A FAIR Phase-0 experiment to determine the π^0 electromagnetic transition form factor at MAMI

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Helmholtz Institute Mainz

–10th workshop of the APS Topical Group on Hadronic Physics–
Minneapolis, Minnesota
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Bundesministerium für Bildung und Forschung

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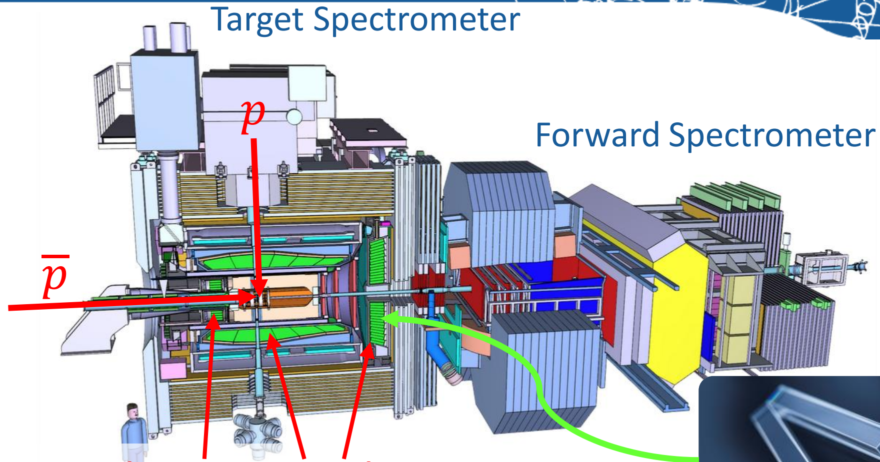
Outline

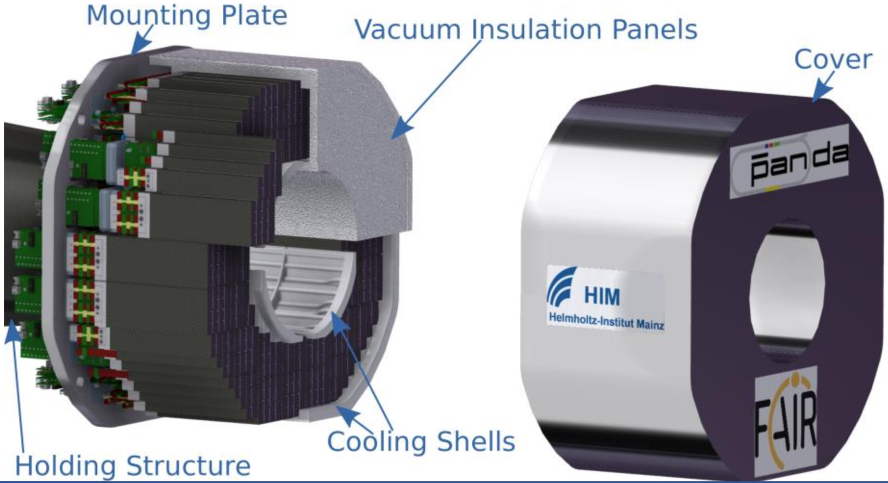
1. The FAIR Phase-0 Experiment at MAMI
2. Realisation of the Experiment
3. Test Measurements and Simulations
4. Ongoing Preparations
5. Summary and Time Plan

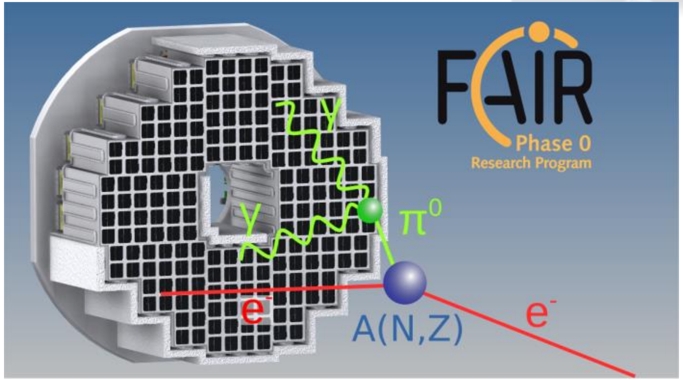
FAIR, PANDA and FAIR Phase-0

- Facility for Antiproton and Ion Research (FAIR)
- **antiProton ANnihilation at DArmstadt (PANDA)**
  - **1.5 GeV/c – 15 GeV/c** $(\Delta p/p \sim 10^{-4})$
  - Fixed target experiment
  - $\mathbf{2 \cdot 10^7}$ $\bar{p}p$ annihilations/second
  - Excellent particle identification
  - Radiation tolerance of the materials



Electromagnetic Calorimeter:
Measurement of $\boldsymbol{e^-}$, $\boldsymbol{e^+}$ and $\boldsymbol{\gamma}$ properties





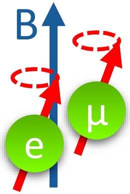
A FAIR Phase-0 Experiment at the Mainz Microtron – In a Nutshell

The $g_\mu - 2$-Puzzle

$g = \frac{\mu_S}{\mu_L} = \mathbf{2}$, point-like spin-$\frac{1}{2}$ particles (Dirac-Theory)

$a_l = \frac{g_l - 2}{2} = \mathbf{0}$, anomalous magnetic moment

Radiative corrections → $a_l \neq 0$



$a_\mu^{\mathrm{SM}} = 0.00116591782(43)$

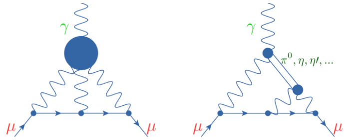
$a_\mu^{\mathrm{Exp.}} = 0.00116592061(41)$

4.2 σ

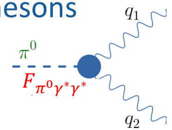
FermiLabs, 2021

Standard Modell Calculation

$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had.}}$ ← nonperturbative



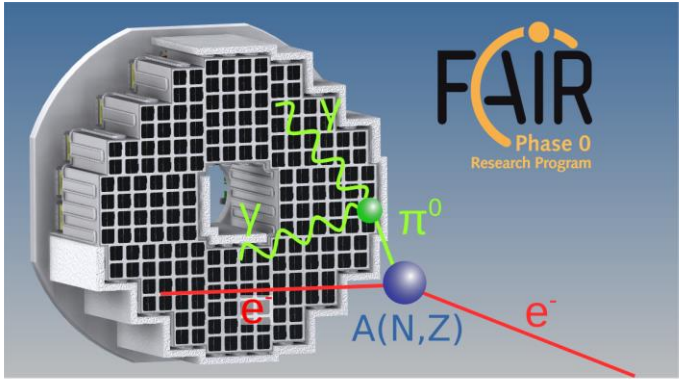
- Hadronic Light-by-Light scattering
- Huge contribution to uncertainty
- Pseudo scalar (PS) mesons π^0, η, η'



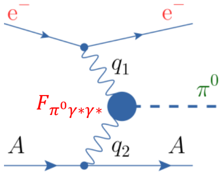
Data-driven approach

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

V. Pauk, M. Vanderhaeghen 2014, M. Hoferichter 2018



- FAIR Phase-0: FAIR detectors in stand-alone experiments
- PANDA backward calorimeter is completely developed
- Measurement of the **double virtual** pion transition form factor (TFF) $F_{\pi^0\gamma*\gamma*}$ for spacelike momenta
- Primakoff electroproduction
- A1 experimental hall of Mainz Microtron
- Electron beam on highly charged target

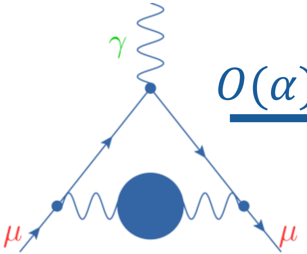


Measurement of the Electromagnetic Transition Form Factor of the π^0 in the Space-Like Region via Primakoff Electroproduction. Letter of Intent, 2020

Dominant Hadronic Contributions to $g_\mu - 2$

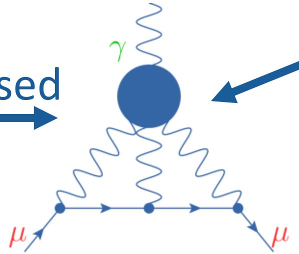
$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had.}}$$

Vacuum Polarisation



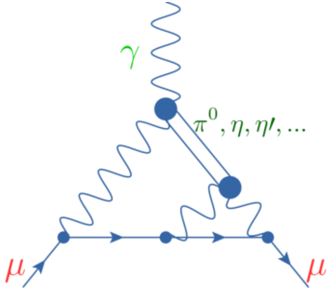
$\mathcal{O}(\alpha)$-suppressed

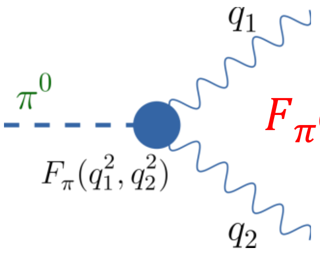
Light-by-Light



$\Delta a_\mu^{\mathrm{HVP}} = 3.25 \cdot 10^{-10}$

$\Delta a_\mu^{\mathrm{HLbL}} = 2.88 \cdot 10^{-10}$





$F_{\pi^0\gamma^*\gamma^*}$

- π^0 effective coupling
- $q_1, q_2 < 0$: space-like regime
- double virtuality

Fred Jegerlehner. Variations on Photon Vacuum Polarization. EPJ Web Conf., 218:01003, 2019

Data on π^0 Transition Form Factor (TFF)

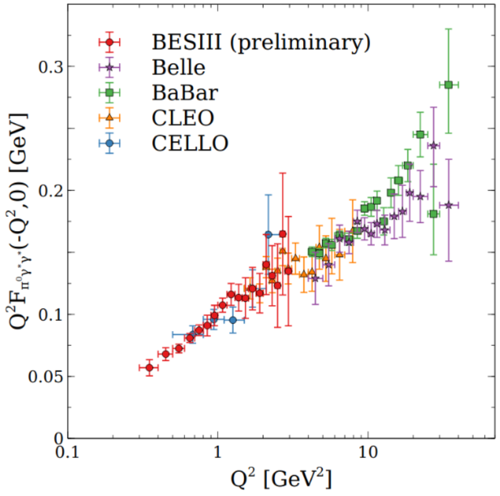
Time-like

- Dalitz decay $\pi^0 \rightarrow \gamma^*\gamma$
- Precise data from A2@MAMI and NA62
- Down to very low (single) virtuality
- Extracting of π^0TFF slope

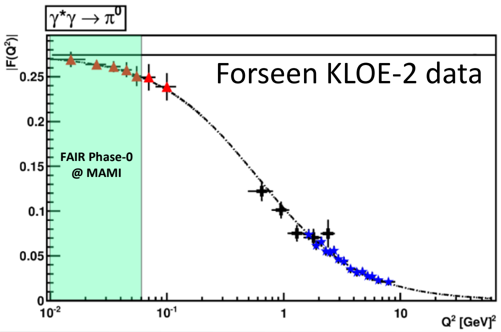
Space-like

- e^+e^-colliders
- All measurements singularly virtual $\gamma^*\gamma \rightarrow \pi^0$
    - Older data from CLEO and CELLO
    - Down to 0.6 GeV²
    - Newer data from BABAR and Belle
    - Down to 4.0 GeV²
    - Preliminary precise data from BESIII
    - Down to 0.3 GeV²
    - Planned measured from KLOE-2
    - Down to 0.01 GeV²
- Missing: $\gamma^*\gamma^* \rightarrow \pi^0$

Phys. Rept. 887 (2020) 1-166



arXiv:1311.2198 [hep-ph]



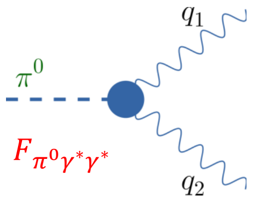
Data-Driven Approach for HLbL Contribution to $g_\mu - 2$

- Integral over the meson transition form factor $F_{PS\gamma^*\gamma^*}(Q_1^2, Q_2^2)$ with space-like photon virtualities:

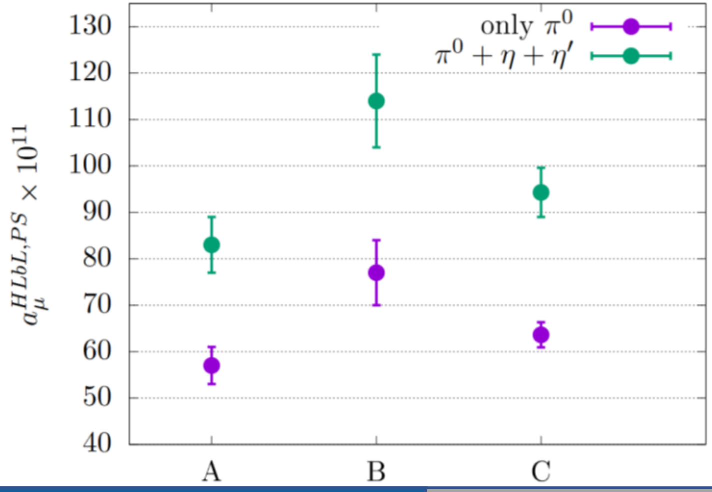
$$a_\mu^{HLbL,PS} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^{1} d\tau\, w(Q_1, Q_2, \tau) F_{PS\gamma^*\gamma^*}(-Q_1^2, -(Q_1+Q_2)^2) F_{PS\gamma^*\gamma^*}(-Q_2^2, 0)$$

kinematical weight function

$PS = \pi^0, \eta, \eta'$



- Model dependence



A: Vector Meson Dominance (VMD)
Phys. Rev. D 57 (1998) 465

B: VMD with constraints from operator product expansion
Phys. Rev. D 70 (2004) 113006

C: Rational approximants
Phys. Rev. D 95 (2017) 054026

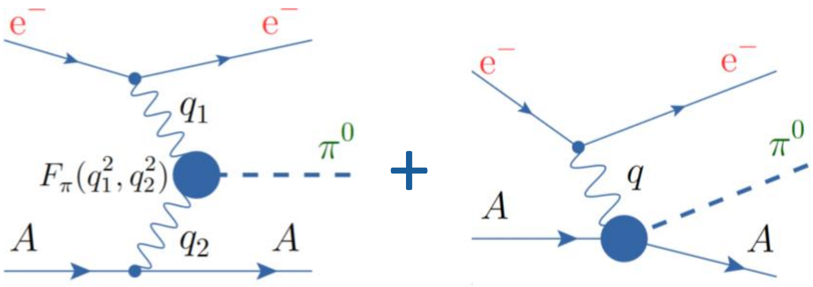
The Primakoff π^0 Electroproduction

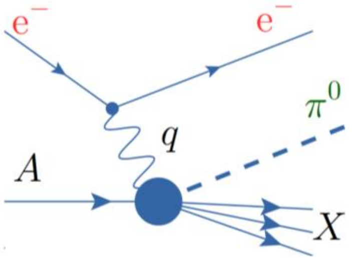
- Coherent π^0 electroproduction on nuclei
  - $e^- + A(Z,N) \rightarrow e^- + \pi^0 + A(Z,N)$
- Primakoff contribution sensitive to TFF
- Suppressed by $\alpha_{\mathrm{e.m.}}$
- But enhanced at low t by $t^{-1} = 1/q_2^2$
- t is finite → double virtuality
- Proportional to Z^2 → high Z target
  - $^{181}_{73}$Ta target
- Strong interference → hadronic production to be calculated for our kinematics

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

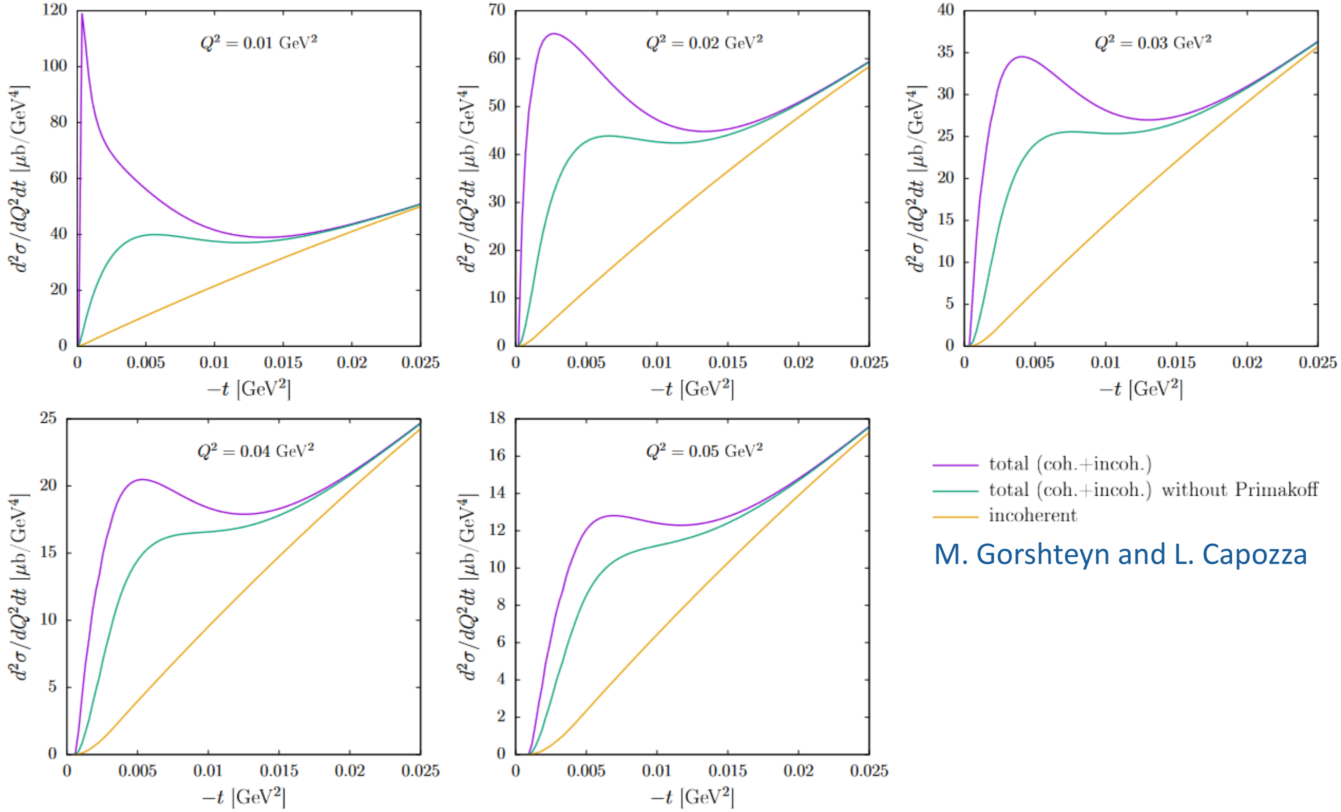
  S. Gevorkyan et al., Phys. Rev. C80 (2009) 055201
- Model dependence to be estimated
- Background process : incoherent π^0 production
  - $e^- + A(Z,N) \rightarrow e^- + \pi^0 + X$

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





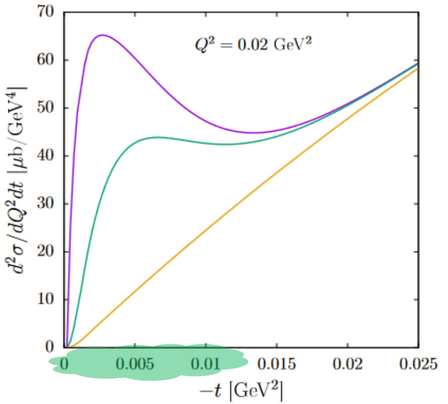
The Primakoff π^0 Electroproduction - Cross Section Estimation



M. Gorshteyn and L. Capozza

- Beam energy: 1.5 GeV
- $^{181}_{73}$Ta target
- Electron scattering angle: 6° to 17°

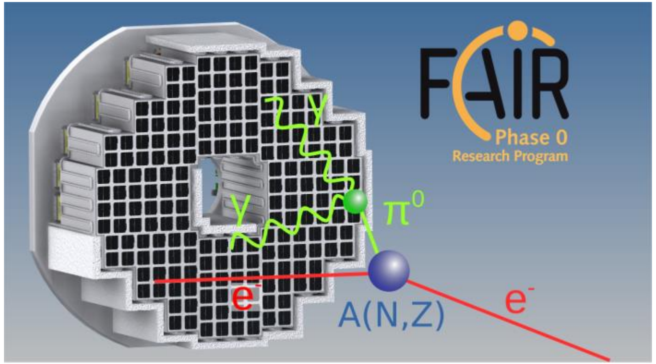
Experiment Requirements



- Need to detect both e^- and π^0 in coincidence (exclusive reaction)
- Electromagnetic calorimeter (EMC) is the proper device
  - $\pi^0 \rightarrow \gamma\gamma$
- Need to measure at small t (q_2):

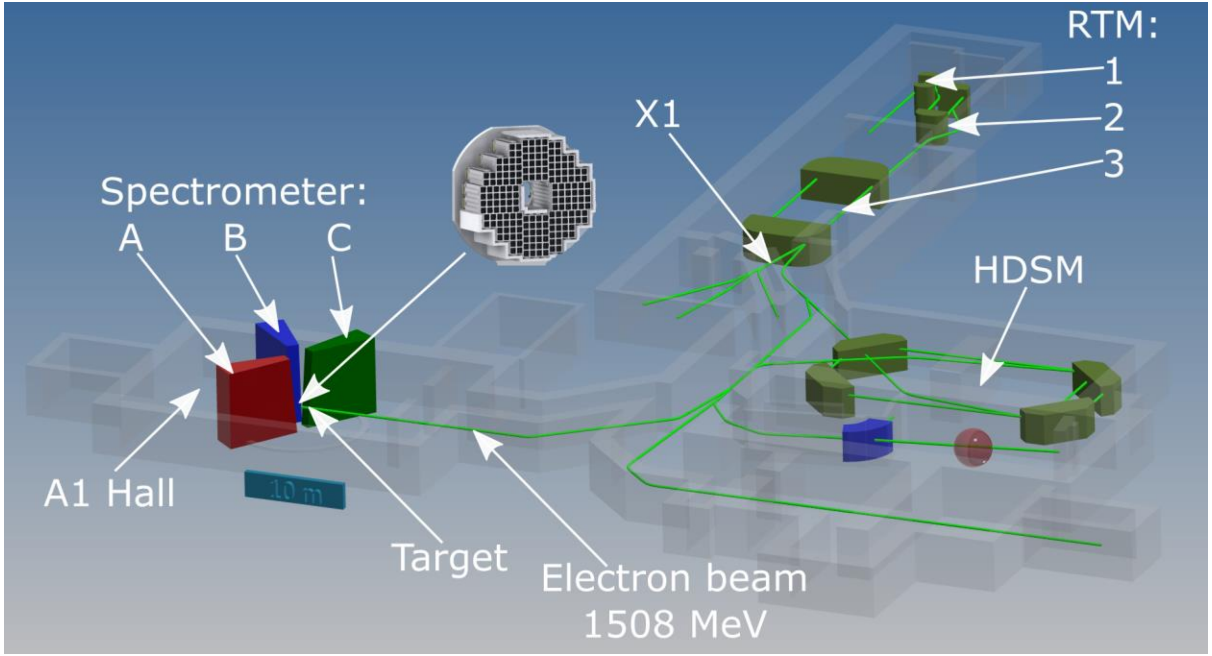
$$-t = 2\nu^2 + Q^2 - m_\pi^2 - 2\sqrt{\nu^2 + Q^2}\sqrt{\nu^2 - m_\pi^2}\,\cos\Theta_{\pi q}$$

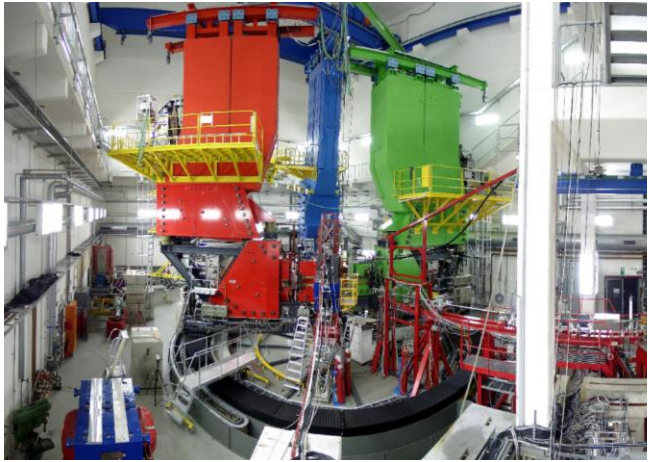
pion energy (ν^2) — momentum transfer from electron (Q^2) — angle btw. pion and mom. transfer ($\Theta_{\pi q}$)



- High pion energy and small $\Theta_{\pi q}$ → EMC at forward angle
- Small Q^2 → small electron scattering angle → e^- also in EMC acceptance
- Needed t resolution ~ 10^{-4} GeV²
  - Relative energy resolution ~ some %
  - $\Theta_{\pi q}$ angle resolution ~ 0.4° → position resolution ~ 4 mm

The MAMI Electron Scattering Facility – A1 Hall

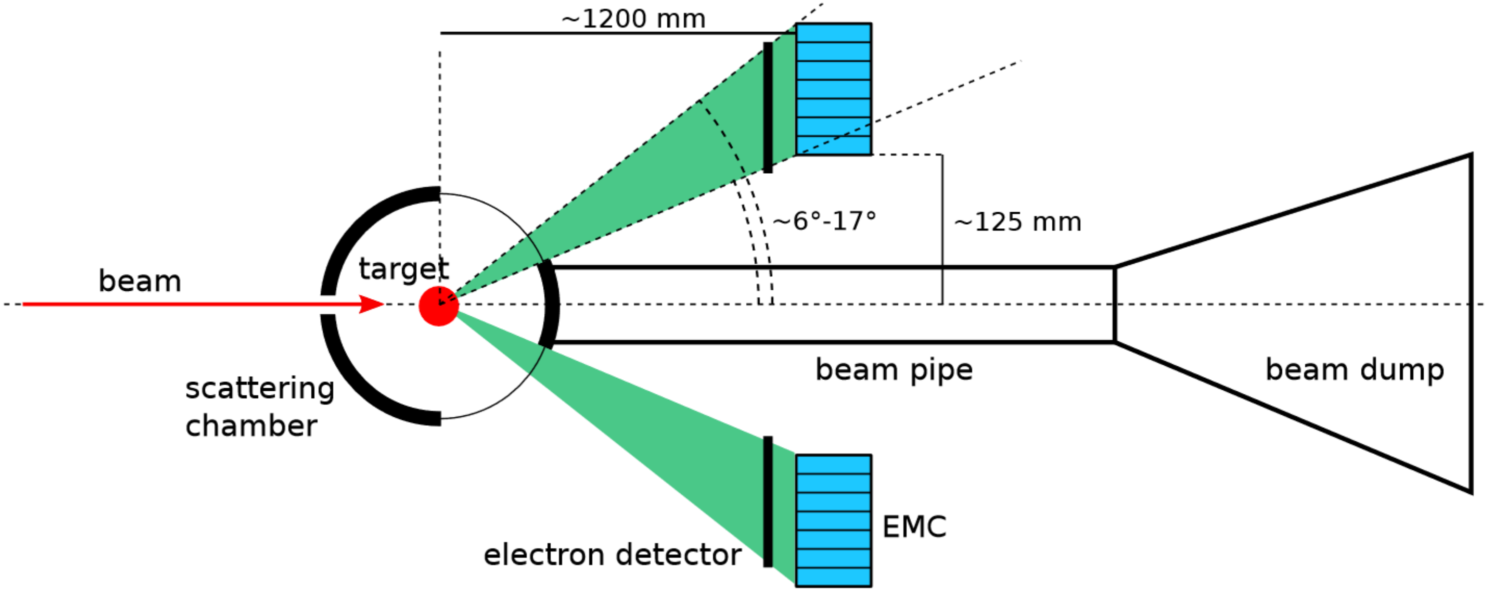




- 3 high-resolution magnetic spectrometers
  - $\delta p/p \cong 10^{-4}, \delta\Theta < 3$ mrad
- Wide angular range (but $\Theta_e \geq 15°$)
- Limited acceptance
- Only charged particles

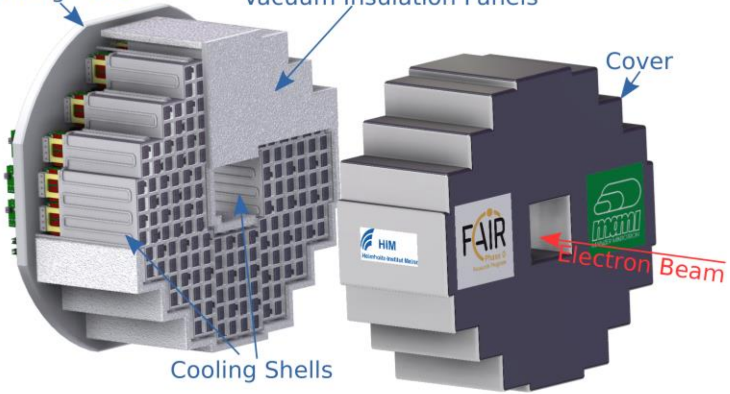
- CW electron beam
- Beam energies up to 1.5 GeV

Planned Setup at A1

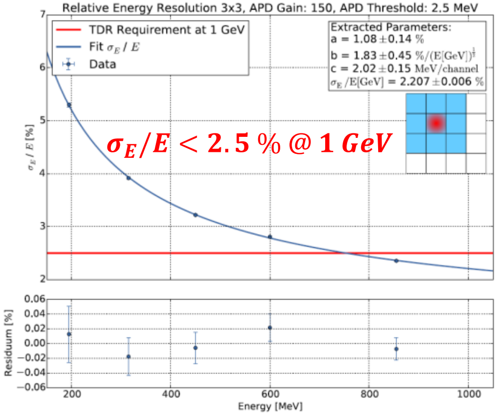


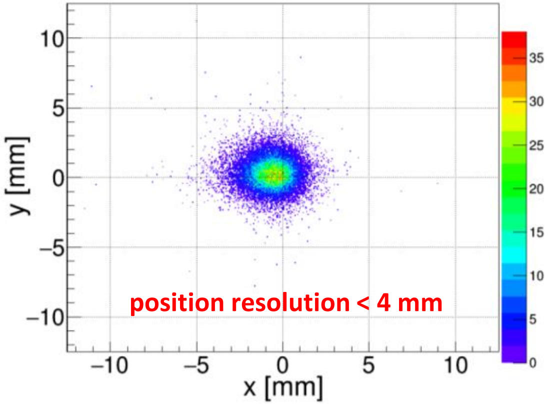
- Ring-shaped EMC around exit beam pipe
- Distance to target ~ 1.2 m
- Plastic scintillator for separating e^- and γs (or a tracker? → under study)
- Magnetic spectrometer for dedicated alignment measurements

PWO Calorimeter

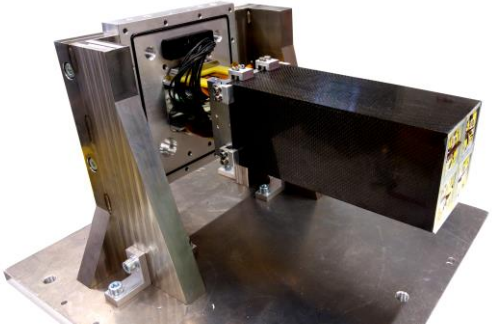


- PANDA backward calorimeter (FAIR Phase-0)
- Substantial adaptation for this experiment
- 640 PbWO4 crystals
- Inner/outer diameter: 25 cm/75 cm
- RD finished, under construction
- Tested several times with beam at MAMI



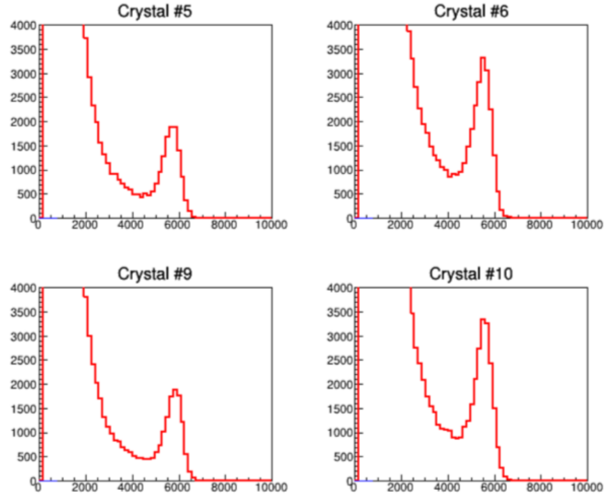


4x4 crystal prototype

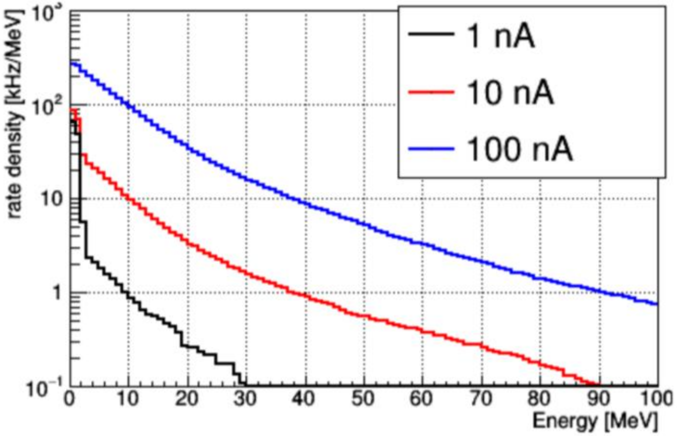


Beam Test at A1

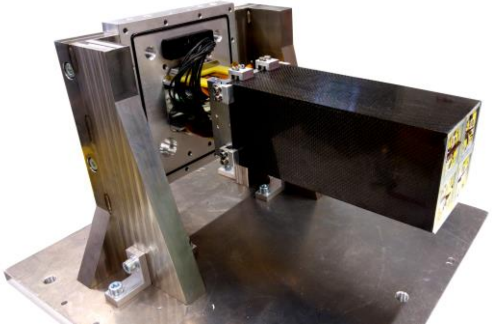
Energy Spectra



Total Rate at small Angles

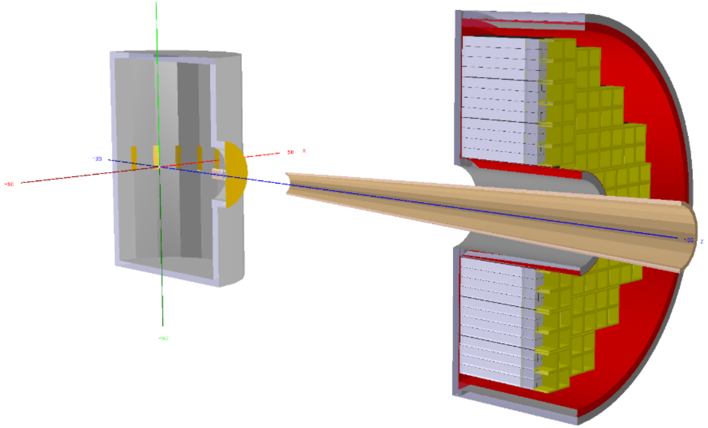


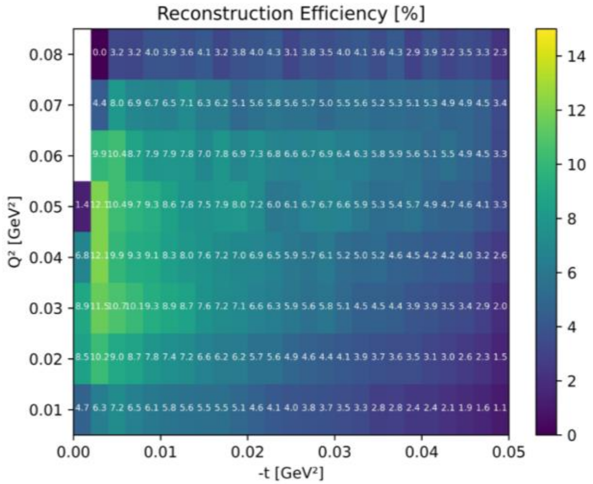
4x4 crystal prototype



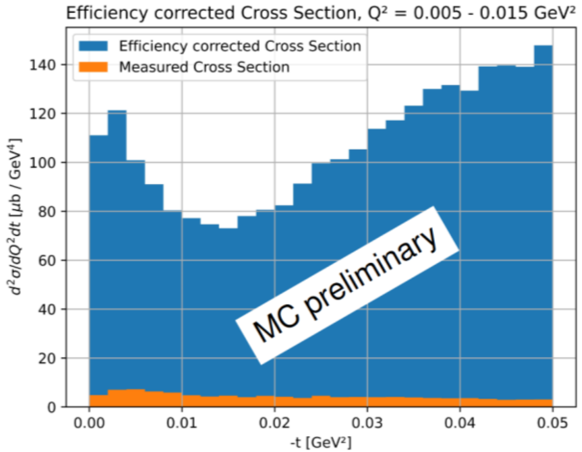
- 3 test beams since 2018
- Beam energy: 1.5 GeV and 855 MeV
- Beam current up to 200 nA
- Targets: C, Ta, polyethylene
- Using 1 and 2 prototypes (coincidence measurement)
- Luminosity of at least 5.5 $\mu b^{-1} s^{-1}$ feasible! ✓

Simulation Studies

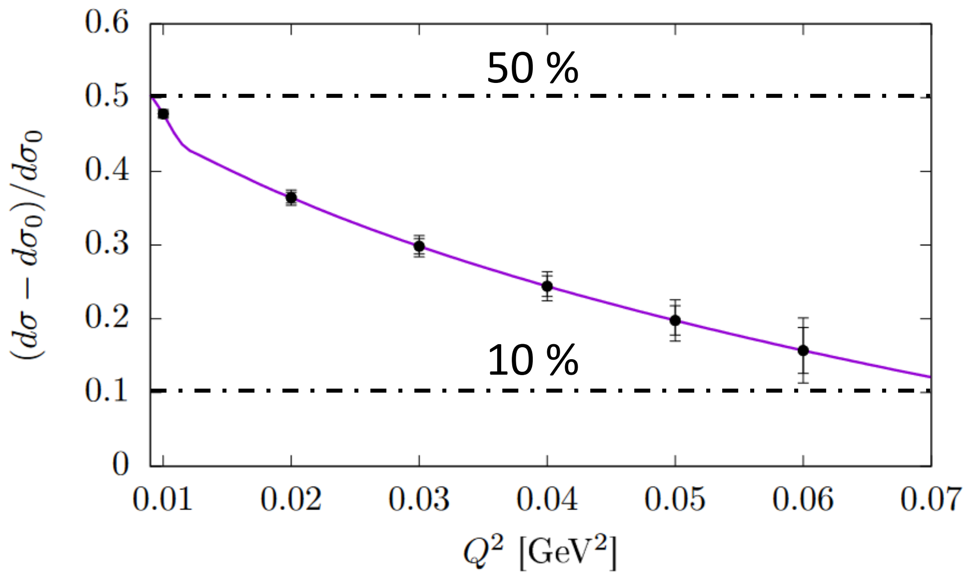




- GEANT4 simulation with detailed geometry
- Relevant geometry included
- π^0 acceptance studies
- Radiation studies
- Physics event generator
- e^- detector studies

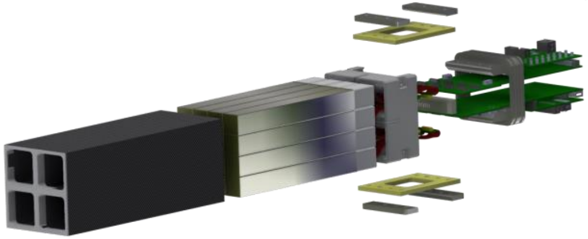


Sensitivity to Primakoff Amplitude

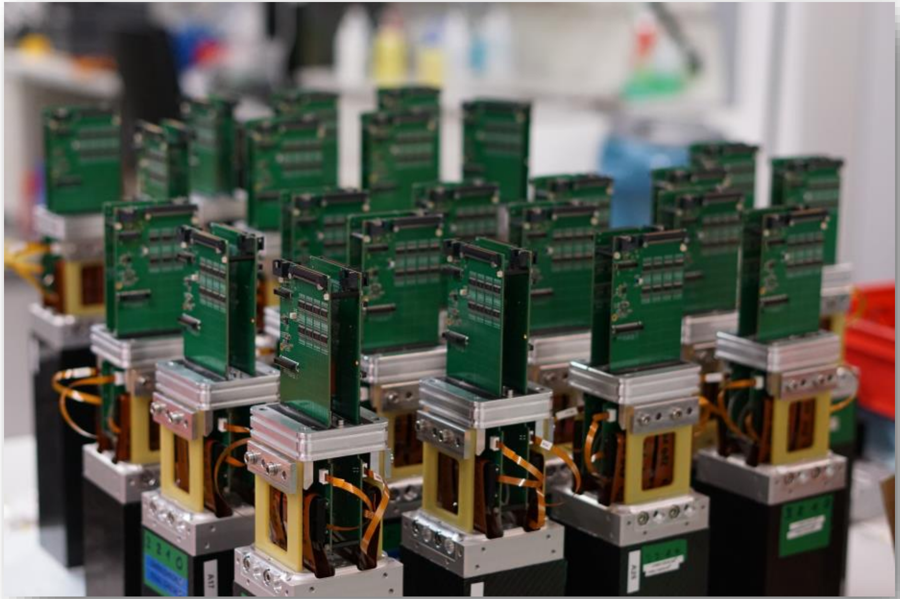


- $d\sigma$: tot. Cross section (coh. + incoh.)
- $d\sigma_0$: same without Primakoff contr.
- Target: $^{181}_{73}\mathrm{Ta}$
- Beam energy: 1.5 GeV
- Effective cross section: 2.951 nb to 0.127 nb
- Luminosity: 5.5 $\mu\mathrm{b}^{-1}\mathrm{s}^{-1}$ (100 nA)
- Angle range (e^- and $\gamma\gamma$): 5° to 15°
- π^0 detector acceptance included
- Error bars (stat. only): 1000 h, 500 h

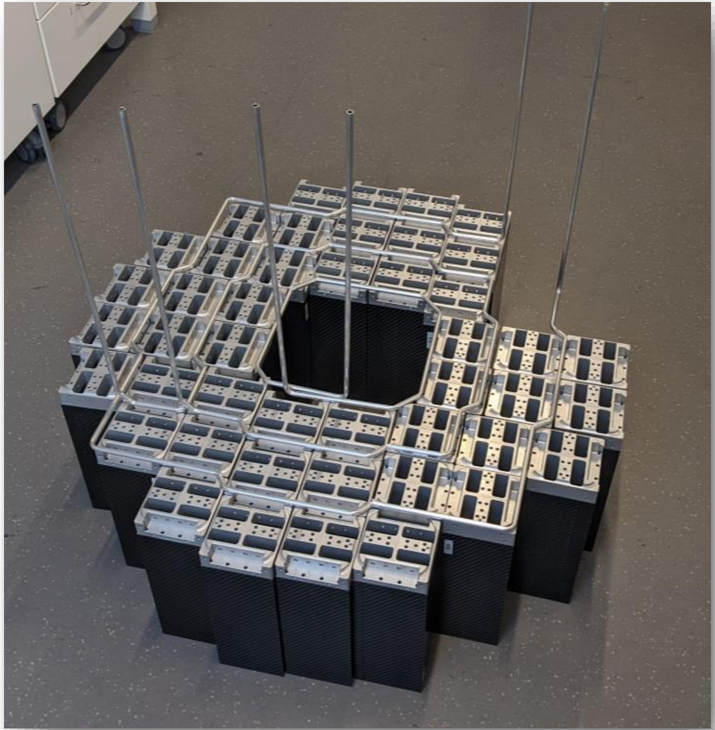
FAIR Phase-0 Detector Status

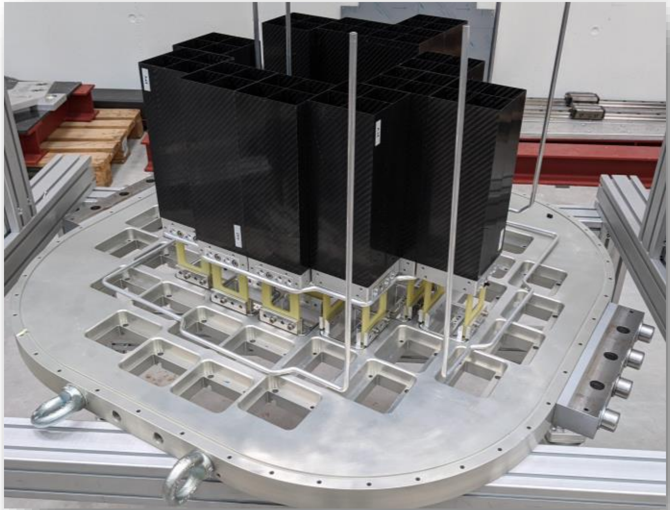


- 578/640 crystals wrapped
- 32/32 full equipped submodules are built ✓
- 32/32 full equipped submodules succeeded pre-test ✓
- Pre-calibration of submodules is ongoing



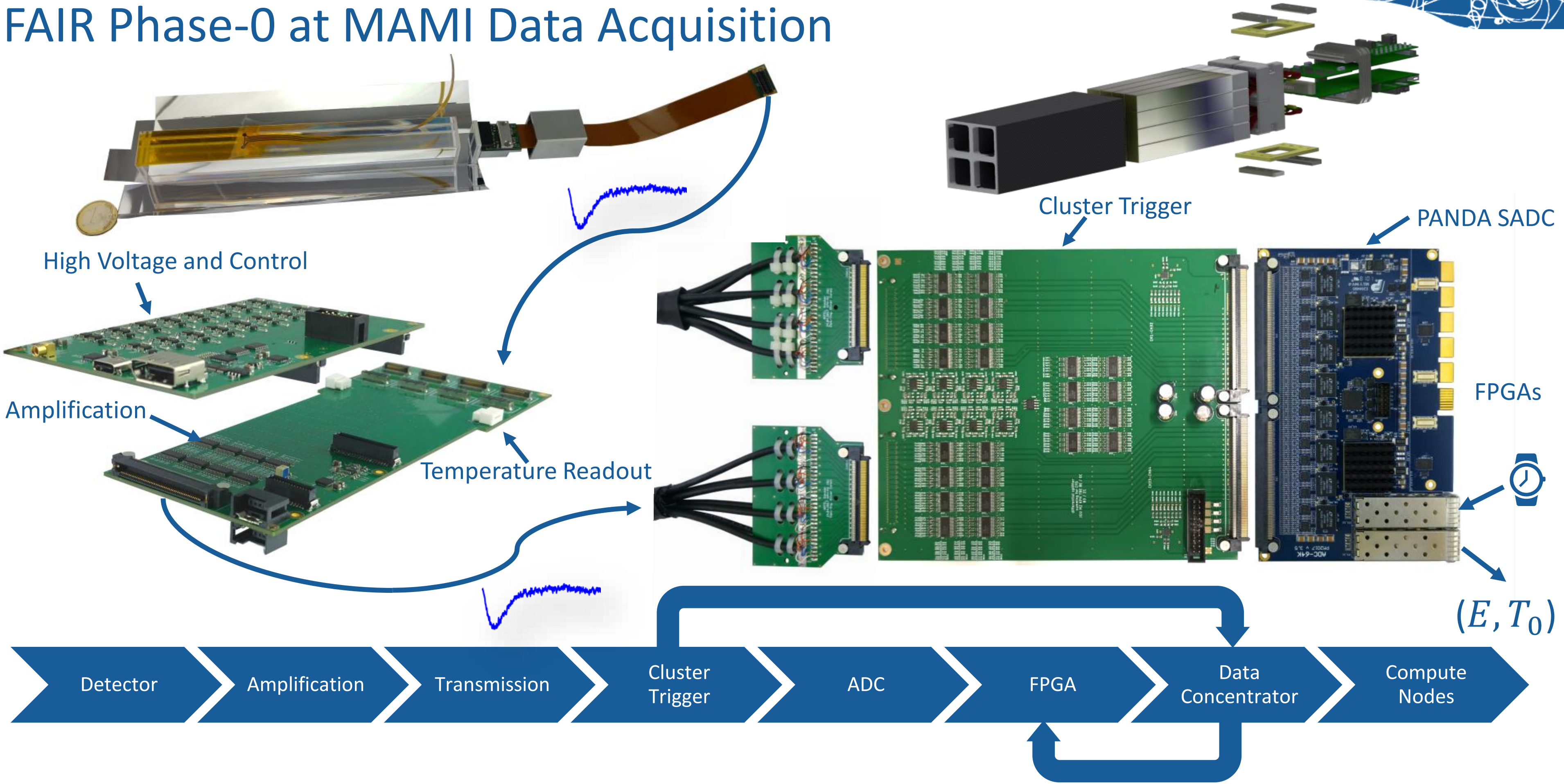
FAIR Phase-0 Detector Status



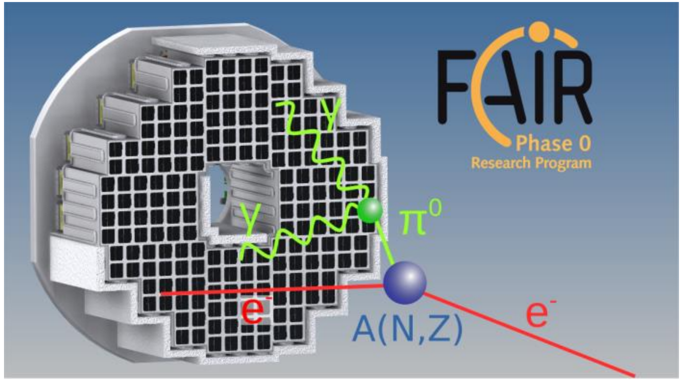


- Mounting plate ✓
- Cooling (EMC operates at – 25 C°) ✓
- Detector mounting structure ✓

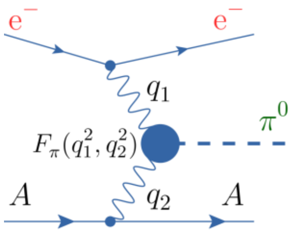
FAIR Phase-0 at MAMI Data Acquisition



Summary and Possible Time Plan



- FAIR Phase-0: FAIR detectors in stand-alone experiments
- Utilising PANDA backward calorimeter
- Measurement of the **double virtual** pion **transition form factor** (TFF) $F_{\pi^0\gamma*\gamma*}$ for **spacelike momenta**
- Primakoff electroproduction
- A1 experimental hall of Mainz Microtron
- Electron beam on highly charged target
- Test Measurements and Simulations
- Detector construction ongoing



2023
- Complete detector
- Repeat beam test with 2 prototypes
- Hall installation

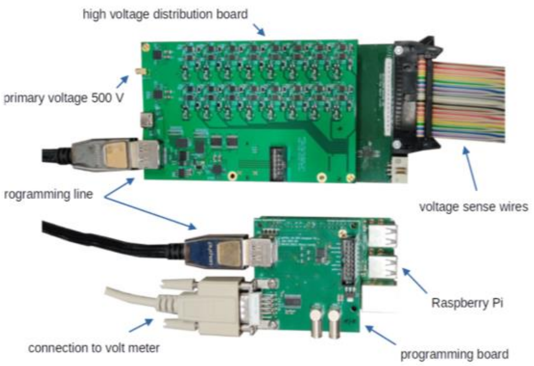
2024
- Commissioning with beam
- Pilot experiment $\sim$ 100 h
- First analysis
- Possible improvements

2025
- Complete run
- 500 h to 1000 h
- …?

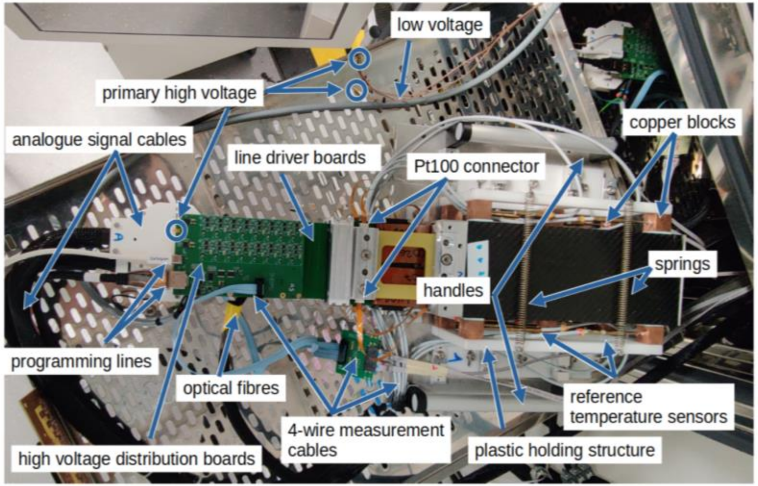
Backup

Calibration of Detector Submodules

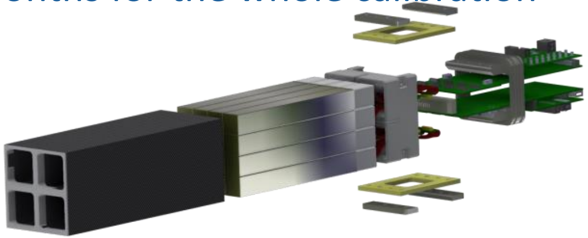
- Master Thesis finished (Samet Katilmis)
- Calibration consists of
  1. Calibration of high voltage distribution boards
  2. In-situ temperature sensor calibration
  3. In-situ APD gain determination (crosscheck)
  4. Energy calibration utilising cosmics
- Full automatised setup
- Three submodules per cycle
- 72 h per cycle
- 48 submodules (32 full, 16 half)
- ~2 months for the whole calibration



High voltage distribution board calibration setup

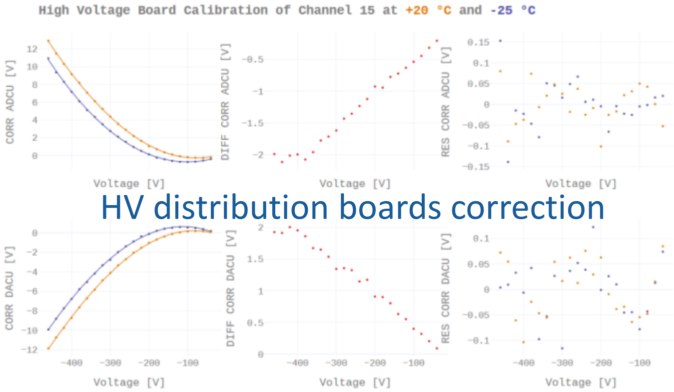


Bird's eye view of a drawer with a full equipped submodule

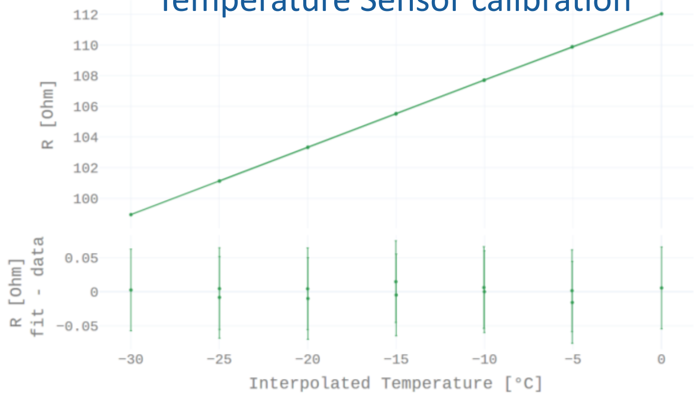


Calibration of Detector Modules for the PANDA Backward Electromagnetic Calorimeter
Master Thesis, Samet Katilmis, March 2023

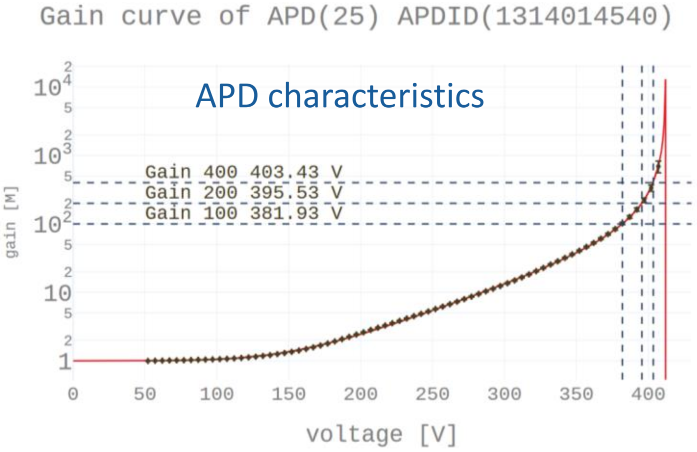
Calibration of Detector Submodules



HV distribution boards correction



Temperature Sensor calibration



APD characteristics

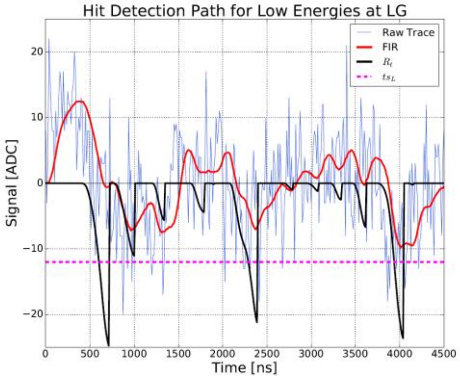
Output of calibration:

1. Data sheet for every subunit
2. Data base entries for all necessary parameters

Calibration of Detector Modules for the PANDA Backward Electromagnetic Calorimeter
Master Thesis, Samet Katilmis, March 2023

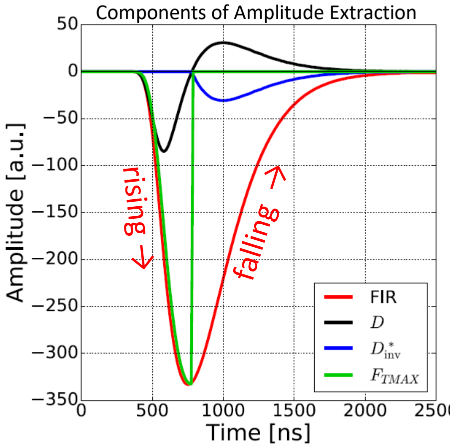
Digital Pulse Identification and Parameter Extraction on FPGA

Identification



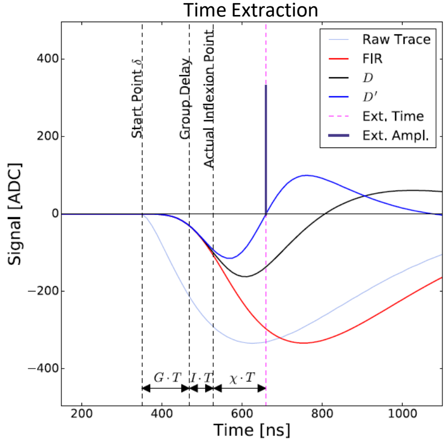
- Extraction function
- Highly sensitive on pulse shape
- Improvement of detection efficiency (small energies!)

Digital Pulse Shaping



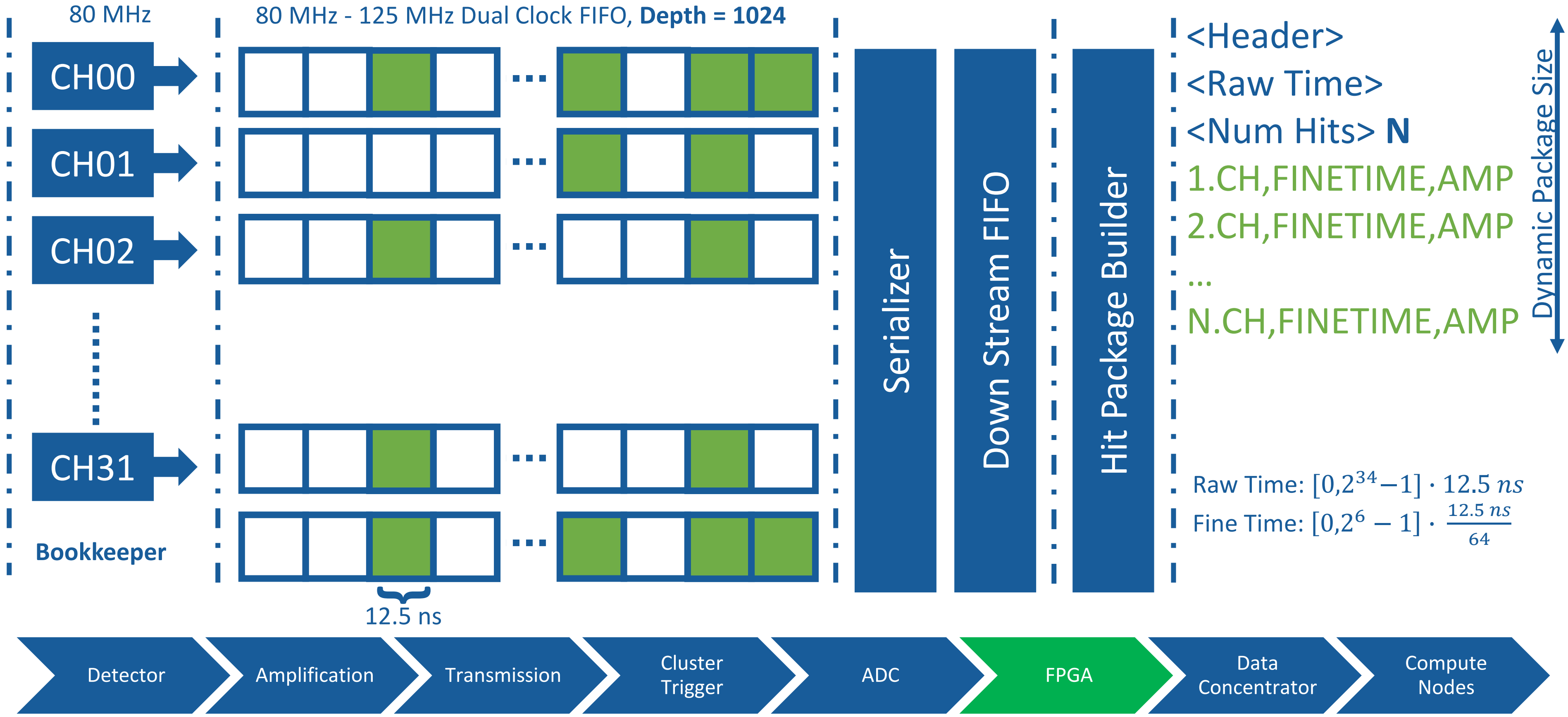
- Derivation → Integration
- Built-in baseline follower
- Elimination of falling edge
- Pileup detection and correction

Time

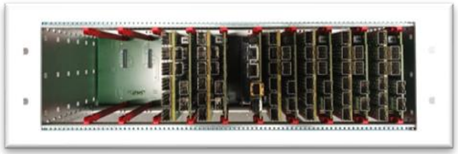


- T_0 at inflexion point ($f''(x) = 0$)
- Discrete derivation → Interpolation

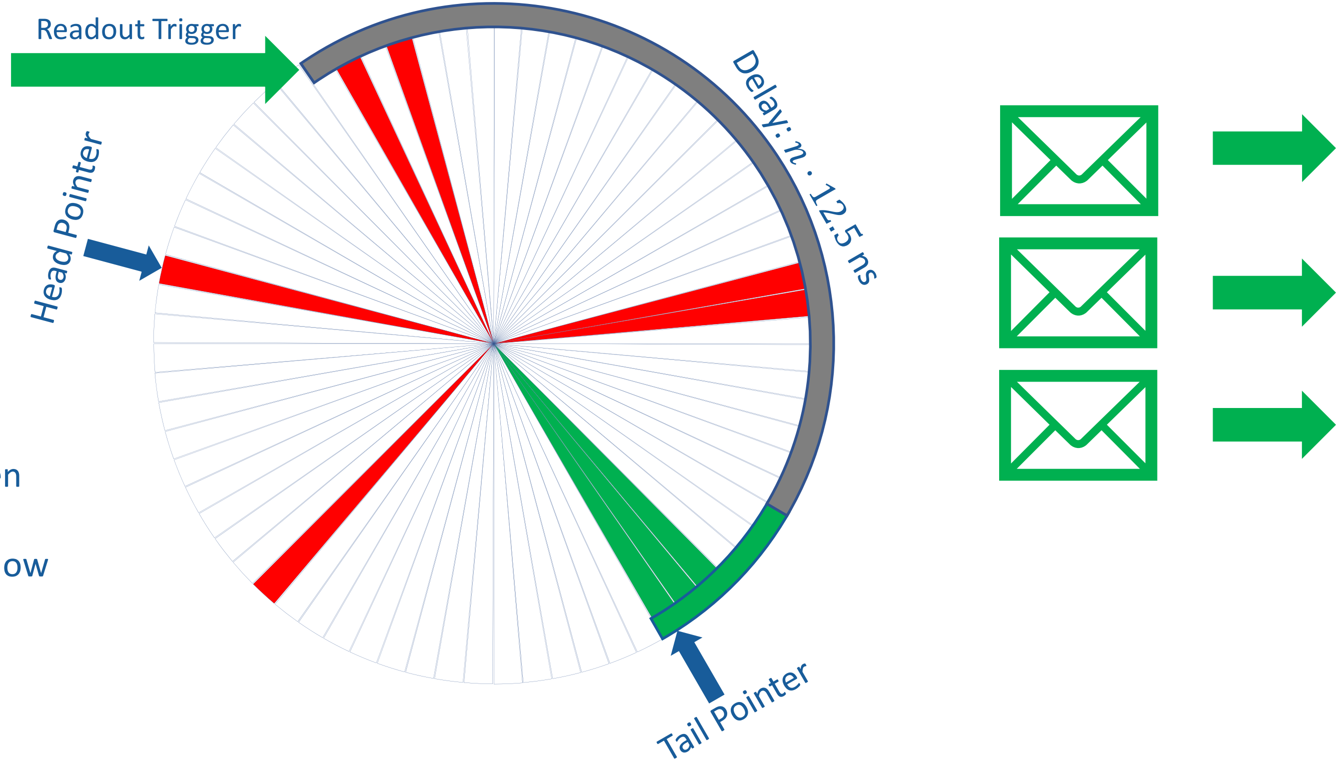
Time Sorted Hit Packaging on FPGA



Time Sorted Hit Packaging on FPGA – Bookkeeper



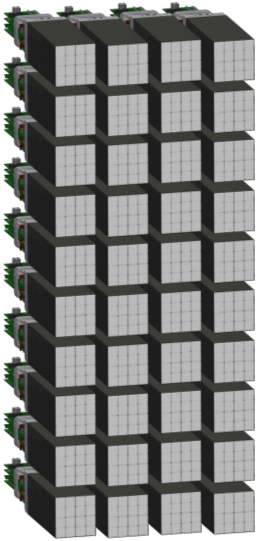
Data Concentrator TRB3 SC (GSI)



- Readout trigger from data concentrator ($\sim$ 200 ns)
- DSP on FPGA $\sim O(\mu s)$
- Configurable delay between trigger readout column
- Configurable readout window
- Also freestream ready (triggerless)

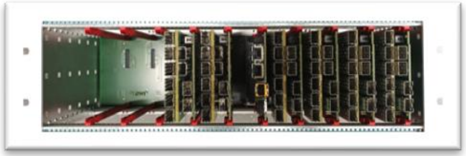
FAIR Phase-0 Data Acquisition Benchmarks

- 640 Crystals
- 1280 APDs

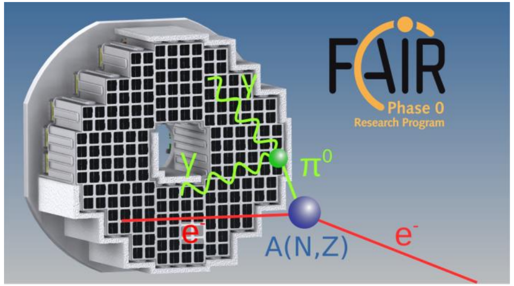


- 40 SADCs
- 2560 Channels

- Data Concentrator
  - Clock
  - Trigger



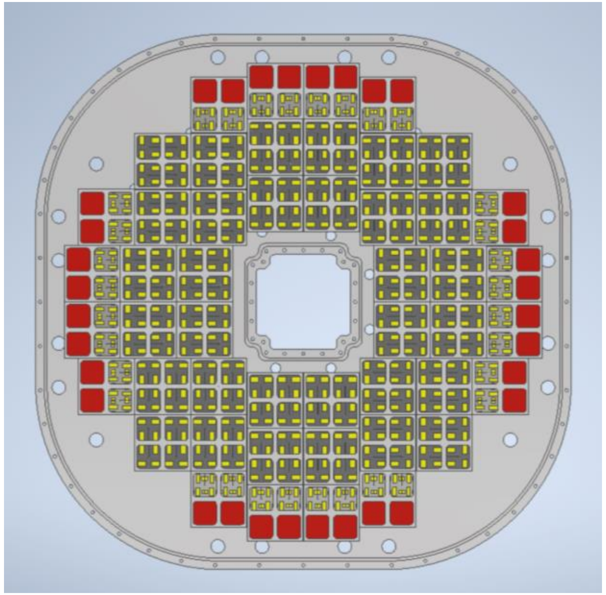
- Data Throughput

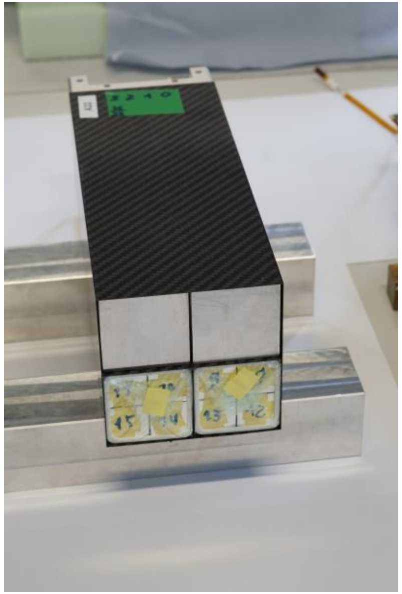


- Exclusive event rate O(mHz)
- Event hit rate ~ 200 kHz/Channel
- Free streaming bandwidth O(40 Gbit/s)
- Trigger mode bandwidth O(2 Gbit/s)

FAIR Phase-0 Detector Component Status - $^{1}/_{2}$-Submodules

- First half submodule is built 1/16
- Aluminum dummies





The Anomalous Magnetic Moment of the Muon

Dirac Theory:

Dirac equation with EM-field:

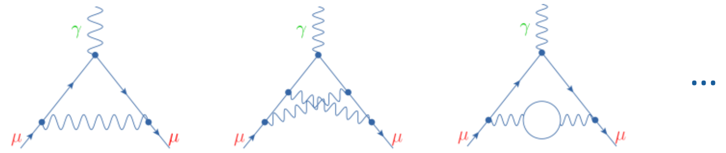
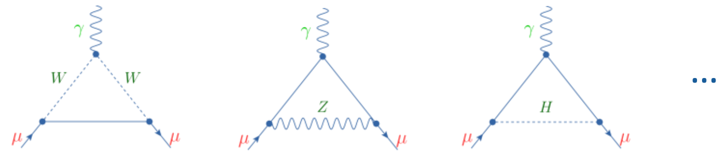
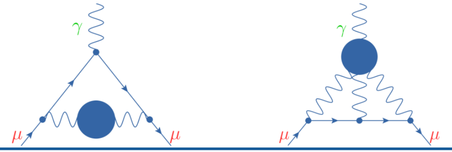
$$(i\gamma^\mu \partial_\mu - e\gamma^\mu A_\mu - m)\psi = 0$$

Nonrelativistic limit ($E \approx m$):

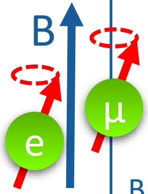
$$\frac{1}{2m}\left|\vec{p} - e\vec{A}\right|^2 \psi - \underbrace{\frac{e}{m}}_{\mu_s} \vec{S} \cdot \vec{B}\psi = 0$$

$$g = \frac{\mu_s}{\mu_L} = 2 \qquad a_l = \frac{g_l - 2}{2} = 0$$

$$a_\mu^{\text{SM}} = \text{a}_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{QCD}}$$

	Δa_μ^{SM}
	0.01×10^{-10} T. Aoyama et al. 2012
	0.10×10^{-10} C. Gnendiger et al. 2013
	Each: $\sim 3 \times 10^{-10}$ F. Jegerlehner 2019

Messung:



$$\omega_L = \frac{g}{2} \cdot \frac{eB}{m} \qquad \omega_c = \frac{eB}{m}$$

$$a_\mu^{\text{Exp.}} = 0.00116592089(63)$$

BNL (E821) 2006

$$a_\mu^{\text{SM}} = 0.00116591782(43)$$

$$a_\mu^{\text{Exp.}} = 0.00116592089(63)$$

4σ