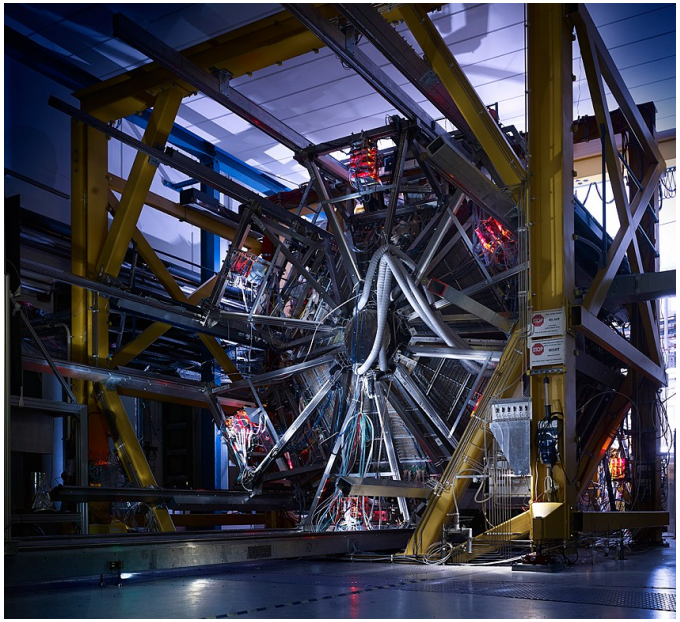
ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

Prospects for studies of production, decays and structure of light mesons with HADES

HADES



Outline:

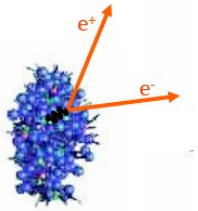
1) Main motivations of the HADES experiment,
2) HADES spectrometer,
3) Test of VMD for barions in the timelike region,
4) Neutral mesons production in pp@ 4.5 GeV,
5) Hadronic decays of $\eta/\omega/f_1(1285)$ mesons,
6) Di-leptonic Dalitz decays of η/ω mesons (eTFF),
7) Rare decays and CP-violation.

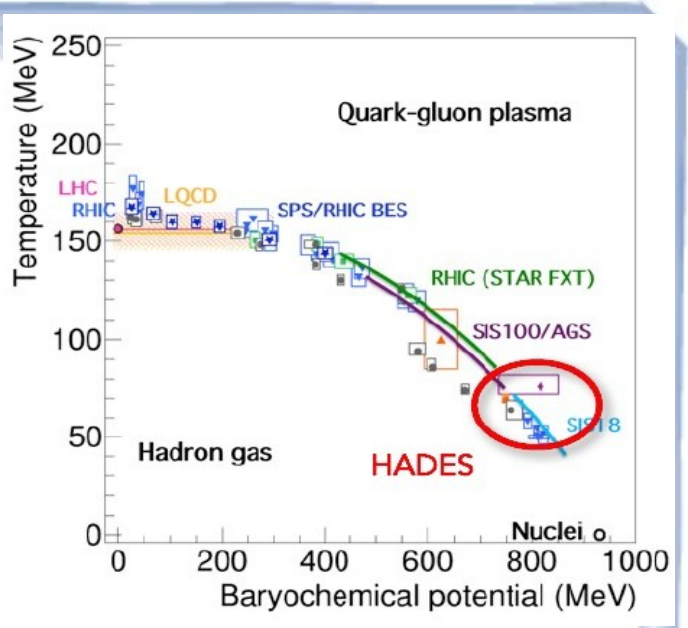
Izabela Ciepał

GSI FAIR
GSI Helmholtzzentrum für Schwerionenforschung

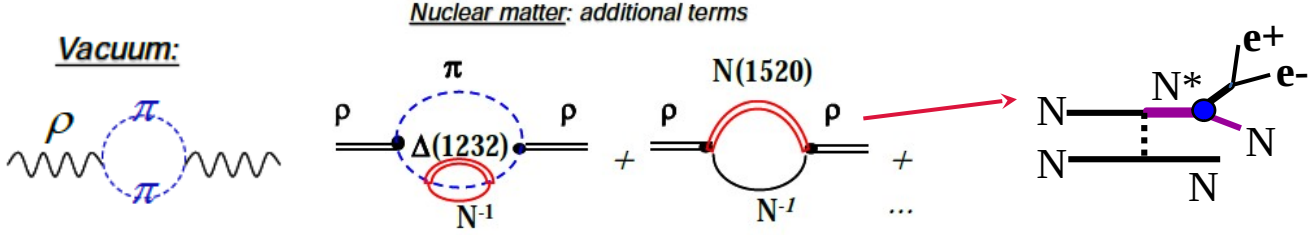
Main motivation of the HADES experiment

- hadron properties in hot and dense nuclear matter
- hadron electromagnetic structure
- role of vector mesons
- dielectrons - important probe



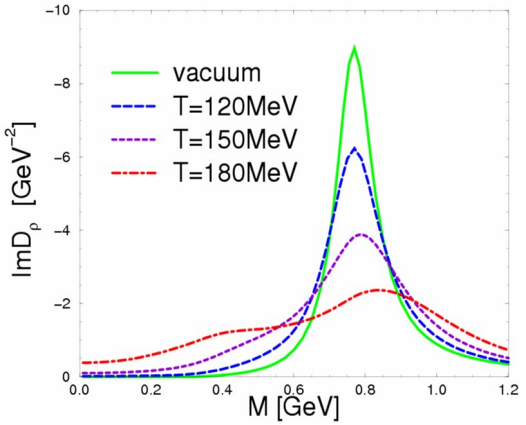


ρ meson



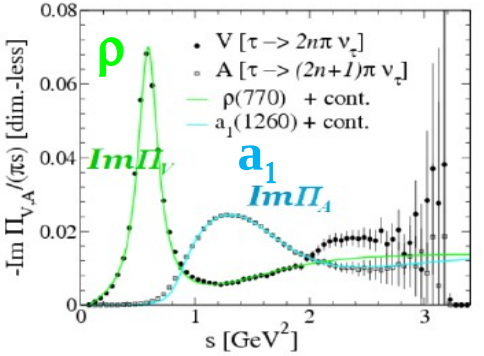
in-medium **spectral function** depends on **ρNN* coupling** (N(1520), Δ(1720), N(1910), ….) studied in **NN, πN collisions** via N*(Δ) → N**e+e−** Dalitz decays

in-medium ρ broadening



chiral symmetry restoration

$\rho(760)/a_1(1260)$ become degenerate at $T \sim T_c$, $\mu_b = 0$



P. Hohler, R. Rapp, NPA 892, 58 (2012)
P. Hohler, R. Rapp, PLB 731, 103 (2014)

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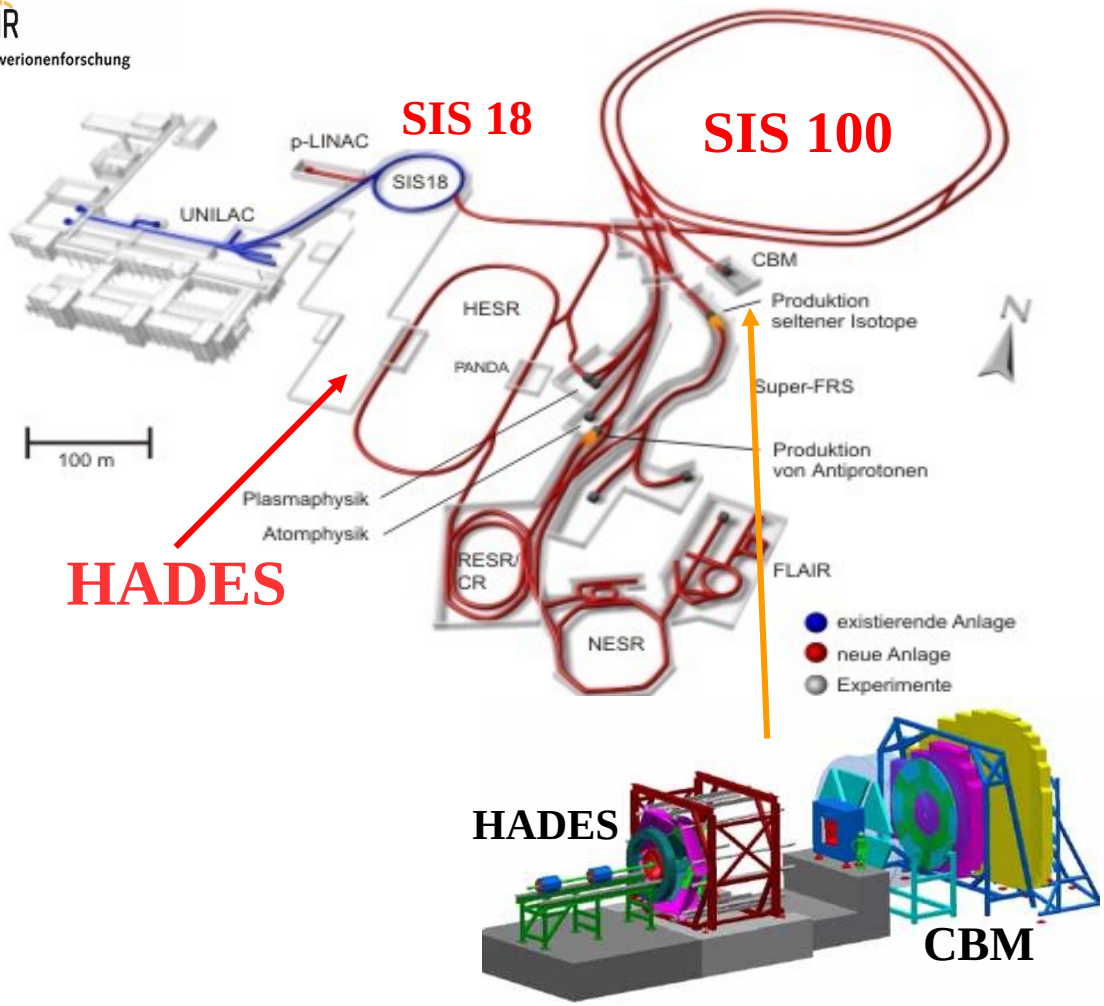


SIS 18

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

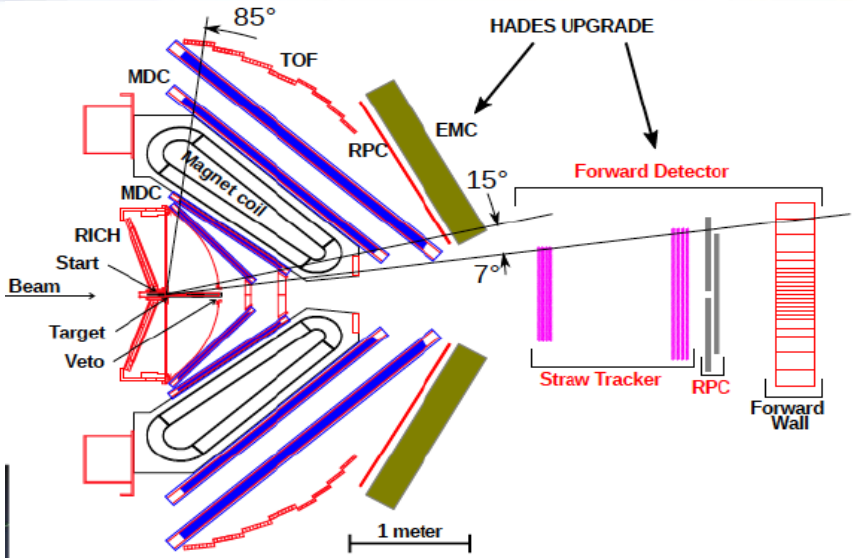
Secondary beams

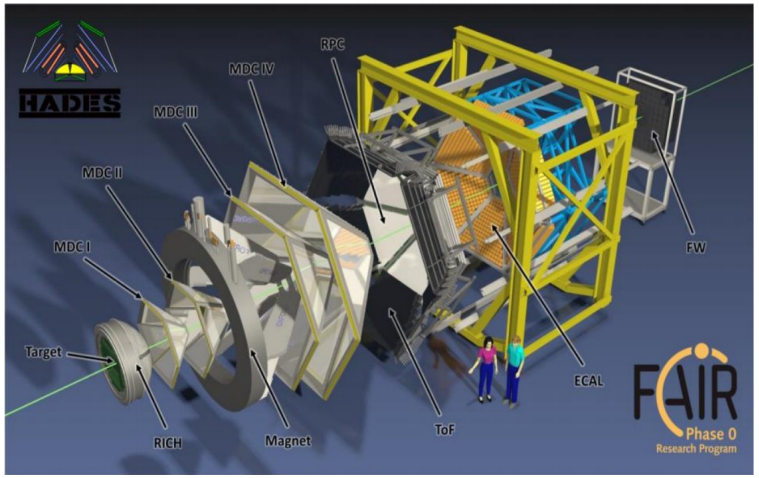
Radioctive beams 1.5 GeV/u

Anty-protons 30 GeV

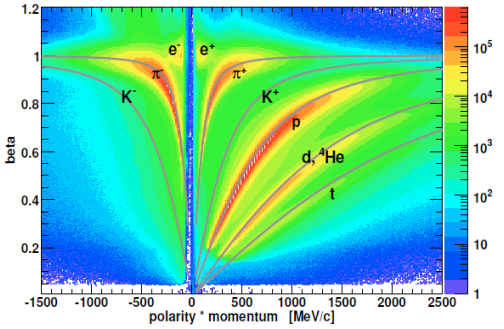
HADES - first detector of FAIR Phase0 (2018-2022)

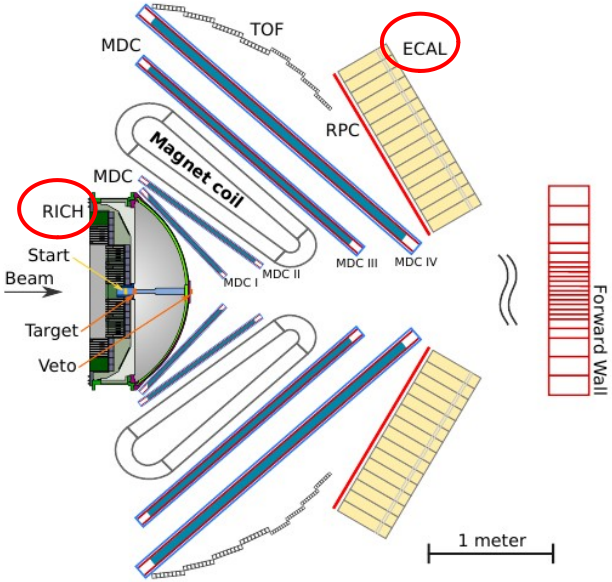
HADES Spectrometer





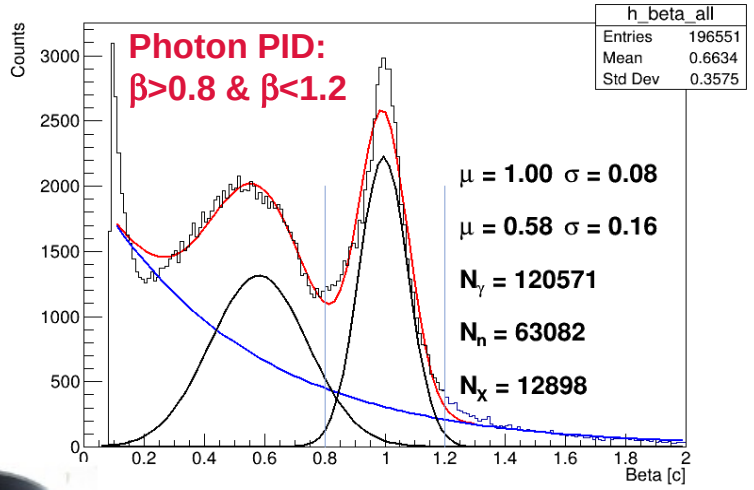
- ✓ SIS18 beams: protons (1-4.5GeV), nuclei (1-2AGeV), pions (0.4-2 GeV) secondary beam
- ✓ Spectrometer with $\Delta M/M \sim 2\%$ at ρ/ω
- ✓ PID (π/p/K): ToF (TOF/RPC, T0 detector), tracking (dE/dx)
- ✓ momenta, angles: MDC+ magnetic field
- ✓ electrons: RICH
- ✓ neutral particles: ECAL
- ✓ full azimuthal,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



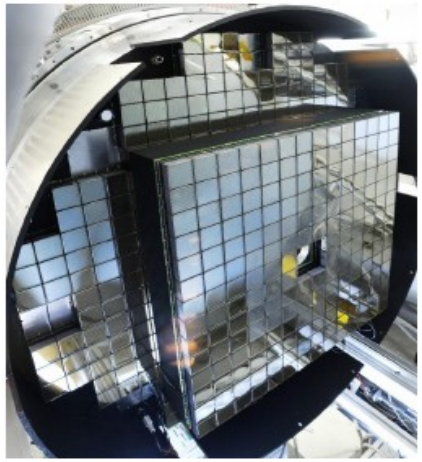


ECAL – photons detection 15° – 45°

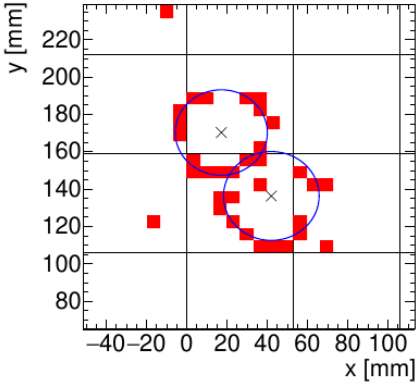
Lead glass



RICH – di-electrons detection 18° – 85°

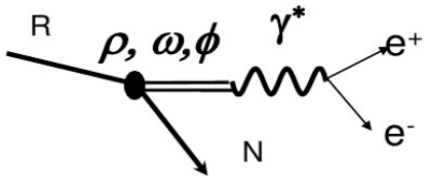


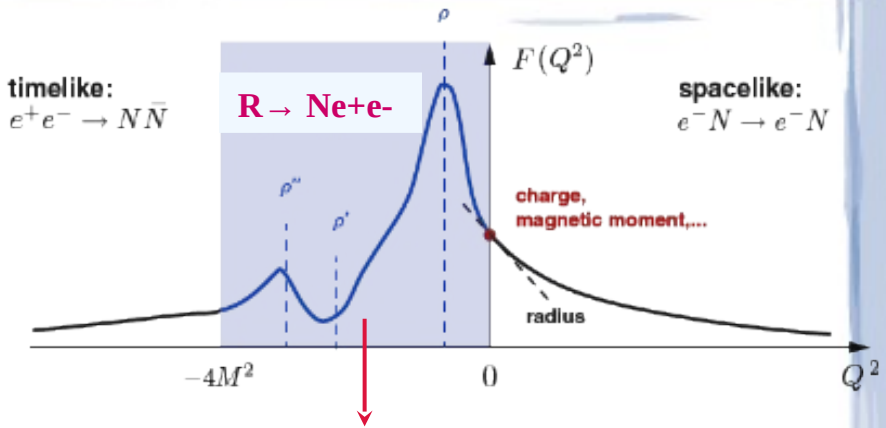
Multi-anode PMTs



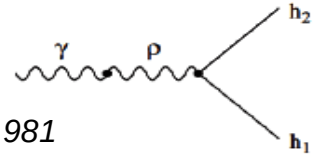
Baryon eTFF in π^-p @ 0.7 GeV/c – VMD test

Vector Meson Dominance Models (VMD)





➔ *strict* VDM



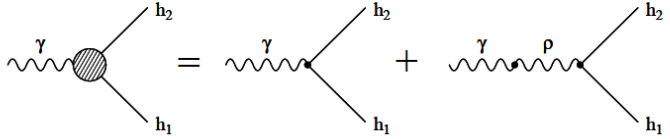
***Sakurai**, Phys. Rev 22 (1969) 981*
M. I. Krivoruchenko et al.,
Ann. Phys. 296, 299 (2002)

- Nρ coupling
- used in HI transport models

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

- accessible via Dalitz decays $\mathbf{q^2=M^2_{inv}(e+e-)}$
- electromagnetic tFF measured with HADES: Δ→pe+e-, N(1520)→ ne+e-

➔ 2-component VDM



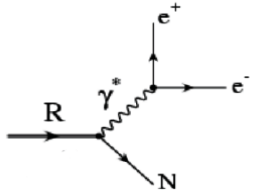
Kroll, Lee & Zuminio
Phys. Rev. 157, 1376 (1967)

- Nρ and Nγ couplings
- used in calculations of in-medium ρ spectral functions

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

➔ QED "point-like"

R-γ^* vertex

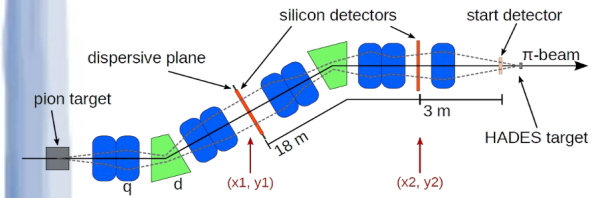


M. Zetenyi et al.,
PRC 67, 044002 (2003)

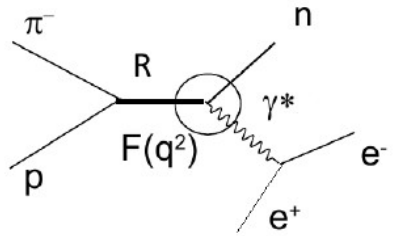
Baryon eTFF in π^-p @ 0.7 GeV/c – VMD test

HADES: Phys. Rev. C 102, 024001, (2020)
HADES coll. arXiv:2205.15914 [nucl-ex]

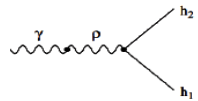
Pion Beam @ GSI

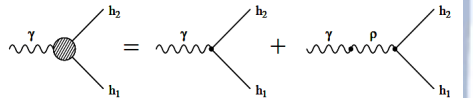


- secondary π^- with **I ~ 2-3 10^5/s**
- **PE $(CH_2)_n$** and **C** targets
- $\sqrt{s}$ 1.46-1.55 GeV in 2nd resonance region
- combined analysis of 2π and e+e-
- from 2π chan.=> ρ mass distribution (Bonn-Gatchina PWA *pwa.hisp.uni-bonn.de*)

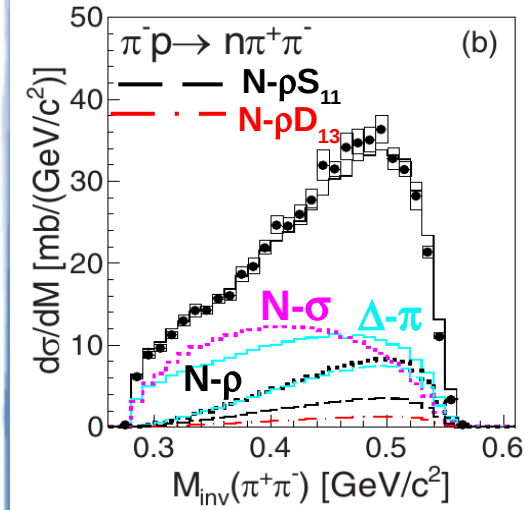


$$\Gamma_{tot}(M) = \Gamma_{\pi^+\pi^-}(M) + \Gamma_{e^+e^-}(M)$$

VDM2 

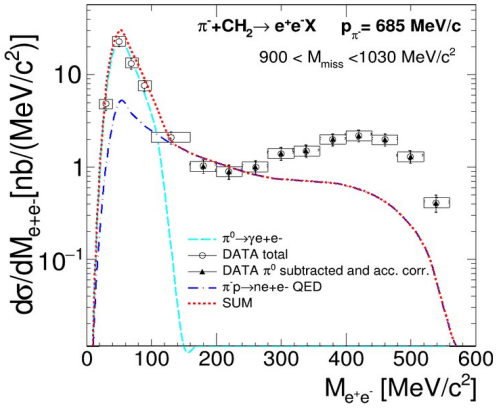
VDM1 

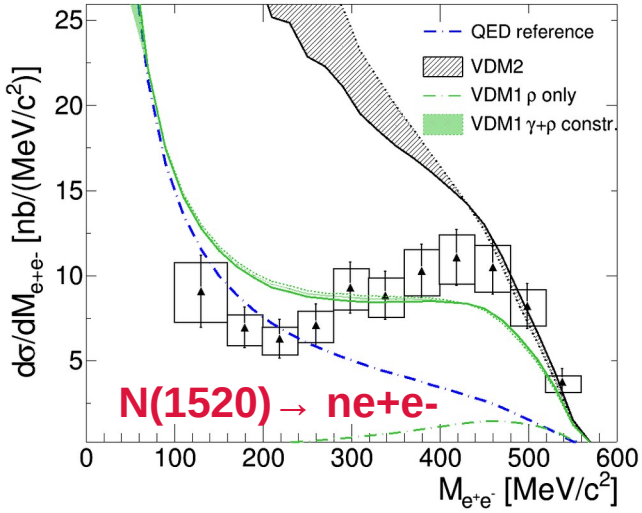
PWA: $M_{inv}(\pi^+\pi^-)$



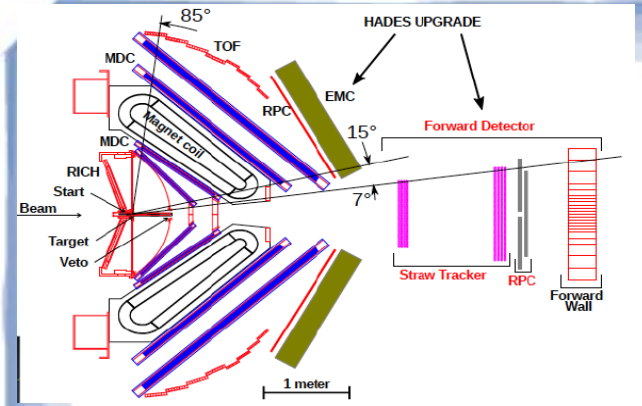
→ **D_{13} (N*(1520)) dominant conribution in ρ production**

→ **D_{13} (1520) coupling to ρN: 12+/-2 %**

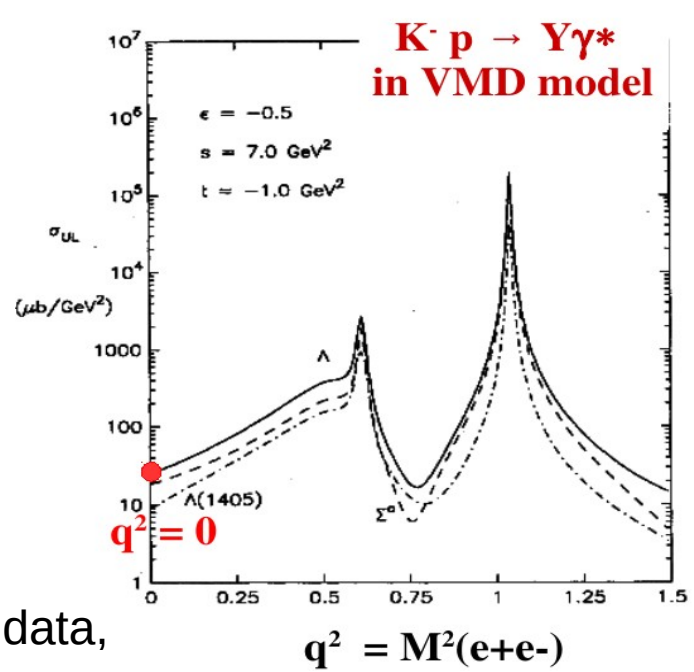




Experimental program pp @ 4.5 GeV



- studies hadronic hyperon decays (Λ, Σ),
- Dalitz decays of Λ(1520)→ L(1116) e+e- (study of **eTFF**),
- production of double strangeness (Ξ(1321), ΛΛ),
- hidden strangeness (φ),
- inclusive di-electron production as reference for p+A and HI data,
- **studies of light mesons production, decays and structure,**
- **important for dileptons,**



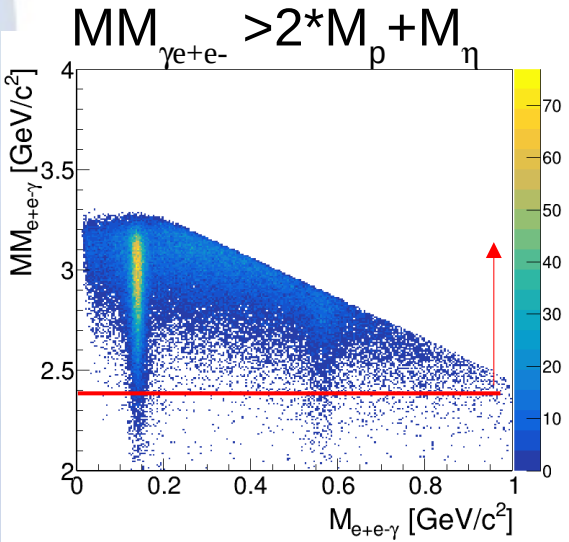
VMD: huge enhancement predicted
R. Williams et. al. PRC48, 1381 (1993)

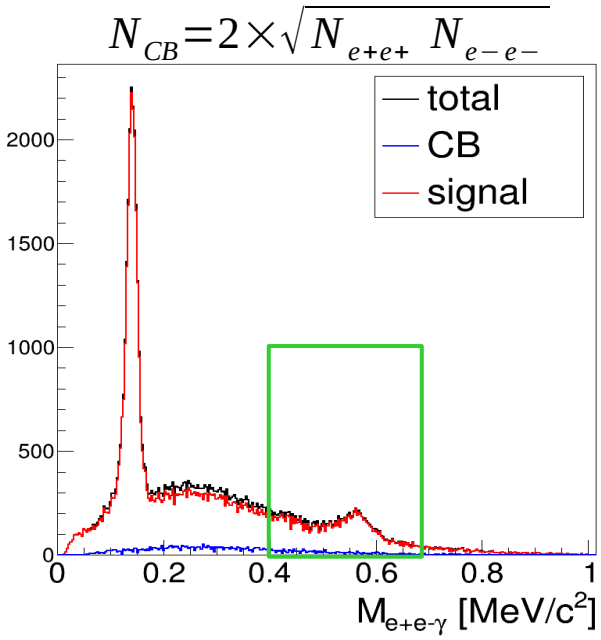
Motivations - mesons

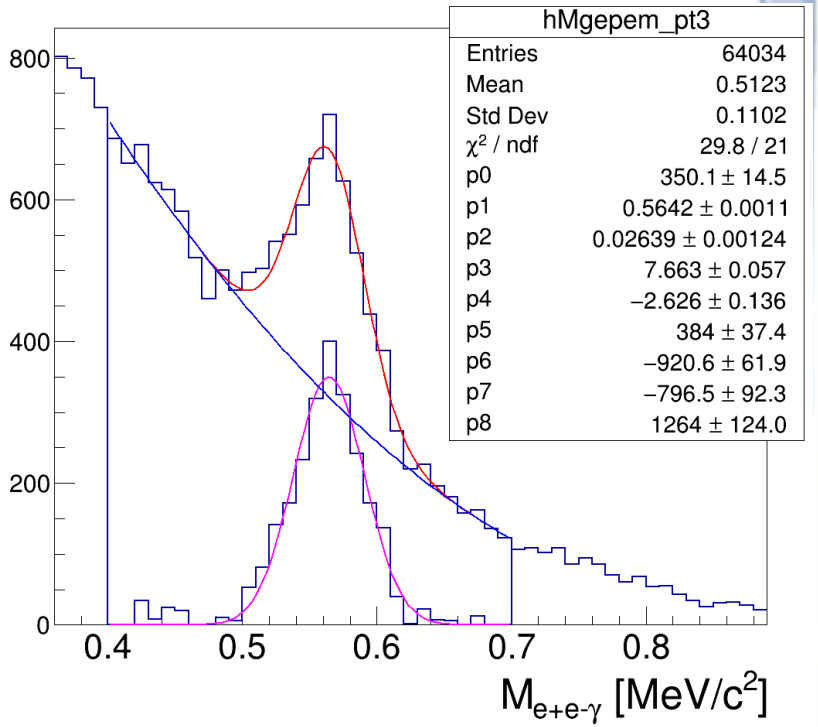
- inclusive and exclusive cross sections for $\pi^0/\eta/\omega/f_1(1285)$ at 4.5 GeV,
- production mechanism of $\eta/\omega/f_1(1285)$ at low energies:
  - → test of effective Lagrangian approach (A. Szczurek, P.Lebiedowicz IFJ PAN),
  - → $f_1(1285)$ - “exotic state”, can be produced in vector-vector fusion,
- η – important decay channel of N* e.g. $S_{11}(1535)$ have large ηN BR,
- study of the Dalitz plot parameters in $\eta/\omega \rightarrow \pi^+\pi^-\pi^0$ dacays,
- studies of η/ω form factors in $\eta \rightarrow \gamma e+e-$ / $\omega \rightarrow \pi^0 e+e-$,
- studies of CP violation in $\eta \rightarrow e^+e^-\pi^+\pi^-$ decay,
- neutral decay modes:
  - → $\pi^0 \rightarrow 2\gamma$, $\eta \rightarrow 2\gamma$, $\omega \rightarrow \pi^0\gamma$
  - → $\eta/\omega \rightarrow \pi^+\pi^-\pi^0(\gamma\gamma)$

$\eta \to \gamma$ e+e-

$pp \to \eta + X$ ($\eta \to \gamma$ e+e-) BR=$6.9*10^{-3}$







➔ Expected statistics: ~$2.2*10^4$ of $\eta \to \gamma$ e+e- decays.

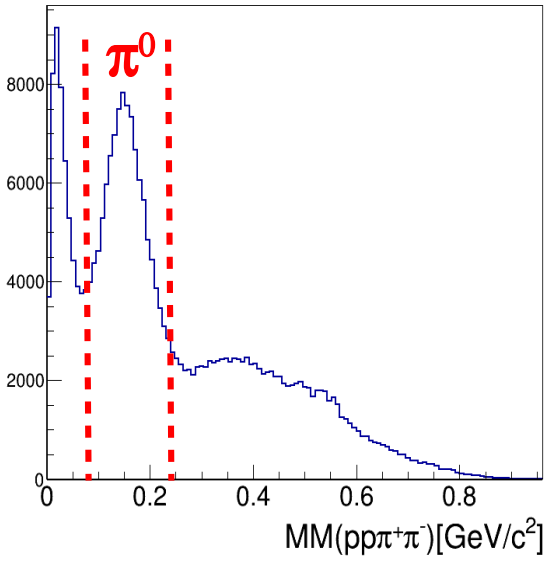
➔ Previous measurements:

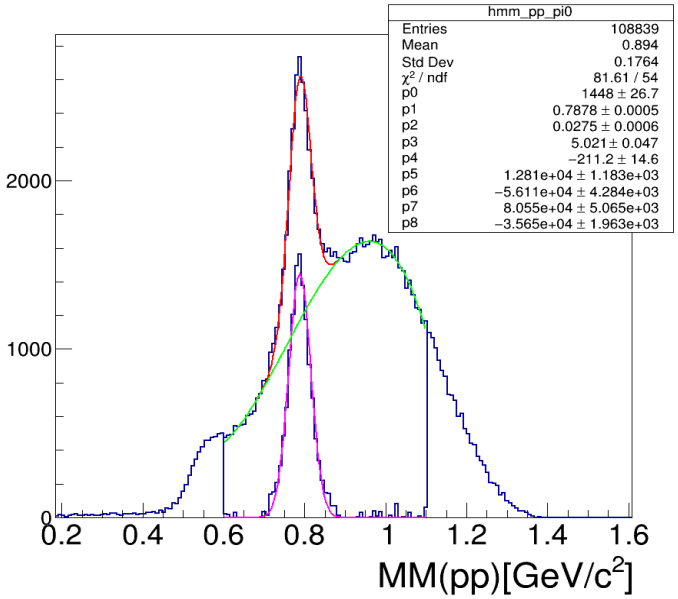
- Crystal Ball, Taps: 1350,
- WASA: $1.4*10^4$,
- A2@ MAMI: $5.4*10^4$.

➢ extraction of η form factor

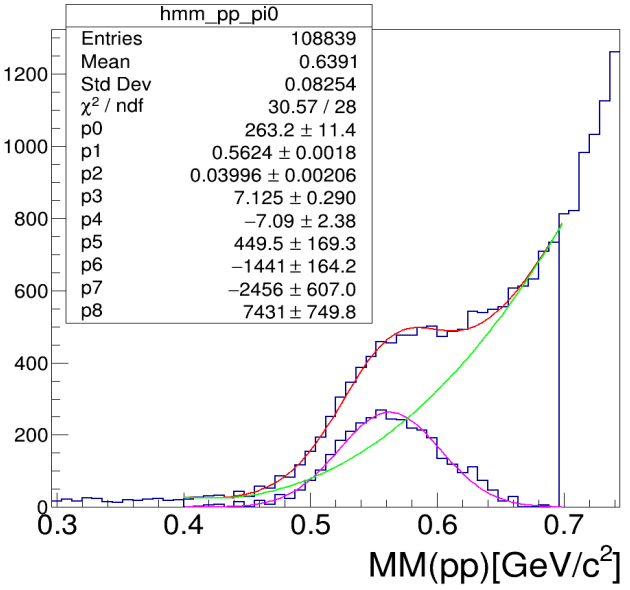
η/ω exclusive analysis

$pp \to pp\omega\,(\to \pi^+\,\pi^-\,\pi^0)$





$pp \to pp\eta\,(\to \pi^+\,\pi^-\,\pi^0)$



- expected statistics: ~3.5*10^6 of pp$\omega(\to\pi^0\pi^+\pi^-)$ and ~9.2*10^5 of pp$\eta(\to\pi^0\pi^+\pi^-)$,
- previous measurements:

  $\to\omega\to\pi^0\pi^+\pi^-$ WASA: 4.4*10^4, BESIII: 2.5*10^5

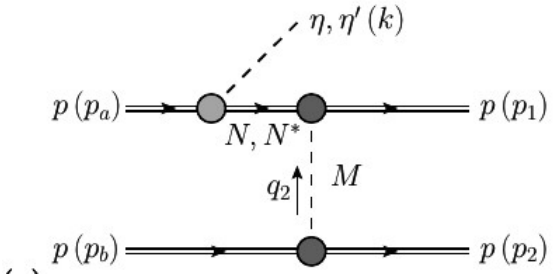
  $\to\eta\to\pi^0\pi^+\pi^-$ WASA: 1.2*10^7, KLOE: 4.7*10^6

- production mechanism and cross sections,
- Dalitz plot parameters (X,Y), (Z, Φ)

η production in pp@ 4.5 GeV

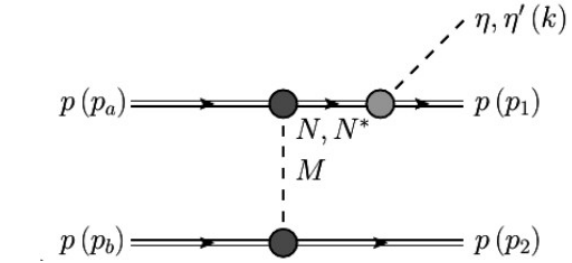
effective Lagrangian approach

(A. Szczurek, P. Lebiedowicz IFJ PAN)

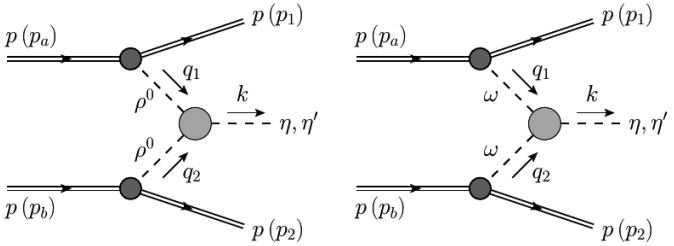


- intermediate nucleon and nucleon resonances
- M=π^0, σ, a_0, η, η', **ρ^0, ω**

$$F_{MNN}(q^2) = \frac{\Lambda^2_{MNN} - m^2_M}{\Lambda^2_{MNN} - q^2} \qquad F_M(q^2) = \frac{\Lambda^2_{MNN^*} - m^2_M}{\Lambda^2_{MNN^*} - q^2}$$



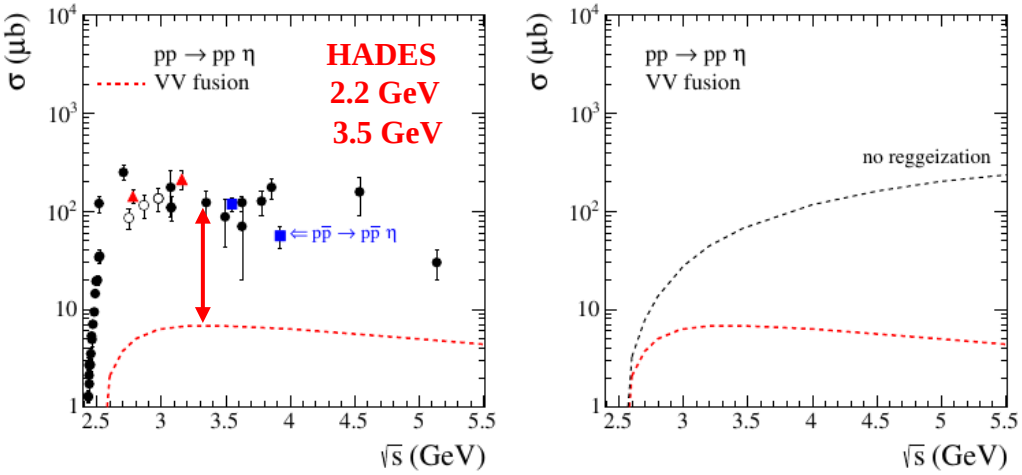
- bremsstrachlung (η emission from N, N*)
- VV(ρρ, ωω) fusion



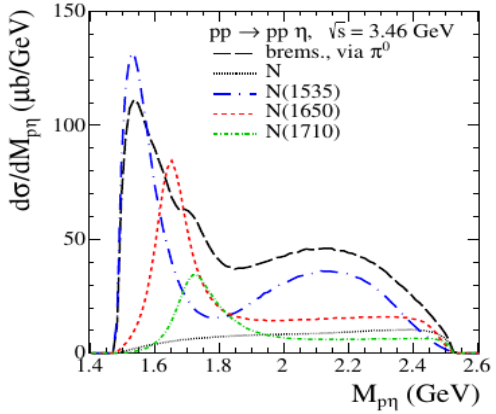
- reggeization
  (reggeon – coherent sum of mesons $1^- + 3^- + 5^- \ldots$ in Regge trajectory)

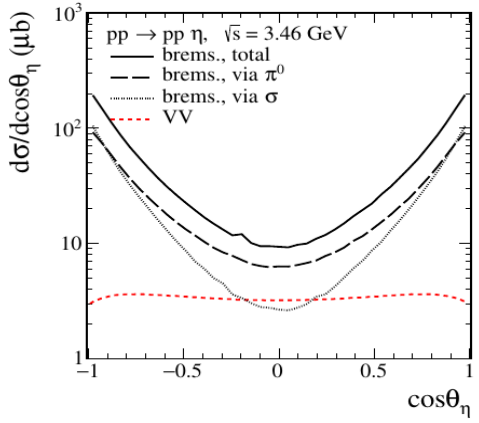
HADES/PANDA
small s – standard meson propagator
larger s – reggeon exchange

η production in pp @4.5 GeV



Preliminary calculations (P. Lebiedowicz)





- very large contributions from nucleon resonances
- reggeization is important far from the threshold

- pp data at 4.5 GeV important for the model tunning
  - → VV fusion
  - → role of reggeization (Regge theory, large s, small |t|, s>> |t|)

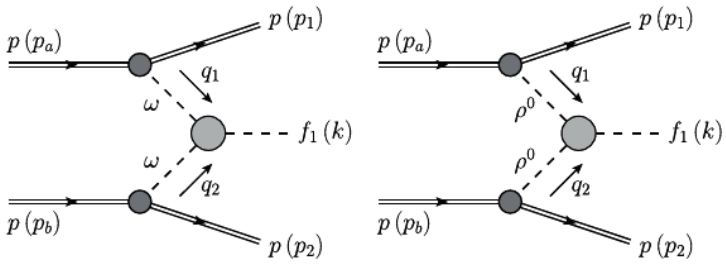
$f_1(1285)$ production in pp@ 4.5 GeV

A. Szczurek, PRD 102, 113015 (2020)
P. Lebiedowicz et al., PRD 104, 034031 (2021)

- production mechanism of $f_1(1285)$ - axial-vector meson ($J^{PC}=1^{++}$), $q\bar{q}$ or $\bar{K}K^*$?
- coupling to photons – important for calculations of magnetic moment of muon
- uncertain LbL contribution: $\gamma^*\gamma^* \to f_1(1285)$

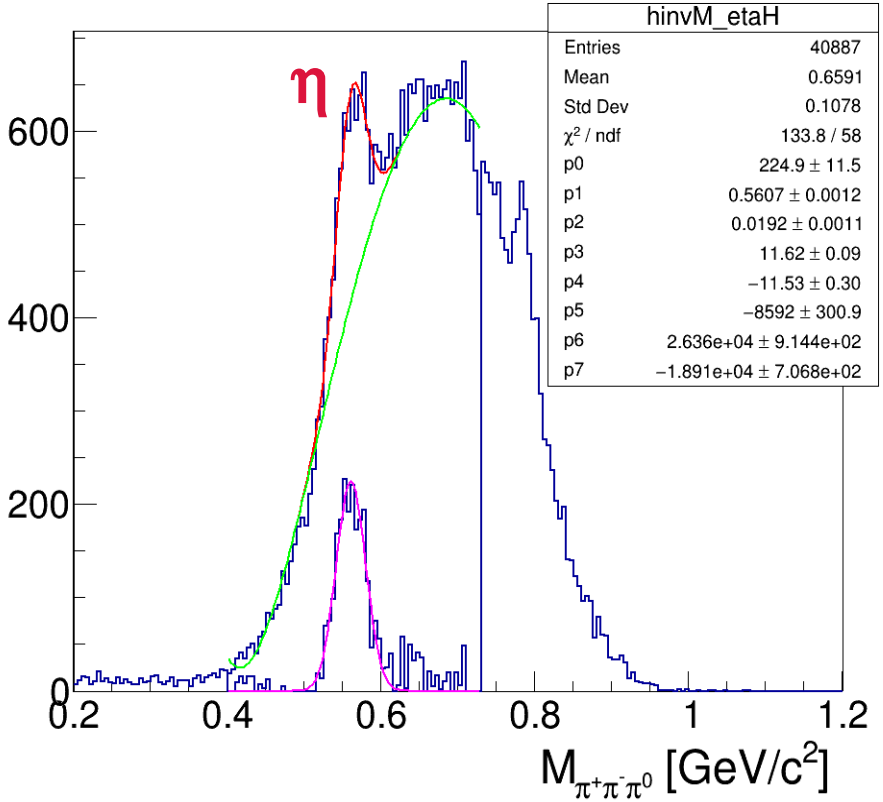
$$i\Gamma^{\gamma^*\gamma^*\to f_1}_{\mu\nu\alpha} = \left(\frac{e}{\gamma_\rho}\right)^2 F_{\rho\rho\to f_1}(t_1,t_2)\, i\Gamma^{\rho^0\rho^0\to f_1}_{\mu\nu\alpha} \frac{m_\rho^2}{m_\rho^2+Q_1^2}\frac{m_\rho^2}{m_\rho^2+Q_2^2} + \left(\frac{e}{\gamma_\omega}\right)^2 F_{\omega\omega\to f_1}(t_1,t_2)\, i\Gamma^{\omega\omega\to f_1}_{\mu\nu\alpha} \frac{m_\omega^2}{m_\omega^2+Q_1^2}\frac{m_\omega^2}{m_\omega^2+Q_2^2}$$

- production only via VV fusion (close to the threshold)
- constraint on $VV \to f_1$ vertex based on the HADES pp data
- $g_{\rho\rho f1} = g_{\omega\omega f1}$ constraint from $f_1 \to \gamma\rho^0 \to \gamma\pi^+\pi^-$ (VMD)
- f_1 cross sec. 150 nb (theory) in exclusive channel: $pp \to pp f_1 (\to \pi^+ \pi^- \eta (\to \pi^+ \pi^- \pi^0))$



$f_1(1285)$ production in pp@ 4.5 GeV

$pp \to pp f_1 (\to \pi^+ \pi^- \eta (\to \pi^+ \pi^- \pi^0))$

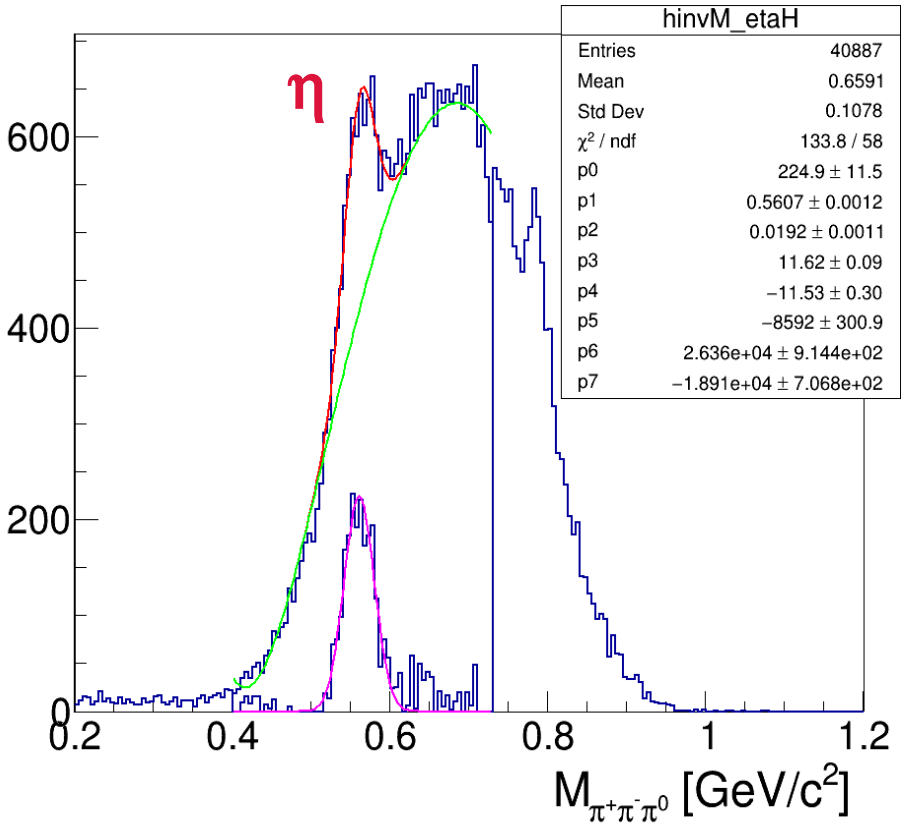


Contribution	Cross section (μb)
(1) $pp \to pp\pi^+\pi^-\pi^+\pi^-\pi^0$	88
(2) $pp \to pp\pi^+\pi^-\eta(\to \pi^+\pi^-\pi^0)$	0.18
(3) $pp \to pp\pi^+\pi^-\omega(\to \pi^+\pi^-\pi^0)$	0.07
(4) $pp \to pp f_1[\to \pi^+\pi^-\eta(\to \pi^+\pi^-\pi^0)]$	0.012

- ➔ (2), (4) – contribute to the η peak
- ➔ expected statistics: ~4*10^3

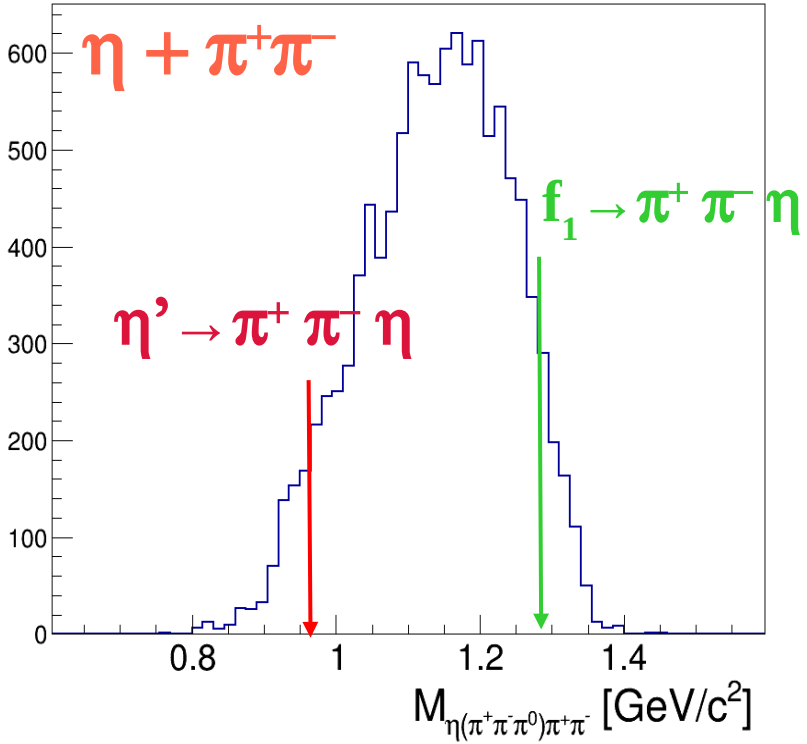
$f_1(1285)$ production in pp@ 4.5 GeV

$pp \to pp f_1 \ (\to \pi^+ \pi^- \eta \ (\to \pi^+ \pi^- \pi^0))$



so far f_1 signal not visible ….

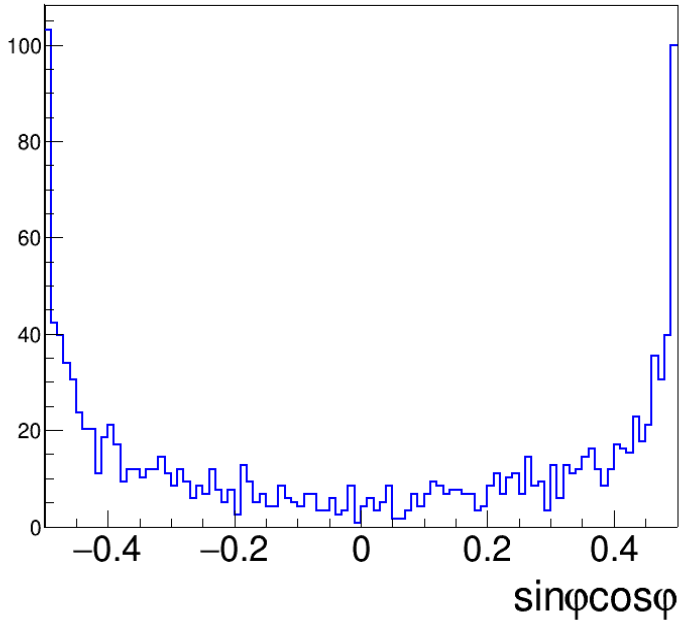
expected stat. ~500 f_1



➔ extraction of η' production cross section also possible

$\eta \rightarrow \pi^+\pi^- e^+e^-$

- rates estimations and bkg simulations,



N (η -> π^+ π^- e^+ e^-) = σ × BR × Ɛ × L = 1600 events

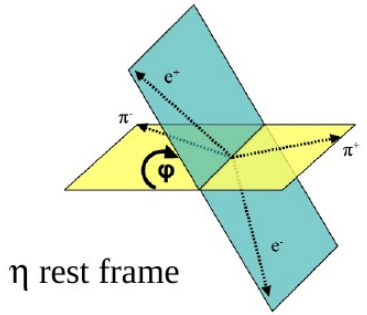
σ = 1.5 [mb] - inclusive (DISTO)

BR = 2.7 × 10^{-4} - WASA-at-COSY 2016

Ɛ = 0.08 % - based on the simulation

L = 5 [1/pb] - beam time estimation

➔ acceptance is quite large



η rest frame

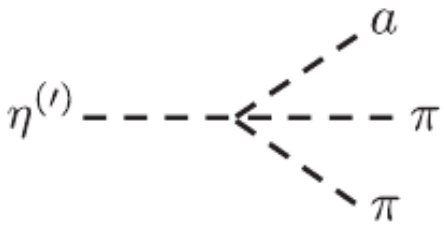
$$A_\phi = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$

$\eta \rightarrow \pi^+\pi^- X17\ (\rightarrow e^+e^-)$

First observation of X17: A. J. Krasznahorkay *et al.*
PRL 116, 042501 (2016)

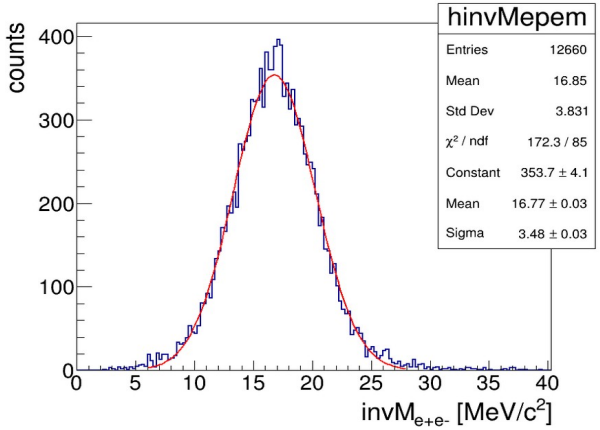
anomalies in the internal pair creation of isovector (17.6 MeV) and isoscalar (18.15 MeV) M1 transitions in ^{8}Be (^{4}He, ^{12}C).

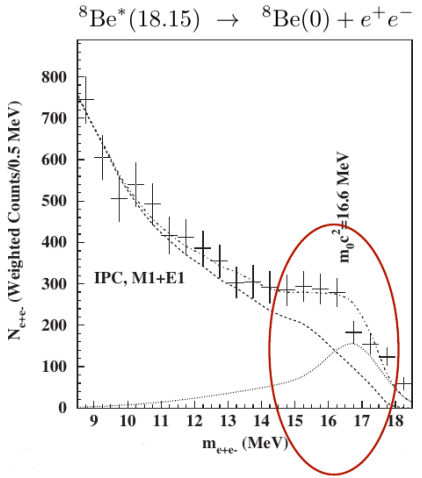
D. S. M. Alves,
Signals of the QCD axion with mass of 17 MeV/c^2 : Nuclear transitions and light meson decays,
Phys. Rev. D 103, 055018 (2021).

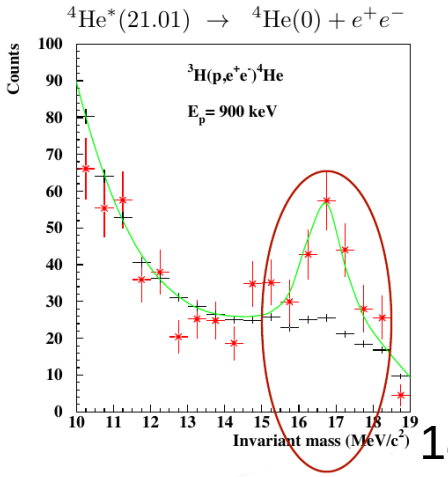


BR($\eta \rightarrow \pi\pi a$)~ 10^{-4} - 10^{-2}

Pluto and full reconstruction chain,
reconstruction efficiency:
0.5% => 202 events







SUMMARY

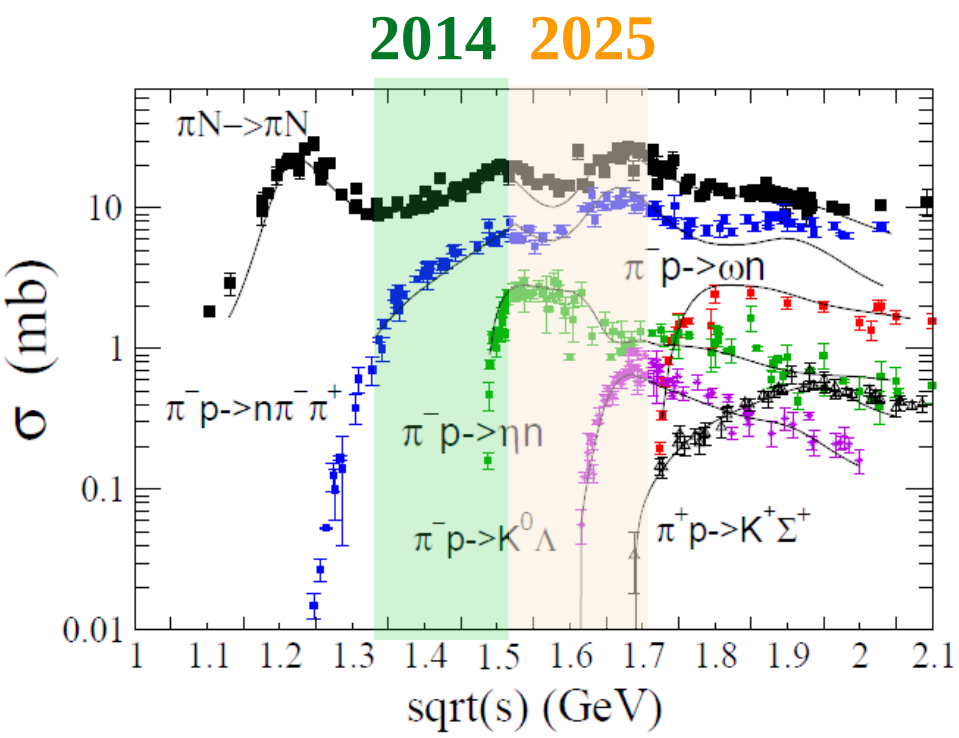
- **Very interesting physics program with mesons:**
  - studies of production mechanisms of $f_1(1285)$, η, ω and the role of VV fusion,
  - inclusive and exclusive cross sections for π^0, η and ω,
  - η/ω form factors,
  - CP violation with $\eta \rightarrow \pi^+\pi^- e^+e^-$,
  - X17 – upper limit (?),
  - study of the Dalitz plot parameters in $\eta/\omega \rightarrow \pi^+\pi^-\pi^0$ dacays.

THANK U

FOR

YOUR ATTENTION

HADES Physics Program with Pion Beams
explore the 3rd resonance region $\sqrt{s} = 1.7$ GeV

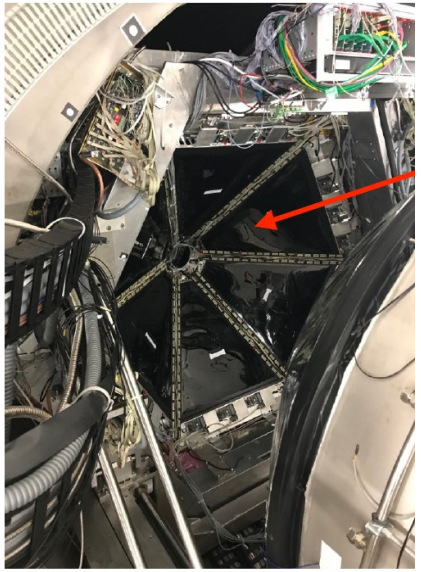


High statistics beam energy scan: continuation and extension to 3rd resonance region

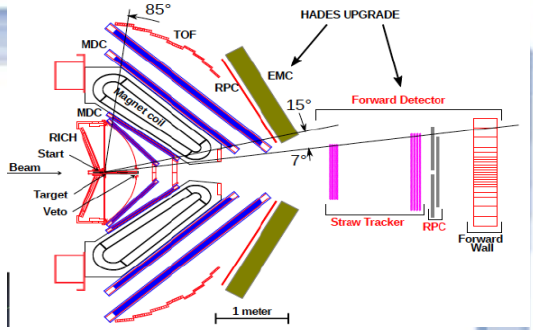
1) **Baryon-meson couplings:**
   - → ππN, ωn, ηn, $K^0\Lambda$, $K^0\Sigma$, …
     including neutral mesons (ECAL),
   - → ρR couplings S31(1620), D33(1700), P13(1720),..
2) **Time-like em. baryon transitions**
   - → π^-p → ne+e-,
   - → test of VMD for ρ and ω,
   - → spin-density matrix elements,
3) **Cold nuclear matter studies:**
   - → ω absorption
   - → ρ spectral function
   - → strangeness production

HADES Spectrometer UPGRADE

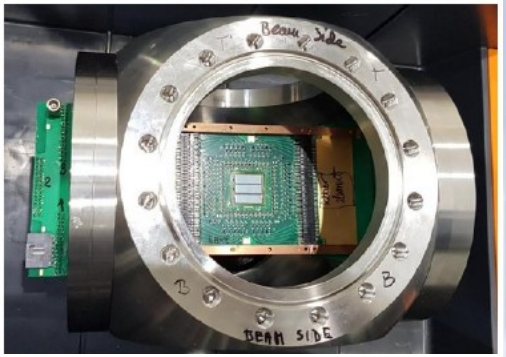
HODO, fRPC, STS2, STS1



innerTOF
(fast trigger)



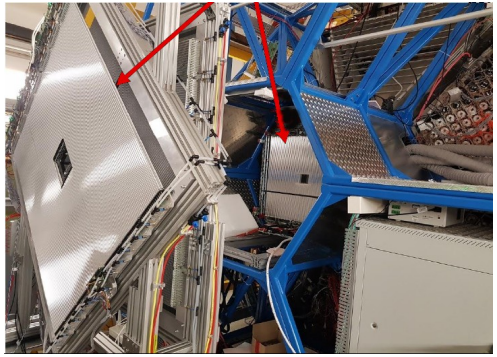
START T0 detector



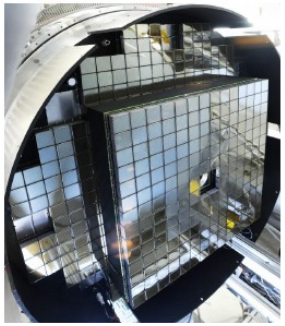
- timing < 100 ps
- PCB in the beam vacuum
- rate capability 10^8 p/s
- 2 cm x 2 cm, 96 channels
- pitch 387 µm

ECAL (lead glass)

STS2 STS1



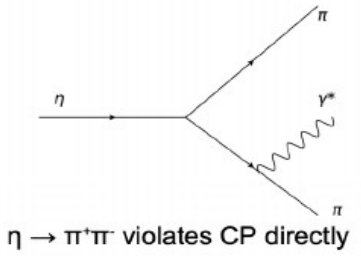
new RICH



MWPC → MAPMT

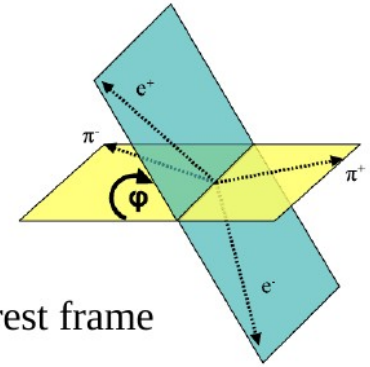
CP violation in $\eta \to \pi^+\pi^- e^+e^-$

- CP violation have been observed in:
  - → K_L leptonic decays (KTeV and NA48)
  - → B mesons decays (Belle and BaBar)
  - → flavour-conserving reactions: KLOE (1555 events), WASA-at-COSY (251)



$\eta \to \pi^+\pi^-$ violates CP directly

CP violation source:
interference between electric and magnetic amplitudes responsible for significant linear polarization of the photon in the $\eta \to \pi^+\pi^-\gamma^*$



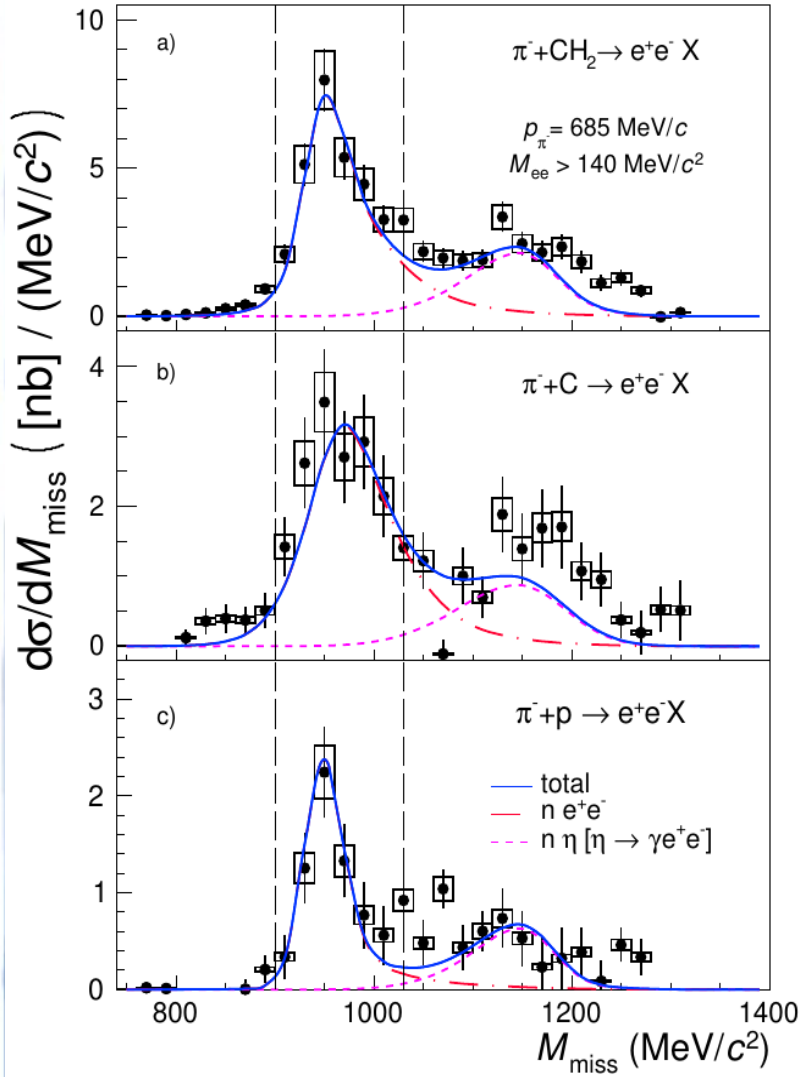
η rest frame

polarization can be studied via asymmetry:

$$A_\phi = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$

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

HADES coll. arXiv:2205.15914 [nucl-ex]



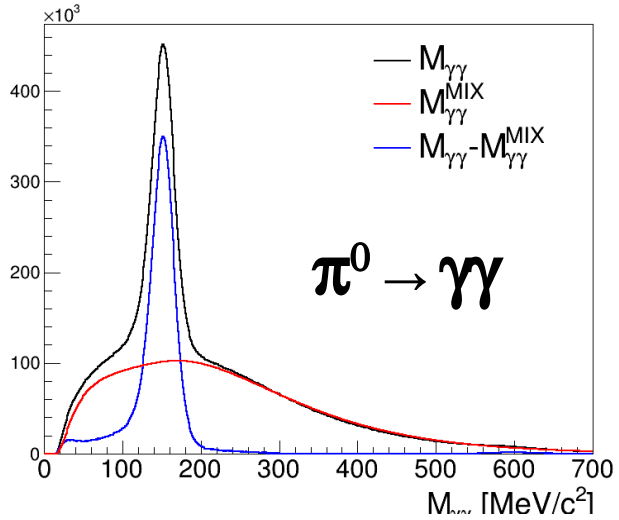
- cut on **invMe$^+$e$^-$** >140 MeV (above π^0 mass)
- missing mass cut on $\mathbf{M_{miss}}$ (η removed)

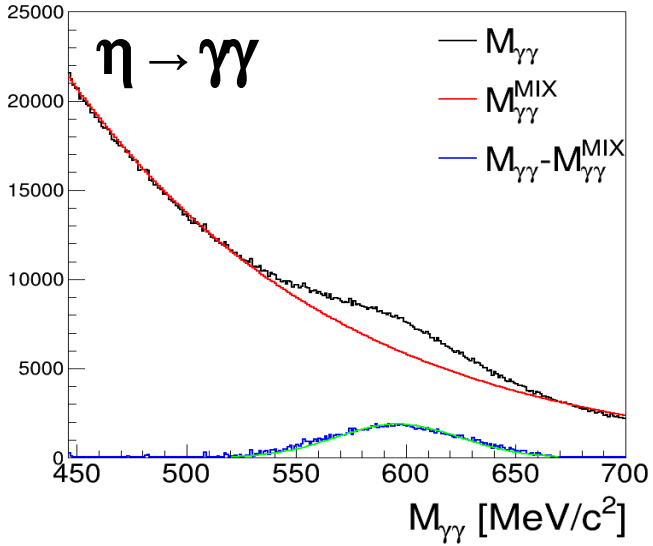
- **π^-C** simulations using Pluto (qfs participant-spectator model)
- production cross sec. on C for: π^0, η, ρ, γ deduced from the scaling: $R_{C/H} = \sigma_C / \sigma_H$

- **CH_2** target:

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

Inclusive production





Event mixing normalized to the tail above 200 MeV

ALL γγ combinations

MIX CB

signal=ALL - CB