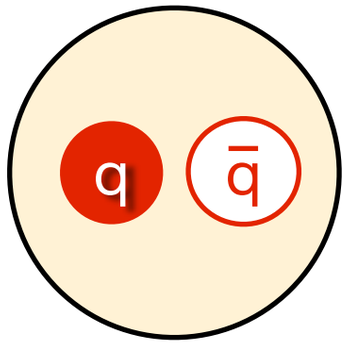
Meson spectroscopy through photoproduction: from Jefferson Lab to the EIC

Justin Stevens

WILLIAM & MARY
CHARTERED 1693

Meson spectroscopy: "bump hunting"

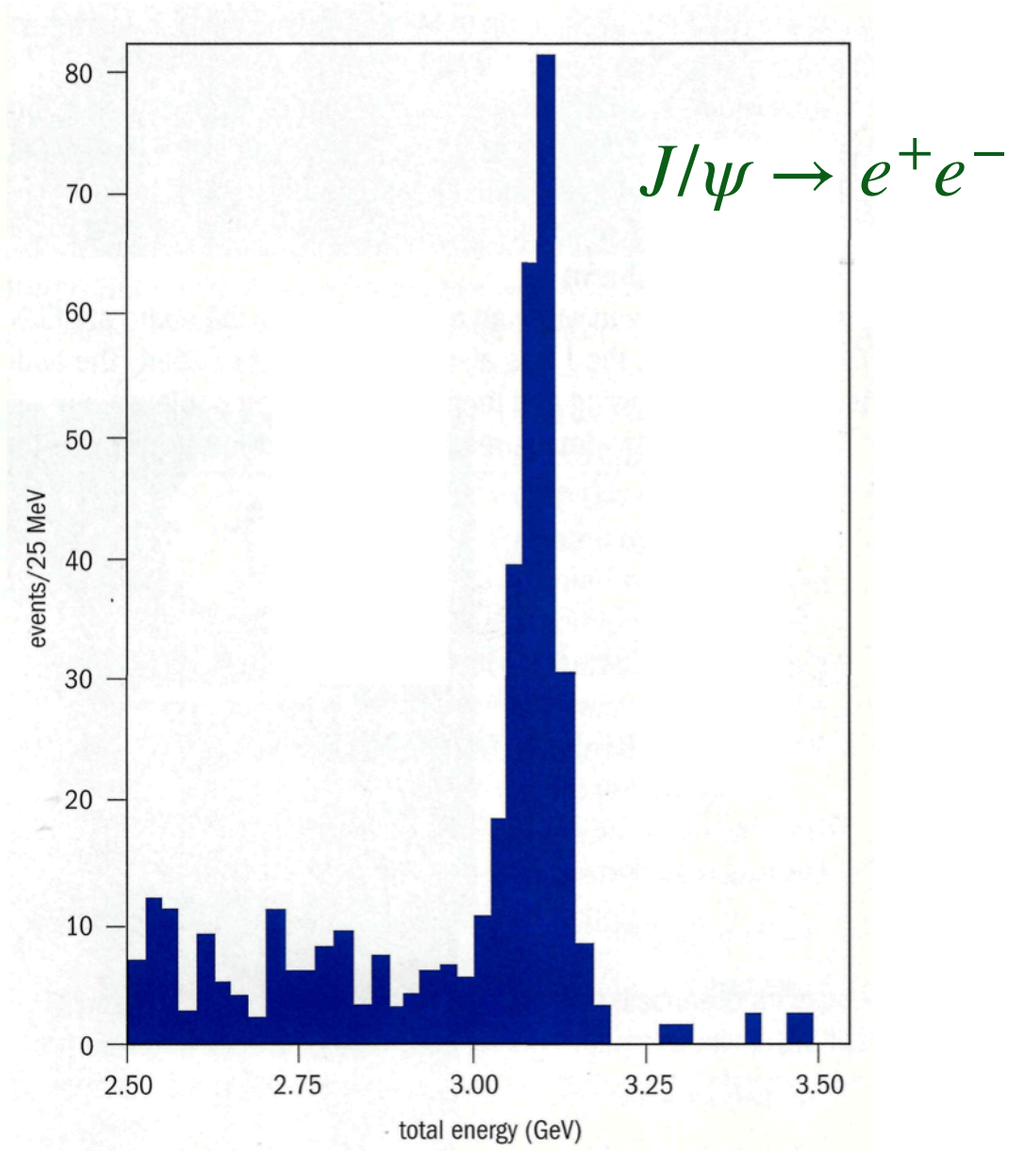


mesons

Historically search through "bump hunting"

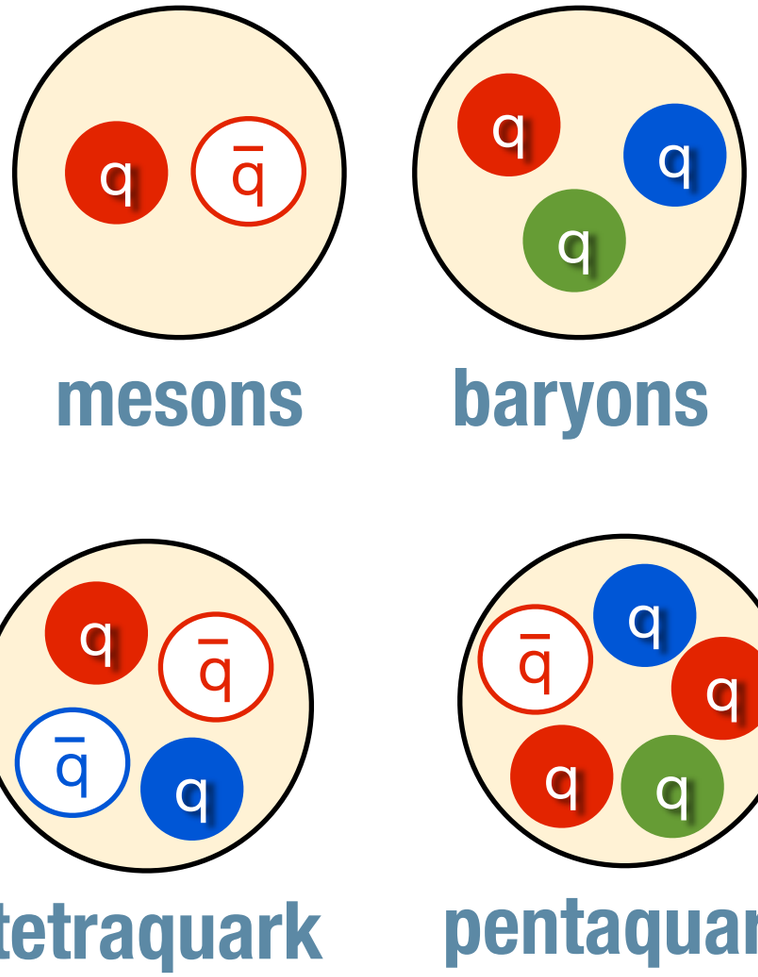
November Revolution (1974)

$$pBe \to e^+e^-X$$



Invariant Mass

Confined states of quarks and gluons



Observed mesons and baryons well described by 1st principles QCD

But these aren't the only states permitted by QCD

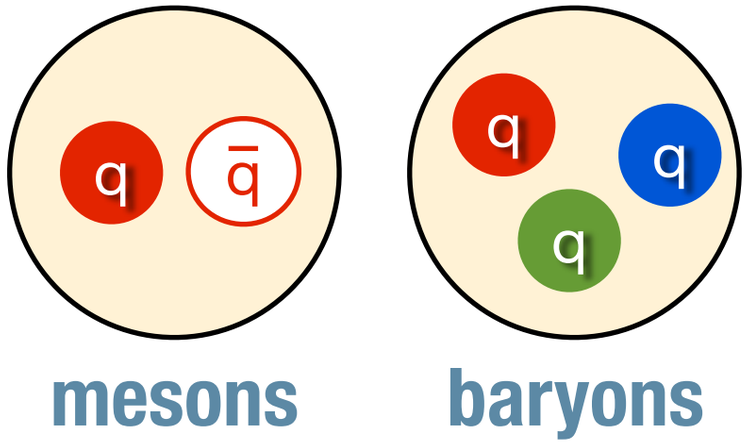
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

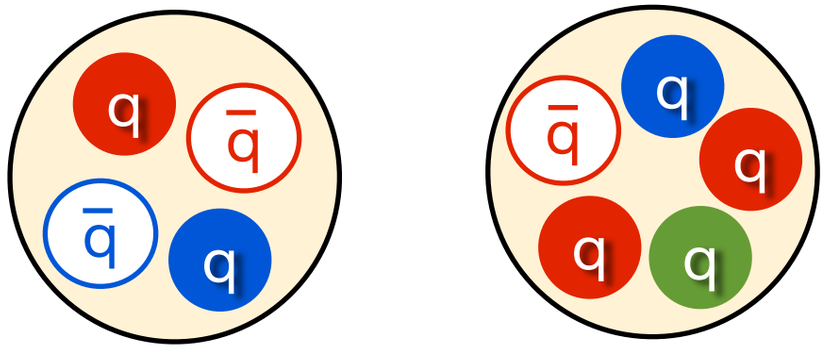
... Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. ...

Phys. Lett. 8 (1964) 214

Confined states of quarks and gluons



mesons baryons

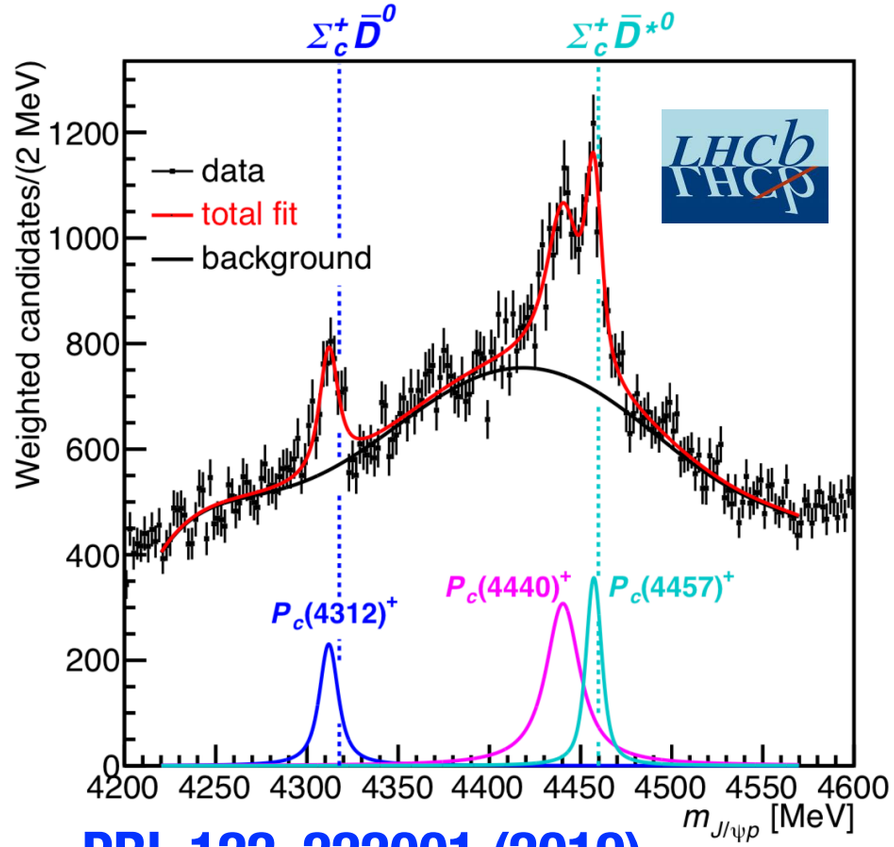


tetraquark pentaquark

Observed mesons and baryons well described by 1st principles QCD

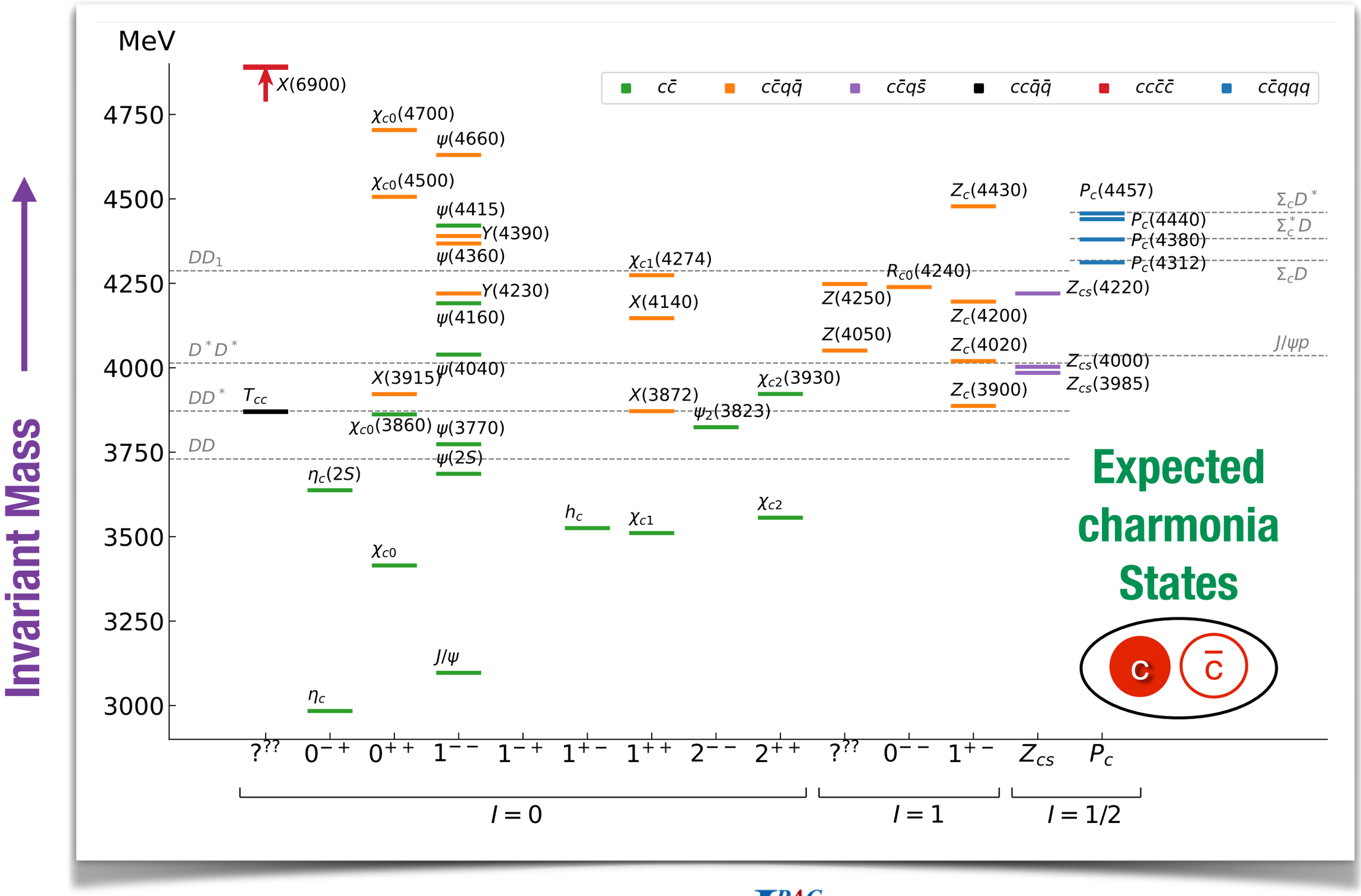
But these aren't the only states permitted by QCD

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



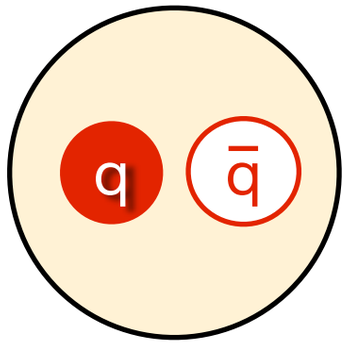
PRL 122, 222001 (2019)

Recent discoveries in charm sector "$XYZP_c$"

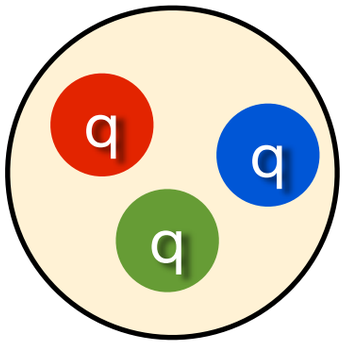


Recent review: JPAC **Prog. Part. Nucl. Phys. 127 (2022) 103981**

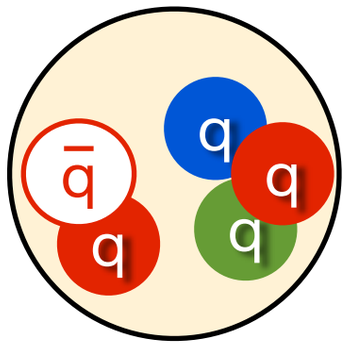
Open questions in exotic spectroscopy



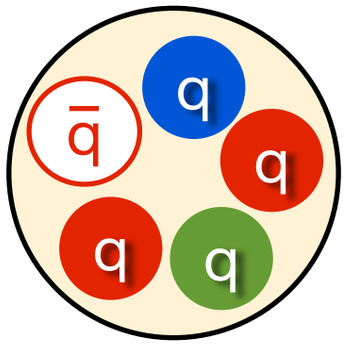
mesons



baryons



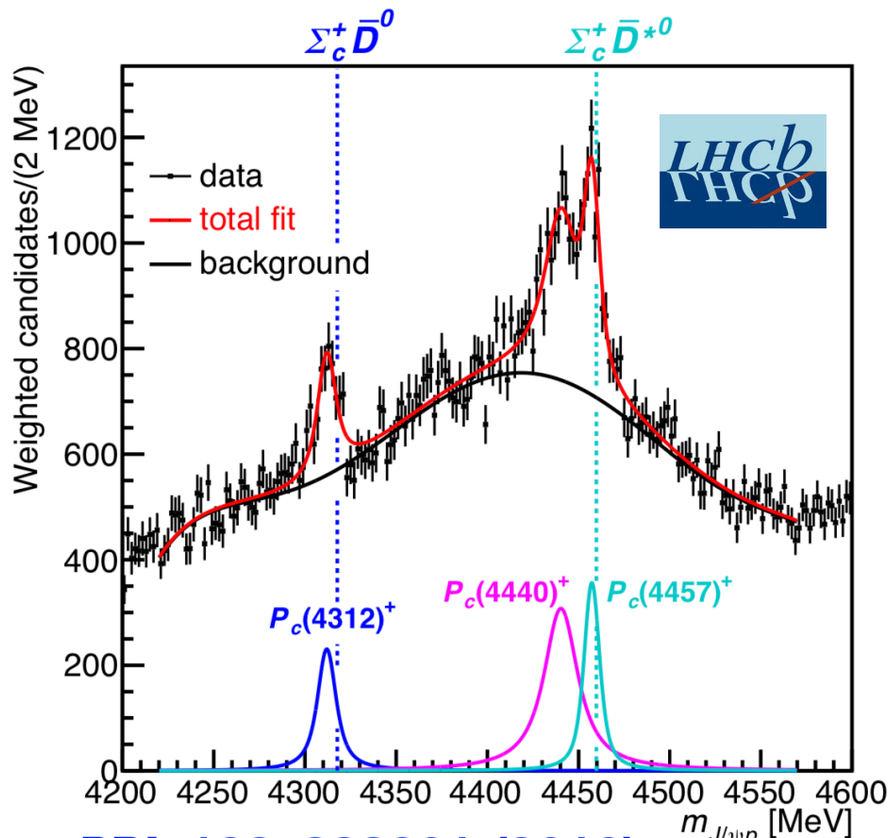
molecules



pentaquark

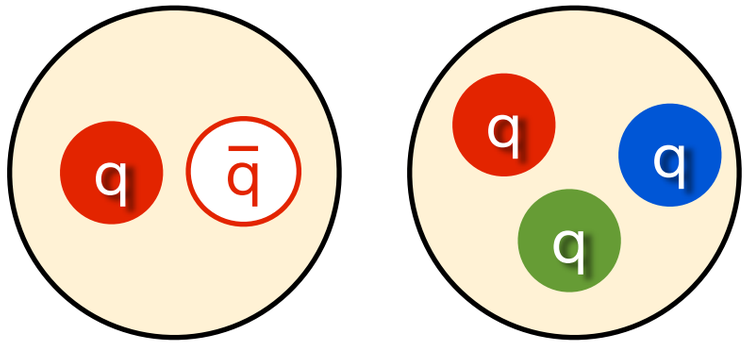
What is the nature/structure of the exotic candidates we've observed?

- **Less exotic:** hadronic molecules, final-state rescattering, etc.
- **More exotic:** tightly bound multi-quark states, etc.

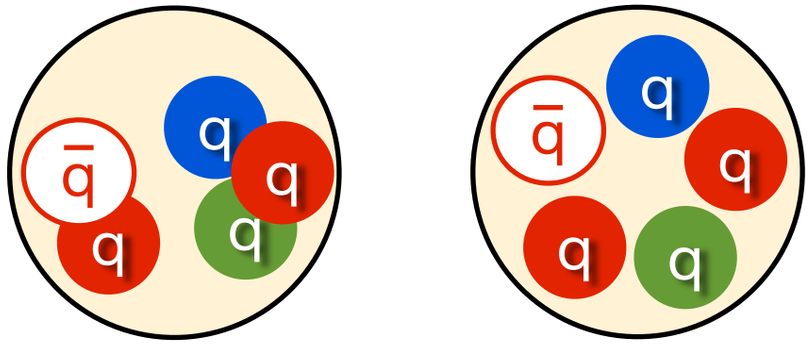


PRL 122, 222001 (2019)

Open questions in exotic spectroscopy



mesons baryons



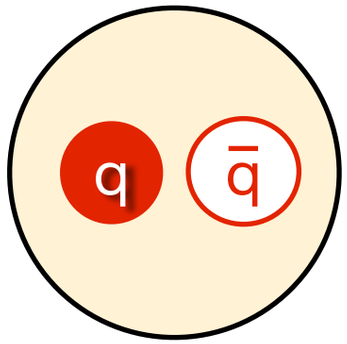
molecules pentaquark

What is the nature/structure of the exotic candidates we've observed?

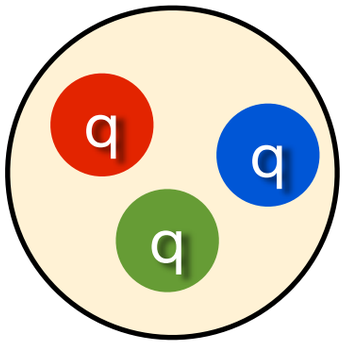
Can we identify alternative production mechanisms to confirm exotic signals and shed light on their nature?

- **Yes,** photoproduction at JLab and EIC

Open questions in exotic spectroscopy



mesons



baryons

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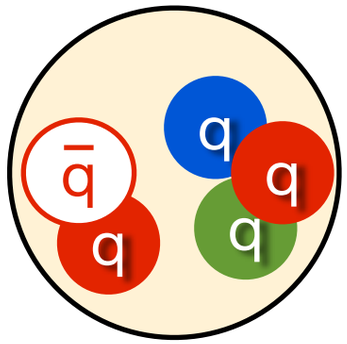
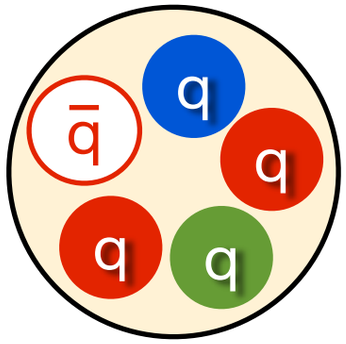


molecules



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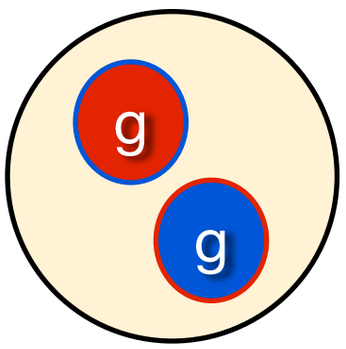
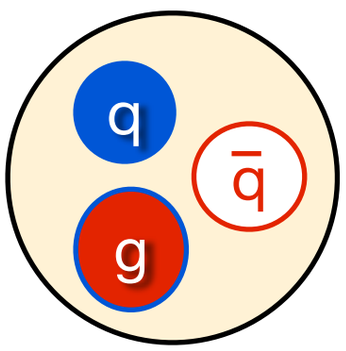


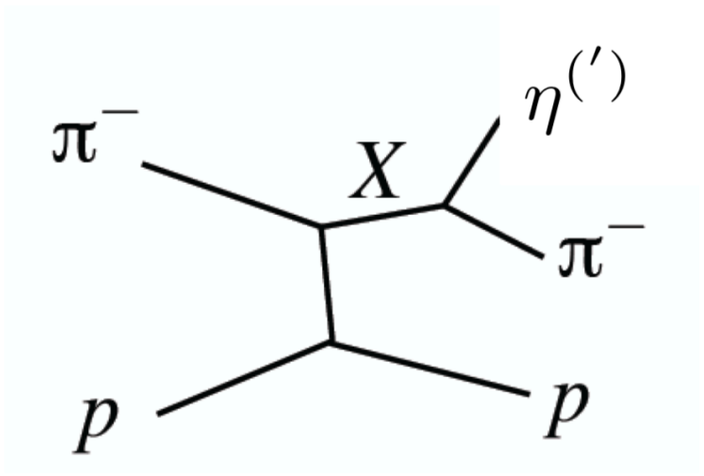
glueball

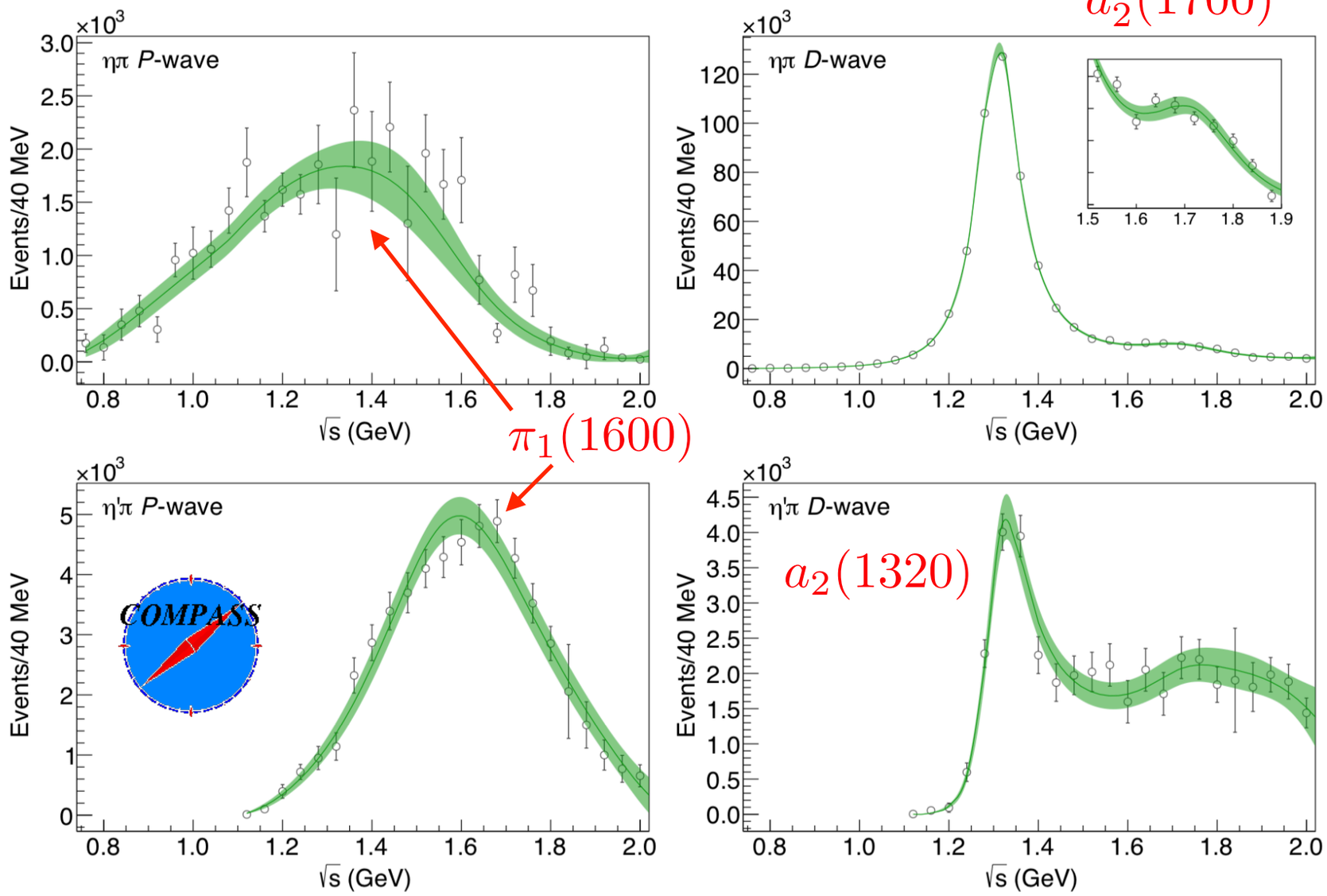


hybrid meson

Do gluonic degrees of freedom manifest themselves in the hadronic states we observe in nature?

Evidence for hybrids: $\eta^{(\prime)}\pi$ spectroscopy





JPAC coupled channel fit to $\eta\pi$ and $\eta'\pi$ determine pole positions for a_2, a_2' and single exotic $\pi_1(1600)$

Alessandro Pilloni
Wed @ 9:00

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

Spectroscopy: a global endeavor

Heavy quarks ⟷ Light quarks

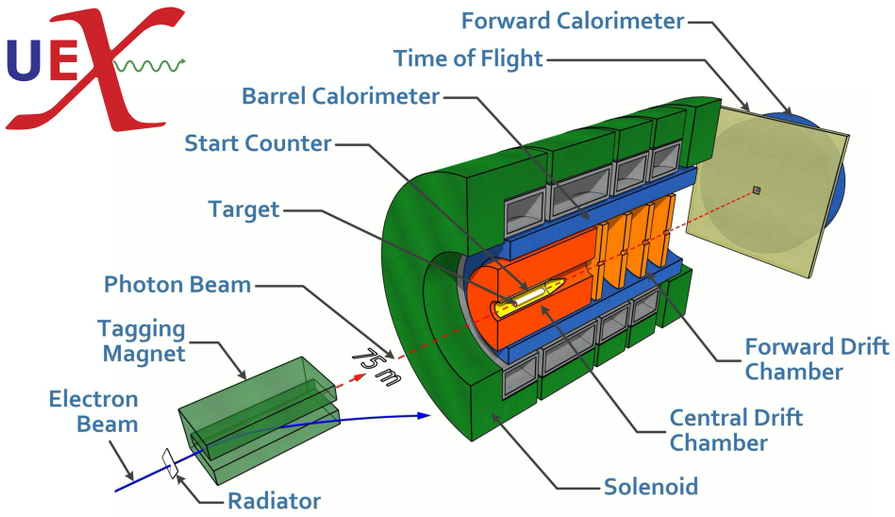
This Talk!

	e^+e^-	$ep/\gamma p$
Electromagnetic probes	BELLE, BESIII, Belle II, BABAR	CLAS (CEBAF Large Acceptance Spectrometer), GlueX, EIC, ePIC **MAMI, ELSA, LEPS, etc.**
Hadronic probes	$\bar{p}p$: D0, CDF pp: CMS, ATLAS, LHCb	$\bar{p}p$: PANDA πp: COMPASS **J-PARC, HADES, etc.**

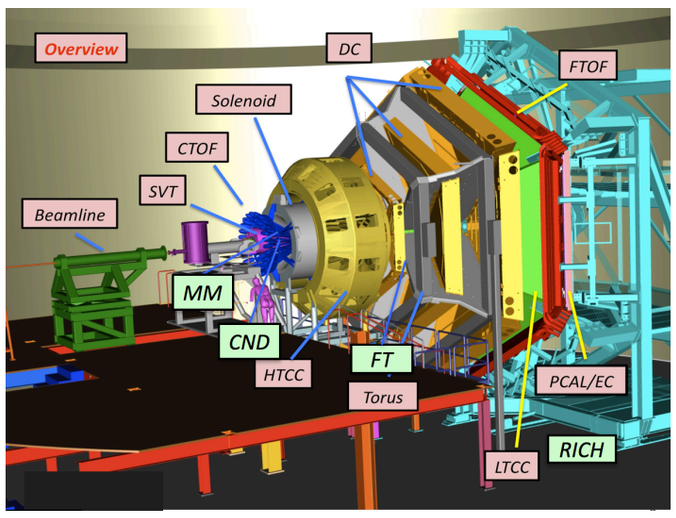
Jefferson Lab

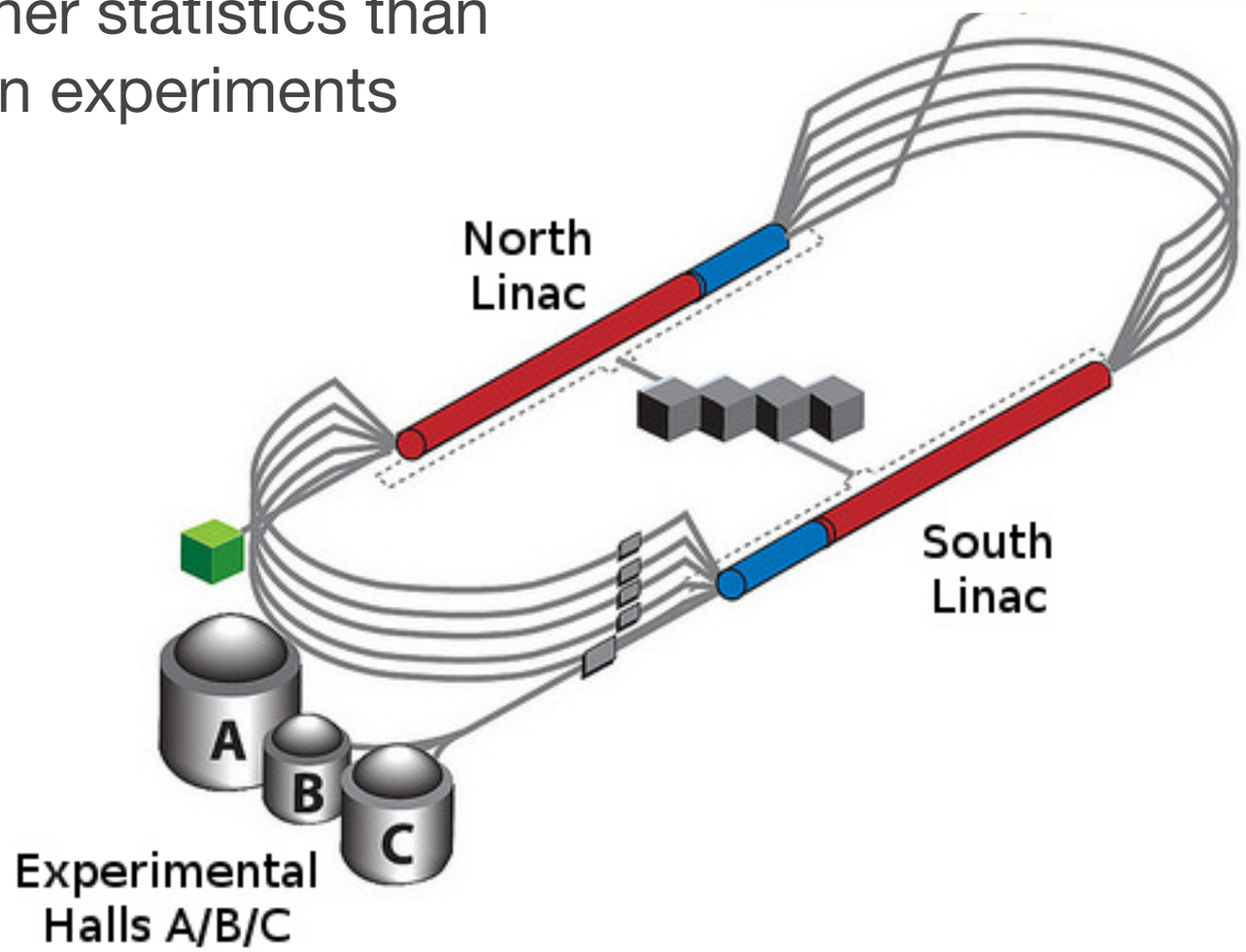
- JLab 12 GeV running since 2017: programs in hadron spectroscopy, nucleon and nuclear structure, etc.
- Photoproduction process provides access to many proposed exotic decay channels
- Orders of magnitude higher statistics than previous photoproduction experiments

GlueX



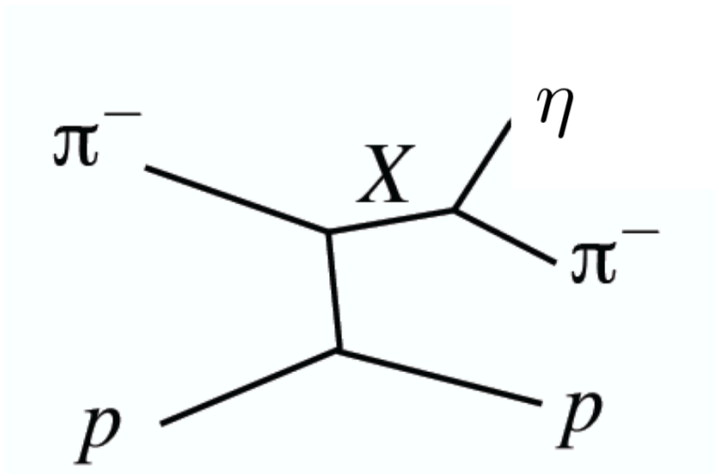
clas
CEBAF Large Acceptance Spectrometer

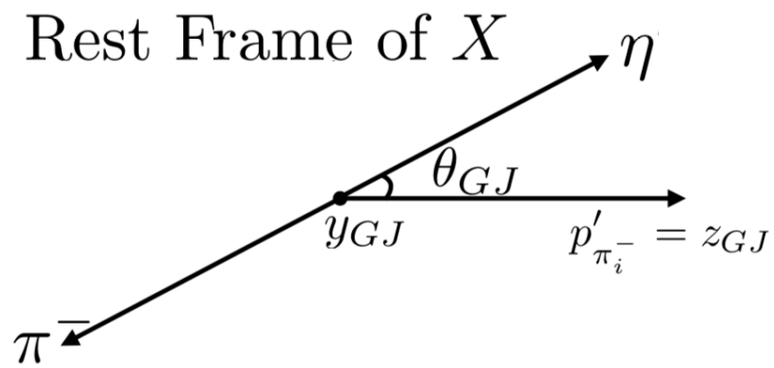


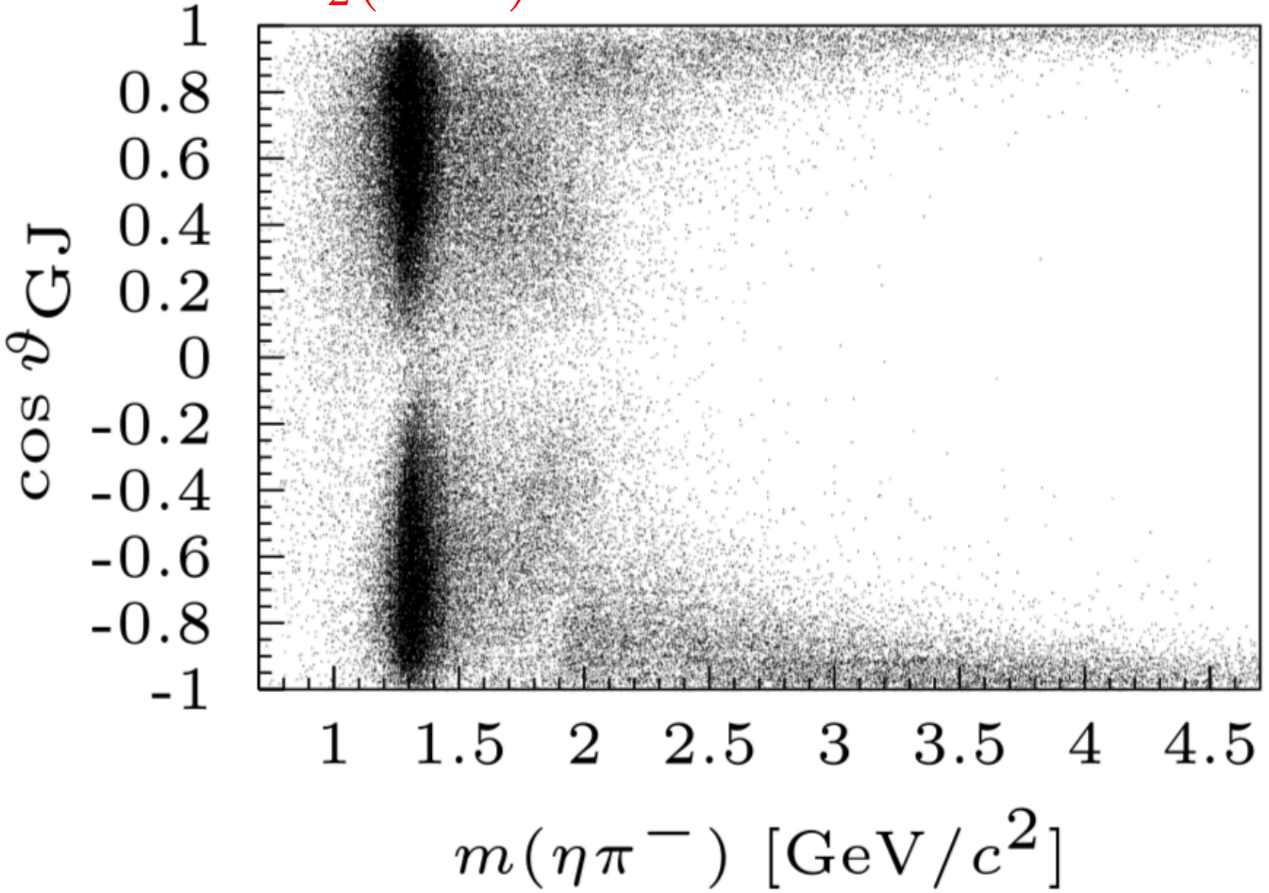


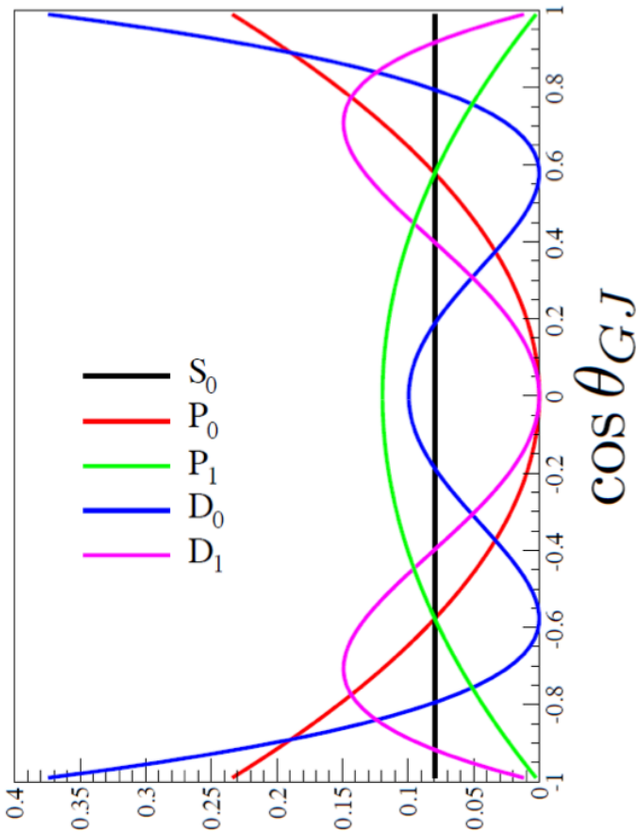
$\eta\pi$ spectroscopy at

- Broad overlapping resonances requires amplitude, described by decay angles θ, ϕ



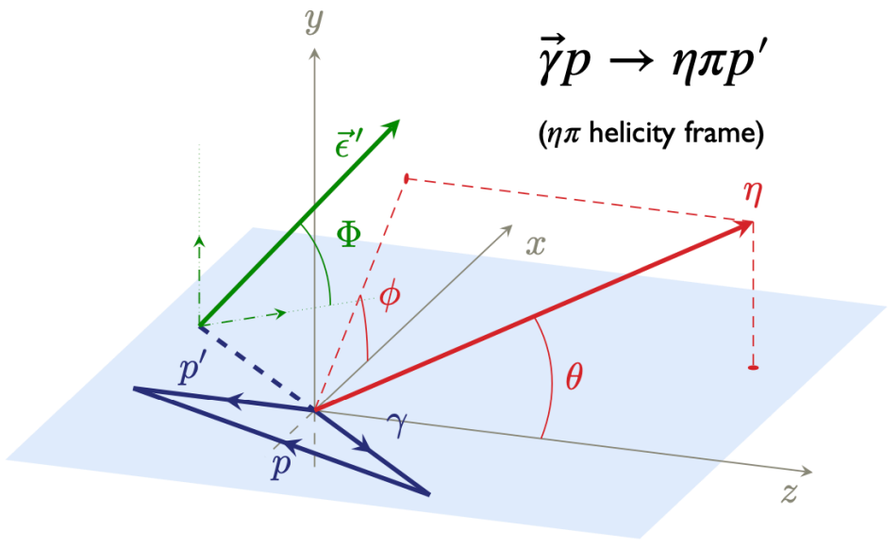


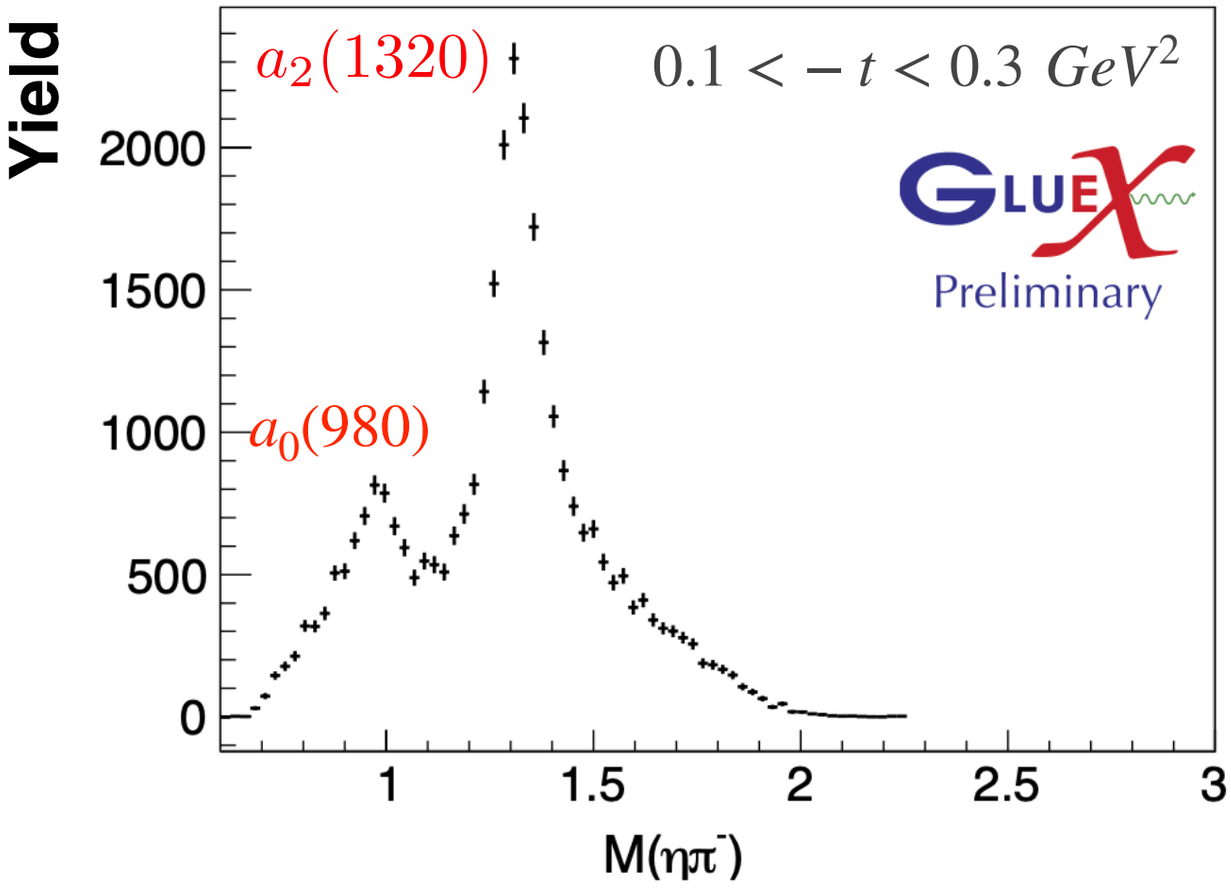


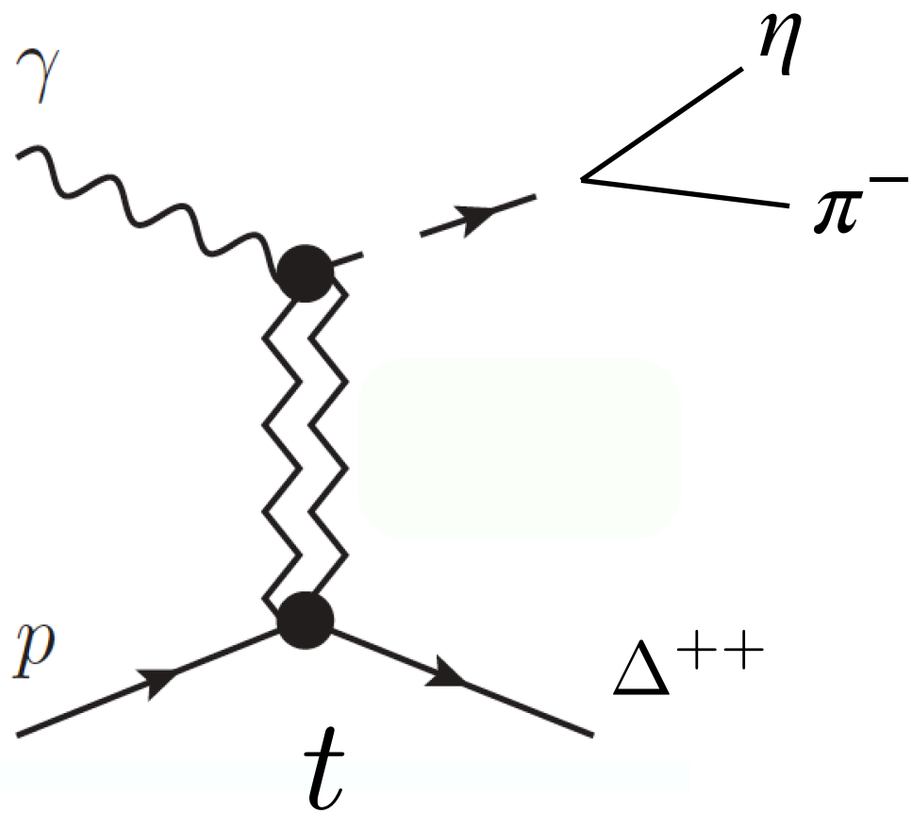


$\eta\pi$ spectroscopy at GlueX

- Broad overlapping resonances requires amplitude, described by decay angles θ, ϕ
- Polarized photon beam provides new information on production mechanism, collaborating with JPAC on amplitudes







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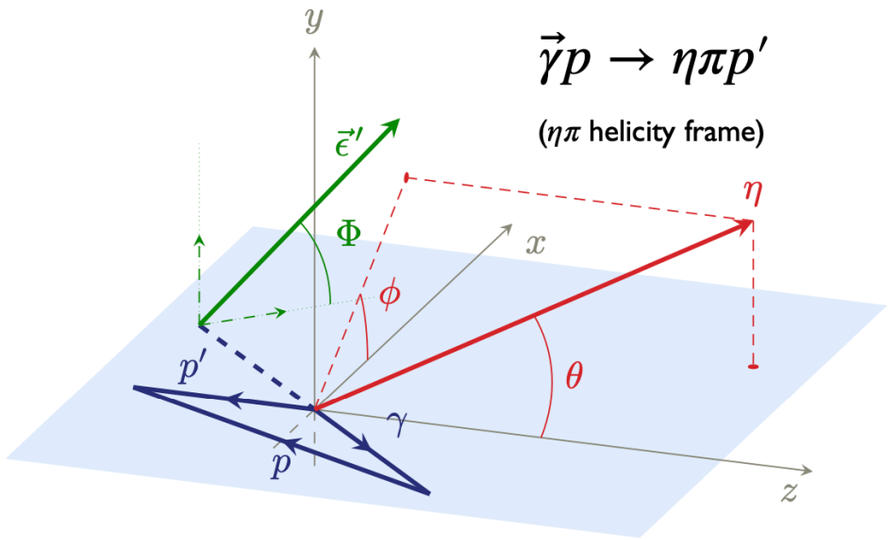
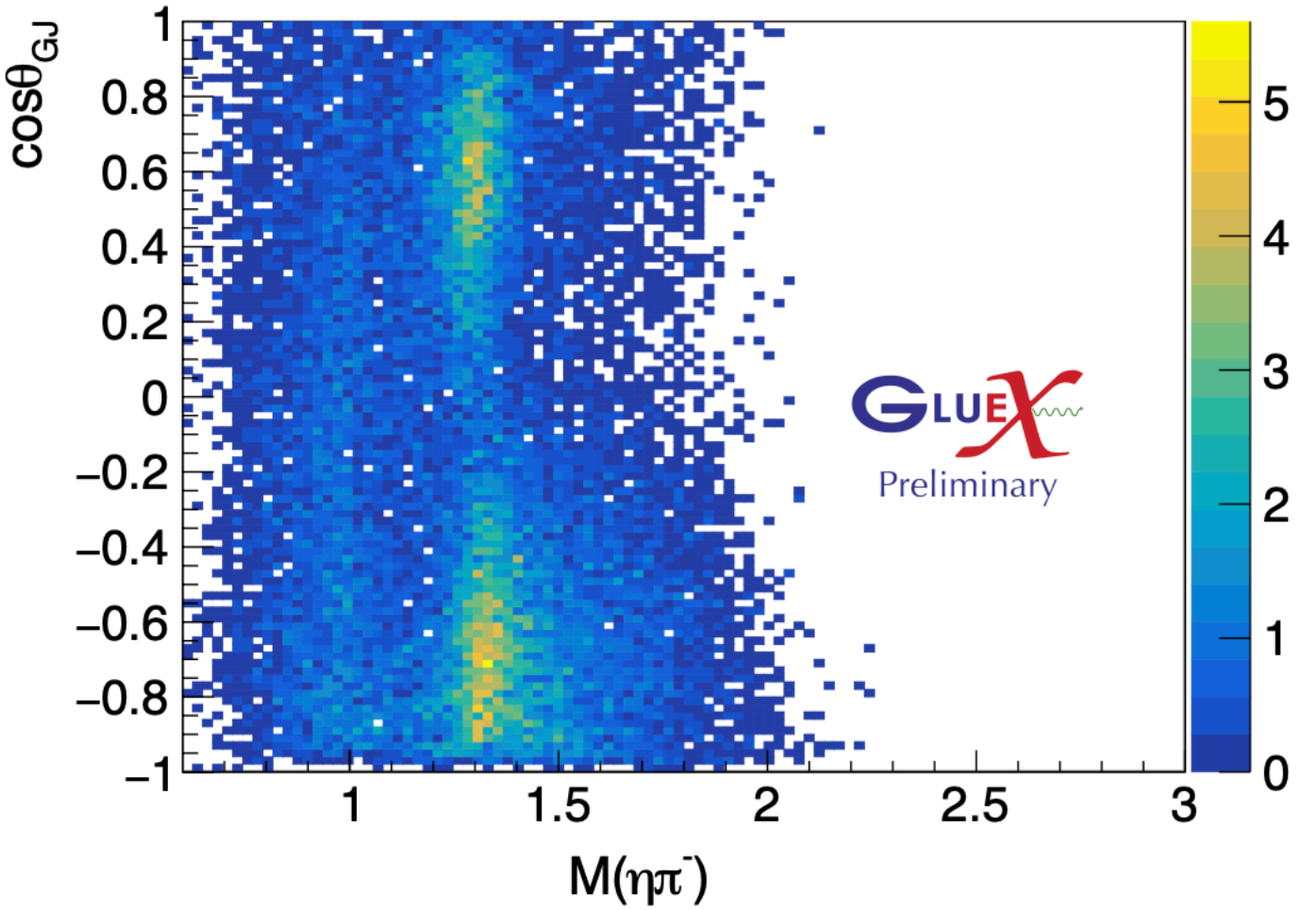
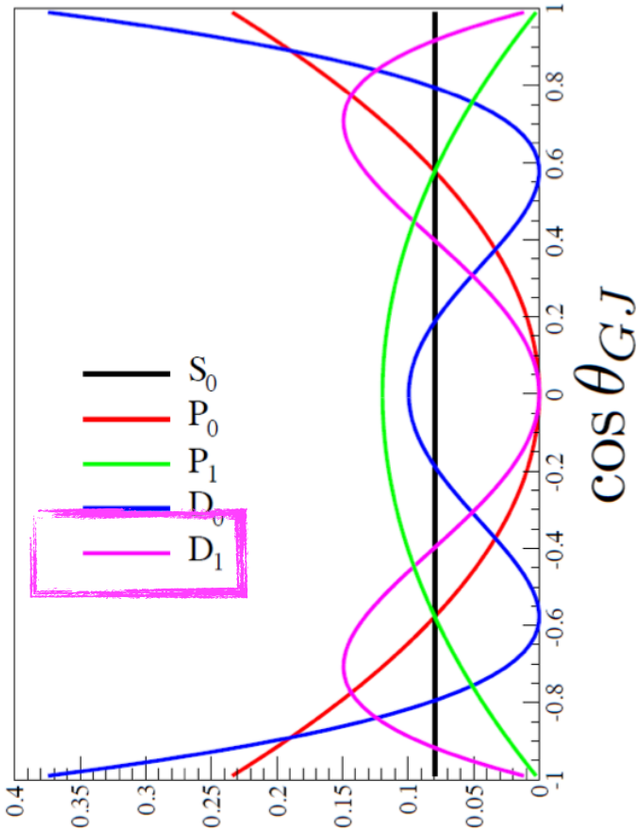


a_0 a_2 $\gamma p \to \eta\pi^- \Delta^{++}$





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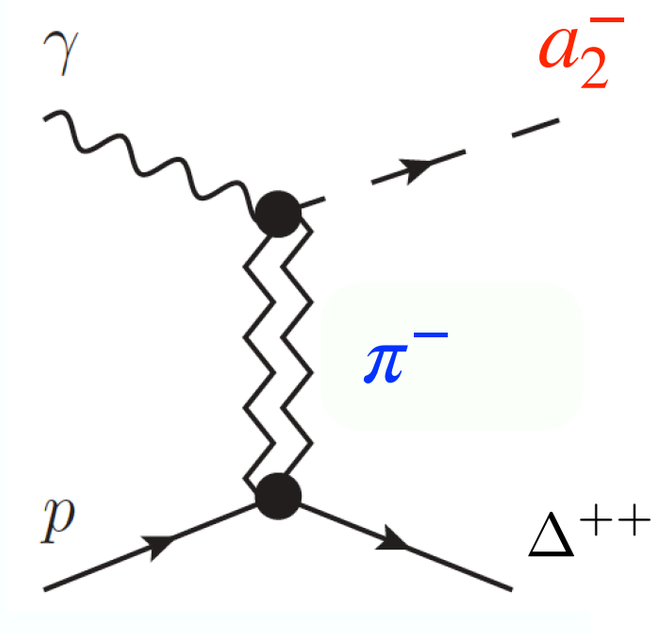
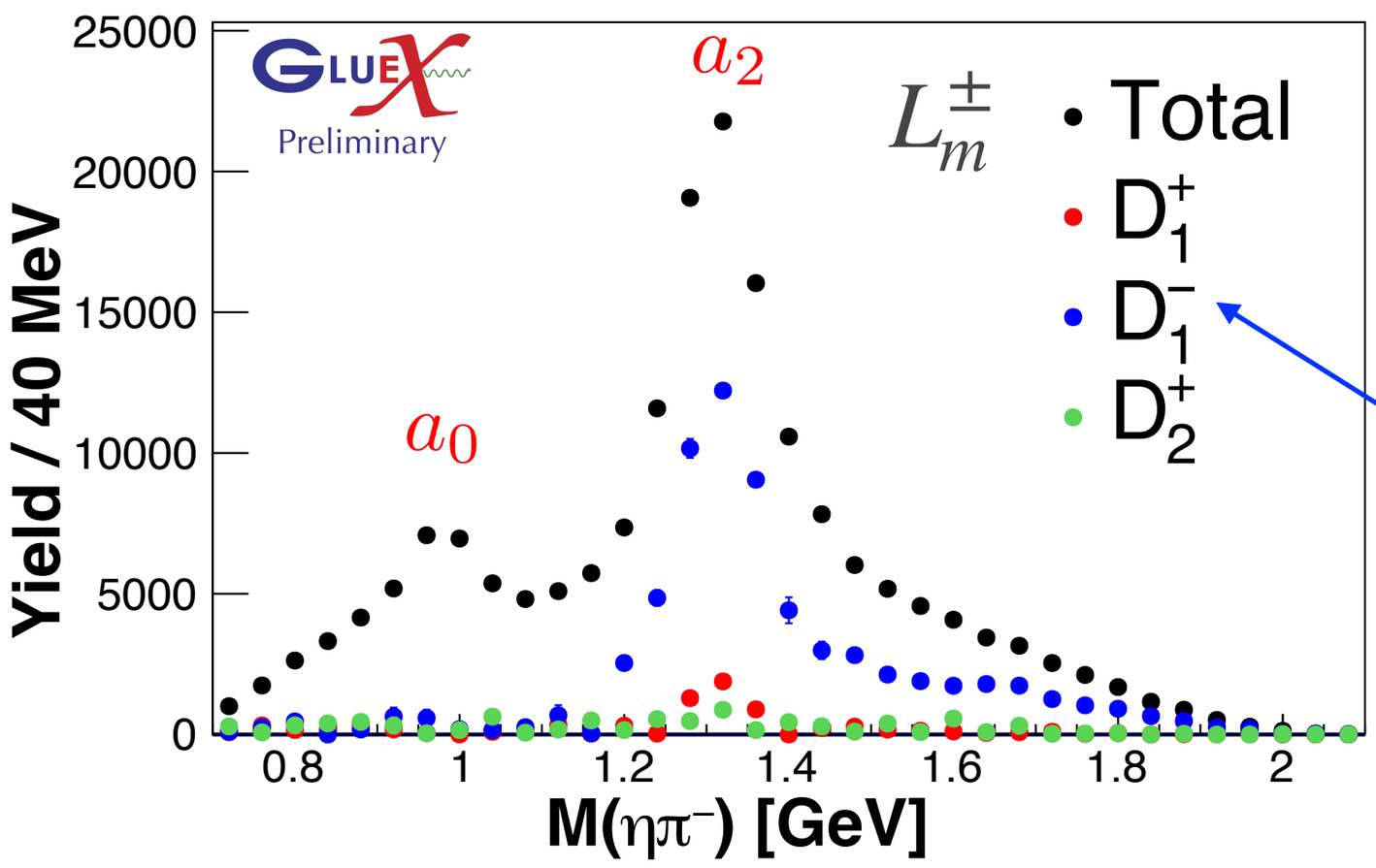


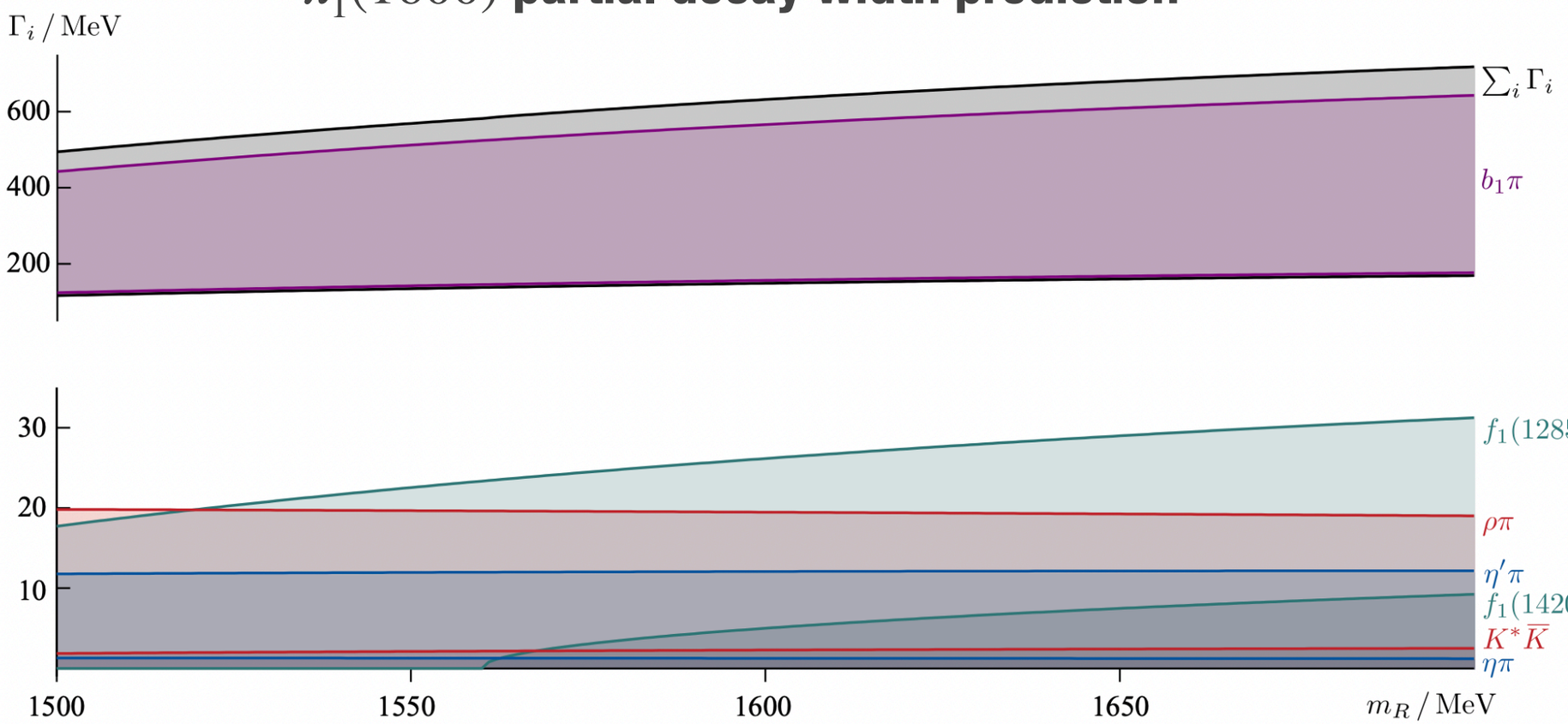


- Understanding production mechanism for conventional mesons, *e.g.* a_2^- through unnatural π exchange

Where to search for $\pi_1(1600)$?

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

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



dominant coupling to $b_1\pi \to \omega\pi\pi$

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

had spec **Woss et al. PRD 103 (2021) 054502**

Search for $\pi_1 \to b_1\pi$ at GlueX

- If π_1 decays to $b_1\pi$, should observe in isospin-1 $\omega\pi\pi$ amplitude

- Measure $\omega\pi\pi$ cross sections and isolate I=1 contributions through

$$\sigma((\omega\pi\pi)^0)_{I=1} = \sigma(\omega\pi^+\pi^-) - 2\sigma(\omega\pi^0\pi^0)$$

$$\sigma((\omega\pi\pi)^-)_{I=1} = \sigma(\omega\pi^-\pi^0)$$

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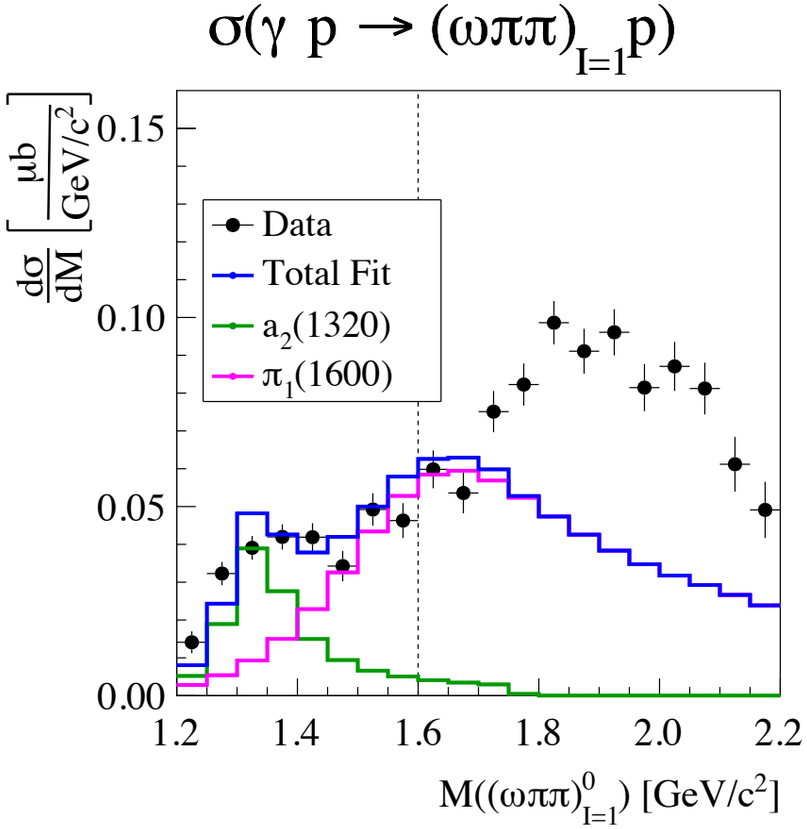
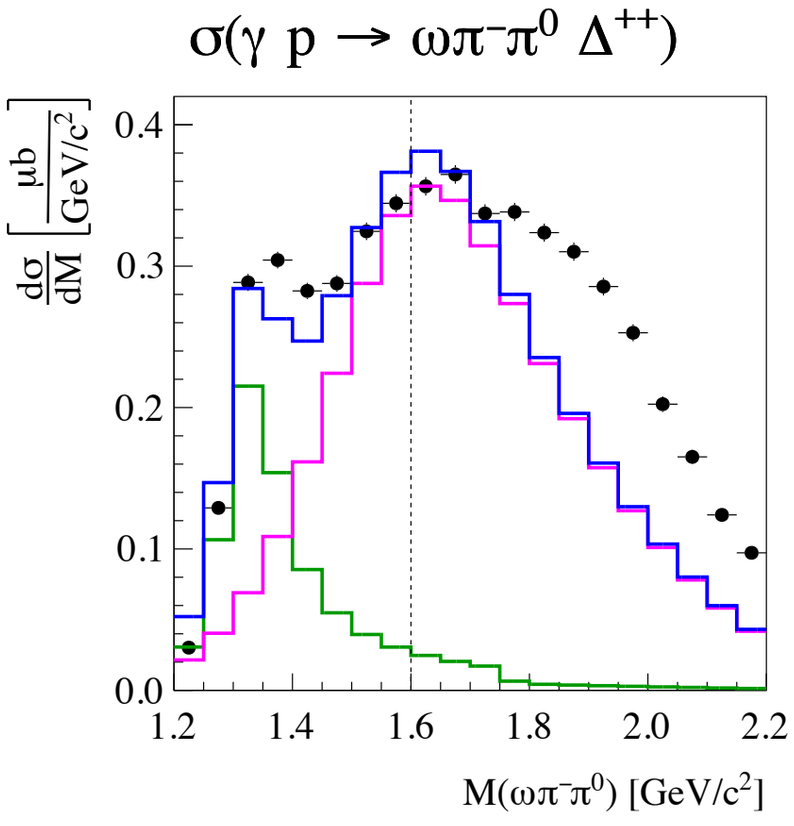
- No clear $\pi_1 \to b_1\pi \to \omega\pi\pi$ signal in I=1 → set upper limit





- Fixed BW shapes for a_2 and π_1

- Upper limit on photoproduction cross section ratio $\sigma(\pi_1)_{ul}/\sigma(a_2)$

arXiv:2407.03316
Submitted to PRL

Status of exotic π_1 search with GlueX

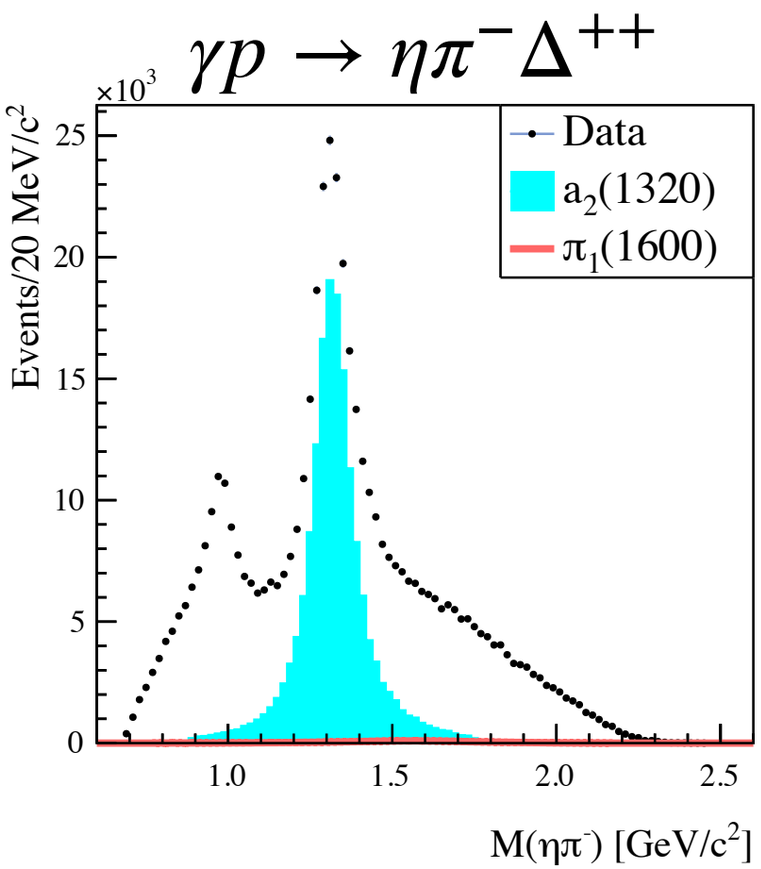
- Recent Lattice QCD prediction for $\pi_1(1600)$ decay widths allowed us to set the first upper limit on exotic photoproduction

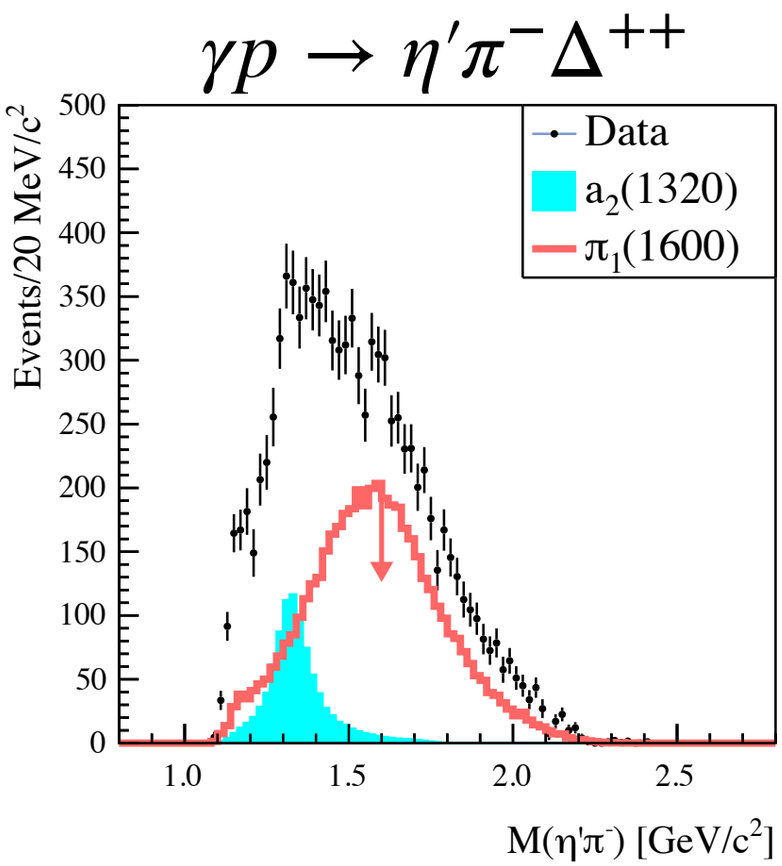
An Upper Limit on the Photoproduction Cross Section of the Spin-Exotic $\pi_1(1600)$

arXiv:2407.03316
Submitted to PRL

- Project upper limits onto $\pi_1(1600)$ decay modes for observation in pion production: $\eta\pi$ and $\eta'\pi$

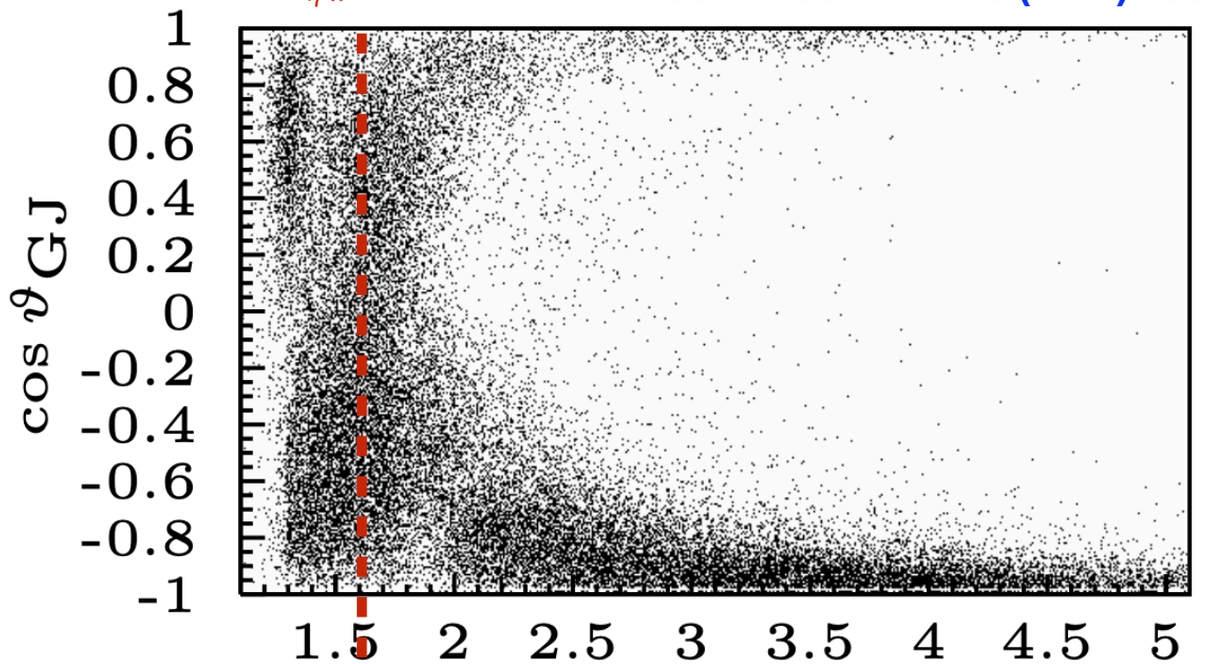
Large π_1 excluded from $\eta\pi$





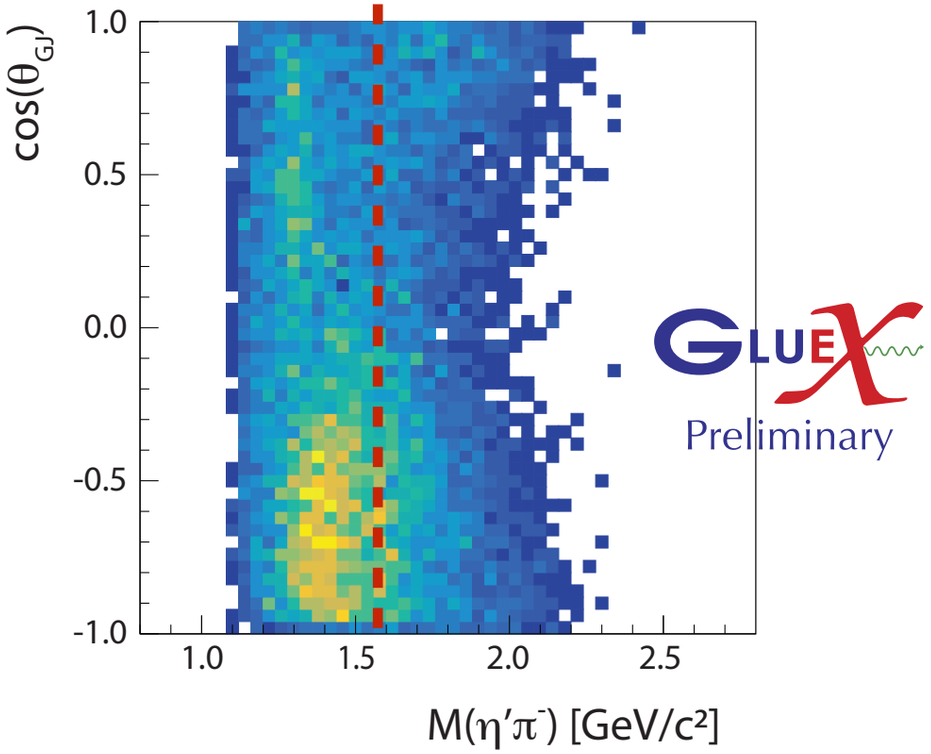
π_1 could be significant relative to a_2

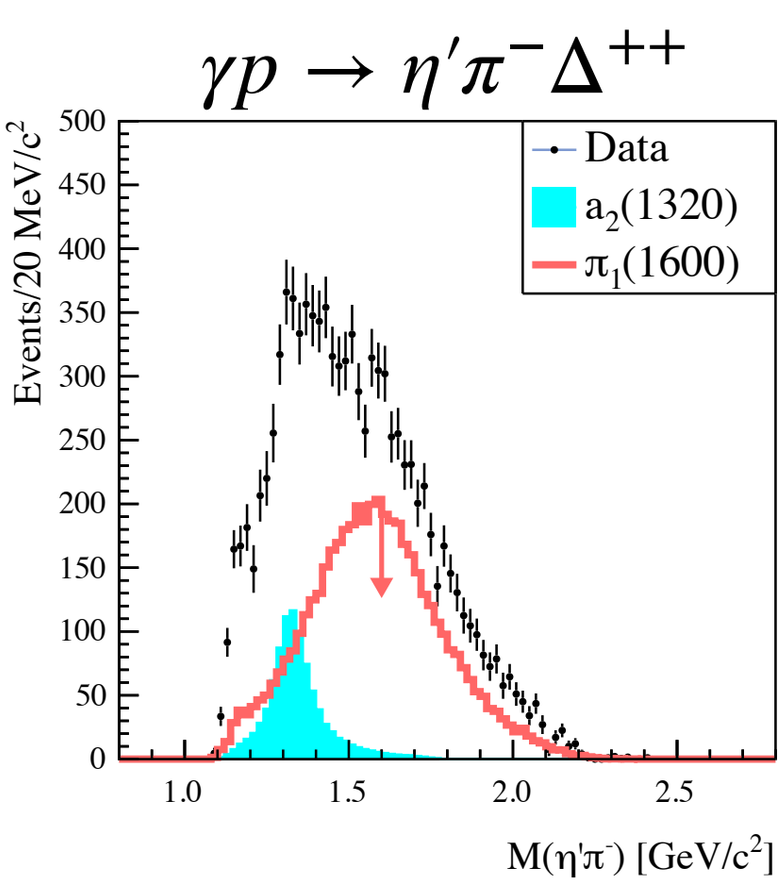
Prospects for $\pi_1 \to \eta^{(\prime)}\pi$ with GlueX



COMPASS: PLB 740 (2015) 303

- Promising $\eta'\pi^-$ channel with similar forward/backward asymmetry to COMPASS
- Potential for interference between odd (π_1 P-wave) and even (a_2 D-wave) partial waves





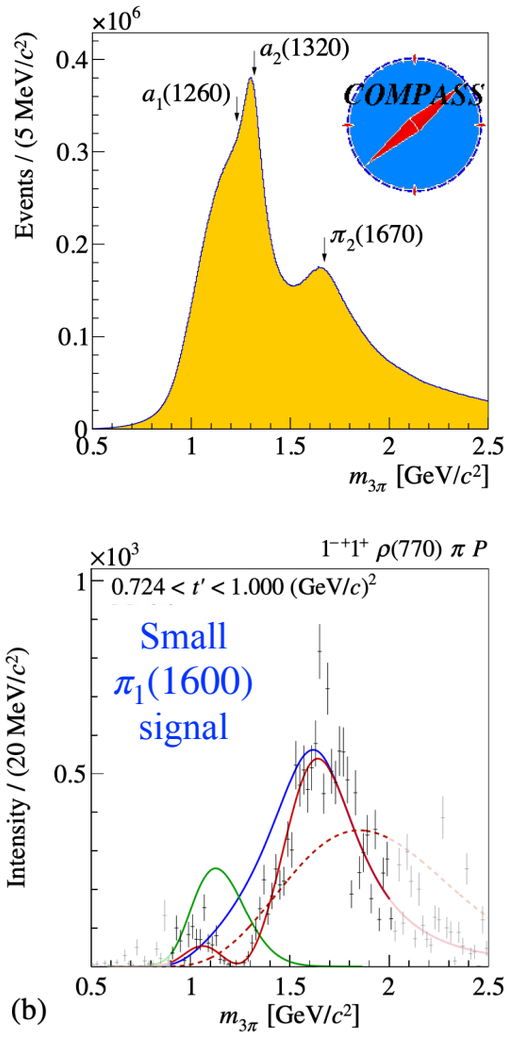
π_1 could be significant relative to a_2

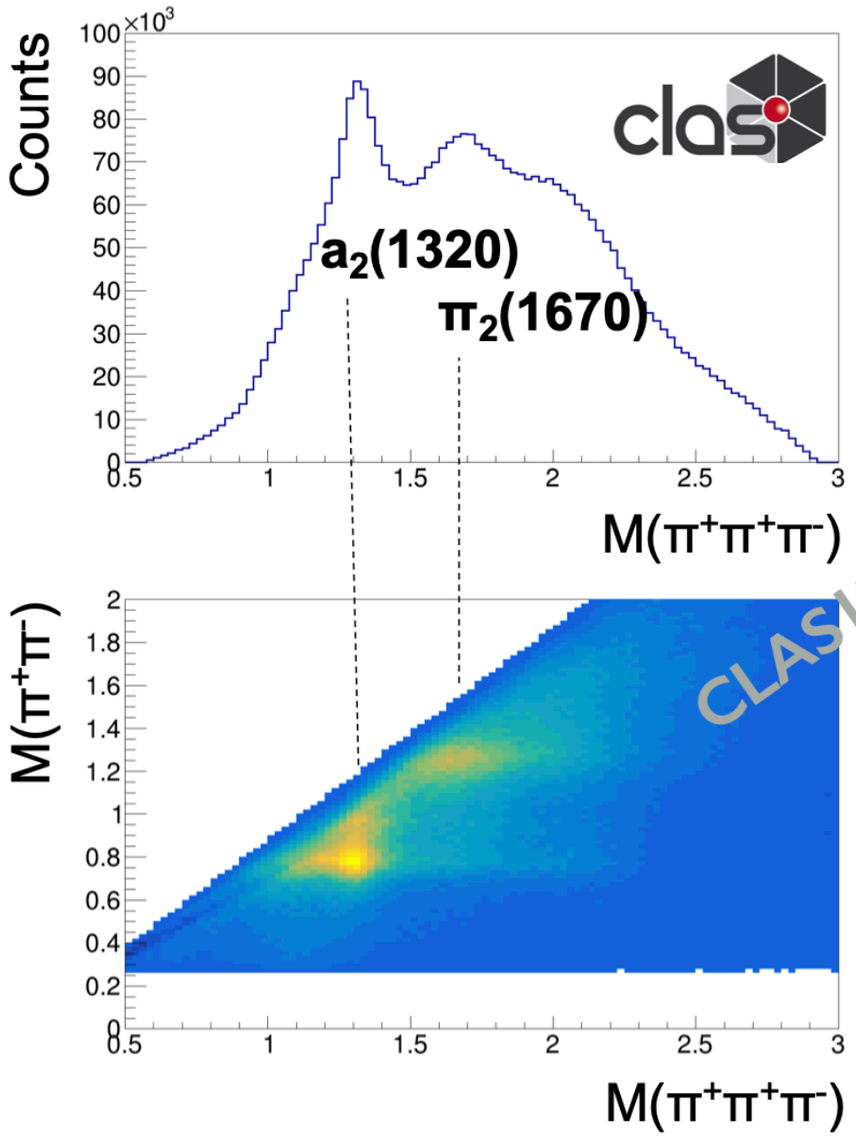
arXiv:2407.03316
Submitted to PRL

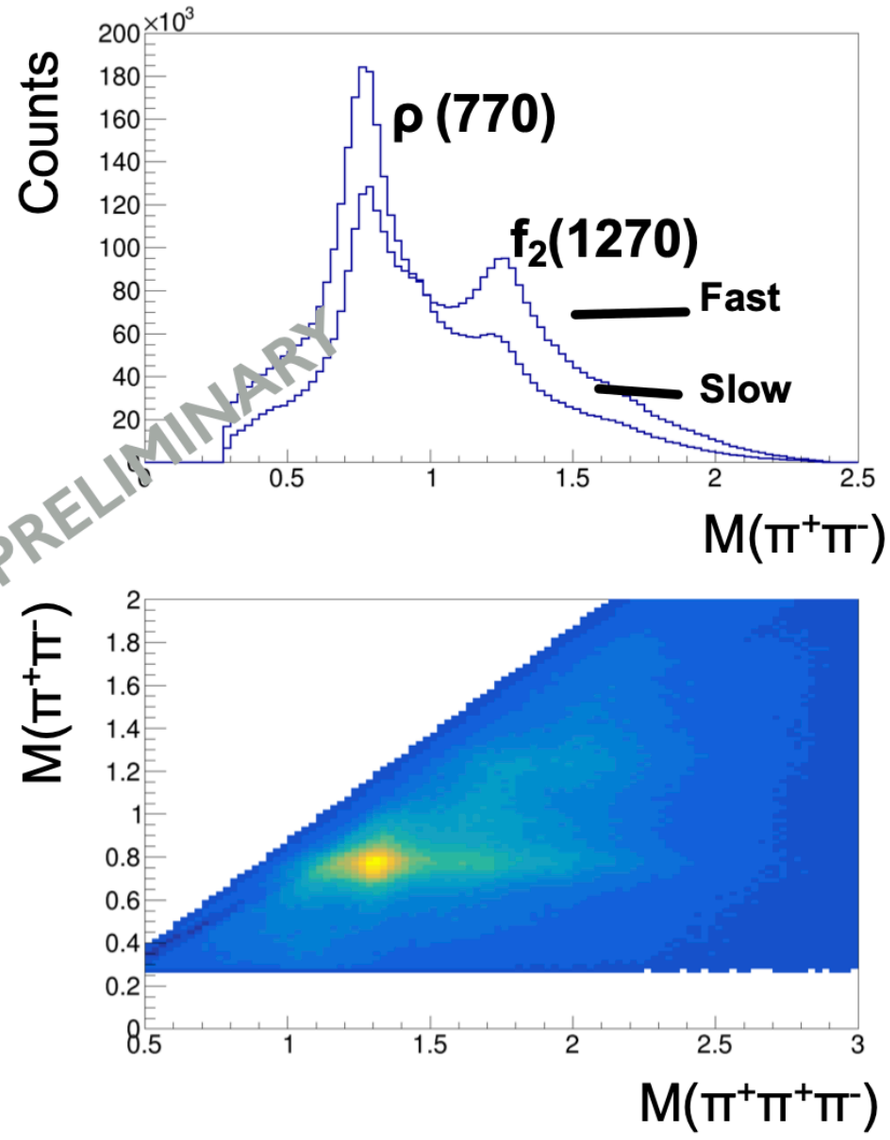
Another example: $\pi^+\pi^+\pi^-$ at CLAS12

COMPASS

PRD 105, 012005 (2022)

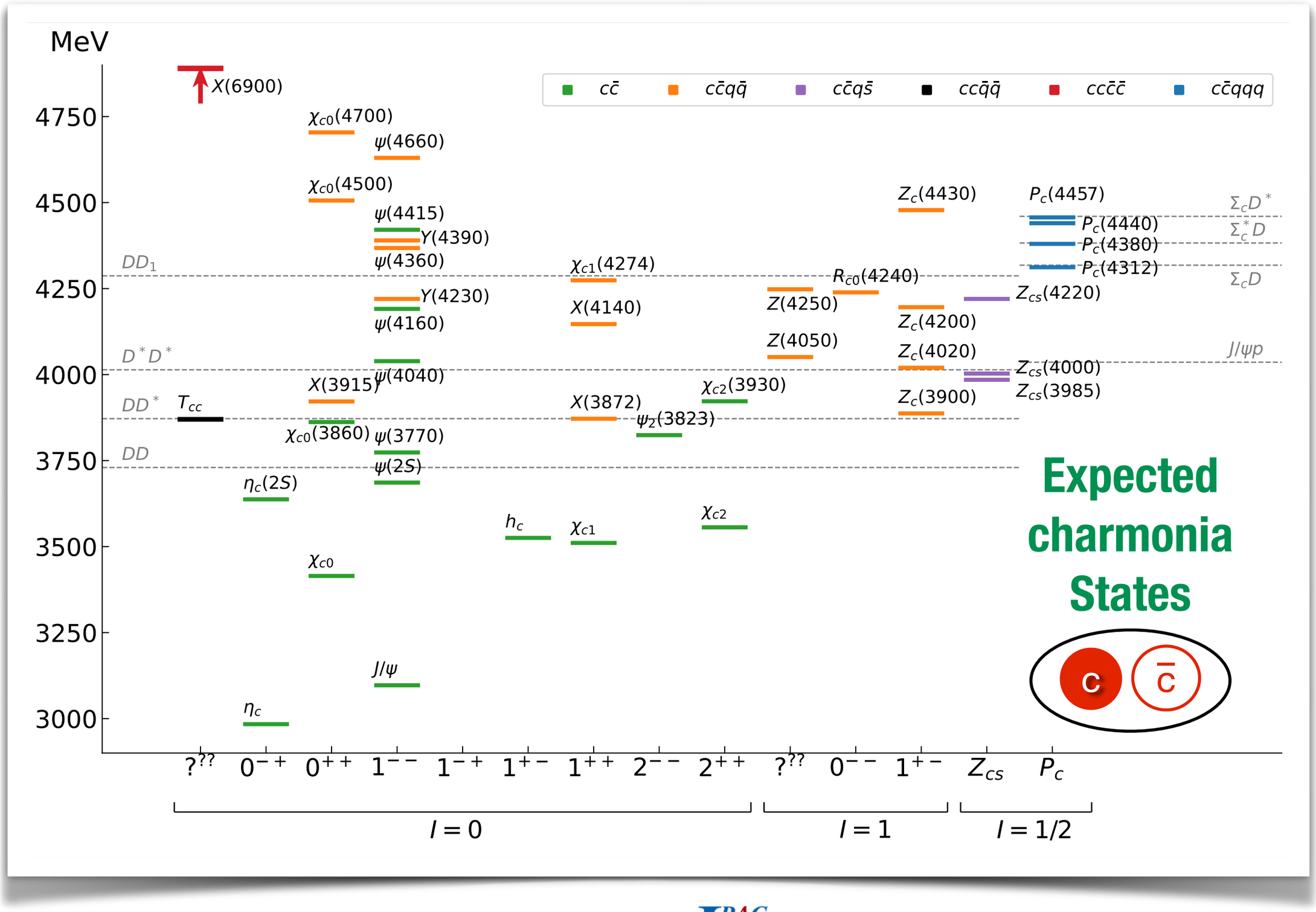






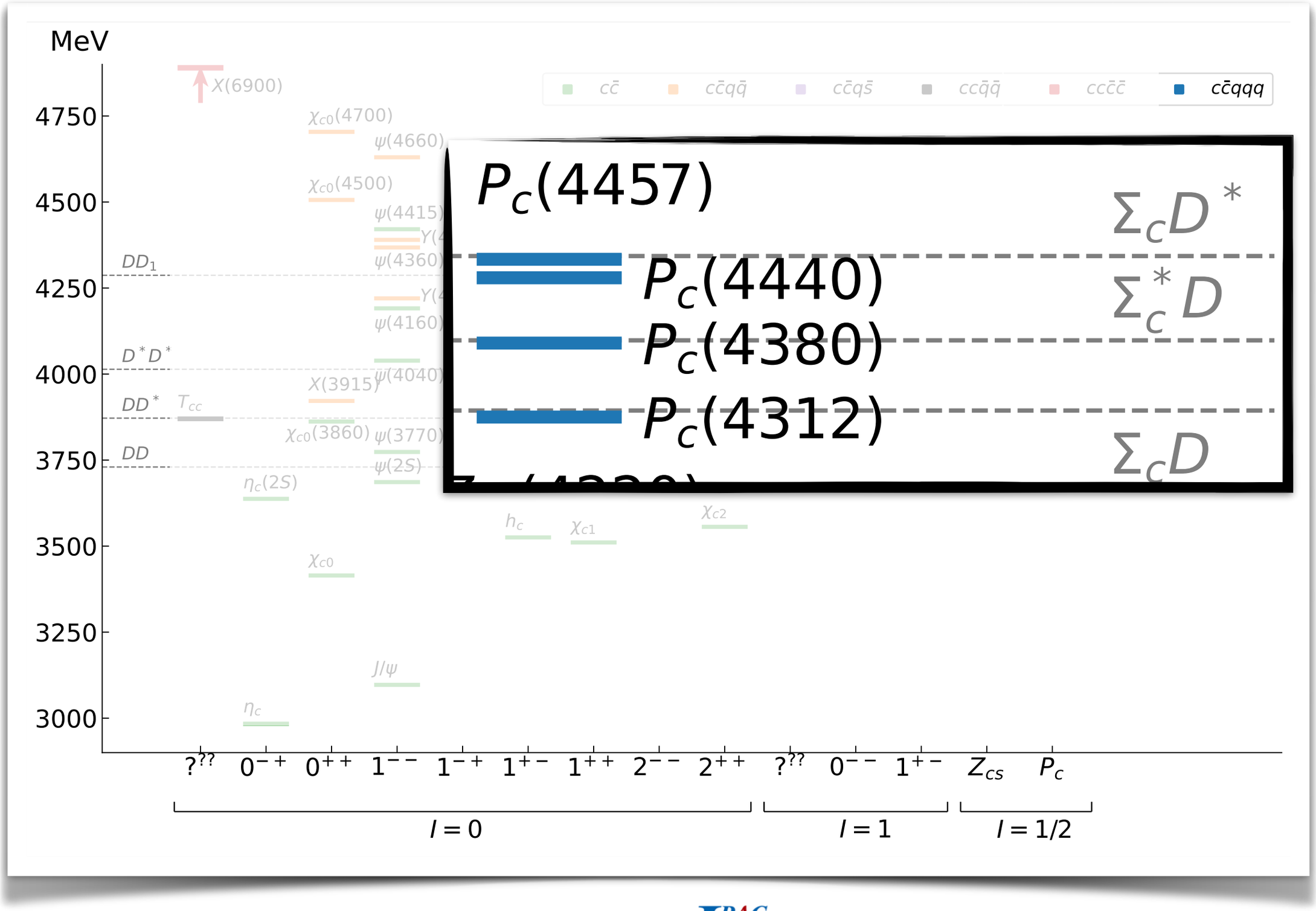
- Unique $\pi^+\pi^+\pi^-$ dataset from only a portion of CLAS12 beam time to compare with observations of $\pi_1(1600)$ signal from COMPASS

Heavy quark spectroscopy: $XYZP_c$



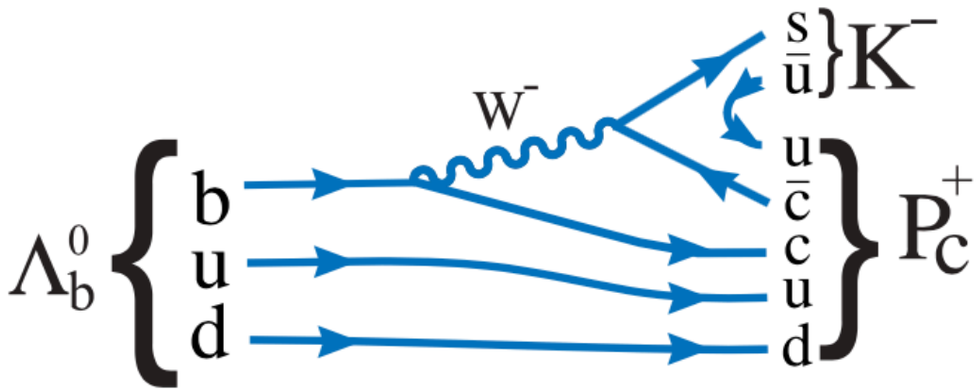
Recent review: JPAC **Prog. Part. Nucl. Phys. 127 (2022) 103981**

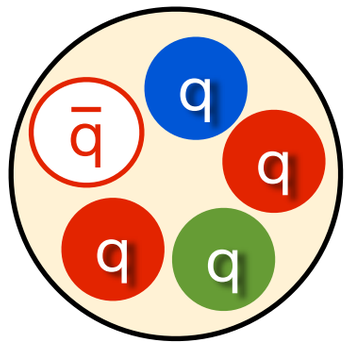
Pentaquarks



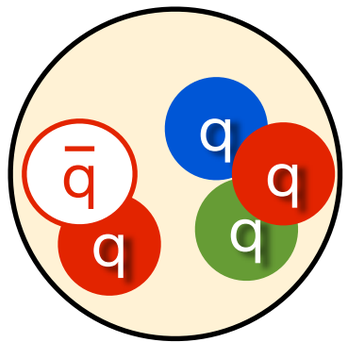
Recent review: JPAC **Prog. Part. Nucl. Phys. 127 (2022) 103981**

Pentaquark observation and interpretation

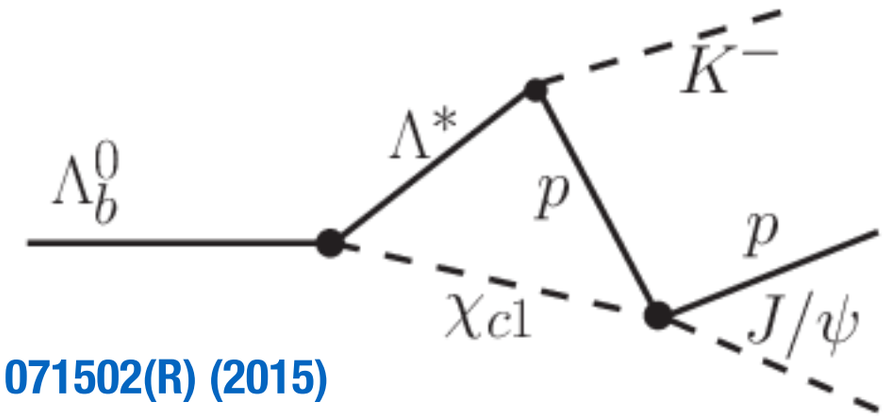




pentaquark



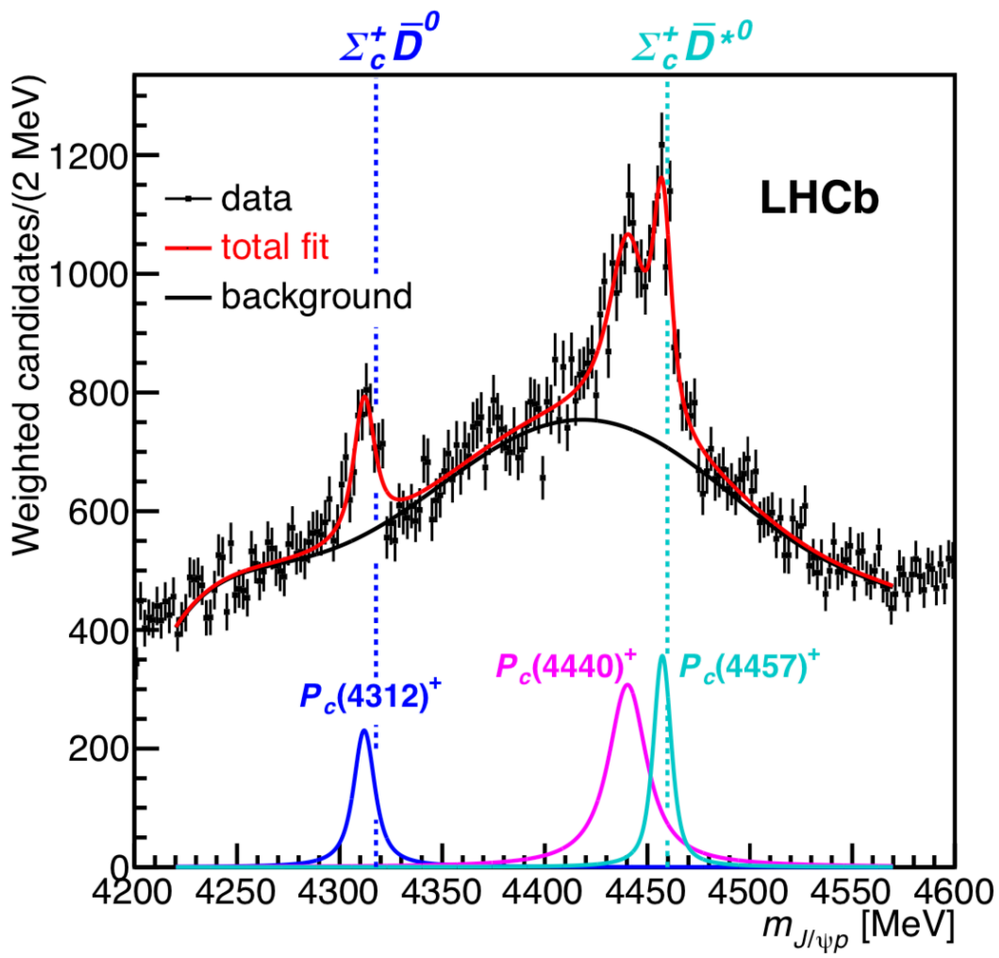
molecular



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

rescattering (triangle singularity)

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

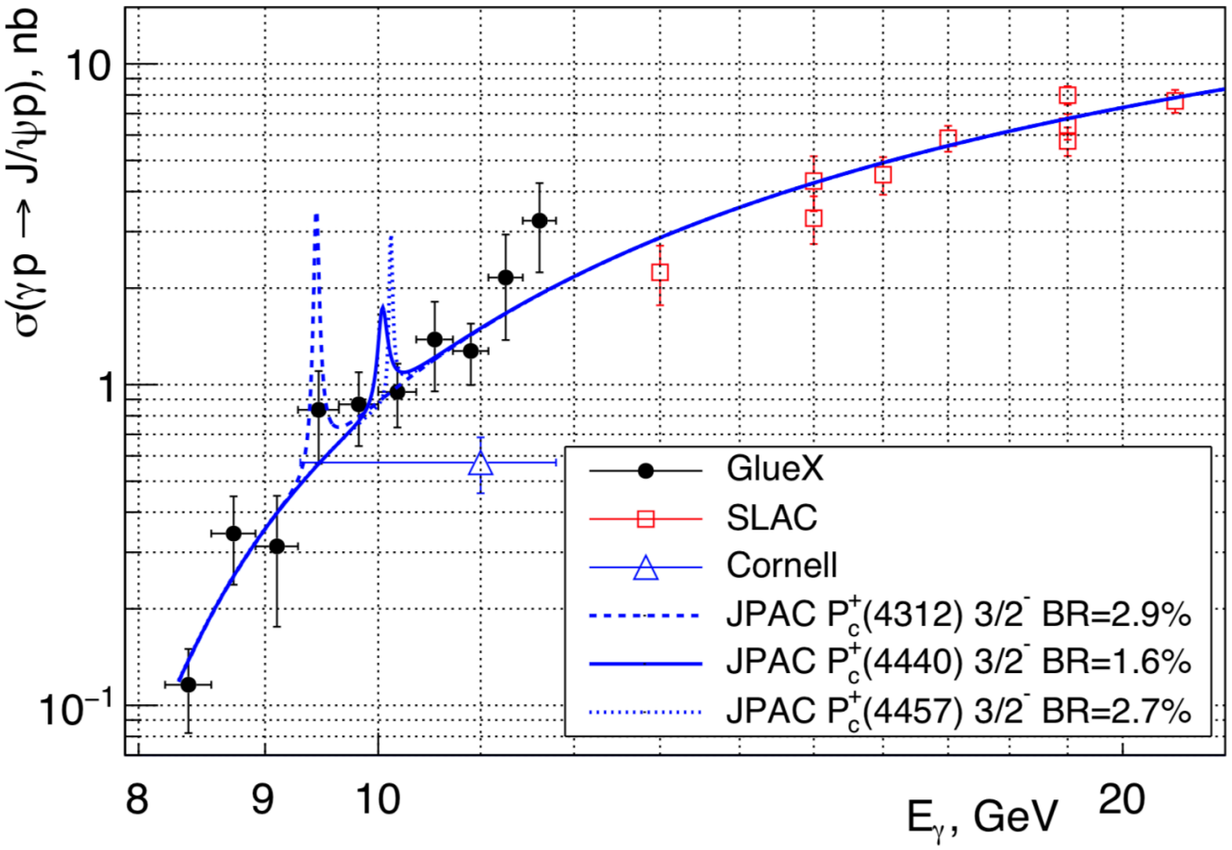


PRL 122, 222001 (2019)

Pentaquark photoproduction

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

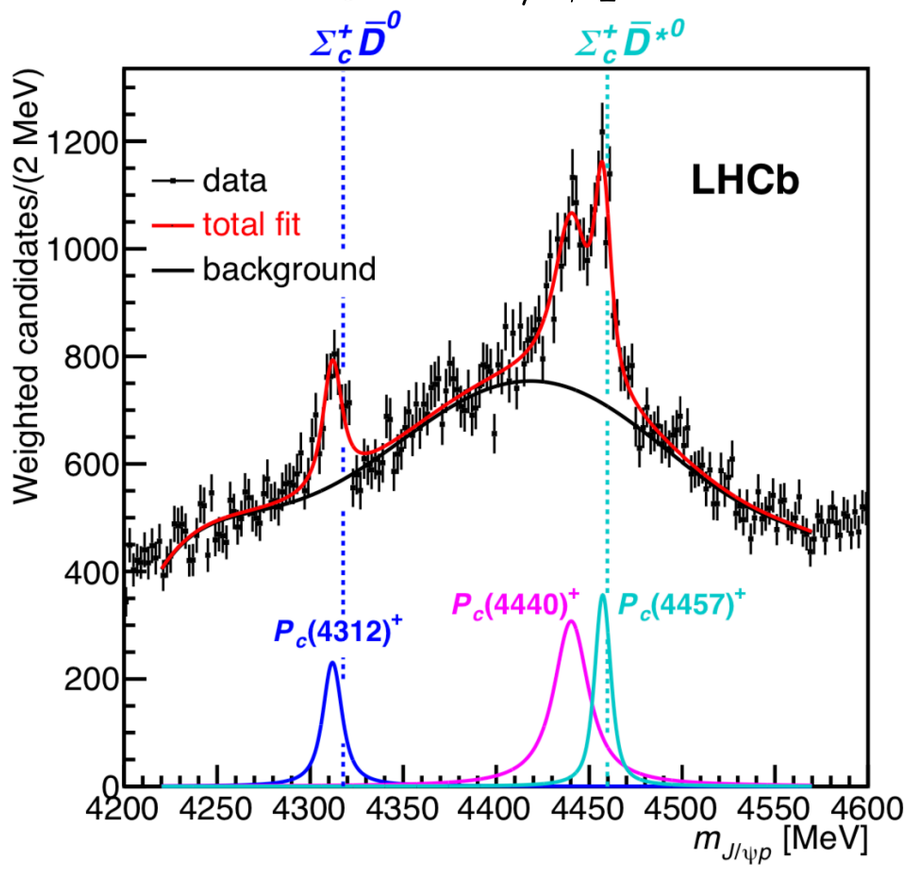
GlueX **PRL 123, 072001 (2019)**

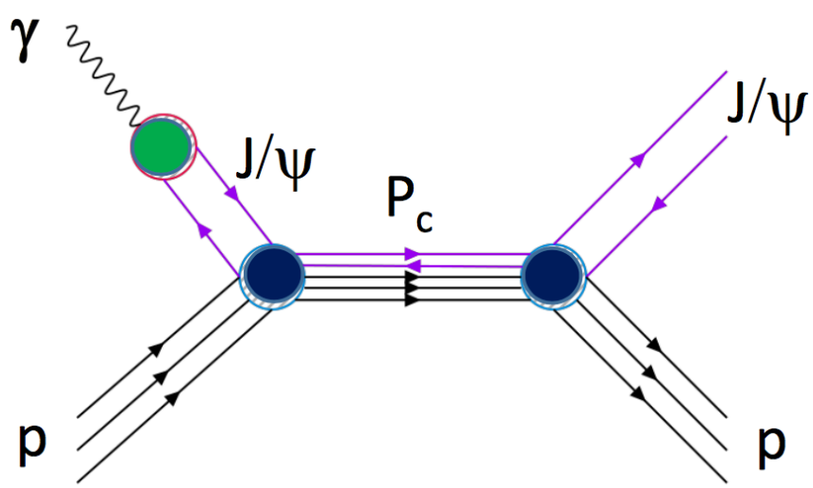


Model-dependent limits on

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

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



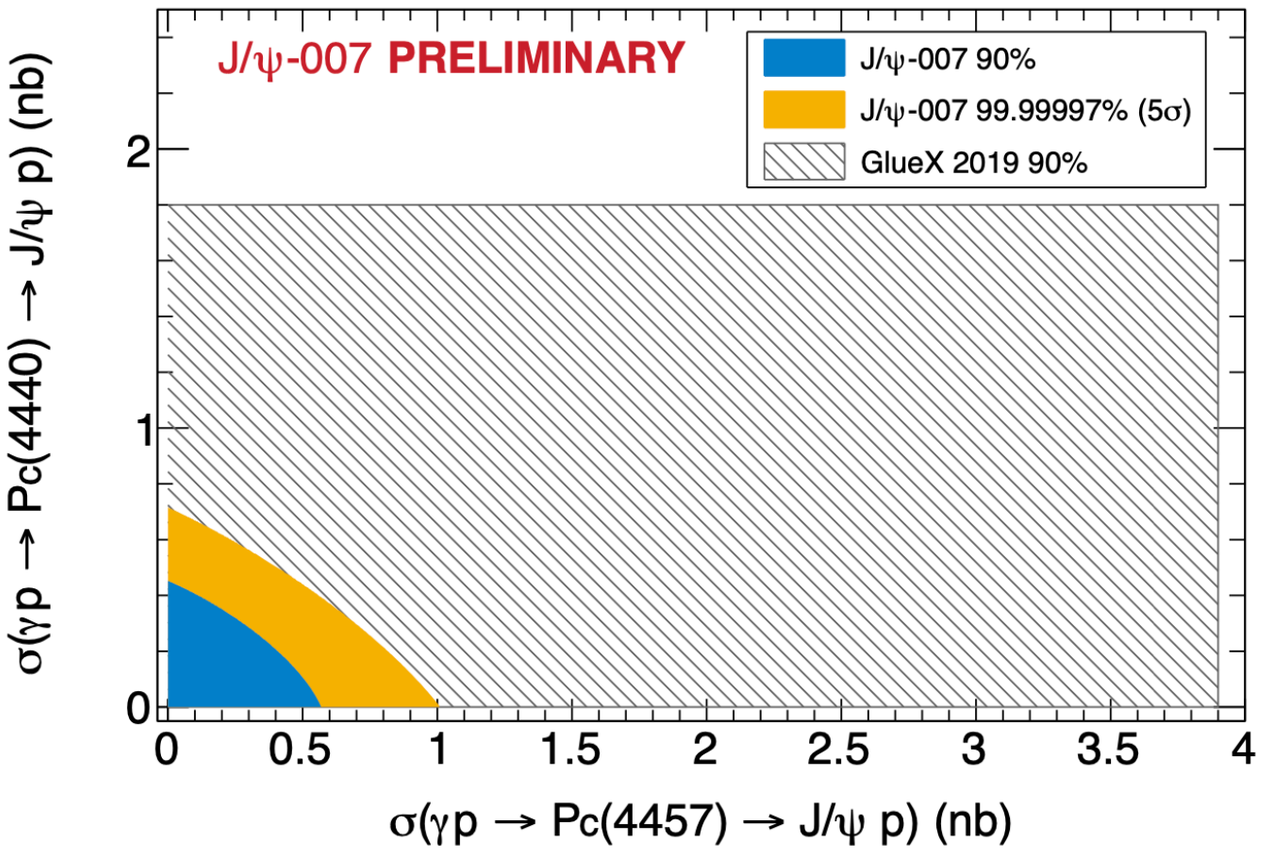


Proportional to $BR(P_c \to J/\psi p)^2$

Pentaquark photoproduction

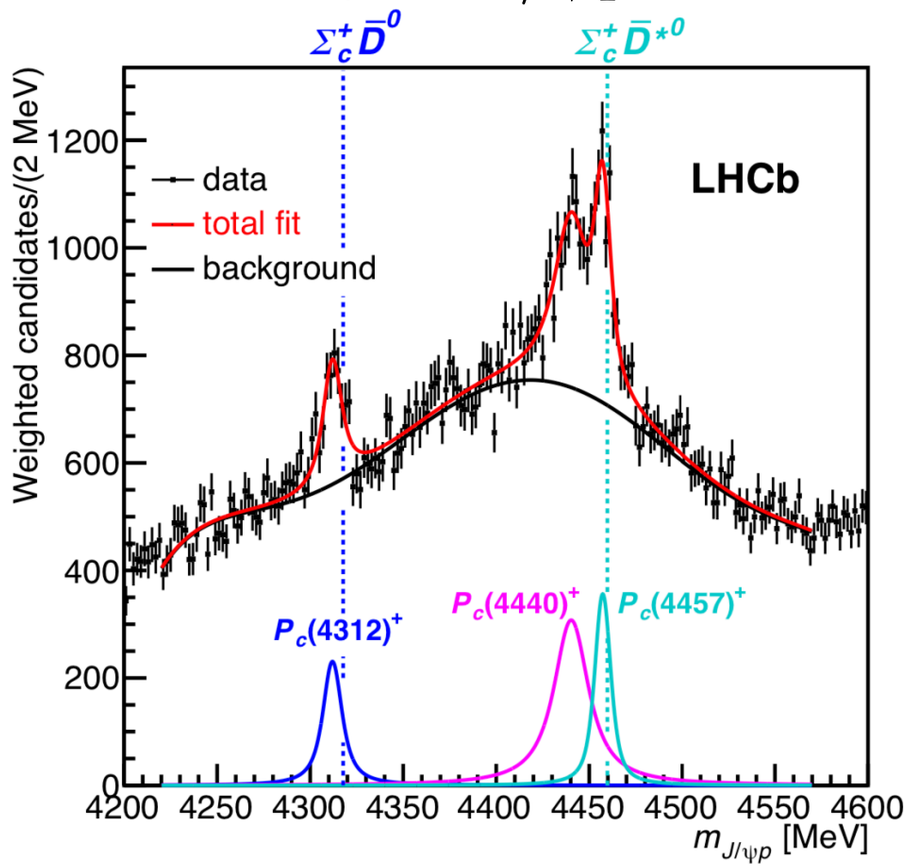
$$\gamma p \to J/\psi p$$

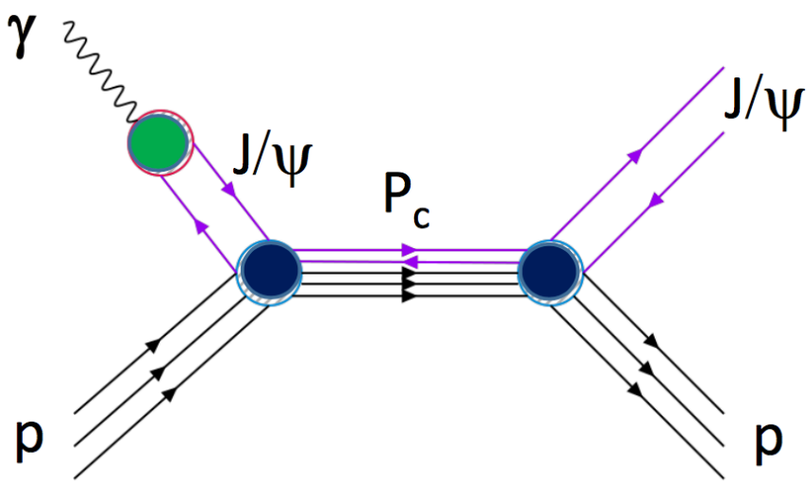
Hall C: J/ψ-007 experiment



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

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



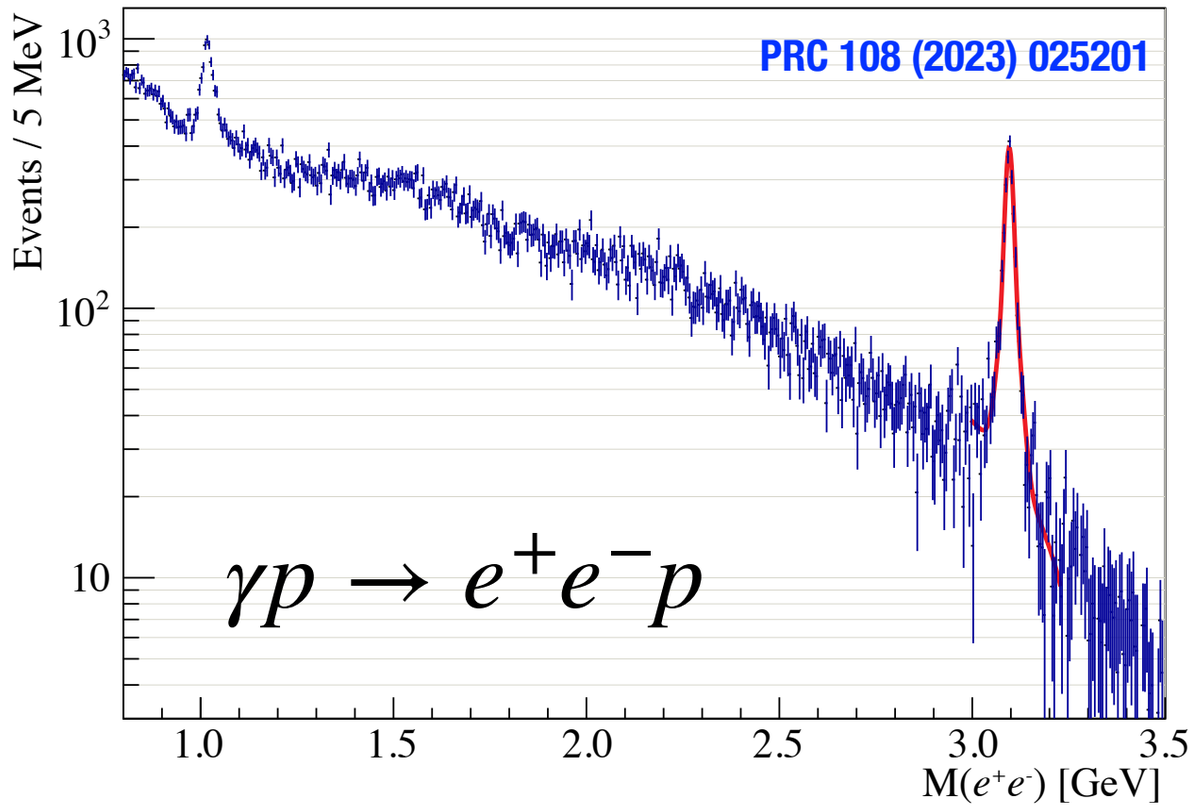


Proportional to $BR(P_c \to J/\psi p)^2$

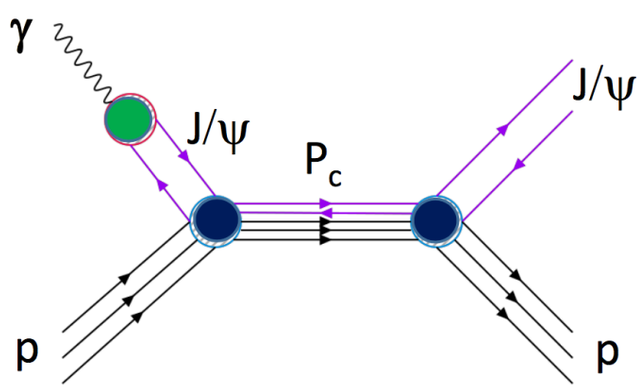
J/ψ photoproduction at GlueX

Farah Afzal
Wed @ 10:00

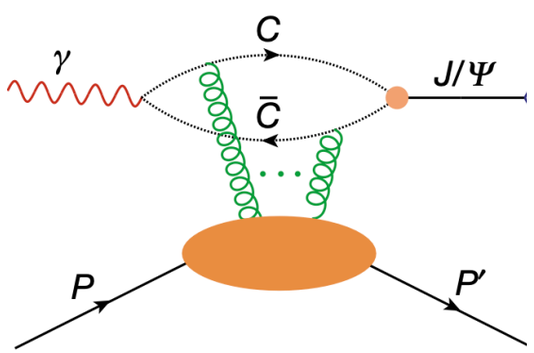
- Experimentally clean and rare probe with ~2.2k J/ψ observed in GlueX-I
- Broad physics program driven by different production mechanisms



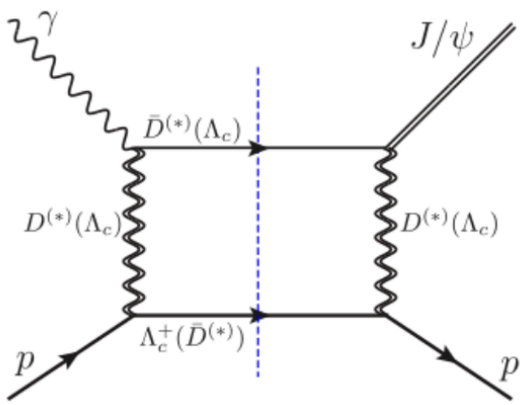
s-channel: pentaquarks



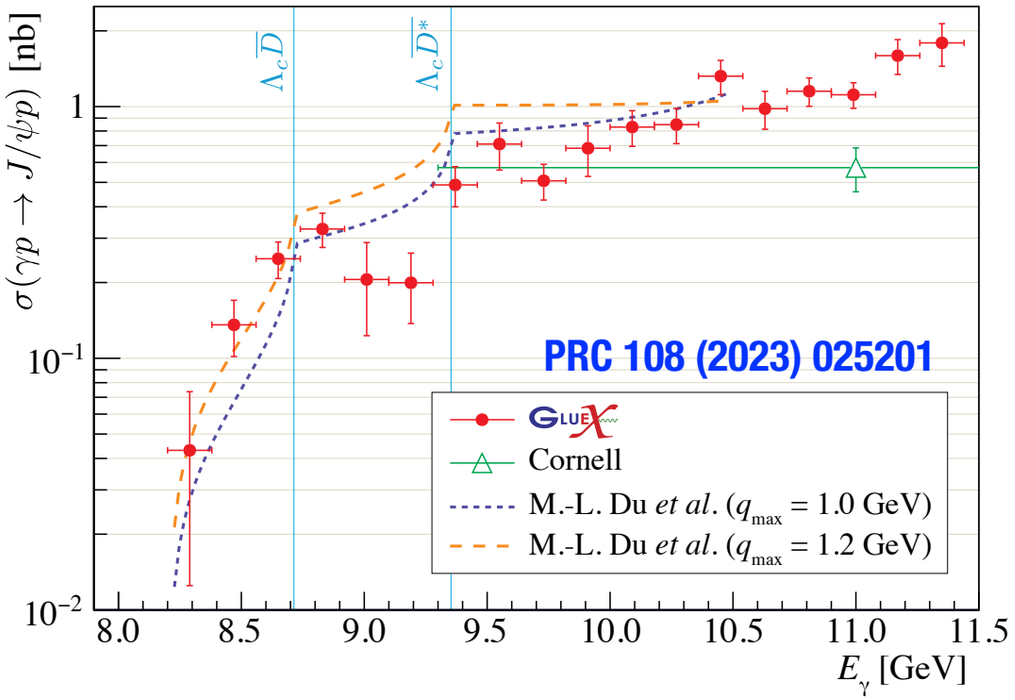
t-channel: gluon GPDs, mass radius

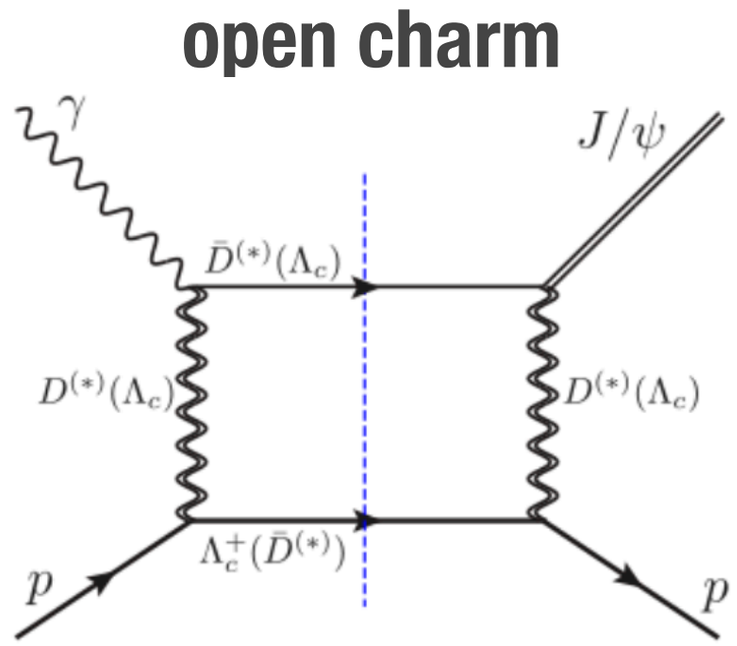


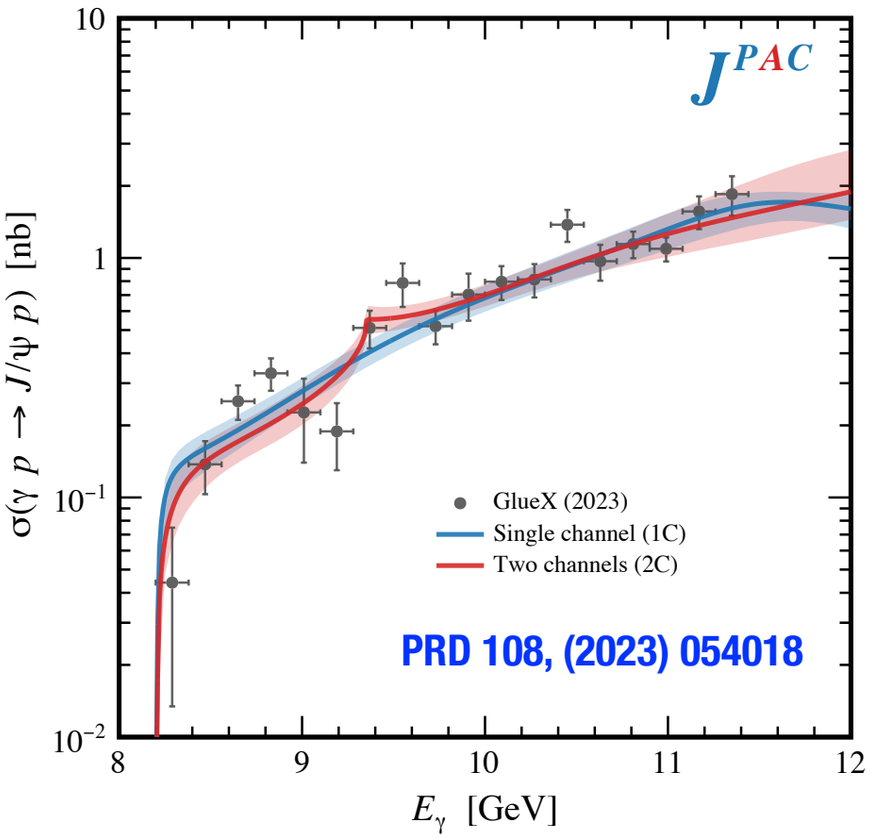
open charm



Interpretation of GlueX results

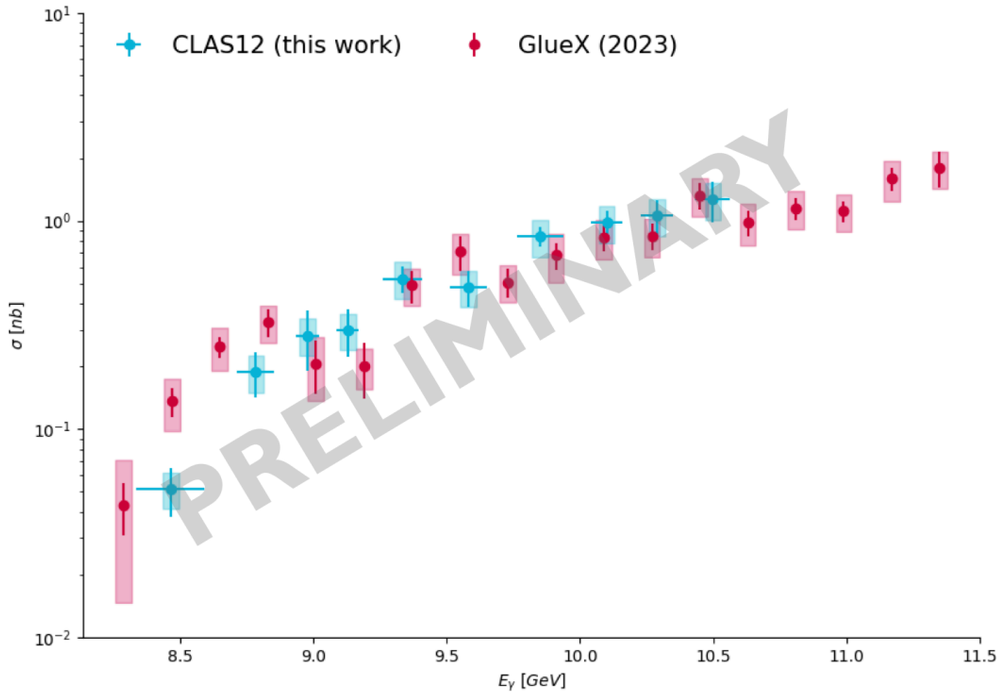




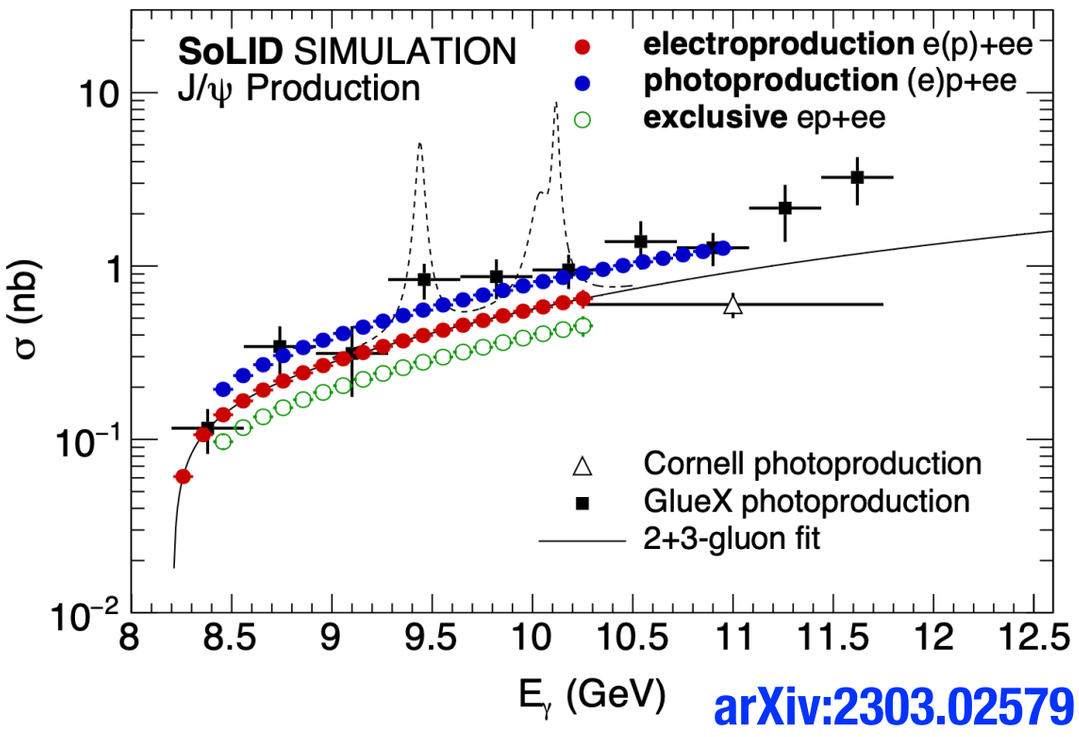


- Mesonic approach sensitive to “cusps” near opening of open charm thresholds in total cross section
- Fits with both single channel (Pomeron) exchange and multichannel (Pomeron + open charm) are compatible with GlueX-I and $J/\psi - 007$ data

Uniqueness of 12 GeV $c\bar{c}$ program



Pierre Chatagnon (QNP 2024)



arXiv:2303.02579

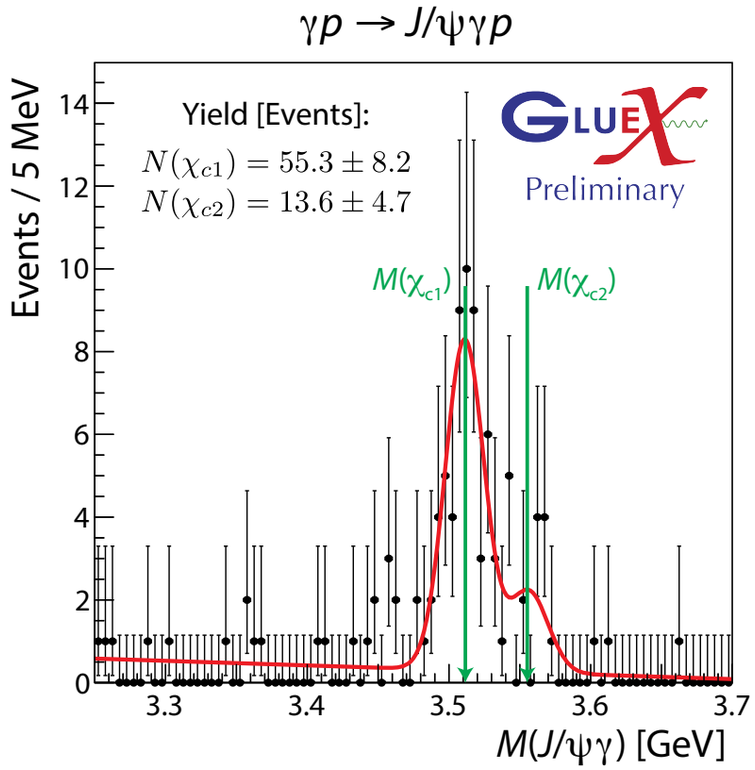
- Recent preliminary results from CLAS12 and upcoming GlueX data will definitively distinguish single and multichannel exchanges
- Exploit full JLab luminosity with the SOLID experiment in both photo- and electro-production
- Precise measurements of both total and differential ($d\sigma/dt$) cross sections are critical for both spectroscopy (pentaquark) and structure (gluon GPD, mass radius)

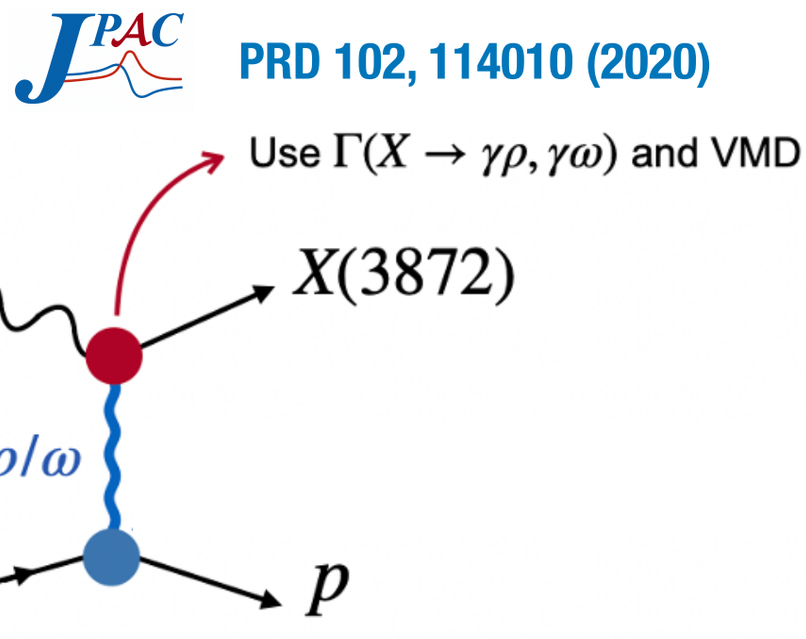
Uniqueness of 12 GeV $c\bar{c}$ program

- First observation of C-even χ_{cJ} photoproduction with current GlueX data (and much more data to come!)

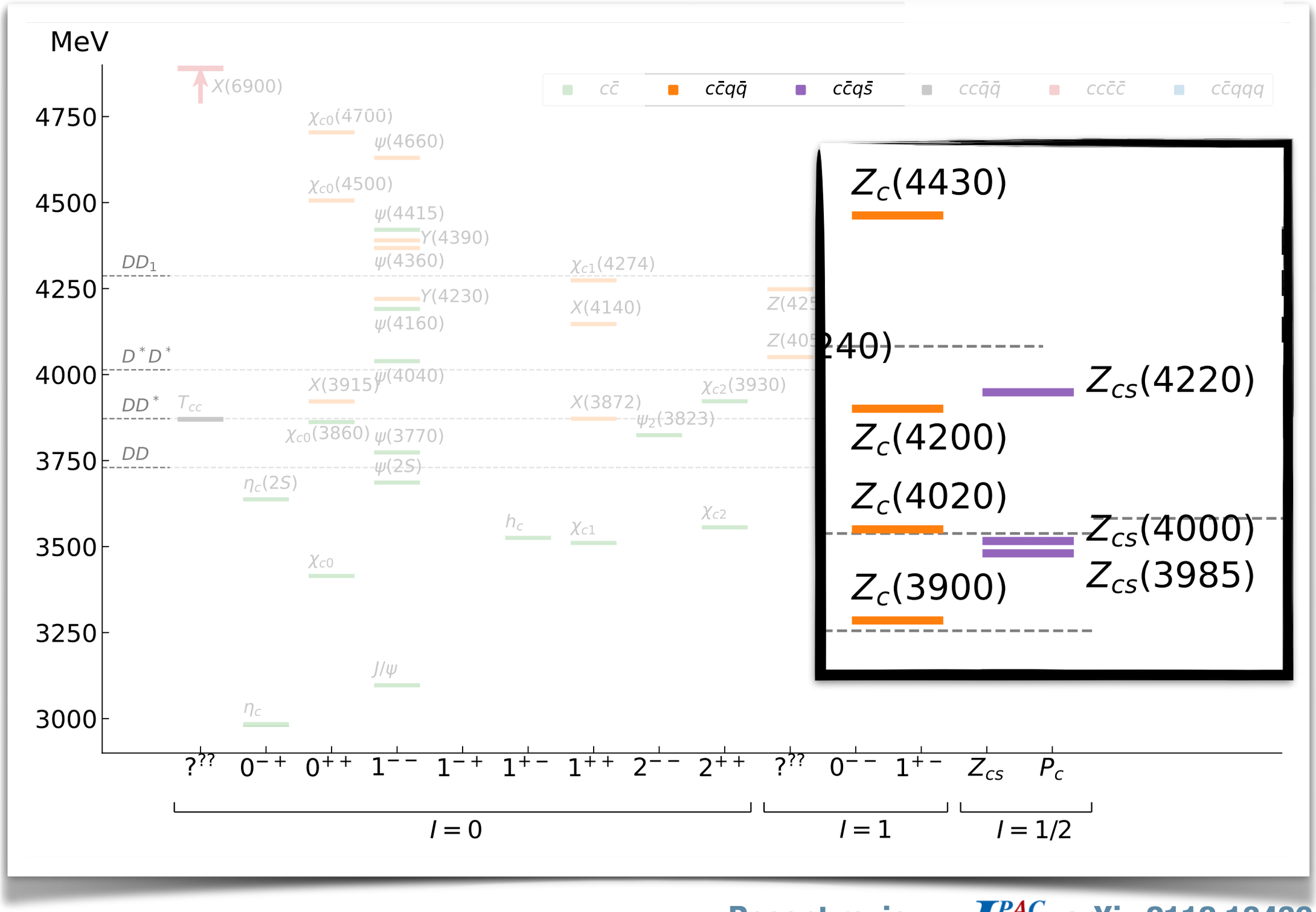
- Future GlueX data will allow for a holistic theoretical description of threshold $c\bar{c}$ production: $J/\psi, \chi_{cJ}, \psi(2S)$

- Important to validate production models for $c\bar{c}$ and potentially more exotic states at EIC and JLab 22 GeV





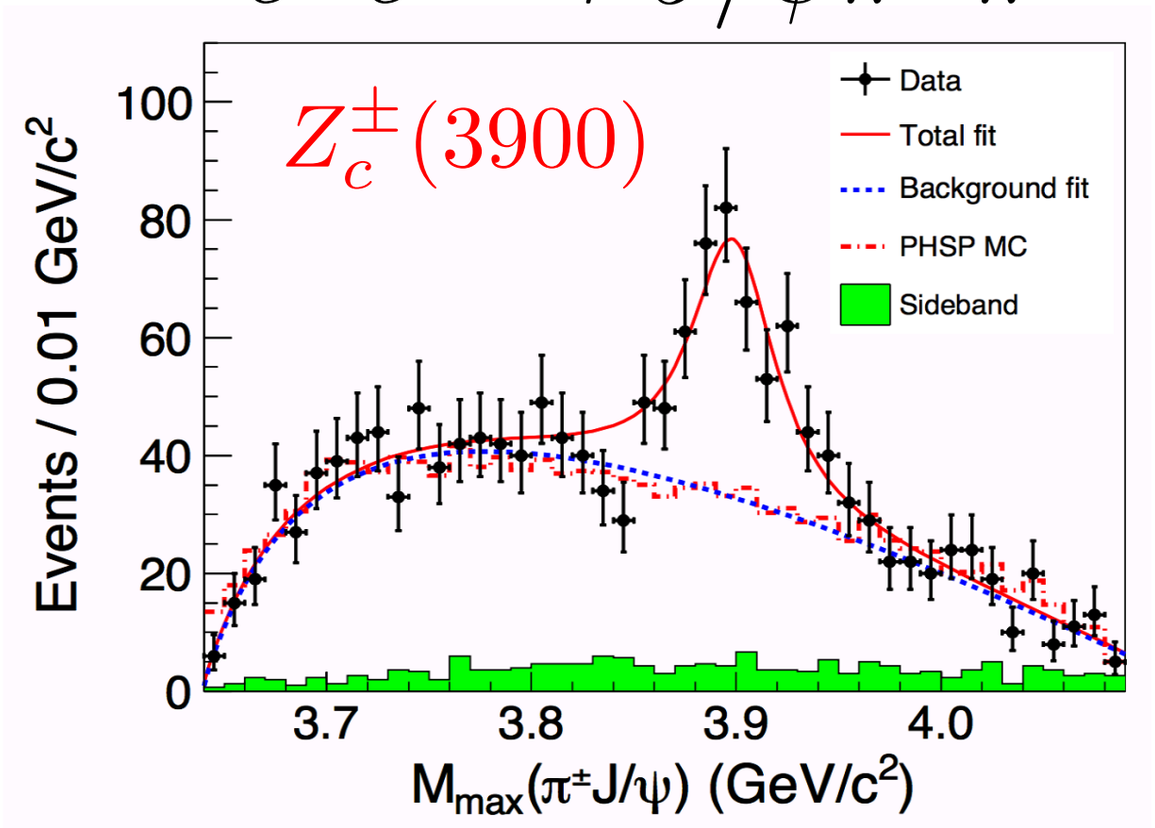
Charged tetraquark candidates: Z_c



Recent review: JPAC **arXiv:2112.13436**

Charged tetraquark candidates: Z_c

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

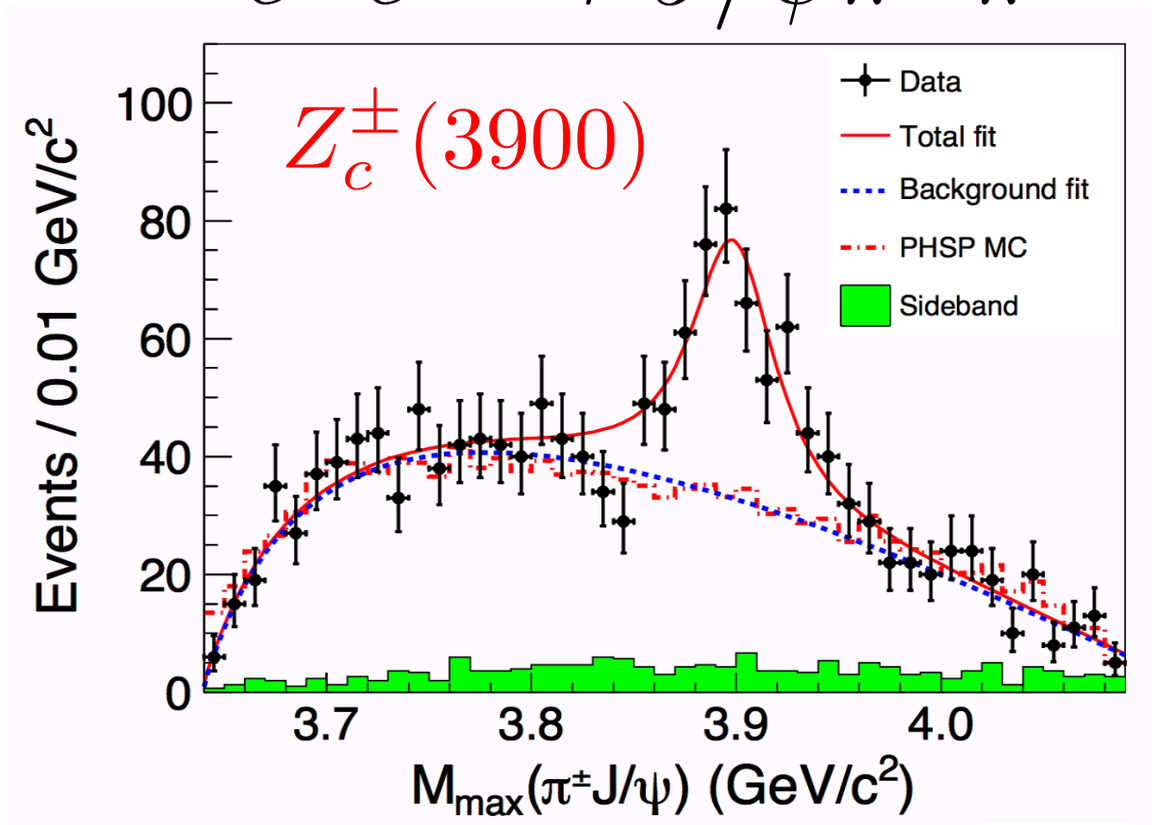


PRL 110, 252001 (2013) BESIII

PRL 110, 252002 (2013) BELLE

Charged tetraquark candidates: Z_c

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

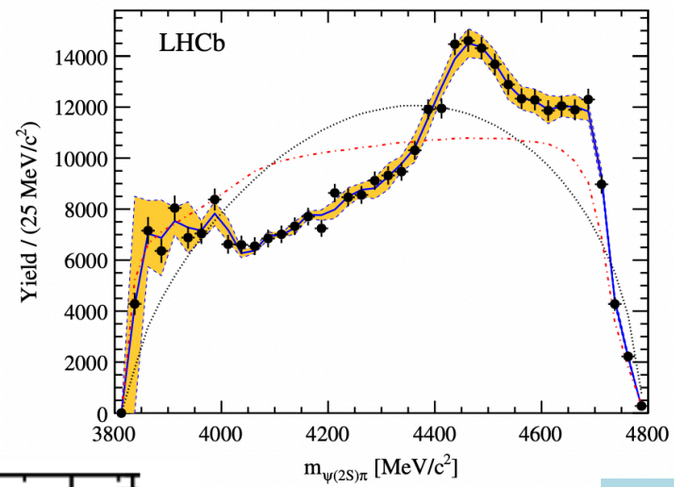


PRL 110, 252001 (2013) BESIII

PRL 110, 252002 (2013) BELLE

$Z_c^-(4430)$

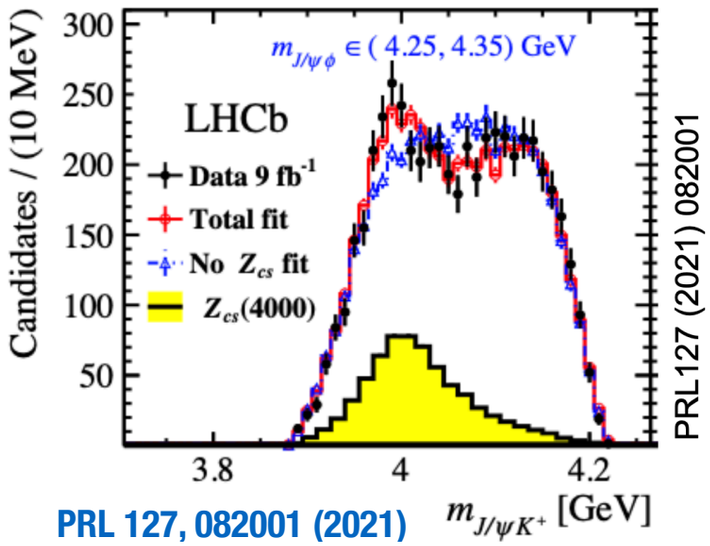
$$B^0 \to \psi(2S)K^+\pi^-$$



PRD 92, 112009 (2015) LHCb

$Z_{cs}^+(4000)$

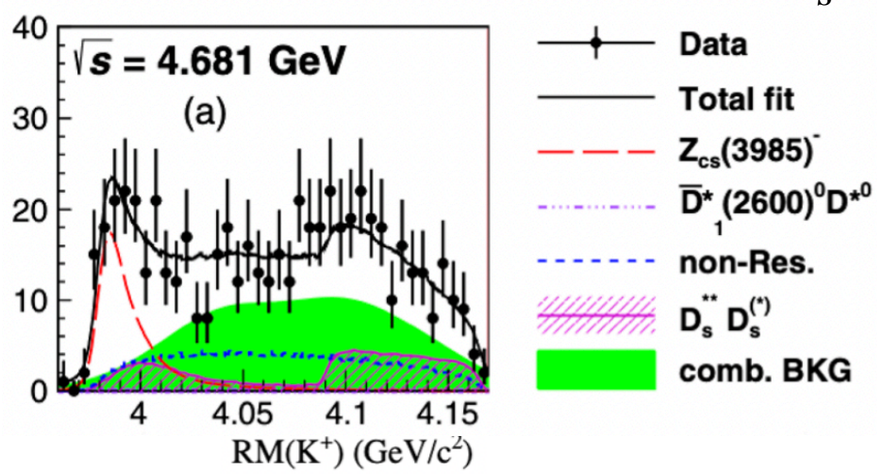
$$B^+ \to J/\psi\phi K^+$$



PRL 127, 082001 (2021)

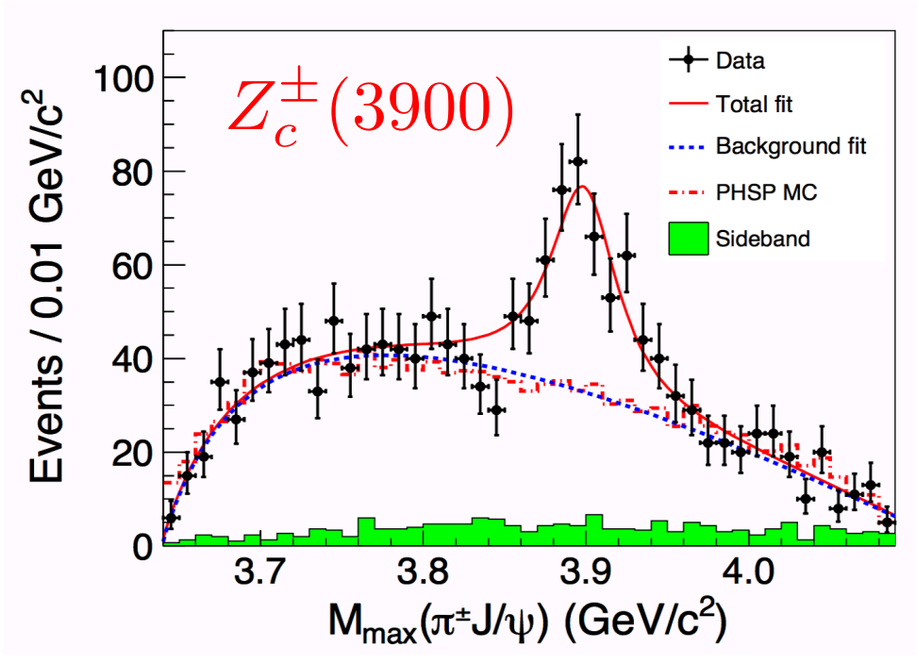
$Z_{cs}^+(3985)$

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

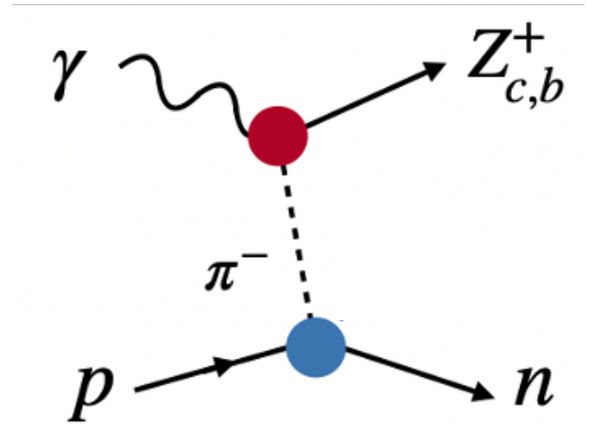


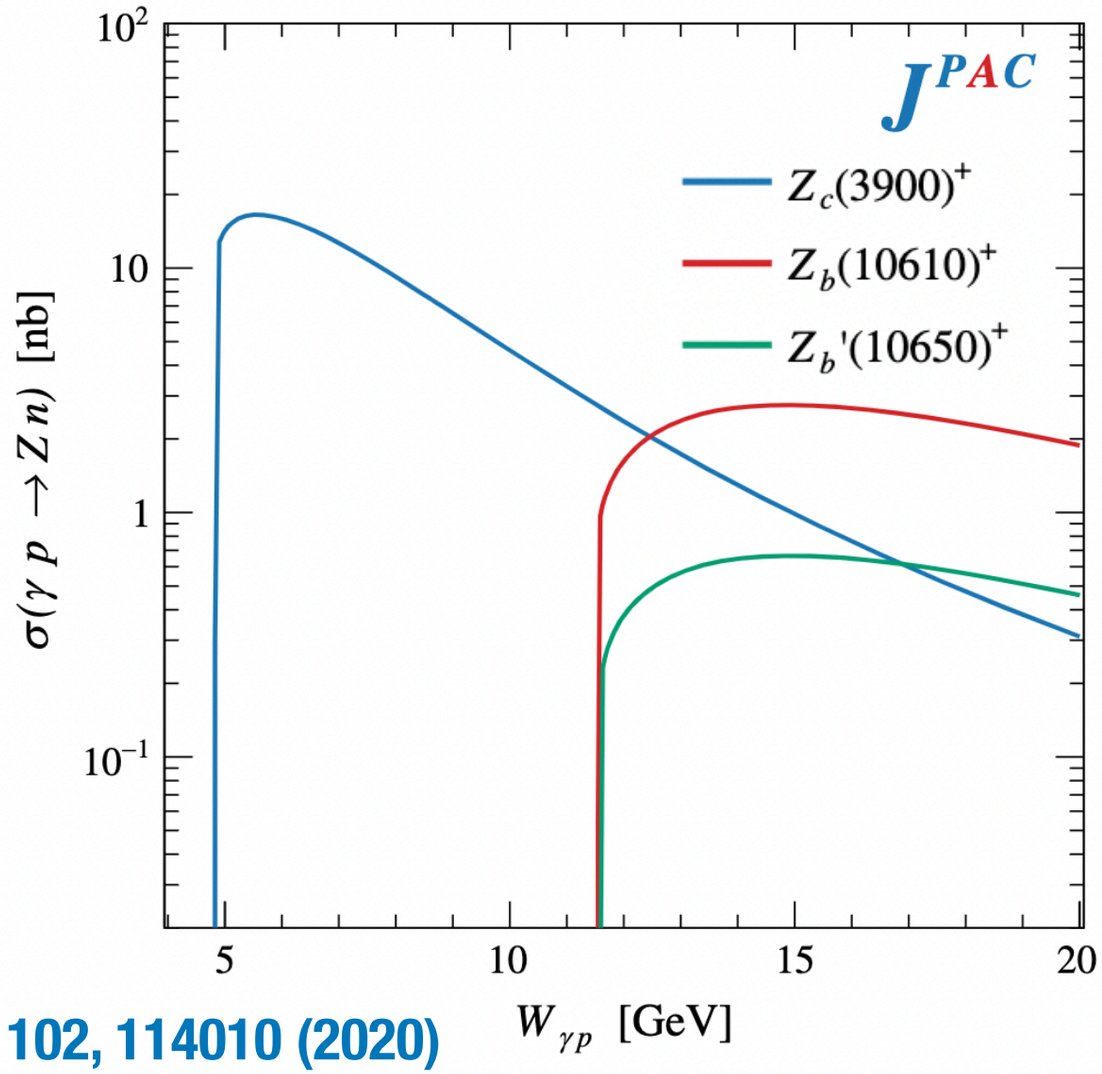
- Many observations of charged Z_c $(c\bar{c}q\bar{q})$ and Z_{cs} $(c\bar{c}s\bar{q})$
- Production mechanism dependent masses and widths (e^+e^- vs B decay)

Charged tetraquark candidates: Z_c



- 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



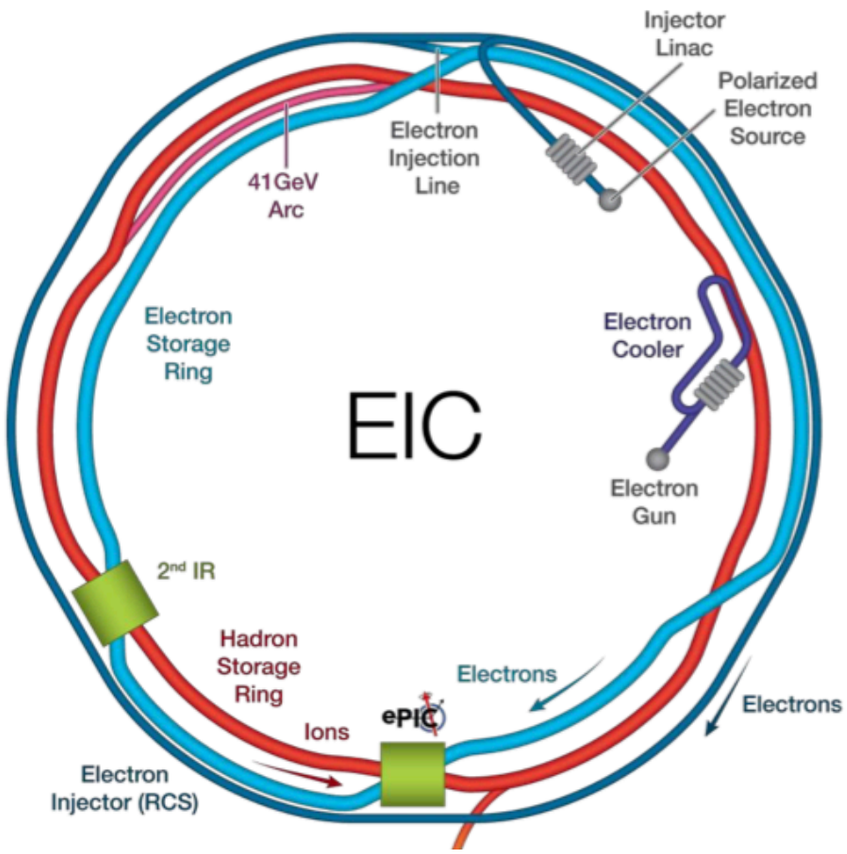


PRD 102, 114010 (2020)

Future XYZ photoproduction facilities

Electron Ion Collider (EIC)

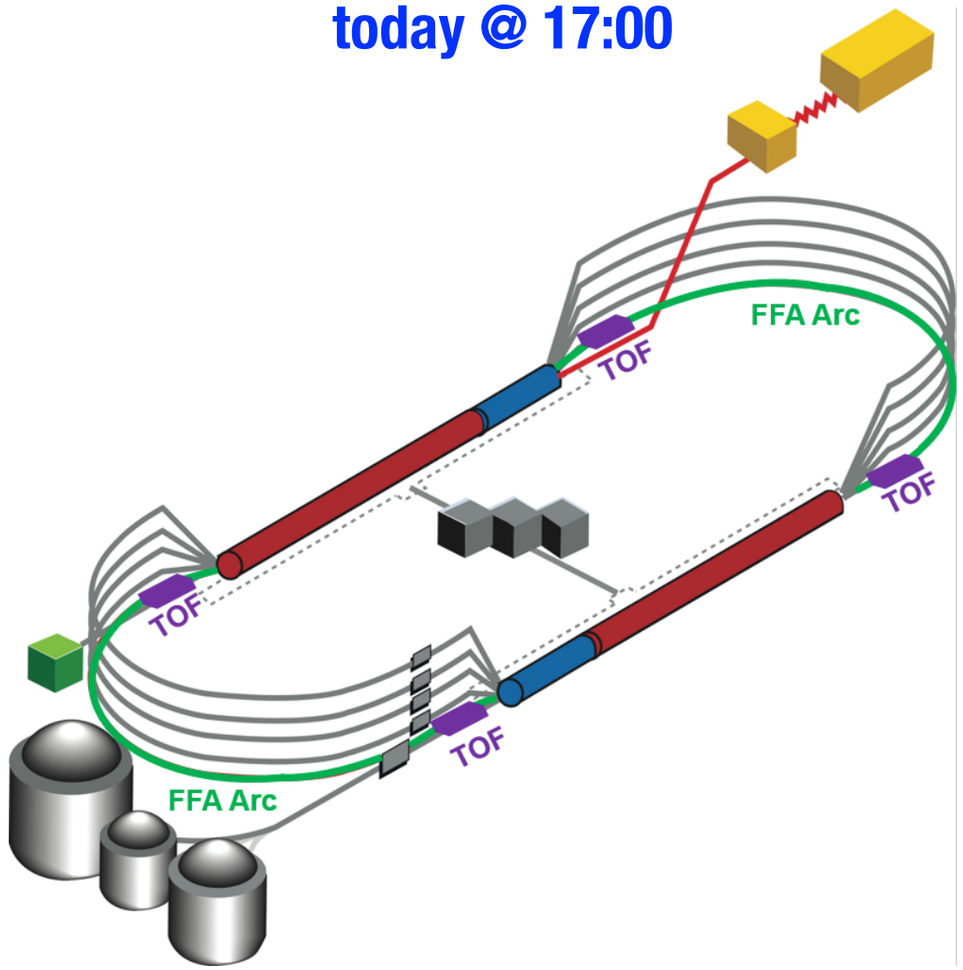
Abhay Deshpande
Today @ 16:30



CFNS Workshop: Exotic heavy meson spectroscopy with the EIC
https://www.stonybrook.edu/cfns/activities/conferences.php
Stony Brook, USA April 14-17 2025

Jefferson Lab upgrade:
E_e = 12 → 22 GeV

Patrizia Rossi
today @ 17:00

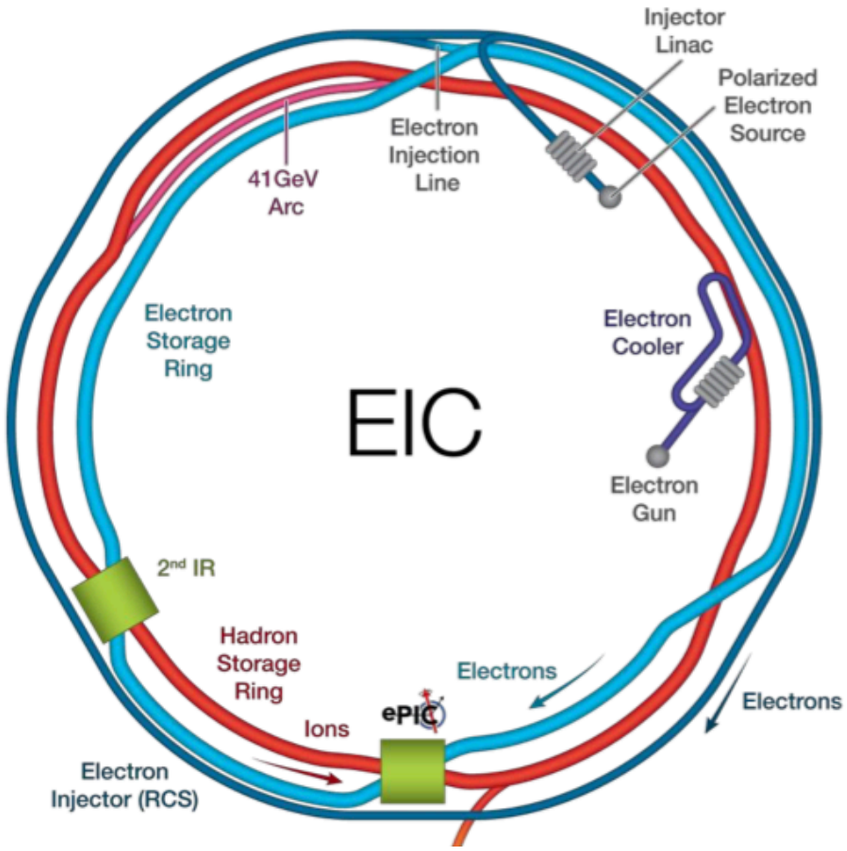


Workshop on Science at the Luminosity Frontier: Jefferson Lab at 22 GeV
https://www.jlab.org/conference/dec24luminosity22gev
Frascati, Italy December 9-13, 2025

Future XYZ photoproduction facilities

Complementary access to charmonium photoproduction with higher energy facilities

Electron Ion Collider (EIC)

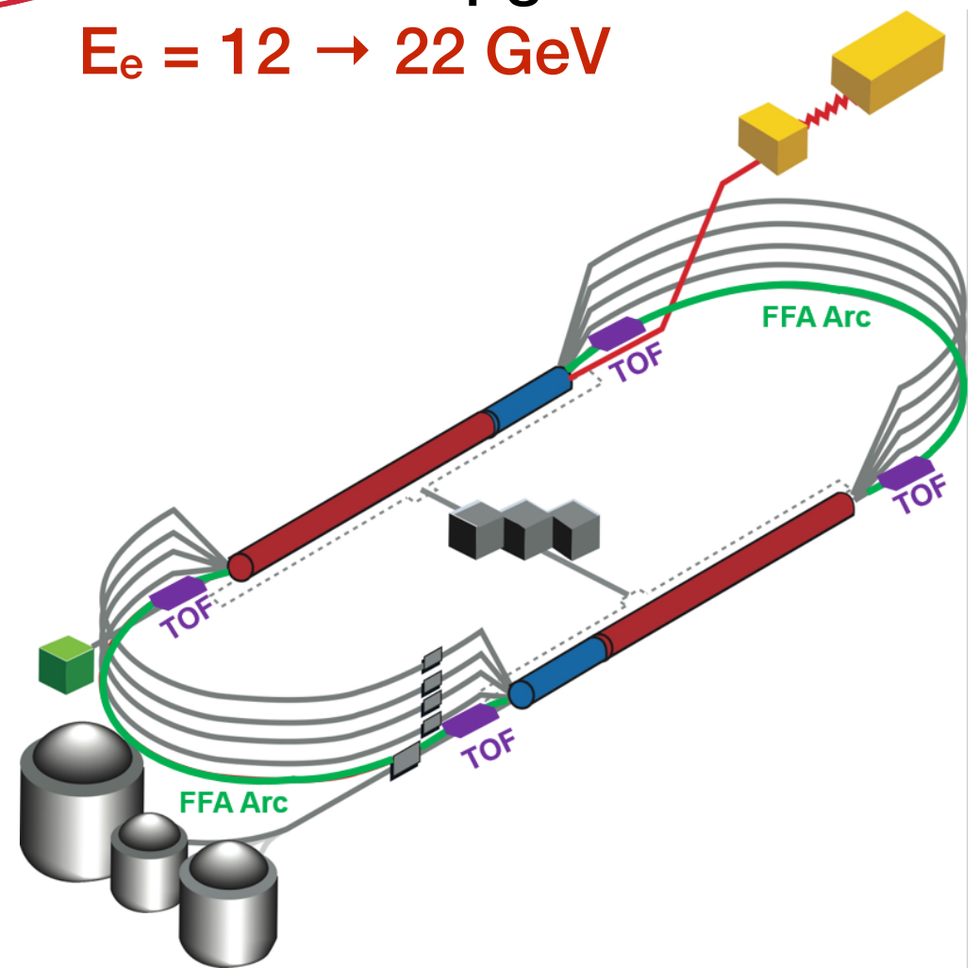


$$\sqrt{s}_{\gamma p} = 5 - 141 \text{ GeV}$$

$$\mathscr{L}_{ep} = 10^{33} - 10^{34}\ cm^{-2}s^{-1}$$

Jefferson Lab upgrade:

$E_e = 12 \rightarrow 22$ GeV

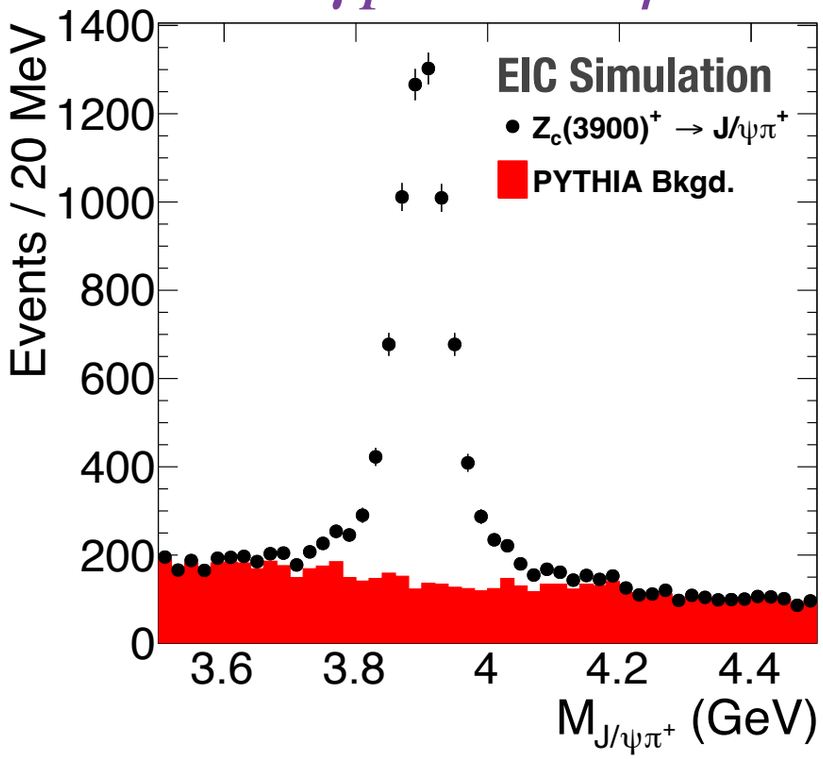


$$\sqrt{s}_{\gamma p} = 1.5 - 6.5 \text{ GeV}$$

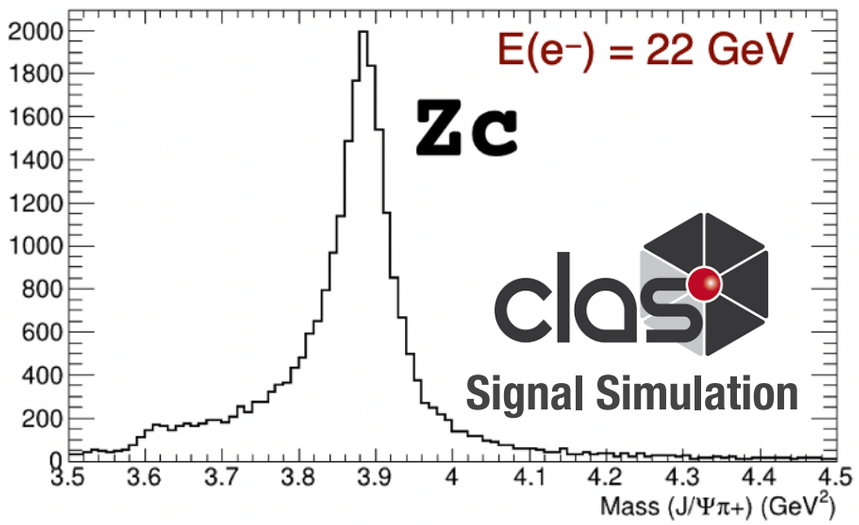
$$\mathscr{L}_{ep} = 10^{35} - 10^{37}\ cm^{-2}s^{-1}$$

Photoproduction of $Z_c^+(3900)$

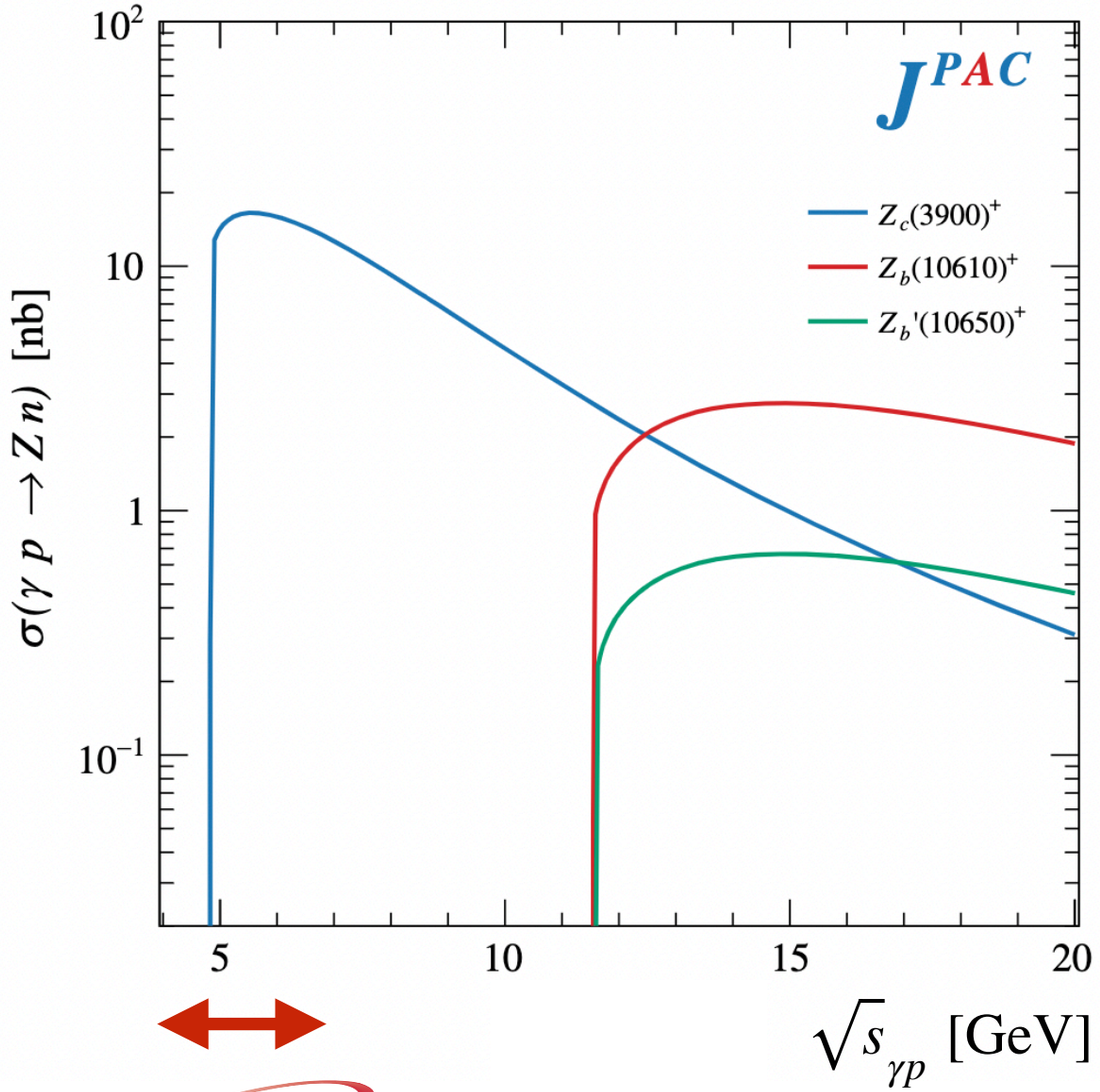
EIC: $\gamma p \to n J/\psi \pi^+$



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 with US-based photoproduction facilities
- Critical collaboration with theory: direct connections to first-principles calculations and phenomenological framework for fitting and interpreting data
- 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

JRS supported by DE-SC0023978

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