MesonEx : Meson Spectroscopy with CLAS12

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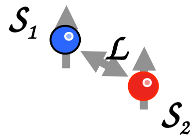
Light Quark Meson Spectroscopy



$S=S_1+S_2$ $J= L+S$

$P = (-1)^{L+1}$ $C= (-1)^{L+S}$

Not all the J^{PC} combinations are allowed:

0^{++} 0^{+-} 0^{-+} 0^{--} 1^{++} 1^{+-} 1^{-+} 1^{--} 2^{++} 2^{+-} 2^{-+} 2^{--} 3^{++} …

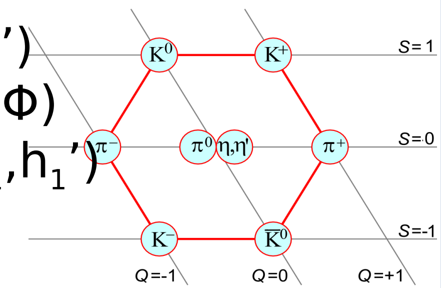
Each J^{PC} decomposed into nonet of degenerate states

$J^{PC}=0^{-+} \Rightarrow (\pi,K,\eta,\eta')$

$1^{--} \Rightarrow (\rho,K^*,\omega,\Phi)$

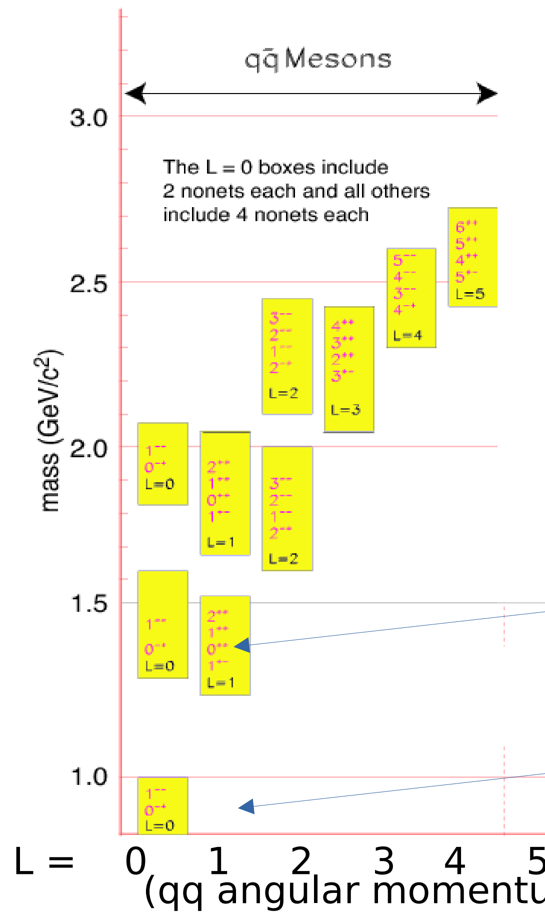
$1^{+-} \Rightarrow (b_1,K_1,h_1,h_1')$

…



- Quark model explains much of the observed states
- Some states not well established or not definitively assigned
- Some additional unassigned states
- Particular ?? with 0++ scalars

Consider light quarks: u,d,s



a,K,f,f'
b,K,h,h'

ρ,K*,ω,φ
π,K,η,η'

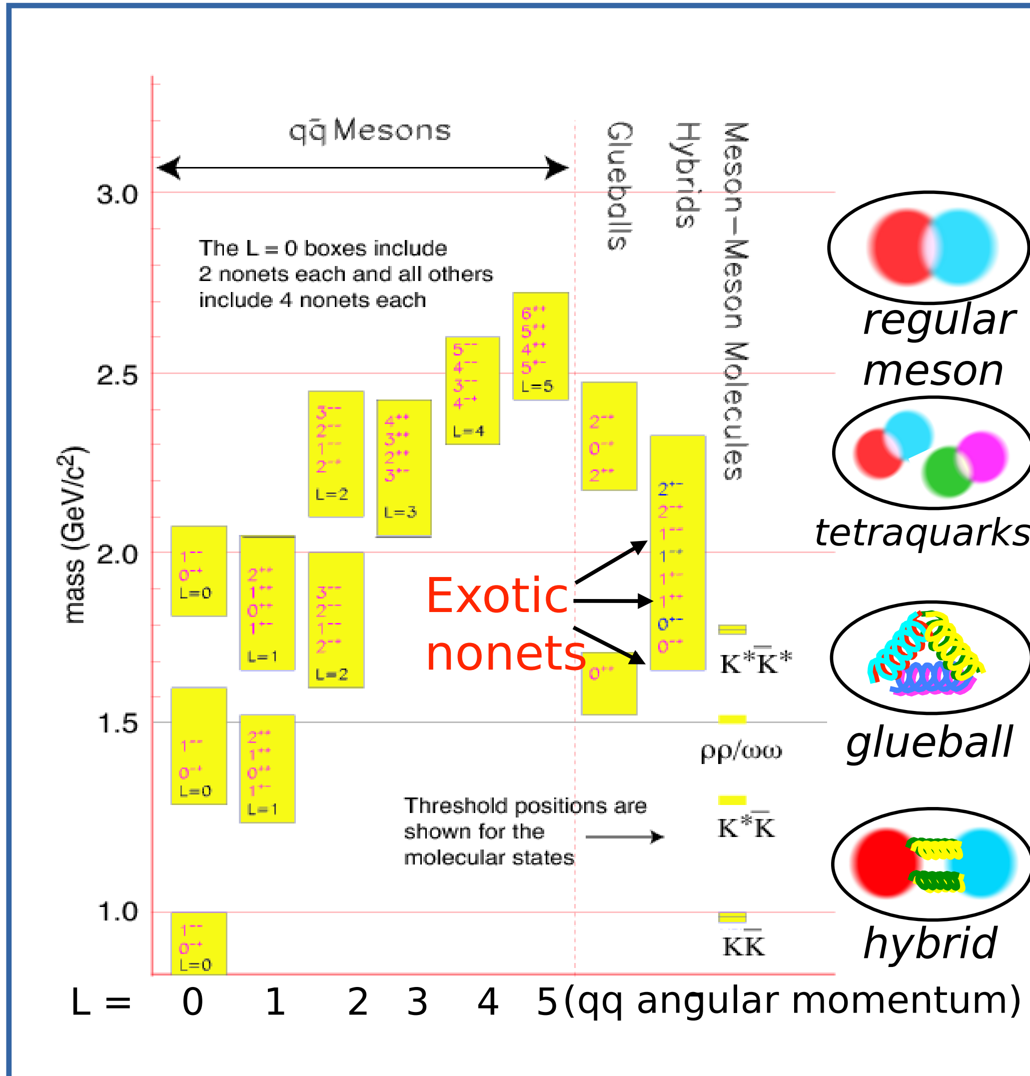
What else might exist

QCD does not forbid other compositions

Some states predicted by theory

Evidence for some states found experimentally

Hybrids include states of exotic quantum numbers



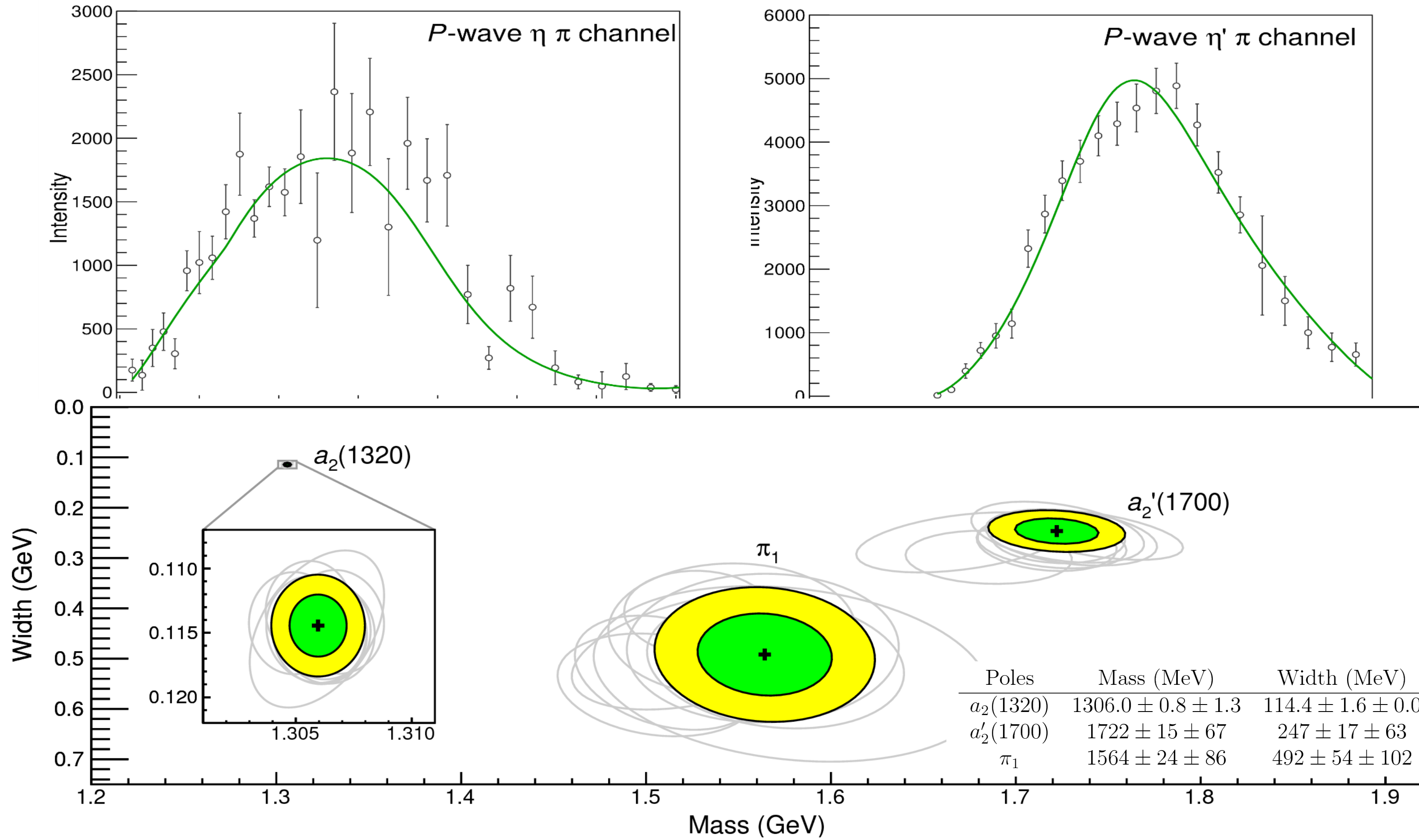
$\pi_1(1600)$ from COMPASS $\eta(')\pi$

Determination of the Pole Position of the Lightest Hybrid Meson Candidate

A. Rodas, A. Pilloni, M. Albaladejo, C. Fernández-Ramírez, A. Jackura, V. Mathieu, M. Mikhasenko, J. Nys, V. Pauk, B. Ketzer, and A. P. Szczepaniak (Joint Physics Analysis Center)

Phys. Rev. Lett. **122**, 042002 – Published 29 January 2019

Coubled analysis of $\eta\pi$ and $\eta'\pi$



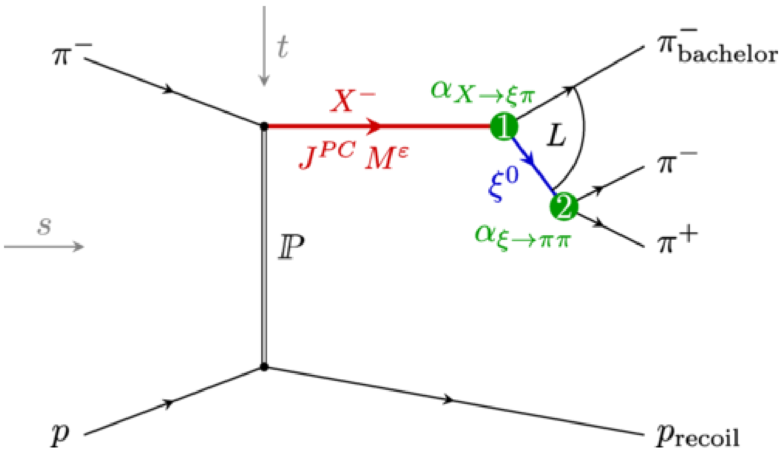
Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

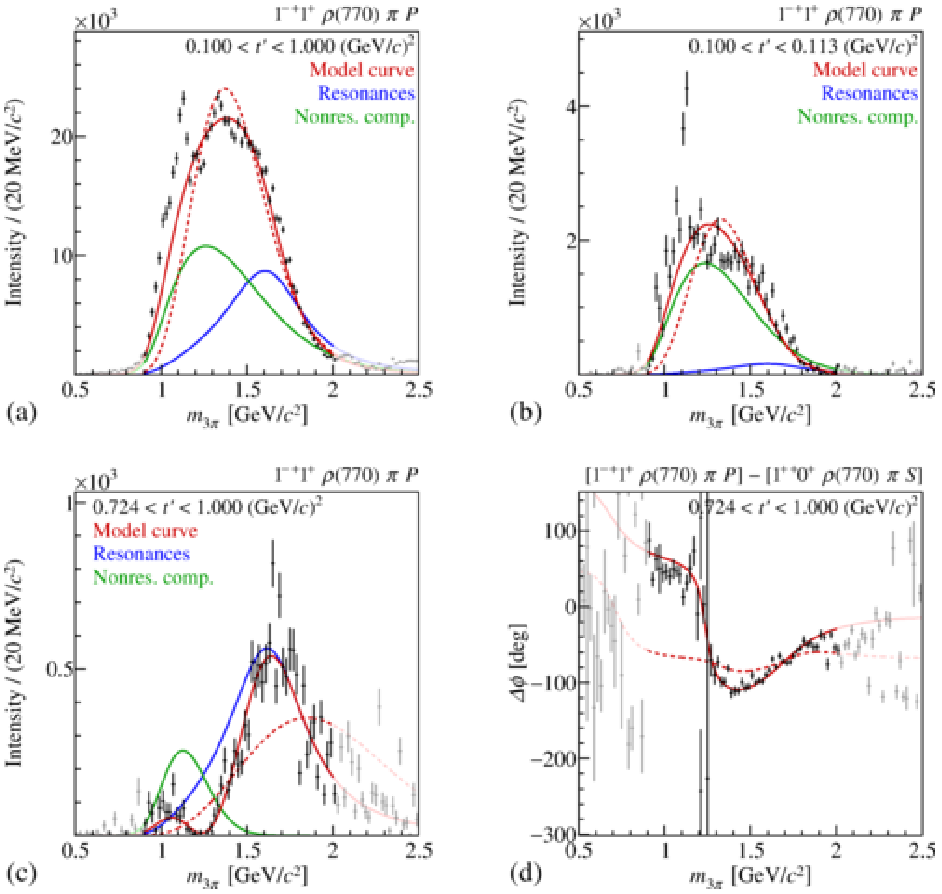
$\pi_1(1600)$ from COMPASS 3π

Light isovector resonances in $\pi^- p \to \pi^-\pi^-\pi^+ p$ at $190\ \mathrm{GeV}/c$

M. Aghasyan *et al.*

Phys. Rev. D **98**, 092003 – Published 2 November 2018





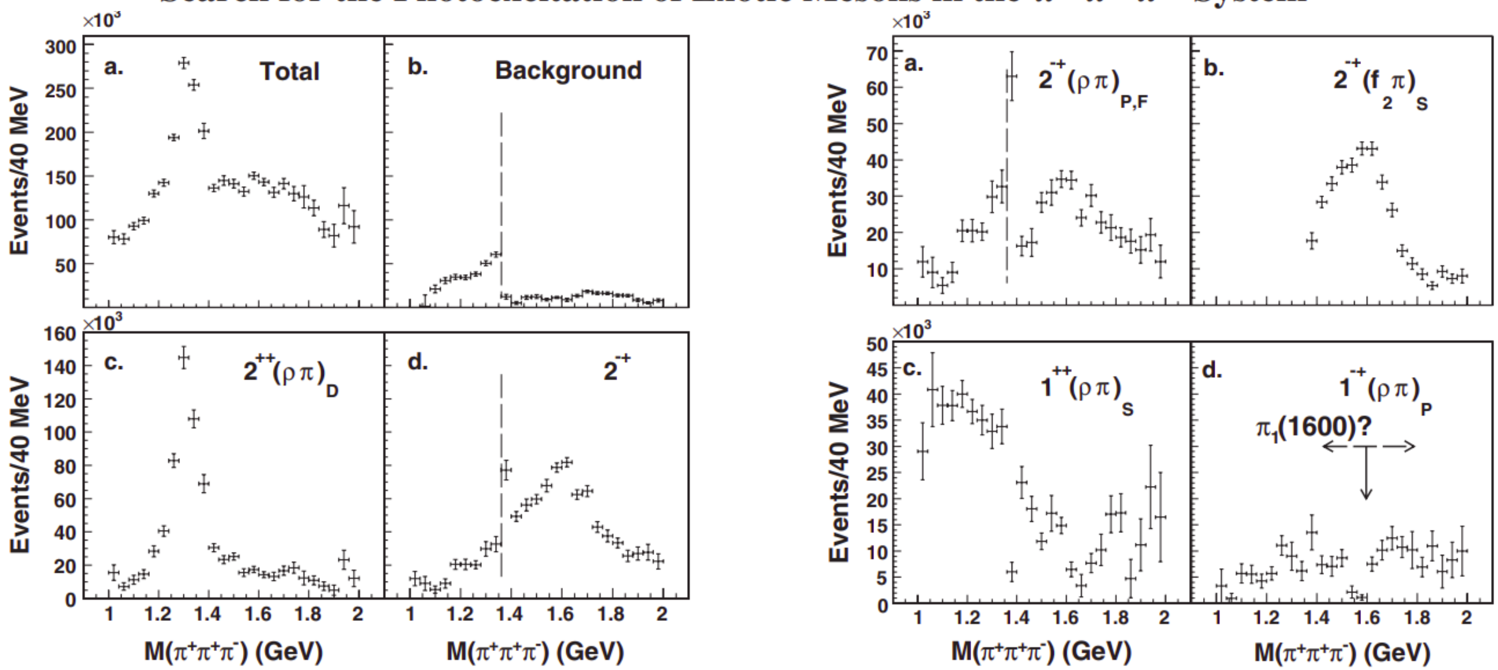
Clear signal for $\pi_1(1600)$

Large background contribution

Photoproduction with CLAS6

PRL **102,** 102002 (2009) PHYSICAL REVIEW LETTERS week ending 13 MARCH 2009

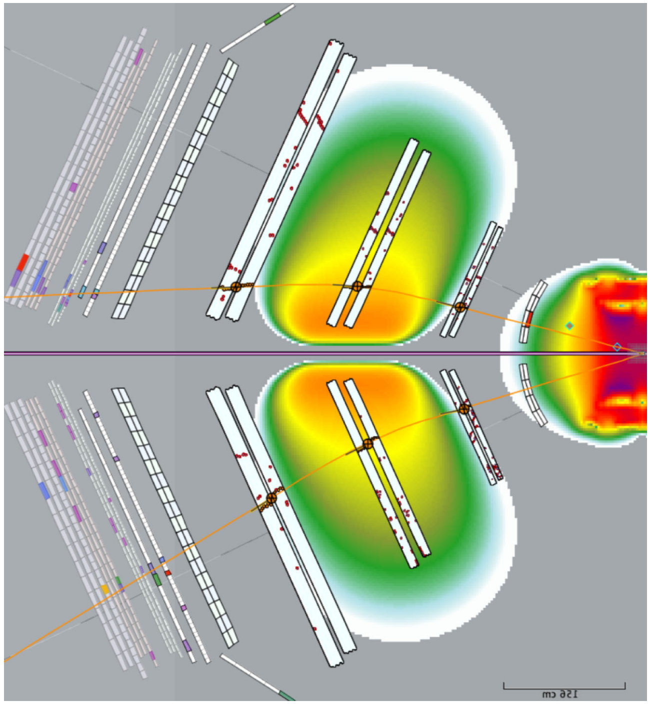
Search for the Photoexcitation of Exotic Mesons in the $\pi^+\pi^+\pi^-$ System

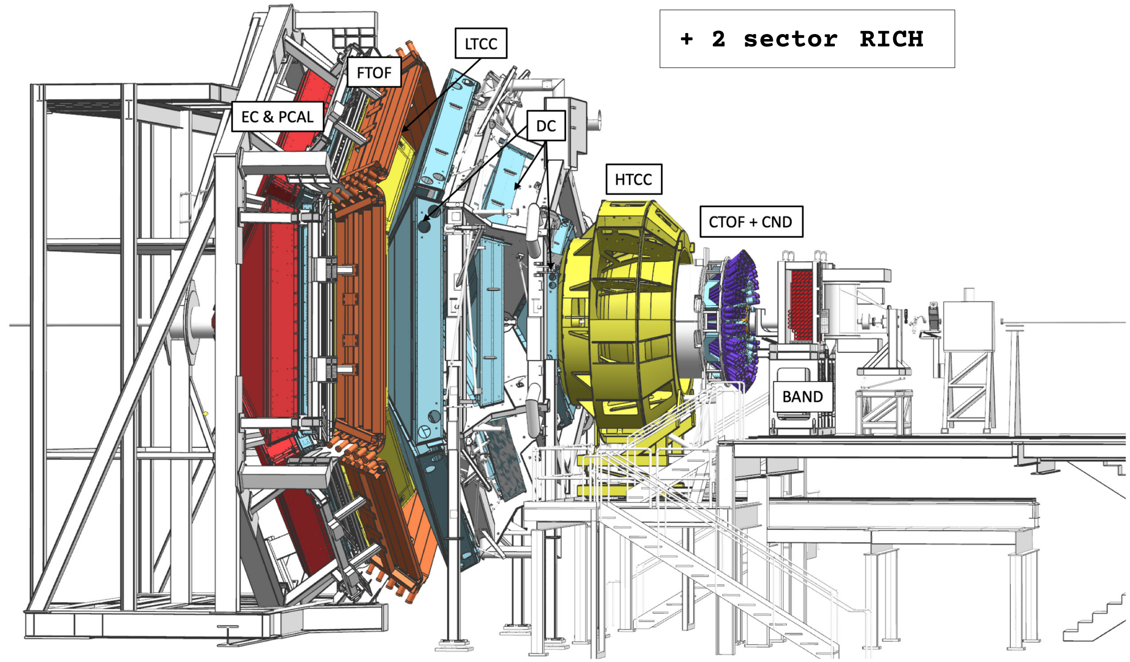


Only hints of a dip in $1^{-+}(\rho\pi)$ at 1.6 GeV

Subsequent CLAS experiment found similar results

CLAS12 at Jefferson Lab





High luminosity electron scattering (10^{35} cm^{-2}s^{-1}) produces high flux of nearly real photons.

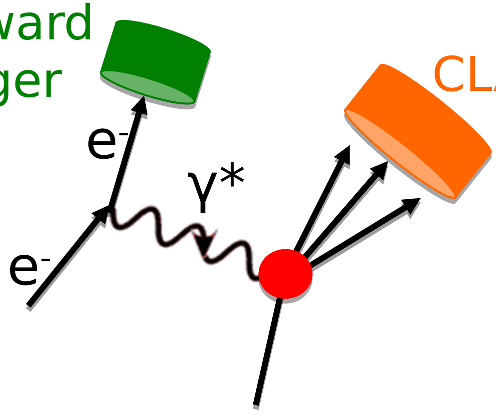
High resolution tracking spectrometer, (1% momentum, 1 mrad angle)

Excellent PID e−, K, p, π, n,γ

Can make measurements with missing particles

Can run MesonEx simultaneously with other experiments

Quasi-real photoproduction with CLAS12

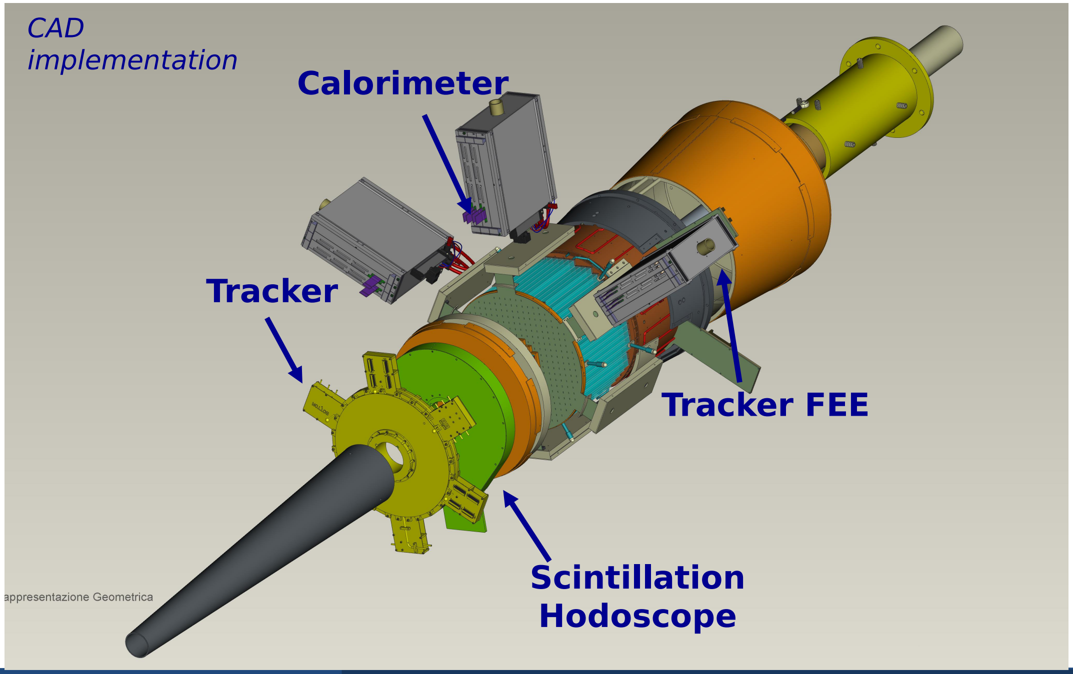


Trigger → FT e- + 2 charged CLAS12

Forward Tagger	
E’	0.5-4.5 GeV
ν	6-10 GeV
θ	2.5-4.5 deg
Q^2	0.007 – 0.3 GeV^2
W	3.6-4.5 GeV
Photon Flux	5 x 10^7 γ/s @ $L_e=10^{35}$

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-polarization tagged “photon” beam; degree of polarization determined event-by-event from the electron kinematics

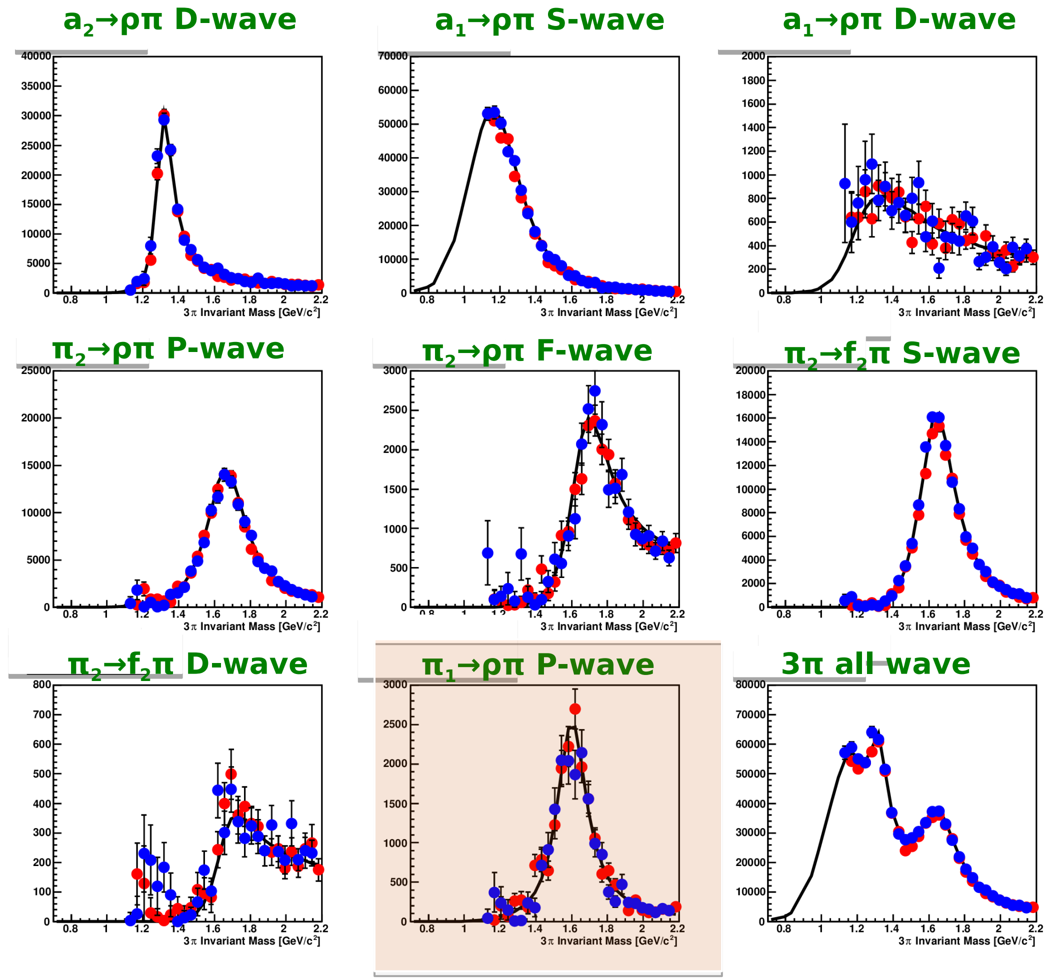


MesonEx program

Meson spectroscopy in the light-quark sector:

- Investigating of the meson spectrum up to masses of 2.5 GeV
- Search for rare or poorly known states (strangeness-rich, scalars, …)
- Search states with unconventional quark-gluon configurations

Benchmark 3π Simulations



Note poor acceptance below 1.3GeV (half field)

MesonEx : Status

Approximately 10% of expected data ready for preliminary analysis

Focus on charged decay products (better resolution)

First extract two pseudoscalar ($\pi^+\pi^-$, K^+K^-)

Fourier Analyse angular distributions == extract moments

- more general expansion than just partial waves
- check acceptance corrections
- check distortions from backgrounds
- model independent formalism

Extract partial waves from moments or directly fit partial waves

Expand to vector-pseudoscalar final states

MesonEx : Polarised 2 meson production

arXiv.org > hep-ph > arXiv:1906.04841

High Energy Physics - Phenomenology

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, A. P. Szczepaniak (JPAC collaboration)

(Submitted on 11 Jun 2019)

Linear polarisation

$$I(\Omega,\Phi)=I^0(\Omega)-P_\gamma I^1(\Omega)\cos(2\Phi)-P_\gamma I^2(\Omega)\sin(2\Phi)$$

$$I^0(\Omega)=\sum_L\sum_{M=0}^{M\leq L}\sqrt{\left(\frac{2L+1}{4\pi}\right)}(2-\delta_{M,0})H^0(L,M)\Re\left[Y_L^M(\Omega)\right]$$

$$I^1(\Omega)=-\sum_L\sum_{M=0}^{M\leq L}\sqrt{\left(\frac{2L+1}{4\pi}\right)}(2-\delta_{M,0})H^1(L,M)\Re\left[Y_L^M(\Omega)\right]$$

$$I^2(\Omega)=2\sum_L\sum_{M=0}^{M\leq L}\sqrt{\left(\frac{2L+1}{4\pi}\right)}\Im\left[H^2(L,M)\right]\Im\left[Y_L^M(\Omega)\right]$$

Moments relate directly to partial wave amplitues

$$H^0(11)=H^1(11)+2\sqrt{\frac{2}{5}}\,\mathrm{Re}(P_1^{(+)}D_2^{(+)*})\ ,$$

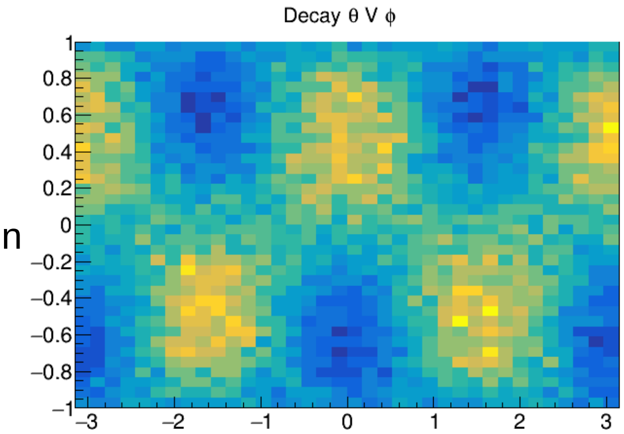
$$H^1(11)=\frac{2}{15}\left[3\sqrt{5}\,\mathrm{Re}(P_0^{(+)}D_1^{(+)*})-\sqrt{15}\,\mathrm{Re}(P_1^{(+)}D_0^{(+)*})+5\sqrt{3}\,\mathrm{Re}(S_0^{(+)}P_1^{(+)*})\right]\ ,$$

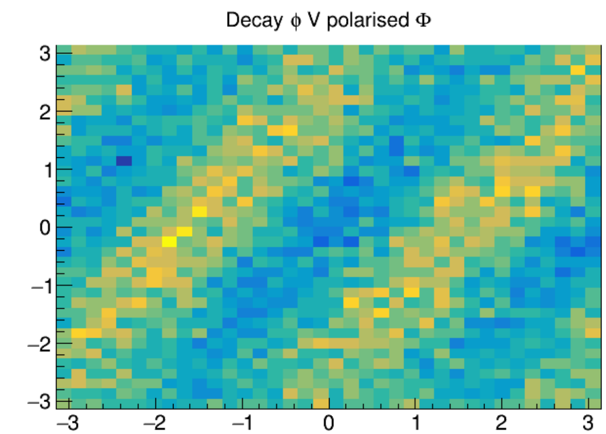
$$H^0(20)=H^1(20)-\frac{2}{35}\left[7|P_1^{(+)}|^2-5|D_1^{(+)}|^2+10|D_2^{(+)}|^2\right]\ ,$$

$$H^1(20)=\frac{4}{35}\left[7|P_0^{(+)}|^2+5|D_0^{(+)}|^2+7\sqrt{5}\,\mathrm{Re}(S_0^{(+)}D_0^{(+)*})\right]\ ,$$

$$H^0(21)=H^1(21)+\frac{2}{7}\sqrt{6}\,\mathrm{Re}(D_1^{(+)}D_2^{(+)*})\ ,$$

$$H^1(21)=\frac{2}{35}\left[7\sqrt{5}\,\mathrm{Re}(S_0^{(+)}D_1^{(+)*})+7\sqrt{3}\,\mathrm{Re}(P_0^{(+)}P_1^{(+)*})+5\,\mathrm{Re}(D_0^{(+)}D_1^{(+)*})\right]\ ,$$





Moments can be determined from Fourier analysis of decay angles

MesonEx : BruFit (Interface to RooFit)

PDF :

observables — Model parameters

$$p(x_i:\theta_j) = \frac{f(x_i:\theta_j)}{\int f(x_i:\theta_j)dx}$$

Physics model — Detect accept

$$f(x_i:\theta_j) = I(x_i:\theta_j).\eta(x_i)$$

$$p(x_i:\theta_j) = \frac{I(x_i:\theta_j)\eta(x_i)}{\sum_k^M I(x_k:\theta_j)}$$

Approximate integral by sum over *M,* accepted, Monte-Carlo Events (brufit part)

$$\mathcal{L} = \prod^N p(x_i:\theta_j)e^{-Y}\frac{Y^N}{N!}$$

Likelihood

Y yield of expected events from fit
N number of observed events in data

$$-\ln\mathcal{L} = -\sum^N \ln[p(x_i:\theta_j)] + Y - N\ln Y$$

Log Likelihood (RooFit)

$$-\ln\mathcal{L} = -\sum^N \ln\frac{I(x_i:\theta_j)}{\sum_k^M I(x_k:\theta_j)} + Y - N\ln Y$$

Log Likelihood (BruFit)

* Terms dependent on $\eta(x_i)$ add a constant to log likelihood and can be neglected

MesonEx : Additional Speed ups

If we can factorise model into sum of parameter dependent and observable dependent parts

$$I(x_i : \theta_j) = \sum_c t_c(\theta_j).g_c(x_k).$$

$g_c(x_k)$ can be pre-calculated and cached (RooFit)

For the integrals

$$\sum_k^M I(x_k : \theta_j) = \sum_c t_c(\theta_j) \sum_k^M g_c(x_k)$$

Sum over $g_c(x_k)$ can be pre-calculated and cached (BruFit)

For example, Moments of two meson decays

$$I(\Omega, \Phi) = I^0(\Omega) - P_\gamma I^1(\Omega)\cos(2\Phi) - P_\gamma I^2(\Omega)\sin(2\Phi),$$

$$\mathcal{I}_0(\Omega) = \sum_{LM} \frac{2L+1}{4\pi} H^0(LM) D^{L*}_{M0}(\phi, \theta, 0)$$

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

Wigner D functions

with

$$x_i = \{\Omega, \Phi\} = \{\theta, \phi, \Phi\}$$

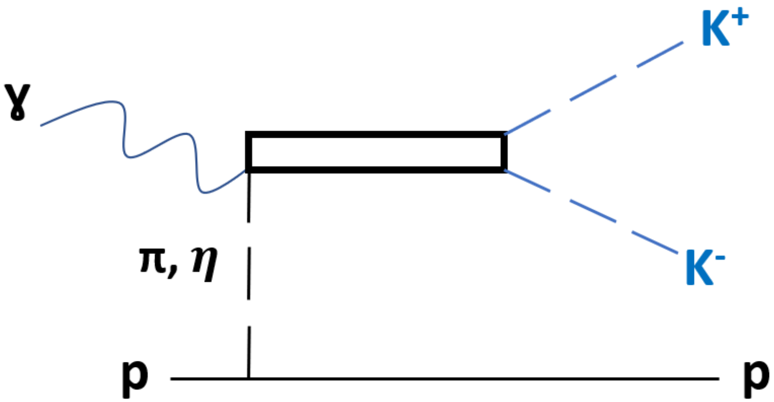
$$\theta_j = H^\alpha(LM)$$

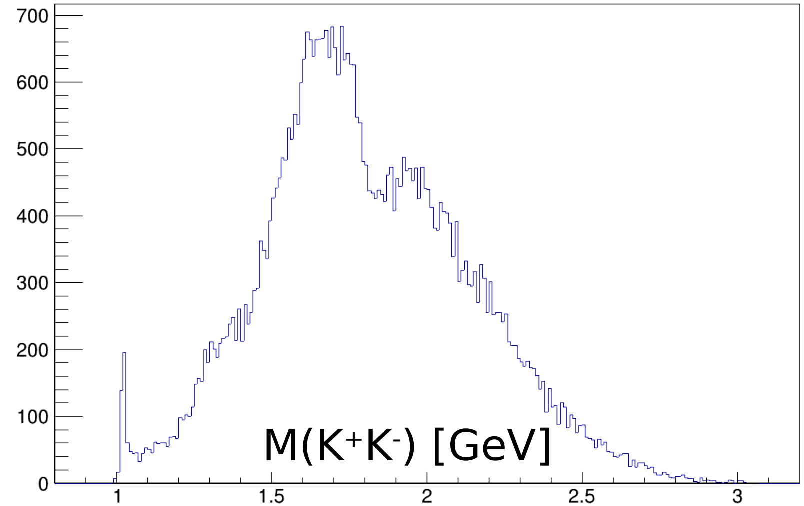
$$t_c(\theta_j) = t_{\alpha LM}(H^\alpha(LM)) = \frac{2L+1}{4\pi} H^\alpha(LM)$$

$$g_c(x_i) = D^{L*}_{M0}(\phi, \theta, 0)$$

And to do Partial Wave Analysis we just calculate H(LM) in terms of $[I]^{\varepsilon}_{m}$

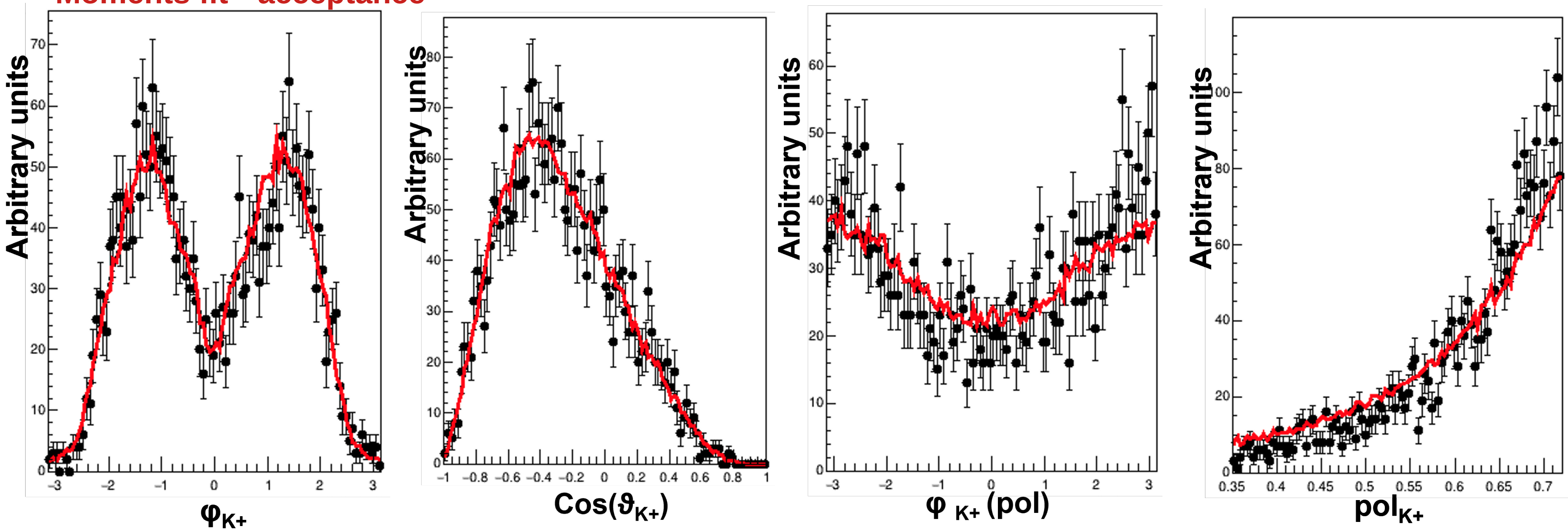
MesonEx : K^+K^- p Preliminary Data





Experiment

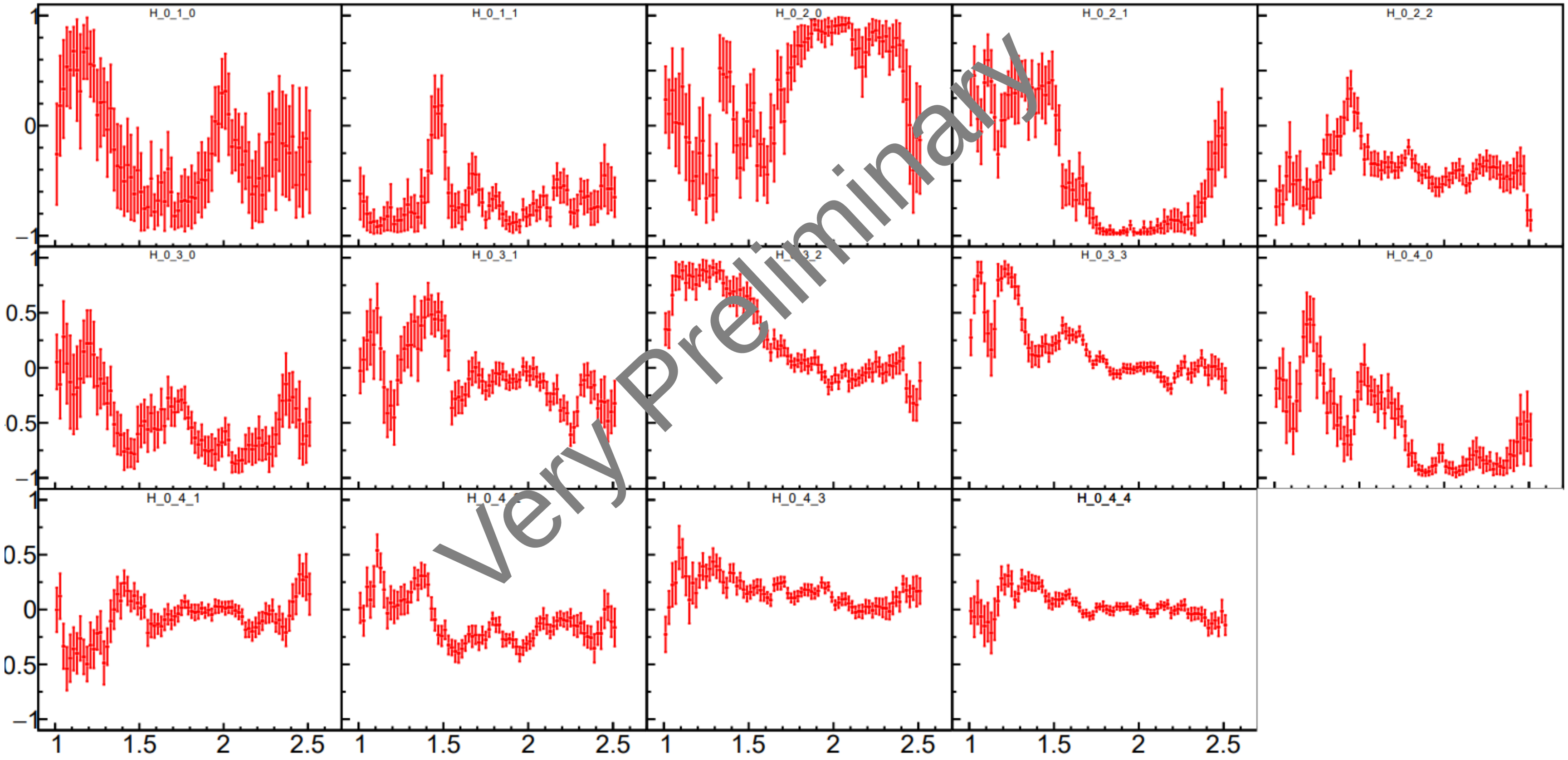
Moments fit * acceptance



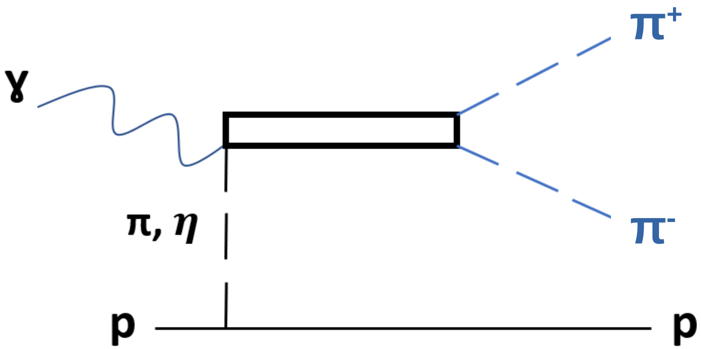
MesonEx : K^+K^- p Preliminary Data

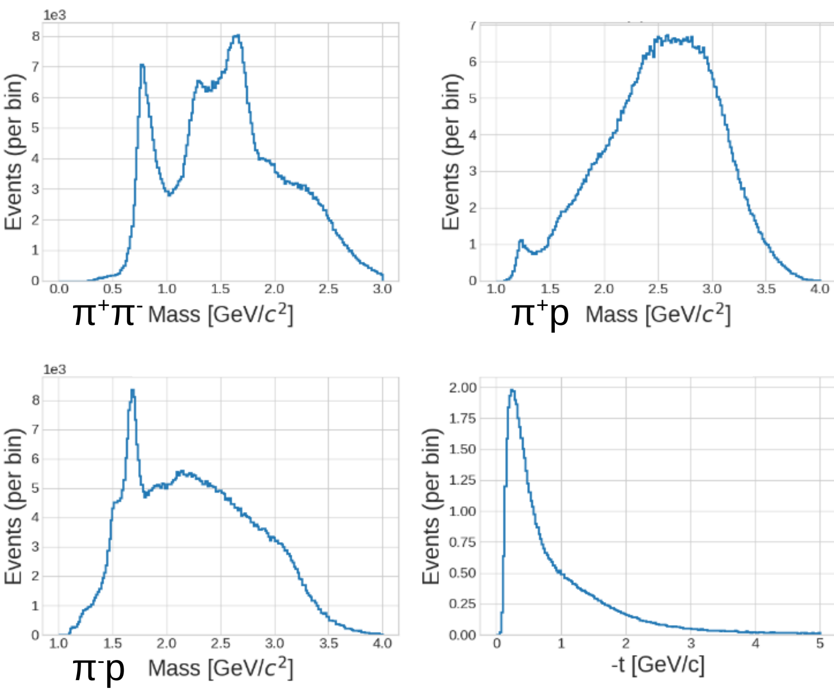
Allowed partial waves J^{PC} (I^G) : $0^{++}(0^+,1^-)$, $1^{--}(0^+,1^-)$, $2^{++}(0^+,1^-)$, $3^{--}(0^+,1^-)$, ...

Unpolarised Moments

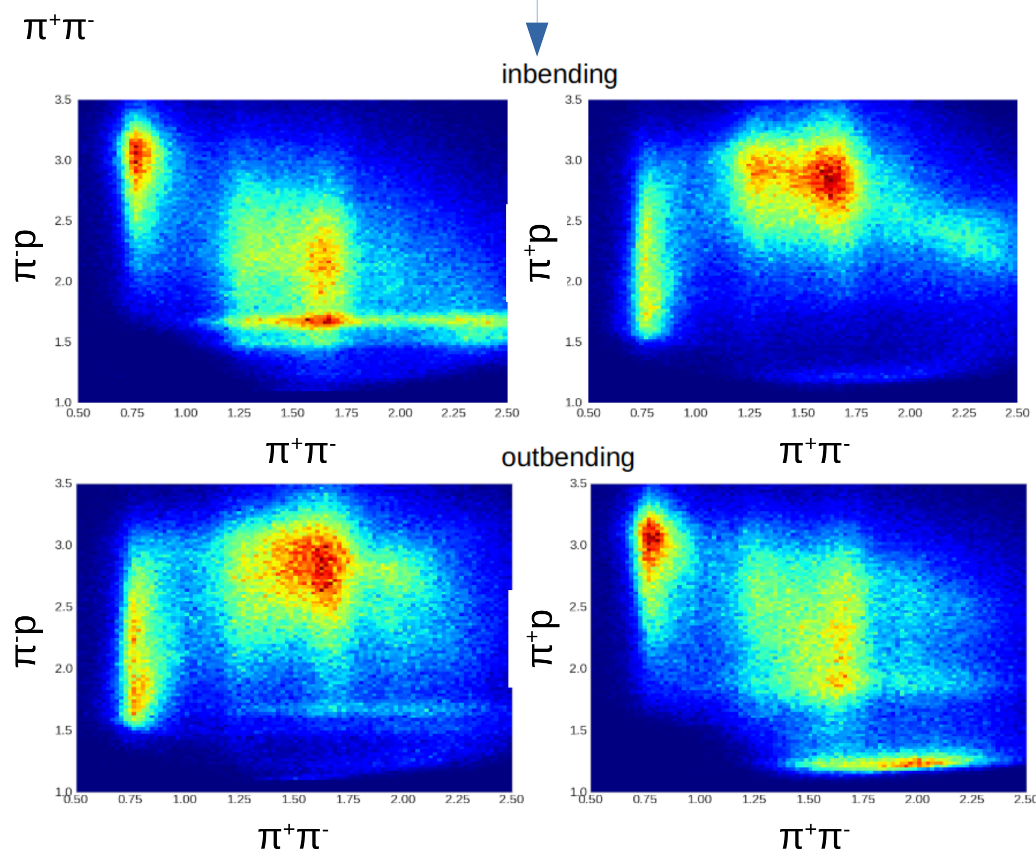


MesonEx Trigger : $\pi^+\pi^- p$ Final State





Data taking with toroidal field bending negative particles inward or outward



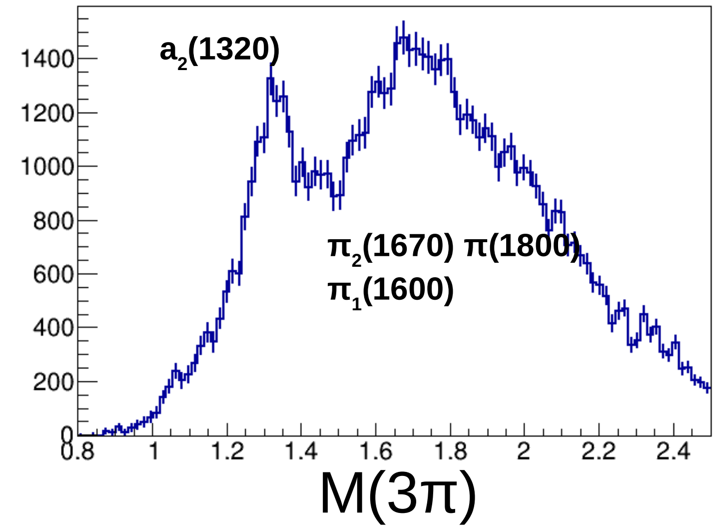
Data with both fields gives improved acceptance

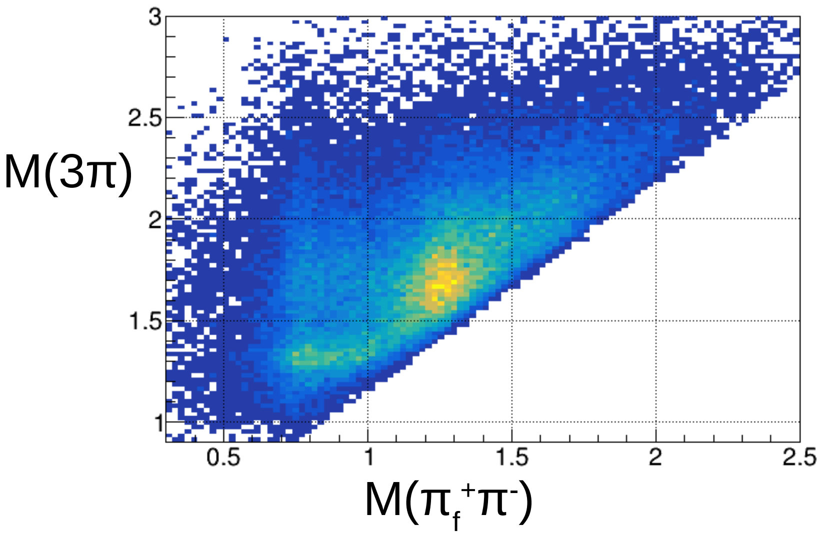
MesonEx : $\pi^+\pi^+\pi^-$ n Preliminary Data

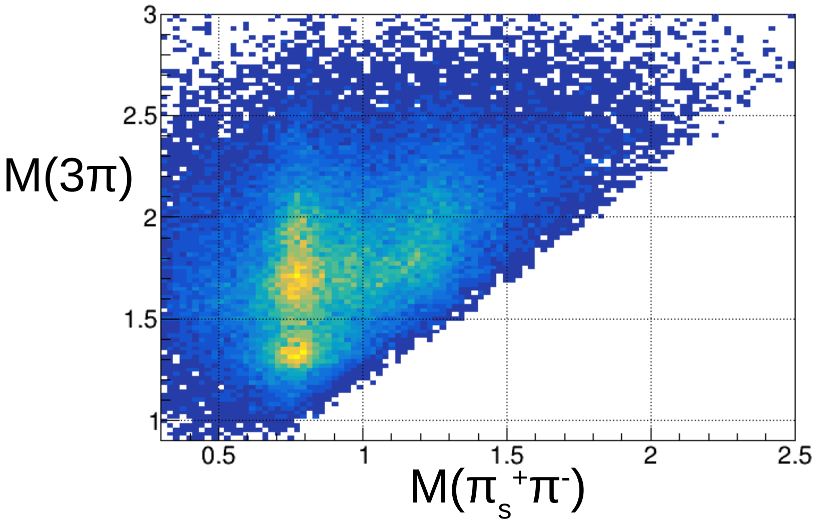
Missing neutron final state

$|t| < 2$ and $6 < E_\gamma < 10$ Gev

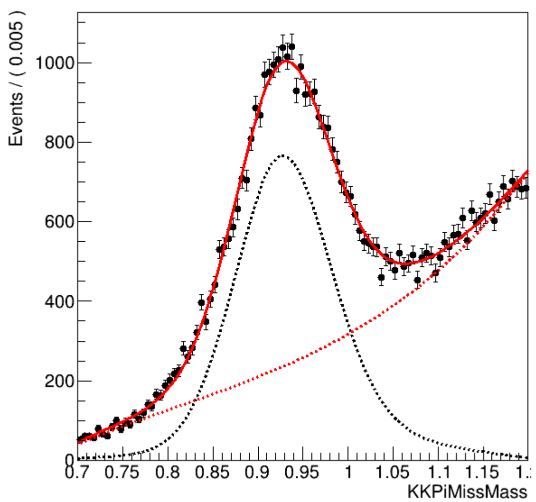
Trigger/Torus Field /Detector
=> Low acceptance below 1.3 GeV

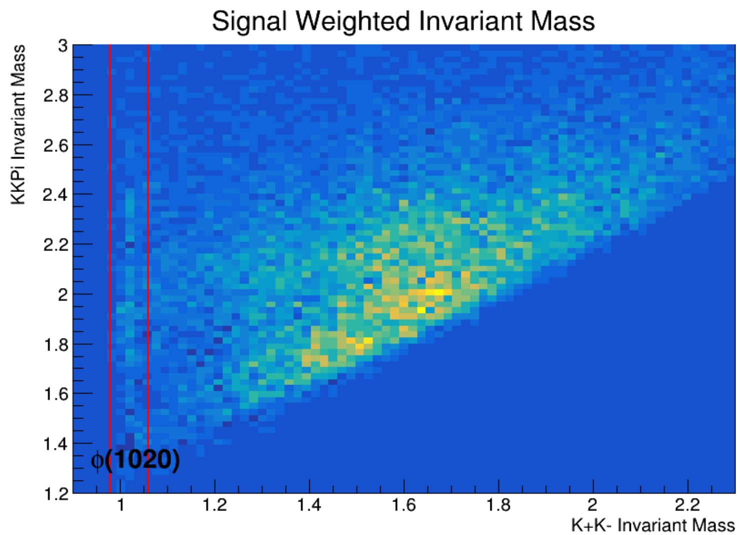






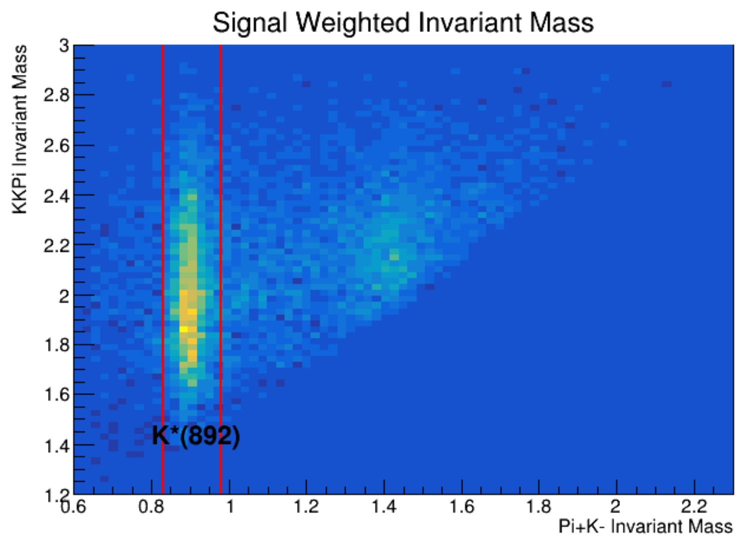
MesonEx : $\pi^+ K^+ K^-$ n Preliminary Data

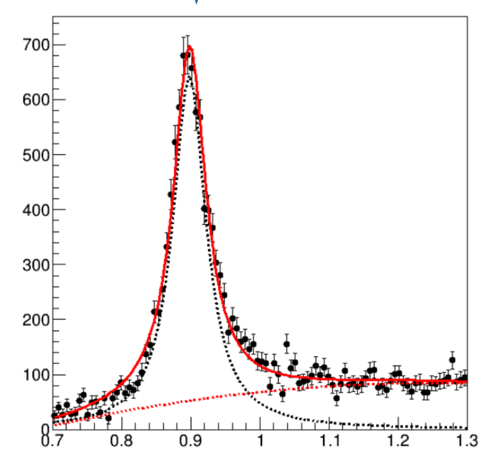




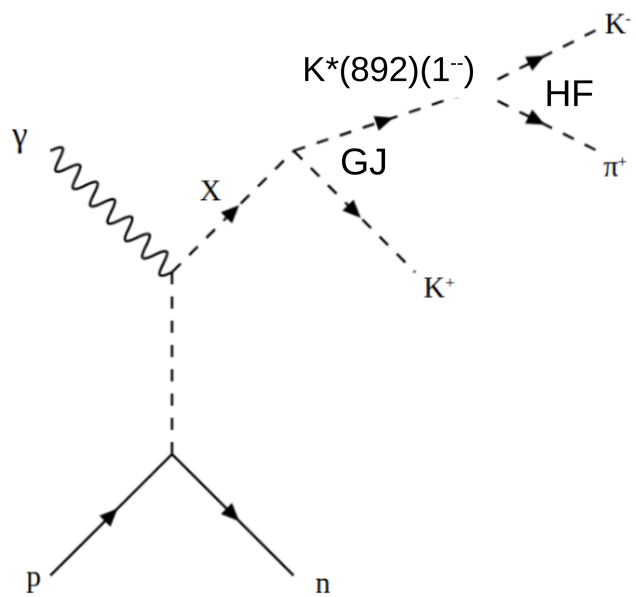
Use sPlot to isolate K*(892)

Reconstruct neutron mass to subtract backgrounds via sPlot technique





Vector-Scalar Formalism



Write intensity in terms of decay angles and linear polarisation

$$\mathcal{I}(\Omega,\Phi) = \mathcal{I}_0(\Omega) - \mathcal{P}_\gamma.\mathcal{I}_1(\Omega)\cos 2\Phi - \mathcal{P}_\gamma.\mathcal{I}_2(\Omega)\sin 2\Phi.$$

Expand polarised intensity components in moments of D-Wigner function products (depend on 4 decay angles)

$$\mathcal{I}^\alpha(\Omega) = \sum_{JMS\Lambda}\left(\frac{2J+1}{4\pi}\right)\left(\frac{2S+1}{4\pi}\right)H^\alpha(JMS\Lambda) \times D^{J*}_{M,\Lambda}(\phi_{GJ},\theta_{GJ},0)D^{S*}_{\Lambda,0}(\phi_{HF},\theta_{HF},0).$$

Relate moments to production Spin Density Matrix Elements

$$b = \{j = J_X, l = L_X, m = M_X, s = S_X\}$$

=1

Currently measure these

$$H^\alpha(JMS\Lambda) = \sum_{b,b'}\sum_{\lambda,\lambda'}\left(\frac{\sqrt{(2l'+1)(2l+1)}}{2j'+1}\right)\left(\sqrt{\frac{2s+1}{2s'+1}}\right)(l,0;s,\lambda|j,\lambda)(l',0;s',\lambda'|j',\lambda') \times (s,\lambda;S,\Lambda|s',\lambda')(s,0;S,0|s',0)(j,m;J,M|j',m')(j,\lambda;J,\Lambda|j',\lambda') \times \rho^\alpha_{bb'} \times R_{Yi}(m_Y)R^*_{Yi'}(m_Y),$$

Relate Spin Density Matrix Elements to Partial Waves dependent On meson X spin and parity

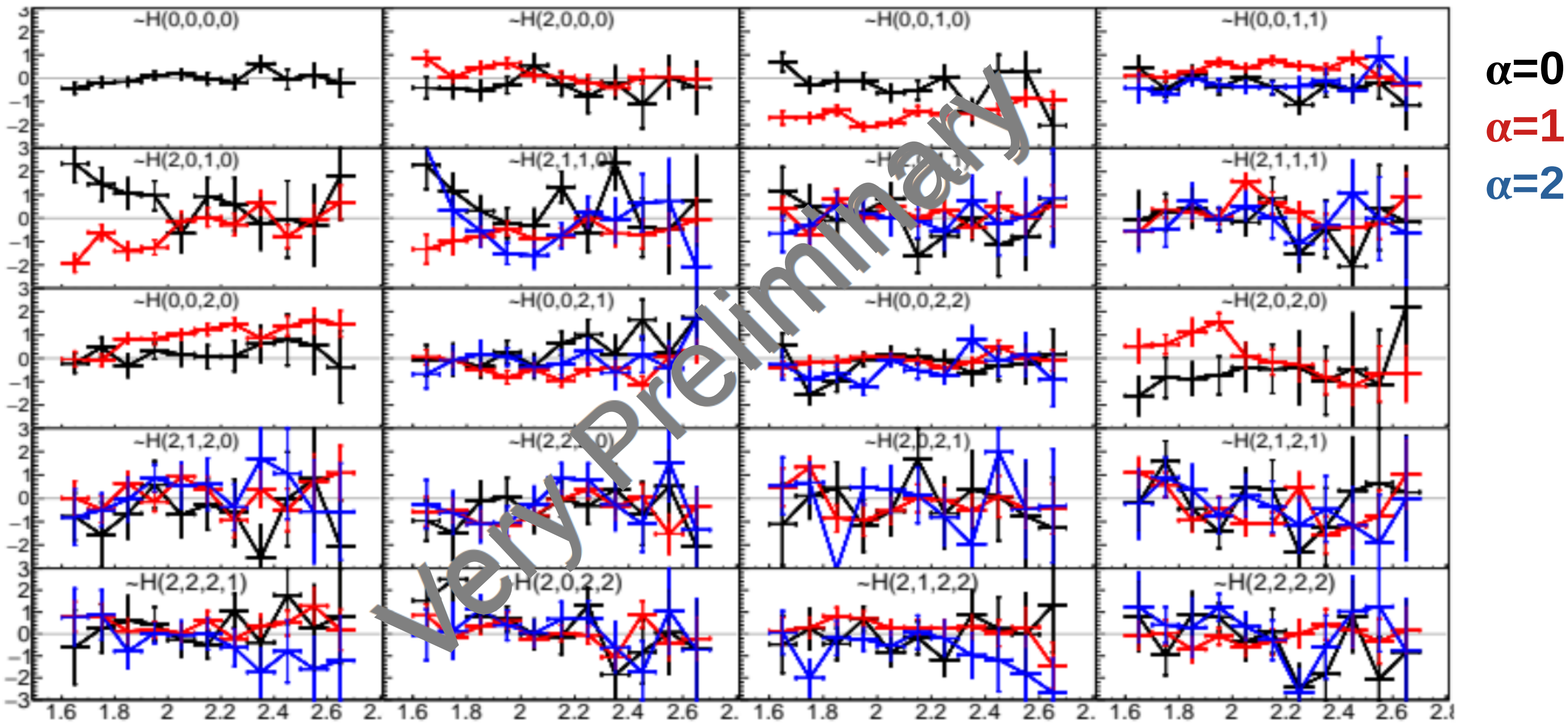
Extract these J^P

$${}^{(\varepsilon)}\rho^0_{ii',mm'} = \sum_k [J_X^{P_X}]^{(\varepsilon)}_{m,k}[J'^{P'_X}_X]^{(\varepsilon')*}_{m',k} + \eta_X\eta'_X(-1)^{m+m'}[J_X^{P_X}]^{(\varepsilon)}_{-m,k}[J'^{P'_X}_X]^{(\varepsilon')*}_{-m',k},$$

From Robert Wishart, University of Glasgow

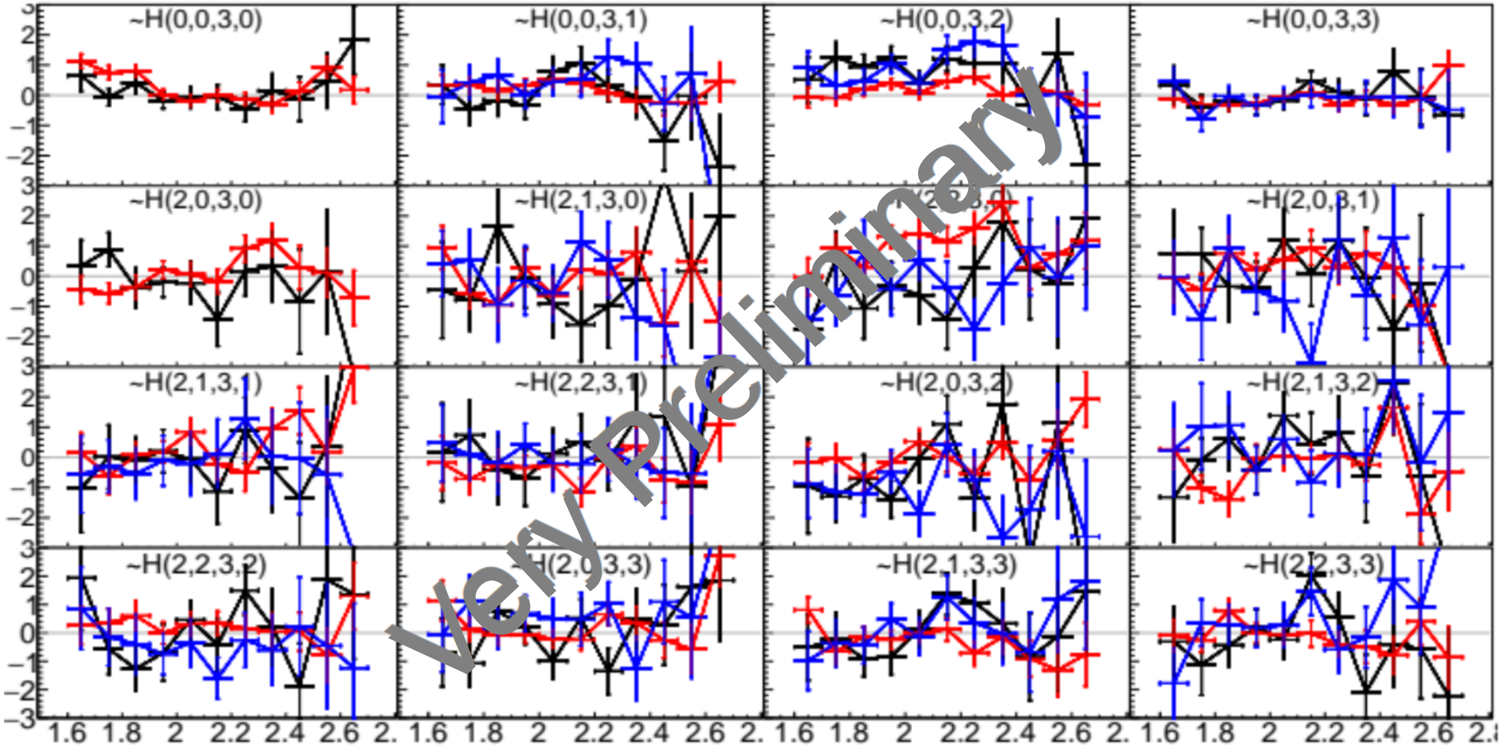
MesonEx : $\pi^+K^+K^-$ n Preliminary Data

Vector-Scalar Moments fit results for J up to 2



MesonEx : $\pi^+K^+K^-$ n Preliminary Data

Vector-Scalar Moments fit results for J = 3



α=0
α=1
α=2

Moments to Partial Waves (Two-Body)

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

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

Clebsch Gordan Coef.

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

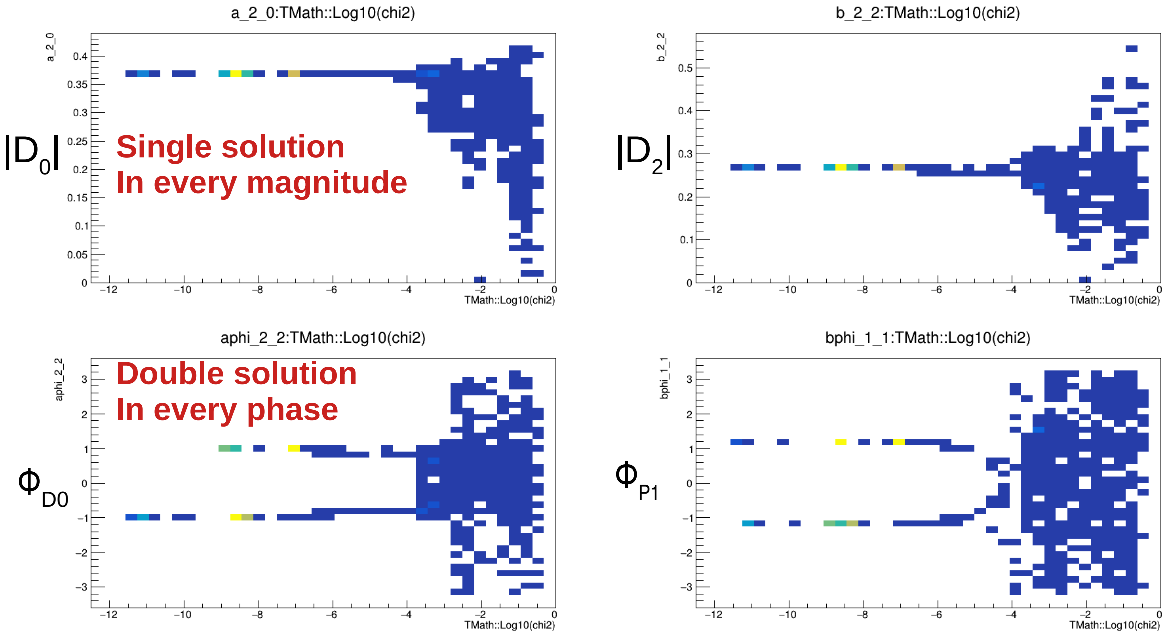
$$^{(\epsilon)}\rho^{1,\ell\ell'}_{mm'} = -\epsilon\kappa \sum_k \left((-1)^{m} [\ell]^{(\epsilon)}_{-m;k} [\ell']^{(\epsilon)*}_{m';k} + (-1)^{m'} [\ell]^{(\epsilon)}_{m;k} [\ell']^{(\epsilon)*}_{-m';k} \right) ,$$

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

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

[l] = total spin
M = spin projection
ε = reflectivity

The moments can be expanded in partial waves via the SDMEs (ρ)
=> a system of simultaneous equations
=> if sufficient moments can numerically extract the partial waves (e.g. with Minuit)



Need to run many times!
For linearly polarised photoproduction find we can invert equations with 2 (trivial) complex conjugate solution sets of partial waves.
i.e. there are 2 solutions,
Or 1 if 1 partial wave is forced +ve real part

See also
W. Smith, Mathematical ambiguities in eta-pi photoproduction. Thursday 1435

MesonEx : Markov Chain Monte Carlo

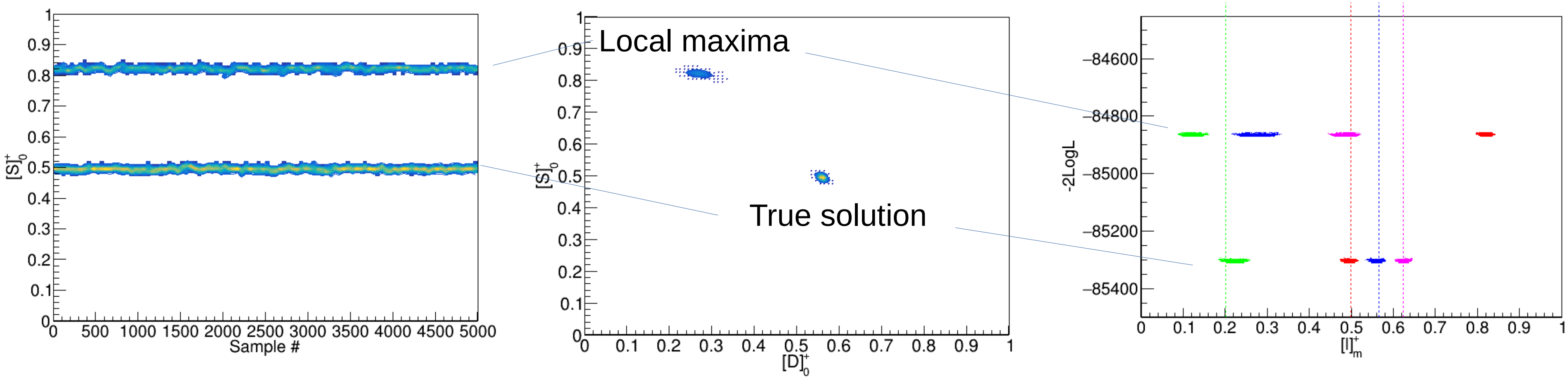
Used for finding best fit parameters. We find,

- More robust than with Minuit (gradient decent)
- Can provide samples from posterior for further analysis
- Slower with few parameter fits, not so bad with many parameters

BruFit Algorithm

Start multiple chains
Step in a single parameter (different one each step) for N samples
Step in all parameters for N samples
Generate covariance matrix C
Draw step from Covariance Matrix for N samples

For example fitting amplitudes



Summary

CLAS12 has successfully taken data for ~ 5 years

Several analyses on beam spin asymmetries already published

Data with forward tagger allows measurement of meson photoproduction events

Currently analysing several two-body final states

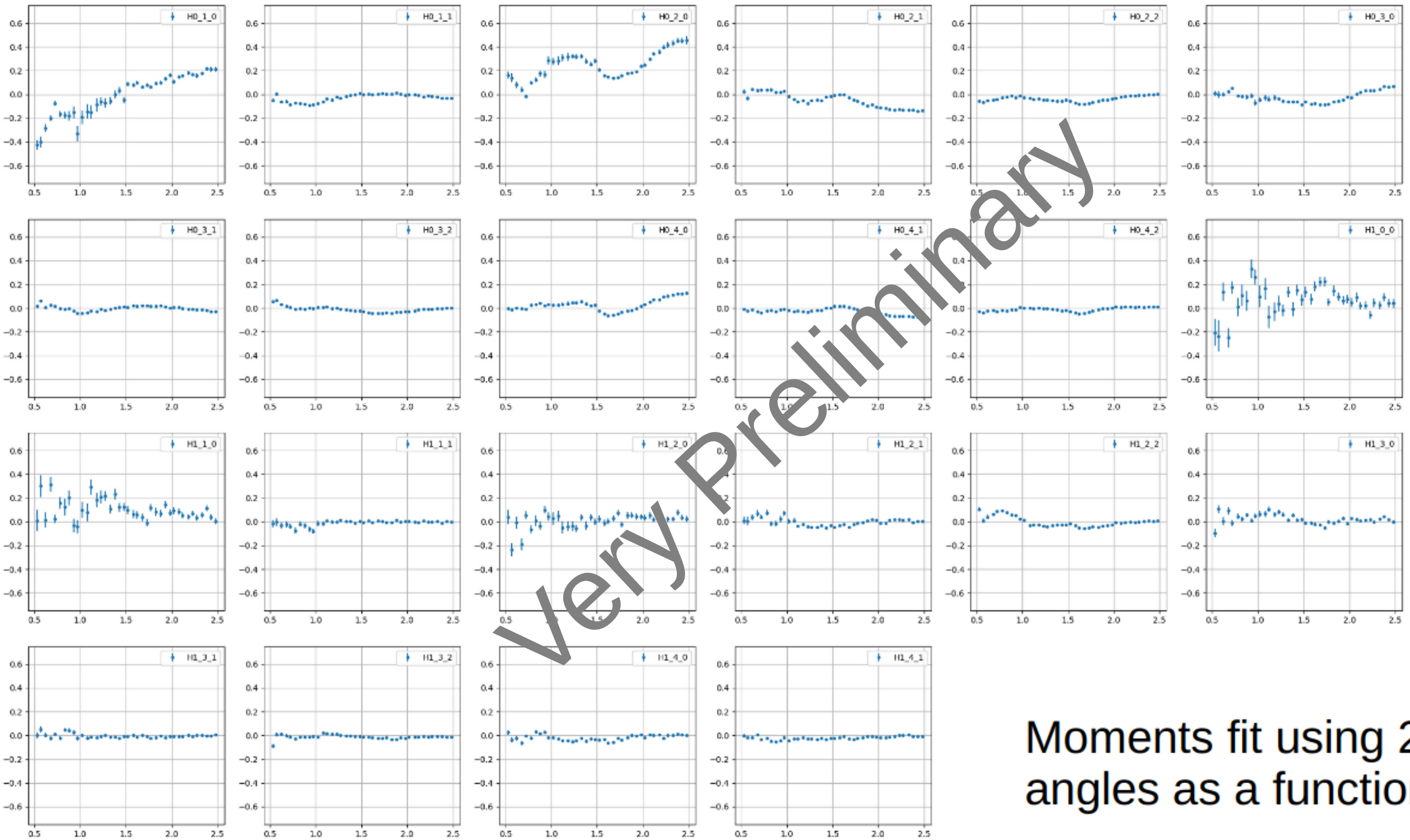
Working on extracting moments of angular distributions then partial waves

May also perform mass dependent fits directly to moments

MesonEx : Status

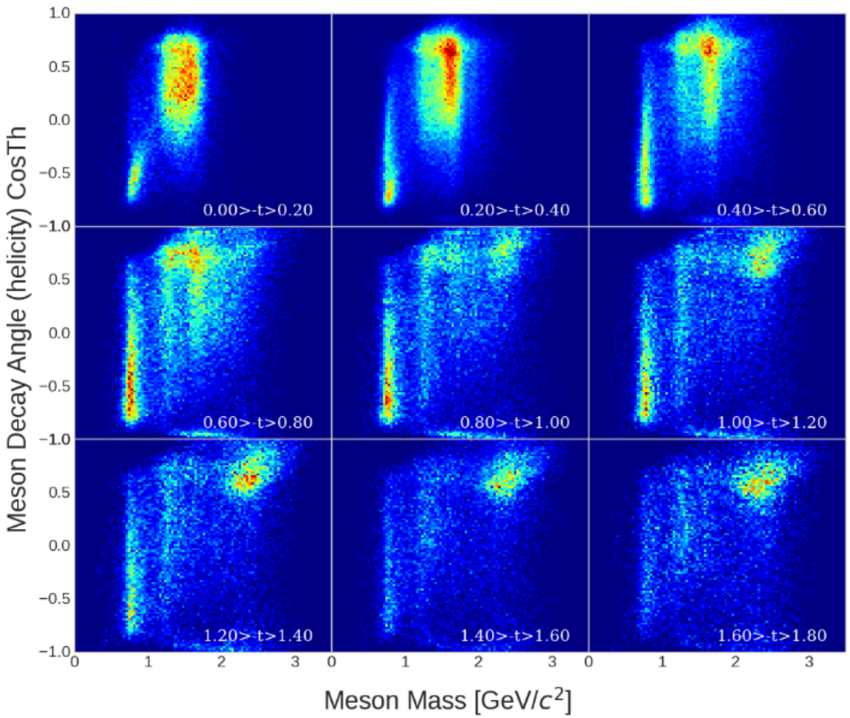
MesonEx : $\pi^+\pi^-$ p Preliminary Moments

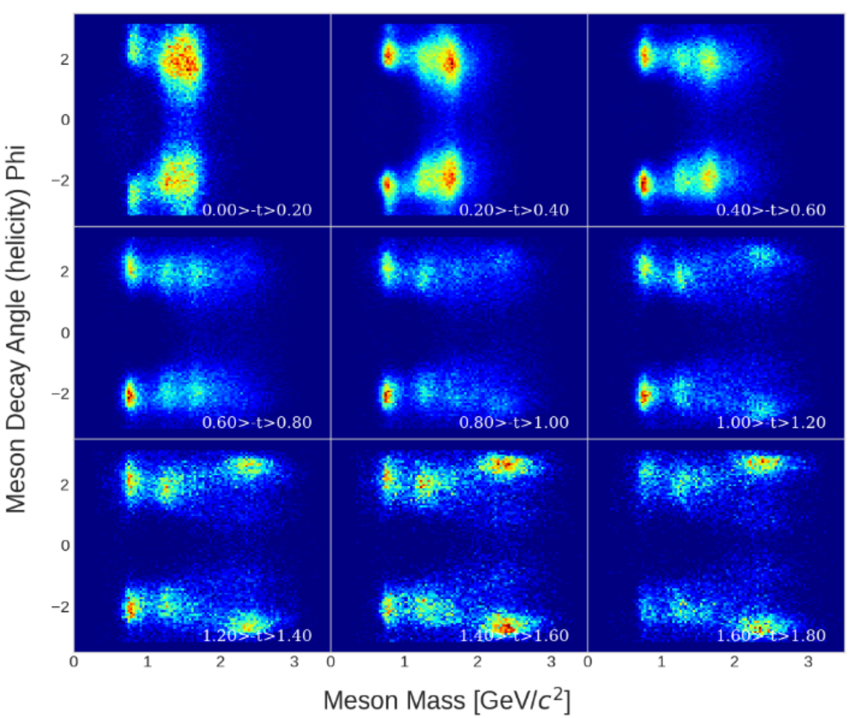
Allowed partial waves J^{PC} (I^G) : : $0^{++}(0^+)$, $1^{--}(1^+)$, $2^{++}(0^+)$, $3^{--}(1^+)$, ...



Moments fit using 2pi decay angles as a function of 2pi mass

MesonEx : $\pi^+\pi^-$ p Preliminary Data

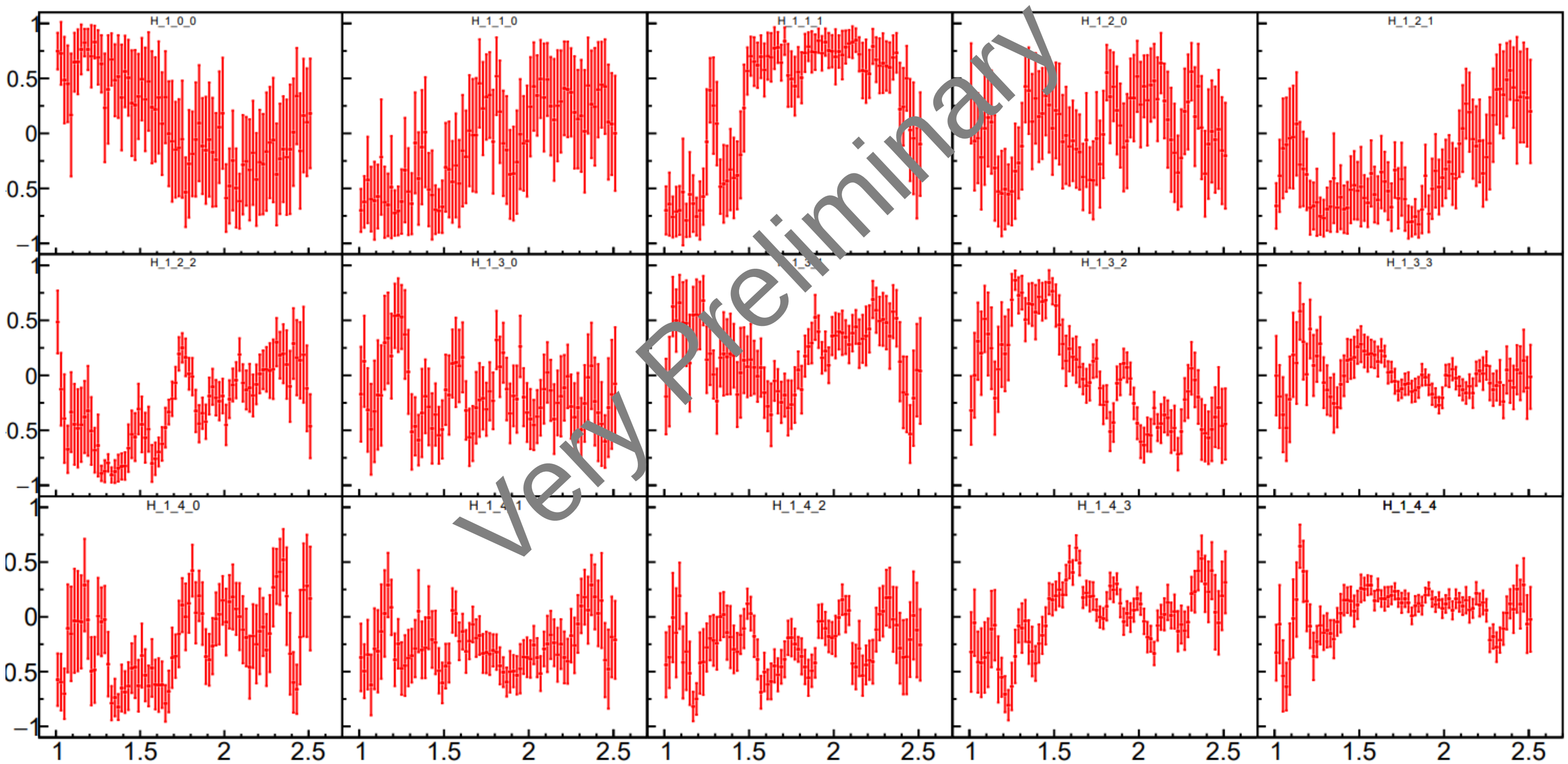




MesonEx : K^+K^- p Preliminary Data

Allowed partial waves J^{PC} (I^G) : $0^{++}(0^+,1^-)$, $1^{--}(0^+,1^-)$, $2^{++}(0^+,1^-)$, $3^{--}(0^+,1^-)$, ...

Polarised Moments



Machine Learning Approach

Other approaches,

Deep Learning for Amplitude Analysis in Spectroscopy, W. Phelps, CHEP2023

https://indico.jlab.org/event/459/contributions/11724/attachments/9419/13661/chep_pypwa_2023_phelps_v0.pdf

A(I)DAPT

AI for Data Analysis and PreservaTion, A.N. Hiller Blin, AI4EIC

https://indico.bnl.gov/event/16586/contributions/68737/attachments/43744/73698/Astrid-Hiller-Blin_AI4EIC%20%281%29.pdf

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