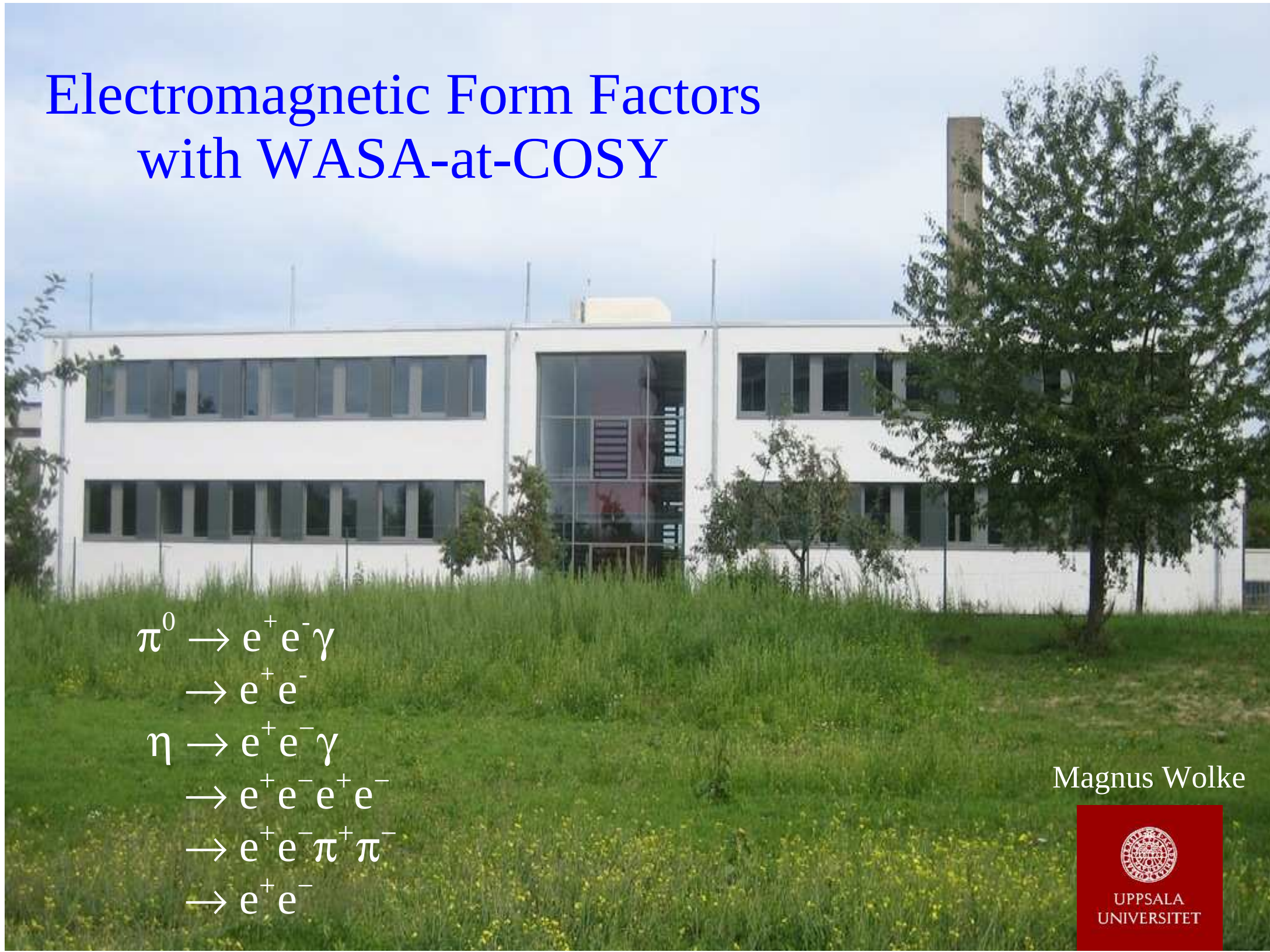
Electromagnetic Form Factors with WASA-at-COSY

CRC Workshop (g-2)mu: Quo Vadis?

Mainz, Apr 9, 2014

Magnus Wolke

Electromagnetic Form Factors with WASA-at-COSY



$\pi^0 \rightarrow e^+e^-\gamma$
$\rightarrow e^+e^-$
$\eta \rightarrow e^+e^-\gamma$
$\rightarrow e^+e^-e^+e^-$
$\rightarrow e^+e^-\pi^+\pi^-$
$\rightarrow e^+e^-$

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UPPSALA UNIVERSITET

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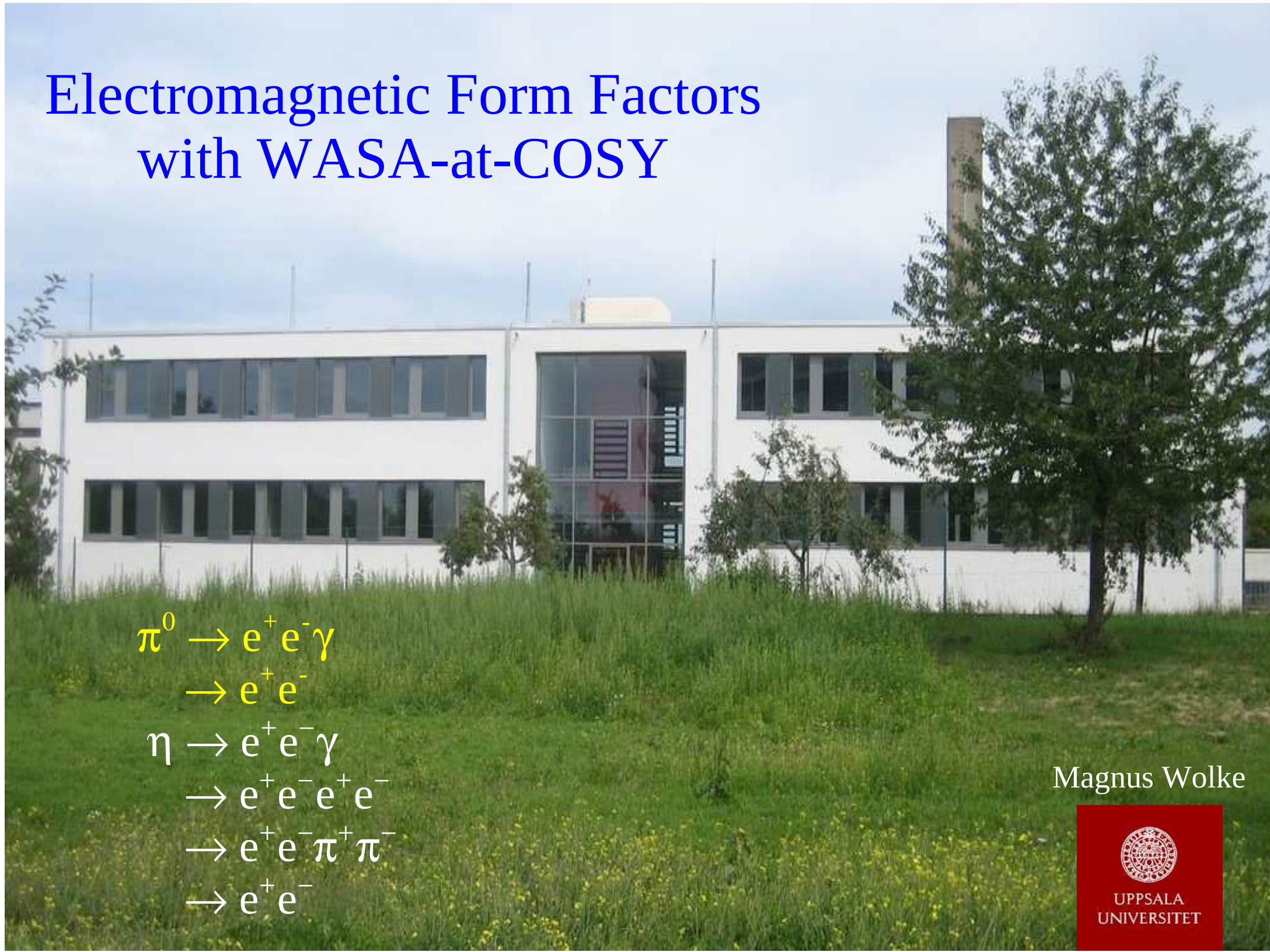

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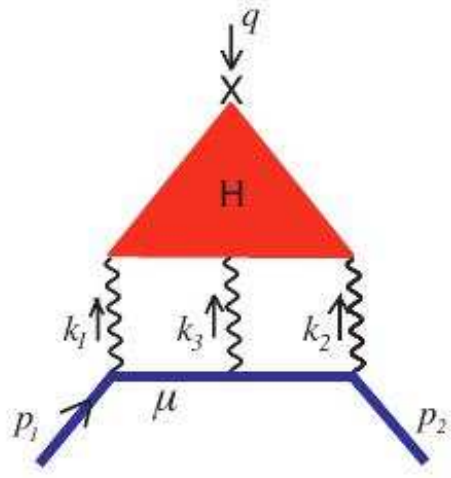
π^0 Transition Form Factors

Hadronic light-by-light contribution



$\Rightarrow$ confirm neutral pion exchange results

π^0 Dalitz decay

experimental results for slope parameter a_π from π^0 Dalitz decay:

-0.11 ± 0.03 ± 0.08 (37k events) H. Fonvieille et al., PLB 233 (1989) 65

+0.026 ± 0.024 ± 0.0048 (10k events) F. Farzanpay et al., PLB 278 (1992) 413

+0.025 ± 0.014 ± 0.0025 (54k events) R. Meijer Drees et al. (SINDRUM-I Collab.), PRD 45 (1992) 1439

compare with: VDM prediction: +0.031

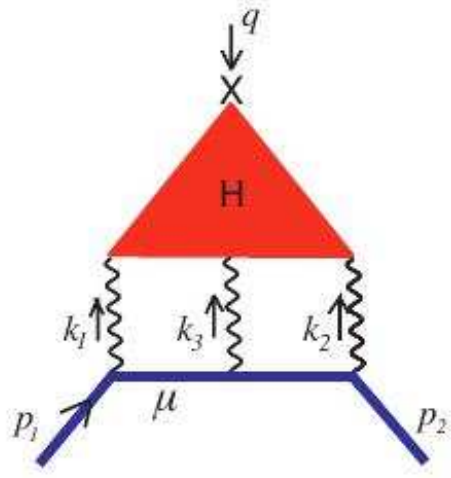
ChPT 2-loop: +0.029 ± 0.005

M. Kampf, M. Knecht, J. Novotný, EPJ C46 (2006) 191

quote from ChPT calculation: "**...we think that a precise measurement of a_π which would not rely on any kind of extrapolation remains an interesting issue.**"

π^0 Transition Form Factors

Hadronic light-by-light contribution

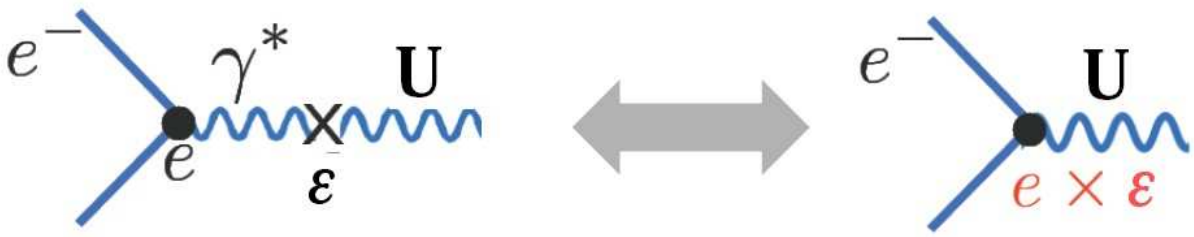


$\Rightarrow$ confirm neutral pion exchange results

Search for Light Dark Matter

dark photon (a_μ, U) of $U(1)_d$ group couples vectorially to SM charged fields
(coupling to SM weak currents suppressed)

M.Reece, L.T.Wang, JHEP 07 (2009) 051



$m_U \sim 1\,\text{MeV}$ - few GeV
$\varepsilon \sim 10^{-2} - 10^{-4}$

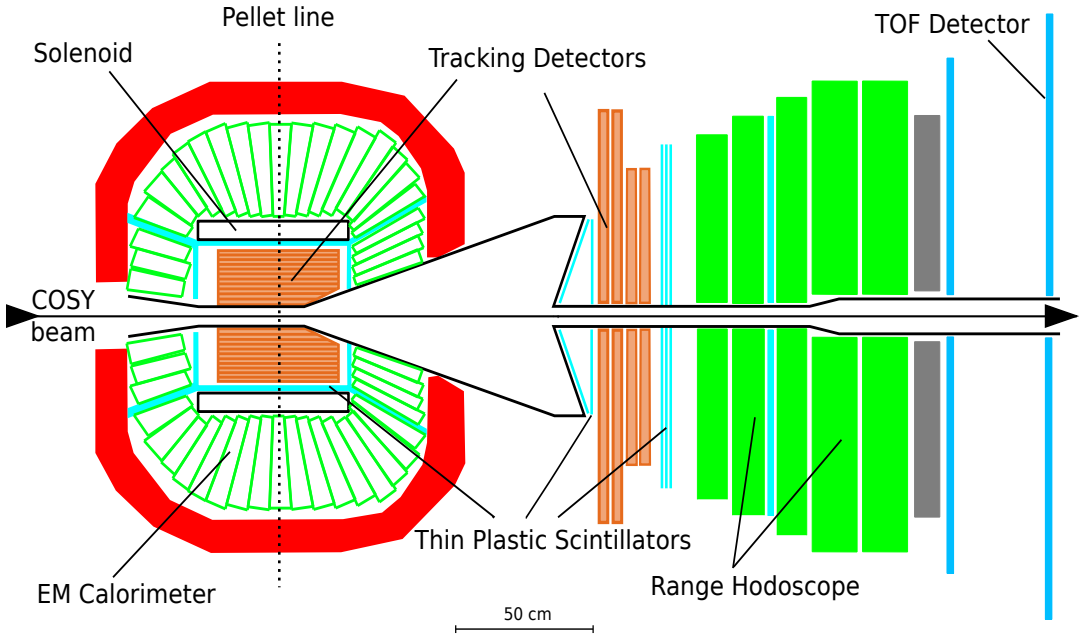
search channels: $\phi \to \eta U\ (U \to e^+e^-)$, $\eta \to \gamma U\ (U \to e^+e^-)$, $\pi^0 \to \gamma U\ (U \to e^+e^-)$

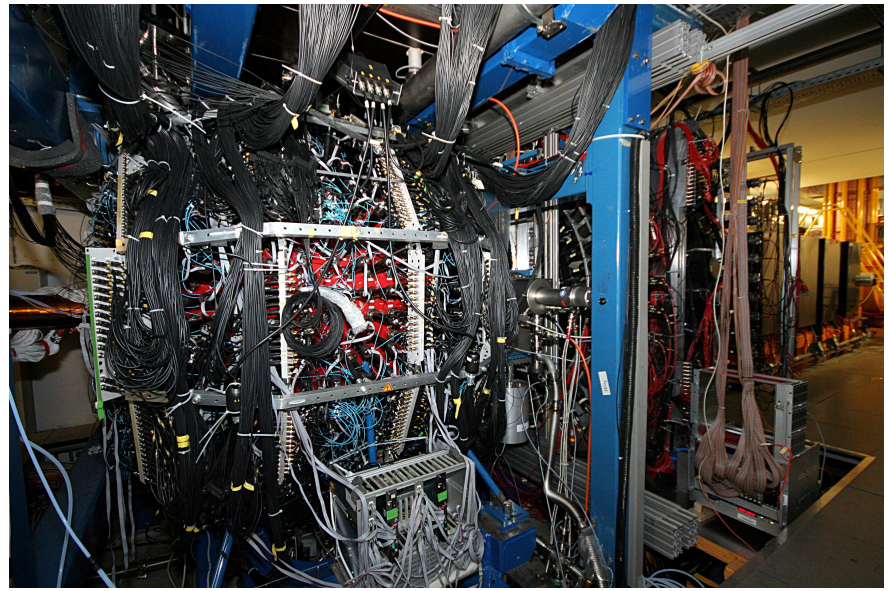
The WASA Facility

an internal 4π detector

H.-H. Adam et al. (proposal), nucl-ex/0411038

http://collaborations.fz-juelich.de/ikp/wasa/





Central Detector

...light meson decay products

- Superconducting Solenoid
- Plastic Scintillator Barrel
- Straw Chamber
- Scintillator Electromagnetic Calorimeter

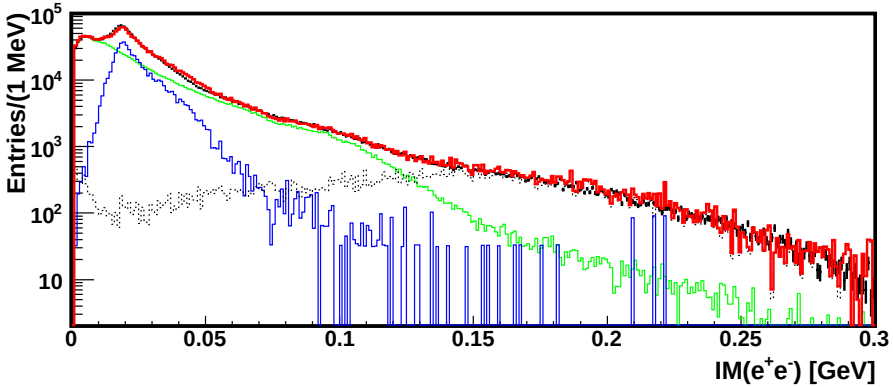
Forward Detector

...scattered projectiles and charged recoil particles

- Plastic Scintillators
- Forward Straw Tracker

Search $\pi^0 \to \gamma U$ with WASA

P.Adlarson et al.,
PLB 726 (2013) 187



- data
- MC sum
- $\pi^0 \to e^+e^-\gamma$
- $\pi^0 \to \gamma\gamma$
- accidentals

$\Rightarrow$ considerable background from γ conversion

Search $\pi^0 \rightarrow \gamma U$ with WASA

P.Adlarson et al.,
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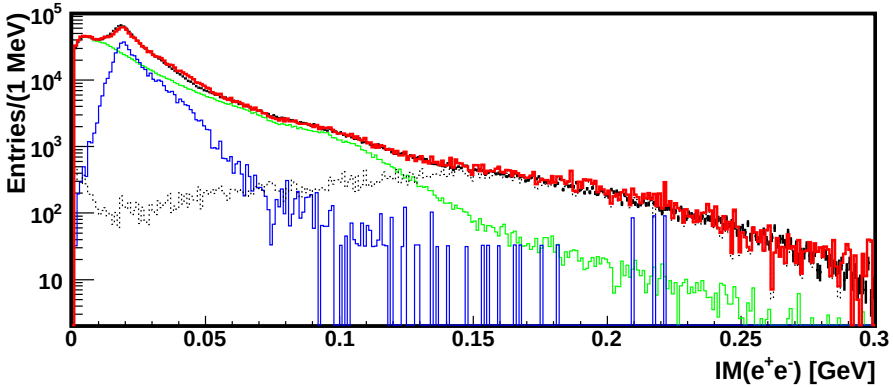

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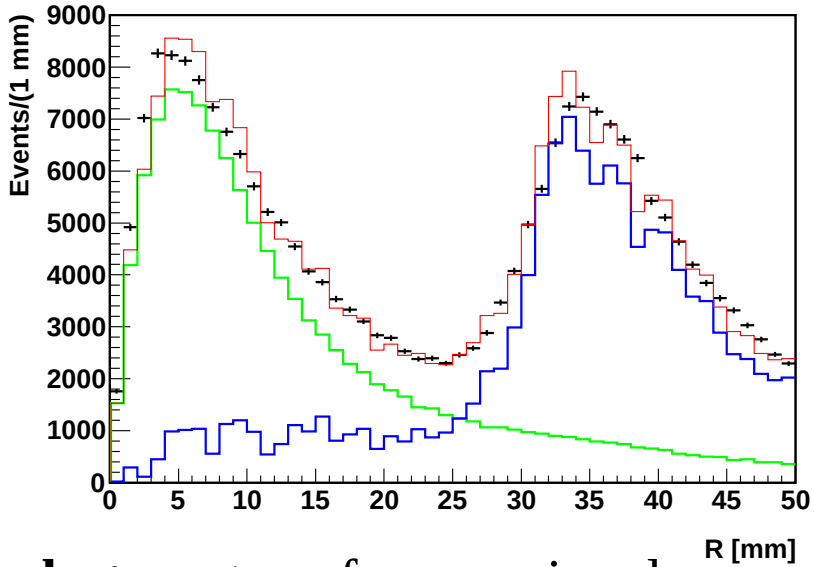

but: vertex of conversion decays is not at the target point

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P.Adlarson et al.,
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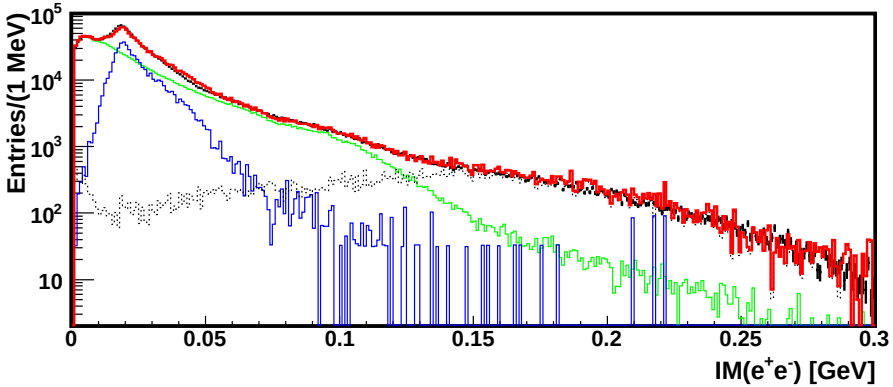

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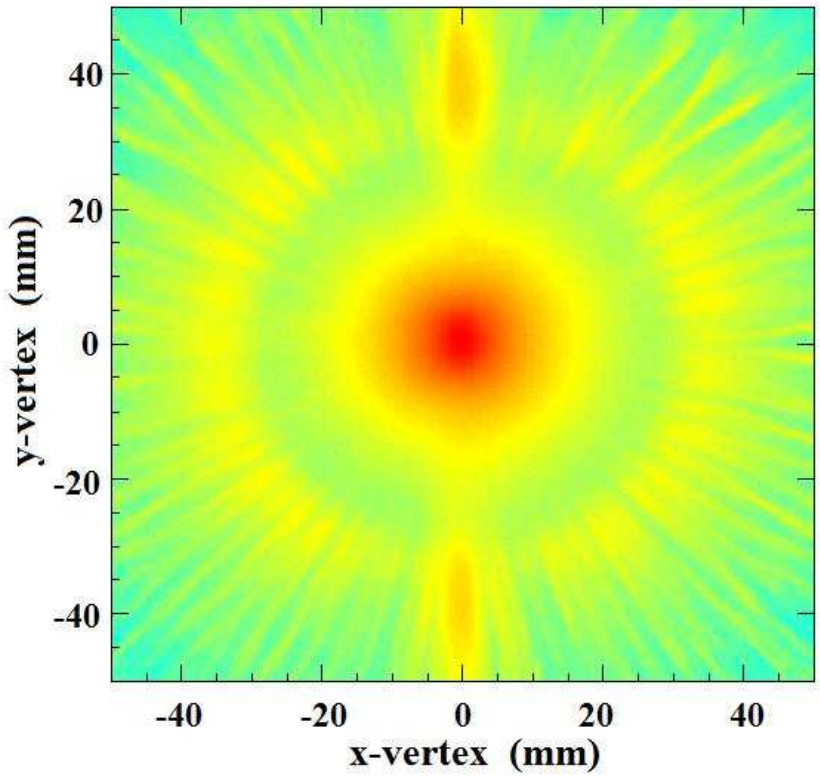
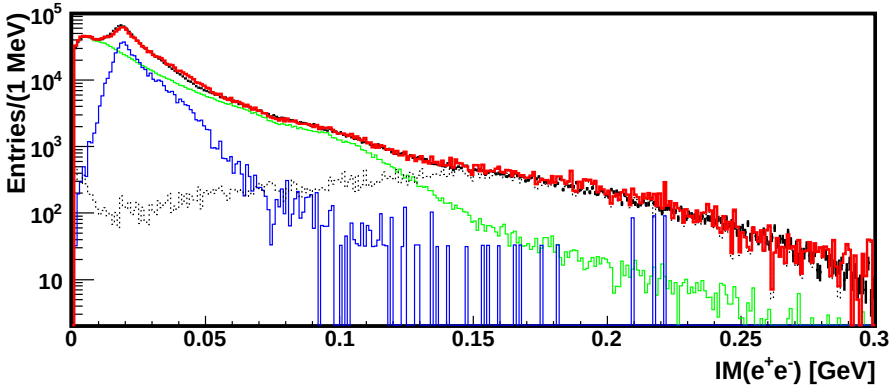


target and conversion decays
from reconstructed vertices

Search $\pi^0 \rightarrow \gamma U$ with WASA

P.Adlarson et al.,
PLB 726 (2013) 187



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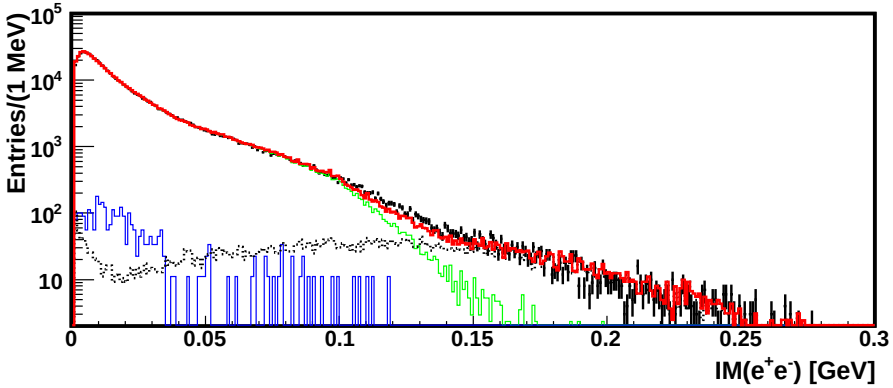
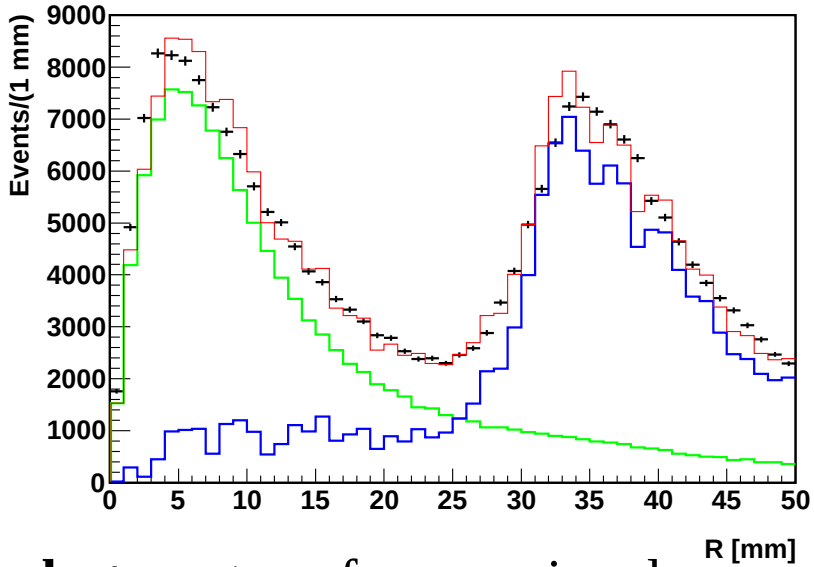


$\Rightarrow$ considerable background from γ conversion



but: vertex of conversion decays is not at the target point

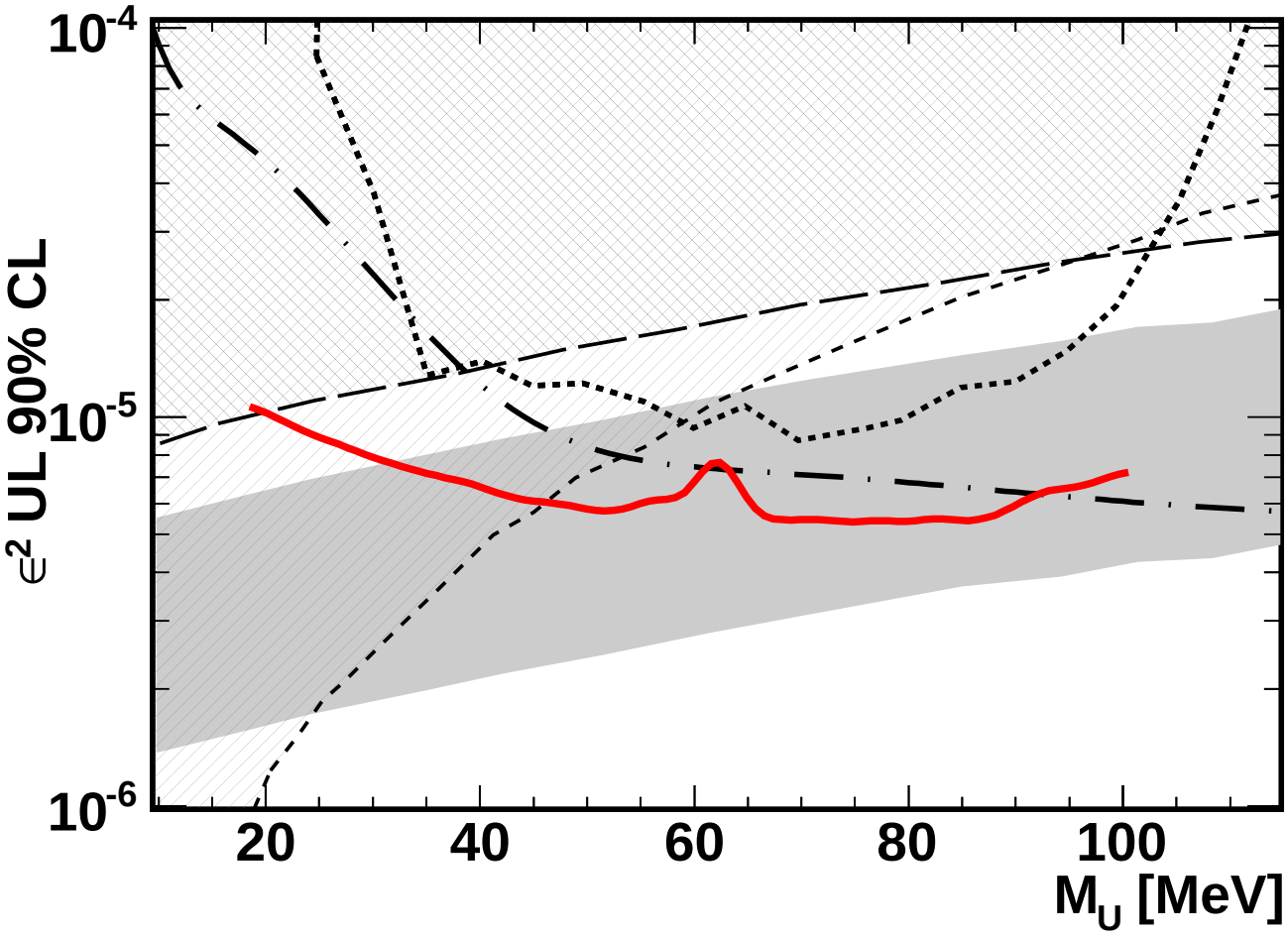
$\Rightarrow$ almost background free
$\pi^0 \rightarrow e^+e^-\gamma$ events (~ 500k)

Dark photon mixing parameter ε

P.Adlarson et al.,
PLB 726 (2013) 187

$$\frac{\Gamma(\pi^0 \to \gamma U)}{\Gamma(\pi^0 \to \gamma\gamma)} = 2\varepsilon^2 \, |F(M_U^2)|^2 \, (1 - \frac{M_U^2}{M^2})^2$$

M.Reece, L.-T.Wang, JHEP 0907 (2009) 051



SINDRUM
PRL 68 (1992) 3845

WASA-at-COSY
PLB 726 (2013) 187

KLOE
PLB 720 (2013) 111

e g-2

μ g-2
PR D 86 (2012) 095029

preferred μ g-2 ±2σ

Dark photon mixing parameter ε

P.Adlarson et al.,
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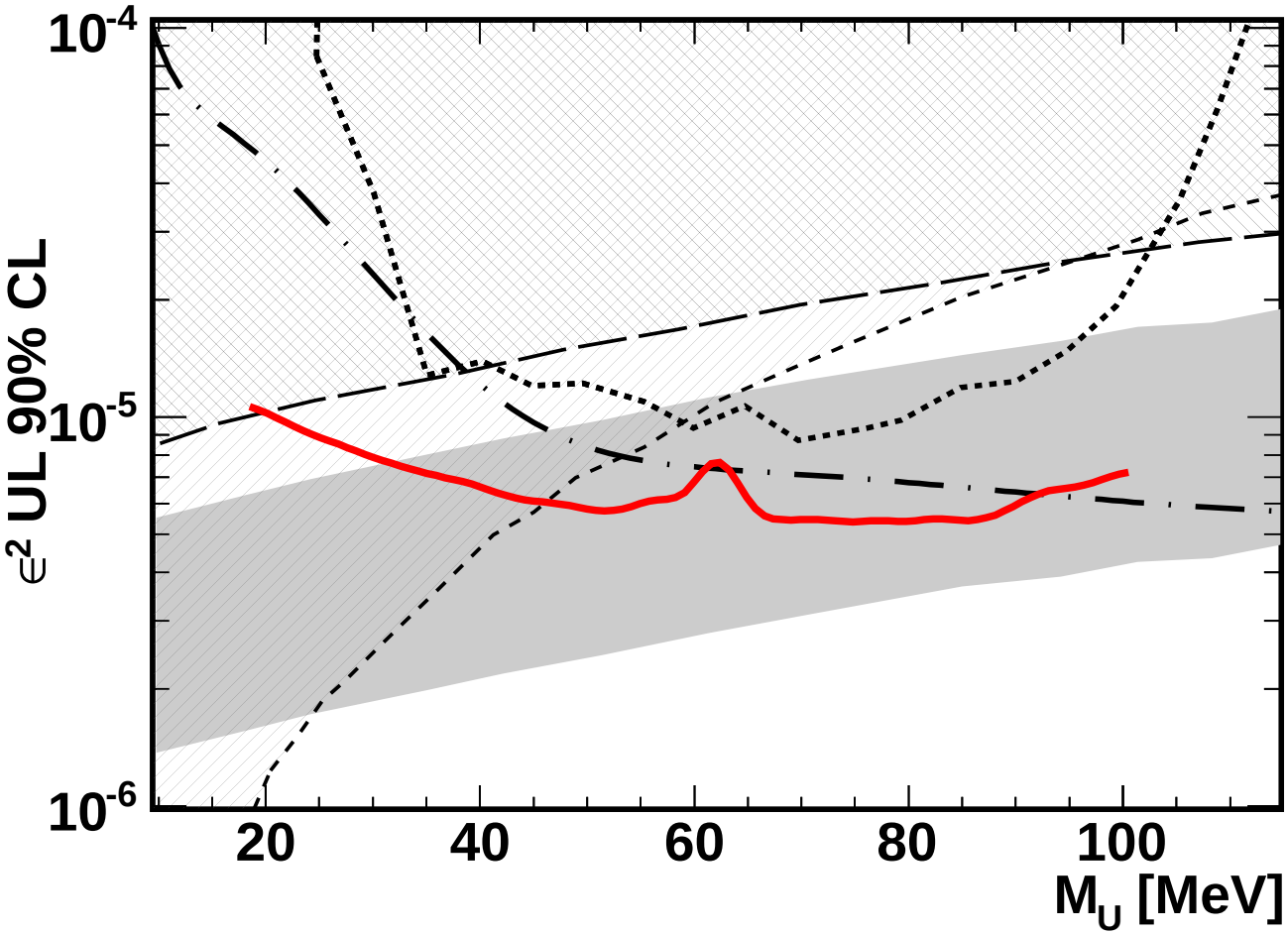
M.Reece, L.-T.Wang, JHEP 0907 (2009) 051

published statistics: 5×10^5 $\pi^0 \to \gamma e^+ e^-$

still to be analyzed: ~8×10^6 $\pi^0 \to \gamma e^+ e^-$



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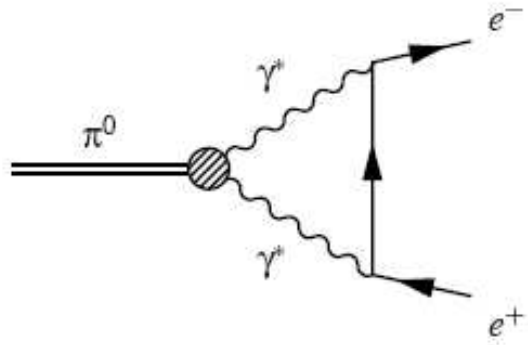
$\pi^0 \to e^+e^-$

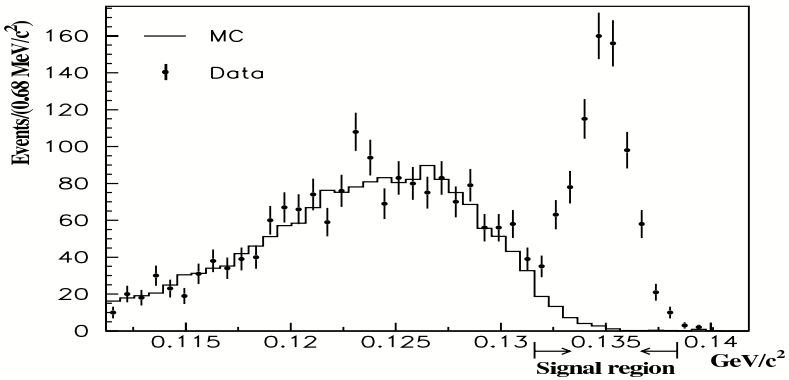


- lowest order Standard Model contribution:
  1-loop process with $2\gamma^*$ intermediate state
- amplitude suppressed by helicity conservation and α^2
  $\Rightarrow$ extremely small decay width
- theory estimate: A. Dorokhov, M. Ivanov, PRD 75 (2007) 114007

$$BR^{SM}(\pi^0 \to e^+e^-) = (6.2 \pm 0.1) \times 10^{-8}$$

- KTeV result: E. Abouzaid et al., PRD 75 (2007) 012004

$$BR^{exp}(\pi^0 \to e^+e^-) = (7.48 \pm 0.29 \pm 0.25) \times 10^{-8}$$



Experimental result:
3.3σ excess over SM calculation

Light Dark Matter

C. Boehm, P. Fayet, NPB 683 (2004) 219
Y. Kahn, M. Schmitt, T.M.P. Tait, PRD 78 (2008) 115002

- postulate: neutral scalar dark mattar particle χ with mass 1-10 MeV
- annihilation $\chi\chi \rightarrow e^+e^-$

  $\Rightarrow$ excess positrons from 511 keV line from galactic center

recent results:
G. Weidenspointner et al.,
Nature 451 (2008) 159

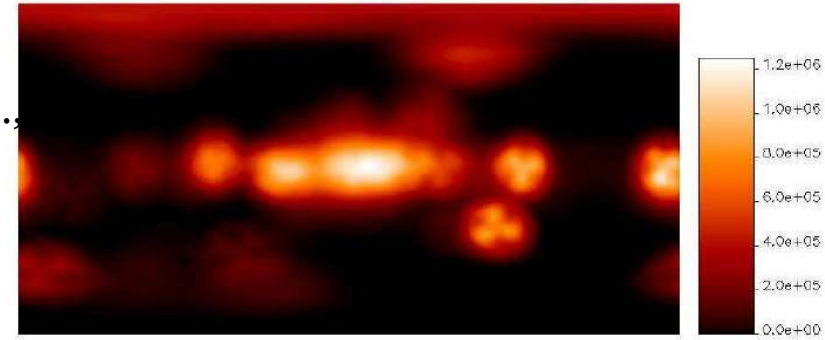


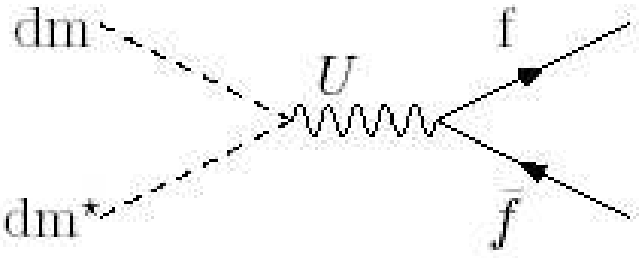
Fig. 1.— INTEGRAL/SPI Exposure map of the Galaxy for the first 10 months of operation of INTEGRAL. Horizontal range is 180° to − 180° . Vertical range is −90° to 90°. A large fraction of the observations are concentrated in the Galactic Plane. The characteristic pinwheel patterns in some regions are due to modulation of the light bucket response by the SPI coded-aperture mask. Color bar units are seconds.

- annihilation via neutral vector boson *U*,

  m(*U*) ~ 10-100 MeV

  small couplings to SM fermions

  $\rightarrow$ small contribution to decay rate

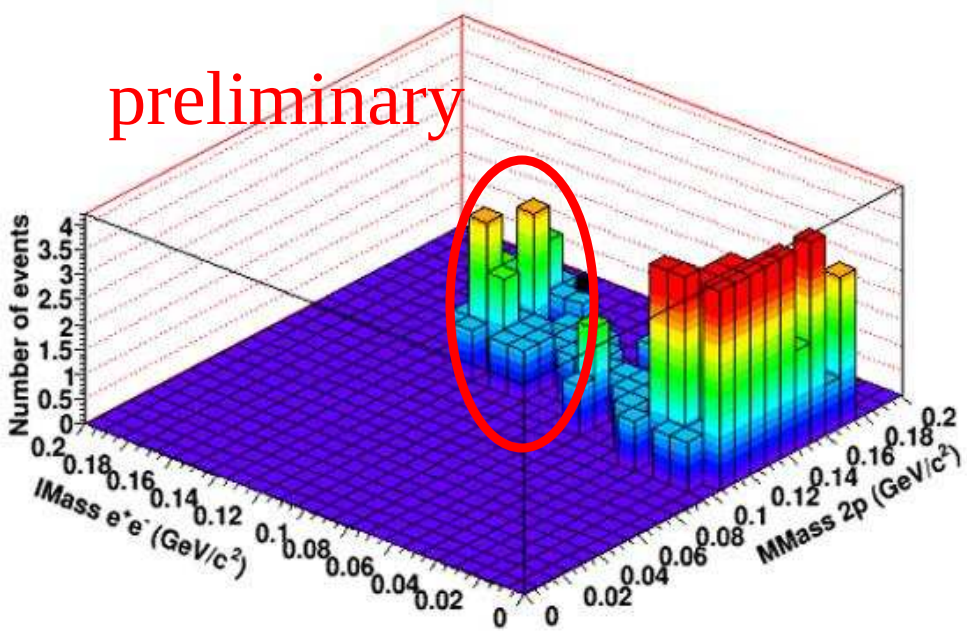


LDM model U boson
might explain $\pi^0 \rightarrow e^+e^-$ excess

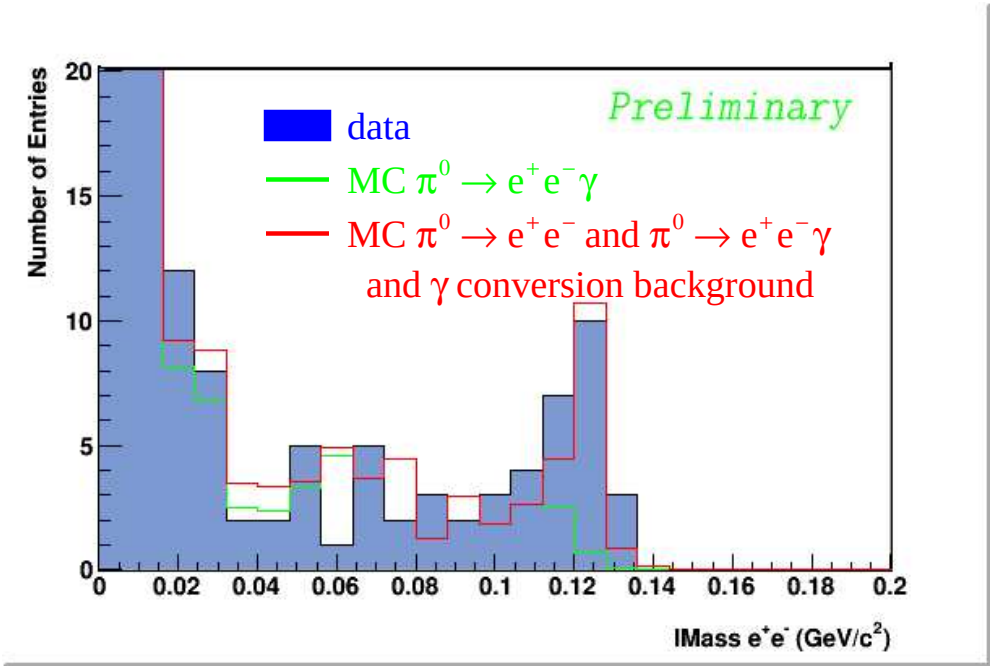
$\pi^0 \rightarrow e^+e^-$ with WASA

4 days data taking
analysis: C.-O. Gullström

inv mass (e^+e^-) vs miss mass (pp)



projection on inv mass (e^+e^-)



$\Rightarrow$ 15 event candidates in 4 days data sample

$\pi^0 \rightarrow e^+e^-$ with WASA

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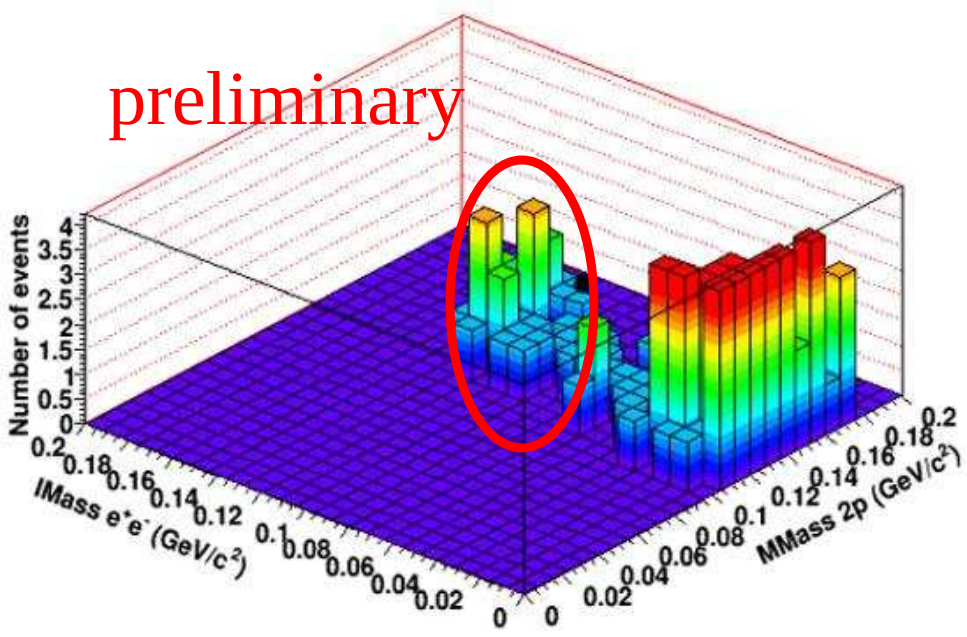

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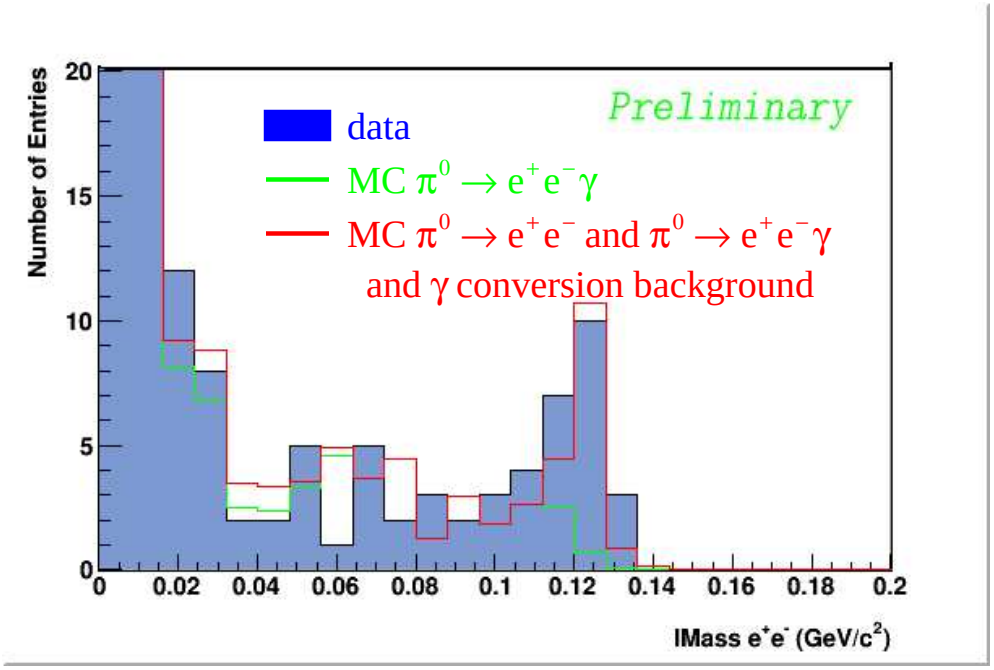

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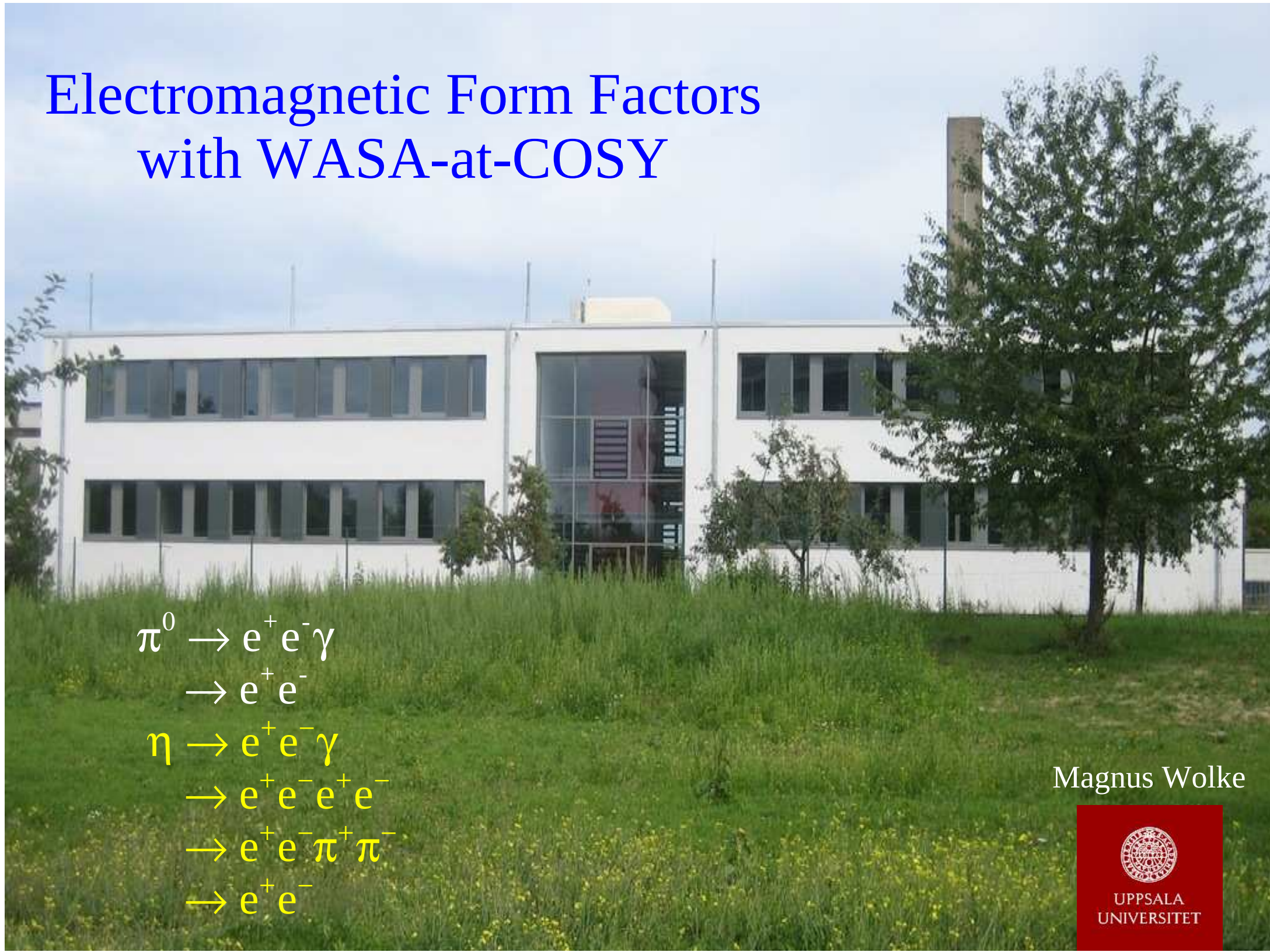
8 weeks of additional data taking in 2012 and 2013

WASA has been designed to measure this decay channel

Electromagnetic Form Factors with WASA-at-COSY



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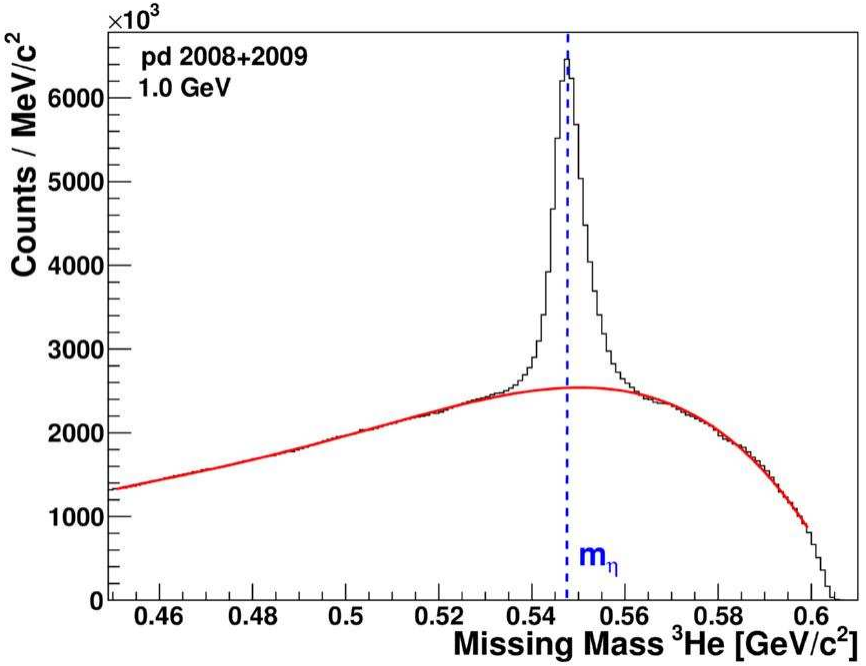
η tagging with WASA-at-COSY

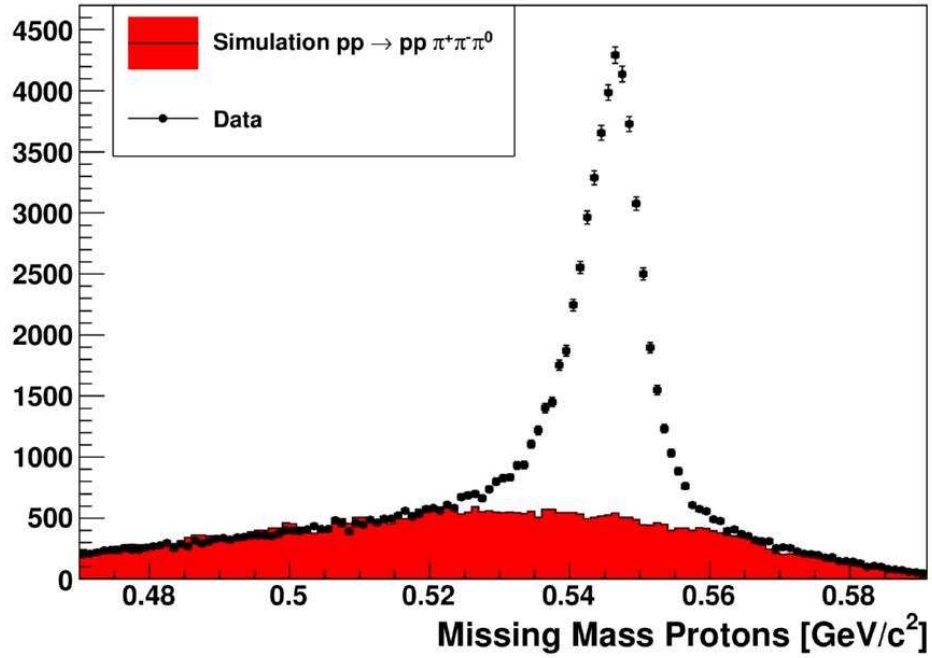
$pd \rightarrow {}^3He\eta$



- lower cross section
- unbiased trigger
- 3×10^7 η mesons tagged

⇒ precision studies for common decays

$pp \rightarrow pp\eta$

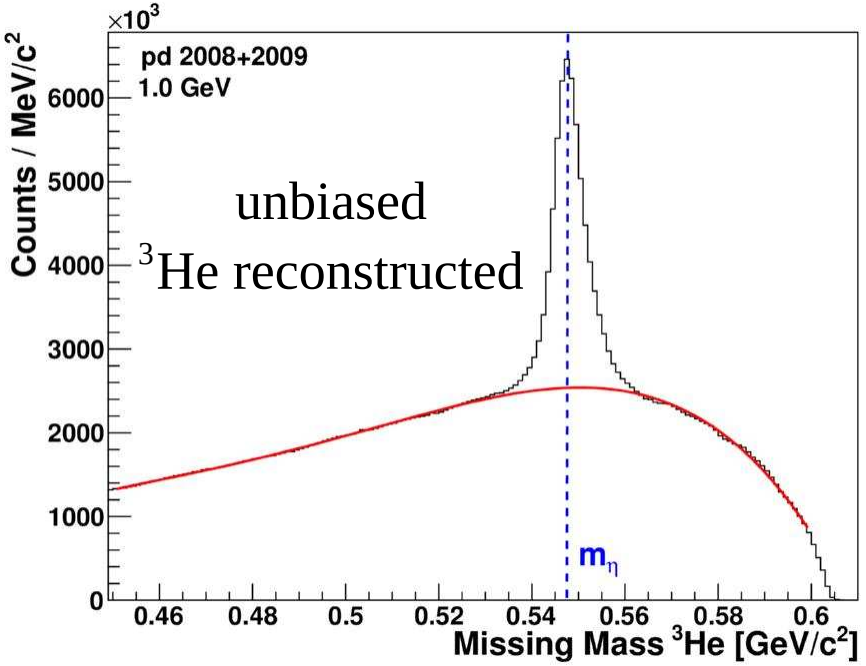


- larger cross section
- decay selective trigger required
- ~5×10^8 η mesons tagged

⇒ large statistics studies, rare decays

η tagging with WASA-at-COSY

$pd \rightarrow {}^3He\eta$



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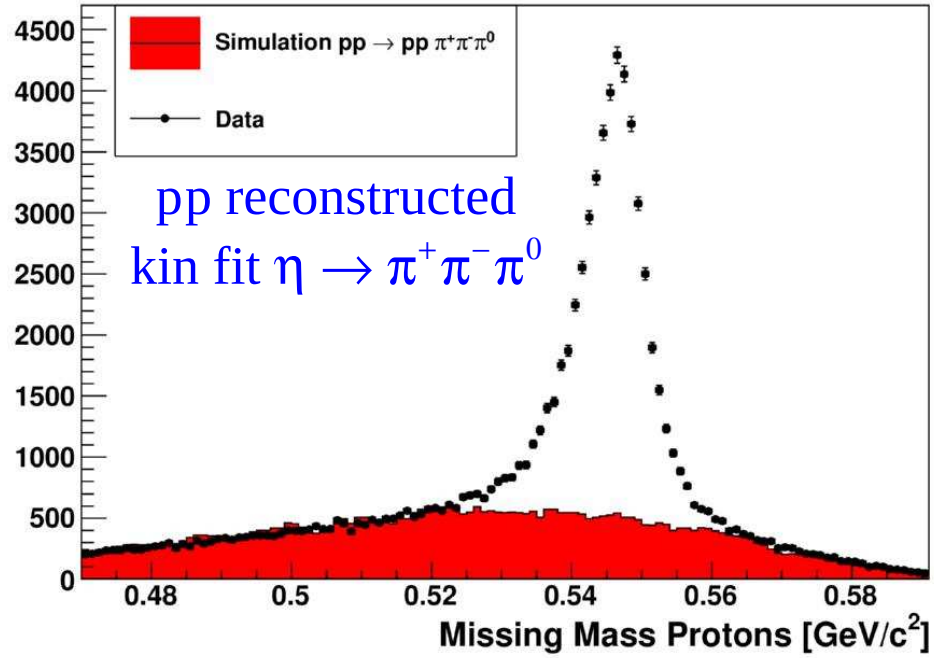

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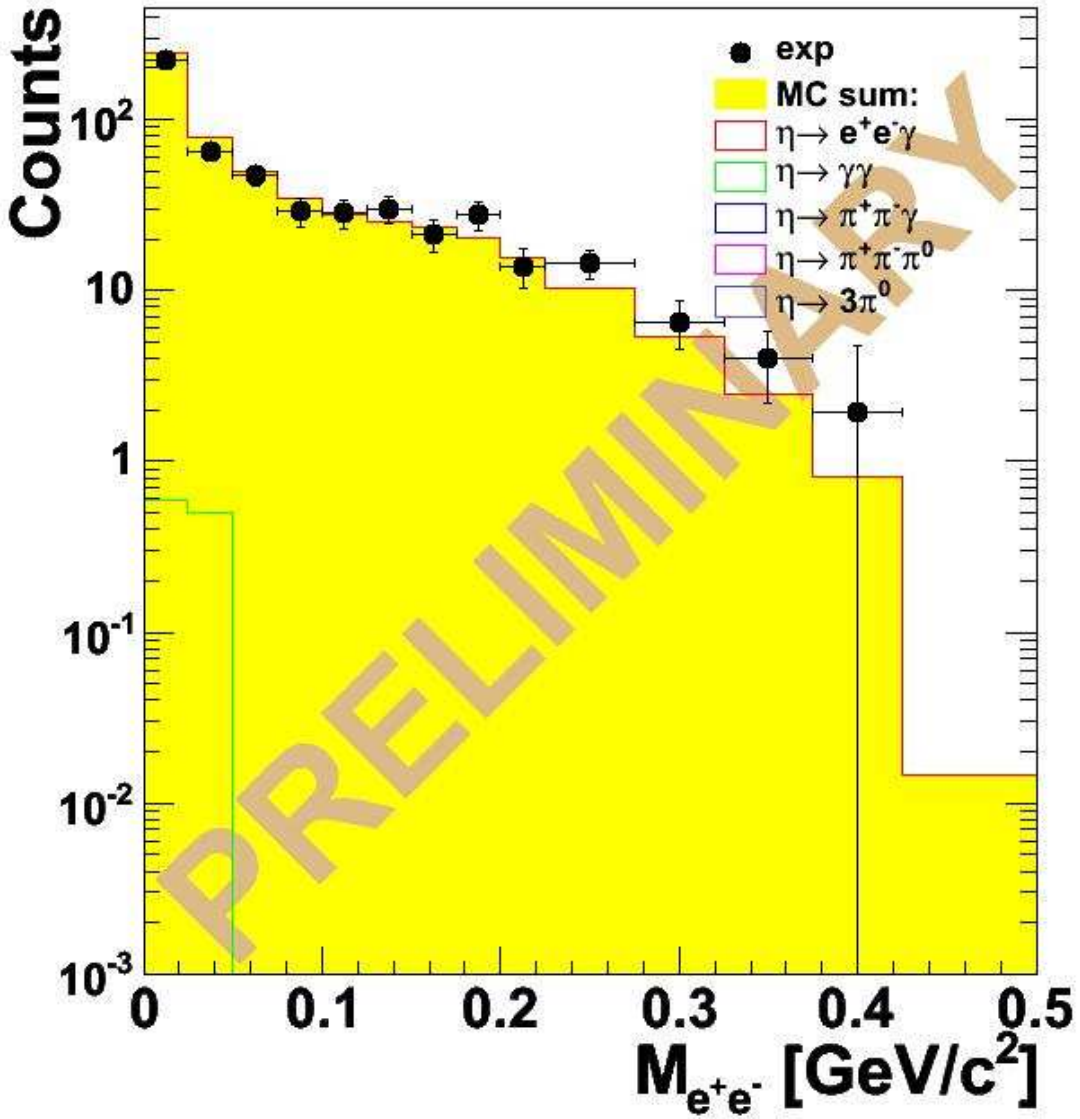
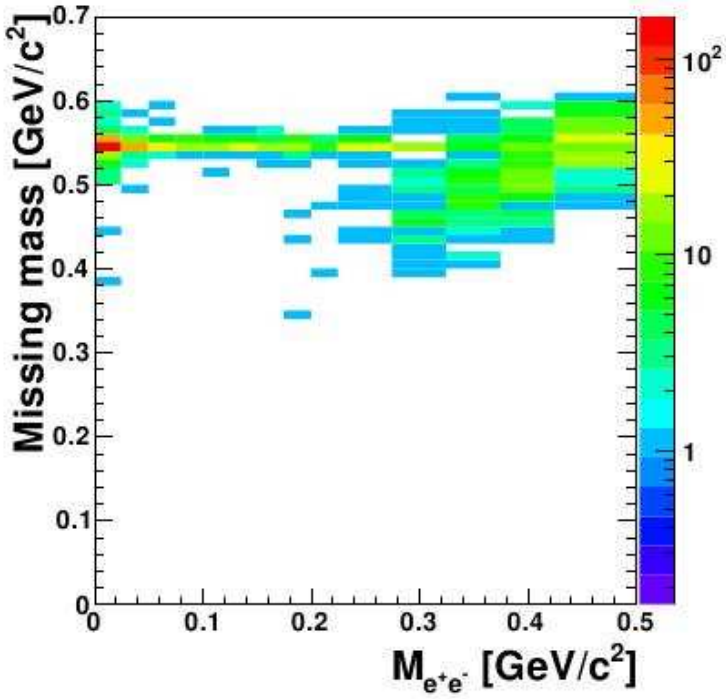
$\eta \to \gamma e^+ e^-$ transition form factor

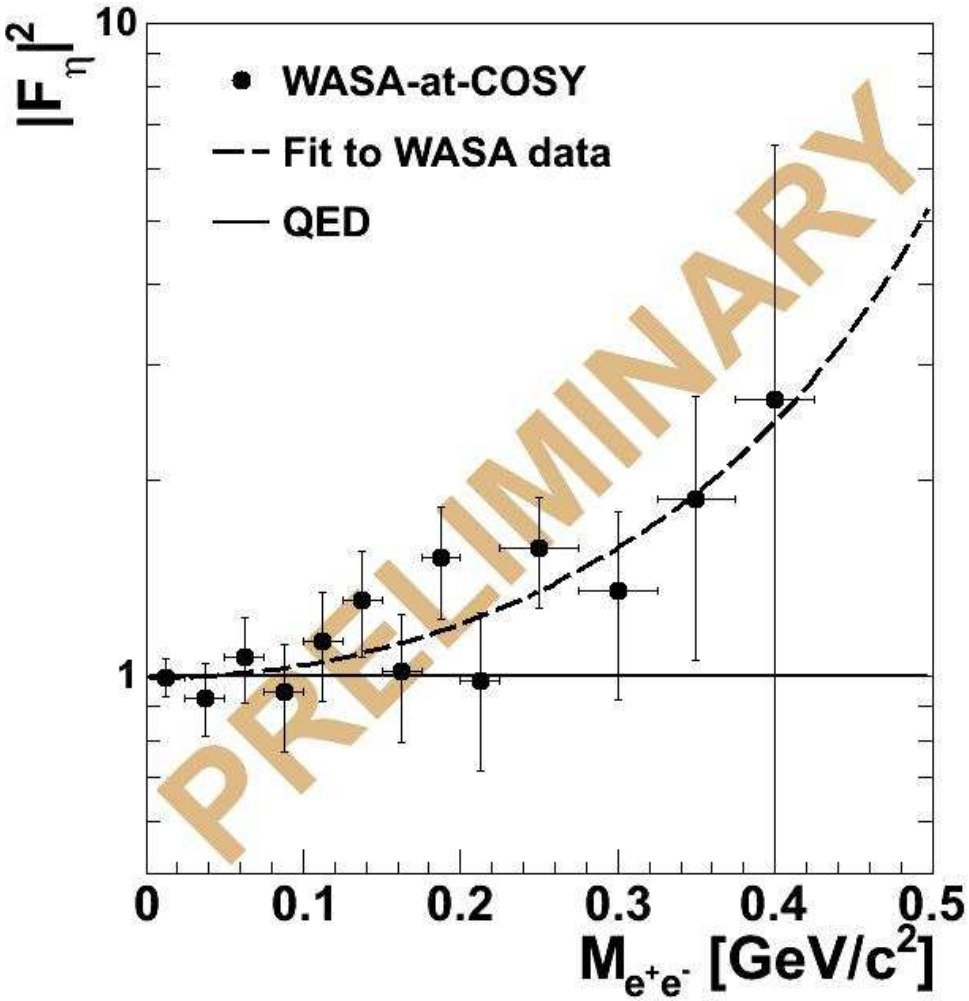


- 1×10^7 tagged $pd \to {}^3He\eta$ events (1/3 of pd data)
- ~520 signal events (prel., selective cuts)



M.Hodana, PhD thesis (2012), arXiv: 1203.5756[nucl-ex]

$\eta \to \gamma e^+ e^-$ transition form factor



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- ~520 signal events (prel., selective cuts)

fit $[F_P(q^2)]^2 = [\alpha(1 - \frac{q^2}{\Lambda_p^2})^{-1}]^2$

$\alpha = 0.998 \pm 0.025$

$\Lambda_p^{-2} = (2.27 \pm 0.73_{stat} \pm 0.46_{sys})$ GeV^{-2}

in agreement with $\Lambda_p^{-2} = (1.95 \pm 0.15_{stat} \pm 0.10_{sys})$ GeV^{-2}

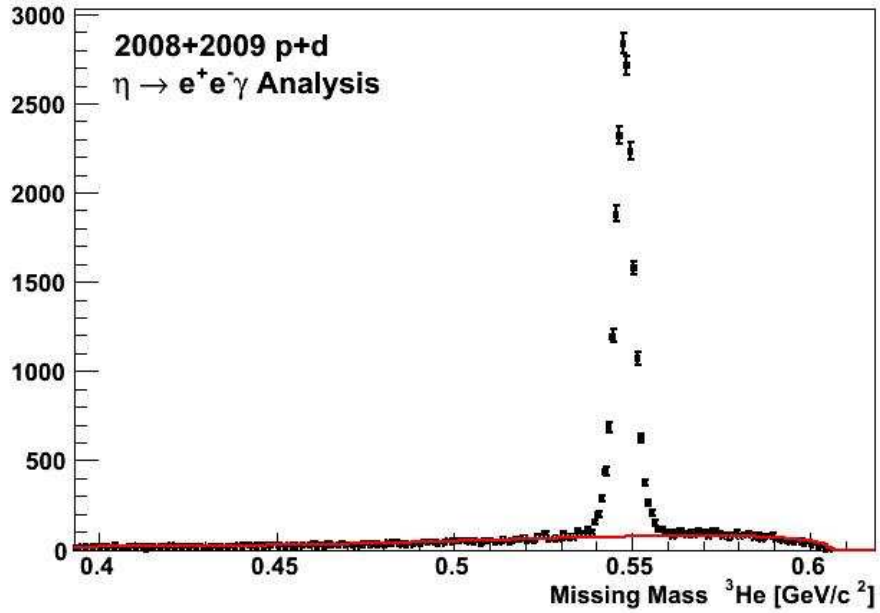
CB/TAPS

arXiv: 1309.5648 [hep-ex]

$\eta \to \gamma e^+ e^-$ statistics

Experiment	$N(\eta \to l^+ l^- \gamma)$ $l = e, \mu$	
Rutherford lab	50	M.R. Jane et al., PLB 59 (1975) 103
SND	109	N.N. Achasov et al., PLB 504 (2001) 275
CB/TAPS	1345	H. Berghauser et al., PLB 701 (2011) 562
CB/TAPS	1.8×10^4	P. Aguar-Bartolomé et al. arXiv: 1309.5648 [hep-ex]
WASA pd	1.6×10^4	
WASA pp	1×10^5 expected	
LEPTON-G	600	R.I. Dzhelyadin et al., PLB 94 (1980) 548
NA-60	9000	R. Arnaldi et al., PLB 677 (2009) 260
NA-60 prel.	8×10^4	A. Uras et al., ActaPhysPolon S5 (2012) 465

- 1×10^7 tagged $pd \to {}^3He\eta$ events
- 1.6×10^4 signal events

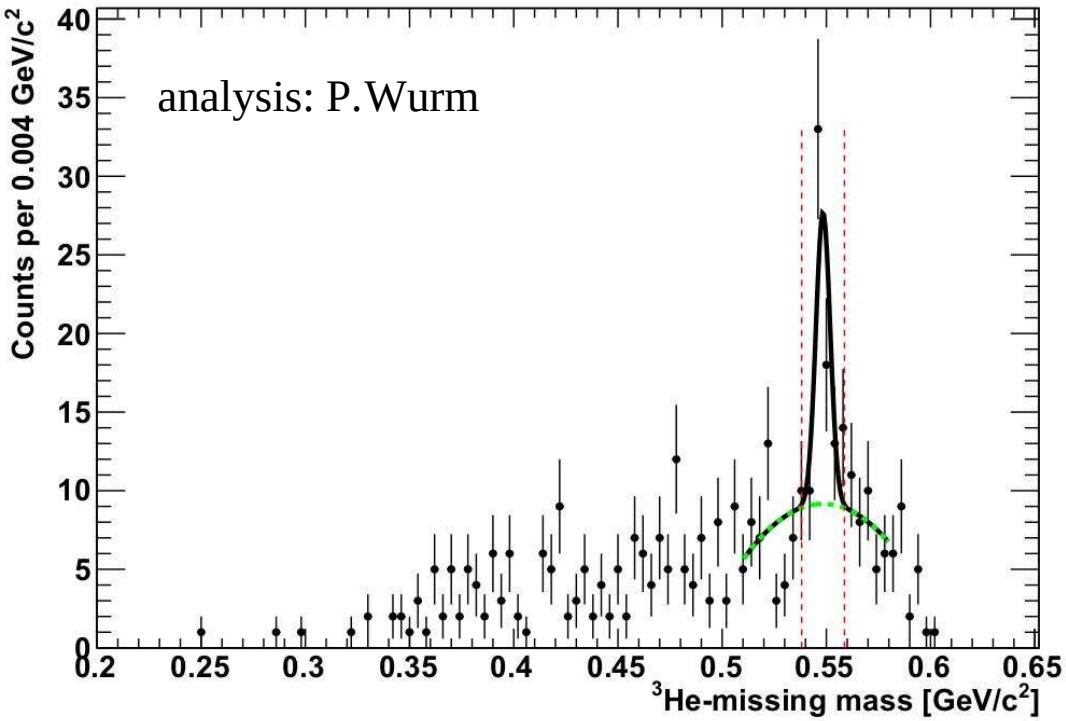


- purity ~98%

$\eta \to e^+e^-e^+e^-$ with WASA

present goal: determine branching ratio

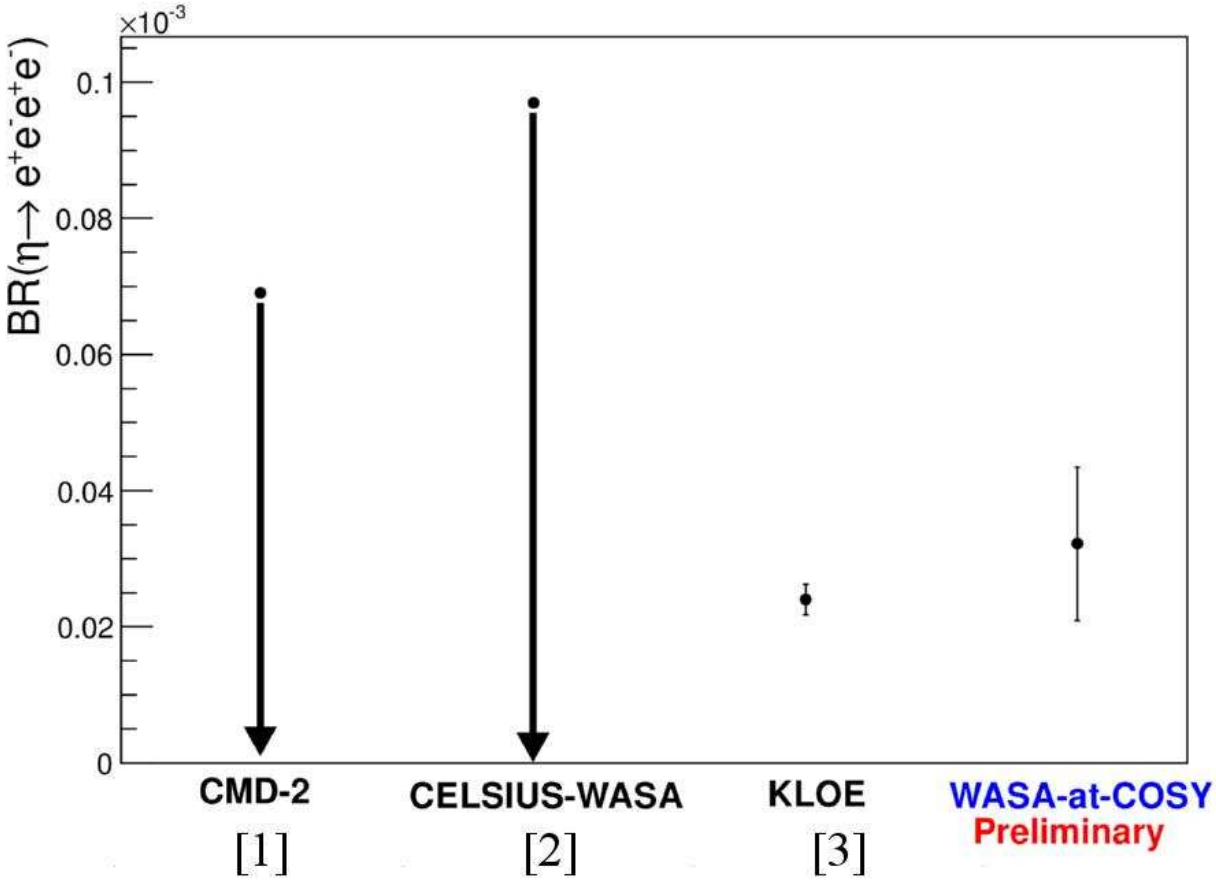
future goal: measurement of double form factor



- 3×10^7 tagged $pd \to {}^3He\eta$ events
- $(50 \pm 13_{stat})$ signal events
- result here from cut-based analysis
- new analysis with kinematic fit (consistent, but lower bg)

preliminary result: $BR(\eta \to e^+e^-e^+e^-) = (3.0 \pm 0.8_{stat} \pm 0.7_{sys}) \times 10^{-5}$

$\eta \to e^+e^-e^+e^-$ with WASA



- 3×10^7 tagged $pd \to {}^3He\eta$ events
- $(50 \pm 13_{stat})$ signal events

[1] R.R. Akhmetshin et al. (CMD-2), PLB 501 (2001) 191

[2] M. Berlowski et al. (CELSIUS-WASA), PRD 77 (2008) 032004

[1] F. Ambrosino et al. (KLOE), PLB 702 (2011) 324

$\Rightarrow$ expectation for WASA pp data: hundreds of events

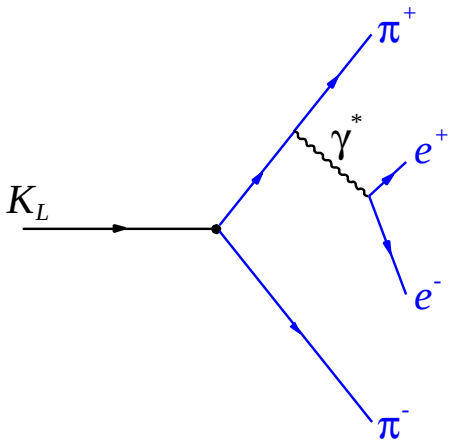
$\Rightarrow$ first look at double form factor?

CP violation in $K_L \to \pi^+\pi^- e^+ e^-$

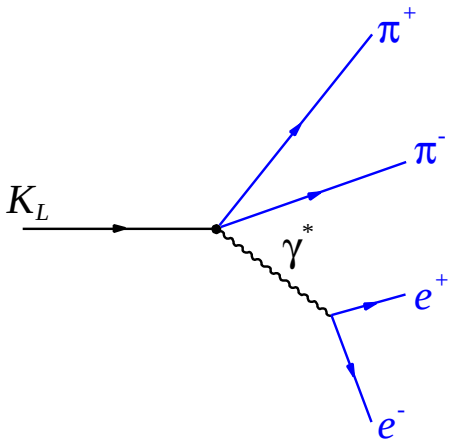
L.M. Sehgal, M. Wanninger,
PRD 46 (1992) 1035
P. Heiliger, L.M. Sehgal,
PRD 48 (1993) 4146

dominant amplitudes

CP violating bremsstrahlung



CP conserving M1 γ emission



interference of amplitudes

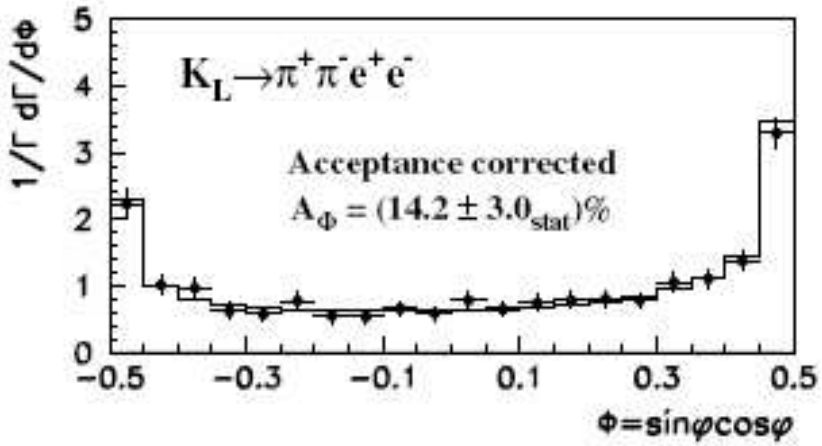
$\Rightarrow$ CP violating linear photon polarisation

$\Rightarrow$ CP violating asymmetry in $\sin\varphi\cos\varphi$

$\varphi = \angle\,(\pi^+\pi^-), (e^+e^-)$ planes in K_L cms

$$A_\phi = \frac{N_{\sin\varphi\cos\varphi>0} - N_{\sin\varphi\cos\varphi<0}}{N_{\sin\varphi\cos\varphi>0} + N_{\sin\varphi\cos\varphi<0}}$$

NA48 result A. Lai et al., EPJC 30 (2003) 33

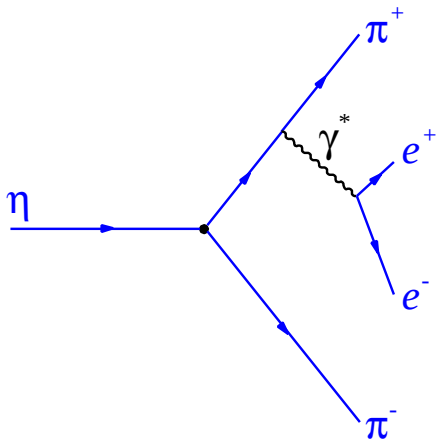


CP violation in $\eta \to \pi^+\pi^- e^+ e^-$

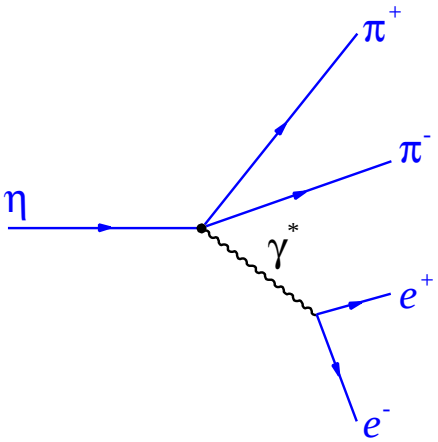
C.Q.Geng, J.N.Ng, T.H.Wu,
MPLA 17 (2002) 1489
D.N.Gao, MPLA 17 (2002) 1583

dominant amplitudes

CP violating bremsstrahlung



CP conserving M1 γ emission



Standard Model constraint from BR($\eta \to \pi^+\pi^-$):

experimental upper bound $\Rightarrow A_\phi < 10^{-4}$

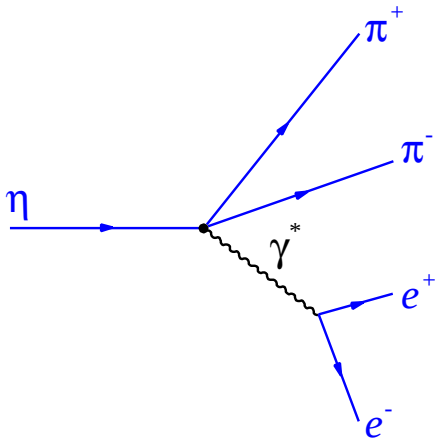
theoretical prediction $\Rightarrow A_\phi \sim 10^{-15}$

CP violation in $\eta \to \pi^+\pi^- e^+ e^-$

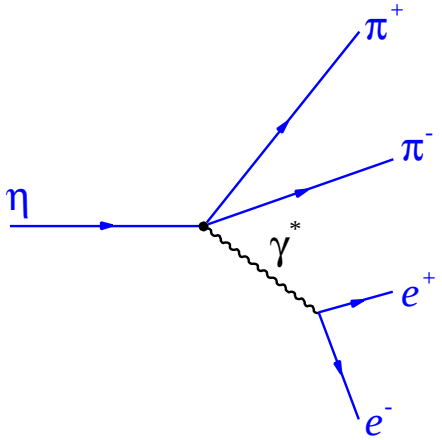
C.Q.Geng, J.N.Ng, T.H.Wu,
MPLA 17 (2002) 1489
D.N.Gao, MPLA 17 (2002) 1583

dominant amplitudes

CP violating E1 γ emission



CP conserving M1 γ emission



interference of amplitudes

$\Rightarrow$ CP violating linear photon polarisation

$\Rightarrow$ CP violating asymmetry in $\sin\varphi\cos\varphi$

$\varphi = \angle\,(\pi^+\pi^-), (e^+e^-)$ planes in η cms

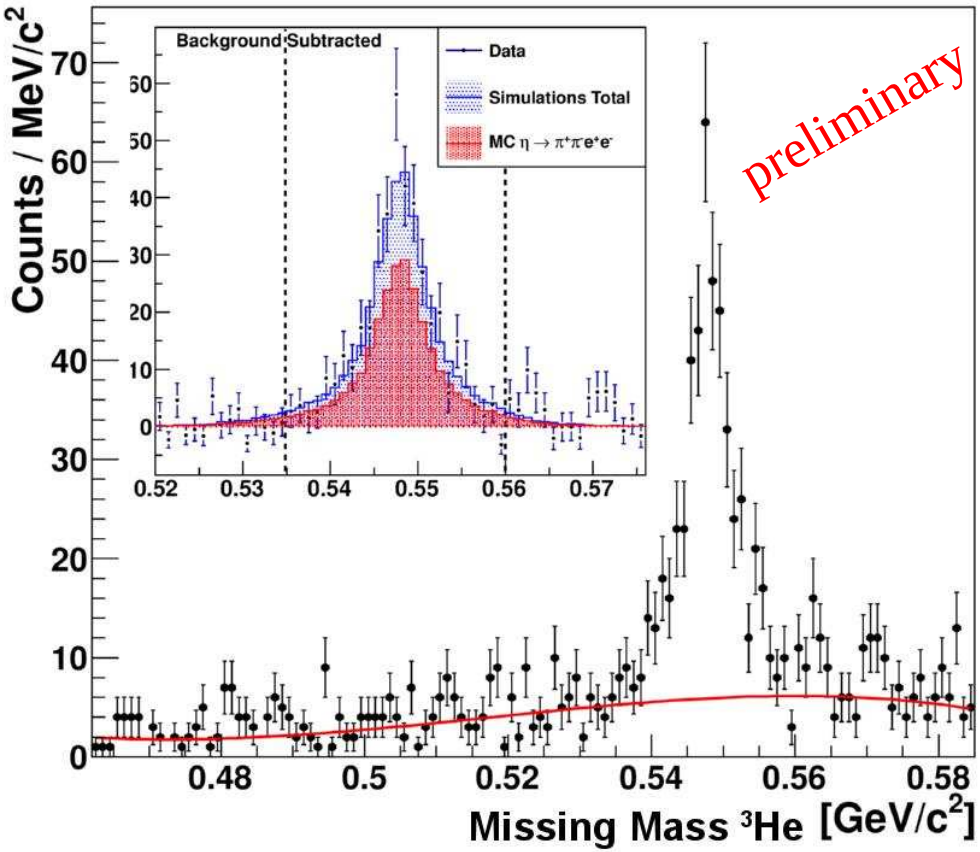
$$A_\phi = \frac{N_{\sin\varphi\cos\varphi>0} - N_{\sin\varphi\cos\varphi<0}}{N_{\sin\varphi\cos\varphi>0} + N_{\sin\varphi\cos\varphi<0}}$$

$\Rightarrow$ construct operators, that do not contribute directly to $\eta \to \pi^+\pi^-$ and K^0 decays

$\Rightarrow$ flavor conserving CP violating four-fermion operators involving two s-quarks

A_ϕ up to 2%

$\eta \to \pi^+\pi^-e^+e^-$ at WASA

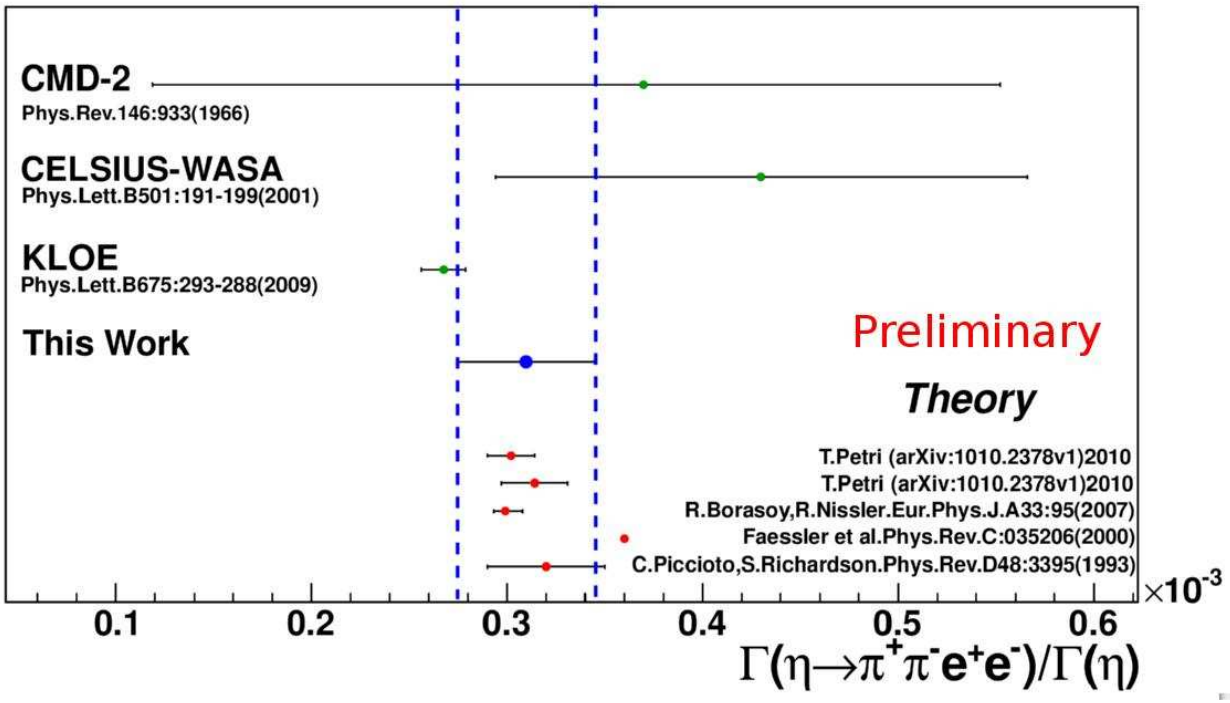


- 3×10^7 tagged $pd \to {}^3He\eta$ events
- $263 \pm 24_{stat}$ signal events

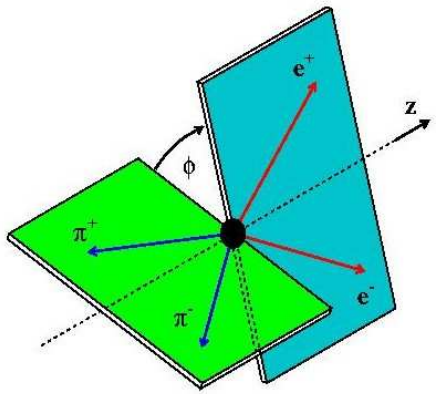
preliminary results: $BR(\eta \to \pi^+\pi^-e^+e^-) = (3.10 \pm 0.27_{stat} \pm 0.22_{sys}) \times 10^{-4}$

$A_\phi = (0.4 \pm 9.0_{stat} \pm 2.8_{sys}) \times 10^{-2}$

$\eta \to \pi^+\pi^-e^+e^-$



- branching ratio in agreement with previous measurements
- statistics benchmark KLOE: $1555 \pm 53_{stat}$ events

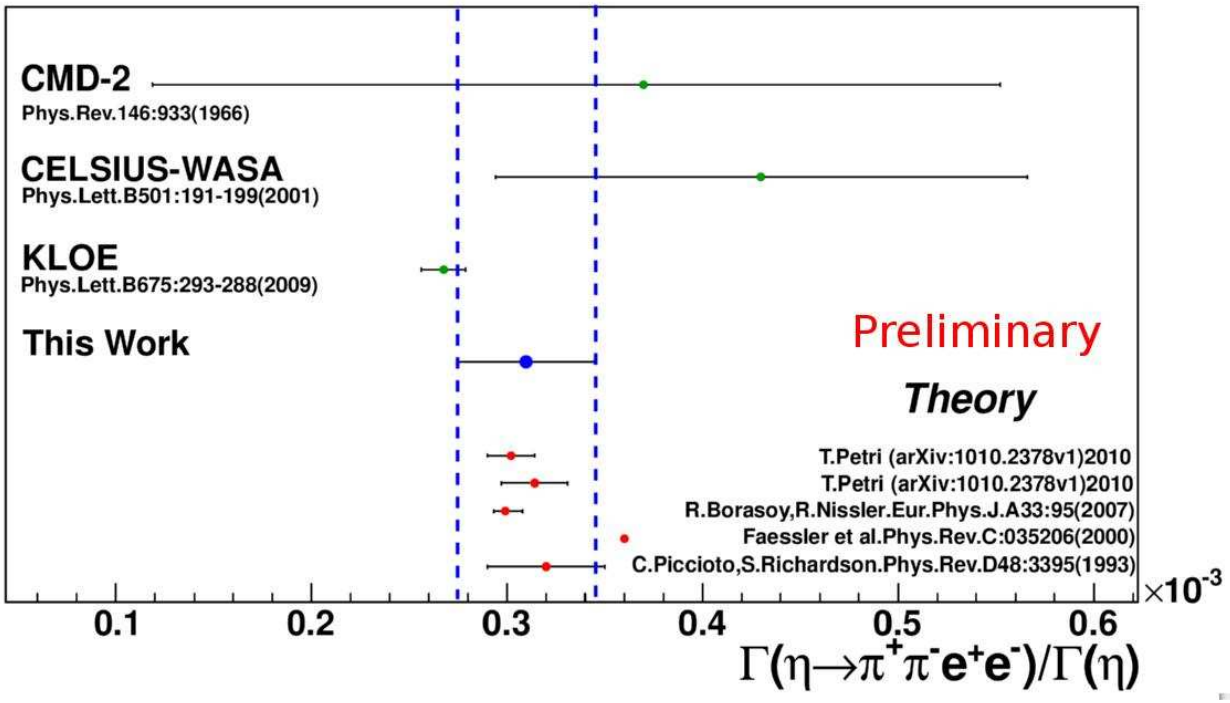


- A_ϕ limited by statistics

KLOE $\quad A_\phi = (-0.6 \pm 2.5_{stat} \pm 1.8_{sys}) \times 10^{-2}$

WASA preliminary $\quad A_\phi = (0.4 \pm 9.0_{stat} \pm 2.8_{sys}) \times 10^{-2}$

$\eta \to \pi^+\pi^-e^+e^-$



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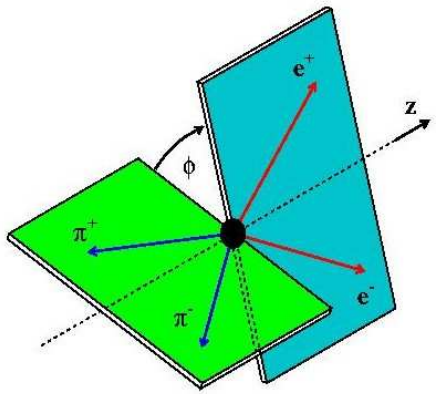

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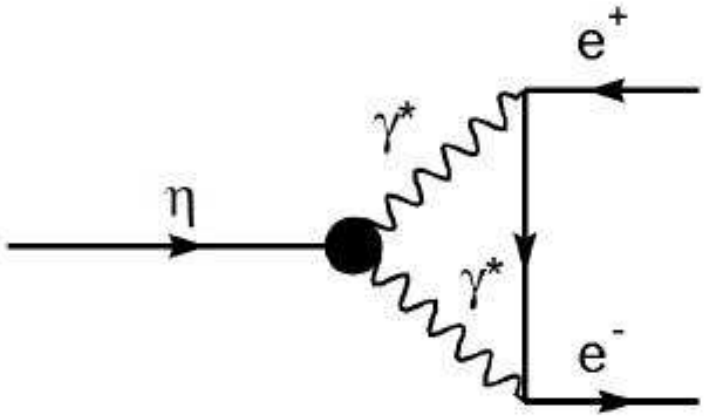
WASA preliminary $\quad A_\phi = (0.4 \pm 9.0_{stat} \pm 2.8_{sys}) \times 10^{-2}$

$\Rightarrow$ one order of magnitude larger statistics in WASA pp data expected

$\Rightarrow$ KLOE-2 is expected to reduce statistical error by a factor of two

Towards rare decays: $\eta \to e^+e^-$



- SM: decay via two virtual photons
- further suppressed by helicity factors m_e/m_η at each γe^+e^- vertex
- unitarity limit: $BR(\eta \to e^+e^-) = 1.8 \times 10^{-9}$

theoretical estimate:

$BR(\eta \to e^+e^-) = (5 \pm 1) \times 10^{-9}$

L. Ametller, A. Bramon, E. Masso,
PRD 48 (1993) 3388

M. Savage, M. Luke, M. Wise,
PLB 291 (1992) 481

$\Gamma(e^+e^-)/\Gamma_{total}$ Γ_{13}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.6 × 10⁻⁶	90	[22] AGAKISHIEV	12A	SPEC	$pp \to \eta + X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.7 × 10⁻⁵	90	BERLOWSKI	08	WASA	$pd \to {}^3\mathrm{He}\,\eta$
<0.77 × 10⁻⁴	90	BROWDER	97B	CLE2	$e^+e^- \simeq 10.5$ GeV
<2 × 10⁻⁴	90	WHITE	96	SPEC	$pd \to \eta\,{}^3\mathrm{He}$
<3 × 10⁻⁴	90	DAVIES	74	RVUE	Uses ESTEN 67

[22] AGAKISHIEV 12A uses a data sample of 3.5 GeV proton beam collisions on liquid hydrogen target collected by the HADES detector.

$\Rightarrow$ sensitive to non-Standard Model contributions

Towards rare decays: $\eta \to e^+e^-$

theoretical estimate:

$BR(\eta \to e^+e^-) = (5 \pm 1) \times 10^{-9}$

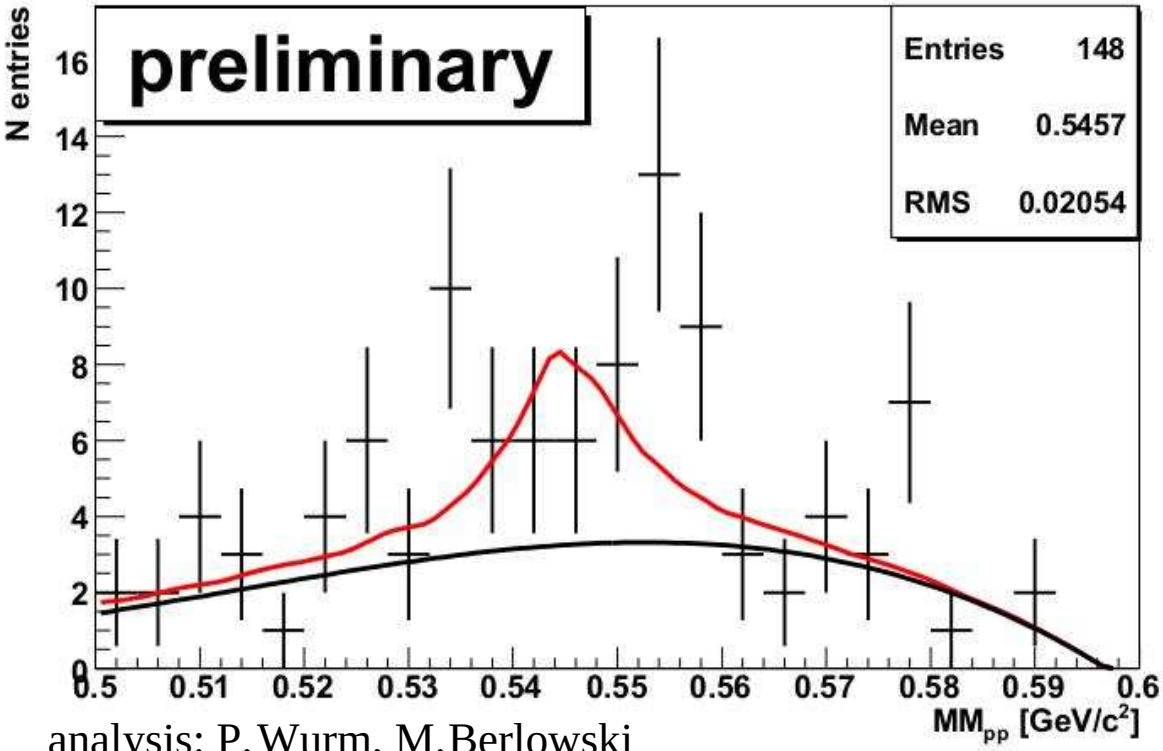
L. Ametller, A. Bramon, E. Masso,
PRD 48 (1993) 3388

M. Savage, M. Luke, M. Wise,
PLB 291 (1992) 481

experimental limit (HADES):

$BR(\eta \to e^+e^-) < 5.6 \times 10^{-6}$

G. Agakishiev et al.,
EPJA 48 (2012) 64



analysis: P. Wurm, M. Berlowski

WASA-at-COSY

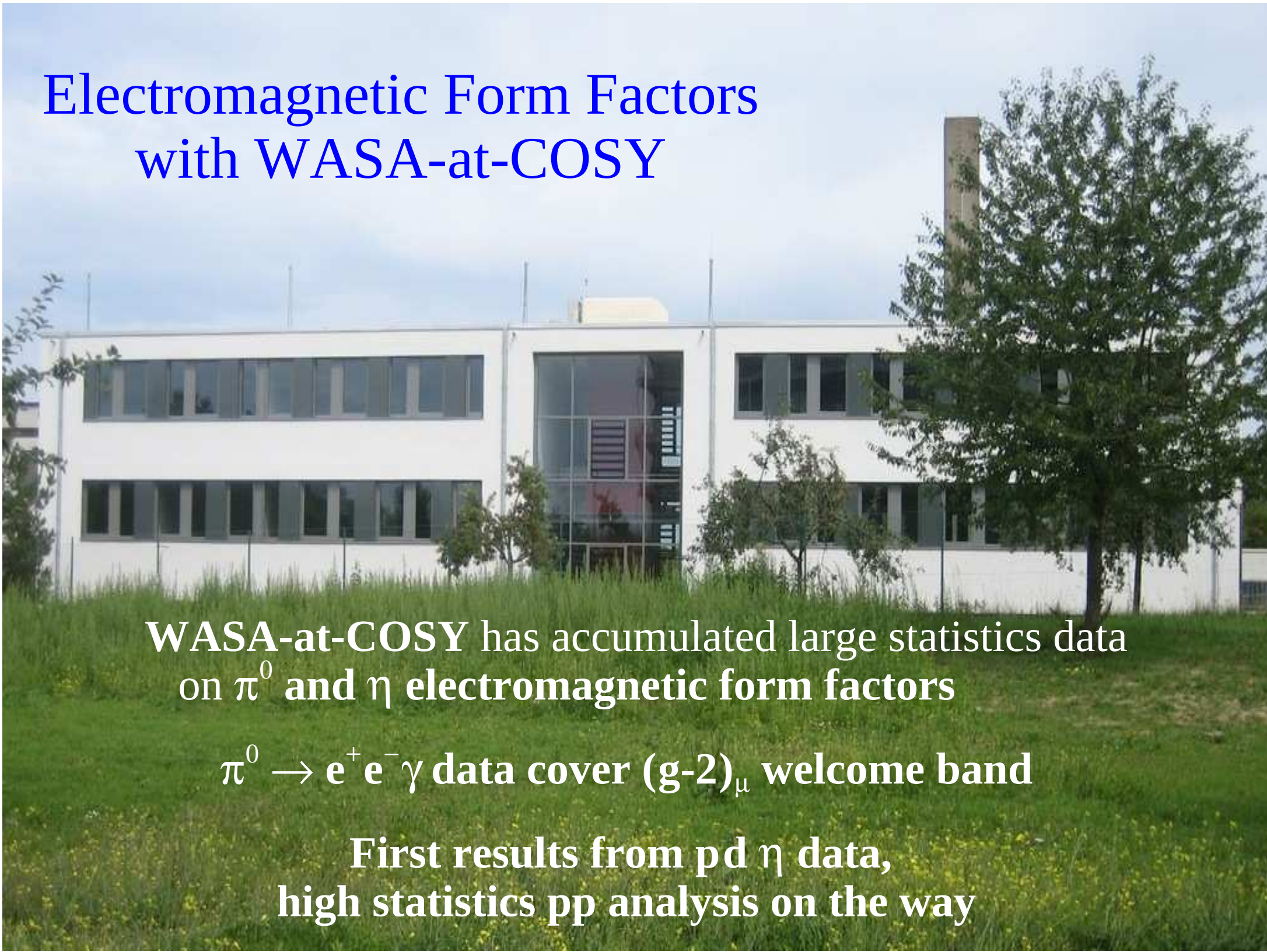
$pd \to {}^3He\eta$ (all data)

$BR < 6 \times 10^{-6}$ 90% CL, prel.

$pp \to pp\eta$ (1/9 data)

$BR < 4.6 \times 10^{-6}$ 90% CL, prel.

Electromagnetic Form Factors with WASA-at-COSY



WASA-at-COSY has accumulated large statistics data on π^0 **and** η **electromagnetic form factors**

$\pi^0 \rightarrow e^+e^-\gamma$ **data cover** $(g-2)_\mu$ **welcome band**

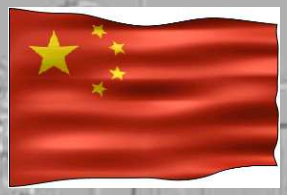
First results from pd η **data,**
high statistics pp analysis on the way

WASA-at-COSY Collaboration

147 members
27 institutions


Sofia

Spokesperson: M. Wolke (Uppsala)
Deputy: P. Moskal (Cracow)




Lanzhou

Physics Coordinator:
A. Kupsc (Uppsala)

Bochum

Bonn


Erlangen

Technical Coordinators:
H. Calen (Uppsala)
F. Goldenbaum (Jülich)

Jülich

Münster

Tübingen

IT Coordinator: V. Hejny (Jülich)


Uppsala





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