Opportunities for hadron spectroscopy @JLab hi-lumi/hi-energy

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NStar, October 19th, 2022

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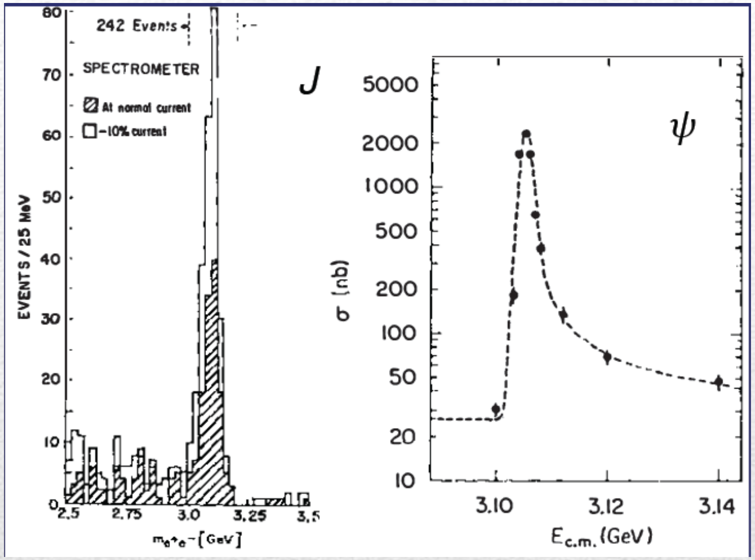
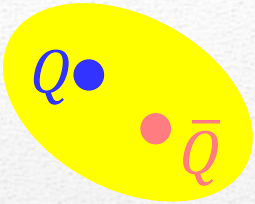
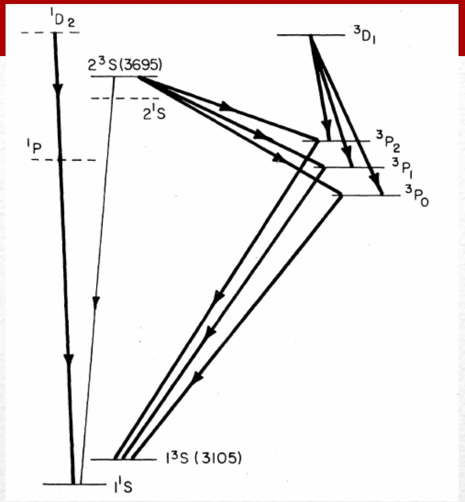
Quarkonium orthodoxy







$$\alpha_s(M_Q) \sim 0.3$$

(perturbative regime)

OZI-rule, QCD multipole

Heavy quark spin flip suppressed by quark mass, approximate heavy quark spin symmetry (HQSS)

Potential models

(meaningful when $M_Q \to \infty$)

$$V(r) = -\frac{C_F\alpha_s}{r} + \sigma r$$

(Cornell potential)

Solve NR Schrödinger eq. → spectrum

Effective theories

(HQET, NRQCD, pNRQCD...)

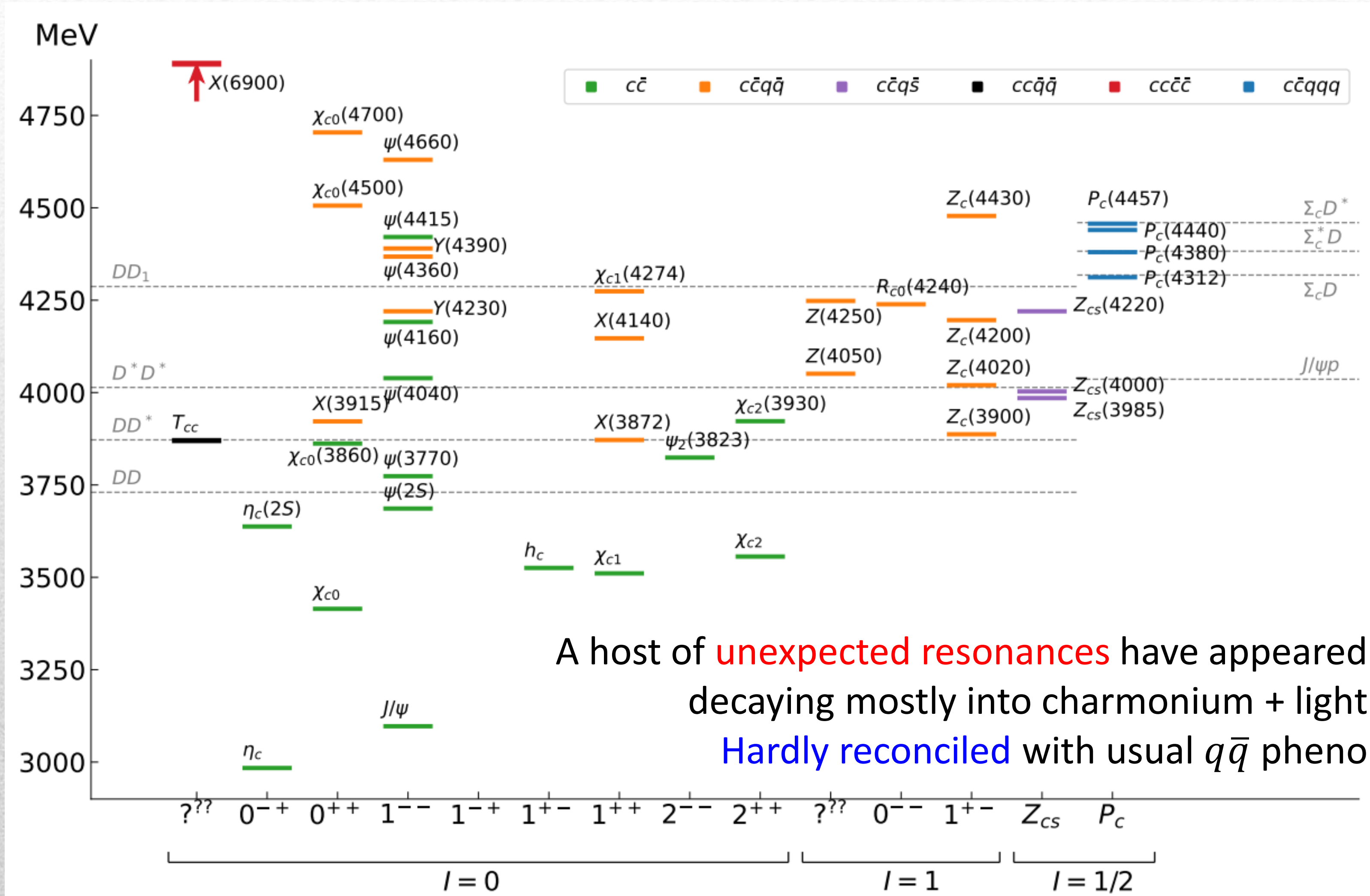
Integrate out heavy DOF

↓

(spectrum), decay & production rates

Exotic landscape in $c\bar{c}$

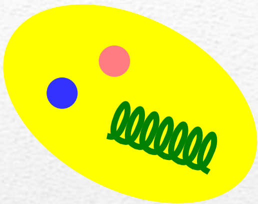
Esposito, AP, Polosa, Phys.Rept. 668
JPAC, arXiv:2112.13436



A host of unexpected resonances have appeared
decaying mostly into charmonium + light
Hardly reconciled with usual $q\bar{q}$ pheno

Models

Compact

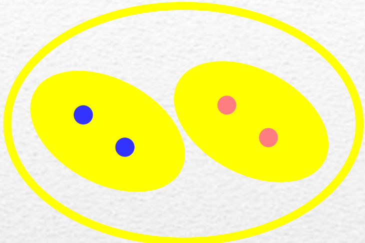


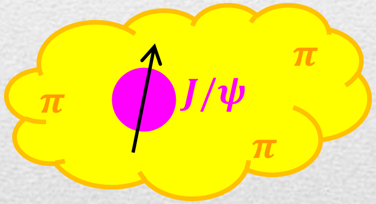
Hybrids

Containing gluonic degrees of freedom

Multiquark

Several (cluster) of valence quarks



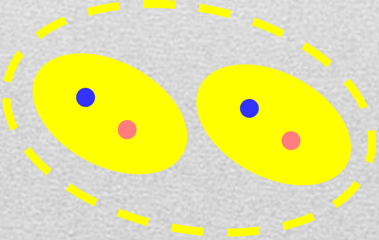


Hadroquarkonium

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^-:
$X(3872), Y(4260), Z_{c,b}^{(\prime)}$

XYZ at Jefferson Lab

***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]

arXiv:2203.08290

LoI RF7_RF0_120

arXiv:2112.00060

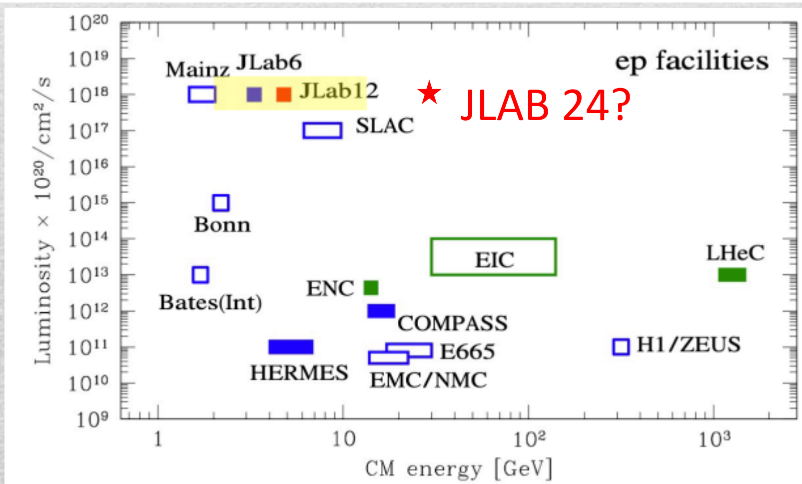
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Hadron Spectroscopy in Photoproduction

Miguel Albaladejo[1], Lukasz 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]

Physics with CEBAF at 12 GeV and Future Opportunities

J. Arrington[1], M. Battaglieri[2,15], A. Boehnlein[2], S.A. Bogacz[2], W.K. Brooks[10], E. Chudakov[2], I. Cloët[3], R. Ent[2],
H. Gao[4], J. Grames[2], L. Harwood[2], X. Ji[5,6], C. Keppel[2], G. Krafft[2], R. D. McKeown[2,8,*], J. Napolitano[7], J.W. Qiu[2,8],
P. Rossi[2,14], M. Schram[2], S. Stepanyan[2], J. Stevens[8], A.P. Szczepaniak[12,13,2], N. Toro[9], X. Zheng[11]



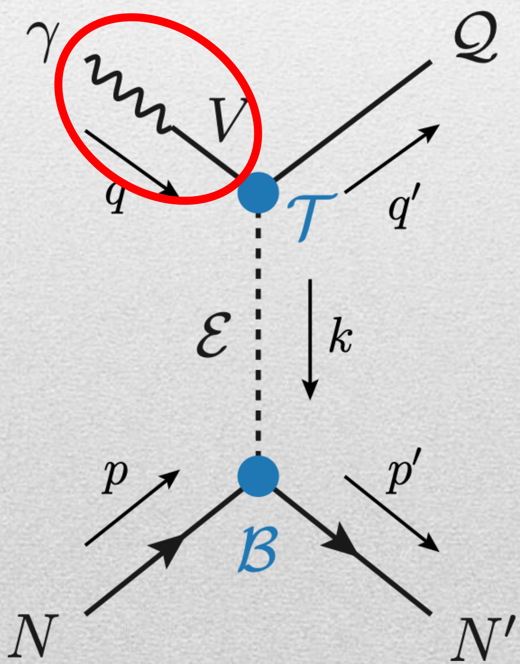
Explore the complementarity
wrt the forthcoming Electron Ion Collider

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



M. Albaladejo et al. [JPAC], PRD

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

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

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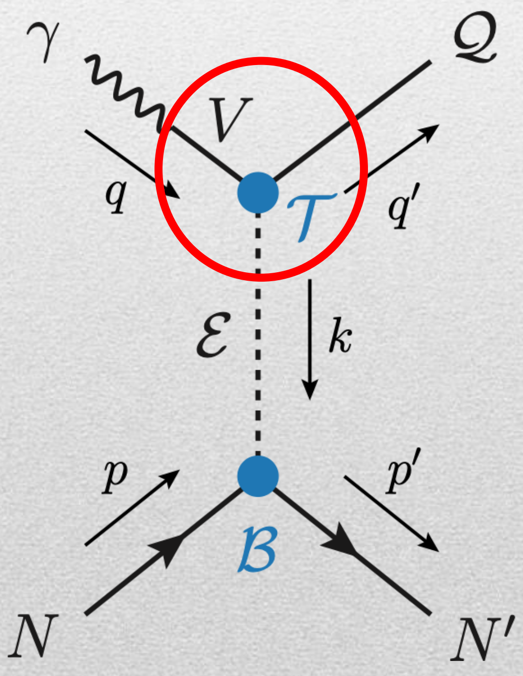

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Top vertex from measured $\mathcal{Q} \to V\mathcal{E}$ decay width

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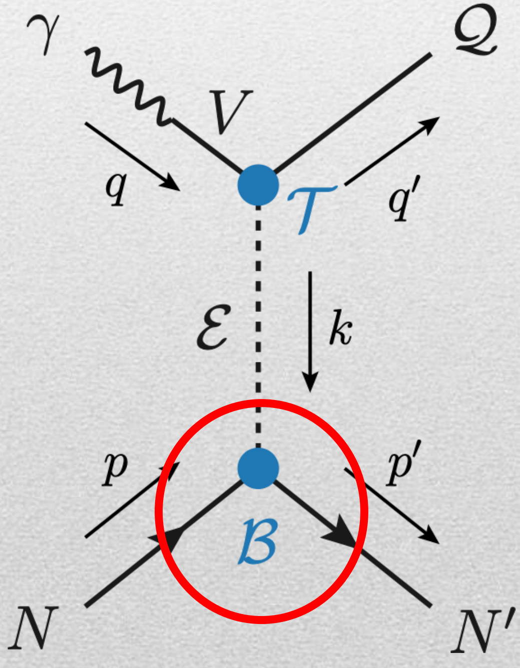

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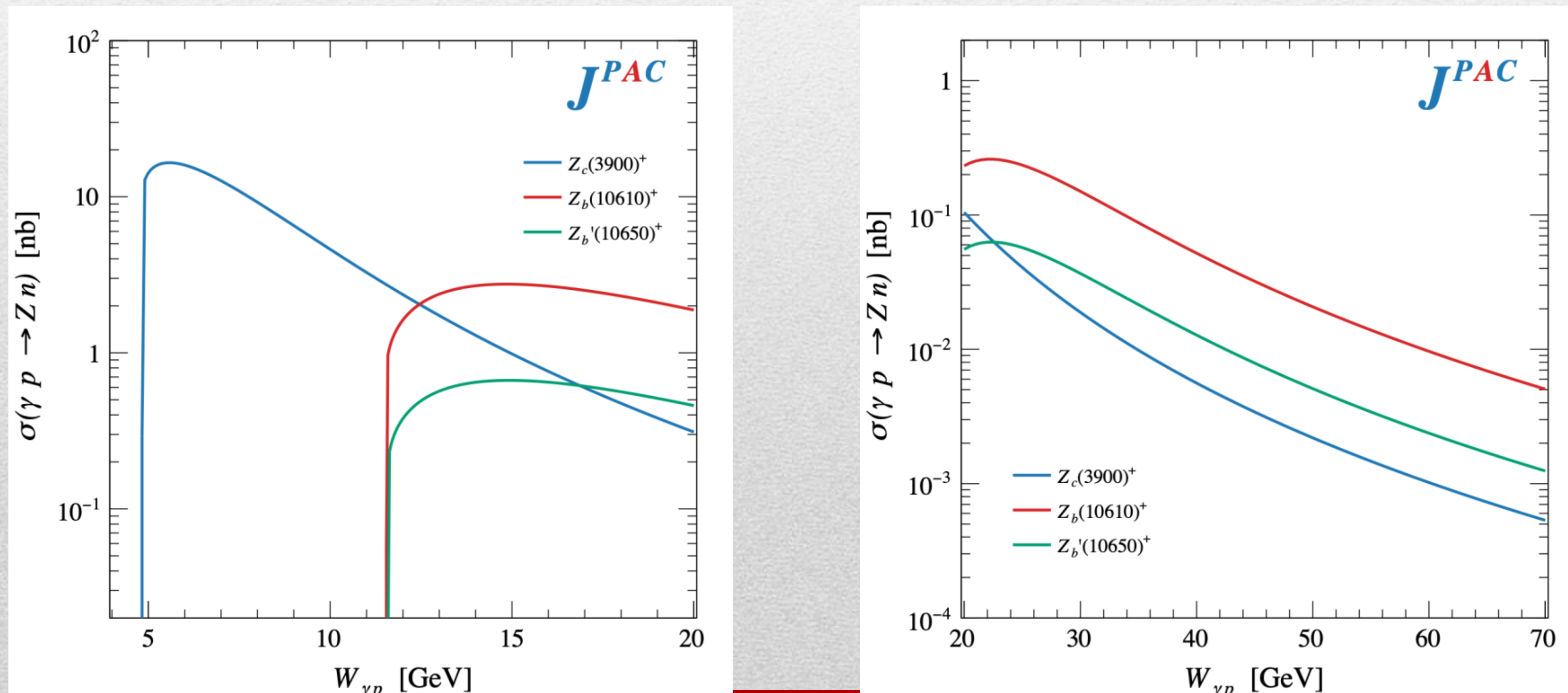
Bottom vertex from standard photoproduction pheno, exponential form factors to further suppress large t

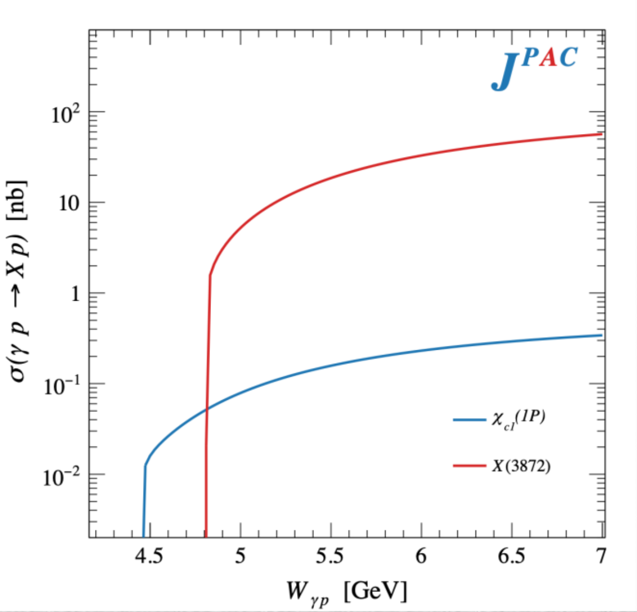
Z photoproduction

- 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

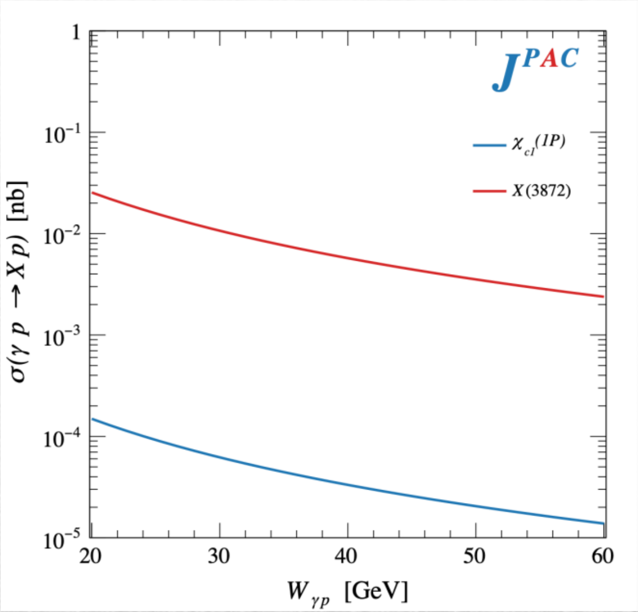


X photoproduction

- Focus on the famous 1^{++} $X(3872) \to J/\psi\ \rho, \omega$
- **ω** and **ρ** exchanges give main contributions:



Large theory uncertainty in the intermediate region



Y (vector) photoproduction

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

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

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

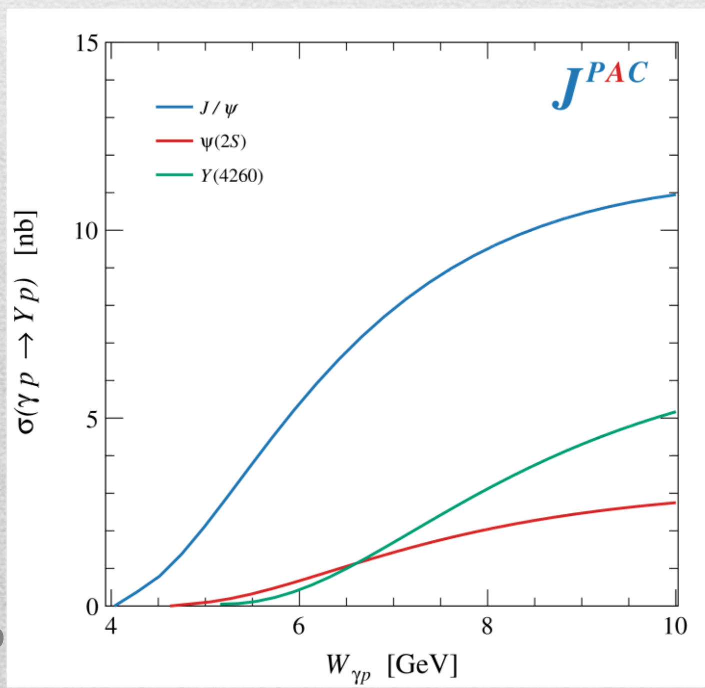
Assuming previous formula, one gets:

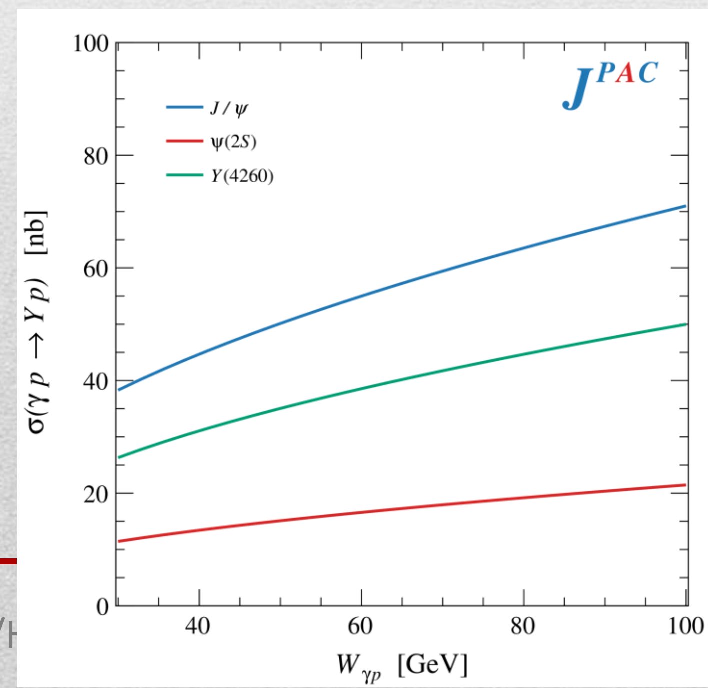
$\Gamma_{ee}^{Y} = 930\ eV$

(cfr. hep-ex/0603024, 2002.05641)

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

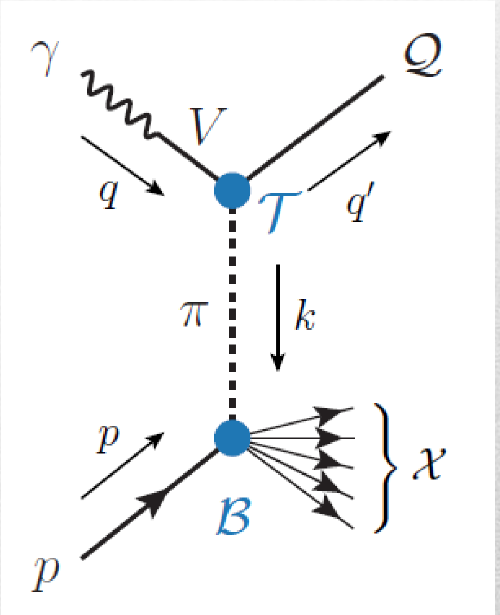
$R_Y = 0.84$

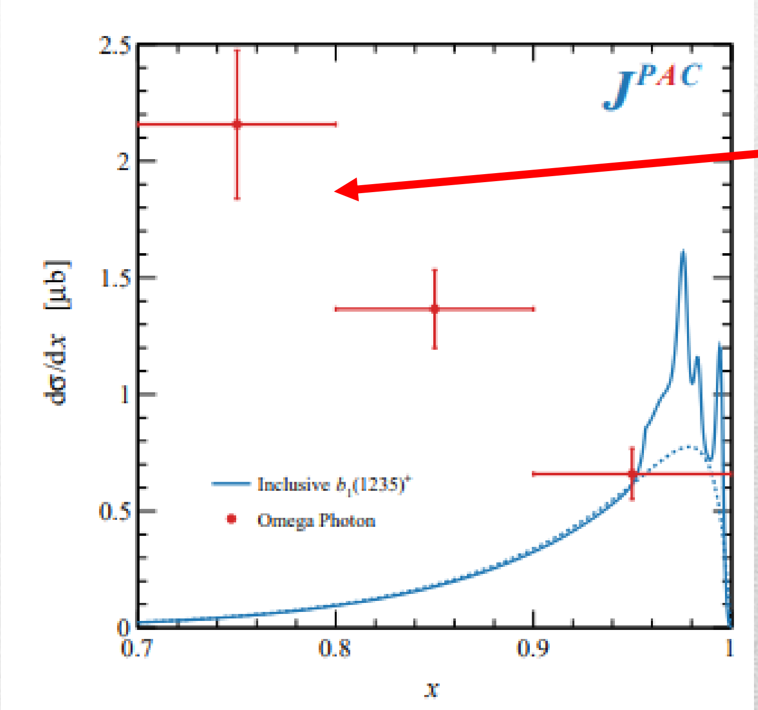




Semi-inclusive photoproduction

- Semi-inclusive cross sections are typically larger
- For small t and large x, one can assume the process to be dominated by pion exchange
- The bottom vertex depends on the (known) pion-proton total cross section
- The pion is exchanged in the t-channel
- Model benchmarked on b_1 production



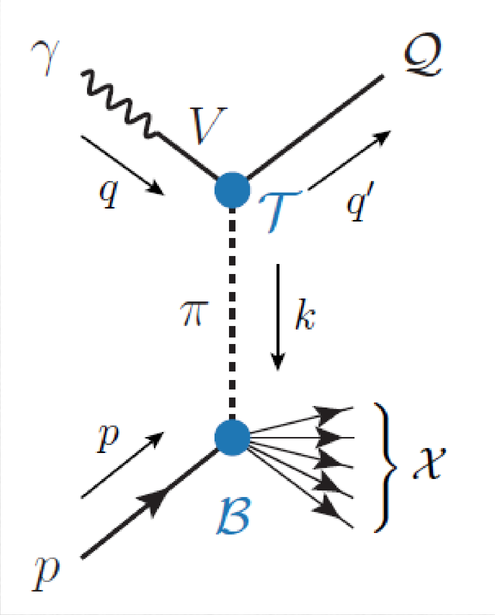


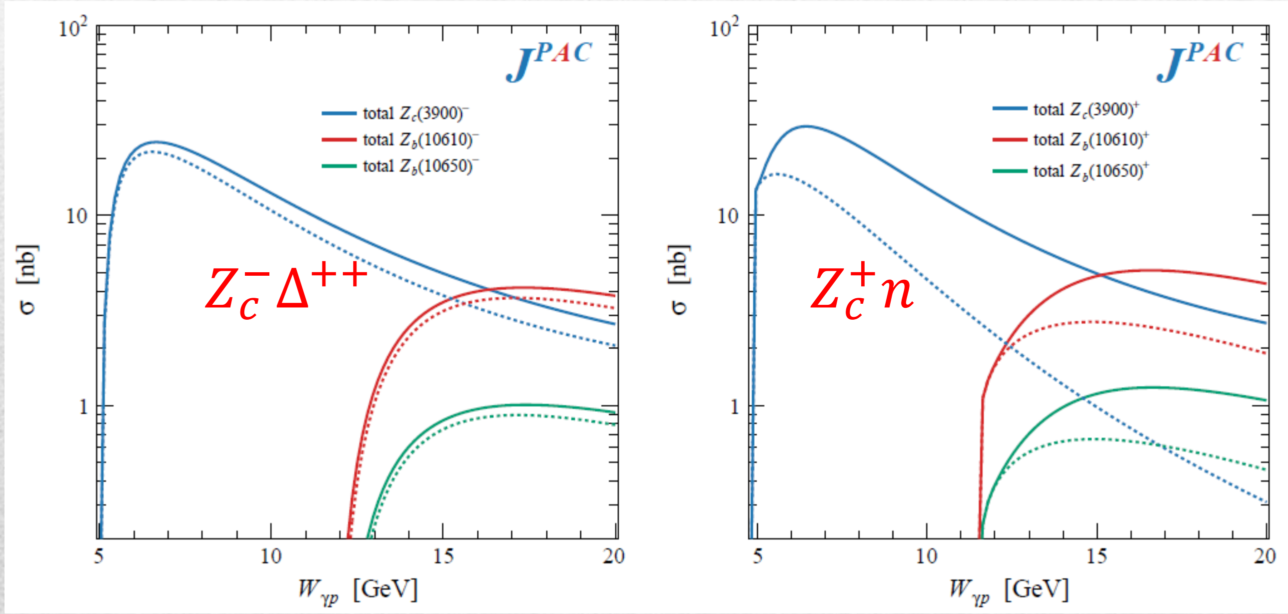
Model underestimates lower bins, conservative estimates

The model is expected to hold in the highest bin

Semi-inclusive photoproduction

- For the Z_c^+, the inclusive cross section is sizably larger than the exclusive process



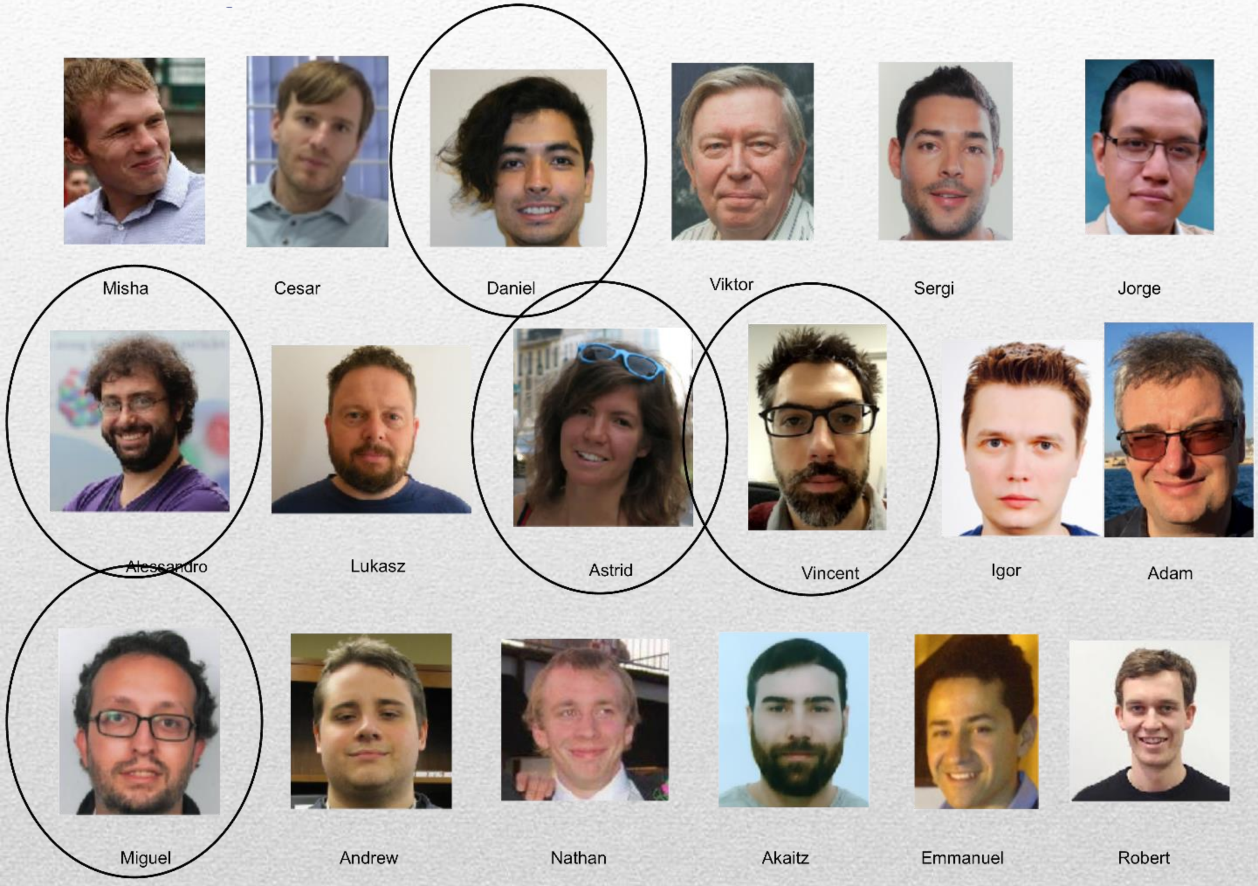


Conclusions

- 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:
2209.05882

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

BACKUP

Some thoughts about high intensity

- At current energies, the only heavy exotic accessible are pentaquarks, negative results from JLab pose a conundrum:
  - Rescattering mechanisms proposed so far are not doing a good job in describing all the peaks
  - All models point to direct-channel physics:
    must see in photoproduction!
    Need estimates of BR that go beyond VMD

- Light spectroscopy notoriously requires complicated PWA, high statistics can be a blessing and a curse
  - Looking for rare channels simpler to reconstruct of interest,
    ex.: radiative decays of (hybrid) mesons?
    Requires more theory effort

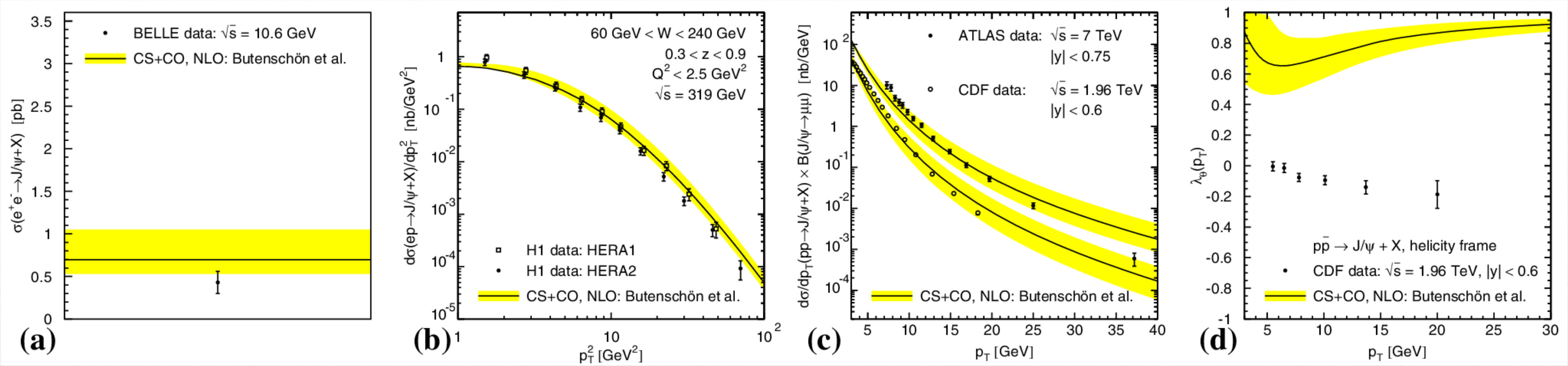
Multiscale system

Systematically integrate out the heavy scale, $m_Q \gg \Lambda_{QCD}$

$$m_Q \gg m_Q v \gg m_Q v^2$$

Full QCD → NRQCD → pNRQCD

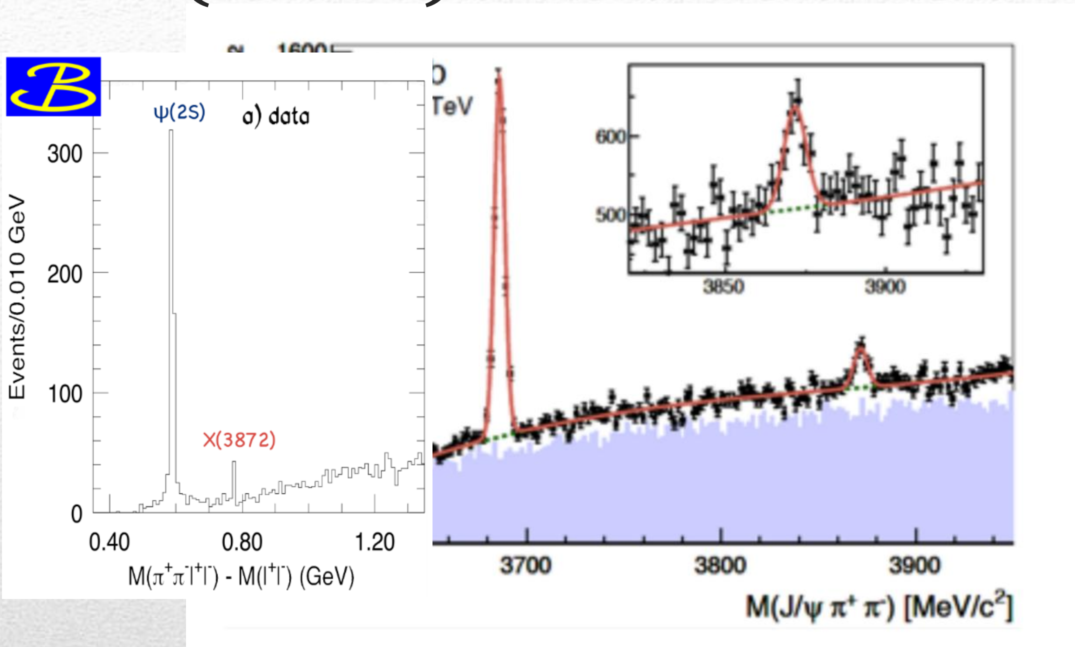
$m_b \sim 5\ \text{GeV}, m_c \sim 1.5\ \text{GeV}$
$v_b^2 \sim 0.1, v_c^2 \sim 0.3$



Factorization (to be proved) of universal LDMEs

Good description of many production channels, some known puzzles (polarizations)

$X(3872)$

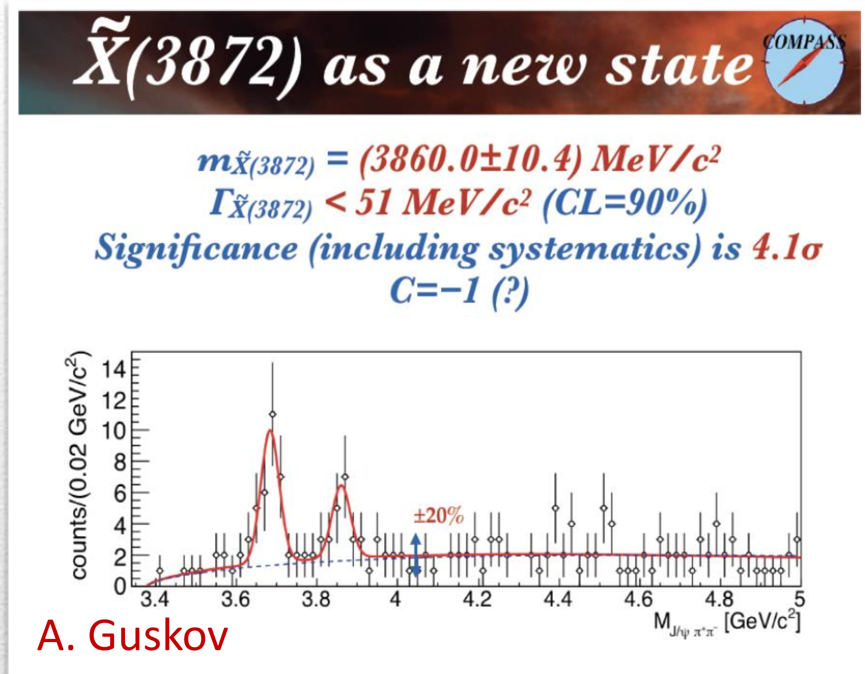


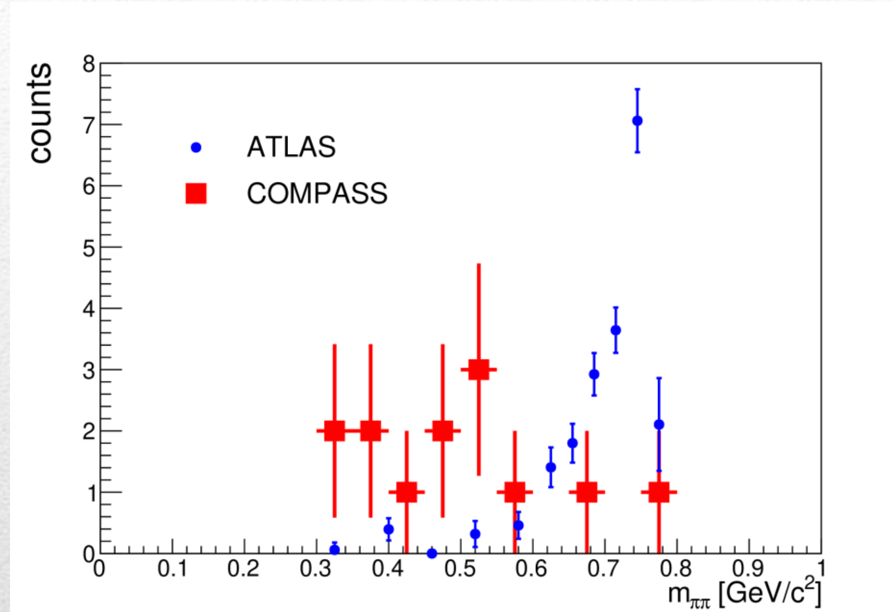
- Discovered in
  $B \to K\, X \to K\, J/\psi\, \pi\pi$
- Quantum numbers 1^{++}
- Very close to DD^* threshold
- Too narrow for an above-treshold charmonium
- Isospin violation too big
  $\frac{\Gamma(X\to J/\psi\ \ \omega)}{\Gamma(X\to J/\psi\ \ \rho)} \sim 1.1 \pm 0.4$
- Mass prediction not compatible with $\chi_{c1}(2P)$

$$M = 3871.65 \pm 0.06\ \mathrm{MeV}$$
$$M_X - M_{DD^*} = -44 \pm 120\ \mathrm{keV}$$
$$\Gamma = 1.19 \pm 0.19\ \mathrm{MeV}$$

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

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:

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

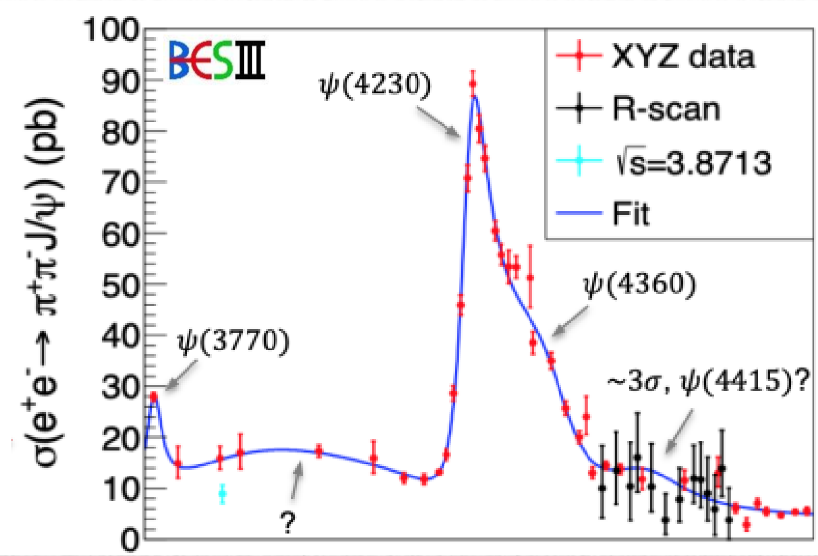
EIC **L=10^{34} cm^{-2} s^{-1}**

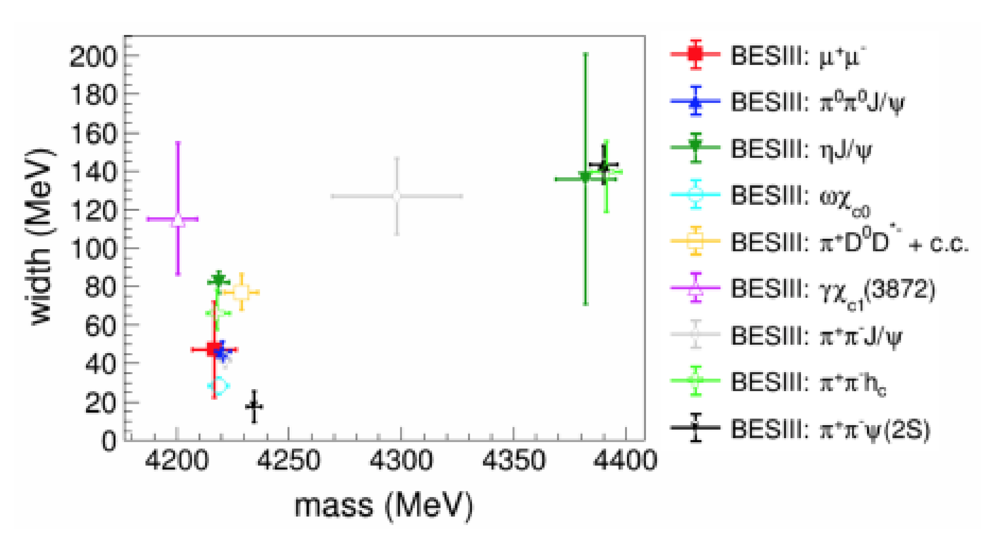
$$e^- N \to e^- \widetilde{X}(3872)\pi^\pm N' \to$$
$$\to e^- J/\psi \pi^+\pi^-\pi^\pm N' \to e^- \mu^+\mu^-\pi^+\pi^-\pi^\pm N'$$

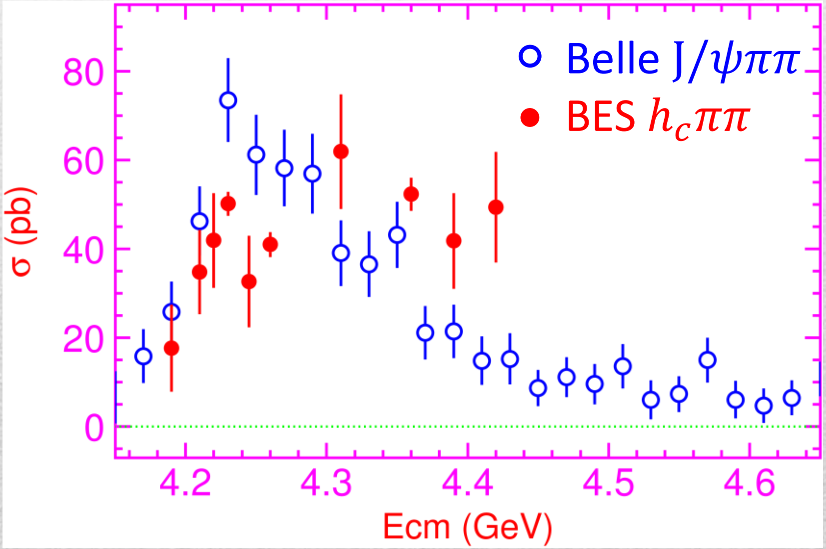
~10 events per day

Vector Y states

- Lots of unexpected $J^{PC} = 1^{--}$ states found in ISR/direct production (and nowhere else!)
- Seen in few final states, scarce consistency in different channels
- Large HQSS violation

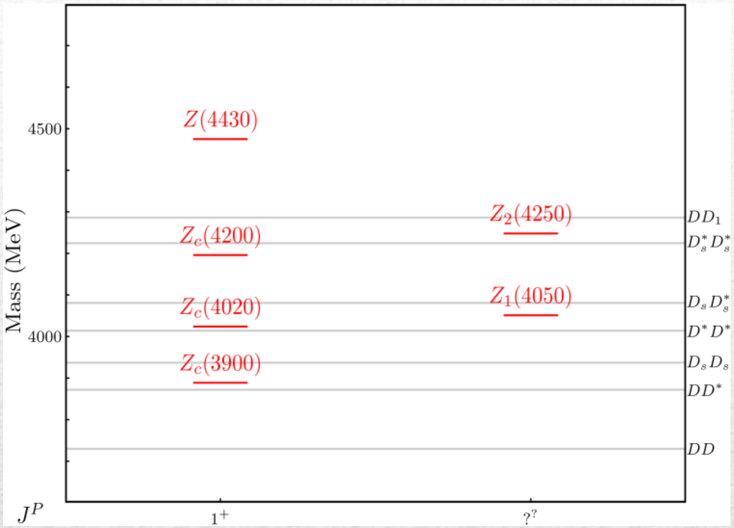






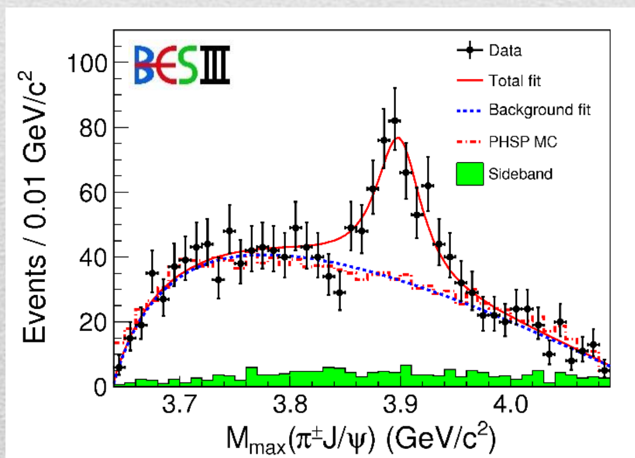
Charged Z states: $Z_c(3900), Z_c'(4020)$

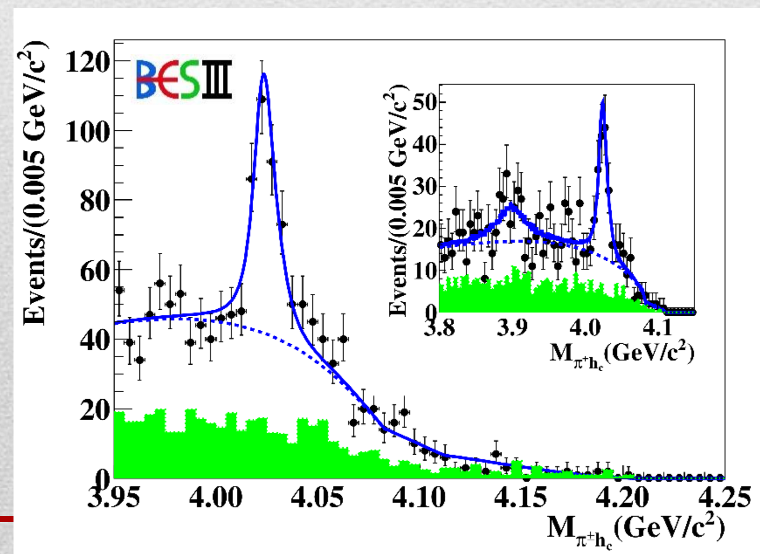
Charged quarkonium-like resonances have been found, **4q needed**



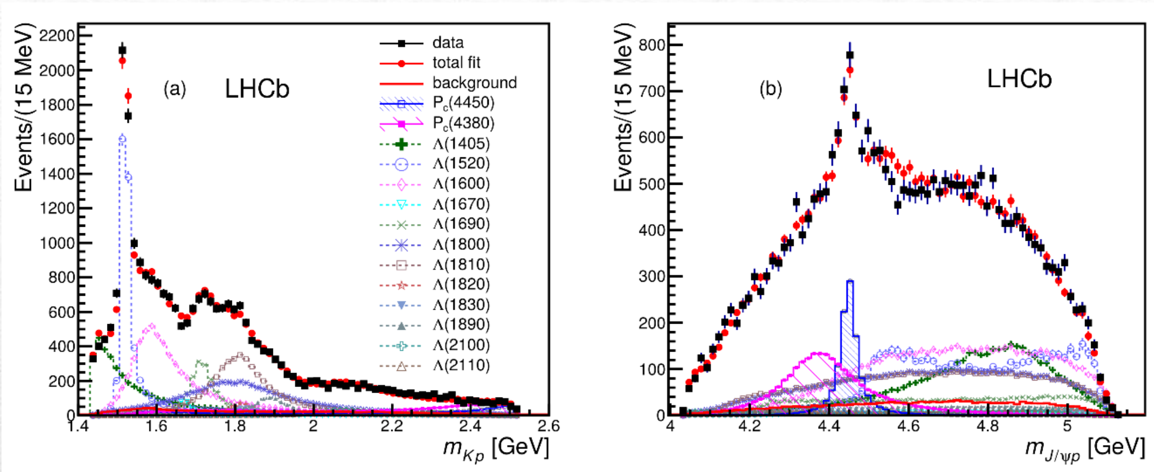
Two states $J^{PC} = 1^{+-}$ appear slightly above $D^{(*)}D^*$ thresholds

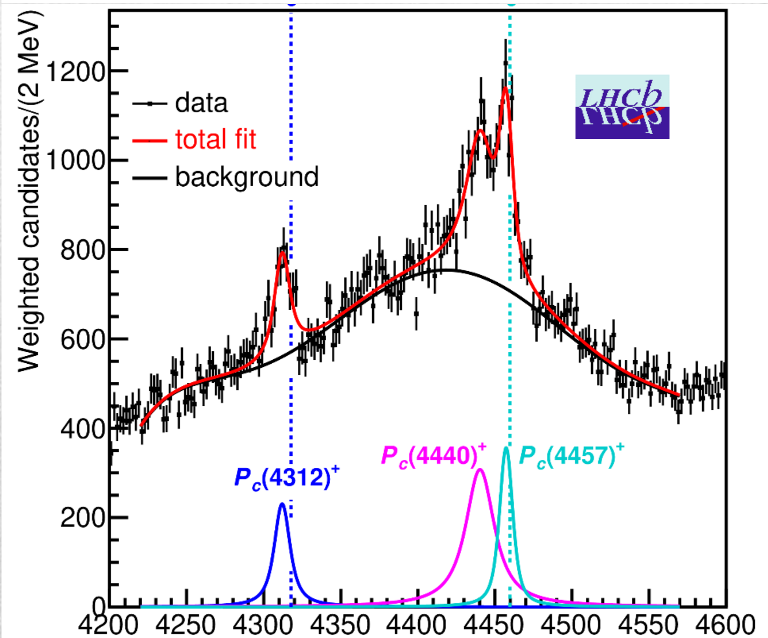
$$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\,\pi^+\pi^- \text{ and} \to (DD^*)^+\pi^-$$
$$M = 3888.7 \pm 3.4 \text{ MeV}, \Gamma = 35 \pm 7 \text{ MeV}$$
$$e^+e^- \to Z_c'(4020)^+\pi^- \to h_c\,\pi^+\pi^- \text{ and} \to \bar{D}^{*0}D^{*+}\pi^-$$
$$M = 4023.9 \pm 2.4 \text{ MeV}, \Gamma = 10 \pm 6 \text{ MeV}$$





Pentaquarks!





LHCb, PRL 115, 072001
LHCb, PRL 122, 222001

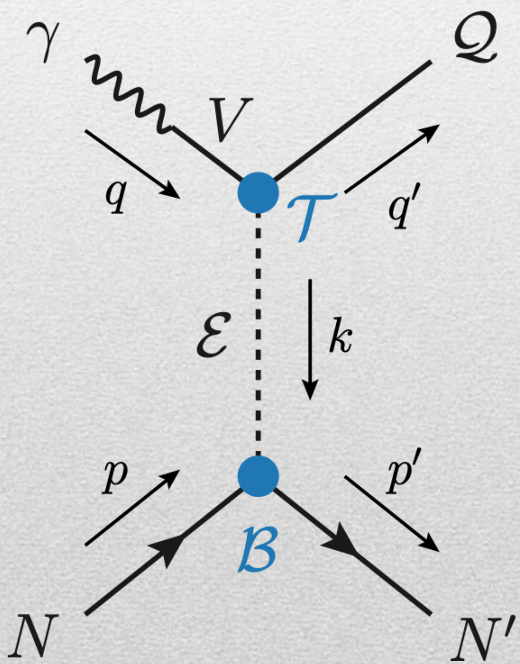
Three narrow states seen in
$\Lambda_b \to (J/\psi\, p)\, K^-$,
Plus a possible broad one

One narrow strange state in
$B^- \to (J/\psi\, \Lambda)\, \bar{p}$,

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

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

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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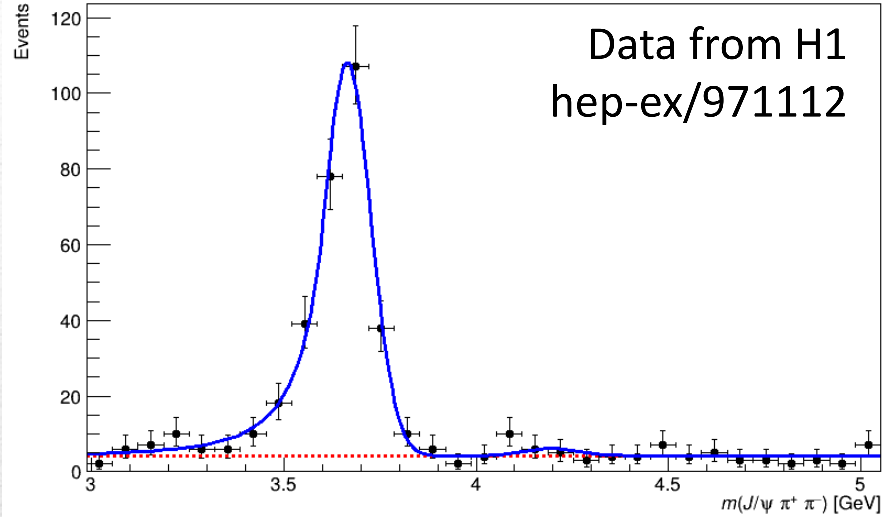
How to rescale from J/ψ to $Y(4260)$?

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

Y (vector) photoproduction



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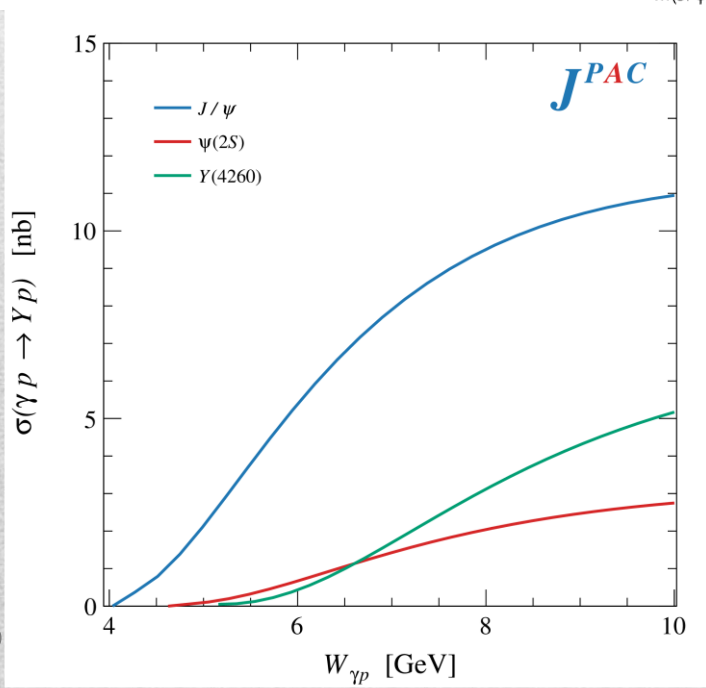
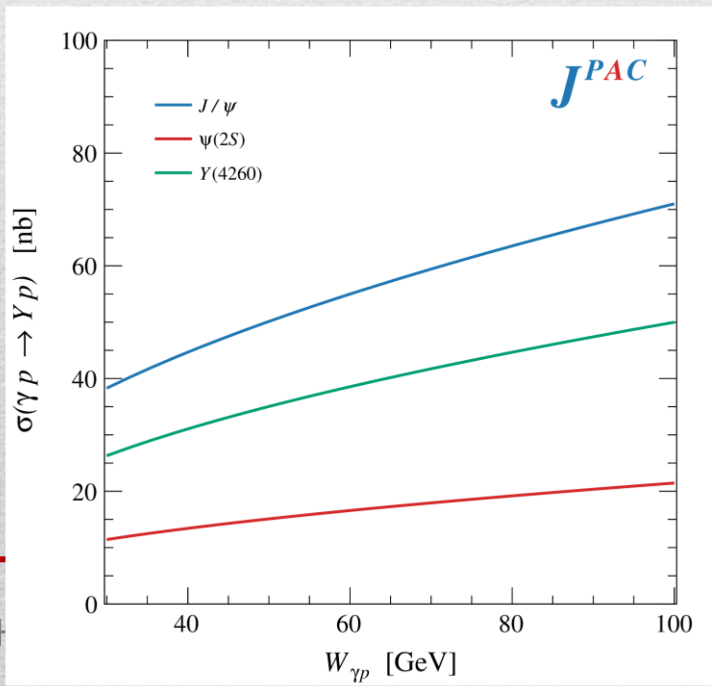
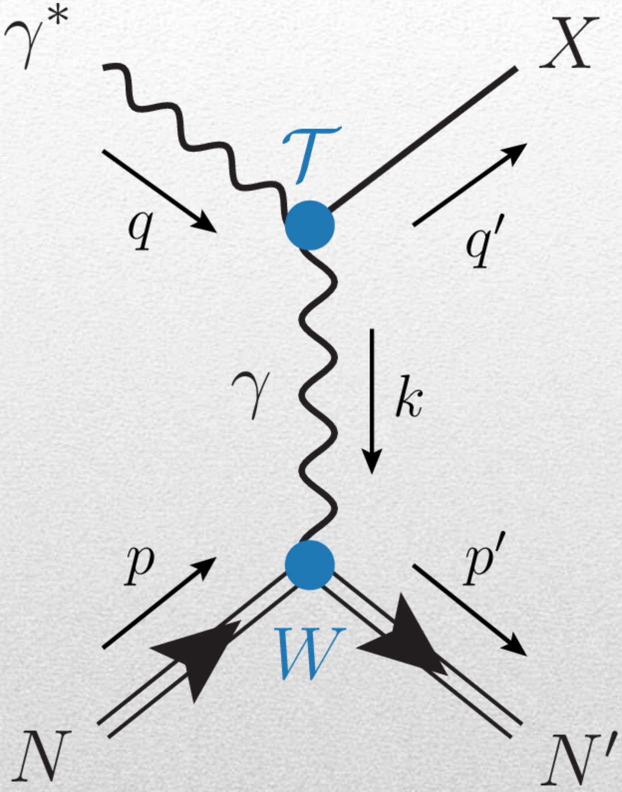
$BR(Y \to J/\psi\pi\pi) = 0.96\%$

$R_Y = 0.84$



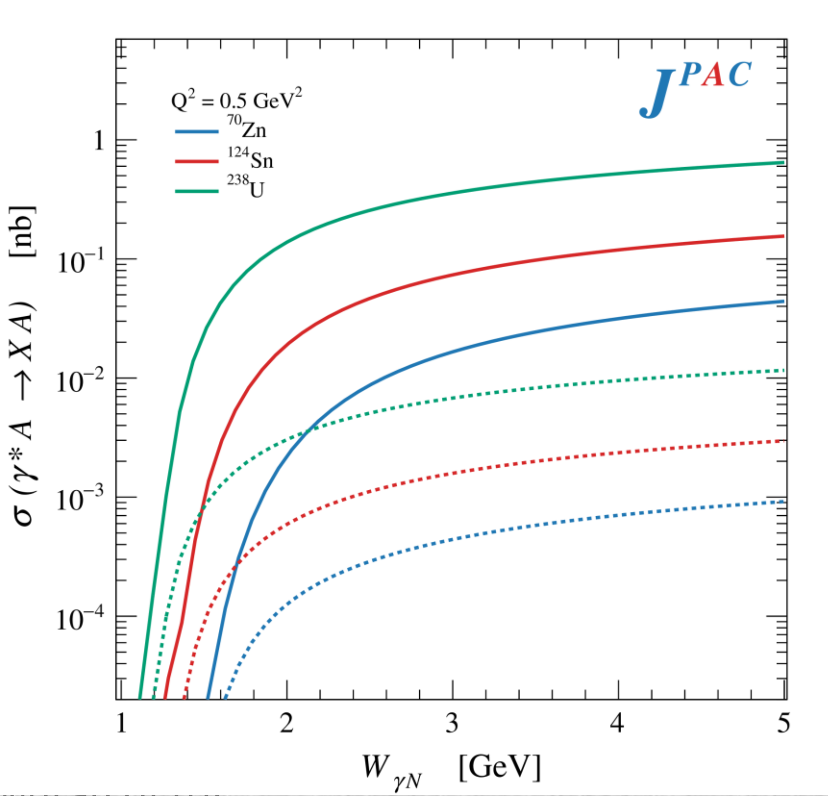


Primakoff X photoproduction



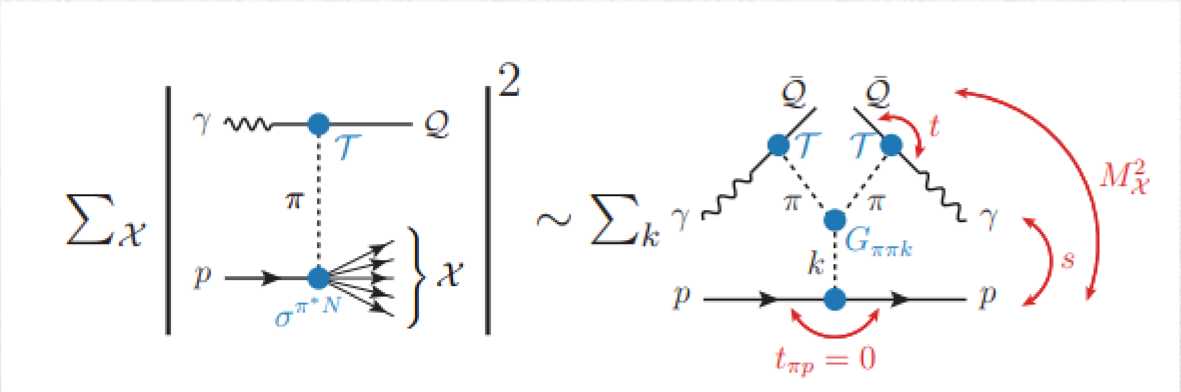
Using measurement of $\Gamma(\mathrm{X} \to \gamma\gamma^*)$ from Belle, one can get predictions for Primakoff

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



Semi-inclusive photoproduction

- At higher energies the triple Regge regime is reached, cross sections saturate



	$\sigma(\gamma p \to \mathcal{Q}^{\pm}\,\mathcal{X})$ [pb]			$\sigma(\gamma p \to \mathcal{Q}^{+} n)$ [pb]		
$\mathcal{Q}$	30 GeV	60 GeV	90 GeV	30 GeV	60 GeV	90 GeV
$b_1(1235)$	$60 \cdot 10^3$	$60 \cdot 10^3$	$61 \cdot 10^3$	43	2.3	$< 10^{-8}$
$Z_c(3900)$	187	146	140	19	1.0	$< 10^{-8}$
$Z_b(10610)$	163	15	5	150	10	$< 10^{-8}$
$Z_b(10650)$	40	4	1	37	2.4	$< 10^{-8}$