Exotic Hadron Photoproduction

HADRON 2021

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Phys. Rev. D94 (2016) 034002

1606.08912 [hep-ph]

Phys. Rev. D100 (2019) 034010

1907.09393 [hep-ph]

Phys. Rev. D102 (2020) 114010

2008.01001 [hep-ph]

July 26, 2021

Spectroscopy of exotic states

- Since 2003, a plethora of "**exotic**" resonance candidates has been measured: new challenges for quark model.

Choi et al., PRL 91 (2003) 262001
Ablikim et al., PRL 110 (2013) 252001
Adolph et al., PLB 740 (2015) 303
Aaij et al., PRL 115 (2015) 072001
Ablikim et al., PRL 118 (2017) 092001
Aaij et al., PRL 122 (2019) 222001

- Even conventional quarkonium production is interesting: entangles perturbative ($Q\bar{Q}$ production) and non-perturbative (hadronization) regimes.

- Hadron collisions (pp@LHC and $p\bar{p}$@Tevatron) indispensable in advancing knowledge.

- They suffer from **kinematical effects** from 3-body dynamics: might lead to model-dependent misinterpretation of signals.

Guo et al., PPNP 112 (2020) 103757

- **Resonances** arise due to poles of non-perturbative **dynamical nature** due to the interaction strength between quarks and gluons and among hadrons.

- **Kinematical singularities** are determined by masses and energies of reaction particles: while **two-body branch points** are more easily distinguishable from resonances, **triangle singularities** are close to pertinent thresholds and might be misidentified.

Esposito et al., PR 668 (2017) 1
Brambilla et al., PR 873(2020) 1
Hosaka et al., PTEP 2016 (2016) 062C01
Brambilla et al., EPJC 71 (2011) 1534

Distinguishing resonances

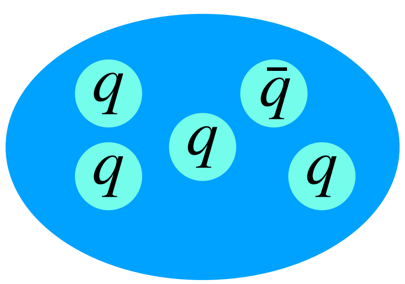
- Triangle singularities are strongly sensitive to kinematic variables: peaks in invariant mass distribution should depend on choice of kinematical bin.
- Quantum numbers constrained to S-wave pair of internal particles.

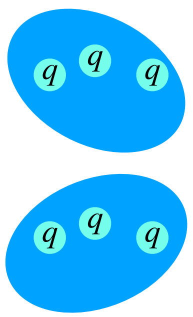
- In electro- and photoproduction, we have **beams of point-like particles**: efficient, **complementary** measurements of the hadron spectrum and structure.
- **COMPASS**, **BES**, **Belle** and **Jefferson Lab** have strongly furthered our understanding.

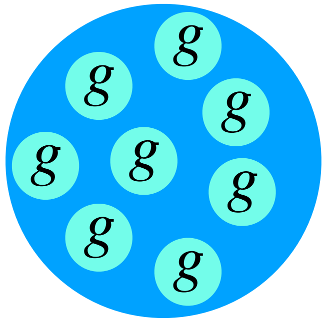
- Limited statistics so far — we need higher luminosities at appropriate energies: **well achievable in the electron-ion collider era!**

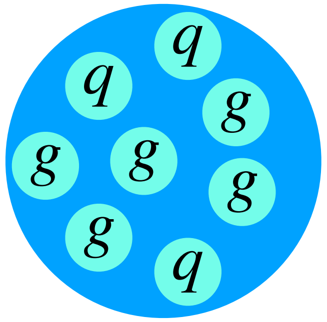
The family of exotics

- Mesons whose J^{PC} **cannot be matched by $q\bar{q}$ content**:
  hybrid smoking guns such as π_1 in $\eta(')\pi$ system, charged quarkonium Z, …
- **Exotic charmonium/bottomonium** - X and Y (vector) states:
  tetraquarks, hybrids, gluonium, …
- Baryons with **exotic flavor** (positive strangeness, negative charm),
  hidden-charm(beauty) **pentaquarks**, …
- Di-baryons, meson-baryon molecules
  (just below threshold and with sizable spatial extension), …









- Need for confirmation and independent studies:
  promising for high-luminosity searches at JLab and electron-ion colliders!

Production formalism - phenomenological constraints
Results: XYZ and pentaquarks
What can the future of electron-ion colliders bring us?

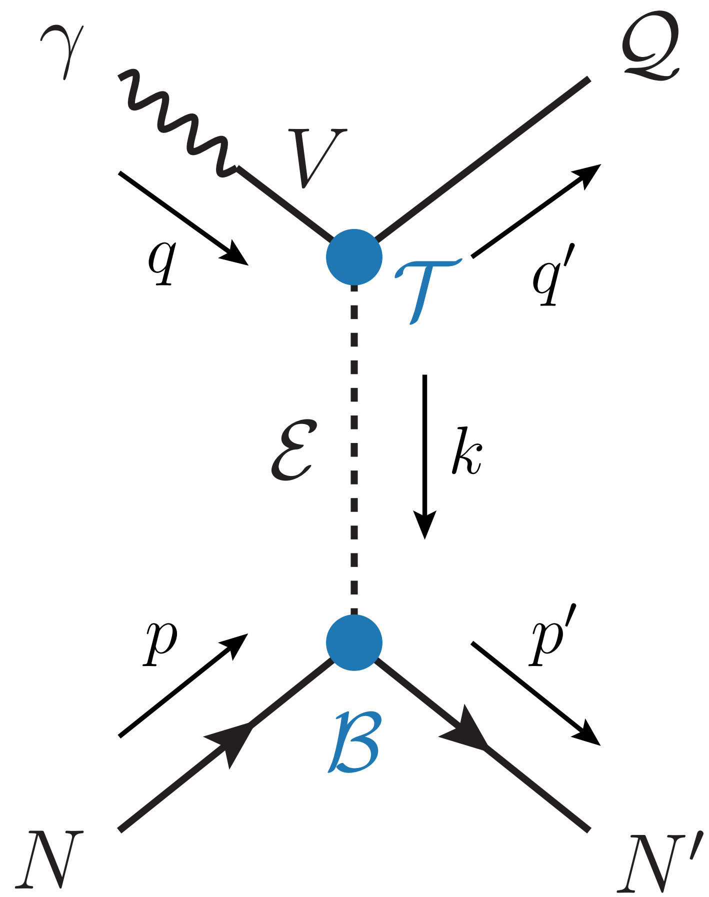
Production formalism - phenomenological constraints

Results: XYZ and pentaquarks

What can the future of electron-ion colliders bring us?

Photoproduction dynamics

- Description via t-channel exchanges.
- **Fixed spin** near threshold:
  full s dependence; but asymptotically s^j (exceeds unitarity bound).
- **Reggeization** at high energies: tower of particles with increasing spin.
- Couplings determined from known experimental branching fractions.
- Vector-meson dominance (VMD) assumed for estimation of top couplings.



Low energies **High energies**

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

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

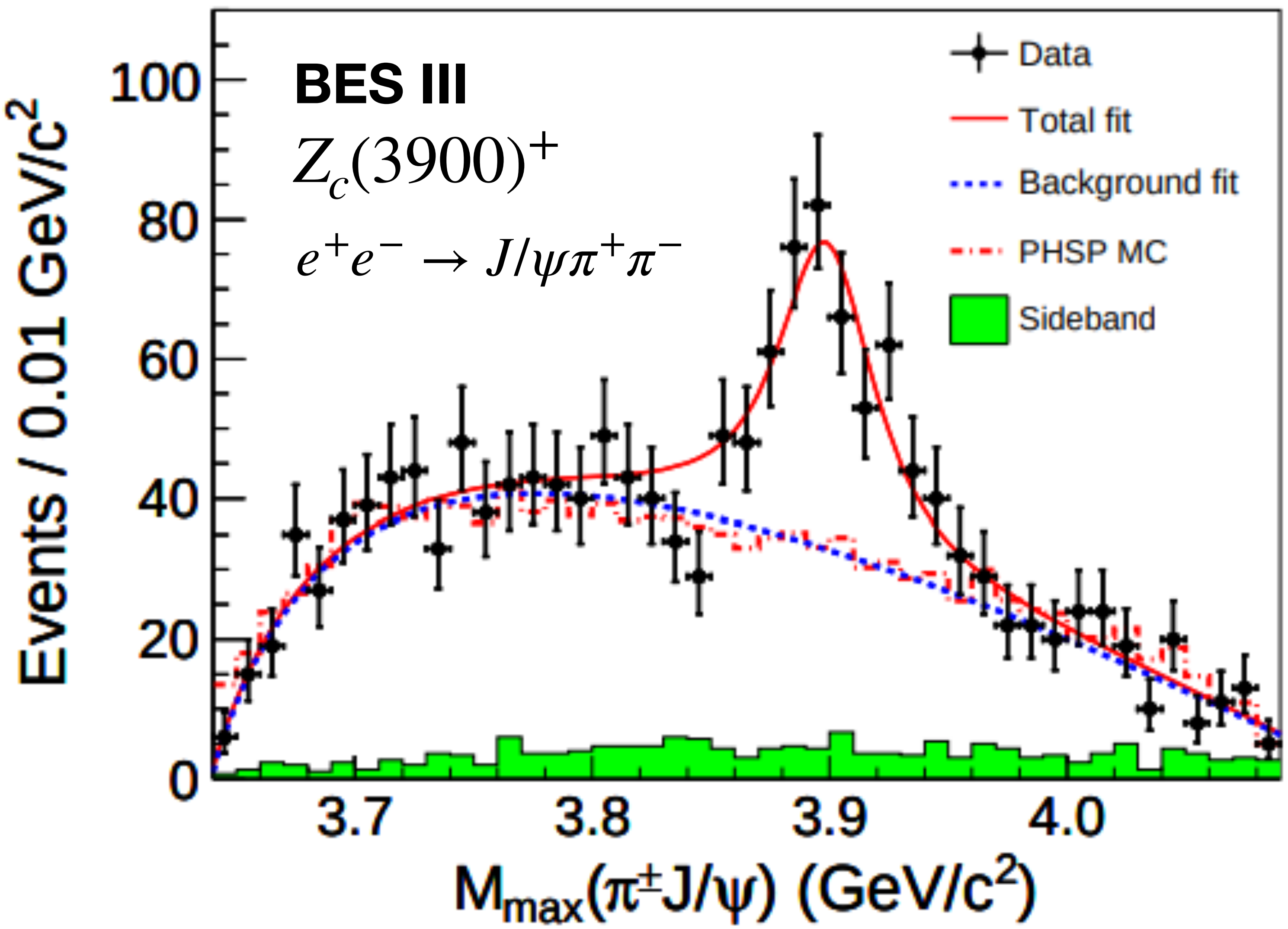
Production formalism - phenomenological constraints

Results: XYZ and pentaquarks

What can the future of electron-ion colliders bring us?

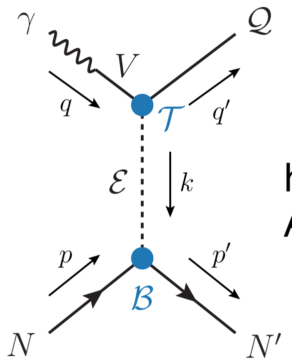
Z^+ states: 1^{+-}

- Exotic minimum quark content: $Q\bar{Q}q_1\bar{q}_2$.
- Most are either broad or close to open-charm thresholds:
  we focus on narrow ones with large branching fractions into vector + π.
- Three-body final state interactions and coupled channel effects:
  need for independent confirmation.

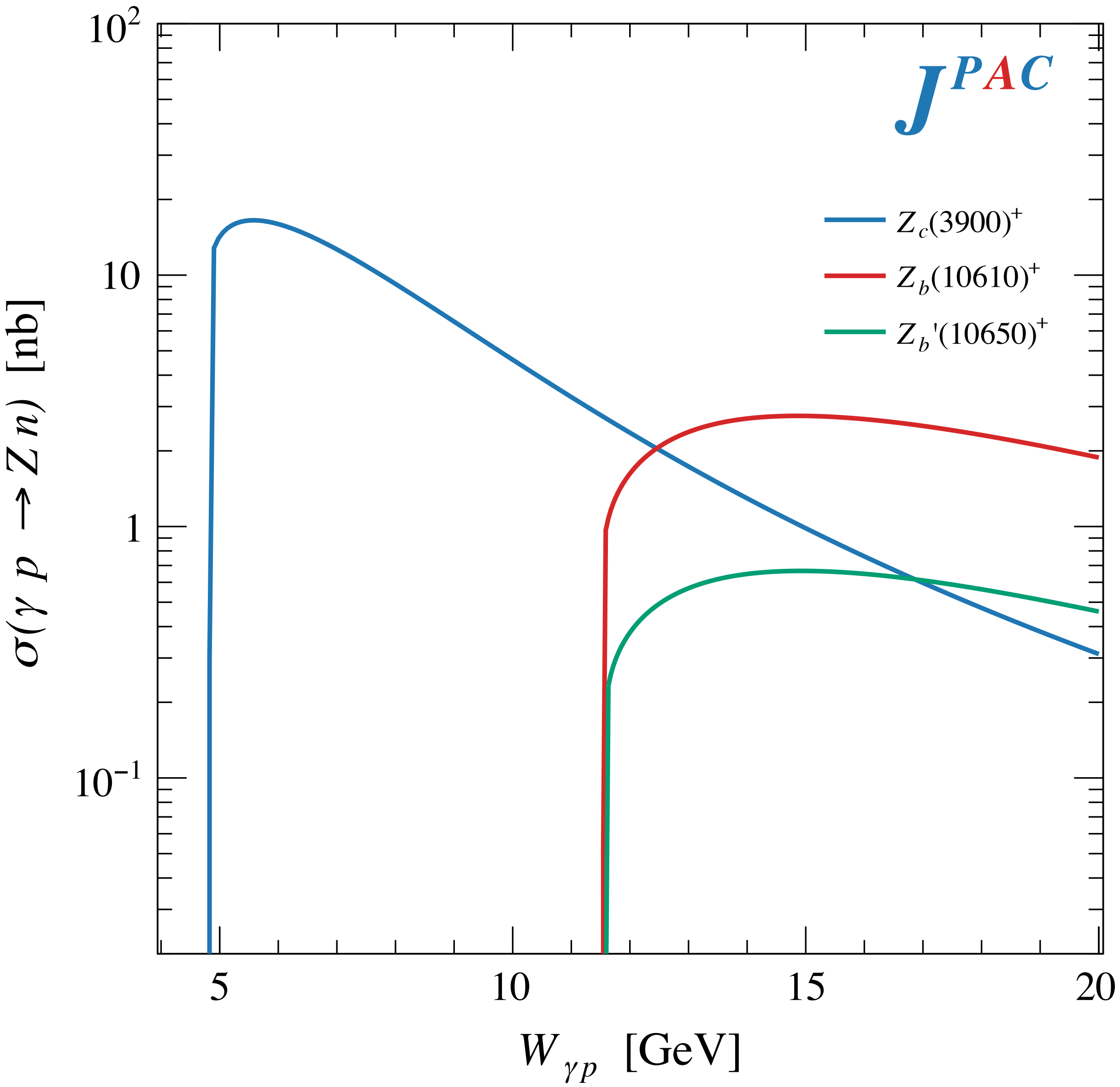


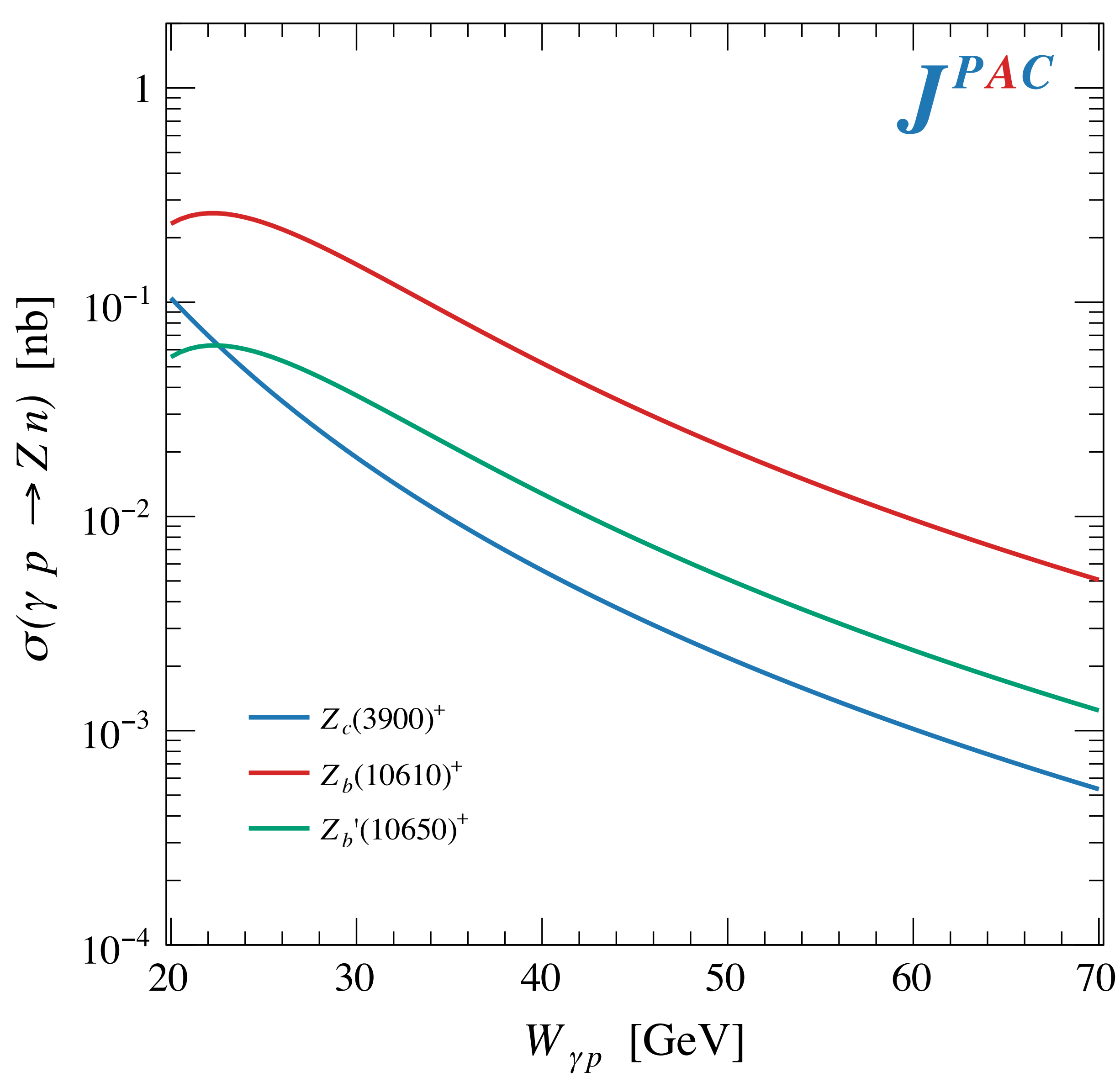
Z+ photoproduction

Sizable photoproduction cross sections expected especially at low energies.



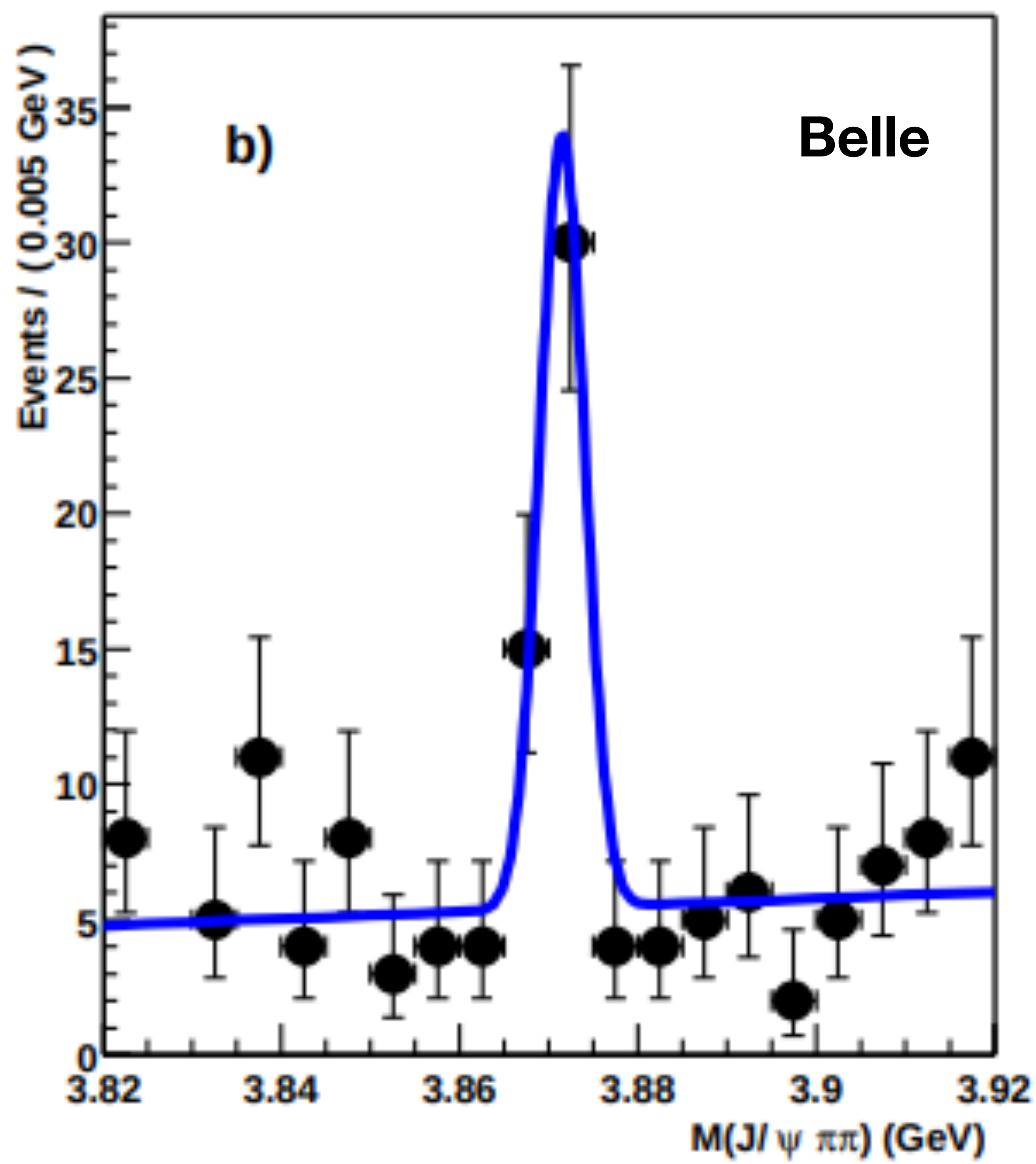
https://github.com/dwinney/jpacPhoto
Albaladejo et al., Phys. Rev. D 102 (2020) 114010





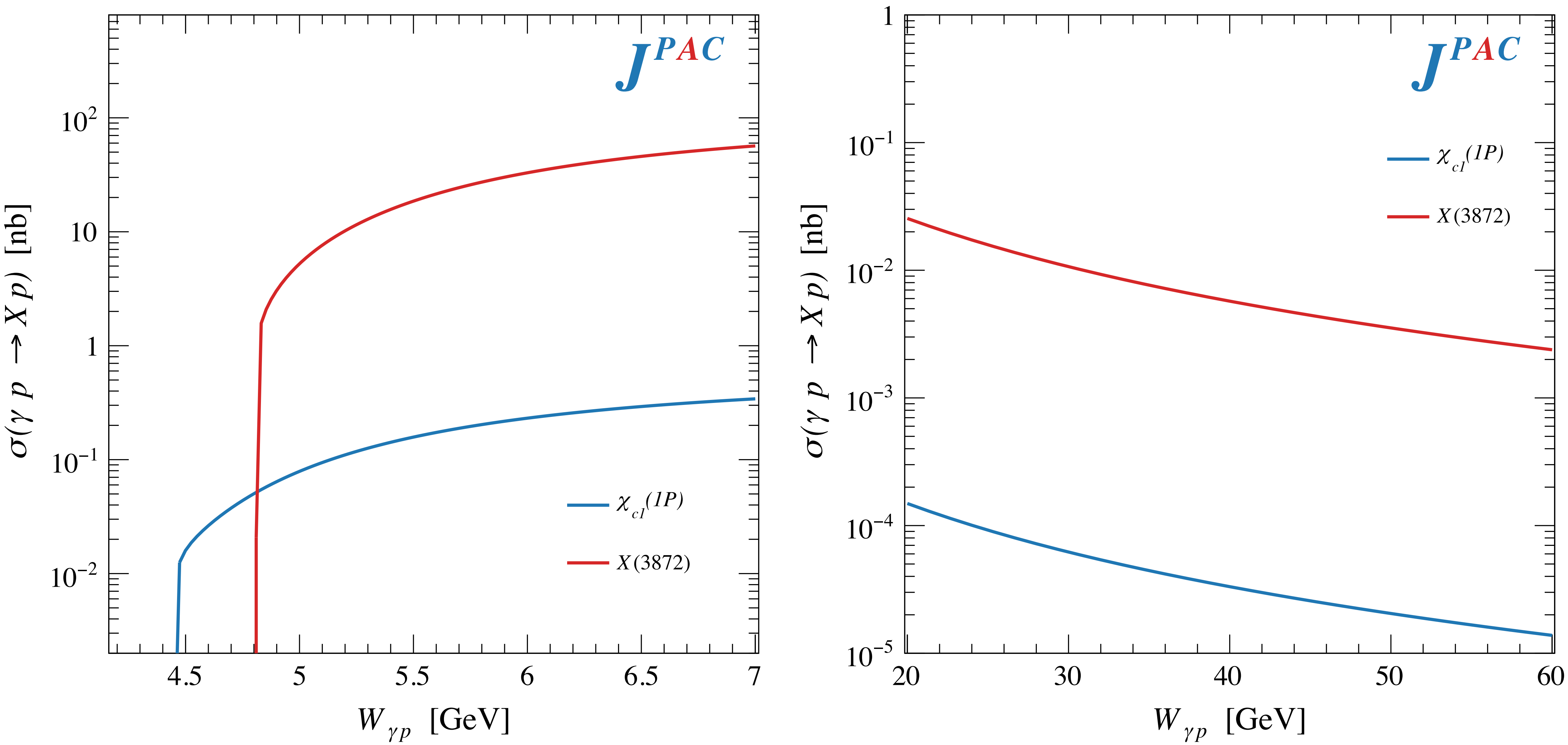
X(3872): 1^{++}

We focus on the famous X(3872), **strongly isospin violating:**
narrow state with large branching into low-lying charmonium (loosely bound molecule).



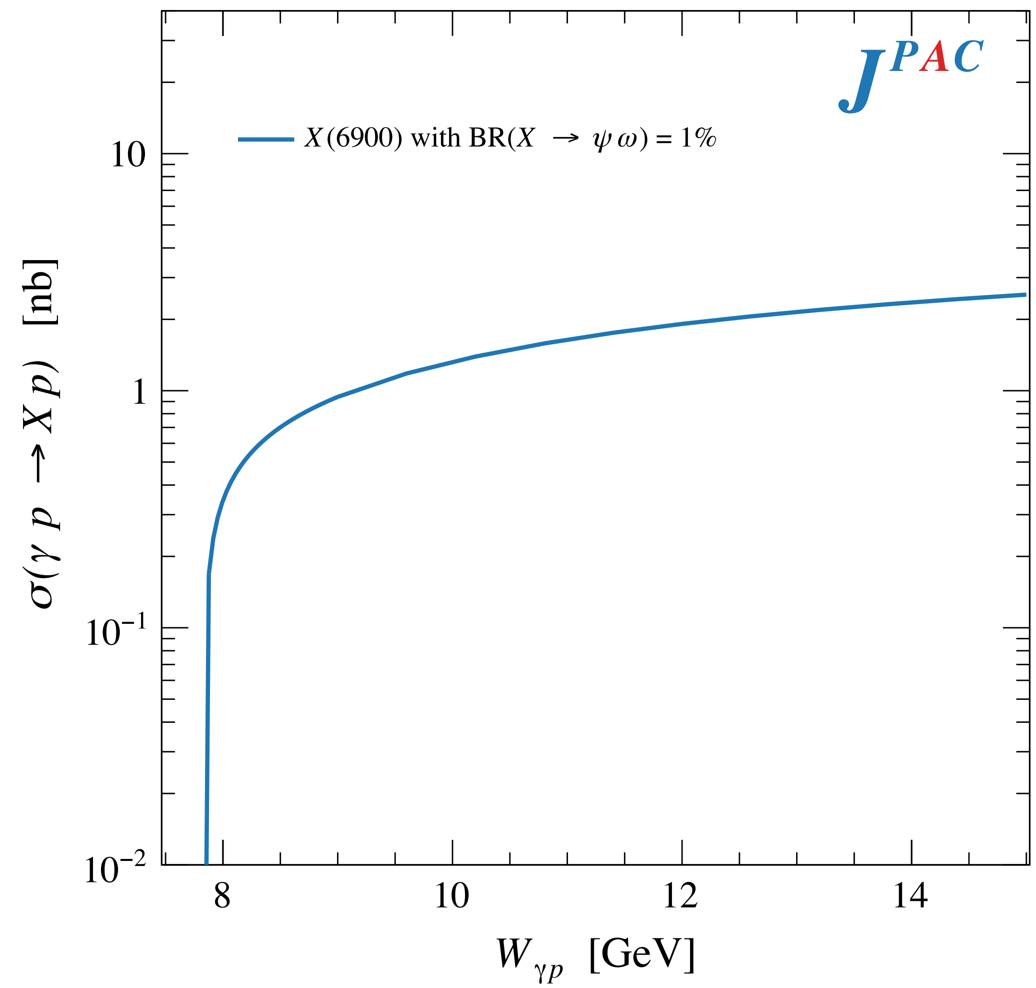
X(3872) photoproduction

- ω and ρ exchanges give main contributions.
- Extremely suppressed cross sections at high energies: threshold most promising.



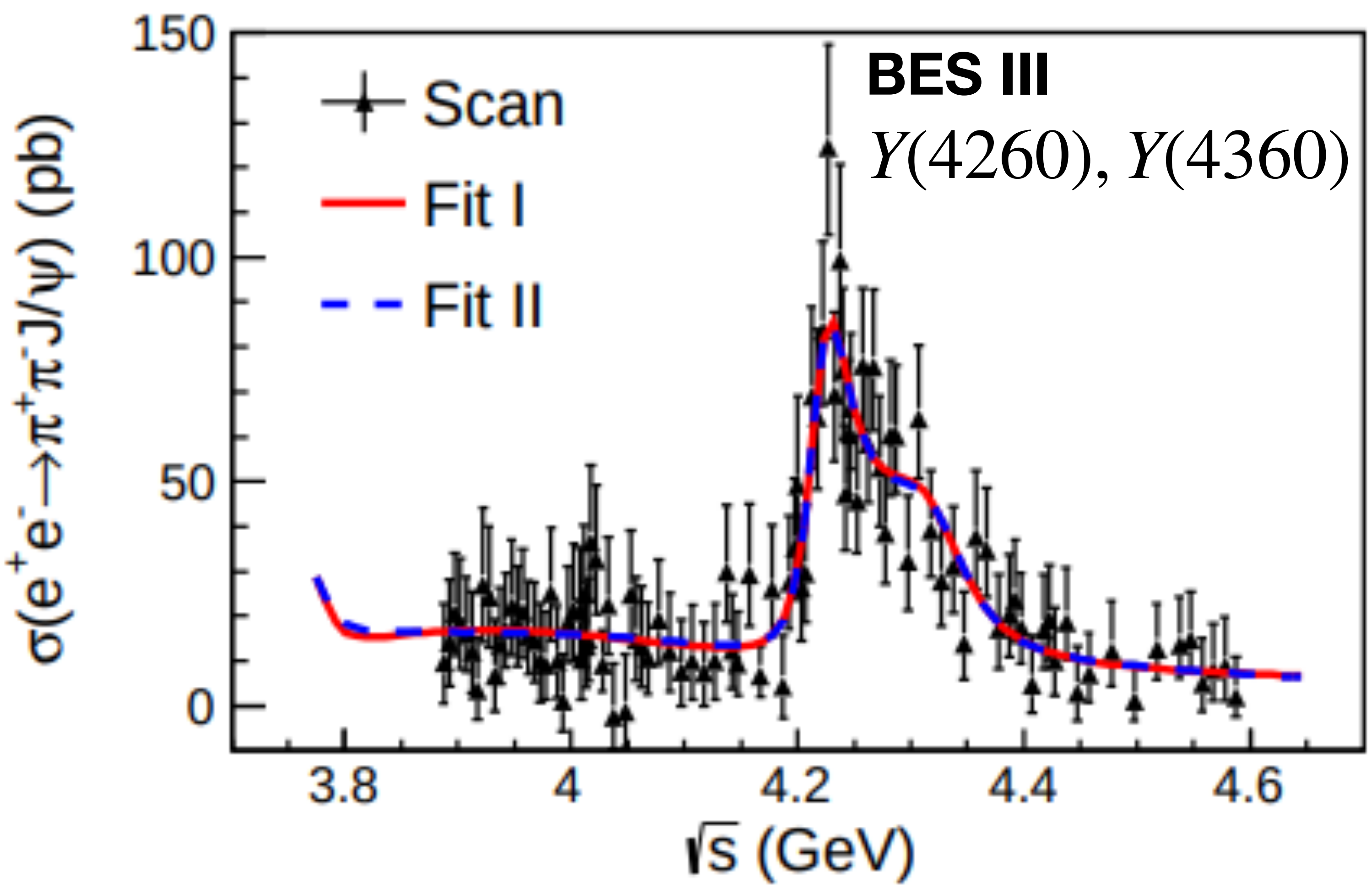
X(6900): 0^{++}?

- The new di-J/ψ X(6900) is assumed to be a scalar here.
- Couplings for J/ψ exchange too small for detection:
  for ω exchange with assumed 1% branching fraction still sizable cross sections (OZI suppressed but possible as in known $\psi(3770) \to \phi\,\eta$).
- Extremely suppressed cross sections at HE: threshold (LE) most promising.



Y photoproduction: 1^{--}

- Well studied experimentally because they can be produced in e^+e^- annihilation: BES III, Belle, BaBar, CLEO.
- Probably not conventional charmonium:
  decay mostly into hidden-charm states, instead of open;
  overpopulate predictions of vector charmonium spectrum.
- Could be hybrids, tetraquarks, hadronic molecules, …



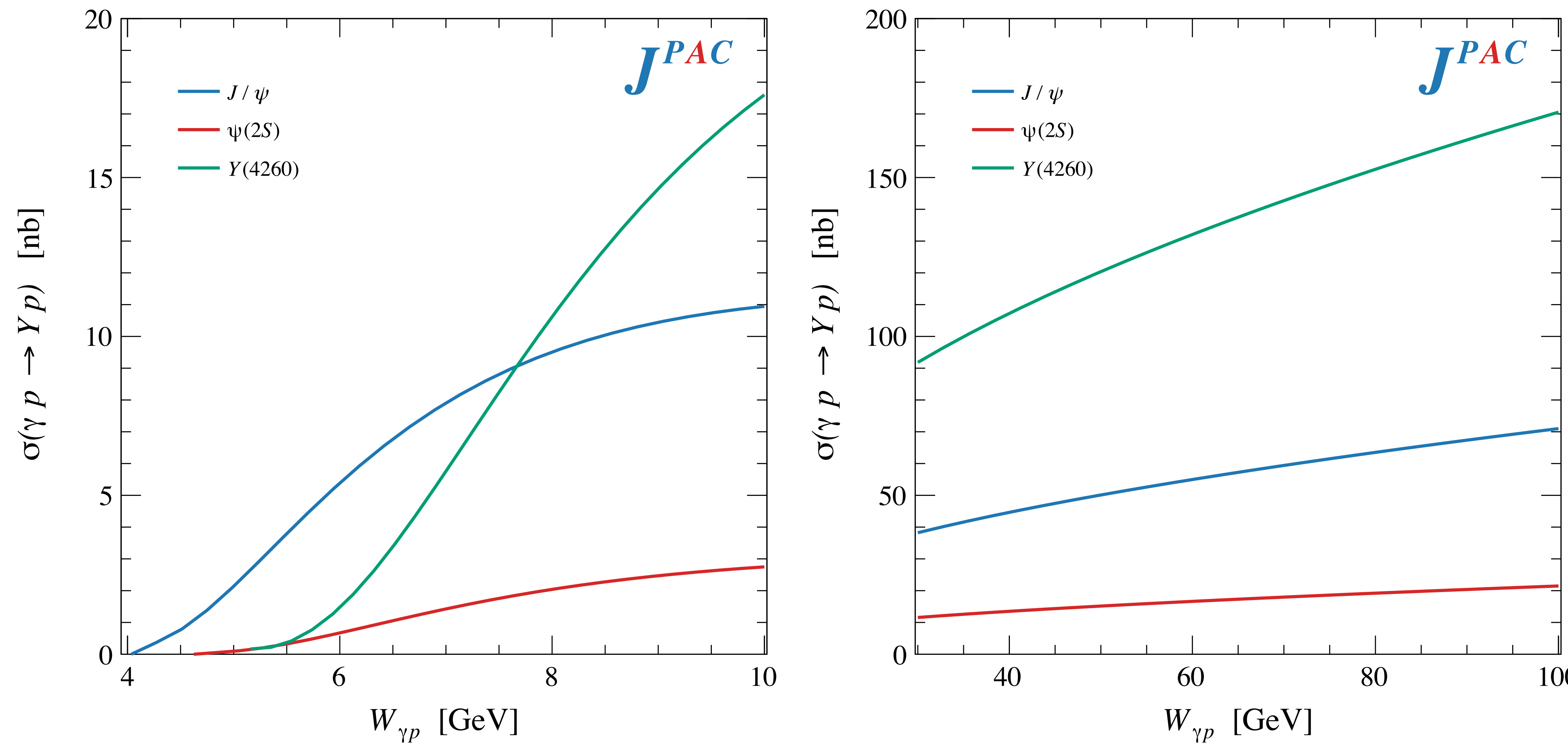
Y: perhaps the most promising EIC candidates

- Known to be **well described by diffractive Pomeron ($\mathscr{P}$ ~ 2-gluon 0^{++}) exchange**: fits to GlueX/SLAC and HERA/ZEUS.

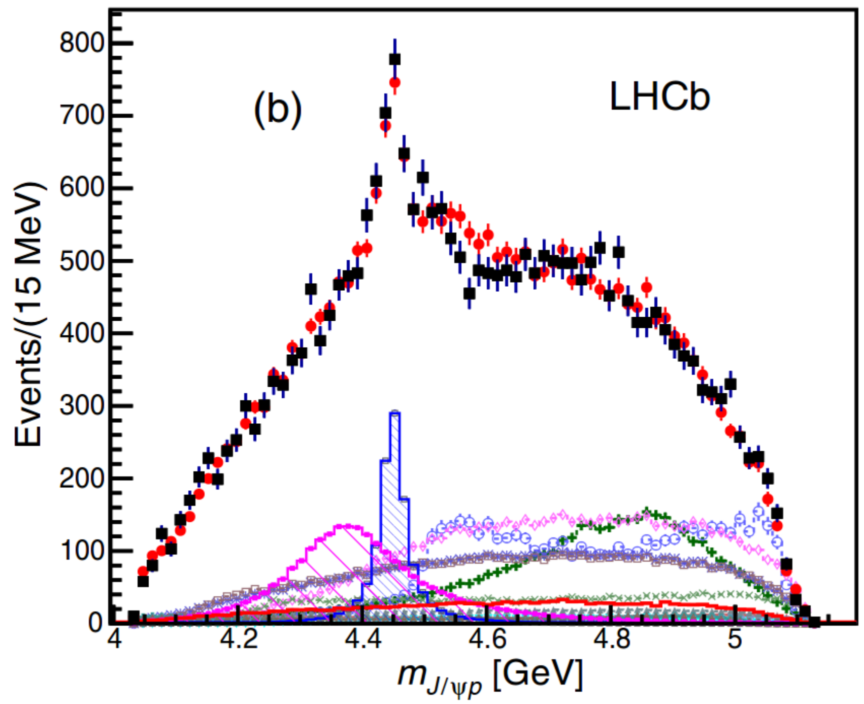
- Top-coupling ($\gamma \rightarrow V\mathscr{P}$) ratio to J/$\boldsymbol{\psi}$ estimated from decay ratios into gg$\boldsymbol{\gamma}$:
$R_Y \approx 1.5$ **suggests affinity to gluons as expected for a hybrid Y.**

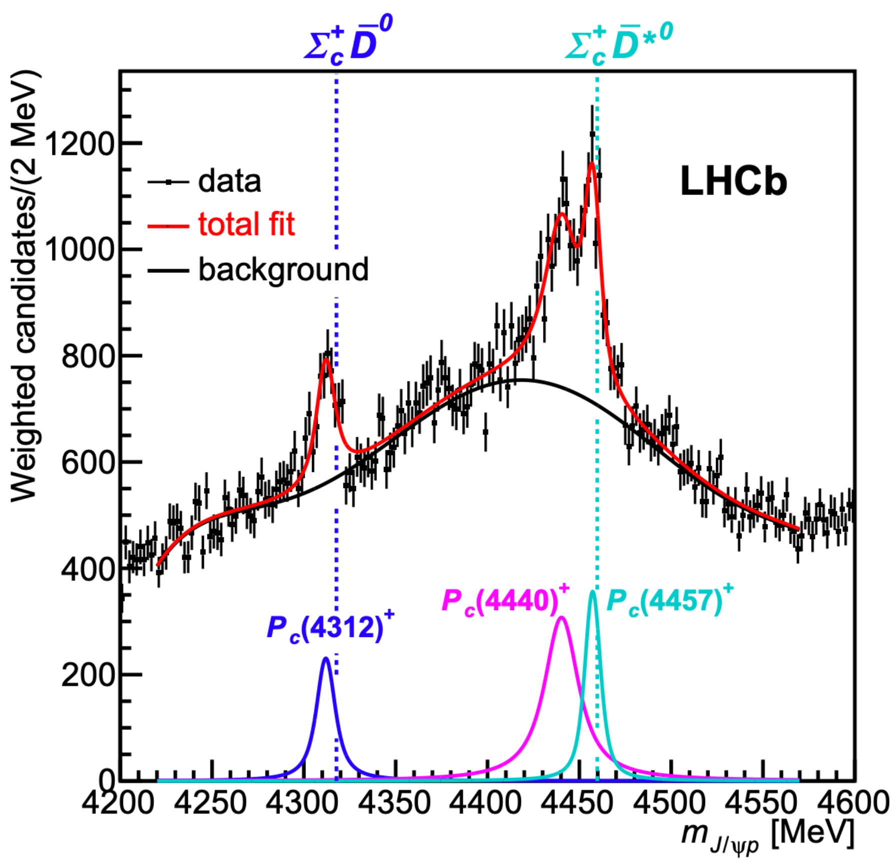
- Diffractive production increases with energy!

ANHB et al., Phys. Rev. D 94 (2016) 034002
Winney et al., Phys. Rev. D 100 (2019) 034019



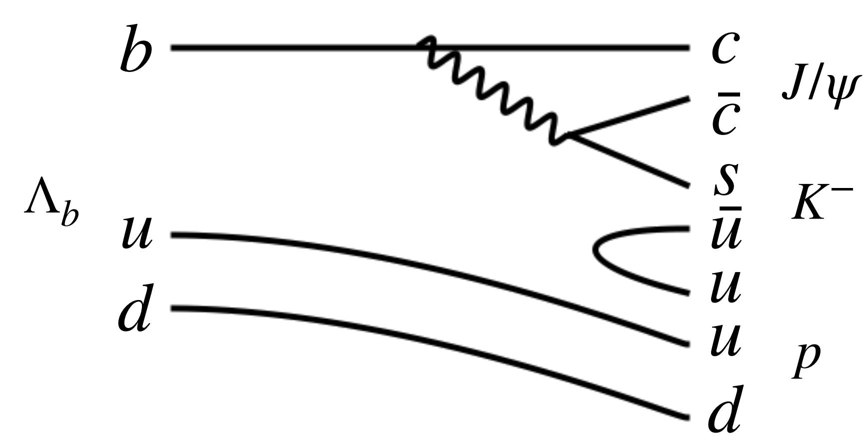
LHCb pentaquark discovery





- **2015:** **exotic-like** structures in $J/\psi\, p$ channel found.

LHCb collaboration, PRL 115 (2015) 072001; PRL 122 (2019) 222001



$$P_c \equiv c\bar{c}uud$$

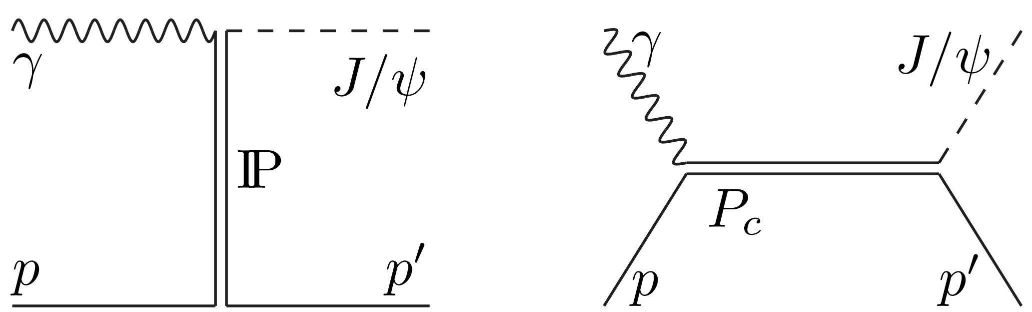
- Possible interpretations: **compact** 5-quark state;

- Weakly-bound $\bar{D}^*\Sigma_c^{(*)}$: mass consistent with predictions; would be **strongly isospin breaking** ($J/\psi\, p$ vs $J/\psi\, \Delta$) and require discovery of **more multiplet members**;

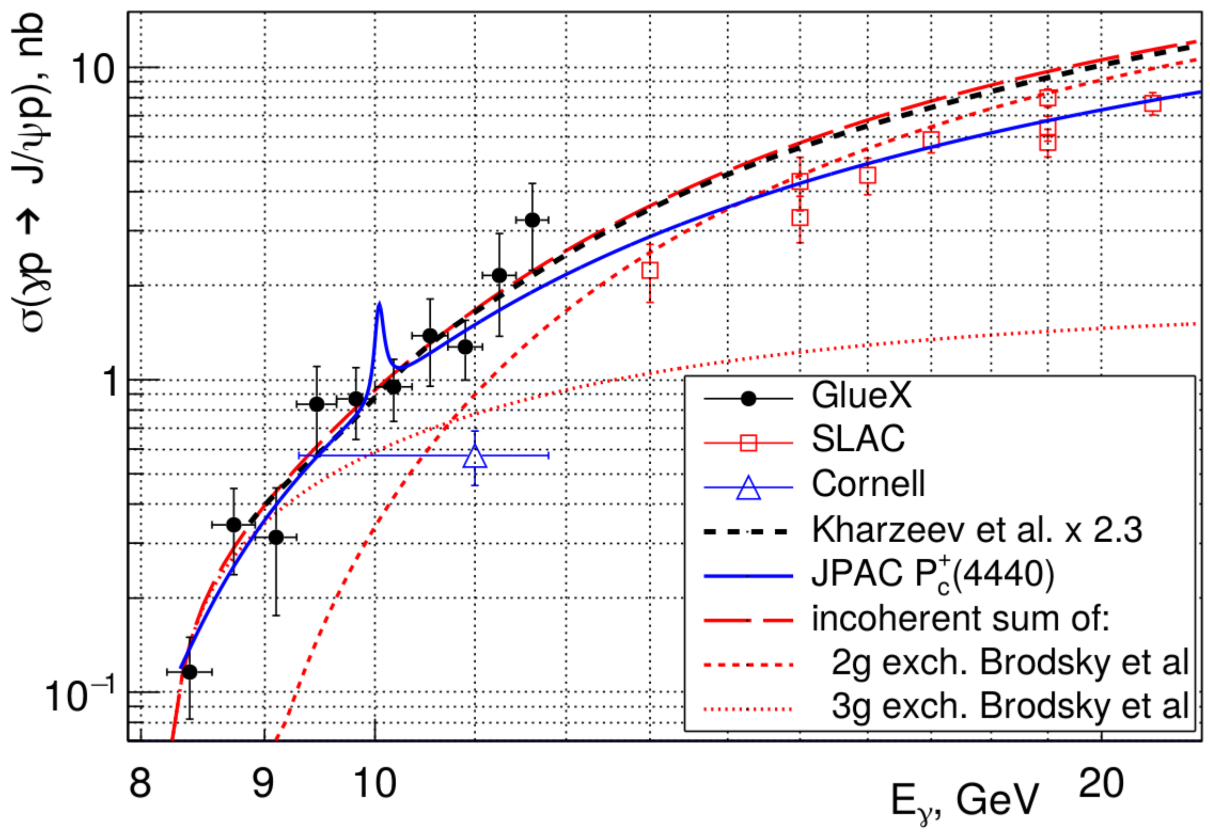
- Or possibly just **kinematic effects**:
LHCb showed that this kind of fits only is good if all exchanged resonances have narrow width (not so realistic).

Pentaquarks in J/ψ photoproduction

- Confirmation of **resonant nature** vs kinematic effects.
- Peak close to threshold: **low background.**
- Non-resonant contribution — Pomeron exchange;
  Resonant amplitude — Breit-Wigner ansatz and VMD assumption.



ANHB et al., Phys. Rev. D 94 (2016) 034002
Winney et al., Phys. Rev. D 100 (2019) 034019

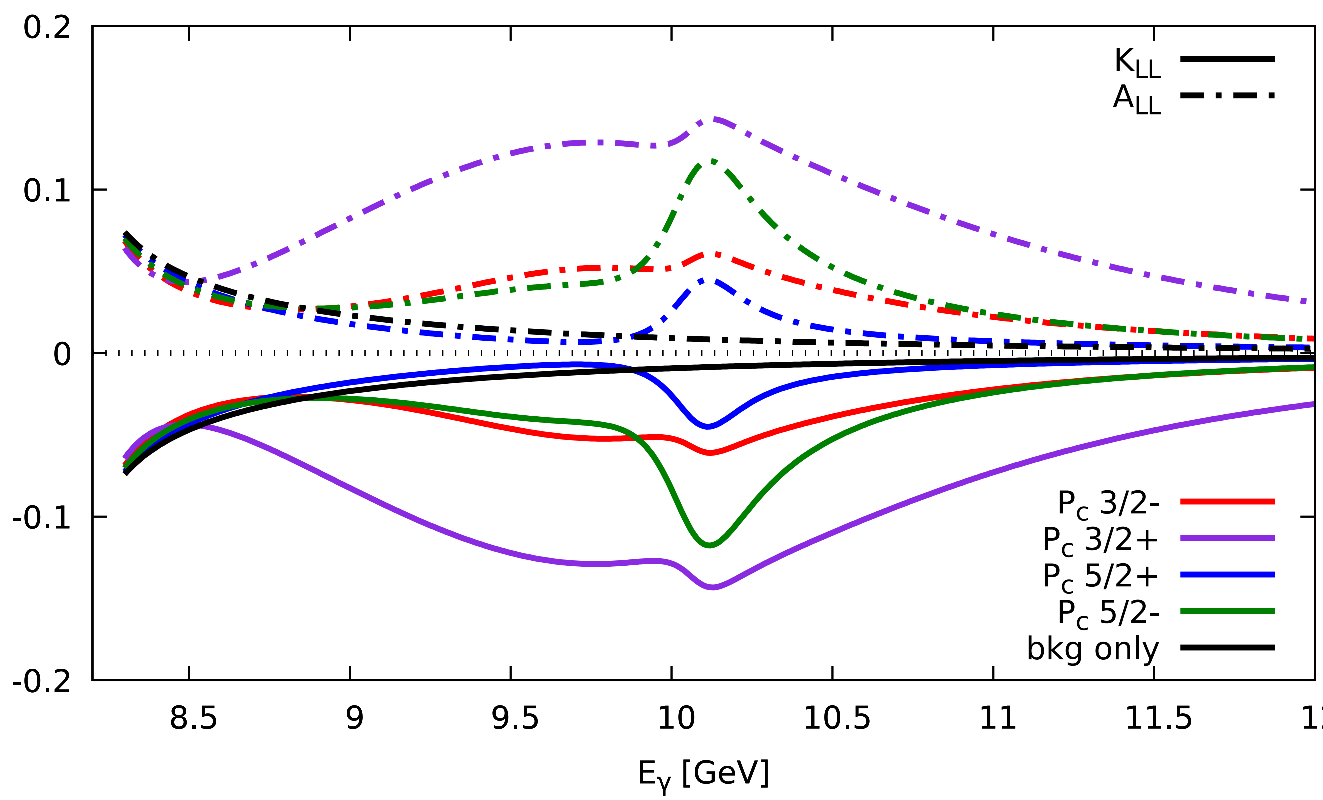


- Fits to GlueX data (no peak evidence) allowed for P_c branching fractions of 1-5%: model dependent, thus ruling out some models.
- If photoproduction experiments fail in finding signals (Hall A/C update coming soon), the scenario of LHCb signals being kinematic effects in the final-state is favoured.

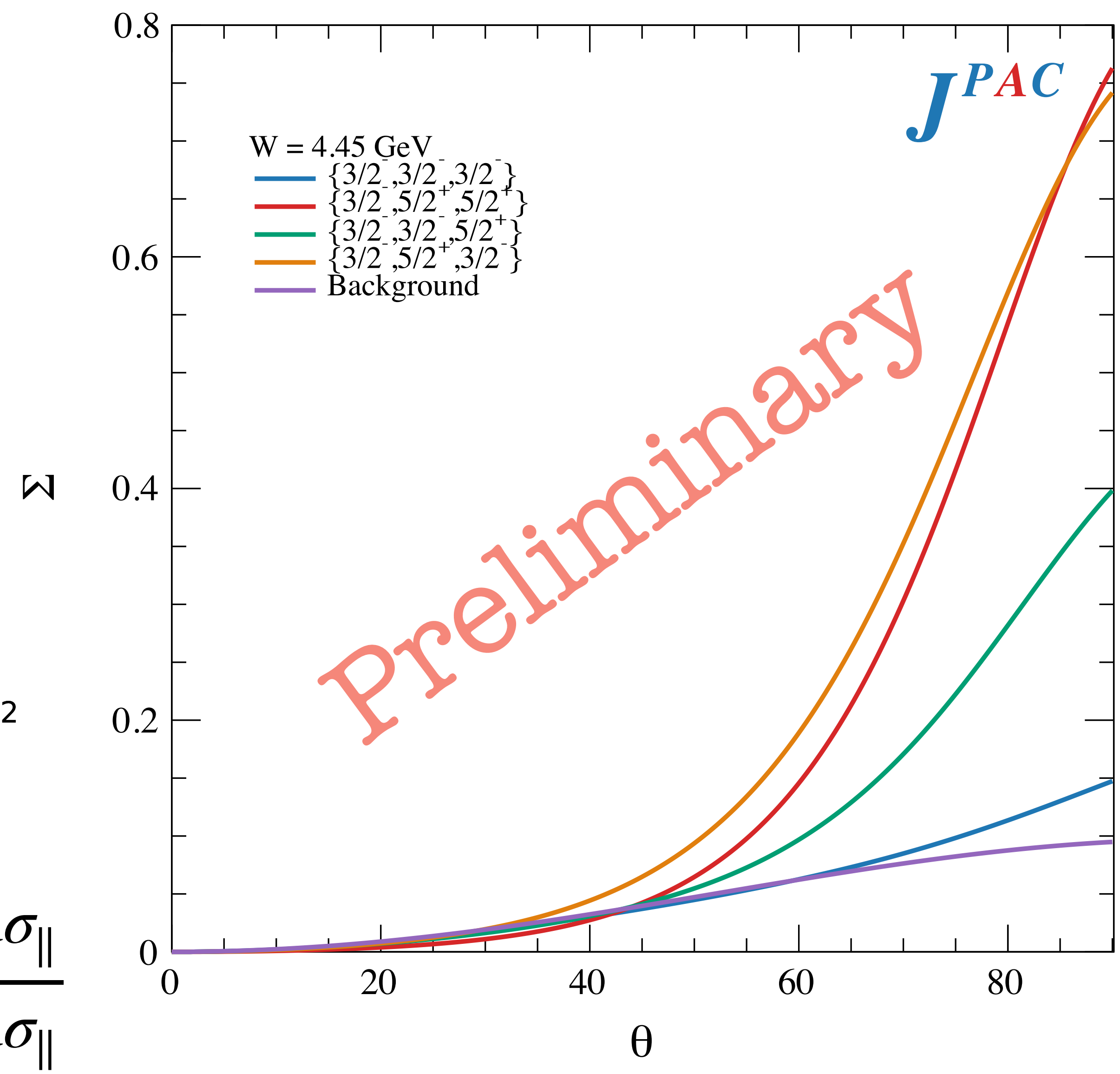
Discriminatory power of polarization observables

- Polarization observables more sensitive to broader or overlapping signals.
- Helpful information for determining quantum numbers.
- With sensitivity studies provided by JPAC, Hall A LoI submitted: measuring $A(K)_{LL}$.

LoI12-18-001 (PAC 46)
C. Fanelli, L. Pentchev, B. Wojtsekhowski



Winney et al., Phys. Rev. D 100 (2019) 034019
https://github.com/dwinney/jpacPhoto



$$A(K)_{LL} = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)} \qquad \Sigma = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}$$

- Beam asymmetries Σ can provide complementary information!

Wang et al., Phys. Rev. D 99 (2019) 114007

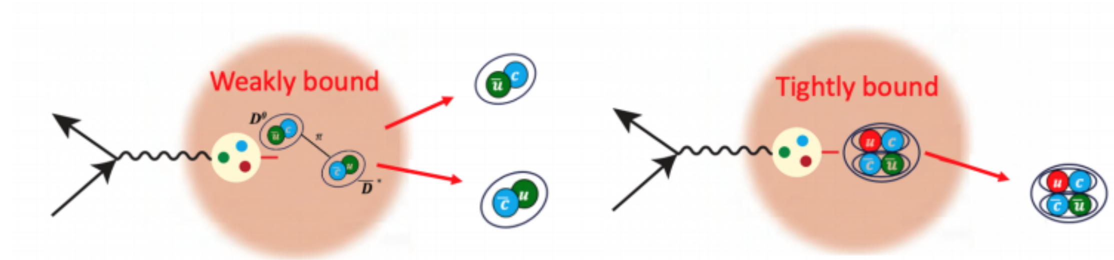
Production formalism - phenomenological constraints

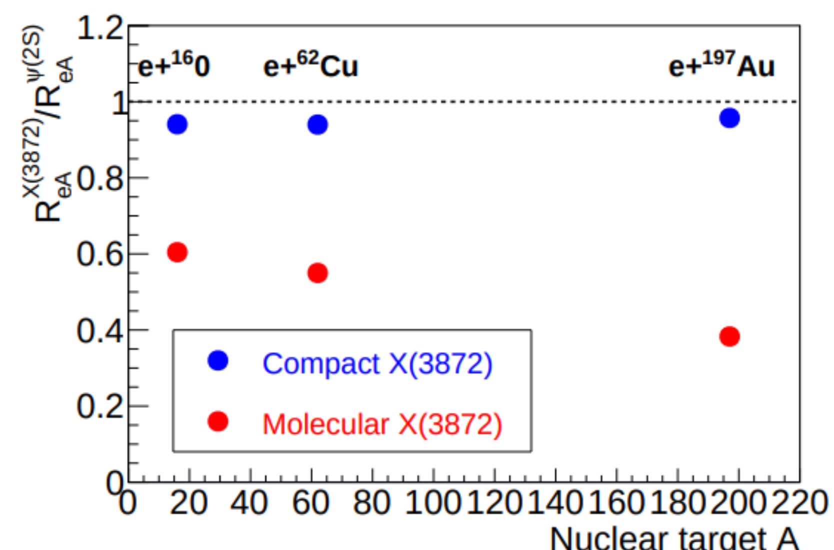
Results: XYZ and pentaquarks

<u>**What can the future of electron-ion colliders bring us?**</u>

The nature of the beast

- The EIC offers the possibility to study exotics in **nuclear medium**:
  while traversing the nucleus, large, weakly bound **hadronic molecules** undergo significantly **more disruption** than **compact states**.





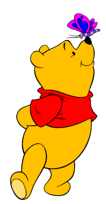
- **From spectroscopy to structure**:
  e.g. study of magnetic moments predicts different behavior between models (molecular vs diquark-antidiquark-quark).

- Combination with existing theory works:
  effective Lagrangians, lattice QCD, QCD sum rules, quark model, …

Summary

- X and Z exclusive production most promising close to threshold.
- **Diffractive states such as the Y are good candidates for the EIC.**
- P_c searches require higher luminosity: **polarization observables!**

See Daniel Winney's talk!



Outlook

Albaladejo et al., SNOWMASS21-RF7_RF0-120
Albaladejo et al., SNOWMASS21-RF7_RF0-090
Albaladejo et al., SNOWMASS21-RF7_RF0-081
Abdul Khalek et al., EIC Yellow Report 2103.05419

- **Semi-inclusive** reactions:
  complicate the identification of final states, but have larger cross sections.
- **Electroproduction:** better experimental feasibility.
- Studies trivially extended to other XYZP once information about them is available.
- Structure and nature of the exotic states!