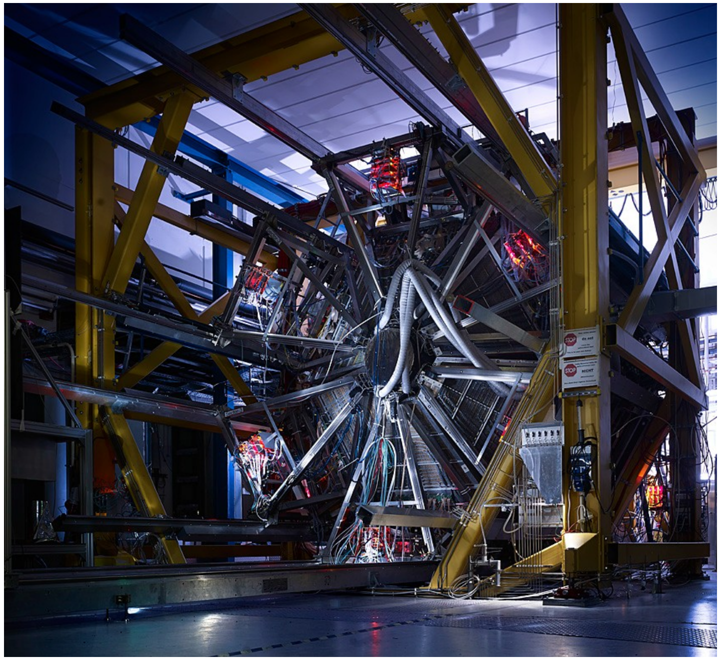
Studies of pion-induced reactions with HADES

UJ Particle Physics Phenomenology and Experiments Seminar



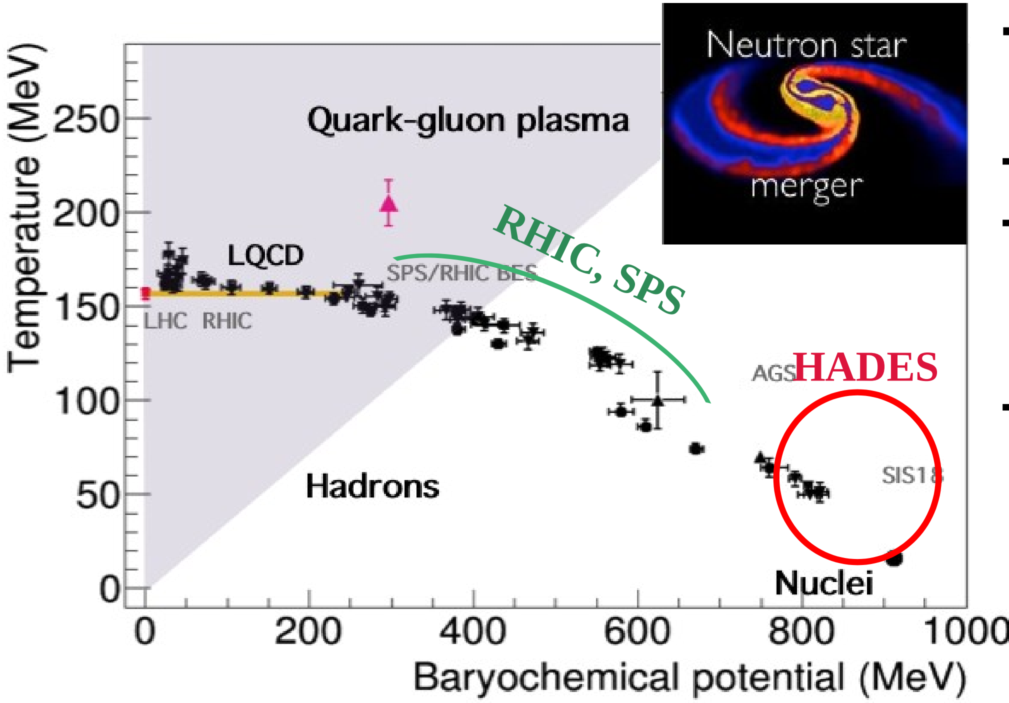
OUTLINE:

1) Motivations of the HADES experiment,
2) HADES detector,
3) Pion-induced reactions at $p_{\pi} = 0.7$ GeV/c:
   I. Studies of baryon structure with pion beam,
   II. Studies of pion and proton emission channels with C target (INCL, SMASH, GiBUU, RQMD),
4) Conclusions and outlook.

Izabela Ciepał

06. 02. 2023

HADES: exploring dense QCD matter

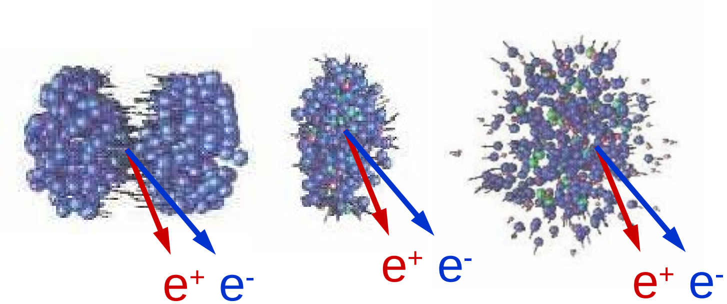


- ➔ Equation-of-State: First order transition ? Search for a critical point
- ➔ Chiral symmetry restoration
- ➔ Microscopic structure of baryon dominated matter
  Role of baryonic resonances, hyperons
- ➔ Complementary to SPS, RHIC,..

A+A: 1-3A GeV
$\sqrt{s}$=2-2.4 GeV

Observables:

- ✓ Correlations and fluctuations
- ✓ Collective effects
- ✓ Strangeness
- ✓ **Dileptons**

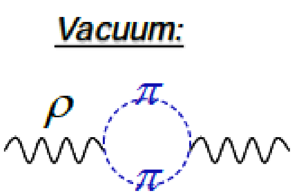


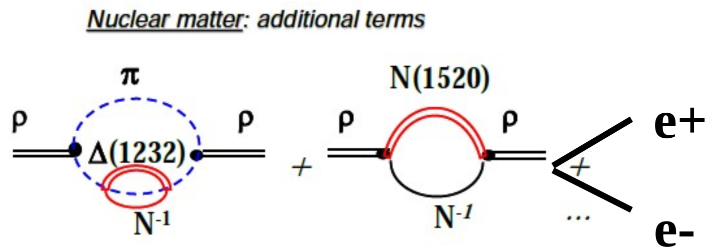
HI and elementary collisions

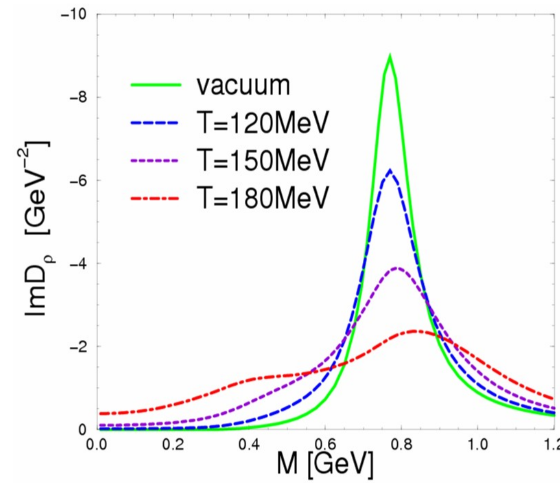
- ➔ baryon-dominated matter
- ➔ role of vector mesons

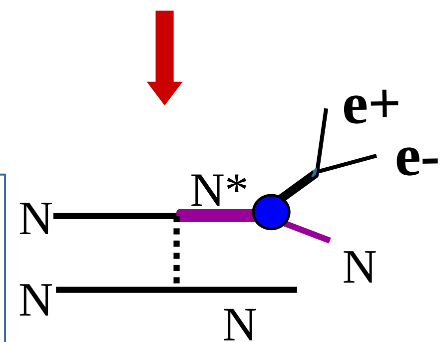
P. Hohler, R. Rapp,
Phys. Lett. B 731 (2014) 103

ρ-meson







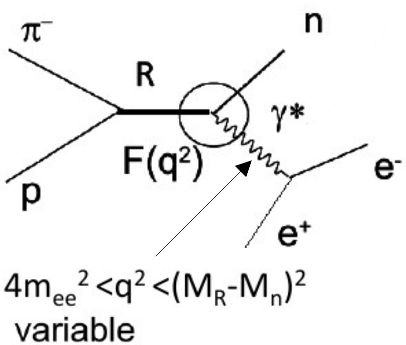


in-medium **spectral function** depends on **ρNN* coupling** (N(1520), Δ(1720), N(1910), ….) studied in **NN, πN collisions** via $N^*(\Delta) \rightarrow$ N**e+e−** Dalitz decays

- ➔ **in-medium ρ broadening**
- ➔ **chiral symmetry restoration**

ρ(760)/a_1(1260) become degenerate at T ~ T_c , μ_b =0

Electromagnetic structure of baryons



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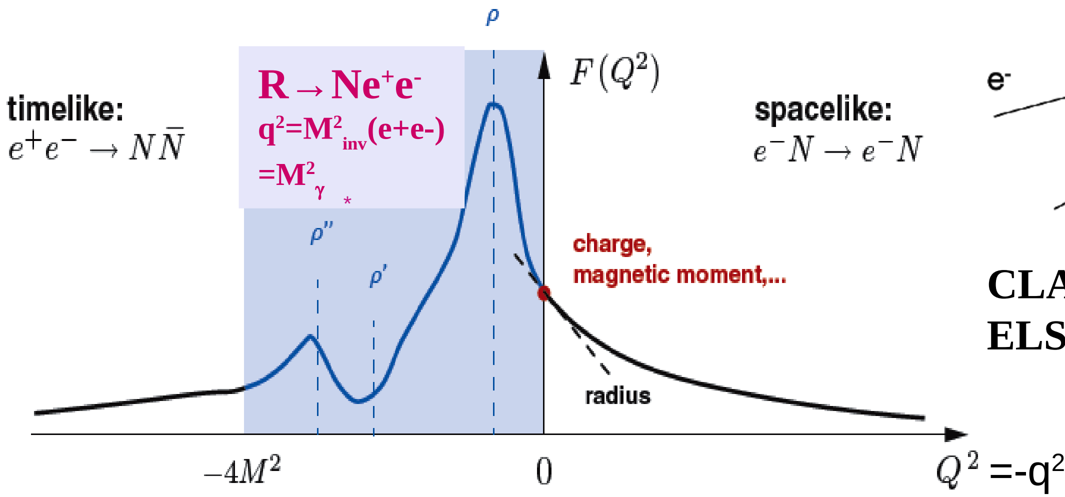
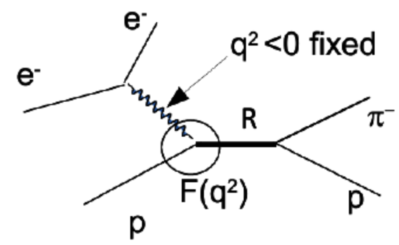
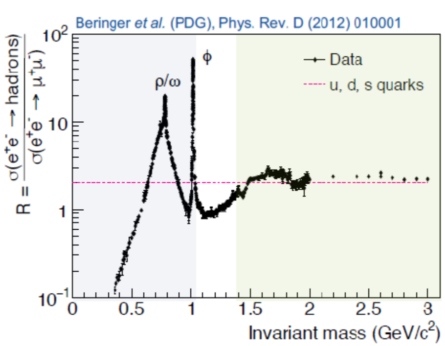




CLAS/Jlab, MAMI, ELSA, JLab-Hall A, ...

Rezonans → Nucleon Transition Form Factor – **baryon Dalitz decay**

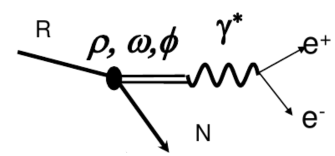
$$\frac{d\Gamma(\Delta \to Ne^+e^-)}{dq^2} = f\left(m_\Delta, q^2\right)\left(\left|G_M^2(q^2)\right| + 3\left|G_E^2(q^2)\right| + \frac{q^2}{2m_\Delta^2}\left|G_C^2(q^2)\right|\right)$$



QED
transition of point-like particles

$G_{M/E/C}$: Form-Factors
internal structure of hadrons
(various models)

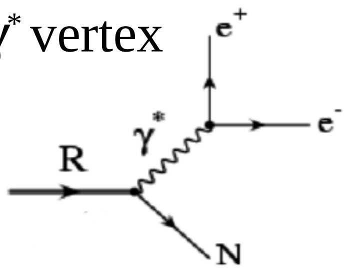
Important role of vector mesons: $J^{PC} = 1^{--}$ (=γ)



Dalitz decays of baryon resonances

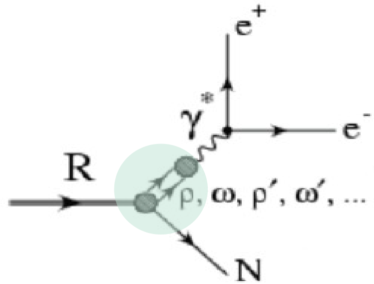
QED "point-like"

R-γ^* vertex

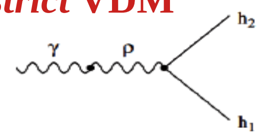


M. Zetenyi et al.,
PRC 67, 044002 (2003)

Vector Meson Dominance Model (VDM)

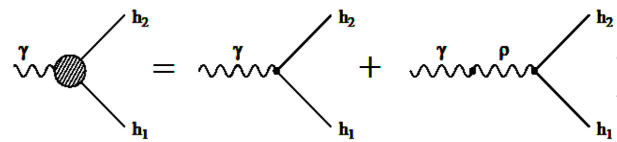


➔ *strict* VDM



***Sakurai**, Phys. Rev 22 (1969) 981*
M. I. Krivoruchenko et al.,
Ann. Phys. 296, 299 (2002)

➔ 2-component VDM

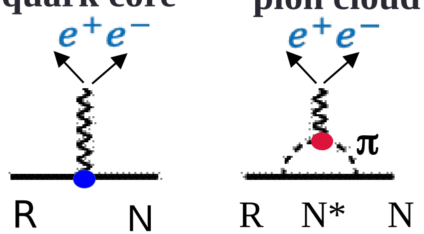


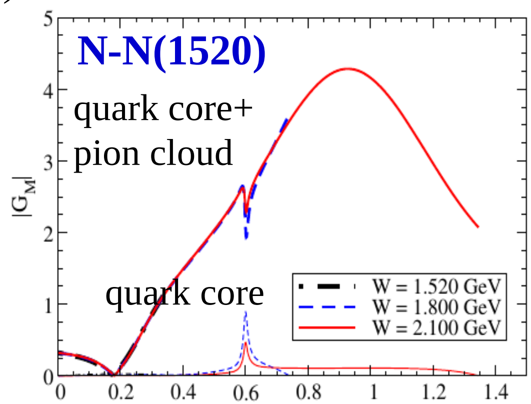
Kroll, Lee & Zuminio
Phys. Rev. 157, 1376 (1967)

Covariant quark model +VMD

T. Pena & G. Ramalho

Phys. Rev. D95, (2017) 014003





VDM:
quark FF
pion FF

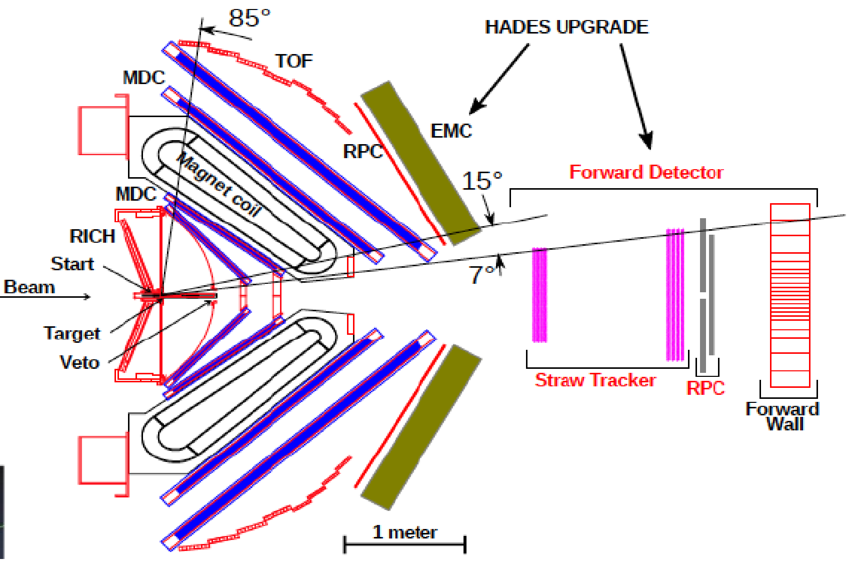
Two-component Lagrangian model

M.Zetenyi & G. Wolf

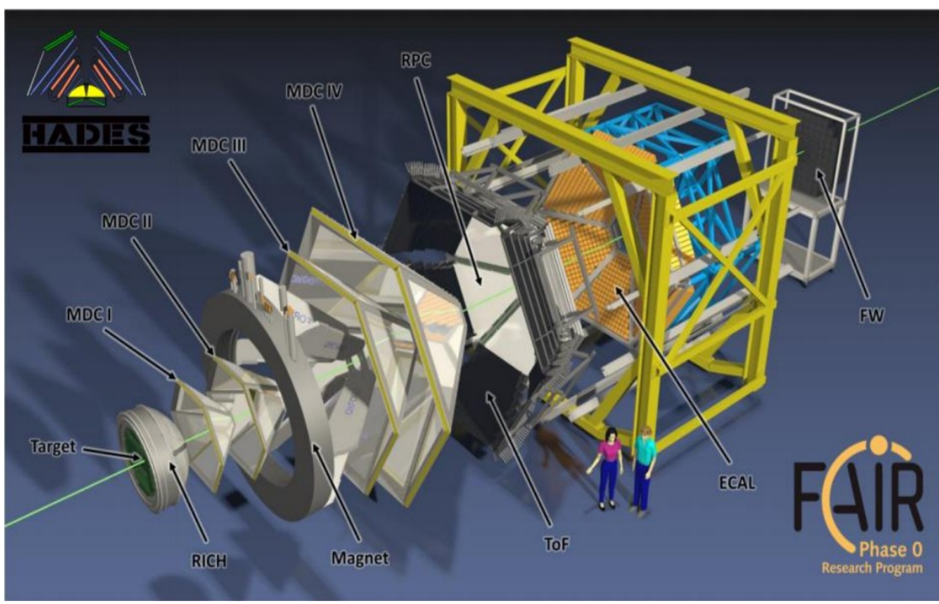
Phys. Rev. C 104, 015201 (2021)

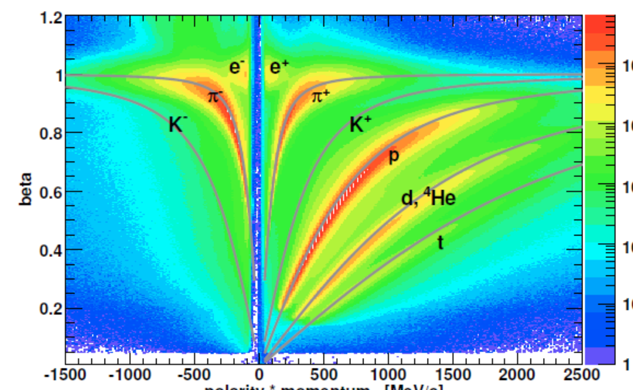
- Microscopic calculations based on 2-component VDM Lagrangian

High Acceptance DiEelectron Spectrometer



- ✓ SIS18 beams: protons (1-4.5GeV), nuclei (1-2AGeV), pions (0.4-2 GeV) secondary beam
- ✓ Spectrometer with ΔM/M~ 2% at ρ/ω
- ✓ PID (π/p/K): ToF (TOF/RPC, T0 detector), tracking (dE/dx)
- ✓ momenta, angles: MDC+ magnetic field
- ✓ electrons: RICH
- ✓ neutral particles: ECAL
- ✓ full azimuthal, polar angles $18^{O} – 85^{O}$
- ✓ e+e- pair acceptance ~0.35



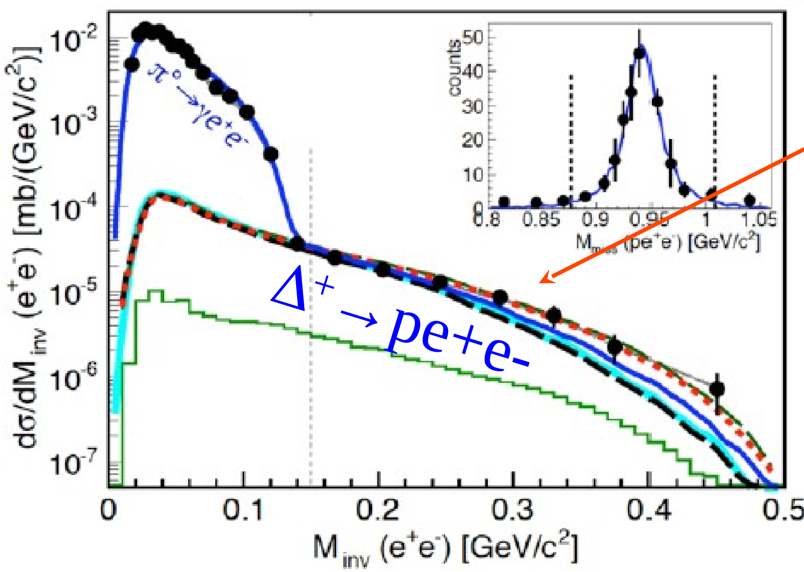


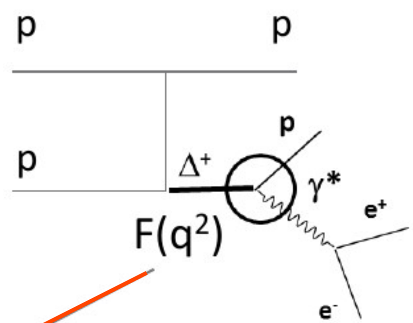
Baryon resonances - exclusive e+e- analysis

HADES: Phys. Rev. C 95, 065205 (2017)

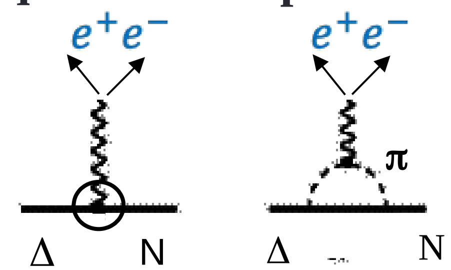
pp → ppe+e- @1.25 GeV

→ cross sections for $pn\pi^+$, $pp\pi^0$ using PWA

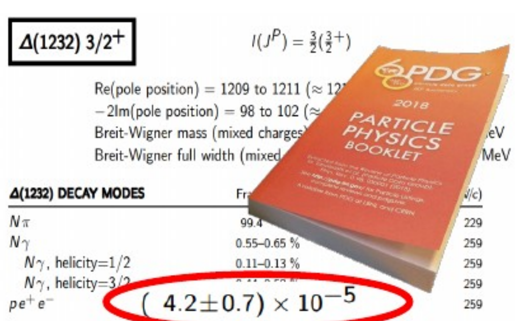




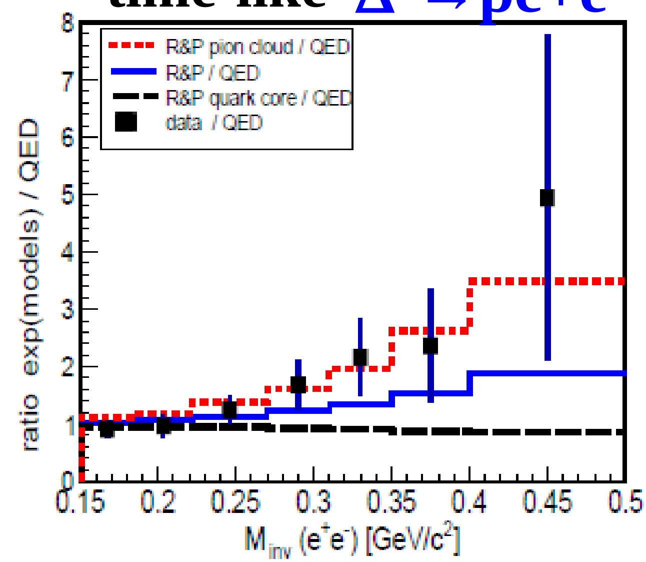
quark core pion cloud



G. Ramalho, T. Peña, Phys. Rev. D 93, 033004 (2016)

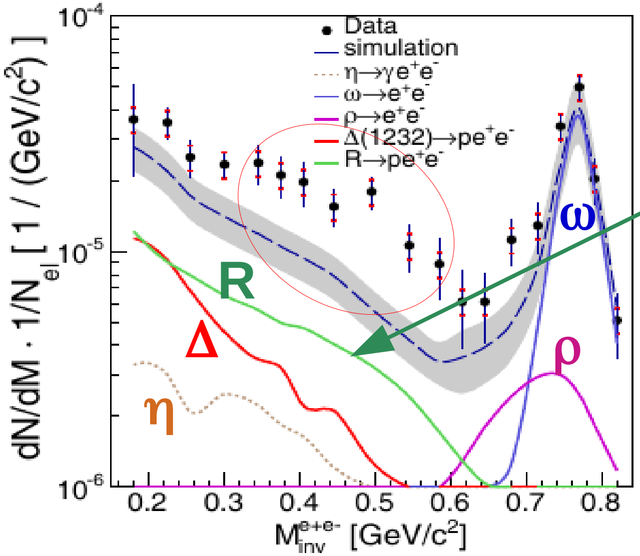


time-like $\Delta^+ \to$ pe+e-



Dalitz decay studies of heavier baryons

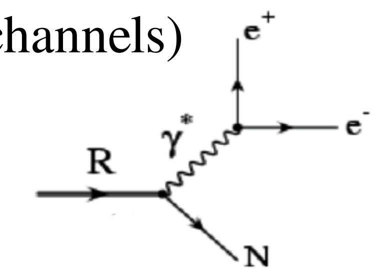
HADES: EPJ A50, 82 (2014)

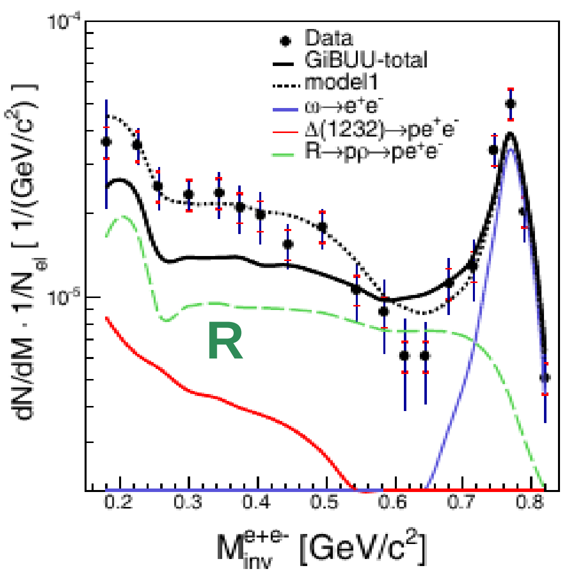


$pp \rightarrow ppe^+e^-$ @3.5 GeV

Dalitz decays of **point-like** baryonic resonances (constrained by $pp\pi^0$ and pnp^+ channels)
QED reference

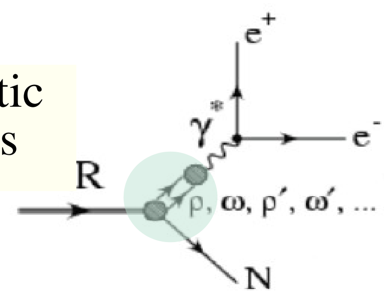
R → pe+e-





effect of electromagnetic transition Form Factors

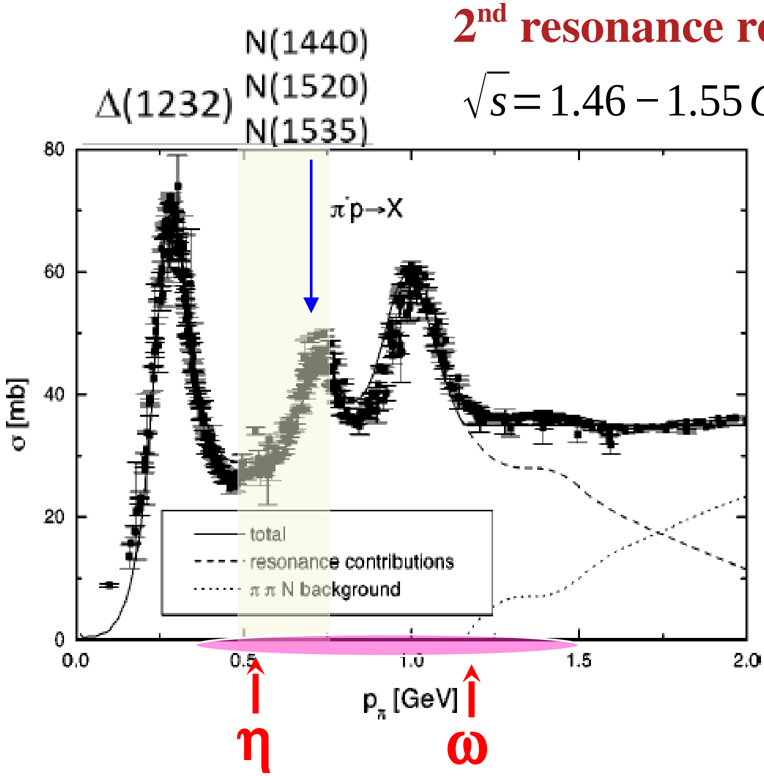
R → pρ → pe+e-



R= $\Delta^+(1232)$, $N^*(1440)$, $N^*(1520)$, $N^*(1535)$, $N^*(1680)$, $\Delta^+(1700)$, $\Delta^+(1910)$

model 1 = GiBUU, but with modified cross sections (HADES simul.)

Motivations for pion beam experiments with HADES

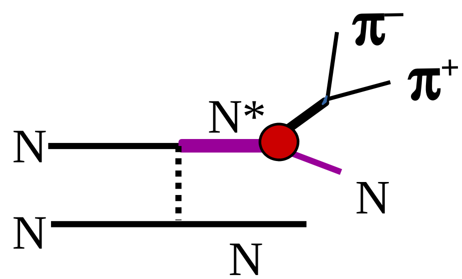


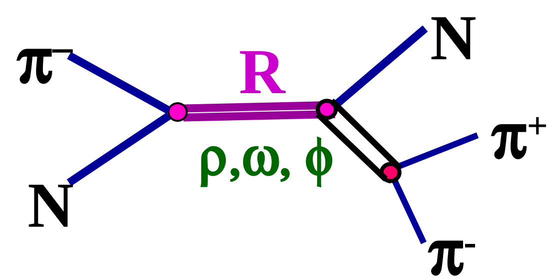
2nd resonance region

$\sqrt{s} = 1.46 - 1.55\, GeV$

selectivity:

producion of resonance with given mass in s-channel





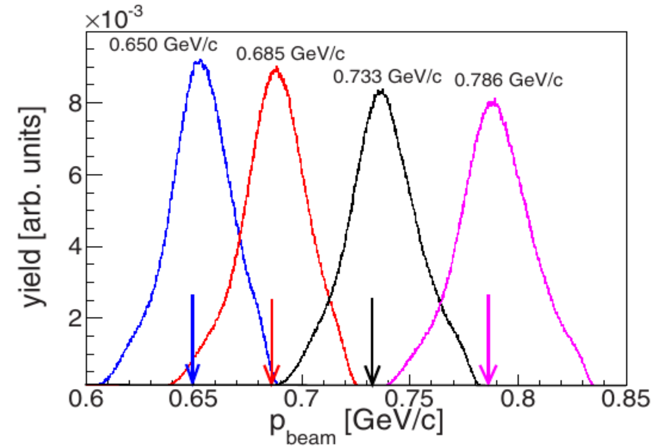
HADES + GSI pion beam is an ideal (unique in world) tool to:

- Study the time-like electromagnetic structure of baryons
- Complete the very scarce pion beam data base for hadronic couplings
- **Dilepton channel** R→ Ne+e-, **never** measured in pion induced reactions

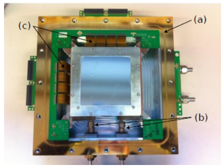
Pion beam facility @ GSI

Eur. Phys. J. A 53, 188 (2017)

- reaction **N+Be**, 8-10*10^{10} N_2 ions/spill (4s)
- secondary π^- with **I ~ 2-3 10^5/s**
- p = 650, **685**, 733, 786 (+/- 1) MeV/c
- **PE $(CH_2)_n$** and **C** targets

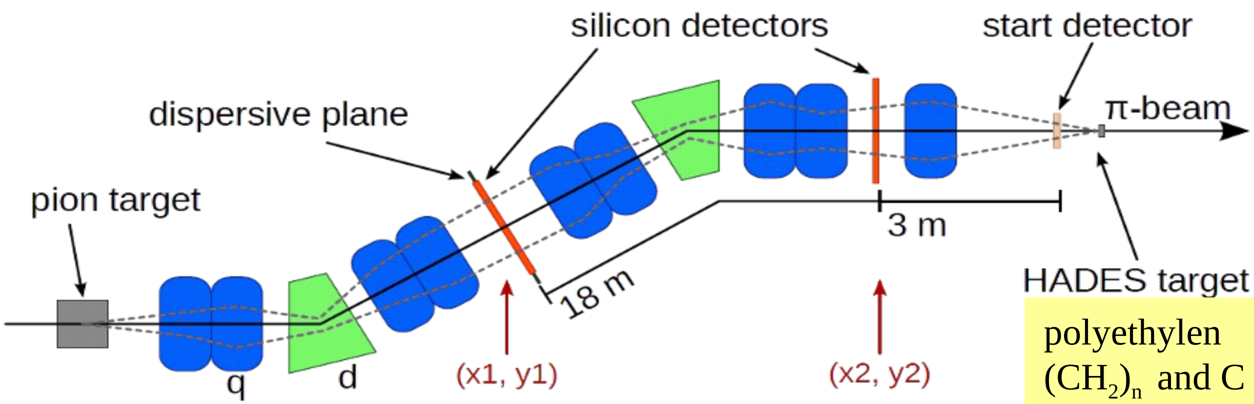


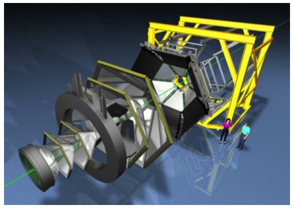
- pion momentum $\Delta p/p$ =2.2% (σ)
- ~50% acceptance of pion beam line



pion beam tracker

diamond detector

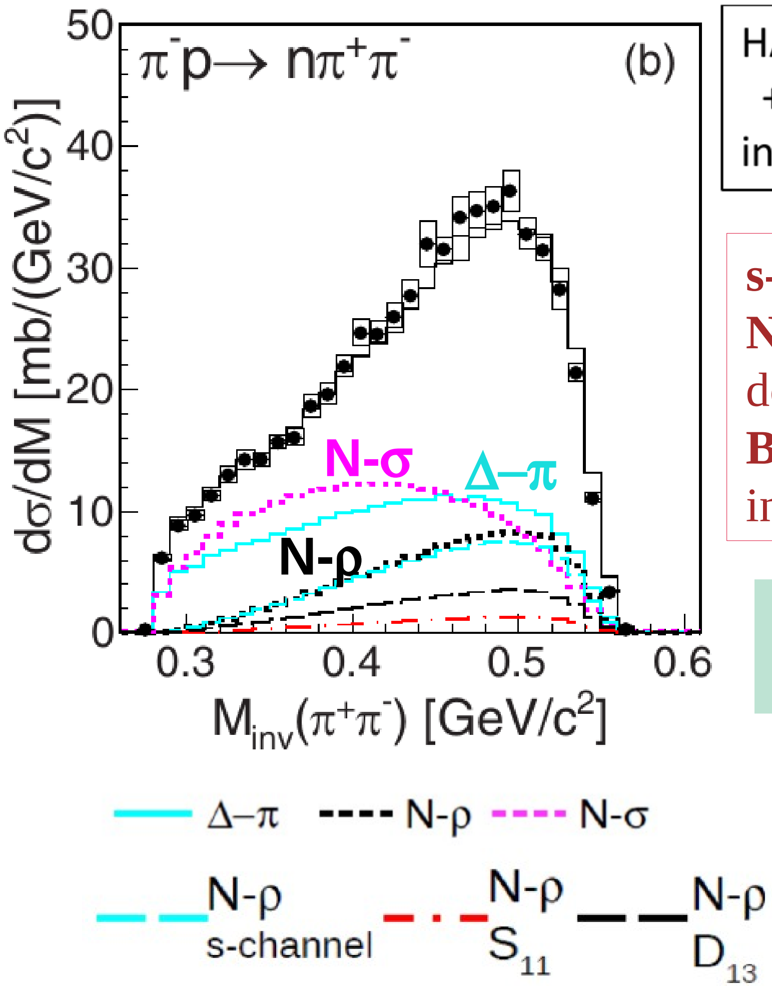




polyethylen $(CH_2)_n$ and C

2-pion production in $\pi^- p$

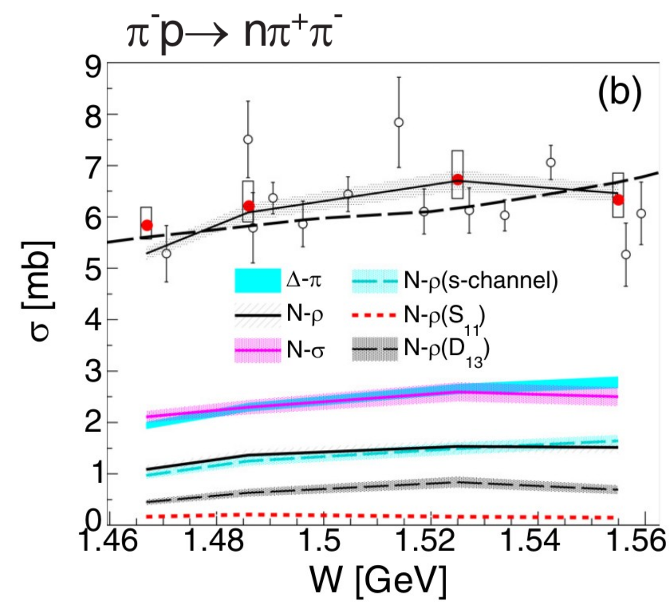
HADES: Phys. Rev. C 102, 024001, (2020)



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

s-channel
N(1520) $3/2^-$
dominant contribution
BR=11.8 +/- 1.9 %
in ρ production

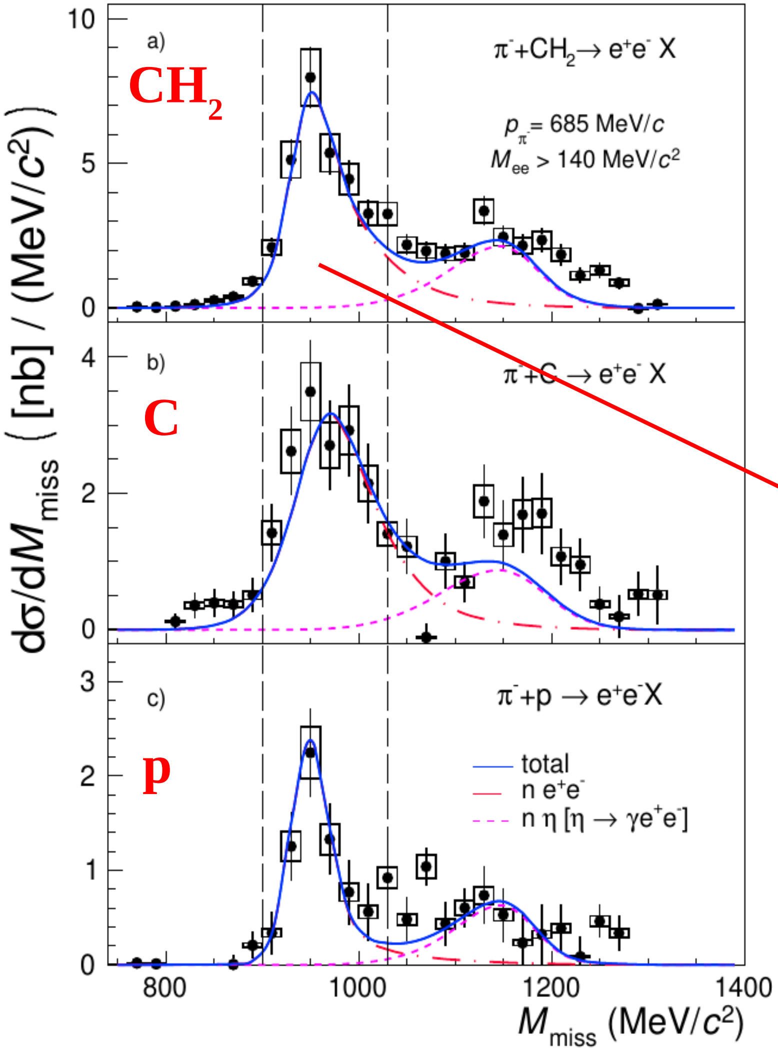
crucial
for e+e- analysis



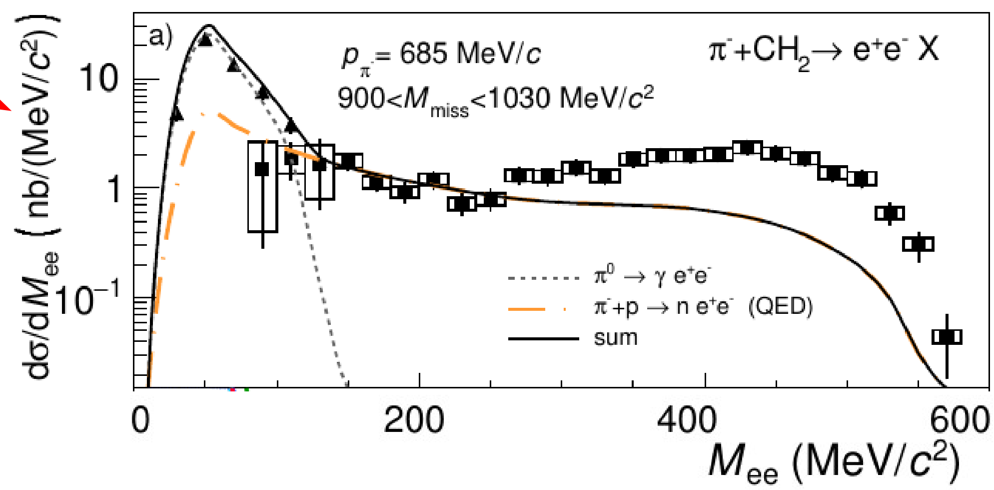
Branching ratios of N(1440), N(1535), N(1520) to 2π channels (Δ π, σN, ρN)
→ 8 new entries (4 first + 4 additional entries)

Selection of quasi-free $\pi^- p \rightarrow ne^+e^-$

HADES Coll. arXiv:2205.15914 [nucl-ex]



- cut on inv$M_{e^+e^-}$ >140 MeV (π^0 removed)
- selection of $\pi^- p \rightarrow ne^+e^-$ exclusive channel using missing mass cut (η removed)
- quasi-free treatment of π^-C interaction

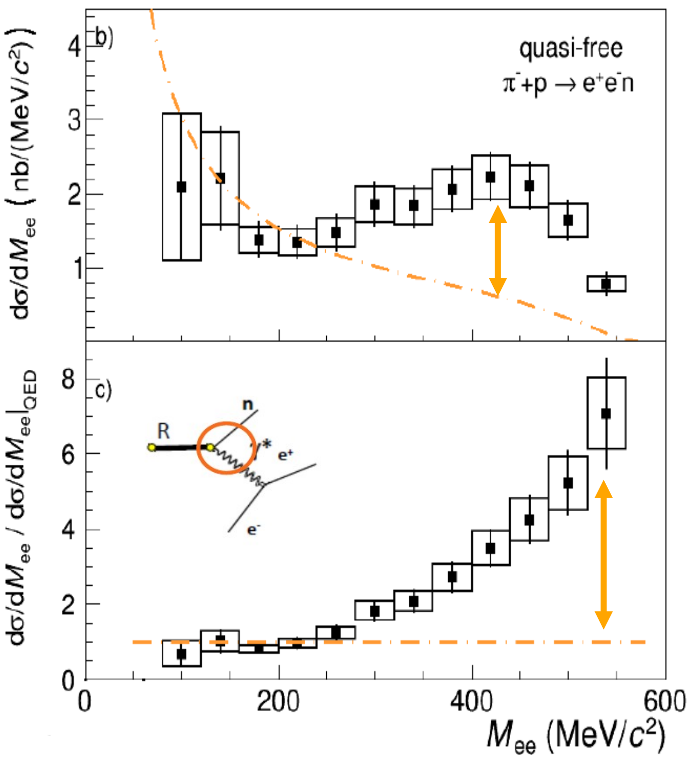


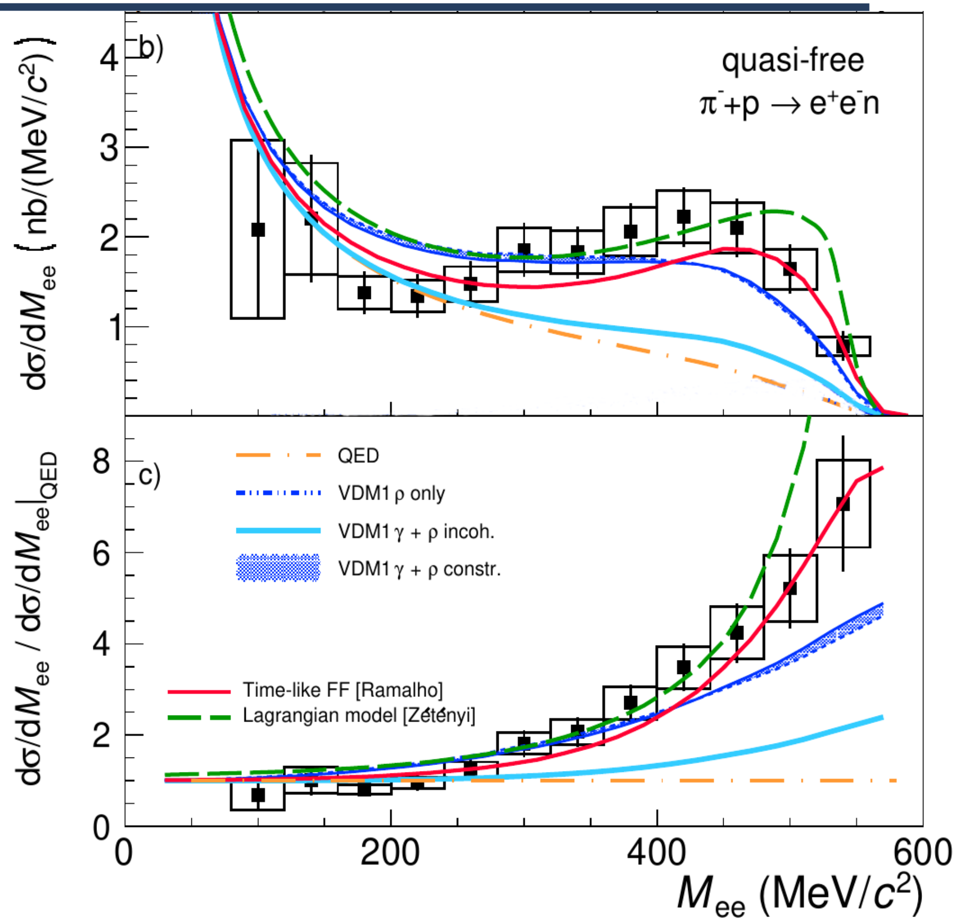
Effective time-like transition form factor

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

HADES Coll. arXiv:2205.15914 [nucl-ex]

huge excess over point-like QED



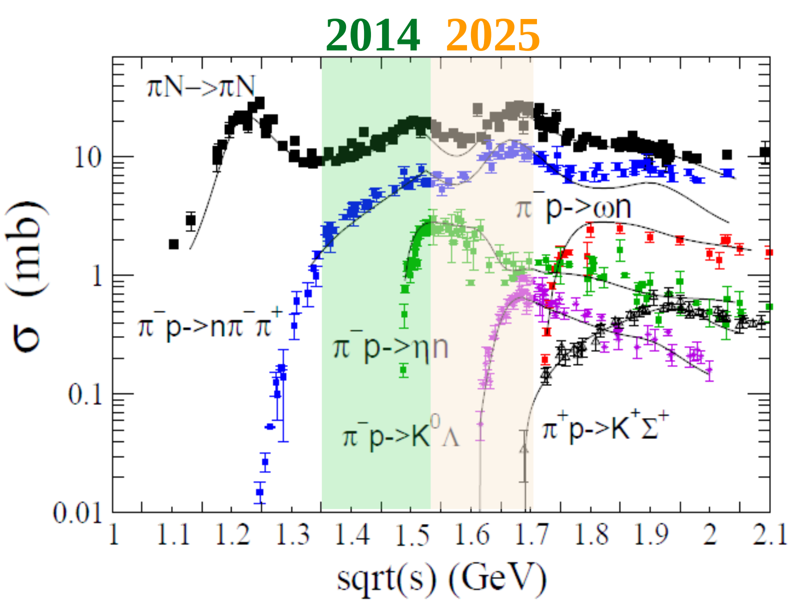


- $M_{ee} < 200$ MeV/c^2 consistency with QED reference
- Strong excess at larger M_{ee} (up to a factor 5)

VDM1 - gives reasonable description
Lagrangian model – very promising
Time-like FF - dominant pion cloud contribution (pion emFF)

Summary

- HADES & **pion beam** is an unique tool to understand in details baryon-couplings:
  - → significant off-shell contribution originating from N(1520)D_{13} shown by combined PWA,
  - → D_{13}(1520) coupling to -N: 12+/-2 %,
  - → very new information on electromagnetic baryon transitions in the time-like region,
- Proposal for pion beam experiment in 2025 in the third resonance region.



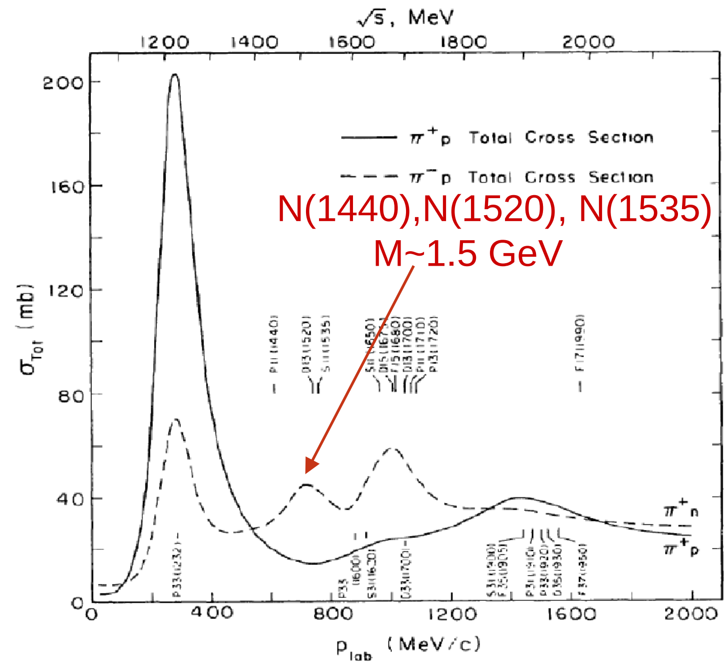
Investigate heavier resonances N(1620), N(1720), …
in e+e- channels and many hadronic channels, e.g. ππN, ωn, ηn, $K^0\Lambda$, $K^0\Sigma$, ….

Studies of pion and proton emission channels with C target

Main goal: microscopic structure of baryon dominated matter and role of baryonic resonances in the 2nd resonace region.

- test of transport models used as a tool to identify medium effects (study of various reaction mechanisms)
- in heavy-ion collisions at a few AGeV, **pion dynamics** crucial to describe the evolution of the collision:

  → real pions copiously produced

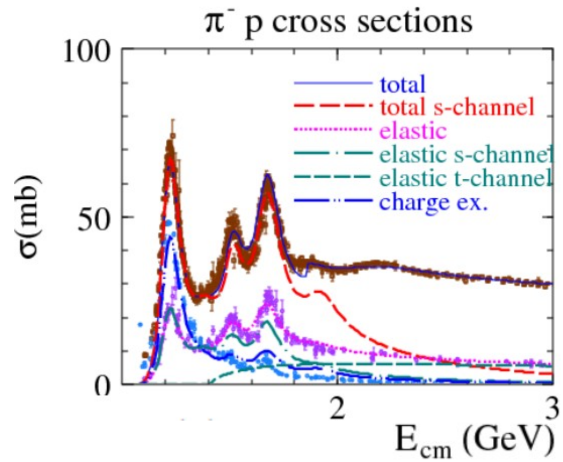


Previous investigations with pion beam:

- **P_π<250 MeV/c:** Δ(1232) resonance region well-known.
- **300<P_π<500 MeV/c**: few measurements (π, πx) or (π, ππx) (LAMPF, TRIUMF, KEK).
- **P_π>500 MeV/c:** only total cross sections (Saturne-1, NIMROD, BNL) and differential elastic cross sections (KEK).

Transport models

- Nucleon Fermi gas,
- Binary interactions: inelastic collisions through resonance/string excitation and decay,
- All **baryonic resonances** included (Δ(1232), N(1440), N(1520), ... up to M=2 GeV/c²),
- Elementary cross-sections adjusted to data.



πN → R(string), R → πN, ππN
pp → pR, R → πN

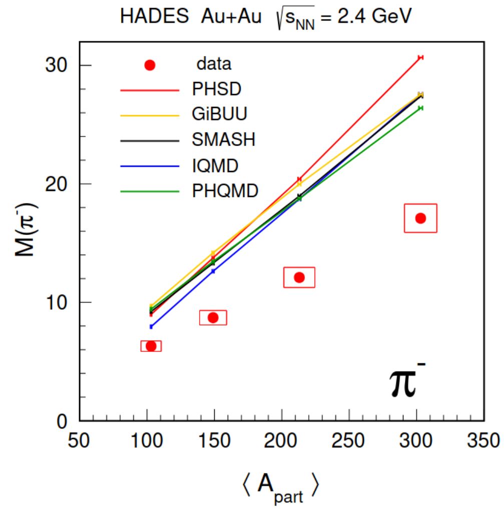
BUU (Boltzmann-Uehling-Uhlenbeck transport equation)		QMD (Quantum Molecular Dynamics)	
GiBUU	**SMASH**	**RQMD.rmf**	**UrQMD**
https://gibuu.hepforge.org	**https://smash-transport.github.io**		**http://urqmd.org**
momentum-dependent mean field potential	mean field potential	potential: sum of potentials from surrounding particles (wave packets)	
		mom.-dep.	non mom.-dep.
only field-type (continuous) interaction via the mean field, no N-N int. (except for collisions)		particle moves in the potential + collides with neighbours	
		N-N interaction	

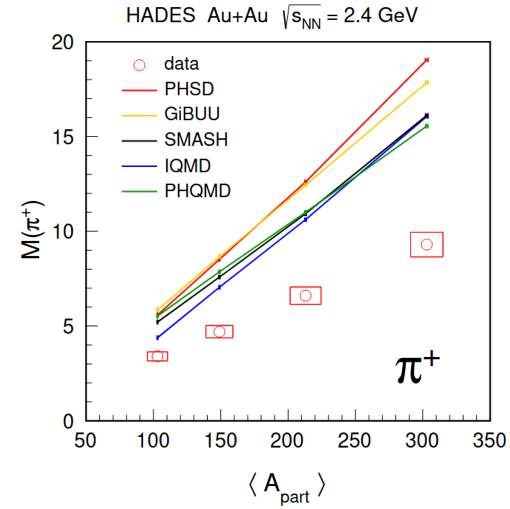
Open issues …..

- **HI collisions with HADES**

overestimation of pion production

HADES: Eur. Phys. J. A 56, 259 (2020)



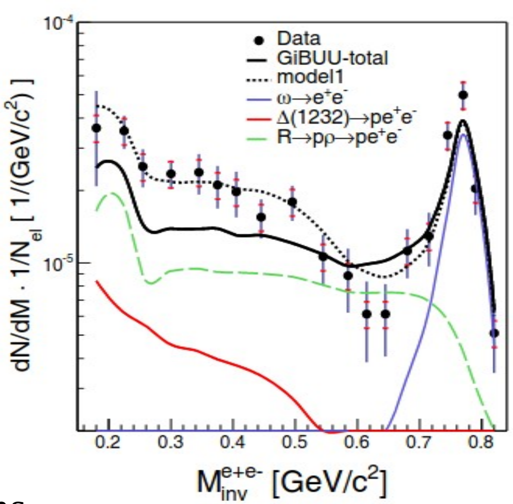


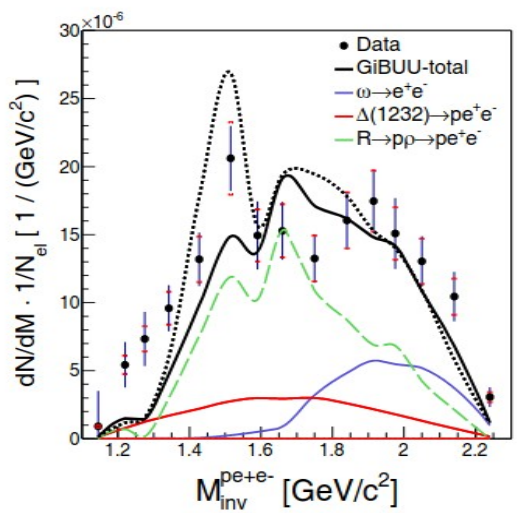
- **pp → ppe$^+$e$^-$ @3.5 GeV**

HADES: EPJ A48, 64 (2012)

model 1 = GiBUU, but with modified cross sections (HADES simul.)

R= N*(1520) - 38%
N*(1720) - 22%
Δ^+(1620) - 15%
Δ^+(1905) - 7%





➔ pp validates only the primary NN collisions….

INCL++ cascade model

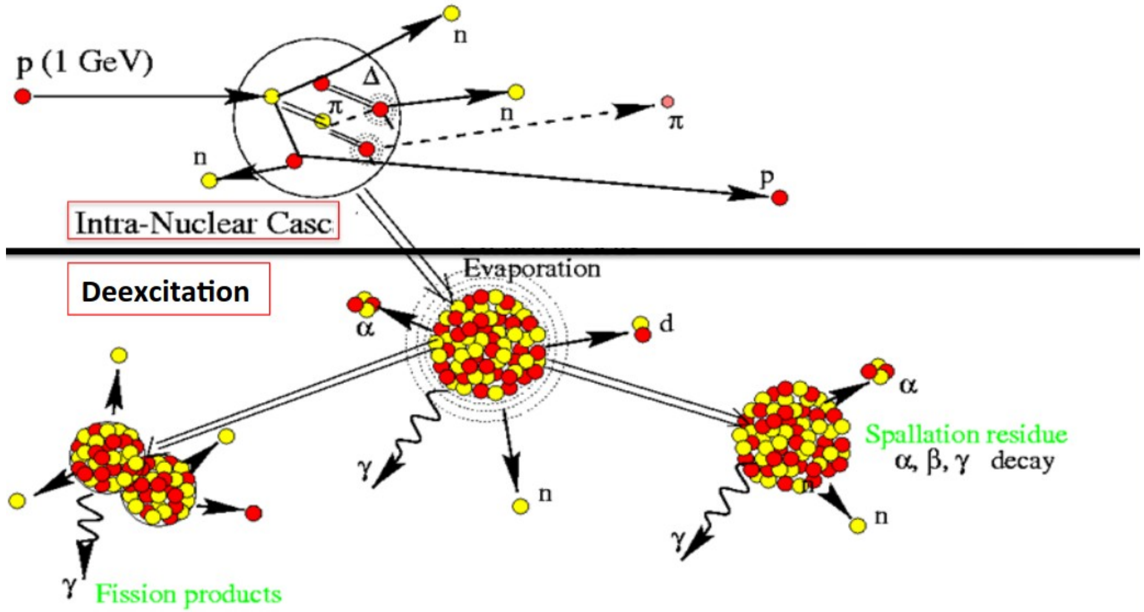
https://irfu.cea.fr/dphn/Spallation/incl.html

- Based on transport equations, but constant potentials are applied.
- Baryon spectrum: only Δ(1232) resonance is included.
- Dynamic creation of composity nuclear products (surface coalescnece).

Applications:

- GEANT4
- Interaction of pions in detectors (e/π discrimination)
- Neutrino physics.

p/π/light ions + A



$\pi^- + {}^{12}C$ @ 685 MeV/c

Our strategy:

- ➢ Test transport models and INCL++: investigate various exit channels of $\pi^- + {}^{12}C$ in the 2nd resonance region to constrain the description of various processes:
- ➢ quasi-elastic, rescattering, pion absorption,…

- ➢ Generation of events following different models,
- ➢ Events processed through detector material (GEANT),
- ➢ Reconstruction of simulated events same as data events.

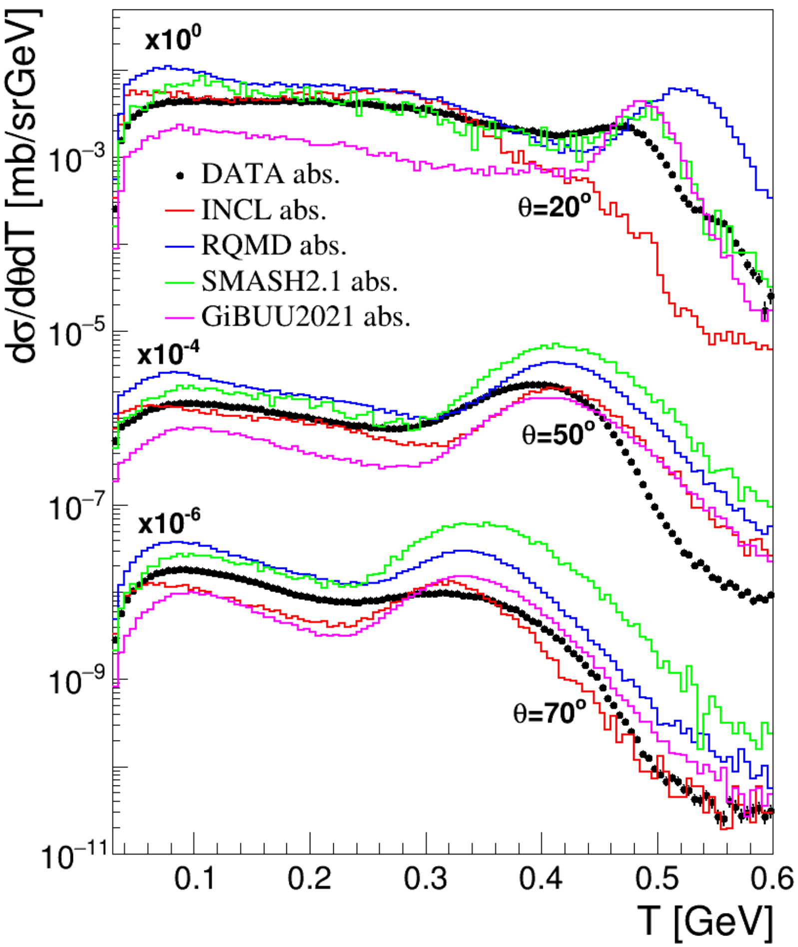
- "inclusive": p, π^+, π^-, d, t (TOF/RPC Mult2 trigger)
- quasi-elastic: $\pi^- + {}^{12}C \rightarrow p + \pi^- + X$ (SRC, rescattering)
- 2-particle: $\pi^-\pi^-$, $\pi^-\pi^+$, pp, $p\pi^+$, $p\pi^-$
- 3-particle: $p\pi^-\pi^-$, $p\pi^+\pi^-$, $pp\pi^-$, ppp

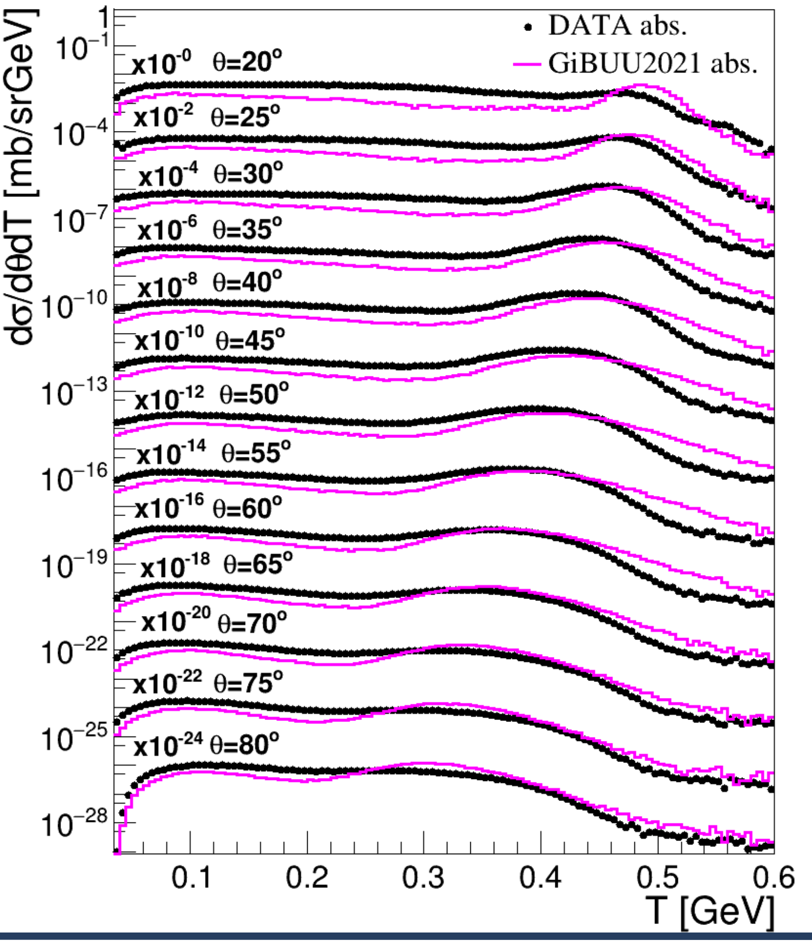
Models:

- **INCL**
- RQMD.rmf
- SMASH
- GiBUU

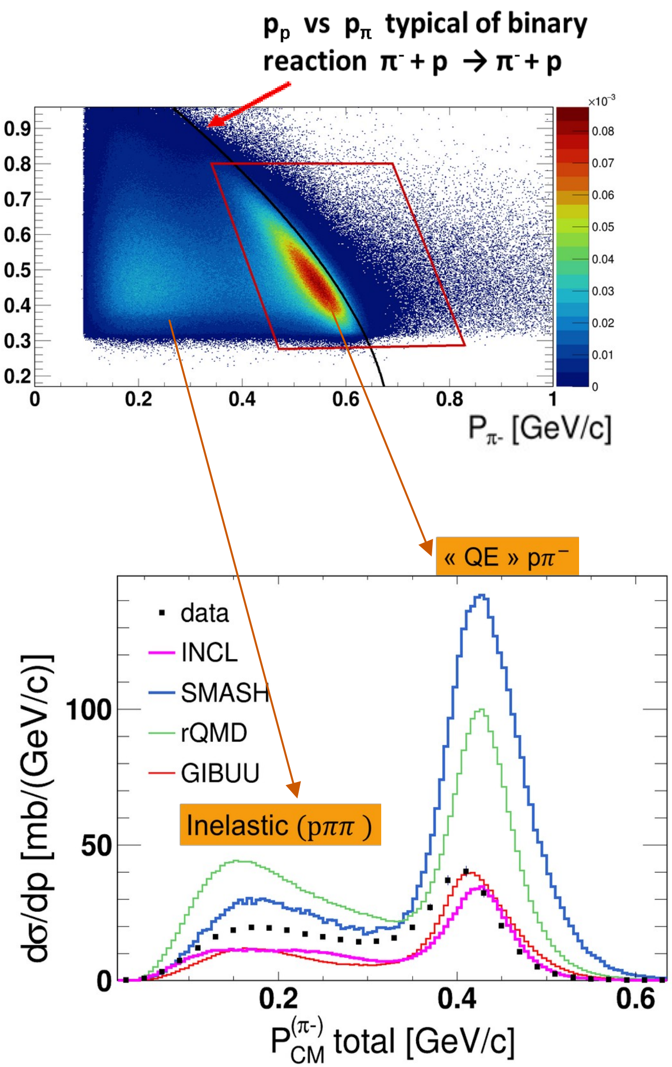
$\pi^- + {}^{12}C \rightarrow \pi^- + X$ inclusive

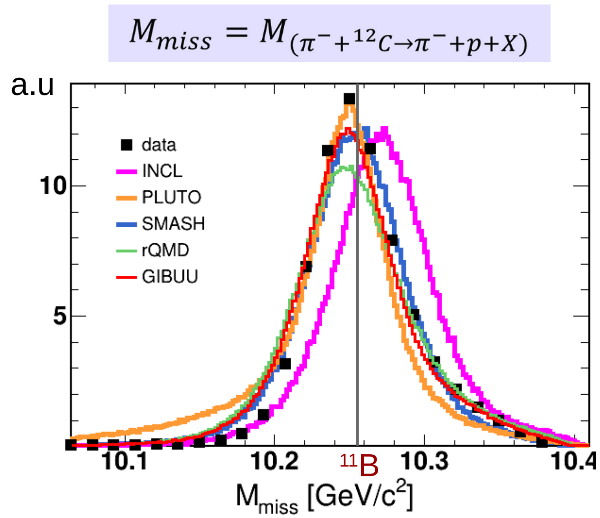
PRELIMINARY – ongoing analysis



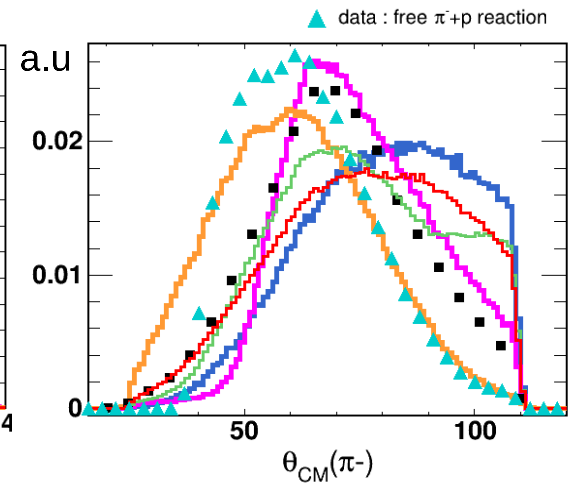


$\pi^- + {}^{12}C \rightarrow \pi^- + p + X$
quasi elastic

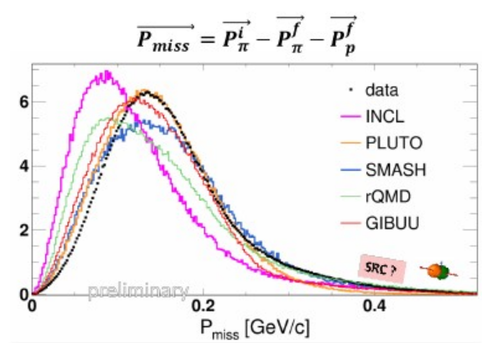




missing mass shifted in INCL



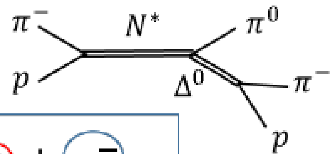
INCL reproduces well pion angular distribution



- SMASH & rQMD overestimate data
- INCL underestimates data

$\pi^- + {}^{12}C$ @ 685 MeV/c

$p\pi^-$: Inelastic



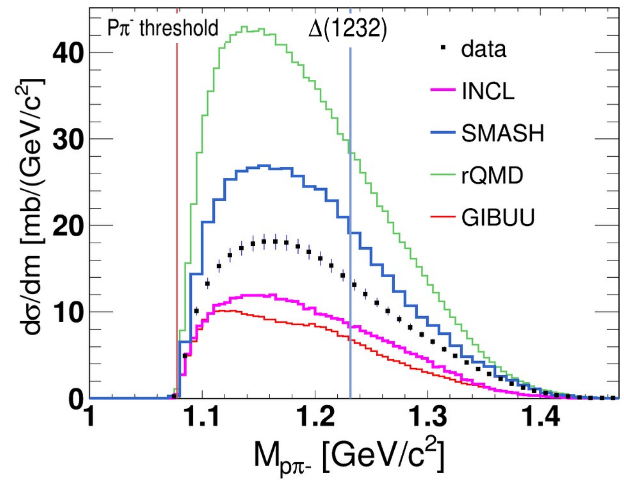
Single step

$$\pi^- + p \rightarrow \pi^0 + p + \pi^-$$

Multi step

$$\pi^- + p \rightarrow \pi^- + p$$
$$\pi^- + p \rightarrow n + \pi^- + \pi^+$$

$$\pi^- + p \rightarrow \pi^0 + n$$
$$\pi^0 + p \rightarrow p + \pi^- + \pi^+$$



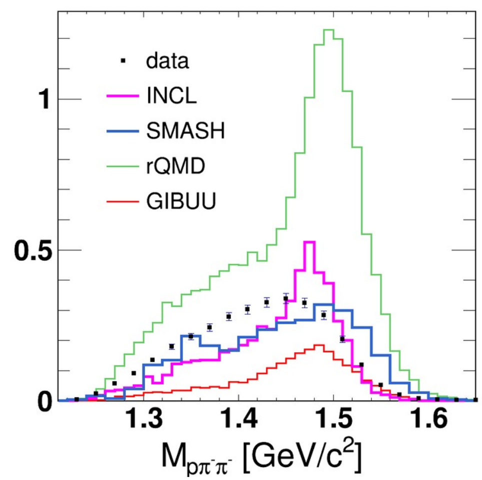
$p\pi^-\pi^-$

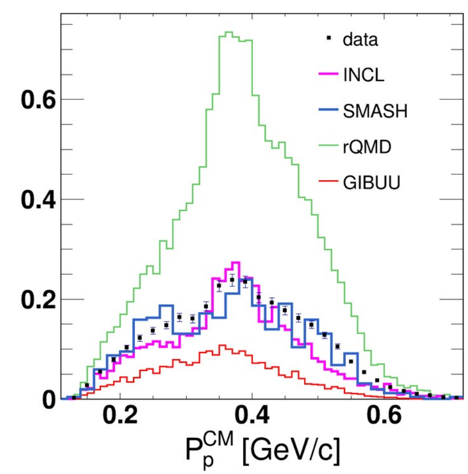
Single step production:

$\pi^- + n \rightarrow p + \pi^- + \pi^-$; **recoiling 11C**

Two step production:

$$\pi^- + p \rightarrow \pi^- + p$$
$$\pi^- + n \rightarrow p + \pi^- + \pi^-$$



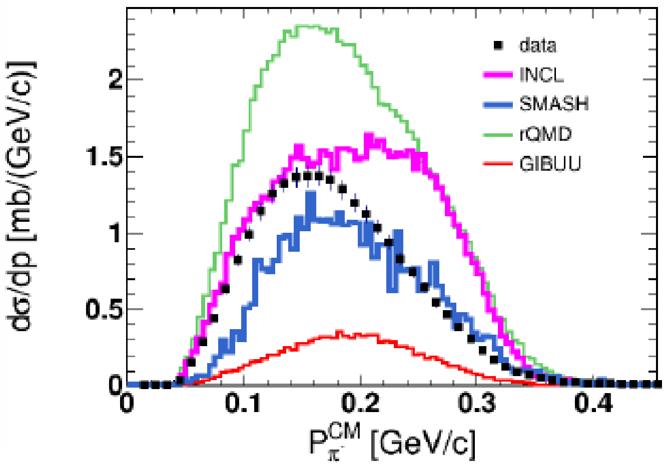


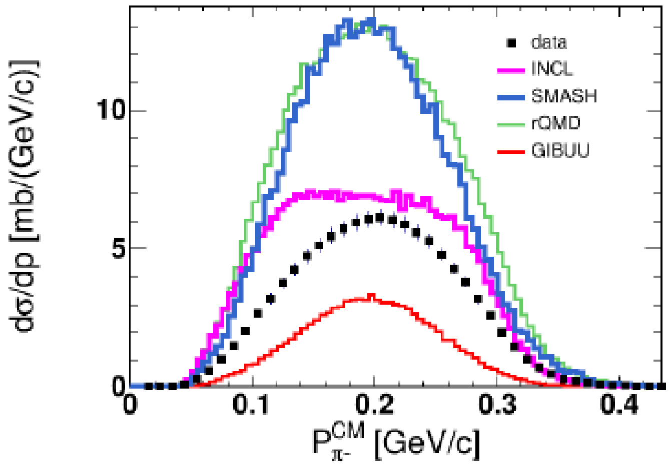
$\pi^- + {}^{12}C$ @ 685 MeV/c

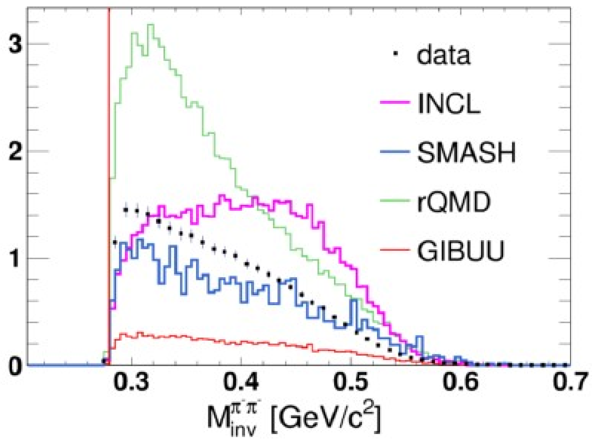
$\pi^-\pi^-$

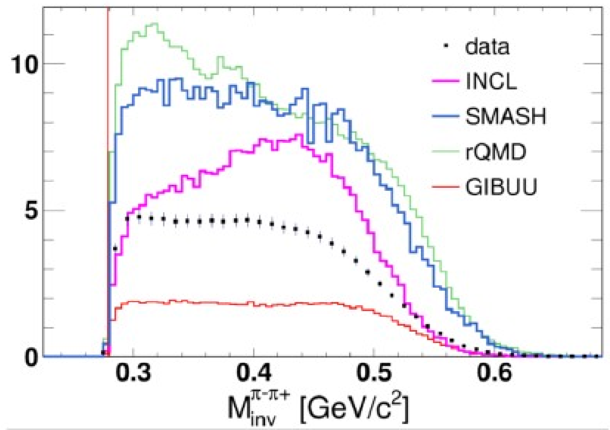
- $\pi^-\pi^-$ **same 2-step processes as** $p\,\pi^-\pi^-$
- $\pi^-\pi^+$ **can be produced in** $\pi^- + p \rightarrow n + \pi^- + \pi^+$
  $\sigma = 6.2$ mb $\rightarrow$ higher yields

$\pi^-\pi^+$









Summary and outlook

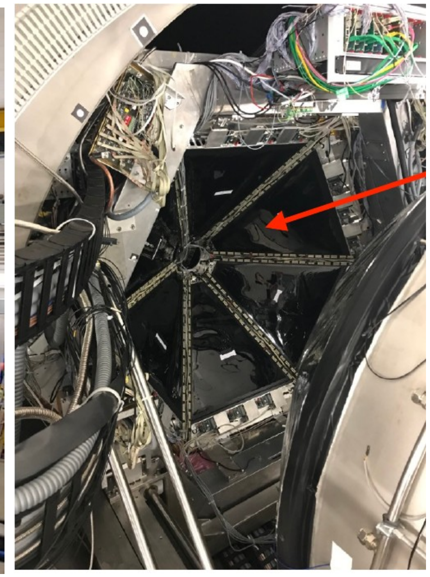
- **Pion on carbon reactions** are under investigation:
  - → comprehensive analysis of inclusive, quasi-free and 2-3-particle correlations,
  - → comparison to various transport models (SMASH, GIBUU, RQMD) and cascade INCL model – large dispersion of the predictions (!)
  - → INCL++ does a **rather** good job for channels with detected pion $p\pi^+$, $p\pi^-$,
- New paper on π^-+C, π^-+W at p_π= 1.7 GeV/c
  HADES Collab. arXiv:2301.03940 [nucl-ex]

- HADES and GSI pion beam facility is very unique tool to study electromagnetic structure of baryons via Dalitz decays.
- Cold nuclear matter studies with C target: important for the interpretation of in-medium hadron properties studied in HI collisions.

Thank You
for
Your Attention

HADES Spectrometer UPGRADE

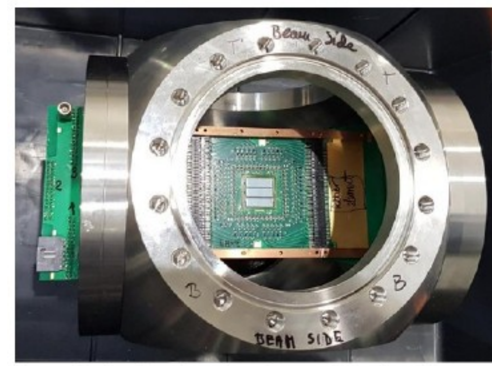
HODO, fRPC, STS2, STS1



➔ NEW Trigger Box innerTOF & TOF/RPC

innerTOF (fast trigger)

- START T0 detector

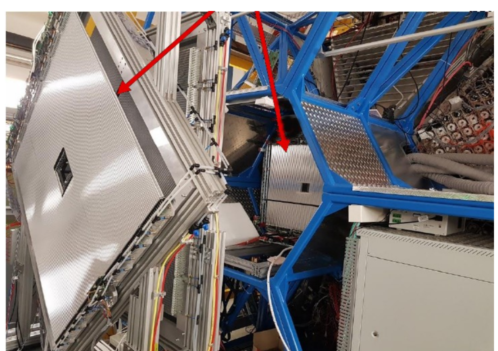


Low Gain Avalanche Detectors for the HADES reaction time (T) detector upgrade (Eur. Phys. J. A (2020) 56: 183)

- timing < 100 ps
- PCB in the beam vacuum
- rate capability 10^8 p/s
- 2 cm x 2 cm, 96 channels
- pitch 387 μm

- ECAL (lead glass)

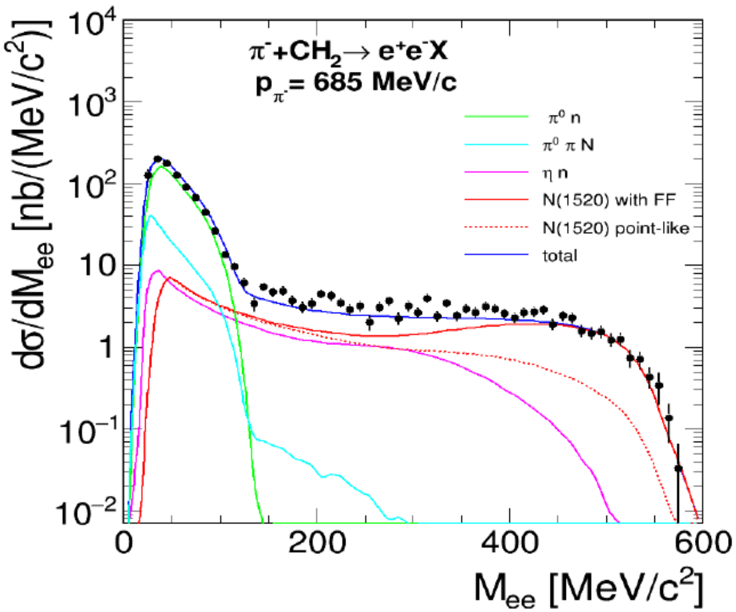
STS2 STS1



- new RICH

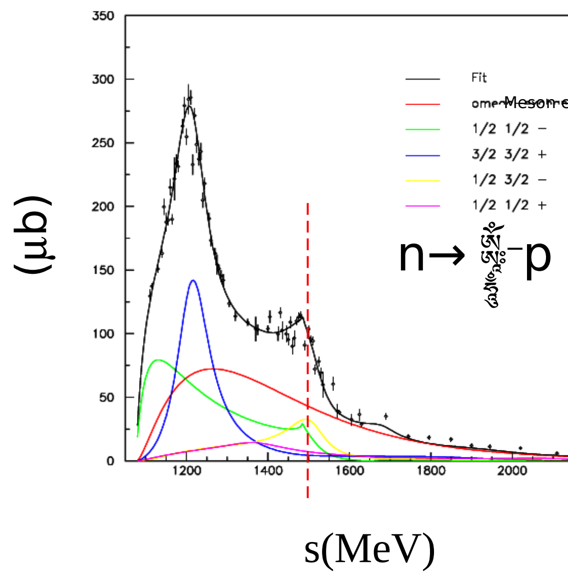
MWPC → MAPMT

Inclusive e+e- cocktail
Fixing cocktail ingredients



$\pi^- p \rightarrow n\pi^0$ [9 mb] (SAID)
$\pi^- p \rightarrow n\pi^0\pi^0$ [1.9 mb] (L.-B.)
$\pi^- p \rightarrow p\pi^0\pi^-$ [4.0 mb] (L.-B.)
$\pi^- p \rightarrow n\eta$ [0.83 mb] Arndt et al., PRC**72** (2005) 045202

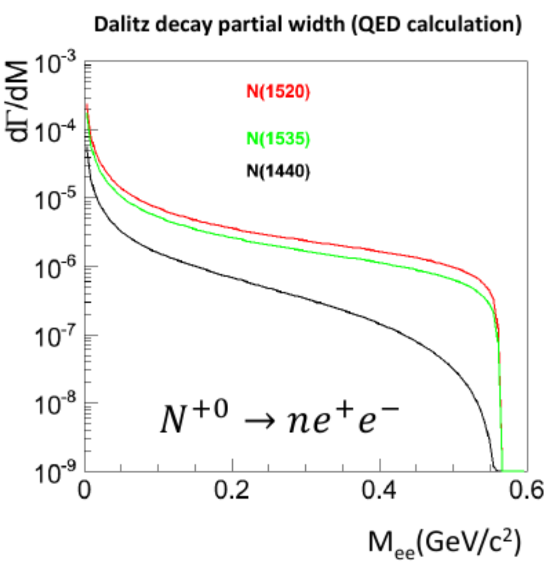
Dalitz Decay BR
π^0: 0.012
η: 0.006



Bonn-Gatchina PWA

N(1520) to π⁻p→γn: 21%
N(1535) to π⁻p→γn: 15%

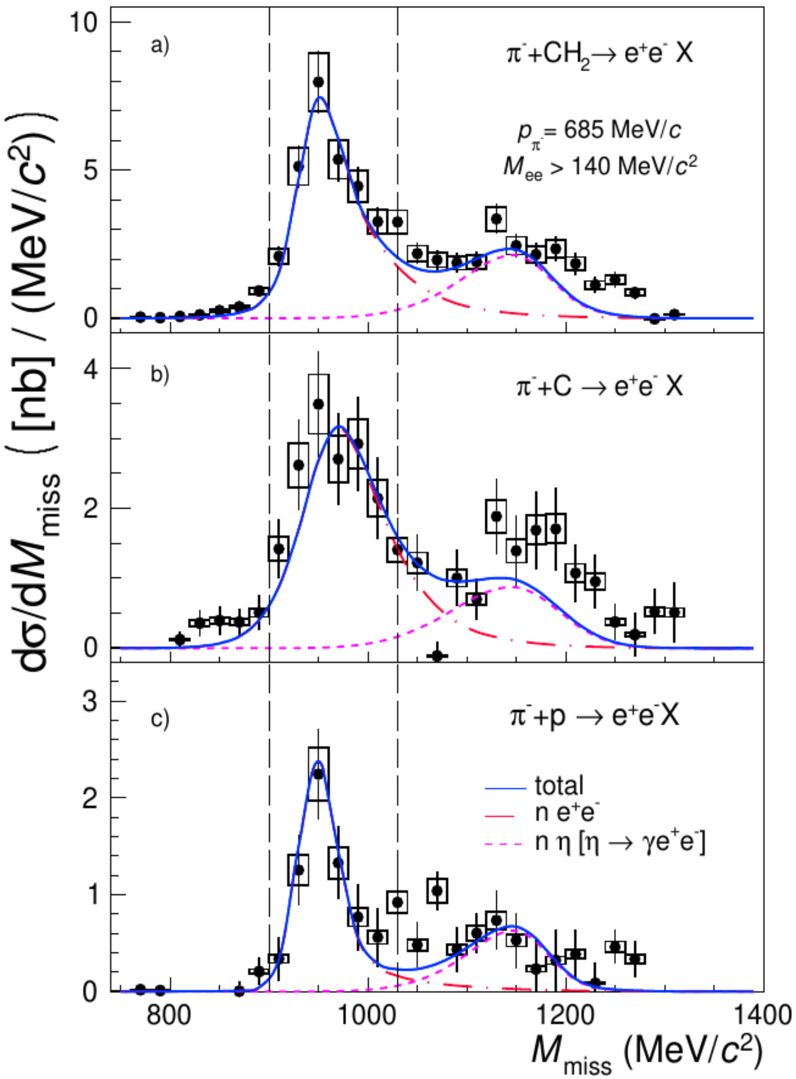
$$\sigma(\pi^- p \rightarrow n e^+ e^-) \sim$$
$$1.35\ \alpha\ \sigma(\pi^- p \rightarrow n\gamma) = 2\ \mu b$$



input for $\pi^- p \rightarrow \gamma^*(e^+e^-)n$
QED Dalitz decay contribution

Selection of quasi-free $\pi^- p \rightarrow ne^+e^-$

HADES coll. arXiv:2205.15914 [nucl-ex]



- cut on **invMe$^+$e$^-$** >140 MeV (above π^0 mass)
- missing mass cut on **M$_{miss}$** (η removed)

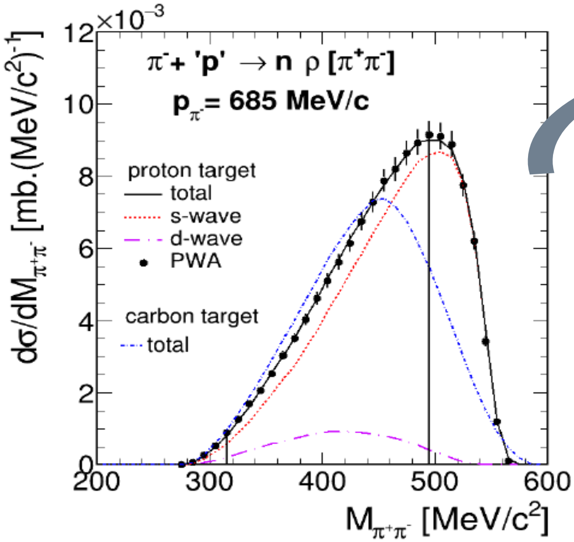
- **π^-C** simulations using Pluto (qfs participant-spectator model)
- production cross sec. on C for: π^0, η, ρ, γ deduced from the scaling: $R_{C/H} = \sigma_C/\sigma_H$

- **CH_2** target:

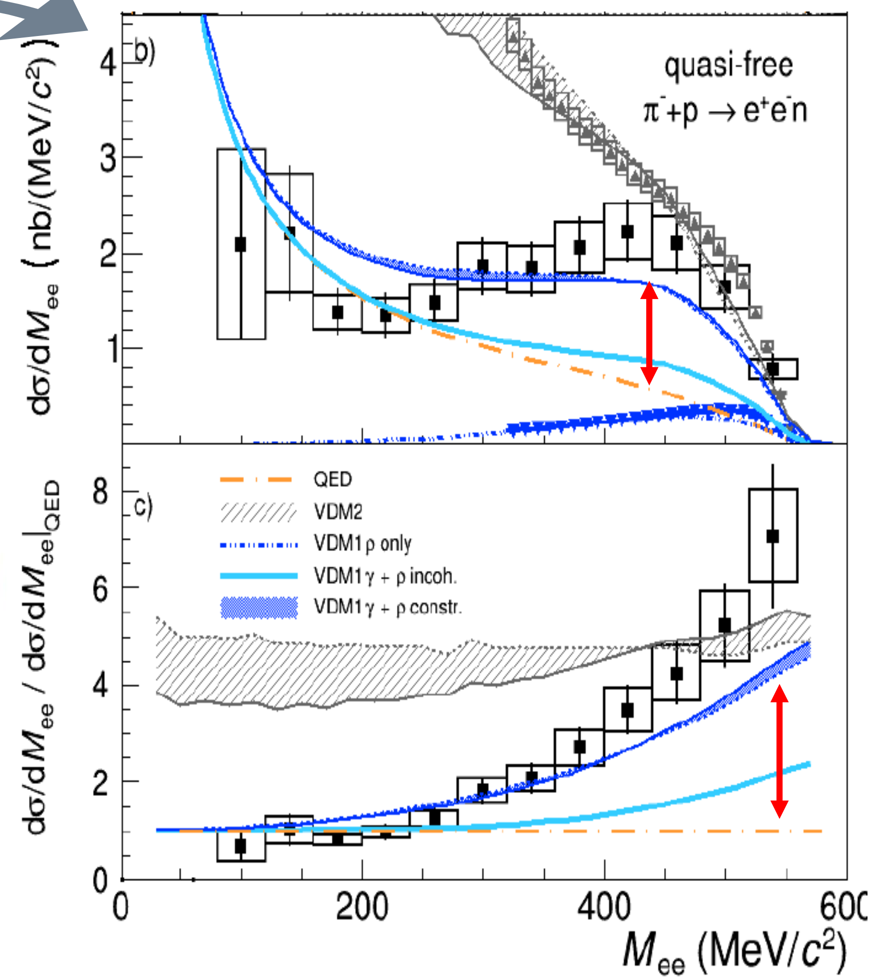
$$\left(\frac{d\sigma}{dM_{ee}}\right)_{CH_2} = \left(\frac{d\sigma}{dM_{ee}}\right)_C + 2\left(\frac{d\sigma}{dM_{ee}}\right)_H$$

Exclusive e+e- cocktail

comparison to VMD1 and VDM2

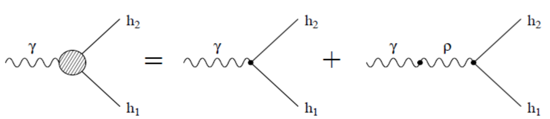


HADES coll. arXiv:2205.15914 [nucl-ex]



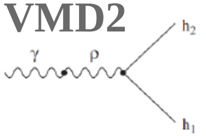
$$\left(\frac{d\sigma_{ee}}{dM_{ee}}\right)_{M_{ee}=M} = \left(\frac{d\sigma_{\pi\pi}}{dM_{\pi\pi}}\right)_{M_{\pi\pi}=M} \frac{\Gamma_{\rho\to e^+e^-}(M)}{\Gamma_{\rho\to\pi^+\pi^-}(M)}$$

VMD1



reasonable description

VMD2

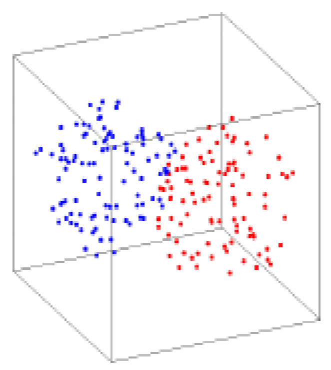


large overestimation

- Bolzmann–Ühling–Uhlenbeck transport equation. Exemplary introductions:

B.Serot, J.Walecka, arXiv:nucl/th/9701058 section 7A
C.Hartnack et al., Eur. Phys. J. A 1, 151 (1998)

- Outline. We consider *N* particles moving in the phase space (x^3, p^3). Their distribution is described by the function $f(\mathbf{r}, \mathbf{p}, t)$. Particles are in a field described by a potential *U* (mean field; it's the BUU's feature)



$$N = \int d^3\mathbf{r} \int d^3\mathbf{p} \; f(\mathbf{r}, \mathbf{p}, t)$$

$$df \equiv \frac{\partial f}{\partial t} dt + \frac{\partial f}{\partial r_i} dr_i + \frac{\partial f}{\partial p_i} dp_i$$

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \nabla_r f \cdot \mathbf{v} - \nabla_p f \cdot \nabla_r U$$

$$\left\{ \begin{array}{c} \frac{\partial f}{\partial r_i} dr_i = (\nabla_r f) \cdot d\mathbf{r}_i \\ d\mathbf{r} = \mathbf{v}\, dt \\ d\mathbf{p} = -\nabla_r U\, dt \end{array} \right\}$$

- Potential *U* of the mean field:

$$U = U(\rho) + U_{Coulomb} + U(\vec{p})$$

$$U(\rho) = \alpha \frac{\rho}{\rho_0} + \beta \left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

(*nuclear matter "equation of state", typical parameterization*)

$$U(\vec{p}) = \delta \frac{8}{\rho_0 (2\pi)^3} \int d^3 p' \frac{f(\mathbf{r}, \mathbf{p}')}{1 + \left(\frac{\mathbf{p} - \mathbf{p}'}{\Lambda}\right)^2}$$

(*momentum-dependent term of potential typical parameterization*)

- If $N = const$, we would have: $$\frac{df}{dt} = 0$$

- In **QMD** models the objects are the particle wave packets:

e.g. C.Hartnack et al.
Eur. Phys. J. A 1, 151 (1998)
arxiv.org/abs/nucl-th/9811015

$$\Psi = \prod_i \psi_i \sim \prod_i \exp\left[-\frac{(\boldsymbol{x}_i - \boldsymbol{r}_i(t))^2}{L}\right] \cdot \exp\left[i\,\boldsymbol{x}_i\,\boldsymbol{p}_i(t)\right]$$

Parameter L describes the packet size. It is found such that Ψ describes the density drop at the nucleus' skin.

- An *i*-th particle moves in the potential ⊕ collides with neighbours.

However, the potential is built from a sum of potentials from '*j-th*' particles surrounding the '*i*-th' one.

Quantum hamiltonian:

$$\langle H\rangle = \langle T\rangle + \langle V\rangle = \sum_i T_i + \sum_i \sum_{j>i} \int \psi_i^* \psi_j^* \; V^{ij}(x_1, x_2) \; \psi_i \psi_j \; dx_1 dx_2$$

Equation of motion:

$$\begin{cases} \dot{\boldsymbol{r}}_i = \dfrac{\boldsymbol{p}_i}{m} + \nabla_{p_i} \sum_j \langle V_{ij}\rangle \\ \dot{\boldsymbol{p}}_i = -\nabla_{r_i} \sum_{j\neq i} \langle V_{ij}\rangle \end{cases}$$

(in fact, the simulation traces the centroids of wave packets)

- **N_i–N_j interactions :**

$$V_{ij} = V_{ij}^{Skyrme} + V_{ij}^{Yukawa} + V_{ij}^{p-dependent} + V_{ij}^{Coulomb} + V_{ij}^{p-n\ \ assymetry}$$

$$= \left[t_1 + t_2\,\rho^{\gamma-1}(\boldsymbol{x}_i)\right] \cdot \delta(\boldsymbol{x}_i - \boldsymbol{x}_j) + t_3 \frac{\exp\left\{-|\boldsymbol{x}_i - \boldsymbol{x}_j|/\mu\right\}}{|\boldsymbol{x}_i - \boldsymbol{x}_j|/\mu} +$$

$$+ t_4 \ln^2\left(1 + t_5(\boldsymbol{p}_i - \boldsymbol{p}_j)^2\right) \cdot \delta(\boldsymbol{x}_i - \boldsymbol{x}_j) + \frac{Z_i Z_j e^2}{|\boldsymbol{x}_i - \boldsymbol{x}_j|} + t_6 \frac{1}{\rho_0} T_i^3 T_j^3 \cdot \delta(\boldsymbol{x}_i - \boldsymbol{x}_j)$$

- Characteristics of main properties of selected (”currently on market”) transport models

Property	GiBUU	IQMD	UrQMD	RQMD.RMF	SMASH	PHSD
Relativistic Kinematics	optionally	n,p : no K : yes	yes	yes	yes	yes
Potential = Mean field	yes	n,p : no K : yes	no	optionally	yes	yes
Potential = sum of nucleon pots.	no	yes	yes	optionally	no	no
Electromagnetic potential	yes	yes	yes for baryons no for π	optionally	no	no
Momentum-dependent potential	yes	yes	no	yes	no	yes
Creation of LCP (clusters)	at end of simulation	at end of simulation	no	at end of simulation	at end of simulation	no
modifications of hadron mass in the medium	yes	yes	no	baryons: yes K, π: no	no	yes
quark-gluon phase described by ”strings”	yes	no	yes	yes	yes	yes

Data: 2016-2018
130 datasets
solutions: A. Sarantsev

$$A = \sum_{IJ\xi,\alpha} \bar{u}(q_1) A^{IJ\xi,\alpha}_{\gamma_1\ldots\gamma_n} F^{\gamma_1\ldots\gamma_n}_{\mu_1\ldots\mu_n}(p) N^{\xi}_{\mu_1\ldots\mu_n}(k^{\perp}) u(k_1)$$

event-by-event

cross sec. calculated for every fitted data event

$$f = -\sum_{j}^{N(data)} ln \frac{\sigma_j(PWA)^{data}}{\sum_{m}^{N(recMC)} \sigma_m(PWA)}$$

2π data included in the fit

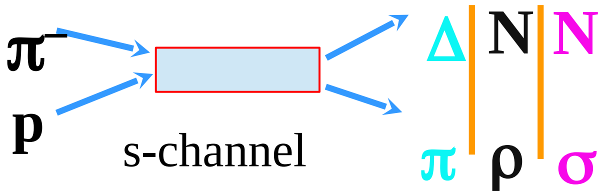
Reaction	Observable	W (GeV)	
$\gamma p \to \pi^0\pi^0 p$	DCS, Tot	1.2-1.9	MAMI
$\gamma p \to \pi^0\pi^0 p$	E	1.2-1.9	MAMI
$\gamma p \to \pi^0\pi^0 p$	DCS,Tot	1.4-2.38	CB-ELSA
$\gamma p \to \pi^0\pi^0 p$	P, H	1.45-1.65	CB-ELSA
$\gamma p \to \pi^0\pi^0 p$	T, P_x, P_y	1.45-2.28	CB-ELSA
$\gamma p \to \pi^0\pi^0 p$	P_x, P_x^c, P_x^s (4D)	1.45-1.8	CB-ELSA
$\gamma p \to \pi^0\pi^0 p$	P_y, P_y^c, P_y^s (4D)	1.45-1.8	CB-ELSA
$\gamma p \to \pi^+\pi^- p$	DCS	1.7-2.3	CLAS
$\gamma p \to \pi^+\pi^- p$	I^c, I^s	1.74-2.08	CLAS
$\pi^- p \to \pi^0\pi^0 n$	DCS	1.29-1.55	Crystal Ball
$\pi^- p \to \pi^+\pi^- n$	DCS	1.45-1.55	HADES
$\pi^- p \to \pi^0\pi^- p$	DCS	1.45-1.55	HADES

HADES unique data sets

Bonn-Gatchina PWA

HADES: Phys. Rev. C 102, 024001, (2020)

Amplitude: from πN to meson-N



$$A=\sum_{IJ\xi,\alpha}\bar{u}(q_1)A^{IJ\xi,\alpha}_{\gamma_1\ldots\gamma_n}F^{\gamma_1\ldots\gamma_n}_{\mu_1\ldots\mu_n}(p)N^{\xi}_{\mu_1\ldots\mu_n}(k^{\perp})u(k_1)$$

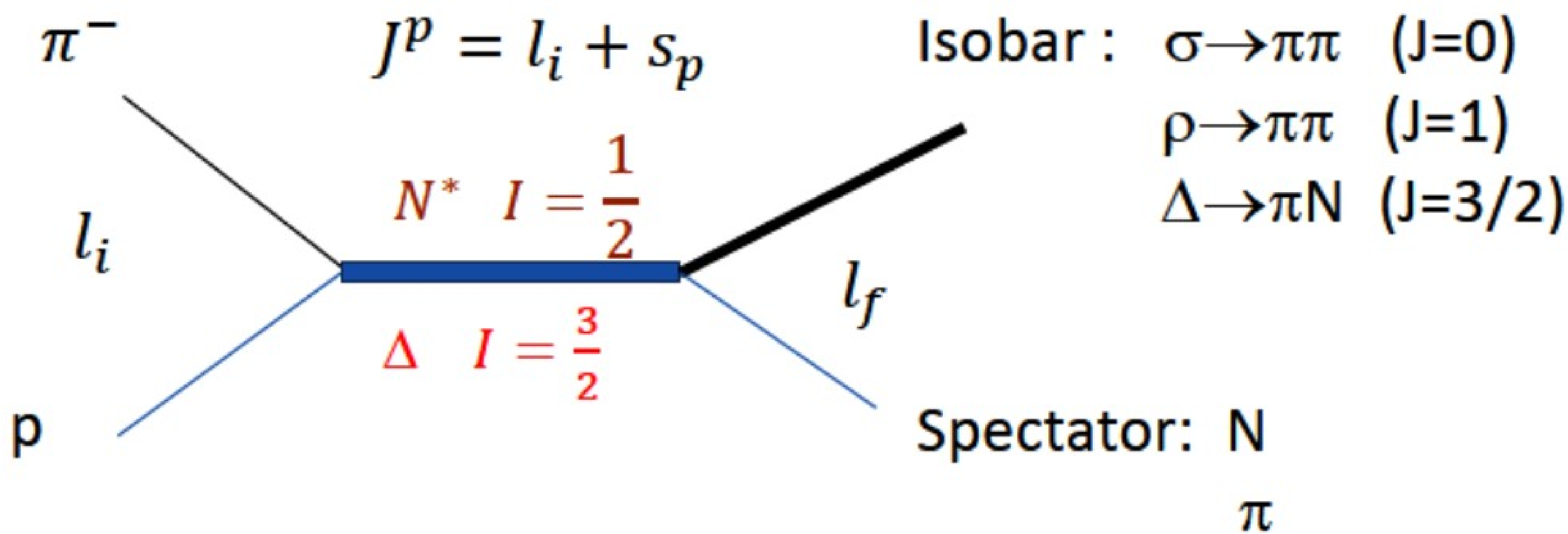
F- tensor propagator of the initial system (πN)

N- production vertex

TABLE I. The reactions, observables, and energy ranges of the two-pion production data used in the PWA. $d\sigma/d\Omega$ and σ_{tot} refer to the differential and total photoproduction cross section, respectively, while the other observables (E, P, H, T) are defined in Ref. [55].

Reaction	Observable	W (GeV)	Experiment
$\gamma p\to\pi^0\pi^0 p$	$d\sigma/d\Omega$, σ_{tot}	1.2–1.9	MAMI [56]
$\gamma p\to\pi^0\pi^0 p$	E	1.2–1.9	MAMI [56]
$\gamma p\to\pi^0\pi^0 p$	$d\sigma/d\Omega$, σ_{tot}	1.4–2.38	CB-ELSA [57,58]
$\gamma p\to\pi^0\pi^0 p$	P, H	1.45–1.65	CB-ELSA [59,60]
$\gamma p\to\pi^0\pi^0 p$	T, P_x, P_y	1.45–2.28	CB-ELSA [59,60]
$\gamma p\to\pi^0\pi^0 p$	P_x, P_x^c, P_x^s (4D)	1.45–1.8	CB-ELSA [59,60]
$\gamma p\to\pi^0\pi^0 p$	P_y, P_y^c, P_y^s (4D)	1.45–1.8	CB-ELSA [59,60]
$\pi^- p\to\pi^0\pi^0 n$	$d\sigma/d\Omega$	1.29–1.55	Crystal Ball [10]
$\pi^- p\to\pi^+\pi^- n$	$d\sigma/d\Omega$	1.45–1.55	HADES (this work)
$\pi^- p\to\pi^0\pi^- p$	$d\sigma/d\Omega$	1.45–1.55	HADES (this work)

D. M. Manley *et al.*
Phys. Rev. D 30 (1984) 904



→ **coherent sum of I=1/2 and I=3/2**

→ **two kinds of separation after fit: into initial (J^P=1/2$^{+/-}$, 3/2$^{+/-}$, L=0,1,2) and final states**

$N(mass)L_{2I,2J}$

$N(1535)1/2^-$

$N(1440)1/2^+$

$N(1520)3/2^-$

Structure of Baryon Transitions Lagrangian Model

E. Speranza et al. Phys. Lett. B764, 282 (2017)

$\pi N \rightarrow Ne^+e^-$

spin density matrix elements (SDME)

information on photon polarization

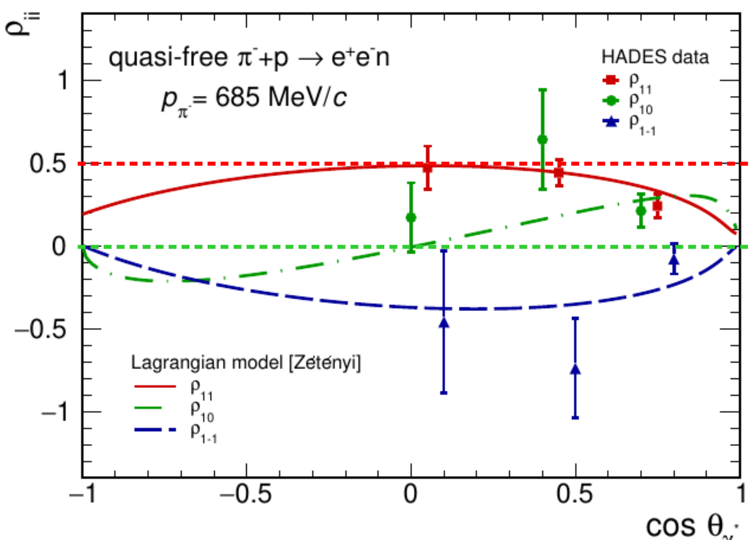
$$\frac{d^3\sigma}{dM_{ee}d\Omega_{\gamma_*}d\Omega_e} \sim |A|^2 = \frac{e^2}{Q^4}\sum_{\Lambda\Lambda'} \rho^{(H)}_{\Lambda\Lambda'}\rho^{(dec)}_{\Lambda\Lambda'}$$

QED: $\gamma^* \rightarrow e^+e^-$

hadron decay to γ^*

$$\frac{|A|^2}{\sigma} = \frac{1}{N}\left(8m_e^2 + 8|\mathrm{k}|^2\left[1 - \tilde{\rho}^{(H)}_{11} + \cos^2\theta(3\tilde{\rho}^{(H)}_{11} - 1) + \sqrt{2}\sin(2\theta)\cos\phi\,\mathrm{Re}\tilde{\rho}^{(H)}_{10} + \sin^2\theta\cos(2\phi)\,\mathrm{Re}\tilde{\rho}^{(H)}_{1-1}\right]\right)$$

SDME ρ_{11}, ρ_{10}, ρ_{1-1} extracted taking into account acceptance and efficiency (A. Sarantsev) in 3 bins in $\cos\theta\gamma$



SDME sensitive to:

- resonance J^P (for s=1/2 no dependence on $\theta\gamma$)
- ρ_{11}=0.5, ρ_{10}=0 for transverse polarization (real photon)
- angular dependence → contributions of spins larger than ½: N(1520) resonance
- more precise data needed

PDG Verification

ρN coupling not present in PDG since 2016

$\Gamma(N(1520) \to \Delta(1232)\pi \text{ , } S\text{−}wave)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
12.1 ±2.1	ADAMCZEWSKI- 2020

$\Gamma(N(1520) \to \Delta(1232)\pi \text{ , } D\text{−}wave)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
6 ±2	ADAMCZEWSKI- 2020

$\Gamma(N(1520) \to N\rho \text{ , } S\text{=3/2 , } S\text{−}wave)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
11.8 ±1.9	ADAMCZEWSKI- 2020

$\Gamma(N(1520) \to N\rho \text{ , } S\text{=1/2 , } D\text{−}wave)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
0.4 ±0.2	ADAMCZEWSKI- 2020

$\Gamma(N(1520) \to N\sigma)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
7 ±3	ADAMCZEWSKI- 2020

$\Gamma(N(1535) \to \Delta(1232)\pi \text{ , } D\text{−}wave)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
3 ±1	ADAMCZEWSKI- 2020

$\Gamma(N(1535) \to N\rho \text{ , } S = 1/2)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
2.7 ±0.6	ADAMCZEWSKI- 2020

$\Gamma(N(1535) \to N\rho \text{ , } S\text{=3/2 , } D\text{−}wave)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
0.5 ±0.5	ADAMCZEWSKI- 2020