Exploring Polarization Variables in Two-Pion Photoproduction: Insights from the CLAS Experiment

Alessandra Filippi
INFN Torino, Italy

Istituto Nazionale di Fisica Nucleare

NSTAR24

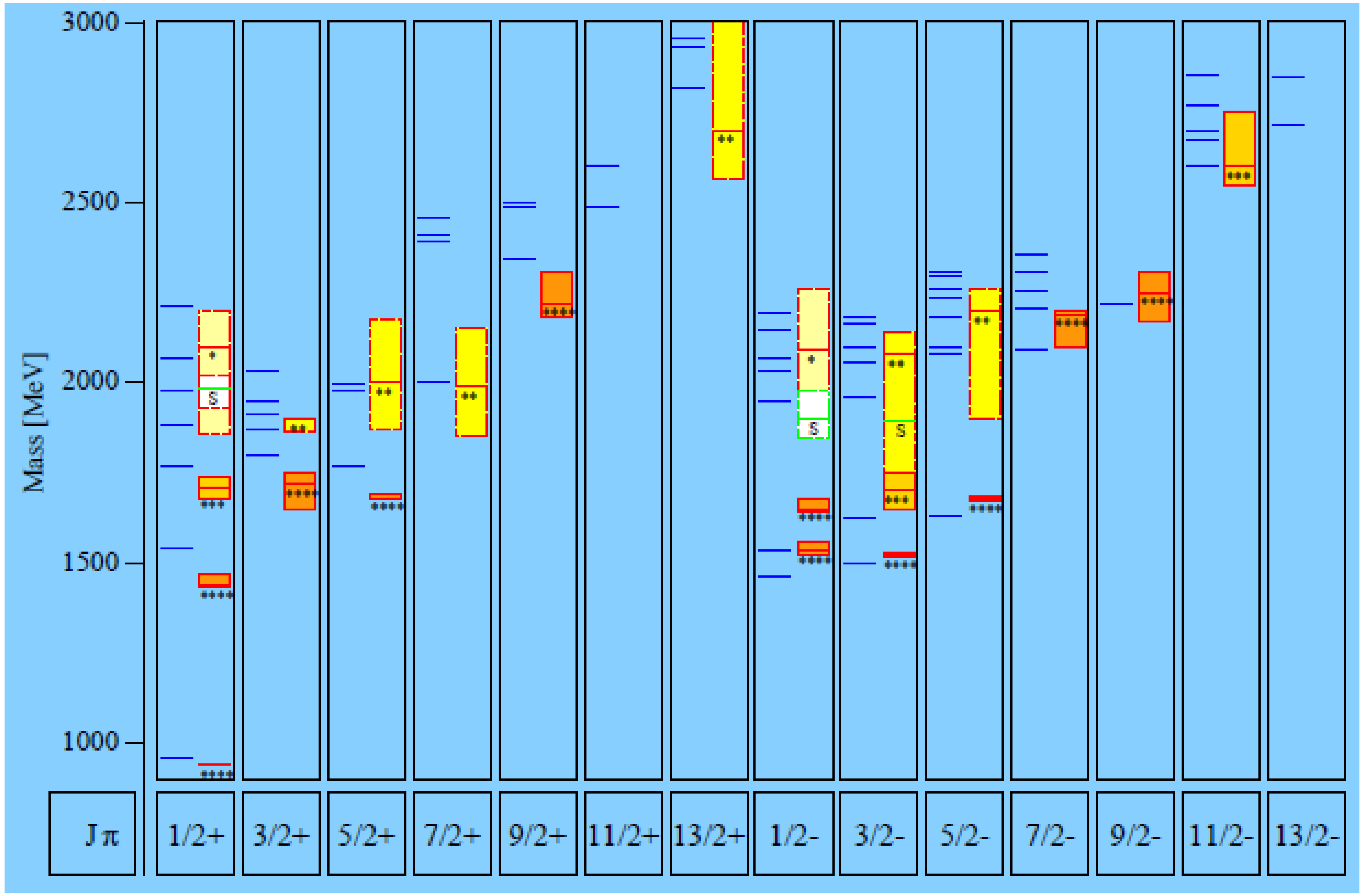
14th International Workshop on the Physics of Excited Nucleons

York, UK, June 20, 2024

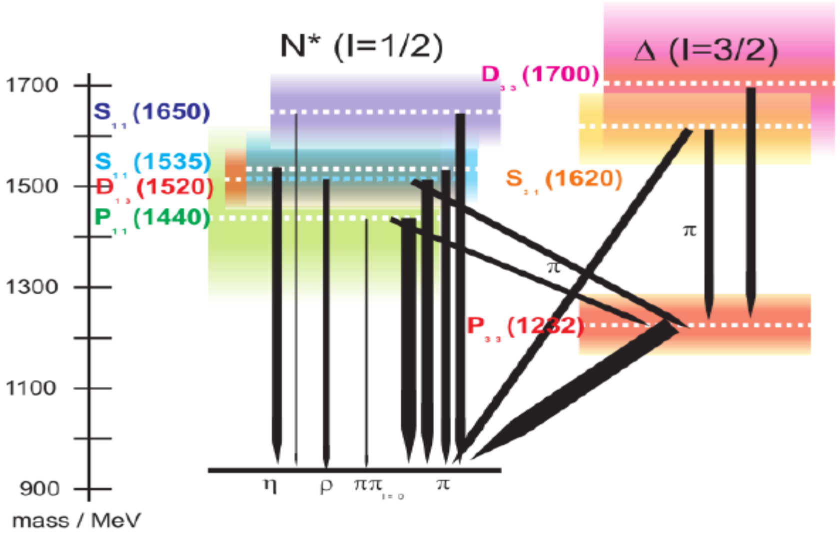
The light baryon (N*, Δ) spectrum in the Constituent Quark Model

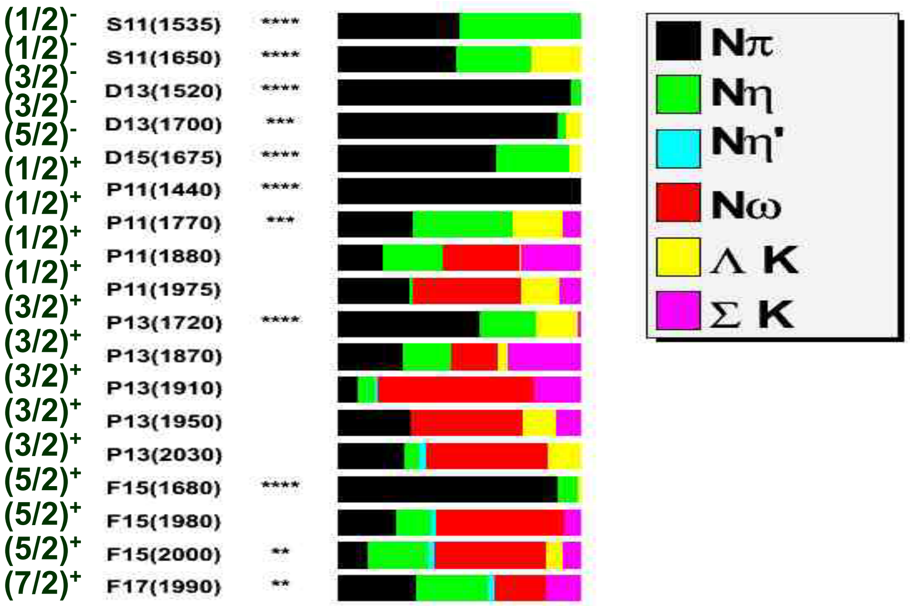
- Quarks confined into colorless hadrons

- Description by first principle QCD and constituent Quark Models:
  - Blue lines: expected states
  - Yellow/orange boxes: observations



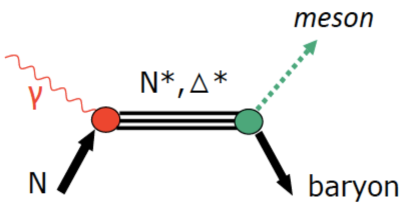
The light baryon spectrum: experimental status





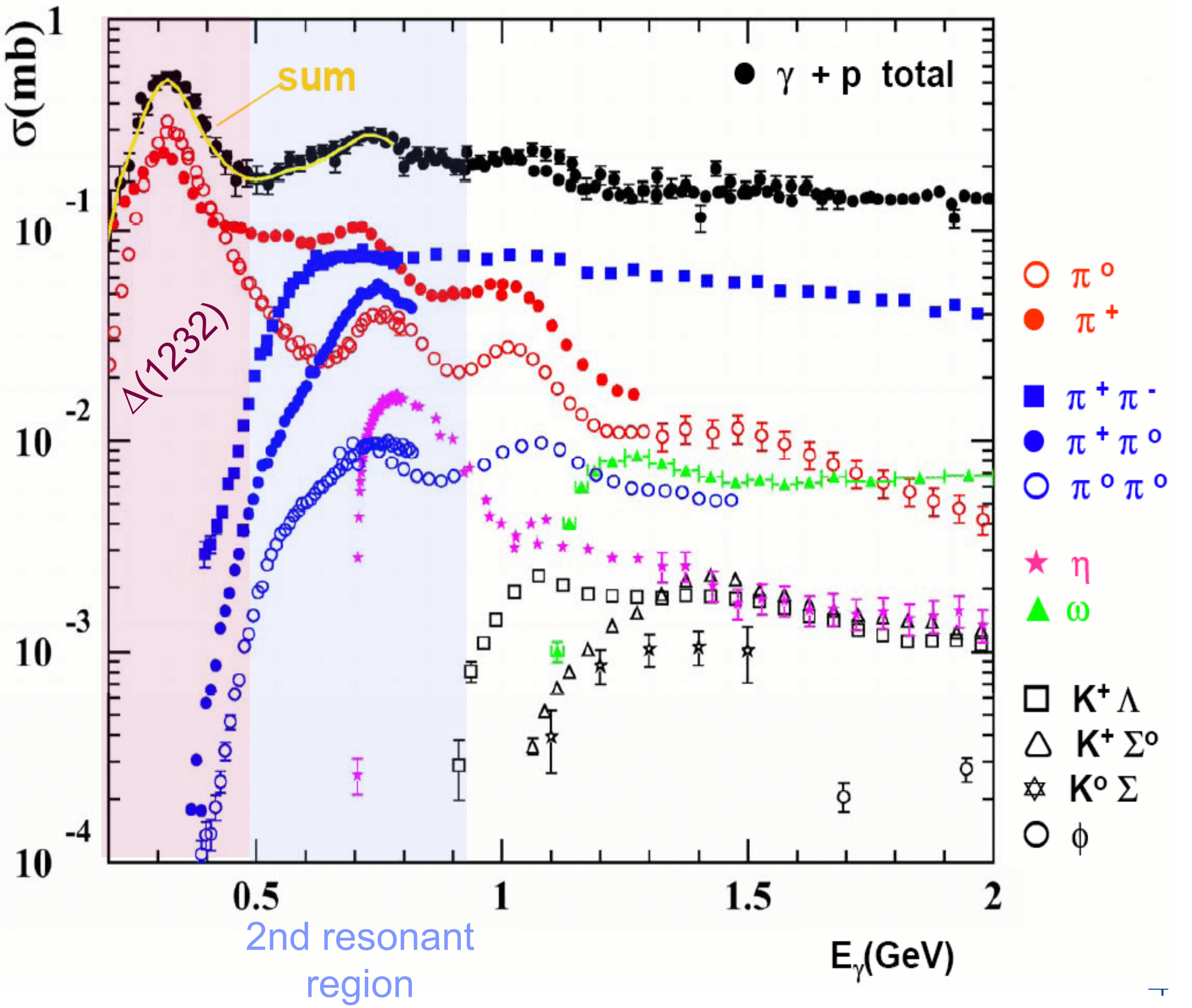
- Lowest lying N* and Δ* resonances
  - 1.3-2 GeV mass range: second resonant region
  - Overlapping states in the same mass region
  - Broad widths (short lifetimes)
  - Shared decay modes
- Most of the available information from pion/kaon beams experiments
  - Missing states: too small couplings with mesons
- How to disentangle each signal and spot missing resonances?
  - Difficult task if based only on the measurement of cross-sections
  - Use new approaches: analysis of polarization observables (additional information: spin)
  - Perform precision measurements in as many reactions as possible

N*/Δ* in photoproduction reactions



- Photon induced reaction could favor the formation of missing resonances which might couple strongly to the γN vertex
- γ reactions not studied extensively in the past - lack of good enough (energy/intensity) photon beams
- Dominant contributions to the “second resonant region”: double-pion and η channels
  - Double-pion photoproduction: good tool to investigate this mass region

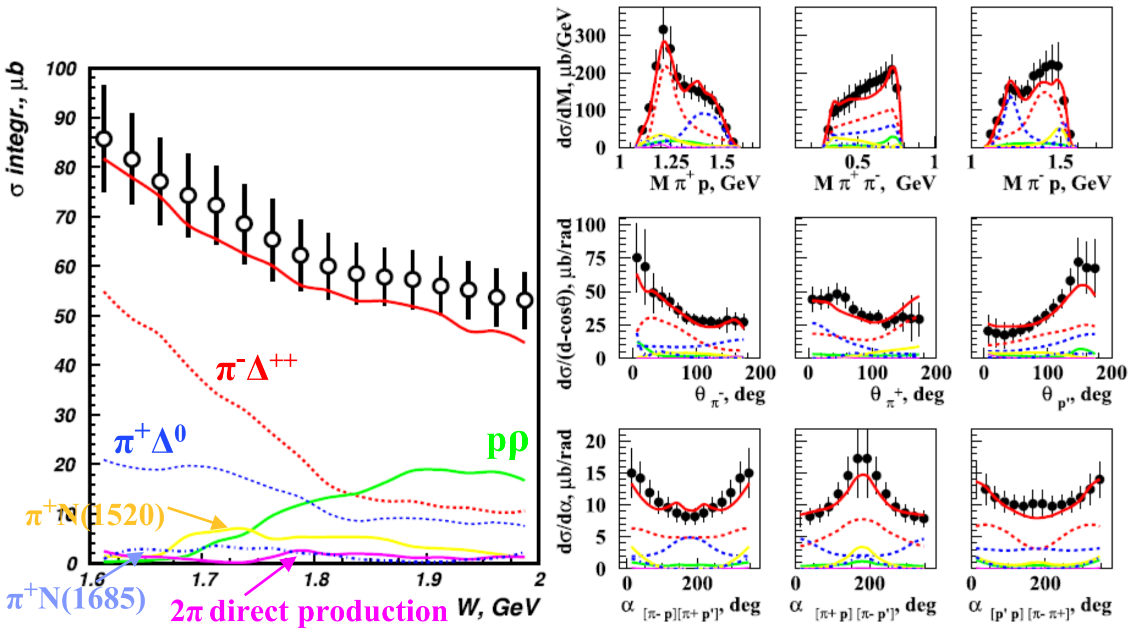
Photonuclear cross sections

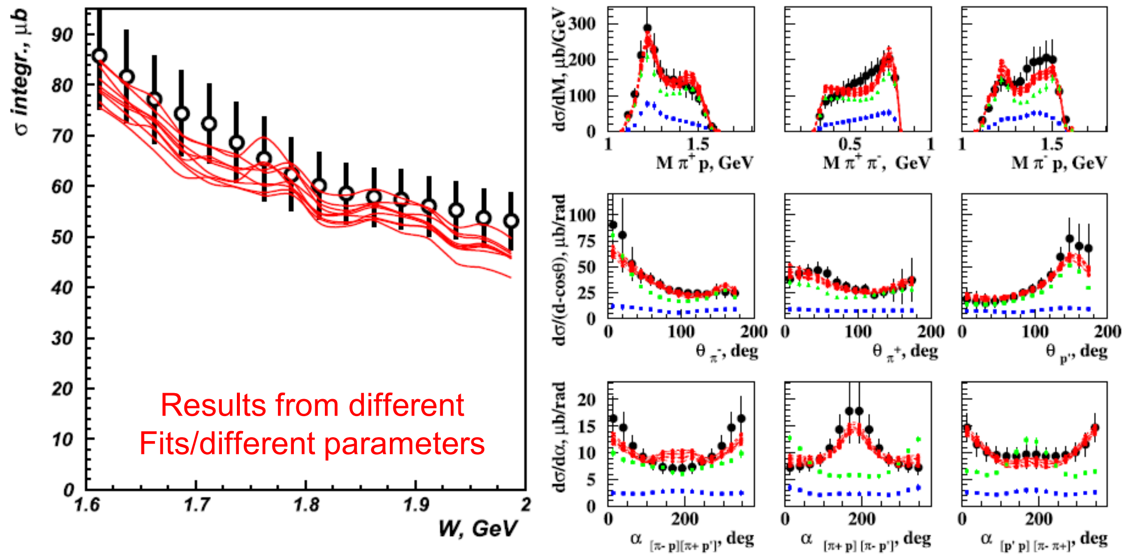


Photoproduction of $\pi^+\pi^-$ pairs off protons (unpolarized)

E. Golovatch (CLAS) PL B788 (2019), 371

- Measurement of 9x 1-fold differential cross sections of the $\gamma p \to \pi^+\pi^- p$ reaction in the (1.6, 2) GeV range
- Attempt to reproduce the cross-sections using the JM17 meson-baryon reaction model
  - Reasonable description
  - A PWA fit provides the intermediate resonances contributions & parameters
    - Intermediate channels: $\pi^-\Delta^{++}$, $\pi^+\Delta^0$, $p\rho^0$, $\pi^-\pi^+p$ direct production, $\pi^+N(1530)$ $3/2^-$, $\pi^+N(1685)$ $5/2^+$
    - Extraction of masses, widths, photocouplings
    - (new) Excited states required in the model:
      - **N(1440) 1/2⁺**, **N(1520) 3/2⁻**, N(1535) 1/2⁻, N(1650) 1/2⁻, N(1680) 5/2⁻, N'(1720) 3/2⁺, **N(2190) 7/2⁻**
      - **Δ(1620) 1/2⁻**, Δ(1700) 3/2⁻, Δ(1905) 5/2⁺, Δ(1950) 7/2⁺





Photoproduction of $\pi^+\pi^-$ pairs from protons with circularly polarized beam

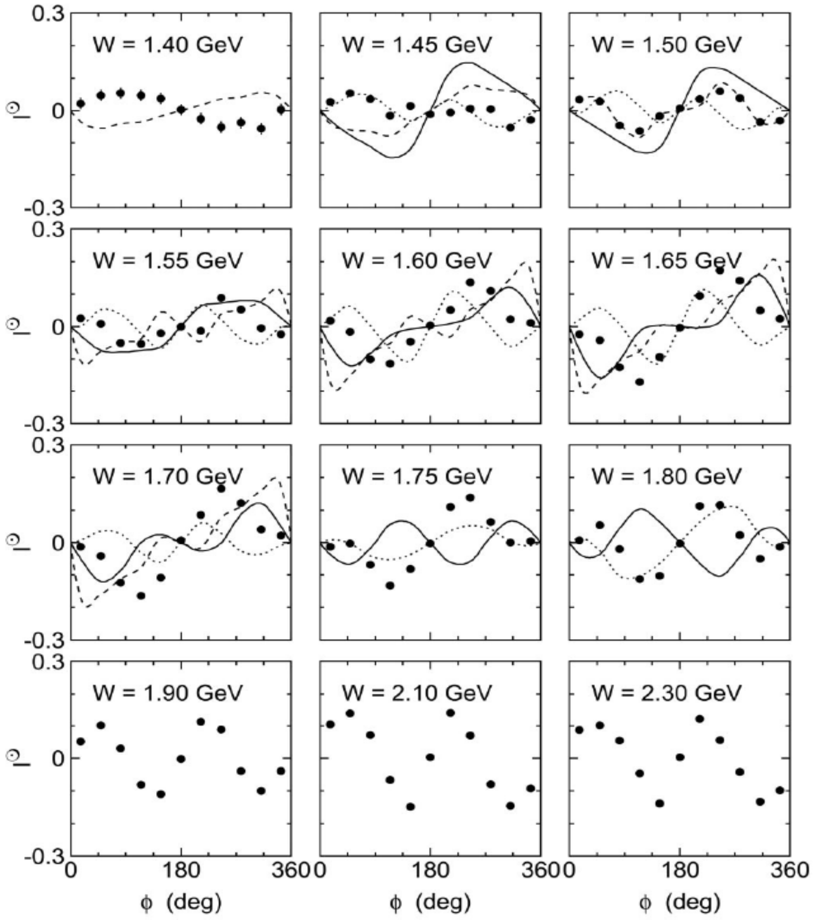
S. Strauch et al. (CLAS) PLR95 (2005), 162003

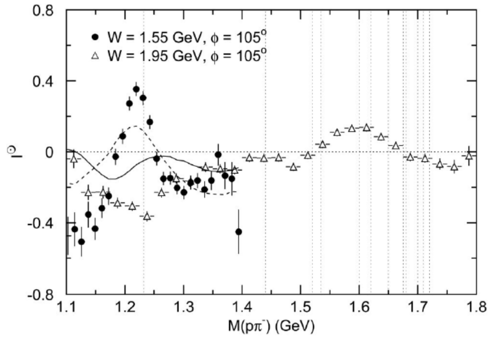
- CLAS data: 1.35 < W < 2.30 GeV
  - Missing resonances predicted to lie in the region W > 1.8 GeV

- Circularly polarized photon beam, no polarization specified for target and recoil proton
- First measurement of beam-helicity asymmetry distributions as a function of the helicity angle:

$$I^{\odot} = \frac{1}{P_\gamma}\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

  - Odd trend in all W sub-ranges
  - Compared with models based on electroproduction of double-charged pions including a set of quasi-two body intermediate states (Mokeev et al.):
    - *πΔ, ρN, πN(1520), πN(1680)* + contributions from *Δ(1600), N(1700), N(1710), N(1720)*
    - The agreement is not satisfactory, calls for a more detailed description
    - The $I^{\odot}$ observable is critically sensitive to interferences

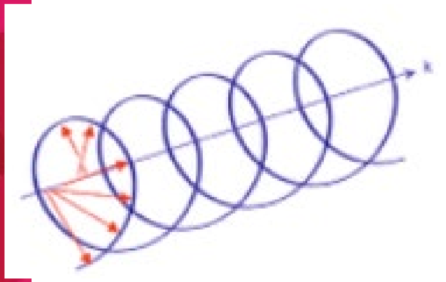




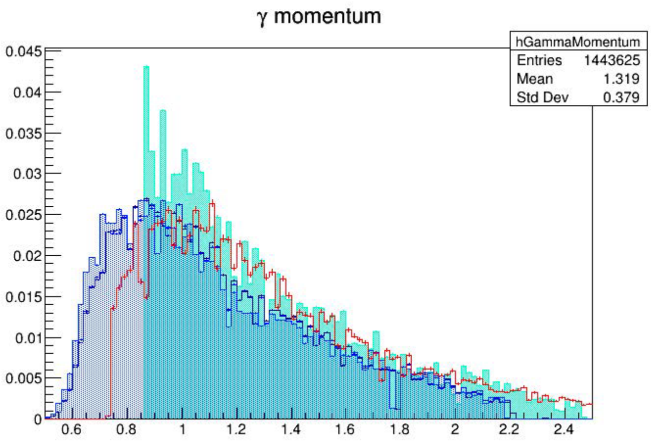
Experimental method – polarized beam and target

- CLAS-g14 data taking (2011-2012): *circularly polarized* photon beam with momentum up to 2.5 GeV/c interacting on a cryogenic HD *longitudinally* polarized target

- **Beam:** circularly polarized photons by bremsstrahlung from a longitudinally polarized electron beam (>85%) through a gold foil radiator
  - Circular: ↑/↓ (960 Hz flip frequency)
  - Energy dependent γ polarization

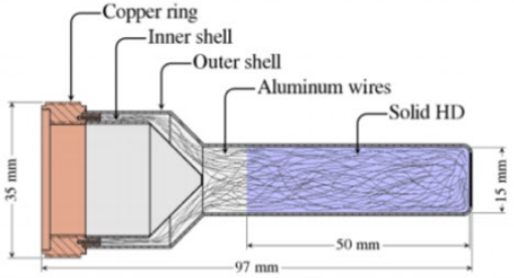


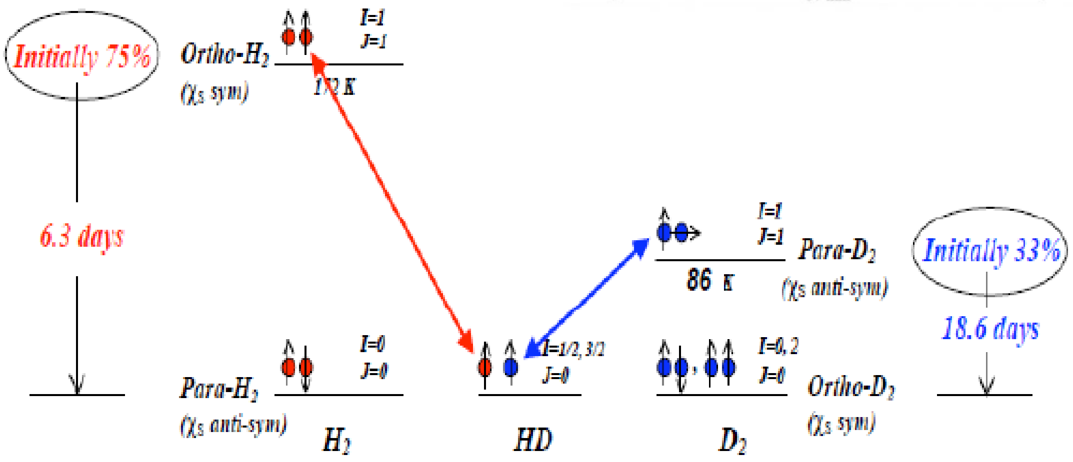
$$x = \frac{E_\gamma}{E_{beam}}$$



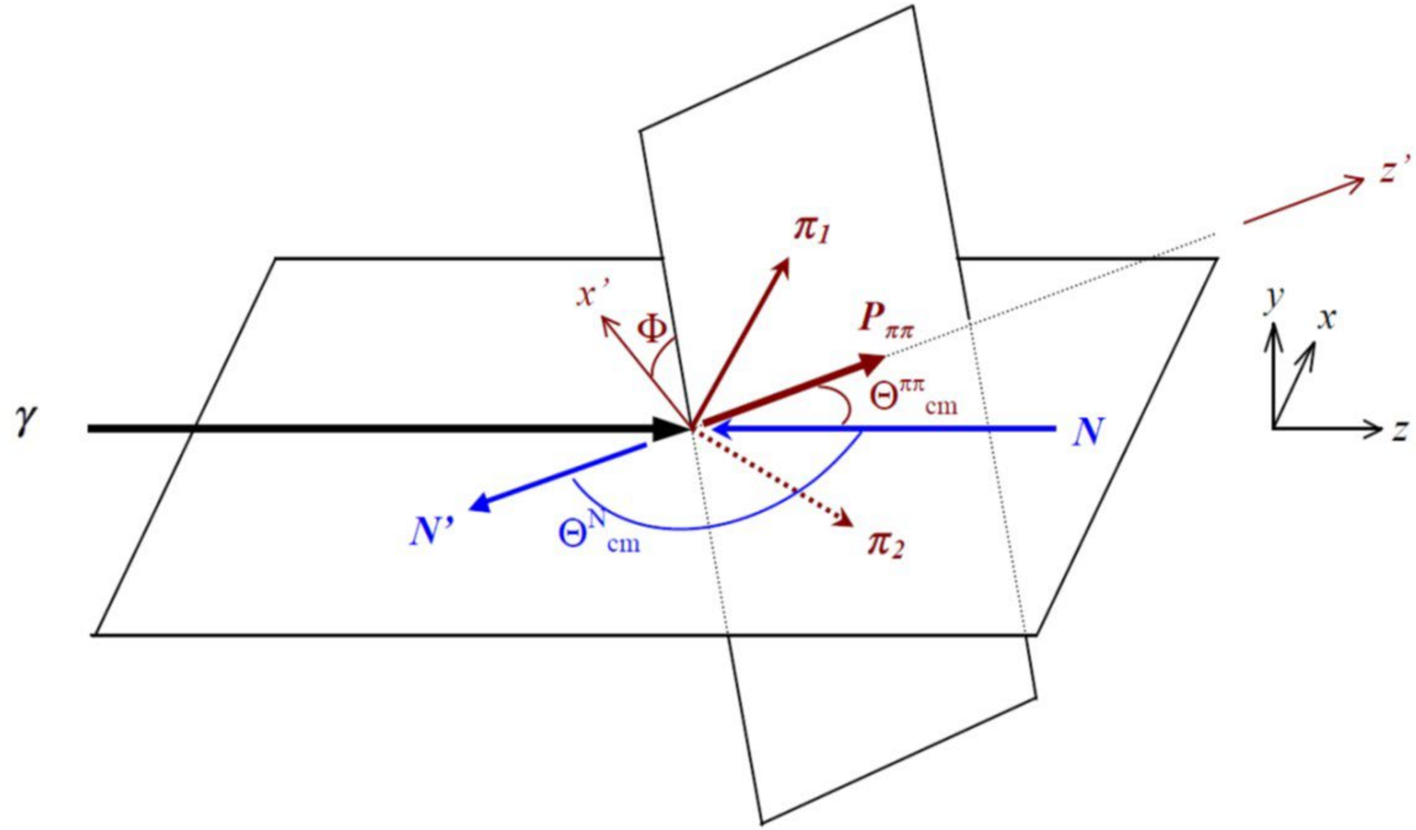
$$\delta_\odot = P_{el}\frac{4x - x^2}{4 - 4x + 3x^2}$$

- **Target:** "brute-force + aging" polarization method (< 30%)
  - Longitudinal (along beam direction): ⇒/⇐
  - Fixed in different data-sets
  - Protons + neutrons





Study of polarization observables in the $\vec{\gamma}\vec{N} \rightarrow \pi^+\pi^-N$ reaction



$$\frac{d\sigma}{dx_i} = \sigma_0\{(1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_\odot(\mathbf{I}^\odot + \Lambda_z \cdot \mathbf{P}_z^\odot)\}$$

- Differential cross-section expressed as a function of polarization observables, weighted by the amount of beam $\delta_\odot$ and/or target Λ polarization
- The trend of the polarization observables depends on the resonance content in a given energy range
- **Polarization observables are bilinear combinations of partial amplitudes** (Roberts, Oed PRC71 (2005), 0552001): **very sensitive to interference effects**

Polarization observables extraction

Problem: extract from the number of collected events the $I^{\odot}$, P, $P^{\odot}$ observables as a function of the Φ azimuthal angle in the helicity reference system, in W energy ranges

$$P_z = \frac{1}{\Lambda_z} \frac{[N(\rightarrow\Rightarrow) + N(\leftarrow\Rightarrow)] - [N(\rightarrow\Leftarrow) + N(\leftarrow\Leftarrow)]}{[N(\rightarrow\Rightarrow) + N(\leftarrow\Rightarrow)] + [N(\rightarrow\Leftarrow) + N(\leftarrow\Leftarrow)]}$$

$$I^{\odot} = \frac{1}{\delta_{\odot}} \frac{[N(\rightarrow\Rightarrow) + N(\rightarrow\Leftarrow)] - [N(\leftarrow\Rightarrow) + N(\leftarrow\Leftarrow)]}{[N(\rightarrow\Rightarrow) + N(\rightarrow\Leftarrow)] + [N(\leftarrow\Rightarrow) + N(\leftarrow\Leftarrow)]}$$

$$P_z^{\odot} = \frac{1}{\Lambda_z \delta_{\odot}} \frac{[N(\rightarrow\Rightarrow) + N(\leftarrow\Leftarrow)] - [N(\rightarrow\Leftarrow) + N(\leftarrow\Rightarrow)]}{[N(\rightarrow\Rightarrow) + N(\leftarrow\Leftarrow)] + [N(\rightarrow\Leftarrow) + N(\leftarrow\Rightarrow)]}$$

- Related to differential cross-section asymmetries
- Depending on the relative beam/target spin configurations
- Two data sets with opposite target ($\Rightarrow$/$\Leftarrow$) polarizations needed (with proper normalization)
- Each data-set contains both helicities

Polarization asymmetries in φ_{hel} bins

$$\frac{d\sigma}{dx_i} = \sigma_0\{(1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_\odot(\mathbf{I}^\odot + \Lambda_z \cdot \mathbf{P}_z^\odot)\}$$

- This equation (Roberts et al., PRC 718(2005), 055201) can be split in four depending on the orientation of beam helicity and target polarization (along z)
- Two data sets with opposite target polarization need to be used (properly normalized)
- The system of equations can be solved analytically extracting, in every φ bin, $I^\odot$, P_z, $P^\odot{}_z$ and σ_0

$$N_{exp}^{\rightarrow\Rightarrow} = \left(\frac{d\sigma}{d\Omega}\right)_0 \mathsf{L}\,\varepsilon\left[1 + \Lambda_z P_z + \delta_\odot(I_\odot + \Lambda_z P_z^\odot)\right]$$

$$N_{exp}^{\leftarrow\Rightarrow} = \left(\frac{d\sigma}{d\Omega}\right)_0 \mathsf{L}\,\varepsilon\left[1 + \Lambda_z P_z - \delta_\odot(I_\odot + \Lambda_z P_z^\odot)\right]$$

$$N_{exp}^{\rightarrow\Leftarrow} = \left(\frac{d\sigma}{d\Omega}\right)_0 \mathsf{L}\,\varepsilon\left[1 - \Lambda_z P_z + \delta_\odot(I_\odot - \Lambda_z P_z^\odot)\right]$$

$$N_{exp}^{\leftarrow\Leftarrow} = \left(\frac{d\sigma}{d\Omega}\right)_0 \mathsf{L}\,\varepsilon\left[1 - \Lambda_z P_z - \delta_\odot(I_\odot - \Lambda_z P_z^\odot)\right]$$

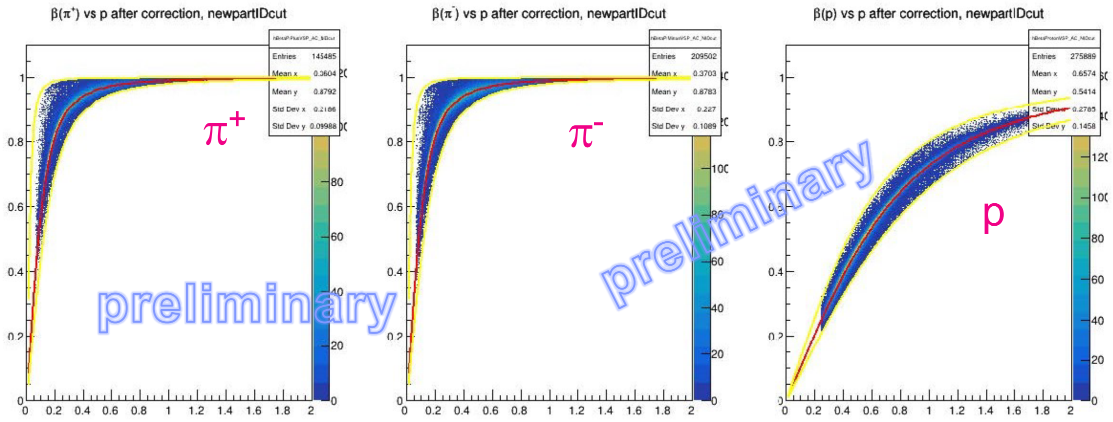
$$I_\odot = \frac{\frac{N_1^{\rightarrow\Rightarrow} - N_1^{\leftarrow\Rightarrow}}{\delta_{\odot 1}} + \frac{\Lambda_{z1}}{\Lambda_{z2}} \cdot \frac{\mathsf{L}_{eff1}}{\mathsf{L}_{eff2}} \cdot \frac{N_2^{\rightarrow\Leftarrow} - N_2^{\leftarrow\Leftarrow}}{\delta_{\odot 2}}}{(N_1^{\rightarrow\Rightarrow} + N_1^{\leftarrow\Rightarrow}) + \frac{\Lambda_{z1}}{\Lambda_{z2}} \cdot \frac{\mathsf{L}_{eff1}}{\mathsf{L}_{eff2}} (N_2^{\rightarrow\Leftarrow} + N_2^{\leftarrow\Leftarrow})}$$

$$P_z^\odot = \frac{1}{\Lambda_{z2}} \cdot \frac{\frac{N_1^{\rightarrow\Rightarrow} - N_1^{\leftarrow\Rightarrow}}{\delta_{\odot 1}} - \frac{\mathsf{L}_{eff1}}{\mathsf{L}_{eff2}} \cdot \frac{N_2^{\rightarrow\Leftarrow} - N_2^{\leftarrow\Leftarrow}}{\delta_{\odot 2}}}{(N_1^{\rightarrow\Rightarrow} + N_1^{\leftarrow\Rightarrow}) + \frac{\Lambda_{z1}}{\Lambda_{z2}} \cdot \frac{\mathsf{L}_{eff1}}{\mathsf{L}_{eff2}} (N_2^{\rightarrow\Leftarrow} + N_2^{\leftarrow\Leftarrow})}$$

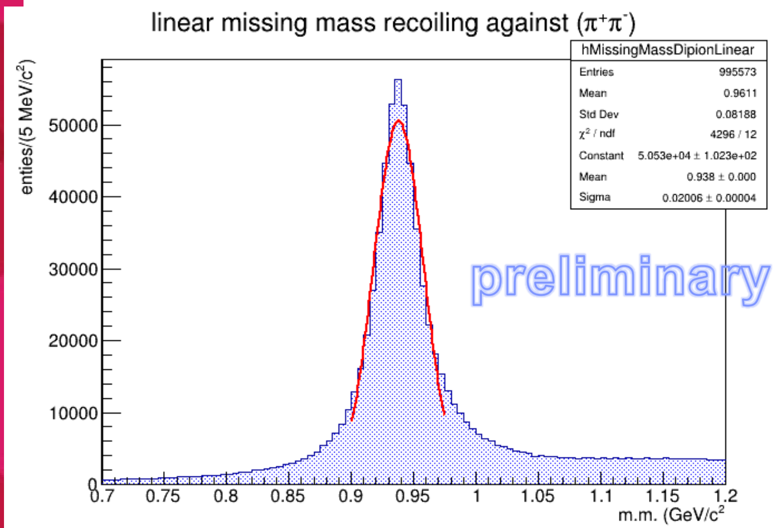
$$P_z = \frac{1}{\Lambda_{z2}} \cdot \frac{(N_1^{\rightarrow\Rightarrow} + N_1^{\leftarrow\Rightarrow}) - \frac{\mathsf{L}_{eff1}}{\mathsf{L}_{eff2}} \cdot (N_2^{\rightarrow\Leftarrow} + N_2^{\leftarrow\Leftarrow})}{(N_1^{\rightarrow\Rightarrow} + N_1^{\leftarrow\Rightarrow}) + \frac{\Lambda_{z1}}{\Lambda_{z2}} \cdot \frac{\mathsf{L}_{eff1}}{\mathsf{L}_{eff2}} (N_2^{\rightarrow\Leftarrow} + N_2^{\leftarrow\Leftarrow})}$$

Data selection – exclusive $\vec{\gamma}\vec{p} \rightarrow \pi^+\pi^- p$ reaction

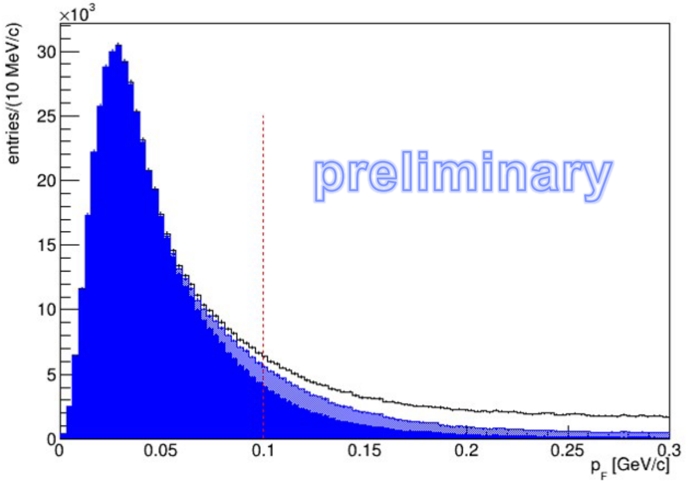
Description	Cut
Particle multiplicity	1 negative, 2 positives
Time coincidence	Time coincidence between: 1 proton, 1 π^+, 1 π^-
$2\pi p$ z-vertex in HD target	$-9.5 < z_{vertex} < -5.8$ cm
$2\pi p$ pId: β_{corr}	$p_{\pi^\pm}/\sqrt{p_{\pi^\pm m}^2 + (m_\pi - 80\ [\mathrm{MeV}])^2} \leq \beta_{\pi^\pm}^{corr} \leq p_{\pi^\pm}/\sqrt{p_{\pi^\pm}^2 + (m_\pi + 80\ [\mathrm{MeV}])^2}$ $p_p/\sqrt{p_p^2 + (m_p - 200\ [\mathrm{MeV}])^2} \leq \beta_p^{corr} \leq p_p/\sqrt{p_p^2 + (m_p + 200\ [\mathrm{MeV}])^2}$
$2\pi p$ pId: $\lvert\Delta\beta\rvert$	$\lvert\Delta(\beta_p)\rvert < 0.08$ $p_{\pi^\pm} \leq 500\ [\mathrm{MeV}/c]$: $\lvert\Delta(\beta_{\pi^\pm})\rvert < 0.08$ $p_{\pi^\pm} \geq 500\ [\mathrm{MeV}/c]$: $\lvert\Delta(\beta_{pi^\pm})\rvert < 0.2$
$2\pi p$ fiducial cuts	π^+ && π^- && p within fiducial volume
Missing mass for proton pId Total missing mass	$0.824 \leq \mathrm{m.m.}(\pi^+\pi^-) \leq 1.052\ [\mathrm{GeV}/c^2]$ $\mathrm{m.m.}(\pi^+\pi^- p) < 0\ [\mathrm{GeV}/c^2]$
Fermi momentum	$p_F < 100$ MeV/c
Coplanarity	$\lvert$coplanarity$\rvert < 10°$



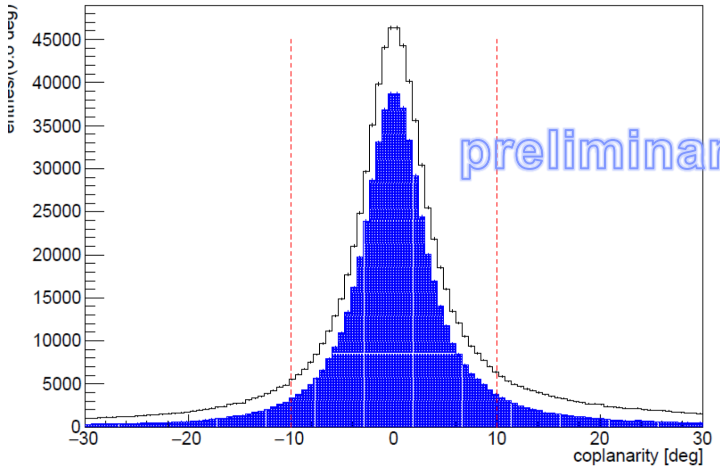
Particle ID for $\pi^+\pi^-$ and p based on TOF
Further selection on ($\pi^+\pi^-$) missing mass to identify the proton



Total missing mass cut



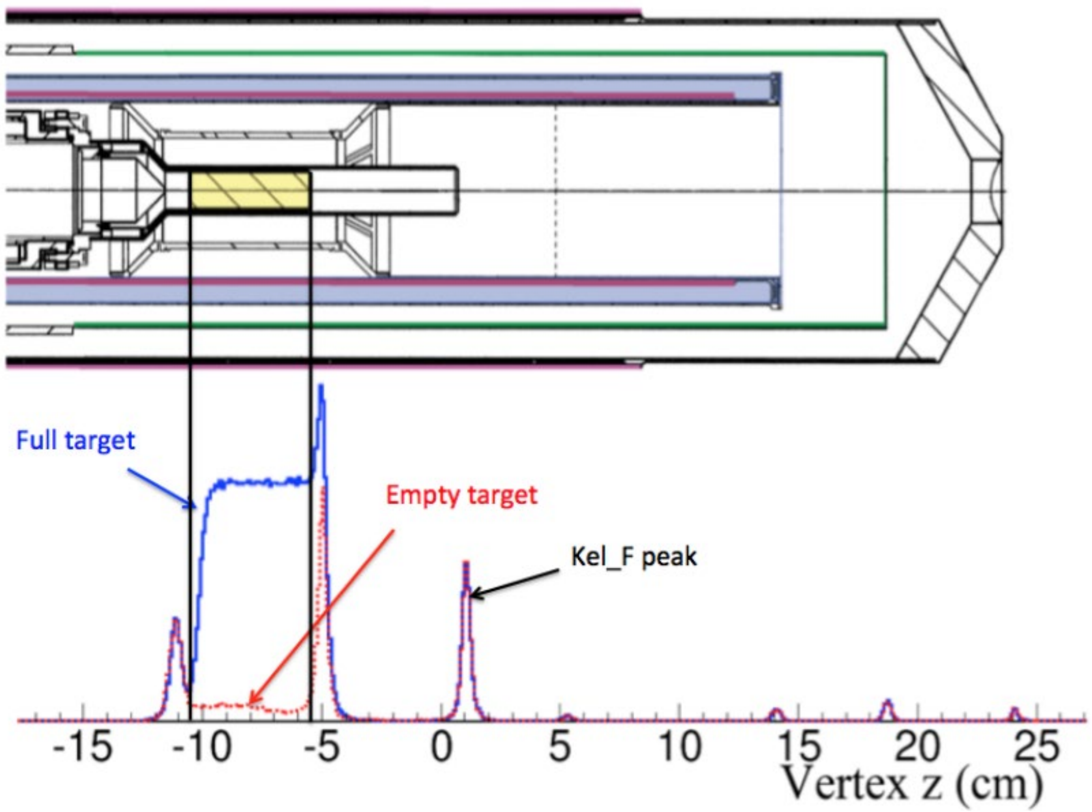
Missing momentum cut: reject reactions without spectator at rest



Coplanarity cut for pion pairs

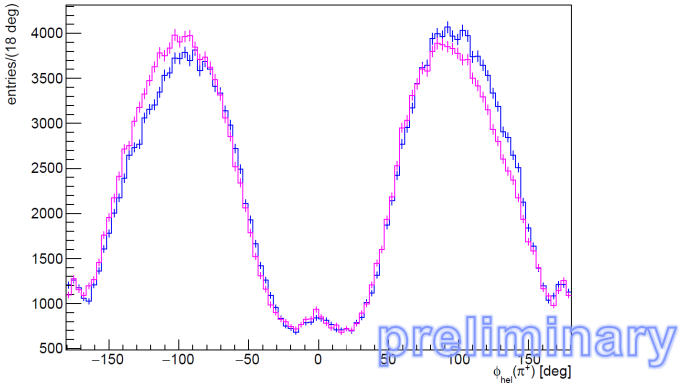
Experimental data: empty target subtraction

- Selection of events from the HD target: fiducial cut in r and z
- The events selected in the fiducial volume of the target contain the contribution from the target walls (unpolarized)
  - Empty target subtraction needed
  - Relative normalization of different runs: height of Kel-F wall peak
  - Subtraction with empty-target runs
- Events in the Kel-F peak also used for relative luminosity normalizations between different data sets

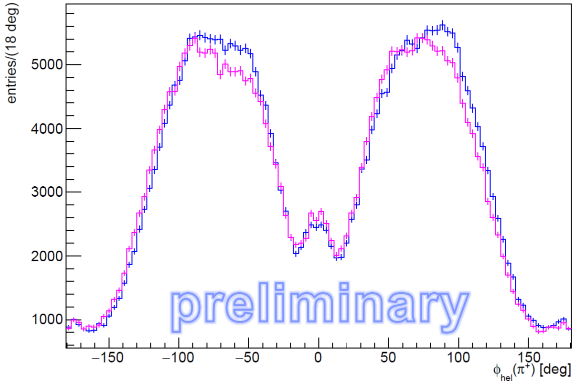


Experimental angular distributions

Set w/ positive target polarization

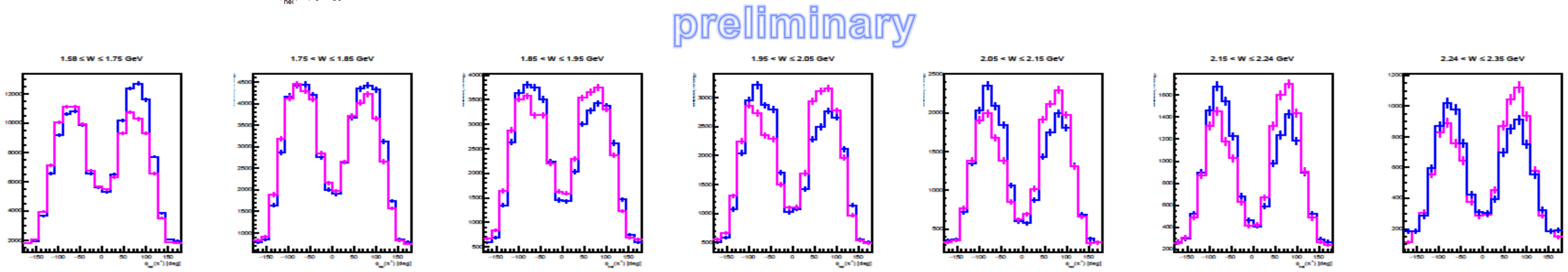


Set w/ negative target polarization



- Inputs: azimuthal angular distributions (φ_{hel})
- Bin by bin: number of events selected with
  - given helicity (positive/negative in the same data set)
  - given target polarization (in different data sets)
  - selection in W energy ranges (~100 MeV wide window)
  - counts to be properly normalized between different data sets

- Slight differences when selecting different combinations of helicities/target polarization: physics!



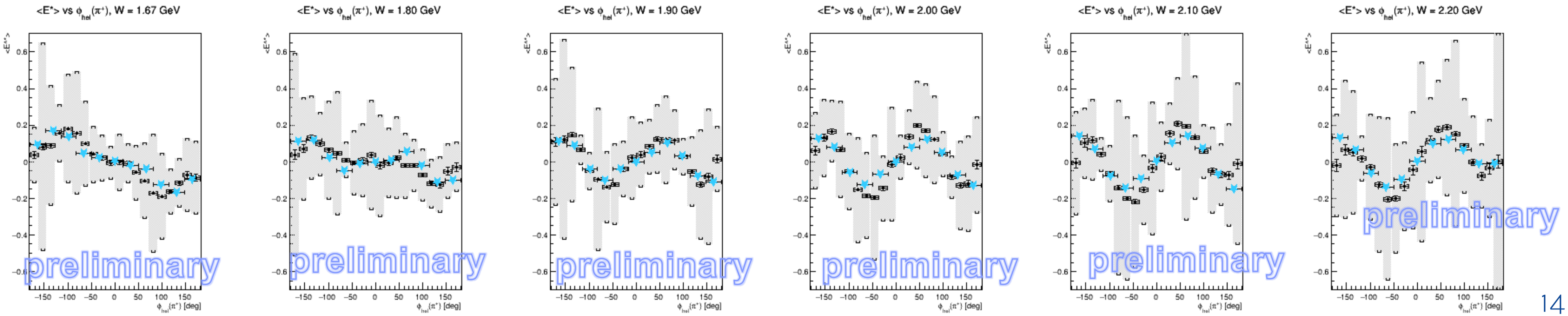
Evaluation of experimental beam-helicity asymmetries E*

- E* can be extracted from all available data samples (with similar experimental conditions)
- For each data set:

$$E^* = \frac{1}{\delta_{\odot}} \frac{N^+ - N^-}{N^+ + N^-}$$

- The E* values agree with previous measurements with polarized beam only (blue points)
- Gigantic systematic errors (grey bars) from the spread of values obtained with different data sets – to be refined!

Blue points from S. Strauch et al., CLAS Coll., PRL**95** (2005), 162003



Again on the observables extraction

- **Recall**: two data sets needed to extract the polarization observables
  - Each has its own normalization (i.e. luminosity)
  - Each data set was acquired with a given trigger (which might have different efficiency)
  - Each data set is characterized by a different acceptance
- The L_{eff1}/L_{eff2} factor is crucial

$$I_{\odot} = \frac{\frac{N_1^{\rightarrow\Rightarrow} - N_1^{\leftarrow\Rightarrow}}{\delta_{\odot 1}} + \frac{\Lambda_{z1}}{\Lambda_{z2}} \cdot \frac{L_{eff1}}{L_{eff2}} \cdot \frac{N_2^{\rightarrow\Leftarrow} - N_2^{\leftarrow\Leftarrow}}{\delta_{\odot 2}}}{(N_1^{\rightarrow\Rightarrow} + N_1^{\leftarrow\Rightarrow}) + \frac{\Lambda_{z1}}{\Lambda_{z2}} \cdot \frac{L_{eff1}}{L_{eff2}} (N_2^{\rightarrow\Leftarrow} + N_2^{\leftarrow\Leftarrow})}$$

$$P_z^{\odot} = \frac{1}{\Lambda_{z2}} \cdot \frac{\frac{N_1^{\rightarrow\Rightarrow} - N_1^{\leftarrow\Rightarrow}}{\delta_{\odot 1}} - \frac{L_{eff1}}{L_{eff2}} \cdot \frac{N_2^{\rightarrow\Leftarrow} - N_2^{\leftarrow\Leftarrow}}{\delta_{\odot 2}}}{(N_1^{\rightarrow\Rightarrow} + N_1^{\leftarrow\Rightarrow}) + \frac{\Lambda_{z1}}{\Lambda_{z2}} \cdot \frac{L_{eff1}}{L_{eff2}} (N_2^{\rightarrow\Leftarrow} + N_2^{\leftarrow\Leftarrow})}$$

$$P_z = \frac{1}{\Lambda_{z2}} \cdot \frac{(N_1^{\rightarrow\Rightarrow} + N_1^{\leftarrow\Rightarrow}) - \frac{L_{eff1}}{L_{eff2}} \cdot (N_2^{\rightarrow\Leftarrow} + N_2^{\leftarrow\Leftarrow})}{(N_1^{\rightarrow\Rightarrow} + N_1^{\leftarrow\Rightarrow}) + \frac{\Lambda_{z1}}{\Lambda_{z2}} \cdot \frac{L_{eff1}}{L_{eff2}} (N_2^{\rightarrow\Leftarrow} + N_2^{\leftarrow\Leftarrow})}$$

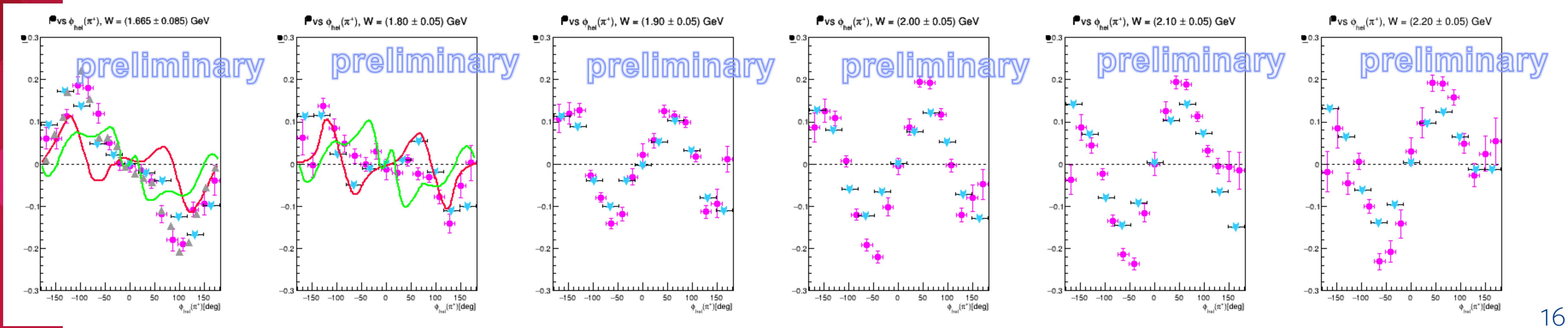
- L_{eff1}/L_{eff2} is extracted from the data based on the assumption of the equality of $\left(\frac{d\sigma}{d\Omega}\right)_0$ in all data taking periods

Preliminary results - $I^{\odot}$ on proton

- According to general symmetry principles $I^{\odot}$ is expected to be an *odd* function of the helicity angle
  - It depends only on the ratio of target polarization amounts

- The trend is in reasonable agreement with the earlier observations by CLAS based on a different data-set (E* with unpolarized target)
- Counts are acceptance corrected

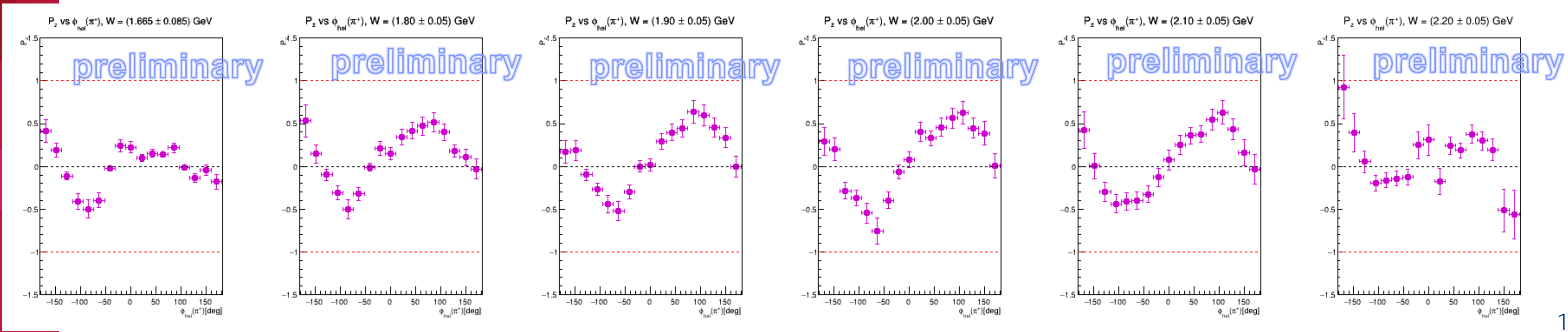
Blue points from S. Strauch et al., CLAS Coll., PRL **95** (2005), 162003



Preliminary results – P_z on proton

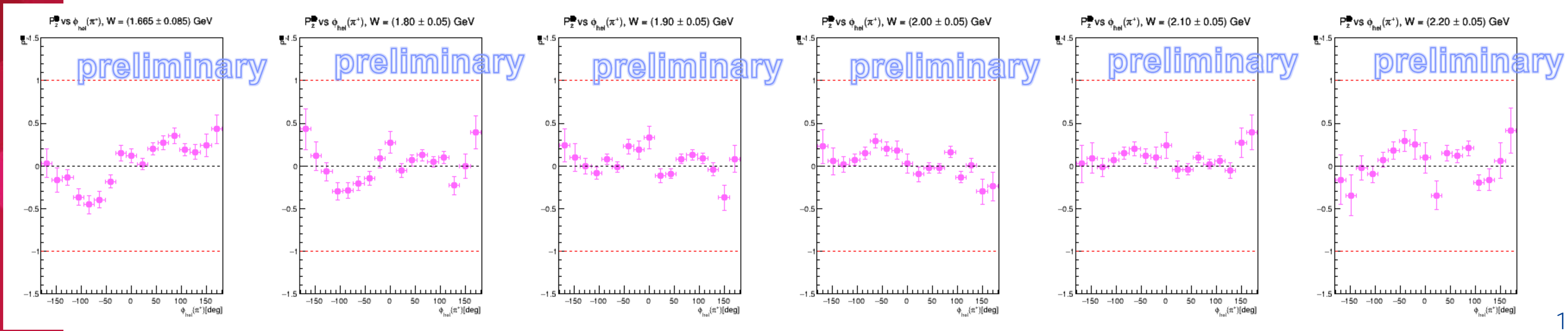
- No other results available for comparisons: first results ever
- P_z expected to be odd based on partial amplitudes symmetry
  - Vanishing at zero angle: coplanarity condition
  - When the helicity angle is oriented in the bottom hemisphere a sign flip occurs in Roberts' equations and, consequently, in the parity of the solutions

- Improvingly symmetric odd trend with W increase
  - The lack of left/right symmetry in some bins could be due to instrumental biases (different acceptance for forward/backward hemispheres, unprecise assessment of target polarization, …)



Preliminary results – $P_z^{\odot}$ on proton

- No other results available for comparisons: first results ever
- $P_z^{\odot}$ expected to be even based on partial amplitudes symmetry
- $P_z^{\odot}$ does not show a clear-cut symmetry
  - Statistical uncertainties mostly obtained from the error propagation of the system solutions – small extent overall of target polarization (23% max.)
  - Including systematic uncertainties (work in progress expected <20%) most probably the trend will become consistent with zero



Summary and outlook

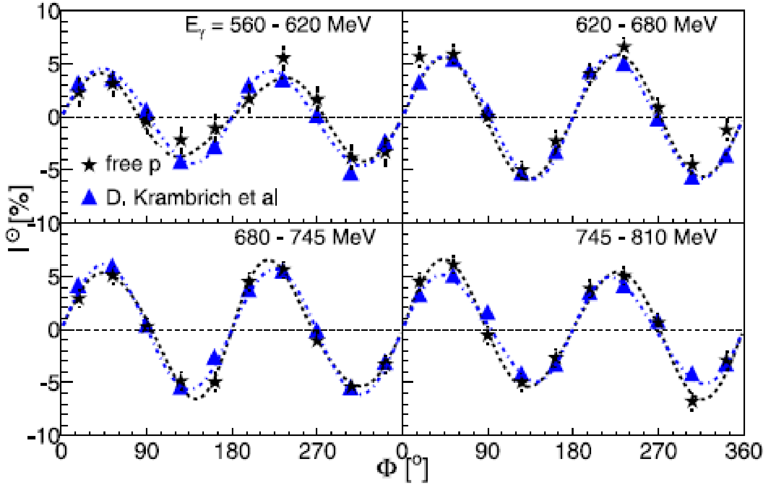
- The study of polarization observables in double-pion photoproduction with polarized beam and target is a novel tool to extract information about the baryonic spectrum
  - γp channel
    - Extraction of results for all compatible data sets pairs underway, to deliver final averages (problem: data-sets are badly correlated! Only one set with negative target polarization)
    - Final evaluation of systematics in progress
  - Outlook: γn channel – in progress
    - Same data analysis chain used for γp to be applied to the $\pi^+\pi^-n(p)$ final state
      - Use the same W binning and overall analysis approach
- The interpretation of results in terms of partial amplitudes contributions calls for new models to reproduce the new observables suitably updating the interference patterns
  - So far, none of the available reaction models agrees satisfactorily with the extracted asymmetries

Backup slides

Photoproduction of $\pi^0\pi^0$ pairs from protons and neutrons

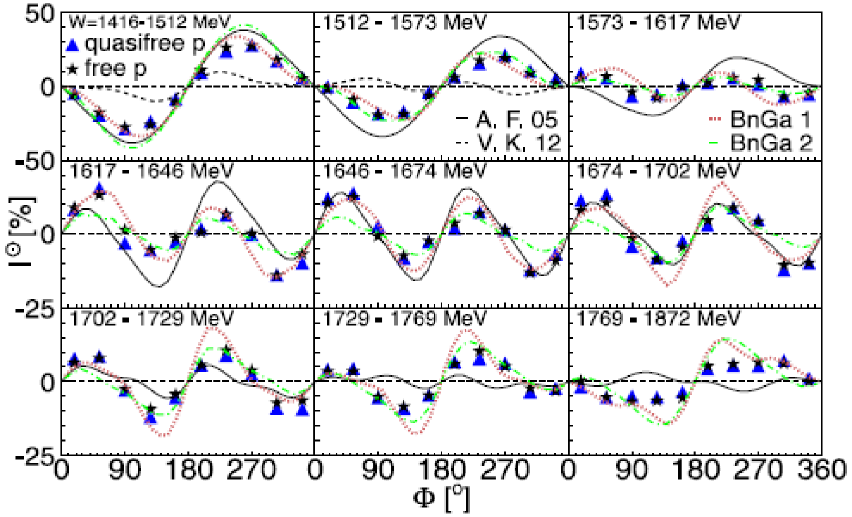
M. Oberle et al. (CB, TAPS & A2 @MAMI) PLB271 (2013), 237

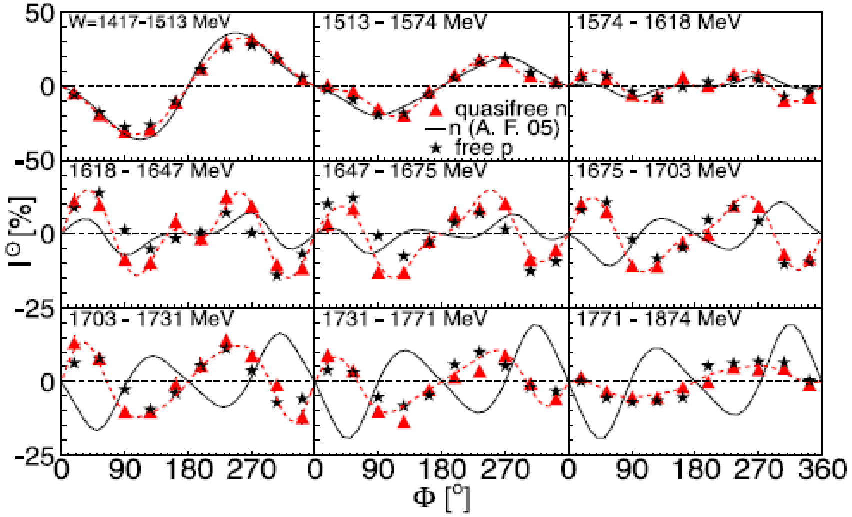
- Beam-helicity asymmetries in double-π^0 production on LH_2/LD_2 target (free p + quasi-free p & n) with circularly polarized photons up to 1.4 GeV @MAMI
- $I^{\odot}$ evaluated through cross-section asymmetries
- Identical beam-helicity asymmetry measured for free and quasi-free protons; very similar results from neutrons
  - Expected up to the second resonance region (W < 1.6 GeV)
  - Surprising at larger energies due to difference resonances produced
- Reasonable reproduction of $I^{\odot}$ trend by Bonn-Gatchina and two-pion MAID models (much worse for Valencia), at least up to the second resonance region



$$I^{\odot}(\varphi) = \sum_{n=1}^{\infty} A_n \sin(n\varphi)$$

Free and quasi-free p

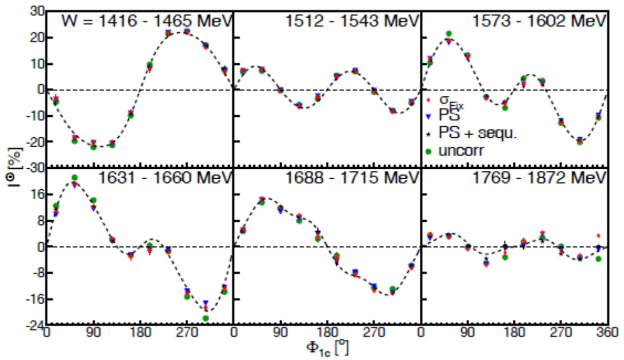




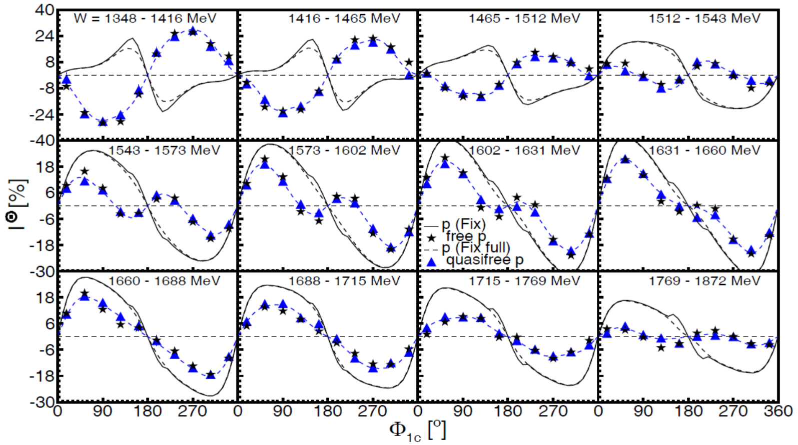
quasi-free n

Photoproduction of $\pi^0\pi^\pm$ pairs from protons and neutrons

M. Oberle et al. (CB, TAPS & A2 @MAMI) EPJ A (2014), 50

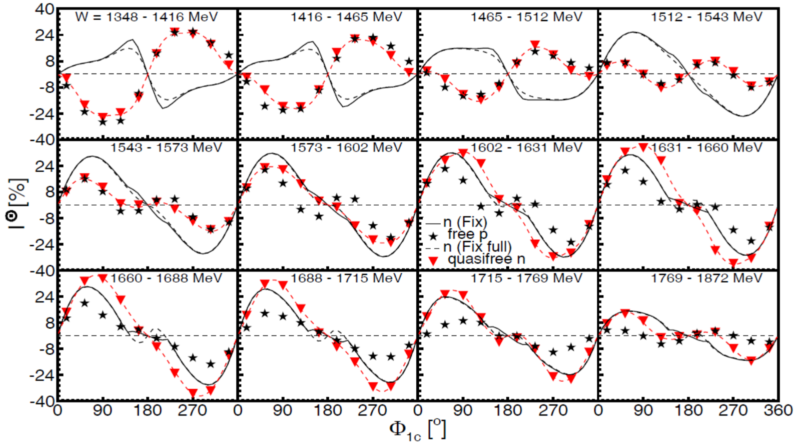


- Beam-helicity asymmetries in double mixed-charge π production on LH_2/LD_2 target (free p + quasi-free p & n) with circularly polarized photons up to 1.4 GeV @MAMI
  - Sensitive channels to $\rho^\pm$ production effects
  - More background-populating channels compared to $2\pi^0$



- $I^\odot$ evaluated through cross-section asymmetries ordering particles by charge and by mass

- Good agreement between measurements on free and quasi-free proton, reasonable with quasi-free neutrons



- Worse agreement with models compared to $2\pi^0$, especially at higher energies:
  - more contributions from mixed charge channels, call to finer tuning of models
  - Two-pions MAID model behaves better, overall
  - Beam-helicity asymmetries are very sensitive to interference terms

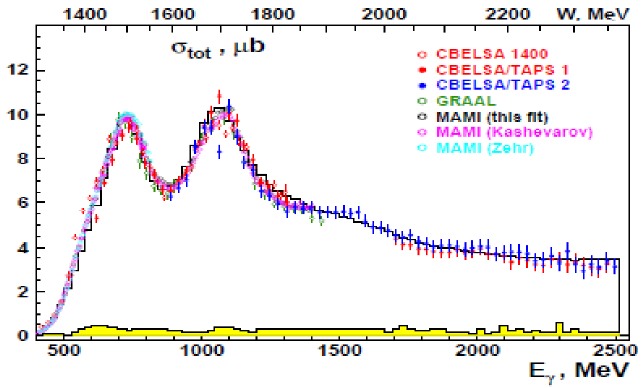
Photoproduction of $\pi^0\pi^0$ pairs off protons

V. Sokhoyan (CB@ELSA/TAPS) EPJ A51 (2015), 95

- The double-π^0 production is suitable to investigate the $\Delta(1232)\pi$ intermediate channel
  - Less channels contribute compared to the charged pion channel, especially to the non resonant background
    - Diffractive ρ production
    - Dissociation of the proton into $\Delta^{++}\pi^-$
    - π exchange is not possible

- Use of real linearly polarized photons (ELSA) from 600 MeV to 2500 MeV: access to the 4th resonance region

- Extraction of:
  - total cross section
  - PWA of the Dalitz plot
  - Beam-helicity asymmetries for double-π^0 production on the proton



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