JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Meson Decays with Crystal Ball at MAMI

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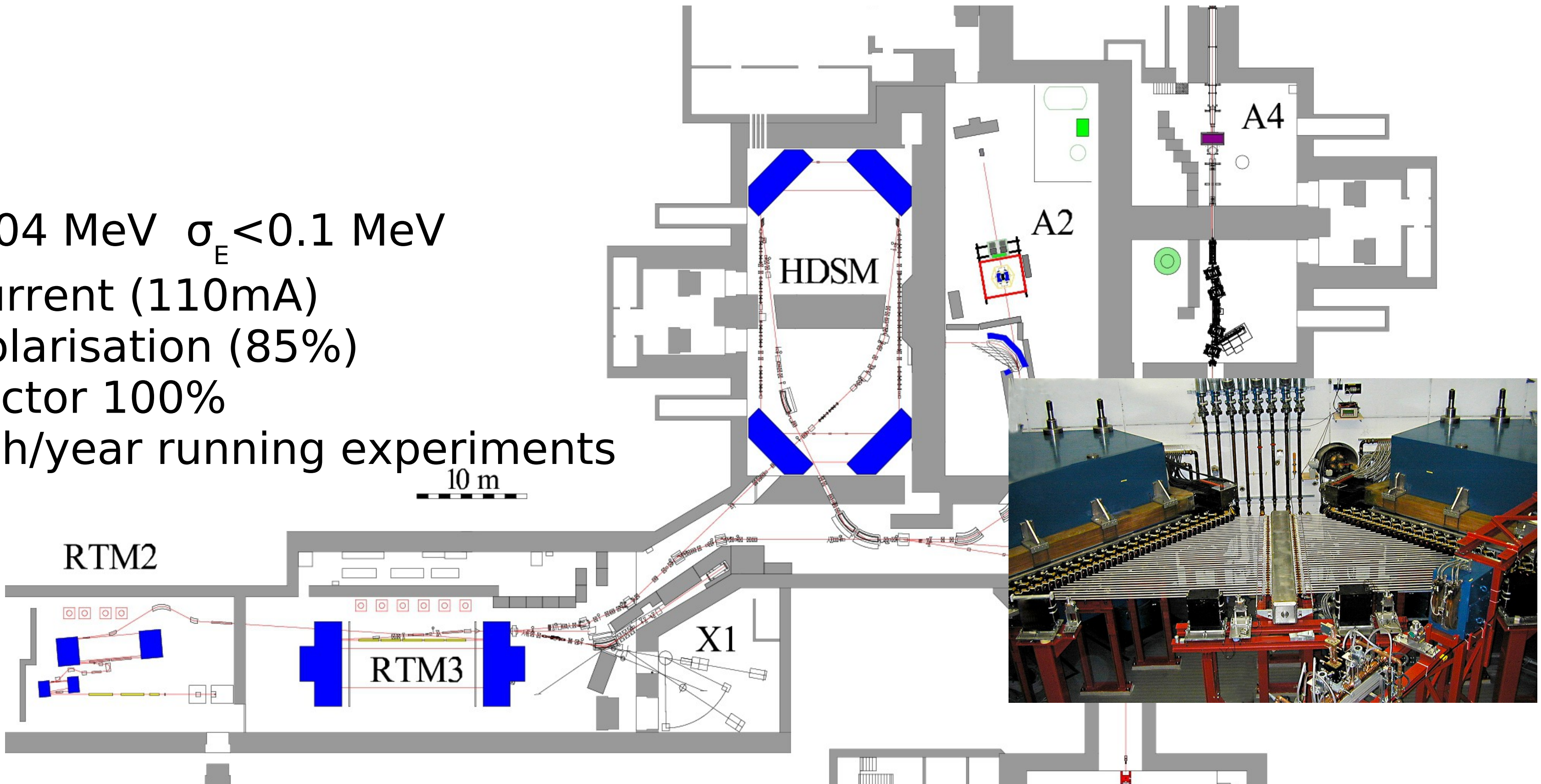
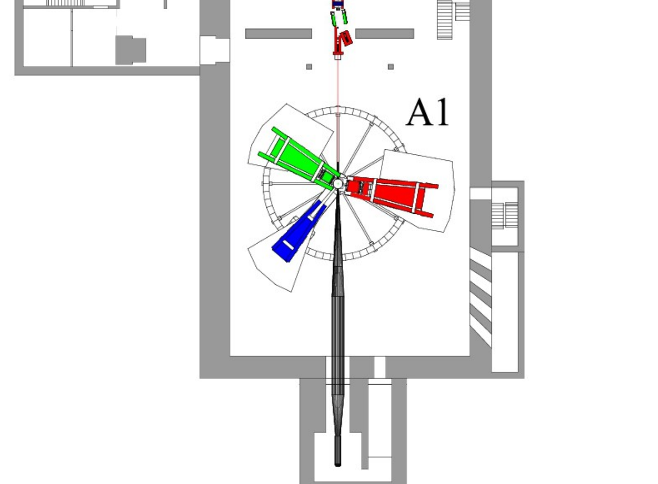
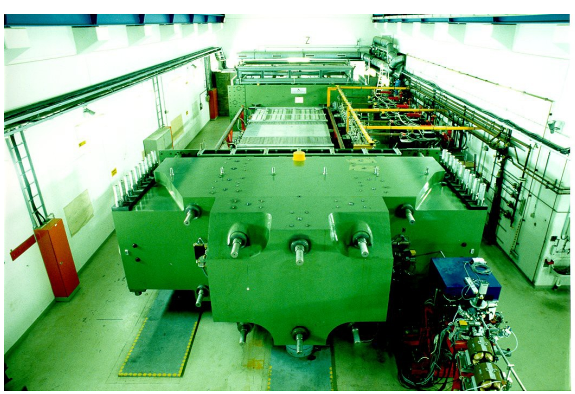
Institute for Nuclear Physics in Mainz

- E_e-<1604 MeV σ_E<0.1 MeV
- High current (110mA)
- High polarisation (85%)
- Duty factor 100%
- ~7000 h/year running experiments

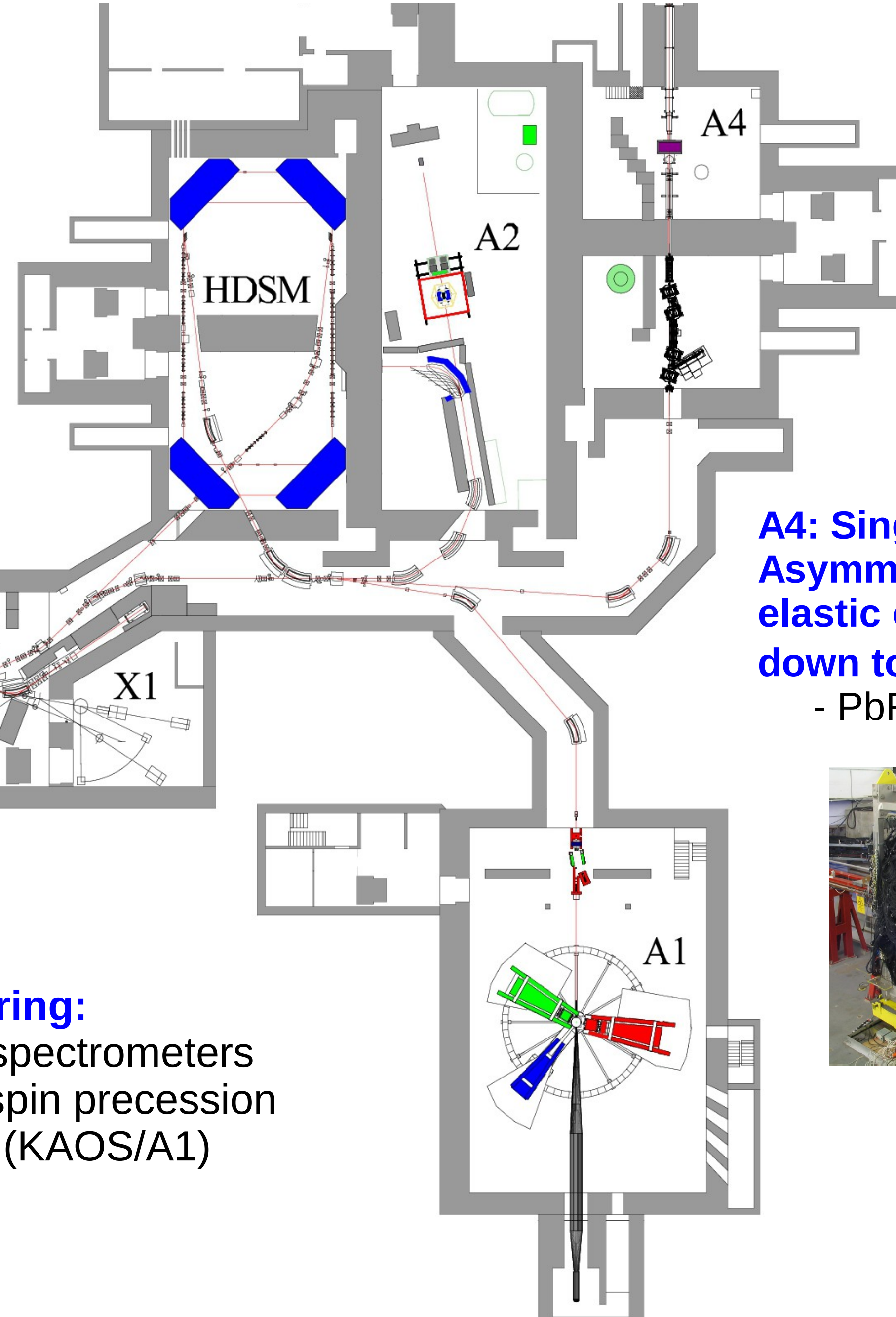


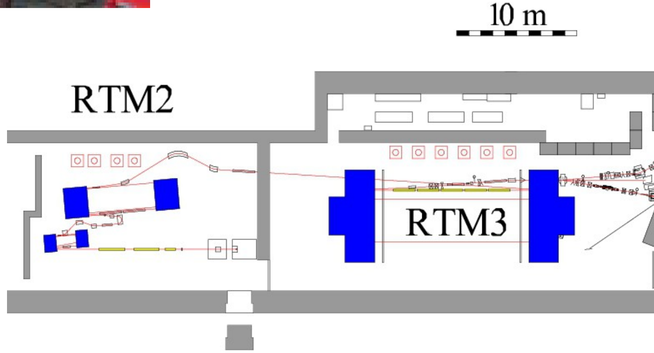




Experiments at MAMI

A2: Real Photon Experiments:
- Glasgow tagging spectrometer
- Crystal Ball / TAPS
  hermetic photon spectrometer

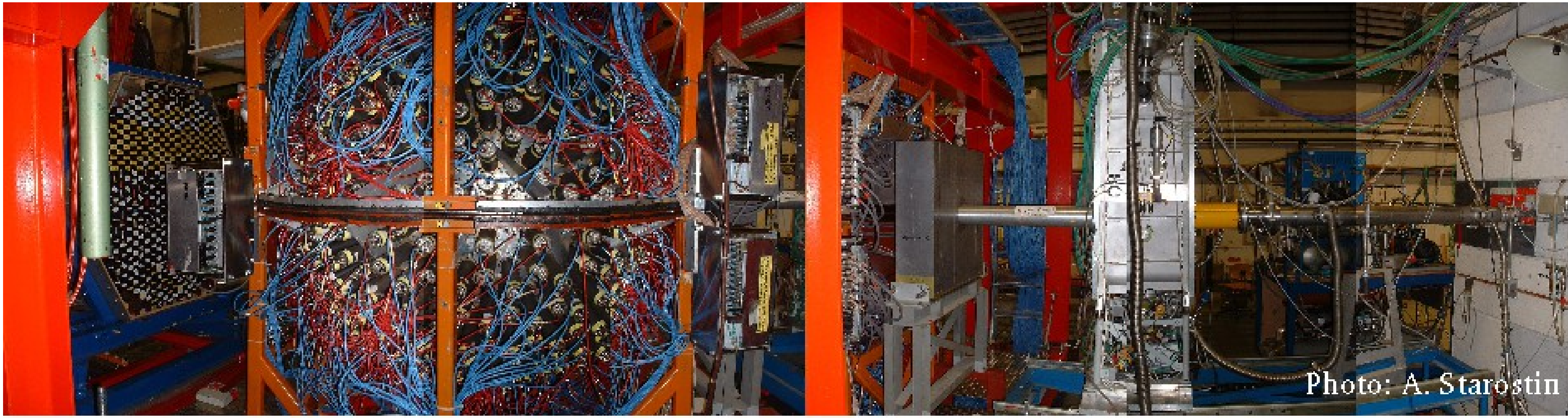




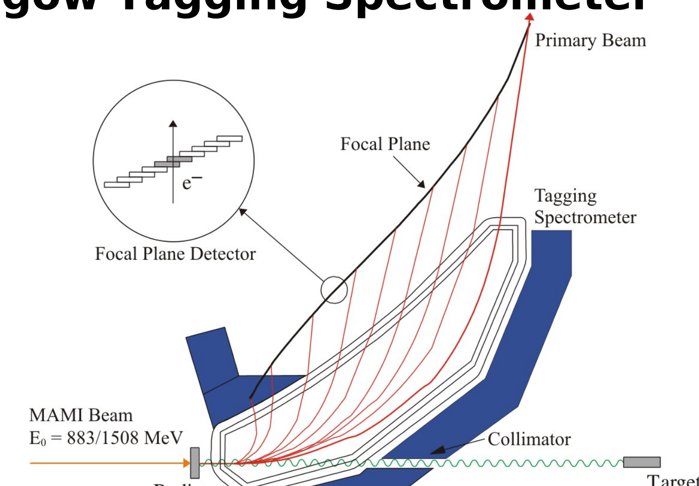
A4: Single Spin Asymmetries in elastic eN Scattering down to 10^{-6}
- PbF_2 calorimeter

A1: Electron Scattering:
- focusing magnetic spectrometers
- neutron detection, spin precession
- Kaon spectrometer (KAOS/A1)

Crystal Ball at MAMI



Glasgow Tagging Spectrometer

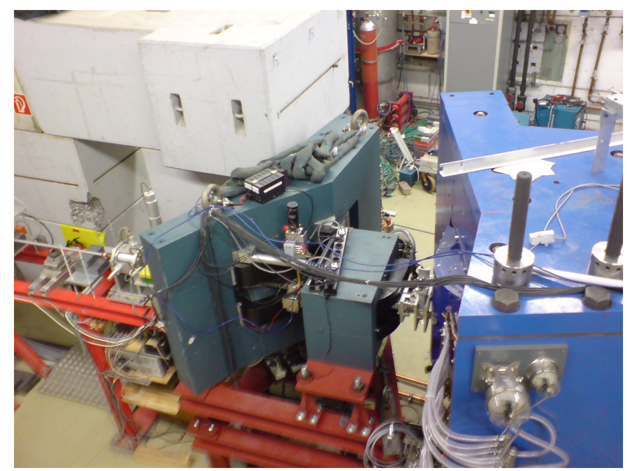


$E_\gamma = E_0 - E_{e-}$

High energy resolution: $\Delta E_\gamma \approx 2$MeV at E_{e-}=883 MeV
$\Delta E_\gamma \approx 4$MeV at E_{e-}=1558 MeV

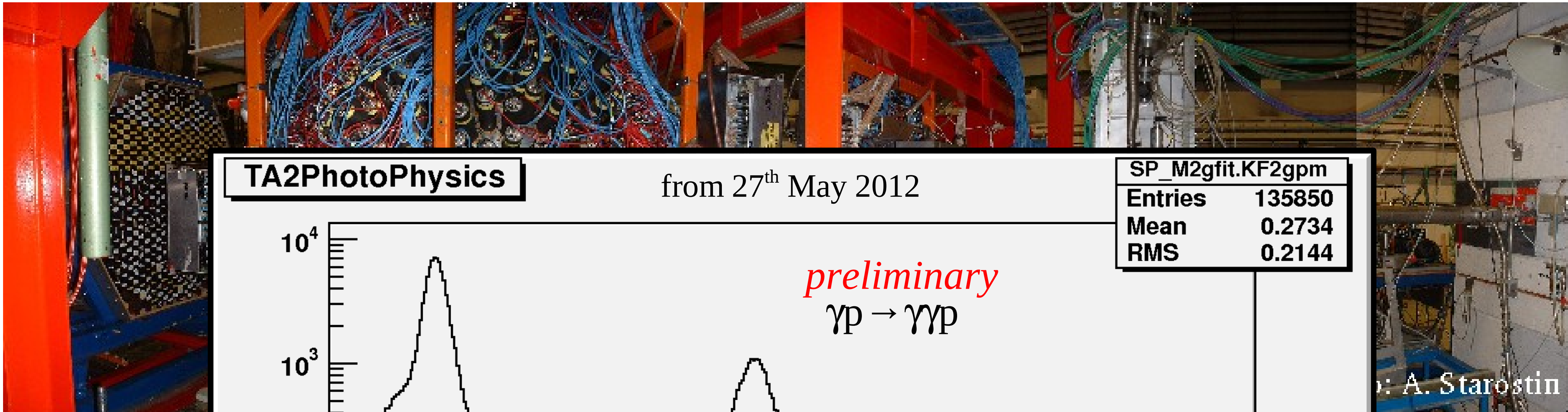
Tagging range: 4.7 to 93% of $E_\gamma \rightarrow E_{max}$ =1491 MeV

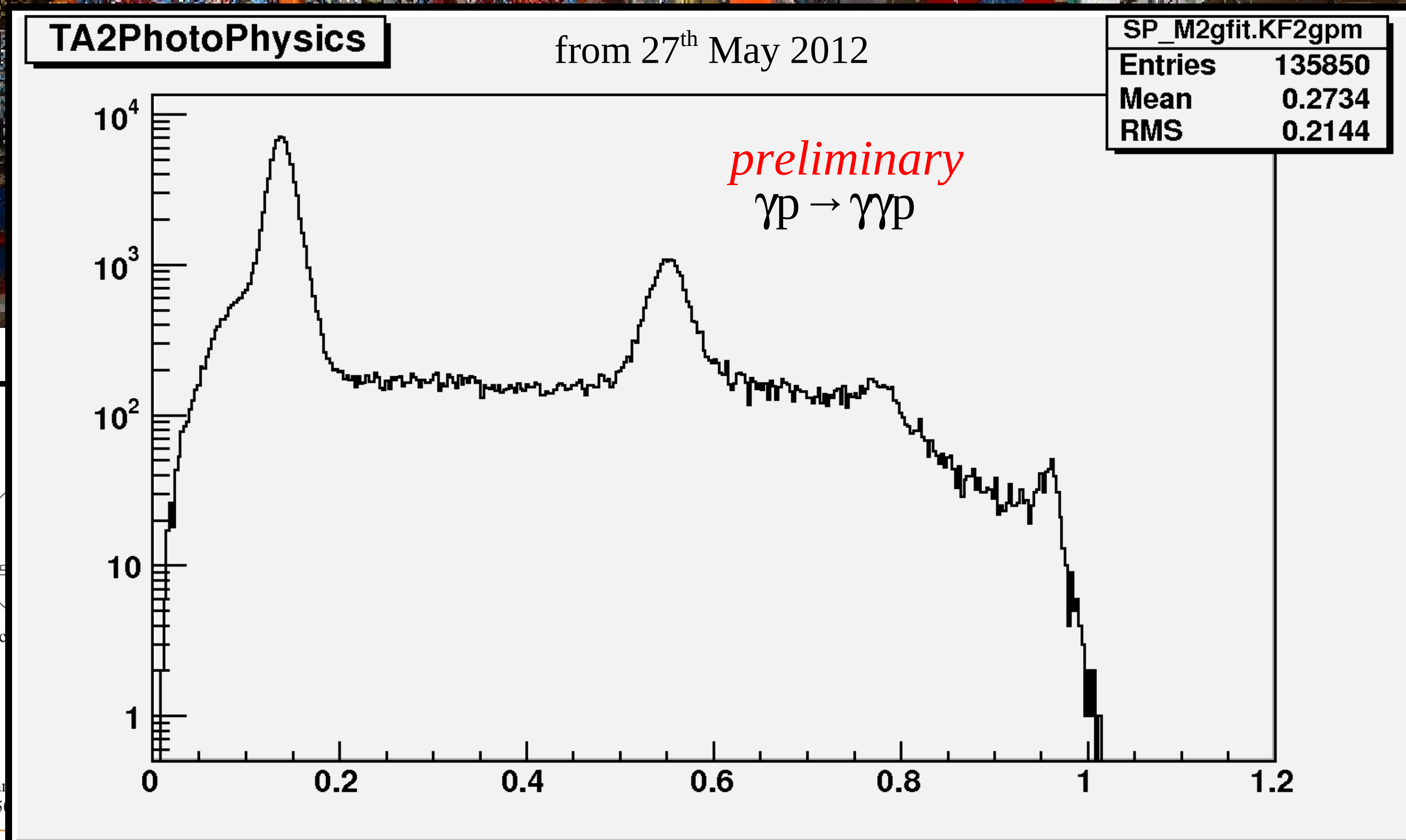
End-Point Tagger



- Covers ~1440 < E_γ[MeV] < ~1590 Mev
- Essential for tagged η' production
- Successfully commissioned in March 2010

Crystal Ball at MAMI





Glasgow T

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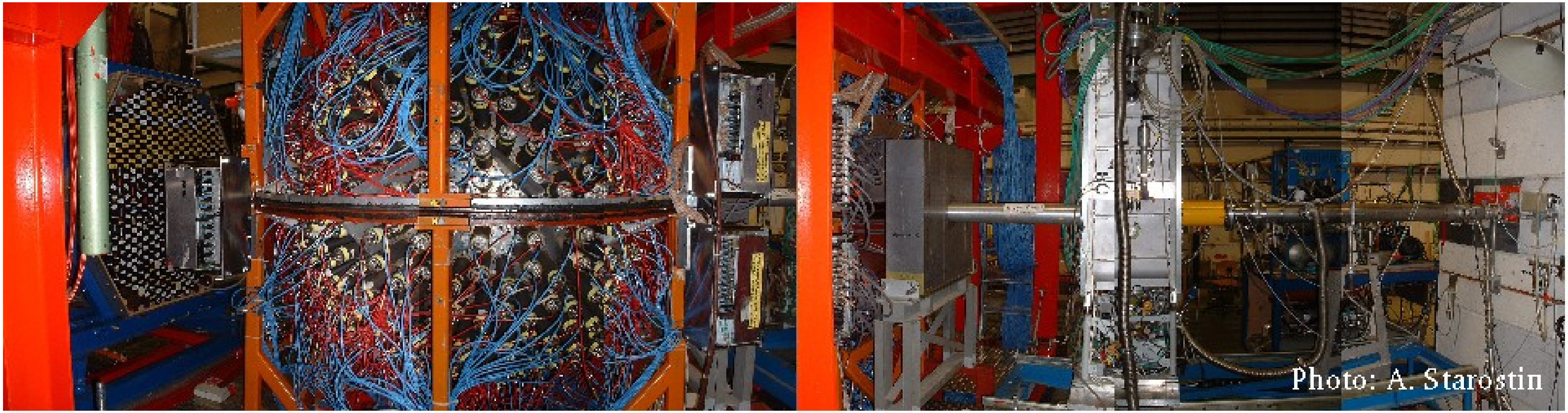
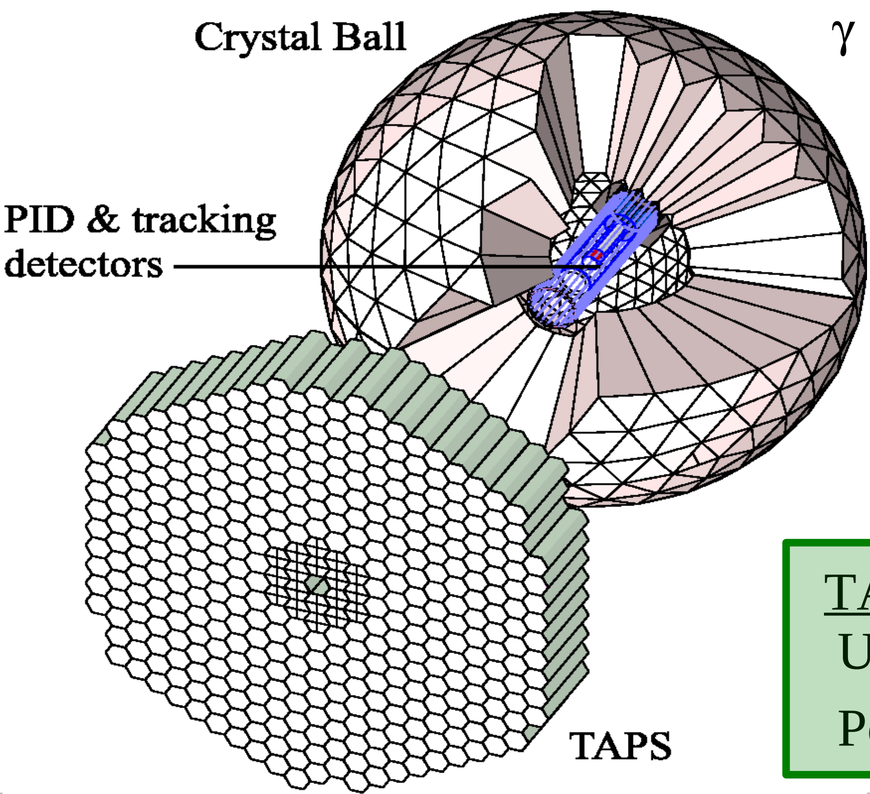




<u>Crystal Ball:</u>

672 NaI(Tl) crystals
93,3% of total solid angle
Each crystal equipped with PMT

$$\frac{\sigma}{E_\gamma} = \frac{2\,\%}{(E_\gamma / GeV)^{0.25}}$$

Δt = 2.5 ns FWHM

$$\sigma(\theta) = 2^\circ \ldots 3^\circ \qquad \sigma(\phi) = \frac{2^\circ \ldots 3^\circ}{\sin(\theta)}$$

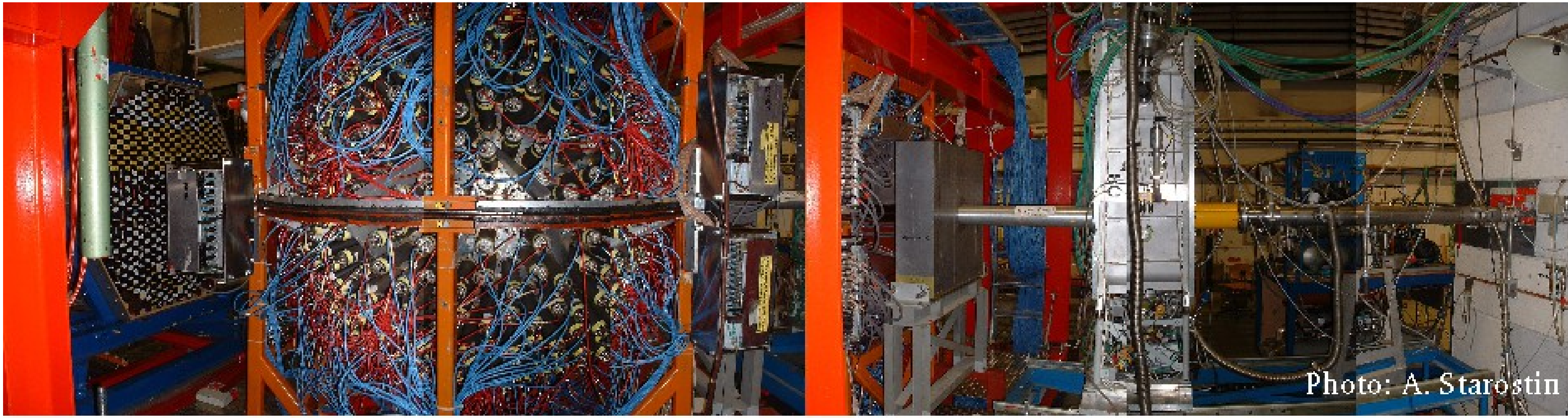
<u>TAPS:</u>

Up to 510 BaF_2 crystals
Polar acceptance: 4-20°

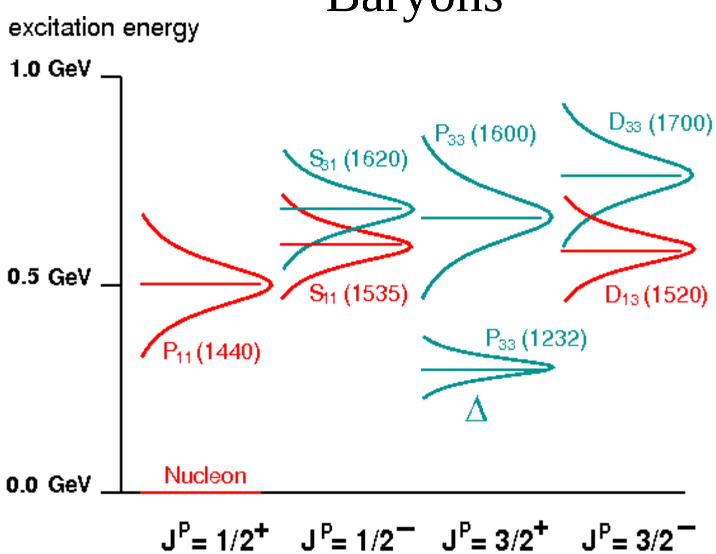
Δt = 0.5 ns FWHM

$$\frac{\sigma}{E_\gamma} = \frac{0{,}79\,‰}{\sqrt{E_\gamma / GeV}} + 1{,}8\,‰$$

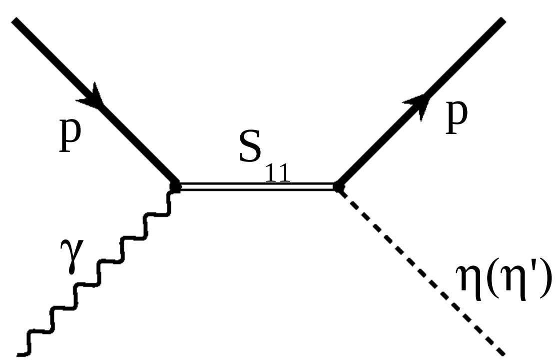
Crystal Ball at MAMI



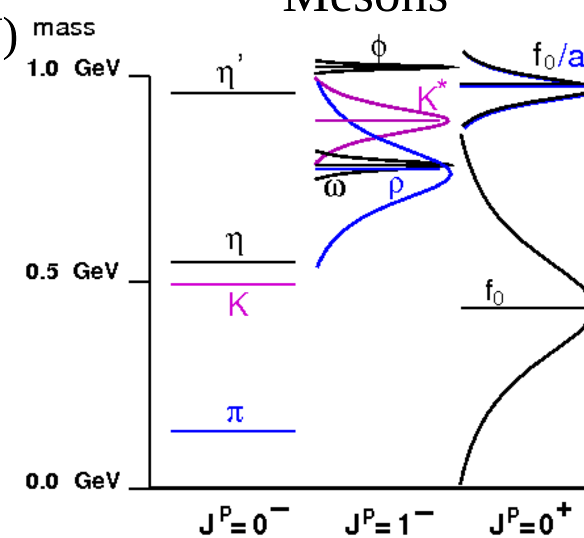
Baryons



Photoproduction ($E_\gamma \leq 1604$ MeV)



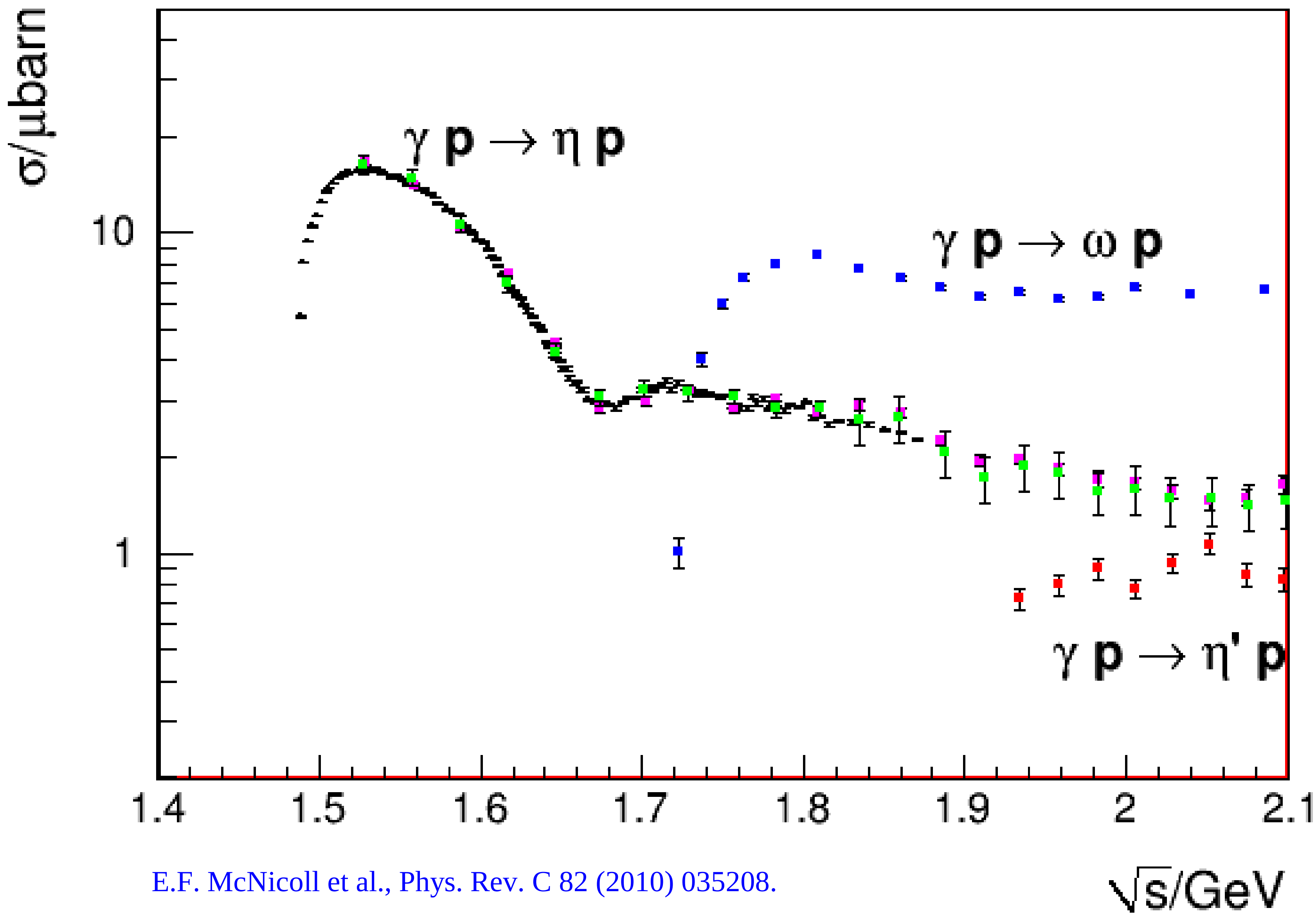
Mesons



- *Meson decays and meson properties*
- *Polarisabilities of nucleons and pions*
- *Properties of the first nucleon excitations*

Experimental Results

Photoproduction Cross Sections



E.F. McNicoll et al., Phys. Rev. C 82 (2010) 035208.

Data from Crystal Ball, Crystal Barrel, SAPHIR, CLAS

$\eta \rightarrow \pi^0 \pi^0 \pi^0$

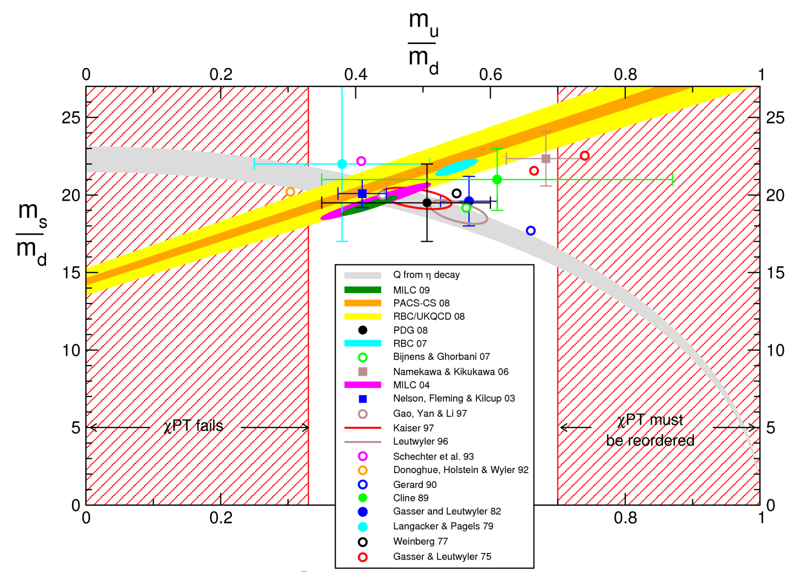
- Isospin violating process
  - electromagnetic contributions small (Sutherland's Theorem)
  - sensitive to quark mass difference

$$\Gamma_{\exp} = \left(\frac{Q_D}{Q} \right)^4 \cdot \bar{\Gamma}$$

$$Q^2 = \frac{m_d^2 - m_u^2}{m_s^2 - (m_d + m_u)^2 / 4}$$

$$(Q_D)^2 = \frac{\left(m_K^2 + \frac{1}{2}(m_{\pi^0}^2 - m_{\pi^+}^2)\right)(m_K^2 - m_{\pi^0}^2)}{m_{\pi^0}^2 (m_{K^0}^2 - m_{K^+}^2)} = (24.2)^2$$

$\bar{\Gamma}$: Γ calculated at Dashen limit



H. Leutwyler, arXiv:0911.1416, CD2009

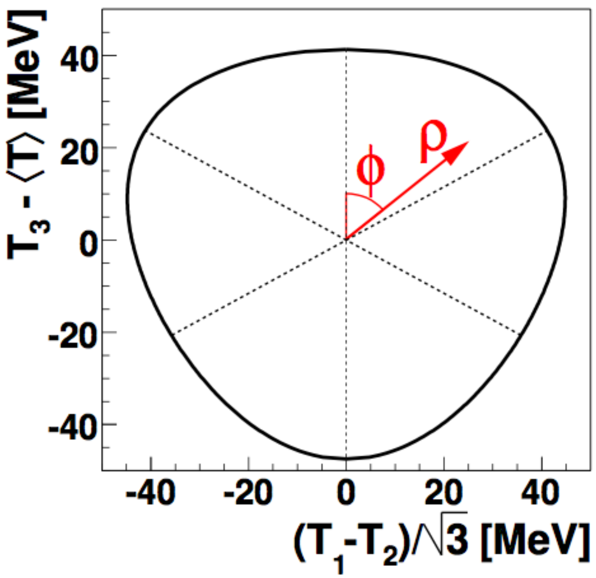
- Good understanding of decay in ChPT is crucial
  - Study Dalitz plot to test ChPT (implementation of ππ scattering)

Dalitz-Plot Analysis

- Parametrize Dalitz plot density:
  - $\Gamma \propto |A(X,Y)|^2 = N\cdot(1 + aY + bY^2 + dX^2 + fY^3 + \ldots)$

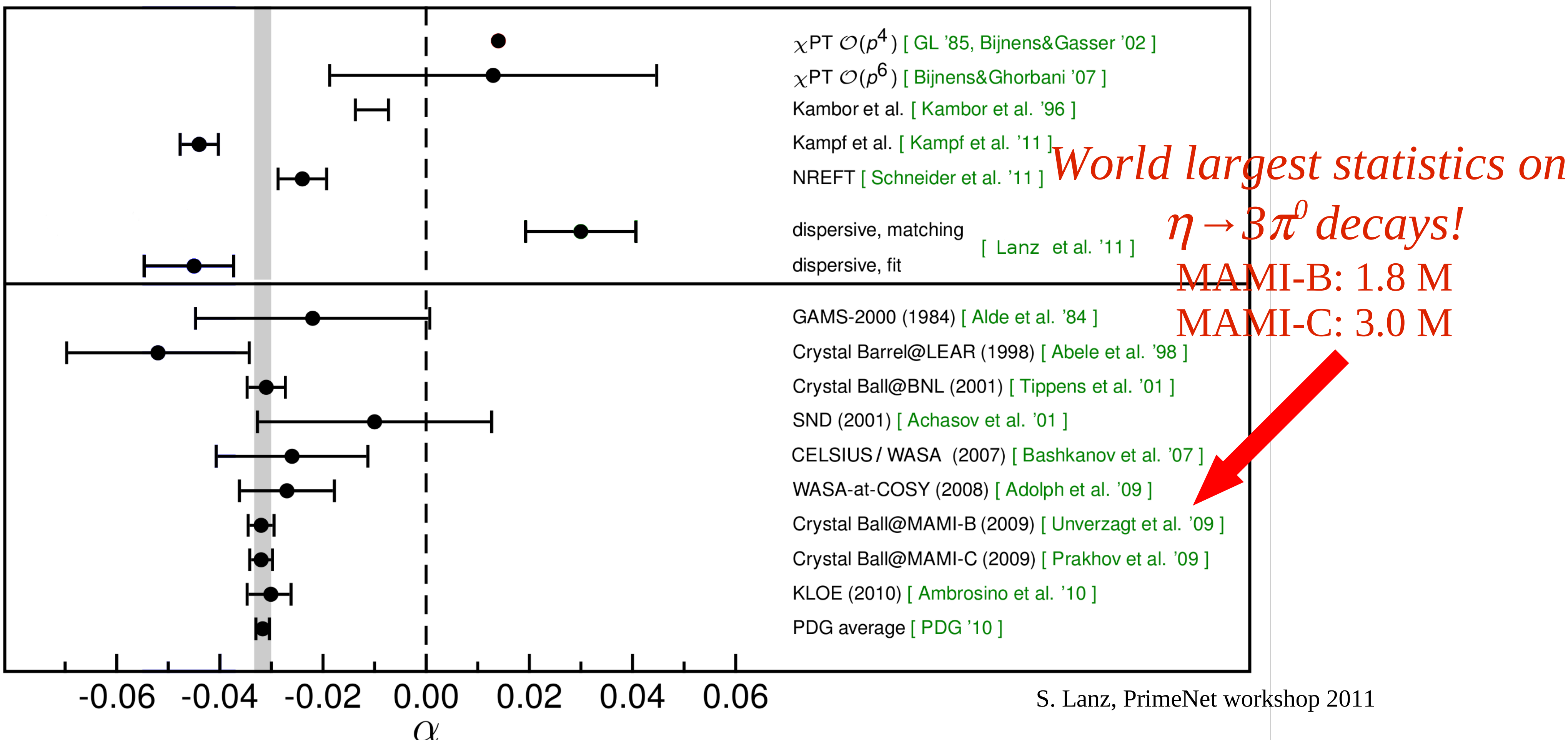
$$X = \frac{\sqrt{3}(T_1 - T_2)}{T_1 + T_2 + T_3}$$

$$Y = \frac{3T_3}{T_1 + T_2 + T_3} - 1$$



- Polar coordinates more convenient for 3 identical particles
  - $\Gamma \propto |A(Z,\varphi)|^2 = N\cdot(1 + 2\alpha Z + \ldots)$

Results for α



S. Lanz, PrimeNet workshop 2011

- Well established experimental database
  - Enough precision to look for higher order effects, e.g. cusp

C/CP-Violating Meson Decays

Citation: K. Nakamura et al. (Particle Data Group), JP G **37**, 075021 (2010) and 2011 partial update for the 2012 edition (URL: http://pdg.lbl.gov)

TESTS OF DISCRETE SPACE-TIME SYMMETRIES

CHARGE CONJUGATION (C) INVARIANCE

$\Gamma(\pi^0 \to 3\gamma)/\Gamma_{total}$		$<3.1 \times 10^{-8}$, CL = 90%
η C-nonconserving decay parameters		
$\pi^+\pi^-\pi^0$ left-right asymmetry		$(0.09^{+0.11}_{-0.12}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ sextant asymmetry		$(0.12^{+0.10}_{-0.11}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ quadrant asymmetry		$(-0.09 \pm 0.09) \times 10^{-2}$
$\pi^+\pi^-\gamma$ left-right asymmetry		$(0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ parameter β (D-wave)		-0.02 ± 0.07 (S = 1.3)
$\Gamma(\eta \to \pi^0\gamma)/\Gamma_{total}$		$<9 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 2\pi^0\gamma)/\Gamma_{total}$		$<5 \times 10^{-4}$, CL = 90%
$\Gamma(\eta \to 3\pi^0\gamma)/\Gamma_{total}$		$<6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 3\gamma)/\Gamma_{total}$		$<1.6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 e^+ e^-)/\Gamma_{total}$	[a]	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 \mu^+ \mu^-)/\Gamma_{total}$	[a]	$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\omega(782) \to \eta\pi^0)/\Gamma_{total}$		$<2.1 \times 10^{-4}$, CL = 90%
$\Gamma(\omega(782) \to 2\pi^0)/\Gamma_{total}$		$<2.1 \times 10^{-4}$, CL = 90%
$\Gamma(\omega(782) \to 3\pi^0)/\Gamma_{total}$		$<2.3 \times 10^{-4}$, CL = 90%
asymmetry parameter for $\eta'(958) \to \pi^+\pi^-\gamma$ decay		-0.03 ± 0.04
$\Gamma(\eta'(958) \to \pi^0 e^+ e^-)/\Gamma_{total}$	[a]	$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to \eta e^+ e^-)/\Gamma_{total}$	[a]	$<2.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to 3\gamma)/\Gamma_{total}$		$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\pi^0)/\Gamma_{total}$	[a]	$<6.0 \times 10^{-5}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\eta)/\Gamma_{total}$	[a]	$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(J/\psi(1S) \to \gamma\gamma)/\Gamma_{total}$		$<5 \times 10^{-6}$, CL = 90%

CP INVARIANCE

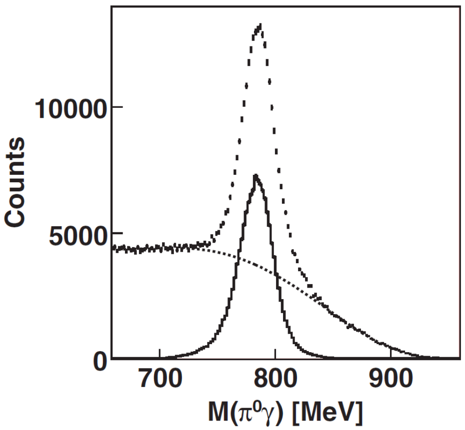
$\mathrm{Re}(d^W_\tau)$	$<0.50 \times 10^{-17}$ e cm, CL = 95%
$\mathrm{Im}(d^W_\tau)$	$<1.1 \times 10^{-17}$ e cm, CL = 95%
$\eta \to \pi^+\pi^- e^+ e^-$ decay-plane asymmetry	$(-0.6 \pm 3.1) \times 10^{-2}$
$\Gamma(\eta \to \pi^+\pi^-)/\Gamma_{total}$	$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 2\pi^0)/\Gamma_{total}$	$<3.5 \times 10^{-4}$, CL = 90%
$\Gamma(\eta \to 4\pi^0)/\Gamma_{total}$	$<6.9 \times 10^{-7}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^+\pi^-)/\Gamma_{total}$	$<2.9 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^0\pi^0)/\Gamma_{total}$	$<1.0 \times 10^{-3}$, CL = 90%
$K^\pm \to \pi^\pm\pi^+\pi^-$ rate difference/average	$(0.08 \pm 0.12)\%$
$K^\pm \to \pi^\pm\pi^0\pi^0$ rate difference/average	$(0.0 \pm 0.6)\%$
$K^\pm \to \pi^\pm\pi^0\gamma$ rate difference/average	$(0.9 \pm 3.3)\%$
$K^\pm \to \pi^\pm\pi^+\pi^-$ $(g_+ - g_-)$ / $(g_+ + g_-)$	(-1.5+-2.2) $\times 10^{-4}$
$K^\pm \to \pi^\pm\pi^0\pi^0$ $(g_+ - g_-)$ / $(g_+ + g_-)$	(1.8+-1.8) $\times 10^{-4}$

Only weak upper limits

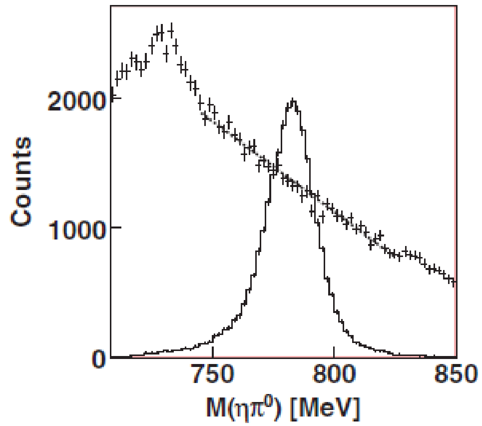
Improve upper limits by factor >10

C-Violation in ω Decays

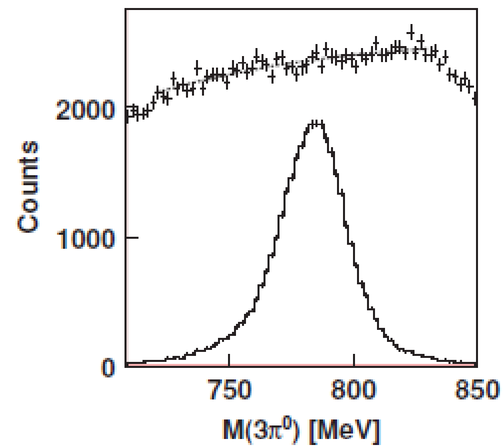
A. Starostin et al., Phys. Rev. C 79, 065201 (2009).



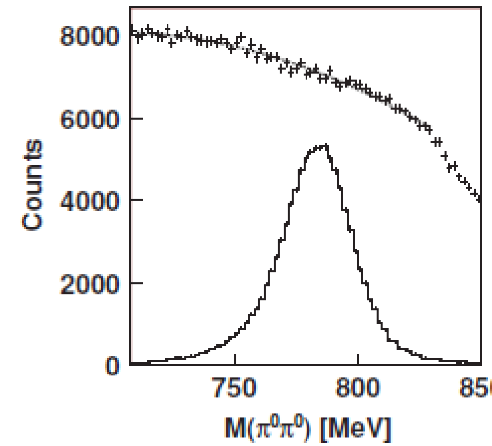
$1.5 \cdot 10^5$ events



<60 events



<219 events



<336 events

Different beam energy interval!

PDG 2010:

$\Gamma(\omega(782) \to \eta\pi^0)/\Gamma_{total}$	$<2.1 \times 10^{-4}$, CL = 90%	
$\Gamma(\omega(782) \to 2\pi^0)/\Gamma_{total}$	$<2.1 \times 10^{-4}$, CL = 90%	never done before
$\Gamma(\omega(782) \to 3\pi^0)/\Gamma_{total}$	$<2.3 \times 10^{-4}$, CL = 90%	

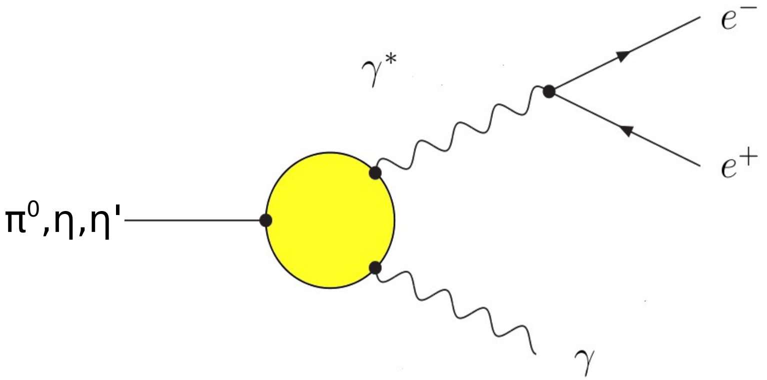
CB at MAMI results are dominating!

Transition Form Factors

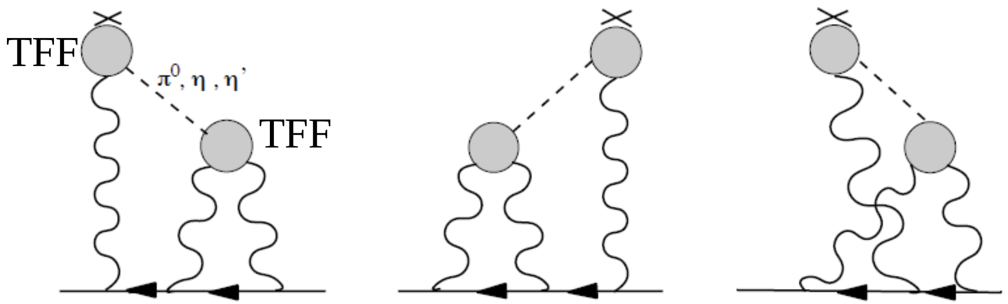
- Dalitz decays of light mesons allow to determine the transition form factor in the time-like region
  - study el.-mag. structure of the decaying neutral meson

$$\frac{d\Gamma_{e^+e^+\gamma}}{dq^2} = \left[\frac{d\Gamma_{e^+e^+\gamma}}{dq^2}\right]_{QED} \cdot \left|F(q^2)\right|^2$$

$$F(q^2) \approx 1 + \frac{q^2}{\Lambda^2} = 1 + b\,q^2$$

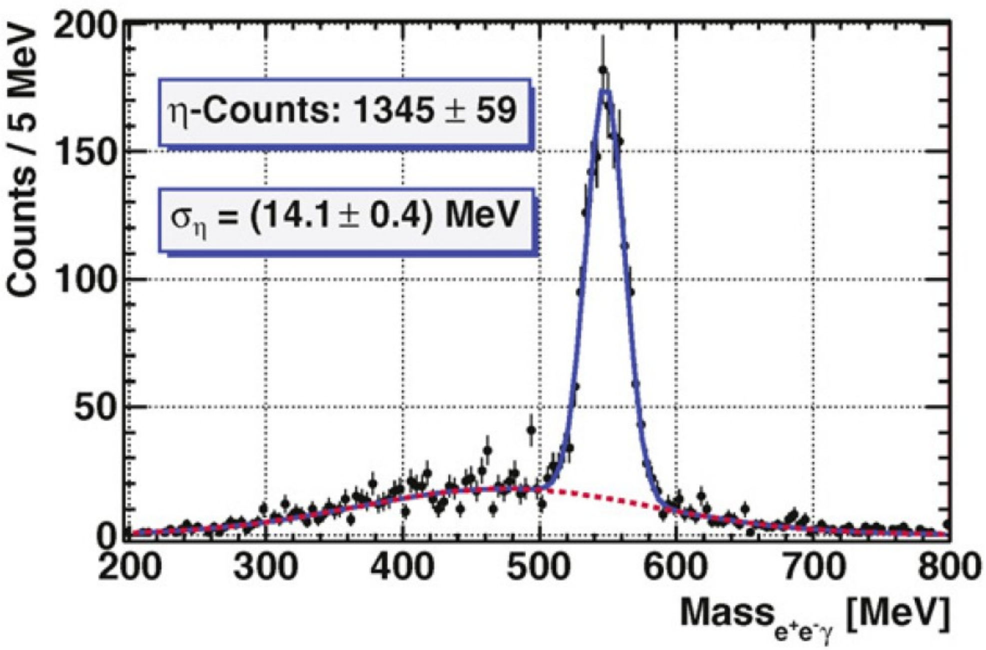


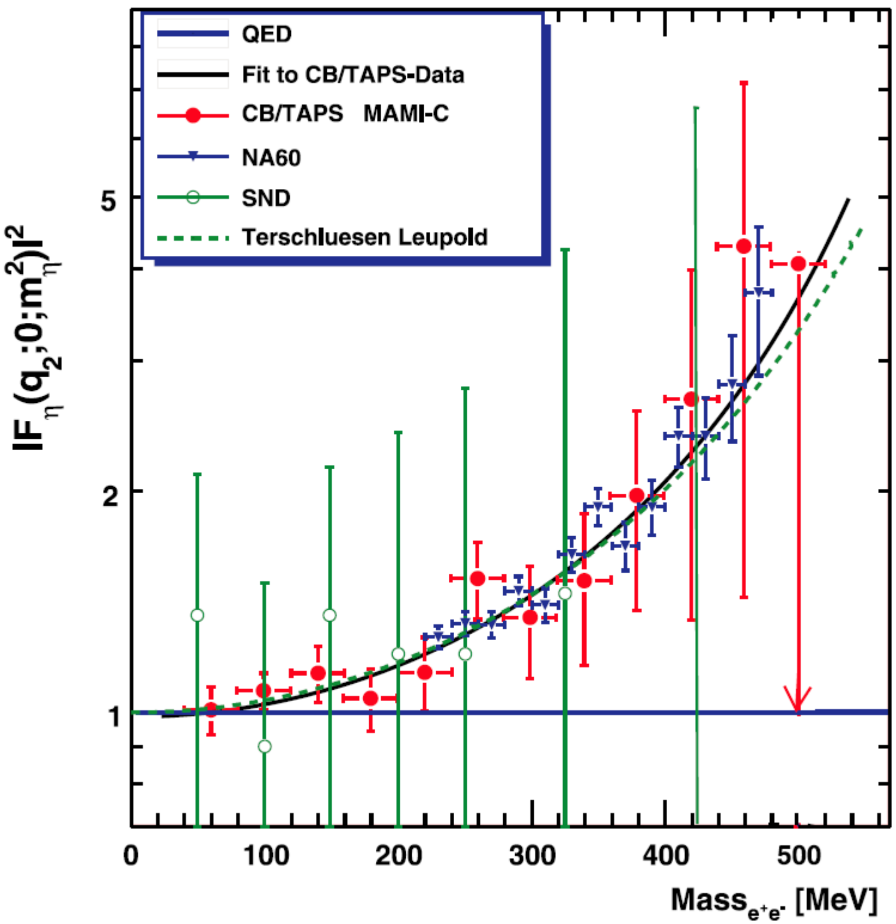
- Important input to calculations of the hadronic light-by-light scattering
  - Important contribution to $(g-2)_\mu$
    - One of the largest uncertainties



TFF in $\eta \to e^+e^-\gamma$

H. Berghäuser et al., Phys. Rev. B 701 (2011) 562-567.





Fit to CB/TAPS data:

$\Lambda = (720 \pm 60_{stat} \pm 25_{syst})$ MeV

C. Terschlüsen, S. Leupold, private communication
M.N. Achasov et al. (SND), Phys. Lett. B 504 (2001) 275-281.
R. Arnaldi et al. (NA60), Phys. Lett. B 677 (2009) 260-266.

New Collaborative Research Center

The Low Energy Frontier of the Standard Model:

From Quarks and Gluons
To Hadrons and Nuclei

CRC1044

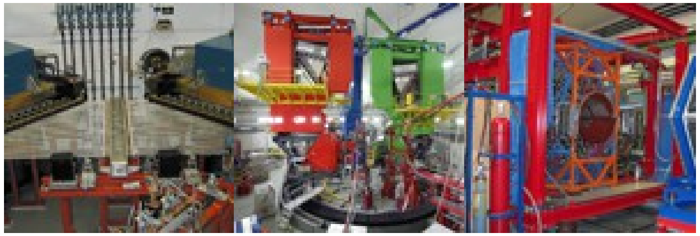
12 years physics program

- The impact of hadron physics for precision tests of the Standard Model
- Timelike and spacelike observables of hadron structure
- Structure and dynamics of light mesons
- Nuclear few-body systems and baryon-baryon interactions

4 years DFG funding guaranteed with extension up to 12 years

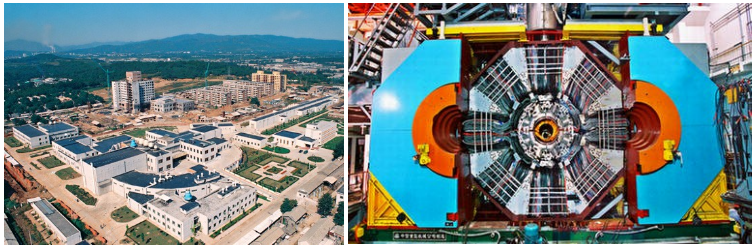
Complementary aspects at

MAMI



BES-III/BEPC-II

e+e- collider at $\sqrt{s}$ *= 2 …. 4.5 GeV:*



Role of Crystal Ball at MAMI in CRC1044

- Electromagnetic decays of light mesons
  - Production aims for the next 4 years
    - $5 \cdot 10^8$ η
    - $2 \cdot 10^8$ ω
    - $5 \cdot 10^7$ η'
- Time-like transition form factors
  - $\eta \rightarrow e^+e^-\gamma$ 30000 events expected
  - $\eta' \rightarrow e^+e^-\gamma$ 200-300 events expected
  - $\omega \rightarrow \pi^0 e^+e^-$ 250-500 events expected
- Goals for 2nd and 3rd funding period
  - TPC for improved tracking and PID
  - Detailed studies of
    - $\eta' \rightarrow e^+e^-\gamma$
    - $\eta' \rightarrow e^+e^-\omega$
    - $\eta' \rightarrow e^+e^-\rho$

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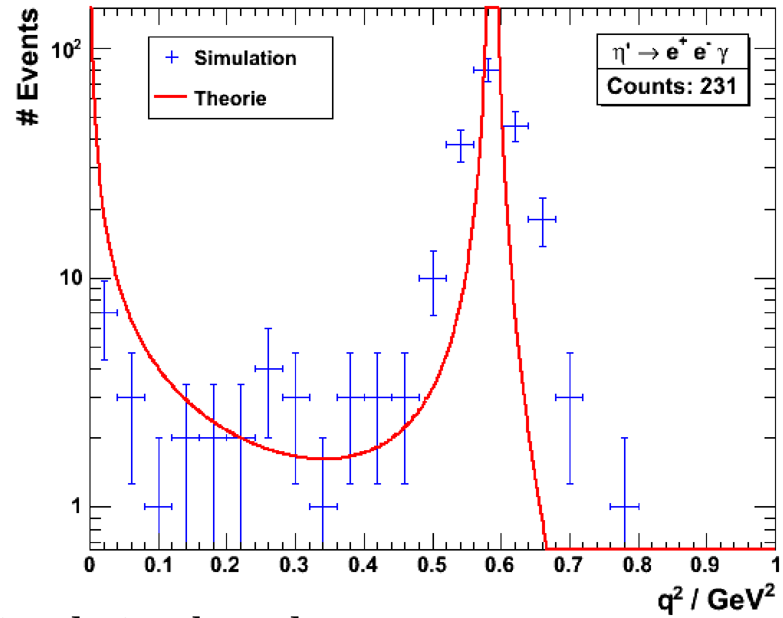

Simulation based on
- PDG upper limit for branching ratio
- Estimated η' production rate at MAMI-C (6 weeks, total 18 million η')
- Efficiency from $\eta \rightarrow e^+e^-\gamma$ (~2%)

S. Wagner, Bachelor thesis, University Mainz, 2011
M. Unverzagt, A. Denig

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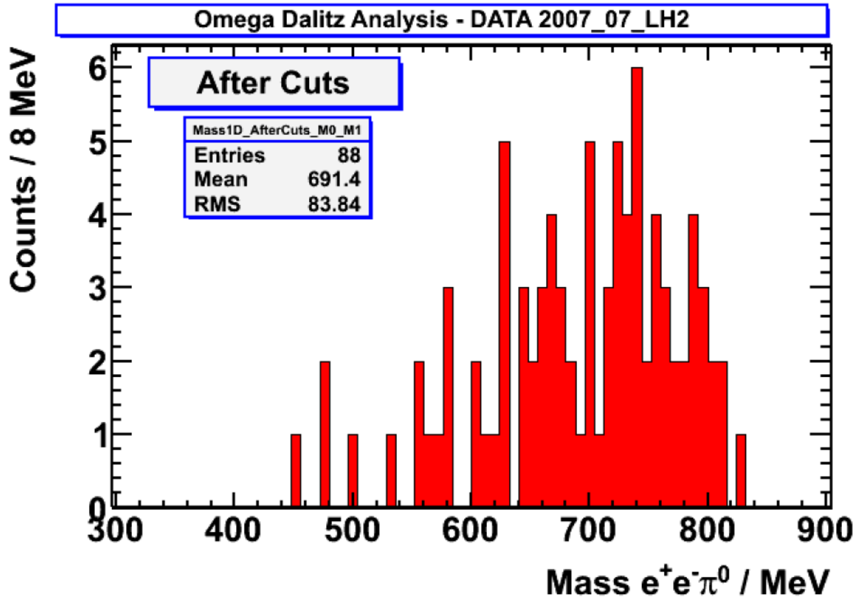
    - $\eta' \to e^+e^-\rho$

First study did not yield conclusive result

more statistics from 2009 available



H. Berghäuser, PhD thesis, University Gießen, 2010.
A2-Collaboration

Role of Crystal Ball at MAMI in CRC1044

- Meson decays with unprecedented accuracy
  - Production aims for the next 4 years
    - $5 \cdot 10^8$ η
    - $2 \cdot 10^8$ ω
    - $5 \cdot 10^7$ η'
- Branching Ratios
  - $BR(\omega \to \eta\gamma / \omega \to \pi^0\gamma) = 0.0098 \pm 0.0024$
  - $BR(\eta' \to \omega\gamma / \eta' \to \eta\pi^0\pi^0) = 0.147 \pm 0.016$

Improve by factor 2 - 5

- Decay dynamics / Tests of ChPT
  - $\eta/\eta' \to \pi^0\pi^0\pi^0$
  - $\eta' \to \eta\pi^0\pi^0$ 400000 events expected
- Goals for 2nd and 3rd funding period
  - TPC, new trigger concepts and forward trigger detector
    - Detailed studies of charged decay modes
      - $\eta/\eta' \to \pi^+\pi^-\gamma$, $\eta/\eta' \to \pi^+\pi^-\gamma\gamma$, $\eta' \to e^+e^-\rho$
    - Measurement of absolute branching ratios

Summary

- Crystal Ball at MAMI is ideal for high rate η, η' and ω experiments
  - leading role in neutral decays of η, η' and ω
    - Decay Dynamics
    - Branching Ratios
    - Transition form factor

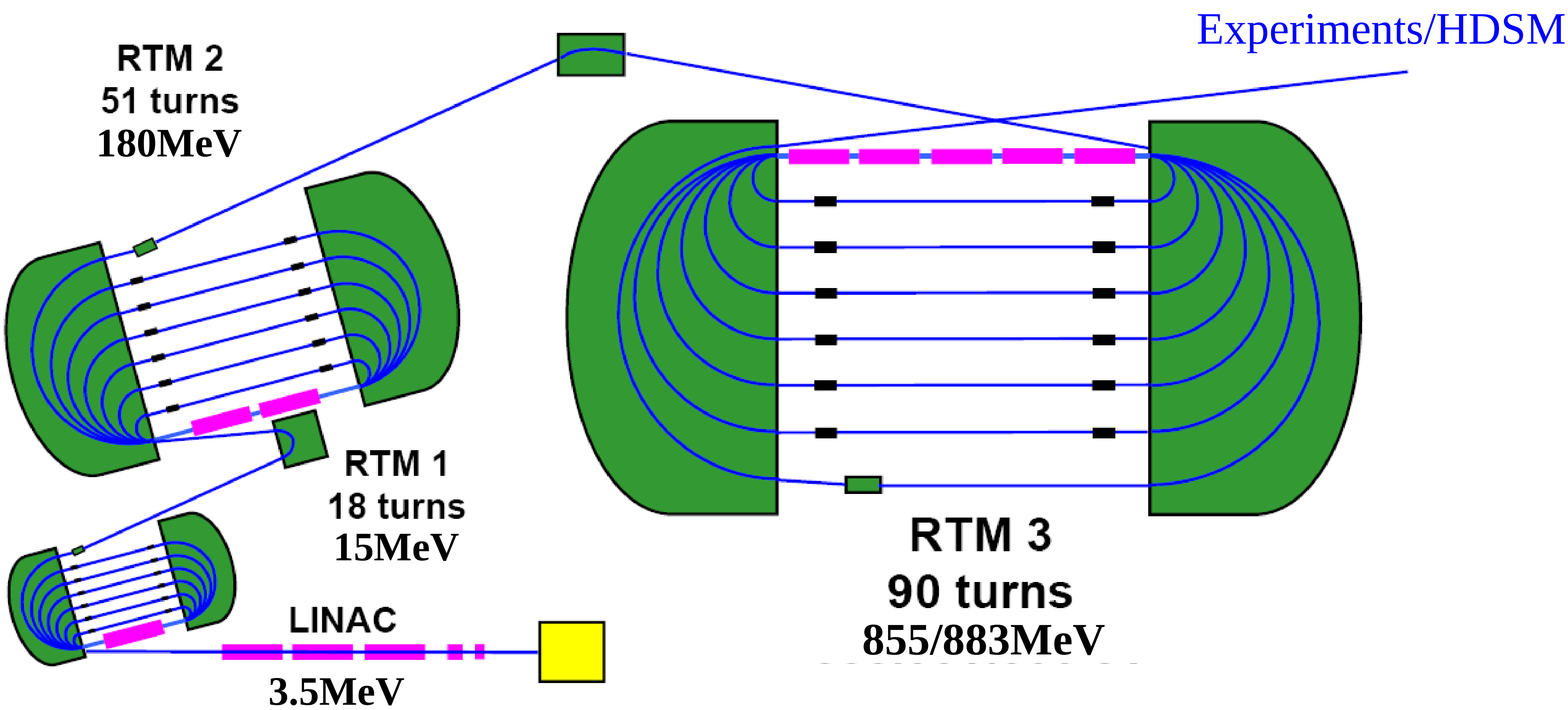
- New Collaborative Research Centre established at MAMI
  - 4 years of DFG funding guaranteed
  - extension up to 12 years for the full physics program

- First η' run with Crystal Ball successful in March 2012
  - End-point tagger installed and working
  - Taking data right now

- New detector developments:
  - TPC with high rate capability (prototype under construction)
  - forward trigger and tracking detectors under consideration
    - improved detection of charged decays of η, η' and ω

Backup

Mainz Microtron (MAMI-B)



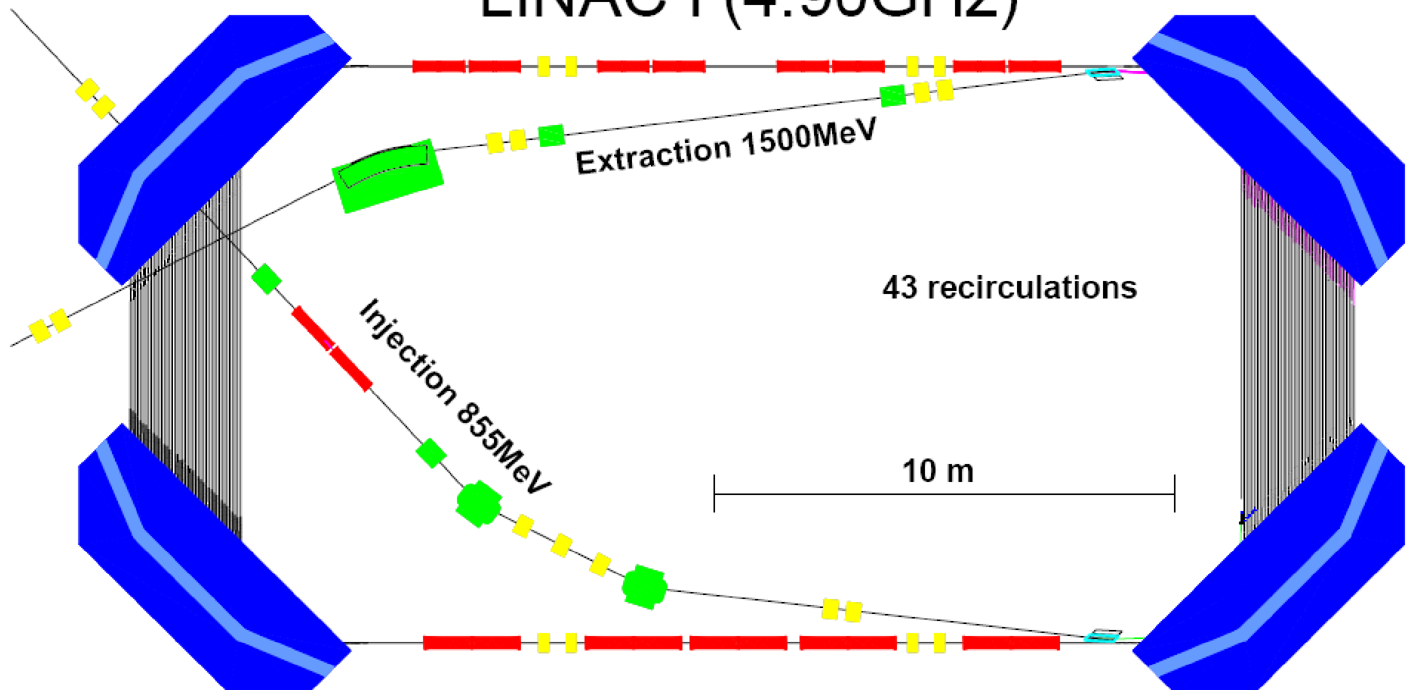
Acceleration via em wave (2.45GHz)
cw: bunch structure ~0.4ns
Injektion LINAC
3 cascaded Race-Track-Microtrons
Magnet of RTM 3 ~450t per Magnet, 1.28T

HDSM (MAMI-C)

9.0 MV / turn max gain

From MAMI-B

LINAC I (4.90GHz)

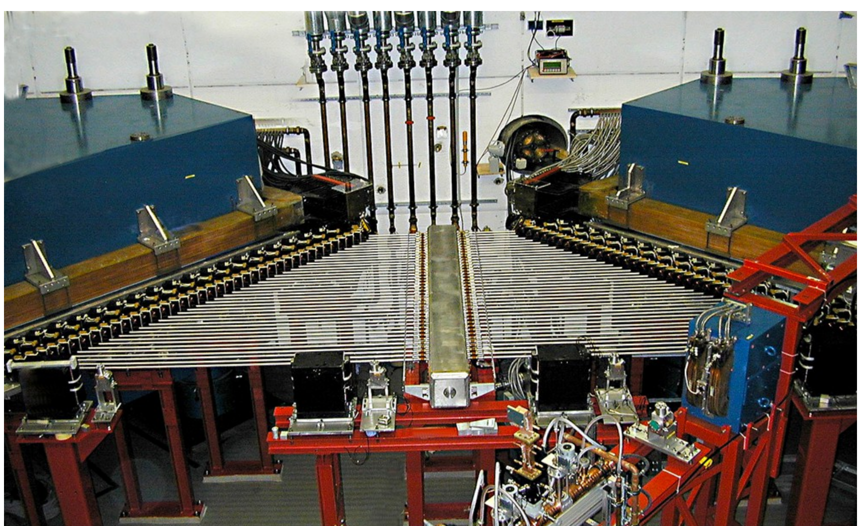


To Experiments
2007: 1508MeV
2008: 1558MeV
2009: 1604MeV

LINAC II (2.45GHz)

B_{max}=1.539T

9.3 MV / turn max gain

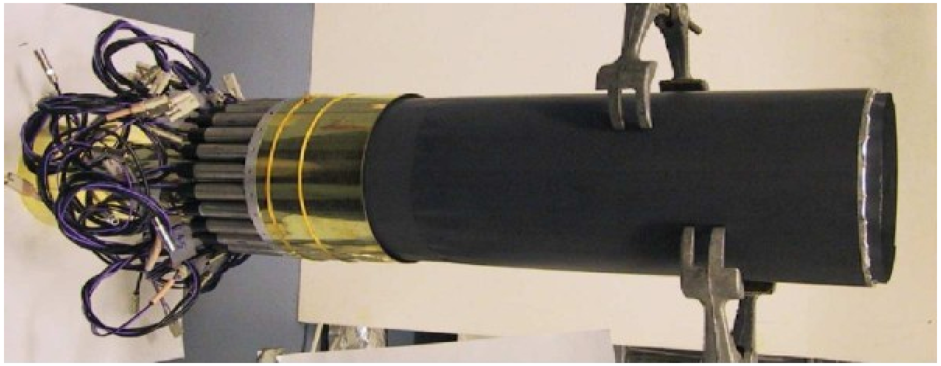


Harmonic Doubled Sided Microtron (HDSM)

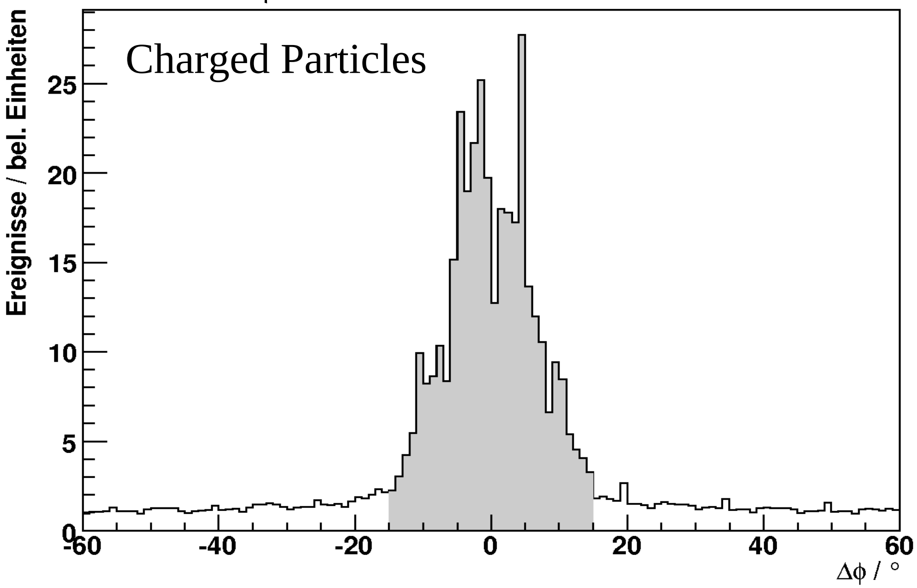
K.-H. Kaiser et al., NIM A 593, 159 (2008).

Particle Identificaton Detector (PID):

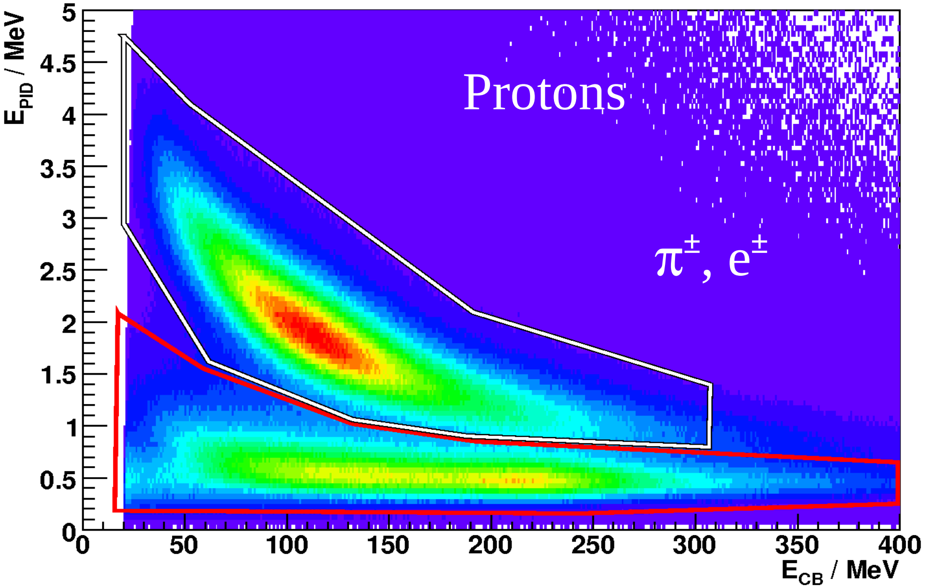
- Cylindrical Detector inside CB
- 24 scintillator strips
- PMT readout



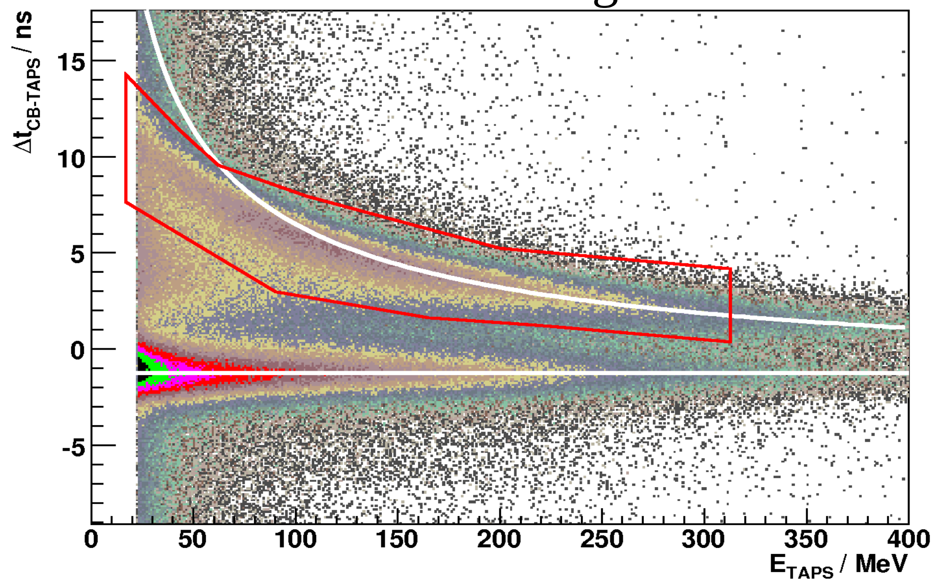
Δϕ- between CB and PID

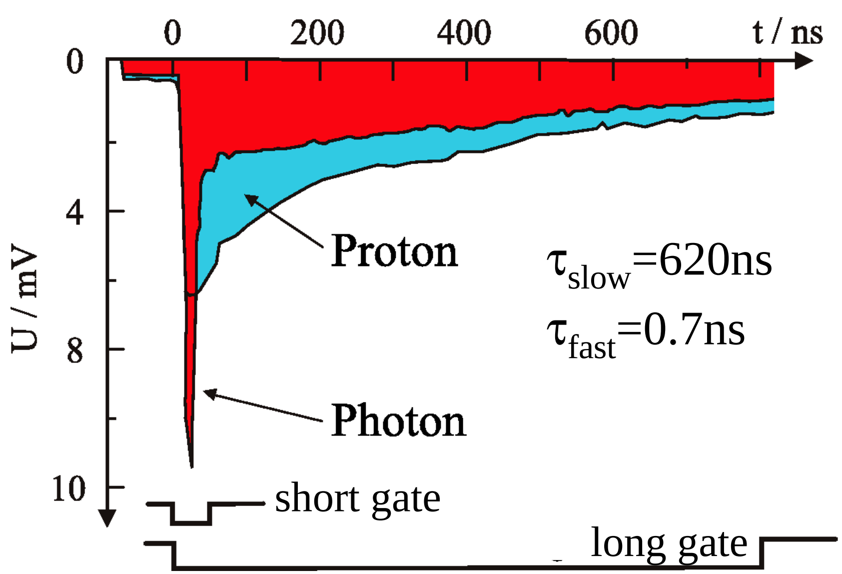


Energy Dependence



Time-of-Flight

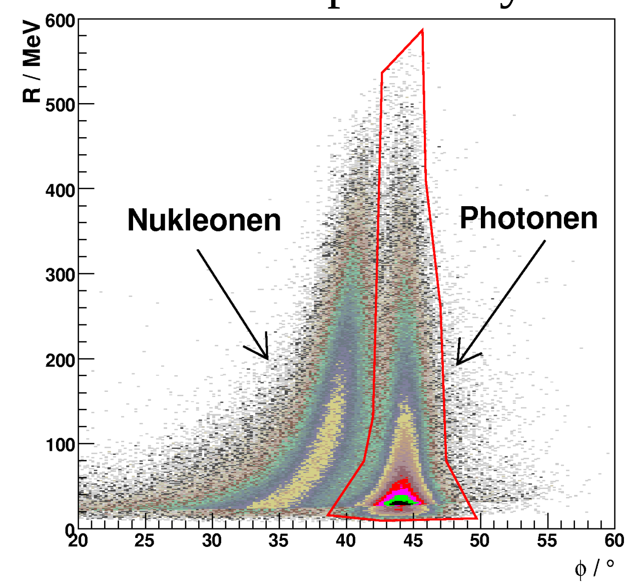




$$R = \sqrt{E_{short}^2 + E_{long}^2}$$

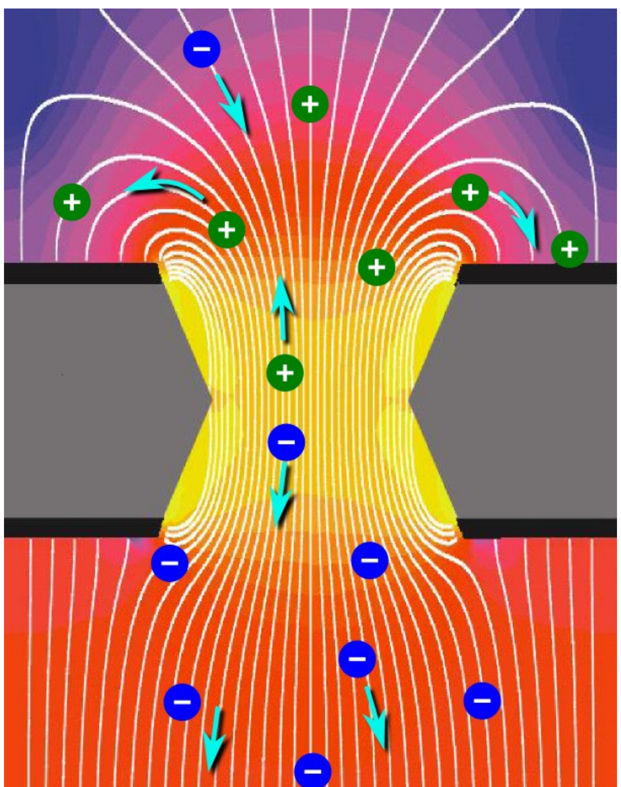
$$\phi = \arctan\left(\frac{E_{short}}{E_{long}}\right)$$

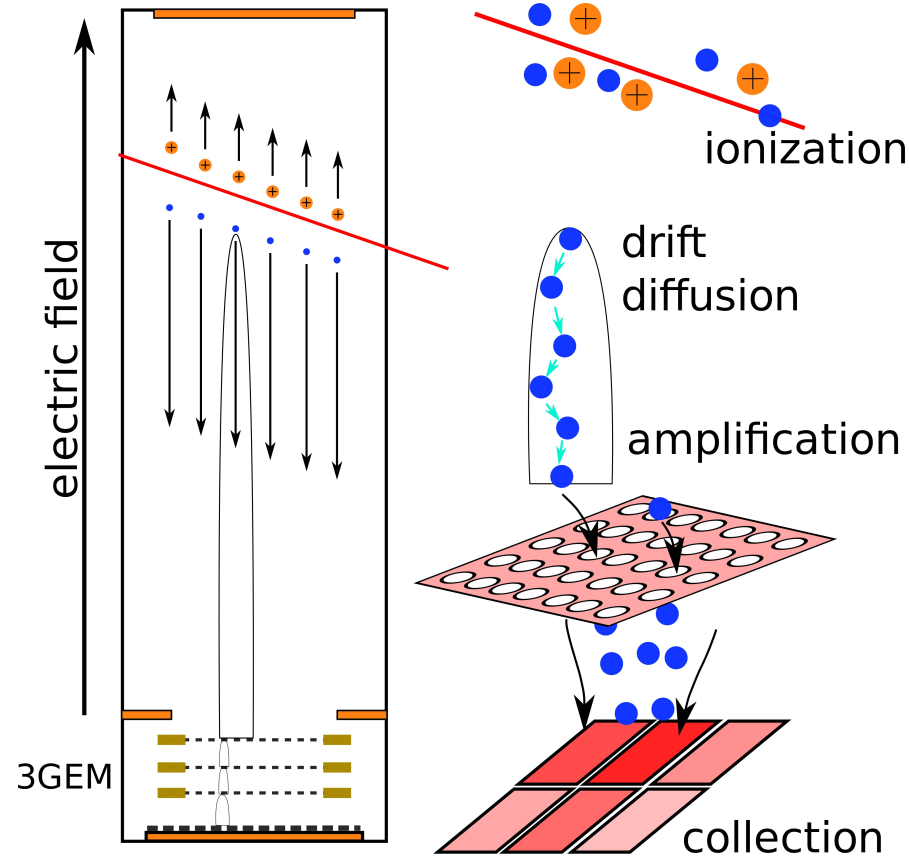
Pulse-Shape-Analysis

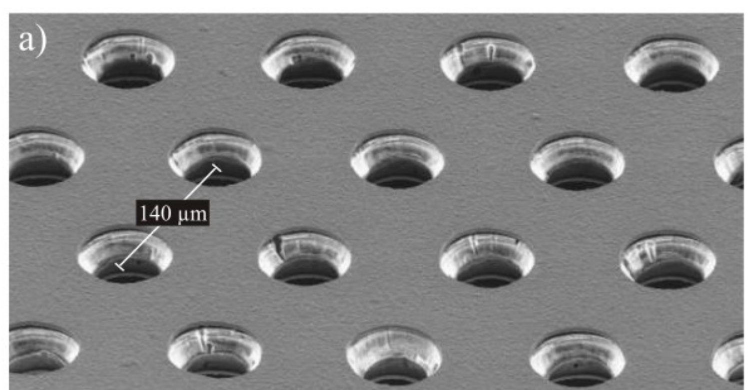


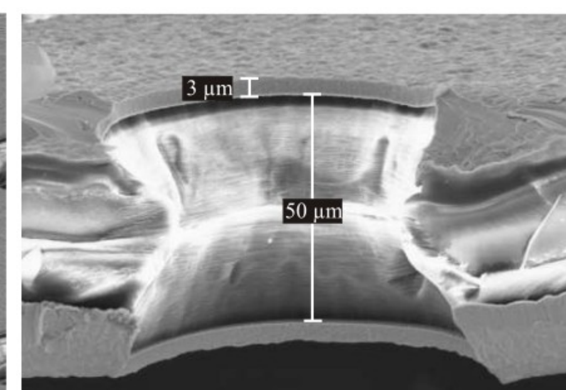
Existing MWPCs are not working for high rate meson decay experiments

TPC advantages:
- Improve resolution
- Higher rate capability
- Contribute to particle ID (dE/dx measurement)
- Track reconstruction

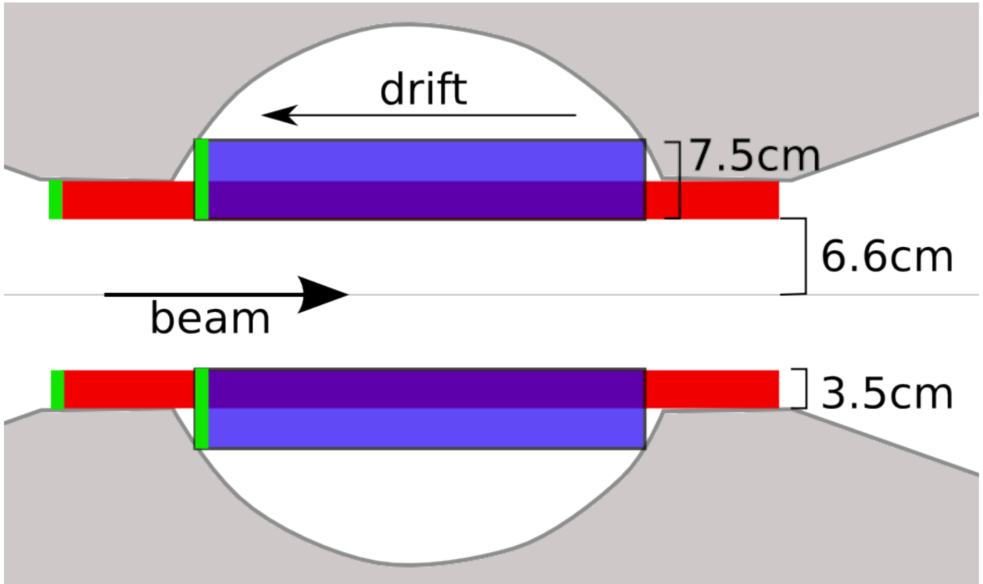








TPC in CB



- Readout on backward end
- Space needed for target and PID
- Pad size: ≈ 2 mm x 5 mm
- →2000 to 5000 channels

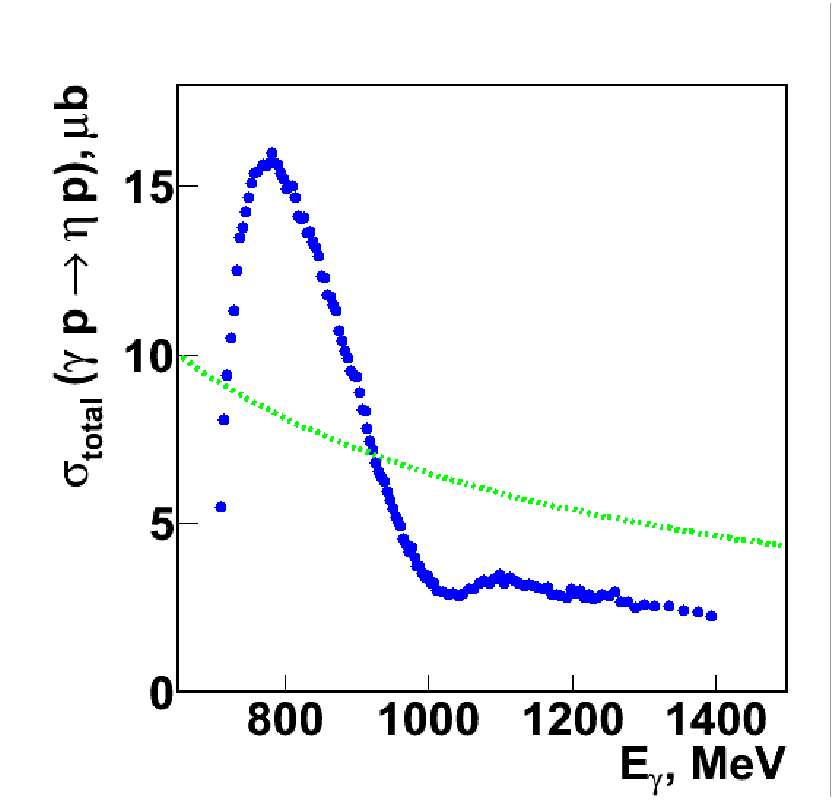
Long version:
- ≈ 3.5 cm effective radius
- Only few pad rows
- Easier installation

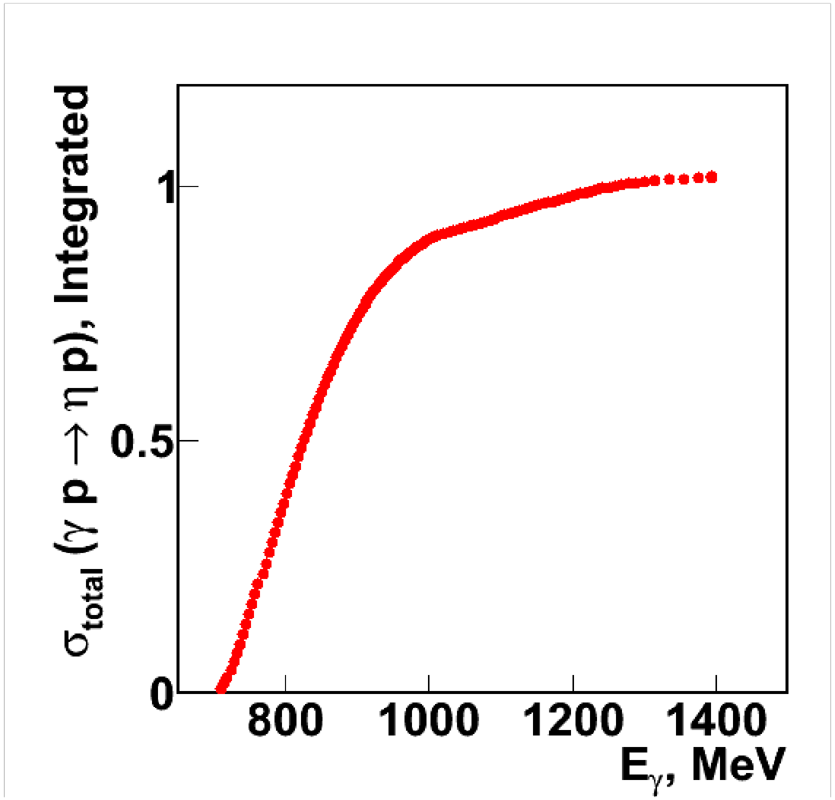
?

Short version:
- ≈ 7 cm effective radius
- More data points
- End caps cover lowest crystals
- But end caps very thin

- First test with old TPC from Karlsruhe successful
- 2011: construct prototype

η-Photoproduction





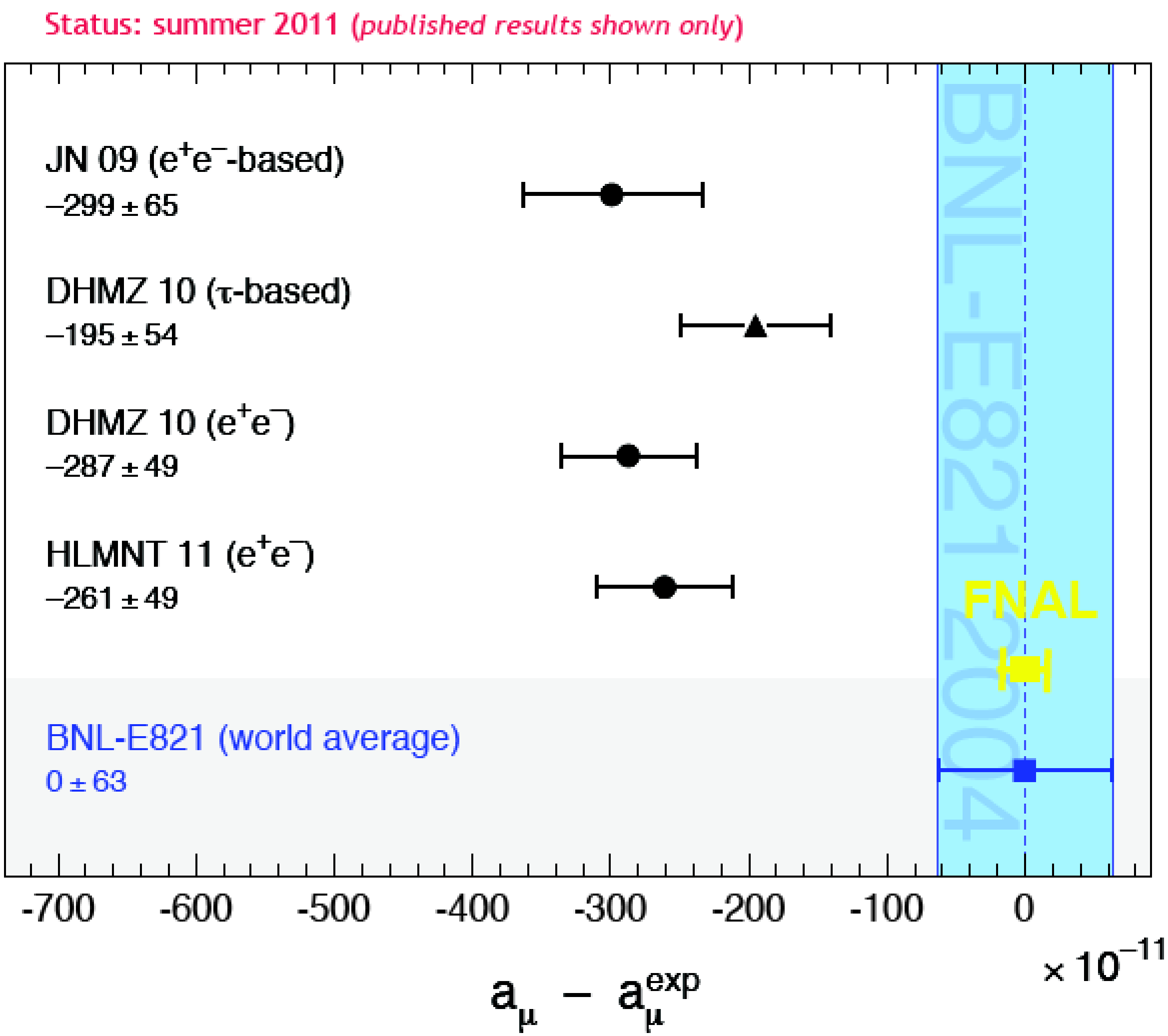
At MAMI a beam of tagged photons of excellent quality is available:

- High intensity photon beam
- Fine energy resolution
- Outstanding stability

Beam energy nearly perfect for high statistics η photoproduction

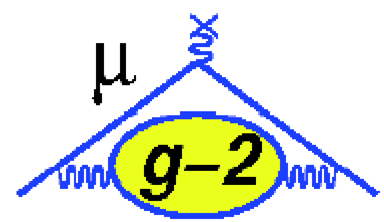
$(g\text{-}2)_\mu$ Theorie vs. Experiment

Standard Model: $(116\,591\,834 \pm 49)\cdot 10^{-10}$
Experiment: $(116\,592\,089 \pm 63)\cdot 10^{-10}$



Striking result:
$a_\mu^{exp} - a_\mu^{theo\,(SM)}$
> 3 standard deviations

New FNAL $(g\text{-}2)_\mu$ measurement E969:



Factor 4 improvement of experimental error

Contributions to $(g-2)_\mu$

- QED contributions:

  $(116584718.09 \pm 0.16) * 10^{-11}$

- Electro-Weak Contribution:

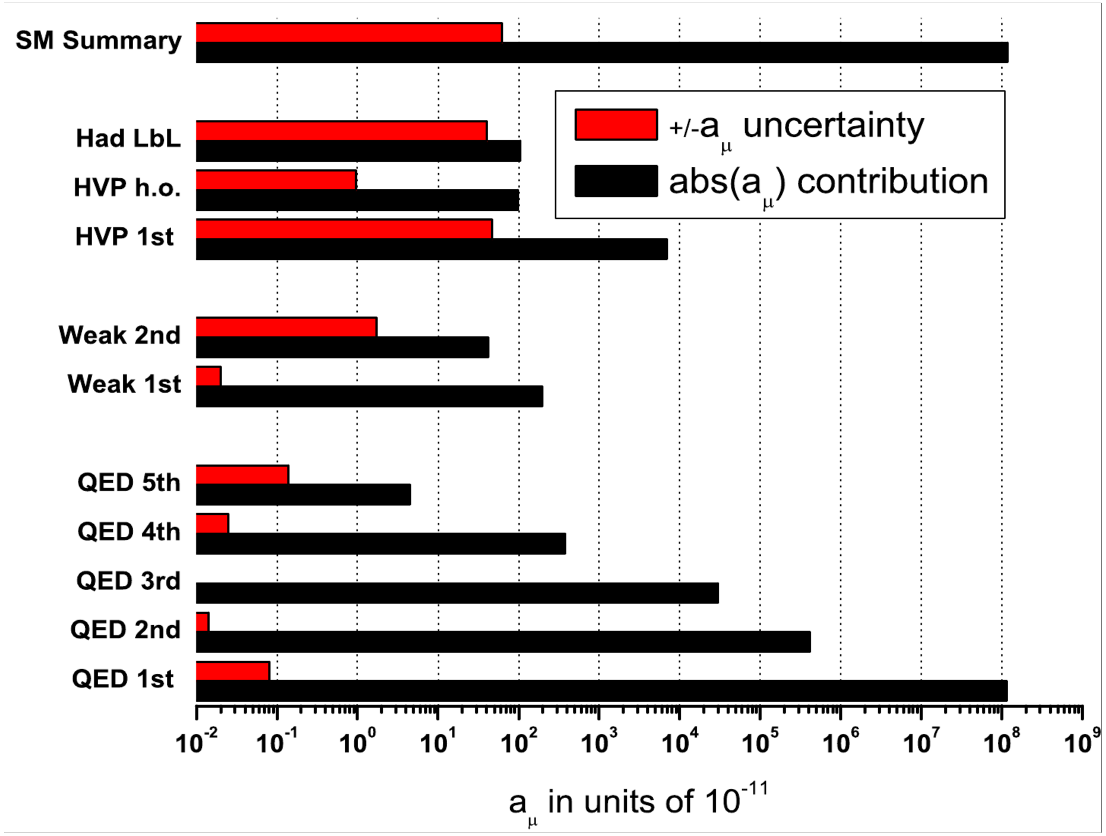
  $(154 \pm 2) * 10^{-11}$

- Hadronic vacuum polarization:

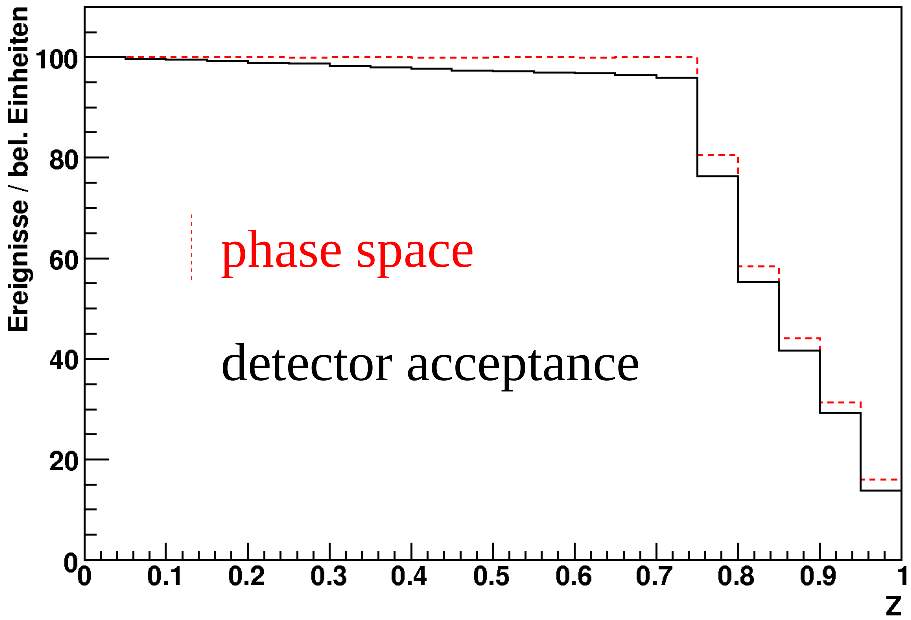
  $(6955 \pm 41) * 10^{-11}$

- Hadronic light-by-light:

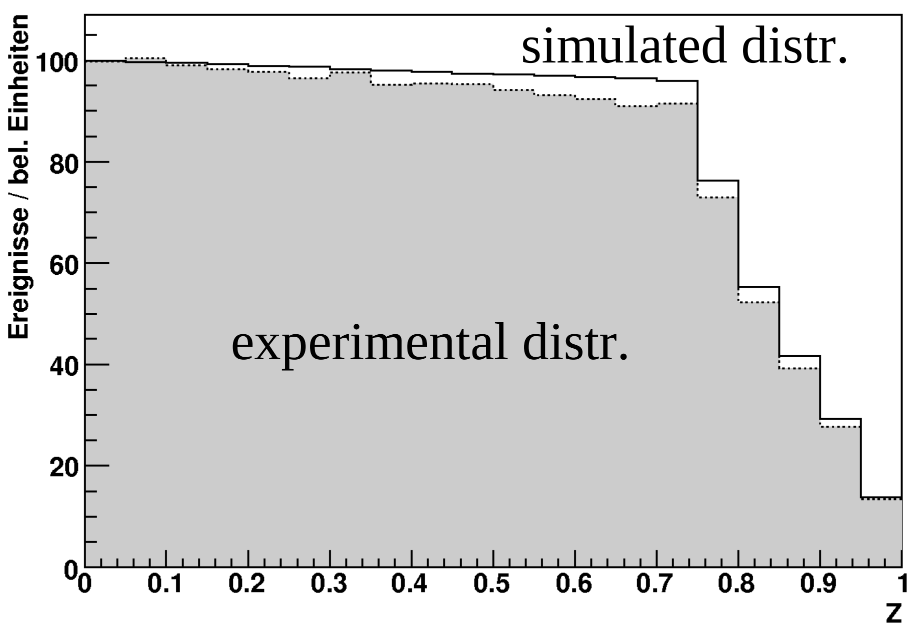
  $(105 \pm 26) * 10^{-11}$

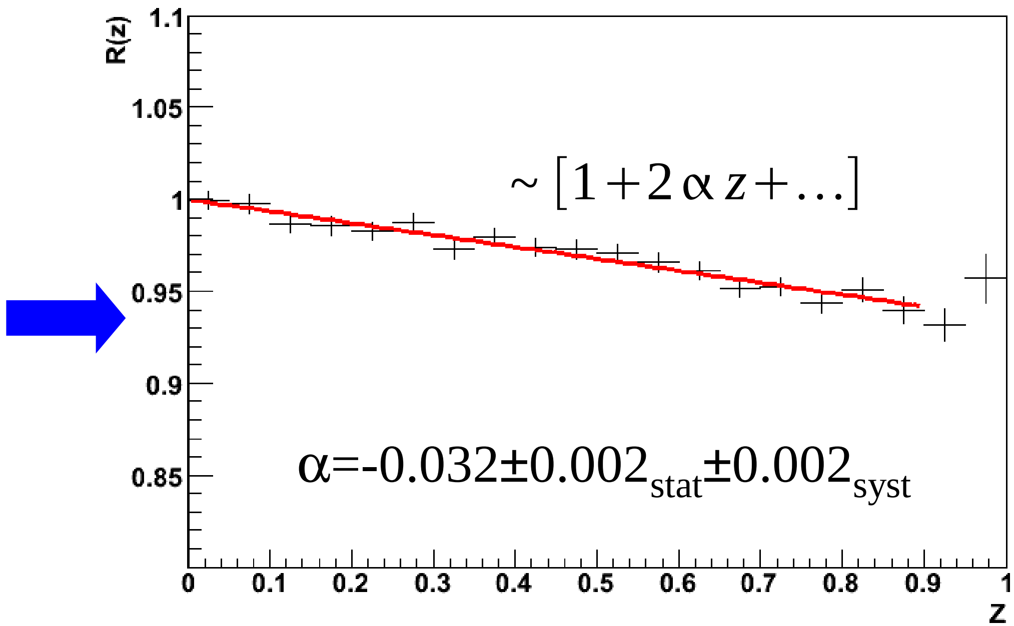


Uncertainty of the light-by-light hadronic contribution is expected to be dominant for the next generation of the g-2 measurements

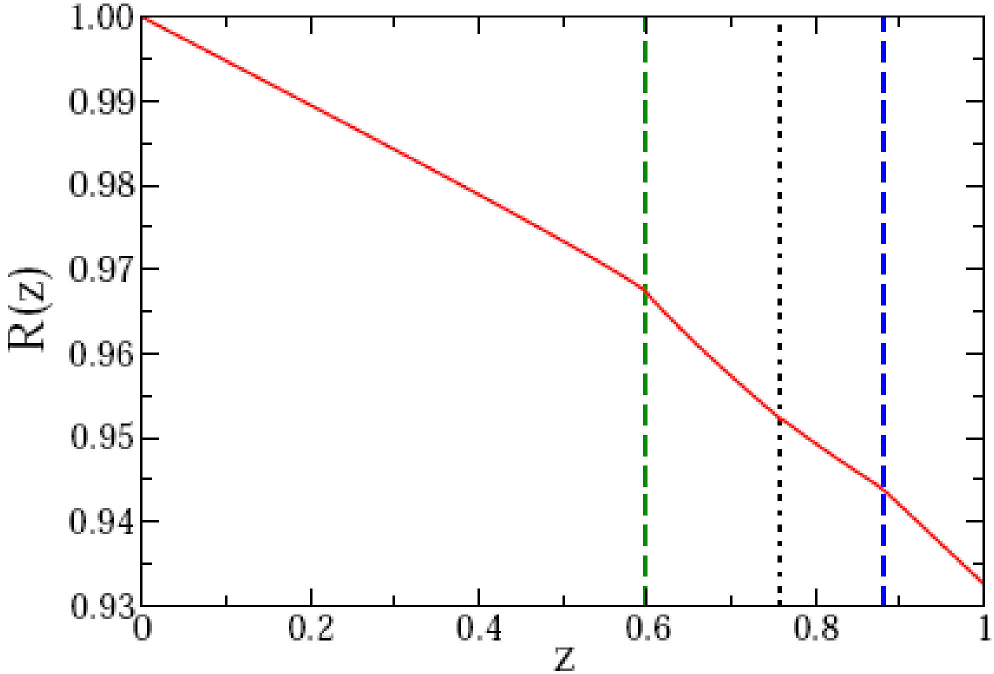


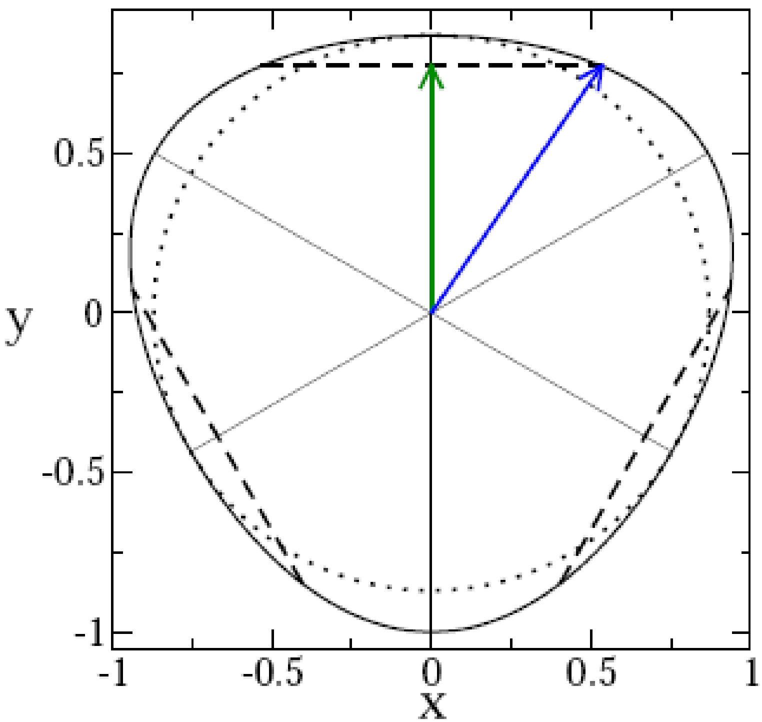
• precise simulation required





Effect of Cusp on α





Cusp has 5% effect on Dalitz Plot Parameter

C. Ditsche, B. Kubis, Ulf-G. Meißner, Eur. Phys. J. C 60, 83 (2009).

Further effects:

- Kinematic boundaries
- Second order in amplitude expansion

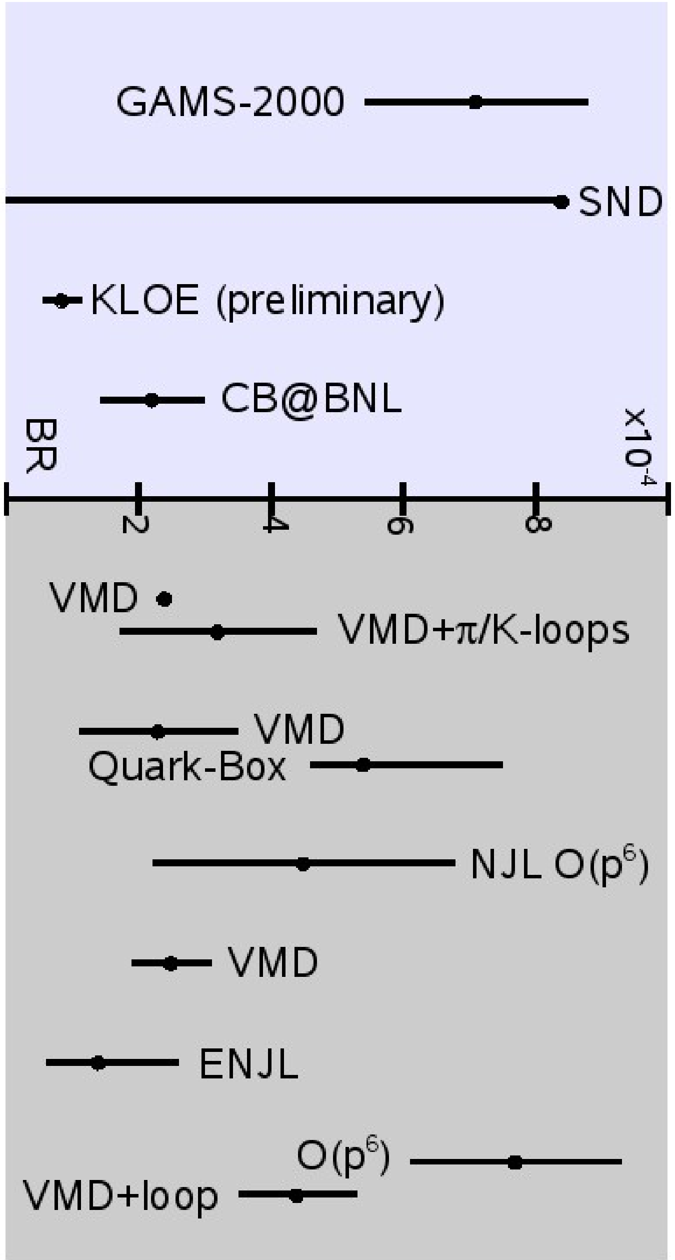
Tests with $\eta \to \pi^0\gamma\gamma$

$$L_{eff} = L_2 + L_4 + L_6 + \ldots$$

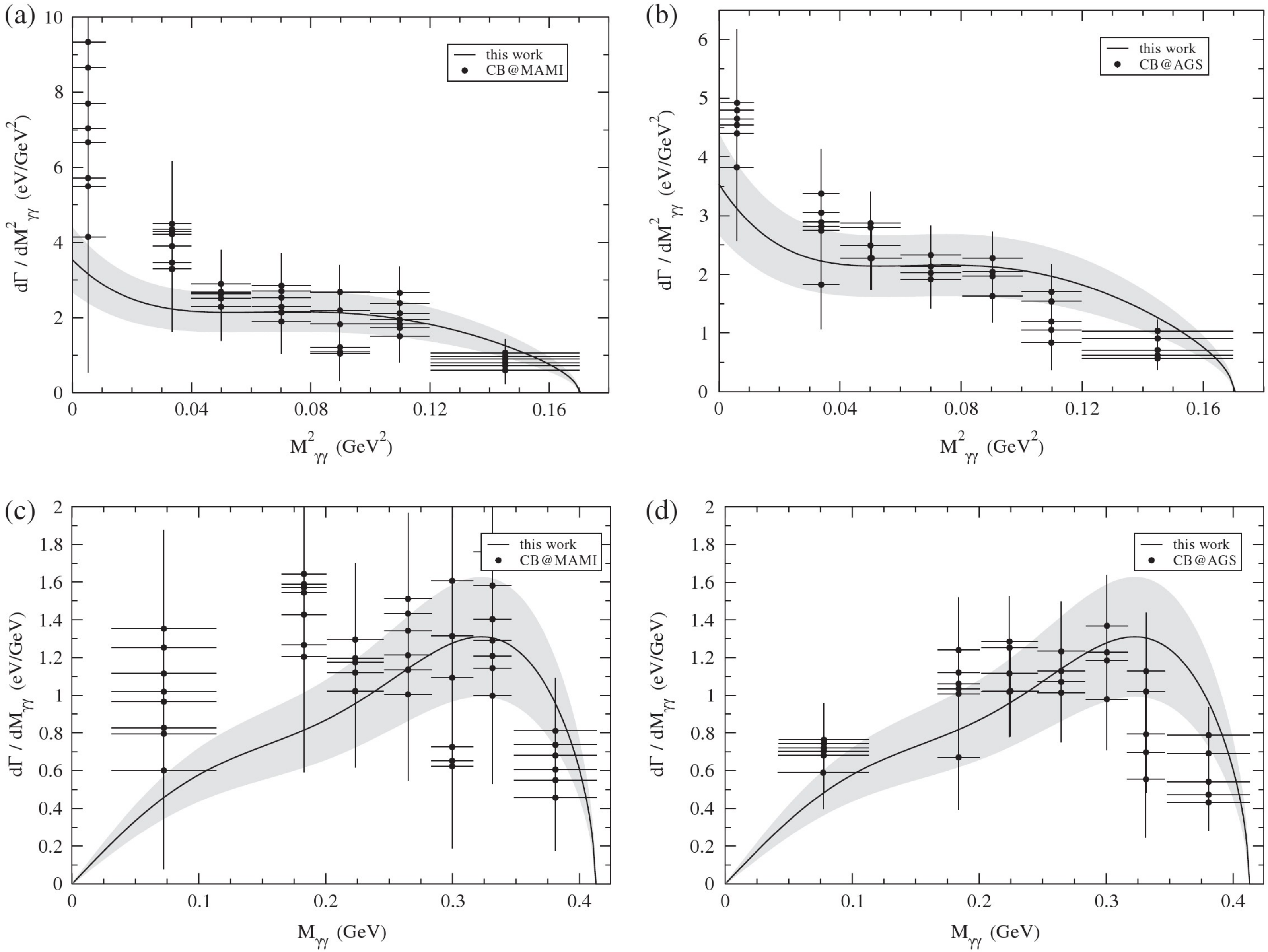
Tree level amplitude at $O(p^2)$ vanishes as neither π^0 nor η can emit a photon

Tree level amplitude at $O(p^4)$ vanishes as neither π^0 nor η can emit a photon, π and K loops largely supressed by G-parity violation and the large Kaon mass, respectively

First sizable contribution from $O(p^6)$, but coefficients must be determined using models (e.g. VMD)



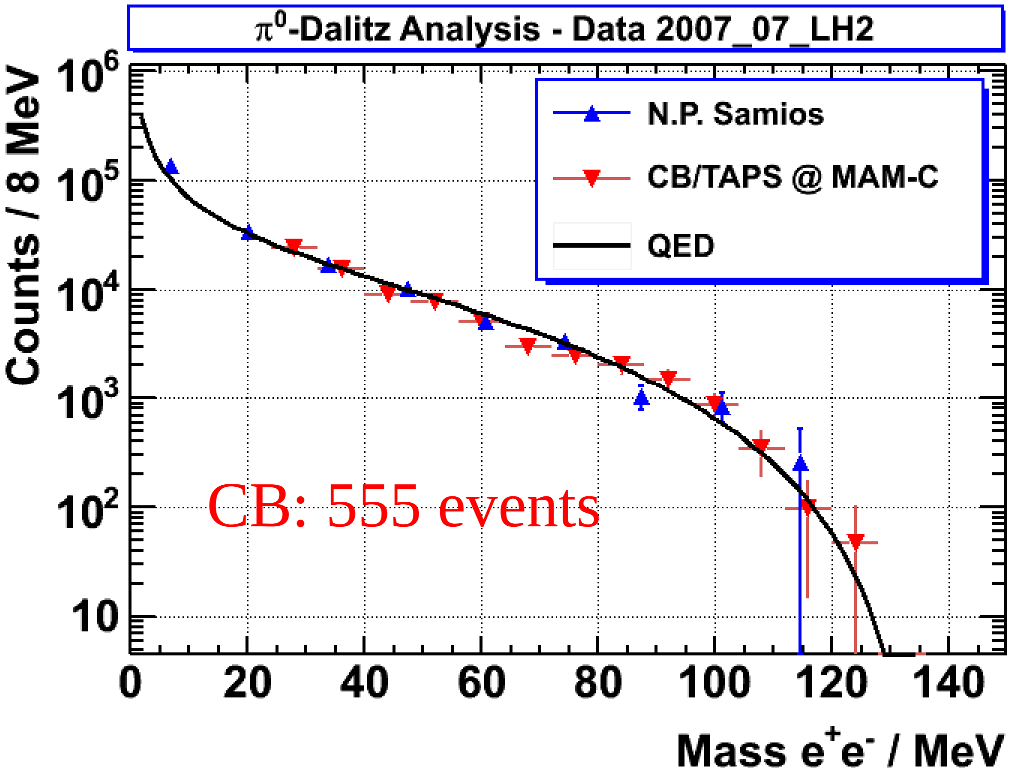
Branching Ratio of $\eta \rightarrow \pi^0\gamma\gamma$



$$BR(\eta \rightarrow \pi^0 \gamma \gamma) = (2.290 \pm 0.059_{stat} \pm 0.022_{syst}) \cdot 10^{-4} (\textit{preliminary})$$

S. Prakhov (UCLA)

H. Berghäuser, PhD thesis, Gießen, 2010.



N.P. Samios et al. (BNL), Phys. Rev. 121 (1961) 275-281.

- Expected behaviour:

$$F(m^2) = \frac{1}{1 - \frac{m^2}{\Lambda^2}} \qquad m_\pi << \Lambda \qquad \Rightarrow \qquad F(m^2) \approx 1$$

$\eta' \rightarrow e^+e^-\gamma$