Exclusive $\pi^+\pi^-$ photoproduction with polarized target and beam at CLAS

Alessandra Filippi
INFN Torino, Italy

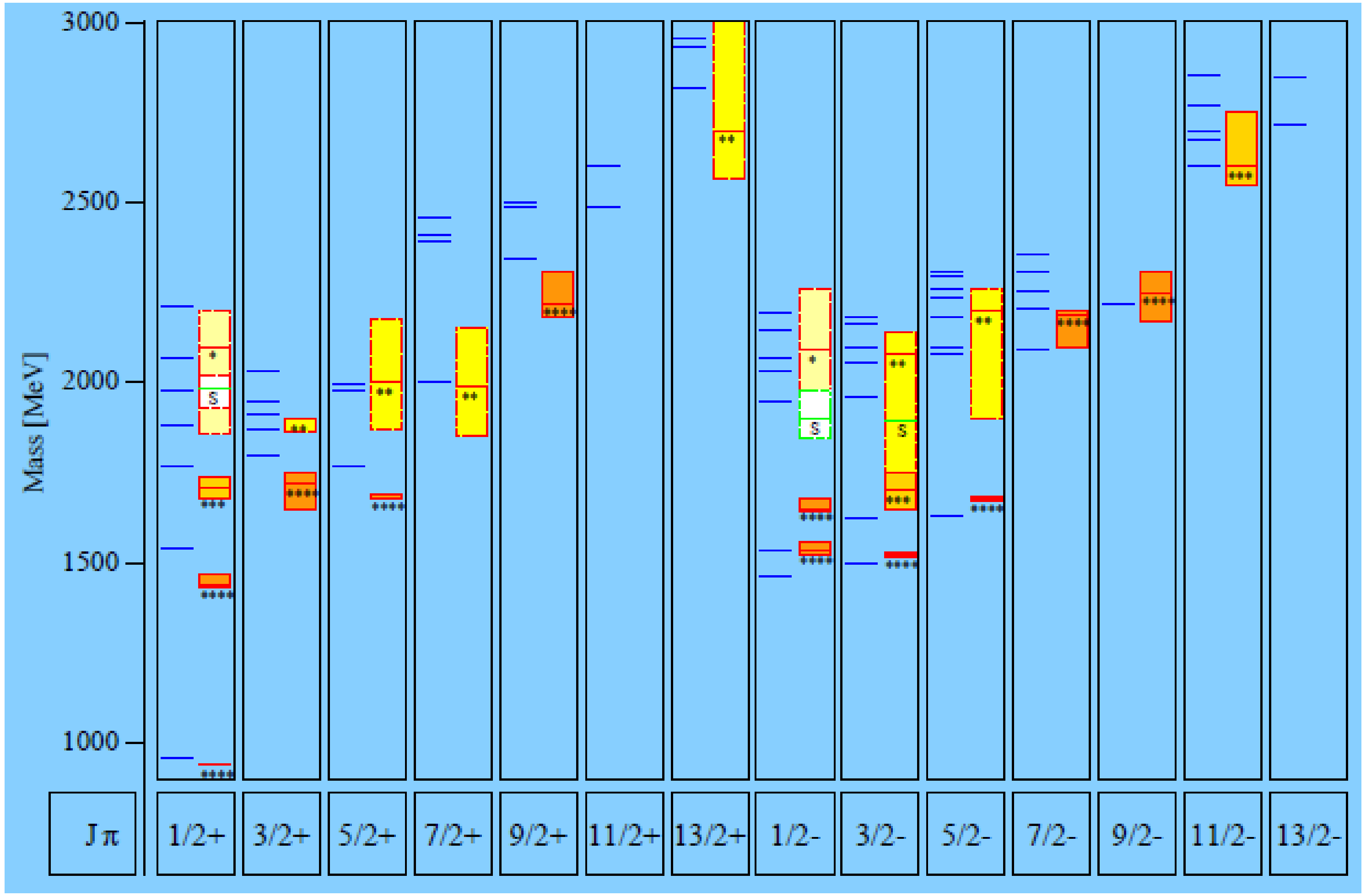
On behalf of the CLAS Collaboration

CEBAF Large Acceptance Spectrometer

HADRON2023, Genova, Italy - June 5, 2023

HADRON 2023

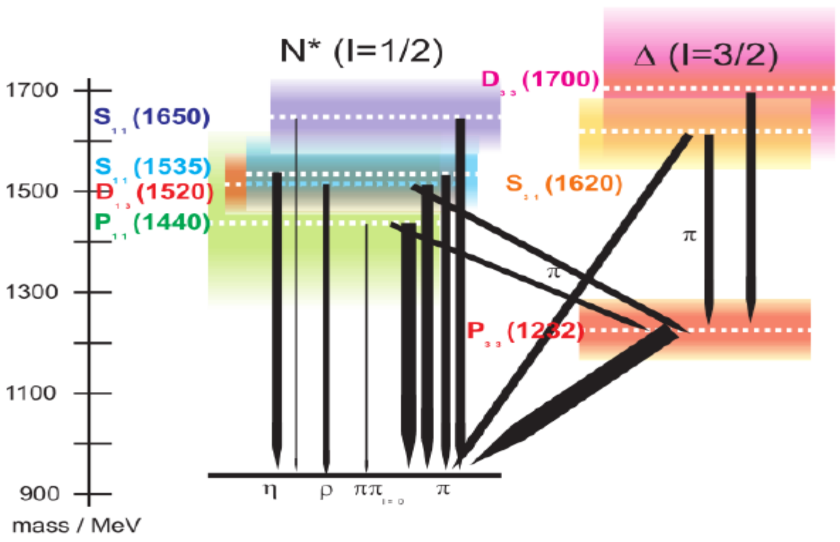
The light baryon (N*, Δ) spectrum in the Constituent Quark Model

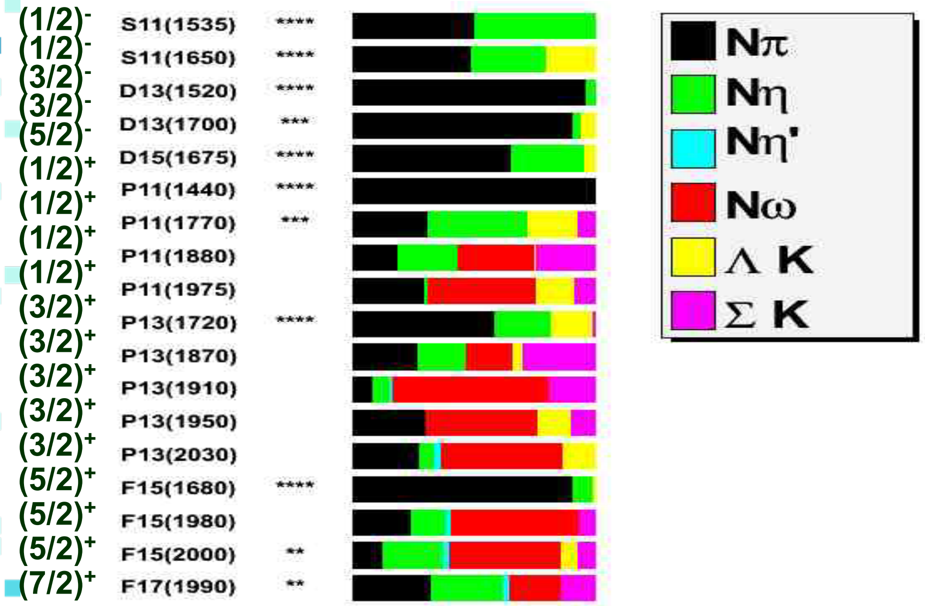


- Quarks confined into colorless hadrons

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

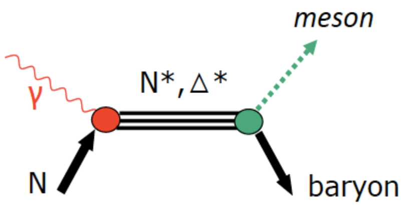
The light baryon spectrum: experimental status



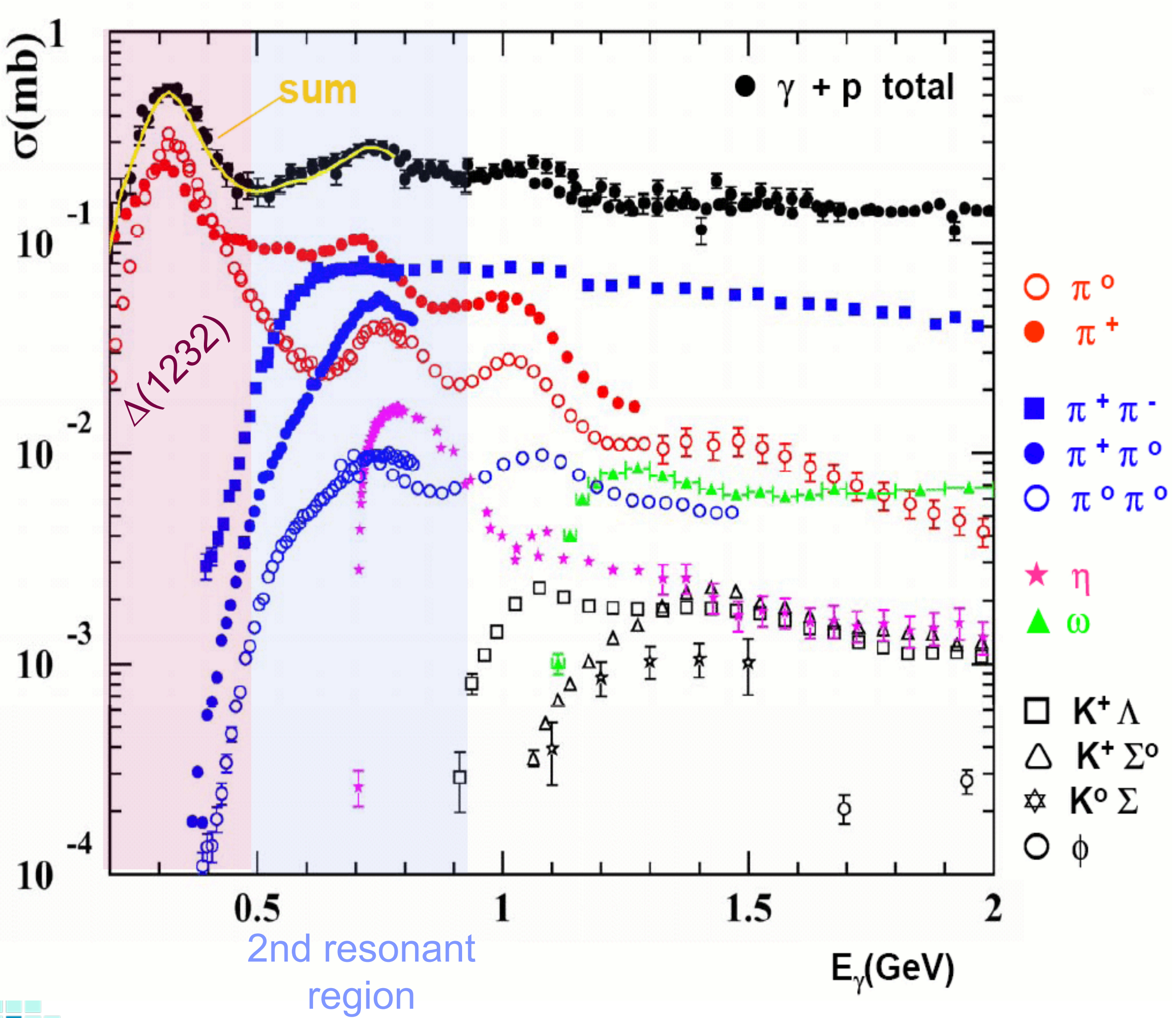


- Lowest lying N* and Δ* resonances
  - 1.3-2 GeV mass range: second resonant region
  - Overlapping states in the same mass region
  - Broad widths (short lifetimes)
  - Shared decay modes
- Most of the available information from pion/kaon beams experiments
  - Missing states: too small couplings with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



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

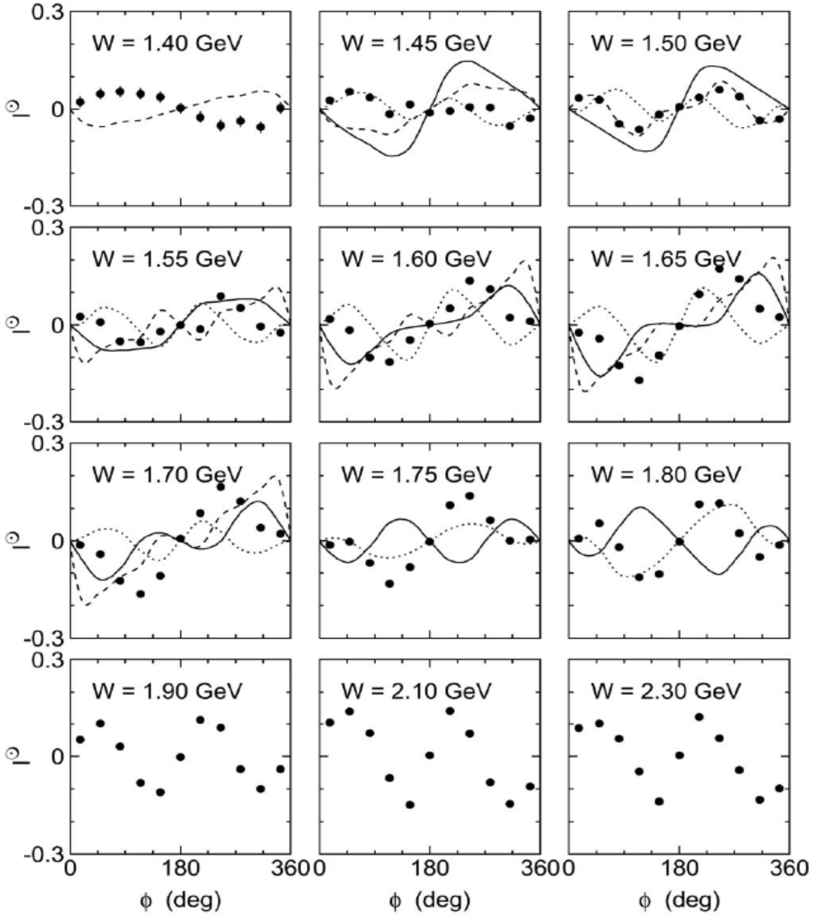
Photoproduction of $\pi^+\pi^-$ pairs from protons with circularly polarized beam

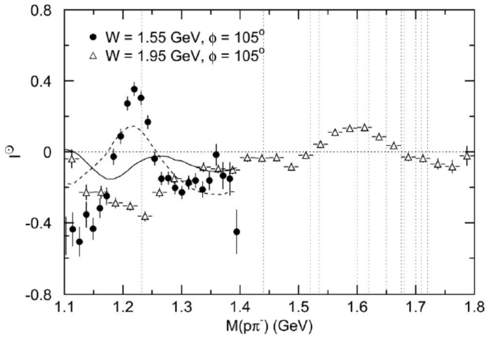
S. Strauch et al. (CLAS) PLR95 (2005), 162003

- 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
  - 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

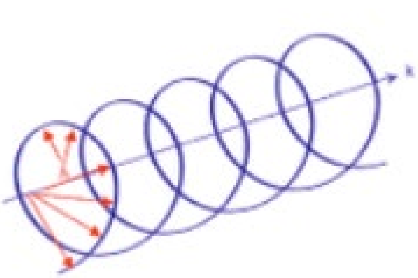


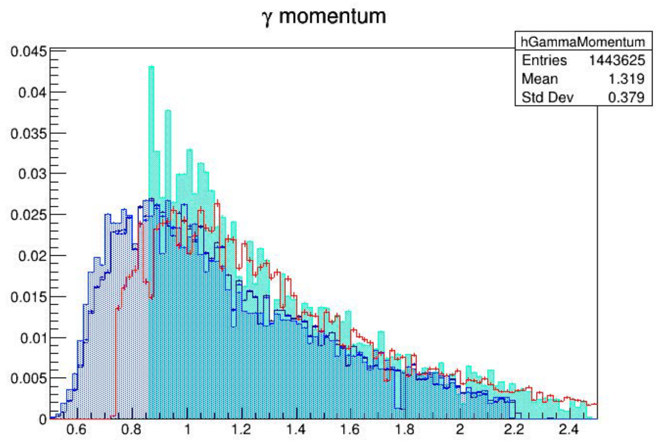


Experimental method – polarized beam and target

- 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

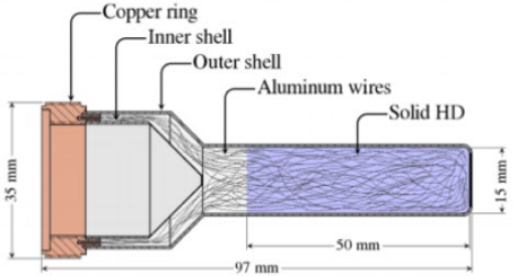


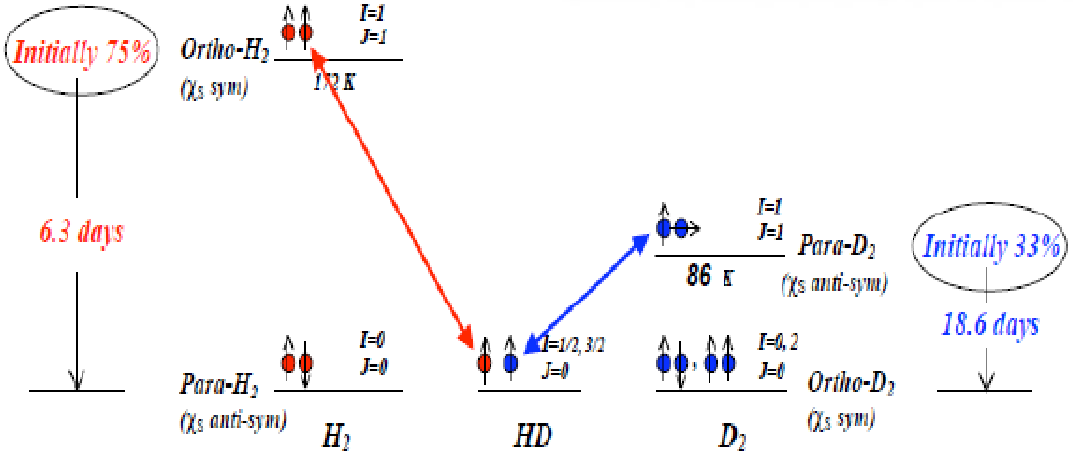


$$x = \frac{E_\gamma}{E_{beam}}$$

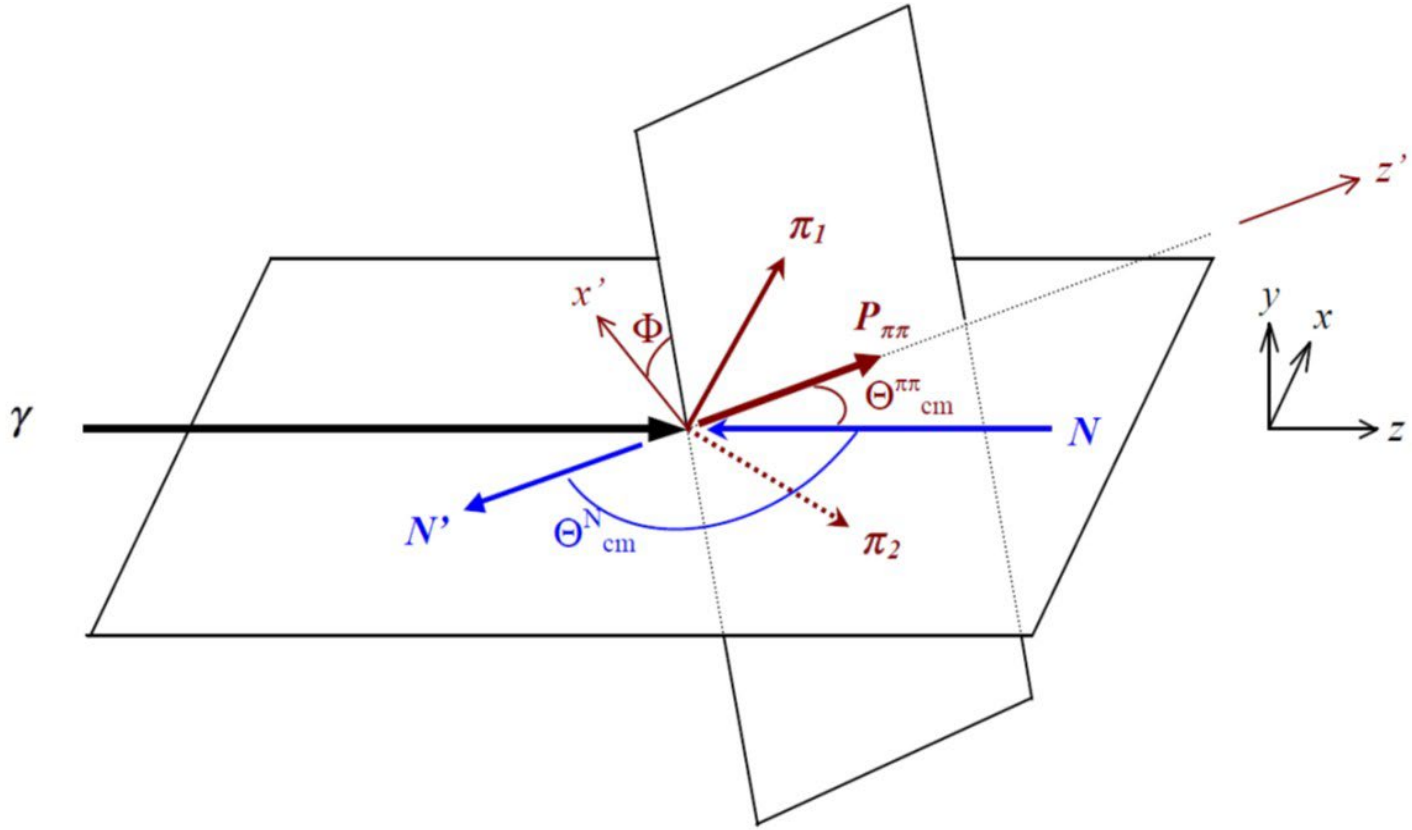
$$\delta_\odot = P_{el}\frac{4x - x^2}{4 - 4x + 3x^2}$$

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





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



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

- Differential cross-section 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 $I^{\odot}$, 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 (⇒/⇐) polarizations needed (with proper normalization)

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 (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

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

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

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

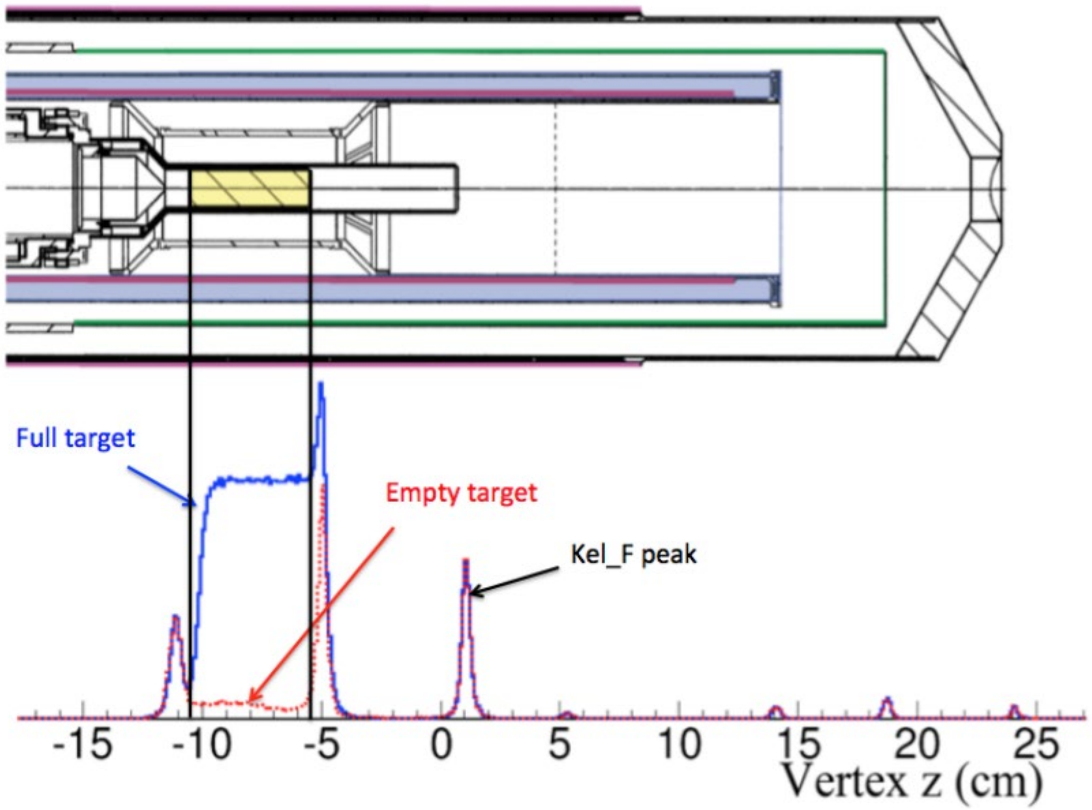
$$N_{exp}^{\leftarrow\Leftarrow} = \left(\frac{d\sigma}{d\Omega}\right)_0 \mathsf{L}\,\boldsymbol{\varepsilon}\left[1 - \Lambda_z P_z - \delta_\odot(I_\odot - \Lambda_z P_z^\odot)\right]$$

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

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

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

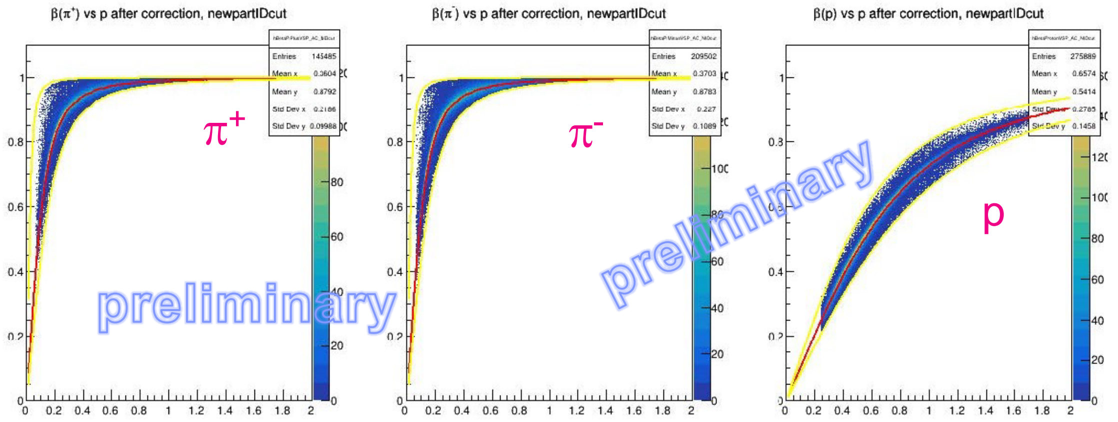
Experimental data: empty target subtraction



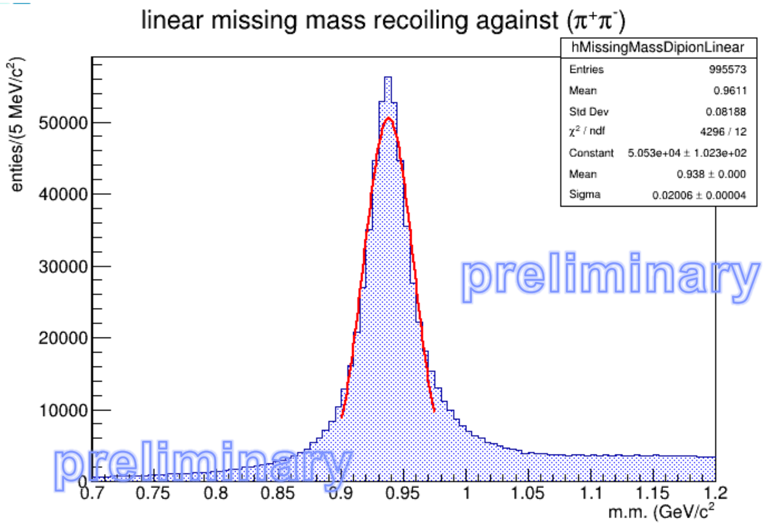
- Selection of events from the HD target: fiducial cut in r and z
- The events selected in the fiducial volume of the target contain the contribution from the target walls (unpolarized)
  - Empty target subtraction needed
  - Relative normalization of different runs: height of Kel-F wall peak
  - Subtraction 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

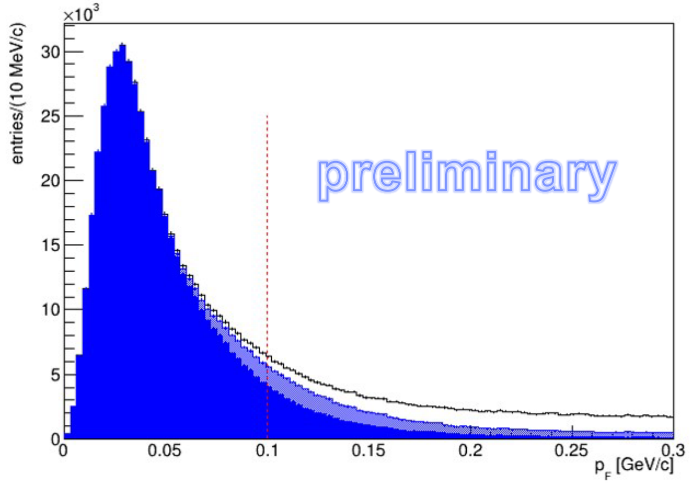
Description	Cut
Particle multiplicity	1 negative, 2 positives
Time coincidence	Time coincidence between: 1 proton, 1 π^+, 1 π^-
$2\pi p$ z-vertex in HD target	$-9.5 < z_{vertex} < -5.8$ cm
$2\pi p$ pId: β_{corr}	$p_{\pi\pm}/\sqrt{p^2_{\pi^\pm m} + (m_\pi - 80\ [\mathrm{MeV}])^2} \le \beta^{corr}_{\pi^\pm}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



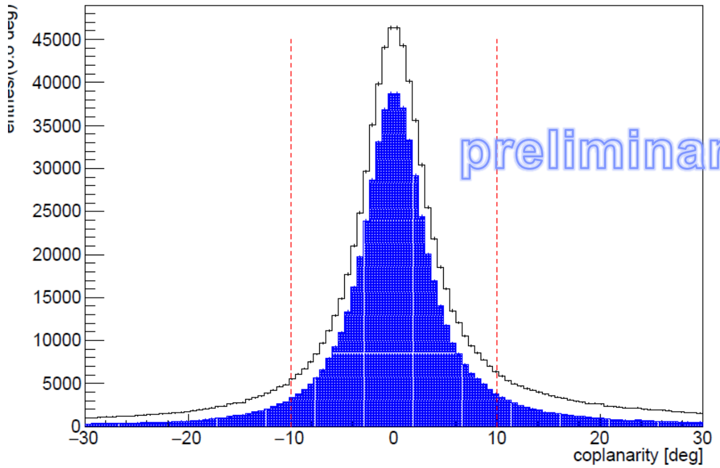
Particle ID for $\pi^+\pi^-$ and p based on TOF
Further selection on $(\pi^+\pi^-)$ missing mass to identify the proton



Total missing mass cut



Missing momentum cut: reject reactions without spectator at rest



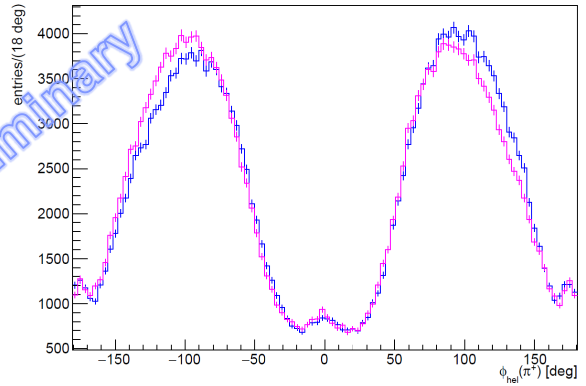
Coplanarity cut for pion pairs

Experimental angular distributions

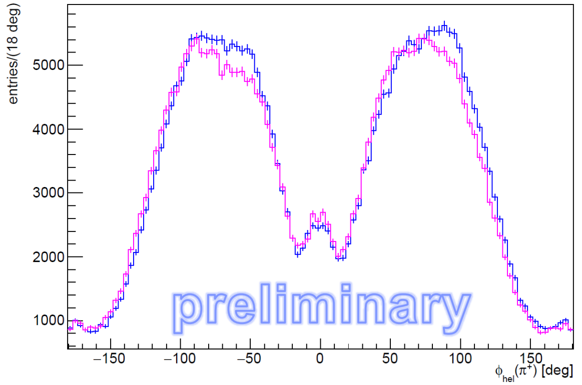
- Inputs: azimuthal angular distributions (φ_{hel})
- Bin by bin: number of events selected with
  - Given helicity (positive/negative in the same data set)
  - Given target polarization (in different data sets)
  - Selection in W energy ranges (~100 MeV wide window)
  - Counts to be properly normalized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

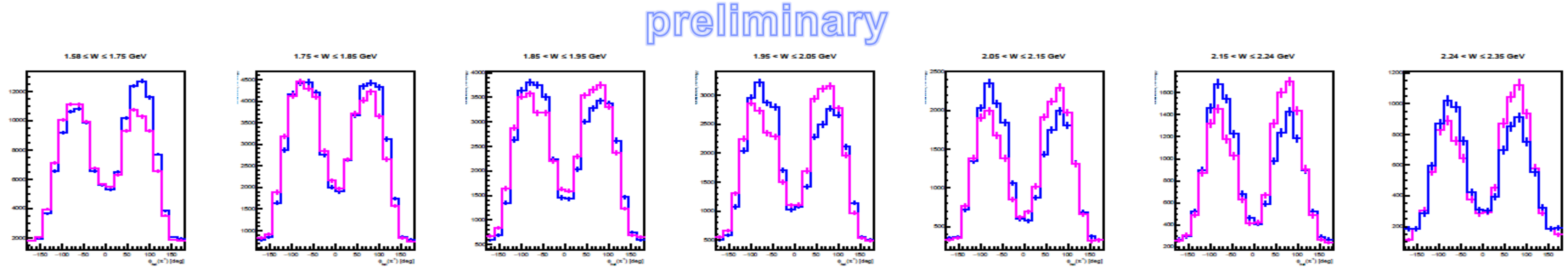
- Slight differences when selecting different combinations of helicities/target polarization: origin of the investigated asymmetries

Set w/ positive target polarization



Set w/ negative target polarization





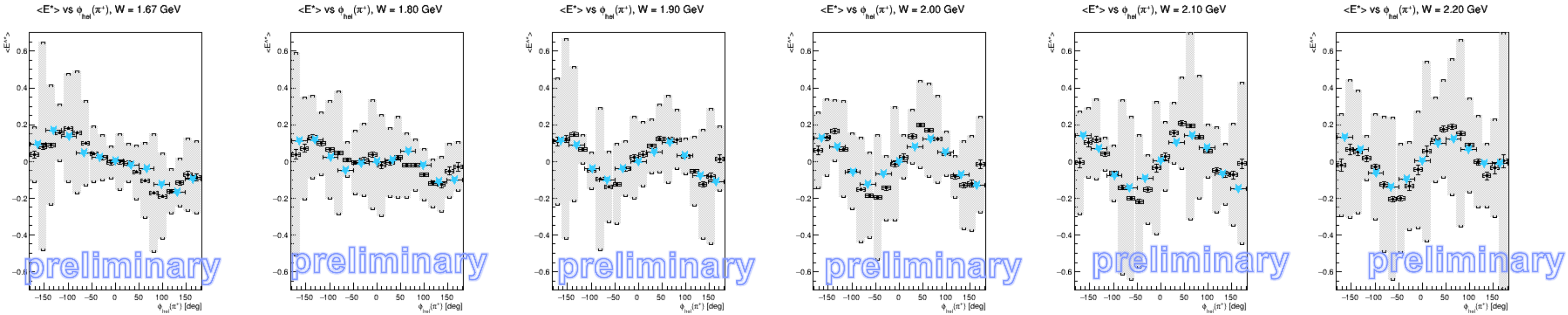
Evaluation of experimental beam-helicity asymmetries E*

- E* can be extracted from 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)
- Systematic errors (grey bars) from the spread of values obtained with different data sets

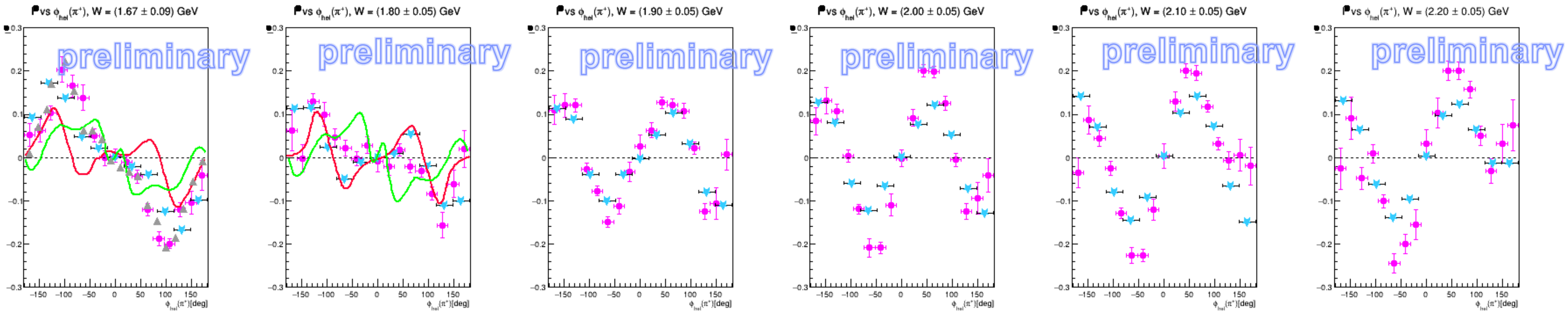
Blue points from S. Strauch et al., CLAS Coll., PRL**95** (2005), 162003



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

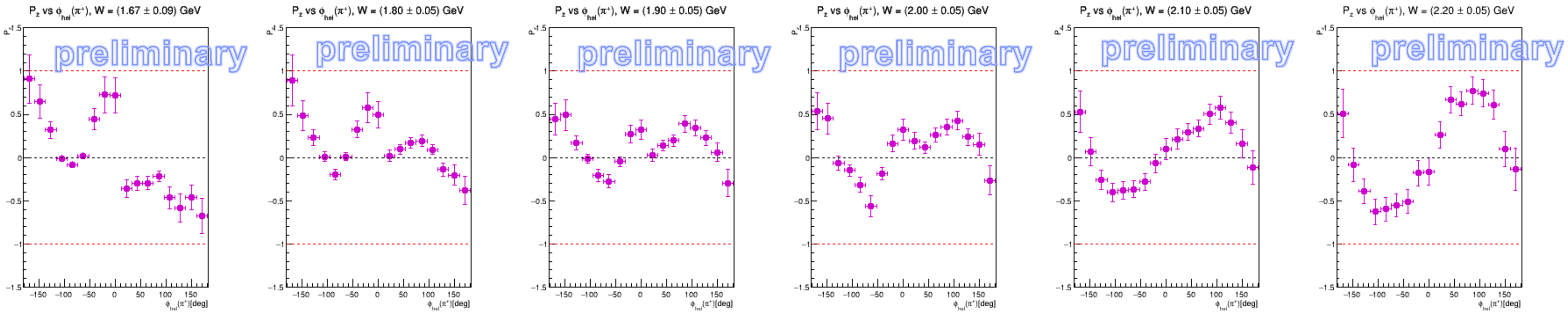
Blue points from S. Strauch et al., CLAS Coll., PRL **95** (2005), 162003



Preliminary results – P_z on proton

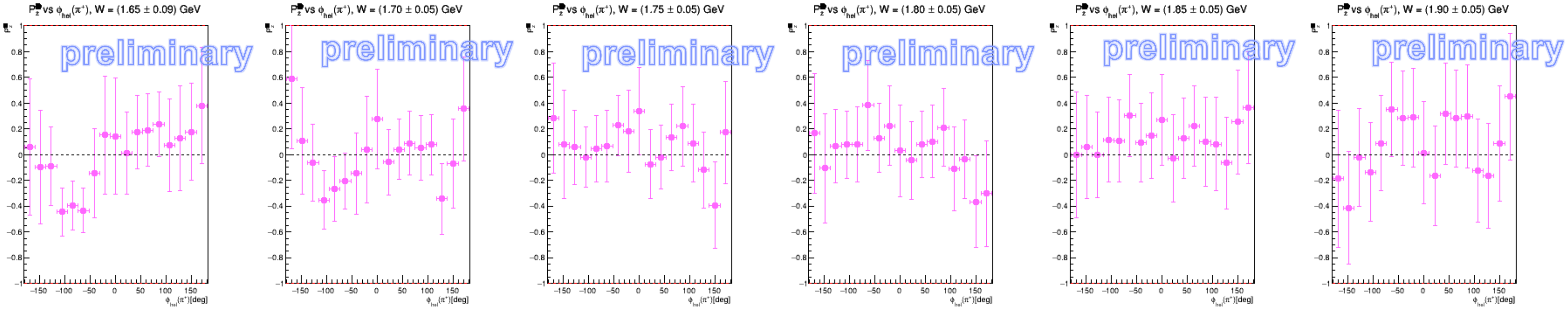
- No other results available for comparisons: first results ever
- P_z expected to be odd based on partial amplitudes symmetry
    - Vanishing at zero angle: coplanarity condition
    - *W*hen the helicity angle is oriented in the bottom hemisphere a sign flip occurs in Roberts' equations and, consequently, 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 on the richest data sets, extraction of results for other available compatible data sets 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 contributions calls for new models updating the interference patterns and reproducing the new observables
  - So far, none of the available reaction models agrees satisfactorily with the extracted asymmetries