Probing nucleons and nuclei with photons: Selected results from MAMI and ELSA

Vahe Sokhoyan

Seminar talk
University of Basel
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Institut für Kernphysik

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Supported by the Carl-Zeiss-Stiftung

Finding the Higgs boson: 2 win Nobel prize in physics for unlocking mysteries of the universe

By Associated Press, October 08, 2013

Belgian physicist Francois Englert (L) and British physicist Peter Higgs... (MARTIAL TREZZINI/EPA)

STOCKHOLM — Nearly 50 years after they came up with the theory, but little more than a year since the world's biggest atom smasher delivered the proof, Britain's Peter Higgs and Belgian colleague Francois Englert won the Nobel Prize in physics Tuesday for helping to explain how matter formed after the Big Bang.

Working independently in the 1960s, they came up with a theory for how the fundamental building blocks of the universe clumped together, gained mass and formed everything we see around us today. The theory hinged on the existence of a subatomic particle that came to be called the Higgs boson — or the "God particle."

8 October 2013 Last updated at 10:01 ET

Higgs boson scientists win Nobel prize in physics

COMMENTS (643)

By James Morgan
Science reporter, BBC News

The Nobel committee decided Englert and Higgs should jointly take the accolade for the boson, discovered at Cern in 2012

Two scientists have won the Nobel prize in physics for their work on the theory of the Higgs boson.

Peter Higgs, from the UK, and Francois Englert from Belgium, share the prize.

In the 1960s, they were among several physicists who proposed a mechanism to explain why the most basic building blocks of the Universe have mass.

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Profile: Peter Higgs
Q&A: The Higgs boson
Reactions to Nobel win

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The Higgs Boson and the N... Why We Call It the 'God Pa...

+ Comment Now + Follow Comments

This article is by Ned Potter, a senior vice president at the com... firm RLM Finsbury and a former science correspondent for AB... and CBS News.

The Higgs boson, the subatomic particle that has brought a Nobel Prize to Francois Englert and Peter Higgs, is so small that its discovery took 40 years. It is so big for physics, though, that it took on the nickname the "God particle."

Peter Higgs, after...

Higgs, Englert, and their colleagues theorized in 1964 that there must be something that explains why other particles have mass, why things hold together, why you and I are able to exist. That something is the Higgs boson.

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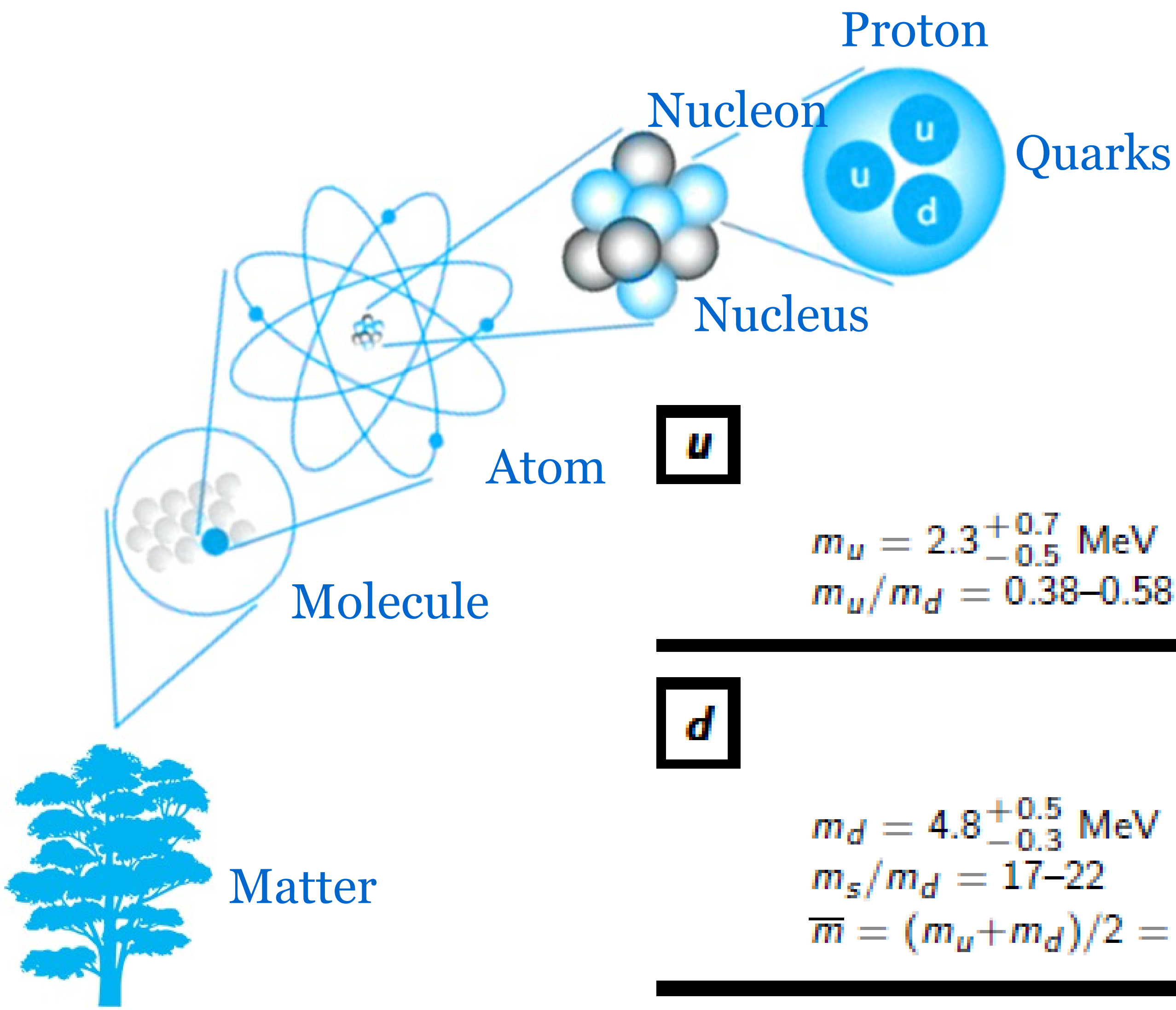
Introduction



u $\quad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$m_u = 2.3^{+0.7}_{-0.5}$ MeV $\quad$ Charge $= \frac{2}{3}\,e \quad I_z = +\frac{1}{2}$

$m_u/m_d = 0.38$–0.58

d $\quad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

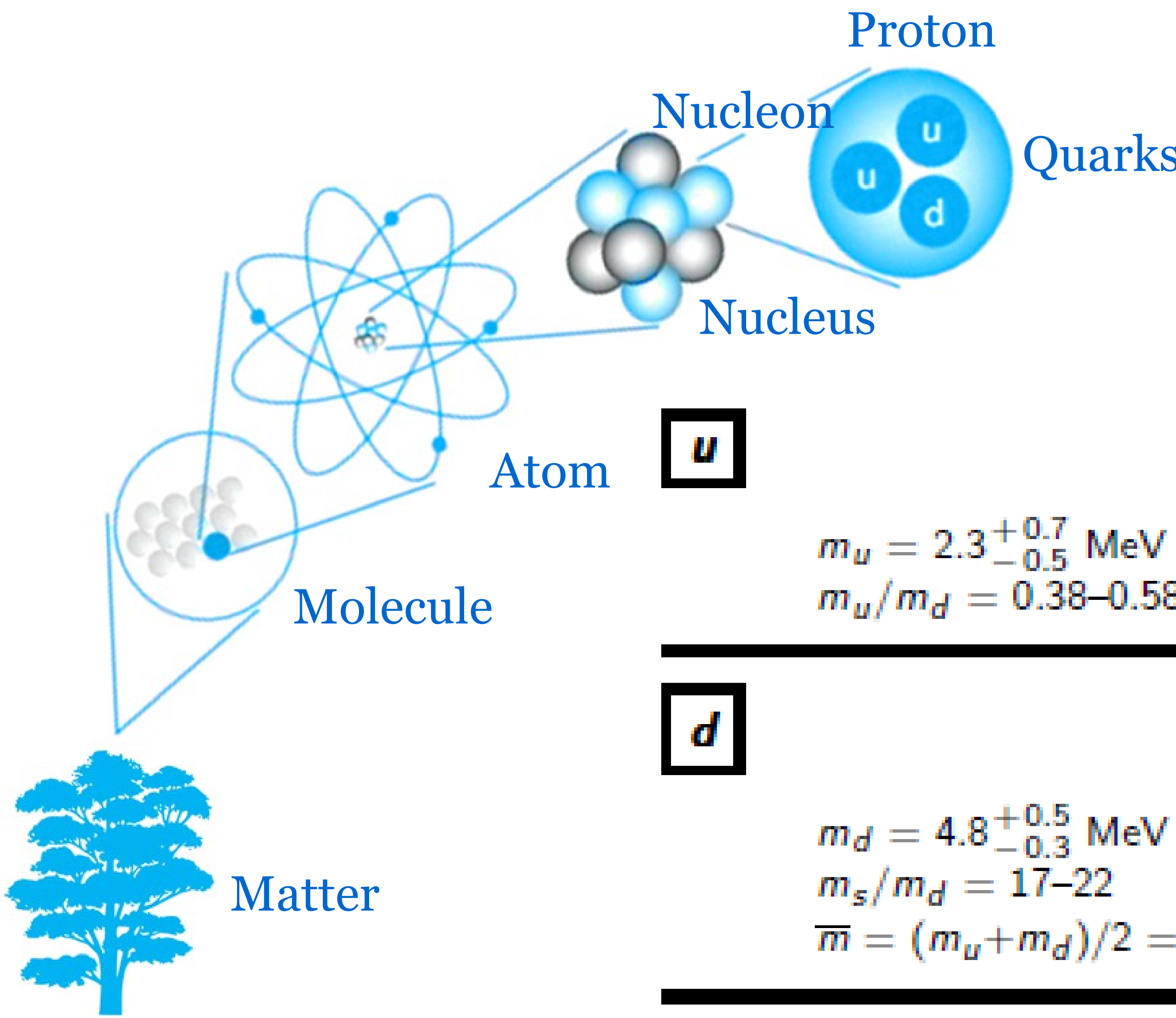
$m_d = 4.8^{+0.5}_{-0.3}$ MeV $\quad$ Charge $= -\frac{1}{3}\,e \quad I_z = -\frac{1}{2}$

$m_s/m_d = 17$–22

$\overline{m} = (m_u + m_d)/2 = 3.5^{+0.7}_{-0.2}$ MeV

PDG (live)

Introduction



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$2m_u + m_d \approx$ 1% of the proton mass!

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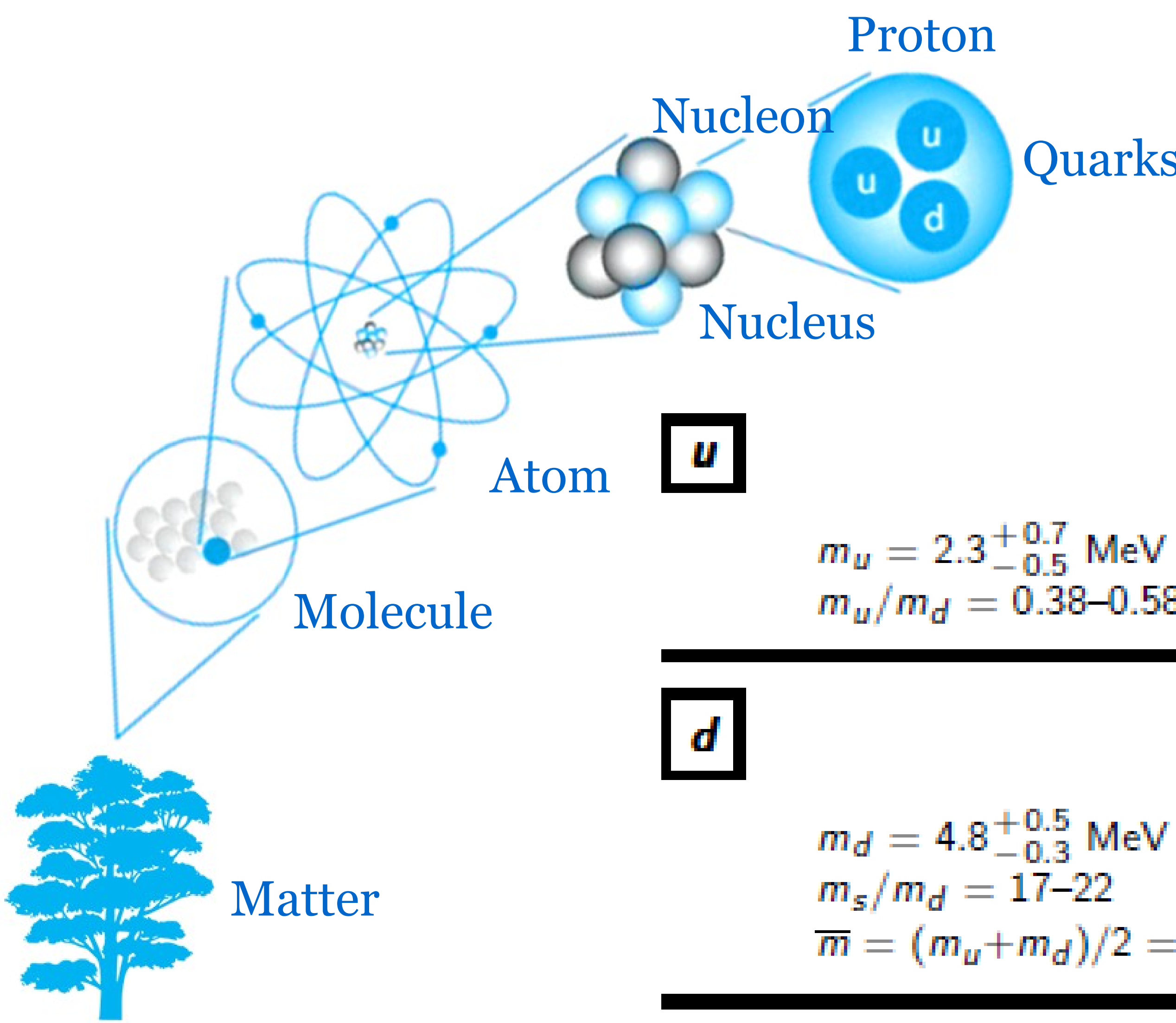

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What about remaining 99%?

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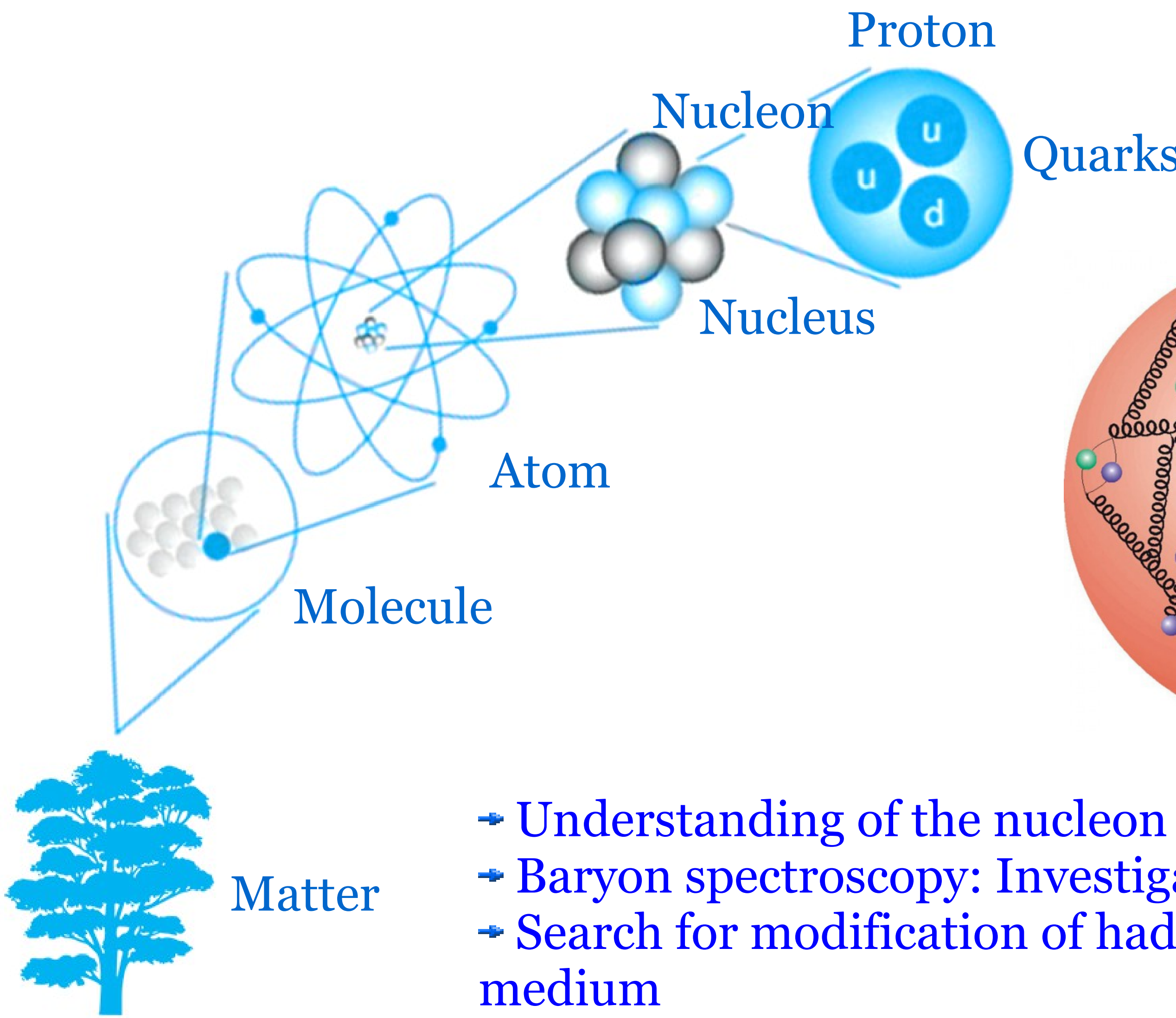
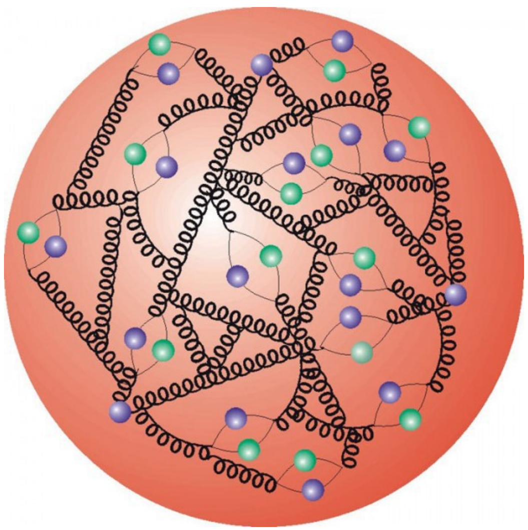


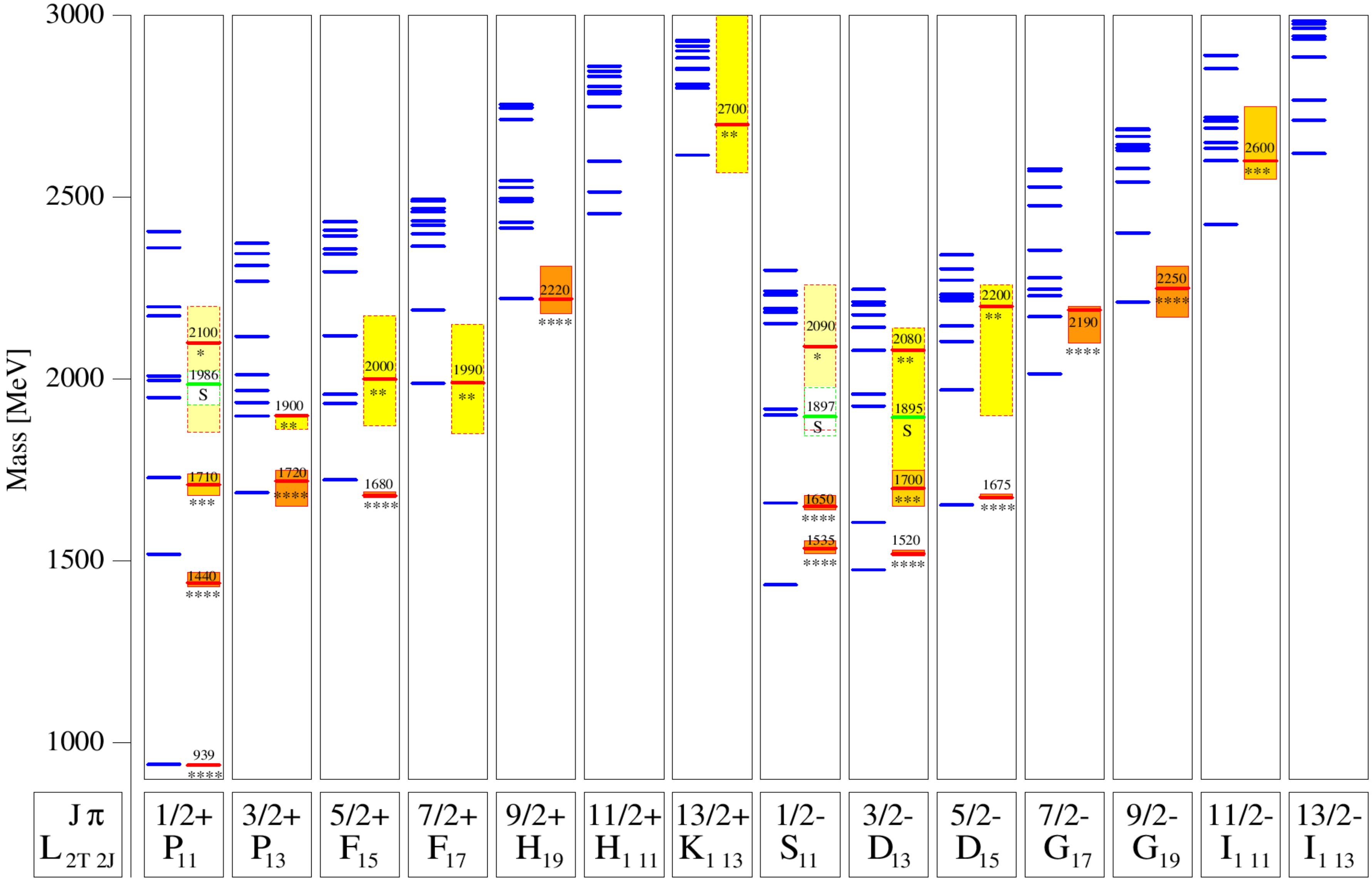


- Understanding of the nucleon structure
- Baryon spectroscopy: Investigation of excited states
- Search for modification of hadrons in the nuclear medium
- Compton scattering: Extraction of polarizabilities

Nucleon resonances

Goal: Gain a good understanding of the spectrum and properties of baryon resonances

Above 1.9 GeV missing resonances are predicted by the symmetric quark models



U. Löring et al., Eur. Phys. J. A 10 (2001) 309, 395, 447

Resonances

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Lattice QCD confirms the number of the states in symmetric quark models

R. G. Edwards et al., Phys. Rev. D 84, 074508 (2011)

Experimentally: Broad overlapping resonances

- Partial Wave Analysis necessary
- Measurement of cross-sections and polarization observables
- Different production channels

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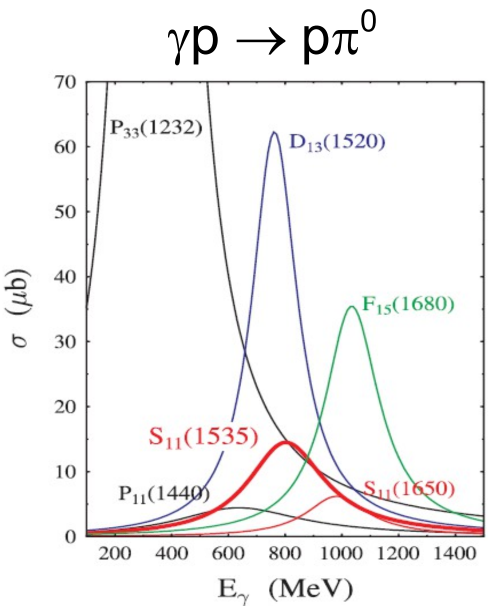

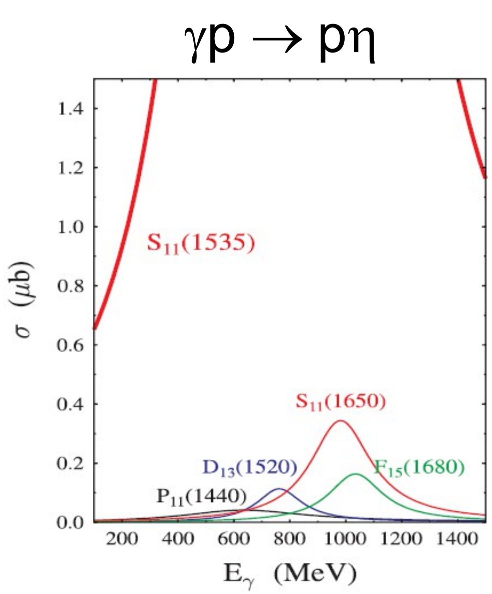

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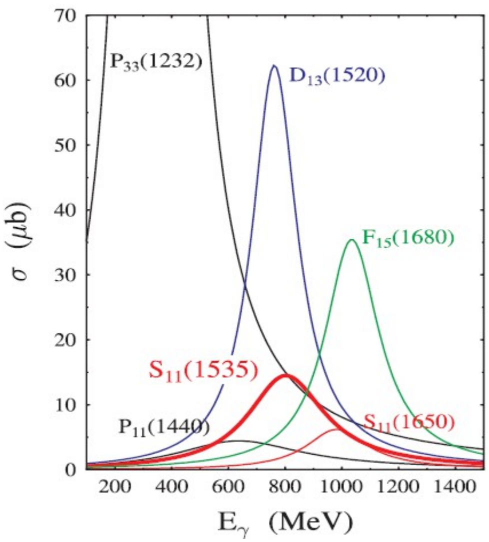
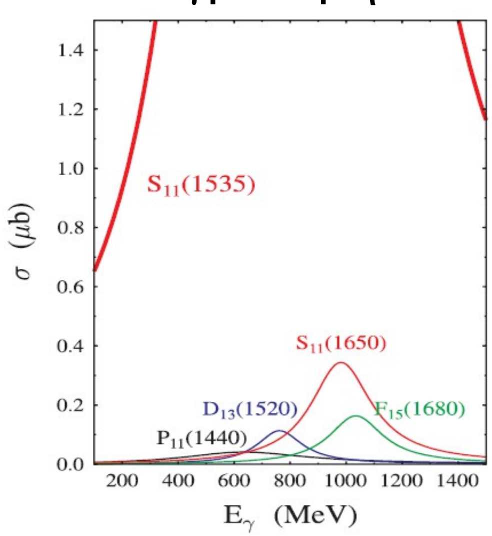
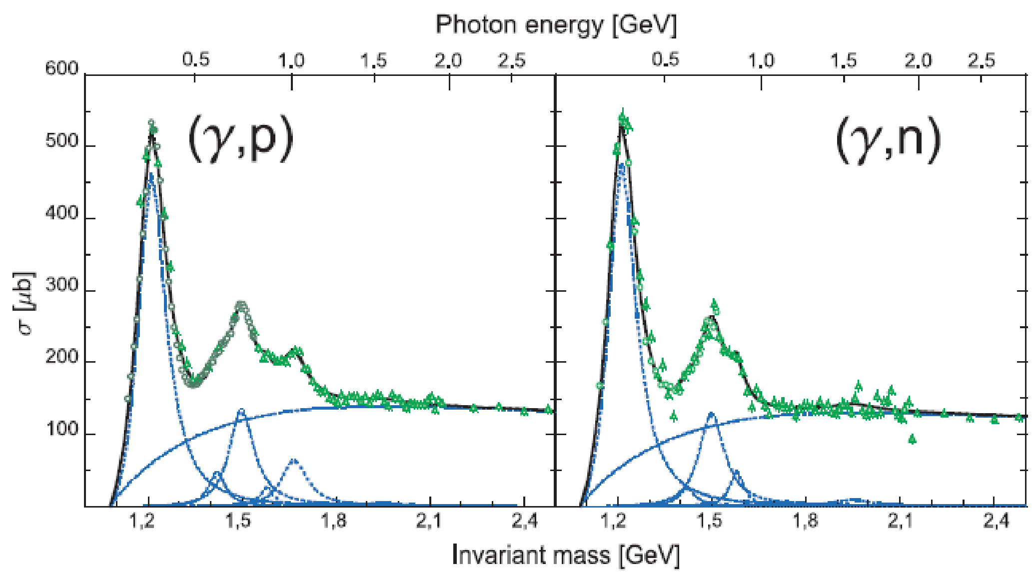


$\gamma p \rightarrow p\eta$





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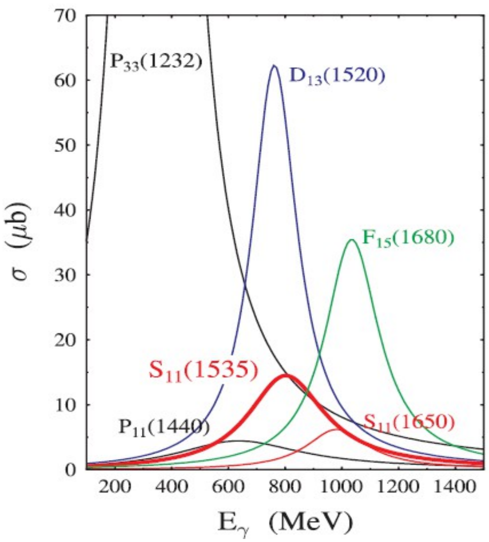

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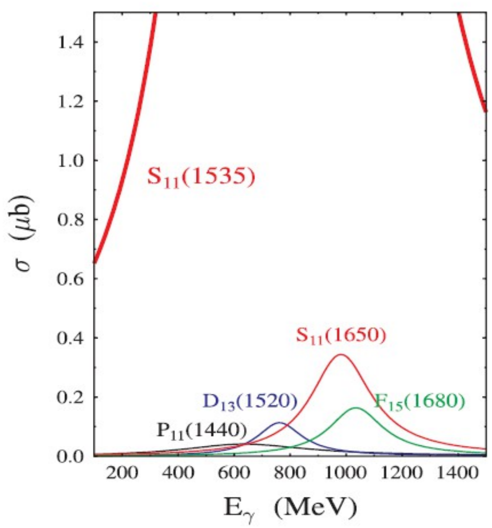
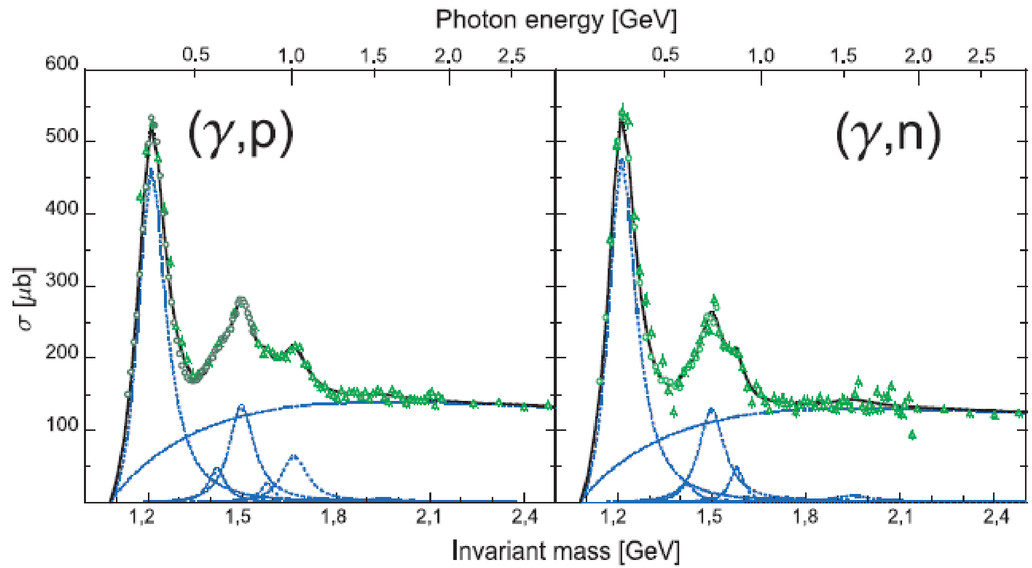


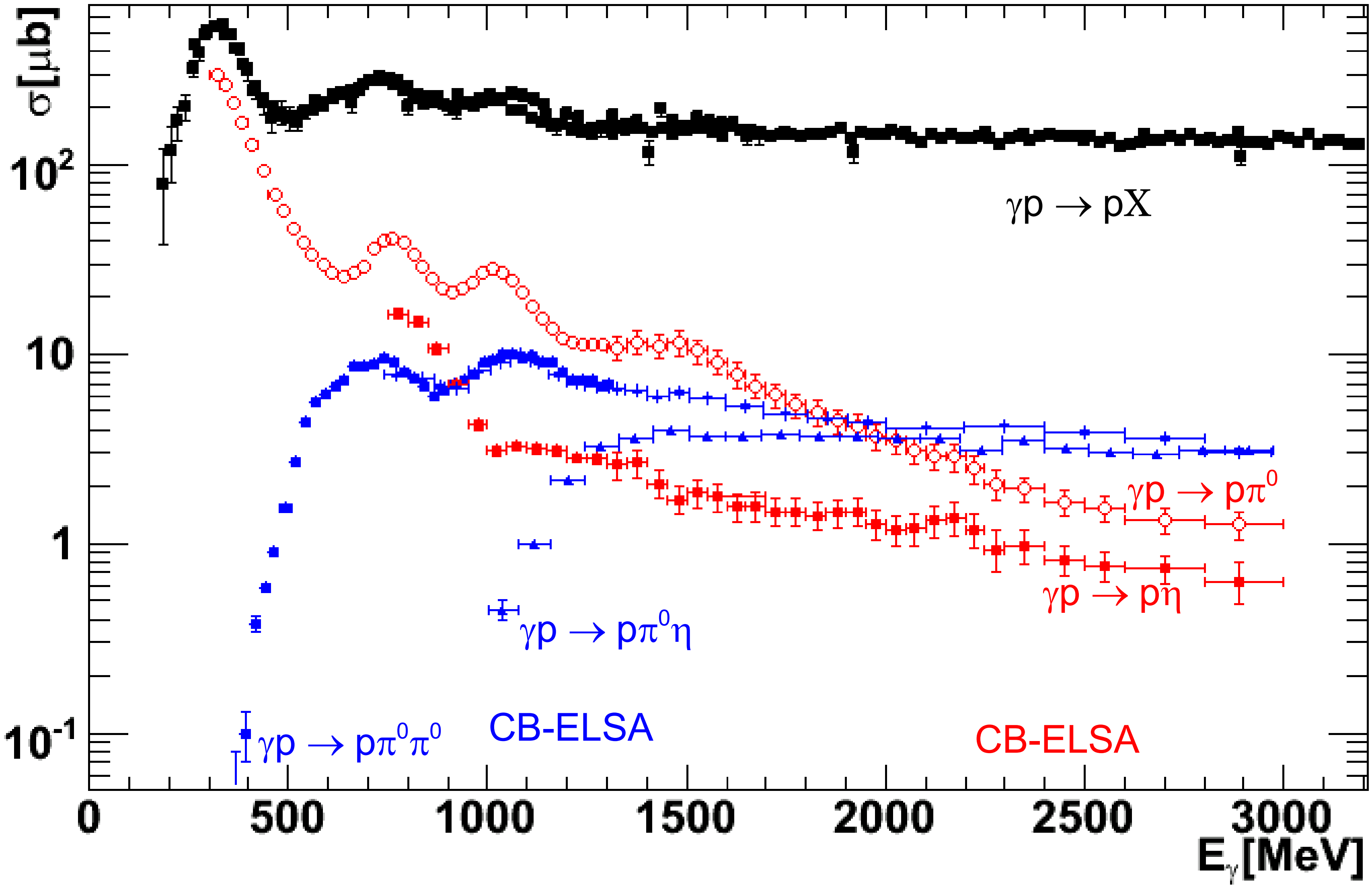


Most of the data obtained with πN scattering

Channels different from πN → Photoproduction experiments

Photoproduction

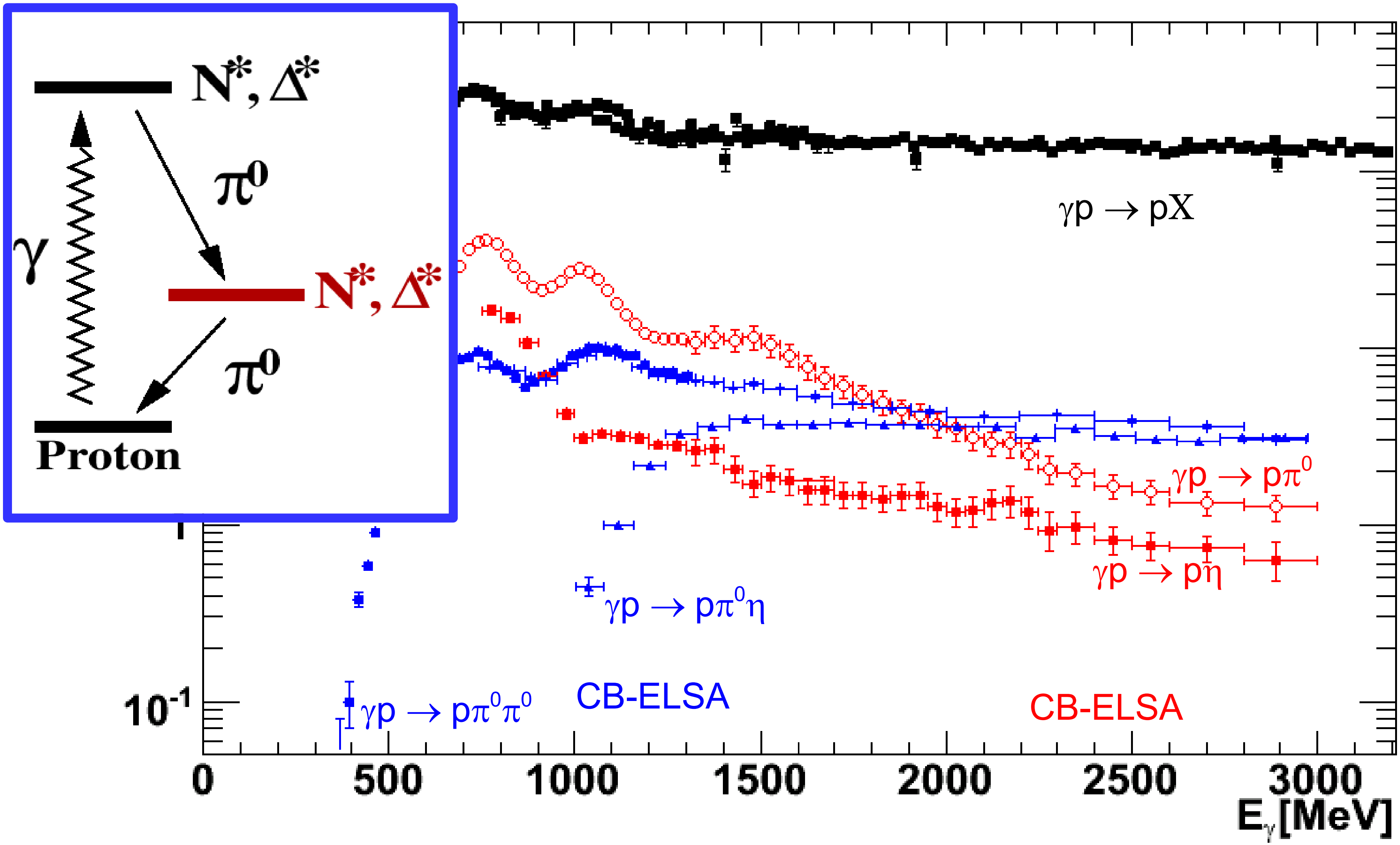
<u>Goal</u>: Gain a good understanding of the spectrum and properties of baryon resonances



➜ At high energies: Multi-meson final states play a role of increasing importance!

Photoproduction

Goal: Gain a good understanding of the spectrum and properties of baryon resonances



- At high energies: Multi-meson final states play a role of increasing importance!
- Access to resonances with cascading decays

Polarization observables

Systematic way to go: the complete experiment
for pesudoscalar single meson photoproduction:
8 carefully selected observables
(with beam, target and recoil polarization required) are needed to
predict all other experiments

photon polarization	target polarization -	x	y	z
unpolarized	σ	-	T	-
linearly	Σ	H	-P	-G
circularly	-	F	-	-E

set		observables			
single	S	dσ/dΩ	Σ	T	P
beam-target	BT	G	H	E	F
beam-recoil	BR	Ox´	Oz´	Cx´	Cz´
target-recoil	TR	Tx´	Tz´	Lx´	Lz´

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beam-recoil	BR	Ox´	Oz´	Cx´	Cz´
target-recoil	TR	Tx´	Tz´	Lx´	Lz´

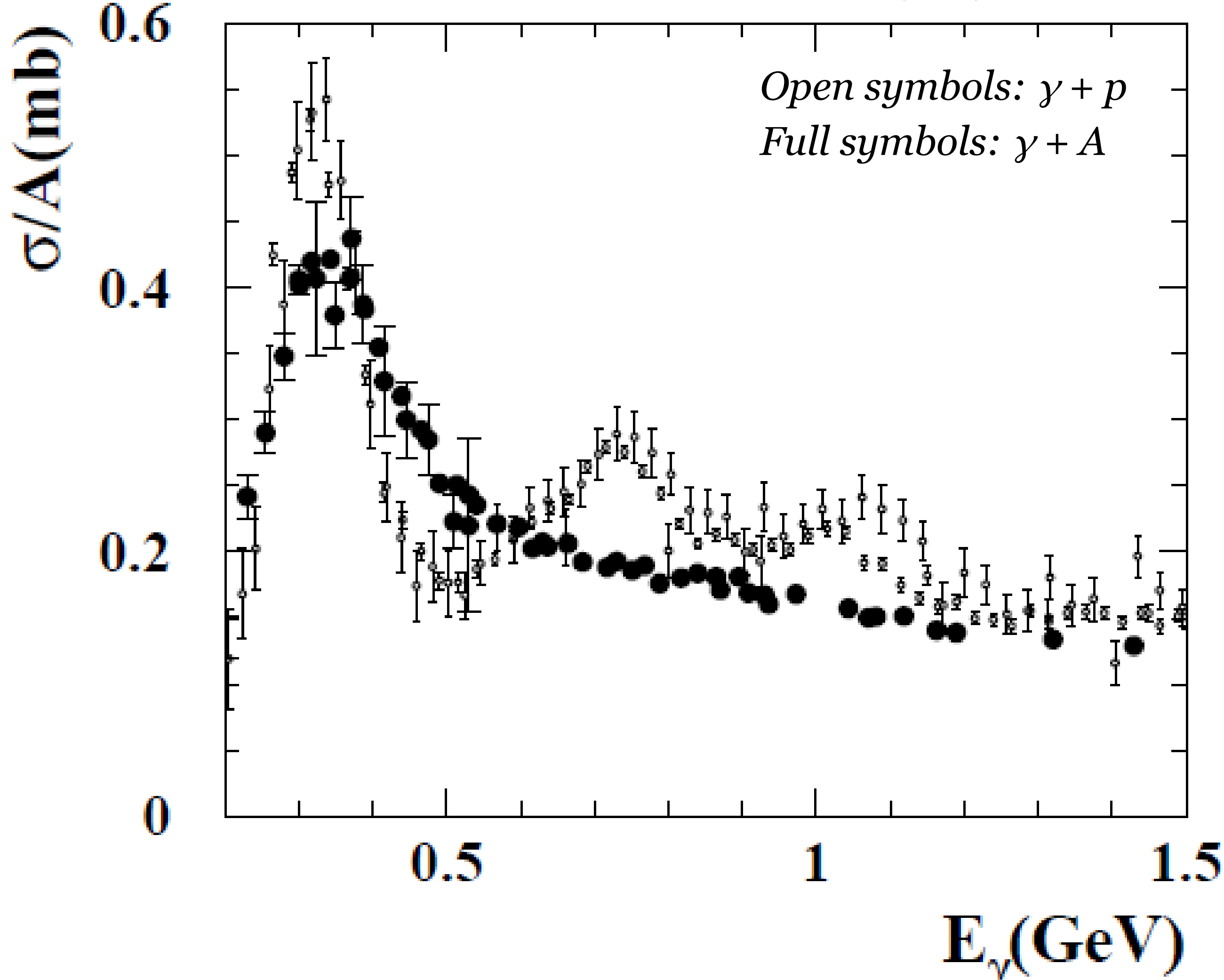
Double meson final states:
For a complete experiment, 15 observables are needed!
W. Roberts and T. Oed, Phys. Rev. C 71, 055201 (2005)

In-medium modifications

Goal: Search for in-medium modifications of baryon resonances

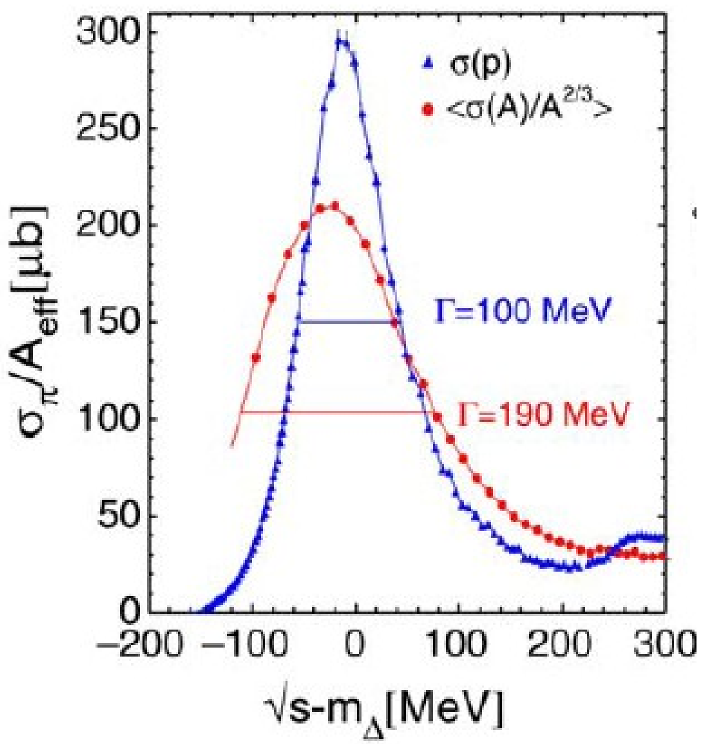
- Pronounced in-medium effect:
  No bump structure in the photoabsorption cross-section measured for $\gamma + A$
  $\rightarrow$ not fully explained in a model-independent way

V. Muccifora, et al., Phys. Rev. C60 (1999) 064616



In-medium modifications

- The width for Δ(1232) is changed in the nuclear medium from 100 MeV to ~190 MeV in good agreement with the BUU model (University Gießen) calculations



B. Krusche, Progress in Particle and Nuclear Physics 55 (2005) 46–70

M. Post, J. Lehr, U. Mosel, Nuclear Phys. A 741 (2004) 81

- Second resonance region: No strong experimental indication for significant modifications of $D_{13}(1520)$ or $S_{11}(1535)$

In-medium modifications

New experiment at MAMI:

- First study of the modifications of the $D_{33}(1700)$ resonance
- First measurement and interpretation of polarization observables for the
- Investigation of in-medium modifications along with differential cross-sections

Additional questions:

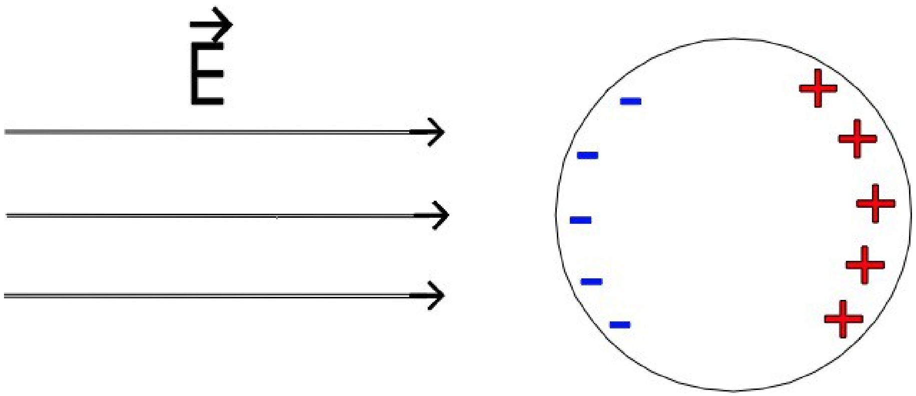
- Better understanding of the Final State Interaction (FSI)
- Understanding of the nature of the $D_{33}(1700)$: Is it dynamically generated?

We will extract:

Differential cross-sections and beam helicity asymmetry close to the $\pi^0\eta$ production threshold with C, Al, and Pb targets

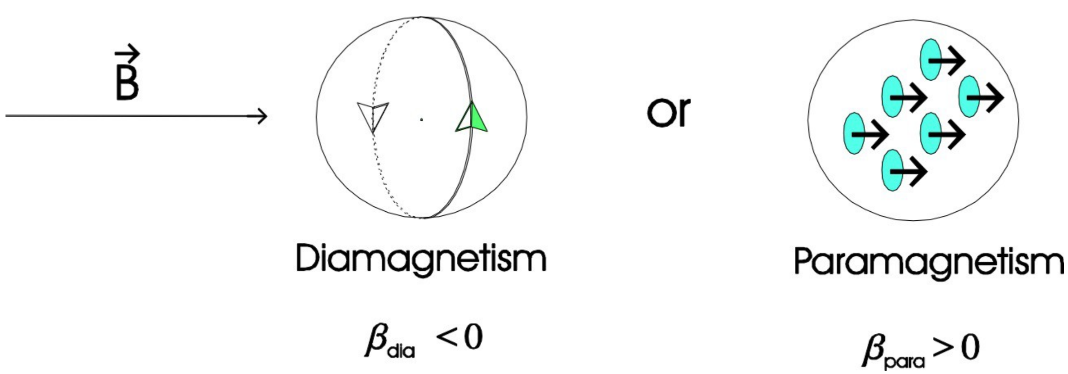
Scalar polarizabilities

Proton Electric Polarizability



- α_{E1}: electric polarizability
- Proton between charged parallel plates: "stretchability"

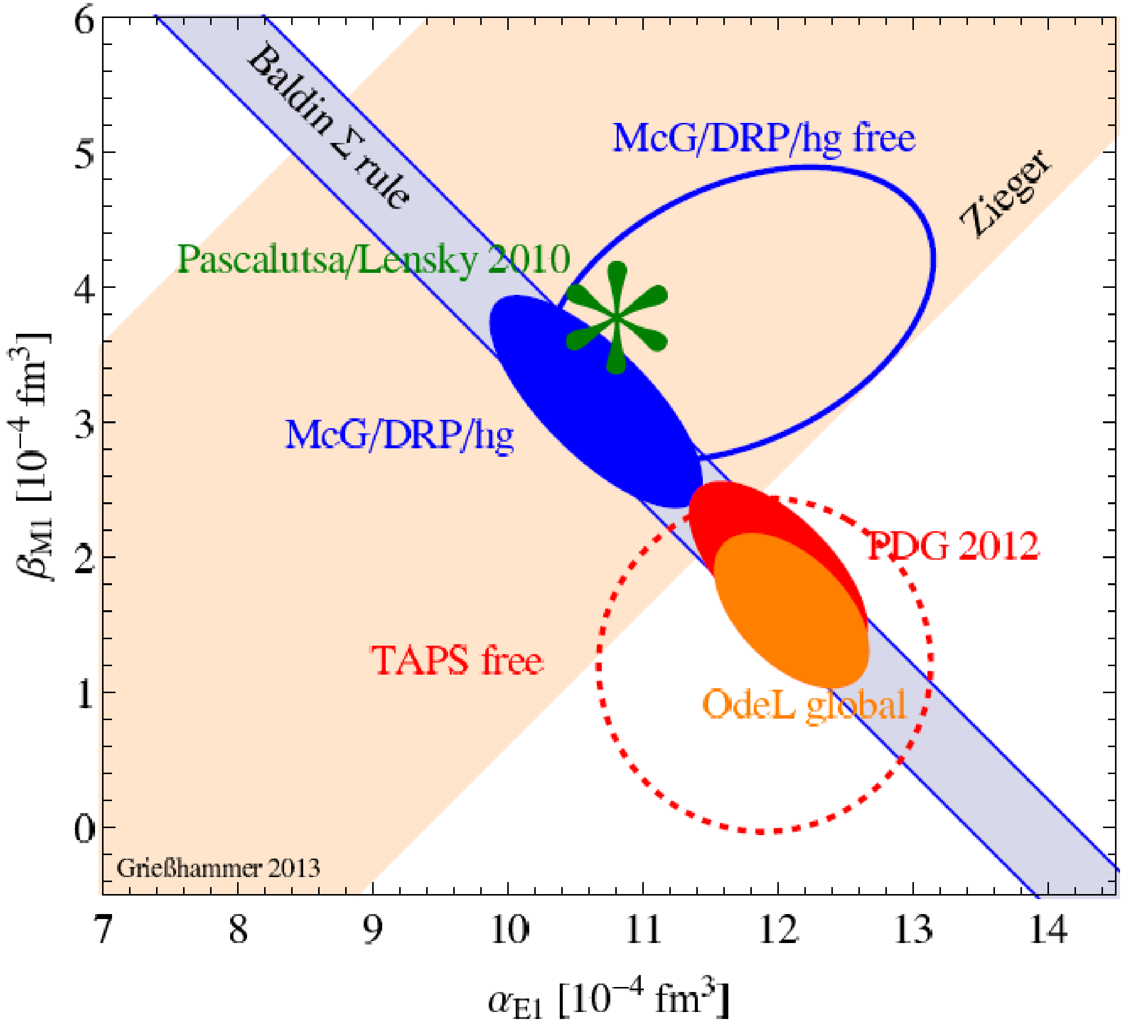
Proton Magnetic Polarizability



- β_{M1}: magnetic polarizability
- Proton between poles of a magnet: "alignability"

- Fundamental properties of the proton
- Important to astrophysics, atomic physics, spin polarizability measurements, etc.

Polarizabilities: data and model predictions



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$\alpha_{E1} = (12.0 \pm 0.6) \times 10^{-4}\ \mathrm{fm}^3$

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New (2014) PDG values:

$\alpha_{E1} = (11.2 \pm 0.4) \times 10^{-4}\ \mathrm{fm}^3$

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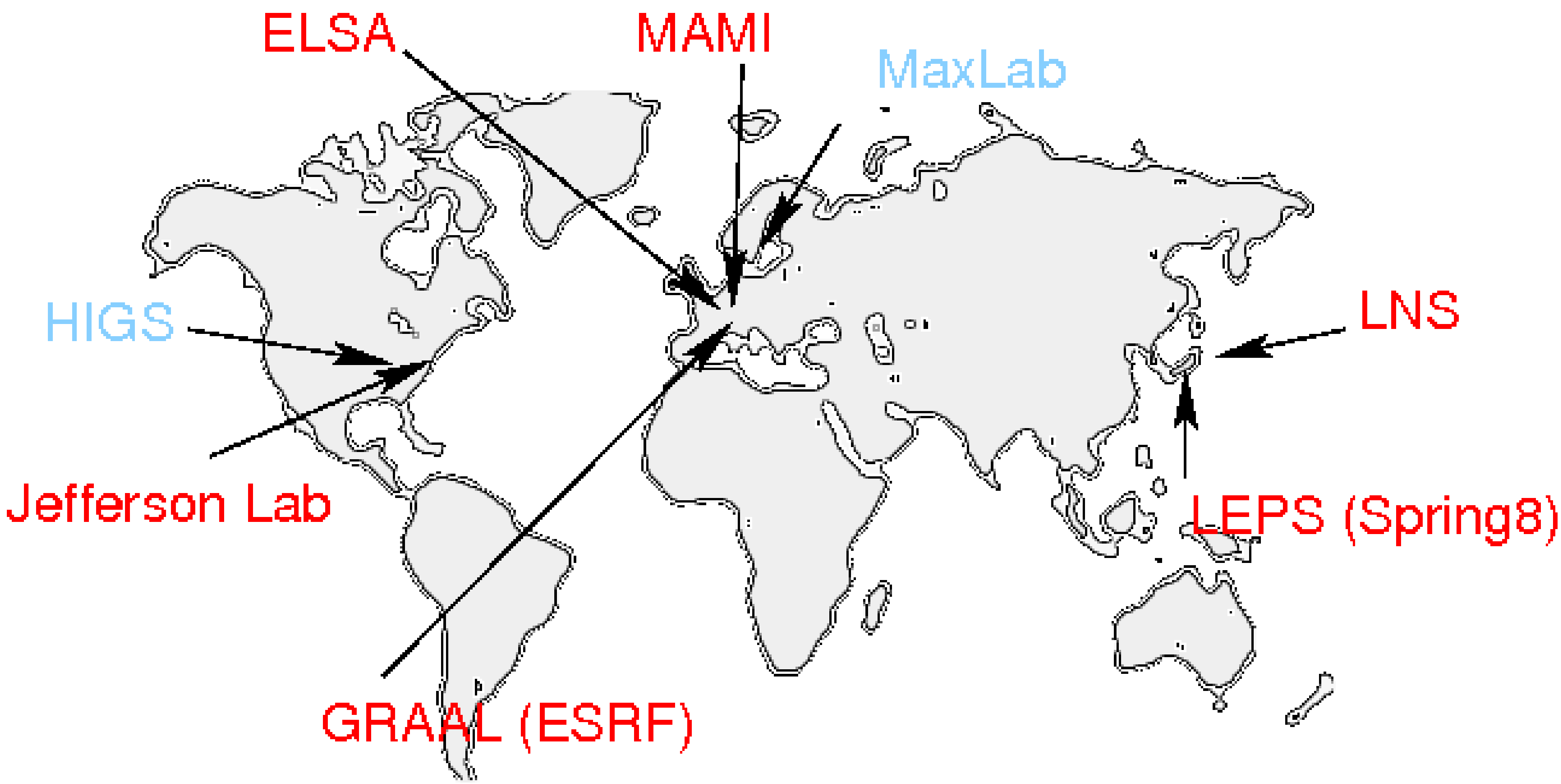
Significant change between reviews without introducing new experimental data? New quality data needed!

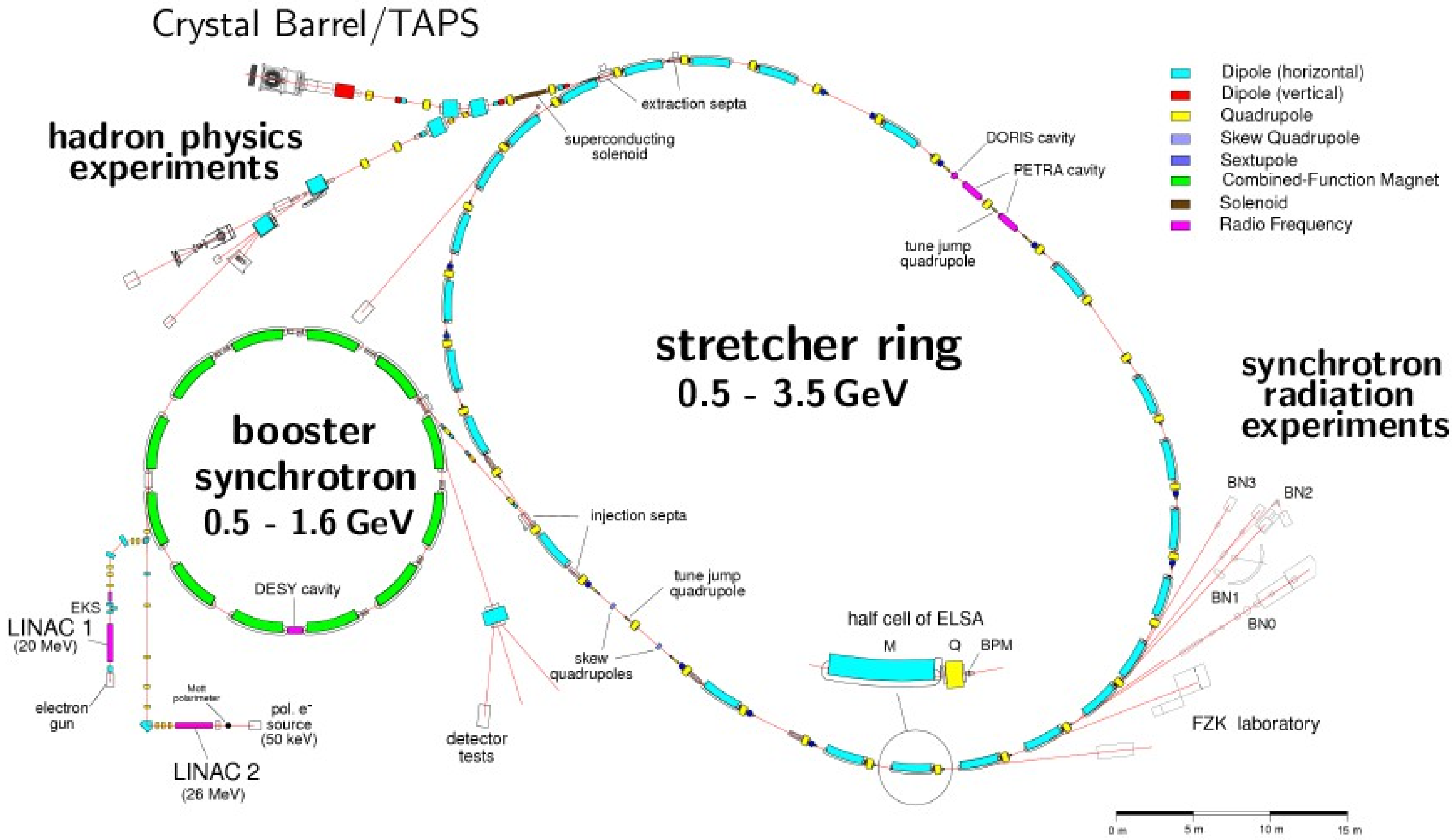
In the low energy range Σ_3 is purely dependent on β

Krupina and Pascalutsa, PRL 110, 262001 (2013)

Experiments

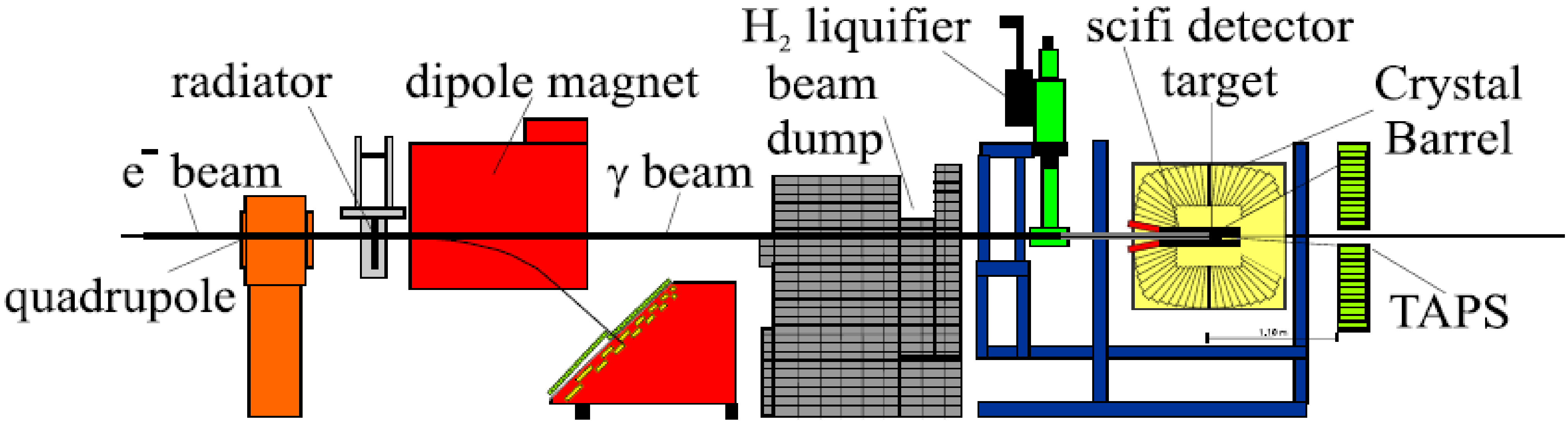


ELSA

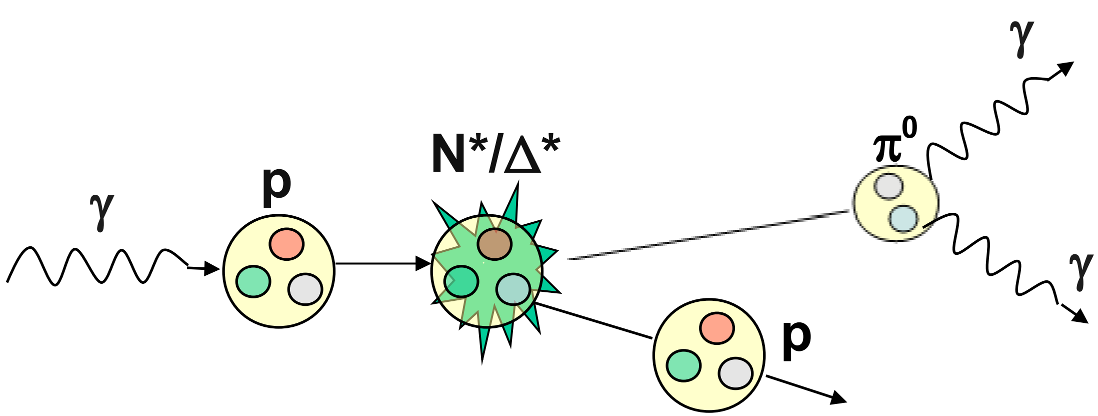


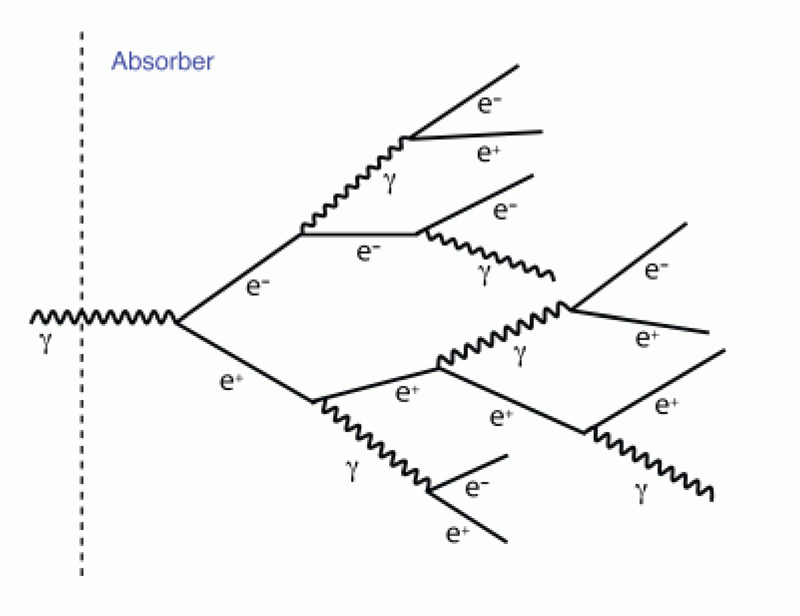
Crystal Barrel/TAPS
hadron physics experiments
extraction septa
superconducting solenoid
DORIS cavity
PETRA cavity
tune jump quadrupole
Dipole (horizontal)
Dipole (vertical)
Quadrupole
Skew Quadrupole
Sextupole
Combined-Function Magnet
Solenoid
Radio Frequency
stretcher ring
0.5 - 3.5 GeV
synchrotron radiation experiments
booster synchrotron
0.5 - 1.6 GeV
injection septa
tune jump quadrupole
skew quadrupoles
DESY cavity
EKS
LINAC 1
(20 MeV)
electron gun
Mott polarimeter
pol. e⁻ source
(50 keV)
LINAC 2
(26 MeV)
detector tests
half cell of ELSA
M
Q
BPM
BN3
BN2
BN1
BN0
FZK laboratory
0 m
5 m
10 m
15 m

The CBELSA/TAPS experiment



Example: $\gamma\, p \rightarrow p\, \pi^0 \rightarrow p\, 2\gamma$





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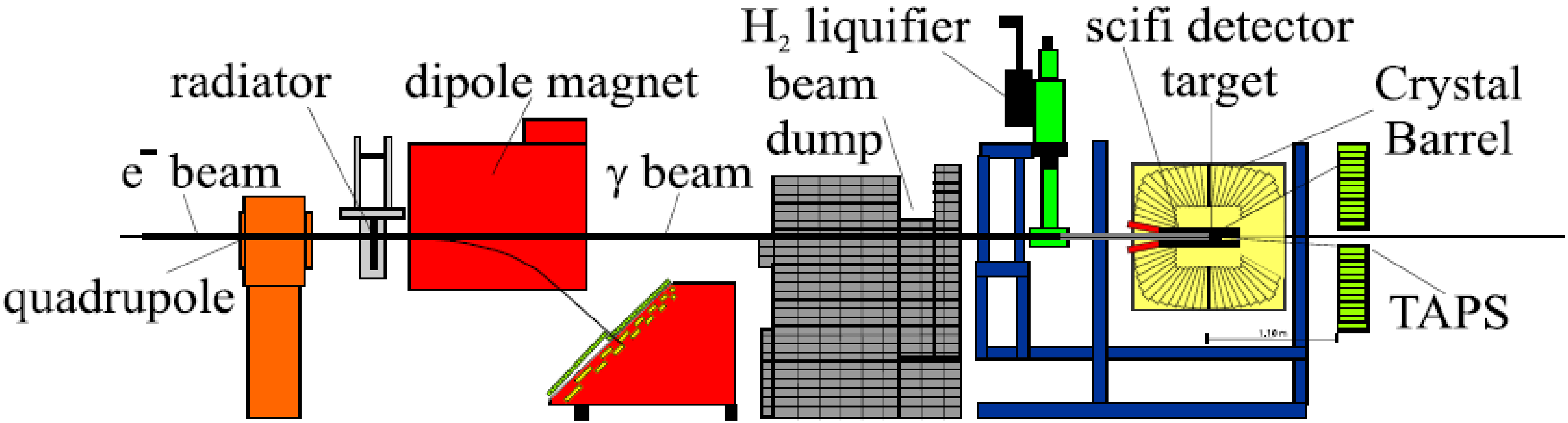
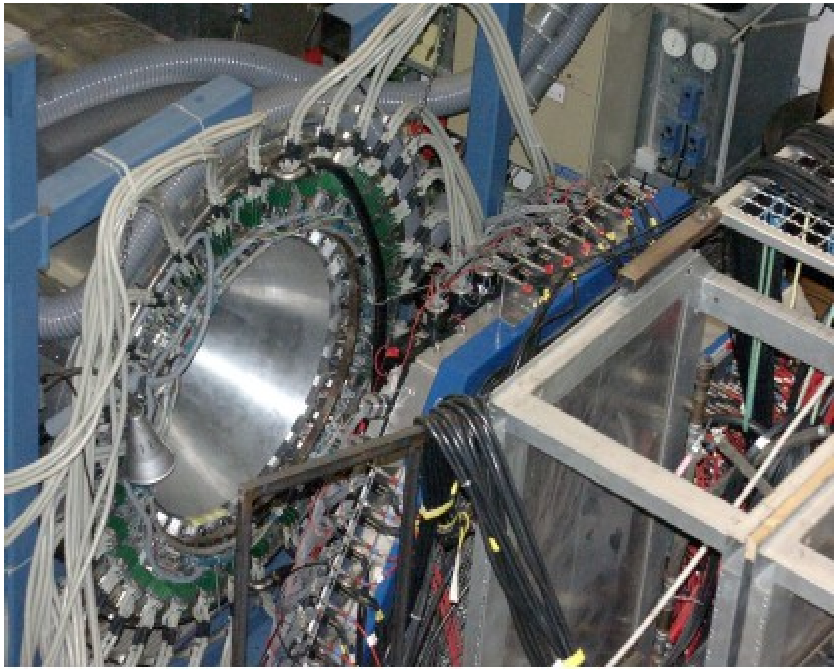
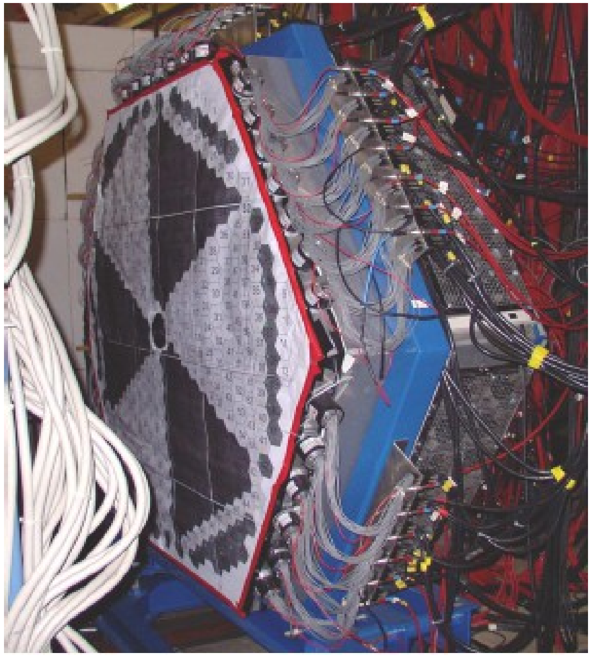


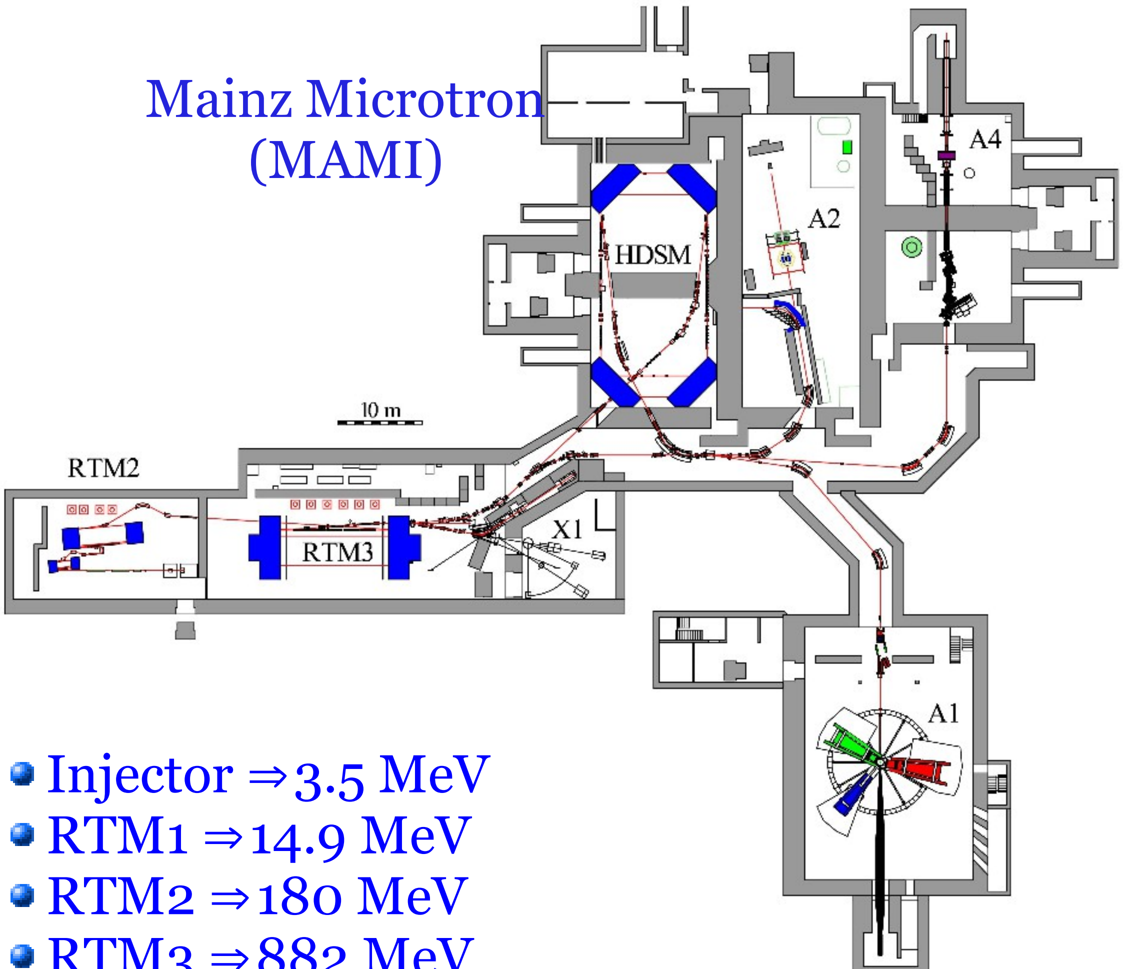
Almost 4π coverage!



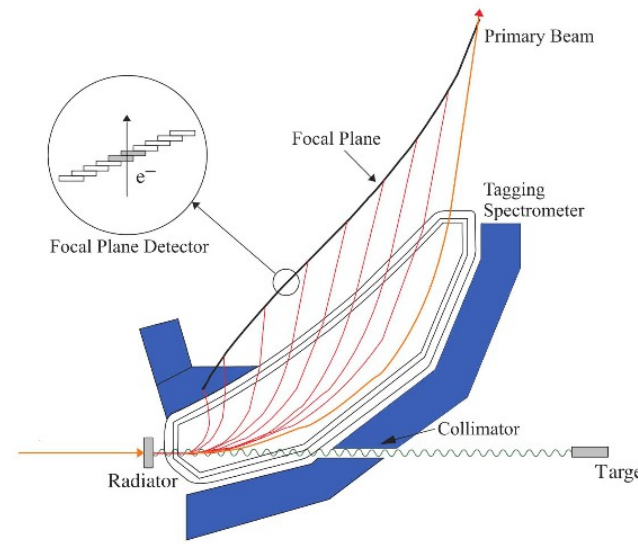


MAMI and Crystal Ball experiment

Mainz Microtron
(MAMI)



Tagger

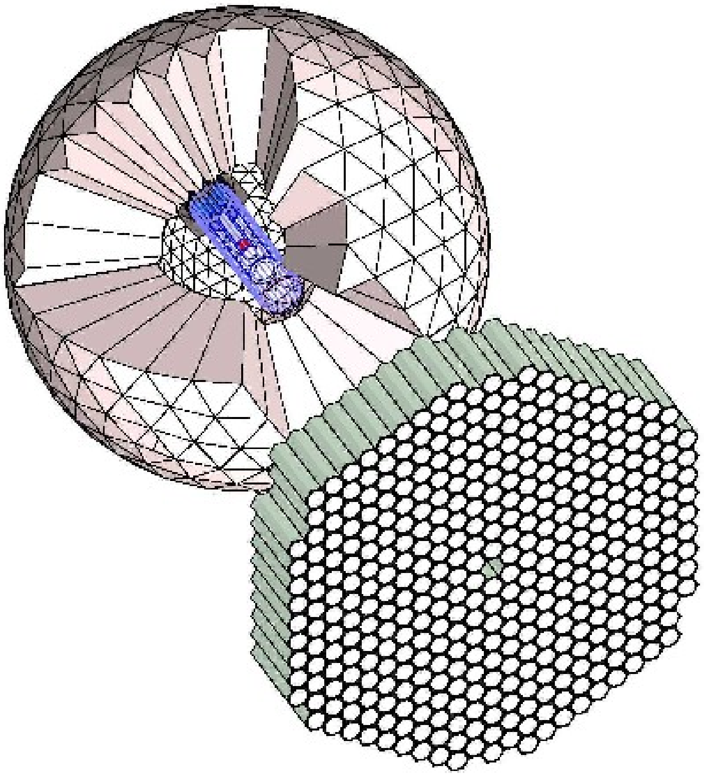


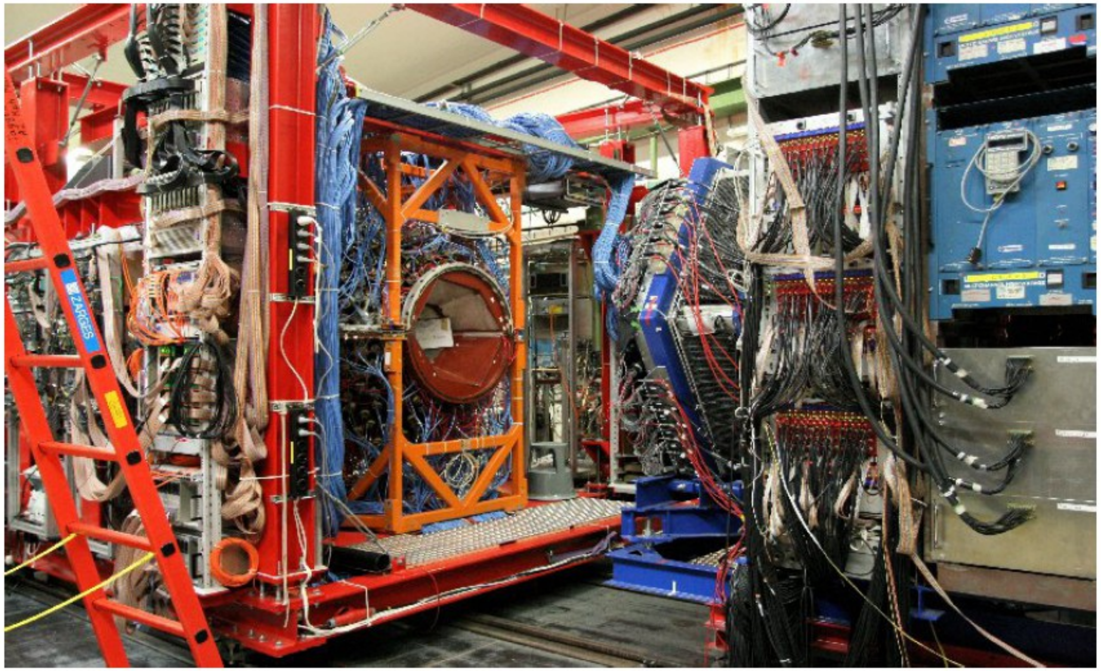
$E_\gamma = E_o - E_{e-}$

- Injector ⇒ 3.5 MeV
- RTM1 ⇒ 14.9 MeV
- RTM2 ⇒ 180 MeV
- RTM3 ⇒ 882 MeV
- HDSM ⇒ 1.6 GeV

- High-Flux, Tagged, Bremsstrahlung Photon Beam: Unpolarized, Linear, and Circular
- Polarized and Unpolarized Targets

Crystal Ball/TAPS experiment





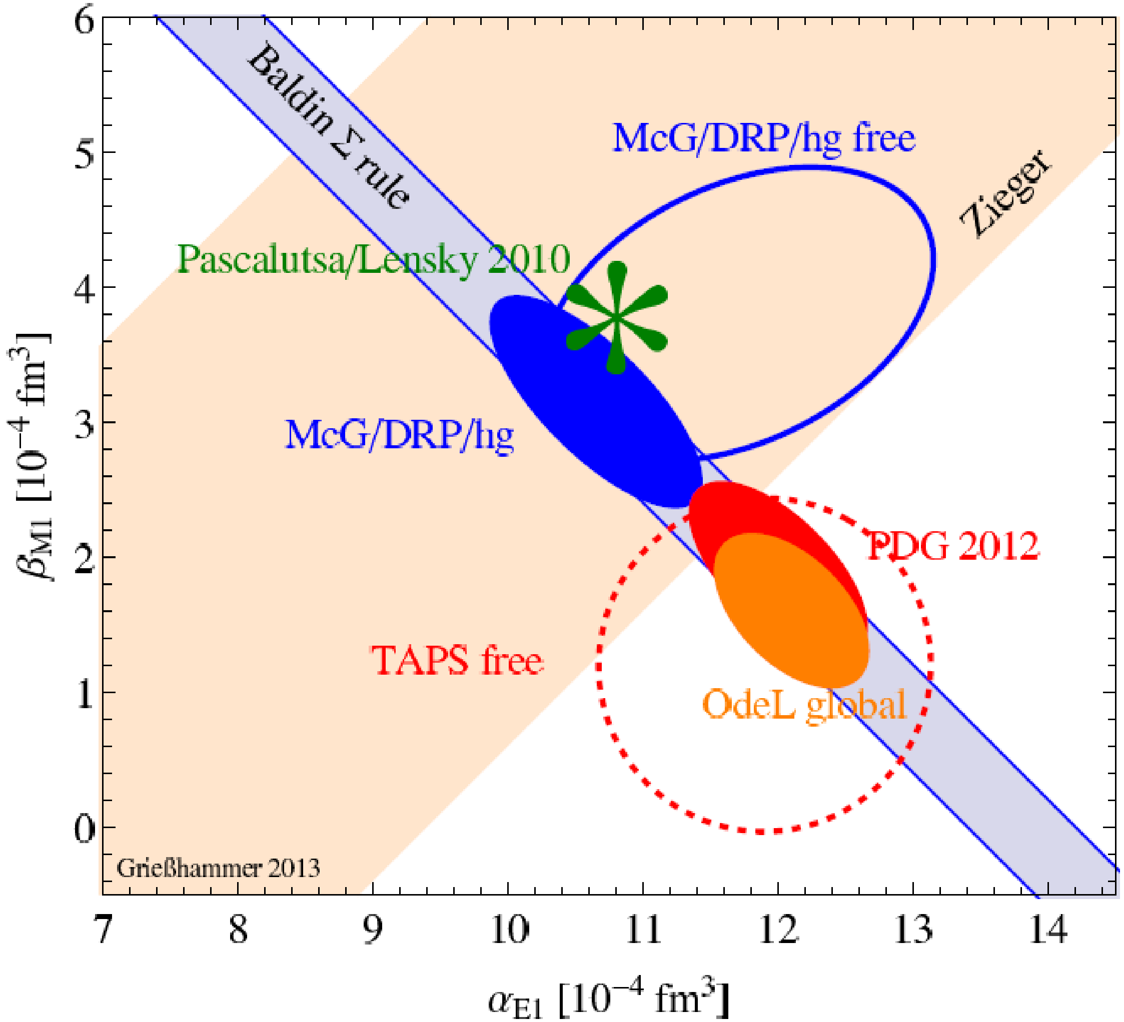
Crystal Ball:

- 672 NaI Crystals
- 24 Particle Identification Detector Paddles
- 2 Multiwire Proportional Chambers

TAPS:

- 366 BaF_2 and 72 $PbWO_4$ Crystals
- 384 Veto Detectors

Polarizabilities: Existing data and model predictions



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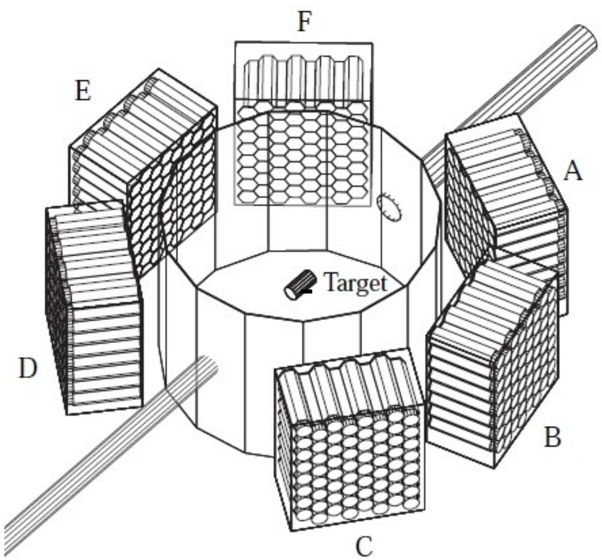
Krupina and Pascalutsa, PRL 110, 262001 (2013)

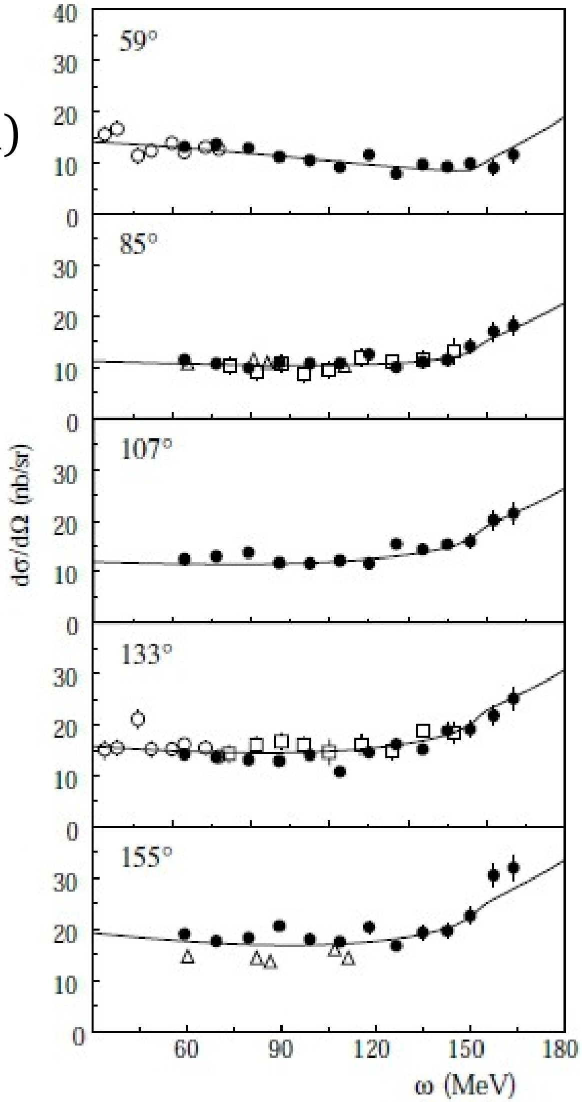
Compton Scattering: existing data

- Highest statistics data set:

V. Olmos de Leon et al. Eur. Phys. J. A 10, 207–215 (2001)

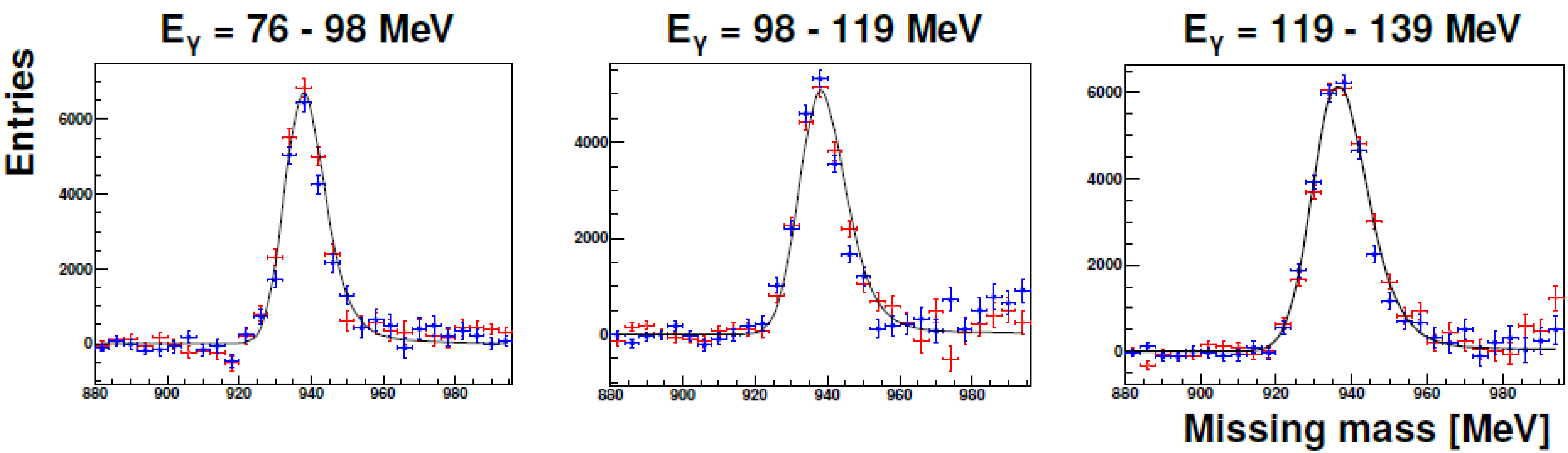
- 200 hours of Compton scattering
- 20 cm lH_2 target with TAPS
- 180 MeV electron beam
- E_γ = 55-165 MeV, 59° < Θ < 155°
- 1/3 acceptance of CB System!





Triangles: P.S. Baranov et al., Phys. Lett. B 52, 22 (1974);
P.S. Baranov et al., Sov. J. Nucl. Phys. 21, 355 (1975)
Open circles: F.J. Federspiel et al., Phys. Rev. Lett. 67, 1511 (1991)
Squares B.E. MacGibbon et al., Phys. Rev. C 52, 2097 (1995)
Curve: R.A. Arndt et al., Phys. Rev. C 53, 430 (1996)

Compton scattering: missing mass spectra

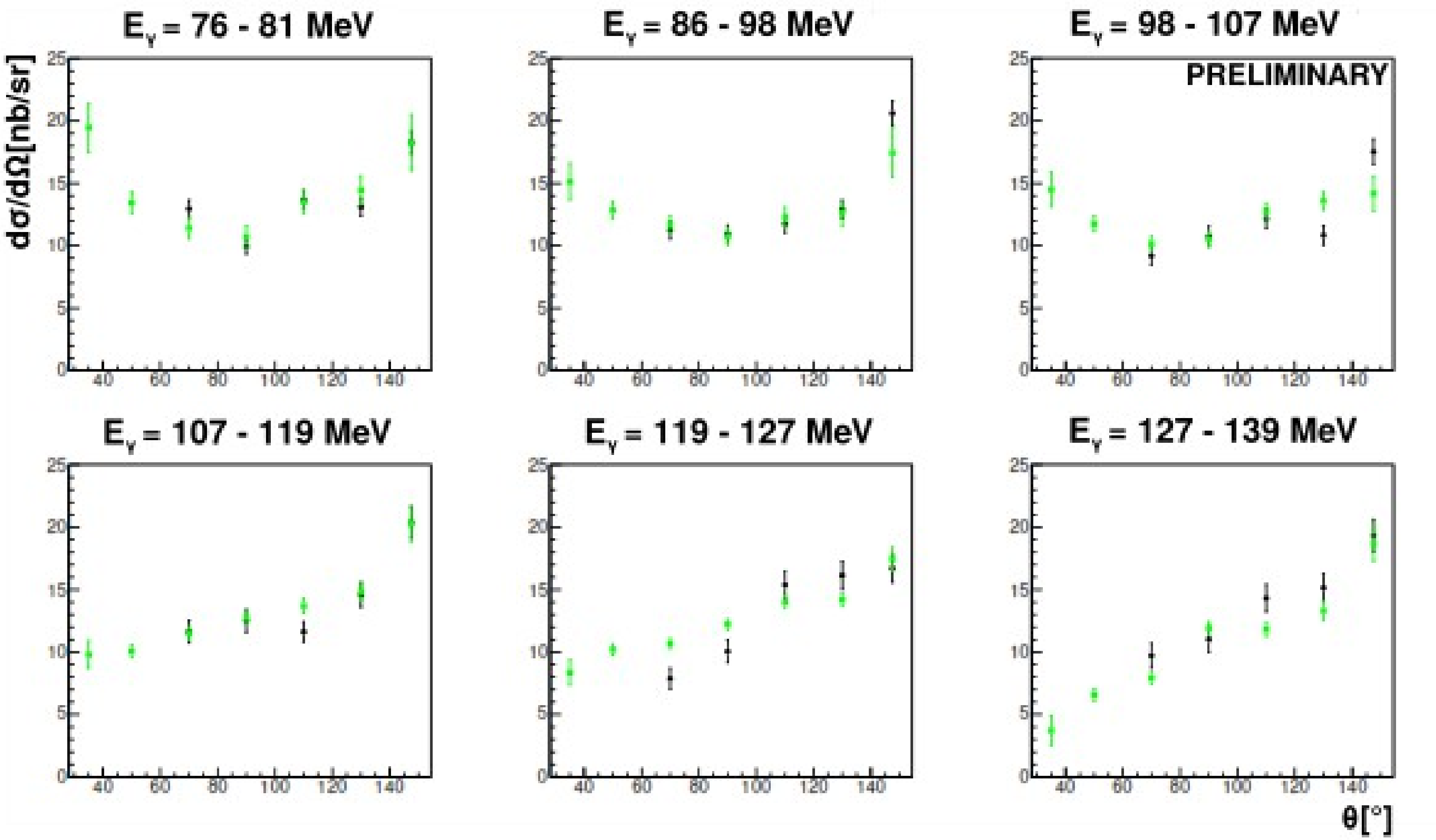


Good agreement in missing mass distribution for PARA, PERP and Monte Carlo simulation

$\Rightarrow$ **Low background data set**

E. Mornacchi (Mainz), V. S., E. J. Downie (GWU)

Compton scattering: new cross-section data



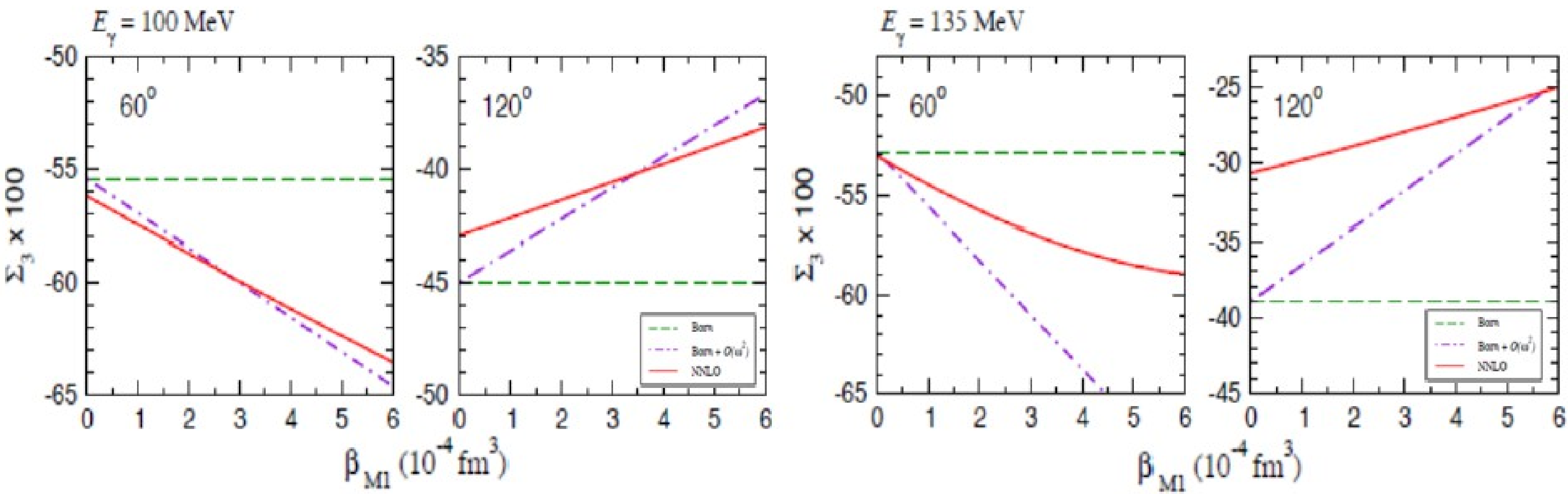
Good agreement between *old* and *new* data
Improvement in statistics!

E. Mornacchi (Mainz), V.S., E. J. Downie (GWU)

Extraction of the magnetic polarizability β

⇒ At low energy, β_{M1} can be extracted from the measurement of the beam asymmetry Σ_3:

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta)\left[1 + p_\gamma \Sigma_3 cos(2\phi)\right] \text{ where } \boldsymbol{\Sigma_3 = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}}$$



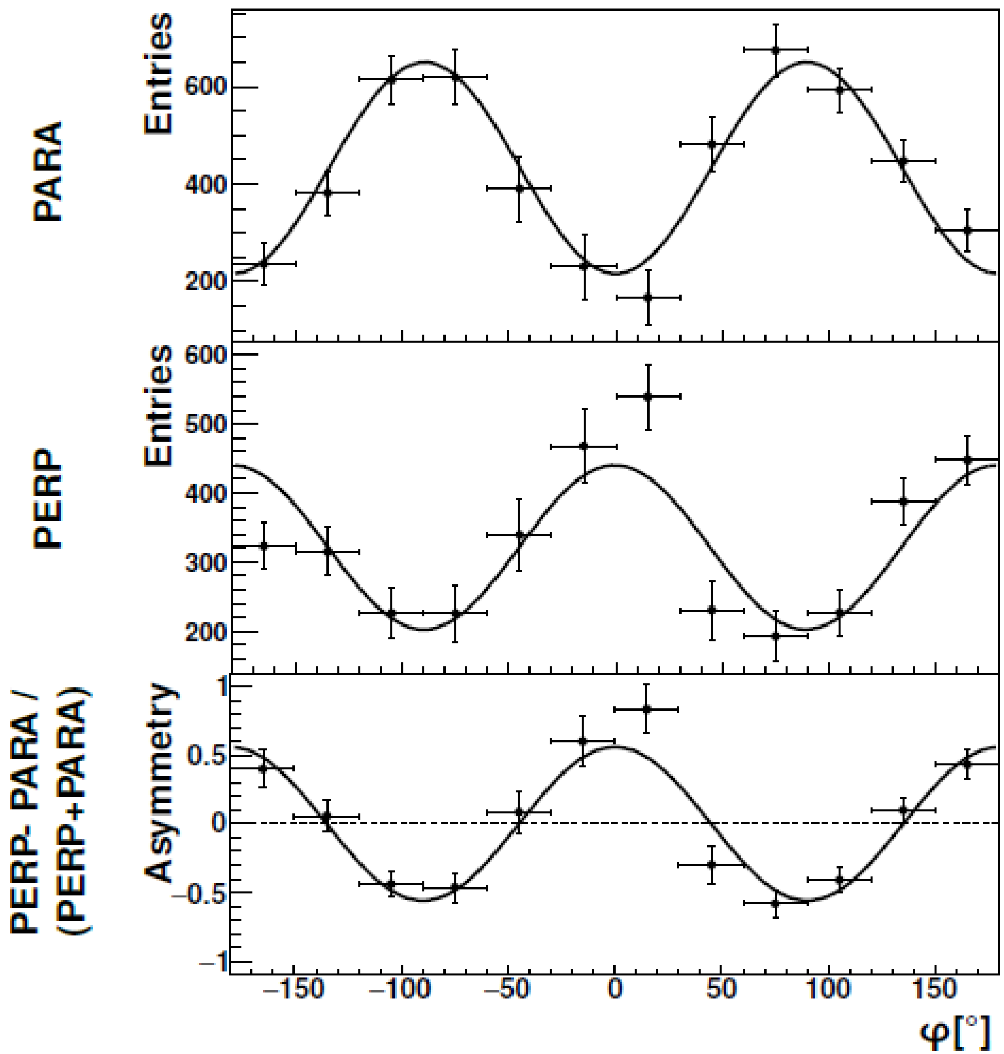
Krupina and Pascalutsa, PRL 110, 262001 (2013)

Compton scattering: angular distributions

ϕ distribution for PARA and PERP data.

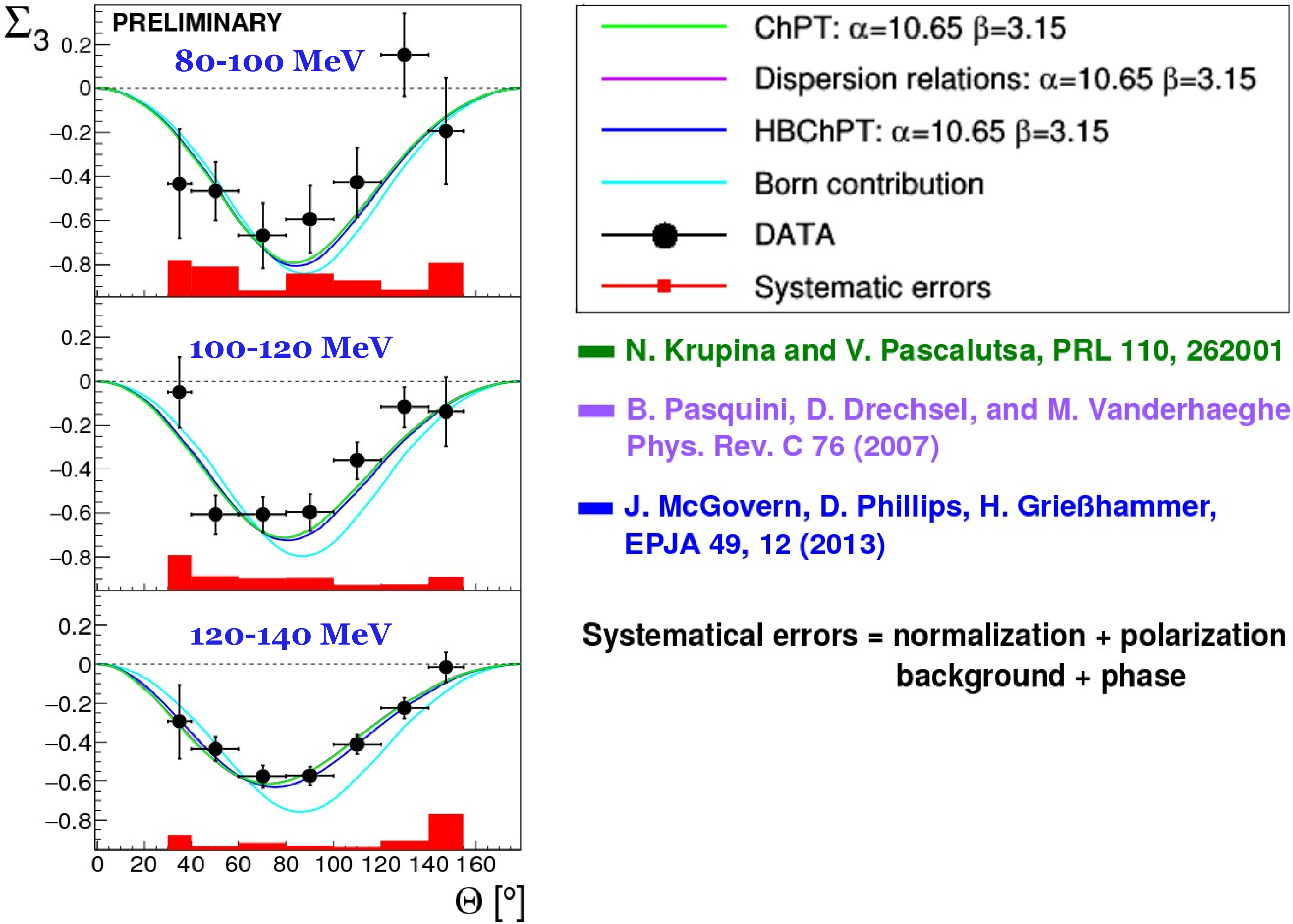
$\cos(2\phi)$ modulation coming from polarized cross-section.

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta)\left[1 + p_\gamma \Sigma_3 cos(2\phi)\right]$$



E. Mornachhi (Mainz), V.S., E. J. Downie (GWU)

Compton scattering: beam asymmetry



N. Krupina and V. Pascalutsa, PRL 110, 262001 (2013)

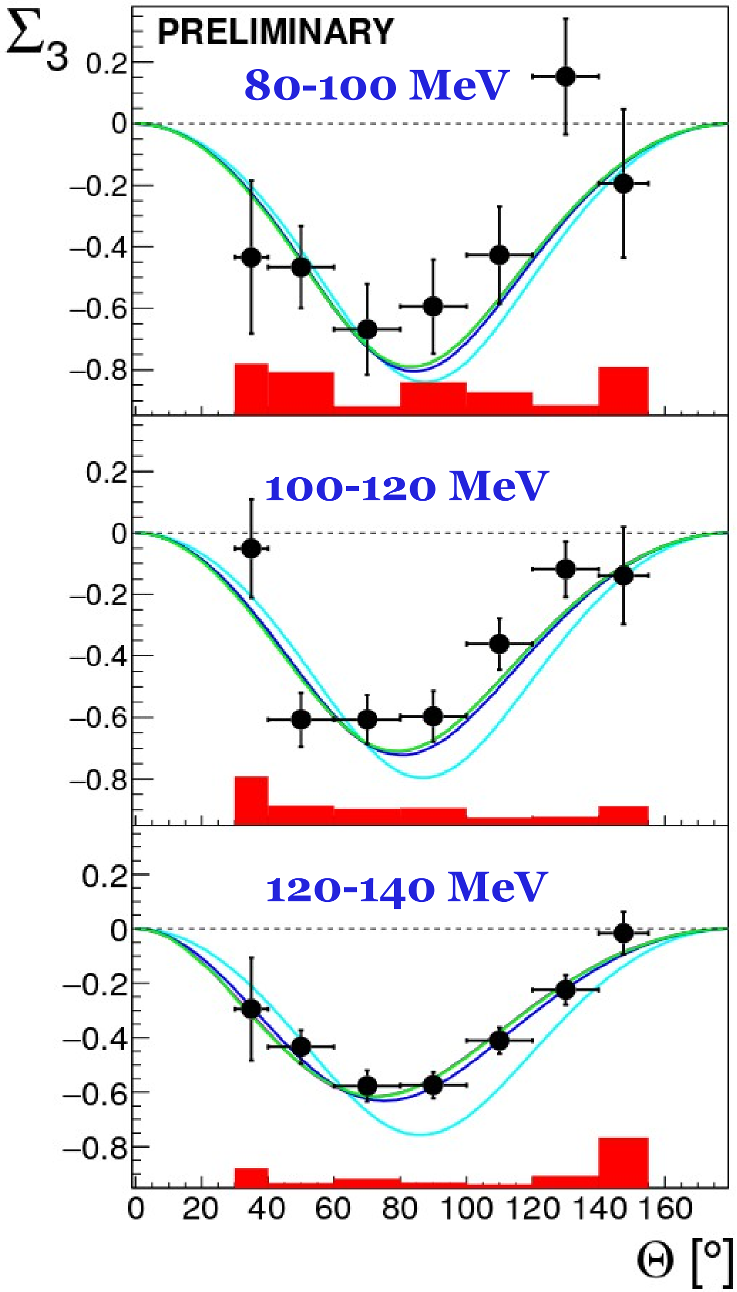
B. Pasquini, D. Drechsel, and M. Vanderhaeghen, Phys. Rev. C 76 (2007)

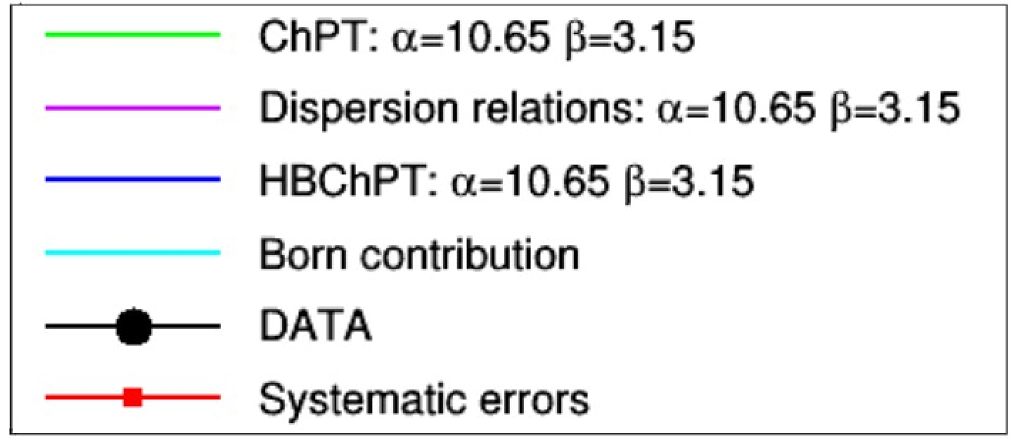
J. McGovern, D. Phillips, H. Grießhammer, EPJA 49, 12 (2013)

Systematical errors = normalization + polarization + background + phase

E. Mornachhi (Mainz), V.S., E. J. Downie (GWU)

Compton scattering: beam asymmetry





- N. Krupina and V. Pascalutsa, PRL 110, 262001 (2013)
- B. Pasquini, D. Drechsel, and M. Vanderhaeghen, Phys. Rev. C 76 (2007)
- J. McGovern, D. Phillips, H. Grießhammer, EPJA 49, 12 (2013)

Systematical errors = normalization + polarization + background + phase

Fit on our Σ_3 results using ChPT theory and Baldin sum rule constrain gives:

$\beta = (1.15 \pm 2.6) \times 10^{-4}\ \mathrm{fm}^3$

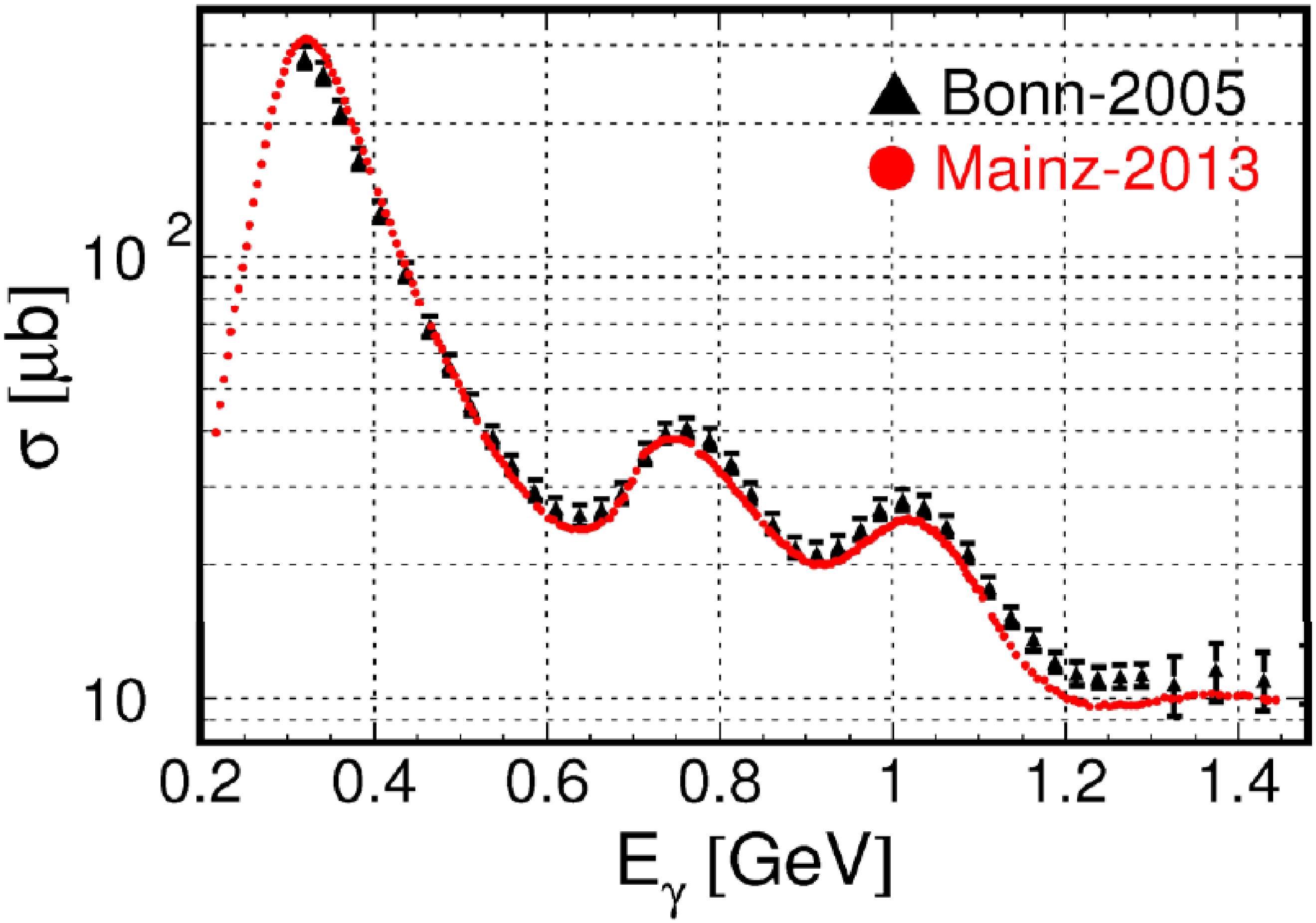
Fit by N. Krupina

Higher statistics data set will be taken in the future at MAMI facility in Mainz!

E. Mornachhi (Mainz), V.S., E. J. Downie (GWU)

Single π^o production

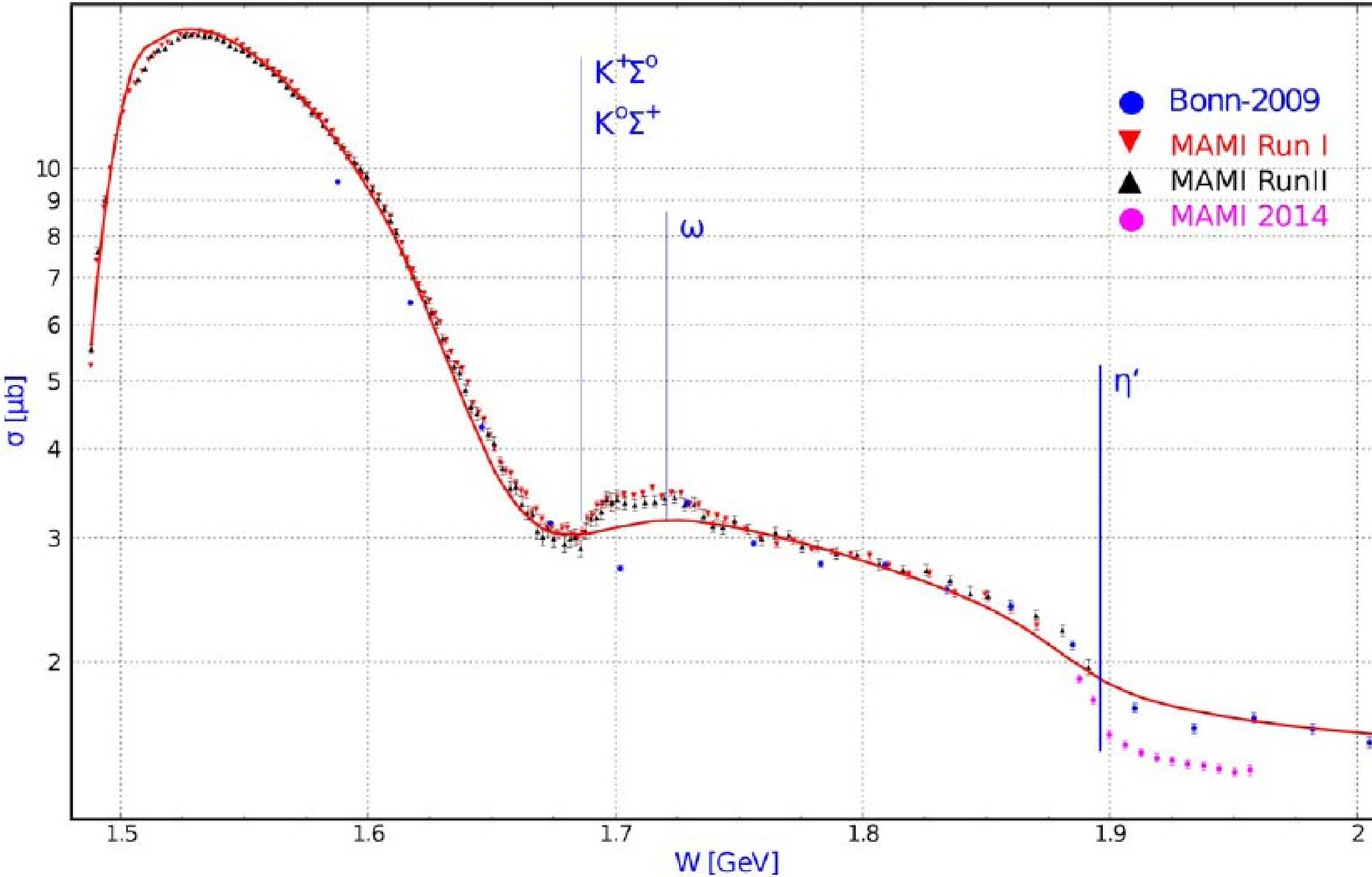
total cross section of MAMI γ,π^0 data



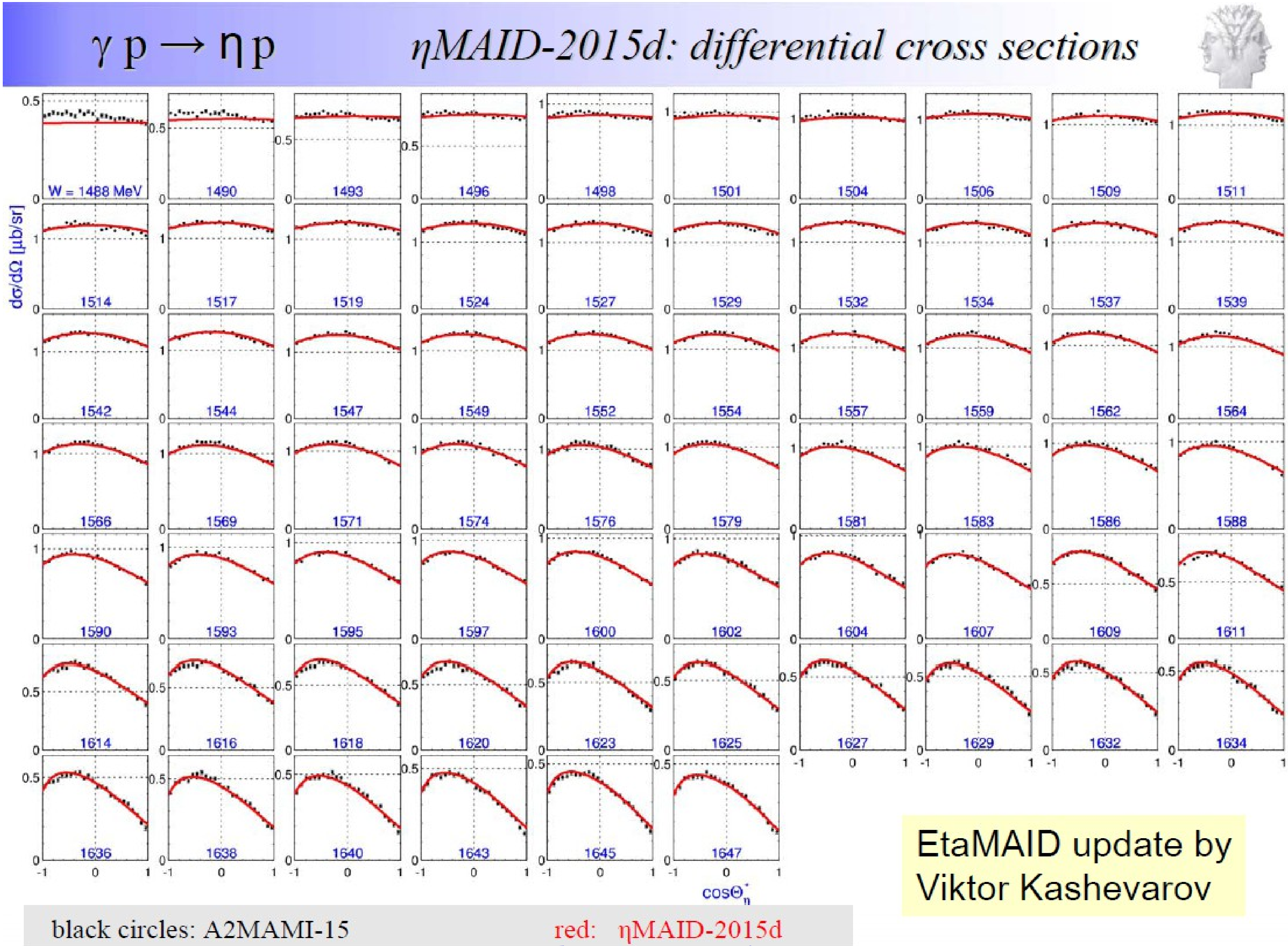
the red points are not a calculation, it is data!

P. Adlarson et al., Phys.Rev. C92 (2015) no.2, 024617

Single η production



Single η production



EtaMAID update by Viktor Kashevarov

V. Kashevarov (Mainz)

Single η and η' production

Eta-MAID update 2015 (with V. Kashevarov)

update for η photoproduction with new high-precision data: dσ/dΩ, Σ, T, F, E

using the previous EtaMAID2001/2003 model extended by new resonances N*

Particle J^P	overall	$N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$N(1440)\,1/2^+$	****	****	****		***				*	***
$N(1520)\,3/2^-$	****	****	****	***					***	***
$N(1535)\,1/2^-$	****	****	****	****					**	*
$N(1650)\,1/2^-$	****	****	****	***			***	**	**	***
$N(1675)\,5/2^-$	****	****	****	*			*		*	***
$N(1680)\,5/2^+$	****	****	****	*	**				***	***
$N(1700)\,3/2^-$	***	**	***	*			*	*	*	***
$N(1710)\,1/2^+$	****	****	****	***		**	****	**	*	**
$N(1720)\,3/2^+$	****	****	****	***			**	**	**	*
$N(1860)\,5/2^+$	**		**						*	*
$N(1875)\,3/2^-$	***	***	*			**	***	**		***
$N(1880)\,1/2^+$	**	*	*		**		*			
$N(1895)\,1/2^-$	**	**	*	**			**	*		
$N(1900)\,3/2^+$	***	***	**	**		**	***	**	*	**
$N(1990)\,7/2^+$	**	**	**					*		
$N(2000)\,5/2^+$	**	**	*	**			**	*	**	
$N(2040)\,3/2^+$	*		*							
$N(2060)\,5/2^-$	**	**	**	*				**		
$N(2100)\,1/2^+$	*		*							
$N(2120)\,3/2^-$	**	**	**				*	*		
$N(2190)\,7/2^-$	****	***	****			*	**		*	
$N(2220)\,9/2^+$	****		****							
$N(2250)\,9/2^-$	****		****							
$N(2300)\,1/2^+$	**		**							
$N(2570)\,5/2^-$	**		**							

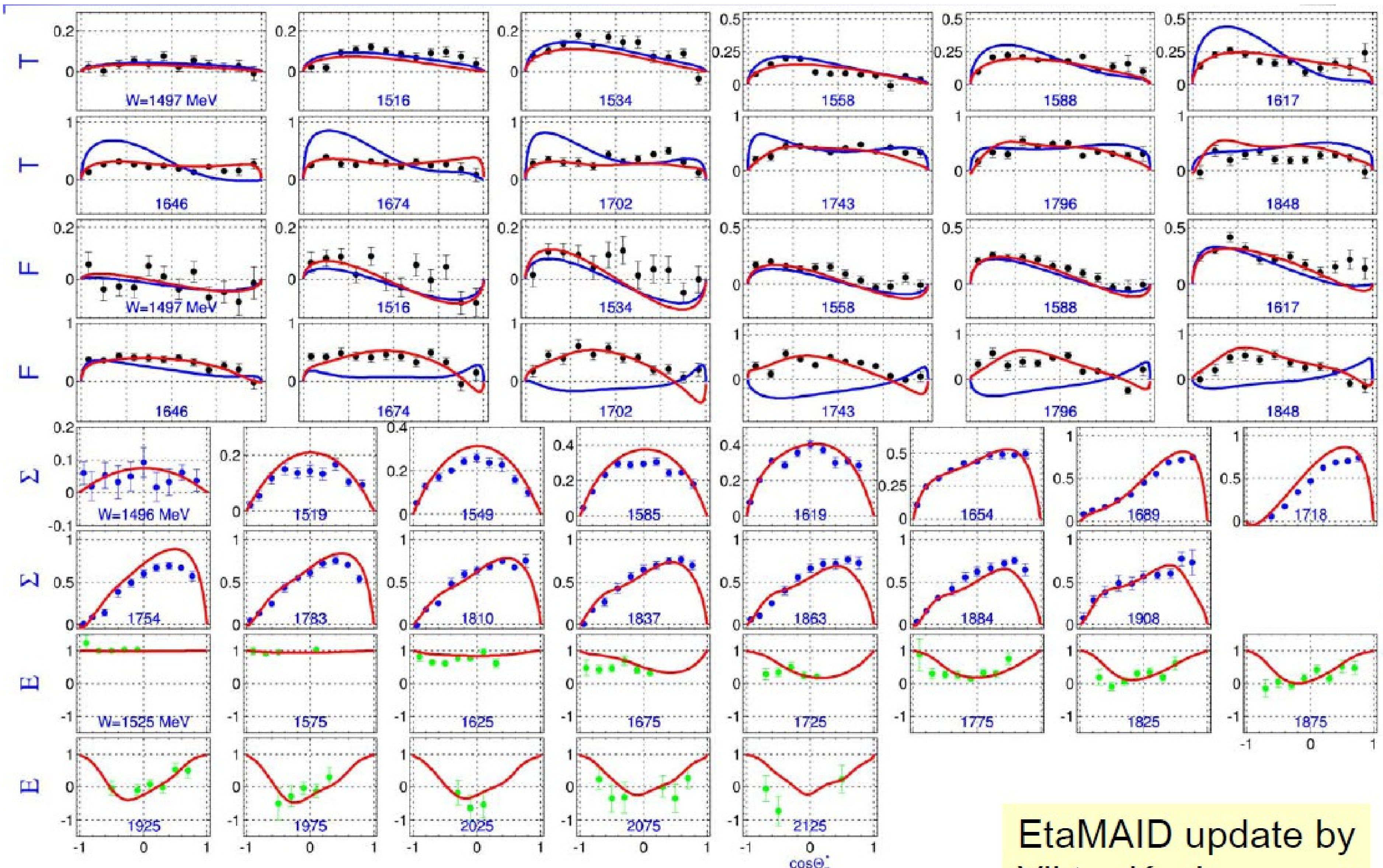
7 N* in 2001/2003

15 N* new in 2015

only 3 N* resonances in PDG below 2.6 GeV, where we do not find evidence for γ,η

but everything is still preliminary

Single η production



black circles: A2MAMI-14
blue circles: GRAAL-07; green: CLAS-15

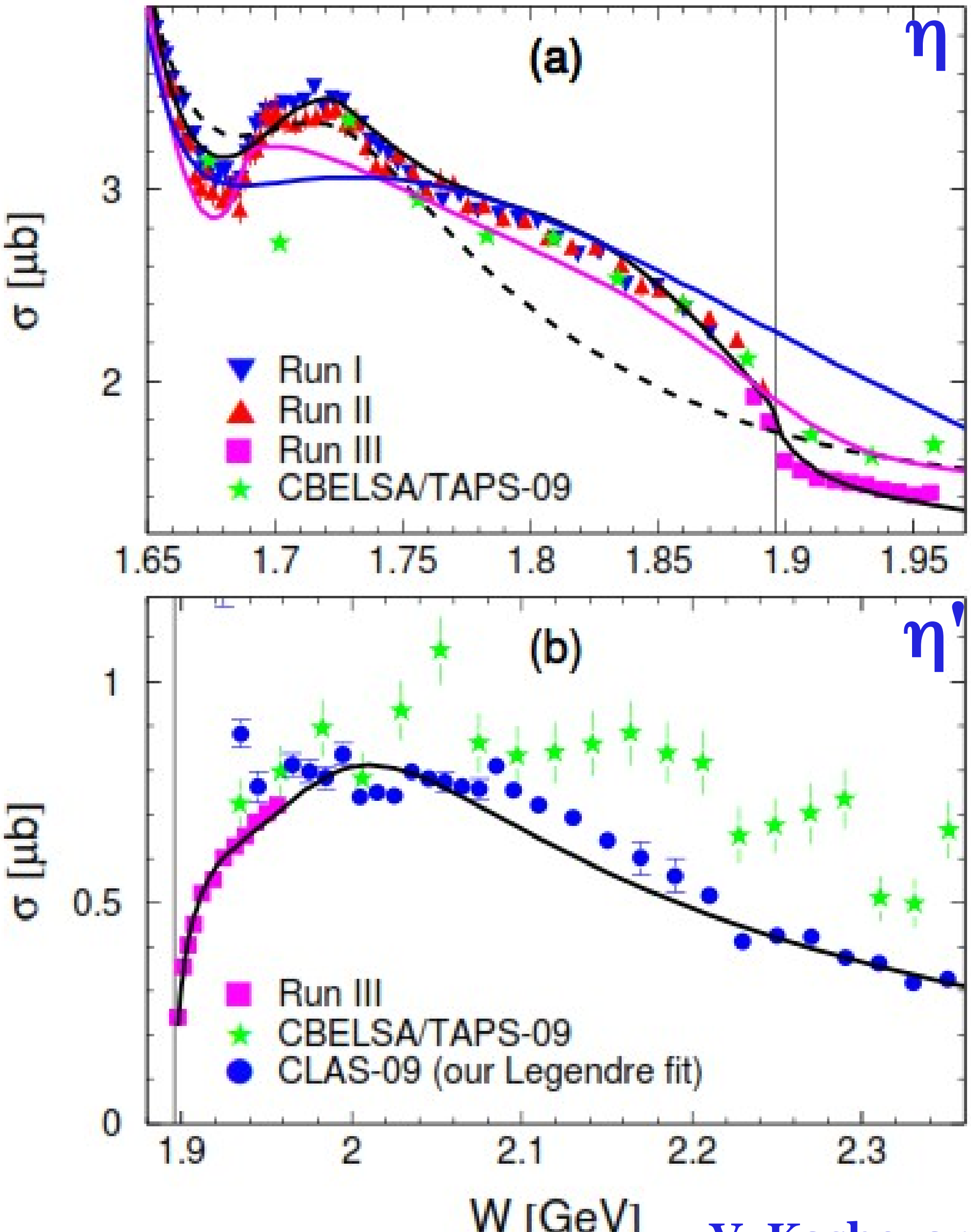
blue lines: ηMAID-2003
red lines: ηMAID-2015d

EtaMAID update by Viktor Kashevarov

V. Kashevarov (Mainz)

Single η and η' production

Black line: present solution, dashed: ηMAID-2003, magenta: BG2014-2; blue: SAID GE09



Particle J^P	overall	$N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$N(1440)\ 1/2^+$	****	****	****		***				*	***
$N(1520)\ 3/2^-$	****	****	****	***					***	***
$N(1535)\ 1/2^-$	****	****	****	****					**	*
$N(1650)\ 1/2^-$	****	****	****	***			***	**	**	***
$N(1675)\ 5/2^-$	****	****	****	*			*		*	***
$N(1680)\ 5/2^+$	****	****	****	*	**				***	***
$N(1700)\ 3/2^-$	***	**	***	*			*	*	*	***
$N(1710)\ 1/2^+$	****	****	****	***		**	****	**	*	**
$N(1720)\ 3/2^+$	****	****	****	***			**	**	**	*
$N(1860)\ 5/2^+$	**		**						*	*
$N(1875)\ 3/2^-$	***	***	*			**	***	**		***
$N(1880)\ 1/2^+$	**	*	*		**		*			
$N(1895)\ 1/2^-$	**	**	*	**			**	*		
$N(1900)\ 3/2^+$	***	***	**	**		**	***	**	*	**
$N(1990)\ 7/2^+$	**	**	**					*		
$N(2000)\ 5/2^+$	**	**	*	**			**	*	**	
$N(2040)\ 3/2^+$	*		*							
$N(2060)\ 5/2^-$	**	**	**	*				**		
$N(2100)\ 1/2^+$	*		*							
$N(2120)\ 3/2^-$	**	**	**				*	*		
$N(2190)\ 7/2^-$	****	***	****			*	**		*	
$N(2220)\ 9/2^+$	****		****							
$N(2250)\ 9/2^-$	****		****							
$N(2300)\ 1/2^+$	**		**							
$N(2570)\ 5/2^-$	**		**							

Double π^0 photoproduction

CBELSA/TAPS:

A: Pol_{max} = 49.2% @E_γ = 1300 MeV

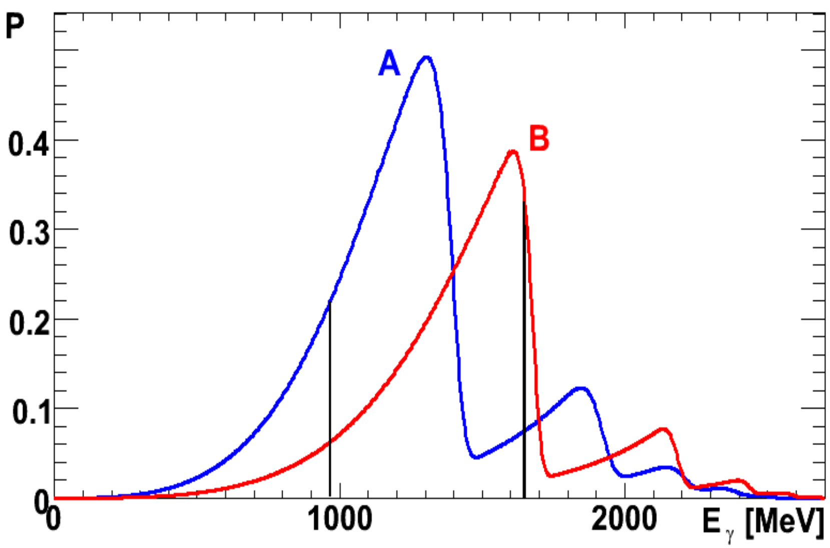
B: Pol_{max} = 38.7% @E_γ = 1600 MeV

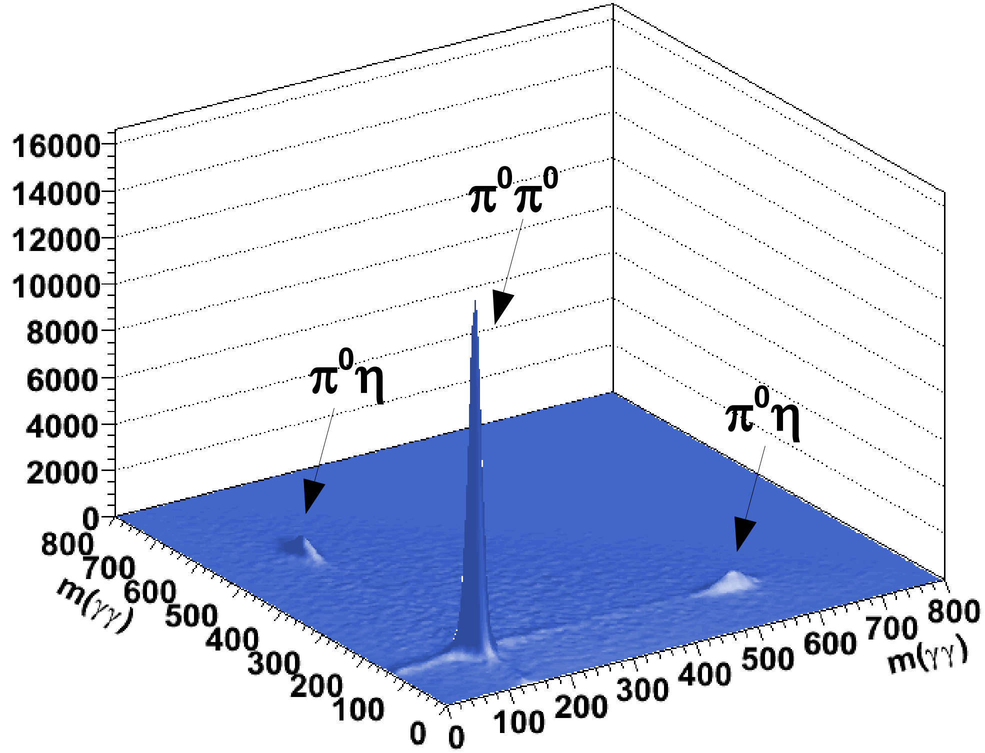
- Produced via coherent bremsstrahlung at a diamond crystal

- Liquid hydrogen as target material

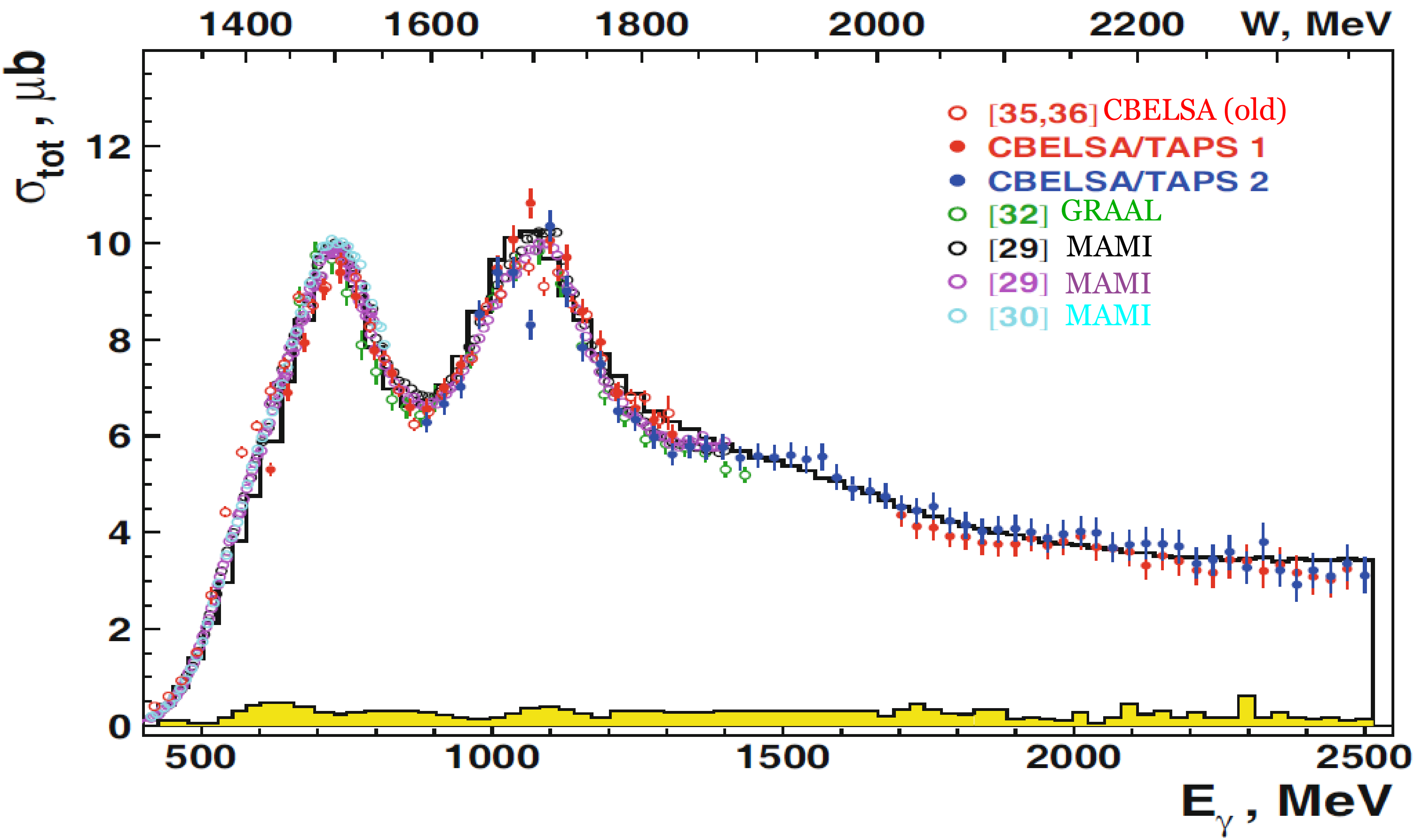
Data selected for 4γ (+proton) events

$\gamma p \rightarrow p \pi^0 \pi^0$ clearly observed!





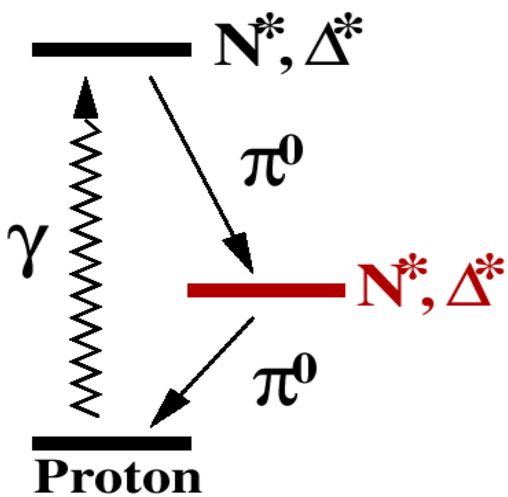
Double π^0 photoproduction

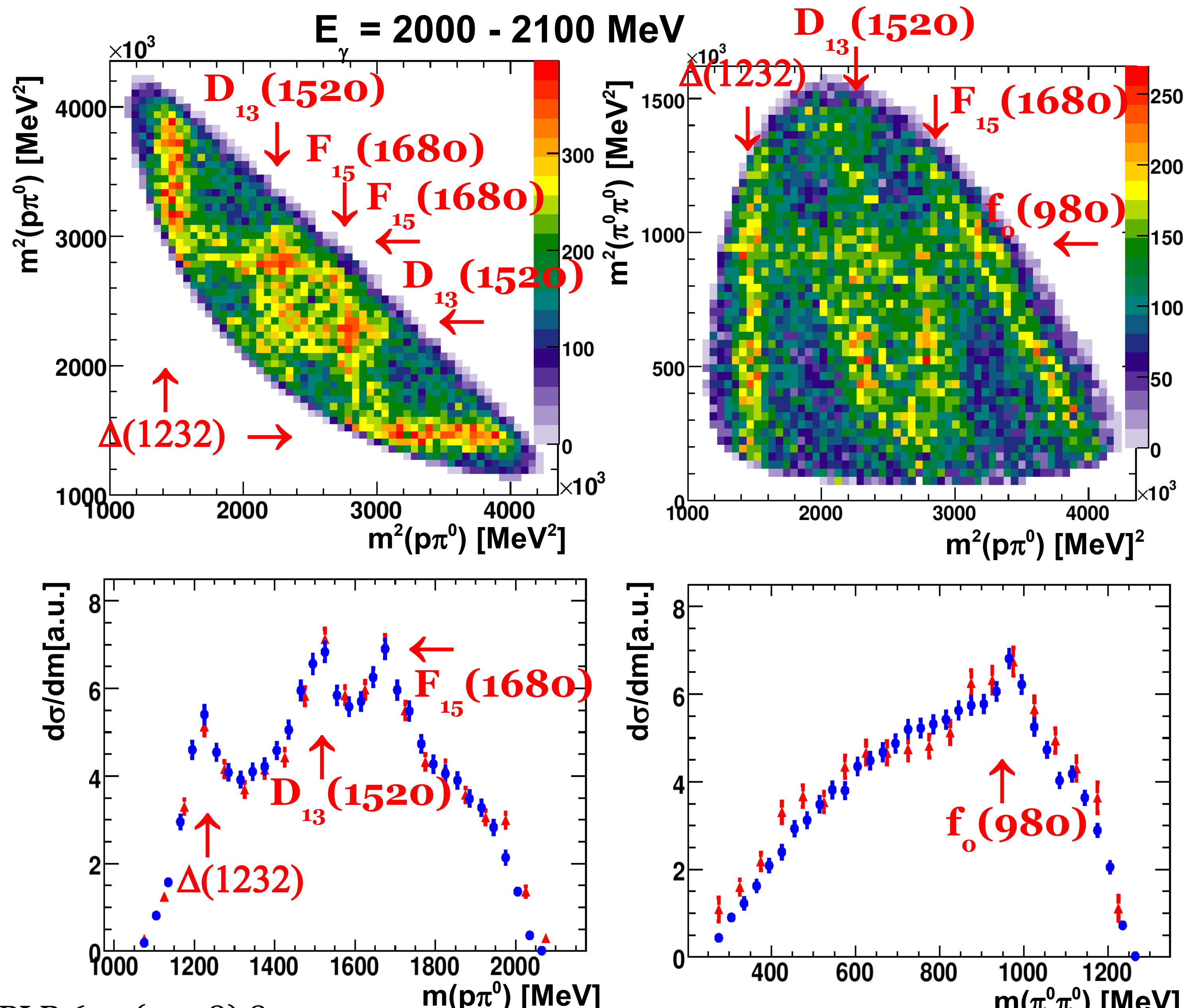


V. S., E. Gutz, V. Crede, H. van Pee, et al., Eur. Phys. J. A51 (2015) no.8, 95

A. Thiel , V. S., E. Gutz, H. van Pee et al., Phys.Rev.Lett. 114 (2015) no.9, 091803

Sequential decays in double π° production





CB-ELSA data

E_γ = 2000 - 2200 MeV

U. Thoma, M. Fuchs et al., PLB 659 (2008) 87

CBELSA/TAPS data

V. S., E. Gutz, V. Crede, H. van Pee, et al., Eur. Phys. J. A51 (2015) no.8, 95

Clear observation of cascading decays!

Polarization observables in double meson production

Linearly polarized photon beam, unpolarized target:

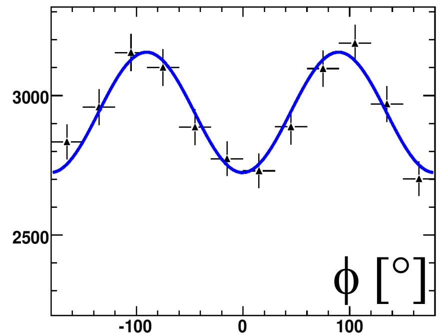
Quasi two-body consideration:

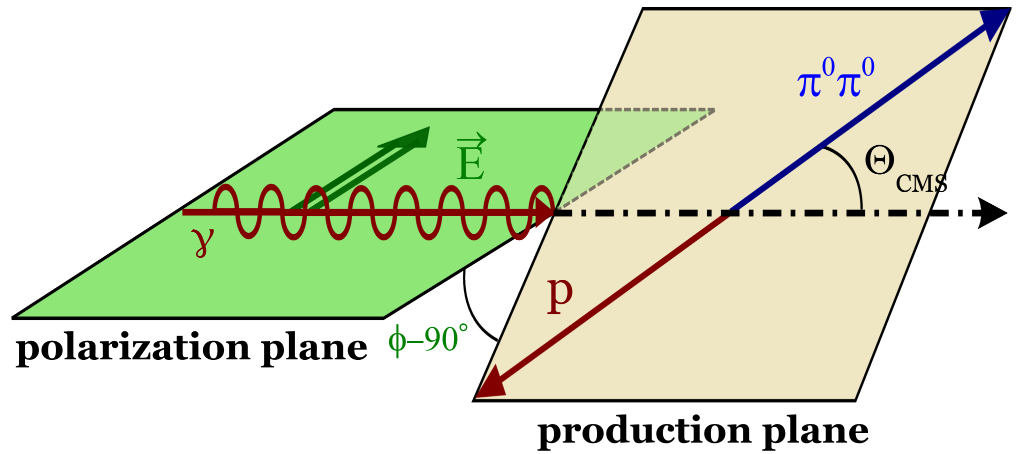
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 [1 + \delta_l \Sigma \cos(2\phi)]$$

$640 \le m_{\pi\pi} \le 700$ MeV/c²

E_γ = 1200-1450 MeV

$f(\phi) = A(1+\delta_l B\cos 2\phi)$





- Three-particle final state: additional plane!
- Additional polarization observables!

Polarization observables

Linearly polarized photon beam, unpolarized target:

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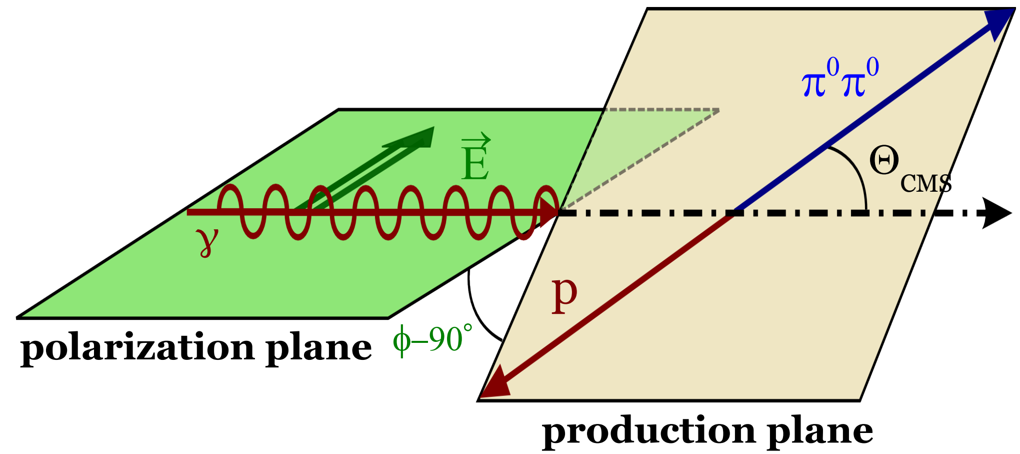
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 [1 + \delta_l \Sigma \cos(2\phi)]$$



$640 \leq m_{\pi\pi} \leq 700$ MeV/c²

E_γ = 1200-1450 MeV

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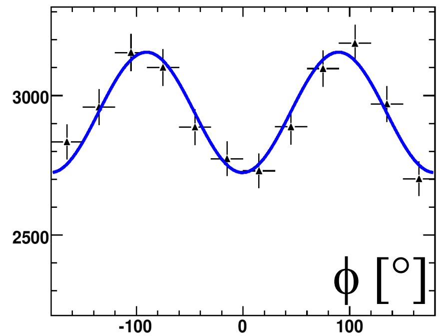


- Three-particle final state: additional plane!
- Additional polarization observables!

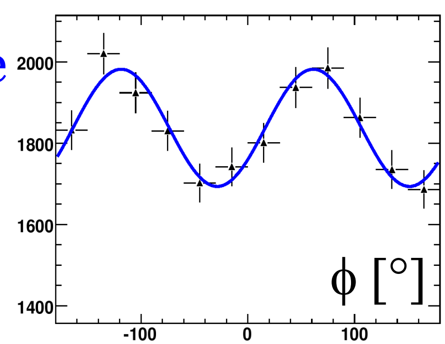
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \{1 + \delta_l [I^s \sin(2\phi) + I^c \cos(2\phi)]\}$$

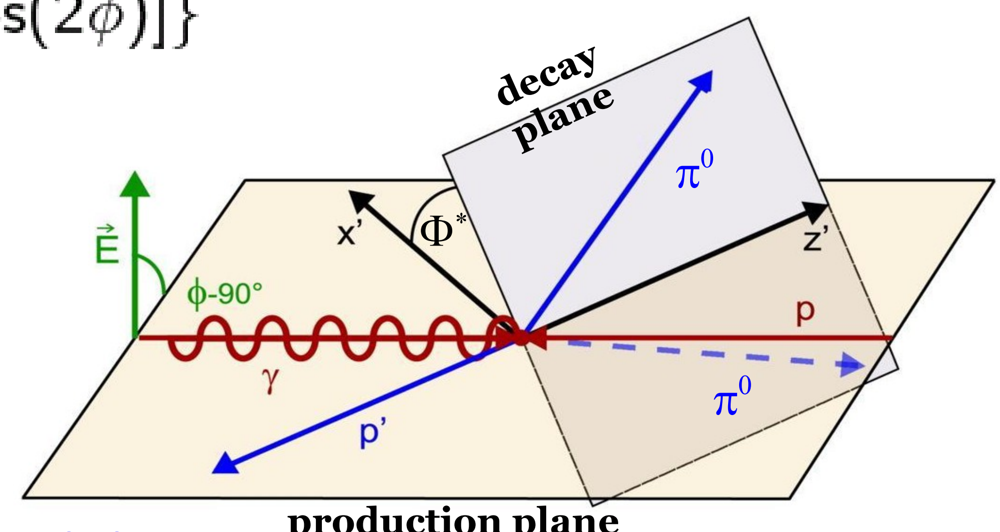
$f(\phi) = A(1+\delta_l(B\sin 2\phi + C\cos 2\phi))$

Limited Φ^* range →

$18^\circ \leq \Phi^* \leq 36^\circ$

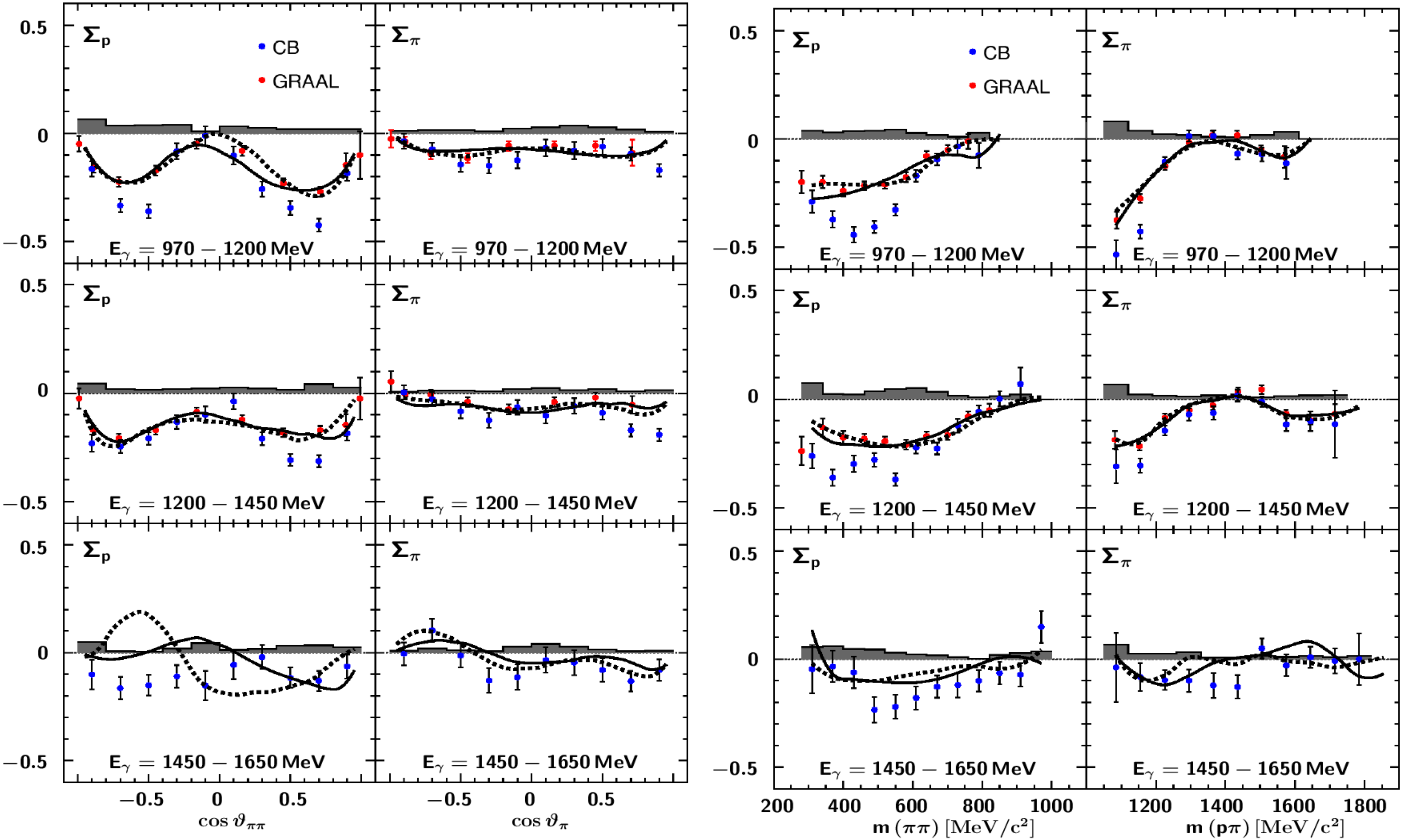
E_γ = 970-1200 MeV





First measurement of I^s and I^c in $\vec{\gamma} p \rightarrow p\pi^0\pi^0$!

Polarization observable Σ



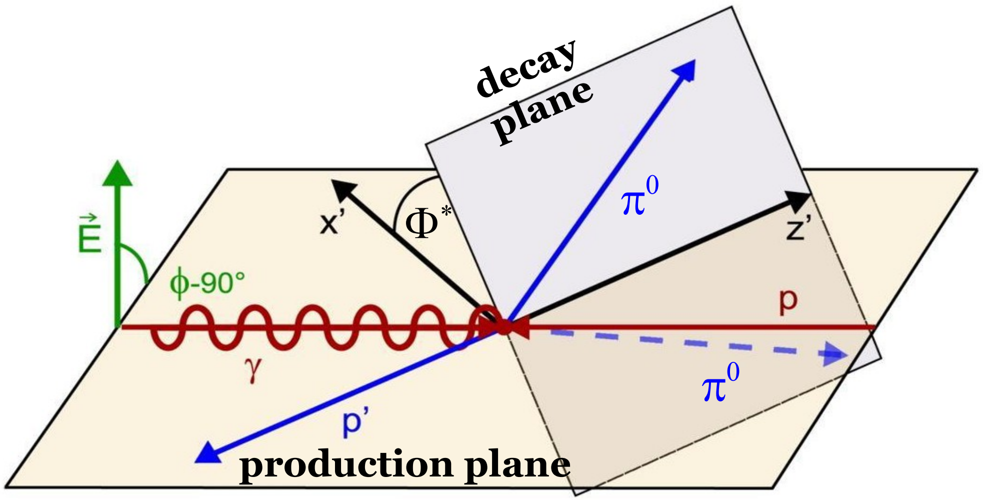
Solid: D_{33}(1700)→ $\Delta\pi_{\text{(D-wave)}}$, Dashed: D_{33}(1700)→ $\Delta\pi_{\text{(S-wave)}}$ dominant

V. S., E. Gutz, V. Crede, H. van Pee, et al., Eur. Phys. J. A51 (2015) no.8, 95

V. S., E. Gutz, H. van Pee et al., Phys.Lett. B746 (2015) 127-131

First measurement of I^s and I^c in $\gamma p \to p\pi^0\pi^0$

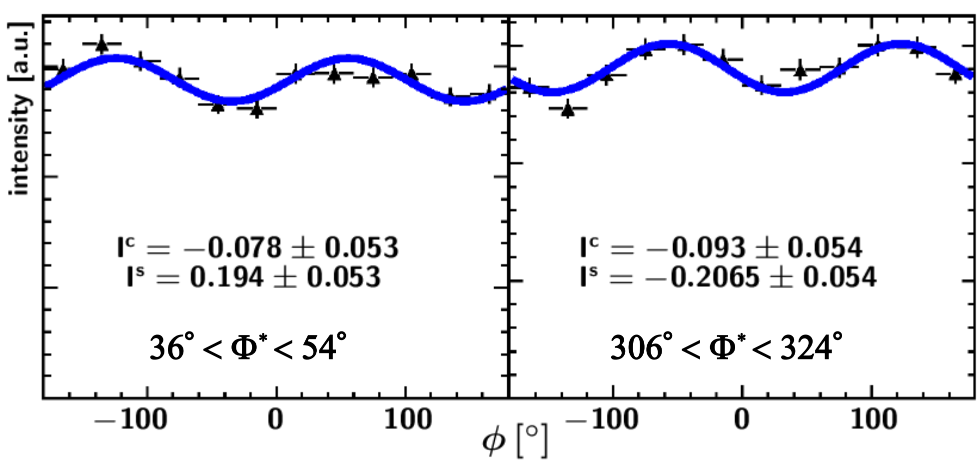
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \{1 + \delta_l[I^s \sin(2\phi) + I^c \cos(2\phi)]\}$$



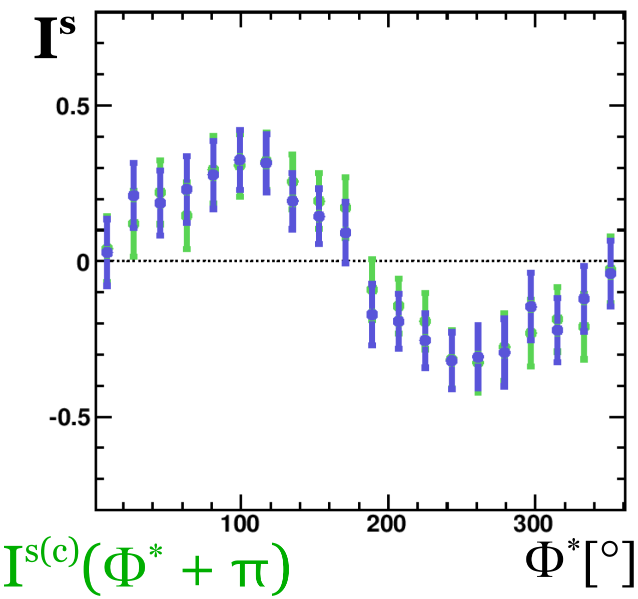
$I^c(\Phi^*) = I^c(2\pi - \Phi^*)$

$I^s(\Phi^*) = -I^s(2\pi - \Phi^*)$

$f(\phi) = A(1+\delta_l(B\sin 2\phi + C\cos 2\phi))$

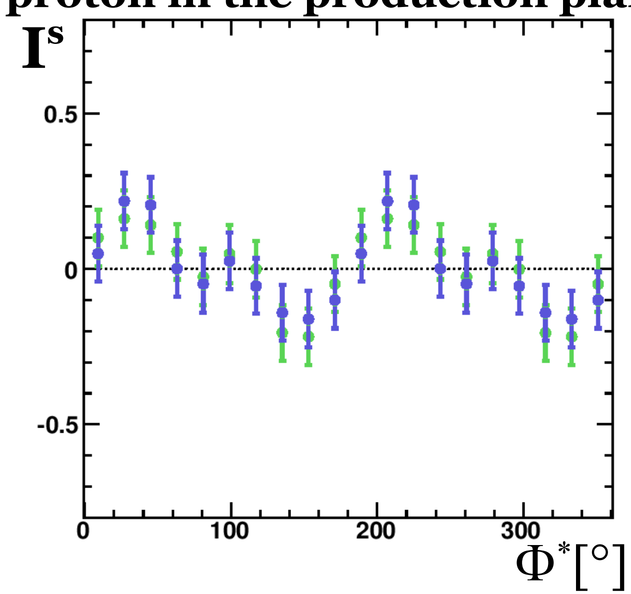


π^0 in the production plane

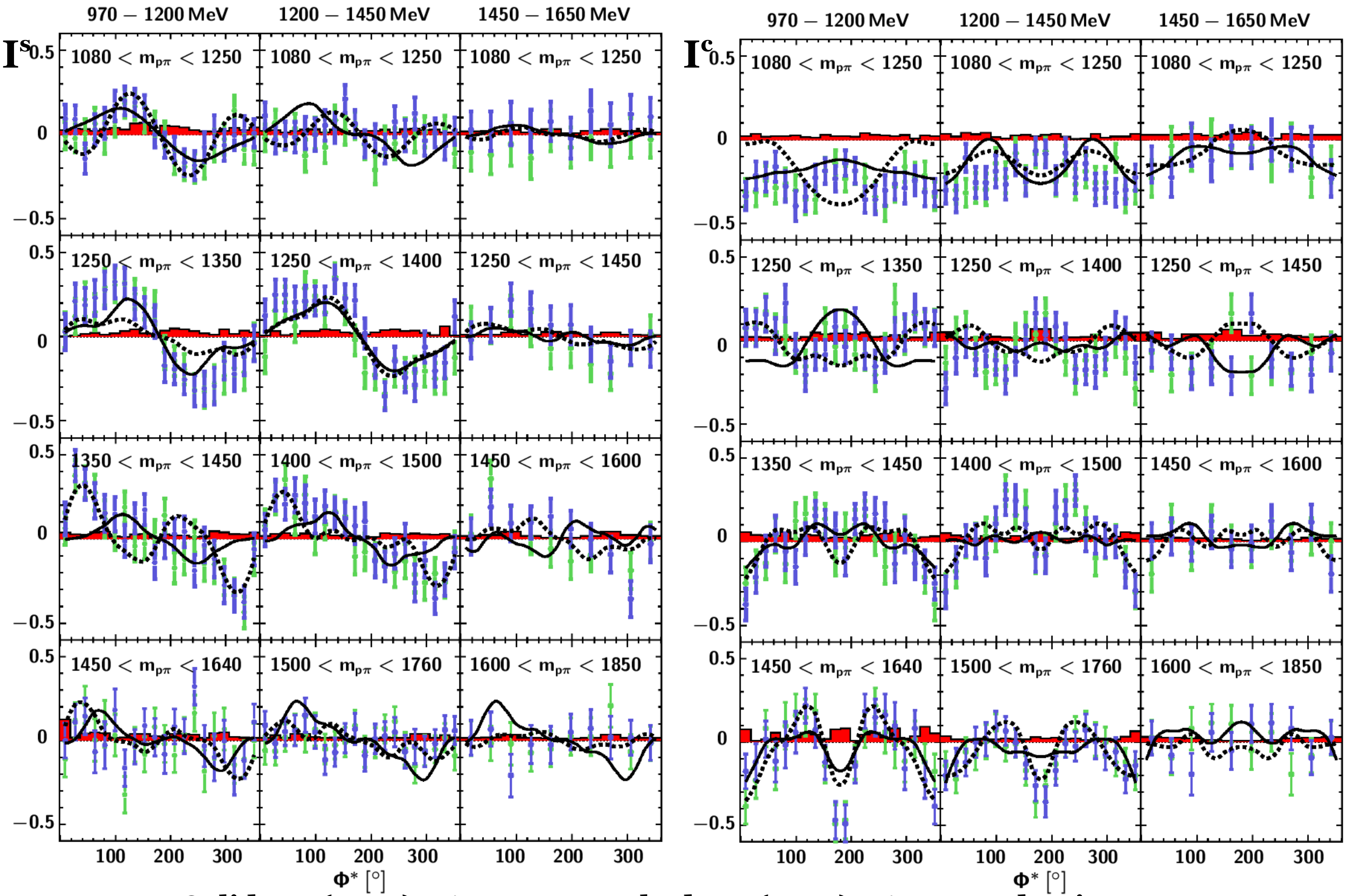


$I^{s(c)}(\Phi^*) = I^{s(c)}(\Phi^* + \pi)$

proton in the production plane



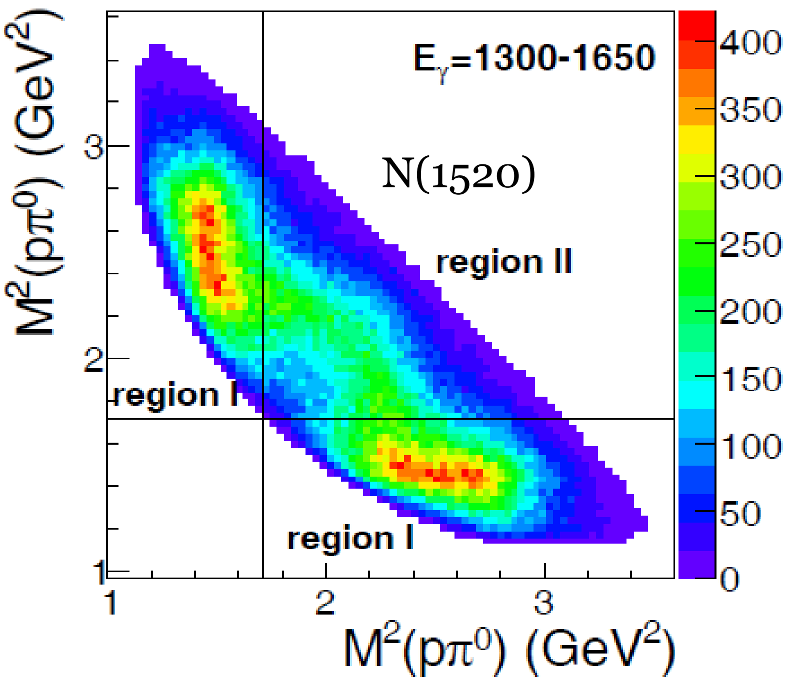
$I^s(\Phi^*) = -I^s(2\pi - \Phi^*)$ $I^c(\Phi^*) = I^c(2\pi - \Phi^*)$

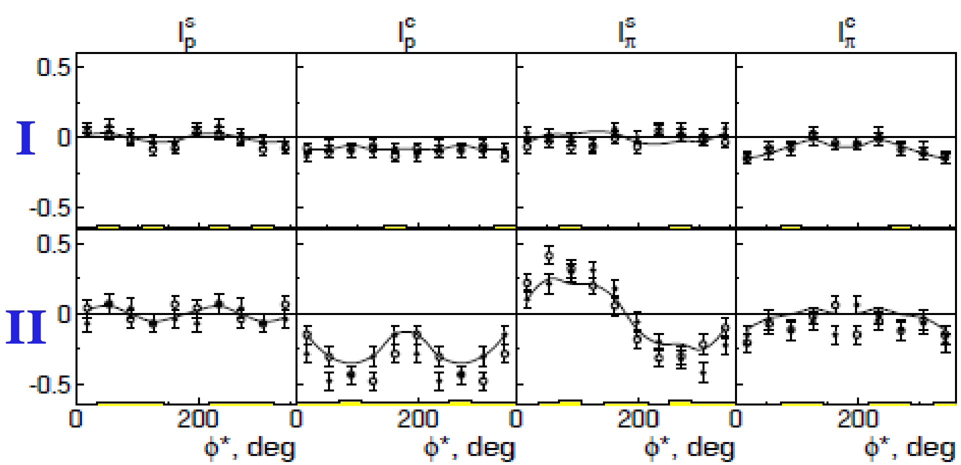


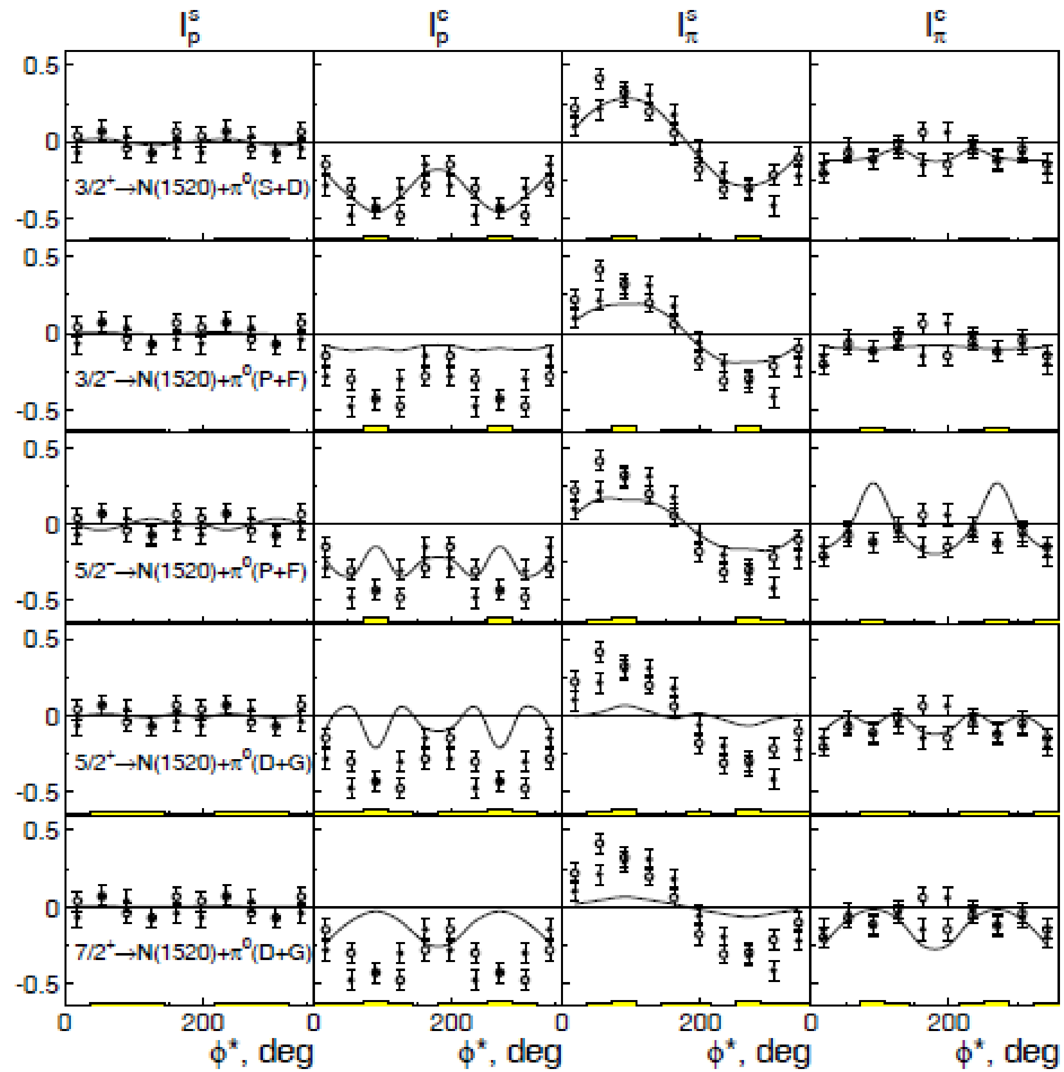
Solid: $D_{33}(1700) \rightarrow \Delta\pi_{(D\text{-wave})}$, Dashed: $D_{33}(1700) \rightarrow \Delta\pi_{(S\text{-wave})}$ dominant

V. S., E. Gutz, V. Crede, H. van Pee, et al., Eur. Phys. J. A51 (2015) no.8, 95

I^s and I^c in $\gamma p \to p\pi^0\pi^0$ and N(1900)3/2$^+$ resonance





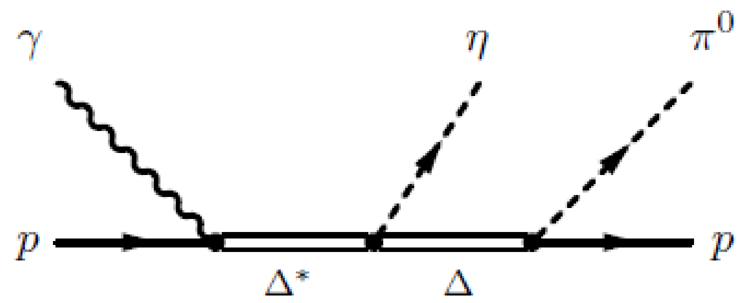


Dominance of the N(1900)3/2$^+$resonance directly seen in the data

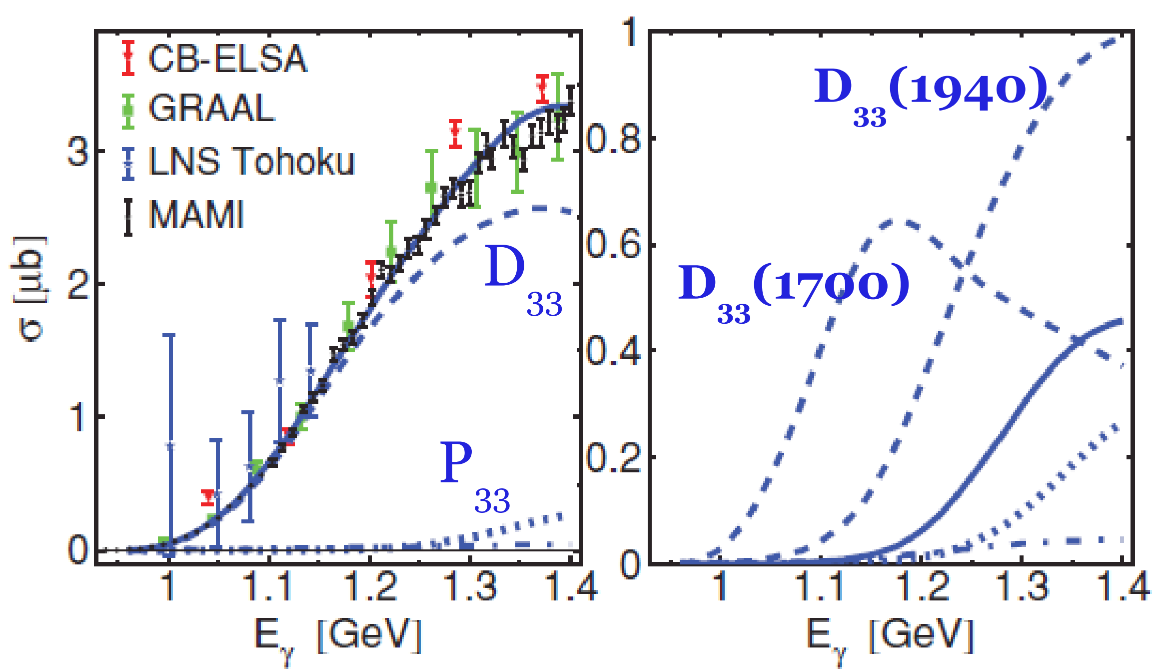
V. S., E. Gutz, H. van Pee et al., Phys.Lett. B746 (2015) 127-131

$\pi^0\eta$ photoproduction (proton target)

- The production of $\pi^0\eta$ pairs best suited to study the $D_{33}(1700)$ resonance
- η acts as an isospin filter: Access to $\gamma p \to D_{33}(1700) \to \Delta(1232)\eta \to p\pi^0\eta$

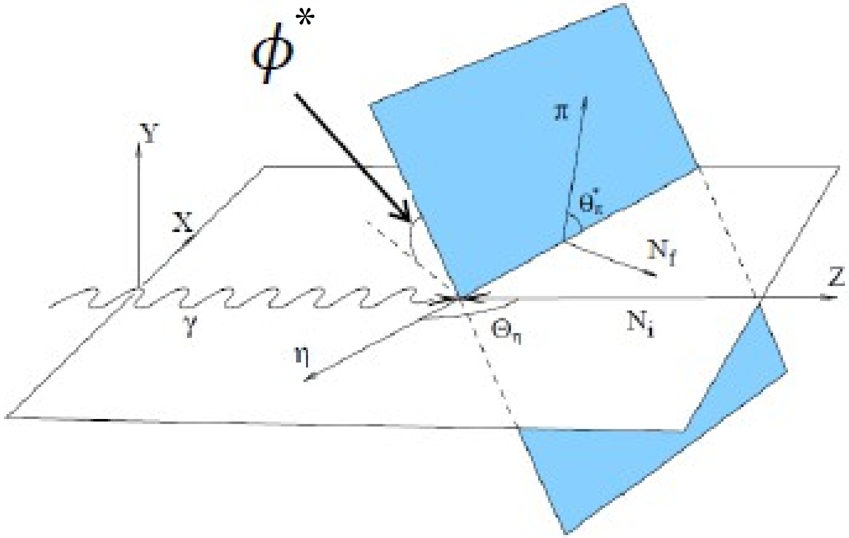


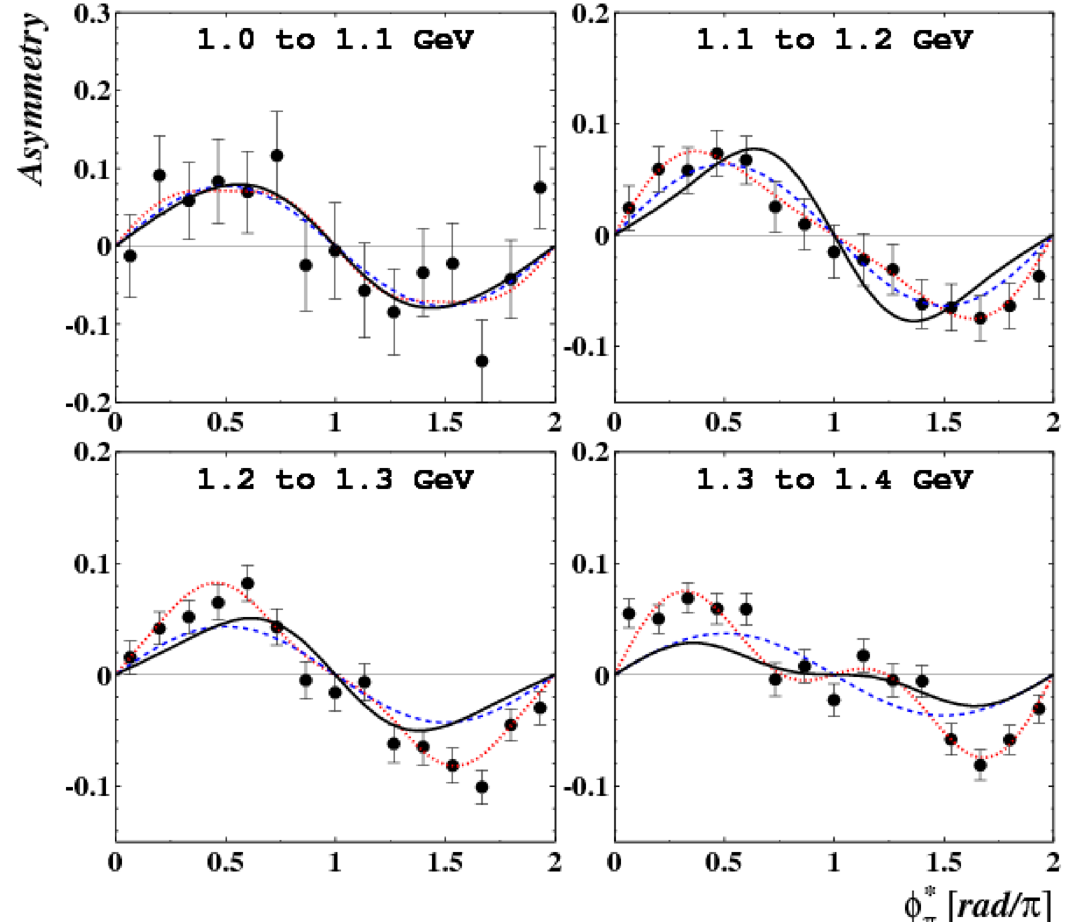
- $D_{33}(1700)$ dominates close to the production threshold



V. L. Kashevarov, A. Fix et al., Eur. Phys., J. A 42, 141 (2009) [A2 Collaboration]

Beam helicity asymmetry (proton target)





Beam helicity asymmetry:

$$W^c(\phi) \sim \sigma^+(\phi) - \sigma^-(\phi)$$

$W^c(\phi)$ can be expanded as:

$$W^c(\phi) = \sum_{n=1}^{n_{max}} A_n \sin n\phi$$

Dotted line: fit with the first 3 terms of the sine expansion (A1, A2, A3)
Solid line: isobar model with 6 resonances
Dashed line: only D33 wave

V. L. Kashevarov, et al., Phys. Lett. B 693, 551 (2010)

[A2 Collaboration]

Both unpolarized and polarized data indicate the dominance of the D_{33} wave at energies E_γ < 1.2 GeV

Nuclear targets

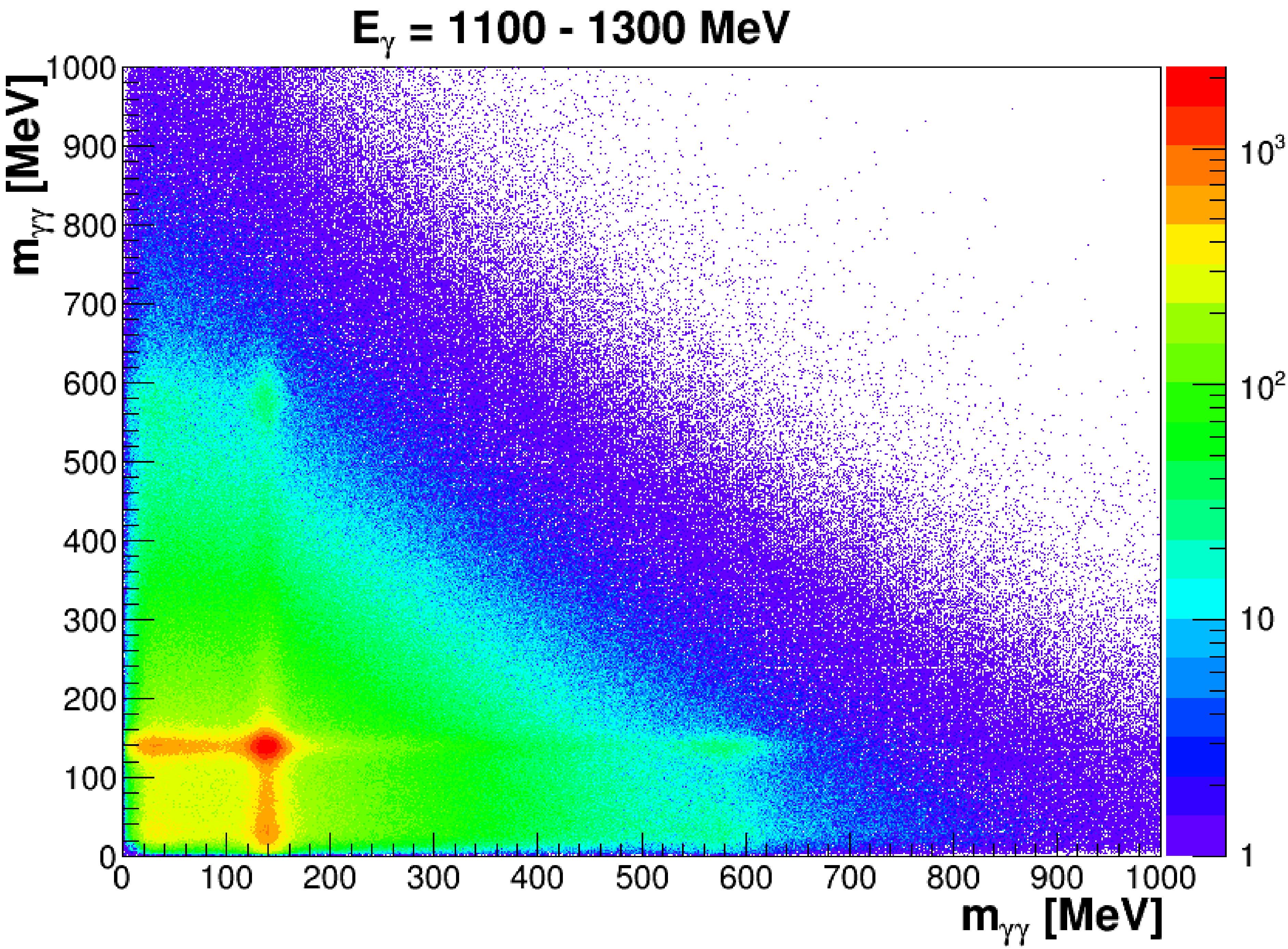
Existing data sets:

- Measurements performed by the A2 Collaboration with proton and deuteron targets
- Data on ^{4}He will be acquired in the near future

We are extracting:

- **Differential cross-sections and beam helicity asymmetry close to the $\pi^0\eta$ production threshold with C, Al and Pb targets**
- The structure in these observables is reasonably described by the $D_{33}(1700)$ resonance within the isobar model for the proton target at $E_\gamma < 1.2$ GeV (A. Fix, et al.)
- Any changes of these observables beyond FSI will allow access to the in-medium properties of the $D_{33}(1700)$

Example Spectra (Carbon target)



Understanding of the FSI

Experimental method:

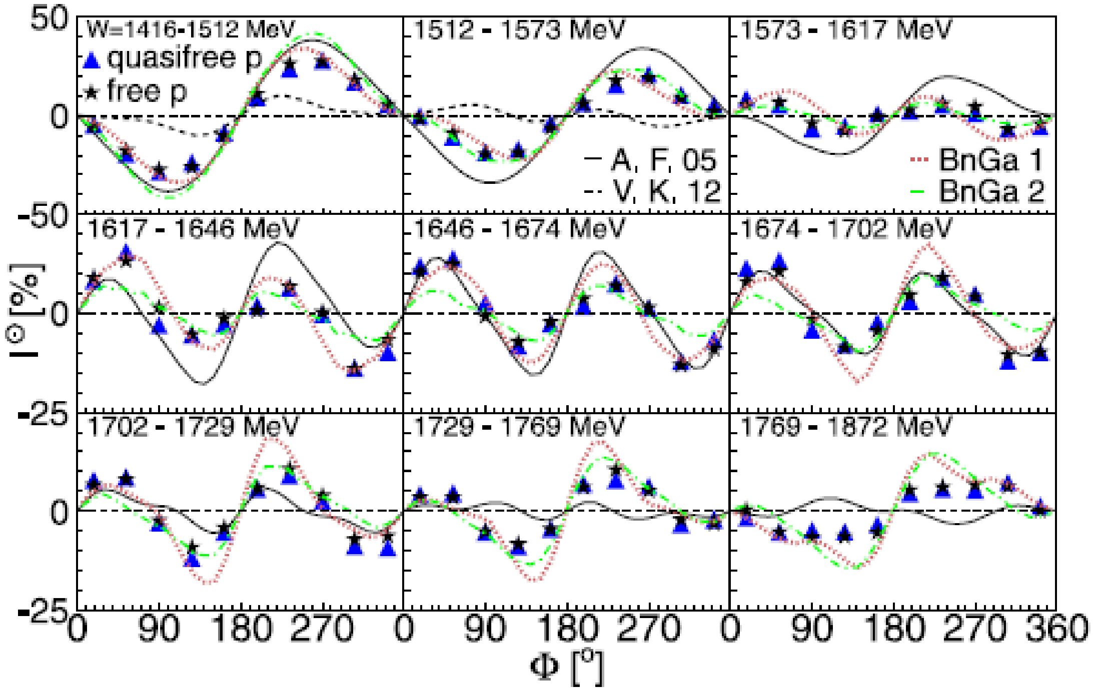
- Investigation of the FSI with light nuclei (deuteron, helium isotopes)
- Investigation of the coherent component
- Measurements with different targets
- New asymmetry data can be useful for the understanding of the mechanisms of the FSI

and:

- Theoretical estimates: calculations for the dilution of the desired signal with models such as the BUU transport model

Nuclear targets

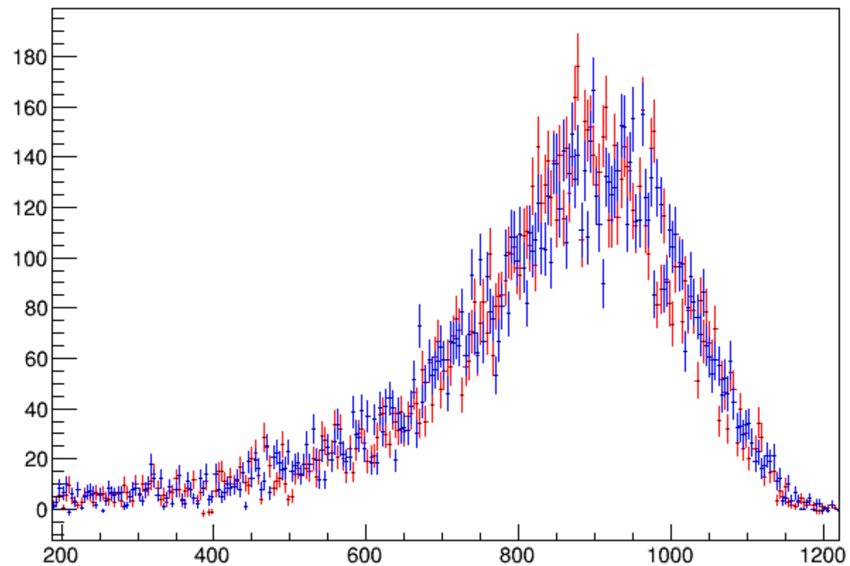
Example: Significant reduction of the total cross-section was observed for the deuteron target in several reactions, indicating strong FSI effects, but e.g. for the production of 2 neutral pions, the beam helicity asymmetry is in excellent agreement for the free proton (hydrogen target) and quasi-free proton (deuteron target) data



Black: free proton, Blue: quasi-free proton
M. Oberle, B. Krusche et al., Phys.Lett. B721 (2013) 237-243
[A2 Collaboration]

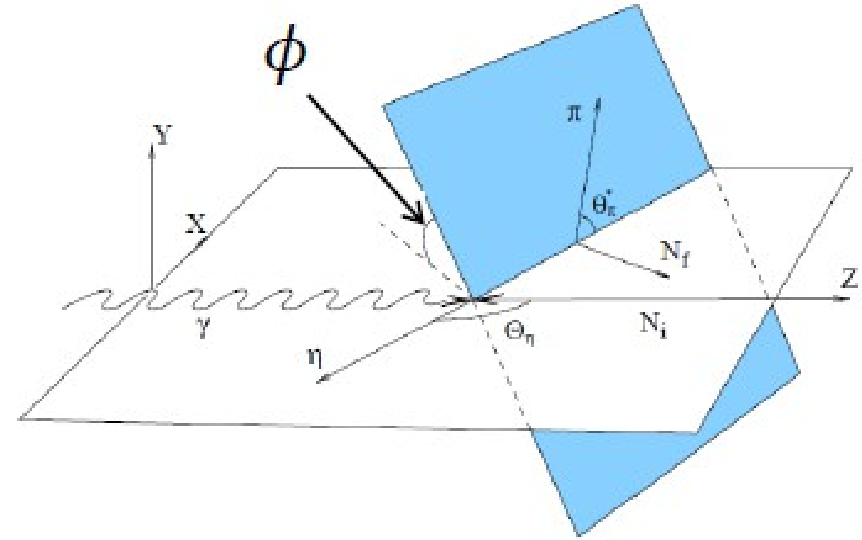
Example Spectra (Aluminium target)

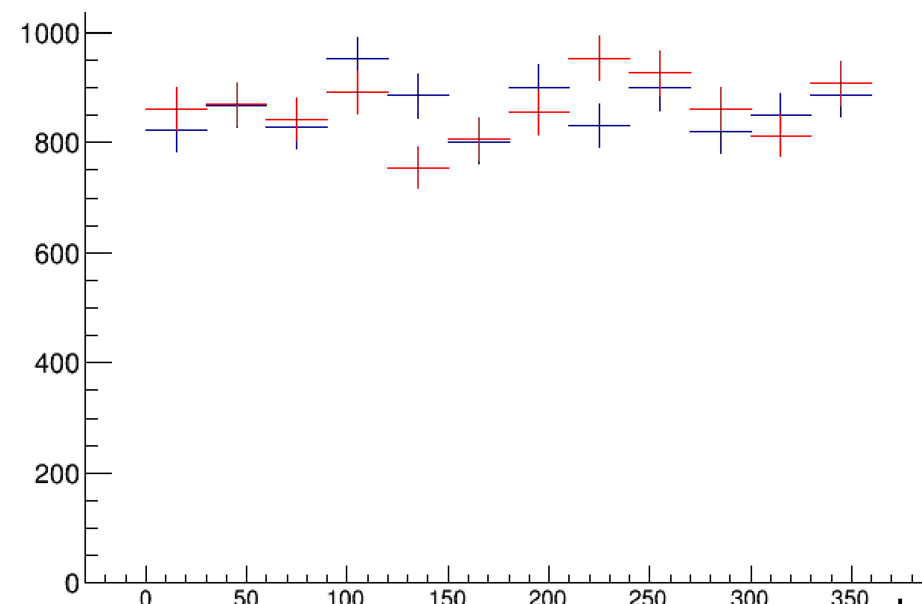
E_γ = 950 – 1450 MeV



Missing Mass [MeV]

Agreement between "unpolarized" distributions with different helicity

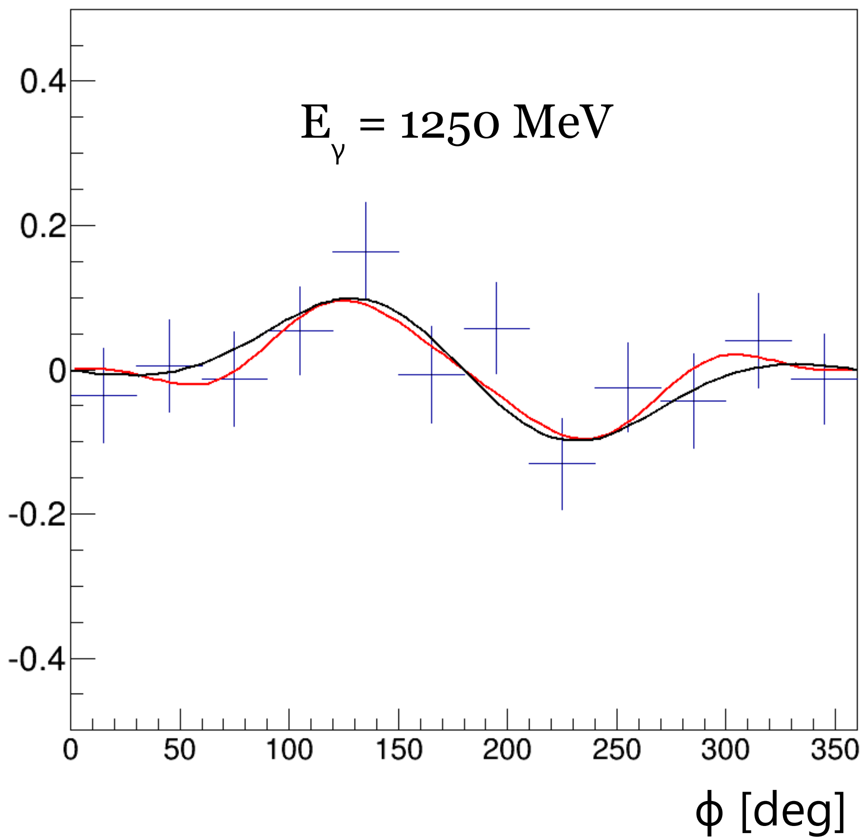


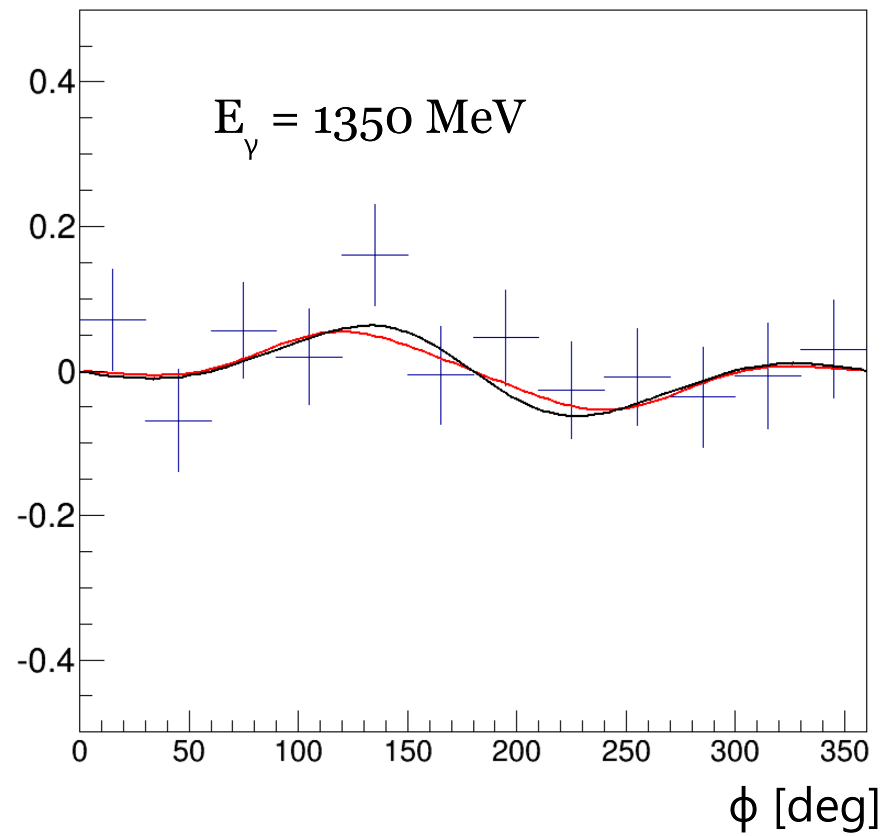


ϕ [deg]

Difference in 3-body kinematics:
ϕ dependence seen in the data

Example Spectra (Aluminium target)





- Preliminary asymmetries seen in ~35% of Aluminium data
- Curves: red fit to the data, black calculation within isobar model with FSI (Alexander Fix)
- Small asymmetry in energy binning → differential distributions
- Detailed analysis in progress

Summary

- Understanding of the nucleon: Investigation of baryon resonances, measurement of polarizabilities using Compton scattering
- Search for in-medium effects
- Measurement of the cross-sections and polarization observables
- Several complex experimental facilities involved in the effort
- New input for theoretical models to be obtained
- Still a lot to do to, e.g to achieve a complete experiment in meson production!
- Ambitious program aiming to extract scalar and spin polarizabilities
- Long-term programs progressing successfully at ELSA and MAMI

Summary

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- Still a lot to do to, e.g to achieve a complete experiment in meson production!
- Ambitious program aiming to extract scalar and spin polarizabilities
- Long-term programs progressing successfully at ELSA and MAMI
- → Ongoing detector upgrades
- → New experimental technique (e.g. active targets)
- → Unprecedentedly high-quality data will be taken in the future
- → Further development of theoretical models

Thank you for your attention!

Backup

Baryon resonances

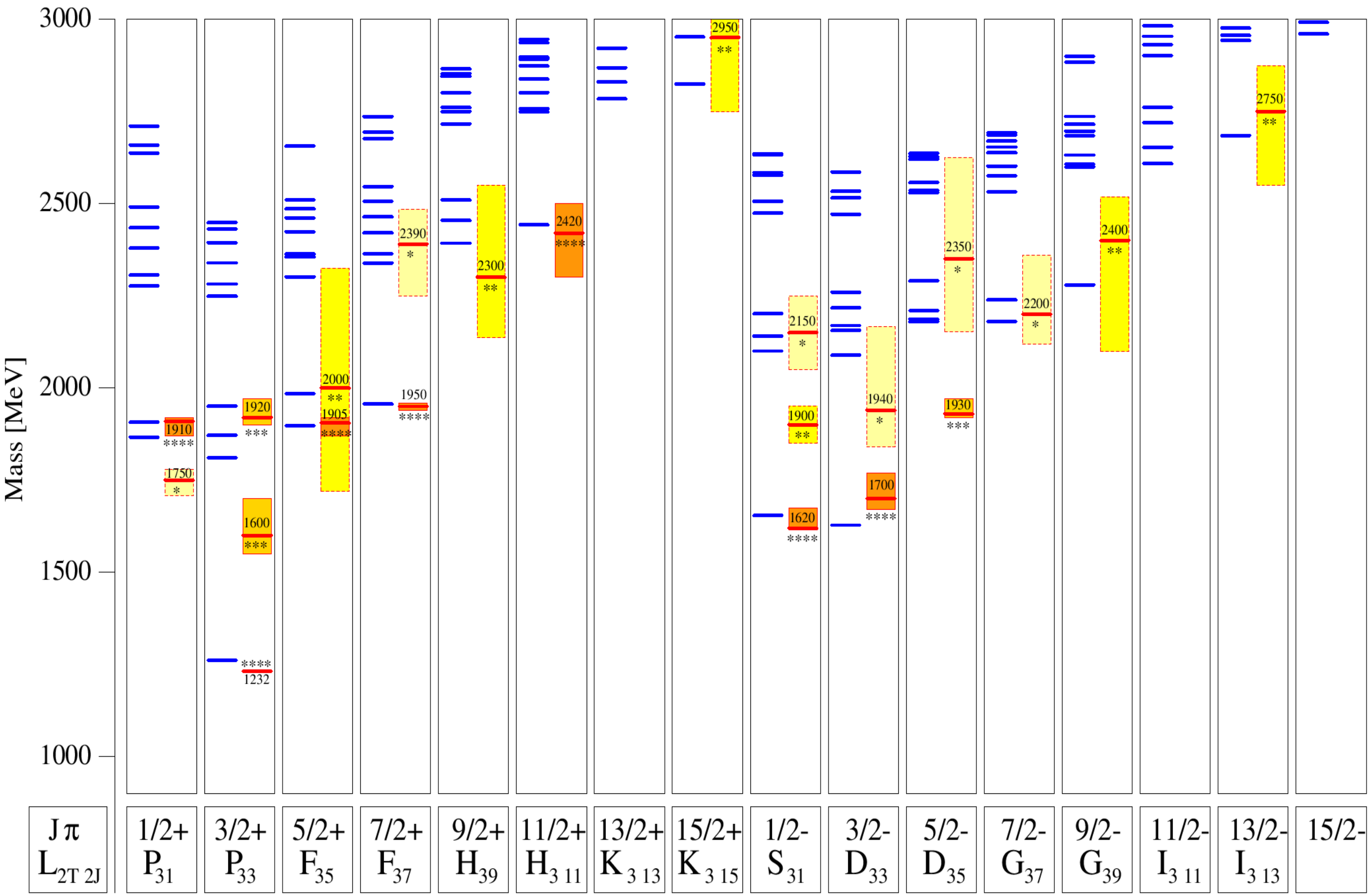
56	S=1/2;L=0;N=0		$N_{1/2^+}$(939)			939 MeV
	S=3/2;L=0;N=0			$\Delta_{3/2^+}$(1232)		1232 MeV
70	S=1/2;L=1;N=0		$N_{1/2^-}$(1535)	$N_{3/2^-}$(1520)		1530 MeV
	S=3/2;L=1;N=0		$N_{1/2^-}$(1650)	$N_{3/2^-}$(1700)	$N_{5/2^-}$(1675)	1631 MeV
	S=1/2;L=1;N=0		$\Delta_{1/2^-}$(1620)	$\Delta_{3/2^-}$(1700)		1631 MeV
70	S=1/2;L=1;N=2		$N_{1/2^-}$(2090)	$N_{3/2^-}$(2080)		2151 MeV
	S=3/2;L=1;N=2		$N_{1/2^-}$	$N_{3/2^-}$	$N_{5/2^-}$	2223 MeV
	S=1/2;L=1;N=2		$\Delta_{1/2^-}$(2150)	$\Delta_{3/2^-}$		2223 MeV
56	S=1/2;L=1;N=1		$N_{1/2^-}$	$N_{3/2^-}$		1779 MeV
	S=3/2;L=1;N=1		$\Delta_{1/2^-}$(1900)	$\Delta_{3/2^-}$(1940)	$\Delta_{5/2^-}$(1930)	1950 MeV
56	S=1/2;L=2;N=0		$N_{3/2^+}$(1720)	$N_{5/2^+}$(1620)		1779 MeV
	S=3/2;L=2;N=0	$\Delta_{1/2^+}$(1910)	$\Delta_{3/2^+}$(1920)	$\Delta_{5/2^+}$(1905)	$\Delta_{7/2^+}$(1950)	1950 MeV
70	S=1/2;L=2;N=0		$N_{3/2^+}$	$N_{5/2^+}$		1866 MeV
	S=3/2;L=2;N=0	$N_{1/2^+}$	$N_{3/2^+}$(1900)	$N_{5/2^+}$(2000)	$N_{7/2^+}$(1990)	1950 MeV
	S=1/2;L=2;N=0		$\Delta_{3/2^+}$	$\Delta_{5/2^+}$		1950 MeV
70	S=1/2;L=3;N=0		$N_{5/2^-}$	$N_{7/2^-}$		2151 MeV
	S=3/2;L=3;N=0	$N_{3/2^-}$	$N_{5/2^-}$(2200)	$N_{7/2^-}$(2190)	$N_{9/2^-}$(2250)	2223 MeV
	S=1/2;L=3;N=0		$\Delta_{5/2^-}$	$\Delta_{7/2^-}$(2200)		2223 MeV
56	S=1/2;L=3;N=1		$N_{5/2^-}$	$N_{7/2^-}$		2334 MeV
	S=3/2;L=3;N=1	$\Delta_{3/2^-}$	$\Delta_{5/2^-}$(2350)	$\Delta_{7/2^-}$	$\Delta_{9/2^-}$(2400)	2467 MeV
56	S=1/2;L=4;N=0		$N_{7/2^+}$	$N_{9/2^+}$(2220)		2334 MeV
	S=3/2;L=4;N=0	$\Delta_{5/2^+}$	$\Delta_{7/2^+}$(2390)	$\Delta_{9/2^+}$(2300)	$\Delta_{11/2^+}$(2420)	2467 MeV
70	S=1/2;L=5;N=0		$N_{9/2^-}$	$N_{11/2^-}$(2600)		2629 MeV
56	S=3/2;L=5;N=1	$\Delta_{7/2^-}$	$\Delta_{9/2^-}$	$\Delta_{11/2^-}$	$\Delta_{13/2^-}$(2750)	2893 MeV
56	S=1/2;L=6;N=0		$N_{11/2^+}$	$N_{13/2^+}$(2700)		2781 MeV
	S=3/2;L=6;N=0	$\Delta_{9/2^+}$	$\Delta_{11/2^+}$	$\Delta_{13/2^+}$	$\Delta_{15/2^+}$(2950)	2893 MeV
70	S=1/2;L=7;N=0		$N_{13/2^-}$	$N_{15/2^-}$		3033 MeV
56	S=3/2;L=7;N=1	$\Delta_{11/2^-}$	$\Delta_{13/2^-}$	$\Delta_{15/2^-}$	$\Delta_{17/2^-}$	3264 MeV
56	S=1/2;L=8;N=0		$N_{15/2^+}$	$N_{17/2^+}$		3165 MeV
	S=3/2;L=8;N=0	$\Delta_{13/2^+}$	$\Delta_{15/2^+}$	$\Delta_{17/2^+}$	$\Delta_{19/2^+}$	3264 MeV

Table 20: Multiplet structure of nucleon and Δ resonances. The table contains all known resonances except radial excitations of the $N_{1/2^+}$(939) and $\Delta_{3/2^+}$(1232).

Introduction

<u>Goal</u>: Gain a good understanding of the spectrum and properties of baryon resonances

Above 1.9 GeV missing resonances are predicted by the symmetric quark models

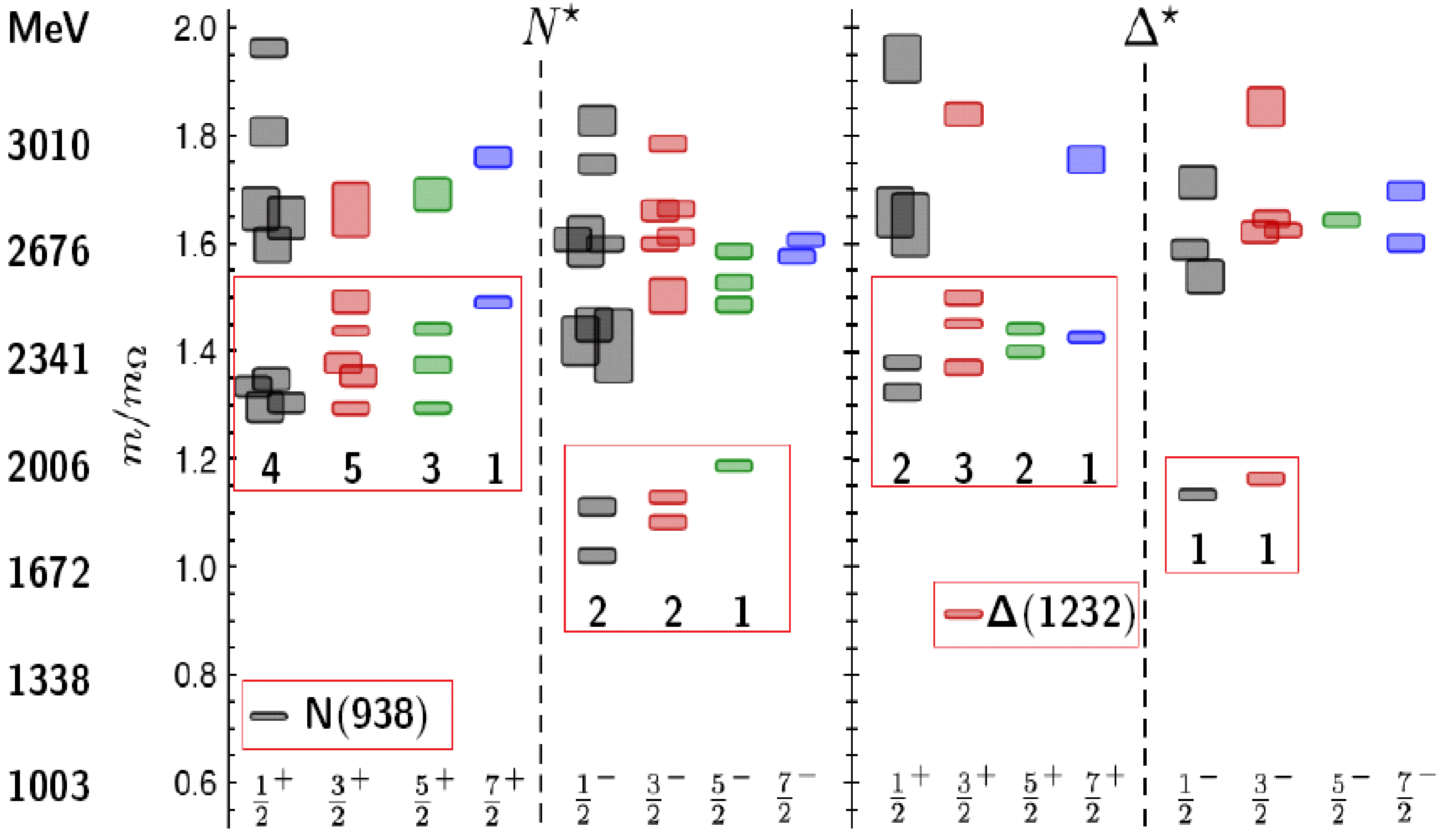


Introduction

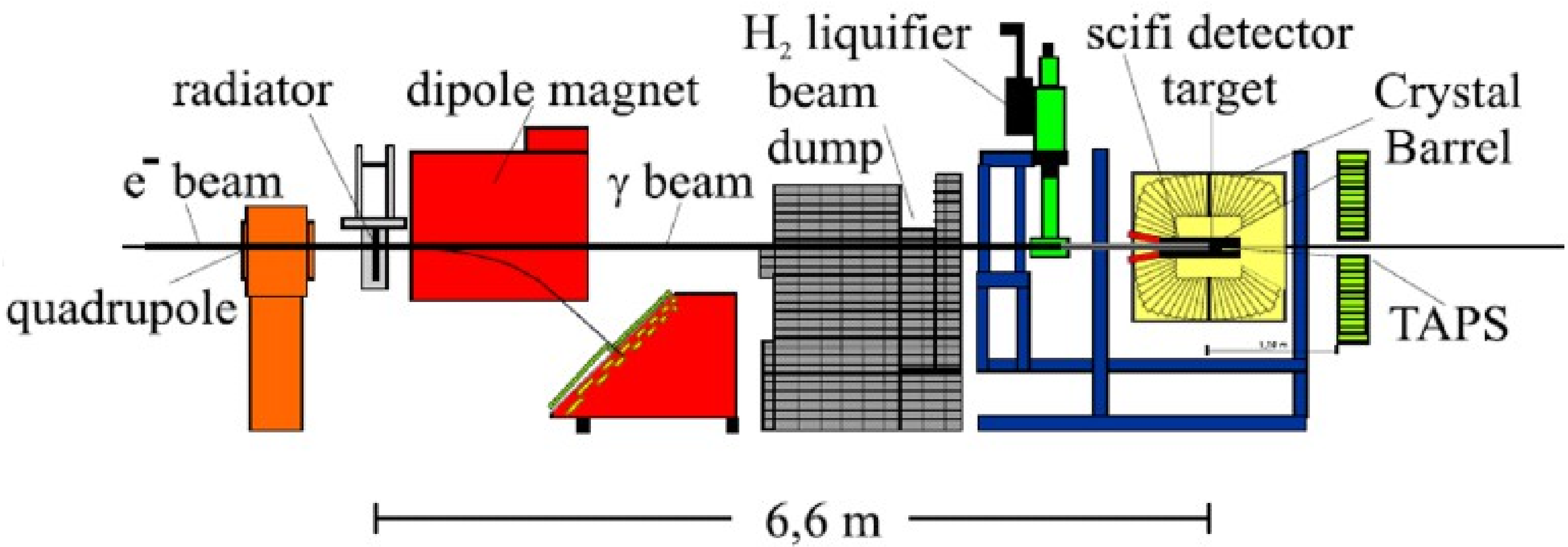
Goal: Gain a good understanding of the spectrum and properties of baryon resonances

$m_\pi = 396$ MeV

R. G. Edwards et al., Phys. Rev. D 84, 074508 (2011)

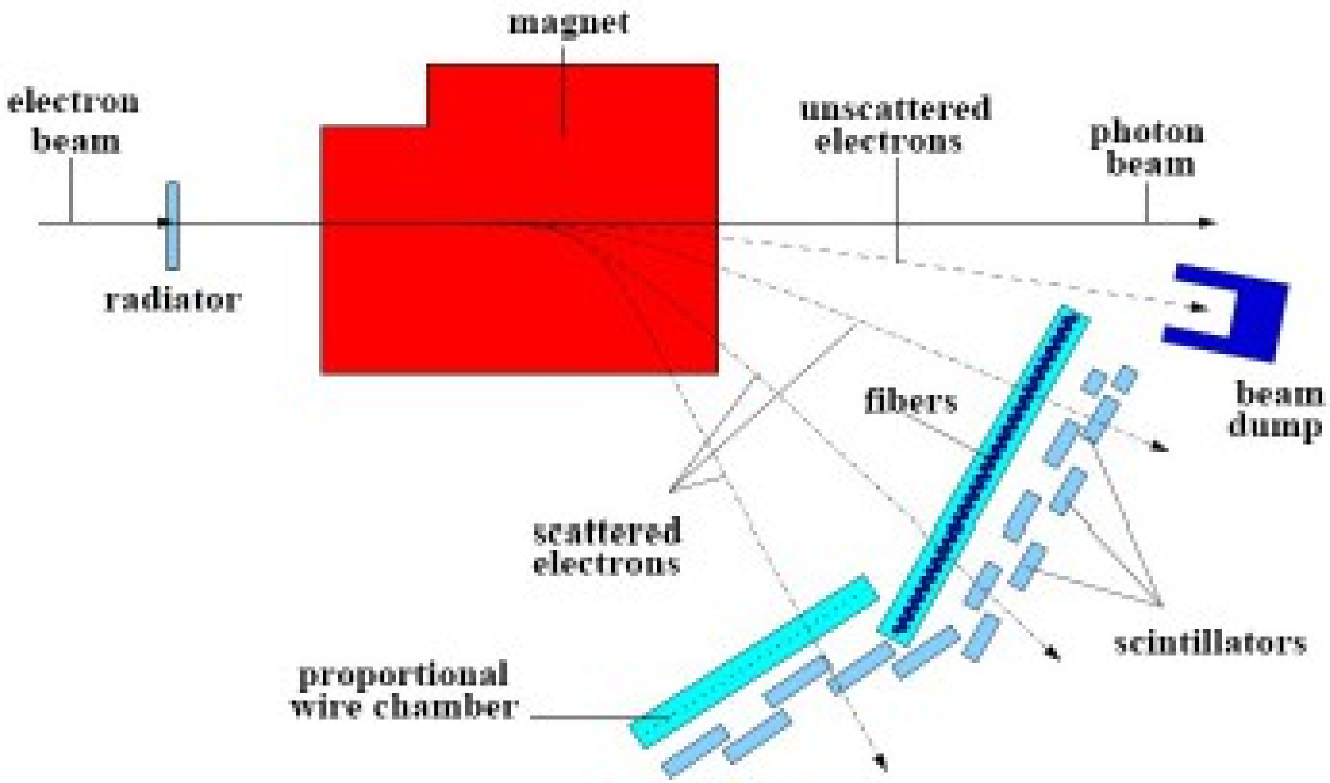


The CBELSA/TAPS experiment



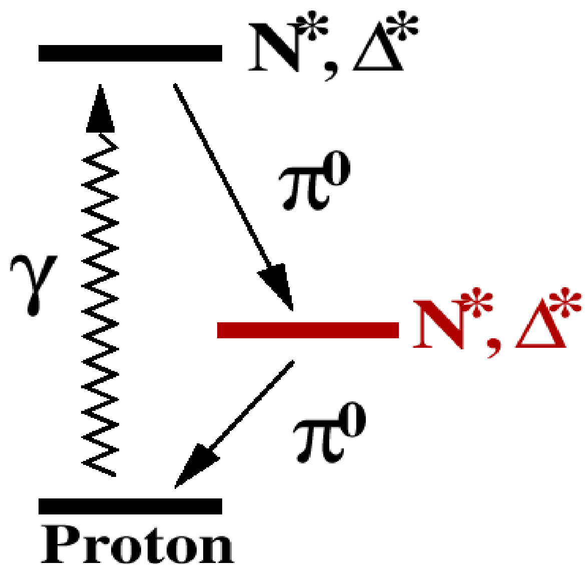
- Tagger
  - 14 scintillator bars
  - MWPC
  - 480 scintillating fibres
- Inner detector
  - 513 scintillating fibres
  - Θ-coverage 28°-172°
- Crystal Barrel
  - 1290 CsI(Tl) crystals
  - Θ-coverage 30°-168°
- TAPS
  - 528 BaF_2 modules
  - Plastic vetos
  - Θ-coverage 5.8°-30°

Backup

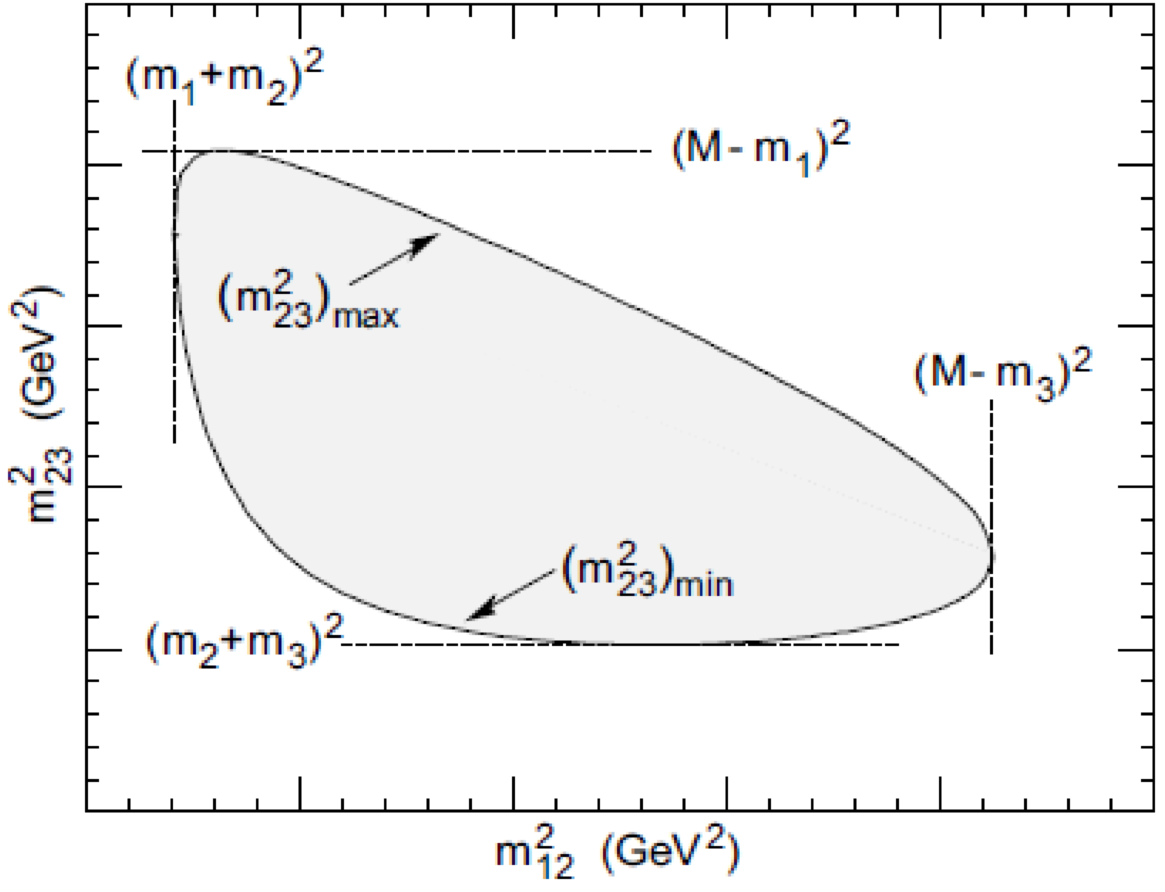


magnet
electron
beam
unscattered
electrons
photon
beam
radiator
beam
dump
fibers
scattered
electrons
scintillators
proportional
wire chamber

Sequential decays

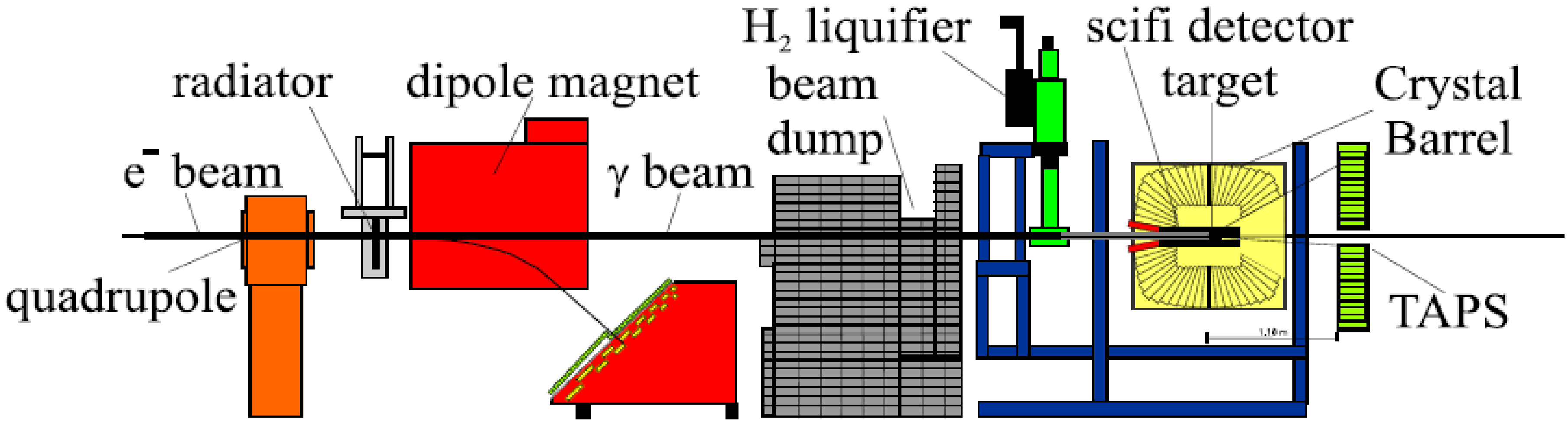


Example Dalitz plot

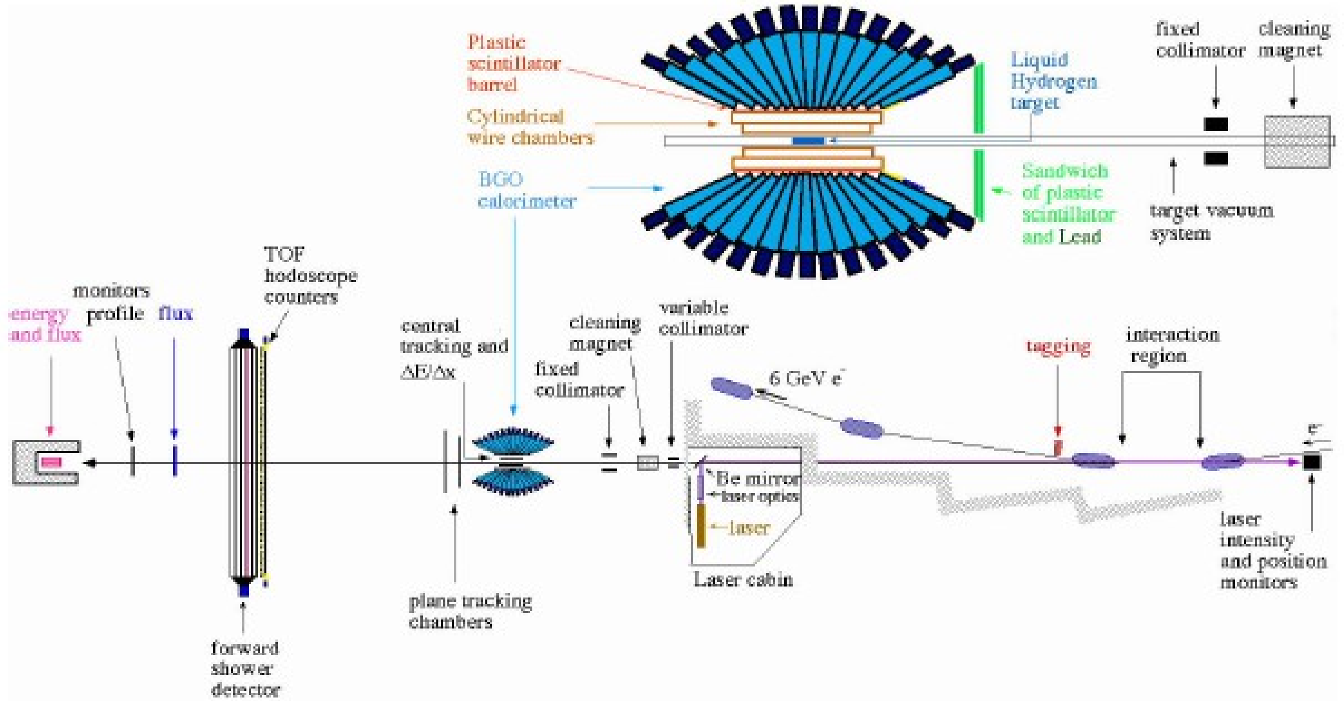


Compatibility of the data sets

The CBELSA/TAPS experiment (Bonn, Germany)

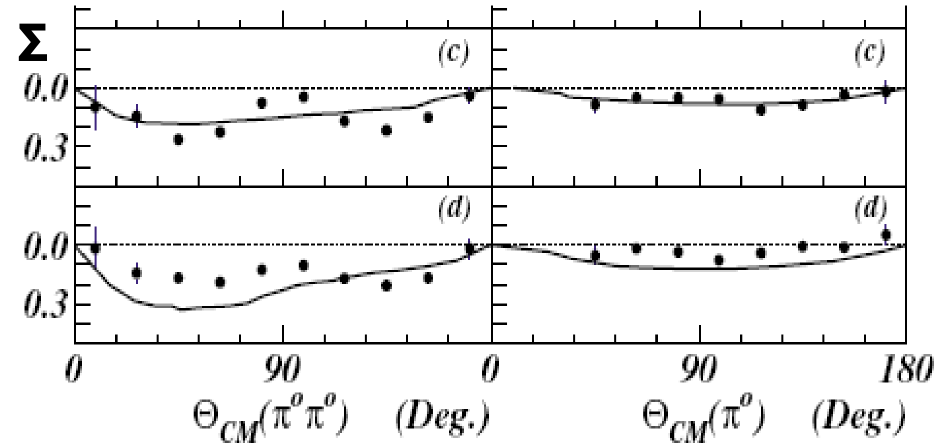


The GRAAL experiment (Grenoble, France)

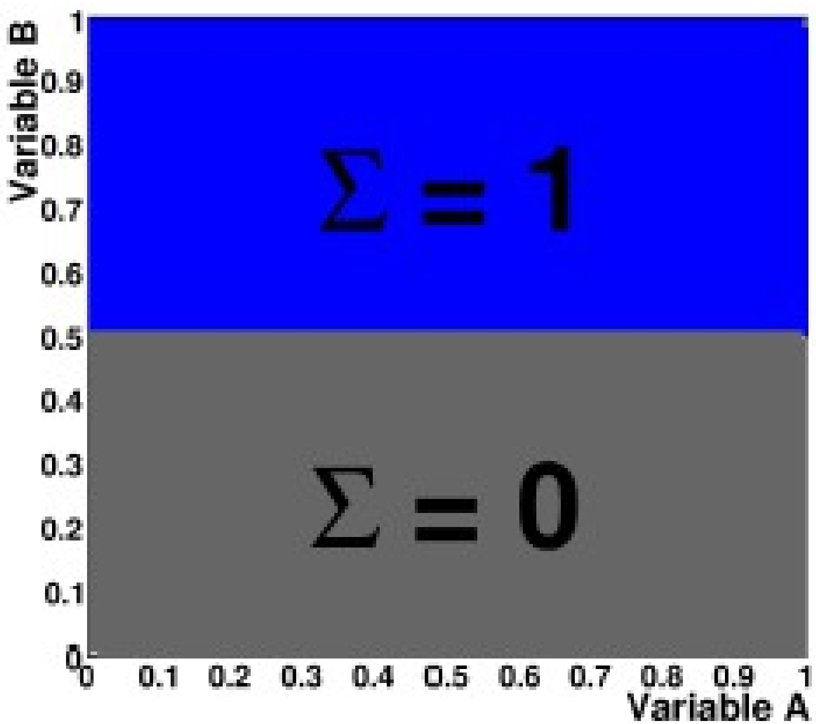


Compatibility of the data sets

- Different phase space coverage
- Different efficiencies
- GRAAL coverage ~ 70% of events retained by CBELSA/TAPS



Assafiri, et al., Phys. Rev. Lett. 90 (2003) 222001.



3-body final state → 5-dimensional phase space

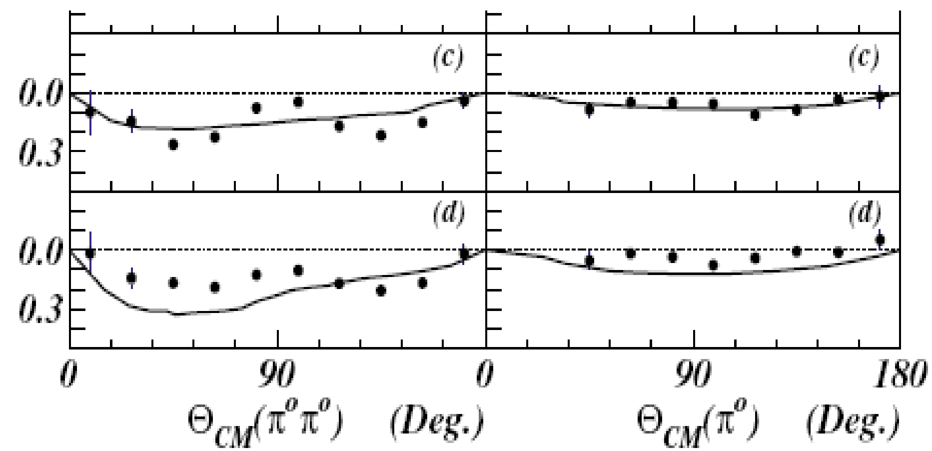
Projections can be misleading!

Compatibility of the data sets

Different phase space coverage

Different efficiencies

GRAAL coverage ~ 70% of events retained by CBELSA/TAPS



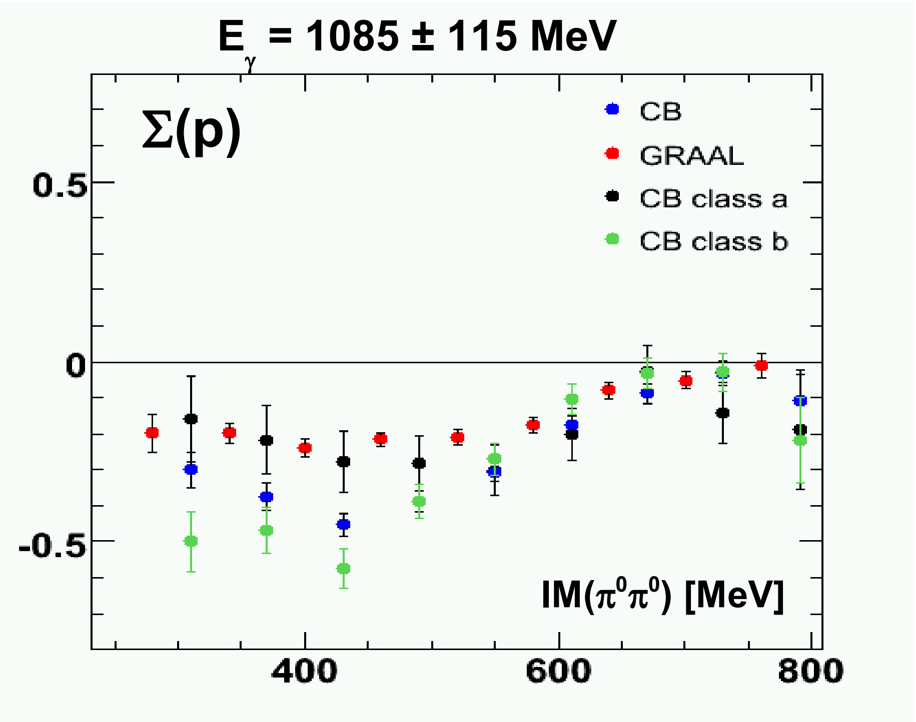
Assafiri, et al., Phys. Rev. Lett. 90 (2003) 222001.

Trying to repeat the acceptance of GRAAL experiment approximately:

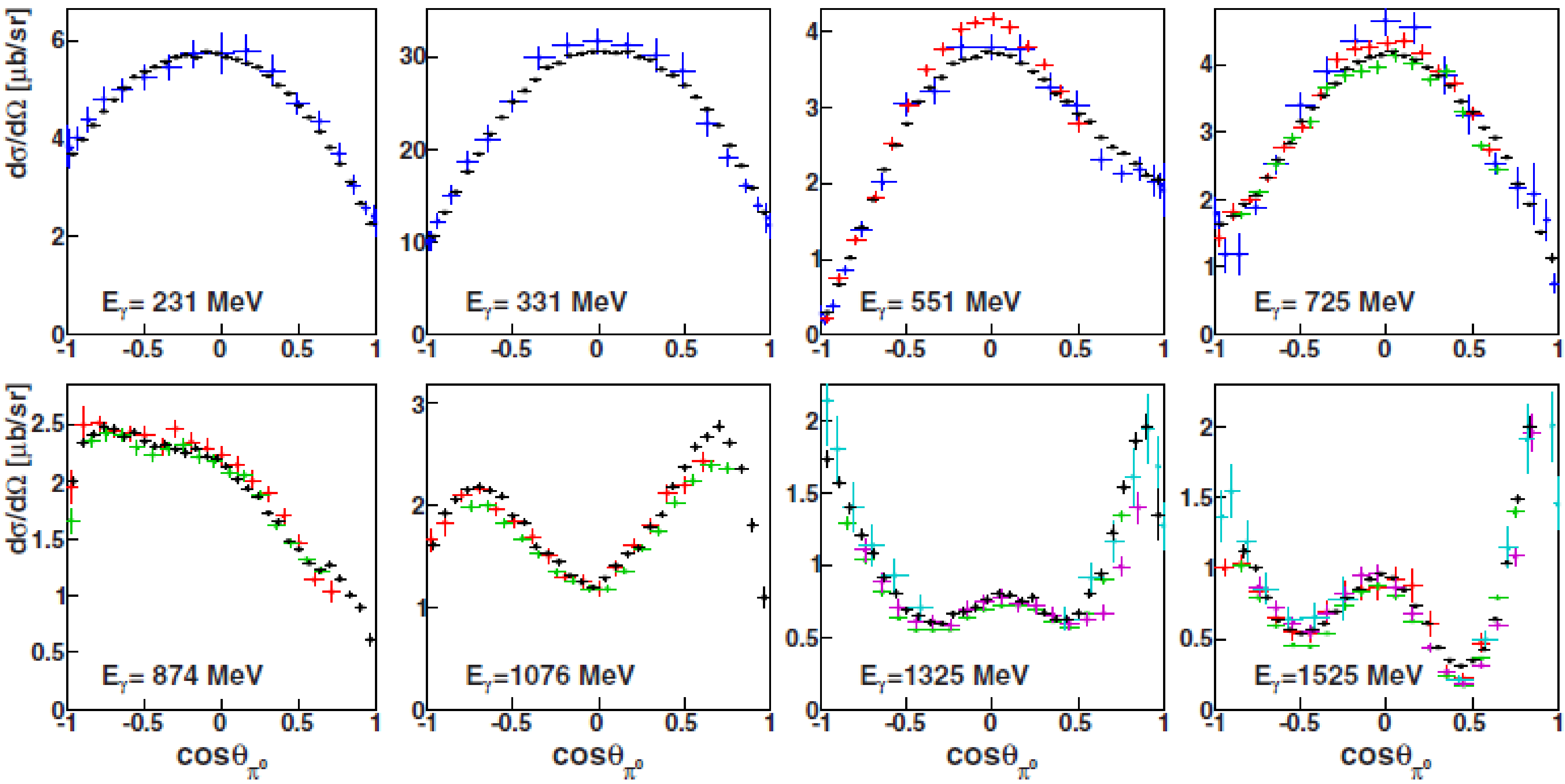
a) **4 γ (25<Θ<155)**

b) 3 γ (25<Θ<155) +

γ (Θ<25)

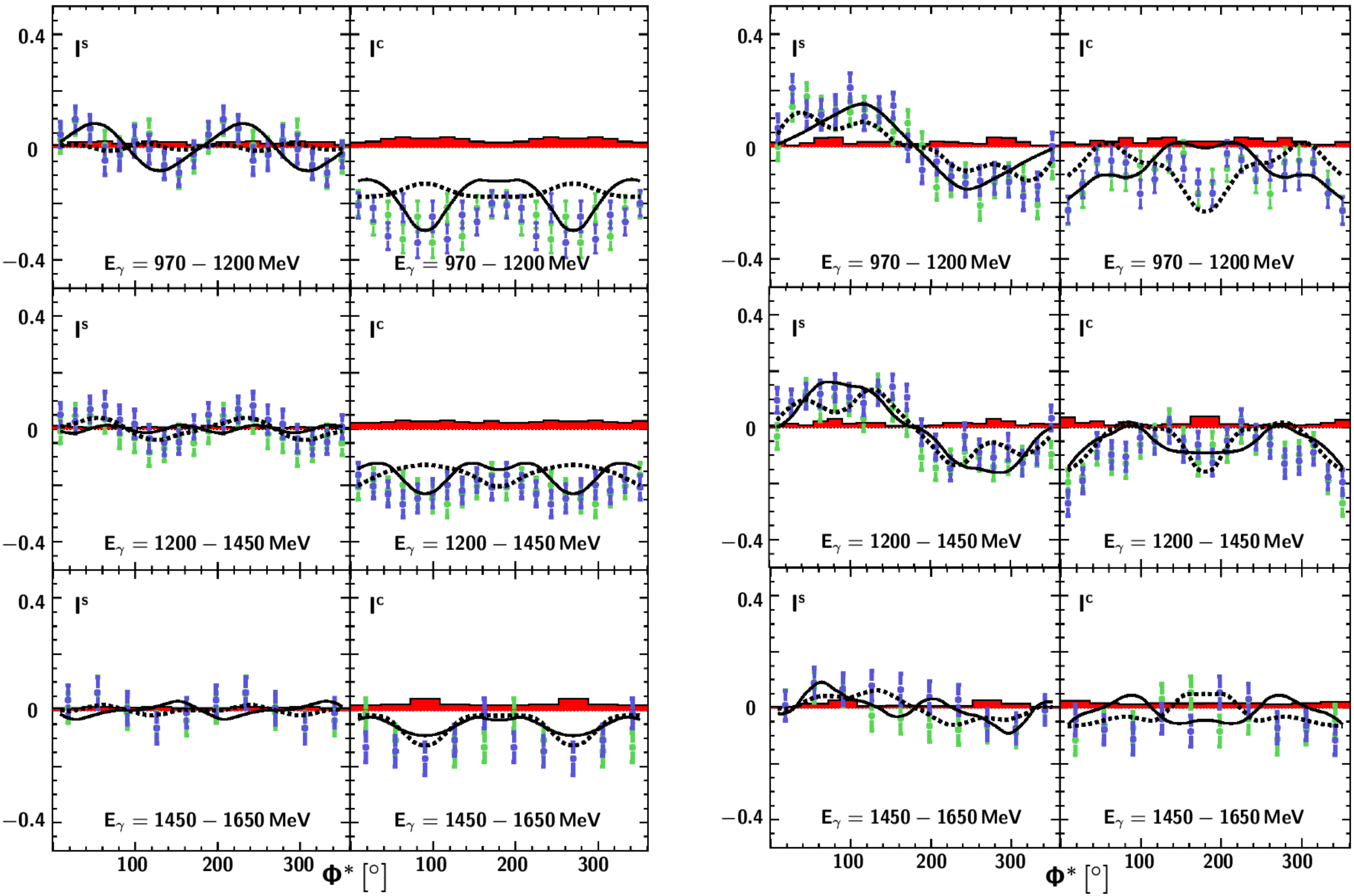


Single π^0 production



P. Adlarson et al., Phys.Rev. C92 (2015) no.2, 024617

Proton recoiling **Pion recoiling**

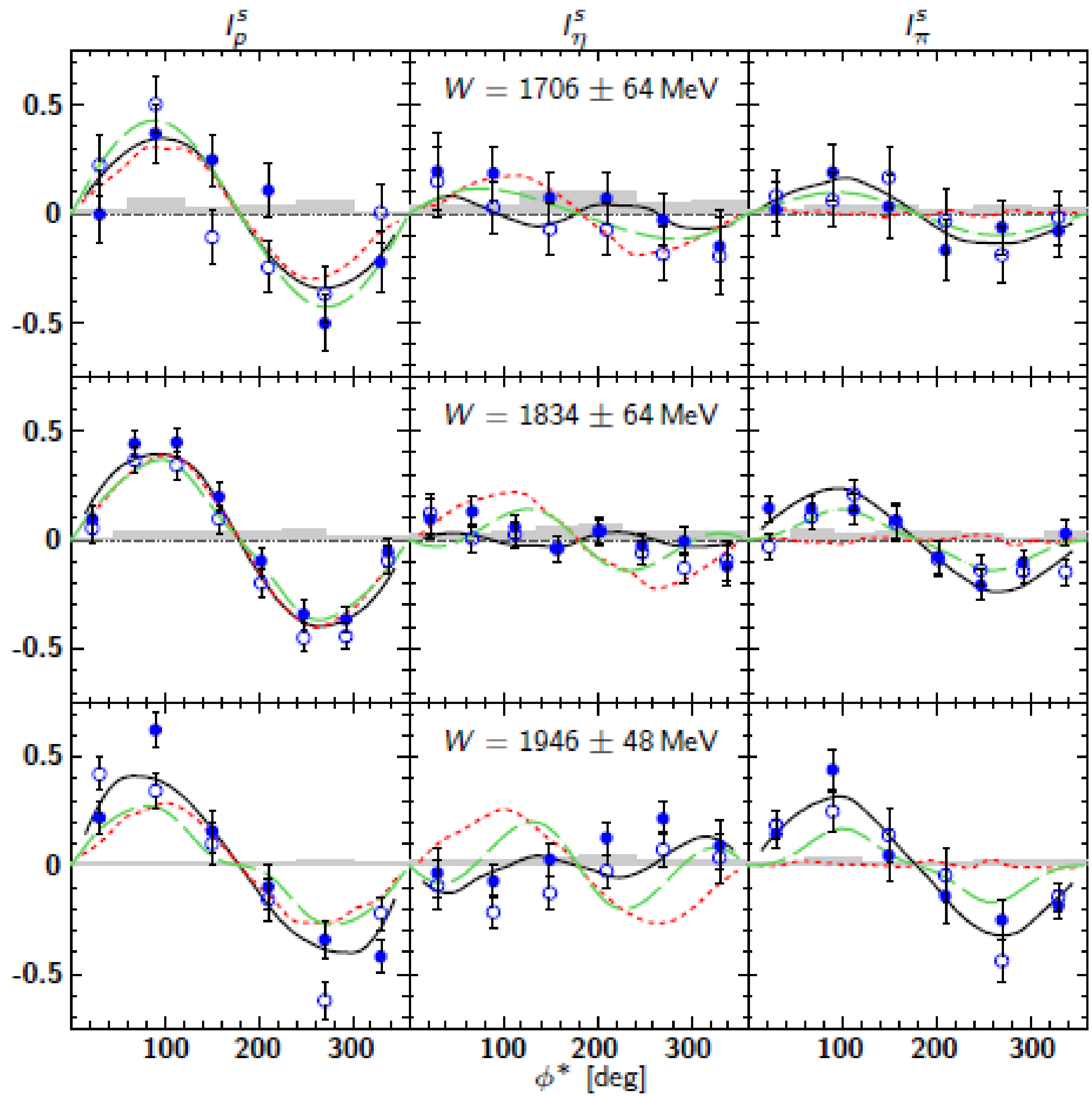


$I^s(\Phi^*) = -I^s(2\pi - \Phi^*)$ and $I^c(\Phi^*) = I^c(2\pi - \Phi^*)$

Solid: $D_{33}(1700) \rightarrow \Delta\pi_{(D\text{-wave})}$ dominant

Dashed: $D_{33}(1700) \rightarrow \Delta\pi_{(S\text{-wave})}$ dominant

$\pi^o\eta$ photoproduction, Eric Gutz (Bonn)



E.G., V. Sokhoyan, H. van Pee et al.
Phys. Lett. B 687 (2010), 11

Closed symbols:
$I^s(\phi^*)$
Open symbols:
$-I^s(2\pi - \phi^*)$

Bars: Systematic error estimate

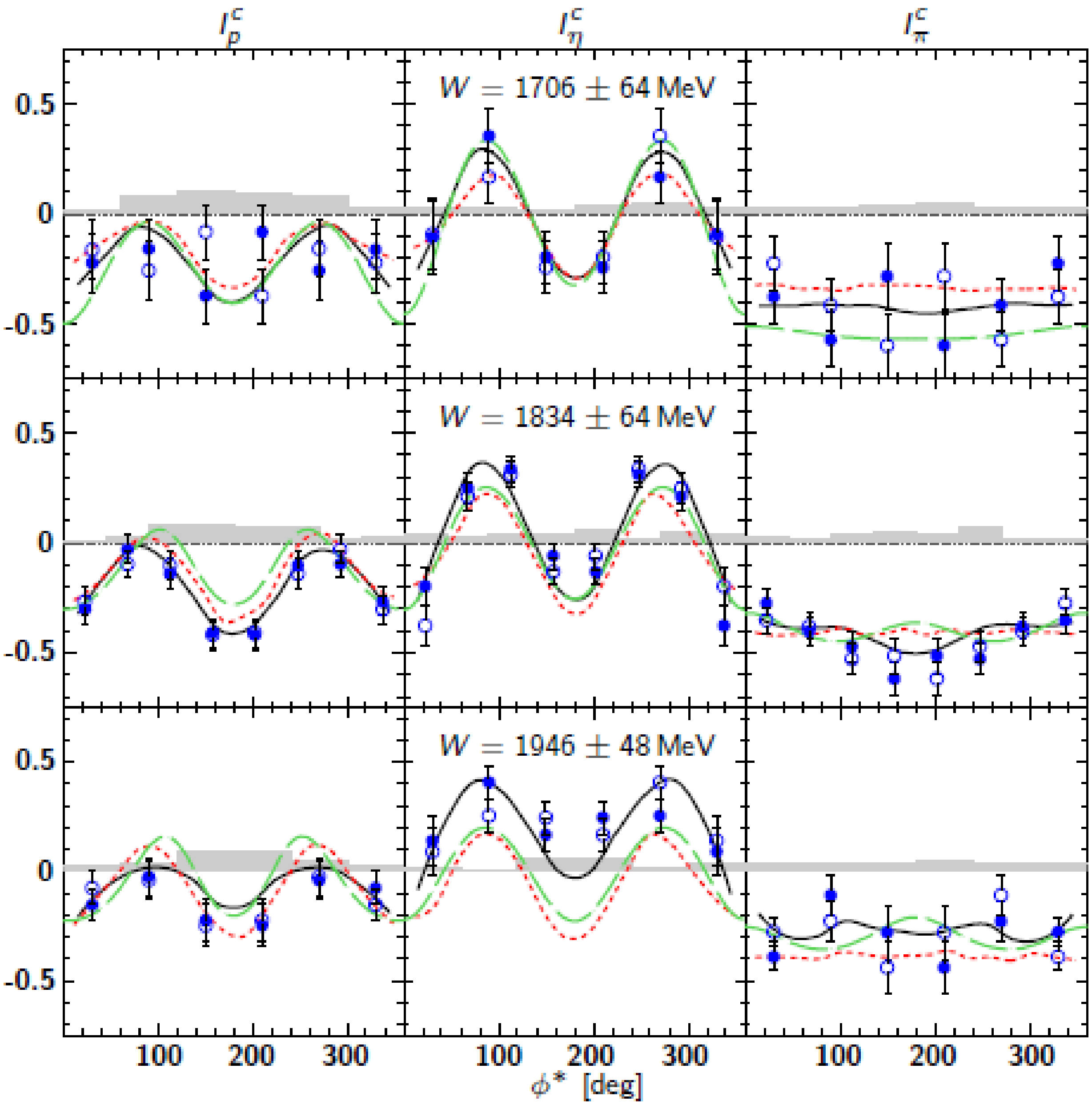
Curves:

— BnGa-PWA

— Valencia model
M. Döring, E. Oset, U.-G. Meißner
Eur. Phys. J. A 46 (2010) 315

— Fix isobar model
A. Fix et al., Phys. Rev. C 82 (2010) 035207

π⁰η photoproduction, Eric Gutz (Bonn)



E.G., V. Sokhoyan, H. van Pee et al.
Phys. Lett. B 687 (2010), 11

Closed symbols:
$I^c(\phi^*)$
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— BnGa-PWA

— Valencia model
M. Döring, E. Oset, U.-G. Meißner
Eur. Phys. J. A 46 (2010) 315

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A. Fix et al., Phys. Rev. C 82 (2010) 035207

Maximum Likelihood

The Method: Event-based maximum likelihood fit

Function which has to be maximised:

$$\mathcal{L} = \prod_{i=1}^{N} \omega(\vec{x}_i, \vec{p})$$

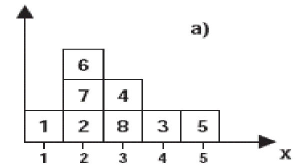
Product over N data points $\vec{x}_i$
ω: probability density distribution
$\vec{p}$: parameter vector

$\mathcal{L}$ = Probability to reproduce the data sample $\{\vec{x}_1, \ldots, \vec{x}_N\}$ with a given probability density distribution

Maximum of $\mathcal{L}$ reached
$\Rightarrow$ best description of the data.

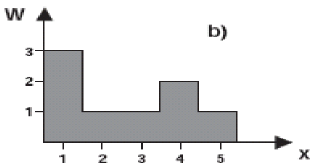
Additional advantage:
No binning needed !

Data points:



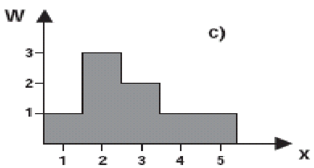
Probablity distributions:

ω_1 :



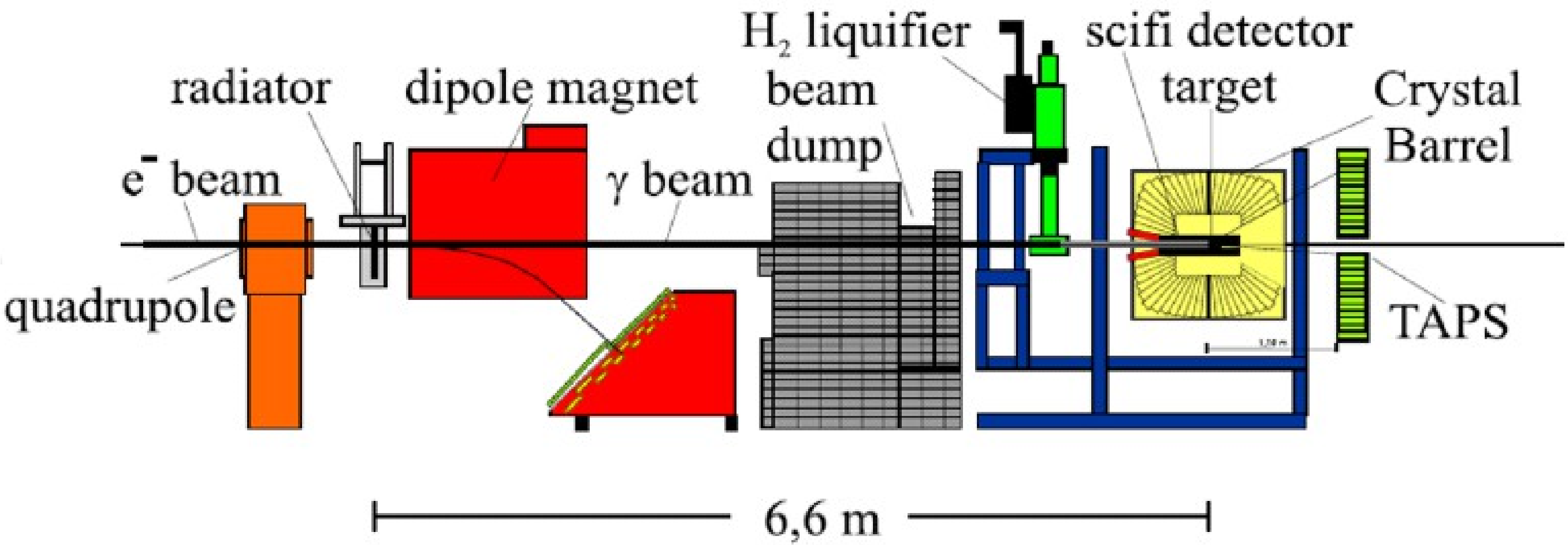
$$\Rightarrow 3 \cdot 1 \cdot 2 \cdot 1 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = 6$$

ω_2 :



$$\Rightarrow 1 \cdot 3 \cdot 1 \cdot 2 \cdot 1 \cdot 3 \cdot 3 \cdot 2 = 108$$

The CBELSA/TAPS experiment



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Measurement of α and β

$$\Sigma_3 = \Sigma_3^{(B)} - \frac{4M\omega^2 \cos\theta \sin^2\theta}{\alpha_{em}(1+\cos^2\theta)^2}\,\beta_{M1} + O(\omega^4), \qquad (6)$$

where $\Sigma_3^{(B)}$ is the pure Born contribution, while

$$\omega = \frac{s - M^2 + \frac{1}{2}t}{\sqrt{4M^2 - t}}, \quad \theta = \arccos\left(1 + \frac{t}{2\omega^2}\right) \qquad (7)$$

are the photon energy and scattering angle in the Breit (brick-wall) reference frame. In fact, to this order in the LEX the formula is valid for ω and θ being the energy and angle in the lab or center-of-mass frame.

Polarization observables

Single meson production:

W.-T. Chiang, F. Tabakin, Phys. Rev. C 55 (1997) 2054

$$I_0\Sigma = \frac{1}{2}(|b_1|^2 + |b_2|^2 - |b_3|^2 - |b_4|^2)$$

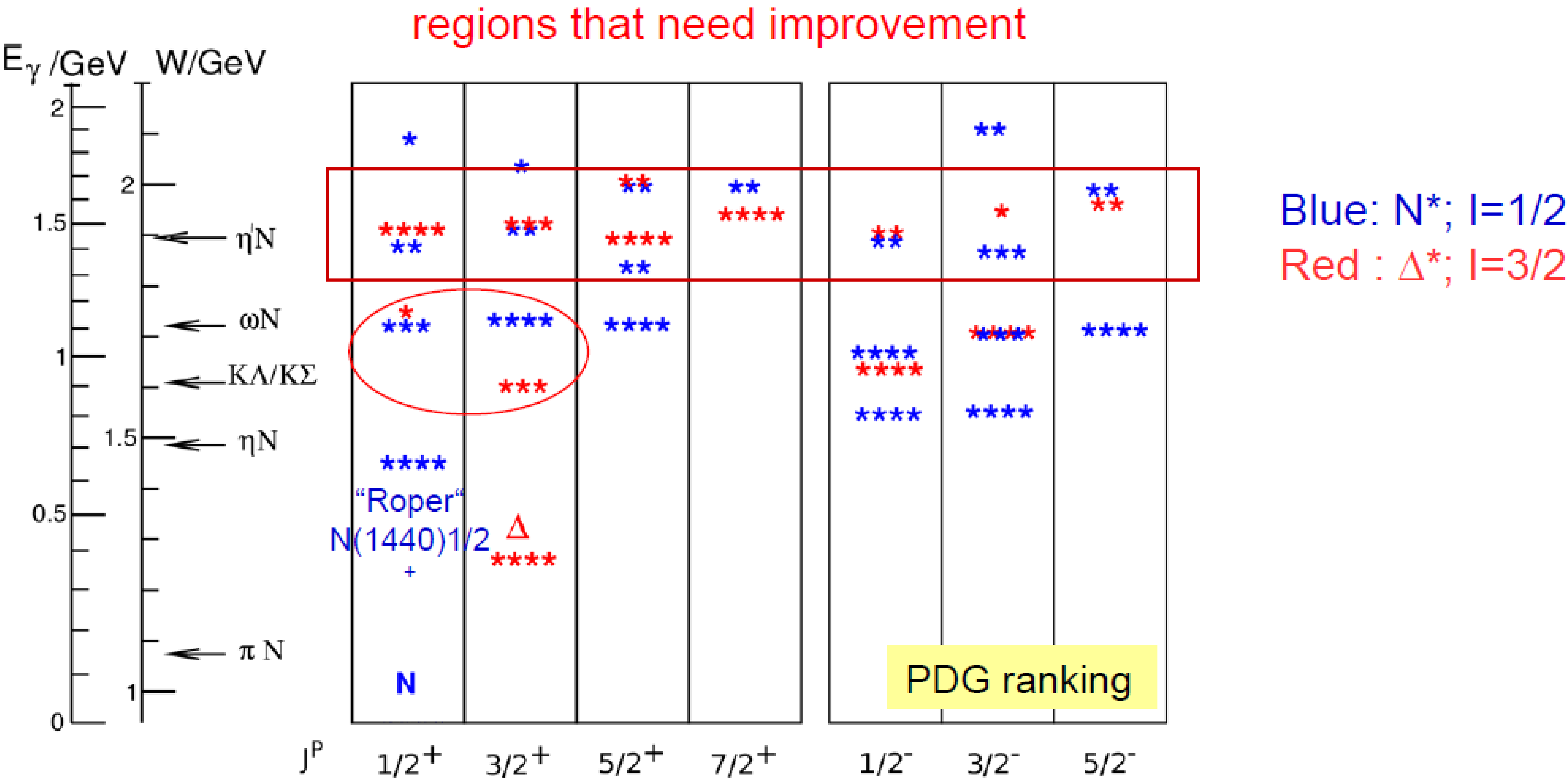
Double meson production:

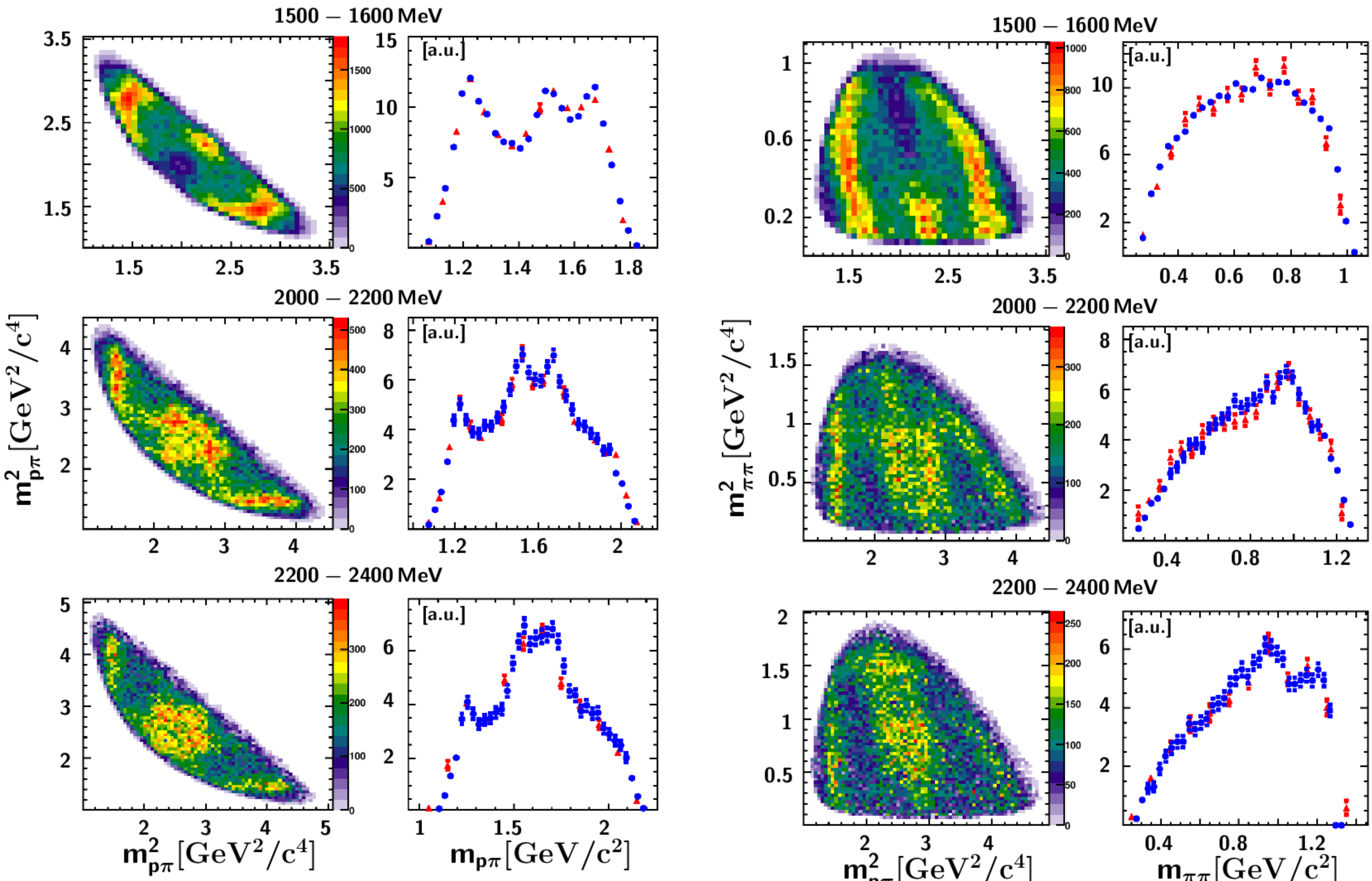
W. Roberts, T. Oed, Phys. Rev. C 71 (2005) 052002

$$\begin{aligned} I_0 I^c &= 2\Re\left(-(b_1^+ b_1^{-*}) - b_2^+ b_2^{-*} - b_3^+ b_3^{-*} - b_4^+ b_4^{-*}\right) \\ I_0 I^s &= 2\Im\left(b_1^+ b_1^{-*} + b_2^+ b_2^{-*} + b_3^+ b_3^{-*} + b_4^+ b_4^{-*}\right) \end{aligned}$$

b_i: Transversity amplitudes

In-medium modifications





1500 — 1600 MeV
2000 — 2200 MeV
2200 — 2400 MeV
[a.u.]
$m^2_{p\pi}$ [GeV^2/c^4]
$m_{p\pi}$ [GeV/c^2]
1500 — 1600 MeV
2000 — 2200 MeV
2200 — 2400 MeV
[a.u.]
$m^2_{\pi\pi}$ [GeV^2/c^4]
$m^2_{p\pi}$ [GeV^2/c^4]
$m_{\pi\pi}$ [GeV/c^2]