Spectroscopy with Quasi-real Photoproduction at the EIC

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Exotic heavy meson spectroscopy and structure with the EIC

CFNS Stony Brook, 14-17 April

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.

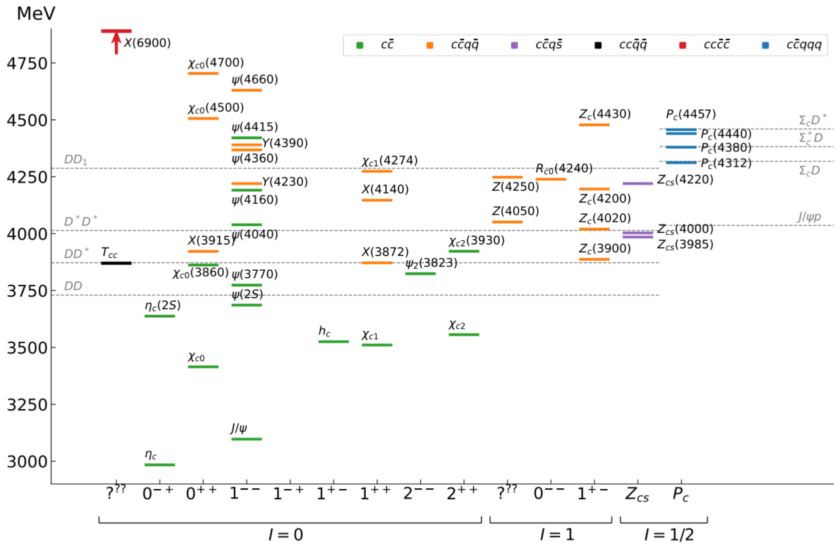
2) As photoproduction can produce any state we may see states that haven't been produced in other mechanisms. For example no "exotic" tensor mesons have been identified yet.

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.

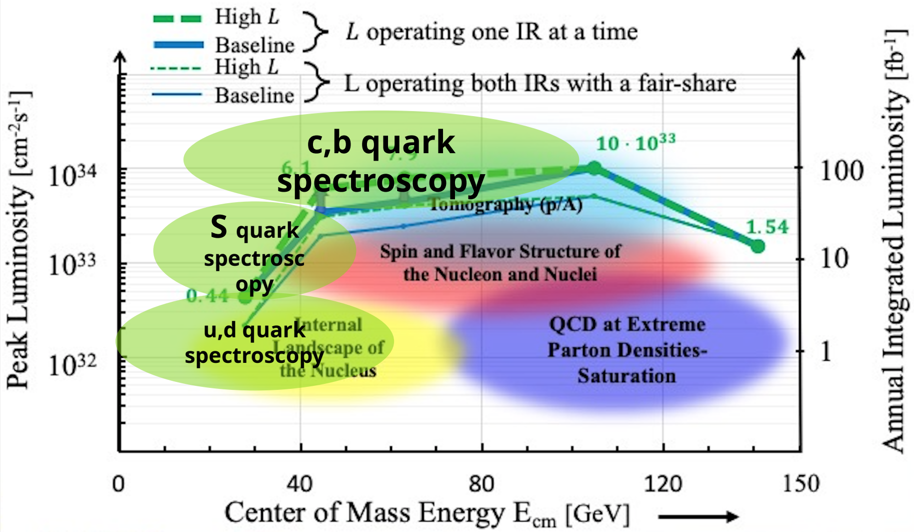
4) The nature of the observed states is a matter of great discussion. How these states behave in different production mechanism can help us understand the underlying dynamics (tetraquark, molecules, hybrids). Things like photocouplings, polarisations or even Q2 dependences can be helpful here.

Charmonium-like Spectrosopy & EIC

Many interesting states found



These states should be produced at EIC



Progress in Particle and Nuclear Physics
Available online 4 March 2023, 104032
In Press, Corrected Proof What's this?

Review

Precision studies of QCD in the low energy domain of the EIC

Production rate estimates only

TABLE II. Summary of results for production of some states of interest at the EIC electron and proton beam momentum $5 \times 100 (GeV/c)$ (for electron x proton). Columns show : the meson name; our estimate of the total cross section; production rate per day, assuming a luminosity of 6.1×10^{33} cm^{-2}s^{-1}; the decay branch to a particular measurable final state; its ratio; the rate per day of the meson decaying to the given final state.

Meson	Cross Section (nb)	Production rate (per day)	Decay Branch	Branch Ratio (%)	Events (per day)
$\chi_{c1}(3872)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	5	6.1 k
$Y(4260)$	2.3	2.0 M	$J/\Psi\ \pi^+\pi^-$	1	1.2 k
$Z_c(3900)$	0.3	0.26 M	$J/\Psi\ \pi^+$	10	1.6 k
$X(6900)$	0.015	0.013 M	$J/\Psi\ J/\Psi$	100	46
$Z_{cs}(4000)$	0.23	0.20 M	$J/\Psi\ K^+$	10	1.2 k
$Z_b(10610)$	0.04	0.034 M	$\Upsilon(2S)\ \pi^+$	3.6	24

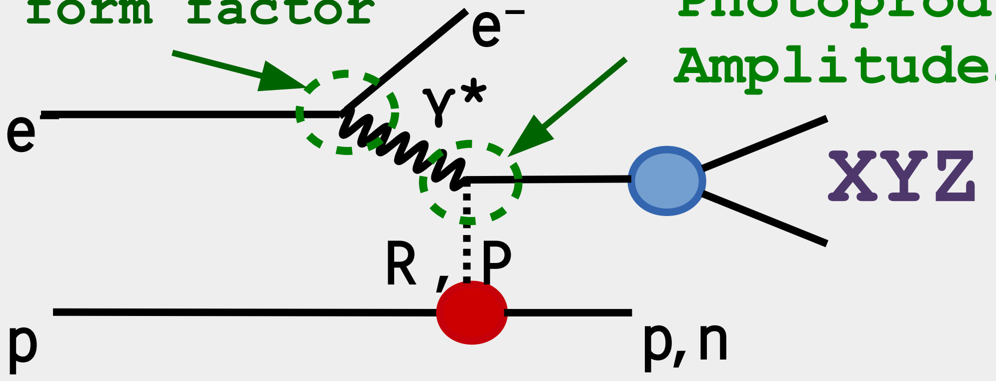
Detection not included

Quasi-real Photoproduction

Virtual photon flux
+ form factor

Photoproduction → from jpacPhoto
Amplitudes

based on
Regge exchanges
and VMD



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

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

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

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

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

Leads to high production rates

Inclusive elSpectro algorithm

Specify meson – baryon final state e.g. rho + proton ; Zc + Δ

Use PDG to define decay branches of meson and baryon

Use JPACPhoto to define photoproduction amplitude

Numerically Integrate 2D xsection (t) to get function of s: $XS_i(s)$

Use integration samples for initial sampling envelope in t SE(t:s)

Integrate 3D xsection (s,t,Q2) $TotXS_i$, for reaction rate

Choose meson – baryon final state i based on $TotXS_i(s)$

Sample (s, Q2) from virtual photon flux

Accept/Reject event on $Xs_i(s)*F(Q2)$, where F(Q2)→ H1 param.

Choose decay channels for all subsequent meson/baryon decays, based on branch ratios

Sample intermediate masses, and N-body mass phase space

Sample t from sampling envelope SE(t:s) at current s, save sample weight SW

Calculate XS(s,t,Mmeson,Mbaryon,Q2) Accept/Reject accounting for SW

Fully decay meson and baryon final states

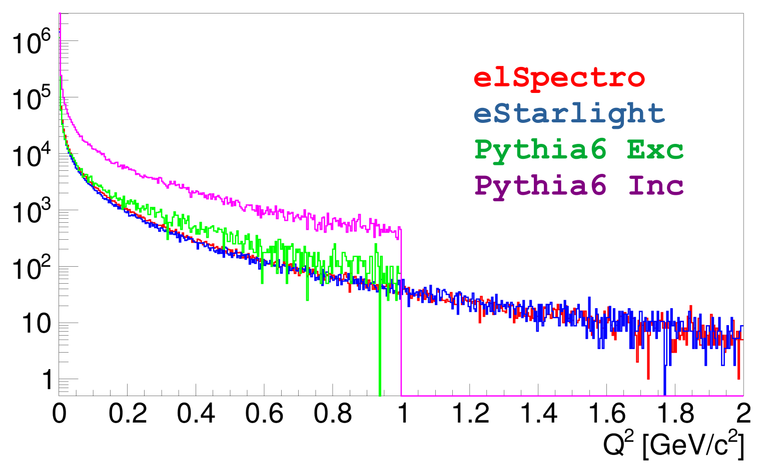
Under Development

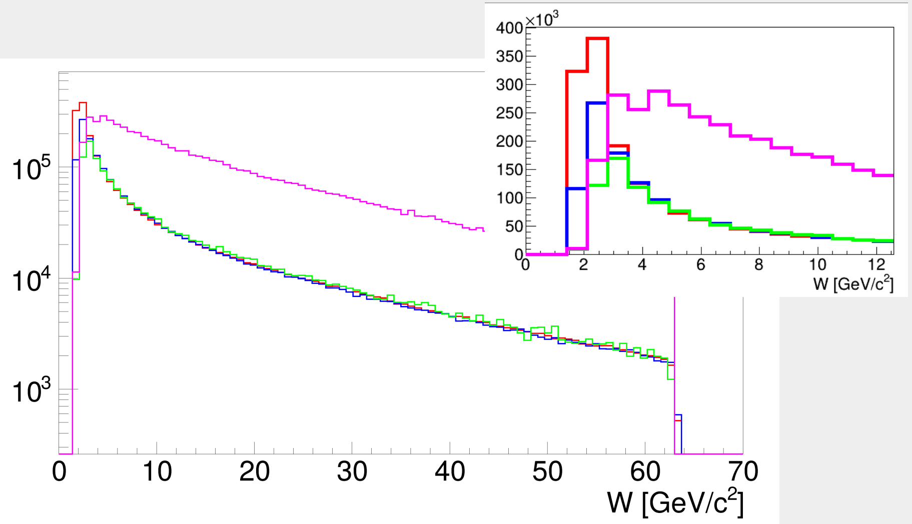
ρ Quasi-real Photoproduction

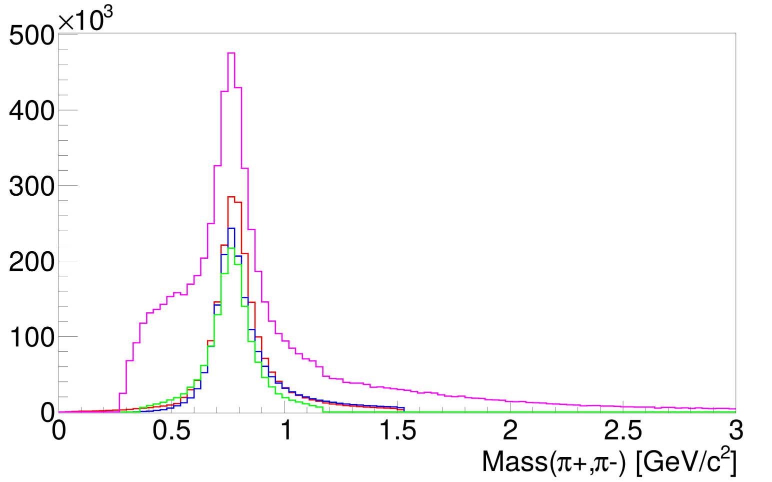
Benchmark elSpectro 10x100 versus :
eStarlight
EIC Pythia6 (SIDIS/pythia-eic/1.0.0)

Relative Scaling arbitrary,
elSpectro normalised to 1 minute@$6.1x10^{33}$

elSpectro cross section 1.3x larger
than estarlight, mostly at low W.
 - effect of f_2 exchanges in JPAC model







Generator has all X Decays

$\chi_{c1}(3872)$

$\pi^+\pi^- J/\psi(1S)$	$(3.5 \pm 0.9)\%$
$\omega J/\psi(1S)$	$(4.1 \pm 1.4)\%$

$J/\psi(1S)$

e^+e^-	$(5.971 \pm 0.032)\%$
$\mu^+\mu^-$	$(5.961 \pm 0.033)\%$

$\omega(782)$

$\pi^+\pi^-\pi^0$	$(89.2 \pm 0.7)\%$
$\pi^0\gamma$	$(8.35 \pm 0.27)\%$

$\chi_{c1}(3872)$

$D^0\overline{D}^0\pi^0$	$(45 \pm 21)\%$
$\overline{D}^{*0}D^0$	$(34 \pm 12)\%$

D^0

$K^-\pi^+$	$(3.947 \pm 0.030)\%$
$K^-\pi^+\pi^0$	[5] $(14.4 \pm 0.6)\%$

Branching Ratios to detectable final states

```
X → e+e-π+π-          =  0.0021
X → e+e-π+π-π0        =  0.0022
X → K+K-π+π-π0        =  0.0007
X → K+K-π+π-π0π0      =  0.0048
X → K+K-π+π-π0π0π0    =  0.0088
```

Requires detection of 10 particles + e-',p'

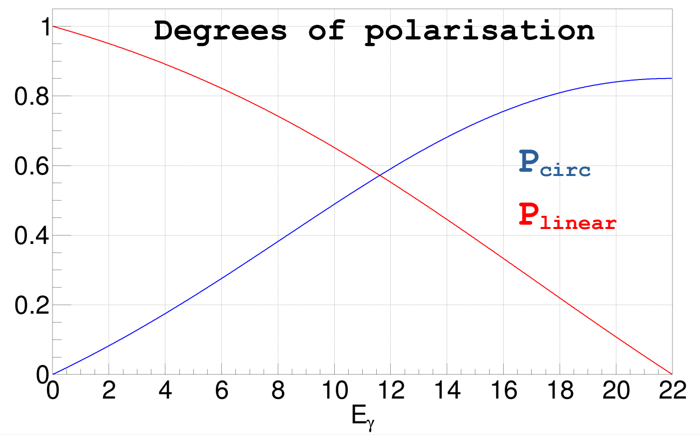
Virtual Photon Polarisation

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

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

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

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

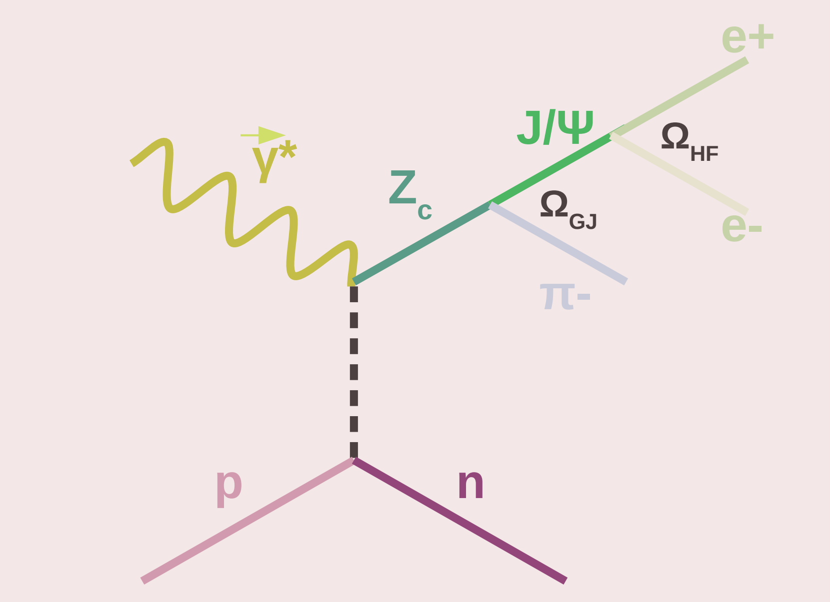
$$\begin{aligned}\mathcal{I}^\alpha(\Omega,\Phi)=\sum_{r,r'}\sum_{m,m'}\sum_{\lambda,\lambda'}&\sqrt{\frac{2l+1}{4\pi}}\sqrt{\frac{2s+1}{4\pi}}\sqrt{\frac{2l'+1}{4\pi}}\sqrt{\frac{2s'+1}{4\pi}}\\ &\times(l,0;s,\lambda|j,\lambda)(l',0;s',\lambda'|j',\lambda')\\ &\times D^j_{m,\lambda}(\phi_{GJ},\theta_{GJ},0)D^s_{\lambda,0}(\phi_{HF},\theta_{HF},0)R_{Yi}(m_Y)\\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

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

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

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

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

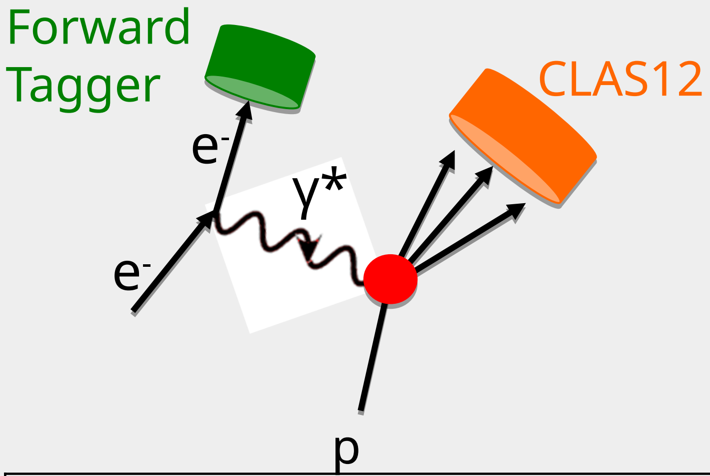


Could determine production amplitudes for partial waves in terms of J,L,S,M,P of resonance, photon helicity

Can this give any information on structure/nature ?

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

Quasi-real photoproduction - CLAS12

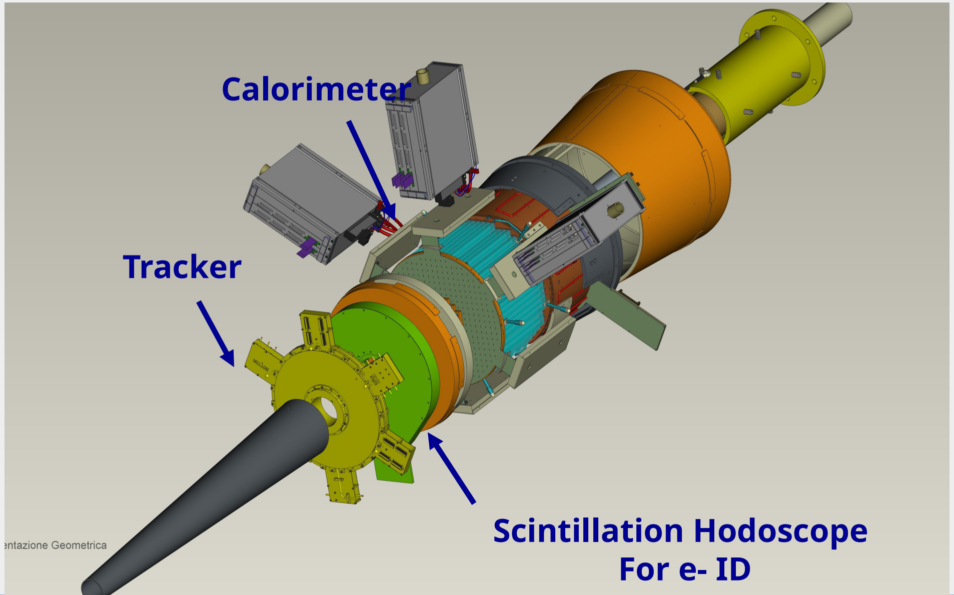


Quasi-real photoproduction:

- 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

- PbW Calorimeter → e- momentum
- Scinitllation Hodoscope → PID

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}



CLAS12 - 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 $\pi^+\pi^+\pi^-$:

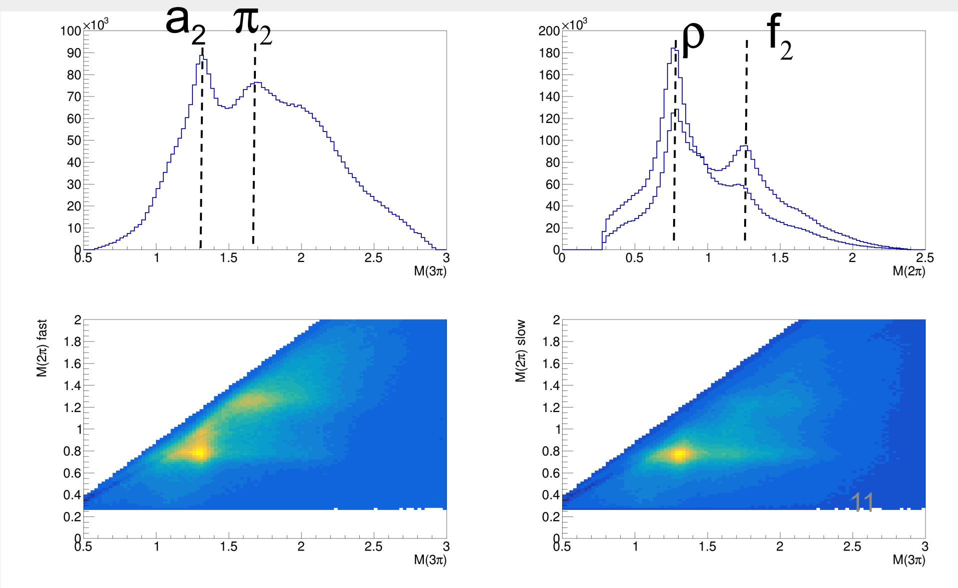


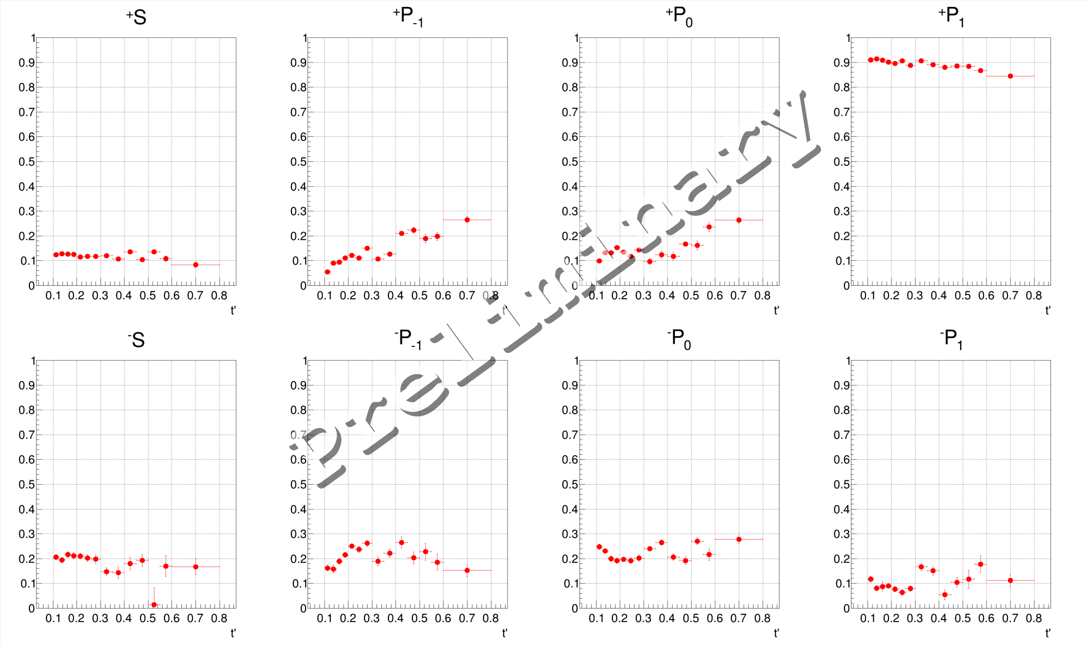
Fig. Mass distributions for $\pi^+\pi^+\pi^-$ final state.

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

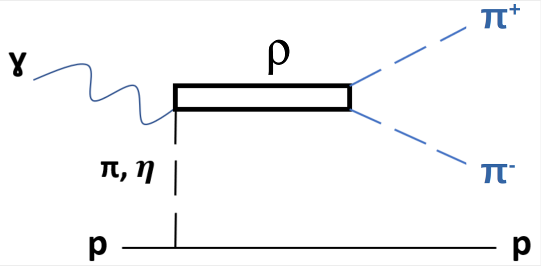
- **Amplitude analysis allows us to determine quantum numbers of contributing resonances**
- **Photon polarization provides a means of filtering smaller contributions (reflectivity waves)**
- **First results on $\pi^+\pi^-$ partial waves in the ρ resonance region below**



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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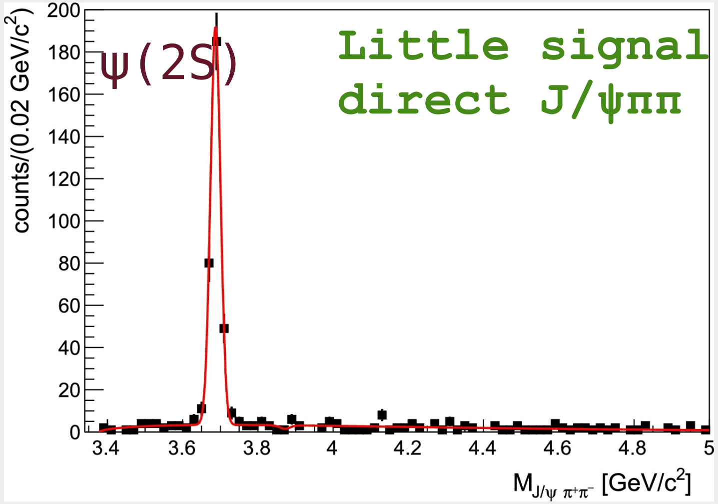
Quasi-real photoproduction: COMPASS

Such production experiments have been done for exotics with mixed results

Relatively low integrated luminosity

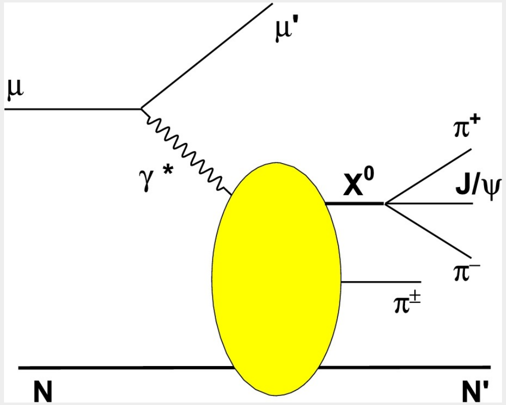
Physics Letters B
Volume 783, 10 August 2018, Pages 334-340

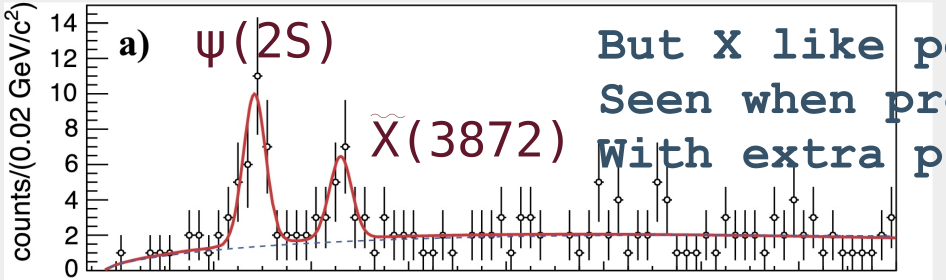
Search for muoproduction of $X(3872)$ at COMPASS and indication of a new state $\widetilde{X}(3872)$



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

Similar production mechanism





But X like peak
Seen when produced
With extra pion

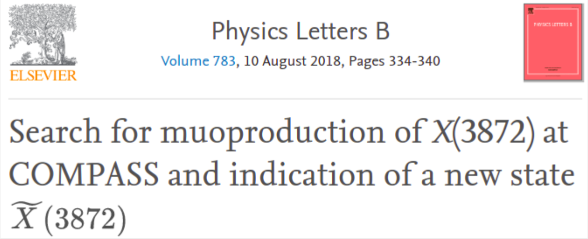
???????

Suggest a 1+- state instead of 1++ …

Quasi-real photoproduction: COMPASS

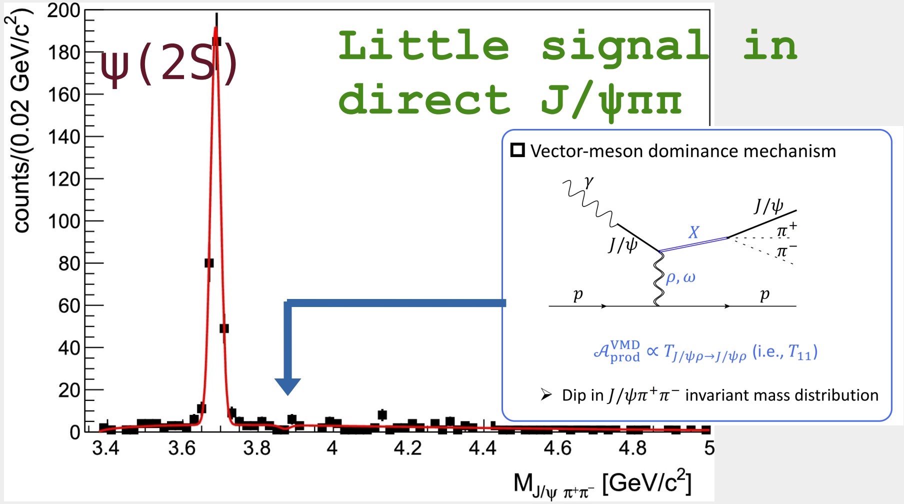
Such production experiments have been done for exotics with mixed results

Relatively low integrated luminosity

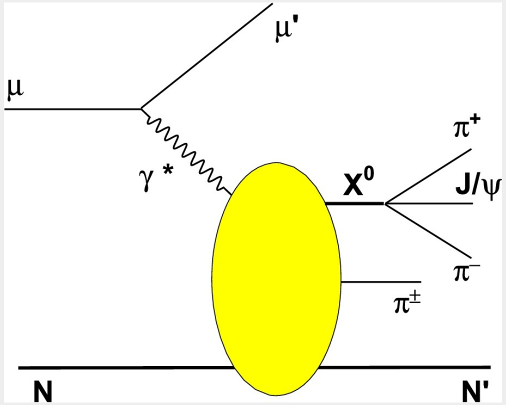

Physics Letters B
Volume 783, 10 August 2018, Pages 334-340

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

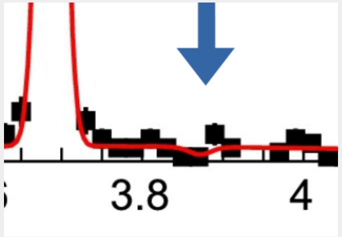
Little signal in direct J/ψππ



Similar production mechanism



See Feng-Kun Guo Moday 9.30am :Exotic heavy quarkonium structure and production from a hadronic perspective



X Photoproduction at EIC

XYZ **spectroscopy at electron-hadron facilities: Exclusive processes**

M. Albaladejo[1,*], A. N. Hiller Blin[1,†], A. Pilloni[2,3,4,‡], D. Winney[5,6,§], C. Fernández-Ramírez[7], V. Mathieu[8], and A. Szczepaniak[1,5,6] (Joint Physics Analysis Center)

Show more

Phys. Rev. D **102**, 114010 – **Published 7 December, 2020**

DOI: https://doi.org/10.1103/PhysRevD.102.114010

From COMPASS W=13.7 GeV

$\tilde{X}(3872)$ cross section

X(3872) upper limit

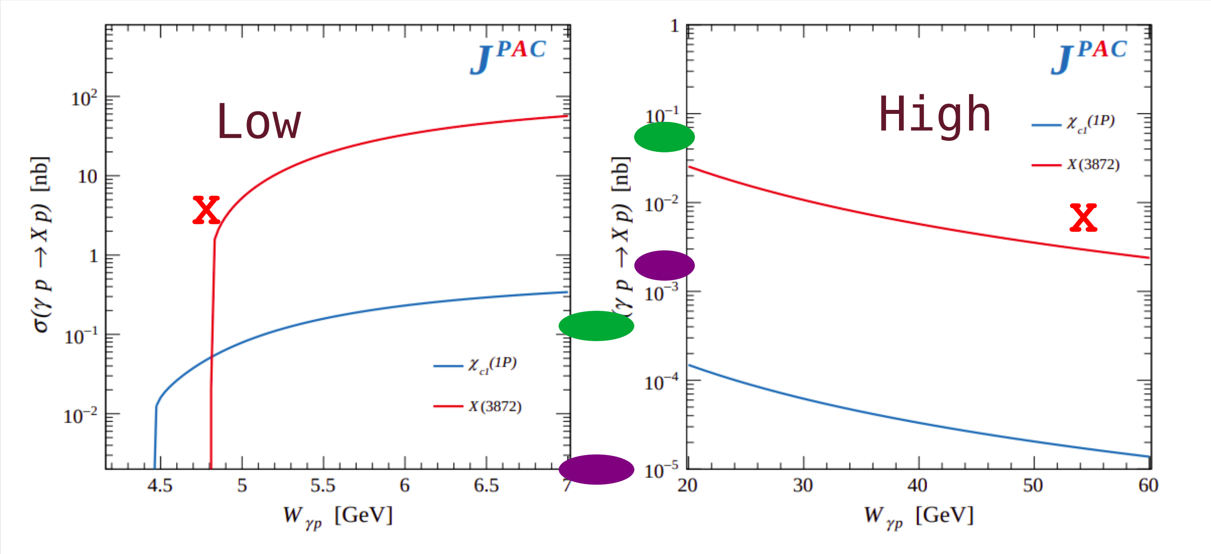
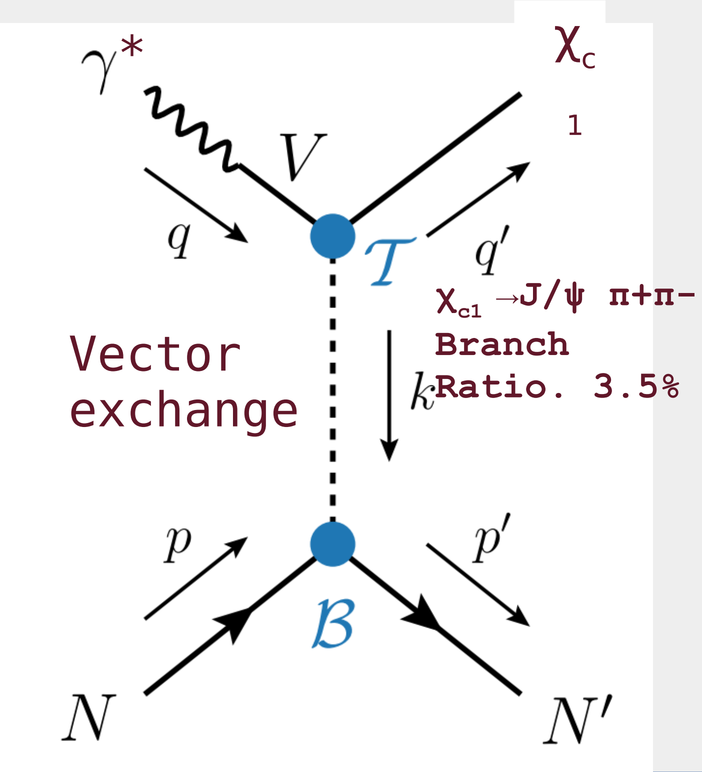


FIG. 3. Integrated cross sections for the axial $\chi_{c1}(1P)$ and $X(3872)$. Left panel: predictions for fixed-spin exchange, valid at low energies. Right panel: predictions for Regge exchange, valid at high energies.

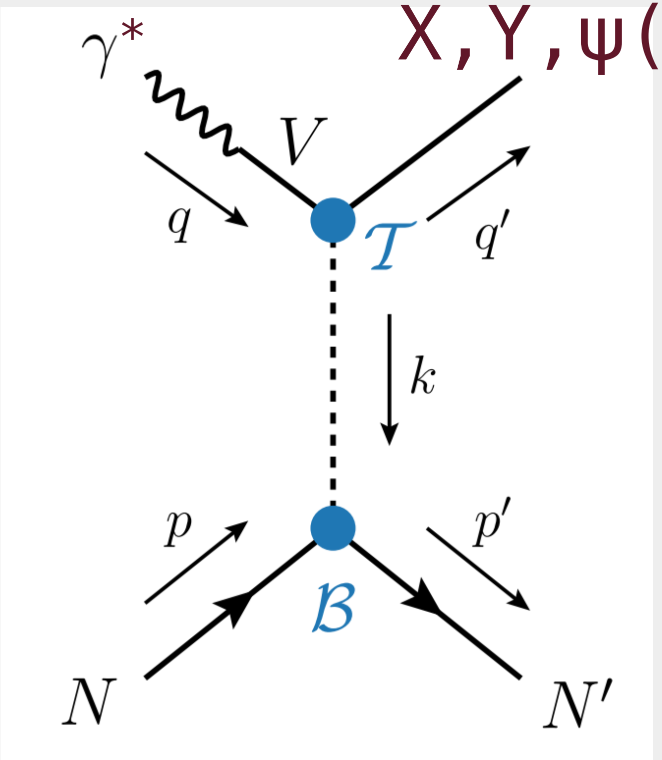


Exotics with EIC : ECCE

ePIC design/simulation/reconstruction in progress.

Can consider previous studies instead

X,Y,ψ(2s)



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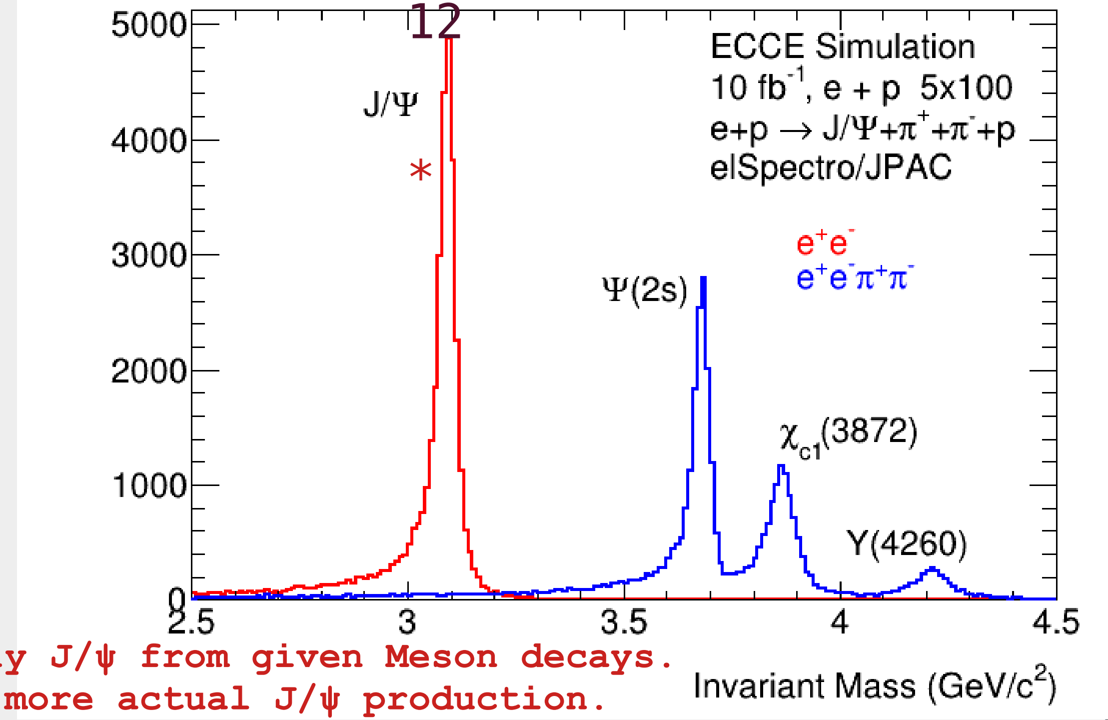


* only J/ψ from given Meson decays.
Many more actual J/ψ production.

* COMPASS measured 314 ψ(2s)

ePIC Integrated Luminosity for early science

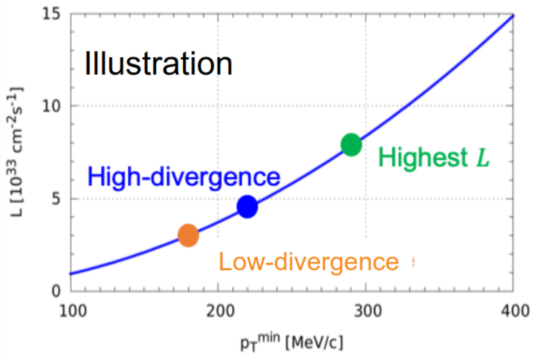
ep Luminosity for Phase-1

High Divergence	Lumi per Fill (5 h)	Lumi per Year
5 GeV e x 250 GeV p	9.26 pb^{-1}	6.48 fb^{-1}
10 GeV e x 250 GeV p	13.12 pb^{-1}	9.18 fb^{-1}
5 GeV e x 130 GeV p	6.3 pb^{-1}	4.36 fb-1
10 GeV e x 130 GeV p	7.6 pb^{-1}	5.33 fb^{-1}

Low Divergence	Lumi per Fill (5 h)	Lumi per Year
5 GeV e x 250 GeV p	6.81 pb^{-1}	4.78 fb^{-1}
10 GeV e x 250 GeV p	8.8 pb^{-1}	6.19 fb^{-1}
5 GeV e x 130 GeV p	5.8 pb^{-1}	4.1 fb^{-1}
10 GeV e x 130 GeV p	7.1 pb^{-1}	4.95 fb^{-1}

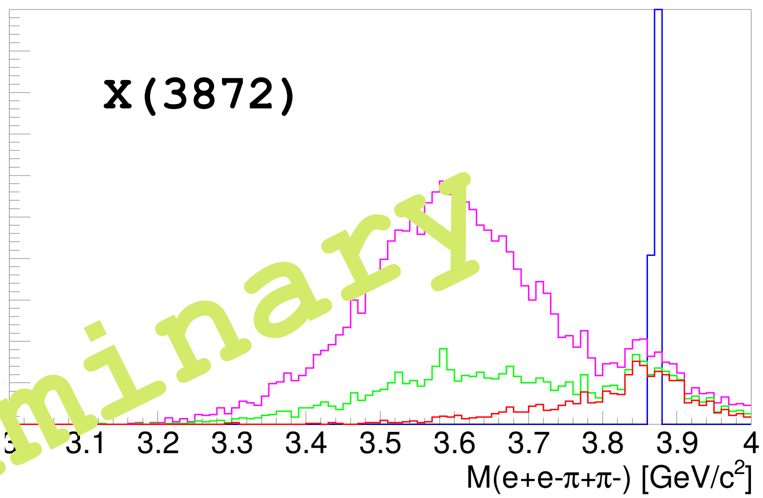
Compare to HERA integrated luminosity 1992 – 2007: 0.6 fb^{-1}

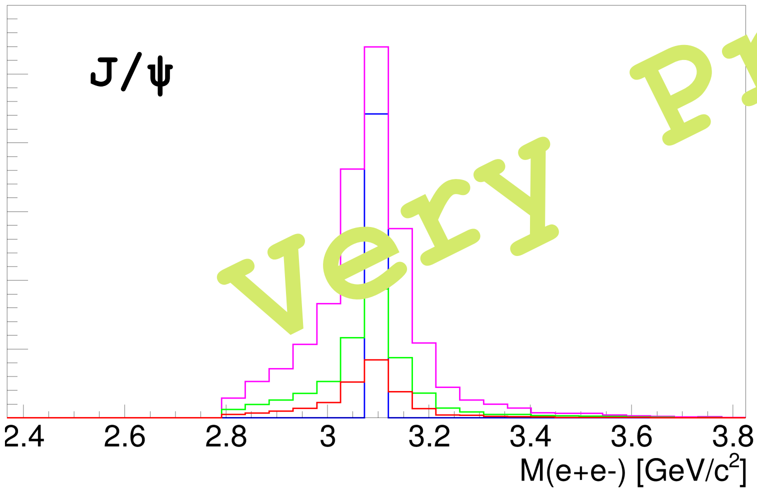
Remember:
high divergence: higher lumi, but reduced acceptance for low forward particle p_T^{min}
low divergence: lower lumi, but increased acceptance for low forward particle p_T^{min}
→ important for exclusive processes

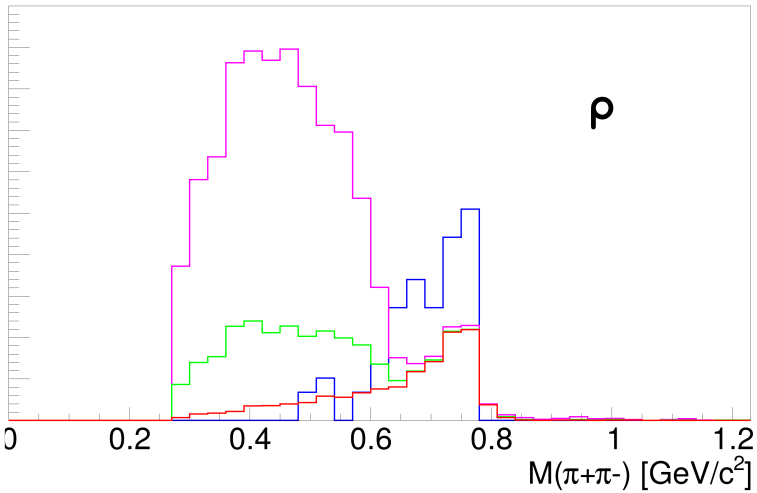


ePIC Simulations : X(3872)

X→ J/ψ ρ 10x100 2hour @ 6.11×10^{33} cm^2s^{-1}
Integrated Luminosity = 0.04 fb^{-1}
Combined Branch ratio = 0.0021
Generated events = 265
Reconstructed inclusive e+e-π+π- = 1115
Includes background
Reconstructed e+e-π+π- + veto γs = 375
Reconstructed e+e-π+π- + true = 157







Very Preliminary

ePIC Simulations : X(3872)

X→ D$\bar{D}\pi^0$ 10x100 2hour @ 6.11x10^{33} cm^{2}s^{-1}

Integrated Luminosity = 0.04 fb^{-1}

Combined Branch ratio = 0.0024

Generated

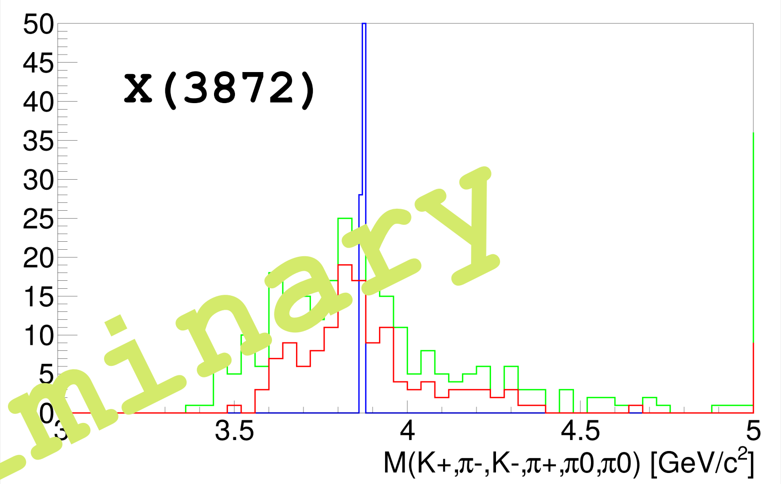
D(K-π+π0)$\bar{D}$(K+π-)π^0 events = 550

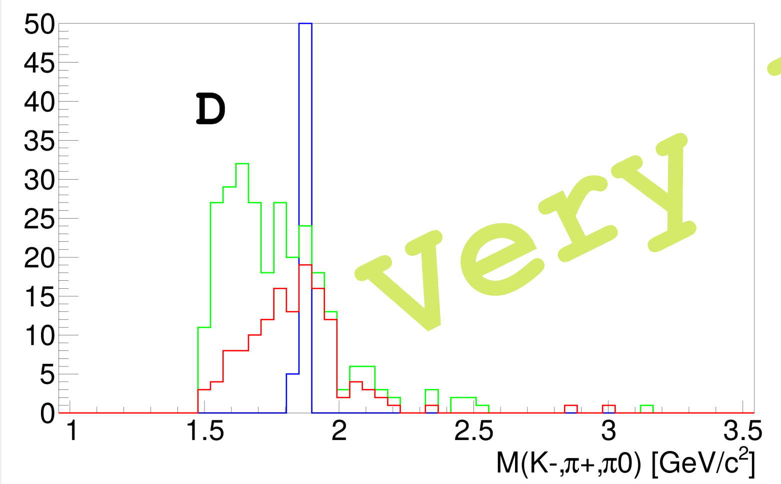
All Reconstructed (includes combi BG)

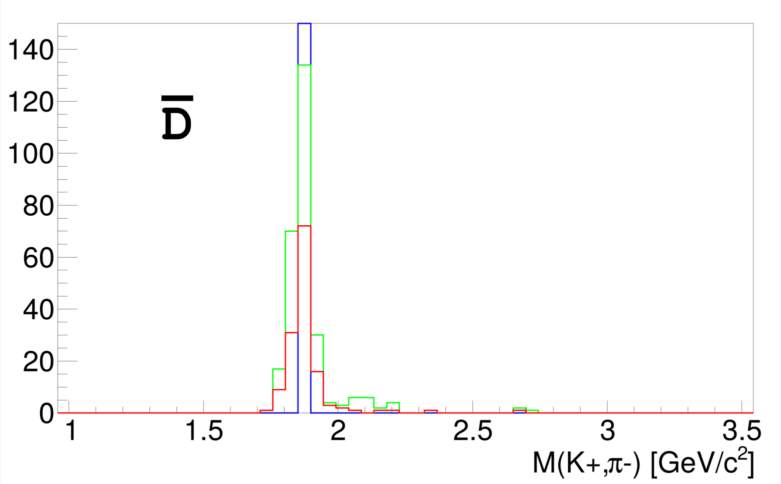
D(K-π+π0)$\bar{D}$(K+π-)π^0 events = 290

True Reconstructed

D(K-π+π0)$\bar{D}$(K+π-)π^0 events = 140







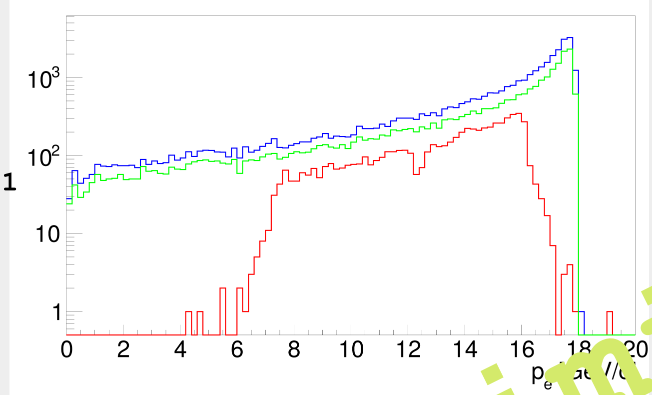
Very Preliminary

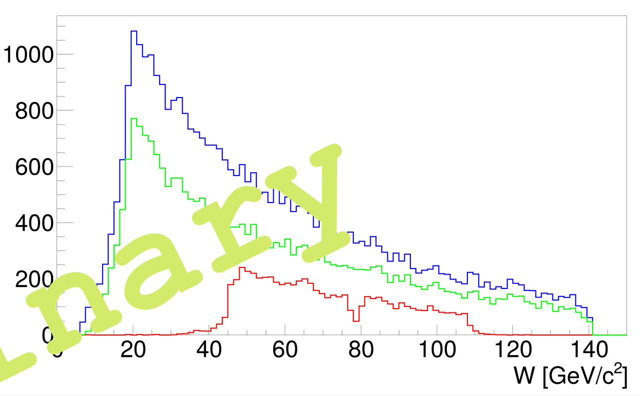
+ same again for other π0 combi D

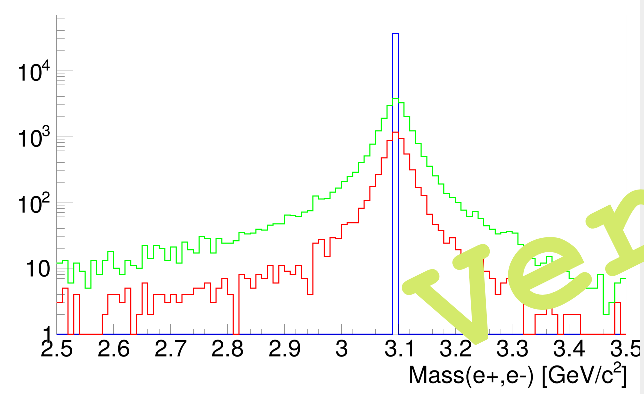
ePIC Simulations : Y(4230)

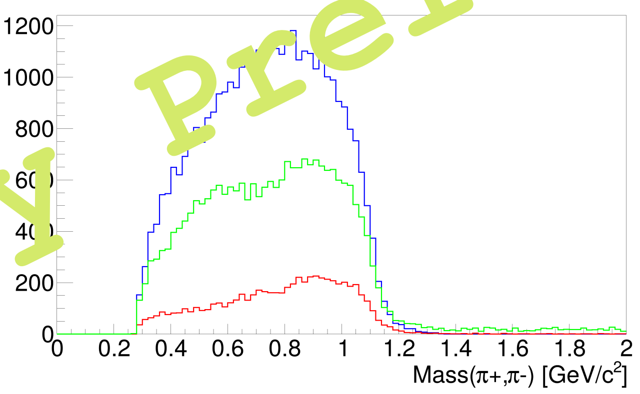
Y → J/ψ π+π-
Expected 10days 18x275
Luminosity 6.1x10^{33}cm^{2}s^{-1}
Int. Luminosity =5.3 fb^{-1}

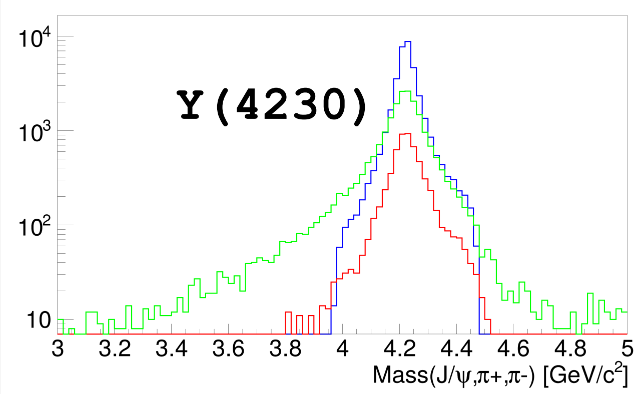
~18,000 e+e-π+π- decays
~12,000 e+e-π+π- recon
~3,000 recon + lowQ2 e-









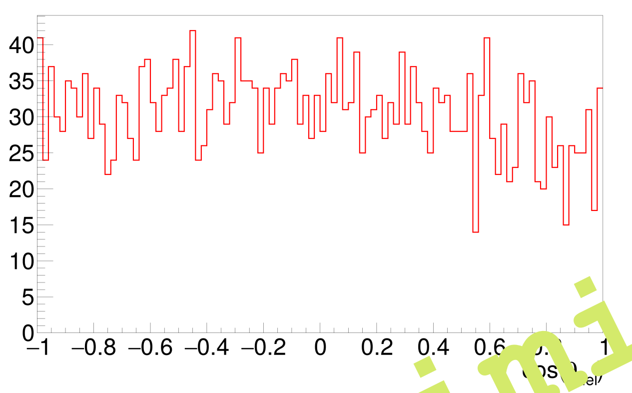


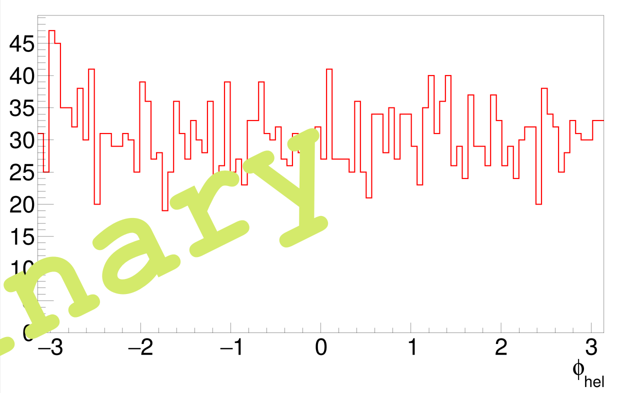
Very Preliminary

ePIC Simulations : Y(4230)

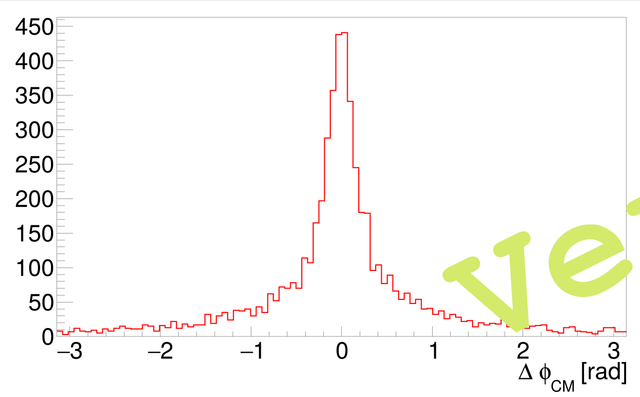
Physics with LowQ2

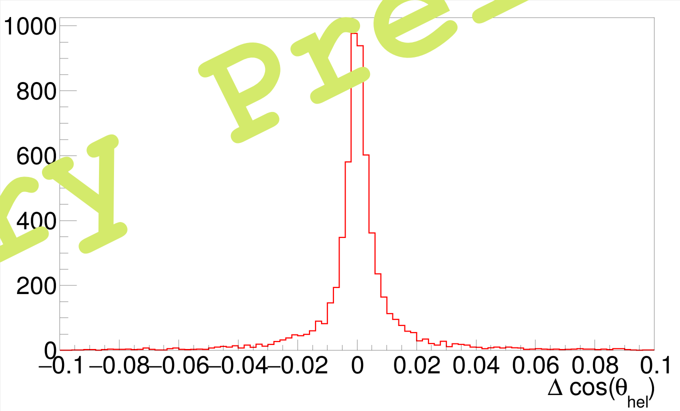
Production and decay angles
- required for PWA

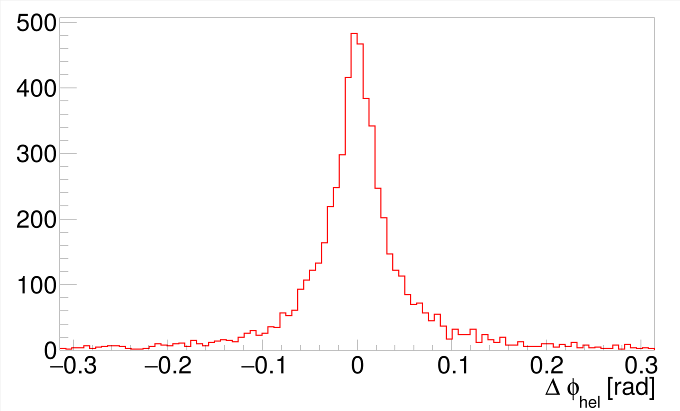




Very Preliminary







Semi-Inclusive Z production @EIC

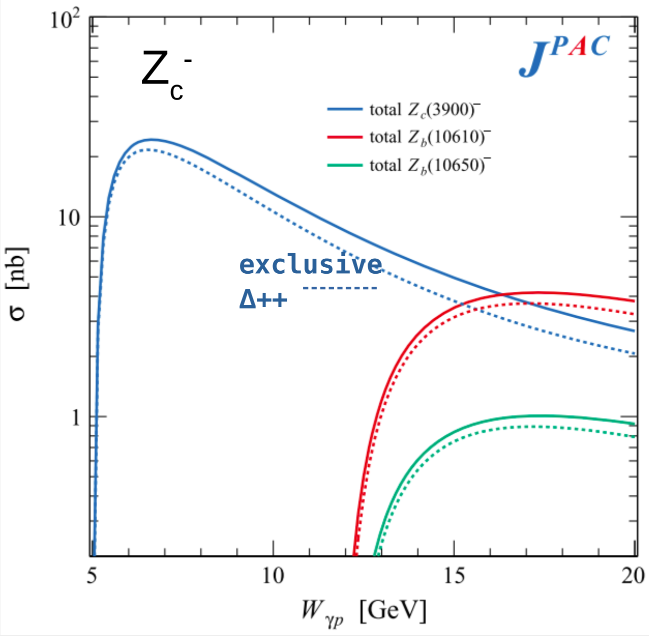
XYZ spectroscopy at electron-hadron facilities. II. Semi-inclusive processes with pion exchange

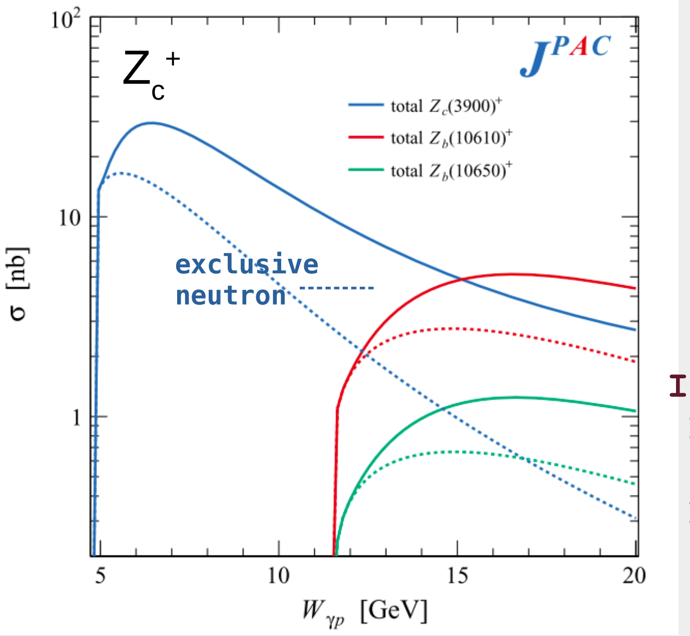
D. Winney, A. Pilloni, V. Mathieu, A. N. Hiller Blin, M. Albaladejo, W. A. Smith, and A. Szczepaniak (Joint Physics Analysis Center)

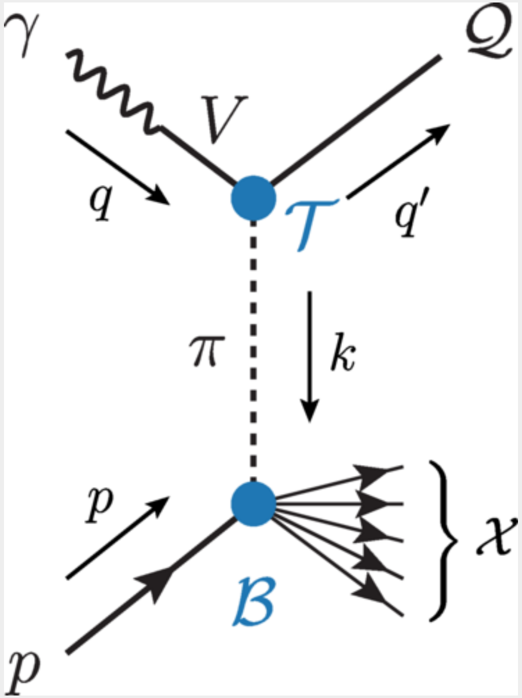
Phys. Rev. D **106**, 094009 – Published 7 November 2022

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

Bottom vertex => SAID pion scattering







$= Z_c$

$= p\pi^-$

Inclusive higher at high W =>

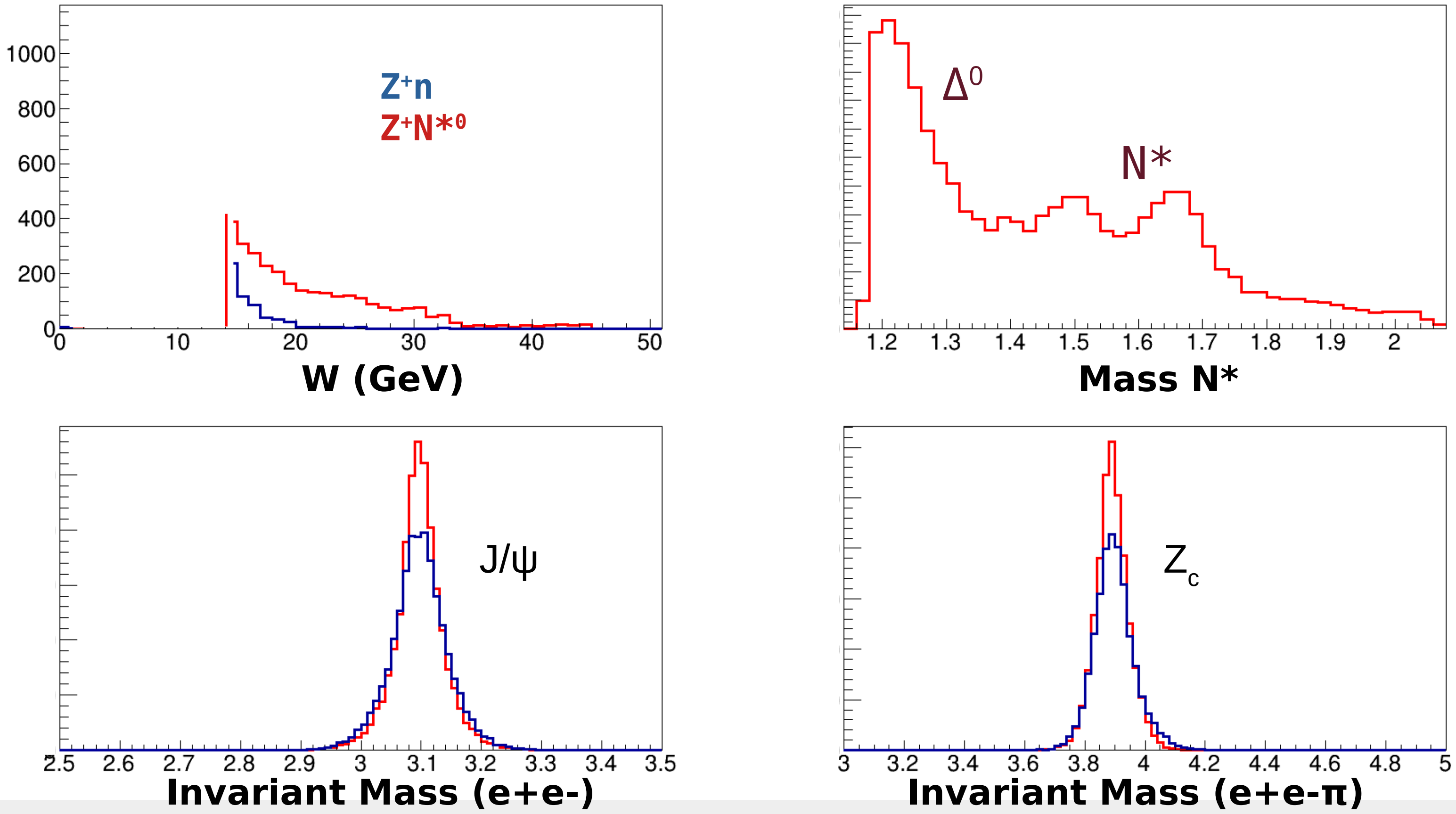
Better meson detection

- 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)

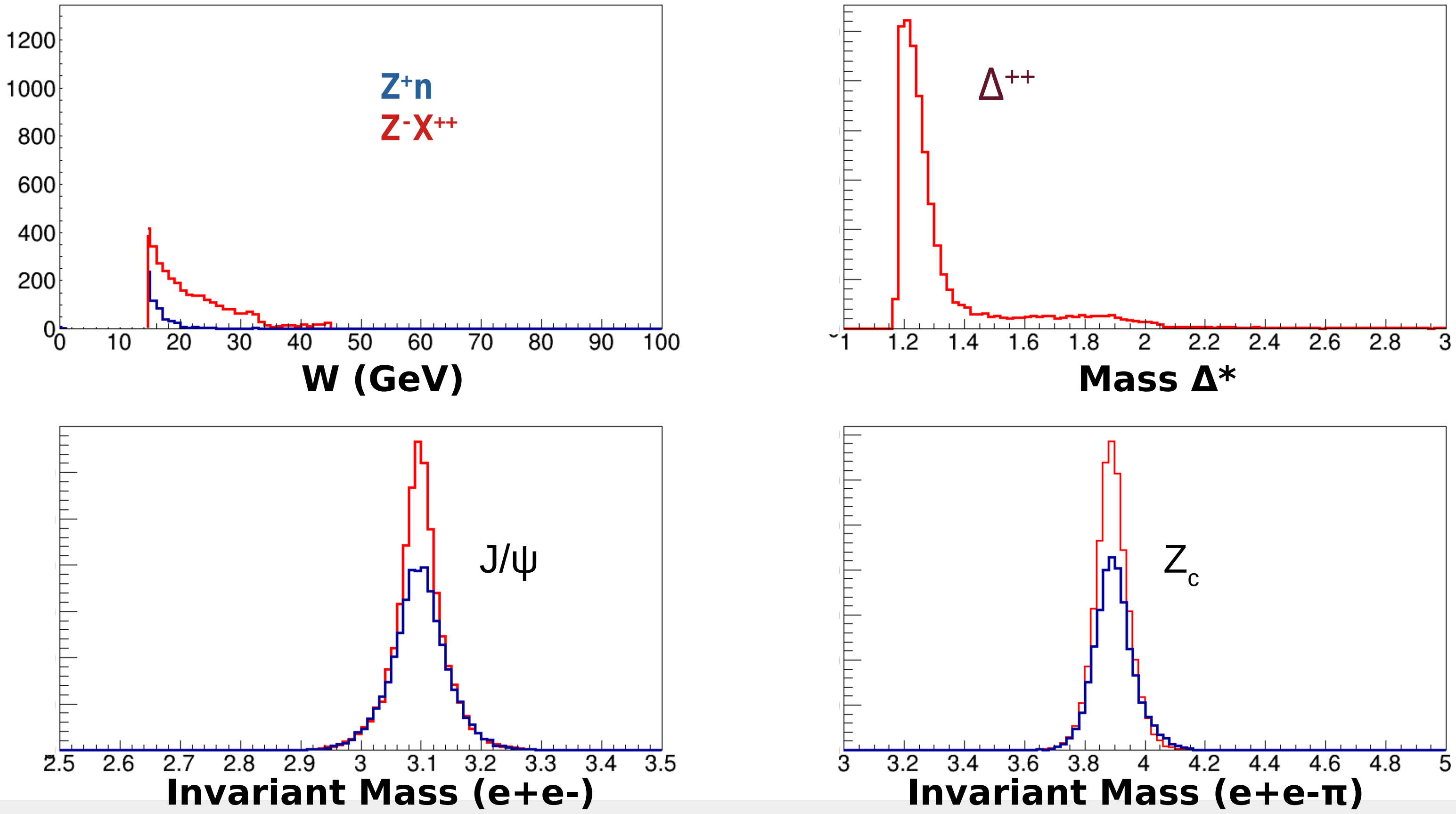
Semi-inc σ 30% lower

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^{++}

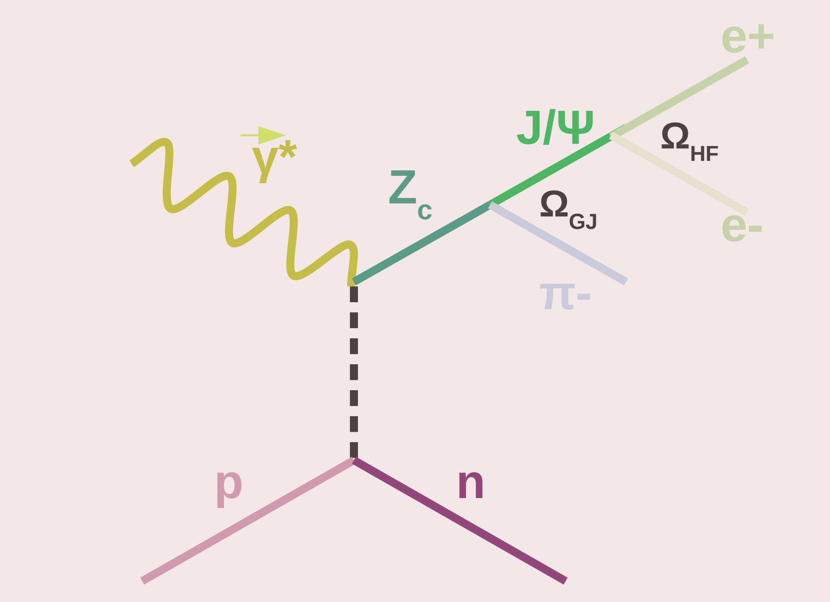
Overall Potential to tag O(1000) inclusive produced Zc

Production Amplitudes

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

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

$$\rho^0_{rr',mm'} = \sum_k T^{k,\eta}_{r,m}T^{k,\eta}_{r',m'} + T^{k,\eta'}_{r,m}T^{k,\eta'}_{r',m'},$$
$$\rho^1_{rr',mm'} = \sum_k T^{k,\eta'}_{r,m}T^{k,\eta}_{r',m'} + T^{k,\eta}_{r,m}T^{k,\eta'}_{r',m'},$$
$$\rho^2_{rr',mm'} = i\sum_k -T^{k,\eta'}_{r,m}T^{k,\eta}_{r',m'} + T^{k,\eta}_{r,m}T^{k,\eta'}_{r',m'},$$



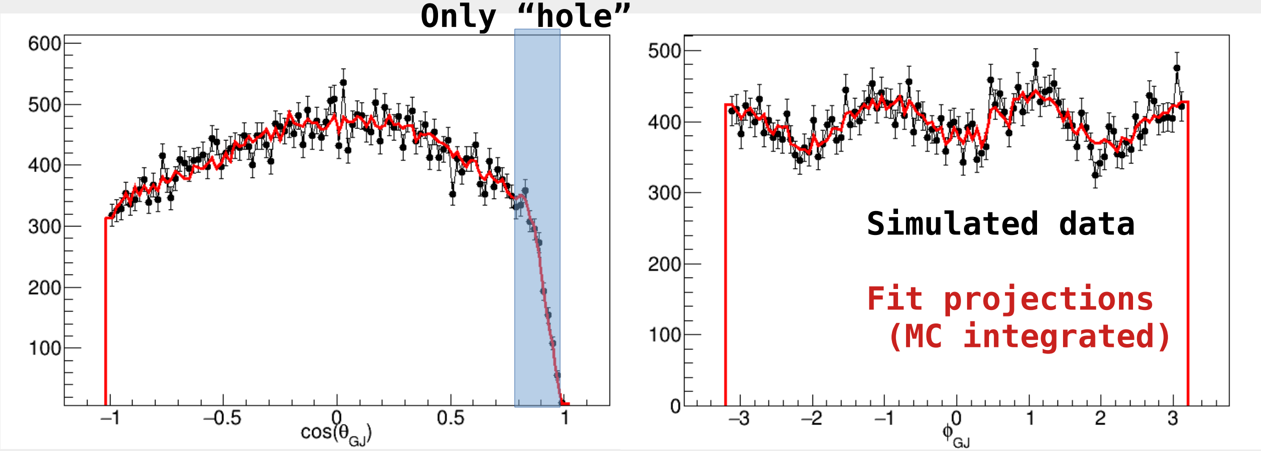
r = {j,l,s} = {j=1,l=(0,2),s=1}
And m = -1,0,1 for Z→ J/Ψ+π
k = spin of proton
η = photon helicity

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



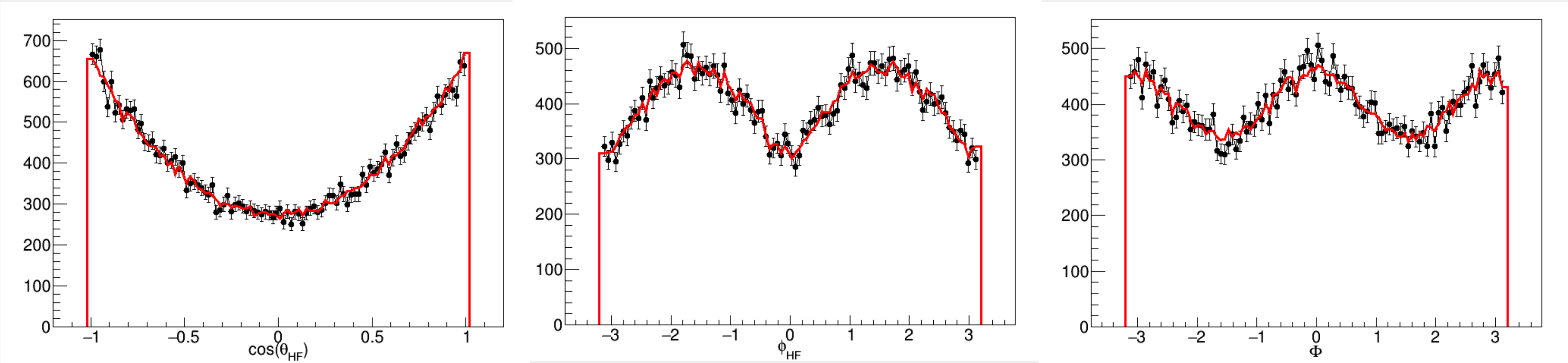
Generate data with given Transition amplitudes.

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

With the EIC we could produce 1000s exotic mesons per day and reconstruct a large fraction of these

With LowQ2 tagger for intermediate W events we could provide exclusivity constraints and perform partial wave analysis with well reconstructed decay angles

But cross section and branching ratios are small. Backgrounds will be large. Detailed studies now need done.

Low Q2 tagger likely to miss most exclusive X and Z production, but well suited for Y (pomeron exchange) production

To aid with this, currently developing inclusive event generator and analysis framework (see interactive session)

Summary

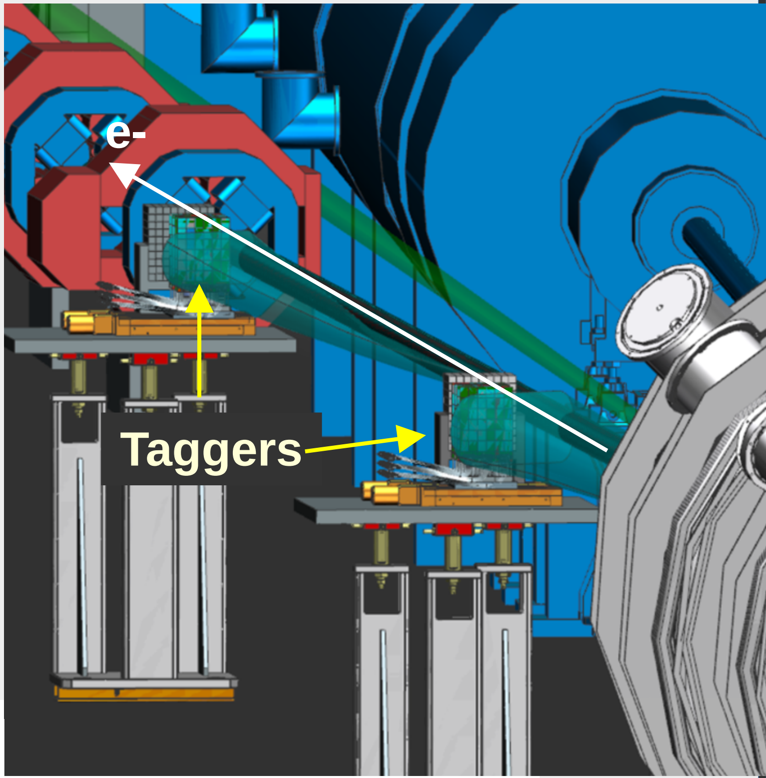
EIC Low Q^2 Tagger – Glasgow University

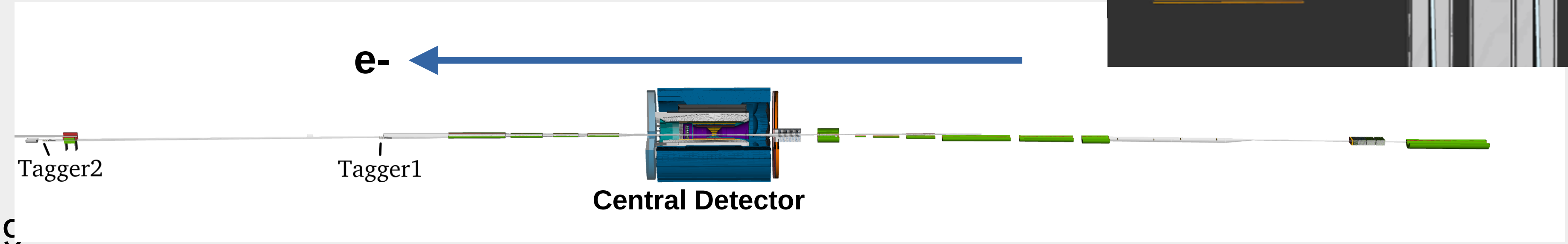
The ePIC Low-Q2 Tagger extends the reach of the central detector down to effectively Q^2=0.

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.

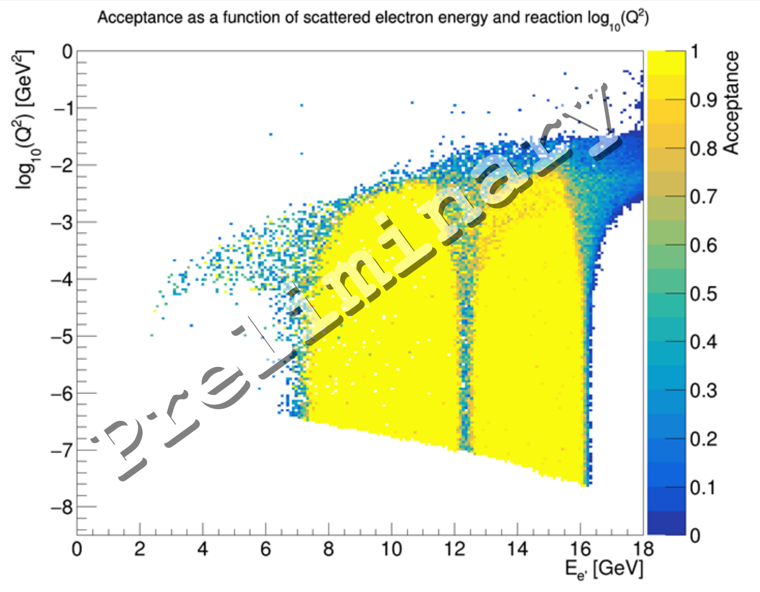
Trackers consisting of 4 layers of Timepix4 pixel detectors (50µm pitch).





Idealistic Proposed Tagger

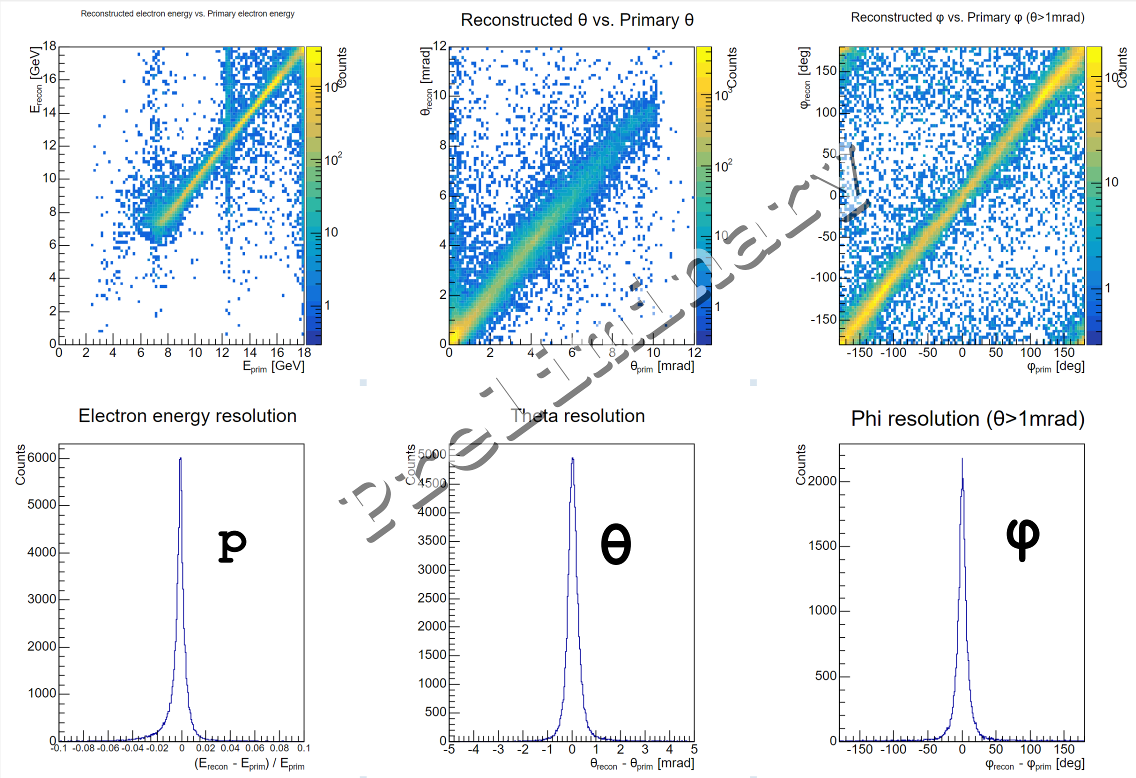
Acceptance



Low e- Energy acceptance limit by magnets

High e- Energy acceptance limit by beam

Resolutions



*** Final design/performance dependent on beam pipe/vaccuum/integration**

Z_c Photoproduction

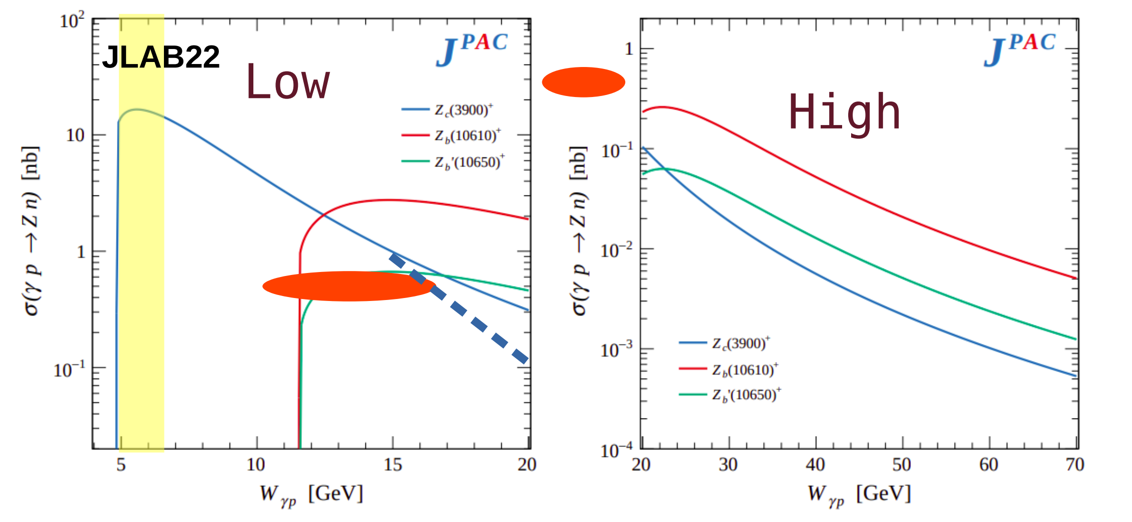
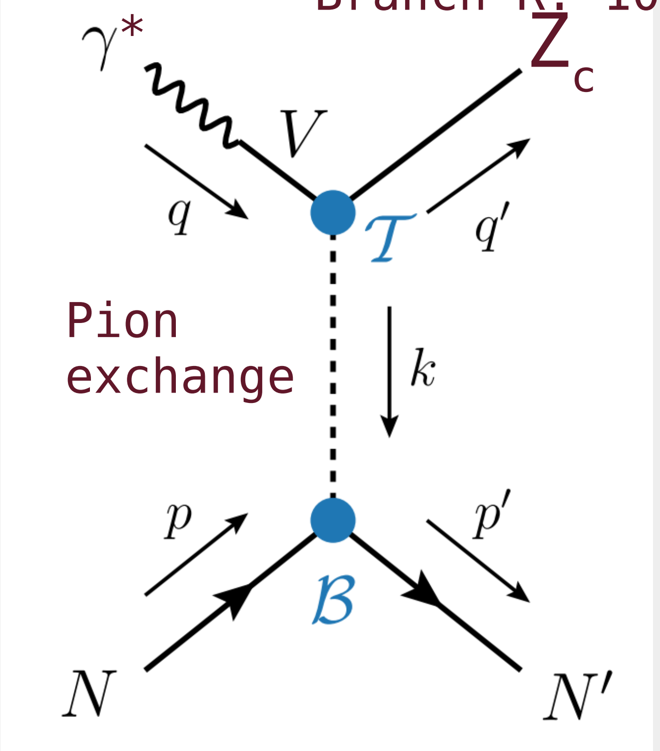


FIG. 2. Integrated cross sections for the three Z states considered. Left panel: predictions for fixed-spin exchange, which we expect to be valid up to approximately 10 GeV above each threshold. Right panel: predictions for Regge exchange, valid at high energies.

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



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