Light Meson Physics with Crystal Ball at MAMI

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Mainz, 11th February 2014

Outline

- Crystal Ball Set-up at MAMI
- η/η' Cross Sections
- Results from Crystal Ball at MAMI
  - Dalitz Plot Parameter for $\eta \rightarrow 3\pi^0$
  - Preliminary Result for $\eta \rightarrow \pi^0 \gamma\gamma$
  - Timelike Transition Form Factor from $\eta \rightarrow e^+e^-\gamma$
  - C-violation in ω decays
- Future Plans
- Summary

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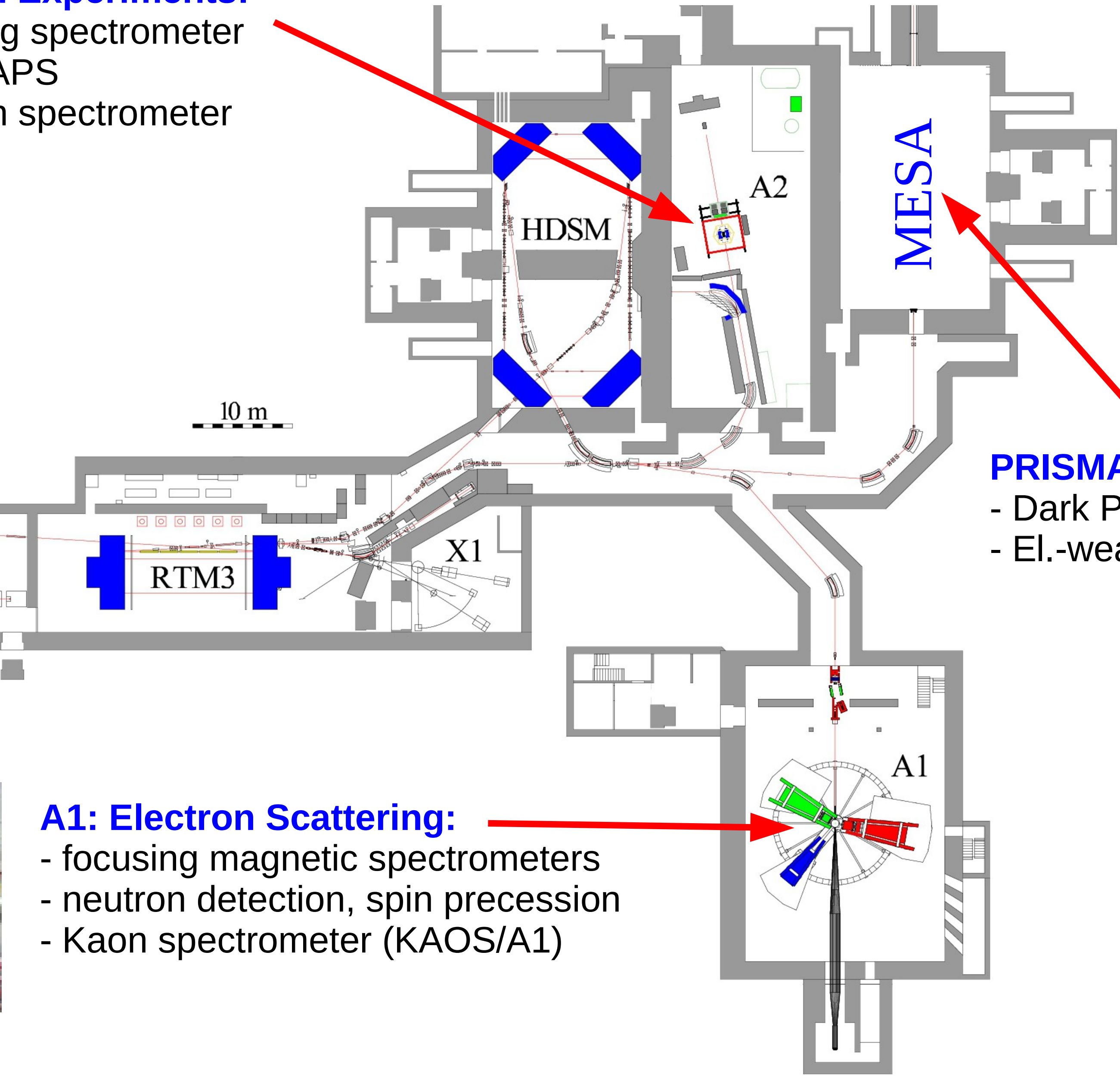
Experiments at MAMI

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

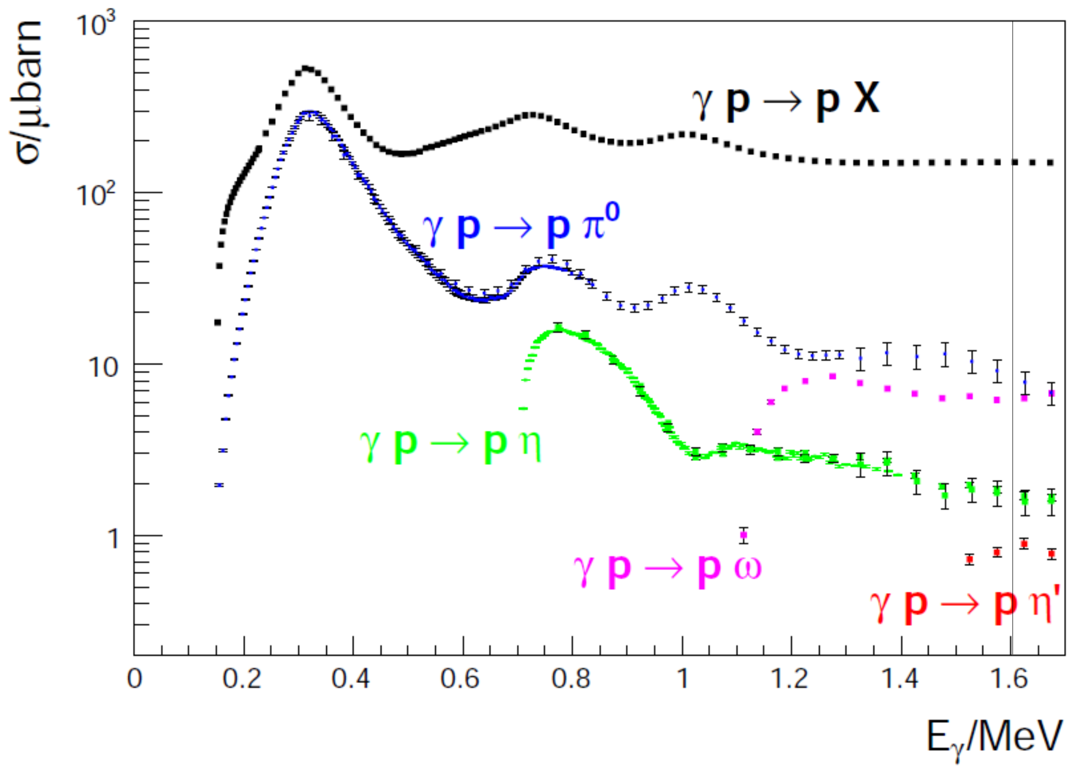


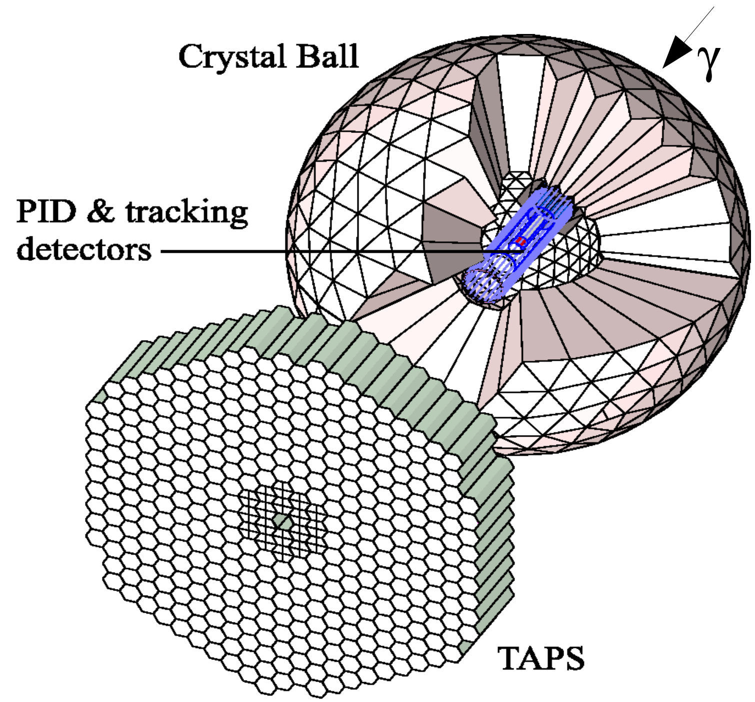
PRISMA/SFB 1044:
- Dark Photon Search
- El.-weak Mixing Angle

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 (Meson Factory):

- 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

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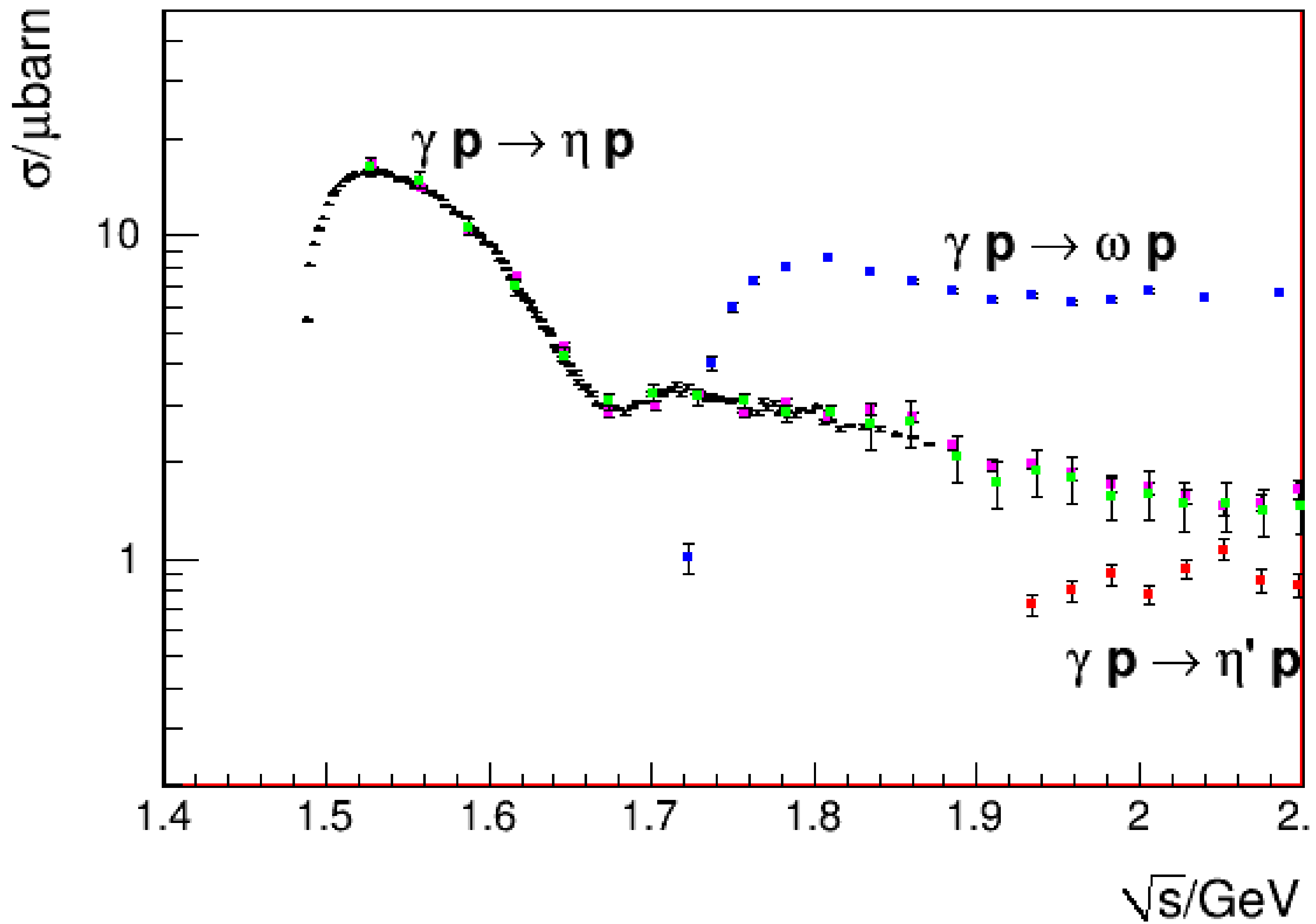
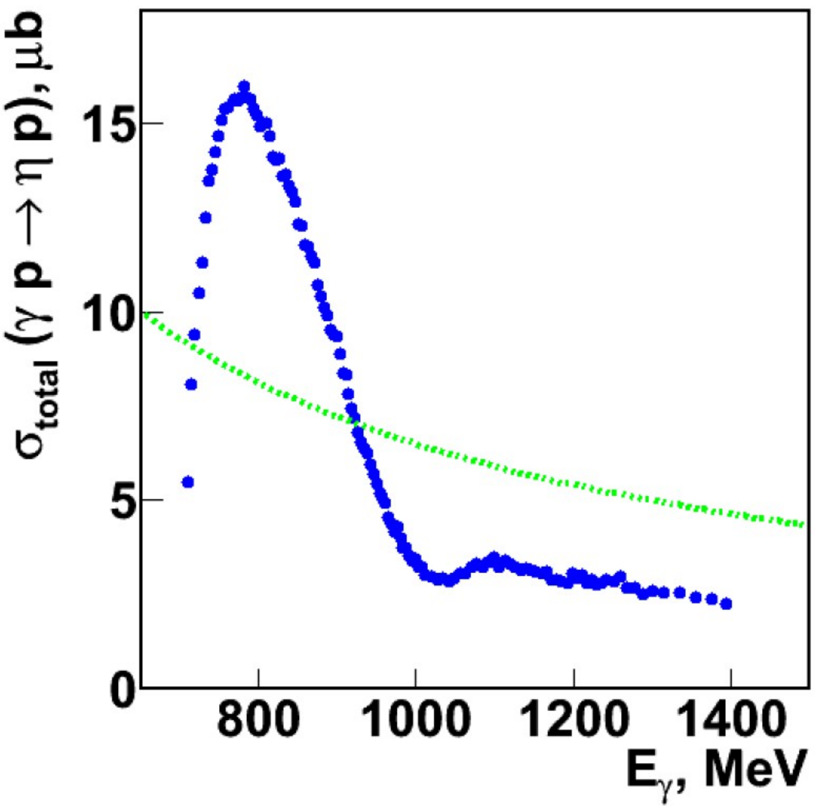
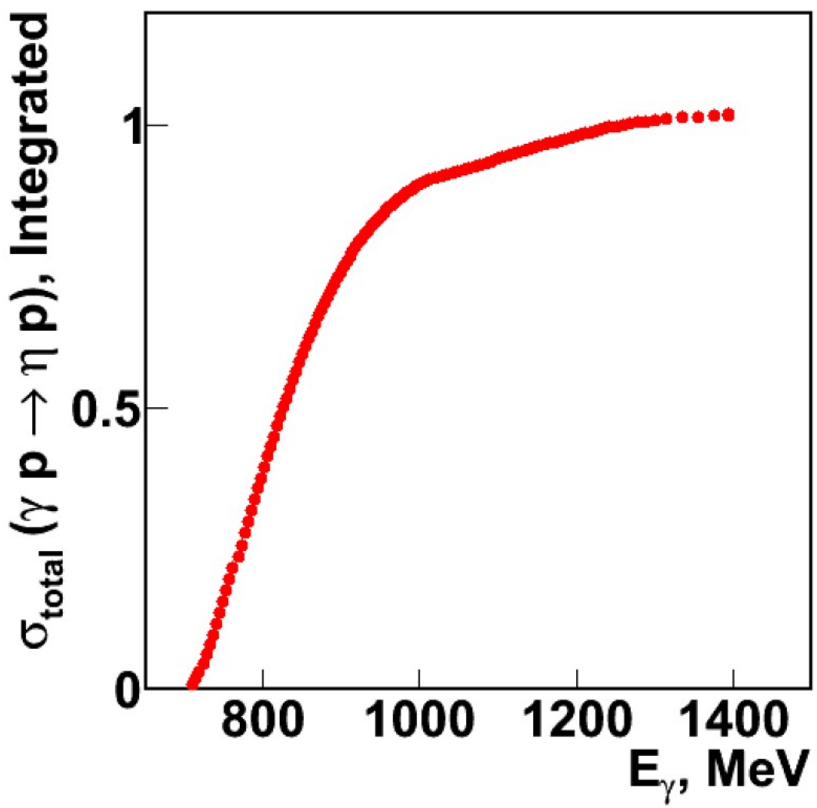
η Photoproduction Cross Section



Crystal Ball: E.F. McNicoll et al., Phys. Rev. C 82 (2010) 035208.
Crystal Barrel: V. Crede et al., Phys. Rev. Lett. 94 (2005) 012004.
CLAS: M. Dugger et al., Phys. Rev. Lett. 89 (2002) 222002.
Erratum-ibid. 89 (20002) 249904.
SAPHIR: J. Barth et al., Eur. Phys. J. A 18 (2003) 117.
Crystal Barrel: V. Crede et al., Phys. Rev. C 80 (2009) 055202.

η Photoproduction



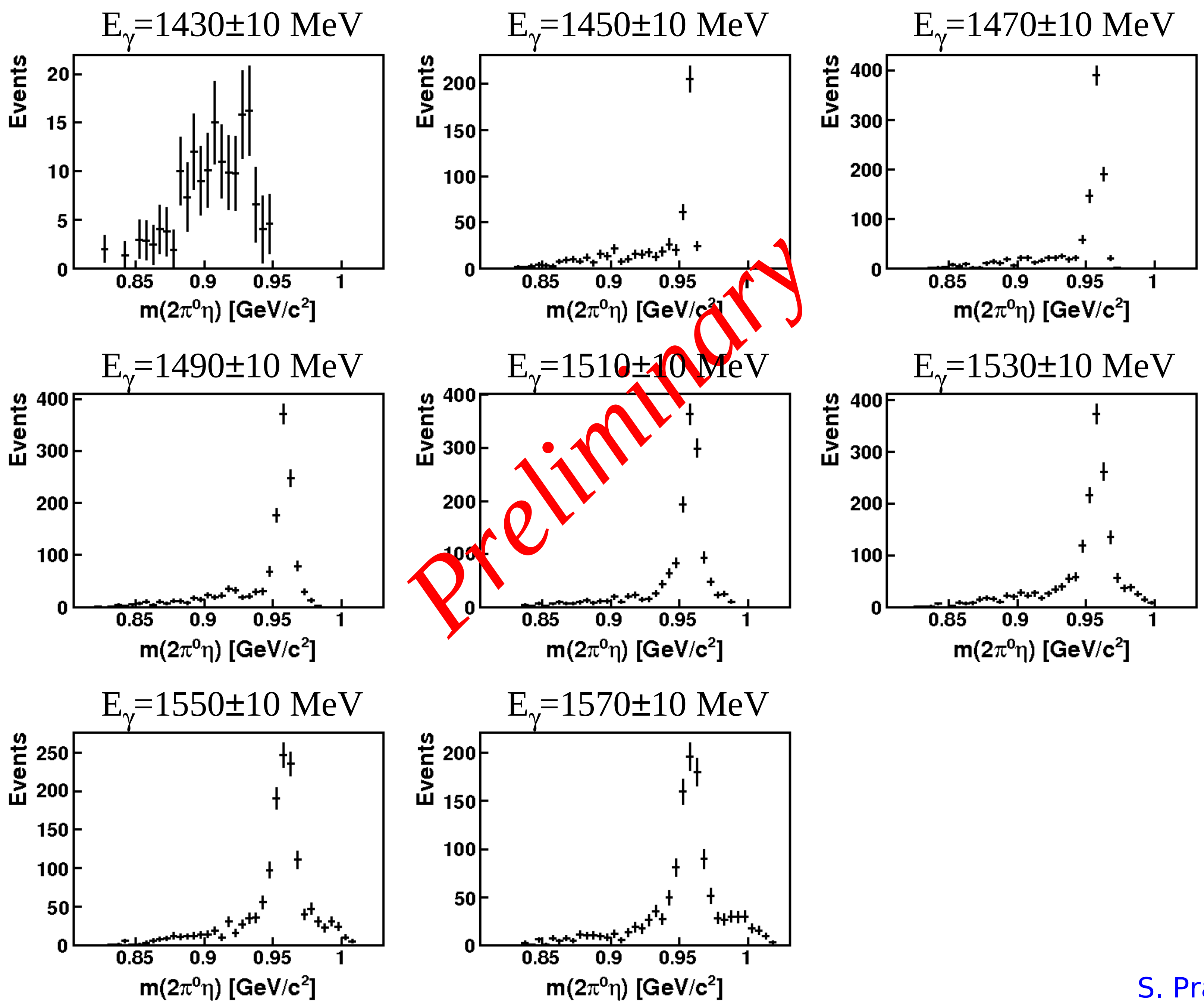


At MAMI a beam of tagged photons of excellent quality is available:

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

Beam energy nearly perfect for high statistics η photoproduction

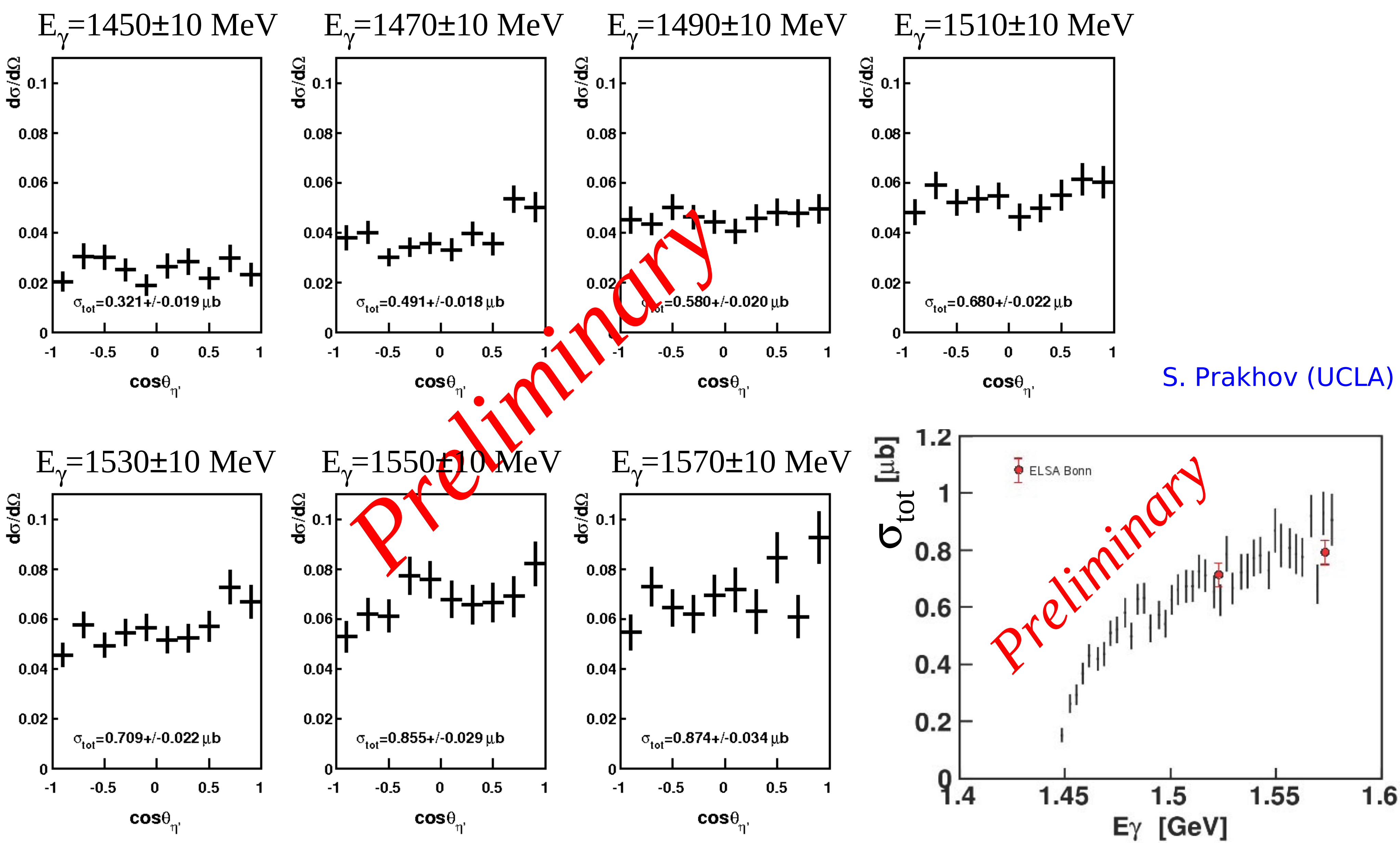
$\eta' \to \eta\pi^0\pi^0$ Invariant Mass



S. Prakhov (UCLA)

η' Cross Section

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



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$\eta \to 3\pi^0$

$\eta \to 3\pi$ → Isospin breaking

$$H_{\not{I}} = \frac{1}{2}(m_u - m_d)(\bar{u}u - \bar{d}d)$$

Lowest Order χPT:

$$A(\eta \to 3\pi^0) = \frac{B_0(m_u - m_d)}{\sqrt{3}F_\pi^2} \propto (m_u - m_d)$$

$$\Gamma(\eta \to 3\pi) \propto |A|^2 \propto Q^{-4}$$

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

Allows to extract information on quark masses!

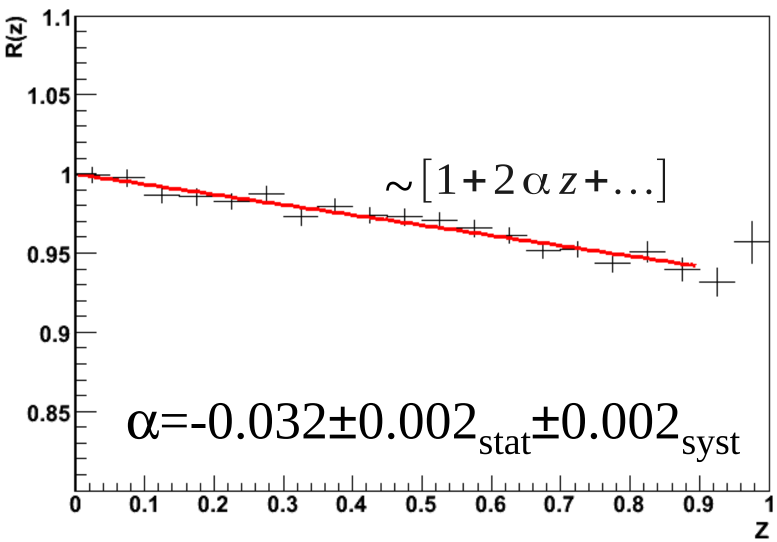
Parametrization of $\eta \to 3\pi^0$ Dalitz plot:

$$|A(\eta \to 3\pi^0)|^2 = N \cdot (1 + 2\alpha z + \ldots)$$

$$z = 6\sum_{i=1}^{3}\left(\frac{E_i - m_\eta/3}{m_\eta - 3m_{\pi^0}}\right)^2 = \frac{\rho^2}{\rho_{max}^2}$$

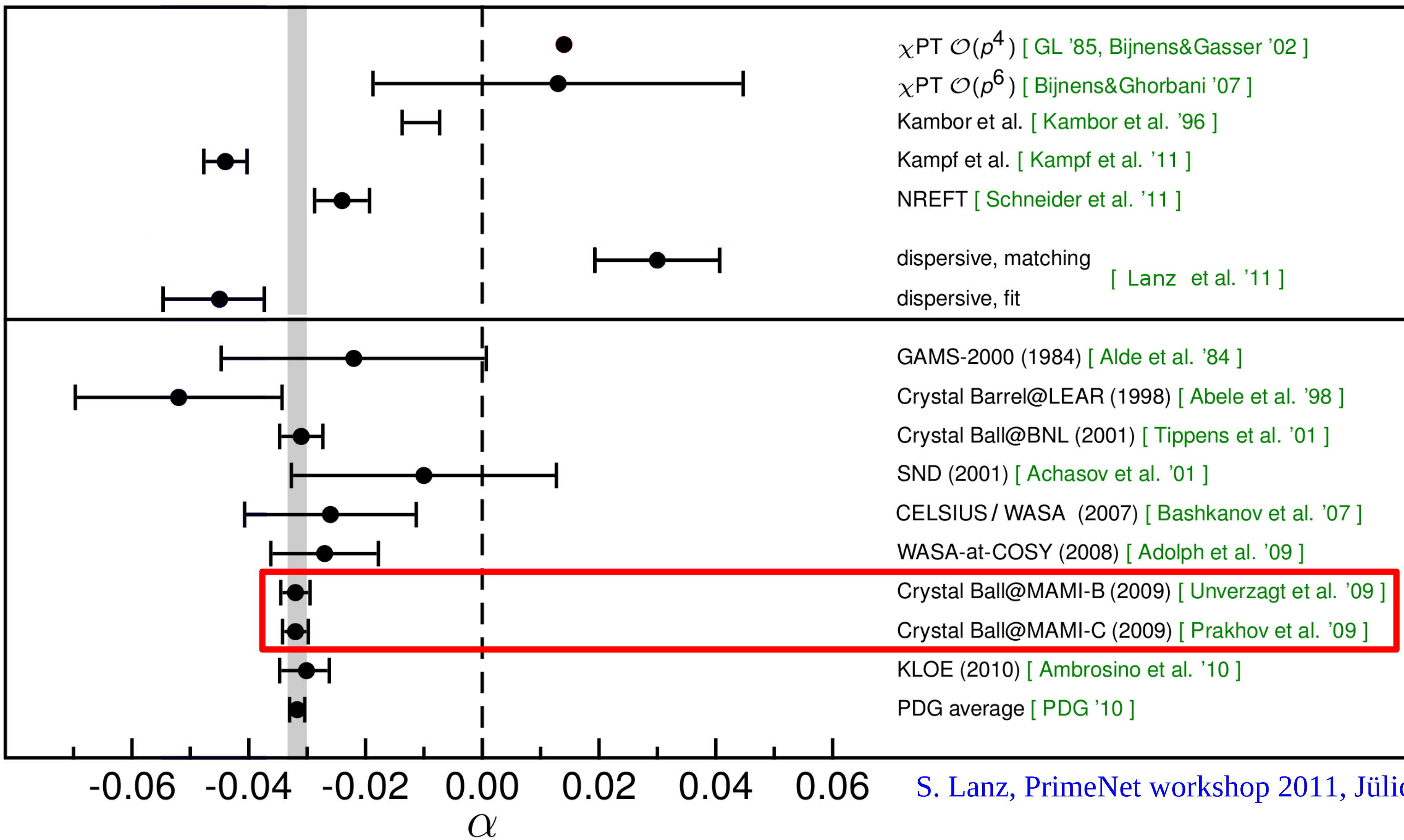
E_i: π^0 energies in η rest frame,

ρ: radial distance to center of Dalitz plot



$\eta \rightarrow 3\pi^0$ Dalitz Plot Parameter

- World's most precise results on $\eta \rightarrow 3\pi^0$ decay from CB at MAMI



S. Lanz, PrimeNet workshop 2011, Jülich

Experiments reach precision where higher order effects (cusp-effect, second order term in expansion) become visible

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

- 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)

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

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

- 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

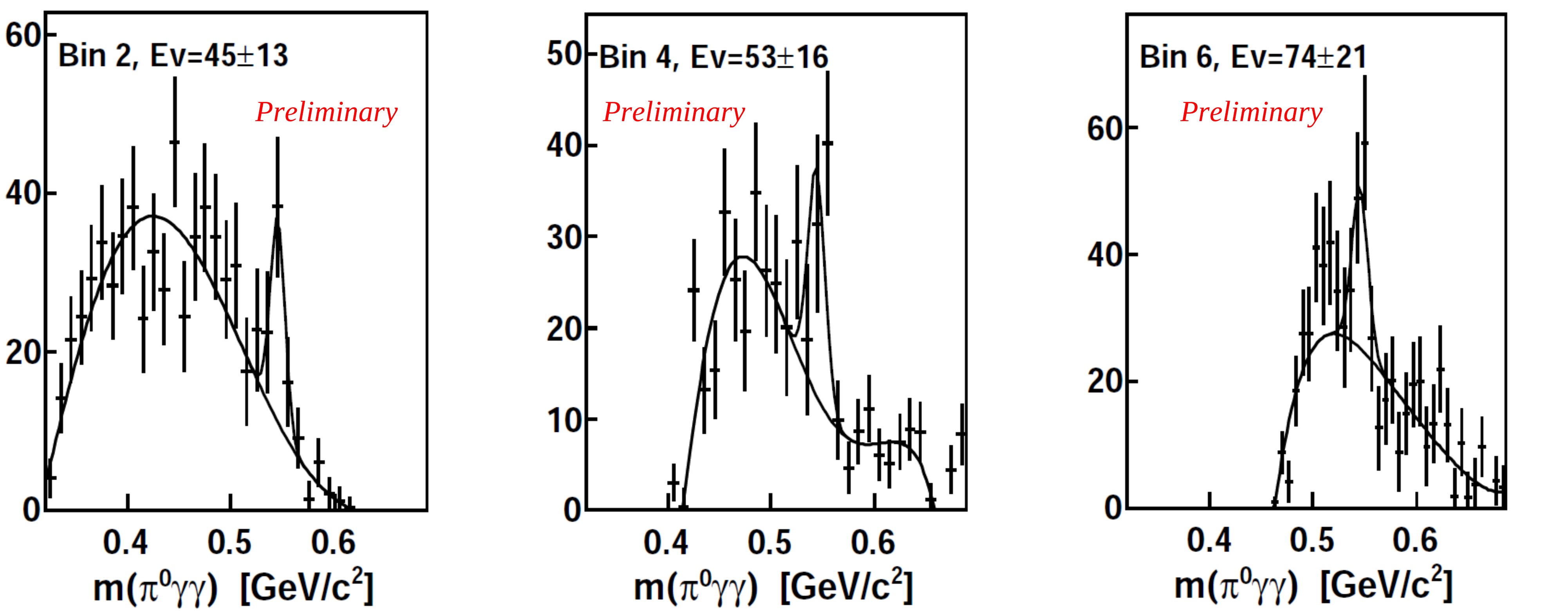
- New CB@MAMI analysis based on data taken in 2007 and 2009 ($6\cdot 10^7$ η produced)

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

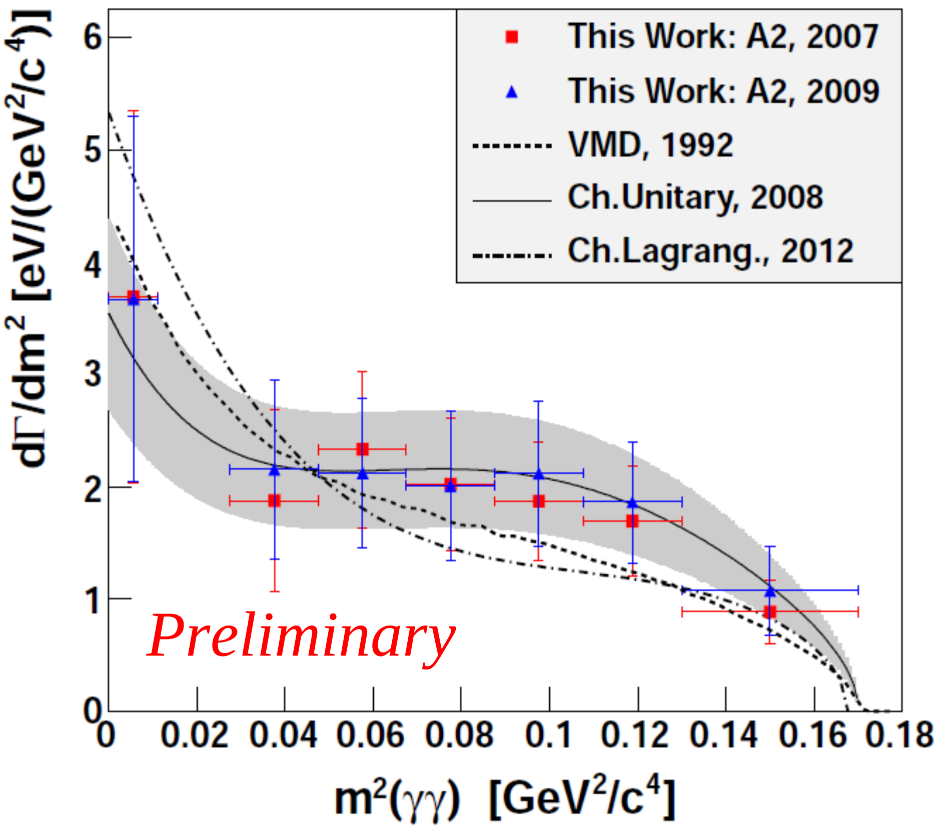
- Based on kinematic fitting
- $\pi^0\pi^0$ background suppressed by anti-hypothesis
- Results based on $1.2\cdot10^3$ $\eta\rightarrow\pi^0\gamma\gamma$ events

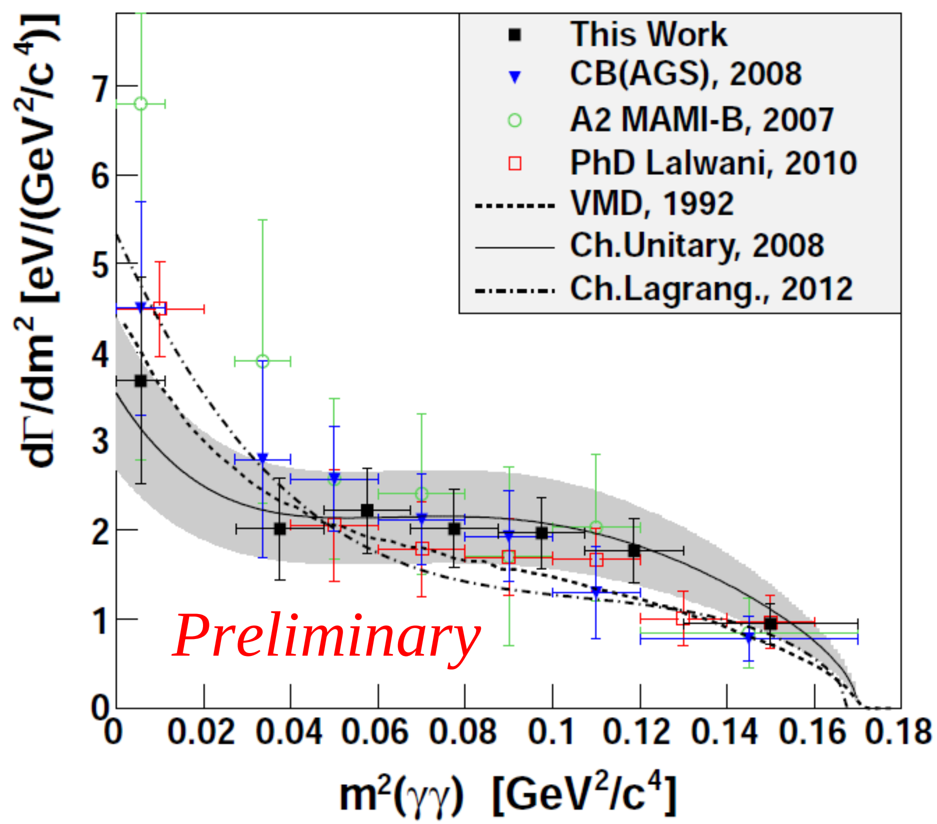
- Below preliminary results from 2009

$m^2(\gamma\gamma) = (0.0375 \pm 0.0100)\ \mathrm{GeV}^2/c^4$ $m^2(\gamma\gamma) = (0.0775 \pm 0.0100)\ \mathrm{GeV}^2/c^4$ $m^2(\gamma\gamma) = (0.11875 \pm 0.01125)\ \mathrm{GeV}^2/c^4$



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, Eur. Phys. J. C73 (2013) 2358.

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

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

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

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

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

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

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

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

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

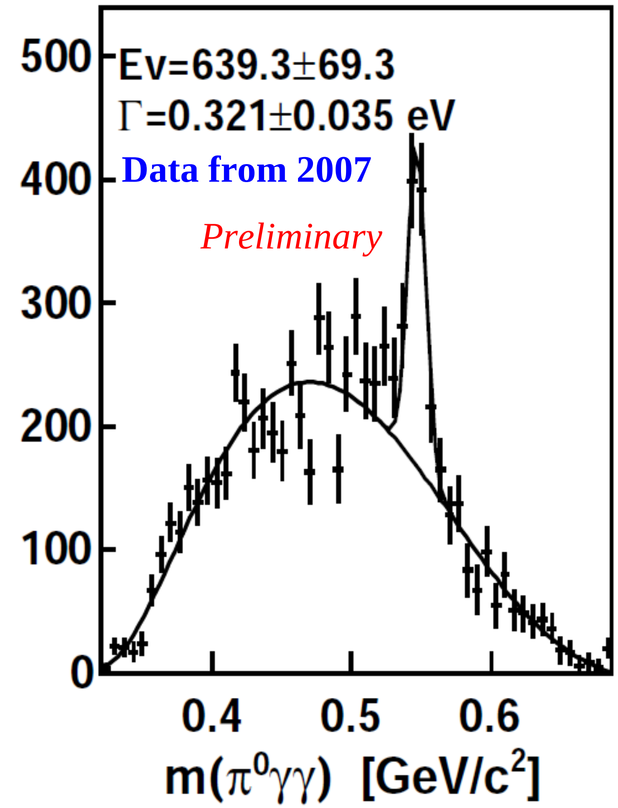
$$\Gamma = 0.31\ \mathrm{eV},\ \ \mathrm{Ch.\ Lagrang., 2012}$$

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

- Data from 2007 and 2009 combined:

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

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



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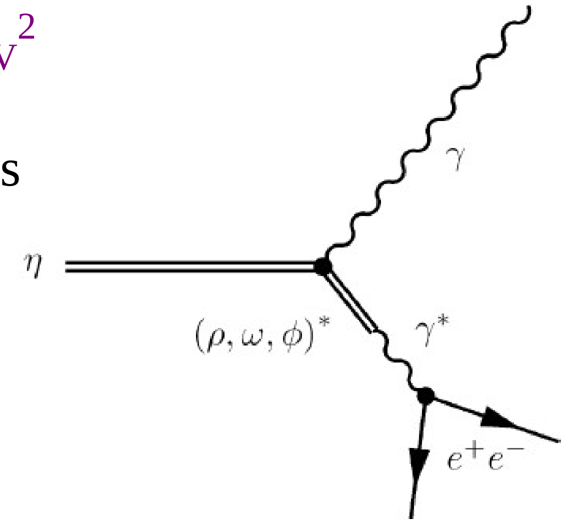
Transition Form Factor with VMD

- 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:

$$\left|F(m^2)\right|^2 = \left(1 - \frac{m^2}{\Lambda^2}\right)^{-2}$$

Exp: $\Lambda \approx 0.72\ \mathrm{GeV} \quad \Rightarrow \quad \Lambda^{-2} = 1.93\ \mathrm{GeV}^{-2}$

VMD: $\Lambda \approx m_\rho = 0.77\ \mathrm{GeV}$

- For η' resonance shape:

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

$\Lambda \approx 0.76\ \mathrm{GeV} \quad \gamma \approx 0.10\ \mathrm{GeV}$

- Gain information on structure of transition, structure of meson and η/η' mixing, (dark photon?)

Hadronic LbL Contribution to a_μ=(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:

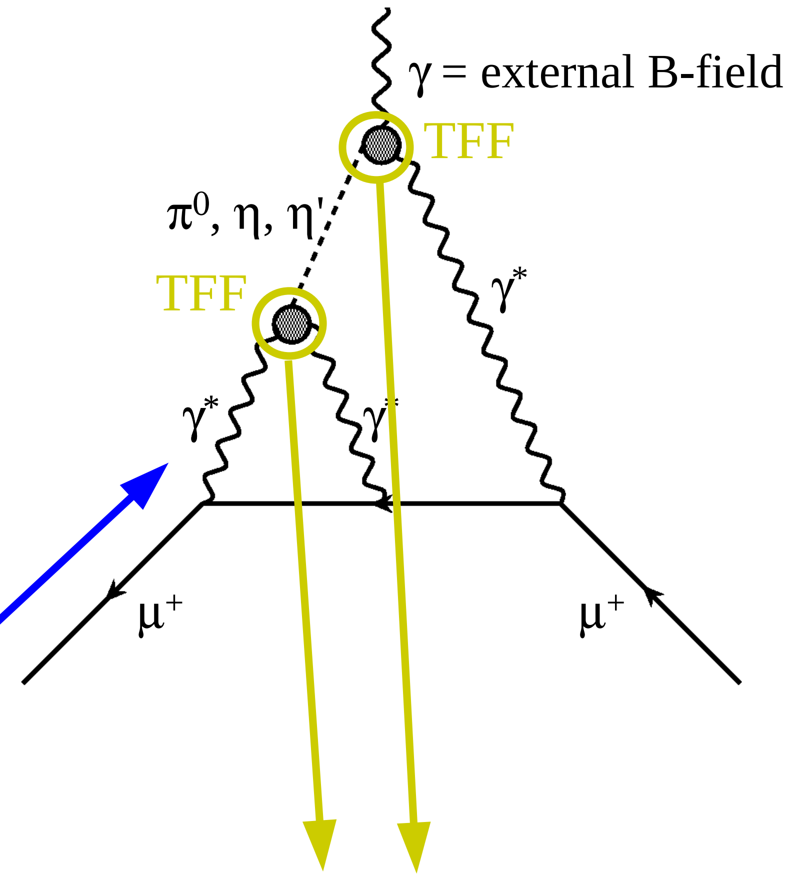
$$a_\mu^{\mathrm{VP}} = (692.3 \pm 4.2) \cdot 10^{-10}$$

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).

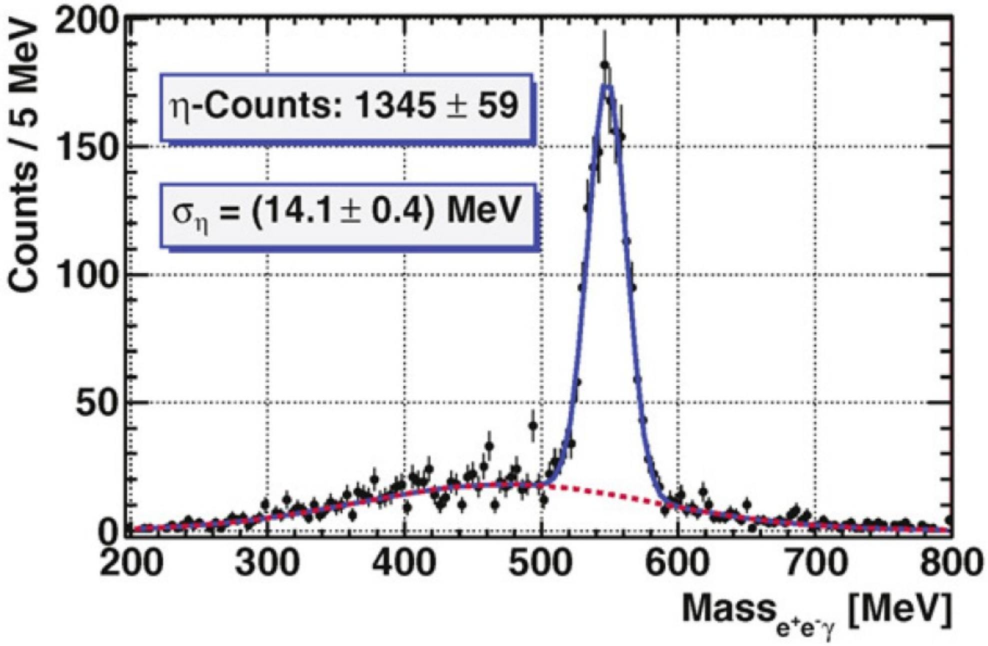


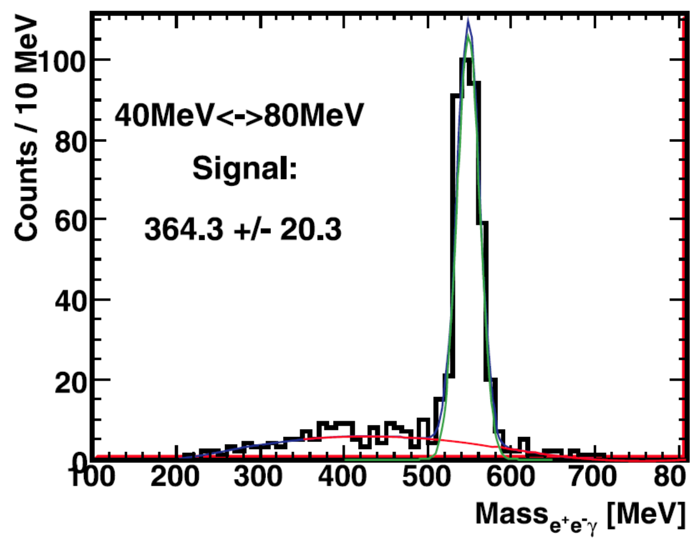
Transition Form Factors of light pseudoscalar mesons could give important input for SM calculations of (g-2)$_\mu$

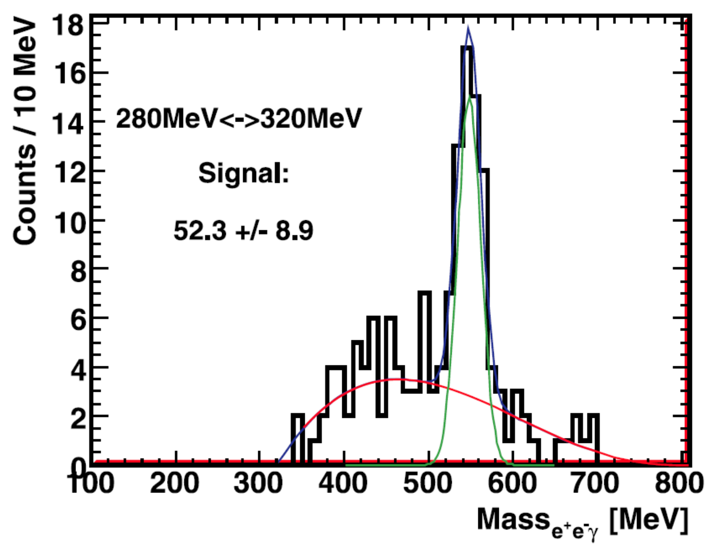
First A2 Analysis for η TFF

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

- Using $\eta \to e^+e^-\gamma$
- Based on kinematic cuts
- Small amount of data
- Limited photoproduction energy range

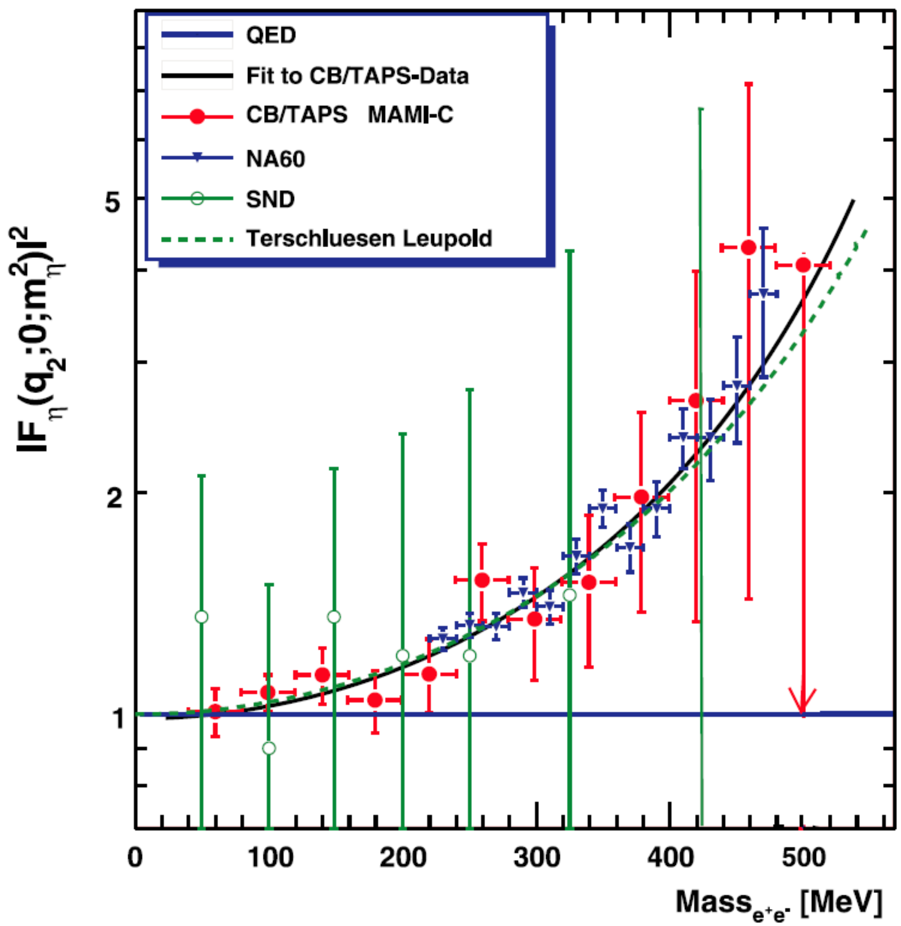






First A2 Result for η TFF

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



CB/TAPS MAMI-C: 1350 $\eta \to e^+e^-\gamma$ events

NA60: 9000 $\eta \to \mu^+\mu^-\gamma$ events

SND: 109 $\eta \to e^+e^-\gamma$ events

$$|F(m^2)|^2 = \left(1 - \frac{m^2}{\Lambda^2}\right)^{-2}$$

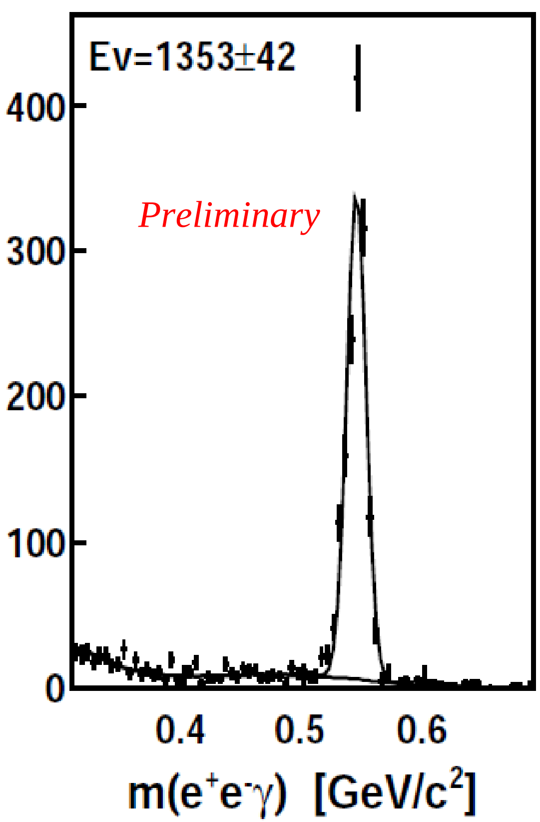
$\Lambda^{-2} = (1.92 \pm 0.35_{stat} \pm 0.13_{syst})\ GeV^{-2}$

NA60, In-In: R. Arnaldi et al., Phys. Lett. B **677** (2009) 260.
SND: M.N. Achasov et al., Phys. Lett. B **504** (2001) 275.
Terschluesen Leupold: C. Terschlüsen, Diploma thesis, University Gießen, Germany, 2010.

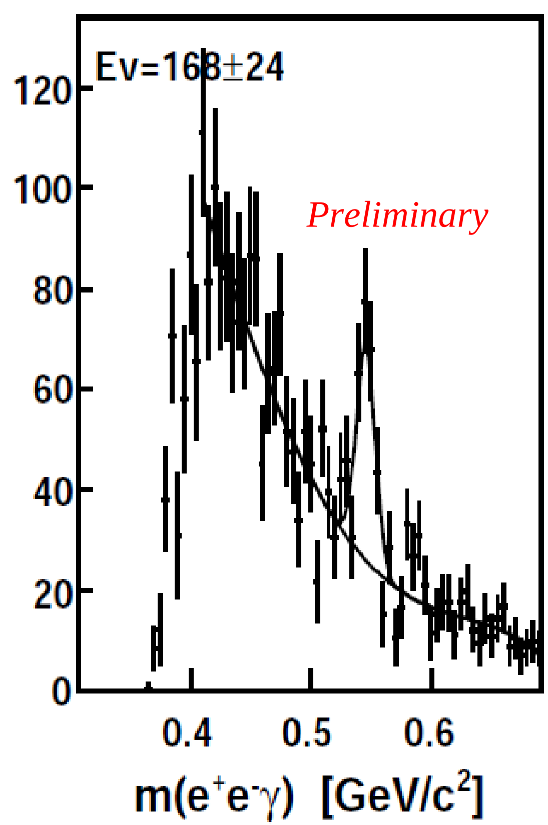
New Analysis of η TFF

- Based on kinematic fitting
- 3x more data
- Full η photoproduction range accessible at MAMI used
- 18,000 events (no proton requirement: 22,000 events), most precise $\eta \rightarrow e^+e^-\gamma$ up to now

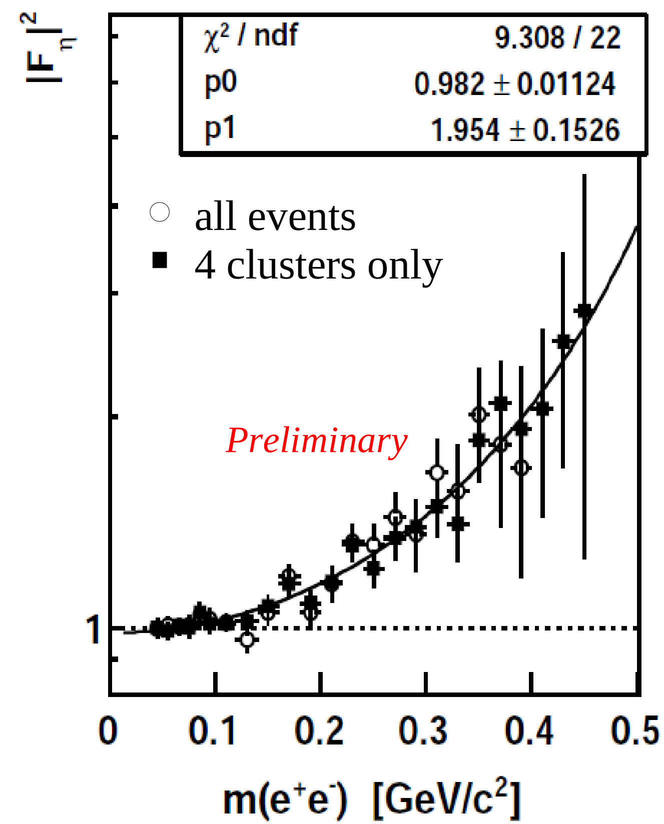
$m(e^+e^-)$=45±5 MeV



$m(e^+e^-)$=285±5 MeV

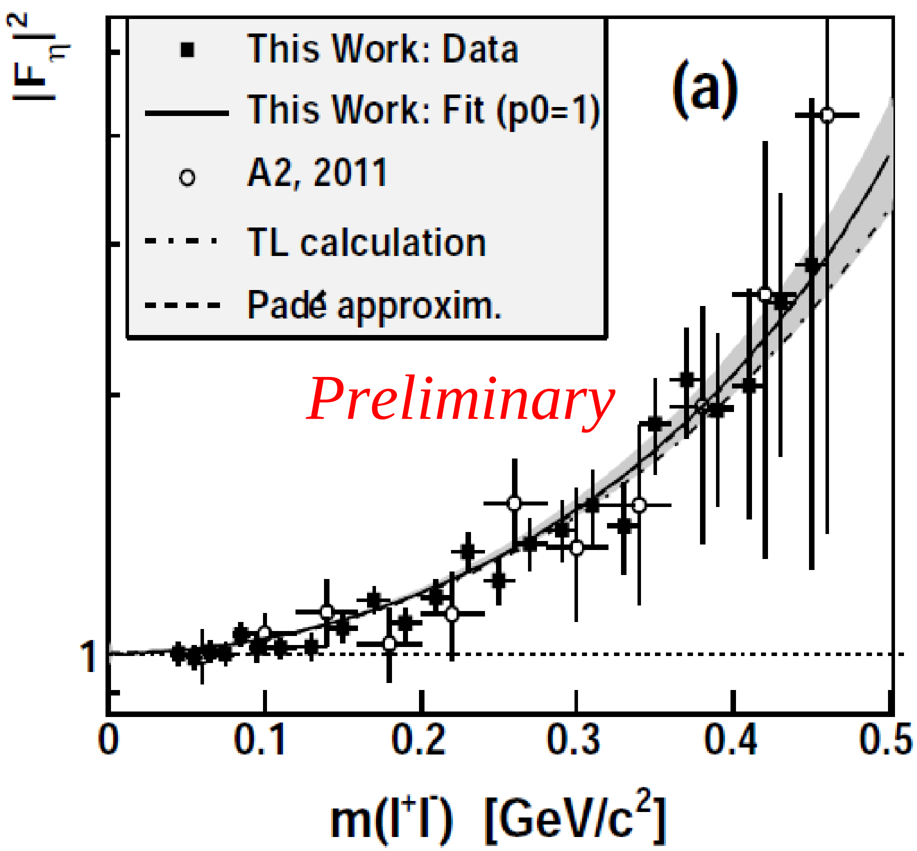


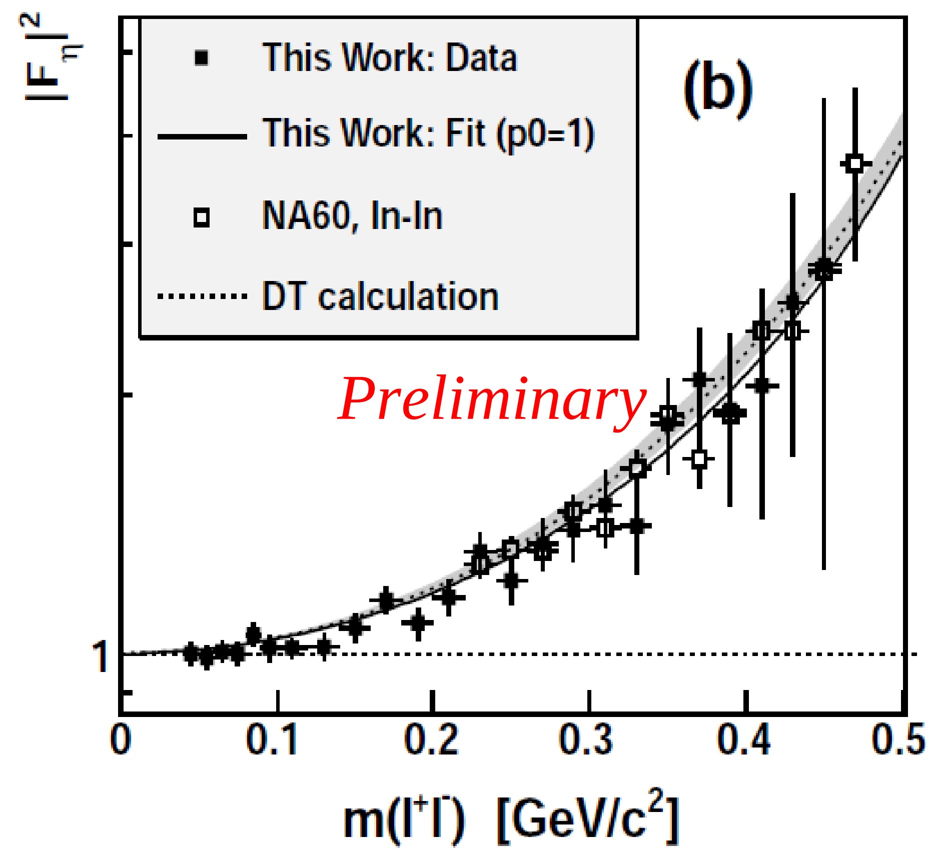
Solid line: Pole-approximation fit
Normalisation p0 and Λ^{-2}=p1 as free parameters



New A2 Result for η TFF

S. Prakhov, M. Unverzagt et al., submitted to Phys. Rev. C, arXiv: 1309.5648 [hep-ex]





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

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, Eur. Phys. J. C73 (2013) 2668.

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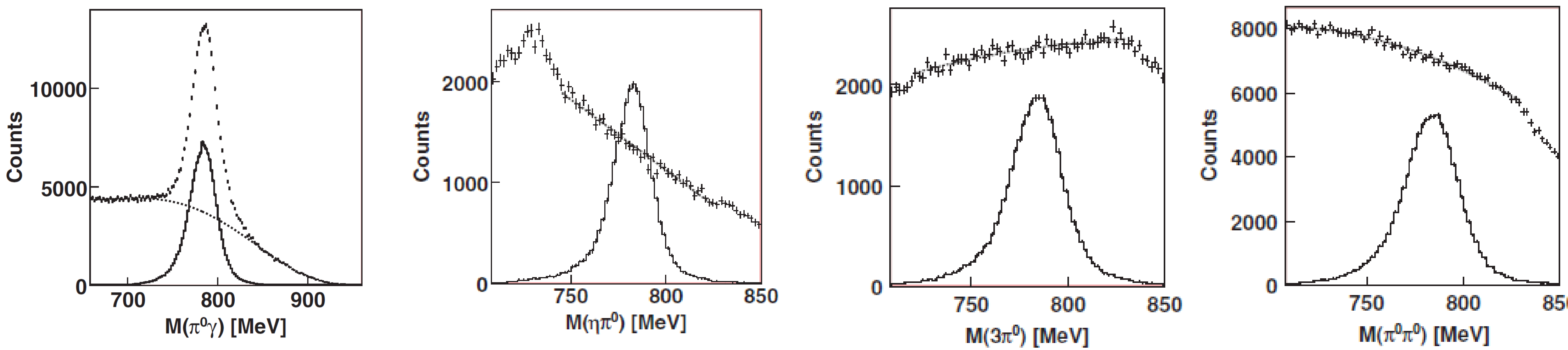
C-Violating ω Decays

- $7 \cdot 10^6$ ω events produced in 3 weeks (parallel to η production)



$1.5 \cdot 10^5$ events

$\Gamma(\omega \rightarrow \eta\pi^0)/\Gamma_{tot} < 2.3 \cdot 10^{-4}$ at 90% C.L.

$\Gamma(\omega \rightarrow 3\pi^0)/\Gamma_{tot} < 2.3 \cdot 10^{-4}$ at 90% C.L.

$\Gamma(\omega \rightarrow 2\pi^0)/\Gamma_{tot} < 2.4 \cdot 10^{-4}$ at 90% C.L. never been done before

Only CB at MAMI results used by PDG!

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

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Perspectives for η

Proposed production yields with Crystal Ball at MAMI:

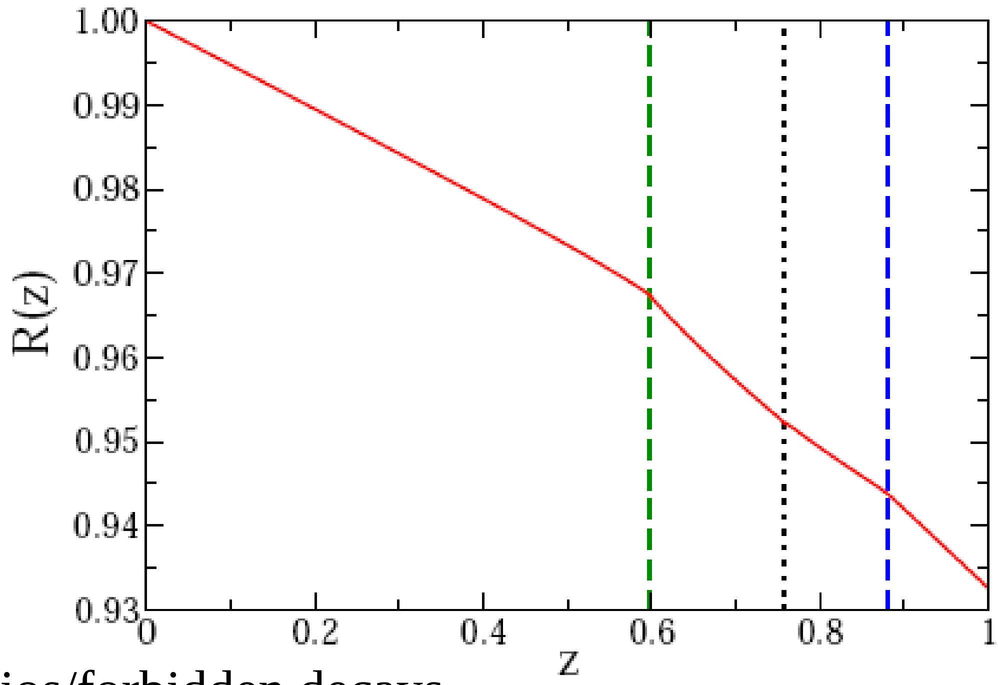
10 weeks: $5 \cdot 10^8$ η (factor 10 improvement)

- Neutral decay modes with unprecedented accuracy with CB:
  QCD/χPT related (Dalitz plot analysis): $\eta \rightarrow 3\pi^0$
  Further effects: kinematic boundaries, second order term in expansion,
  cusp effect (few %), $\pi\pi$-scattering

- Transition Form Factor:
  Improve single Dalitz decay
  Double Dalitz decays?

- C/CP-violation:
  $\eta \rightarrow 2\pi^0\gamma$, $\eta \rightarrow 3\pi^0\gamma$, $\eta \rightarrow 3\gamma$, $\eta \rightarrow 4\pi^0$

- Fix parameters for EFT
  Charged decays $\eta \rightarrow \pi^+\pi^-\gamma$, $\eta \rightarrow \pi^+\pi^-\gamma\gamma$



- Measurements of absolute branching ratios/forbidden decays

A. Denig, W. Gradl, M. Ostrick, M. Unverzagt (University Mainz), S. Prakhov, (UCLA/Mainz)

Perspectives for η'

Proposed production yields with Crystal Ball at MAMI:

10 weeks: $2\cdot10^7$ η' (factor 4 improvement) in fall 2014

- Neutral decay modes with unprecedented accuracy with CB: unstable particles in EFT
  BR($\eta'\to\omega\gamma/\eta'\to\eta\pi^0\pi^0$) improve by factor 2-5
  PDG 2012: BR($\eta'\to\omega\gamma/\eta'\to\eta\pi^0\pi^0$) = 0.147±0.016

- QCD/χPT related (Dalitz plot analyses) $\eta'\to3\pi^0$, $\eta'\to\eta\pi^0\pi^0$ (~400.000 events expected)
  Further effects: cusp effect (8%), $\pi\pi$- and $\pi\eta$-scattering

- Transition Form Factor:
  Single Dalitz decay (800 events proposed)

A. Denig, W. Gradl, M. Ostrick, M. Unverzagt (University Mainz), S. Prakhov, (UCLA/Mainz)

Rate Estimation

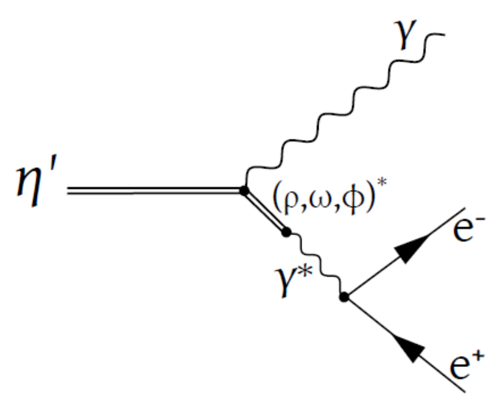
S. Wagner, Master thesis, University Mainz, 2013
M. Unverzagt, A. Denig

- $\eta' \rightarrow e^+e^-\gamma$ no observation published yet worldwide
- 5.5 weeks of η' photoproduction in 2012
  - Analysis of $\eta' \rightarrow \eta\pi^0\pi^0$
    - → Total 1.5 million η' produced
- Simulation based on
  - PDG upper limit for branching ratio
  - 20 background channels simulated
  - Kinematic cuts (try kinematic fit ?)
  - Most critical backgrounds: $\pi^0\pi^0$, $\pi^0\eta$
  - Acceptance ~8.5% (preliminary)
- Expected: ~80 $\eta' \rightarrow e^+e^-\gamma$ events from 2012 data

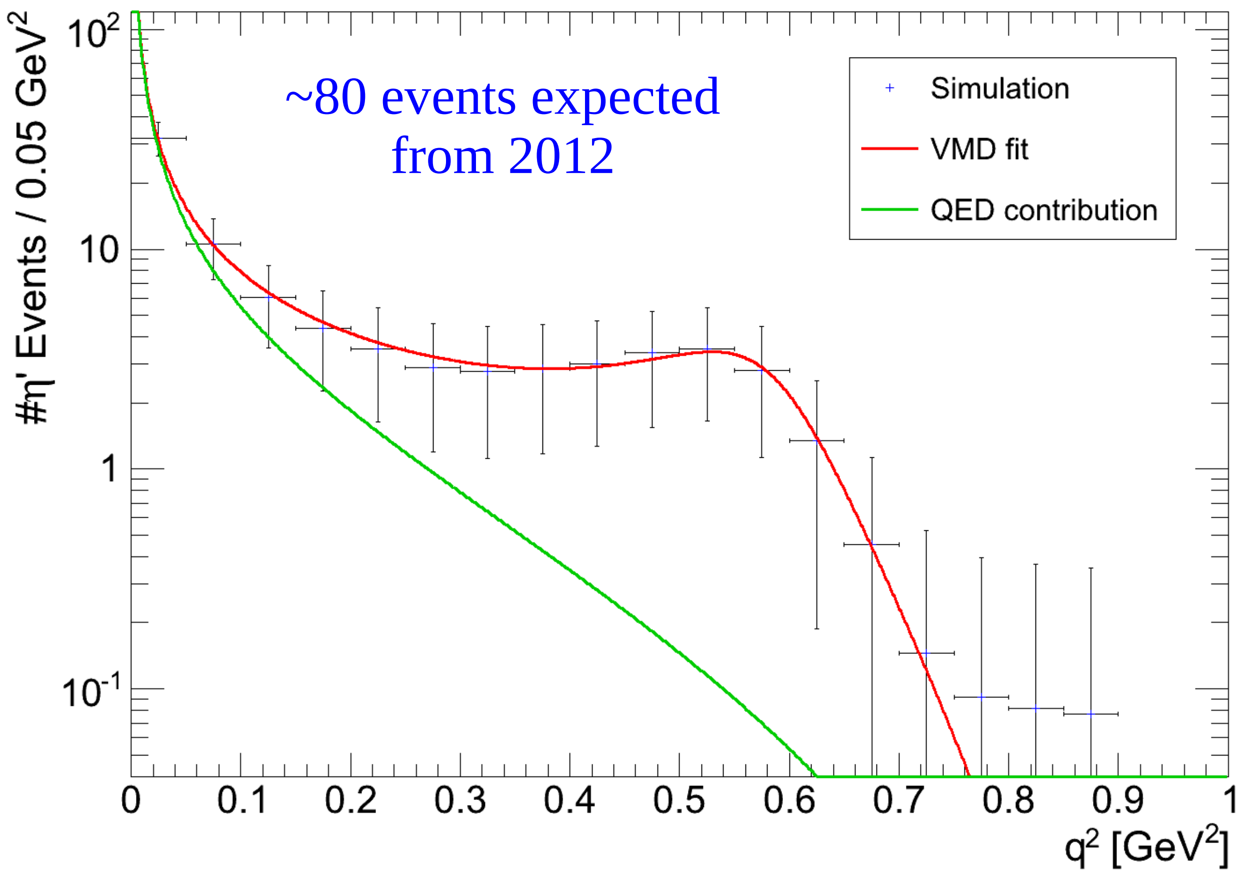
Kanal	σ [μb]	BR	simulierte Statistik
$\eta' \to e^+e^-\gamma$	0,76	$< 9 \cdot 10^{-4}$	10M
$\eta' \to \pi^+\pi^-\eta$	0,76	43,40 %	5M
$\eta' \to \rho^0\gamma$	0,76	29,30 %	8M
$\eta' \to \mu^+\mu^-\gamma$	0,76	$1{,}07 \cdot 10^{-4}$	5M
$\eta' \to \gamma\gamma$	0,76	2,18 %	6M
$\eta \to e^+e^-\gamma$	1,85	$6{,}9 \cdot 10^{-3}$	5M
$\eta \to \pi^+\pi^-\gamma$	1,85	4,60 %	5M
$\eta \to \pi^+\pi^-\pi^0$	1,85	22,74 %	5M
$\eta \to \mu^+\mu^-\gamma$	1,85	$3{,}1 \cdot 10^{-4}$	5M
$\eta \to \gamma\gamma$	1,85	39,31 %	5M
$\omega \to e^+e^-\pi^0$	6,44	$7{,}7 \cdot 10^{-4}$	5M
$\omega \to \pi^+\pi^-\pi^0$	6,44	89,20 %	5M
$\omega \to \pi^+\pi^-$	6,44	1,53 %	5M
$\rho^0 \to e^+e^-$	19,00	$4{,}72 \cdot 10^{-5}$	5M
$\rho^0 \to \pi^+\pi^-$	19,00	~100 %	5M
$\pi^0 \to e^+e^-\gamma$	10,52	1,17 %	5M
$\pi^0 \to \gamma\gamma$	10,52	98,82 %	10M
$\gamma p \to \pi^+\pi^-\pi^0$	15,00	—	5M
$\gamma p \to \pi^+\pi^-$	68,62	—	10M
$\pi^0\pi^0 \to 4\gamma$	6,87	97,65 %	20M
$\pi^0\eta \to 4\gamma$	4,09	38,85 %	20M

Time-like TFF for η'

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



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



- New Goal: ~800 $\eta' \to e^+e^-\gamma$ events in fall 2014 measurement
- Only possible if acceptance holds, has to be improved (use kinematic fit?)
- Next: analyse old data (S. Prakhov, S. Wagner)

Perspectives for η'

Proposed production yields with Crystal Ball at MAMI:

10 weeks: $2\cdot10^7$ η' (factor 4 improvement) in fall 2014

- Neutral decay modes with unprecedented accuracy with CB: unstable particles in EFT
  BR($\eta' \to \omega\gamma / \eta' \to \eta\pi^0\pi^0$) improve by factor 2-5
  PDG 2012: BR($\eta' \to \omega\gamma / \eta' \to \eta\pi^0\pi^0$) = 0.147±0.016
- QCD/χPT related (Dalitz plot analyses) $\eta' \to 3\pi^0$, $\eta' \to \eta\pi^0\pi^0$ (~400.000 events expected)
  Further effects: cusp effect (8%), ππ- and πη-scattering
- Transition Form Factor:
  Single Dalitz decay (800 events proposed)
  Double Dalitz decays?
- Fix parameters for EFT
  Charged decays $\eta' \to \pi^+\pi^-\gamma$, $\eta' \to \pi^+\pi^-\gamma\gamma$
- Measurements of absolute branching ratios/forbidden decays

A. Denig, W. Gradl, M. Ostrick, M. Unverzagt (University Mainz), S. Prakhov, (UCLA/Mainz)

Perspectives for ω

Proposed production yields with Crystal Ball at MAMI:

8 weeks: $2 \cdot 10^8$ ω (factor 30 improvement)

Neutral decay modes with unprecedented accuracy with CB:

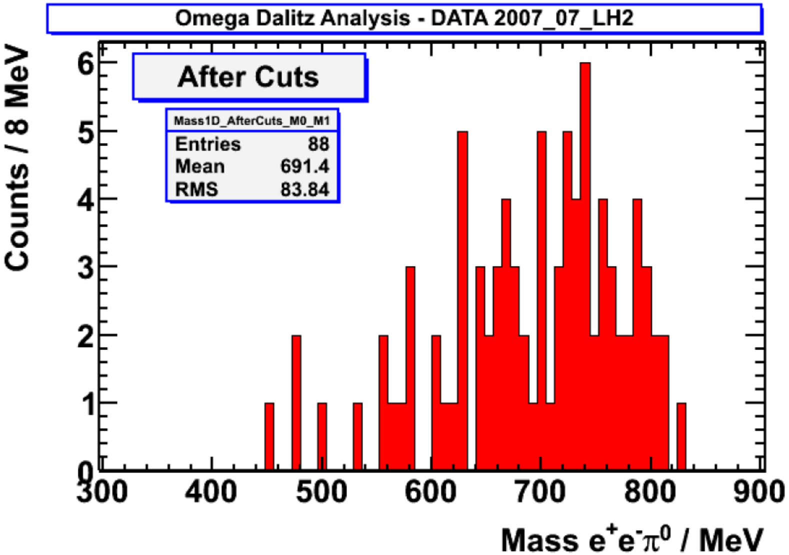
- BR($\omega \to \eta\gamma / \omega \to \pi^0\gamma$) improve by factor 2-5

  PDG 2010: BR($\omega \to \eta\gamma / \omega \to \pi^0\gamma$) = 0.0098±0.0024 (not used anymore)

- $\omega \to \eta\gamma / \omega \to \pi^0\gamma$: power counting for unstable particles in effective field theory

- Transition Form Factors for $\omega \to \pi^0 e^+ e^-$?

H. Berghäuser, PhD Thesis, University, Gießen, Germany, 2010.



A. Denig, W. Gradl, M. Ostrick, M. Unverzagt (University Mainz), S. Prakhov, (UCLA/Mainz)

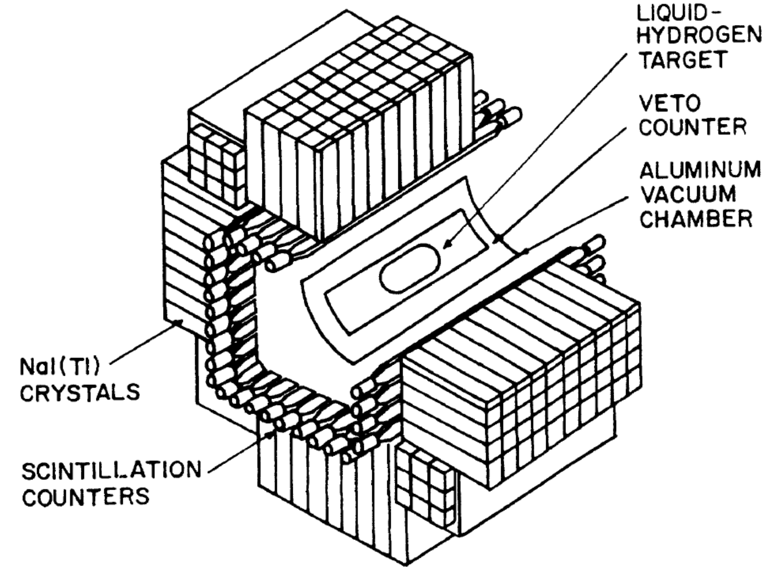
Perspectives for π^0

C-violating decay: $\pi^0 \to 3\gamma$

Current bound: $\mathrm{BR}(\pi^0 \to 3\gamma) < 3.1 \cdot 10^{-8} \quad (90\ \%\mathrm{C.L.})$

Crystal Box Experiment at Los Alamos in $\pi^- + p \to \pi^0 + n$

J. McDonough et al., Phys. Rev. **D38** (1988) 2121.



Main background channels:

- $\pi^0 \to 2\gamma$
- $\pi^0 \to e^+ e^- \gamma$
- $\pi^0 \pi^0$ production

Reduce at trigger level by factor 100!

$\pi^0 \to 4\gamma$ (allowed high order process, never seen yet, can be improved in parallel)

$\mathrm{BR}(\pi^0 \to 4\gamma) < 2 \cdot 10^{-8} \quad (90\ \%\mathrm{C.L.})$

J. McDonough et al., Phys. Rev. **D38** (1988) 2121.

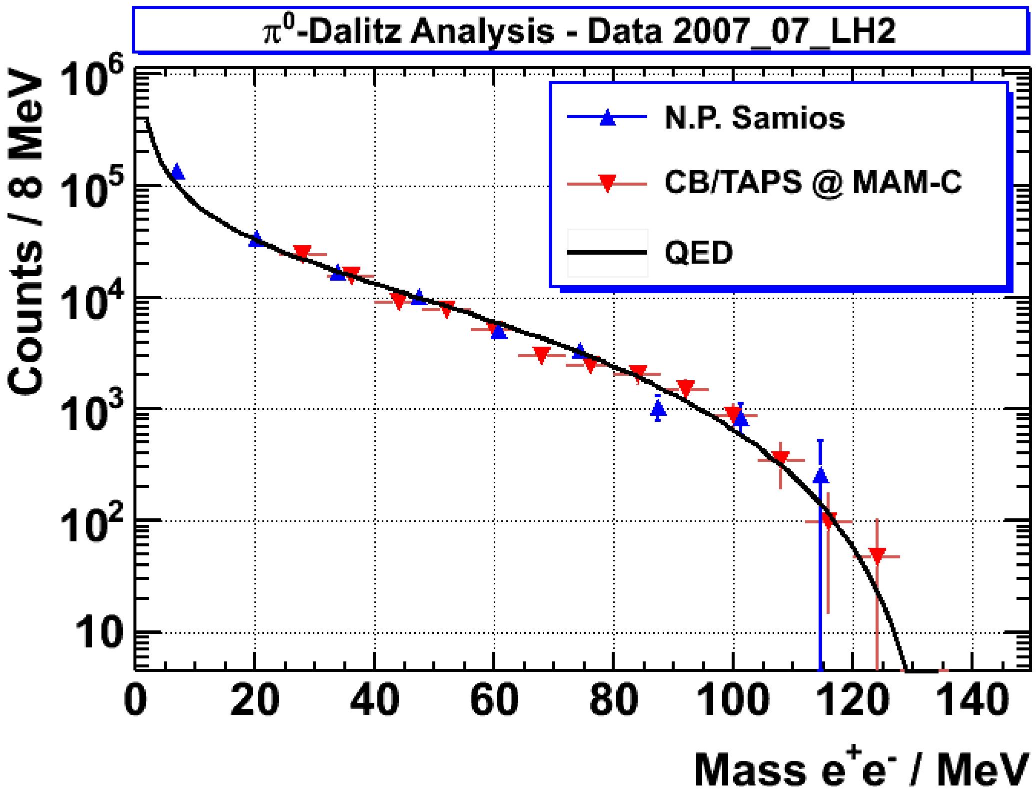
$$BR_{4\gamma}^{\mathrm{QED}} = \frac{\Gamma_{\pi^0 \to 4\gamma}}{\Gamma_{\pi^0 \to 2\gamma}} \sim 2.6 \cdot 10^{-11} \quad \Longleftrightarrow \quad BR_{4\gamma}^{\mathrm{hadr}} \sim 10^{-9} - 7.1 \cdot 10^{-18}$$

W. Gradl, M. Unverzagt, Jennifer Wettig (University Mainz), G. Ron (Jerusalem)

Conclusion

- Within 100h of beamtime on ^{208}Pb or ^{236}U upper limits for $\pi^0 \rightarrow 3\gamma/4\gamma$ may be improved by up to two orders of magnitude, deviations from Standard Model indicate New Physics

- Pilot test for more rare decays (also η/ω?) and possibly decay studies with higher rate



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

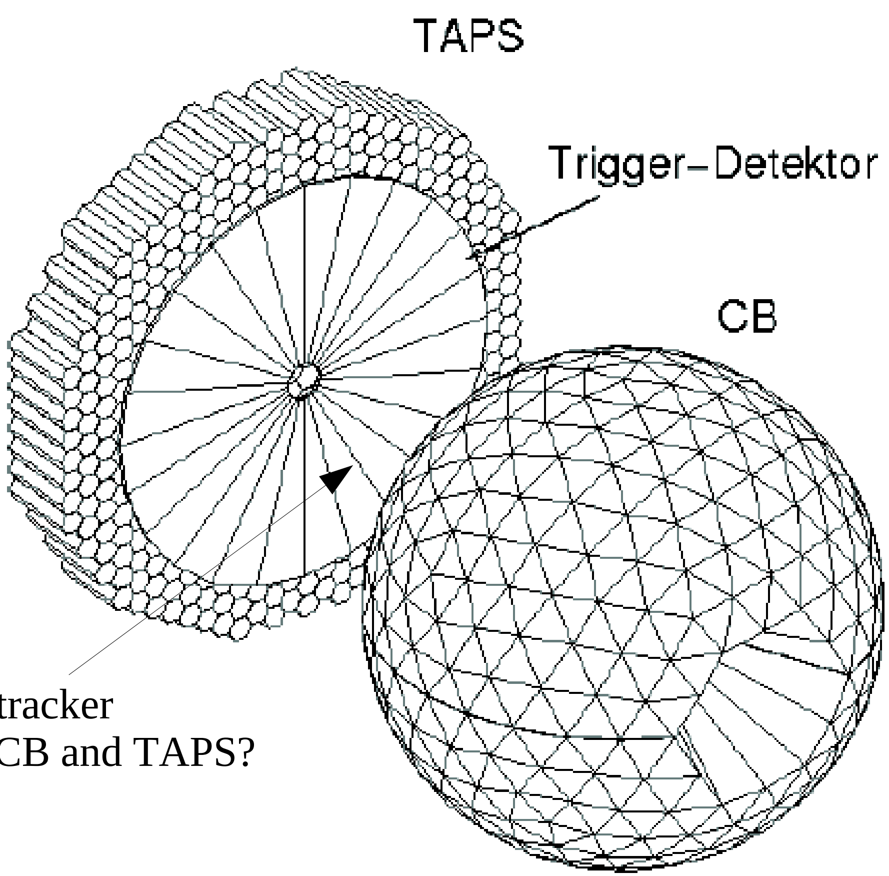
H. Berghäuser, PhD Thesis, University Gießen, Germany, 2010.

W. Gradl, M. Unverzagt, Jennifer Wettig (University Mainz), G. Ron (Jerusalem)

Setup Upgrades?

- Old trigger scheme replaced by FPGA based trigger module
- Triggerless readout (TRB boards)? (A. Neiser, W. Gradl)
- Branching fractions: trigger detector under consrtuction (M. Hillenbrand, M. Ostrick)
- Charged decays e.g. $\eta \rightarrow \pi^+\pi^-\gamma(\gamma)$ need dedicated tracking detector
- High resolution forward tracking system?
- New detector setup?

  Development of high-rate TPC with?
  Complete new setup?



Forward tracker
between CB and TAPS?

Outline

- Crystal Ball Set-up at MAMI
- η/η' Cross Sections
- Results from Crystal Ball at MAMI
  - Dalitz Plot Parameter for $\eta\rightarrow3\pi^0$
  - Preliminary Result for $\eta\rightarrow\pi^0\gamma\gamma$
  - Timelike Transition Form Factor from $\eta\rightarrow e^+e^-\gamma$
  - C-violation in ω decays
- Future Plans
- **Summary**

Summary

- World leading results from Crystal Ball at MAMI
  Dalitz plot parameter: $\eta \to 3\pi^0$
  XPT, VMD: $\eta \to \pi^0\gamma\gamma$
  Transition Form Factor: $\eta \to e^+e^-\gamma$
  C-violation: neutral ω decays

- Further analyses in η/ω decays possible with existing data

- Main focus: η' studies
  Data taking planned for 2nd half of 2014
  Goals: 400,000 $\eta' \to \eta\pi^0\pi^0$
  800 $\eta' \to e^+e^-\gamma$

- New programme with very rare decays under investigation
  $\pi^0 \to 3\gamma/4\gamma$, extend to other rare π^0, η, ω decays

- New detector possibilities under discussion

Chiral Symmetry Breaking

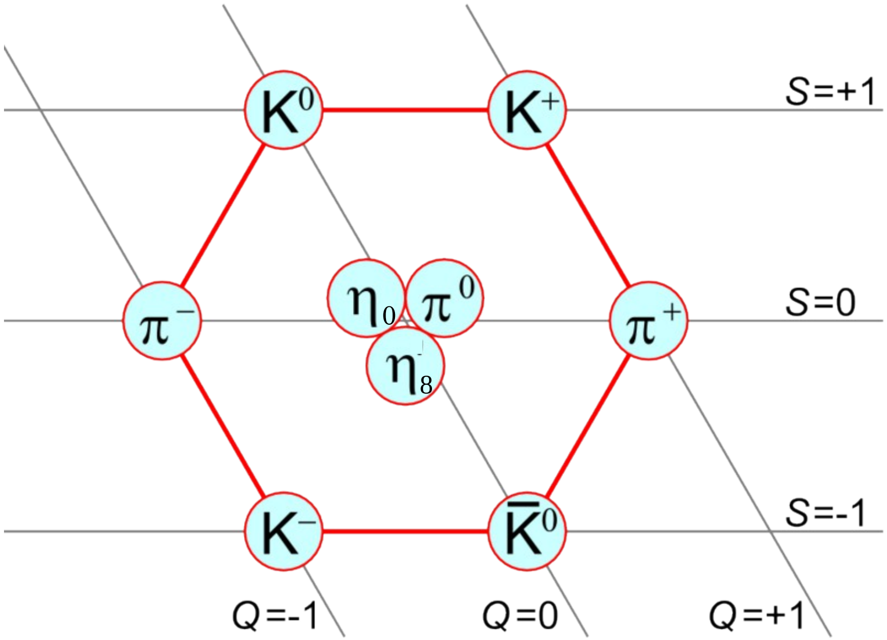
$$L_{\text{QCD}} = \bar{q}\,(i\,\not{D} - M)\,q - \sum_{a=1}^{8} \frac{1}{4}\, G_{\mu\nu,a}\, G_a^{\mu\nu}$$

- Chiral limit ($m_u = m_d = m_s = 0$):

$U(3)_L$ x $U(3)_R$ = $SU(3)_L$ x $SU(3)_R$ x $U(1)_V$ x $U(1)_A$ symmetry

Hadrons do not come in parity doublets
→ Chiral symmetry must be broken (spontaneously)

- $SU(3)_L$ x $SU(3)_R$ → $SU(3)_V$ gives rise to 8 massless, pseudoscalar Goldstone bosons



Explicit Symmetry Breaking

Quarks have finite masses

- SU(3) flavor symmetry: $m_u = m_d = m_s \neq 0$
- SU(2) isospin symmetry: $m_u = m_d \neq m_s$
- Isospin breaking: $m_u \neq m_d$
- Electromagnetic effects also break isospin symmetry

Using: $\eta \to 3\pi$, $\eta' \to 3\pi$; $\eta' \to 2\pi\eta$

Extract:

$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} \qquad \hat{m} = \frac{m_u + m_d}{2}$$

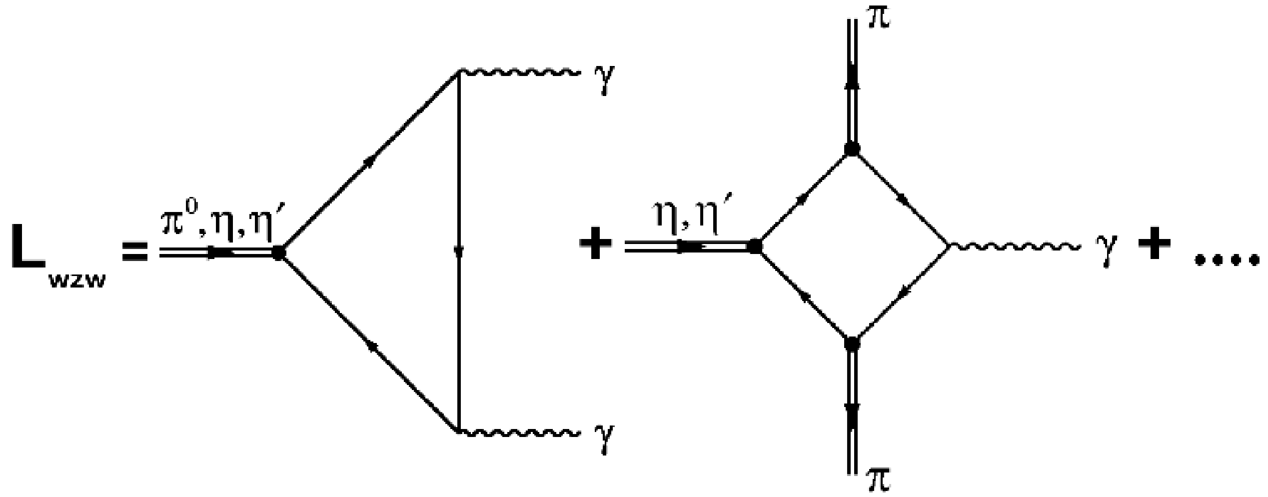
η/η' mixing

η and η' are admixtures of pure SU(3) singlet and octet states

$$\eta = \eta_0 \sin\theta - \eta_8 \cos\theta$$
$$\eta' = \eta_0 \cos\theta + \eta_8 \sin\theta$$

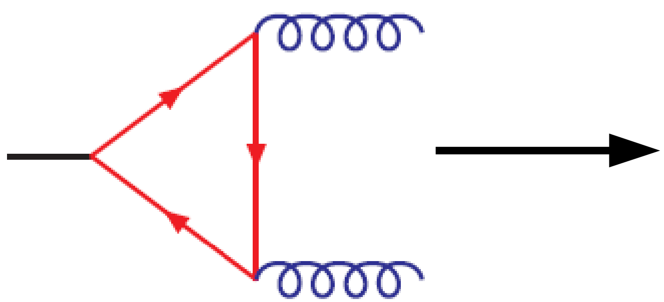
η/η': $I^G(J^{PC}) = 0^+(0^{-+})$

- Mixing caused by SU(3) breaking due to strange quark mass AND the chiral anomaly
- Beyond leading-order single mixing angle not sufficient, possible gluonium content



$U(1)_A$ Anomaly

- Quantum fluctuations destroy singlet axial-vector current conservation



$$\partial_\mu A^{0\mu} = 2\sqrt{N_C}\,\omega = \frac{2\sqrt{N_C}}{16\pi^2}\varepsilon^{\mu\nu\alpha\beta}\, tr\, G_{\mu\nu} G_{\alpha\beta} \neq 0$$

- Why is the η' so heavy?

- ω-term includes gluons → strongly interacting → η' heavy

- Applicability of χPT to η'? (chiral symmetry breaking scale: $4\pi f_\pi \approx 1.2$ GeV, η' as a Goldstone boson) (theory)

C/CP-Violation

Sacharov criterium: C/CP-violation is one of three criteria to explain dominance of matter over antimatter (Baryogenesis)

Electromagnetism, and strong force are assumed to be invariant under C and CP transformation

CP-violation in weak interaction not strong enough to explain Baryogenesis

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 ± 0.12)%
$K^\pm \to \pi^\pm\pi^0\pi^0$ rate difference/average	(0.0 ± 0.6)%
$K^\pm \to \pi^\pm\pi^0\gamma$ rate difference/average	(0.9 ± 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

CP-Violation in SM

CP-violation in SM: quark mass eigenstates are different from weak eigenstates:
→ quark mixing matrix (Cabibbo, Kobayashi, Maskawa)
→ different mixing matrices for quarks and antiquarks → CP-violation
CKM-matrix complex and unitary → 4 parameters (e.g. 3 angles and one phase)
Single phase in CKM-matrix responsible for CP-violation

weak states — CKM matrix — mass states

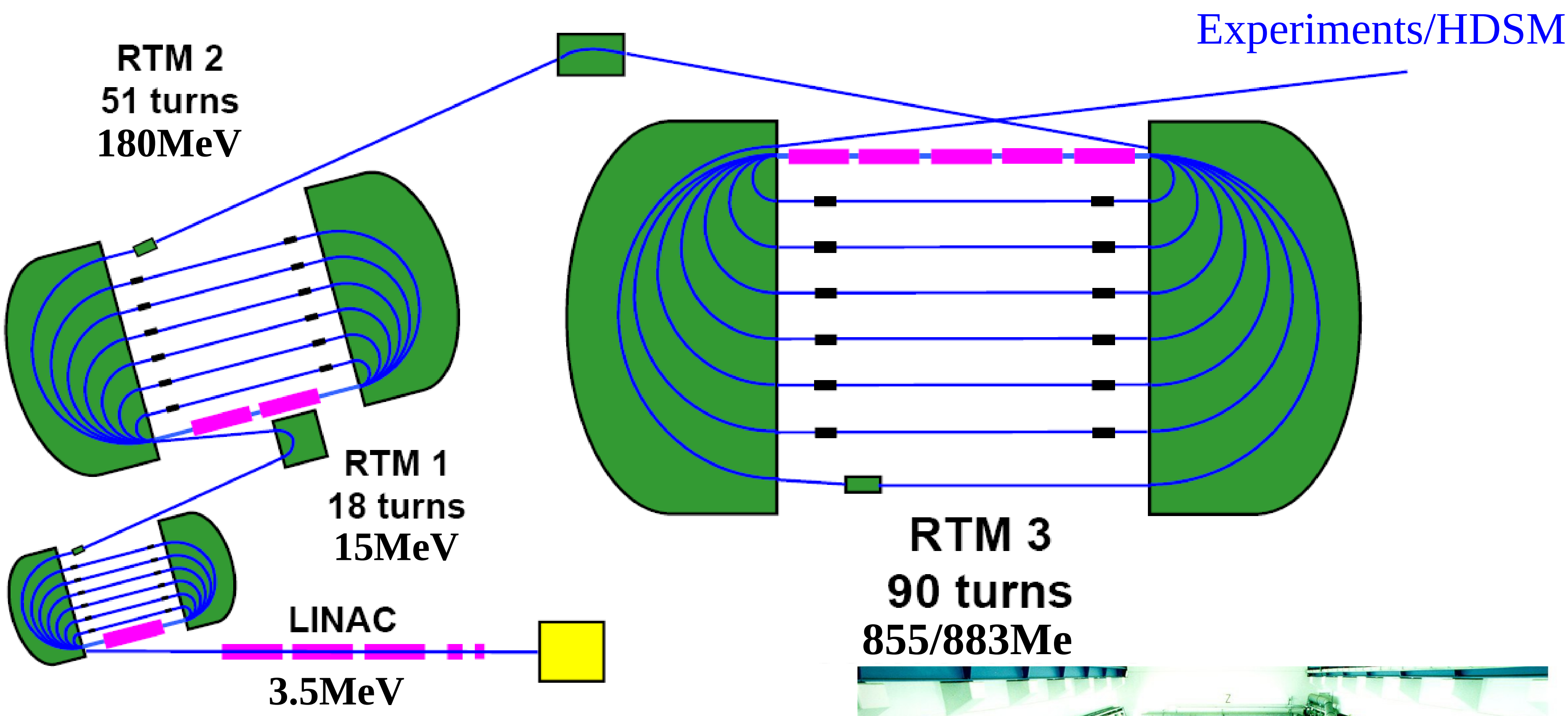
Quarks

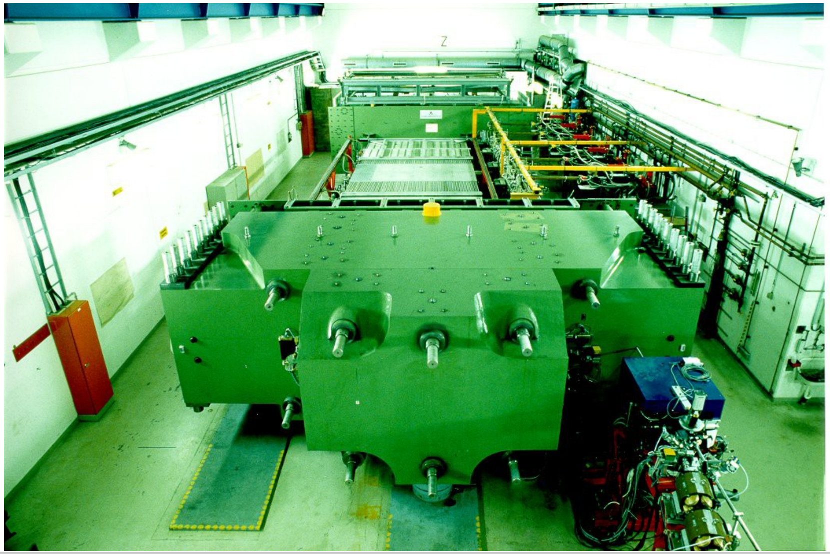
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{CKM matrix}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Anti-quarks

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$

Mainz Microtron (MAMI-B)





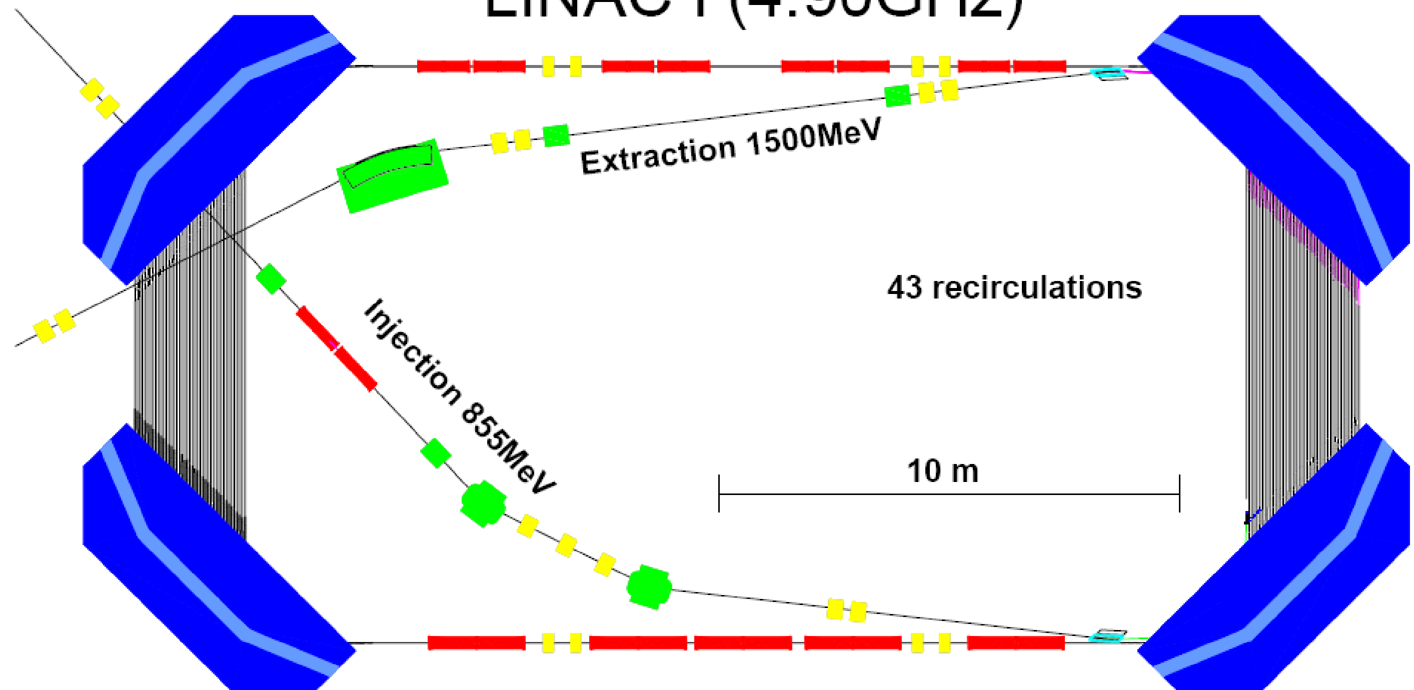
Acceleration via em wave (2.45GHz)
cw: bunch structure ~0.4ns
Injektion LINAC
3 cascaded Race-Track-Microtrons
Magnet of RTM 3 ~450t per Magnet, 1.28T

HDSM (MAMI-C)

9.0 MV / turn max gain

From MAMI-B

LINAC I (4.90GHz)

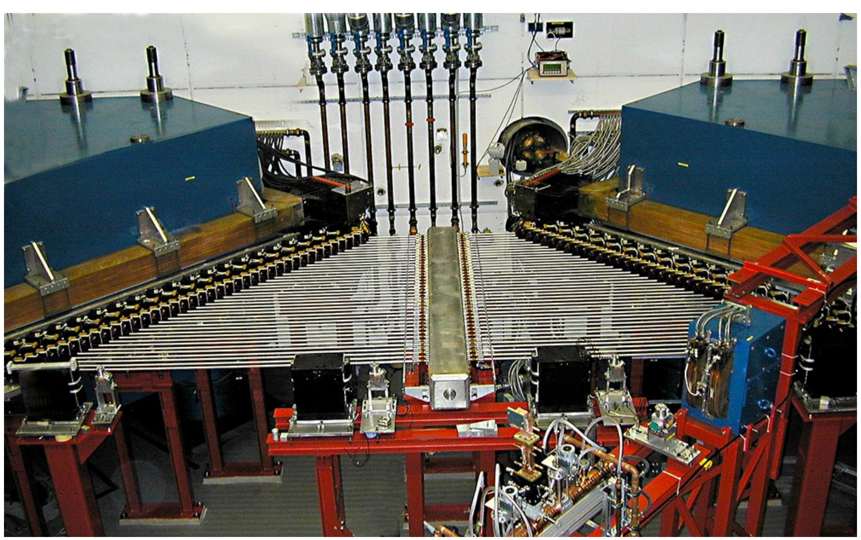


To Experiments
2007: 1508MeV
2008: 1558MeV
2009: 1604MeV

LINAC II (2.45GHz)

B_{max}=1.539T

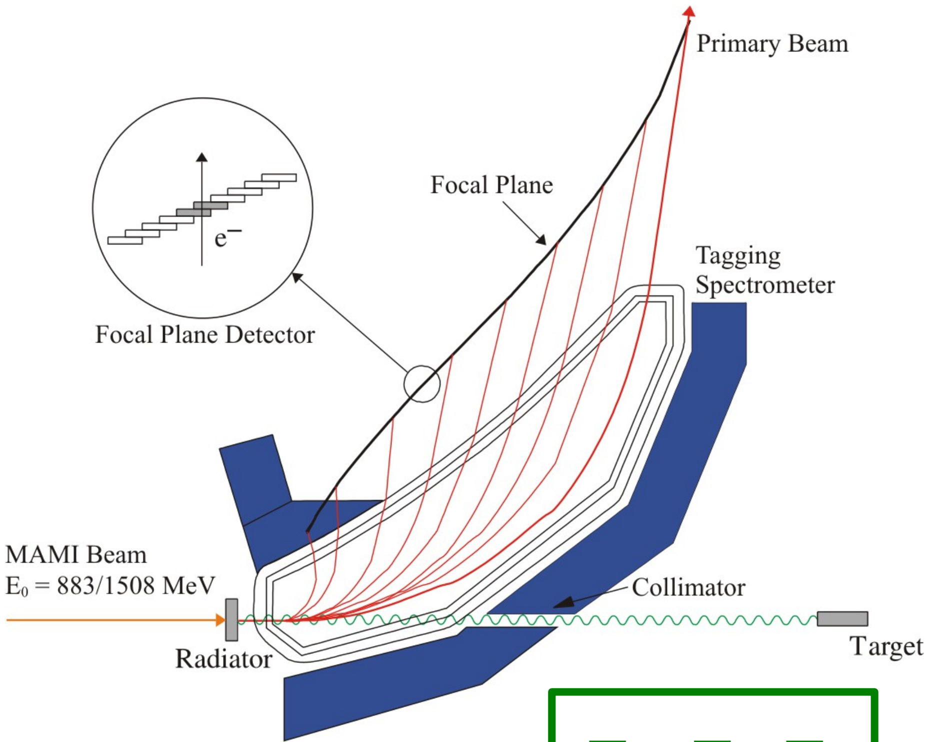
9.3 MV / turn max gain



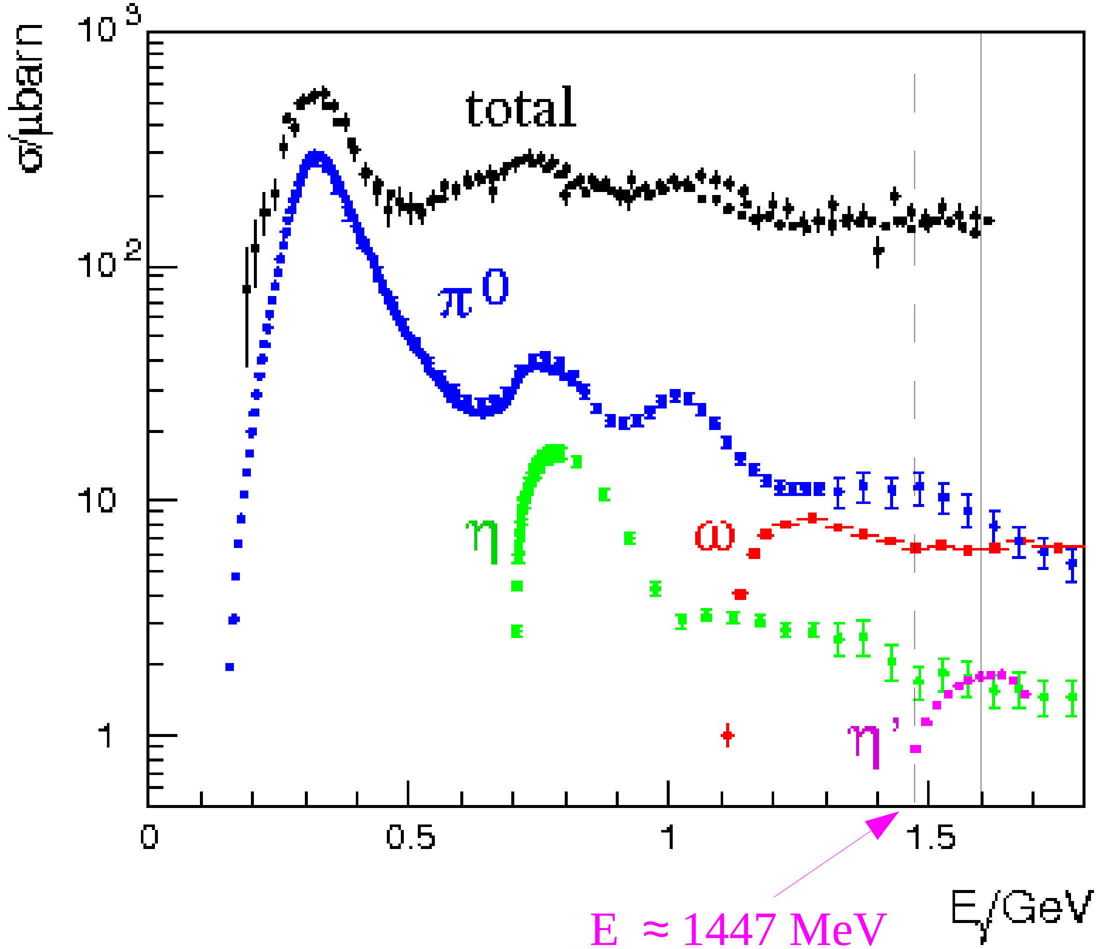
Harmonic Doubled Sided Microtron (HDSM)

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

Tagging Spectrometer



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



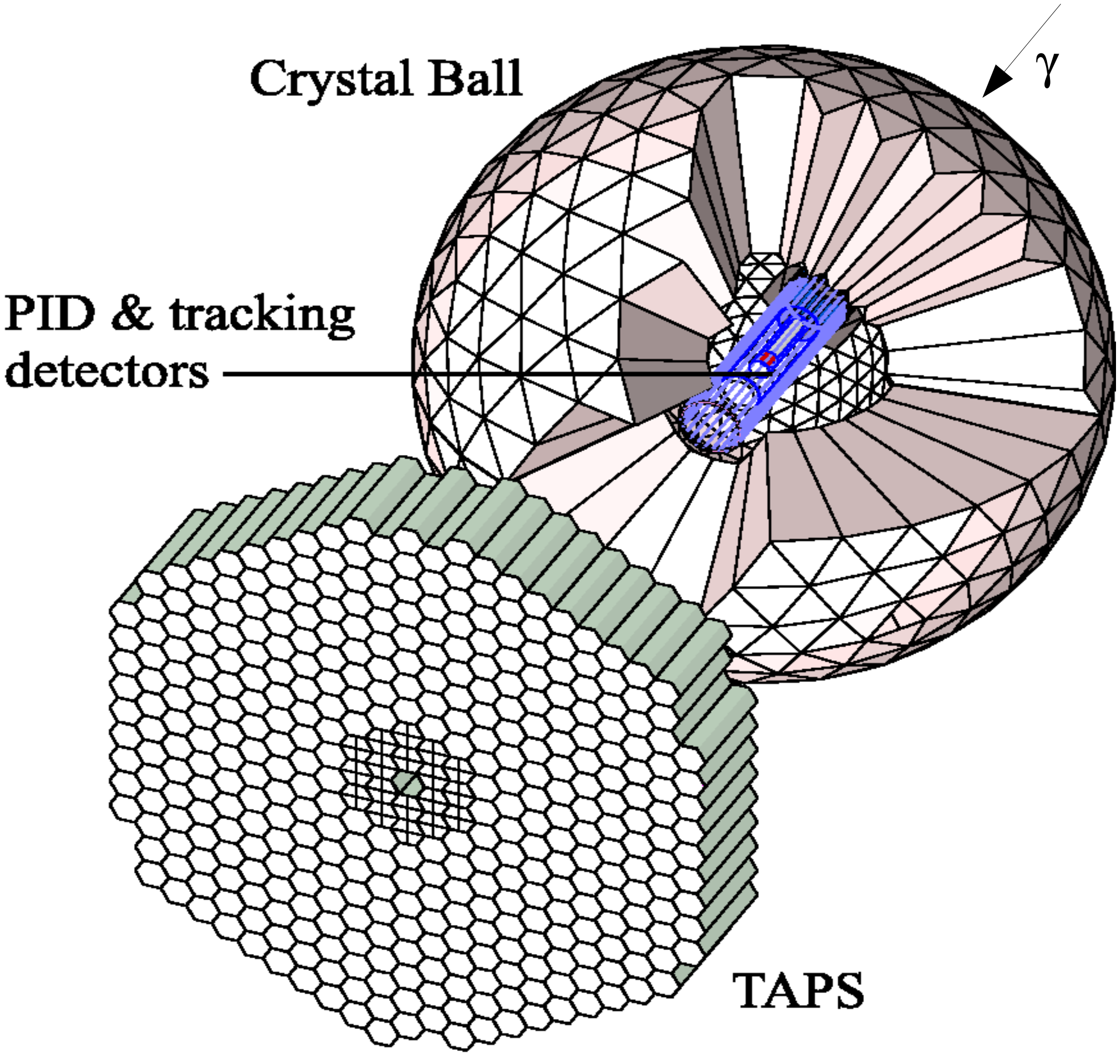
$E_\gamma \approx 1447$ MeV

Tagging range: 5.1 to 93% of E_0

Maximum energy tagged for E_0=1604 MeV is 1491 MeV

→ New tagging device for η' experiments needed!

4π-Setup



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

$$\frac{\sigma}{E_\gamma} = \frac{2\,\%}{(E_\gamma/GeV)^{0.25}} \qquad \sigma(\theta) = 2^\circ \ldots 3^\circ$$

$$\Delta t = 2.5 \text{ ns FWHM} \qquad \sigma(\phi) = \frac{2^\circ \ldots 3^\circ}{\sin(\theta)}$$

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

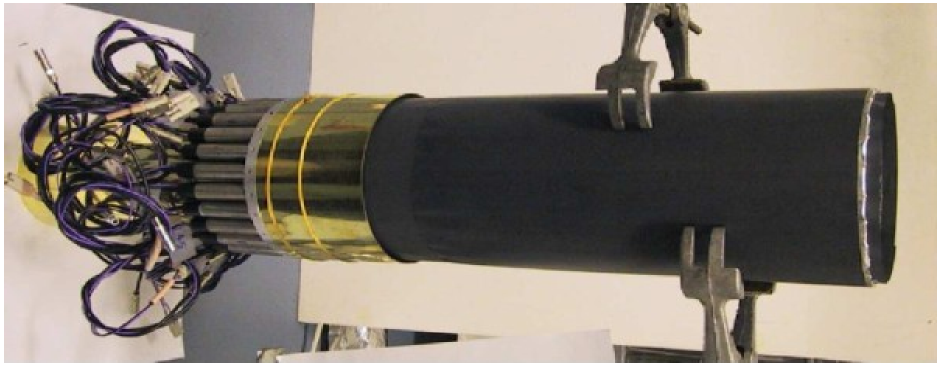
$\Delta t = 0.5$ ns FWHM

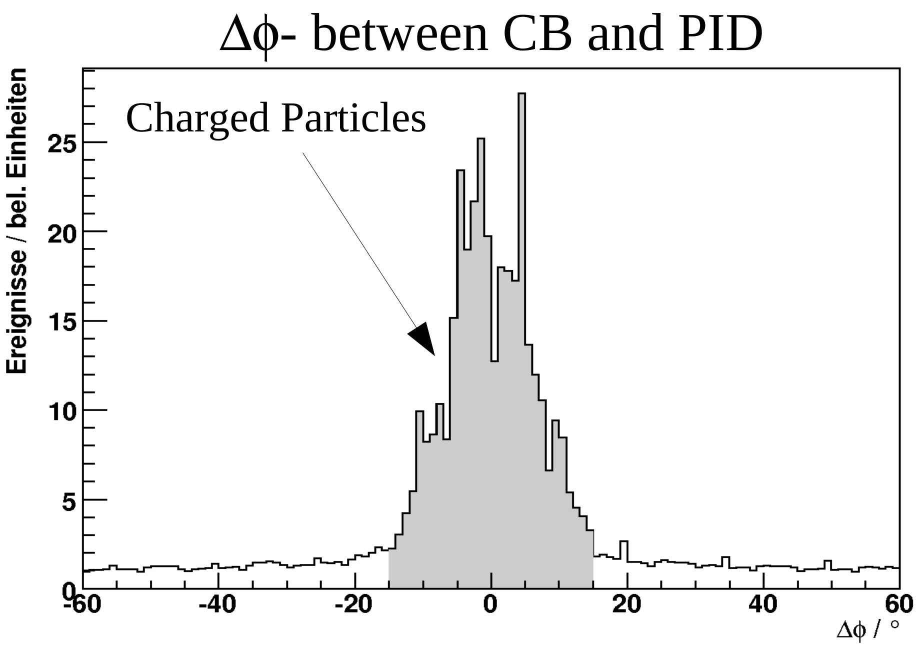
$$\frac{\sigma}{E_\gamma} = \frac{0{,}79\,\%}{\sqrt{E_\gamma/GeV}} + 1{,}8\,\%$$

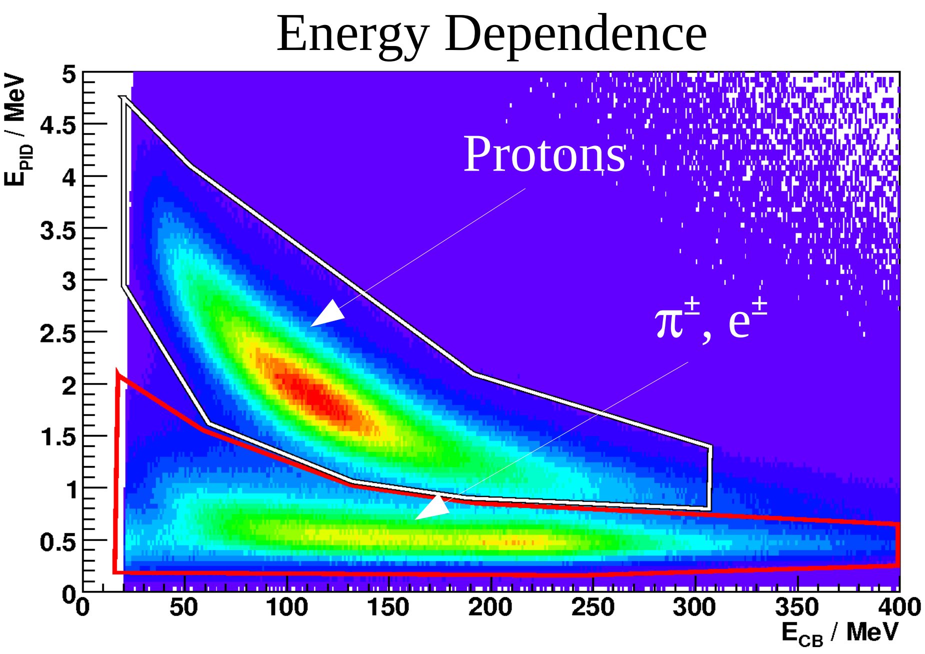
CB PID

Particle Identificaton Detector (PID):

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

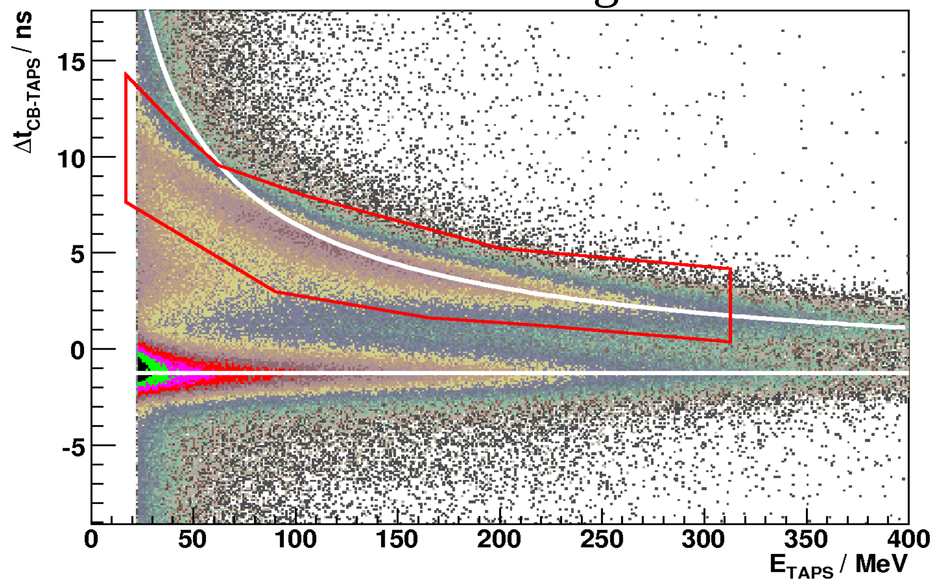


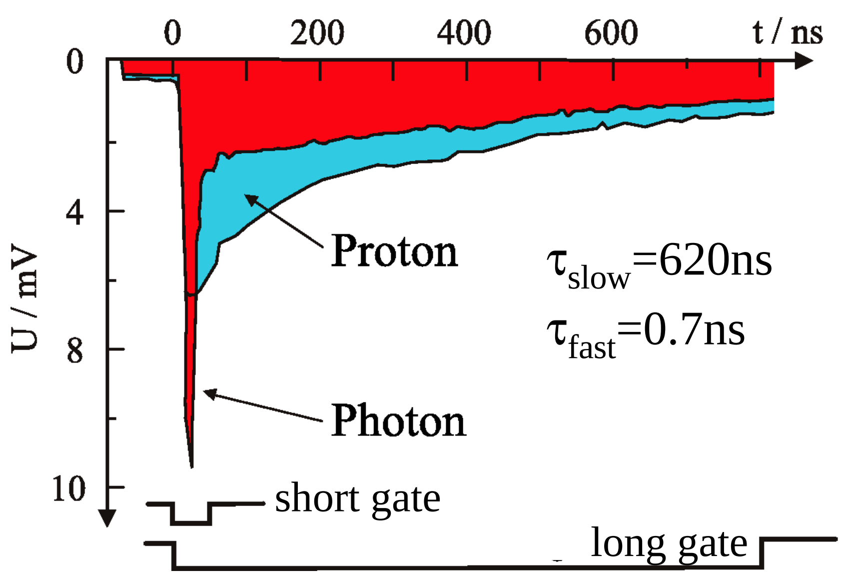




TAPS PI

Time-of-Flight

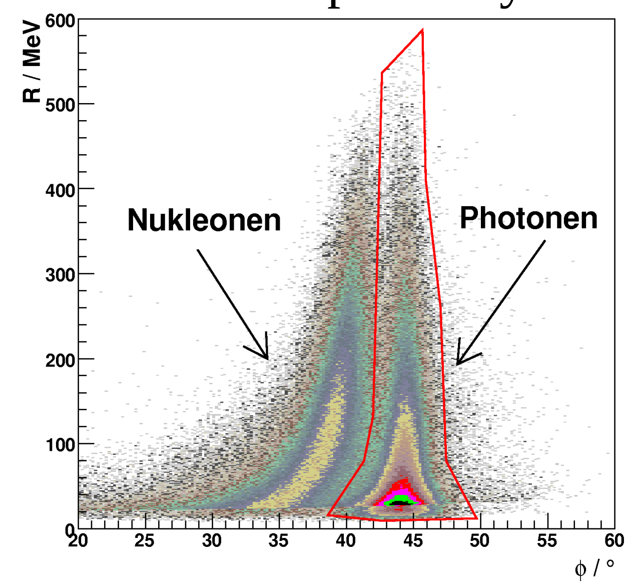




$$R = \sqrt{E_{short}^2 + E_{long}^2}$$

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

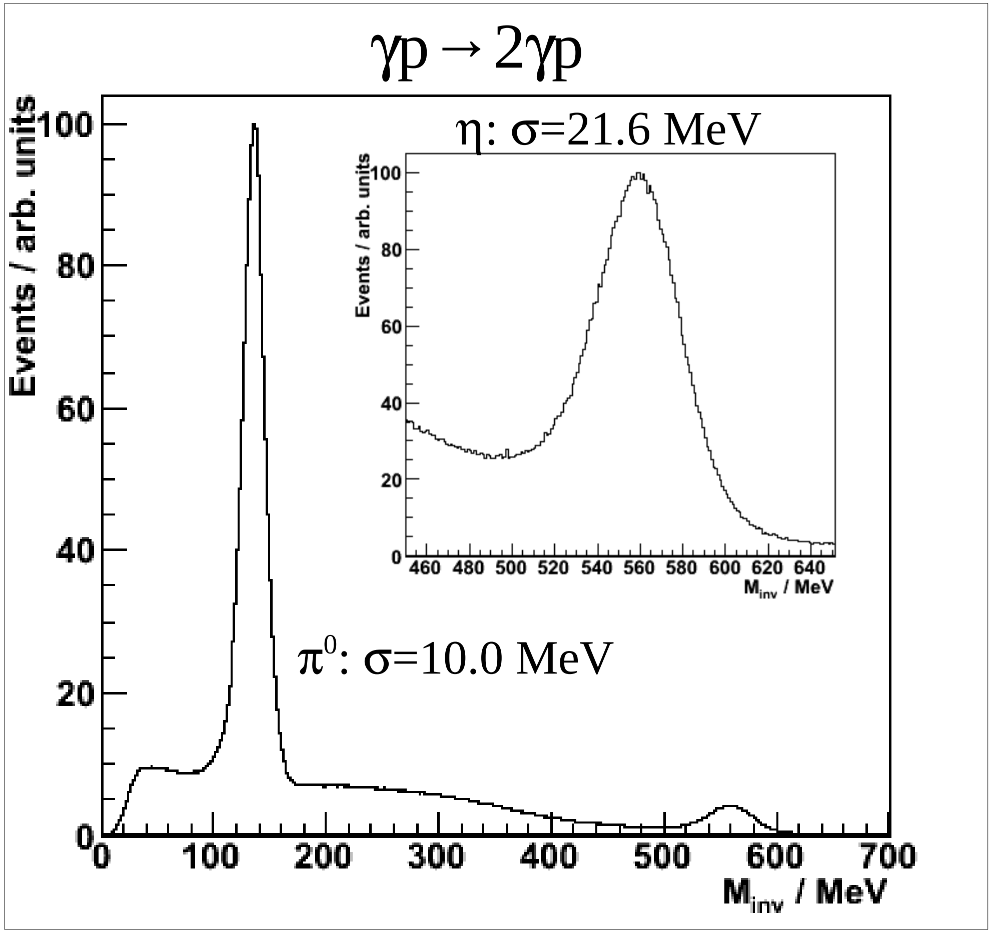
Pulse-Shape-Analysis

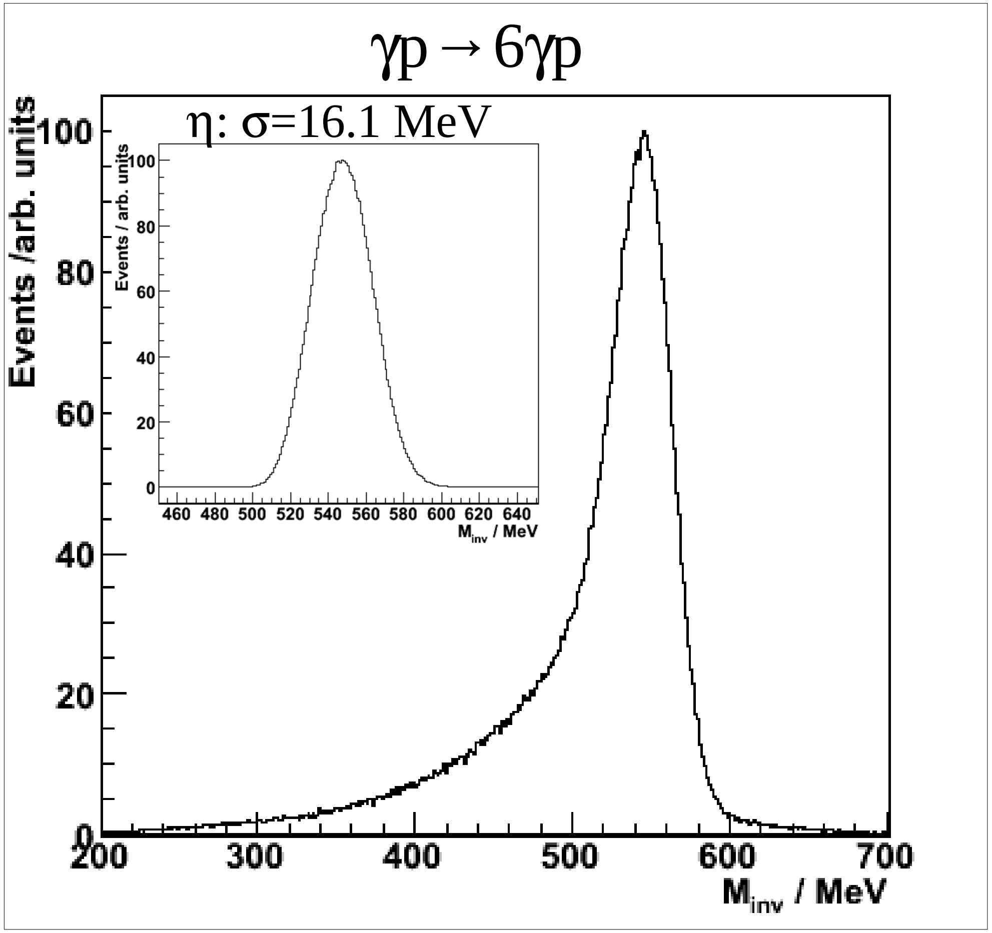


Setup Performance

<u>Two main η decay modes:</u>

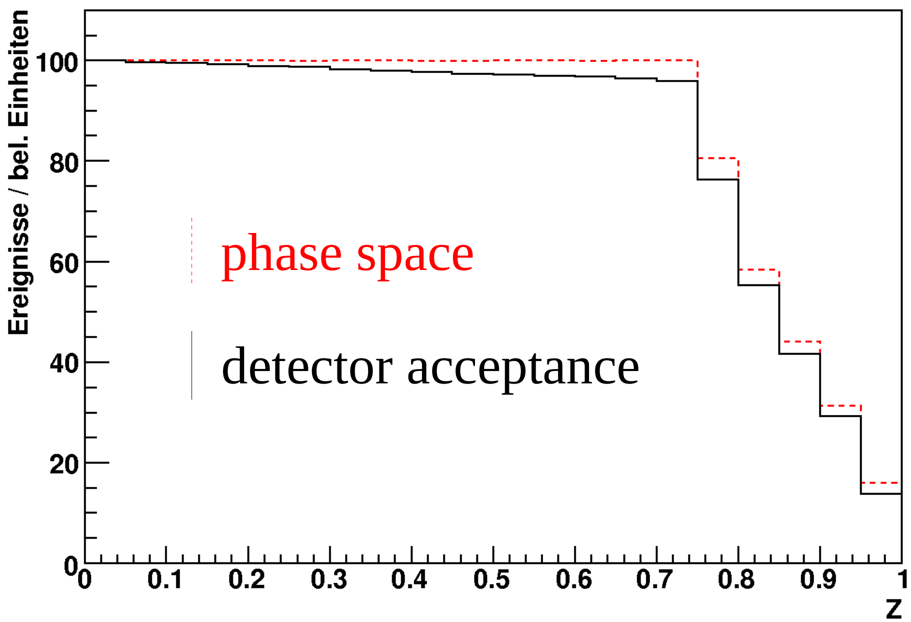
$BR(\eta \rightarrow 2\gamma) = 39.38\%$ $BR(\eta \rightarrow 3\pi^0) = 32.51\%$



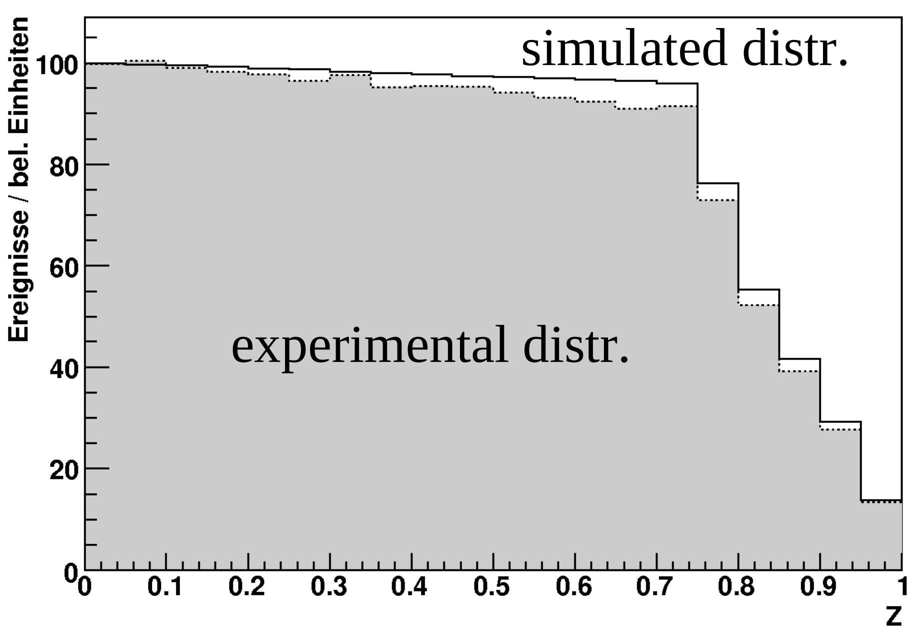


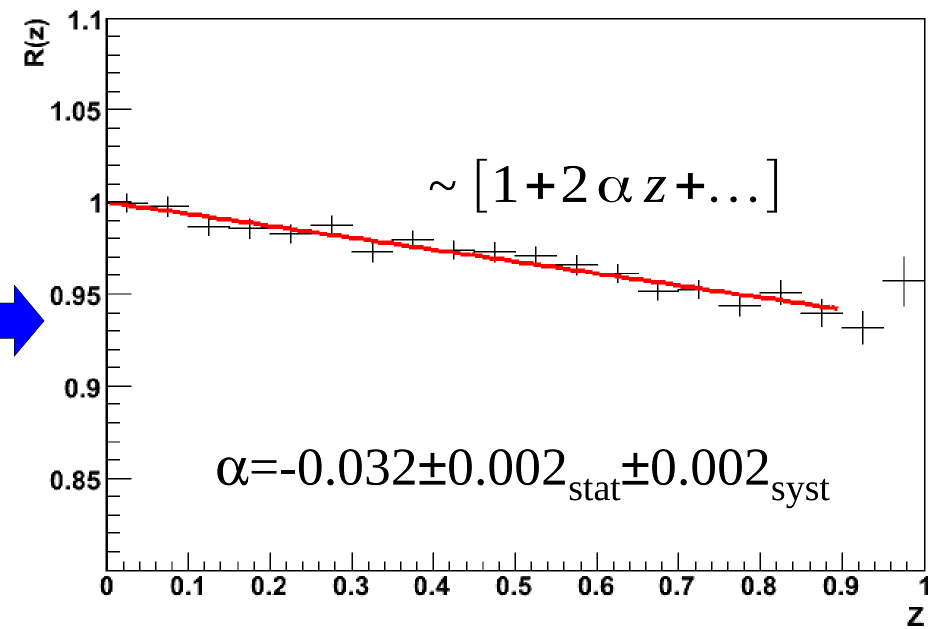
$3 \cdot 10^6$ $\eta \rightarrow 3\pi^0$ analysed from ~6 weeks $\rightarrow$ 30M η produced

Result for α

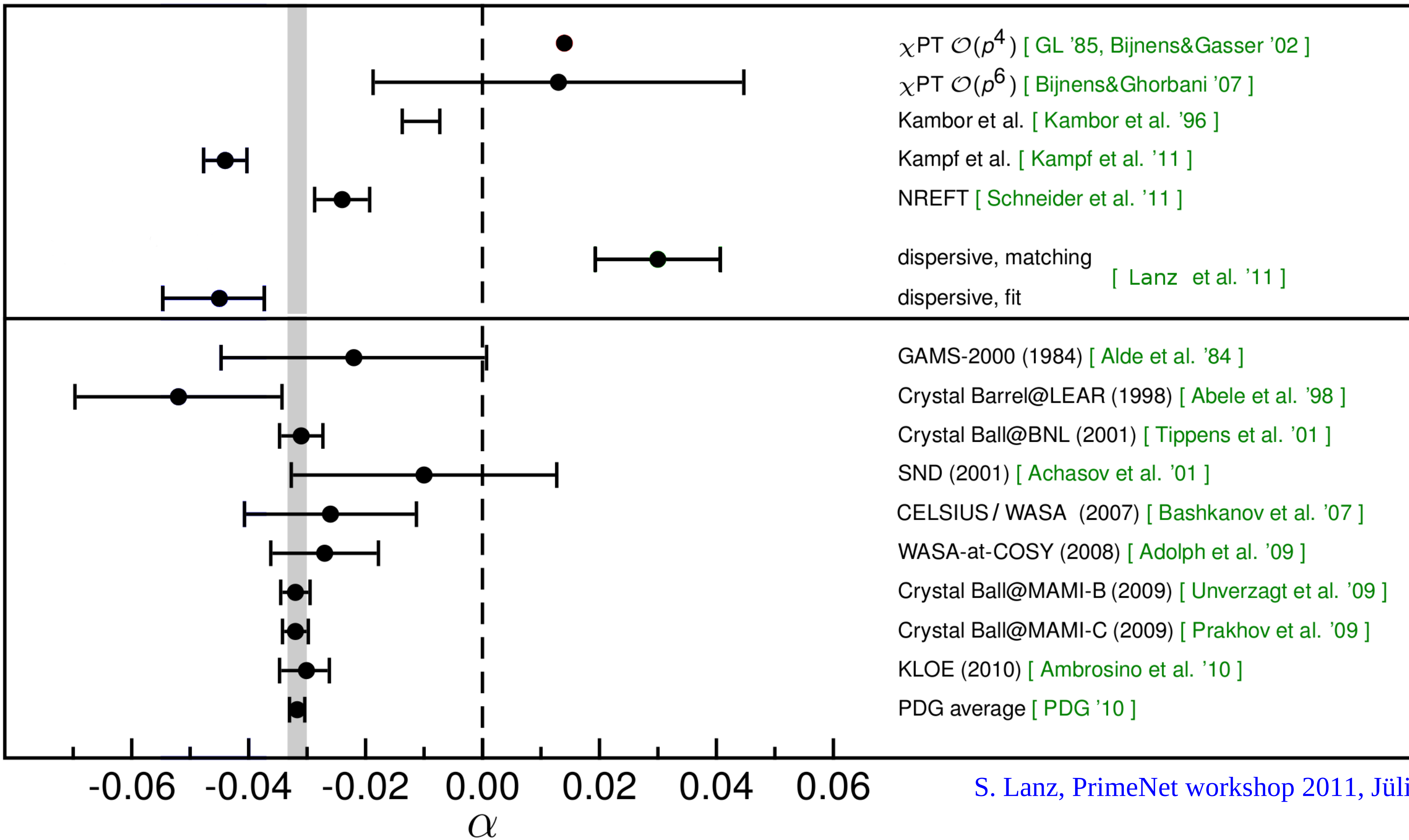


- precise simulation required





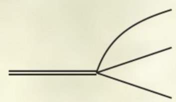
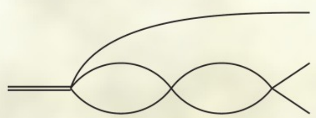
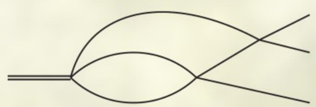
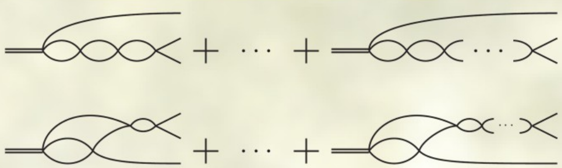
$\eta \to 3\pi^0$



S. Lanz, PrimeNet workshop 2011, Jülich

Experiments reach precision where higher order effects (cusp-effect, second order term in expansion) become visible

Understanding α: order-by-order decomposition

	$\alpha \times 10^{-3}$
	$+11.3$
	$+11.7$
	-43.5
	$+1.7$
	(-5.6)
isospin-breaking effects	-0.6
	$\mathbf{-22.2 \pm 5.0}$

- representation up to $\mathcal{O}(a_{\pi\pi}^2 \epsilon^4)$, partial $\mathcal{O}(a_{\pi\pi}^2 \epsilon^6)$, $\mathcal{O}(a_{\pi\pi}^2 \epsilon^8)$

error: (1) $\pi\pi$ scattering — Ananthanarayan et al. 2001 vs. Kamiński et al. 2008

(2) estimate of higher orders ("bubble resummation")

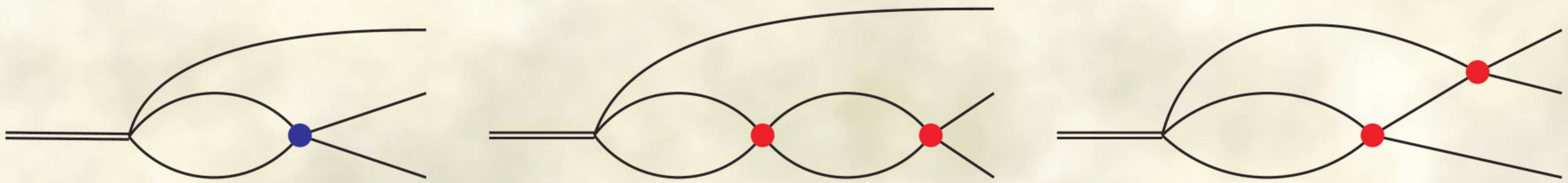
Understanding α: interpretation of the ChPT result

Remember: ChPT at $\mathcal{O}(p^6)$ Bijnens,Ghorbani 2007

$$\alpha_{\text{ChPT}} = (13 \pm 32) \times 10^{-3} \quad \text{vs.} \quad \alpha_{\text{NREFT}} = (-22.2 \pm 5.0) \times 10^{-3}$$

- Why the difference?

Emulate ChPT $\mathcal{O}(p^6)$ calculation:



- rescattering parameters at $\mathcal{O}(p^4)$ in one-loop graphs
- rescattering parameters at $\mathcal{O}(p^2)$ in two-loop graphs ($a_0^0 = 0.16\,, \ldots$)

Result:

- we find $\alpha = (-0.7 \times 10^{-3})$
  $\Rightarrow$ "weaker" rescattering leads to completely different result!

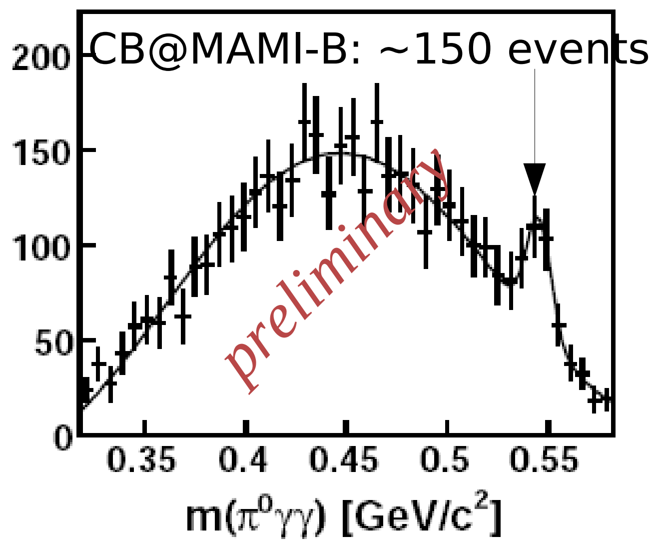
Cusp-Effect

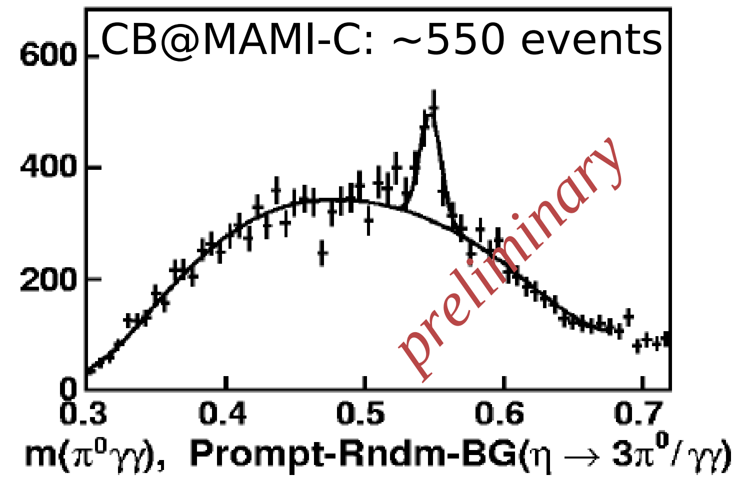
- $\eta \to \pi^0\pi^+\pi^-$ contributes via $\pi^+\pi^- \to \pi^0\pi^0$
- Cabibbo, Isidori and Bissegger *et al.* have developed framework to extract a_0-a_2 from $K \to 3\pi$ (NA48) and $\eta \to 3\pi$ invariant $\pi^0\pi^0$ mass spectra
- Cusp effect in η decay only at 1% level → need high precision

MAMI-C

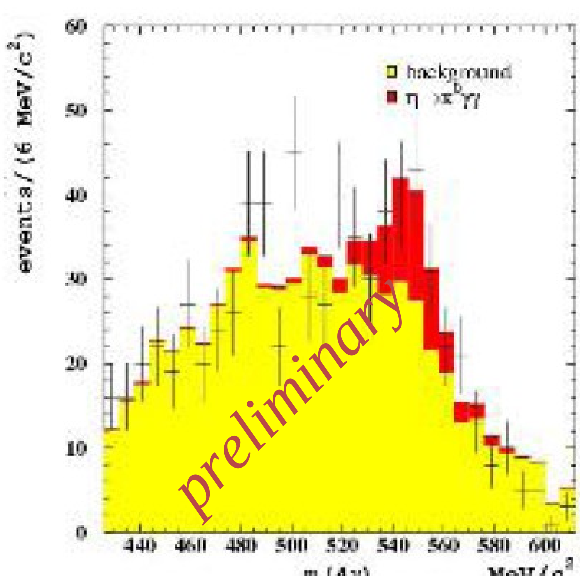
Bissegger, Fuhrer, Gasser, Kubis, Rusetsky, Phys.Lett. B659, (2008), 576 (solid line)
J. Belina, Diploma thesis,University Bern, Switzerland (dashed line).

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

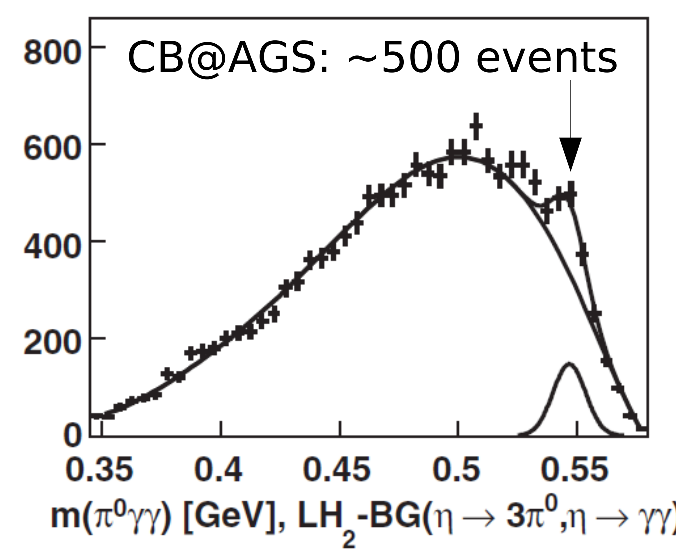




S. Prakhov (UCLA), private communication



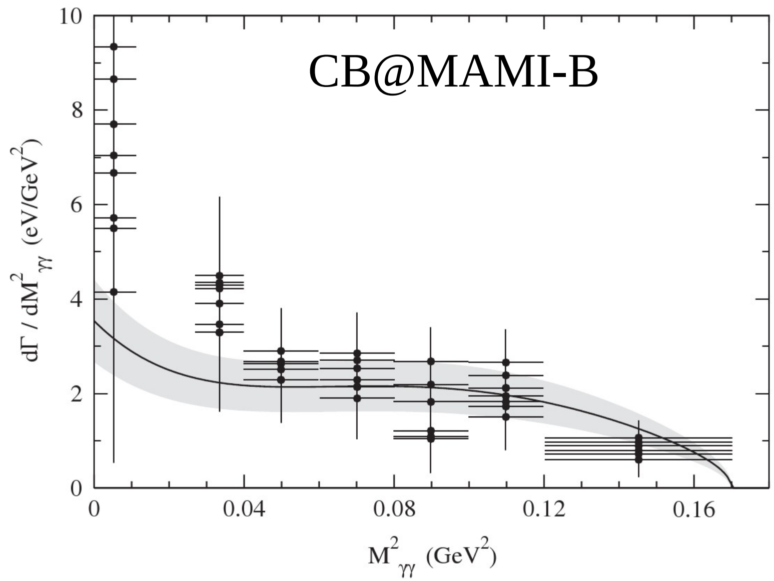
P. Gauzzi (KLOE), J. Phys. Conf. Ser. 349 (2012) 012002

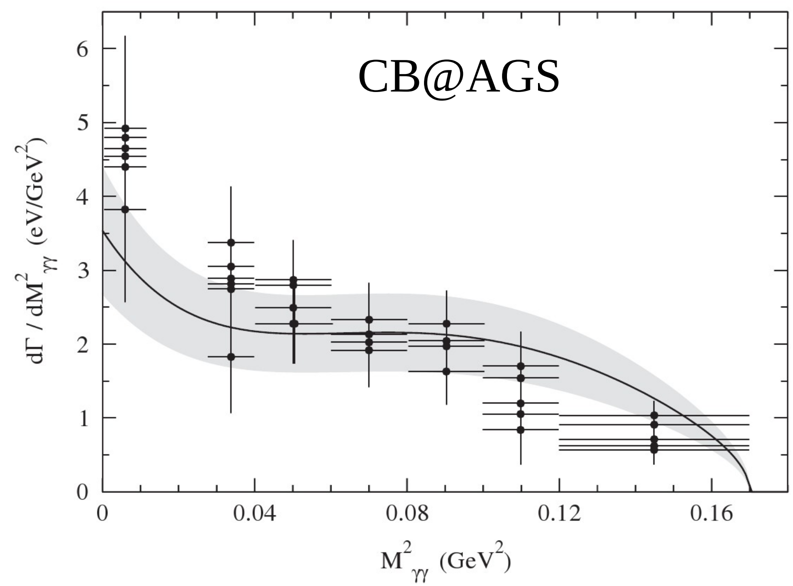


S. Prakhov et al. (CB@AGS), Phys. Rev. C 78, 015206 (2008)

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

VMD (solid line):
J.N. Ng, D.J. Peters,
Phys. Rev. D 46 5034 (1





CB@MAMI-B: $BR(\eta \rightarrow \pi^0 \gamma\gamma) = (2.25 \pm 0.46_{stat} \pm 0.17_{syst}) \cdot 10^{-4} (\textit{preliminary})$

CB@AGS: $BR(\eta \rightarrow \pi^0 \gamma\gamma) = (2.21 \pm 0.24_{stat} \pm 0.47_{syst}) \cdot 10^{-4}$

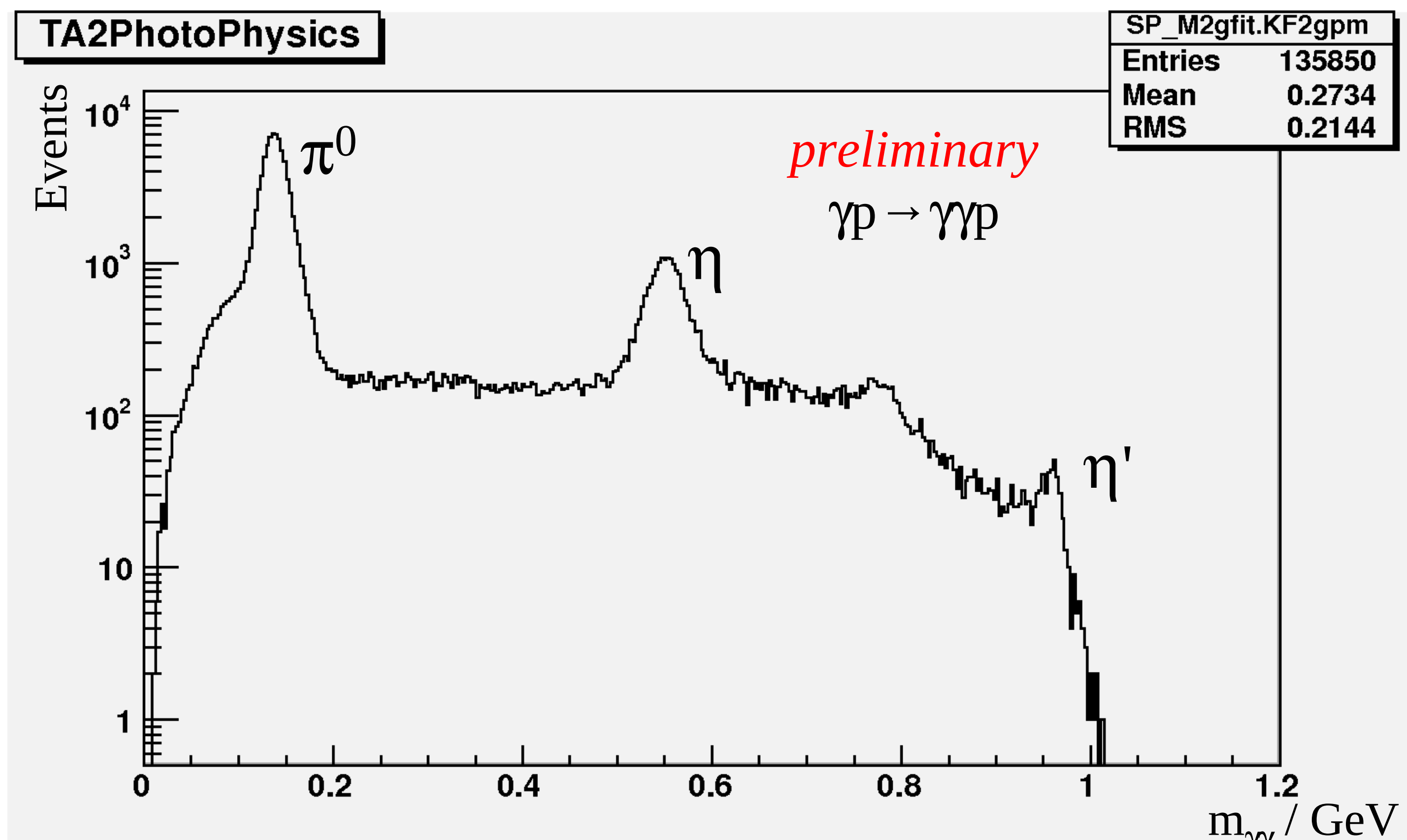
Contradiction

KLOE: $BR(\eta \rightarrow \pi^0 \gamma\gamma) = (0.84 \pm 0.27_{stat} \pm 0.14_{syst}) \cdot 10^{-4} (\textit{preliminary})$

Both, the Branching ratio and the Dalitz plot required to fully understand c

η' Production

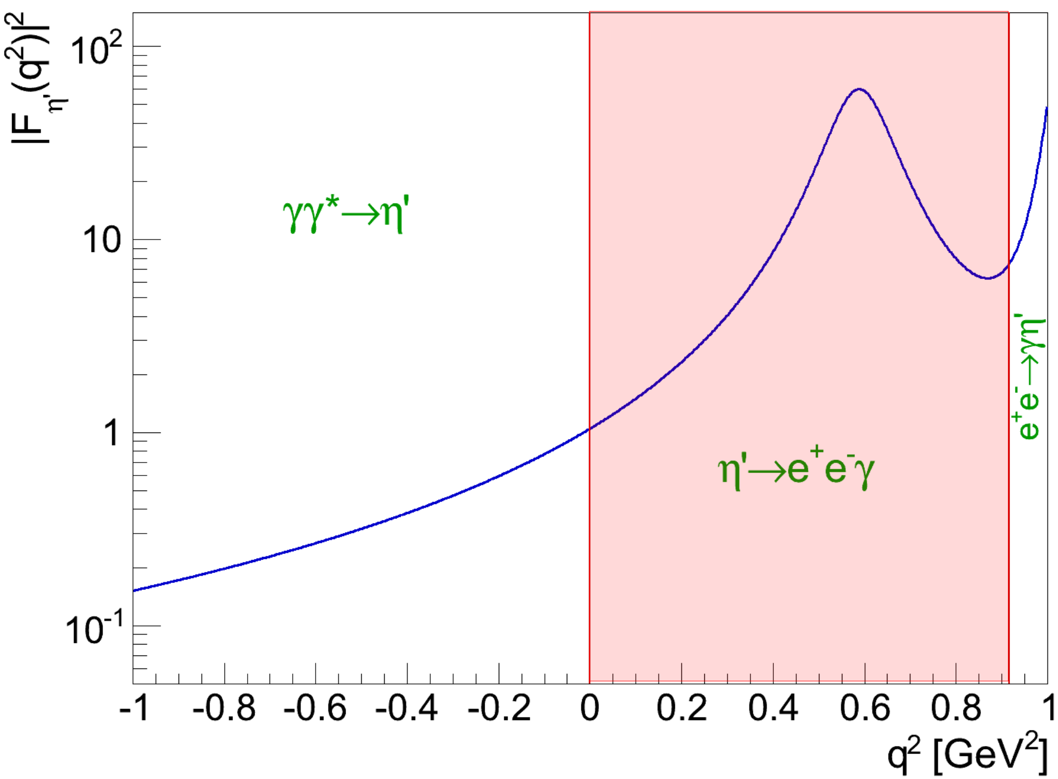
- Installation EPT fall 2011
- First test run December 2011
- First test/production measurement successful in March 2012!
- η' production runs (each 2,5 weeks) successful May/August 2012!



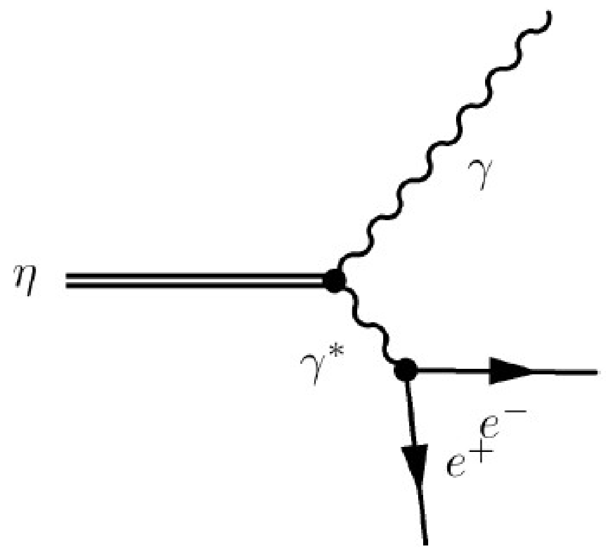
Only small part of available statistics

S. Prakhov (UCLA)

Time-like TFF at MAMI



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



Time-like momentum transfer (meson decays):

- $(2m_l)^2 < q^2 < M^2$
- Crystal Ball, WASA, KLOE, Crystal Barrel, BESIII, CLAS

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

- Also $\mu^+\mu^-\gamma$ decays possible: NA60