Results on $\pi^+\pi^-$ photoproduction on the nucleon

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On behalf of the CLAS Collaboration

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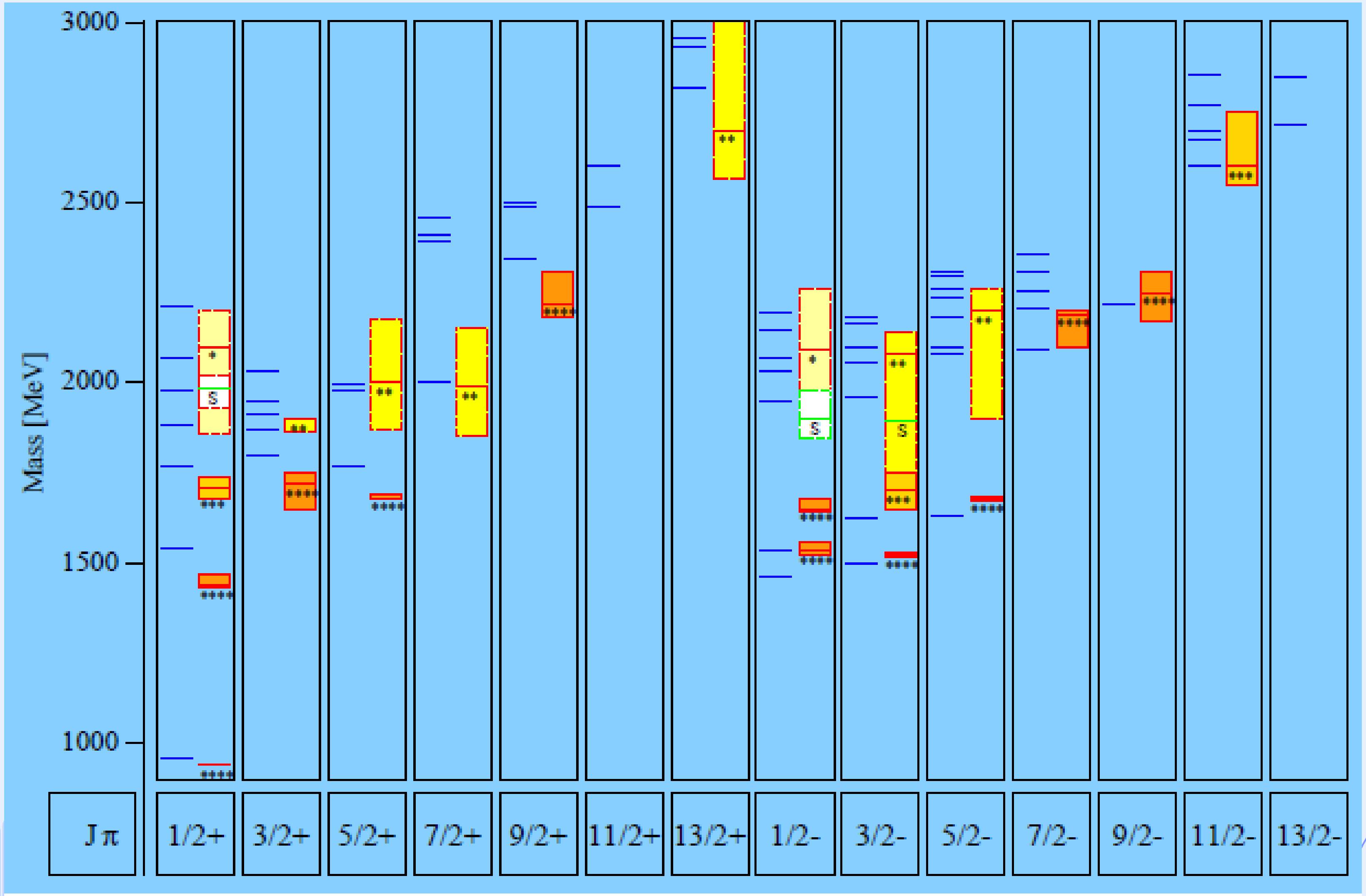
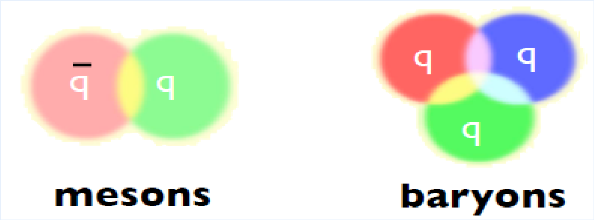
The light baryon (N*, Δ) spectrum in the Constituent Quark Model

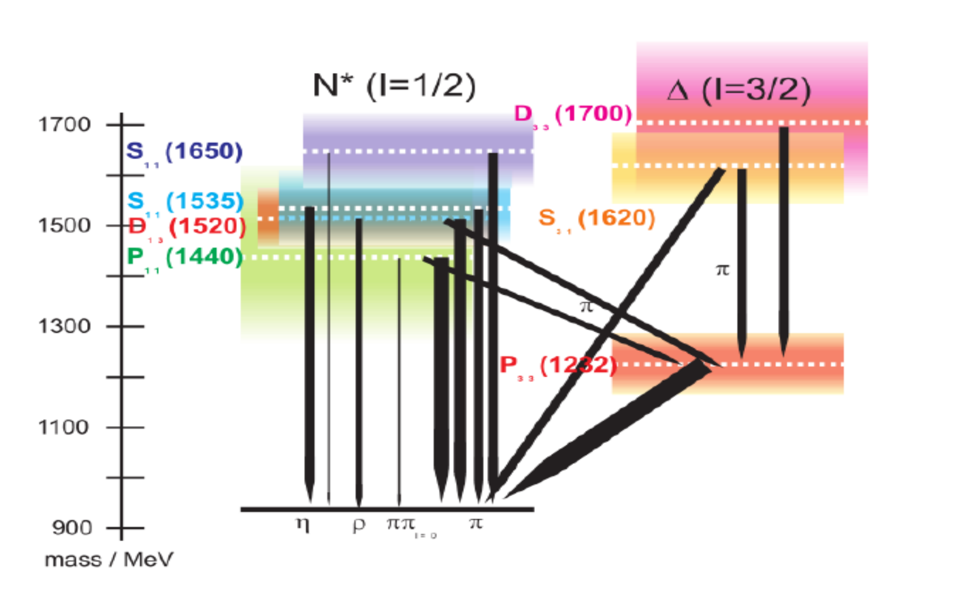


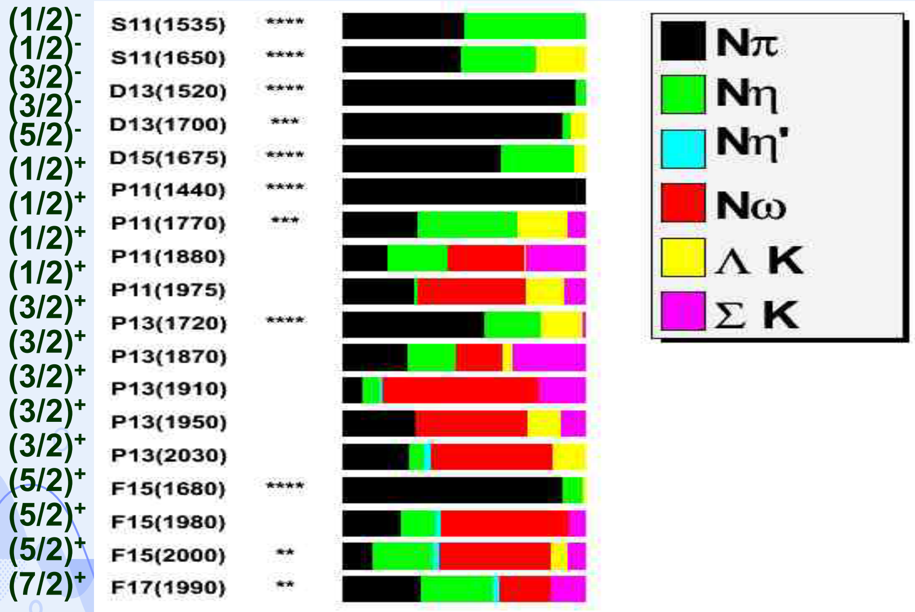
- Quarks confined into colorless hadrons



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

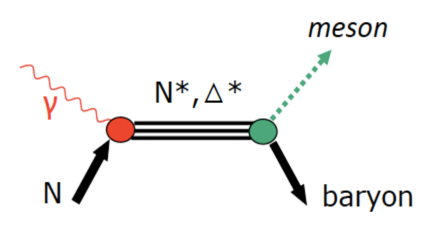
The light baryon spectrum: experimental situation



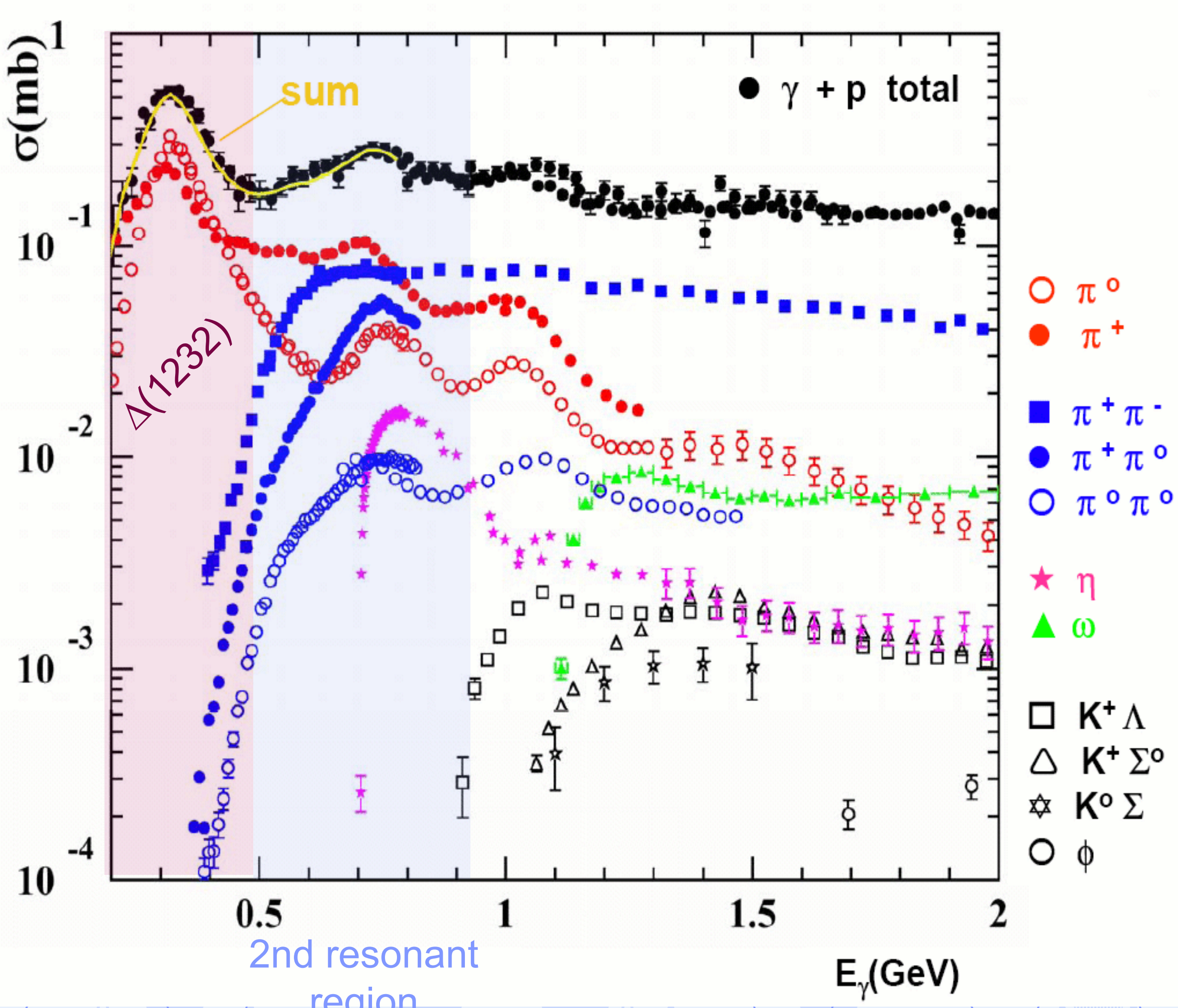


- Lowest lying N* and Δ* resonances
  - 1.3-2 GeV mass range: second resonant region
  - Overlapping states in the same mass region
  - Broad widths (short lifetimes)
  - Shared decay modes
- Most of the available information from pion/kaon beams experiments
  - Missing states: too small couplings with 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



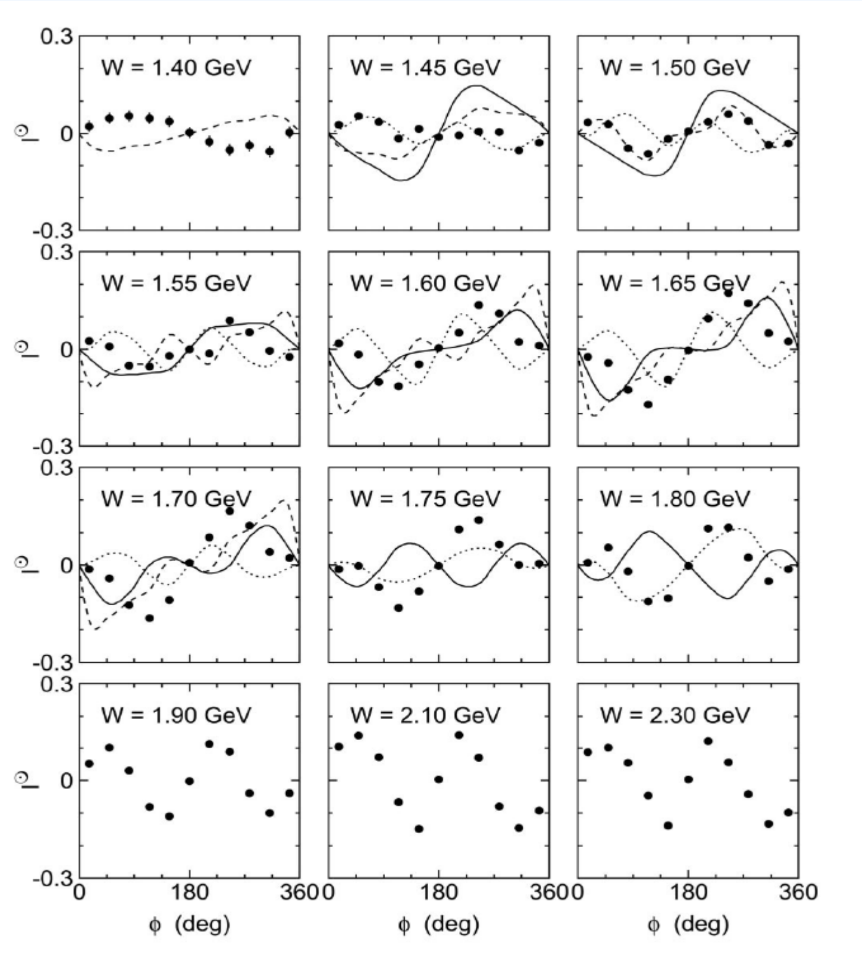
Photonuclear cross sections



- 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

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

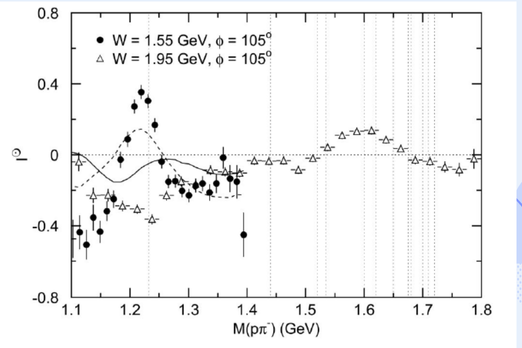
S. Strauch et al. (CLAS) PLR95 (2005), 162003



- 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:

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

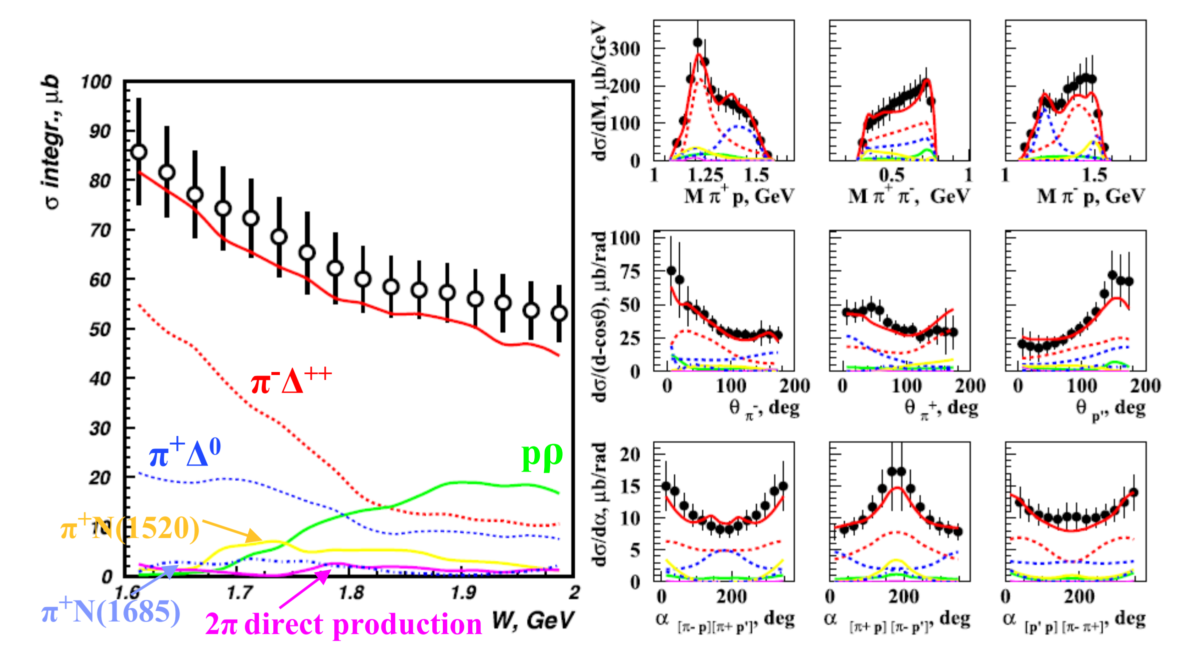
  - Odd trend in all W sub-ranges
  - Large asymmetries which change with W up to 1.8 GeV
  - Compared with models based on electroproduction of double-charged pions including a set of quasi-two body intermediate states (Mokeev et al.):
    - *πΔ, ρN, πN(1520), πN(1680)* + contributions from *Δ(1600), 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

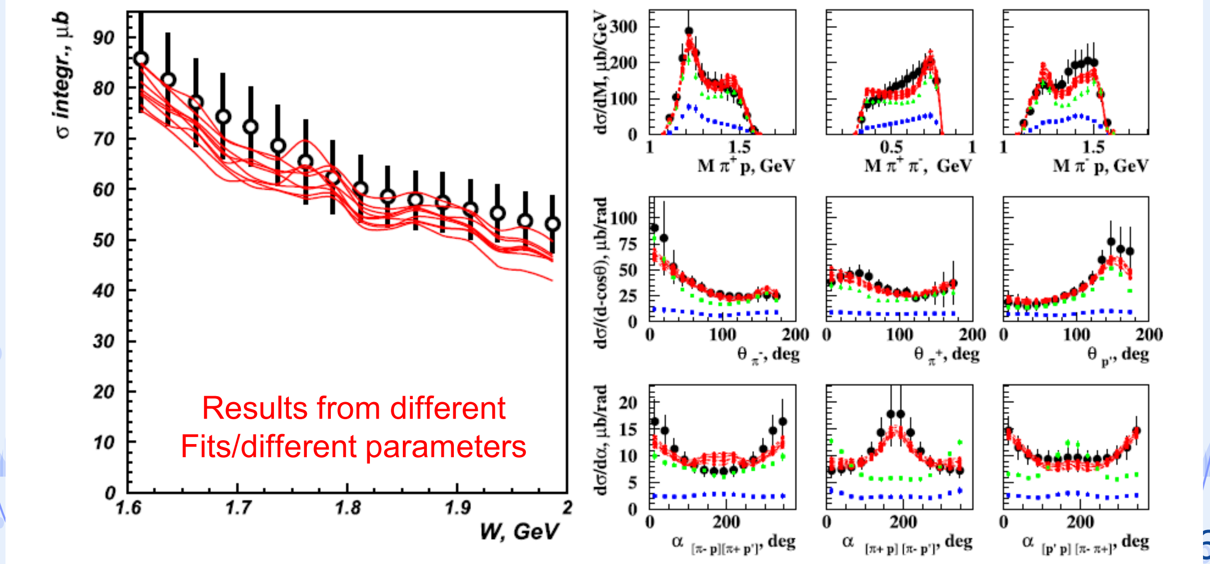


Photoproduction of $\pi^+\pi^-$ pairs off protons (unpolarized)

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⁺

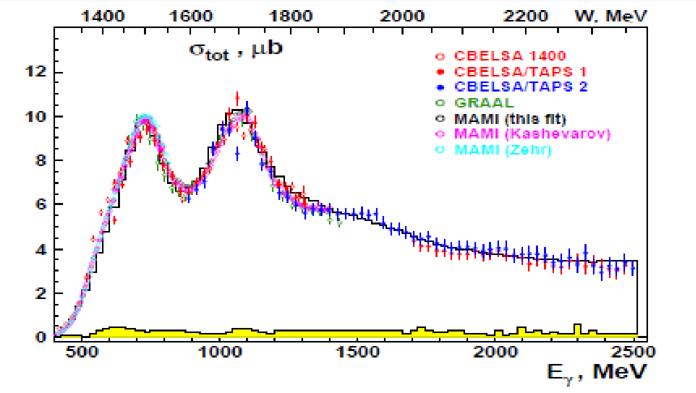




Photoproduction of $\pi^0\pi^0$ pairs off protons

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

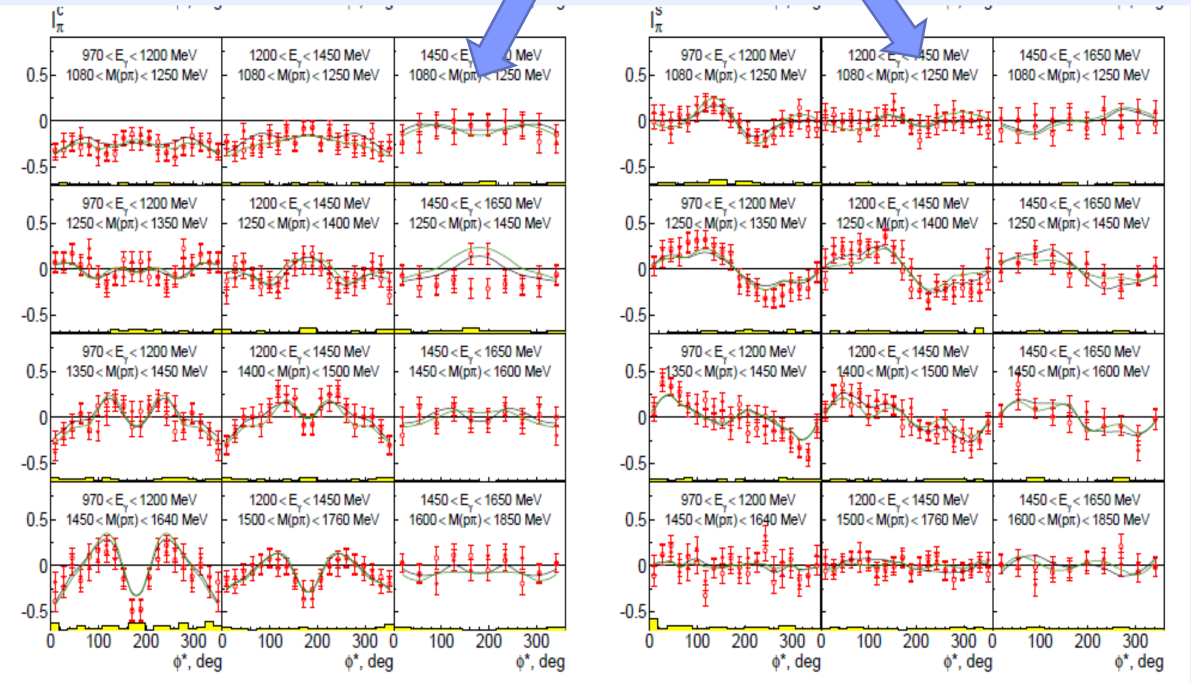
- The double-π^0 production is suitable to investigate the $\Delta(1232)\pi$ intermediate channel
  - Less channels contribute compared to the charged pion channel, especially to the non resonant background
    - Diffractive ρ production
    - Dissociation of the proton into $\Delta^{++}\pi^-$
    -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



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

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

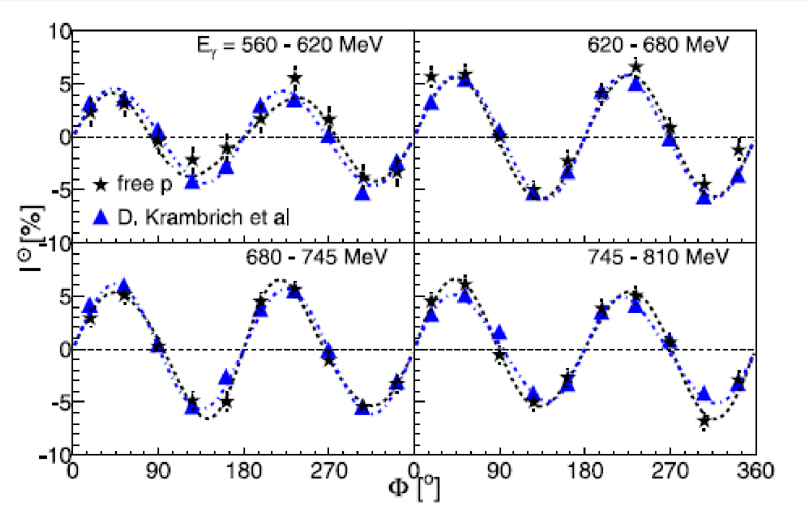
- Extraction of:
  - total cross section
  - PWA of the Dalitz plot
  - Beam-helicity asymmetries for double-π^0 production on the proton



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

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

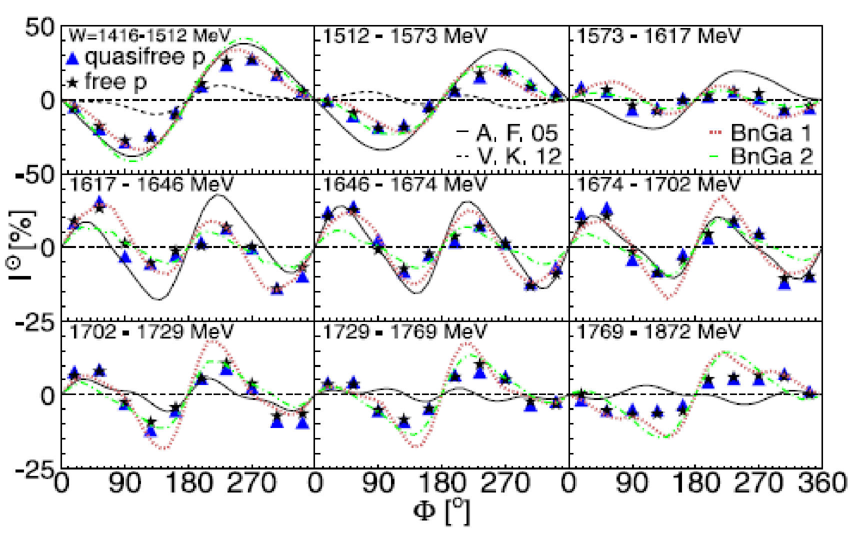
- Beam-helicity asymmetries in double-π^0 production on LH_2/LD_2 target (free p + quasi-free p & n) with circularly polarized photons up to 1.4 GeV @MAMI
- $I^\odot$ evaluated through cross-section asymmetries
- Identical beam-helicity asymmetry measured for free and quasi-free protons; very similar results from neutrons
  - Expected up to the second resonance region (W < 1.6 GeV)
  - Surprising at larger energies due to difference resonances produced

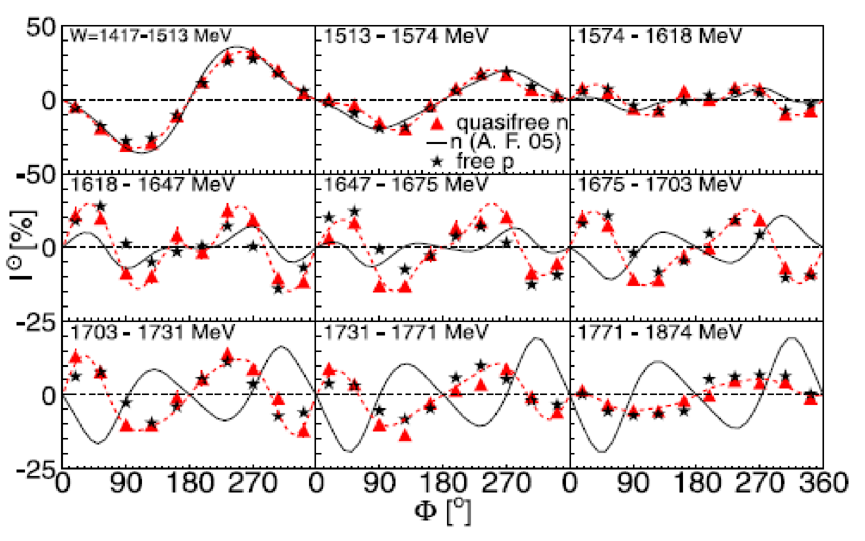


- Reasonable reproduction of $I^\odot$ trend by Bonn-Gatchina and two-pion MAID models (much worse for Valencia), at least up to the second resonance region

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

Free and quasi-free p



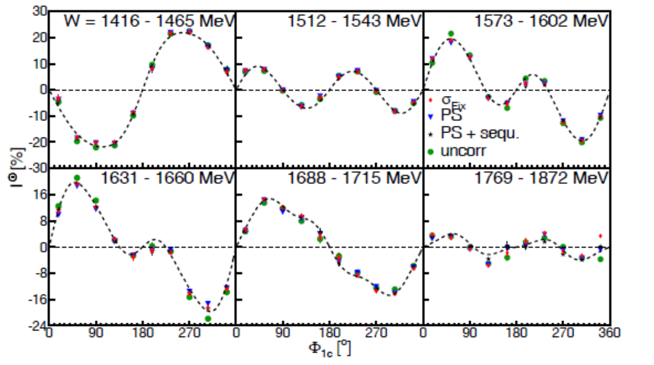


quasi-free n

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

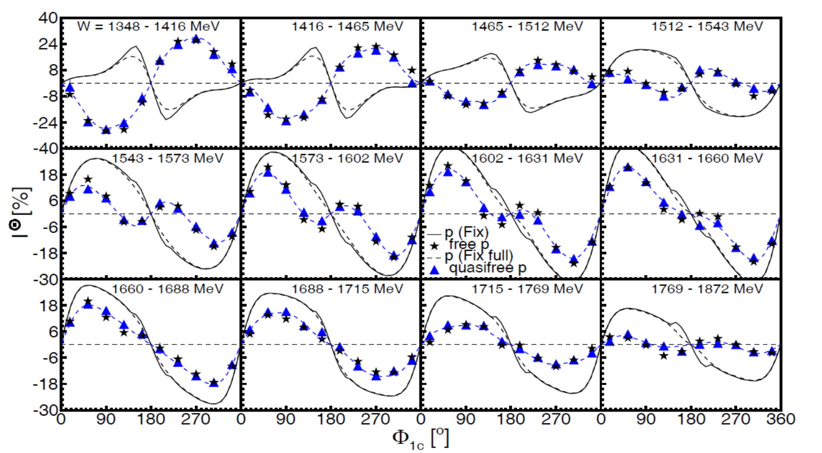
M. Oberle et al. (CB, TAPS & A2 @MAMI) EPJ A (2014), 50

- 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 $2\pi^0$

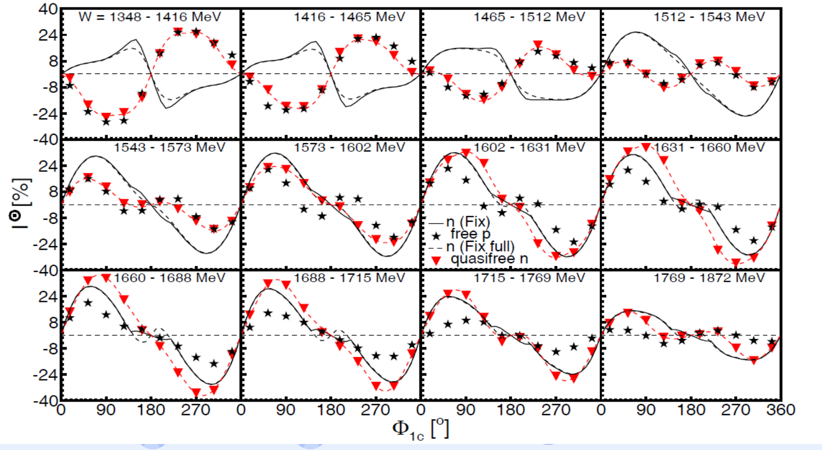


- $I^\odot$ evaluated through cross-section asymmetries ordering particles by charge and by mass

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



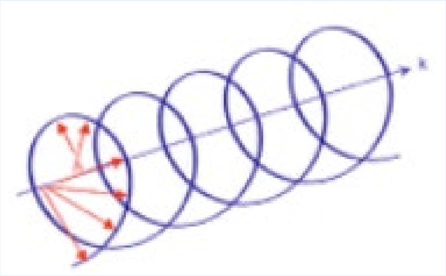
- Worse agreement with models compared to $2\pi^0$, especially at higher energies:
  - more contributions from mixed charge channels, call to finer tuning of models
  - Two-pions MAID model behaves better, overall
  - Beam-helicity asymmetries are very sensitive to interference terms



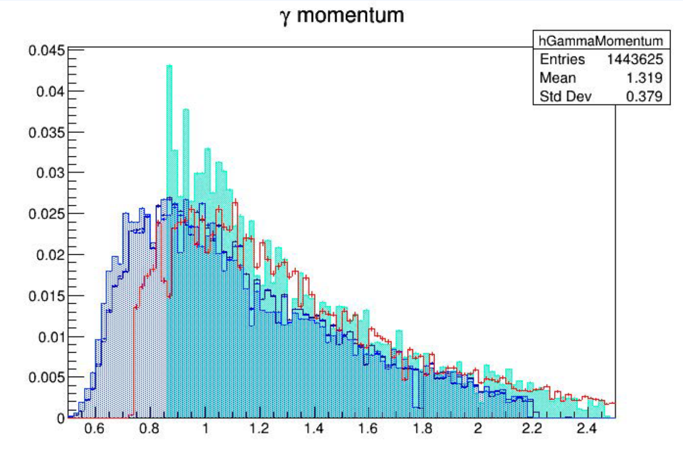
Experimental method – polarized beam and target

- 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

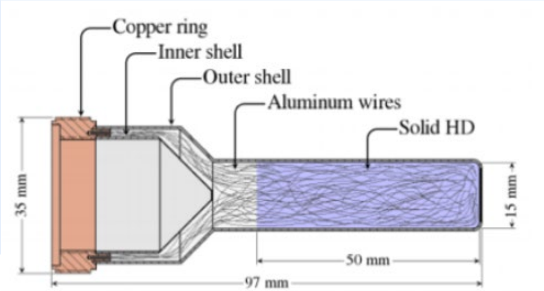


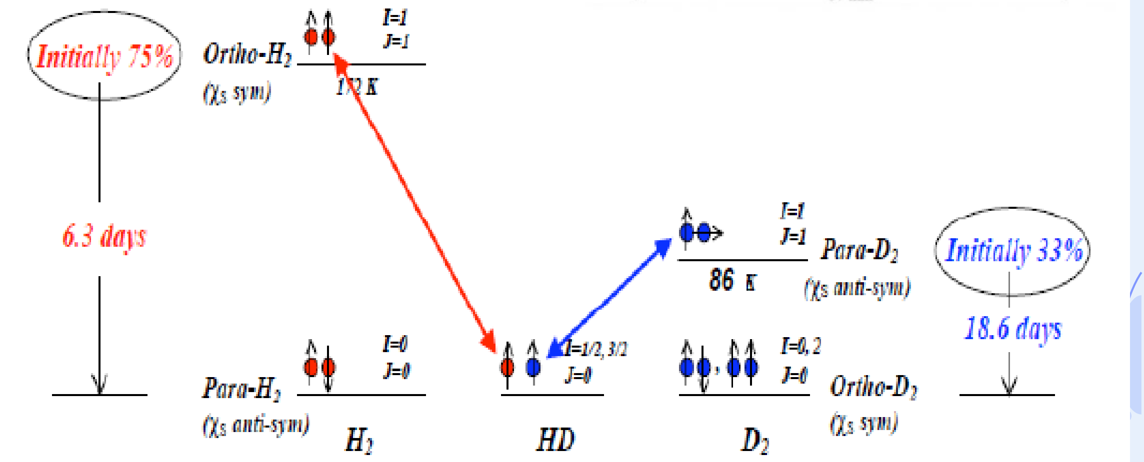
$$x = \frac{E_\gamma}{E_{beam}}$$



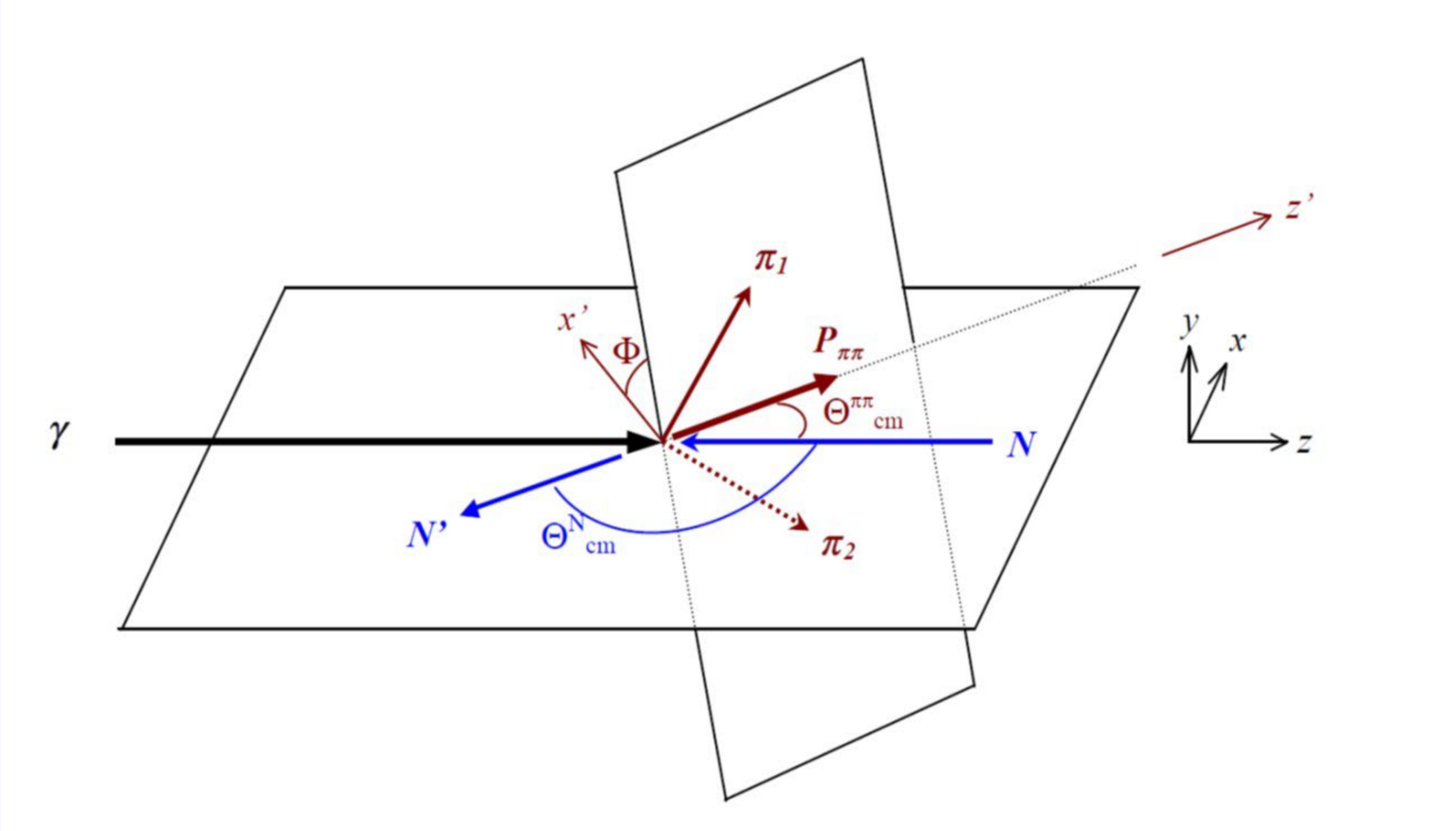
$$\delta_\odot = P_{el}\frac{4x - x^2}{4 - 4x + 3x^2}$$

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





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



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

- The differential cross-section can be expressed by **four contributions** which depend on polarization observables weighted by the extent 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 $\boldsymbol{I^{\odot}}$, $\boldsymbol{P}$, $\boldsymbol{P^{\odot}}$ 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

Polarization asymmetries in every φ_{hel} bin

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

- 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 (but properly normalized)
- The system of equations can be solved analytically extracting, in every bin, $I^\odot$, P_z, $P^\odot_z$ and σ_0 as solutions

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

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

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

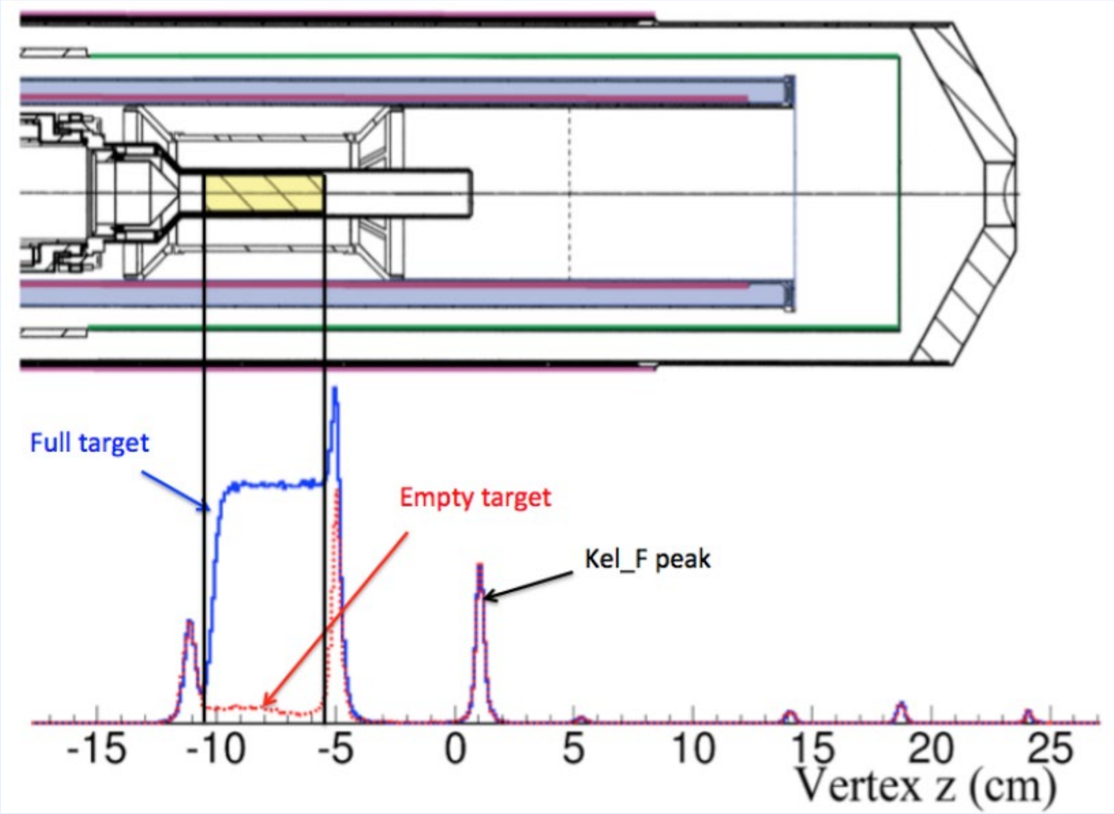
$$N_{exp}^{\leftarrow\Leftarrow} = \left(\frac{d\sigma}{d\Omega}\right)_0 \mathrm{L}\,\boldsymbol{\varepsilon}\left[1 - \Lambda_z P_z - \delta_\odot(I_\odot - \Lambda_z P_z^\odot)\right]$$

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

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

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

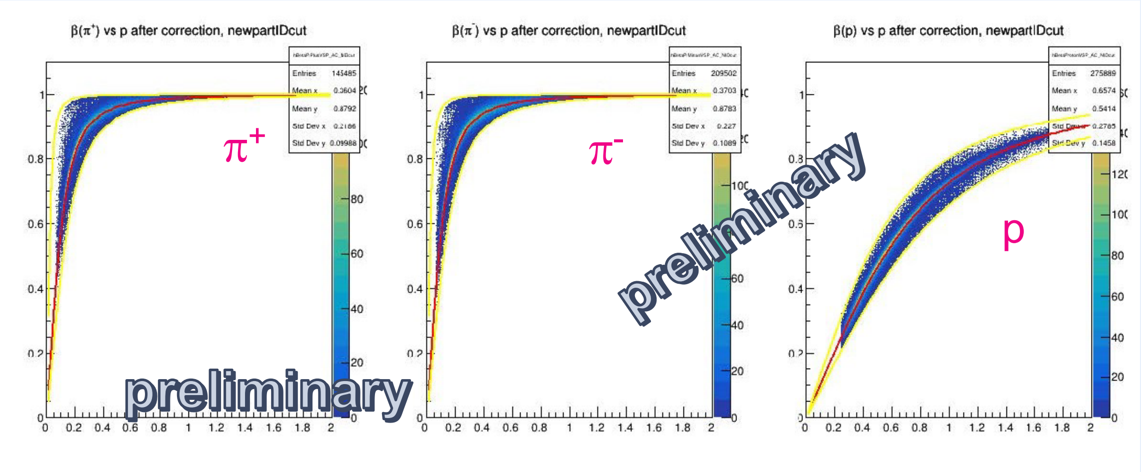
Experimental data: empty target subtraction



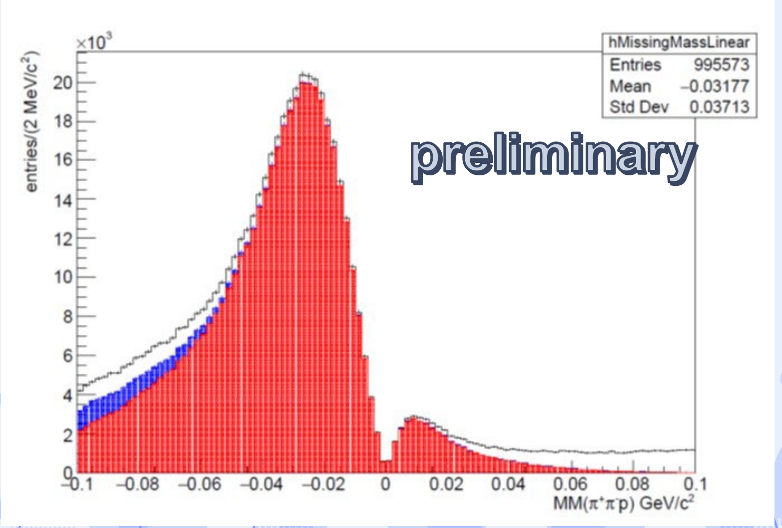
- Selection of events from the HD target: fiducial cut in r and z
- The events selected in the fiducial volume of the target contain the contribution from the target walls (unpolarized)
  - Empty target subtraction needed
  - Relative normalization of different runs: height of Kel-F wall peak
  - Subtraction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

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

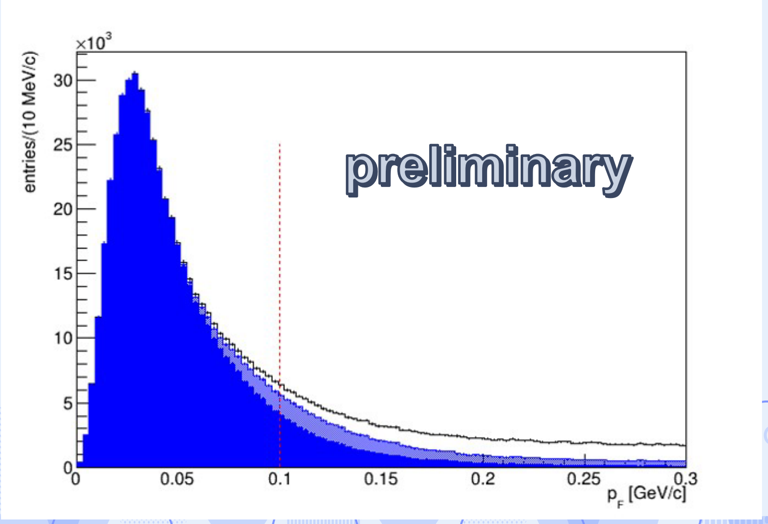
Description	Cut
Particle multiplicity	1 negative, 2 positives
Time coincidence	Time coincidence between: 1 proton, 1 π^+, 1 π^-
$2\pi p$ z-vertex in HD target	$-9.5 < z_{vertex} < -5.8$ cm
$2\pi p$ pId: β_{corr}	$p_{\pi^\pm}/\sqrt{p^2_{\pi p_m} + (m_\pi - 80\ [\mathrm{MeV}])^2} \le \beta^{corr}_{\pi^\pm}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



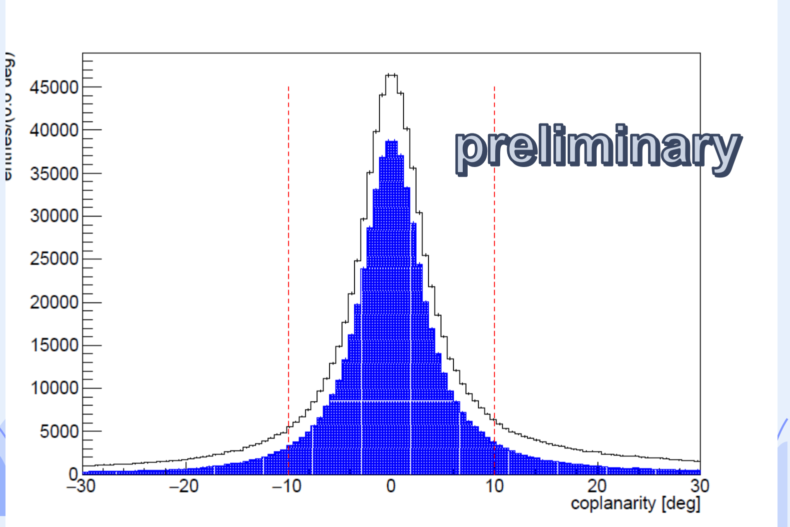
Particle ID for $\pi^+\pi^-$ and p based on TOF
Further selection on $(\pi^+\pi^-)$ missing mass to identify the proton



Total missing mass cut



Missing momentum cut: reject reactions without spectator at rest



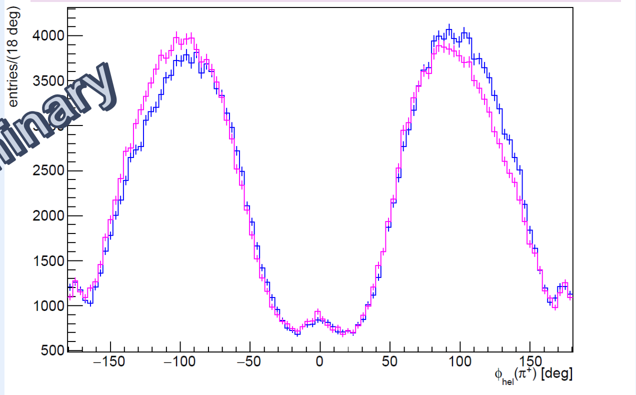
Coplanarity cut for pion pairs

Experimental angular distributions

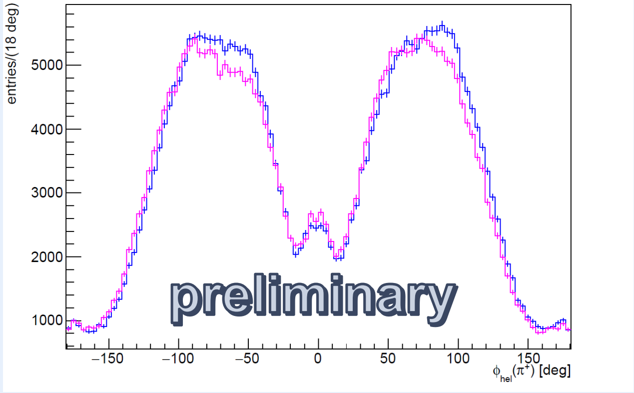
- Needed input: angular distributions (φ_{hel})
- Bin by bin: number of events selected with
  - Given helicity (positive/negative in the same data set)
  - Given target polarization (in different data sets)
  - Selection in W energy ranges (~100 MeV wide window)
  - Counts to be properly normalized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

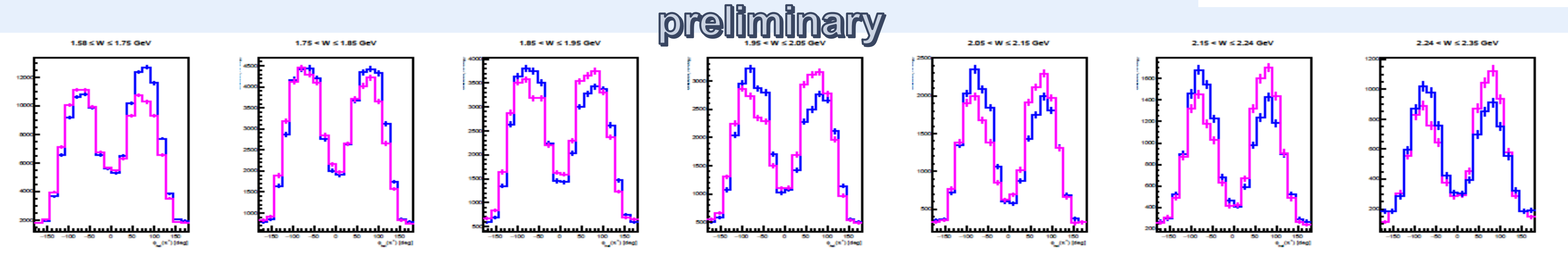
- Slight differences when selecting different combinations of helicities/target polarization: origin of the investigated asymmetries

Set w/ positive target polarization



Set w/ negative target polarization





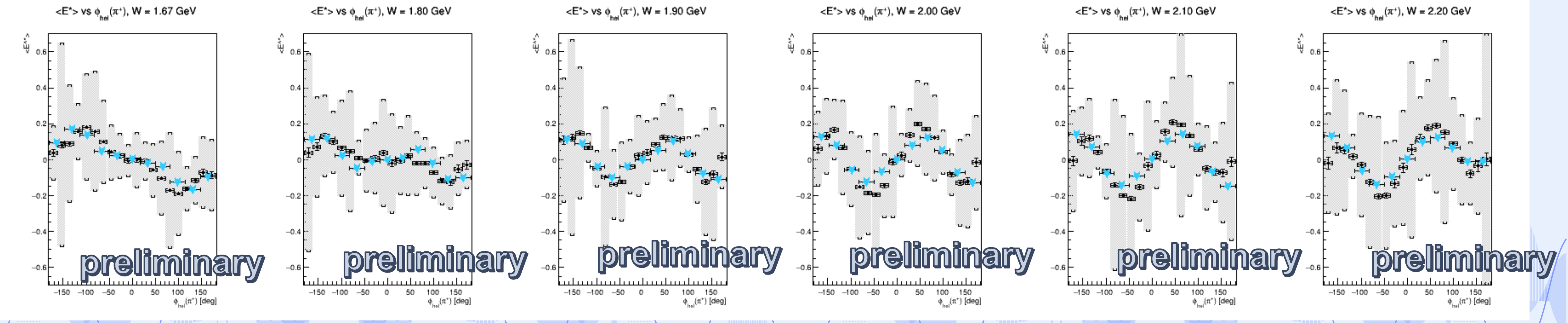
Evaluation of experimental beam-helicity asymmetries E*

- E* can be extracted from the data matching proper samples (with similar experimental conditions, and extracting the weighted average for all samples)
- 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)
- Systematic errors (grey bars) from spread of values obtained using different data sets

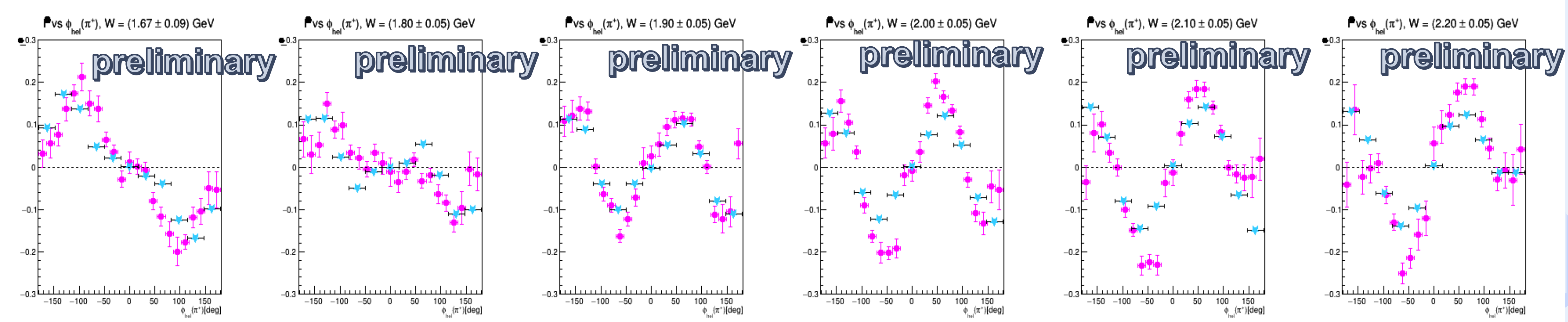
Blue points from S. Strauch et al., CLAS Coll., PRL**95** (2005), 162003



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

- Extraction of polarization asymmetries from the equation by Roberts et al.
- 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 polarizations
- The trend is in reasonable agreement with the earlier observations by CLAS based on a different data-set (unpolarized target)

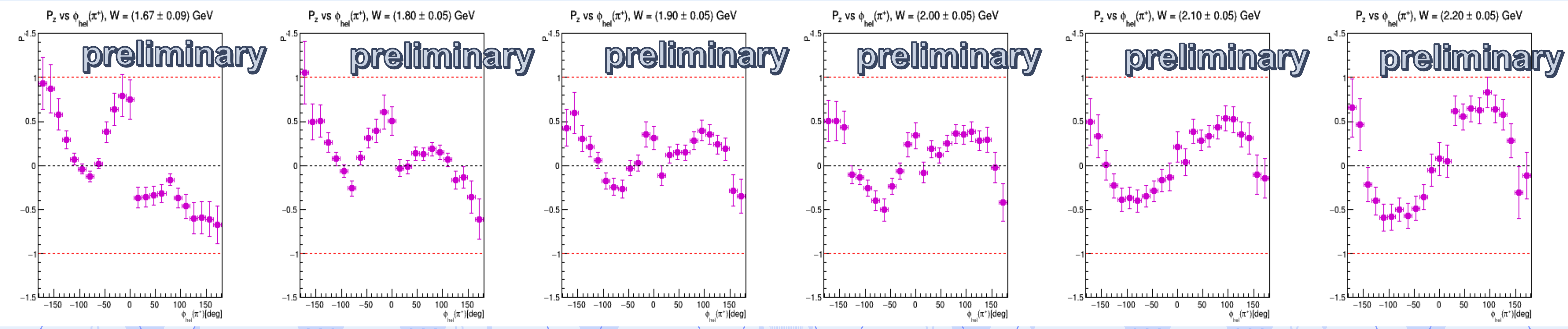
Blue points from S. Strauch et al., CLAS Coll., PRL **95** (2005), 162003



Preliminary results – P_z on proton

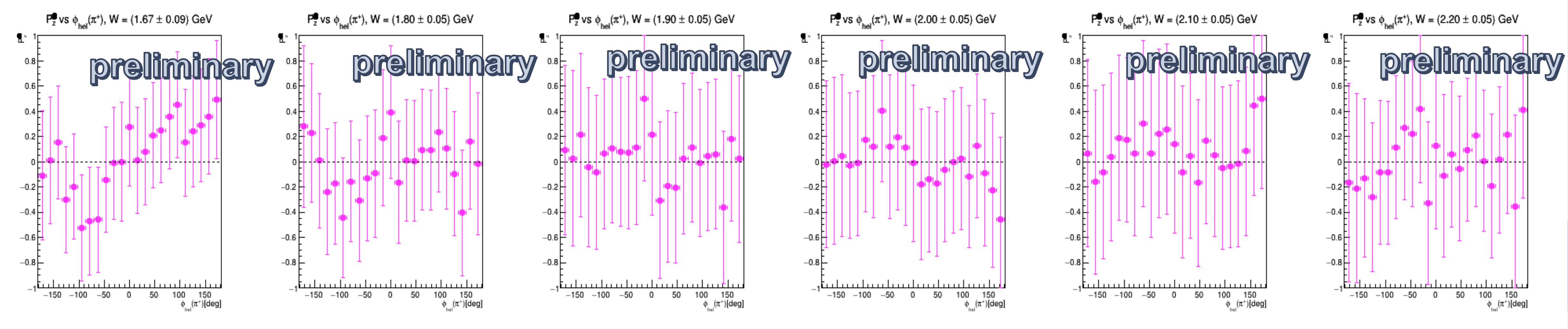
- No other results available for comparisons: first results ever
- P_z expected to be odd based on partial amplitudes symmetry
  - Vanishing at zero angle: coplanarity condition
  - *Beware*: when the helicity angle is oriented in the bottom hemisphere a sign flip occurs in Roberts' equations and, consequently,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

- Improvingly symmetric odd trend with W increase
  - The lack of left/right symmetry could be due to instrumental reasons (different acceptance, …)



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
- $P_z^{\odot}$ is compatible with zero (within errors)
  - Large statistical uncertainties obtained from the error propagation of the system solutions – small extent overall of target polarization (23% max.)



Summary and outlook

- Double-pion photoproduction with polarized beam and/or target as a novel tool to extract information about the baryonic spectrum
  - γp channel
    - Analysis completed, extraction of results for all compatible data set pairs underway
    - Final evaluation of systematics in progress (take care of correlations among the sets)
  - 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
      - Stay tuned: some novel results upcoming!
- The interpretation of results in terms of partial amplitudes contribution call for new models updating the interaction pattern and reproducing all the new extracted observables
  - So far, none of the available reaction models agrees completely with the asymmetries extracted from reactions involving the production of charged pion pairs