Spectroscopy with EIC
- XYZ production

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Spectroscopy Working group for EIC

Collaboration of different experimentalists
- GlueX, BES, CLAS12, …

And theorists
- Joint Physics Analysis Centre (JPAC)

Biweekly meetings (Wednesday 10am EDT) for ~ 1 year

Primary focus on XYZ spectroscopy programme
- also others

Plan to simulate with all EIC detector proposals

Exclusive Photoproduction (Quasi-real)

Observation of XYZ states in photoproduction
- independent confirmation

Different production mechanism, different kinematics

Measurement of polarisation observables and photocouplings
- insights into production mechanisms and internal structure

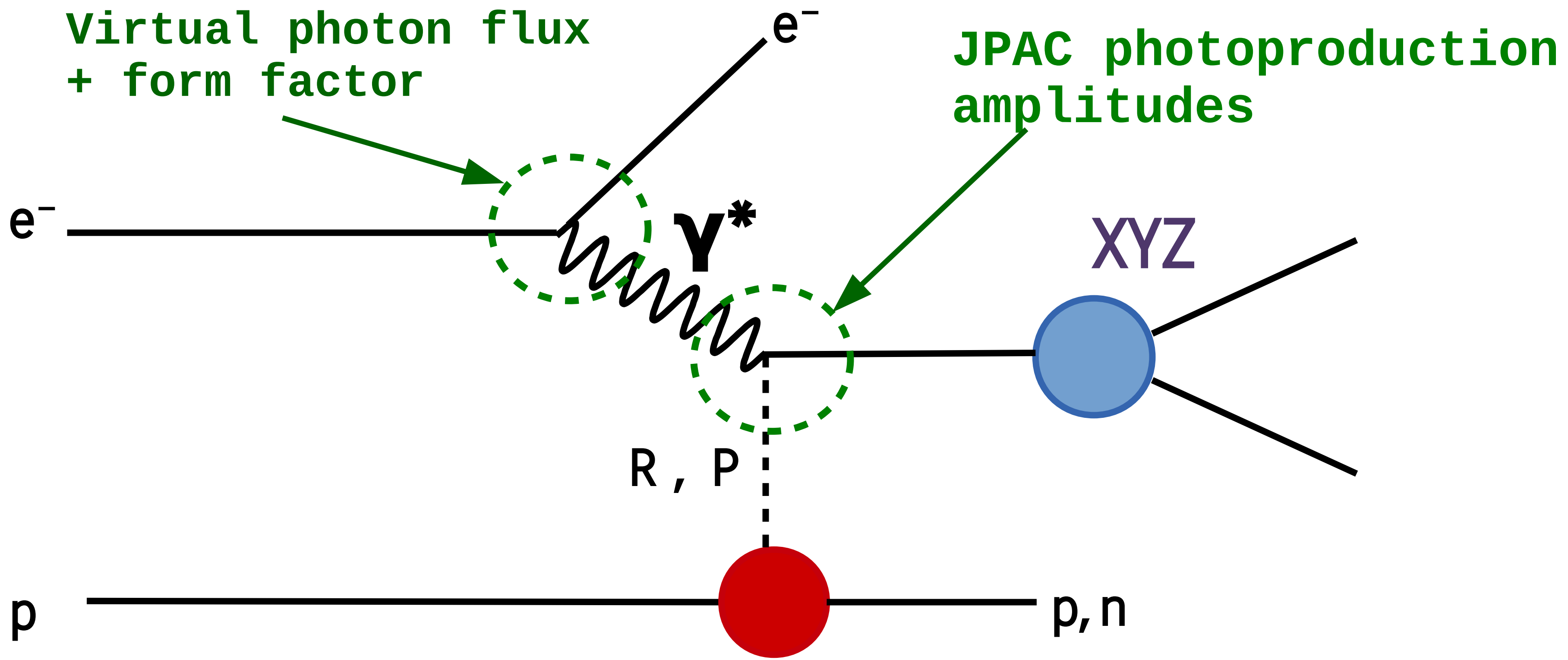
XYZ spectroscopy at electron-hadron facilities: Exclusive processes

M. Albaladejo, A. N. Hiller Blin, A. Pilloni, D. Winney, C. Fernández-Ramírez, V. Mathieu, and A. Szczepaniak
(Joint Physics Analysis Center)
Phys. Rev. D **102**, 114010 – Published 7 December 2020

- qualitative behaviour and order of magnitude estimates

Event Generator (Pictorial)

Factorise 2 photon vertices



ElSpectro - Event Generator (Formal)

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

→ Integrate for event rate

$$Q^2=2E\,M\,x\,y$$

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

$$W^2=M^2+2E\,M\,y-Q^2$$

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

$$\frac{d^2\sigma_{\gamma*+p}}{d\phi\,dt}=\frac{d\sigma^T(Q^2,s)}{d\phi\,dt}+(\epsilon+\delta)\frac{d\sigma^L(Q^2,s)}{d\phi\,dt}$$

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

$$\frac{d^2\sigma^T(Q^2,s)}{d\phi\,dt}=\frac{d^2\sigma_{\gamma+p\to V+p}}{d\phi\,dt}F(Q^2)$$

$$\frac{d^2\sigma^L(Q^2,s)}{d\phi\,dt}=0$$

$$\frac{d^2\sigma_{\gamma+p\to V+p}}{d\phi\,dt}=\frac{1}{128\pi^2s}\frac{1}{|\mathbf{p}_{\gamma*cm}|^2}|M(s,t)|^2$$

→ $|M(s,t)|^2$ JPAC Photoproduction Amplitudes

elSpectro Generator

General exclusive electron scattering final state generator
Can apply 2-body photoproduction cross sections
Includes class specific for Jpacphoto cross section
Integrates cross section to get event rate estimates
Write events in LUND / HEPMC3 formats

Recent updates

- -Crossing angle
- -Quasi free production on deuteron (e.g. for Z-)
- -Vector and Tensor spin formalisms
  - \- also use JPACPhoto SDME calculations

JPAC Photo code

https://github.com/dwinney/jpacPhoto   object orientated C++ design

```
// ---------------------------------------------------------------------------
// AMPLITUDES
// ---------------------------------------------------------------------------

double g_NN = sqrt(4. * M_PI * 13.81); // Nucleon coupling same for all
double LamPi = .9;  // 900 MeV cutoff for formfactor
double bPi = 1. / (LamPi * LamPi);

// Zc(3900)
auto kZc = reaction_kinematics{M_ZC3900};
kZc.set_JP(1, 1);

double gc_Psi = 1.91; // psi coupling before VMD scaling
double gc_Gamma = E * F_JPSI * gc_Psi / M_JPSI;
std::vector<double> Zc_couplings = {gc_Gamma, g_NN};

// Pion trajectory
int signature = +1;
double alpha_prime = 0.7; // GeV^-2
double alpha_0 =  - alpha_prime * M2_PION;
auto alpha = linear_trajectory{signature, alpha_0, alpha_prime};

pseudoscalar_exchange* ampZc{nullptr};
// ---------------------------------------------------------------------------
// low => Fixed-spin amplitudes
// ---------------------------------------------------------------------------
if(ampPar=="low") ampZc = new pseudoscalar_exchange{&kZc, M_PION, "#it{Z_{c}} (3900)^{+}"};
ampZc->set_params(Zc_couplings);
ampZc->set_formfactor(true, bPi);
```

elSpectro Code

Steered via ROOT scripts

```
// ------------------------------------------------------------------------
// elSpectro
// ------------------------------------------------------------------------
//create a Z decaying to J/psi pi+

auto jpsi=particle(443,model(new PhaseSpaceDecay({},{11,-11})));

//Zc
double minMass = 3.5;
double maxMass = 4.4;
mass_distribution(9995,new DistTF1{TF1("hh",Form("TMath::BreitWigner(x,%lf,0.05)",M_ZC3900),minMass,maxMass)});
auto Z=particle(9995,model(new PhaseSpaceDecay{{jpsi},{211}}));
Z->SetPdgMass(M_ZC3900);

//create eic electroproduction of X + proton
auto pGammaStarDecay = JpacModelst{ampZc, {Z},{2112} }; //photo-nucleon system
auto photoprod = DecayModelQ2W{0,&pGammaStarDecay,new TwoBody_stu{0., 1.0, 2.5}};

//combine beam, target and reaction products
double angle=0.025;
auto production=eic( ebeamE, TMath::Pi()-angle,pbeamE, angle,&photoprod );
```

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```

Z(3900)

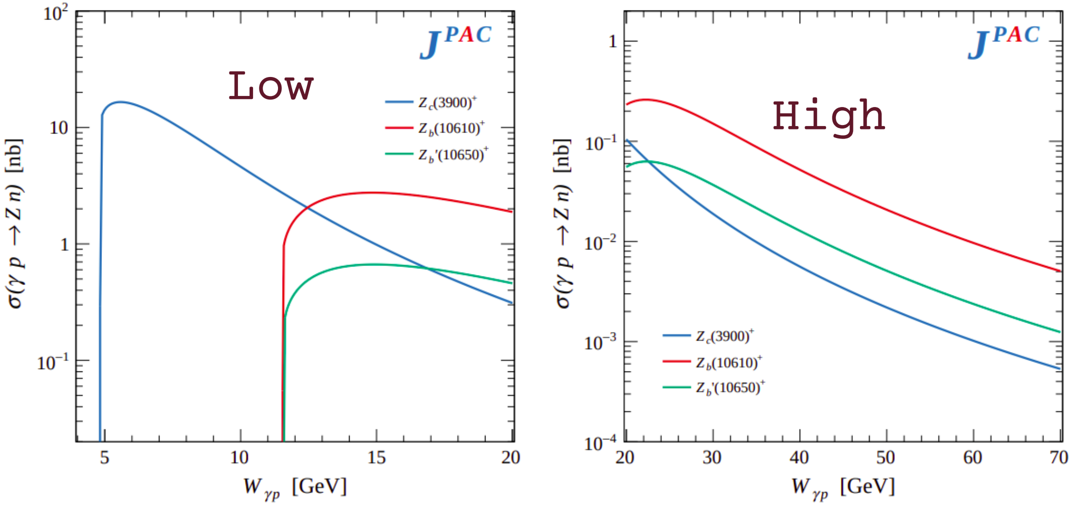
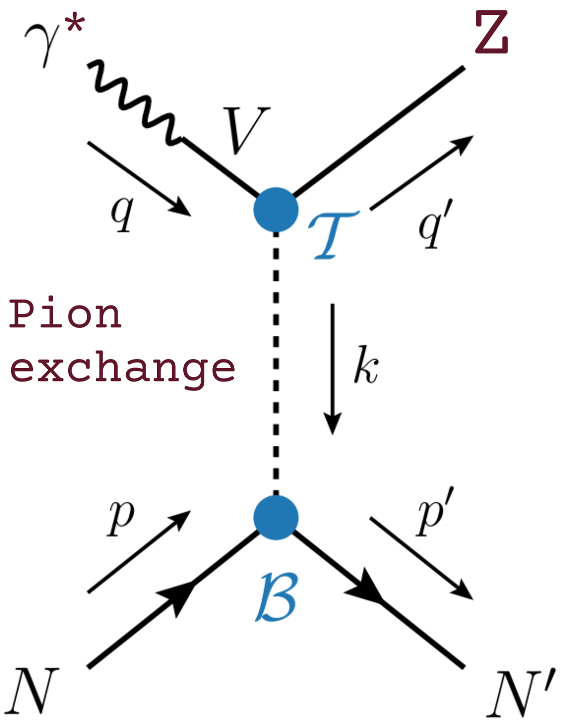
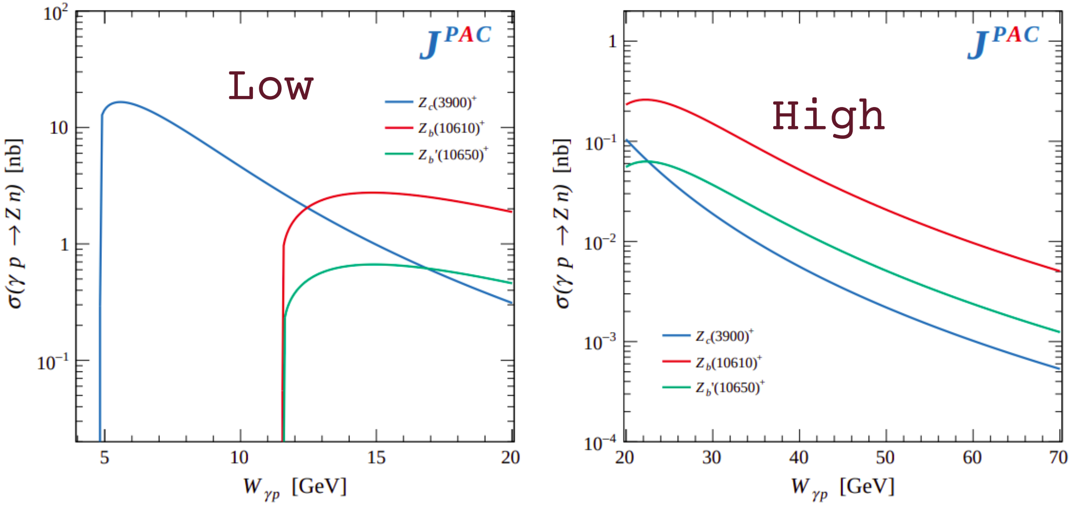


FIG. 2. Integrated cross sections for the three Z states considered. Left panel: predictions for fixed-spin exchange, which we expect to be valid up to approximately 10 GeV above each threshold. Right panel: predictions for Regge exchange, valid at high energies.



Larger at Low W,
Small at High W

Z(3900)



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$e^- + p \to e^{-'} + Z(3900) + n$
$Z \to J/\psi\, \pi^+$ (10%)
$J/\psi \to e^+e^-$ (6%)

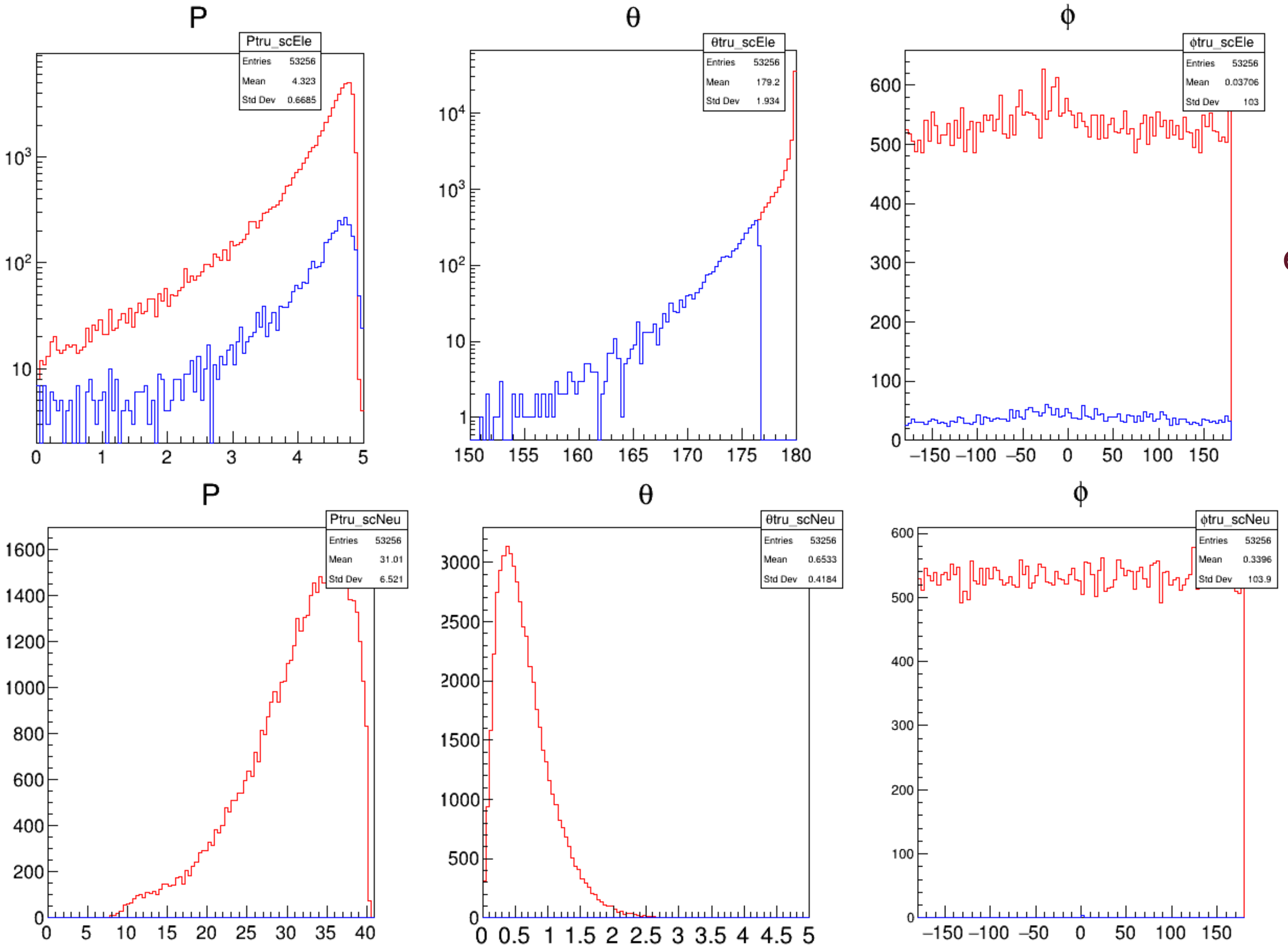
For 1 fb^{-1} ~11 days @ 10^{33}cm-2s-1

Use eic-smear with
MATRIXDETECTOR_0_2_B1_5T

Ngen → number generated
NZ → number detected
NZ e- → NZ with detected scattered electron

	Ngen low	NZ low	Nze- low	Ngenhigh	NZ high	NZe-high	Wmax
5-41	5.3k	4.8k	340	730	700	50	29
5-100	6.0k	4.0k	260	850	730	50	45
10-100	6.3k	4.3k	70	900	750	10	64
18-275	5.2k	2.2k	10	780	350	2	100

Z 5-41 low MATRIXDETECTOR_0_2_B1_5T

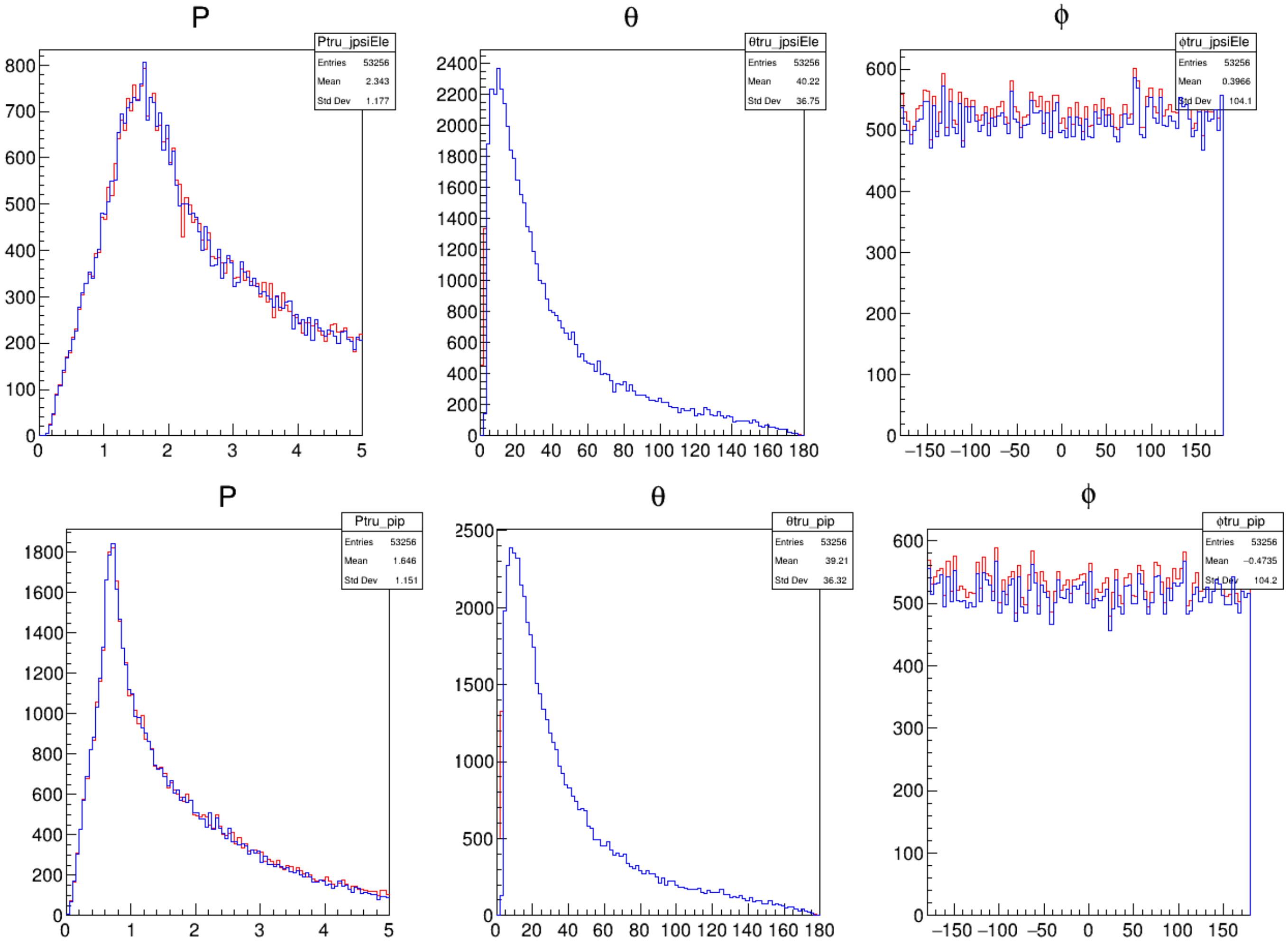


e-'

n

Generated
EIC-Smeared

Z 5-41 low MATRIXDETECTOR_0_2_B1_5T



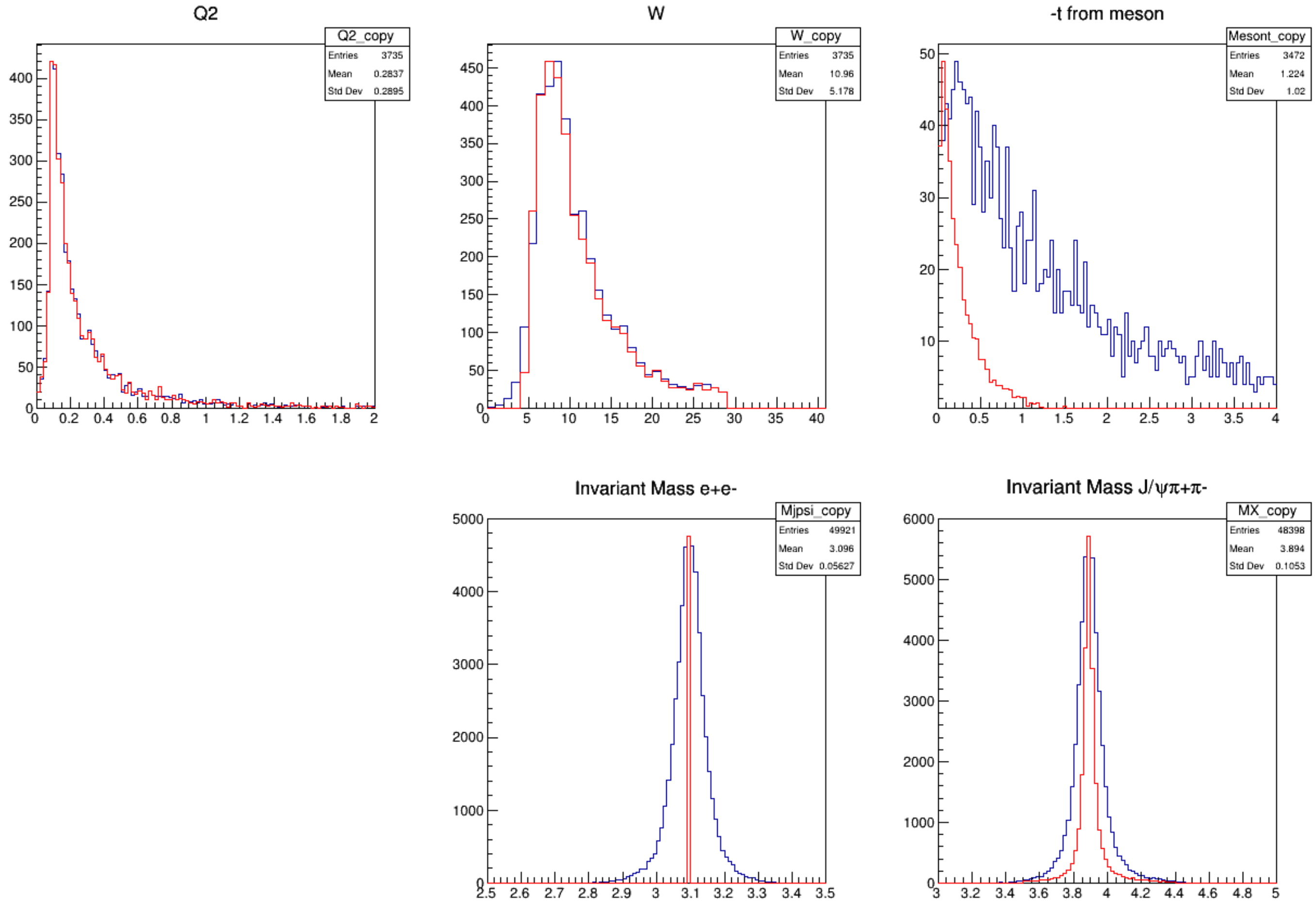
Generated

EIC-Smeared

π+

e- from J/ψ

Z 5-41 low MATRIXDETECTOR_0_2_B1_5T



Generated
EIC-Smeared

Normalised to
Same max value

Y(4260)

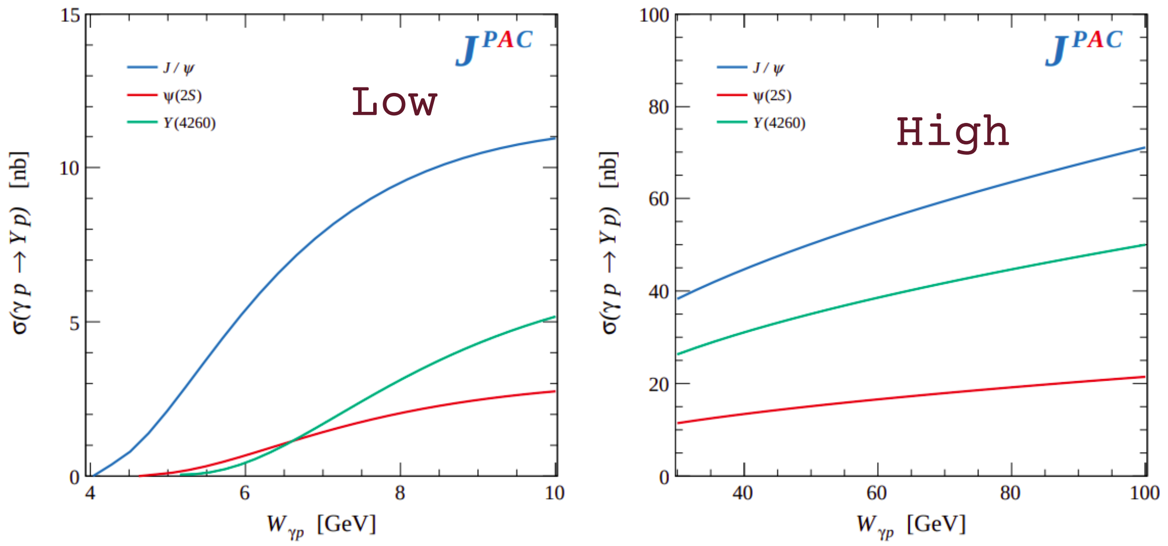
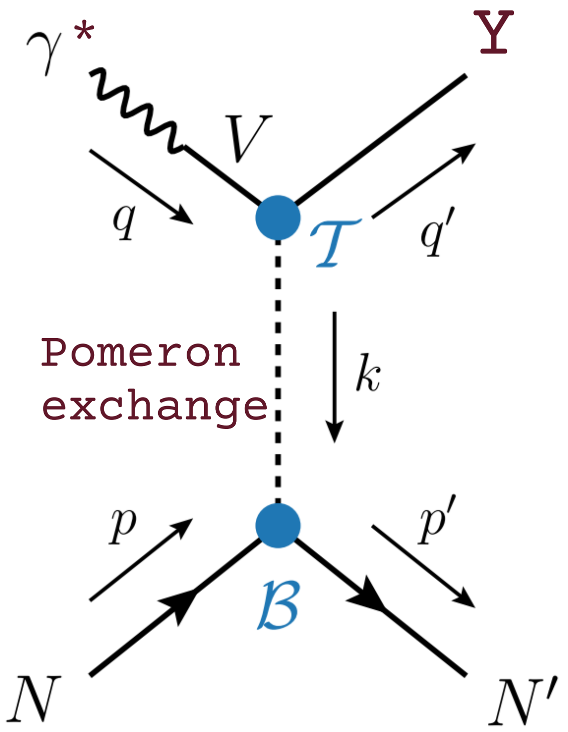


FIG. 7. Cross sections for $Y(4260)$ photoproduction compared to the J/ψ and $\psi(2S)$ at low (left) and high (right) energies.



Increases with W

X(3872)

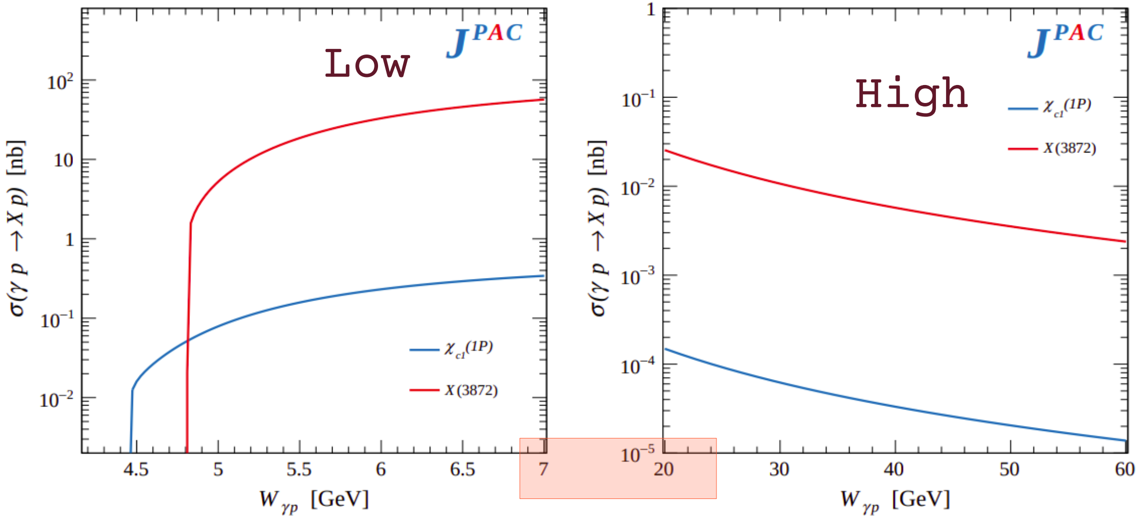
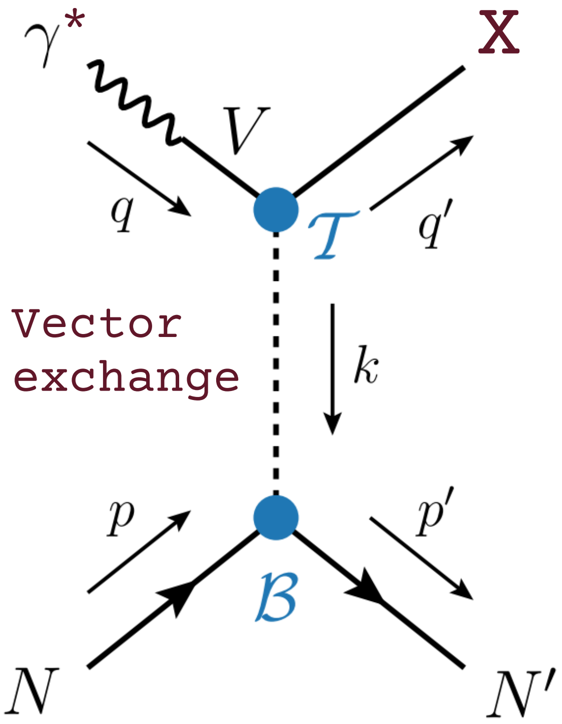


FIG. 3. Integrated cross sections for the axial $\chi_{c1}(1P)$ and $X(3872)$. Left panel: predictions for fixed-spin exchange, valid at low energies. Right panel: predictions for Regge exchange, valid at high energies.

Larger model uncertainty



Summary Table from IR2 Workshop

Take 1 month @ $10^{33}cm^{-2}s^{-1}$ → 1.5 fb^{-1}
6 months → 9 fb^{-1} i.e. scale previous numbers by 9

Take mean of "high" and "low" JPAC estimates

Take Luminosity(W) for low (estimates from plot) and high W optimisation

	L ($10^{33}cm^{-2}s^{-1}$)	N Z	N Z + e-	N Y	N Y + e-	N X *	N X +e- *
5-41	0.44 (1.2)	11k (30k)	770 (2k)	7.1k (19k)	1k (2.9k)	47k (129k)	6.5k (17k)
5-100	3.68 (10)	78k (213k)	5.1k (14k)	81k (220k)	11k (31k)	0.4M (1.1M)	57k (157k)
10-100	4.48 (12)	101k (272k)	1.6k (4.3k)	130k (350k)	8k (21k)	0.5M (1.6M)	26k (86k)
18-275	1.54	17k	83	45k	1k	194k	3.5k

* Numbers for X probably too high

Summary

Implemented JPAC photoproduction amplitudes for XYZ

Produced events for 5-41 , 5-100, 10-100, 18-275
beam momentum distributions

Used Eic-smear of variety of detector configurations including
Yellow Report Matrix_0_2_1_5T

Detection of XYZ decay products very good in all configurations

Lower e- beam momentum results in larger fraction of detected e'-
and better resolution in invariant masses

- Probably gives more measurable polarisation observables

Higher beam energies can give larger production yields

An IR2 low W optimised, 5-100 beam configuration looks promising for XYZ