Measurement of the π^0 Transition Form Factor via the Primakoff Effect at MAMI

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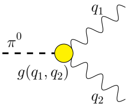
Content

- Introduction to the π^0 TFF
- Measurement with single pion electroproduction
- The planned experiment at MAMI
- Status of preparation

Introduction

Interesting parameter:

- $\pi^0\gamma\gamma$ effective coupling

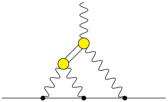


$$= F_{\pi^0\gamma^*\gamma^*}\left(q_1^2, q_2^2\right)$$

- in this talk $q_1, q_2 < 0$: space-like regime
- double virtuality

Motivation:

- hadronic correction to $g-2$ of the muon (light by light scattering)



Data on π^0 TFF

Time-like

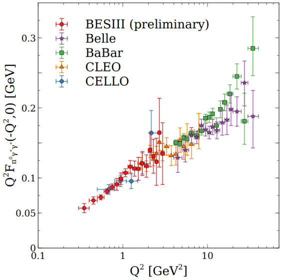
- from Dalitz decay
- precise data from A2@MAMI and NA62
- down to very low (single) virtuality

Space-like

- from e^+e^- colliders
- all measurements singularly virtual
- older data from CLEO and CELLO down to 0.6 GeV^2
- newer data from BABAR and Belle down to 4.0 GeV^2
- preliminary precise data from BESIII down to 0.3 GeV^2
- planned measured from KLOE-2 down to 0.01 GeV^2

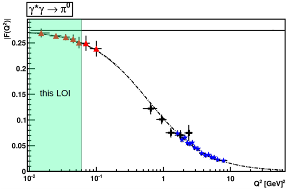
Preliminary BESIII data:

Phys. Rept. 887 (2020) 1-166



Foreseen KLOE-2 data:

arXiv:1311.2198 [hep-ph]



Primakoff π^0 Electroproduction

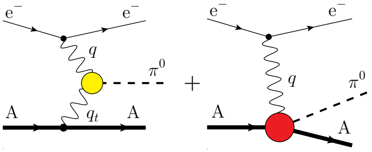
- coherent π^0 electroproduction on nuclei

$$e^- + A(Z,N) \to e^- + \pi^0 + A(Z,N)$$

- Primakoff contribution sensitive to TFF
- suppressed by $\alpha_{\text{e.m.}}$
- but enhanced at low t by $t^{-1} = 1/q_t^2$
- t is finite $\Rightarrow$ double virtuality
- proportional to Z^2 $\Rightarrow$ high Z needed (we consider $^{181}_{73}$Ta as target)
- strong interference $\Rightarrow$ hadronic production to be calculated for our kinematics

  G. Faeldt, Nucl. Phys. B 43 (1972) 591

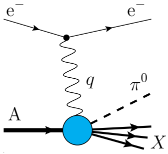
  S. Gevorkyan et al., Phys. Rev. C80 (2009) 055201



- model dependence to be estimated
- partially separable background: incoherent π^0 production

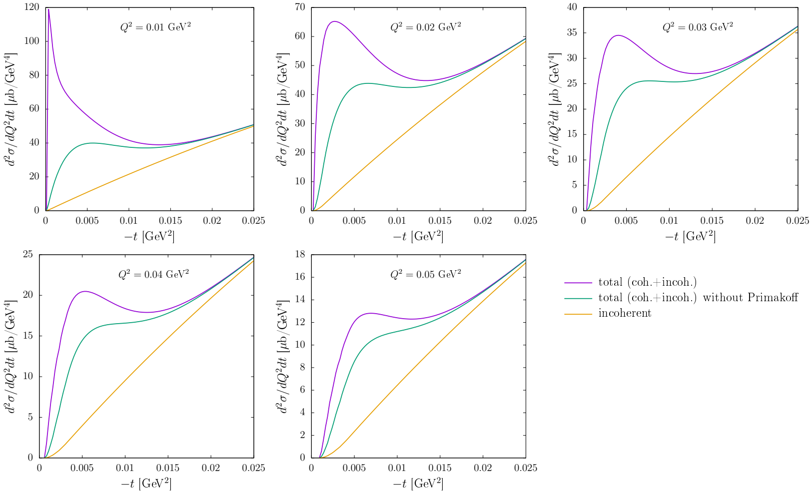
$$e^- + A(Z,N) \to e^- + \pi^0 + X$$

S. Gevorkyan et al., Phys. Part. Nucl. Lett. 9 (2012) 18



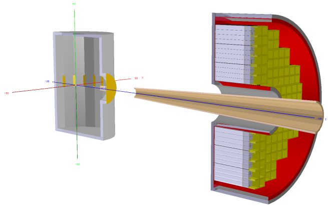
Cross Section Estimation

M. Gorshteyn and L.C.

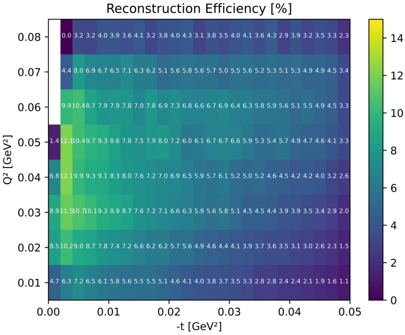


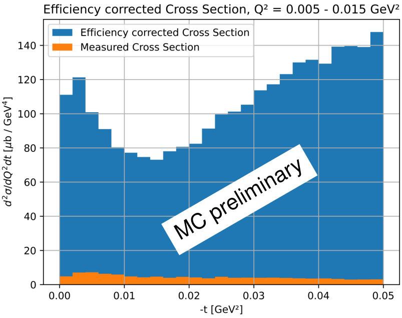
- beam energy: 1.5 GeV
- ^{181}Ta target
- electron scattering angle: 6° to 17°

Simulation Studies



- GEANT4 simulation with detailed geometry
- relevant geometry included
- π^0 acceptance studies
- radiation studies
- physics event generator





J. Moik, Master Thesis

Experiment Requirements

- need to detect both e$^-$ and π^0 in coincidence (exclusive reaction)
- $\pi^0 \Rightarrow$ electromagnetic calorimeter (EMC) to detect pion decay γs
- need to measure at small t

momentum transfer from the electron

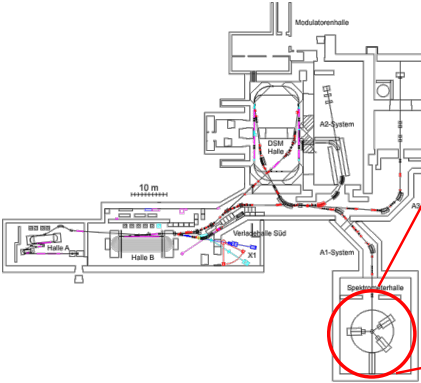
$$-t = 2\nu^2 + Q^2 - m_\pi^2 - 2\sqrt{\nu^2 + Q^2}\sqrt{\nu^2 - m_\pi^2}\cos\theta_{\pi q}$$

pion energy

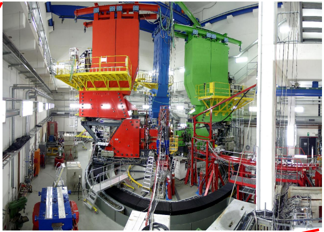
angle btw. pion and mom. transfer

- high pion energy and small $\theta_{\pi q} \Rightarrow$ EMC at forward angle
- small $Q^2 \Rightarrow$ small electron scattering angle $\Rightarrow$ e$^-$ also in the EMC acceptance
- needed t resolution $\sim 10^{-4}$ GeV^2
  $\Rightarrow$ energy resolution $\sim$ some %
  $\Rightarrow \theta_{\pi q}$ angle resolution $\sim 0.4^\circ \Rightarrow$ position resolution ~ 4 mm

The MAMI electron scattering facility



A1 spectrometer facility

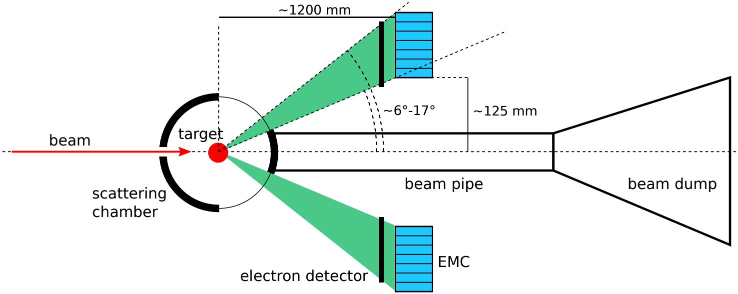


- CW electron beam
- intensity up to 100 μA
  here: 100 nA needed
- beam energies up to 1.5 GeV

- 3 high-resolution magnetic spectrometers
  $\delta p/p \simeq 10^{-4}$, $\delta\theta < 3$ mrad
  $\rightarrow$ useful for alignment! ✓
- wide angular range (but $\theta_e \geq 15°$)
- limited acceptance
- only charged particles

} need for an EMC!

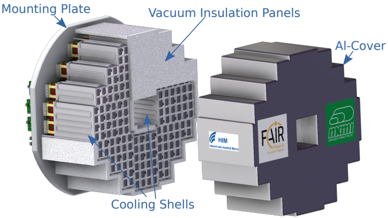
Planned Setup at A1

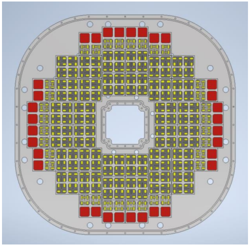


- ring-shaped EMC around the exit beam pipe
- distance to target $\sim$1.2 m
- plastic scintillator for separating e^- and γs (or a tracker? $\Rightarrow$ under study)
- magnetic spectrometer for dedicated alignment measurements

PWO Calorimeter

- PANDA backward calorimeter
  (FAIR phase 0)
- substantial adaptation for this experiment
- inner/outer diameter: 25 cm/75 cm
- 640 $PbWO_4$ crystals
- 48 modules:
  – 32 à 4×4 crystals
  – 16 à 4×2 crystals

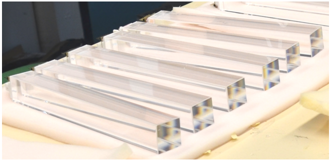


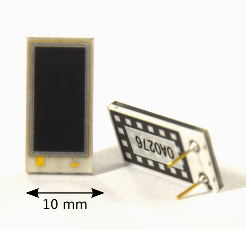


Basic calorimeter components

Active material

- PWO-II lead tungstate ($PbWO_4$)
- Similar to CMS, material improved
- Cooling to -25°C: $4\times$light yield
- Straight crystals: $200\times24\times24$ mm^3

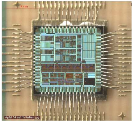




Photosensors

- Large-Area Avalanche Photodiodes (APD) from Hamamatsu
- QE @ 420 nm $\sim$ 70%
- Active area: 7×14 mm^2
- $2\times$APD / crystal

APFEL ASIC

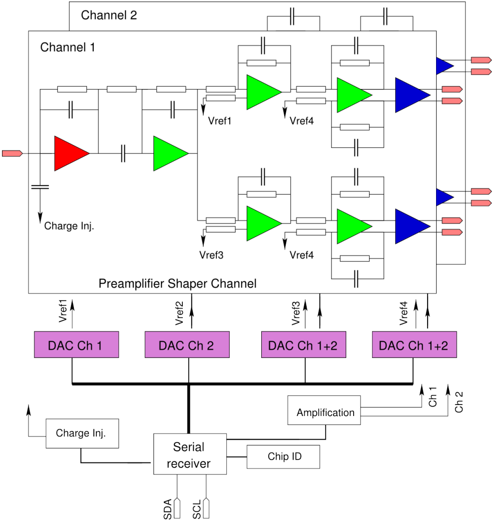


6.5 mm

- reads out 2 APDs
- charge sensitive preamplifier
- shaper (pulse width $\sim \mu$s, rise time $\sim$120 ns)
- 2 main amplifiers (2 gains, dynamic range $\sim$10000)
- 4 differential output channels

200 mm

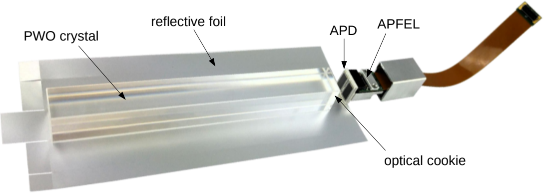
- power and programming lines
- HV lines for the APDs
- output signal lines

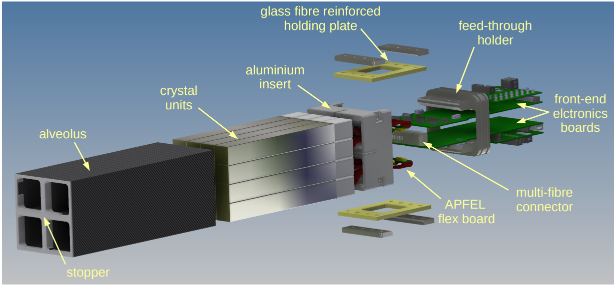


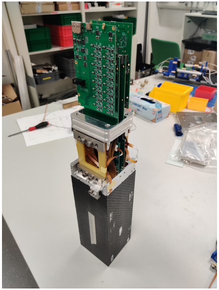
P. Wieczorek, H. Flemming, IEEE Nucl.Sci.Symp.Conf.Rec. 2010, 1319-1322

Calorimeter Module

Crystal unit:



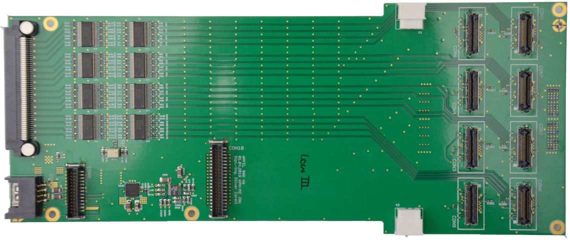




Front-end boards

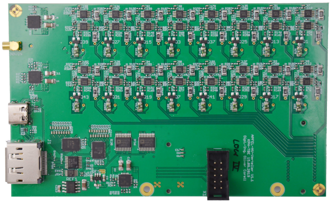
Line driver board

- feed-through (warm/cold)
- 8 APFEL (crystals)
- 32 diff. amplifiers (10 m cables)
- 2 Pt100 sensors

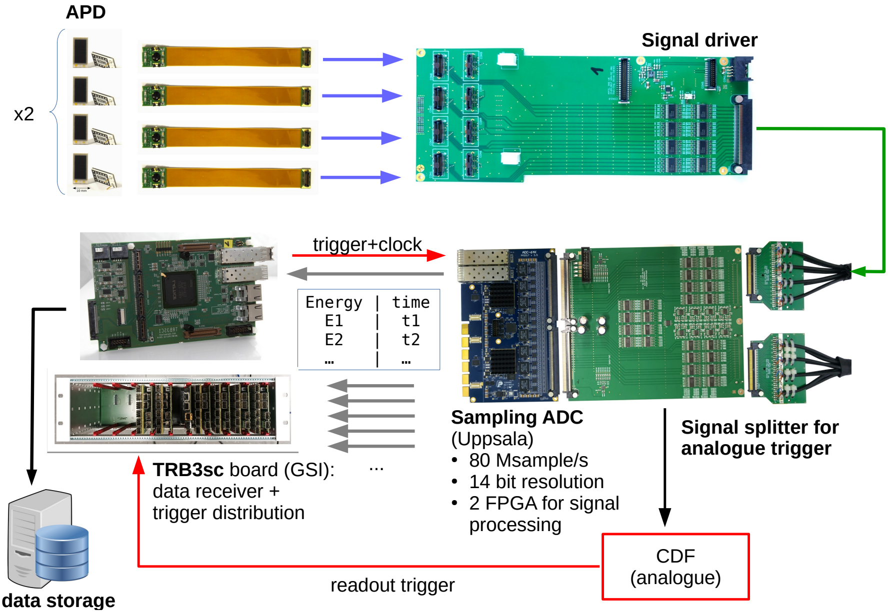


Service board

- HV distribution and controller
  - 16 singularly adjustable bias voltages
  - 16 PID regulation circuits
- Communication interface for APFEL and HV (serial protocols)

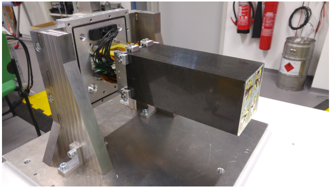


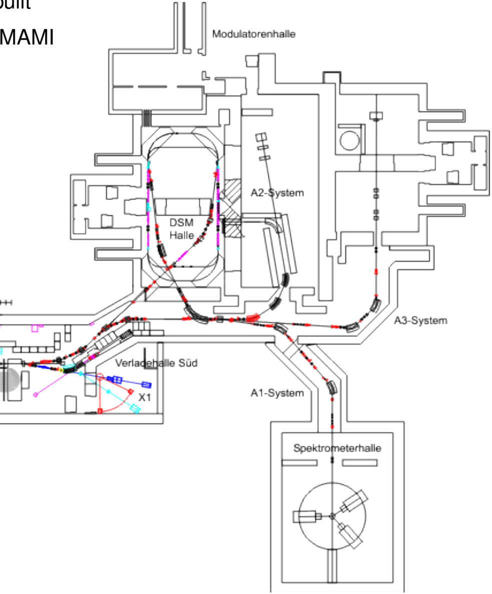
Readout Chain and DAQ



Prototype Beam Tests

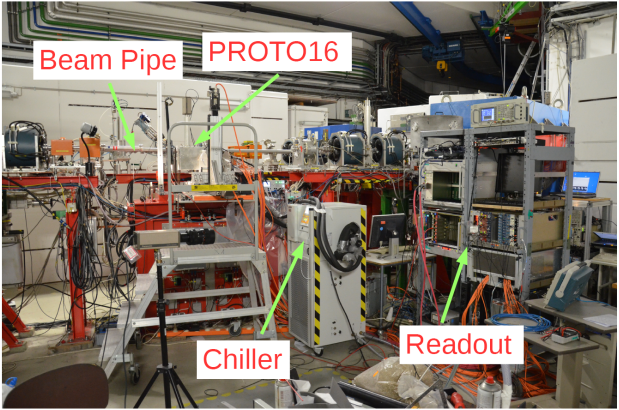
- two prototypes with 4×4 crystals built
- tested several times with beam at MAMI

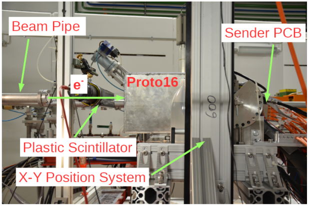


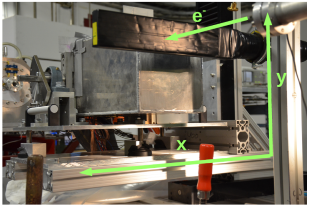


Beam tests at MAMI

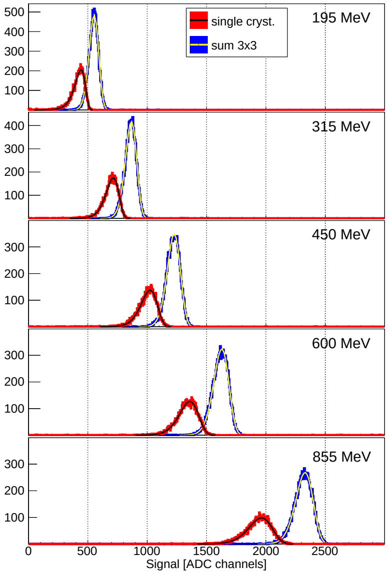
- XY-table for centering each crystal on beam
- Plastic scintillator for coincidence event triggering

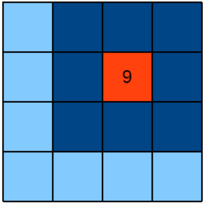


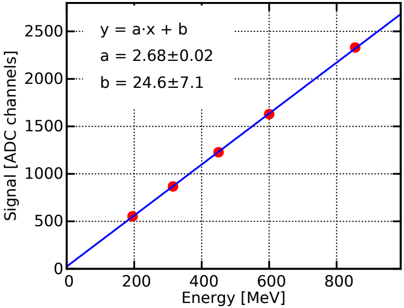




Detector response

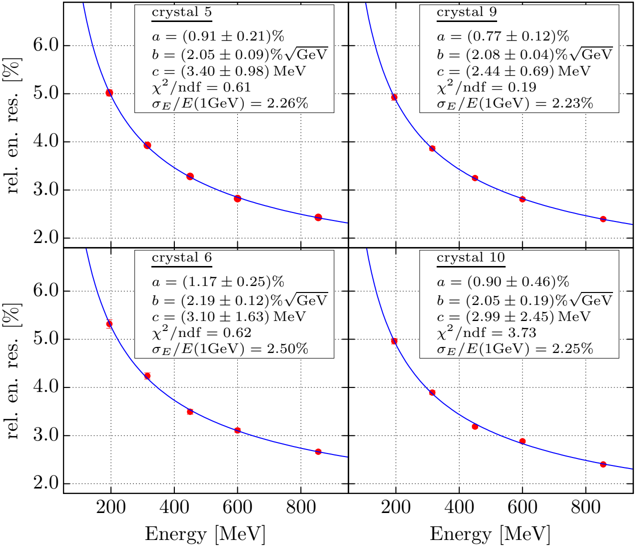




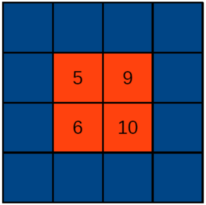


Energy resolution

Only low gain:



$$\frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E/\mathrm{GeV}}} \oplus \frac{c}{E}$$



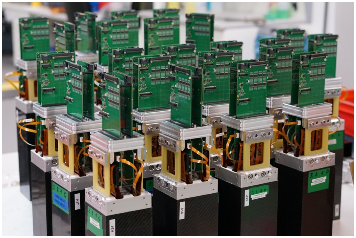
Status Detector Construction

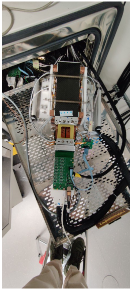
Submodule Series Production

- 4×4 submodules
  32/32 units assembled and pretested
- 4×2 submodules
  14/16 being assembled and pretested

- Pretests
  at room temperature
  before and after stopper gluing
  check of all contacts
  test of main functionalities

- Full tests and calibrations
  inside a climate chamber (−25°C)
  3 submodules at the same time
  Pt100 calibration (in-situ)
  HV scans
  noise characterisation
  cosmic measurements

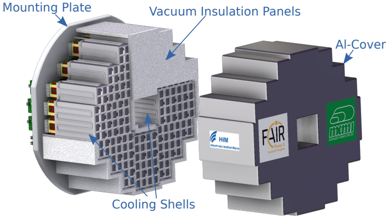


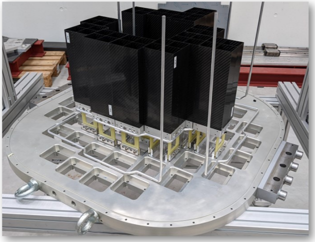


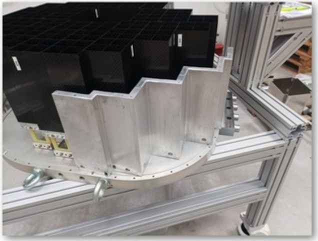
Status Detector Construction

Full Detector

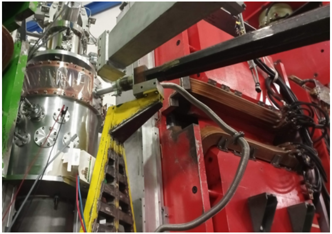
- Almost all components available







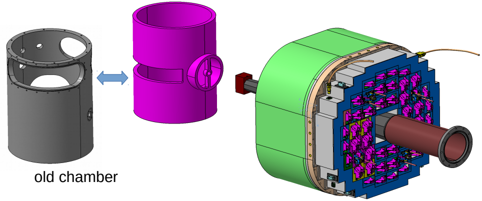
Hall Integration



Design work ongoing

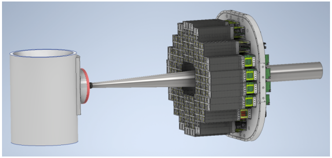
- new target chamber with φ-symmetric window needed
- current beam pipe very close to detector surface
- made of steel for beam magnetic shielding
  $\Rightarrow$ higher radiation in the EMC
- can be smaller and in aluminium for this experiment
- supporting platform for the detector

new scattering chamber

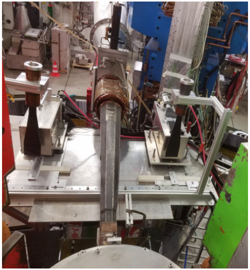


old chamber

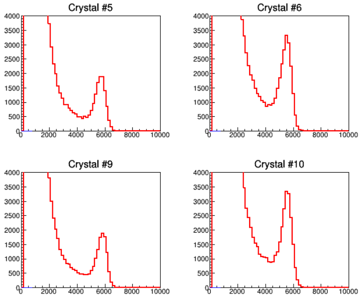
detector around beam pipe

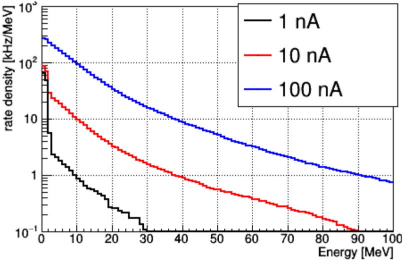


Beam Tests at A1



- since 2018: 3 beam tests
- beam energy: 1.5 GeV and 855 MeV
- beam current up to 200 nA
- targets: C, Ta (Z=73), polyethylene
- using 1 and 2 prototypes (4×4 crystals)
- measurement of energy spectra
- determination of total rate at small angles
  ⇒ luminosity of at least 5.5 $\mu b^{-1} s^{-1}$ feasible!





Reconstructed π^0 Events

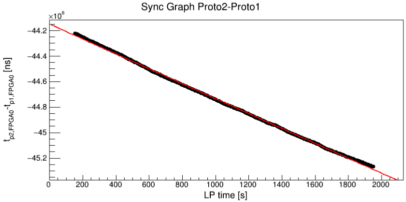
Coincidence measurement with two prototypes

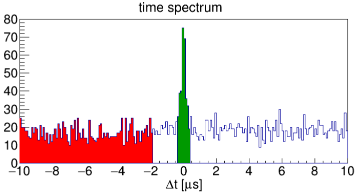
- 2 prototypes: 2 different **SADC boards**
- clocked by **different** oscillators
- time stamps **drift** apart

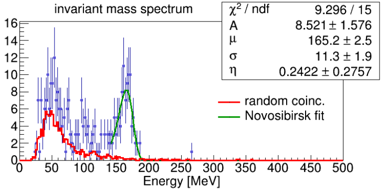
$\Rightarrow$ need for synchronisation!

Synchronisation by LED pulser

- light pulses sent periodically to all crystals simultaneously
  (typically every 5 s)
- events can be easily distinguished:
  very high pulses on every channel at the "same" time
- linear interpolation between pulser event times







- Ta target, about 1 h of data taking
- prototype angles 14° and 18° (combined)
- coinc. time window: ±300 ns
  $\Rightarrow$ about **100 π^0 events**
- energy calibration needs improvement
- good resolution

Summary

- Measurement of π^0 TFF via Primakoff electroproduction planned at MAMI
- Use of the PANDA backward EMC at A1 (FAIR phase 0)
- Detector RD finished: extensive prototype tests
- Detector construction ongoing
- Monte Carlo studies ongoing
- Assessment of systematics (e.g. model dependence): to be done

Possible Time Plan

- Finishing calorimeter construction: 2023
- Repeat test with 2 prototypes: Fall 2023
- Hall integration: winter break 2023/24
- Commissioning: Spring 2024
- Pilot run ($\sim$100h): 2024
  (depending on MAMI operation/availability)
- Full run: 2024/2025

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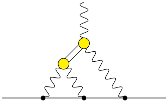
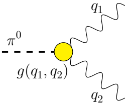
Thank you!

Backup

π^0 Transition Form Factor

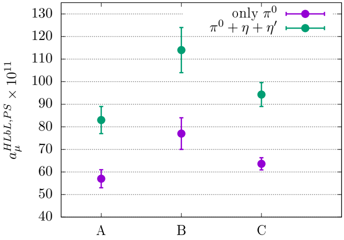
Dispersion theory $\Rightarrow$  $\Rightarrow$ HLbL related to $\gamma^*\gamma^* \to$ hadrons

Connection to 

$= F_{\pi^0\gamma^*\gamma^*}\left(-Q_1^2, -Q_2^2\right)$ through $(\mathrm{PS} = \pi^0, \eta, \eta')$:

$$a_\mu^{HLbL,\,PS} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^{1} d\tau\; w(Q_1, Q_2, \tau) F_{\mathrm{PS}\gamma^*\gamma^*}(-Q_1^2, -(Q_1+Q_2)^2) F_{\mathrm{PS}\gamma^*\gamma^*}(-Q_2^2, 0),$$

Model dependence:



A) Phys. Rev. D 57 (1998) 465
B) Phys. Rev. D 70 (2004) 113006
C) Phys. Rev. D 95 (2017) 054026

Cross Section Model

Primakoff amplitude

$$T_{\text{Prim}} \sim \frac{Z\, e^3}{t} \, F_{\text{Ch}}(t) \, F_{\pi^0\gamma^*\gamma^*}(-Q^2, t) \, f(q, k_\pi)$$

Strong amplitude (ω dominance, no ρ)

$$T_{\text{St}}^{\text{VMD}} \sim \frac{e}{t - m_\omega^2} \, F_{\text{St}}(t) \, F_{\pi^0\omega\gamma^*}(-Q^2, t) \, f(q, k_\pi)$$

Assumptions:

- $|t| \ll m_\omega^2$
- nuclear density $\sim$ charge density
- ω interacts with surface nucleons $A \to A^{2/3}$
- VMD applies to $F_{\pi^0\gamma^*\gamma^*}$ too
- γ-ω coupling $g_\omega = 17.1$ from $\omega \to \mathrm{e}^+\mathrm{e}^-$ decay

$$\Rightarrow \quad \left| \frac{T_{\text{St}}^{\text{VMD}}}{T_{\text{Prim}}} \right| \sim \frac{A^{2/3}}{Z} \frac{g_\omega^2}{16\pi\alpha} \frac{|t|}{m_\omega^2}$$

Coherent production cross section

$$\frac{d\sigma}{d\Omega_\pi} \approx \frac{d\sigma^{\text{Primakoff}}}{d\Omega_\pi} \left| 1 + e^{i\phi} \frac{A^{2/3}}{Z} \frac{g_\omega^2}{16\pi\alpha} \frac{|t|}{m_\omega^2} \right|^2$$

$(\phi = 0.88)$

Incoherent production cross section

$$\frac{d\sigma}{d\Omega_\pi} \approx \frac{d\sigma^{\text{Primakoff}}}{d\Omega_\pi} \frac{A_{\text{eff}}}{Z^2} \left| \frac{g_\omega^2}{16\pi\alpha} \frac{t}{m_\omega^2} \frac{G_E^p(t)}{F_{Ch}(t)} \right|^2$$

$(A_{\text{eff}} = 0.6\, A)$