



# $\eta$ and $\eta'$ Decays with Crystal Ball at MAMI (and more)

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Mainz, 10<sup>th</sup> April 2014

# Outline

- Crystal Ball Set-up at MAMI
- Results from Crystal Ball at MAMI
  - Preliminary Result for  $\eta \rightarrow \pi^0 \gamma\gamma$
  - Timelike Transition Form Factor from  $\eta \rightarrow e^+ e^- \gamma$
- Future Perspectives
- Summary

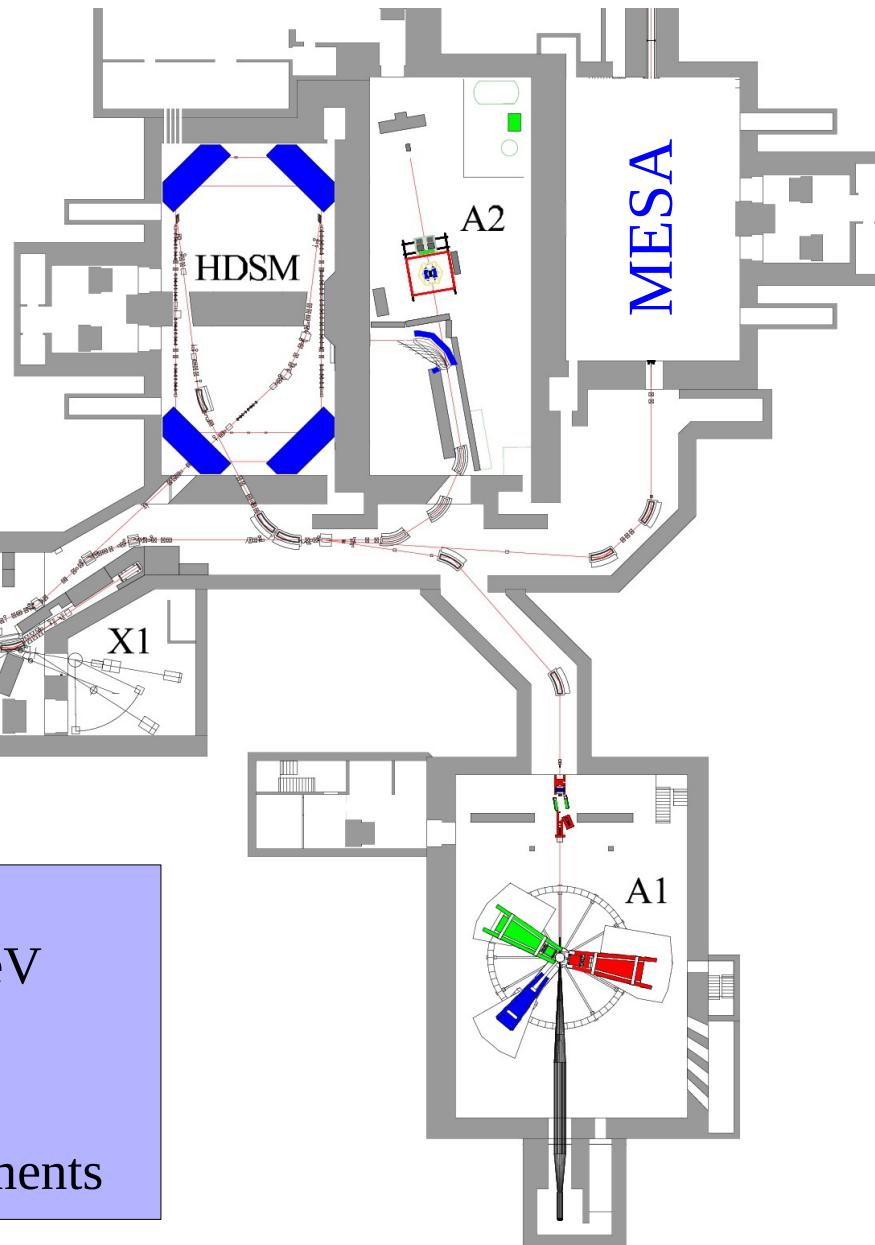


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# Mainz Microtron (MAMI)



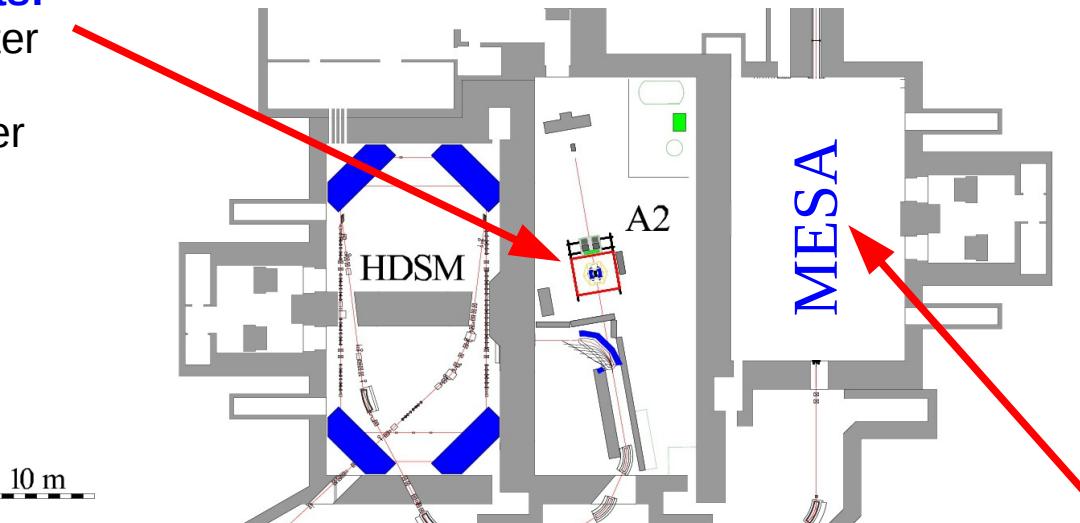
## MAMI Parameters:

- Up to 1604 MeV,  $\sigma_E < 0.1$  MeV
- High current ( $110\mu\text{A}$ )
- High polarisation (80%)
- $\sim 7000$  h/year running experiments

# Experiments at MAMI

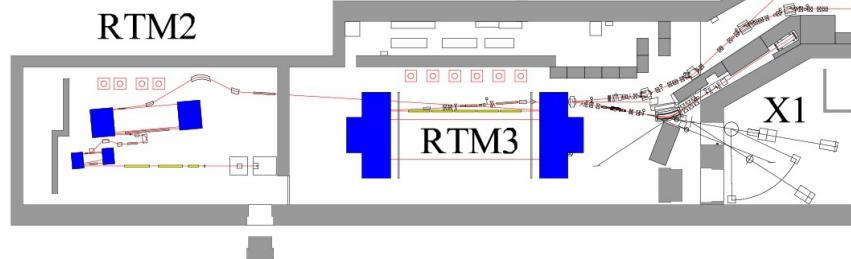
## A2: Real Photon Experiments:

- Glasgow tagging spectrometer
- Crystal Ball / TAPS hermetic photon spectrometer
- Meson Factory



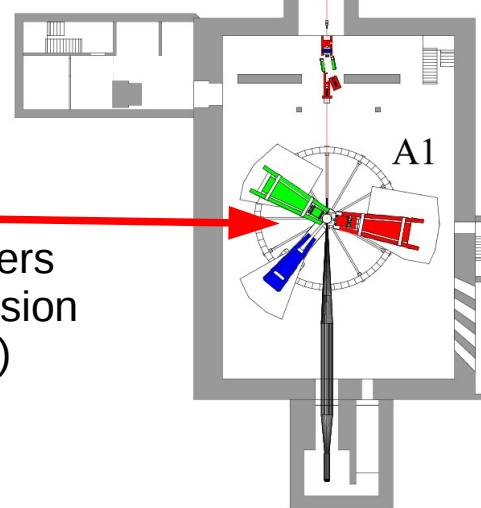
## PRISMA/SFB 1044:

- Dark Photon Search
- El.-weak Mixing Angle



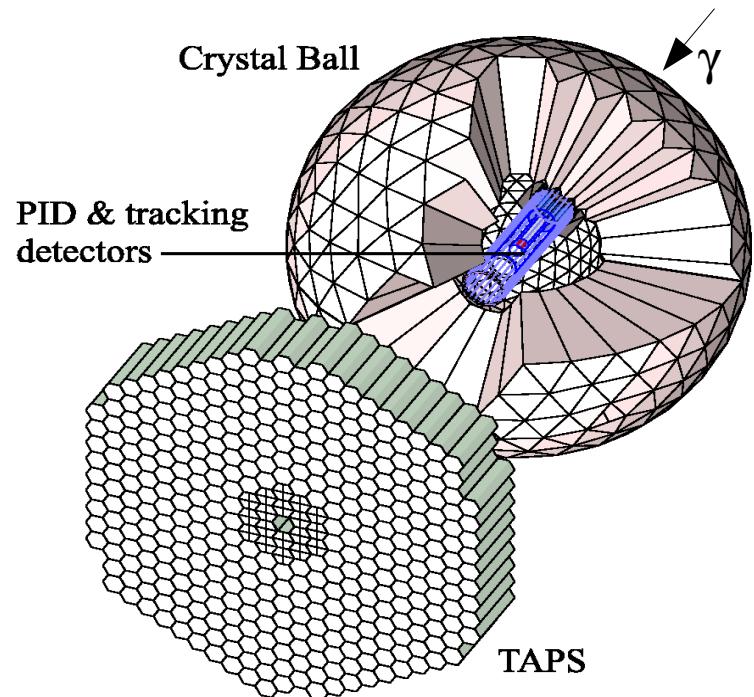
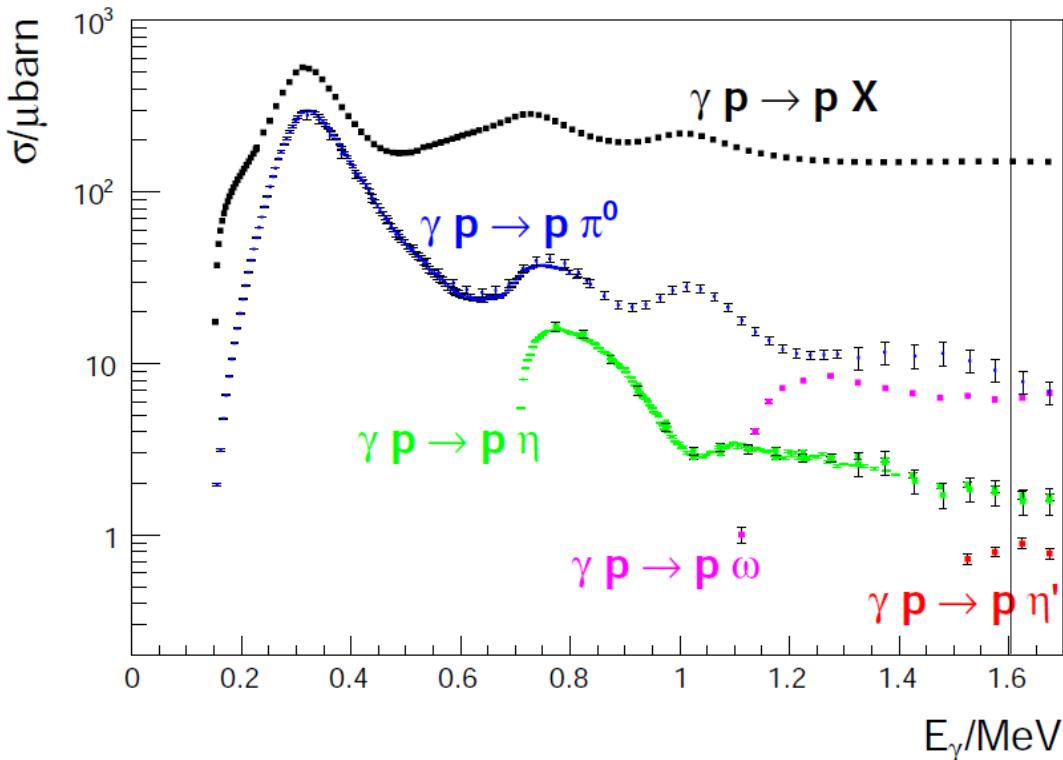
## A1: Electron Scattering:

- 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  $\text{IH}_2$  target feasible for taking data (Meson Factory):

$$\eta: 10^5 \text{ h}^{-1} \Rightarrow \text{Goal } 10^6 \text{ h}^{-1}$$

$$\eta': 2 \cdot 10^3 \text{ h}^{-1} \Rightarrow \text{Goal } 1.5 \cdot 10^4 \text{ h}^{-1}$$

Has to be imposed by detection and analysis efficiencies

- ⇒  $4\pi$  Crystal Ball/TAPS setup, e.m. Production mechanism very clean
- ⇒ Ideally suited to measure high rates of meson decays

# Outline

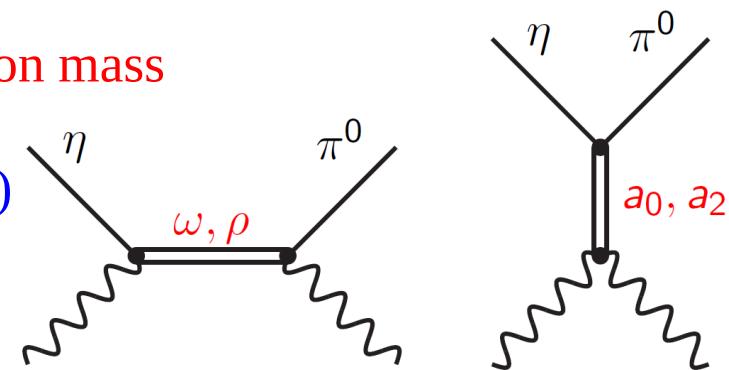
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# Double Radiative $\eta \rightarrow \pi^0\gamma\gamma$

- Tree level amplitudes at  $O(p^2)$  and  $O(p^4)$  vanish
- $\pi$  and K loops largely 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  $\chi$ PT at  $O(p^6)$  as well as models

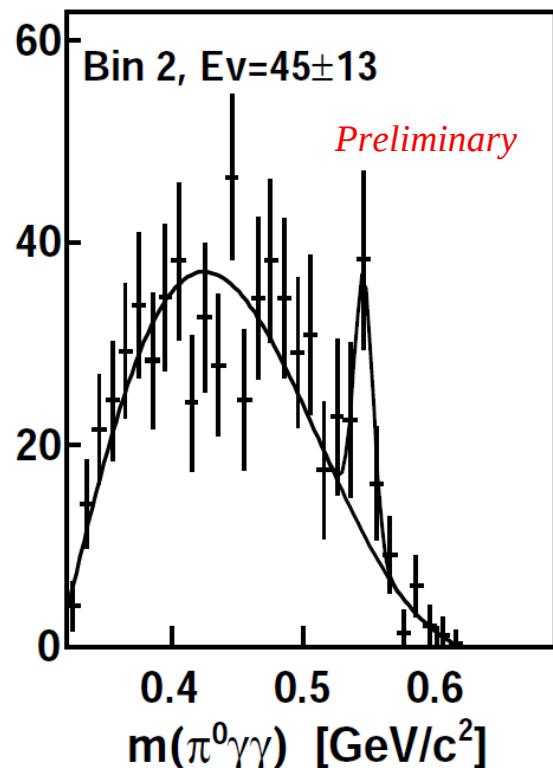


- Calculations must describe  $\Gamma(\eta \rightarrow \pi^0\gamma\gamma)$  and differential decay width  $d\Gamma/dm^2(\gamma\gamma)$
- Discrepancies between models in  $d\Gamma/dm^2(\gamma\gamma)$
- Discrepancies in experimental results for  $\Gamma(\eta \rightarrow \pi^0\gamma\gamma)$
- Experimental 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 ( $6 \cdot 10^7 \eta$  produced)

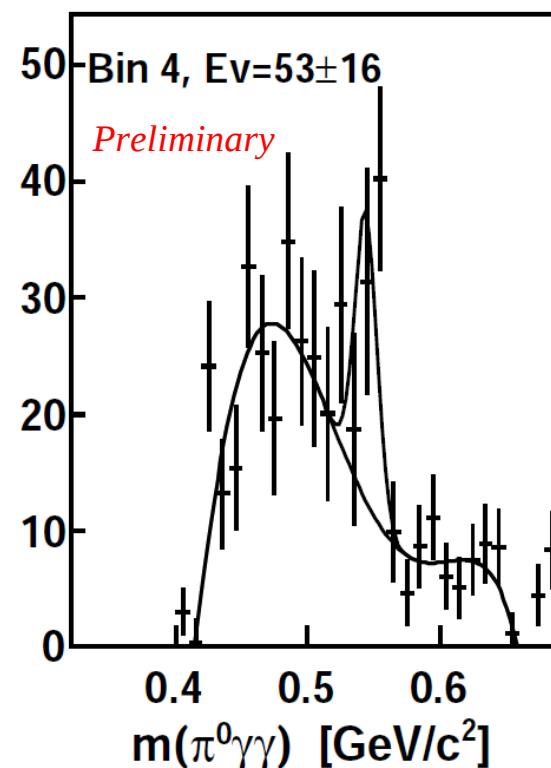
# Analysis of $\eta \rightarrow \pi^0\gamma\gamma$

- Based on kinematic fitting
  - $\pi^0\pi^0$  background suppressed by anti-hypothesis
  - Results based on  $1.2 \cdot 10^3$   $\eta \rightarrow \pi^0\gamma\gamma$  events
- 
- Below preliminary results from 2009

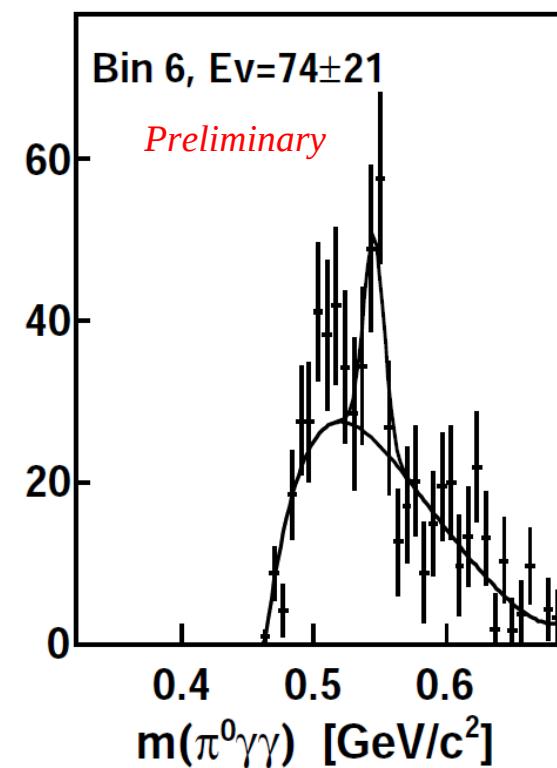
$$m^2(\gamma\gamma) = (0.0375 \pm 0.0100) \text{ GeV}^2/c^4$$



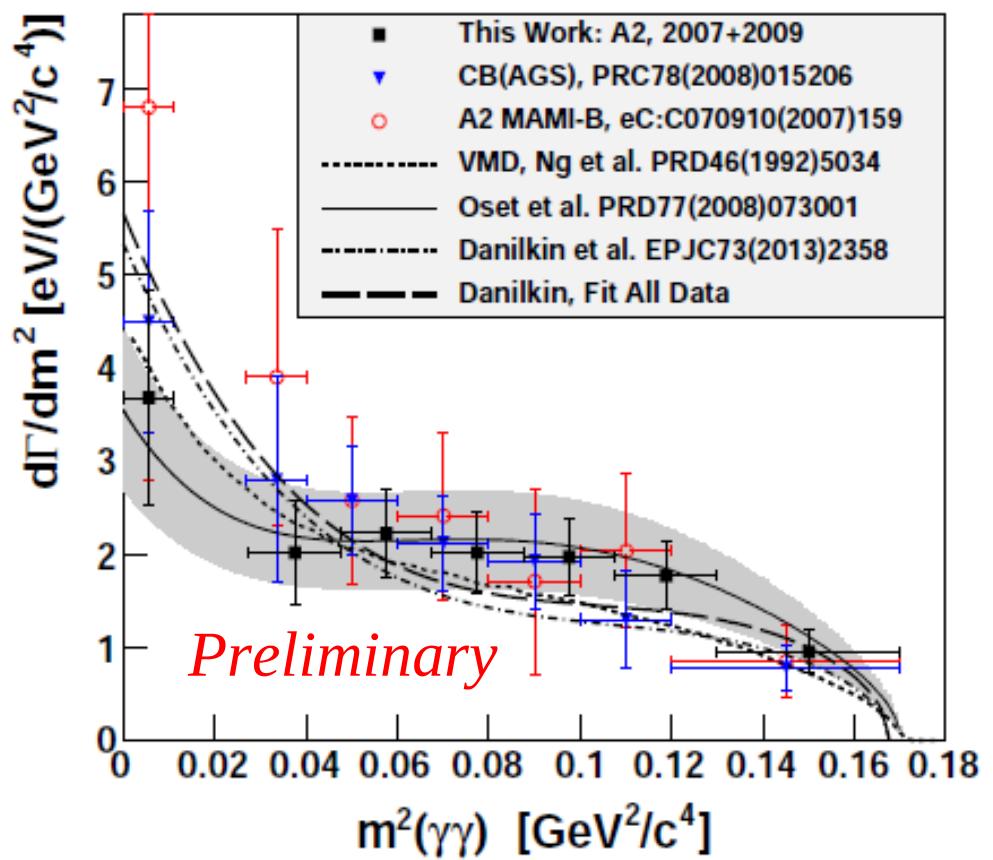
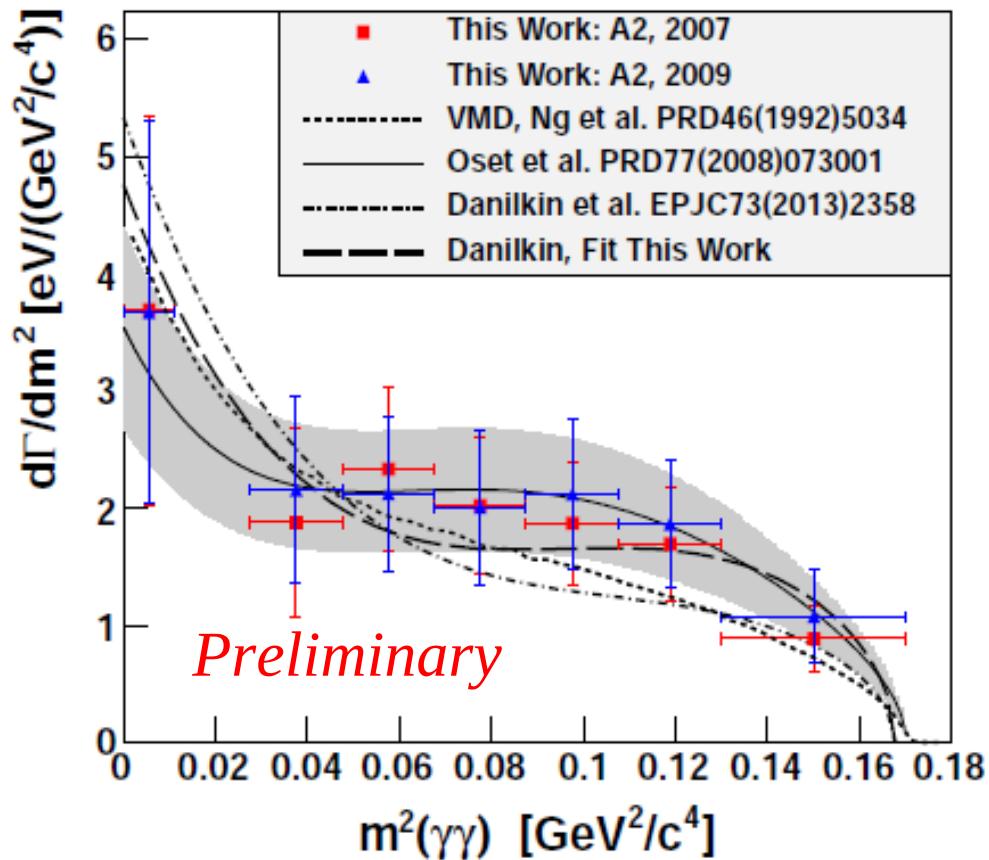
$$m^2(\gamma\gamma) = (0.0775 \pm 0.0100) \text{ GeV}^2/c^4$$



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



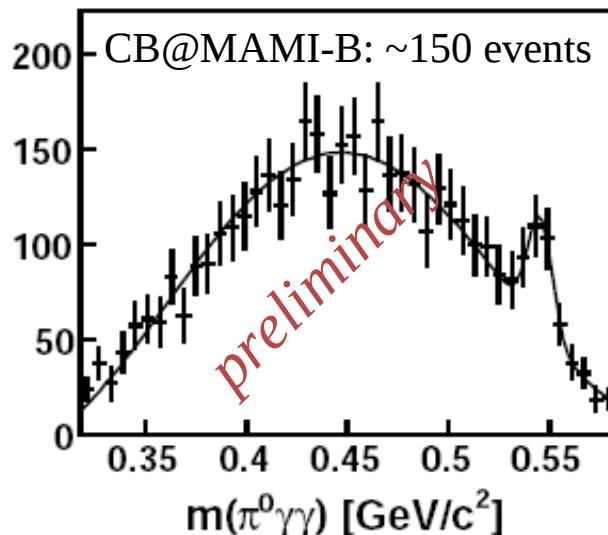
# Decay Rate $\eta \rightarrow \pi^0 \gamma\gamma$



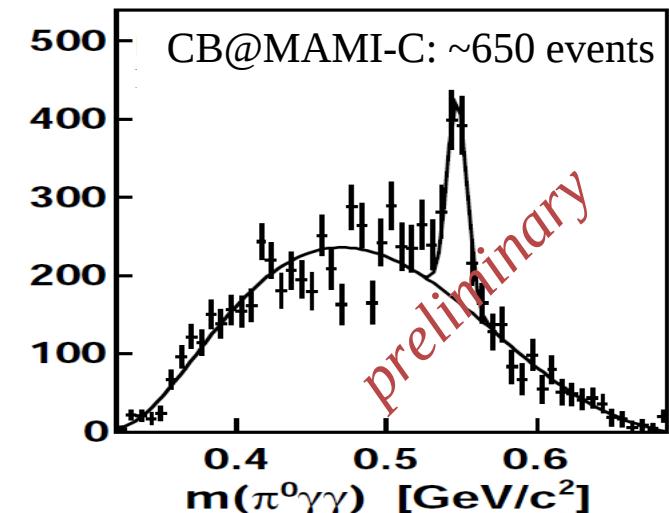
General agreement but statistics still not sufficient to distinguish between models!  
 Need more statistics to examine Dalitz plot!  
 To be submitted soon!

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

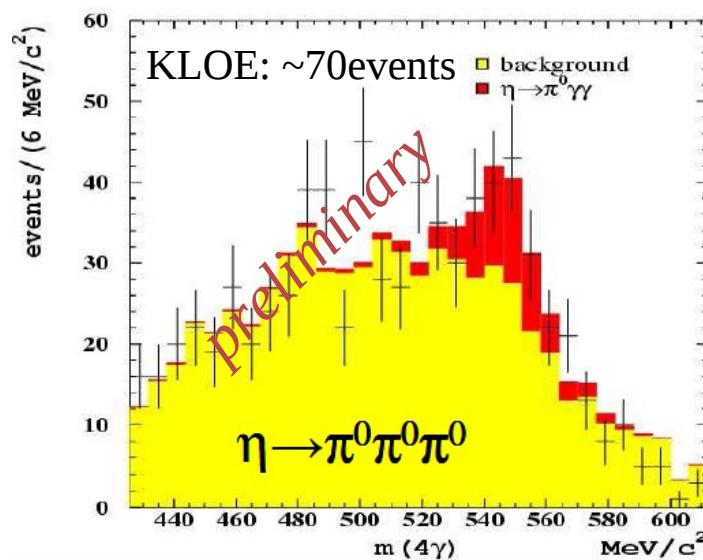
A2



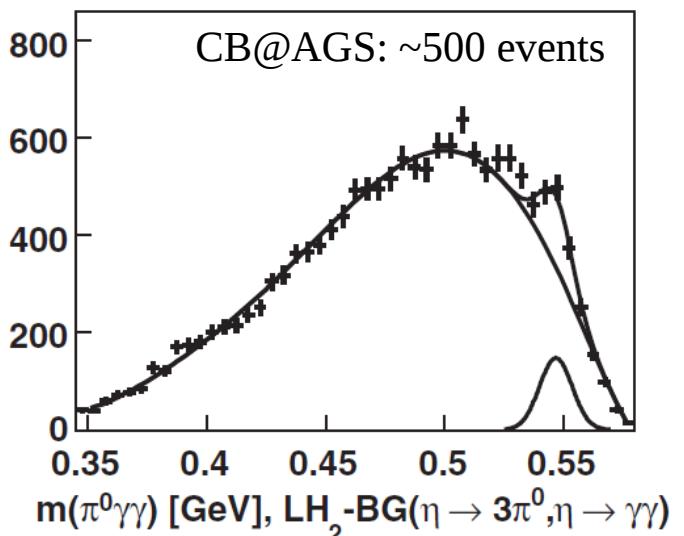
S. Prakhov (UCLA), private communication



S. Prakhov (UCLA), private communication  
Only 2007 data set. 2009 has ~400 events.



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



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

# Decay Width of $\eta \rightarrow \pi^0 \gamma\gamma$

$\Gamma = (0.84 \pm 0.19)$  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:

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

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

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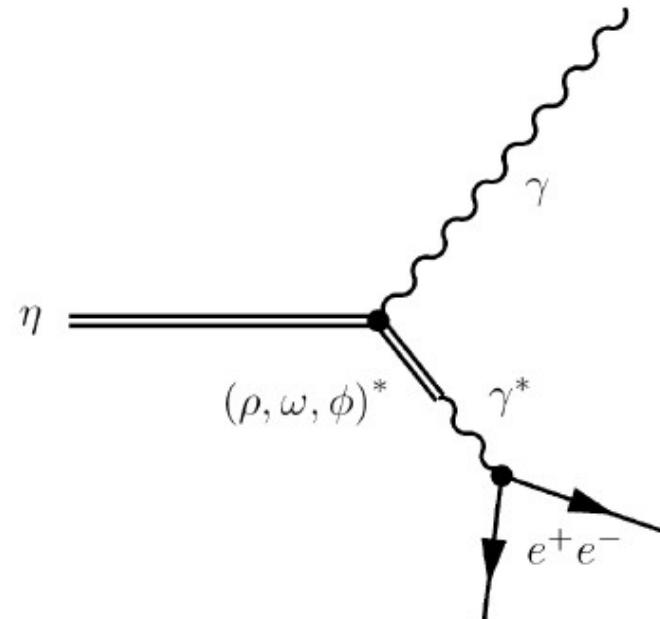
# Transition Form Factor with VMD

- 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  $\eta'$ , not well known
- TFF modifies differential decay width

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

- For  $\eta$  often one-pole approximation used:

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



- For  $\eta'$  resonance shape:

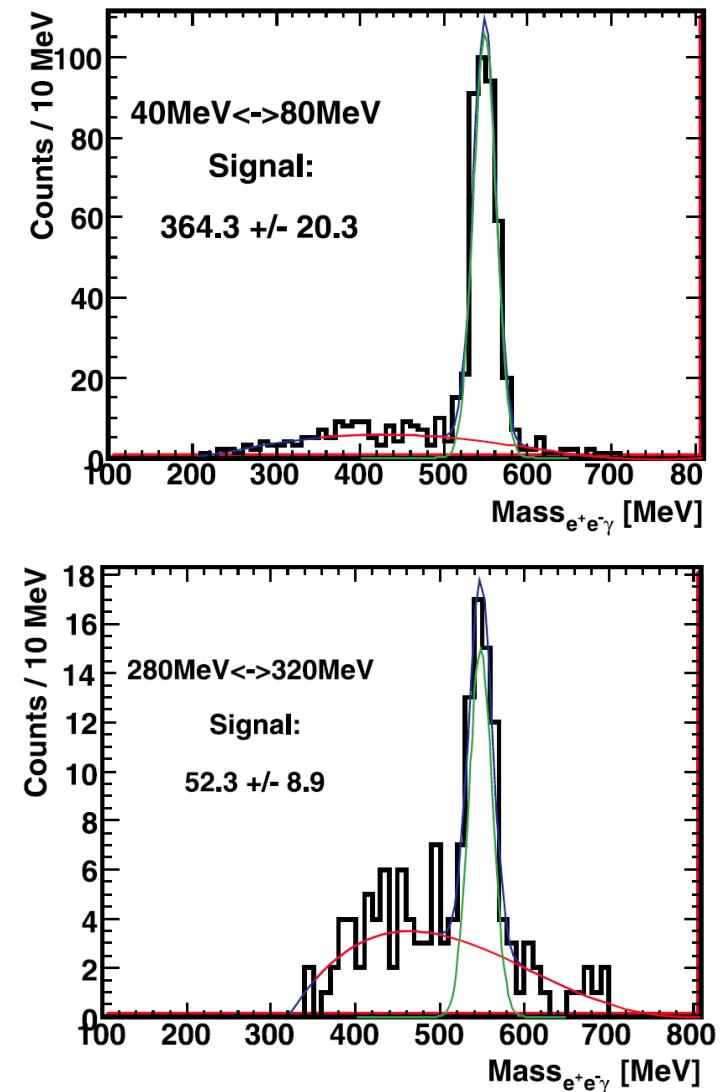
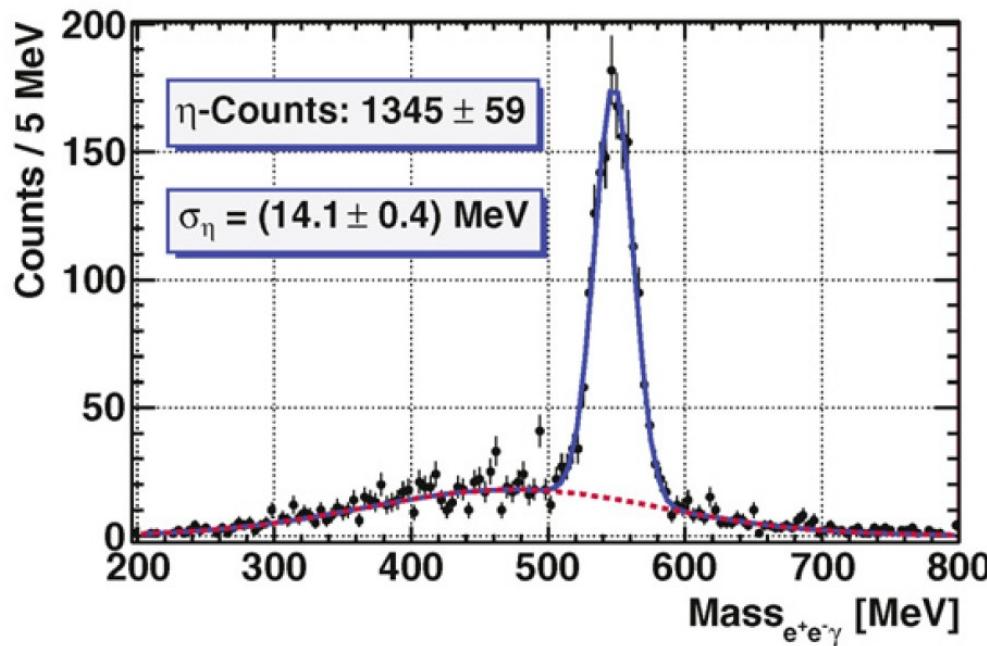
$$|F(m^2)|^2 = \frac{\Lambda^2(\Lambda^2 + \gamma^2)}{(\Lambda^2 - m^2)^2 + \Lambda^2\gamma^2}$$

- Gain information on structure of meson and  $\eta/\eta'$  mixing, (dark photon?  $\eta \rightarrow \gamma'\gamma \rightarrow e^+e^-\gamma$ )
  - In addition to input for had. LbL scattering contribution to  $(g-2)_\mu$

# First A2 Analysis for $\eta$ TFF

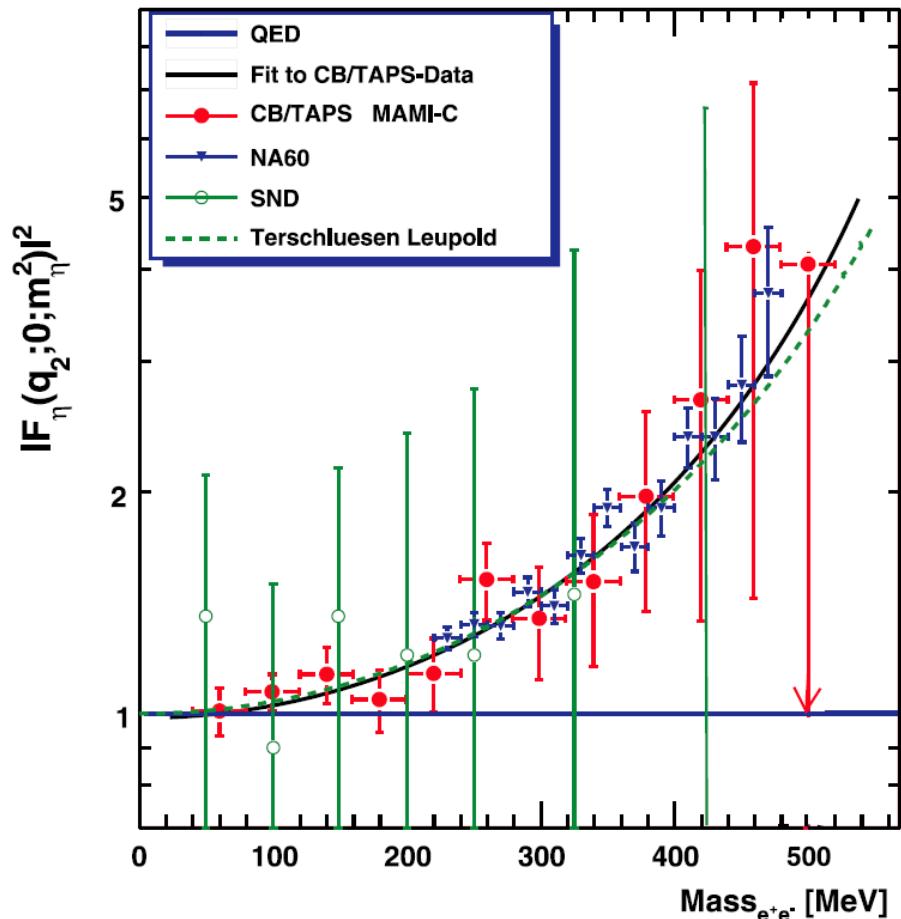
H. Berghäuser et al. (A2-Collaboration), Phys. Rev. B 701 (2011) 562-567.

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



# First A2 Result for $\eta$ TFF

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



CB/TAPS MAMI-C: 1350  $\eta \rightarrow e^+e^-\gamma$  events  
 NA60: 9000  $\eta \rightarrow \mu^+\mu^-\gamma$  events  
 SND: 109  $\eta \rightarrow e^+e^-\gamma$  events

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

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

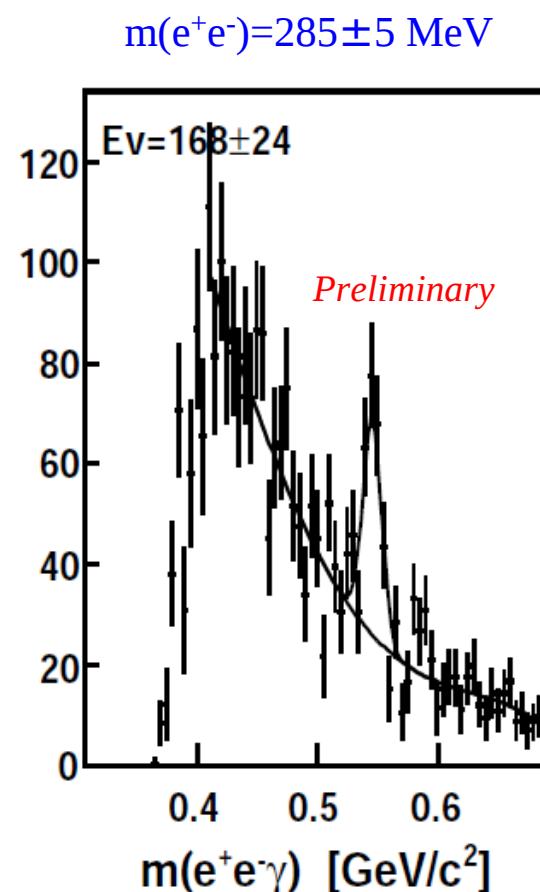
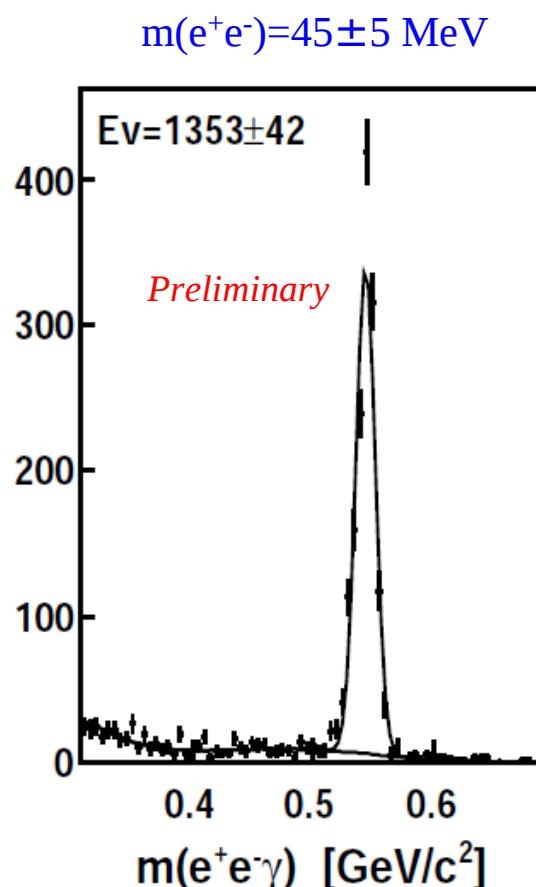
NA60, In-In: R. Arnaldi et al., Phys. Lett. B 677 (2009) 260.

SND: M.N. Achasov et al., Phys. Lett. B 504 (2001) 275.

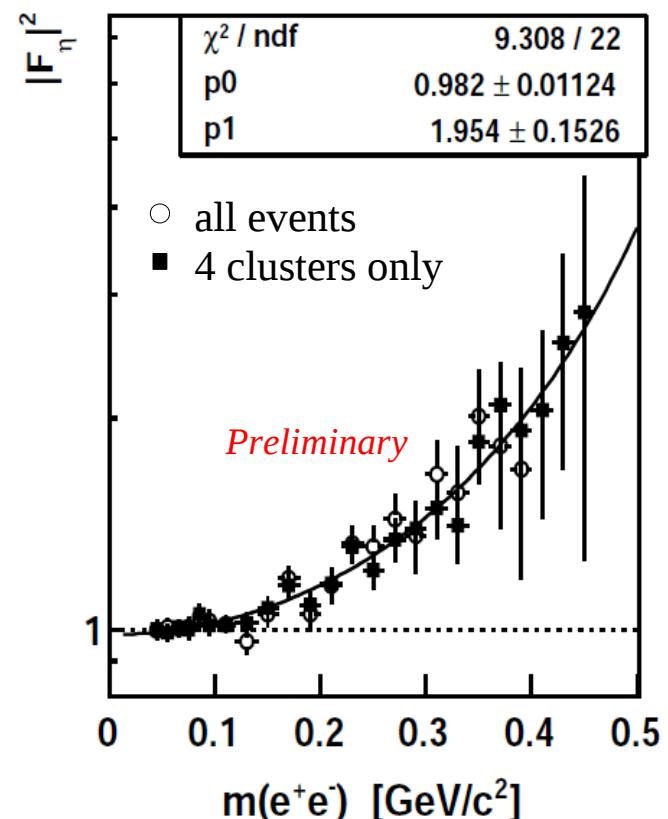
Terschluesen Leupold: C. Terschlüsen, Diploma thesis, University Gießen, Germany, 2010.

# New Analysis of $\eta$ TFF

- Based on kinematic fitting
- 3x more data
- Full  $\eta$  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

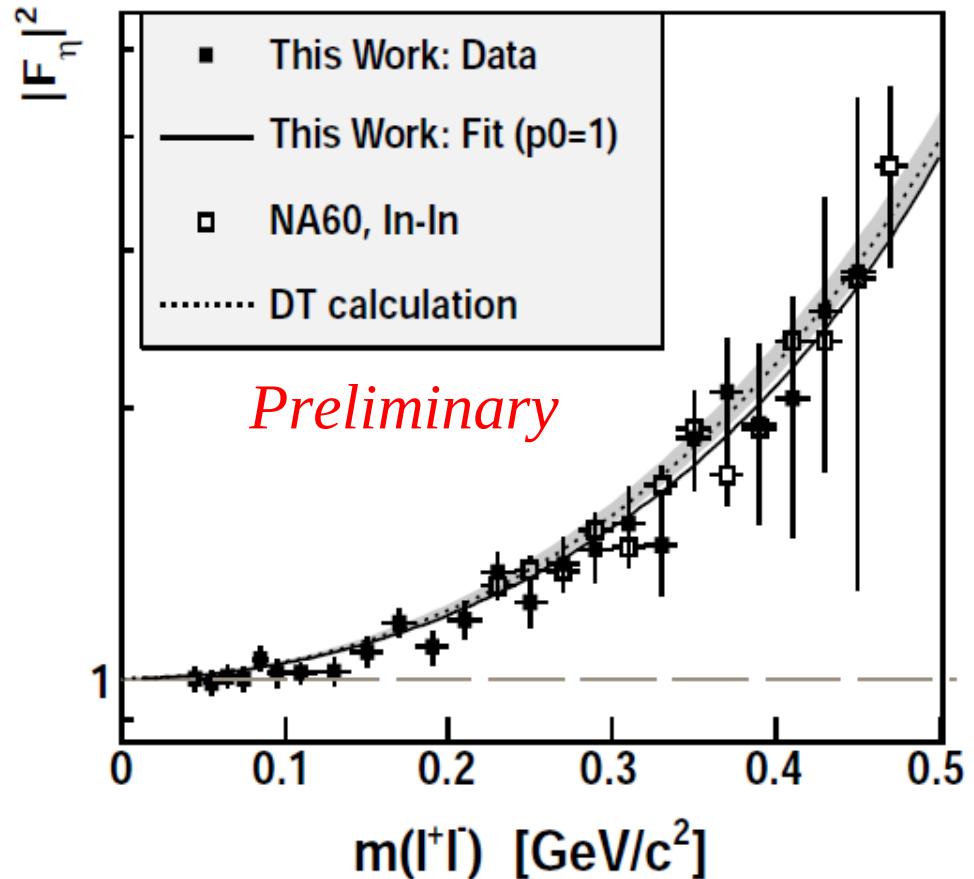
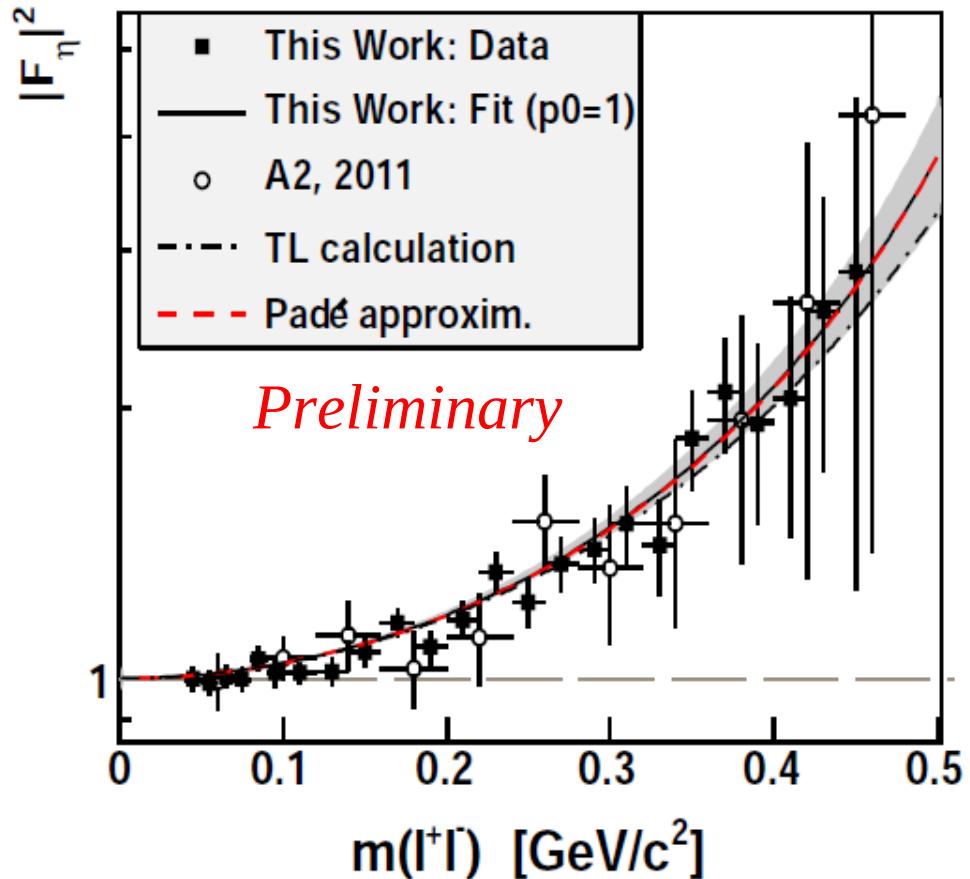


Solid line: Pole-approximation fit  
Normalisation  $p_0$  and  $\Lambda^{-2}=p_1$  as free parameters



# New A2 Result for $\eta$ TFF

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



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

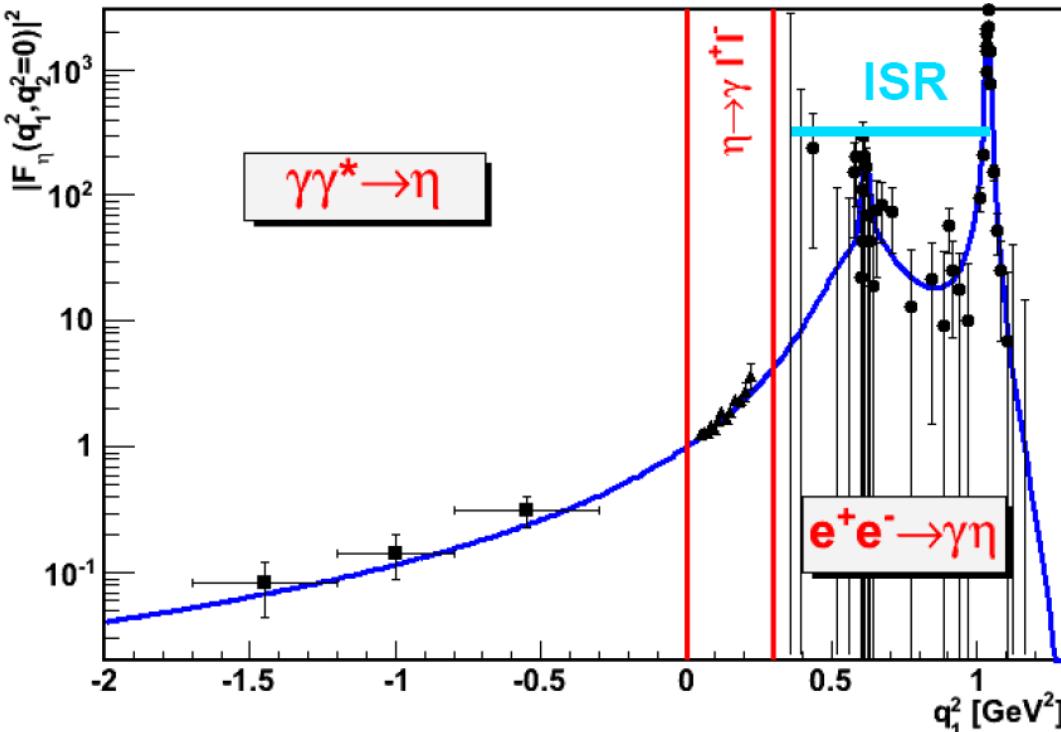
NA60, In-In: R. Arnaldi et al., Phys. Lett. B **677** (2009) 260.

TL calculation: C. Terschlüsen, Diploma thesis, University Gießen, 2010.

Padé-approximants: R. Escribano, P. Masjuan, P. Sanchez-Puertas, Phys. Rev. D **89** (2014) 034014.

DT calculation: C. Hahnhart, A. Kupść, U.-G. Meißner, F. Stollenwerk, A. Wirzba, Eur. Phys. J. C73 (2013) 2668.

# $\eta$ TFF Slope



Andrzej Kupsc, ACFI Workshop on  
Hadronic Probes of Fundamental Symmetries,  
Amherst, April 2014.

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

$$\Rightarrow \frac{dF(q^2)}{dq^2} \Big|_{q^2=0} = \Lambda^{-2}$$

Slope  $\Lambda^{-2}$  can be measured from  
both sides!

VMD-like models used for  $\eta$  TFF using  
CLEO (spacelike data  $1.5 \text{ GeV}^2 < Q^2 < 20 \text{ GeV}^2$ ):

F. Jegerlehner, A. Nyffeler, Phys. Rept. 477 (2009) 1-110.

$\Lambda = (774 \pm 29) \text{ MeV} \approx m_\rho$   
J. Gronberg et al., Phys. Rev. D 57 (1998) 33.

VMD ( $\rho, \omega, \phi$ ):  $\Lambda = 745 \text{ MeV}$

L.G. Landsberg, Phys. Rep. 128 (1985) 301.

MAMI:  $\Lambda^{-2} = (1.95 \pm 0.15_{\text{stat}} \pm 0.10_{\text{syst}}) \text{ GeV}^{-2} \Rightarrow \Lambda = (716 \pm 0.033) \text{ MeV}$

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

Conclusions: indication of higher resonances and use lower  $\Lambda$  in VMD-like models  $[(g-2)_\mu]$

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# Perspectives for $\eta$

Proposed production yields with Crystal Ball at MAMI:

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

- Neutral decay modes with unprecedented accuracy with CB:  
QCD/ $\chi$ PT 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  $\eta \rightarrow e^+e^-\gamma$   
**Double Dalitz** decay  $\eta \rightarrow e^+e^-e^+e^-?$
- 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 $\eta'$

Proposed production yields with Crystal Ball at MAMI:

10 weeks:  $2 \cdot 10^7 \eta'$  (factor 4 improvement) in 2<sup>nd</sup> half of 2014

- Neutral decay modes with unprecedented accuracy with CB: unstable particles in EFT  
 $\text{BR}(\eta' \rightarrow \omega\gamma/\eta' \rightarrow \eta\pi^0\pi^0)$  improve by factor 2-5  
PDG 2012:  $\text{BR}(\eta' \rightarrow \omega\gamma/\eta' \rightarrow \eta\pi^0\pi^0) = 0.147 \pm 0.016$
- QCD/ $\chi$ PT related (Dalitz plot analyses)  $\eta' \rightarrow 3\pi^0$ ,  $\eta' \rightarrow \eta\pi^0\pi^0$  ( $\sim 400.000$  events expected)  
Further effects: **cusp effect (8%)**,  $\pi\pi$ - and  $\pi\eta$ -scattering
- Transition Form Factor:  
Single Dalitz decay  $\eta' \rightarrow e^+e^-\gamma$  (800 events proposed)

A. Denig, W. Gradl, M. Ostrick, M. Unverzagt (University Mainz), S. Prakhov, (UCLA/Mainz)  
PhD students: A. Neiser, O. Steffen, S. Wagner, M. Wolfes (University Mainz)

# Rate Estimation $\eta' \rightarrow e^+e^-\gamma$

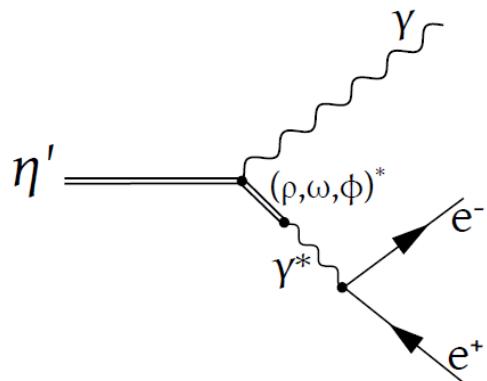
S. Wagner, Master thesis, University Mainz, 2013  
M. Unverzagt, A. Denig

- $\eta' \rightarrow e^+e^-\gamma$  no observation published yet worldwide
- 5.5 weeks of  $\eta'$  photoproduction in 2012
  - Analysis of  $\eta' \rightarrow \eta\pi^0\pi^0$   
→ Total 1.5 million  $\eta'$  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	$\sigma$ [ $\mu b$ ]	BR	simulierte Statistik
$\eta' \rightarrow e^+e^-\gamma$	0,76	$< 9 \cdot 10^{-4}$	10M
$\eta' \rightarrow \pi^+\pi^-\eta$	0,76	43,40 %	5M
$\eta' \rightarrow \rho^0\gamma$	0,76	29,30 %	8M
$\eta' \rightarrow \mu^+\mu^-\gamma$	0,76	$1,07 \cdot 10^{-4}$	5M
$\eta' \rightarrow \gamma\gamma$	0,76	2,18 %	6M
$\eta \rightarrow e^+e^-\gamma$	1,85	$6,9 \cdot 10^{-3}$	5M
$\eta \rightarrow \pi^+\pi^-\gamma$	1,85	4,60 %	5M
$\eta \rightarrow \pi^+\pi^-\pi^0$	1,85	22,74 %	5M
$\eta \rightarrow \mu^+\mu^-\gamma$	1,85	$3,1 \cdot 10^{-4}$	5M
$\eta \rightarrow \gamma\gamma$	1,85	39,31 %	5M
$\omega \rightarrow e^+e^-\pi^0$	6,44	$7,7 \cdot 10^{-4}$	5M
$\omega \rightarrow \pi^+\pi^-\pi^0$	6,44	89,20 %	5M
$\omega \rightarrow \pi^+\pi^-$	6,44	1,53 %	5M
$\rho^0 \rightarrow e^+e^-$	19,00	$4,72 \cdot 10^{-5}$	5M
$\rho^0 \rightarrow \pi^+\pi^-$	19,00	~100 %	5M
$\pi^0 \rightarrow e^+e^-\gamma$	10,52	1,17 %	5M
$\pi^0 \rightarrow \gamma\gamma$	10,52	98,82 %	10M
$\gamma p \rightarrow \pi^+\pi^-\pi^0$	15,00	—	5M
$\gamma p \rightarrow \pi^+\pi^-$	68,62	—	10M
$\pi^0\pi^0 \rightarrow 4\gamma$	6,87	97,65 %	20M
$\pi^0\eta \rightarrow 4\gamma$	4,09	38,85 %	20M

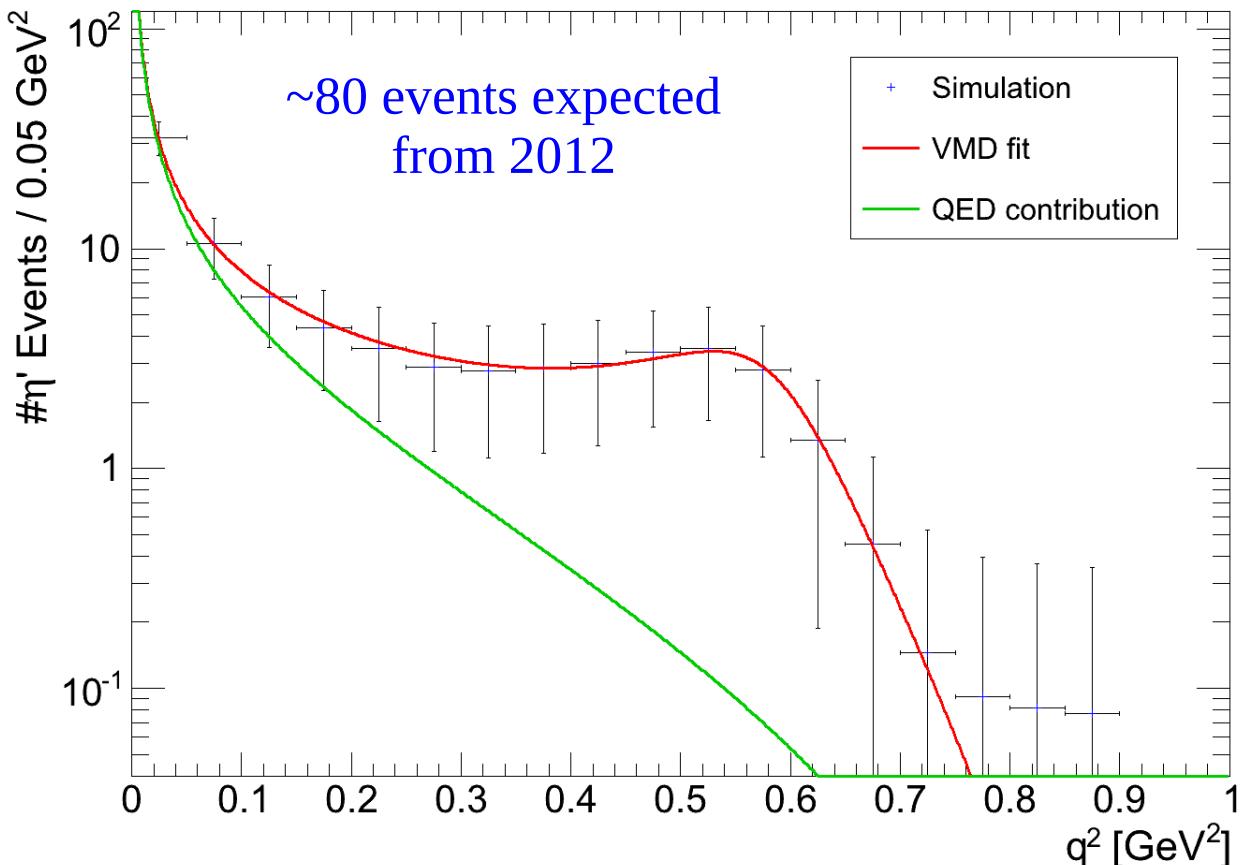
# Time-like TFF for $\eta'$

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



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

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



- New Goal:  $\sim 800 \eta' \rightarrow e^+e^-\gamma$  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)

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Further effects: cusp effect (8%),  $\pi\pi$ - and  $\pi\eta$ -scattering
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Double Dalitz decay  $\eta' \rightarrow e^+e^-e^+e^-$ ?
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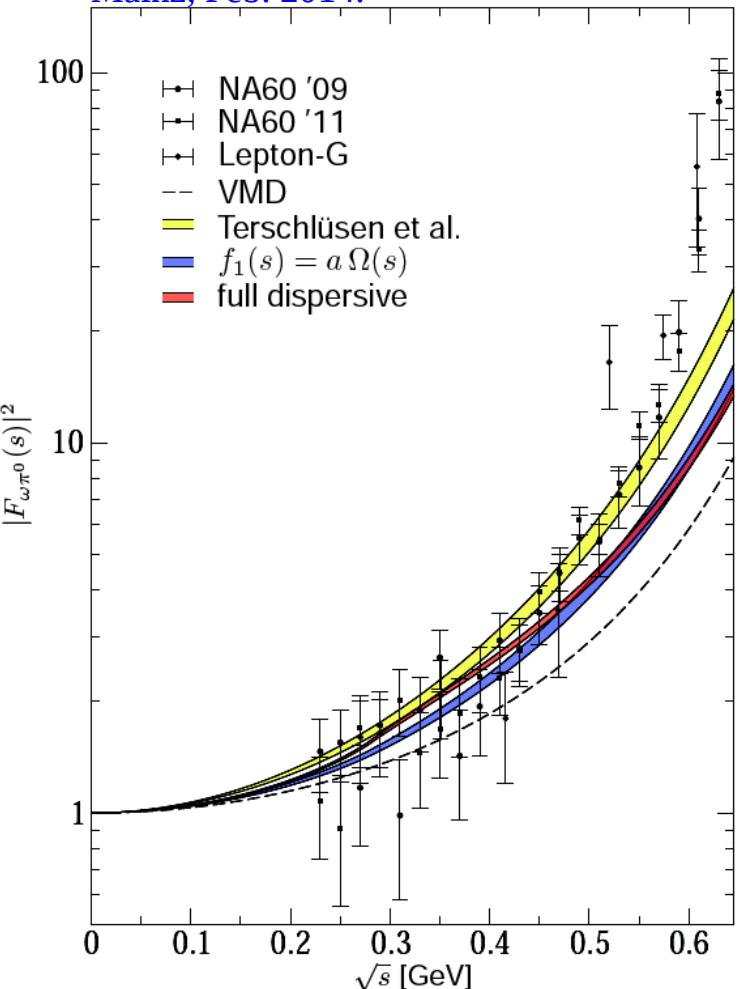
# Perspectives for $\omega$

Proposed production yields with Crystal Ball at MAMI:

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

- Neutral decay modes with unprecedented accuracy:  
 $\text{BR}(\omega \rightarrow \eta\gamma/\omega \rightarrow \pi^0\gamma)$  improve by factor 2-5  
PDG 2010:  $\text{BR}(\omega \rightarrow \eta\gamma/\omega \rightarrow \pi^0\gamma) = 0.0098 \pm 0.0024$   
(not used anymore)  
 $\omega \rightarrow \eta\gamma/\omega \rightarrow \pi^0\gamma$ : power counting for unstable particles in effective field theory
- Transition Form Factor for  $\omega \rightarrow \pi^0 e^+ e^-$
- Another LbL contribution (S. Leupold):  $\gamma \rightarrow \omega \rightarrow 3\gamma^{(*)}$   
Related to scattering amplitude  $\gamma\omega \rightarrow \pi\pi \rightarrow \gamma\gamma$   
Mainz could contribute to  $\omega \rightarrow \pi^0\pi^0\gamma$

B. Kubis, Light Meson Dynamics Workshop,  
Mainz, Feb. 2014.



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

# Perspectives for $\pi^0$

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

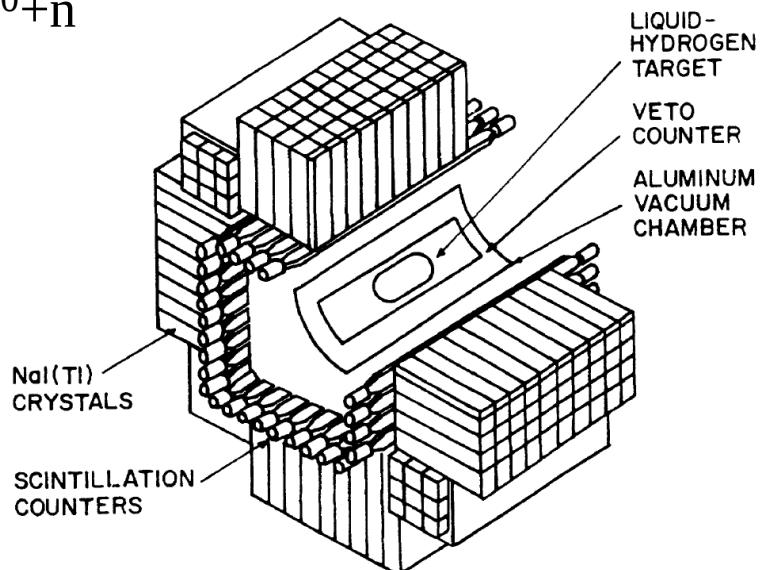
Current bound:  $\text{BR}(\pi^0 \rightarrow 3\gamma) < 3.1 \cdot 10^{-8}$  (90 %C.L.)

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

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

Main background channels:

$\pi^0 \rightarrow 2\gamma$   
 $\pi^0 \rightarrow e^+ e^- \gamma$   
 $\pi^0 \pi^0$  production } Reduce at trigger level by factor 100!



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

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

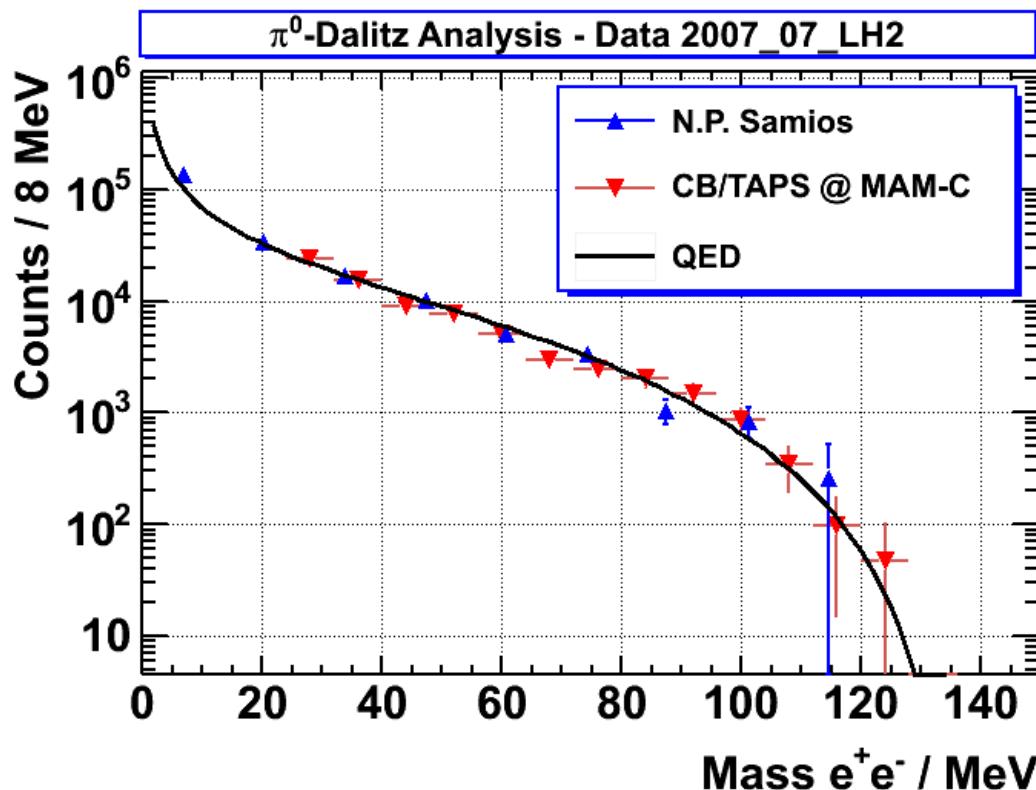
J. McDonough et al., Phys. Rev. D38 (1988) 2121.

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

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

# Perspectives for $\pi^0$

- Within 100h of beamtime on  $^{208}\text{Pb}$  or  $^{236}\text{U}$  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  $\eta/\omega?$ ) and possibly decay studies with higher rate
- Especially look at  $\pi^0 \rightarrow e^+ e^- \gamma$



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)

# Perspectives for $\pi^0$

- Within 100h of beamtime on  $^{208}\text{Pb}$  or  $^{236}\text{U}$  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  $\eta/\omega$ ?) and possibly decay studies with higher rate
- Especially look at  $\pi^0 \rightarrow e^+ e^- \gamma$ ,  $\pi^0 \rightarrow e^+ e^-$  (?)
- But: NA62 plans to collect  $2.5 \cdot 10^{12} \pi^0$  decays in 2 years

$\pi^0 \rightarrow e^+ e^- (\gamma)$	dark photon	—
$\pi^0 \rightarrow e^+ e^- e^+ e^-$	T violation	$C = -0.77 \pm 0.53$
$\pi^0 \rightarrow \gamma \gamma \gamma$	C violation	$< 3.1 \times 10^{-8}$
$\pi^0 \rightarrow \gamma \gamma \gamma \gamma$	light scalar	$< 2 \times 10^{-8}$
$\pi^0 \rightarrow \nu \bar{\nu}$	RH neutrino	$< 2.7 \times 10^{-7}$

Can we compete?

Rainer Wanke, Light Meson Dynamics Workshop, Mainz, Feb. 2014.

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

# Outline

- Crystal Ball Set-up at MAMI
- Results from Crystal Ball at MAMI
  - Preliminary Result for  $\eta \rightarrow \pi^0 \gamma\gamma$
  - Timelike Transition Form Factor from  $\eta \rightarrow e^+ e^- \gamma$
- Future Perspectives
- **Summary**



# Summary

- World leading results from Crystal Ball at MAMI  
Dalitz plot parameter:  $\eta \rightarrow 3\pi^0$   
 $\chi$ PT, VMD:  $\eta \rightarrow \pi^0\gamma\gamma$   
Transition Form Factor:  $\eta \rightarrow e^+e^-\gamma$   
C-violation: neutral  $\omega$  decays (not mentioned here)
- Further analyses in  $\eta/\omega$  decays possible with existing data
- Main focus:  $\eta'$  studies  
Data taking planned for 2<sup>nd</sup> half of 2014  
Goals: 400,000  $\eta' \rightarrow \eta\pi^0\pi^0$   
800  $\eta' \rightarrow e^+e^-\gamma$
- New programme with very rare decays under investigation  
 $\pi^0 \rightarrow 3\gamma/4\gamma$ , extend to other rare  $\pi^0$ ,  $\eta$ ,  $\omega$  decays
- New detector possibilities under discussion

# Chiral Symmetry Breaking

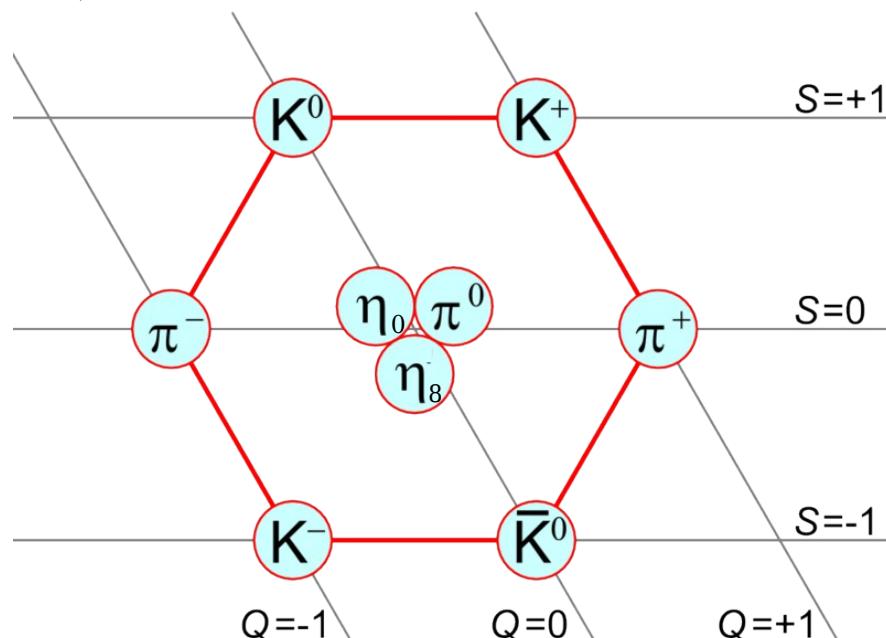
$$L_{\text{QCD}} = \bar{q} (i \not{D} - M) q - \sum_{a=1}^8 \frac{1}{4} G_{\mu\nu,a} G_a^{\mu\nu}$$

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

$$U(3)_L \times U(3)_R = SU(3)_L \times SU(3)_R \times U(1)_V \times U(1)_A \text{ symmetry}$$

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

- $SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$  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:  $\eta \rightarrow 3\pi$ ,  $\eta' \rightarrow 3\pi$ ;  $\eta' \rightarrow 2\pi\eta$

Extract:

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

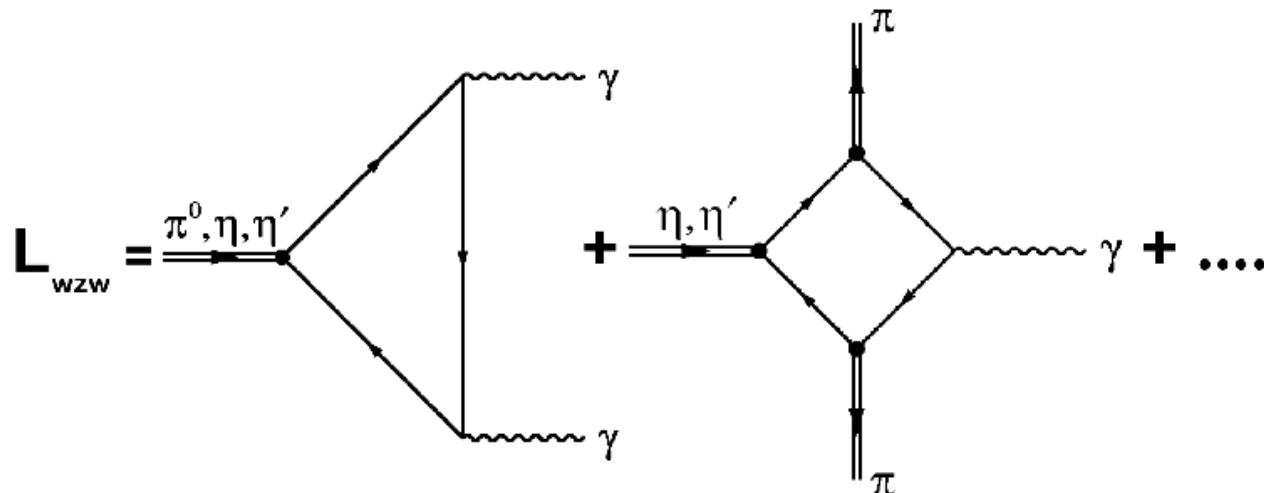
# $\eta/\eta'$ mixing

$\eta$  and  $\eta'$  are admixtures of pure SU(3) singlet and octet states

$$\begin{aligned}\eta &= \eta_0 \sin\theta - \eta_8 \cos\theta \\ \eta' &= \eta_0 \cos\theta + \eta_8 \sin\theta\end{aligned}$$

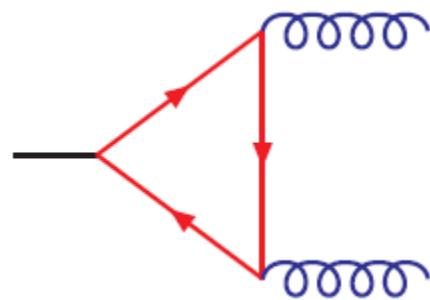
$$\eta/\eta': I^G(J^{PC}) = 0^+(0^{-+})$$

- 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



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

- Why is the  $\eta'$  so heavy?
- $\omega$ -term includes gluons  $\rightarrow$  strongly interacting  $\rightarrow \eta'$  heavy
- Applicability of  $\chi$ PT to  $\eta'$ ? (chiral symmetry breaking scale:  $4\pi f_\pi \approx 1.2$  GeV,  $\eta'$  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

$\Gamma(\pi^0 \rightarrow 3\gamma)/\Gamma_{\text{total}}$	$<3.1 \times 10^{-8}$ , CL = 90%
$\eta$ 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 $\beta$ (D-wave)	$-0.02 \pm 0.07$ (S = 1.3)
$\Gamma(\eta \rightarrow \pi^0 \gamma)/\Gamma_{\text{total}}$	$<9 \times 10^{-5}$ , CL = 90%
$\Gamma(\eta \rightarrow 2\pi^0 \gamma)/\Gamma_{\text{total}}$	$<5 \times 10^{-4}$ , CL = 90%
$\Gamma(\eta \rightarrow 3\pi^0 \gamma)/\Gamma_{\text{total}}$	$<6 \times 10^{-5}$ , CL = 90%
$\Gamma(\eta \rightarrow 3\gamma)/\Gamma_{\text{total}}$	$<1.6 \times 10^{-5}$ , CL = 90%
$\Gamma(\eta \rightarrow \pi^0 e^+ e^-)/\Gamma_{\text{total}}$	[a] $<4 \times 10^{-5}$ , CL = 90%
$\Gamma(\eta \rightarrow \pi^0 \mu^+ \mu^-)/\Gamma_{\text{total}}$	[a] $<5 \times 10^{-6}$ , CL = 90%
$\Gamma(\omega(782) \rightarrow \eta \pi^0)/\Gamma_{\text{total}}$	$<2.1 \times 10^{-4}$ , CL = 90%
$\Gamma(\omega(782) \rightarrow 2\pi^0)/\Gamma_{\text{total}}$	$<2.1 \times 10^{-4}$ , CL = 90%
$\Gamma(\omega(782) \rightarrow 3\pi^0)/\Gamma_{\text{total}}$	$<2.3 \times 10^{-4}$ , CL = 90%
asymmetry parameter for $\eta'(958) \rightarrow \pi^+ \pi^- \gamma$ decay	$-0.03 \pm 0.04$
$\Gamma(\eta'(958) \rightarrow \pi^0 e^+ e^-)/\Gamma_{\text{total}}$	[a] $<1.4 \times 10^{-3}$ , CL = 90%
$\Gamma(\eta'(958) \rightarrow \eta e^+ e^-)/\Gamma_{\text{total}}$	[a] $<2.4 \times 10^{-3}$ , CL = 90%
$\Gamma(\eta'(958) \rightarrow 3\gamma)/\Gamma_{\text{total}}$	$<1.0 \times 10^{-4}$ , CL = 90%
$\Gamma(\eta'(958) \rightarrow \mu^+ \mu^- \pi^0)/\Gamma_{\text{total}}$	[a] $<6.0 \times 10^{-5}$ , CL = 90%
$\Gamma(\eta'(958) \rightarrow \mu^+ \mu^- \eta)/\Gamma_{\text{total}}$	[a] $<1.5 \times 10^{-5}$ , CL = 90%
$\Gamma(J/\psi(1S) \rightarrow \gamma\gamma)/\Gamma_{\text{total}}$	$<5 \times 10^{-6}$ , CL = 90%

## CP INVARIANCE

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

*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**

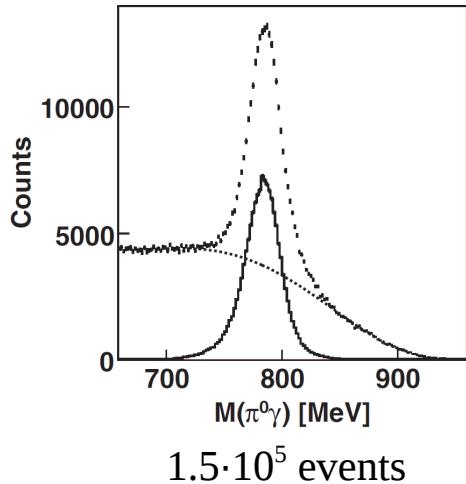
**CKM-matrix** complex and unitary → 4 parameters (e.g. 3 angles and one phase)

Single phase in **CKM-matrix** responsible for CP-violation

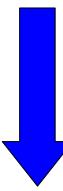
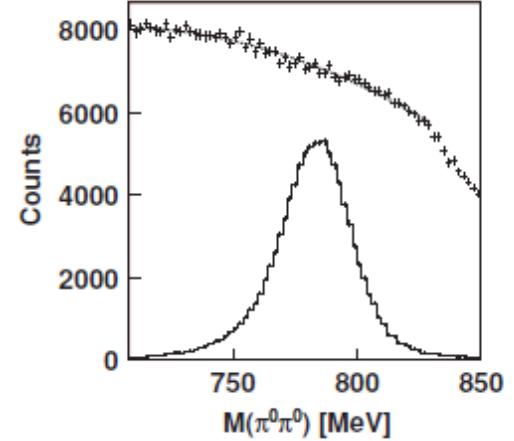
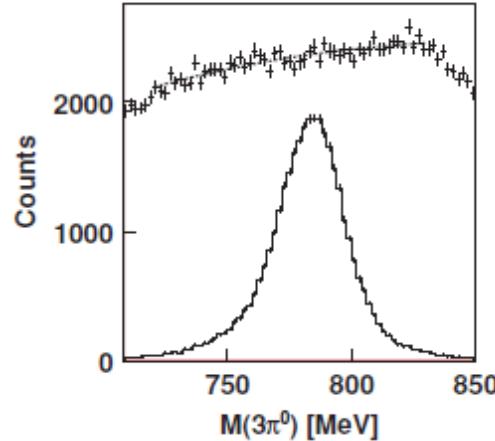
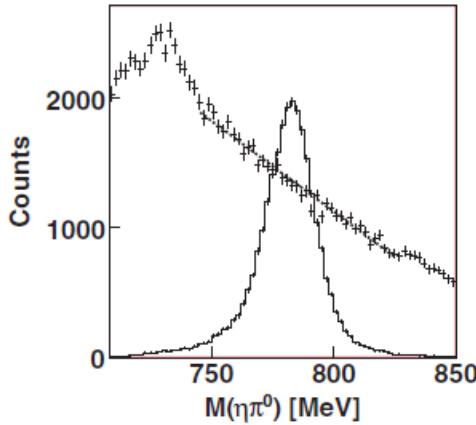
	weak states	
Quarks	$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$	$\overbrace{\quad\quad\quad\quad\quad\quad}^{\text{CKM matrix}}$
	$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$	$\begin{pmatrix} d \\ s \\ b \end{pmatrix}$
Anti-quarks	$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix}$	$\begin{pmatrix} V_{ud}^* & V_{us}^* & V_{ub}^* \\ V_{cd}^* & V_{cs}^* & V_{cb}^* \\ V_{td}^* & V_{ts}^* & V_{tb}^* \end{pmatrix}$
	$\begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$	

# C-Violating $\omega$ Decays

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



$1.5 \cdot 10^5$  events



$$\Gamma(\omega \rightarrow \eta\pi^0)/\Gamma_{\text{tot}} < 2.3 \cdot 10^{-4}$$

at 90% C.L.

$$\Gamma(\omega \rightarrow 3\pi^0)/\Gamma_{\text{tot}} < 2.3 \cdot 10^{-4}$$

at 90% C.L.

$$\Gamma(\omega \rightarrow 2\pi^0)/\Gamma_{\text{tot}} < 2.4 \cdot 10^{-4}$$

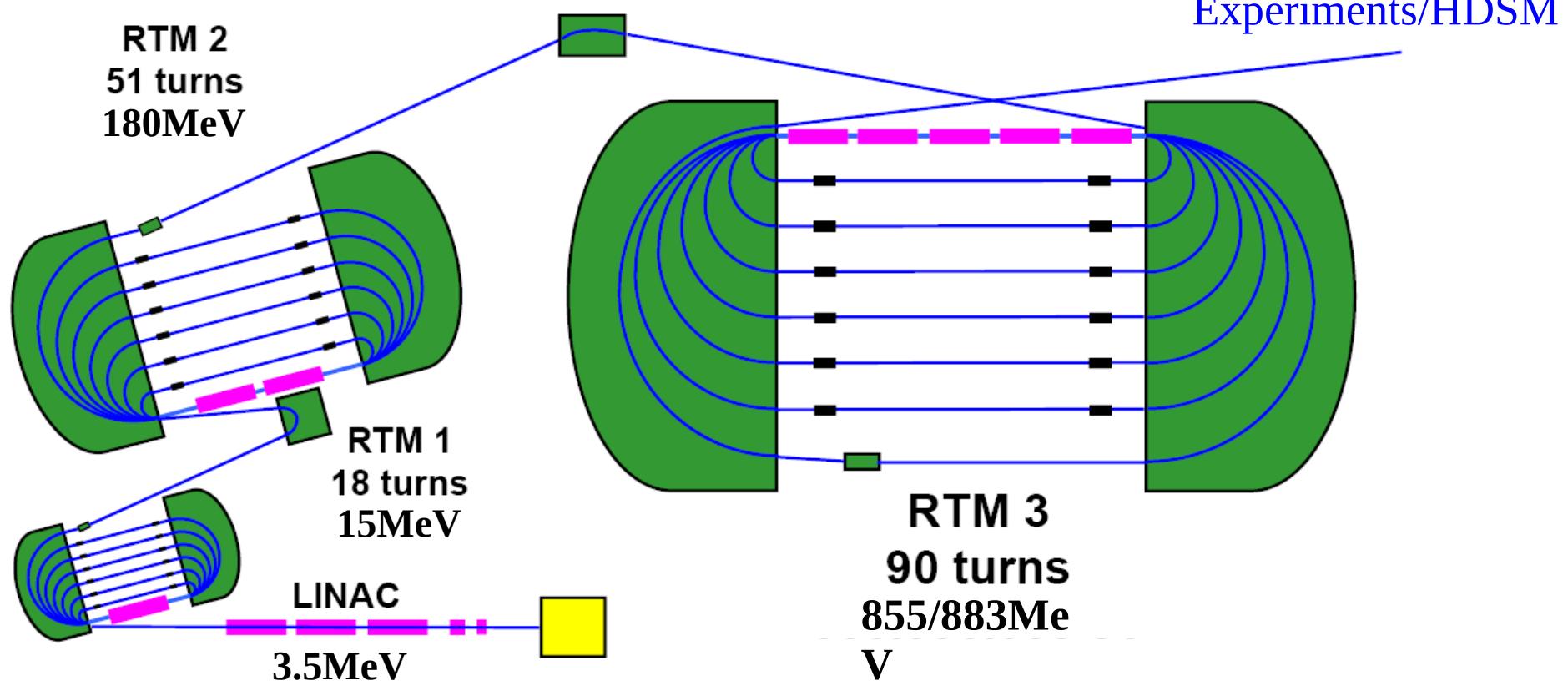
at 90% C.L.

never been done before

Only CB at MAMI results used by PDG!

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

# 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

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

LINAC I (4.90GHz)

Extraction 1500MeV

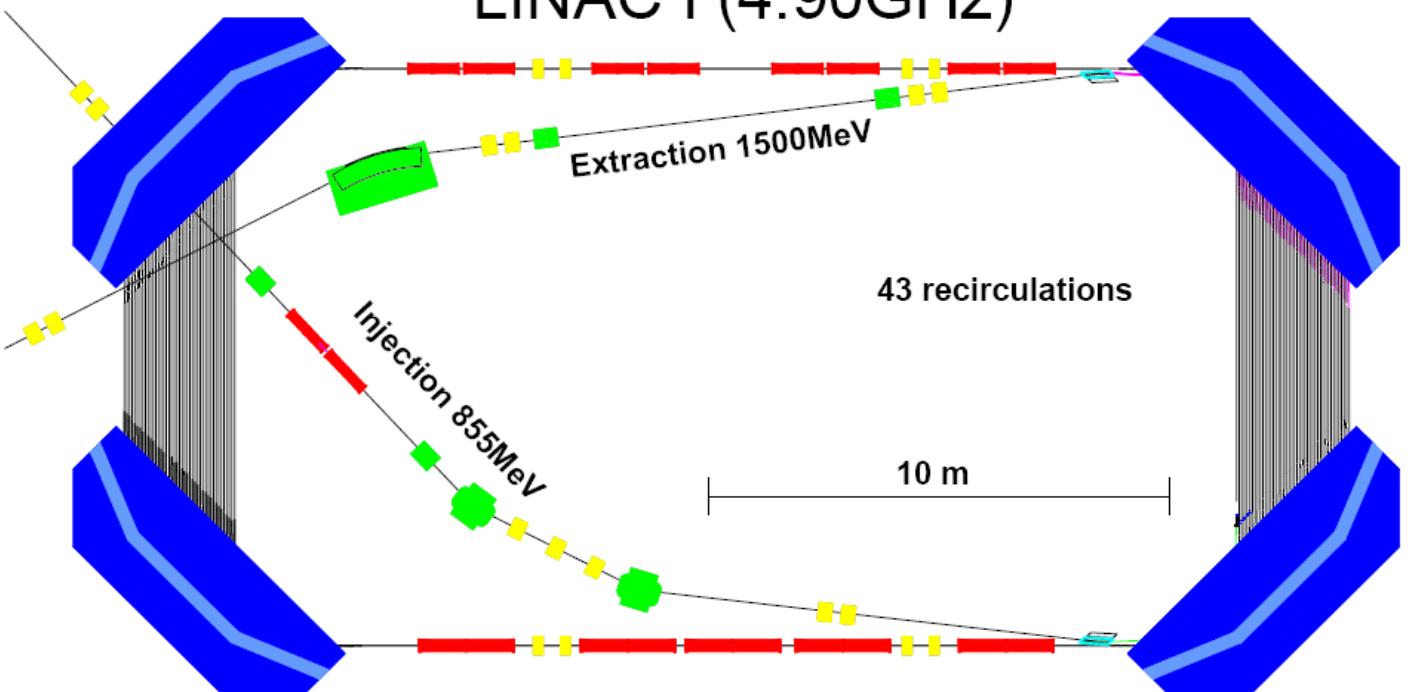
43 recirculations

10 m

LINAC II (2.45GHz)

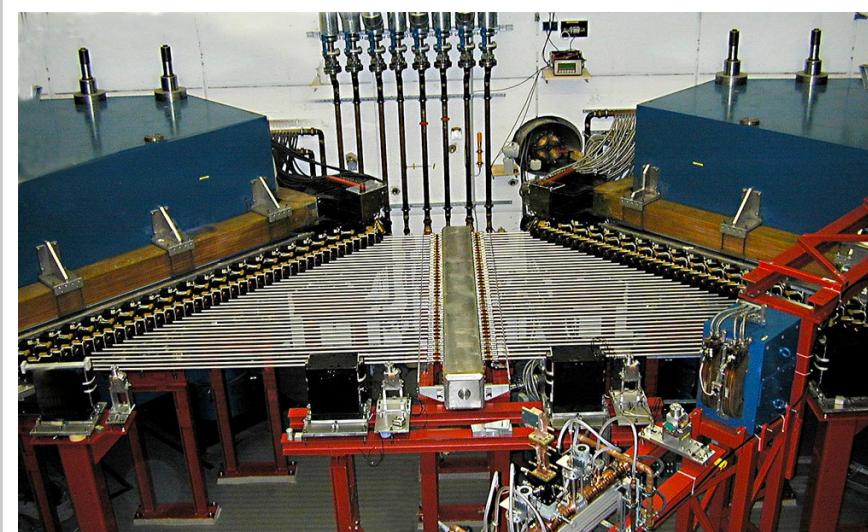
$B_{\max} = 1.539\text{T}$

9.3 MV / turn max gain

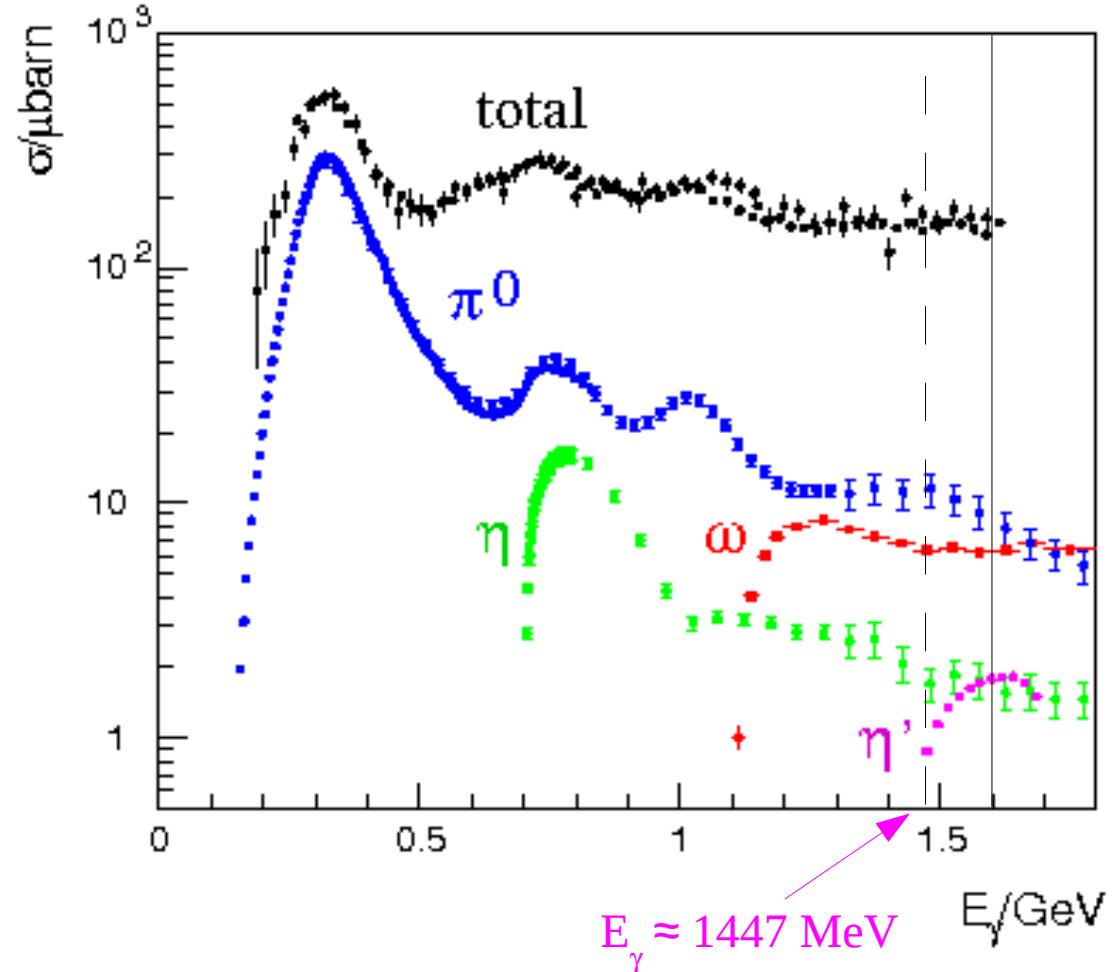
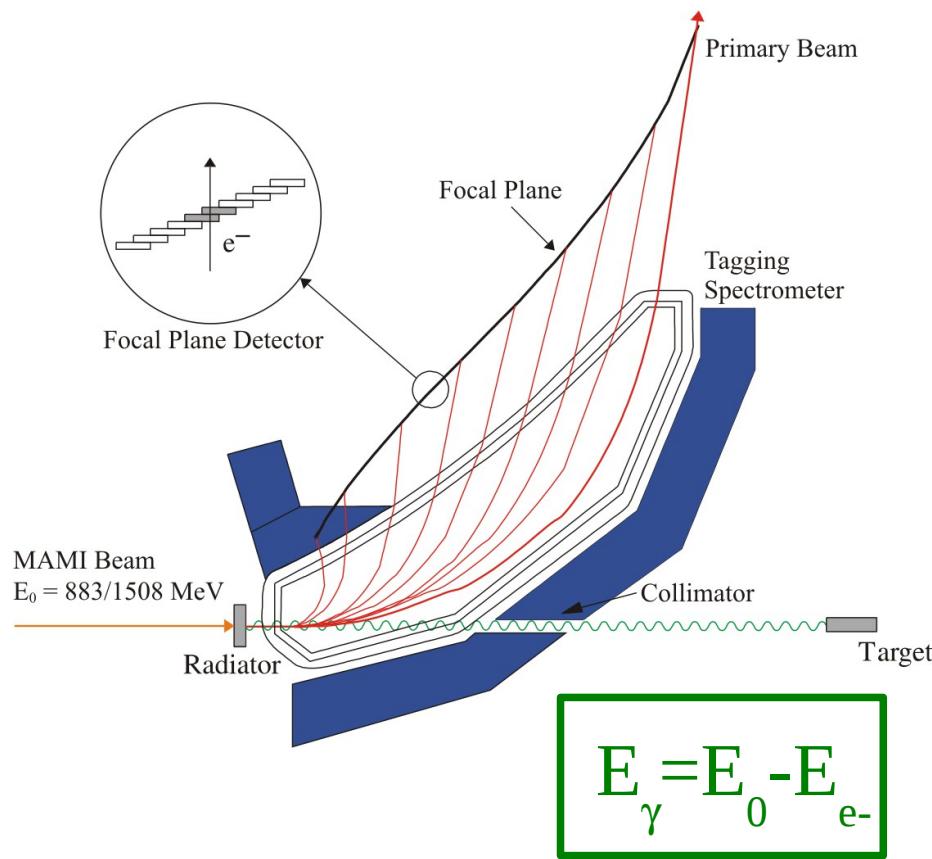


*Harmonic Doubled Sided Microtron (HDSM)*

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



# Tagging Spectrometer

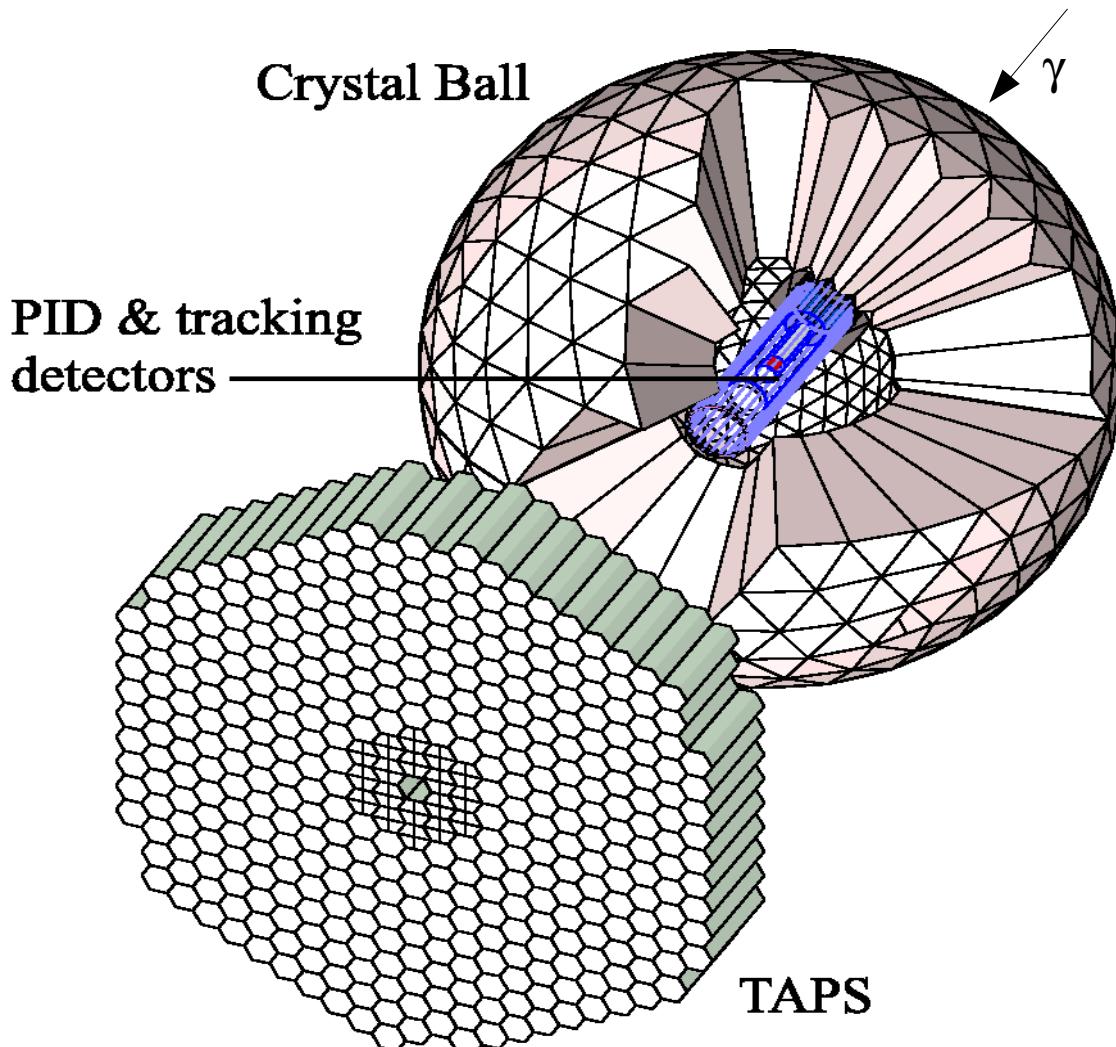


Tagging range: 5.1 to 93% of  $E_0$

Maximum energy tagged for  $E_0 = 1604 \text{ MeV}$  is 1491 MeV

→ New tagging device for  $\eta'$  experiments needed!

# 4π-Setup



## Crystal Ball:

672 NaI(Tl) crystals

93,3% of total solid angle

Each crystal equipped with PMT

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

$\Delta t = 2.5 \text{ ns FWHM}$

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

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

## TAPS:

Up to 510 BaF<sub>2</sub> crystals

Polar acceptance: 4-20°

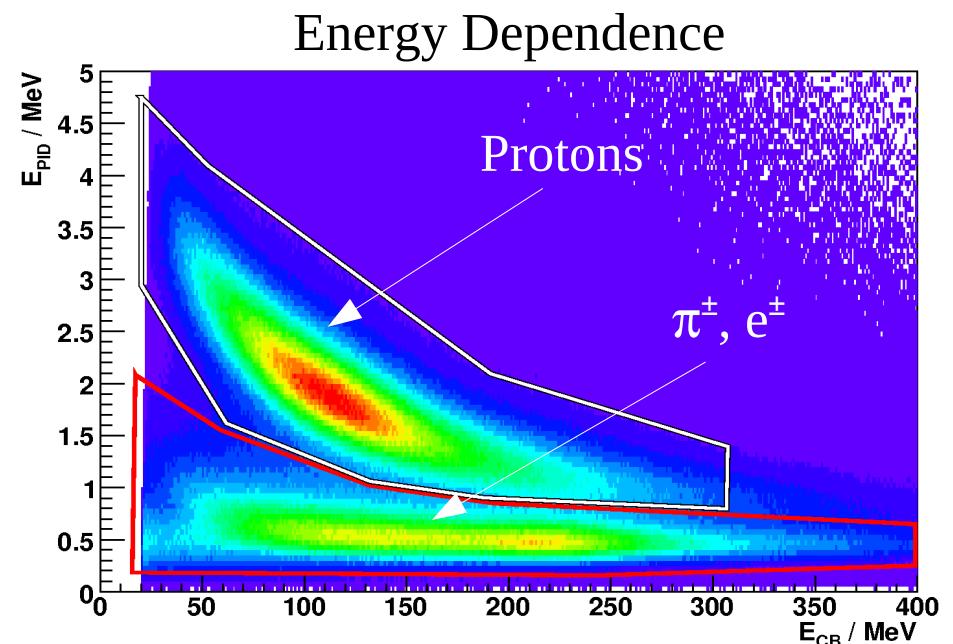
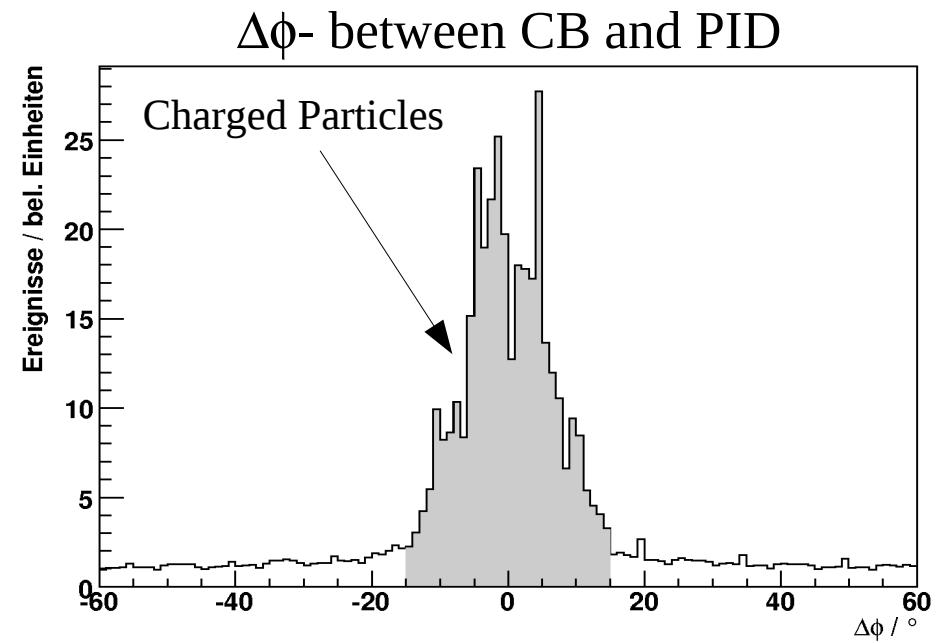
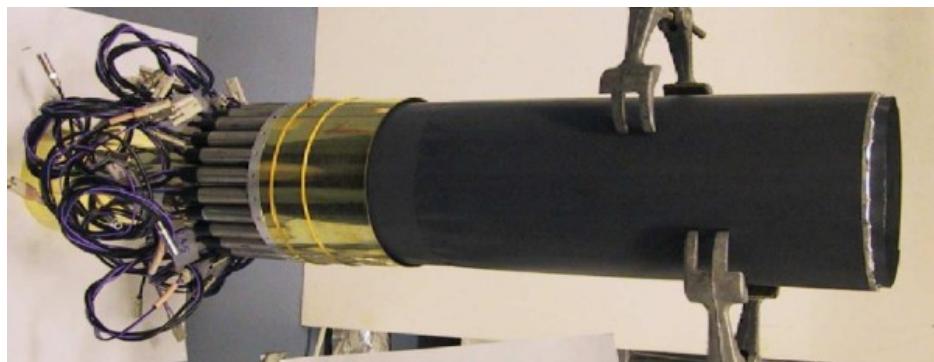
$\Delta t = 0.5 \text{ ns FWHM}$

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

# CB PID

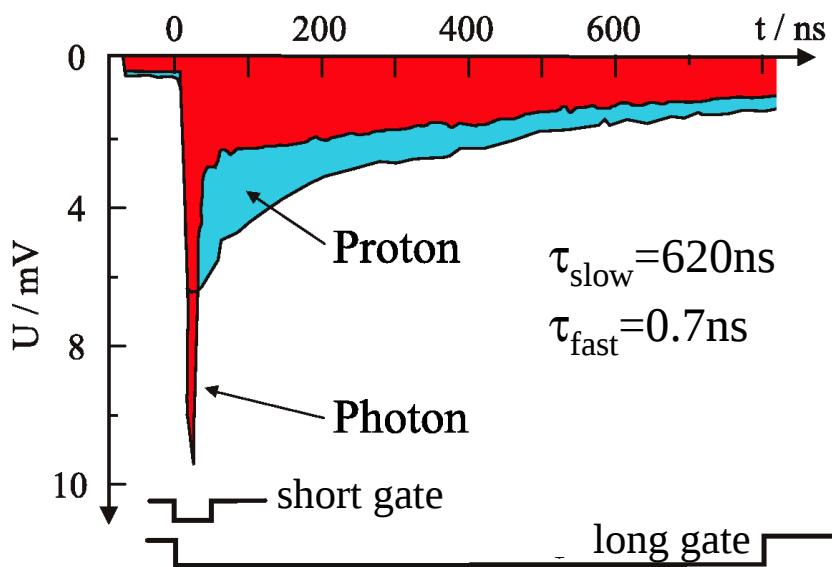
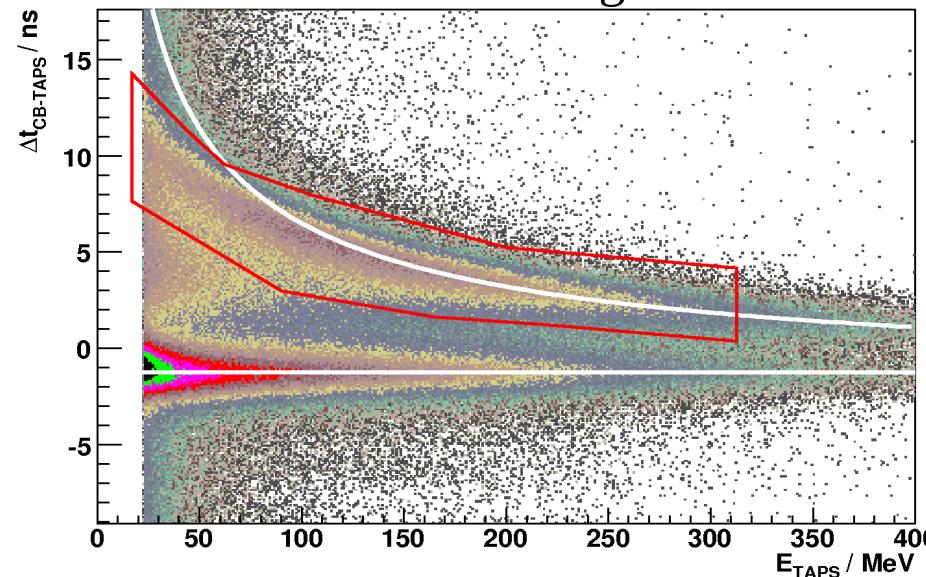
## Particle Identificaton Detector (PID):

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



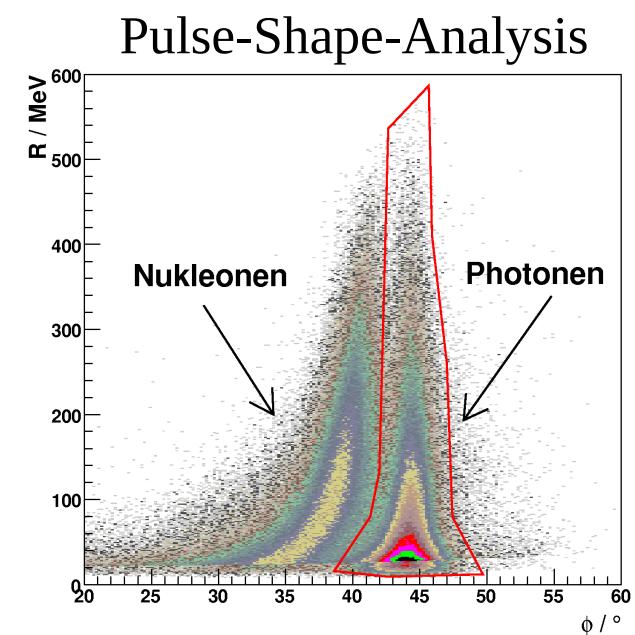
# TAPS PI

## Time-of-Flight



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

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

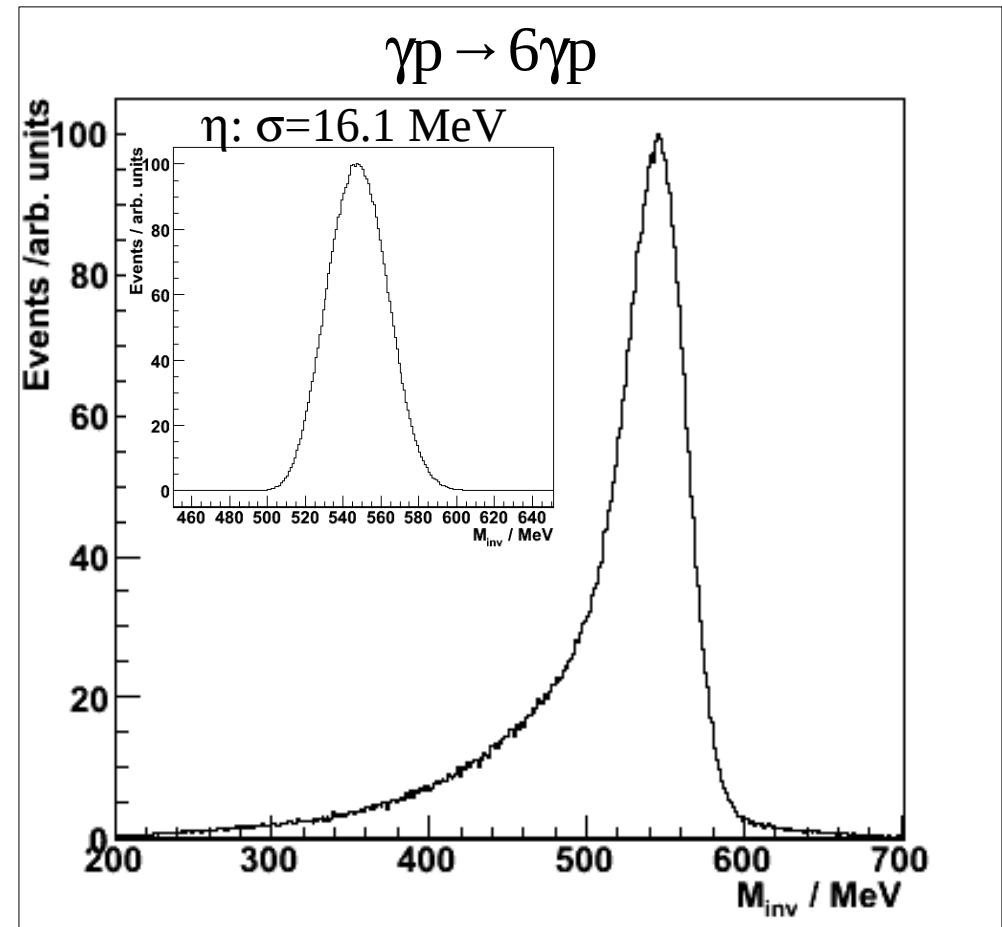
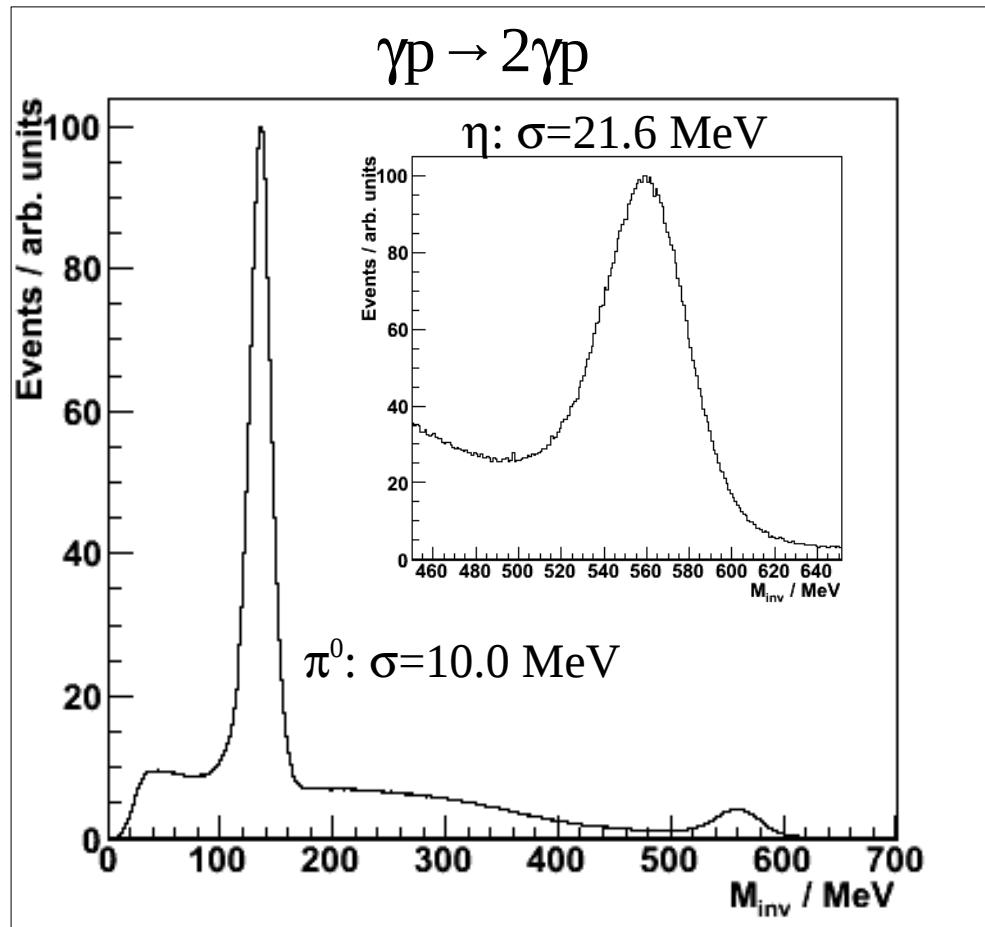


# Setup Performance

Two main  $\eta$  decay modes:

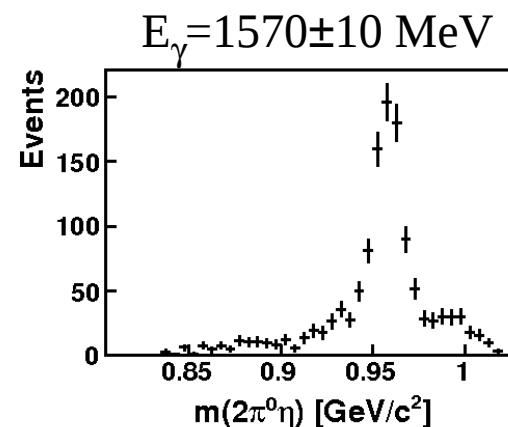
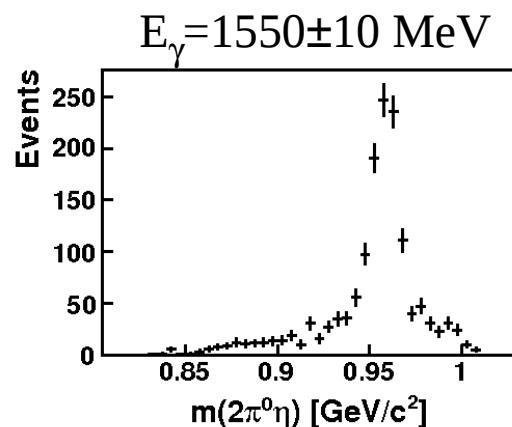
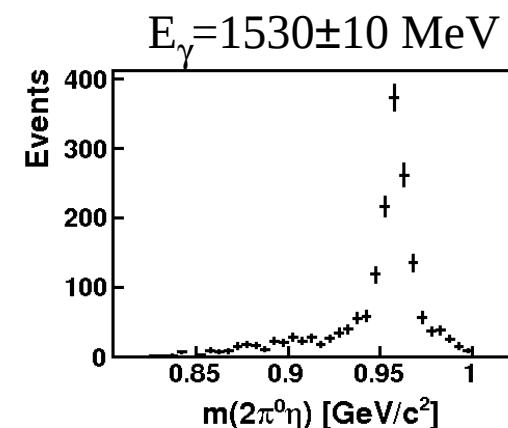
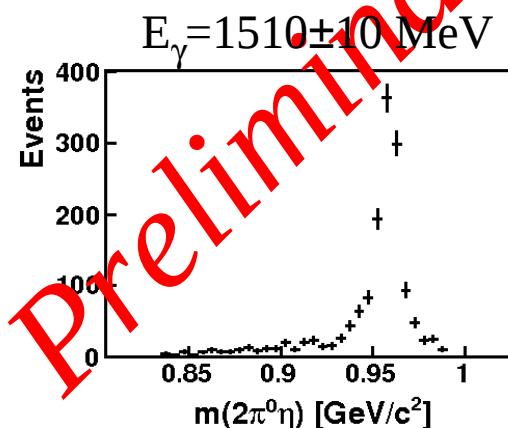
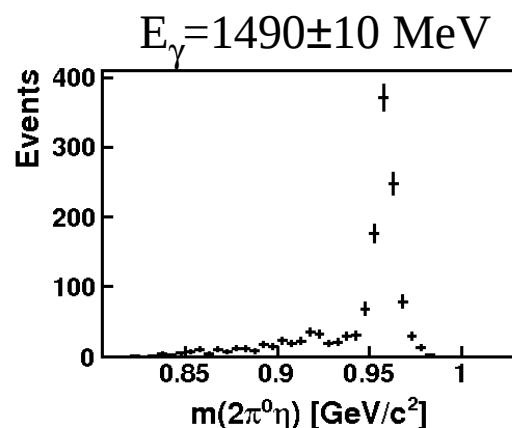
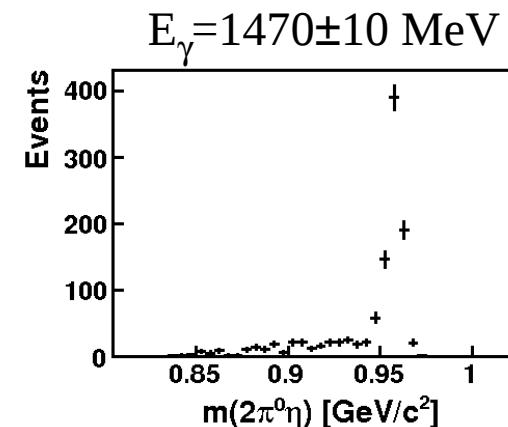
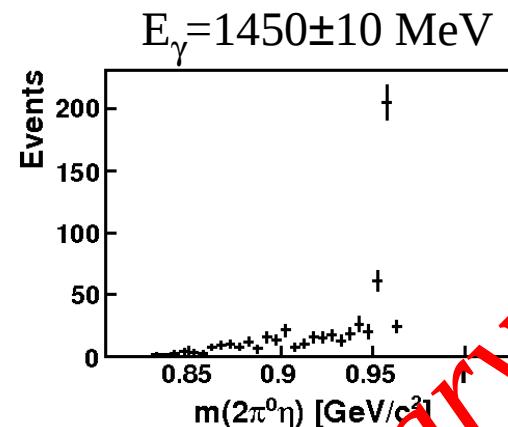
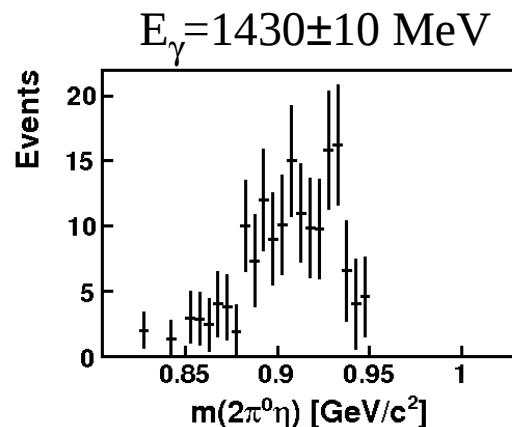
$$\text{BR}(\eta \rightarrow 2\gamma) = 39.38\%$$

$$\text{BR}(\eta \rightarrow 3\pi^0) = 32.51\%$$



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

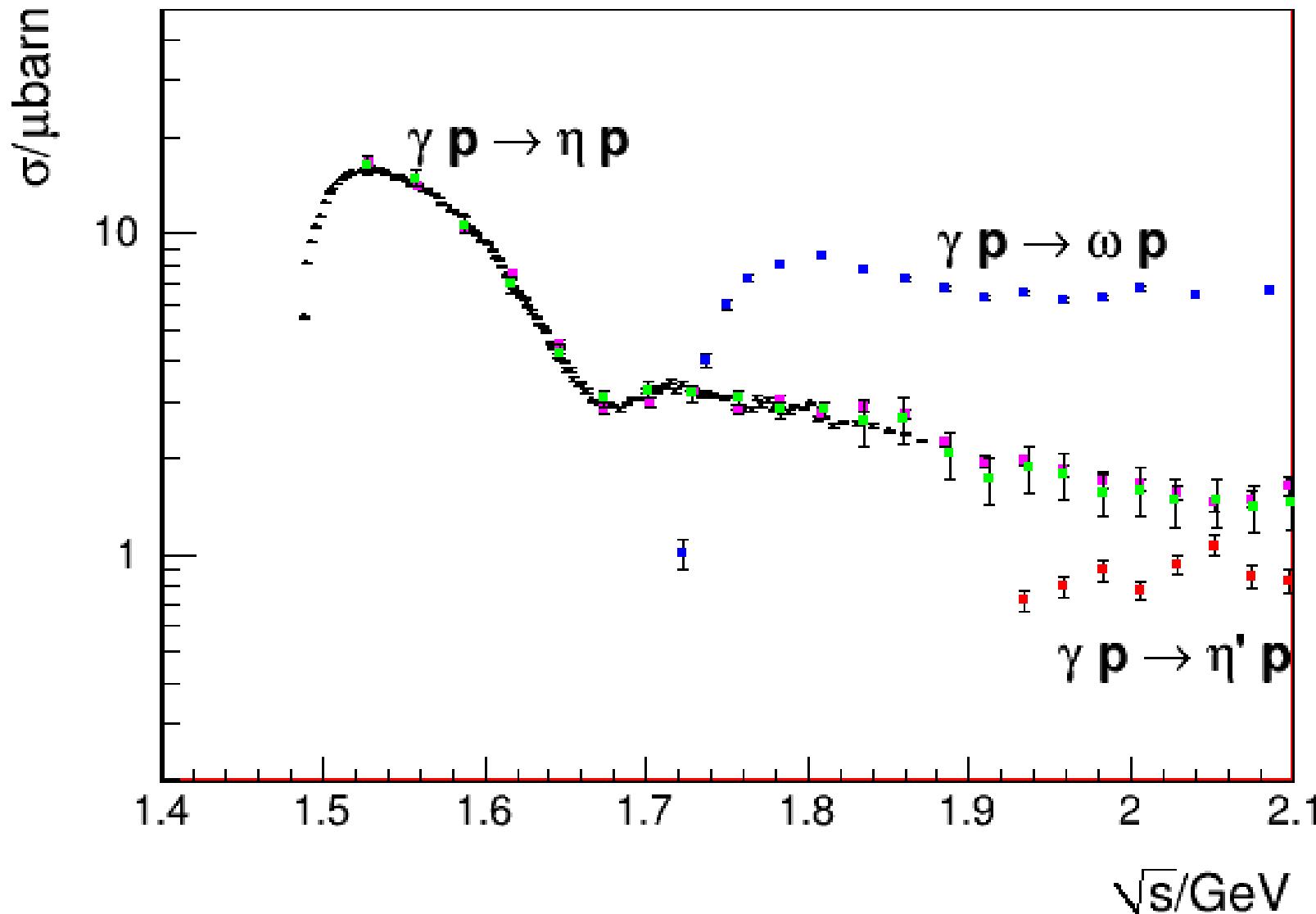
# $\eta' \rightarrow \eta\pi^0\pi^0$ Invariant Mass



Preliminary

S. Prakhov (UCLA)

# $\eta$ 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 (2002) 249904.

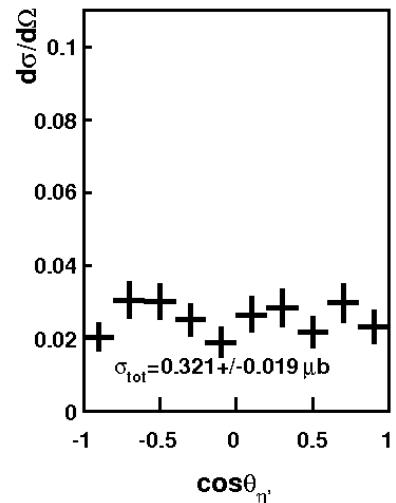
SAPHIR: J. Barth et al., Eur. Phys. J. A 18 (2003) 117.

Crystal Barrel: V. Crede et al., Phys. Rev. C 80 (2009) 055202.

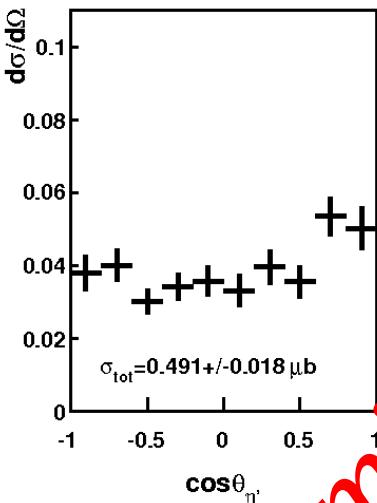
# $\eta'$ Cross Section

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

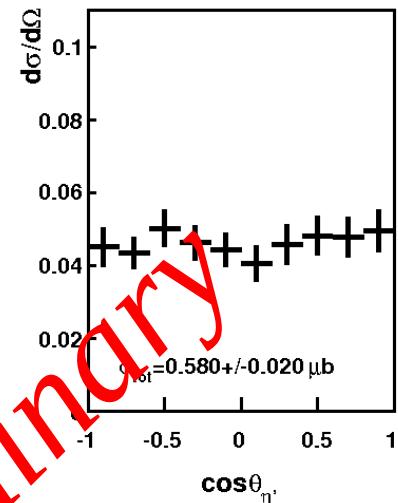
$$E_\gamma = 1450 \pm 10 \text{ MeV}$$



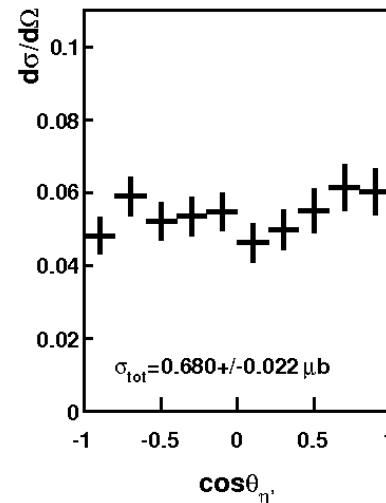
$$E_\gamma = 1470 \pm 10 \text{ MeV}$$



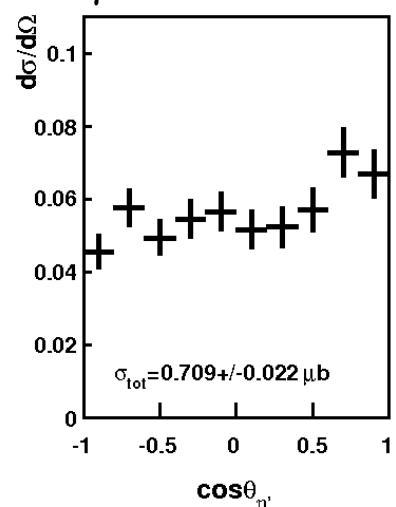
$$E_\gamma = 1490 \pm 10 \text{ MeV}$$



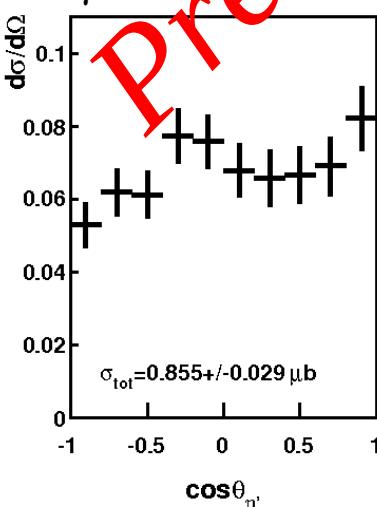
$$E_\gamma = 1510 \pm 10 \text{ MeV}$$



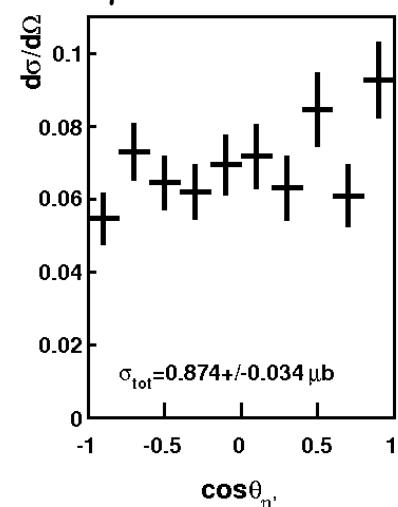
$$E_\gamma = 1530 \pm 10 \text{ MeV}$$



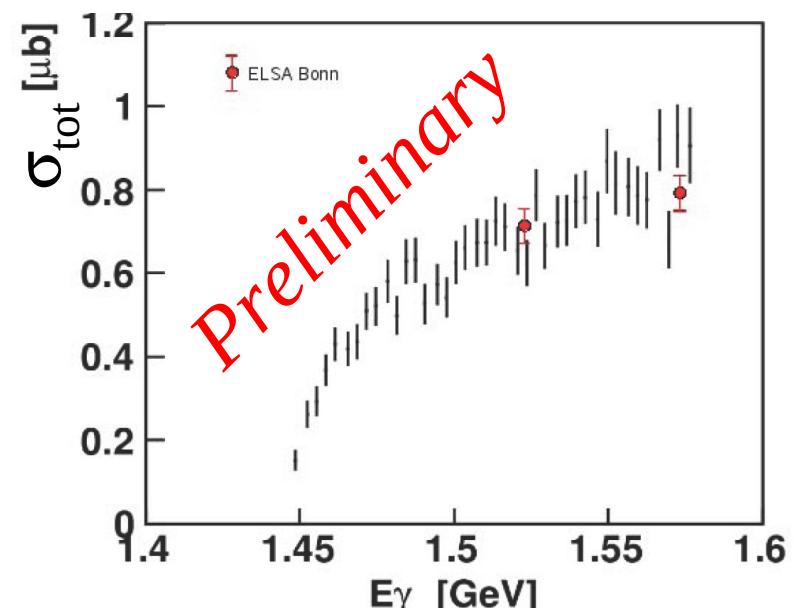
$$E_\gamma = 1550 \pm 10 \text{ MeV}$$



$$E_\gamma = 1570 \pm 10 \text{ MeV}$$



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Preliminary

# $\eta \rightarrow 3\pi$

$\eta \rightarrow 3\pi \rightarrow$  Isospin breaking

$$H_Y = \frac{1}{2}(m_u - m_d)(\bar{u}u - \bar{d}d)$$

Lowest Order  $\chi$ PT:

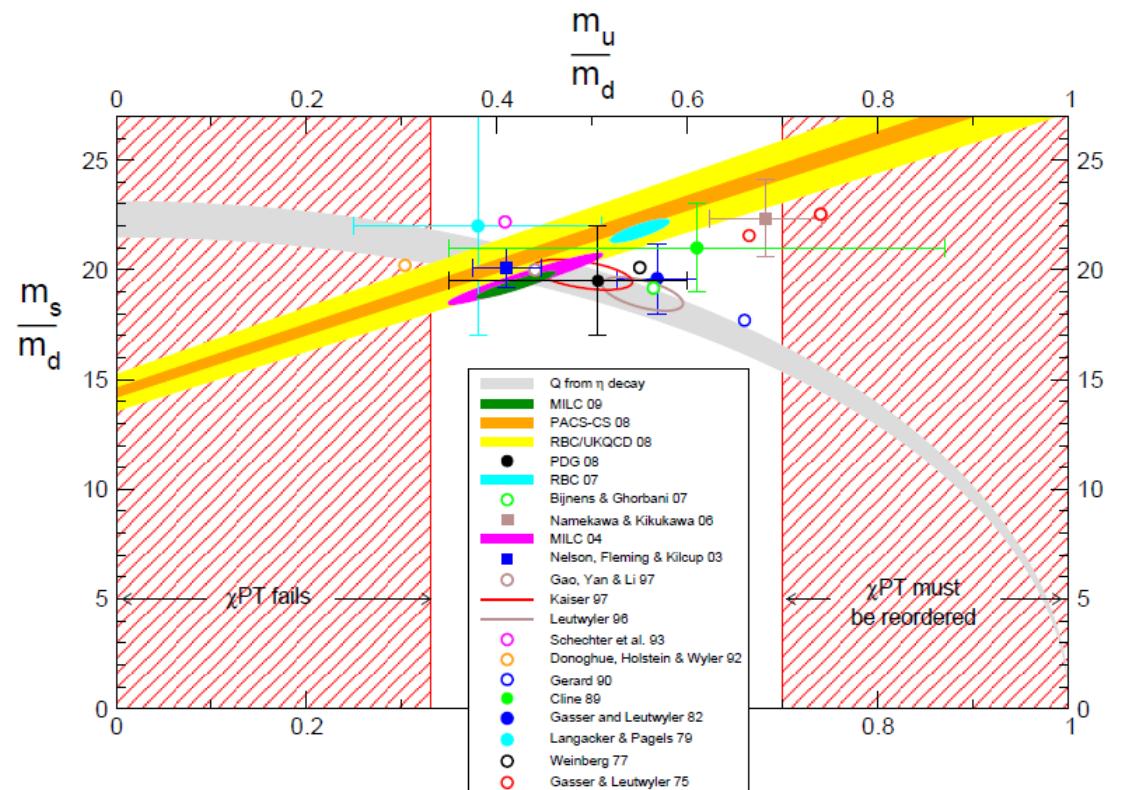
$$A(\eta \rightarrow \pi^+ \pi^- \pi^0) = \frac{B_0(m_u - m_d)}{3\sqrt{3}F_\pi^2} \cdot \frac{3s - 4m_\pi^2}{m_\eta^2 - m_\pi^2}$$

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

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

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

Allows to extract information  
on  
quark masses



H. Leutwyler, arXiv:0911.1416

# $\eta \rightarrow 3\pi^0$

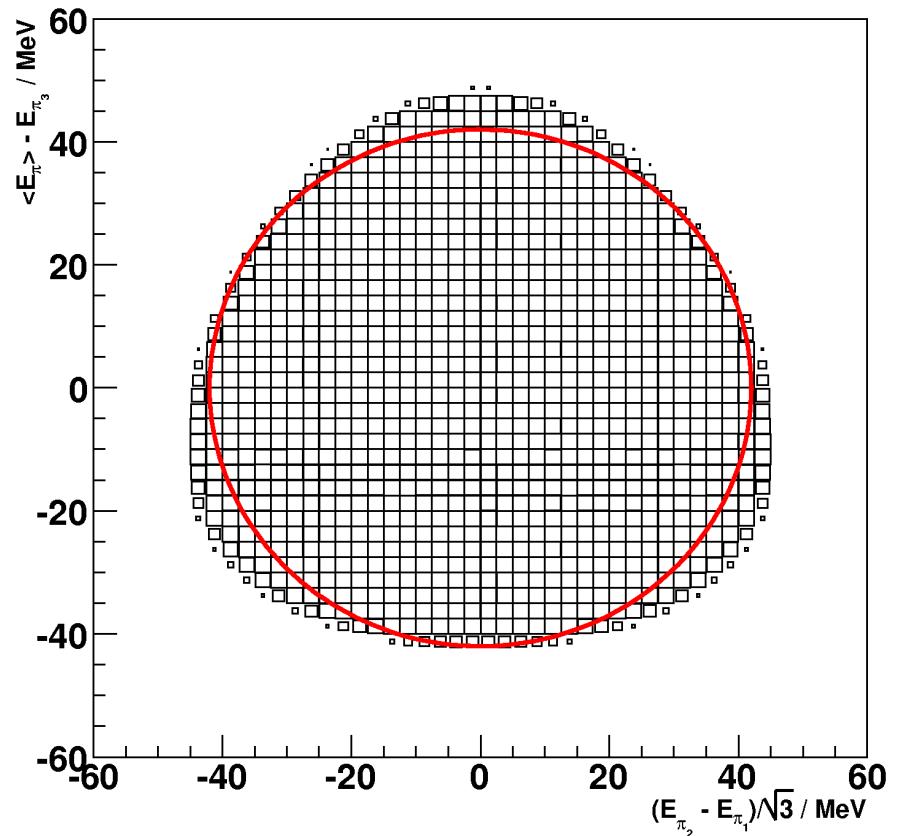
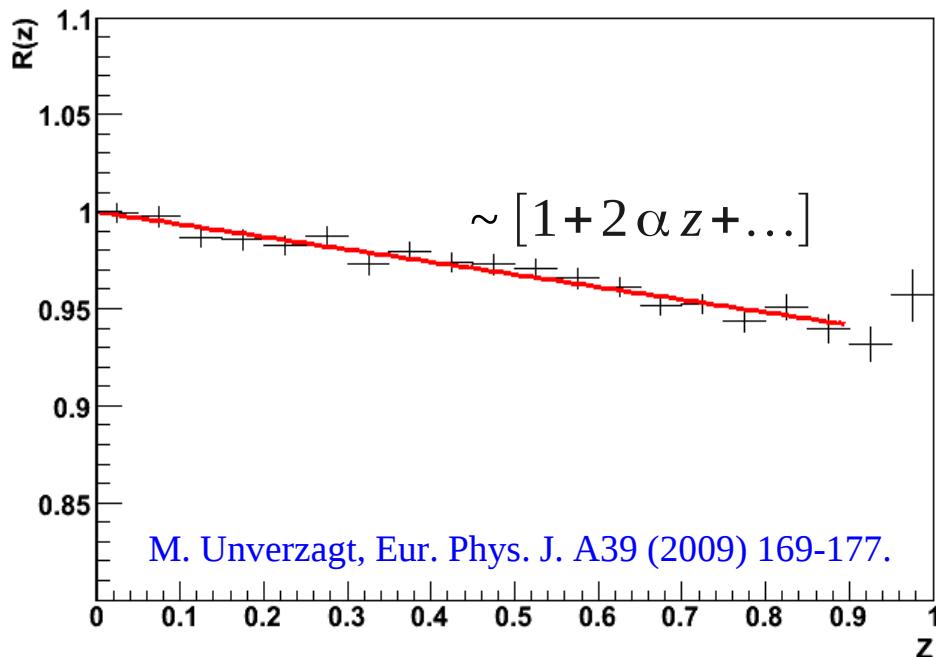
Parametrization of  $\eta \rightarrow 3\pi^0$  Dalitz plot:

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

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

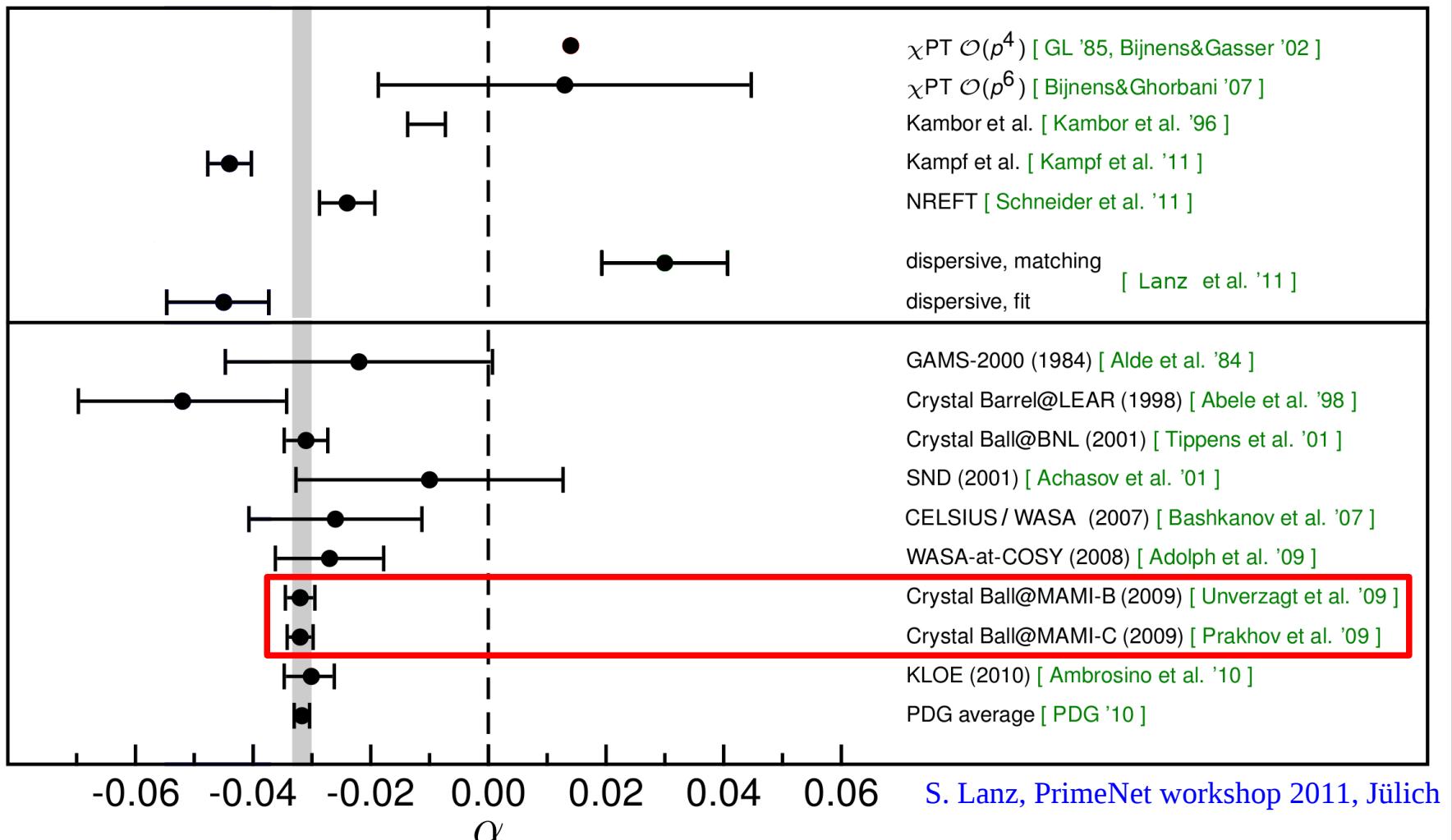
$E_i$ :  $\pi^0$  energies in  $\eta$  rest frame,

$\rho$ : 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

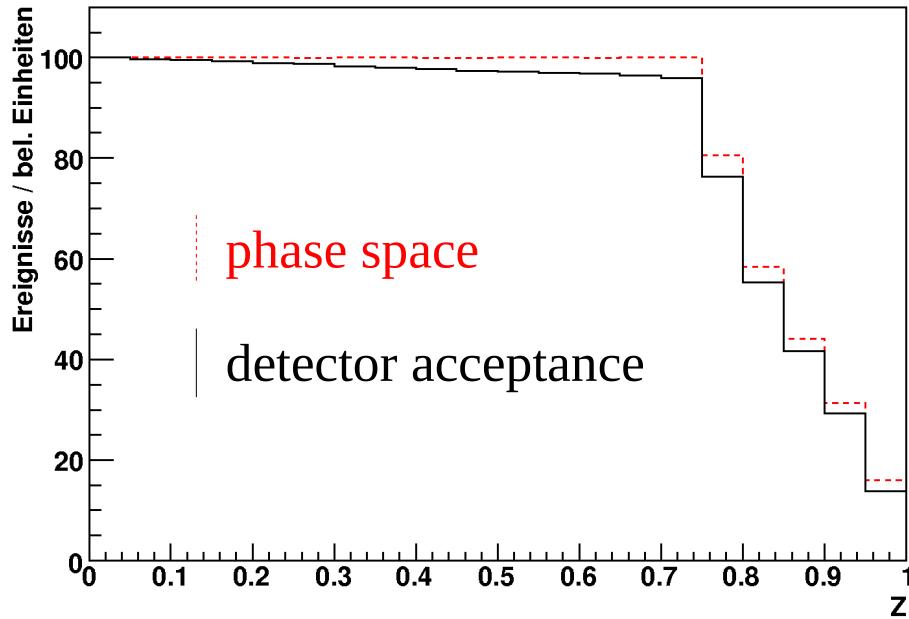


$\alpha$

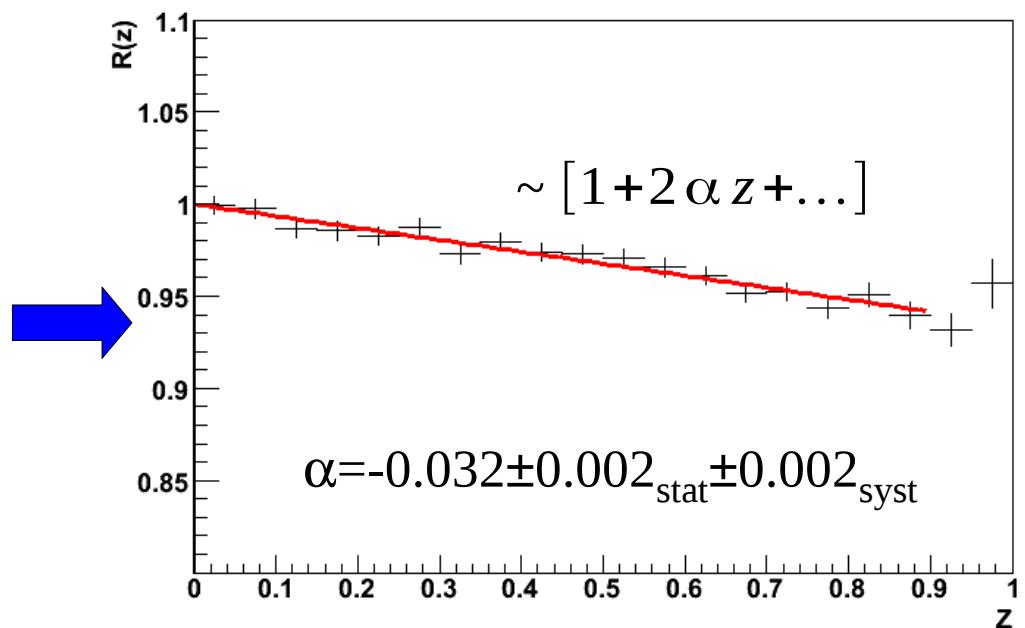
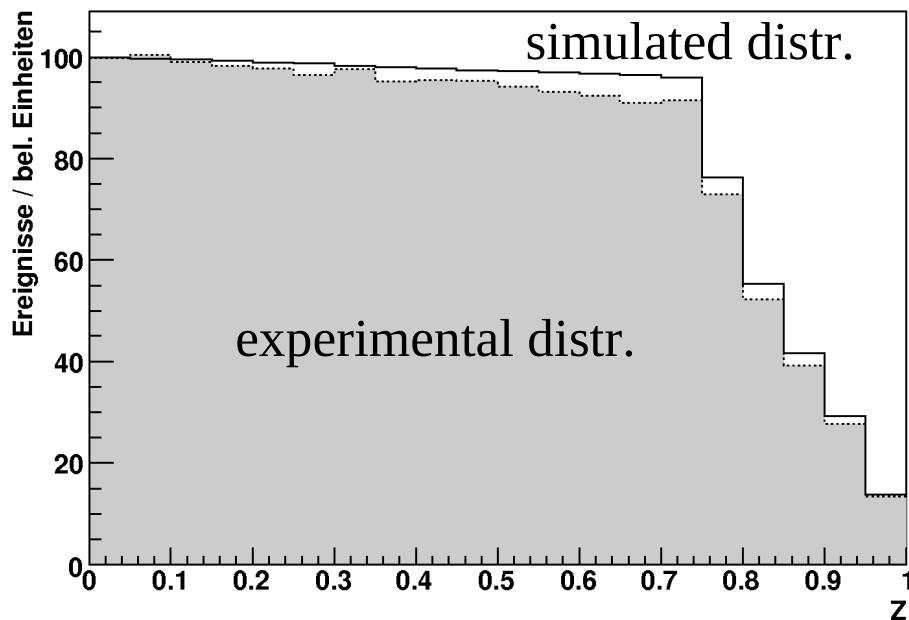
S. Lanz, PrimeNet workshop 2011, Jülich

Experiments (CB, KLOE, Crystal Barrel, PrimeEx, BESIII?)  
reach precision where higher order effects  
(cusp-effect, second order term in expansion) become visible

# Result for $\alpha$

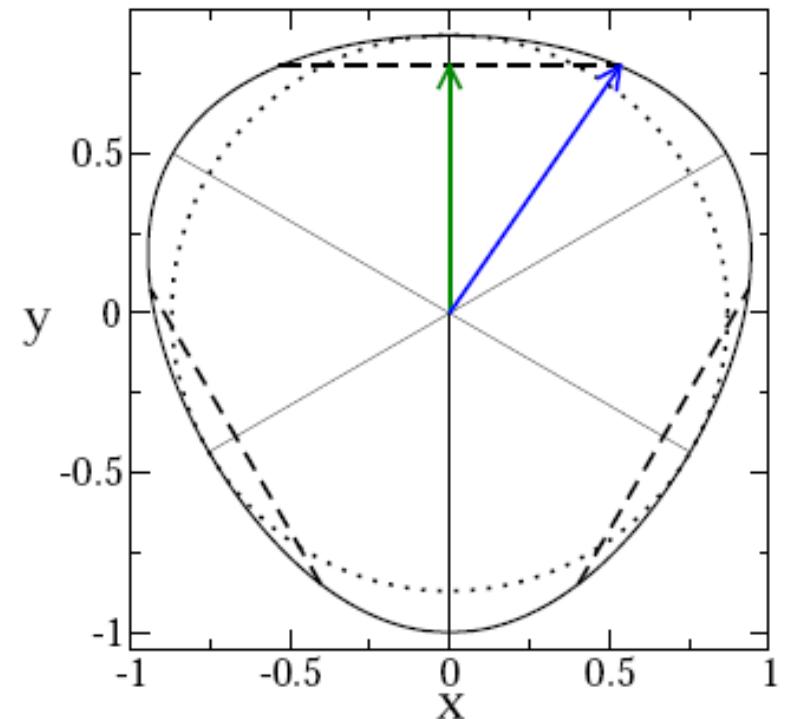
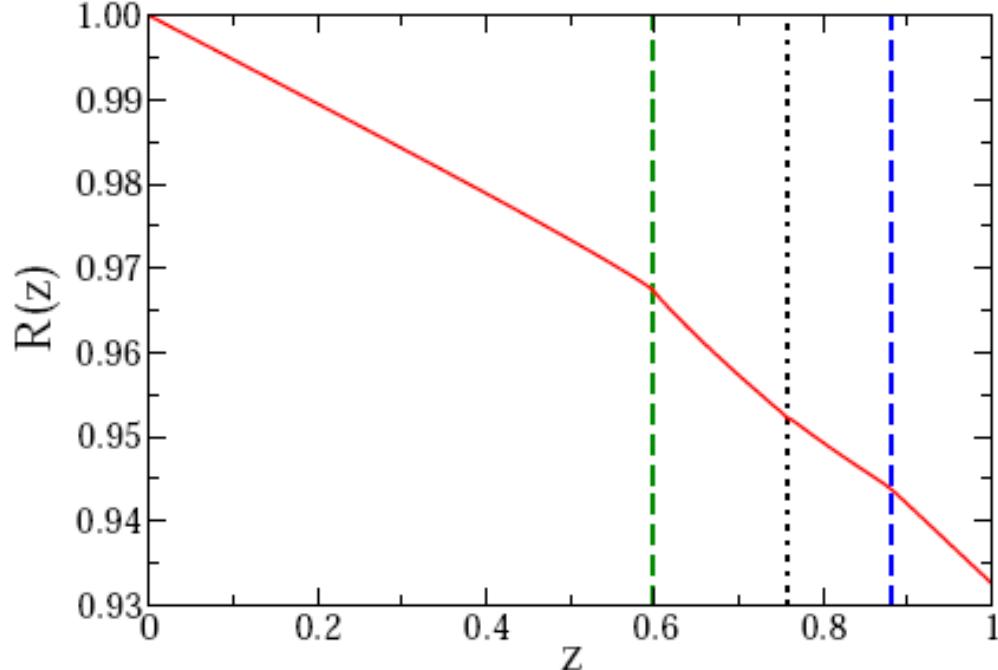


- precise simulation required



# Effect of Cusp in $\alpha$

Taken from PhD thesis of R. Nissler, University Bonn, 2007.



Cusp has 5% effect on Dalitz Plot Parameter

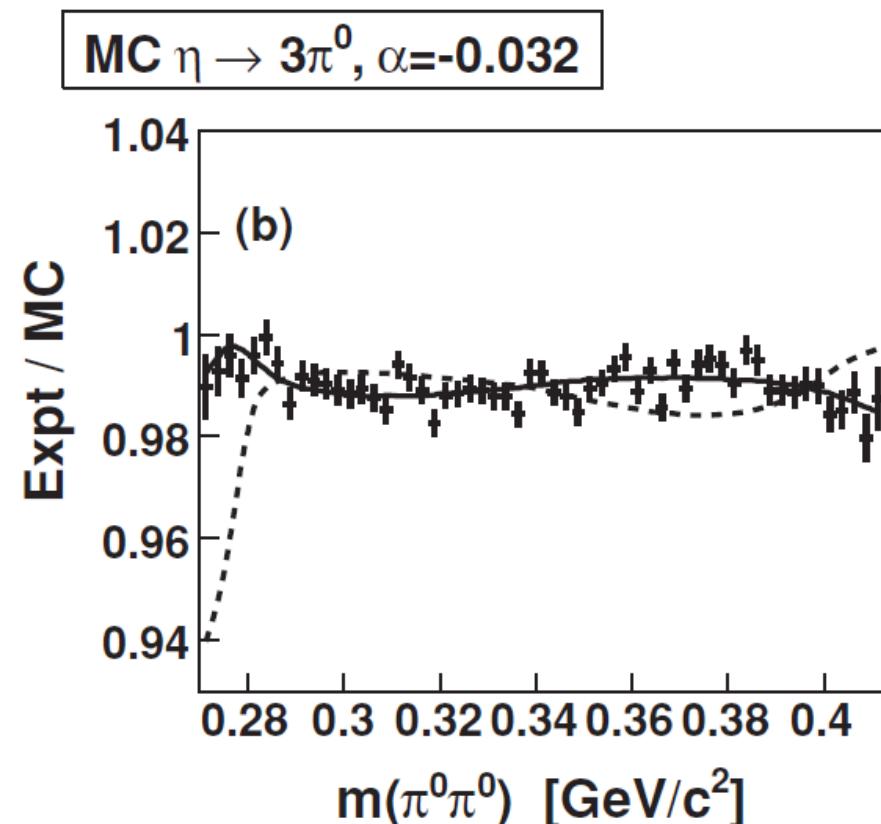
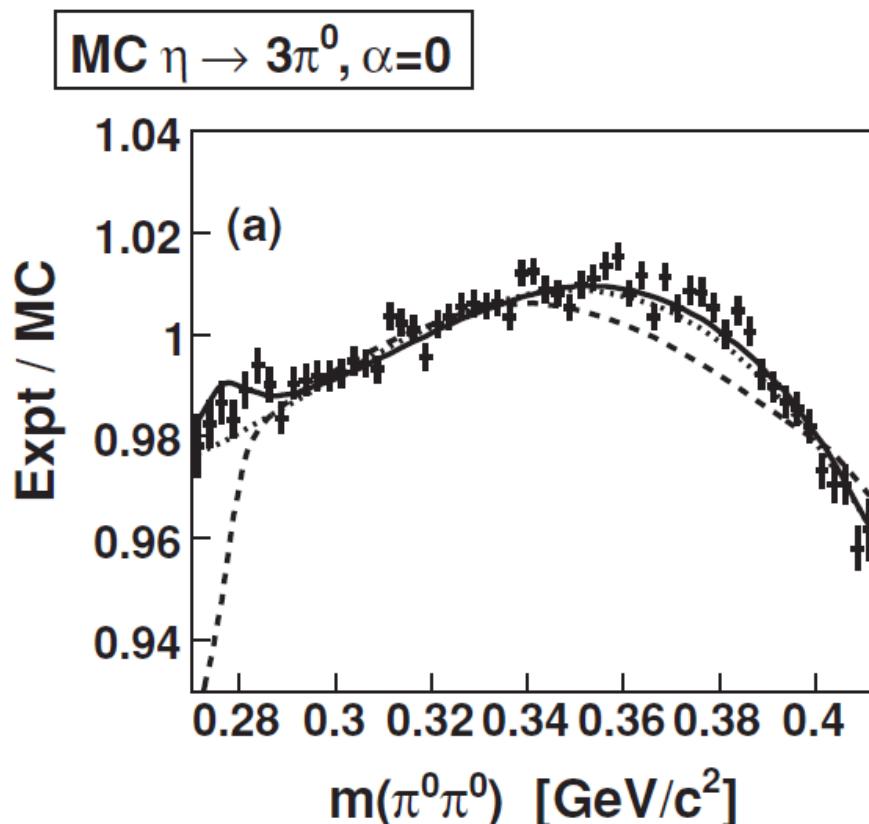
C. Ditsche, B. Kubis, Ulf-G. Meißner, Eur. Phys. J. C 60, 83 (2009).

Further effects:

- Kinematic boundaries
- Second order in amplitude expansion

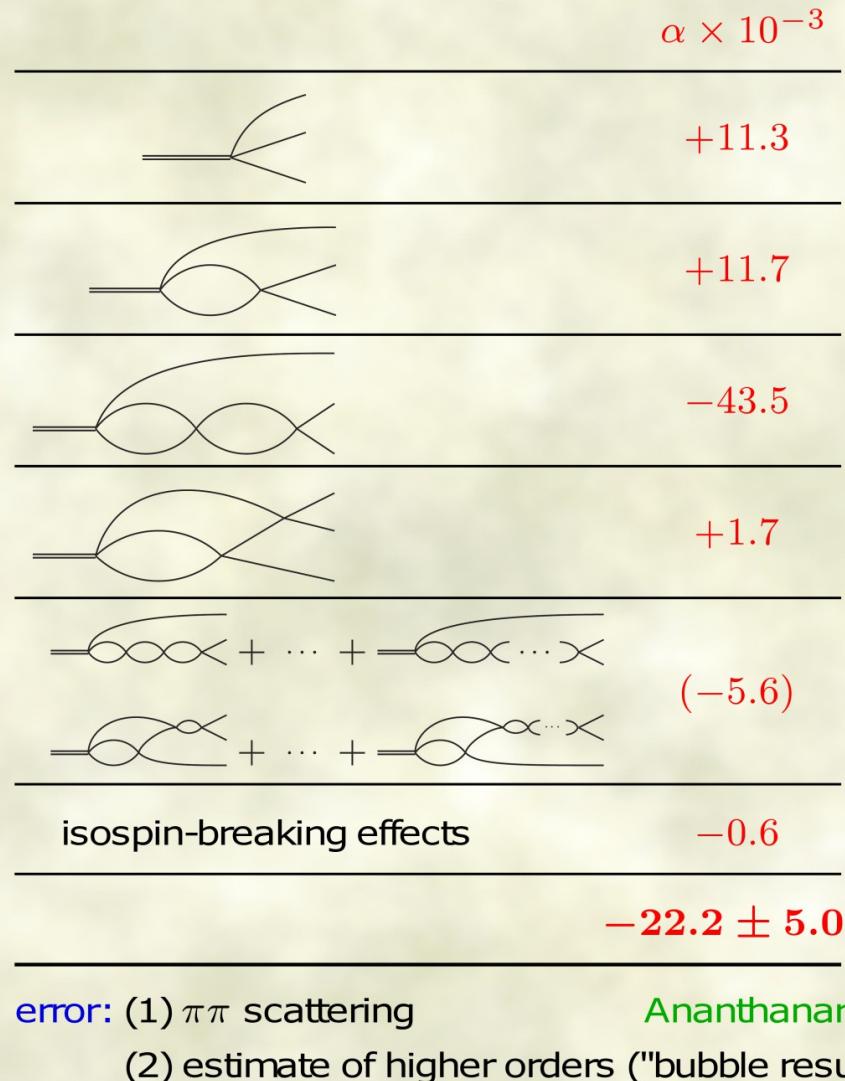
# Cusp-Effect

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



S. Prakhov et al. (Crystal Ball at MAMI), Phys. Rev. C **79** (2009) 035204.  
Bissegger, Fuhrer, Gasser, Kubis, Rusetsky, Phys.Lett. B **659** (2008), 576 (solid line)  
J. Belina, Diploma thesis, University Bern, Switzerland (dashed line).

## Understanding $\alpha$ : order-by-order decomposition



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

Ananthanarayan et al. 2001 vs. Kamiński et al. 2008

## Understanding $\alpha$ : interpretation of the ChPT result

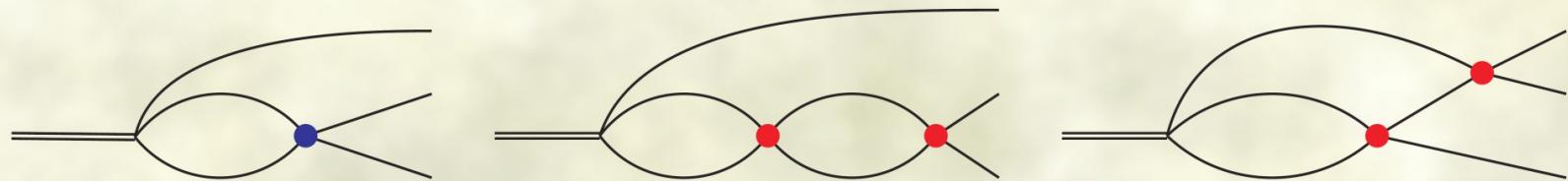
**Remember: ChPT at  $\mathcal{O}(p^6)$**

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:**



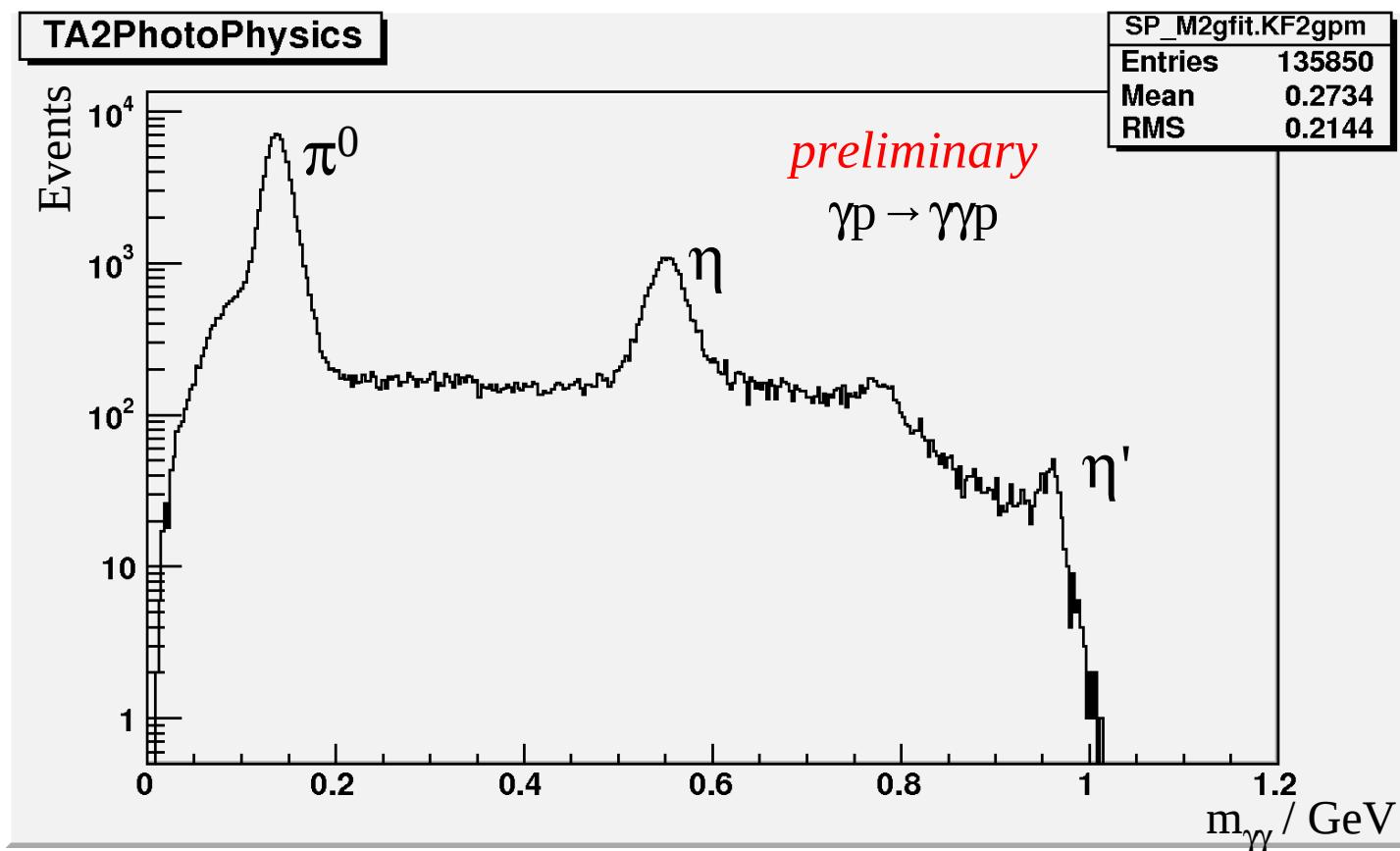
- rescattering parameters at  $\mathcal{O}(p^4)$  in one-loop graphs
- rescattering parameters at  $\mathcal{O}(p^2)$  in two-loop graphs ( $a_0^0 = 0.16, \dots$ )

**Result:**

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

# $\eta'$ Production

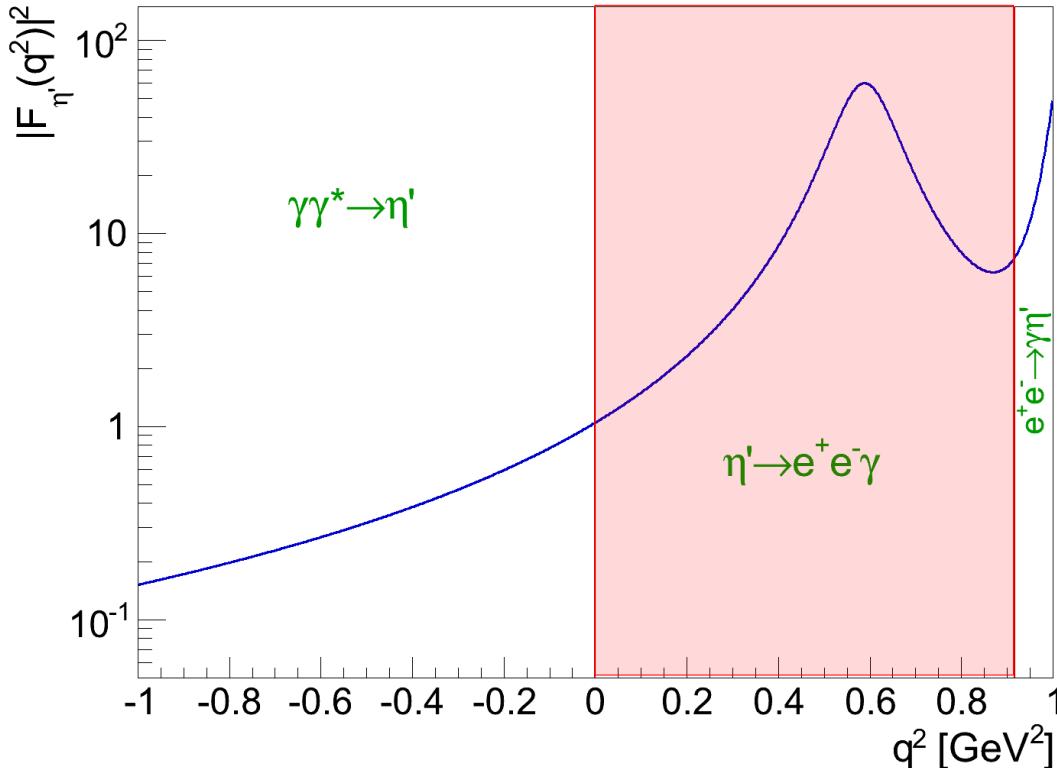
- Installation EPT fall 2011
- First test run December 2011
- First test/production measurement successful in March 2012!
- $\eta'$  production runs (each 2,5 weeks) successful May/August 2012!



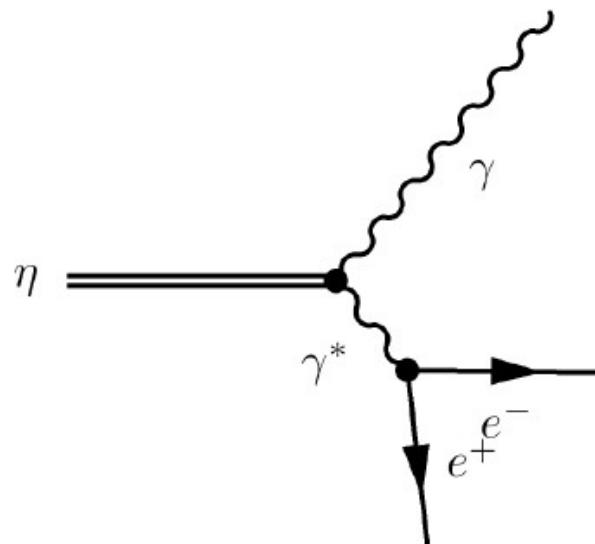
Only small part of available statistics

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# 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

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

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

# Setup Upgrades?

- Old trigger scheme replaced by **FPGA** based trigger module
- Triggerless readout (TRB boards)? (**A. Neiser, W. Gradl**)
- Branching fractions: **trigger detector** under construction (**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?**

