Physics with higher energy electrons

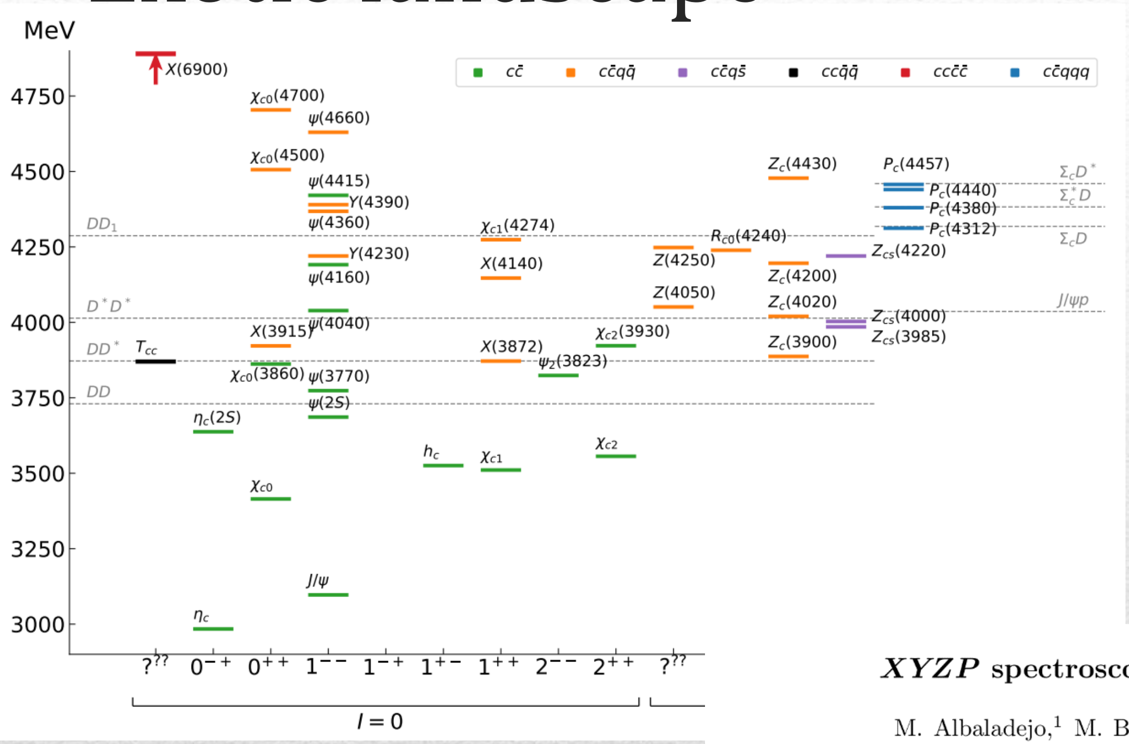
Alessandro Pilloni

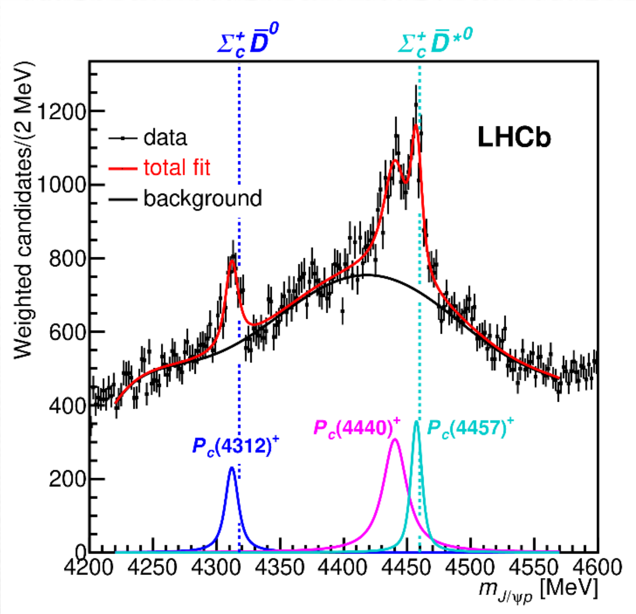
GlueX Collaboration Meeting, May 25th, 2022

Università degli Studi di Messina

Istituto Nazionale di Fisica Nucleare

Exotic landscape





$XYZP$ spectroscopy at a charm photoproduction factory

M. Albaladejo,[1] M. Battaglieri,[2,3] A. Esposito,[4] C. Fernández-Ramírez,[5] A. N. Hiller Blin,[1] V. Mathieu,[6] W. Melnitchouk,[1] M. Mikhasenko,[7] V. I. Mokeev,[2] A. Pilloni,[3,8,*] A. D. Polosa,[9] J.-W. Qiu,[1] A. P. Szczepaniak,[1,10,11] and D. Winney[10,11]

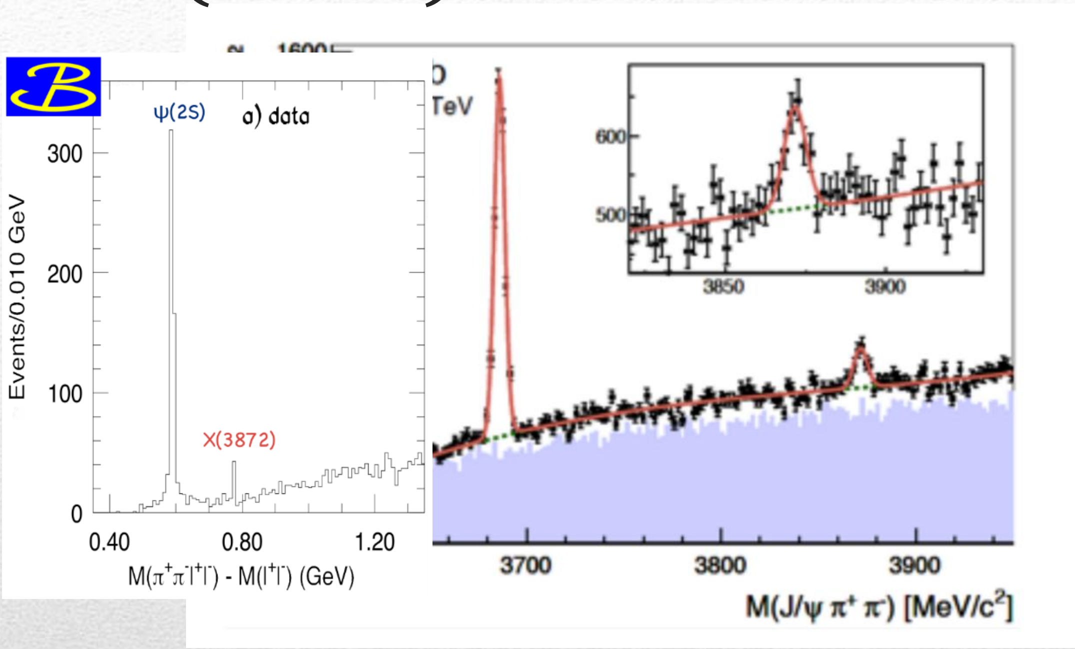
Estimates in
M. Albaladejo et al. [JPAC],
2008.01001

Hadron Spectroscopy in Photoproduction

Miguel Albaladejo[1], Łukasz Bibrzycki[2], Sean Dobbs[3], César Fernández-Ramírez[4,5], Astrid N. Hiller Blin[6], Vincent Mathieu[7,8], Alessandro Pilloni[9,10], Justin Stevens[11], Adam P. Szczepaniak[12,13,14], and Daniel Winney[13,14,15,16]

Snowmass LoI RF7_RF0_120,
White paper 2203.08290

$X(3872)$



- Discovered in
  $B \to K\,X \to K\,J/\psi\,\pi\pi$
- Quantum numbers 1^{++}
- Very close to DD^* threshold
- Too narrow for an above-treshold charmonium
- Isospin violation too big
  $\frac{\Gamma(X\to J/\psi\ \omega)}{\Gamma(X\to J/\psi\ \rho)} \sim 0.8 \pm 0.3$
- Mass prediction not compatible with $\chi_{c1}(2P)$

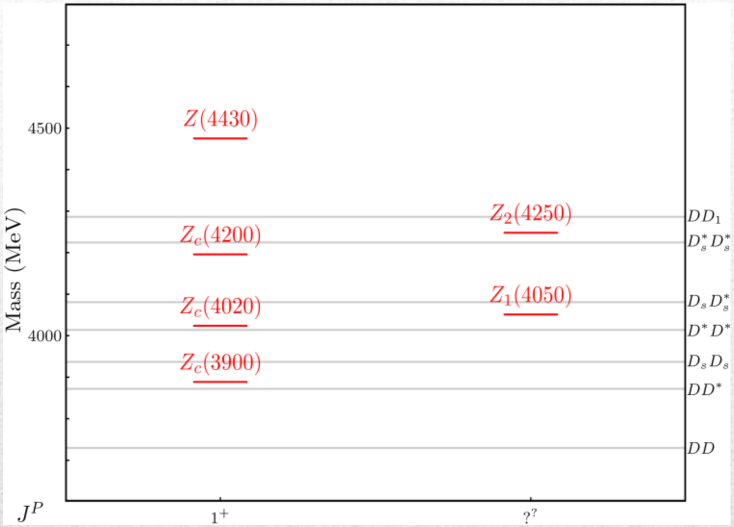
Sizeable prompt production at hadron colliders, $\sim$ 5% of $\psi(2S)$

$\sigma_{PR} \times B(X \to J/\psi\pi\pi) = (1.06 \pm 0.11 \pm 0.15)$ nb @CMS

$$M = 3871.68 \pm 0.17 \text{ MeV}$$
$$M_X - M_{DD^*} = -3 \pm 192 \text{ keV}$$
$$\Gamma = 1.19 \pm 0.19 \text{ MeV}$$

Charged Z states: $Z_c(3900), Z_c'(4020)$

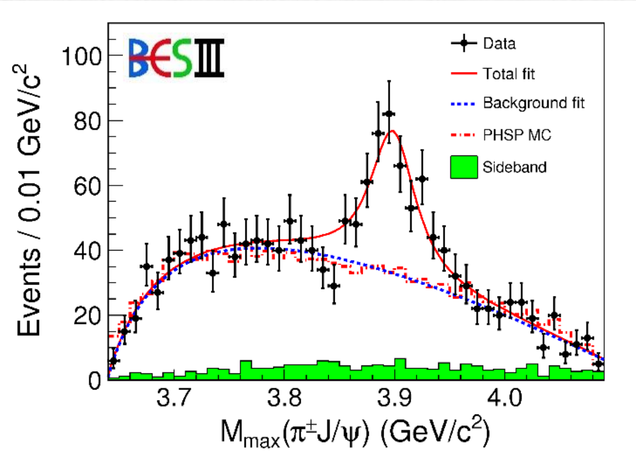
Charged quarkonium-like resonances have been found, **4q needed**

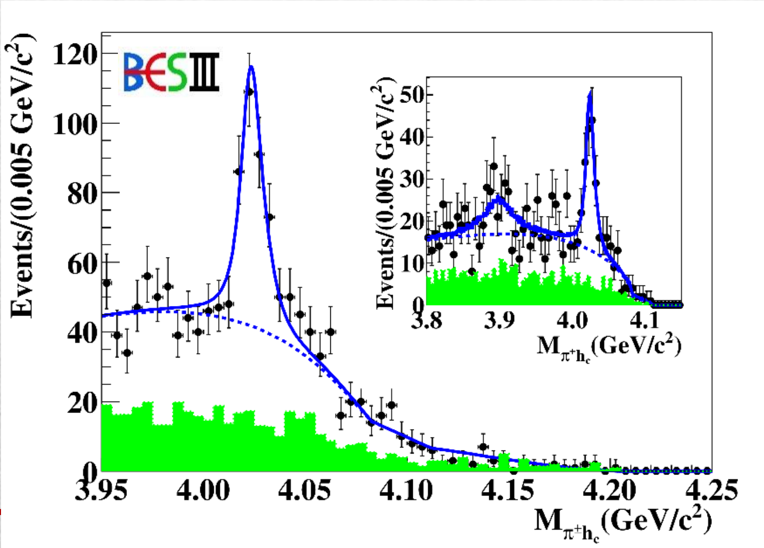


Two states $J^{PC} = 1^{+-}$ appear
slightly above $D^{(*)}D^*$ thresholds

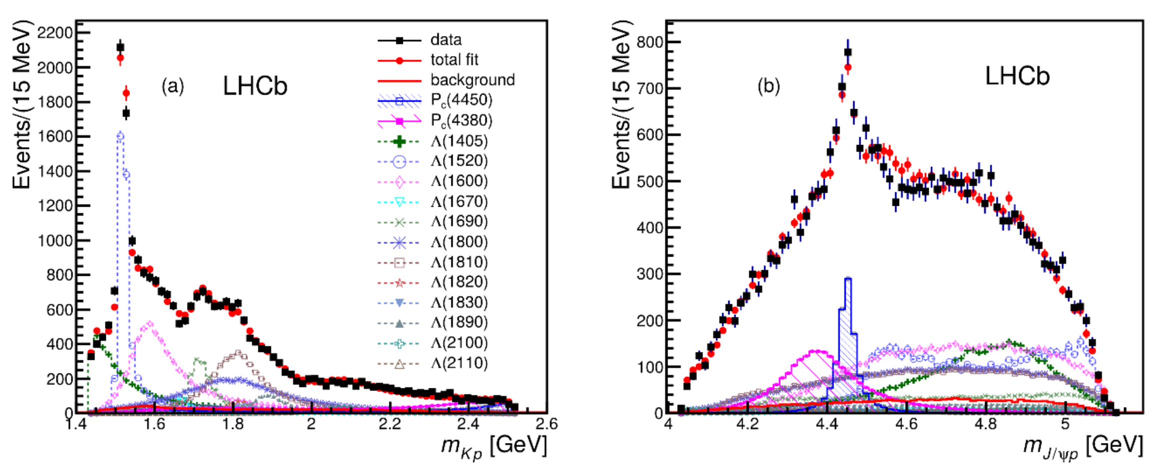
$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\,\pi^+\pi^-$ and $\to (DD^*)^+\pi^-$
$M = 3888.7 \pm 3.4$ MeV, $\Gamma = 35 \pm 7$ MeV

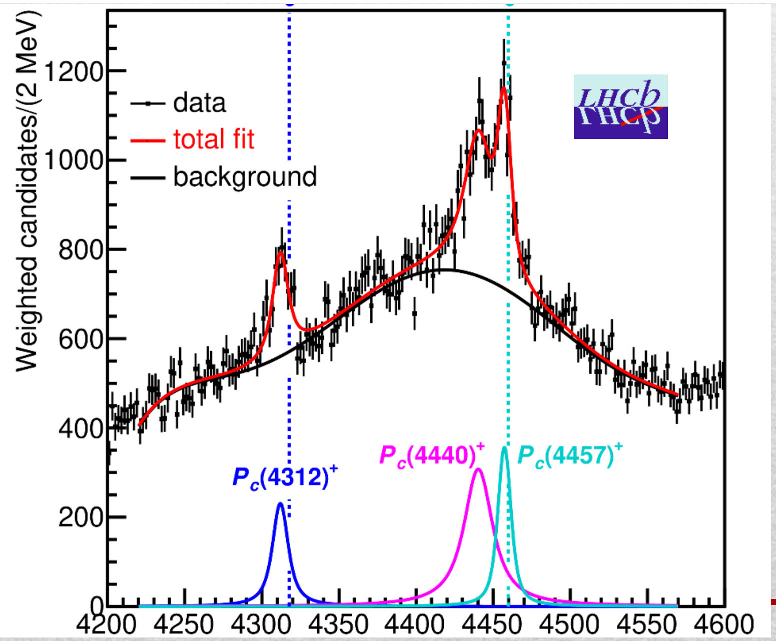
$e^+e^- \to Z_c'(4020)^+\pi^- \to h_c\,\pi^+\pi^-$ and $\to \bar{D}^{*0}D^{*+}\pi^-$
$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV





Pentaquarks!





LHCb, PRL 115, 072001
LHCb, PRL 117, 082003

Two states seen in $\Lambda_b \to (J/\psi\, p)\, K^-$, evidence in $\Lambda_b \to (J/\psi\, p)\, \pi^-$

$$M_1 = 4380 \pm 8 \pm 29 \text{ MeV}$$
$$\Gamma_1 = 205 \pm 18 \pm 86 \text{ MeV}$$
$$M_2 = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$$
$$\Gamma_2 = 39 \pm 5 \pm 19 \text{ MeV}$$

Quantum numbers

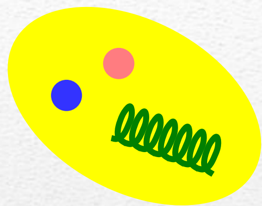
$$J^P = \left(\frac{3}{2}^-, \frac{5}{2}^+\right) \text{ or } \left(\frac{3}{2}^+, \frac{5}{2}^-\right) \text{ or } \left(\frac{5}{2}^+, \frac{3}{2}^-\right)$$

LHCb, PRL 122, 222001

Higher statistics analysis revealed a two-peak structure of the narrow state, plus a new lighter one
Quantum numbers still unknown

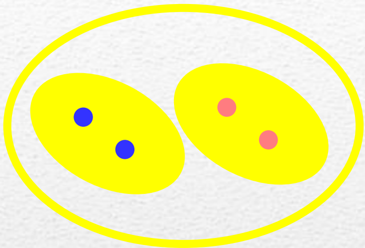
Models

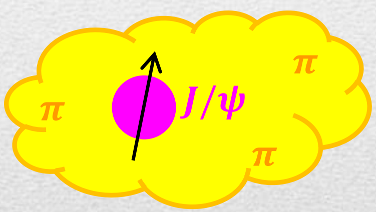
Compact



Hybrids
Containing gluonic degrees of freedom

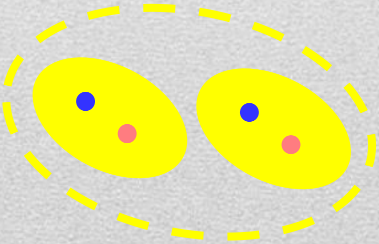
Multiquark
Several (cluster) of valence quarks





Hadroquarkonium
Heavy core interacting with a light cloud via Van der Waals forces

Rescattering effects
Structures generated by cross-channel rescattering, very process-dependent



Molecule
Bound or virtual state generated by long-range exchange forces

Extended

Exotic landscape

Broad mesons seen in b decay:
$X(4140)$, Z(4430), $Z_{cs}(4000)$...

Scarce consistency between various production mechanisms

Narrow structures seen in b decay:
$X(3872), P_c, (P_{cs})$

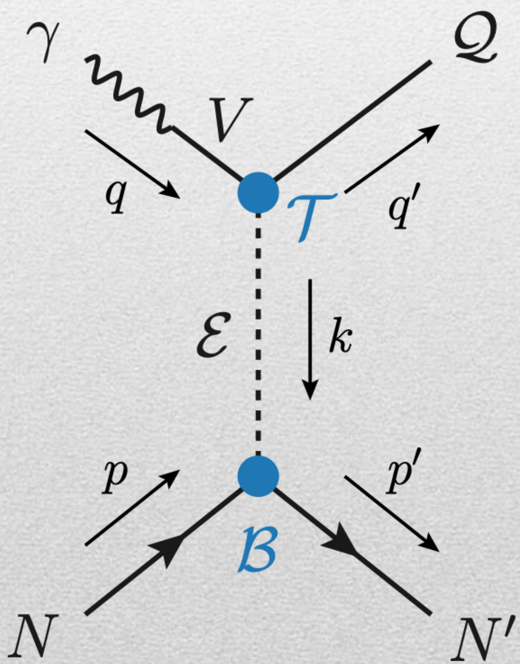
Narrow structures seen in e^+e^-:
$X(3872), Y(4260), Z_{c,b}^{(\prime)}$

Why photoproduction?

- It’s new: no XYZ state has been uncontroversially seen so far
- It is free from rescattering mechanisms that could mimic resonances in multibody decays
- The framework is (relatively) clean from a theory point of view
- Radiative decays offer another way of discerning the nature of the states

Exclusive (quasi-real) photoproduction

- XYZ have not been seen in photoproduction so far : independent confirmation
- Not affected by 3-body dynamics: determination of resonant nature
- Experiments in the appropriate energy range are promising
- We study near-threshold (LE) and high energies (HE)
- Couplings from data as much as possible, not relying on the nature of XYZ



M. Albaladejo et al. [JPAC], PRD

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

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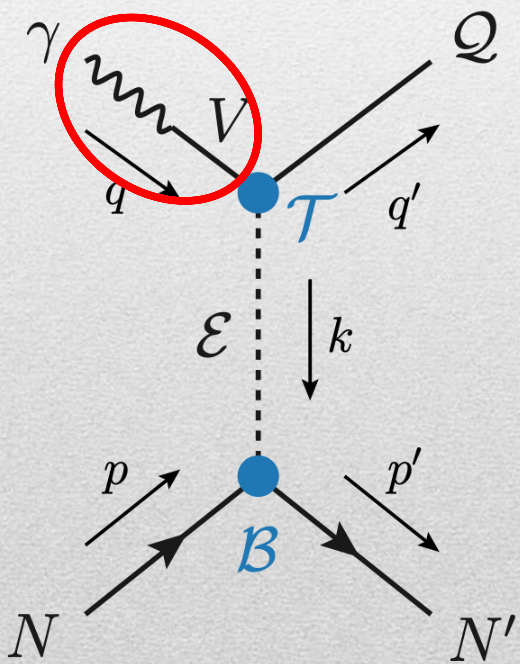

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VMD is used to couple the incoming photon to a vector quarkonium V

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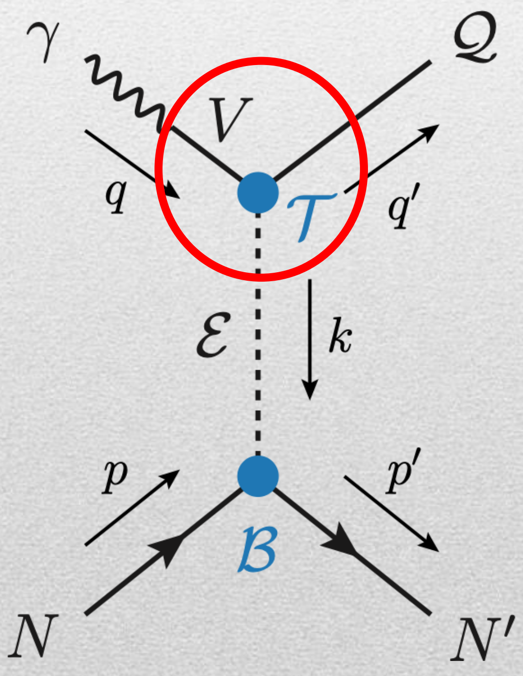

$$< \lambda_Q \lambda'_N | T | \lambda_\gamma \lambda_N >= \sum_{V,\mathcal{E}} \frac{e f_V}{m_V} \mathcal{T}^{\alpha_1 \cdots \alpha_j}_{\lambda_V = \lambda_\gamma, \lambda_Q} \mathcal{P}_{\alpha_1 \cdots \alpha_j ; \beta_1 \cdots \beta_j} \mathcal{B}^{\beta_1 \cdots \beta_j}_{\lambda_N \lambda'_N}$$

Top vertex from measured $\mathcal{Q} \to V\mathcal{E}$ decay width

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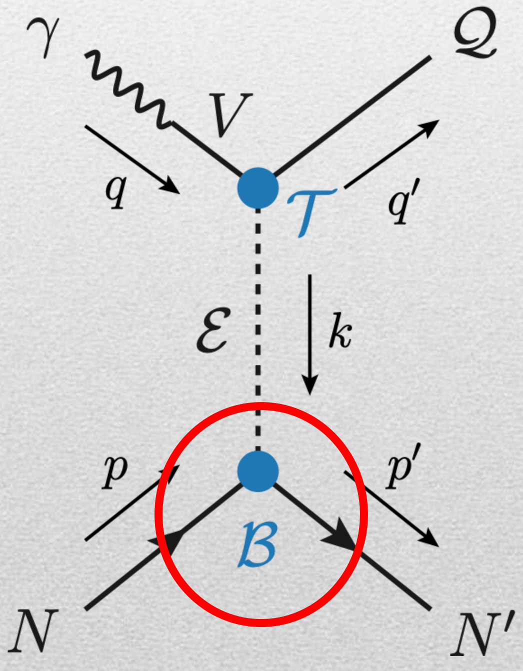
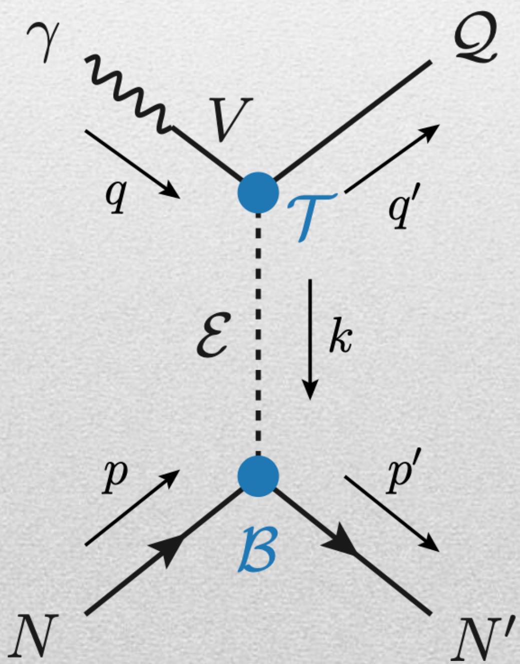


$$< \lambda_\mathcal{Q} \lambda'_N | T | \lambda_\gamma \lambda_N > = \sum_{V,\mathcal{E}} \frac{e f_V}{m_V} \mathcal{T}^{\alpha_1 \cdots \alpha_j}_{\lambda_V = \lambda_\gamma, \lambda_\mathcal{Q}} \mathcal{P}_{\alpha_1 \cdots \alpha_j; \beta_1 \cdots \beta_j} \mathcal{B}^{\beta_1 \cdots \beta_j}_{\lambda_N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

Bottom vertex from standard photoproduction pheno, exponential form factors to further suppress large t

Threshold vs. high energy

- Fixed-spin exchanges expected to hold in the low energy region
- t channel grows as s^j, exceeding unitarity bound, Regge physics kicks in: Reggeized tower of particles with arbitrary spin at HE



$$s^j \longrightarrow s^{\alpha_0+\alpha' t}$$

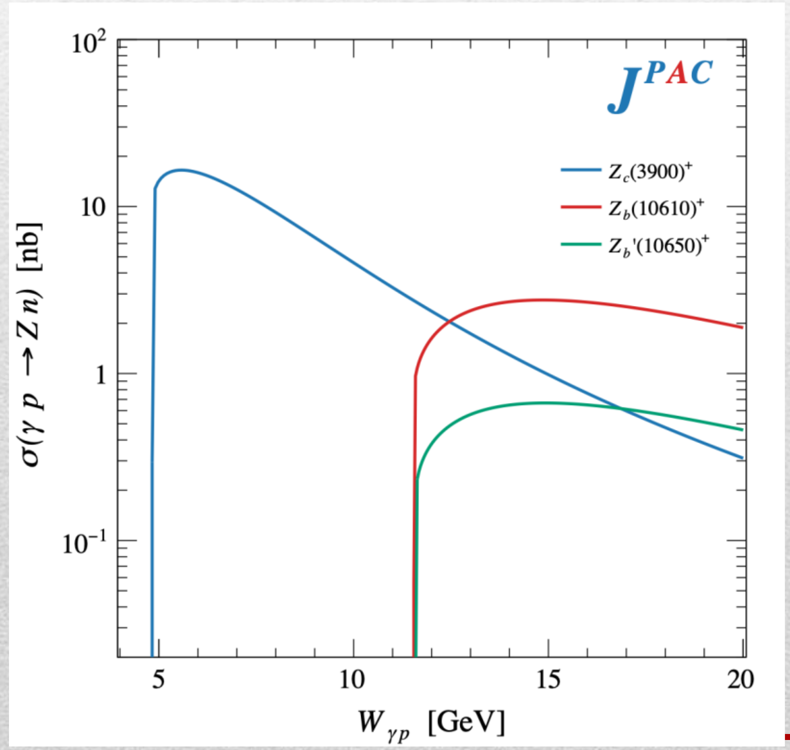
Holds at low energy, fixed spin

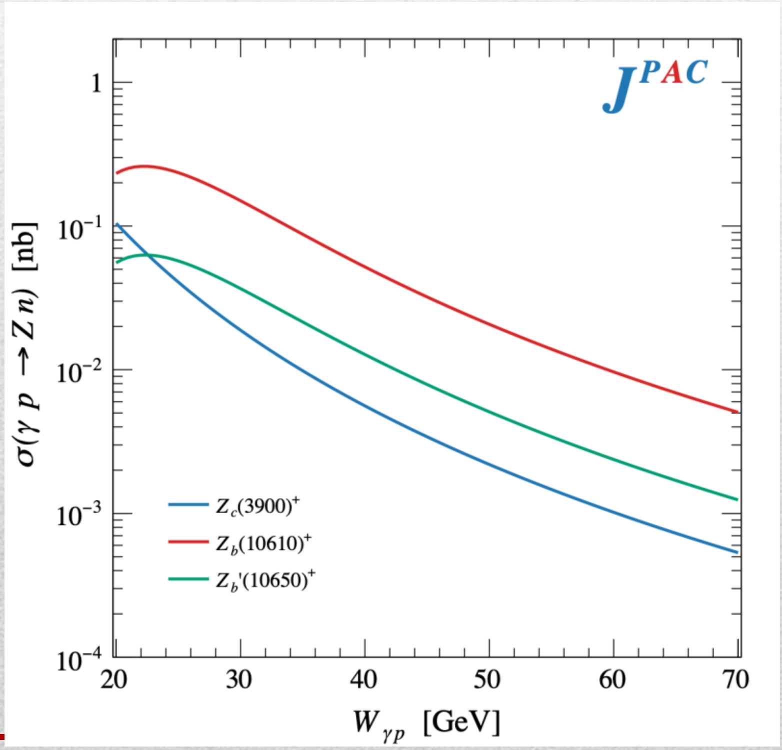
Holds at high energy, resummation of leading s power

- If $\varepsilon \neq \mathbb{P}$, $\alpha_0 < 1$, $d\sigma/dt$ decreases with energy
- Exchange of heavy particles further suppressed

Z photoproduction

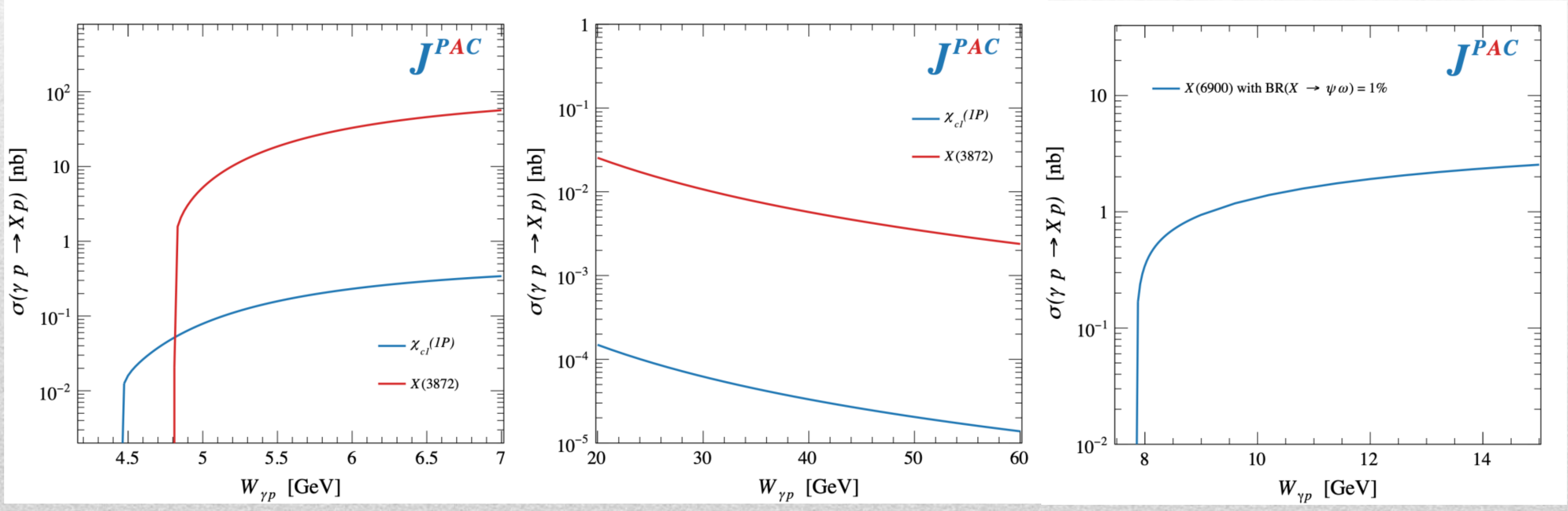
- The Zs are charged charmoniumlike 1^{+-} states close to open flavor thresholds
- Focus on $Z_c(3900)^+ \to J/\psi\,\pi^+$, $Z_b(10610)^+$, $Z_b'(10650)^+ \to \Upsilon(nS)\,\pi^+$
- The pion is exchanged in the t-channel



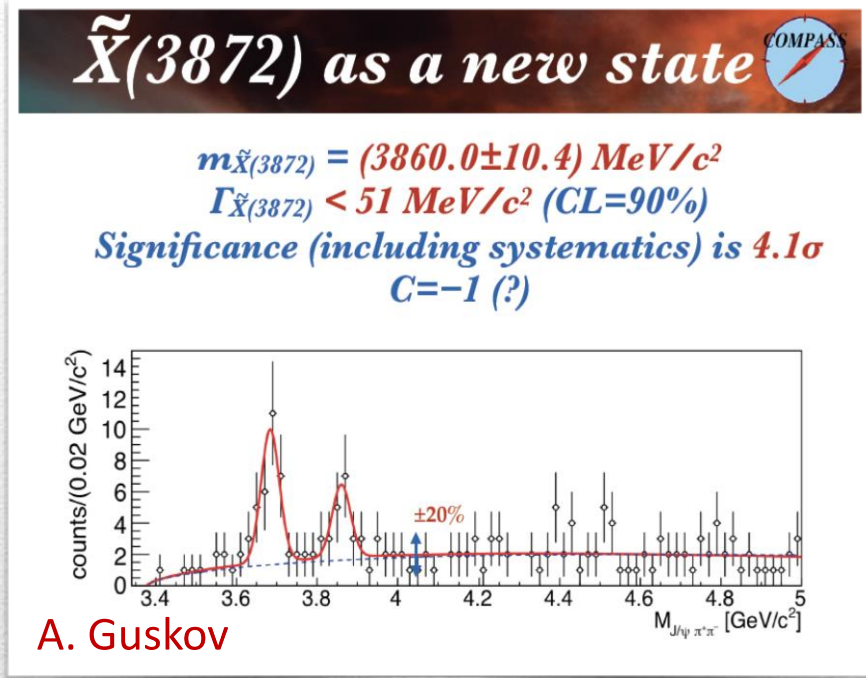


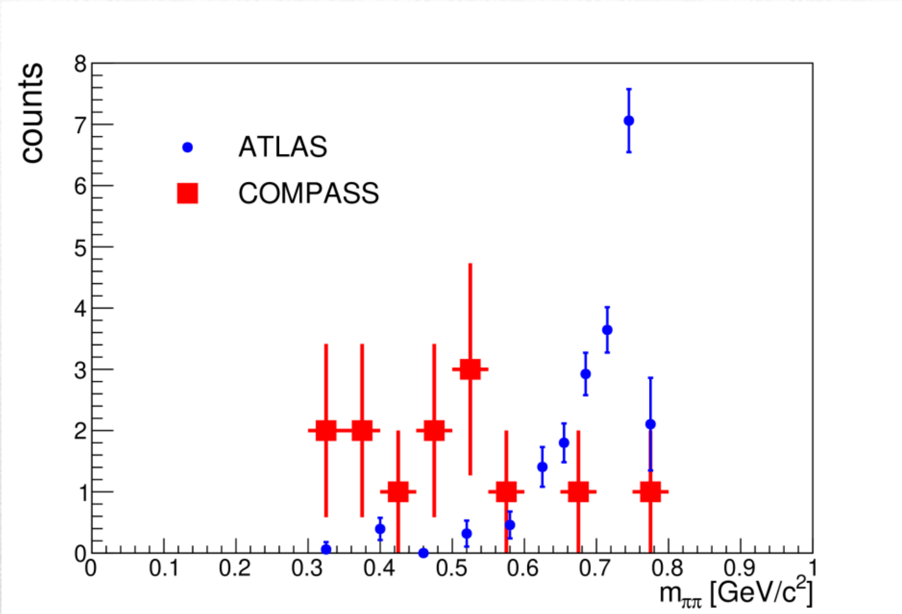
X photoproduction

- Focus on the famous 1^{++} $X(3872) \to J/\psi\, \rho, \omega$
- Studying also $X(6900) \to J/\psi\, J/\psi$ (assumed 0^{++})
- **ω** and **ρ** exchanges give main contributions:
  need to assume the existence of a OZI-suppressed $X(6900) \to J/\psi\, \omega$



Another $\tilde{X}$?





COMPASS claimed the existence of a state degenerate with the $X(3872)$, but with $C = 1$

Large photoproduction cross section

A. Guskov

At COMPASS conditions:

$\sigma_{\mu N} \approx \sigma_{\gamma N} / 300$

EIC $L = 10^{34}\ cm^{-2}\ s^{-1}$

$e^- N \to e^- \widetilde{X}(3872) \pi^\pm N' \to$

$\to e^- J/\psi \pi^+ \pi^- \pi^\pm N' \to e^- \mu^+ \mu^- \pi^+ \pi^- \pi^\pm N'$

~10 events per day

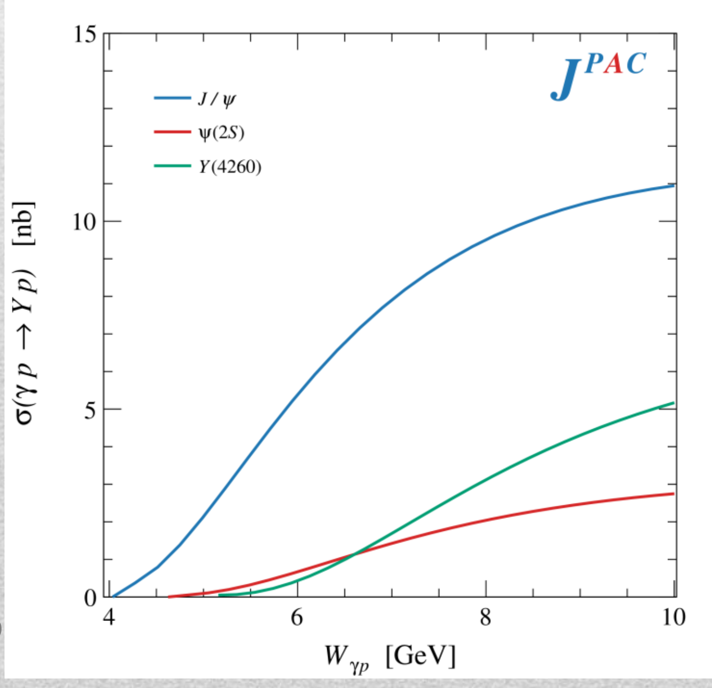
Y (vector) photoproduction

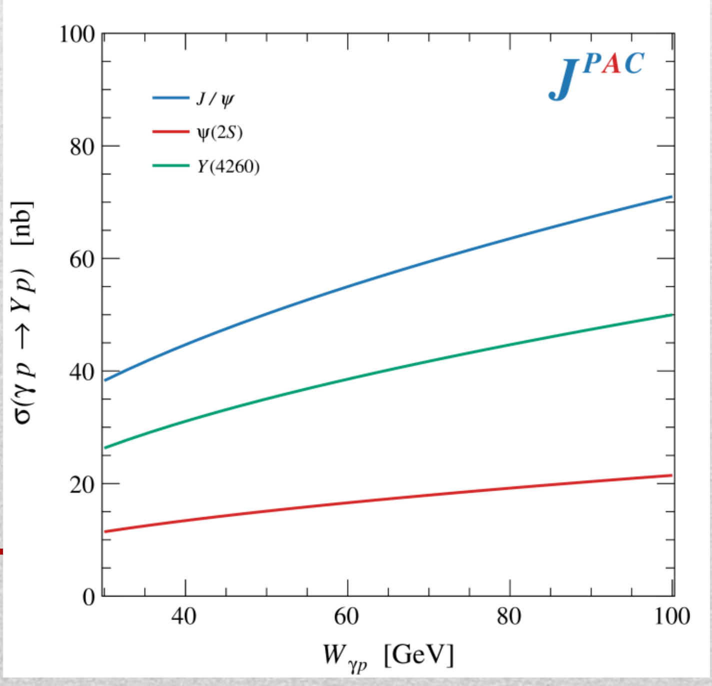
Diffractive production, dominated by Pomeron (2-gluon) exchange

$$R_Y = \frac{e f_\psi}{m_\psi} \sqrt{\frac{g^2(Y \to \psi\pi\pi)}{g^2(\psi \to \gamma g g)} \frac{g^2(\psi' \to \psi g g)}{g^2(\psi' \to \psi\pi\pi)}}$$

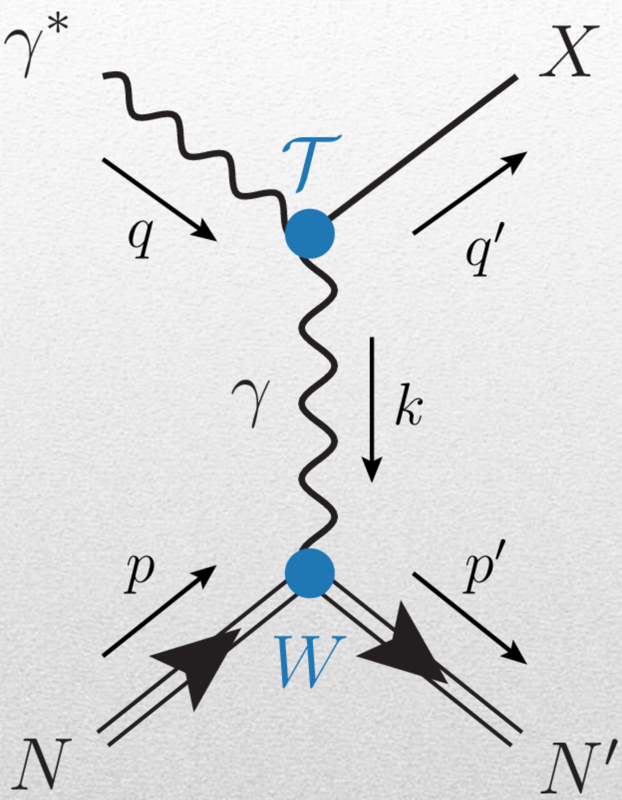
Existing data allow to put a 95% upper limit on the ratio of $\psi'/Y(4260)$ yields

Assuming previous formula, one gets:
$\Gamma_{ee}^{Y} = 930\ eV$
(cfr. hep-ex/0603024, 2002.05641)
$BR(Y \to J/\psi\pi\pi) = 0.96\%$
$R_Y = 0.84$



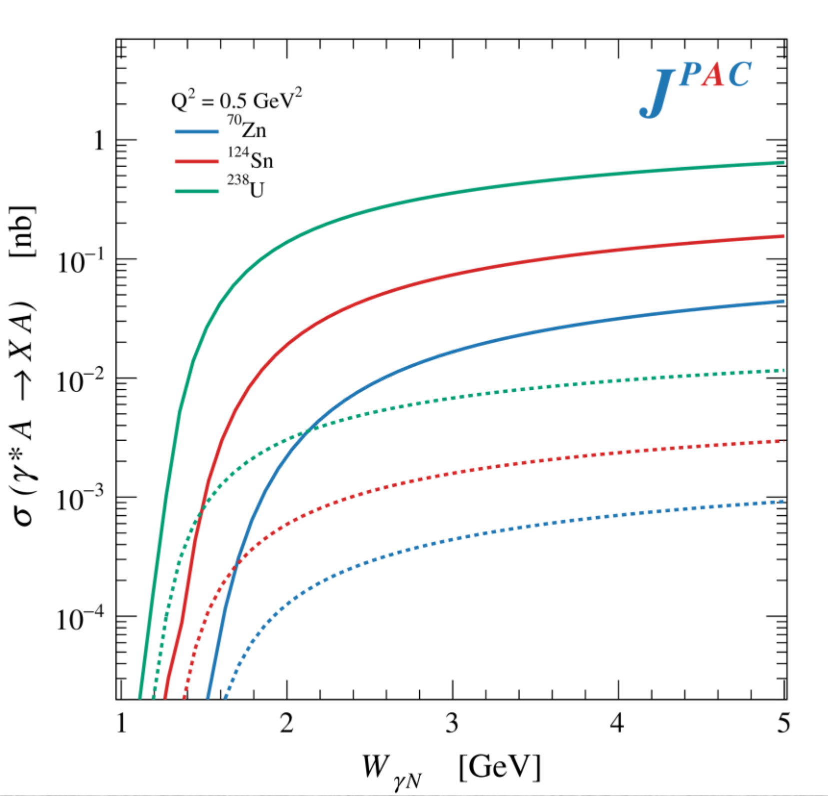


Primakoff X photoproduction

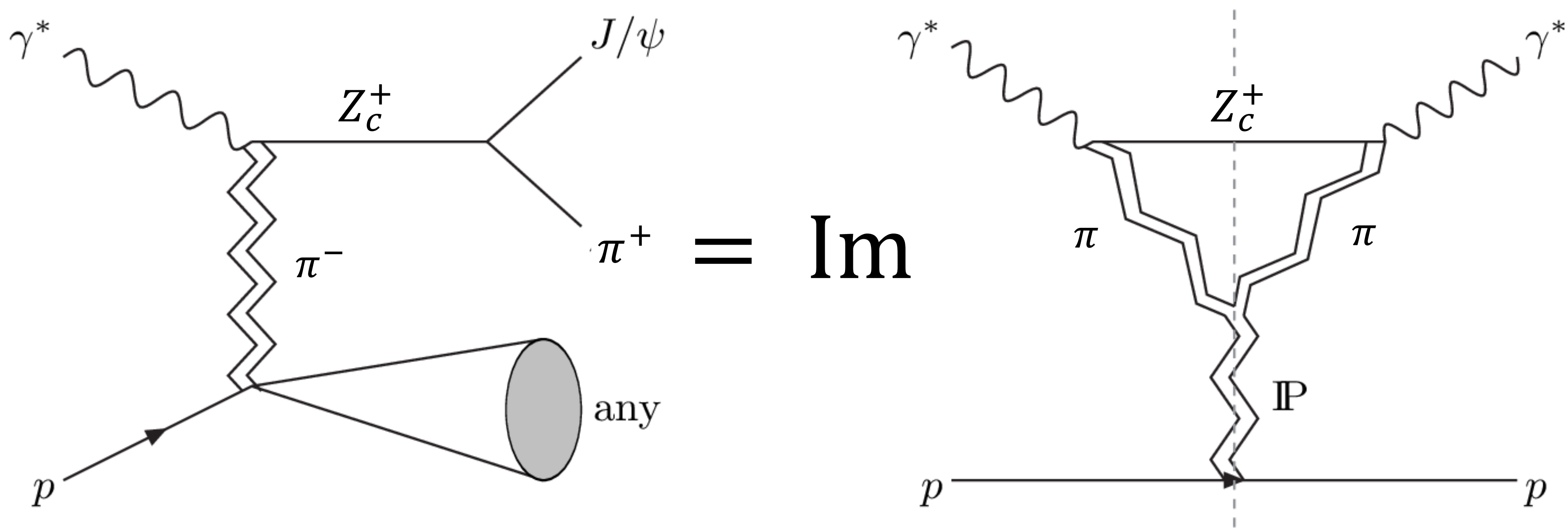


Using measurement of $\Gamma(X \to \gamma\gamma^*)$ from Belle, one can get predictions for Primakoff

Makes use of ion targets, enhancement of cross sections as Z^2



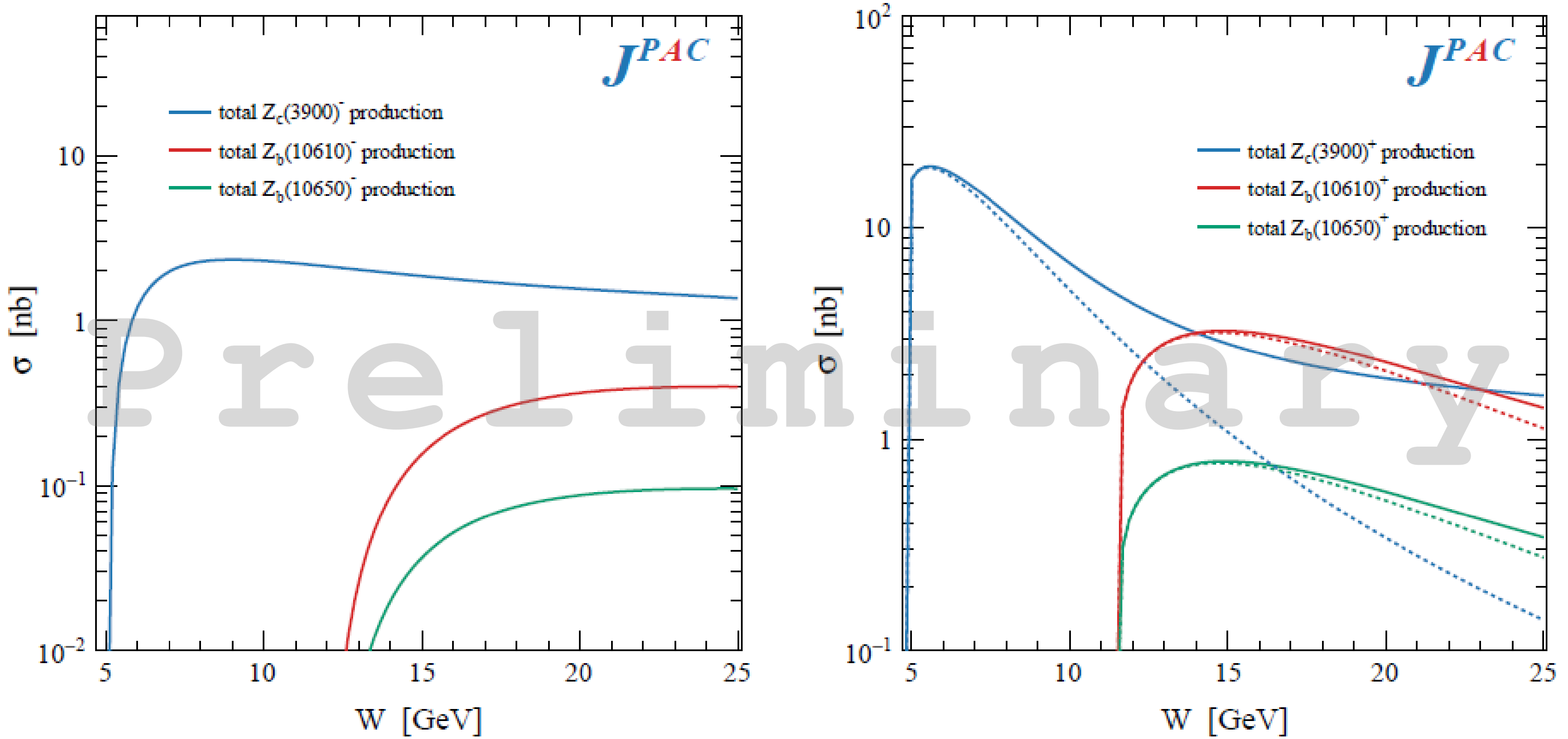
Diffractive semi-inclusive Z_c ph.



If the target fragments are separated from the beam ones, one can invoke Regge factorization

Quark-Regge duality allows to replace the intermediate hadrons with Pomeron , prediction reliable for $x_B \sim 1$, $t \ll W_{\gamma p}^2$

Diffractive semi-inclusive Z_c ph.



An example of yield estimate

- Example with an ideal SuperCEBAF
- $E_{\text{lab}} \sim 20$ GeV, photon flux $10^8\ \gamma/\text{s}$
- Typical target, $500\ \text{pb}^{-1}$ /yr
- Assuming efficiency 1%

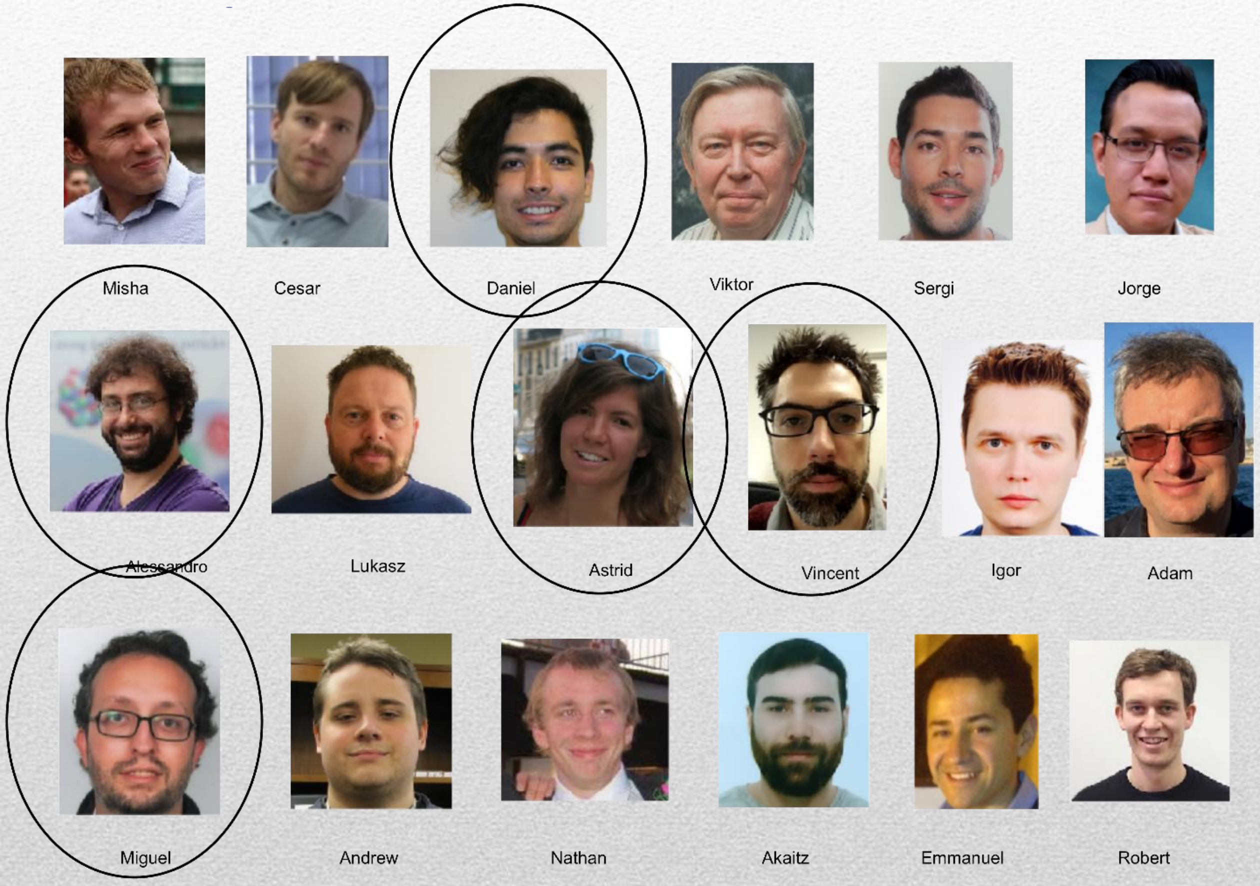
	$W_{\gamma p}$ (GeV)	σ (nb)	$\mathcal{B}(\mathcal{Q} \to \ell^+\ell^-\, n\pi)$ $(\times 10^{-3})$	Counts	Comparison
$X(3872)$	6	33.1	5.3	877	~ 90 [52]
$Z_c(3900)^+$		15.9	12.5	994	~ 1300 [15]
$Z_b(10610)^+$	15	2.8	2.6	36	~ 750 [53]
$Z_b'(10650)^+$		0.66	2.1	7	~ 200 [53]
			$\mathcal{B}(J/\psi \to \ell^+\ell^-)^2$ $(\times 10^{-3})$		
$X(6900)$	12	1.9	14	133	~ 800 [32]

Conclusions

- Photoproduction is a valuable tool to study exotic states
- Complementary infomation to other mechanisms
- Facilities to study photoproduction at low energies are very welcome to pursue this program

Thank you!

Joint Physics Analysis Center



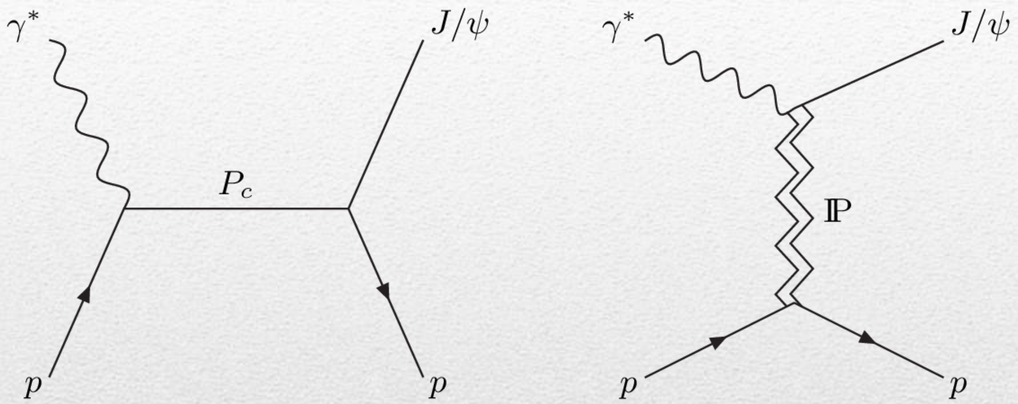
Exclusive reactions: 2008.01001

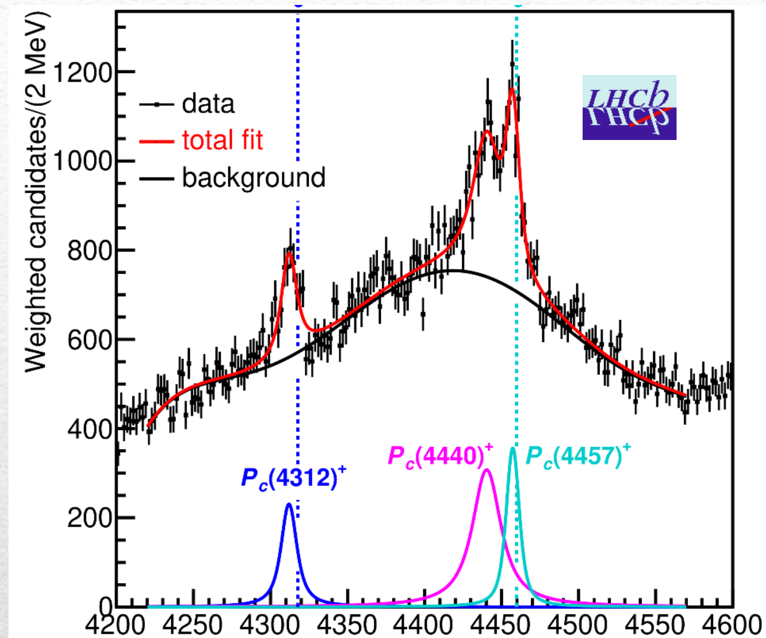
Inclusive reactions: to appear

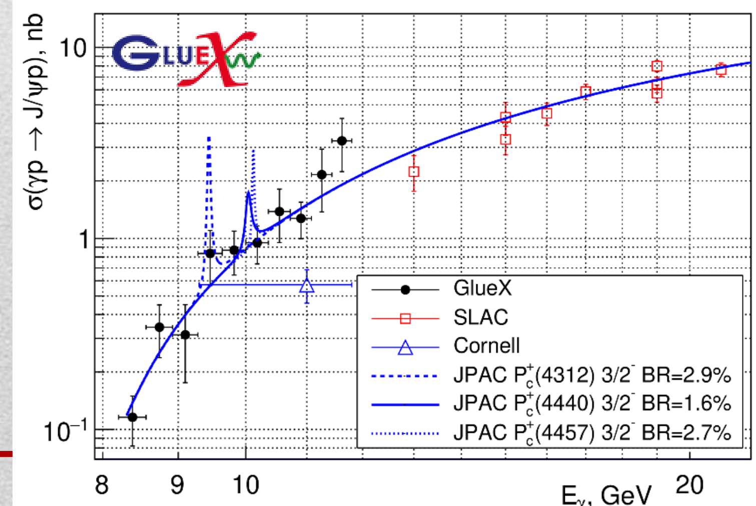
Code available on https://github.com/dwinney/jpacPhoto

BACKUP

Exclusive P_c photoproduction



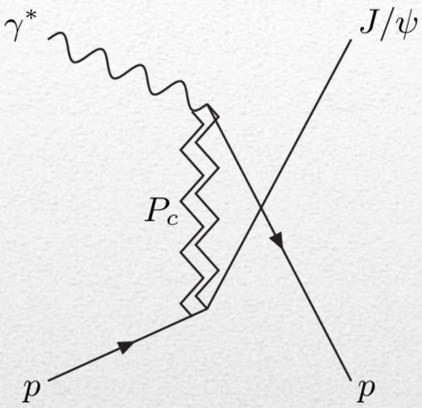


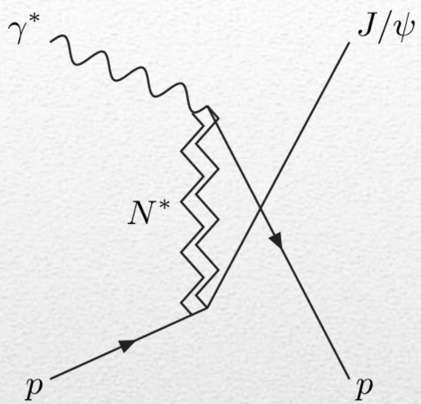


At Jlab12 measurements of direct P_c production are being performed

Using VMD, $\mathrm{BR}(P_c \to J/\psi\, p) \sim 1\%$

Polarized P_c photoproduction





$$\sim s^{\alpha(u)}$$

- s channel resonances significant at low energies:
  u channel dominates at high energies
- Main background from N(*) trajectories
- Estimated P_c coupling upper bound of same order of magnitude as $N^{(*)}$ coupling
- Reggeization suppresses P_c due to larger mass (smaller trajectory intercept)
- We estimate that the P_c trajectories will hardly be visible at the EIC
- P_b searches still possible: s channel at higher energies!

Cao et al., Phys.Rev. D 101, 074010 (2020)
E. Paryev, arXiv:2007.01172 [nucl-th] (2020)

Y (vector) photoproduction

- Focus on the 1^{--} $Y(4260) \to J/\psi\, \pi^+\pi^-$, check with $\psi' \to J/\psi\, \pi^+\pi^-$
- Diffractive production, dominated by Pomeron (2-gluon) exchange
- Good candidates for EIC: diffractive production increases with energy!
- We have $\gamma\psi$-pomeron coupling from our analyses 1606.08912, 1907.09393

How to rescale from J/ψ to ψ' ?

$$R_{\psi'} = \sqrt{\frac{g^2(\psi' \to \gamma g g)}{g^2(\psi \to \gamma g g)}} \sim 0.55$$

$$g^2(\psi \to \gamma g g) = \frac{6 m_\psi \mathcal{B}(\psi \to \gamma g g) \Gamma_\psi}{\mathrm{PS}(\psi \to \gamma g g)}$$

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How to rescale from J/ψ to $Y(4260)$?

We assume VMD and $g^2(Y \to \psi\pi\pi) = g^2(Y \to \psi g g) \times g^2(gg \to \pi\pi)$ (Novikov & Shifman)

$$R_Y = \frac{e f_\psi}{m_\psi} \sqrt{\frac{g^2(Y \to \psi\pi\pi)}{g^2(\psi \to \gamma g g)} \frac{g^2(\psi' \to \psi g g)}{g^2(\psi' \to \psi\pi\pi)}}$$

Caveat : $BR(Y \to \psi\pi\pi)$ only known times the leptonic width Γ_{ee}^Y

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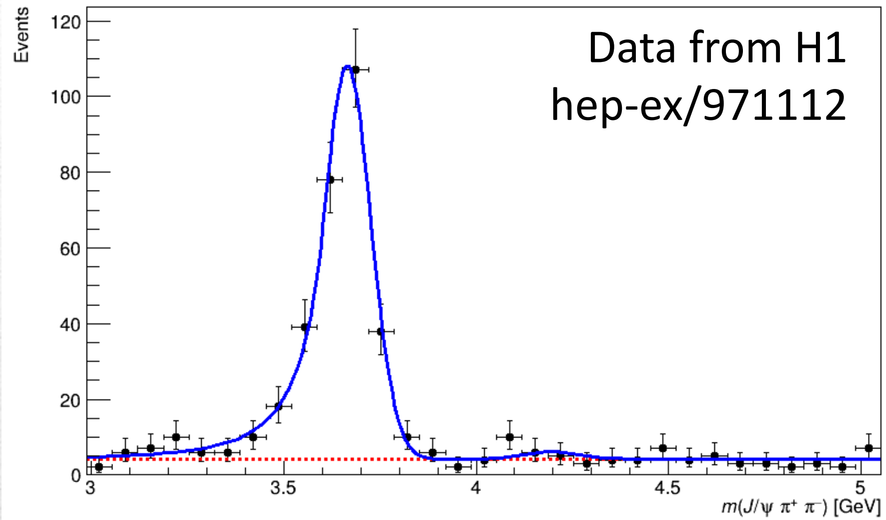

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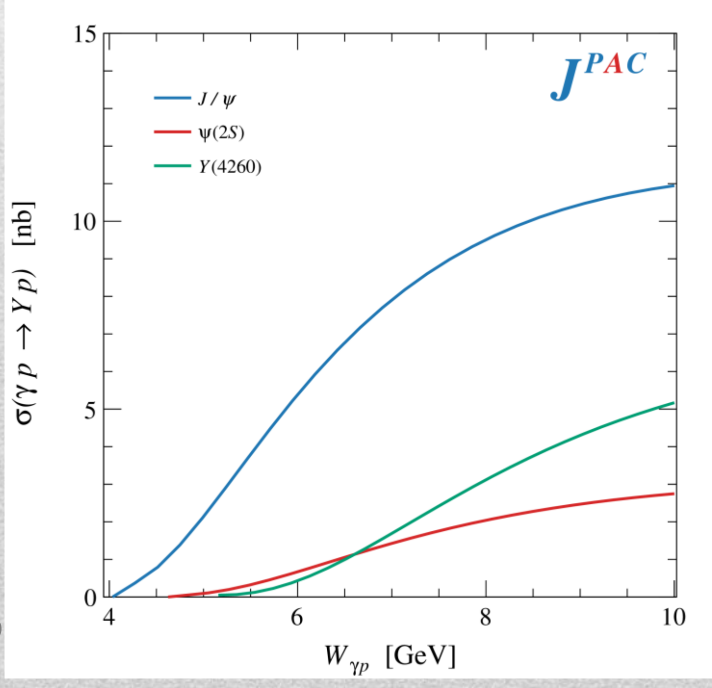
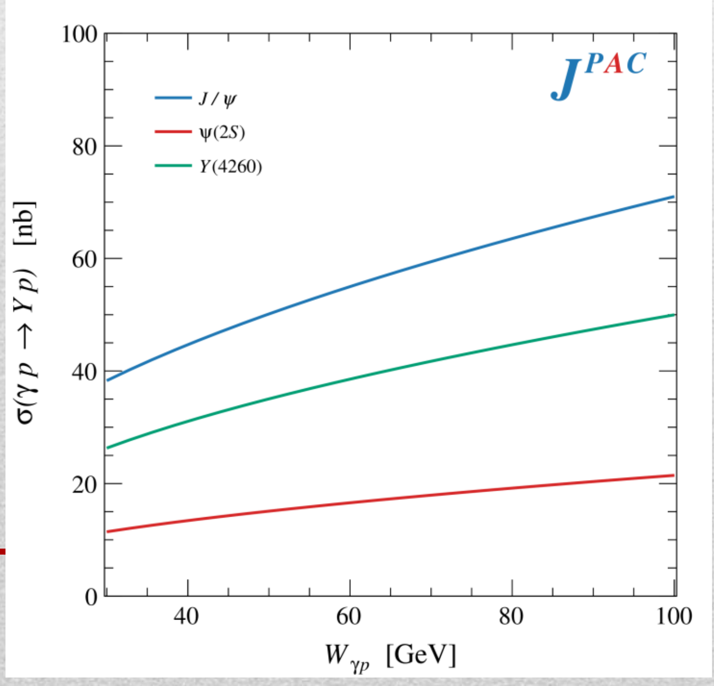
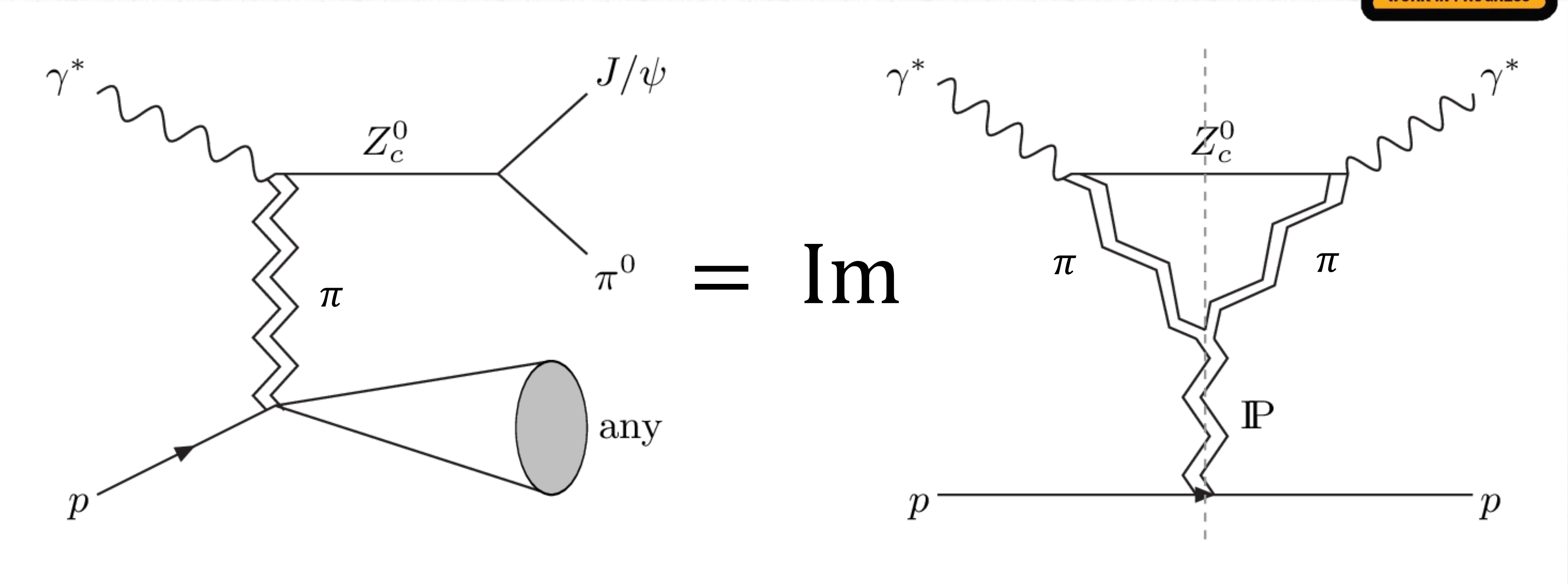
$BR(Y \to J/\psi\pi\pi) = 0.96\%$
$R_Y = 0.84$





Diffractive semi-inclusive Z_c ph.



If the target fragments are separated from the beam ones, one can invoke Regge factorization

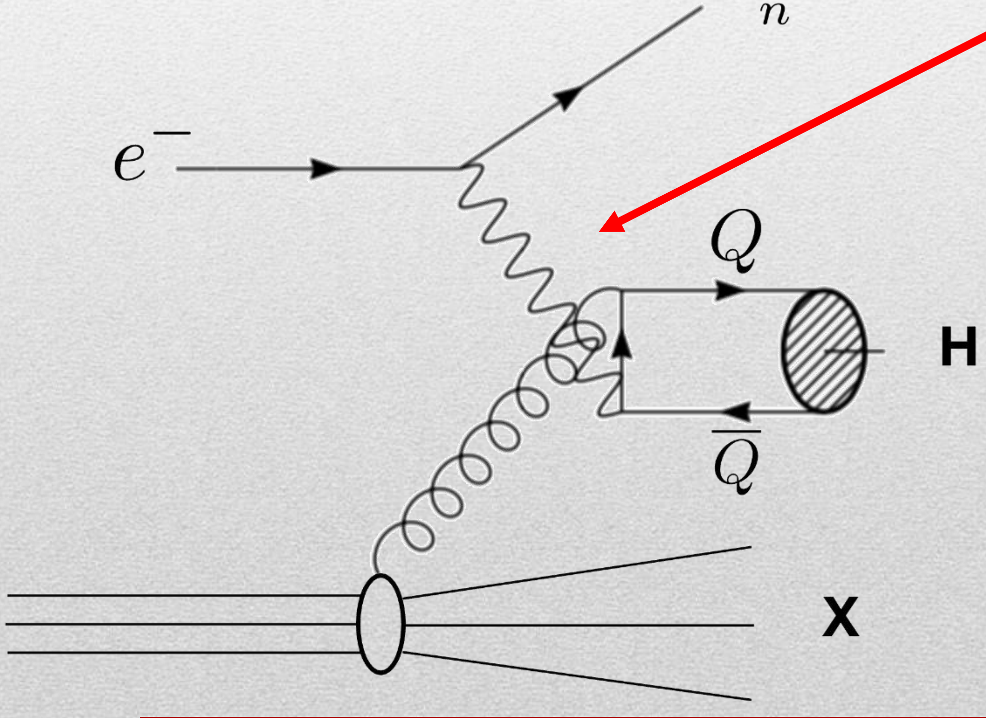
Quark-Regge duality allows to replace the intermediate hadrons with Pomeron , prediction reliable for $x_B \sim 1$, $t \ll W_{\gamma p}^2$

Semi-inclusive X production

X. Yao

For large Q^2 one can invoke NRQCD factorization
to describe quarkonium(-like) production

$$d\sigma(e^- + p \to H + X) = \sum_n d\sigma(e^- + p \to Q\overline{Q}(n) + X)\langle\mathcal{O}^H(n)\rangle$$



Perturbative partonic
matrix element, calculable

Nonperturbative transition
matrix element $Q\bar{Q} \to H$
fitted from data

Semi-inclusive X production

One can assume the same NRQCD factorization for exotics, independent of their internal structure

$$\sigma[X(3872)] = \sum_n \hat{\sigma}[c\bar{c}_n] \, \langle \mathcal{O}_n^X \rangle$$

$$\mathrm{Br}[X \to J/\psi \pi^+ \pi^-] \left(\langle \mathcal{O}_8^X(^3S_1) \rangle + 0.159 \, \langle \mathcal{O}_8^X(^1S_0) \rangle + 0.085 \, \langle \mathcal{O}_1^X(^1S_0) \rangle \right.$$
$$\left. + 0.00024 \, \langle \mathcal{O}_1^X(^3S_1) \rangle \right) = (2.7 \pm 0.6) \times 10^{-4} \ \mathrm{GeV}^3$$

Artoisenet and Braaten, PRD81, 114018 from Tevatron data

If one consider the first term only, it leads to

$$\mathrm{Br}[X \to J/\psi \pi^+ \pi^-] \sigma(X(3872), Q^2 > 1 \ \mathrm{GeV}) \approx 2.6 \ \mathrm{pb} \qquad \sqrt{s} = 100 \ \mathrm{GeV}$$

X. Yao