Polarised Two Pion Photoproduction For MesonEx

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CLAS Collaboration Meeting

Polarised photoproduction of 2 spinless particles

Decay process can be studied in a number of related ways :

Moments of spherical harmonic distributions

Fourier analysis up to some truncation in L
CLAS results (Battaglieri et al, 2000)
still being analysed by JPAC

Spin Density Matrix Elements

Classic Schilling, Seybouth and Wolf paper for Vector mesons
Extended to electroproduction
Assumes only P-wave contributions
Recent GlueX results

Partial Wave Amplitudes

Allows multitude of contributing resonances of all l
Mass dependence allows pole extraction
GOAL for spectroscopy

Greater connection to physics ↓

When analysing final states with CLAS12 that have > 2 particles (+ e′)
We **must** consider the two-body decays when measuring cross sections
and beam spin asymmetries if we integrate over decay angle.
or else they are not reliable (they are a product of detector*physics)

Polarised Photoproduction – Amplitudes and Moments

The vector $\boldsymbol{P}_\gamma$ encodes the information about the polarization of the beam [10]. Similarly, one defines

$$I(\Omega,\Phi) = I^0(\Omega) + \boldsymbol{I}(\Omega)\cdot\boldsymbol{P}_\gamma(\Phi), \qquad \text{(A7)}$$

with the vector of polarized intensities $\boldsymbol{I} = (I^1, I^2, I^3)$. The angular distribution can be expanded in unpolarized moment H^0 and polarized moments $\boldsymbol{H} = (H^1, H^2, H^3)$ via

$$I^0(\Omega) = \sum_{LM}\left(\frac{2L+1}{4\pi}\right) H^0(LM) D^{L*}_{M0}(\phi,\theta,0), \qquad \text{(A8a)}$$

$$\boldsymbol{I}(\Omega) = -\sum_{LM}\left(\frac{2L+1}{4\pi}\right) \boldsymbol{H}(LM) D^{L*}_{M0}(\phi,\theta,0). \qquad \text{(A8b)}$$

The extra minus sign in the definition of $\boldsymbol{H}$ ensures that $H^1(00)$ is positive for positive reflectivity waves, cf. Sect. D. The moments are expressed in terms of the $\eta\pi^0$ SDME:

$$H^0(LM) = \sum_{\substack{\ell\ell' \\ mm'}}\left(\frac{2\ell'+1}{2\ell+1}\right)^{1/2} C^{\ell 0}_{\ell' 0 L 0} C^{\ell m}_{\ell' m' L M}\, \rho^{\alpha,\ell\ell'}_{mm'}, \qquad \text{(A9a)}$$

$$\boldsymbol{H}(LM) = -\sum_{\substack{\ell\ell' \\ mm'}}\left(\frac{2\ell'+1}{2\ell+1}\right)^{1/2} C^{\ell 0}_{\ell' 0 L 0} C^{\ell m}_{\ell' m' L M}\, \boldsymbol{\rho}^{\ell\ell'}_{mm'} \qquad \text{(A9b)}$$

Moments of angular distribution and beam asymmetries in $\eta\pi^0$ photoproduction at GlueX

V. Mathieu, M. Albaladejo, C. Fernández-Ramírez, A. W. Jackura, M. Mikhasenko, A. Pilloni, and A. P. Szczepaniak
(Joint Physics Analysis Center Collaboration)
Phys. Rev. D **100**, 054017 – Published 17 September 2019

And assuming γ spin density matrix,

$$\rho_\gamma(\Phi) = \tfrac{1}{2}\left(1 - P_{\gamma L}\cos 2\Phi\,\sigma_x - P_{\gamma L}\sin 2\Phi\,\sigma_y - P_{\gamma C}\sigma_z\right)$$

* currently checking if dependence on ellipse major axis length

$$^{(\epsilon)}\rho^{0,\ell\ell'}_{mm'} = \kappa\sum_k\left([\ell]^{(\epsilon)}_{m;k}[\ell']^{(\epsilon)*}_{m';k} + (-1)^{m-m'}[\ell]^{(\epsilon)}_{-m;k}[\ell']^{(\epsilon)*}_{-m';k}\right),$$

$$^{(\epsilon)}\rho^{1,\ell\ell'}_{mm'} = -\epsilon\kappa\sum_k\left((-1)^{m}[\ell]^{(\epsilon)}_{-m;k}[\ell']^{(\epsilon)*}_{m';k} + (-1)^{m'}[\ell]^{(\epsilon)}_{m;k}[\ell']^{(\epsilon)*}_{-m';k}\right),$$

$$^{(\epsilon)}\rho^{2,\ell\ell'}_{mm'} = -i\epsilon\kappa\sum_k\left((-1)^{m}[\ell]^{(\epsilon)}_{-m;k}[\ell']^{(\epsilon)*}_{m';k} - (-1)^{m'}[\ell]^{(\epsilon)}_{m;k}[\ell']^{(\epsilon)*}_{-m';k}\right),$$

$$^{(\epsilon)}\rho^{3,\ell\ell'}_{mm'} = \kappa\sum_k\left([\ell]^{(\epsilon)}_{m;k}[\ell']^{(\epsilon)*}_{m';k} - (-1)^{m-m'}[\ell]^{(\epsilon)}_{-m;k}[\ell']^{(\epsilon)*}_{-m';k}\right).$$

→ Real parts of *[l][l']** ∝ cos(Δphase)

→ Imaginary parts of *[l][l']** ∝ sin(Δphase)

I^3 may allow to resolve sign ambiguity in phase
***in principle we have this already with CLAS12**

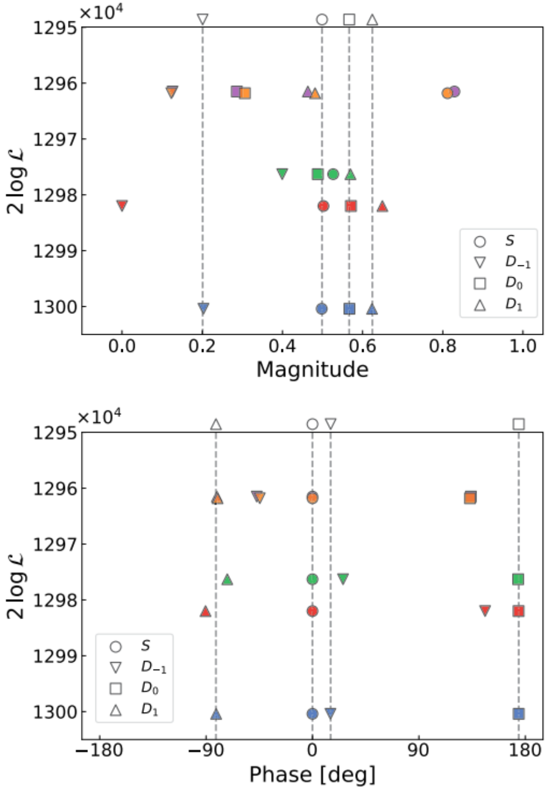
Ambiguities in Linear Polarised PWA

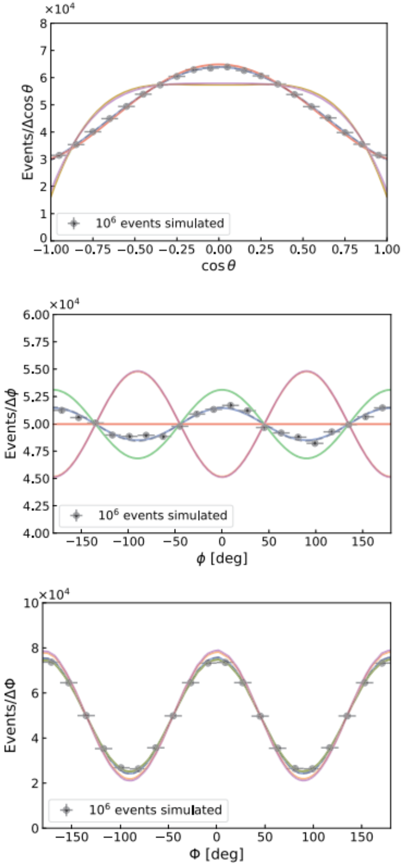
PHYSICAL REVIEW D **108,** 076001 (2023)

Ambiguities in partial wave analysis of two spinless meson photoproduction

W. A. Smith,[1,2,*] D. I. Glazier,[3] V. Mathieu,[4,5] M. Albaladejo,[6] M. Albrecht,[7] Z. Baldwin,[8] C. Fernández-Ramírez,[9,10] N. Hammoud,[11] M. Mikhasenko,[12,13] G. Montaña,[14] R. J. Perry,[4] A. Pilloni,[15,16] V. Shastry,[1,2] A. P. Szczepaniak,[1,2,14] and D. Winney[17,18]

(Joint Physics Analysis Center)





In the general linear polarised case there
is only a single "trivial" complex conjugate ambiguous solution

-Specific cases with 0 magnitude waves, can complicate this

-Should limit 1 wave per reflectivity to have +ve imaginery part

=> Remove ambiguity from MaxLikelihood search

*our plots removed the trivial ambiguity

**but so does the electron polarisation !

Moments in terms of S,P waves

Parameters are normalised :
$H^0(0,0)$ = 2 and PW magnitudes <1

$$
\begin{aligned}
H^0(0,0) =& 2({}^+S^+S) + 2({}^-S^-S) + 2({}^+P^+_{-1}P_{-1}) + 2({}^+P^+_{+1}P_{+1}) \\
&+ 2({}^-P^-_{-1}P_{-1}) + 2({}^-P^-_{+1}P_{+1}) + 2({}^+P^+_0P_0) + 2({}^-P^-_0P_0) \\
H^1(0,0) =& 2({}^+S^+S) + -2({}^-S^-S) + -4({}^+P^+_{+1}P_{-1})\cos({}^+\phi_{P+1} -{}^+\phi_{P-1}) \\
&+ 4({}^-P^-_{+1}P_{-1})\cos({}^-\phi_{P+1} -{}^-\phi_{P-1}) + 2({}^+P^+_0P_0) + -2({}^-P^-_0P_0) \\
H^0(1,0) =& 2.3({}^+S^+P_0)\cos({}^+\phi_S -{}^+\phi_{P0}) \\
&+ 2.3({}^-S^-P_0)\cos({}^-\phi_S -{}^-\phi_{P0}) \\
H^1(1,0) =& 2.3({}^+S^+P_0)\cos({}^+\phi_S -{}^+\phi_{P0}) \\
&- 2.3({}^-S^-P_0)\cos({}^-\phi_S -{}^-\phi_{P0}) \\
H^0(1,1) =& -1.2({}^+S^+P_{-1})\cos({}^+\phi_S -{}^+\phi_{P-1}) + 1.2({}^+S^+P_{+1})\cos({}^+\phi_S -{}^+\phi_{P+1}) \\
&- 1.2({}^-S^-P_{-1})\cos({}^-\phi_S -{}^-\phi_{P-1}) + 1.2({}^-S^-P_{+1})\cos({}^-\phi_S -{}^-\phi_{P+1}) \\
H^1(1,1) =& -1.2({}^+S^+P_{-1})\cos({}^+\phi_S -{}^+\phi_{P-1}) + 1.2({}^+S^+P_{+1})\cos({}^+\phi_S -{}^+\phi_{P+1}) \\
&+ 1.2({}^-S^-P_{-1})\cos({}^-\phi_S -{}^-\phi_{P-1}) + -1.2({}^-S^-P_{+1})\cos({}^-\phi_S -{}^-\phi_{P+1}) \\
H^2(1,1) =& -1.2({}^+S^+P_{-1})\cos({}^+\phi_S -{}^+\phi_{P-1}) + -1.2({}^+S^+P_{+1})\cos({}^+\phi_S -{}^+\phi_{P+1}) \\
&+ 1.2({}^-S^-P_{-1})\cos({}^-\phi_S -{}^-\phi_{P-1}) + 1.2({}^-S^-P_{+1})\cos({}^-\phi_S -{}^-\phi_{P+1}) \\
H^3(1,1) =& 1.2({}^+S^+P_{-1})\sin({}^+\phi_S -{}^+\phi_{P-1}) + 1.2({}^+S^+P_{+1})\sin({}^+\phi_S -{}^+\phi_{P+1}) \\
&+ 1.2({}^-S^-P_{-1})\sin({}^-\phi_S -{}^-\phi_{P-1}) + 1.2({}^-S^-P_{+1})\sin({}^-\phi_S -{}^-\phi_{P+1})
\end{aligned}
$$

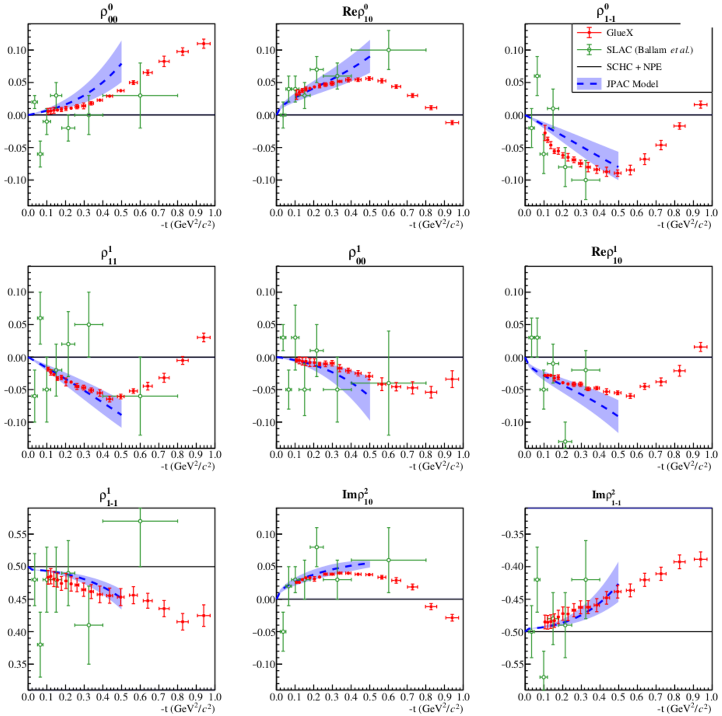
For vector mesons these moments = 0 as S-wave = 0

$$
\begin{aligned}
H^0(2,0) =& -0.4({}^+P^+_{-1}P_{-1}) + -0.4({}^+P^+_{+1}P_{+1}) + -0.4({}^-P^-_{-1}P_{-1}) \\
&- 0.4({}^-P^-_{+1}P_{+1}) + 0.8({}^+P^+_0P_0) + 0.8({}^-P^-_0P_0) \\
H^1(2,0) =& 0.8({}^+P^+_{+1}P_{-1})\cos({}^+\phi_{P+1} -{}^+\phi_{P-1}) - 0.8({}^-P^-_{+1}P_{-1})\cos({}^-\phi_{P+1} -{}^-\phi_{P-1}) \\
&+ 0.8({}^+P^+_0P_0) - 0.8({}^-P^-_0P_0) \\
H^0(2,1) =& -0.7({}^+P^+_0P_{-1})\cos({}^+\phi_{P0} -{}^+\phi_{P-1}) + 0.7({}^+P^+_0P_{+1})\cos({}^+\phi_{P0} -{}^+\phi_{P+1}) \\
&- 0.7({}^-P^-_0P_{-1})\cos({}^-\phi_{P0} -{}^-\phi_{P-1}) + 0.7({}^-P^-_0P_{+1})\cos({}^-\phi_{P0} -{}^-\phi_{P+1}) \\
H^1(2,1) =& -0.7({}^+P^+_0P_{-1})\cos({}^+\phi_{P0} -{}^+\phi_{P-1}) + 0.7({}^+P^+_0P_{+1})\cos({}^+\phi_{P0} -{}^+\phi_{P+1}) \\
&+ 0.7({}^-P^-_0P_{-1})\cos({}^-\phi_{P0} -{}^-\phi_{P-1}) - 0.7({}^-P^-_0P_{+1})\cos({}^-\phi_{P0} -{}^-\phi_{P+1}) \\
H^2(2,1) =& -0.7({}^+P^+_0P_{-1})\cos({}^+\phi_{P0} -{}^+\phi_{P-1}) - 0.7({}^+P^+_0P_{+1})\cos({}^+\phi_{P0} -{}^+\phi_{P+1}) \\
&+ 0.7({}^-P^-_0P_{-1})\cos({}^-\phi_{P0} -{}^-\phi_{P-1}) + 0.7({}^-P^-_0P_{+1})\cos({}^-\phi_{P0} -{}^-\phi_{P+1}) \\
H^3(2,1) =& 0.7({}^+P^+_0P_{-1})\sin({}^+\phi_{P0} -{}^+\phi_{P-1}) + 0.7({}^+P^+_0P_{+1})\sin({}^+\phi_{P0} -{}^+\phi_{P+1}) \\
&+ 0.7({}^-P^-_0P_{-1})\sin({}^-\phi_{P0} -{}^-\phi_{P-1}) + 0.7({}^-P^-_0P_{+1})\sin({}^-\phi_{P0} -{}^-\phi_{P+1}) \\
H^0(2,2) =& -0.98({}^+P^+_{+1}P_{-1})\cos({}^+\phi_{P+1} -{}^+\phi_{P-1}) \\
&- 0.98({}^-P^-_{+1}P_{-1})\cos({}^-\phi_{P+1} -{}^-\phi_{P-1}) \\
H^1(2,2) =& 0.49({}^+P^+_{-1}P_{-1}) + 0.49({}^+P^+_{+1}P_{+1}) \\
&- 0.49({}^-P^-_{-1}P_{-1}) - 0.49({}^-P^-_{+1}P_{+1}) \\
H^2(2,2) =& 0.49({}^+P^+_{-1}P_{-1}) - 0.49({}^+P^+_{+1}P_{+1}) \\
&- 0.49({}^-P^-_{-1}P_{-1}) + 0.49({}^-P^-_{+1}P_{+1}) \\
H^3(2,2) =& 0.98({}^+P^+_{+1}P_{-1})\sin({}^+\phi_{P+1} -{}^+\phi_{P-1}) \\
&+ 0.98({}^-P^-_{+1}P_{-1})\sin({}^-\phi_{P+1} -{}^-\phi_{P-1})
\end{aligned}
$$

*Note approx. CG coefficients

Spin Density Matrix Elements, ρ photoproduction

GlueX results



Measurement of Spin-Density Matrix Elements in $\rho(770)$ Production with a Linearly Polarized Photon Beam at $E_\gamma = 8.2 - 8.8\,\mathrm{GeV}$

$$W^0(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00}-1)\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\vartheta\cos\varphi - \rho^0_{1-1}\sin^2\vartheta\cos 2\varphi\right) \quad (10)$$

$$W^1(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\rho^1_{11}\sin^2\vartheta + \rho^1_{00}\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\vartheta\cos\varphi - \rho^1_{1-1}\sin^2\vartheta\cos 2\varphi\right) \quad (11)$$

$$W^2(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\sqrt{2}\mathrm{Im}\rho^2_{10}\sin 2\vartheta\sin\varphi + \mathrm{Im}\rho^2_{1-1}\sin^2\vartheta\sin 2\varphi\right). \quad (12)$$

$$\rho^0_{00} = \frac{1}{3}(5H^0(20)+1)$$

$$\Re\rho^0_{10} = \frac{5}{\sqrt{12}}H^0(21)$$

$$\rho^0_{1-1} = -\frac{5}{\sqrt{6}}H^0(22)$$

$$\rho^1_{11} = -\frac{1}{3}H^1(00)$$

$$\rho^1_{00} = -\frac{5}{2}H^1(20) - \frac{1}{3}H^1(00)$$

$$\Re\rho^1_{10} = -\frac{5}{\sqrt{12}}H^1(21)$$

$$\rho^1_{1-1} = \frac{5}{\sqrt{6}}H^1(22)$$

$$\Im\rho^2_{10} = -\frac{5}{\sqrt{12}}H^2(21)$$

$$\Im\rho^2_{1-1} = \frac{5}{\sqrt{6}}H^2(22)$$

$$\Im\rho^3_{10} = -\frac{5}{\sqrt{12}}H^3(21)$$

$$\Im\rho^3_{1-1} = \frac{5}{\sqrt{6}}H^3(22)$$

This tells us what our data should look like

Extracting Partial Waves from GlueX SDMEs

$$\mathcal{I}(\Omega,\Phi) = \mathcal{I}_0(\Omega) - \mathcal{I}_1(\Omega)P_{\gamma L}\cos 2\Phi - \mathcal{I}_2(\Omega)P_{\gamma L}\sin 2\Phi - \mathcal{I}_3(\Omega)P_{\gamma C}.$$

Generate events from SDME intensities

$$\mathcal{I}_0(\Omega) = \frac{3}{4\pi}\{\frac{1}{2}(1-\rho^0_{00})+\frac{1}{2}(3\rho^0_{00}-1)\cos^2\theta-\sqrt{2}\Re[\rho^0_{10}]\sin 2\theta\cos\phi-\rho^0_{1-1}\sin^2\theta\cos 2\phi\}$$

$$\mathcal{I}_1(\Omega) = \frac{3}{4\pi}\{\rho^1_{11}\sin^2\theta + \rho^1_{00}\cos^2\theta - \sqrt{2}\rho^1_{10}\sin 2\theta\cos\phi - \rho^1_{1-1}\sin^2\theta\cos 2\phi\}$$

$$\mathcal{I}_2(\Omega) = \frac{3}{4\pi}\{\sqrt{2}\Im\rho^2_{10}\sin 2\theta\sin\phi + \Im\rho^2_{1-1}\sin^2\theta\sin 2\phi\}$$

Then fit to extract partial waves for ρ production, S, P_0, P_1, P_{-1}

$$I^0(\Omega) = \kappa\sum_{\epsilon,k}|U_k^{(\epsilon)}(\Omega)|^2 + |\widetilde{U}_k^{(\epsilon)}(\Omega)|^2\ ,$$

$$I^1(\Omega) = -\kappa\sum_{\epsilon,k}2\epsilon\,\mathrm{Re}\left(U_k^{(\epsilon)}(\Omega)\left[\widetilde{U}_k^{(\epsilon)}(\Omega)\right]^*\right)\ ,$$

$$I^2(\Omega) = -\kappa\sum 2\epsilon\,\mathrm{Im}\left(U_k^{(\epsilon)}(\Omega)\left[\widetilde{U}_k^{(\epsilon)}(\Omega)\right]^*\right)\ ,$$

Then calculate Helicity intensity

$$I^3(\Omega) = \kappa\sum_{\epsilon,k}|U_k^{(\epsilon)}(\Omega)|^2 - |\widetilde{U}_k^{(\epsilon)}(\Omega)|^2\ .$$

i.e. in principle helicity SDMEs already constrained
=> Can perform electron beam polarimetry

Polarisation asymmetries for ρ

$$\mathcal{A}_3 = \frac{\mathcal{I}(\Omega, h=+1) - \mathcal{I}(\Omega, h=-1)}{\mathcal{I}_3(\Omega, h=+1) + \mathcal{I}_3(\Omega, h=-1} = \frac{\mathcal{I}_3(\Omega)}{\mathcal{I}_0(\Omega)}$$

$$= \sum_{L\geq 0, M>0} \sqrt{\frac{2L+1}{4\pi}} \tau(M) \Im H^3(LM) \Im[Y_L^{M*}(\phi,\theta)]/\mathcal{I}_0(\Omega)$$

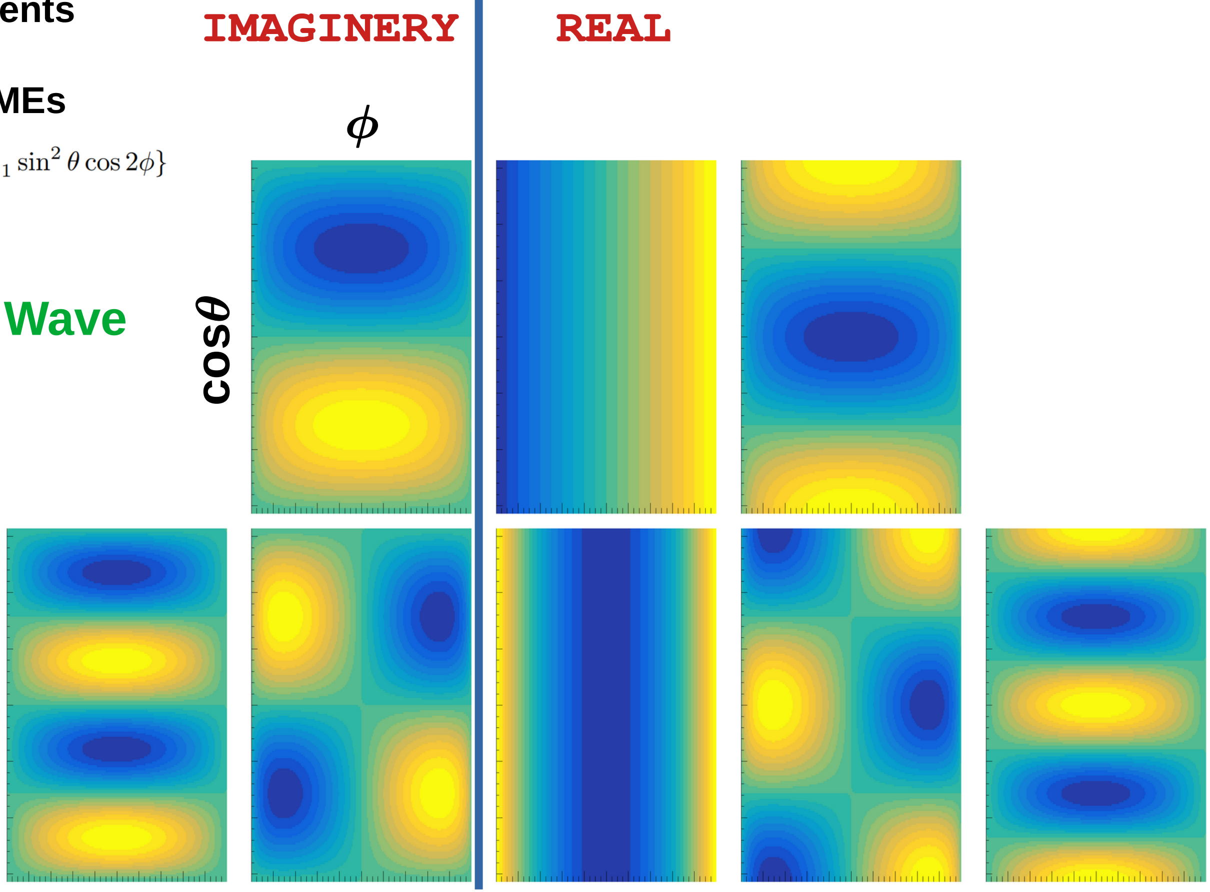
Spherical Harmonic Moments

$$\approx \frac{3}{4\pi}(\sqrt{2}\Im\rho^3_{10}\sin 2\theta \sin\phi + \Im\rho^3_{1-1}\sin^2\theta\sin 2\phi)/\mathcal{I}_0(\Omega)$$

ρ SDMEs

$$\mathcal{I}_0(\Omega) = \frac{3}{4\pi}\{\frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00} - 1)\cos^2\theta - \sqrt{2}\Re[\rho^0_{10}]\sin 2\theta\cos\phi - \rho^0_{1-1}\sin^2\theta\cos 2\phi\}$$

S&P Wave



Similar asymmetries for
Linearly polarised terms

P Wave only

Note unpolarised intensity
On denominator will distort these

Quasi-real Vector Meson Electroproduction

Nuclear Physics B61 (1973) 381–413. North-Holland Publishing Company

HOW TO ANALYSE VECTOR-MESON PRODUCTION IN INELASTIC LEPTON SCATTERING

K. SCHILLING
Fakultät Physik der Universität Bielefeld, Bielefeld

G. WOLF
Deutsches Elektronen-Synchrotron DESY, Hamburg

$$W(\cos\theta, \phi, \Phi, \alpha_2 = 0, \pi) = W^{\text{unpol}}(\cos\theta, \phi, \Phi) \pm W^{\text{long pol}}(\cos\theta, \phi, \Phi)\,; \tag{88}$$

$$W^{\text{unpol}}(\cos\theta, \phi, \Phi) = \frac{1}{1+(\epsilon+\delta)R}\,\frac{3}{4\pi}$$

$$\times\,[\tfrac{1}{2}(1-\rho^0_{00}) + \tfrac{1}{2}(3\rho^0_{00} - 1)\cos^2\theta - \sqrt{2}\,\mathrm{Re}\,\rho^0_{10}\sin 2\theta\cos\phi - \rho^0_{1-1}\sin^2\theta\cos 2\phi$$

$$-\epsilon\cos 2\Phi\,\{\rho^1_{11}\sin^2\theta + \rho^1_{00}\cos^2\theta - \sqrt{2}\,\mathrm{Re}\,\rho^1_{10}\sin 2\theta\cos\phi - \rho^1_{1-1}\sin^2\theta\cos 2\phi\}$$

$$-\epsilon\sin 2\Phi\,\{\sqrt{2}\,\mathrm{Im}\,\rho^2_{10}\sin 2\theta\sin\phi + \mathrm{Im}\,\rho^2_{1-1}\sin^2\theta\sin 2\phi\}$$

$$W^{\text{long pol}}(\cos\theta, \phi, \Phi) = \frac{1}{1+(\epsilon+\delta)R}\,\frac{3}{4\pi}$$

$$\times\,P\,[\sqrt{1-\epsilon^2}\,\{\sqrt{2}\,\mathrm{Im}\,\rho^3_{10}\sin 2\theta\sin\phi + \mathrm{Im}\,\rho^3_{1-1}\sin^2\theta\sin 2\phi\} +$$

For low Q^2 we assume,

$$\rho_\gamma(\Phi) = \frac{1}{2}\left(1 - \epsilon\cos 2\Phi\,\sigma_x - \epsilon\sin 2\Phi\,\sigma_y - P_{beam}\sqrt{1-\epsilon^2}\sigma_z\right)$$

With ε the virtual photon polarisation

Preliminary Pass 2 Spring19 data

Analyse both missing pion topologies

In general these should not pass the mesonex trigger (2*FD tracks)
? But actually most events seem to have this trigger bit

There is a prescaled (32) FT*FD*CD trigger, cut on this trigger bit
! currently trigger is not part of simulation

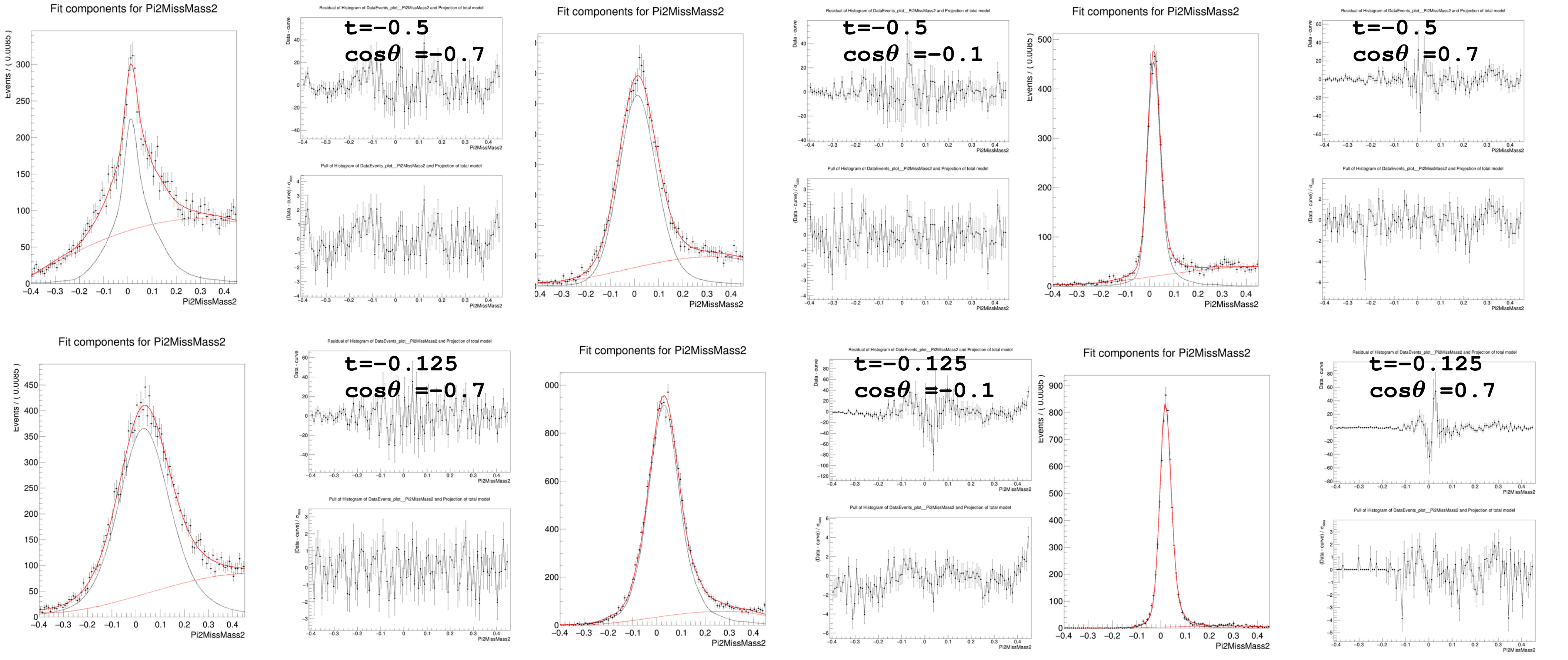
The π− may be detected in the FT and assumed as the e−. This peaks close to missing pion events. Cut on $\theta_\pi > \theta_e$:
removes almost all, but effects acceptance

Additional cut on $70<\theta_p<130°$, removes some background but not signal

Isolate exclusive signal with sPlots fits to missing mass squared
– split data in W, t, and cosθ to reduce dependencies on MM^2

Splot Background Subtraction fits

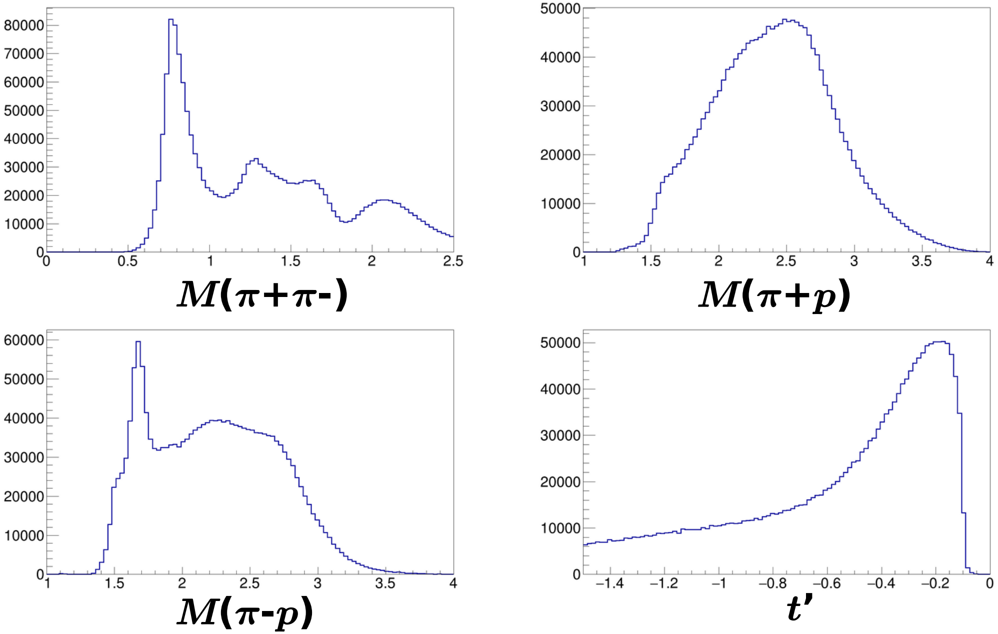
Fit with Simulation template for signal , polynomial for background
Need to add 3 pion simulation template for background



MesonEx $\pi^+\pi^-$ production for ρ

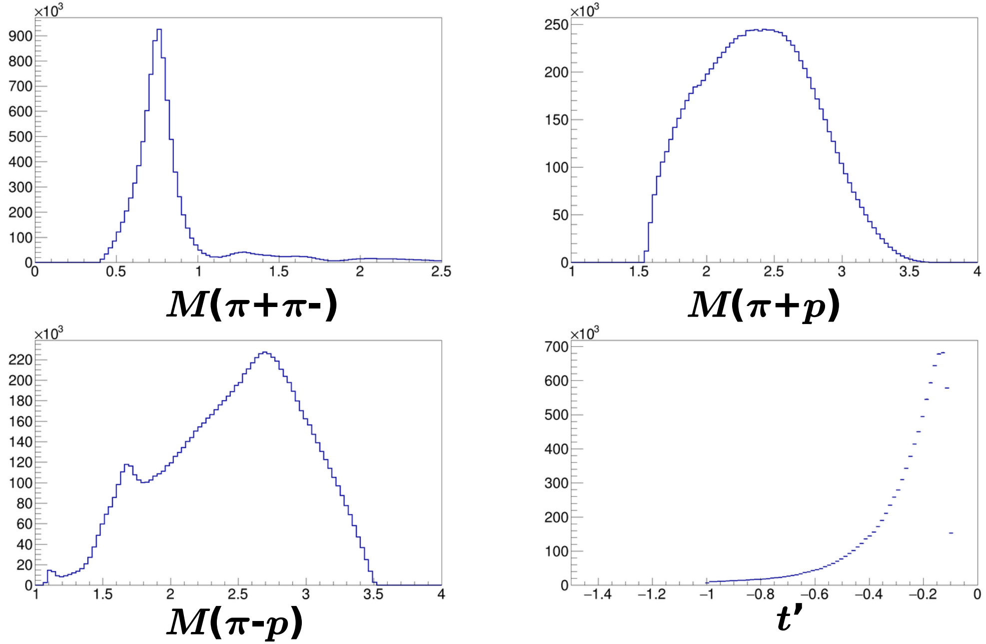
Exclusive Topology

1.8M



Missing pion Topology

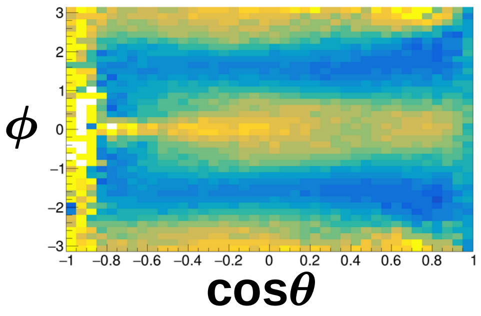
9M



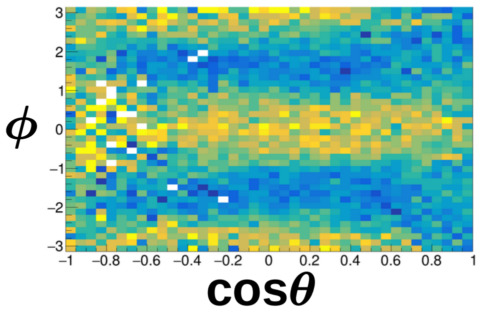
Due to large (8 degree) forward hole, acceptance is low at low mass (opening angle)
Acceptance recovered by reconstructing 1 pion, but prescaled in the trigger

A_1 for ρ

-0.4 < t' < -0.1 | **-0.9 < t' < -0.5**



Actual Data

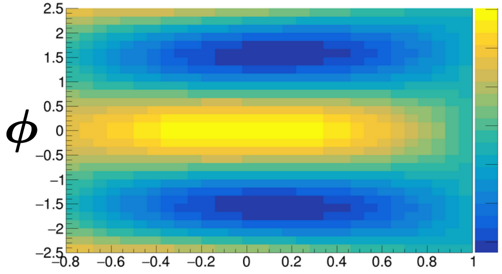


Additional Cuts :

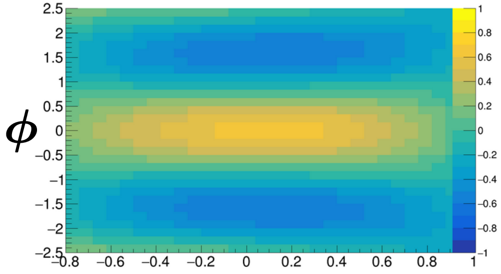
3.0<W<4.2

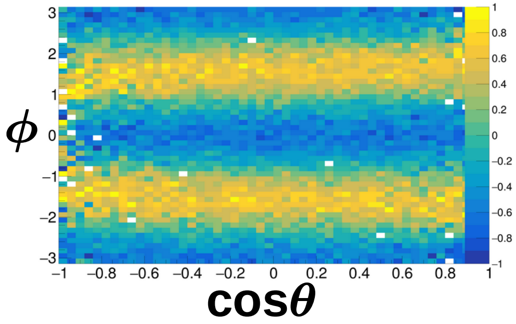
$0.6 < M(2\pi) < 0.9$

Correct for pol.

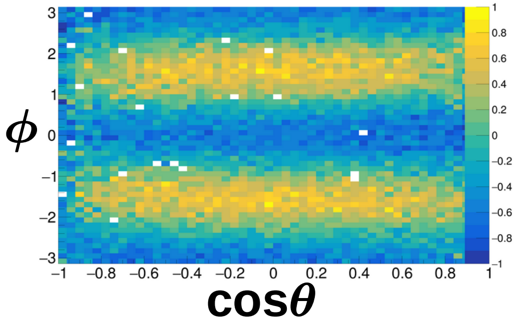


"Fit" to Data





Prediction From GlueX results

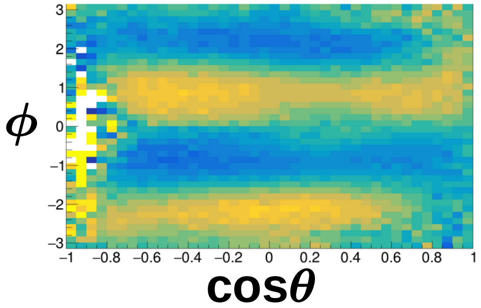


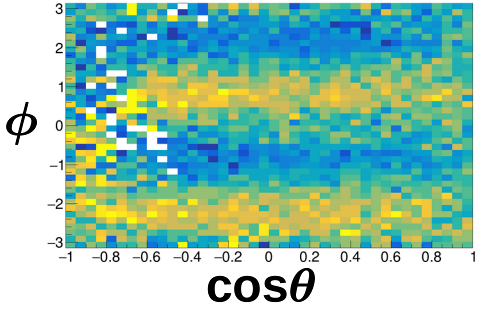
Shape OK
Wrong sign

A_2 for ρ

$-0.4 < t' < -0.1$

$-0.9 < t' < -0.5$





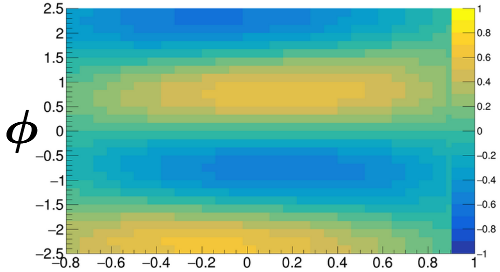
Actual Data

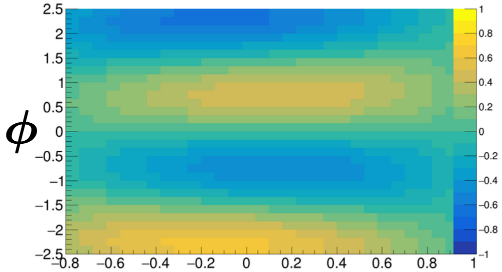
Additional Cuts :

3.0<W<4.2

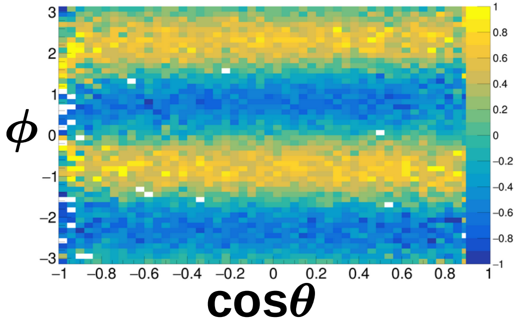
0.6<M(2π)<0.9

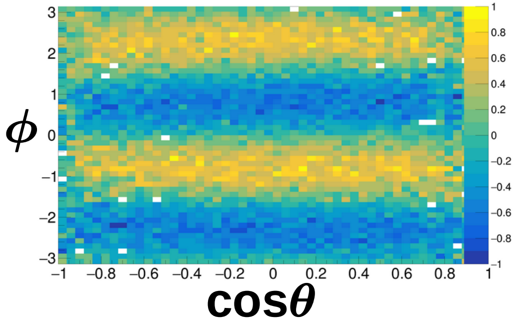
Correct for pol.





"Fit" to Data



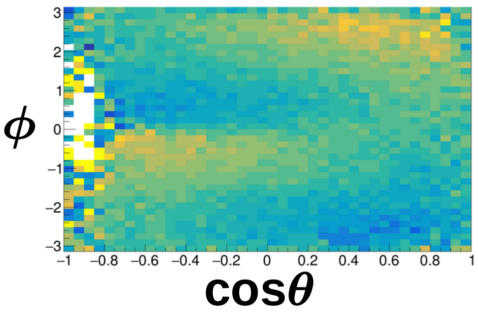


Prediction From GlueX results

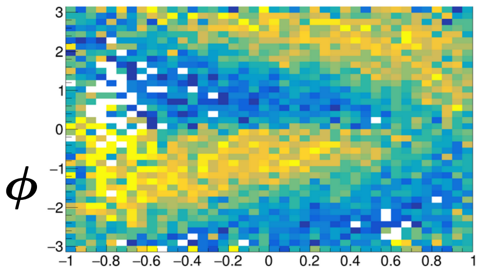
Shape OK
Wrong sign

A_3 for ρ

-0.5 < t' < -0.1



-0.9 < t' < -0.5



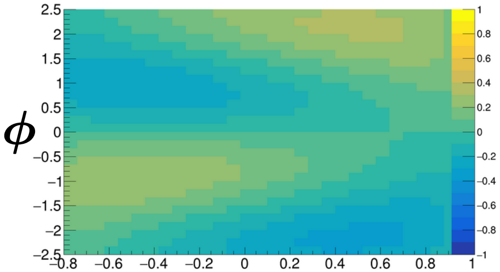
Actual Data

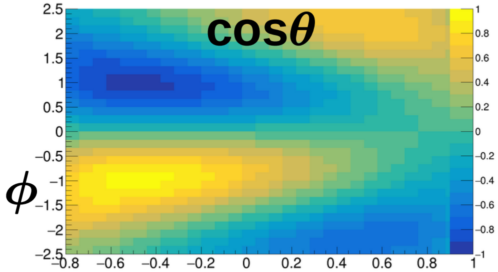
Additional Cuts :

3.0<W<4.2

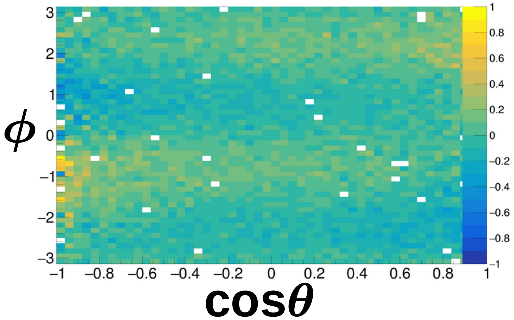
0.6<M(2π)<0.9

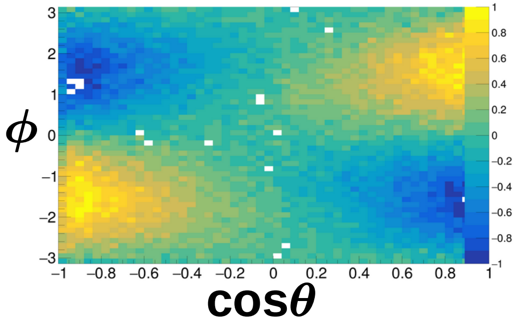
Correct for pol.





"Fit" to Data





Prediction From GlueX results

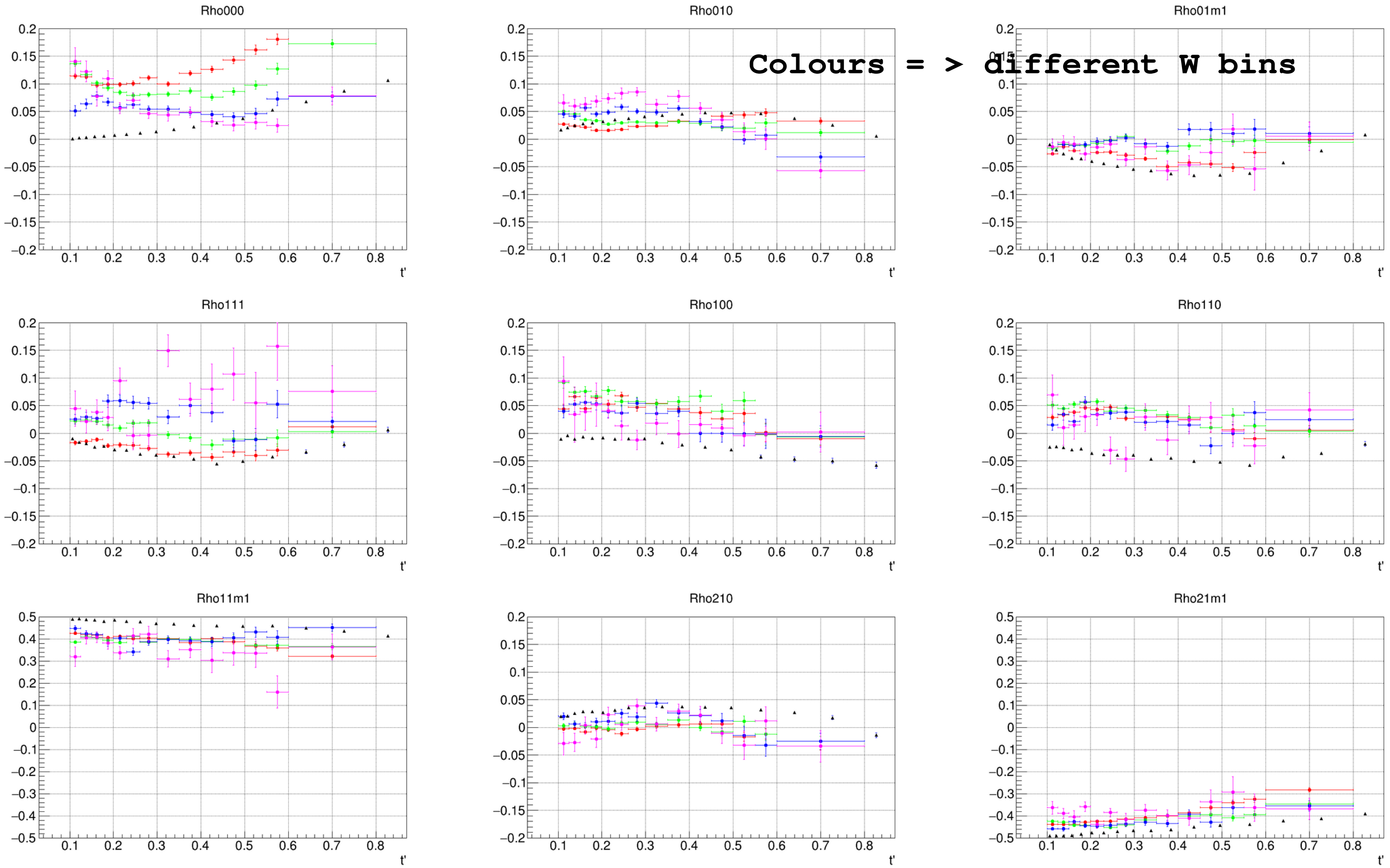
Data has larger H(22) moment.
=> Larger P_{-1}
Smaller P_0

Proper Fits : SDMEs

Not good consistency at the moment with GlueX and between W bins

Particular problem with rho000 due to $\cos\theta$ distribution

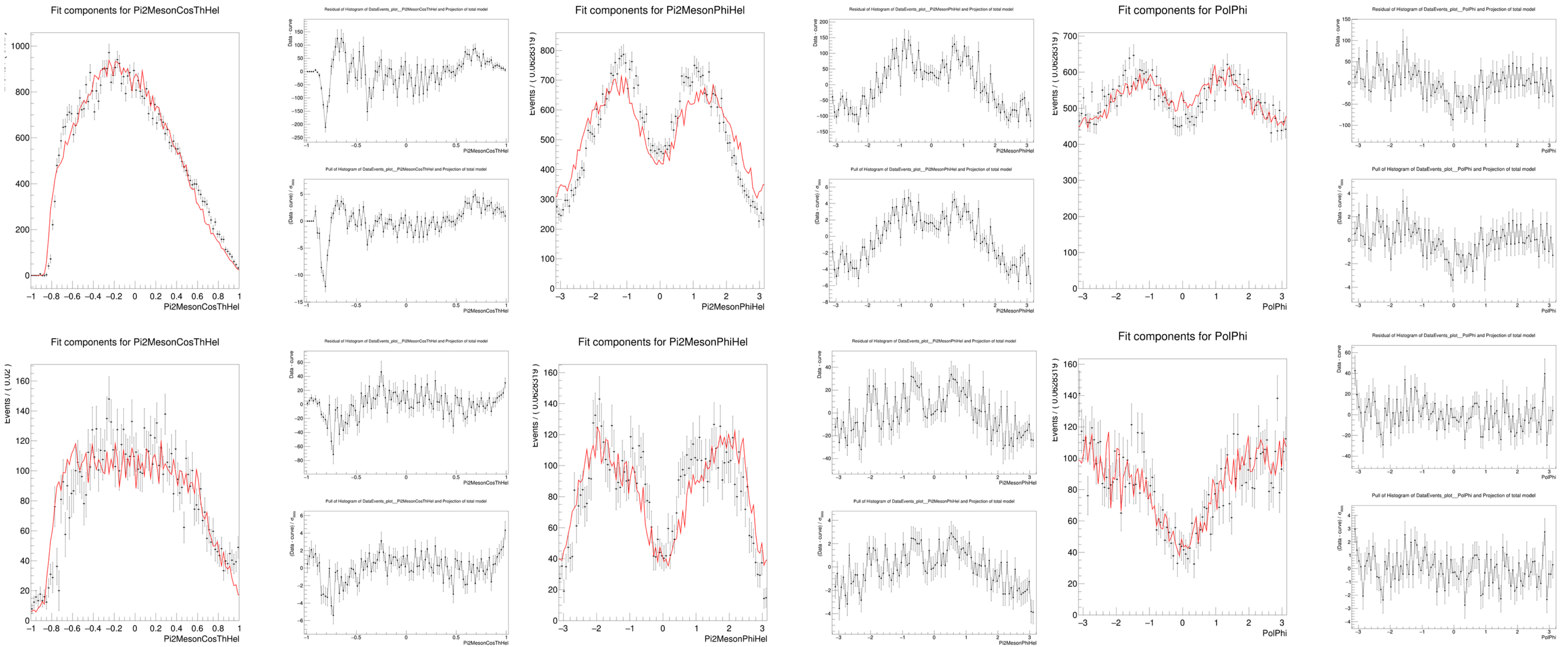
Colours = > different W bins



Fit Projections

Black points – data
Red line Fit – result

Top – low t (−0.1)
Bottom – high t (−0.6)

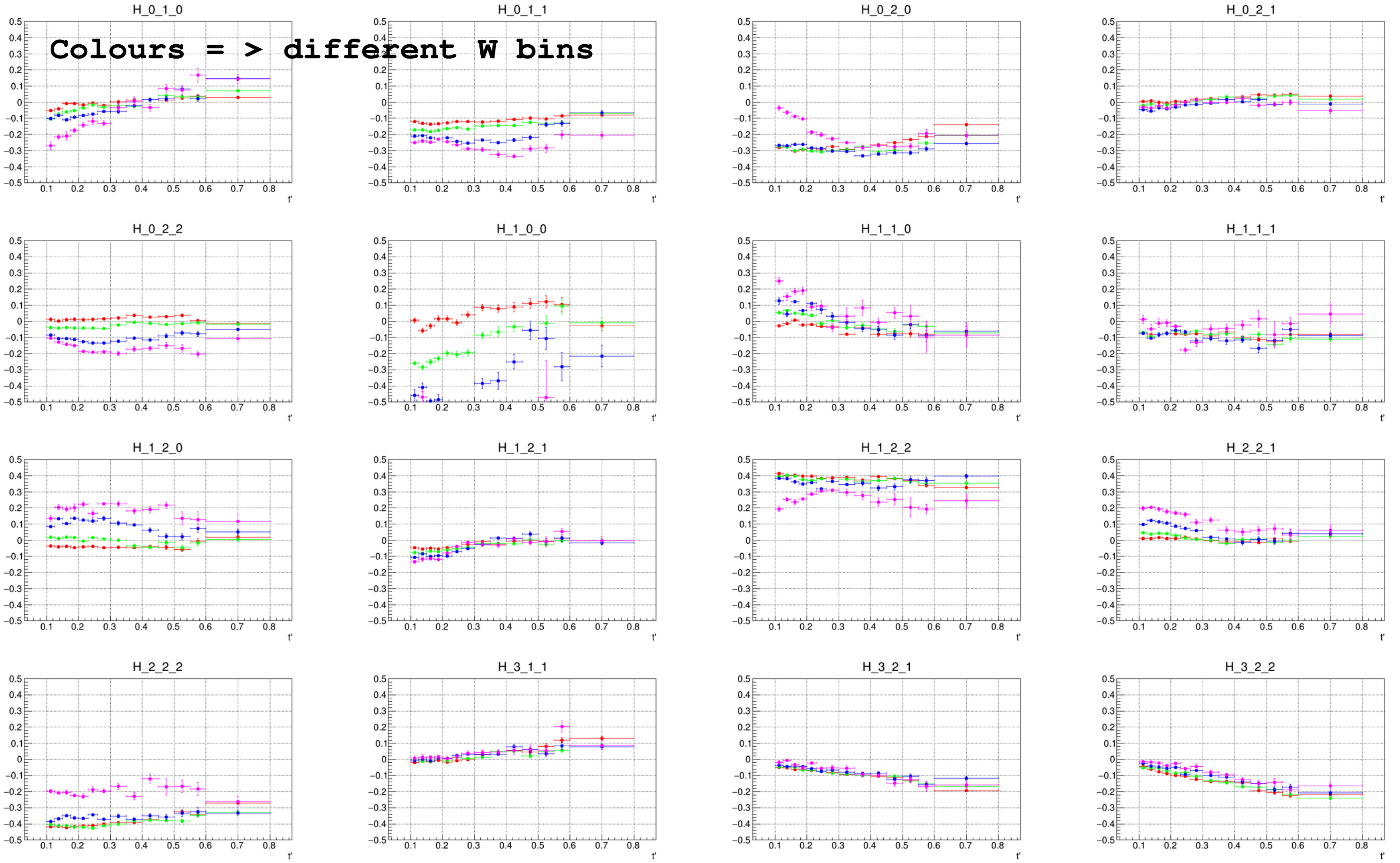


Proper Fits : Moments

H_A_L_M
A=> polarisation
L = Legendre
M = ϕ modulation

Looks a bit more consistent

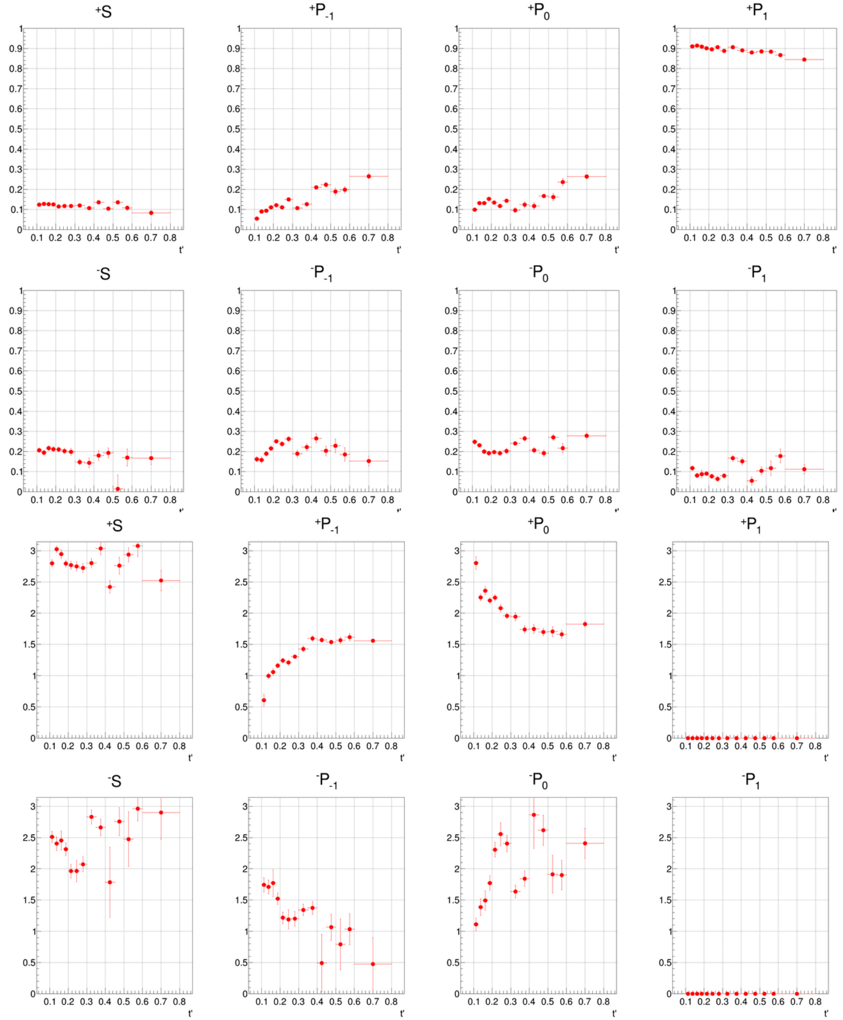
In particular H_3 moments independent of acceptance
And agree well



Proper Fits :Partial Waves

Results more or less follow expectations :

- Large $^{+}\mathbf{P}_{+1}$ (S-channel hel. Cons.)
- Other $^{+}\mathbf{P}$ grow with t'
- -ve reflectivity should be smaller
- S-waves should be small ~0

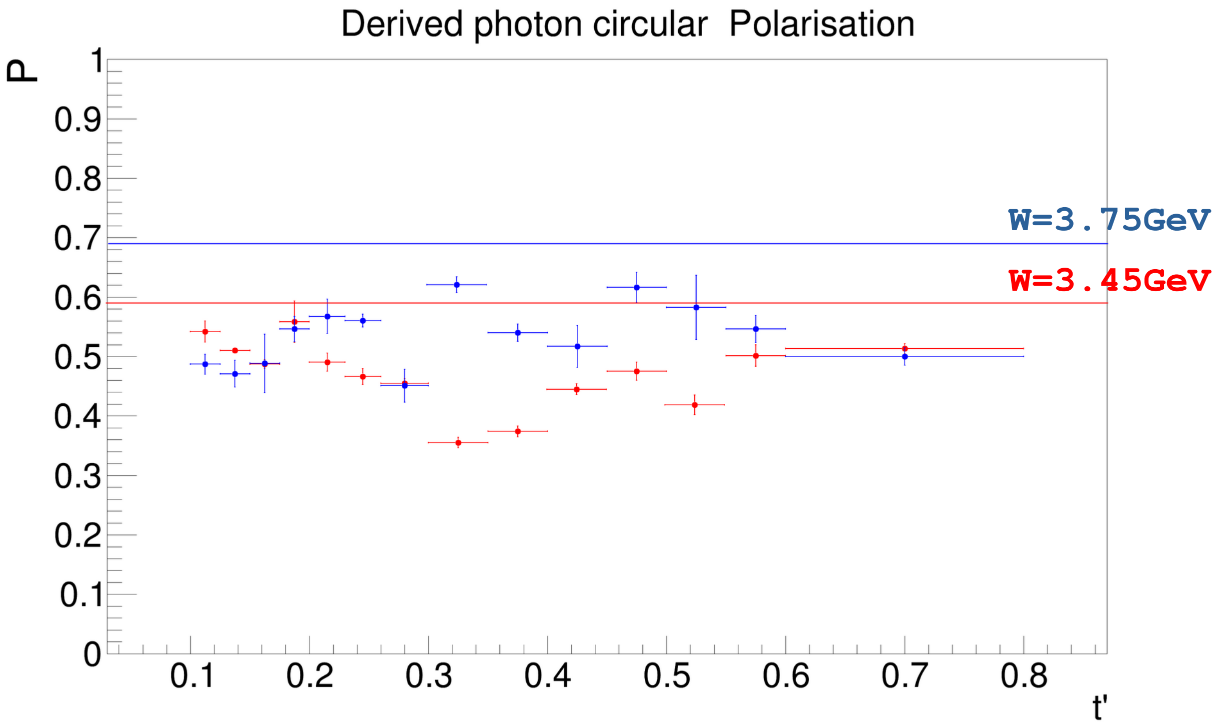


Beam Polarimetry

When performing PWA we leave the "circular" pol. As a free parameter, thereby extracting it.

From this the beam polarisation may be calculated.

To get correct absolute polarisation we require excellent acceptance correction.
Not there yet!!!



Relative Beam Polarisation Monitor

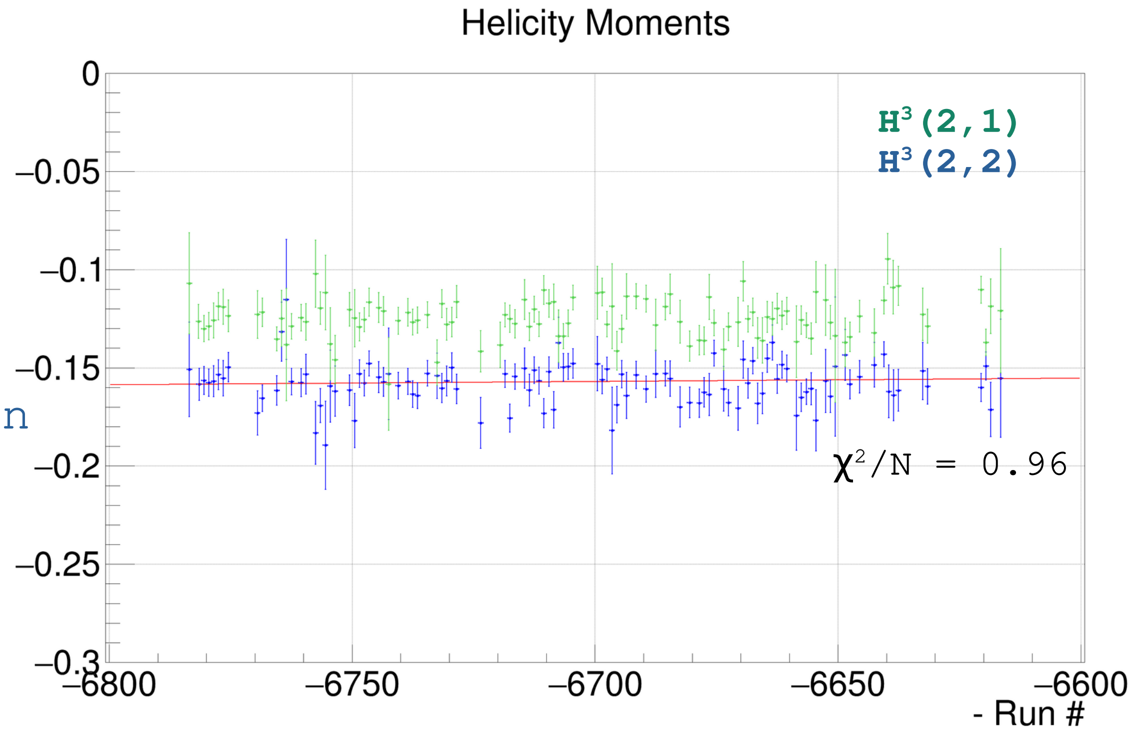
In principle we could use the Helicity dependent Spherical Harmonics to monitor beam polarisation

Here we take all events and Fit H^0 and H^1 moments for each run in Spring 2019 data

Fractional uncertainty 5-10%/run

Note measured P = 84.53+-1.474%

Fall 2018, 86 & 89%



Conclusions

MesonEx aims to extract Partial Wave Amplitudes for a number of reactions

Currently we are using ρ photoproduction as a validation of method and Experimental effects (backgrounds, acceptances)

We also measure SDMEs and Spherical Harmonic moments for this

Currently we see significant discrepancies as a result we need to :

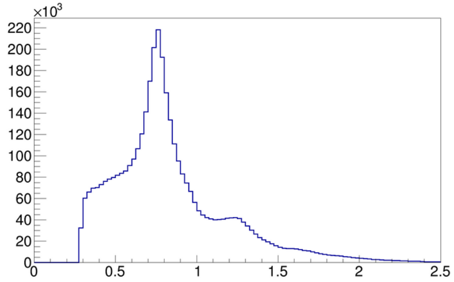
- Analyse exclusive final state – low background, low acceptance for ρ
- Improve background subtractions – use more simulated models
- Apply momentum and efficiency corrections
- Apply trigger effects in simulations

In addition this reaction may potentially be used as an absolute and relative beam polarimeter

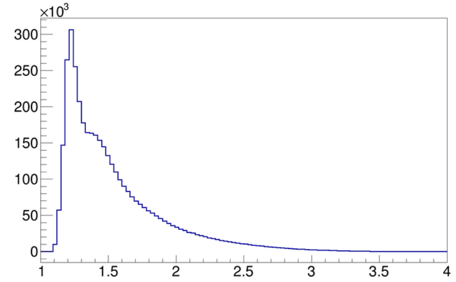
MesonEx $\pi^+\pi^-$ production for ρ

Exclusive Topology Q^2 >1.5

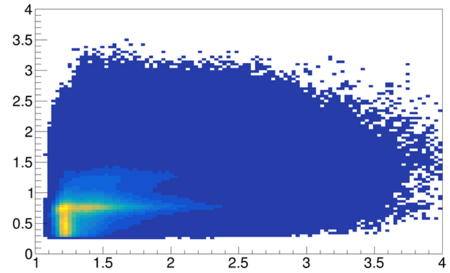
3.8M

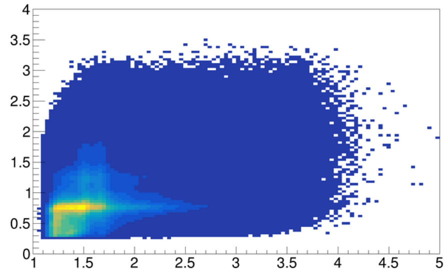


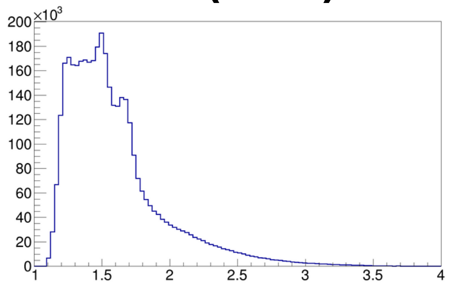
$M(\pi+\pi\text{-})$



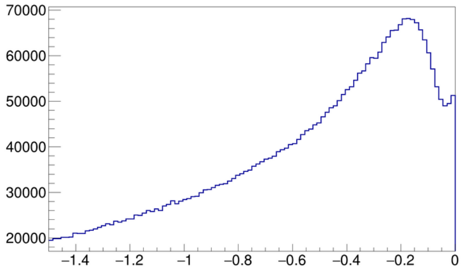
$M(\pi+p)$



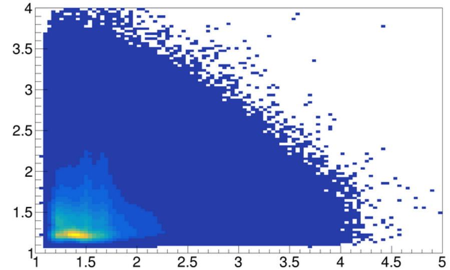


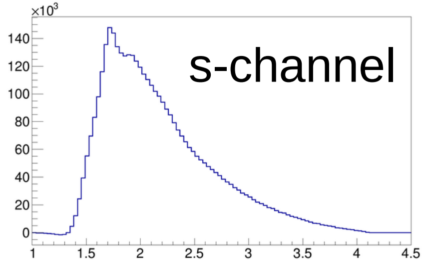


$M(\pi\text{-}p)$



t'



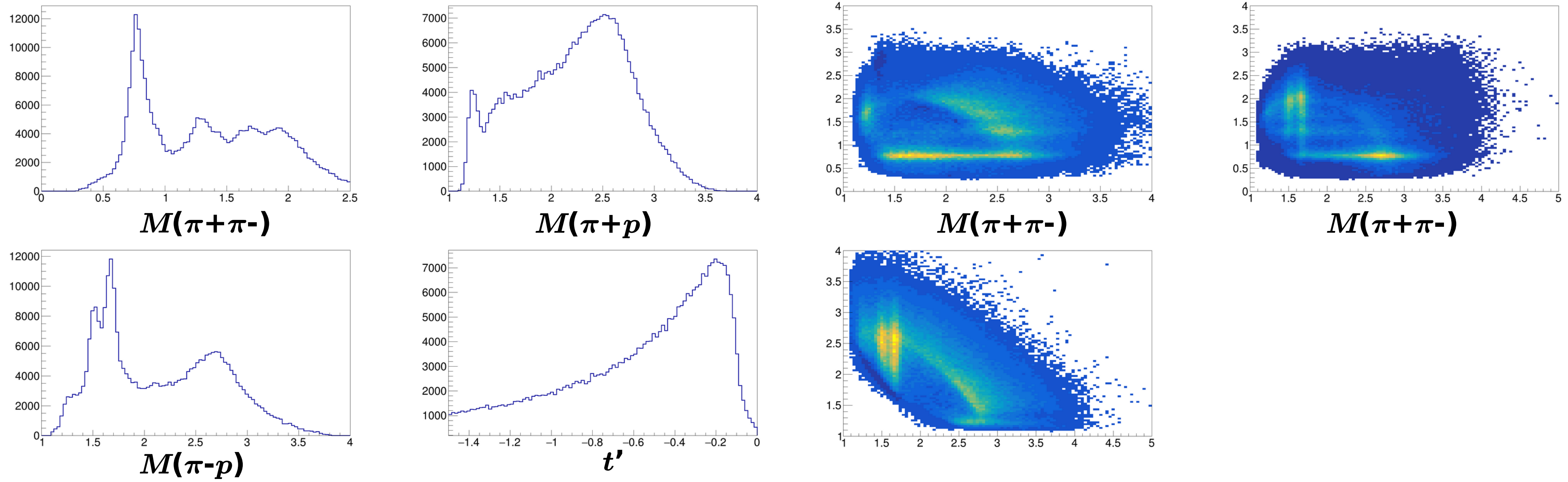


W

MesonEx $\pi^+\pi^-$ production for ρ

Exclusive Topology Q^2 > 1.5 && W > 3

0.3M



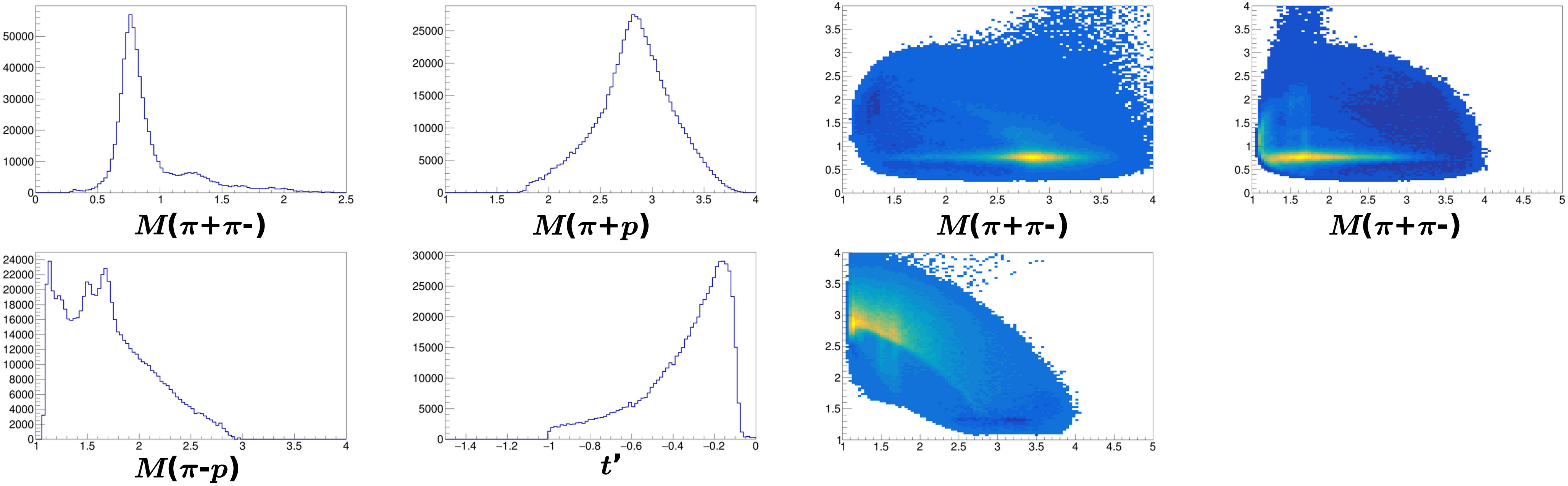
Larger N* contribution than for Quasi-real photoproduction

- possibly just due to acceptance (larger transerver momentum in final state)
- how to analyse ?

MesonEx $\pi^+\pi^-$ production for ρ

Missing pion Topology $Q^2 > 1.5$ && $W > 3$

0.6M



Example Moments

Considering **only +ve reflectivity** S,D-,D0,D+ waves

The expressions for $H^{\alpha}(4,2)$ are relatively straightforward (minus Clebsh Gordan coeffs)

$$H^0(4,2) = -2((D+)(D-)\cos(\varphi_{D+}-\varphi_{D-}))$$

$$H^1(4,2) = (D-)(D-) + (D+)(D+)$$

$$H^2(4,2) = (D-)(D-) - (D+)(D+)$$

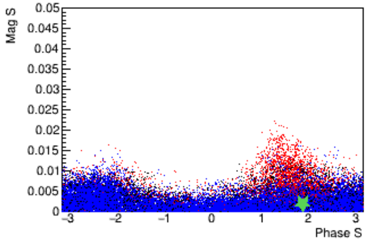
$$H^3(4,2) = 2((D+)(D-)\sin(\varphi_{D+}-\varphi_{D-}))$$

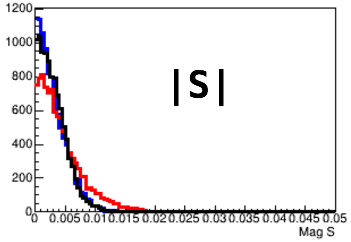
Here we have 4 equations with 4 unknowns and it is clear we can extract

- The magnitudes (sum and difference of $H^1(42)$ and $H^2(42)$
- The phases (from ratio of $H^0(42)$ and $H^3(42)$).

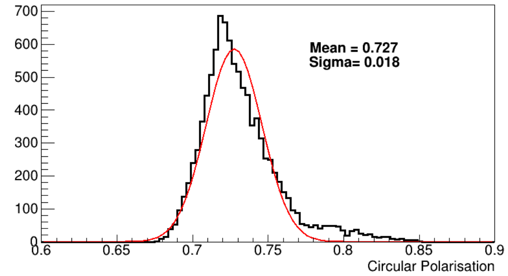
Without $H^3(42)$ we could just extract $\cos(\varphi_{D+}-\varphi_{D-})$ leaving a sign ambiguity in $(\varphi_{D+}-\varphi_{D-})$.

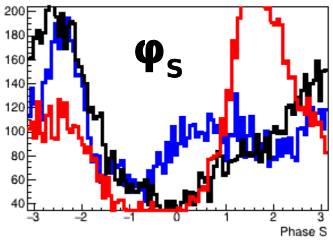
Amplitude Results +ve refectivity

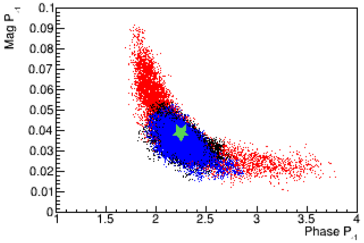


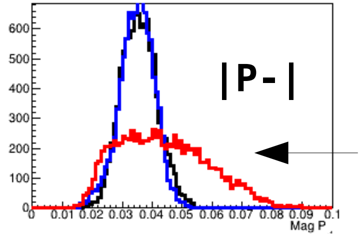


Linear Pol
Elliptical Pol
EllipticalFit Pol
Truth (== SDME fit results)



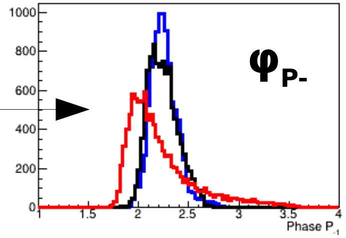


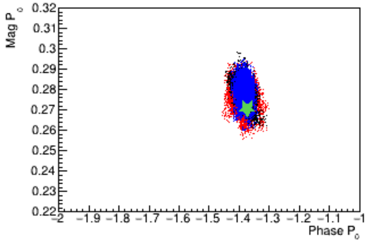


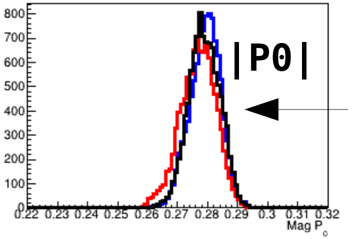


Improve ~200%
Red to blue

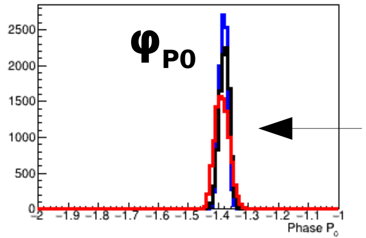
Improve ~25%
Red to blue



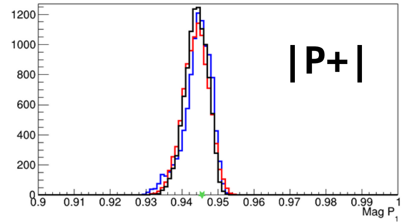




Improve ~15%
Red to blue

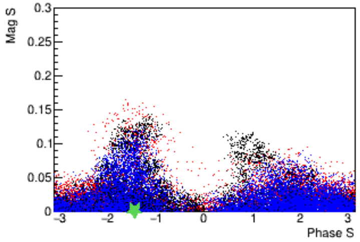


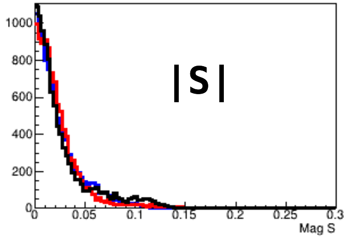
Improve ~67%
Red to blue



Phases relative to P_{+1}

Amplitude Results -ve refectivity





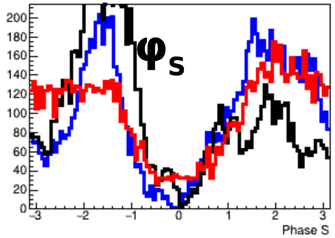
Linear Pol
Elliptical Pol
EllipticalFit Pol
Truth

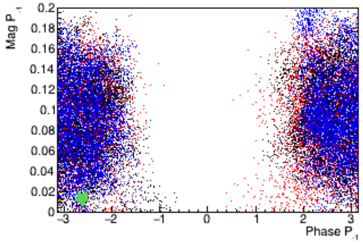
Less accurate results for **-ve** reflectivity

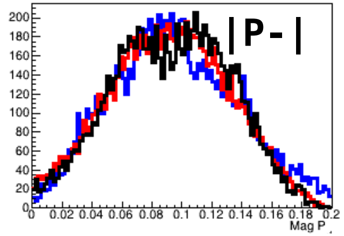
Circular polarisation makes no impact

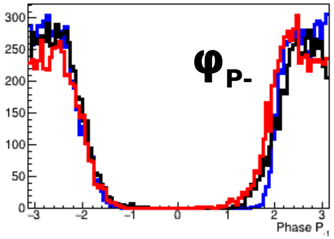
Perhaps because magnitudes are Small ($|+ve|^2=0.97$, $|-ve|^2=0.03$) consistent with truth

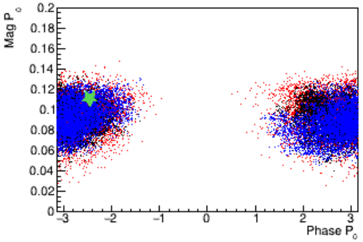
Or small true phase diff(P0-P1)

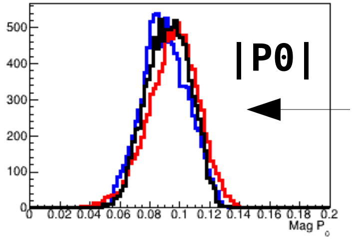


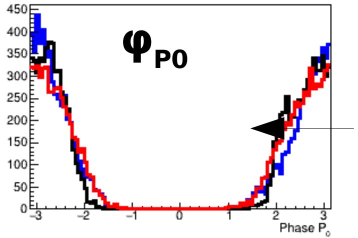


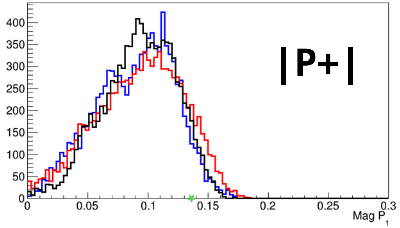






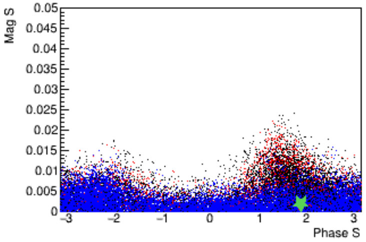


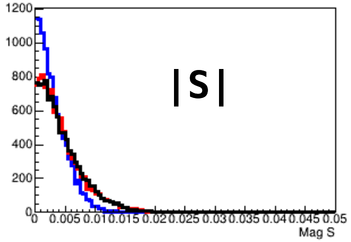




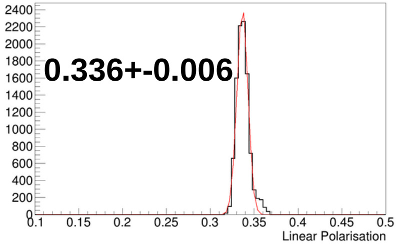
Phases relative to P_{+1}

Amplitude Results, unknown P_{lin}

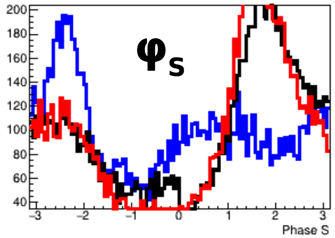


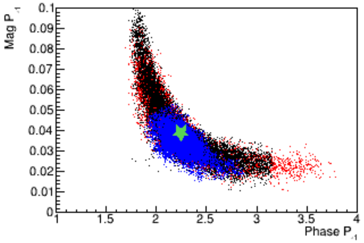


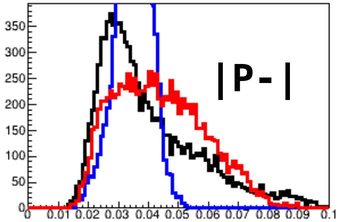
Linear Pol
Elliptical Pol
Linear Fit unknown Pol
Truth (== SDME fit results)

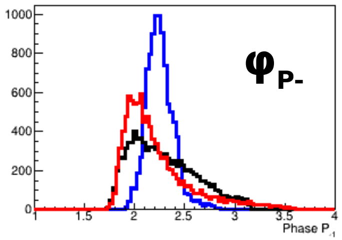


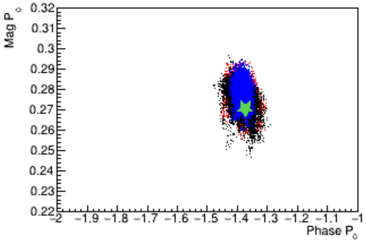
Actual 0.34

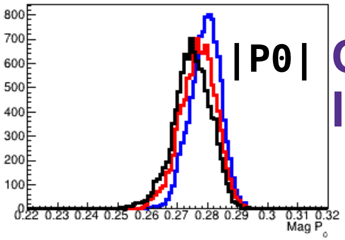




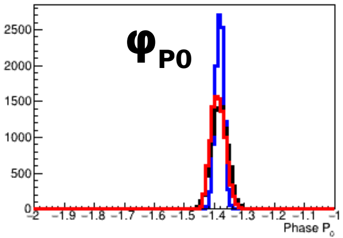


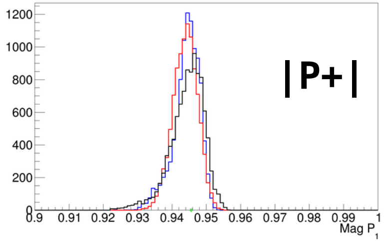






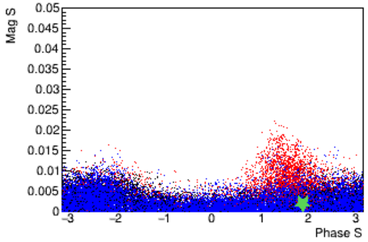
Comparing red to black little loss in accuracy

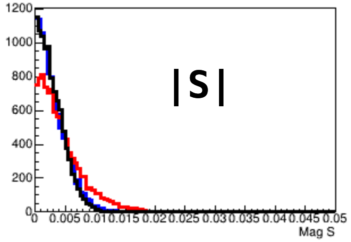




Phases relative to P_{+1}

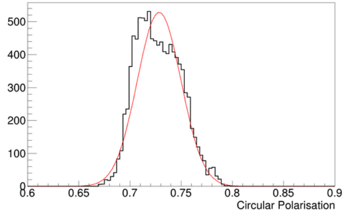
Amplitude Results, unknown P_{lin} and P_{circ}



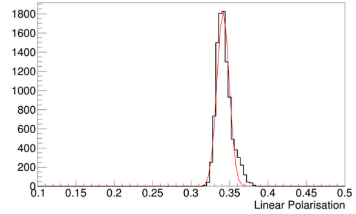


Linear Pol
Elliptical Pol
Elliptical unknown Lin. and circ. Pol
Truth

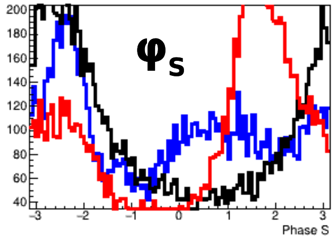
0.728+-0.021

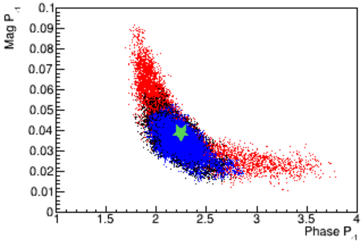


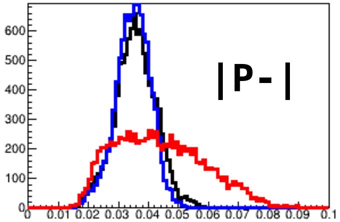
0.341+-0.008

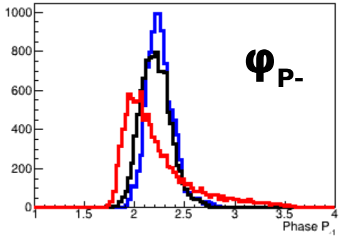


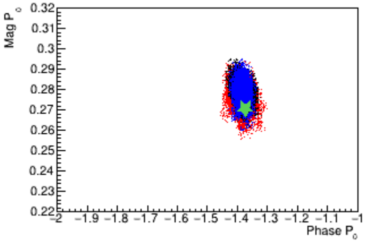
Actual 0.34

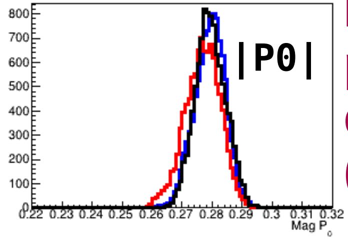




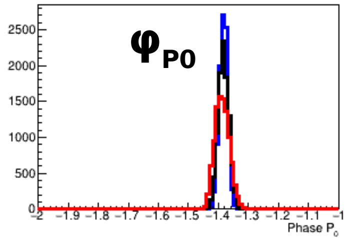


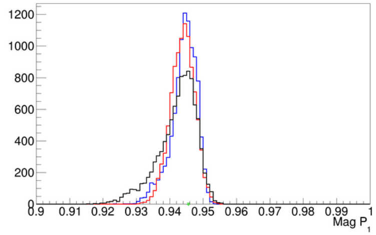






Not knowing polarisations does not effect results! (Blue and black)





Phases relative to P_{+1}

Photon SDM Schilling, Seyboth, Wolf

For linearly polarized photons eq. (11) reads:

$$|\gamma\rangle = -\frac{1}{\sqrt{2}}\left(e^{-i\Phi}|\lambda_\gamma = +1\rangle - e^{i\Phi}|\lambda_\gamma = -1\rangle\right), \quad (14)$$

where Φ is the angle between the polarization vector of the photon, ε = $(\cos\Phi, \sin\Phi, 0)$, and the production plane (x, z plane) (note: our definition of Φ differs by a sign from that of ref. [4]). The density matrix is

$$\rho^{\text{pure}}(\gamma) = \frac{1}{2}\begin{pmatrix} 1 & -e^{-2i\Phi} \\ -e^{2i\Phi} & 1 \end{pmatrix} \quad (15)$$

For elliptically polarized photons, eq. (11) reads:

$$|\gamma\rangle = \frac{1}{\sqrt{2(a^2+b^2)}}\left\{-(a+b)\,e^{-i\Phi}|\lambda_\gamma = +1\rangle + (a-b)\,e^{i\Phi}|\lambda_\gamma = -1\rangle\right\}, \quad (16)$$

where a and b are the lengths of the principal axes of the ellipse and Φ is the azimuthal angle of the principle axis a. The corresponding density matrix is given by:

$$\rho^{\text{pure}}(\gamma) = \frac{1}{2}\begin{pmatrix} 1+2a\sqrt{1-a^2} & e^{-2i\Phi}(1-2a^2) \\ e^{2i\Phi}(1-2a^2) & 1-2a\sqrt{1-a^2} \end{pmatrix}, \quad (17)$$

with a, b normalized to $a^2 + b^2 = 1$. Obviously the cases of circularly or linearly polarized photons can be obtained by specializing eq. (17) to $a = \pm 1/\sqrt{2}$ or $a = 1$ respectively.

We generalize these results to the case of partially polarized photons and put them into a standard form by writing $\rho(\gamma)$ as a linear combination of the matrices I, σ_i ($i = 1, 2, 3$), which from a complete set in the space of 2×2 hermitian matrices

$$\rho(\gamma) = \frac{1}{2}I + \frac{1}{2}\boldsymbol{P}_\gamma \cdot \boldsymbol{\sigma}, \quad (18)$$

where I is the 2×2 unit matrix, σ_i are the three Pauli matrices. The length P_γ of the three-vector $\boldsymbol{P}_\gamma$ is equal to the degree of polarization. The direction of $\boldsymbol{P}_\gamma$ depends on the kind of polarization, e.g. (from eqs. (13) and (15)):

$$\boldsymbol{P}_\gamma = P_\gamma(0, 0, \pm 1)$$

$$\boldsymbol{P}_\gamma = P_\gamma(-\cos 2\Phi, -\sin 2\Phi, 0) \quad (19)$$

for circular polarization with $\lambda_\gamma = \pm 1$ and for linear polarization respectively with $0 \leq P_\gamma \leq 1$.

Quasi-real electroproduction

Nuclear Physics B61 (1973) 381–413. North-Holland Publishing Company

HOW TO ANALYSE VECTOR-MESON PRODUCTION IN INELASTIC LEPTON SCATTERING

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Fakultät Physik der Universität Bielefeld, Bielefeld

G. WOLF
Deutsches Elektronen-Synchrotron DESY, Hamburg

$$\rho(\gamma) = \tfrac{1}{2} \sum_{\alpha=0}^{8} \tilde{\Pi}_\alpha \Sigma^\alpha ;$$

$$\tilde{\Pi} = \{1, -\epsilon\cos 2\Phi, -\epsilon \sin 2\Phi, \frac{2m}{Q}(1-\epsilon)P_0, \epsilon+\delta, \sqrt{2\epsilon(1+\epsilon+2\delta)}\cos\Phi, \sqrt{2\epsilon(1+\epsilon+2\delta)}\sin\Phi, \frac{2m}{Q}(1-\epsilon)(P_1\cos\Phi + P_2\sin\Phi), \frac{2m}{Q}(1-\epsilon)(P_1\sin\Phi - P_2\cos\Phi)\} . \quad (65)$$

$$W(\cos\theta, \phi, \Phi, \alpha_2 = 0, \pi) = W^{\text{unpol}}(\cos\theta, \phi, \Phi) \pm W^{\text{long pol}}(\cos\theta, \phi, \Phi) ; \quad (88)$$

$$W^{\text{unpol}}(\cos\theta, \phi, \Phi) = \frac{1}{1+(\epsilon+\delta)R}\frac{3}{4\pi}$$

$$\times [\tfrac{1}{2}(1-\rho^0_{00}) + \tfrac{1}{2}(3\rho^0_{00}-1)\cos^2\theta - \sqrt{2}\,\mathrm{Re}\,\rho^0_{10}\sin 2\theta\cos\phi - \rho^0_{1-1}\sin^2\theta\cos 2\phi$$

$$-\epsilon\cos 2\Phi\{\rho^1_{11}\sin^2\theta + \rho^1_{00}\cos^2\theta - \sqrt{2}\,\mathrm{Re}\,\rho^1_{10}\sin 2\theta\cos\phi - \rho^1_{1-1}\sin^2\theta\cos 2\phi\}$$

$$-\epsilon\sin 2\Phi\{\sqrt{2}\,\mathrm{Im}\,\rho^2_{10}\sin 2\theta\sin\phi + \mathrm{Im}\,\rho^2_{1-1}\sin^2\theta\sin 2\phi\}$$

$$W^{\text{long pol}}(\cos\theta, \phi, \Phi) = \frac{1}{1+(\epsilon+\delta)R}\frac{3}{4\pi}$$

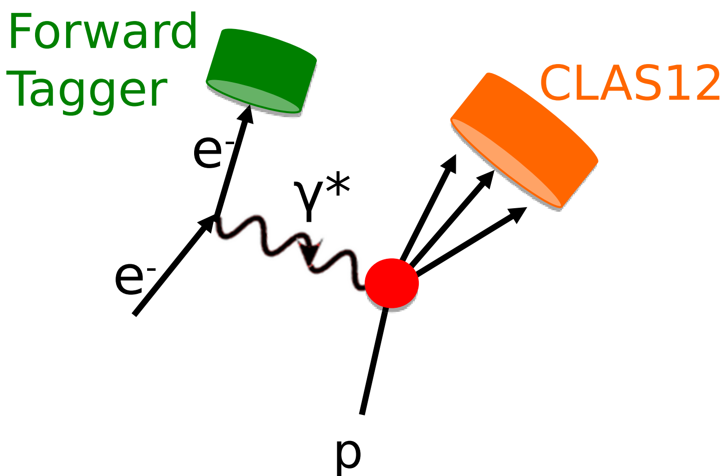
$$\times P\,[\sqrt{1-\epsilon^2}\{\sqrt{2}\,\mathrm{Im}\,\rho^3_{10}\sin 2\theta\sin\phi + \mathrm{Im}\,\rho^3_{1-1}\sin^2\theta\sin 2\phi\} +$$

For low Q^2 we assume,

$$\rho_\gamma(\Phi) = \tfrac{1}{2}\left(1 - \epsilon\cos 2\Phi\,\sigma_x - \epsilon\sin 2\Phi\,\sigma_y - P_{beam}\sqrt{1-\epsilon^2}\sigma_z\right)$$

With ε the virtual photon polarisation

Elliptical Polarisation for MesonEx



Forward Tagger	
E’	0.5-5 GeV
ν	6-10 GeV
θ	2.5-4.5 deg
Q^2	0.007 – 0.3 GeV^2
W	3.2-4.2 GeV
Photon Flux	5 x 10^7 γ/s

Quasi-real photoproduction:

- Detection of multiparticle final state from meson decay in the large acceptance spectrometer CLAS
- Detection of the scattered electron for the tagging of the quasi-real photon in the CLAS12 FT
- High-intensity and high linear-polarization tagged “photon” beam; degree of polarization determined event-by-event from the electron kinematics
- Longitudinal e- polarisation transferred to virtual photon as “circular polarisation”
- In FT acceptance P_{lin} and P_{circ} ~ 0.65

Photon Polarisation Simulations

Start with the same waveset as in ambiguity paper

$[\ell]_m$	Magnitude	Phase
S_0	0.499	$0°$
D_{-1}	0.201	$15.4°$
D_0	0.567	$174°$
D_1	0.624	$-81.6°$

No -ve reflectivity (for now)

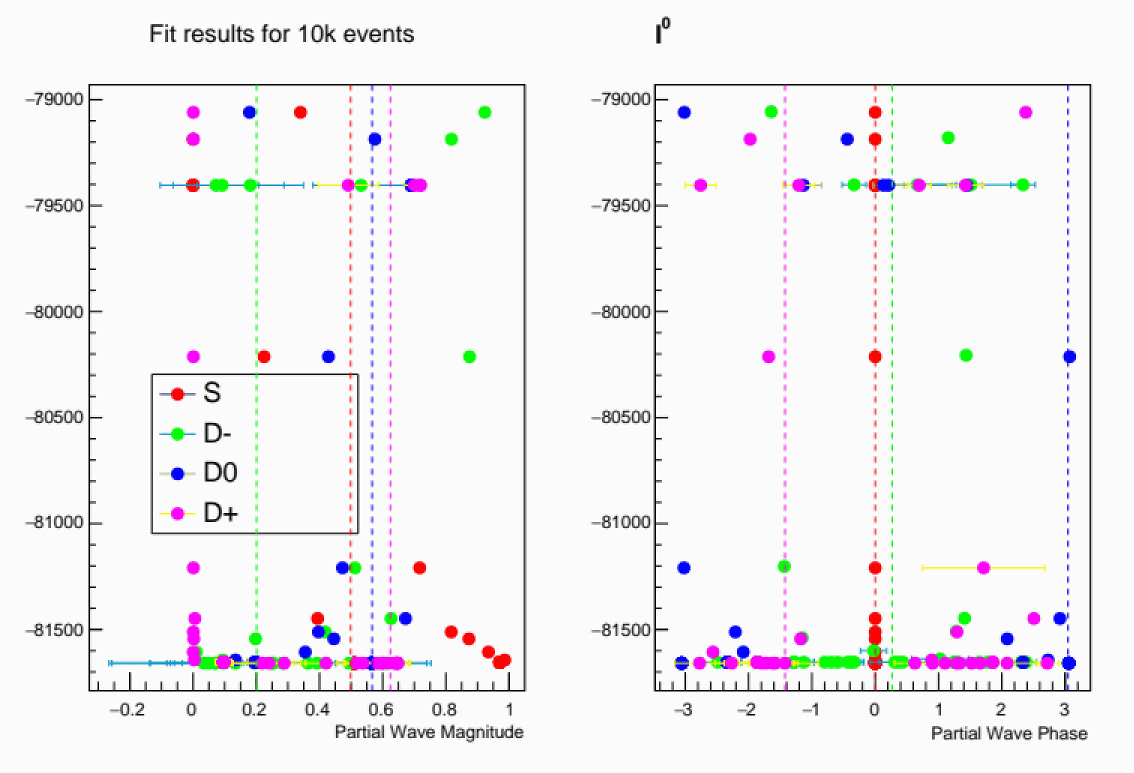
$$\mathcal{I}(\Omega, \Phi) = \mathcal{I}_0(\Omega) - \mathcal{I}_1(\Omega) P_{\gamma L} \cos 2\Phi - \mathcal{I}_2(\Omega) P_{\gamma L} \sin 2\Phi - \mathcal{I}_3(\Omega) P_{\gamma C}.$$

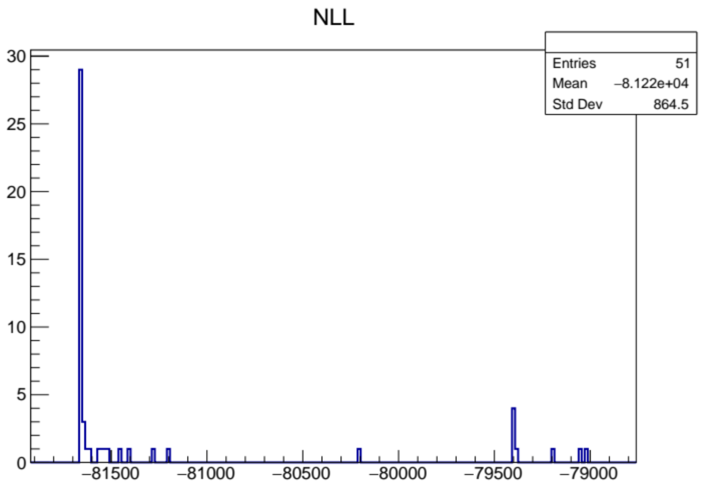
Generate data 10k events with full α=0,1,2,3 intensities
$P_{\gamma C}$, $P_{\gamma L}$ uniform in range 0-0.5

Perform 50 fits with different polarisation information
Only fit for the non-zero generated waves, as in the paper.

Negative Log Likelihood is shown on y-axis, amplitude components on x axis
Solution => highest likelihood

Simulations - Unpolarised



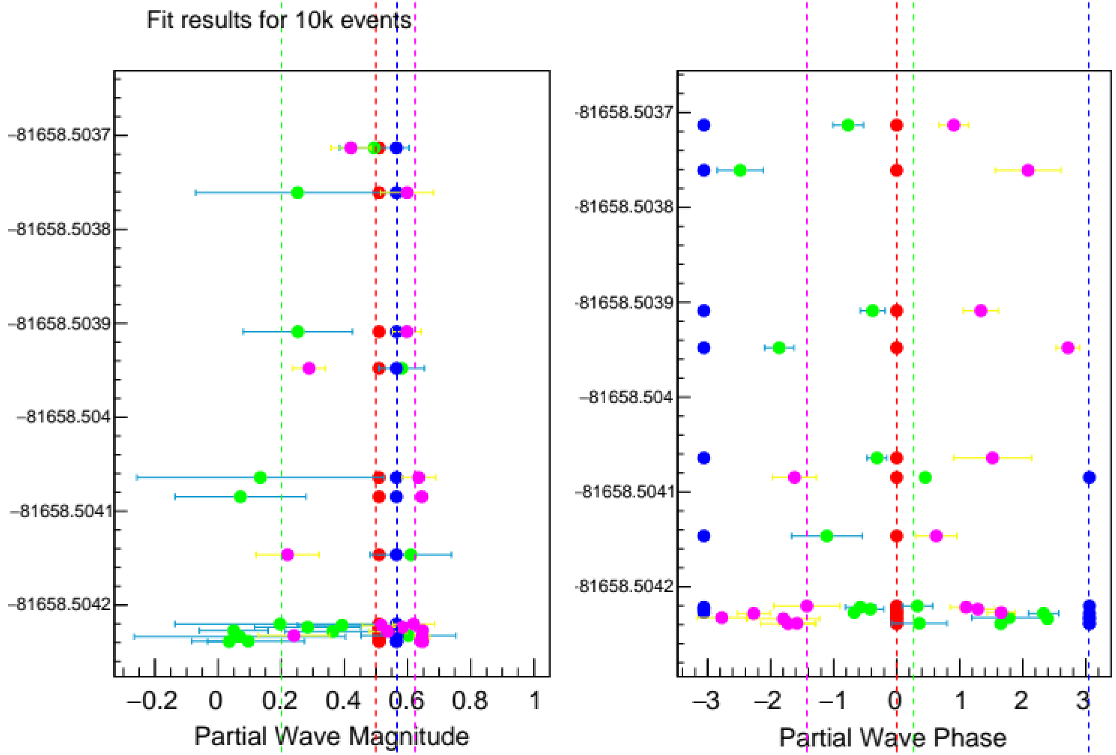


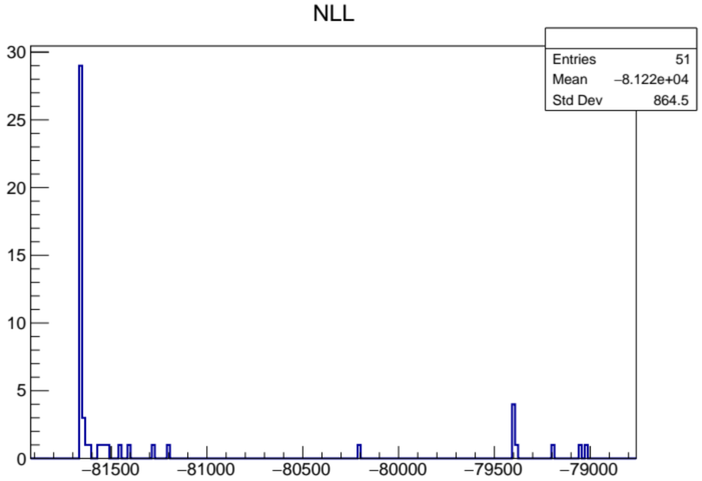
Ambiguous solutions
(for D+ and D-)
and Complex conjugates

But low chance of local max.

Simulations - Unpolarised

Zoom in on likelihood

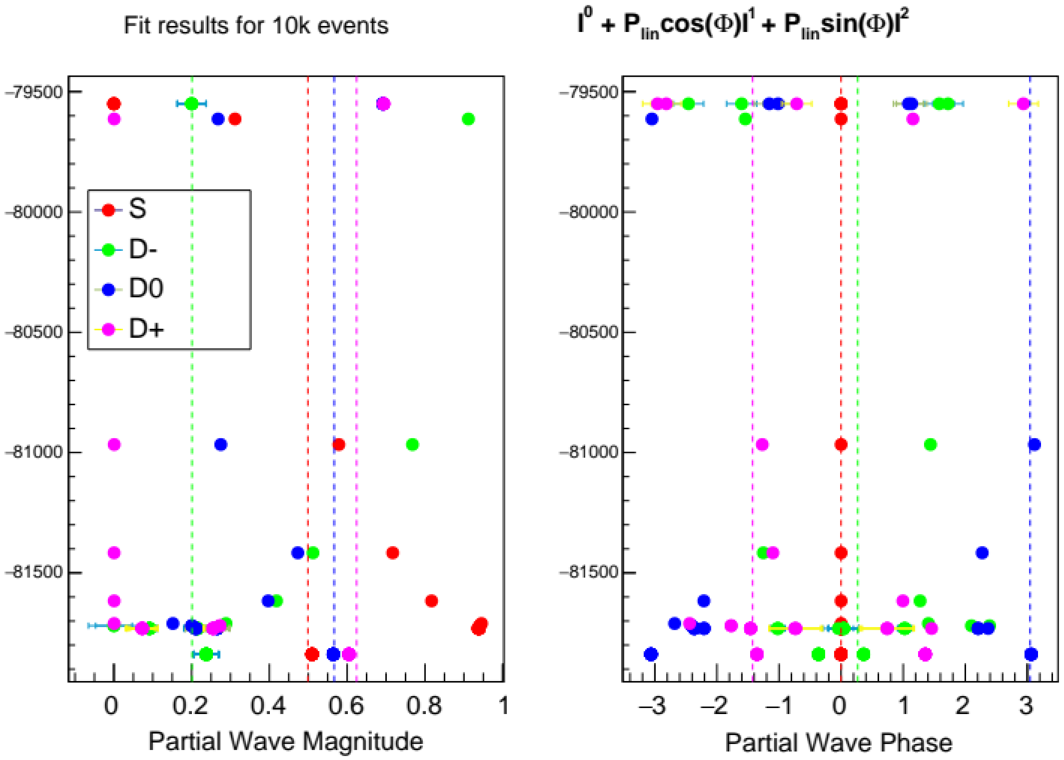


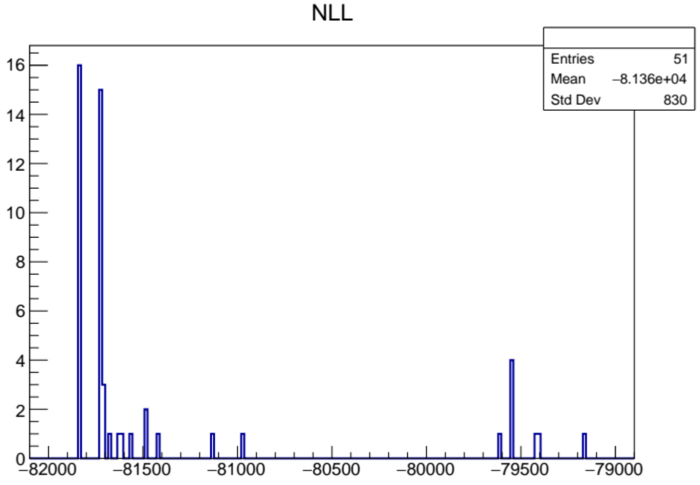


Ambiguous solutions
(for D+ and D-)
and Complex conjugates

Low chance of local max.
Uncertainties large.

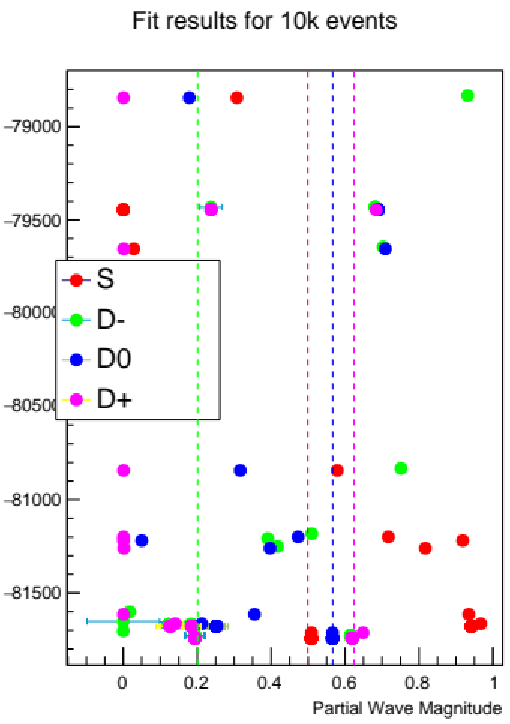
Simulations – Linearly Polarised (as paper)

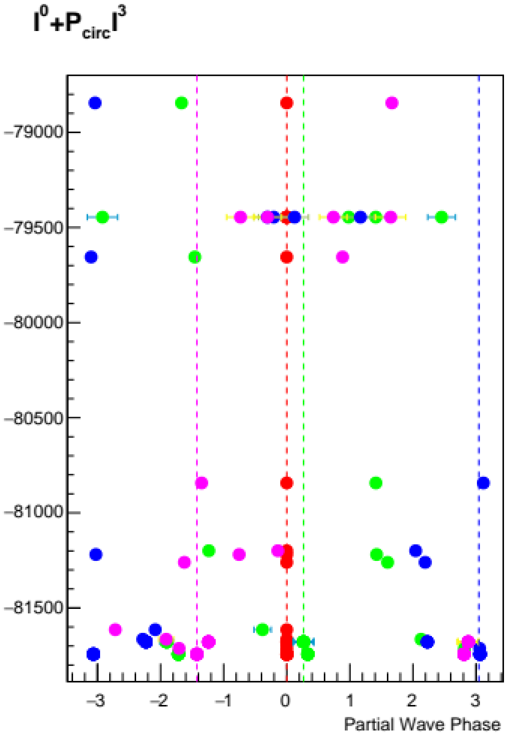


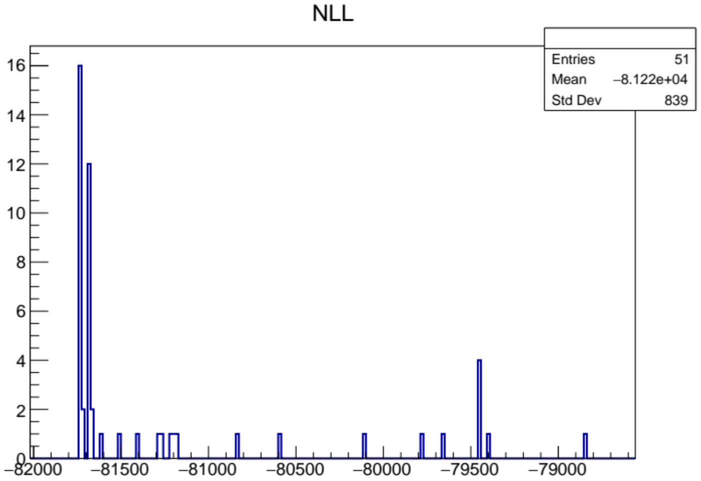


Single solution with
Complex conjugate
Smaller uncertainties

Simulations – Circular polarised

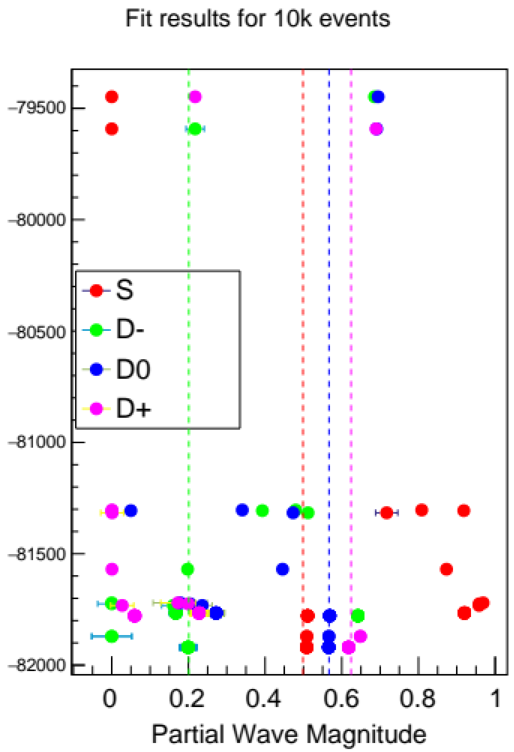


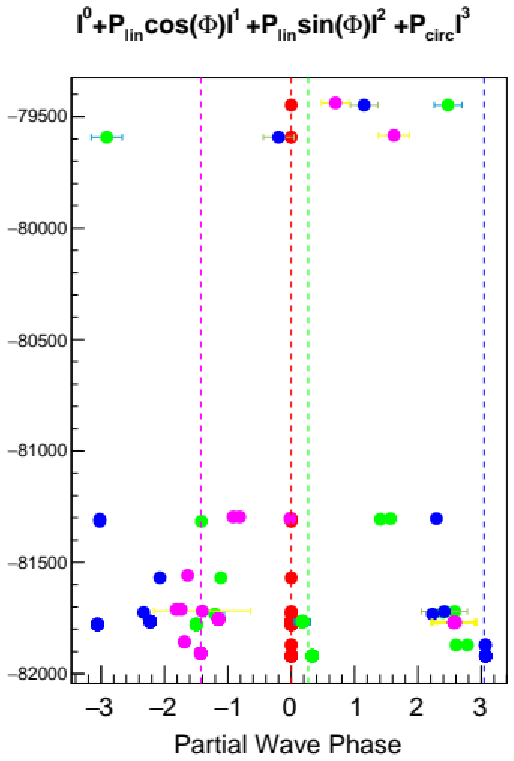


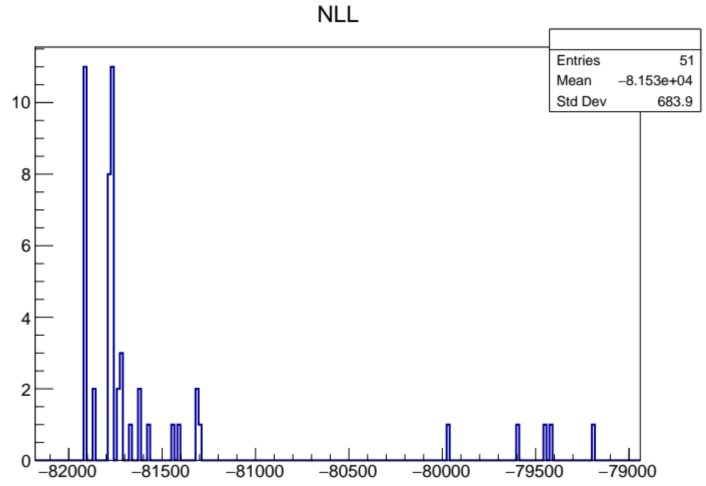


Ambiguous solutions
(D+ and D-)
But no complex conjugate
Smaller uncertainties

Simulations – Elliptically Polarised



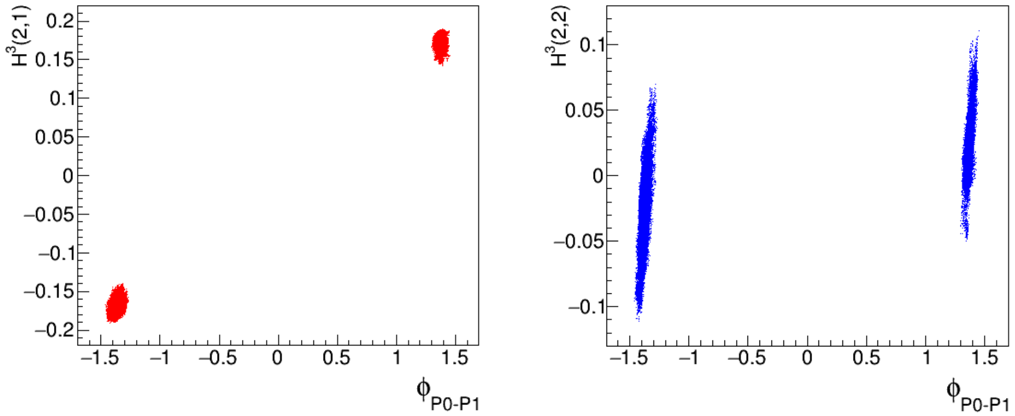




Single Solution no Complex conjugate

Potential polarimetry ?

From linear polarised fit we have fully determined the partial waves
- We can already calculate the I^3 intensity for both complex conjugates

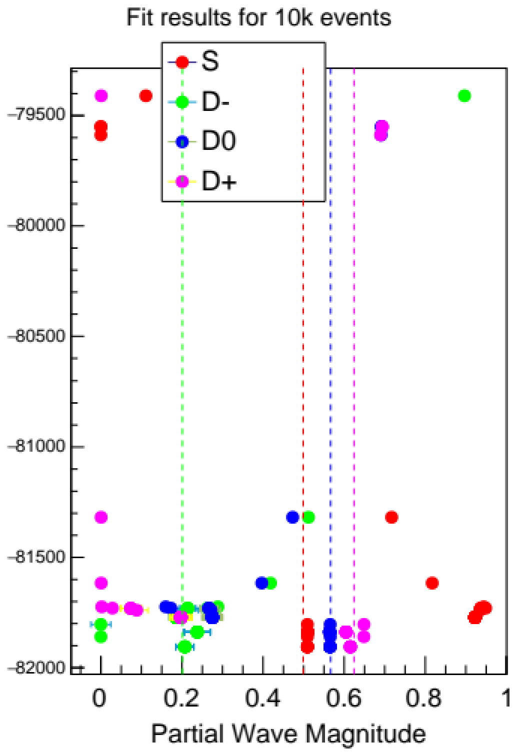


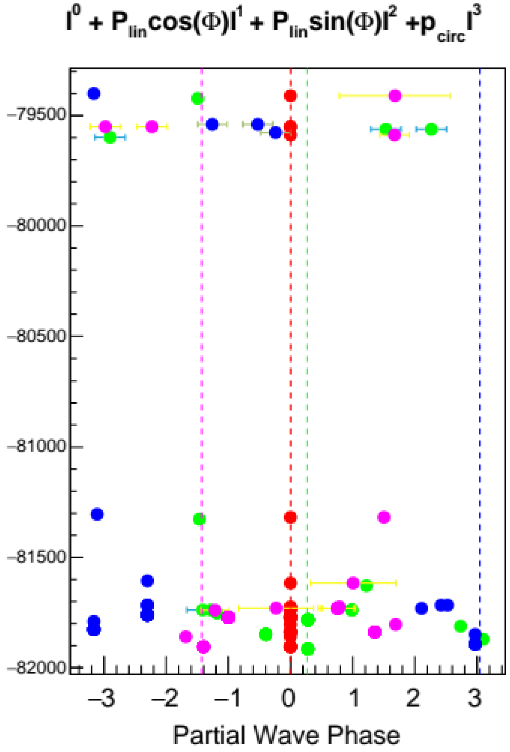
Complex conjugate solutions
H3 moments

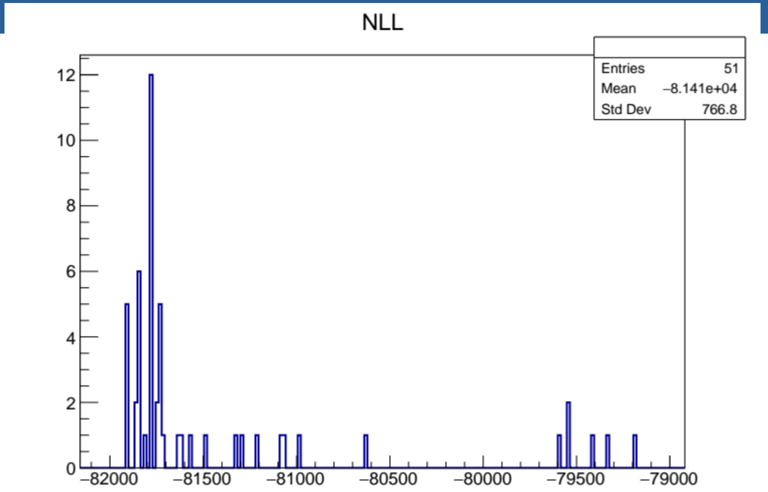
- So we are overconstrained in our fits
  => should result in smaller uncertainties
  => Or we can introduce an additional unknown parameter
    - the photon circular polarisation degree

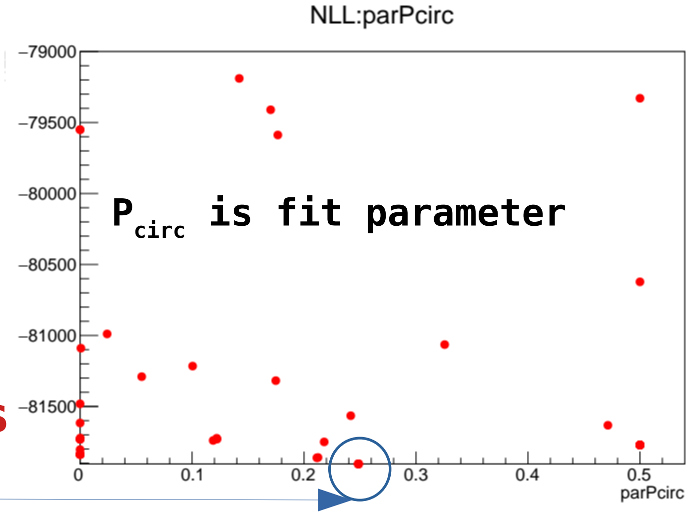
- Next I just redo the elliptically polarised fit with $P_{\gamma C}$ as a parameter not an observable.

Simulations – Elliptical polarised,unknown P_c







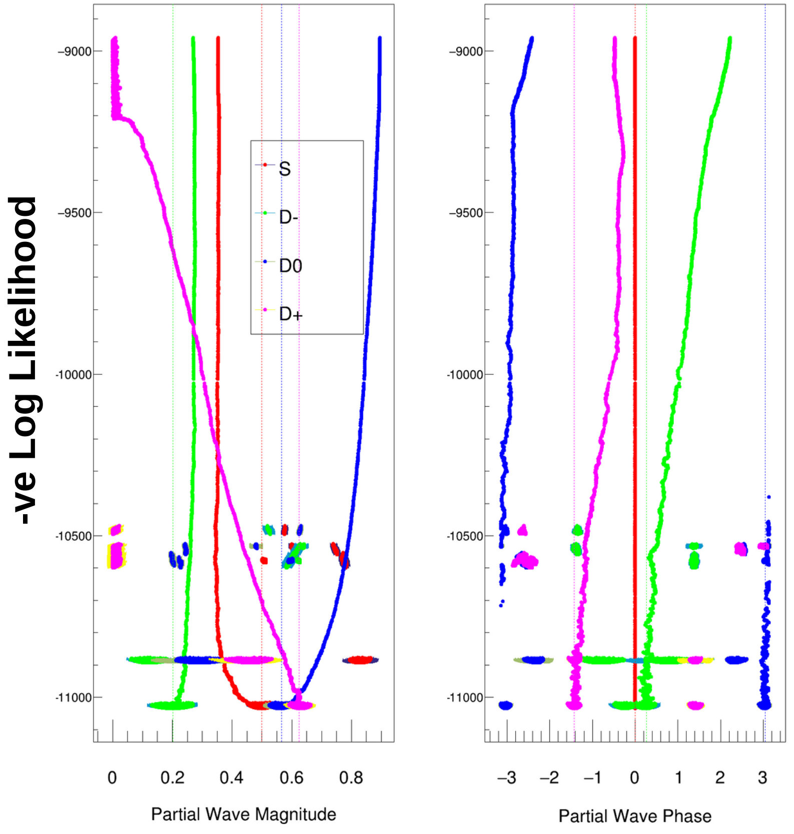


Single Solution no Complex conjugate

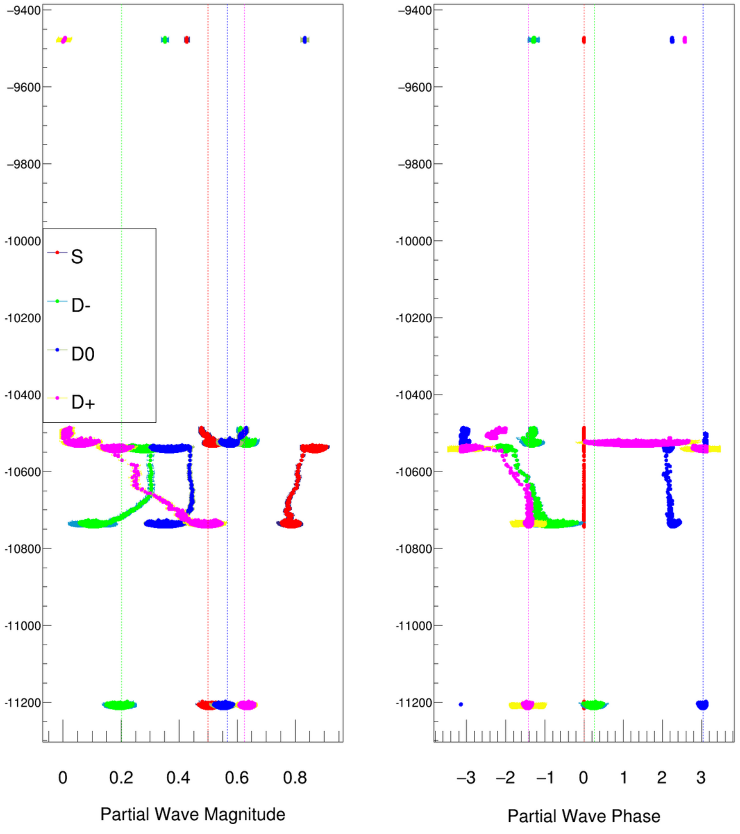
Best solution yields Correct P_{circ}=0.25

Results with MCMC

Fit I , I , I



Fit I , I , I , I



Final uncertanties are similar apart from D- which : 0.17 → 0.10

asymmetry