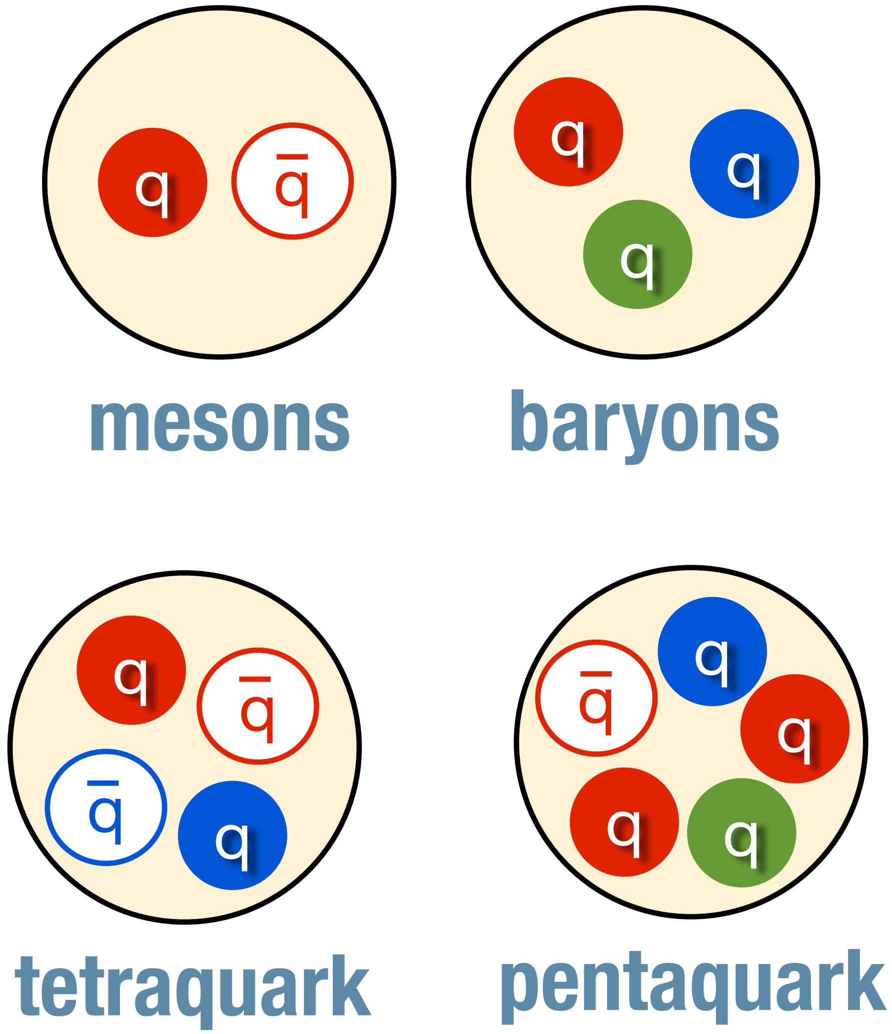
Perspectives for Hadron Spectroscopy in the USA

Justin Stevens

WILLIAM & MARY
CHARTERED 1693

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

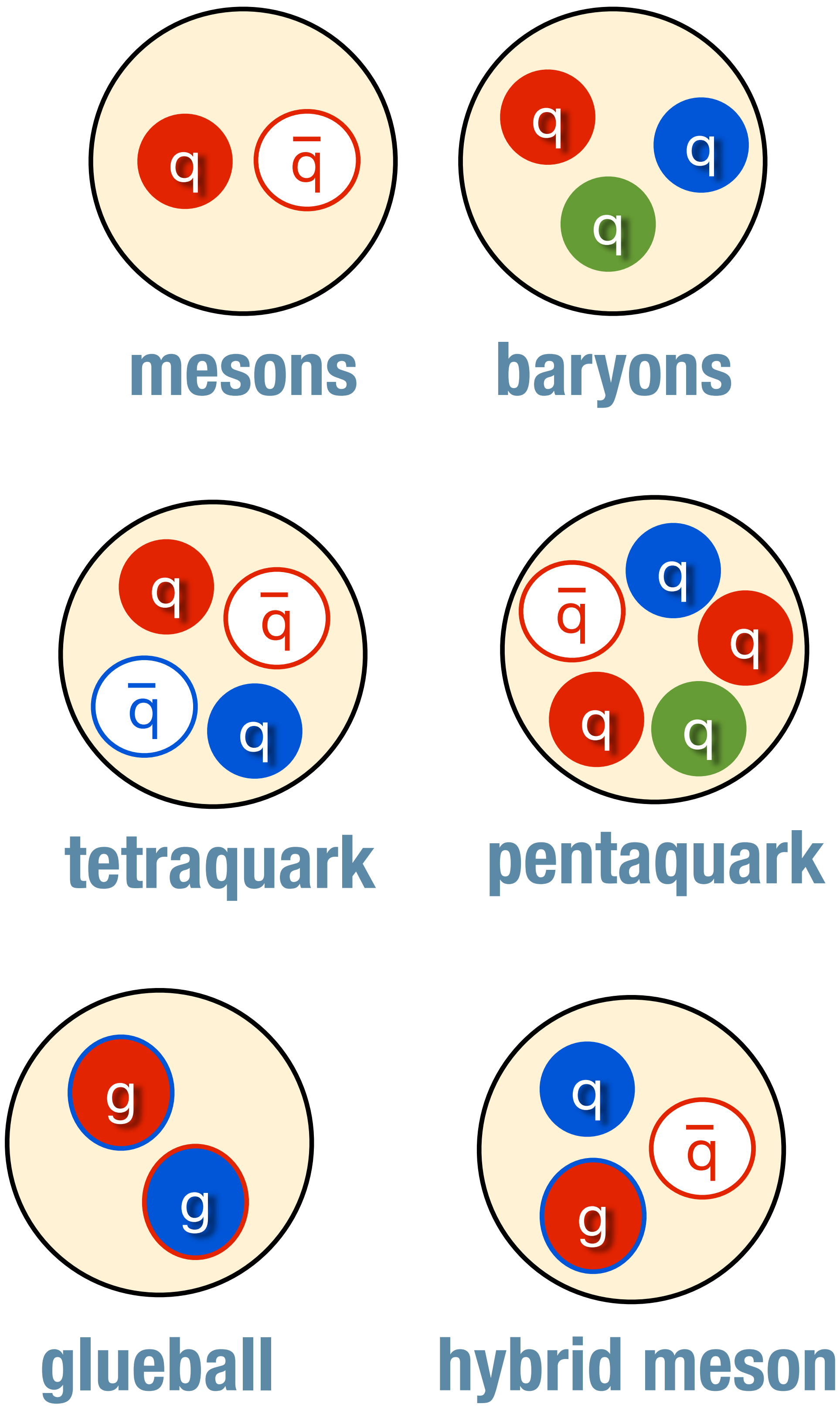
A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Some questions in hadron spectroscopy

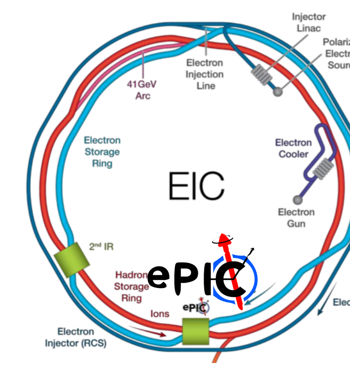


What are the dynamics of the strong interaction that generate hadron mass?

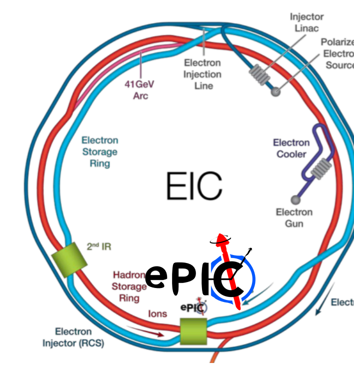
What is the nature/structure of the exotic candidates we've observed, and how can we probe them with new production mechanisms?

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

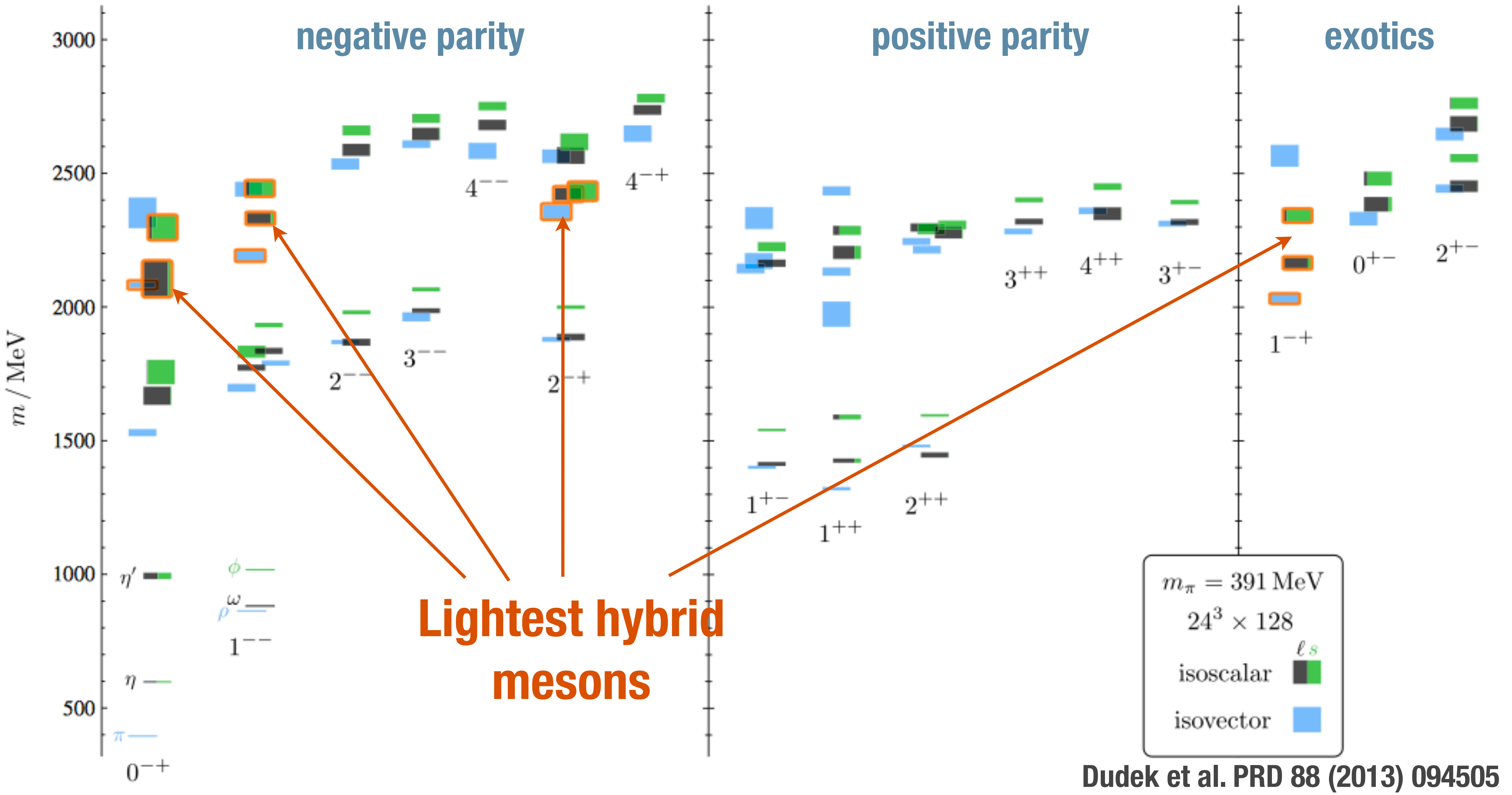
Experiment: international collaborations

	Heavy quarks ⟷	Light quarks
Electromagnetic probes	e^+e^- BELLE, Belle II, BESIII, BaBar	$ep/\gamma p$ clas (CEBAF Large Acceptance Spectrometer), GlueX, EIC  **MAMI, ELSA, LEPS, etc.**
Hadronic probes	$\bar{p}p$: DØ, CDF II pp: CMS, ATLAS, LHCb	$\bar{p}p$: panda πp: COMPASS **J-PARC, HADES, etc.**

Experiment: international collaborations

	Heavy quarks ⟷	Light quarks
		US-based
Electromagnetic probes	e^+e^- BELLE · BESIII Belle II · BaBar	$ep/\gamma p$ clas (CEBAF Large Acceptance Spectrometer) · GlueX ·  **MAMI, ELSA, LEPS, etc.**
Hadronic probes	$\bar{p}p$: DØ, CDF pp: CMS, ATLAS, LHCb	$\bar{p}p$: panda πp: COMPASS **J-PARC, HADES, etc.**

Theory: US-based collaborations

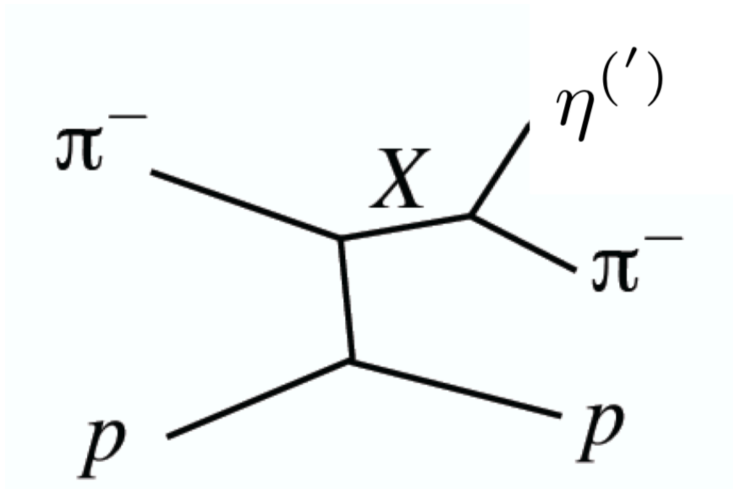


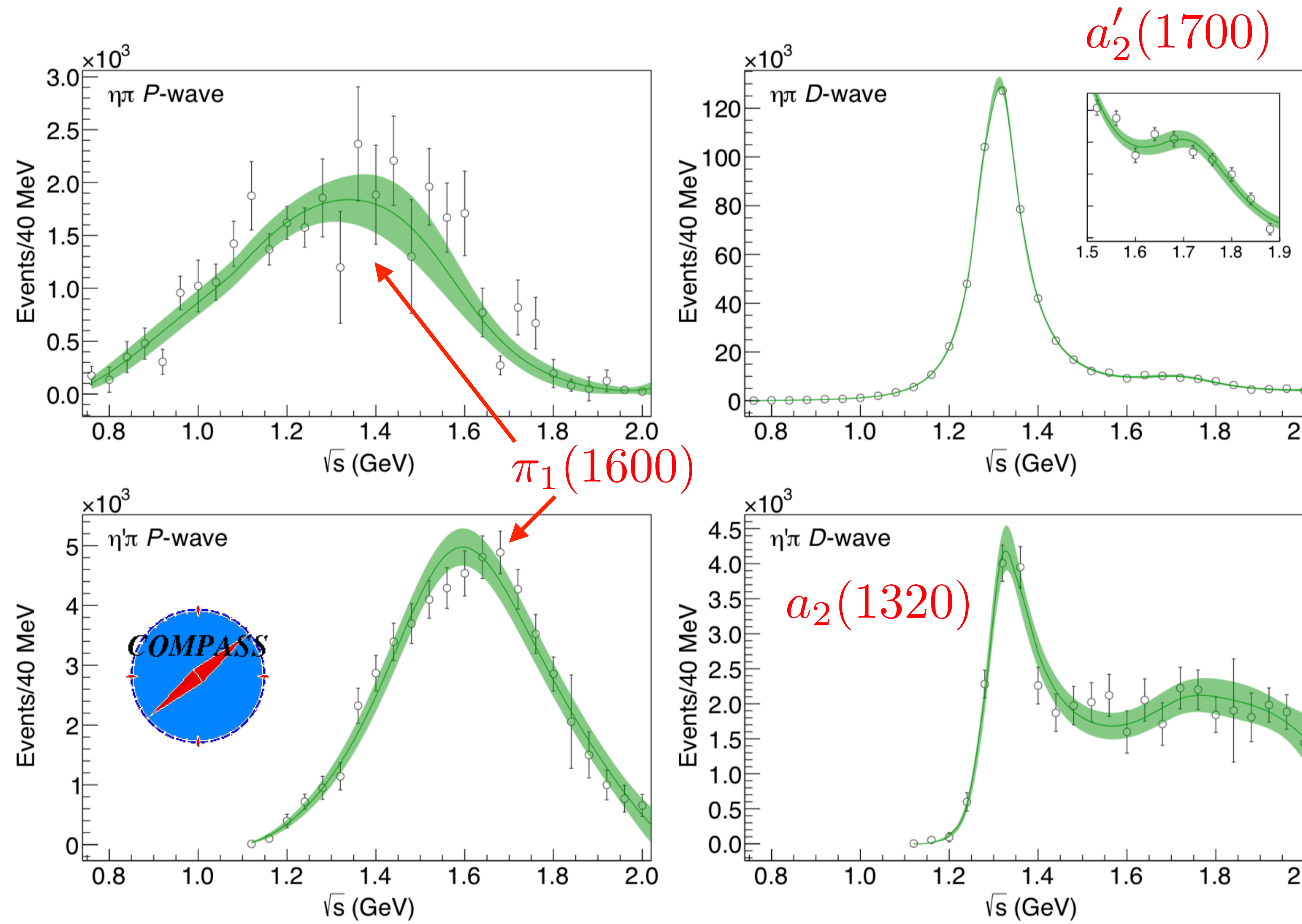
Dudek et al. PRD 88 (2013) 094505

Many calculations of meson-meson coupled channel scattering on the lattice, recently including external electromagnetic currents

Hadron Spectrum Collaboration

Theory: US-based collaborations





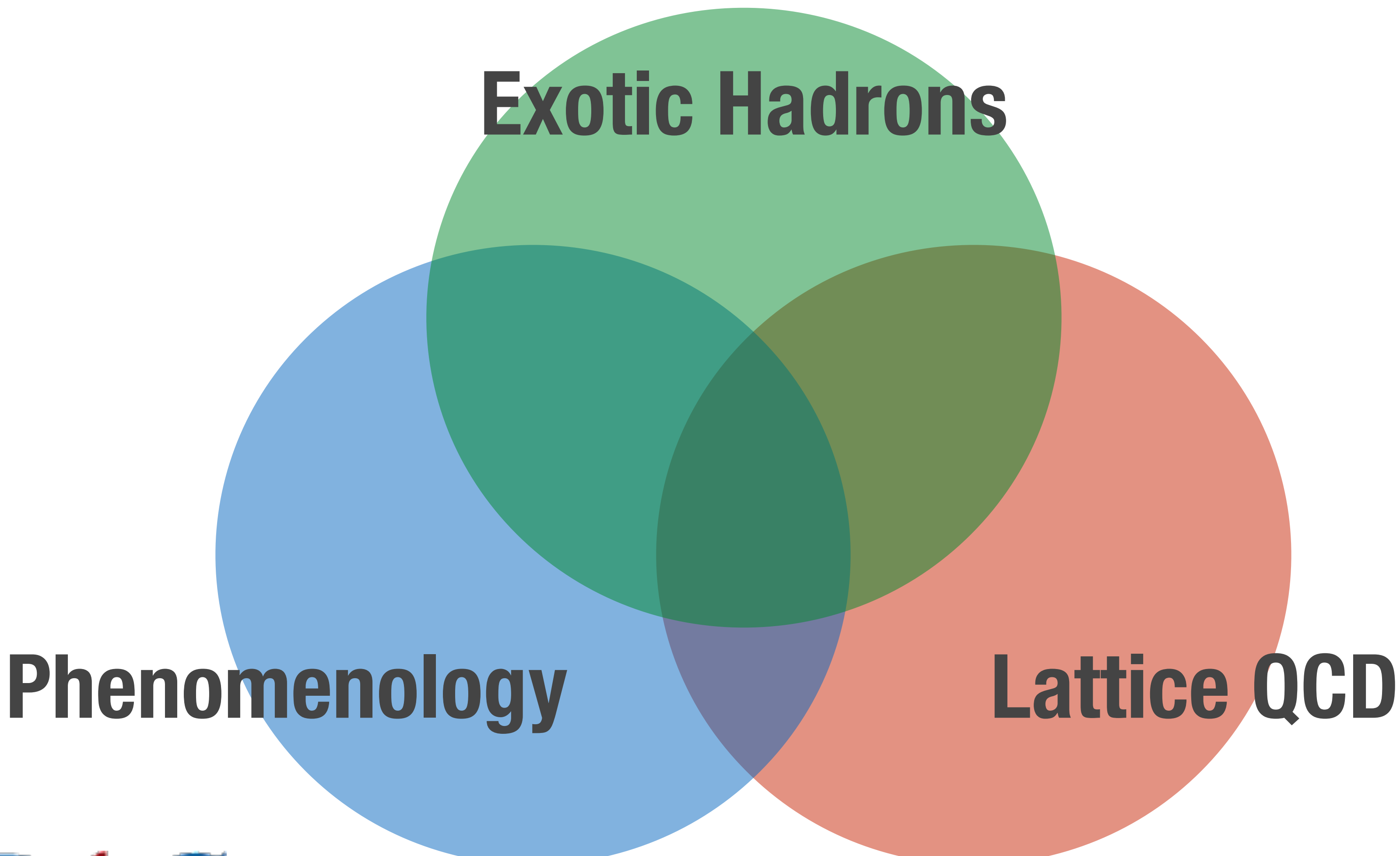
Coupled channel fit to $\eta\pi$ and $\eta'\pi$ determine pole positions for a_2, a_2' and single exotic $\pi_1(1600)$

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

Theory: US-based collaborations

ExoHAD
EXOTIC HADRONS TOPICAL COLLABORATION

DOE Nuclear Theory Topical Collaboration
https://www.exohad.org/



JPAC

hadspec
Hadron Spectrum Collaboration

US Nuclear Physics: Long Range Plan (LRP)

https://nuclearsciencefuture.org/

- Decadal vision for Nuclear Physics in the USA
- Recommendations to US agencies, DOE and NSF, on funding priorities

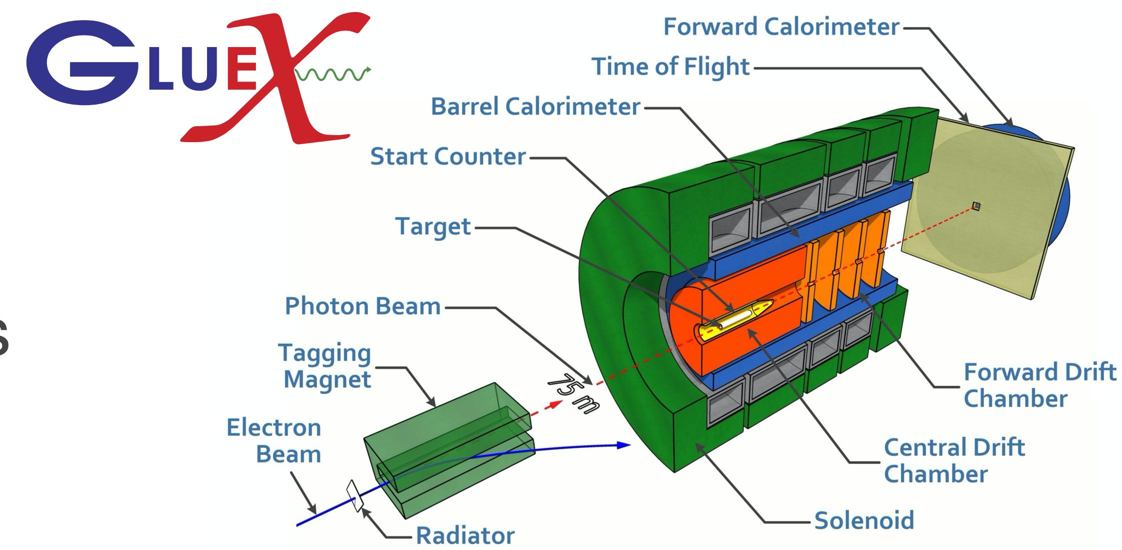
> **LRP RECOMMENDATION 1**
> **The highest priority of the nuclear science community is to capitalize on the extraordinary opportunities for scientific discovery made possible by the substantial and sustained investments of the United States. We must draw on the talents of all in the nation to achieve this goal.**

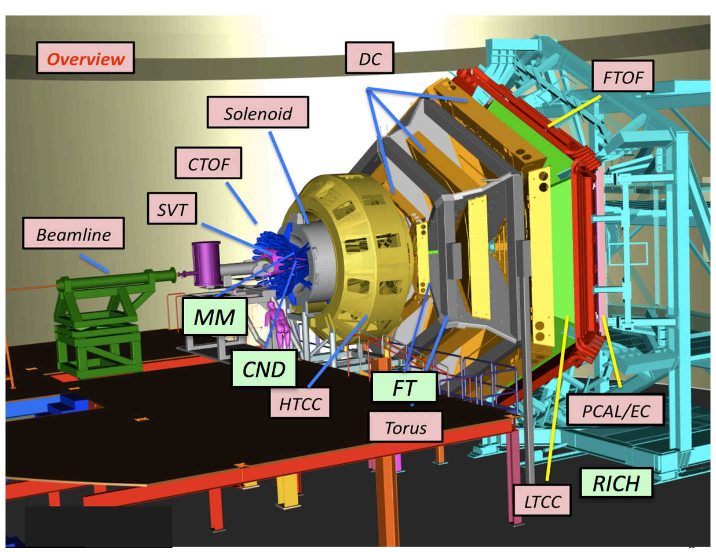
- What does it mean for Hadron Spectroscopy?

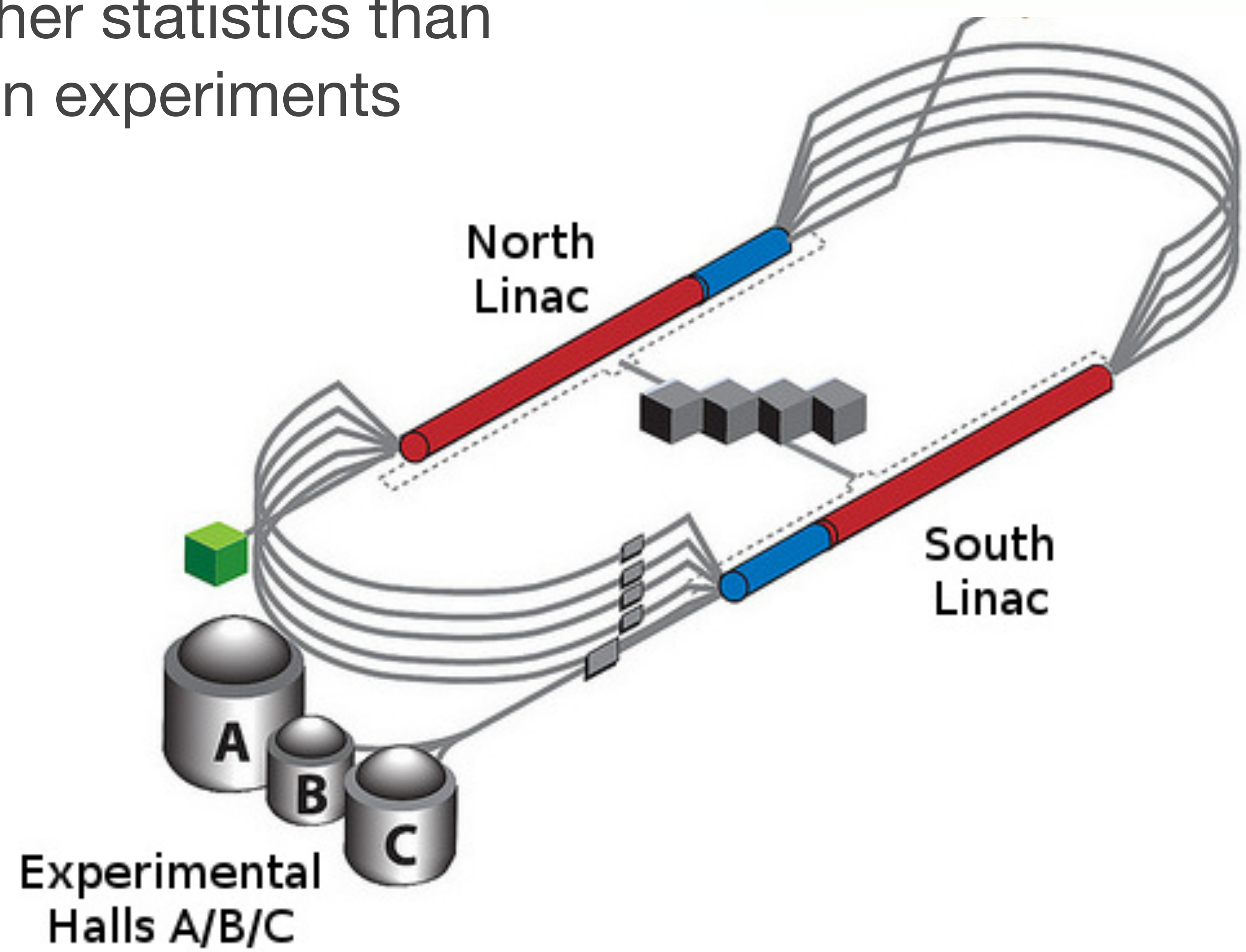
Jefferson Lab

LRP: The GlueX and CLAS12 detectors at Jefferson Lab provide powerful tools for studying the spectrum of hadrons built from light quarks and gluons.

- 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





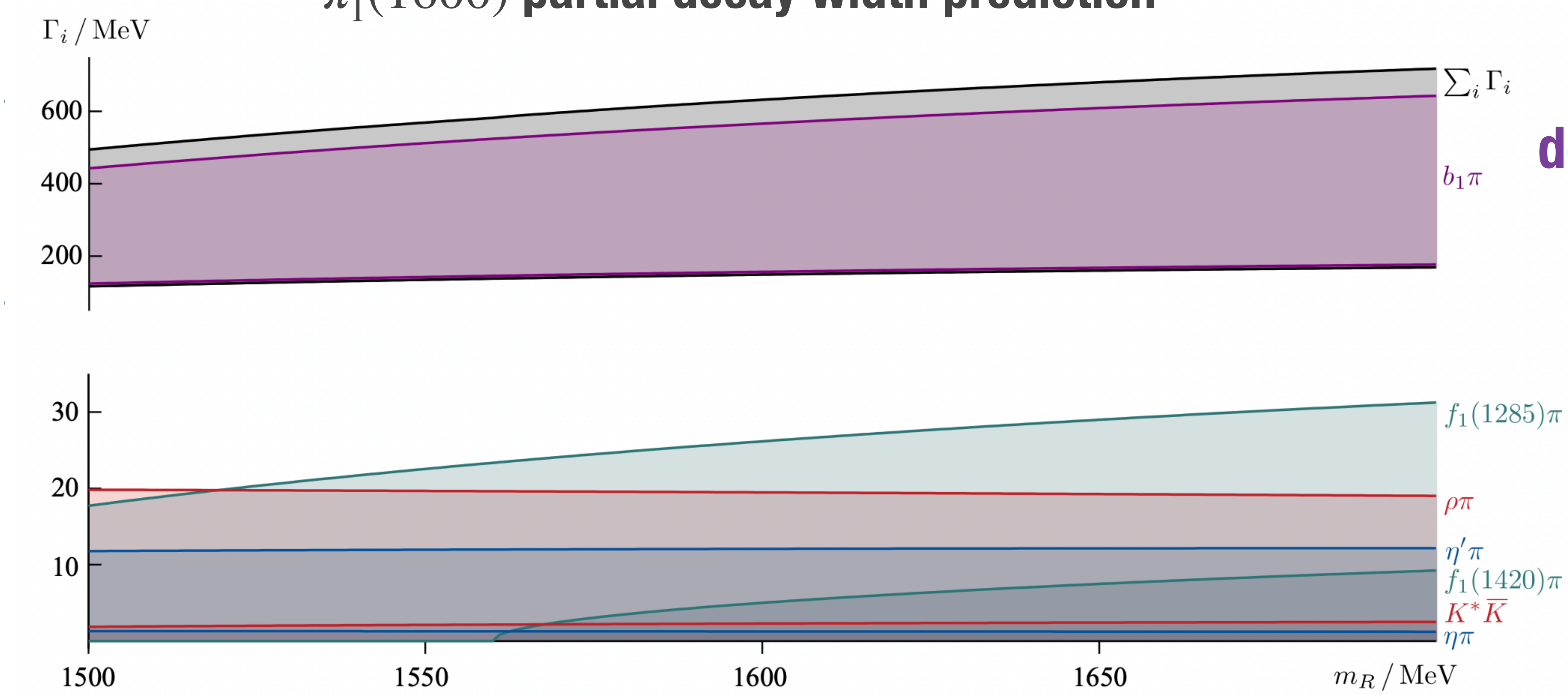


Meson spectroscopy: search for $\pi_1(1600)$

- 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**



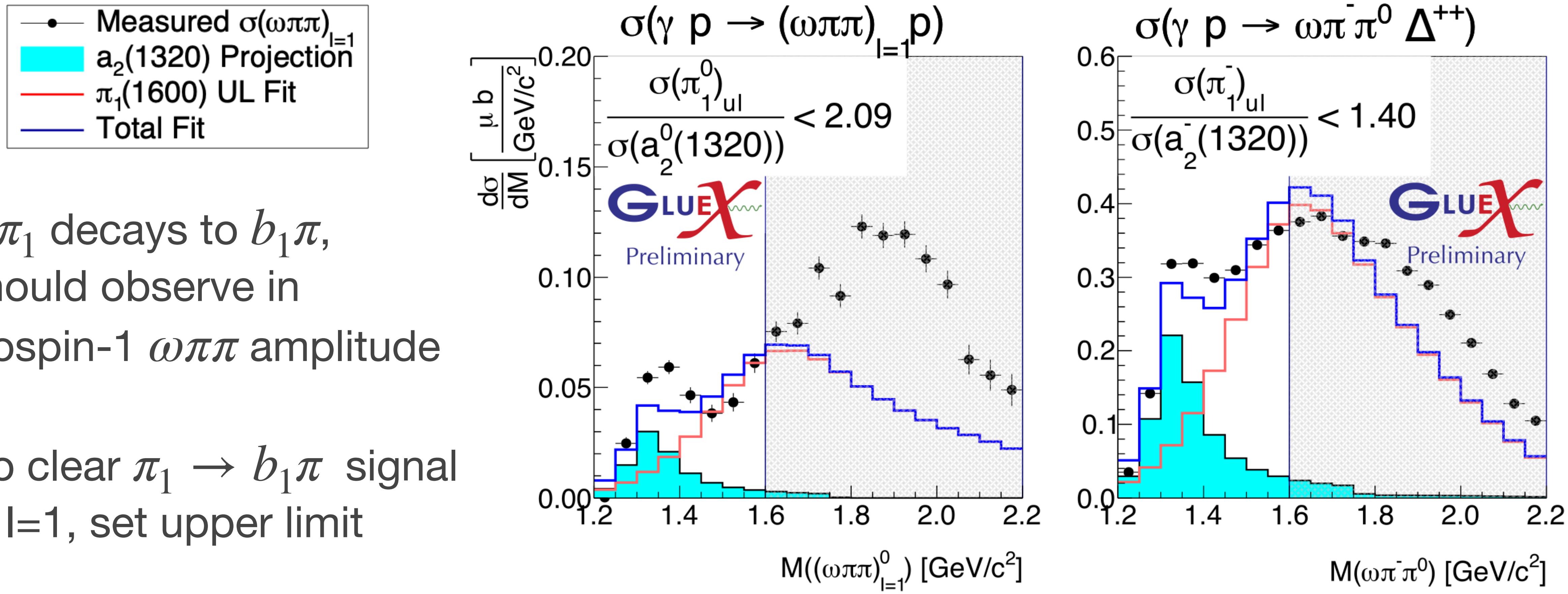
dominant coupling to $b_1\pi \to \omega\pi\pi$

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

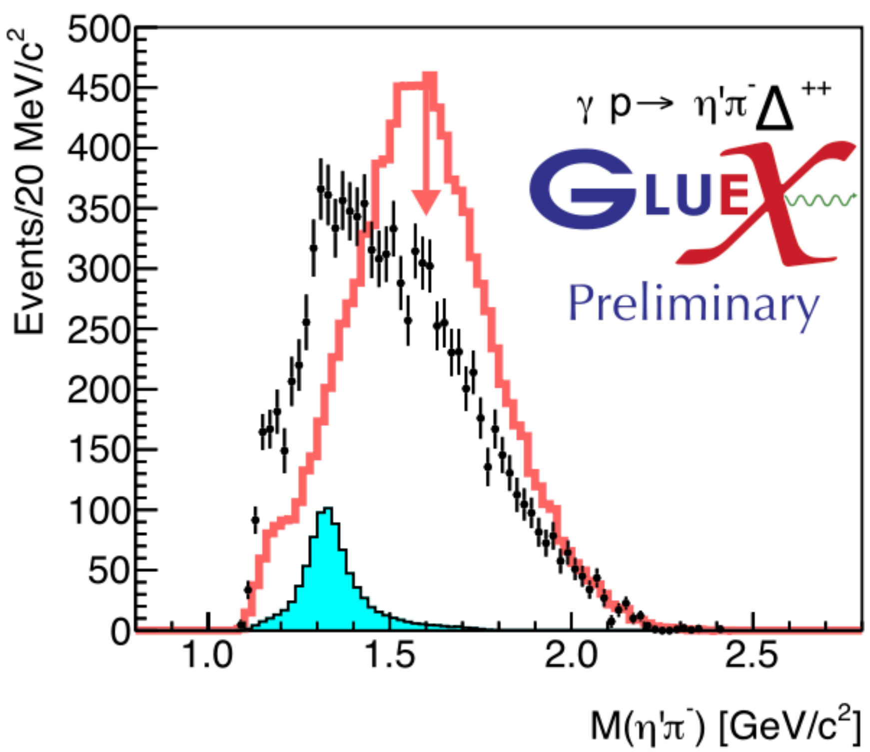
hadspec **Woss et al. PRD 103 (2021) 054502**

Meson spectroscopy: GlueX

Peter Hurck
Mon @ 15:45



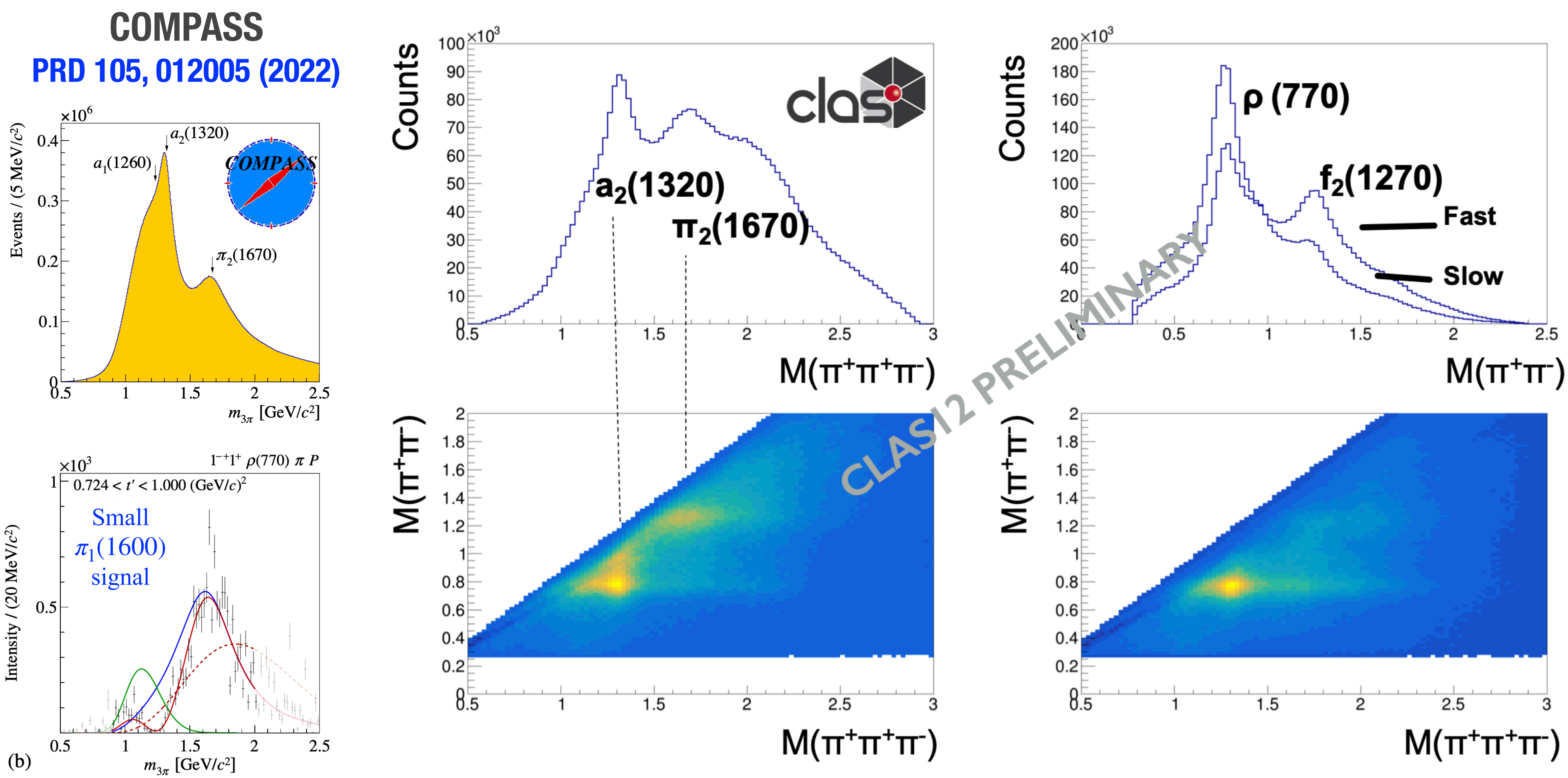
- If π_1 decays to $b_1\pi$, should observe in isospin-1 $\omega\pi\pi$ amplitude
- No clear $\pi_1 \rightarrow b_1\pi$ signal in I=1, set upper limit



- Upper limit on $\sigma(\pi_1)$ used with lattice QCD limits on $BR(\pi_1 \rightarrow \eta^{(\prime)}\pi)$ to project upper limits in these decay modes

LRP: GlueX has already collected a photoproduction dataset of unprecedented size and quality…

Meson spectroscopy: clas

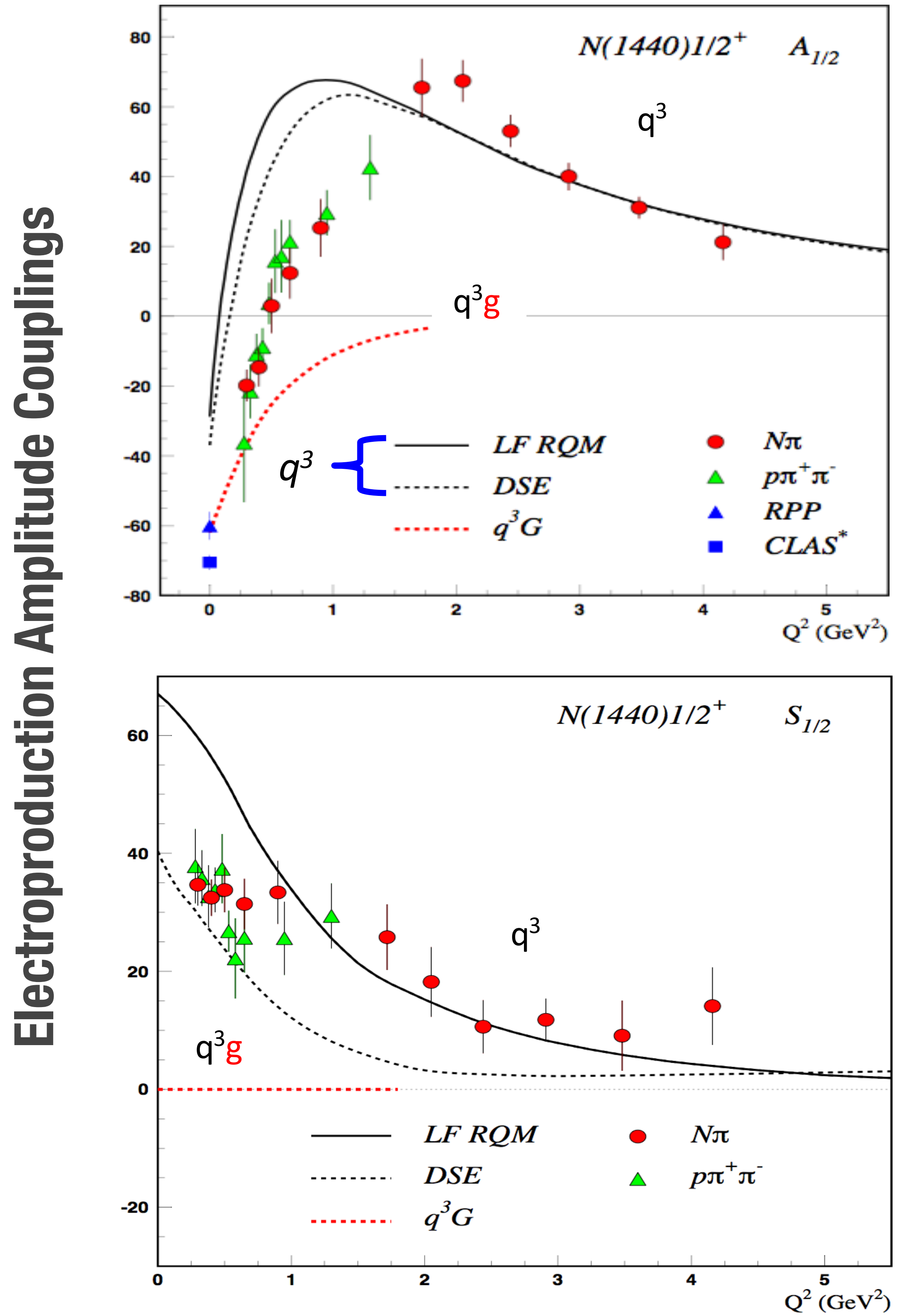


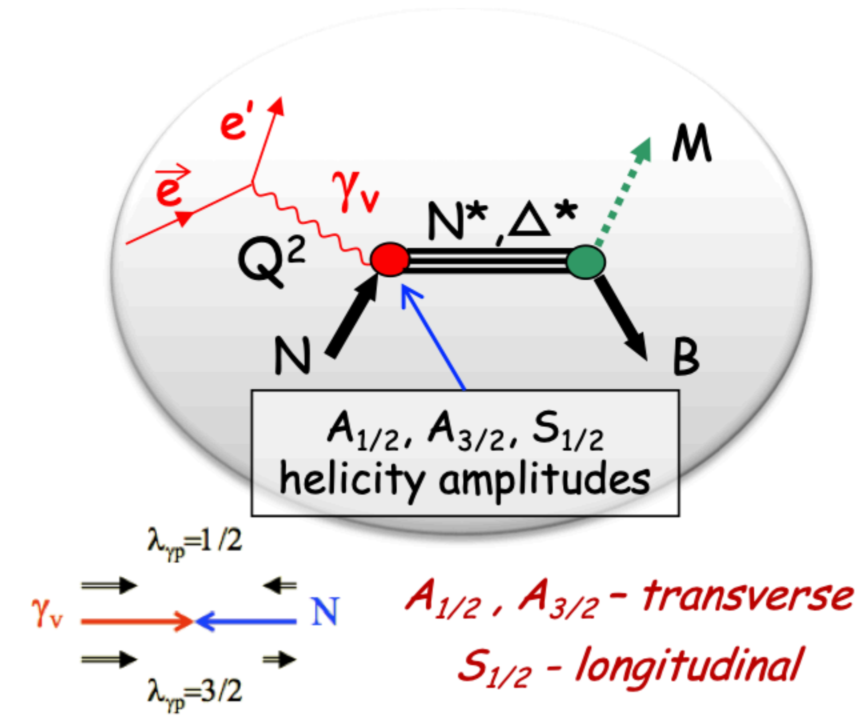
- Unique $\pi^+\pi^+\pi^-$ dataset to compare with observations of $\pi_1(1600)$ signal from COMPASS

Baryon spectroscopy: clas

Patrick Achenbach: next

Daniel Carman
Wed @ 1:30

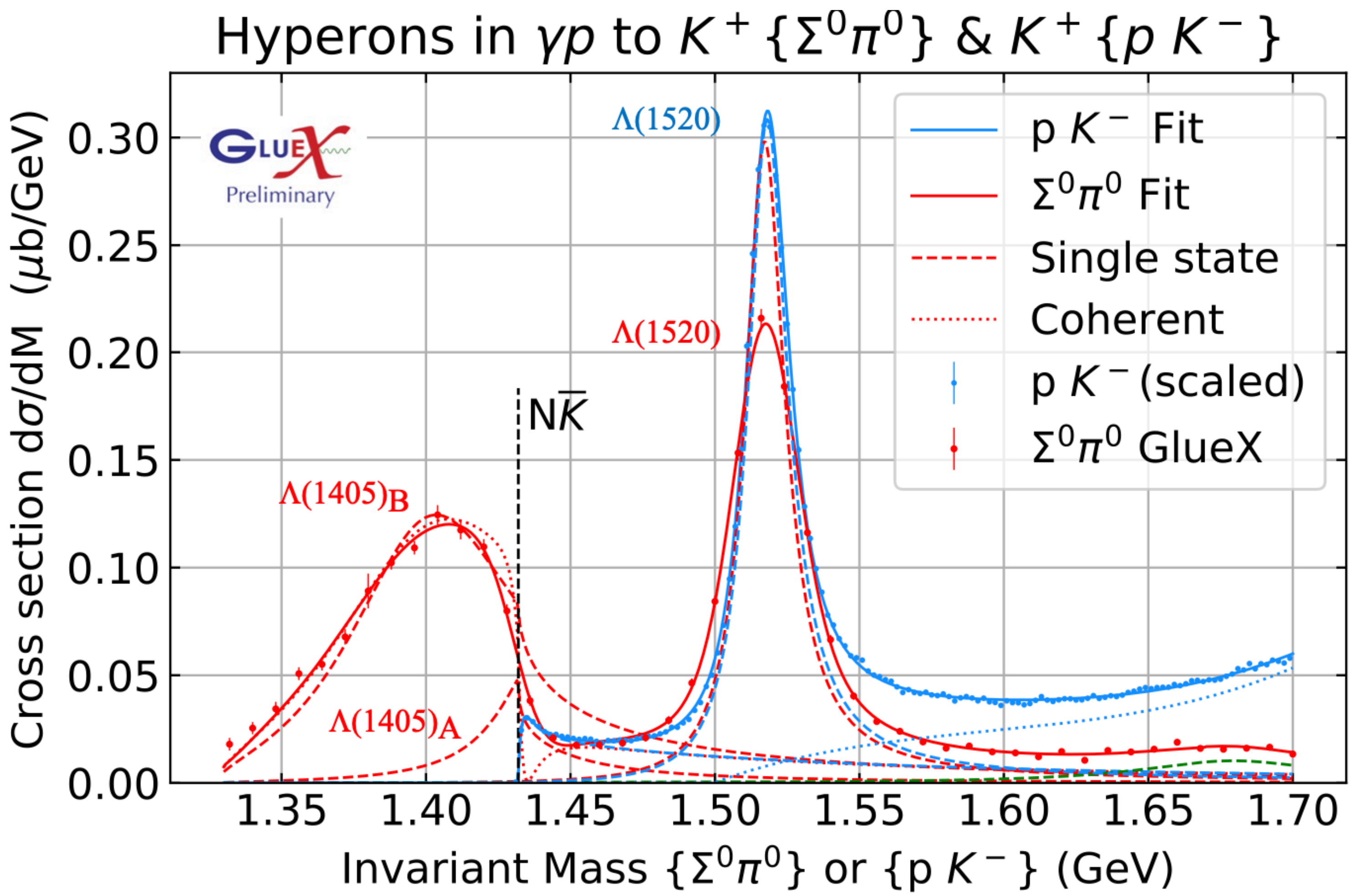


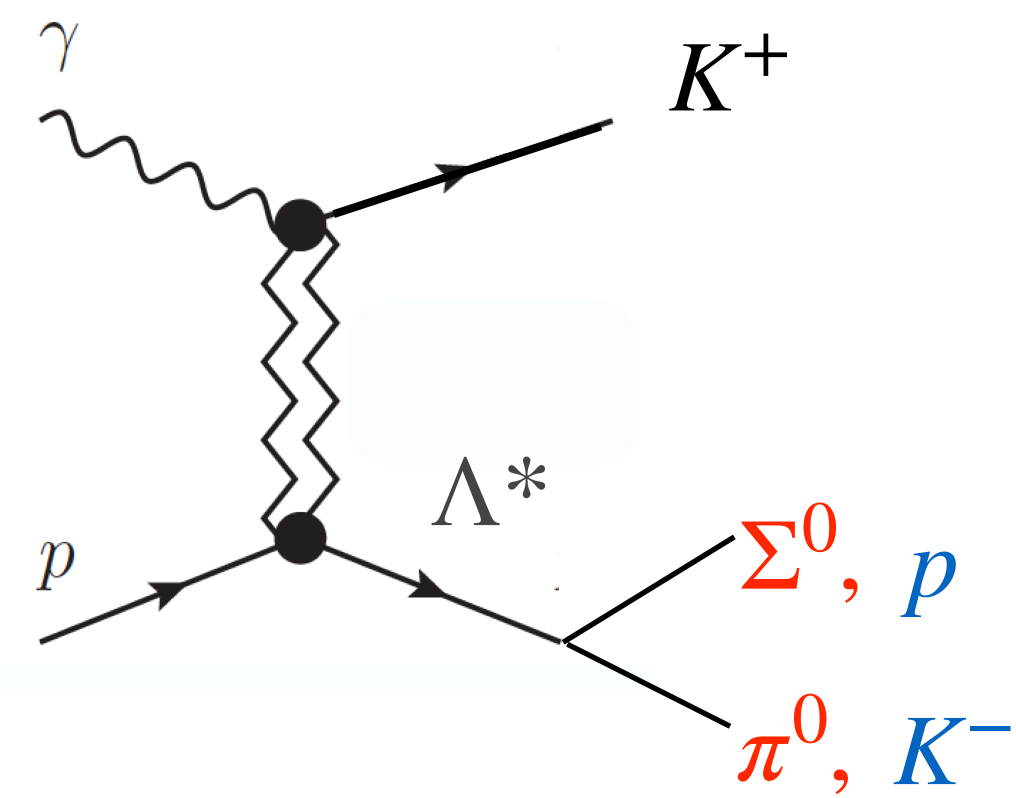


LRP: A robust experimental program with CLAS12 has focused on measurements of the transitions between the ground and excited baryon states for a range of energy and momentum transfer Q^2, which will enable us to study how hadron structure emerges from QCD.

Baryon spectroscopy: GlueX

Reinhard Schumacher
Tue @ 14:00



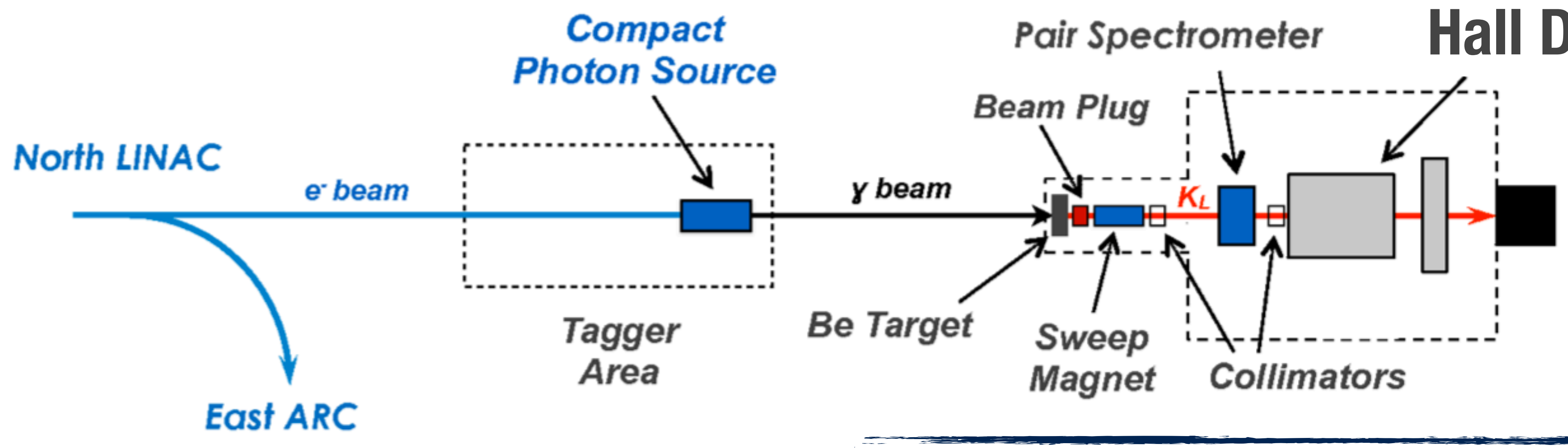


- t-channel photoproduction of exited baryons with both charged and neutral decay detection
- Doubly-strange Ξ^{-*} also accessible

LRP: Continuing to run CEBAF at 12 GeV will allow data to be collected even for relatively rare decay modes; in parallel, analyses of increasingly complex final states will aim to map complete families of exotic hadrons.

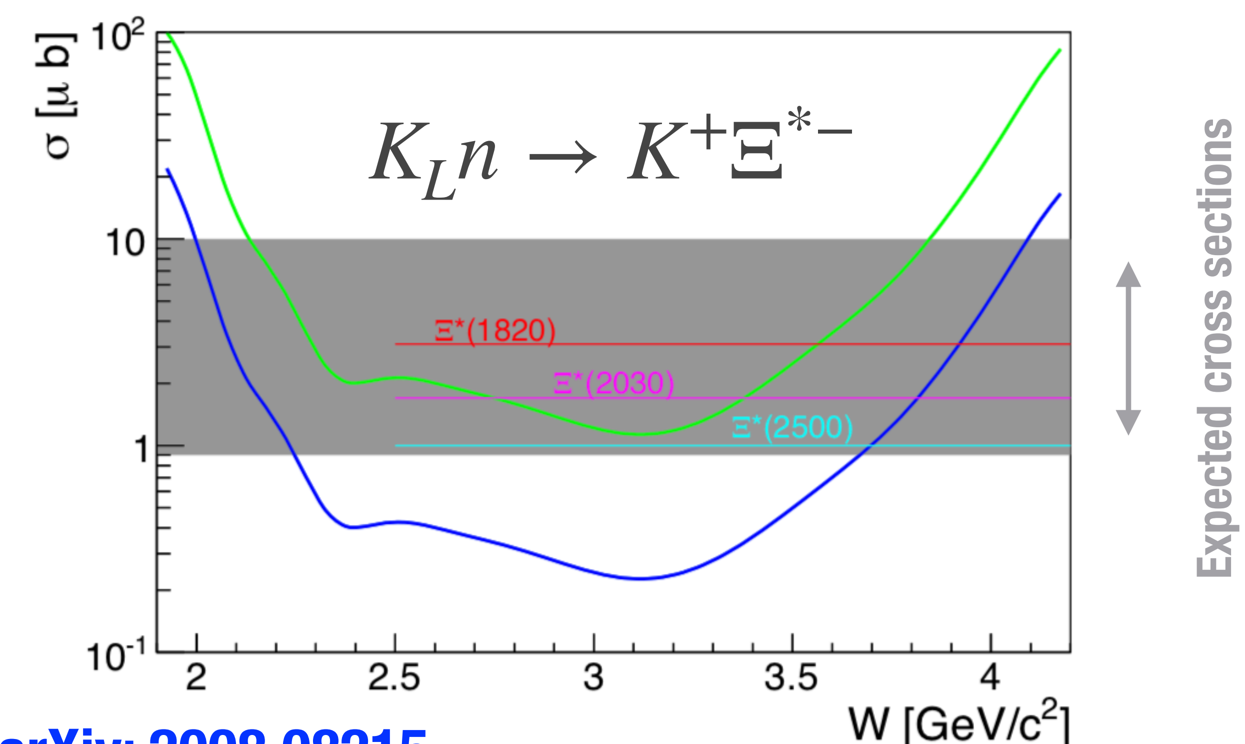
K_{Long} Facility (KLF)

Moskov Amaryan
Plenary Fri @ 10:15



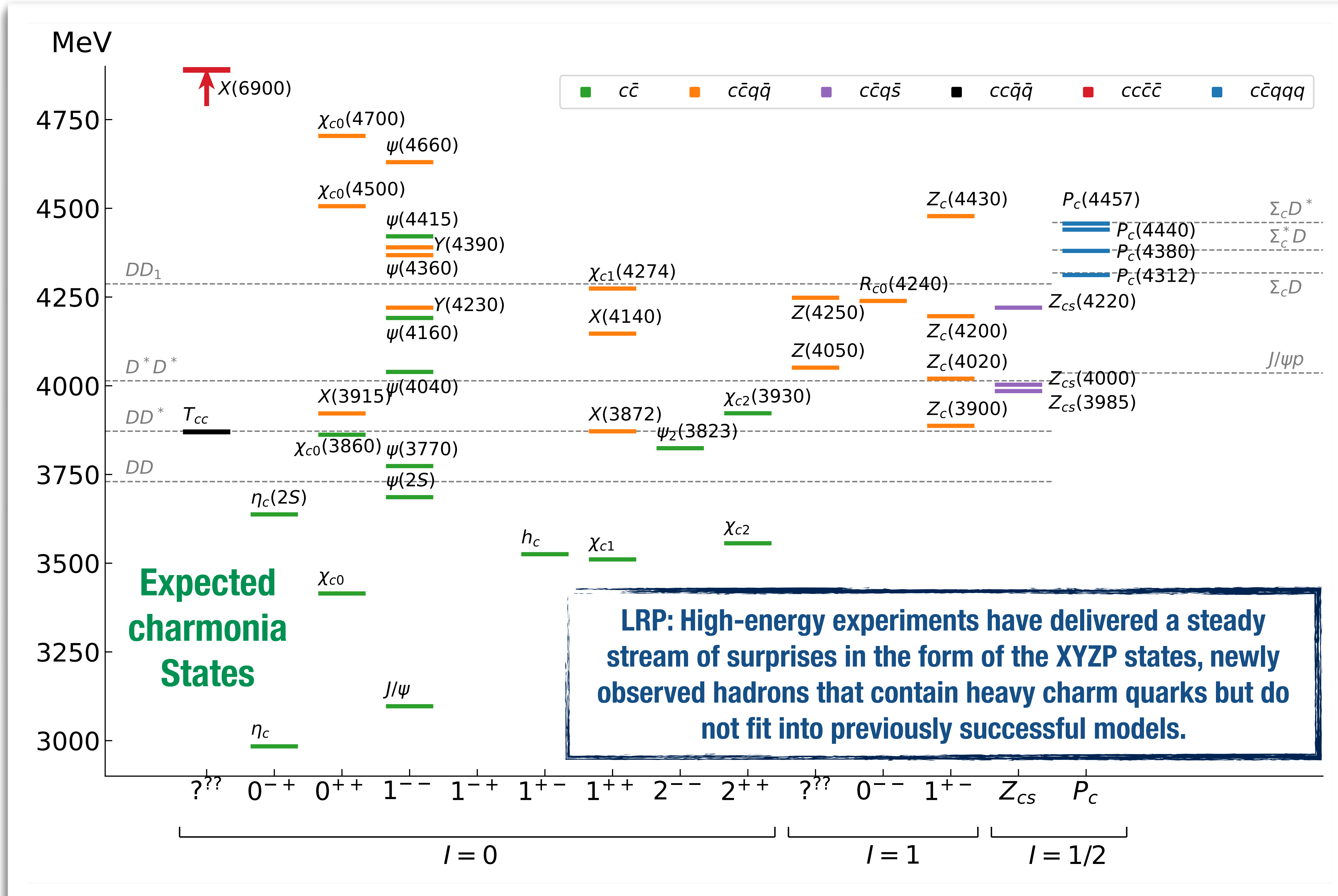
- Create secondary beam of neutral K_L and use Hall D spectrometer to study the $K_L p$ and $K_L n$ interactions
- Strange quark in initial state provides enhanced source of hyperon and strange meson production
- Broad program of searches for expected hyperon states not yet observed experimentally

LRP: Plans for Hall D include the approved eta factory experiment and the proposed intense K–long beamline that would serve new experiments in the GlueX spectrometer.



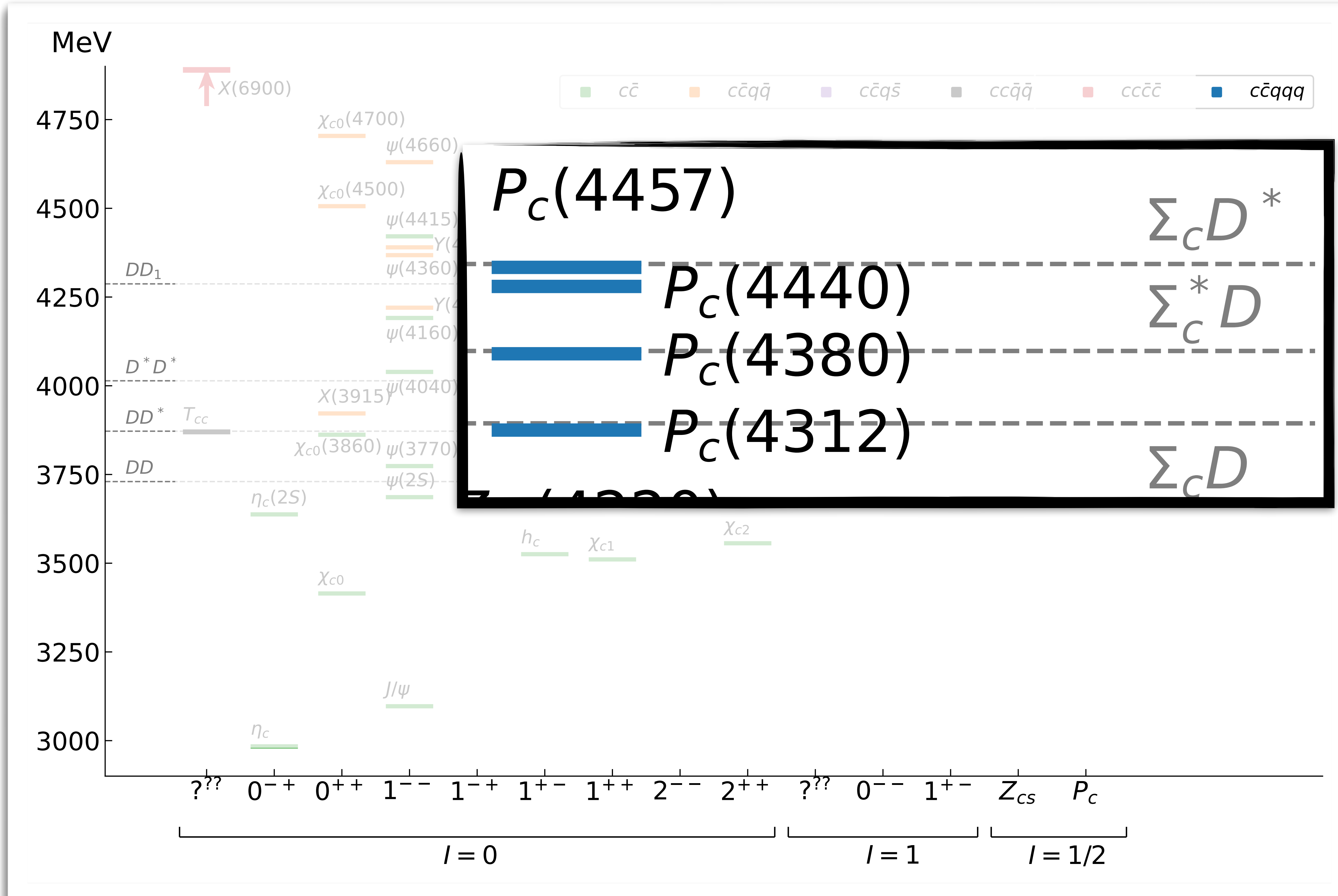
arXiv: 2008.08215

Heavy quark spectroscopy: $XYZP_c$



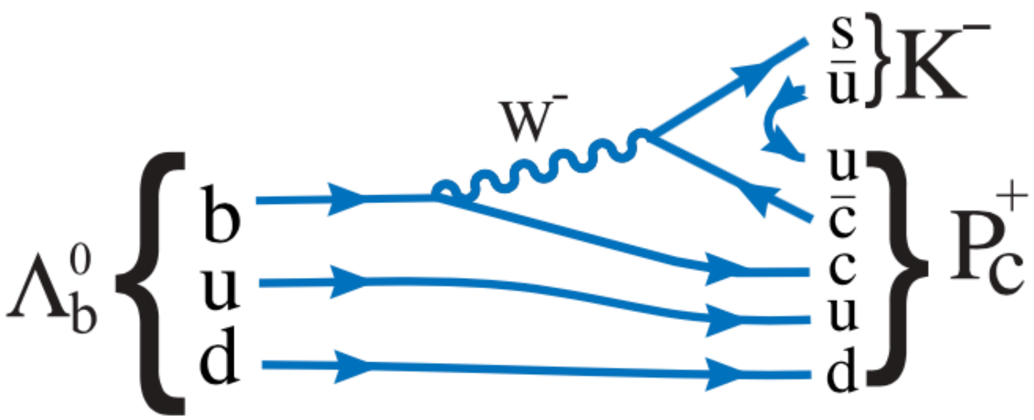
Recent review: JPAC **Prog. Part. Nucl. Phys. 127 (2022) 103981**

Pentaquarks



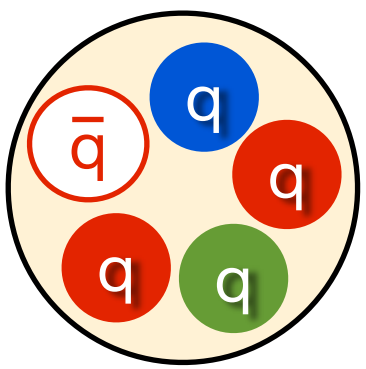
Recent review: JPAC **Prog. Part. Nucl. Phys. 127 (2022) 103981**

Pentaquark observation and interpretation

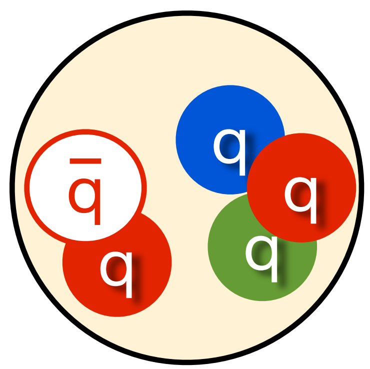


Gary Robertson
Plenary Wed @ 11:30

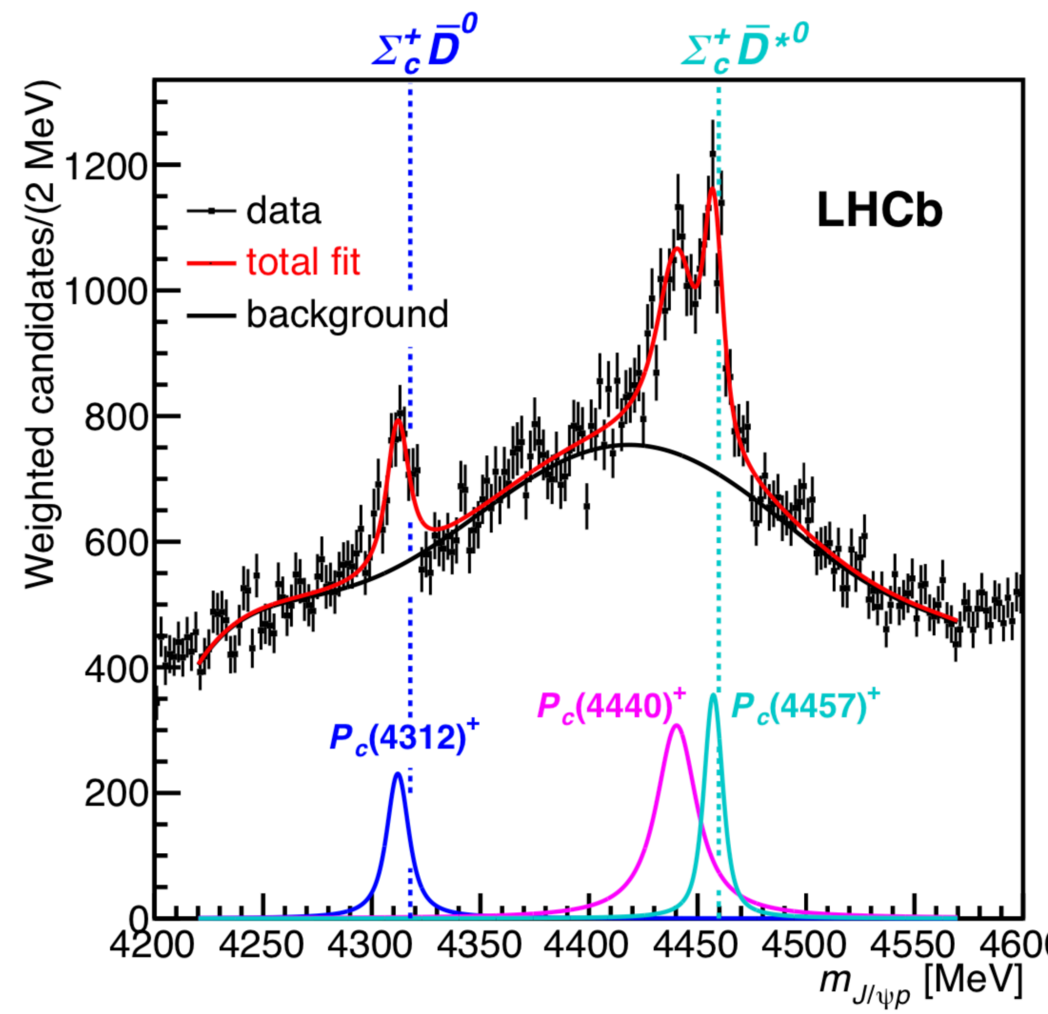
$$\Lambda_b \to J/\psi p K^-$$



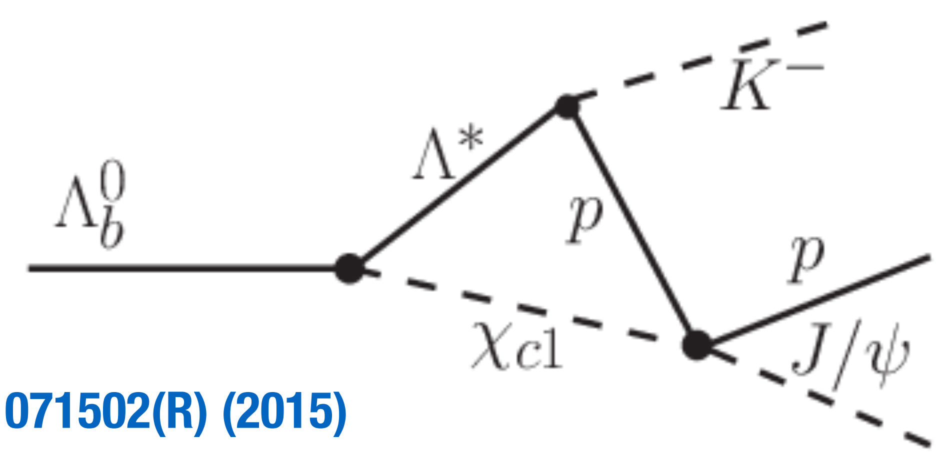
pentaquark



molecular



PRL 122, 222001 (2019)

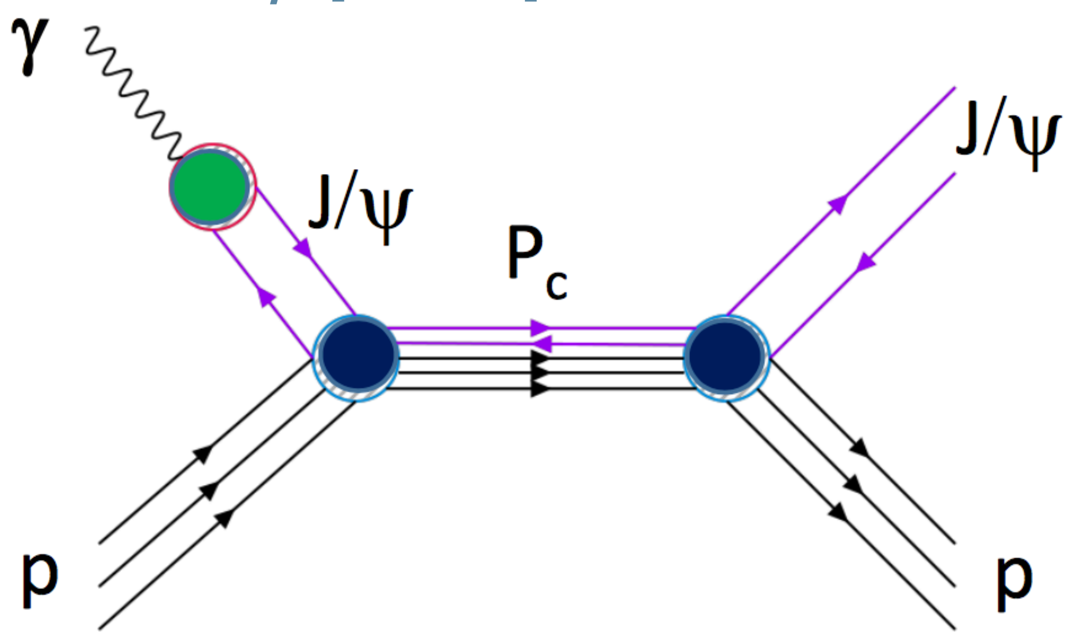


e.g. PRD 92, 071502(R) (2015)

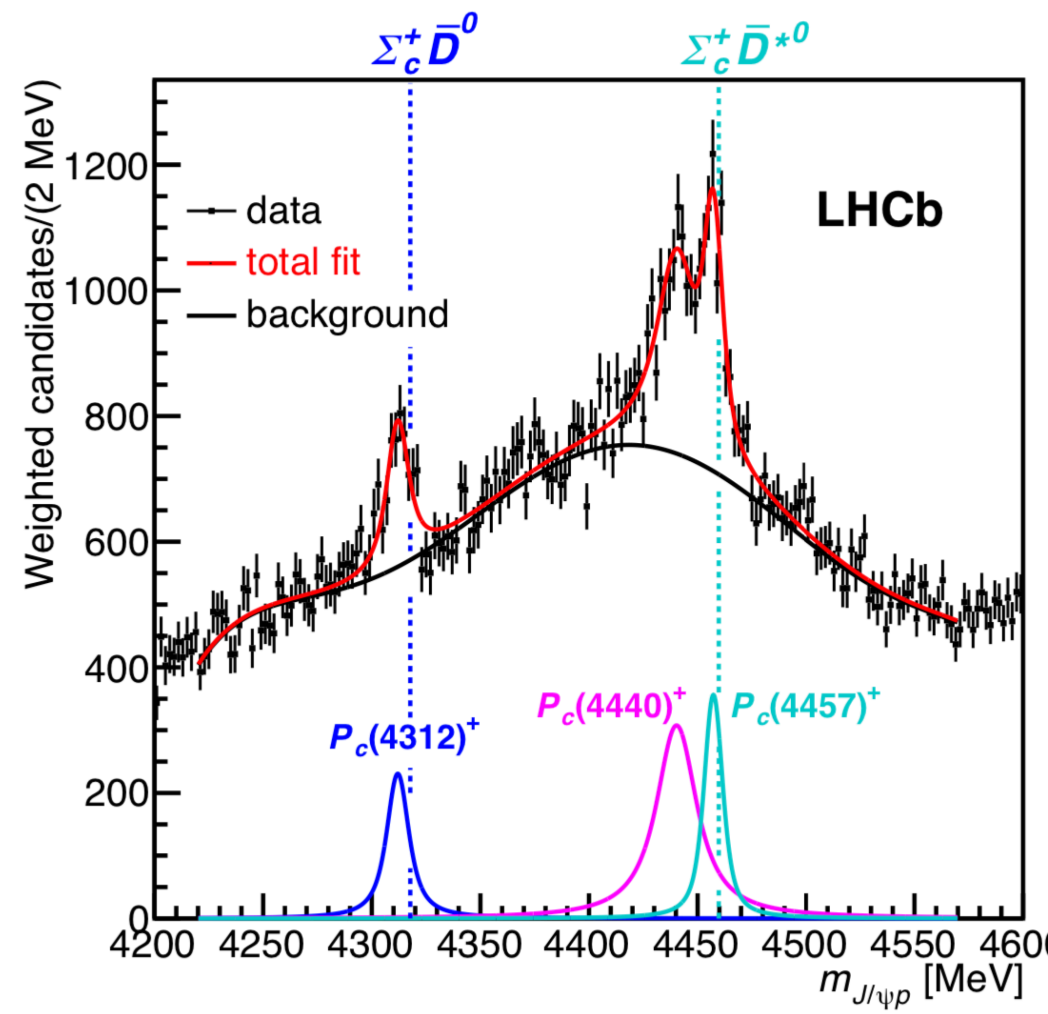
rescattering (triangle singularity)

Pentaquark photoproduction

J/ψ photoproduction



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



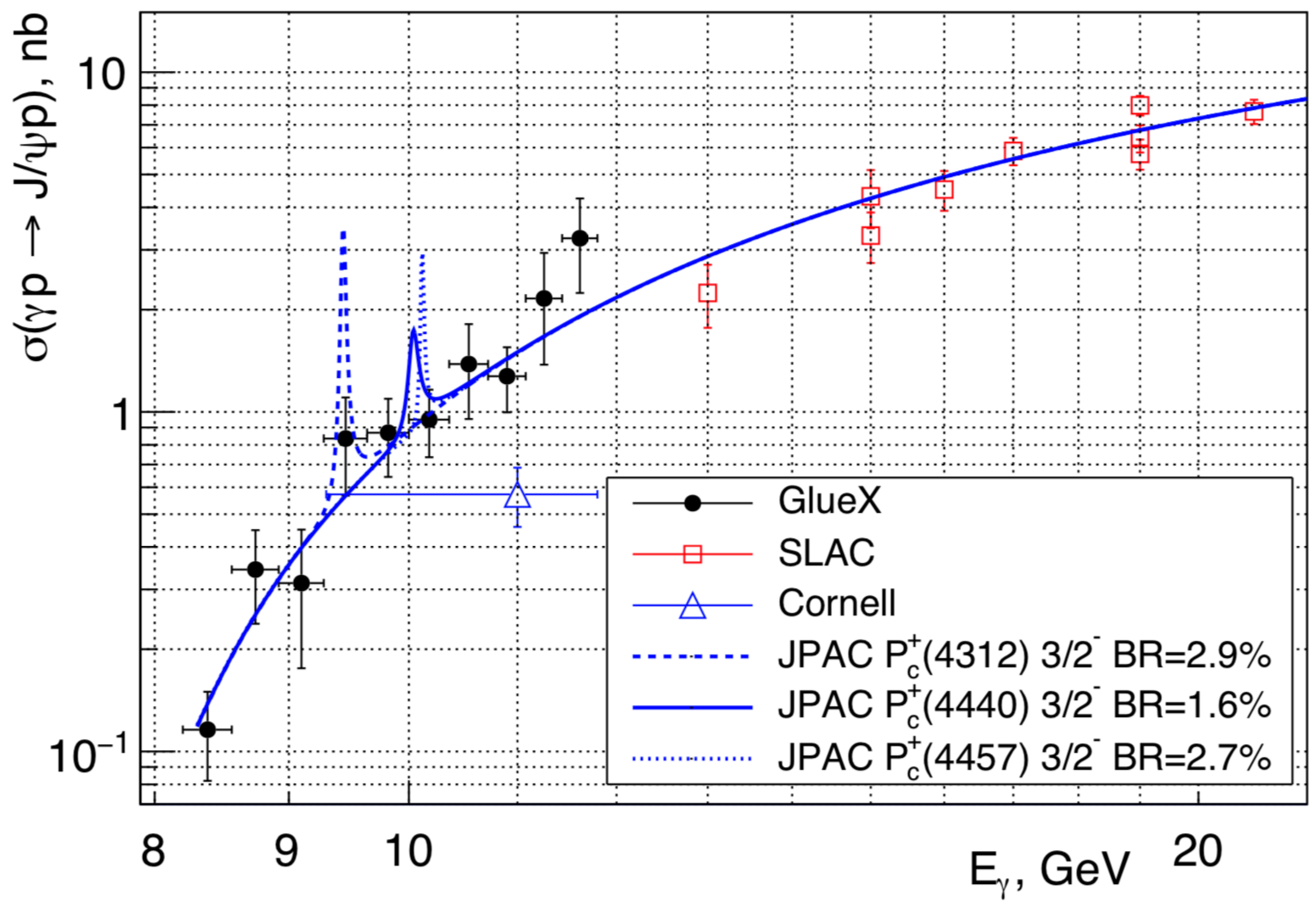
LRP: Nuclear physics facilities can help resolve mysteries generated by these new observations by investigating these states in more direct production processes, free from many of the complications present in the discovery mechanisms. At the limit of the current CEBAF beam energy, searches in Hall C and GlueX have thus far seen no signal for the observed pentaquark candidates, limiting the possible interpretations of the high energy results.

PRL 122, 222001 (2019)

Pentaquark photoproduction

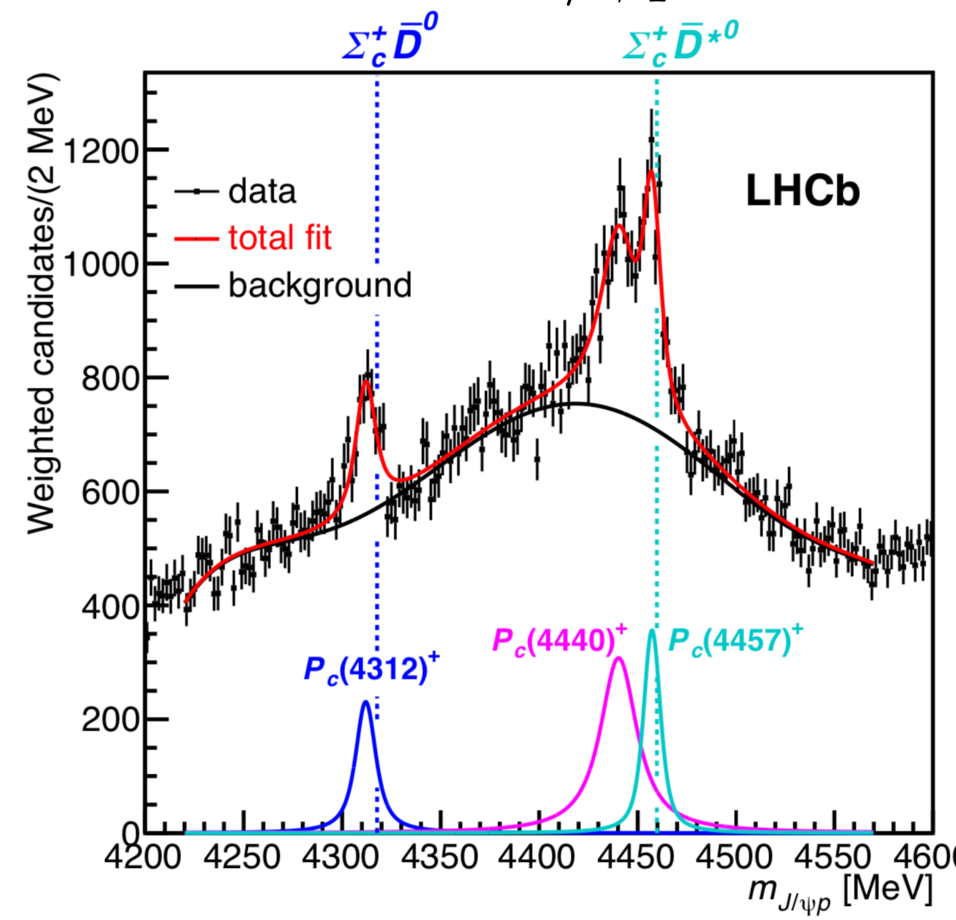
$$\gamma p \to J/\psi p$$

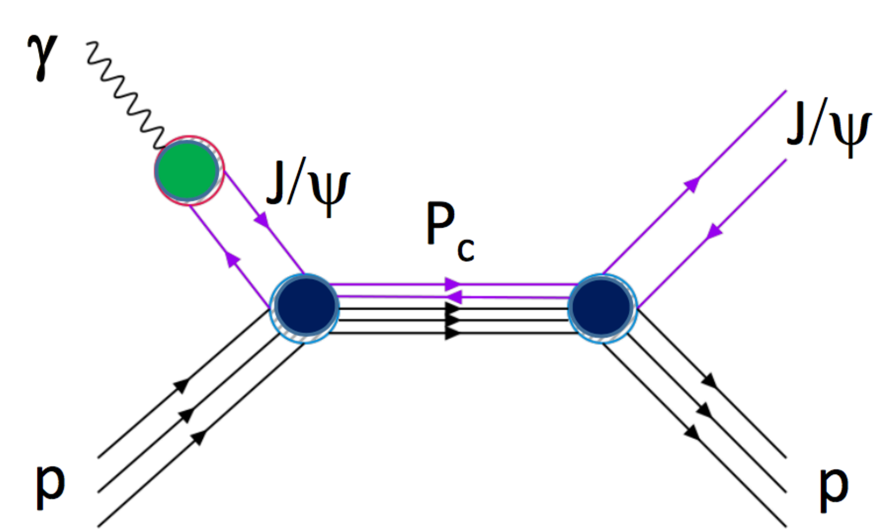
GlueX **PRL 123, 072001 (2019)**



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

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



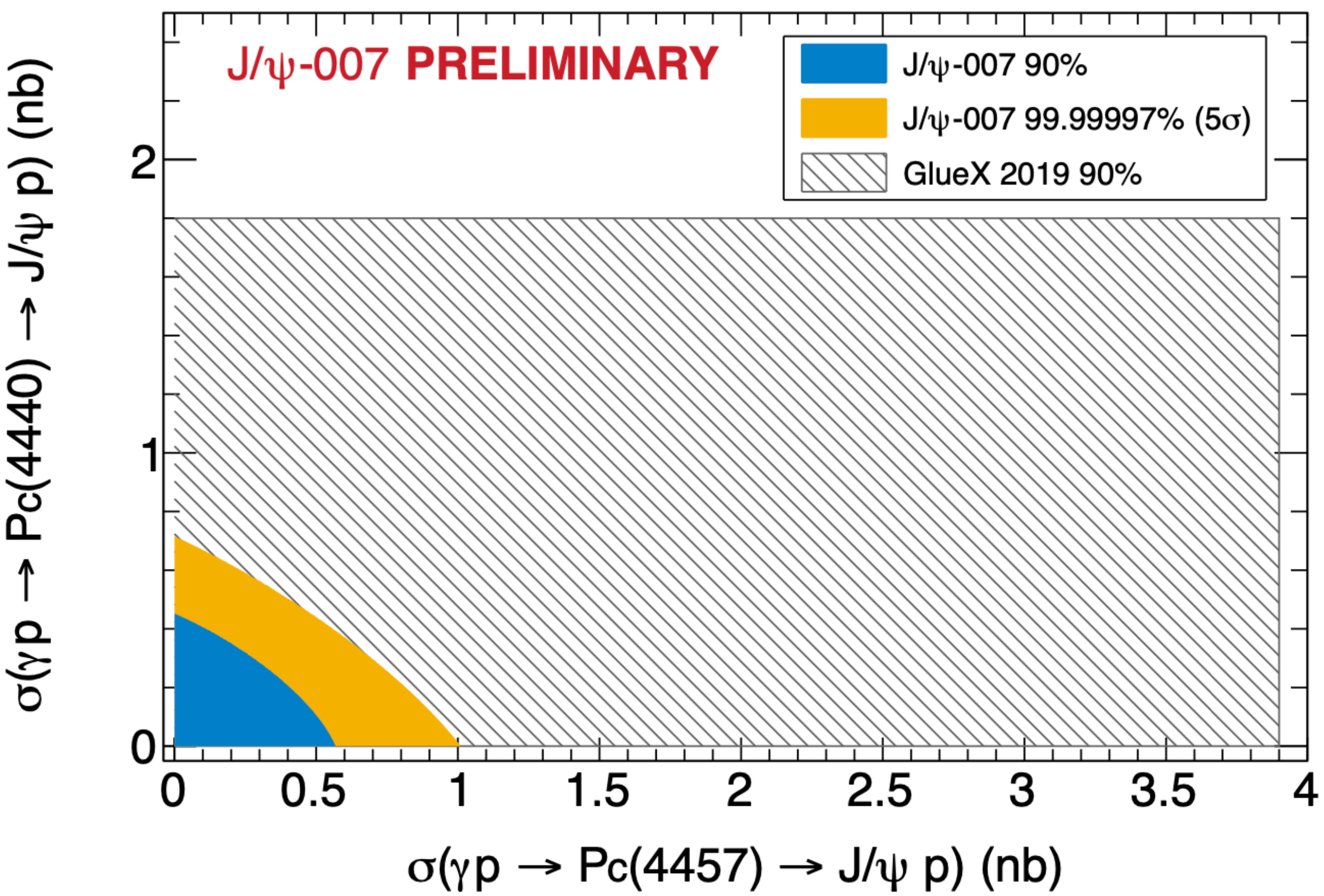


Proportional to $BR(P_c \to J/\psi p)^2$

Pentaquark photoproduction

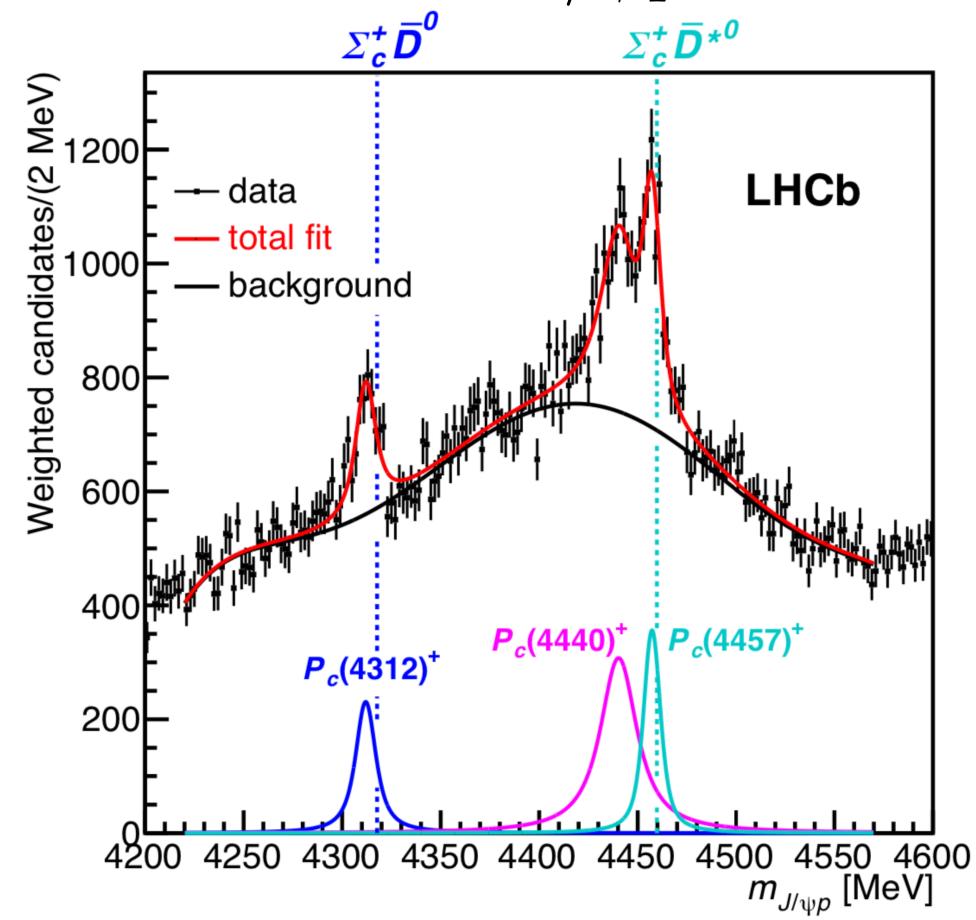
$$\gamma p \rightarrow J/\psi p$$

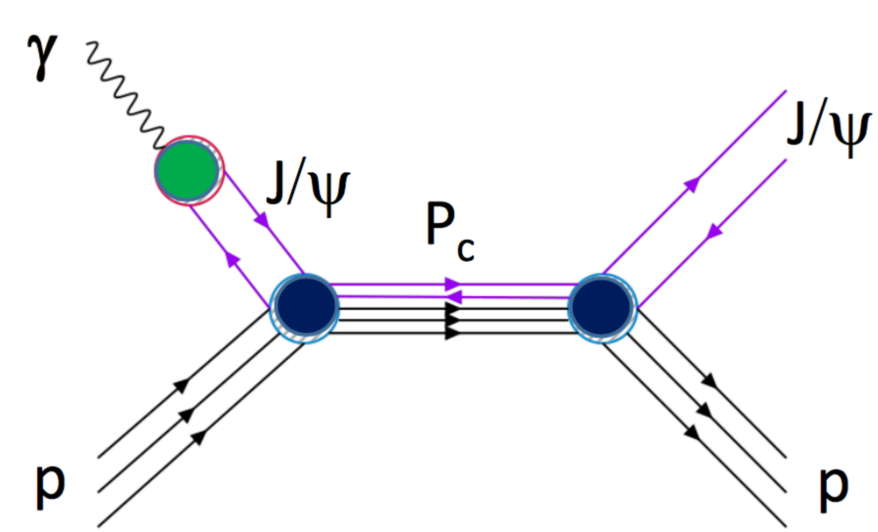
Hall C: J/ψ-007 experiment



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

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



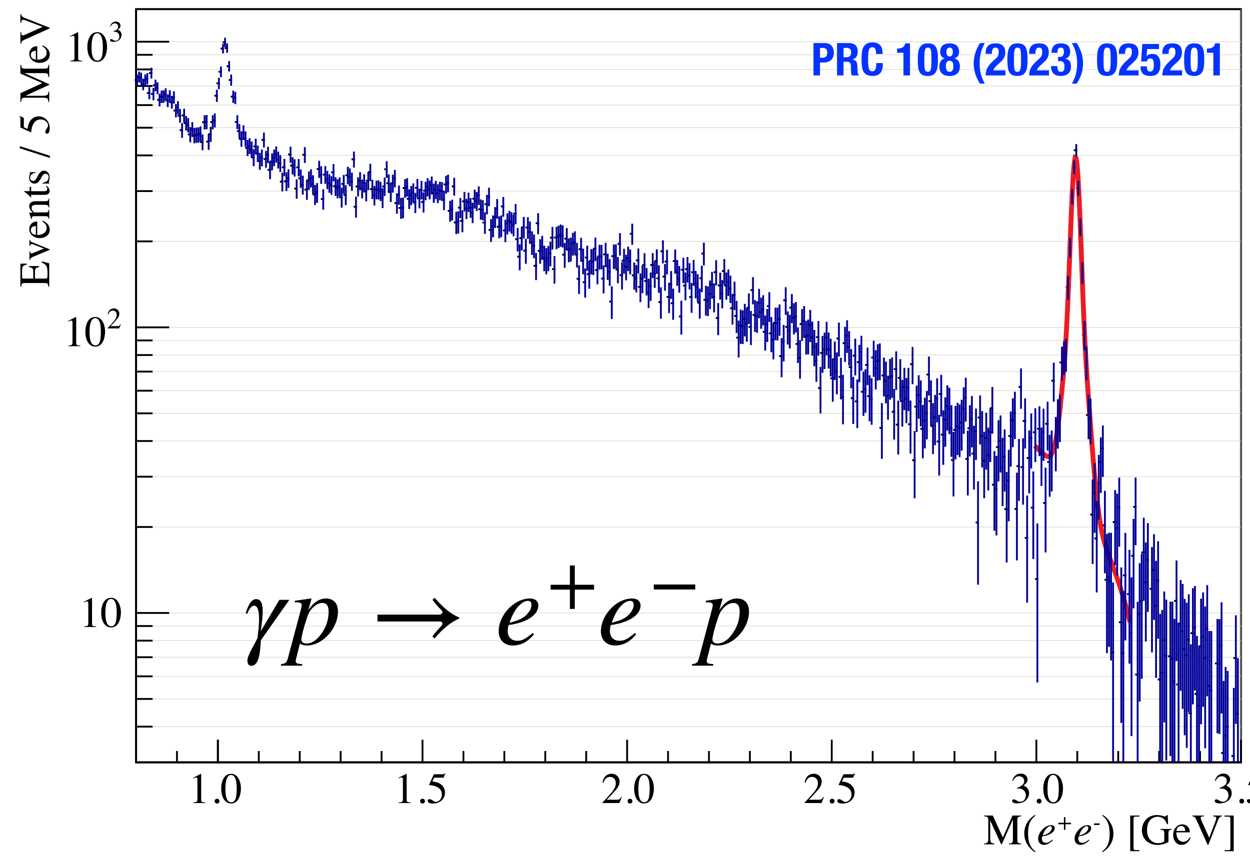


Proportional to BR($P_c \rightarrow J/\psi p$)^2

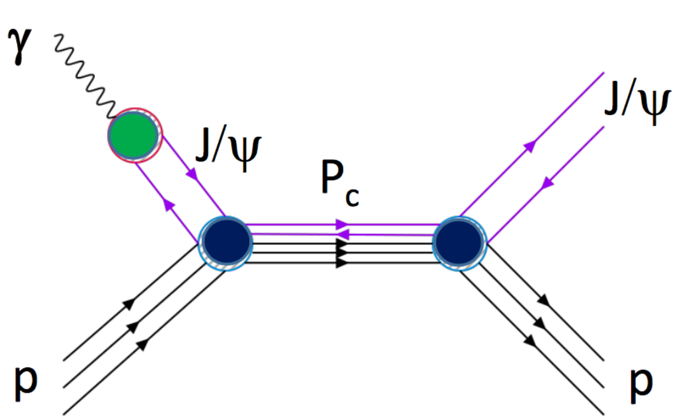
J/ψ photoproduction at GlueX

Sean Dobbs
Plenary Fri @ 11:15

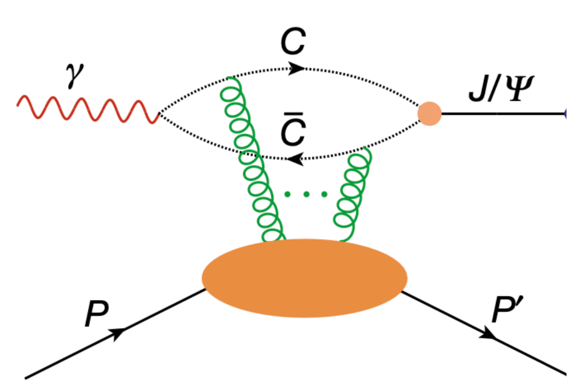
- Experimentally clean and rare probe with ~2.2k J/ψ observed in GlueX-I
- Broad physics program driven by different production mechanisms



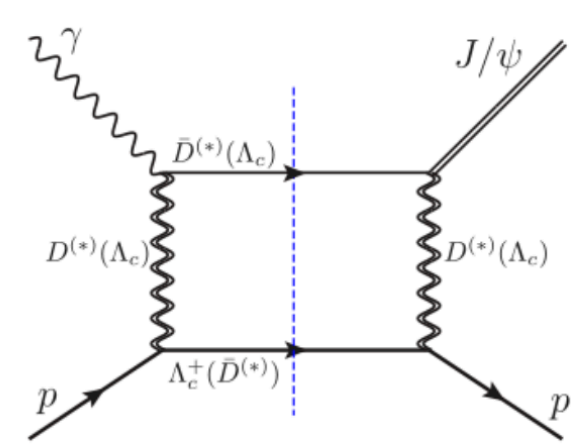
s-channel: pentaquarks



t-channel: gluon GPDs, mass radius



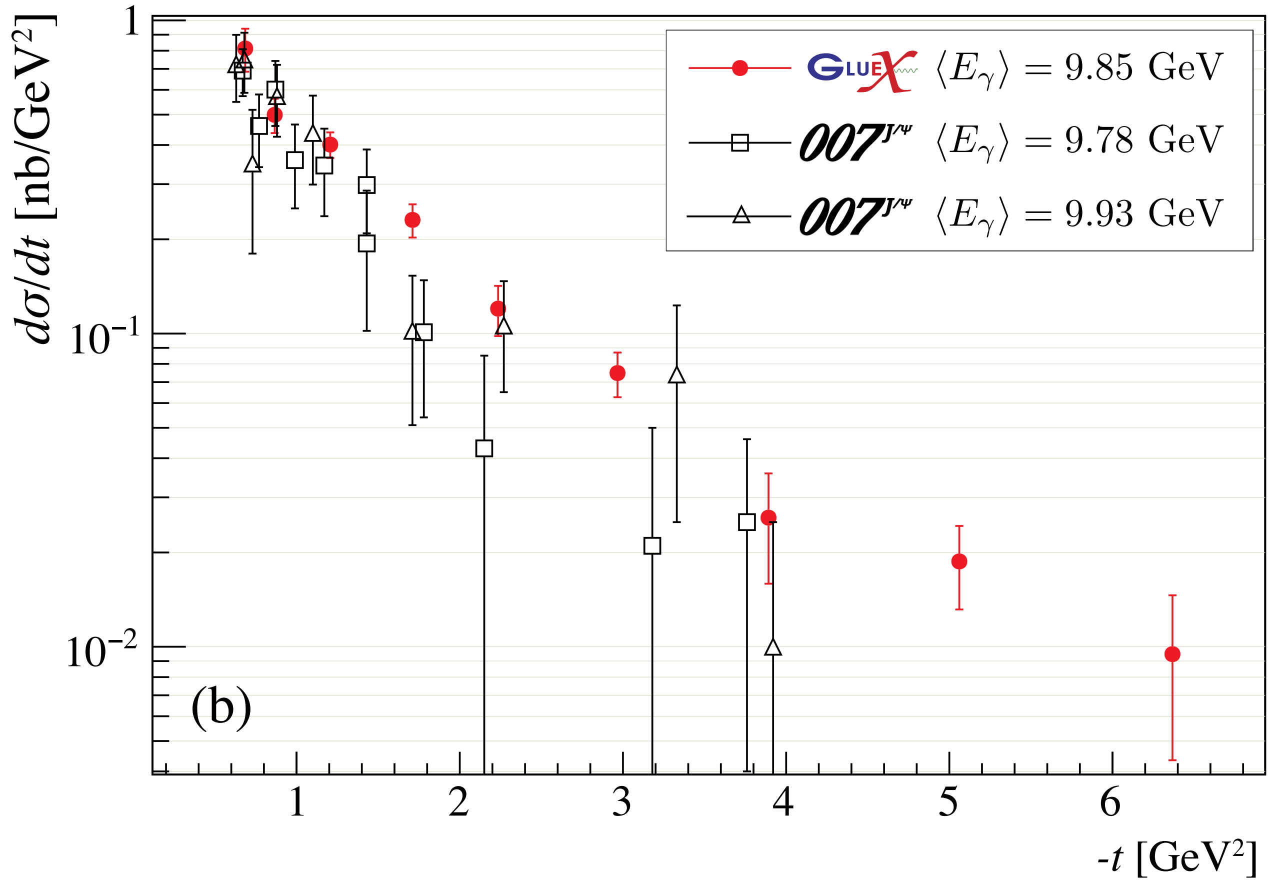
open charm

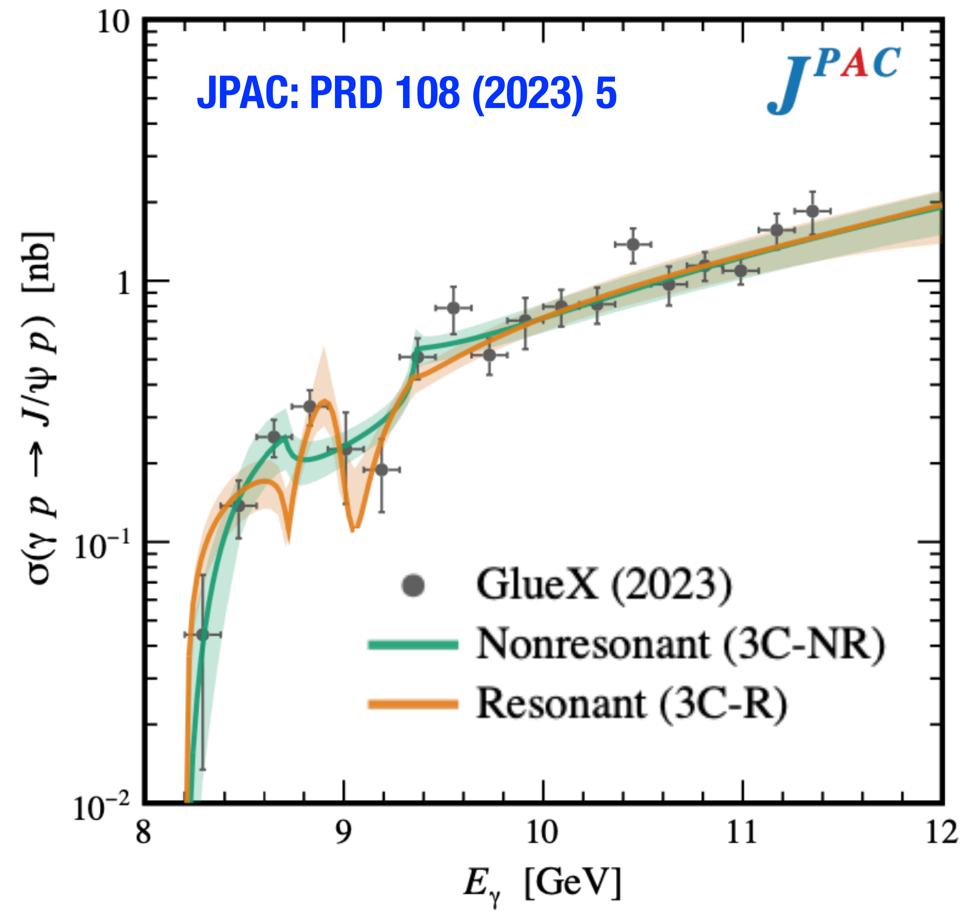


Interpretation of J/ψ results

Sean Dobbs
Plenary Fri @ 11:15

PRC 108 (2023) 025201

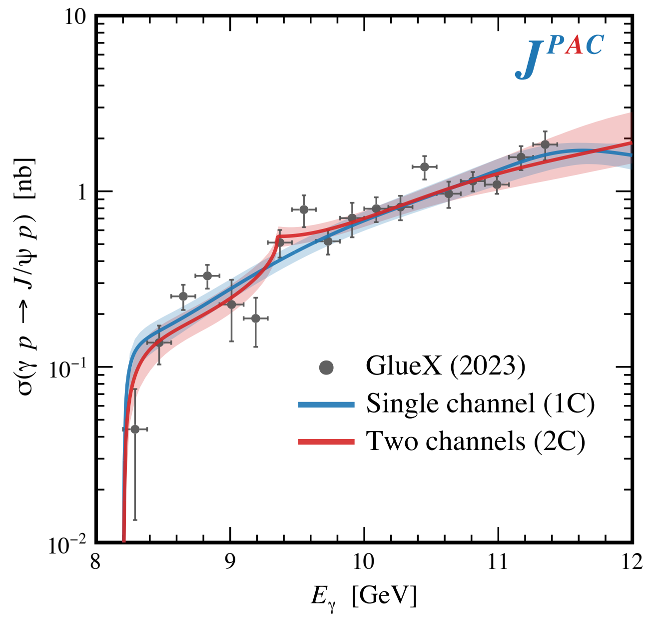




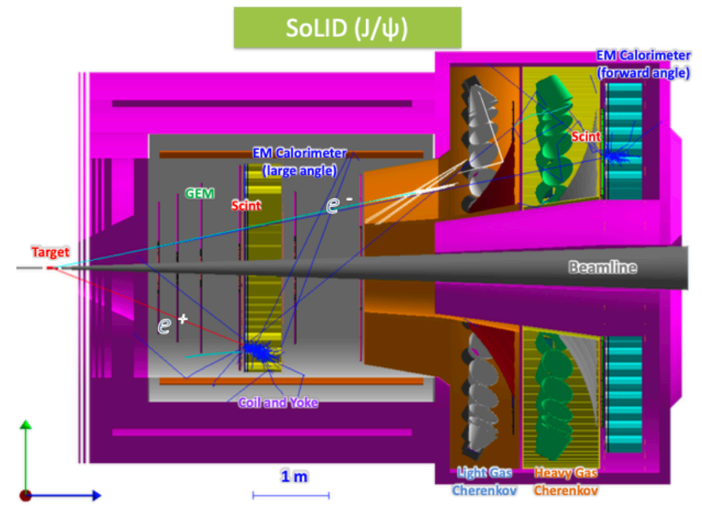
- Differential cross section $d\sigma/dt$ consistent between $J/\psi - 007$ (Hall C) and GlueX — sensitive to gluon GPDs, mass radius, etc. under certain assumptions
- Total cross section sensitive to "cusps" near open charm thresholds — models with both resonant pentaquark and purely non-resonant effects can adequately describe the data
- Improved precision required to differentiate production mechanisms

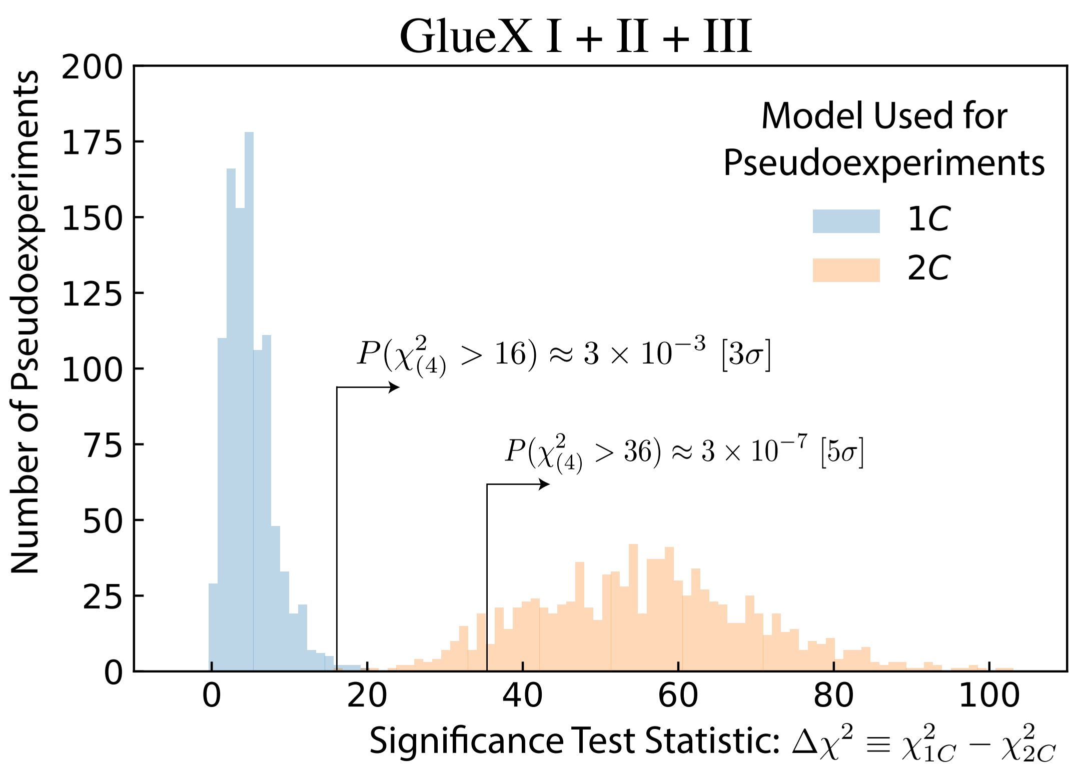
Where will new data come from?

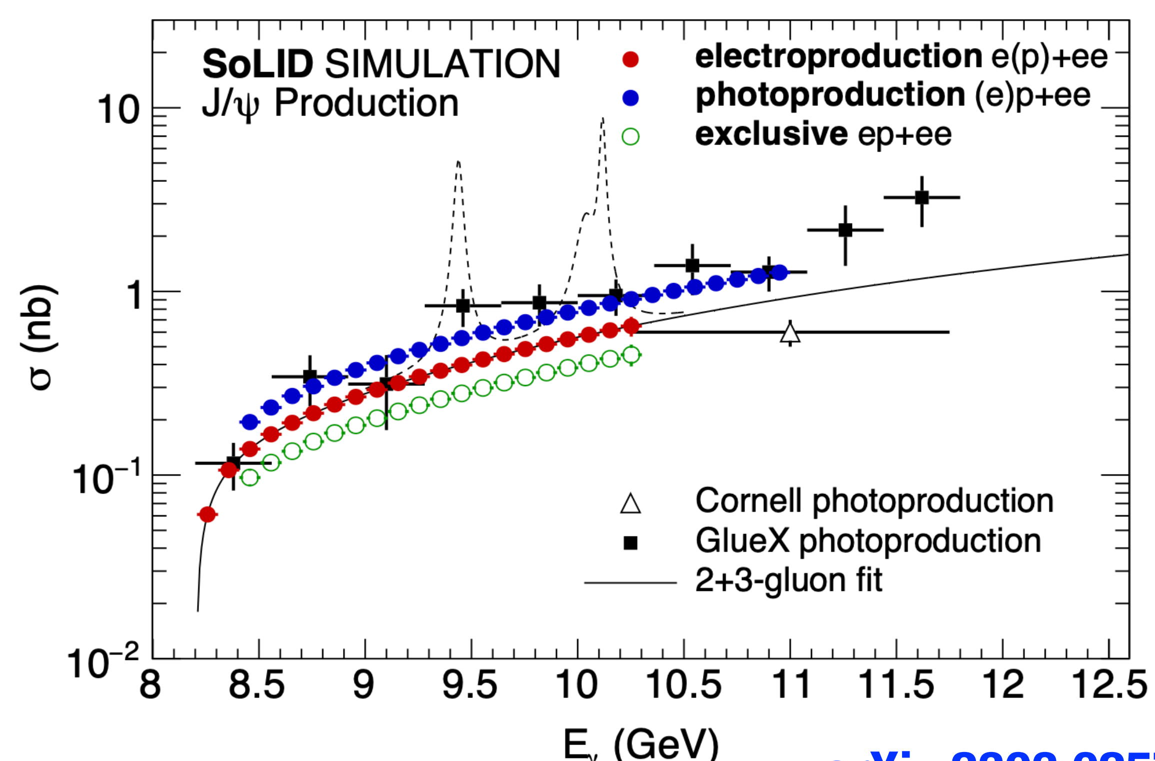
GlueX-III proposal will distinguish single channel vs open charm



Exploit full JLab luminosity With SoLID experiment

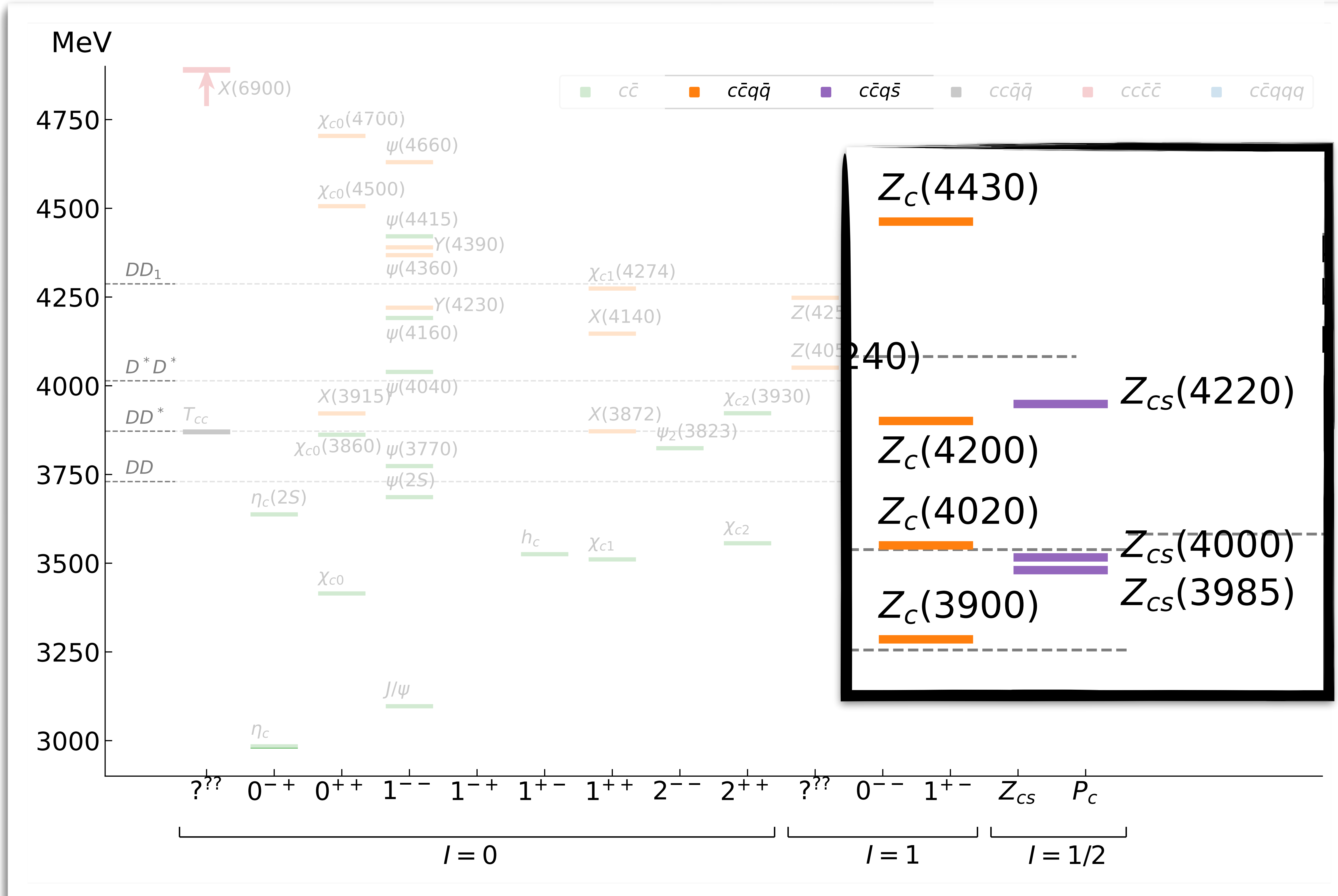






arXiv:2303.02579

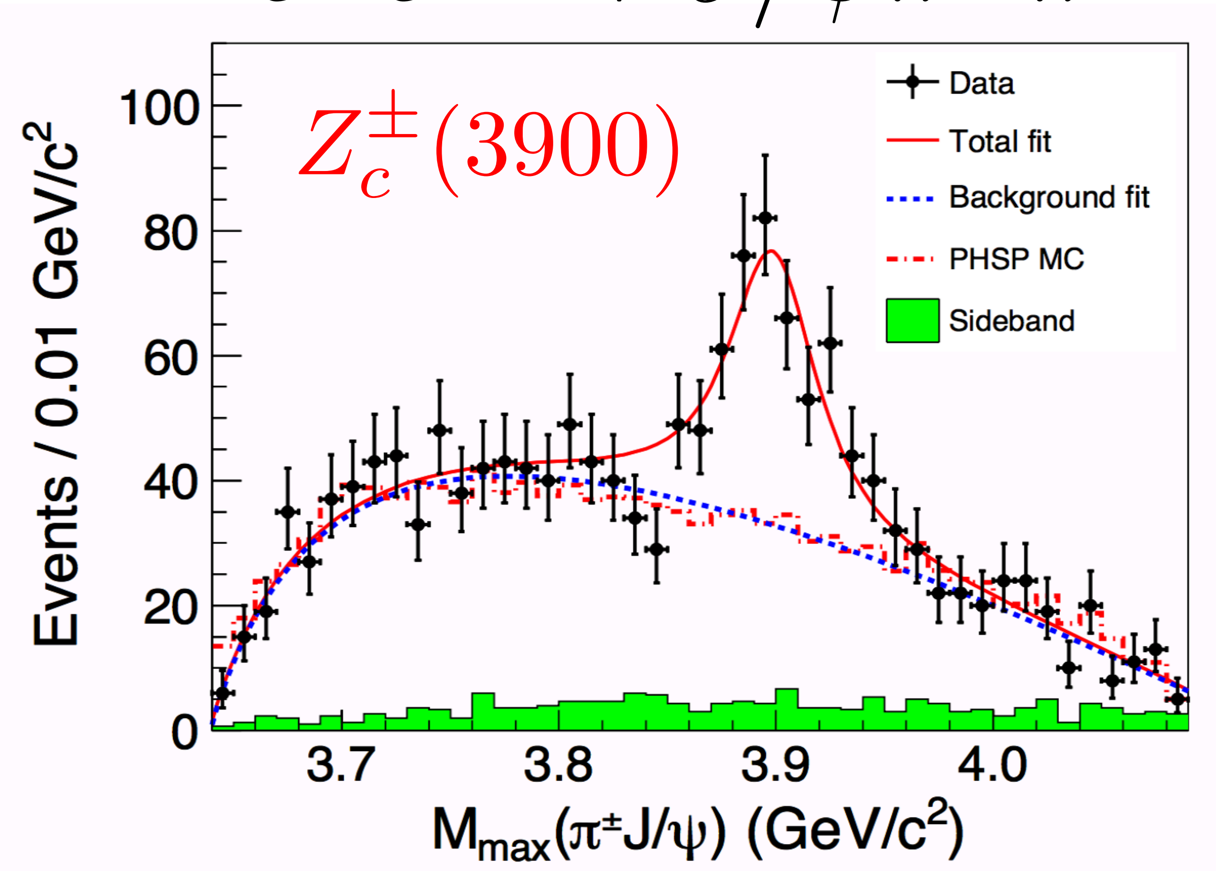
Charged tetraquark candidates: Z_c



Recent review: JPAC **arXiv:2112.13436**

Charged tetraquark candidates: Z_c

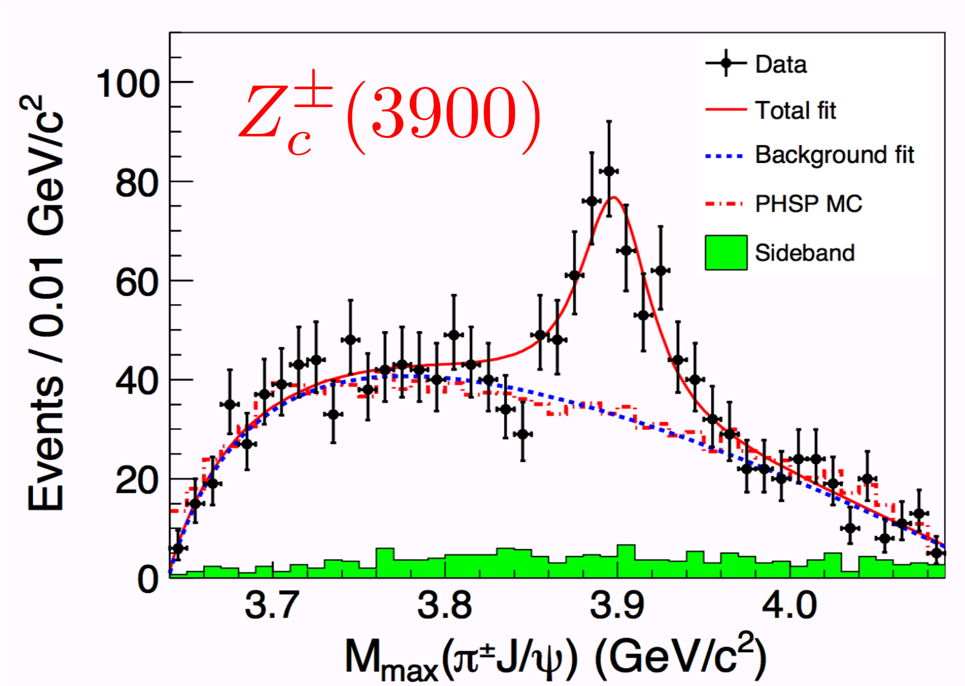
$$e^+e^- \to J/\psi\pi^+\pi^-$$

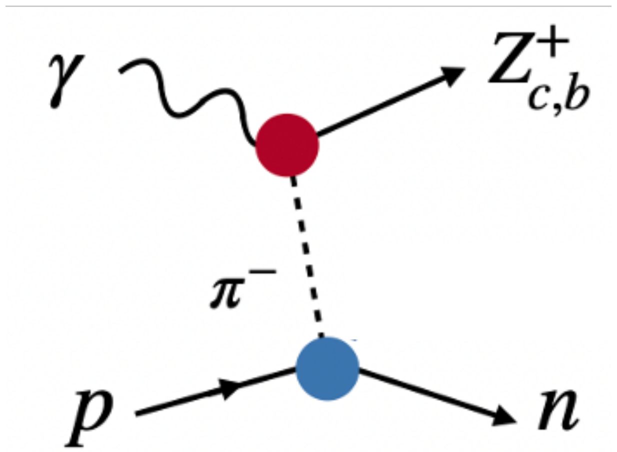


PRL 110, 252001 (2013) BESIII

PRL 110, 252002 (2013) BELLE

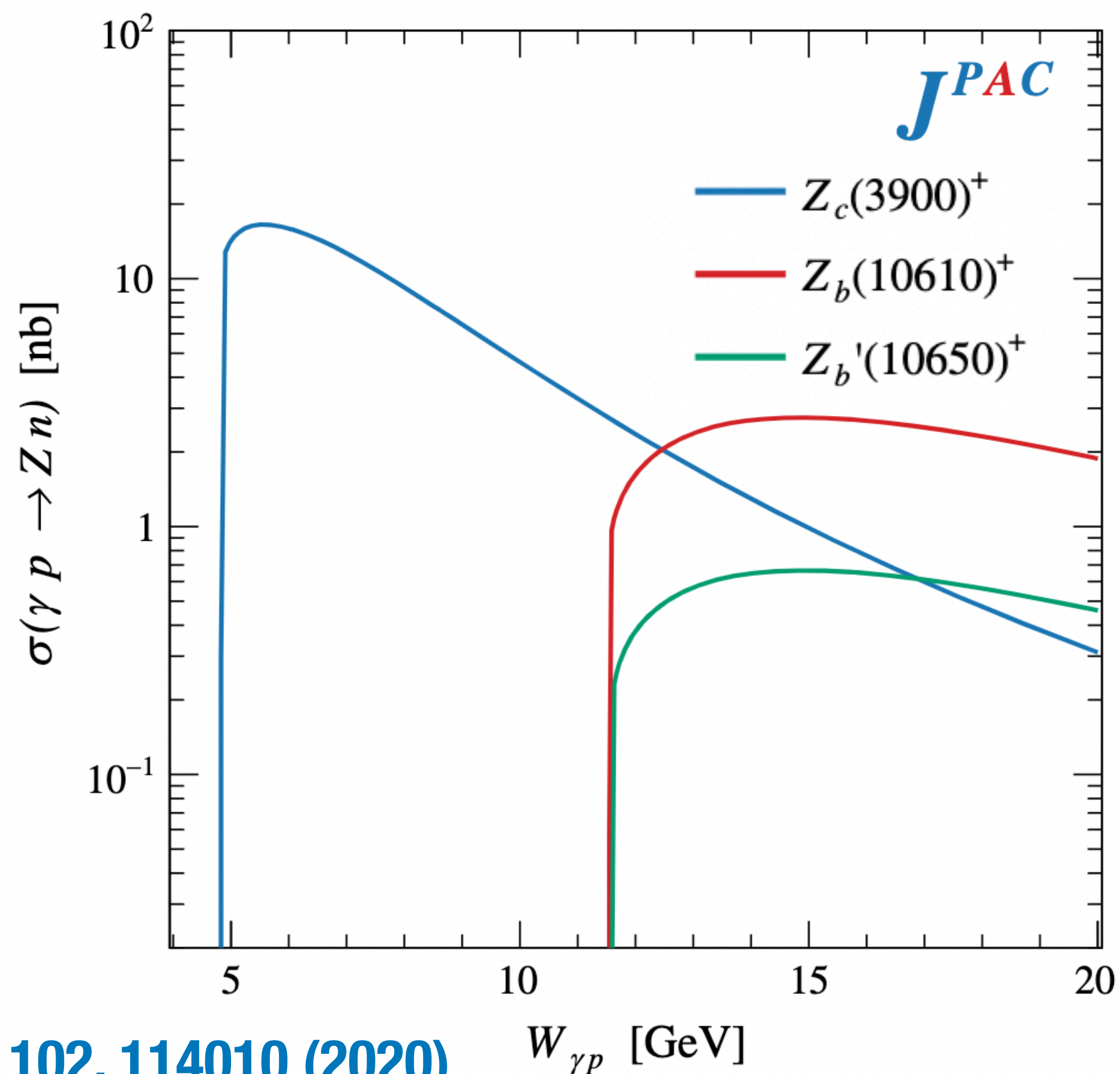
Charged tetraquark candidates: Z_c





* 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

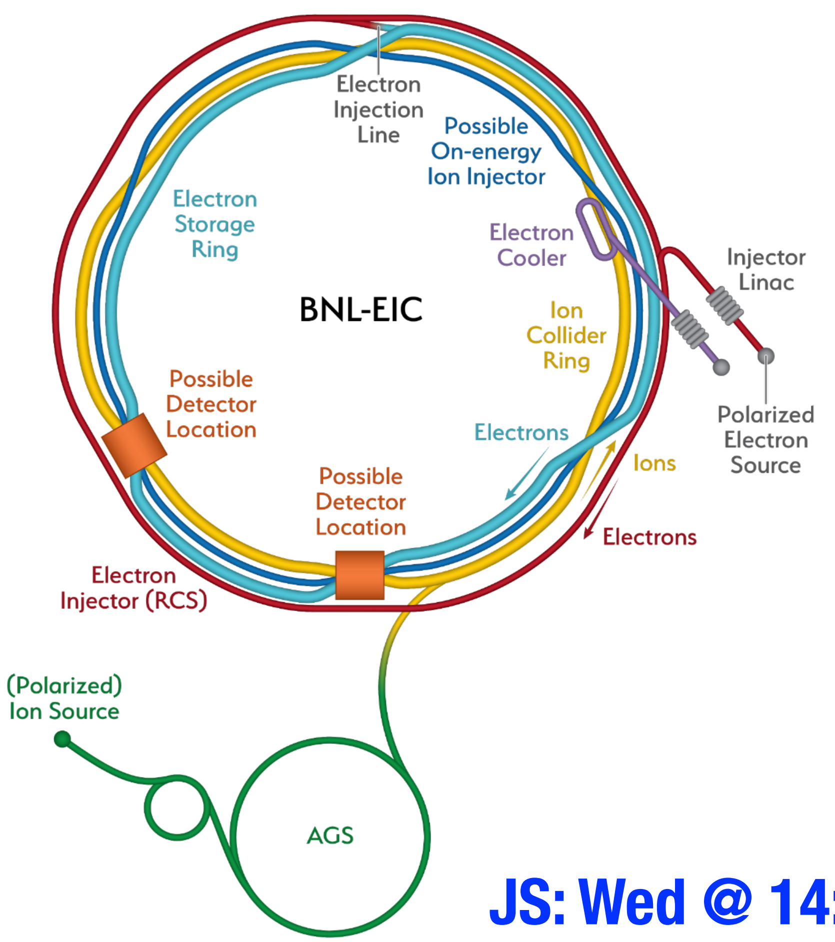


JPAC PRD 102, 114010 (2020)

Future spectroscopy facilities

Electron Ion Collider (EIC)

LRP RECOMMENDATION 3
We recommend the expeditious completion of the EIC as the highest priority for facility construction.



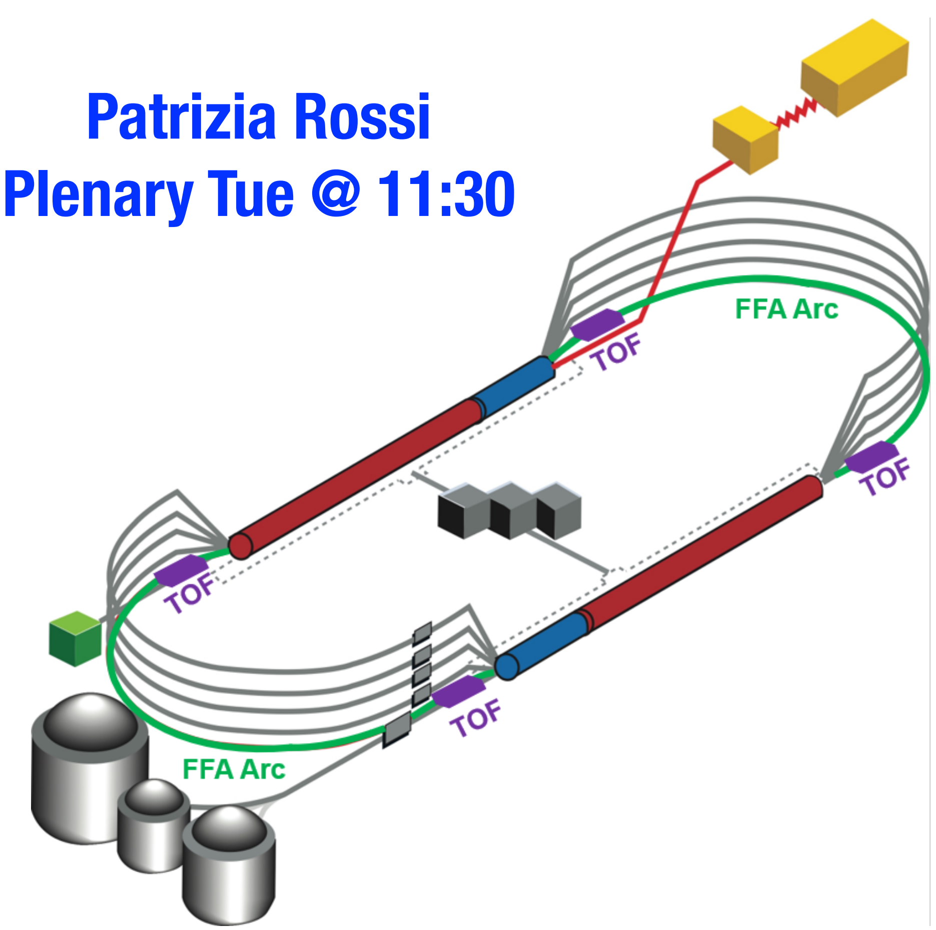
JS: Wed @ 14:25

Jefferson Lab upgrade:

E_e = 12 → 22 GeV

LRP: To investigate the other XYZP states, higher beam energy is required; the tetraquark candidate Zc states would be copiously produced at a high-luminosity, fixed-target electron machine operating above 20 GeV.

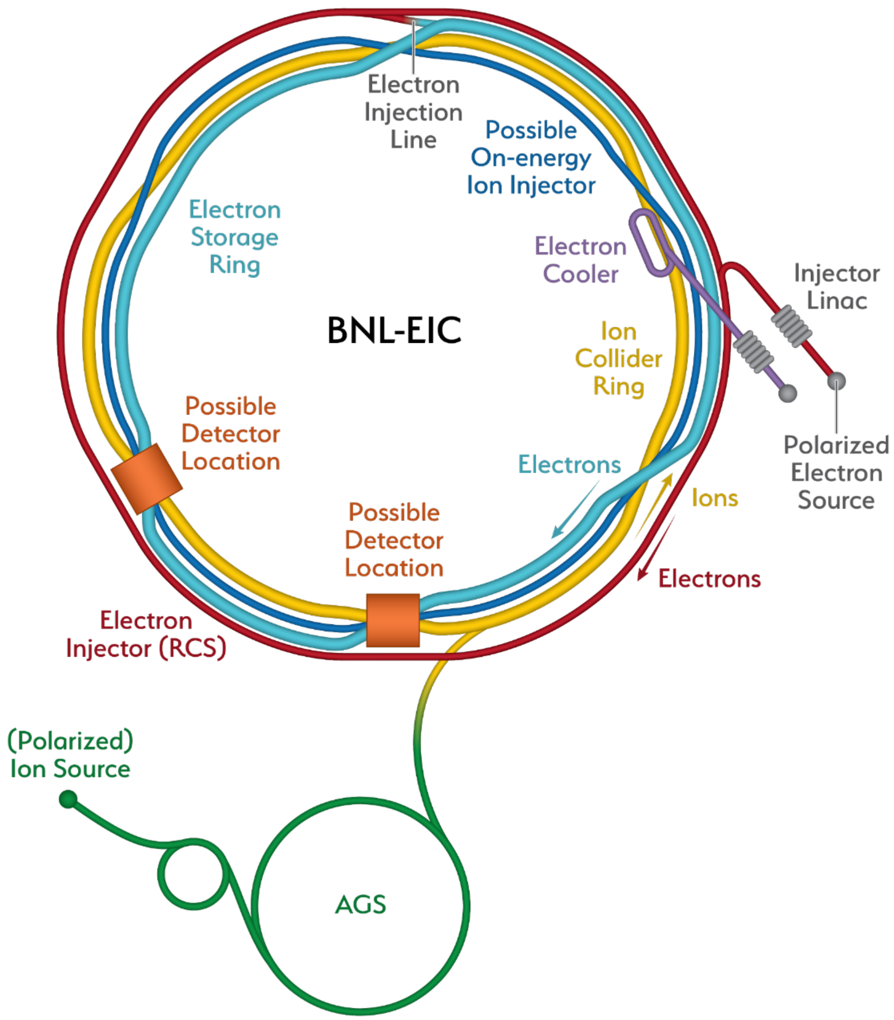
Patrizia Rossi
Plenary Tue @ 11:30



Photoproduction of XYZ states

Complementary access to charmonium photoproduction with higher energy facilities

Electron Ion Collider (EIC)

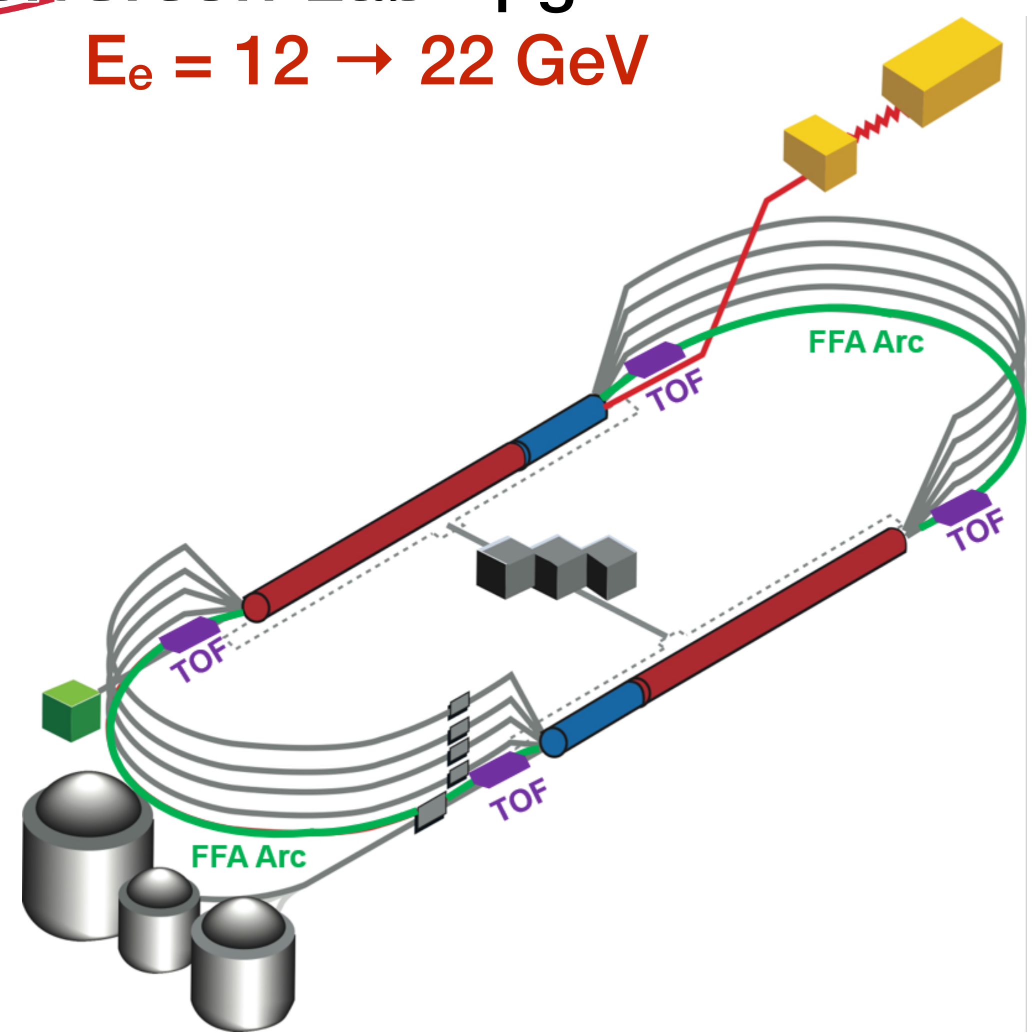


$$\boxed{\sqrt{s}_{\gamma p} = 5 \ - \ 141 \text{ GeV}}$$

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

Jefferson Lab upgrade:

$E_e = 12 \rightarrow 22$ GeV

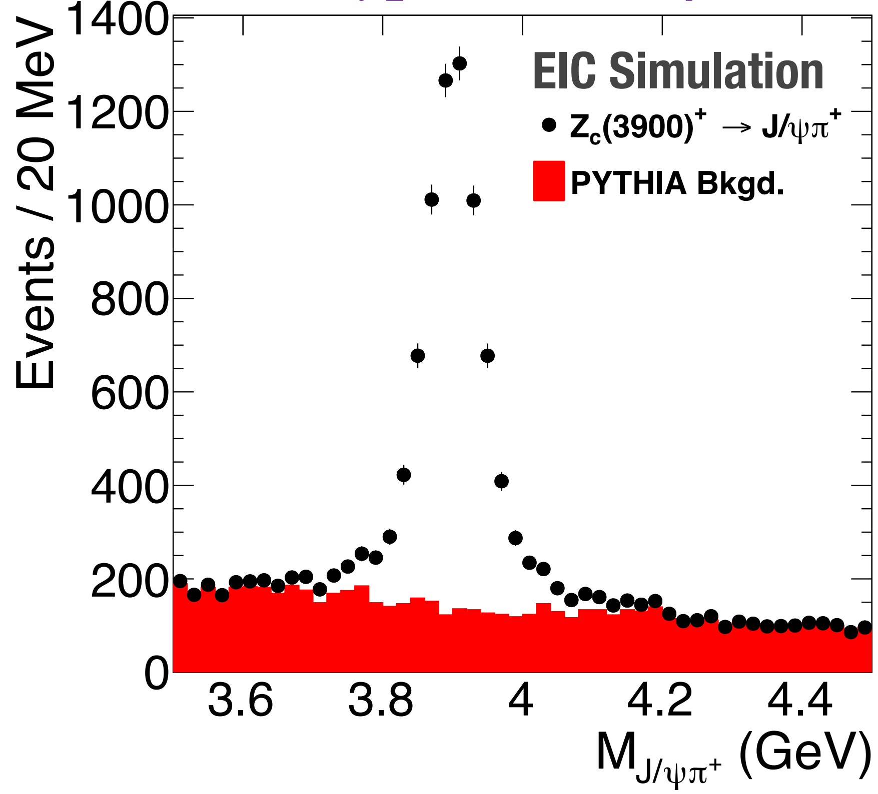


$$\sqrt{s}_{\gamma p} = 1.5 \ - \ 6.5 \text{ GeV}$$

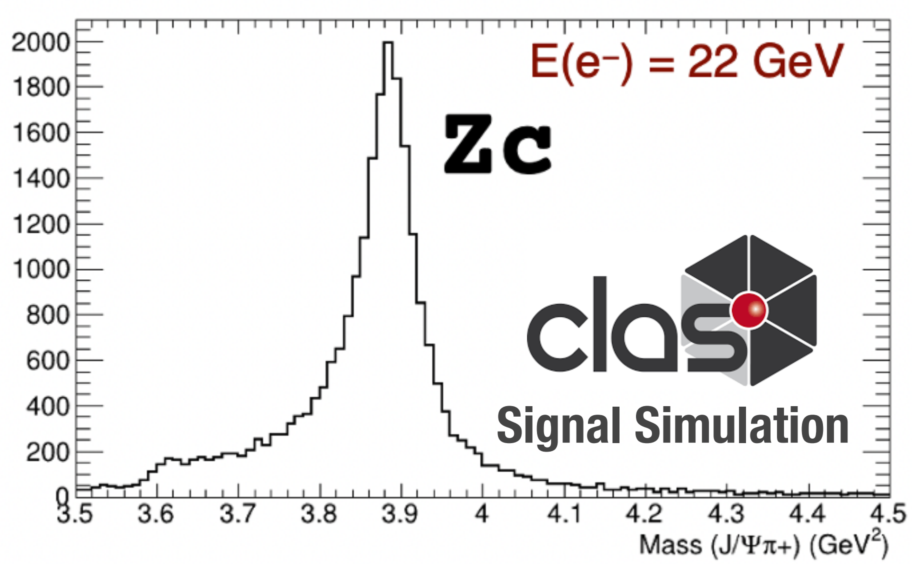
$$\boxed{\mathscr{L}_{ep} = 10^{35} - 10^{37}\ cm^{-2}s^{-1}}$$

Photoproduction of $Z_c^+(3900)$

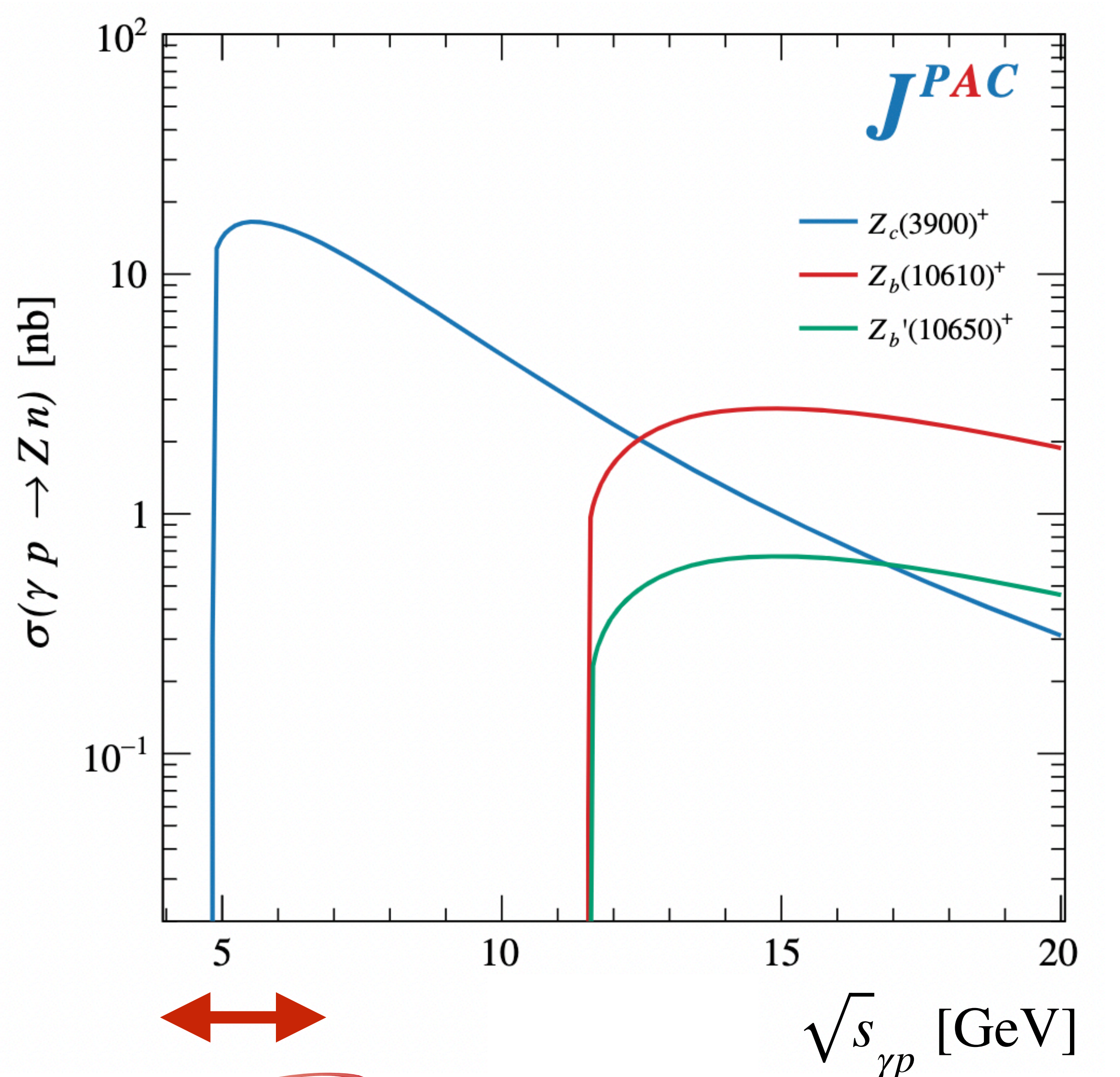
EIC: $\gamma p \to n J/\psi \pi^+$



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



EIC broad energy coverage



Jefferson Lab 22 GeV

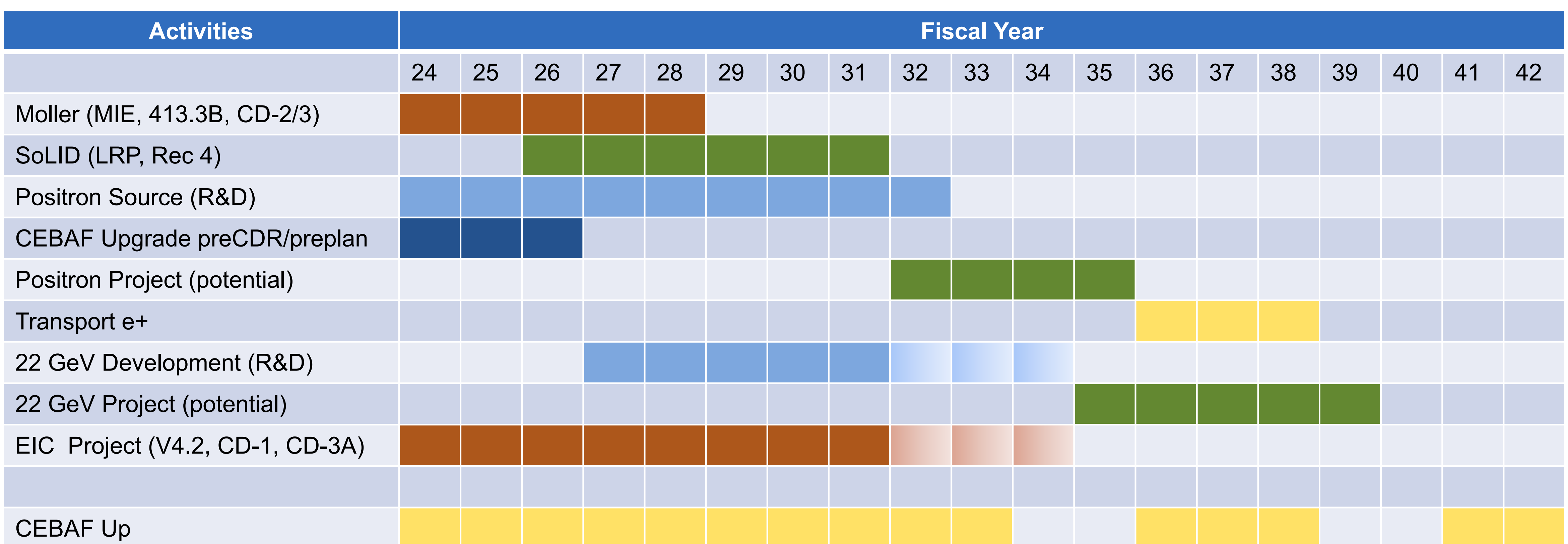
High luminosity near-threshold

Realizing the EIC and JLab 22 GeV

Patrizia Rossi
Plenary Tue @ 11:30

- EIC project passed CD-3A review
  - International ePIC collaboration developing detector
- Jefferson Lab 12 GeV and positron program through 2030s
  - Broad 22 GeV program defined in White Paper [arXiv:2306.09360]

David Dean's slides with "Notional" plan from JLab User Organization meeting last week



Summary and Outlook

- New era of precision spectroscopy measurements from light and heavy quark sectors with US-based experiments
- 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

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