Hadron Spectroscopy Measurements:
Highlights and Future Plans

Justin Stevens

WILLIAM & MARY
CHARTERED 1693

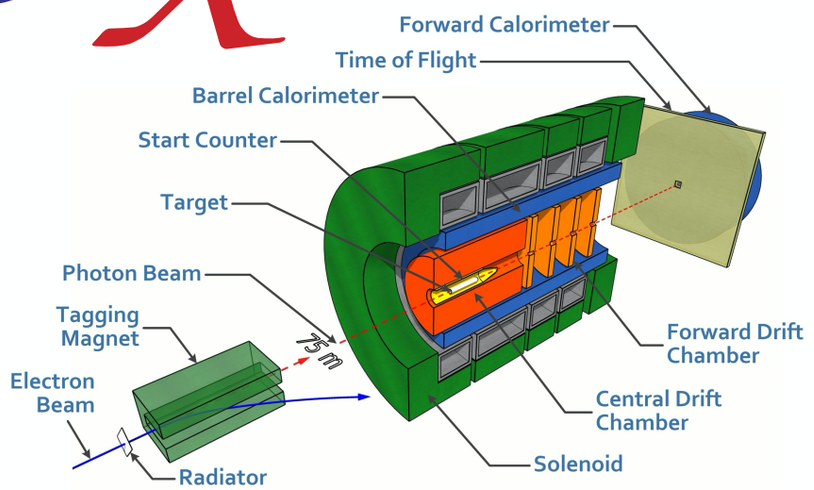
Spectroscopy: a global endeavor

	Heavy quarks ⟷ Light quarks	
Electromagnetic probes	e^+e^-	γp
Hadronic probes	$\bar{p}p$ pp	$\bar{p}p$ πp

Highlights since 2015 LRP: light quarks

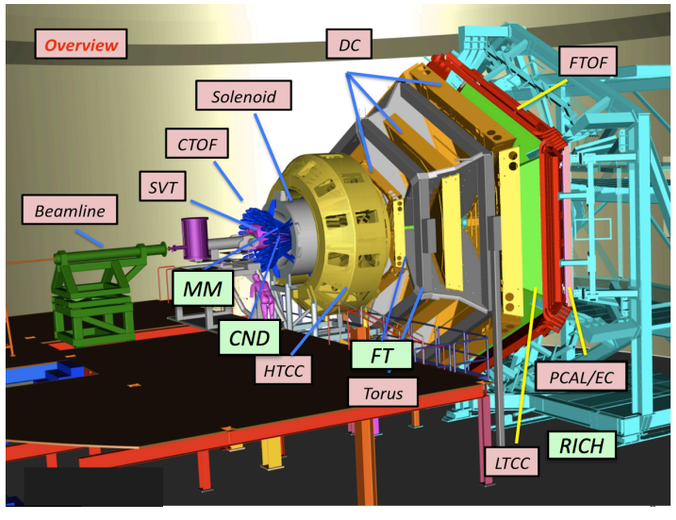
- JLab 12 GeV running since 2017: programs in hadron spectroscopy, nucleon and nuclear structure, etc.
- Photoproduction process provides access to many proposed exotic decay channels
- Orders of magnitude higher statistics than previous photoproduction experiments

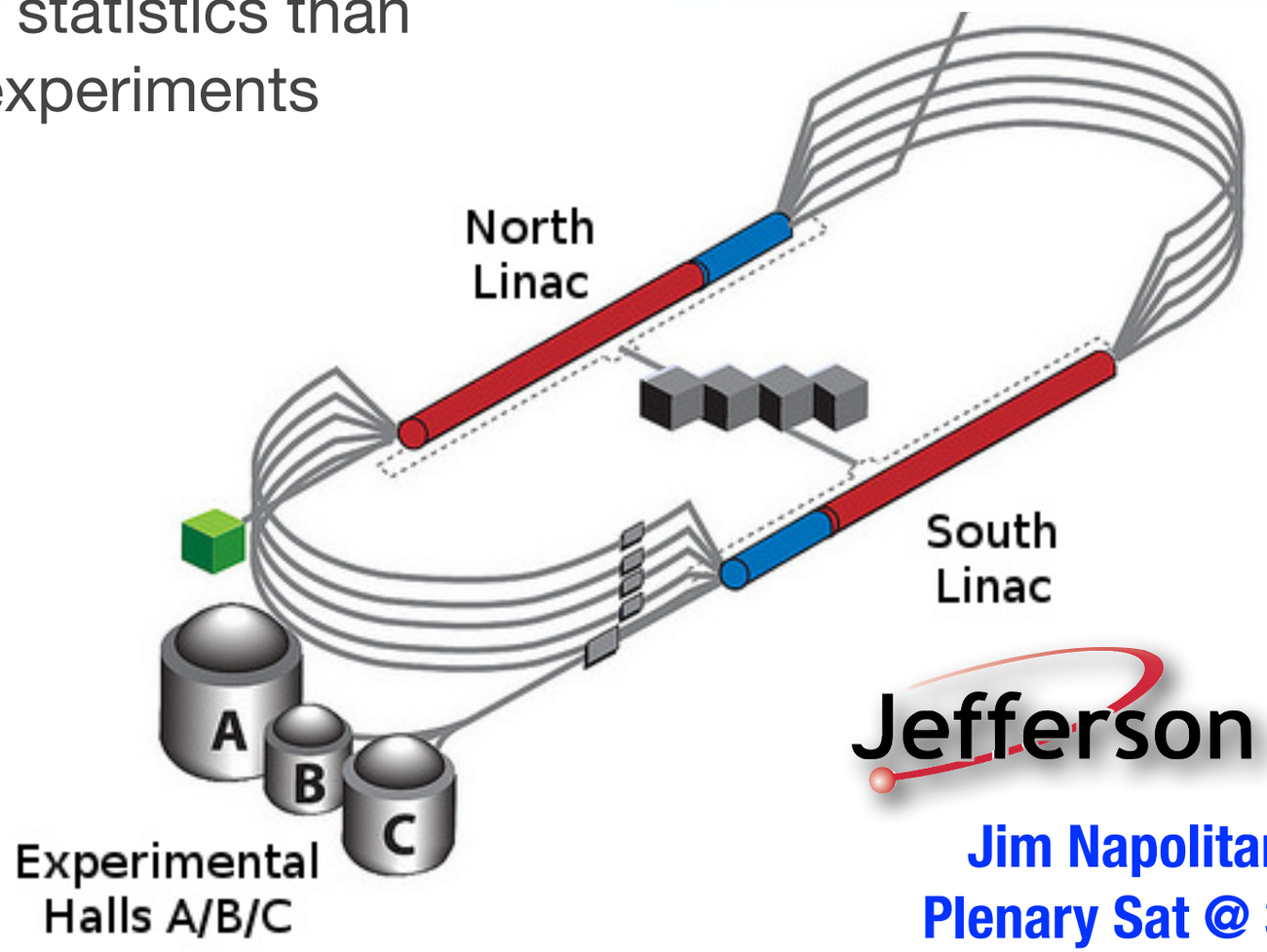
GlueX



CLAS

CEBAF Large Acceptance Spectrometer



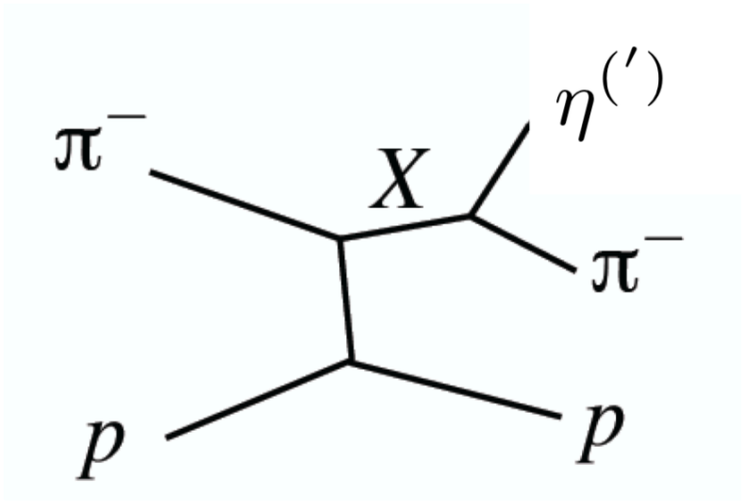


Jefferson Lab

Jim Napolitano

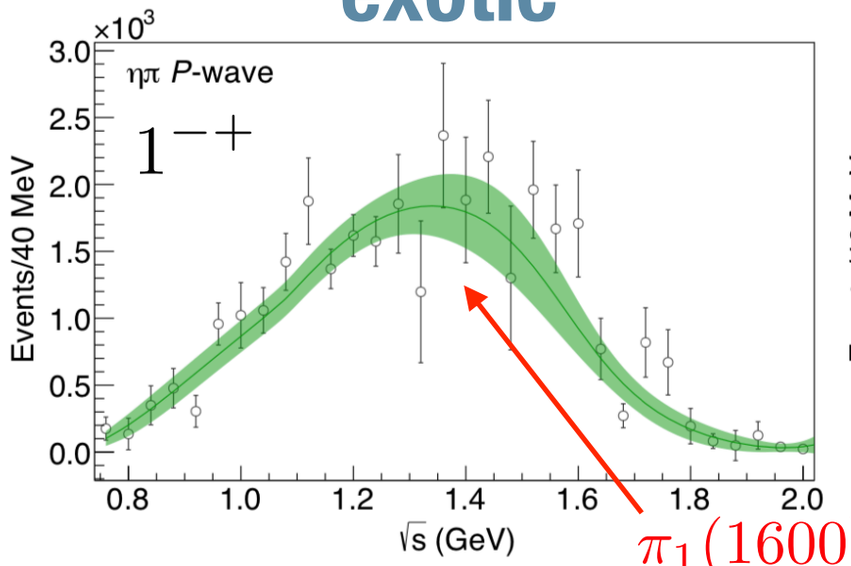
Plenary Sat @ 3:10

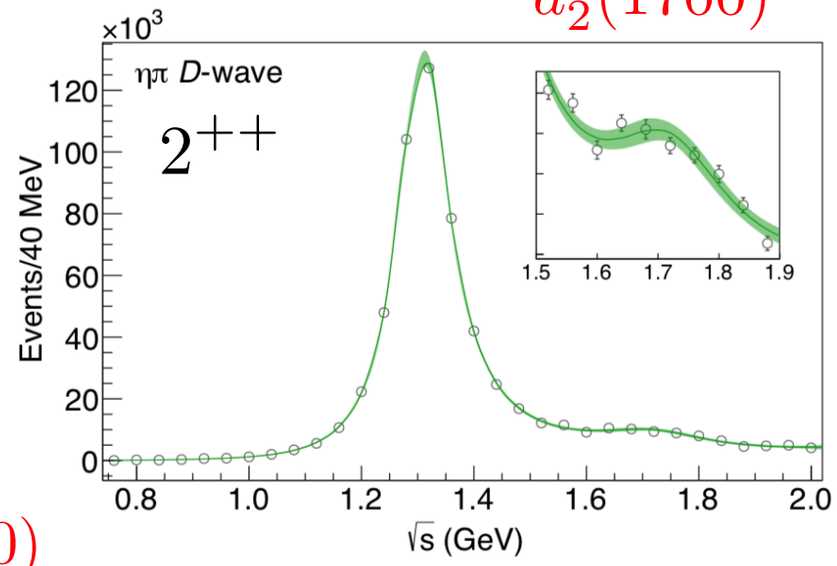
$\eta^{(\prime)}\pi$ spectroscopy at COMPASS with JPAC



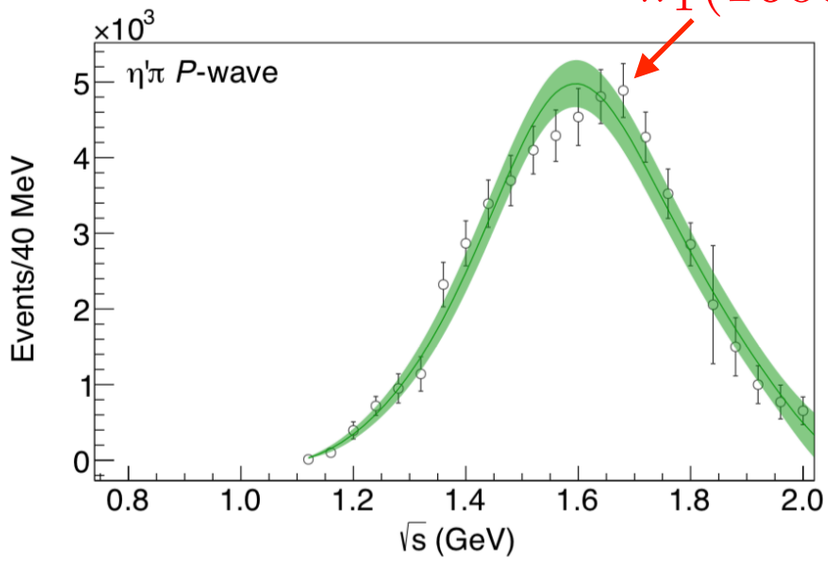
COMPASS: PLB 740 (2015) 303
JPAC: PRL 122 (2019) 042002

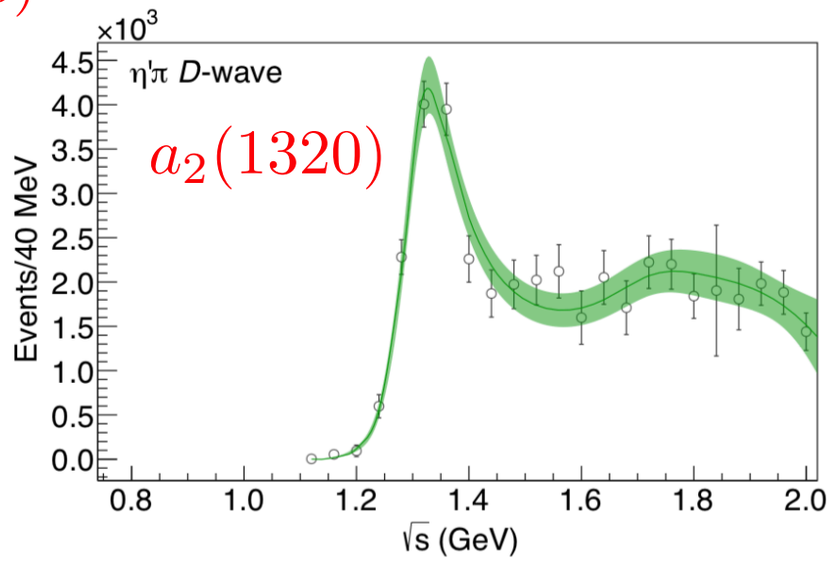
exotic





$\pi_1(1600)$



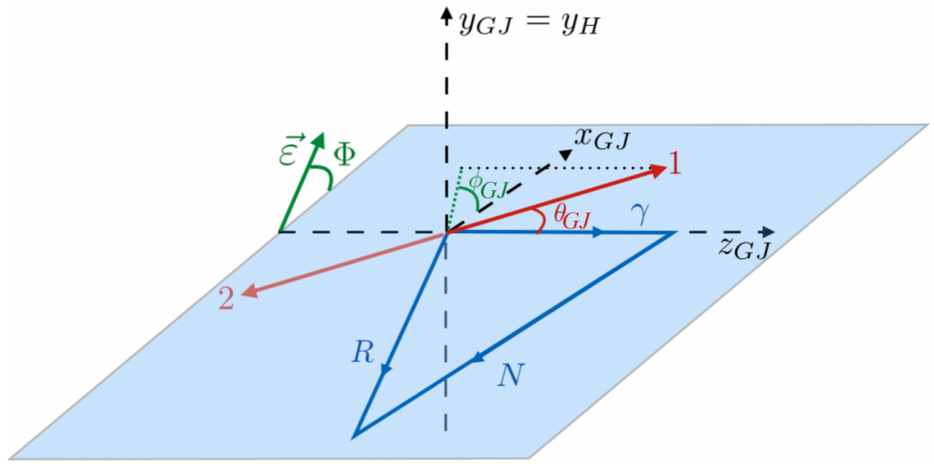


JPAC (Joint Physics Analysis Center) coupled channel fit to $\eta\pi$ and $\eta'\pi$ determine pole positions for a_2, a_2', and exotic π_1

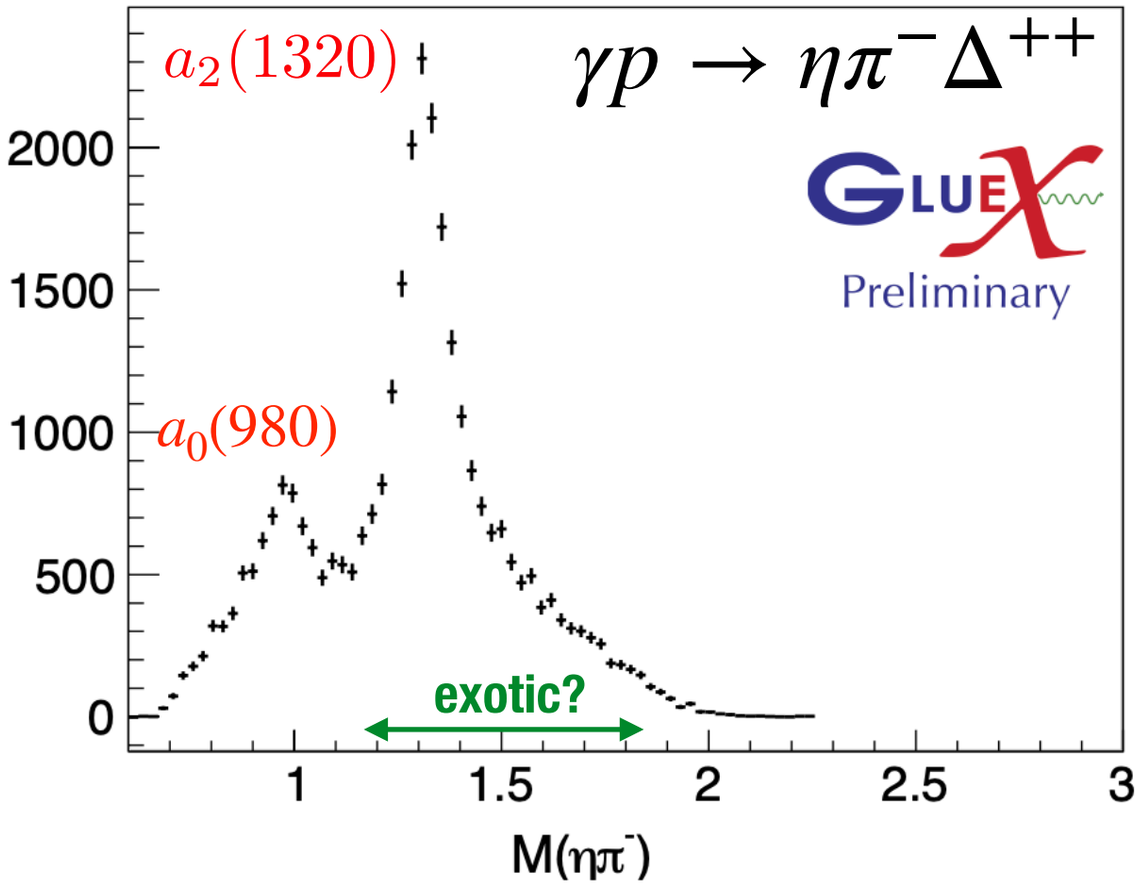
$\eta^{(\prime)}\pi$ spectroscopy at GlueX

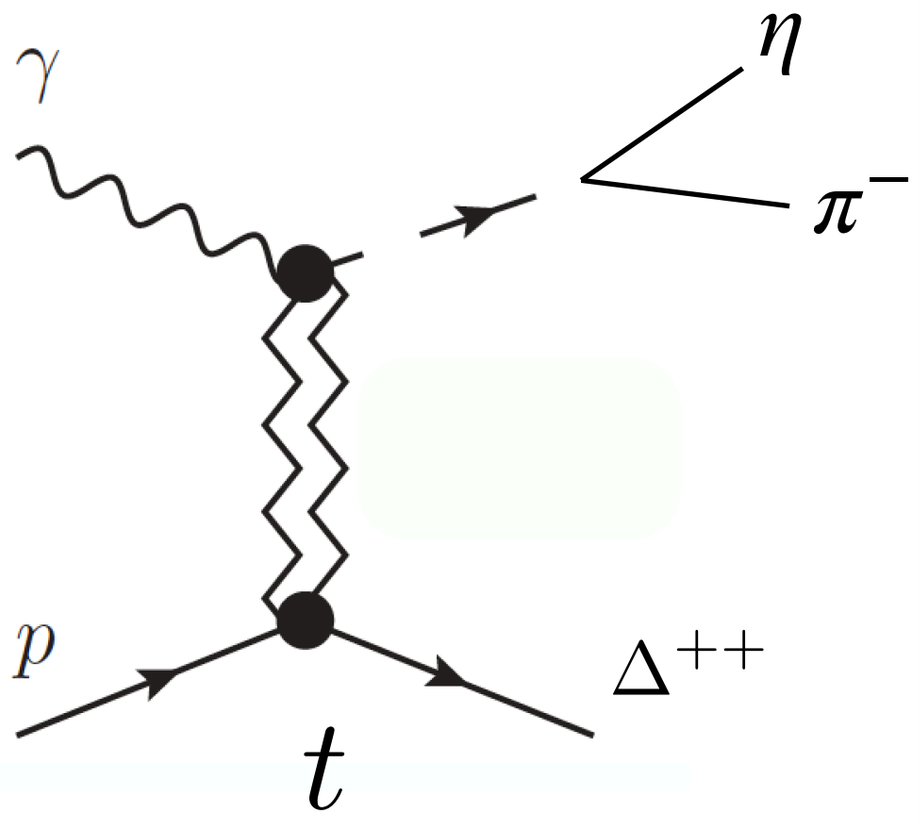
Highlight

- Broad overlapping resonances can't be studied with simple "bump hunting"
- Polarized photon beam provides new information on production mechanism, collaborating with JPAC on amplitudes



$$0.1 < -t < 0.3\ GeV^2$$





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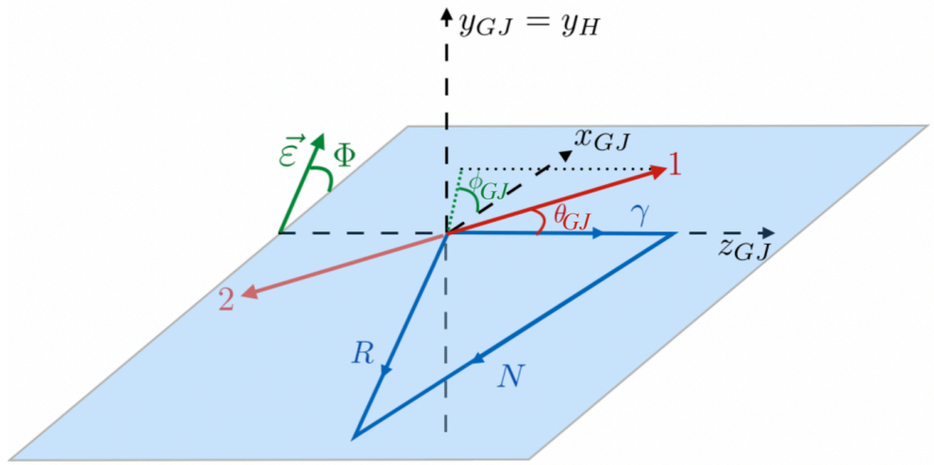
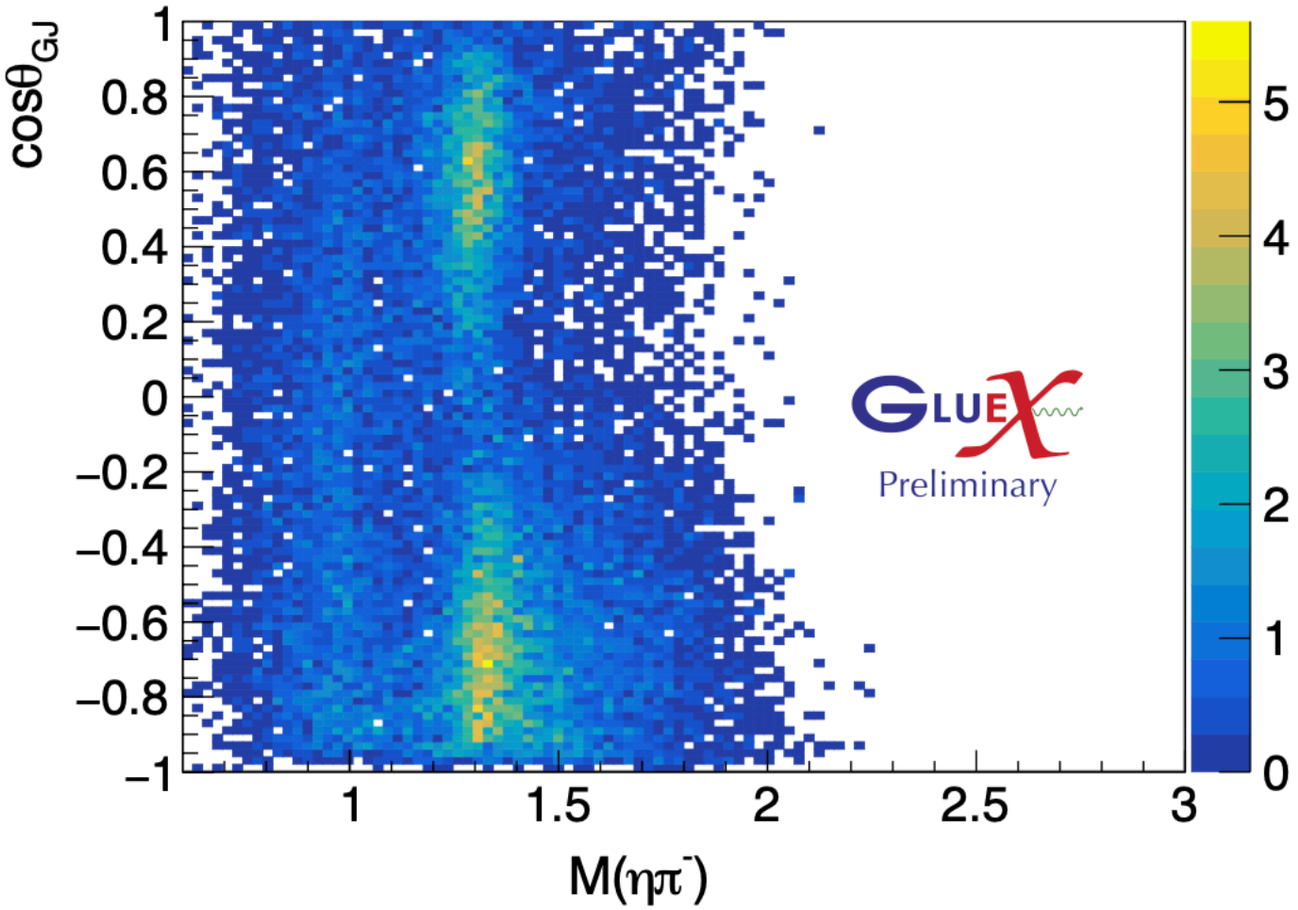
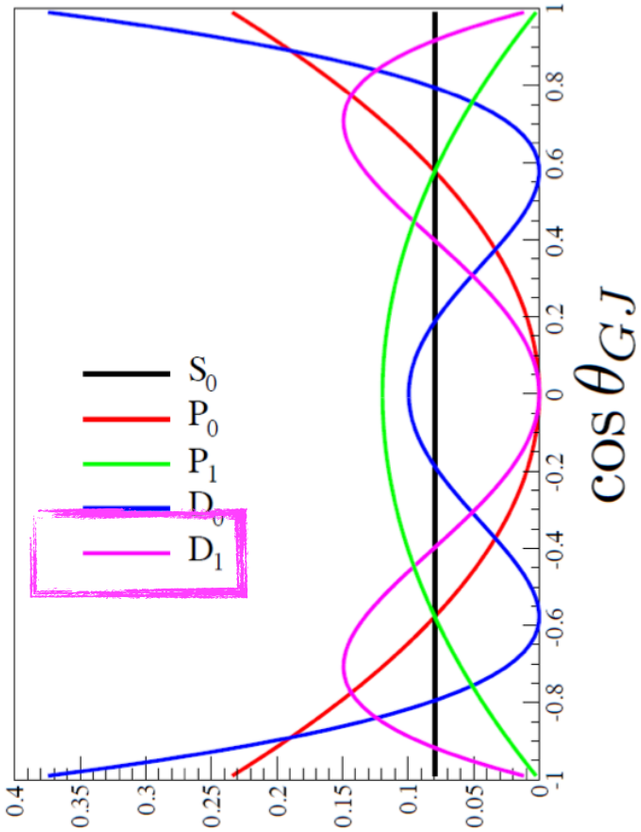


$a_0 \quad a_2 \qquad \gamma p \to \eta\pi^-\Delta^{++}$





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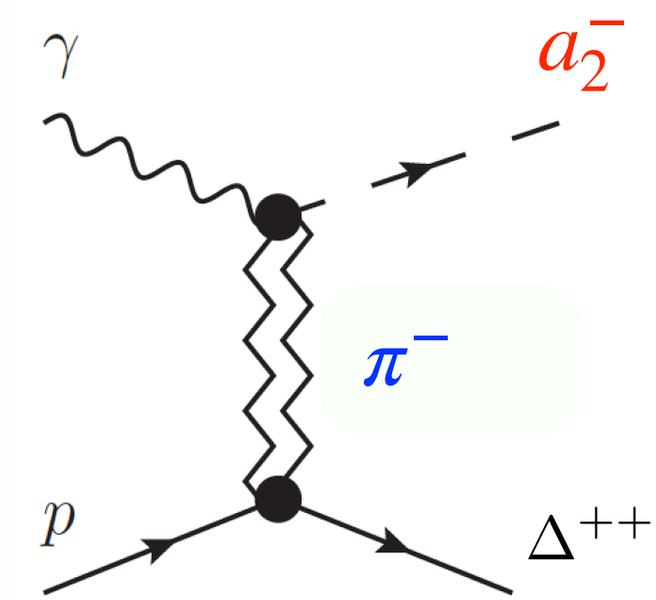
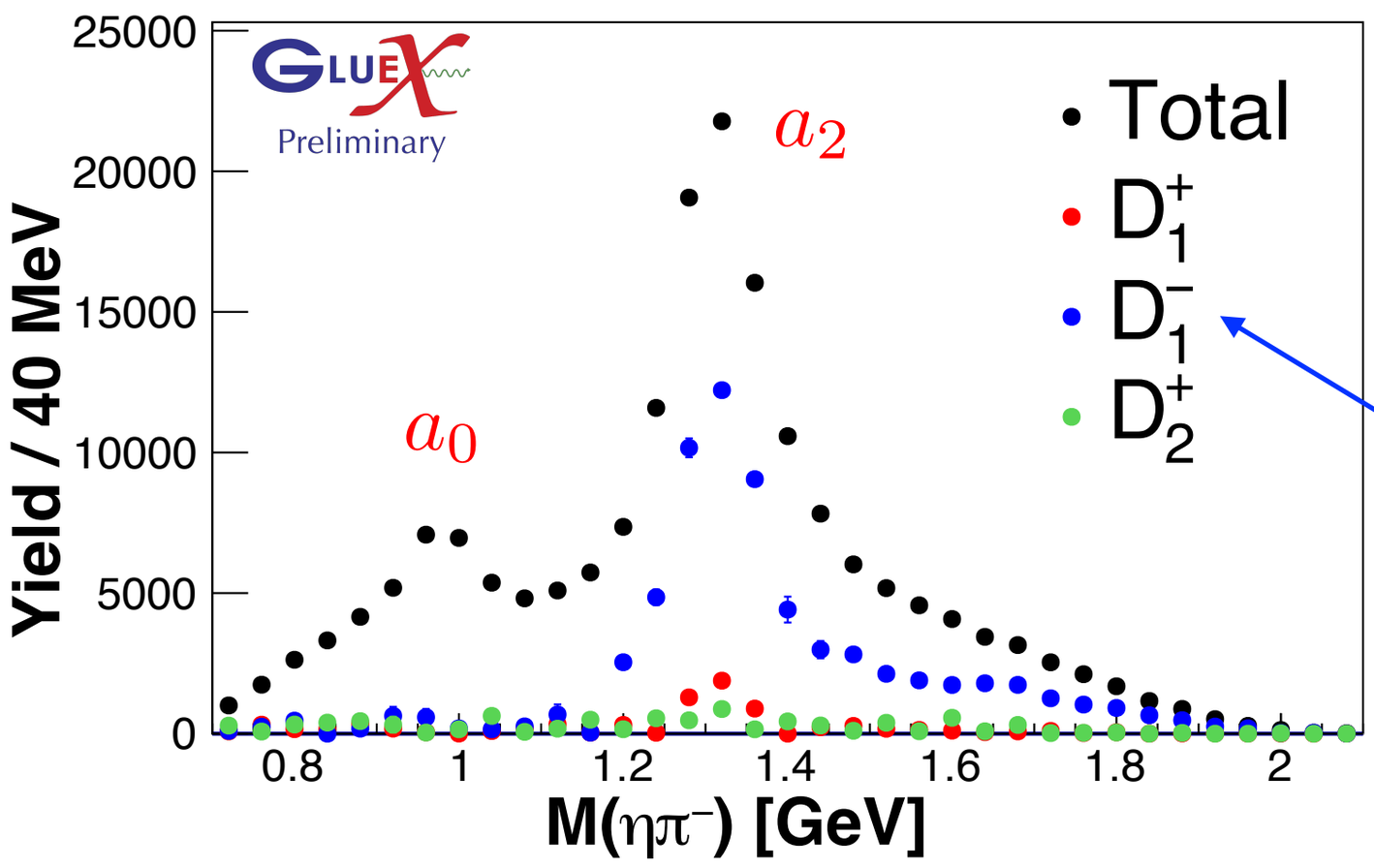




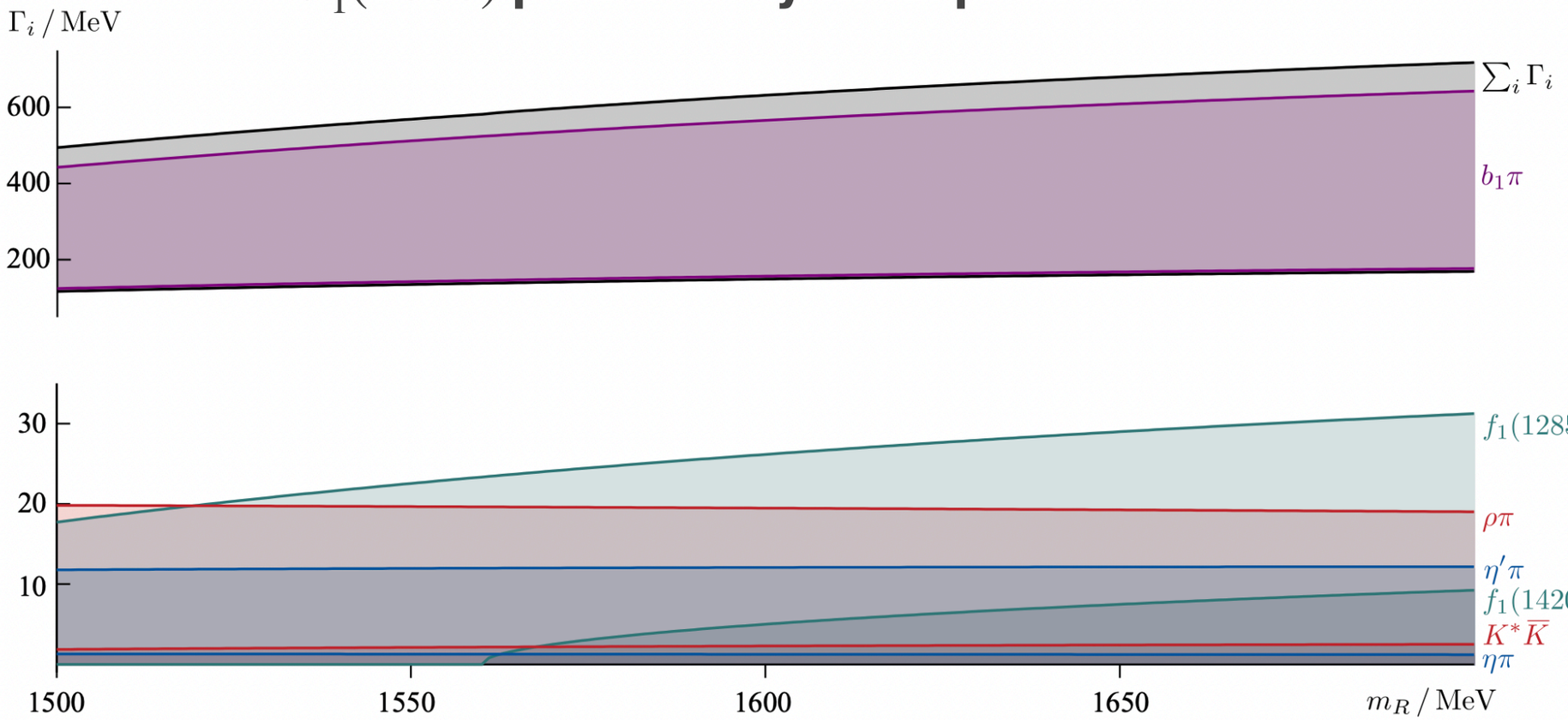
- Understanding production mechanism for conventional mesons, *e.g.* a_2^- through π exchange
- Groundwork laid for exotic $\pi_1(1600)$ search in $\eta\pi$ and $\eta'\pi$

Path forward for light quarks

- Informed by lattice QCD predictions:
  - $\pi_1(1600)$ decay modes → requires studying many final states

Test universality of resonance across production mechanisms and decay modes

$\pi_1(1600)$ **partial decay width prediction**



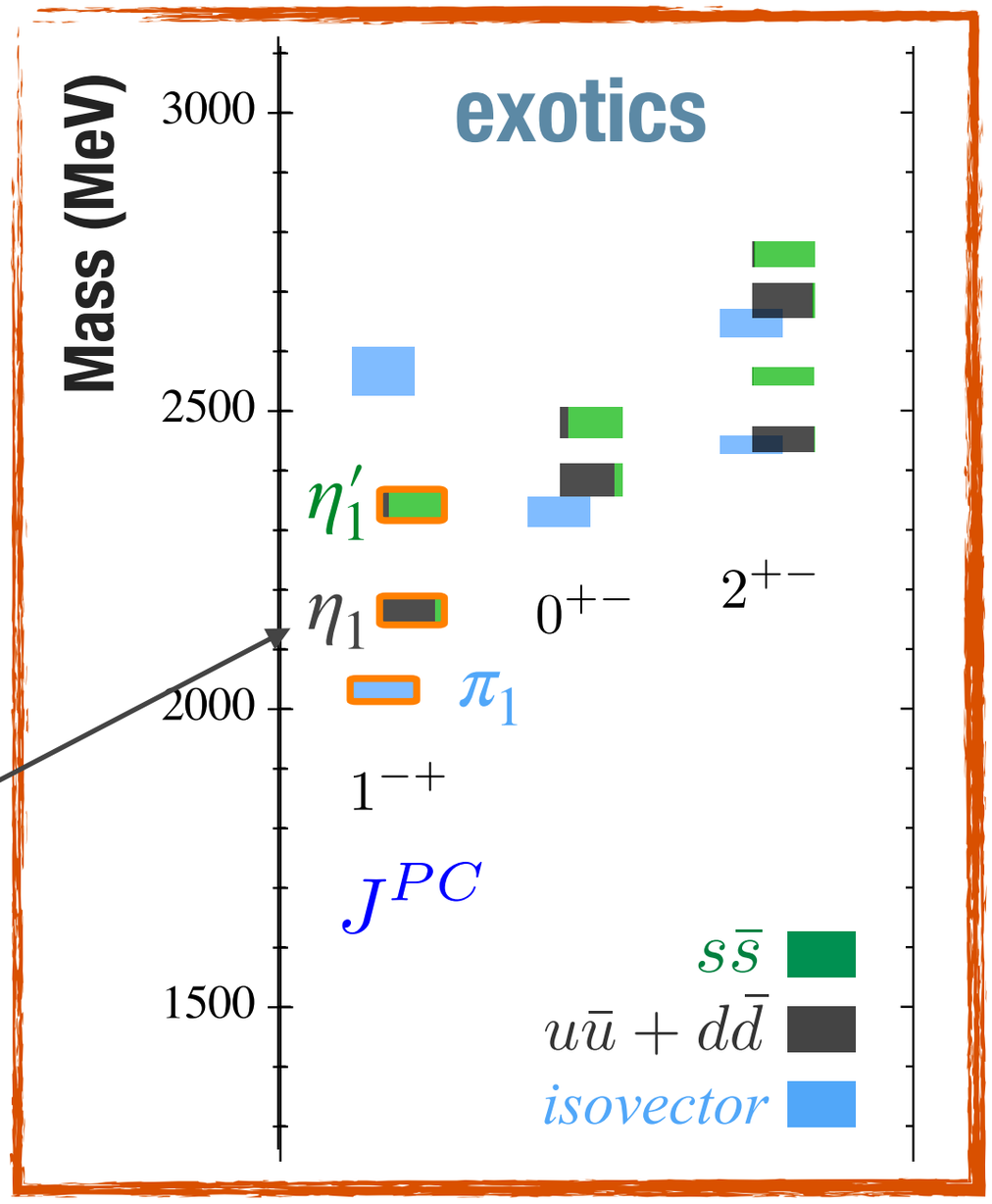
large coupling to axialvector-pseudoscalar

small coupling to $\eta^{(\prime)}\pi$ where exotic is observed

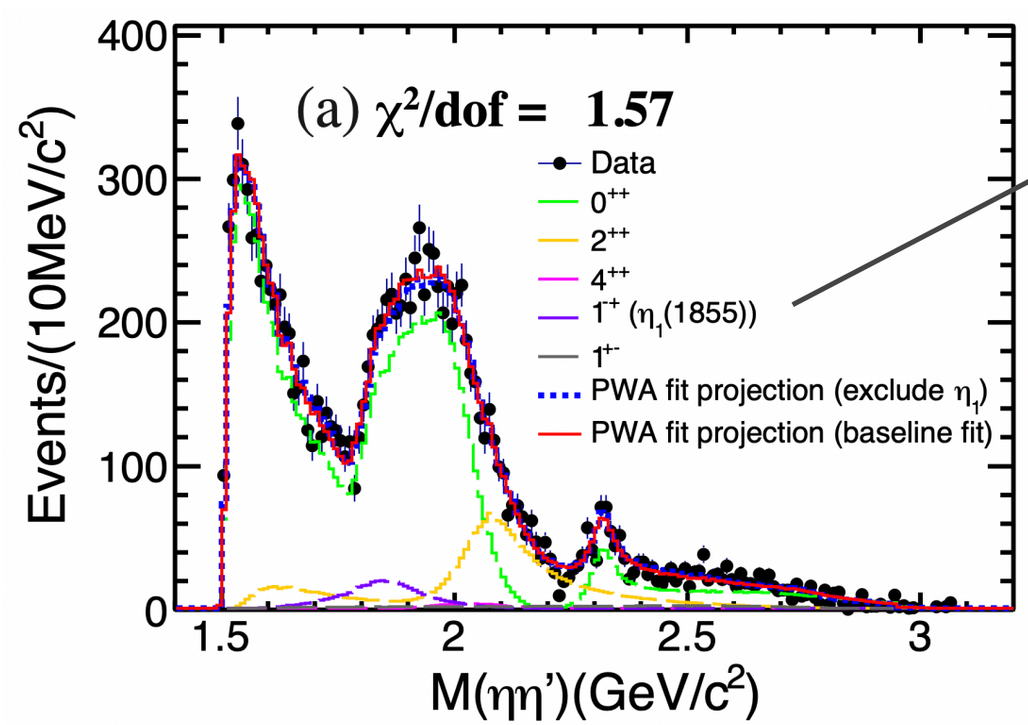
Path forward for light quarks

Highlight

- Informed by lattice QCD predictions:
  - $\pi_1(1600)$ decay modes → requires studying many final states
  - **strange** and **light** quark content for hybrid mesons
- Recent candidate from BESIII for isoscalar partner η_1 in $J/\psi \to \gamma\eta'\eta$



?



PRD 88 (2013) 094505

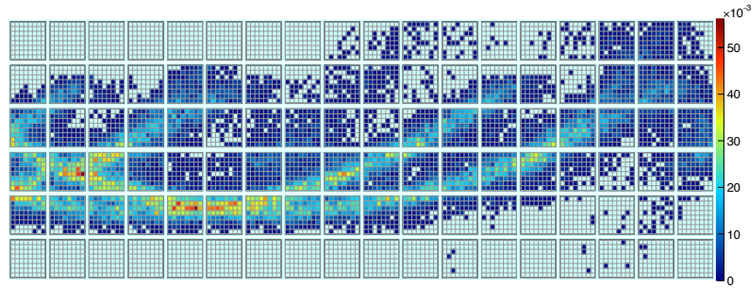
arXiv:2202.00621
arXiv:2202.00623

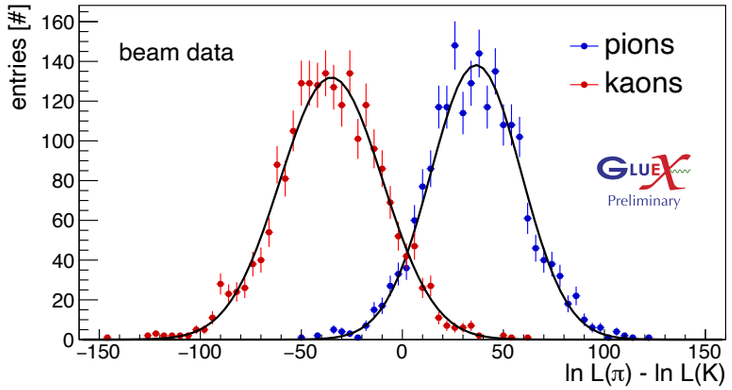
Path forward for light quarks

Highlight & Future

- Informed by lattice QCD predictions:
  - $\pi_1(1600)$ decay modes → requires studying many final states
  - **strange** and **light** quark content for hybrid mesons
- Recent candidate from BESIII for isoscalar partner η_1 in $J/\psi \to \gamma\eta'\eta$
- Detector upgrades completed for kaon identification for hidden strangeness η_1'

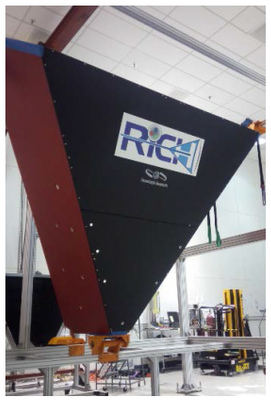
GlueX DIRC

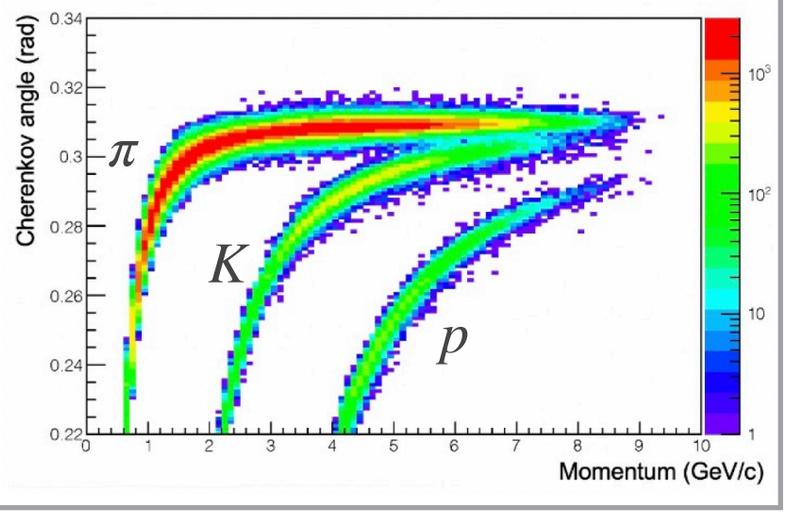




CLAS12 RICH

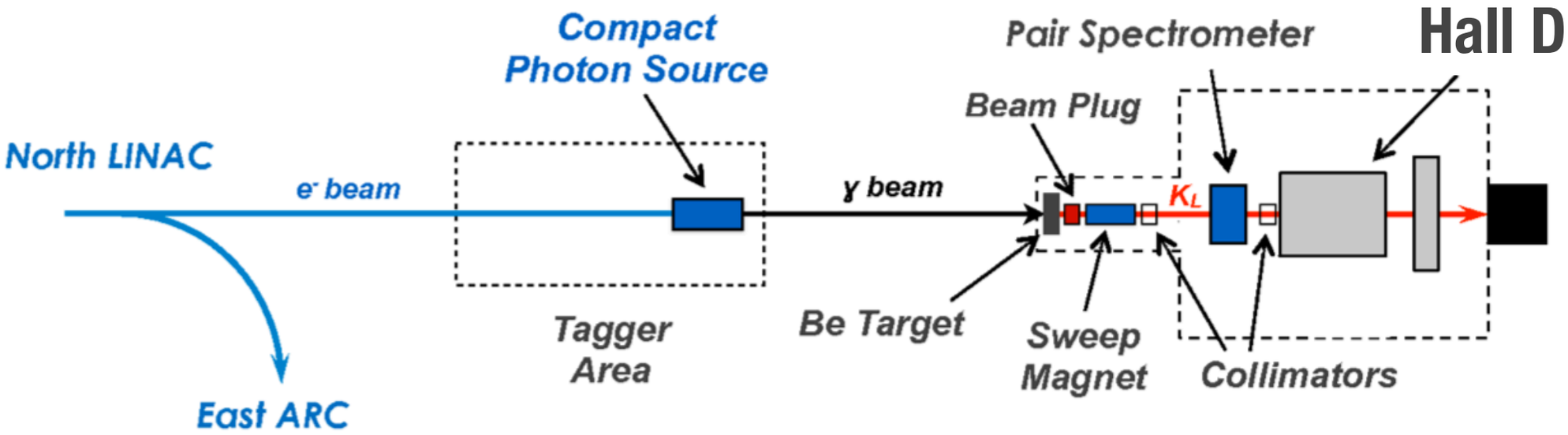
	Final States
π_1	$\omega\pi\pi$, 3π , 5π, $\eta 3\pi$, $\eta'\pi$
η_1	4π, $\eta 4\pi$, $\eta\eta\pi\pi$
η_1'	$KK\pi\pi$, $KK\pi$, $KK\omega$





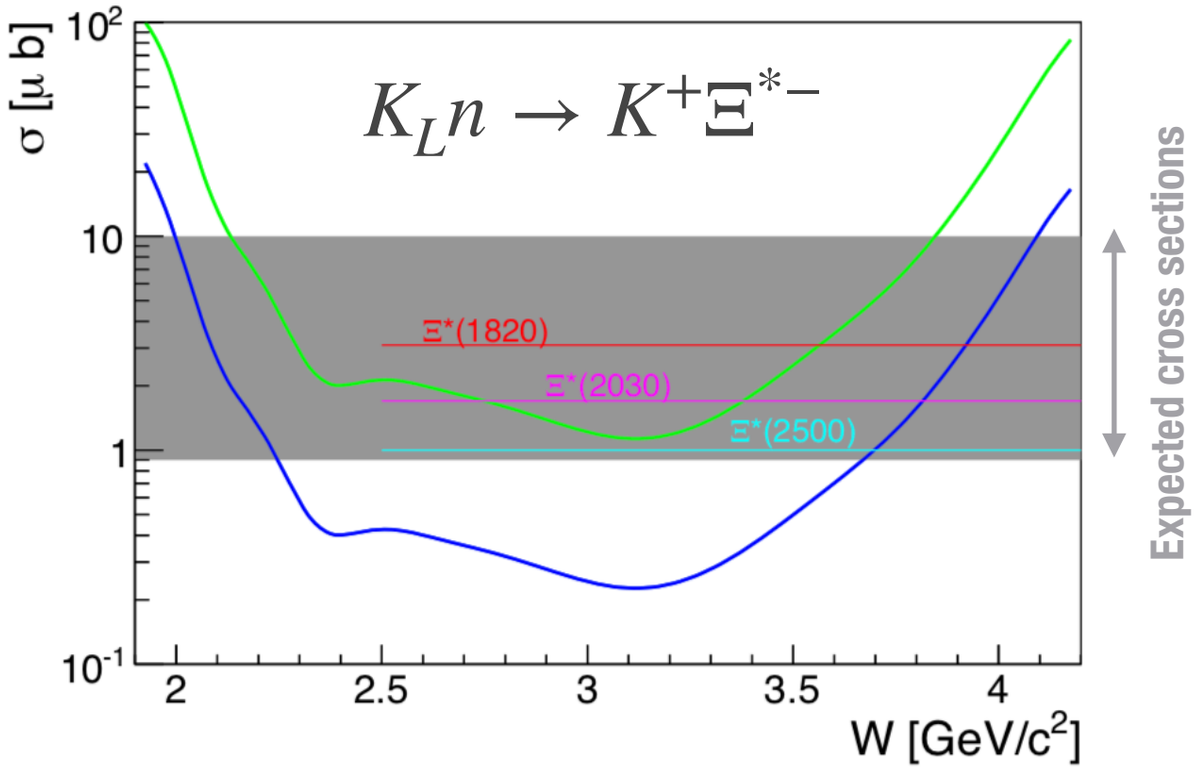
K_{Long} Facility (KLF)

Future

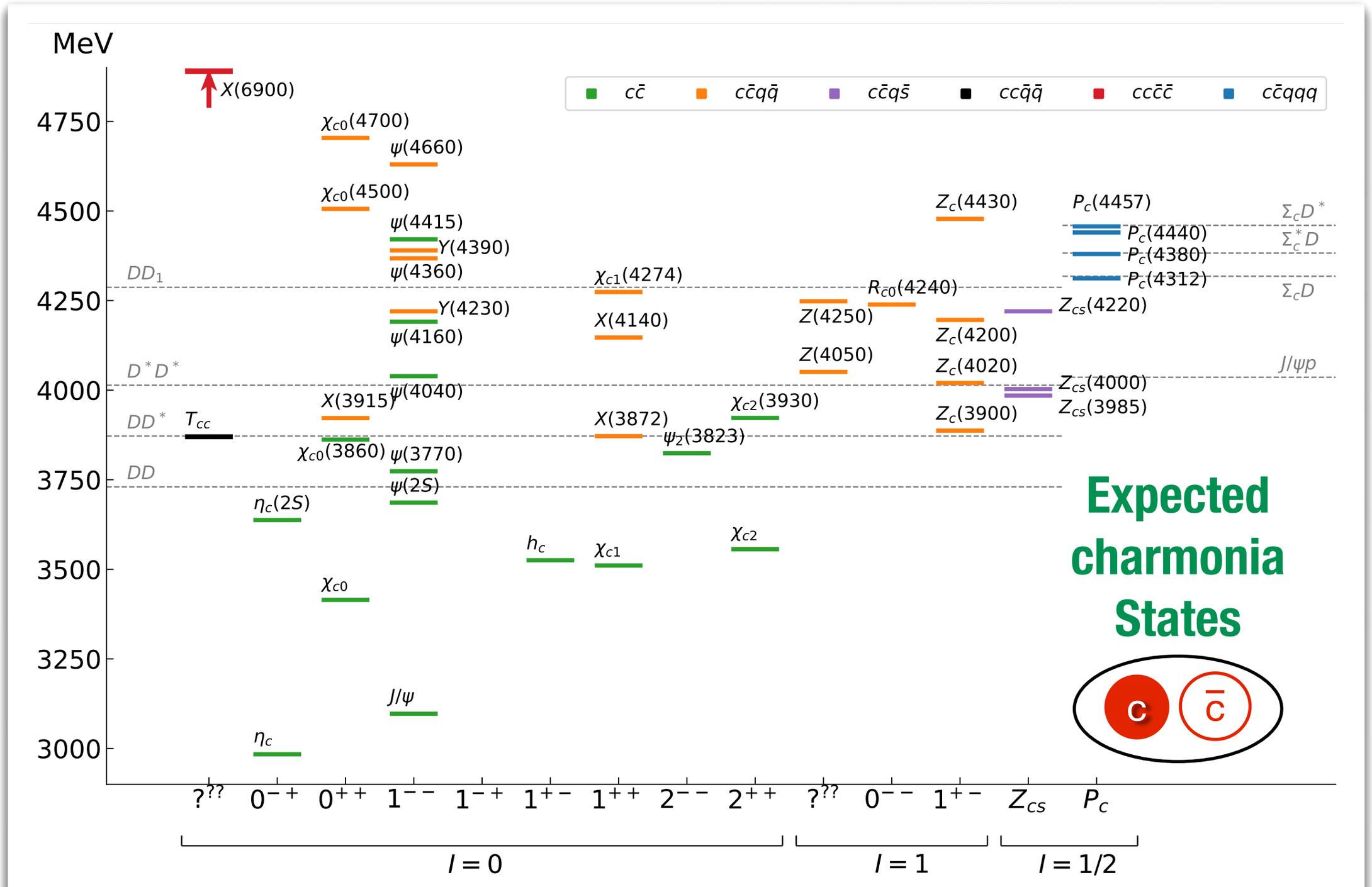


- Create secondary beam of neutral K_L and use Hall D spectrometer to study the $K_L p$ and $K_L n$ interactions
- Strange quark in initial state provides enhanced source of hyperon and strange meson production
- Broad program of searches for expected hyperon states not yet observed experimentally

Projected sensitivity for KLF with 100 days beam time

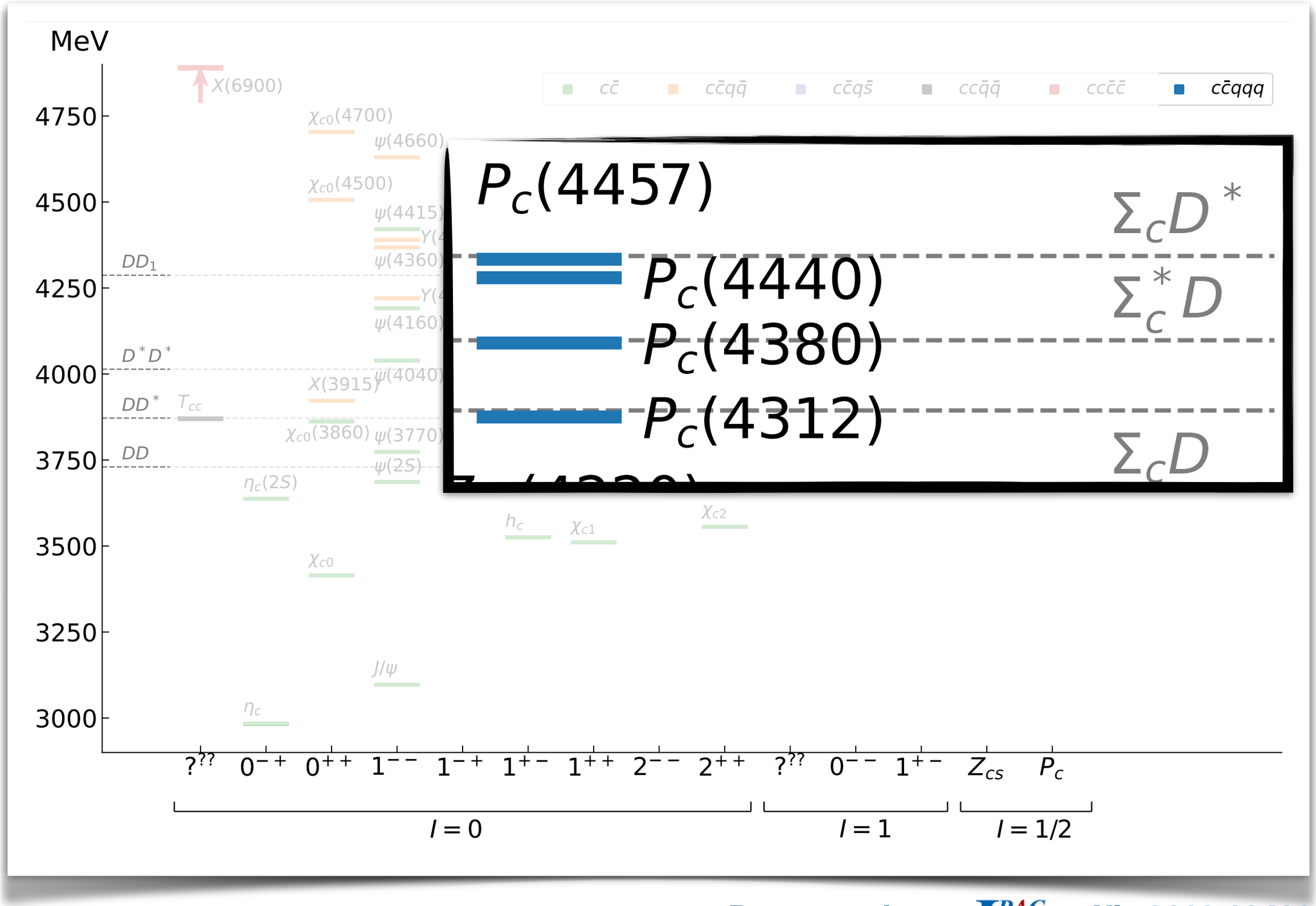


Highlights since 2015 LRP: $XYZP_c$



Recent review: JPAC **arXiv:2112.13436**

Pentaquarks



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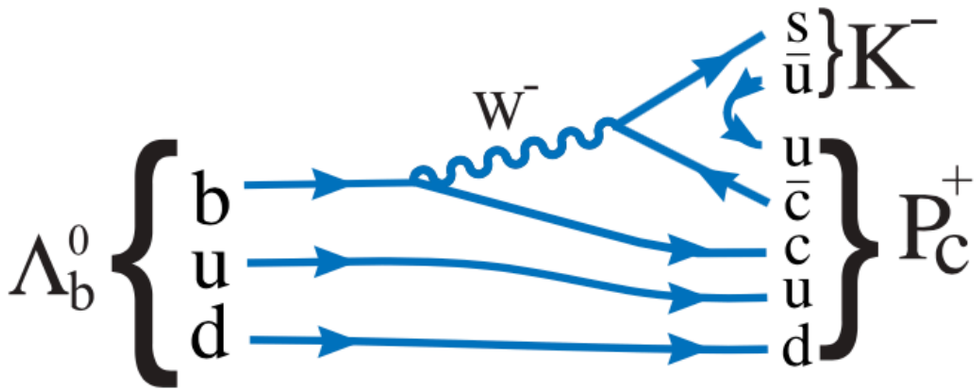
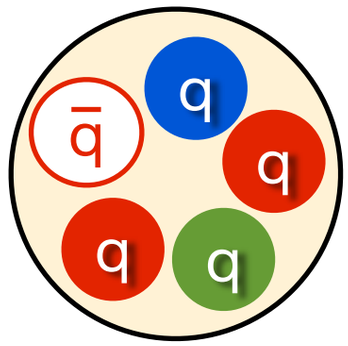
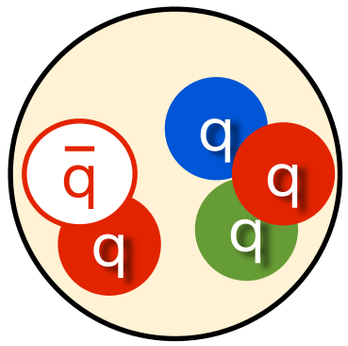
Pentaquark observation and interpretation

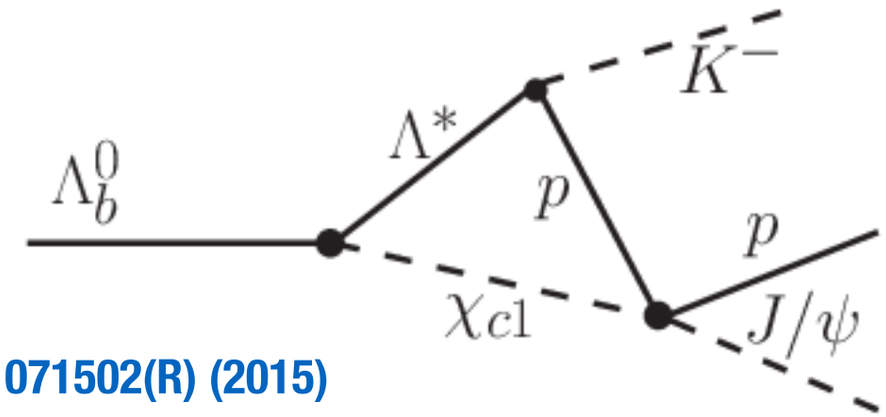




pentaquark



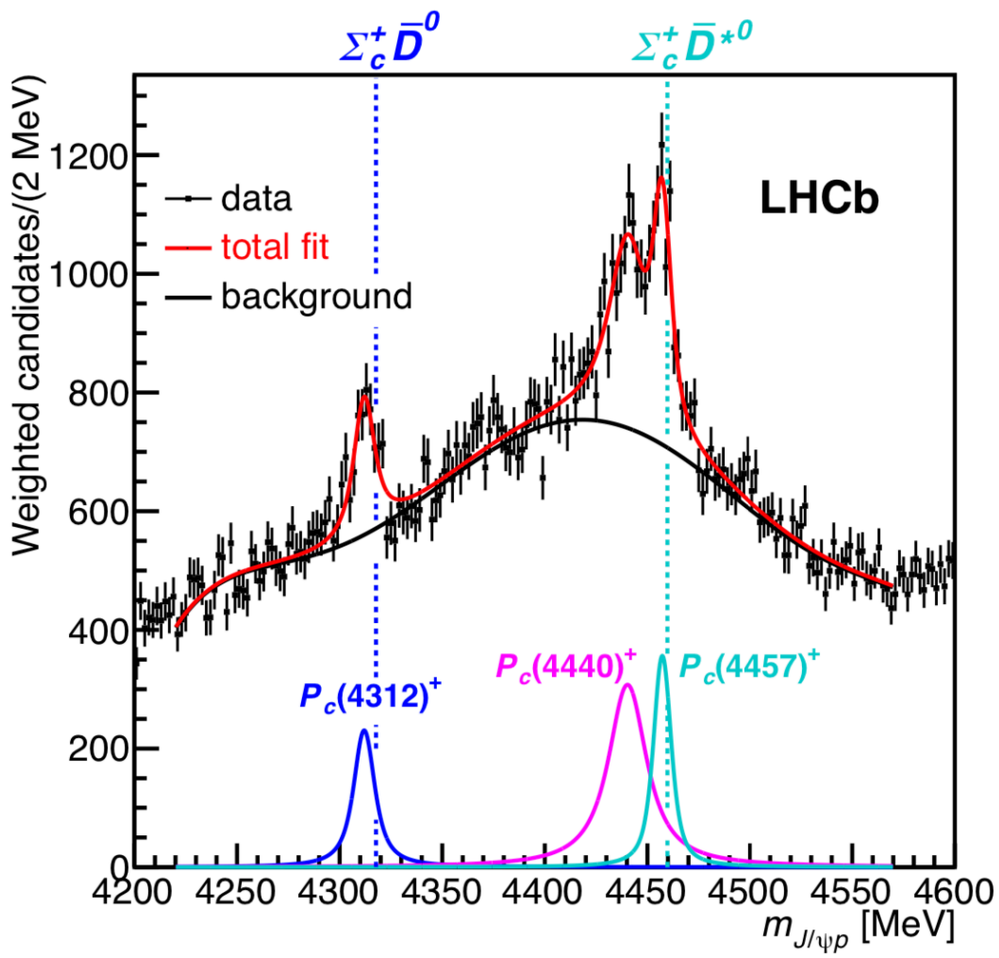
molecular



e.g. PRD 92, 071502(R) (2015)

rescattering (triangle singularity)

$$\Lambda_b \to J/\psi p K^-$$



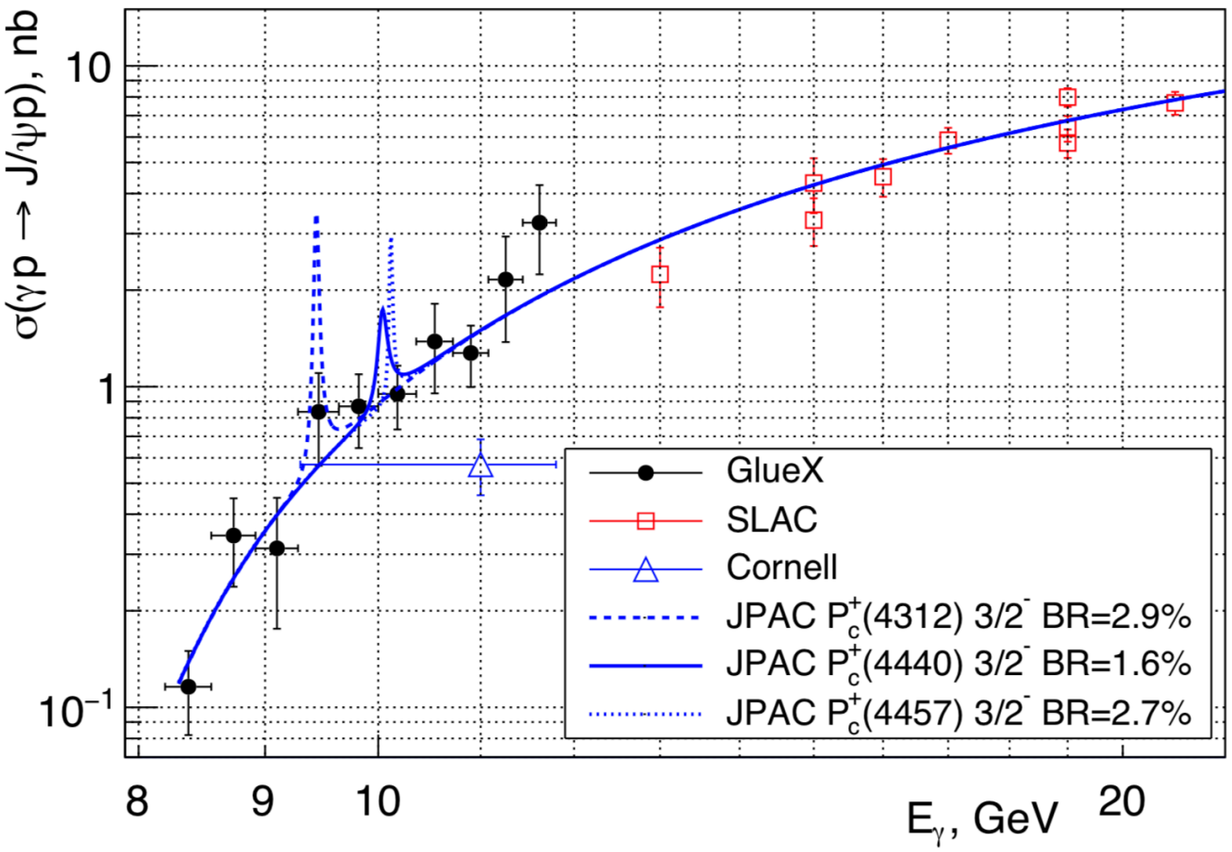
PRL 122, 222001 (2019)

Pentaquark photoproduction

Highlight

$$\gamma p \to J/\psi p$$

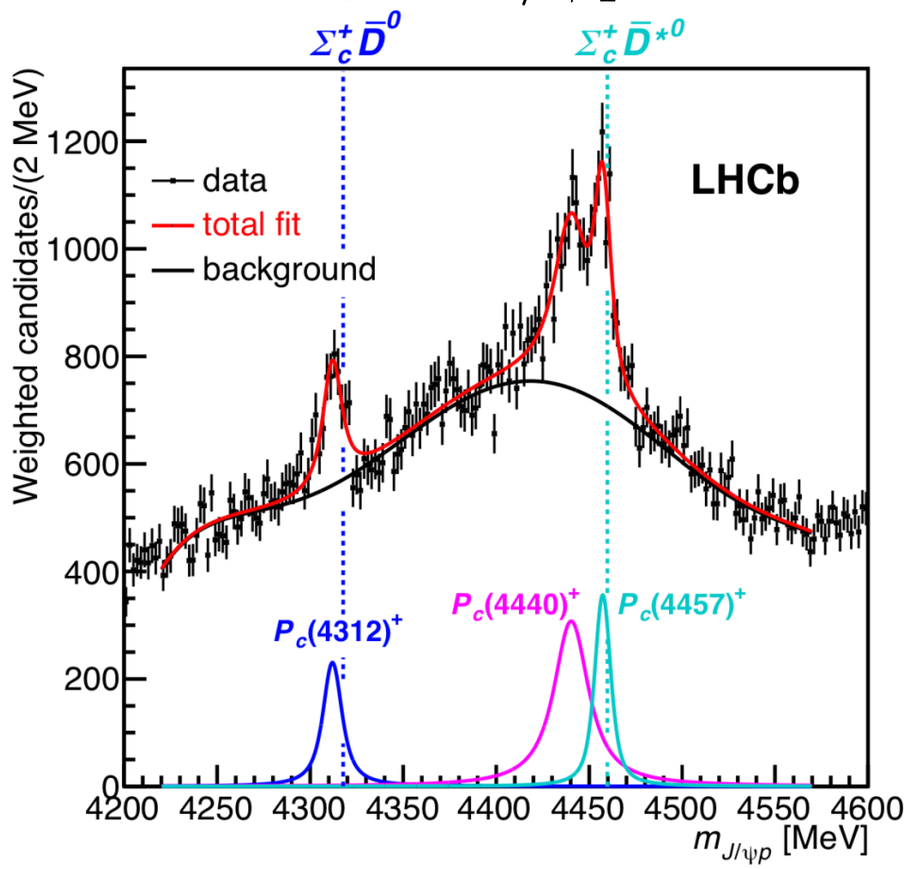
GlueX **PRL 123, 072001 (2019)**

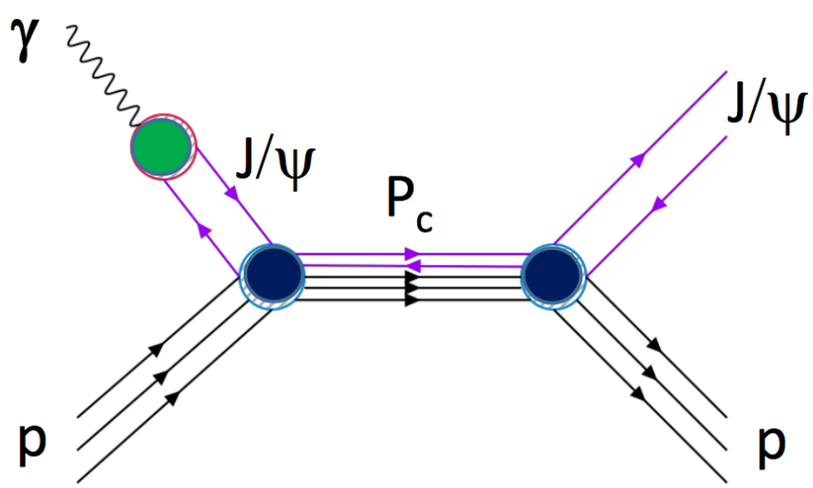


Model-dependent limits on

$BR(P_c \to J/\psi p)$ **< 2-4%**

$$\Lambda_b \to J/\psi p K^-$$





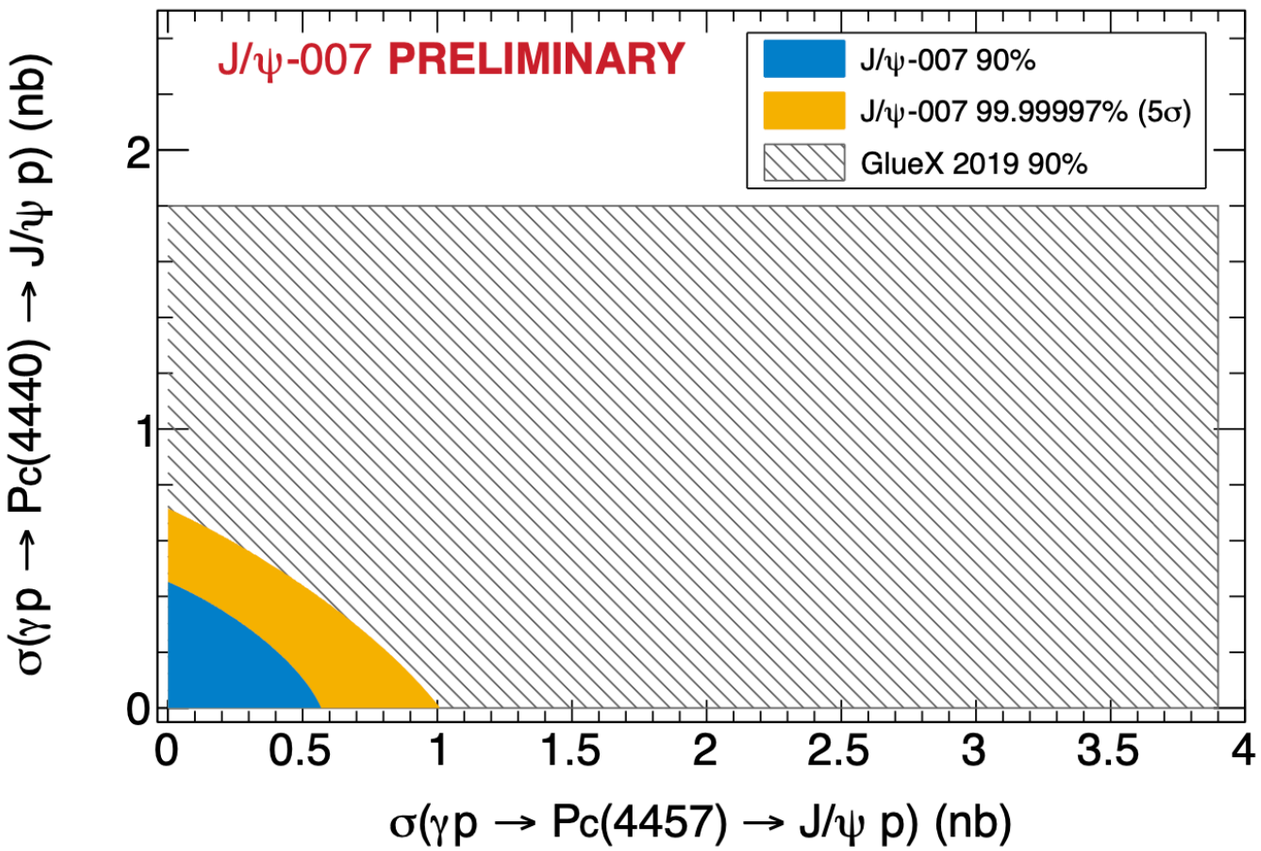
Proportional to $BR(P_c \to J/\psi p)^2$

Pentaquark photoproduction

Highlight

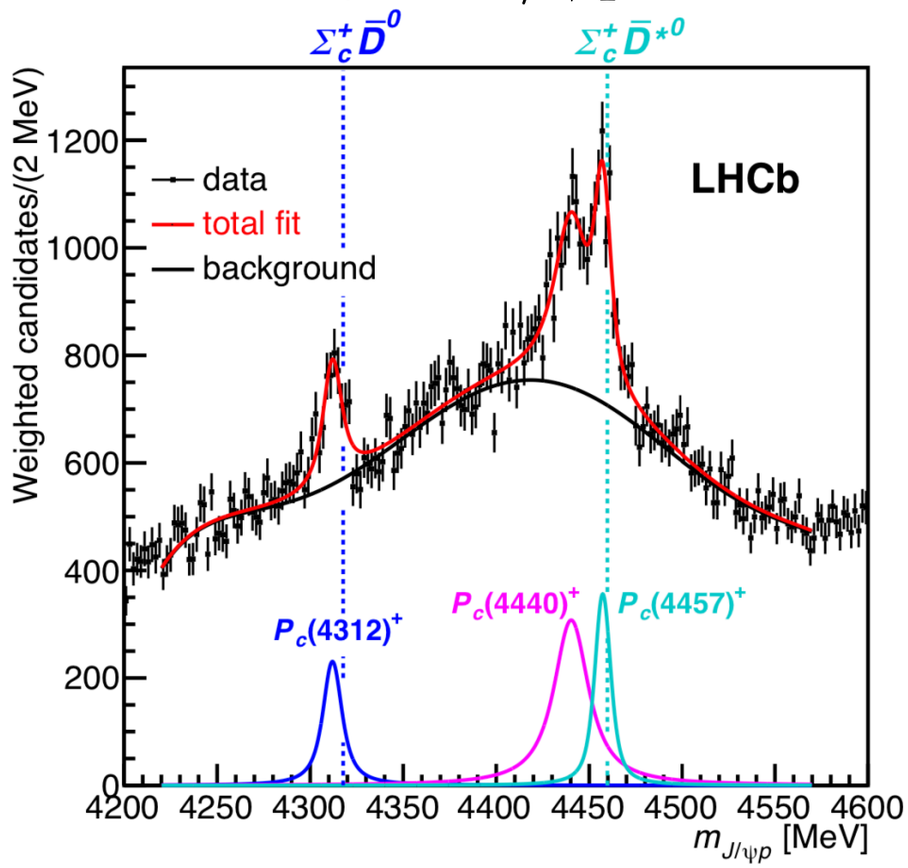
$$\gamma p \to J/\psi p$$

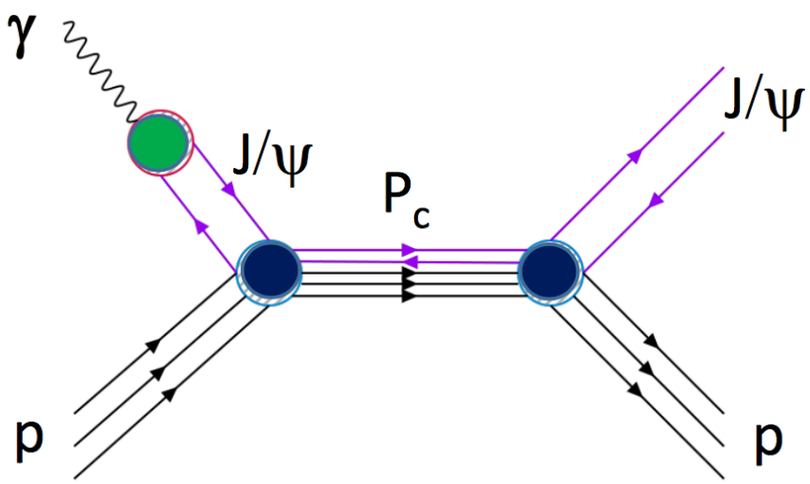
Hall C: J/ψ-007 experiment



Even stricter limits on P_c production taking into account differential cross section $d\sigma/dt$

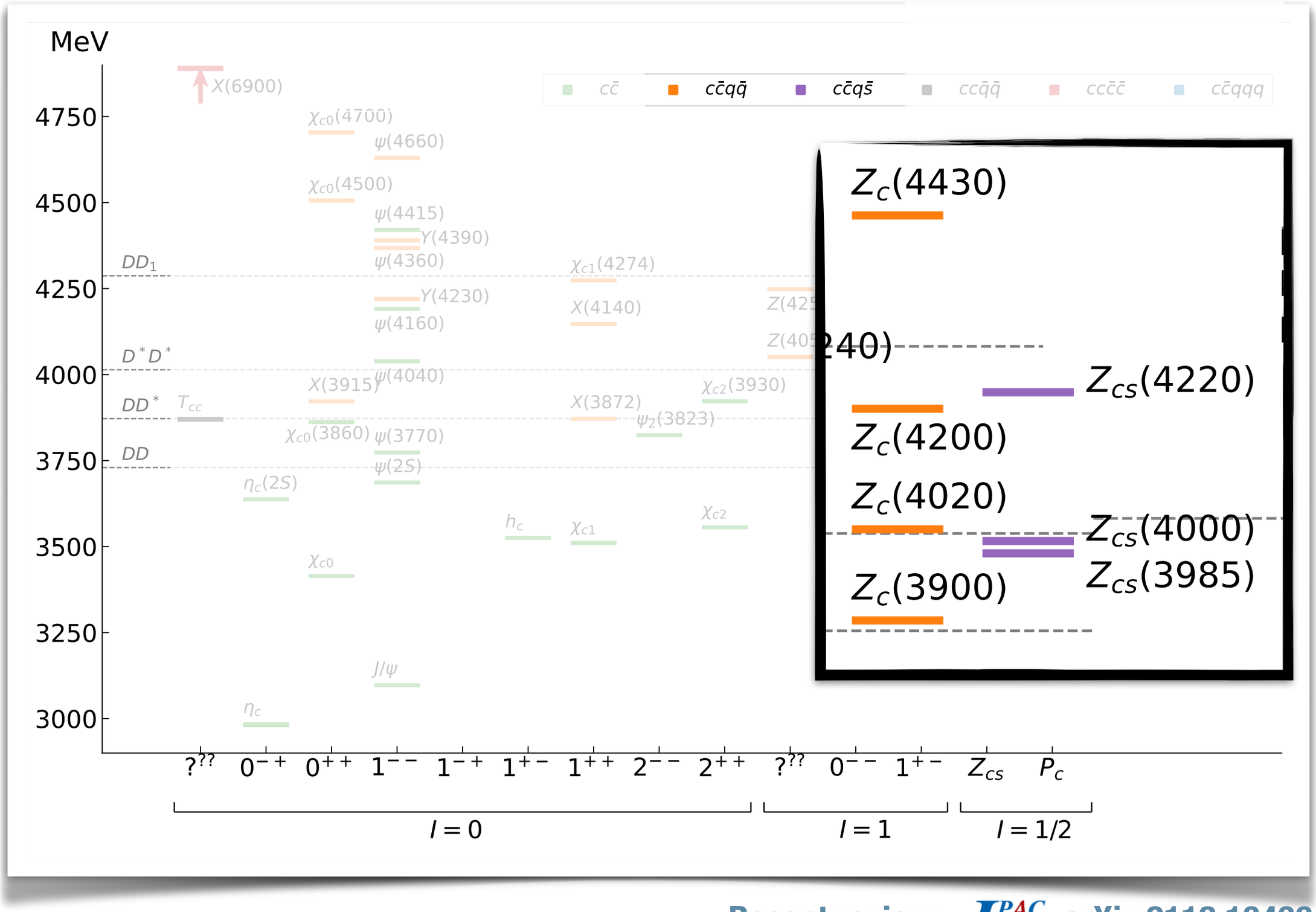
$$\Lambda_b \to J/\psi p K^-$$





Proportional to BR($P_c \to J/\psi p$)^2

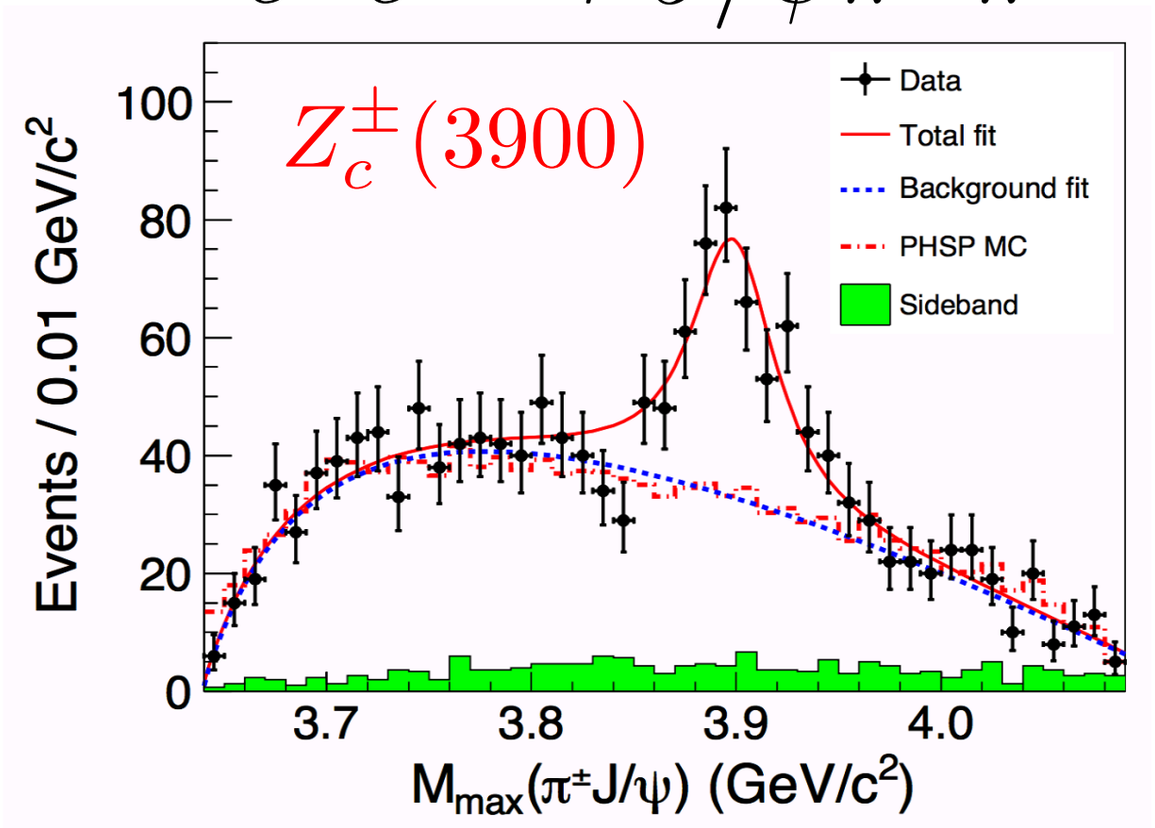
Charged tetraquark candidates: Z_c



Recent review: JPAC **arXiv:2112.13436**

Charged tetraquark candidates: Z_c

$$e^+e^- \to J/\psi\pi^+\pi^-$$

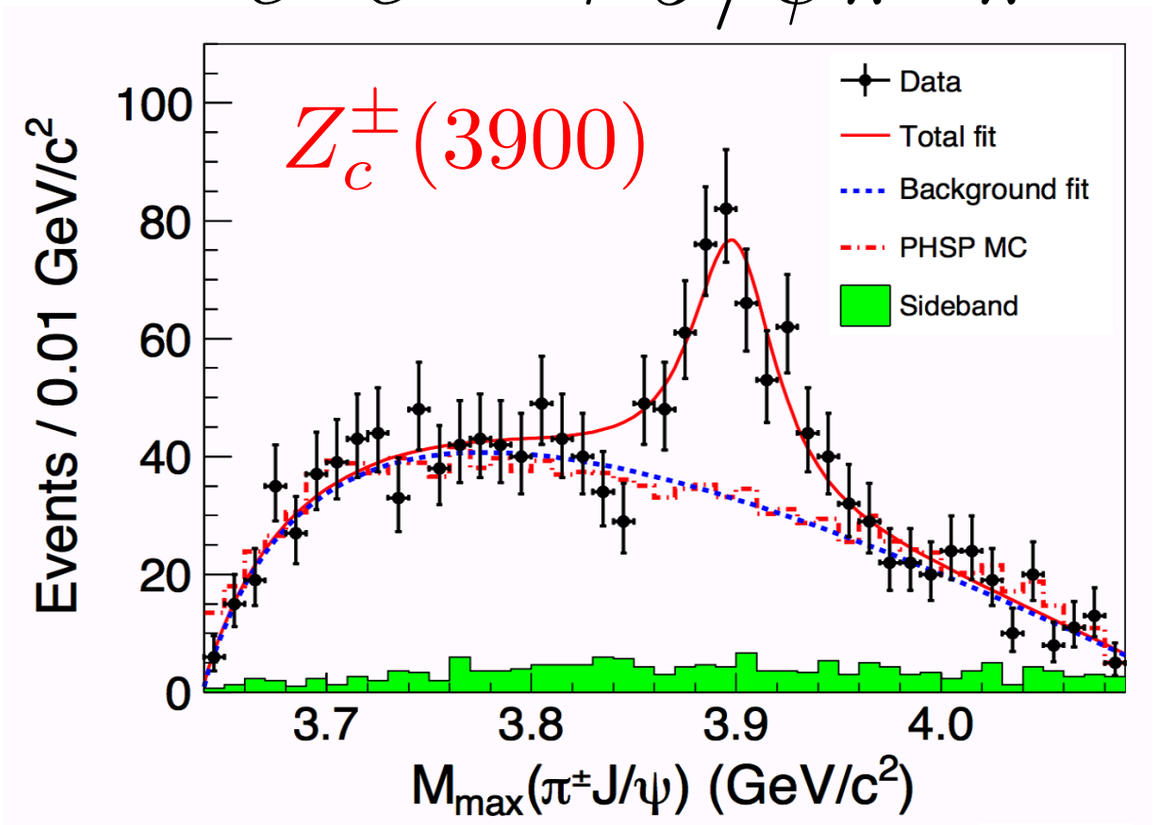


PRL 110, 252001 (2013) BESIII

PRL 110, 252002 (2013) BELLE

Charged tetraquark candidates: Z_c

$$e^+e^- \to J/\psi\pi^+\pi^-$$

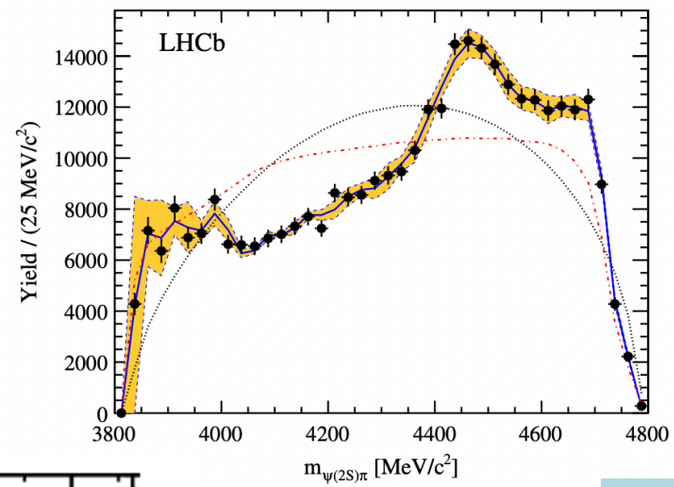


PRL 110, 252001 (2013) BESIII

PRL 110, 252002 (2013) BELLE

$Z_c^-(4430)$

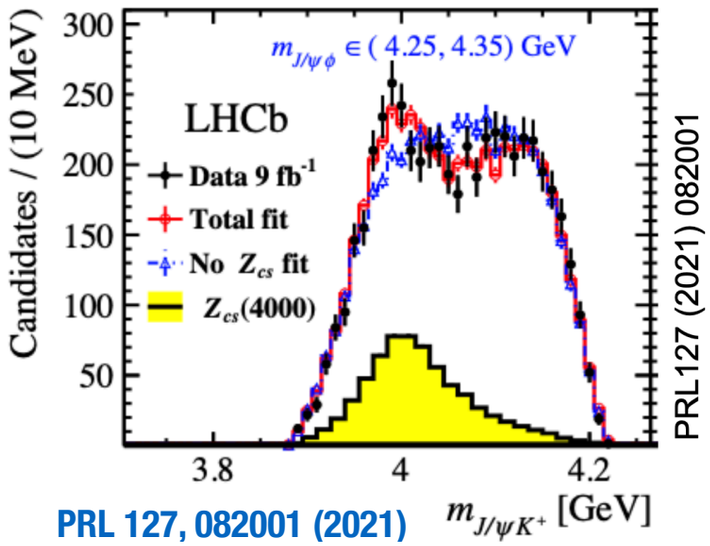
$$B^0 \to \psi(2S)K^+\pi^-$$



PRD 92, 112009 (2015) LHCb

$Z_{cs}^+(4000)$

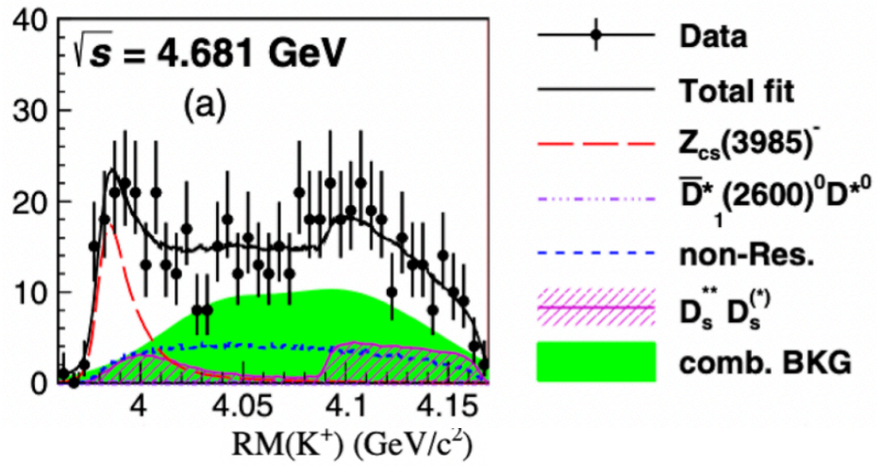
$$B^+ \to J/\psi\phi K^+$$



PRL 127, 082001 (2021)

$Z_{cs}^+(3985)$

$$e^+e^- \to K^+D_s^-X$$

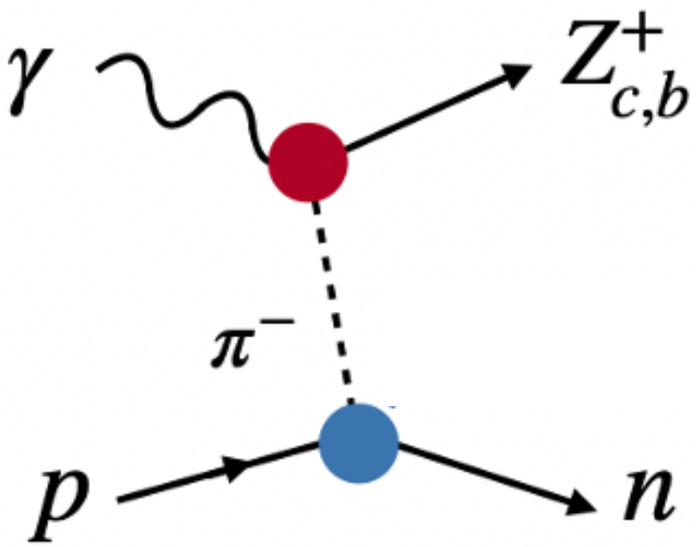


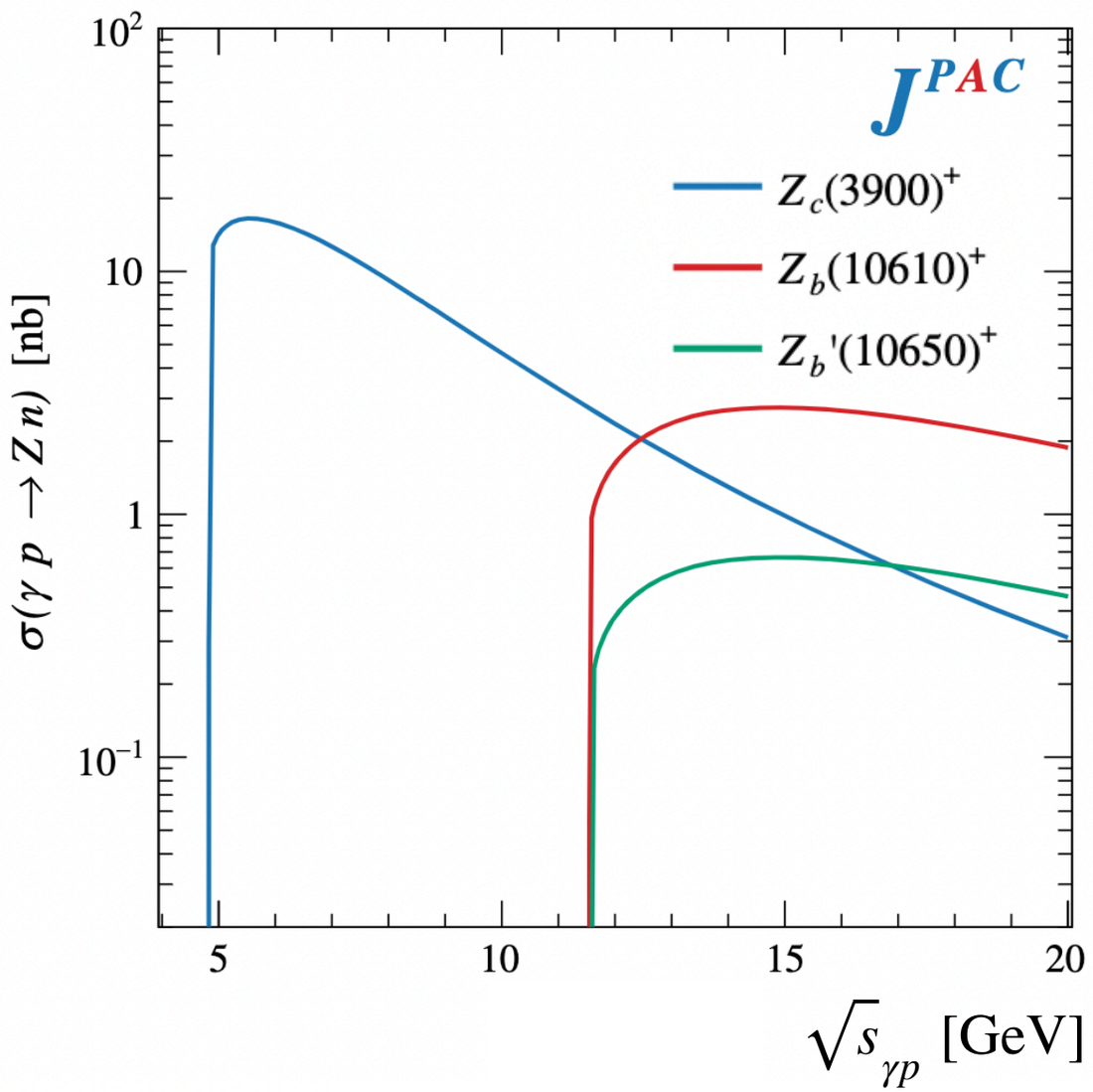
- Many observations of charged Z_c $(c\bar{c}q\bar{q})$ and Z_{cs} $(c\bar{c}s\bar{q})$
- Production mechanism dependent masses and widths (e^+e^- vs B decay)

Photoproduction of $Z_c^+(3900)$

Future

- Alternative production mechanism: free of rescattering effects and sensitive to photo couplings
- Same production mechanism near threshold (π exchange) studied with light quarks in GlueX and CLAS12





JPAC : PRD 102, 114010 (2020)

Photoproduction of XYZ states

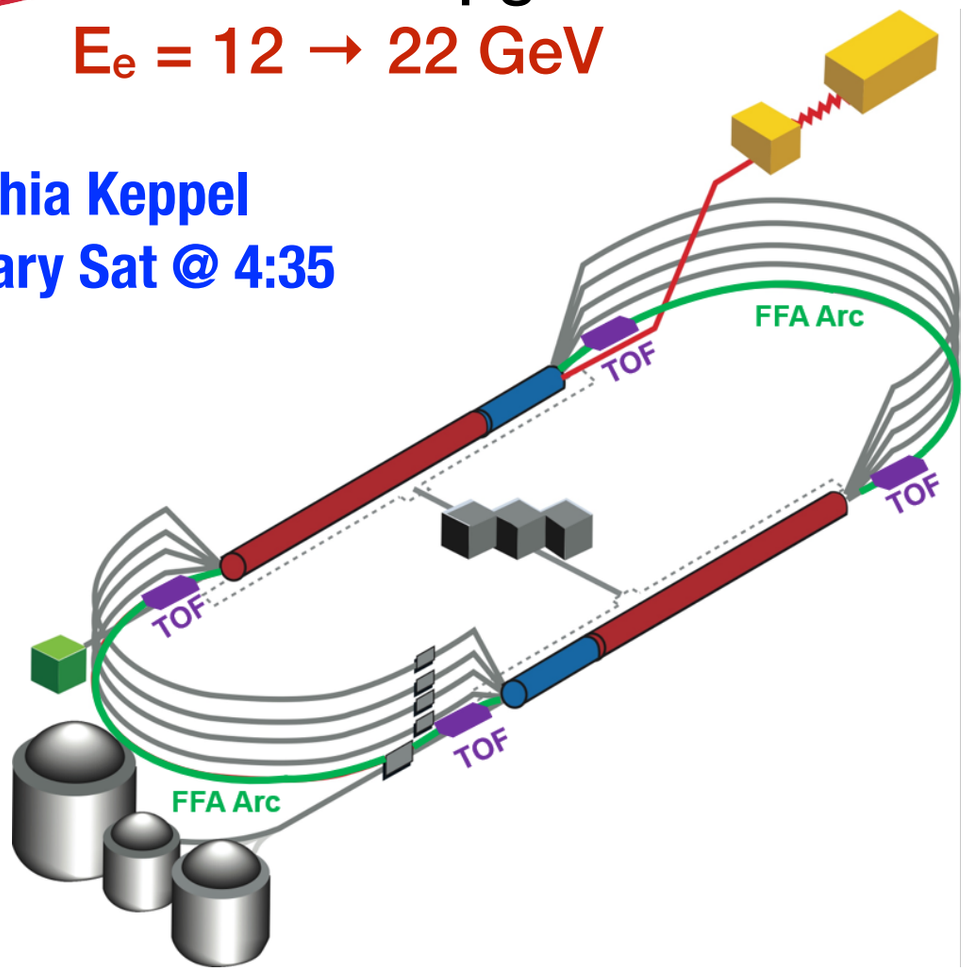
Future

Complementary access to charmonium photoproduction with higher energy facilities

Jefferson Lab upgrade:

$E_e = 12 \rightarrow 22$ GeV

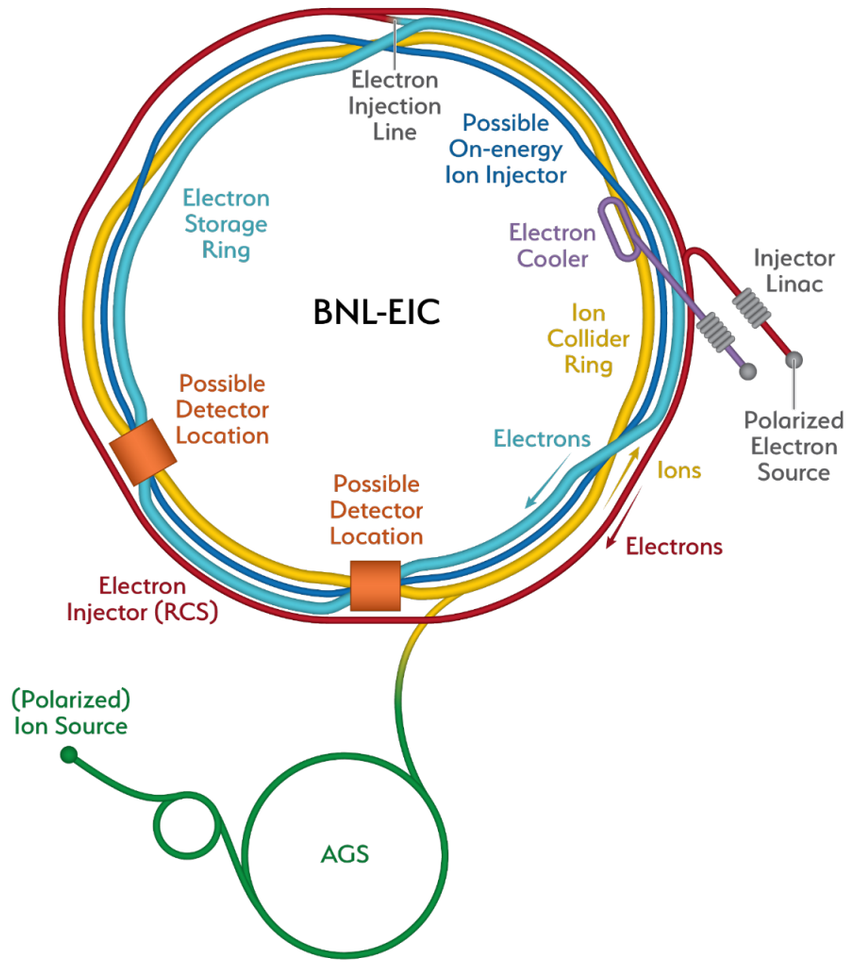
Thia Keppel
Plenary Sat @ 4:35



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

$$\mathscr{L}_{ep} = 10^{35} - 10^{37}\ cm^{-2}s^{-1}$$

Electron Ion Collider (EIC)



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

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

Photoproduction of XYZ states

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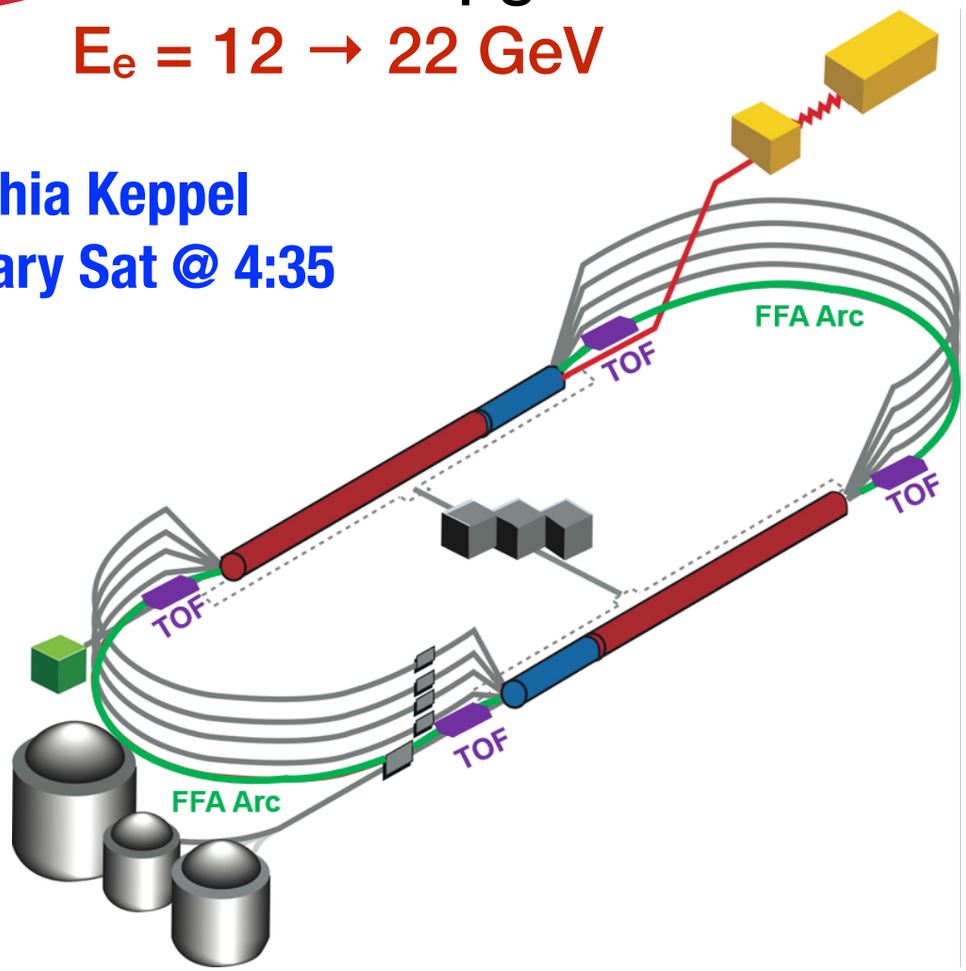
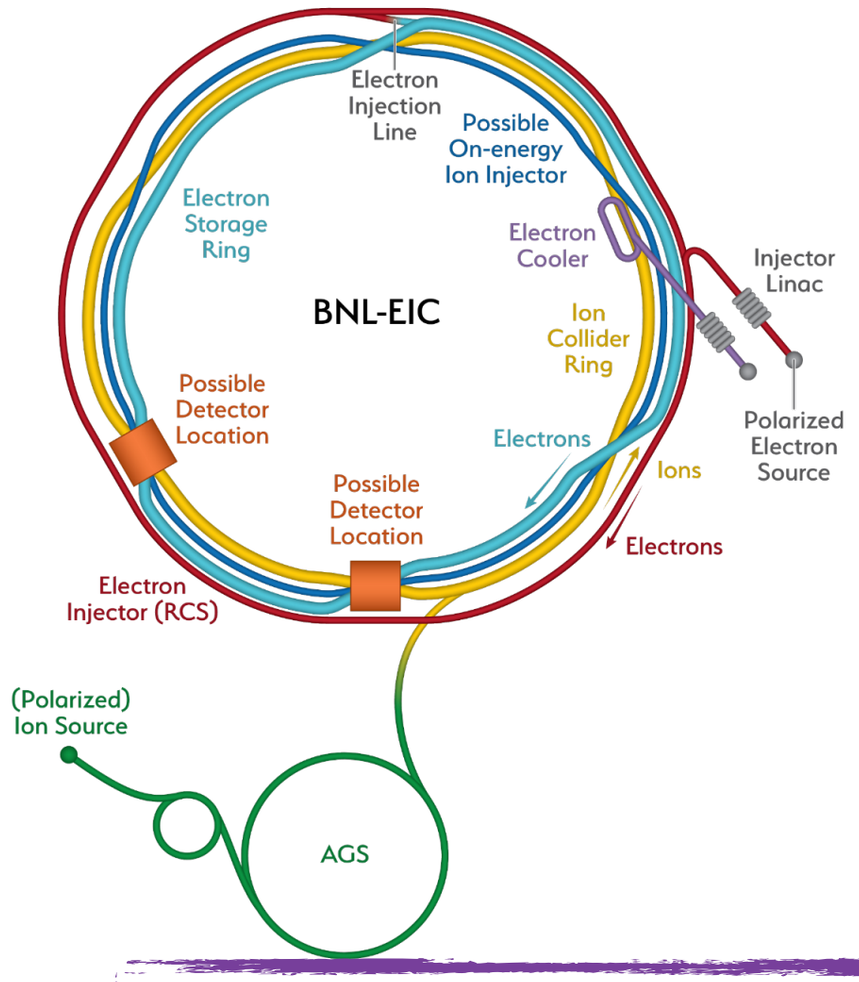
Thia Keppel
Plenary Sat @ 4:35



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

$$\mathscr{L}_{ep} = 10^{35} - 10^{37}\ cm^{-2}s^{-1}$$

Electron Ion Collider (EIC)



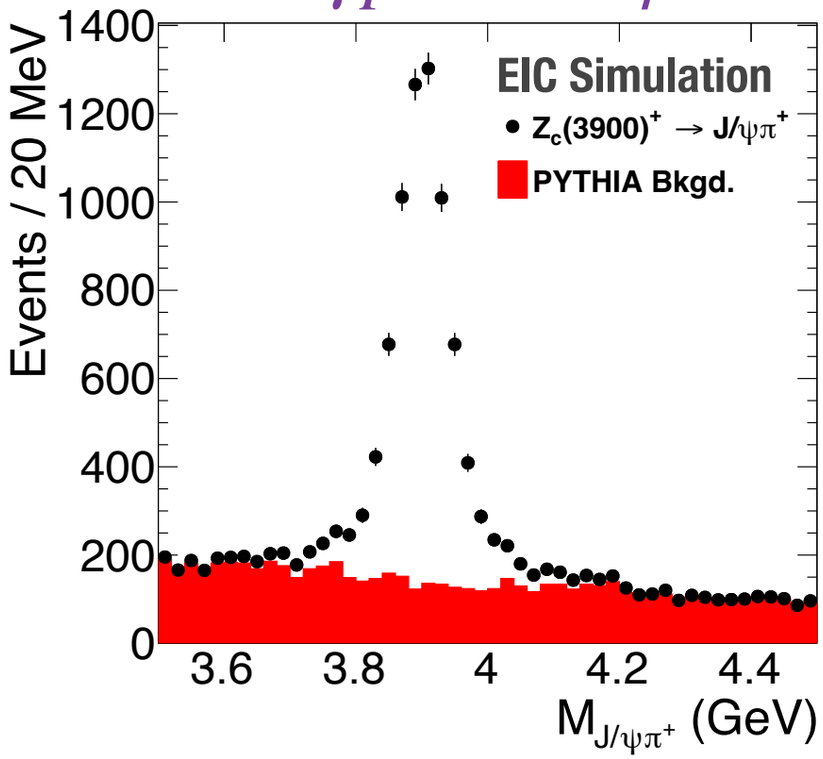
$$\sqrt{s_{\gamma p}} = 5 - 141 \text{ GeV}$$

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

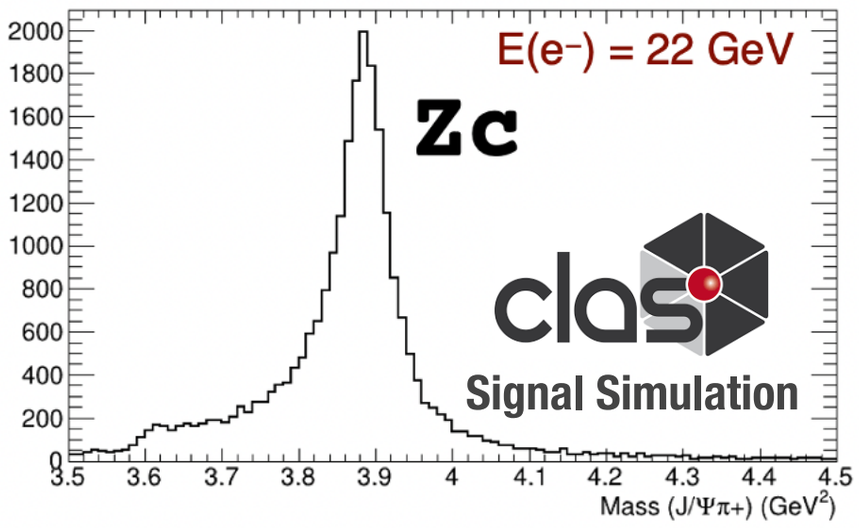
Photoproduction of $Z_c^+(3900)$

Future

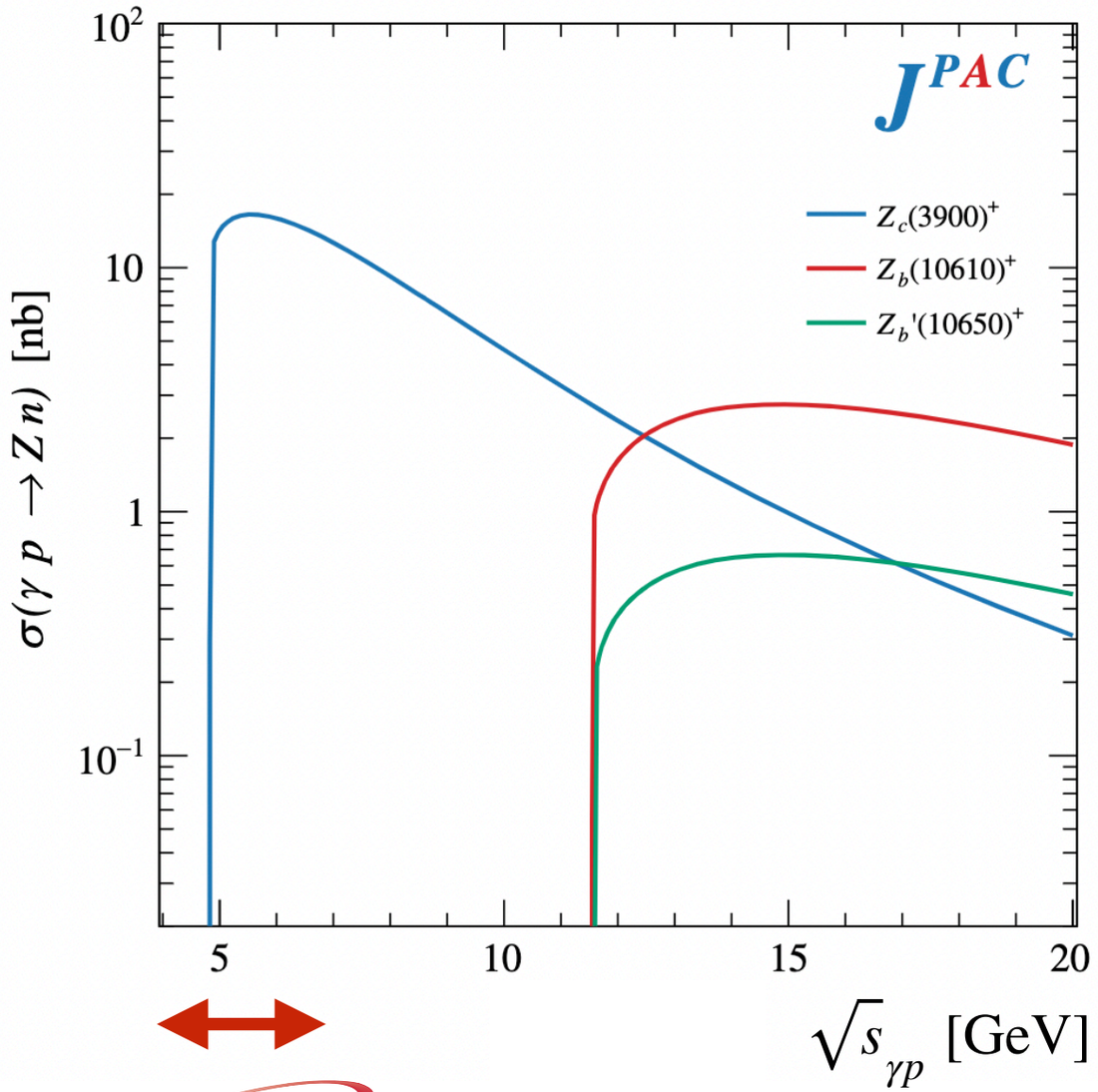
EIC: $\gamma p \to n J/\psi \pi^+$



JLab 22 GeV: $\gamma p \to n J/\psi \pi^+$



EIC broad energy coverage



Jefferson Lab 22 GeV

High luminosity near-threshold

Summary and Outlook

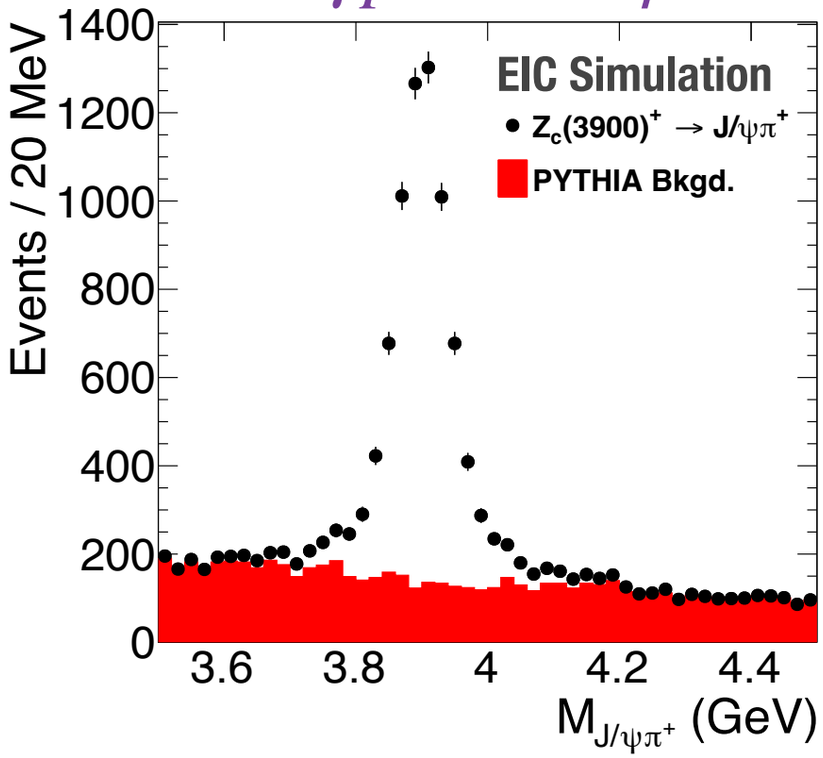
- New era of precision spectroscopy measurements from light and heavy quark sectors from traditionally HEP and NP experiments
- Critical collaboration with theory
  - Phenomenological framework with rigorously defined amplitudes for fitting and interpreting data
  - Direct connection to fundamental theory through lattice QCD
- Photoproduction provides a common production mechanism for hybrid mesons and exotic charmonium
  - GlueX and CLAS12 now have unprecedented datasets to study light quark mesons and baryons
  - JLab 22 GeV upgrade and EIC provide a unique production mechanism for heavy quark exotics

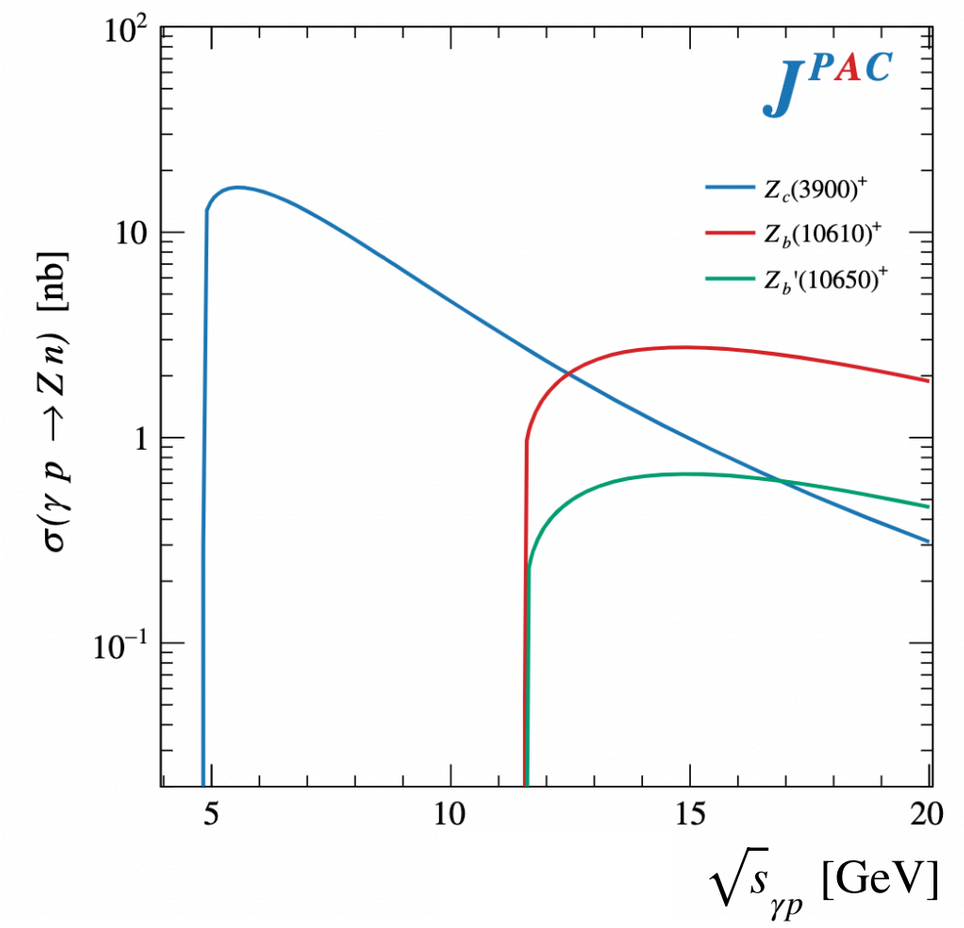
Backup

Photoproduction of $Z_c^+(3900)$

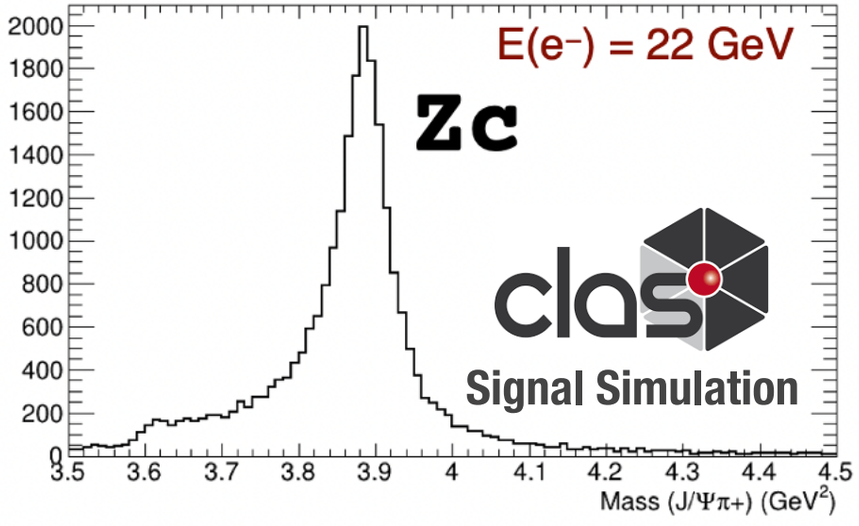
Future

EIC: $\gamma p \to n J/\psi \pi^+$

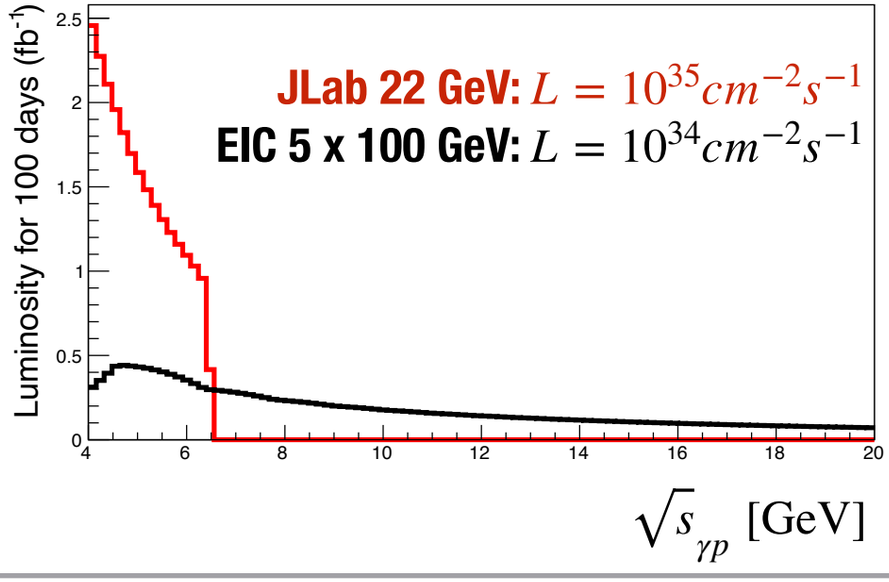




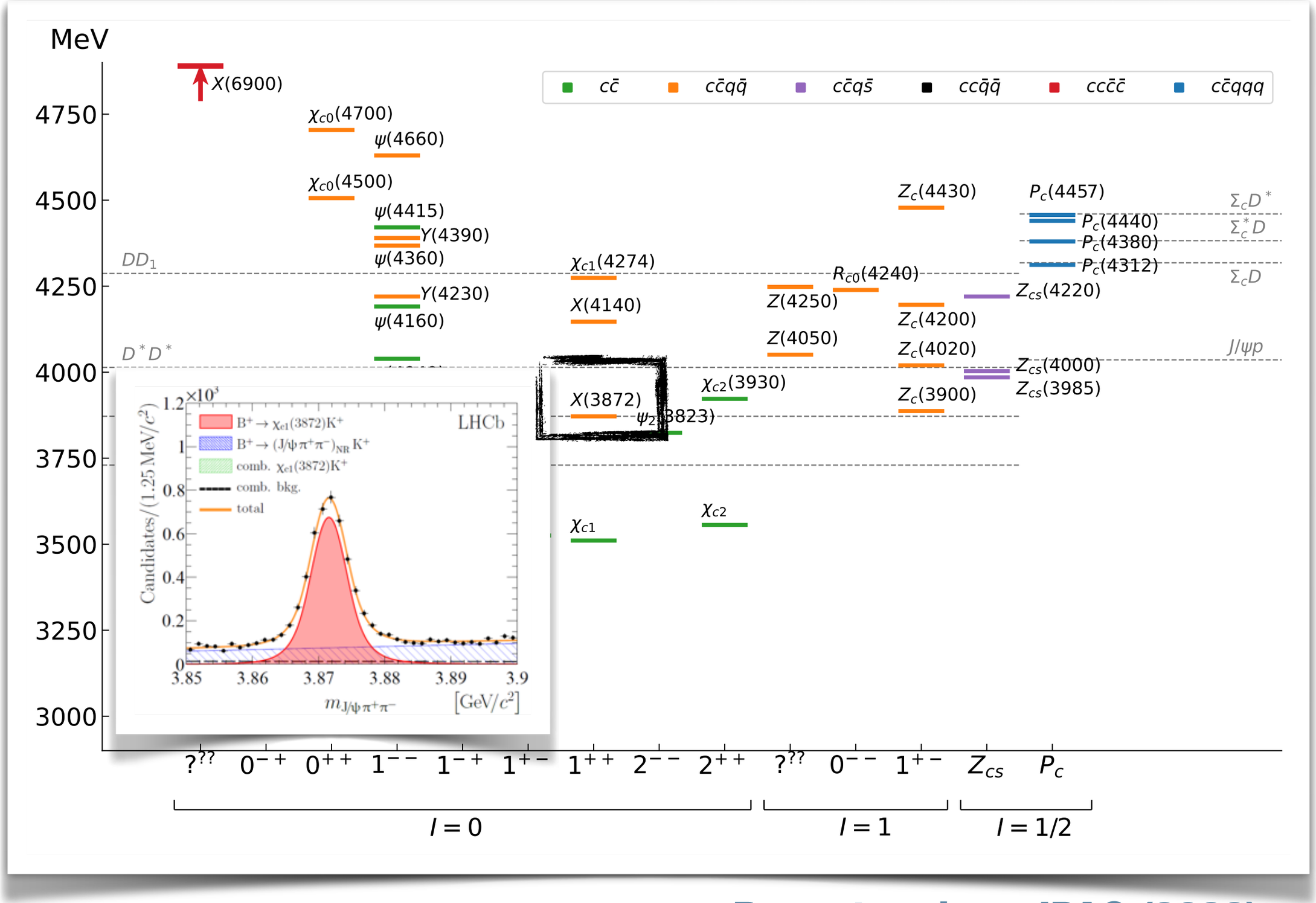
JLab 22 GeV: $\gamma p \to n J/\psi \pi^+$



Photoproduction luminosity



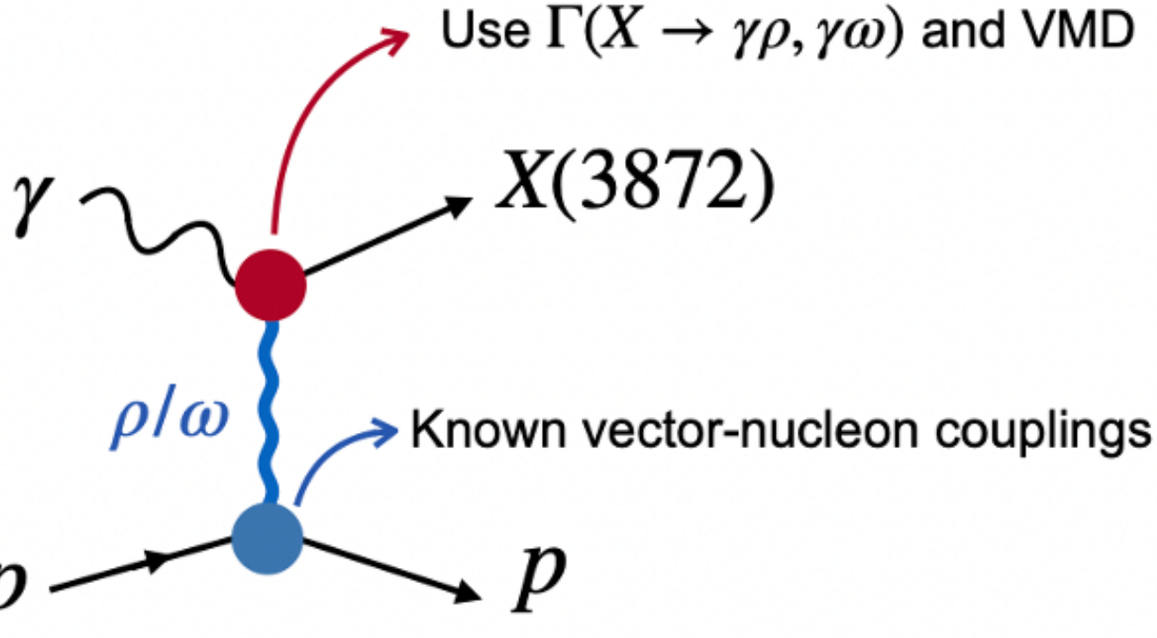
XYZ reminder: $X(3872)$ or $\chi_{c1}(3872)$

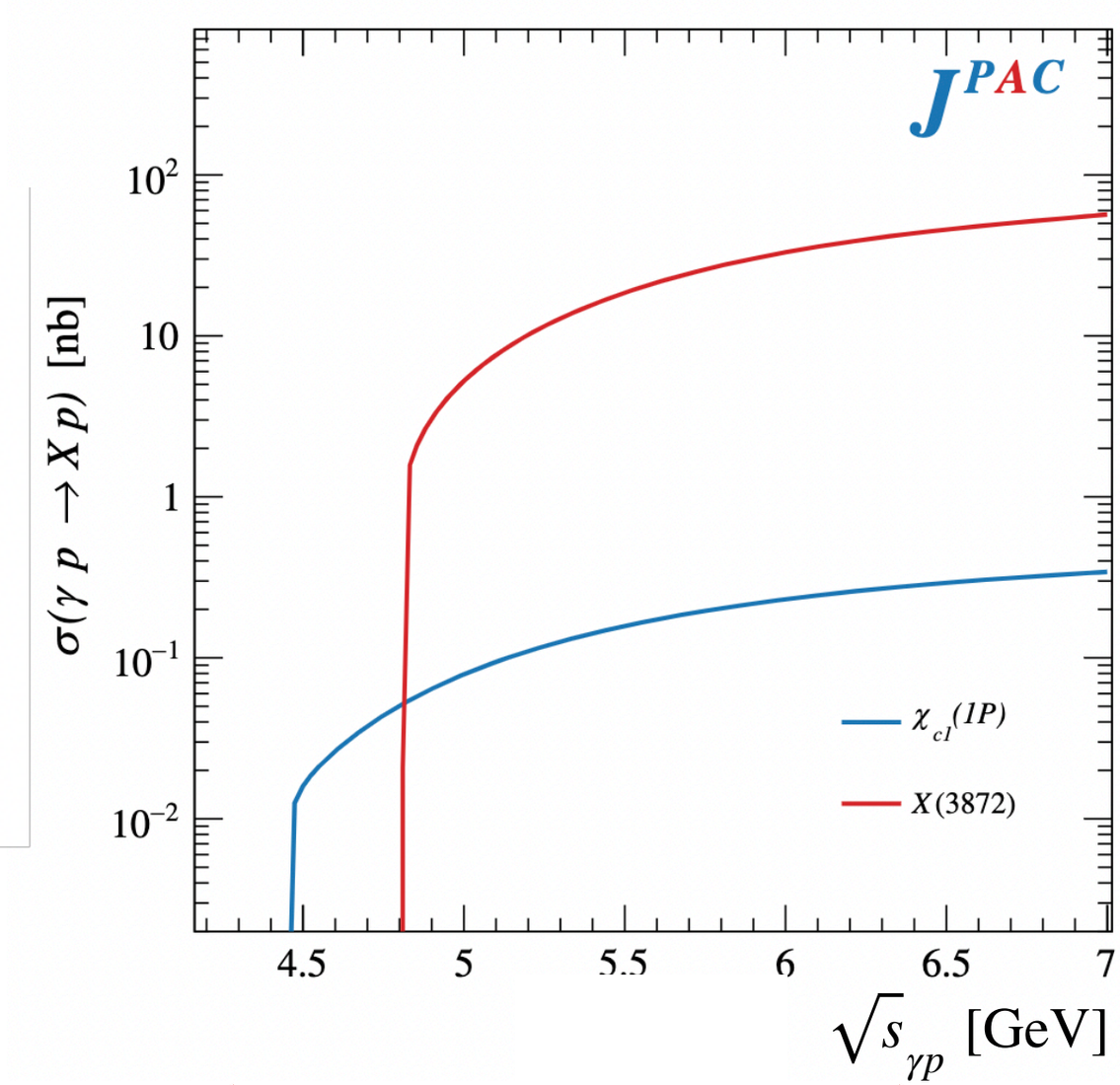


Recent review: JPAC (2022)

Photoproduction of $X(3872)$

JPAC: PRD 102, 114010 (2020)



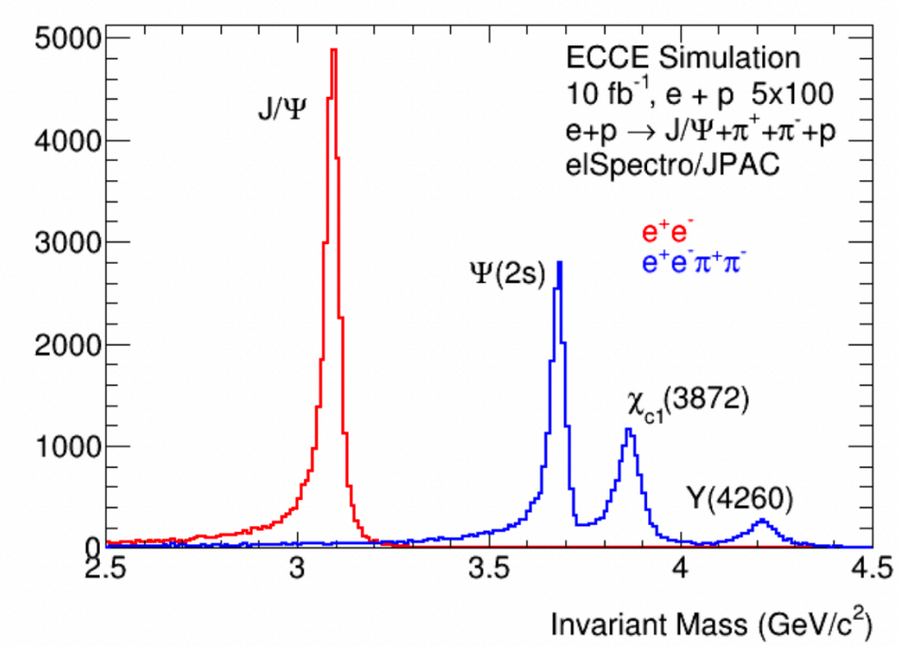


- Alternative production mechanism: free of rescattering effects and sensitive to photo couplings

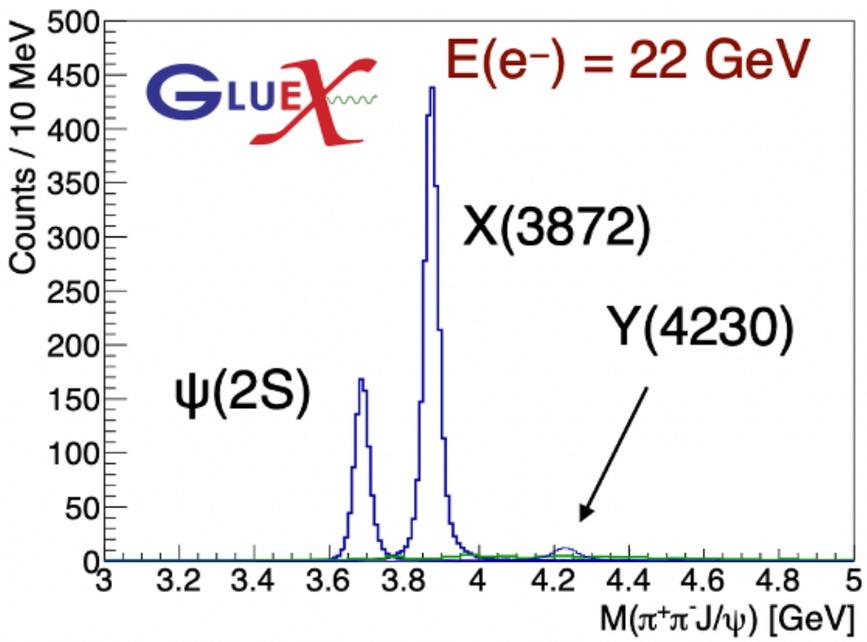
Jefferson Lab 22 GeV

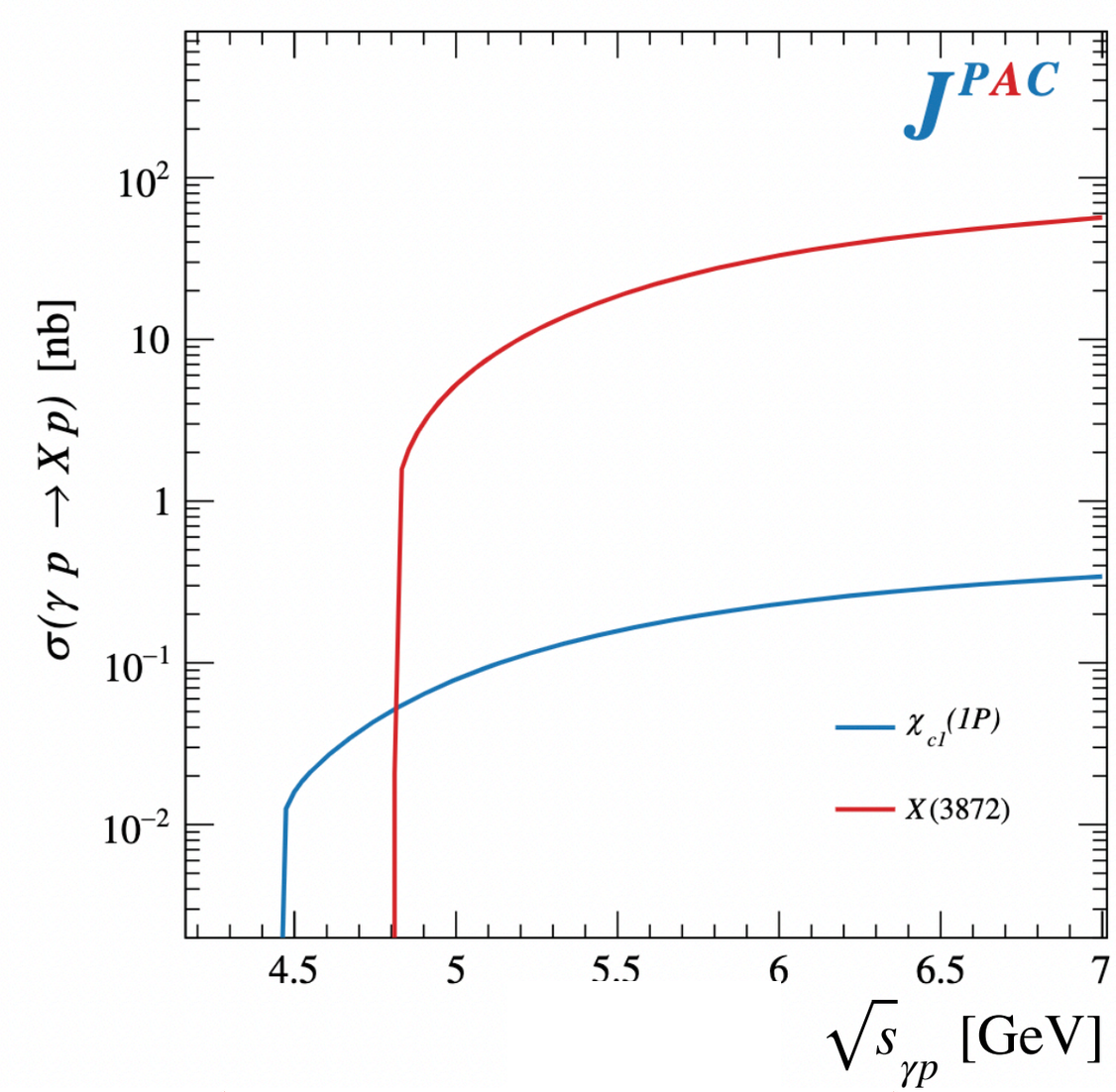
Photoproduction of $X(3872)$

EIC: $\gamma p \to pJ/\psi\pi^+\pi^-$



JLab 22 GeV: $\gamma p \to pJ/\psi\pi^+\pi^-$

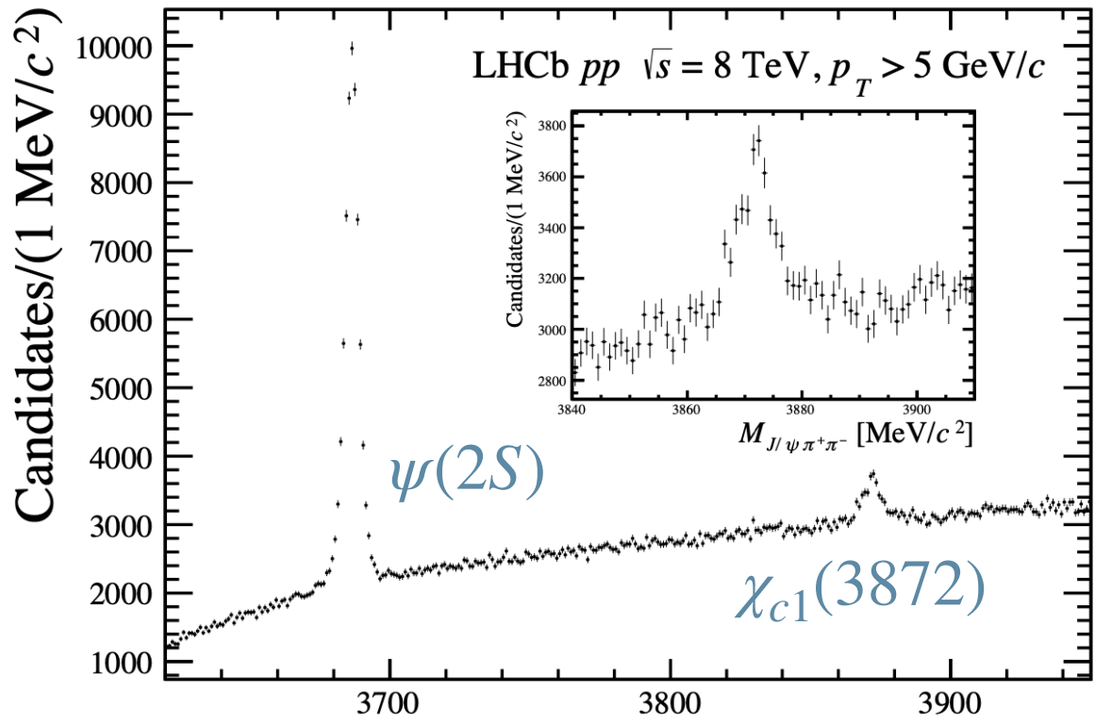




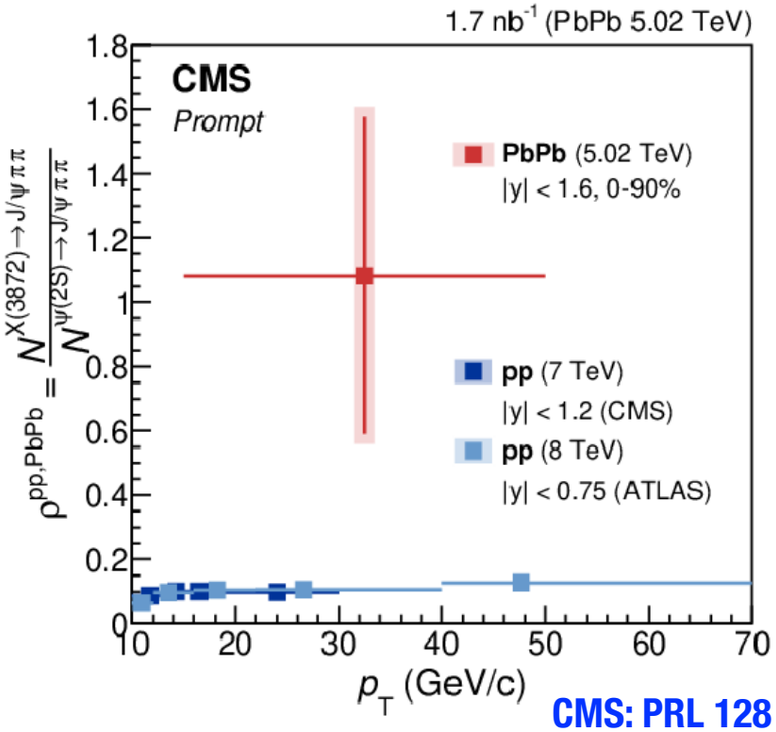
Jefferson Lab 22 GeV

In-medium effects for spectroscopy

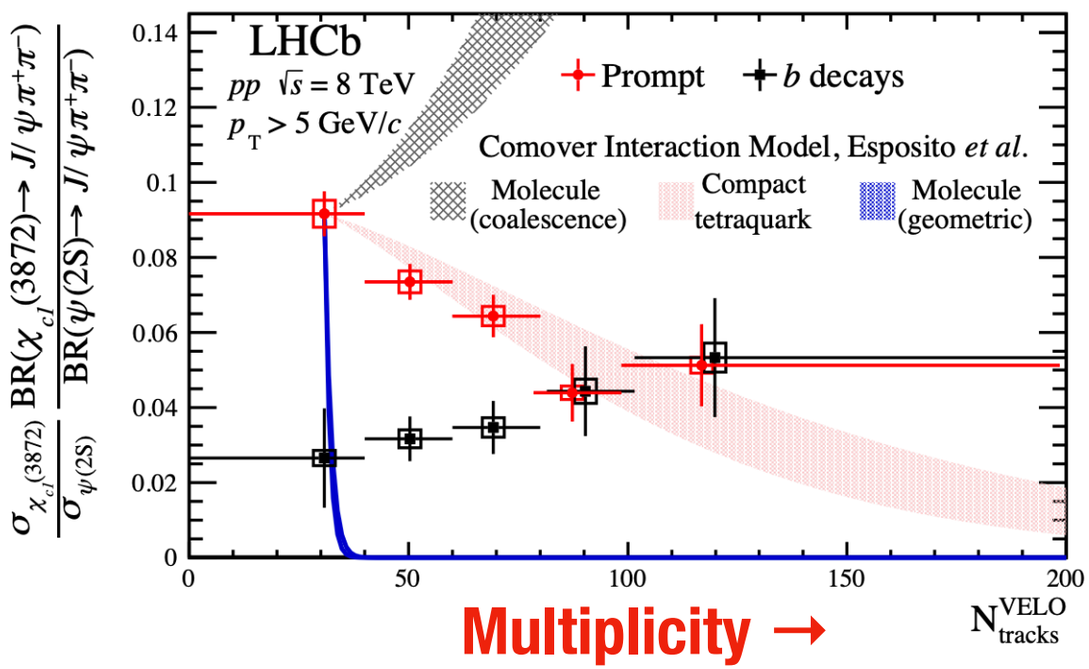
- Recent LHCb results in pp show prompt $\chi_{c1}(3872)$ decreases with multiplicity
- First observation of prompt $\chi_{c1}(3872)$ in PbPb at CMS not suppressed relative to $\psi(2S)$



LHCb: PRL 126 (2021) 9, 092001

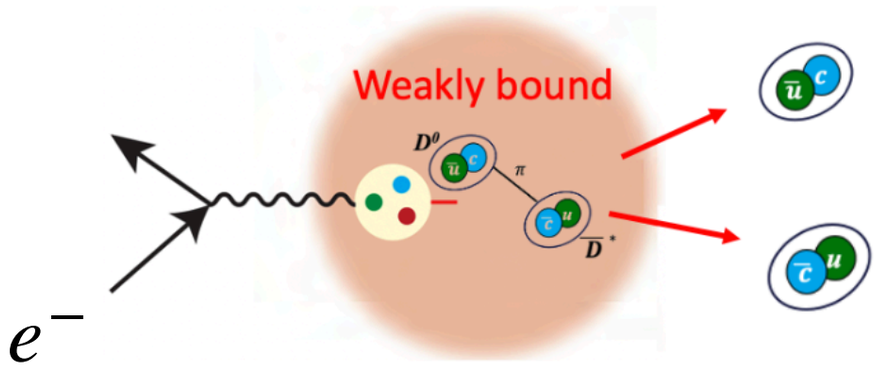


CMS: PRL 128 (2022) 3, 032001

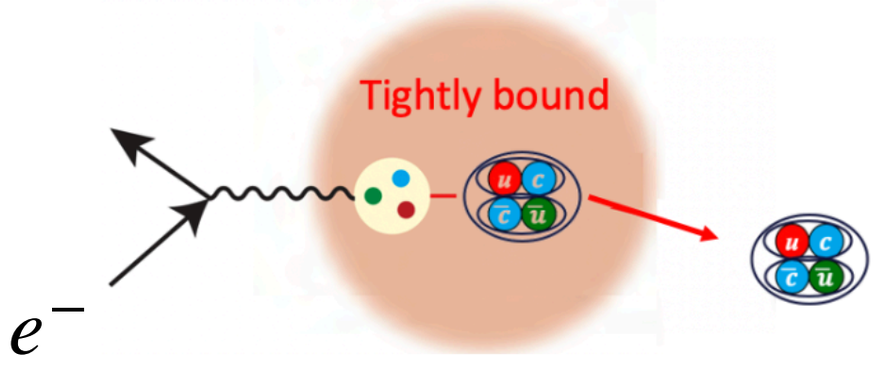


Multiplicity →

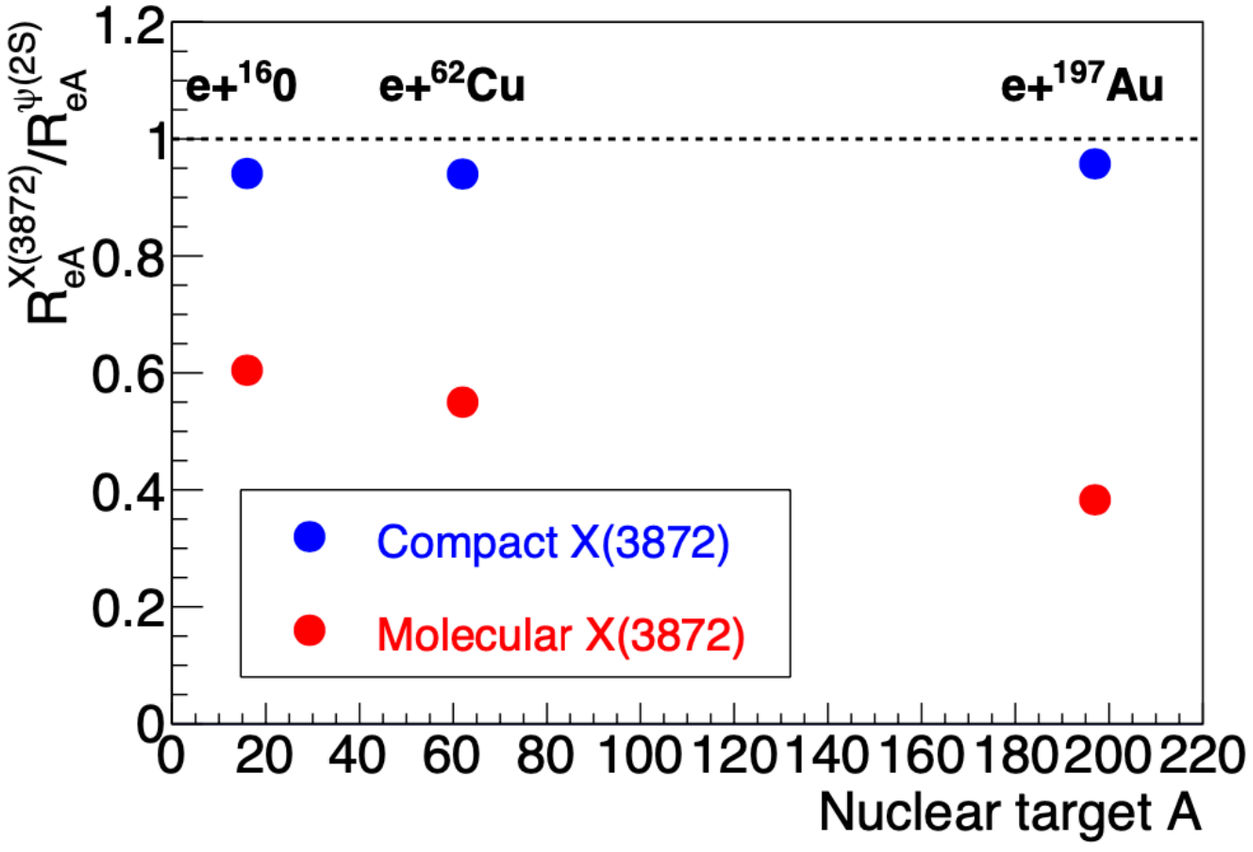
In-medium effects for spectroscopy



Nucleus: A



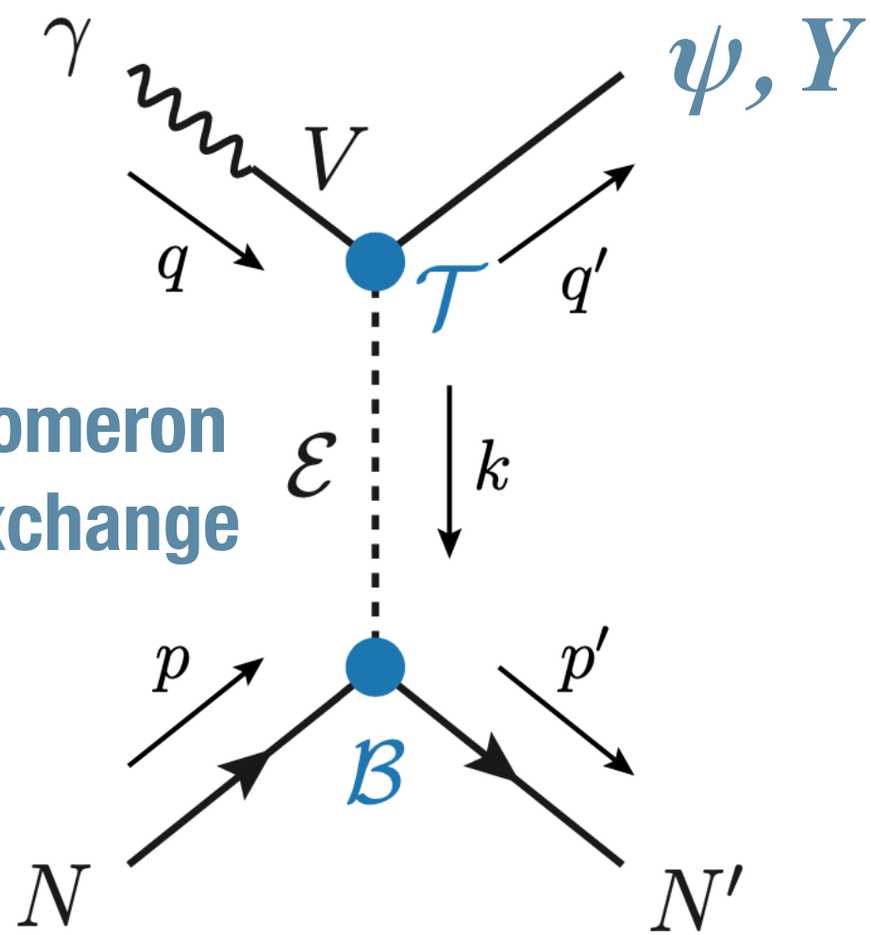
Nucleus: A

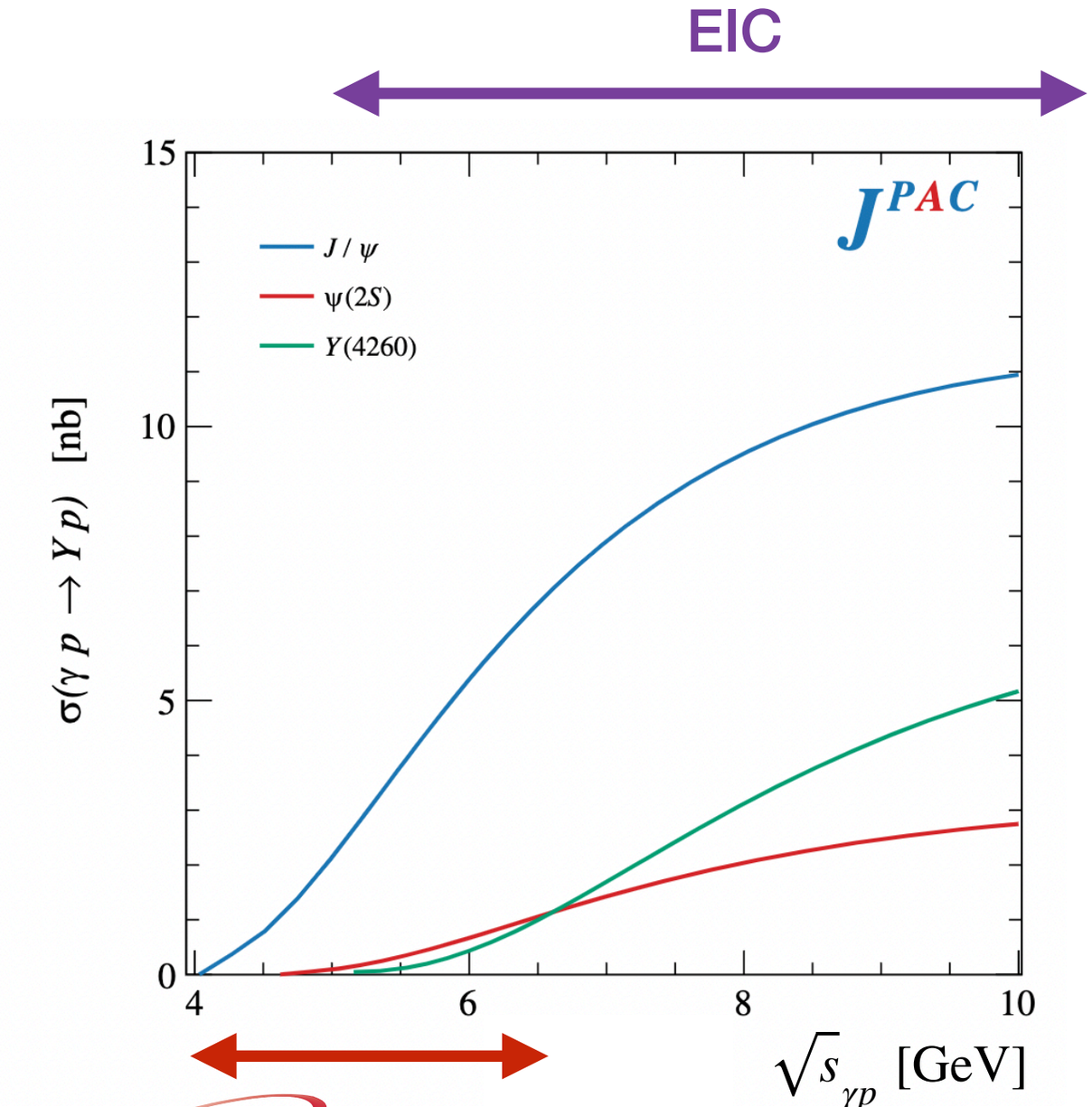


- Dependence on breakup of X(3872) in nuclei?
- Little suppression expected for compact tetraquark configuration
- Expect suppression of molecular (large size) configuration

Photoproduction of XYZ states

JPAC: PRD 102, 114010 (2020)

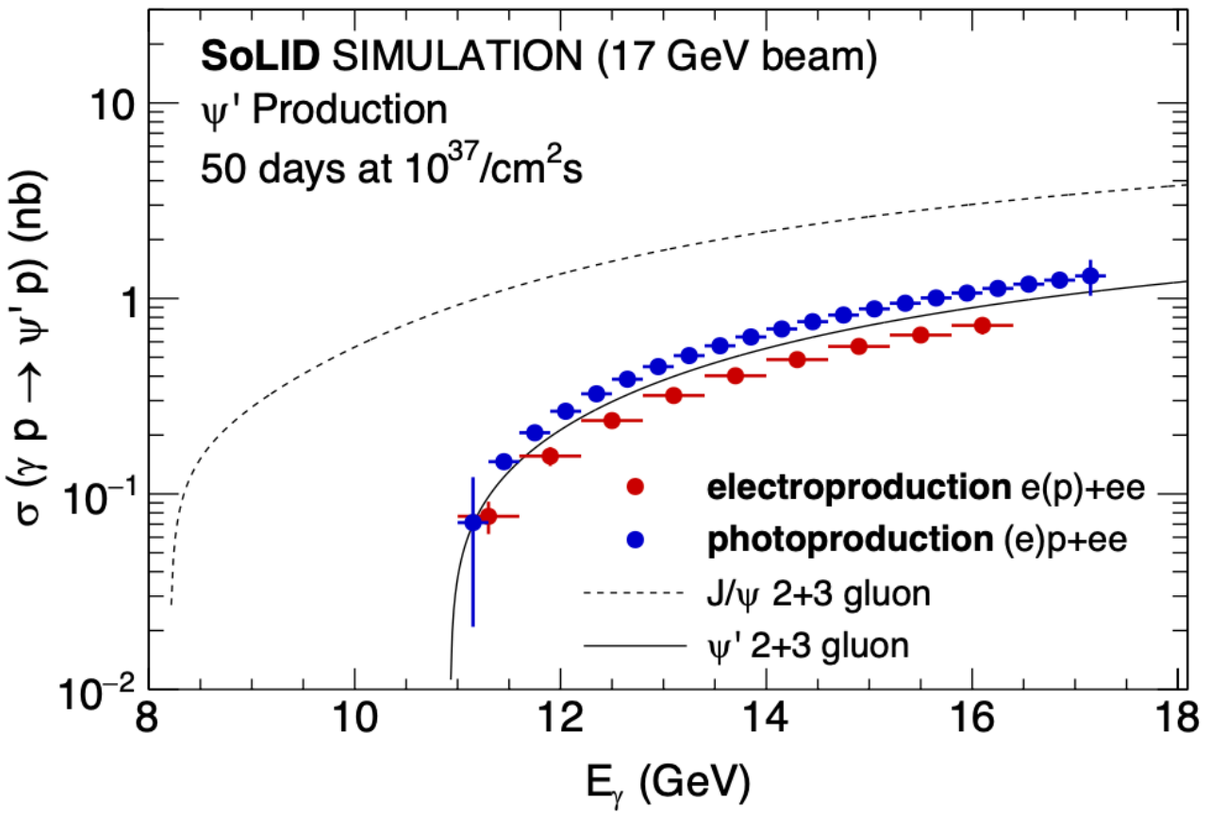




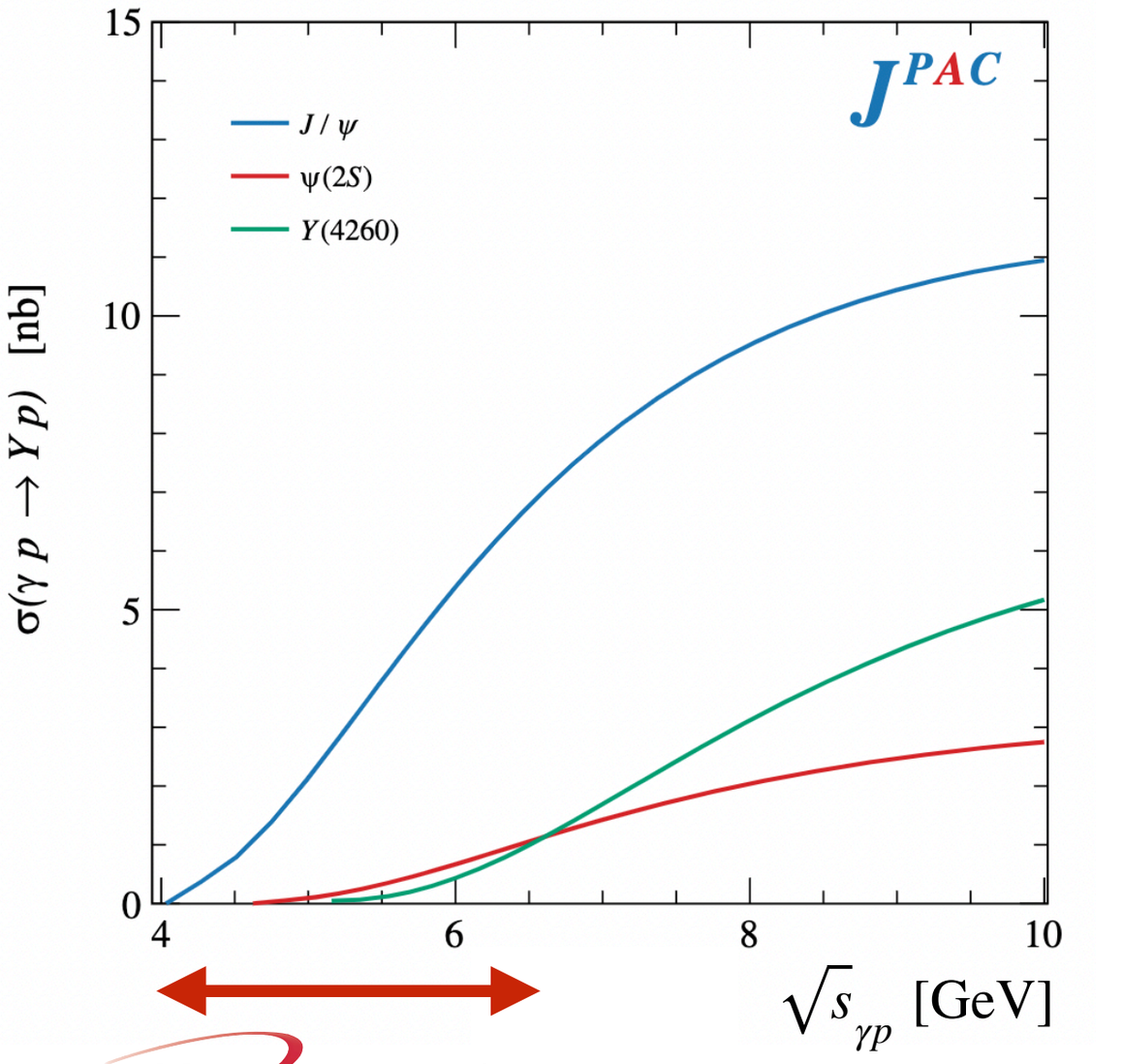
Y(4260) production increases with energy like other vectors, ideal for higher energies accessible at EIC

Photoproduction of $\psi(2S)$

SoLID example at 17 GeV



EIC



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

Jefferson Lab 22 GeV