JPAC studies for Exotic Spectroscopy at the EIC:

Development of photoproduction amplitude tools

● ● ●

Daniel Winney

HADRON @ Mexico City
26 March 2021

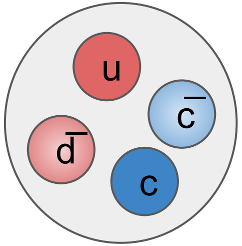
INDIANA UNIVERSITY
BLOOMINGTON

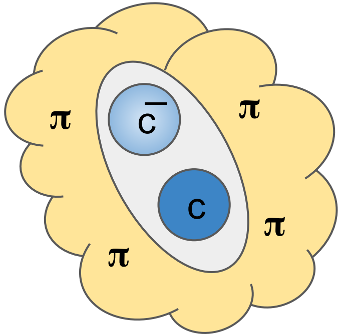
JPAC

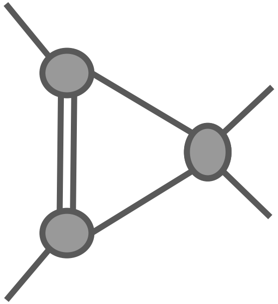
XYZ Mesons

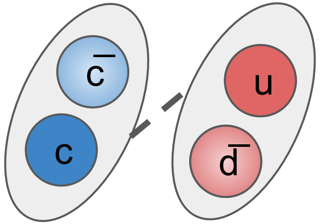
Plethora of quarkonium-like states observed since 2003 which do not fit into conventional $\bar{q}q$ mesons in QCD.

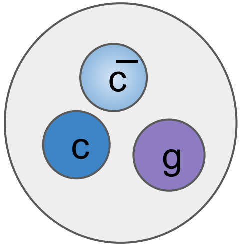
- **X(3872)** - large isospin violation
- **Y(4260)** - anomalous coupling to open charm channels
- **Z(3900)** - charged, charmonium-like state



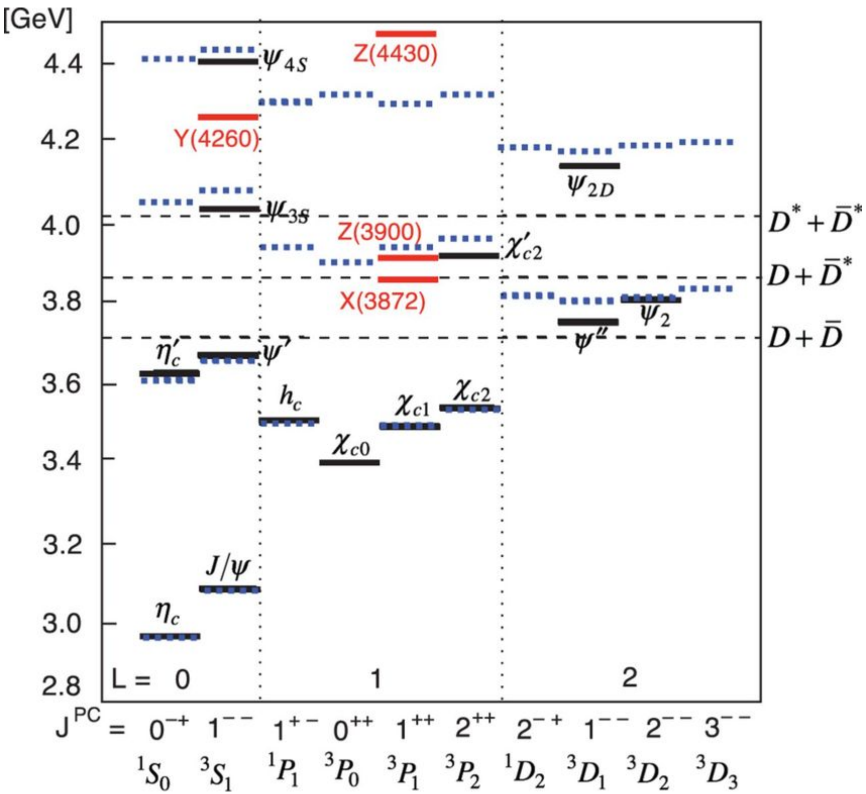








N. Brambilla et al. [Physics Reports 873 (2020) 1-154]



XYZ in Photoproduction

None of the XYZ’s have been observed in photon-induced reactions

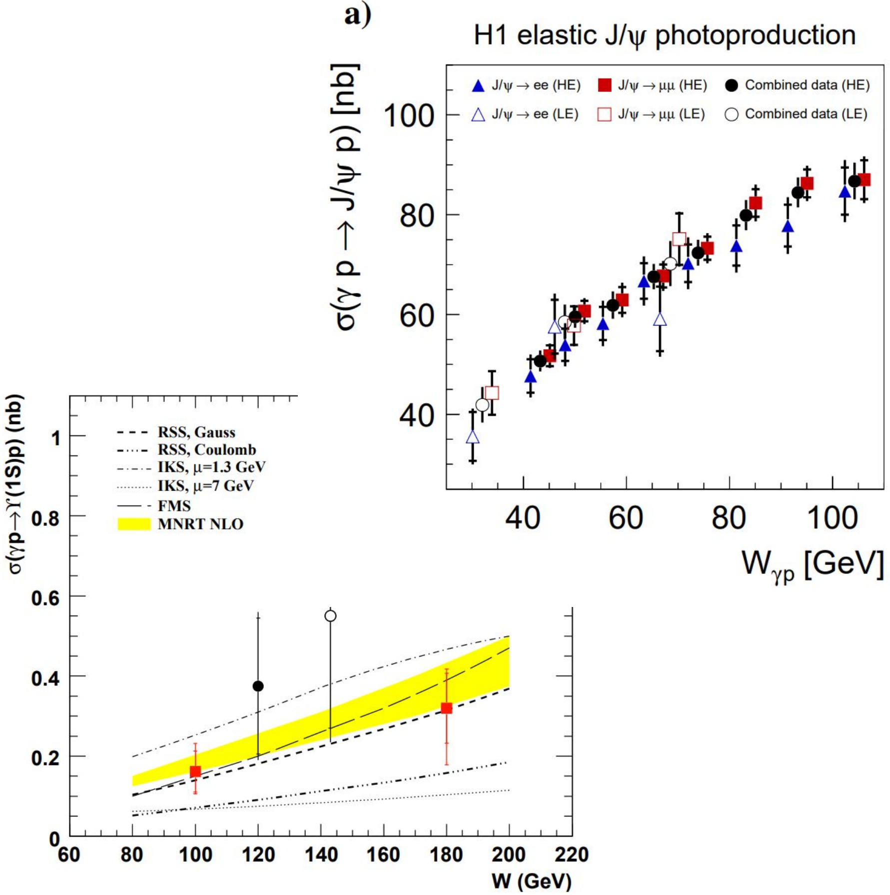
Current dedicated photoproduction facilities (e.g. GlueX@JLab) too low in energy reach.

Ideal laboratory for spectroscopy

- Constrained kinematics ⇒ precise determination of production mechanism
- **Direct production** ⇒ eliminates contribution from triangle rescattering and FSI
- Phenomenology well understood
- Heavy quarkonium photoproduction studies at *ep* colliders demonstrated at HERA

Need a high luminosity, high energy collider!

H1 [Phys.Lett.B483:23-35,2000]



ZEUS [Phys.Lett.B680:4-12,2009]

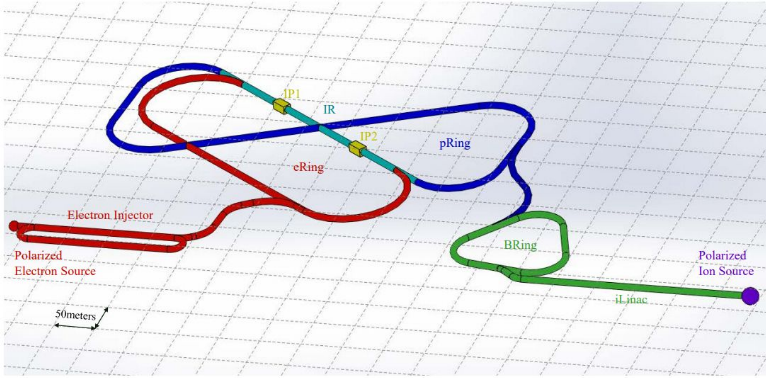
Electron-Hadron Facilities

High-luminosity polarized *ep* and *eA* collider to be built at Brookhaven National Lab (EIC).

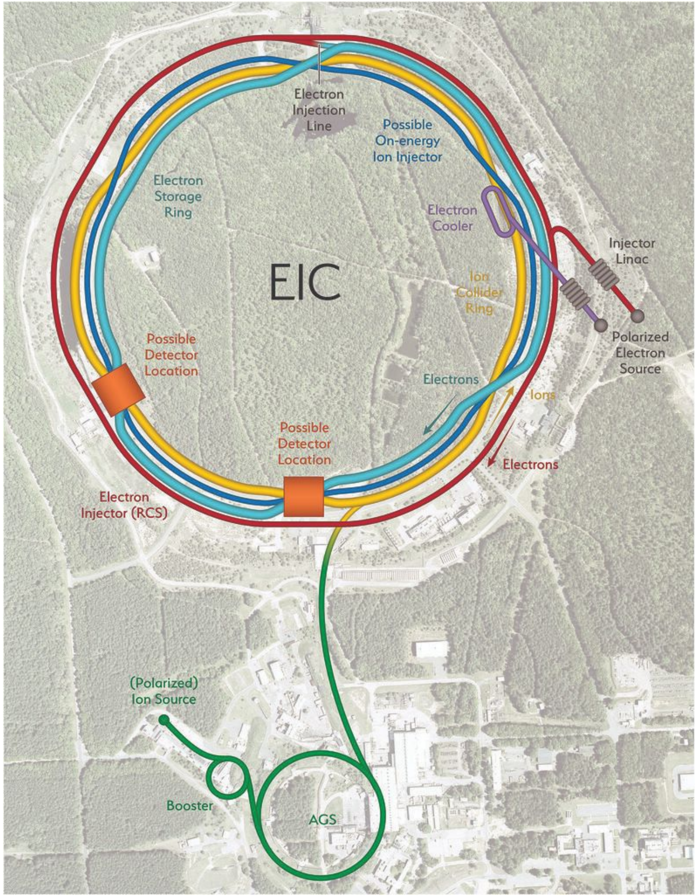
Broad physics program — including **exotic spectroscopy in photoproduction** !

Proposed 2nd interaction region may even be optimized for high-luminosity, low-energy photoproduction.

Similar proposed collider in China (EicC).



EicC White paper [arXiv:2102.09222]



EIC White paper [arXiv:1212.1701]

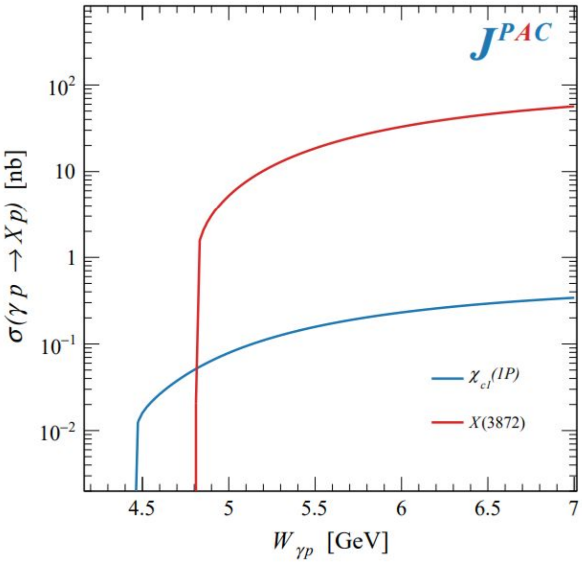
Exclusive XYZ results

JPAC [Phys. Rev. D 102, 114010 (2020)]

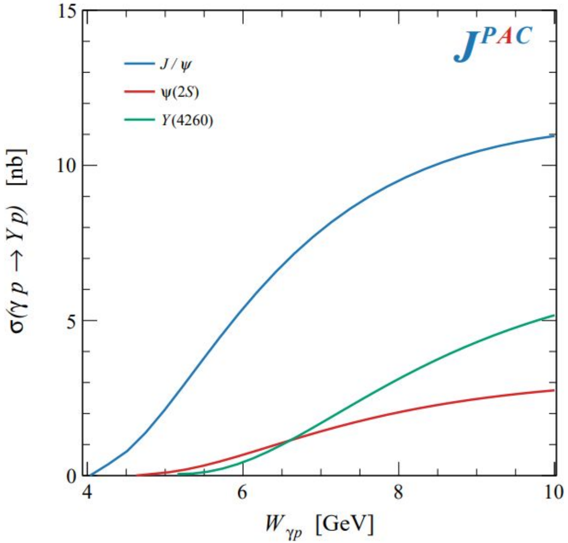
EIC Yellow Report [arXiv:2103.05419]

Phenomenological predictions for all major XYZ mesons at near-threshold...

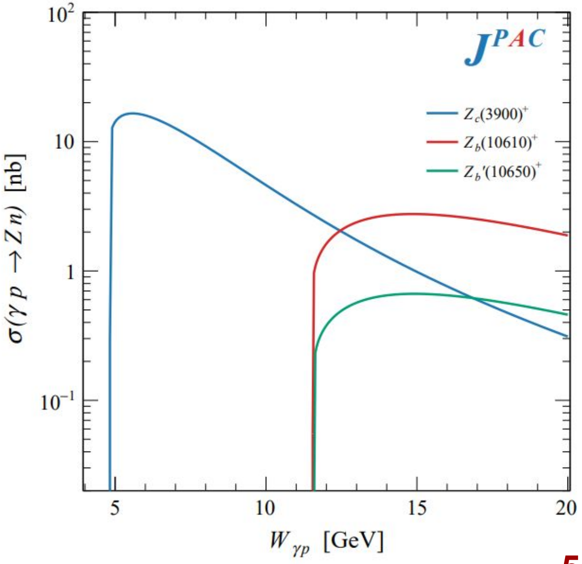
X(3872)



Y(4260)



Z(3900)



Exclusive XYZ results

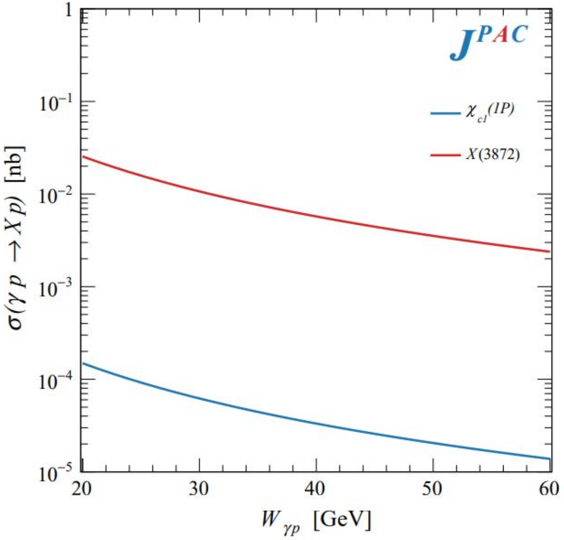
JPAC [Phys. Rev. D 102, 114010 (2020)]

EIC Yellow Report [arXiv:2103.05419]

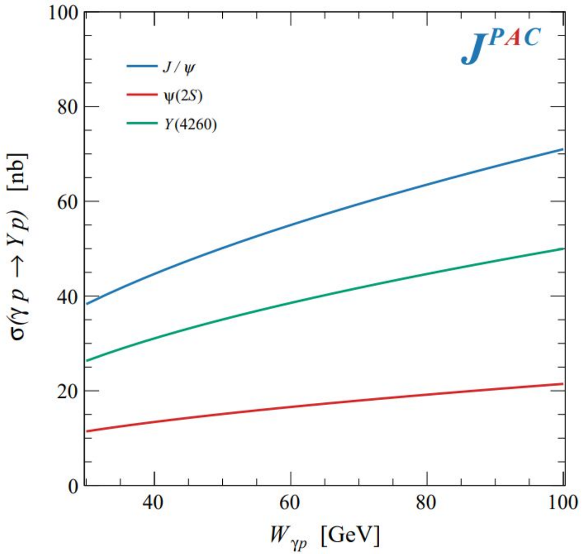
Phenomenological predictions for all major XYZ mesons at near-threshold… and high-energies.

Formalism used is applicable to exclusive XYZ (or other meson) photoproduction at other facilities!

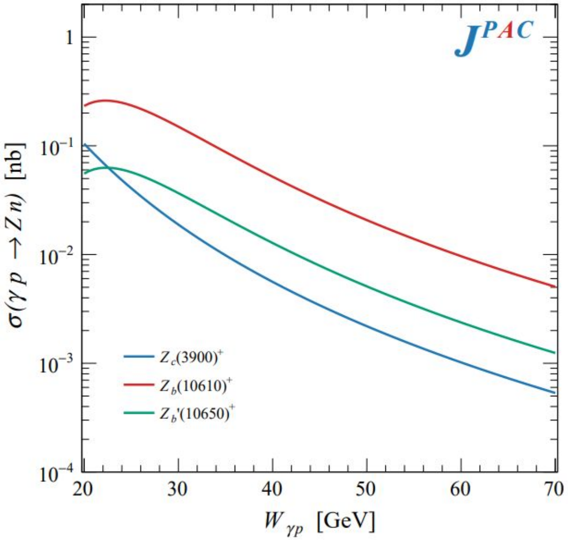
X(3872)



Y(4260)

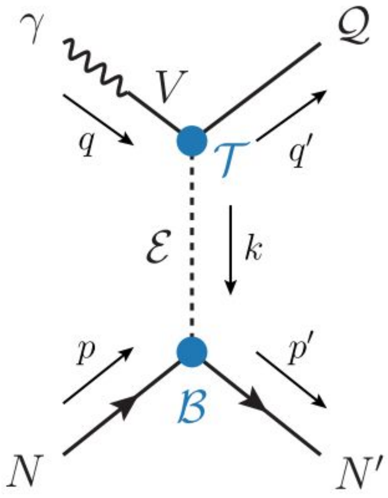


Z(3900)



Exclusive photoproduction

JPAC [Phys. Rev. D 102, 114010 (2020)]



Recipe for an amplitude:

1. Identify relevant **exchanges**
2. Photon couplings fixed by observed decay widths and **VMD**
3. Bottom couplings from other reactions

Extensive use of **effective Lagrangian** methods for **fixed-spin** exchanges.

$$\langle \lambda_{\mathcal{Q}} \lambda'_N | T | \lambda_\gamma \lambda_N \rangle = \sum_{V,\mathcal{E}} \frac{e f_V}{m_V} \mathcal{T}^{\alpha_1\cdots\alpha_j}_{\lambda_V=\lambda_\gamma,\lambda_{\mathcal{Q}}} \mathcal{P}_{\alpha_1\cdots\alpha_j;\beta_1\cdots\beta_j} \mathcal{B}^{\beta_1\cdots\beta_j}_{\lambda_N\lambda'_N}$$

We then match to helicity amplitude expansion in exchange rest frame

$$\mathcal{T}^{\alpha_1\ldots\alpha_j}_{\lambda_V,\lambda_{\mathcal{Q}}} \mathcal{P}_{\alpha_1\ldots\alpha_j,\beta_1\ldots\beta_j} \mathcal{B}^{\beta_1\ldots\beta_j}_{\lambda_N,\lambda'_N} \rightarrow T_{\mu_V\mu_{\mathcal{Q}}}(t)\, d^j_{\mu\mu'}(\theta_t) B_{\mu_N,\mu'_N}(t)$$

At high-energies, exchanges **Reggeize** to conserve unitarity!

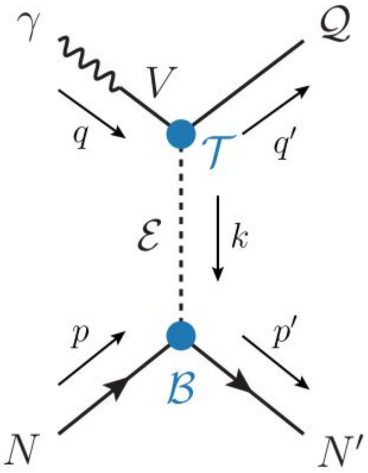
$$\left(\frac{4\,p(t)\,q(t)}{s_0}\right)^{j-M} \mathcal{N}^j_{\mu\mu'} \frac{d^j_{\mu\mu'}(\theta_t)}{\xi^{(t)}_{\mu\mu'}(s,t)} \frac{1}{t-m^2_{\mathcal{E}}} \longrightarrow -\alpha'\,\Gamma(j-\alpha(t))\left[\frac{1+\tau\, e^{-i\pi\alpha(t)}}{2}\right]\left(\frac{s}{s_0}\right)^{\alpha(t)-M}$$

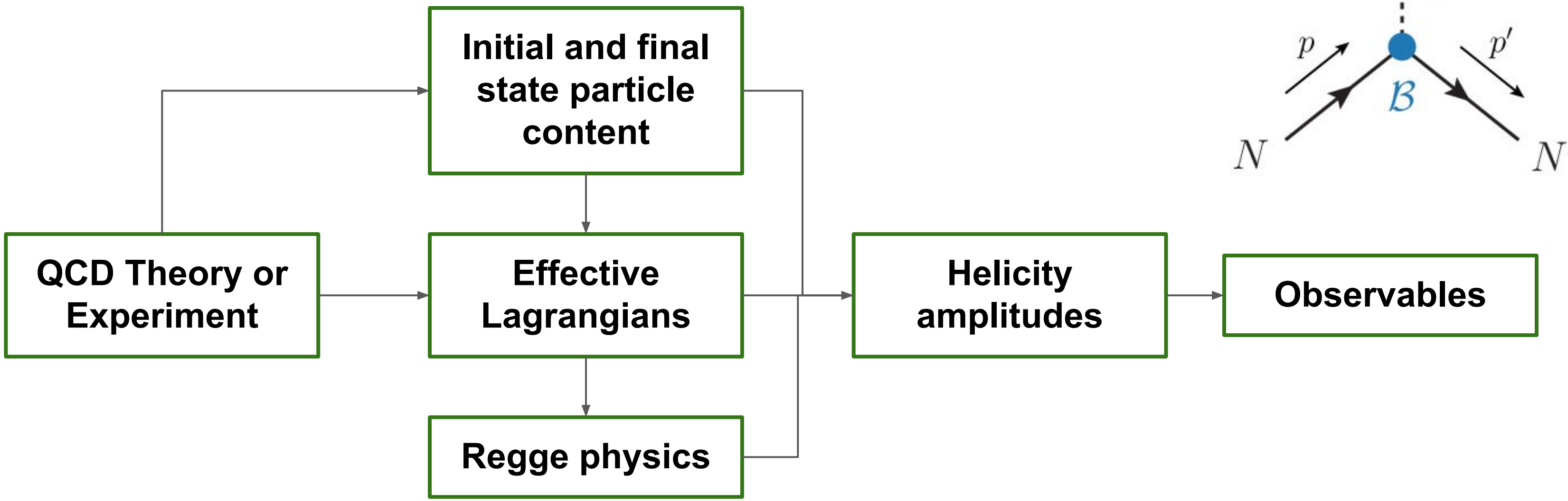
JPAC [Phys. Rev. D 102, 114010 (2020)]

Toolkit for photoproduction

Photoproduction amplitudes may be constructed generically based on exchange-reaction theory.

jpacPhoto assembles JPAC photoproduction amplitudes in an object-oriented library for accessible use.





Initial and final state particle content

QCD Theory or Experiment

Effective Lagrangians

Regge physics

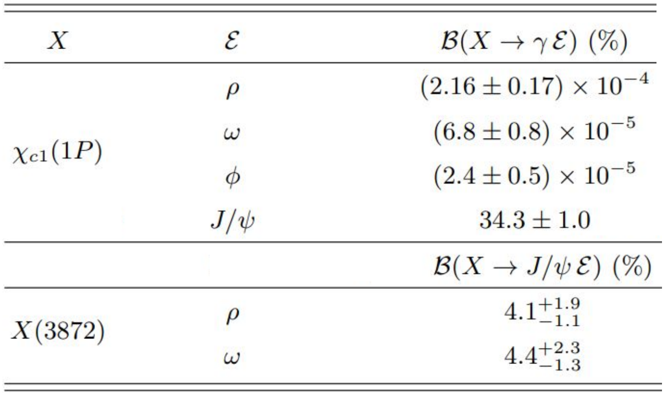
Helicity amplitudes

Observables

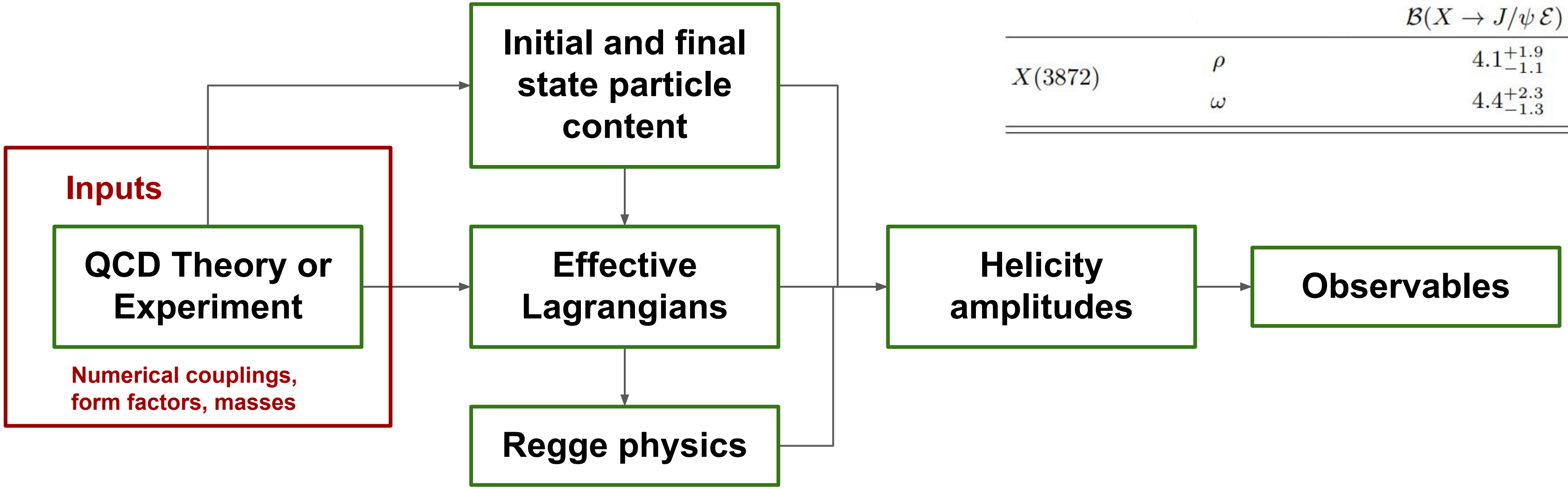
JPAC [Phys. Rev. D 102, 114010 (2020)]

Toolkit for photoproduction

For the purposes of a unified amplitude framework, we assume the masses and widths of particles are known and coupling constants can be estimated.



X	$\mathcal{E}$	$\mathcal{B}(X \to \gamma\, \mathcal{E})$ (%)
$\chi_{c1}(1P)$	ρ	$(2.16 \pm 0.17) \times 10^{-4}$
	ω	$(6.8 \pm 0.8) \times 10^{-5}$
	ϕ	$(2.4 \pm 0.5) \times 10^{-5}$
	J/ψ	34.3 ± 1.0
		$\mathcal{B}(X \to J/\psi\, \mathcal{E})$ (%)
$X(3872)$	ρ	$4.1^{+1.9}_{-1.1}$
	ω	$4.4^{+2.3}_{-1.3}$



Inputs

QCD Theory or Experiment

Numerical couplings, form factors, masses

Initial and final state particle content

Effective Lagrangians

Regge physics

Helicity amplitudes

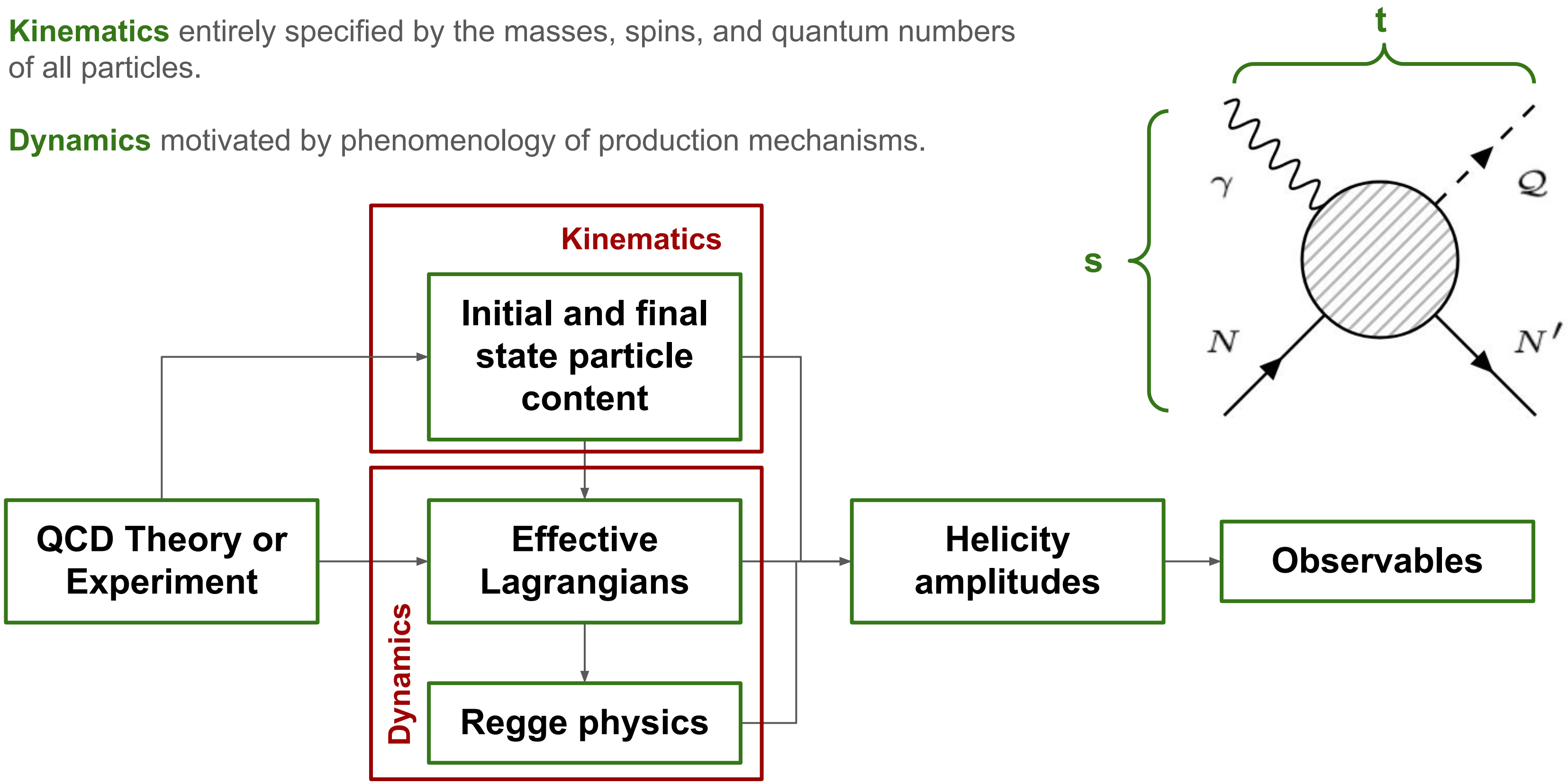
Observables

Toolkit for photoproduction

JPAC [Phys. Rev. D 102, 114010 (2020)]

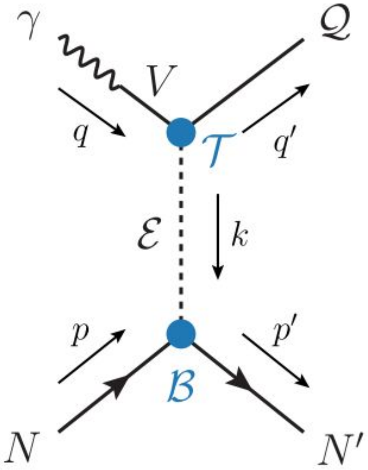
Kinematics entirely specified by the masses, spins, and quantum numbers of all particles.

Dynamics motivated by phenomenology of production mechanisms.



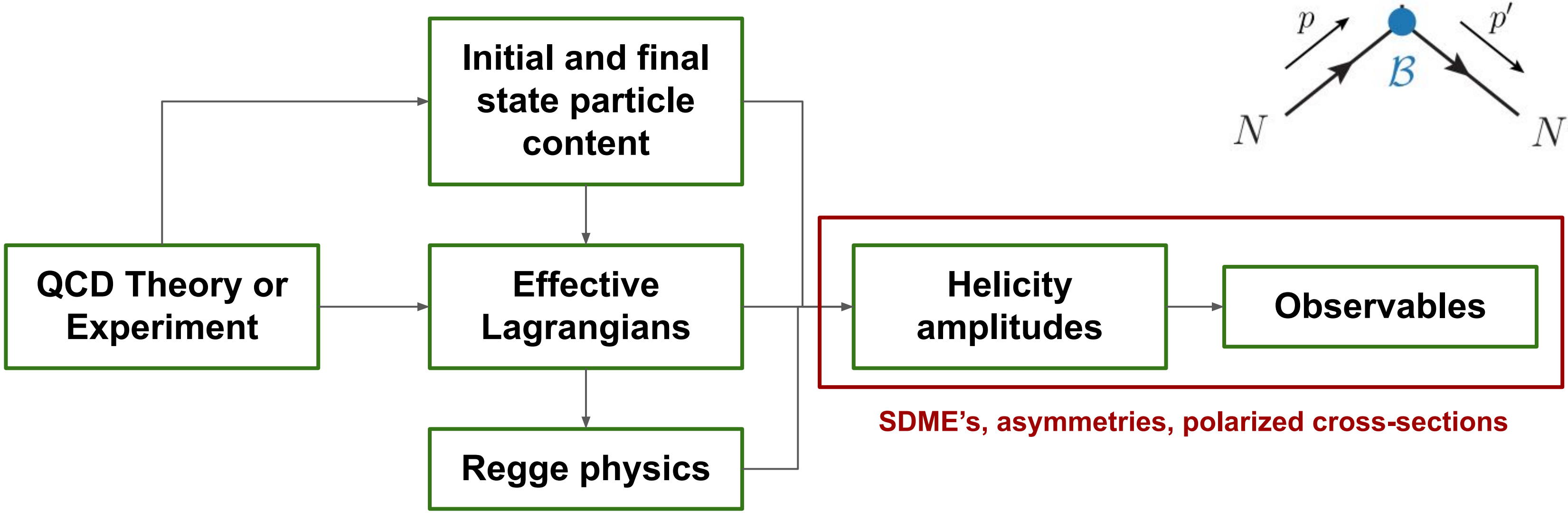
Toolkit for photoproduction

JPAC [Phys. Rev. D 102, 114010 (2020)]



Photoproduction facilities provide unique probes for helicity-dependent observables through polarized beams and/or targets.

Evaluating on a per-helicity-amplitude basis allows wide breadth of **polarization observables** to be calculated.



Initial and final state particle content

QCD Theory or Experiment

Effective Lagrangians

Regge physics

Helicity amplitudes

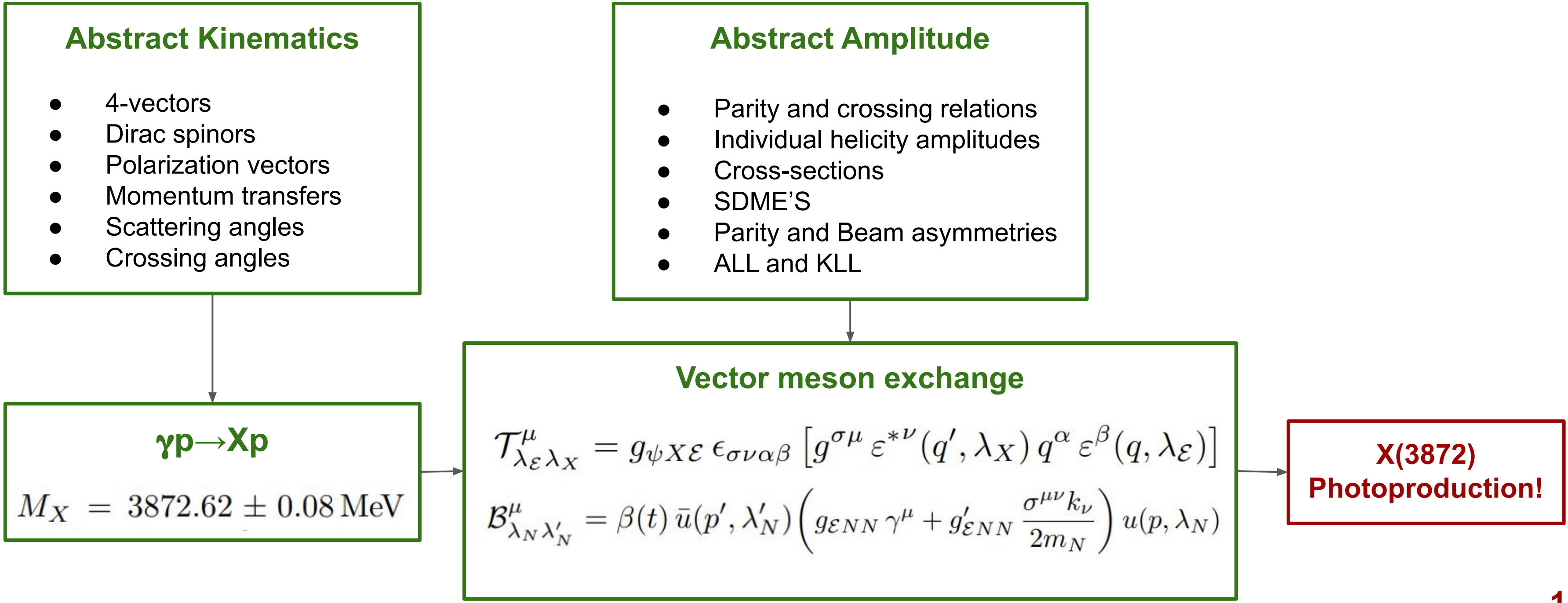
Observables

SDME's, asymmetries, polarized cross-sections

General framework

[github.com/dwinney/jpacPhoto]

Object-oriented structure allows separation of common features of photoproduction processes. Specific processes incorporated as implementations of abstract structures.



Abstract Kinematics

- 4-vectors
- Dirac spinors
- Polarization vectors
- Momentum transfers
- Scattering angles
- Crossing angles

Abstract Amplitude

- Parity and crossing relations
- Individual helicity amplitudes
- Cross-sections
- SDME'S
- Parity and Beam asymmetries
- ALL and KLL

γp→Xp

$$M_X = 3872.62 \pm 0.08\,\mathrm{MeV}$$

Vector meson exchange

$$\mathcal{T}^{\mu}_{\lambda_\varepsilon \lambda_X} = g_{\psi X \varepsilon}\, \epsilon_{\sigma\nu\alpha\beta} \left[g^{\sigma\mu}\, \varepsilon^{*\nu}(q', \lambda_X)\, q^{\alpha}\, \varepsilon^{\beta}(q, \lambda_\varepsilon) \right]$$

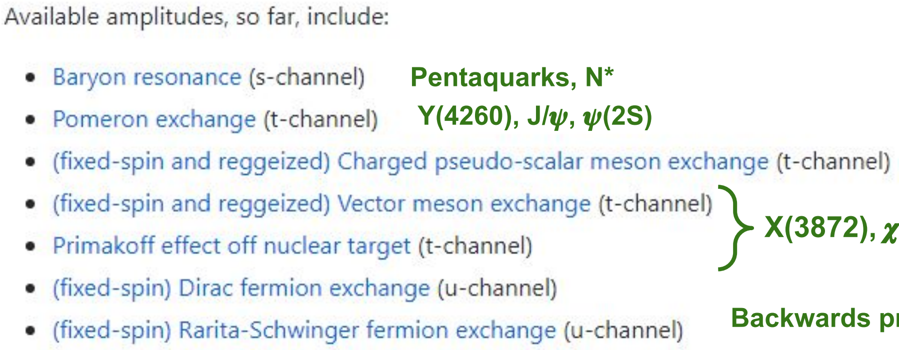
$$\mathcal{B}^{\mu}_{\lambda_N \lambda'_N} = \beta(t)\, \bar{u}(p', \lambda'_N) \left(g_{\varepsilon NN}\, \gamma^{\mu} + g'_{\varepsilon NN}\, \frac{\sigma^{\mu\nu} k_\nu}{2m_N} \right) u(p, \lambda_N)$$

X(3872) Photoproduction!

Amplitudes

[github.com/dwinney/jpacPhoto]

Expandable library to be a one-stop shop for JPAC photoproduction amplitudes.



Available amplitudes, so far, include:

- Baryon resonance (s-channel)
- Pomeron exchange (t-channel)
- (fixed-spin and reggeized) Charged pseudo-scalar meson exchange (t-channel)
- (fixed-spin and reggeized) Vector meson exchange (t-channel)
- Primakoff effect off nuclear target (t-channel)
- (fixed-spin) Dirac fermion exchange (u-channel)
- (fixed-spin) Rarita-Schwinger fermion exchange (u-channel)

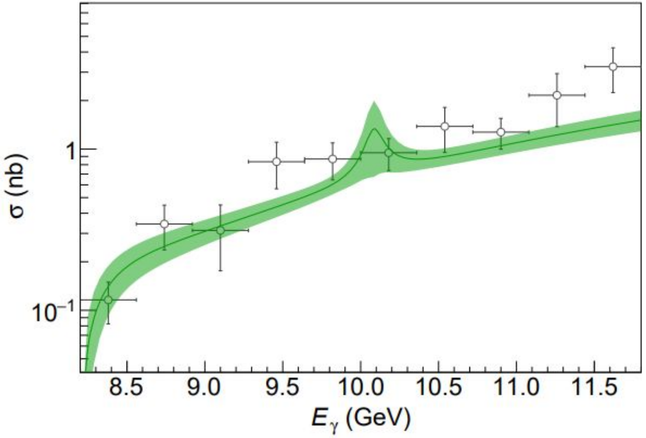
Pentaquarks, N*

Y(4260), J/ψ, ψ(2S)

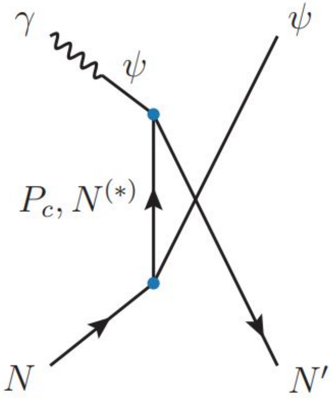
Z(3900)

X(3872), χc1

Backwards production



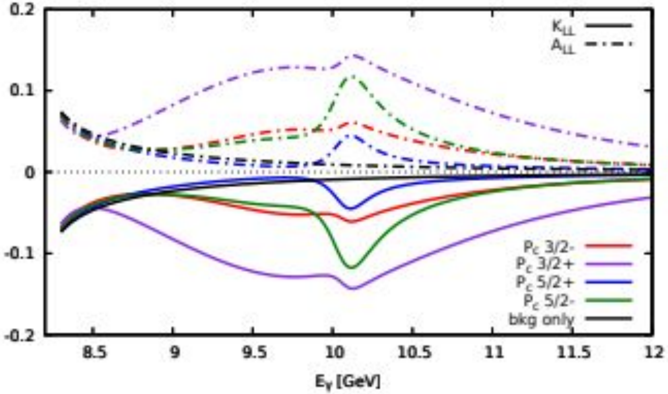
JPAC [Phys. Rev. D 100, 034019 (2019)]



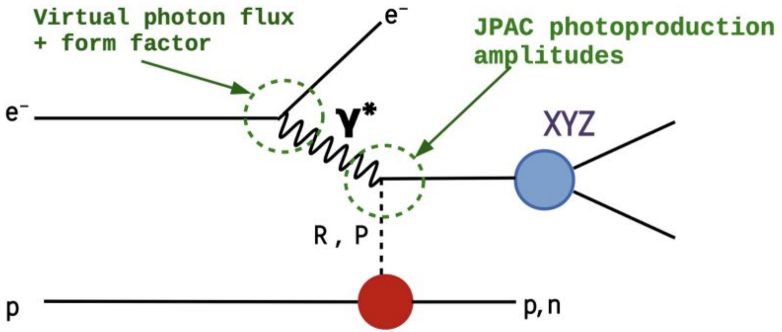
Addition of arbitrarily many (interfering) amplitudes available as well.

Many amplitudes for up to spin-0 and 1 mesons and baryons resonances up to 5/2.

JPAC [Phys. Rev. D 102, 114010 (2020)]

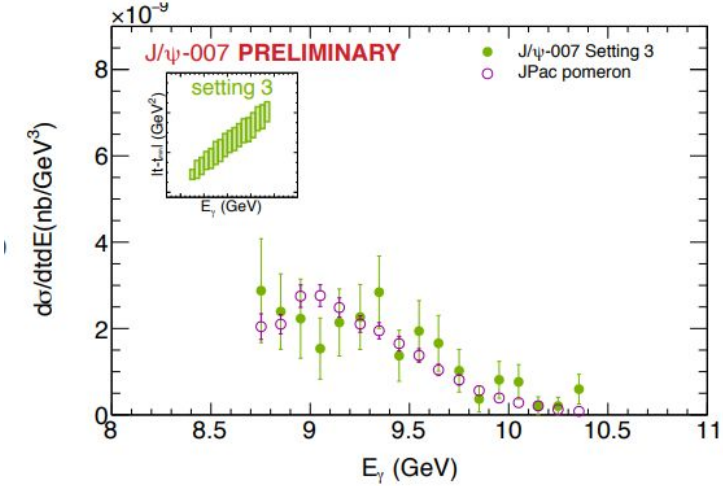


Use in event generators



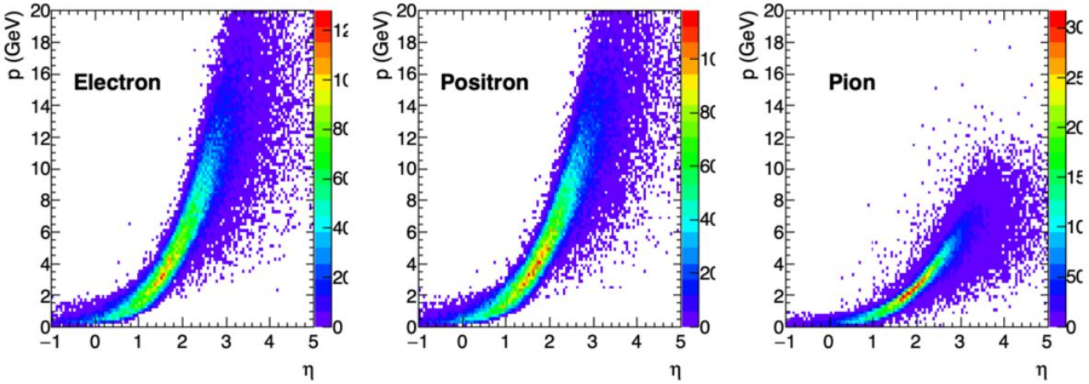
[eic.github.io/software/elspectro.html]
[github.com/dglazier/elSpectro]

Object-oriented structure allows incorporation into event generators and simulation!



S. Joosten for J/ψ-007 [APS GHP Meeting, 16 April 2021]

$Z_c^+ \rightarrow J/\psi\pi^+, J/\psi \rightarrow e^+e^-$

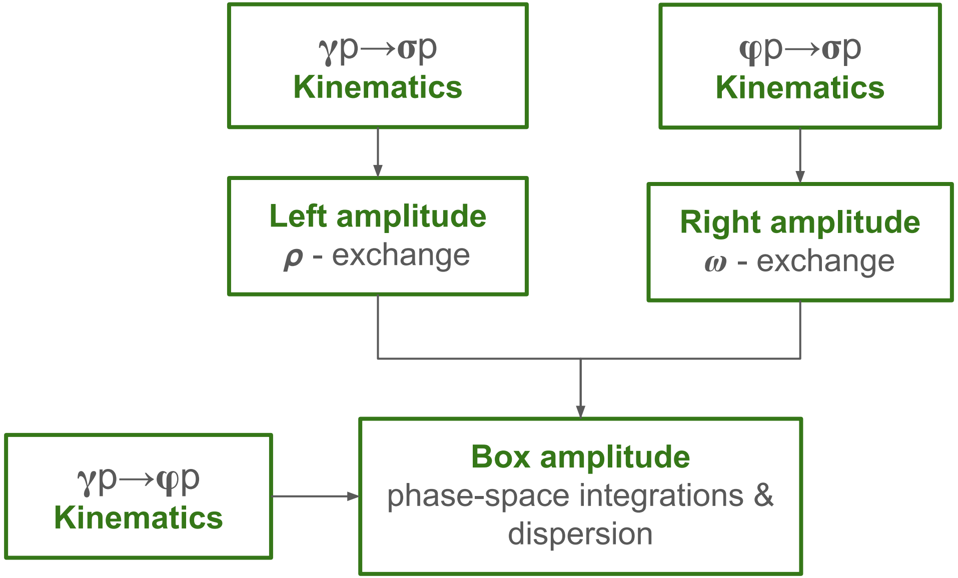


EIC Yellow Report [arXiv:2103.05419]

Box amplitudes

One-loop, box topologies appear as contributions to near-threshold photoproduction.

Reducible to integration over tree-level exchange diagrams!



γp→σp
Kinematics

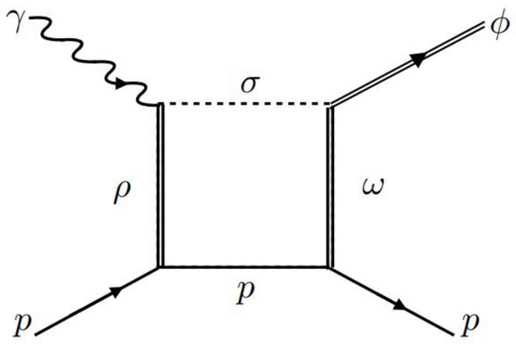
φp→σp
Kinematics

Left amplitude
ρ - exchange

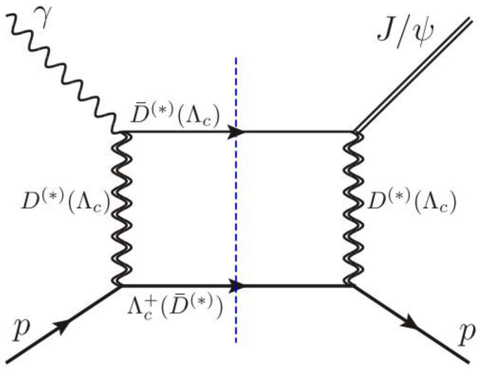
Right amplitude
ω - exchange

γp→φp
Kinematics

Box amplitude
phase-space integrations & dispersion



Ryu et al. [PTEP 2014 (2014) 023D03]



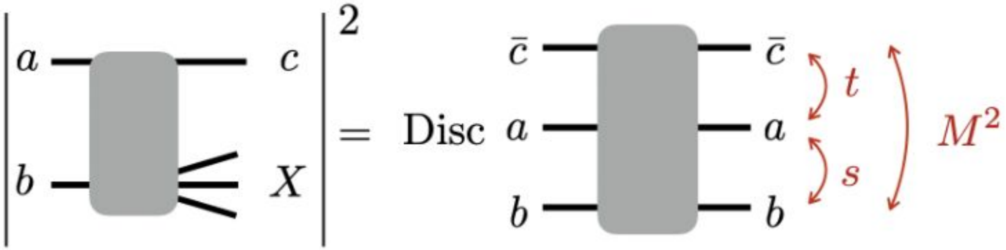
Du et al. [Eur.Phys.J.C 80 (2020) 11, 1053]

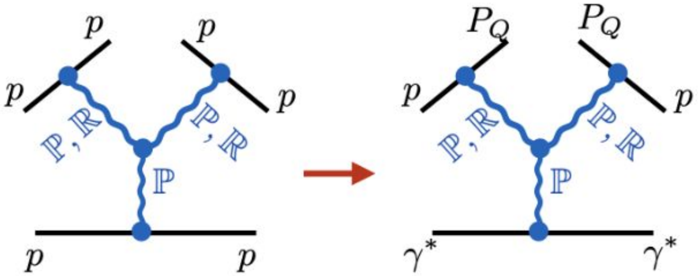
Inclusive photoproduction

Extensions of the amplitude-based analysis and tools to include inclusive kinematics.

Inclusive kinematics is much less constrained than the exclusive production but boasts **higher cross-sections** at EIC energies.

Experimentally easier, less particles to reconstruct.





Phenomenologically, inclusive cross-sections are related to total cross-sections in the **Triple Regge** limit.

Differences between different productions enter primarily as rescaling of couplings → inclusive photoproduction generically implementable similar to the existing exclusive library.

Thank you!