Meson Production and Decays with WASA-at-COSY

Workshop on Light Meson Dynamics

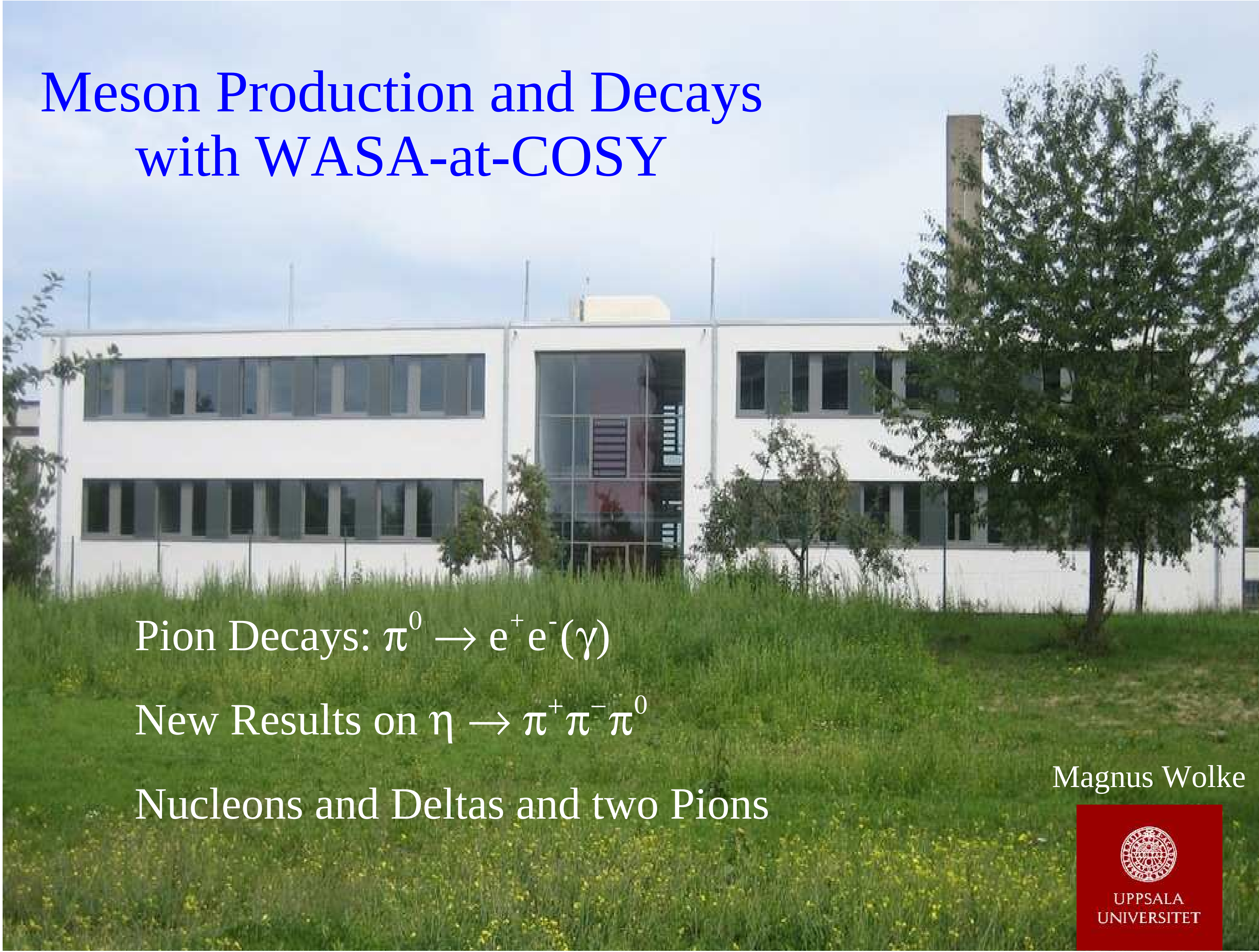
Magnus Wolke

Mainz, Feb 11, 2014

SFB 1044

UPPSALA UNIVERSITET

Meson Production and Decays with WASA-at-COSY



Pion Decays: $\pi^0 \rightarrow e^+e^-(\gamma)$

New Results on $\eta \rightarrow \pi^+\pi^-\pi^0$

Nucleons and Deltas and two Pions

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Pion Decays: $\pi^0 \rightarrow e^+e^-(\gamma)$

New Results on $\eta \rightarrow \pi^+\pi^-\pi^0$

Nucleons and Deltas and two Pions

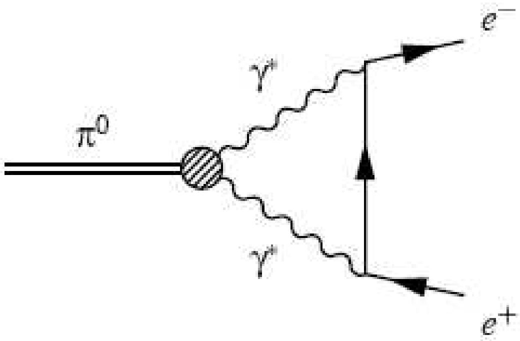
π^0 decay modes

experimentally observed

J. Beringer et al. (PDG), PRD 86 (2012) 010001

2γ	$98.823 \pm 0.034\%$
$e^+e^-\gamma$	$1.174 \pm 0.035\%$
$e^+e^-e^+e^-$	$(3.34 \pm 0.16) \times 10^{-5}$
e^+e^-	$(6.46 \pm 0.33) \times 10^{-8}$

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



- lowest order Standard Model contribution:

  1-loop process with $2\gamma^*$ intermediate state

- amplitude suppressed by helicity conservation and α^2

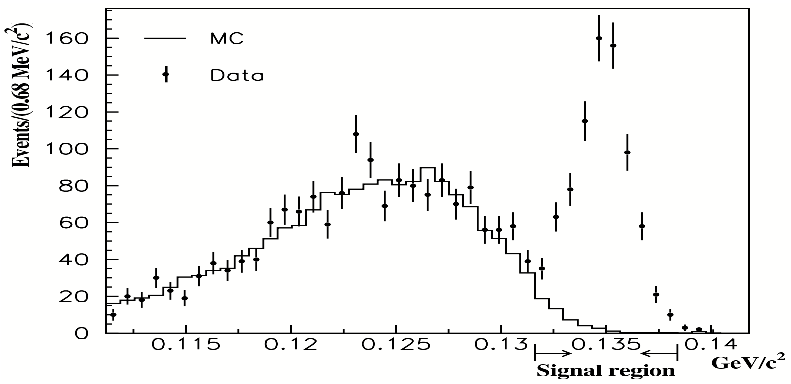
  $\Rightarrow$ extremely small decay width

- 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

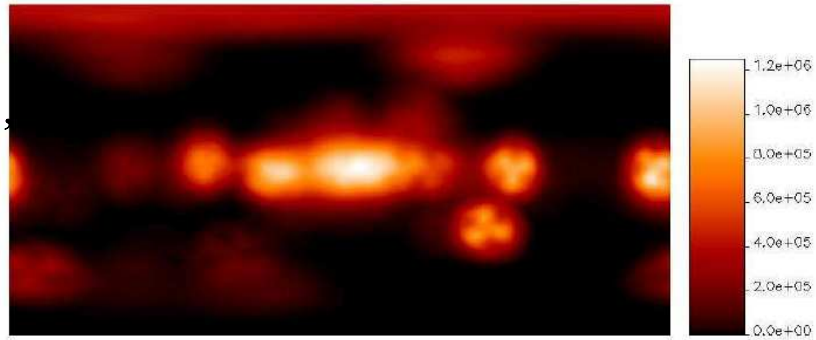
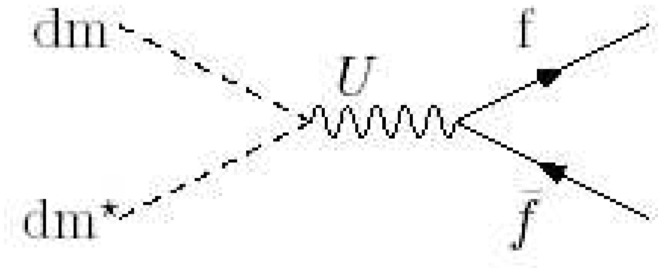


Fig. 1.— INTEGRAL/SPI Exposure map of the Galaxy for the first 10 months of operation of INTEGRAL. Horizontal range is 180° to − 180° . Vertical range is −90° to 90°. A large fraction of the observations are concentrated in the Galactic Plane. The characteristic pinwheel patterns in some regions are 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

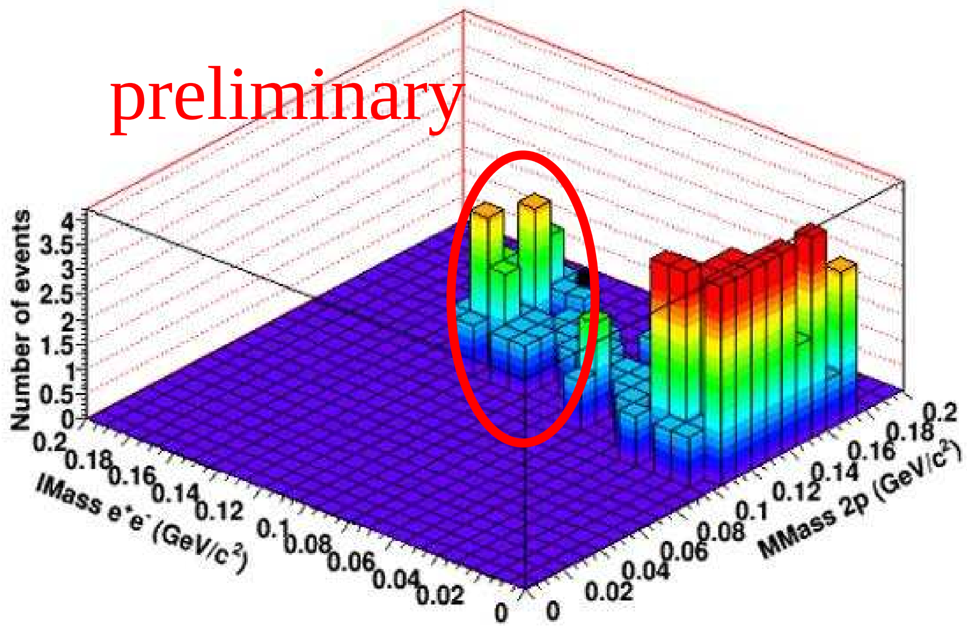


LDM model U boson might explain $\pi^0 \rightarrow e^+e^-$ excess

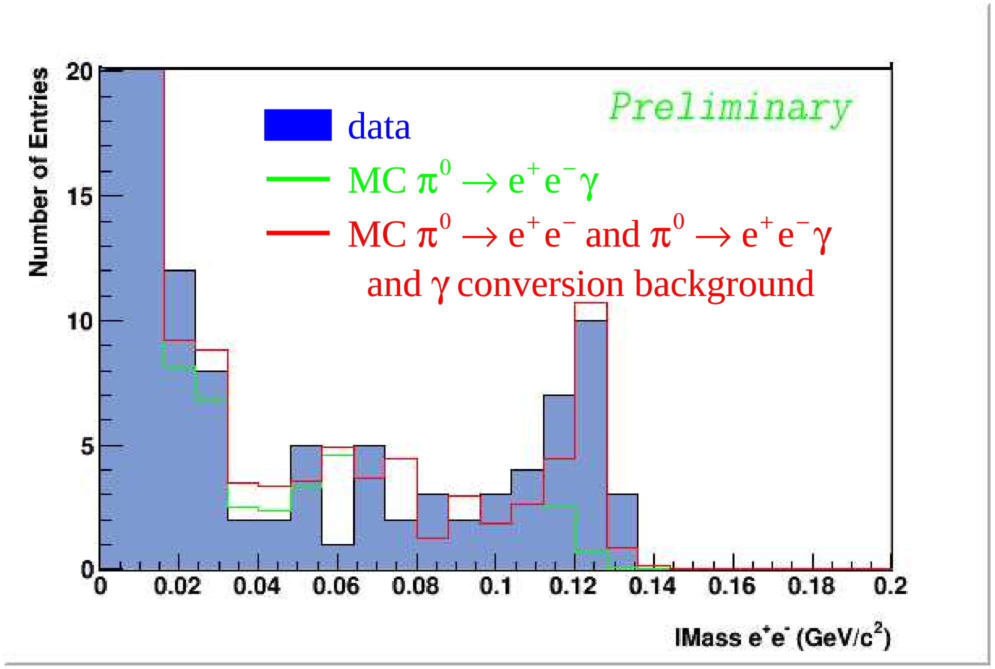
$\pi^0 \to e^+e^-$ with WASA

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

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

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

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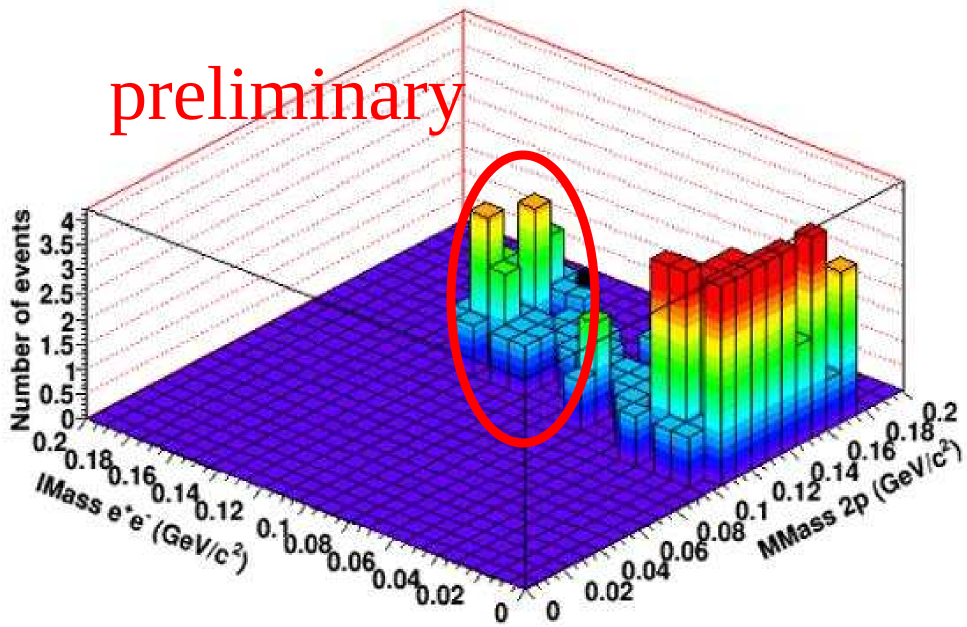
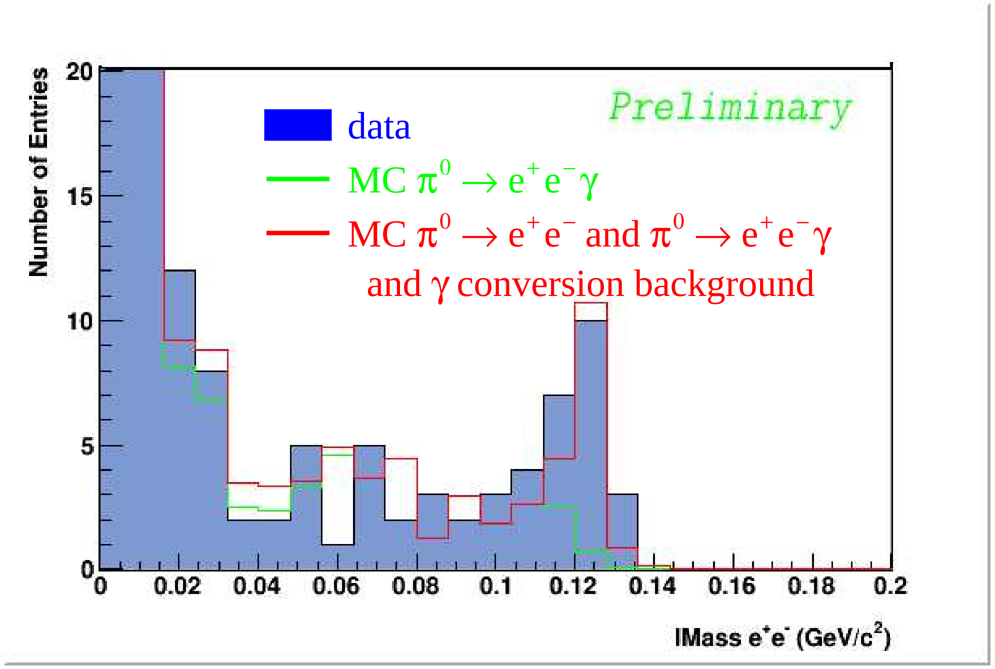


projection on inv mass (e^+e^-)



⇒ 15 event candidates in 4 days data sample

8 weeks of additional data taking in 2012 and 2013

WASA has been designed to measure this decay channel

Light Dark Matter Scenarios

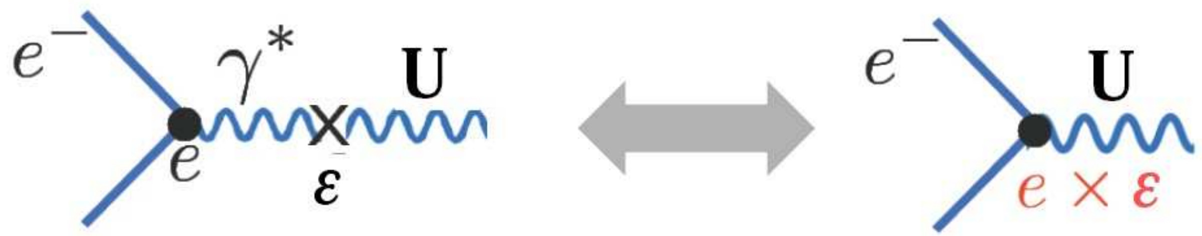
C. Boehm, P. Fayet, NPB 683 (2004) 219
Y. Kahn, M. Schmitt, T.M.P. Tait, PRD 78 (2008) 115002
M. Reece, L.T. Wang, JHEP 07 (2009) 051

Kahn et al.: common axial-vector coupling $g_A \equiv g_A^u - g_A^d = g_A^e$ from fit
(modeled according to $\pi^0 \to Z^0 \to e^+e^-$)

$\Rightarrow$ 10^{-9} contribution to $BR(\eta \to e^+e^-)$
2.0×10^{-5} contribution to $BR(\eta \to \mu^+\mu^-)$

experiment:
$BR(\eta \to e^+e^-) \leq 2.7 \times 10^{-5}$
$BR(\eta \to \mu^+\mu^-) \sim (5.7 \pm 0.9) \times 10^{-6}$

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

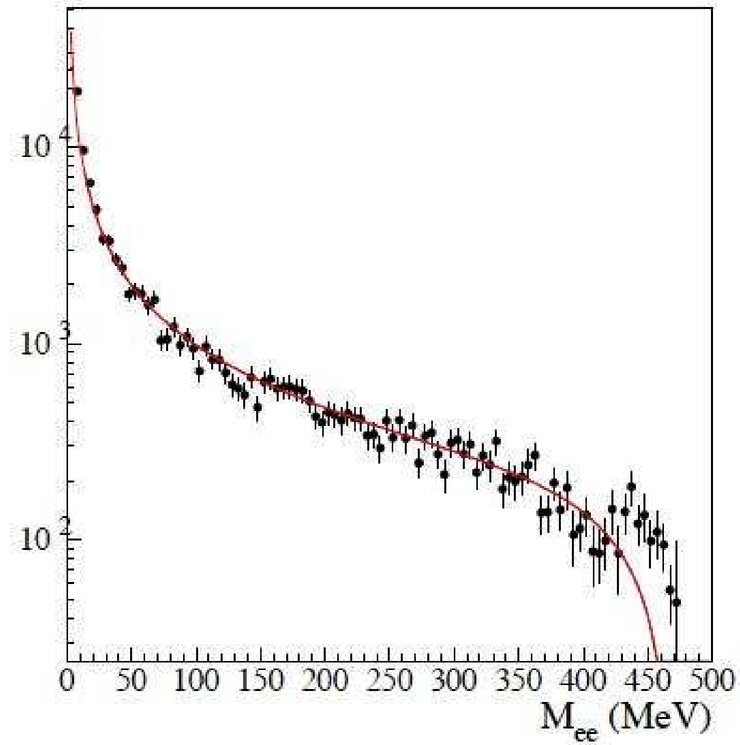


$m_U \sim 1\,\text{MeV}$ - few GeV
$\varepsilon \sim 10^{-2} - 10^{-4}$

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

Search $\phi \to \eta U$ with KLOE

PLB 706 (2012) 251



- 1.5 fb^{-1} analyzed
- η tagged via $\eta \to \pi^+\pi^-\pi^0$
- 14000 event candidates
- **no evidence for U boson**

- $\varepsilon = \alpha'/\alpha \leq 2 \times 10^{-5}$ 90% CL
- $50\,MeV < m_U < 420\,MeV$

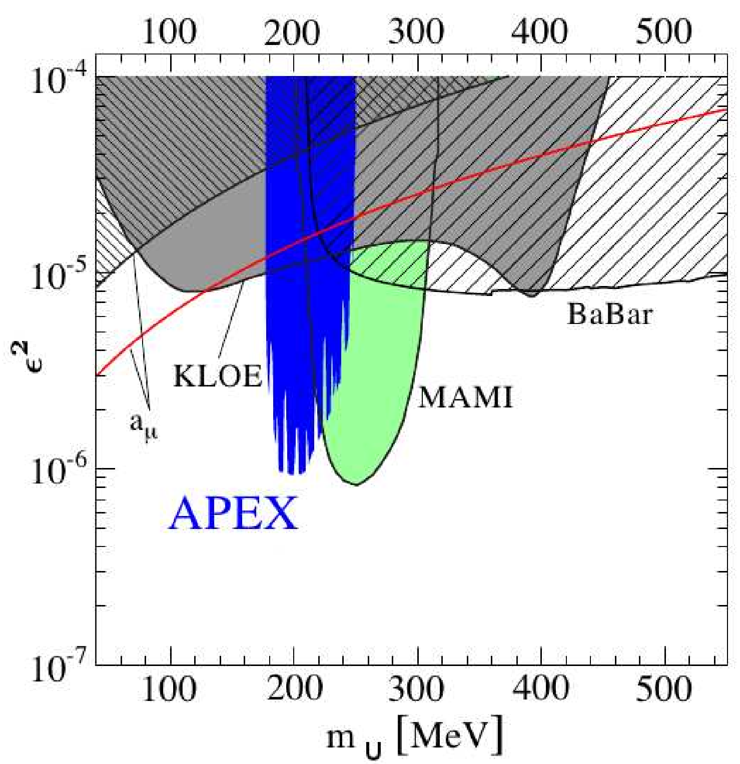
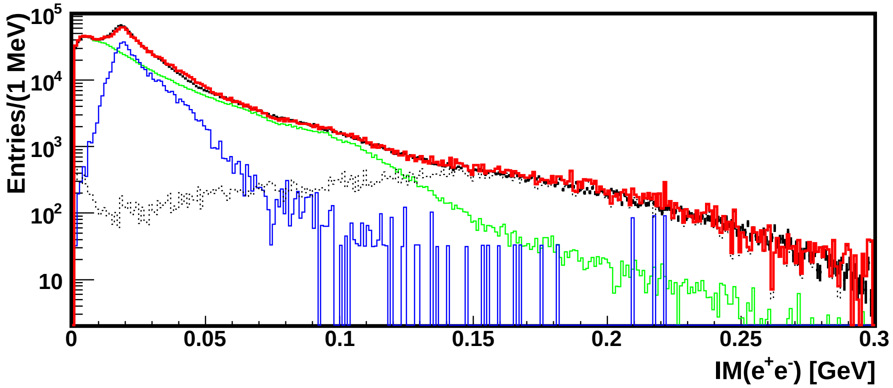


fig. adapted from G.Montagna

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

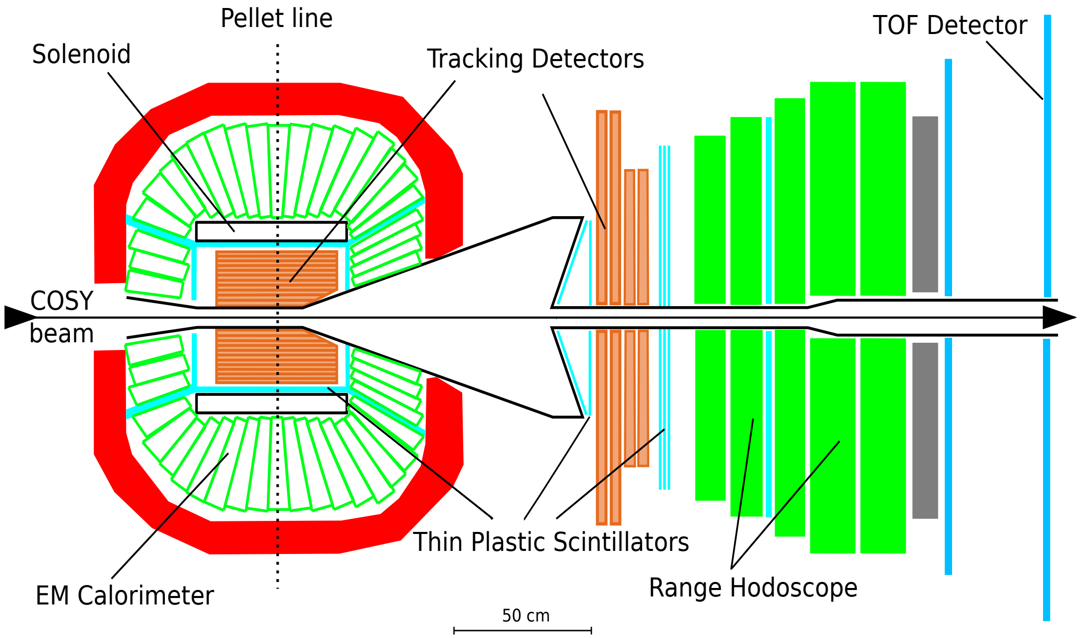
$\Rightarrow$ considerable background from γ conversion

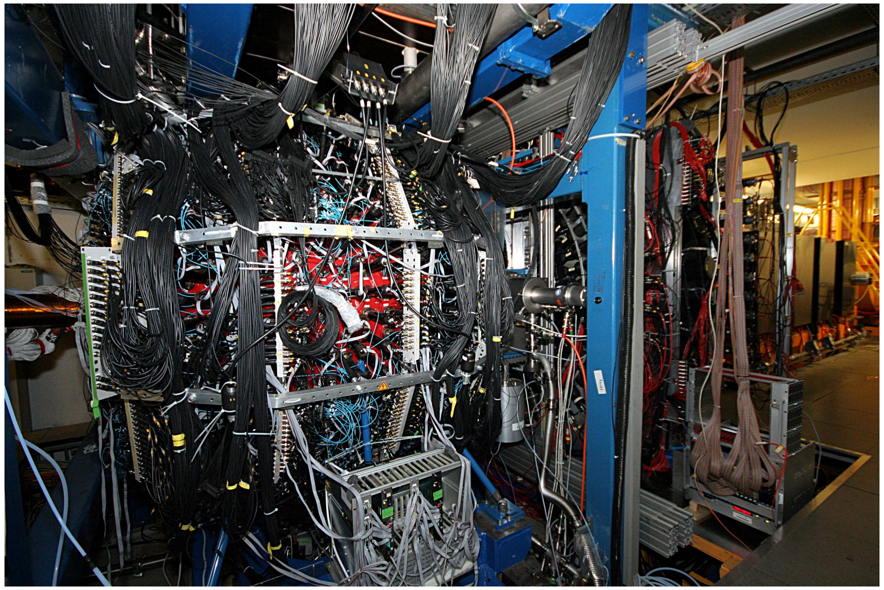
The WASA Facility

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

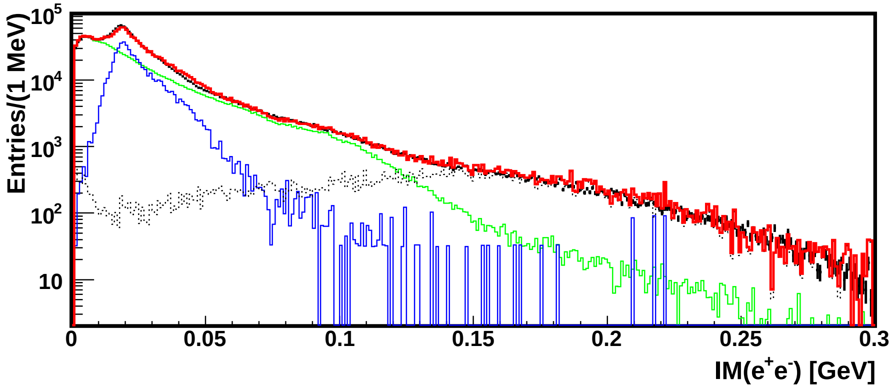
Forward Detector

...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



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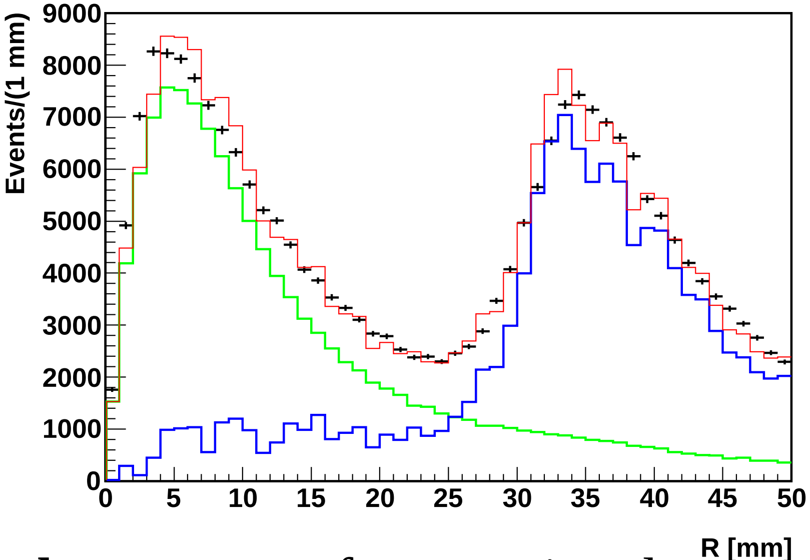
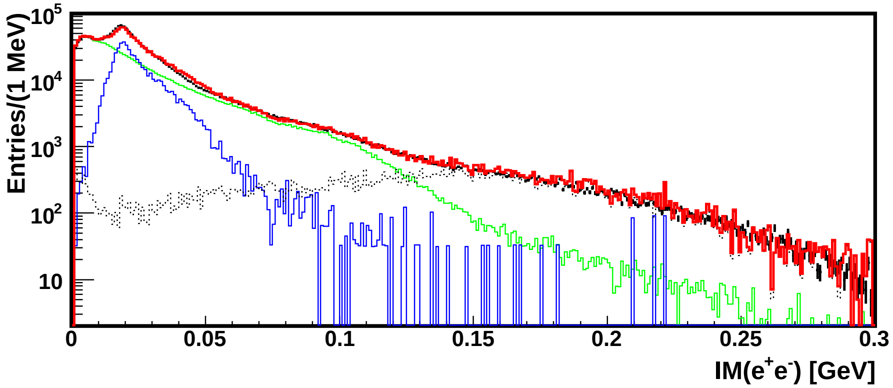


but: vertex of conversion decays is not at the target point

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

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



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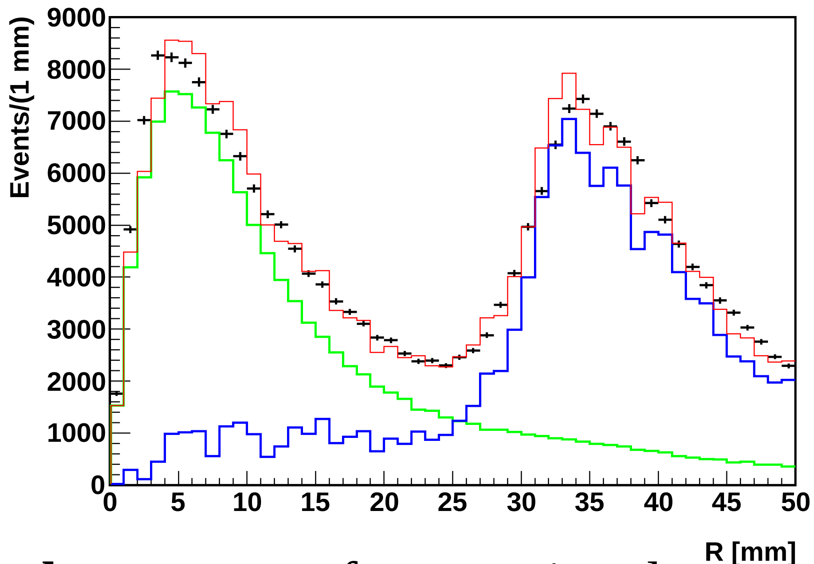

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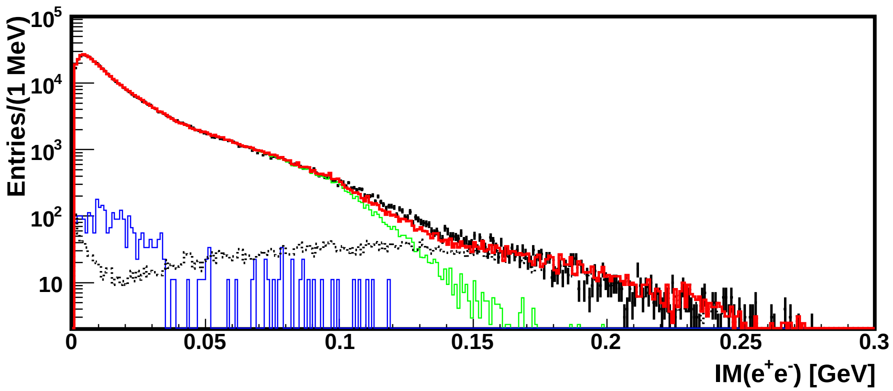


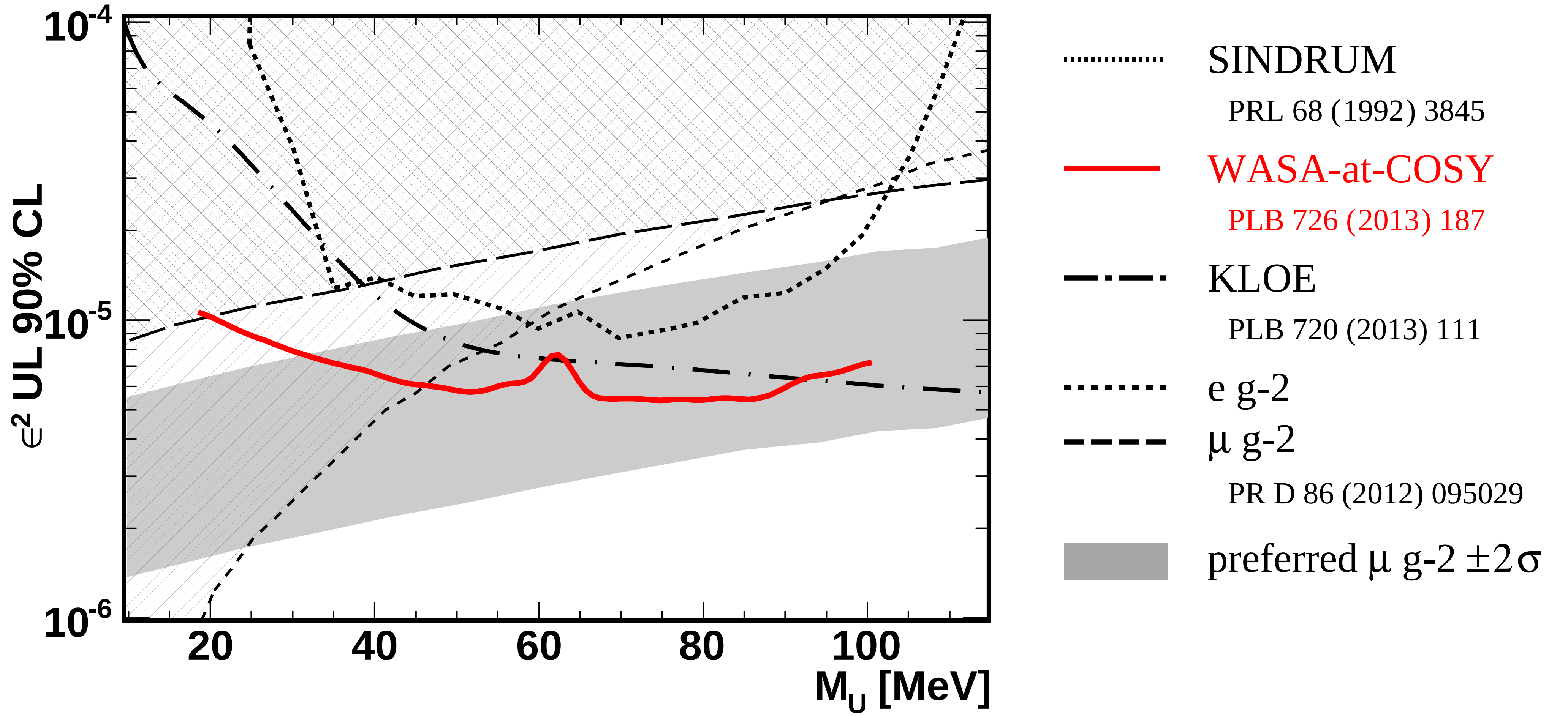
$\Rightarrow$ almost background free $\pi^0 \to e^+e^-\gamma$ events (~ 50k)

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



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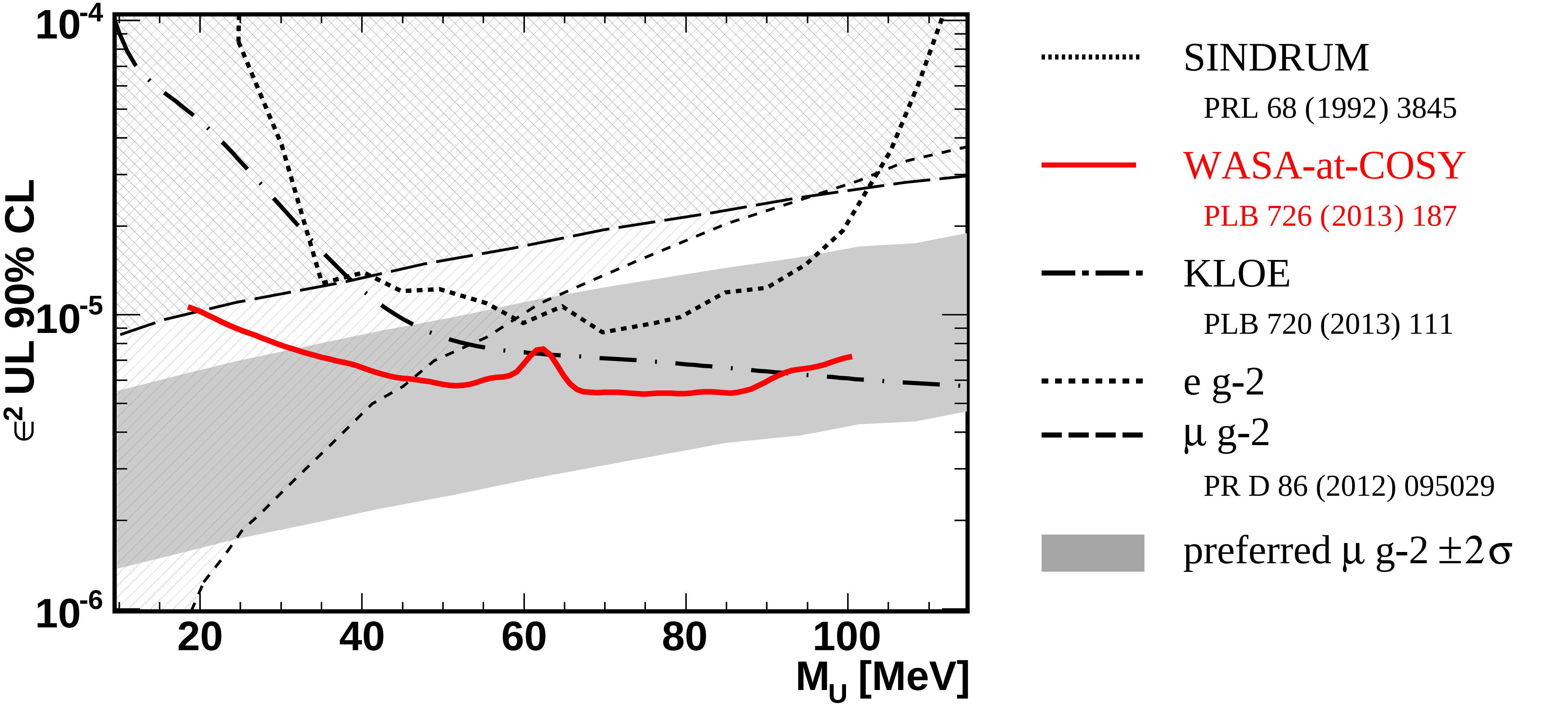
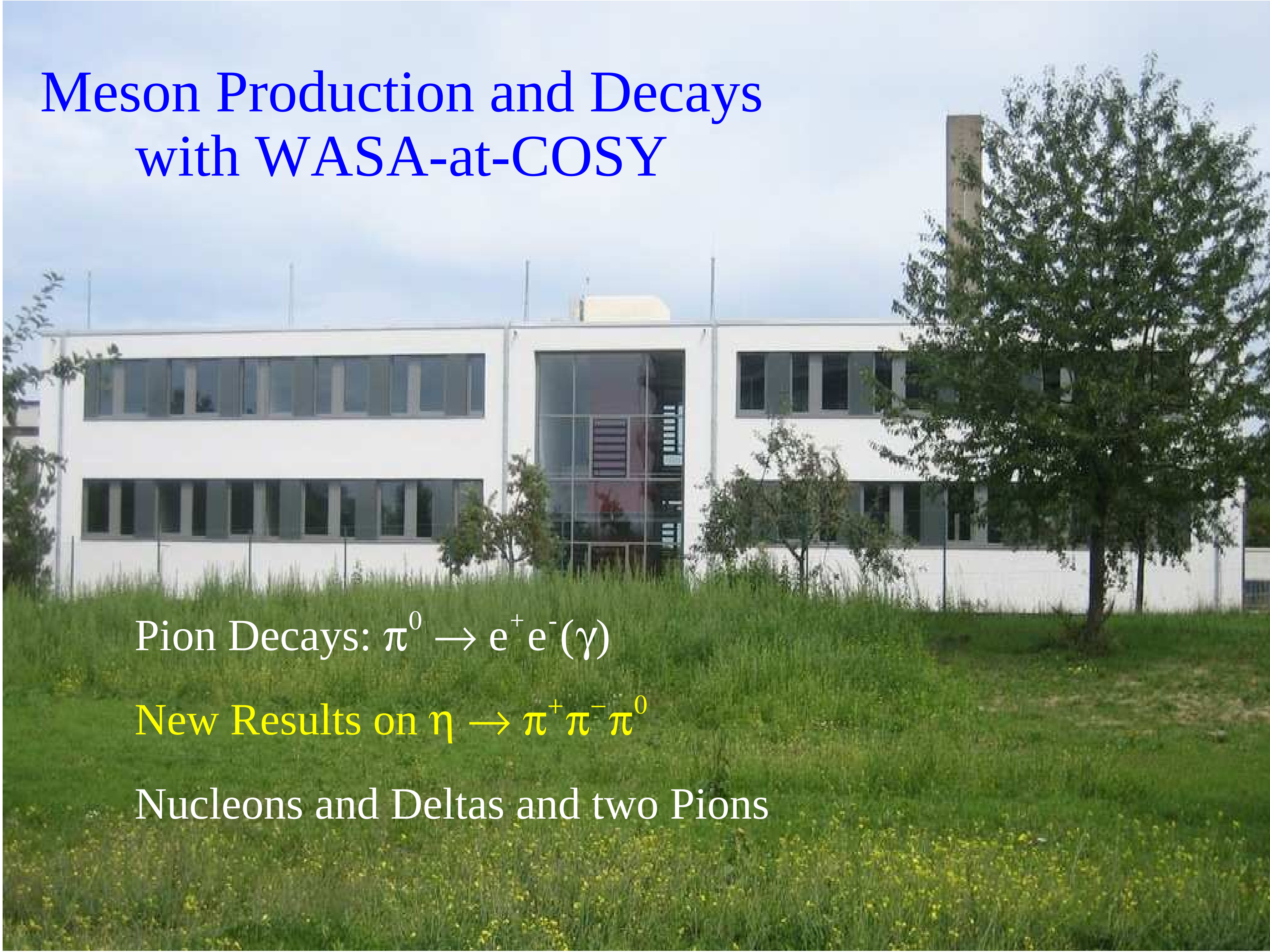
published statistics: $5 \times 10^5 \; \pi^0 \to \gamma e^+ e^-$

still to be analyzed: $\sim 8 \times 10^6 \; \pi^0 \to \gamma e^+ e^-$





Meson Production and Decays with WASA-at-COSY

Pion Decays: $\pi^0 \rightarrow e^+e^-(\gamma)$

New Results on $\eta \rightarrow \pi^+\pi^-\pi^0$

Nucleons and Deltas and two Pions

η Decays — Motivation in short

- all important quantum numbers zero: spin, isospin, electric charge, strangeness, ...

parity: $P|\eta\rangle = -1\,|\eta\rangle$

charge conjugation: $C|\eta\rangle = +1\,|\eta\rangle$

- all first order strong and electromagnetic decays of η are forbidden

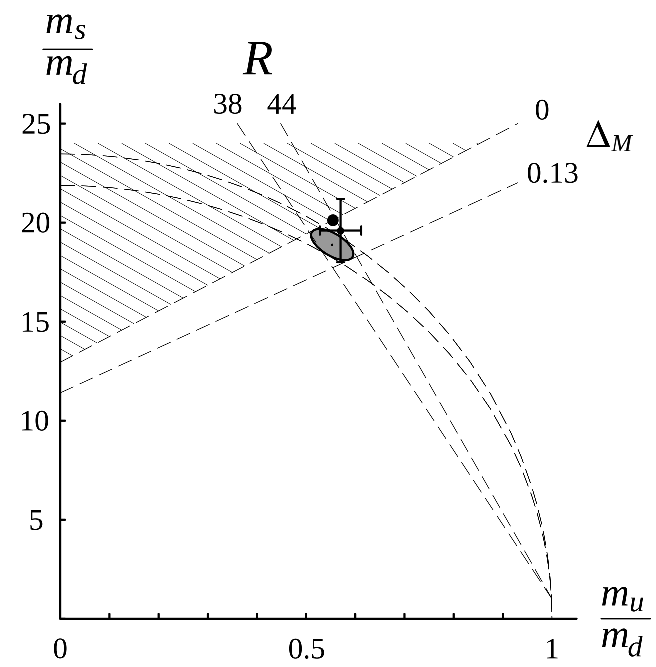
→ study higher order processes

→ test the symmetries that forbid first order decays

→ $\eta \to 3\pi$	isospin symmetry breaking ⇔ $m_d - m_u$
	$\eta \to 3\pi^0$ PLB 677 (2009) 24 $\eta \to \pi^+\pi^-\pi^0$ to be published
$\eta \to \pi^+\pi^-\gamma$	chiral anomaly PLB 707 (2012) 243
$\eta \to \pi^+\pi^-e^+e^-$	CP violation
$\eta \to e^+e^-\gamma$	Transition Form Factor
$\eta \to e^+e^-e^+e^-$	Transition Form Factor
$\eta \to e^+e^-$	SM test

$\eta \rightarrow 3\pi$ Decay

H. Leutwyler, hep-ph/9609465



Motivation: Isospin violationg decay
$\rightarrow$ sensitive to light quark mass difference

$$\Gamma = (Q_{Dashen}/Q)^4\,\bar{\Gamma} \qquad Q^{-2} = \frac{m_d^2 - m_u^2}{m_s^2 - (m_d+m_u)^2/4}$$

$$Q^2_{Dashen} = \frac{m_K^2}{m_\pi^2}\,\frac{m_K^2 - m_\pi^2}{m_{K^0}^2 - m_{K^+}^2 + m_{\pi^+}^2 - m_{\pi^0}^2}$$

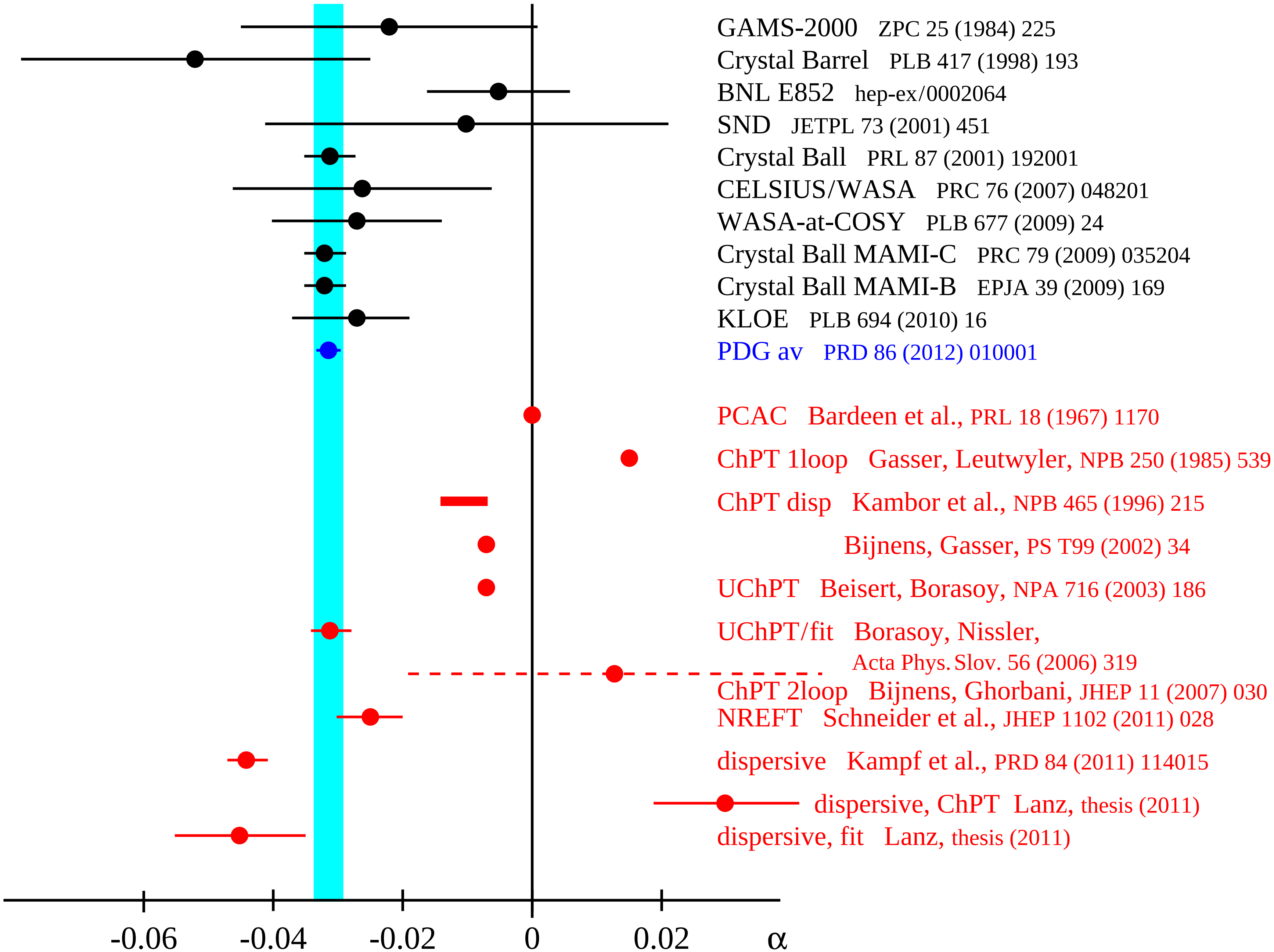
Strategy: measure Γ, and calculate $\bar{\Gamma}$ (ChPT) to extract Q

test dynamics that enter $\bar{\Gamma} \rightarrow$ Dalitz plot

$\eta \rightarrow 3\pi^0$ $\qquad \bar{\Gamma} \propto |A(z)|^2 = c_0(1+2\alpha z)$ $\qquad z = (\rho/\rho_{max})^2 = 6\sum_{i=1}^{3}\left(\frac{E_i - m_\eta/3}{m_\eta - m_\pi}\right)^2$

First step: slope parameter α

$\eta \to 3\pi$ Dalitz Plot: Experiment and Theory



$\eta \to \pi^+\pi^-\pi^0$ at KLOE

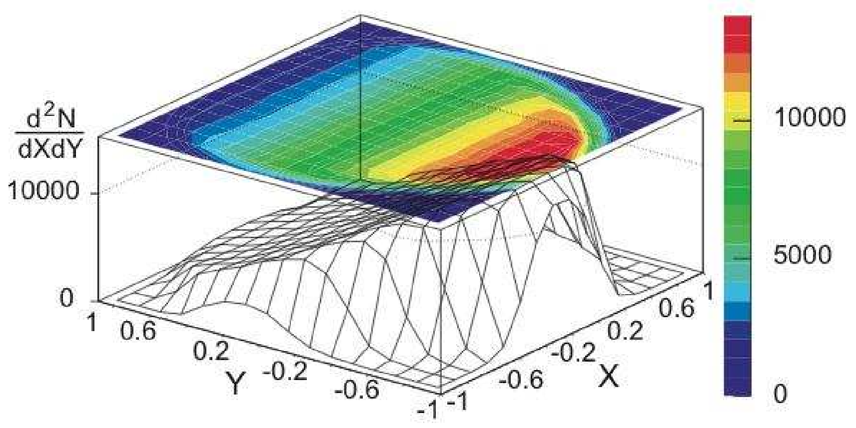
JHEP 05 (2008) 006

$$X = \sqrt{3}\,\frac{T_+ - T_-}{Q_\eta} \qquad Y = \frac{3T_0}{Q_\eta} - 1$$

parametrize Dalitz plot density around X = Y = 0:

$$|A(X,Y)|^2 \propto 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + \dots$$

largest statistics available: KLOE measurement (450 pb^{-1} analyzed, 1.34×10^6 events)



a	**$-1.090 \pm 0.005\ ^{+0.008}_{-0.019}$**
b	**$0.124 \pm 0.006 \pm 0.010$**
c	**$0.002 \pm 0.003 \pm 0.001$**
d	**$0.057 \pm 0.006\ ^{+0.007}_{-0.016}$**
e	**$-0.006 \pm 0.007\ ^{+0.005}_{-0.003}$**
f	**$0.14 \pm 0.01 \pm 0.02$**
$P(\chi^2)$	**73%**

parameters c, e compatible with zero $\to$ no evidence for c violation

parameters a, b at variance with NNLO ChPT

J.Bijnens, K.Ghorbani, JHEP 11 (2007) 230

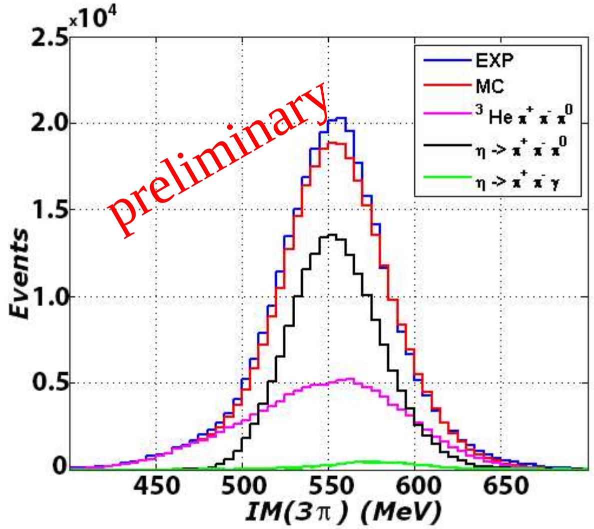
entire KLOE data set: 5 times higher luminosity

$\eta \to \pi^+\pi^-\pi^0$ at WASA

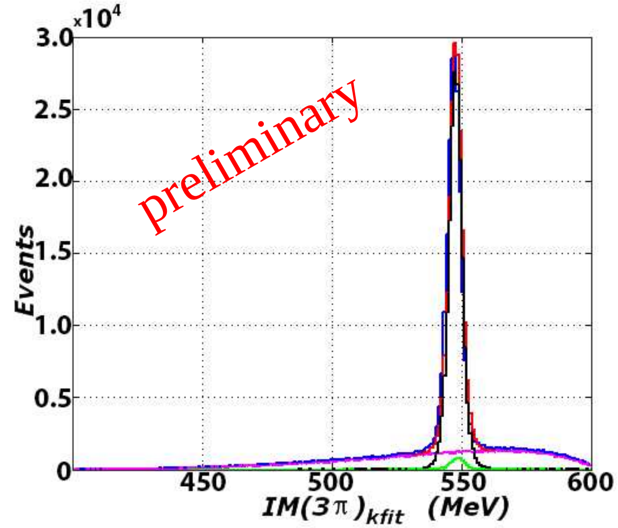
10^7 tagged ($pd \to {}^3\text{He}X$) η meson decays analyzed (P.Adlarson)

invariant mass ($\pi^+\pi^-\pi^0$)

before kinematical fit



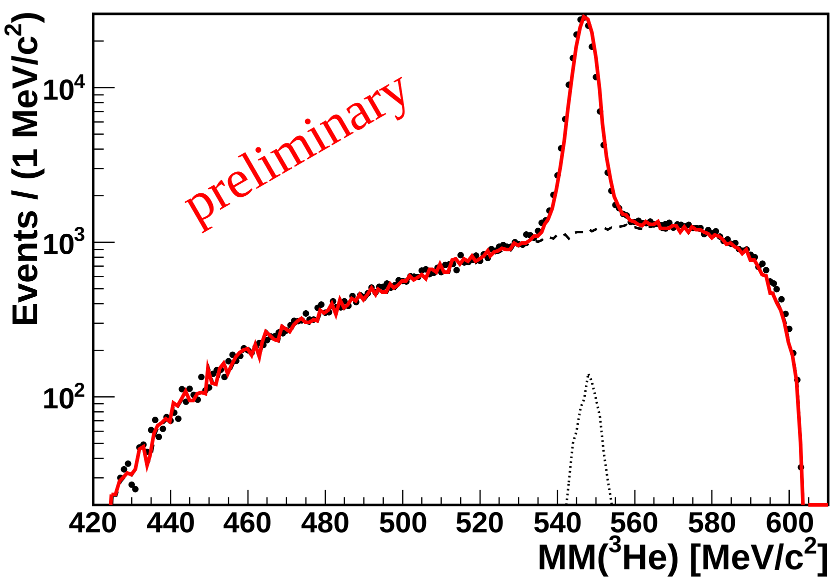
after kinematical fit



FWHM ($\pi^+\pi^-\pi^0$) $\approx$ 60 MeV

FWHM ($\pi^+\pi^-\pi^0$) $\approx$ 6 MeV

final $\eta \to \pi^+\pi^-\pi^0$ event sample

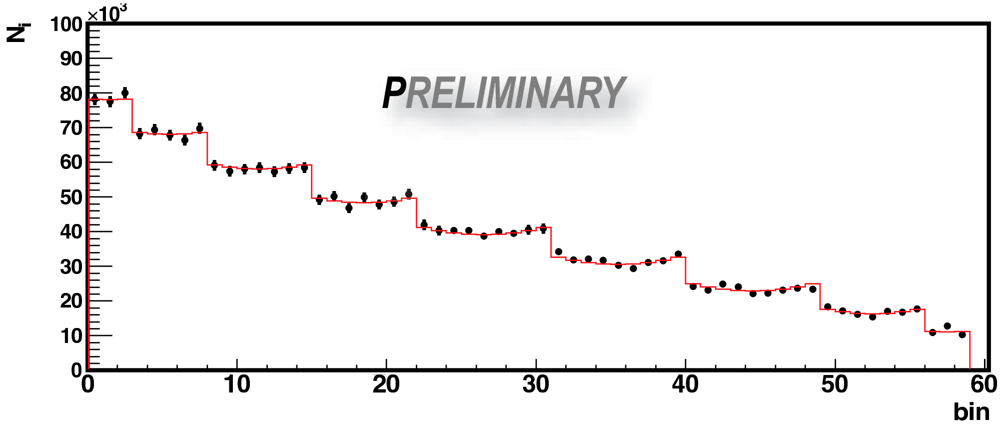


$\Rightarrow 1.74 \times 10^5$ $\eta \to \pi^+\pi^-\pi^0$ events

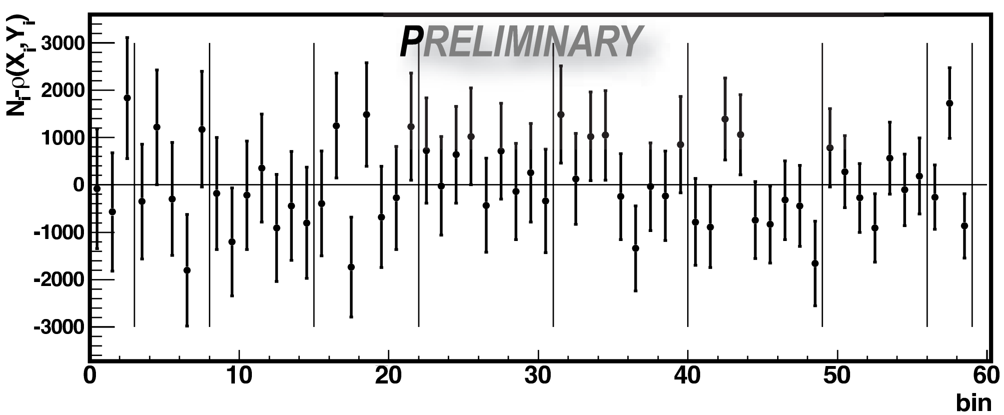
$\eta \to \pi^+\pi^-\pi^0$ Dalitz plot

10^7 tagged ($pd \to {}^3HeX$) η meson decays analyzed (P. Adlarson)

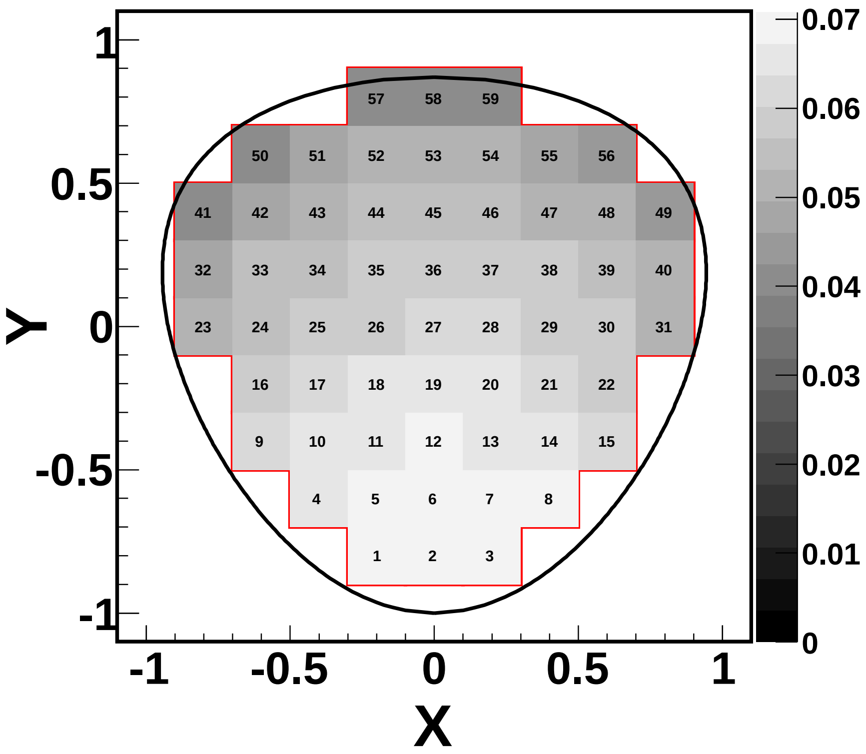
acceptance corrected Dalitz plot occupancy:



residual with respect to fit:



Dalitz plot acceptance:



⇒ preliminary DP parameters released

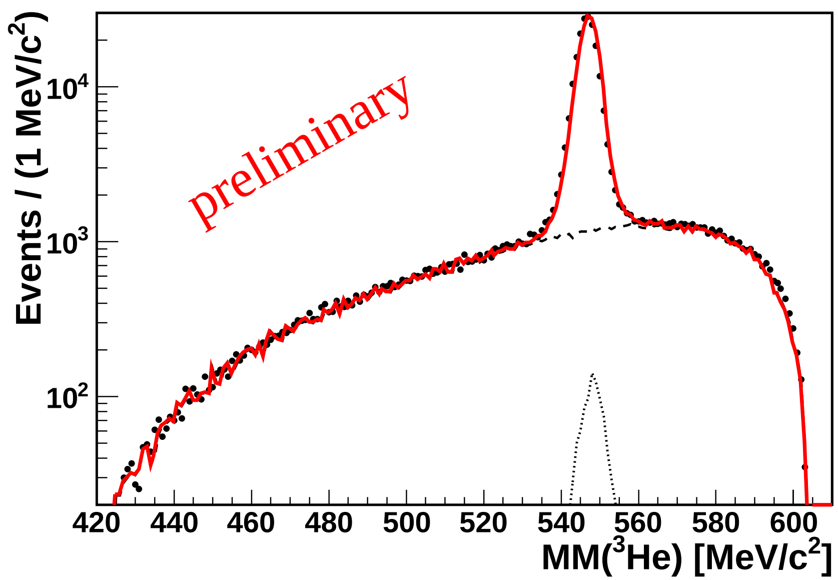
$\eta \to \pi^+\pi^-\pi^0$ Dalitz plot parameters

$$|A(X,Y)|^2 \propto 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + \ldots$$

Theory:	**-a**	**b**	**d**	**f**
ChPT NNLO Bijnens, Ghorbani 07	1.271(75)	0.394(102)	0.055(57)	0.025(160)
NREFT Schneider, Kubis, Ditsche 10	1.213(14)	0.308(23)	0.050(3)	0.083(19)

Experiment:				
KLOE 2008 (0.45 fb^{-1})	$1.090(5)(^{+19}_{-8})$	0.124(6)(10)	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)
KLOE 2013 prel. (1.6 fb^{-1})	1.104(3)	0.144(3)	0.073(3)	0.155(6)
WASA 2014 prel.	1.144(18)	0.219(19)(31)	0.086(18)(18)	0.115(37)
WASA rel KLOE 2008	$+2.3\sigma$	$+2.1\sigma$	$+1.0\sigma$	-0.6σ

$\eta \rightarrow \pi^+\pi^-\pi^0$ at WASA



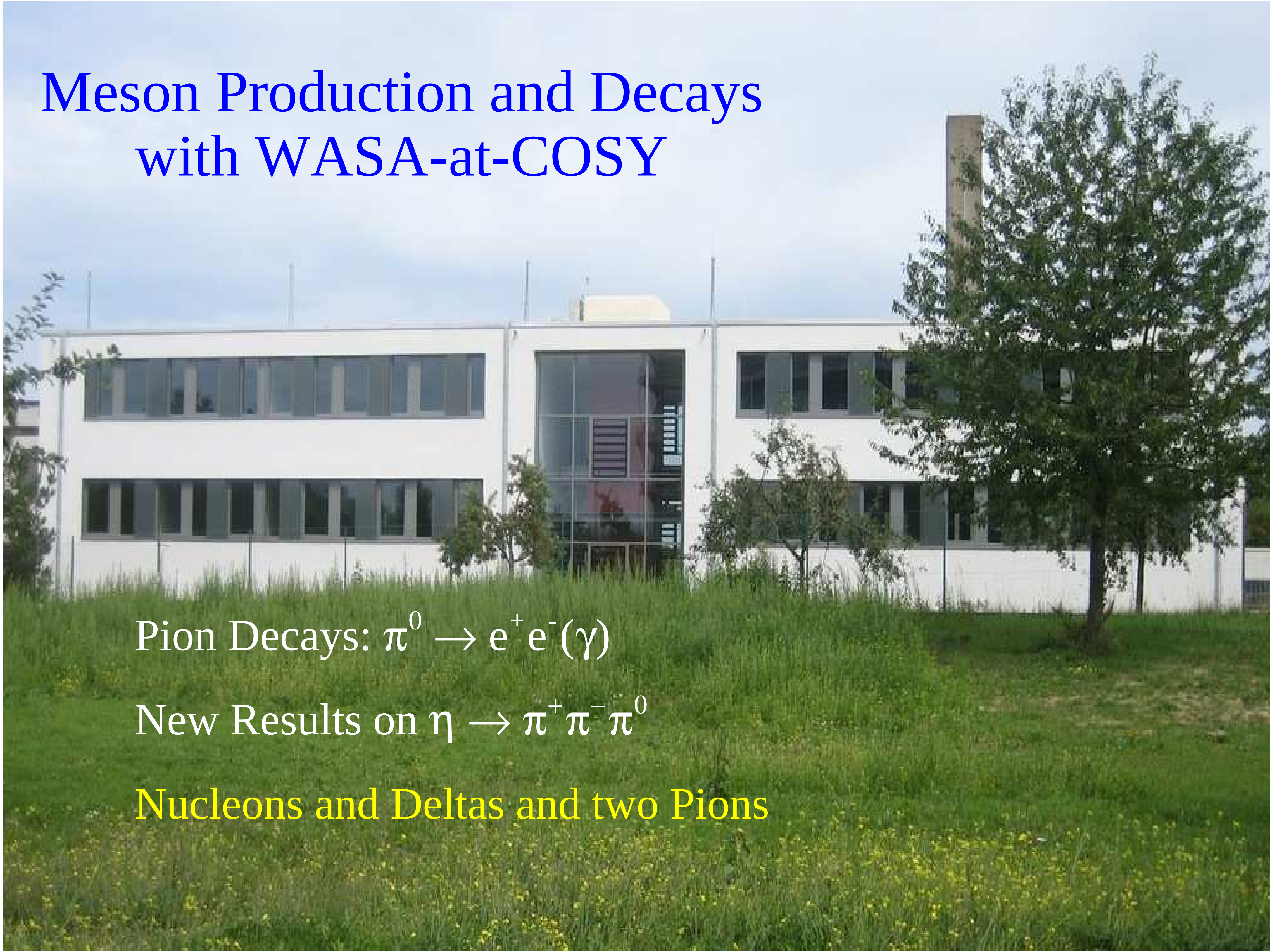
$\Rightarrow 1.74 \times 10^5$
$\eta \rightarrow \pi^+\pi^-\pi^0$ events

result to be submitted for publication soon

statistics correspond to 1/3 of available statistics in $pd \rightarrow {}^3\text{He}\ X$

statistics in $pp \rightarrow pp\ X$ **at least** one order of magnitude larger

Meson Production and Decays with WASA-at-COSY



Pion Decays: $\pi^0 \rightarrow e^+e^-(\gamma)$

New Results on $\eta \rightarrow \pi^+\pi^-\pi^0$

Nucleons and Deltas and two Pions

Introduction: Wild Goose Chases

The fundamentalists believe that *"In the beginning God created the Bag"*, and follow the implications of the Bag with religious fervor. The lunatic fringe believe that the *"n"* in *Big Bang* cosmology is a typographical error and that all multiquark physics is describable with a *Big Bag*.

They lose all contact with the real world as they follow their religion and send experimentalists on wild goose chases for nonexistent objects like narrow baryonium states.

Harry J. Lipkin,

Models of Multiquark States,

CIPANP 86, Lake Louise, Alberta

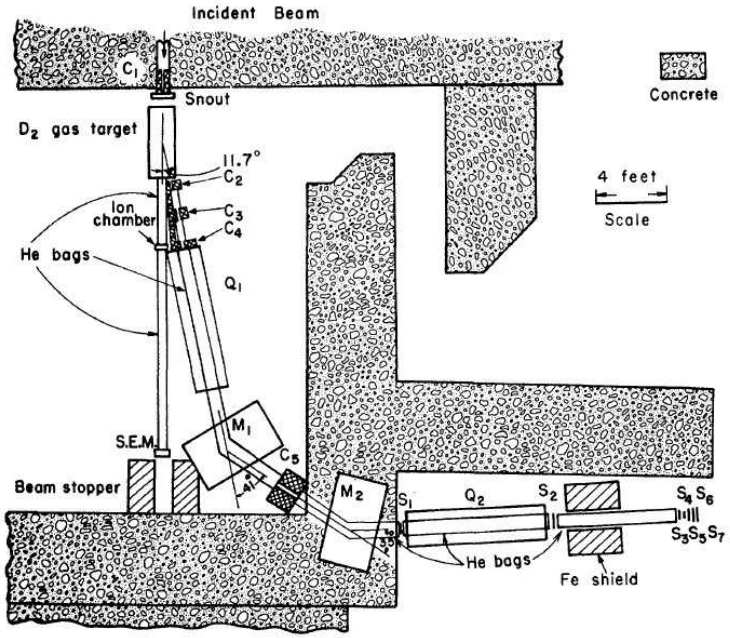
AIP Conf. Proc. Lett. 150 (1986) 657

ABC — first observation

(Abashian, Booth, Crowe)

A. Abashian, N. E. Booth, K. M. Crowe,
Phys. Rev. Lett. 5 (1960) 258

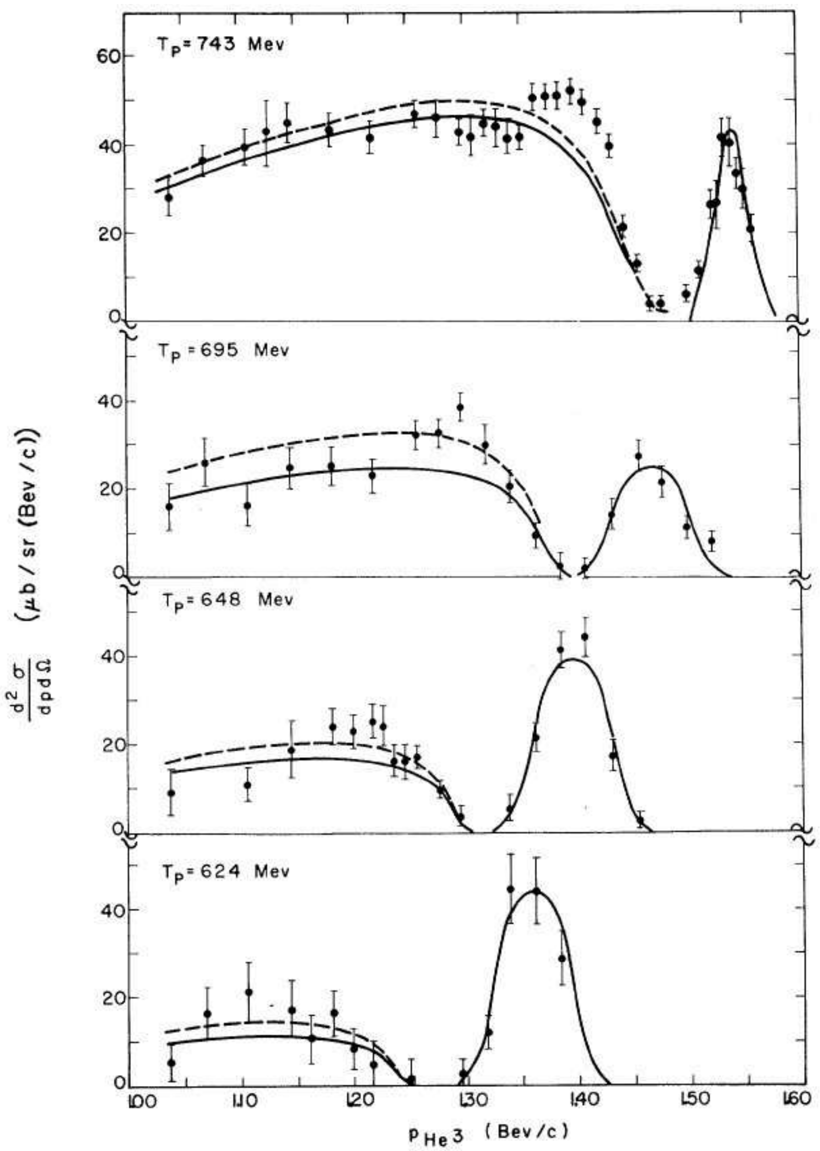
Lawrence Radiation Laboratory
184 inch cyclotron (p), d_2 gas target



at the time of PRL 5 (1960):

"The data are inconsistent with the relativistically invariant phase space assumed. [...] Plausible explanations [...] are the existence of a new neutral particle or a resonant π–π system."

$pd \to {}^3\mathrm{He}X$, $\theta_{He} = 11.5°$



ABC Effect

(Abashian, Booth, Crowe)

A. Abashian, N. E. Booth, K. M. Crowe,
Phys. Rev. Lett. 5 (1960) 258

$pd \rightarrow {}^3He\,X,\ \theta_{He} = 11.5°$

low mass isoscalar enhancement in $m(\pi\pi)$

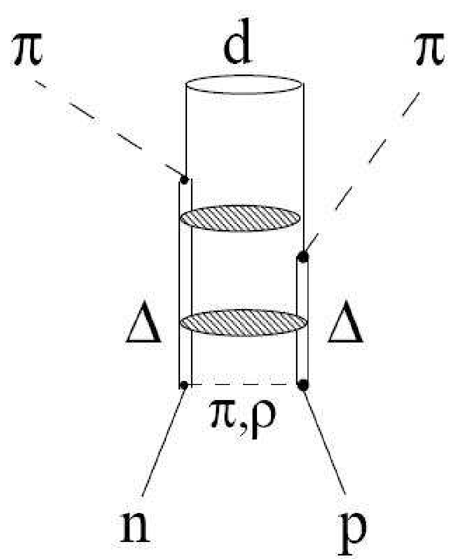
observed in the production of...

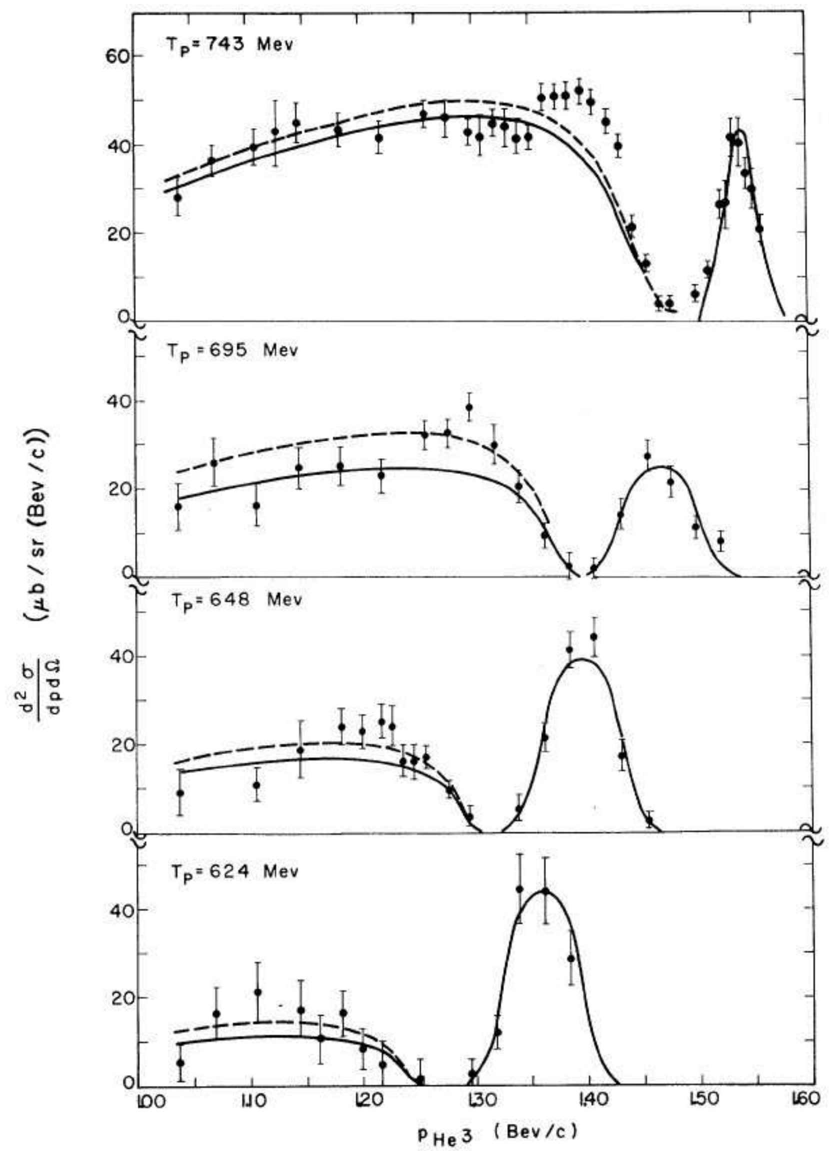
...a scalar-isoscalar pion pair

...on an isoscalar nucleon pair

...which fuses to a bound state

accompanied with
$\Delta\Delta$ excitation





$\pi\pi$ production in few-nucleon systems

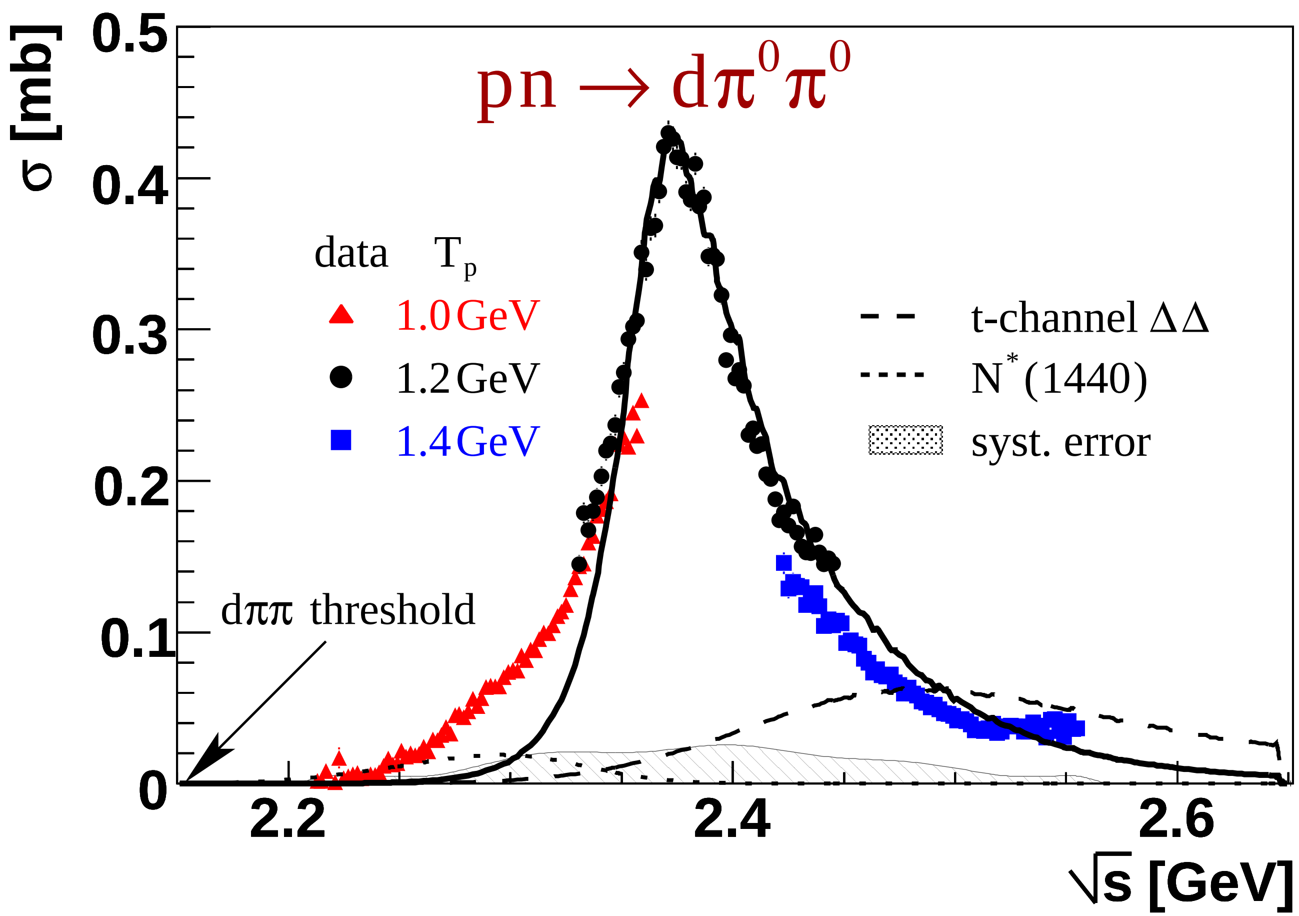
	$\pi\pi$ system
$pp \to pp\pi\pi$	$I = 0,1,2$
$pp \to pn\pi^+\pi^0$	1
$pp \to nn\pi^+\pi^+$	1
$pn \to \ldots$	
$pn \to d\pi\pi$	0,1
$pp \to d\pi^+\pi^0$	1
$pd \to {}^3He\pi\pi$	0,1
$pd \to {}^3H\pi^+\pi^0$	1
$dd \to {}^4He\pi\pi$	0

ππ production in few-nucleon systems

	$\pi^0\pi^0$ system	
$pp \rightarrow pp\pi\pi$	I = 0,~~1~~,2	
$pn \rightarrow \ldots$		
$pn \rightarrow d\pi\pi$	0,~~1~~	ABC effect
$pd \rightarrow {}^3He\pi\pi$	0,~~1~~	ABC effect
$dd \rightarrow {}^4He\pi\pi$	0	ABC effect

$pn \to d\pi^0\pi^0$ — Total cross section

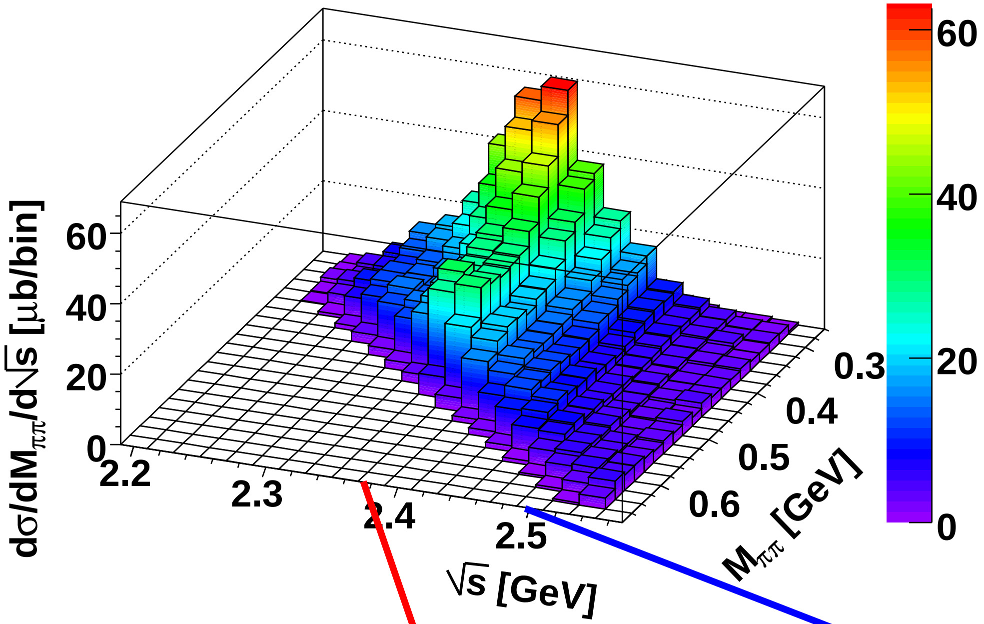
P.Adlarson et al., PRL 106 (2011) 242302

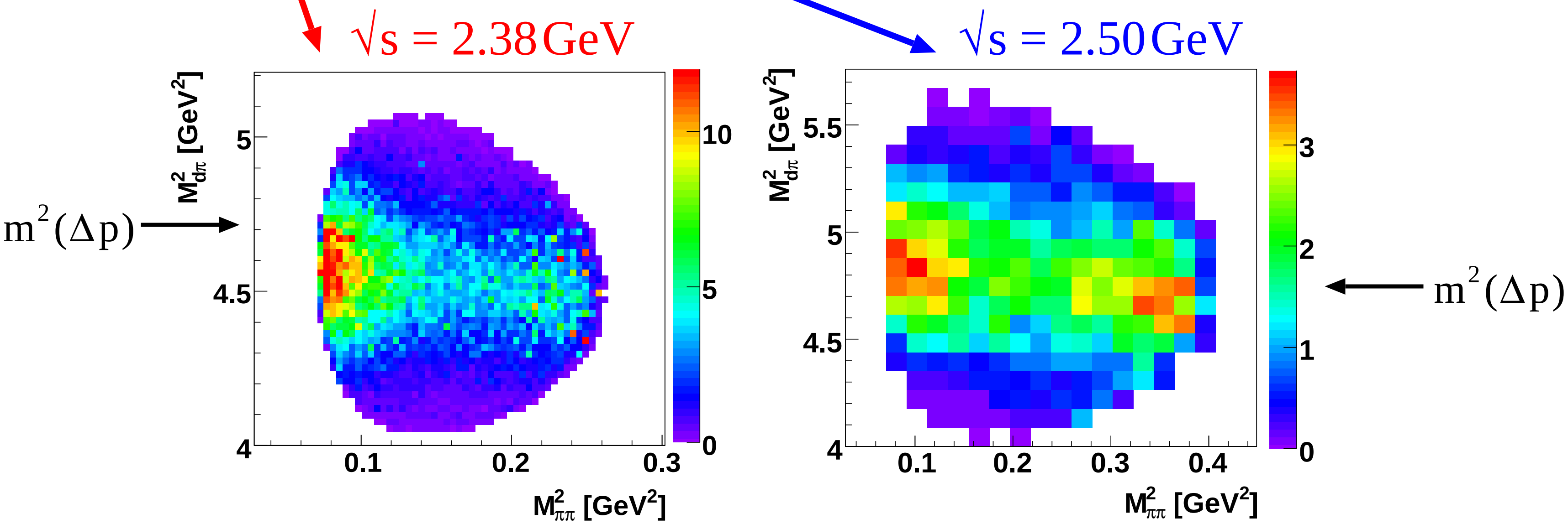


- Lorentzian shaped energy distribution
- 4 times narrower compared with ΔΔ, peak 80 MeV below $2m_\Delta$
- good agreement with CELSIUS/WASA (**but:** 2 orders of magnitude larger statistics!)

$pn \to d\pi^0\pi^0$ Dalitz plots

P.Adlarson et al., PRL 106 (2011) 242302

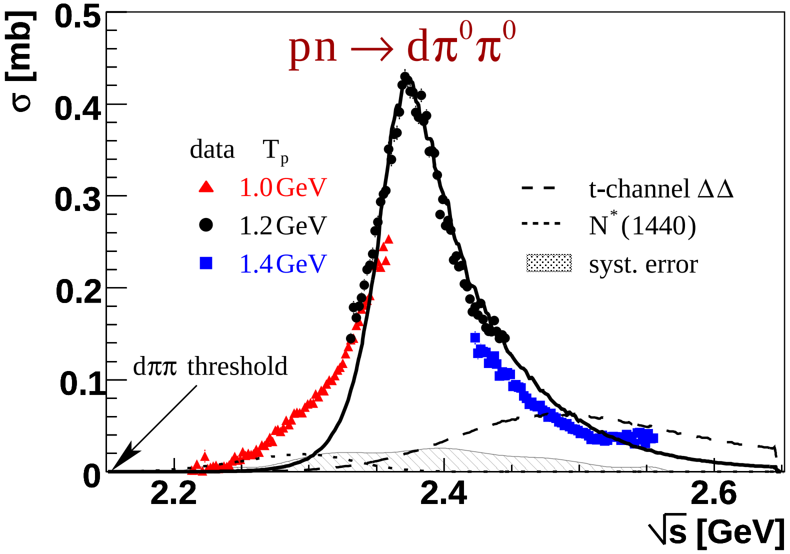


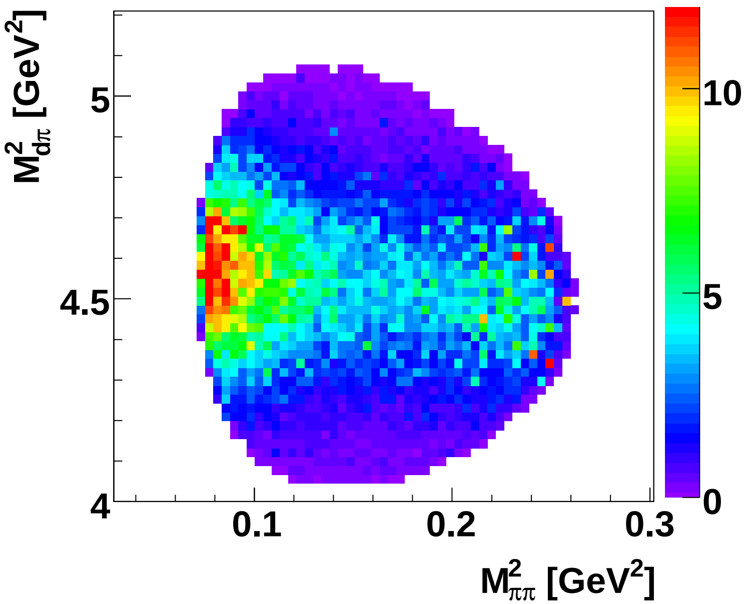


- Excitation of $\Delta\Delta$ intermediate state
- **outside peak** cross section: t-channel $\Delta\Delta$ excitation
- **at peak** cross section: low mass $\pi^0\pi^0$ **ABC** enhancement

$pn \to d\pi^0\pi^0$ and ABC effect

- WASA-at-COSY data link $pn \to d\pi^0\pi^0$
  resonance-like cross section and ABC effect
- still: no conventional explanation at hand
- unconventional explanation:
  s-channel $I(J^P) = 0(3^+)$ resonance
  $m \approx 2.37\,GeV$, $\Gamma \approx 70\,MeV$
- isovector $p\,p \to d\pi^+\pi^0$ shows no ABC effect and
  no resonance-like cross section





$pn \to d\pi^0\pi^0$ and ABC effect

- WASA-at-COSY data link $pn \to d\pi^0\pi^0$
  resonance-like cross section and ABC effect

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- unconventional explanation:
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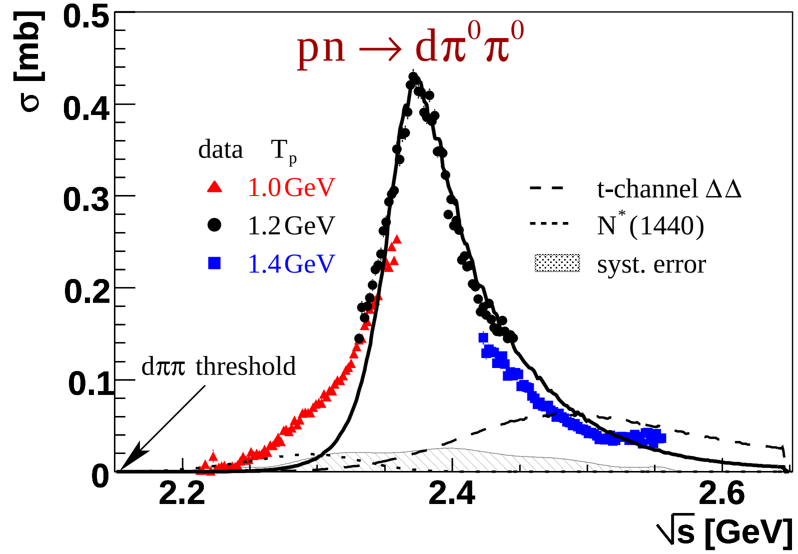
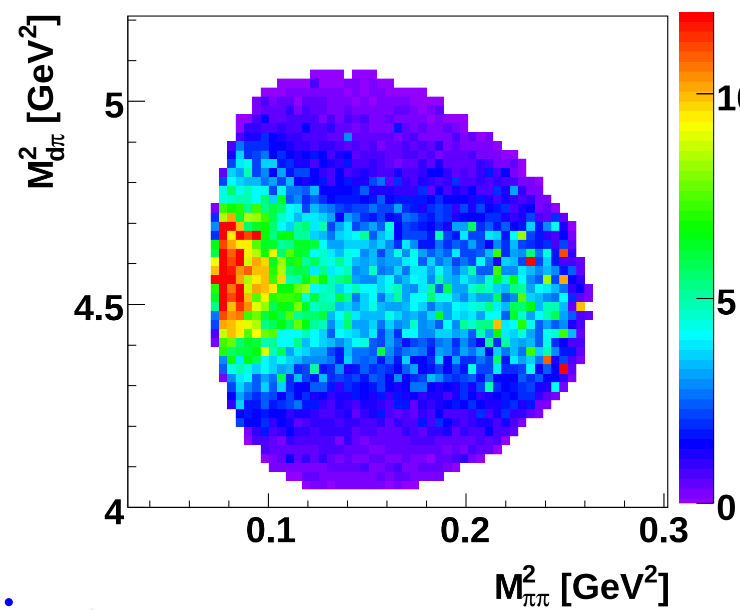


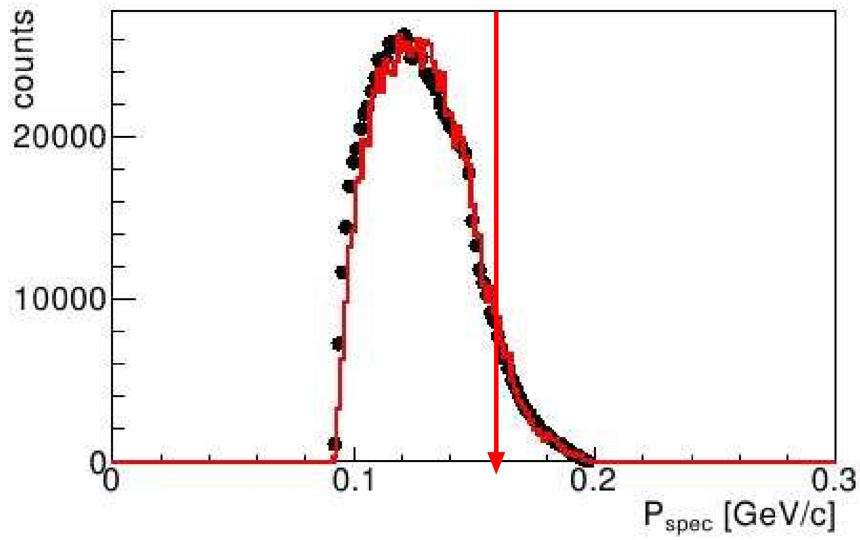


$\Rightarrow$ resonance should be observable in
$(J^P = 3^+)$ proton neutron elastic scattering

Quasifree $\vec{d}p \to np + p_{spectator}$

kinetic energy T_d = 2.27 GeV

spectator proton momentum



● WASA — CD Bonn potential

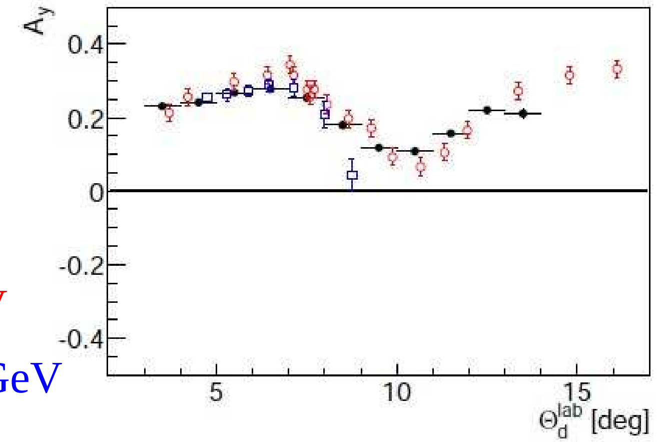
np CM energy $2.37 < \sqrt{s} < 2.40$ GeV

beam polarisations:

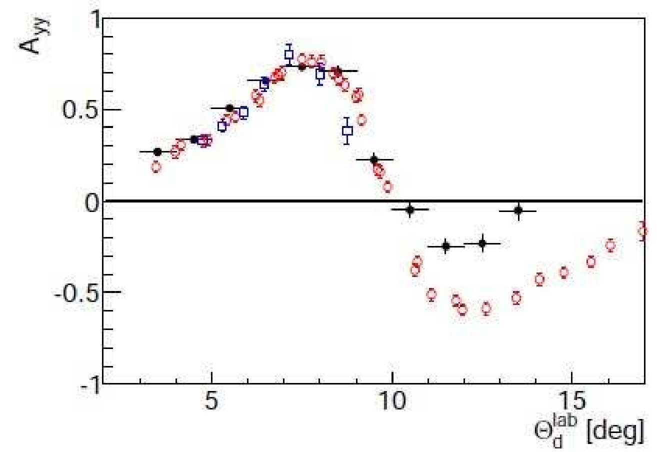
	"up"	"down"
P_z	0.67(2)	-0.45(2)
P_{zz}	0.65(2)	0.17(2)

vector dp

● WASA
○ ANL 2.0 GeV
□ ANKE 2.27 GeV

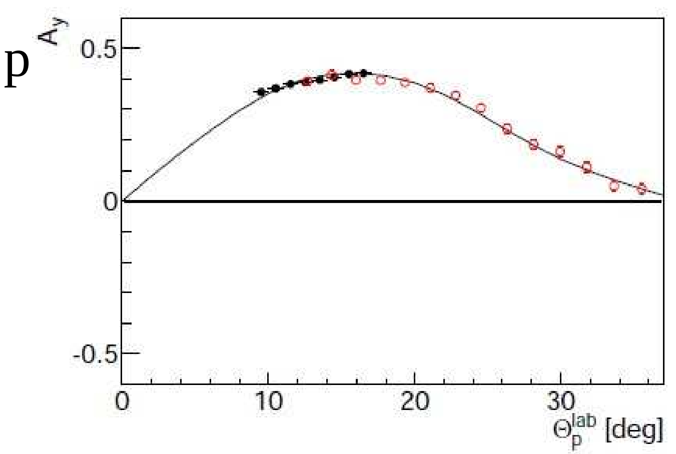


tensor dp



quasifree pp

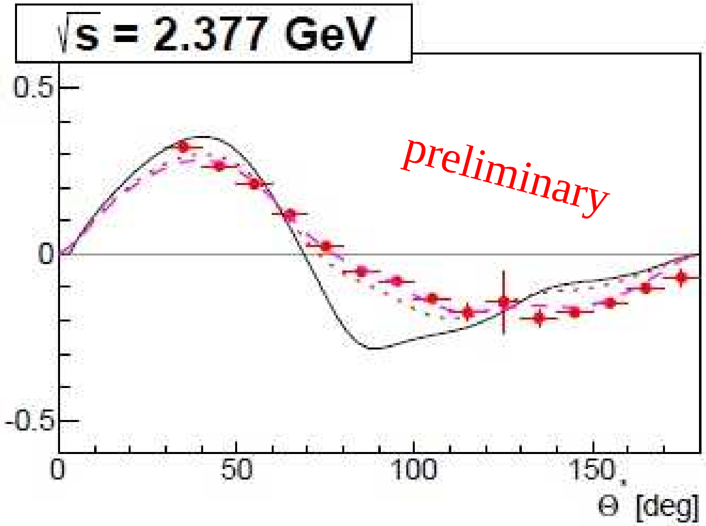
● WASA
○ EDDA
— SAID SP07



Resonance in $J^P = 3^+$ pn scattering?

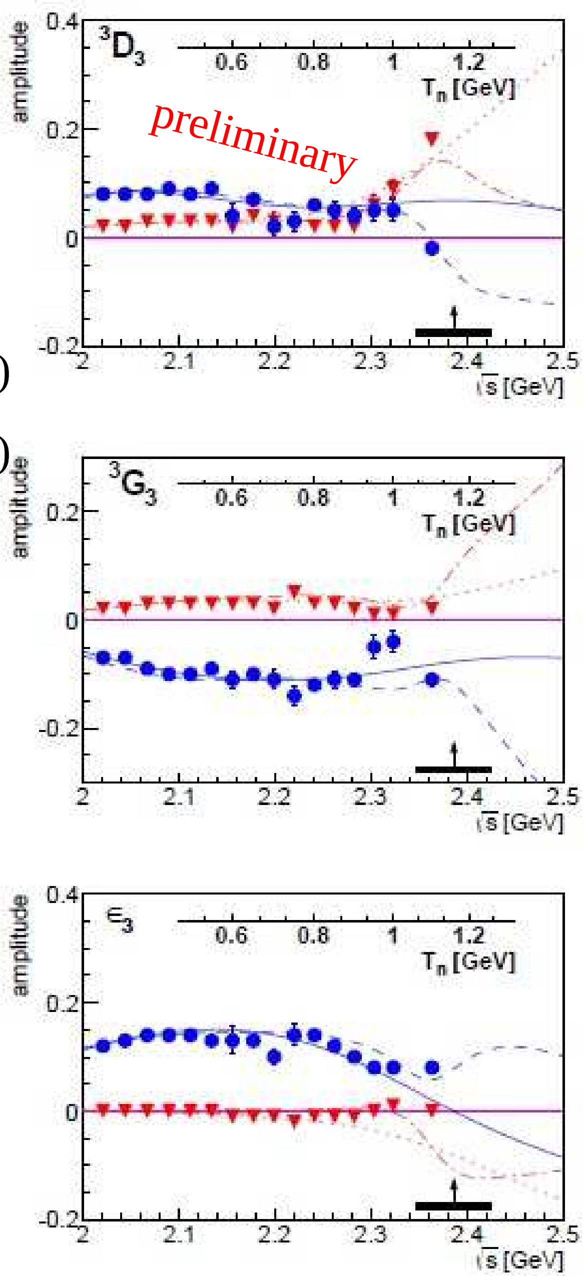
partial wave amplitudes

np analyzing power (no √s selection)



- WASA
- SAID SP07
- SAID new, weighted
- SAID new, unweighted

- Re A (SP07)
- Im A (SP07)
- Re A (new weighted)
- Im A (new weighted)
- Re A (single energy)
- Im A (single energy)

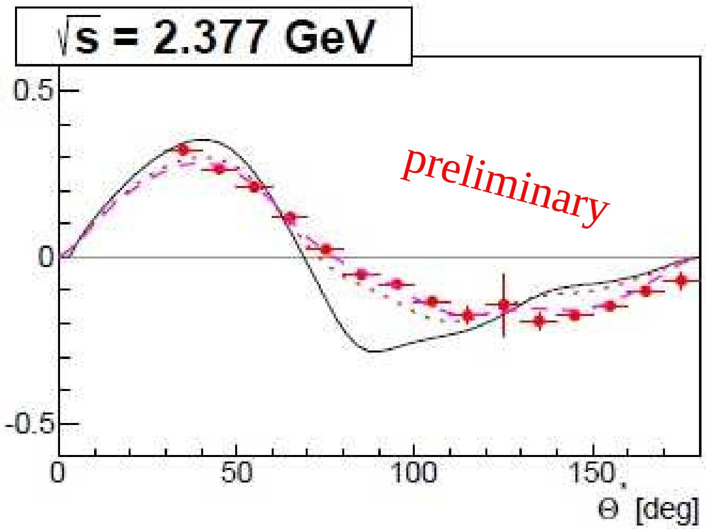


$\Rightarrow$ new SAID PWA:
pole in coupled $^3D_3 - {}^3G_3$ partial waves

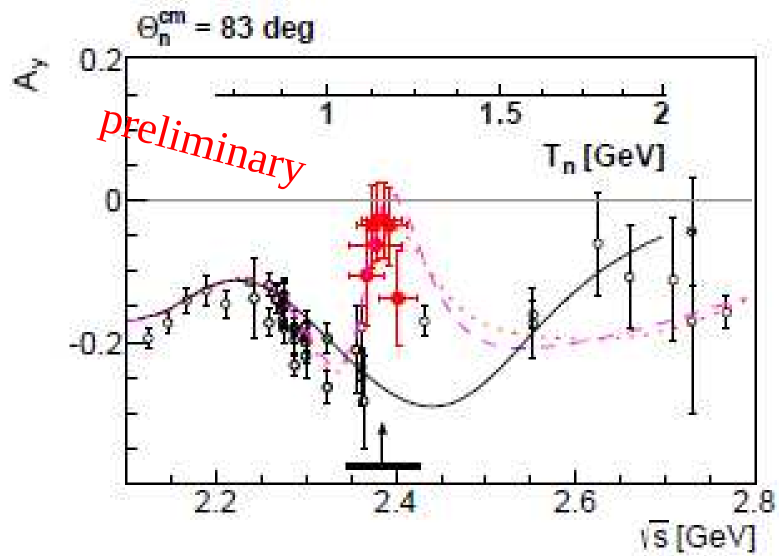
(2380 ± 10 - i40 ± 5) MeV

Resonance in $J^P = 3^+$ pn scattering?

np analyzing power (no √s selection)



energy dependence ($\Theta_n^{cm} = 83°$)



● WASA — SAID SP07 ---- SAID new, weighted ········ SAID new, unweighted

● WASA — SAID SP07 ---- SAID new, weighted ········ SAID new, unweighted

publication to be submitted
WASA-at-COSY Collaboration with
R.L. Workman, W.J. Briscoe, I.I. Strakovsky
(SAID Data Analysis Center)

Existence of $I(J^P) = 0(3^+)\ d^*$?

Experiment

resonance structure in

$pn \to d\pi^0\pi^0$	CELSIUS/WASA	PRL 102 (09) 052301
	WASA-at-COSY	PRL 106 (11) 242302
$pn \to d\pi^+\pi^-$	WASA-at-COSY	PLB 721 (13) 229
$pn \to pp\pi^-\pi^0$	WASA-at-COSY	arXiv: 1306.5130
pn analyzing power	WASA-at-COSY	to be submitted

word of caution

nearby $NN^*(1440)$ D.V.Bugg arXiv: 1311.6252

Theory

"hexaquark" states F.J.Dyson, N.-H.Xuong, PRL 13 (1964) 815

six quark hidden color configuration
M.Bashkanov, S.Brodsky, H.Clement, PLB 727 (2013) 438

three-body calculation
A.Gal, H.Garcilazo, PRL 111 (2013) 172301

quark model calculation
H.Huang, J.Ping, F.Wang, arXiv: 1312.7756

Existence of $I(J^P) = 0(3^+)$ d^*?

Experiment

the AbashianBoothCrowe view

"Alternate explanations may be possible although we have not found any in quantitative agreement with the data."

A. Abashian, N. E. Booth, K. M. Crowe, Phys. Rev. Lett. 5 (1960) 258

Theory

six quark hidden color configuration

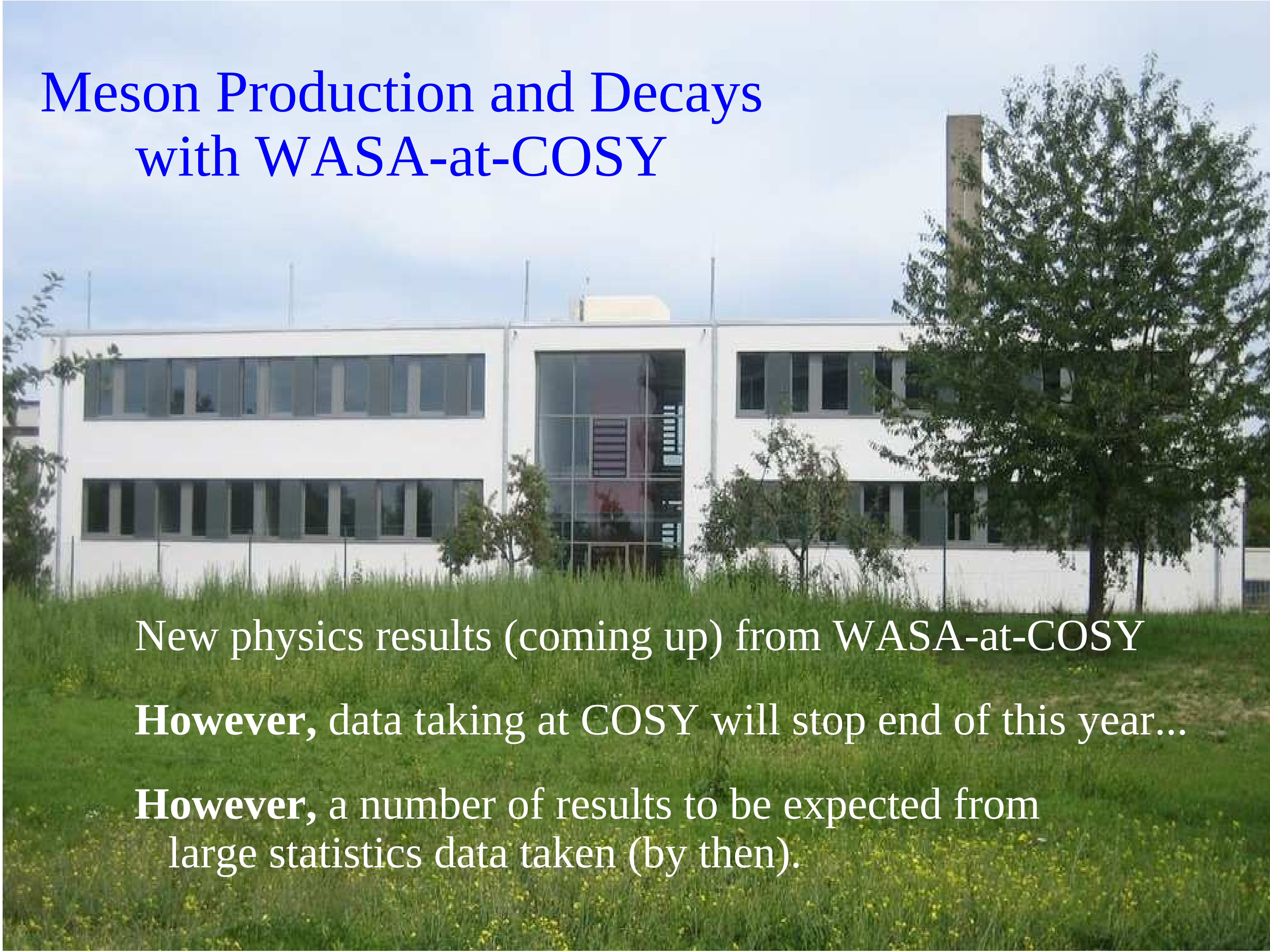
M. Bashkanov, S. Brodsky, H. Clement, PLB 727 (2013) 438

$\Rightarrow$ **proposed experiments for MAMI:**

$\gamma d \to d^* \to d\pi^0\pi^0$

with recoil polarimeter: $\gamma d \to d^* \to \vec{p}\,\vec{n}$

Meson Production and Decays with WASA-at-COSY



New physics results (coming up) from WASA-at-COSY

However, data taking at COSY will stop end of this year...

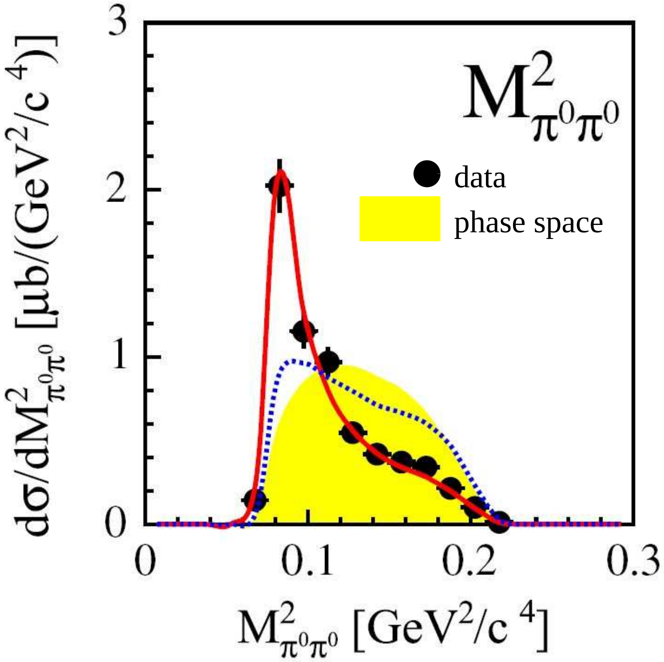
However, a number of results to be expected from large statistics data taken (by then).

The ABC Gallery

CELSIUS/WASA measurements

$pn \to d\pi^0\pi^0$

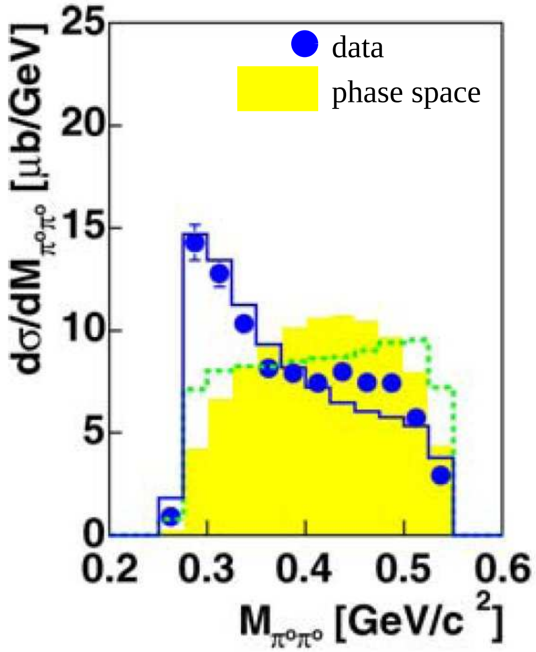
1.0GeV



PRL 102 (2009) 052301

$pd \to {}^3He\pi^0\pi^0$

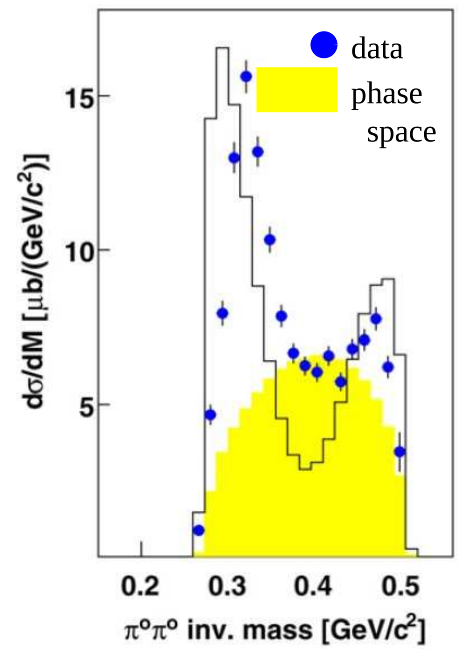
0.9GeV



PLB 637 (2006) 223

$dd \to {}^4He\pi^0\pi^0$

1.0GeV



NPA 825 (2009) 71

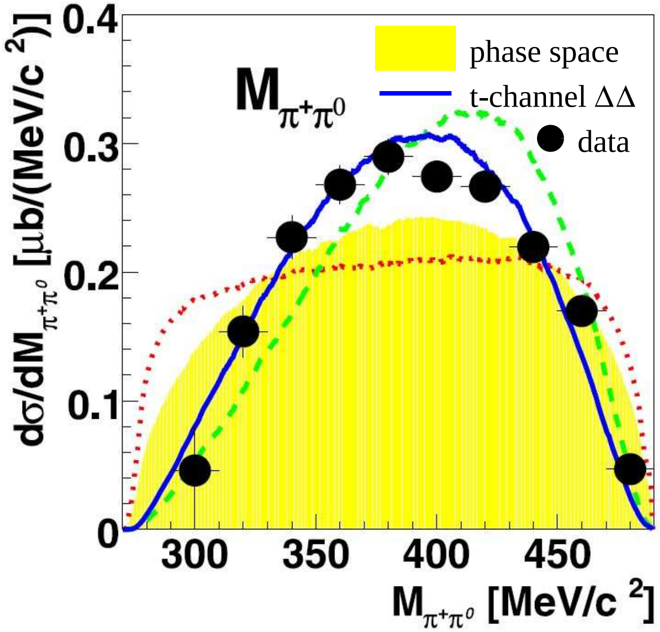
The no-ABC Gallery

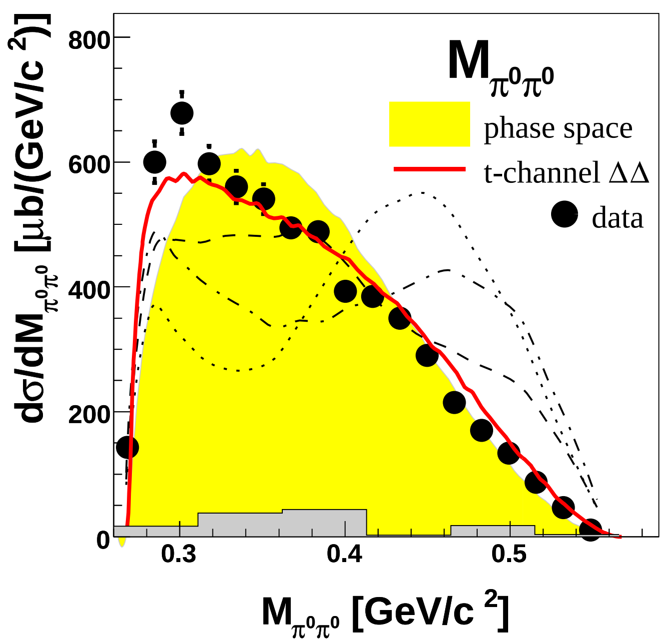
CELSIUS/WASA measurements

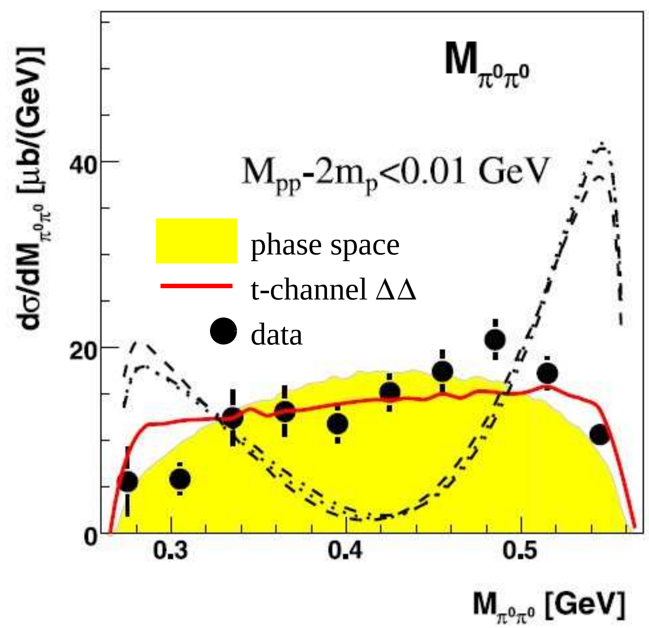
$pp \to d\pi^+\pi^0$ 1.1GeV

$pp \to pp\pi^0\pi^0$ 1.3GeV

$pp \to "^2He"\pi^0\pi^0$ 1.3GeV







PLB 684 (2010) 110

PLB 695 (2011) 115

fully described by
t-channel ΔΔ process