Measurement of the double polarization observables G in pion photoproduction off the proton

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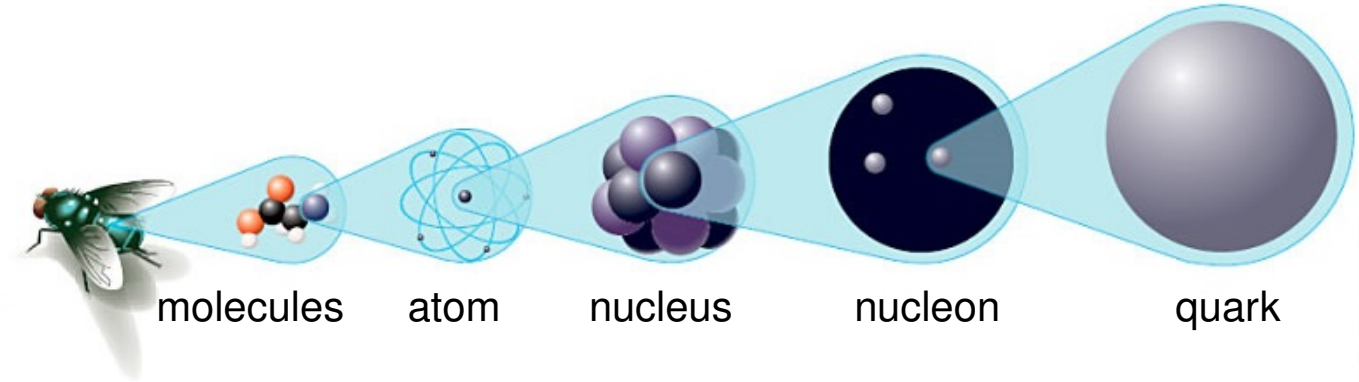
Content

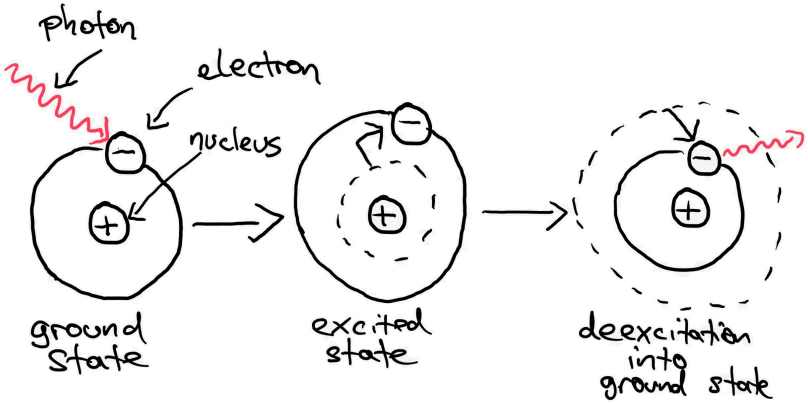
Motivation

Excitation spectrum of the nucleons

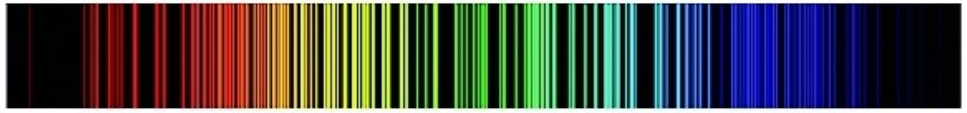
What is matter made of?



Motivation: Analogy to atomic spectroscopy



Neon emission spectrum

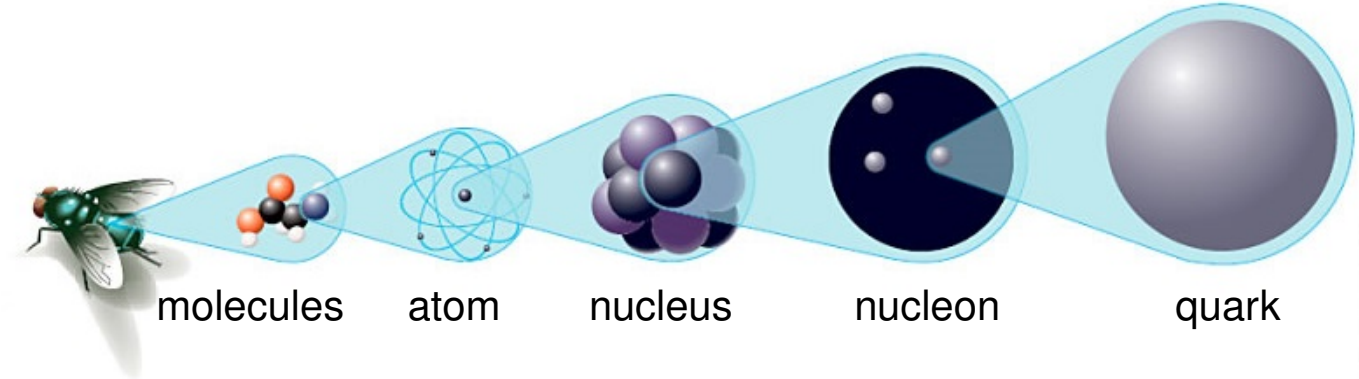


→ **Direct information on the dynamics of the atom, i.e. fine structure!**

Motivation

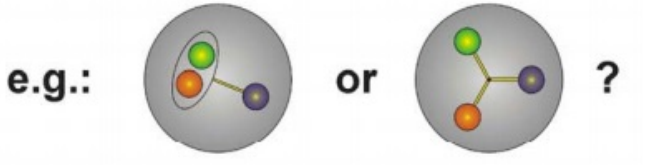
Excitation spectrum of the nucleons

What is matter made of?



Nucleon spectroscopy (open questions)

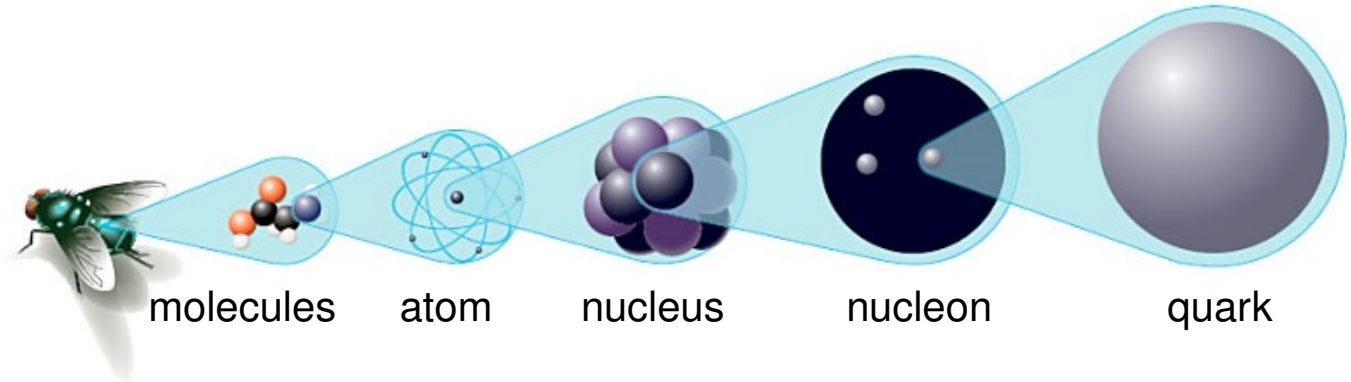
- Excitation spectrum of the nucleon provides information about interaction/dynamics of constituents
- How many degrees of freedom:



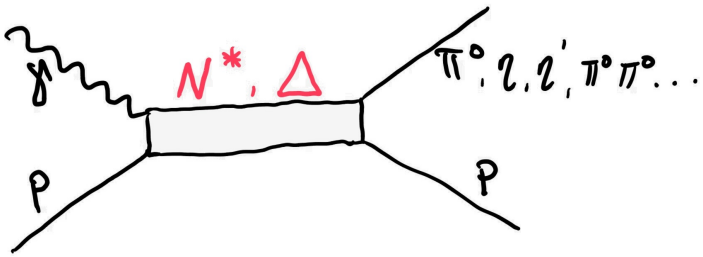
Motivation

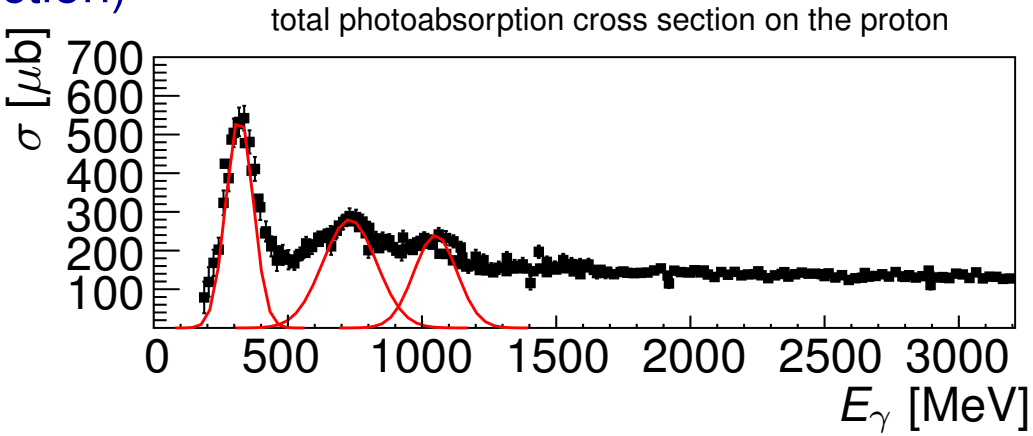
Excitation spectrum of the nucleons

What is matter made of?



Nucleon spectroscopy (photoproduction)





→ Due to short life time, broad and overlapping resonances!

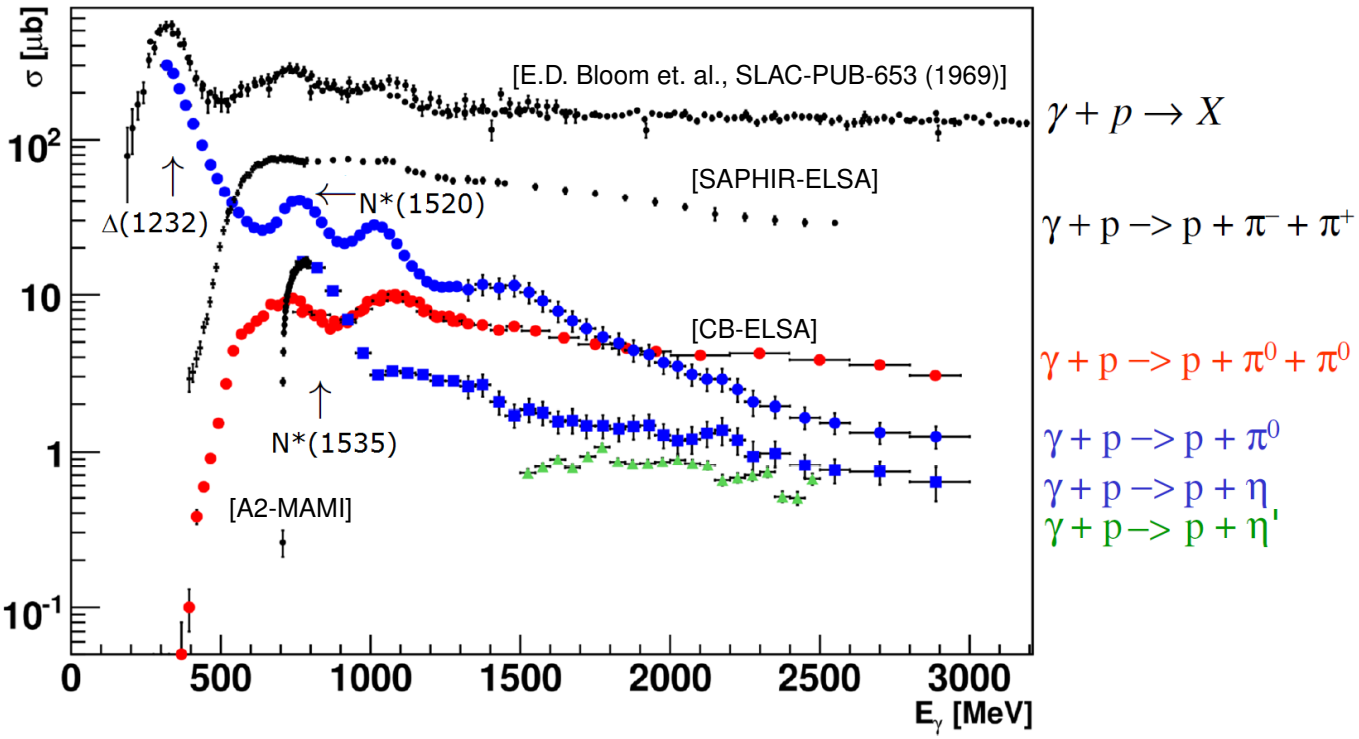
→ **NO direct information on the dynamics of the constituents!**

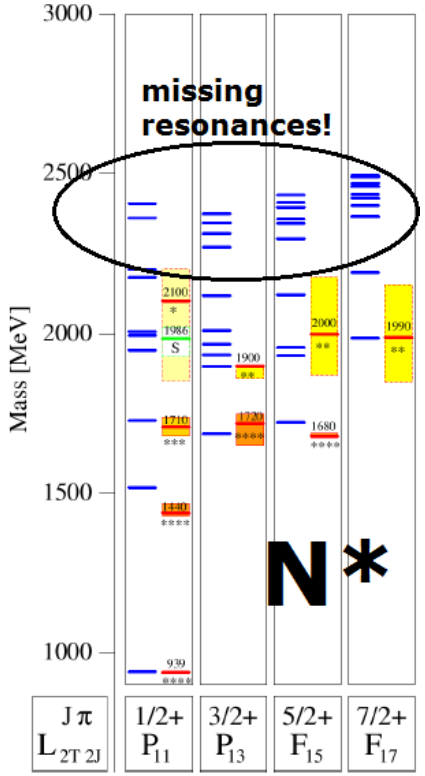
Motivation

Excitation spectrum of the nucleons

How to analyze the excitation spectrum?

- Study $\gamma N \rightarrow N^*/\Delta^* \rightarrow N\,\pi^0, N\,\eta, N\,\eta', , N\,\pi^0\pi^0, N\,\pi^+\pi^- \ldots$
- Experiments, e.g., **Crystal Ball**@MAMI, Crystal Barrel@ELSA, CLAS@Jefferson Lab
- Theory vs Experiment: most resonances found via $\pi N \rightarrow N^*/\Delta^* \rightarrow X$





[U. Loering et al., Eur.Phys.J. A, 10:395-446, 2001]

Motivation

Polarization observables

- Scattering amplitude can be described by 4 complex amplitudes (CGLN-amplitudes)
- These CGLN-amplitudes can be described by **multipoles**
- These multipoles are directly related to **polarization observables**

Overview of the polarization observables in the 2-body kinematic system for the photoproduction of a pseudoscalar meson

Photon polarization		Target polarization			Recoil nucleon polarization			Target and recoil polarizations			
		X	Y	$Z_{(beam)}$	X'	Y'	Z'	X' X	X' Z	Z' X	Z' Z
unpolarized	σ	-	T	-	-	P	-	$T_{x'}$	$L_{x'}$	$T_{z'}$	$L_{z'}$
linear	$-\Sigma$	H	(-P)	-G	$O_{x'}$	(-T)	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(L_{x'})$	$(-T_{x'})$
circular	-	F	-	-E	$C_{x'}$	-	$C_{z'}$	-	-	-	-

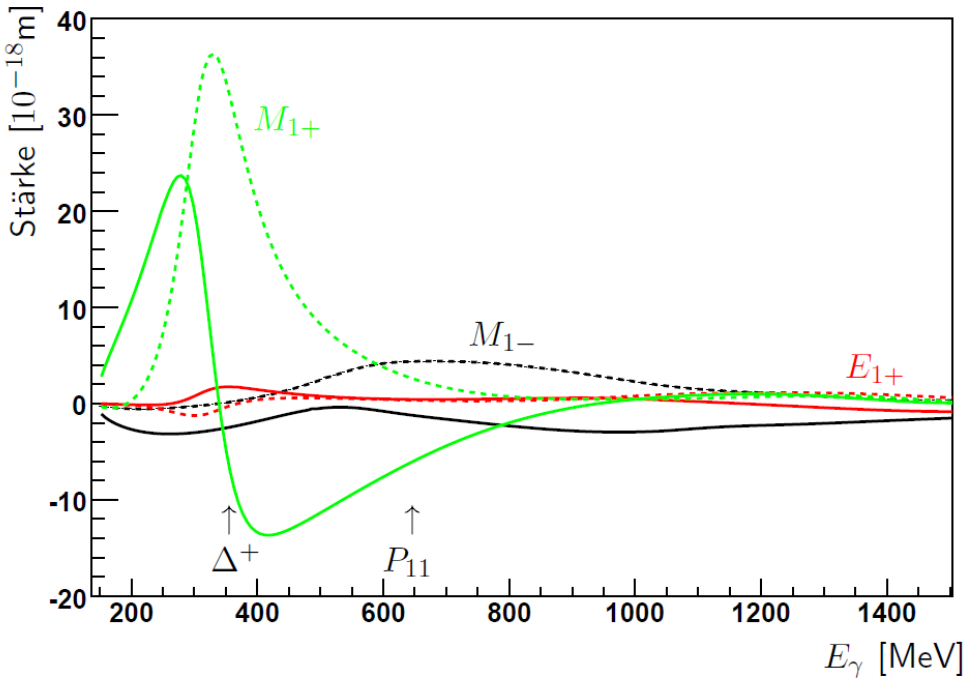
- Note: σ, Σ,T, P + 4 double polarization observables are needed for model independent solution

[W. Chiang and F. Tabakin, Phys. Rev., **C55** (1997) 2054-2066]

Motivation

Multipole expression of G for l $\leq$ 1 in single pion photoproduction off the proton

$$\frac{d\sigma}{d\Omega} \cdot G(\cos\theta) = Im\{M_{1-}^{*}(E_{1+} - M_{1+}) - 2E_{1+}^{*}M_{1+}\} \cdot 3\sin^2\theta$$
$$\approx ImM_{1-}ReM_{1+} \cdot 3\sin^2\theta$$



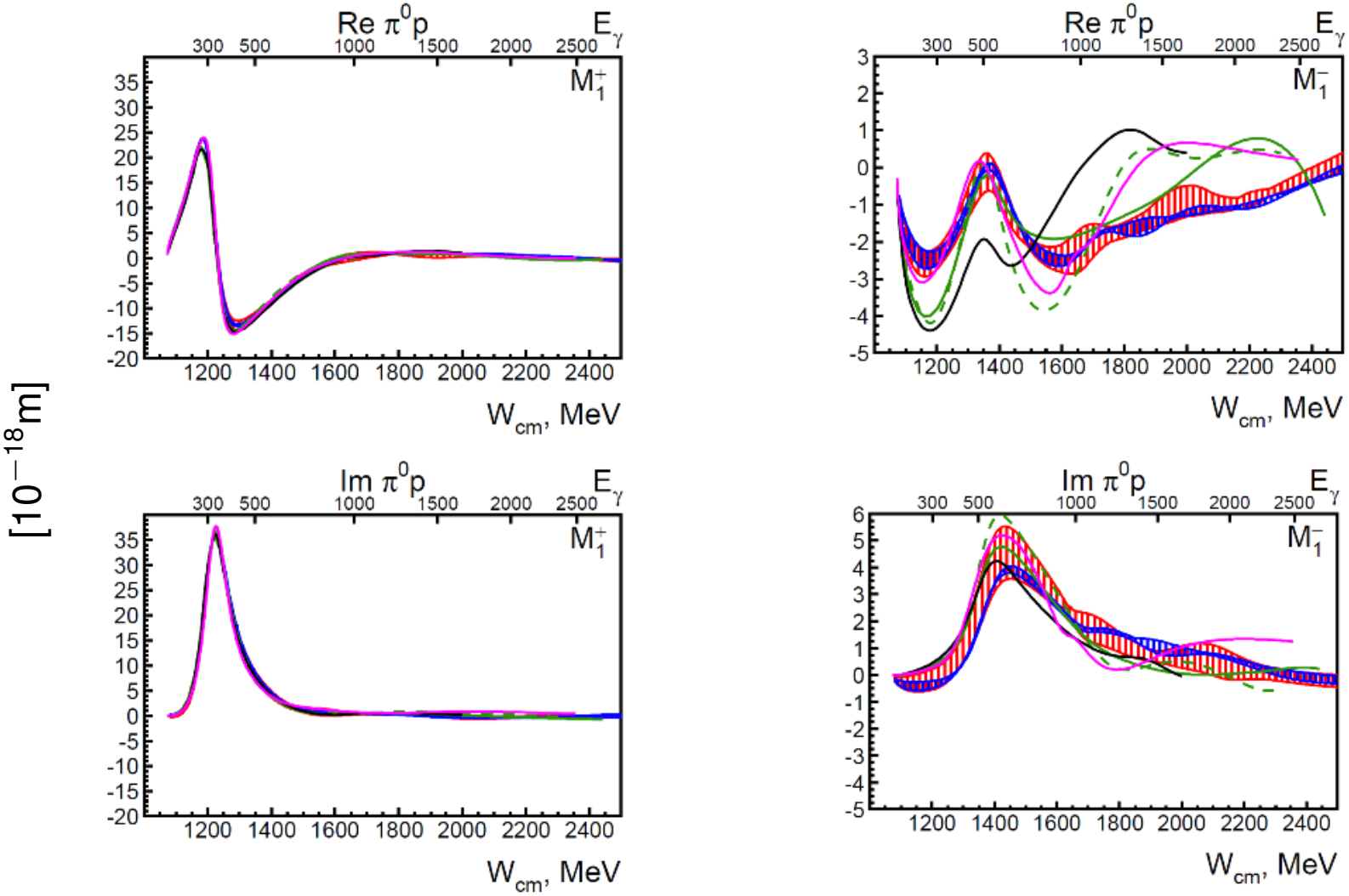
$\rightarrow$ sensitive to the M_{1-} partial wave

$\rightarrow$ **sensitive to Roper Resonance $P_{11}(1440)$!**

solid line: real part, dotted lines: imaginary part

Motivation

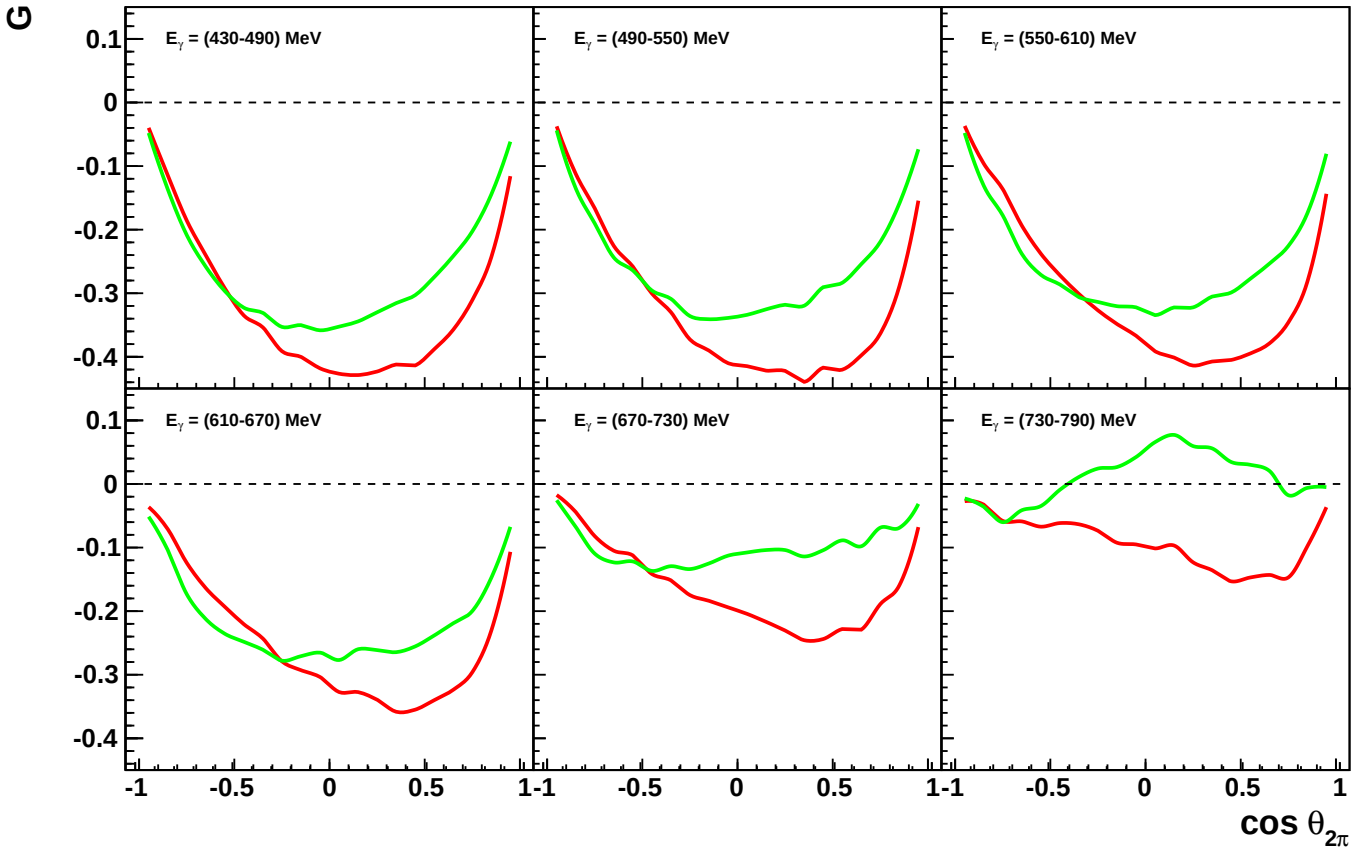
Comparison of dominant multipole contributions from the different PWA



BG2011-02 BG2014-02 MAID-07 SAID-SN11 SAID-CM12 JüBn-2014

Motivation

Sensitivity studies of the BnGa PWA for the $2\pi^0$ channel off the proton



BG2014-01 [1]
BG2014-02 [1]

S/D-wave ratio decay of $D_{13}(1520) \rightarrow \Delta\pi$

BG2014-01: S/D=3

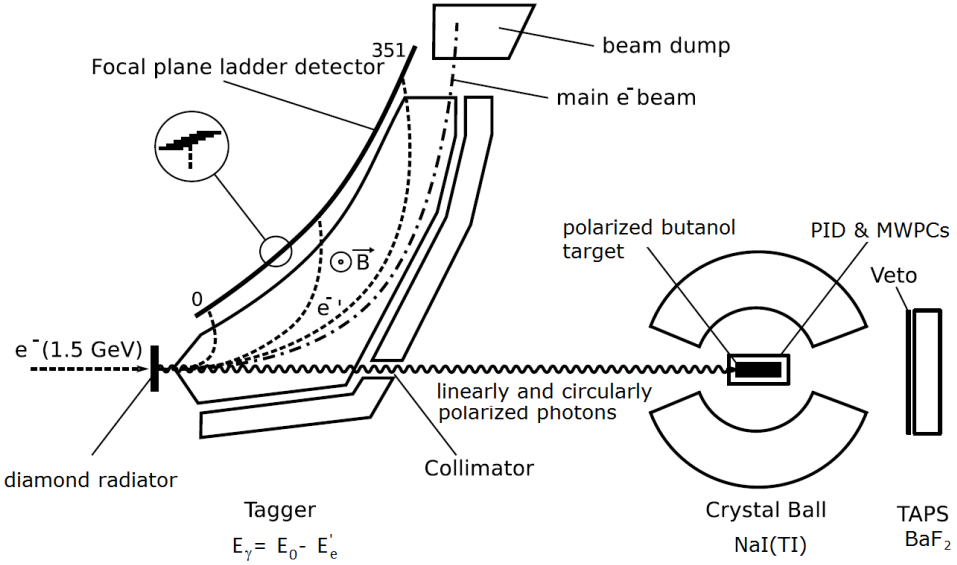
BG2014-02: S/D=1.5

[1] E. Gutz et al, Eur. Phys. J. **A50** (2014) 74

Experimental setup

A2@MAMI

long. polarized electrons incident on diamond crystal in combination with long. polarized butanol target



→ **Measurement of G & E at the same time!**

→ **Perfectly suited to identify charged and neutral final states!**

Experimental setup

A2@MAMI

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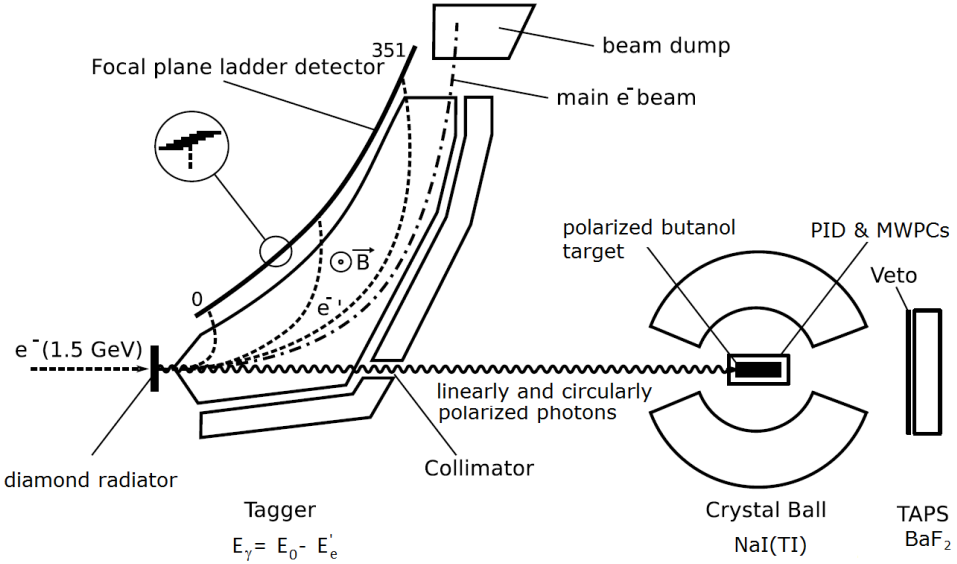
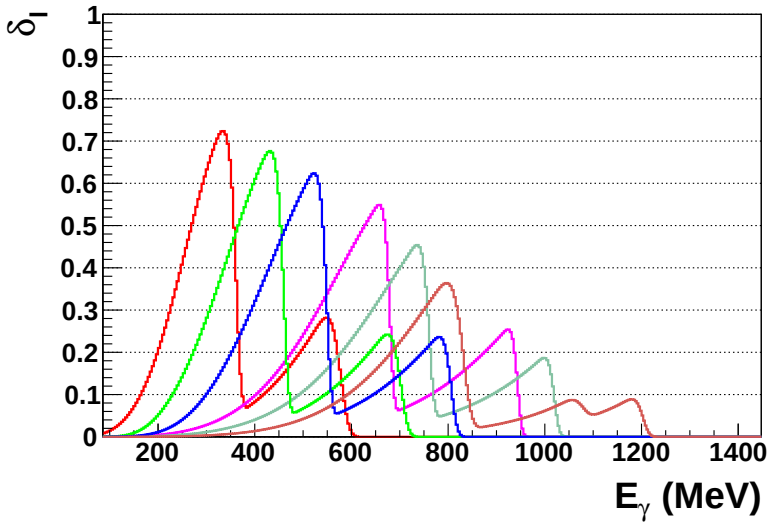


linearly polarized photons



for different coherent edges

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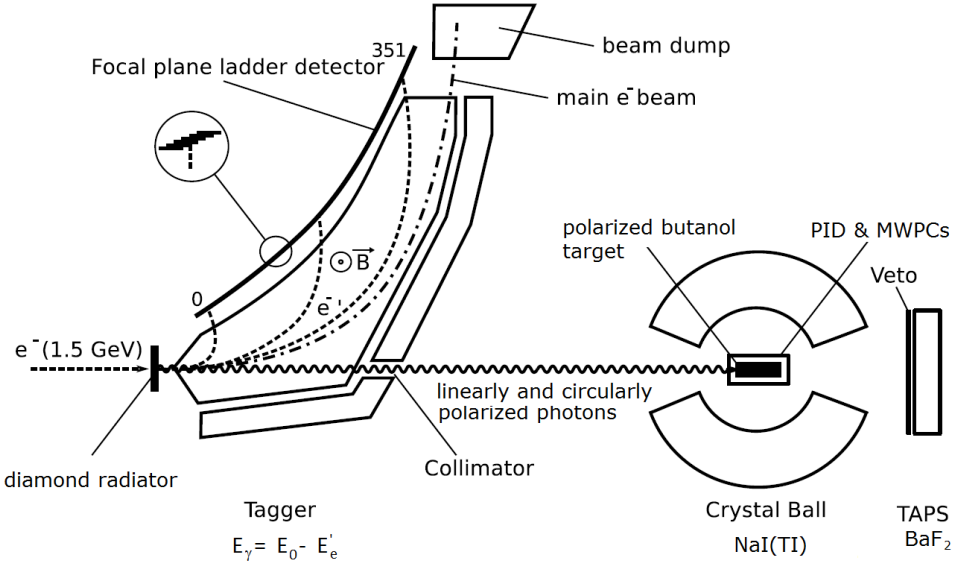
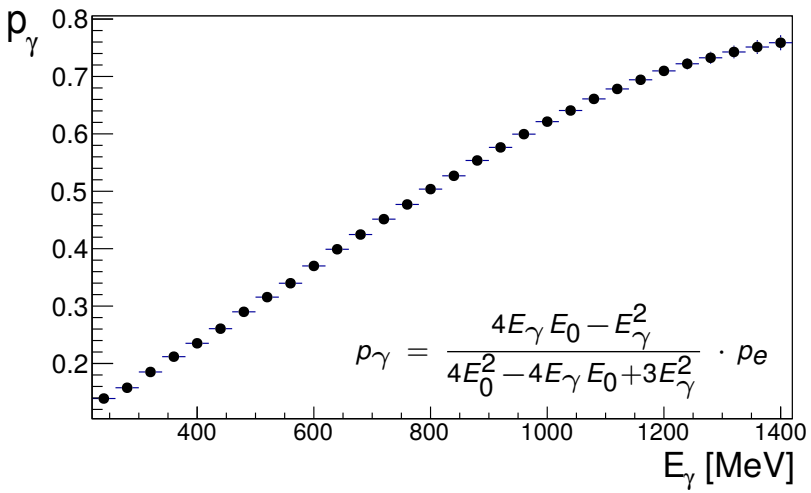


circularly polarized photons



with $p_e \approx 77\%$ (Mott-polarimeter)

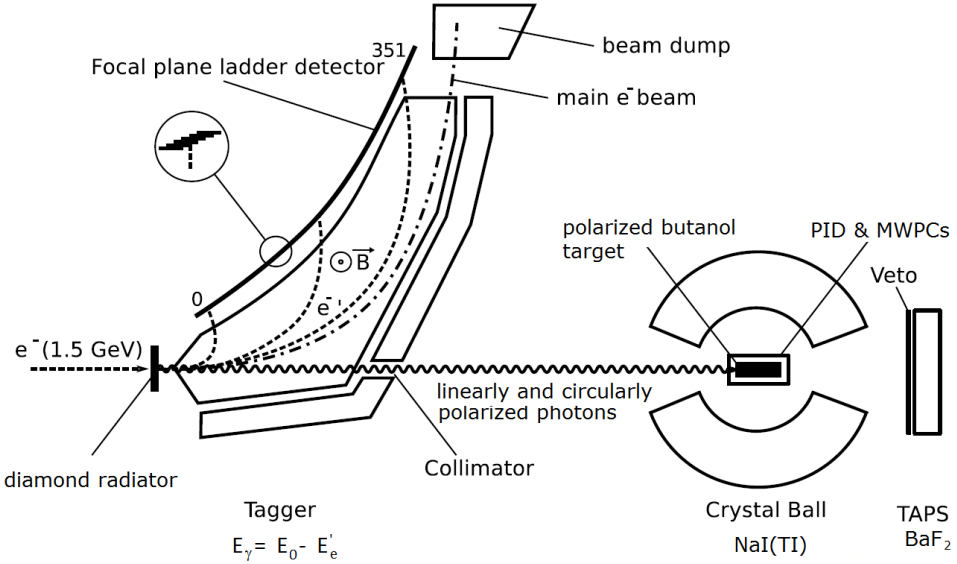
→ Measurement of G & E at the same time!

→ Perfectly suited to identify charged and neutral final states!

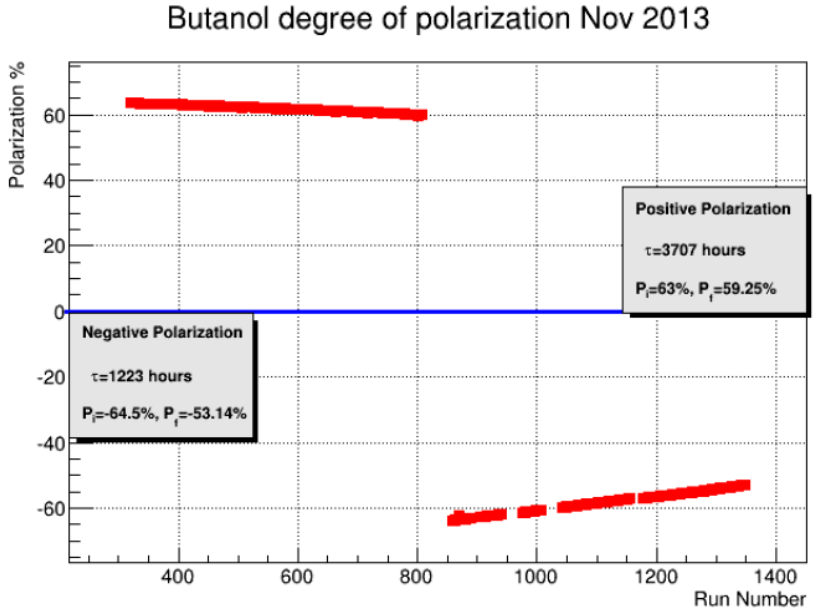
Experimental setup

A2@MAMI

long. polarized electrons incident on diamond crystal in combination with long. polarized butanol target



longitudinally polarized target



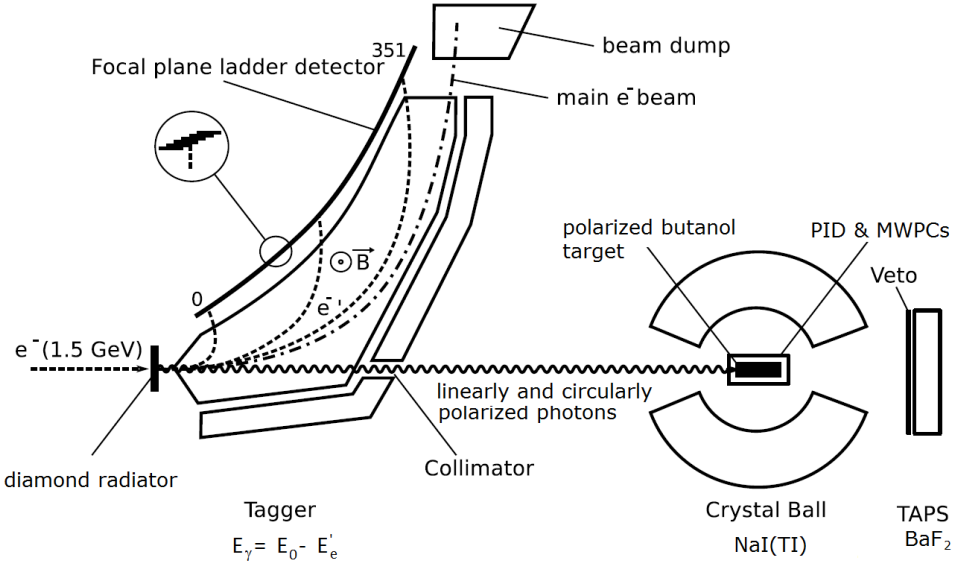
→ **Measurement of G & E at the same time!**

→ **Perfectly suited to identify charged and neutral final states!**

Experimental setup

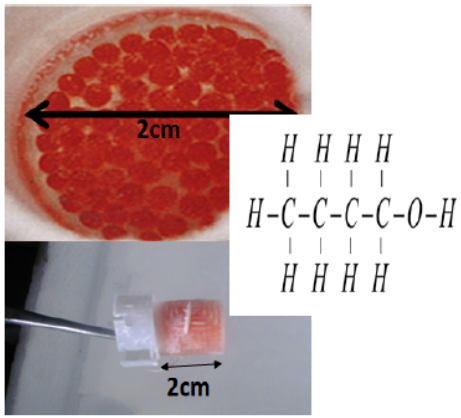
A2@MAMI

long. polarized electrons incident on diamond crystal in combination with long. polarized butanol target



carbon target for background studies

Butanol Target



Carbon Target

→ **Measurement of G & E at the same time!**

→ **Perfectly suited to identify charged and neutral final states!**

Selection of Events

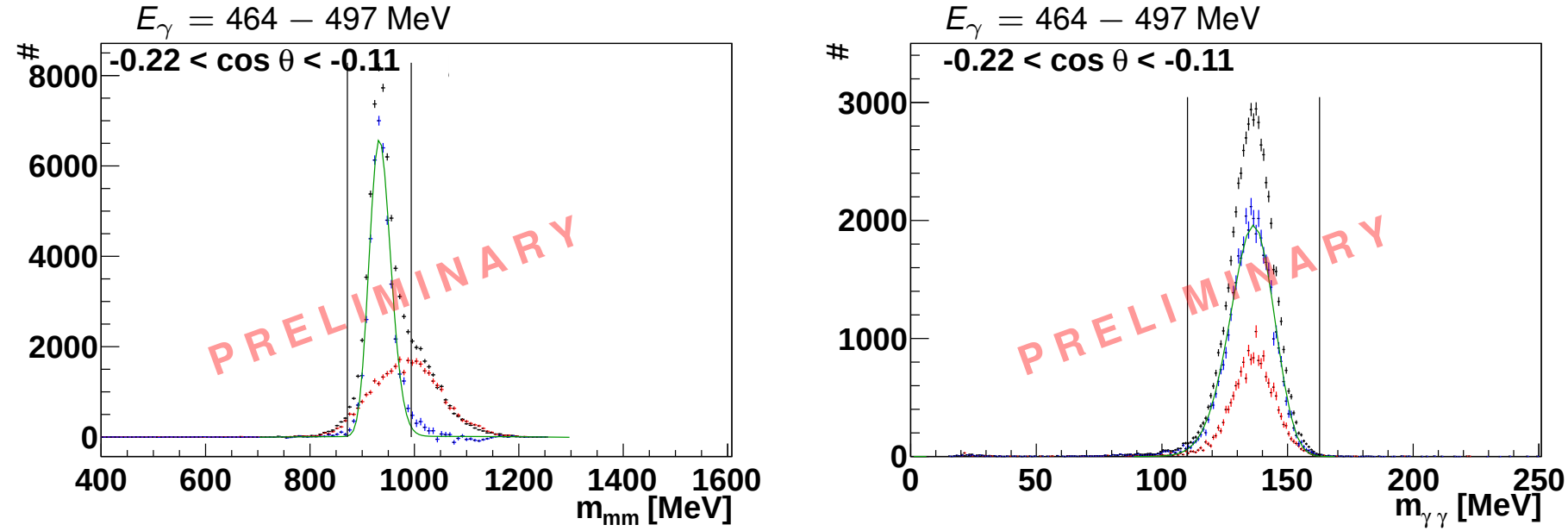
Kinematic Cuts

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

$\rightarrow$ 2 neutral particles + 1 charged particle in the final state!

Mass Cuts

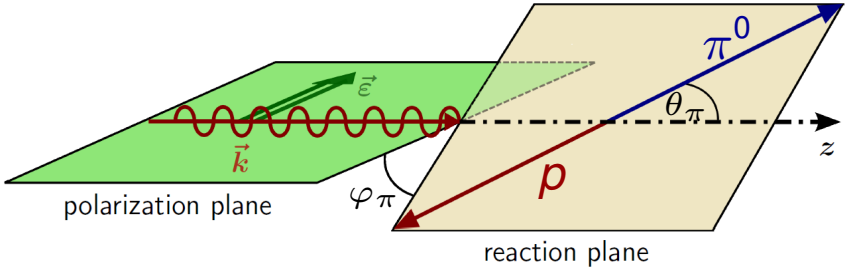
- Cut on the proton mass: $m_{mm} = (938 \pm 3\sigma(E_\gamma))$ MeV
- Cut on the meson mass: $m_{\gamma\gamma} = (135 \pm 3\sigma(E_\gamma))$ MeV



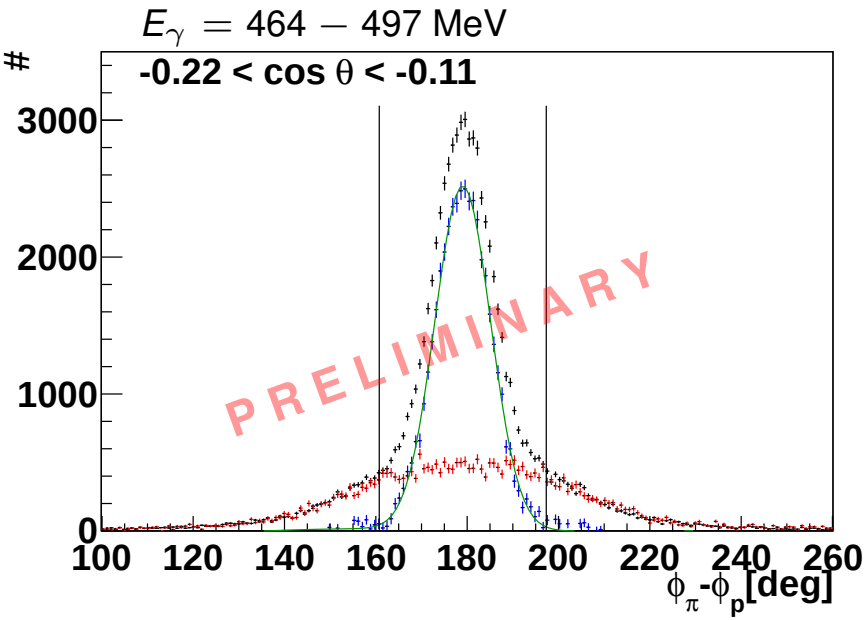
Selection of Events

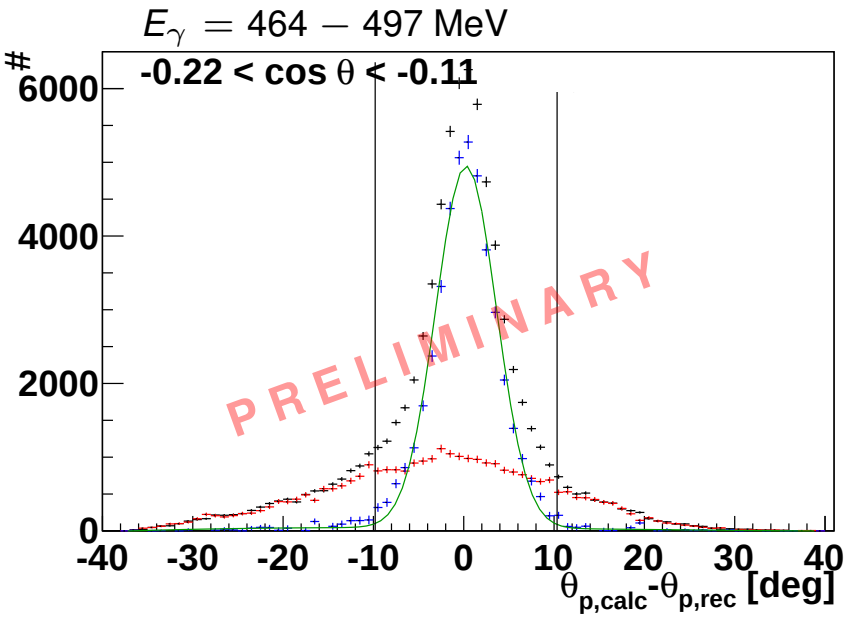
Kinematic Cuts

Angular Cuts



- Reaction products decay in one plane: $\phi_{diff} = |\phi_\pi - \phi_p| = (180 \pm 3\sigma)\,^\circ$
- Comparison of the calculated & reconstructed proton polar angle: $\theta_{diff} = |\theta_{cal} - \theta_{rec}| = (0 \pm 3\sigma)\,^\circ$





butanol — scaled carbon — reconstructed hydrogen — fit function

Extraction of the polarization observables

Angular distribution $N_B(\theta, \phi)$

- Butanol (C_4H_9OH) has unpolarized protons in carbon and oxygen

$$N_B\Big|_{\pm\alpha}^{\pm\Lambda_z}(\theta,\phi) = (\overbrace{N_H + N_C}^{N_B})(\theta)\cdot\left((1-\overbrace{\left(\frac{N_H\Sigma_H + N_C\Sigma_C}{N_H + N_C}\right)}^{\Sigma_B}\delta_l\cos 2(\phi-\alpha)+\overbrace{\left(\frac{N_H}{N_H + N_C}\right)}^{\text{dilution factor D}}\delta_l\Lambda_z G_H\sin 2(\phi-\alpha)\right)$$

→ Σ_B contains distribution from bound protons

→ Double polarization observable G requires longitudinally polarized target → Find the fraction of reaction on polarized protons → Dilution factor

Extraction of the polarization observables

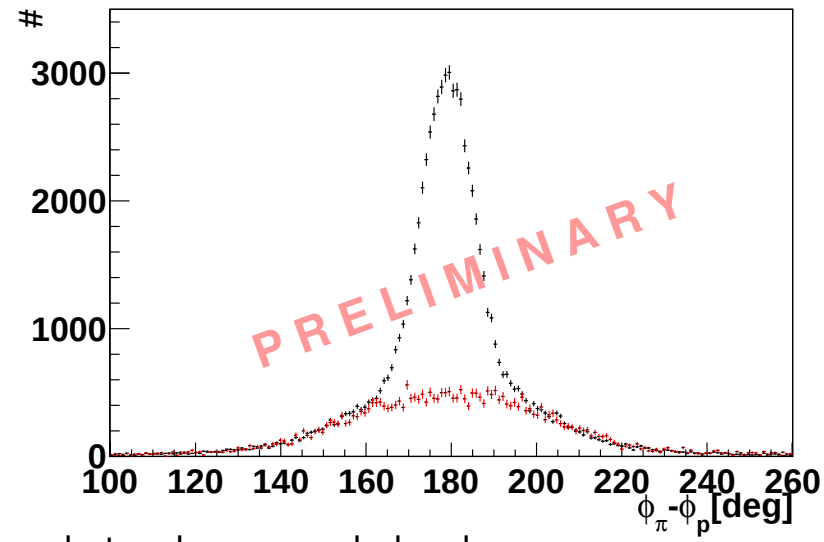
Angular distribution $N_B(\theta, \phi)$

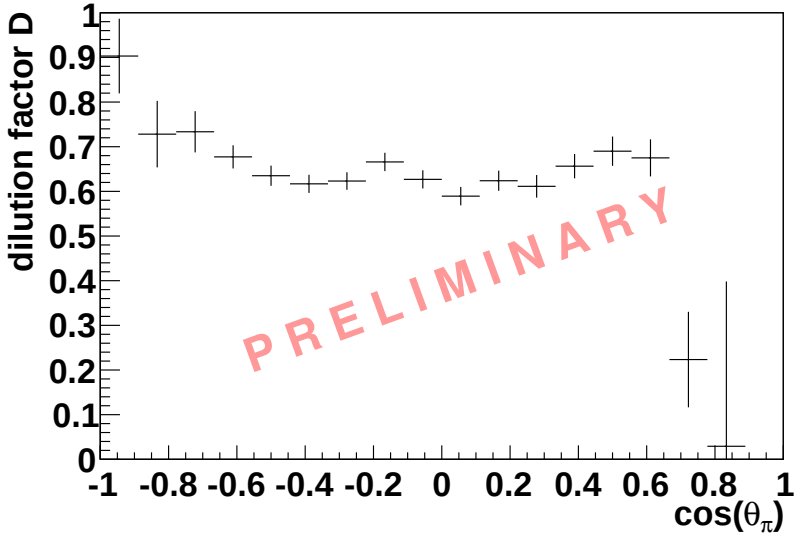
$$N_B\Big|_{\pm\alpha}^{\pm\Lambda_z}(\theta,\phi) = (\overbrace{N_H + N_C}^{N_B})(\theta)\cdot\left((1-\overbrace{\left(\frac{N_H\Sigma_H + N_C\Sigma_C}{N_H + N_C}\right)}^{\Sigma_B}\delta_l \cos 2(\phi-\alpha) + \overbrace{\left(\frac{N_H}{N_H + N_C}\right)}^{\text{dilution factor D}}\delta_l\Lambda_z G_H \sin 2(\phi-\alpha)\right)$$

Dilution Factor

E_γ = (464-497) MeV

$$D = \frac{N_H}{N_H + N_C} = \frac{N_H}{N_B} = \frac{N_B - s(E_\gamma)N_C}{N_B} = 1 - s(E_\gamma)\frac{N_C}{N_B} \text{ with } N_B \approx N_H + N_C$$





butanol scaled carbon

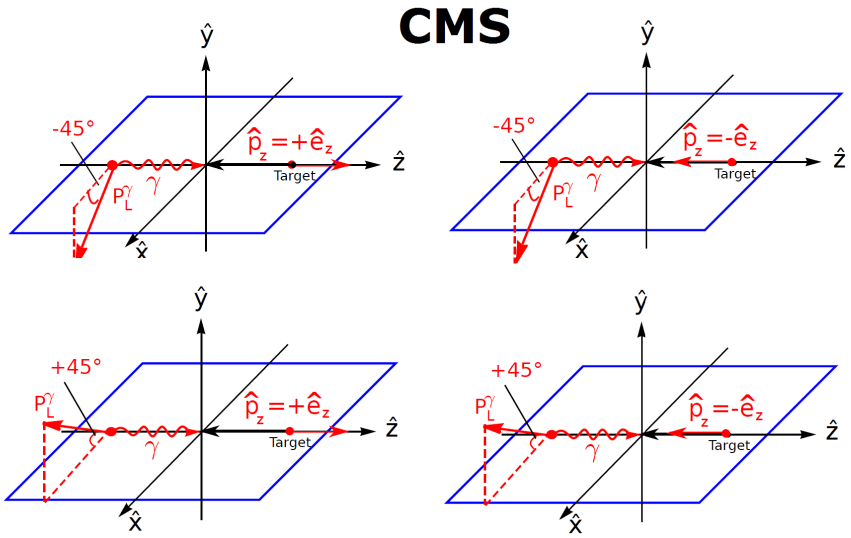
Extraction of the polarization observables

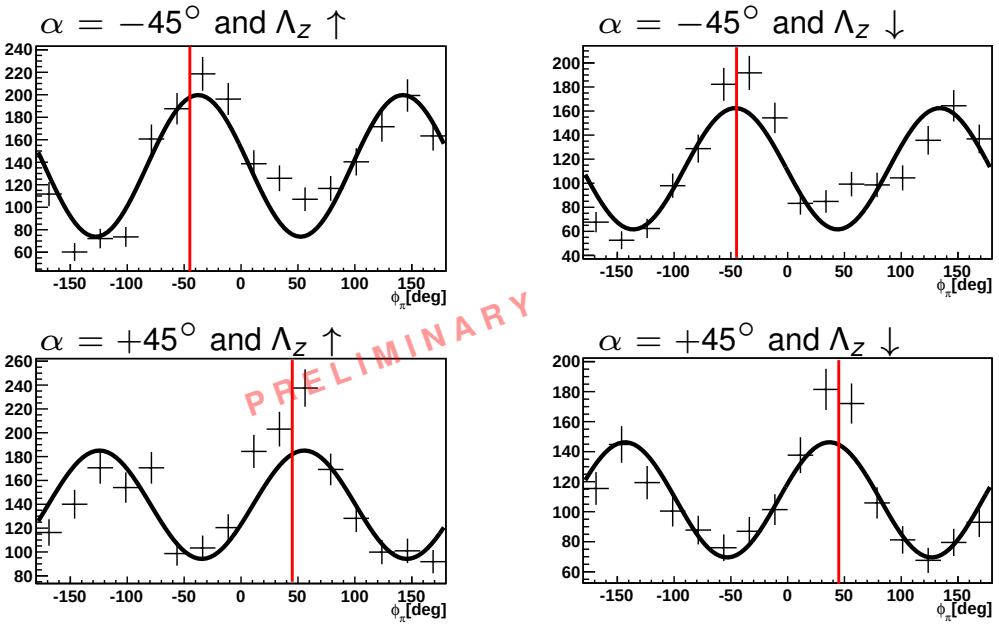
Angular distribution $N_B(\theta, \phi)$

$$N_B\Big|_{\pm\alpha}^{\pm\Lambda_z}(\theta,\phi) = (\overbrace{N_H + N_C}^{N_B})(\theta)\cdot\left((1-\overbrace{\left(\frac{N_H\Sigma_H + N_C\Sigma_C}{N_H + N_C}\right)}^{\Sigma_B}\delta_l\cos 2(\phi-\alpha)+\overbrace{\left(\frac{N_H}{N_H + N_C}\right)}^{\text{dilution factor D}}\delta_l\Lambda_z G_H\sin 2(\phi-\alpha)\right)$$

ϕ-asymmetries for different settings

E_γ = (464-497) MeV and $-0.22 < \cos\theta_\pi \leq -0.11$





Extraction of the polarization observables

Absolute normalized determination

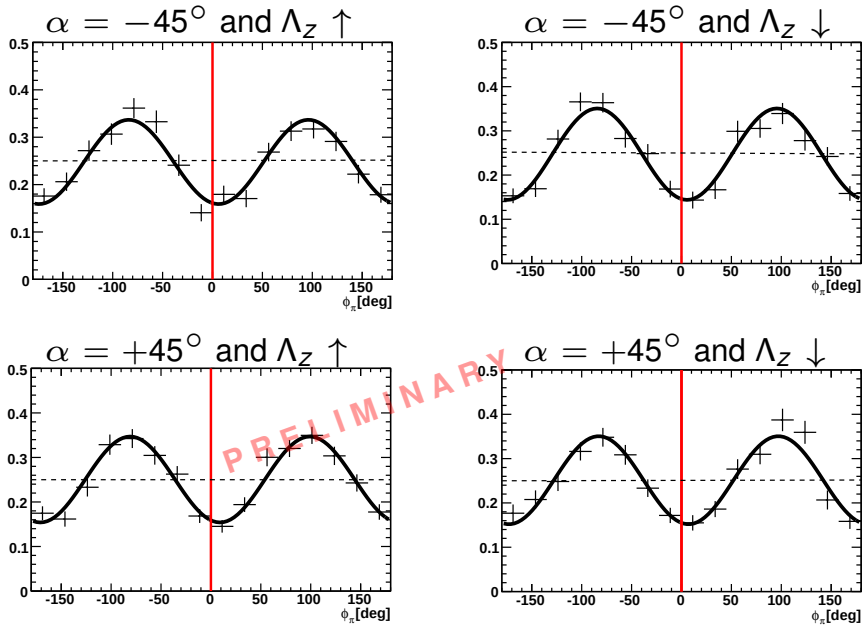
- Sum of different ϕ-asymmetries results in unpolarized cross section

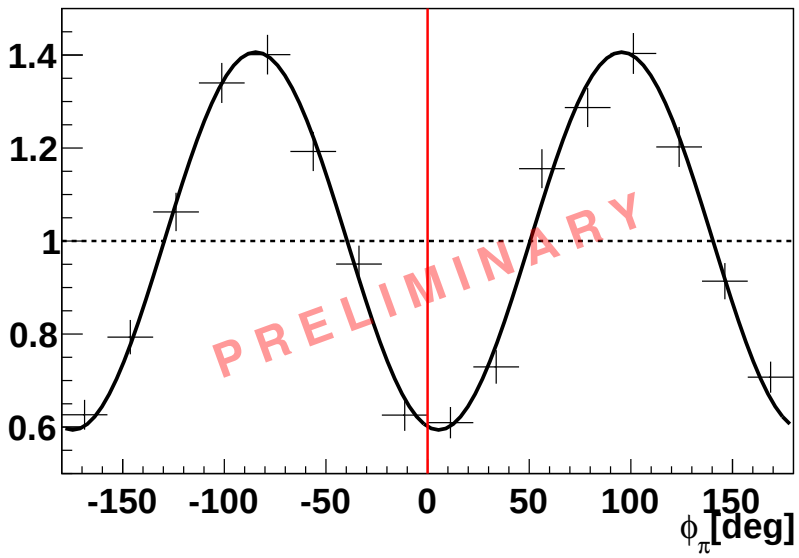
$\rightarrow$ **Normalize the different settings before they are shifted!**

$$N_B(\theta,\phi)' = 1 - \Sigma_B \delta_l \cos 2\phi + D\delta_l \Lambda_z G_H \sin 2\phi$$
$$f(\theta,\phi) = 1 + B\cos 2\phi + C\sin 2\phi$$

Shifted and normalized ϕ-asymmetries and their sum

E_γ = (464-497) MeV and $-0.22 < \cos\theta_\pi \leq -0.11$





Results of the polarization observables

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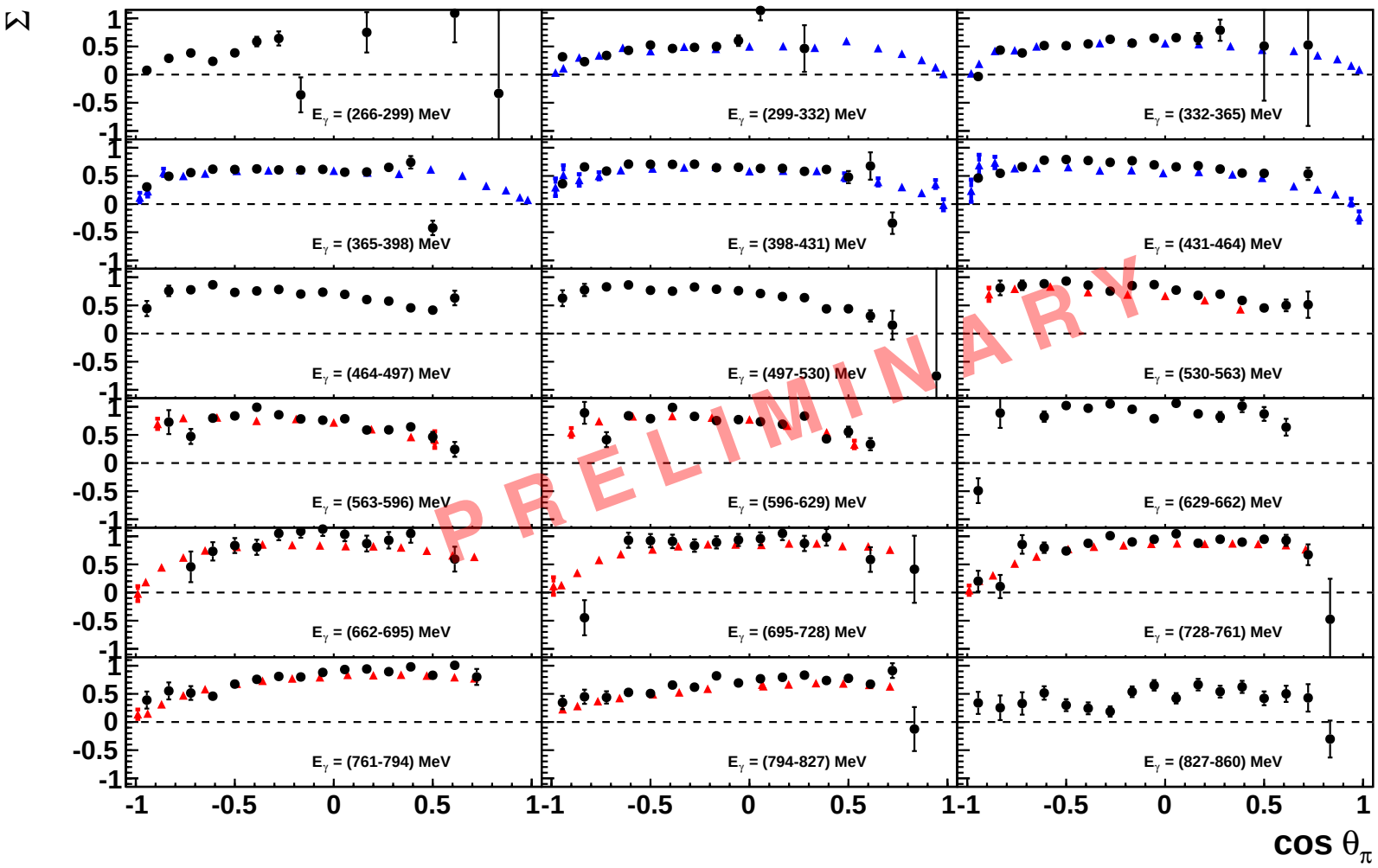
Beam asymmetry Σ_B - Comparison with recent results



▲ MAMI [1] ▲ GRAAL [2] ● this work

[1] R. Beck et al, Eur. Phys. J. **A28** (2006) 173-183 [2] O.Bartalini et al., Eur. Phys.J. **A26** (2005) 399

Results of the polarization observables

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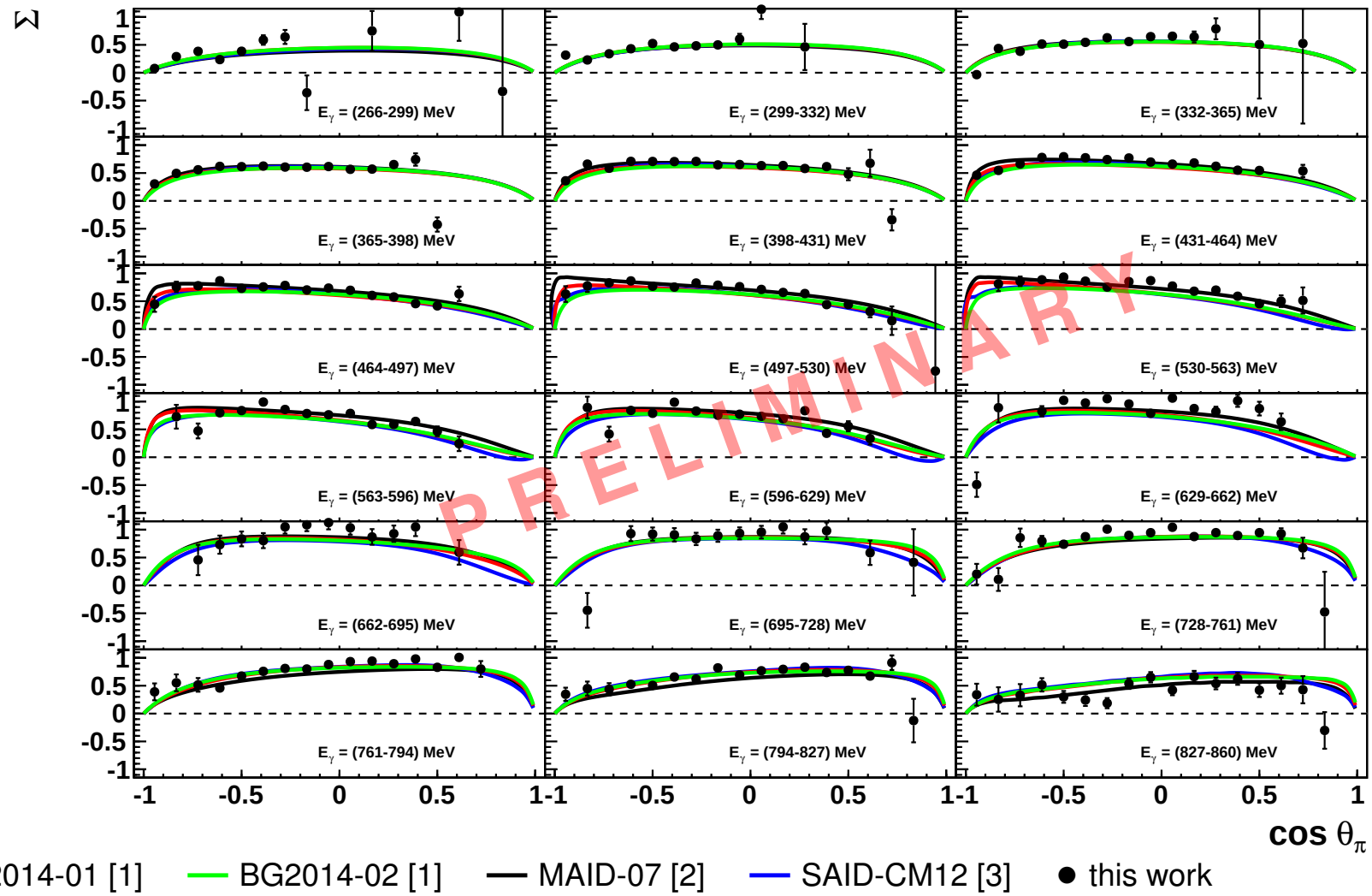
Beam asymmetry Σ_B - Comparison with PWA solutions

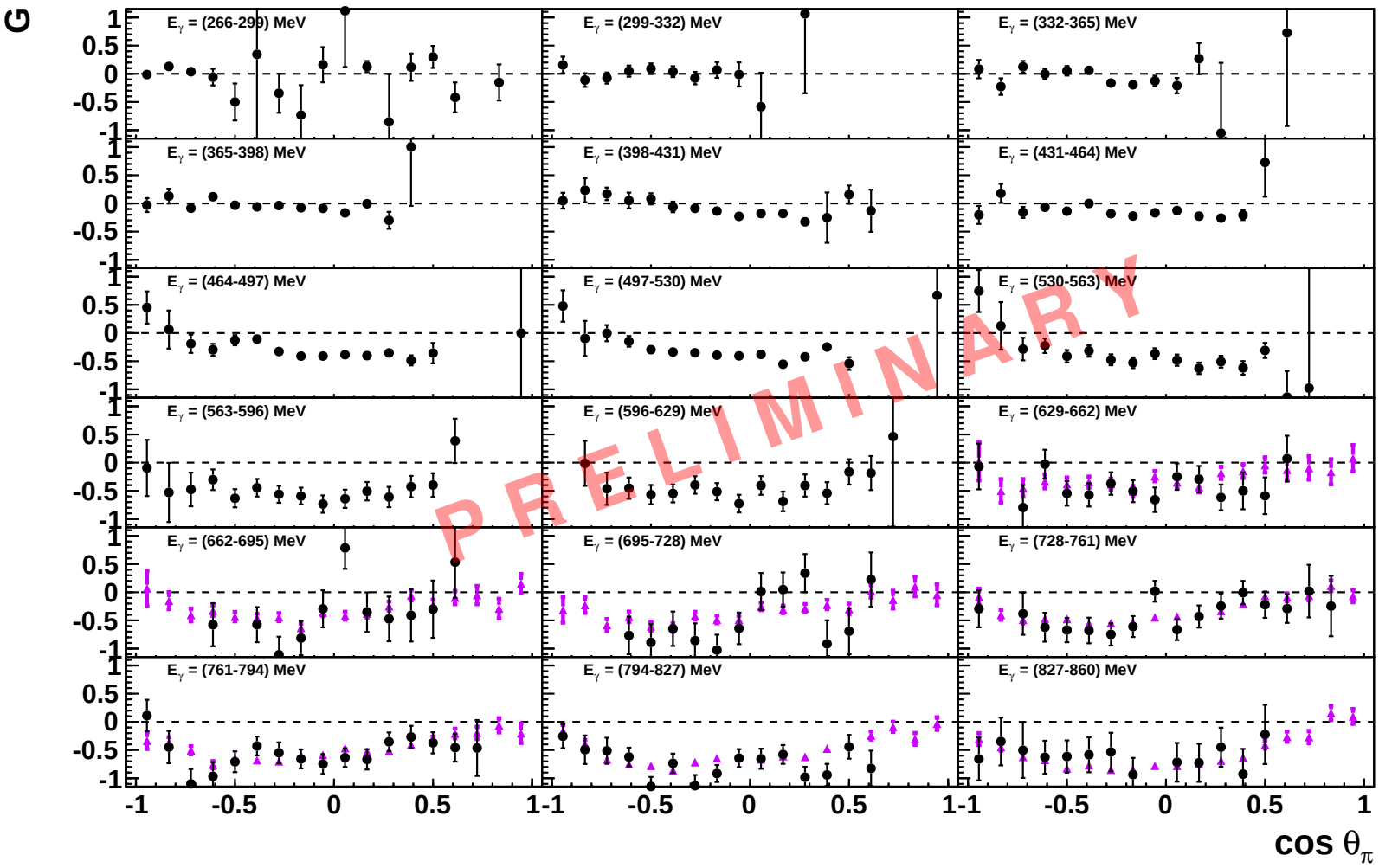


BG2014-01 [1] BG2014-02 [1] MAID-07 [2] SAID-CM12 [3] ● this work

[1] E. Gutz et al, Eur. Phys. J. **A50** (2014) 74 [2] D. Drechsel, S. S. Kamalov, and L. Tiator, Eur. Phys. J. **A34**, (2007) 69-97
[3] R. Workman et al, Phys. Rev. **C86**, (2012) 015202

Results of the polarization observables

Double polarization observable G - Comparison with recent results



▲CBELSA/TAPS [1] ● this work

[1] A. Thiel et al., Phys. Rev. Lett. 109 (2012) 102001

Results of the polarization observables

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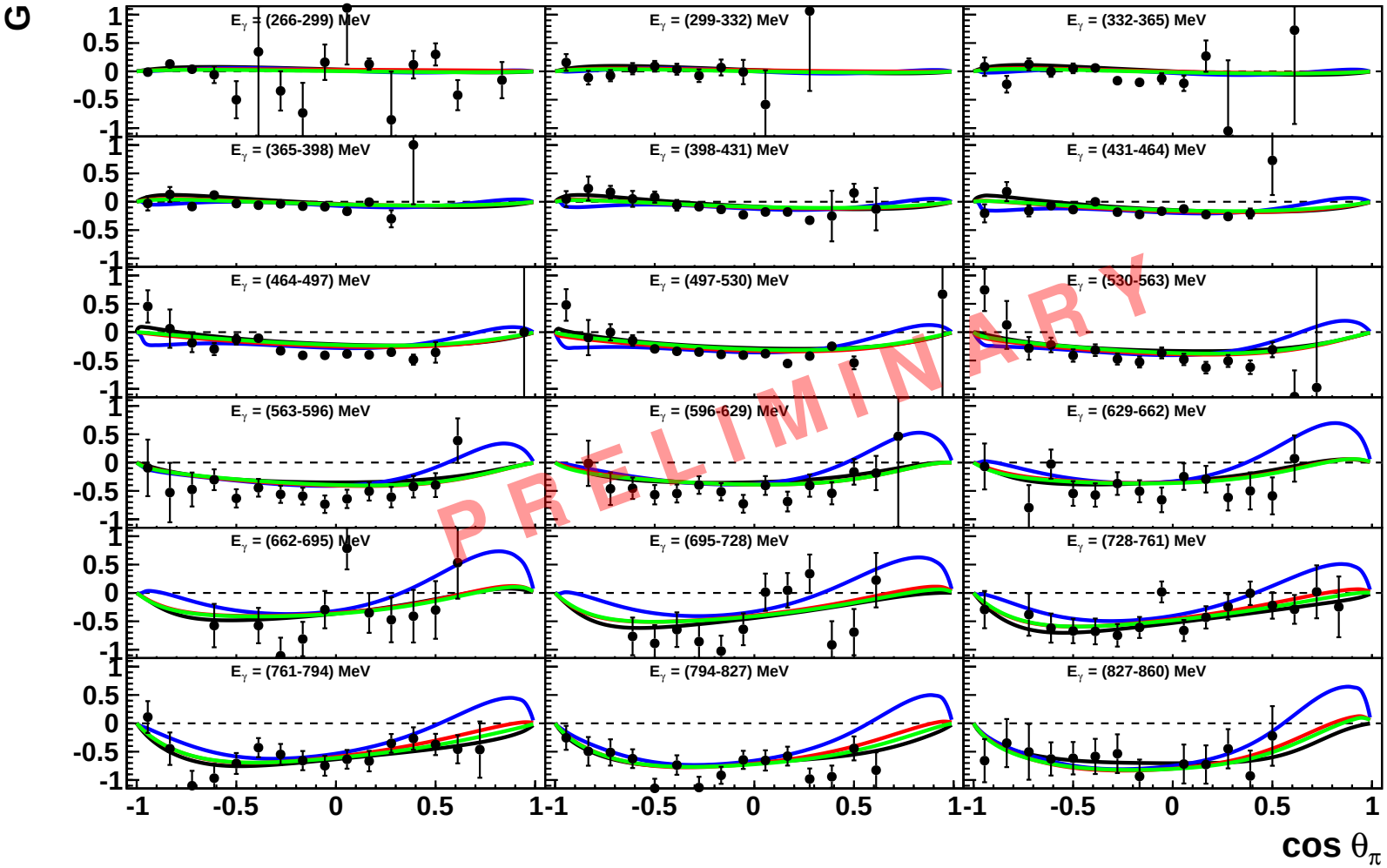
Double polarization observable G - Comparison with PWA solutions



BG2014-01 [1] — BG2014-02 [1] — MAID-07 [2] — SAID-CM12 [3] — this work

[1] E. Gutz et al, Eur. Phys. J. **A50** (2014) 74 [2] D. Drechsel, S. S. Kamalov, and L. Tiator, Eur. Phys. J. **A34**, (2007) 69-97
[3] R. Workman et al, Phys. Rev. **C86**, (2012) 015202

Summary and outlook

Summary:

- Selection of the reaction $\vec{\gamma}\vec{p} \rightarrow p\,\pi^0$
- Measurement of the beam asymmetry Σ_B and double polarization observable G in the single π^0 channel
- Good agreement with recent results for the beam asymmetry Σ_B and double polarization observable G

Outlook:

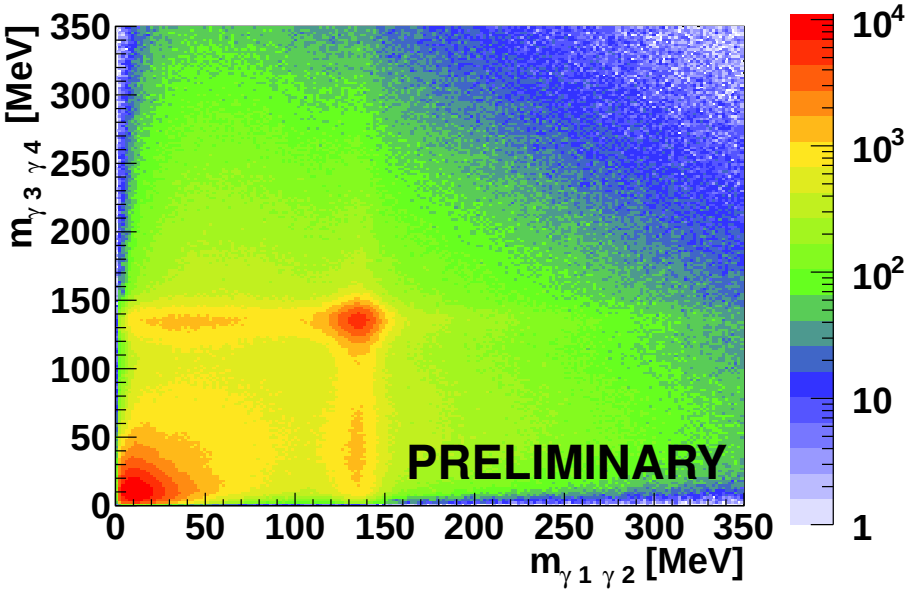
- Extracted the polarization observable E
- Analysis of $n\pi^+$ channel (Isospin seperation of M_{1-} partial wave)
- Analysis of $2\pi^0$ channel (G & E is very sensitive on $D_{13}(1520)$ resonance)

Outlook

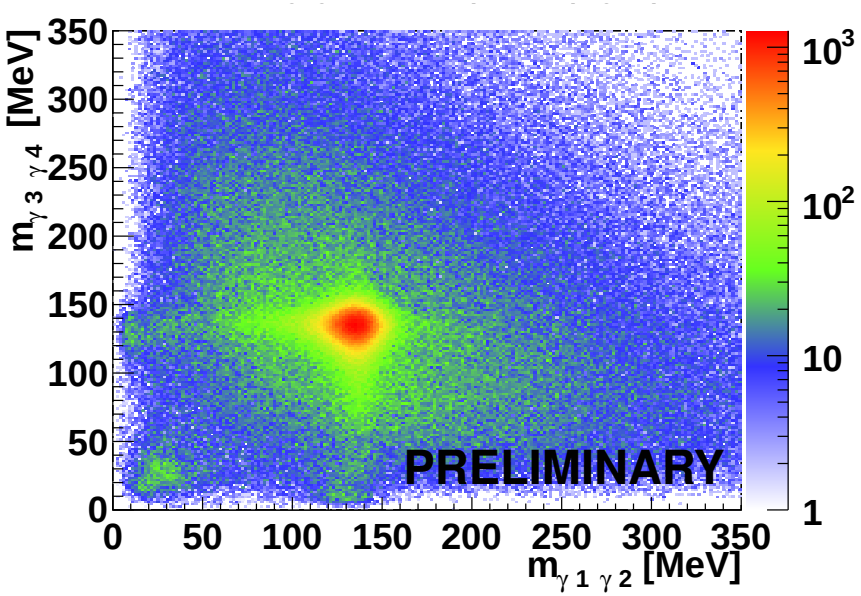
$2\pi^0$ selection - Some first results

2-dimensional invariant mass distribution of the photon pairs

without any cuts (#events ≈ 750.000)



with all introduced cuts (#events ≈ 116.000)



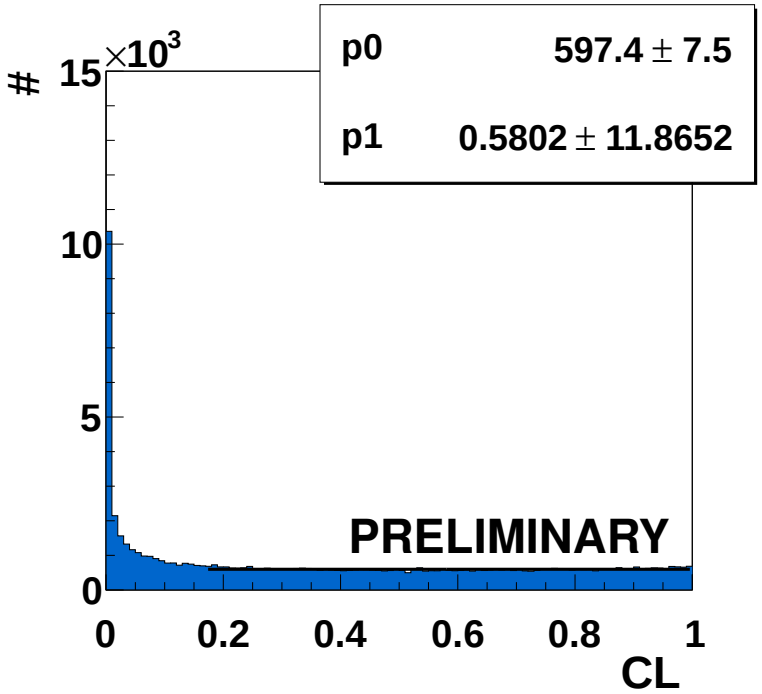
However: Still huge combinatorial background.
→ Use APLCON[1] fitter for solving this problem.

[1] http://www.desy.de/ blobel/wwwcondl.html

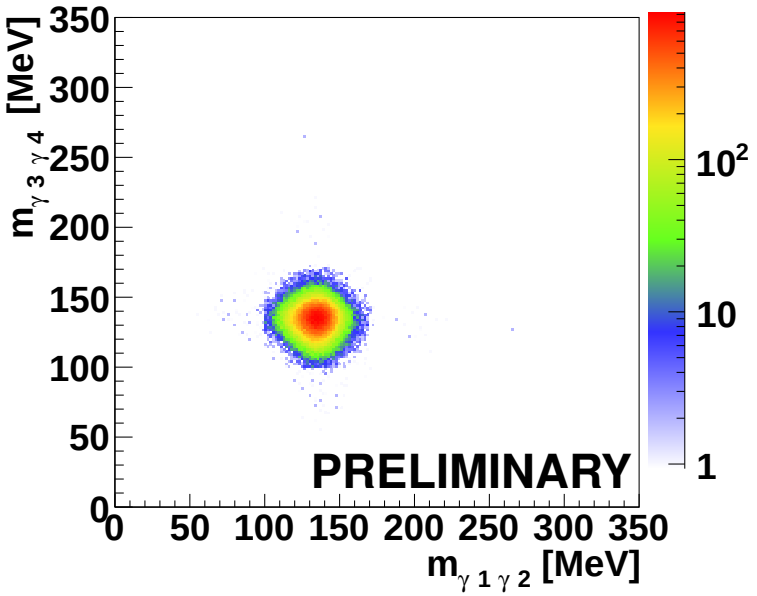
Outlook

$2\pi^0$ selection - CL and result

Convidence Level (CL) and 2-dimensional invariant mass distribution of the photon pairs



with all cuts + CL>0.01 (#events ≈ 67.000)



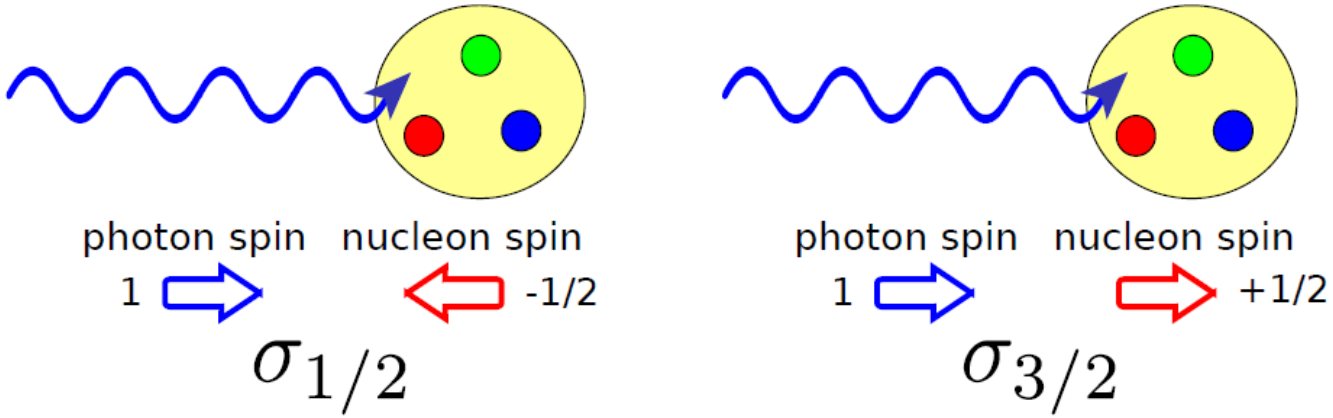
"The important thing is not to stop questioning. Curiosity has its own reason for existing."

(Albert Einstein, 1879-1955)

Appendix

Double polarization observable E

Helicity dependent cross section

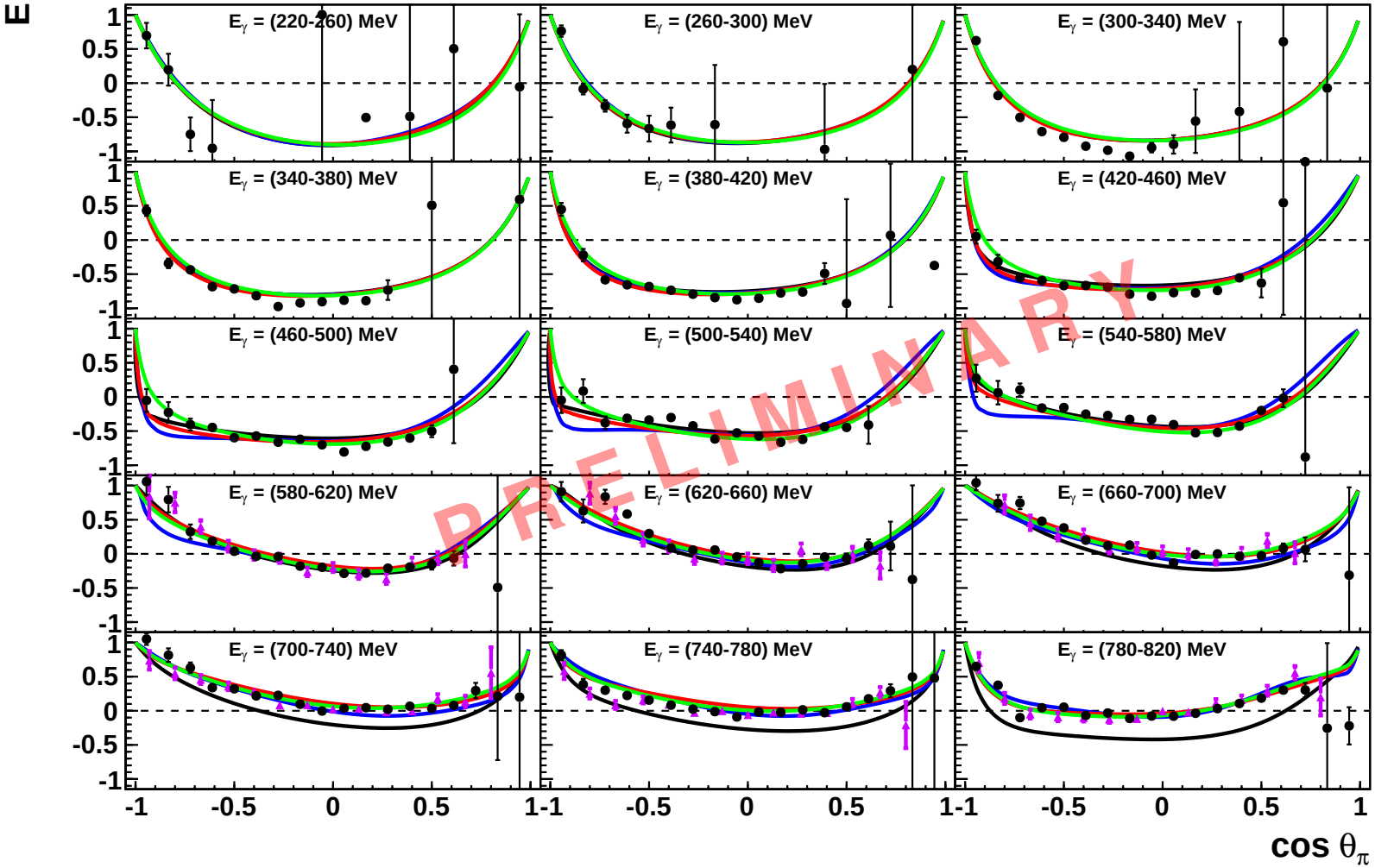


$$N\Big|_{3/2}^{1/2}(\theta) = N_0 \cdot (1 \pm D\delta_c\Lambda_z E)$$

$$\rightarrow E = \frac{1}{D}\frac{1}{\delta_c}\frac{1}{\Lambda_z}\frac{N_{1/2} - N_{3/2}}{N_{1/2} + N_{3/2}}$$

Appendix

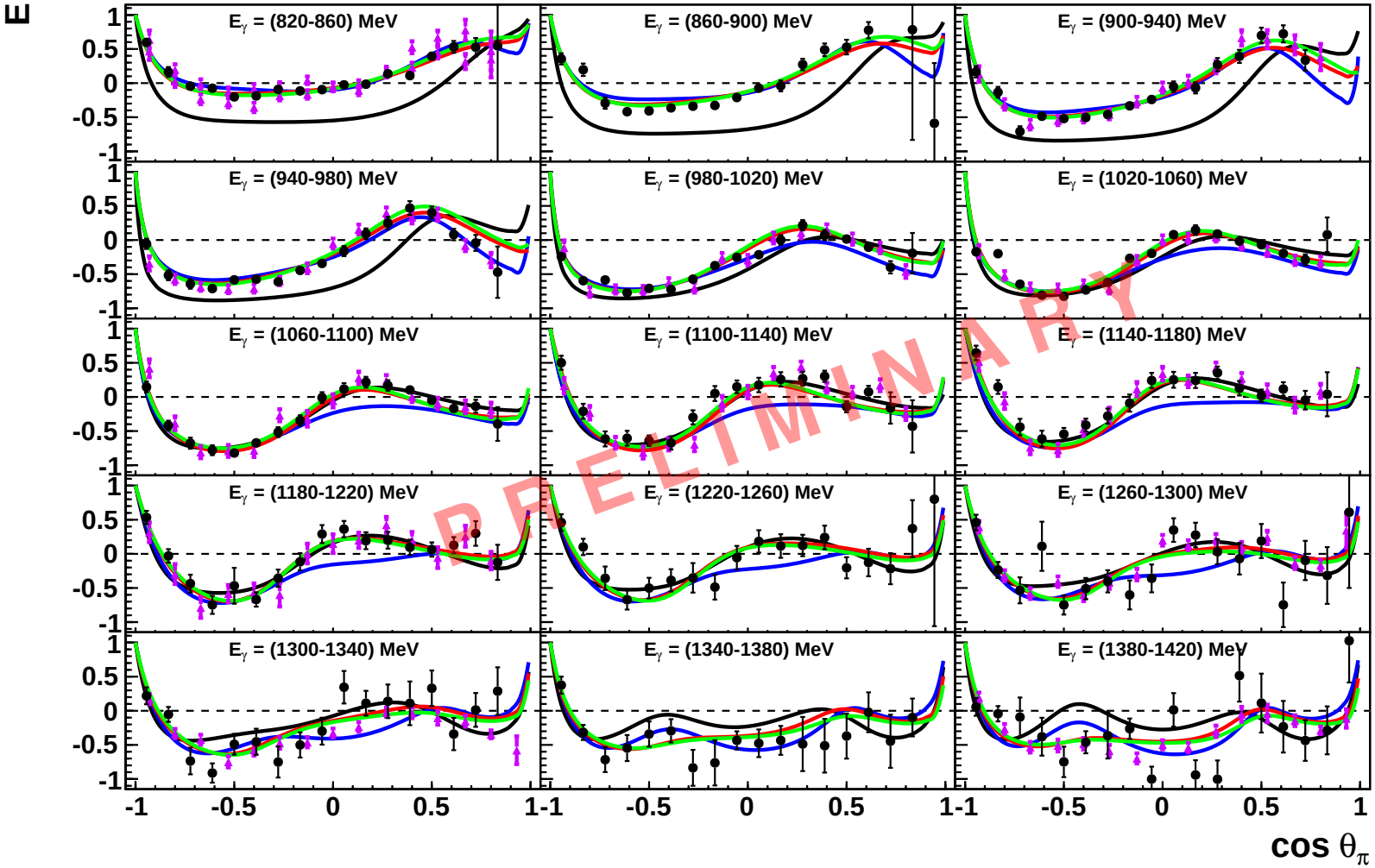
Double polarization observable E - Comparison with PWA solutions



[1] E. Gutz et al, Eur. Phys. J. **A50** (2014) 74 [2] D. Drechsel, S. S. Kamalov, and L. Tiator, Eur. Phys. J. **A34**, (2007) 69-97
[3] R. Workman et al, Phys. Rev. **C86**, (2012) 015202 [4] M. Gottschall et al., Phys. Rev. Lett. 112 (2014) 012003

Appendix

Double polarization observable E - Comparison with PWA solutions

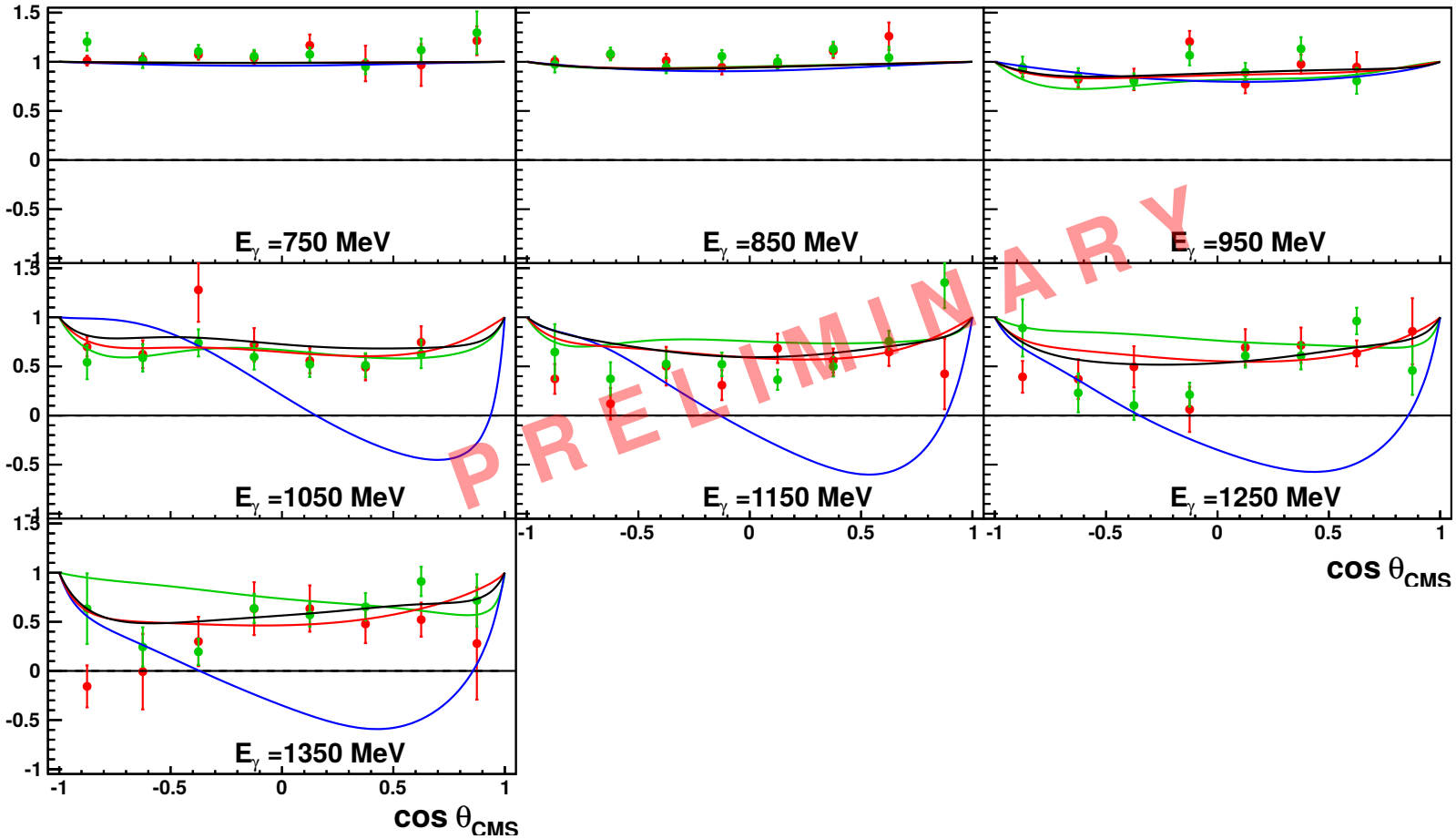


BG2014-01 [1] BG2014-02 [1] MAID-07 [2] SAID-CM12 [3] ● this work ▲ CBELSA/TAPS [4]

[1] E. Gutz et al, Eur. Phys. J. **A50** (2014) 74 [2] D. Drechsel, S. S. Kamalov, and L. Tiator, Eur. Phys. J. **A34**, (2007) 69-97
[3] R. Workman et al, Phys. Rev. **C86**, (2012) 015202 [4] M. Gottschall et al., Phys. Rev. Lett. 112 (2014) 012003

Appendix

Double polarization observable E in η-photoproduction

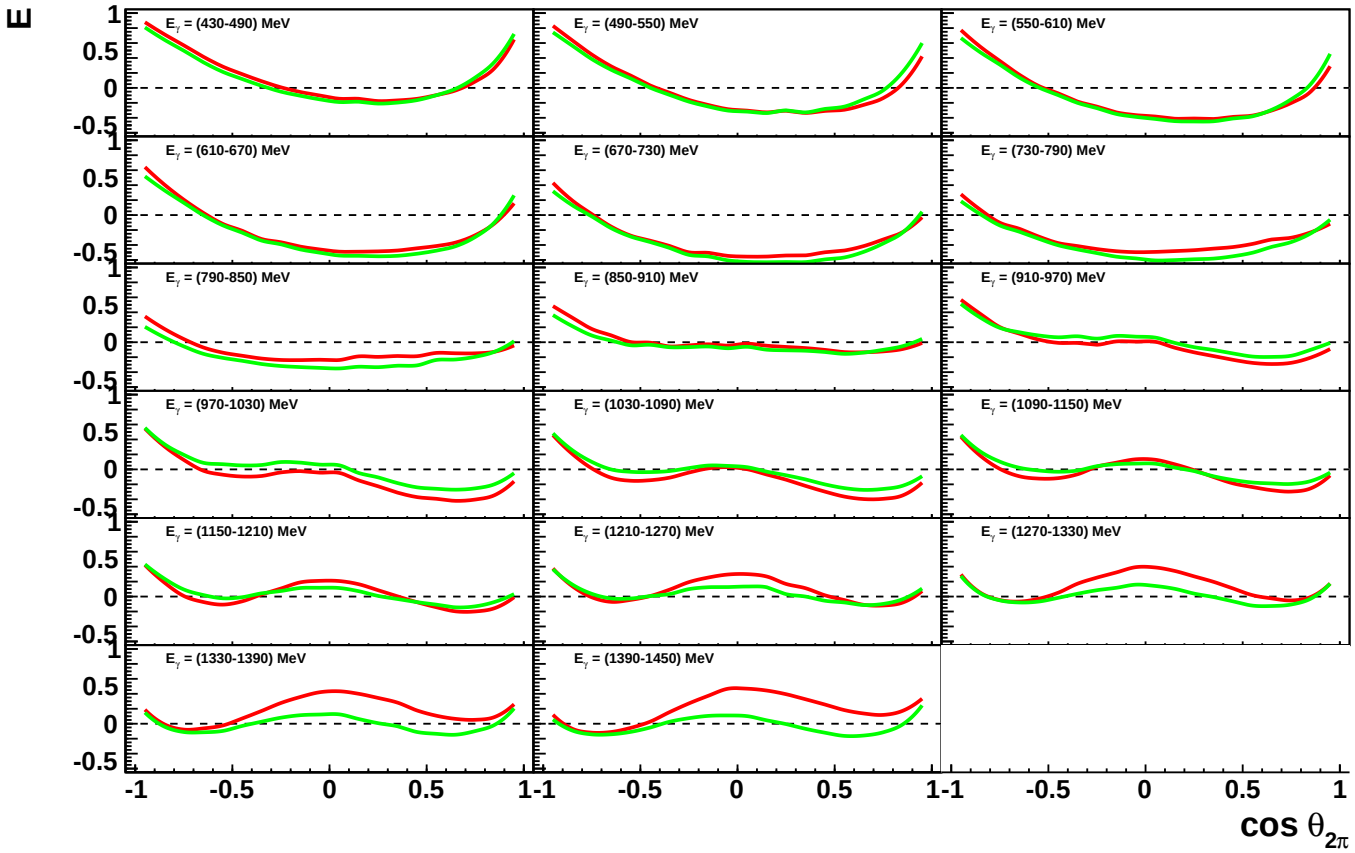


BG2014-01 [1] — BG2014-02 [1] — η MAID — SAID-GE09 — A2 [2] — CBELSA/TAPS [3]

[1] E. Gutz et al, Eur. Phys. J. **A50** (2014) 74 [2] F. Afzal [3] J.Müller et al., to be published soon)

Appendix

Sensitivity studies - BnGa



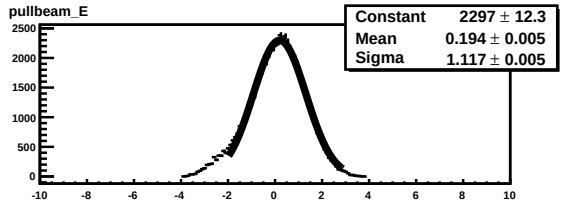
BG2014-01
BG2014-02

S/D-wave ratio decay of $D_{13}(1520) \rightarrow \Delta\pi$
BG2014-01: S/D=3
BG2014-02: S/D=1.5

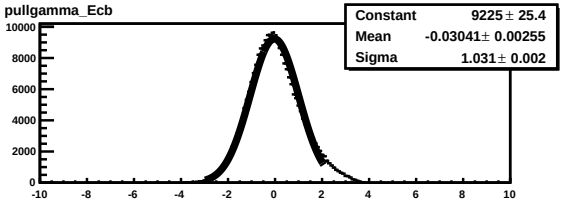
S/D-wave ratio decay of $D_{33}(1940) \rightarrow \Delta\pi$
BG2014-01: S/D=1/5
BG2014-02: S mostly

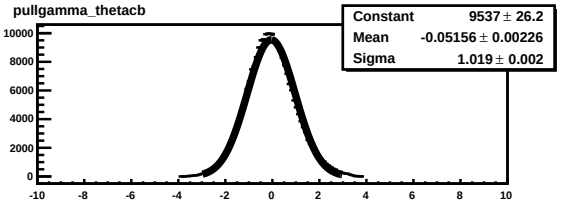
Appendix

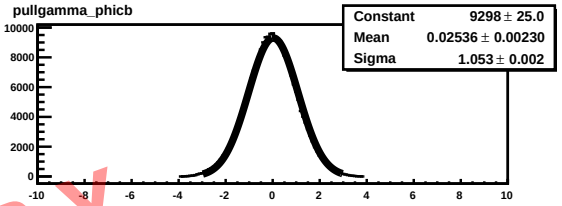
Pull-distributions

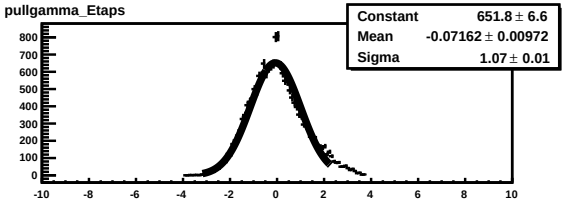


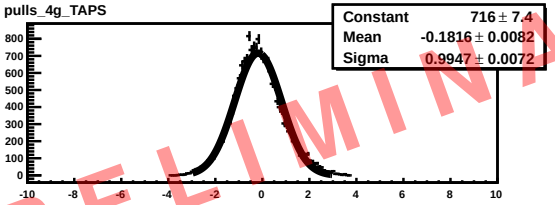
not fitted

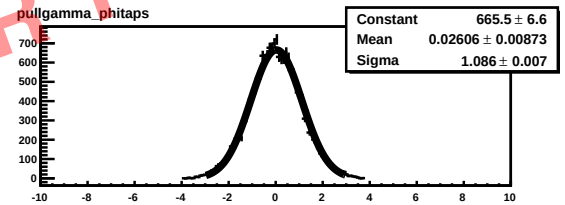


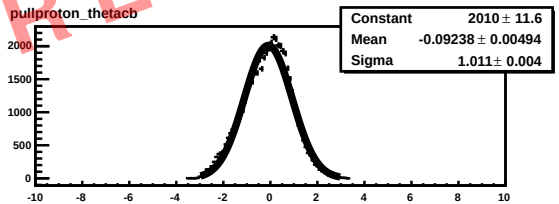


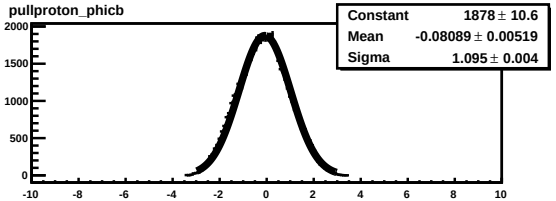




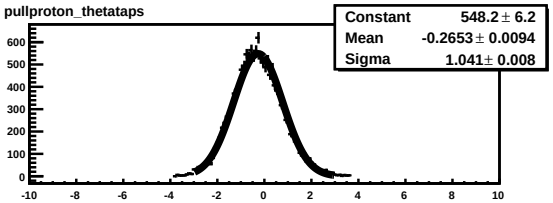


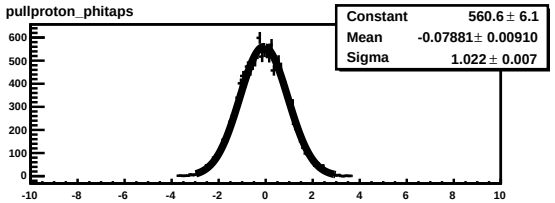






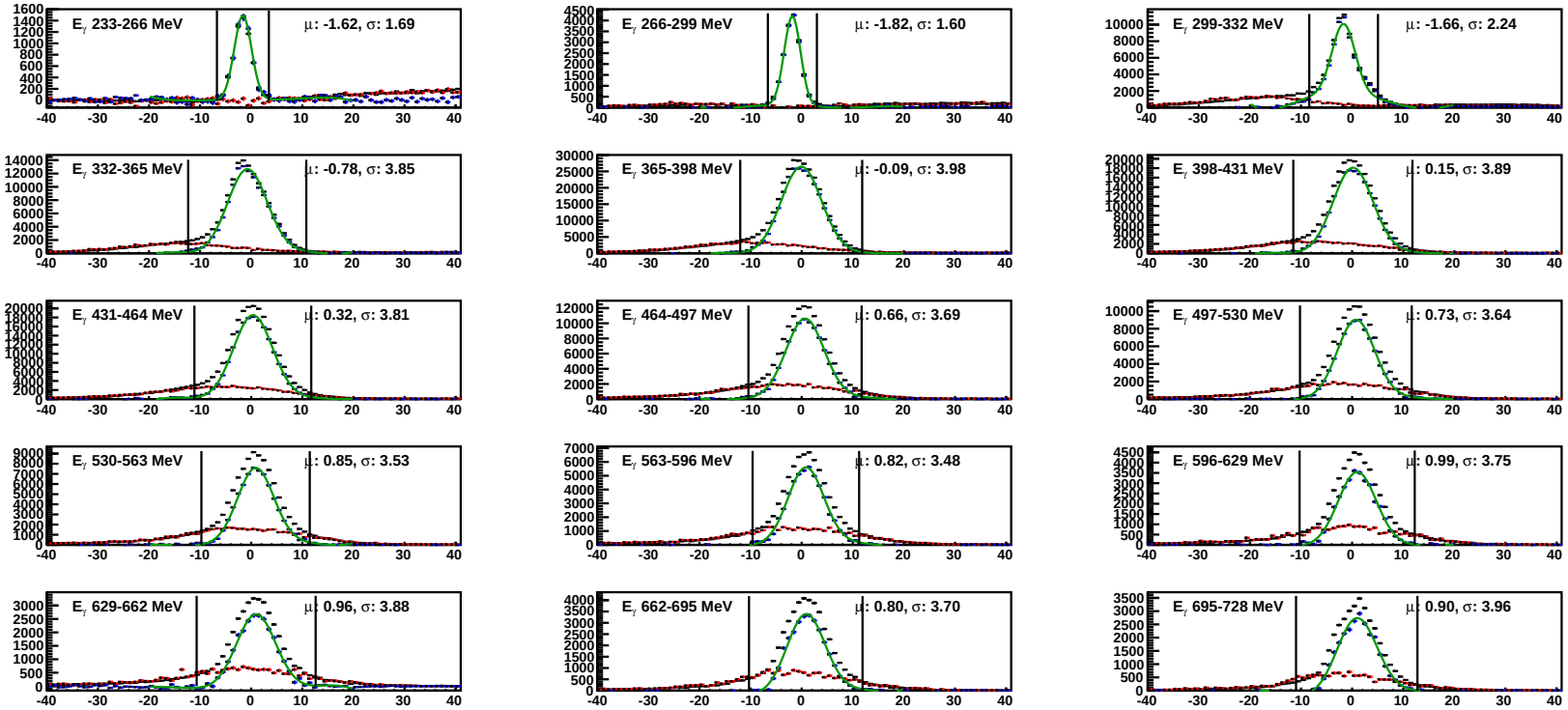
not fitted

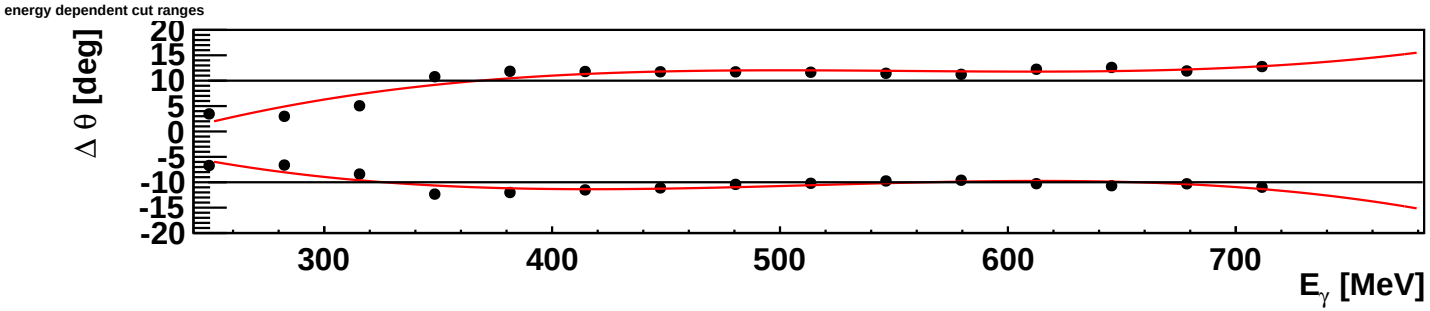




Appendix

Energy dependent selection - Theta

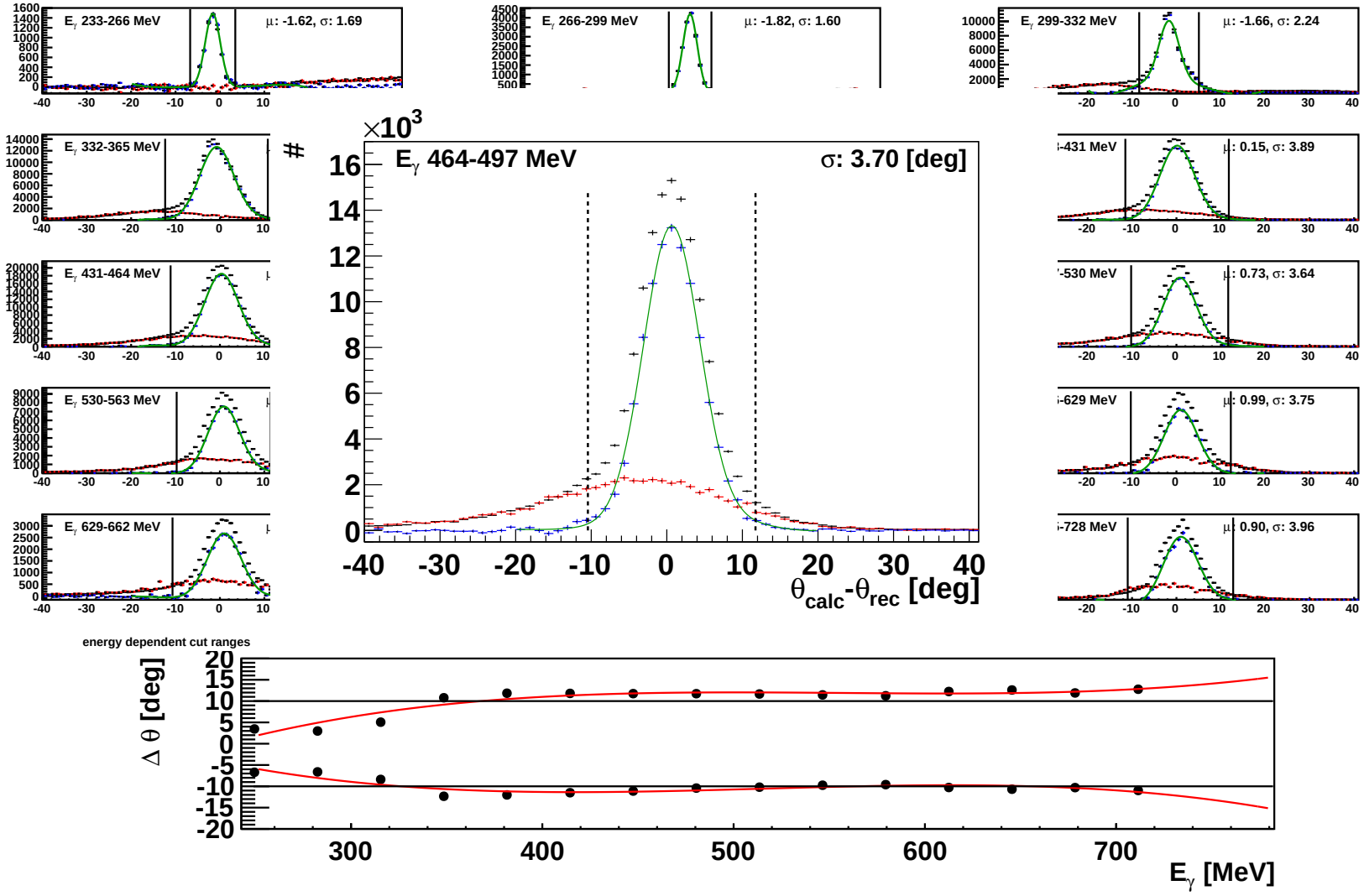




butanol — scaled carbon — reconstructed hydrogen — fit function

Appendix

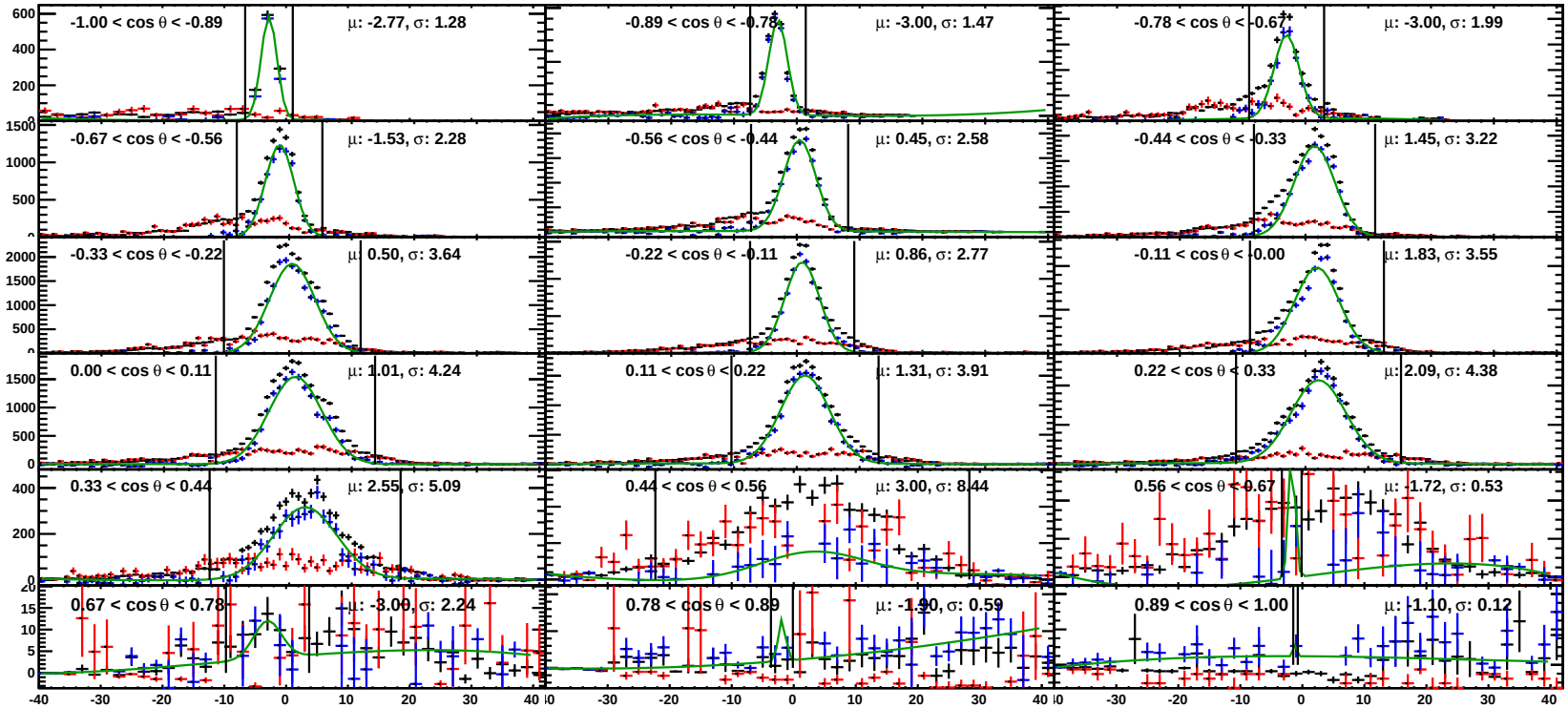
Energy dependent selection - Theta

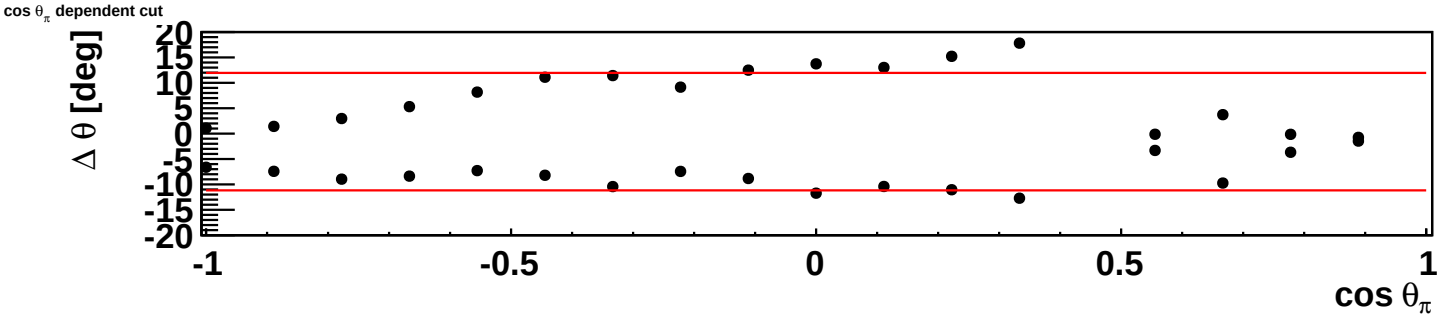


butanol — scaled carbon — reconstructed hydrogen — fit function

Appendix

$\cos\theta_\pi$ dependent selection - Theta for $E_\gamma = (464 - 497)$ MeV

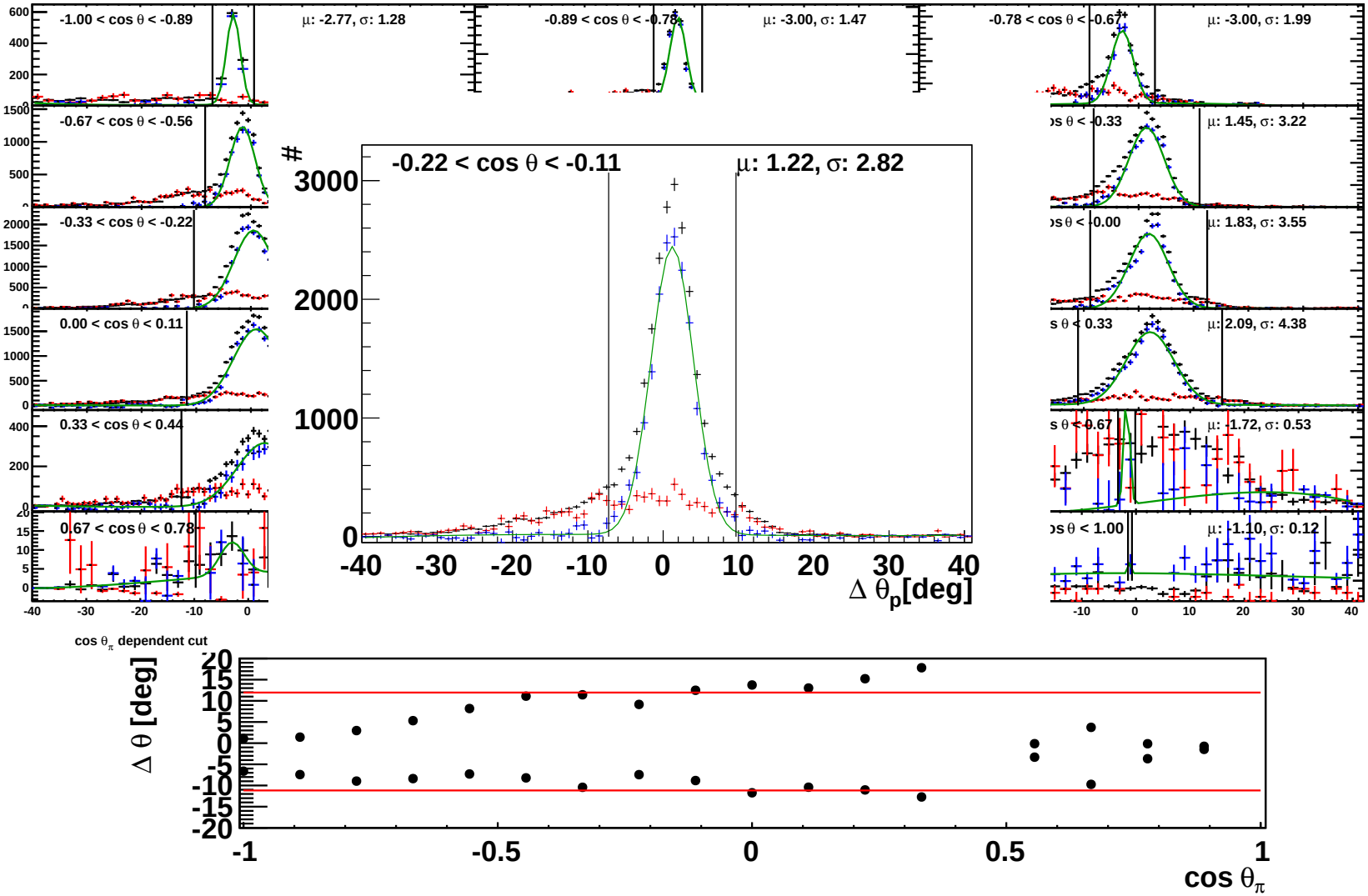




butanol — scaled carbon — reconstructed hydrogen — fit function

Appendix

$\cos\theta_\pi$ dependent selection - Theta for $E_\gamma = (464 - 497)$ MeV



— butanol — scaled carbon — reconstructed hydrogen — fit function

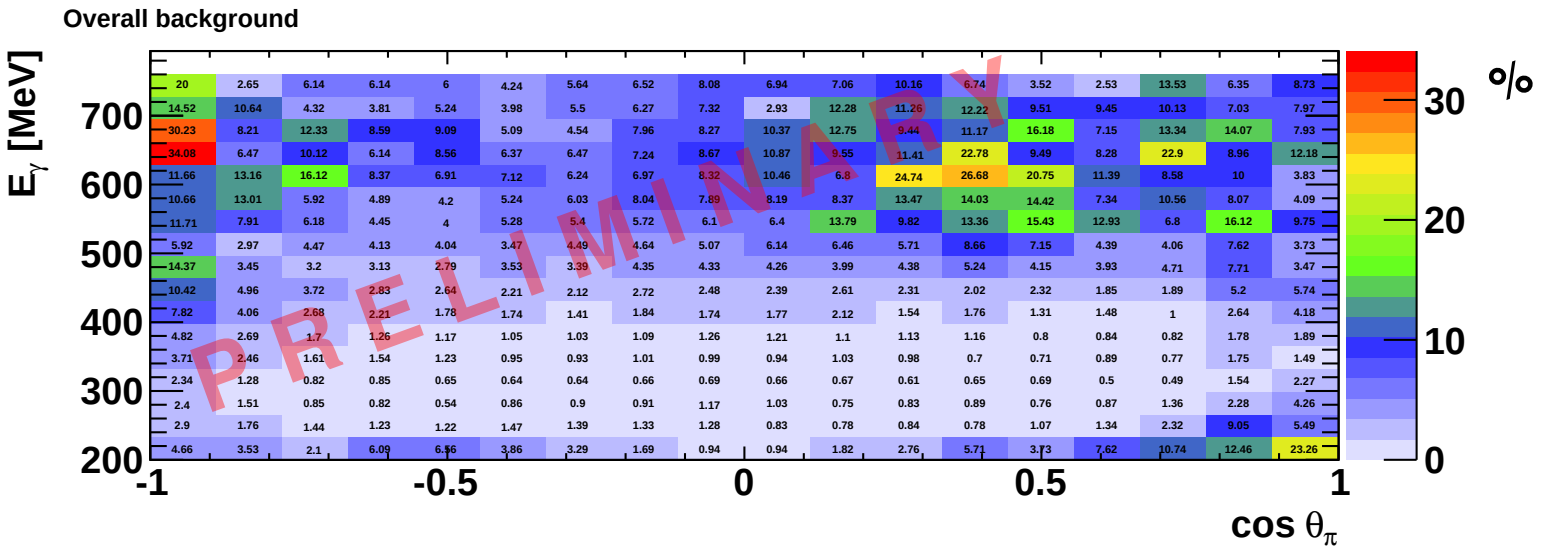
Appendix

Selected events

edge [MeV]	event class 1 [$\times 10^6$]	event class 2 [$\times 10^4$]
350	2.5	9.66
450	1.7	56.43
550	0.54	36.67
660	0.13	15.14
750	0.05	7.96

For eventclass 1 rougly **4.92** $\times 10^6$ and for event class 2 rougly **1.26** $\times 10^6$ reconstructed hydrogen events!

amount of background in event class 1



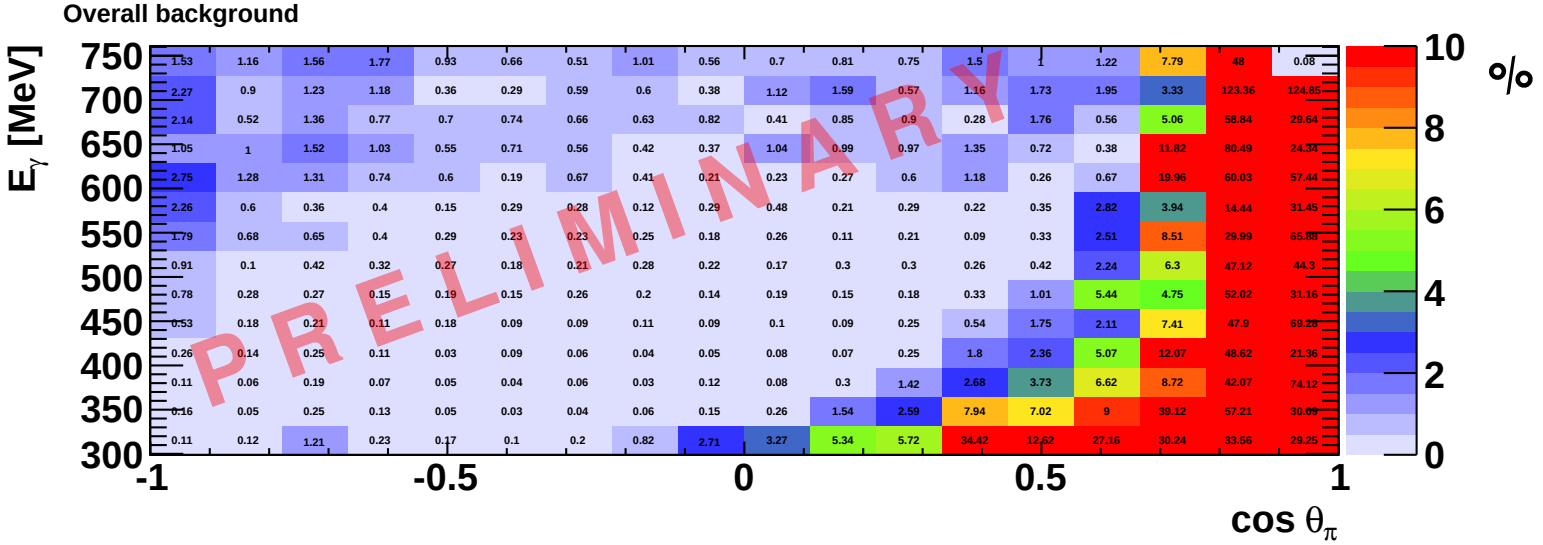
Appendix

Selected events

edge [MeV]	event class 1 [$\times 10^6$]	event class 2 [$\times 10^4$]
350	2.5	9.66
450	1.7	56.43
550	0.54	36.67
660	0.13	15.14
750	0.05	7.96

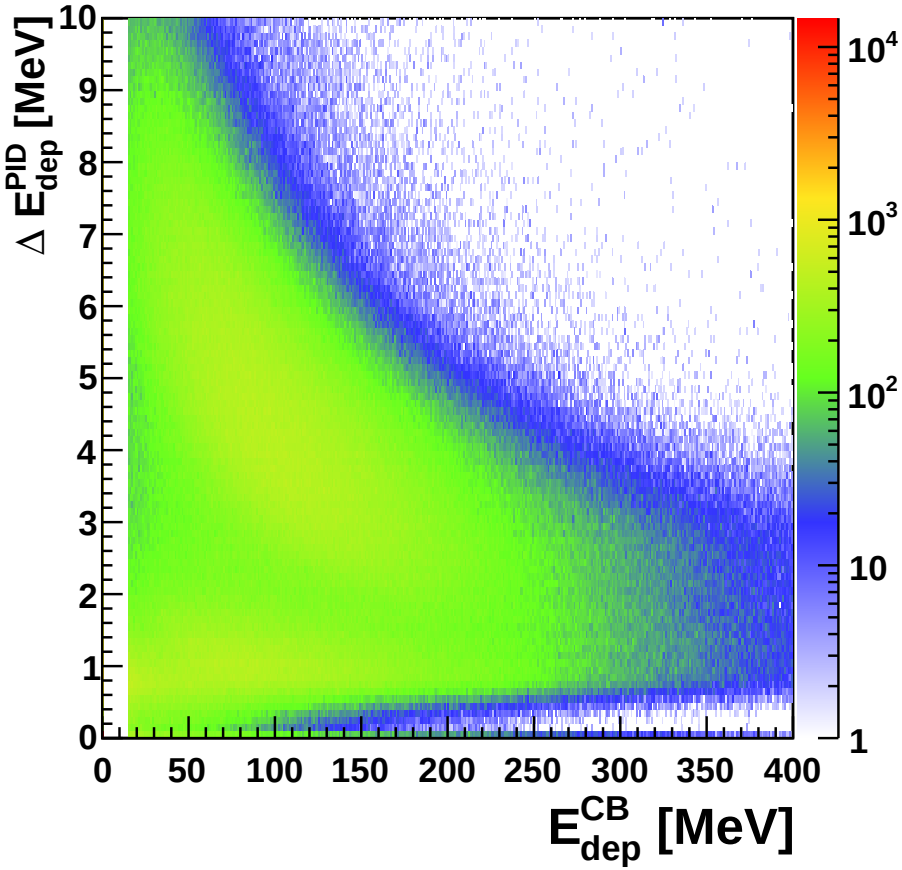
For eventclass 1 rougly **4.92** $\times 10^6$ and for event class 2 rougly **1.26** $\times 10^6$ reconstructed hydrogen events!

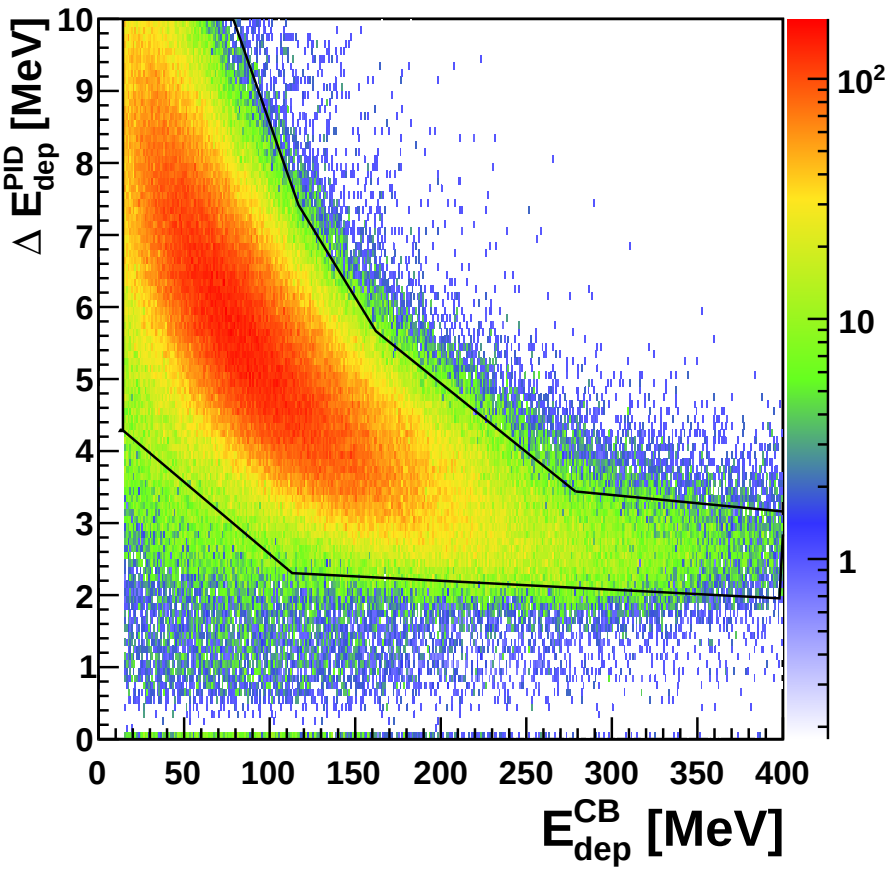
amount of background in event class 2



Appendix

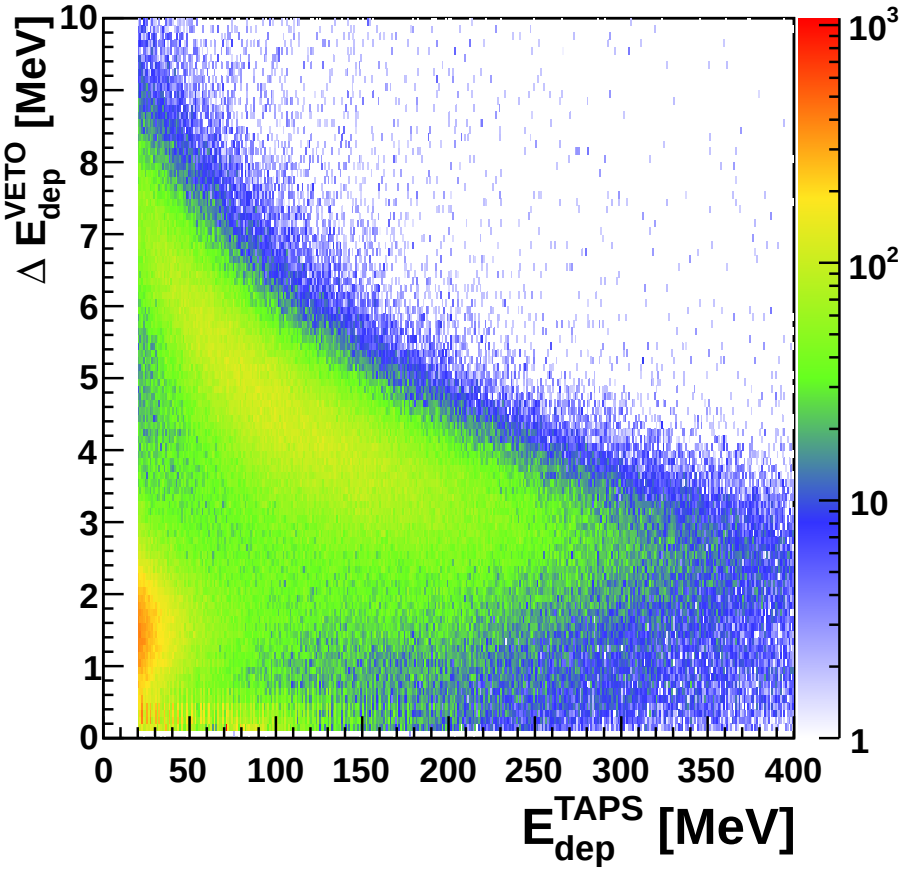
dE over E cuts (CB and PID) -Additional cuts

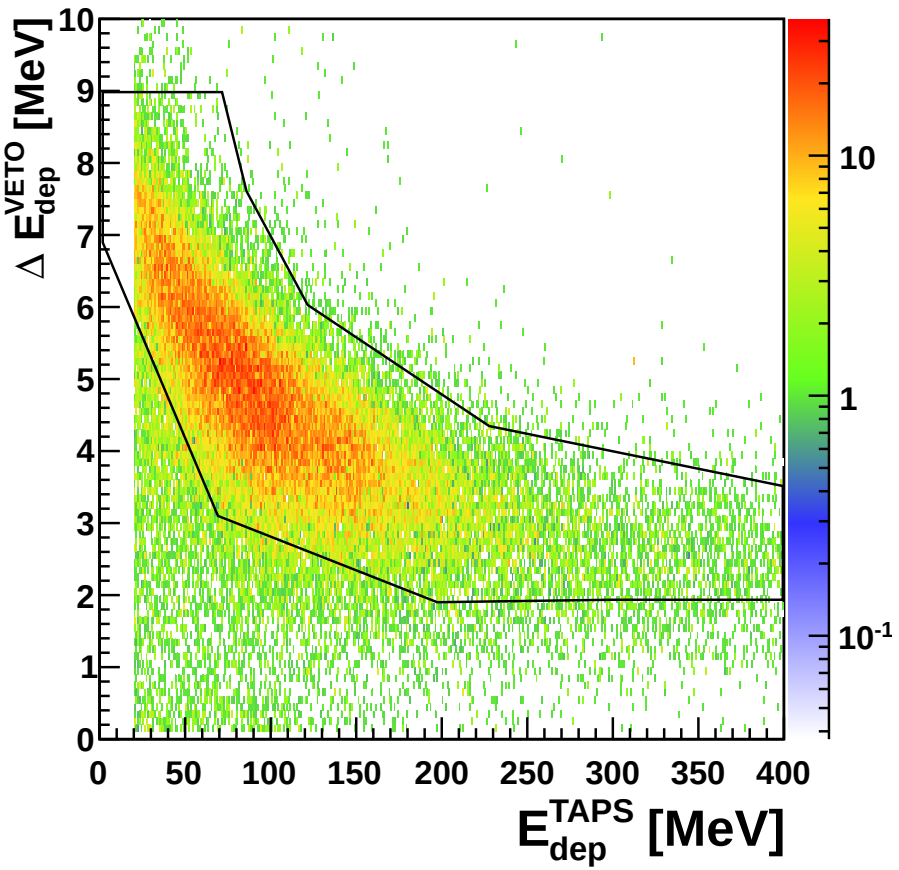




Appendix

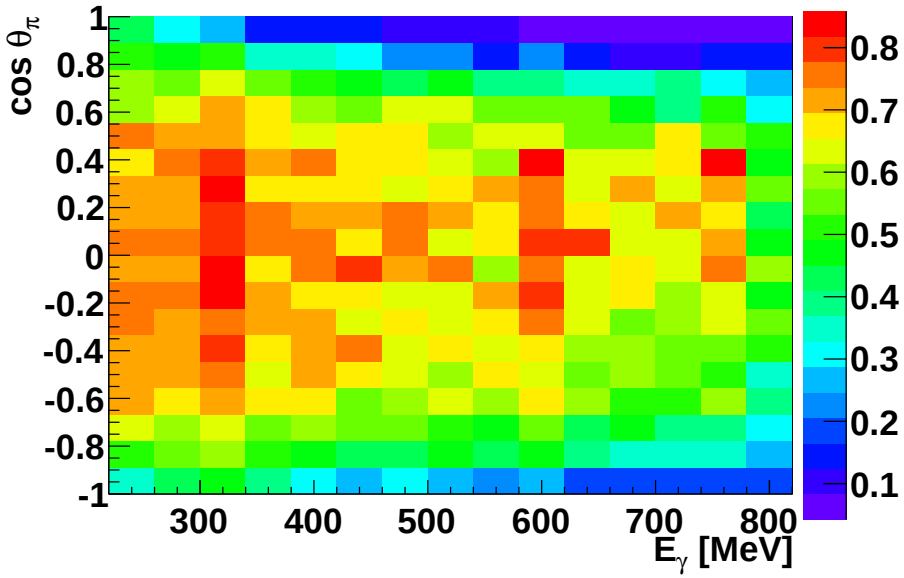
dE over E cuts (TAPS and VETOs) -Additional cuts

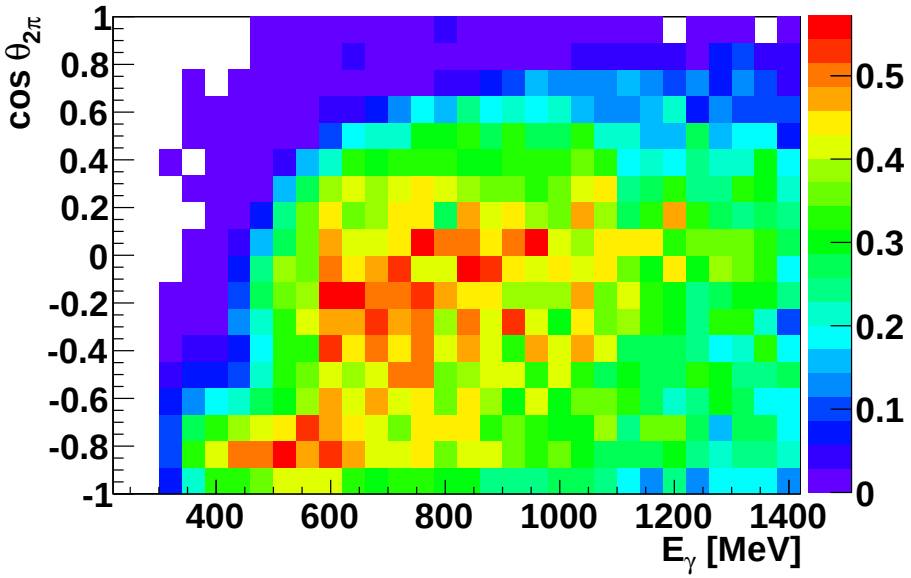




Appendix

Acceptance ϵ





$$\epsilon = \frac{N_{rec}}{N_{gen}}\left(\cos\theta_\pi, E_\gamma\right)$$

Appendix

Determination through differences

- Different settings can be combined in such a way that only terms including Σ_B or G remain

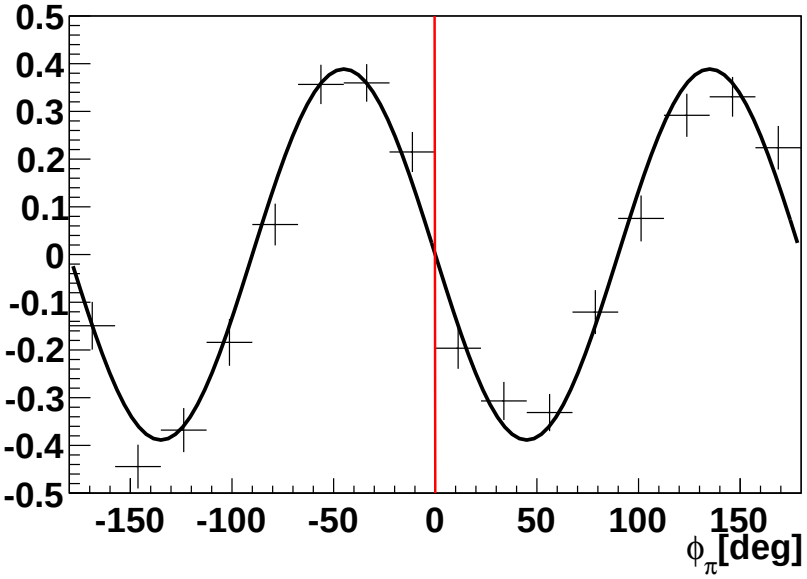
$\rightarrow$ $f(\theta, \phi) = A \sin 2\phi$ with $A = -\delta_l \Sigma_B$

$\rightarrow$ $g(\theta, \phi) = B \cos 2\phi$ with $B = D\delta_l \Lambda_z G$

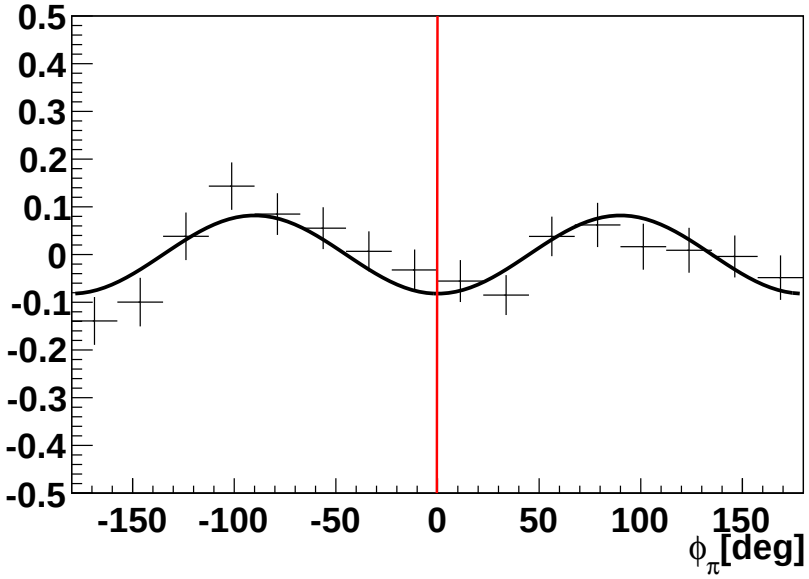
Combination of ϕ-asymmetries for different settings

E_γ = (464-497) MeV and $-0.22 < \cos\theta_\pi \leq -0.11$

ϕ-asymmetry for Σ_B



ϕ-asymmetry for G

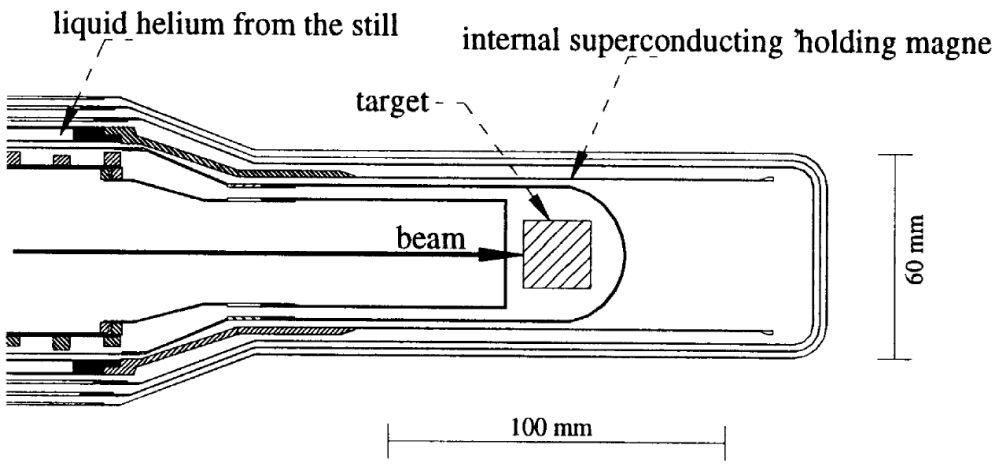


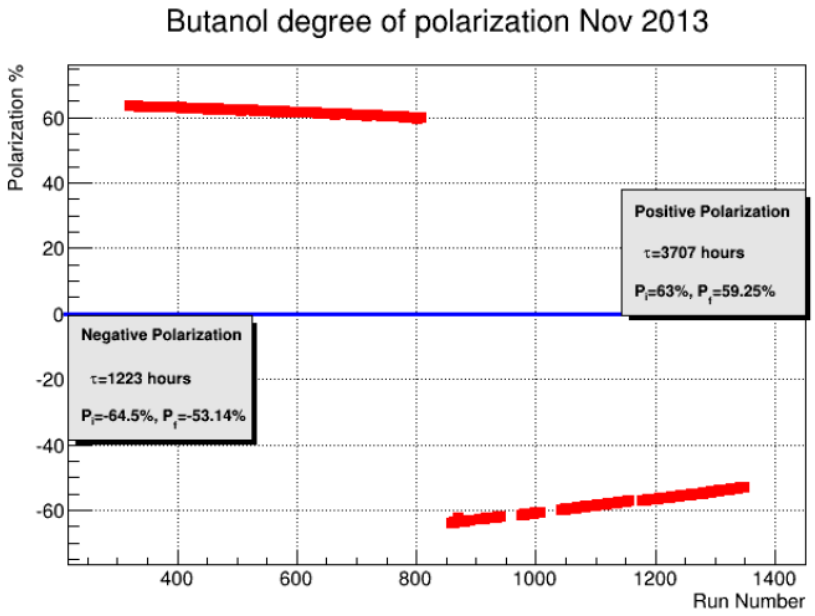
Appendix

Frozen-spin butanol target

Dynamic Nuclear Polarization

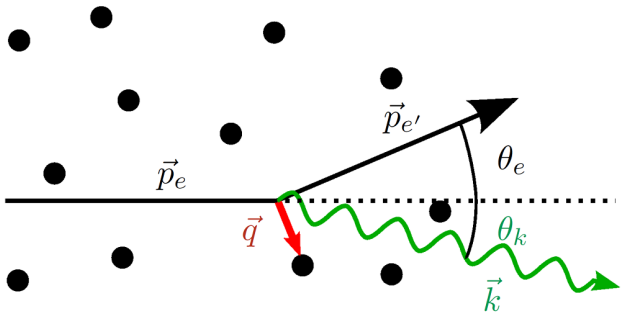
1. butanol target is doped with paramagnetic radicals
2. electrons polarized with a 2.5 T magnetic field at a temperature of 1K
3. electron polarization can be transferred to the nucleons by microwave irradiation
4. ”freeze” the spin ($\approx 25mK$) and combine it with a holding coil $\rightarrow$ long relaxation time

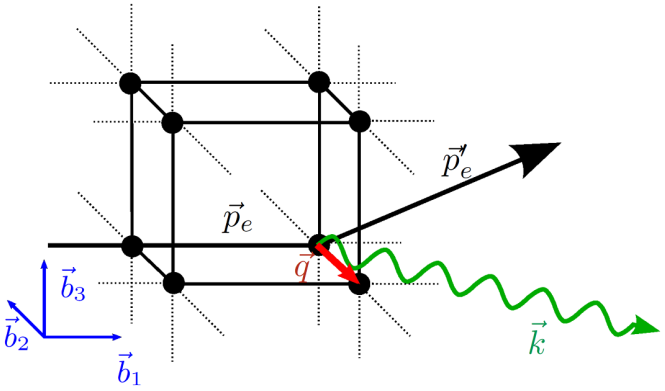


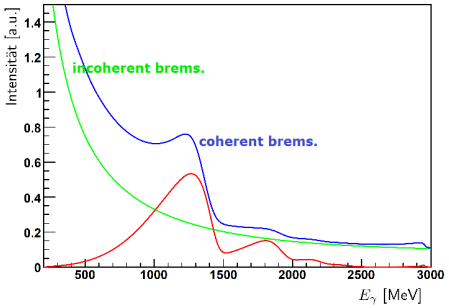


Appendix

Linearly polarized photons



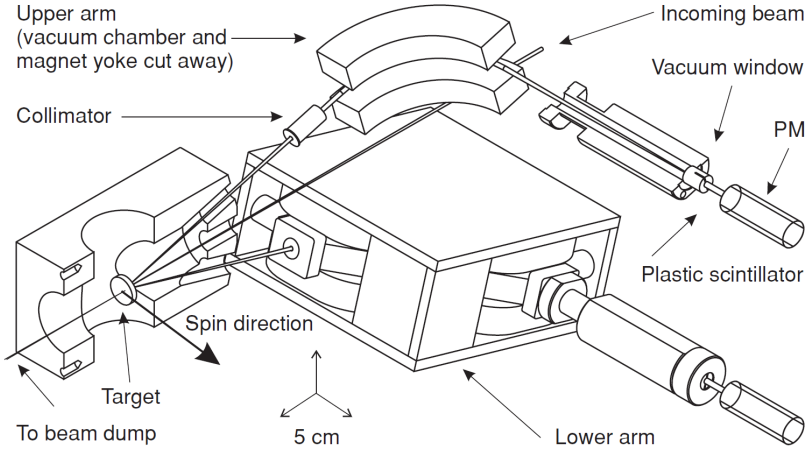


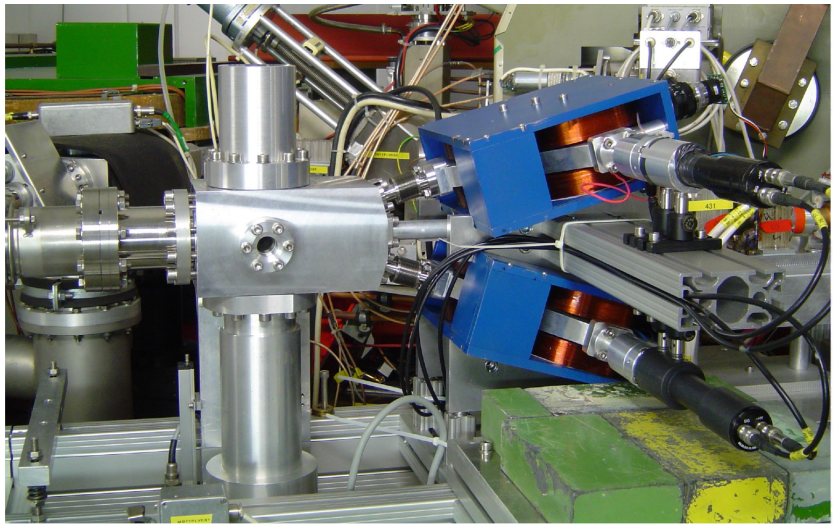


- Incoherent bremsstrahlung: only one single atom of the crystal absorbs the recoiling momentum $\vec{q}$ $\rightarrow$ no preferred plane between incoming electron and outgoing photon $\rightarrow$ no favored orientation of the electric field vector of the photon $\rightarrow$ no polarized photons
- Coherent bremsstrahlung: if $\vec{q} = n\vec{g}$ with $\vec{g} = \sum_{i=1}^{3} \vec{b}_i \cdot h_i$ $\rightarrow$ single atoms can interfere constructively! $\rightarrow$ preferred plane between incoming electron and outgoing photon $\rightarrow$ orientation of the field vector of the photon $\rightarrow$ polarized photons

Appendix

Circularly polarized photons

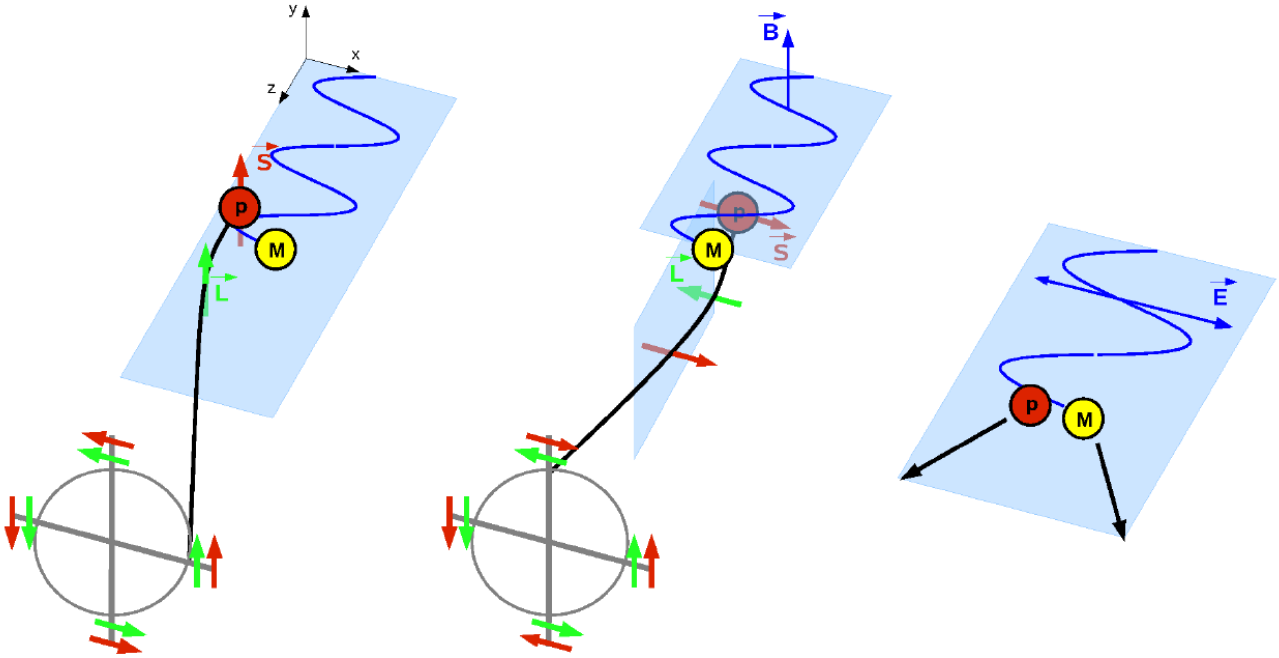




- Mott-scattering: electrons in gold (Z=79) interact via spin-orbit coupling with the longitudinally polarized electrons from MAMI $\rightarrow$ asymmetry in backscattering! $\rightarrow$ polarization degree of electrons
- helicity transfer from electrons to photons $\rightarrow$ circularly polarized photons

Appendix

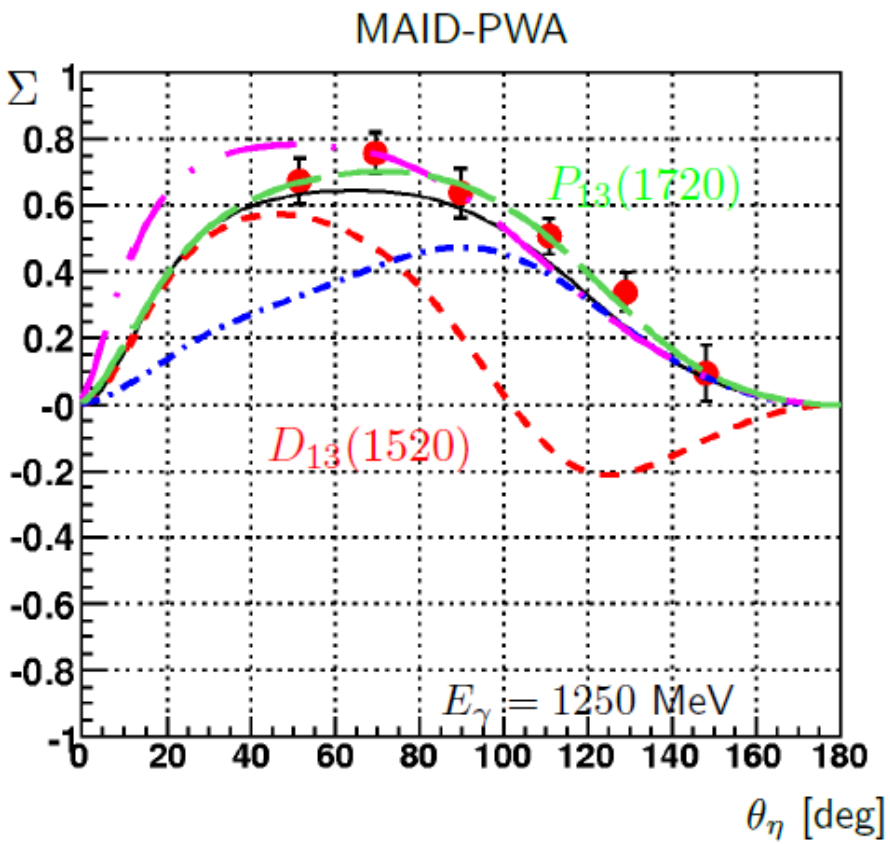
Illustrative presentation of the beam asymmetry Σ

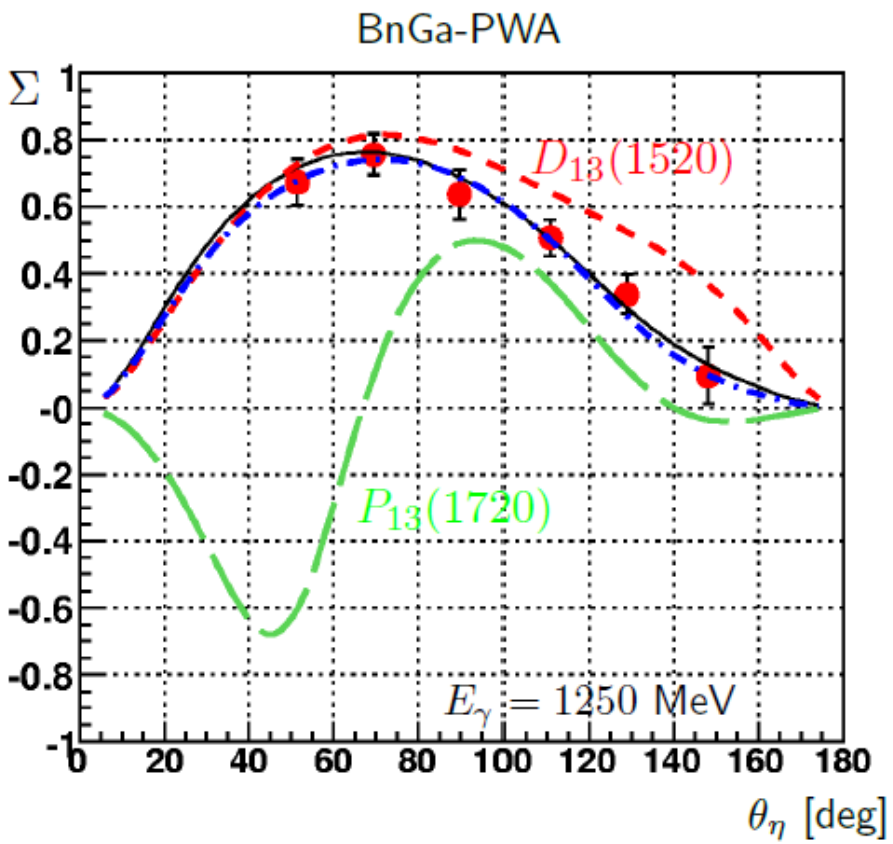


$\vec{L}$ = orbital angular momentum of baryon (B) and meson (M)
$\vec{S}$ = spin of baryon
$\vec{E}$ = electric field
$\vec{B}$ = magnetic field

Appendix

Ambiguity studies - Comparison MAID- and BnGA-PWA

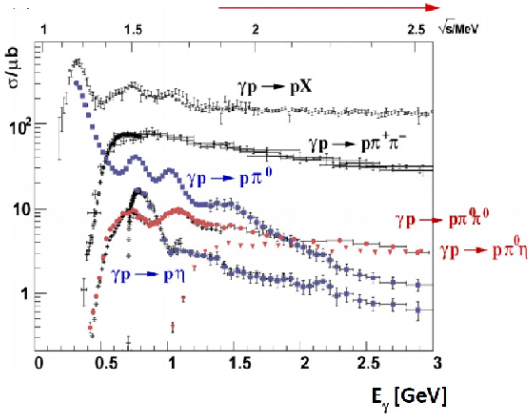


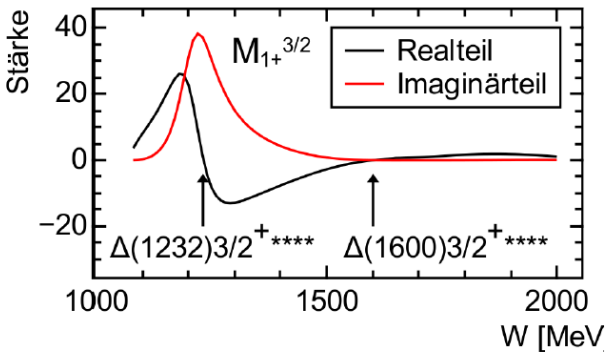


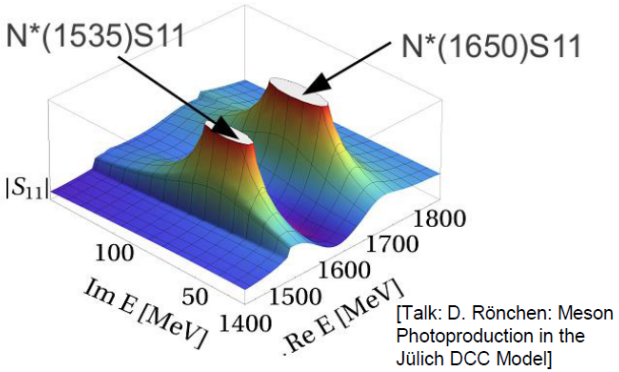
overall solution, without $P_{11}(1770)$, without $D_{15}(1560)$

Appendix

Resonances







[Talk: D. Rönchen: Meson Photoproduction in the Jülich DCC Model]

1. bump in the cross section
2. maximum in imaginary part of the multipole and zero-crossing in real part! (Problem: not unambiguous due to background)
3. **Solution:** scattering amplitude solution can be expanded into the complex energy plane
   - $E \rightarrow E = E_R + E_I$
   - ”mass” of a resonance = real part of the pole position
   - ”width” of a resonance = imaginary part via $\Gamma = -2ImE$