η and η' Physics at MAMI

Marc Unverzagt
Institute for Nuclear Physics
University Mainz
Messina, 14th October 2013

Outline

- Crystal Ball Set-up at MAMI
- η/η' Cross Sections
- Timelike Transition Form Factor from $\eta/\eta' \rightarrow e^+e^-\gamma$
- Preliminary Results for $\eta \rightarrow \pi^0\gamma\gamma$
- Future Plans
- Summary

Outline

- **Crystal Ball Set-up at MAMI**
- η/η' Cross Sections
- Timelike Transition Form Factor from $\eta/\eta' \rightarrow e^+e^-\gamma$
- Preliminary Results for $\eta \rightarrow \pi^0\gamma\gamma$
- Future Plans
- Summary

Experiments at MAMI

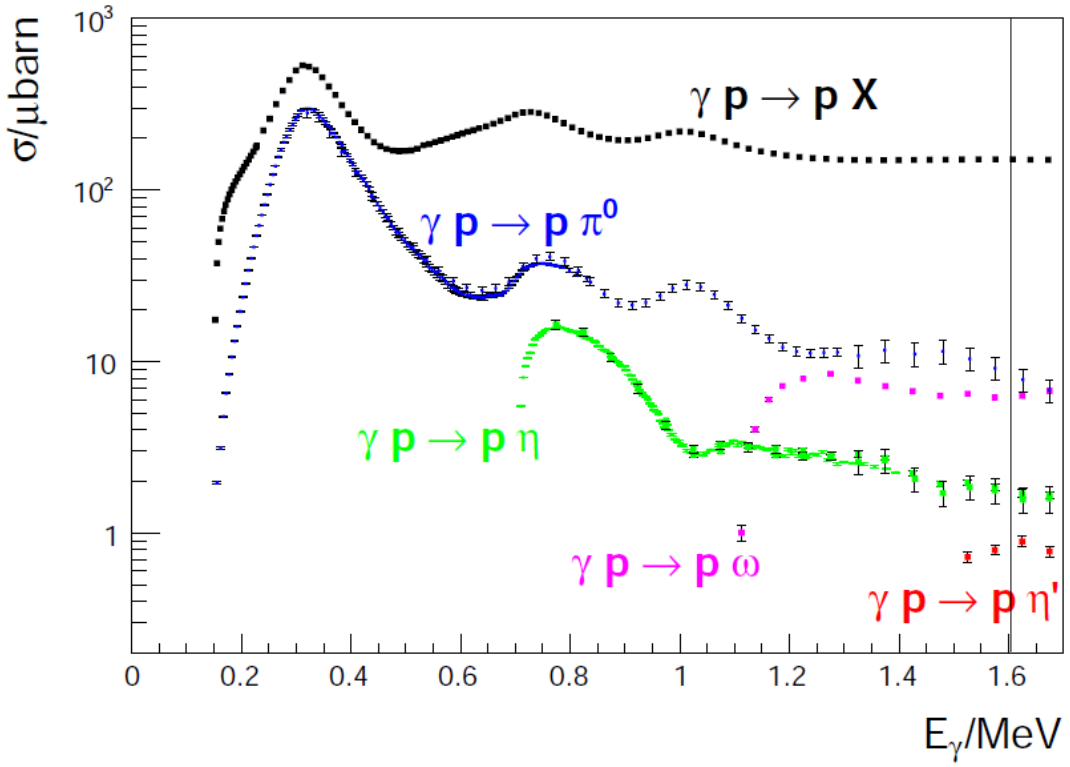
A2: Real Photon Experiments:
- Glasgow tagging spectrometer
- Crystal Ball / TAPS
  hermetic photon spectrometer
- Meson Factory

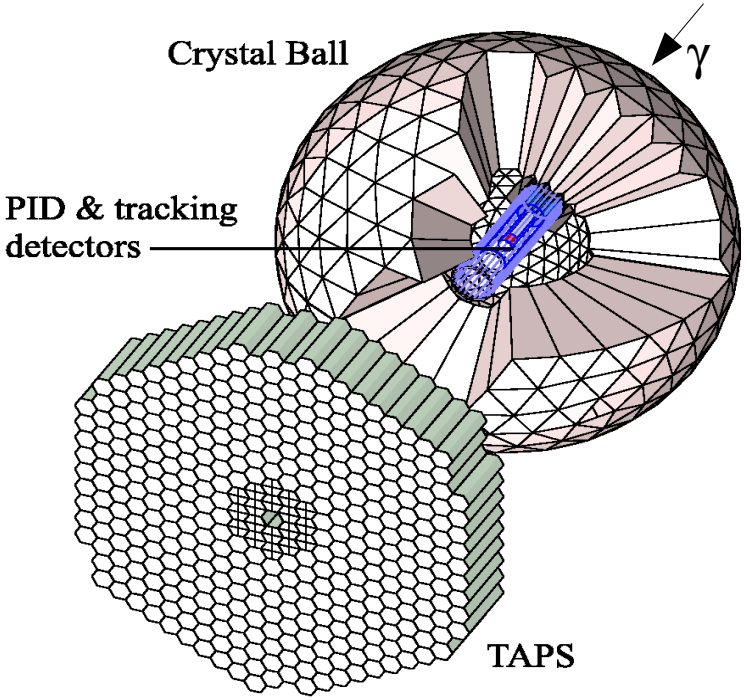
PRISMA/SFB 1044:
- Dark Photon Search
- El.-weak Mixing Angle

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

Meson Production with Real Photons

Data from CB@MAMI, CB@ELSA, CLAS, SAPHIR





Current production rates on lH_2 target feasible for taking data:

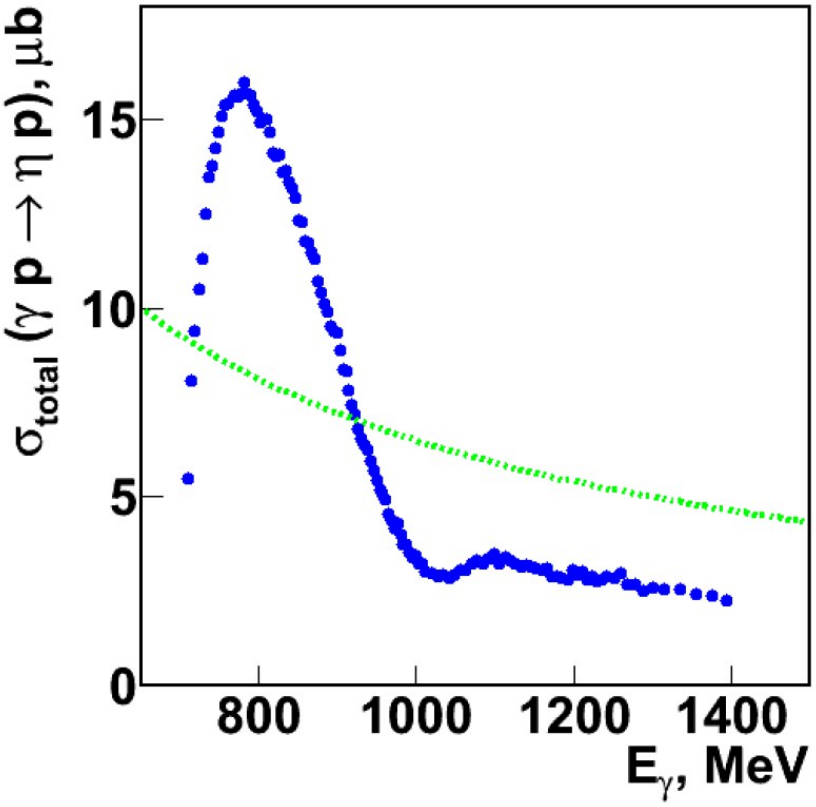
- η: 10^5 h^{-1} ⇒ Goal 10^6 h^{-1}
- η': $2 \cdot 10^3$ h^{-1} ⇒ Goal $1.5 \cdot 10^4$ h^{-1}

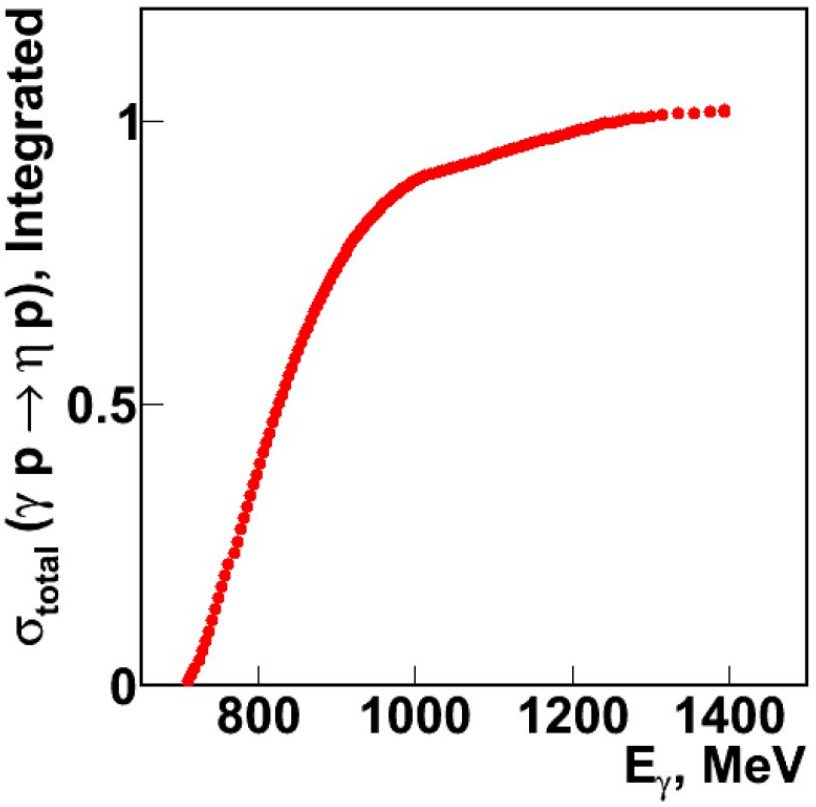
Has to be imposed by detection and anlysis efficiencies

⇒ 4π Crystal Ball/TAPS setup, e.m. Production mechanism very clean

⇒ Ideally suited to measure high rates of meson decays

η-Photoproduction





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

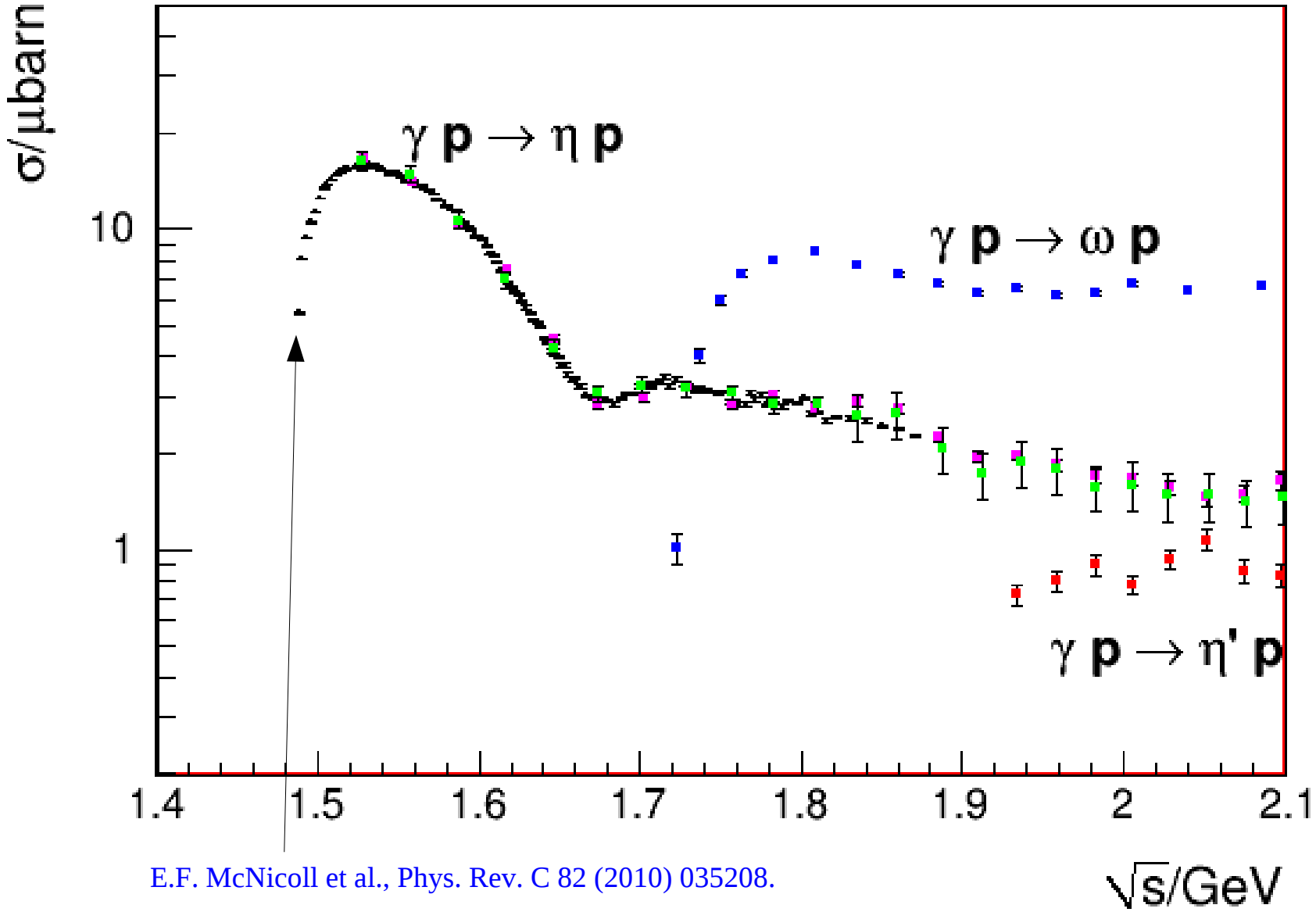
- High intensity photon beam
- Fine energy resolution
- Outstanding stability

Beam energy nearly perfect for high statistics η photoproduction

Outline

- Crystal Ball Set-up at MAMI
- **η/η' Cross Sections**
- Timelike Transition Form Factor from $\eta/\eta' \to e^+e^-\gamma$
- Preliminary Results for $\eta \to \pi^0\gamma\gamma$
- Future Plans
- Summary

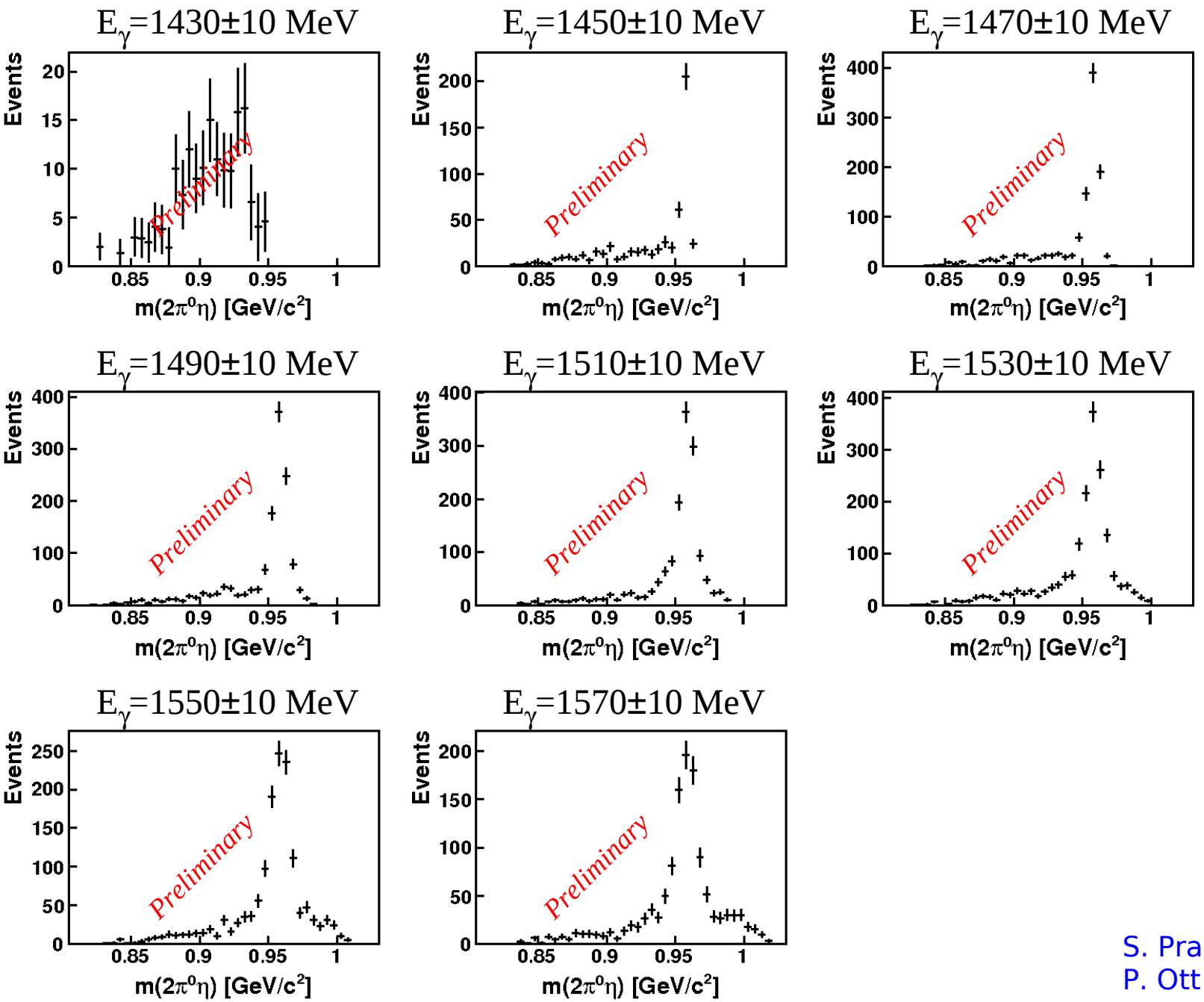
η Production



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

Data from Crystal Ball, Crystal Barrel, SAPHIR, CLAS

$\eta' \to \eta\pi^0\pi^0$ Invariant Mass

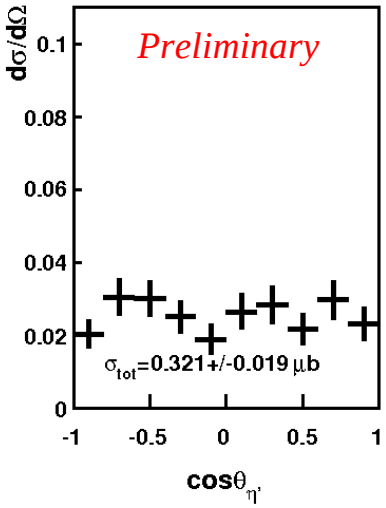


S. Prakhov (UCLA)
P. Ott (Mainz)

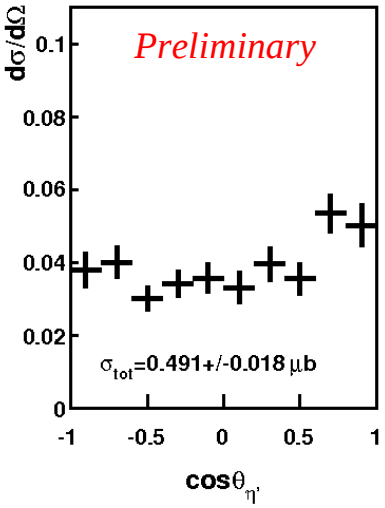
η' Cross Section

Using $\eta' \rightarrow \eta\pi^0\pi^0$

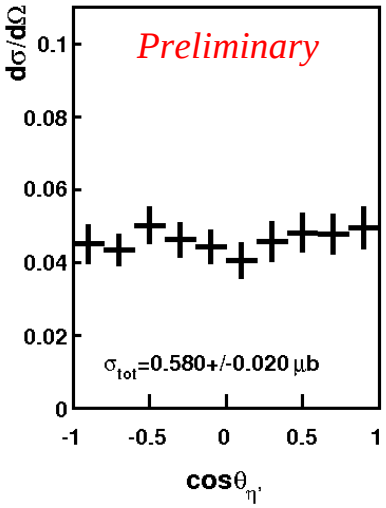
E_γ=1450±10 MeV



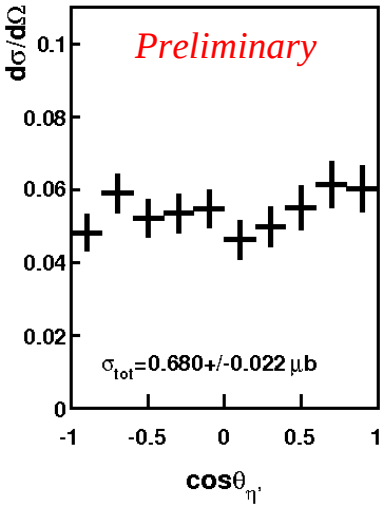
E_γ=1470±10 MeV



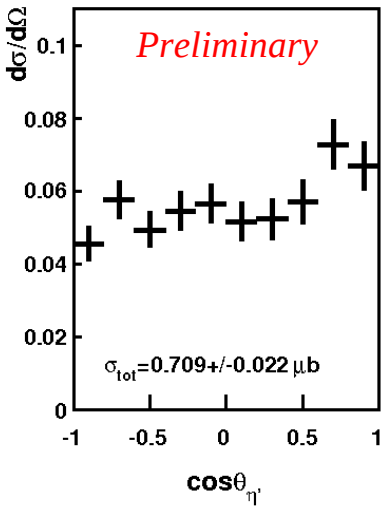
E_γ=1490±10 MeV



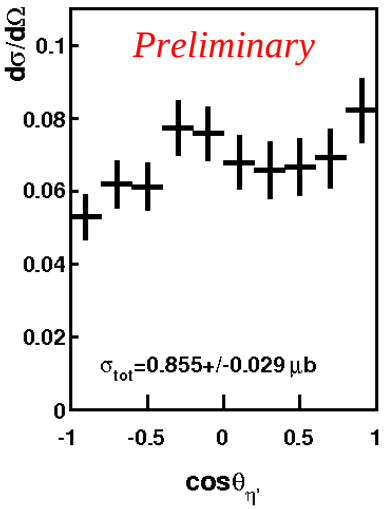
E_γ=1510±10 MeV



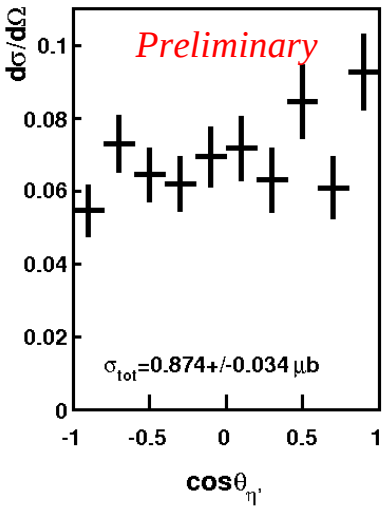
E_γ=1530±10 MeV



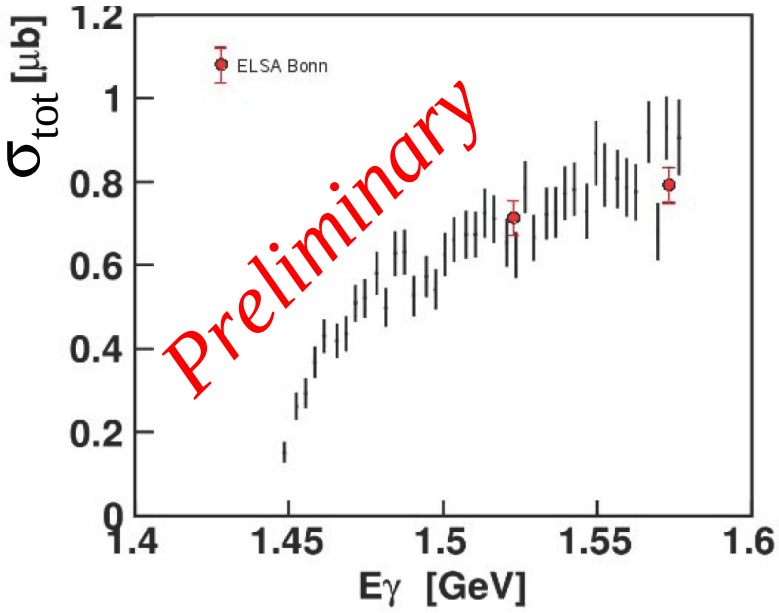
E_γ=1550±10 MeV



E_γ=1570±10 MeV



S. Prakhov (UCLA)
P. Ott (Mainz)

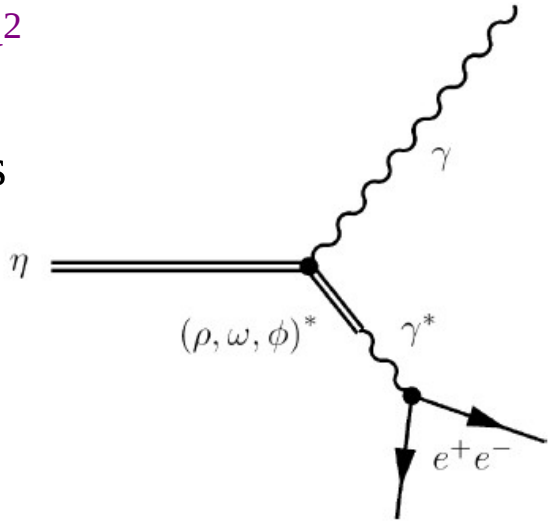


Outline

- Crystal Ball Set-up at MAMI
- η/η' Cross Sections
- **Timelike Transition Form Factor from $\eta/\eta' \rightarrow e^+e^-\gamma$**
- Preliminary Results for $\eta \rightarrow \pi^0\gamma\gamma$
- Future Plans
- Summary

Transition Form Factor with VMD

- Mechanism especially pronounced in timelike region at $q^2 \approx m_V^2$
  - → Virtual meson reaches „mass shell“, becomes real
  - → Strong resonance enhancement around vector meson mass
- TFF behaviour, especially for η', not well known
- TFF modifies differential decay width



$$\frac{d\Gamma}{dm^2} = \left[\frac{d\Gamma}{dm^2}\right]_{\mathrm{QED}} \cdot \left|F(m^2)\right|^2$$

- For η often one-pole approximation used:

$$\left|F(m^2)\right|^2 = \left(1 - \frac{m^2}{\Lambda^2}\right)^{-2} \qquad \Lambda \approx 0.72\ \mathrm{GeV} \qquad \text{VMD: } \Lambda \approx m_\rho = 0.77\ \mathrm{GeV}$$

- For η' resonance shape:

$$\left|F(m^2)\right|^2 = \frac{\Lambda^2(\Lambda^2+\gamma^2)}{(\Lambda^2-m^2)^2+\Lambda^2\gamma^2} \qquad \Lambda \approx 0.76\ \mathrm{GeV} \quad \gamma \approx 0.10\ \mathrm{GeV}$$

Hadronic LbL Contribution to $a_\mu=(g-2)_\mu$

- QED contributions:

$$a_\mu^{\mathrm{QED}} = (11658471.895 \pm 0.008) \cdot 10^{-10}$$

T. Kinoshita et al., Phys. Rev. Lett. **109** (2012) 111808.

- Electro-Weak contribution:

$$a_\mu^{\mathrm{Weak}} = (15.4 \pm 0.2) \cdot 10^{-10}$$

A. Czarnecki et al., Phys. Rev. D **67** (2003) 073006.
Erratum-ibid. D **73** (2006) 119901.
M. Knecht et al., JHEP 0211 (2002) 003.

- Hadronic vacuum polarisation:

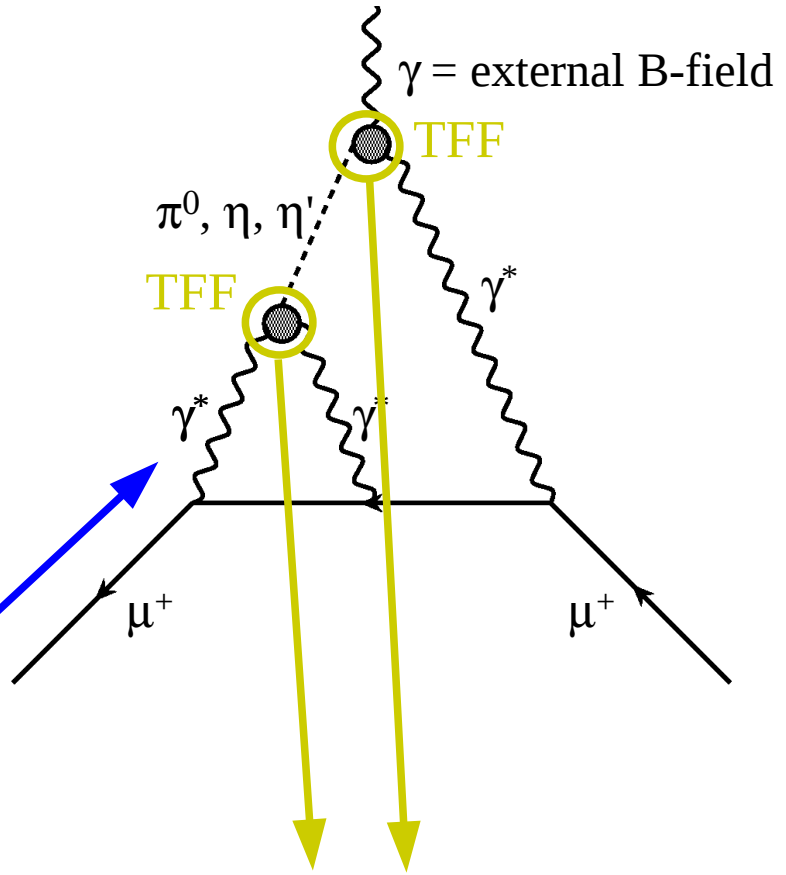
$$a_\mu^{\mathrm{VP}} = (692.3 \pm 4.2) \cdot 10^{-10}$$

M. Davier et al., Eur. Phys. J. C **71** (2011) 1515.

- Hadronic light-by-light:

$$a_\mu^{\mathrm{LbL}} = (10.5 \pm 2.6) \cdot 10^{-10}$$

J. Prades et al., arXiv:0901.0306 (2009).

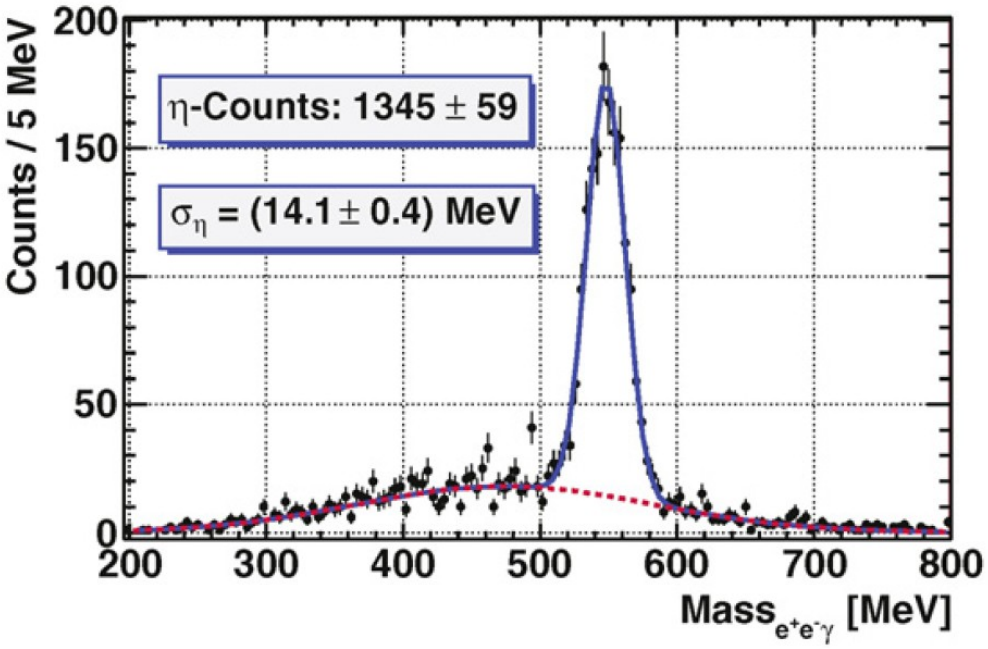


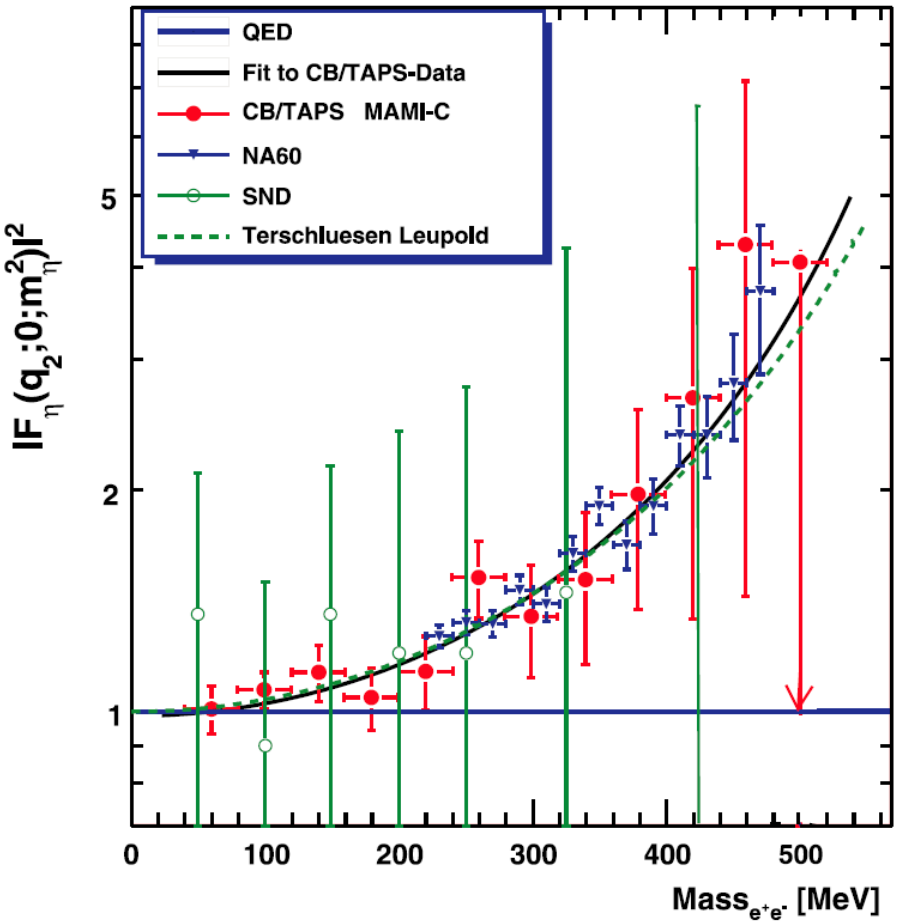
Transition Form Factors of light pseudoscalar mesons could give important input for SM calculations of $(g-2)_\mu$

First A2 Result for η TFF

H. Berghäuser et al. (A2-Collaboration), Phys. Rev. B 701 (2011) 562-567.

- Based on kinematic cuts
- Small amount of data
- Limited photoproduction energy range



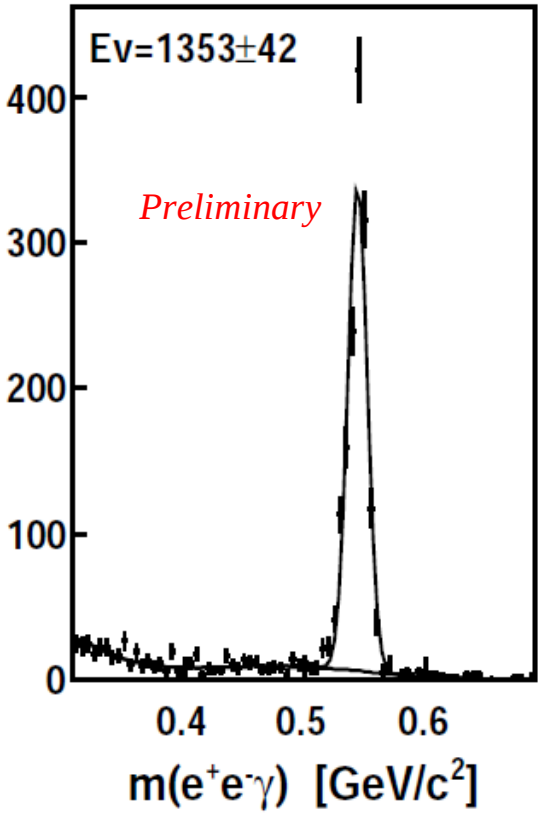


$$\Lambda^{-2} = (1.92 \pm 0.35_{stat} \pm 0.13_{syst})\ GeV^{-2}$$

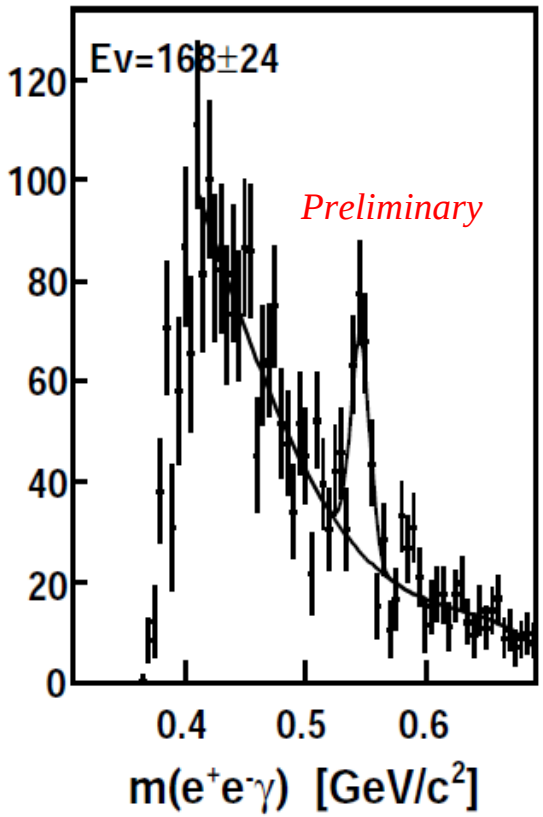
New Analysis of η TFF

- Based on kinematic fitting
- 3x more data
- Full η photoproduction range accessible at MAMI used
- 18,000 events (no proton requirement: 22,000 events)

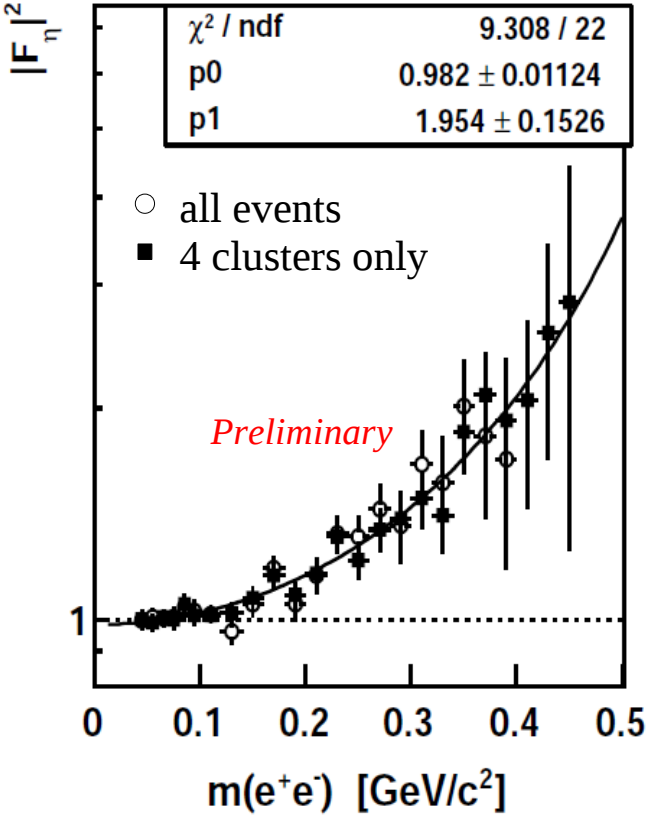
$m(e^+e^-)$=45±5 MeV



$m(e^+e^-)$=285±5 MeV

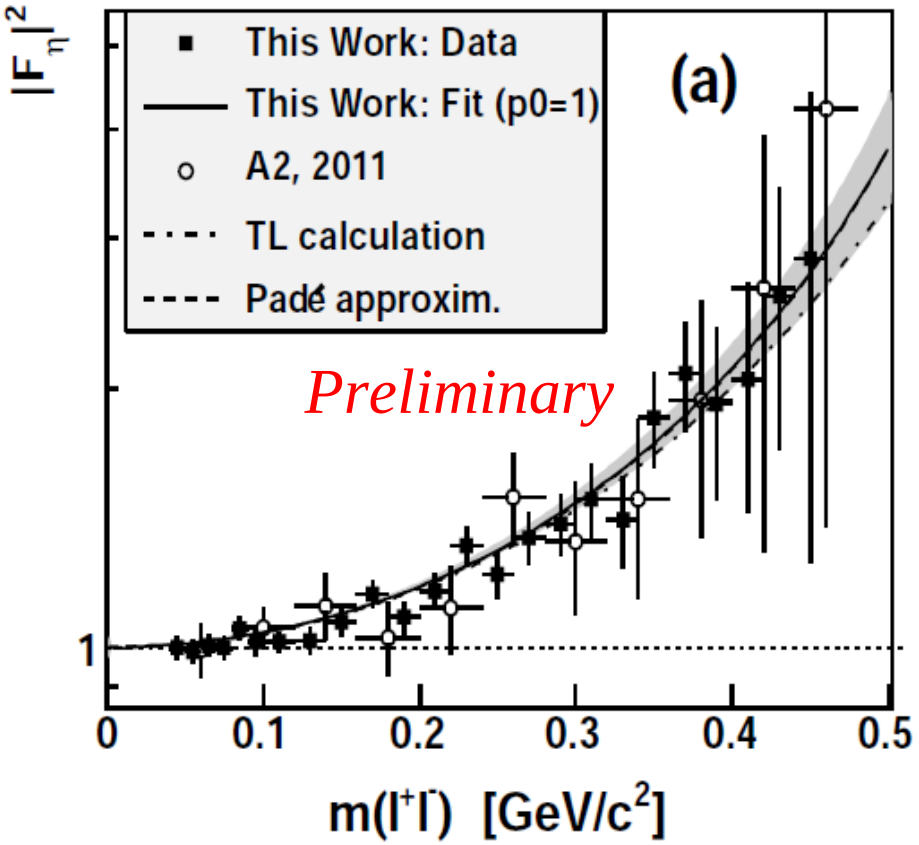


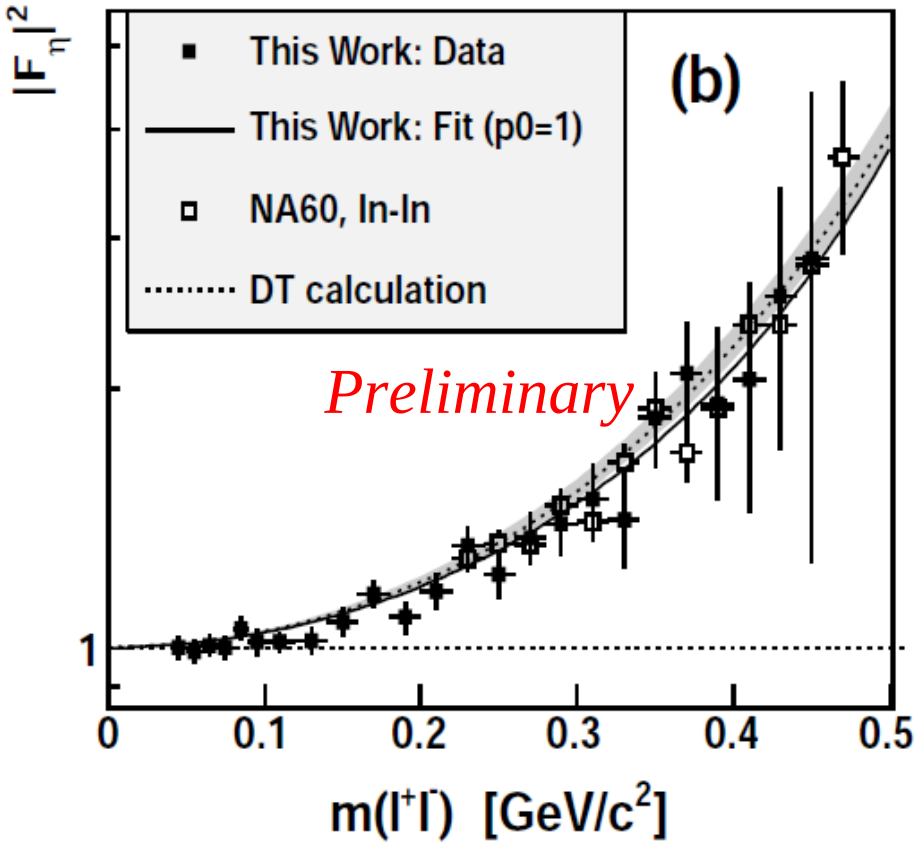
Solid line: Pole-approximation fit
Normalisation p0 and Λ^{-2}=p1 as free parameters



New A2 Result for η TFF

S. Prakhov, M. Unverzagt et al., submitted to Phys. Rev. C





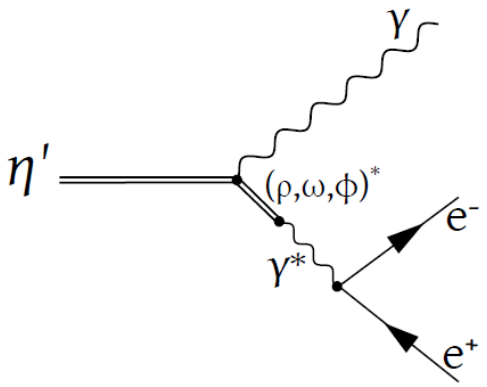
$$\Lambda^{-2} = (1.95 \pm 0.15_{\mathrm{stat}} \pm 0.10_{\mathrm{syst}})\ \mathrm{GeV}^{-2} \quad \textit{preliminary}$$

A2, 2011: H. Berghäuser et al., Phys. Rev. B 701 (2011) 562-567.
NA60, In-In: R. Arnaldi et al., Phys. Lett. B 677 (2009) 260.
TL calculation: C. Terschlüsen, Diploma thesis, University Gießen, 2010.
Padé-approximants: R. Escribano, P. Masjuan, P. Sanchez-Puertas, arXiv:1307.2061 [hep-ph].
DT calculation: C. Hahnhart, A. Kupść, U.-G. Meißner, F. Stollenwerk, A. Wirzba, arXiv: 1307.5654 [hep-ph].

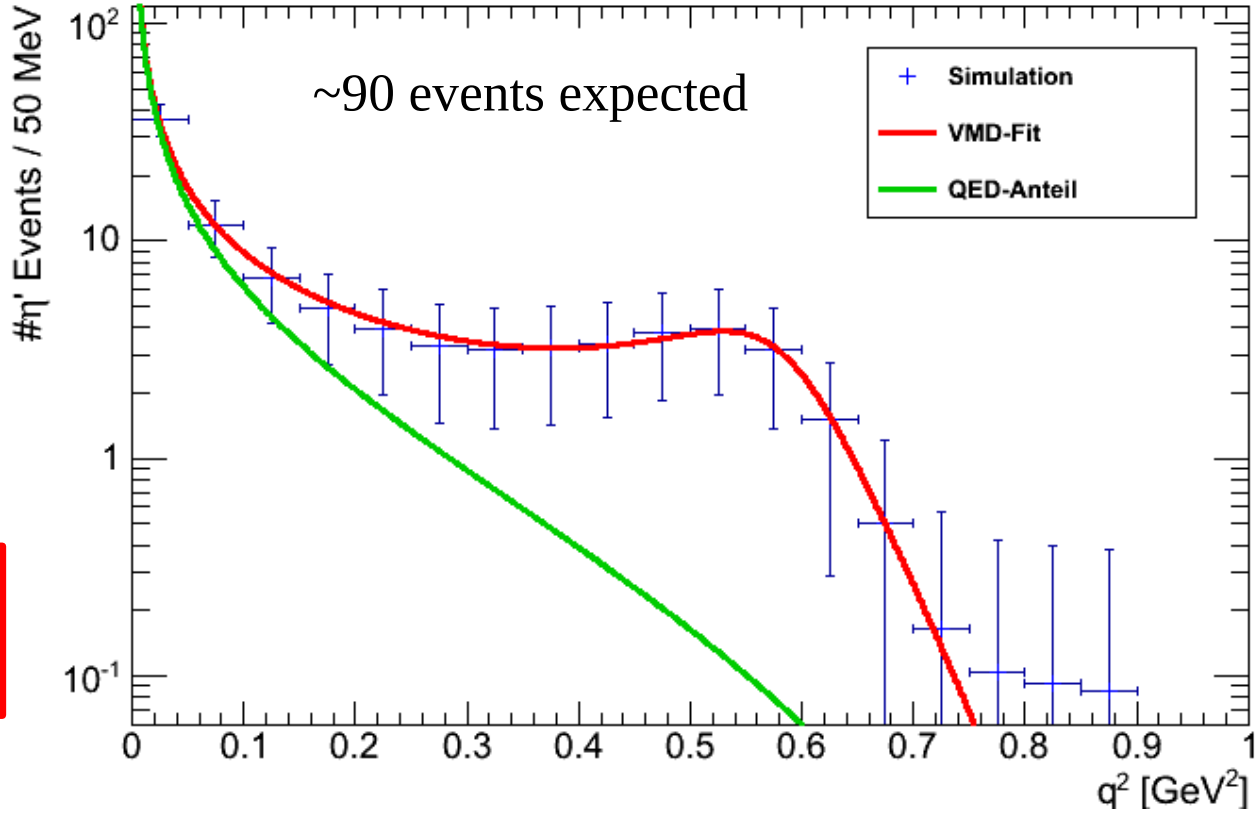
Timelike TFF for η'

S. Wagner, Master thesis, University Mainz, 2013
M. Unverzagt, A. Denig

- $\eta' \to e^+e^-\gamma$ no observation published yet
- Simulation based on
  - PDG upper limit for branching ratio
  - η' production rate at MAMI-C (5 weeks, total 1.65 million η')
  - Acceptance from ~8.5% (after background suppression)



$$\left|F(m^2)\right|^2 = \frac{\Lambda^2(\Lambda^2+\gamma^2)}{(\Lambda^2-m^2)^2+\Lambda^2\gamma^2}$$



Outline

- Crystal Ball Set-up at MAMI
- η/η' Cross Sections
- Timelike Transition Form Factor from $\eta/\eta' \to e^+e^-\gamma$
- **Preliminary Results for $\eta \to \pi^0\gamma\gamma$**
- Future Plans
- Summary

Double Radiative $\eta \rightarrow \pi^0\gamma\gamma$

- Tree level amplitudes at $O(p^2)$ and $O(p^4)$ vanish
- π and K loops largly suppressed by G-parity and large Kaon mass
- First sizable contribution from (p^6)
- Coefficients must be determined using models (e.g. VMD)

⇒ Stringent test for χPT at $O(p^6)$ as well as models

- Calculations must describe $\Gamma(\eta\rightarrow\pi^0\gamma\gamma)$ and differential decay width $d\Gamma/dm^2(\gamma\gamma)$
- Discrepancies between models in $d\Gamma/dm^2(\gamma\gamma)$
- Discrepancies in emperimental results for $\Gamma(\eta\rightarrow\pi^0\gamma\gamma)$

- Experimental challenges:
  - Small rate
  - Large background (e.g. $\pi^0\pi^0$)
  - Only three measurements of $d\Gamma/dm^2(\gamma\gamma)$: CB@AGS, CB@MAMI, WASA@COSY

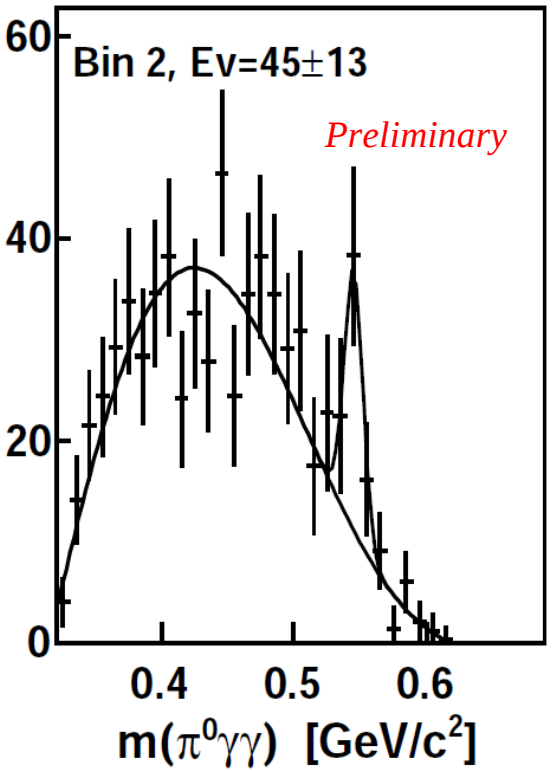
- New CB@MAMI analysis based on data taken in 2007 and 2009 ($6\cdot10^7$ η produced)

Analysis of $\eta \to \pi^0\gamma\gamma$

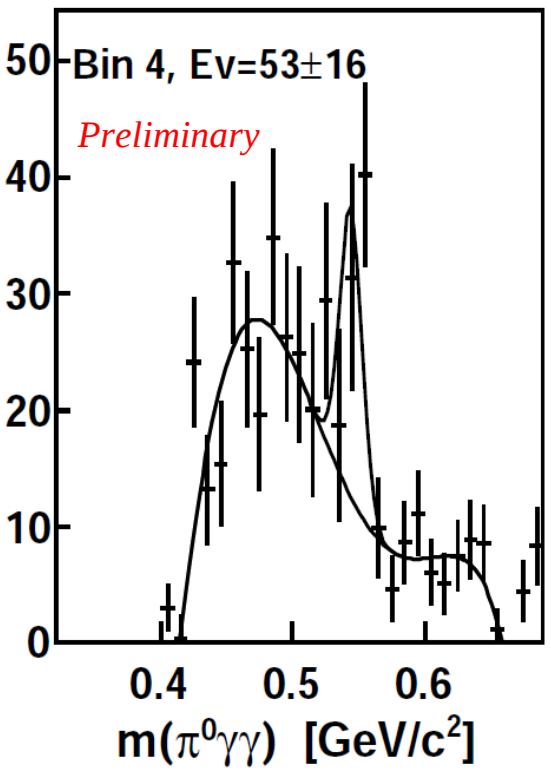
- Based on kinematic fitting
- $\pi^0\pi^0$ background suppressed by anti-hypothesis
- Results based on $1.2 \cdot 10^3$ $\eta \to \pi^0\gamma\gamma$ events

- Below preliminary results from 2009

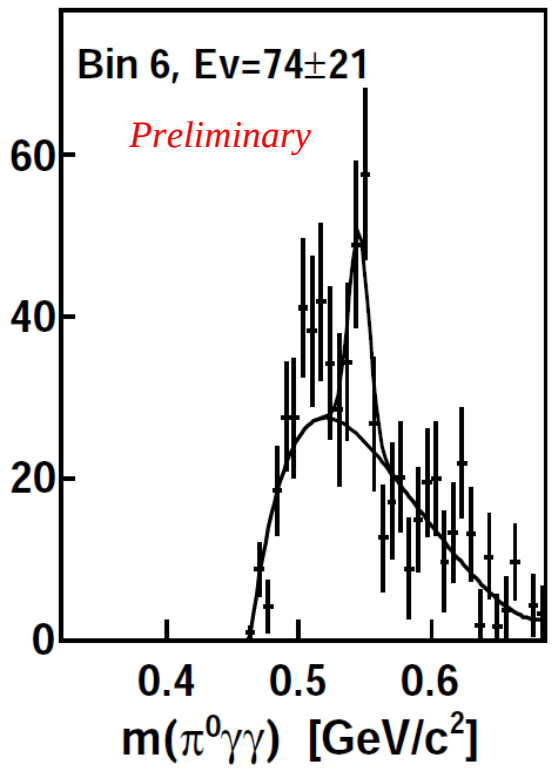
$m^2(\gamma\gamma) = (0.0375 \pm 0.0100)\ \mathrm{GeV}^2/c^4$



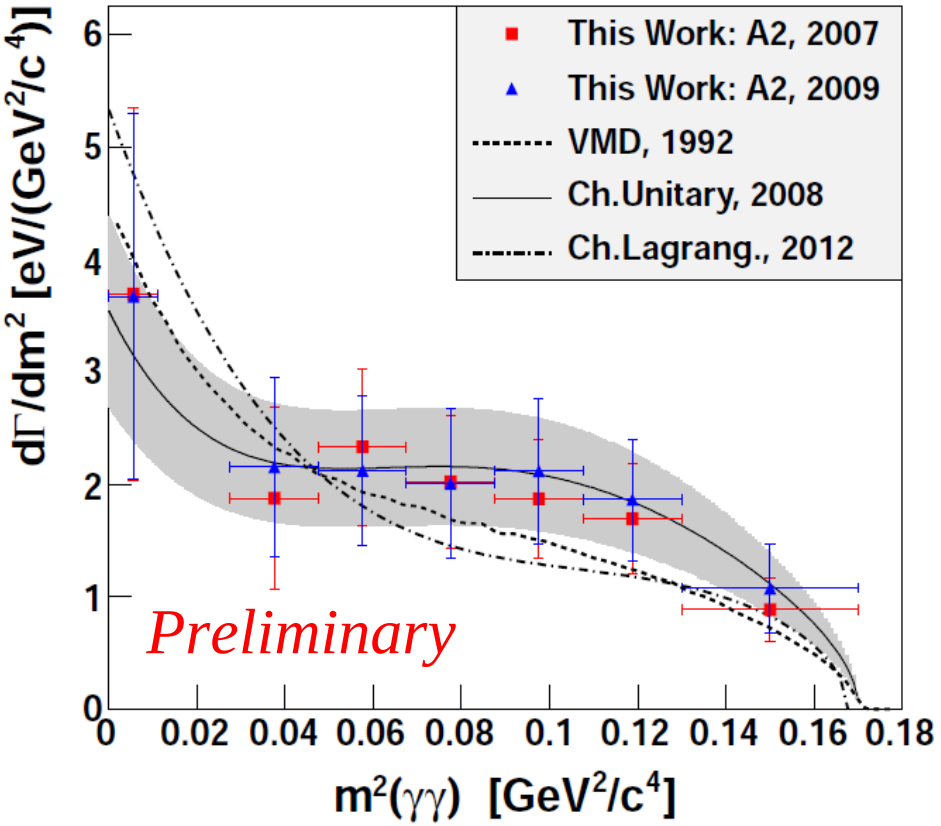
$m^2(\gamma\gamma) = (0.0775 \pm 0.0100)\ \mathrm{GeV}^2/c^4$

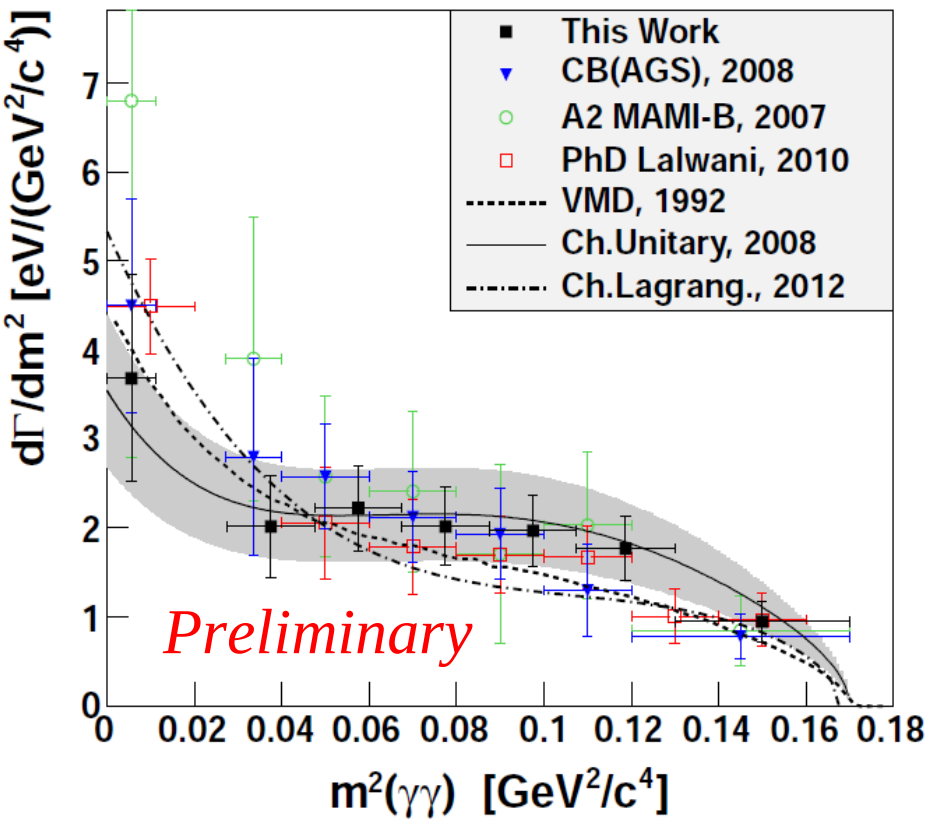


$m^2(\gamma\gamma) = (0.11875 \pm 0.01125)\ \mathrm{GeV}^2/c^4$



Decay Rate $\eta \to \pi^0\gamma\gamma$





General agreement but statistics still not sufficient to distinguish between models.
To be submitted soon!

CB (AGS): S. Prakhov et al., Phys. Rev. C **78** (2008) 015206.
A2 MAMI-B: S.Prakhov, Proceedings of MENU 2007, published in eConf C070910 (2007) 159.
WASA: K. Lalwani, Ph.D. Thesis, Depart. of Physics, Indian Inst. of Technology, Bombay (2010).
VMD: J. N. Ng, D. J. Peters, Phys. Rev. D **46** (1992) 5034.
Ch. Unitary: E. Oset, J.R. Palaez, L. Roca, Phys. Rev. D **77** (2008) 073001.
Ch. Lagrang.: I. V. Danilkin, M. F. M. Lutz, S. Leupold, C. Terschlüsen, arXiv:1211.1503 [hep-ph].

Decay Width of $\eta \to \pi^0\gamma\gamma$

$\Gamma = (0.84 \pm 0.19)$ eV, GAMS2000, 1984

$\Gamma = (0.45 \pm 0.12)$ eV, CB(AGS), 2005

$\Gamma = (0.11 \pm 0.04)$ eV, KLOE, 2006 (preliminary)

$\Gamma = (0.290 \pm 0.063)$ eV, A2(MAMI B), 2007 (preliminary)

$\Gamma = (0.285 \pm 0.068)$ eV, CB(AGS), 2008 (reanalysis of 2005)

$\Gamma = (0.33 \pm 0.11)$ eV, WASA at COSY, Ph.D. thesis of K. Lalwani, 2010 (preliminary)

$\Gamma = (0.30^{+0.16}_{-0.13})$ eV, VMD, 1992

$\Gamma = (0.33 \pm 0.08)$ eV, Ch. Unitary, 2008

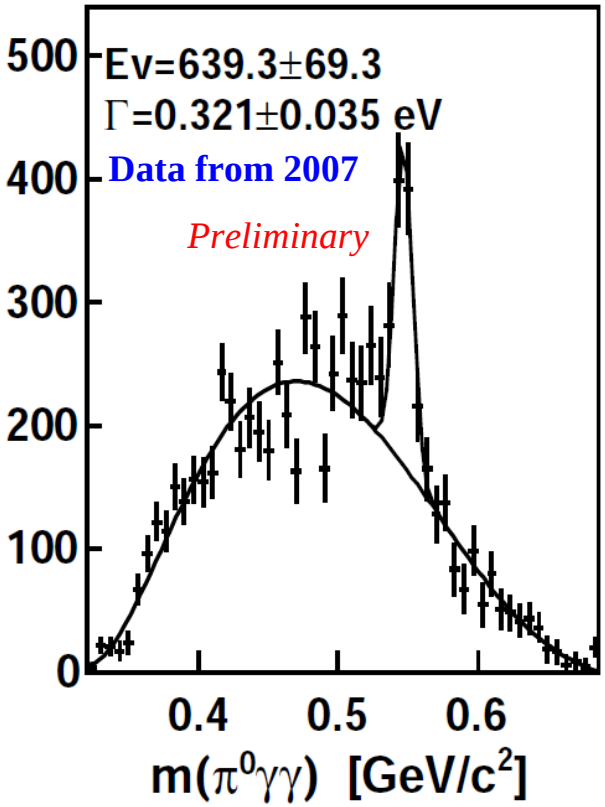
$\Gamma = 0.31$ eV, Ch. Lagrang., 2012

CB at MAMI (2013): S. Prakhov (UCLA, University Mainz)

- Data from 2007 and 2009 combined:

$$\Gamma(\eta \to \pi^0\gamma\gamma) = (0.33 \pm 0.03_{\rm tot})\ \text{eV} \quad \textit{preliminary}$$

- Agreement with latest results, except KLOE
- Most precise value from CB@MAMI



Outline

- Crystal Ball Set-up at MAMI
- η/η' Cross Sections
- Timelike Transition Form Factor from $\eta/\eta' \rightarrow e^+e^-\gamma$
- Preliminary Results for $\eta \rightarrow \pi^0\gamma\gamma$
- **Future Plans**
- Summary

η/η' Programme

Precise Results in η/η' Physics:

- Cross sections, especially precise in threshold region
- $\eta \to 3\pi^0$ (Dalitz plot parameter α), $\eta \to e^+e^-\gamma$ (TFF), $\eta \to \pi^0\gamma\gamma$ (χPT, VMD)
- First glances at $\eta' \to \eta\pi^0\pi^0$, $\eta' \to e^+e^-\gamma$

Next η' Production:

- Summer/fall 2014
- Measure with x4 DAQ speed and longer period
- Goal: 400,000 $\eta' \to \eta\pi^0\pi^0$ (Dalitz plot analysis)
  ~800 $\eta' \to e^+e^-\gamma$ (Transition Form Factor)

Future Goals:

- Improve Transition Form Factors for η/η' (single/double Dalitz decays) (and $\omega \to \pi^0 e^+e^-$?)
- Improve Dalitz plot analyses $\eta/\eta' \to 3\pi^0$, $\eta' \to \eta\pi^0\pi^0$ (cusp effects?)
- Radiative decays $\eta' \to \omega\gamma$, $\omega \to \pi^0/\eta\gamma$
- Long term plan: Charged decays

A. Denig, W. Gradl, A. Neiser, M. Ostrick, P. Ott, S. Prakhov, O. Steffen, M. Unverzagt, S. Wagner, M. Wolfes (University Mainz)

Outline

- Crystal Ball Set-up at MAMI
- η/η' Cross Sections
- Timelike Transition Form Factor from $\eta/\eta' \rightarrow e^+e^-\gamma$
- Preliminary Results for $\eta \rightarrow \pi^0\gamma\gamma$
- Future Plans
- **Summary**

Summary

- Most precise η/η' photoproduction cross sections
  - Especially in the threshold regions up to E_γ=1.6 GeV

- η' production at MAMI possible now
  - Preliminary results on η' photoproduction cross section
  - First glances on $\eta' \to \eta\pi^0\pi^0$ Dalitz plot and η' Transition Form Factor

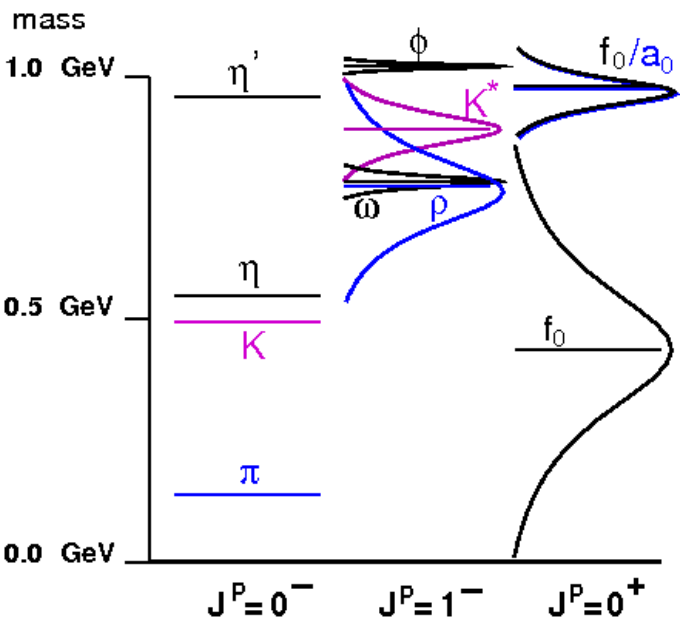
- New determination of the Transition Form Factor in $\eta \to e^+e^-\gamma$
  - More than one order of magnitude more than previous A2 analysis
  - Based on 18,000 events
  - Submitted to Phys. Rev. C

- Very accurate determination of $\eta \to \pi^0\gamma\gamma$ decay rate
  - Most precise result today
  - To be submitted soon

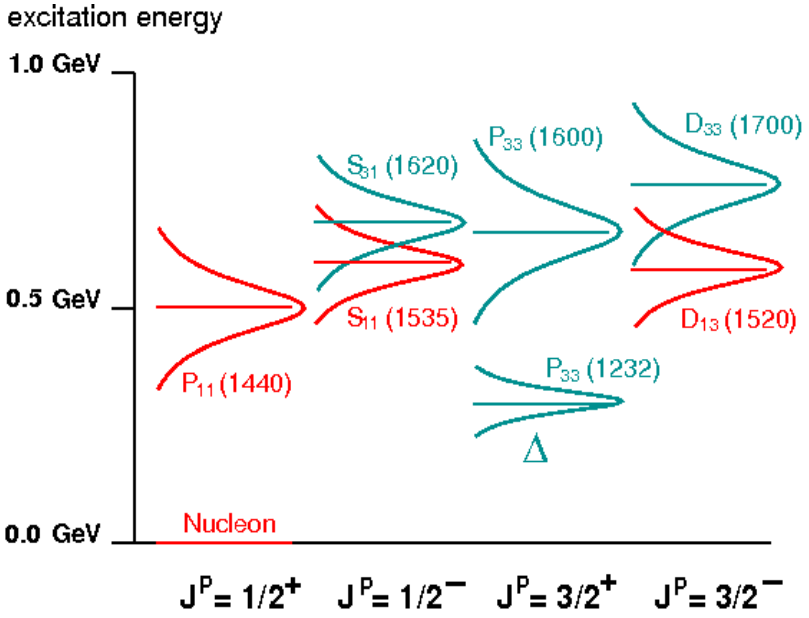
- 12 years physics programme funded through DFG (SFB 1044)
  - Broad physics programme including
    Light Meson Dynamics
    Transition Form Factors of pseudoscalar Mesons

A2 Experiments

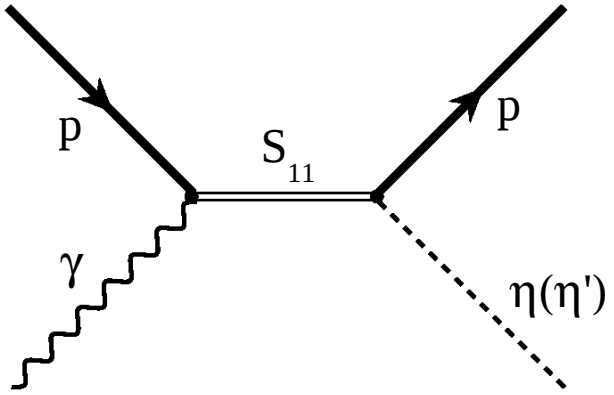
Mesons



Baryons



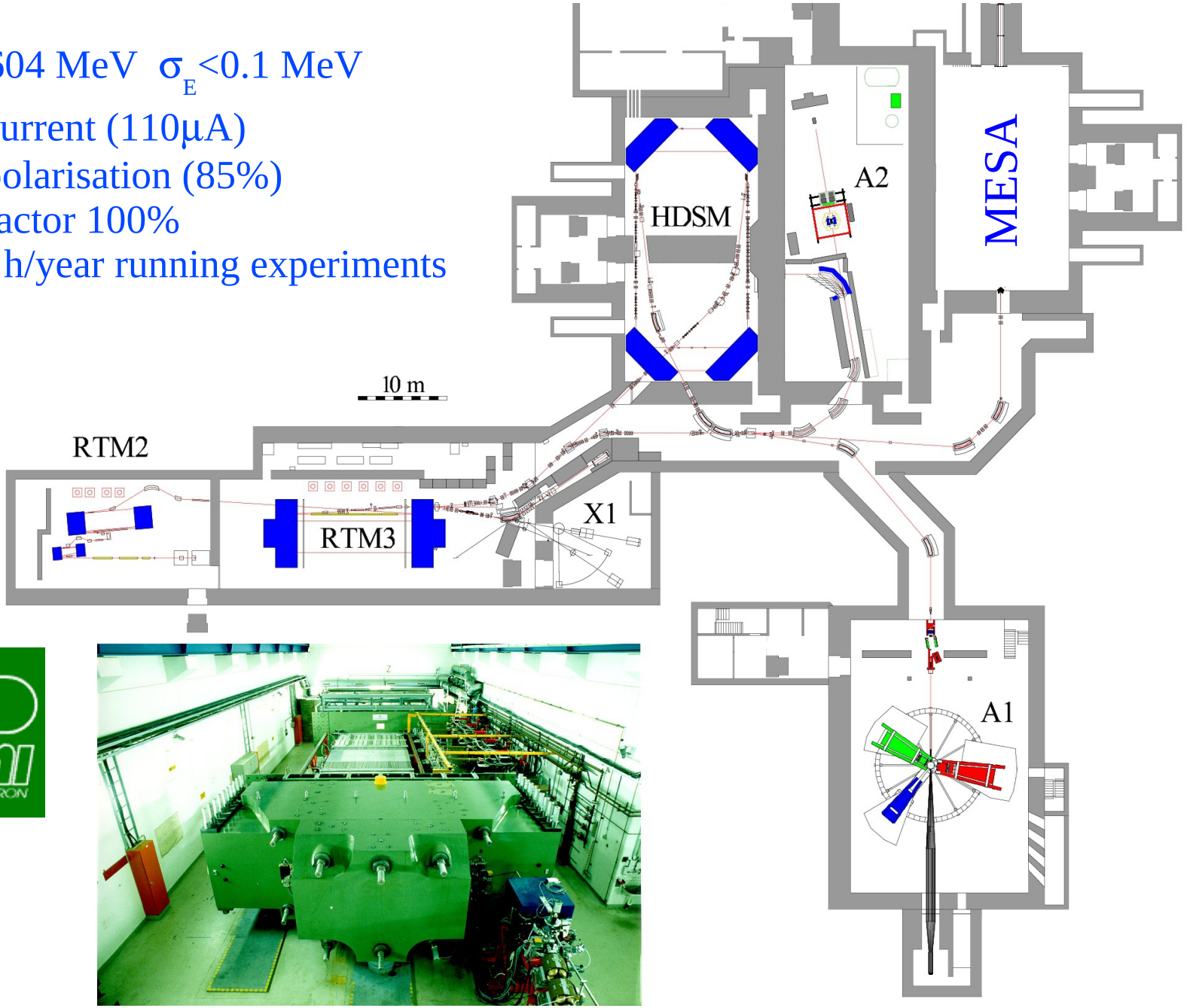
Meson decays with all including physical aspects
Polarisabilities of nucleons and pions
Properties of the first nucleon excitations



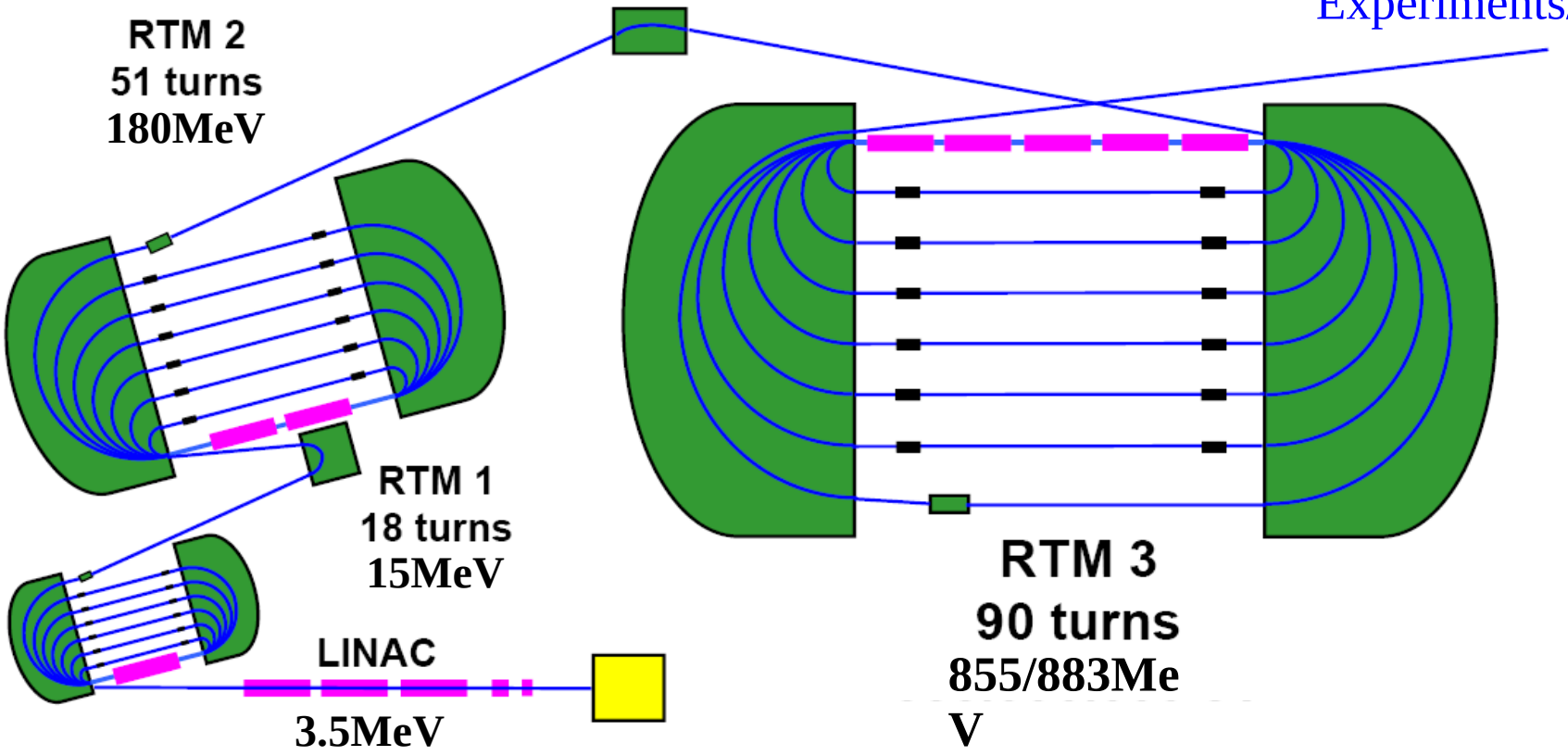
Photoproduction ($E_\gamma \leq 1604$ MeV)

Mainz Microtron

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

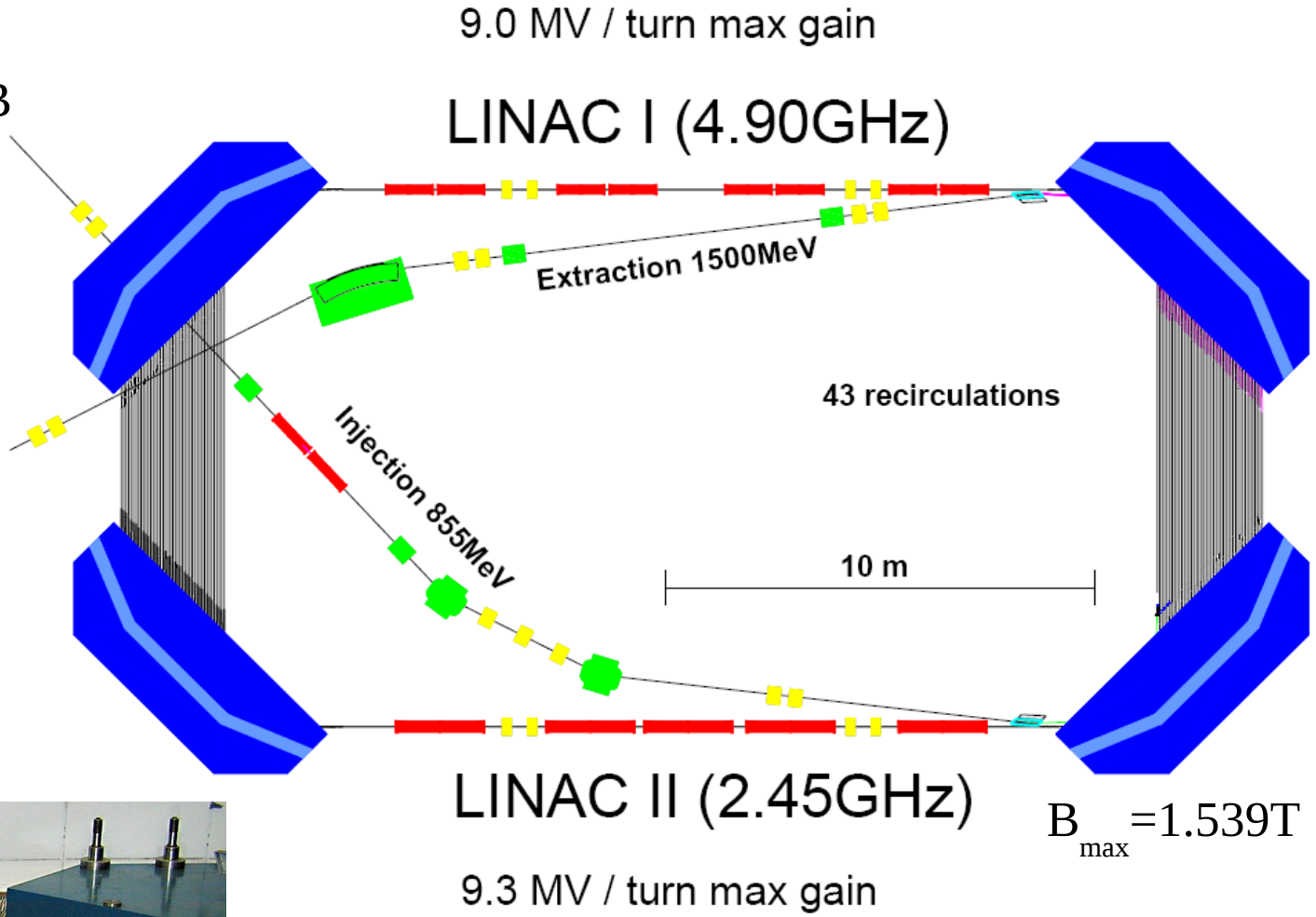


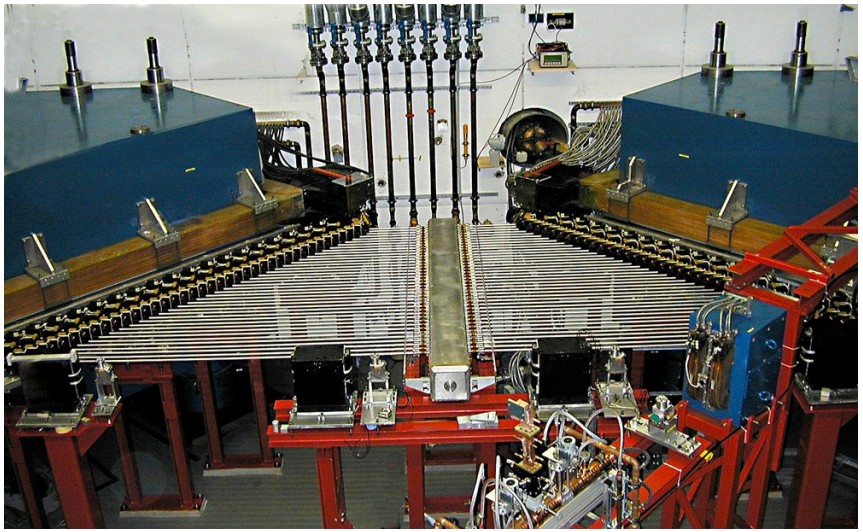
Mainz Microtron (MAMI-B)



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)

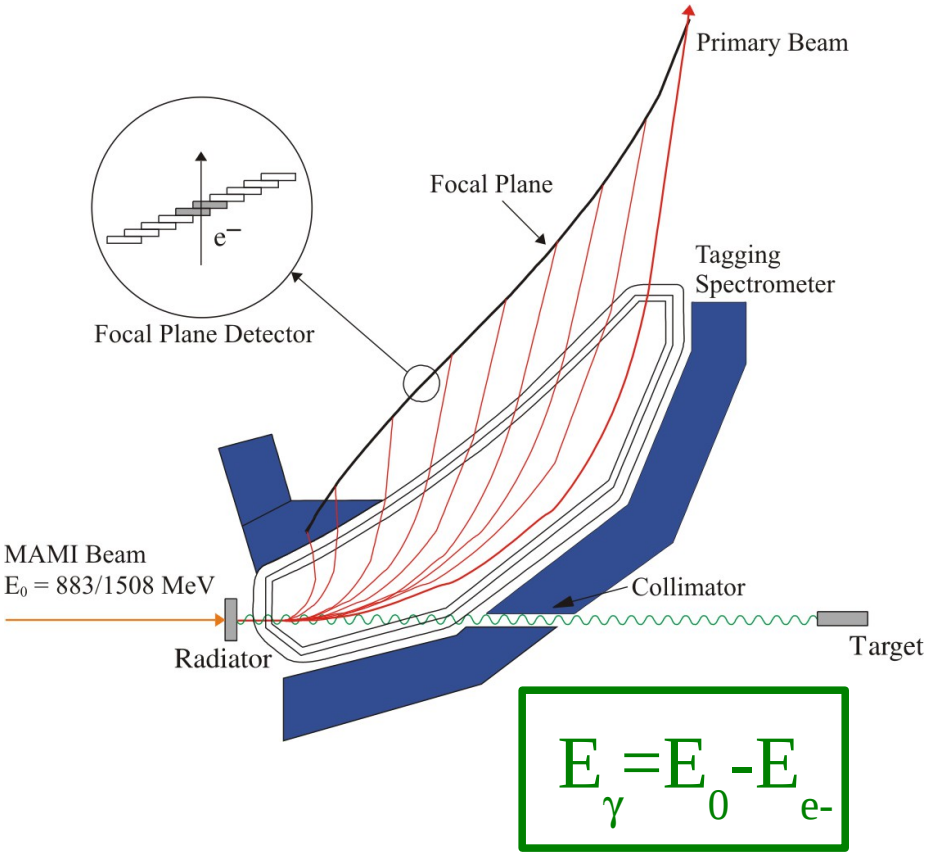




Harmonic Doubled Sided Microtron (HDSM)

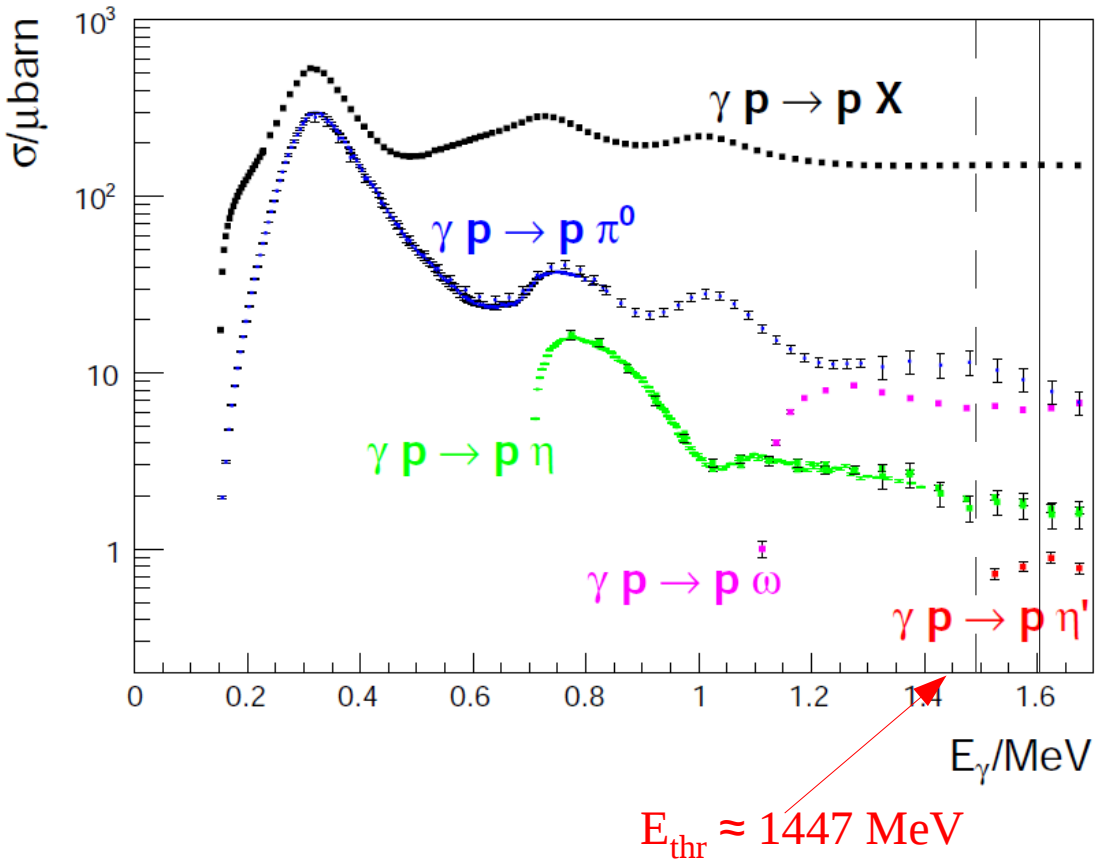
K.-H. Kaiser et al., NIM A 593, 159 (2008).

Real Photons in A2



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

Data form CB@MAMI, CB@ELSA, CLAS, SAPHIR



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

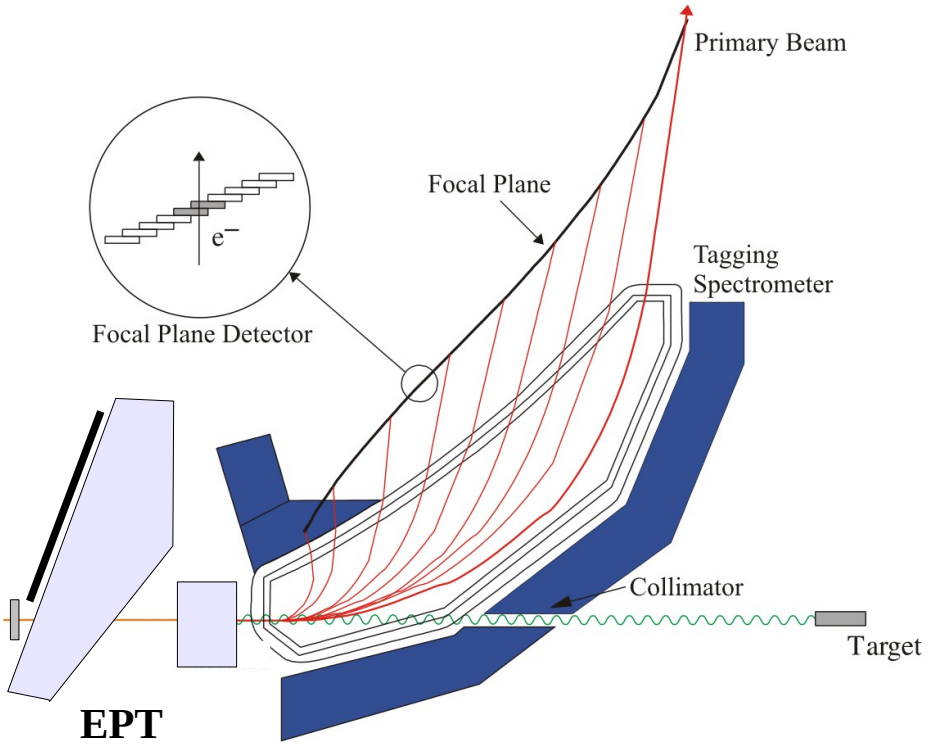
$\Delta E_\gamma \approx 4$MeV at $E_{e^-} = 1558$ MeV

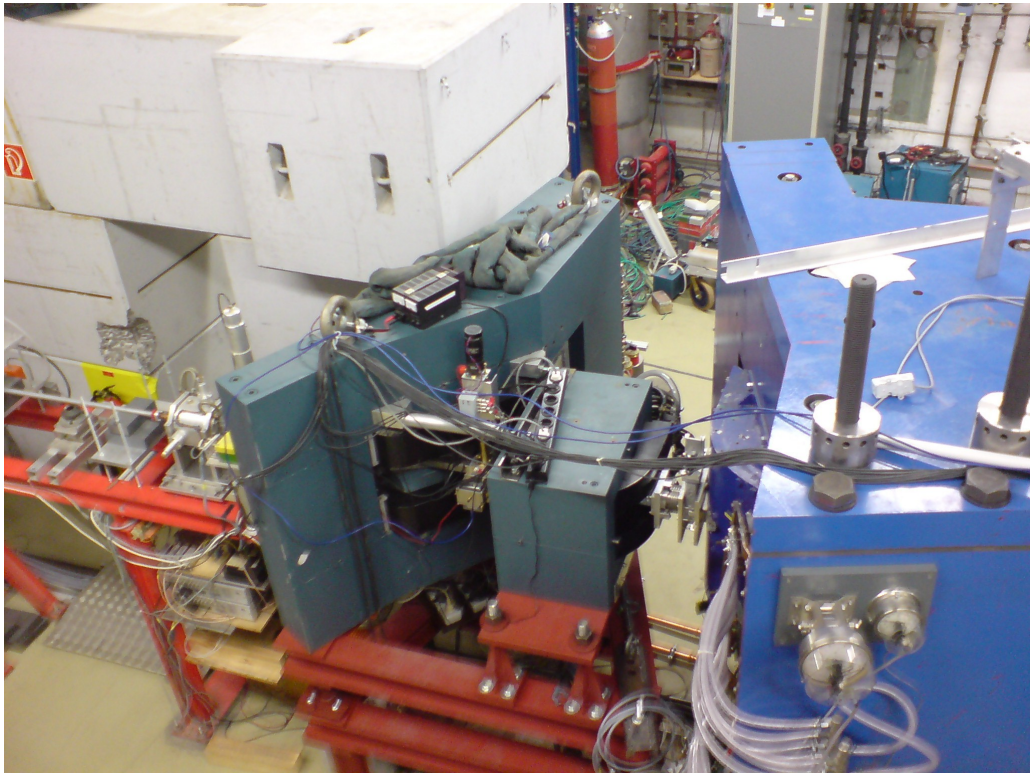
Linearly and circularly polarised photon-beam

Tagging range: 5.1 to 93% of E_γ → Maximum energy tagged for $E_0 = 1604$ MeV is 1491 MeV

End-Point-Tagger

- Installation of EPT during 2012





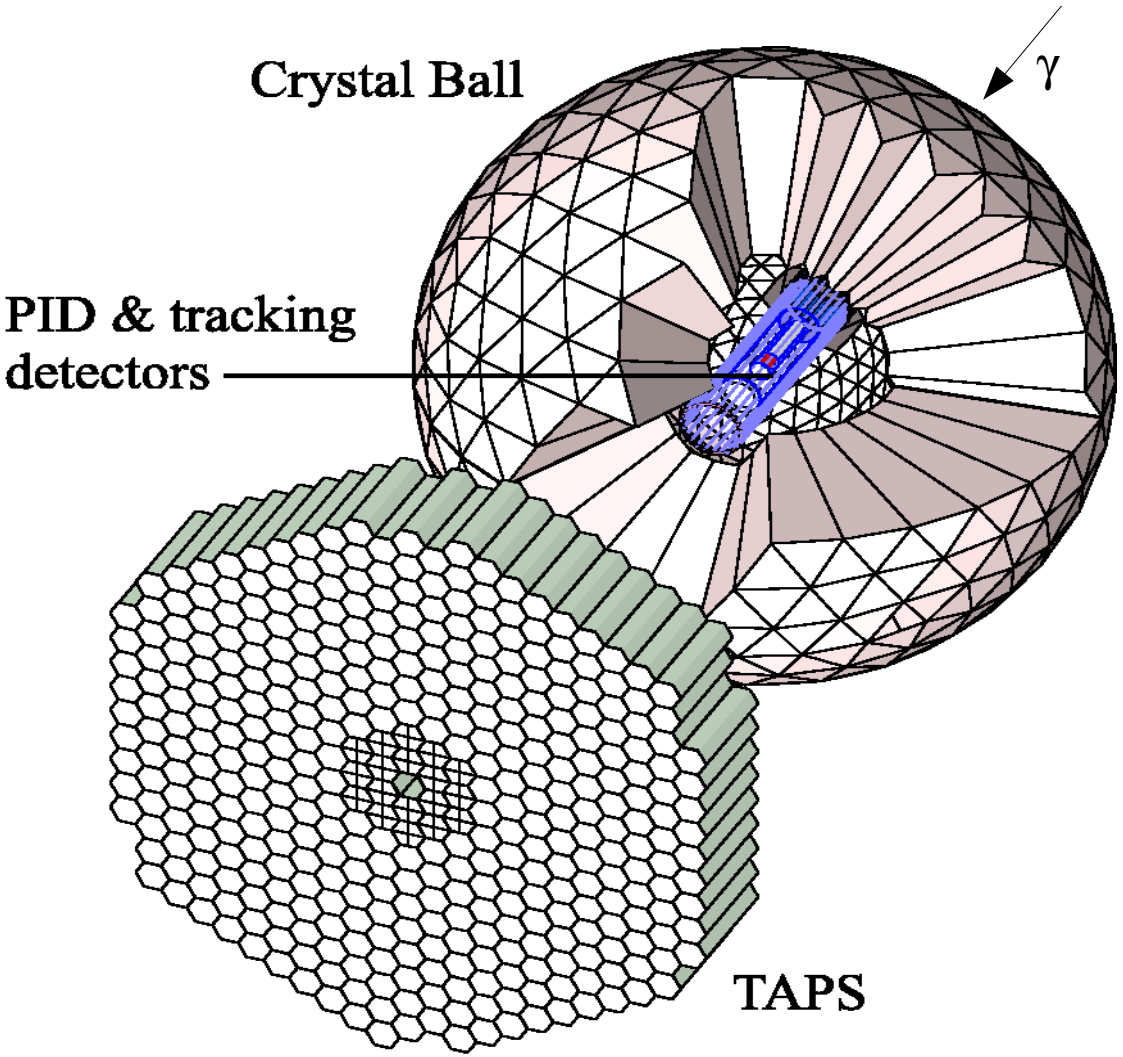
Same working principle as main tagging spectrometer

$E_\gamma \approx 1445\text{-}1595$ MeV

$\Delta E_\gamma \approx 2.5$MeV

Non-permanent installation infront of main Tagger

4π-Setup



Crystal Ball:

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

$$\sigma(\theta) = 2^\circ \ldots 3^\circ$$

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

TAPS:

Up to 510 BaF_2 crystals

Polar acceptance: 4-20°

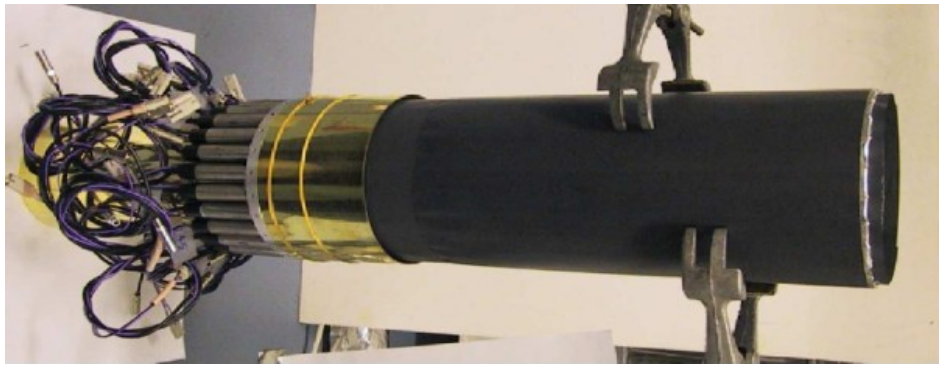
Δt = 0.5 ns FWHM

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

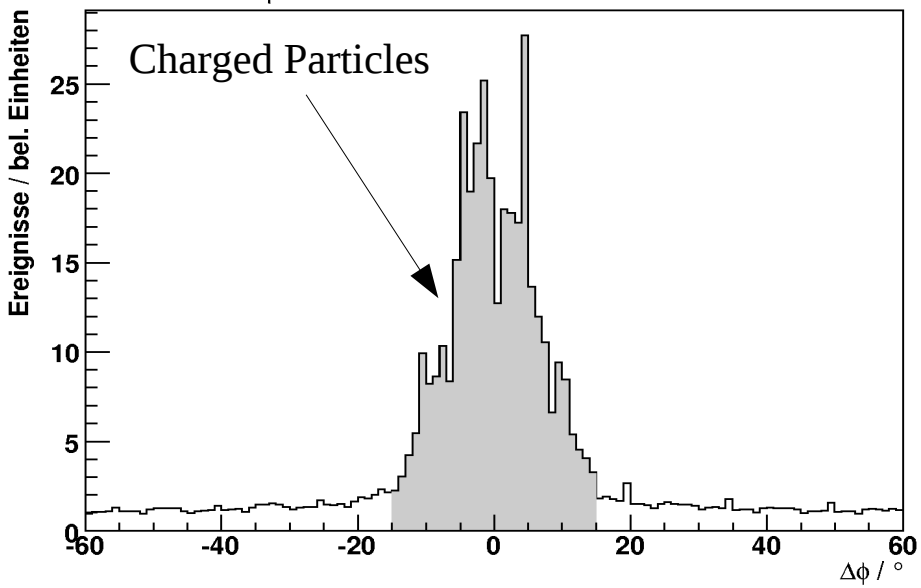
CB PID

Particle Identificaton Detector (PID):

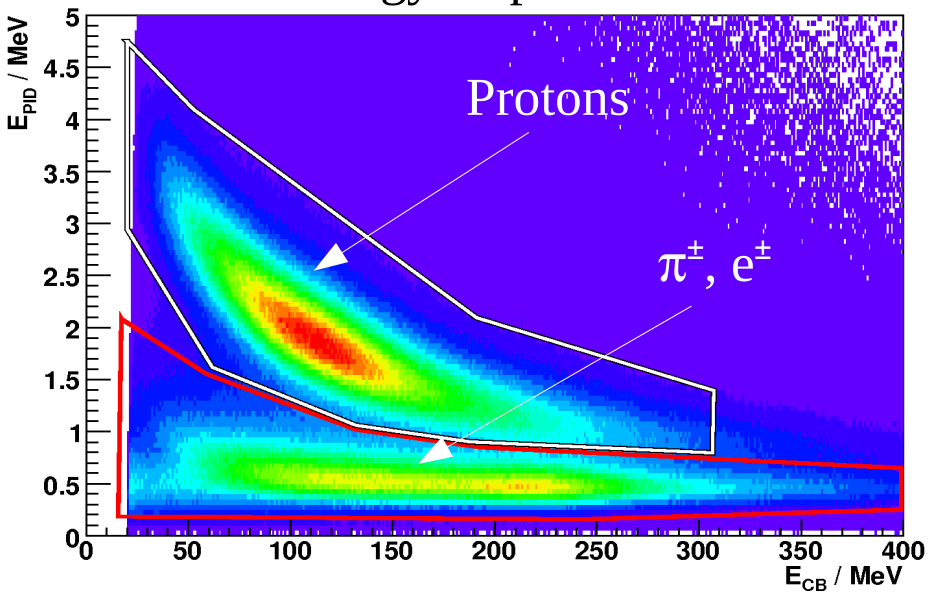
- Cylindrical Detector inside CB
- 24 scintillator strips
- PMT readout



Δϕ- between CB and PID

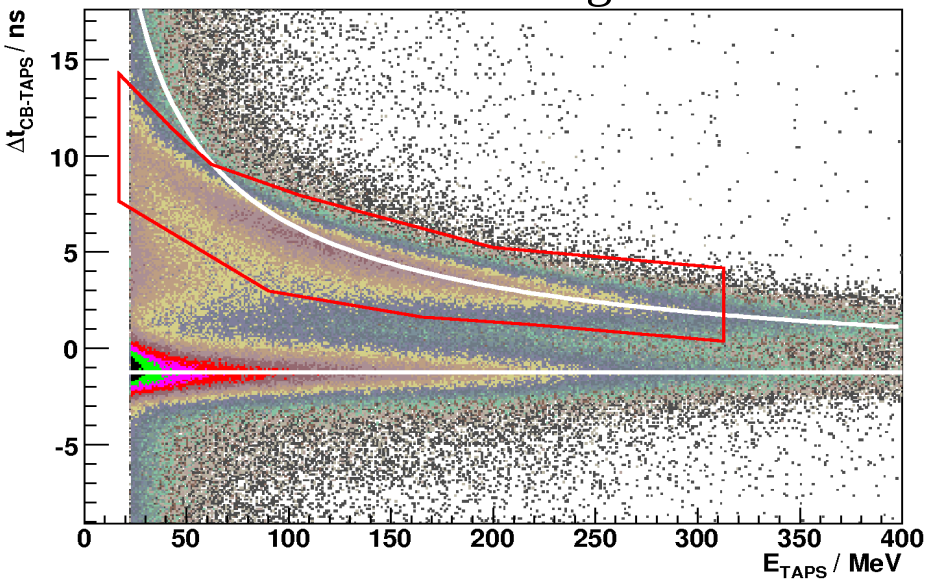


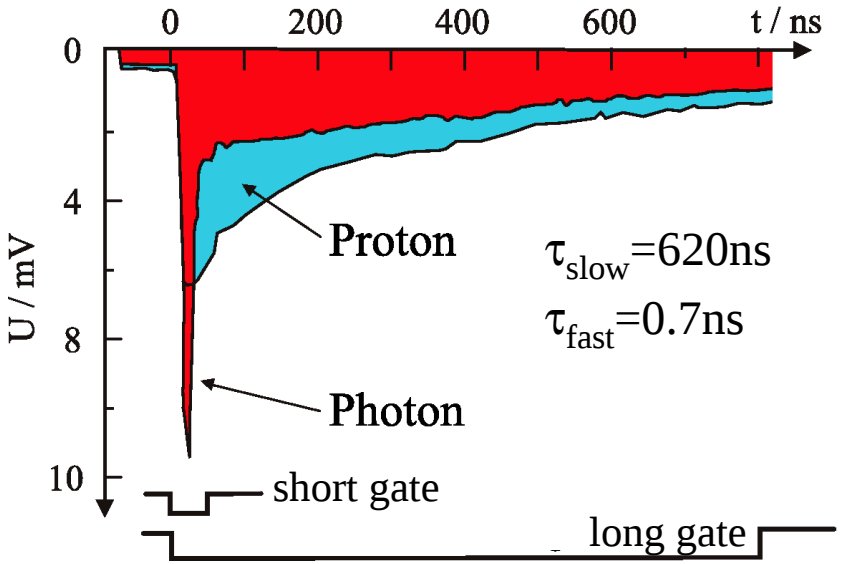
Energy Dependence



TAPS PI

Time-of-Flight





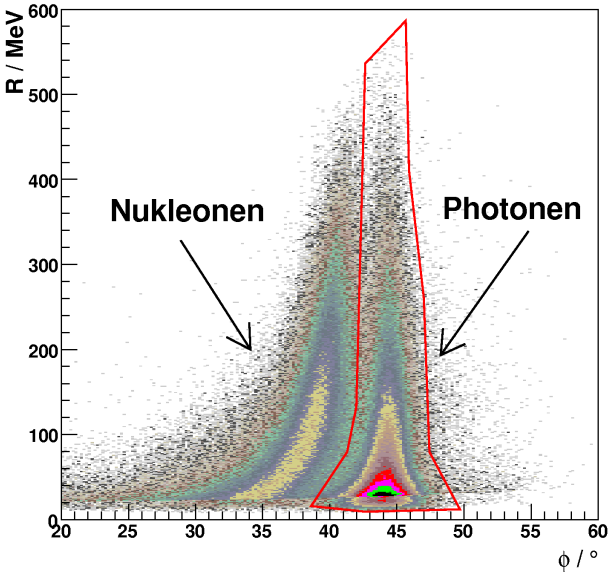
τ_{slow}=620ns

τ_{fast}=0.7ns

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

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

Pulse-Shape-Analysis

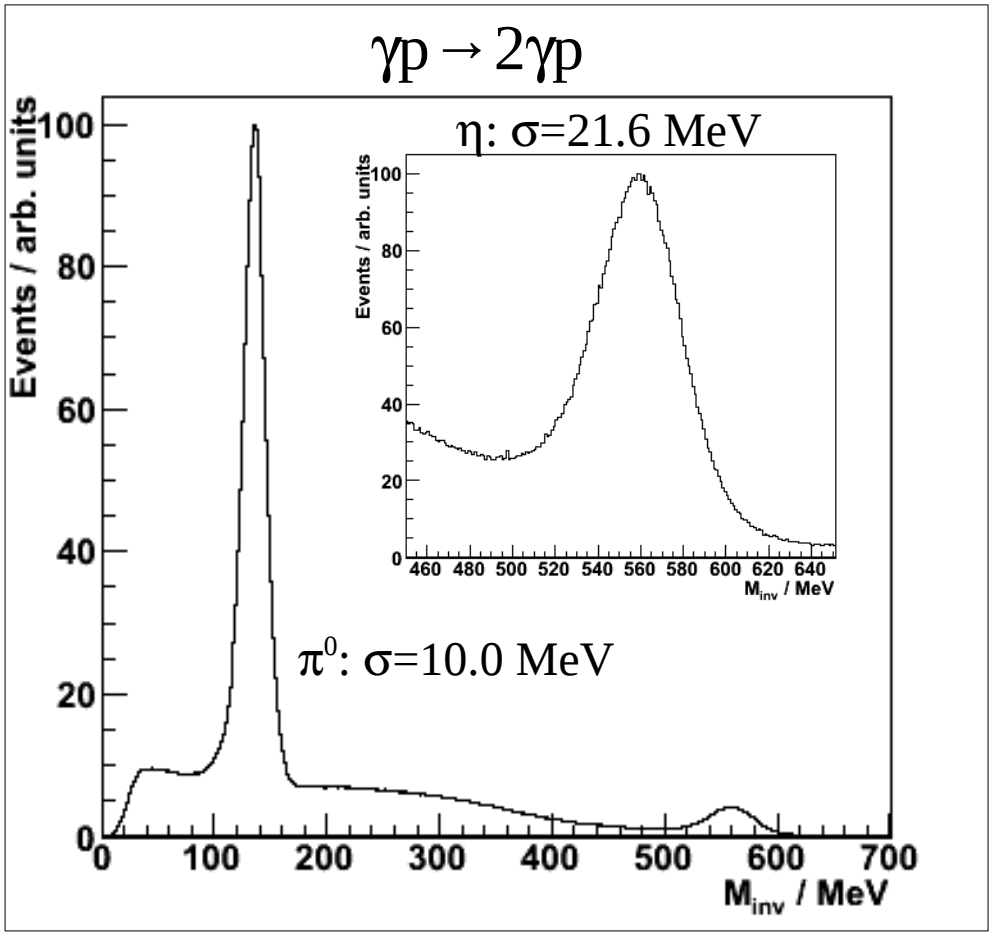


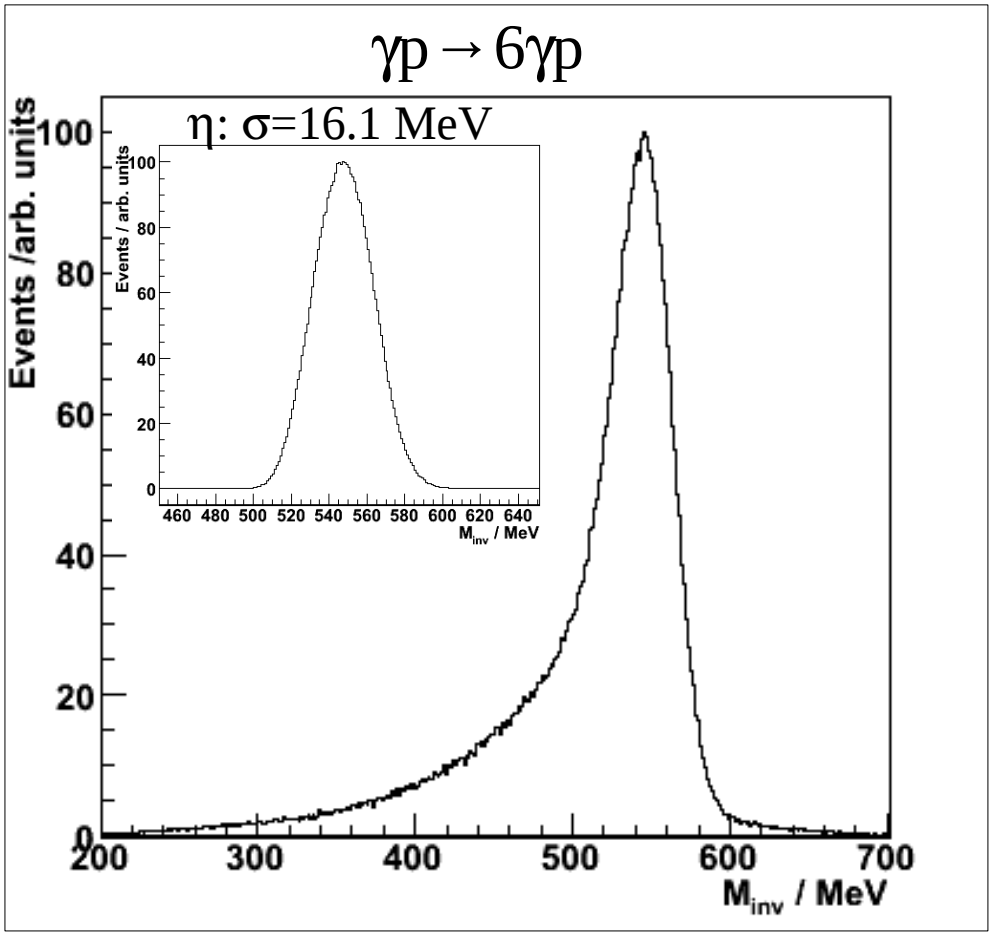
Setup Performance

Two main η decay modes:

BR($\eta \to 2\gamma$)=39.38%

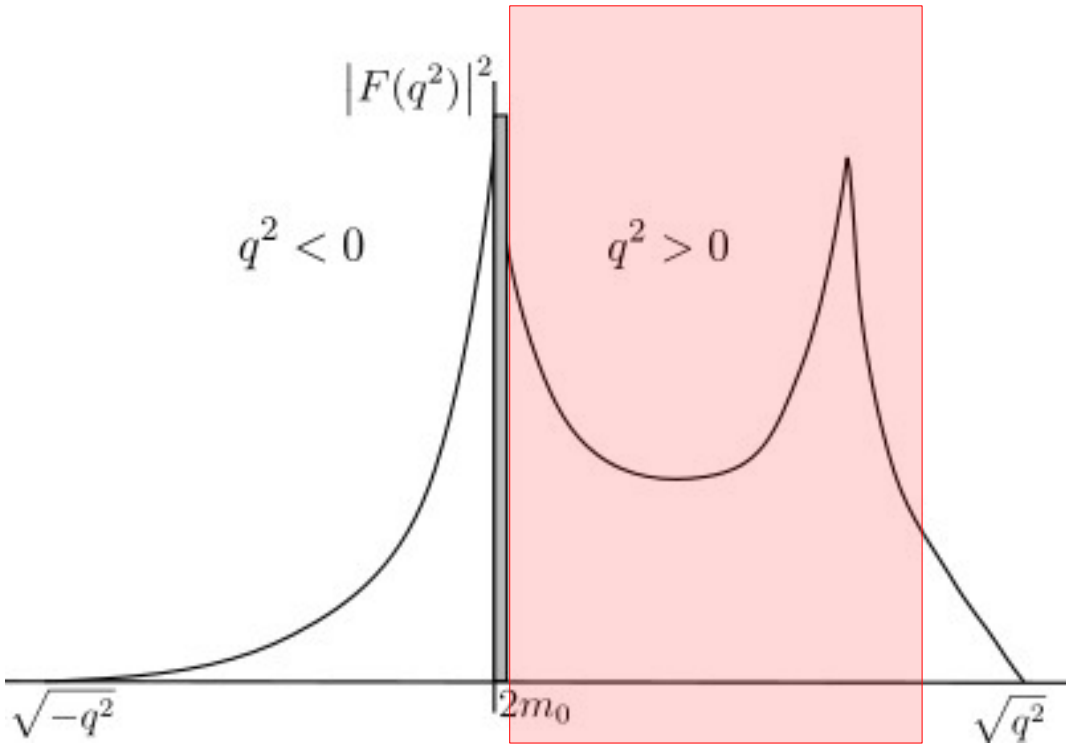
BR($\eta \to 3\pi^0$)=32.51%





$3 \cdot 10^6$ $\eta \to 3\pi^0$ analysed from ~6 weeks → 30M η produced

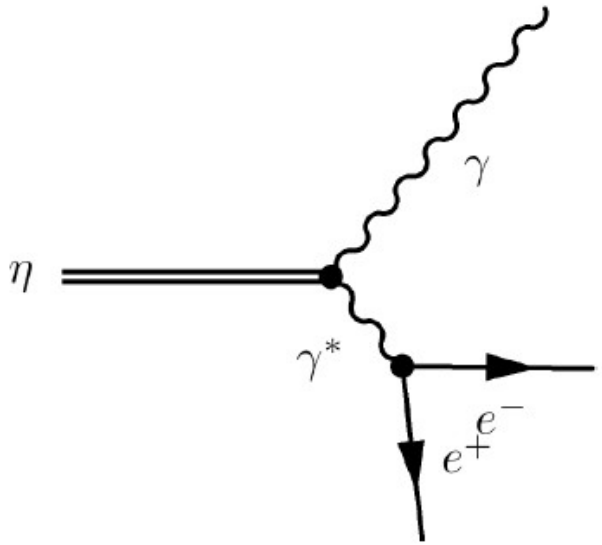
Measurement of TFFs



$q^2 = (\Delta E/c)^2 - \Delta p^2$
momentum transfer carried by virtual photon

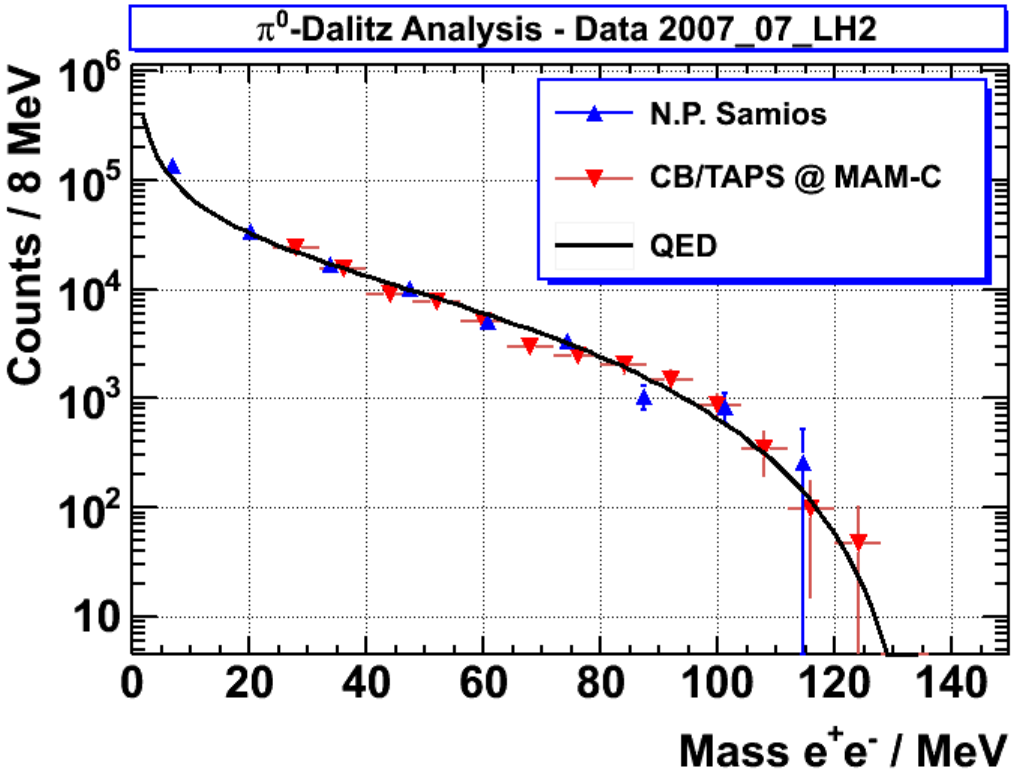
Time-like momentum transfer (meson decays):

- $(2m_0)^2 < q^2 < M^2$
- CB, WASA, KLOE, Crystal Barrel, …
- $$\frac{d\Gamma(P \to e^+e^-\gamma)}{dm\,\Gamma(P \to \gamma\gamma)} = \frac{4\alpha}{3\pi m}\sqrt{1-\frac{4m_e^2}{m^2}}\left(1+\frac{2m_e^2}{m^2}\right)\left[1-\frac{m^2}{m_P^2}\right]^3 |F(q^2)|^2$$



Time-like TFF in $\pi^0 \to e^+e^-\gamma$

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



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

- Expected behaviour:

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