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

Alessandro Pilloni

Opportunities for Jlab upgrade, ECT*, September 26th, 1922

Università degli Studi di Messina

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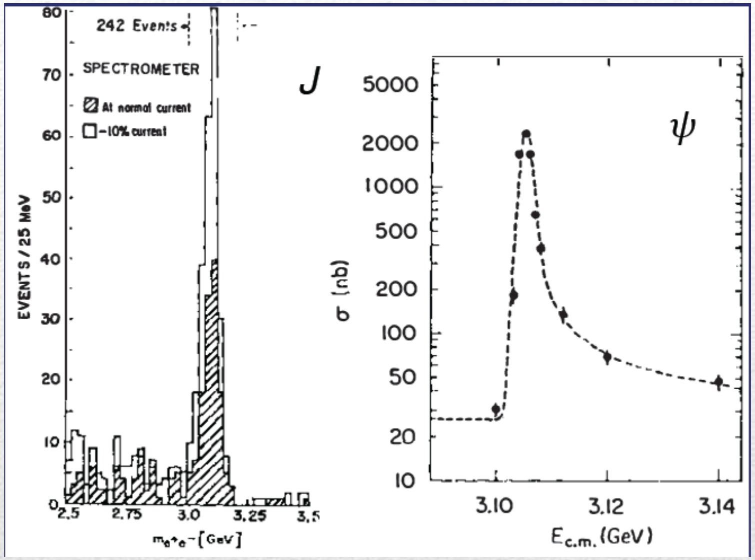
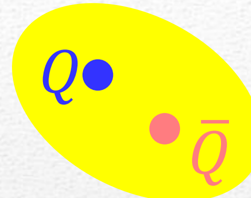
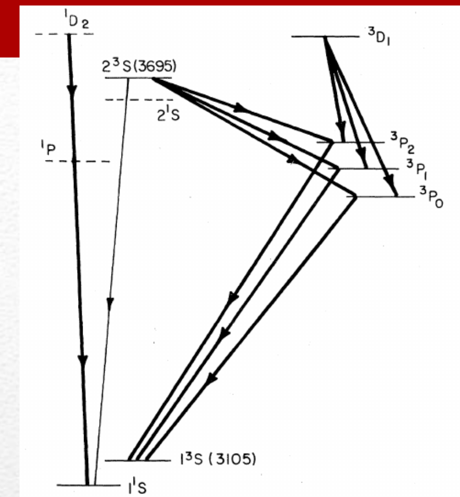
Quarkonium orthodoxy







$\alpha_s(M_Q) \sim 0.3$

(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

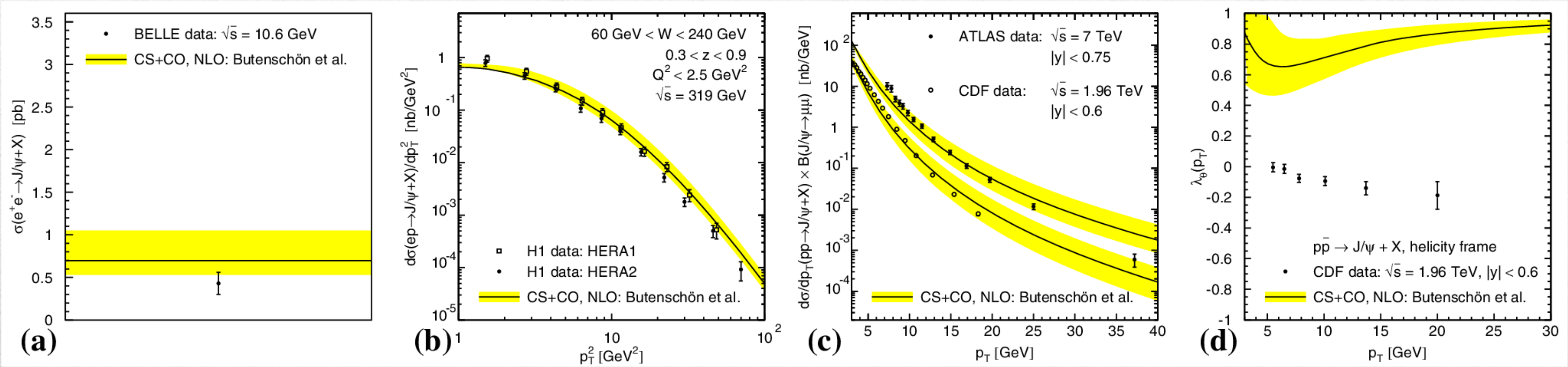
Multiscale system

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

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

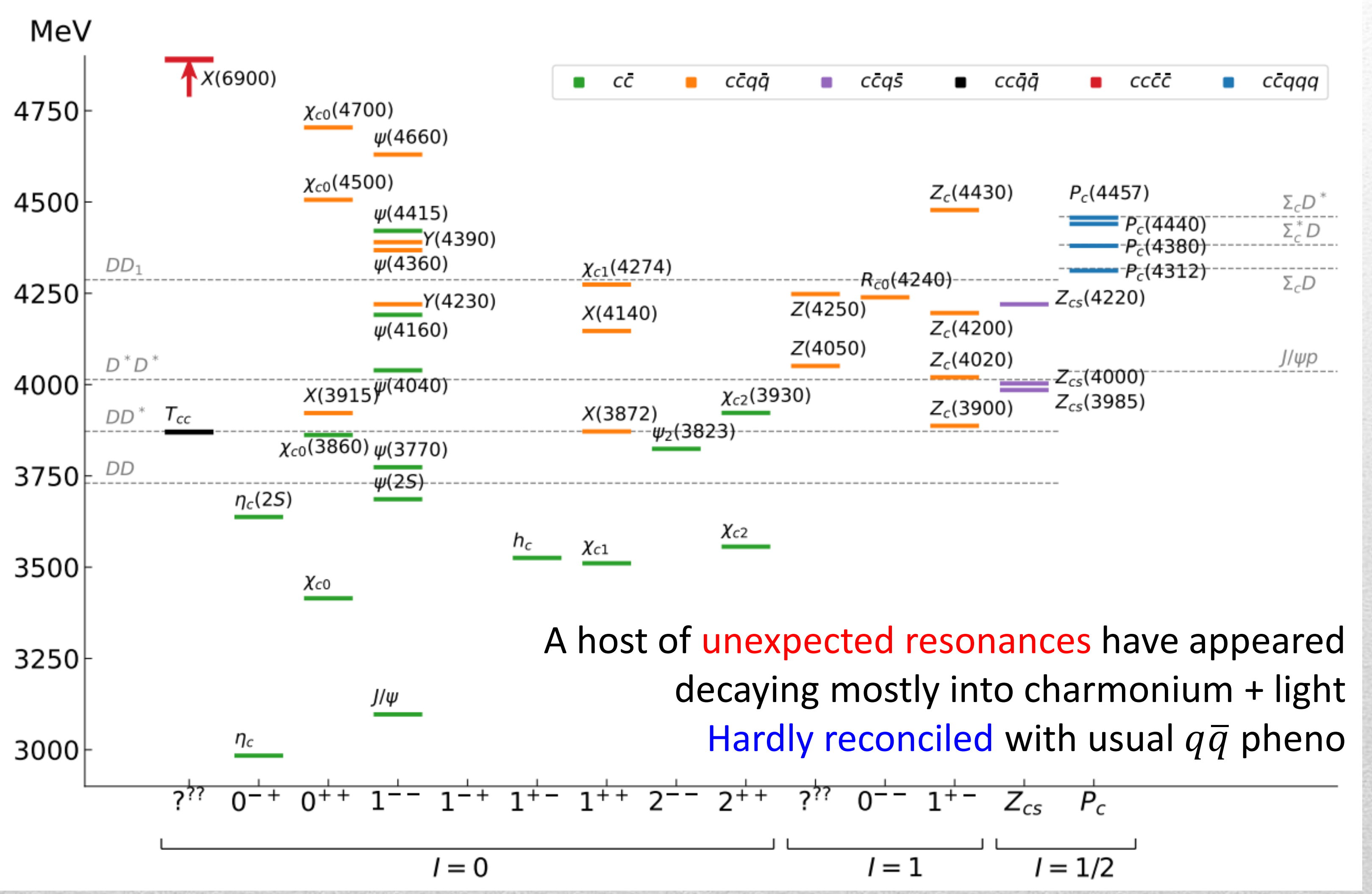


Factorization (to be proved) of universal LDMEs

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

Exotic landscape in $c\bar{c}$

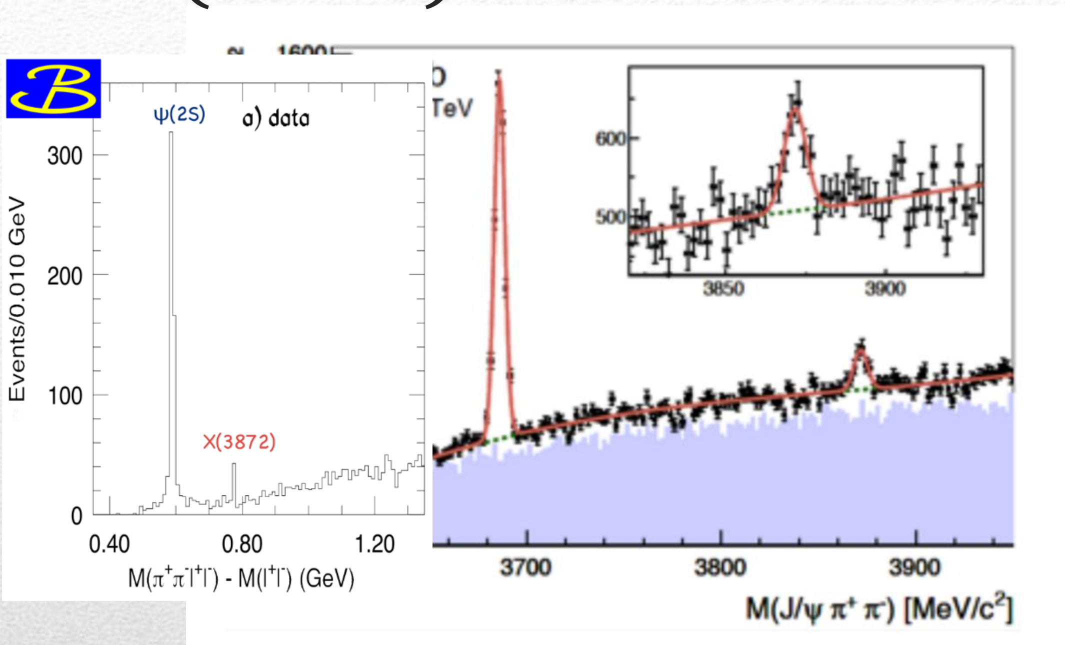
Esposito, AP, Polosa, Phys.Rept. 668
JPAC, arXiv:2112.13436



A host of unexpected resonances have appeared decaying mostly into charmonium + light

Hardly reconciled with usual $q\bar{q}$ pheno

$X(3872)$

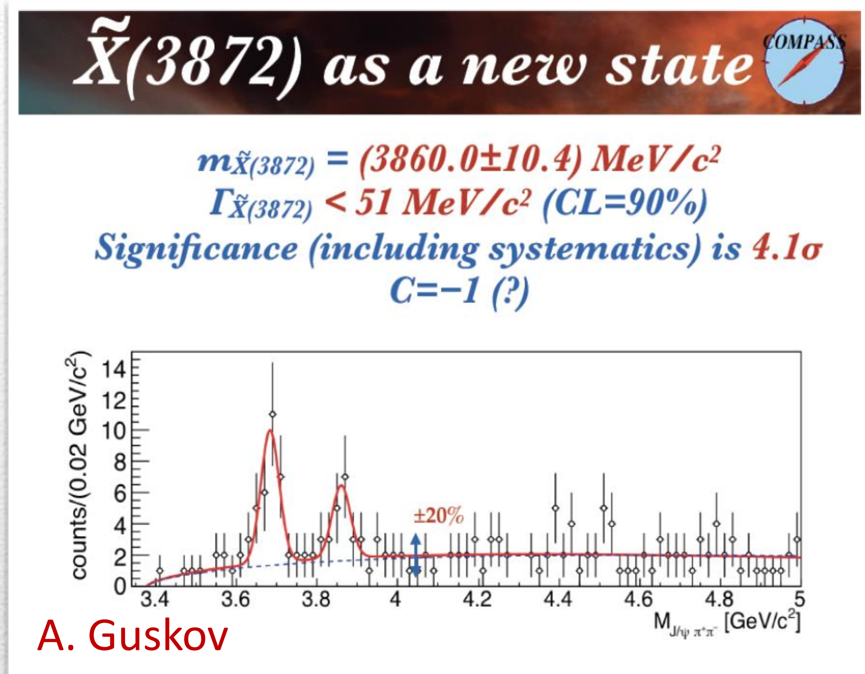


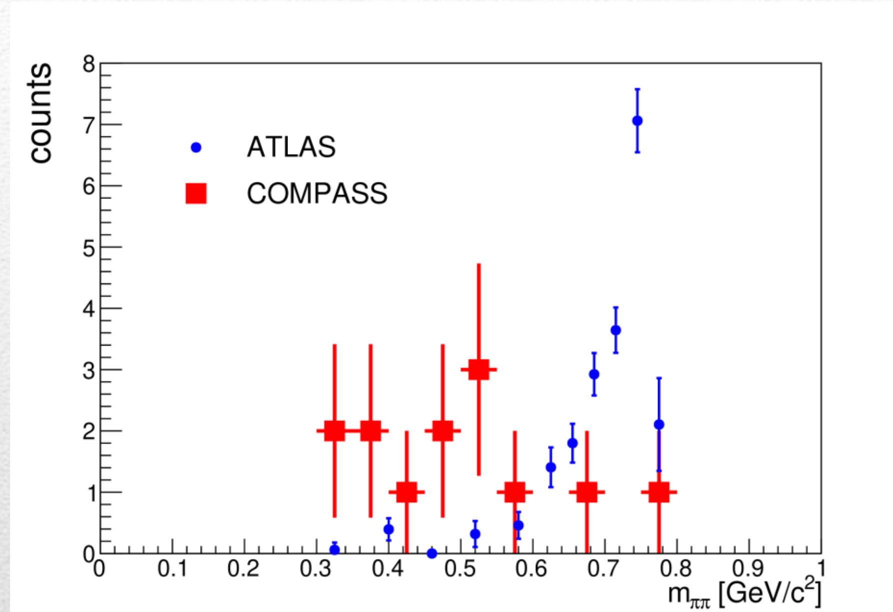
- Discovered in
  $B \to K\,X \to K\,J/\psi\,\pi\pi$
- Quantum numbers 1^{++}
- Very close to DD^* threshold
- Too narrow for an above-treshold charmonium
- Isospin violation too big
  $\frac{\Gamma(X\to J/\psi\ \ \omega)}{\Gamma(X\to J/\psi\ \ \rho)} \sim 1.1 \pm 0.4$
- Mass prediction not compatible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

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

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:

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

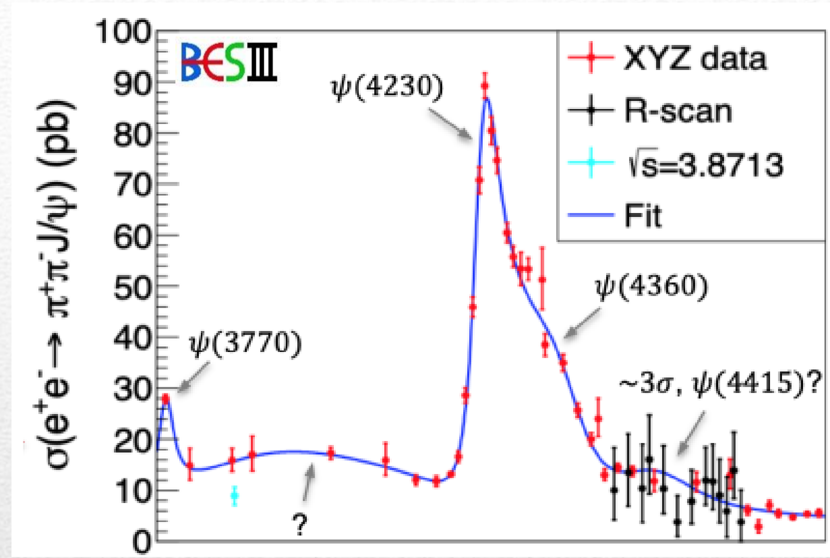
EIC $L = 10^{34}$ cm^{-2} s^{-1}

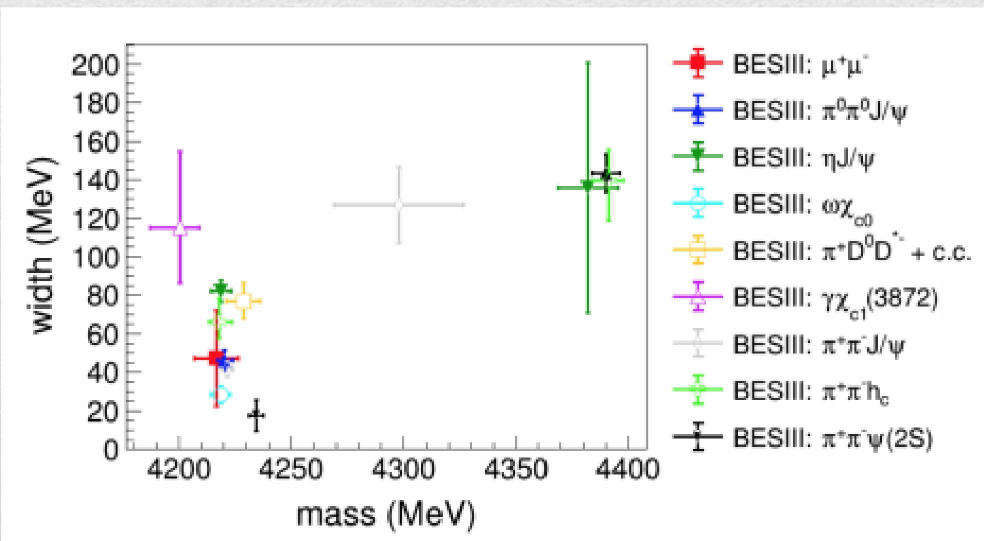
$$e^- N \to e^- \widetilde{X}(3872)\pi^\pm N' \to$$
$$\to e^- J/\psi \pi^+\pi^-\pi^\pm N' \to e^- \mu^+\mu^-\pi^+\pi^-\pi^\pm N'$$

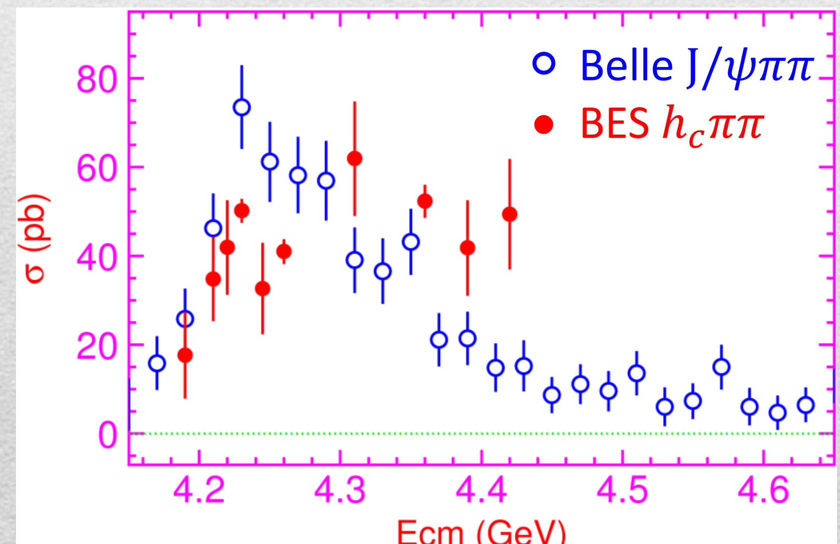
~10 events per day

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

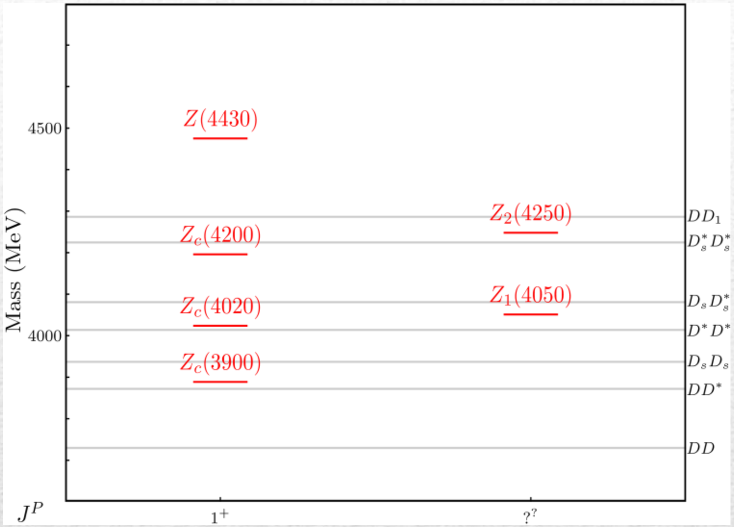






Charged Z states: $Z_c(3900), Z_c'(4020)$

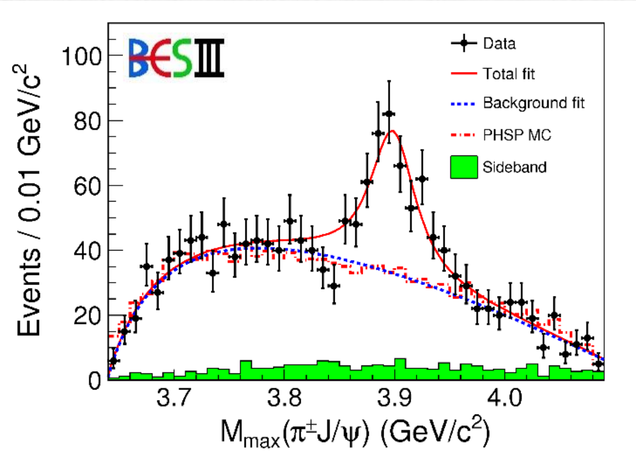
Charged quarkonium-like resonances have been found, **4q needed**

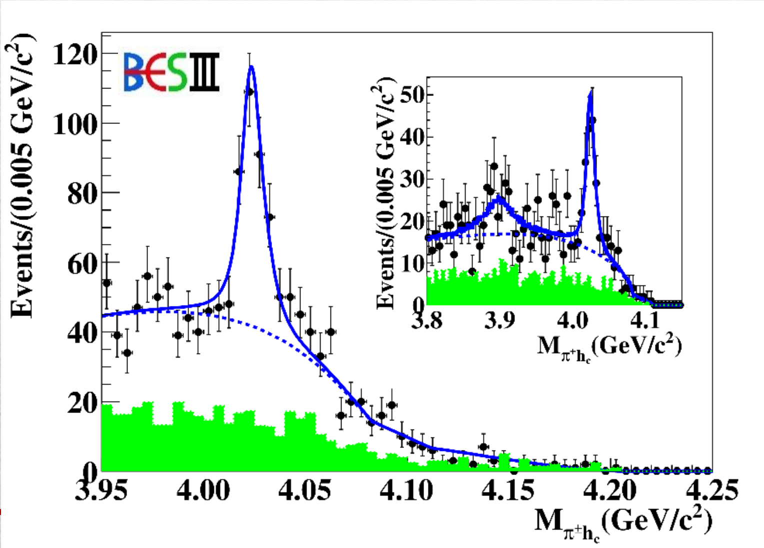


Two states $J^{PC} = 1^{+-}$ appear
slightly above $D^{(*)}D^*$ thresholds

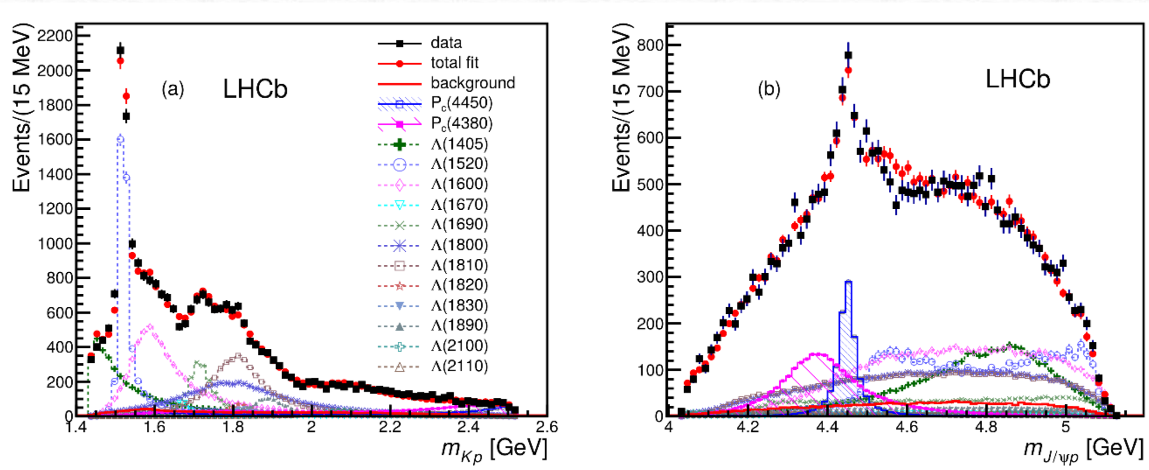
$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\, \pi^+\pi^-$ and $\to (DD^*)^+\pi^-$
$M = 3888.7 \pm 3.4$ MeV, $\Gamma = 35 \pm 7$ MeV

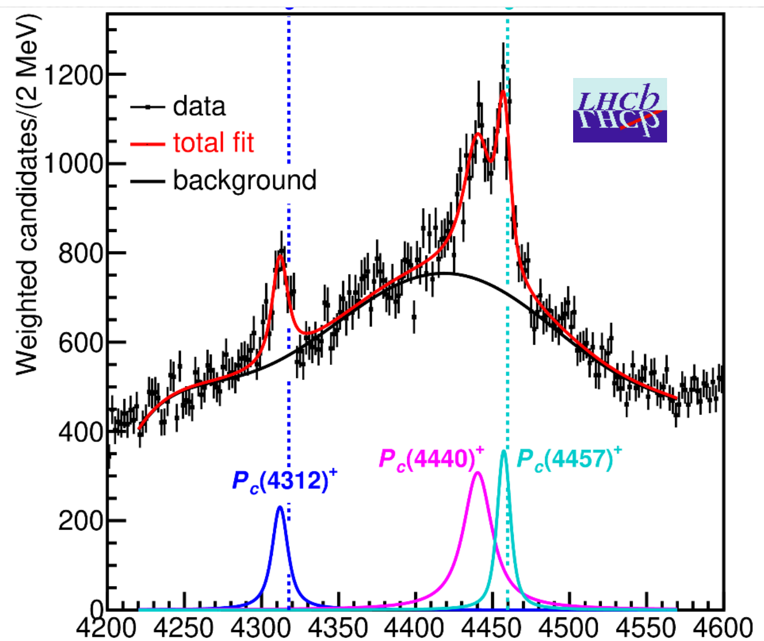
$e^+e^- \to Z_c'(4020)^+\pi^- \to h_c\, \pi^+\pi^-$ and $\to \bar{D}^{*0}D^{*+}\pi^-$
$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV





Pentaquarks!





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

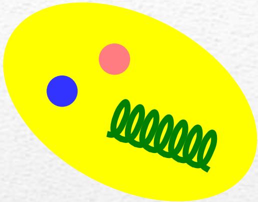
Three narrow states seen in
$\Lambda_b \to (J/\psi\, p)\, K^-$,
Plus a possible broad one

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

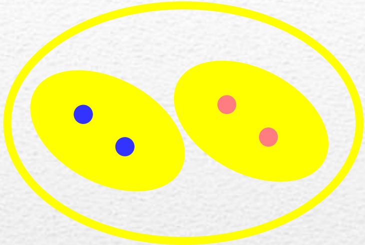
Models

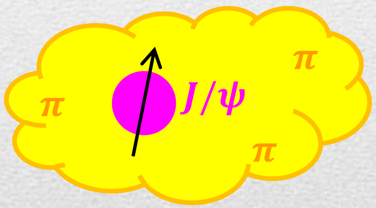
Compact



Hybrids
Containing gluonic degrees of freedom

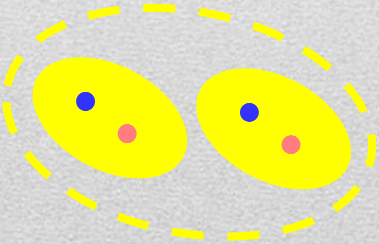
Multiquark
Several (cluster) of valence quarks





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), $Z_{cs}(4000)$…

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

Scarce consistency between various production mechanisms

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

Where XYZ?

Electromagnetic machines

$e^+e^- \to \gamma^* \to \text{hadrons}$

Electrohadron machines

$e^- \to e^-\gamma^{(*)}$

and $\gamma^{(*)}p, \gamma^{(*)}A \to \text{hadrons}$

Hadron machines

$pp, p\bar{p}, \pi^-p, pA, AA \to \text{hadrons}$

Cross sections

Cleanliness

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

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

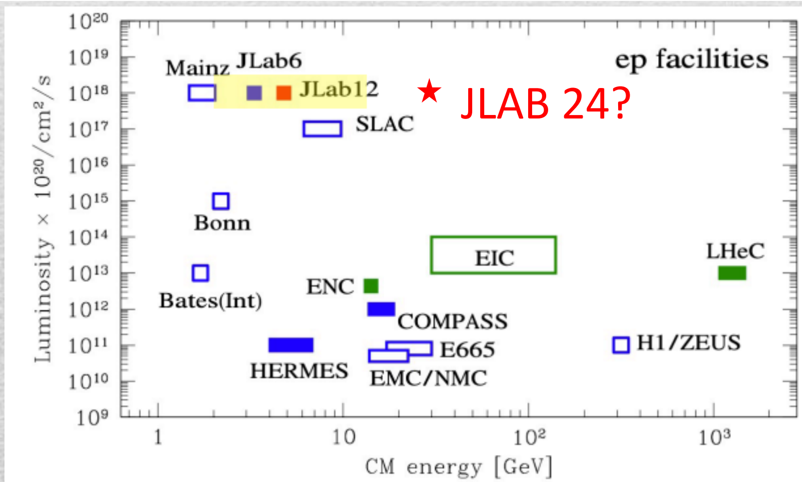
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

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]



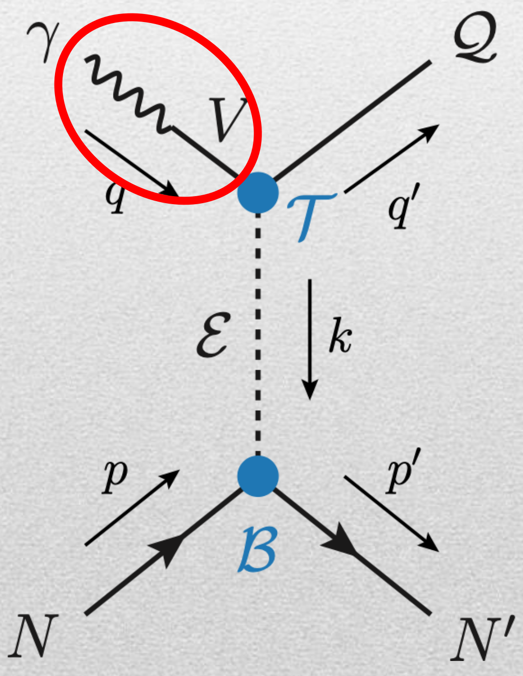
Explore the complementarity
wrt the forthcoming Electron Ion Collider

JLab vs. EIC

JLab	EIC²
✓ Variety of target species, polarization	✓ Variety of beam species, polarization
✓ Detectors well known (zero-angle cal required)	✘ Big «if» on timescale, accelerator and detector performances
✓ High intensity	✘ Low intensity
✘ Smaller acceptance	✓ High acceptance

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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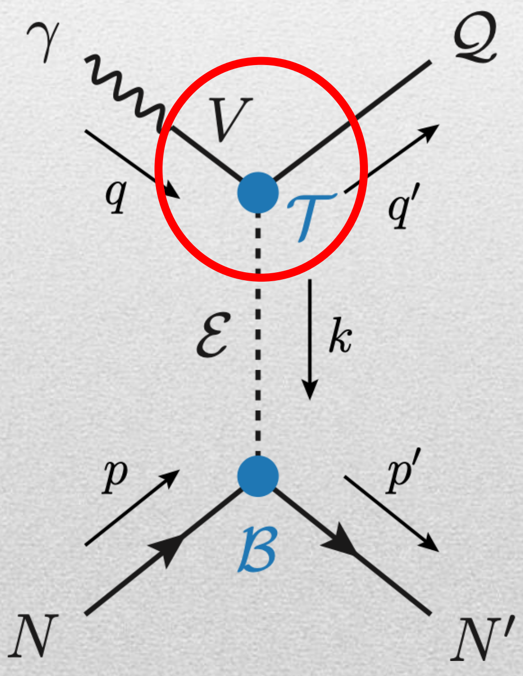

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Top vertex from measured $\mathcal{Q} \to V\mathcal{E}$ decay width

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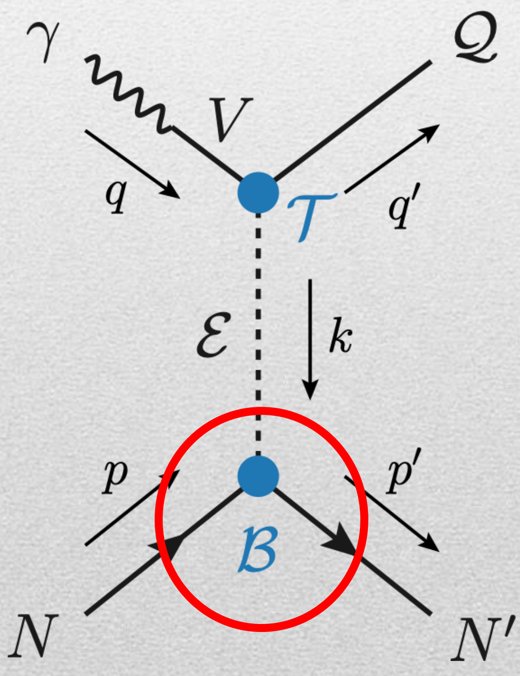

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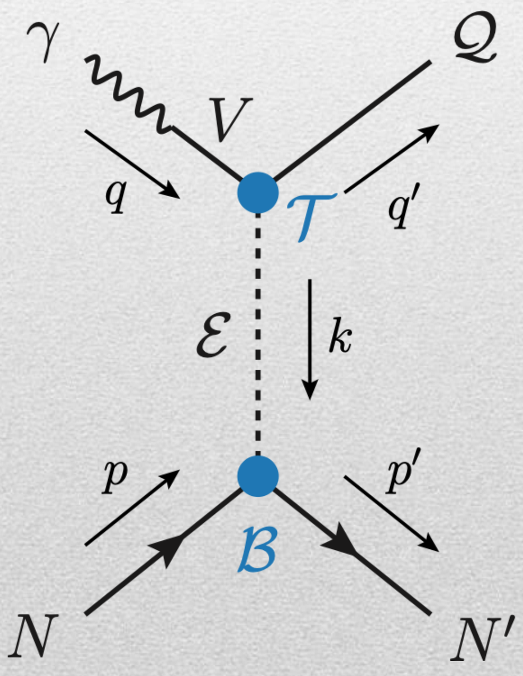
$$< \lambda_Q \lambda'_N | T | \lambda_\gamma \lambda_N >= \sum_{V,\mathcal{E}} \frac{e f_V}{m_V} \mathcal{T}^{\alpha_1 \cdots \alpha_j}_{\lambda_V = \lambda_\gamma, \lambda_Q} \mathcal{P}_{\alpha_1 \cdots \alpha_j ; \beta_1 \cdots \beta_j} \mathcal{B}^{\beta_1 \cdots \beta_j}_{\lambda_N \lambda'_N}$$

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



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

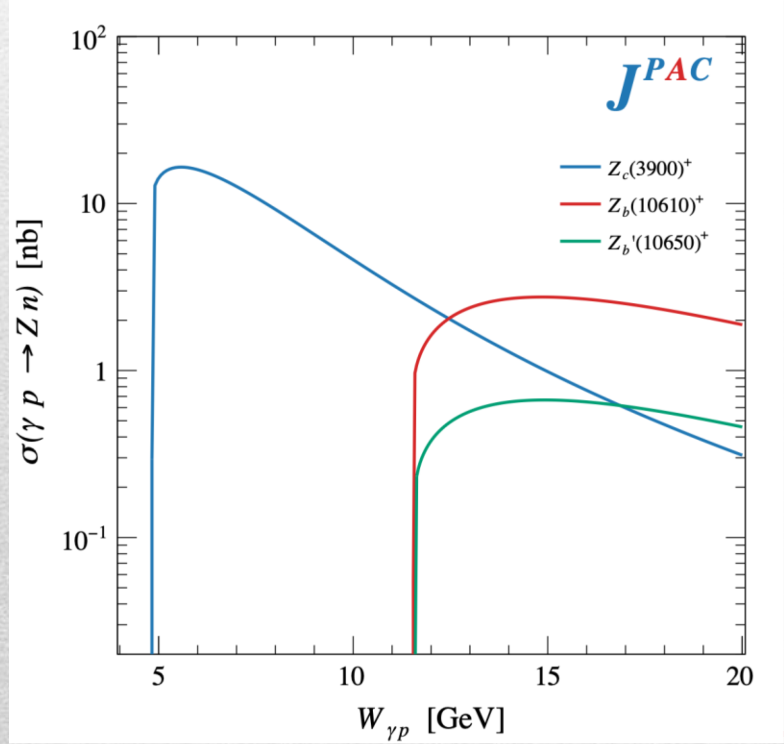
Holds at low energy, fixed spin

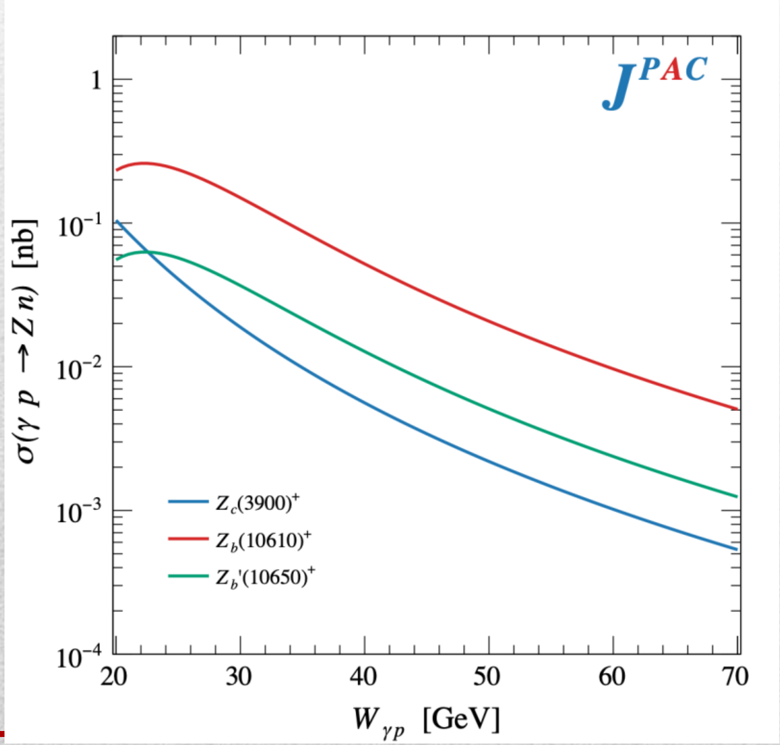
Holds at high energy, resummation of leading s power

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

Z photoproduction

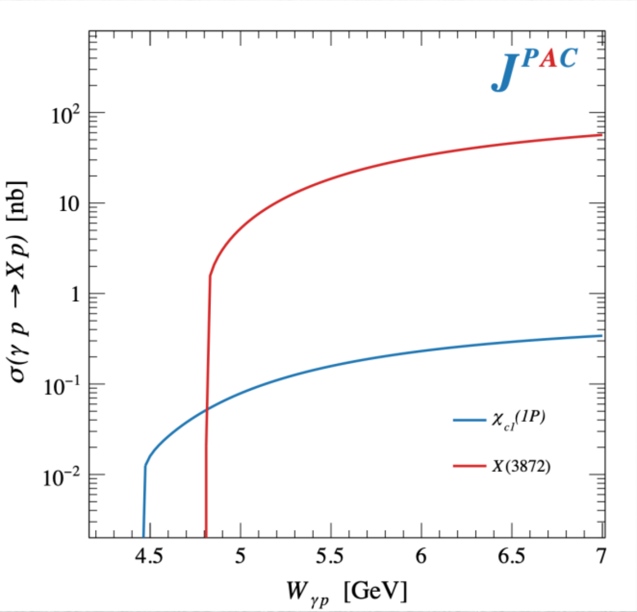
- The Zs are charged charmoniumlike 1^{+-} states close to open flavor thresholds
- Focus on $Z_c(3900)^+ \to J/\psi\, \pi^+$, $Z_b(10610)^+, Z_b'(10650)^+ \to \Upsilon(nS)\, \pi^+$
- The pion is exchanged in the t-channel



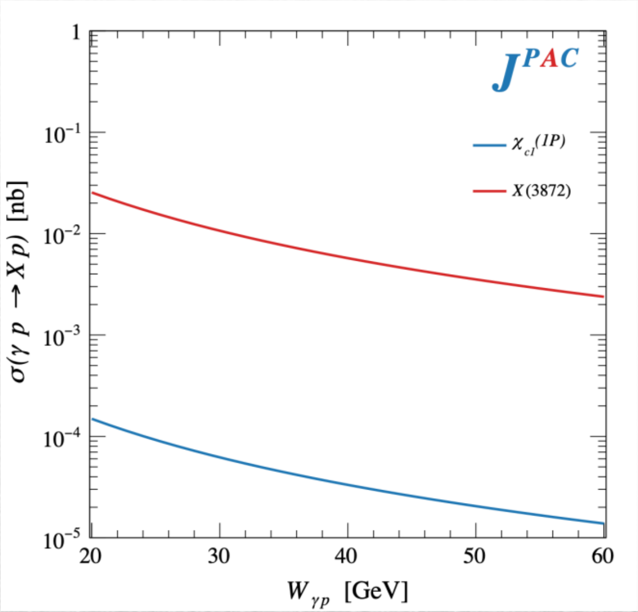


X photoproduction

- Focus on the famous 1^{++} $X(3872) \to J/\psi\, \rho, \omega$
- **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

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

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

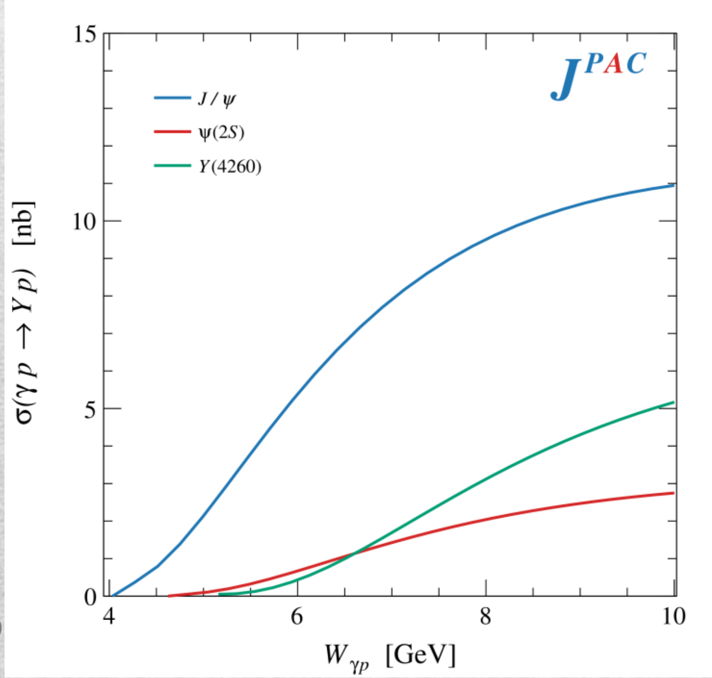
Assuming previous formula, one gets:

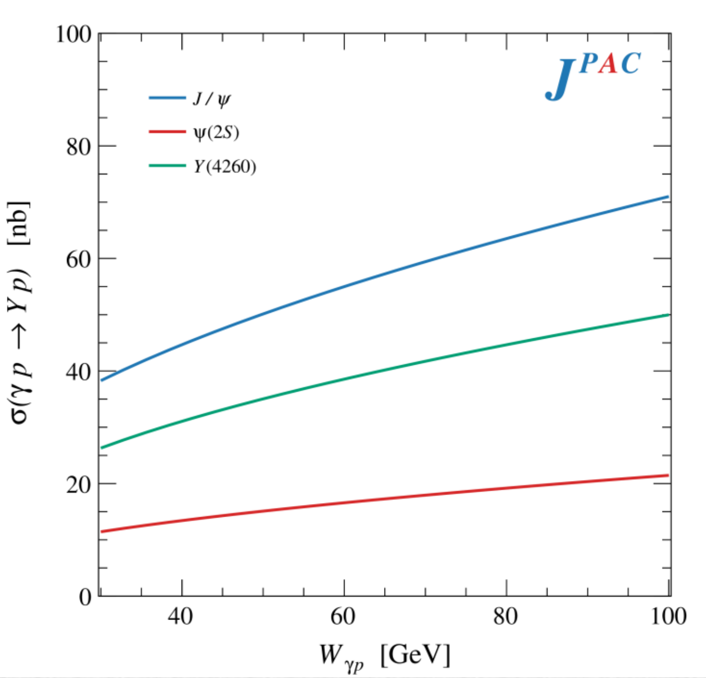
$\Gamma_{ee}^Y = 930\ eV$

(cfr. hep-ex/0603024, 2002.05641)

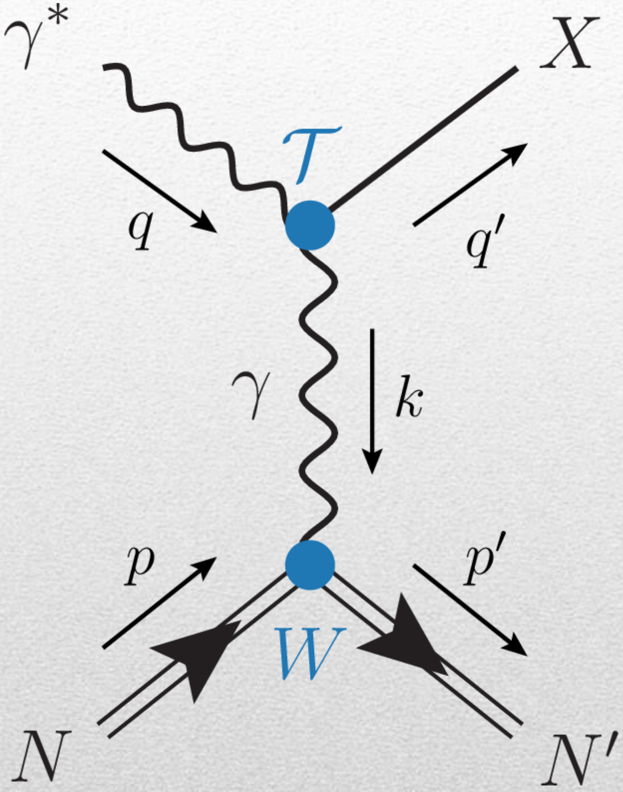
$BR(Y \to J/\psi\pi\pi) = 0.96\%$

$R_Y = 0.84$



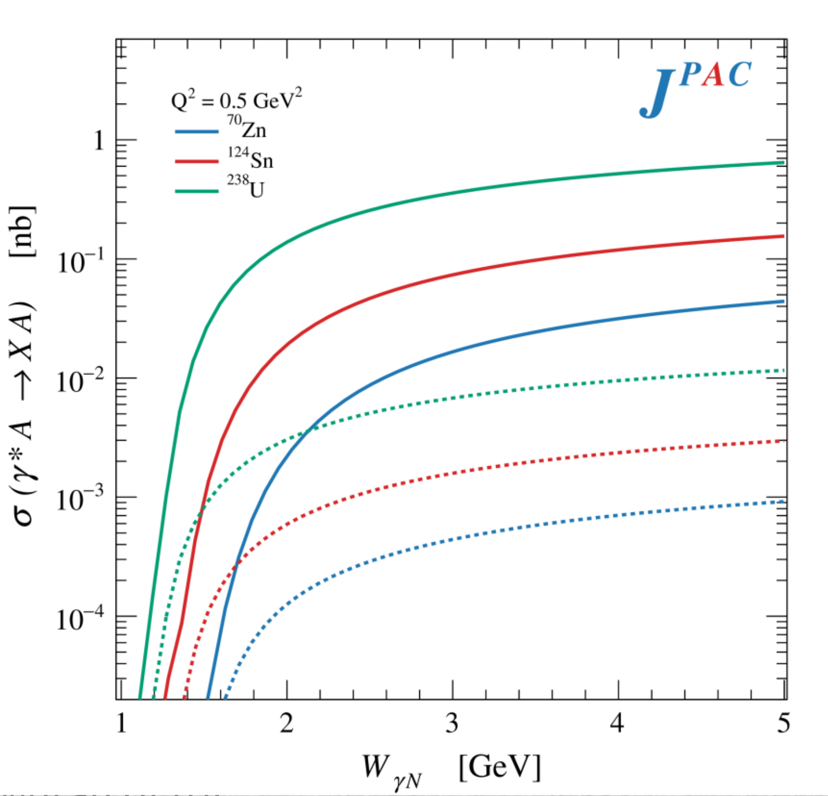


Primakoff X photoproduction



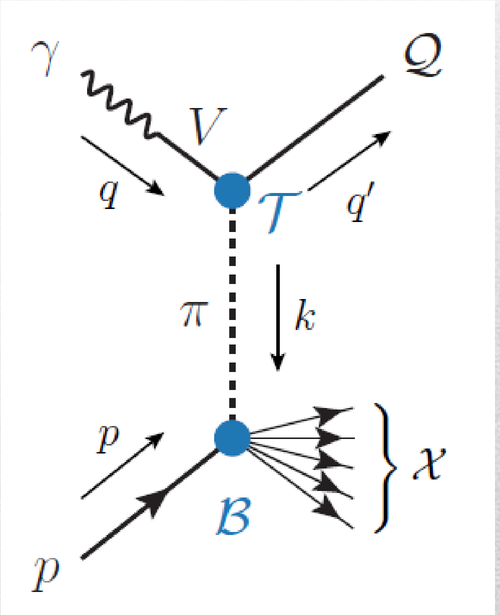
Using measurement of $\Gamma(\mathrm{X} \to \gamma\gamma^*)$ from Belle, one can get predictions for Primakoff

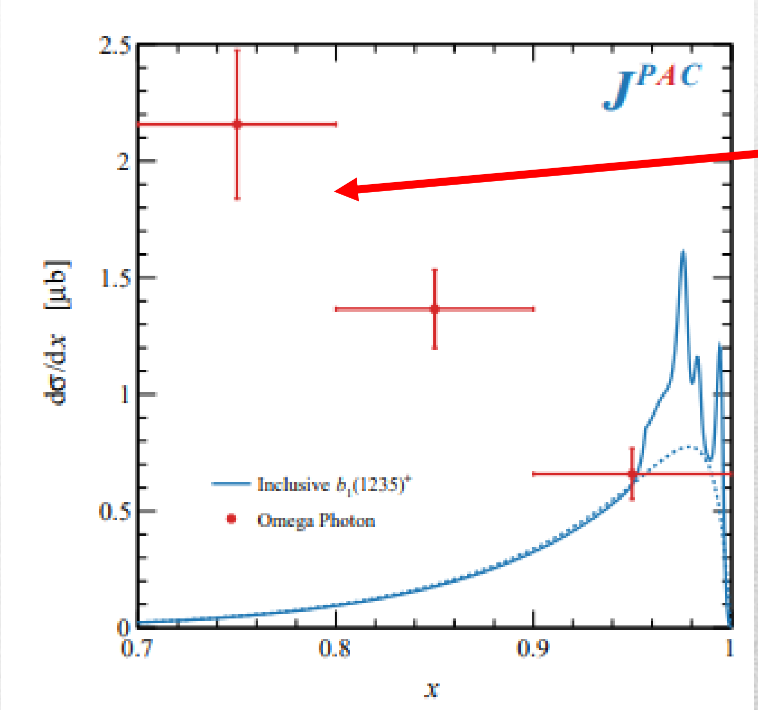
Makes use of ion targets, enhancement of cross sections as Z^2



Semi-inclusive photoproduction

- 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



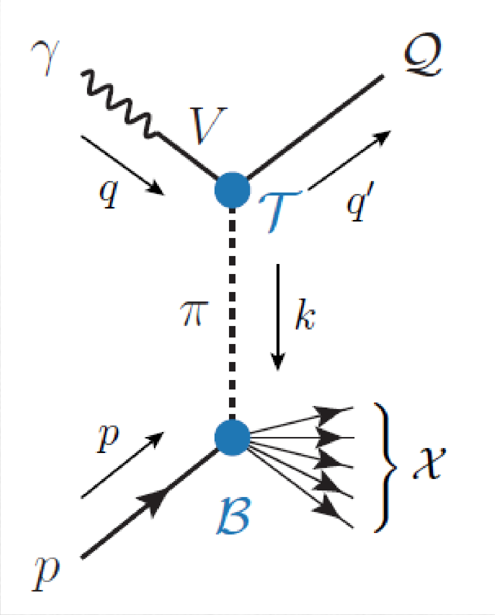


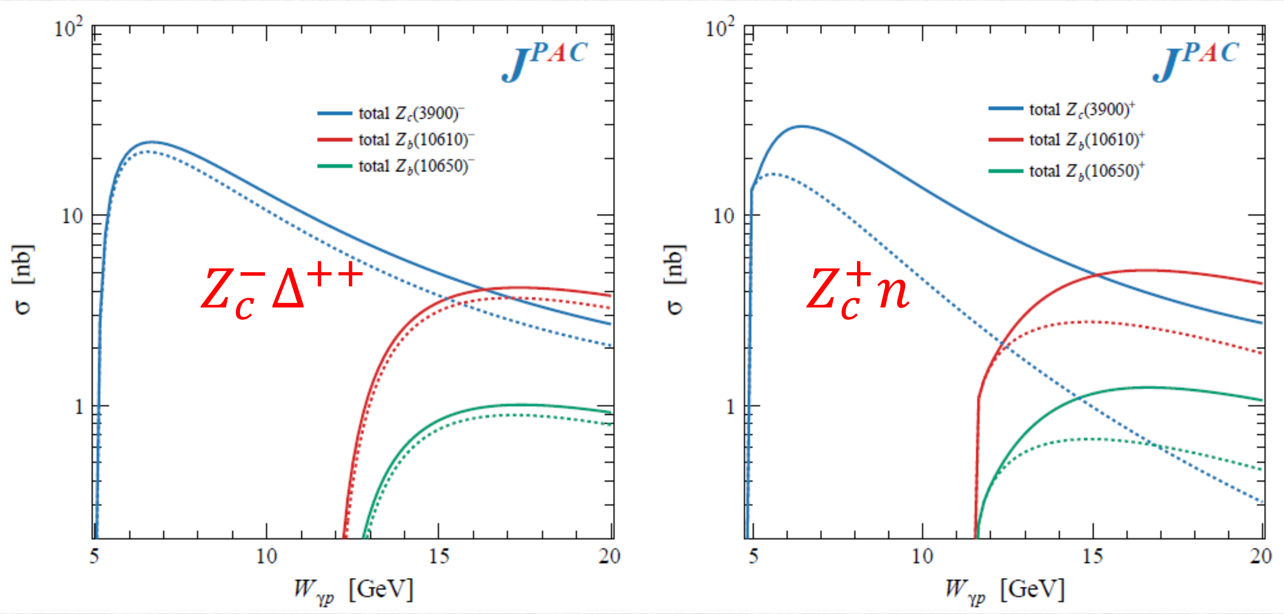
Model underestimates lower bins, conservative estimates

The model is expected to hold in the highest bin

Semi-inclusive photoproduction

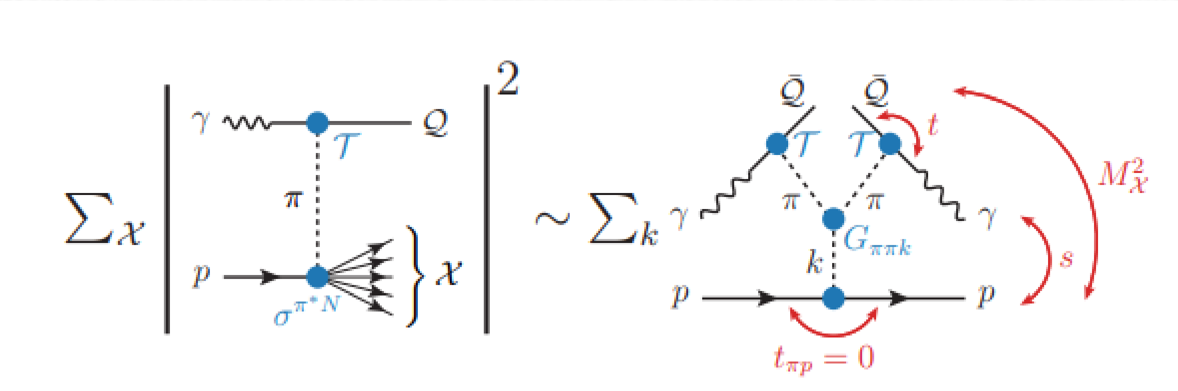
- For the Z_c^+, the inclusive cross section is sizably larger than the exclusive process





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	$< 10^{-8}$

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

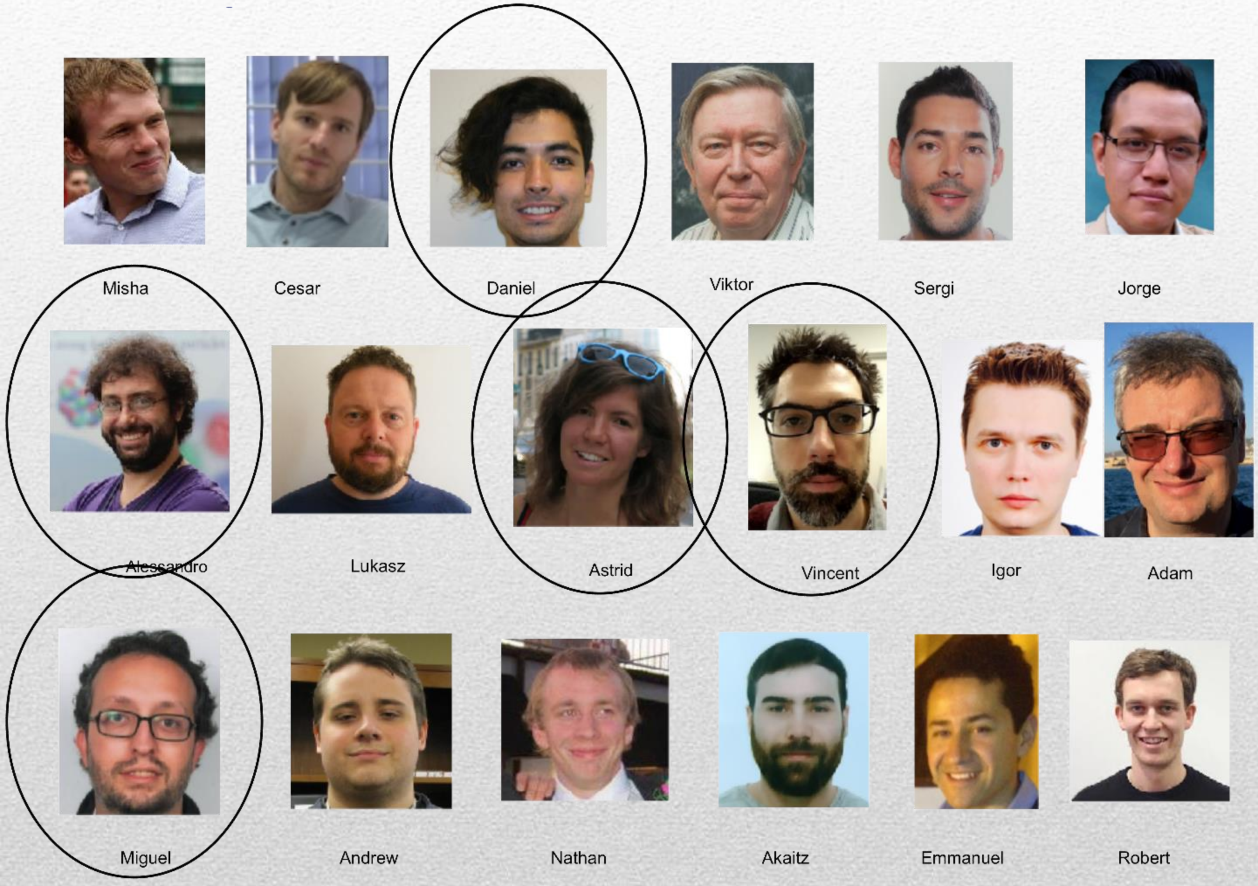
Conclusions

- 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

See also talks by M. Battaglieri and D. Glazier

Thank you!

Joint Physics Analysis Center



Exclusive reactions:
2008.01001

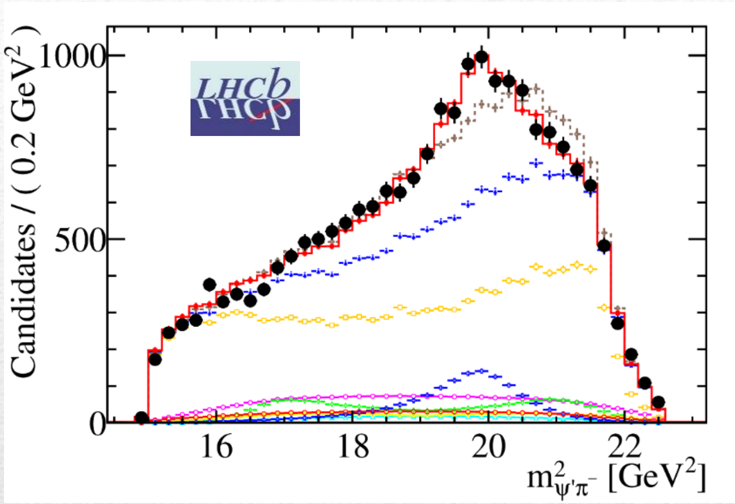
Inclusive reactions:
2209.05882

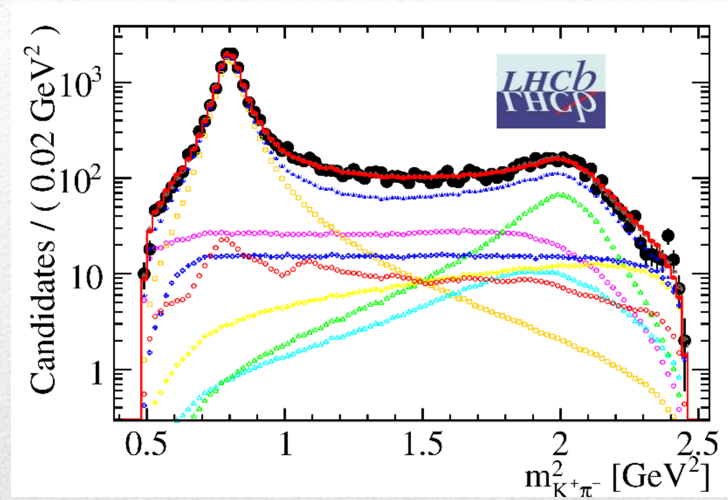
Code available on
https://github.com/dwinney/jpacPhoto

See talk by D. Glazier Tue 11:30

BACKUP

Charged Z states: $Z(4430)$

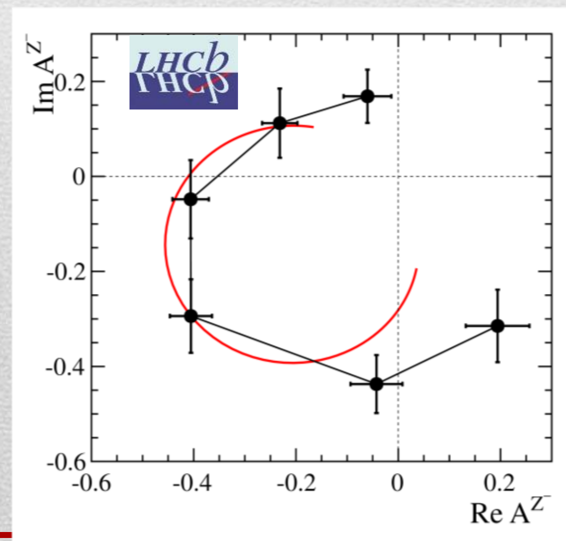




$Z(4430)^+ \to \psi(2S)\,\pi^+$
$I^G J^{PC} = 1^+1^{+-}$

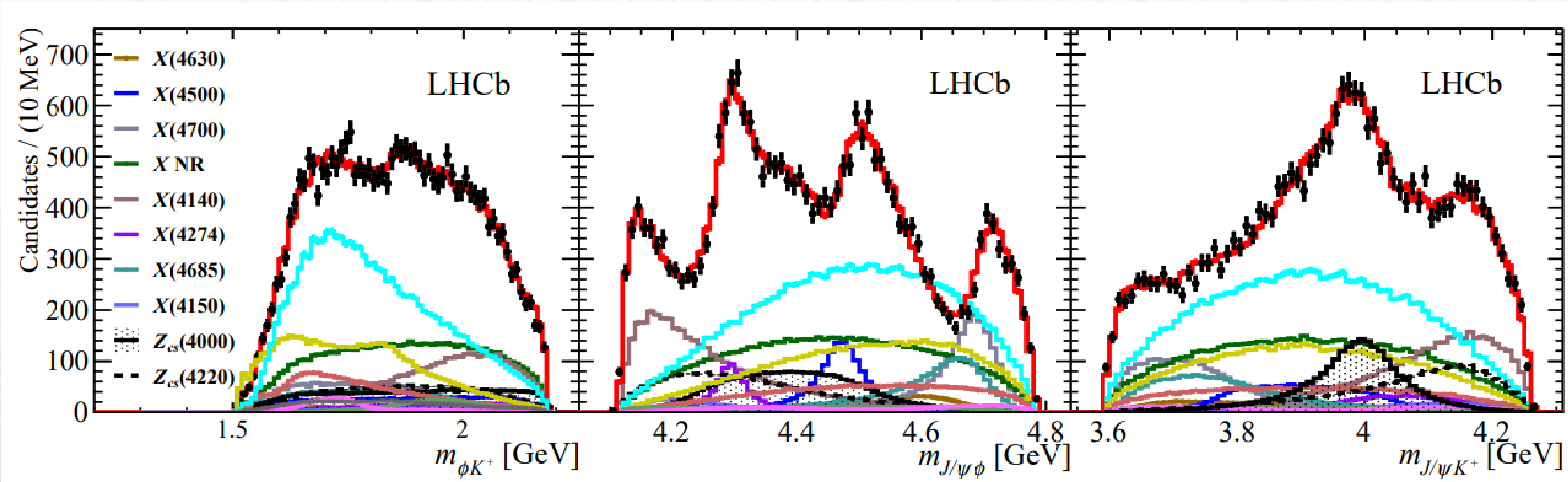
$M = 4475 \pm 7^{+15}_{-25}$ MeV
$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

Far from open charm thresholds



If the amplitude is a free complex number, in each bin of $m^2_{\psi'\pi^-}$,
the resonant behaviour appears as well

Tetraquarks: the $B^+ \to J/\psi\, \phi\, K^+$ decay

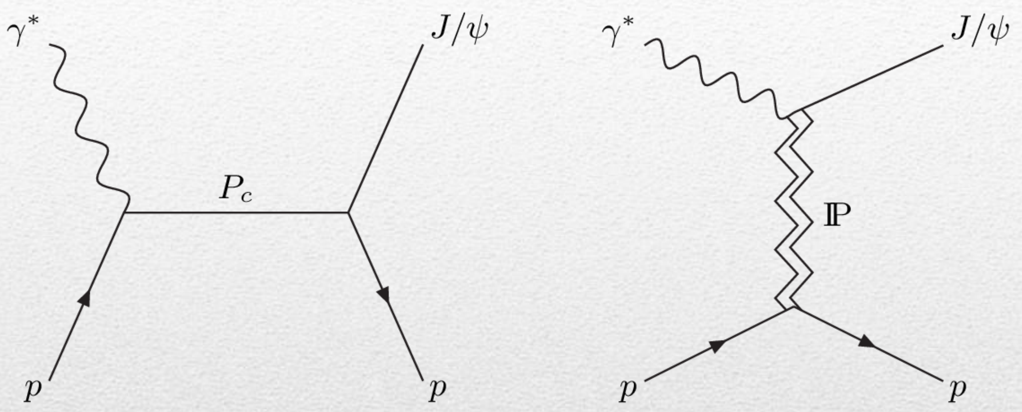


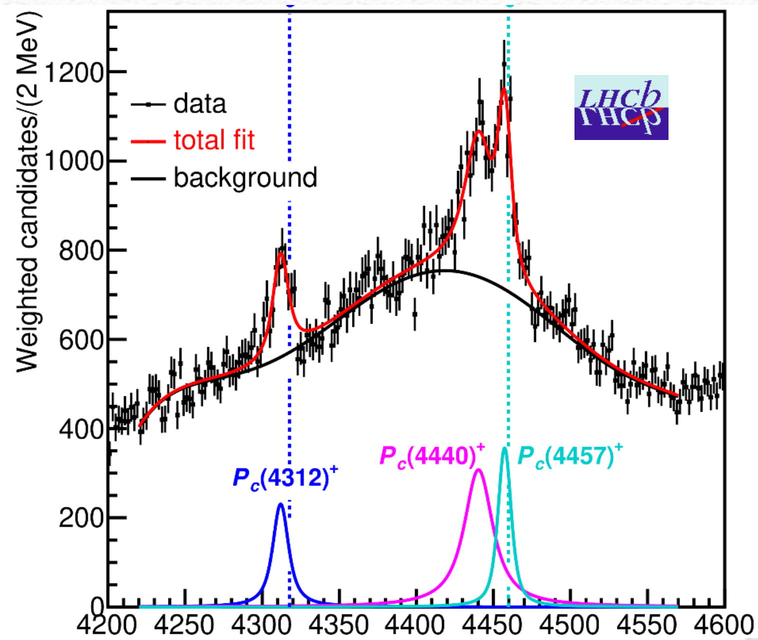
In $J/\psi\, \phi$: $\begin{cases} 1 \times\ 1^{-+} \\ 2 \times\ 0^{++} \\ 3 \times\ 1^{++} \end{cases}$

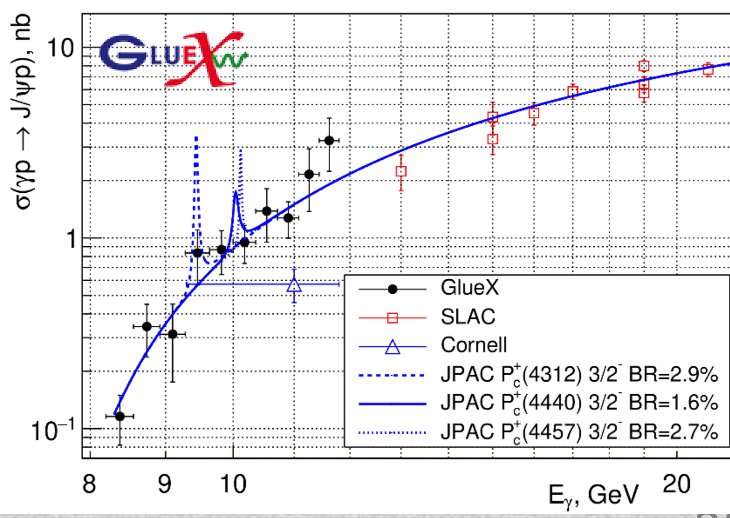
In $J/\psi\, K^+$: $2 \times 1^+$

Widths from 50 to 230 MeV

Exclusive P_c photoproduction



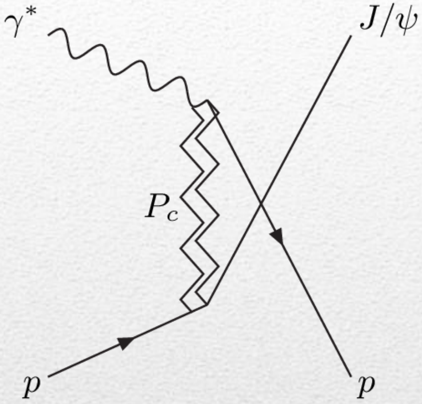


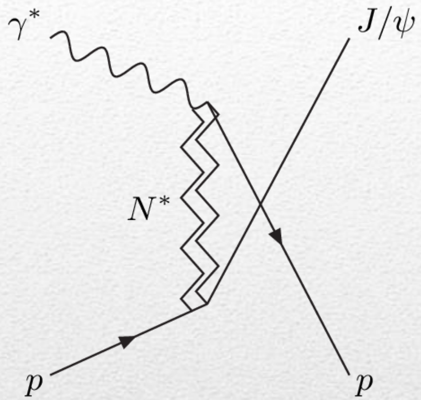


At Jlab12 measurements of direct P_c production are being performed

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' ?

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

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

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

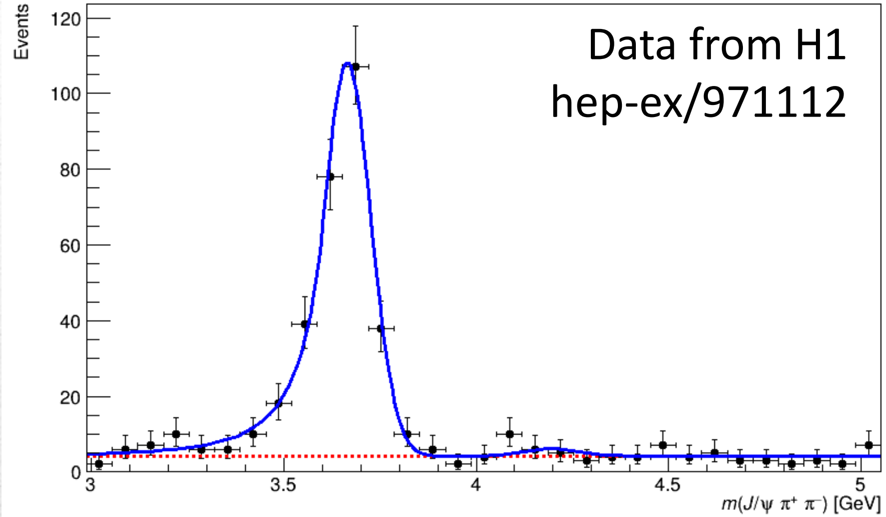
How to rescale from J/ψ to $Y(4260)$?

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

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

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

Y (vector) photoproduction



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

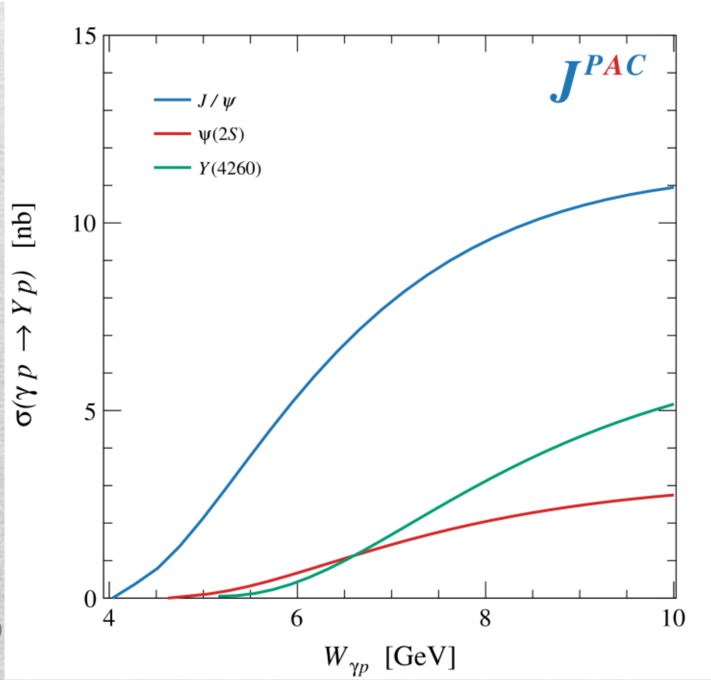
Assuming previous formula, one gets:

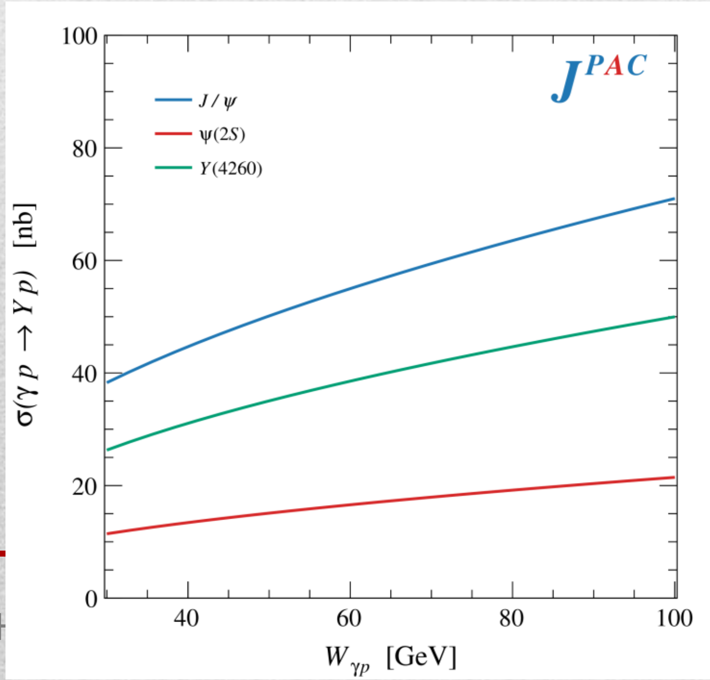
$\Gamma_{ee}^{Y} = 930\ eV$

(cfr. hep-ex/0603024, 2002.05641)

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

$R_Y = 0.84$



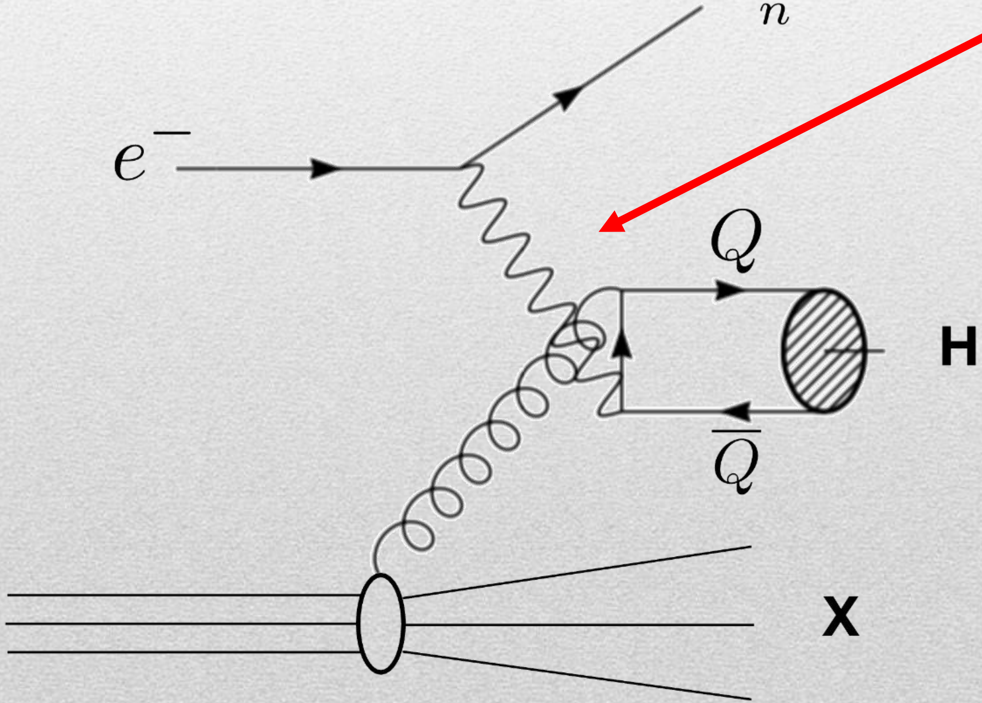


Semi-inclusive X production

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

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

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

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