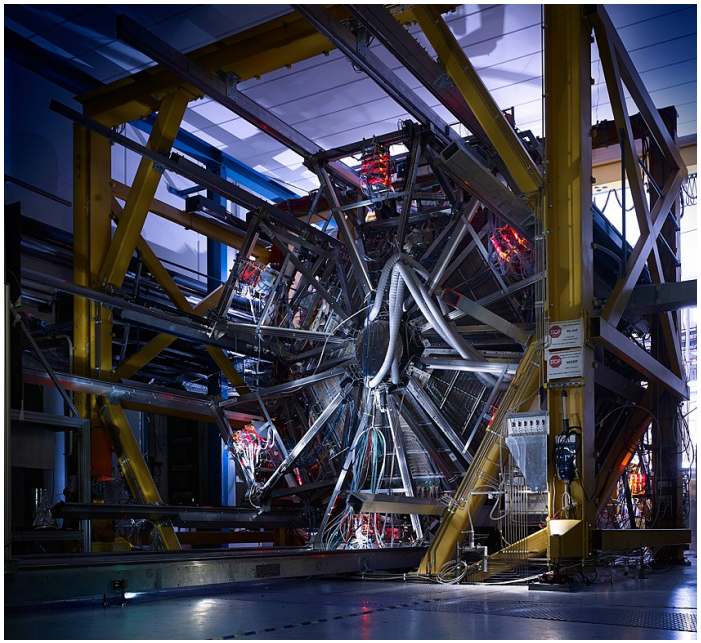
Hadrons and dileptons production in pp and pn reactions in a few AGeV region with HADES



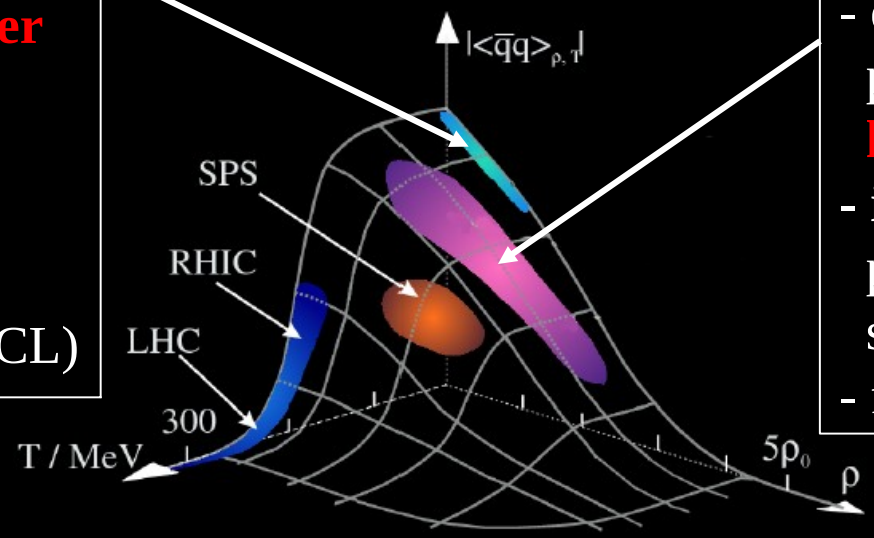
Izabela Ciepał
for the HADES Collaboration

Institute of Nuclear Physics PAS

Outline

1) Motivation of the HADES experiment,
2) The HADES detector,
3) Electromagnetic structure of baryons,
4) Hadron and dilepton production in pp and pn,
5) Hyperons studies with HADES,
6) Conclusions and outlook.

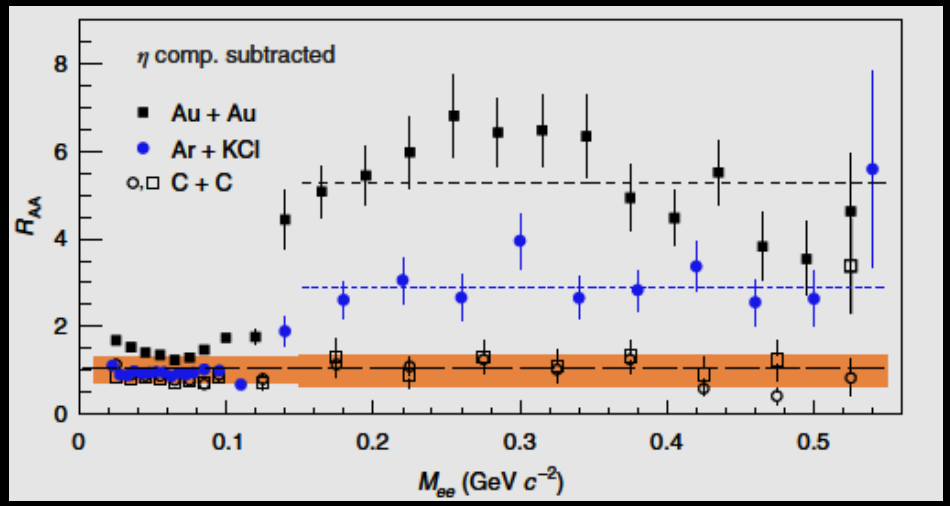
p+A
- **cold nuclear matter** at normal nuclear density,
- spallation physics (cascade model validation e.g. INCL)



HI: A+A
- dilepton and strangeness production in **dense and hot nuclear matter**
- in medium hadron properties (chiral symmetry)
- flow, fluctuations

elementary collisions:
p+p, d(n)+p, π+p

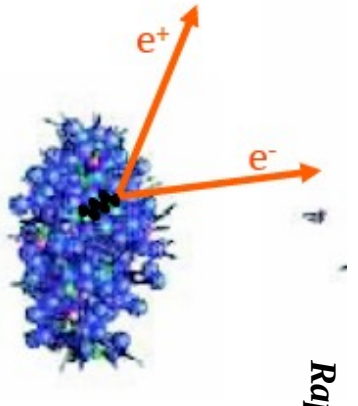
HADES Nat. Phys. 15, 1040 (2019)



e+e- invariant mass yield normalized to reference NN yield

$$R_{AA} = \frac{1}{\langle A_{part}^{AA} \rangle} \frac{dN^{AA}}{dM_{ee}} \left(\frac{dN^{NN}}{dM_{ee}} \right)^{-1}$$

Motivations

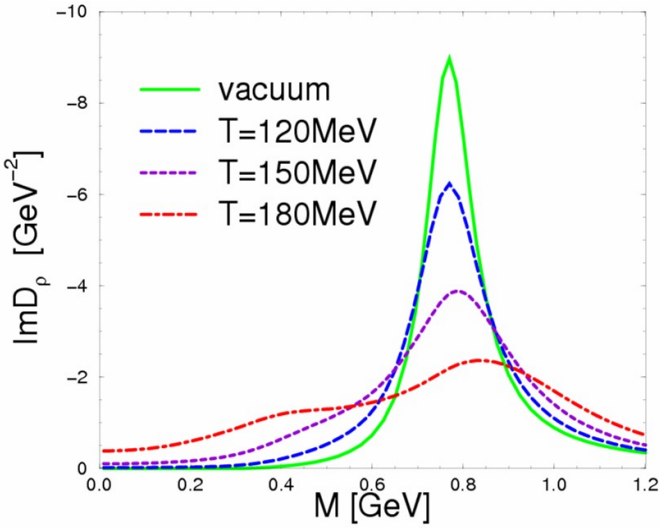


Elementary collisions: p+p, d(n)+p, π+p

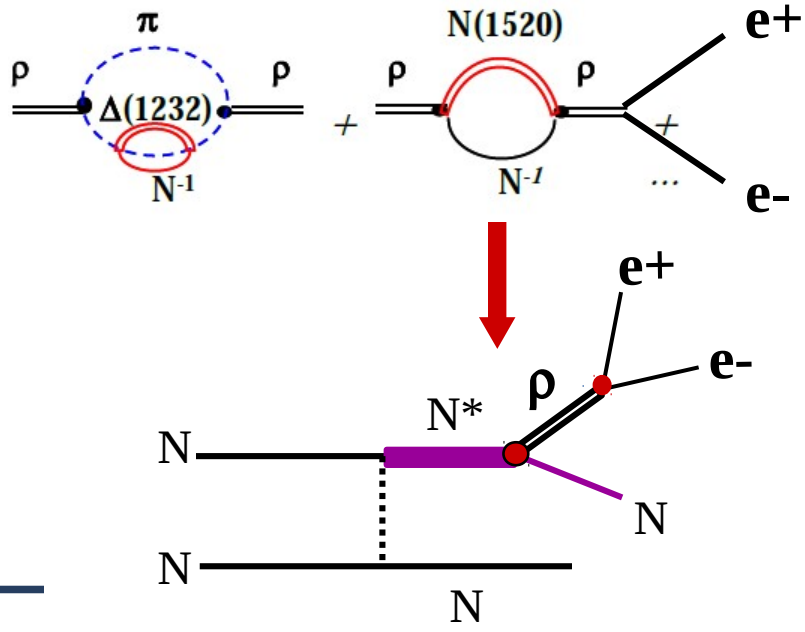
- role of barionic resonances in meson production
- dileptons reference for HI (extraction of excess radiation)
- vector meson-baryon couplings (em. transition FF, baryon structure)

ρ-meson

Vacuum:



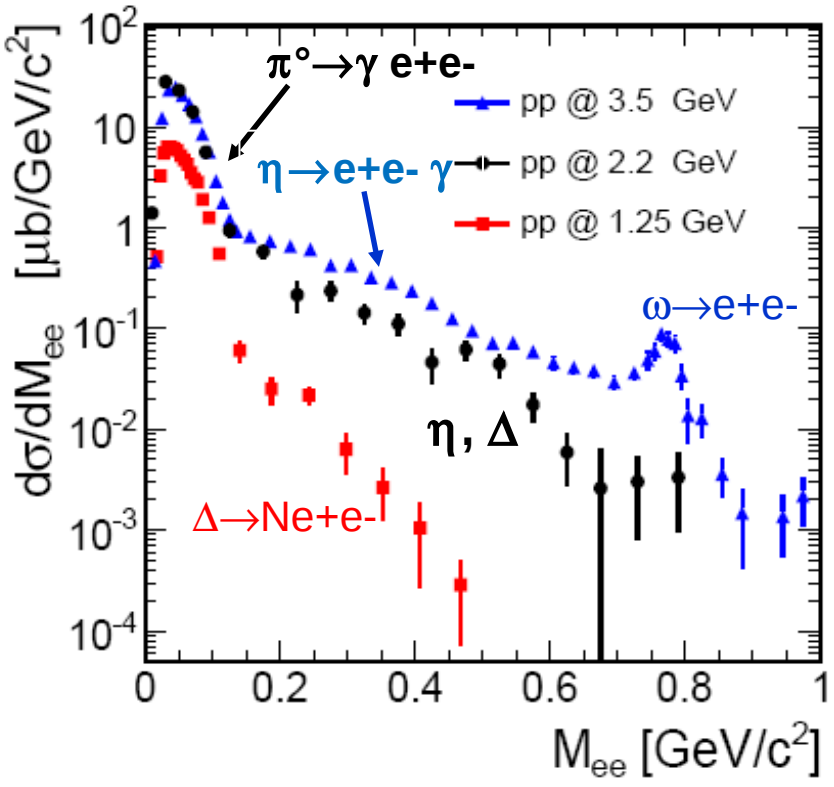
Nuclear matter: additional terms



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

Rapp, Wambach, Adv. Nucl. Phys. A25 (2000)1

e+e- sources @ SIS18 energies reference for HI

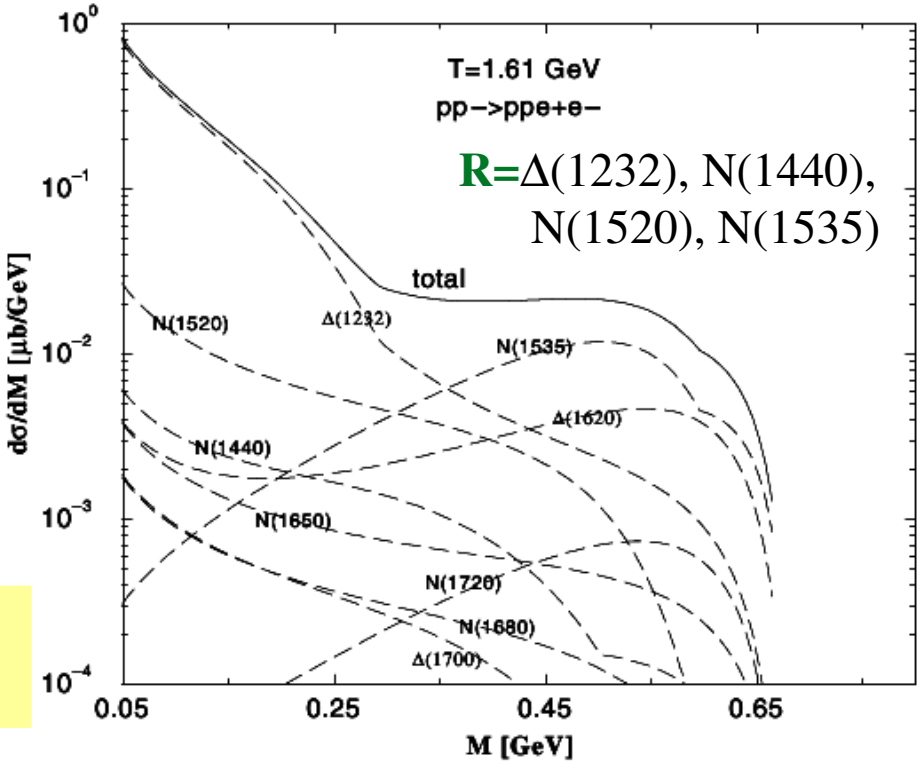


$M_{e+e-} < 0.15$ GeV/c² dominated by π^0 Dalitz,

$M_{e+e-} > 0.15$ GeV/c²:

NN bremsstrahlung, $\eta \rightarrow \gamma e+e-$, $\omega \rightarrow$ e+e-

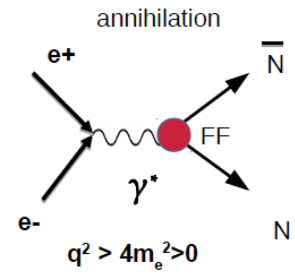
resonances R → Ne+e-

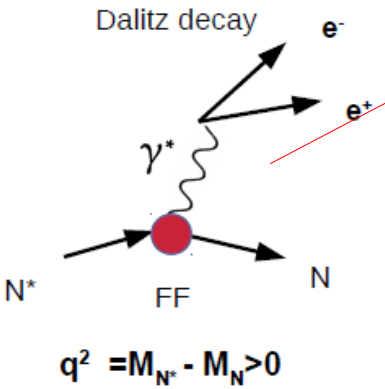


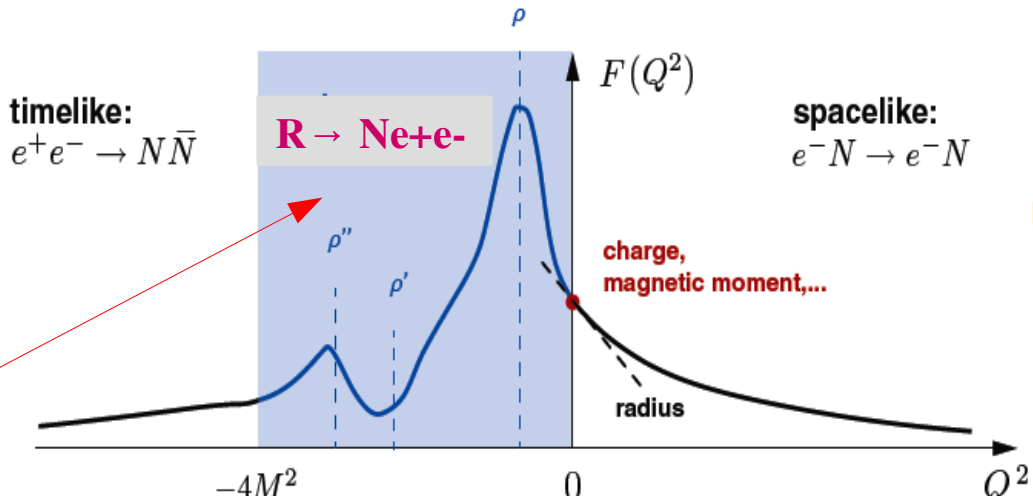
Cocktail - fixing important components (elementary processes) of hadron decays

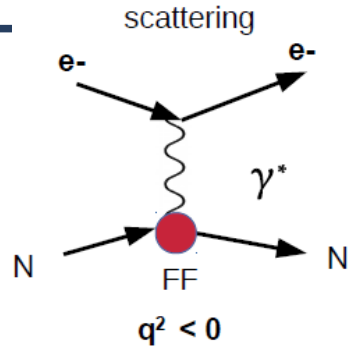
A. Faessler et al,
J. Phys. G: Nucl. Part. Phys. 29, 603 (2003)

Electromagnetic structure of baryons









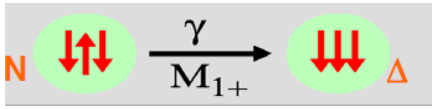
$$q^2 = (E_B - E_A)^2 - (\vec{p}_B - \vec{p}_A)^2 \; (= M^2_{\gamma *} = M^2_{e+e-})$$

Resonance - Nucleon transitions (timelike)
em. Transition Form Factors (for J>= 3/2):
$G_M\ (q^2)$, $G_E\ (q^2)$, $G_C\ (q^2)$

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

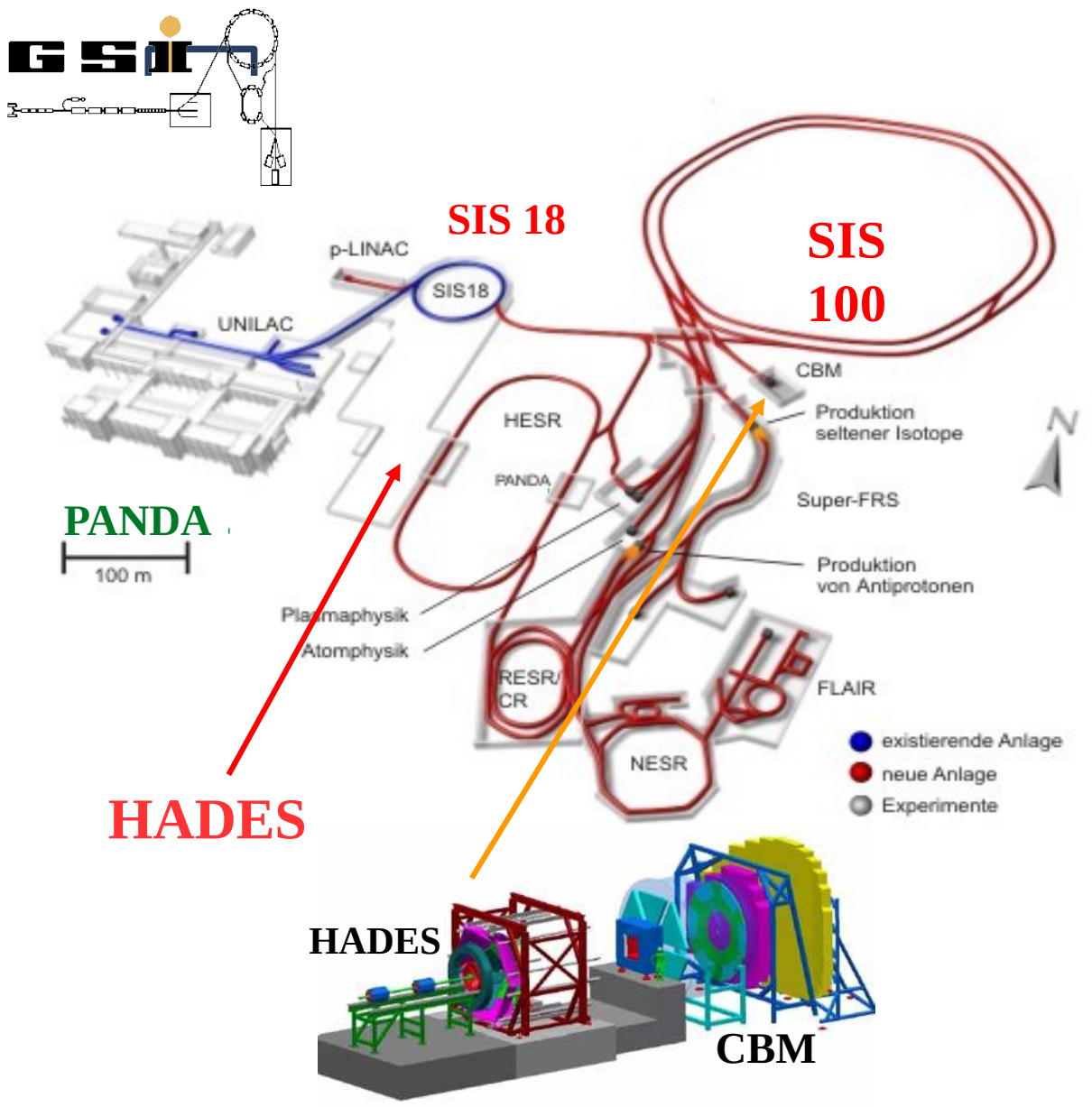
QED
transition
of point-like
particles

Form-Factors
(various models)



« Photon point » : $q^2=0$
$G_M(0)\sim 3$, $G_E(0)\sim 0.04$

Dalitz decays, appearance of intermediate vector mesons!
ρ/ω/ϕ $J^{PC} = 1^{--}$ (= γ !)



SIS 18

18Tm (1.8 T magnets)

U^{73+}: 1.0 GeV/u, 10^9 ions/s

Ni^{26+}: 2.0 GeV/u, 10^{10}

Protons: 4.5 GeV, 2.8×10^{13}/s

Secondary beams

Pions: 0.5-2 GeV/c

SIS 100

2T (4T/s) magnets

Au: up to 8-10 GeV/u

10^{12} ions/s

Protons: up to 30 GeV

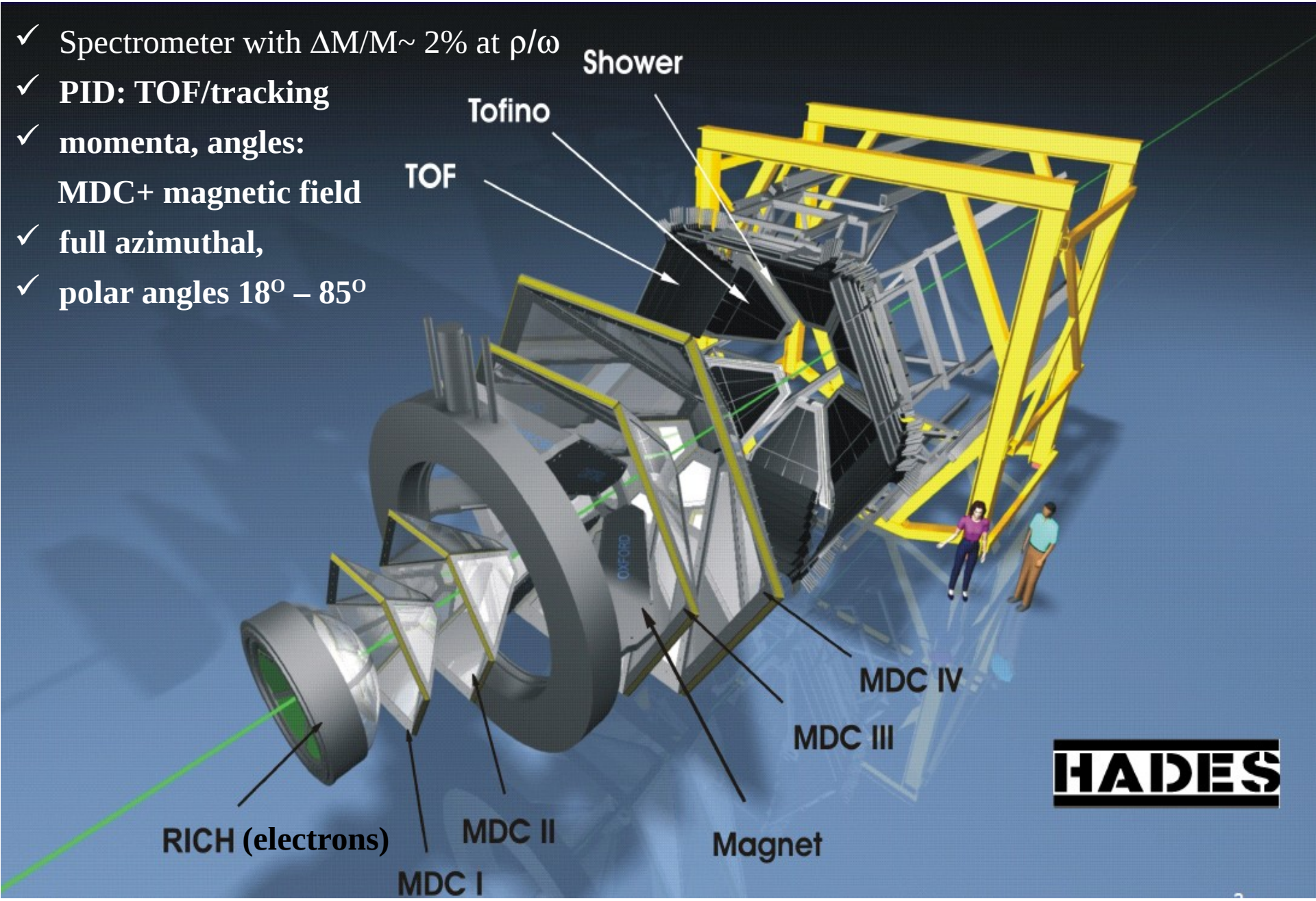
2.8×10^{13} ions/s

Secondary beams

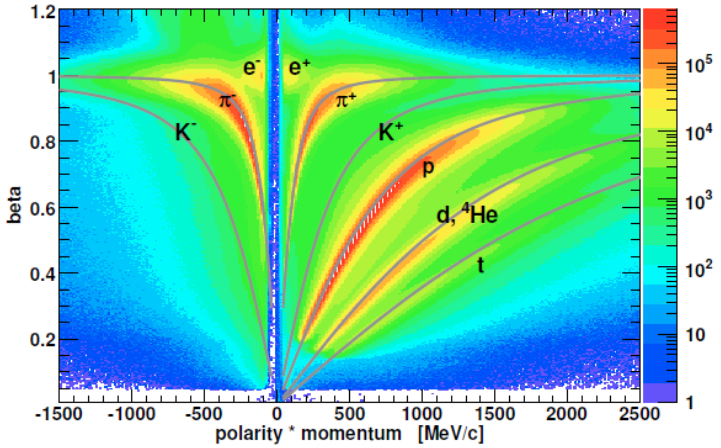
Radioctive beams 1.5 GeV/u

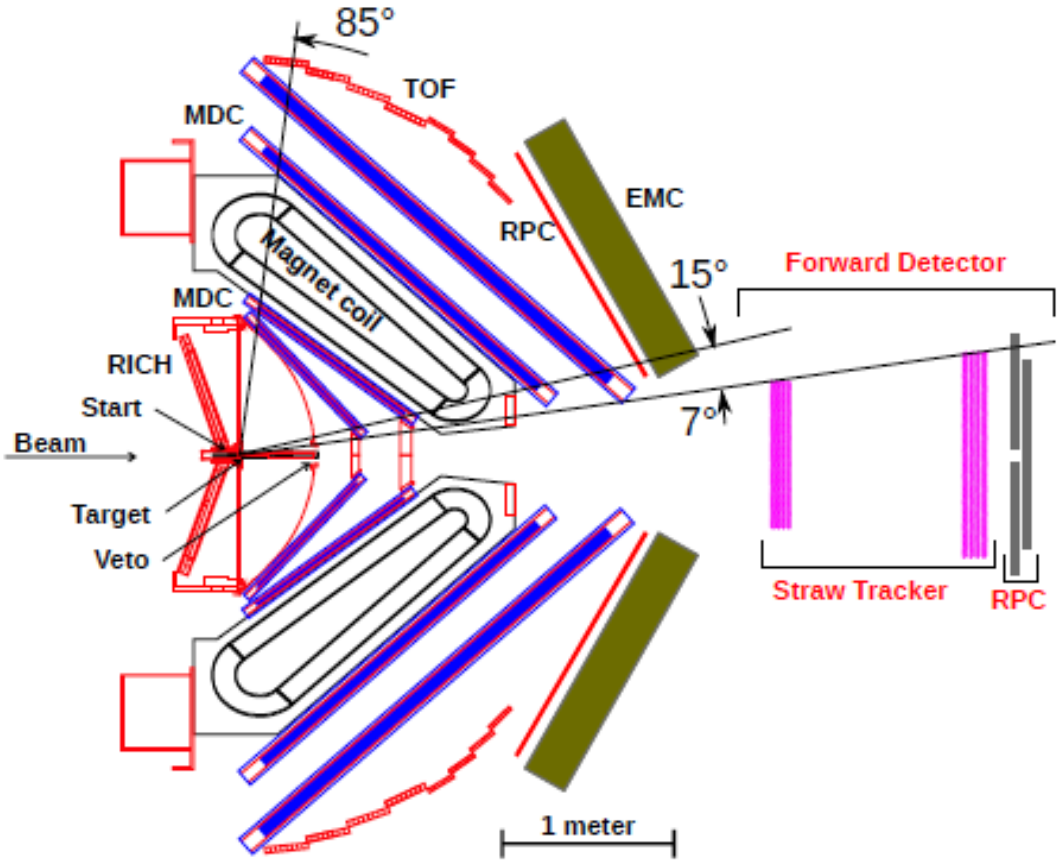
Anty-protons 30 GeV

HADES - first detector of FAIR Phase0 (2018-2021)


✓ Spectrometer with ΔM/M~ 2% at ρ/ω
✓ PID: TOF/tracking
✓ momenta, angles:
MDC+ magnetic field
✓ full azimuthal,
✓ polar angles 18° – 85°
Shower
Tofino
TOF
MDC IV
MDC III
HADES
RICH (electrons)
MDC II
MDC I
Magnet

HADES Detector
High Acceptance Di-Electron Spectrometer





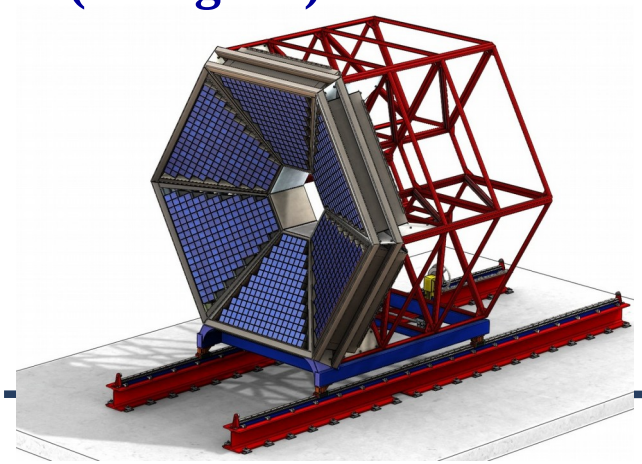
Photon decays:

$\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$

$\eta' \rightarrow \gamma\gamma$, $\omega \rightarrow \pi^0\gamma \rightarrow \gamma\gamma\gamma$

+ Dalitz decays

ECAL (lead glass)



HADES experimental program - elemetary pp and pn collisions

p+p @1.25 GeV	- inclusive e+e-, π^0, η - exclusive ppe+e-, ppe+e-γ, $np\pi^+$, $pp\pi^0$, Δ^+
d(n)+p @1.25 AGeV	- inclusive e+e- - exclusive npe+e-, $np\pi^+\pi^-$ ($\Delta\Delta$ t-channel)
p+p @2.2 GeV	- inclusive e+e-, π^0, η - exclusive ppe+e-, $np\pi^+$, $pp\pi^0$
p+p @3.5 GeV	- inclusive e+e-, π^0, η, ρ, ω - exclusive ppe+e-, $np\pi^+$, $pp\pi^0$ - **hyperons:** $pK^+\mathbf{\Lambda}$, $\mathbf{\Sigma}^{+/-}\pi^{-/+}pK^+$, $\mathbf{\Sigma}^+K^+n$, $\Lambda(1405) \rightarrow \Sigma^{+/-}\pi^{-/+}$, $\mathbf{\Lambda}p\pi^+K^0$, $\mathbf{\Sigma}^0p\pi^+K^0$ (Δ^{++})

Baryon resonances in pp @ 1.25GeV (π^+, π^0)

HADES : Eur. Phys. J. A51 (2015) 137

→ cross sections for resonance production (Δ+, Δ++, N(1440)) and angular distributions

Teis resonance model

S. Teis et al., Z. Phys. A 356, 421 (1997)

→ quite good description of the HADES data but no info on production mechanisms

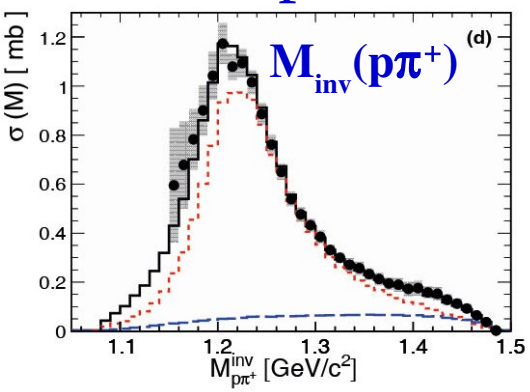
Partial Wave Analysis (PWA) Bonn-Gatchina

K.N. Ermakov et al., Eur. Phys. J. A 47, 159 (2011)

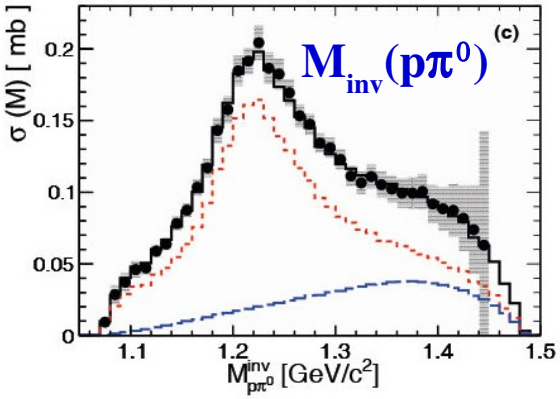
→ **database W: 2066-2422**
13 ppπ^0 and 3 pnπ^+

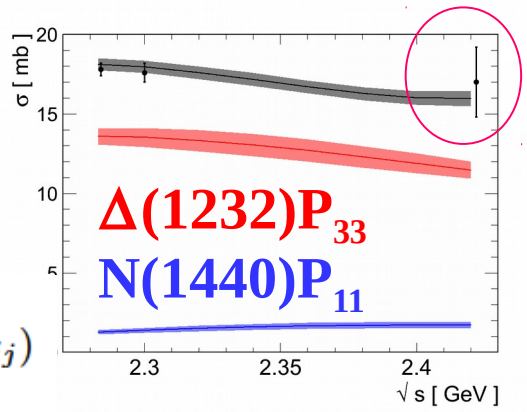
$$A = \sum_{\alpha} A^{\alpha}_{\mathrm{tr}}(s) Q^{\mathrm{in}}_{\mu_1 \ldots \mu_J}(SLJ) A_{2b}(j, S_2 L_2 J_2)(s_j) \times Q^{\mathrm{fin}}_{\mu_1 \ldots \mu_J}(j, S_2 L_2 J_2 S' L' J).$$

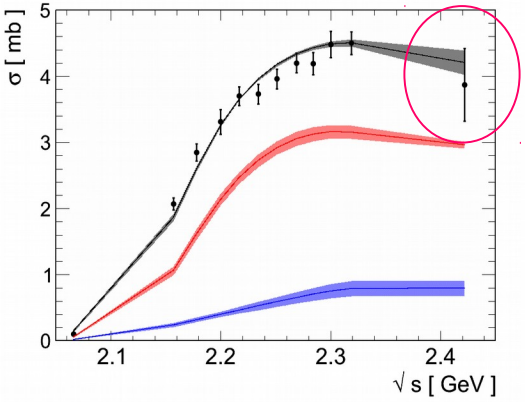
$np\pi^+$



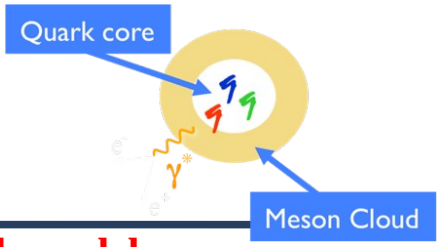
$pp\pi^0$

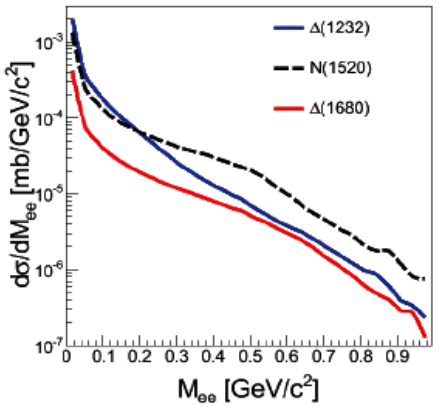






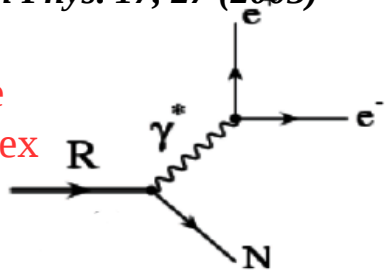
Baryon internal structure in e+e-





F. Dohrmann et al.,
Eur. Phys. J. A 45, 401 (2010)
M. Zétényi, Gy. Wolf,
Heavy Ion Phys. 17, 27 (2003)

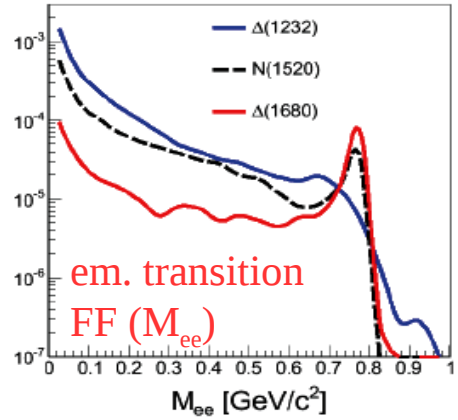
QED:
point-like
R-γ* vertex

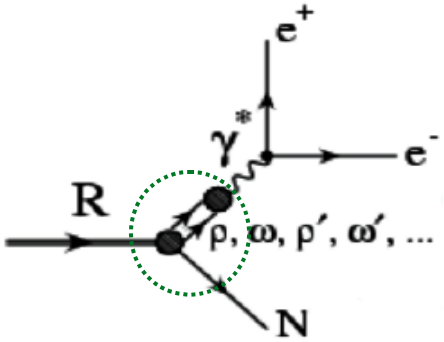


(Extended) Vector Meson Dominance:

$$d\Gamma(N \to e+e-) = \mathrm{QED}_{point-like} \times F(Q^2)_{QCD}$$

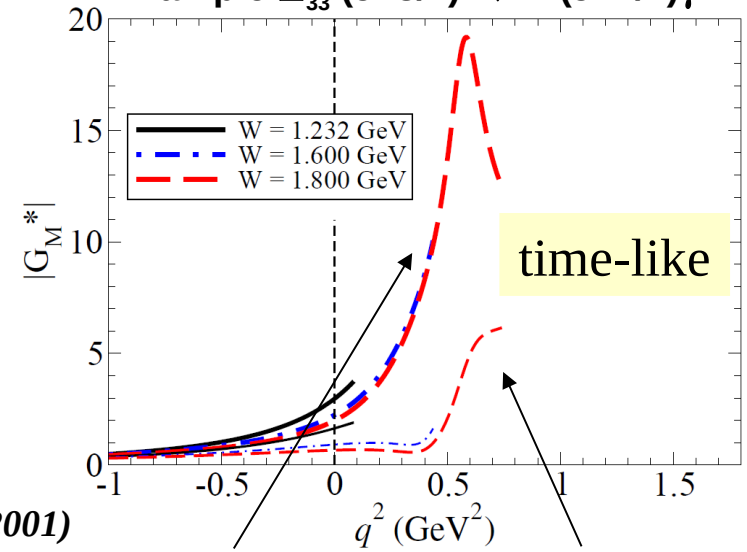
(I&W) *Iachello, Wan, Int. J. Mod. Phys. A20, 1846 (2005)*
(QED) *M. I. Krivoruchenko, A. Faessler, Phys. Rev. D 65, 017502, (2001)*
M. I. Krivoruchenko et al., Ann. Phys. 296, 299 (2002)





Covariant quark model +VMD (R&P):

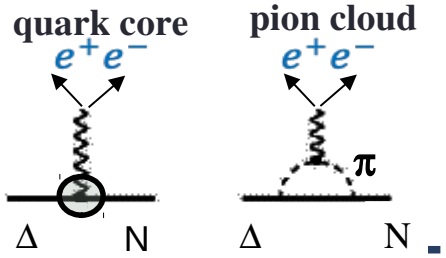
Example: Δ_{33} (J=3/2) → N (J=1/2)γ *



„quark core" + "pion cloud"

„bare quark core" - lattice-QCD

Δ → pe+e-



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

e+e- pairs from pp @ 1.25GeV

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

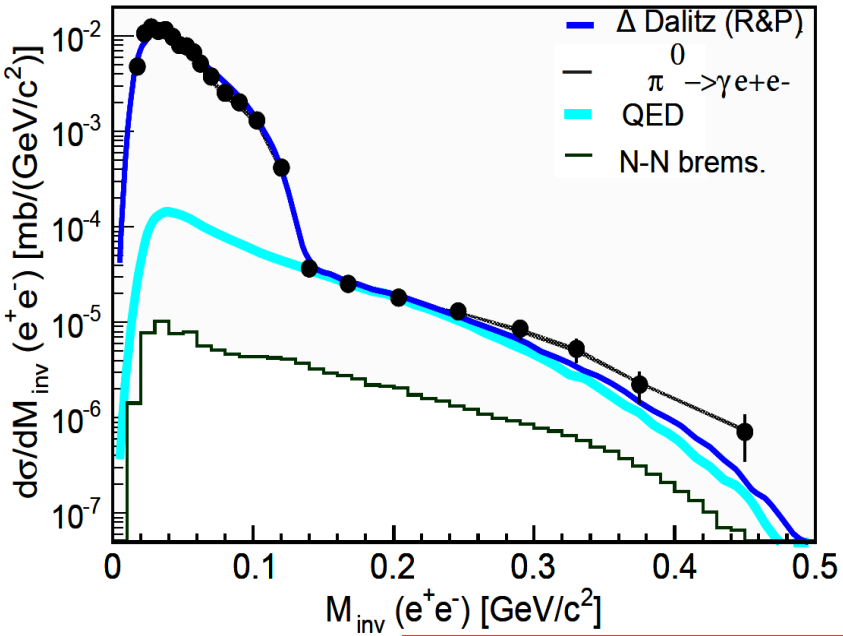
→ Beam energy below η threshold **to favor Δ**

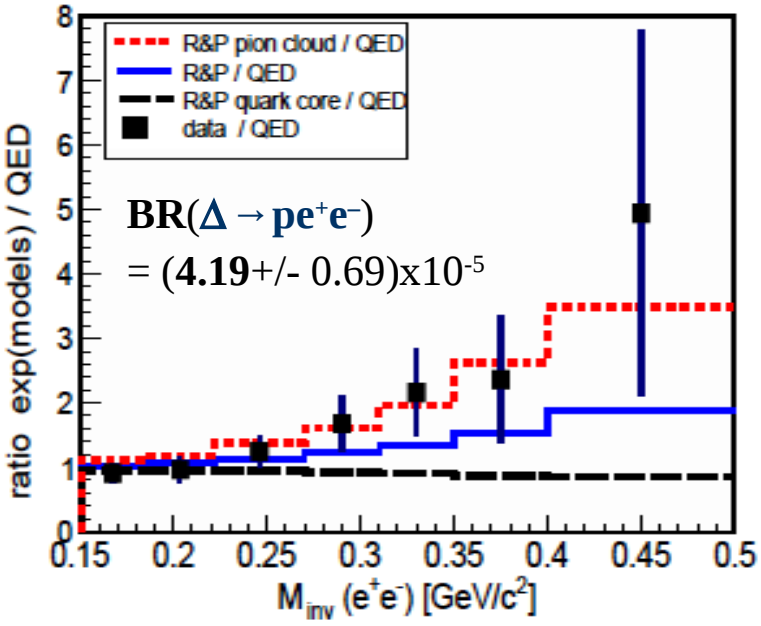
→ Hadronic decay channel fixed from one pion data and Bonn-Gatchina PWA

$\Delta^+(1232) \rightarrow pe^+e^-$ Dalitz decay

$pp \rightarrow ppe^+e^-$ (bremsstrahlung)

First detailed study of a timelike em. Δ tFF





Effective Form Factor

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

np → npπ⁺π⁻ @ 1.25

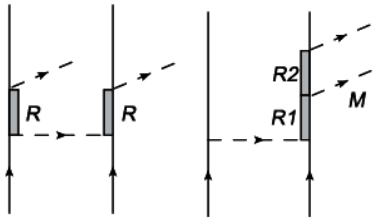
HADES: PLB750, 184 (2015)

Double-π production in NN:
→ simultaneous excitation of the two baryons and their subsequent decays
→ important for inclusive spectra of e+e- (np & pp & HI)
→ N*(1440) → Δπ, N*(1440) → Nσ, N*(1440) → Nρ, ΔΔ

Effective Lagrangian models

1) „modified" Valencia model

L. Alvarez-Ruso, E. Oset et al.
Nucl. Phys. A 633, 519 (1998)



N* → Nσ → Nππ, N* → Δπ → Nππ, ΔΔ
+ non-resonant component+interferences

→ **modifications:**

PLB 679, 30 (2009), PLB695, 115 (2011)
T. Skorotko et al. EPJ A35,317 (2008)

pp → ppπ⁰π⁰

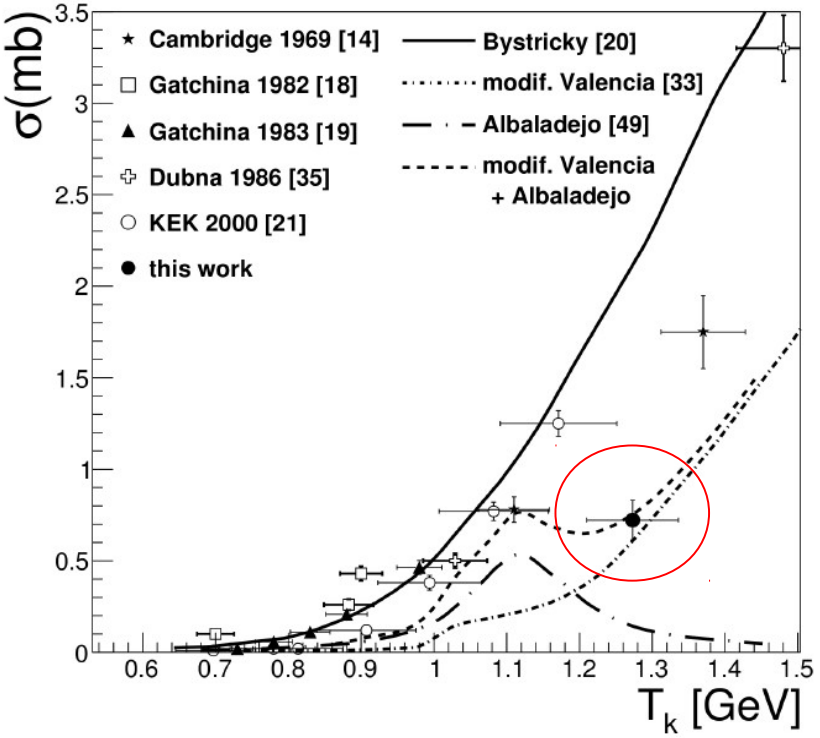
2) Cao model

no interferences, good description of
pp → nn2π⁺, but overestimates pp → pp2π⁰

3) OPER model

A. Jerusalimov: arXiv:1203.3330 [nucl-th]
→ one pion and one boson exchanges

σ_{OPER}, σ_{Cao} 2x higher than data
$\sigma_{Valencia}$ 30% lower than data



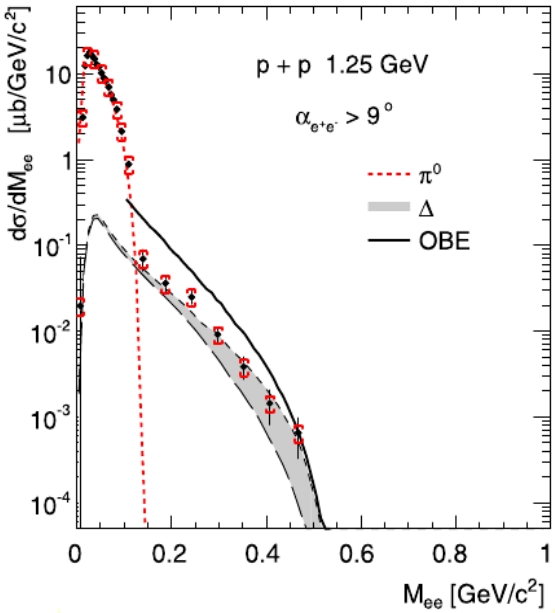
e+e- pairs from pp and np reactions @ 1.25GeV (inclusive)

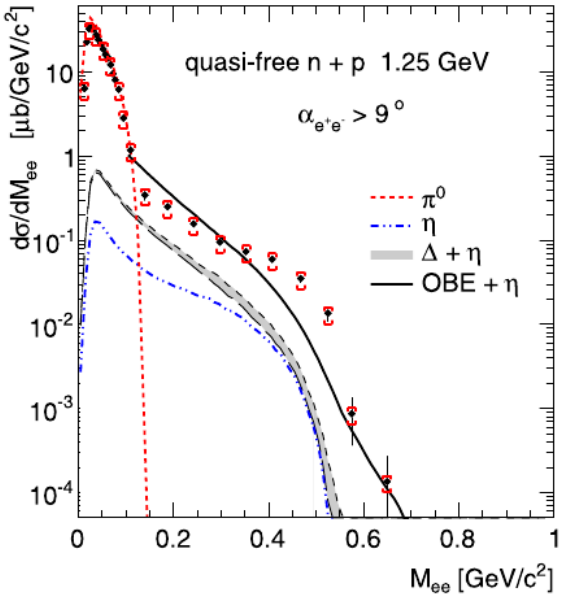
HADES, PLB 690, 118 (2010)

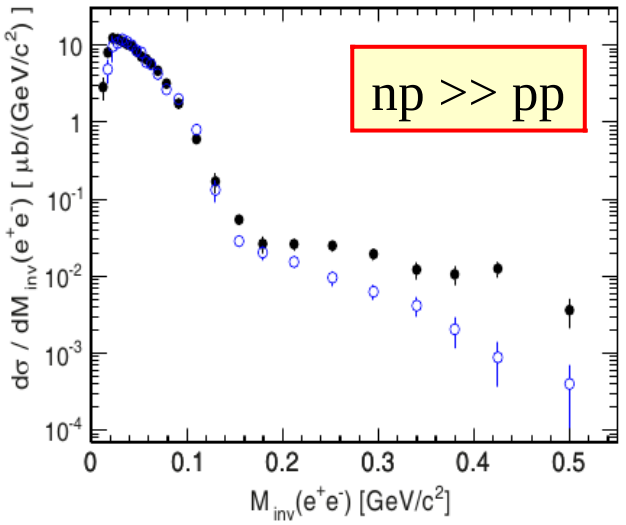
Strong isospin effect !

OBE = **O**ne **B**oson **E**xchange
L.P. Kaptari, B. Kämpfer, NPA 764 (2006) 338

Δ Dalitz decay (gray band)– Iachello, Wan and Krivoruchenko





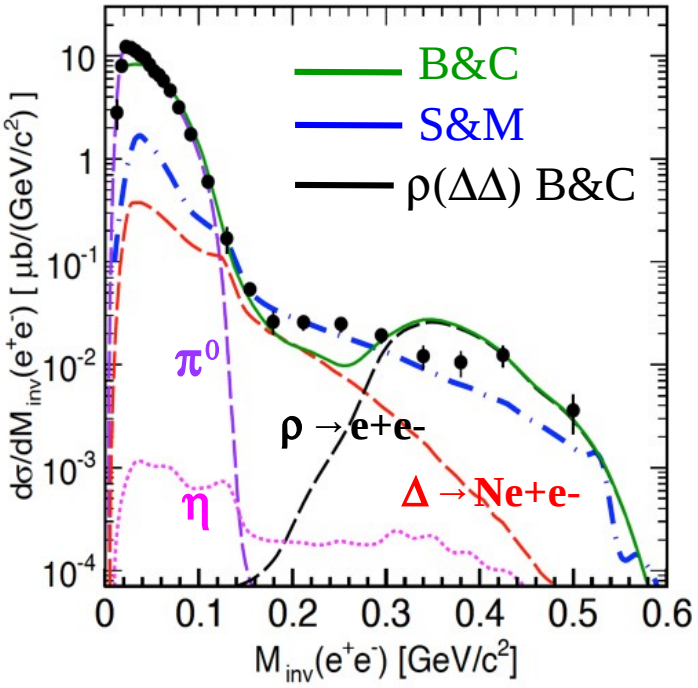


p+p data: very good agreement with Δ^+ only (OBE), bremsstrahlung is suppressed

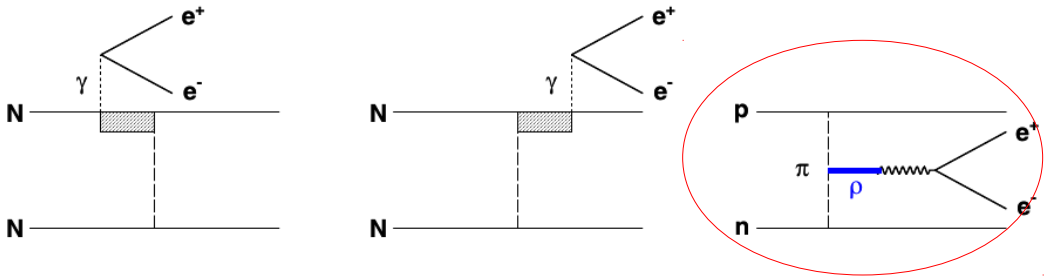
n+p data: data cannot (yet) be described well by OBE calculations

e+e- pairs from np reactions @ 1.25GeV

HADES: Eur. Phys. J. A 53, 149 (2017)



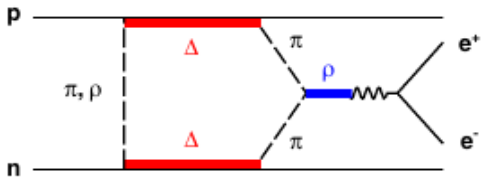
Shyam & Mosel *R. Shyam, U. Mosel, PRC 82, 062201 (2010)*



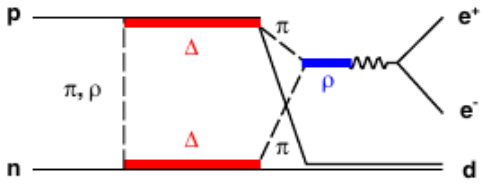
→ pion e-m Form Factor – enhances e+e- yield
→ production of ρ-like state via the charged current

Bashkanov&Clement π+π → ρ

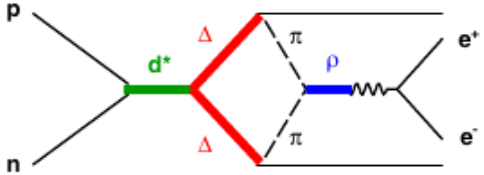
M. Bashkanov, H. Clement, Eur. Phys. J A50, 107 (2014)



ΔΔ → np
t-channel



ΔΔ → d
t-channel



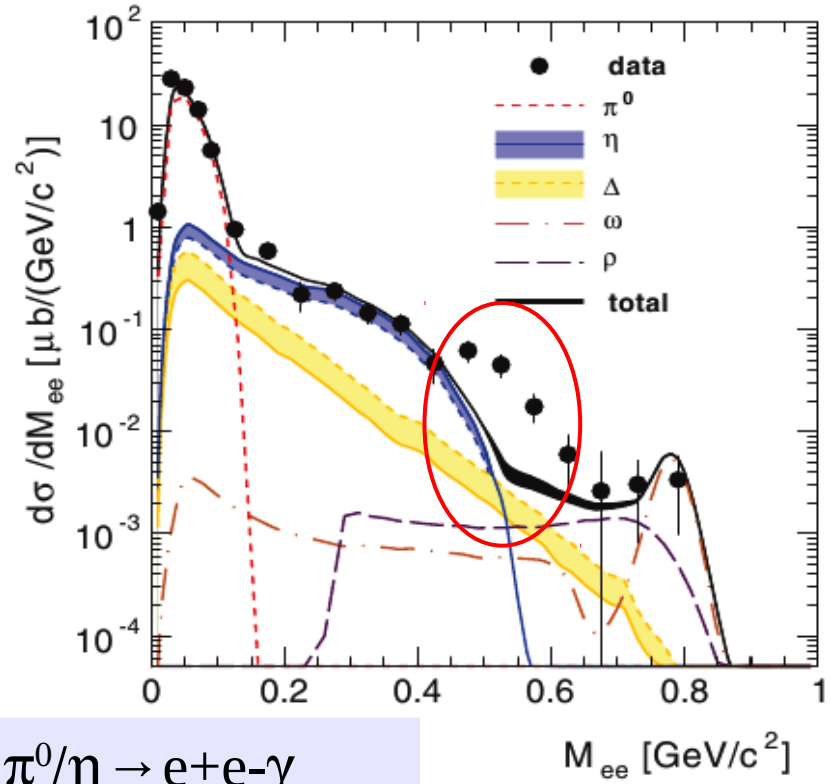
d* pproduced in s-channel

d*: M ~ 2380 MeV
Γ ~70 MeV

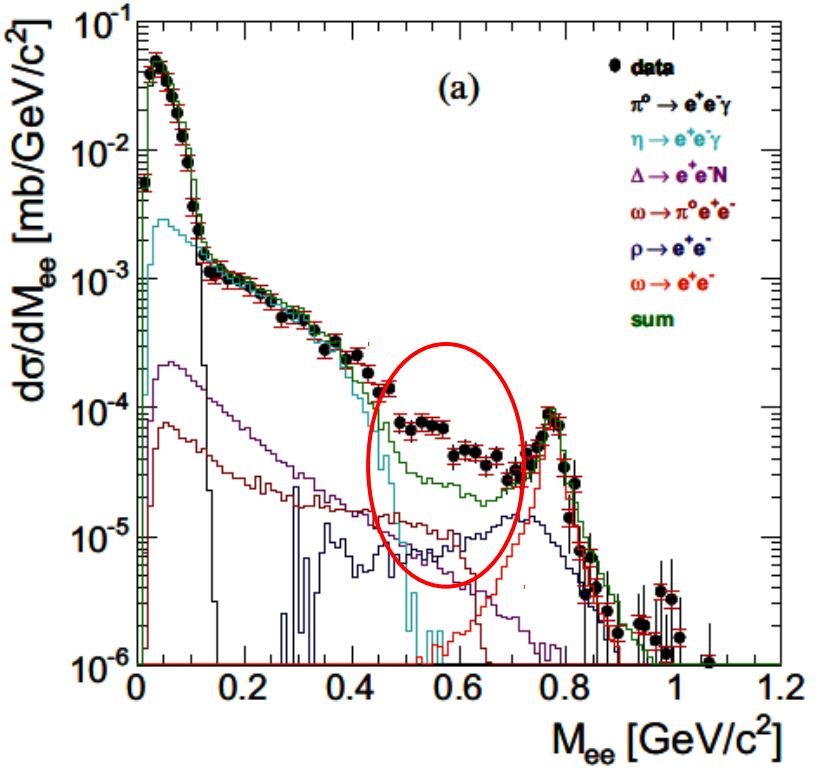
pp → e+e-X pp @ 2.2 & 3.5 GeV

e+e- pair cocktail fixed to known π /Δ /η/ω/ρ cross sections

HADES: PRC85, 054005 (2012)



HADES: Eur. Phys. J. A 48, 64 (2012)



$\pi^0/\eta \rightarrow e+e-\gamma$
$\omega \rightarrow \pi^0 e+e-$
$\rho^0/\omega \rightarrow e+e-$
$\Delta(1232) \rightarrow Ne+e-$

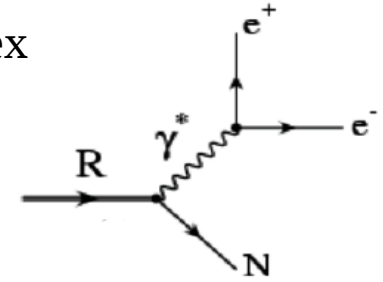
→ Δ form factor fixed at the photon point
→ additional sources of e+e- needed:
N*(1440), N*(1520), N*(1535)….

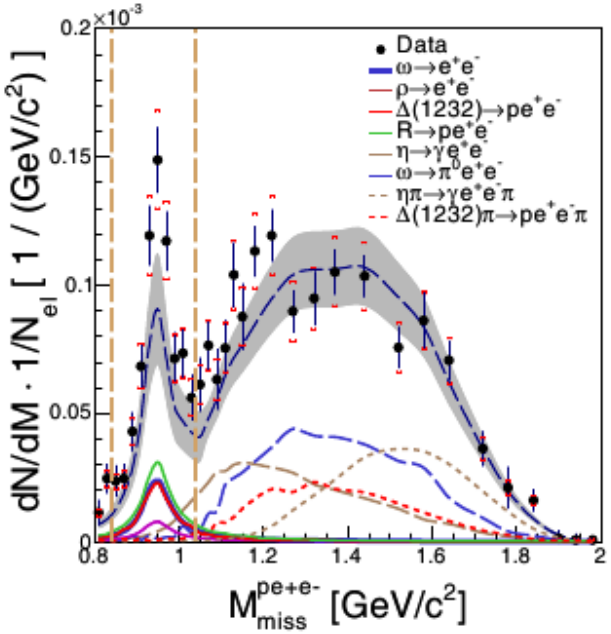
p+p → ppe⁺e⁻ @ 3.5 GeV

HADES: Eur. Phys. J A50 (2014) 82

"QED point-like" R-γ* vertex

M. Zetenyi et al.
PRC 67, 044002 (2003)
M. I. Krivoruchenko et al.
Ann. Phys. 296, 299 (2002)

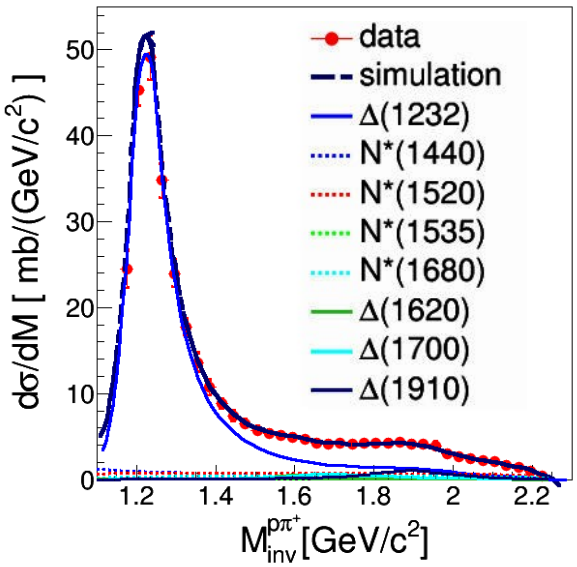




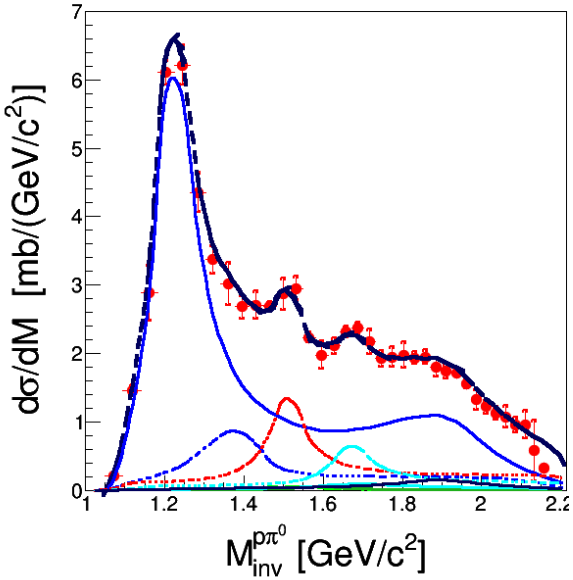
simulation - resonance model

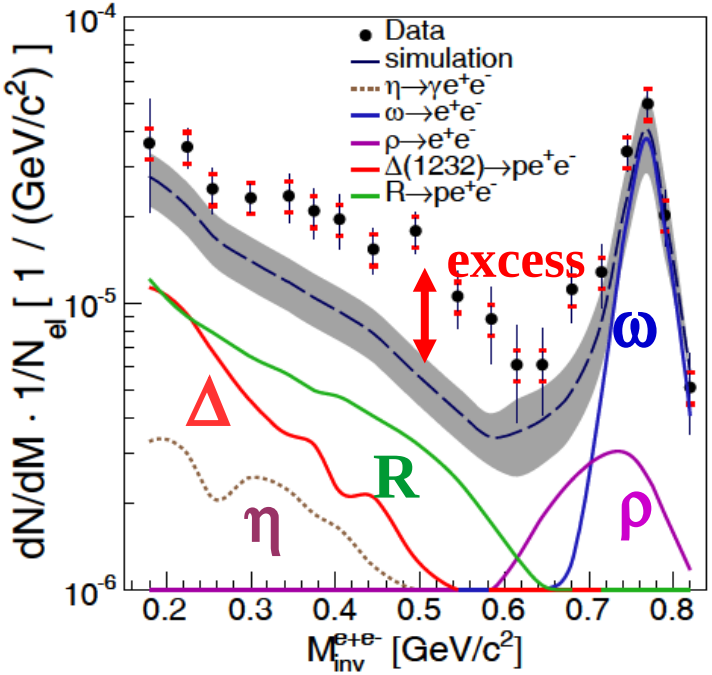
Z. Teis et al., Z. Phys. A356 (1997) 421

npπ⁺



ppπ⁰





p+p → ppe⁺e⁻ @ 3.5 GeV

HADES: Eur. Phys. J A50 (2014) 82

GiBUU includes

J. Weil, H. van Hees, U. Mosel, Eur. Phys. J. A 48, 111 (2012)

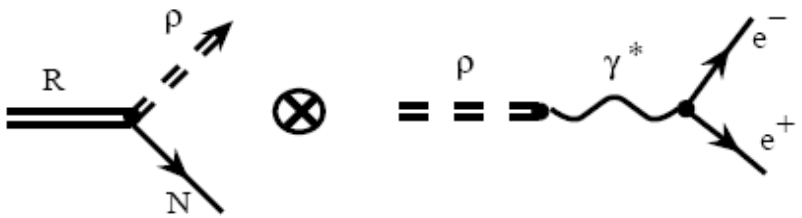
Vector Dominance Model (VDM)

- off-shell ρ coupling to resonances

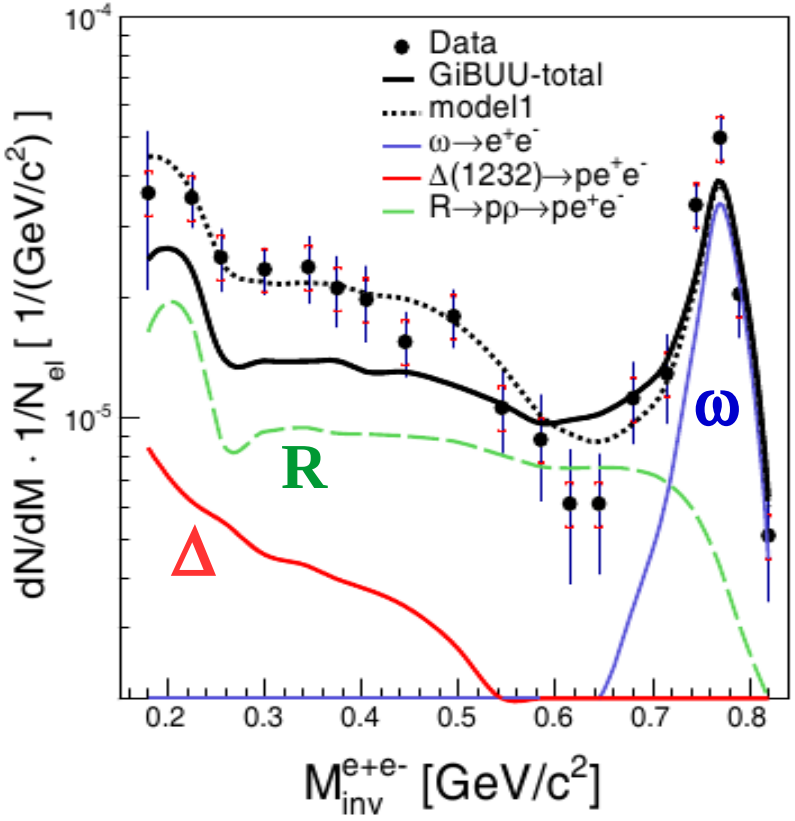
R → pρ → pe+e-

Resonance model + strict VDM with ρ dominance

M. I. Krivoruchenko et al. Ann. Phys. 296, 299 (2002)



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

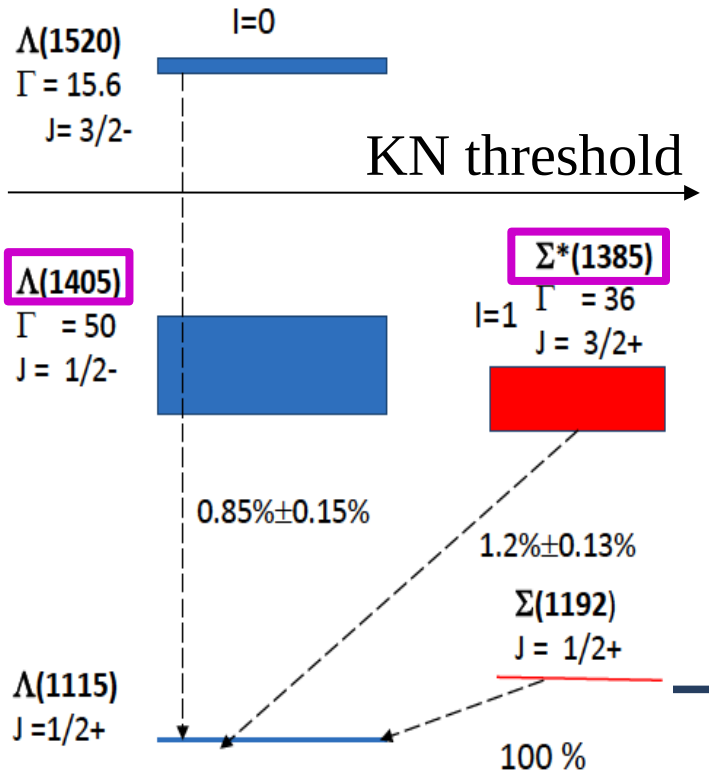


model1 = GiBUU, but with modified cross sections (HADES simul.): higher for N(1520), smaller for N(1440), N(1535)

Strangeness studies with HADES
pp @ 3.5 GeV/c

Main interest:

- Kaon-nucleon potential (ChPT)
- Strange-baryons interactions with matter:
  → Equation Of State (EOS)
  → Neutron Stars compositions
- **Structure of strange baryons (Λ, Σ)** – upcoming measurements @SIS (2021 accepted proposal)



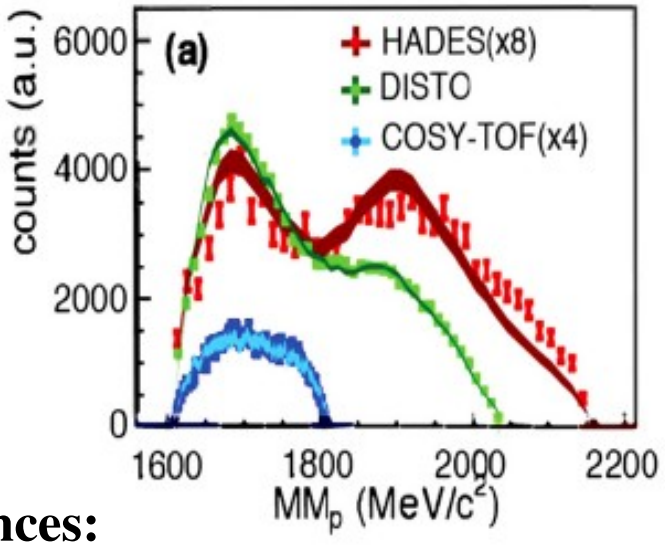
$\Sigma(1385)^+$
HADES: PRC 85, 035203 (2012)
Λ(1405)
HADES: PRC 87, 025201 (2013)
Λ(1520)
(upcoming paper in EPJ)
e-m hyperon decays

Role of N* in strangeness production

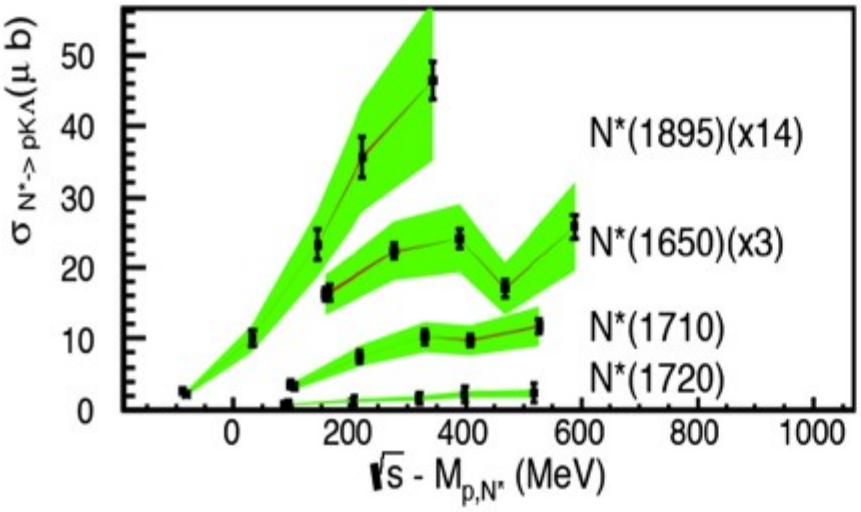
$pp \rightarrow pK^+\Lambda$

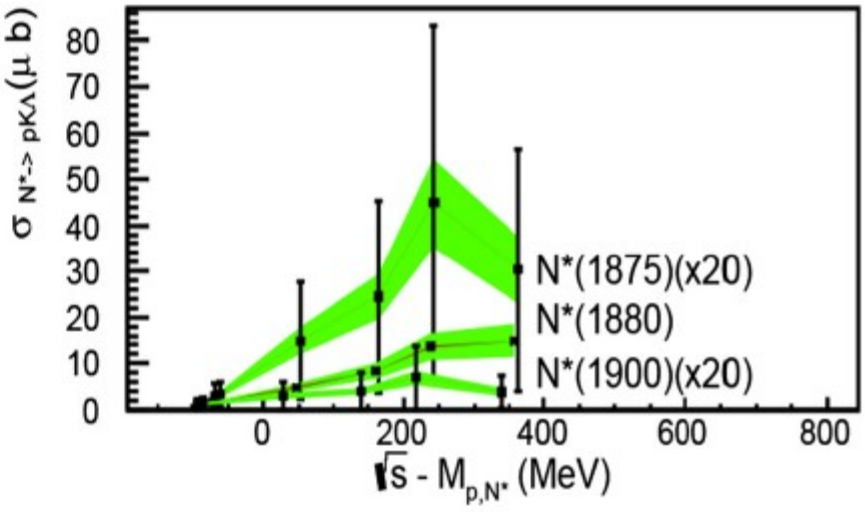
R. Munzer et al., PLB 785, 574 (2018)

- combined PWA of 7 data samples with exclusively reconstructed p+p → pK+
- events measured by the COSY-TOF, DISTO, FOPI and HADES (2.14-3.5 GeV)
- N∗ coupling to Λ-K+ channel and p-Λ FSI



production amplitude of the N* resonances:



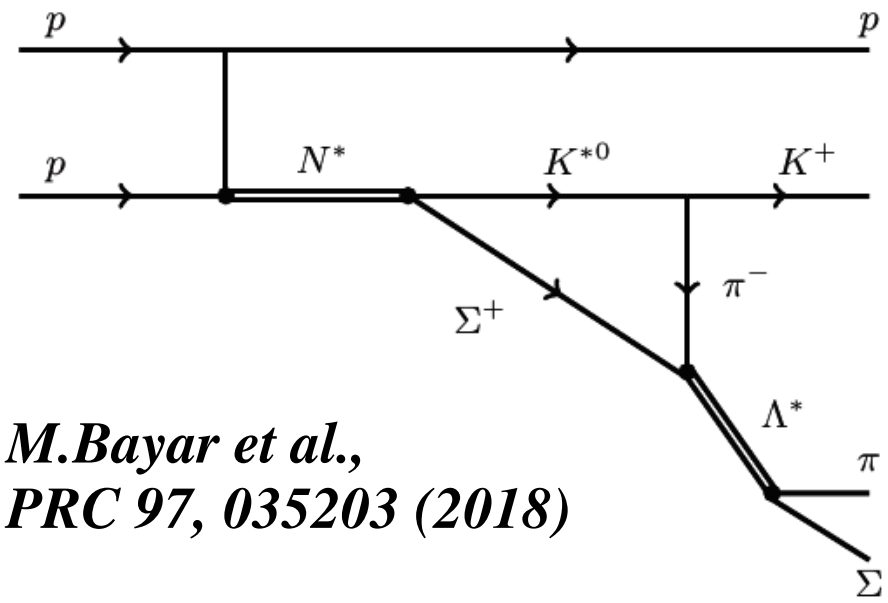


excess energy= $\sqrt{s} - M_{p,K+,\Lambda}$

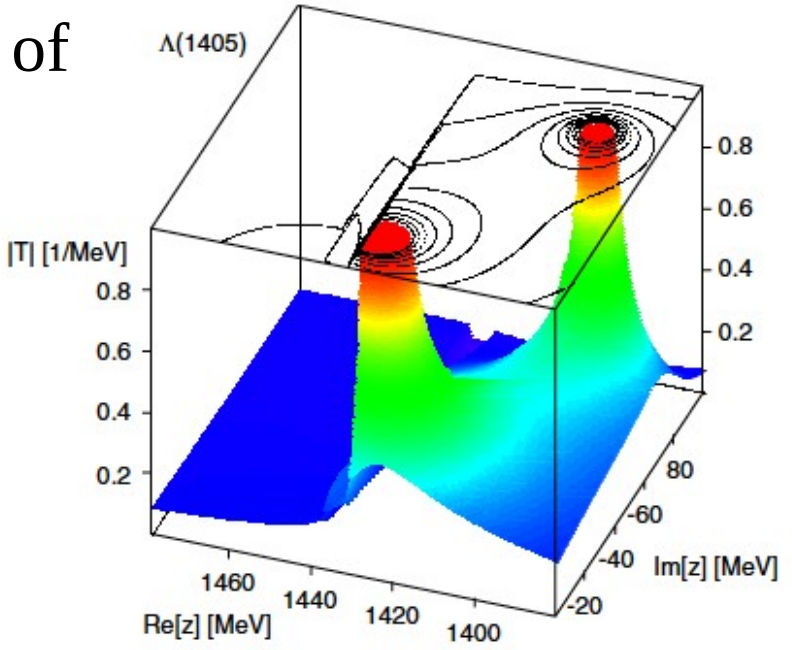
Λ(1405) mass – theory

In the chiral unitarity approach:

- **Λ(1405)** in ChPT is a superposition of
  → quasi-bound KN state
  → two-pole resonance Σπ-KN
- triangle singularity in **$pK^+\pi\Sigma$** ?



M.Bayar et al.,
PRC 97, 035203 (2018)

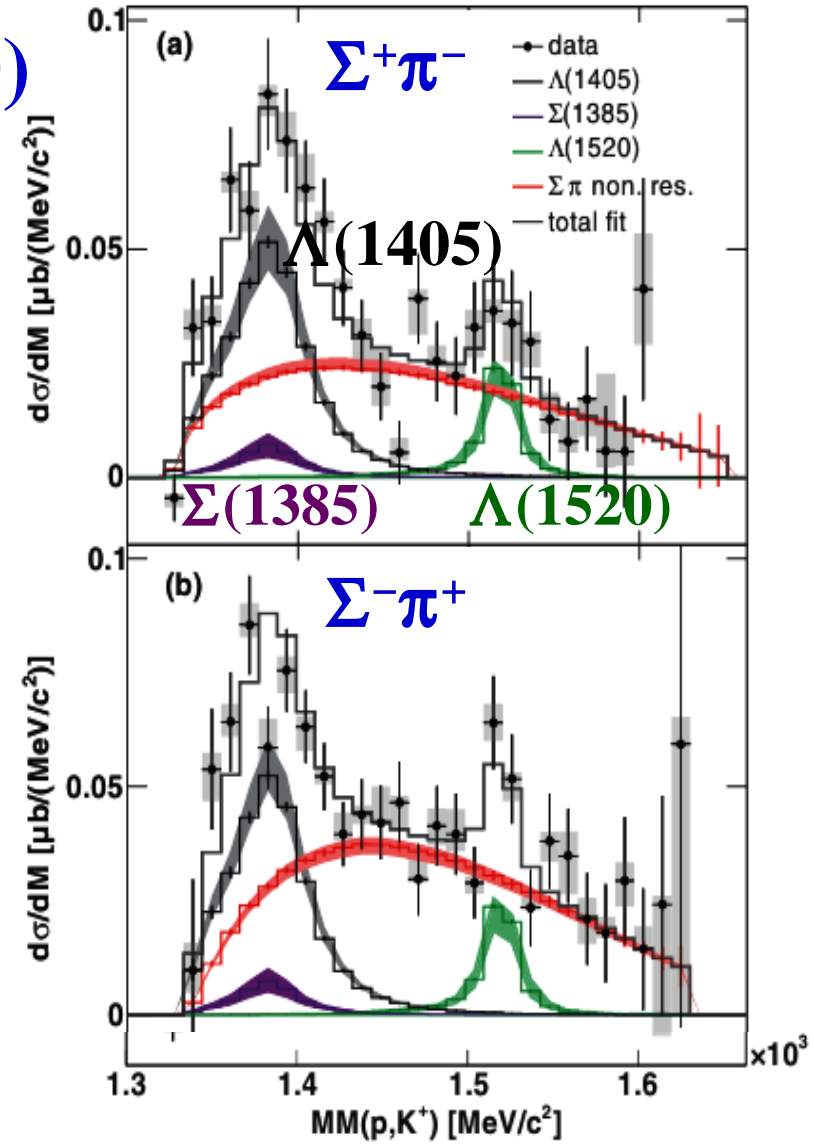


T. Hyodo, D. Jido
Prog.Part.Nucl.Phys., 67, 55 (2012)

Λ(1405) and Λ(1520) pp @ 3.5 GeV/c

$$p + p \xrightarrow{3.5\ \mathrm{GeV}} \Lambda(1405) + K^+ + p$$
$$\hookrightarrow \Sigma^{\pm} + \pi^{\mp}$$
$$\hookrightarrow \pi^{\pm} + n$$

$$\sigma_{pp\to\Lambda(1405)pK^+} = 9.2 \pm 0.9 \pm 0.7^{+3.3}_{-1.0}\ \mu\mathrm{b}$$
$$\sigma_{pp\to\Lambda(1520)pK^+} = 5.6 \pm 1.1 \pm 0.4^{+1.1}_{-1.6}\ \mu\mathrm{b}$$
$$\sigma_{pp\to\Sigma^+\pi^- pK^+} = 5.4 \pm 0.5 \pm 0.4^{+1.0}_{-2.1}\ \mu\mathrm{b}$$
$$\sigma_{pp\to\Delta^{++}\Sigma^- K^+} = 7.7 \pm 0.9 \pm 0.5^{+0.3}_{-0.9}\ \mu\mathrm{b}$$

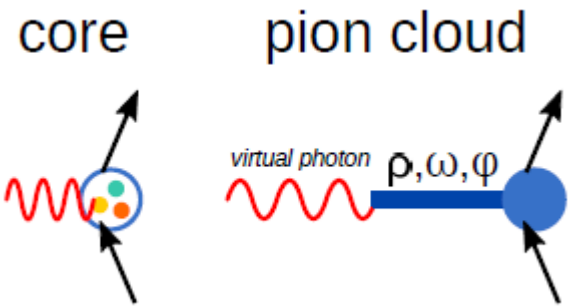


→ the contribution of Σπ is dominant (lower position of Λ peak)
→ the measured cross sec. for Λ(1405) is consistent with the ANKE data
→ angular distributions (CM frame) of Λ(1405) and Λ(1520) are isotropic

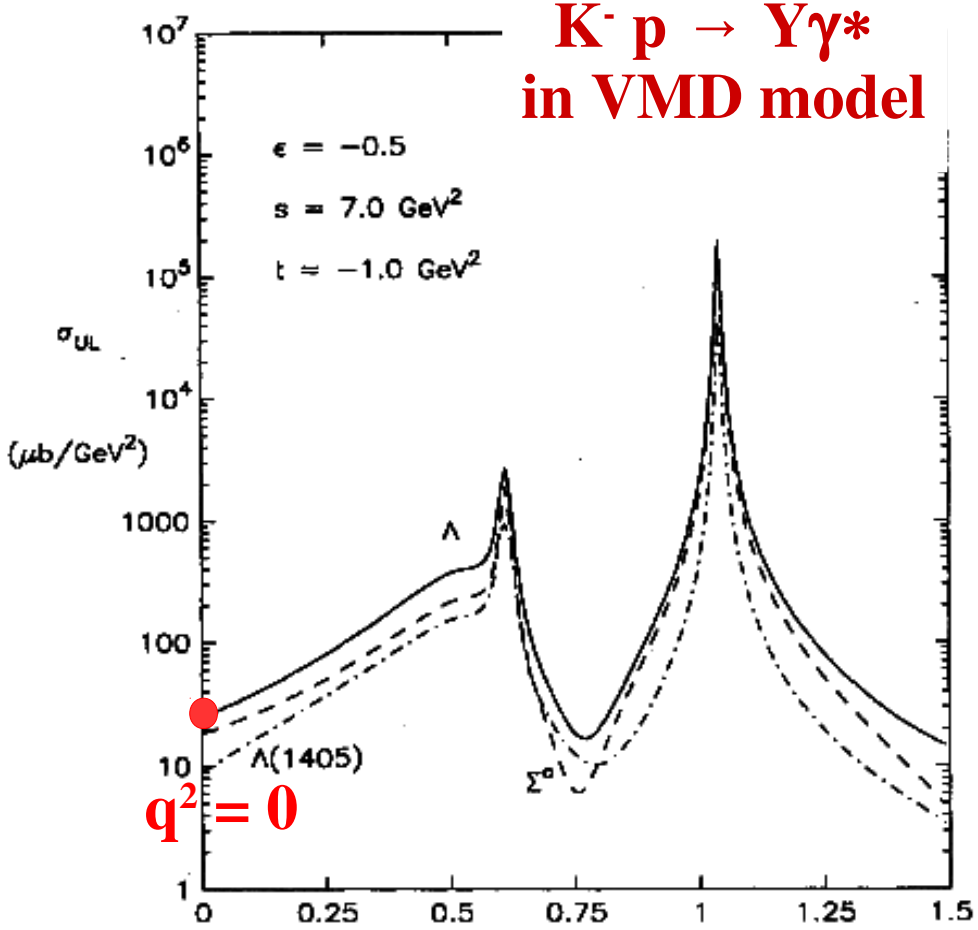
Hyperon Dalitz decays
pp @ 4.5 GeV/c

VMD:
huge enhancement predicted

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



$K^- p \rightarrow Y\gamma^*$ in VMD model



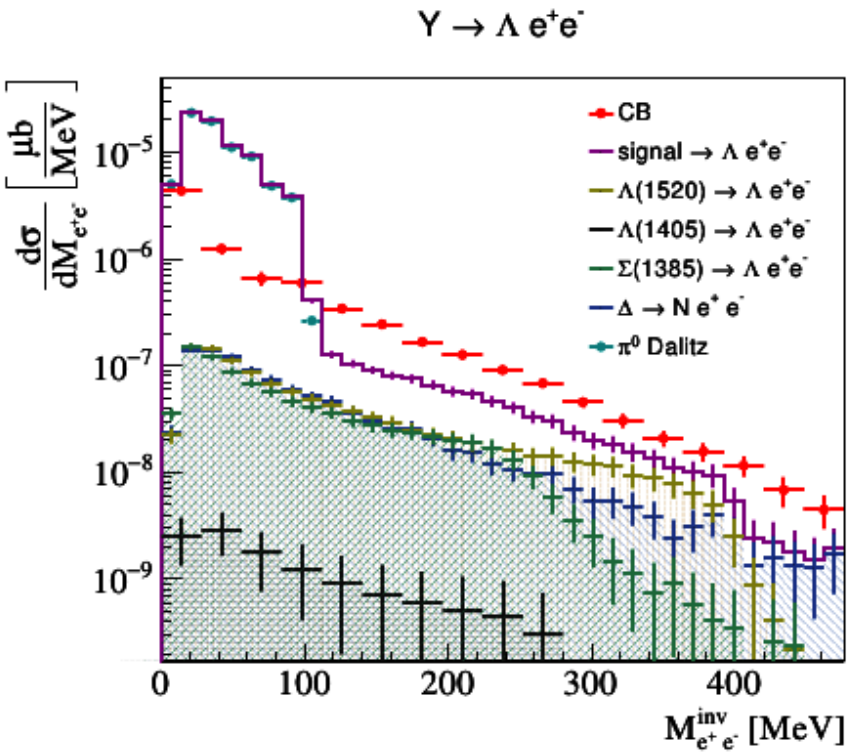
Hyperons Dalitz decay
pp @ 4.5 GeV/c

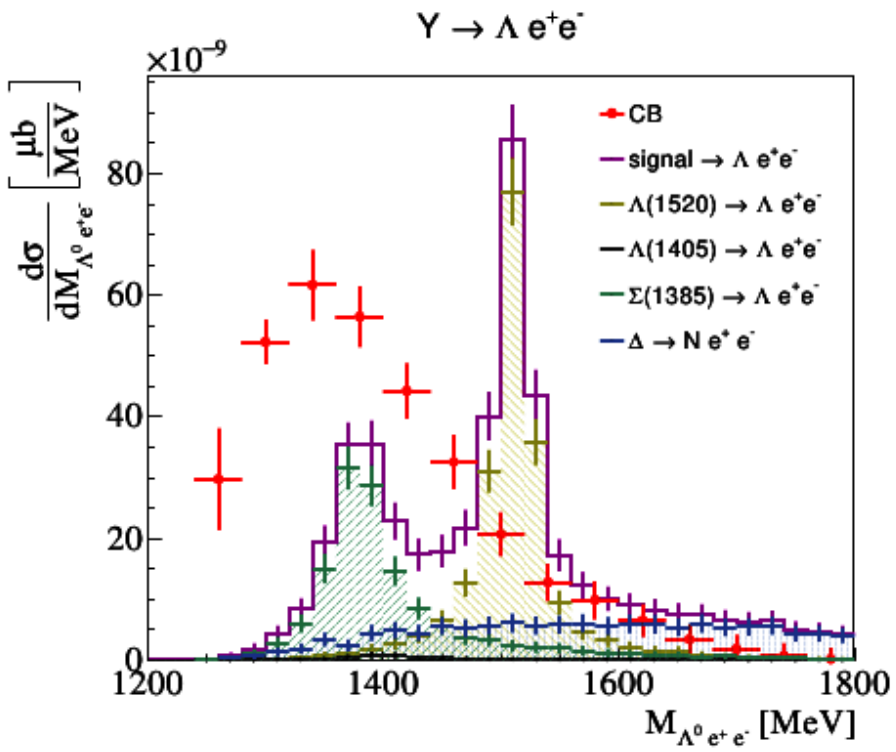
Feasibility study at 4.5 GeV/c – benchmark simulations:

$pK^+\Lambda(1520)[\Lambda e^+e^-]$ **σ=69.6 μb, BR=8.4*10^{-5}**

$pK^+\Lambda(1405)[\Lambda e^+e^-]$ **σ=32.2 μb, BR=5.3*10^{-6}**

$pK^+\Sigma(1385)[\Lambda e^+e^-]$ **σ=56.2 μb, BR=1.1*10^{-4}**





Summary and outlook

- Elementary collisions are very crucial for understanding hadron properties, also in dense nuclear matter,
- Hadronic channels have been studied:
  single and double pion production to obtain production cross sections for resonances,
- Results have been compared to various phenomenological models,
- Dileptons production (cocktail based on known sources):
  - reference for HI collisions
  - studies of em structure of baryons – em tFF via Dalitz decays
  - spectra of decaying resonances
- Studies of strangeness production and em structure of hiperons
- 2021 – accepted proposal at SIS18 to measure pp@ 4.5 GeV

Thank You
for
Your Attention