# Measurement of Polarization Observables $P_z$ , $P^s_z$ and $P^c_z$ in Double-Pion Photoproduction off the Proton

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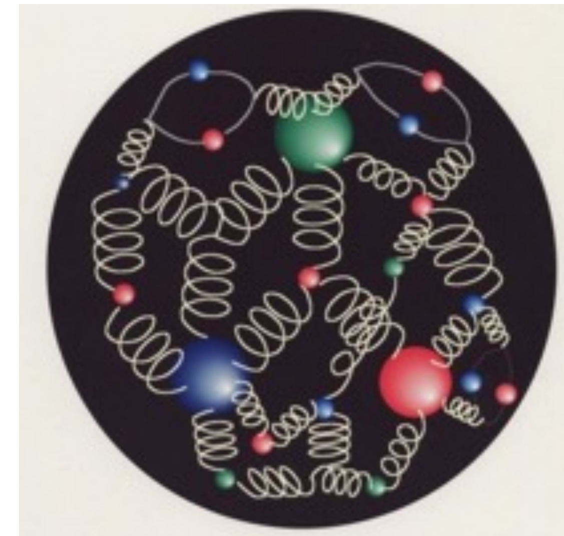
# Outline

- Motivation
- The FROST experiment
- Data analysis
- Results
- Conclusion

# Baryon spectroscopy

The "Triple-Scoop" Baryon
archive.news.softpedia.com

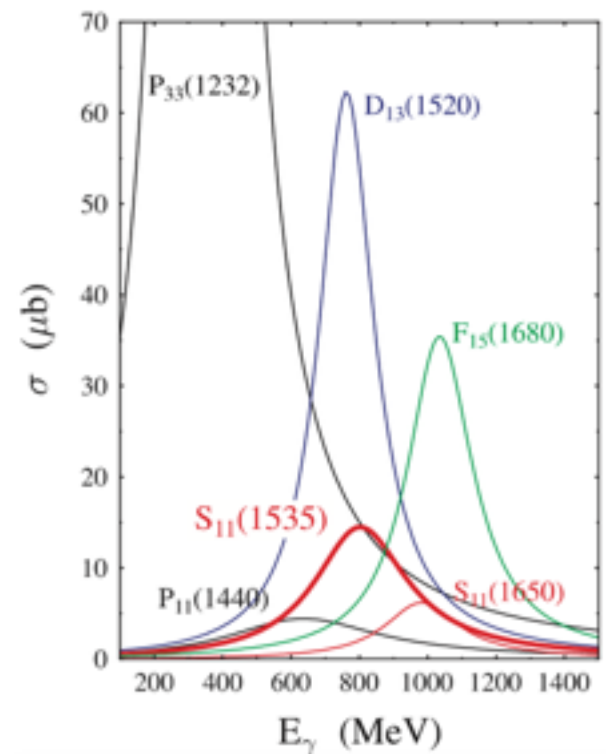


Baryon

## Baryon resonance properties

- Invariant mass
- Charge
- Width
- Decay modes
- Quantum numbers (spin, isospin, parity)

$\gamma + p \rightarrow N^*, \Delta^* \rightarrow N + \pi$




Nucleon excited states

Experimental Observables ⟷ Quark models of Baryons

↘ ↙

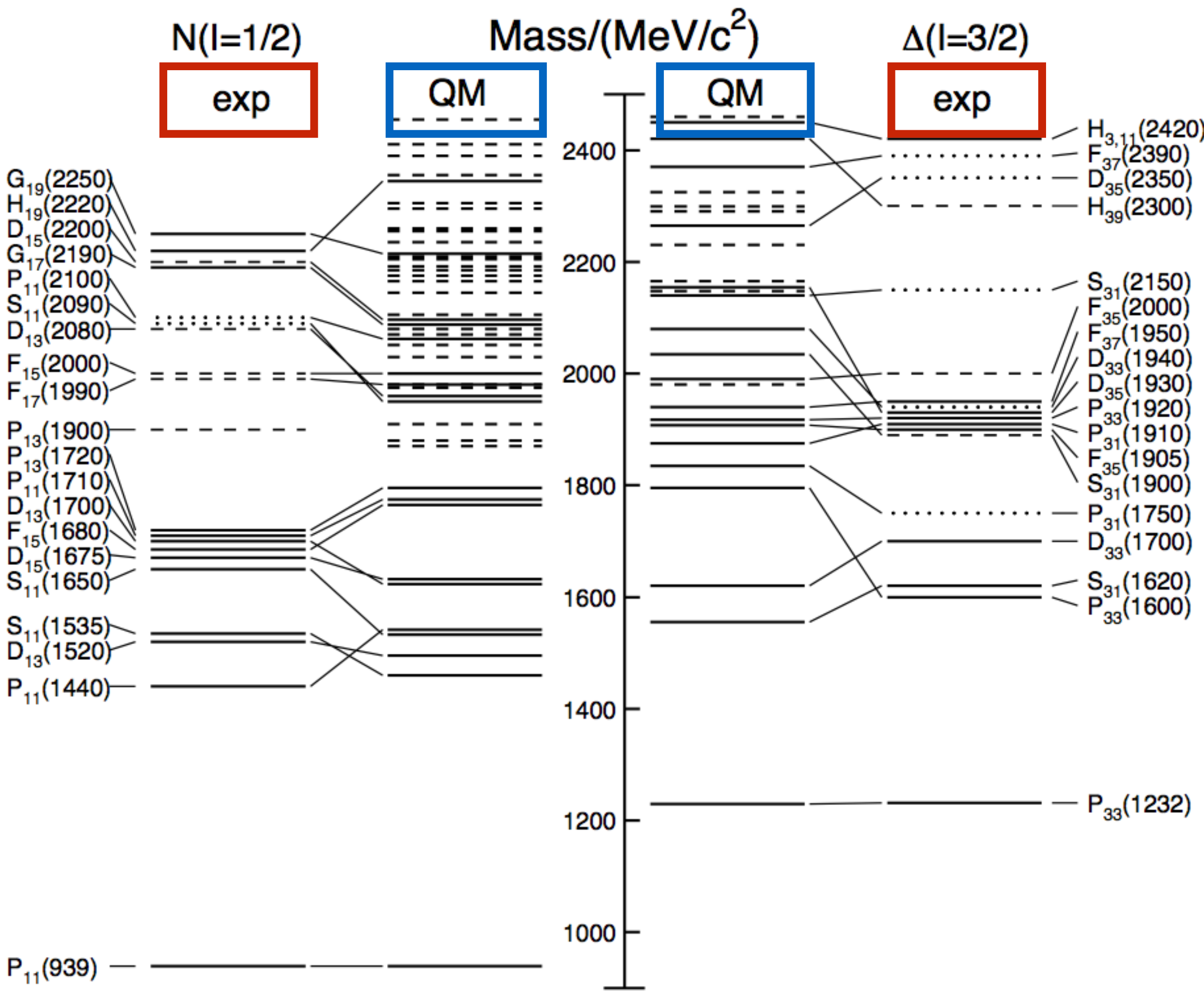
Baryon spectrum

↓

QCD

D. Griffiths, *Introduction to elementary particles*, Wiley. com (2008).

# Missing resonance problem




S. Capstick and W. Roberts, Phys. Rev. **D49**, 4570 (1994); *ibid.*, **D57**, 4301 (1998); *ibid.*, **D58**, 074011 (1998).

**Quark models predict more nucleon resonances than have been observed.**

- Insufficient experimental data?

or

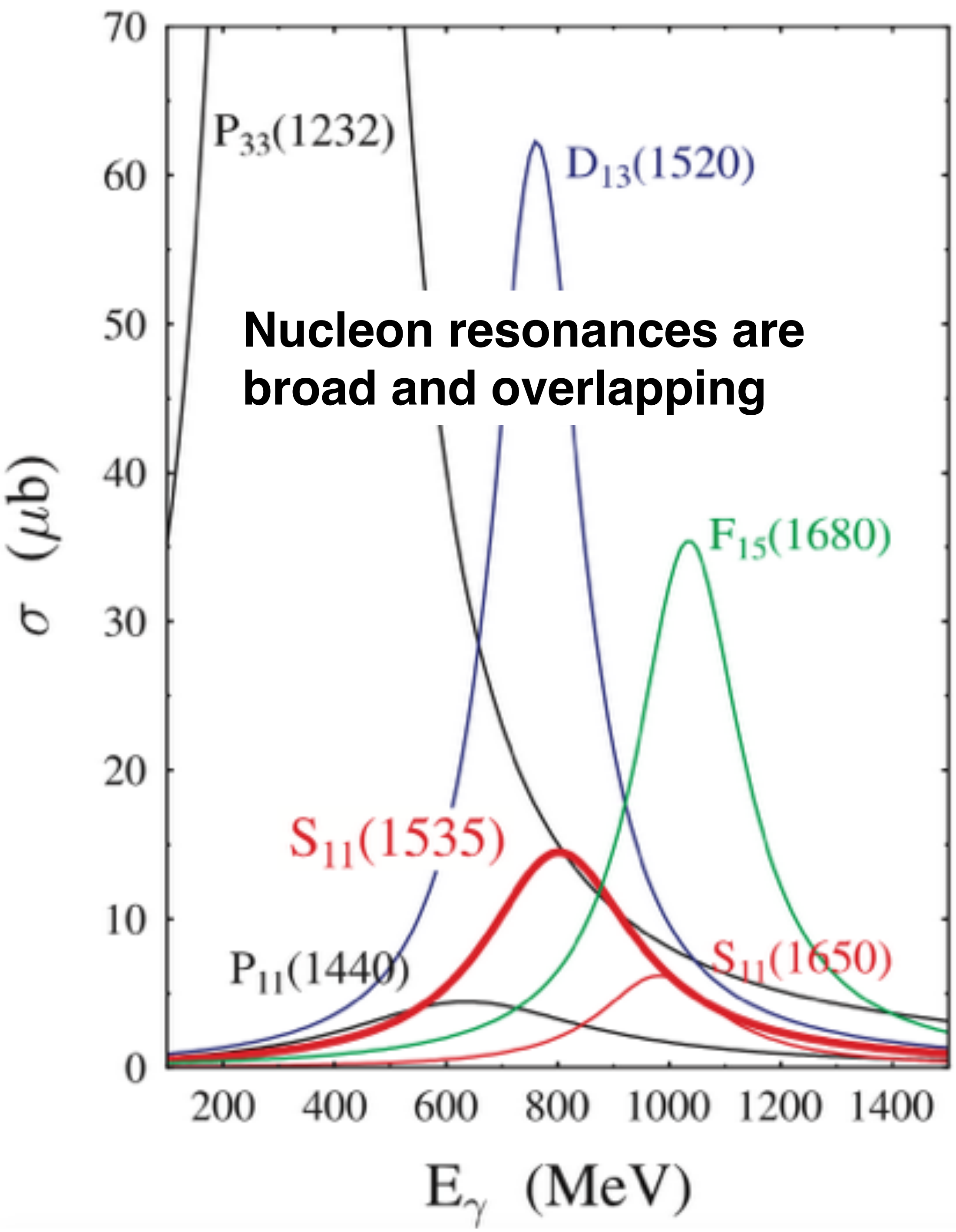
- Incorrect model description of the nucleon?

  (Various models use different effective degrees of freedom)

New resonances have been observed in recent analyses of new data.

# Polarization observables in double-pion photoproduction

$\gamma + \mathrm{p} \rightarrow \mathrm{N}^*, \Delta^* \rightarrow \mathrm{N} + \pi$




- The cross section is proportional to the transition amplitude squared,

$$I \propto |M|^2$$

- The unpolarized cross section is:

$$I_0 \propto \sum_{i=1}^{4} (|M_i^-|^2 + |M_i^+|^2)$$

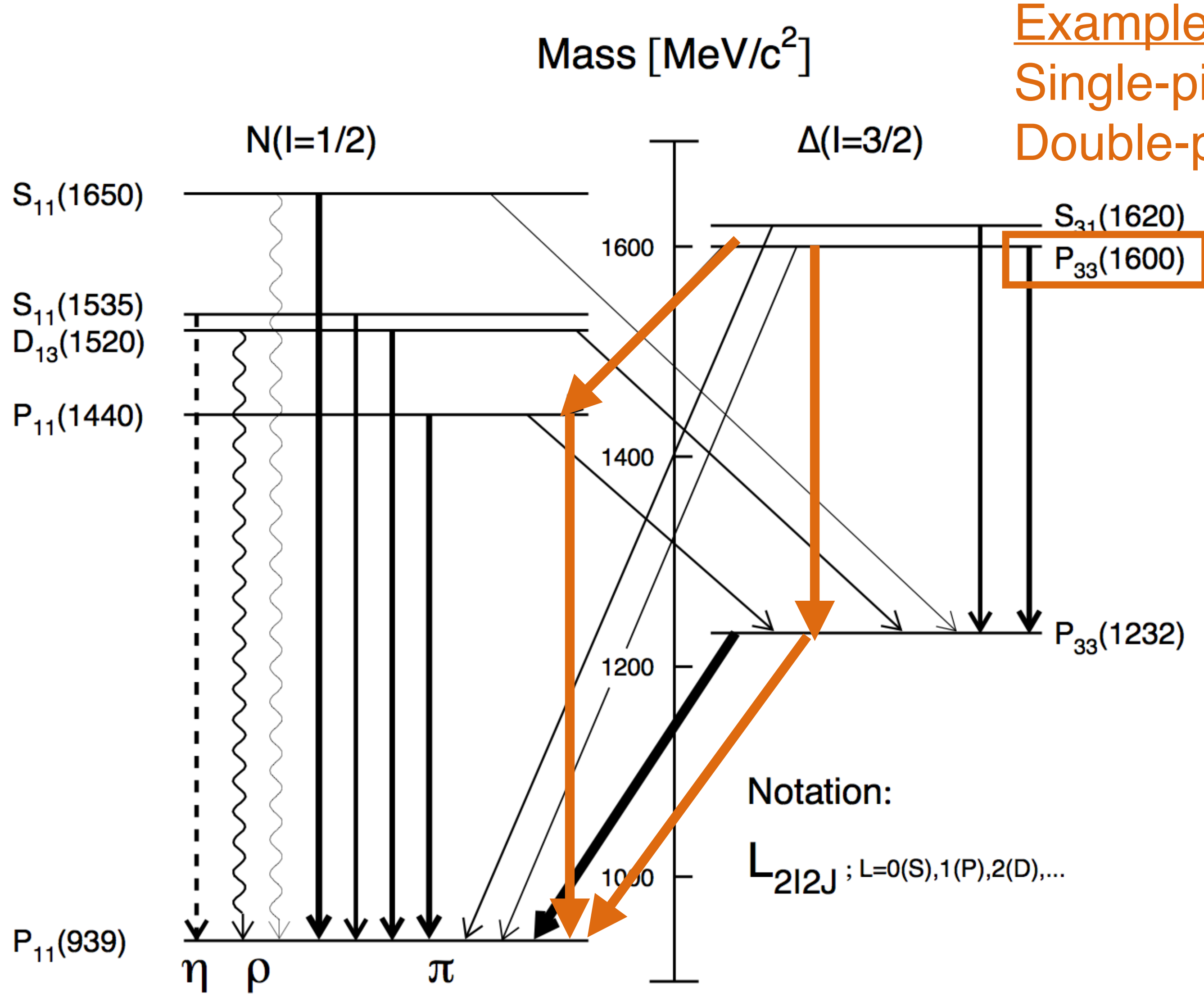
- Double observable $\mathbf{P^c_z}$ involved:

$$I_0 P_z^c \propto \Re(M_1^+ M_1^{-*} + M_2^+ M_2^{-*} - M_3^+ M_3^{-*} - M_4^+ M_4^{-*})$$

Advantage of polarization observables:

- Study phase differences of complex amplitudes
- Study small amplitudes

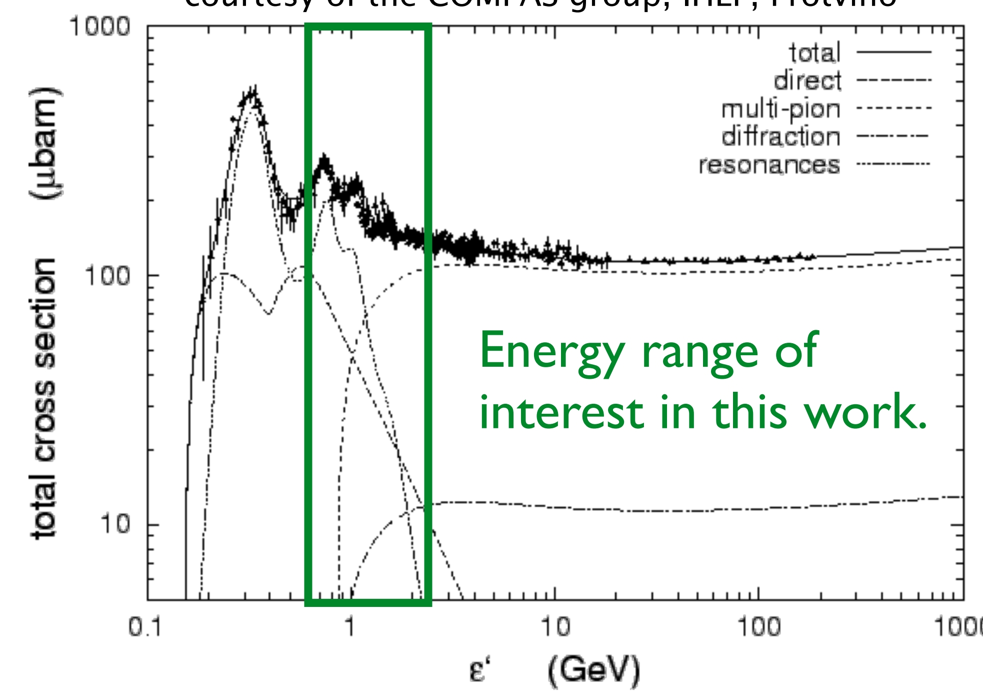
# Double-pion photoproduction




Example: $P_{33}$(1600)
Single-pion (10-25%)
Double-pion (75-90%)

B. Krusche, S. Schadmand / Prog. Part. Nucl. Phys. 51 (2003) 399–485

http://pdg.lbl.gov/current/ xsect/,
courtesy of the COMPAS group, IHEP, Protvino




Double-pion photoproduction allows the study of resonances, which decay through multiple intermediate states.

Double-pion photoproduction channel dominates at photon energies above 600 MeV.

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# Thomas Jefferson National Accelerator Facility

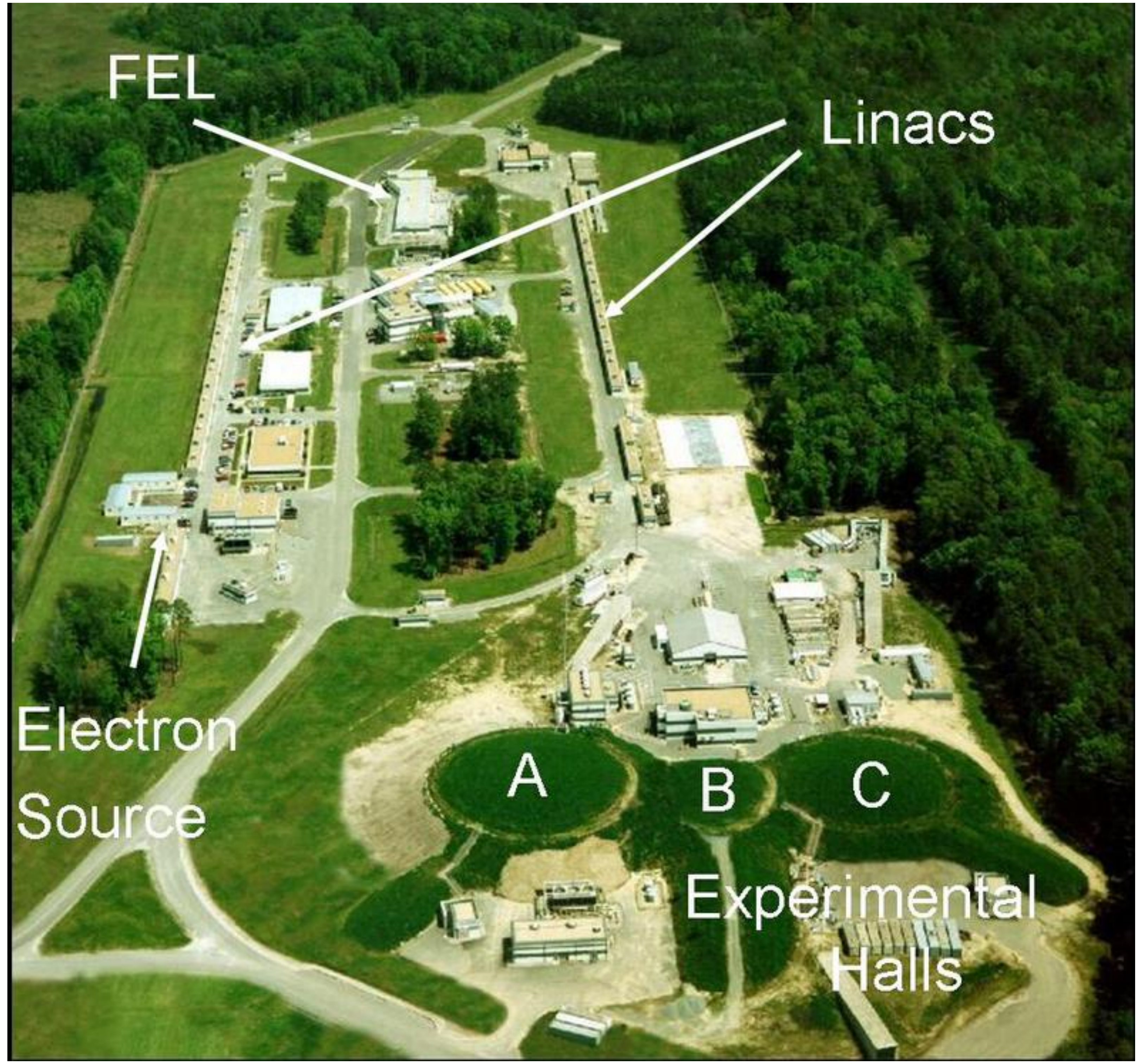
Photoproduction experiment,

$$\gamma p \rightarrow p\pi^+\pi^-$$

with polarized beam and target at center of mass energies,

W = 1.46 - 2.25 GeV.

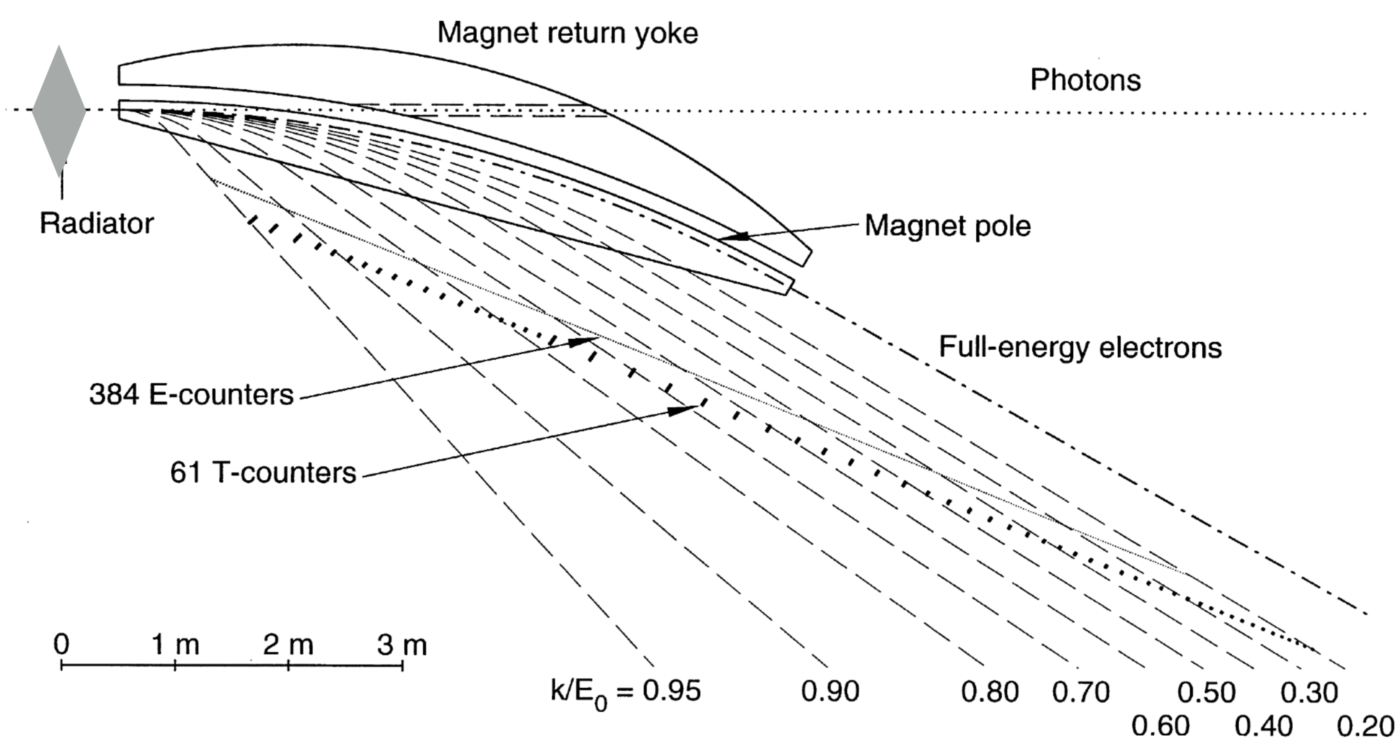
Data were taken as part of the FROST program at Jefferson Lab, Hall B.




http://www.jlab.org/

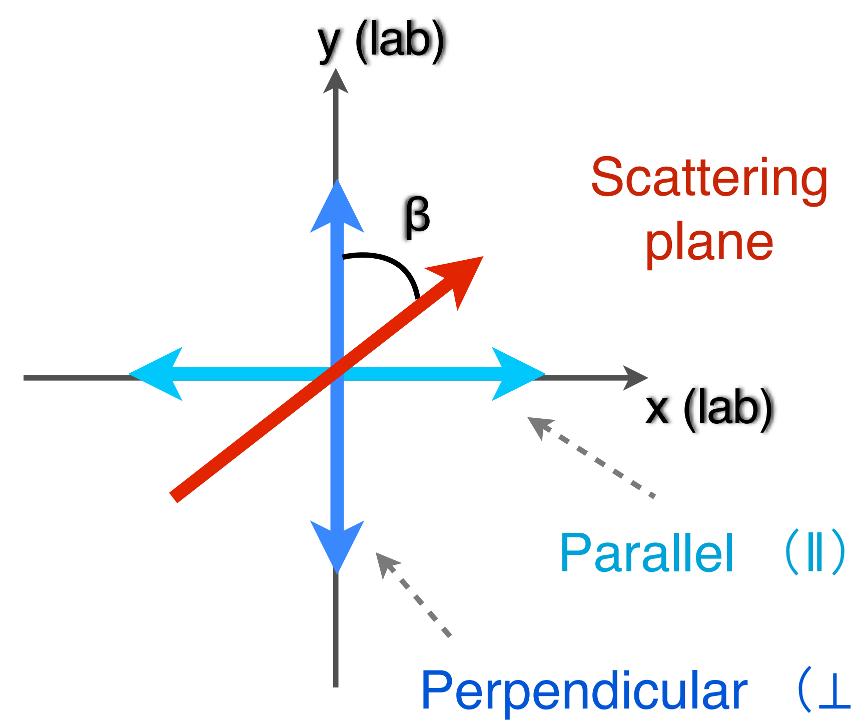
# Linearly polarized photon beam

Side view




D. Sober *et al.*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **440** (2000) 263 .

Downstream view

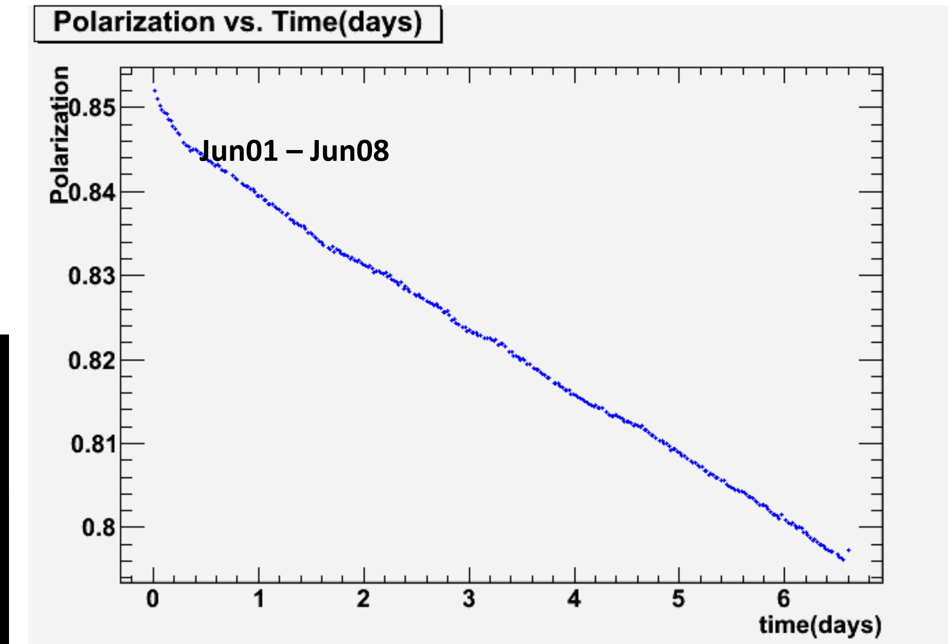


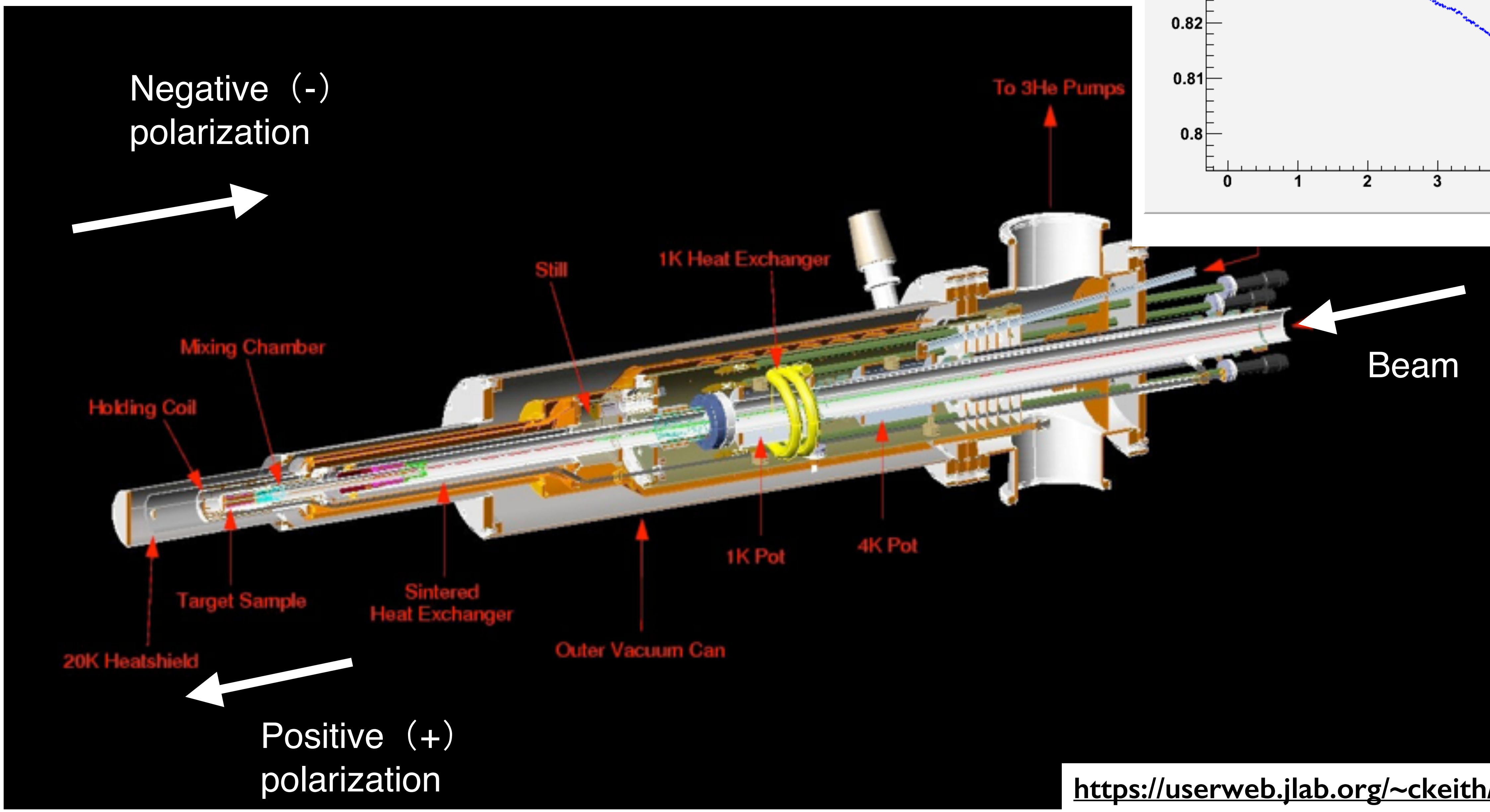

- **Photon tagger**:
  - Diamond radiator for coherent bremsstrahlung
  - Production of linearly polarized photons
  - Detection of recoiling electrons allows determination of photon energy

- **Linearly polarized photons**:
  - Degree of polarization up to 80%
  - Polarization direction: perpendicular or parallel to the floor

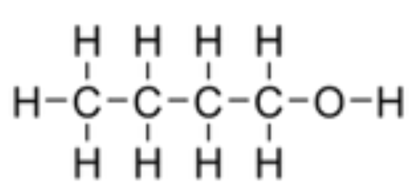
# FRozen Spin Target (FROST)

- Free protons in butanol target are polarized up to 90%
- The polarization direction is either parallel or anti-parallel to the beam direction



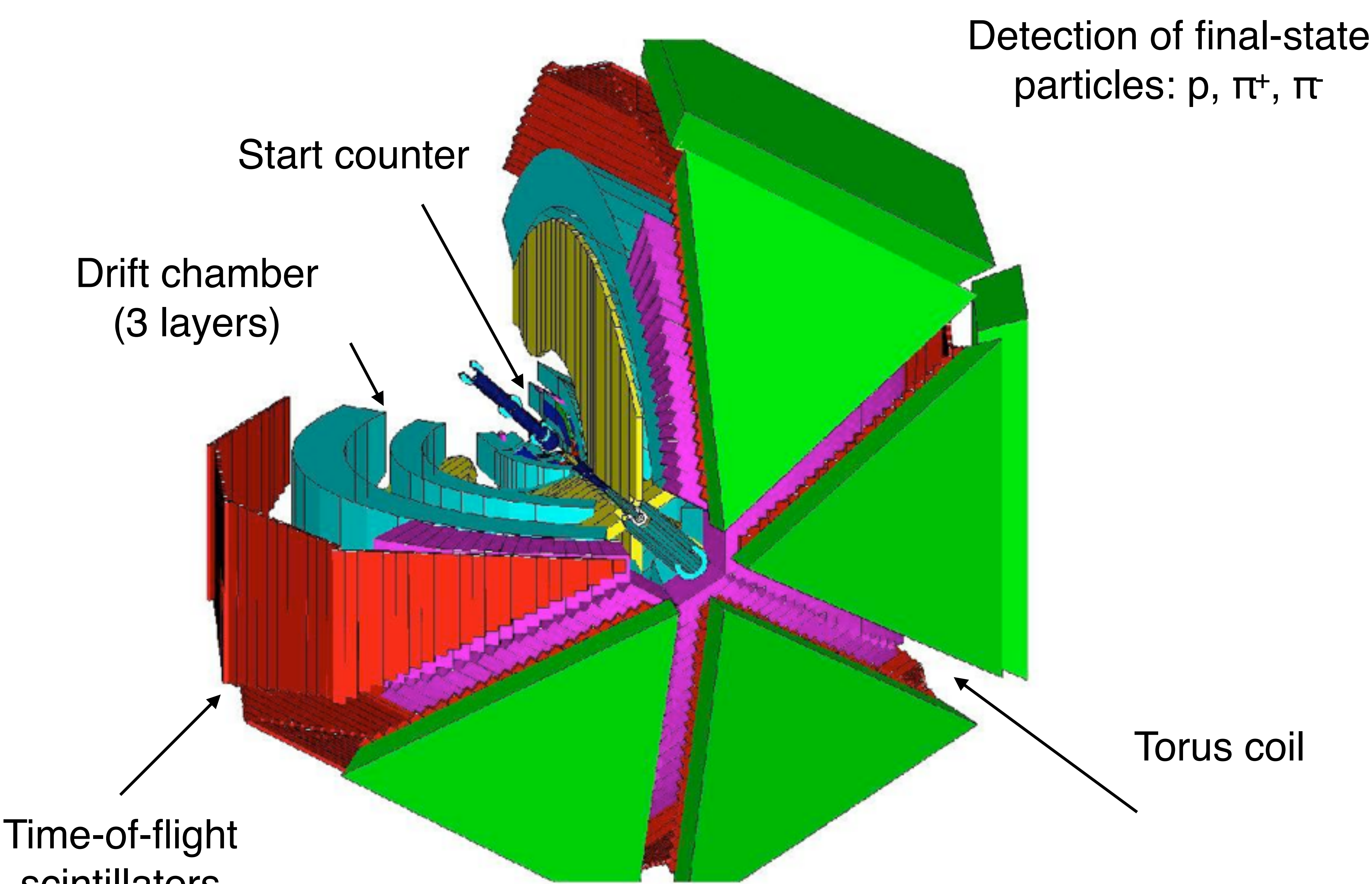




https://userweb.jlab.org/~ckeith/Frozen/Frozen.html

Butanol (polarized) —


Carbon (unpolarized) — $C^{12}$

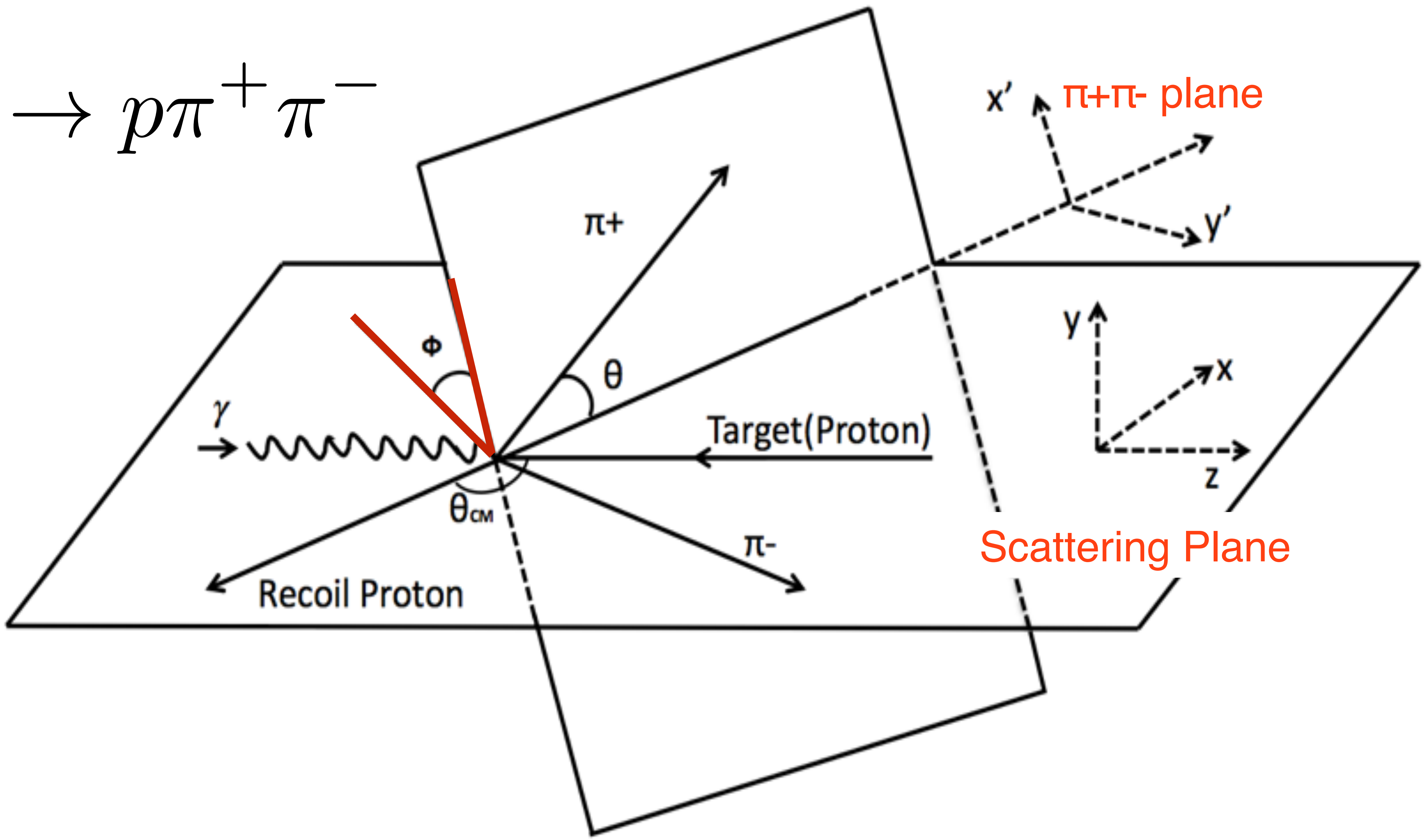
# CEBAF Large Acceptance Spectrometer (CLAS)




M. Mestayer *et al.*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **449** (2000) 81 .

# Definition of kinematic variables

$$\gamma p \to p\pi^+\pi^-$$




- Particle angles in the center-of-mass frame
- Polarization observables are extracted as a function of the azimuthal angle Φ

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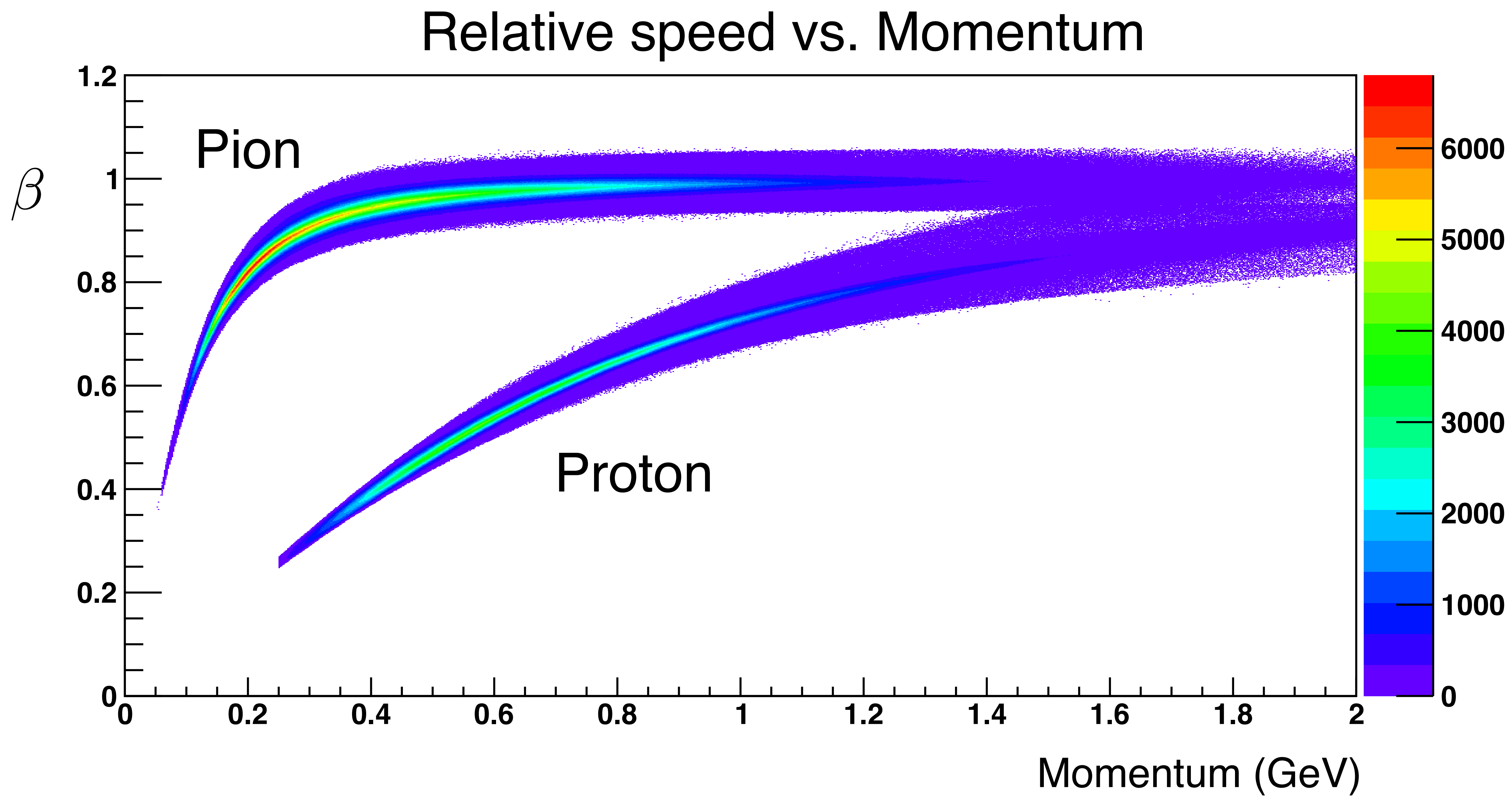
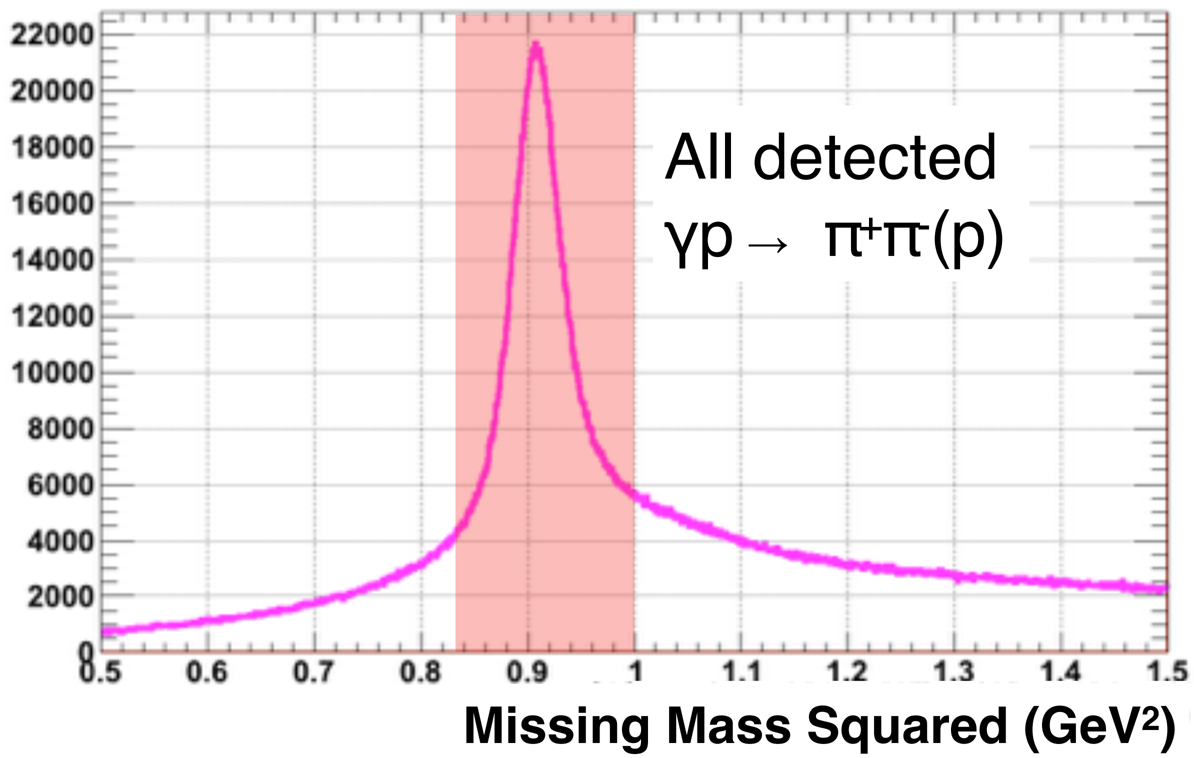
# Particle identification

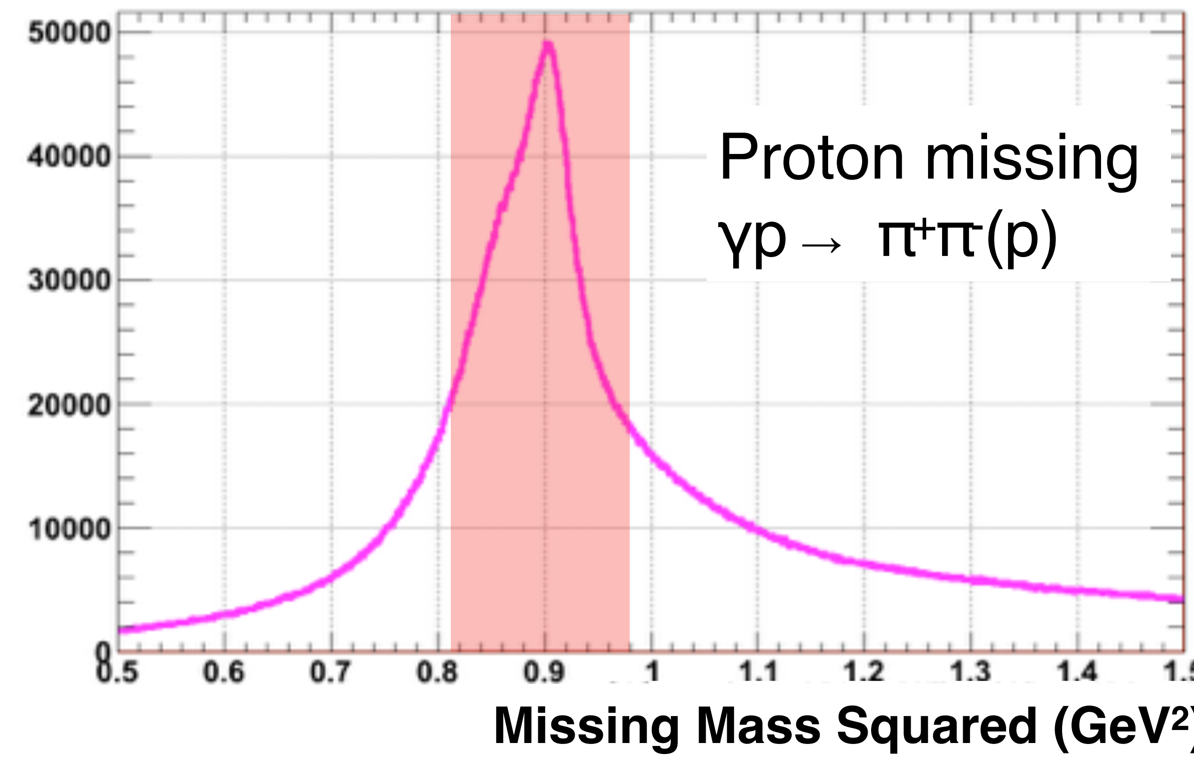
Example: positively charged particles

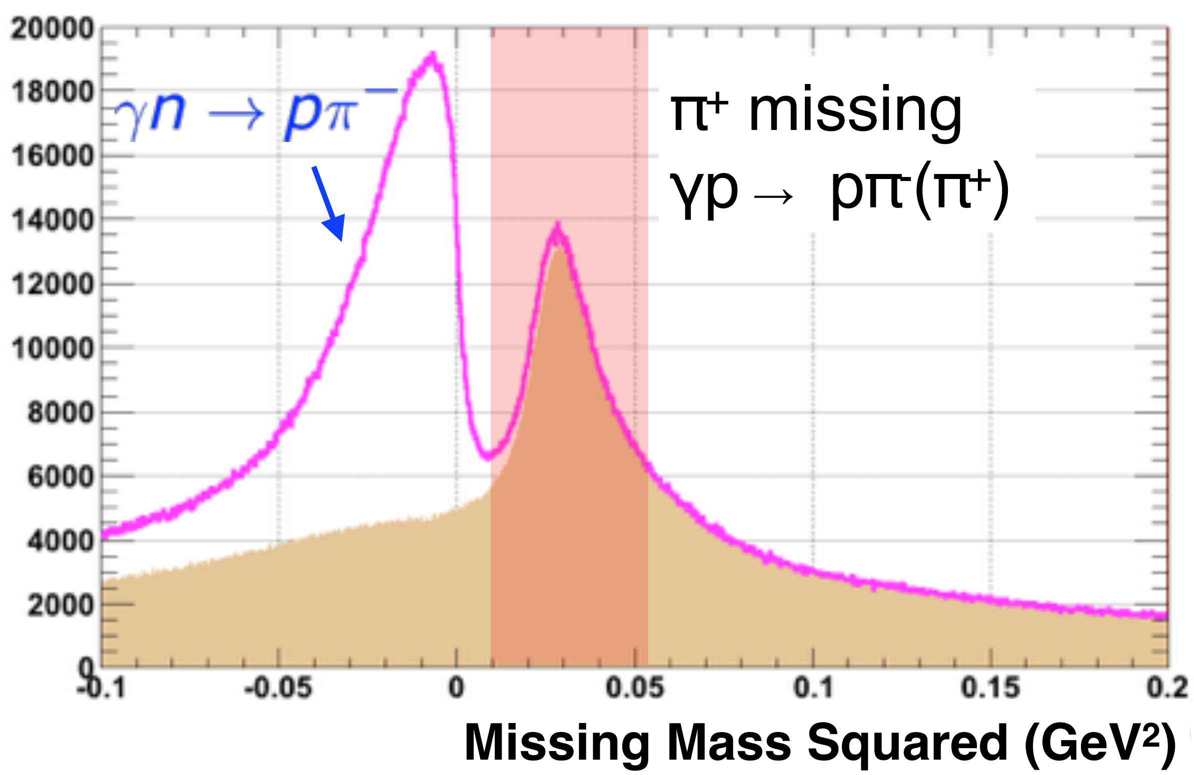


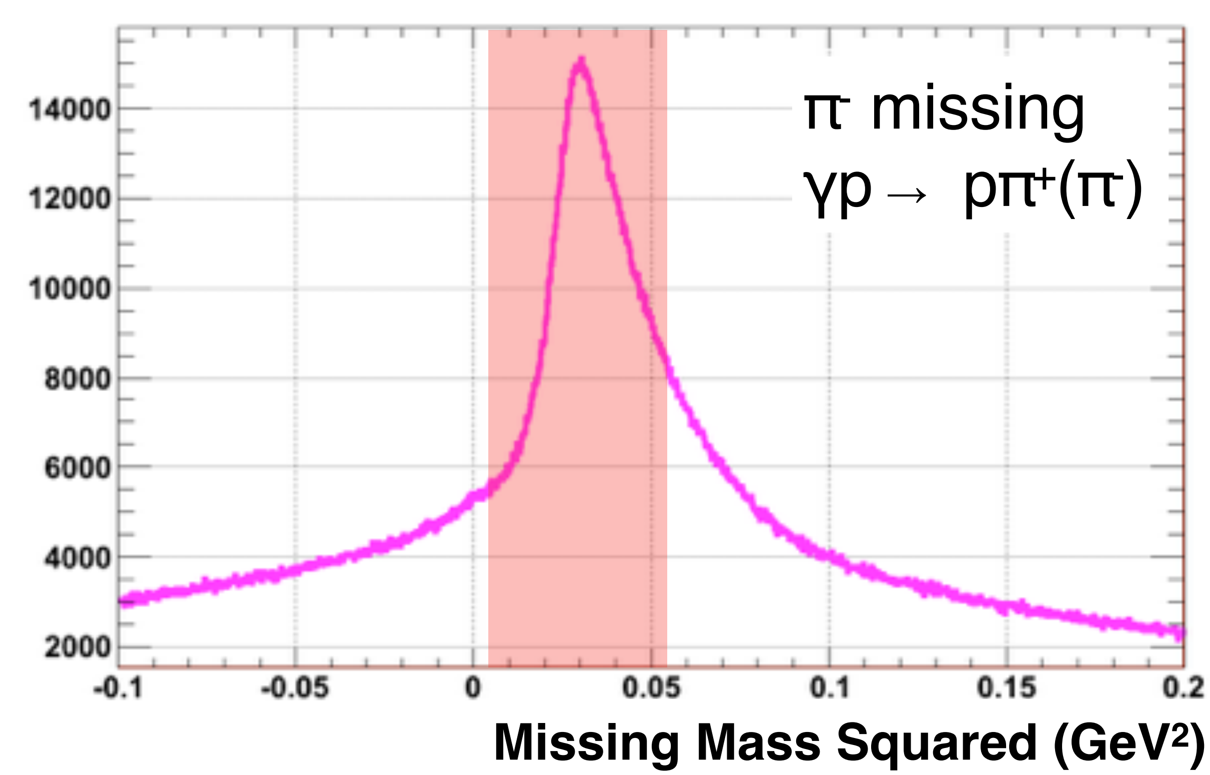
# Reaction ID: Missing-mass technique

Shaded area — Events of interest

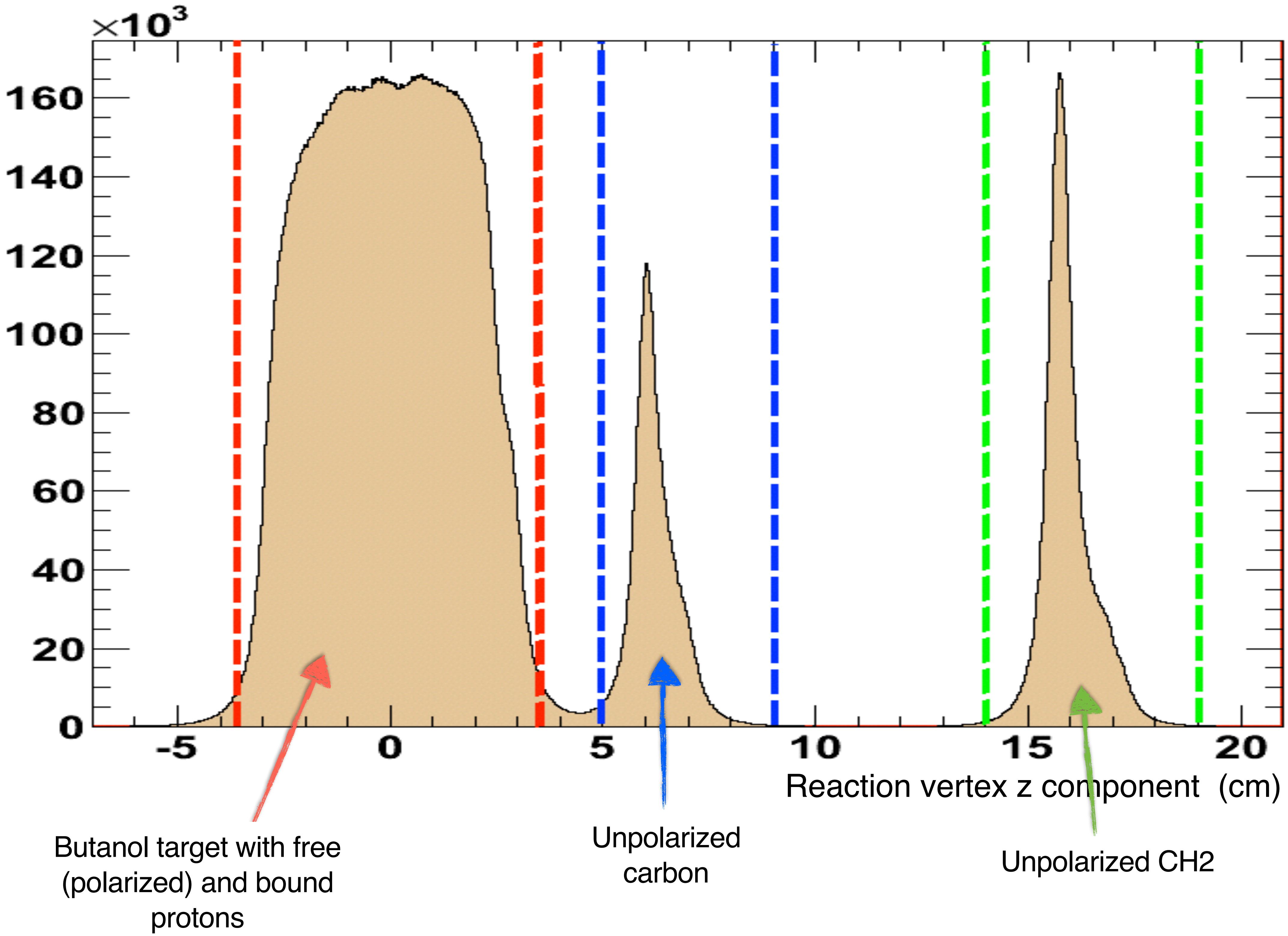


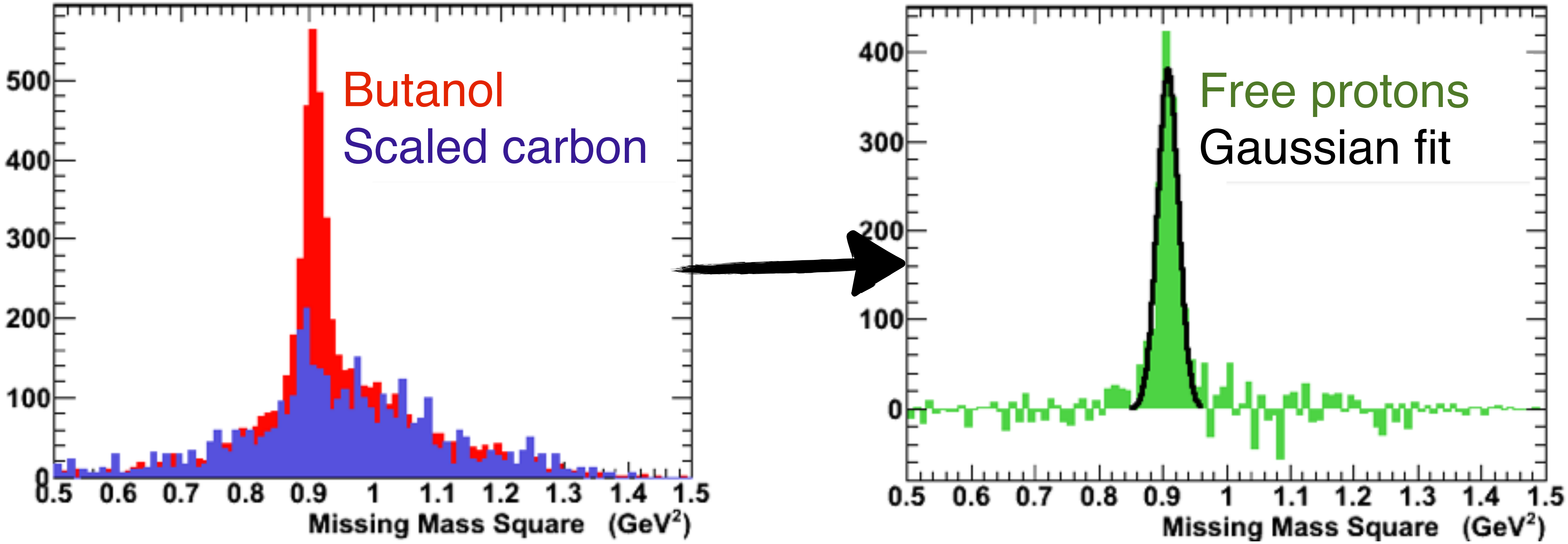
# Target selection



# Background determination

Butanol-target yield is diluted by bound-nucleon background

Topology1 (all particles detected)




**Dilution factor**: Fraction of polarized free-proton events in the sample of butanol-target events

**Definition** $$h = \frac{Y_0}{Y_0 + Y_b}$$

**Calculation** $$h \approx \frac{N_B - \alpha N_C}{N_B}$$

# Polarized cross section

Cross-section formula when (1) Target longitudinally polarized
(2) Photon beam linearly polarized

$$I = I_0\{(1 + \Lambda P_z$$
$$+\delta_l[\sin 2\beta(I^s + \Lambda P_z^s) + \cos 2\beta(I^c + \Lambda P_z^c)]\}$$

| | |
|---|---|
| | Observables of interest: $P_z$, $P^c_z$ and $P^s_z$ |
| | Target polarization vector |
| | Beam polarization degree |
| $I$ | Polarized cross section |
| $I_0$ | Unpolarized cross section |

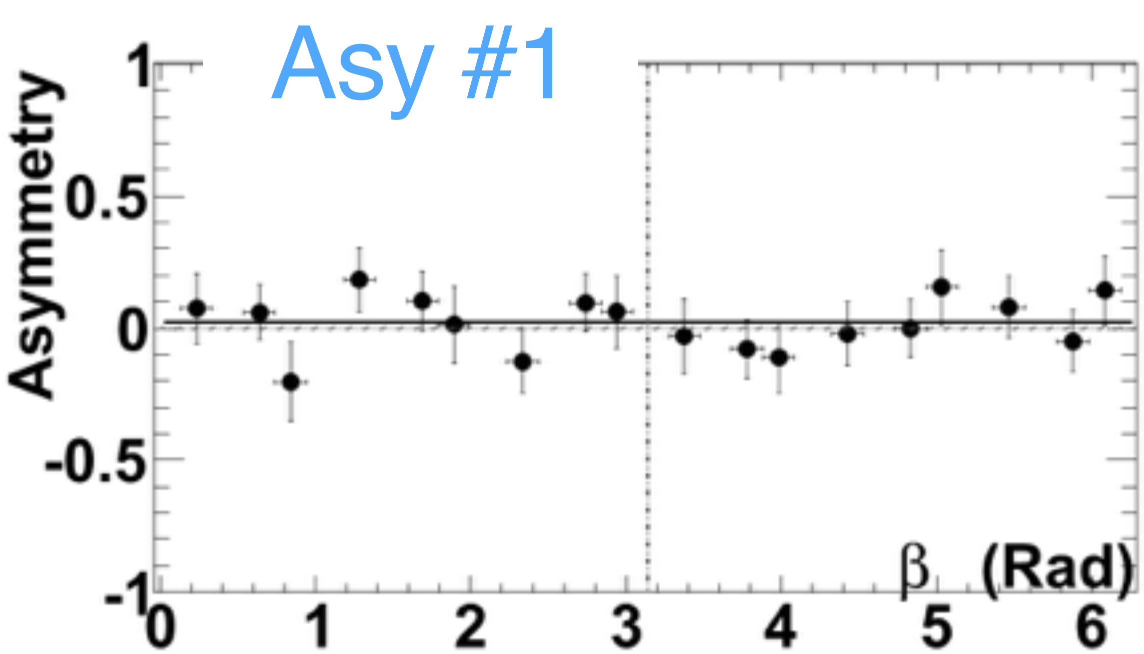
# From asymmetry to observables

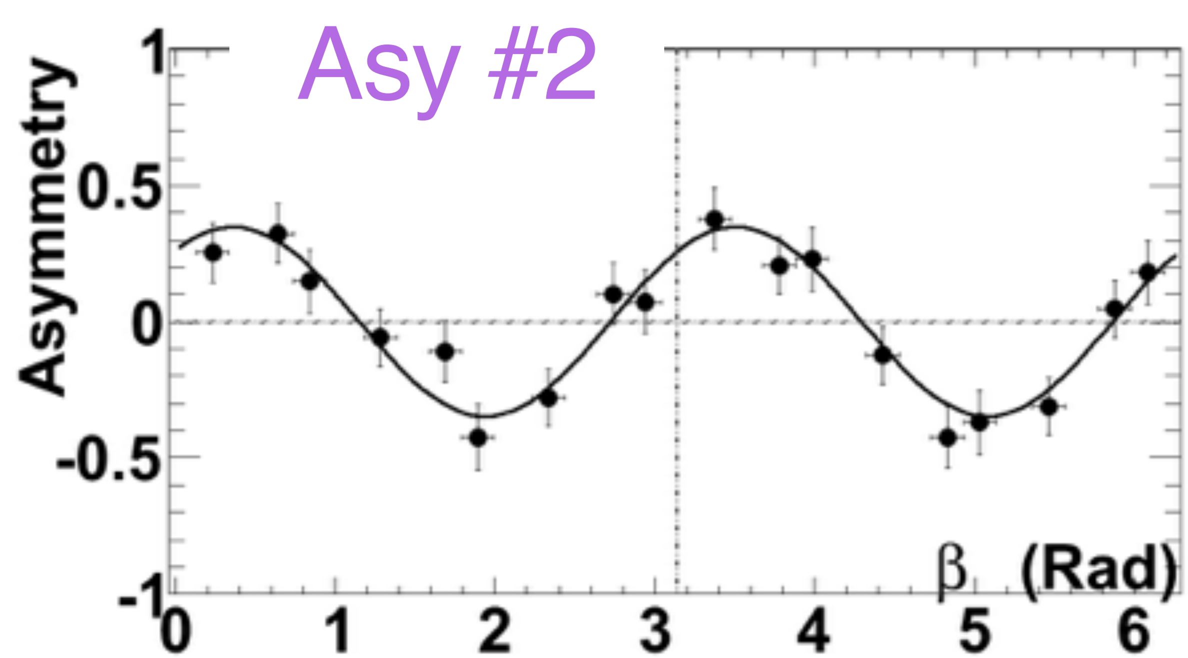
The yields $Y_+^{\parallel}, Y_+^{\perp}, Y_-^{\parallel}, Y_-^{\perp}$, are normalized before asymmetry calculation

**Asy #1:** $$\frac{(Y_+^{\perp}+Y_+^{\parallel})-(Y_-^{\perp}+Y_-^{\parallel})}{(Y_+^{\perp}+Y_+^{\parallel})+(Y_-^{\perp}+Y_-^{\parallel})}=\lambda h P_z$$

**Asy #2:** $$\frac{(Y_+^{\perp}-Y_+^{\parallel})-(Y_-^{\perp}-Y_-^{\parallel})}{(Y_+^{\perp}+Y_+^{\parallel})+(Y_-^{\perp}+Y_-^{\parallel})}=\lambda\delta h(\sin 2\beta\cdot P_z^s+\cos 2\beta\cdot P_z^c)$$

Example: W = 1.67 GeV, ϕ = 75 deg.



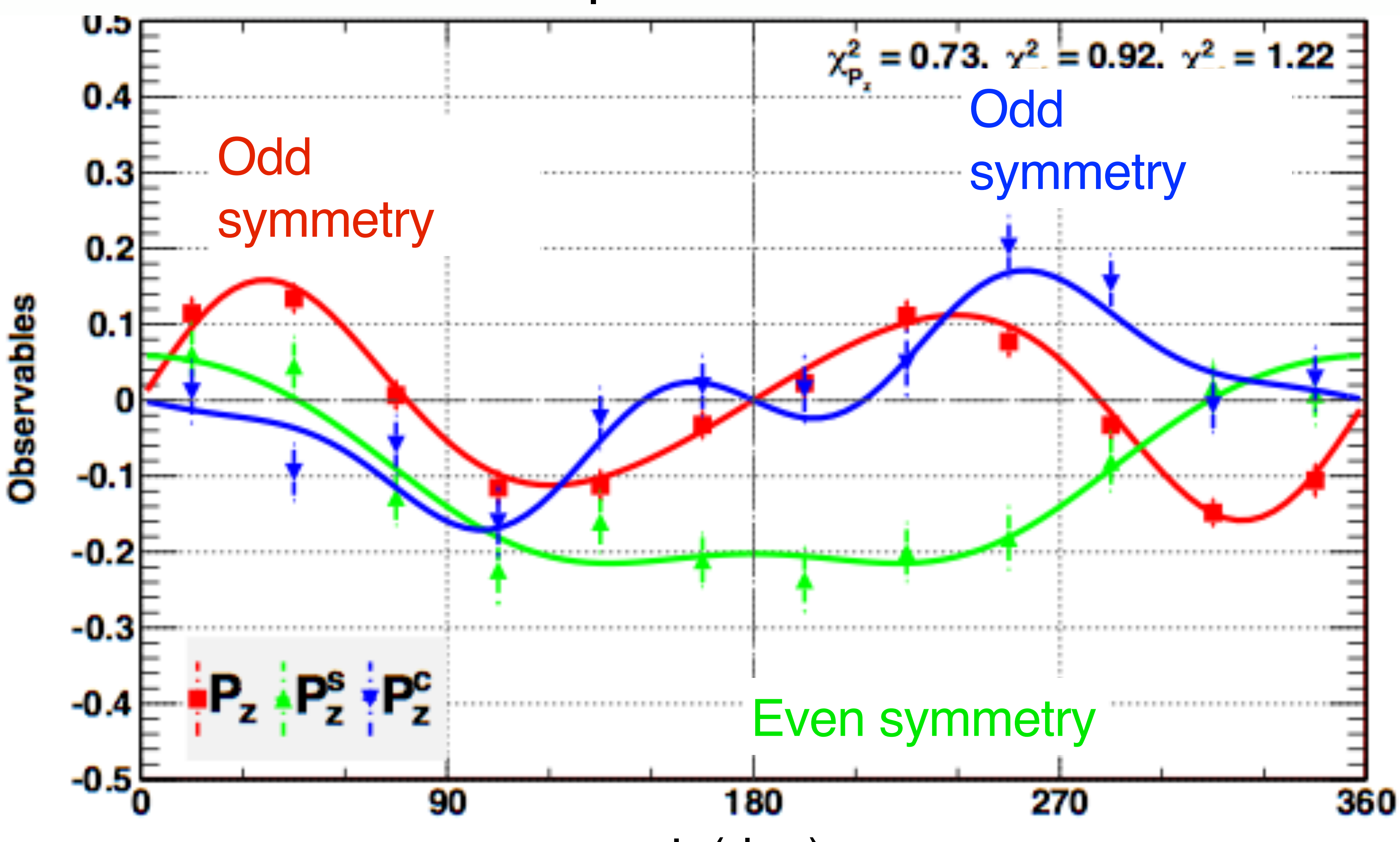




The differences in the degrees of target and beam polarizations were accounted for in the asymmetry calculation

# Angular distribution of observables

12 Φ bins for each W bin
Fit with Fourier series

Example: W=1.67 GeV

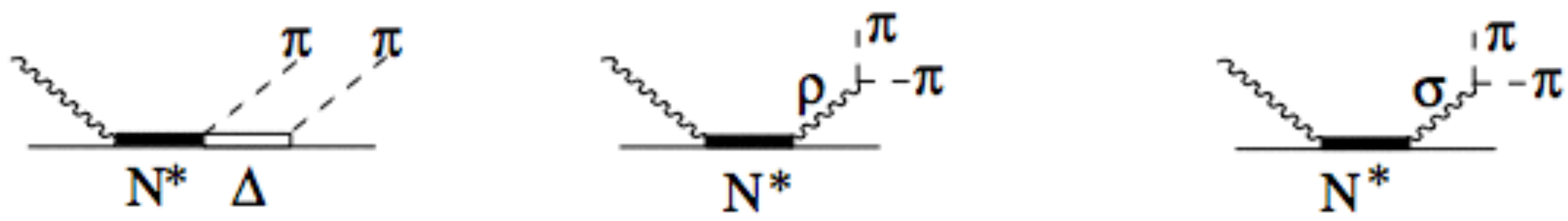



Φ (deg)

# Effective Lagrangian model

Diagrams of N* for the reaction γN → ππN

- N-Born terms
- Δ-Born terms




A. Fix and H. Arenhovel, Eur.Phys.J. **A25** (2005) 115, nucl-th/0503042.

- Model includes N* resonances: →

| | | |
|---|---|---|
| $P_{33}(1232)$ | $S_{11}(1535)$ | $F_{15}(1680)$ |
| $P_{11}(1440)$ | $S_{31}(1620)$ | $D_{33}(1700)$ |
| $D_{13}(1520)$ | $D_{15}(1675)$ | $P_{13}(1720)$ |

- Model calculates polarized cross sections from transition amplitudes and
- observables from polarized cross sections.

- To compare with experimental results, event-weighted averages of the polarization observables are determined for each experimental bin.

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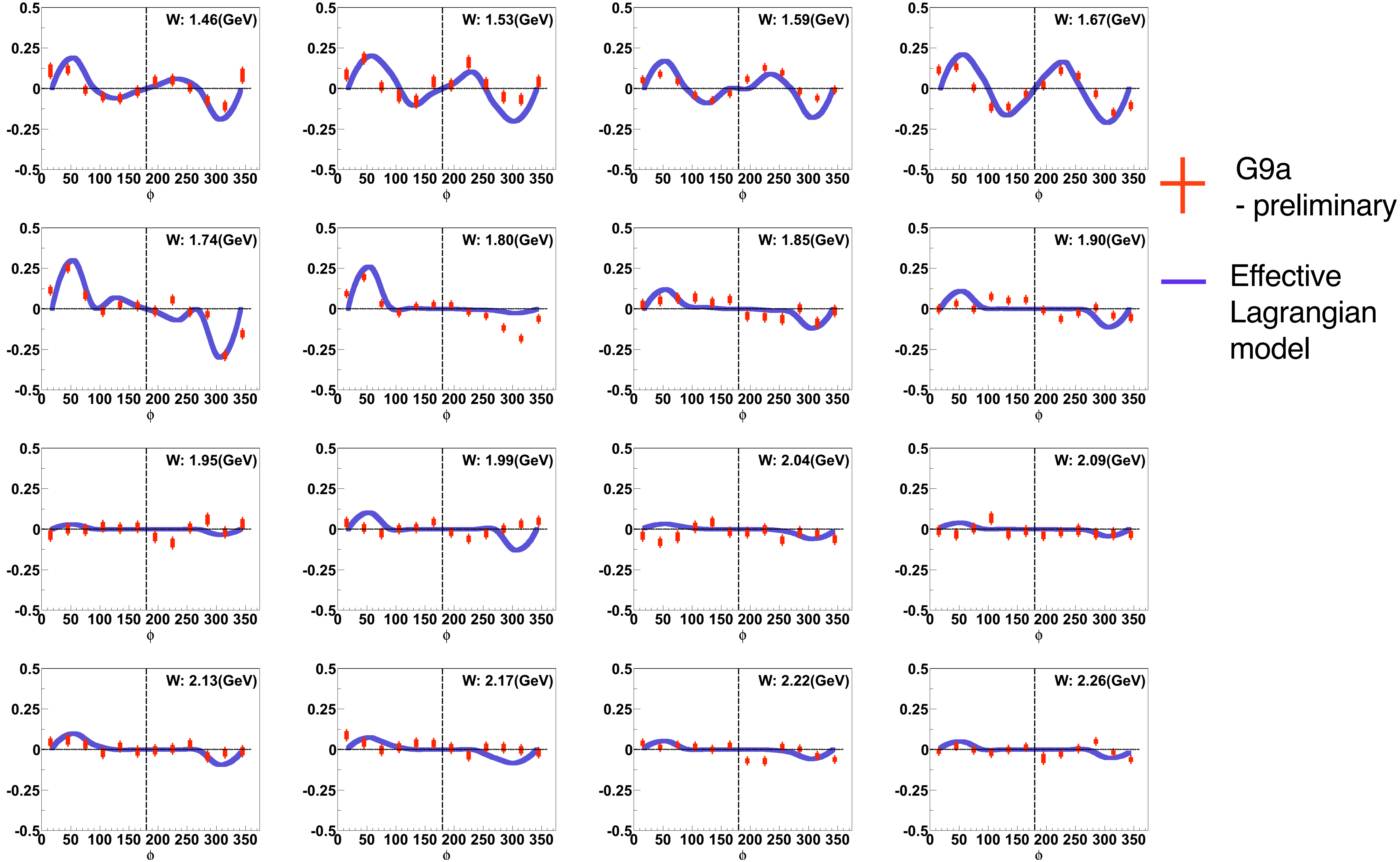
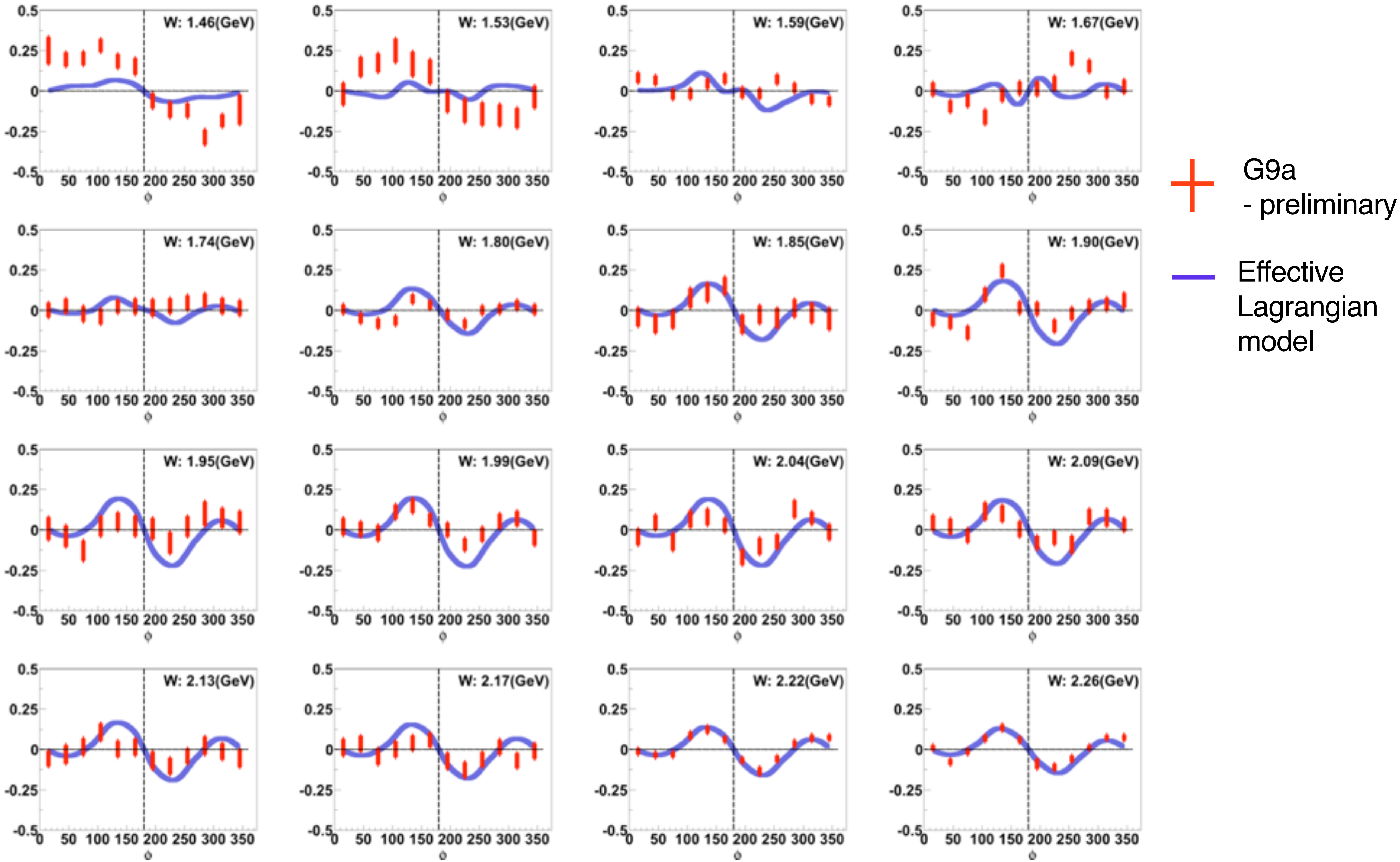
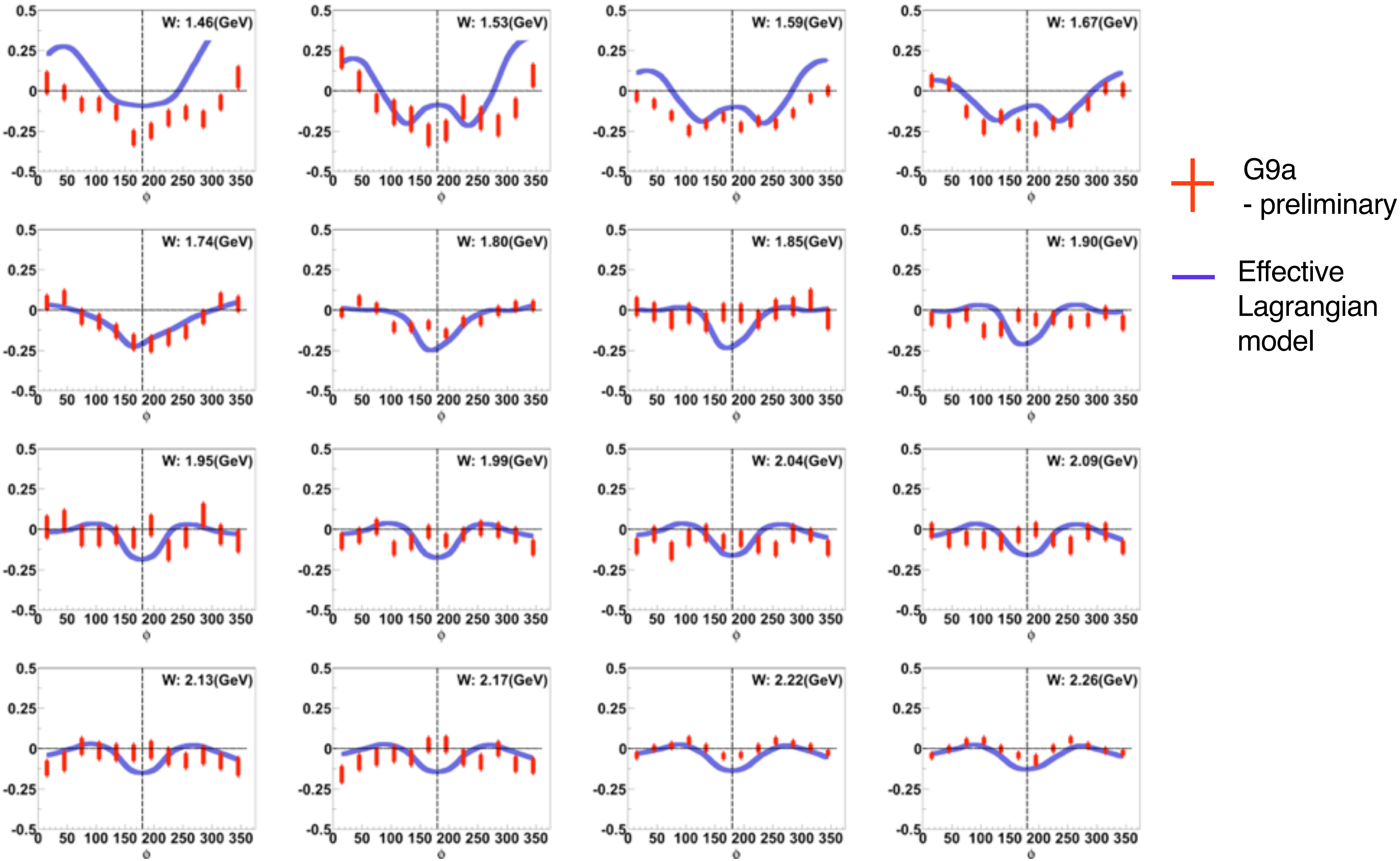
# Comparison with model: $P_z$



# Comparison with model: $P^{c}_{z}$



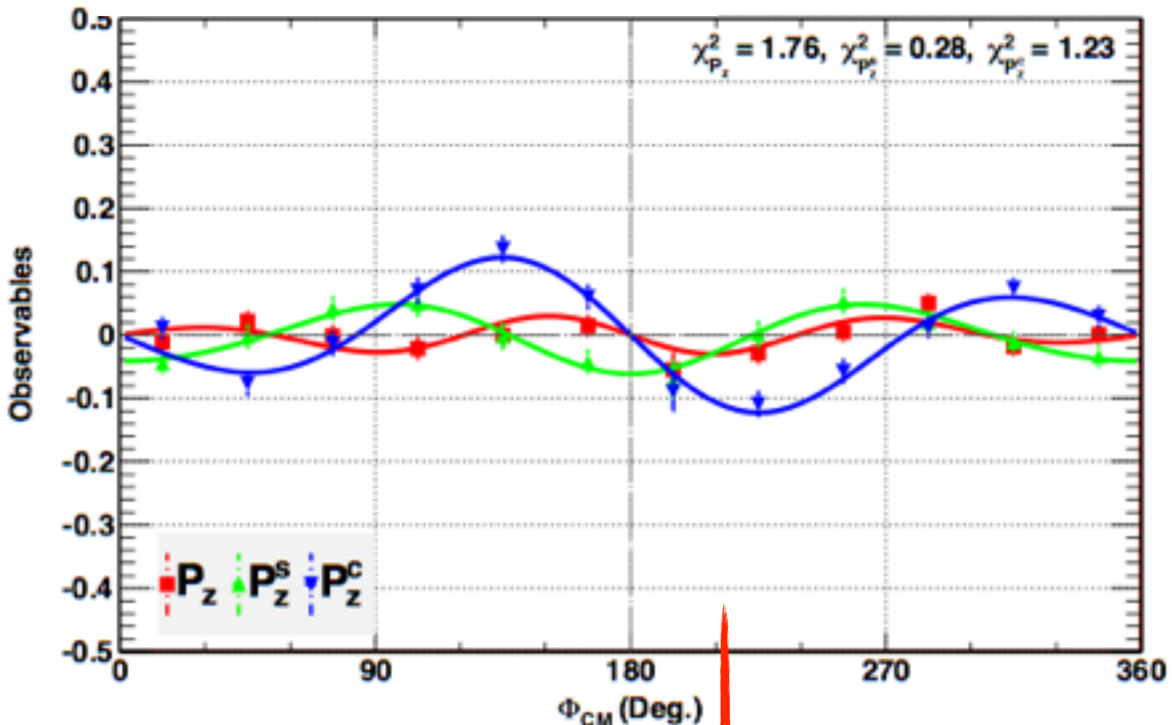
# Comparison with model: $P^s_z$



# Further study: invariant mass (pπ+) cut

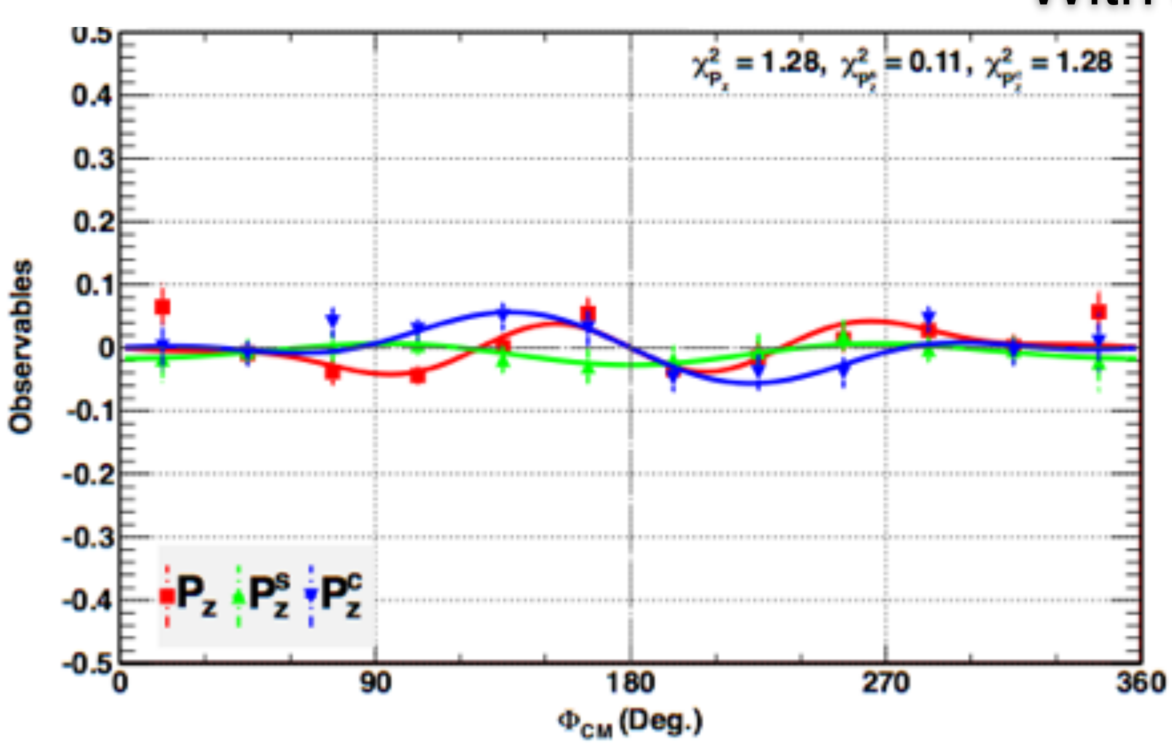
W: 2.26 GeV

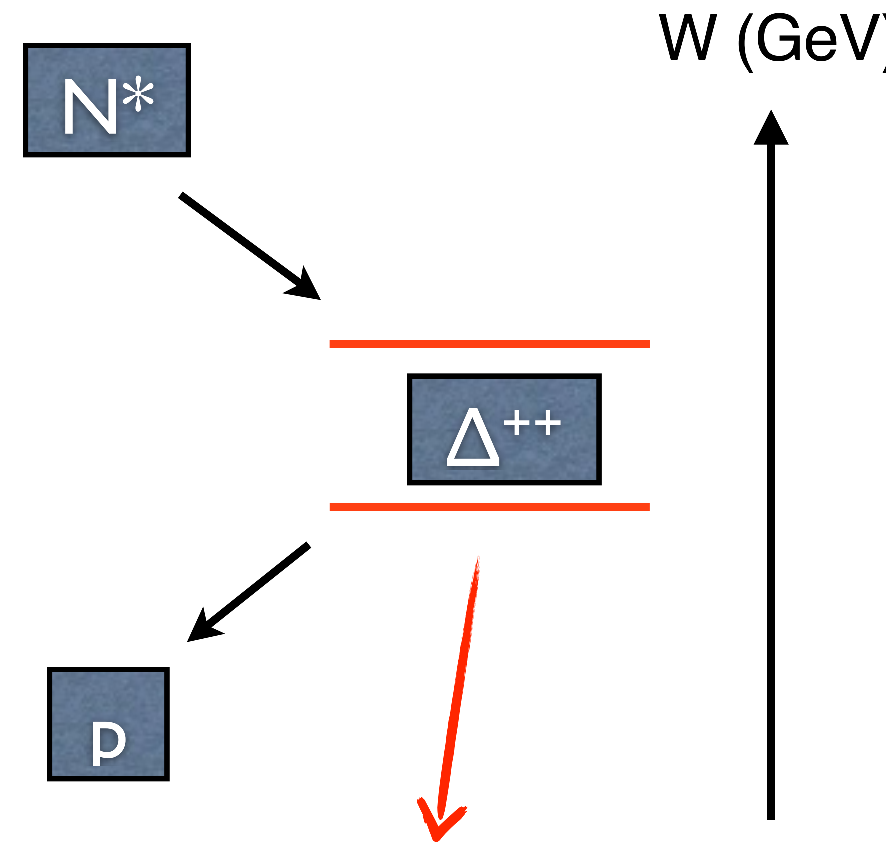
No cut



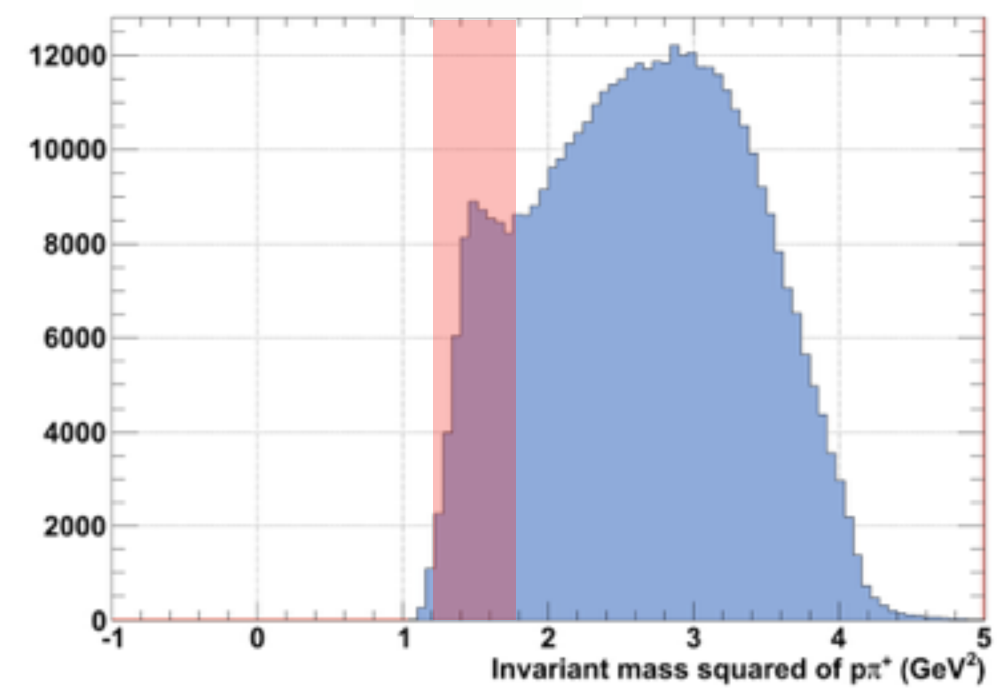

W: 2.26 GeV

With cut




Cut



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# Summary

## Conclusion

- The **FROST** experiment at Jefferson Lab measured photoproduction with polarized beam and frozen-spin butanol target.
- Polarized yields for the **double-charged pion-photoproduction** reaction have been extracted.
- Angular distributions of the **polarization observables $P_z$, $P^c_z$, and $P^s_z$** have been obtained in the energy range, **W = 1.46 - 2.25 GeV**.
- The results are compared to acceptance-corrected model predictions. The **model reproduces main features** of the data in most kinematic bins.

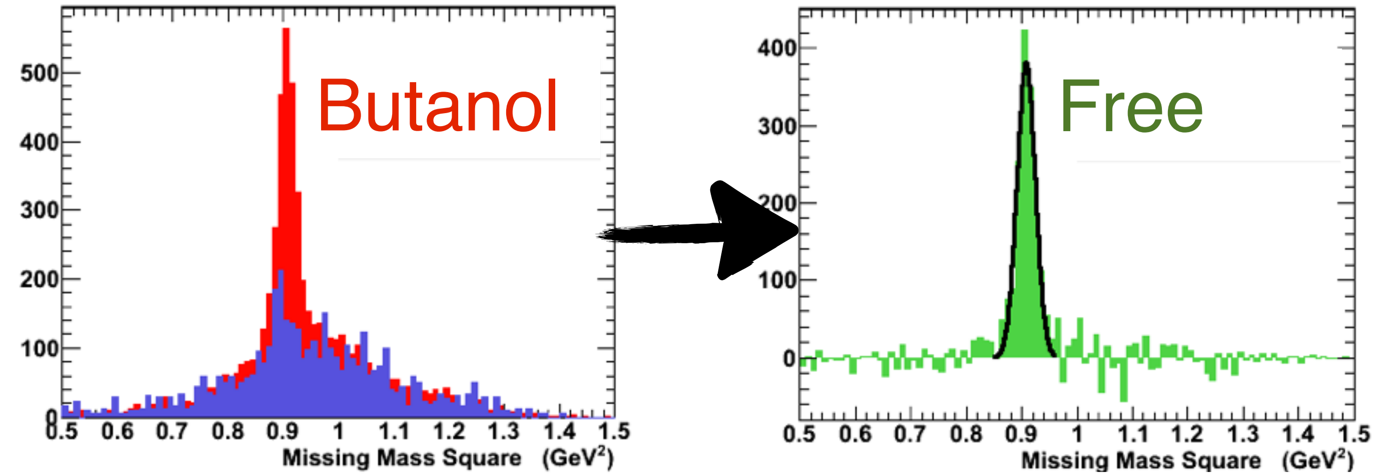
## Future

- Estimate the systematic uncertainties of the data.
- Further study of the observables in statistically rich kinematic bins.
- Improve the model parameters in view of the constraints imposed by the new results.

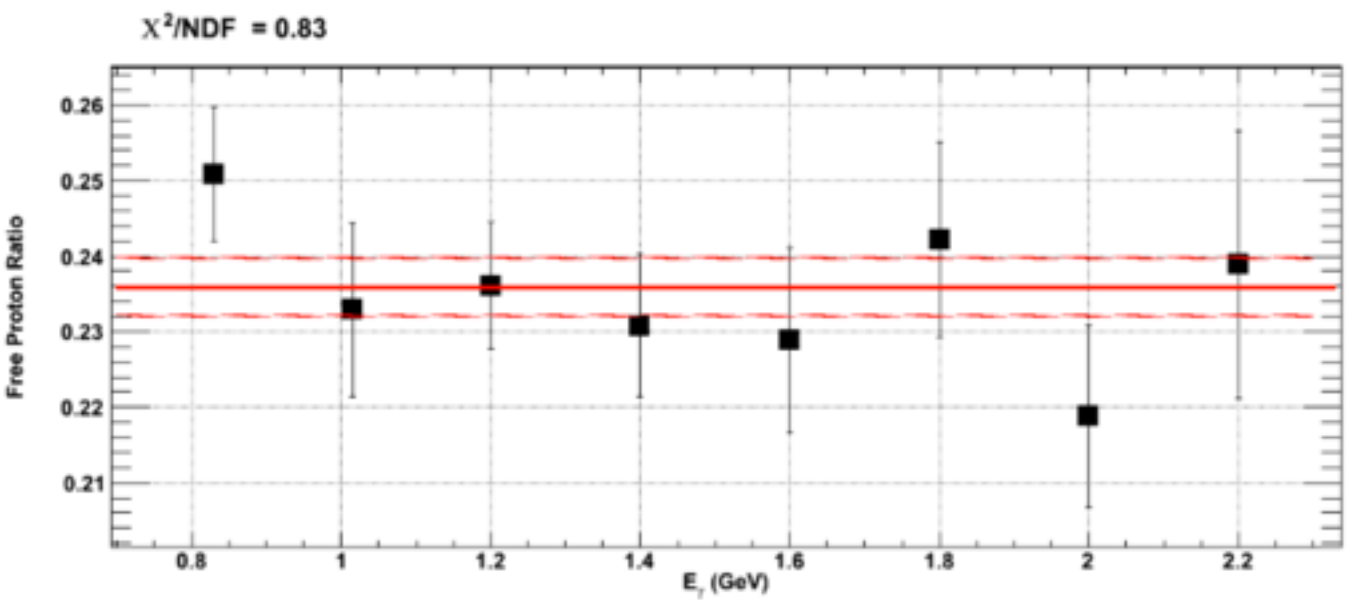
Thanks!

# Backup-Dilution Factor

**$Y_f$ : Yields from Free proton in Carbon**




$$d_1 = \frac{Y_0 - Y_f}{Y_0 + Y_b}$$




$$d_2 = \frac{Y_f}{Y_0}$$

$$\boxed{h = \frac{d_1}{1 - d_2} = \frac{Y_0}{Y_0 + Y_b}}$$