Spectroscopy with Quasi-real Photoproduction

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Science at the Luminosity Frontier: Jefferson Lab at 22 GeV

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Why Quasi-real Photoproduction?

1) Identify photoproduction of the narrow XYZ states. Typically these have only been seen in 1 production mechanism and photoproduction offers a clean mechanism whereby any resonance should be able to be photoproduced and therefore we would validate if these are real poles.

2) As photoproduction can produce any state we may see states that haven't been produced in other mechanisms. For example no "exotic" tensor mesons have been identified yet.

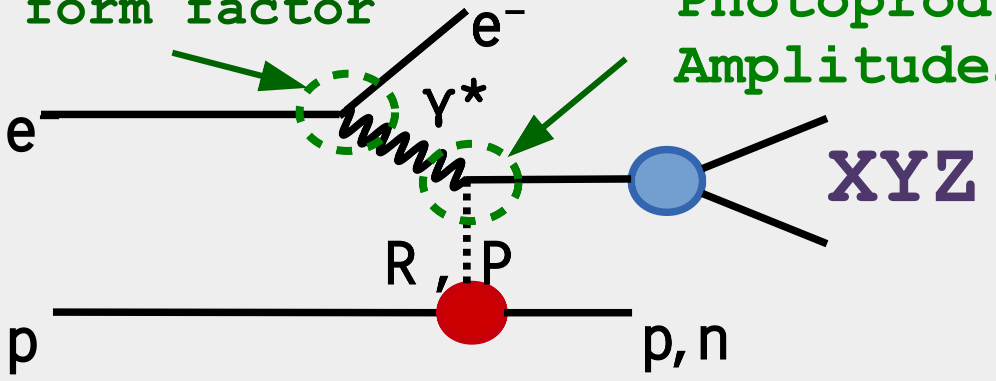
3) Photoproduction offers a means to determine quantum numbers of produced states, in particular we may search for broader overlapping states. Polarised beams give us a greater handle on this.

4) The nature of the observed states is a matter of great discussion. How these states behave in different production mechanism can help us understand the underlying dynamics (tetraquark, molecules, hybrids). Things like photocouplings, polarisations or even Q2 dependences can be helpful here.

Quasi-real Photoproduction

Virtual photon flux
+ form factor

Photoproduction → from jpacPhoto
Amplitudes (see previous talk)



$$L=\frac{1+(1-y)^2}{y}-\frac{2m_e^2 y}{Q^2}$$

$$K=\frac{W^2-M^2}{2M}=\nu(1-x)=Ey(1-x)=\nu-\frac{Q^2}{2M}$$

$$\frac{d^4\sigma}{ds\,dQ^2\,d\phi\,dt}=\frac{d^2\sigma_{e,\gamma*e'}}{dsdQ^2}\frac{d^2\sigma_{\gamma*+p\to V+p}(s,Q^2)}{d\phi\,dt}$$

$$\frac{d^2\sigma_{e,\gamma*e'}}{dsdQ^2}=\frac{\alpha}{2\pi}\cdot\frac{K.L}{E}\cdot\frac{1}{Q^2}\cdot\frac{1}{(s-M^2+Q^2)}$$

Photon flux rises rapidly as :
$Q^2 \to 0$; $W=\sqrt{s} \to M$(proton)

Leads to high production rates

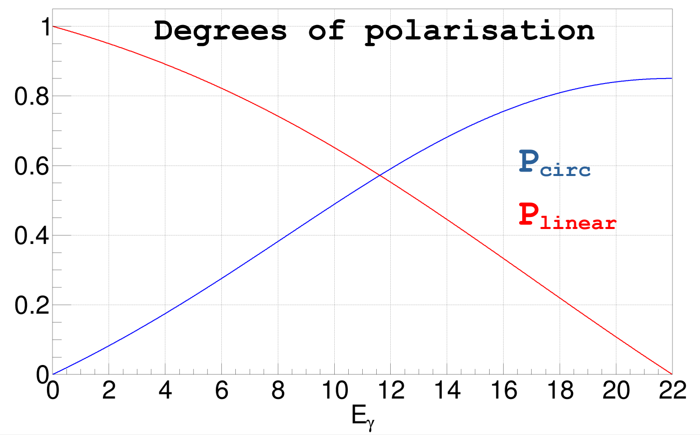
Virtual Photon Polarisation

Photon density matrix as $Q^2 \rightarrow 0$

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

ε = degree of virtual photon polarisation
P_{beam} = degree of longitudinal e- beam polarisation
Φ = angle between scattering and production planes

Very similar to real photon
Requires determination of ε (E_e', θ_e) and Φ
i.e. full scattered e- momentum
Get event-by-event polarisation



Production Amplitudes

$$\mathcal{I}(\Omega,\Phi) = \mathcal{I}^0(\Omega) - \mathcal{P}.\mathcal{I}^1(\Omega)\cos 2\Phi - \mathcal{P}.\mathcal{I}^2(\Omega)\sin 2\Phi.$$

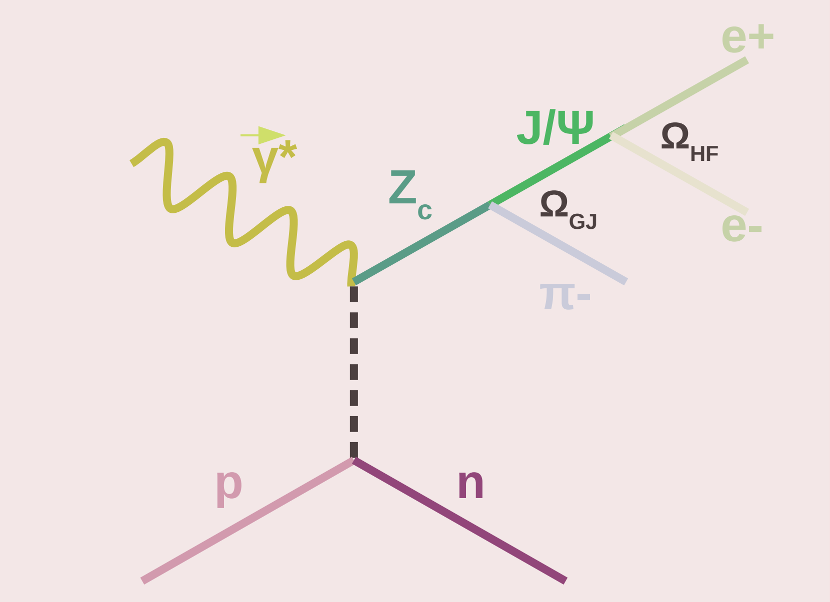
$$\mathcal{I}^\alpha(\Omega,\Phi) = \sum_{r,r'}\sum_{m,m'}\sum_{\lambda,\lambda'}\sqrt{\frac{2l+1}{4\pi}}\sqrt{\frac{2s+1}{4\pi}}\sqrt{\frac{2l'+1}{4\pi}}\sqrt{\frac{2s'+1}{4\pi}} \times (l,0;s,\lambda|j,\lambda)(l',0;s',\lambda'|j',\lambda') \times D^j_{m,\lambda}(\phi_{GJ},\theta_{GJ},0)D^s_{\lambda,0}(\phi_{HF},\theta_{HF},0)R_{Yi}(m_Y) \times D^{j'*}_{m',\lambda'}(\phi_{GJ},\theta_{GJ},0)D^{s'*}_{\lambda',0}(\phi_{HF},\theta_{HF},0)R^*_{Yi'}(m_Y) \times \rho^\alpha_{rr',mm'}.$$

$$\rho^0_{rr',mm'} = \sum_k T^{k,\eta}_{r,m}T^{k,\eta}_{r',m'} + T^{k,\eta'}_{r,m}T^{k,\eta'}_{r',m'},$$

$$\rho^1_{rr',mm'} = \sum_k T^{k,\eta'}_{r,m}T^{k,\eta}_{r',m'} + T^{k,\eta}_{r,m}T^{k,\eta'}_{r',m'},$$

$$\rho^2_{rr',mm'} = i\sum_k -T^{k,\eta'}_{r,m}T^{k,\eta}_{r',m'} + T^{k,\eta}_{r,m}T^{k,\eta'}_{r',m'},$$

r = {j,l,s} = {j=1,l=(0,2),s=1}
And m = -1,0,1 for Z→ J/Ψ+π
k = spin of proton
η = photon helicity

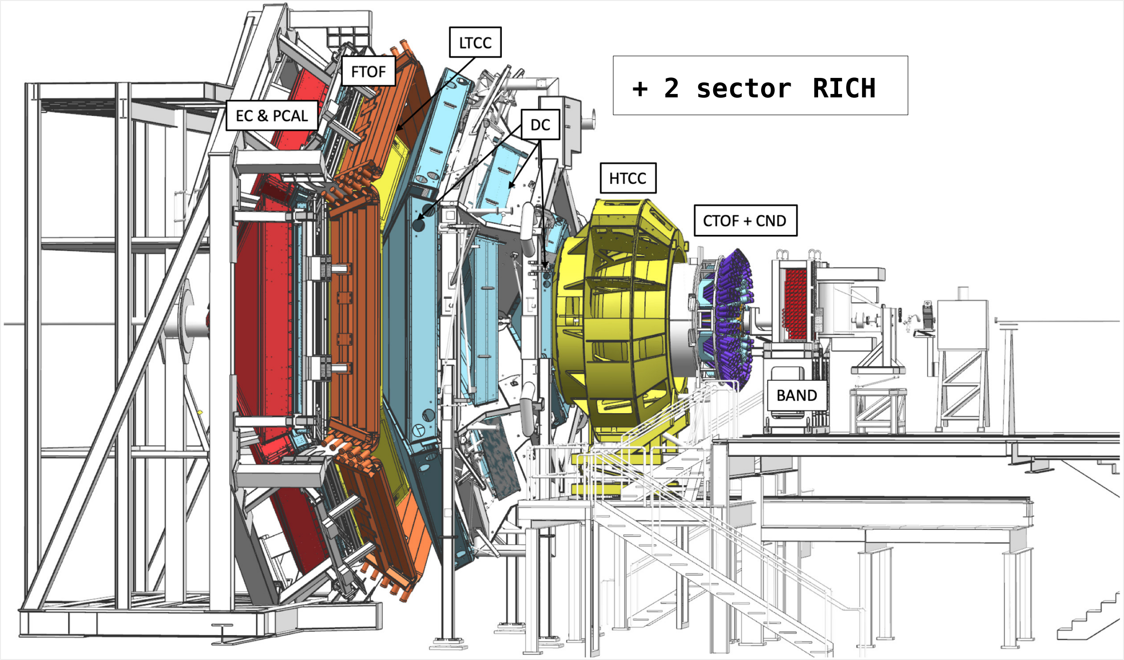


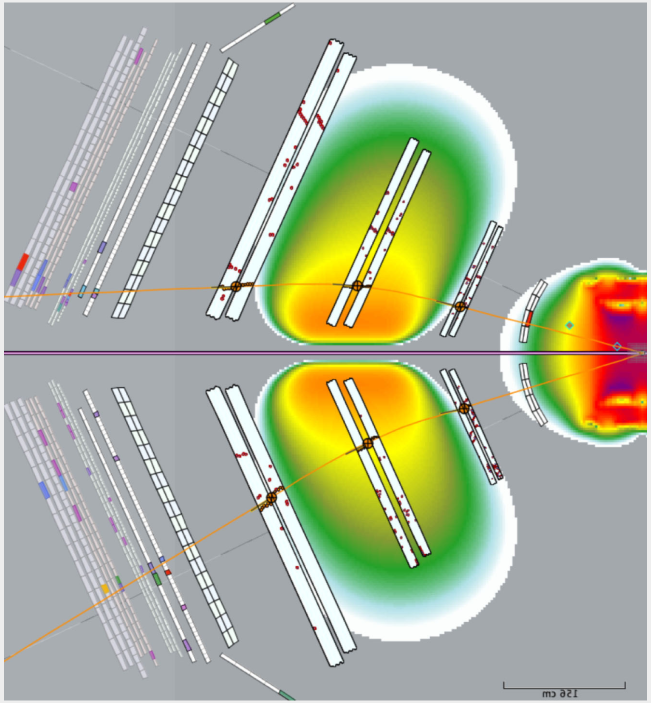
Could determine production amplitudes for partial waves in terms of J,L,S,M,P of resonance, photon helicity

Can this give any information on structure/nature ?

e.g $T_S/T_D \rightarrow 0$ "if molecular", large "if tetraquark"
$|T^{\eta=+1}_{m=1} - T^{\eta=-1}_{m=-1}| \rightarrow 0$ "if tetraquark"

Jlab Hall B CLAS12





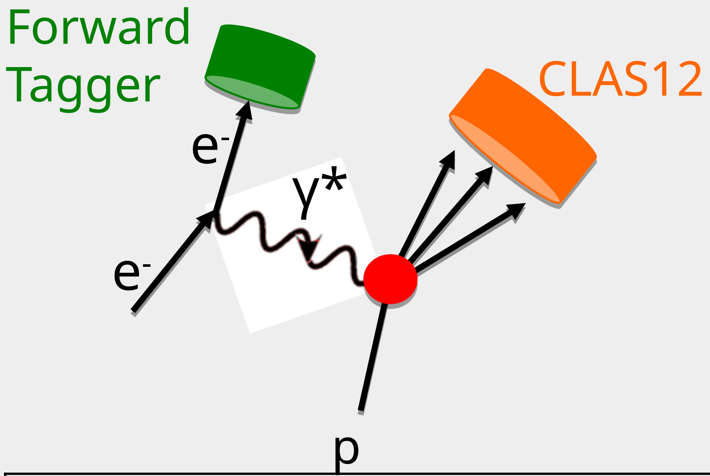
High luminosity electron scattering (10^{35} $cm^{-2}s^{-1}$) produces high flux of nearly real photons.

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

Excellent PID e−, K, p, π, n,γ

Can make measurements with missing particles

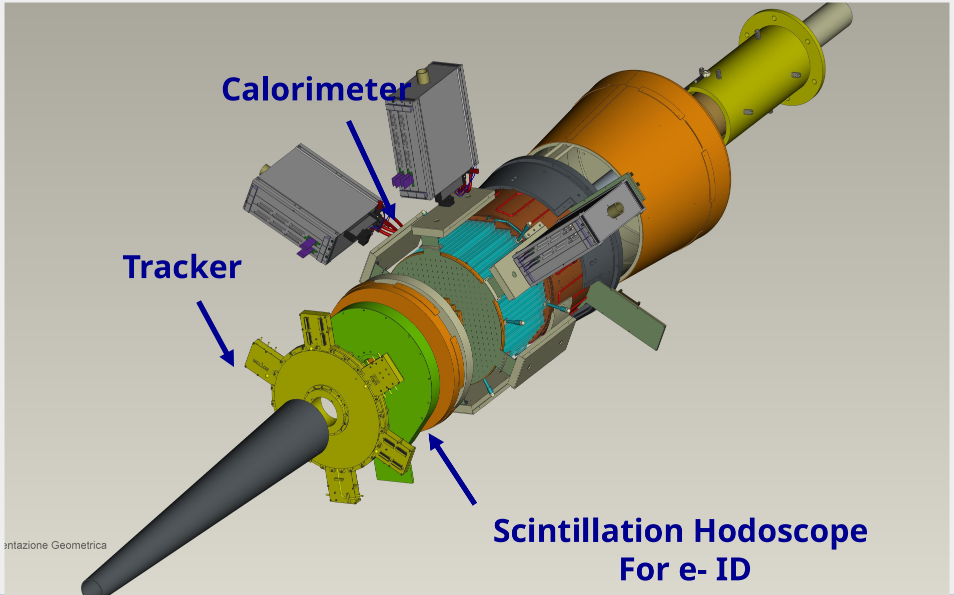
Quasi-real photoproduction @CLAS12



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

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}



MesonEx

- Quasi-real photoproduction provides high flux of meson resonance production
- Tagging the photon with the Forward Tagger provides exclusive reactions
- Quasi-real photon has linear and circular polarisation, essential for Partial Wave Analysis
- Many reactions possible, currently studying : $\pi^+\pi^-$; $\pi^+\pi^+\pi^-$; K^+K^-; $K^+K^-\pi^+$.
- Example distributions from $\pi^+\pi^+\pi^-$:

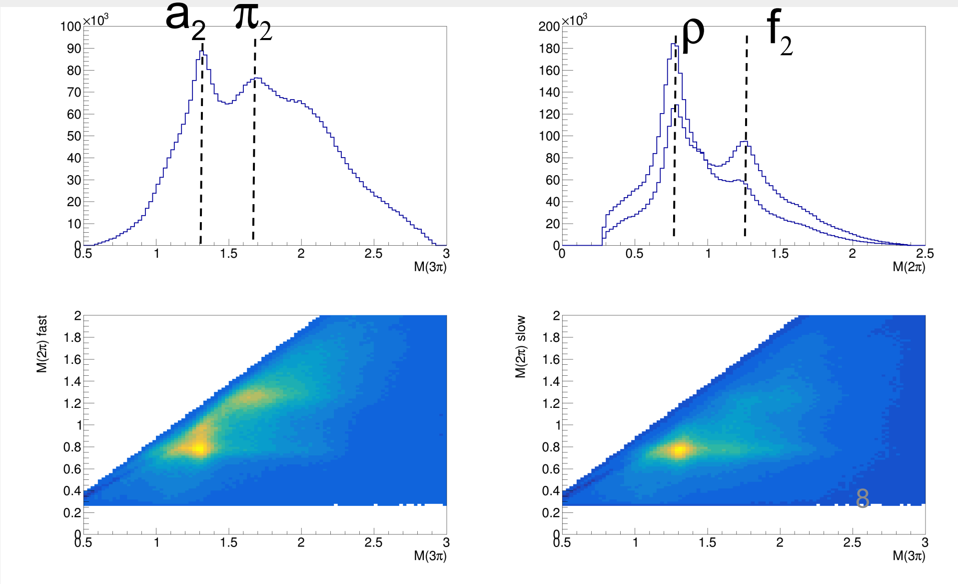


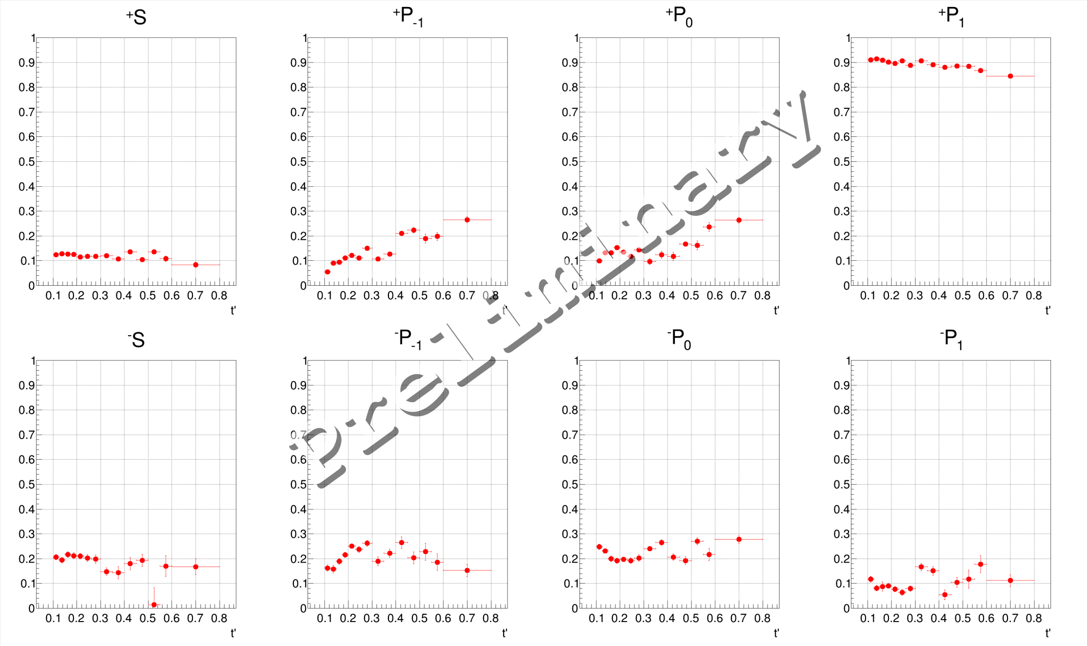
Fig. Mass distributions for $\pi^+\pi^+\pi^-$ final state.

Top Left : Total 3π mass distribution
Top Right : 2π mass distributions

Bottom : 2D, 2π versus 3π mass distributions
Left : Fast 2π mass.
Right: Slow 2π mass

MesonEx Transistion Amplitudes

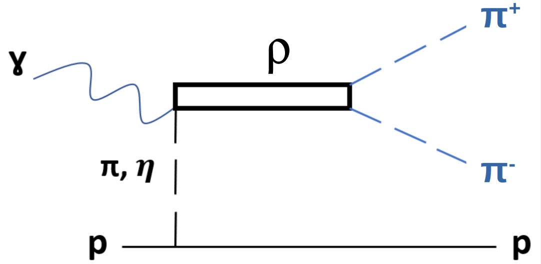
- Amplitude analysis allows us to determine quantum numbers of contributing resonances
- Photon polarization provides a means of filtering smaller contributions (reflectivity waves)
- First results on $\pi^+\pi^-$ partial waves in the ρ resonance region below



Magnitudes of contributing partial waves in the ρ resonance region. (S, P_{-1}, P_0, P_{+1})

Top : +ve reflectivity

Bot : -ve reflectivity



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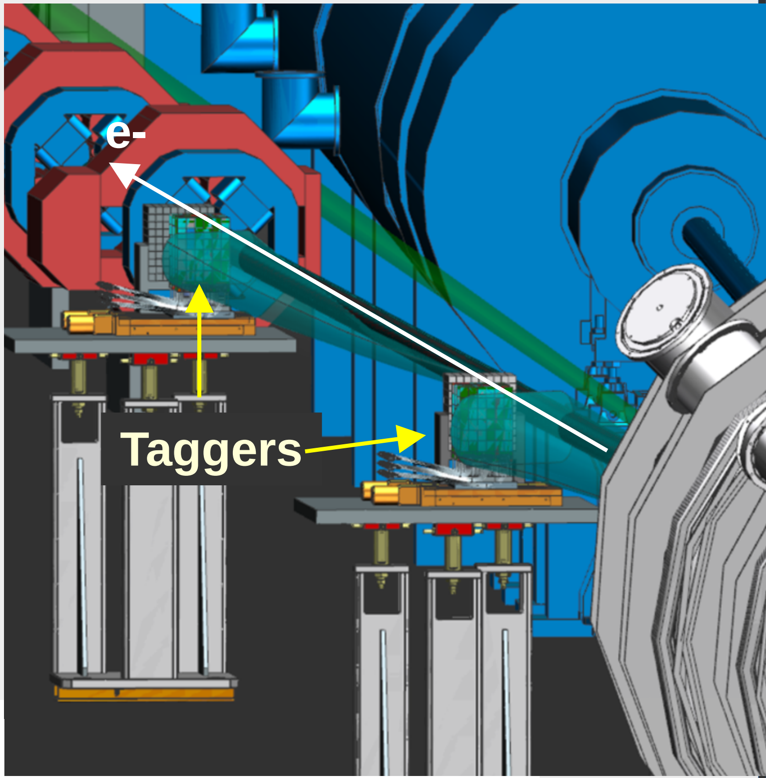
EIC Low Q^2 Tagger

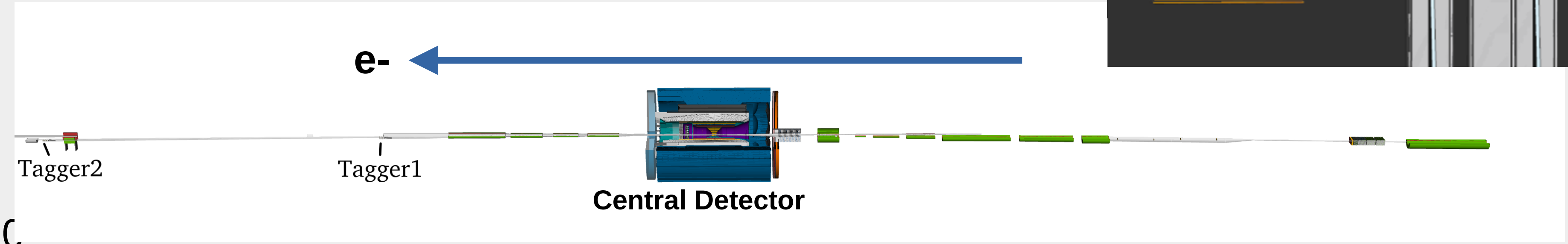
The ePIC Low-Q2 Tagger extends the reach of the central detector down to effectively $Q^2=0$.

Located after the first group of beamline steering and focusing magnets.

Scattered electrons follow deflected through the magnetic optics into tagger facilitating momentum reconstruction through tagger tracks.

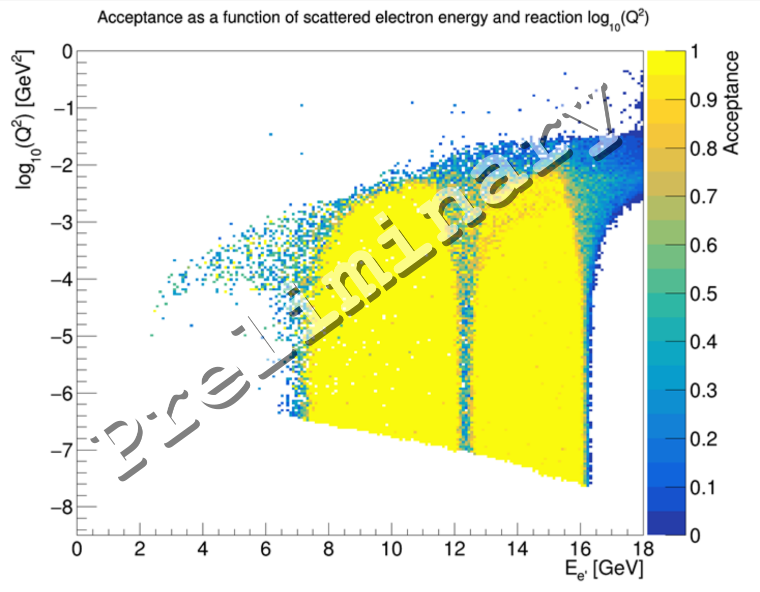
Trackers consisting of 4 layers of Timepix4 pixel detectors (50µm pitch).





Proposed Idealistic Tagger

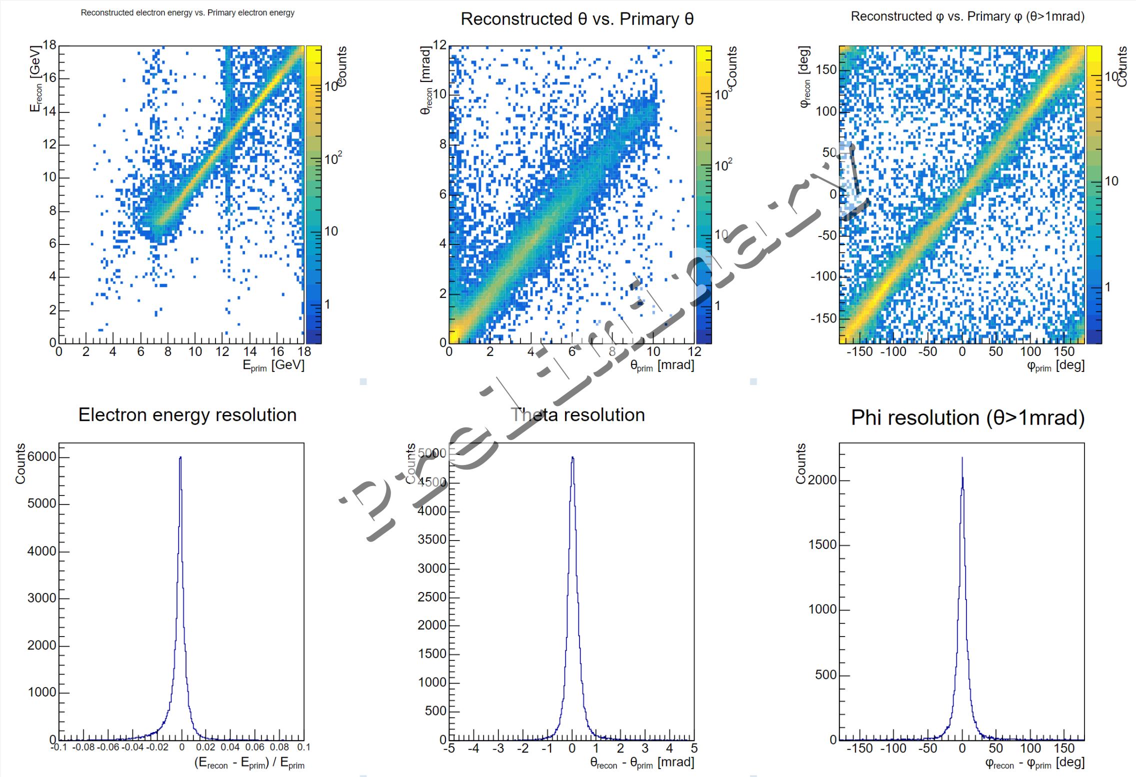
Acceptance



Low e- Energy acceptance limit by magnets

High e- Energy acceptance limit by beam

Resolutions



Tagged Photon Flux CLAS12 22 GeV

Integrate virtual photon flux over allowed Q^2 range
Assume producing particles with mass of Z_c
Corresponds to photon energies > 12 GeV

Integrals Photon Flux

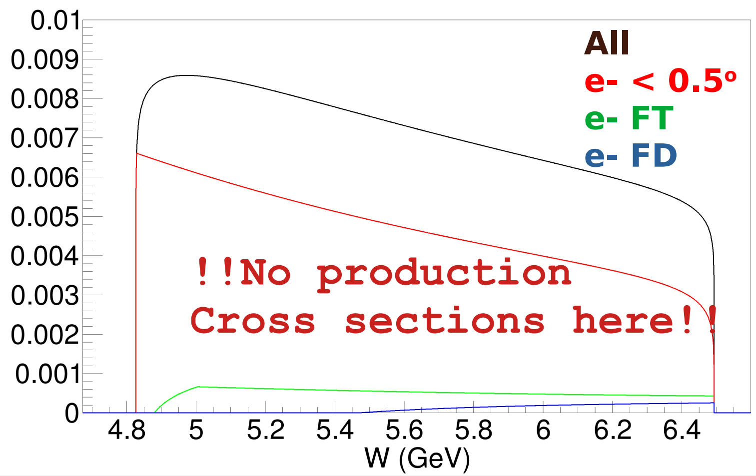
All = 0.012
e- < 0.5° = 0.008 (75%)
e- FT = 0.0008 (7%) Forward Tagger
e- FD = 0.0001 (1%) Forward Detector

Integrals Luminosities @ 10^{35} ($cm^{-2}s^{-1}$) for 50 days

10^{35} ($cm^{-2}s^{-1}$).50(days).0.012 ~ 5200pb^{-1}

Tagging scattered electron <0.5°
10^{35} ($cm^{-2}s^{-1}$).50(days).0.008 ~ 3500 pb^{-1}
Tagging scattered electron Forward Tagger
10^{35} ($cm^{-2}s^{-1}$).50(days).0.0008 ~ 350 pb^{-1}
Tagging scattered electron Forward Detector
10^{35} ($cm^{-2}s^{-1}$).50(days).0.0001 ~ 40 pb^{-1}

Virtual Photon Flux for Zc



Jlab upgrade discussions
GlueX ~ 500 pb^{-1}/year

https://wiki.jlab.org/jlab22/images/b/be/Dobbs_Jlab22_MeasuringXZ.pdf

Tagged Photon Flux JLab and EIC

Integrate virtual photon flux over allowed Q^2 range

Assume producing particles with mass of Z_c

Integrals Photon Flux

CLAS12 All	= 0.012
CLAS12 e- < 0.5°	= 0.008 (75%)
EIC 5x100	= 0.2
EIC lowQ2	= 0.08 (40%)

Integrals Luminosities for 50 days

CLAS12

10^{35} ($cm^{-2}s^{-1}$).50(days).0.012 ~ 5.2 fb^{-1}

Tagging scattered electron <0.5°

10^{35} ($cm^{-2}s^{-1}$).50(days).0.008 ~ 3.5 fb^{-}

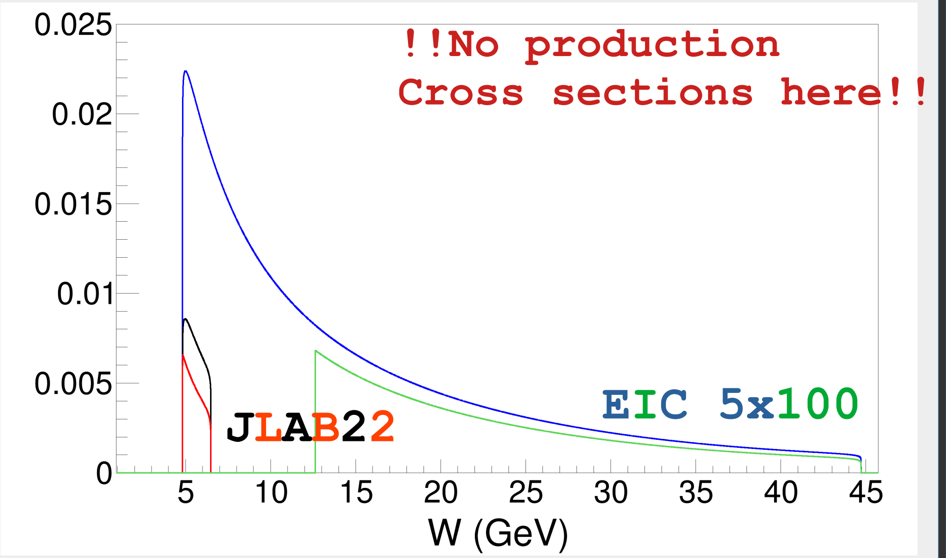
EIC 5 x 100 beam settings (x20 lower luminosity)

5×10^{33} ($cm^{-2}s^{-1}$).50(days).0.2 ~ 4.3 fb^{-1}

Tagging scattered electron LowQ2 tagger

5×10^{33} ($cm^{-2}s^{-1}$).50(days).0.08 ~ 1.7 fb^{-1}

Virtual Photon Flux for Zc

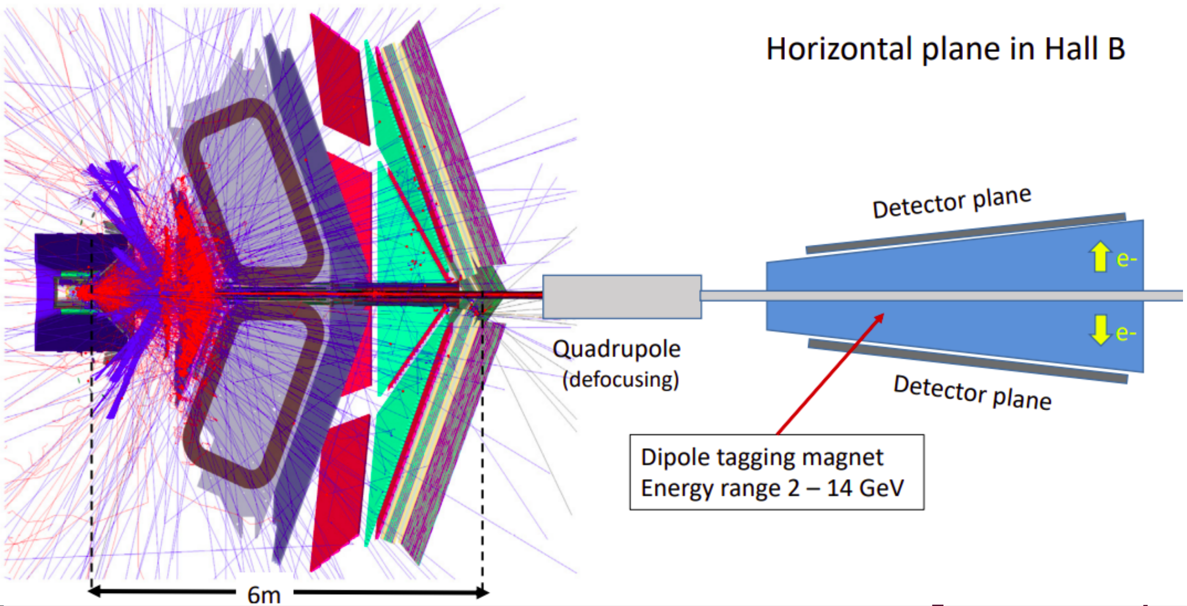


Similar integrated luminosity

JLAB focussed at threshold regions

Zero Degree Spectrometer for CLAS12

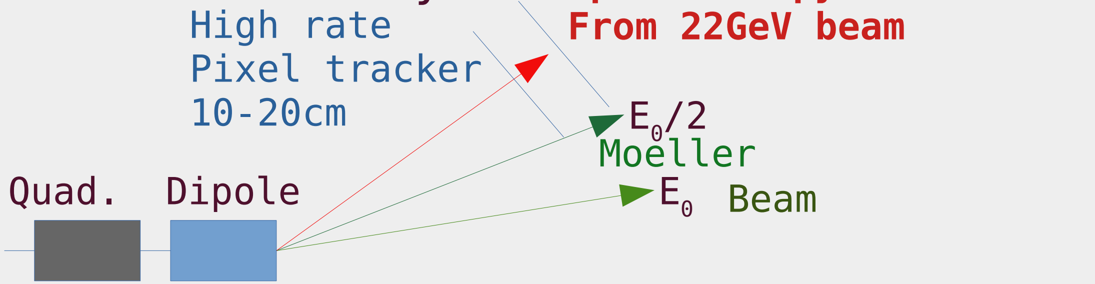
Courtesy: Burkert JFUTURE, Messina.



- Non-interacting electrons, Moller electrons, bremsstrahlung; electrons leave only accidental energy in CLAS12 detectors.
- Hadronically interacting electrons leave significant amount of energy and tracks in CLAS24, O(10GeV).
- The strategy would be to trigger on the event measured in CLAS24 detectors and tag those events with electrons measured in a 0-degree spectrometer.
- This should be studied in simulations to determine what magnitude in instantaneous luminosity can be achieved.
- Note that the Torus magnet open bore of ~ 4 cm accommodates ~0.5° scattering angle without interfering materials.

This would be a major upgrade to Hall B, requiring modifications to dump etc and requiring detailed studies of potential systems

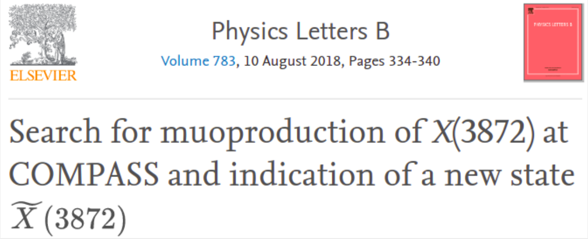
Alternative EIC style



Quasi-real photoproduction: COMPASS

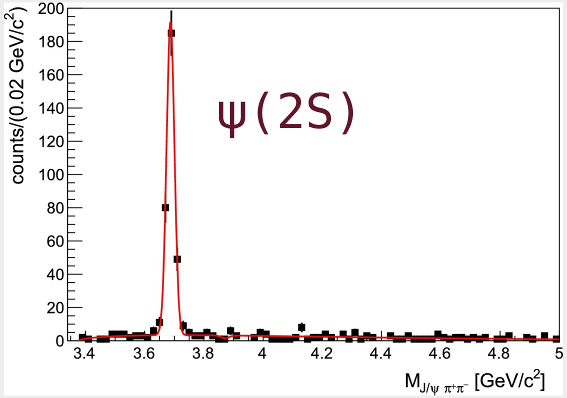
Such production experiments have been done for exotics with mixed results

Relatively low integrated luminosity


Physics Letters B

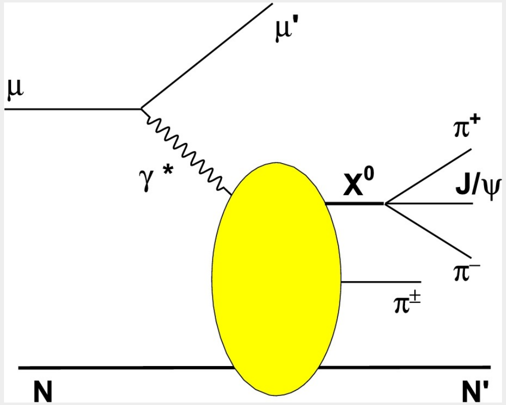
Volume 783, 10 August 2018, Pages 334-340

Search for muoproduction of $X(3872)$ at COMPASS and indication of a new state $\widetilde{X}(3872)$

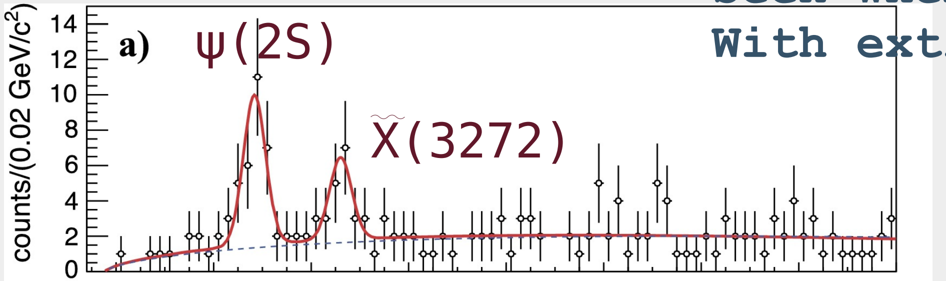


Little signal in direct $J/\psi\pi\pi$

Similar production mechanism



But X like peak
Seen when produced
With extra pion



Suggest a 1+- state instead of 1++ …

???????

Z_c Photoproduction

$Z_c \to J/\psi\ \pi+$
Branch R. 10%

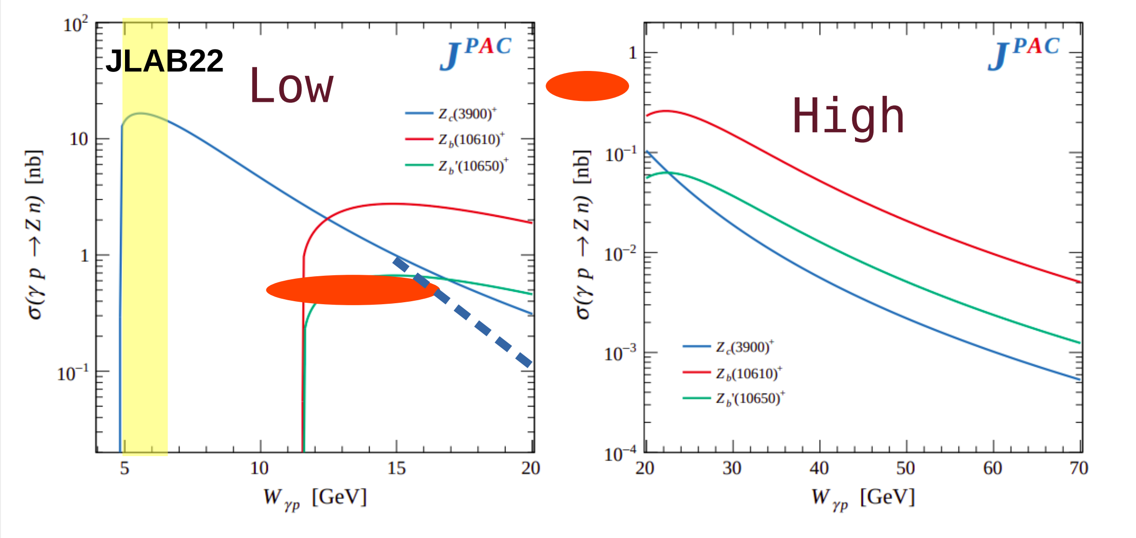
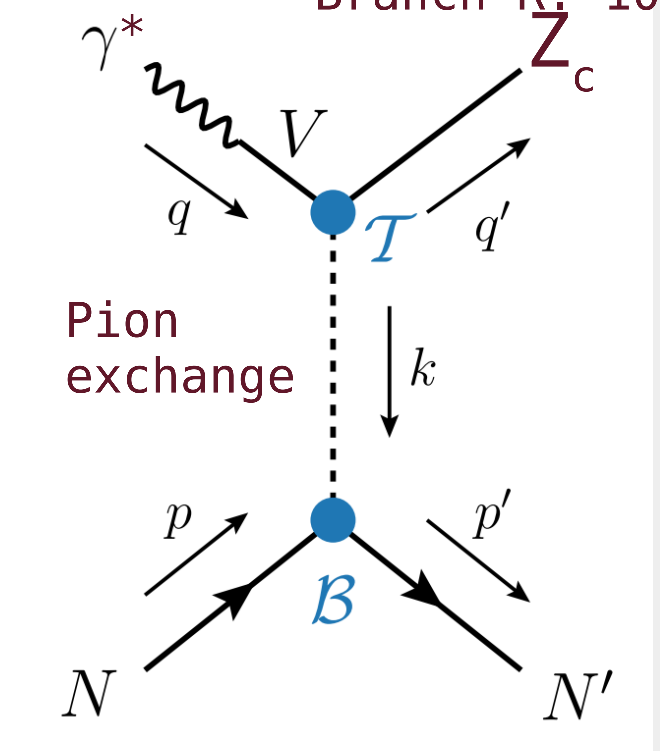


FIG. 2. Integrated cross sections for the three Z states considered. Left panel: predictions for fixed-spin exchange, which we expect to be valid up to approximately 10 GeV above each threshold. Right panel: predictions for Regge exchange, valid at high energies.



Pion exchange

——— JPAC model for Z_c

- - - - Interpolation from low to high

COMPASS upper limit PLB 742,300 2015

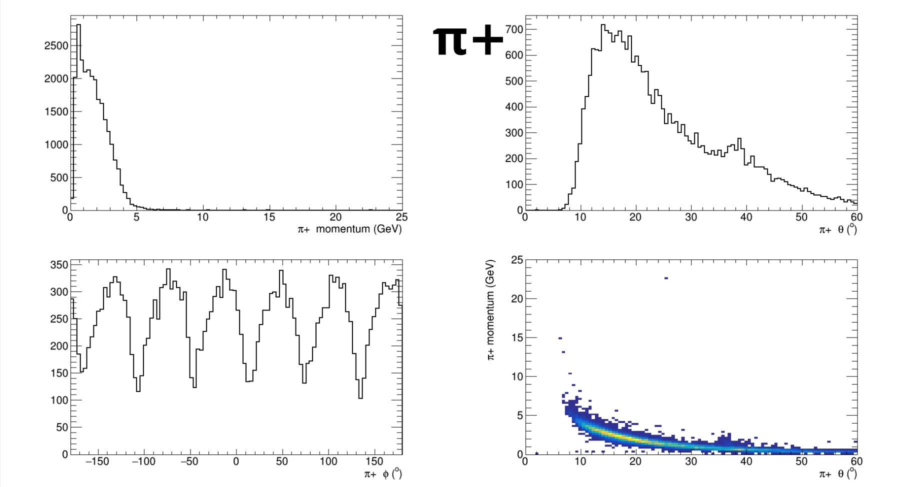
Suggest estimates could be high by order of magnitude at W ~ 10 GeV

May relate to single/multi-spin Regge mechanisms

Potential high cross section region ideal for Jlab22

Z_c Production CLAS12 @ 22 GeV

π+

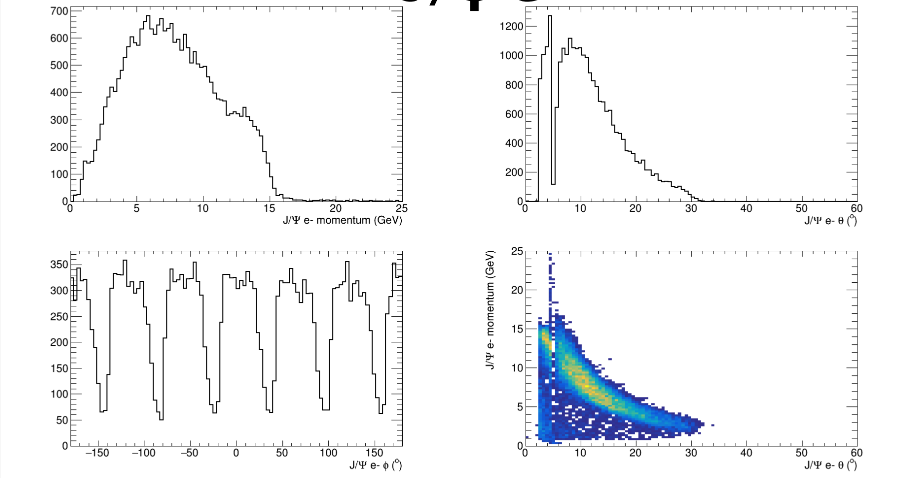


Use CLAS12 gemc simulation with Run Group A settings, outbending e-

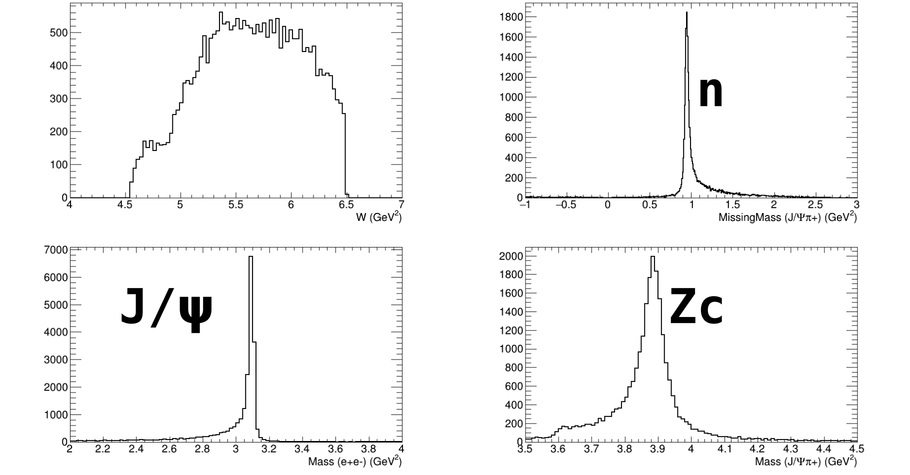
Assume scattered e- detected in “Zero degree spectrometer” <0.5°

Do not detect the recoil neutron
-reconstruct from other particles

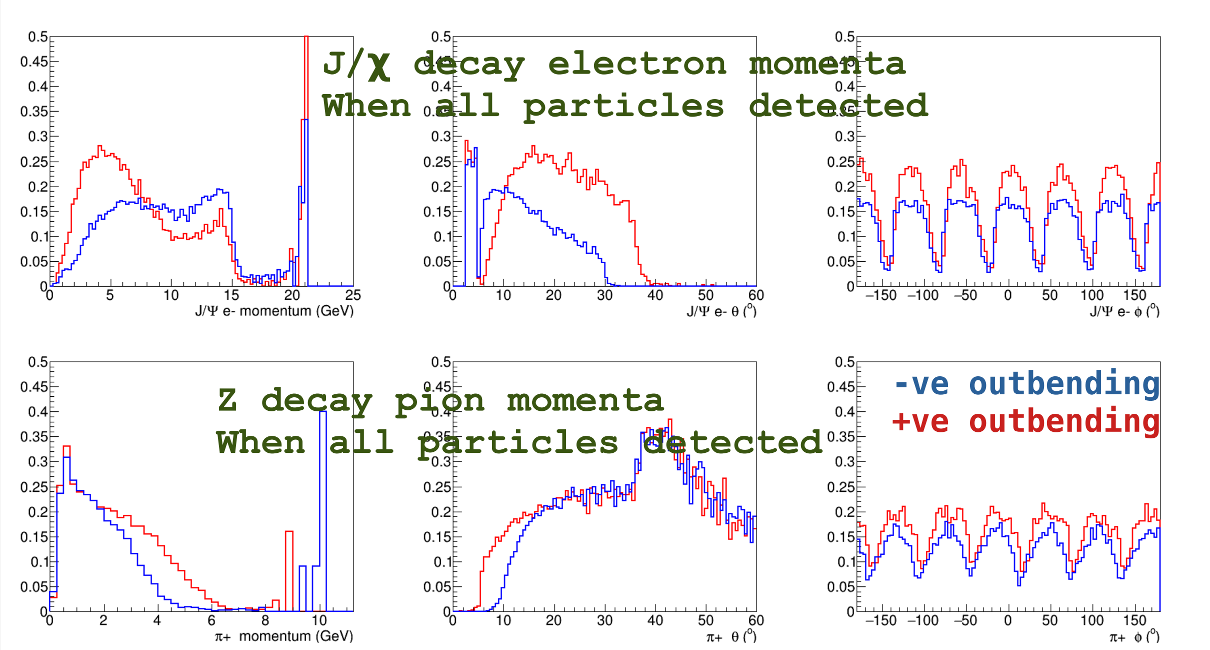
J/ψ e-

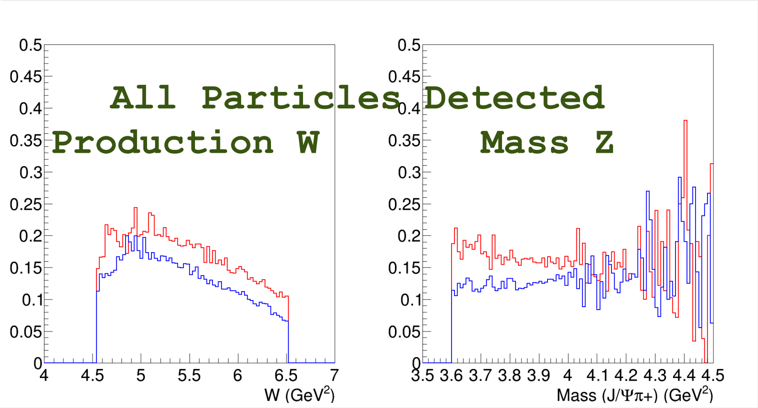


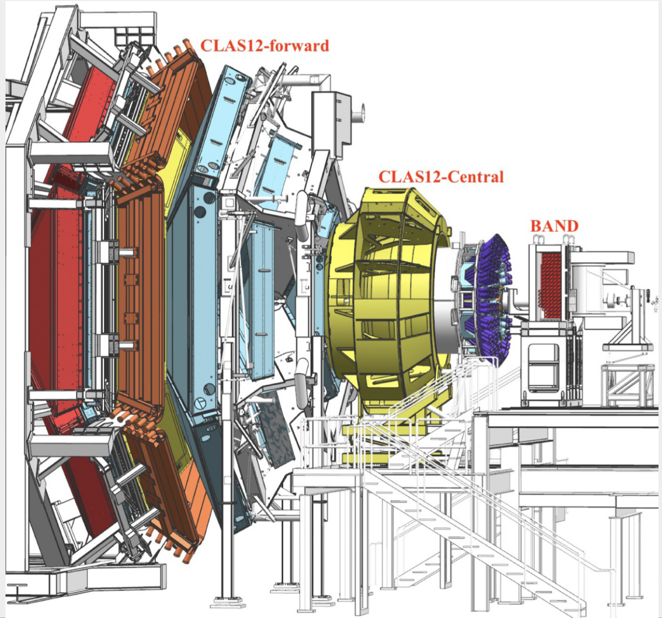
masses



Acceptances CLAS12 @ 22 GeV







Results for combined detection of e−,e+,π+
Assuming luminosity $10^{35} cm^{-2} s^{-1}$
and 50 days gives 210k (109k) produced events.
With 22 (17) GeV beam momentum

Acceptance J/χπ ~ 10% for ~20k events
Tag e- → θ <0.5 Nevents : ~ 15 k ;
FT : 1.5k ; FD : 200

X Photoproduction CLAS12 @ 22 GeV

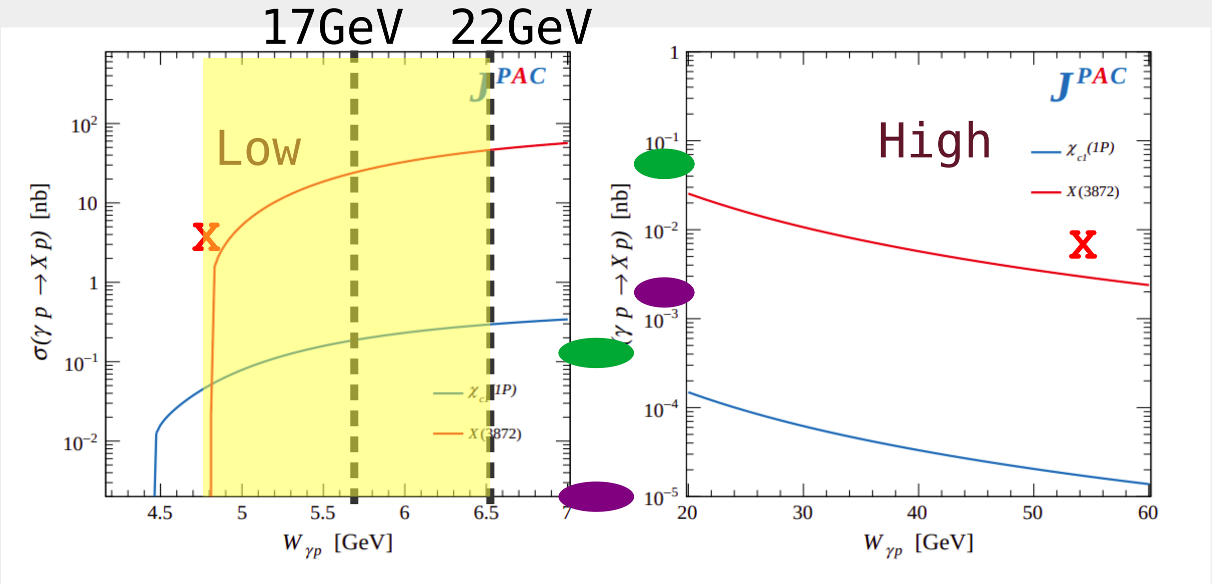
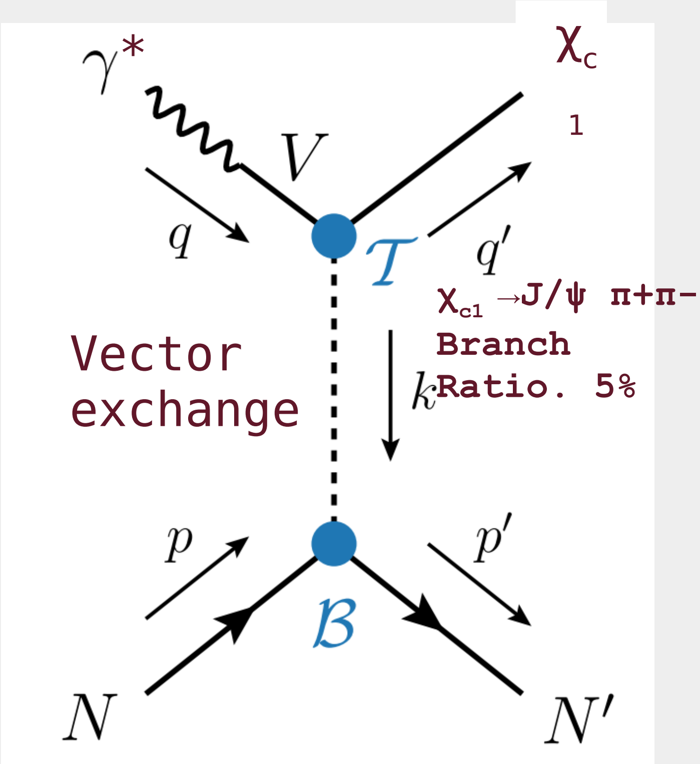


FIG. 3. Integrated cross sections for the axial $\chi_{c1}(1P)$ and $X(3872)$. Left panel: predictions for fixed-spin exchange, valid at low energies. Right panel: predictions for Regge exchange, valid at high energies.

From COMPASS W=13.7 GeV

- X(3872) cross section
- X(3872) upper limit



χc1 →J/ψ π+π- Branch Ratio. 5%

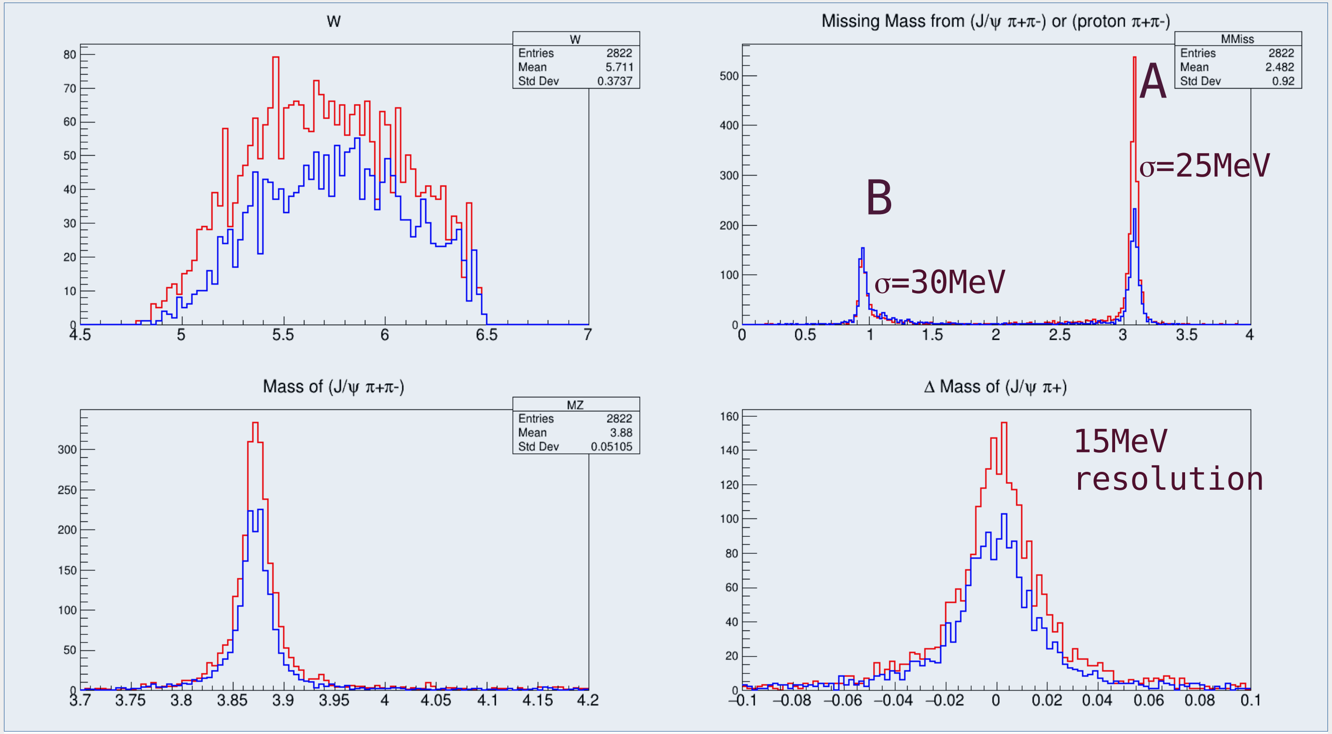
Only require low energy model for JLAB22

Assuming luminosity $10^{35}cm^{-2}s^{-1}$ and 50 days gives 190k (56k) events.
With 22 (17) GeV beam momentum

X Photoproduction CLAS12 @ 22 GeV

Consider two cases. (A) Do not detect Jpsi. (B) Do not detect proton

22 GeV



	outbend	
	+ve	-ve
Expected yield	2800	1900
Acceptance	1.5%	1.0%

Lower acceptance due to extra π

Would still get O(1000) with Zero degree tagger

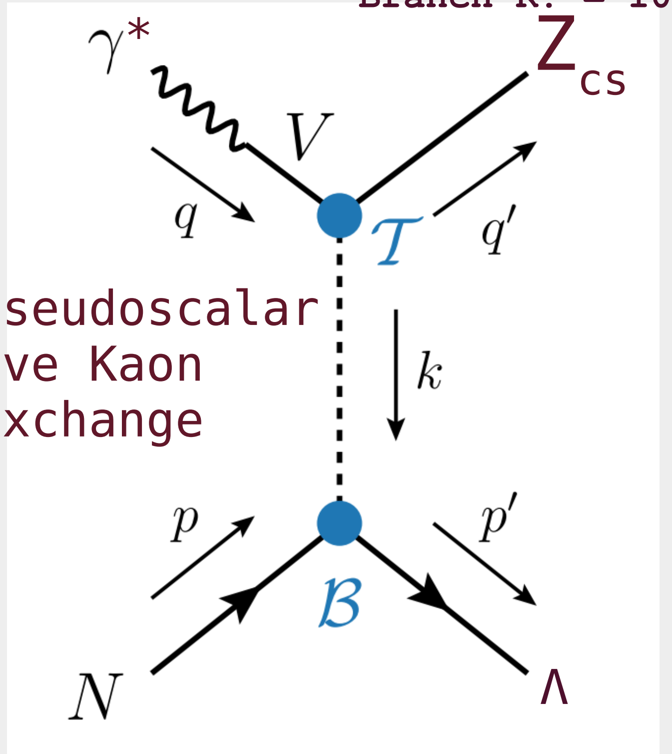
Higher multiplicity final states more suited to GlueX type detector

Z_{cs} Production CLAS12 @ 22 GeV

Not "official" JPAC model
Adapted from jpacPhoto Z_c
with D. Winney

Assuming luminosity $10^{35} cm^{-2} s^{-1}$
and 50 days gives 33k (4.5k) events.
With 22 (17) GeV beam momentum

Z_{cs} → J/ψ K+
Branch R. = 10%



Pseudoscalar
-ve Kaon
exchange

Λ→ pπ-

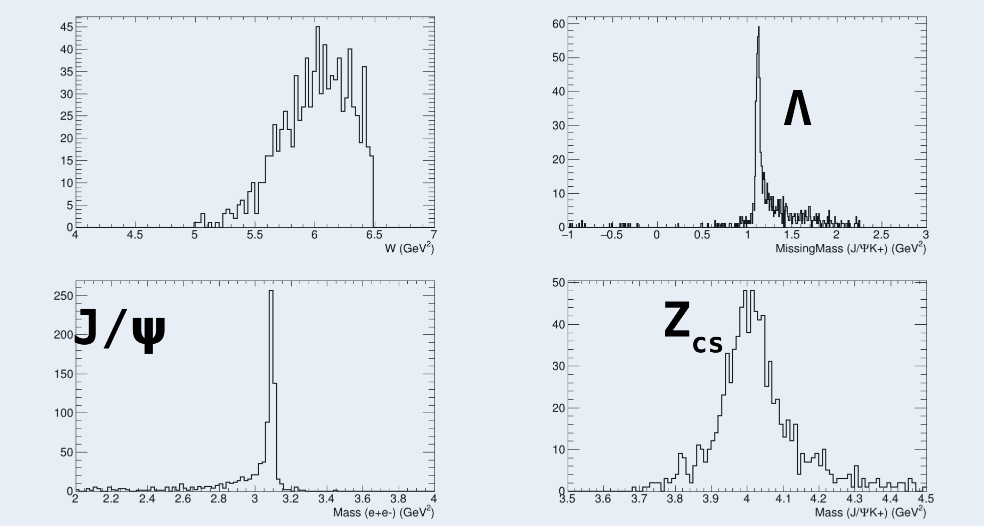
Z_{cs} Production CLAS12 @ 22 GeV

Total 33,000 events produced
Do not detect π-p, reconstruct Λ from E,p conservation

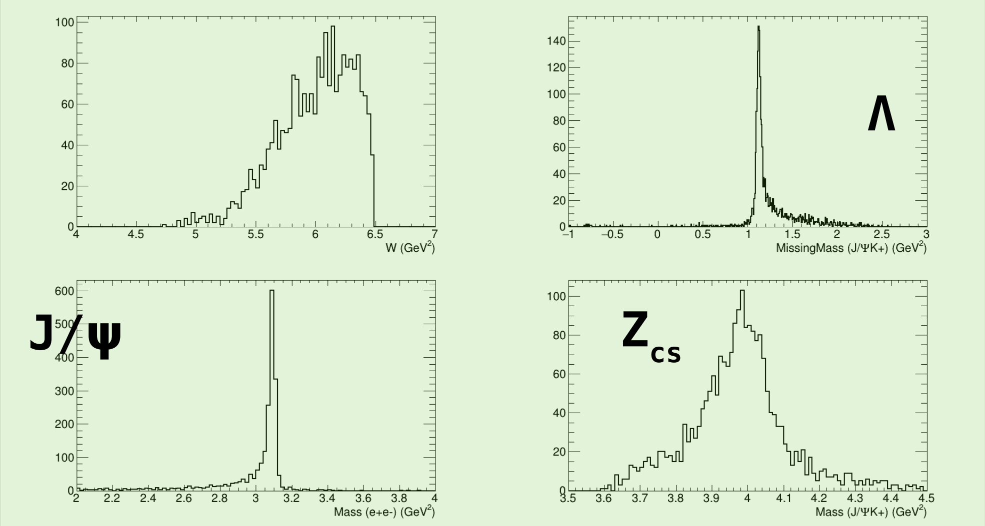
-ve outbend => 900 events, 3% acceptance
+ve outbend => 2000 events, 6% acceptance

Neglecting photon tagging
~75% Zero deg.Spectrometer
~7% Forward Tagger

-ve outbend



+ve outbend



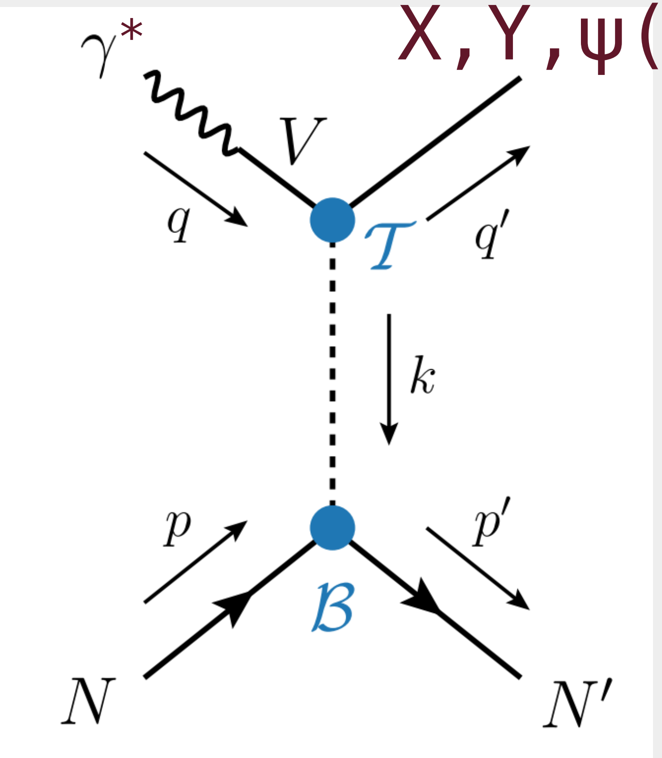
Exotics with EIC : ECCE

ePIC design/simulation/reconstruction in progress.

Can consider previous studies instead

But Tagger acceptance too high here (factor several)

X,Y,ψ(2s)



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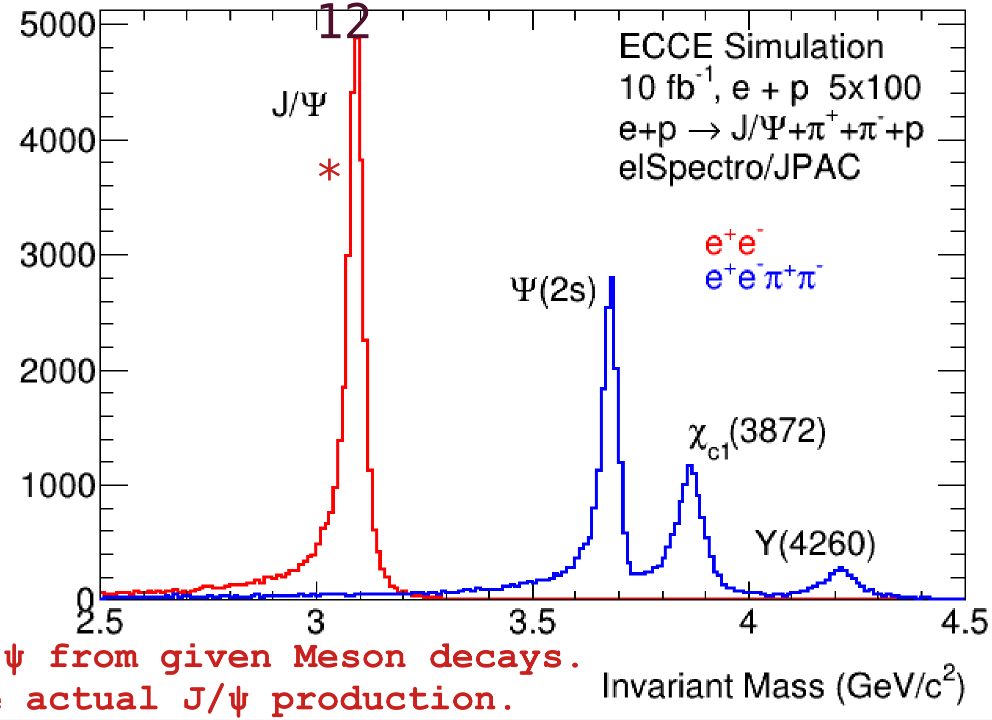


* only J/ψ from given Meson decays.
Many more actual J/ψ production.

* COMPASS measured 314 ψ(2s)

Semi-Inclusive Z production @EIC

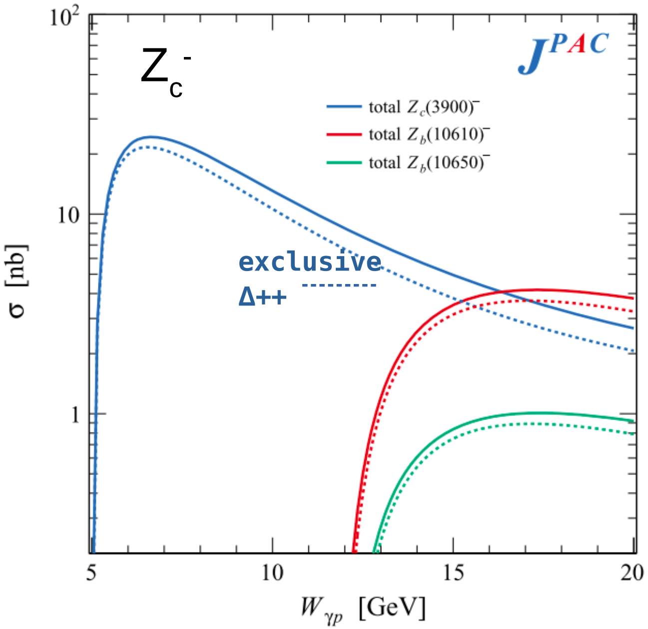
XYZ spectroscopy at electron-hadron facilities. II. Semi-inclusive processes with pion exchange

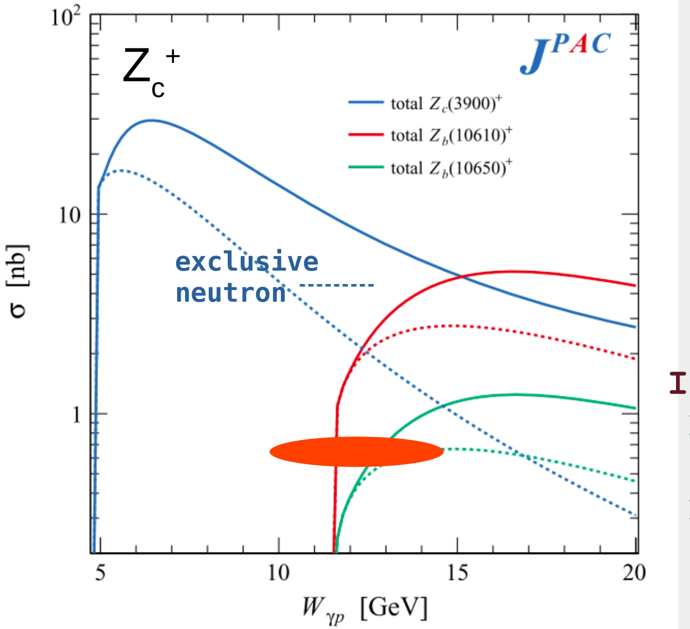
D. Winney, A. Pilloni, V. Mathieu, A. N. Hiller Blin, M. Albaladejo, W. A. Smith, and A. Szczepaniak (Joint Physics Analysis Center)

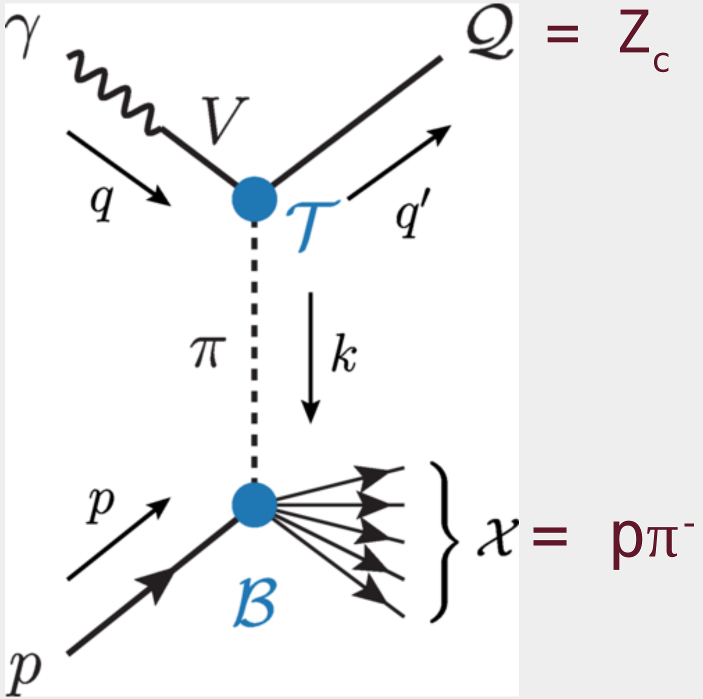
Phys. Rev. D **106**, 094009 – Published 7 November 2022

$$E_{\mathcal{Q}} \frac{d^3\sigma}{d^3 q_f} = \frac{K}{16\pi^3} |T_\pi(t)\mathcal{P}_\pi|^2 \sigma_{\text{tot}}^{\pi^* N},$$

Bottom vertex => SAID pion scattering







Inclusive higher at high W =>

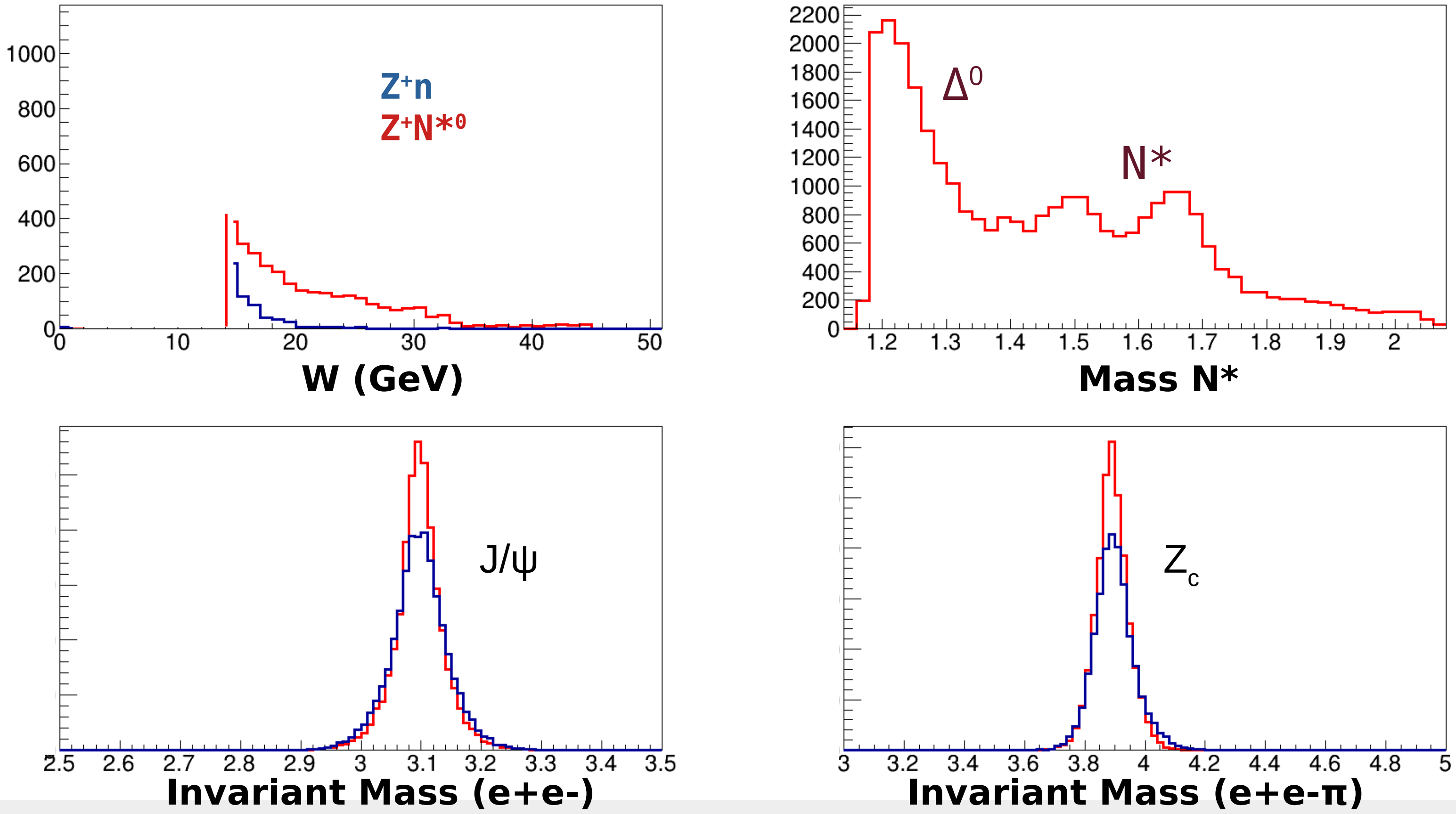
Better meson detection

- more transverse momentum

Better e-′ detection

- higher acceptance at lower $P_{e'}$

Z_c^+ beams :5 x 100 GeV



Require e-′ detection
Quasi-real tagger
$0.45\ E_0 < E < 0.9\ E_0$
$\theta < 6$ mrad, $\sigma_E = 1\%$

"Simulations" with
Eic-smear fastmc
10fb-1 (~2 weeks)

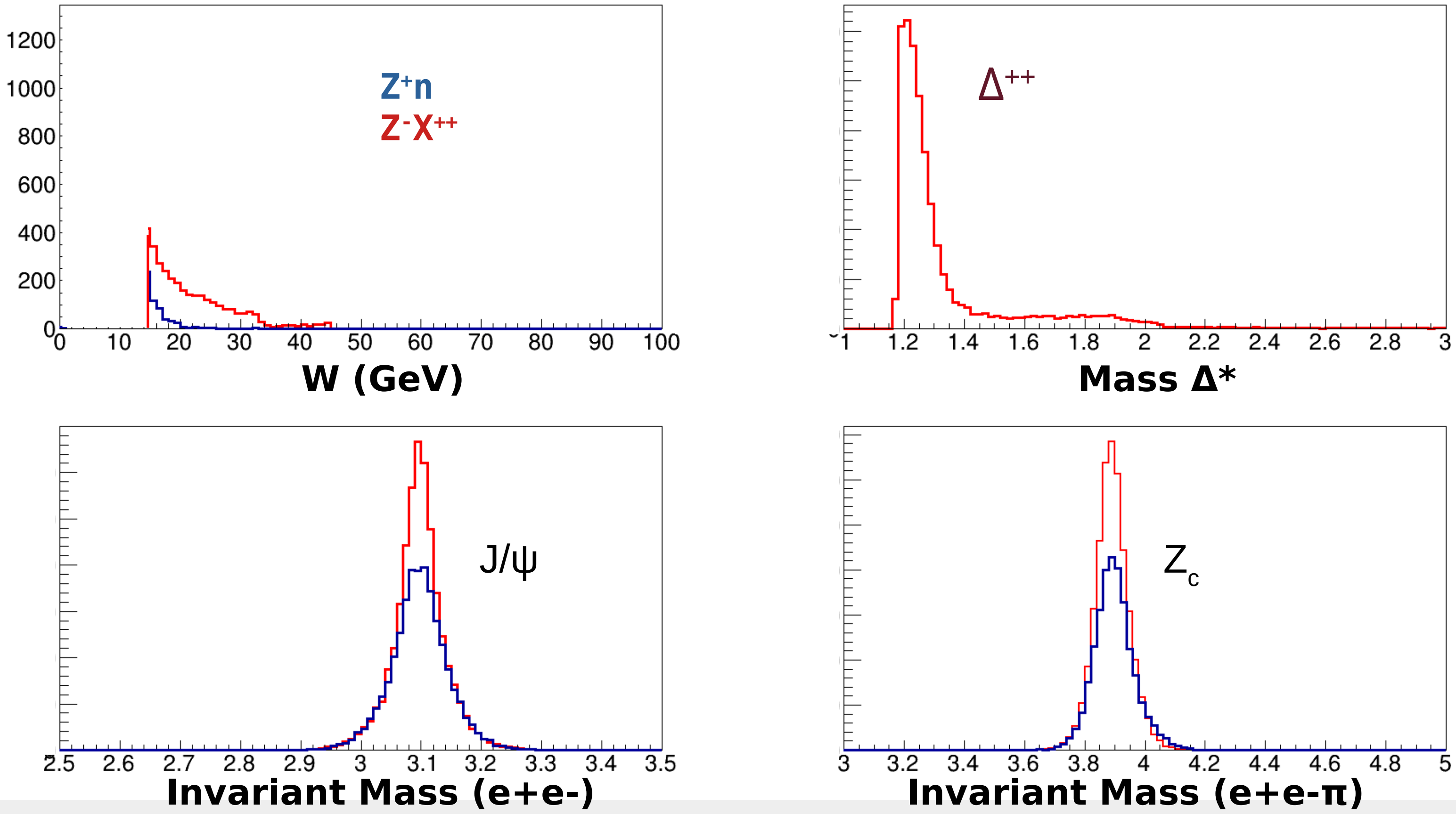
Semi-inc σ 30% lower

But weighted to high W

=> better e- acceptance
better Z+ acceptance

Do not detect Δ^0

Z_c^- beams :5 x 100 GeV



Require e-′ detection
Quasi-real tagger
$0.45\ E_0 < E < 0.9\ E_0$
$\theta < 6$ mrad, $\sigma_E = 1\%$

"Simulations" with
Eic-smear fastmc

Semi-inc σ similar

Weighted to high W

=> better e- acceptance
better Z+ acceptance

Do not detect Δ^{++}

Overall factor ~ 10 more events with inclusive channels

Production Amplitudes

$$\mathcal{I}(\Omega,\Phi) = \mathcal{I}^0(\Omega) - \mathcal{P}.\mathcal{I}^1(\Omega)\cos 2\Phi - \mathcal{P}.\mathcal{I}^2(\Omega)\sin 2\Phi.$$

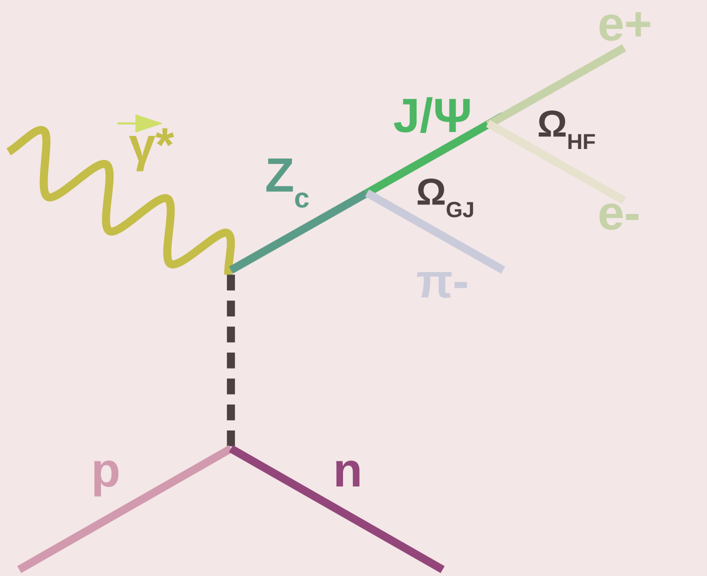
$$\mathcal{I}^\alpha(\Omega,\Phi) = \sum_{r,r'}\sum_{m,m'}\sum_{\lambda,\lambda'}\sqrt{\frac{2l+1}{4\pi}}\sqrt{\frac{2s+1}{4\pi}}\sqrt{\frac{2l'+1}{4\pi}}\sqrt{\frac{2s'+1}{4\pi}} \times (l,0;s,\lambda|j,\lambda)(l',0;s',\lambda'|j',\lambda') \times D^j_{m,\lambda}(\phi_{GJ},\theta_{GJ},0)D^s_{\lambda,0}(\phi_{HF},\theta_{HF},0)R_{Yi}(m_Y) \times D^{j'*}_{m',\lambda'}(\phi_{GJ},\theta_{GJ},0)D^{s'*}_{\lambda',0}(\phi_{HF},\theta_{HF},0)R^*_{Yi'}(m_Y) \times \rho^\alpha_{rr',mm'}.$$

$$\rho^0_{rr',mm'} = \sum_k T^{k,\eta}_{r,m}T^{k,\eta}_{r',m'} + T^{k,\eta'}_{r,m}T^{k,\eta'}_{r',m'},$$

$$\rho^1_{rr',mm'} = \sum_k T^{k,\eta'}_{r,m}T^{k,\eta}_{r',m'} + T^{k,\eta}_{r,m}T^{k,\eta'}_{r',m'},$$

$$\rho^2_{rr',mm'} = i\sum_k -T^{k,\eta'}_{r,m}T^{k,\eta}_{r',m'} + T^{k,\eta}_{r,m}T^{k,\eta'}_{r',m'},$$

r = {j,l,s} = {j=1,l=(0,2),s=1}
And m = -1,0,1 for Z→ J/Ψ+π
k = spin of proton
η = photon helicity

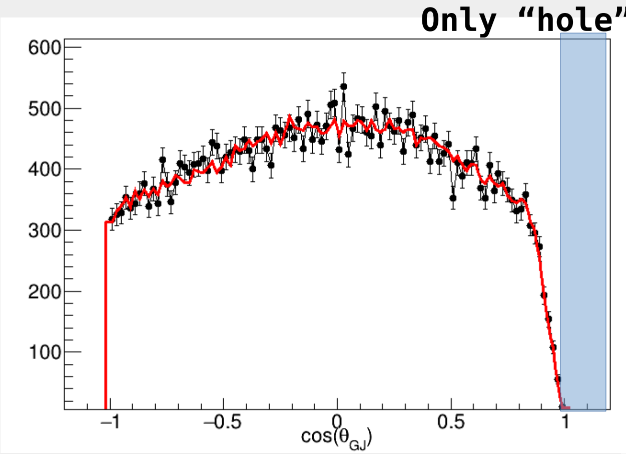


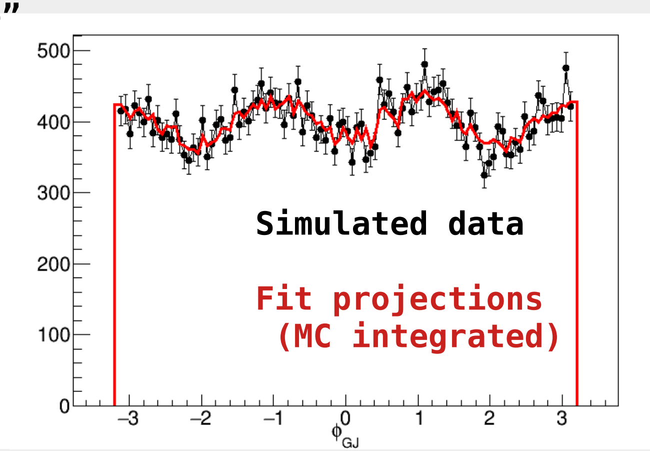
Could determine production amplitudes for partial waves in terms of J,L,S,M,P of resonance, photon helicity

Can this give any information on structure/nature ?

e.g $T_S/T_D \rightarrow 0$ "if molecular", large "if tetraquark"
$|T^{\eta=+1}_{m=1} - T^{\eta=-1}_{m=-1}| \rightarrow 0$ "if tetraquark"

Toy Amplitude Analysis @ EIC





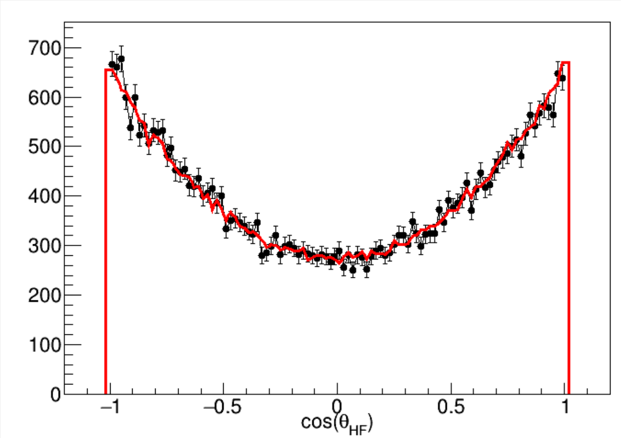
Generate data with given Transition amplitudes.

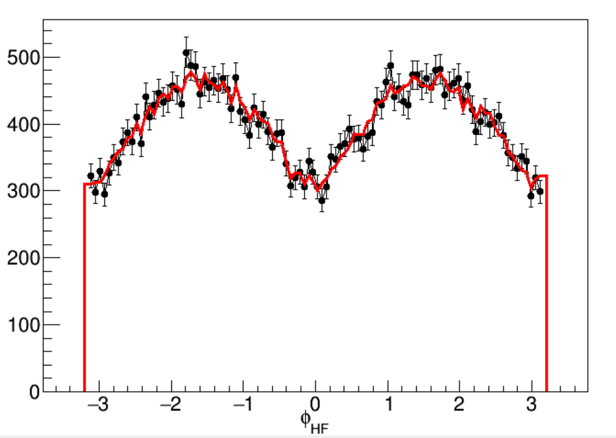
Fit model on simulated data

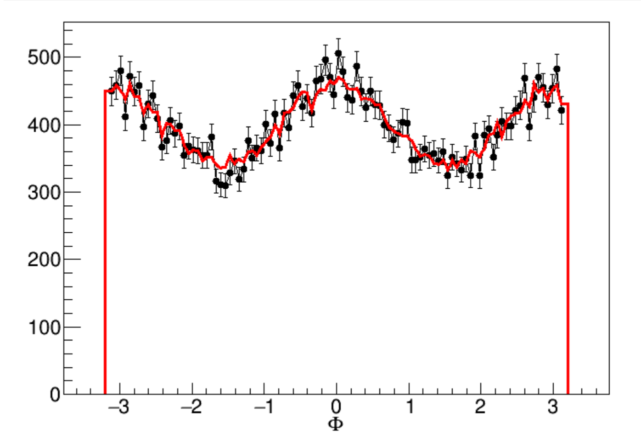
$j<3$, $|m|<j$, $l<4$, $s=1$, $\eta=\pm1$

$\lvert T^{\eta}_{jlsm}\rvert$	T^{+}_{1011}	$=0.34\pm0.01$ (0.35)
	T^{+}_{101-1}	$=0.43\pm0.01$ (0.45)
	T^{+}_{1210}	$=0.55\pm0.01$ (0.55)
ϕ^{η}_{jlsm}	ϕ^{+}_{1011}	$=0.04\pm0.04$ (0.04)
	ϕ^{+}_{101-1}	$=1.24\pm0.04$ (1.20)
	ϕ^{+}_{1210}	$=2.20\pm0.04$ (2.20)

All other amplitudes consistent with 0







Toy dataset consists 40k events, eic-smear.

Summary

Photoproduction provides a means of producing hadron resonances

If charmonium-like states are real resonances they should be produced
This is an intriguing topic in hadron physics

An energy upgraded Jlab would produce such states and in Hall B with CLAS12 quasi-real photoproduction may be used. However a zero-degree spectrometer would really be needed for efficient measurements.

Ideal for Z meson studies, due to large exclusive cross section at threshold which fall rapidly (based on jpacPhoto models). Could measure multiple isospin channels. Similar prospects for Hall B

Highly complementary EIC is more suited to higher W processes like Y or semi-inclusive production, or new discoveries.

Measurement of photoproduction amplitudes would provide a unique window for the study of these states.

But what if they do not exist, or are not strongly photo-produced ?
Do we need more luminosity or alternative physics explanations ?

Summary