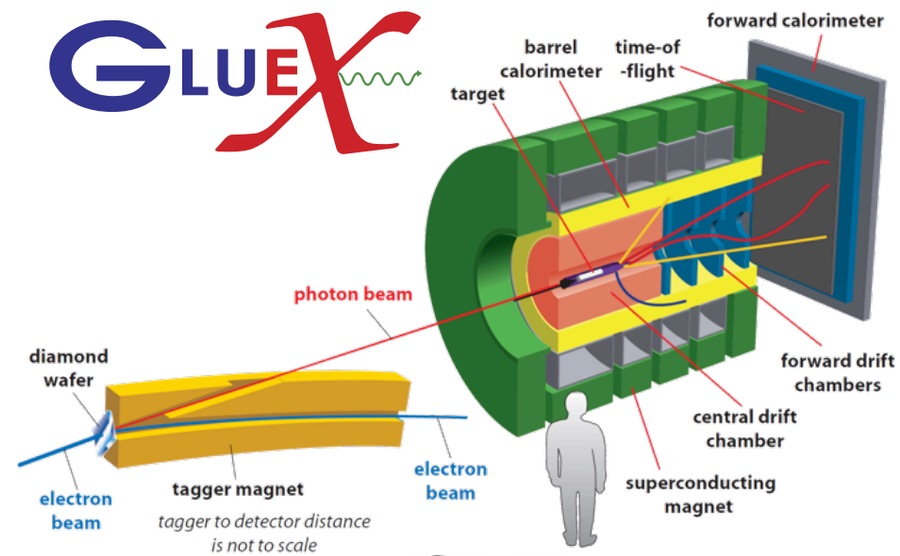
Future of Hadron Spectroscopy in Photoproduction Experiments

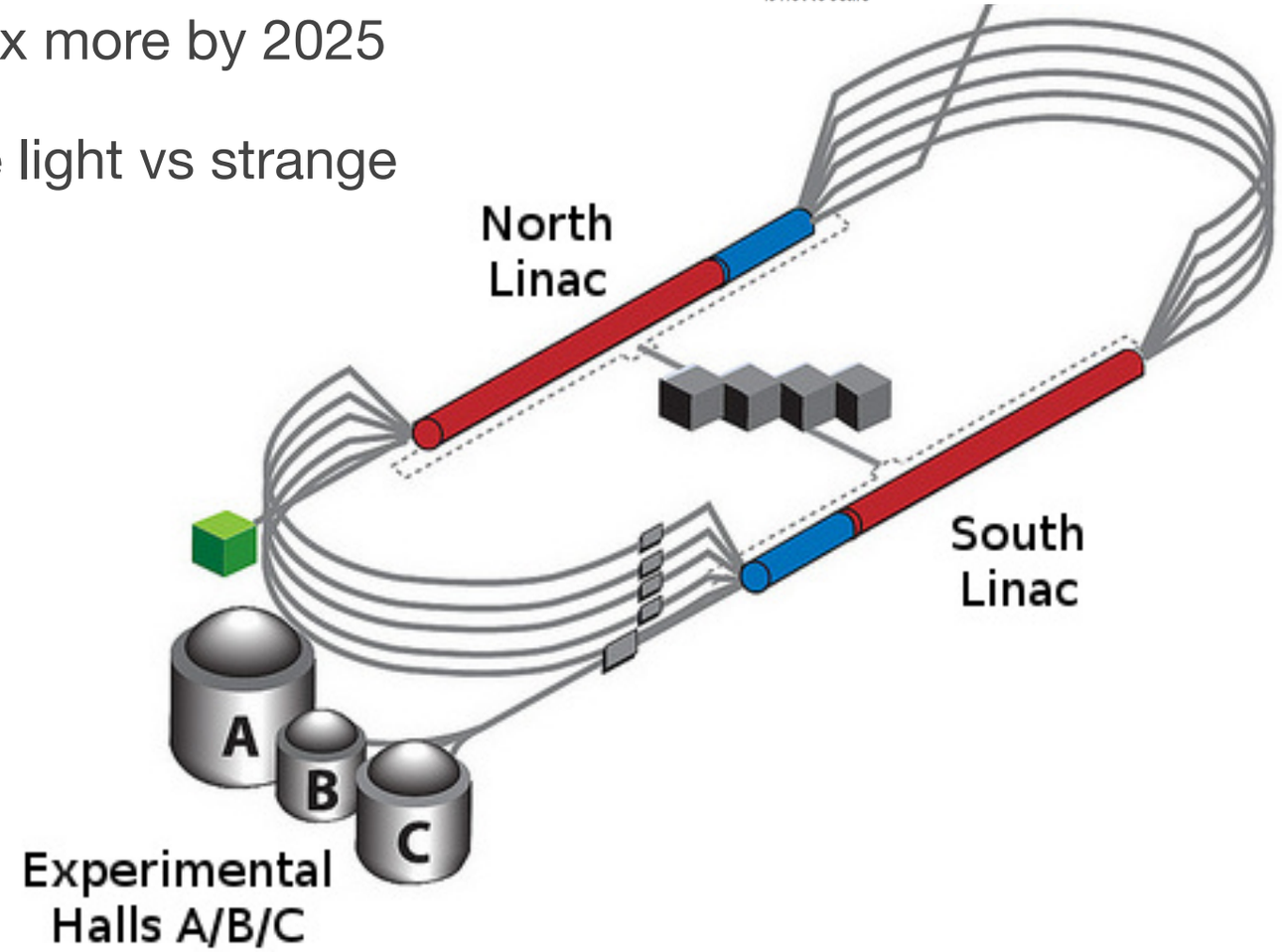
Justin Stevens

WILLIAM & MARY
CHARTERED 1693

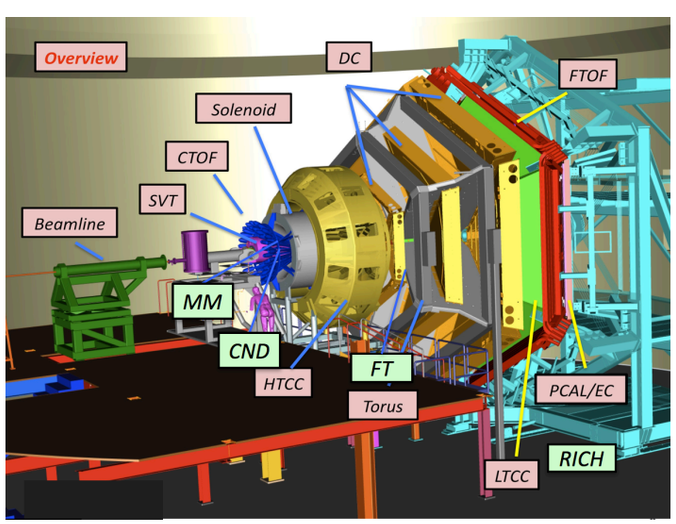
Jefferson Lab 12 GeV e- beam

- Running since 2017: programs in spectroscopy, nucleon structure, etc.
- Photoproduction process provides access to many proposed exotic decay channels
- Orders of magnitude higher statistics than previous experiments: e.g. at GlueX
  - $\mathscr{L} = 0.84\ \mathrm{fb}^{-1}$ so far with 3x more by 2025
- Kaon identification to investigate light vs strange quark content





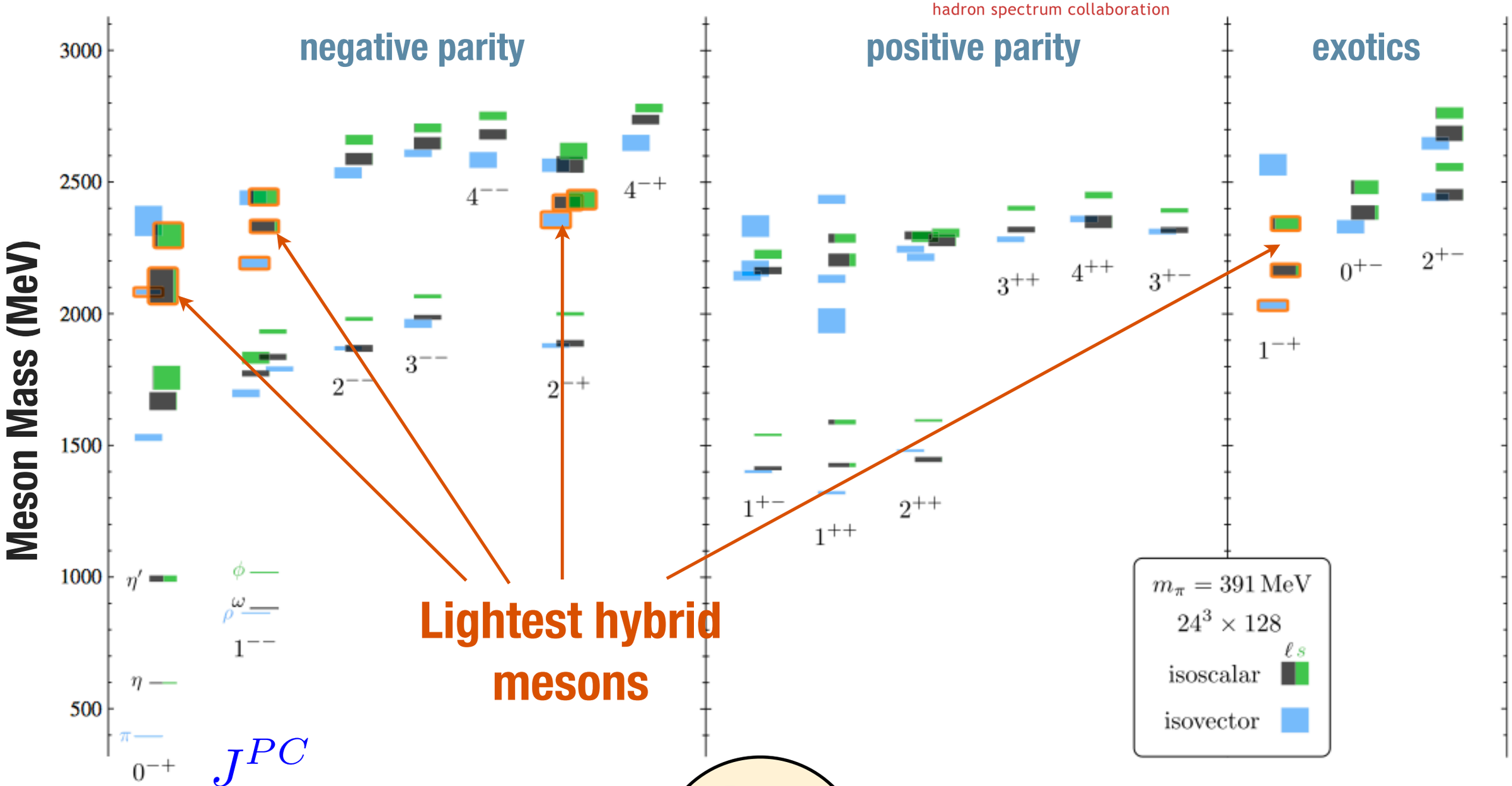
CLAS12

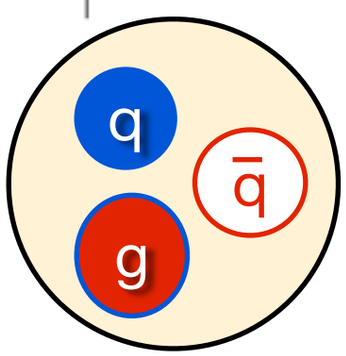


Lattice QCD

hadspec
hadron spectrum collaboration

PRD 88 (2013) 094505





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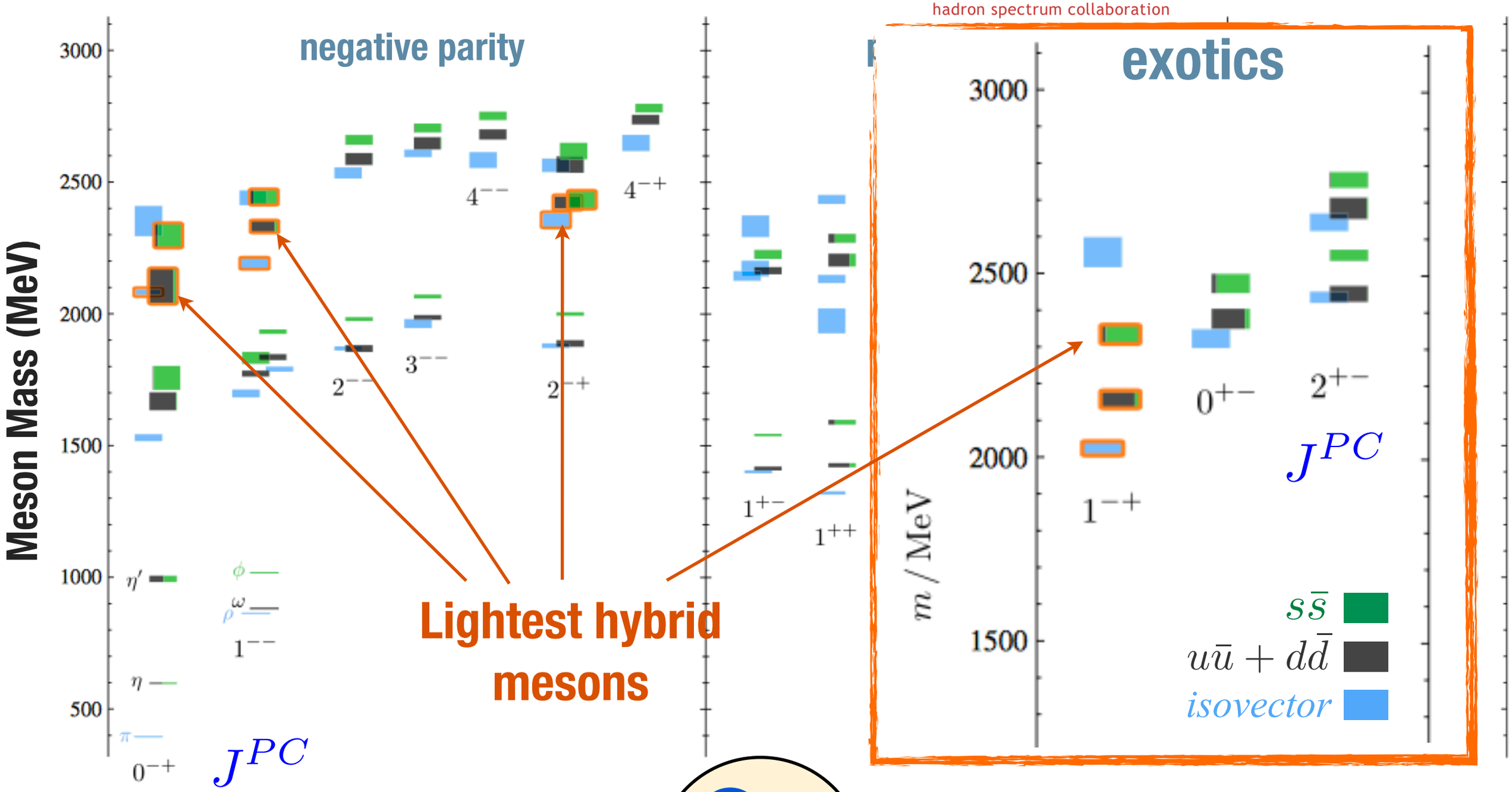
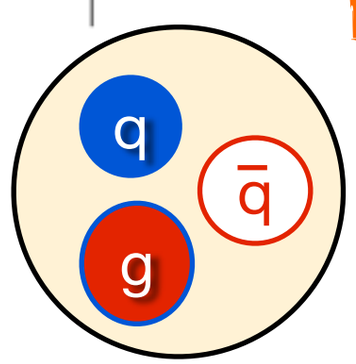
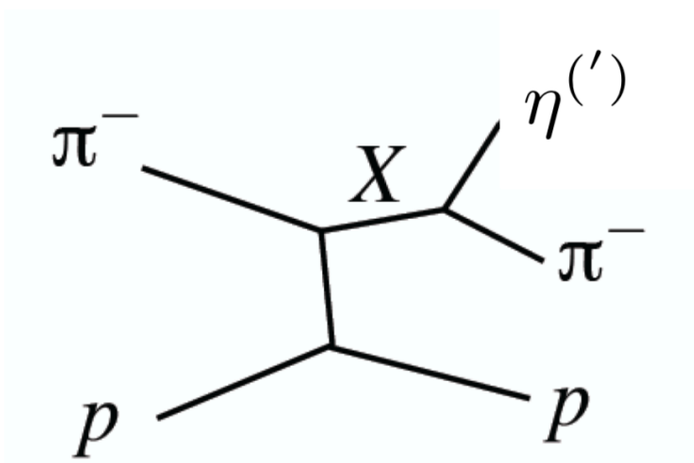
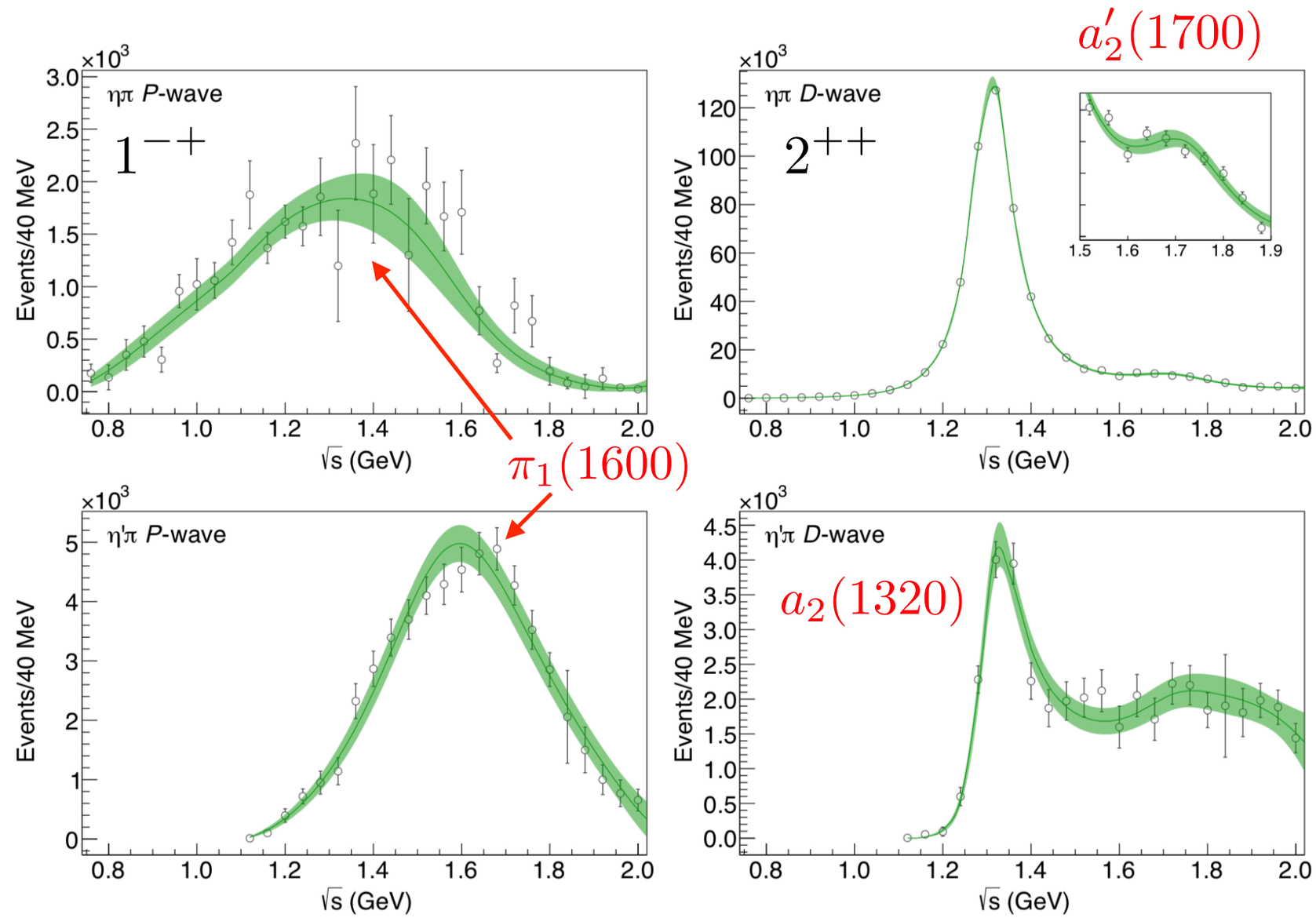




Most experimental searches for hybrids limited to the **π_1 state**

ηπ/η'π spectroscopy at COMPASS with JPAC



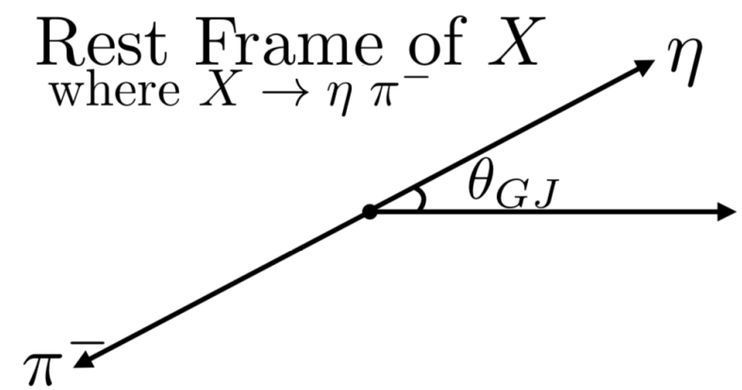


JPAC (Joint Physics Analysis Center) coupled channel fit to ηπ and η'π determine pole positions for a_2, a_2', and exotic π_1

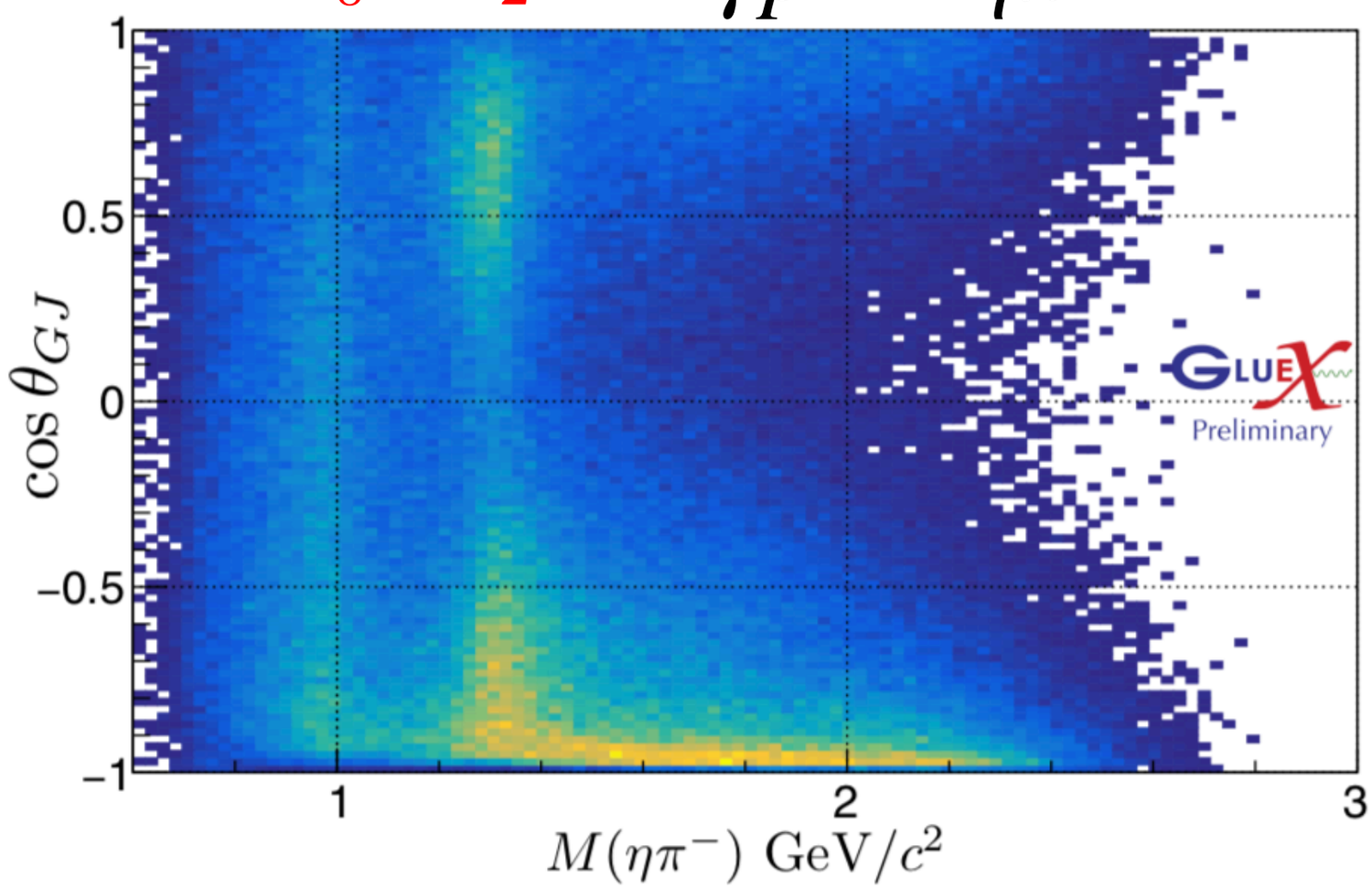
COMPASS: **PLB 740 (2015) 303**
JPAC: **PRL 122 (2019) 042002**

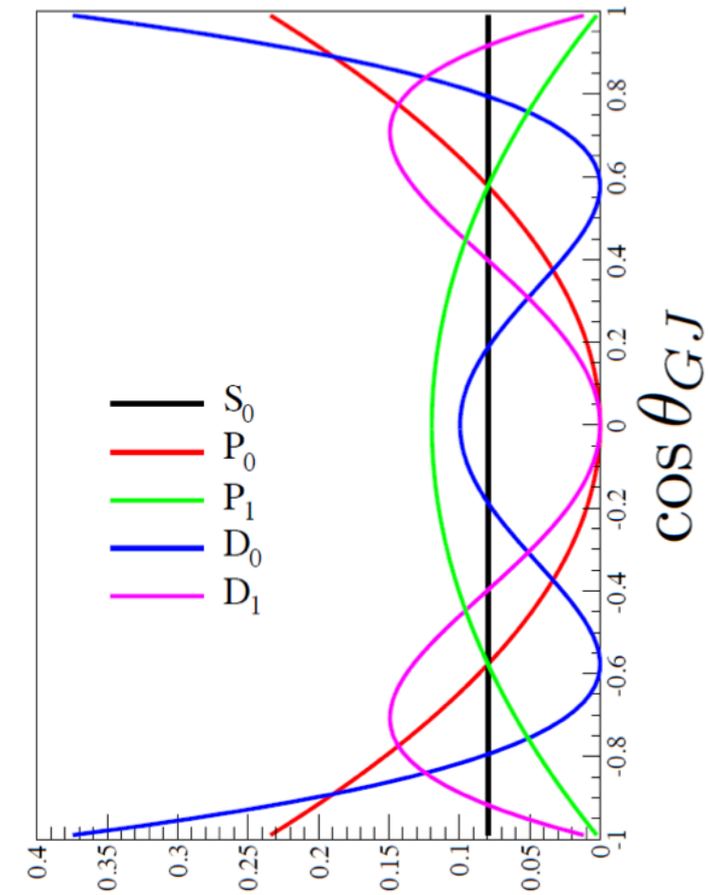
ηπ/η'π spectroscopy at GlueX

- Investigating similar channels as exotic P-wave signals reported by COMPASS
- Polarized photon beam provides new information on production mechanism, collaborating with JPAC on amplitudes



a_0 a_2 $\gamma p \to \eta\pi^-\Delta^{++}$





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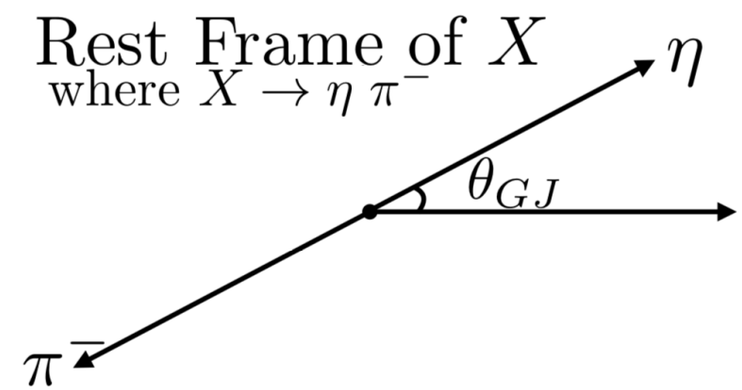
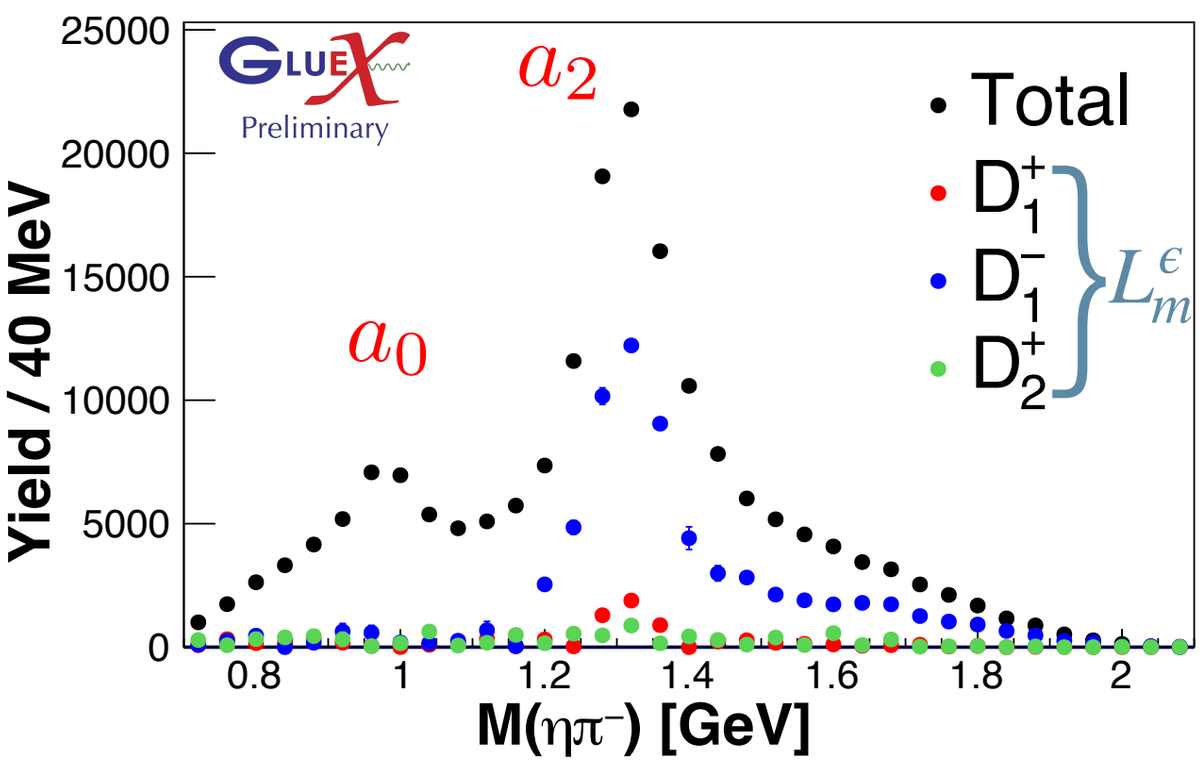
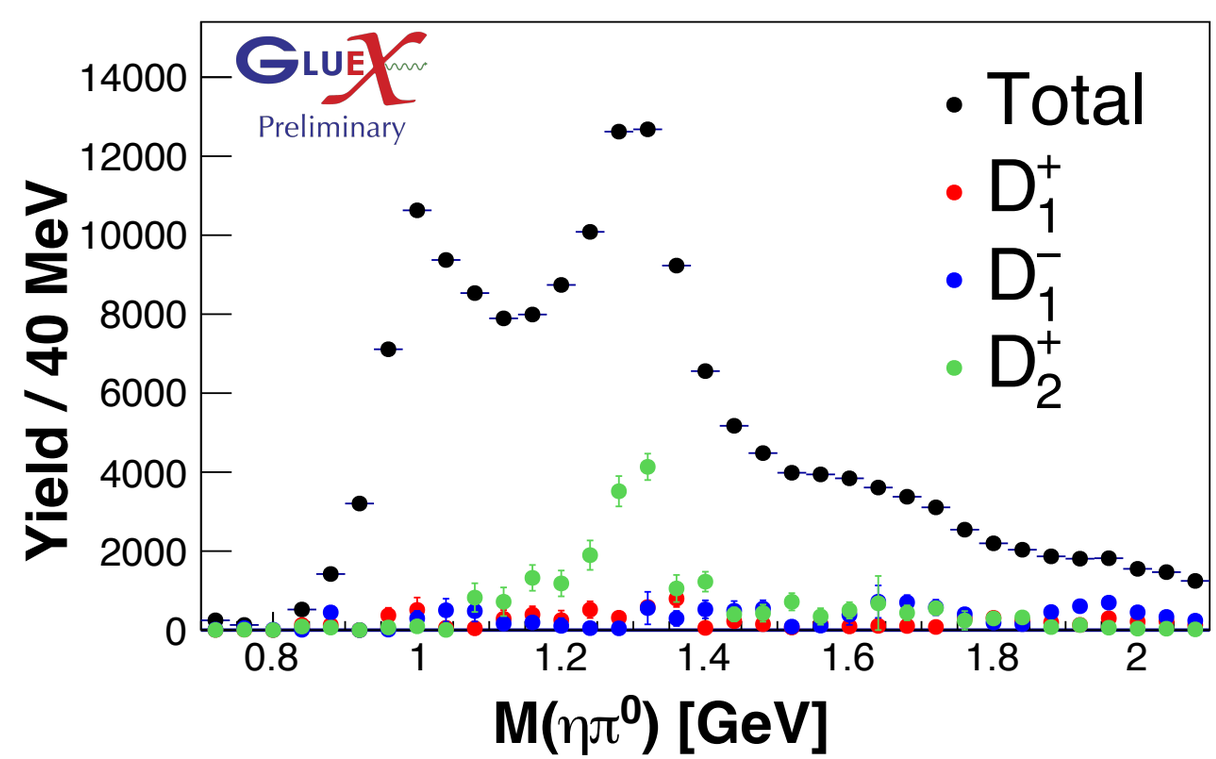


$$\gamma p \to \eta\pi^-\Delta^{++}$$

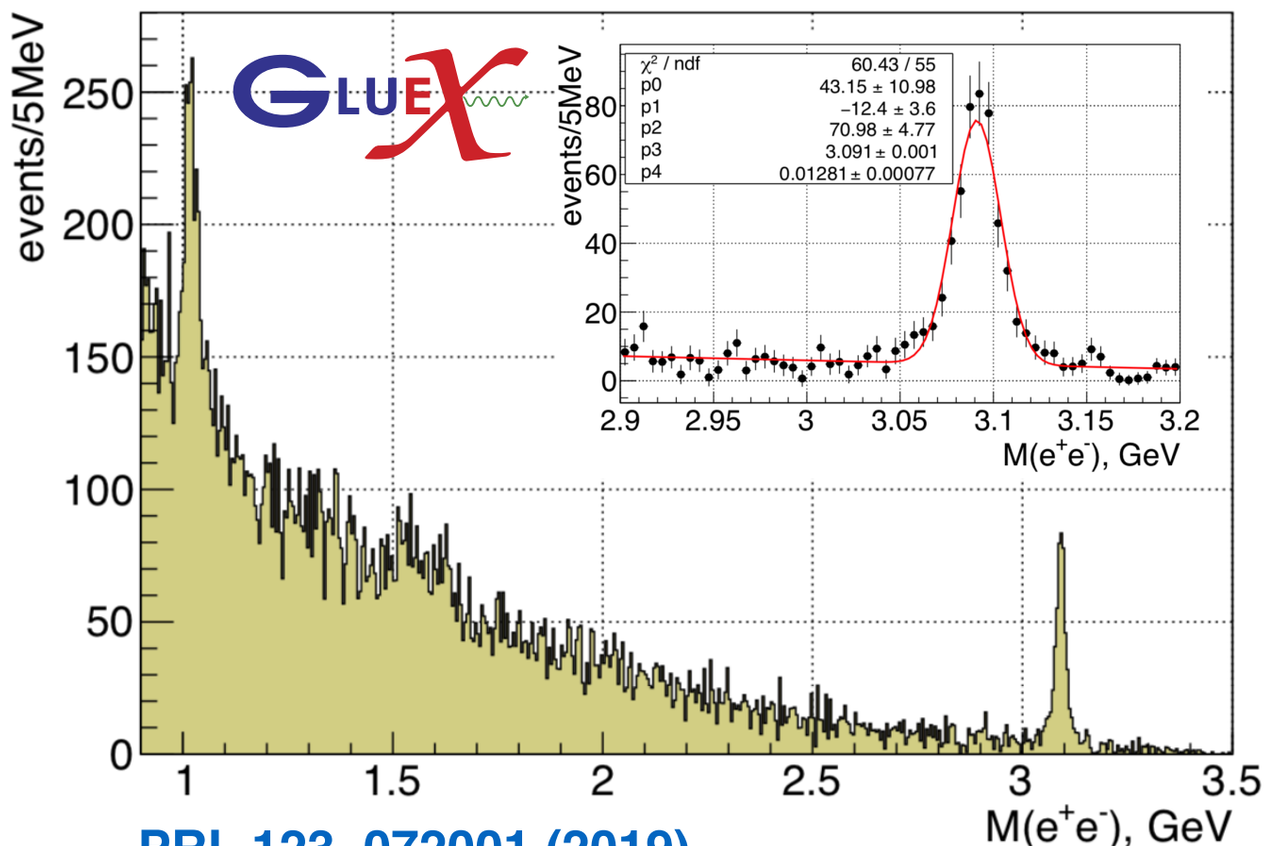


$$\gamma p \to \eta\pi^0 p$$



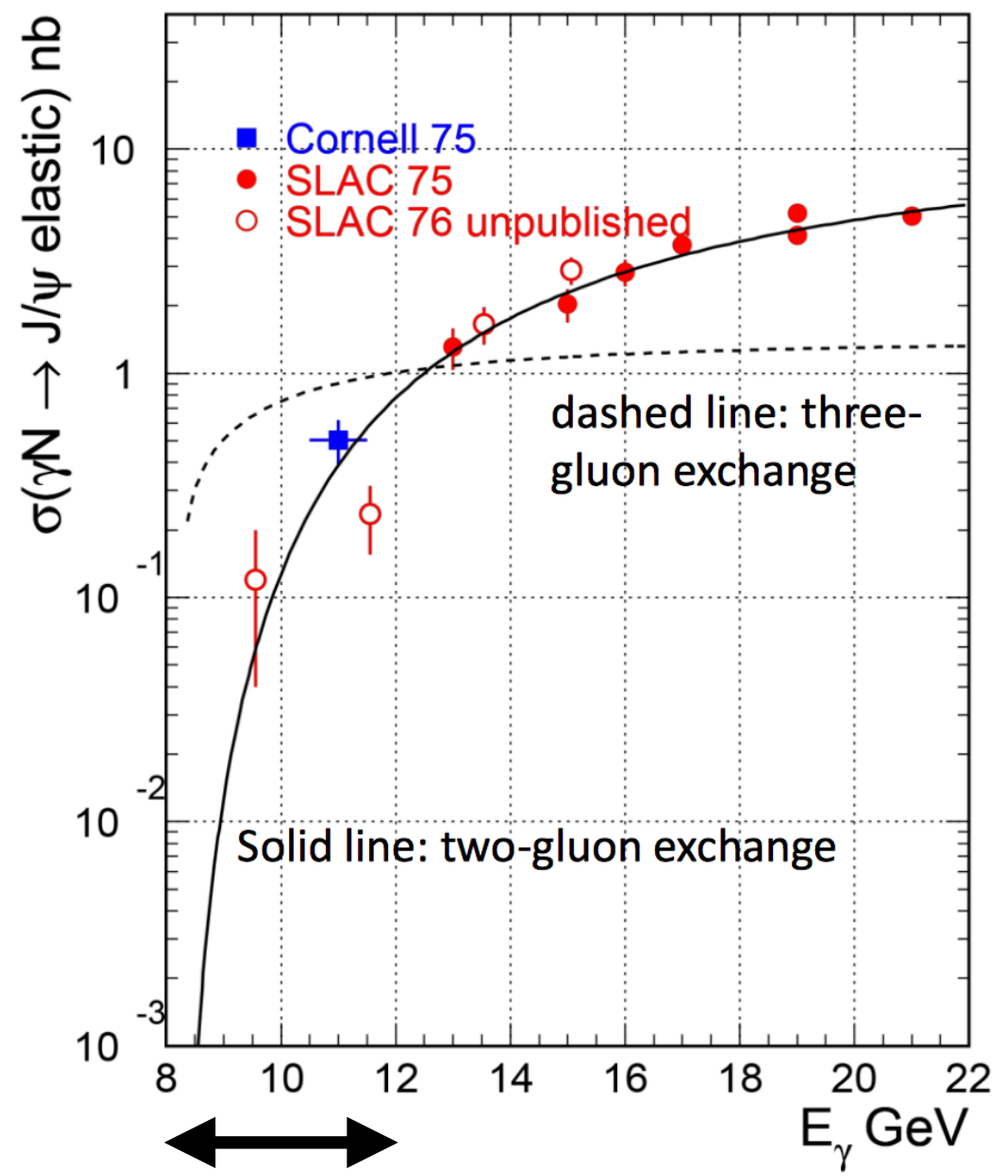
Pentaquarks and threshold charmonium

$$\gamma p \to p e^+ e^-$$



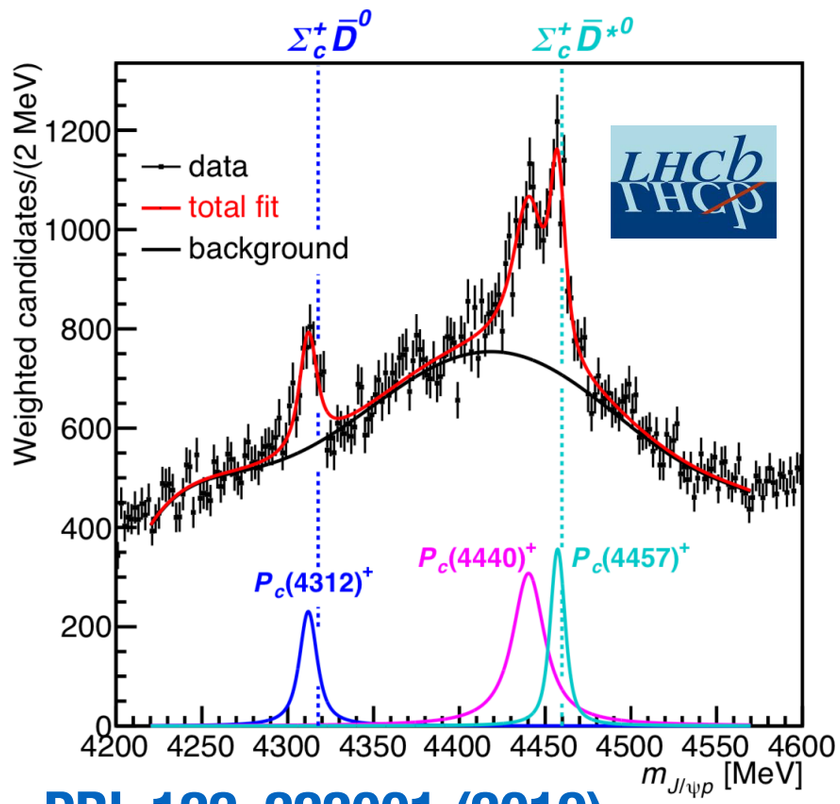
PRL 123, 072001 (2019)

Threshold J/ψ production

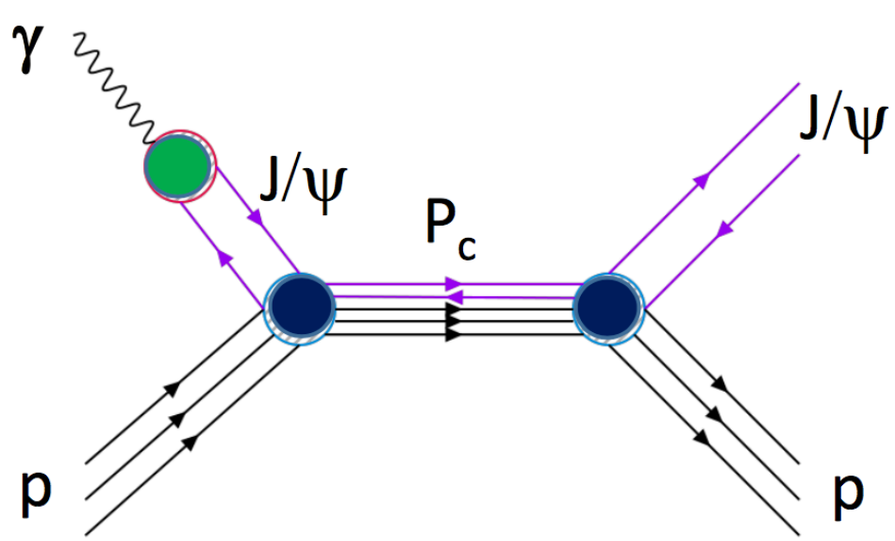


Jefferson Lab 12 GeV

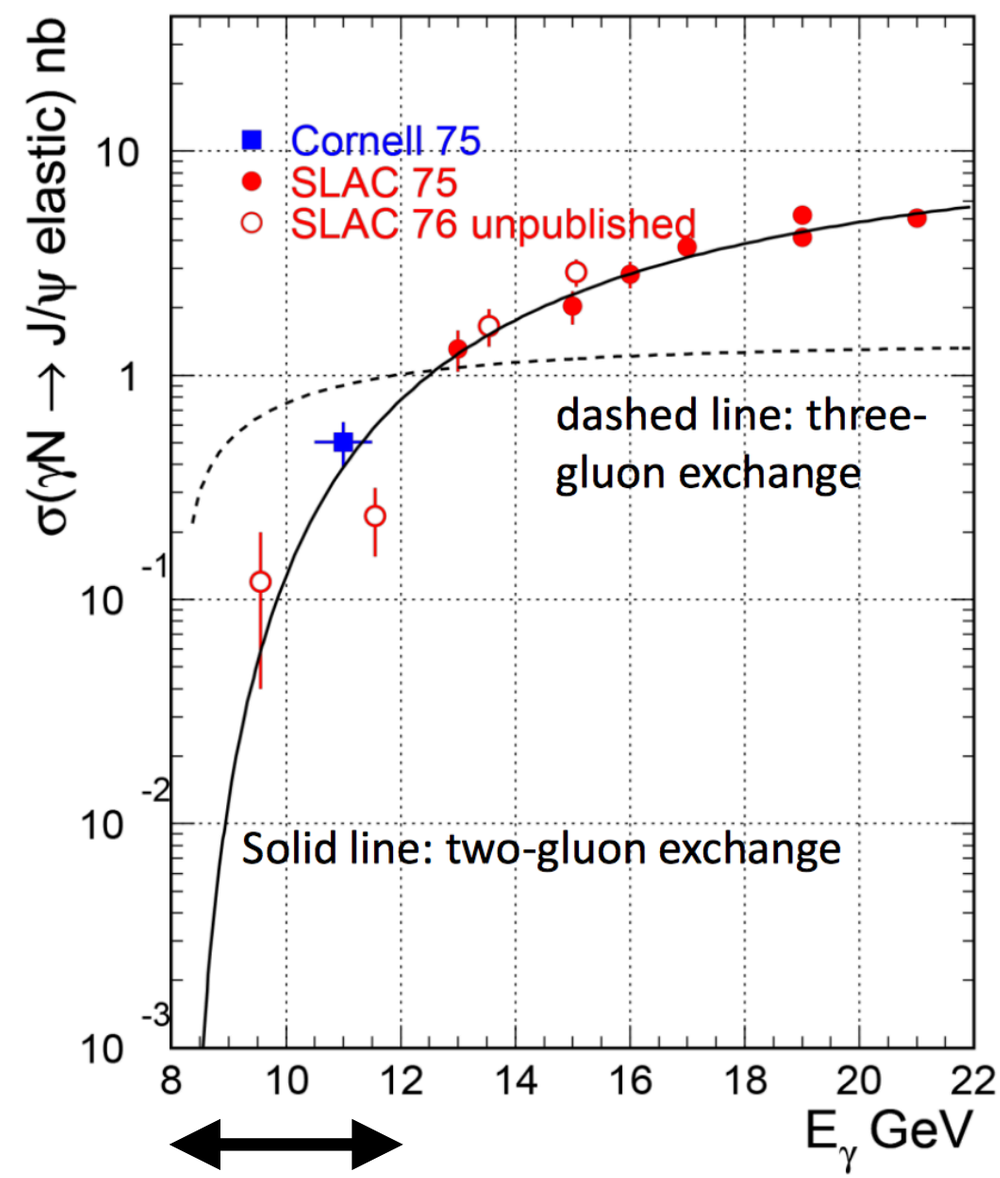
Pentaquarks and threshold charmonium



PRL 122, 222001 (2019)



Threshold J/ψ production



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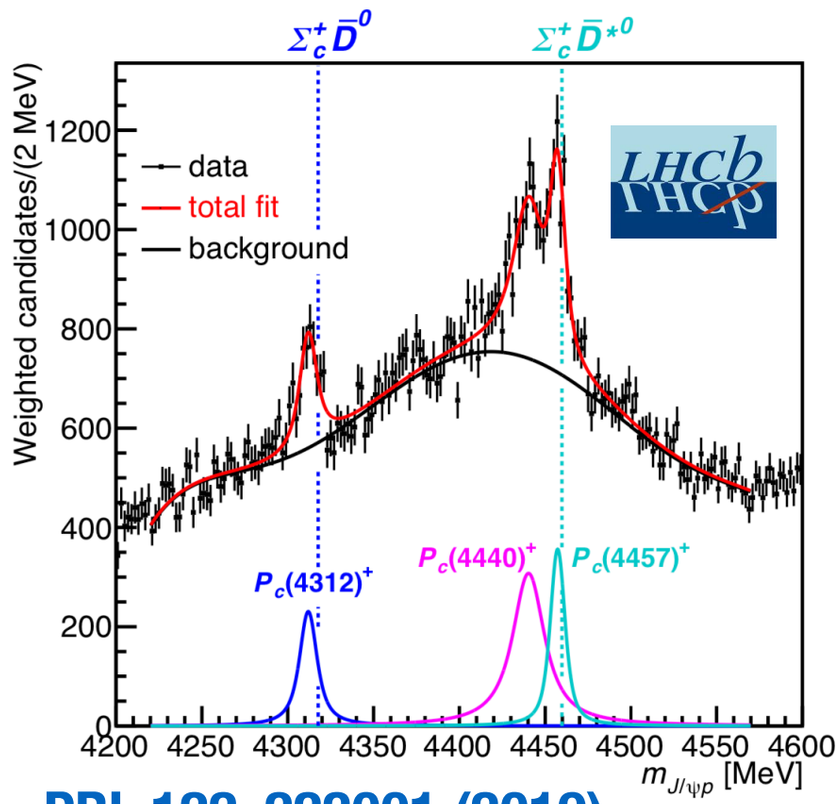

PRL 122, 222001 (2019)

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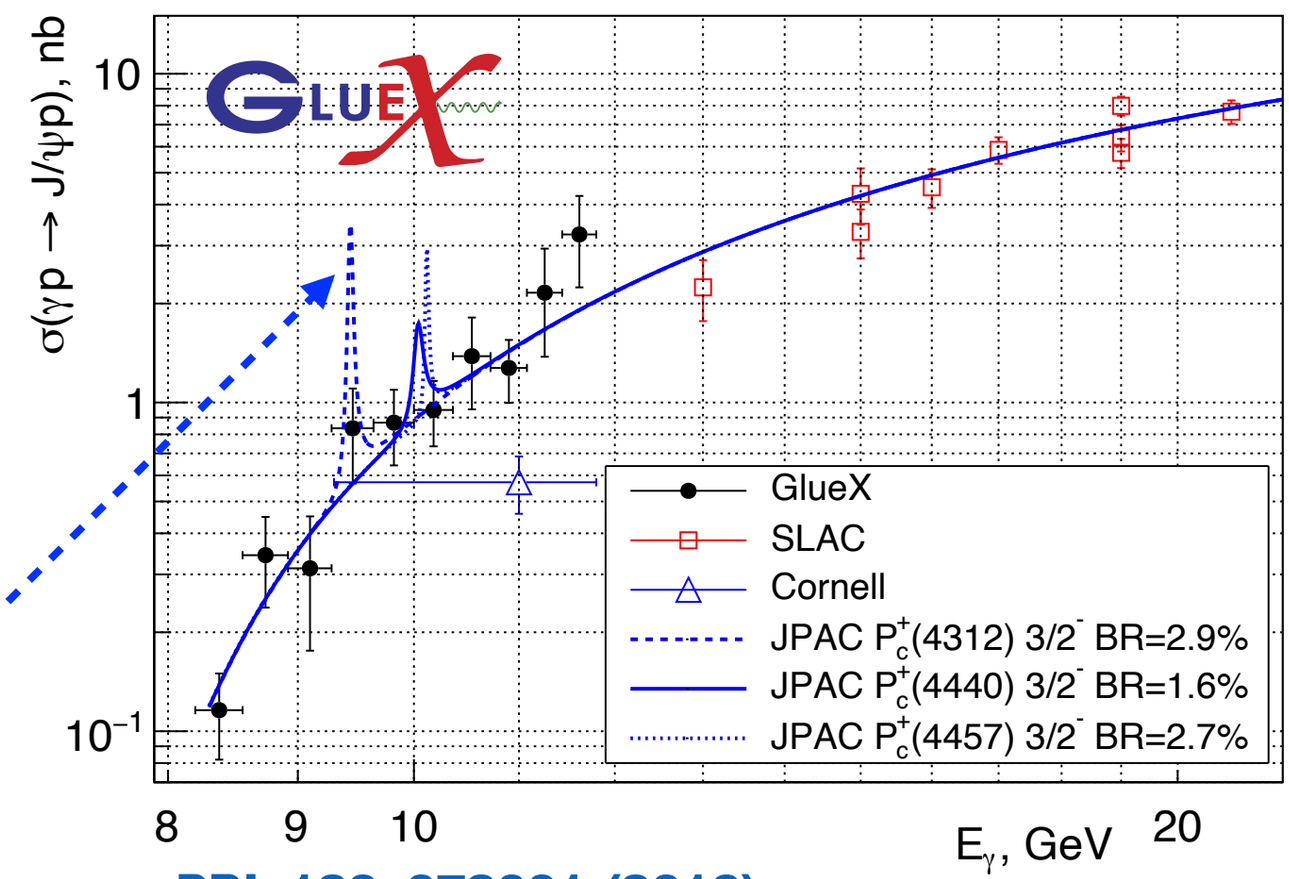
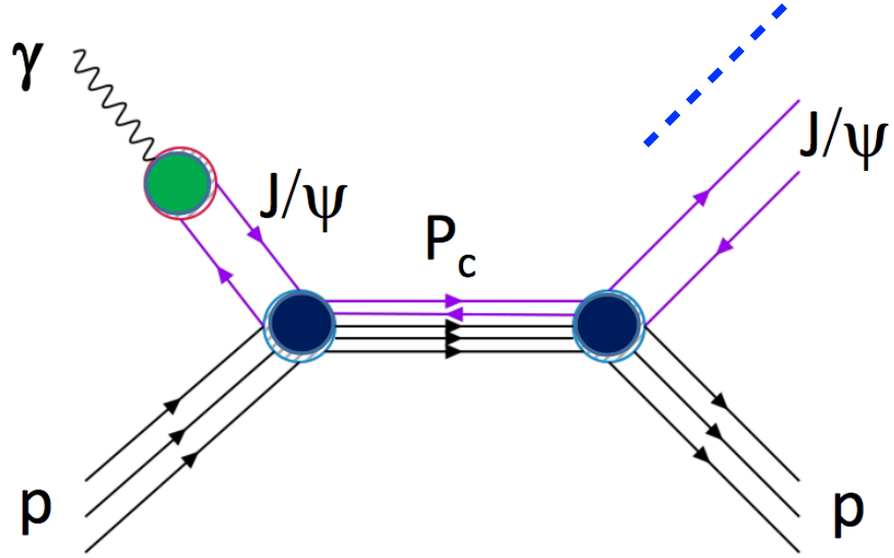
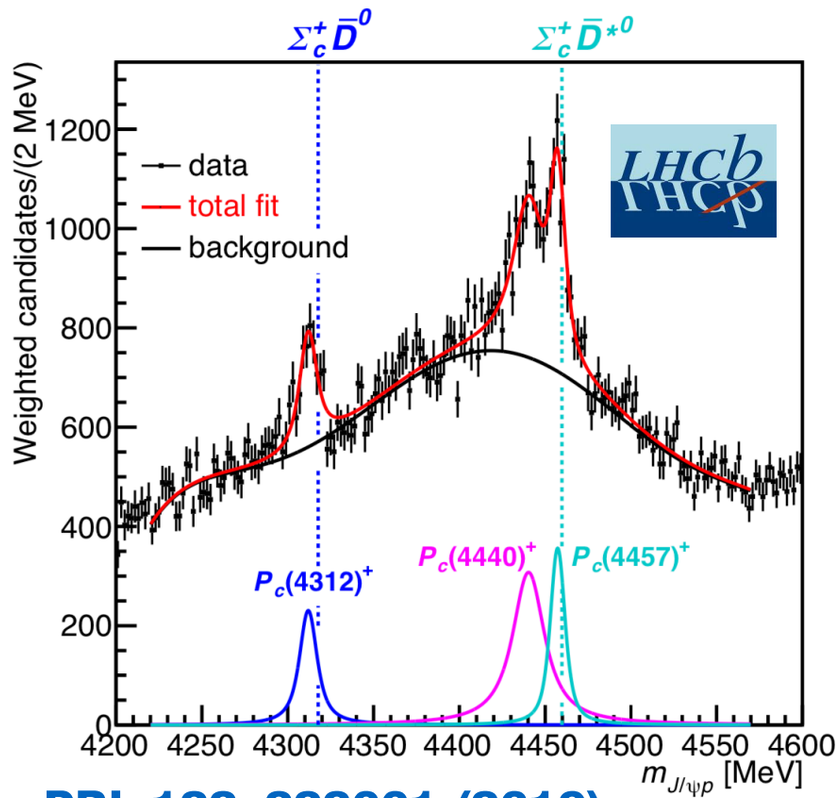


PRL 123, 072001 (2019)

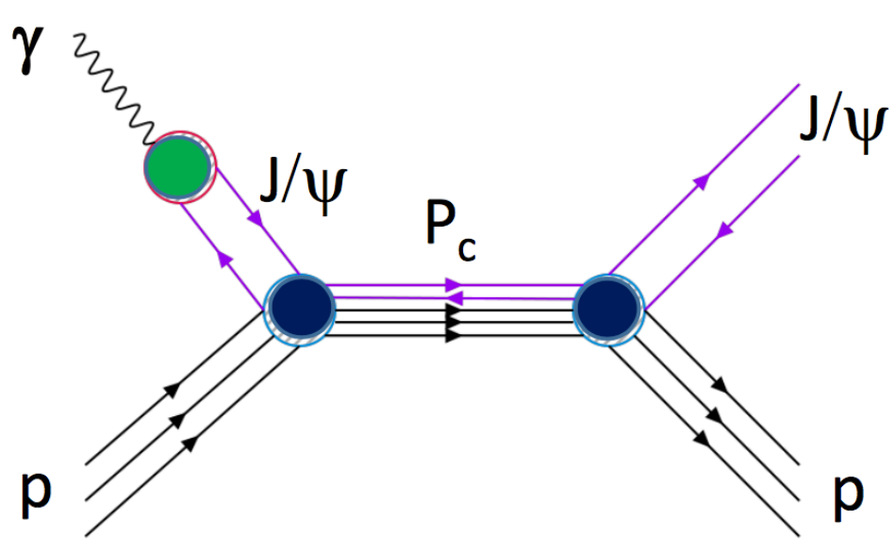


Limits BR($P_c \to J/\psi p$) < 2-4%, providing additional model constraints

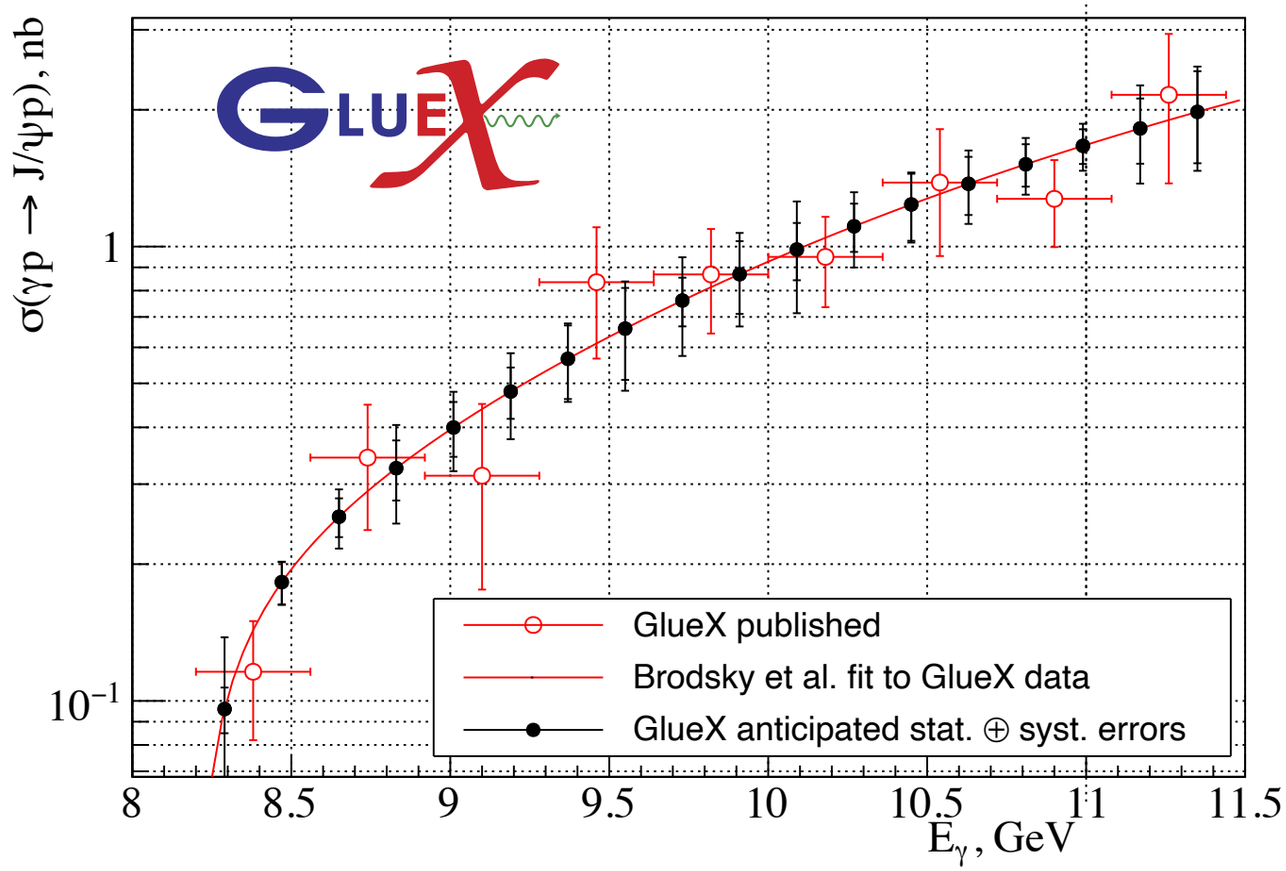
Pentaquarks and threshold charmonium



PRL 122, 222001 (2019)

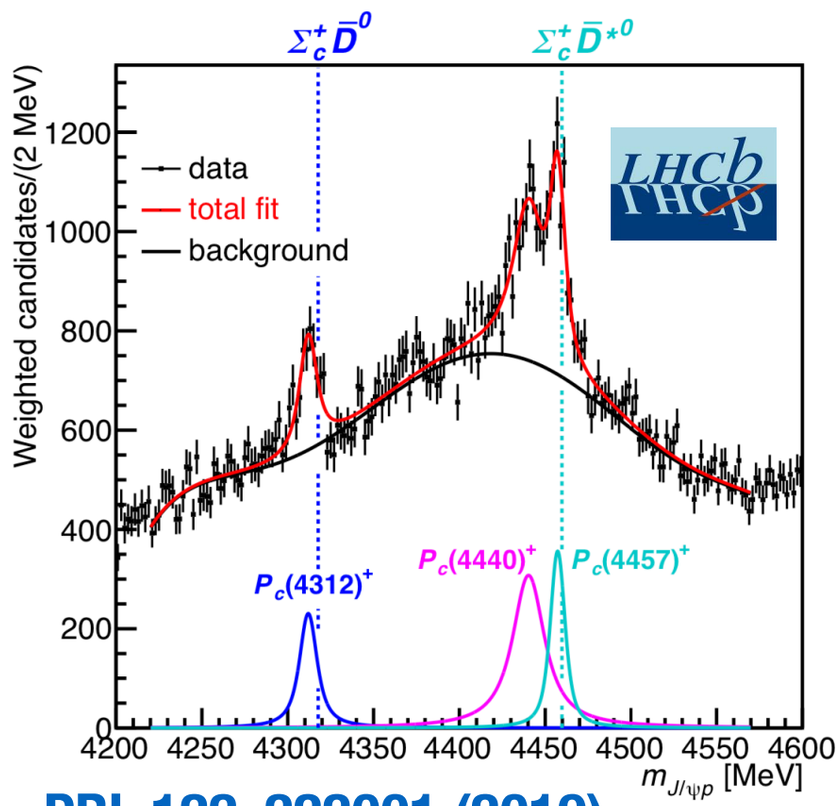


GlueX existing data: Projections



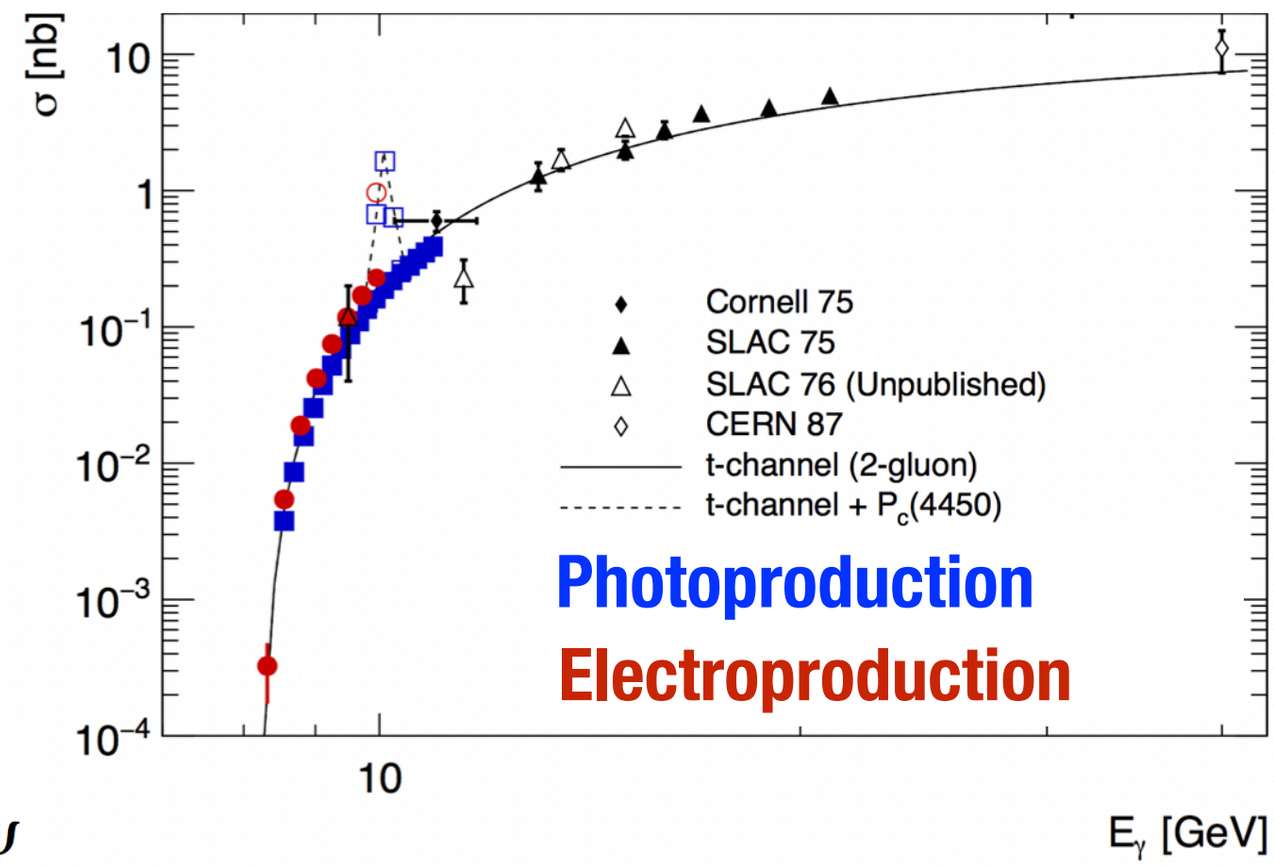
Multiple complementary measurements at JLab will continue to improve limits

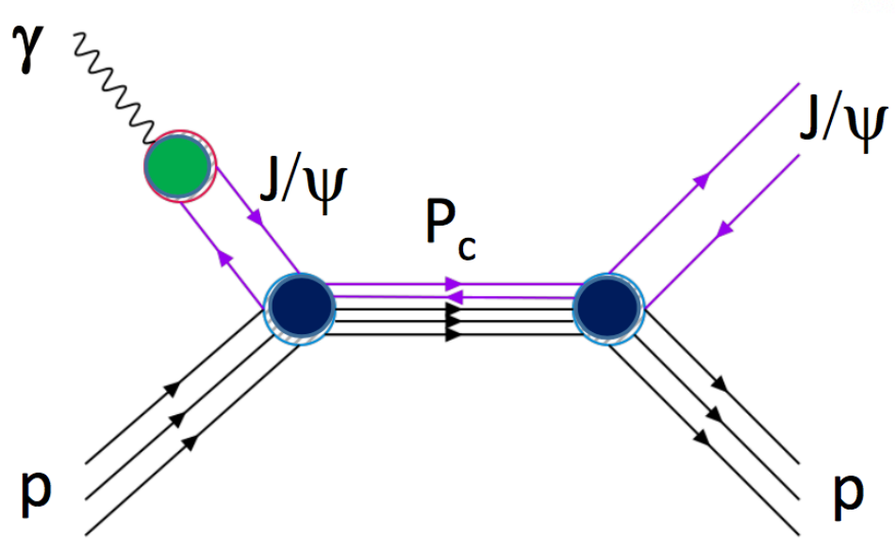
Pentaquarks and threshold charmonium



PRL 122, 222001 (2019)

SoLID: JLab Future



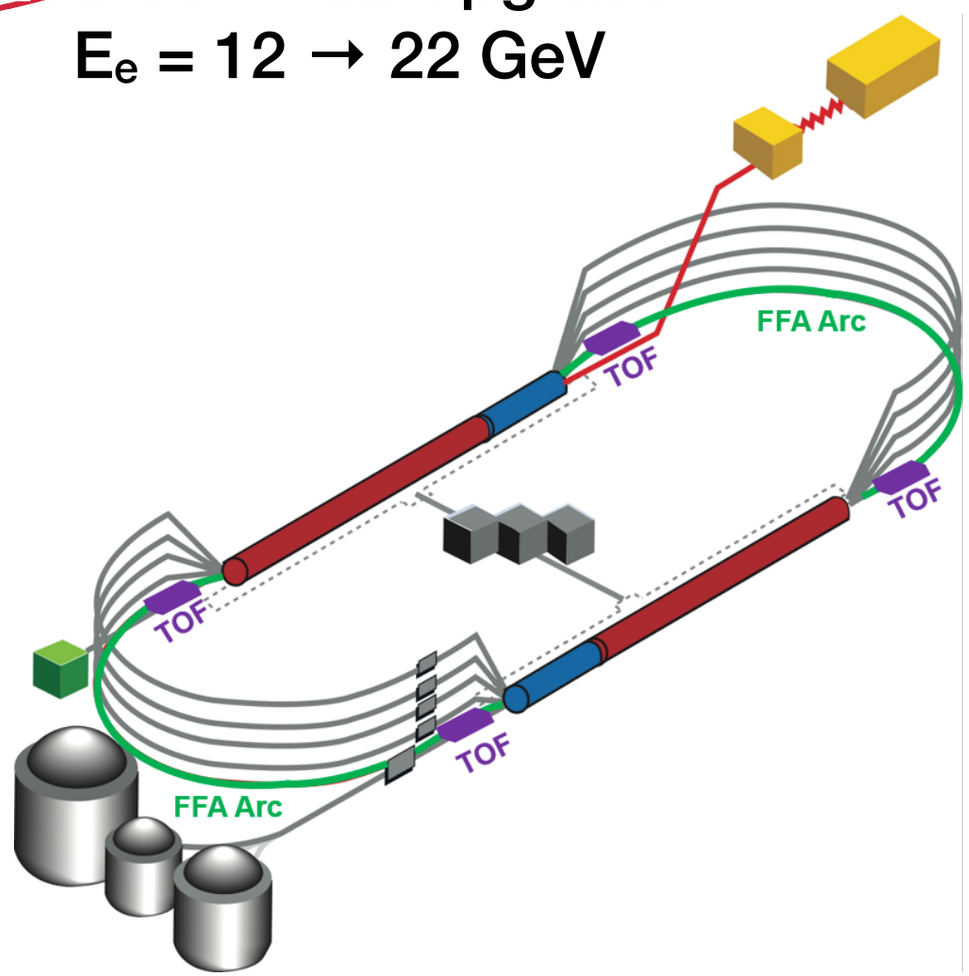


Multiple complementary measurements at JLab will continue to improve limits

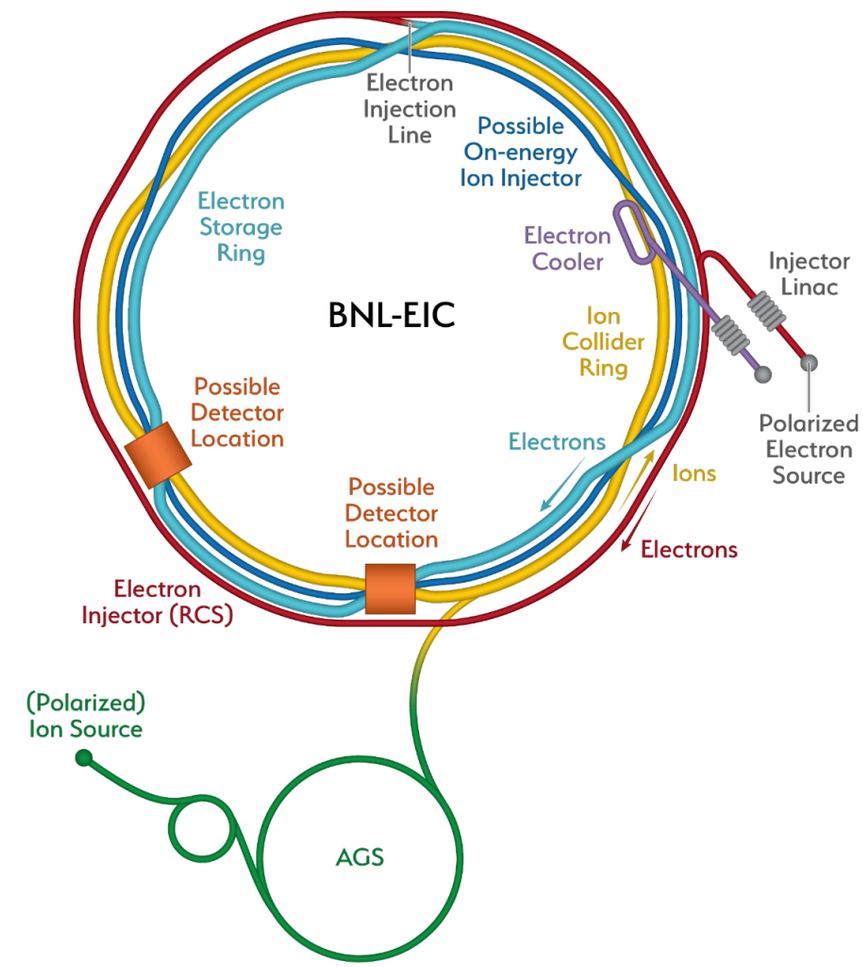
What's next for photoproduction?

Access to charmonium region with higher energy facilities

Jefferson Lab upgrade:
E_e = 12 → 22 GeV



Electron Ion Collider (EIC)



$$\sqrt{s}_{\gamma p} = 1.5 \ - \ 6.5 \text{ GeV}$$

$$\mathscr{L} = 10^{35} - 10^{39} \ cm^{-2}s^{-1}$$

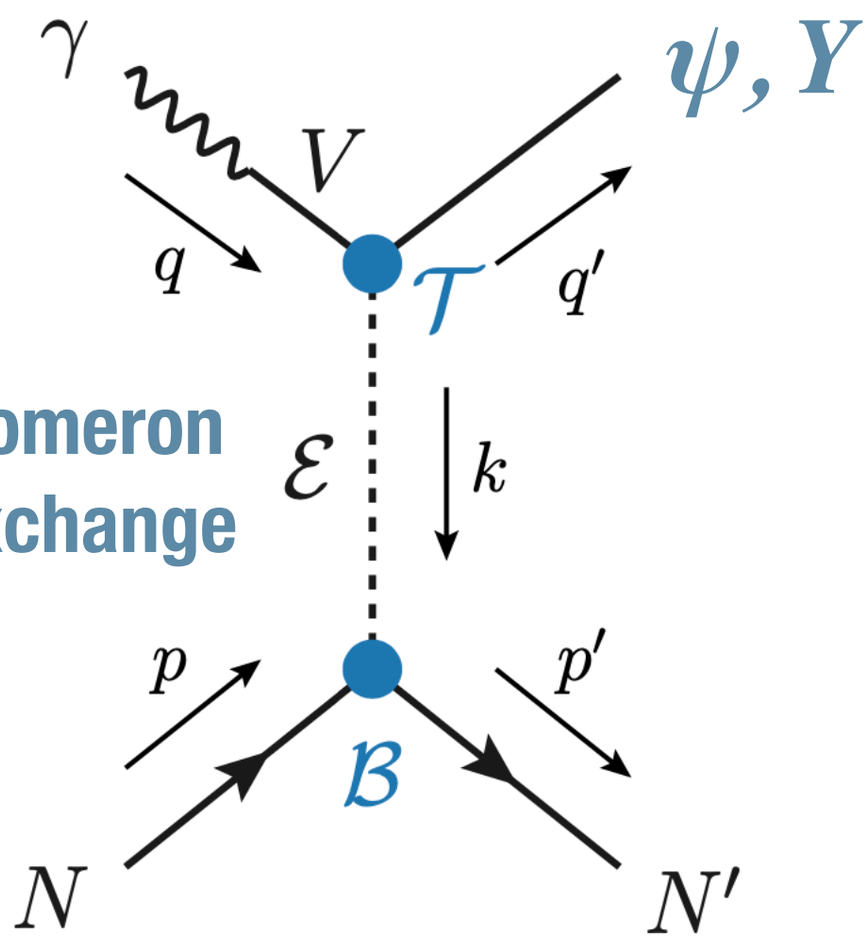
complementary!

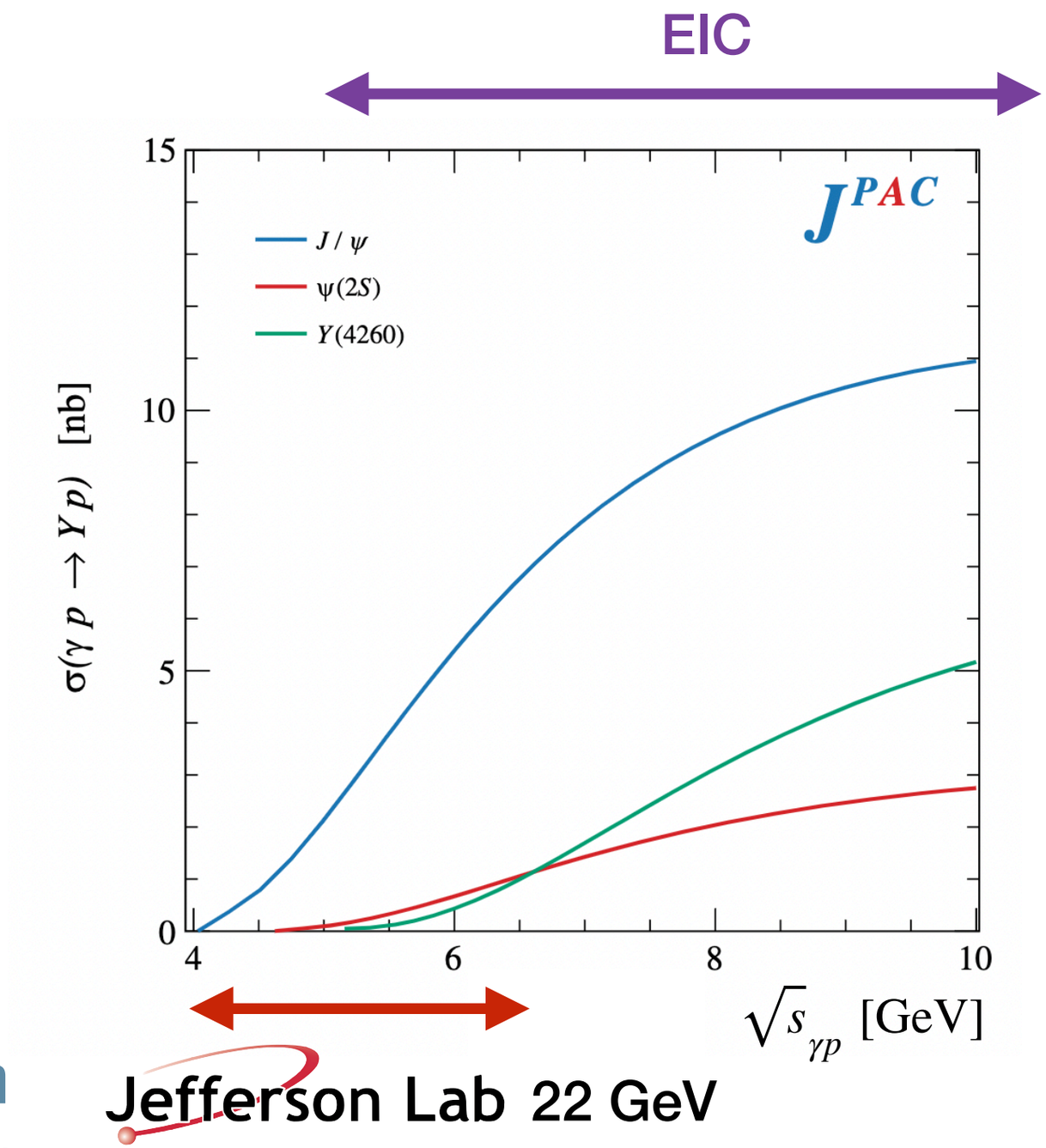
$$\sqrt{s}_{\gamma p} = 5 \ - \ 141 \text{ GeV}$$

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

Photoproduction of XYZ states

JPAC : PRD 102, 114010 (2020)

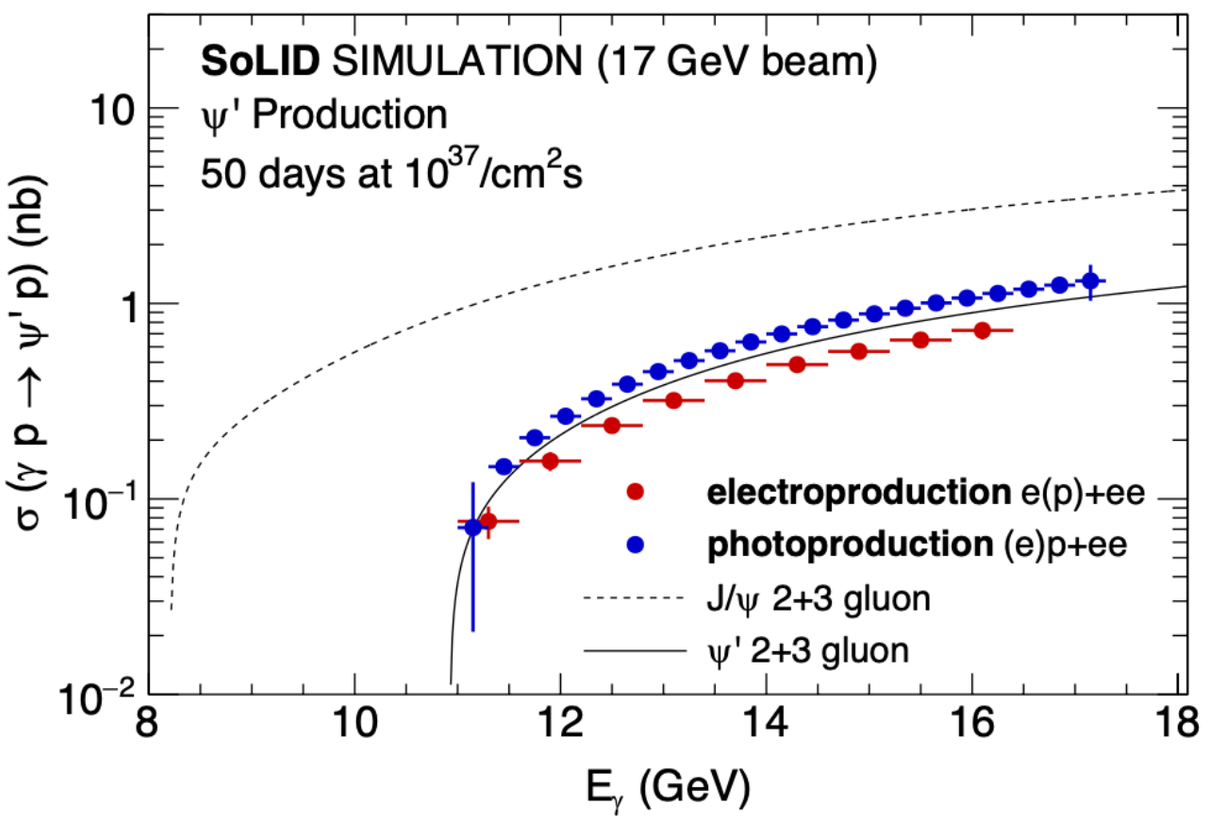




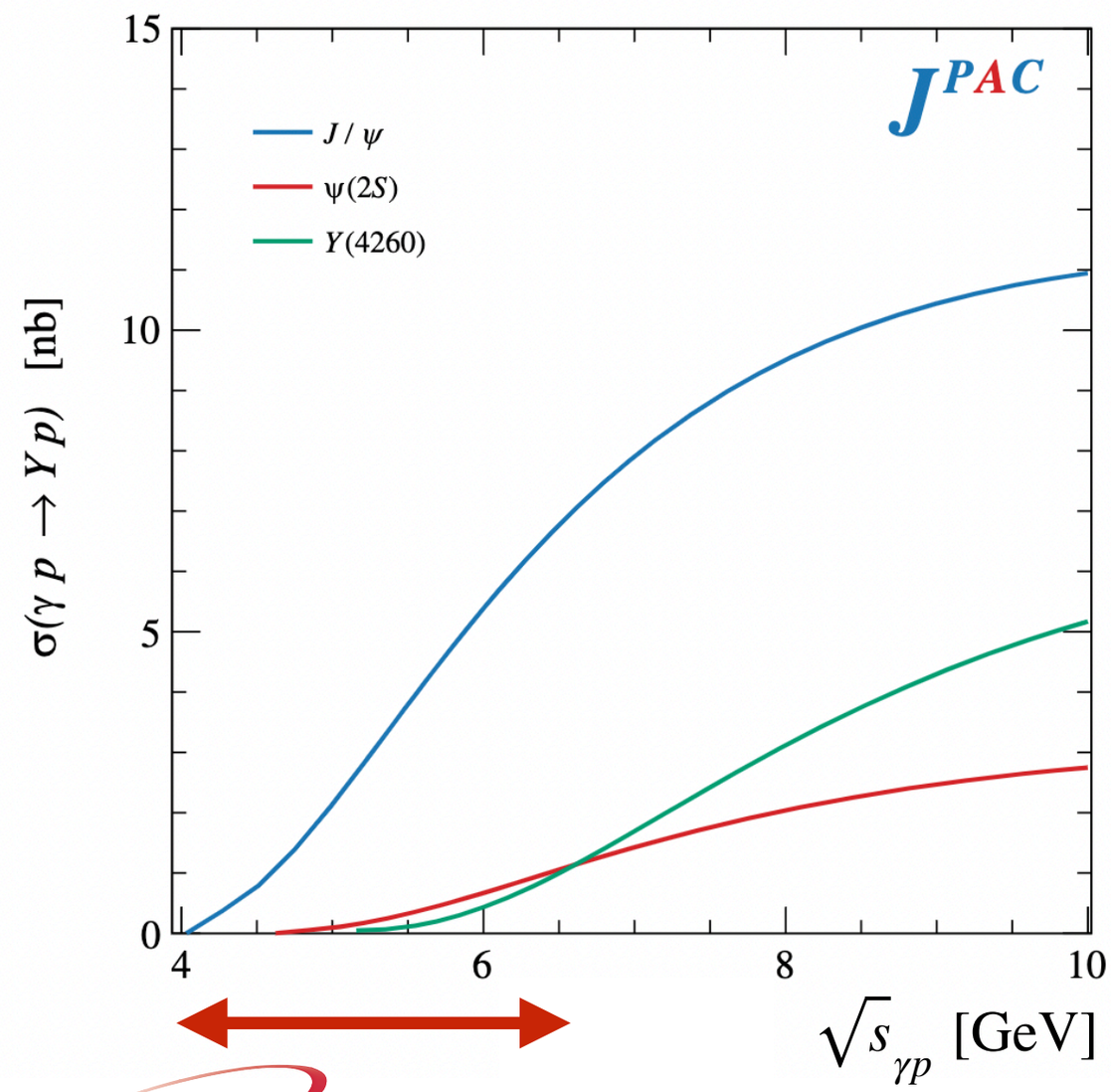
Y(4260) production increases with energy like other vectors, ideal for higher energies accessible at EIC

Photoproduction of $\psi(2S)$

SoLID example at 17 GeV



EIC

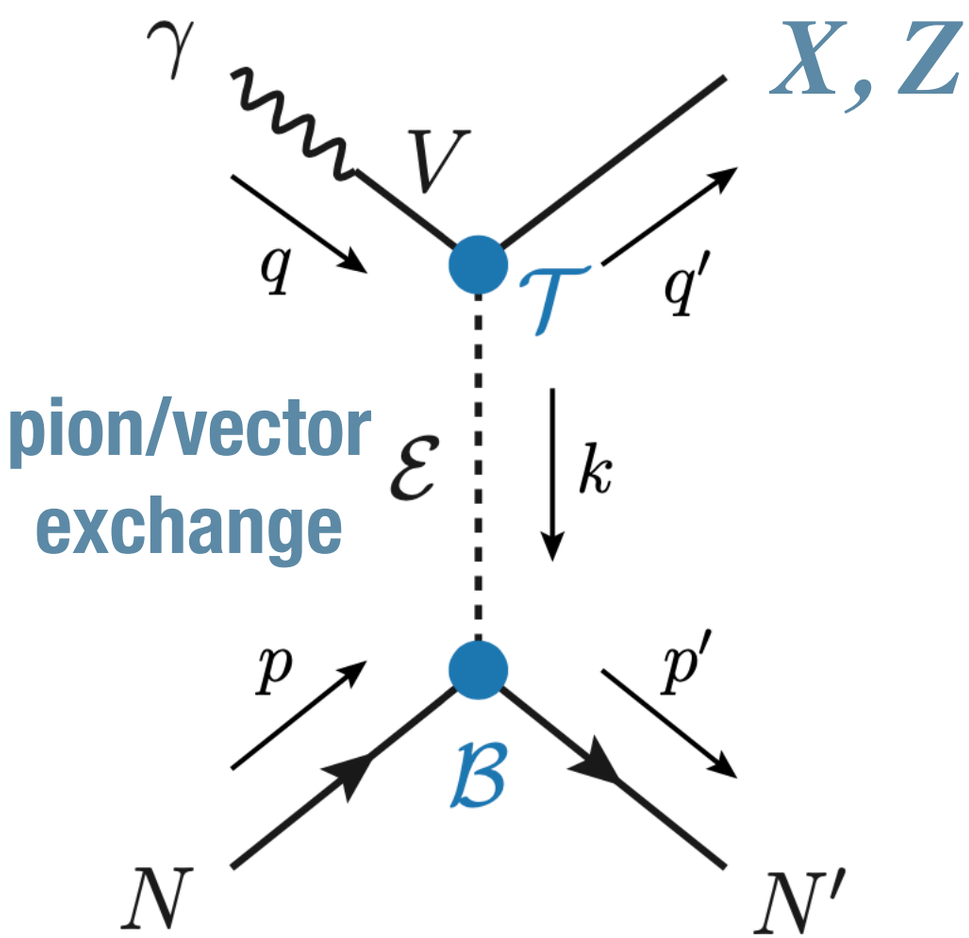


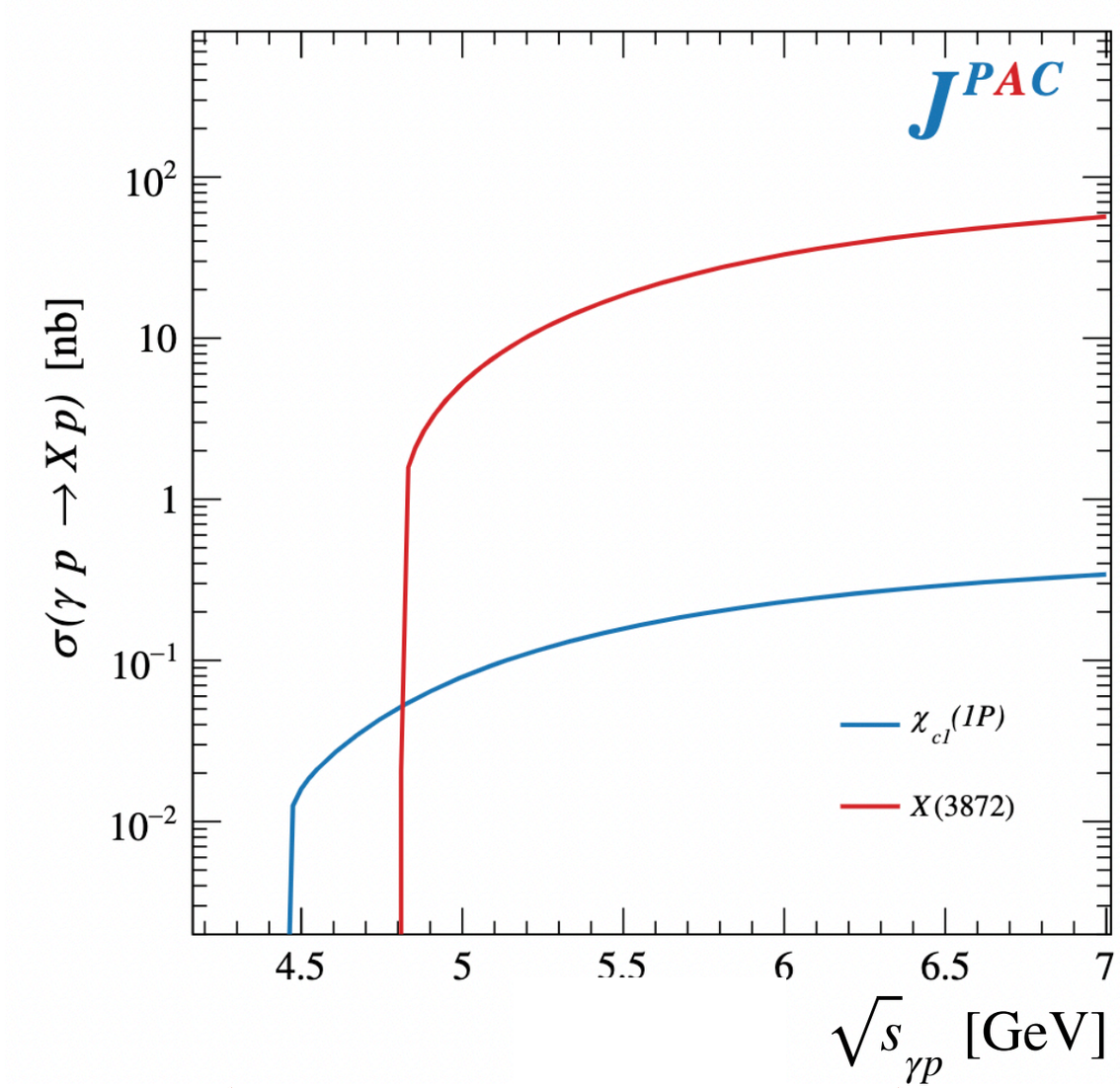
Jefferson Lab 22 GeV

JLab 22 GeV ideal to study threshold $\psi(2S)$ production, but limited access to Y(4260) region

Photoproduction of XYZ states

JPAC : PRD 102, 114010 (2020)



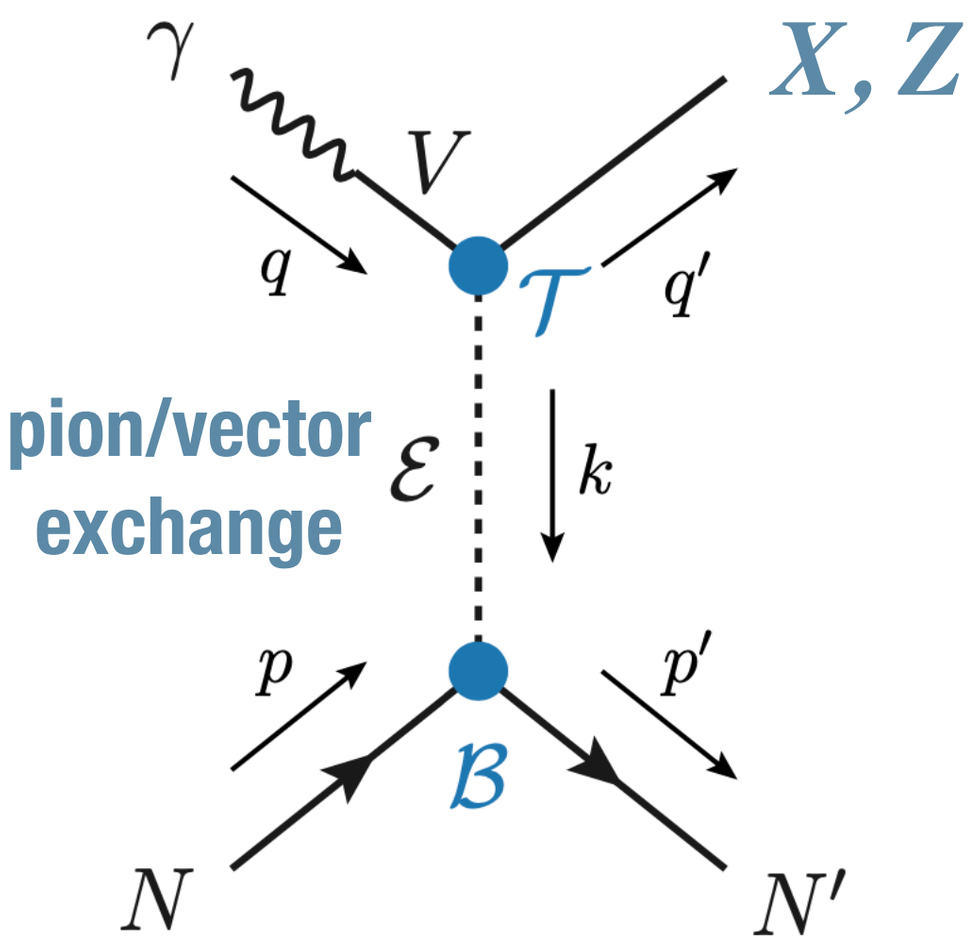


Significant production near threshold for $Z_c(3900)$ and X(3872): accessible at JLab 22 GeV

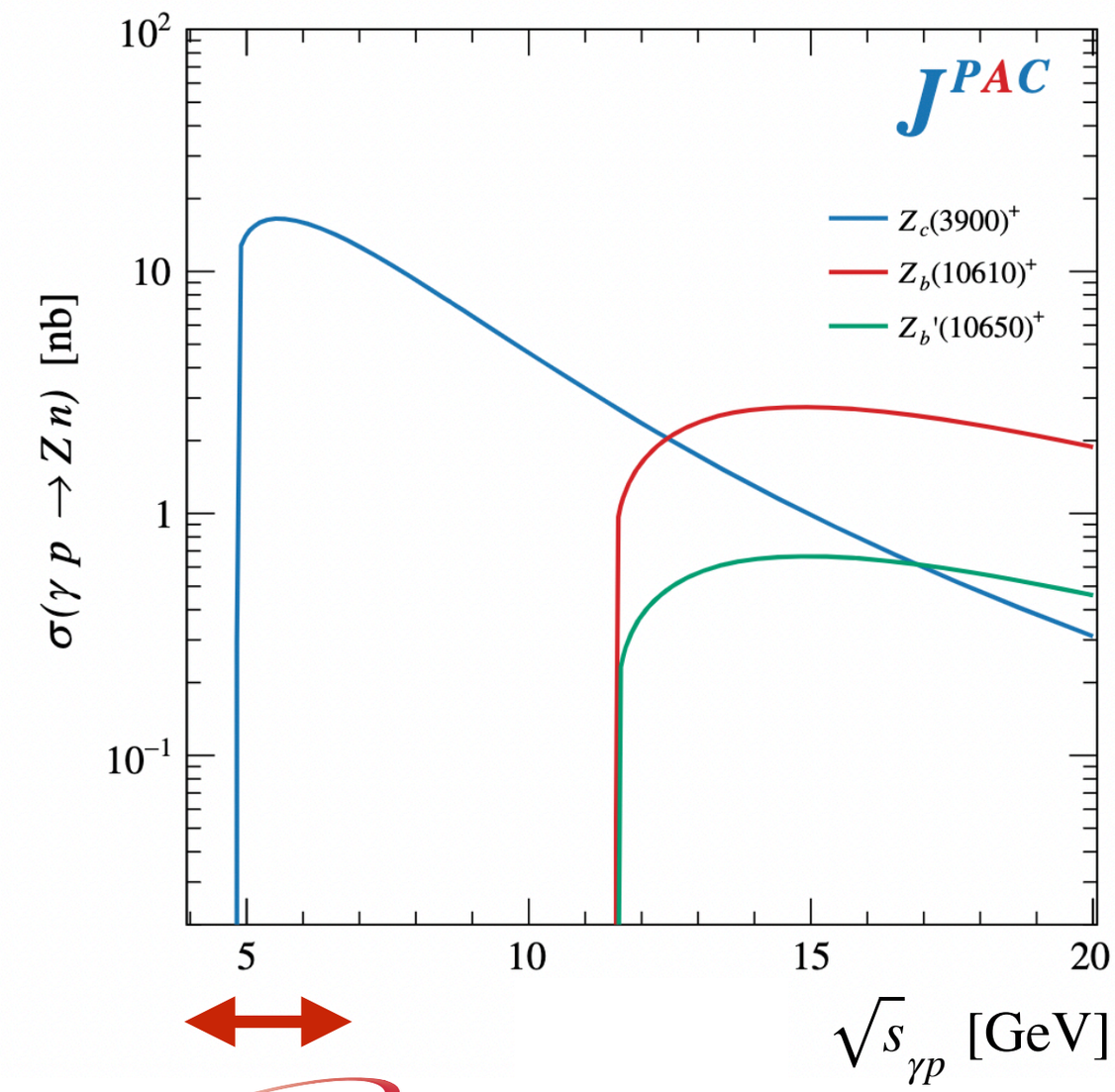
Jefferson Lab 22 GeV

Photoproduction of XYZ states

JPAC : PRD 102, 114010 (2020)



EIC required for Z_b^+

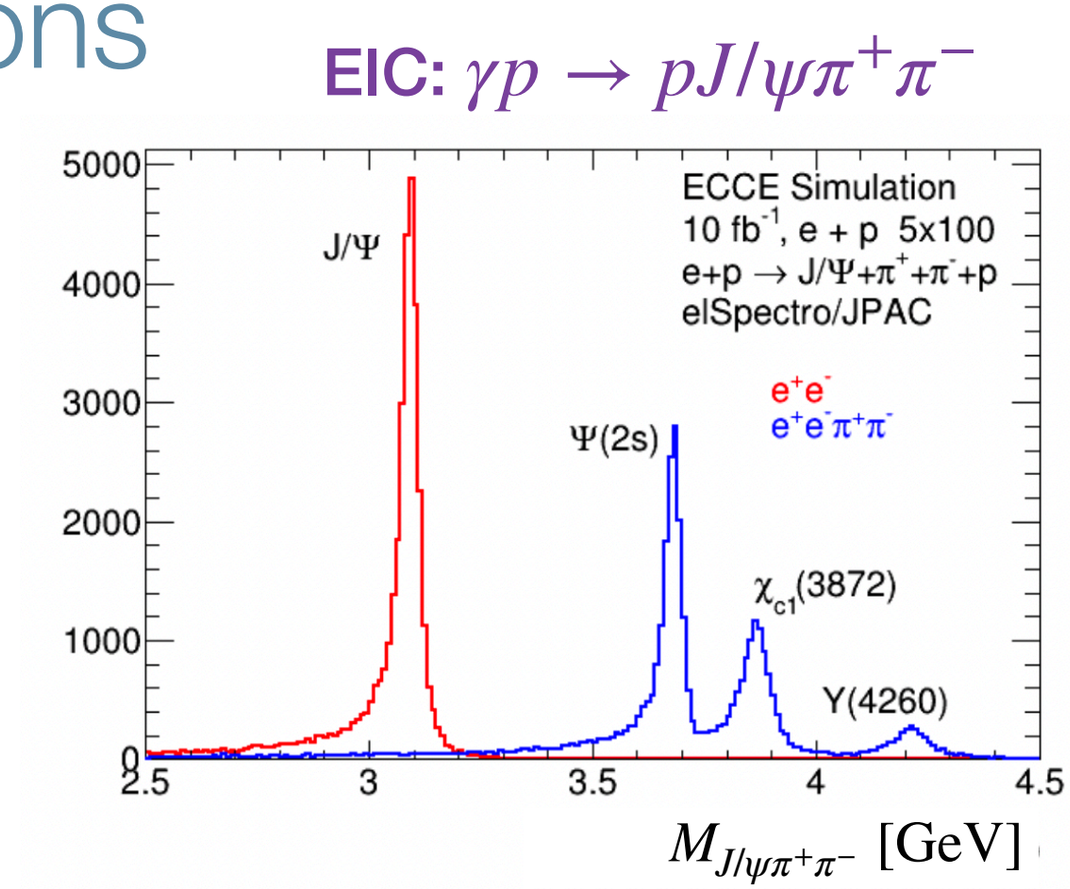


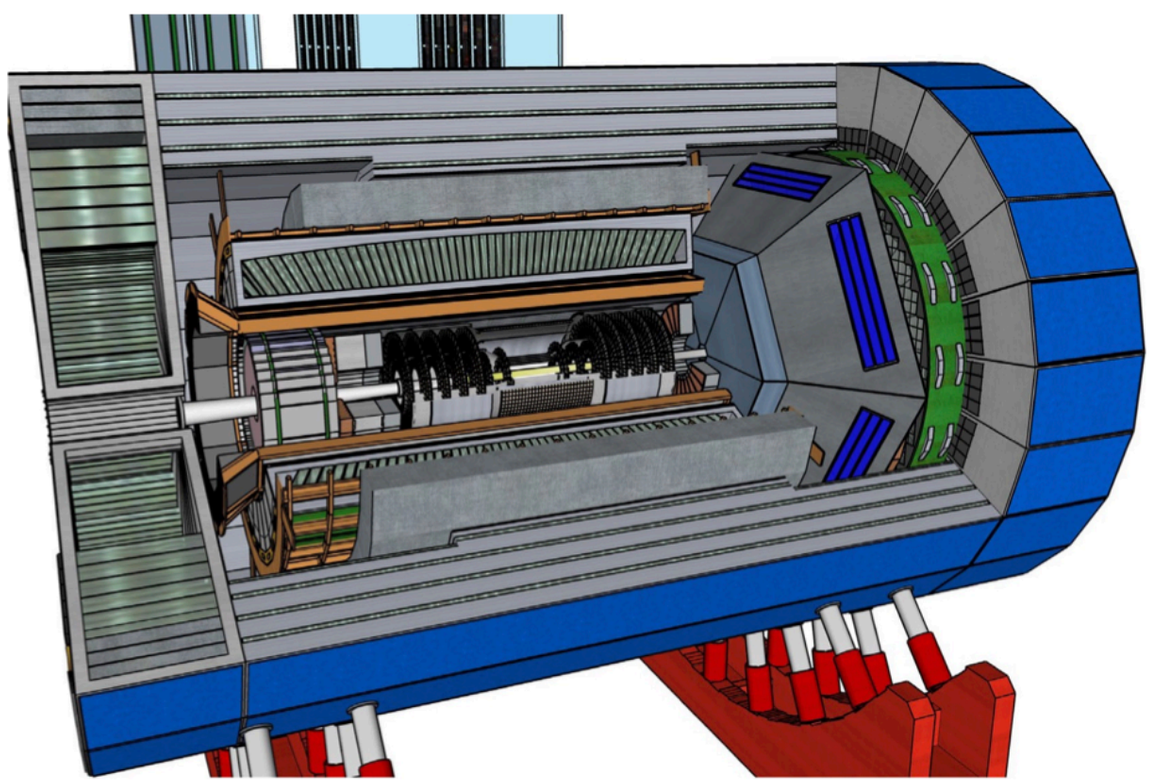
Jefferson Lab 22 GeV

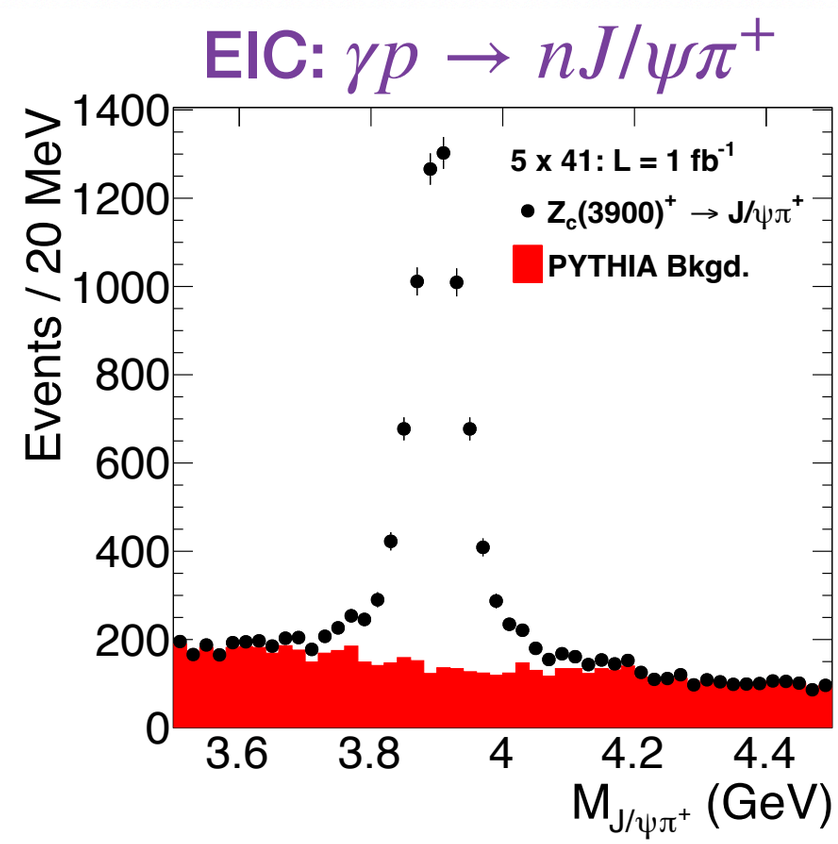
Significant production near threshold for $Z_c(3900)$ and X(3872): accessible at JLab 22 GeV

EIC detector simulations

- Full-acceptance detector based on 1.5T BaBar solenoid selected for EIC project detector
- Active collaboration with working groups formed to complete technical design in the next year

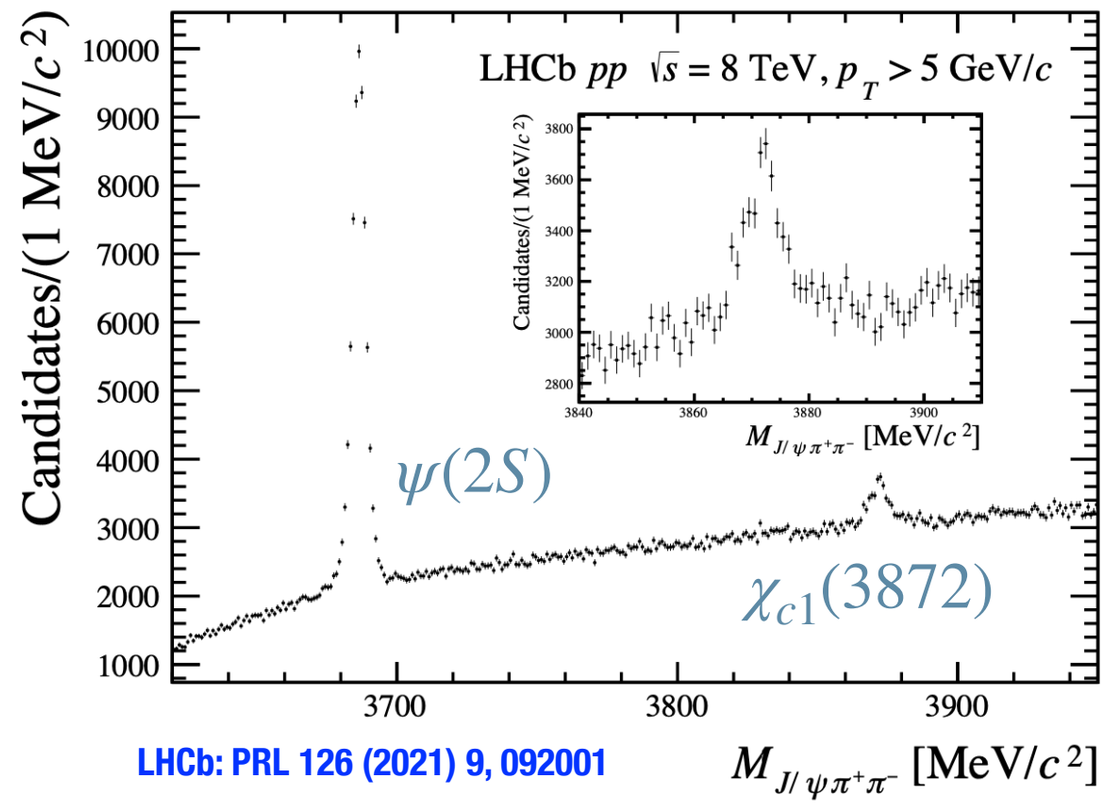




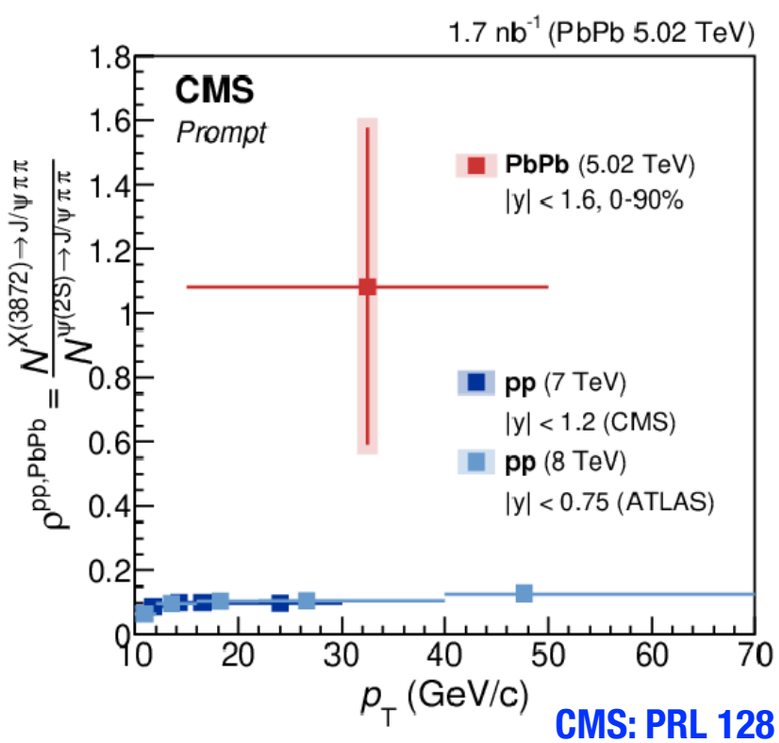


In-medium effects for spectroscopy

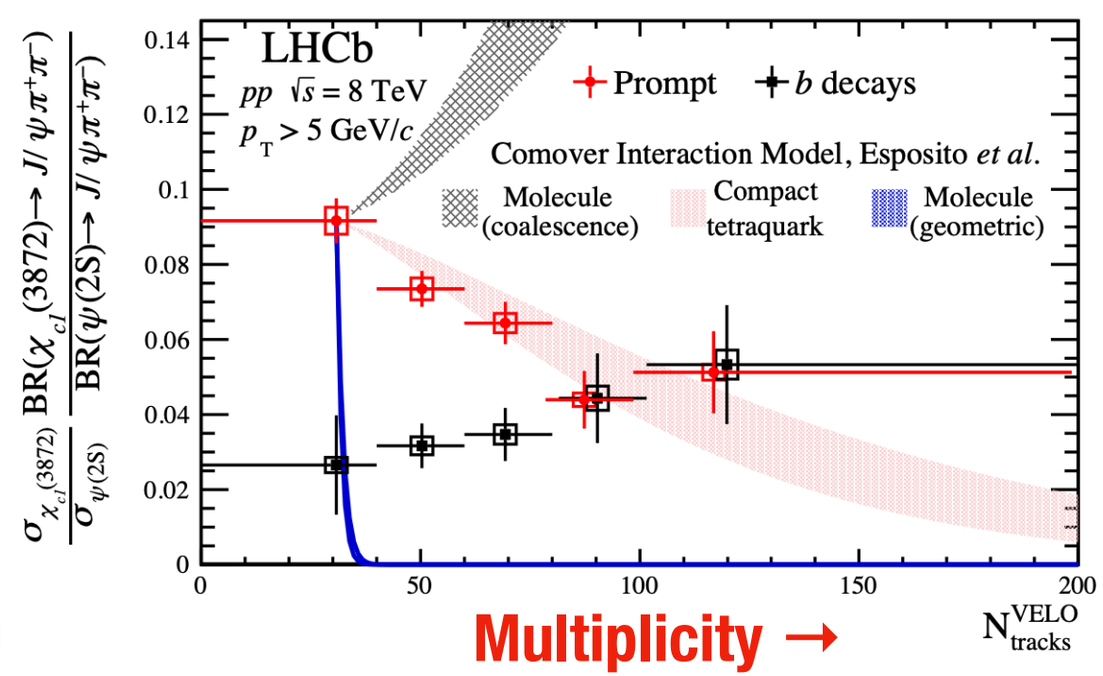
- Recent LHCb results in pp show prompt $\chi_{c1}(3872)$ decreases with multiplicity
- First observation of prompt $\chi_{c1}(3872)$ in PbPb at CMS not suppressed relative to $\psi(2S)$



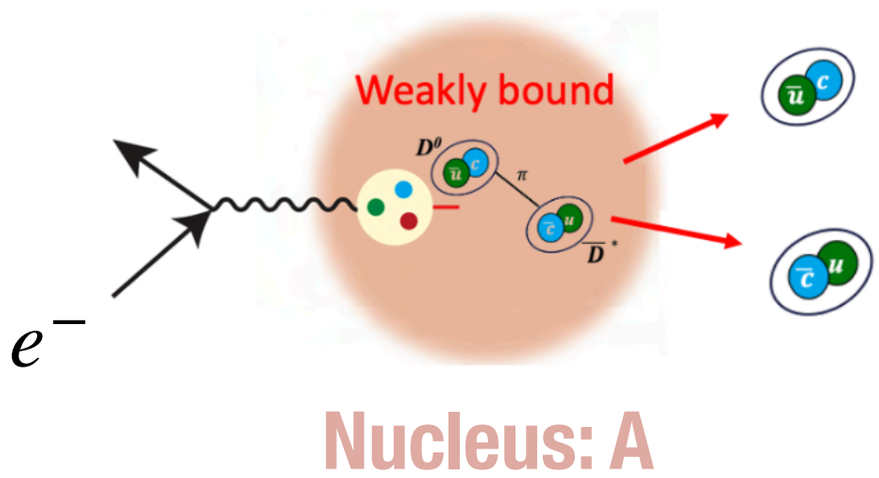
LHCb: PRL 126 (2021) 9, 092001

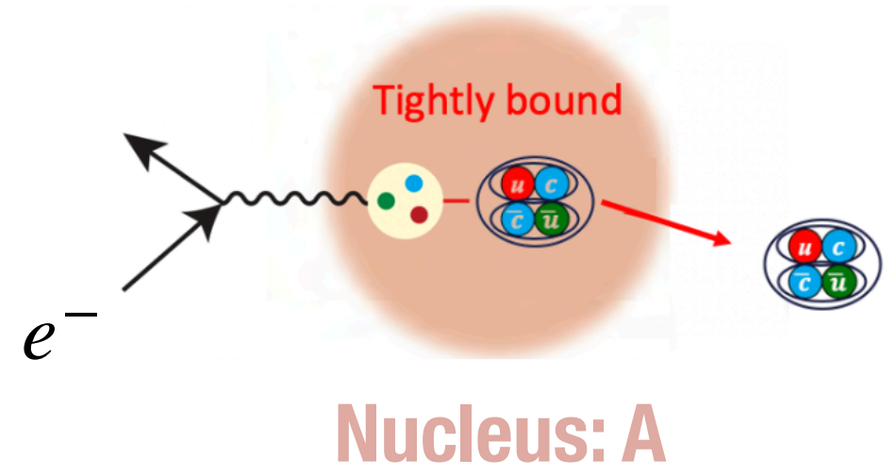


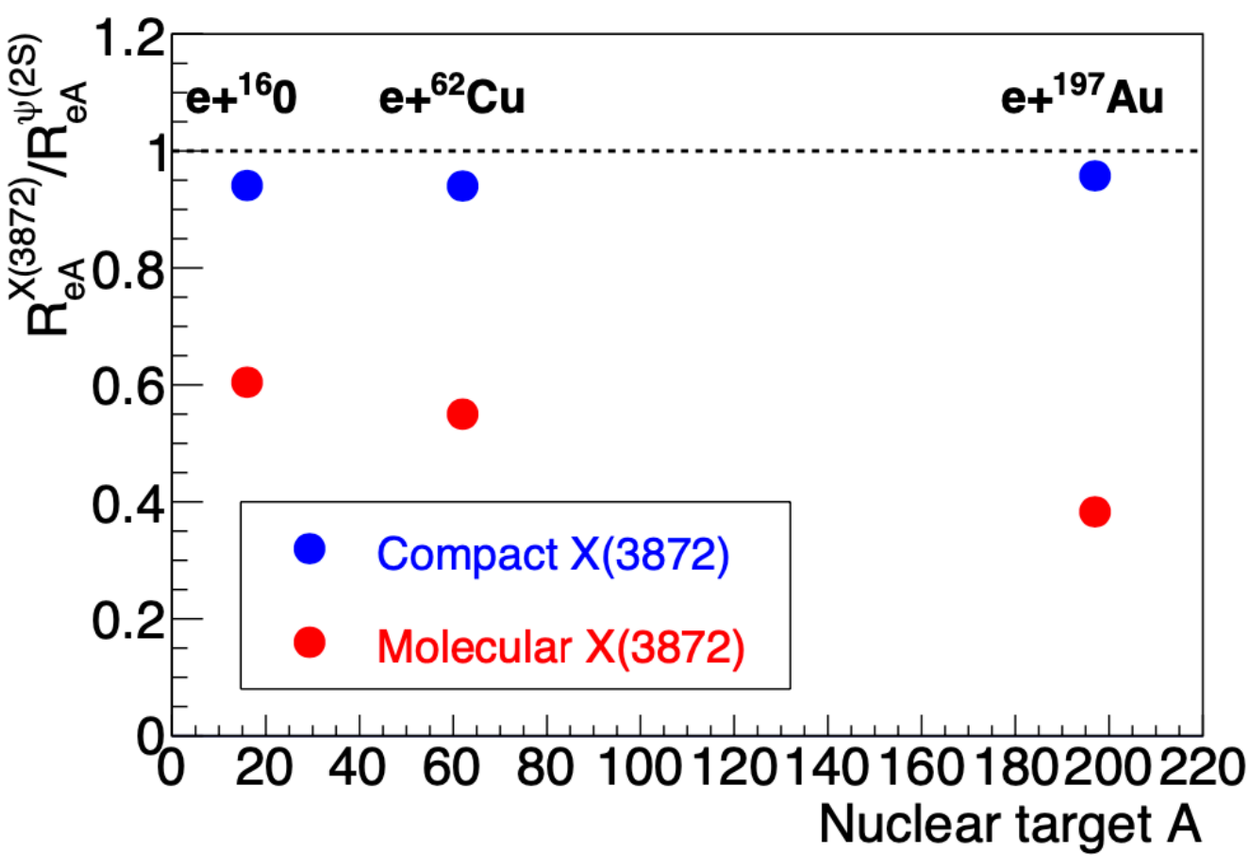
CMS: PRL 128 (2022) 3, 032001



In-medium effects for spectroscopy



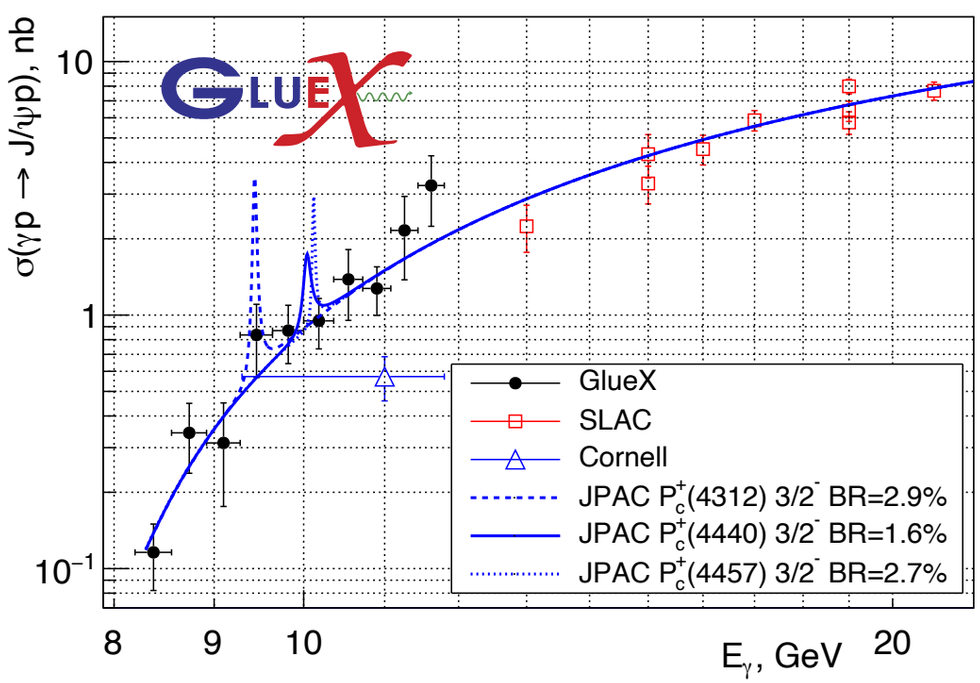




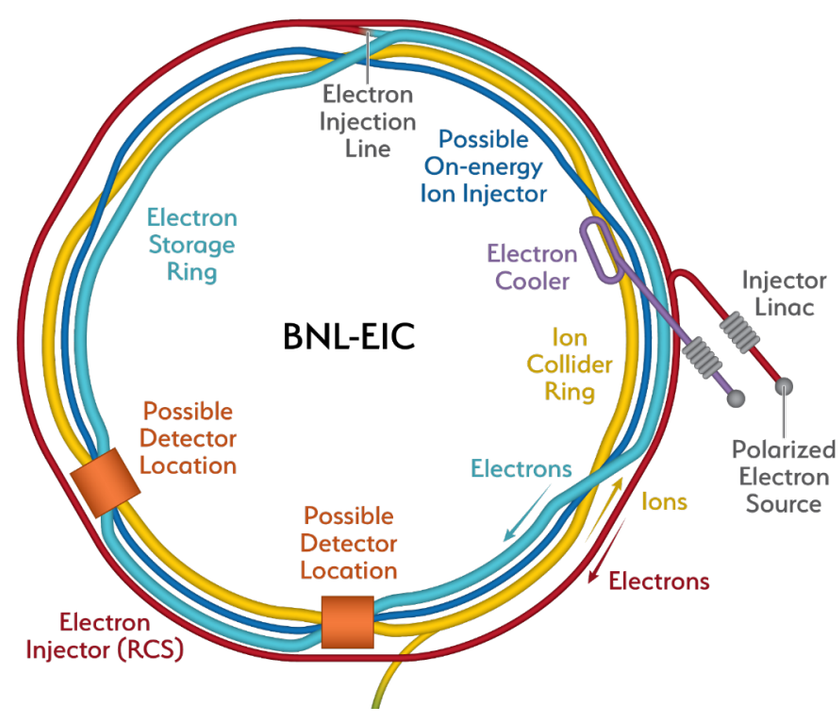
- Dependence on breakup of X(3872) in nuclei?
- Little suppression expected for compact tetraquark configuration
- Expect suppression of molecular (large size) configuration

Summary and Outlook

- Fixed target spectroscopy focused on light quark hybrids and threshold J/ψ production (s-channel P_c)
  - JLab has a decade-long program with GlueX and CLAS12 + proposed energy upgrade (threshold X,Z)
- EIC Spectroscopy program focused on alternative production mechanisms for heavy quark exotics (XYZ)



PRL 123, 072001 (2019)



Summary and Outlook

- Fixed target spectroscopy focused on light quark hybrids and threshold J/ψ production (s-channel P_c)
  - JLab has a decade-long program with GlueX and CLAS12 + proposed energy upgrade (threshold X,Z)
- EIC Spectroscopy program focused on alternative production mechanisms for heavy quark exotics (XYZ)

Upcoming Workshops:

Hadron Spectroscopy with a CEBAF Energy Upgrade
Jefferson Lab: June 16-17

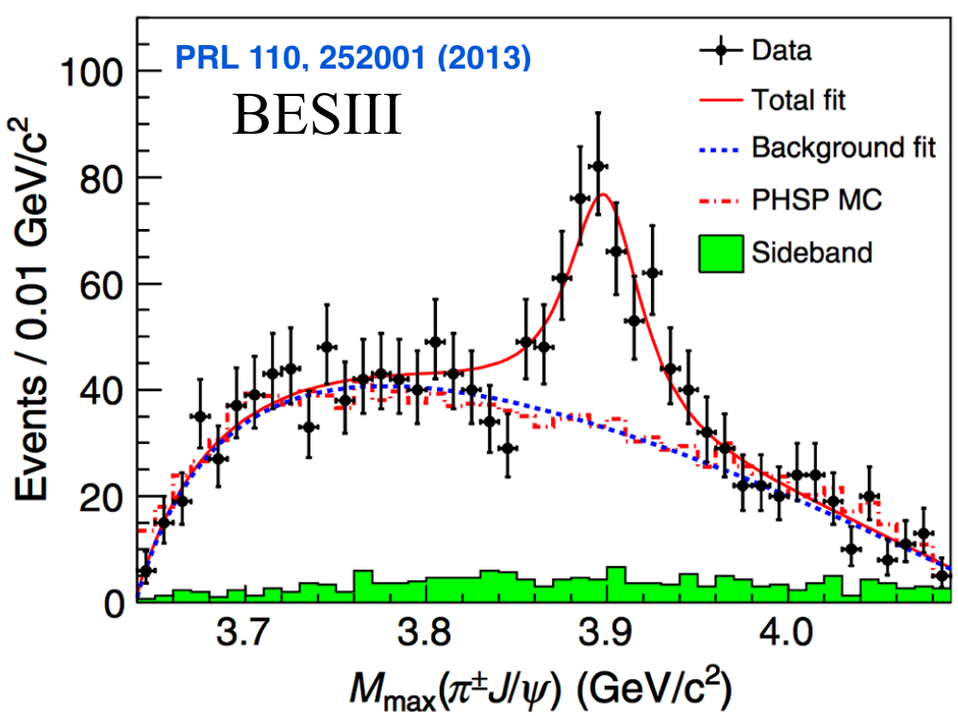
Exotic heavy meson spectroscopy and structure with EIC
Stony Brook CFNS: August 15-19

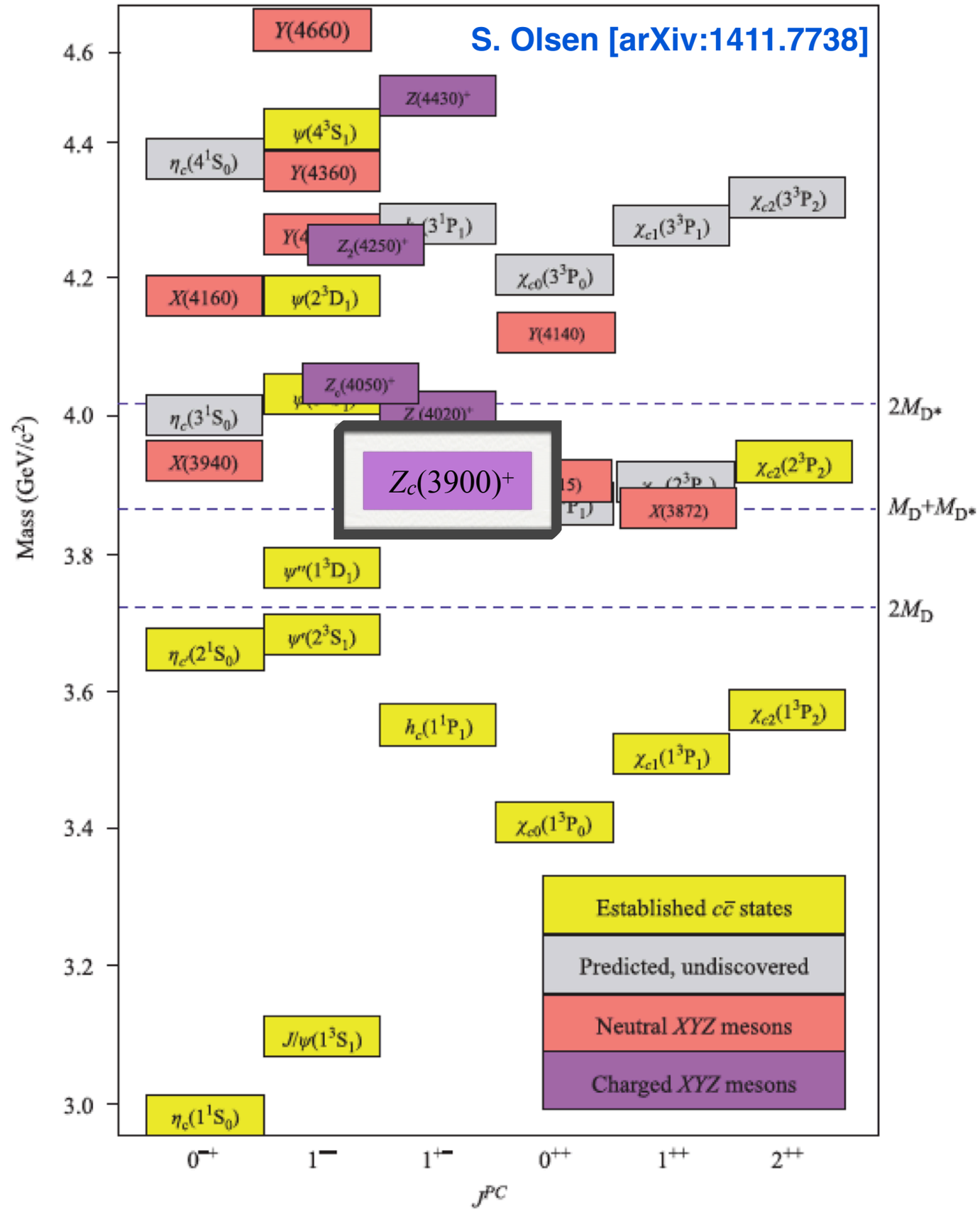
Backup

XYZ states

- Many new states observed in the last ~decade
- Not predicted by the standard charmonium models
- Many models for interpretation: resonant states, meson molecules, re-scattering effects, etc.

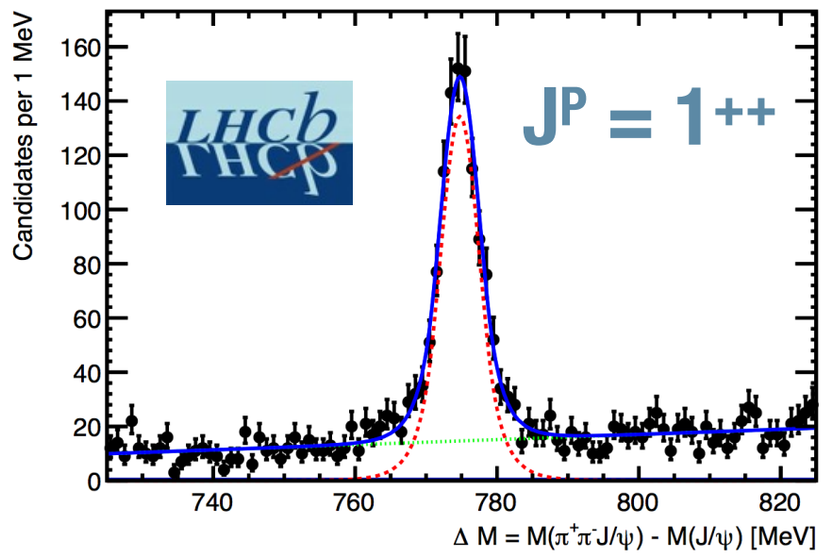
$$e^+e^- \to \pi^+\pi^- J/\psi \ (4260 \text{ MeV})$$

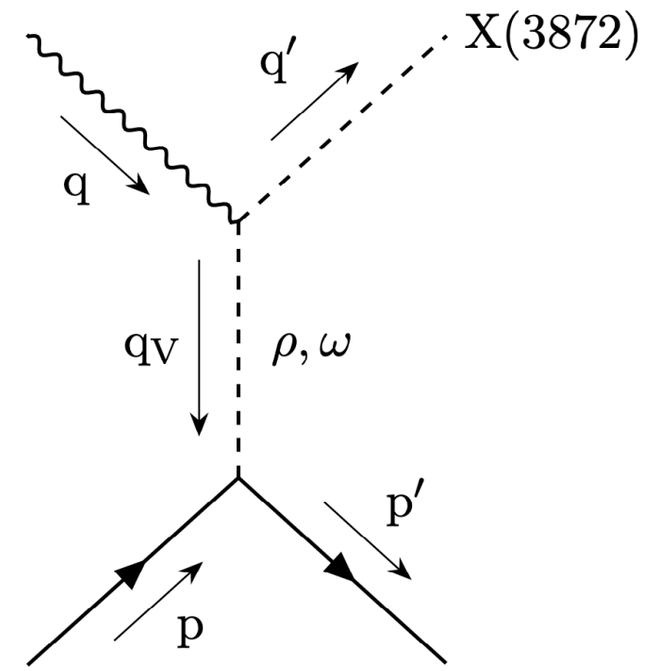




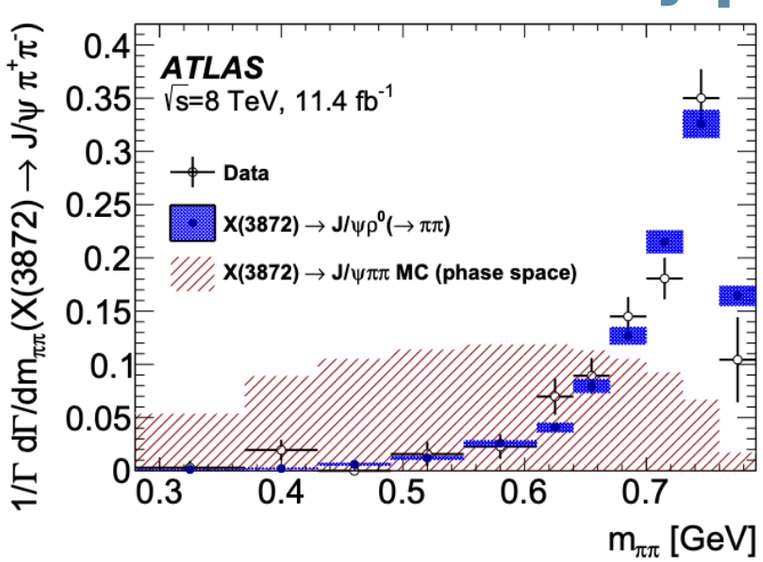
Theoretical developments

X(3872) → J/ψππ





ππ dominated by ρ

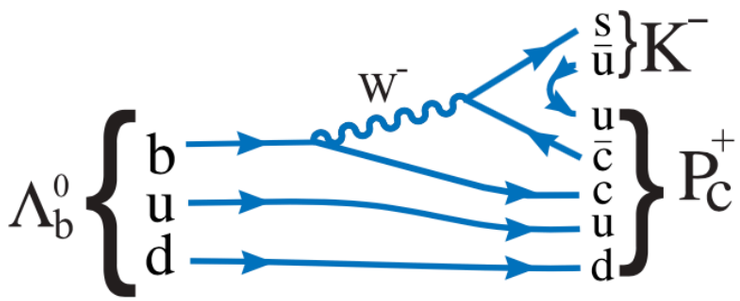


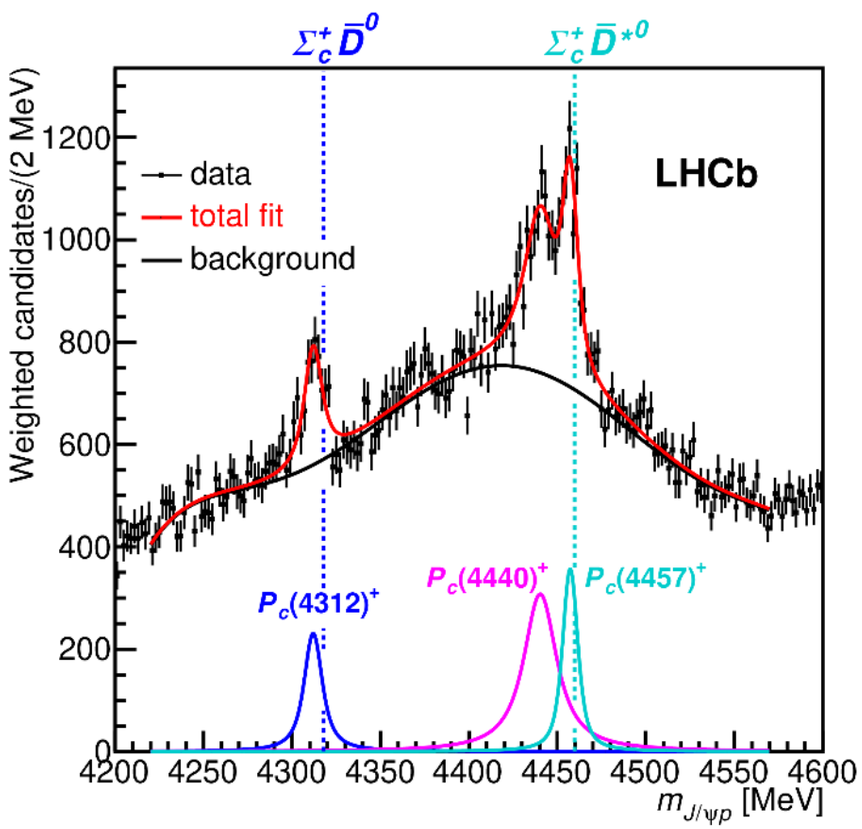
- Modeled through vector meson dominance and X(3872)→J/ψρ decay width
- Ongoing work on Reggeization and contribution from ω exchange

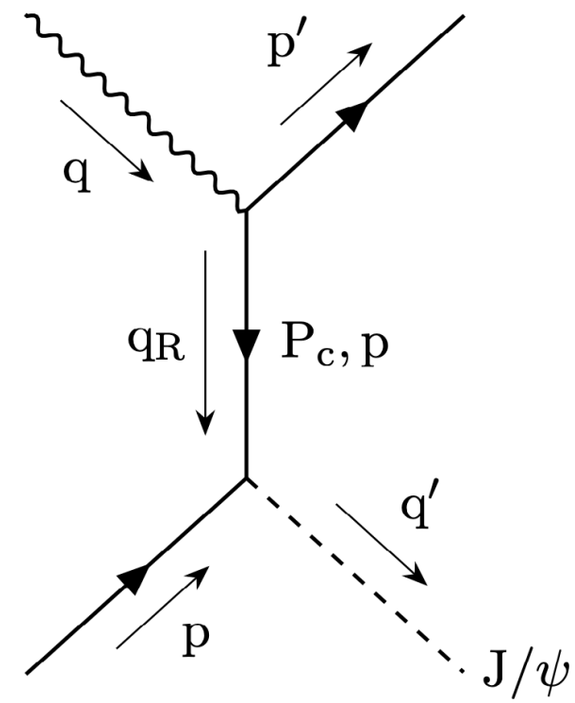
Joint Physics Analysis Center

JPAC: Szczepaniak, Pilloni, Hiller Blin, Winney, Albaladejo, Mathieu

Theoretical developments







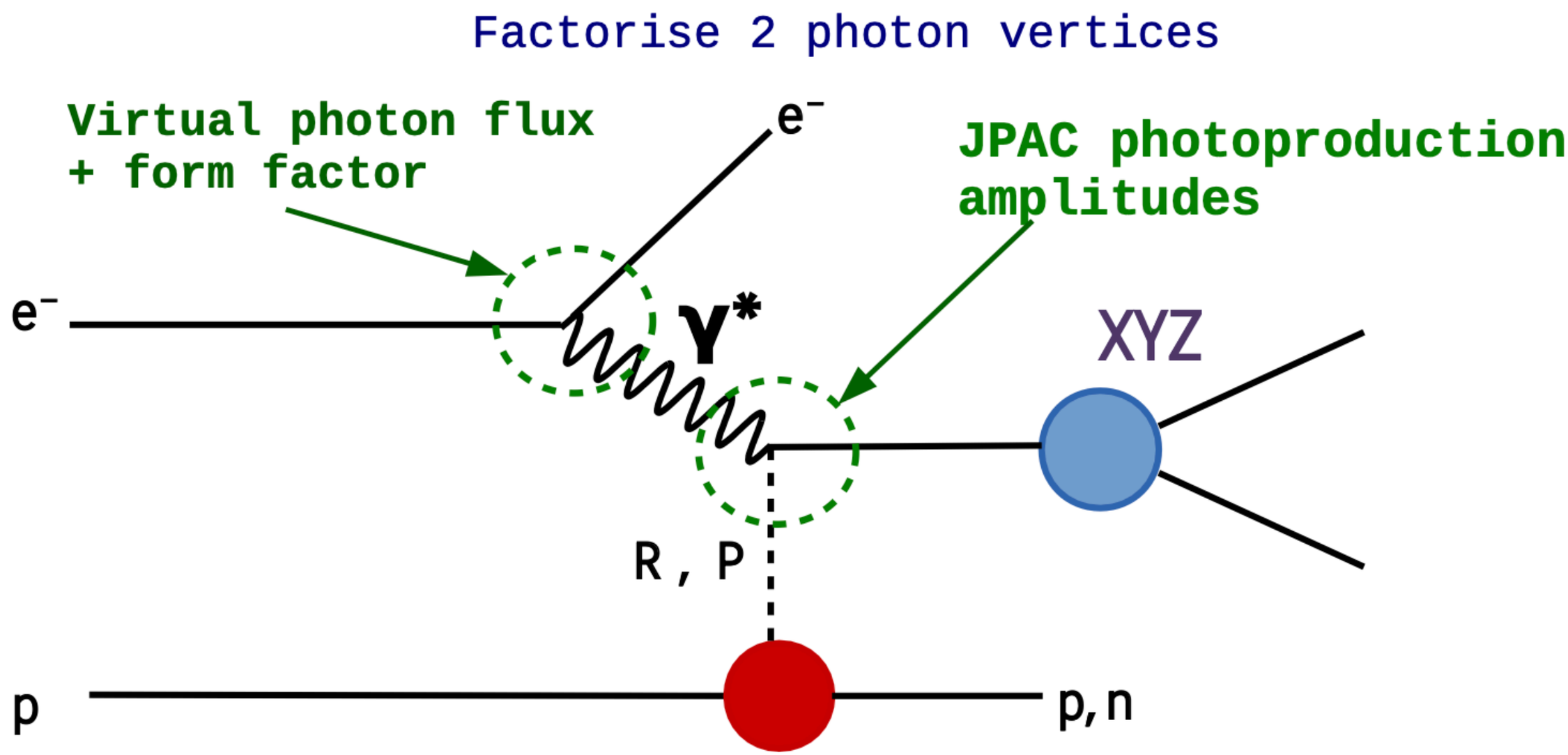
- *u*-channel exchange of pentaquark leads to "backward" going J/ψ
- P_c couplings from Winney et al. [JPAC], PRD 100 (2019) 034019
- Ongoing studies of other baryon trajectories

Joint Physics Analysis Center

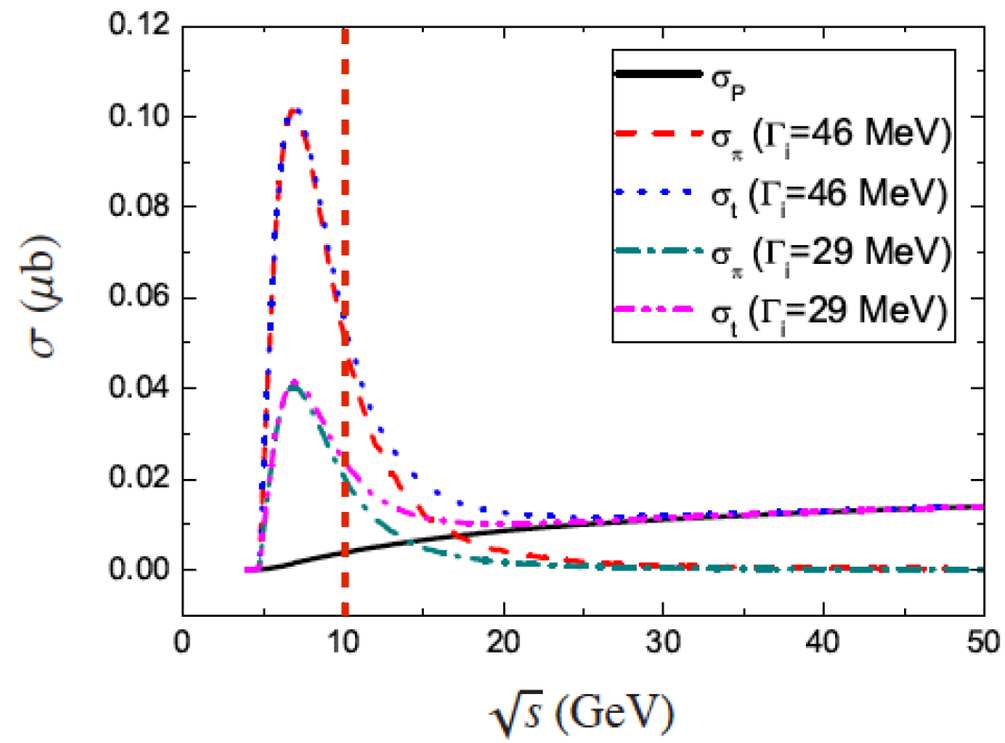
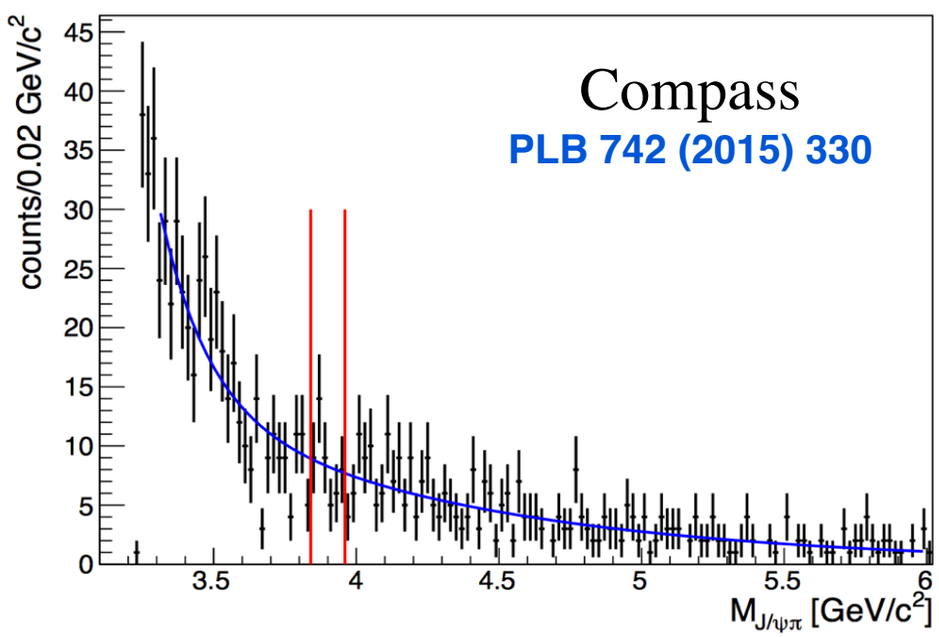
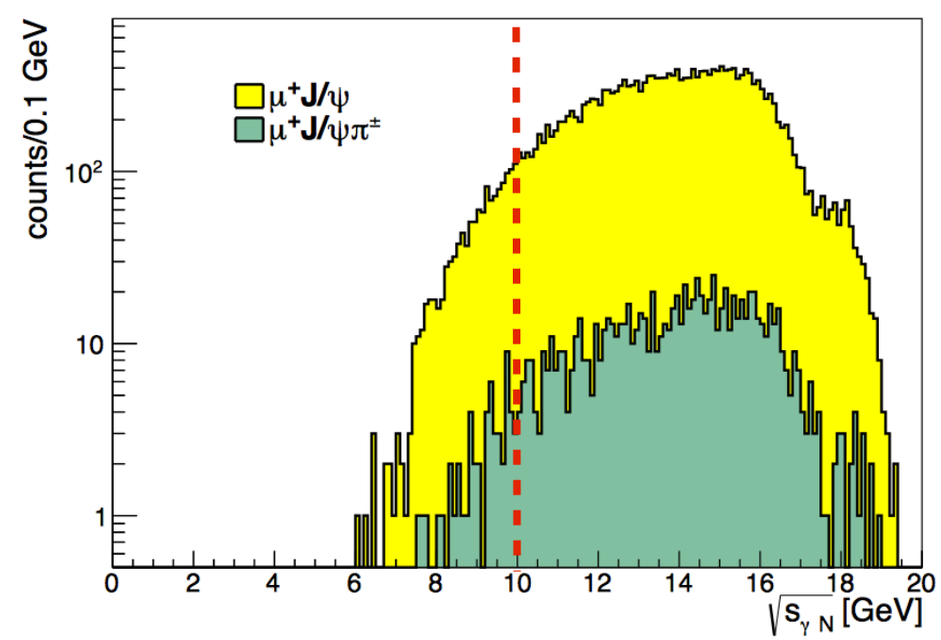
JPAC: Szczepaniak, Pilloni, Hiller Blin, Winney, Albaladejo, Mathieu

Event generator: elSpectro

Derek Glazier



Generator available on GitHub: https://github.com/dglazier/elSpectro

Previous experience at COMPASS

- Result from Compass in μ+p to search for $Z_c(3900)$
  - Most $\sqrt{s_{\gamma p}}$ far above threshold
  - Already some constraints on $Z_c \rightarrow J/\psi\ \pi$ decay width?
- What could the EIC do in e+p?