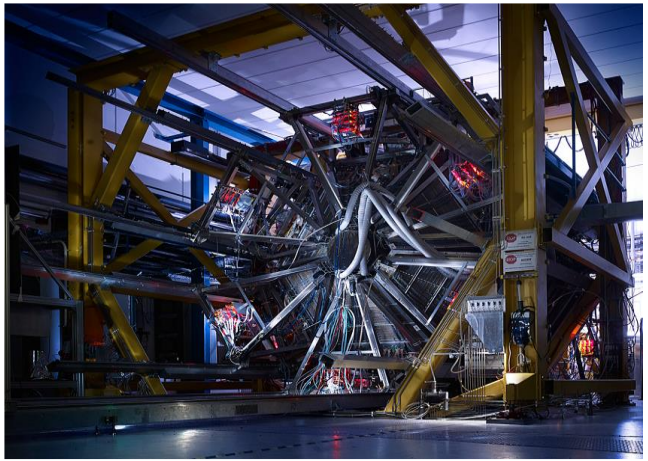
04-111:Leptons in proton and pion-induced reactions with HADES



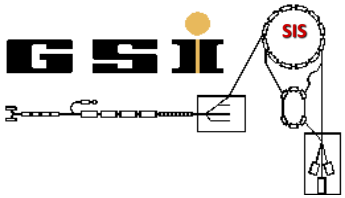
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Jagiellonian University

IFJ PAN

IN2P3-COPIN collaboration agreement workshop, Warsaw, Nov 20, 2023

P. Salabura



The HADES Collaboration

About 120 physicists, 20 institutes

- **Jagiellonian Univ., Cracow, Poland (1994)**
- **IFJ PAN Cracow, Poland (2017)**
- Warsaw Univ. of Technology, Poland (2019)
- Univ. of Warsaw, Poland (2017)
- AGH Cracow , Poland (2021)
- **IPNO → IJCLab Orsay , France (1997)**
- **NPI, Rez,Czech Rep.**
- **Stockholm University, Sweden**
- **Upssala University Sweden**
- **Frederick University, Cyprus**

- **GSI, Darmstadt , Germany**
- **HZDR Dresden, Germany**
- **Frankfurt Univ., Germany**
- **Giessen Univ., Germany**
- **FZJ Jülich, Germany -> FFN , GSI**
- **Univ of Wuppertal , Germany**
- **ITEP Moscow , Russia**
- **MEPhI Moscow, Russia**
- **INR Moscow, Russia**
- **JINR Dubna, Russia**

Collaboration with institutes of the Russian Federation is stopped

French-Polish collaboration on HADES

- IN2P3-COPIN collaboration started in 2004
- Regular visits on both sides
- Joint data analysis, publications (>12), technical activities
- Co-supervised PhDs: H. Kuc 2011 (B. Ramstein /P. Salabura), F. Hojeij last week! (B. Ramstein/I. Ciepal)
- Support from the French P2IO Labex Emilie du Chatelet program:
  2018, 2019, 2023 : visits of I. Ciepal + P. Salabura
- Support from the Polish Nawa program (8 month visit of I. Ciepal at IJCLab in 2021)

IJCLab (formerly IPNO)
B. Ramstein
R. Abou Yassine (2nd year PHD student)
F. Hojeij (4rd year PHD student)
S. Deb (post-doc)

Jagiellionan University
P. Salabura, J. Smyrski, R. Lalik, M. Zielinski, K. Proscinski (1st year PhD), K. Sumara (3d year Phd), A. Władyszewska (1st year PhD)
IFJ PAN Cracow
I. Ciepal

Close connection with GSI collaboration IN2P3-GSI 03-44

HADES detector at FAIR/GSI

Operates since 2003 at GSI/FAIR on SIS18: proton, ion and pion beams

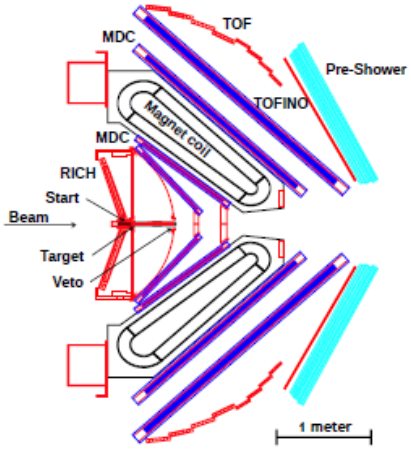
Acceptance:
Full azimuth, polar angles 18° - 85°

Momentum measurement:
$\Delta p/p$ ~ 1-2 %, low material budget optimized for electron detection

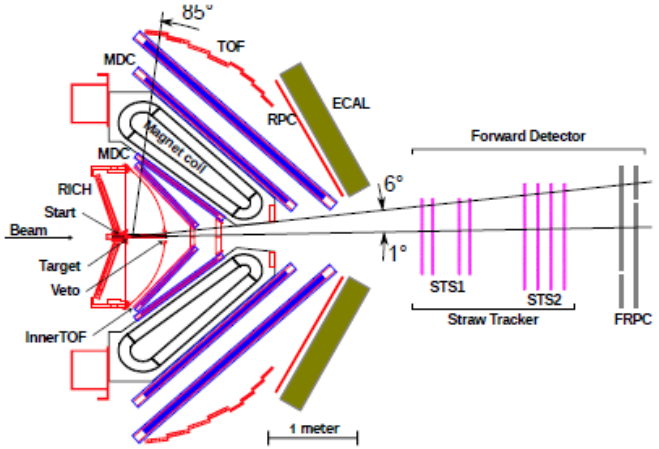
Particle identification:
γ, e^+/e^-, π^+/π^-, K^+/K^-, p

Trigger: < 50 kHz

HADES in 2007



HADES in 2022



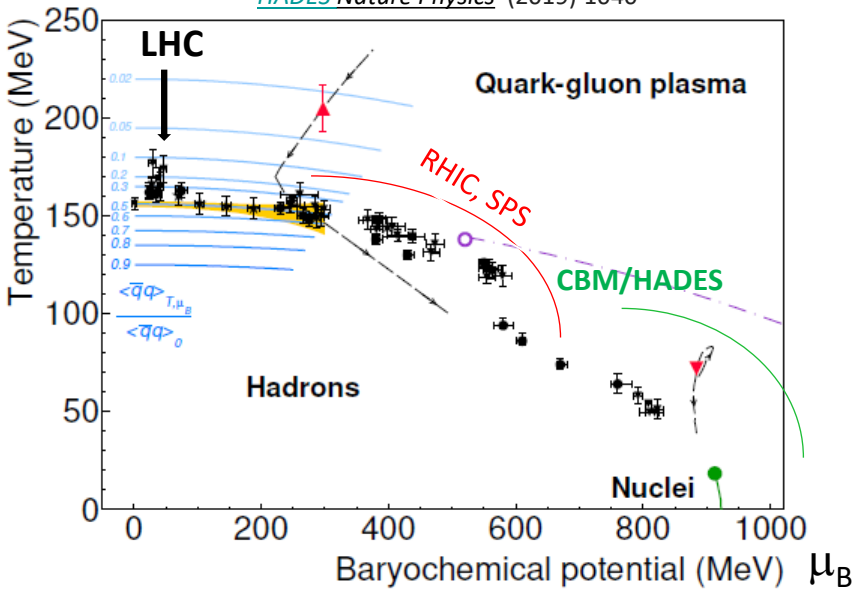
Polish contribution:
- Pre-Shower (replaced in 2019 by ECAL)
- ECAL (Jagiellonian University, mechanical frame)
- Forward detector (Jagiellonian University + IFJ PAN)

STS2 (2nd straw tube station) construction

French contribution:
- MDCIV –largest MDC chamber in HADES
- Forward detector (support mechanics and STS2 financial contribution)
- Liquid Hydrogen Target

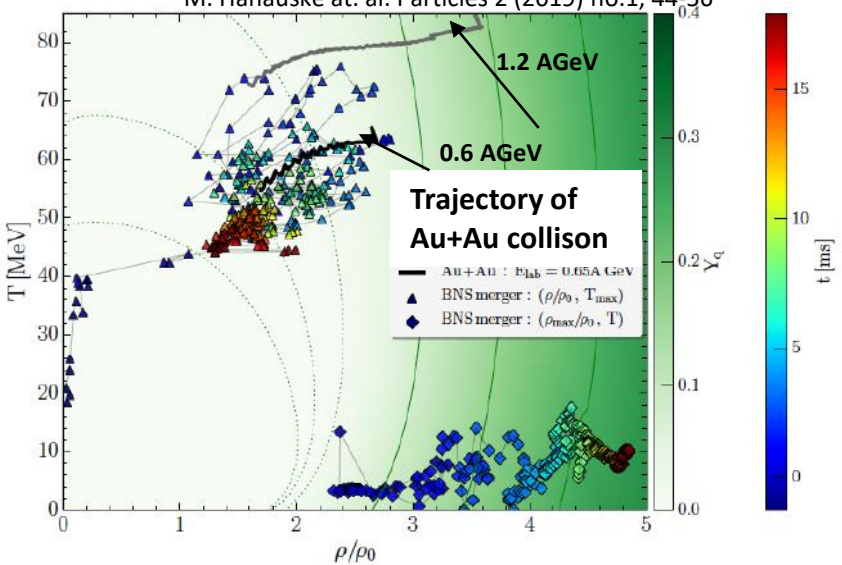
QCD phase diagram and Heavy Ion collisions

HADES Nature Physics (2019) 1040



Binary neutron star merger on QCD phase diagrame

M. Hanauske at. al. Particles 2 (2019) no.1, 44-56

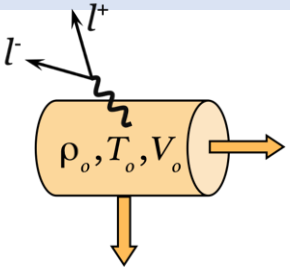


- ❑ at vanishing μ_B Lattice QCD: QGP-hadron cross-over transition associated with chiral symmetry restoration (χSR) studied at colliders LHC, RHIC..
- ❑ large μ_B : no first principle QCD calculations available: model predictions first order phase transition with critical end point and interest from astrophysics: neutron stars, neutron star mergers,.. → new facilities : FAIR, NICA, JPARC. HIAF
- ❑ Dileptons are excelent probe to study QCD matter properties: access to early phase (T, flow) and are promising observable for χSR – **HADES motivation**

Emissivity of QCD matter with dilepton probe

McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

$$\frac{dN_{ll}}{d^4q d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^{BE}(q_0,T)\,\mathrm{Im}\Pi_{em}(M,q,T,\mu_B)$$



- Not disturbed by finite state interactions ! But needs integration over volume and time !
- Thermal distribution $f^{BE}(T)$ – *thermometer*
- Π_{em} *em. current-current correlator* ➡ *Invariant mass distribution of dileptons*

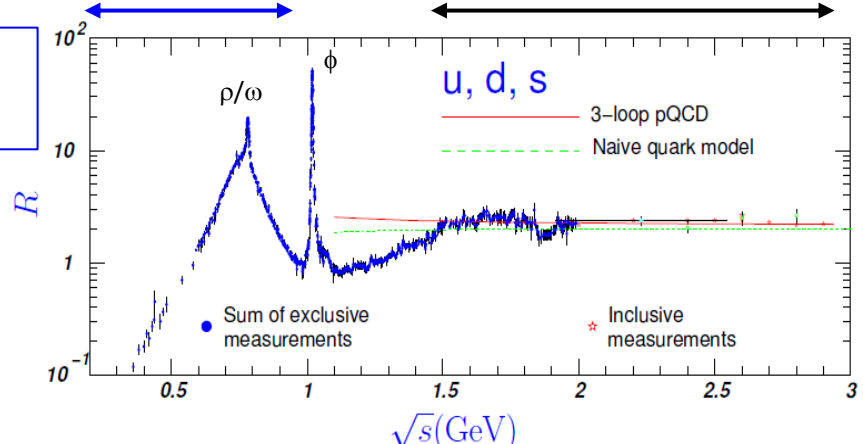
In vacuum:

$$R_{\mathrm{had.}} = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \propto \frac{1}{M^2}\,\mathrm{Im}\,\Pi^{em}$$

$q^2 = m_{l+l-} < 1$ GeV $q^2 = m_{l+l-} > 1.5$GeV *qq radiation pQCD (flat)*

$$\mathrm{Im}\,\Pi_{em}^{\mathrm{had.}} = \sum_{V=\rho,\omega,\phi}\left(\frac{m_V^2}{g_V}\right)^2 \mathrm{Im}\,D_V(M)\,.$$

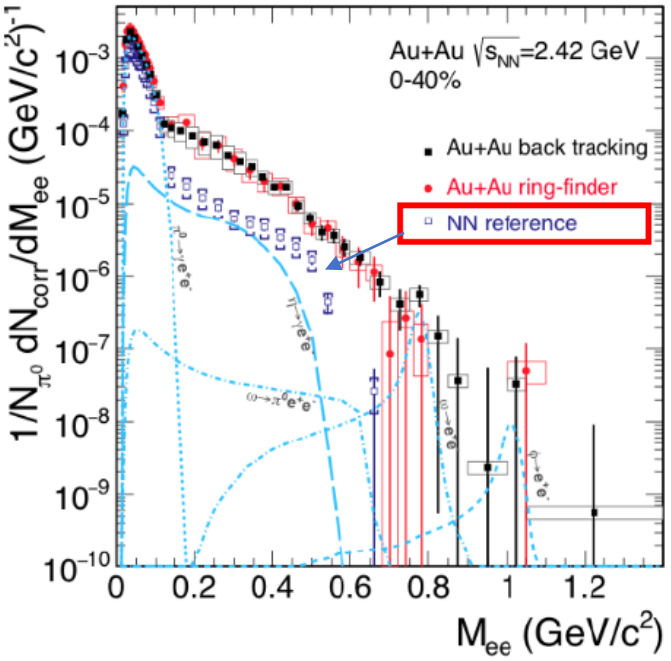
Vector Dominance Model



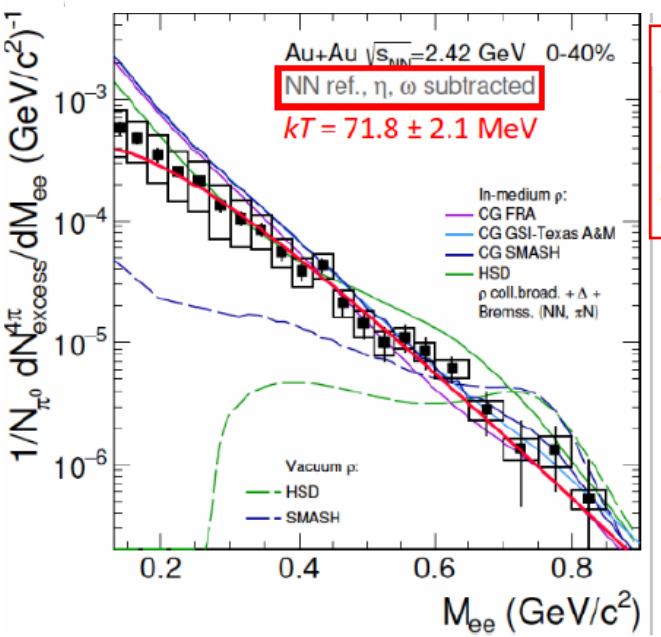
Dilepton yield in low mass region is dominated by ρ meson in-medium propagator-connection to χSR

Dileptons from heavy-ion reactions

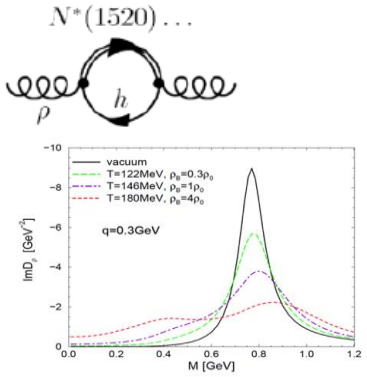
Nature Phys. 15 (2019) no.10, 1040-1045



Excess over NN reference: In-medium e^+e^- emission (emissivity)



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



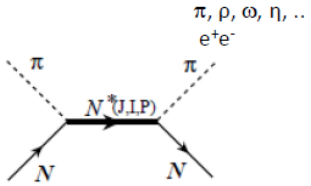
- Understanding of virtual photon (massive) to baryons is essential for the interpretation of results from HI

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

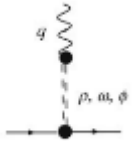
pion induced rections

- Ideal tool to study baryon resonances : direct formation of Resonance $M_R = \sqrt{s}$
- HADES interest:

understand the mechanism of photon coupling to baryon



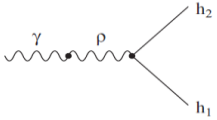
Vector Dominance Model :
coupling through low mass vector mesons (ρ/ω/ϕ) $J^{PC} = 1^{--}$



Not clear how well it works for baryons
Discussed in O'Connell Prog. Part. Nucl. Phys., Vol. 39,pp. 201-252, 1997

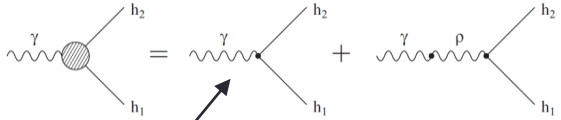
mass dependent
decay width Γ to e+e-

VDM2 : *Sakurai, Phys. Rev 22 (1969) 981*
- one single ρN coupling



$$\Gamma_\rho^{VDM2} = \left(\frac{M_0}{M}\right)^3 \Gamma_\rho^0$$

VDM1 : *Kroll, Lee & Zuminio Phys. Rev. 157 (1967) 1376*
- coupling through ρN + direct photon added coherently

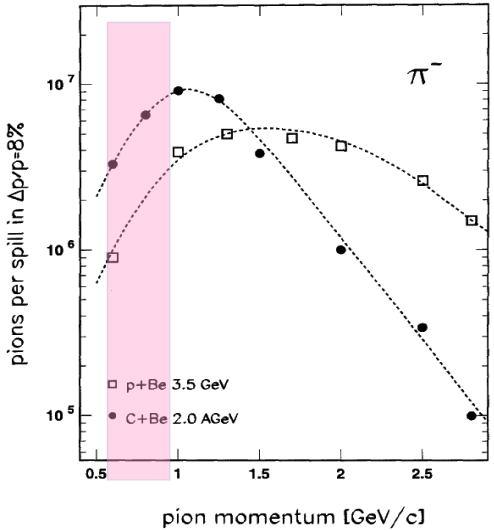


direct photon coupling
QED reference
(point-like particle)

$$\Gamma_\rho^{VDM1} = \left(\frac{M}{M_0}\right) \Gamma_\rho^0$$

Pion Beam @ GSI

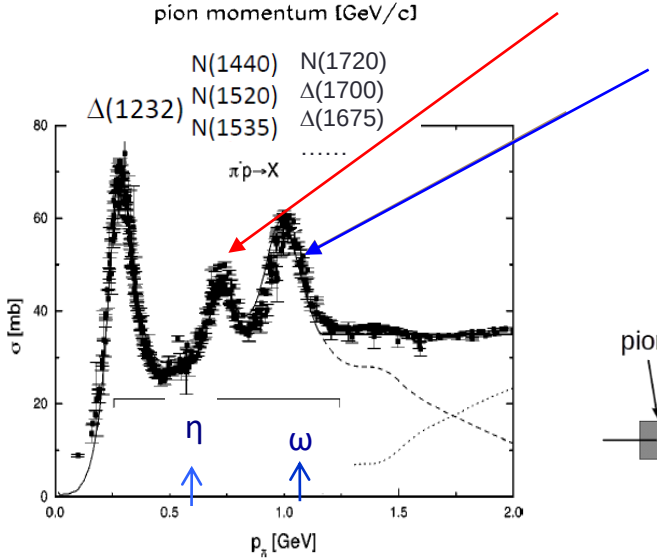
Eur. Phys. J. A (2017) 53: 188

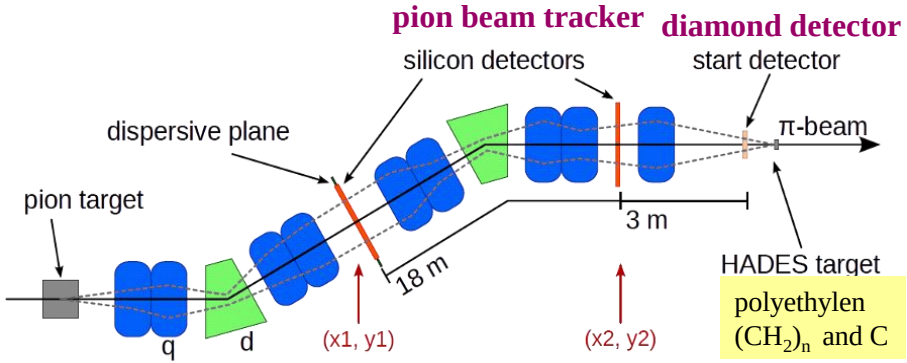


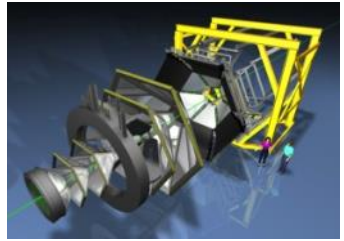
- reaction **N+Be,** 6×10^{10} N_2 ions/spill (4s)
- secondary π^- with **I ~ 2-3 10^5/s**
- pion momentum $\Delta p/p$ =2.2% (σ)
- 50% acceptance of pion beam line (calculations by French group)

- **$\sqrt{s}$ =1.46-1.55 GeV - second resonance region N*(1520/1535) experiment in 2014**

- **$\sqrt{s}$ =1.65-1.75 GeV - third resonance region N*/Δ (~1700) planned for 2025/2026**



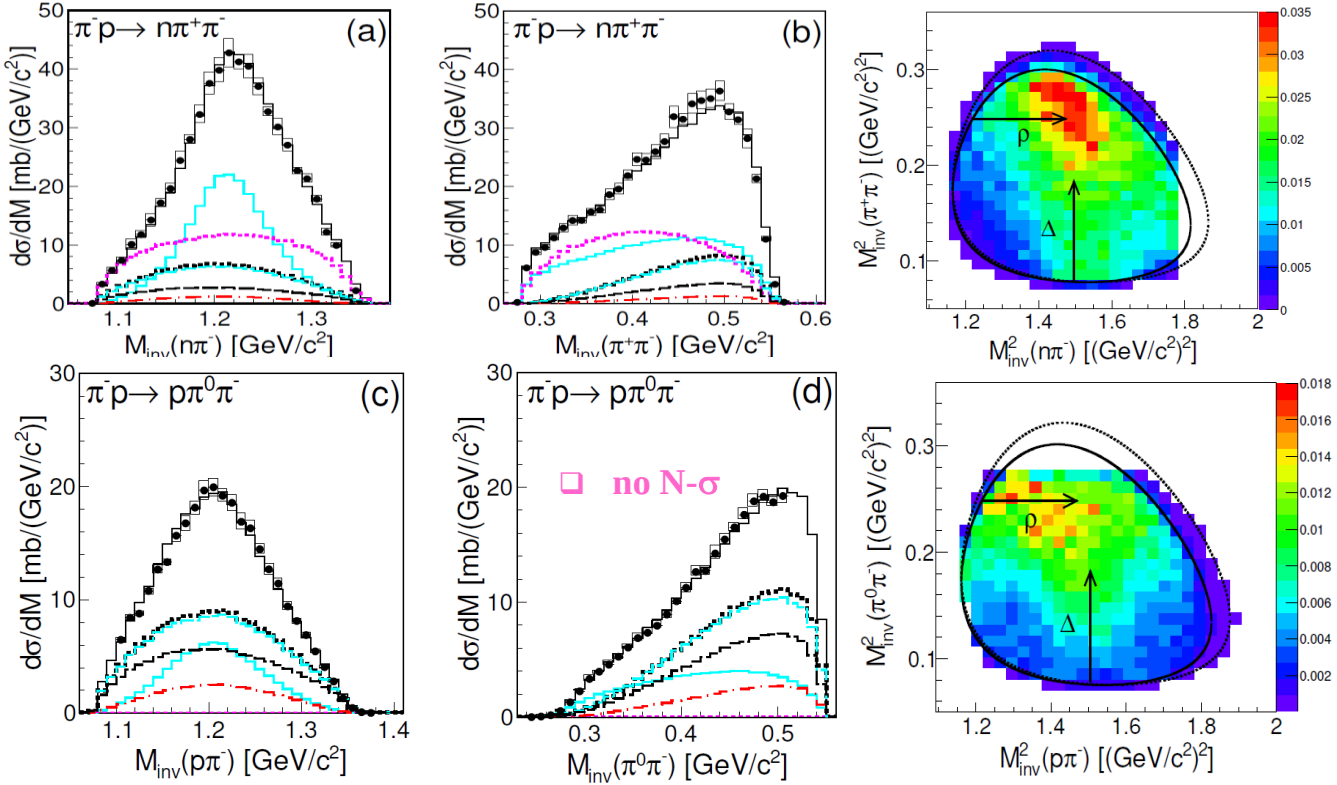




2 pion production: PWA (Bn-Ga) decomposition √s=1.49 GeV

„subthreshold" – no ρ peak in $\pi^+\pi^{-,0}$ mass distributions

$$\pi^- p \to \pi\pi N$$

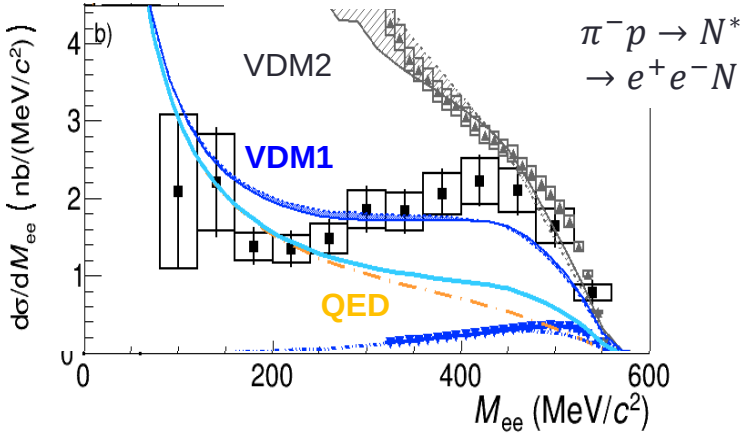


- Goal to extract amplitudes for resonance N*(1535)-S_{11}, N*(1520)-D_{13} excitations and their decay branches into
  Δ(1232) π
  N ρ
  N σ
- Combined Partial Wave Analysis fit with many other channels from $e^- p, \gamma p, \quad p$ reactions
- 8 new entries into Particle Data Group

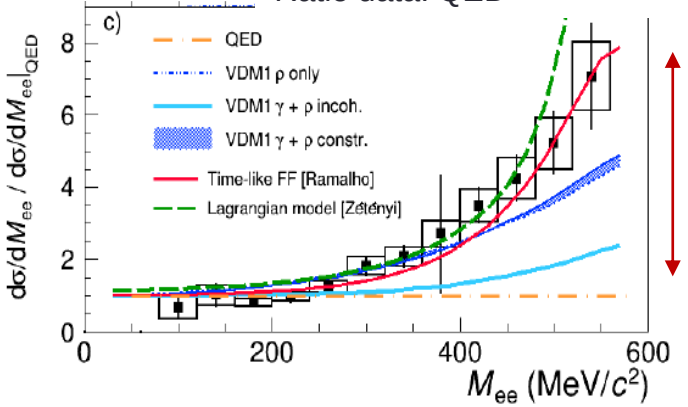
✓ HADES:PRC *C102 (2020) 024001*

Written by polish-french group

„effective" N*/N em. Tranisition Form Factor



Ratio data: QED



QED reference: if baryons would be point-like

- **Model independent results:**
  - Strong excess with respect to the point-like contribution-QED reference (up to a factor 6)

❑ Two component (**direct γ + VDM1**) with constructive interferences gives a **better description of the full spectrum then VDM2**

❑ **Two microscopic models described data very well**

a) Lagrangian (production + baryon Decay with VDM1)
b) eTFF model of N(1520)+N(1535) (quark + meson cloud)

M. Zetenyi et al. PRC 104(2021) 1,015201
G. Ramalho and M. T. Pena, Phys. Rev. D95, 014003 (2017)

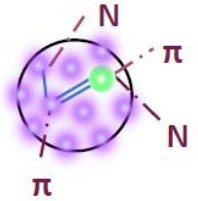
✓ Two papers written by french-polish group and submitted in 2023 (PRC and PRL)

arXiv:2309.13357 arXiv:2205.15914

Pion dynamics for heavy ion collisions at a few AGeV

- Pion production dominates the inelastic NN cross section

→pion-nucleus dynamics crucial to describe evolution of HI collisions thermalization, particle production two step processes via resonance formation

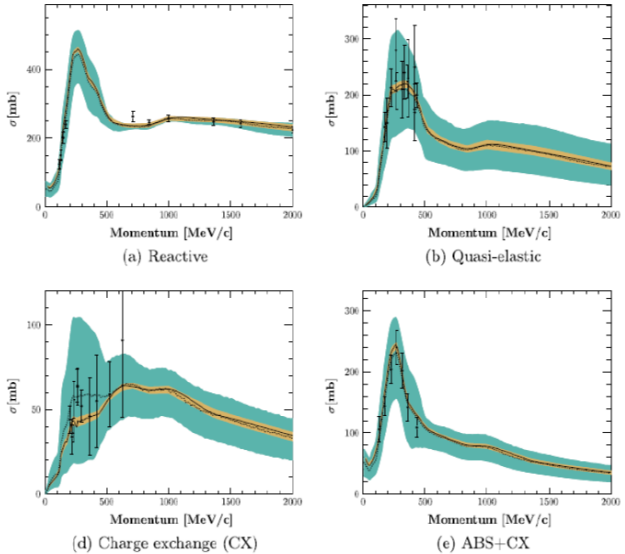


π/η/ω/KΛ…

- Pion-nucleus next step for the understanding of hadron propagation in cold matter

Verification of transport models (UrQMD, SMASH, GiBUU) and cascade models (INCL++)- strong collaboration with french team (J.C. David)

$\pi^+ + {}^{12}C$



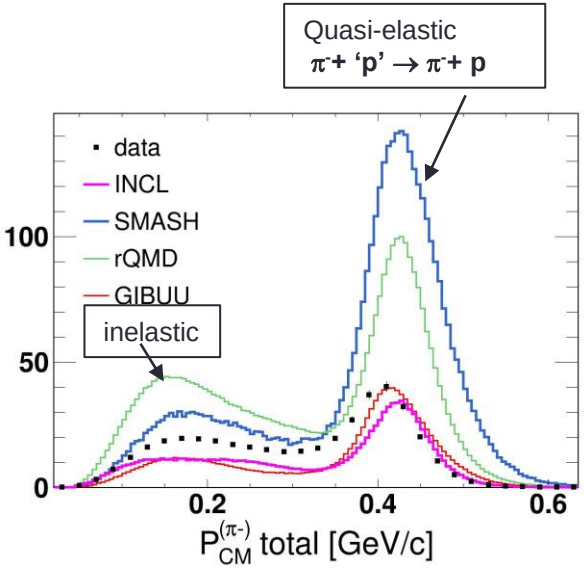
E.S. Pinzon Guerra et al., Phys. Rev. D 99, 052007 (2019)

(π^-+^{12}C is even more scarce !)

Measurements for p_π > 500 MeV/c are highly needed

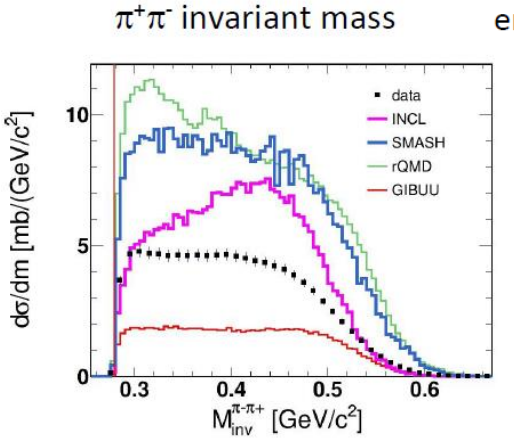
- for hadronic matter studies at $\sqrt{s_{NN}}$ > 2.6 GeV
- for detector studies (e.g. e/π discrimination in calorimeters)
- for neutrino physics (ν flux and ν detection)

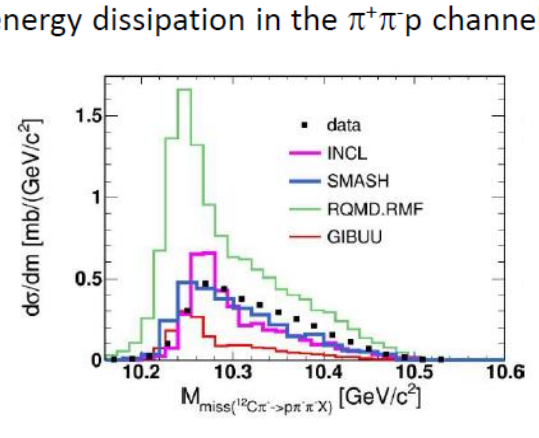
Hadronic channels in π^- + C @ 0.69 GeV.c



examples

Multiparticle final states
π^- + C → π^- + π^+ + p





- Detailed tests of various transport models and INCL++ cascade

✓ Phd of F. Hojeij (co-supervised by I. Ciepal) , talks in Meson2023, NSTAR, IJCLab

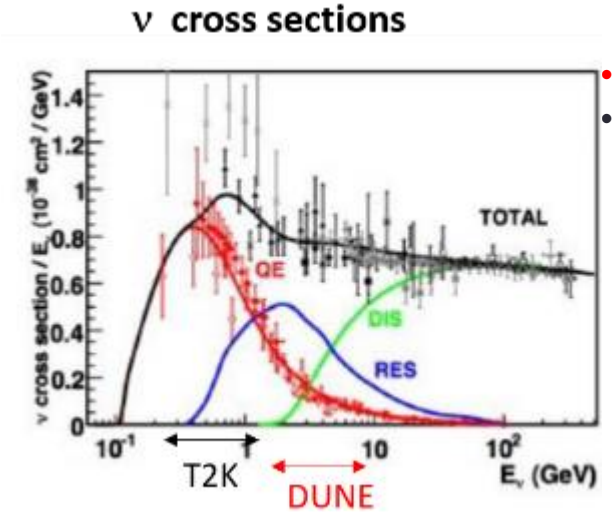
INCL++ validation, impact for Geant4 applications, neutrino experiments, short range correlations

✓ Publication on pion and deuteron and tryton production p+Nb (includes comparison to INCL+) accepted in Phys. Rec. C
arXiv:2301.03940

New HADES-neutrino IJCLab/IFJ PAN collaboration

Proposal : Exploit HADES pion beam induced data to constrain simulations for neutrino physics

Large fraction of the uncertainty on ν oscillation parameters due to hadronic interaction contribution !



- ν reconstruction mostly sensitive to Quasi-Elastic process for E_ν < 0.8 GeV
- importance of pion production (Δ(1232) and higher resonances) above

T2K : presently only muon is detected Future analysis: include nucleon and pion detection (also sensitive to hadronic models !)

Available HADES data from pion induced reactions can help constraining those processes

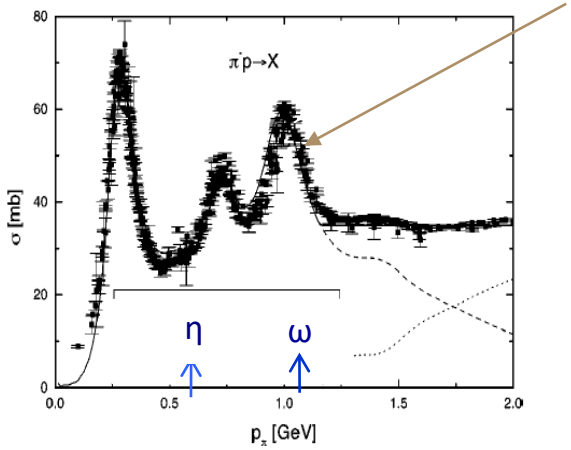
HADES
IJCLab : Béatrice Ramstein
IFJ PAN : Izabela Ciepal

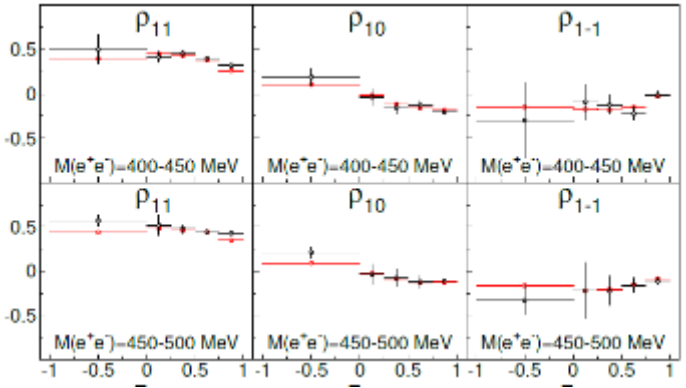
accelerator neutrino physics

IJCLab/DUNE: Fabien Cavalier, Yoann Kermaidic, Thibaut Houdy
IFJPAN/SK, T2K and DUNE: Tomasz Wąchała, Grzegorz Żarnecki

Outlook : experiments with pion beam

Exp. proposal at GSI/SIS18 : 2023-2025: explore the **third resonance region** ($\sqrt{s}$~1.7 GeV/c^2)





prepared by french-polish group

1. Baryon meson couplings : N*/Δ decays to ππN, ωn, ηn , $K^0\Lambda$, KΣ,....

→ *Inputs for Partial Wave Analysis*
→ *Many baryon structure issues: confirmation of N'(1720),*
Cascade decays (R→R'π→ Nπ π), „missing resonances"

2. Time-like electromagnetic baryon transitions $\pi^-p \rightarrow ne^+e^-$

- Broad range of $q^2=(M_{ee})^2 \rightarrow$ sensitivity to form factors
- Check of Vector Dominance Model (both for ρ and ω)
- High prec. measureements of photon polarization - spin density matrix elements

expected sensitivity for N*(1520)

Awaits results of the machine test of pion beam intensity, november 2023

Analysis of new experiment with pp @4.5 GeV

- February 2022: one month of beam time at SIS18 FAIR-Phase0 experiment
- Highest proton beam energy at SIS18 /GSI (Au: Emax = 1.25 AGeV)
- Forward Detector used for the first time → test of technology (STT) for PANDA at FAIR

Scientific highlights:

- Hyperon production close to threshold **Σ(1385), Λ(1520), Λ(1405)** and decays: hadronic and electromagnetic Dalitz decays of hyperons →Λe+e-
- double strangeness production Ξ(1321) ΛΛ
- Meson production π/**η**/ω/ρ/ϕ,**f_1(1280)** and rare **η** decays

complementary to PANDA future program: Feasibility studies *HADES collab, Eur. Phys. J. A57, 138 (2021)*

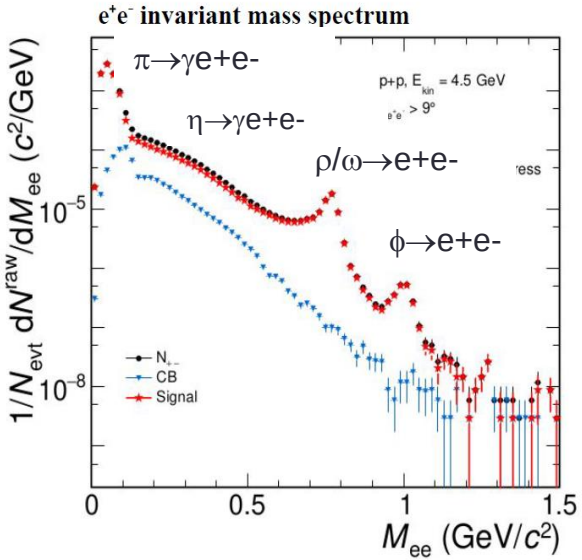
- **dilepton production**:

reference spectra for p+A (HADES at SIS18/GSI) and A+A (HADES and CBM at SIS100/FAIR)

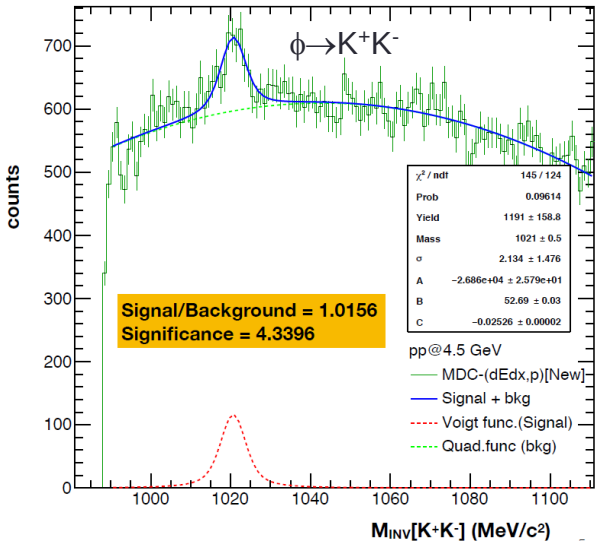
polish and french contributions to HADES analysis

Selected preliminary results from pp

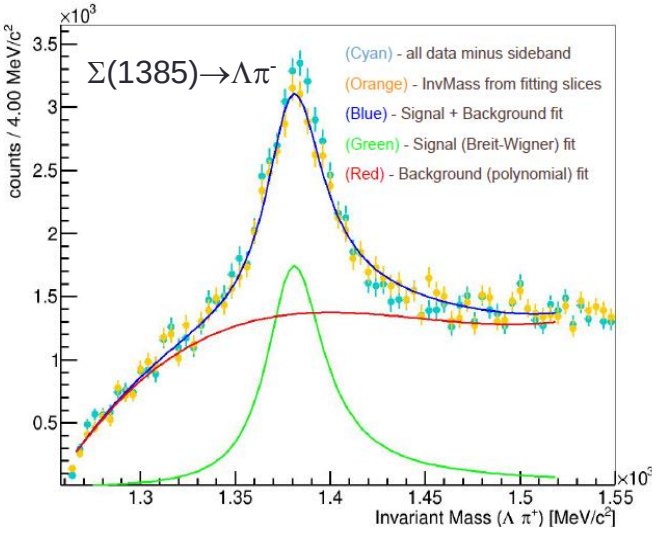
Inclusive channels



R. Abou Yassine IJCLab



S. Deb IJCLab



K. Sumara UJ

SUMMARY : collaboration 03-44

Time used in 2023

French physicists in Poland: 13 days used (25 attributed) Meson conference
B. Ramstein (7 days), R. Abou Yassine (6 days)

Polish physicists in France: 25 days used (25 attributed): I. Ciepal (11 days), J. Lukasik (2 days)
A.Strach (3 days), K. Prościński (3 days), K. Sumara (3 days), A. Władyszewska (3 days) (HADES analysis workshop in IJCLab)

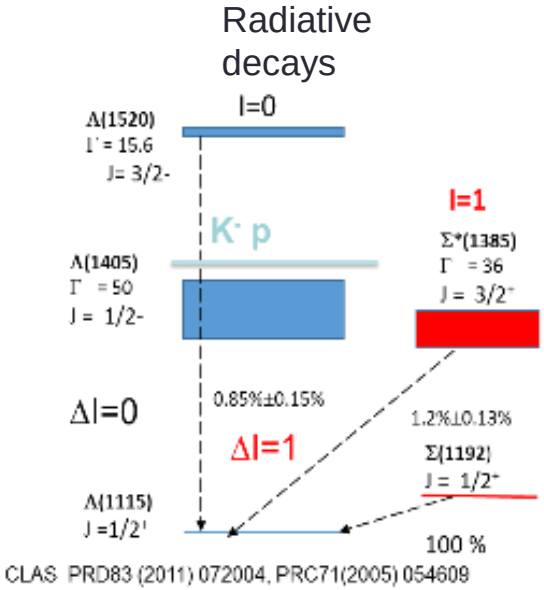
Request for 2025:

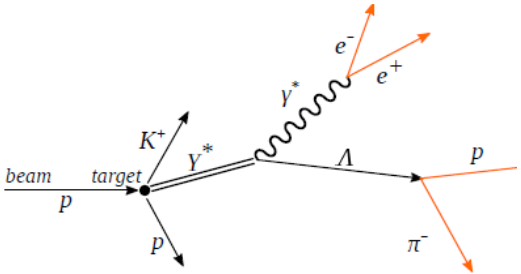
French physicists in Poland: 10 days
Meetings devoted to pp data analysis ad
B. Ramstein 5 days, S. Deb 5 days,

Polish physicists in France: 25 days
Mettings devoted to discussions with INCL++ experts + HADES pp analysis
P. Salabura (4 days), I. Ciepal (5 days), R. Lalik (4 days), K. Proscinski (3 days), K. Sumara(3 days), A.Strach(3 days), Władyszewska (3 days)

Back-up

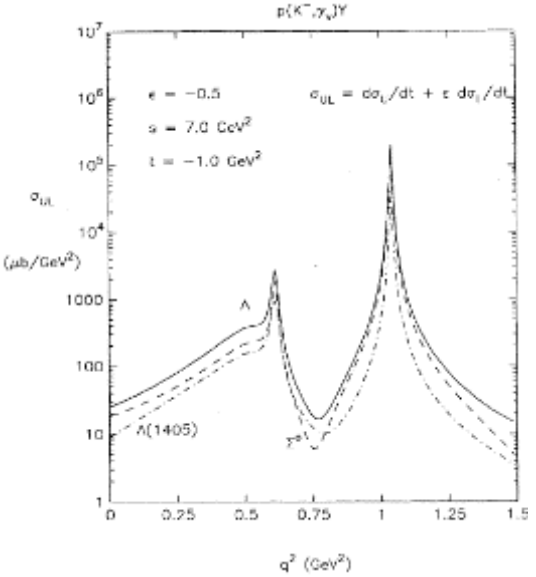
Hyperon Dalitz decays-em. Transition Form Factors





- Well separated states
- VMD: Enhancement in e+e- inv. mass due low mass vector mesons ρ /ω / φ

R. Williams et. al. PRC48(1993)1381



- SU(3) flavour partners

Σ(1385) - Δ(1232)

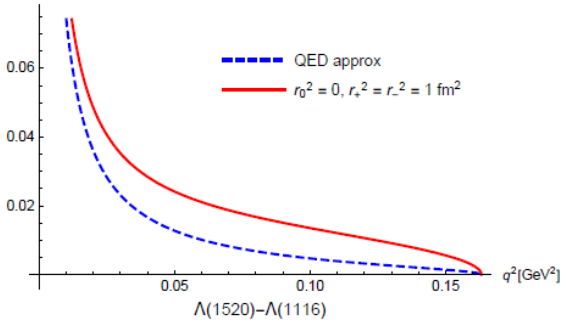
Λ(1520) – N(1520)

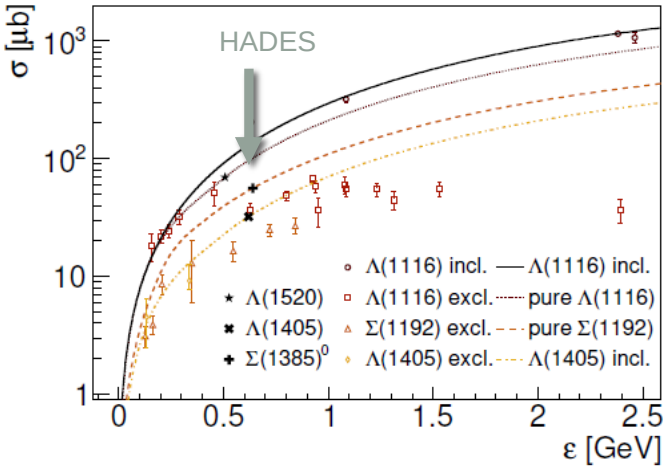
HADES measured Δ(1232) N(1520) transitions – significant enhancement (up to 5) w.r.t point-like (QED) -. Dominated, by pion cloud contribution. Kaon cloud for hyperons ?

Y* radiative/Dalitz decays

- Information on hadron structure (size of hyperon)
- Dalitz decays of e.g. Λ(1405), Σ(1385), Λ(1520),..(narrow states)
- radtiative BR about 10^{-5}
- Large rates needed (→ CBM) and SIS100 beam energy (First attempt by HADES in pp @4.5)

S.Leupold Eur. Phys. J. A (2021) 57 :183





Σ*
Λ*
~1 mb @ 30 GeV
~20 more than at SIS18

G. Ramahlo Phys.Rev.D 102