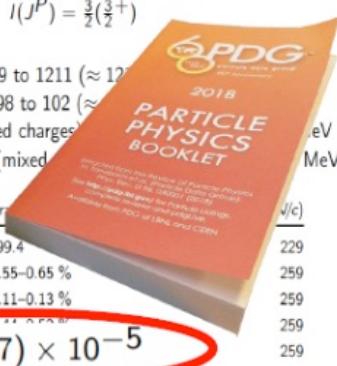
$\Delta(1232) 3/2^+$

$$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$$

Re(pole position) = 1209 to 1211 (≈ 1232)
-2Im(pole position) = 98 to 102 (≈ 100)
Breit-Wigner mass (mixed charges)
Breit-Wigner full width (mixed)

$\Delta(1232)$ DECAY MODES

	Fr. %	\sqrt{s} MeV
$N\pi$	99.4	229
$N\gamma$	0.55-0.65 %	259
$N\gamma$, helicity=1/2	0.11-0.13 %	259
$N\gamma$, helicity=3/2	~0.01 %	259
pe^+e^-	$(4.2 \pm 0.7) \times 10^{-5}$	259

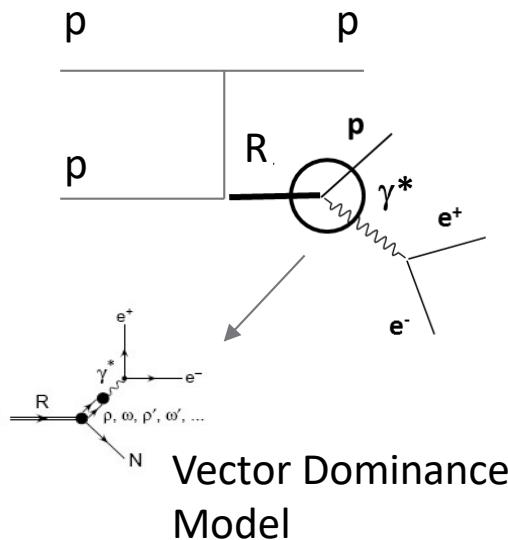


- First measurement of $\Delta(1232)$ Dalitz decay branching ratio ($\Delta^+ \rightarrow pe^+e^-$)
- Sensitivity to the electromagnetic structure (form factor) of the N- Δ transition

Wan and Iachello, Int. J Mod. Phys. A20 (2005) 1846
T. Pena and G. Ramalho, Phys. Rev. D85 (2012) 113014

Dalitz decay studies of heavier baryons with HADES

$p+p \rightarrow pp e^+e^-$ 3.5 GeV



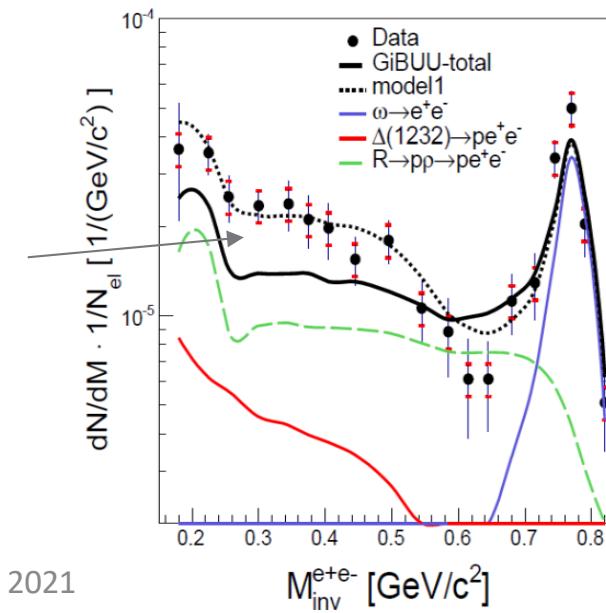
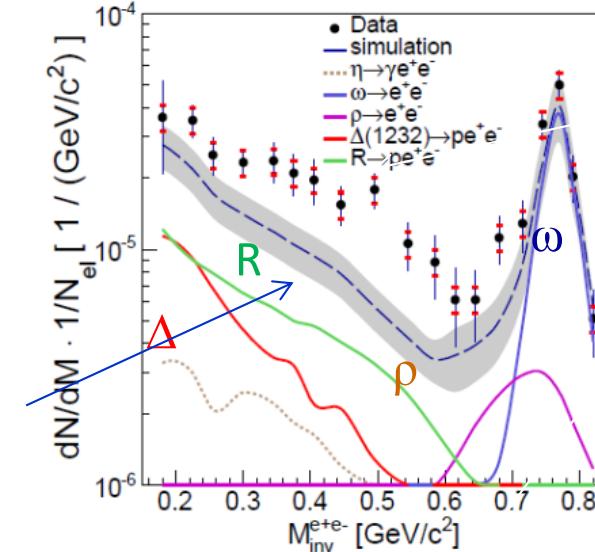
Dalitz decays of point-like baryonic resonance cocktail constrained by $pp\pi^0$ and $pn\pi^+$ channels

+ “direct” ρ and ω

Effect of electromagnetic transition Form Factors for light baryonic resonances ($N(1520), \dots$)

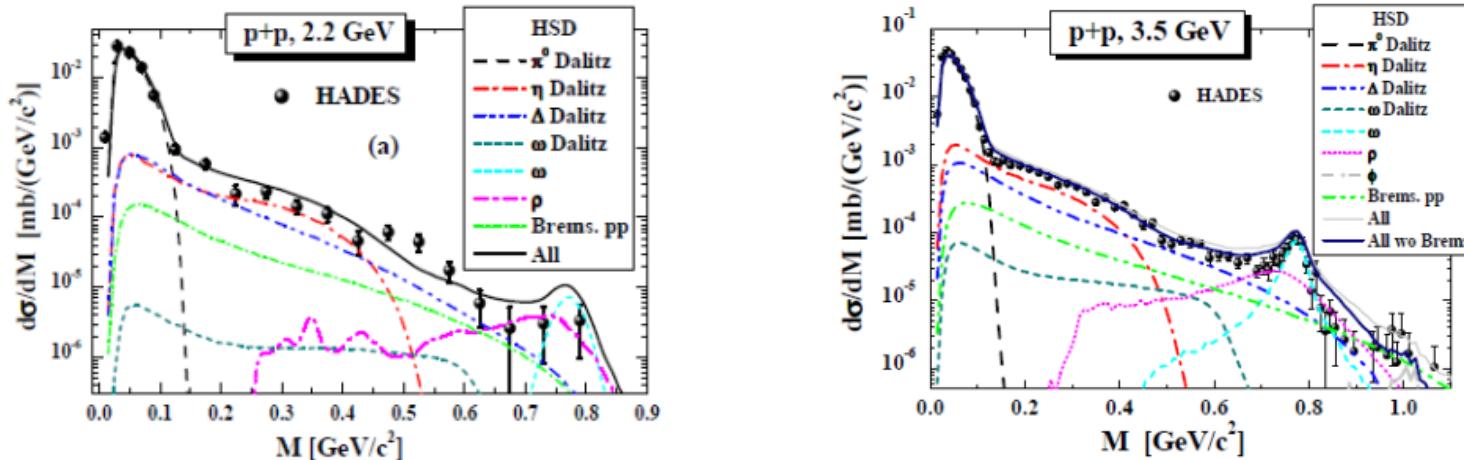
$\Delta(1232)$
 $N^*(1440)$
 $N^*(1520)$
 $N^*(1535)$
 $N^*(1680)$
 $\Delta(1620)$
 $\Delta(1700)$
 $\Delta(1910)$

G. Agakishiev et al.
Eur.Phys.J. A50 (2014) 8

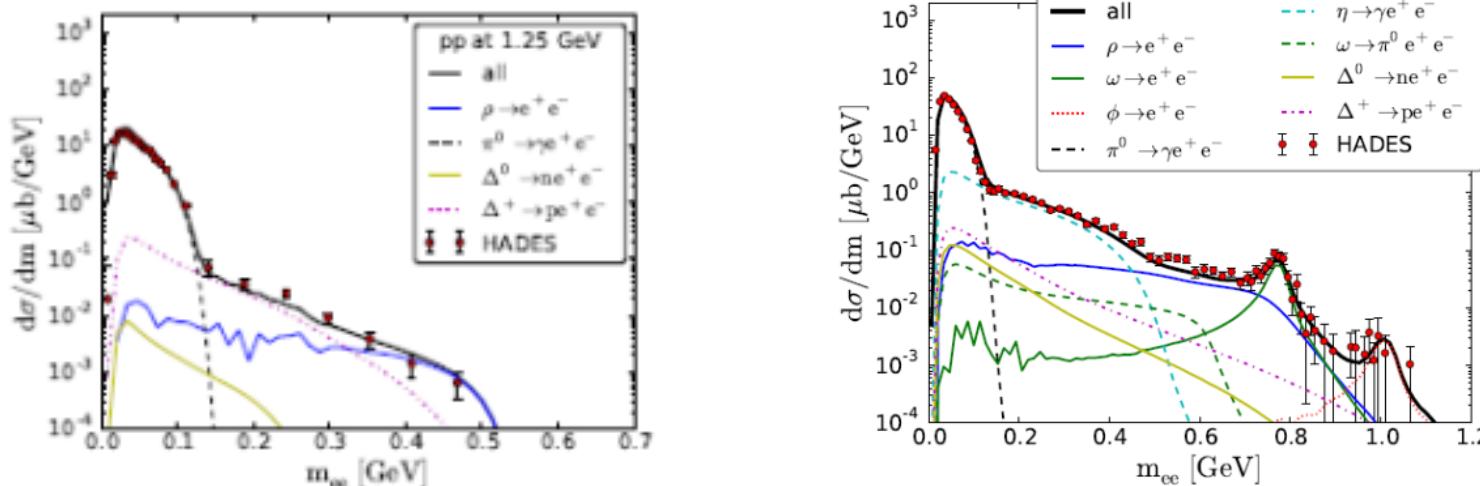


Benchmark tests for models

HSD: *E. Bratkovskaya et al.*, *Phys.Rev.C 87 (2013) 064907*



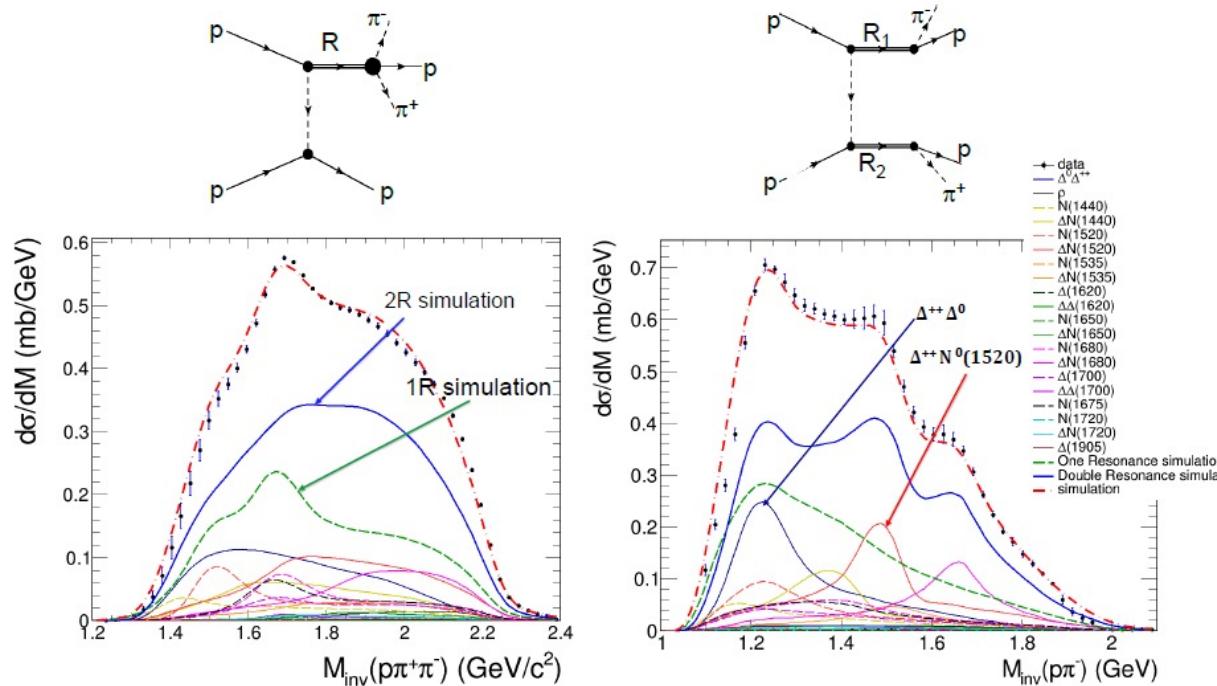
SMASH: *J. Staudenmaier et al.*, *Phys.Rev.C 98 (2018) 5, 054908*



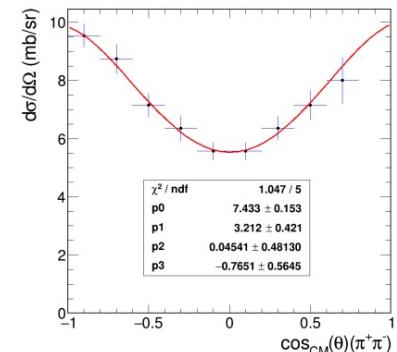
2π production channels:

$pp \rightarrow pp\pi^+\pi^-$ E=3.5 GeV

Single and double baryon excitations



“direct” p production
angular distribution



A. Belounnas, PhD Orsay 2019

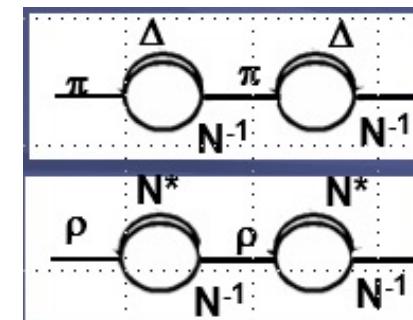
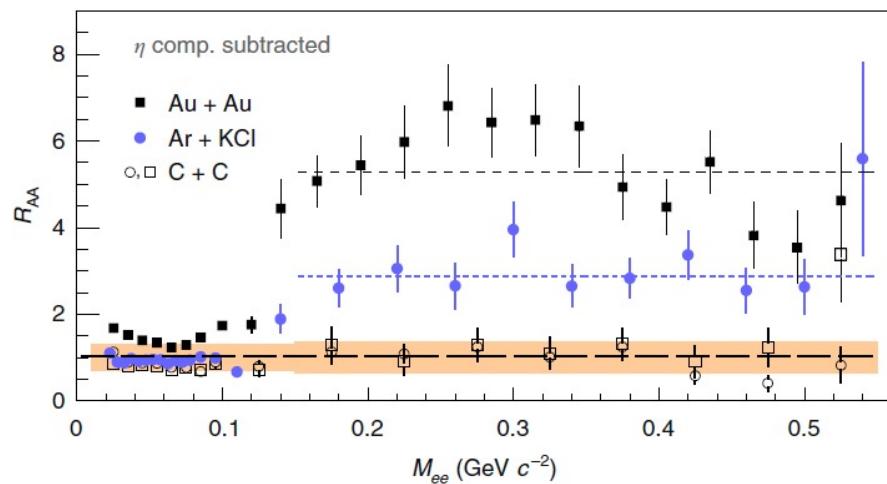
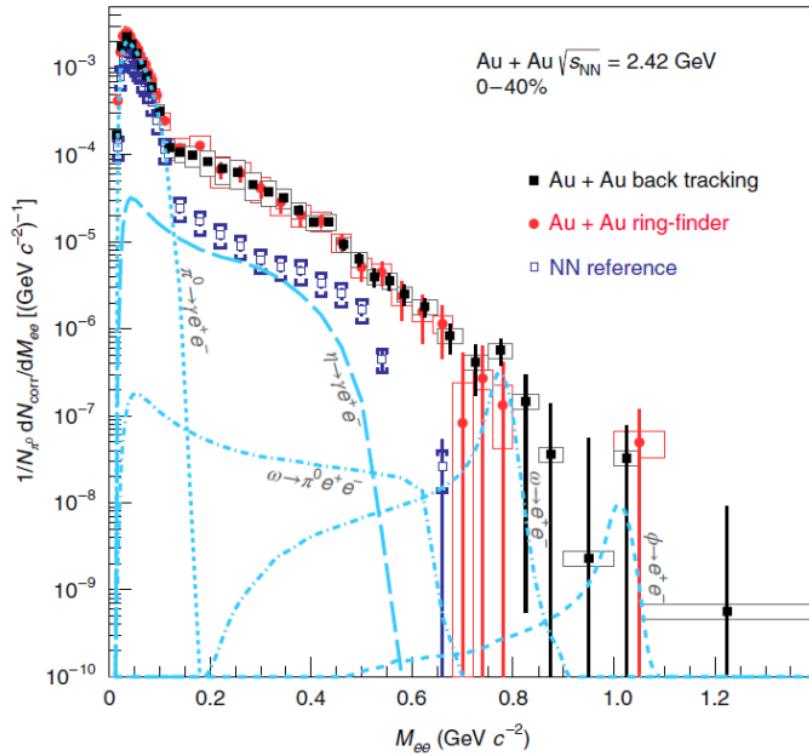
A. Belounnas et al., HADES coll. , Pos(HADRON2017)213

In medium dilepton excess

Subtraction of NN reference and emission from long-lived sources



Radiation from the medium increases with system size

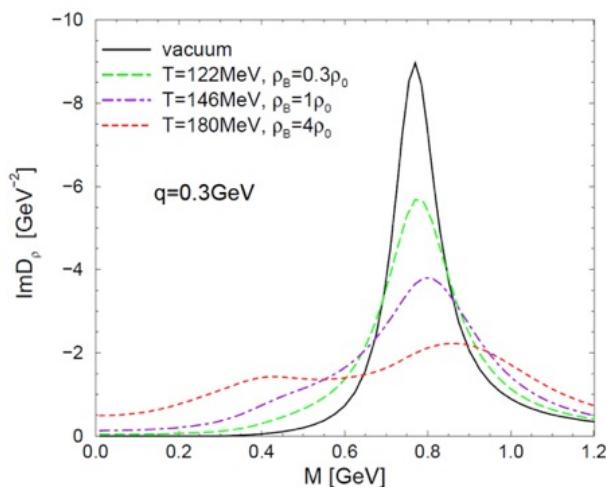


Nature Phys. 15 (2019) no.10, 1040-1045

In medium vector meson spectral functions

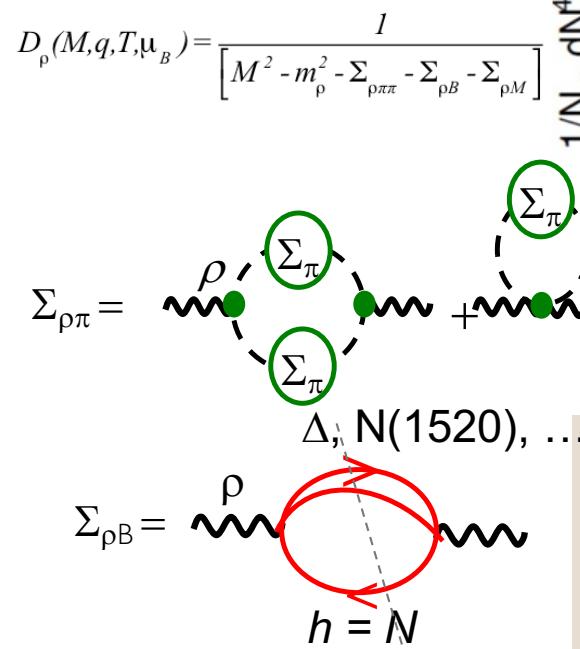
inclusive e^+e^- production Au+Au @ 1.25A GeV
HADES Collab., Nature Phys. 15 (2019) 10, 1040-1045

Strong broadening of **in medium ρ**
 spectral function due to its coupling
 with baryonic resonances.



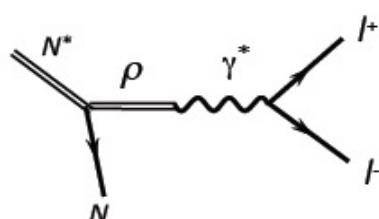
R. Rapp and J. Wambach EPJA 6 (1999) 415

R. Rapp, G. Chanfray and J. Wambach,
Nucl. Phys. A617 (1997) 472



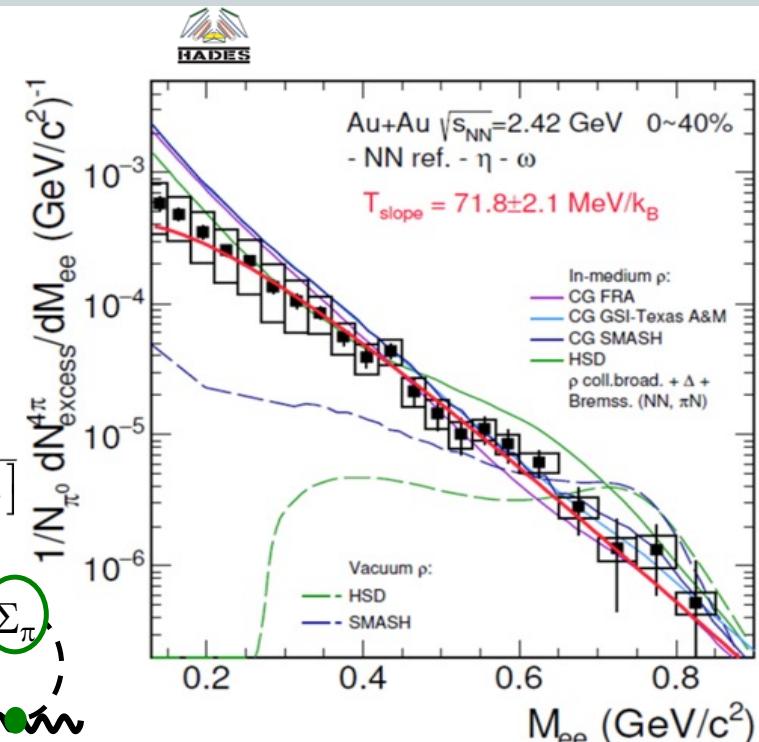
Calculation of e^+e^- production rely on Vector Dominance Model

Model inputs can be tested using NN and πN collisions



B. Ramstein, Toulouse, 30 Novembre 2021

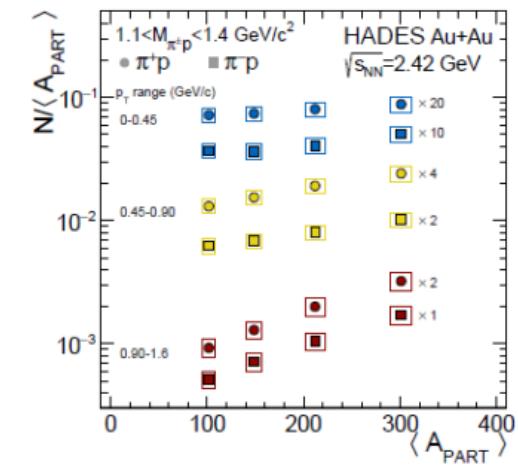
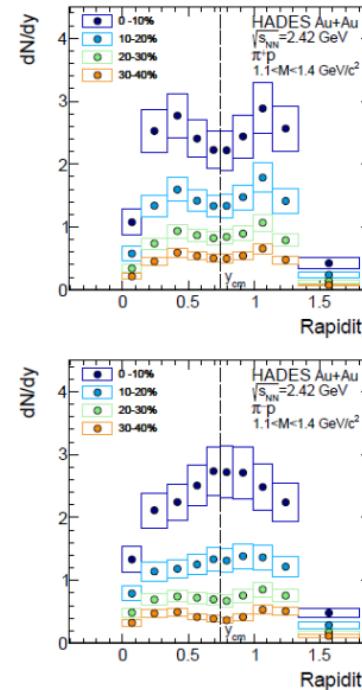
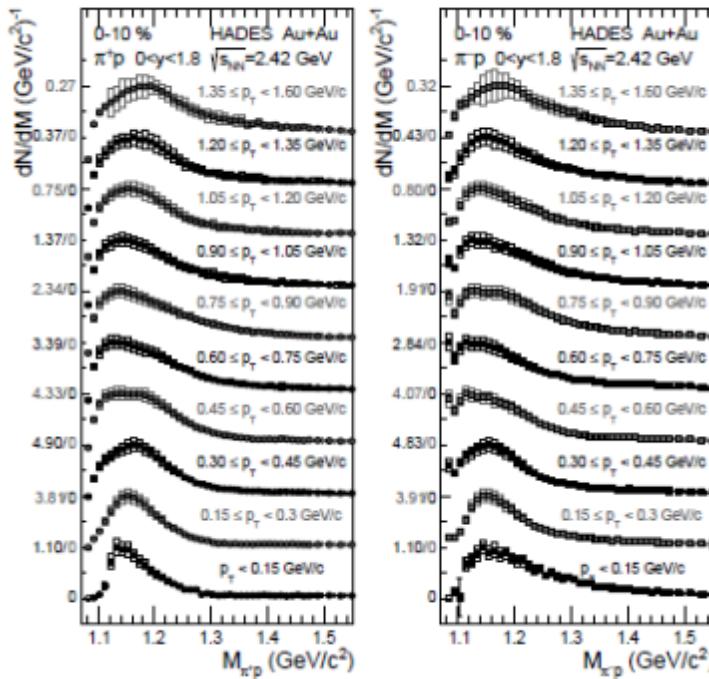
16



- Baryonic loop**
- sensitive to **ρNN^* couplings**
 - related to **baryon Dalitz decay**
 - $\Delta/N^* \rightarrow N e^+ e^-$**

In-medium $\Delta(1232)$ resonance

Iterative method to reconstruct correlated $\pi^- p$ and $\pi^+ p$



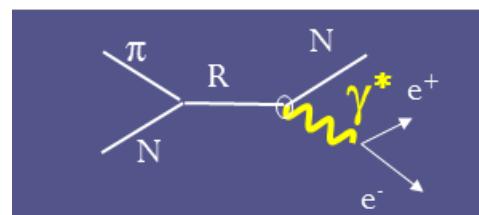
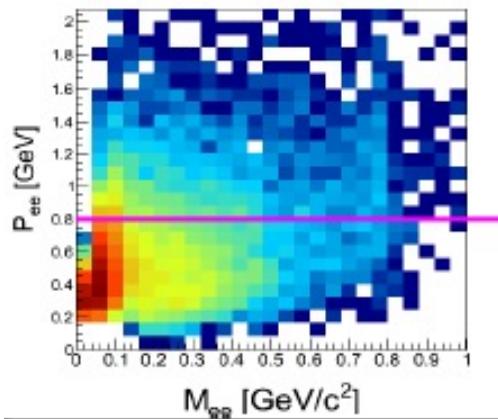
Phys.Lett.B 819 (2021) 136421

Strong medium effects rescatterings, absorption)
Isospin dependence for central collisions

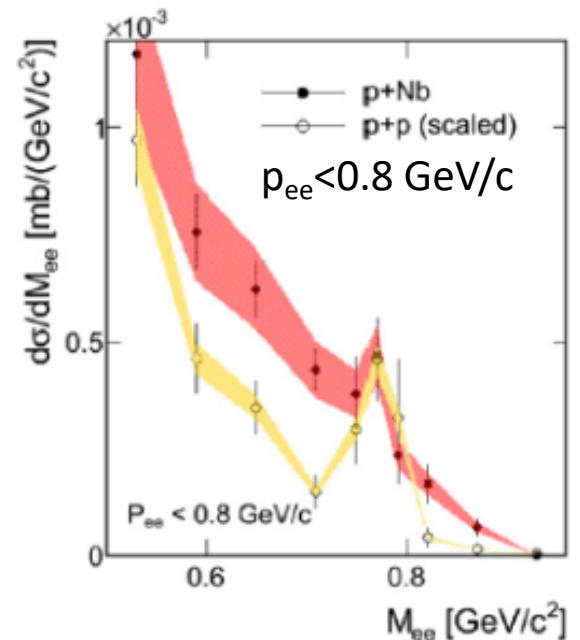
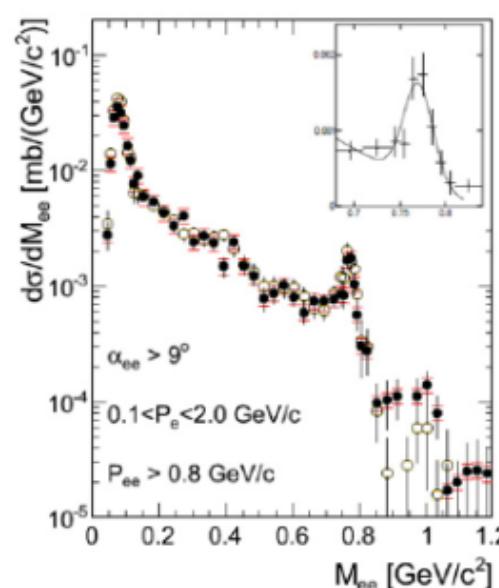
Studying cold nuclear matter

$p+p/p+Nb$
3.5 GeV

**HADES added value
 p_{e+e^-} measured
down to 0.2 GeV/c**



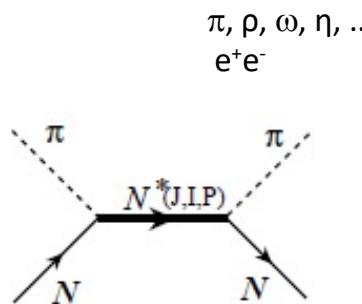
Phys.Lett. B715 (2012) 304



- $p+p$: reference for ω absorption in $p+Nb$
- « ρ -like» contribution strongly distorted
 $\Delta(1720), N^*(1520), \dots \rightarrow N\rho \rightarrow Ne^+e^-$
from primary NN and secondary πN reactions .

Pion induced reactions

Pion beam as a tool for baryonic matter studies



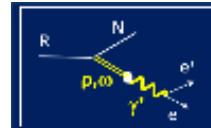
Baryon rich matter studies (SIS18 + SIS100) using (strange) meson and e^+e^- probes
 → Need basic information best provided by pion beams !

- ✓ Selective excitation of baryons ($M_R = \sqrt{s}$)
- ✓ Well known interaction
- ✓ « Recoilless » kinematics : high sensitivity cold matter studies

Baryon-meson couplings
 $(\rho N, \omega N, K\Lambda, K\Sigma, \dots)$

- Missing branching ratios in PDG !
- Very rich γN data base needs to be complemented with **high stat.** πN data → Partial Wave Analysis

Electromagnetic baryon couplings in the time-like region



$$M_{ee} = q^2 > 0$$

Dalitz decay:

$$R \rightarrow Ne^+e^-$$

Validity of Vector Meson Dominance ?
 First measurement of $\Delta(1232) \rightarrow Ne^+e^-$ by HADES

in-medium hadron behaviour
 (scattering, absorption,...)

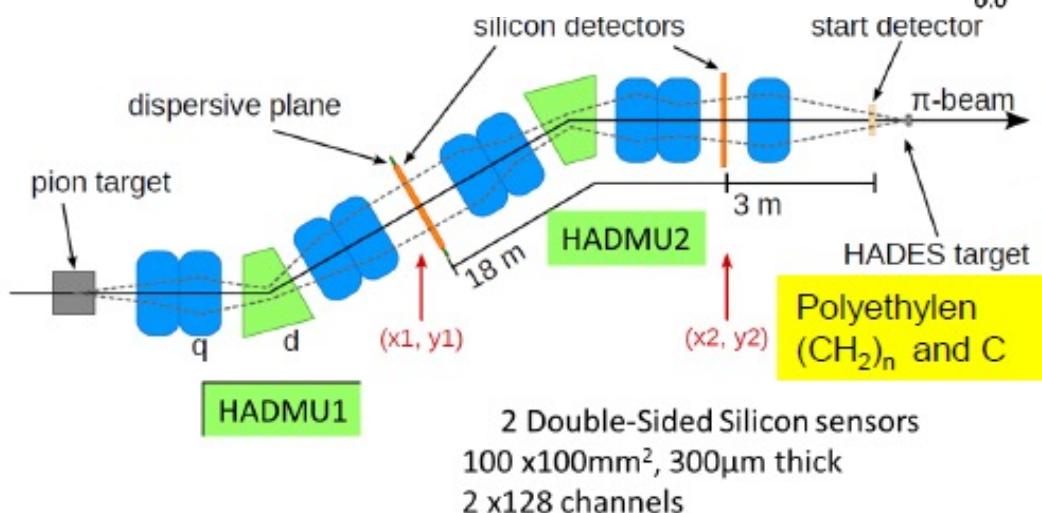
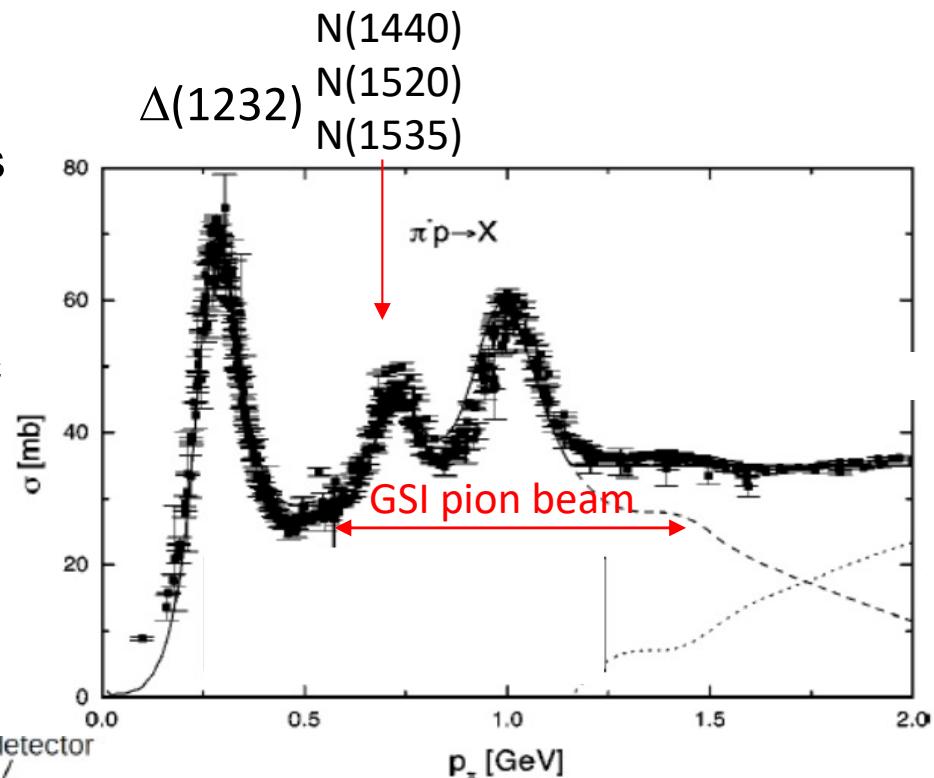
- $\Delta(1232)$ region well documented
- **higher lying resonances** in-medium behavior ?
- **ρ and ω regeneration and absorption ?**

GSI pion beam + HADES: **world-unique** → impact expected for **both hadronic structure and heavy ion communities**

Pion beam at GSI

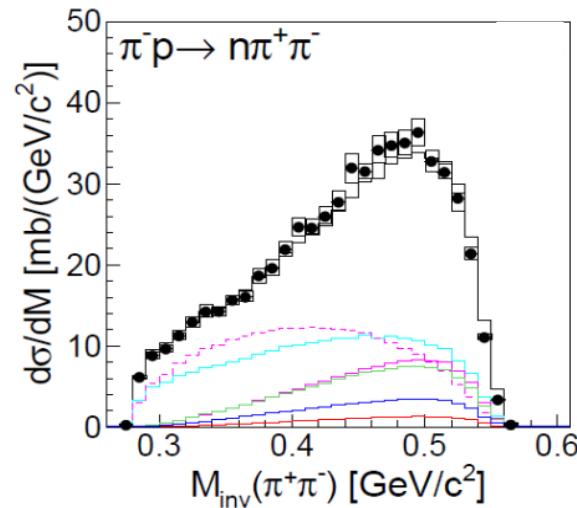
- Primary beam: 6×10^{10} Nitrogen ions/s
- Kinetic beam energy $E = 2A$ GeV
- Momentum acceptance = 1.7 % (rms)
- Momentum range $p_\pi = 0.65 - 1.5$ GeV/c
- Secondary pion beam: $2 \times 10^5 \pi/s$
for p_π around 0.7 GeV/c

Beam optics calculation for pion beam:
T. Hennino, E. Atomssa, B.R.



Partial Wave Analysis in 2π production channels

HADES coll. Phys.Rev.C 102 (2020) 2, 024001



HADES data ($\pi^-p \rightarrow n\pi^+\pi^-$ and $\pi^-p \rightarrow p\pi^0\pi^-$ at 4 energies)
+ photon (CB-ELSA,MAMI) and pion (Crystal Ball) data base
included in **Bonn-Gatchina Partial Wave Analysis**

dominance of N1520 contribution

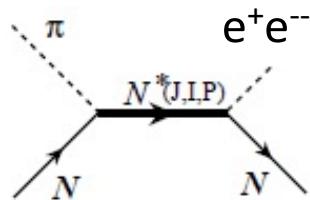


Couplings of $N(1440)$, $N(1535)$, $N(1520)$ to 2π channels ($\Delta\pi$, σN , ρN)
8 new entries (4 first entries, 4 additional entries)

- ρNN^* couplings → direct input for calculation of in-medium ρ meson spectral function
- Still no data on ρ between 1.54 and 1.75 GeV/c^2 (part of HADES future program)

quasi-free $\pi^- p' \rightarrow n e^+ e^-$

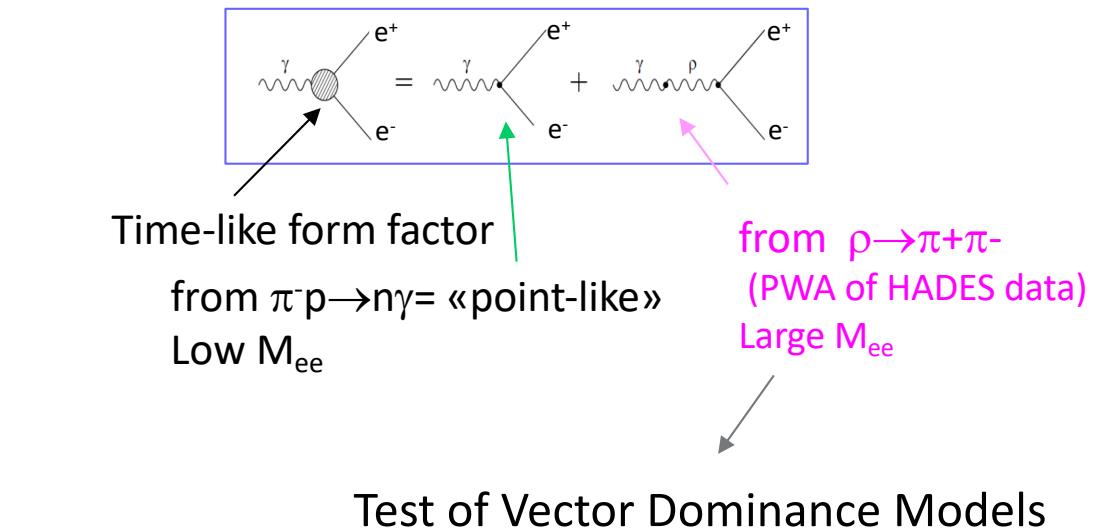
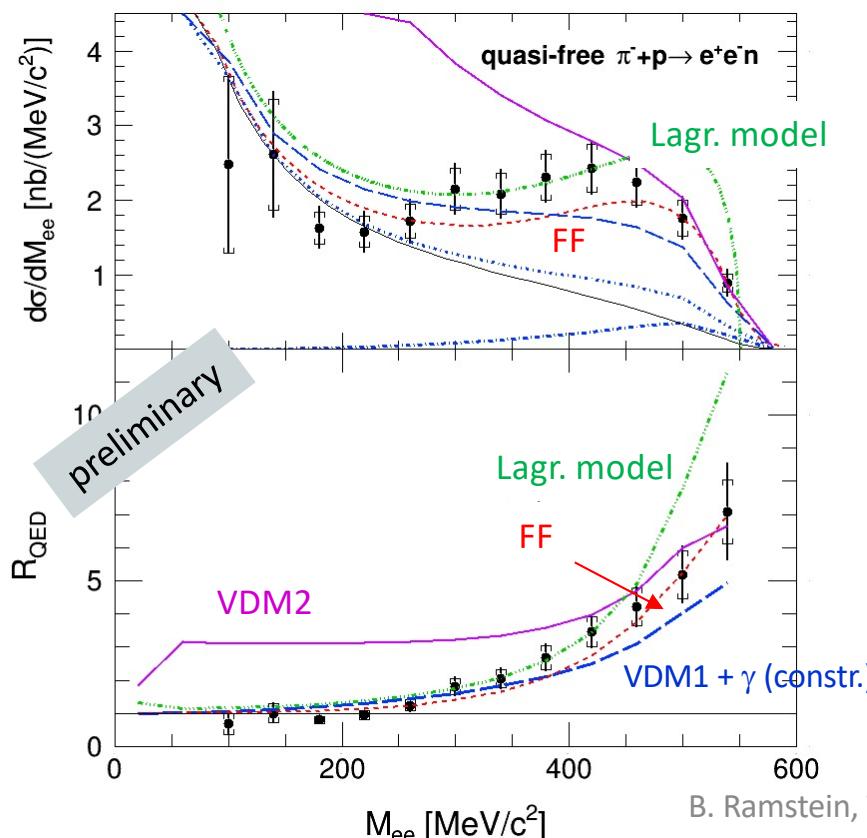
Test of Vector Meson Dominance



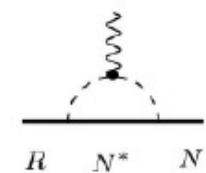
Strong excess with respect to the **point-like contribution** (up to a factor 5)
quantified by an effective Time like transition form factor

$$R_{\text{QED}} = (\frac{d\sigma}{dM}) / (\frac{d\sigma}{dM})_{\text{QED}}$$

After missing mass selection



Alternative description:
Form factor (FF) models with
meson cloud contribution



Complementary analysis of angular distributions

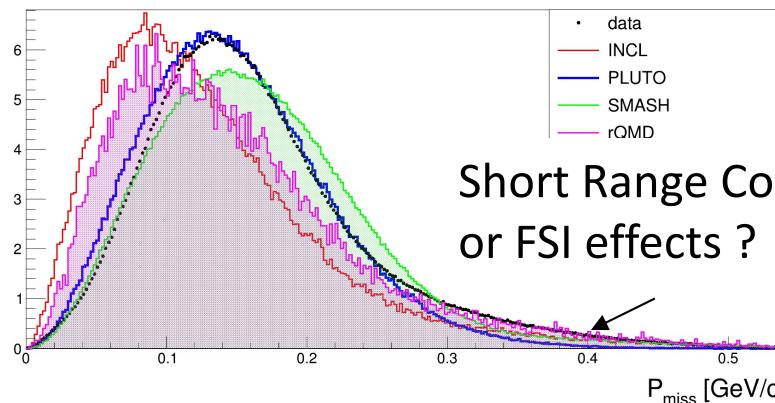
Medium effects in « normal » nuclear matter

Hadronic channels in $\pi^- + C$ 685 MeV/c ($\pi^- p$ quasi-elastic and inelastic, $\pi^- \pi^- p$, pp ..)

→ Sensitive test of π^- absorption, rescattering in carbon nucleus
in transport models (SMASH, rQMD,...)
and INCL++ (Geant4 hadronic model)

Fatima Hojeij PHD (2nd year)
I. Ciepal end of 8 month visit

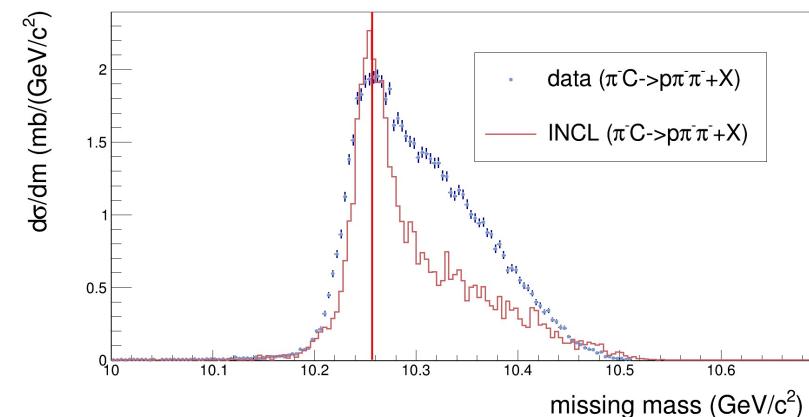
missing momentum in
quasielastic $\pi^+ + p \rightarrow \pi^+ + p$



primary collision

$\pi^- + n \rightarrow p + \pi^- + \pi^-$ (recoiling ^{11}C)

Excitation energy of ^{11}C underestimated by
INCL : scattering effects need to be improved



Next experiment: pp@4.5 GeV

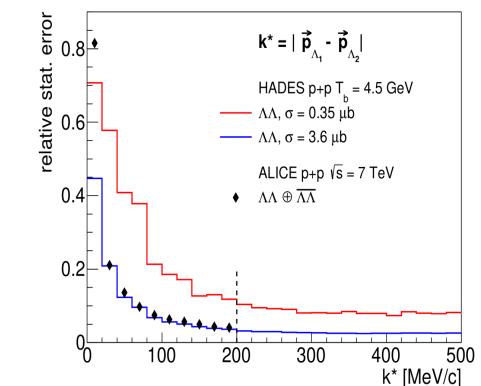
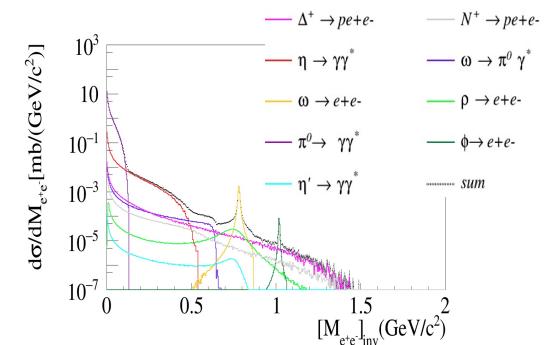
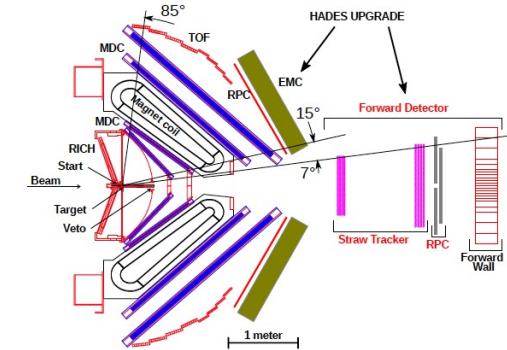
- 1 month beam time in February 2022
- Forward detector to be used for the first time
- Dilepton production: role of baryonic resonance, transition to string fragmentation ?

Cotutelle PhD (Paris-Saclay Darmstadt) staring on dilepton production just started

- Hyperon production and decays $\Xi, \Lambda\Lambda, \Lambda, \Sigma \rightarrow \Lambda\gamma$
Dalitz decays: $pK^+\Lambda(1520)$ [Λe^+e^-], $p K^+\Sigma(1385)$ [Λe^+e^-]
feasibility study Eur. Phys. J. A57, 138 (2021)

Ξ production: understand the unexpectedly large
subthreshold cross section in $p+Nb$ and $Ar+KCl$

Λp and $\Lambda\Lambda$ correlations *Request for an IN2P3 CDD to study*
First HADES measurements for Λp in $p+Nb$ 3.5 GeV,
PRC 94, 025201 (2016)



Future plans at SIS18 (FAIR-Phase0)

Existing exp proposals for 2023-2025 (or later):

1. Au+Au energy scan 0.2-0.8A GeV: 40 A⁻ shifts (Joachim's talk)
EOS, critical effects close to the liquid-gas phase transition
2. $\pi^+p/C/Ag$ $\sqrt{s}_{\pi N} \sim 1.7$ GeV/c²
*hadronic and $e^+e^- N$ decays of baryonic resonances, check of Vector Meson Dominance
modifications of ρ , ω spectral functions and absorption effects*
3. p+Ag 4.5 GeV: cold matter studies, strangeness production, Short Range Correlations Ag(p,ppn) Ag(p,ppp),...
4. d+p (energy scan, reference NN spectra, search for dibaryons)

After 2026..... HADES will move to FAIR

Conclusion

French contribution to HADES mostly focused on reference measurements for medium effects

- Direct reference (dilepton excess)
- Provide or test model inputs (ρN couplings, meson production cross sections,..)
- Normal nuclear effects

... collaboration with French colleagues on medium effects/ EOS is welcome !

Thank you