Exploring MESON Photoproduction with the GlueX Experiment

MESON 2023
June 22-27
Kraków, Poland

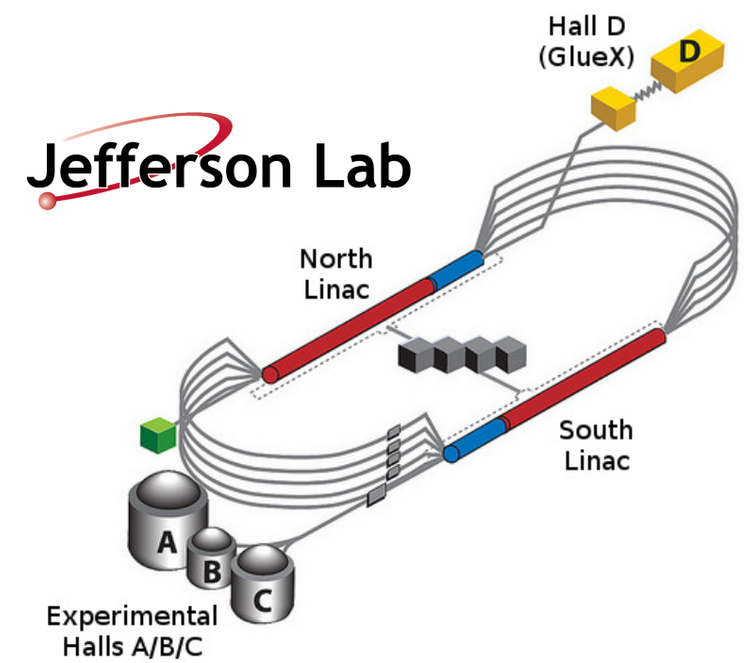
Matthew Shepherd
Indiana University
(on behalf of the GlueX Collaboration)

Outline

- A brief introduction to the GlueX experiment
- Production of conventional mesons
  - Beam asymmetries for π^0, π^-, η production
  - Spin-density matrix elements for ρ production
- Status of the search for hybrid mesons
  - Upper limit on the exotic π_1 cross section
  - Opportunities for π_1 discovery in photoproduction
  - A standard candle: a_2 production properties
- Production of J/ψ at threshold

GlueX Goals

- Conduct a high intensity polarized photoproduction experiment that can explore the hadron spectrum up to $c\bar{c}$ threshold



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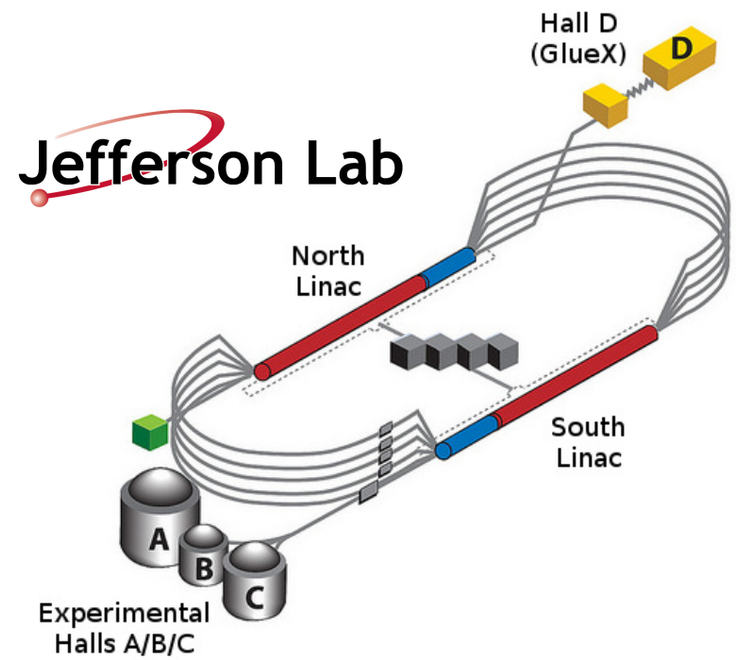
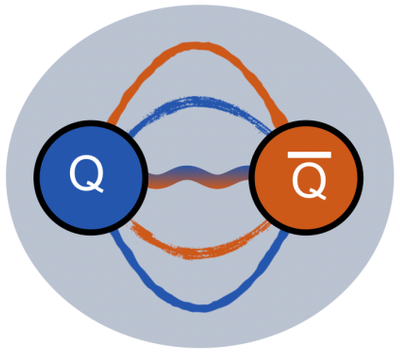


- Conduct a high intensity polarized photoproduction experiment that can explore the hadron spectrum up to $c\bar{c}$ threshold
- Provide a significant contribution to the search for and study exotic hybrid mesons that
  - arise uniquely from the gluon-gluon interaction in QCD
  - some have quantum numbers that are not populated by conventional $q\bar{q}$ mesons



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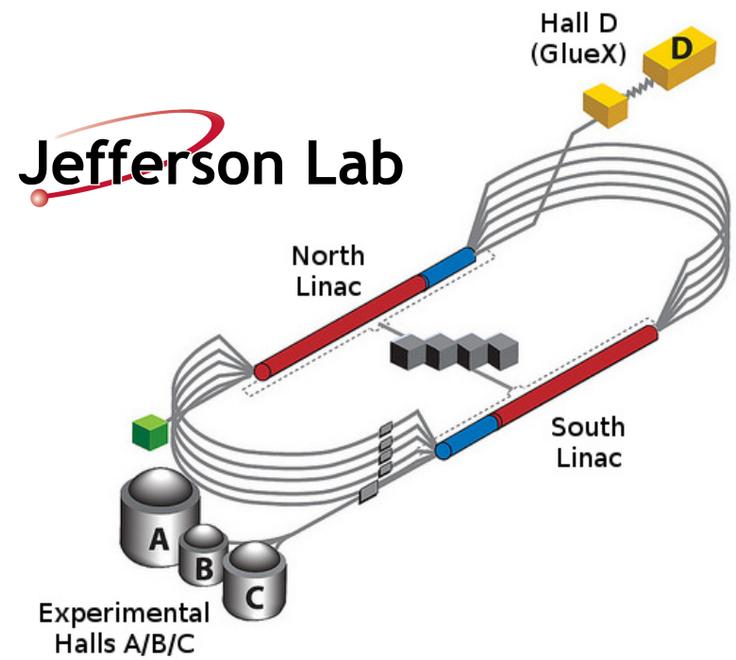

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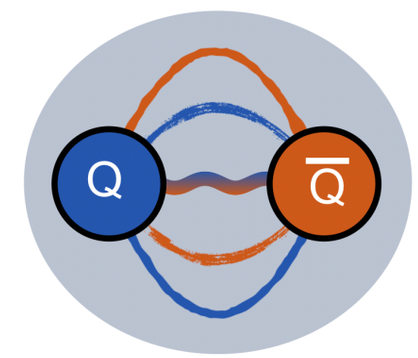
- Provide a significant contribution to the search for and study exotic hybrid mesons that
  - arise uniquely from the gluon-gluon interaction in QCD
  - some have quantum numbers that are not populated by conventional $q\bar{q}$ mesons
- Achieving analysis goals depends on strong theory/ experiment collaboration
  - part of a combined effort at Jefferson Lab with the Joint Physics Analysis Center and HadSpec LQCD effort
  - future work with the ExoHad DOE Topical Collaboration



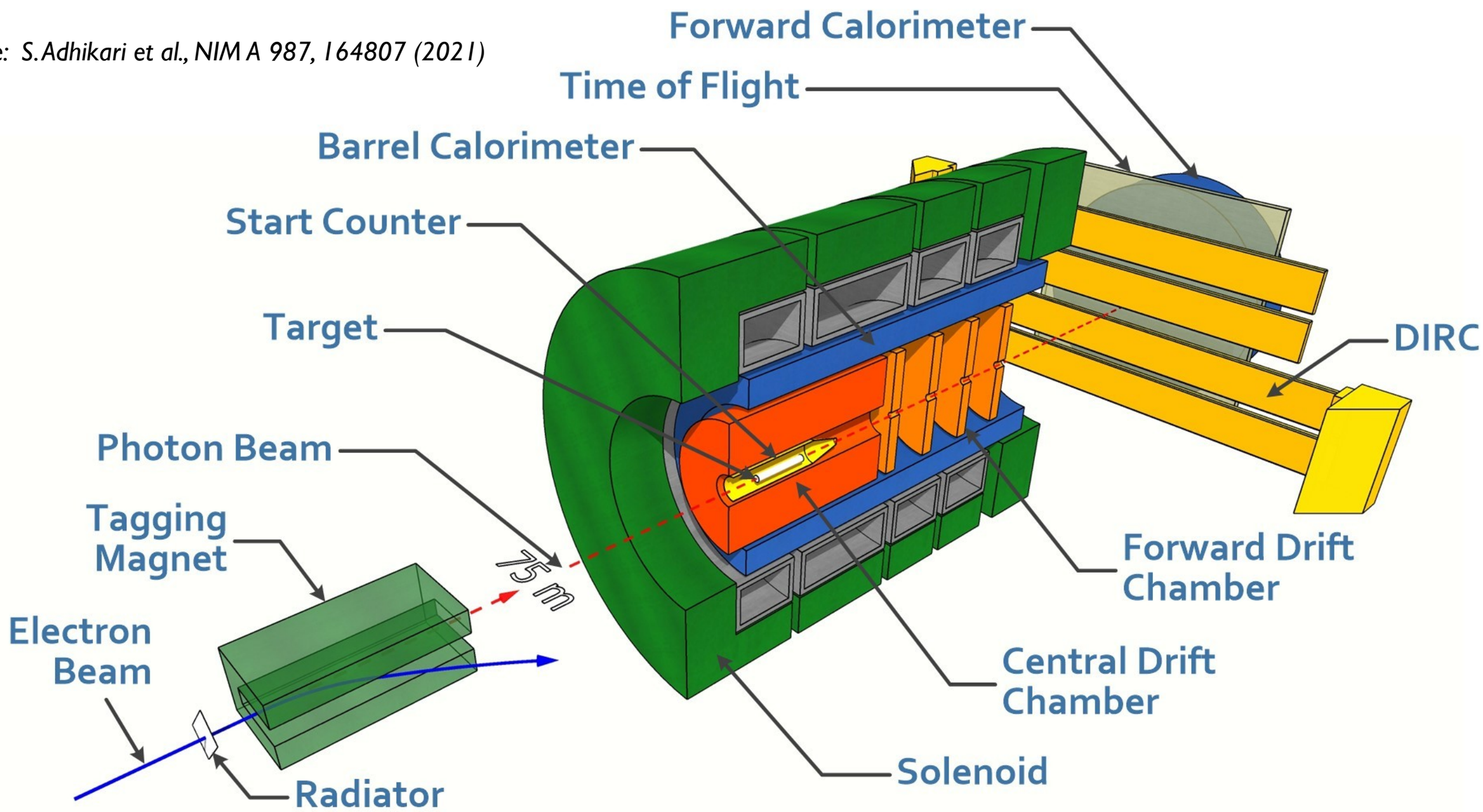
JPAC

had spec

ExoHad
Exotic Hadrons Topical Collaboration

Coverage: $1^\circ < \theta < 120^\circ$, all ϕ
Tracking: $\sigma_p/p \approx 1\% - 5\,\%$
Calorimetry: $\sigma_E/E \approx 6\,\%/\sqrt{E} + 2\,\%$
Liquid Hydrogen Target

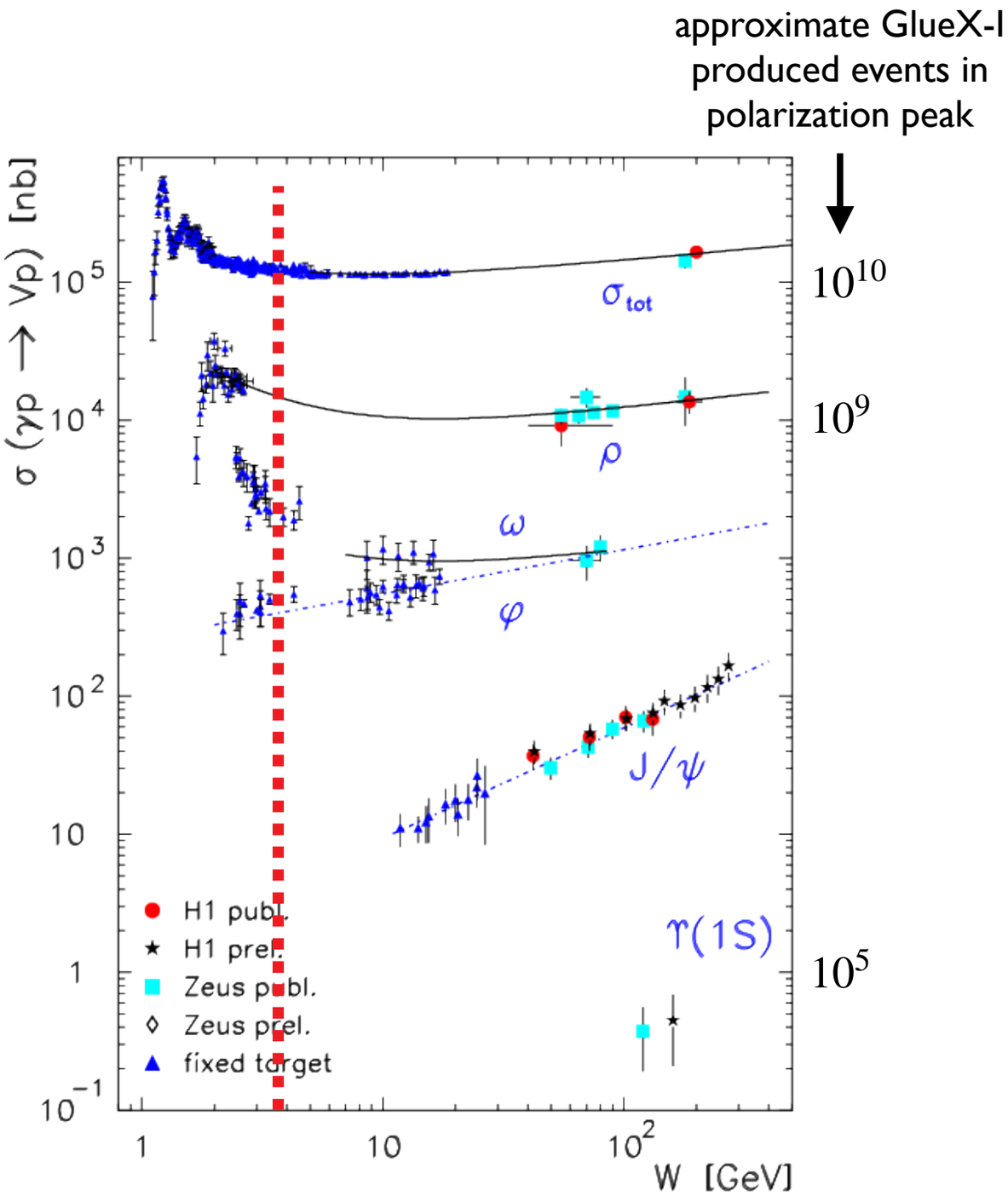
see: S. Adhikari et al., NIM A 987, 164807 (2021)

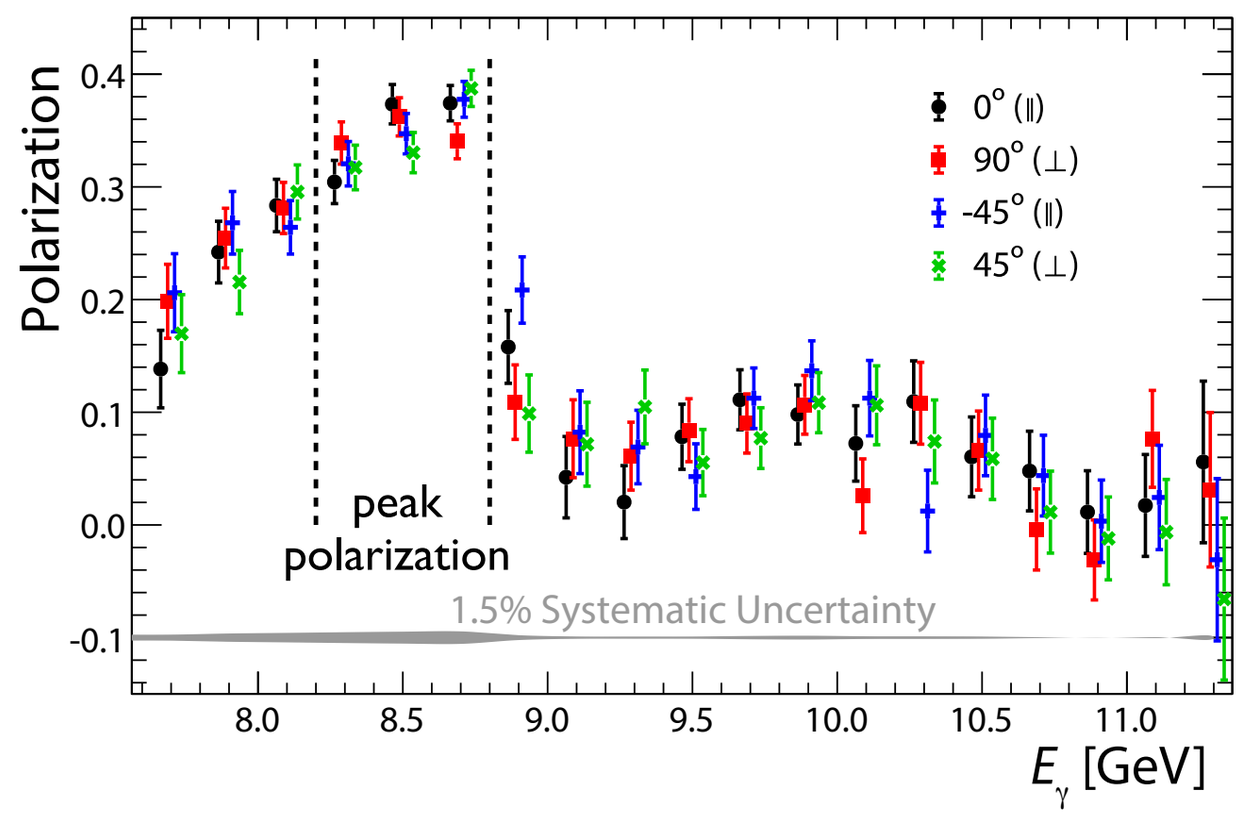


GlueX

May 2023 Collaboration Meeting at Jefferson Lab

GlueX Data Volume





Through 2020 we have collected about $250\ \mathrm{pb}^{-1}$ of integrated luminosity in the *coherent peak region* roughly split 50/50 as "GlueX-I" and "GlueX-II" which has enhanced kaon identification capability

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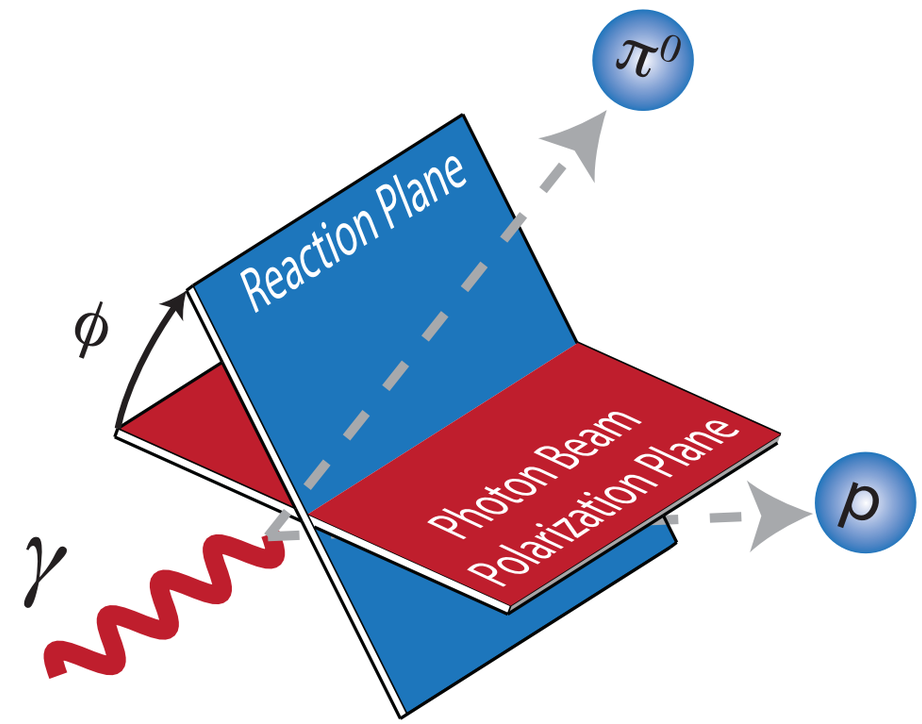
Asymmetry of Pseudoscalar Production

- Angle between beam polarization plane and reaction plane ϕ is sensitive to J^P of exchange
  - $\sigma(\phi) = \sigma_0[1 - P_\gamma \Sigma \cos(2\phi)]$
  - $\Sigma = +1 \implies 0^+, 1^-, 2^+, \ldots$
  - $\Sigma = -1 \implies 0^-, 1^+, 2^-, \ldots$



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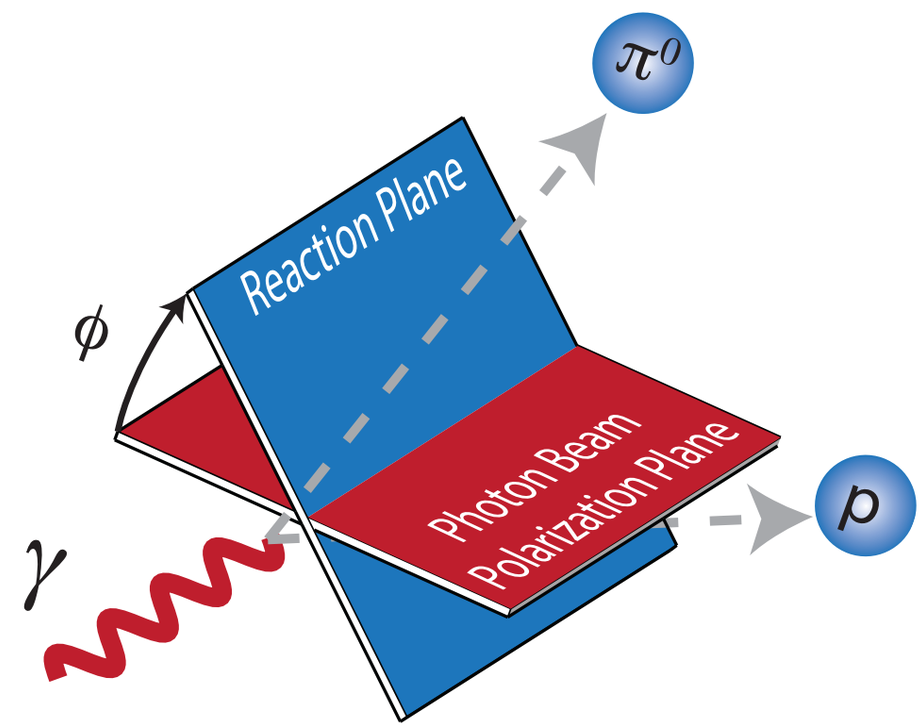
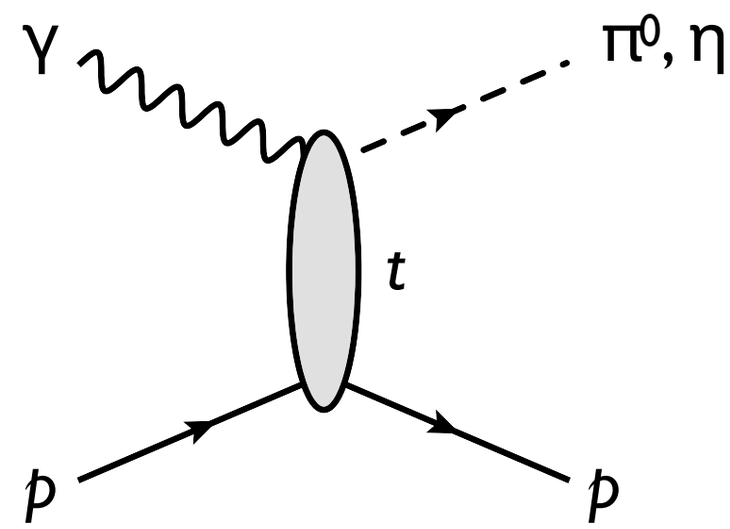
- Asymmetry Σ depends on a *t* in general





Exchange J^{PC}

$1^{--}: \ \omega, \rho$

$1^{+-}: \ b, h$

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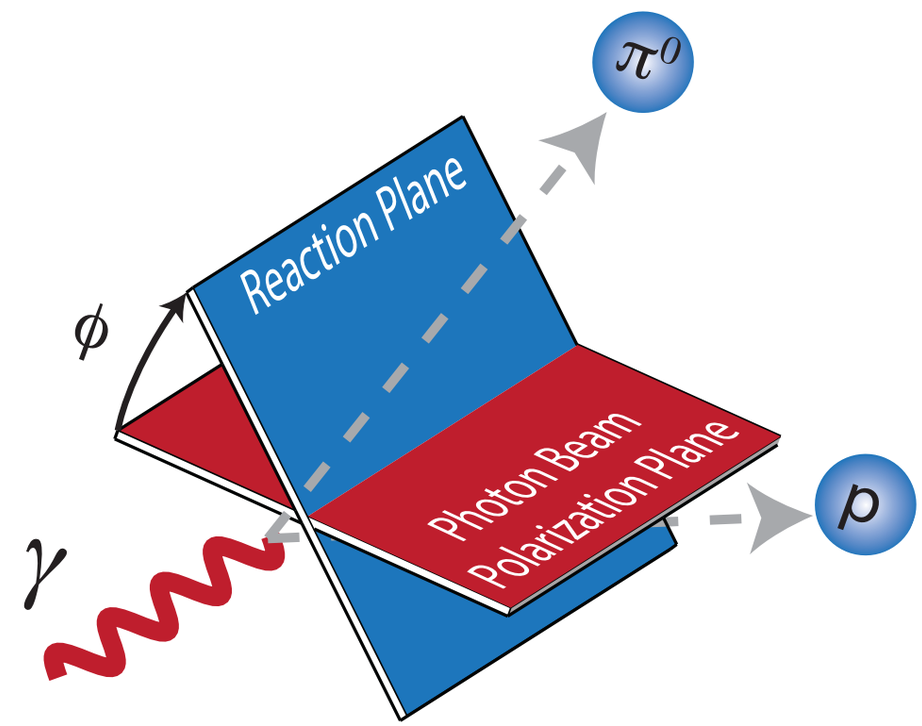
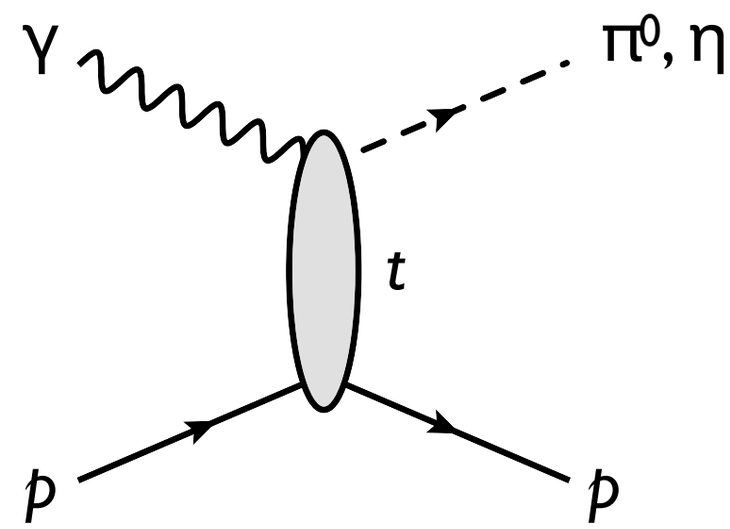
- Goal: understand and develop models for photoproduction of known mesons
  - learn about available production mechanisms
  - leverage in search for hybrid mesons





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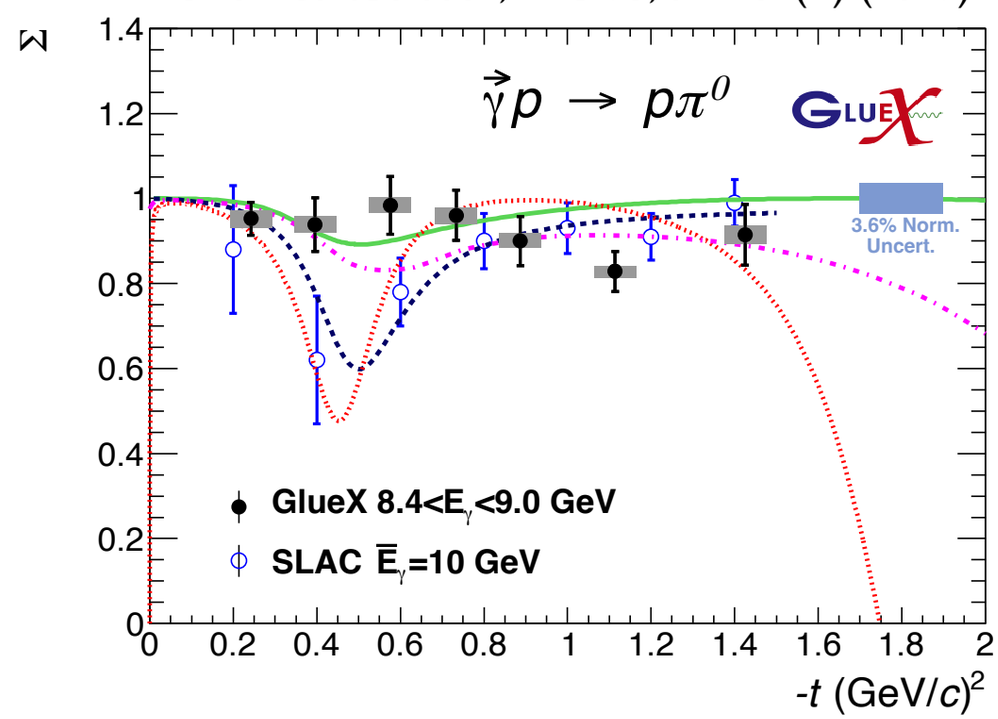
Asymmetry of Pseudoscalar Production

- No sophisticated understanding of detector acceptance required
- GlueX π^0 production asymmetry repeats older measurements by SLAC
- General trend: production dominated by natural parity exchange except when π-exchange is allowed

GlueX Collaboration, PRC 95, 042201(R) (2017)



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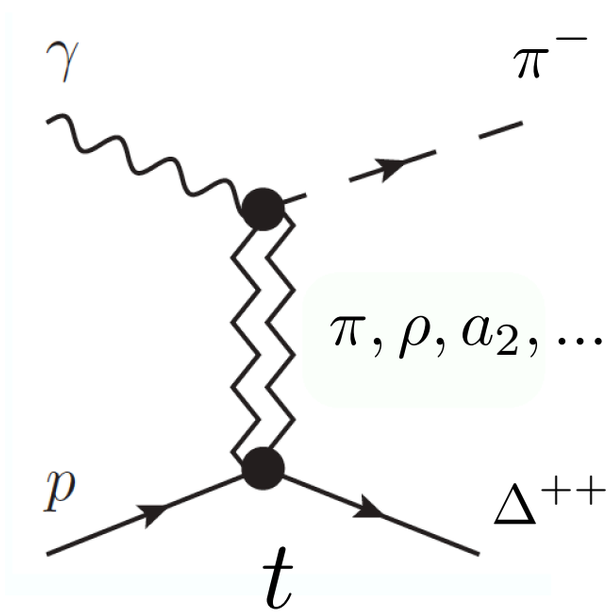

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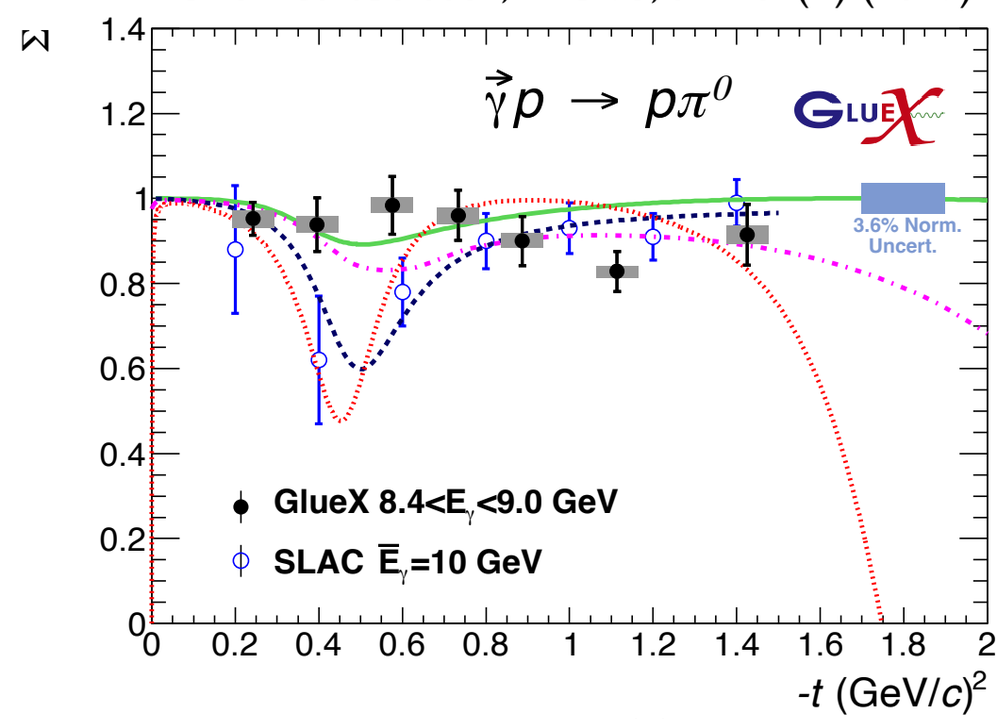
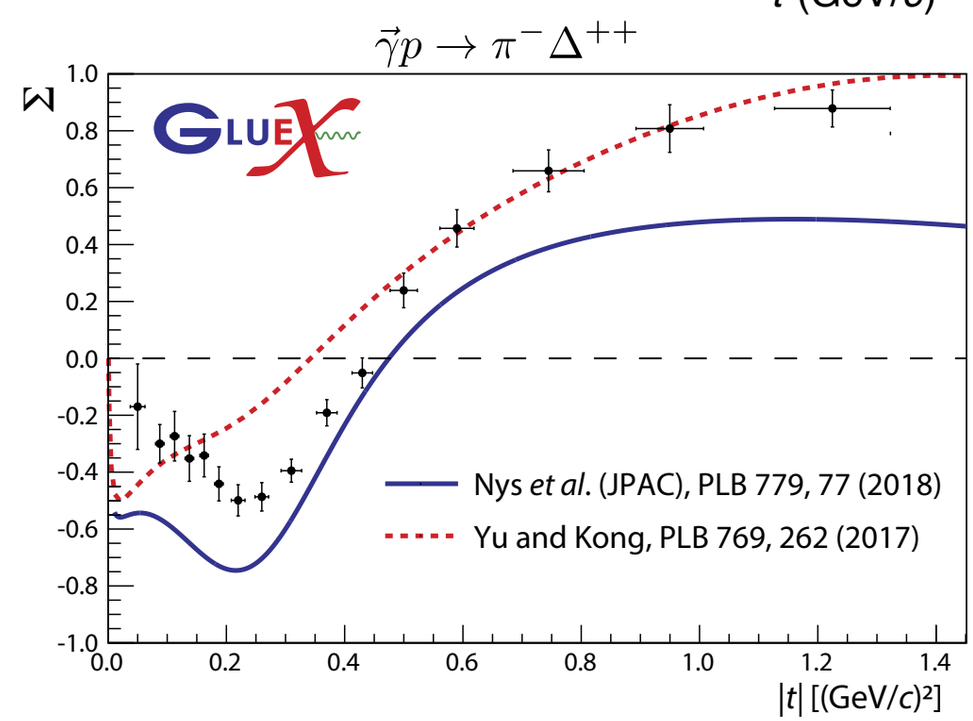
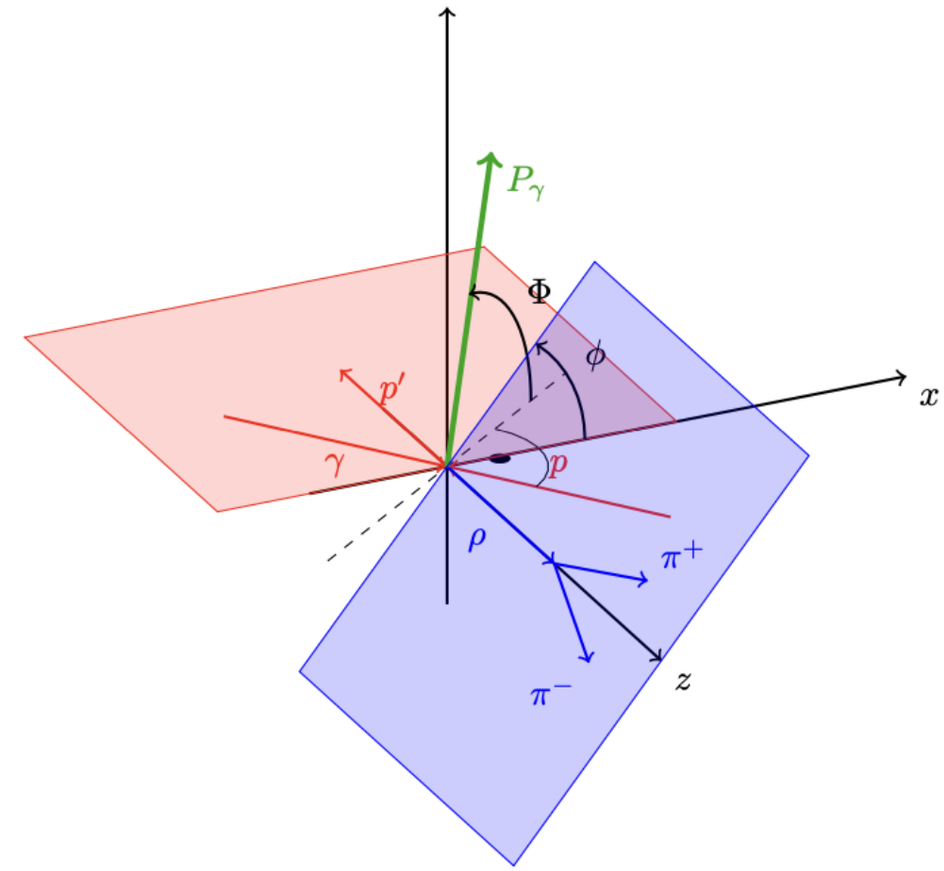




GlueX Collab., Phys. Rev. C 103, 022201 (2021)

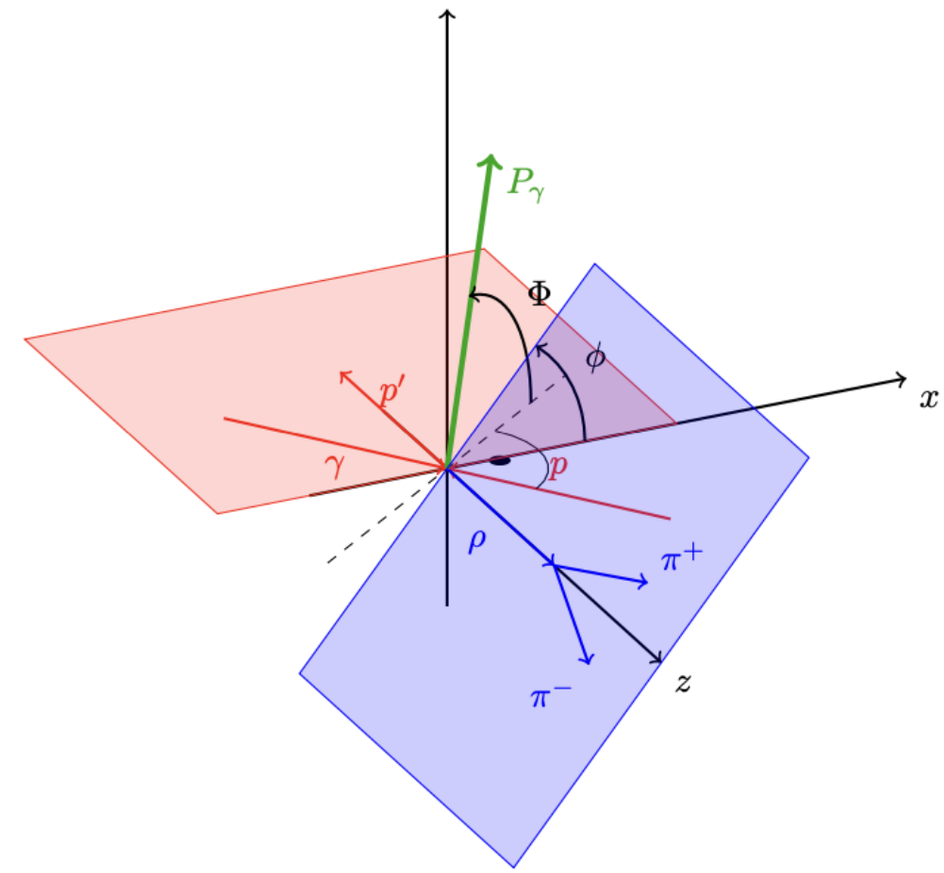
Spin-Density Matrix Elements

- Reaction: $\gamma p \to \rho p$, where $\rho \to \pi^+\pi^-$
- SDMEs describe the transfer of polarization from the beam photon to the ρ meson



Spin-Density Matrix Elements

- Reaction: $\gamma p \to \rho p$, where $\rho \to \pi^+\pi^-$
- SDMEs describe the transfer of polarization from the beam photon to the ρ meson
- Obtain by fitting three-dimensional angular distribution for data
  - requires understanding of detector acceptance
  - extract as a function of *t*
  - systematics limited



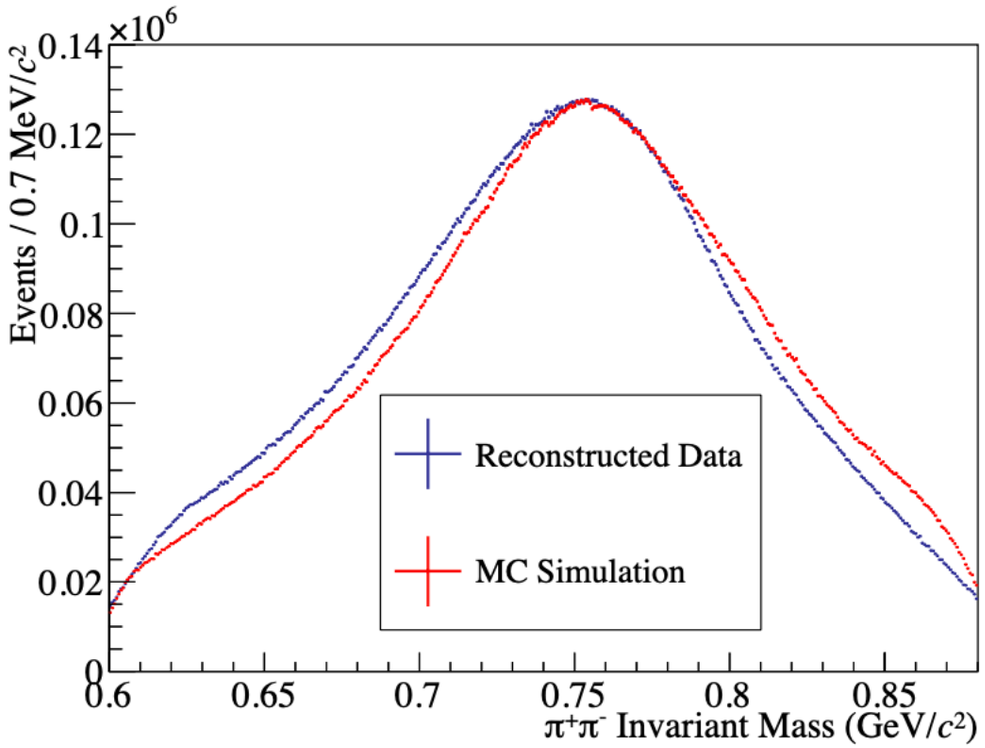
$$W(\cos\vartheta,\varphi,\Phi) = W^0(\cos\vartheta,\varphi) - \mathbf{P}_\gamma \cos(2\Phi) W^1(\cos\vartheta,\varphi) - \mathbf{P}_\gamma \sin(2\Phi) W^2(\cos\vartheta,\varphi)$$

$$W^0(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00}-1)\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\vartheta\cos\varphi - \rho^0_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

$$W^1(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\rho^1_{11}\sin^2\vartheta + \rho^1_{00}\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\vartheta\cos\varphi - \rho^1_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

$$W^2(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\sqrt{2}\mathrm{Im}\rho^2_{10}\sin 2\vartheta\sin\varphi + \mathrm{Im}\rho^2_{1-1}\sin^2\vartheta\sin 2\varphi\right)$$

Spin-Density Matrix Elements



- < 10% of GlueX data collected to date

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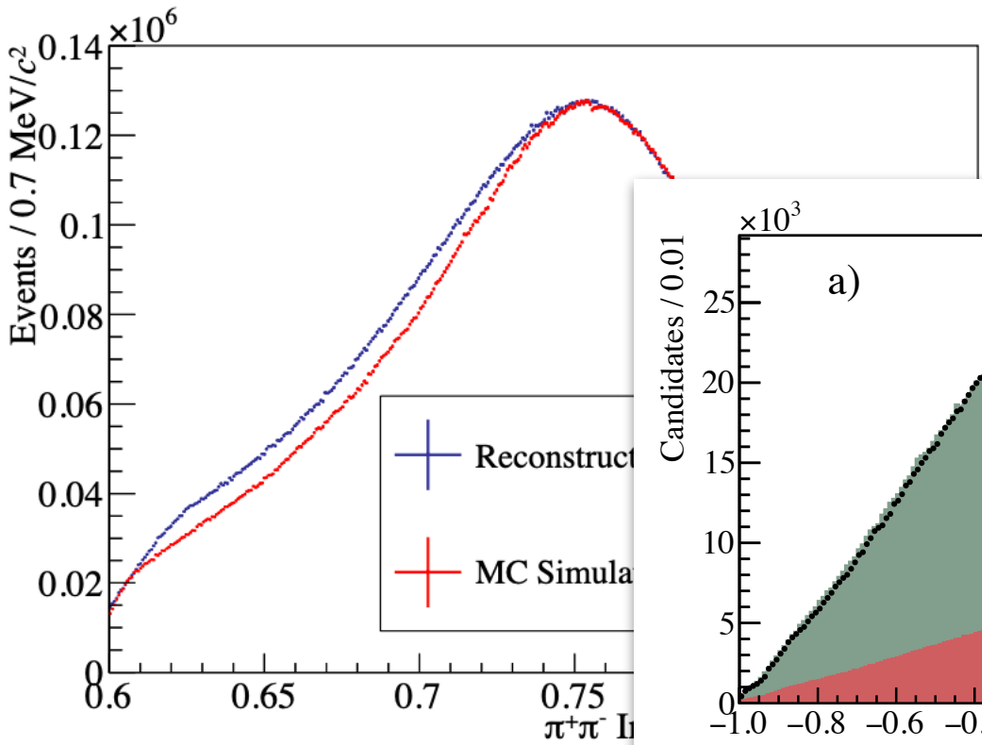
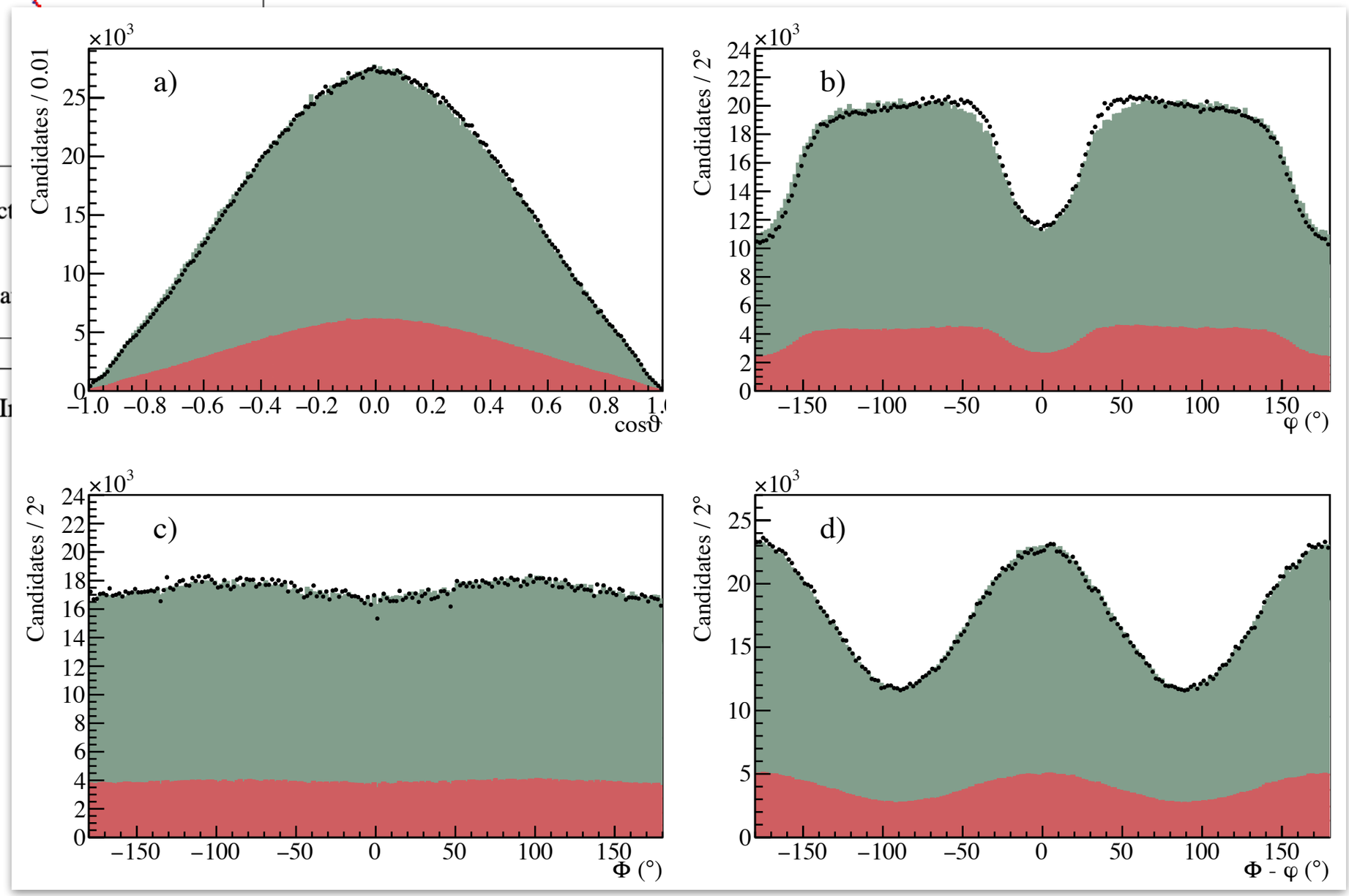
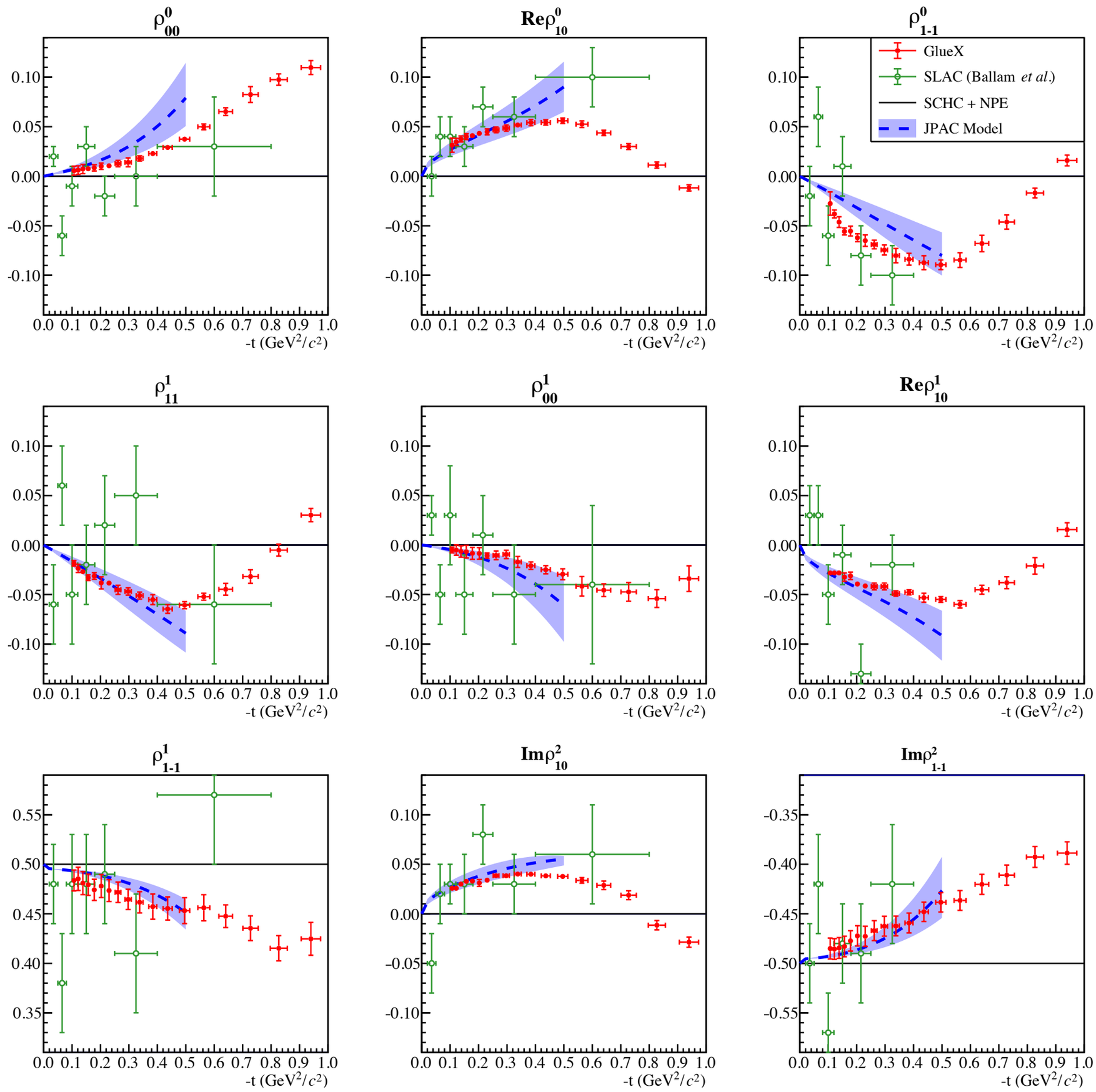




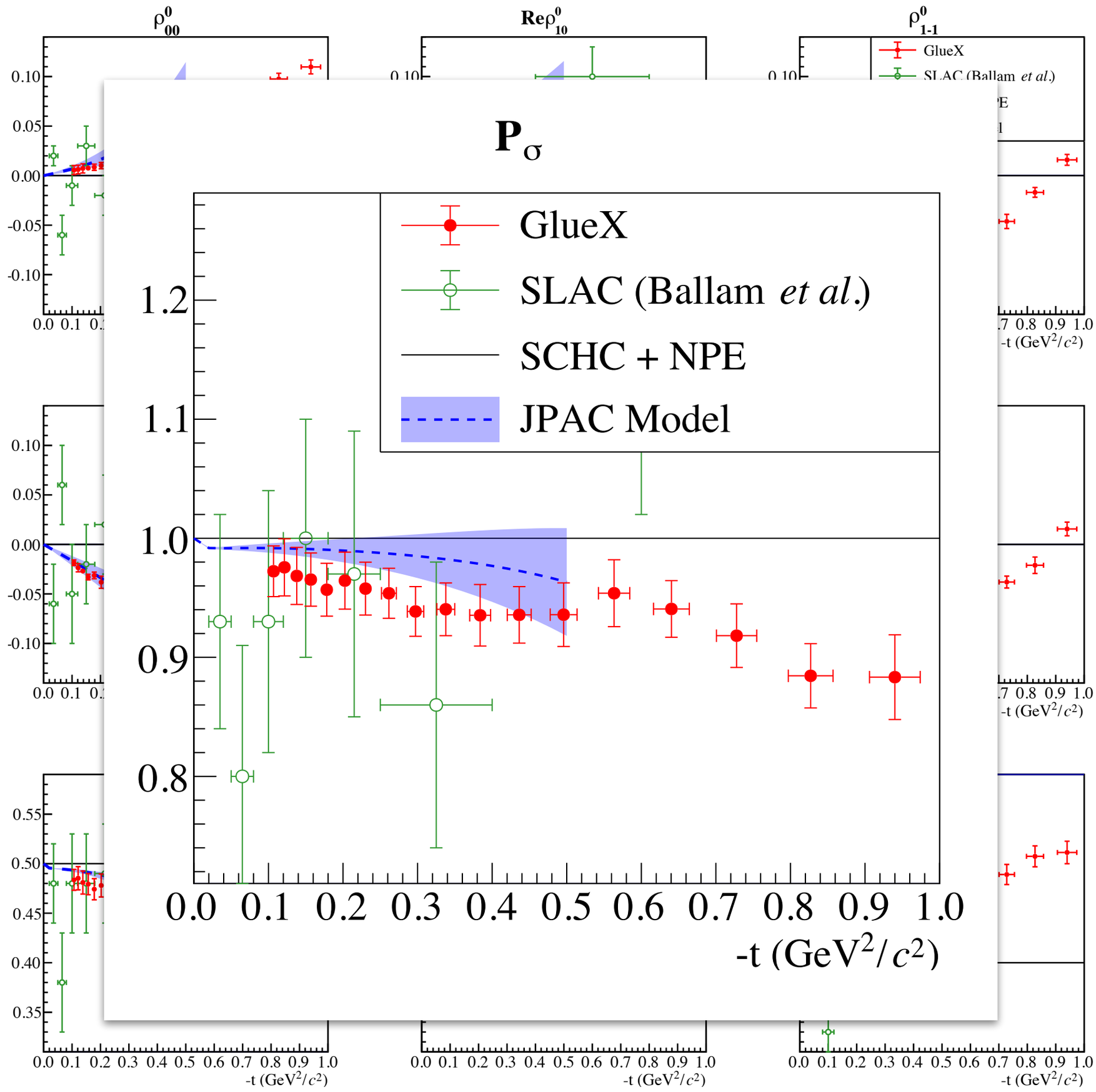
- < 10% of GlueX data collected to date
- Example fit for $-t \approx 0.2\ \mathrm{GeV}^2$
  - Data
  - Signal Model
  - Background



JPAC model [PRD 97, 094003 (2018)] expected to be valid in the region where $-t < m_\rho^2$.

As $t \to 0$ one expects SDMEs consistent with s-channel helicity conservation and natural parity exchange.

GlueX Collab., submitted to PRC
arXiv:2305.09047 (2023)



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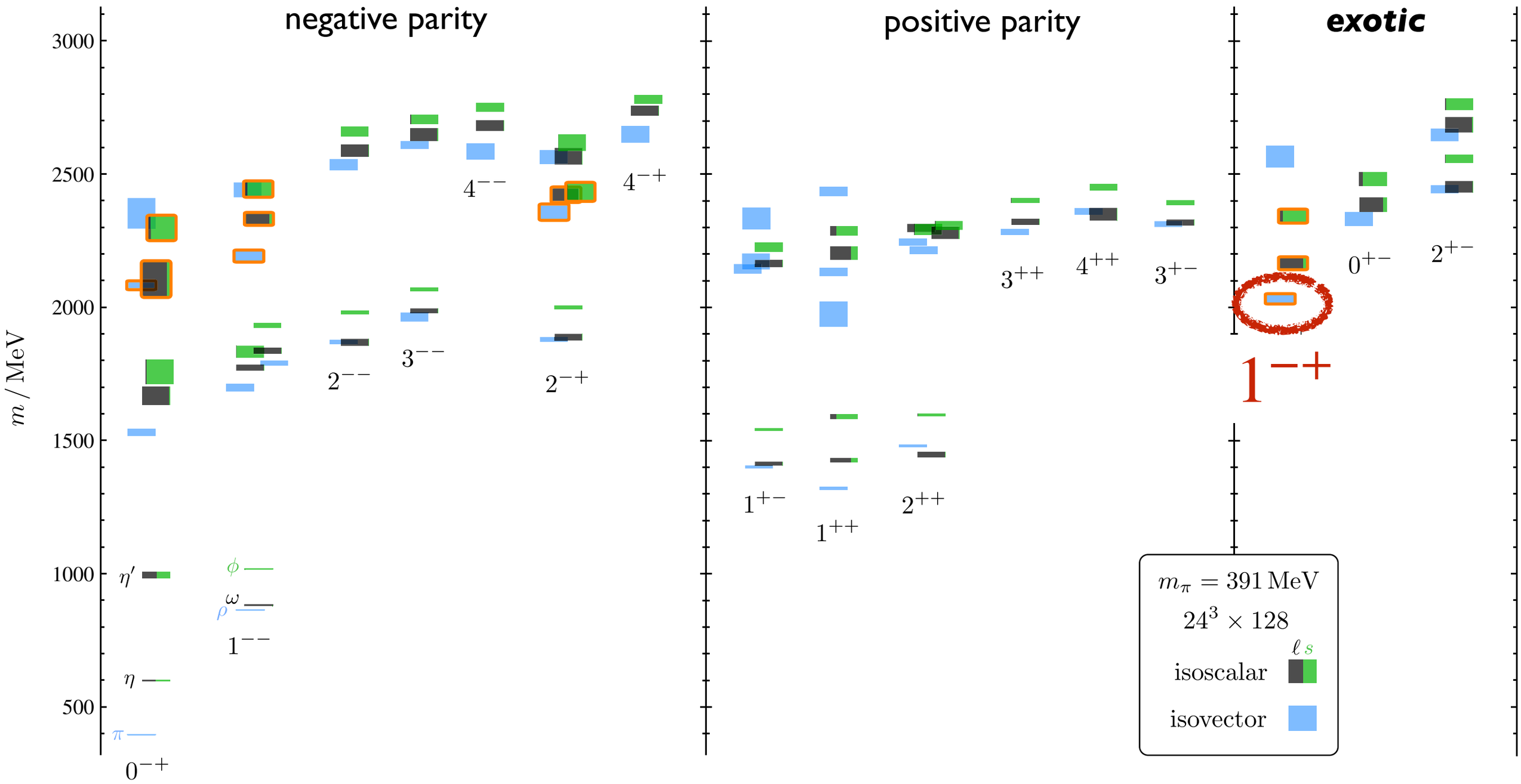
Light Quark Mesons from Lattice QCD

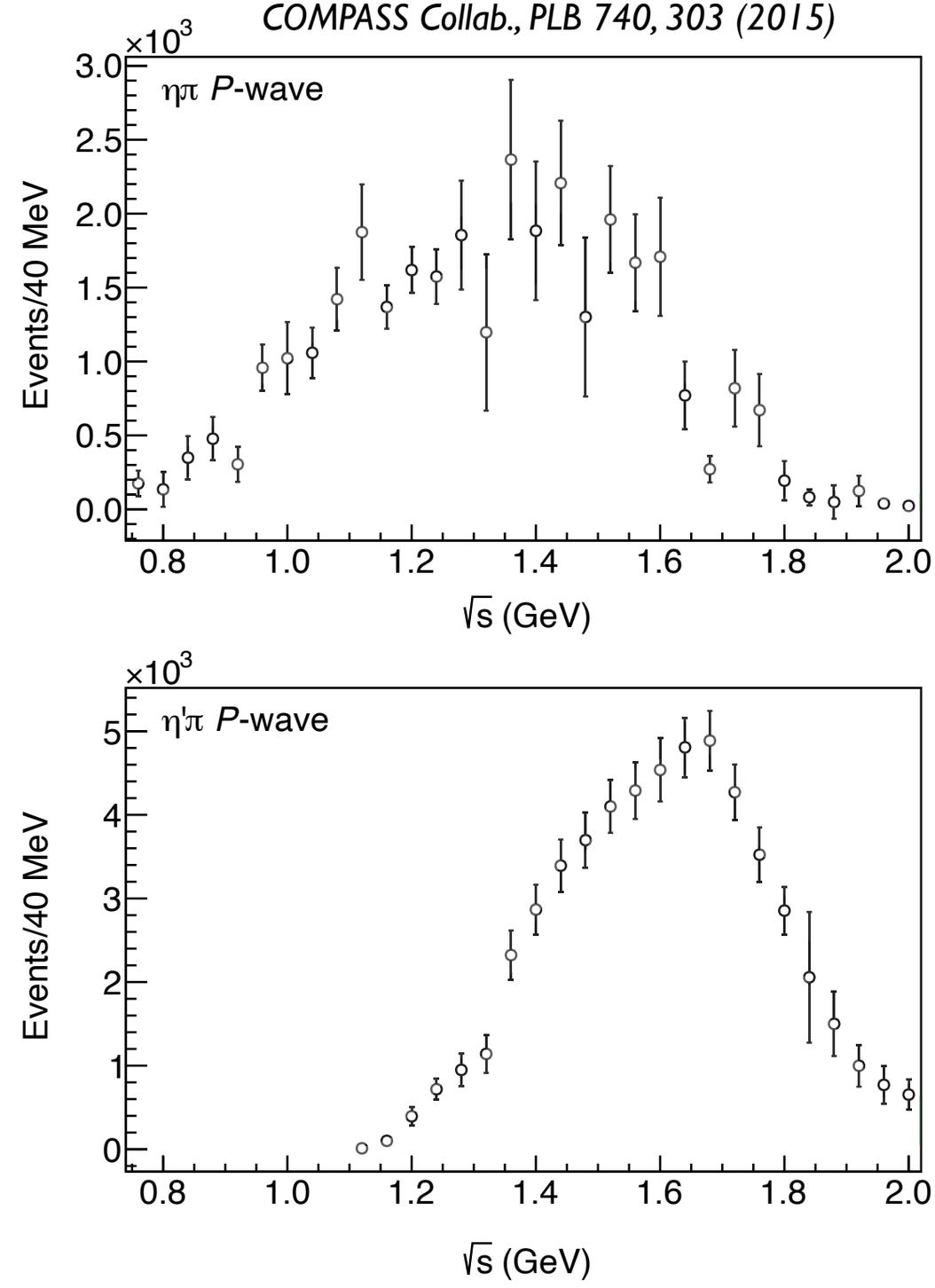
Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)



State of the Art

- Best evidence for existence of exotic hybrid mesons is from pion production at COMPASS which has been analyzed by JPAC
  - only the published partial wave expansion was available for JPAC analysis

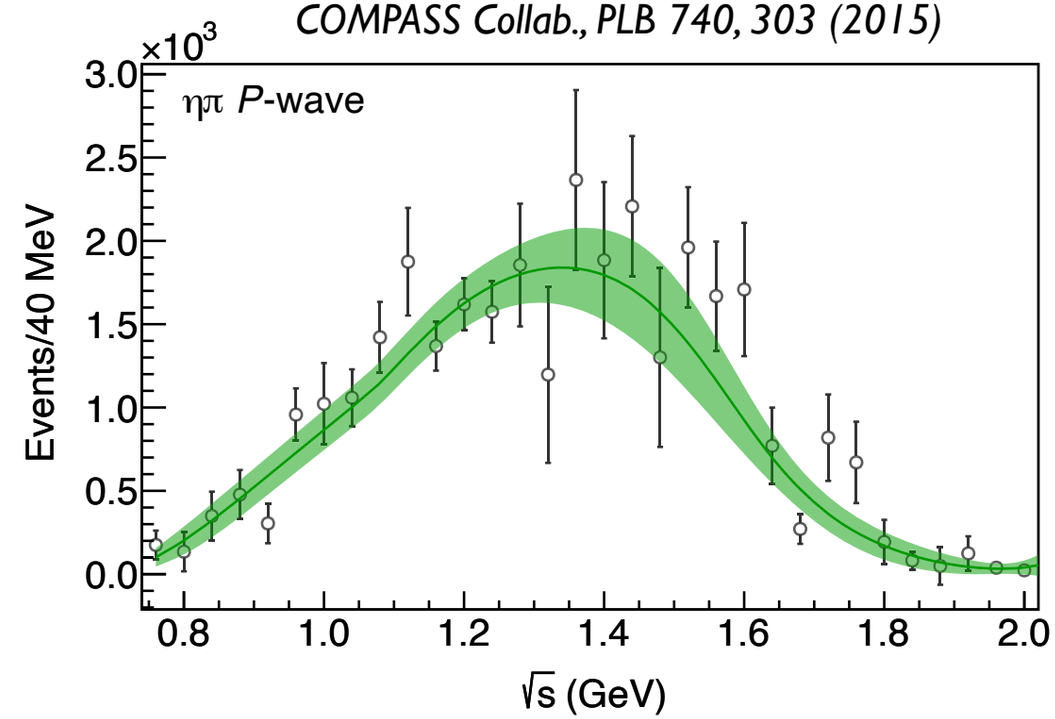
exotic 1^{-+} amplitudes from COMPASS Collab., PLB 740, 303 (2015)

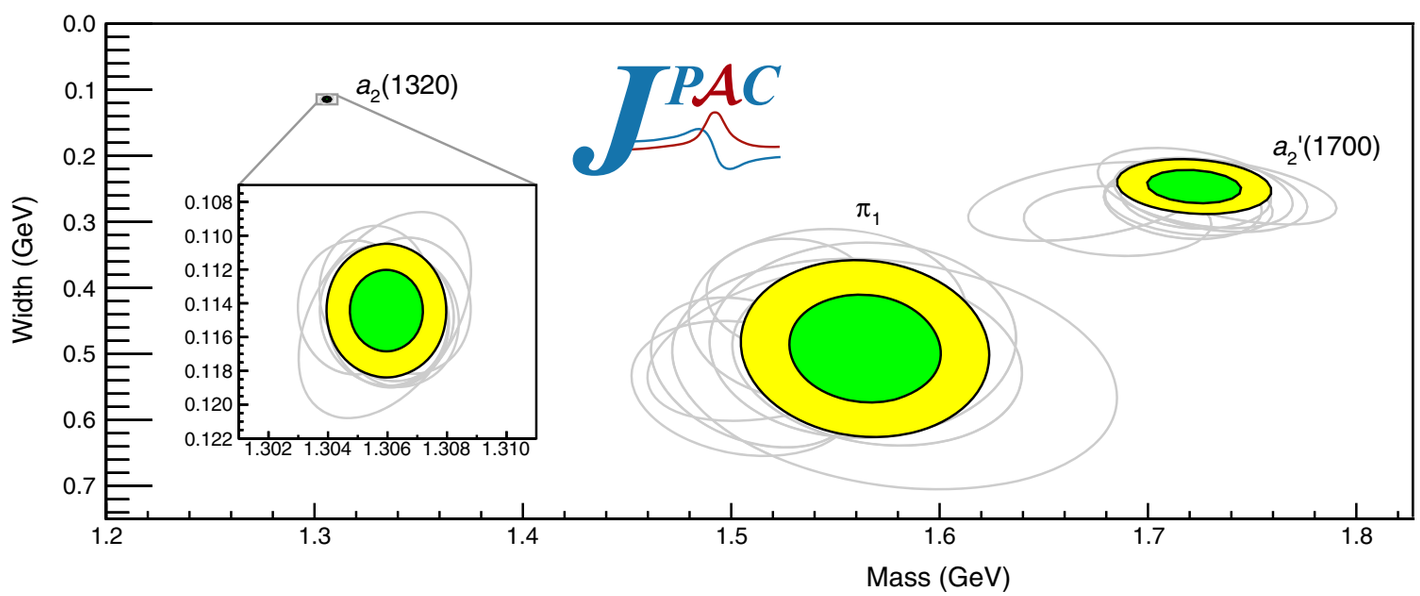


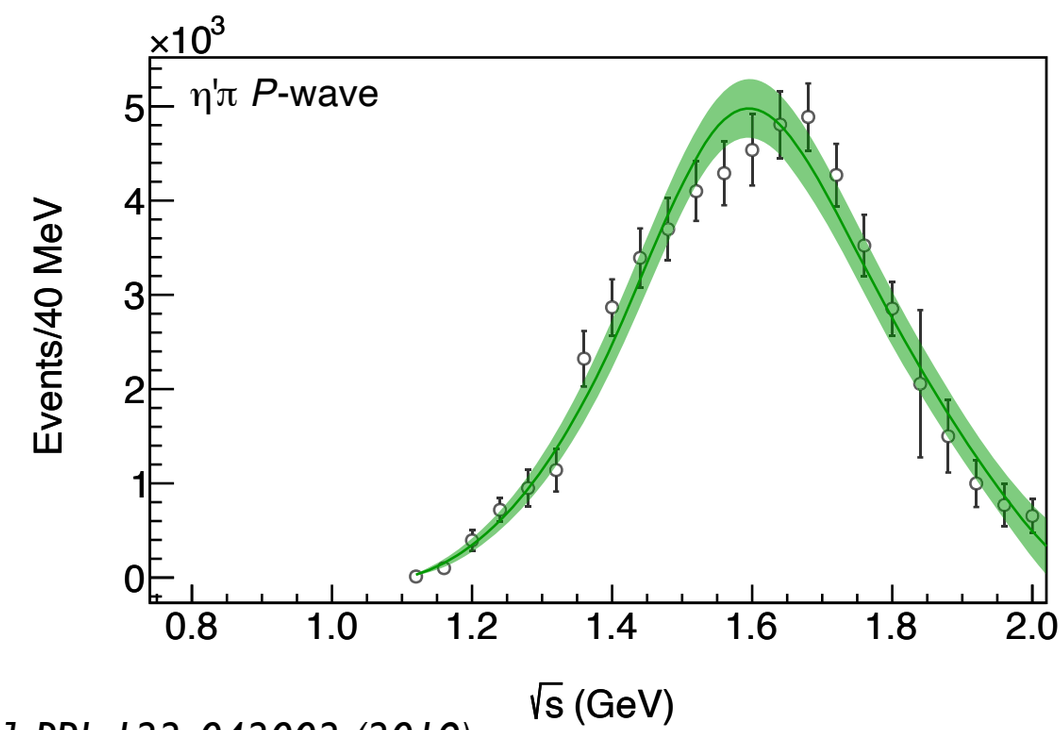
State of the Art

- Best evidence for existence of exotic hybrid mesons is from pion production at COMPASS which has been analyzed by JPAC
  - only the published partial wave expansion was available for JPAC analysis
- Coupled channel fit to $\eta\pi$ and $\eta'\pi$ partial waves in pion production measured by COMPASS
  - data consistent with a single exotic pole
  - recently extended to include Crystal Barrel (LEAR) data: further constrains the width to about 400 MeV

exotic 1^{-+} amplitudes from COMPASS Collab., PLB 740, 303 (2015)







A. Rodas et al. [Joint Physics Analysis Center], PRL 122, 042002 (2019)

How do hybrids decay?

PHYSICAL REVIEW D **103,** 054502 (2021)

Decays of an exotic 1^{-+} hybrid meson resonance in QCD

Antoni J. Woss,[1,*] Jozef J. Dudek,[2,3,†] Robert G. Edwards,[2,‡] Christopher E. Thomas,[1,§] and David J. Wilson[1,‖]

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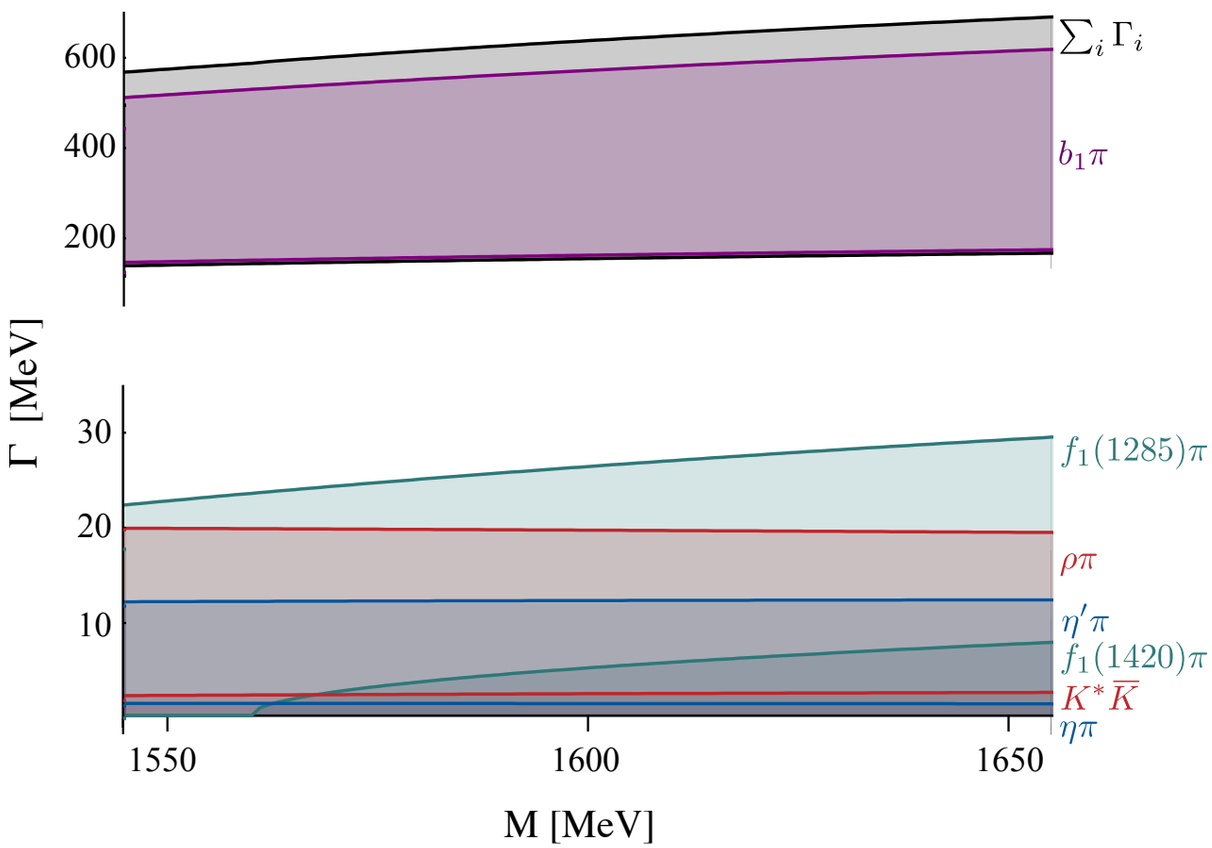

	Γ_i/MeV
$\eta\pi$	$0 \to 1$
$\rho\pi$	$0 \to 20$
$\eta'\pi$	$0 \to 12$
$b_1\pi$	$139 \to 529$
$K^*\overline{K}$	$0 \to 2$
$f_1(1285)\pi$	$0 \to 24$

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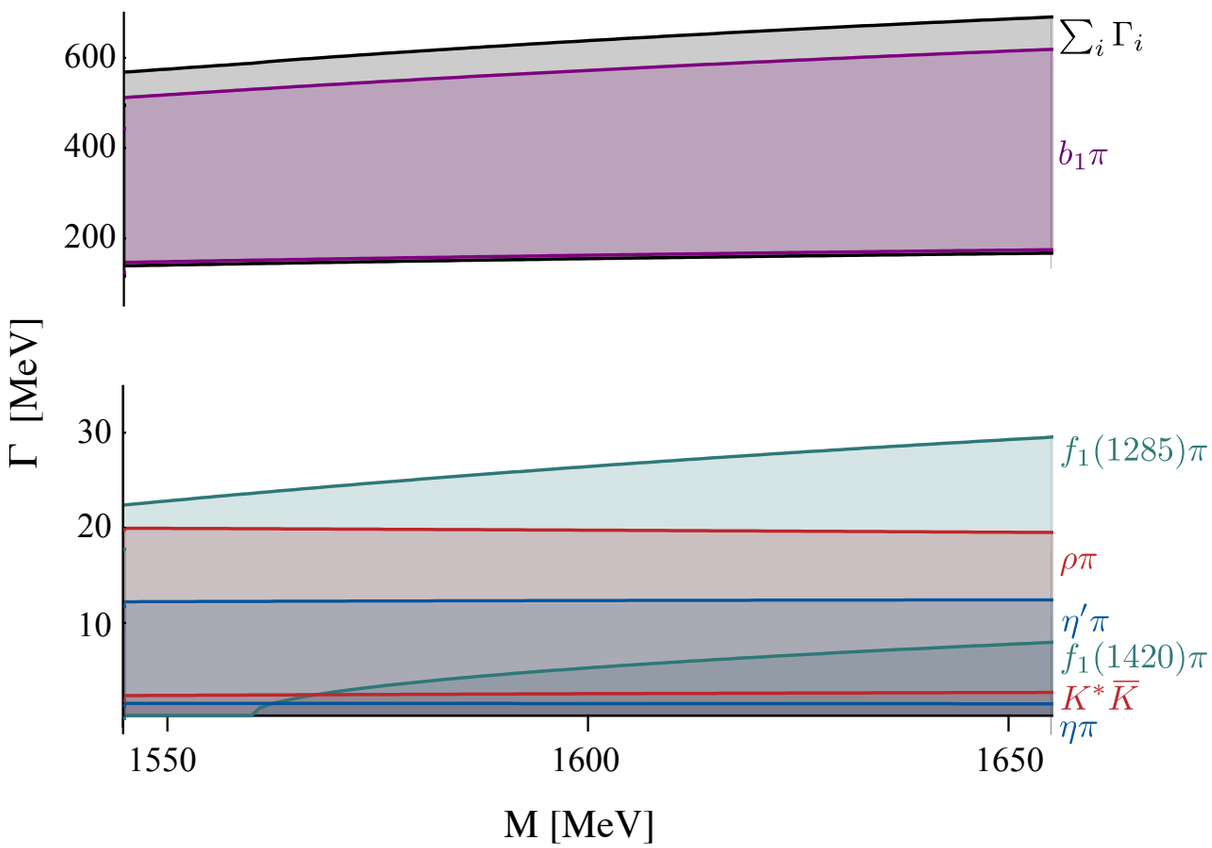

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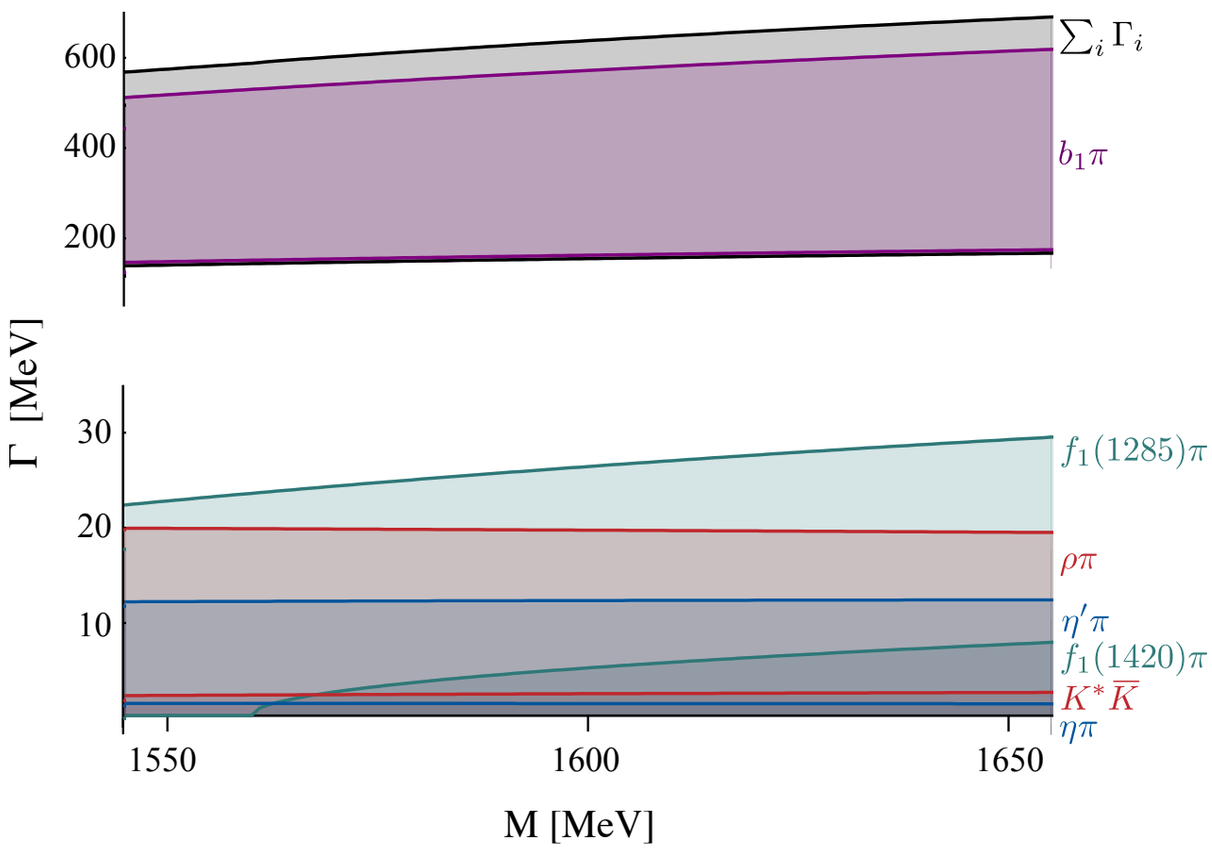

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$$\frac{B(\pi_1 \to b_1\pi)}{B(\pi_1 \to \eta\pi)} > \frac{139}{1} > 100$$

$$\frac{B(\pi_1 \to b_1\pi)}{B(\pi_1 \to \eta'\pi)} > \frac{139}{12} > 10$$

$$B(\pi_1^0 \to b_1^{\pm}\pi^{\mp}) \approx B(\pi_1^0 \to \omega\pi^+\pi^-) \sim 100\,\%$$

$$B(\pi_1^0 \to \eta\pi^0) \lesssim 1\,\%$$

$$B(\pi_1^0 \to \eta'\pi^0) \lesssim 10\,\%$$

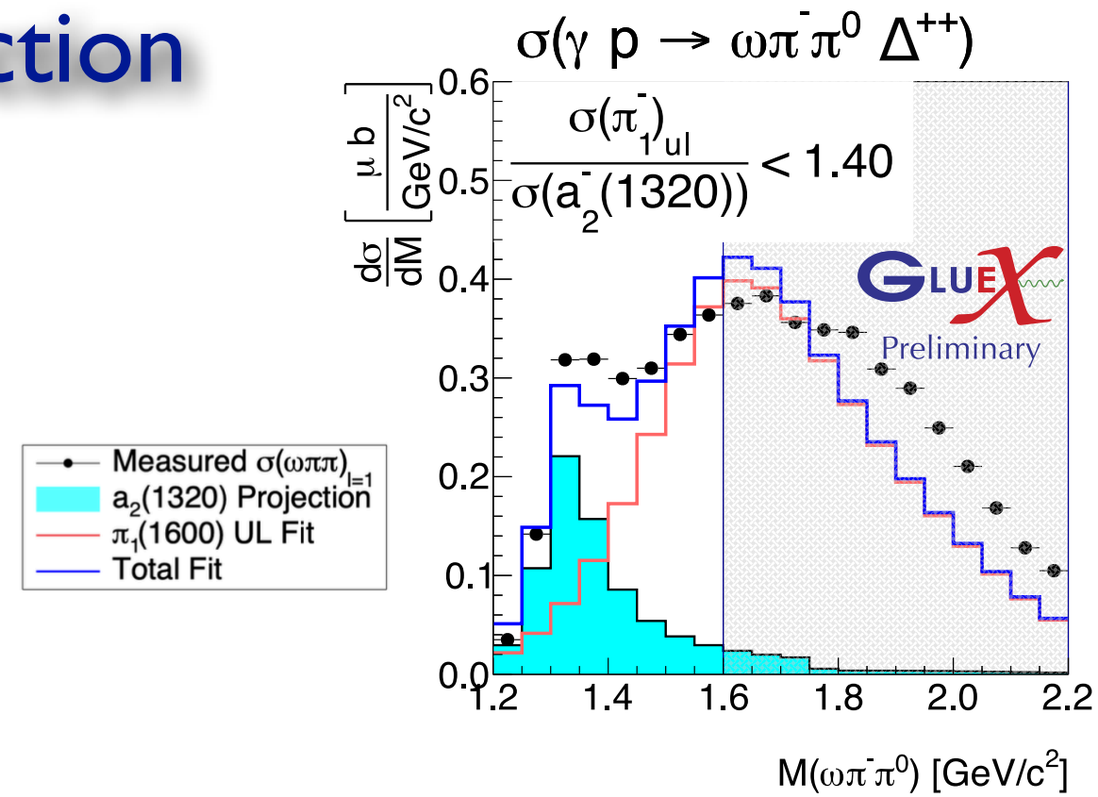
had spec

Setting Limits on π_1 Production

$a_2(1320)$ $\quad I^G(J^{PC}) = 1^-(2^{++})$

Mass $m = 1318.2 \pm 0.6$ MeV (S = 1.2)
Full width $\Gamma = 107 \pm 5$ MeV [i]

$a_2(1320)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
3π	(70.1 ± 2.7) %	S=1.2	624
$\eta\pi$	(14.5 ± 1.2) %		535
$\omega\pi\pi$	(10.6 ± 3.2) %	S=1.3	366
$K\overline{K}$	(4.9 ± 0.8) %		437
$\eta'(958)\pi$	$(5.5 \pm 0.9) \times 10^{-3}$		288
$\pi^\pm\gamma$	$(2.91 \pm 0.27) \times 10^{-3}$		652
$\gamma\gamma$	$(9.4 \pm 0.7) \times 10^{-6}$		659
e^+e^-	$< 5 \times 10^{-9}$	CL=90%	659



- If the π_1 is produced, it will mostly populate the isospin-1 final state of $\omega\pi\pi$ via $\pi_1 \to b_1\pi \to \omega\pi\pi$

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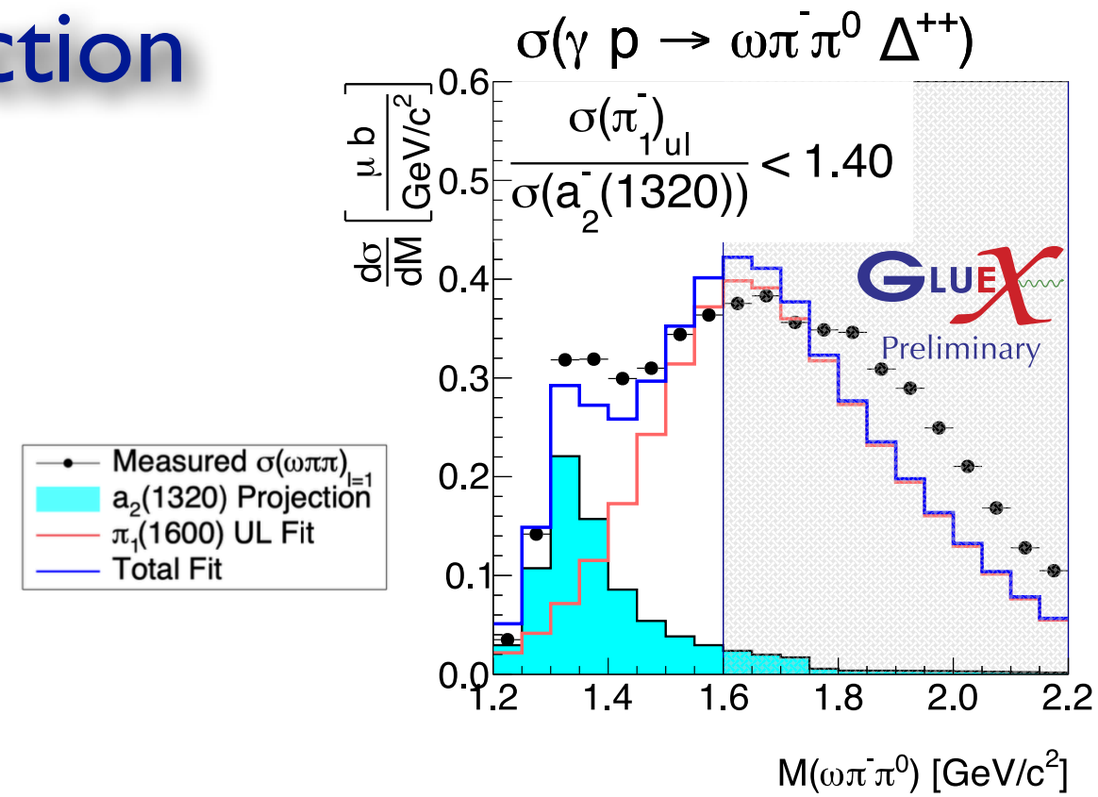
$\pi^\pm\gamma$	$(2.91 \pm 0.27) \times 10^{-3}$		652
$\gamma\gamma$	$(9.4 \pm 0.7) \times 10^{-6}$		659
e^+e^-	$< 5 \times 10^{-9}$	CL=90%	659



- If the π_1 is produced, it will mostly populate the isospin-1 final state of $\omega\pi\pi$ via $\pi_1 \to b_1\pi \to \omega\pi\pi$
- Goals:
  - set limit on $\sigma(\gamma p \to \pi_1^- \Delta^{++}) \times \mathscr{B}(\pi_1 \to b_1\pi)$
  - use LQCD lower limit on $\mathscr{B}(\pi_1 \to b_1\pi)$ to place an upper limit on $\sigma(\pi_1)$
  - repeat for $\Delta^{++} \to p$

Setting Limits on π_1 Production

$a_2(1320)$ $\quad I^G(J^{PC}) = 1^-(2^{++})$

Mass $m = 1318.2 \pm 0.6$ MeV (S = 1.2)
Full width $\Gamma = 107 \pm 5$ MeV [i]

$a_2(1320)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
3π	(70.1 ± 2.7) %	S=1.2	624
$\eta\pi$	(14.5 ± 1.2) %		535
$\omega\pi\pi$	(10.6 ± 3.2) %	S=1.3	366
$K\overline{K}$	(4.9 ± 0.8) %		437
$\eta'(958)\pi$	$(5.5 \pm 0.9) \times 10^{-3}$		288
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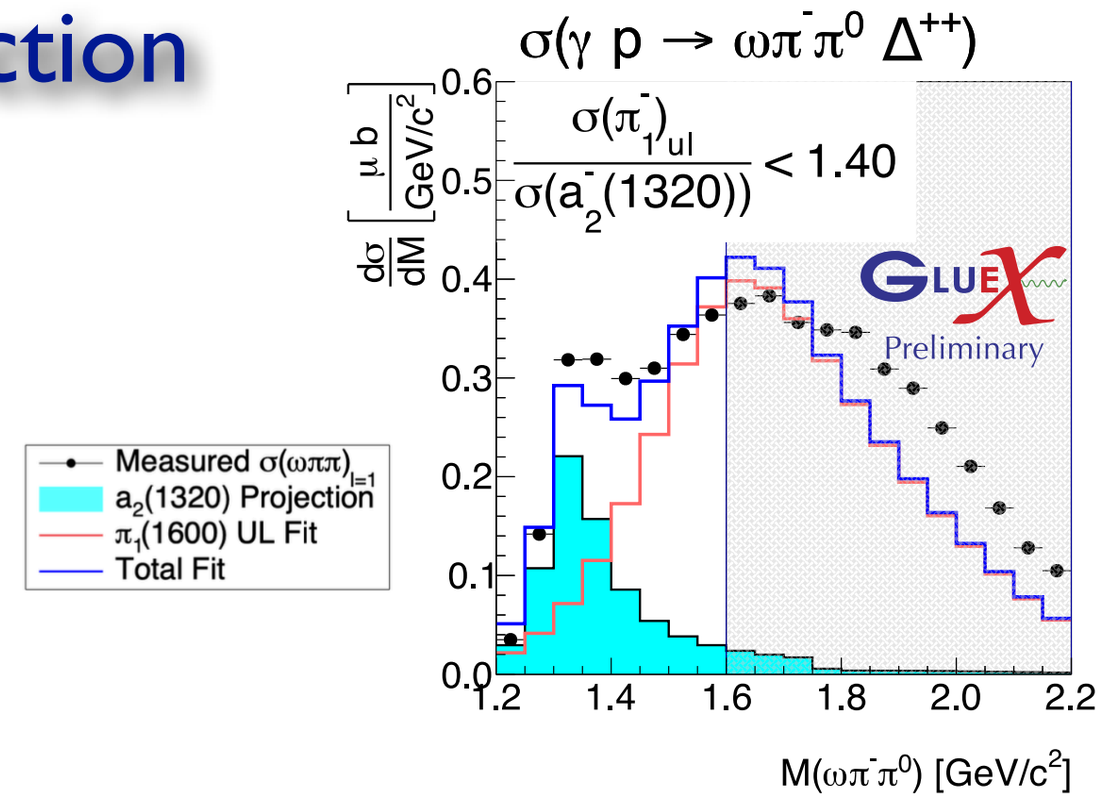

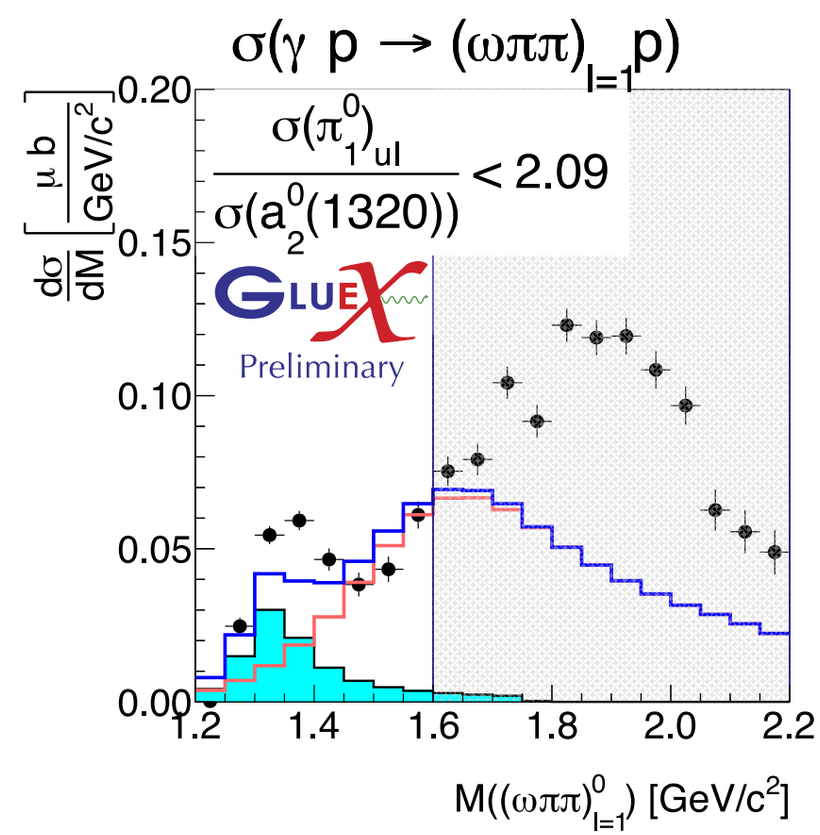

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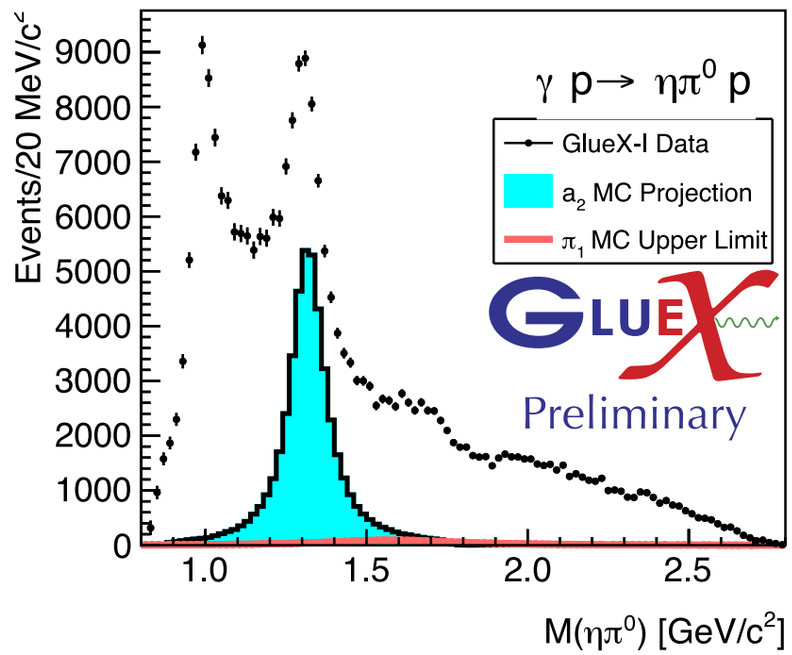
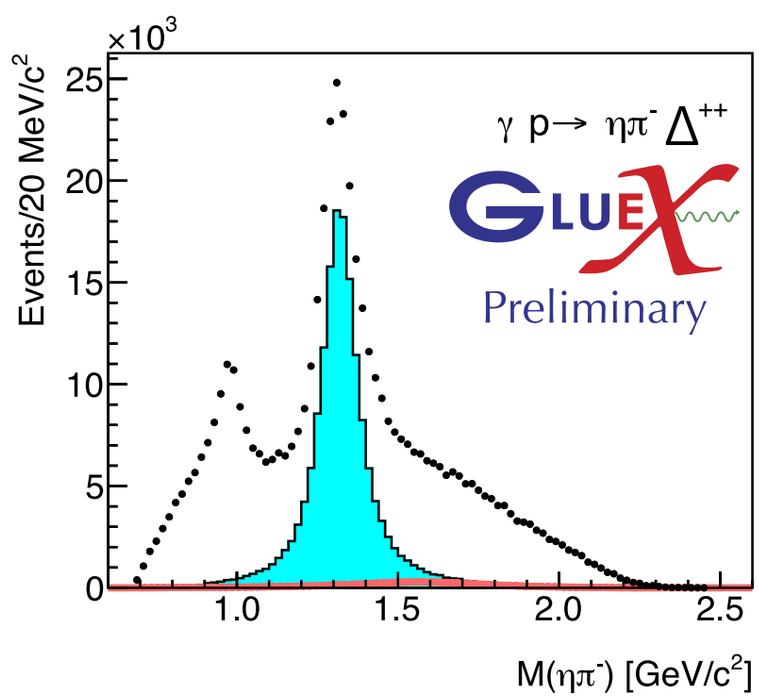
Implications on the Hybrid Search Strategy

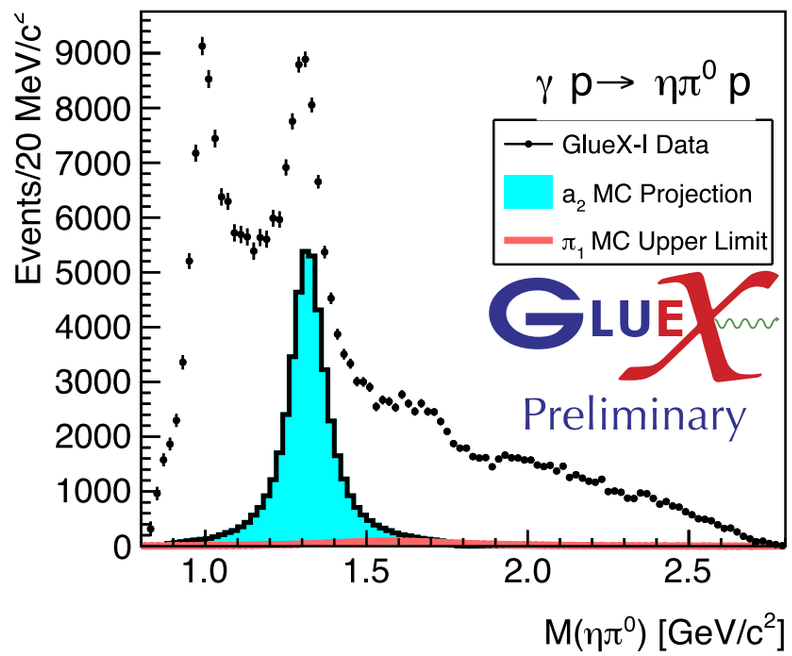
- Use LQCD calculations of partial width limits to guide the exotic hybrid search strategy

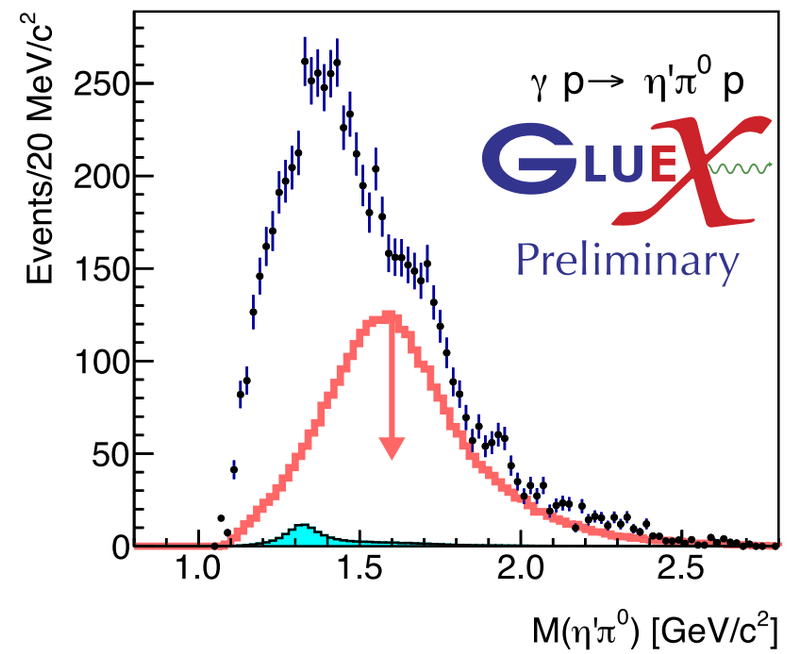


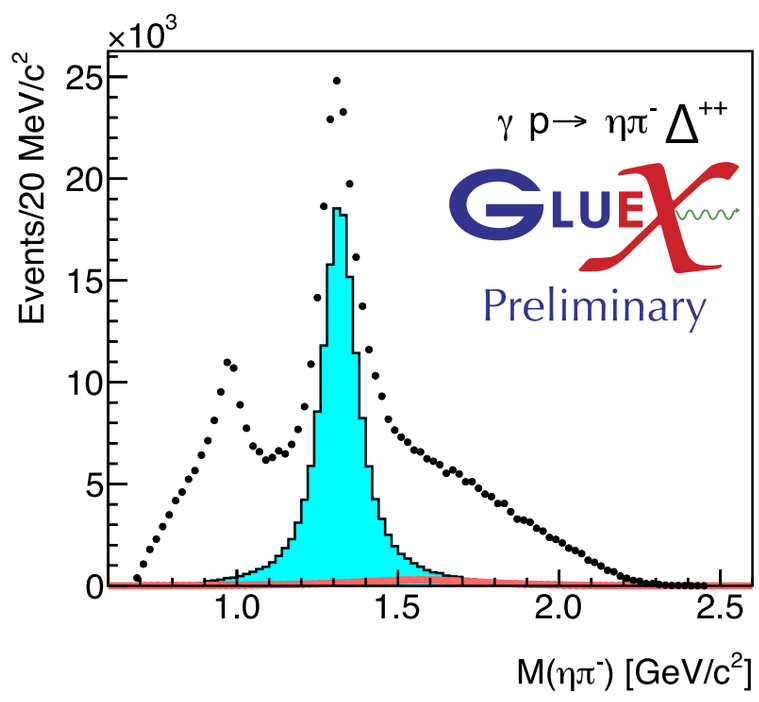


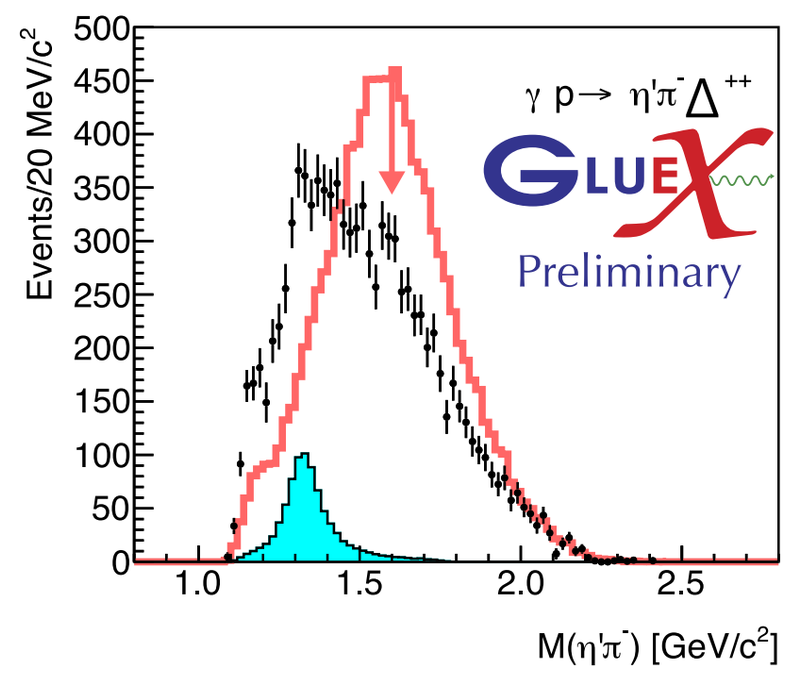
Implications on the Hybrid Search Strategy

- Use LQCD calculations of partial width limits to guide the exotic hybrid search strategy
- Large $P-$wave contribution is excluded for $\eta\pi$ but not $\eta'\pi$
- Need to use $a_2(1320)$ as a "standard candle" and interferometer for the hybrid search



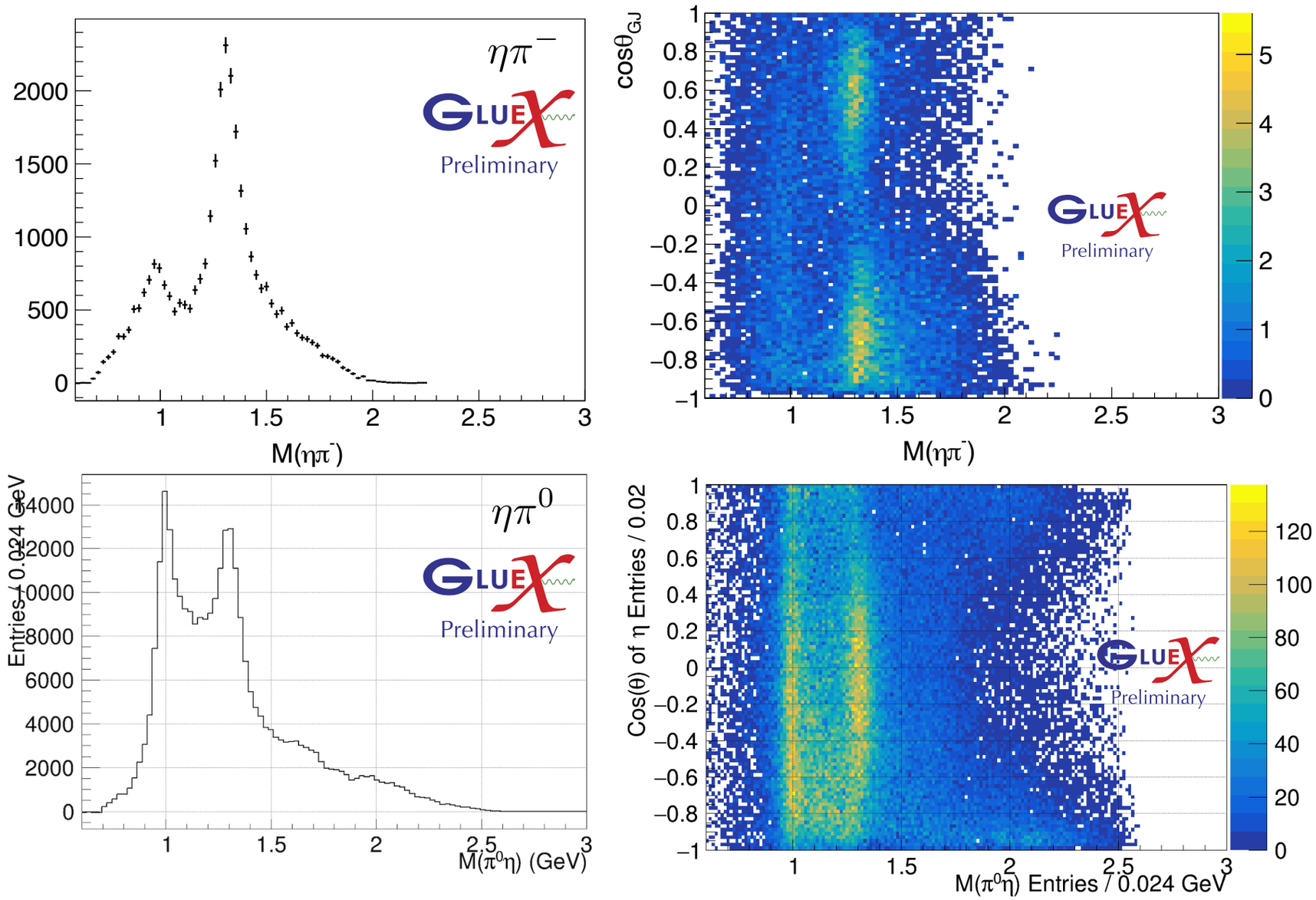






Production of $a_2(1320)^{-,0}$ and $a_0(980)^{-,0}$ at low t

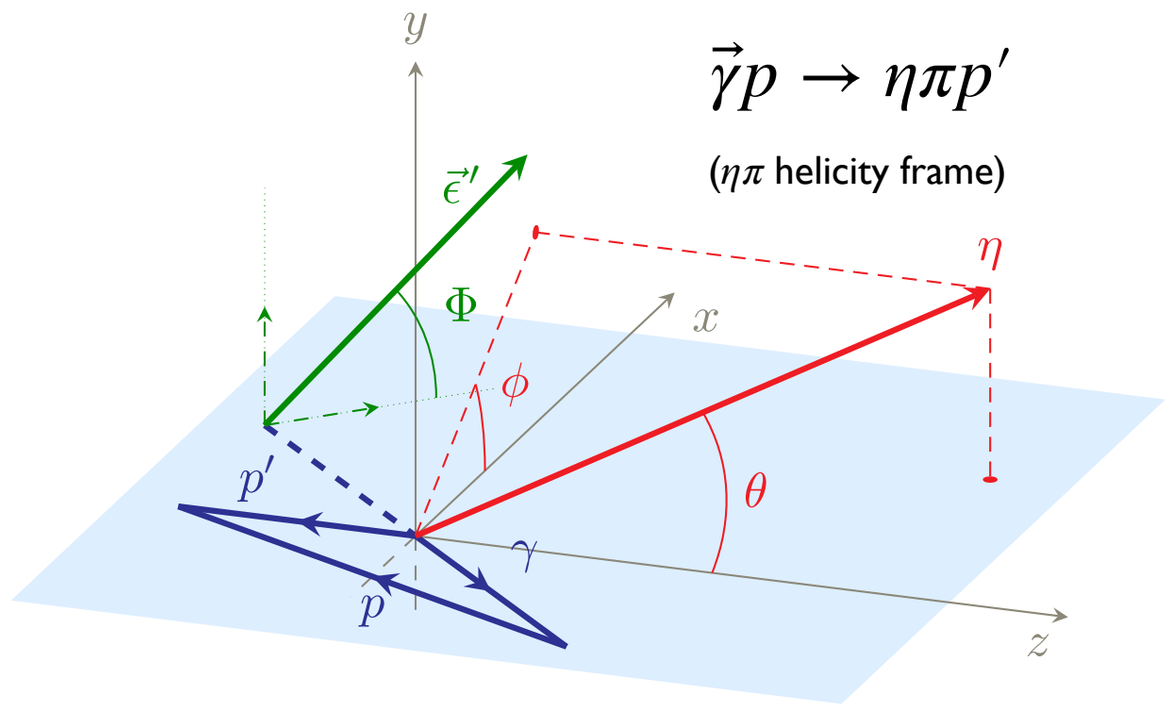
$0.1 < -t < 0.3$ GeV^2



- Production of a_2^- and a_2^0 clearly populate different a_2 polarization states
- a_2 polarization is independent of whether it decays to $\eta\pi$ or $\eta'\pi$
- use high statistics $\eta\pi$ decay to constrain a_2 amplitude in $\eta'\pi$ analysis

Role of Photon Polarization

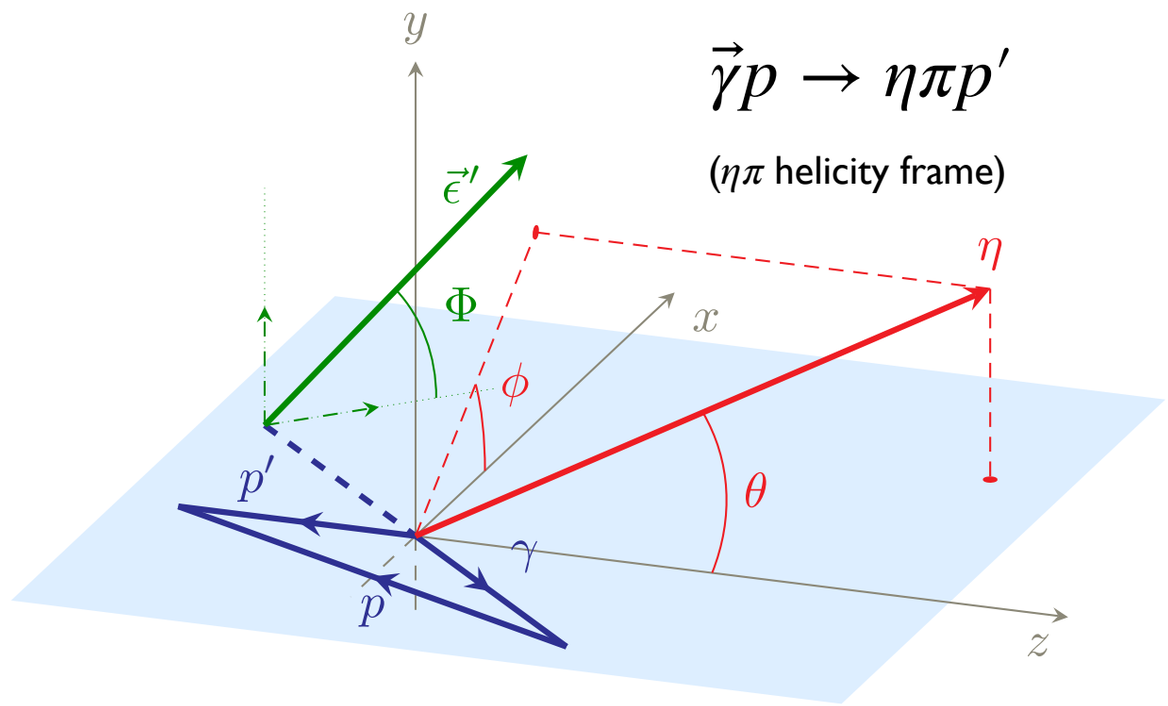
- Make use of this additional dimension (Φ) in the amplitude analysis to gain insight into production mechanisms as well as resonance properties through decay (ϕ, θ)



V. Mathieu et al. [JPAC], PRD 100, 054017 (2019)

Role of Photon Polarization

- Make use of this additional dimension (Φ) in the amplitude analysis to gain insight into production mechanisms as well as resonance properties through decay (ϕ, θ)
- Write amplitudes in the reflectivity basis: $\epsilon = \pm 1$, which have a non-trivial distribution in Φ
- Definine naturality: $P(-1)^J$
  - natural parity: $P(-1)^J = +1$; $J^P = 0^+, 1^-, 2^+, \ldots$
  - unnatural parity: $P(-1)^J = -1$; $J^P = 0^-, 1^+, 2^-, \ldots$
- High energy *t*-channel picture: the reflectivity fixes the product of the naturalities of the exchange particle and the produced resonance



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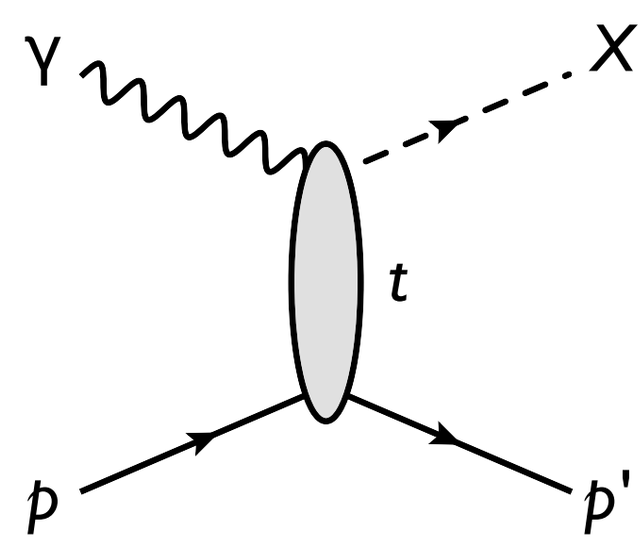
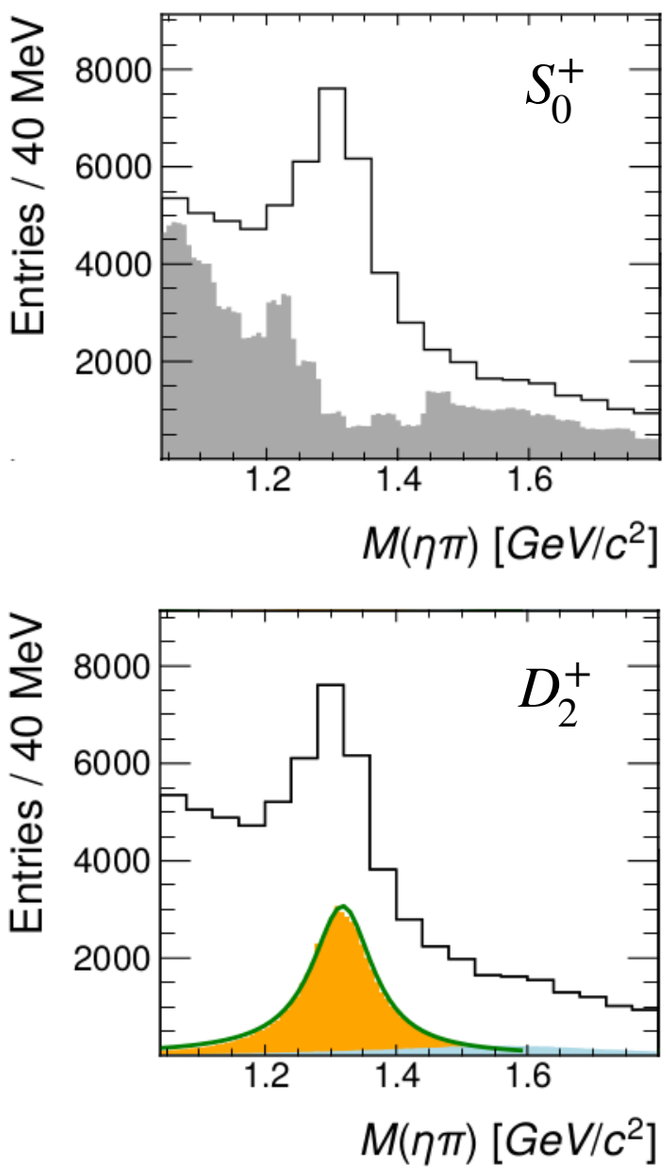


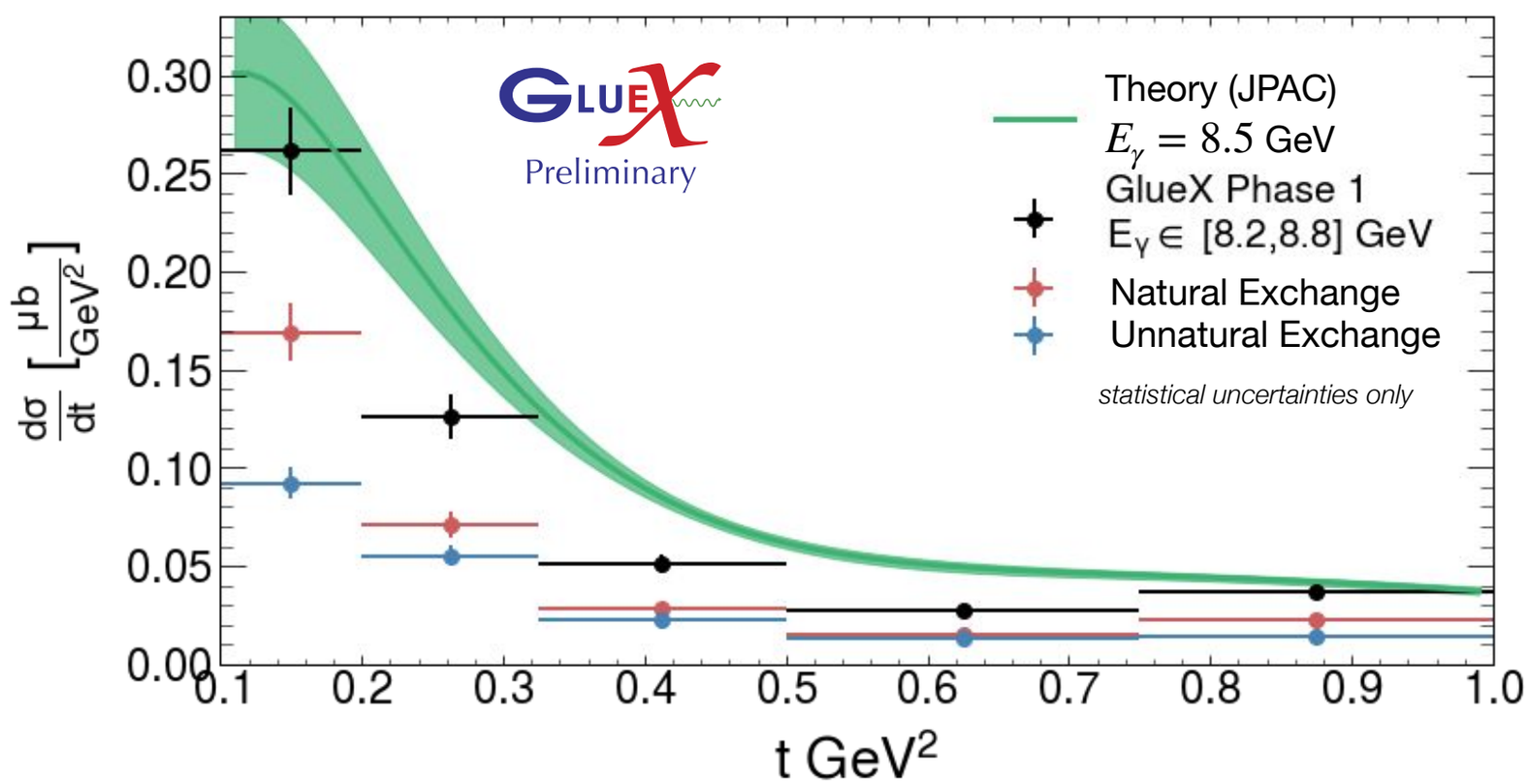
Extracting a_2^0 Production

let $\eta\pi$ $S-$wave take an arbitrary shape/phase



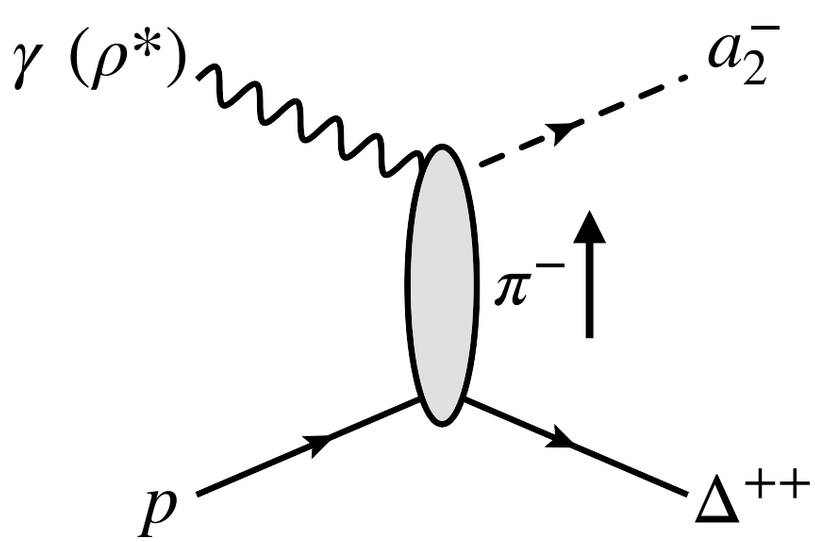
assume a_2 is a textbook Breit-Wigner resonance

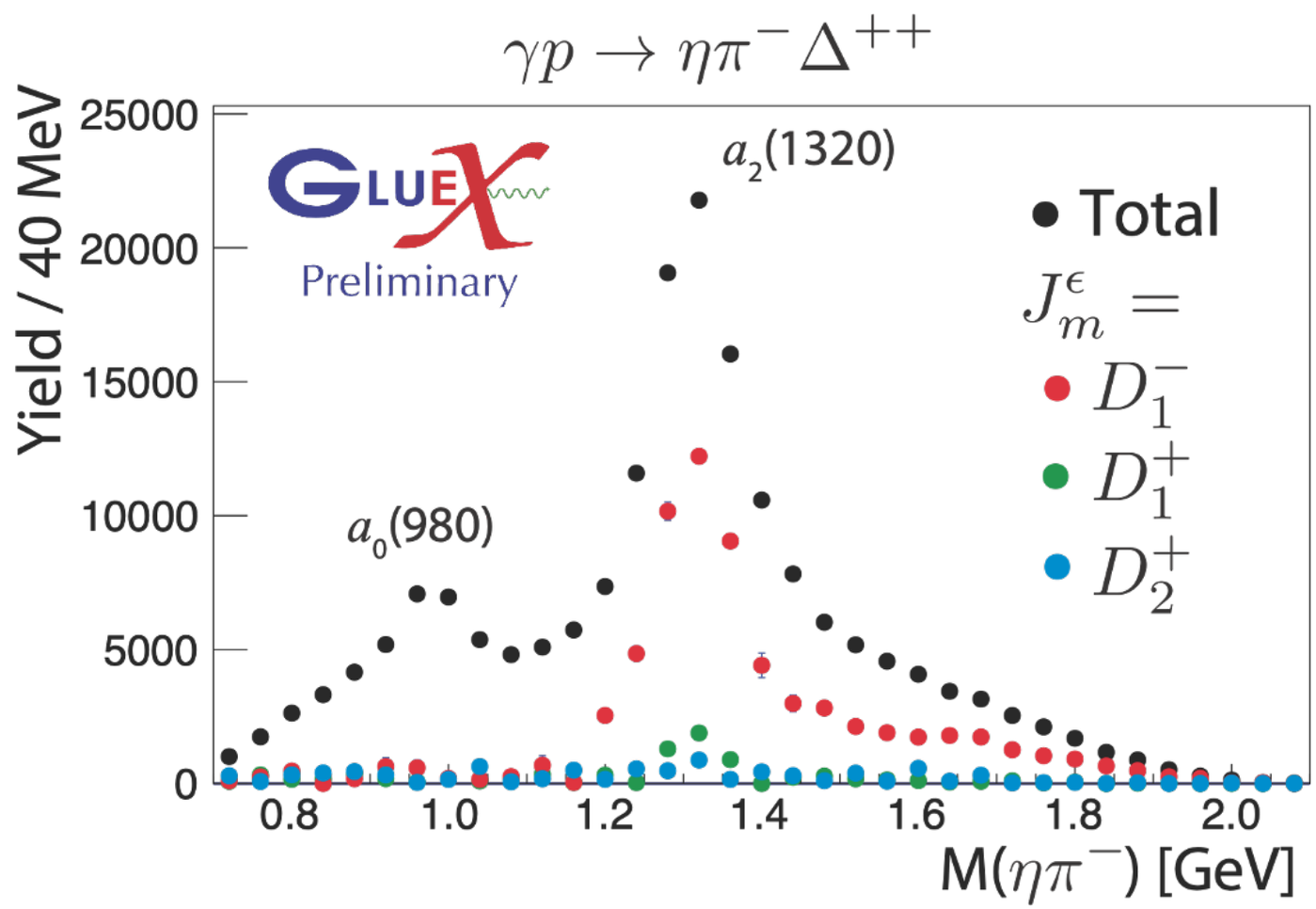
- In general a_2 can be produced in 2 exchanges, each with 5 polarizations
  - theory argues for a small set of dominant amplitudes [JPAC, PRD 102, 014003 (2020)]
- dominant: D_2^+ -- $m = 2$ natural parity
  - similar to a_2 production in two photon collisions
- exchange mechanisms add incoherently: extract differential cross section for each mechanism



Additional Mechanism for a_2^- Production

- Production of a_2^- can proceed by pion exchange
  - large $a_2 \to \rho\pi$ coupling
- Observe polarization transfer from beam to a_2 $(m = 1)$
- The a_2^- cross section is about an order of magnitude larger than a_2^0

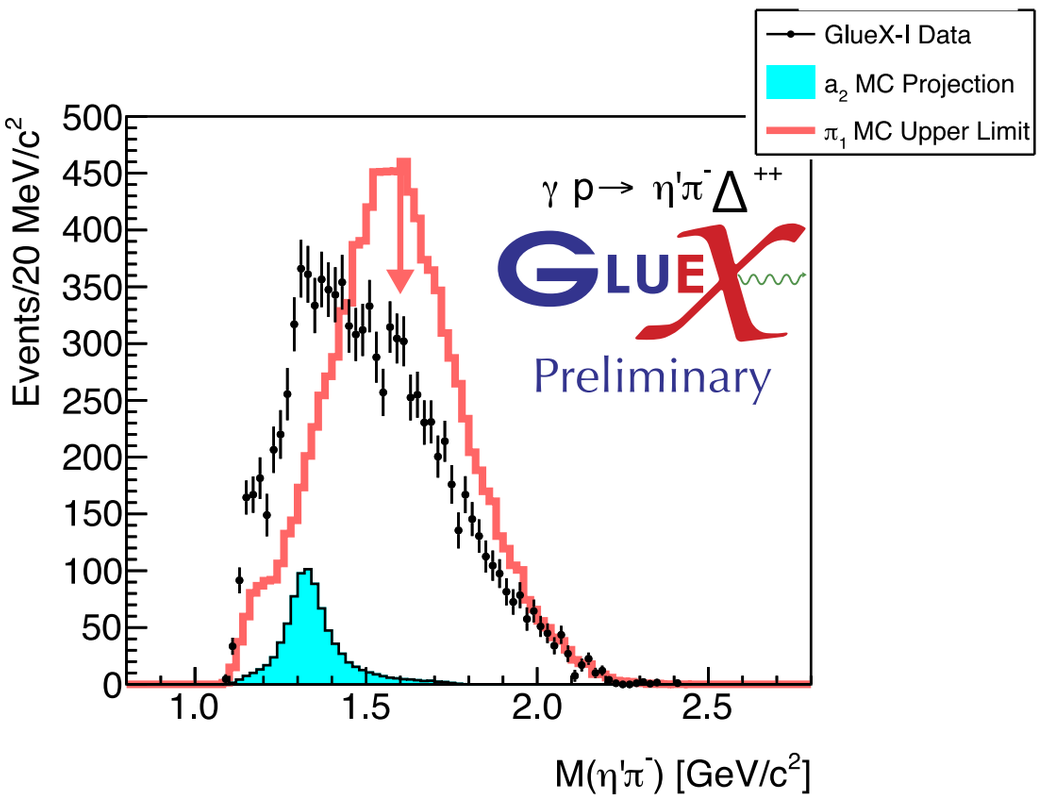




At low momentum transfer, a_2^- production is dominated by unnatural parity $(\epsilon = -)$ exchange.

Current Status of π_1 Search

- Lattice QCD calculations from hadSpec combined with data confirm that $\gamma p \to \eta' \pi^- \Delta^{++}$ is the most promising reaction to search



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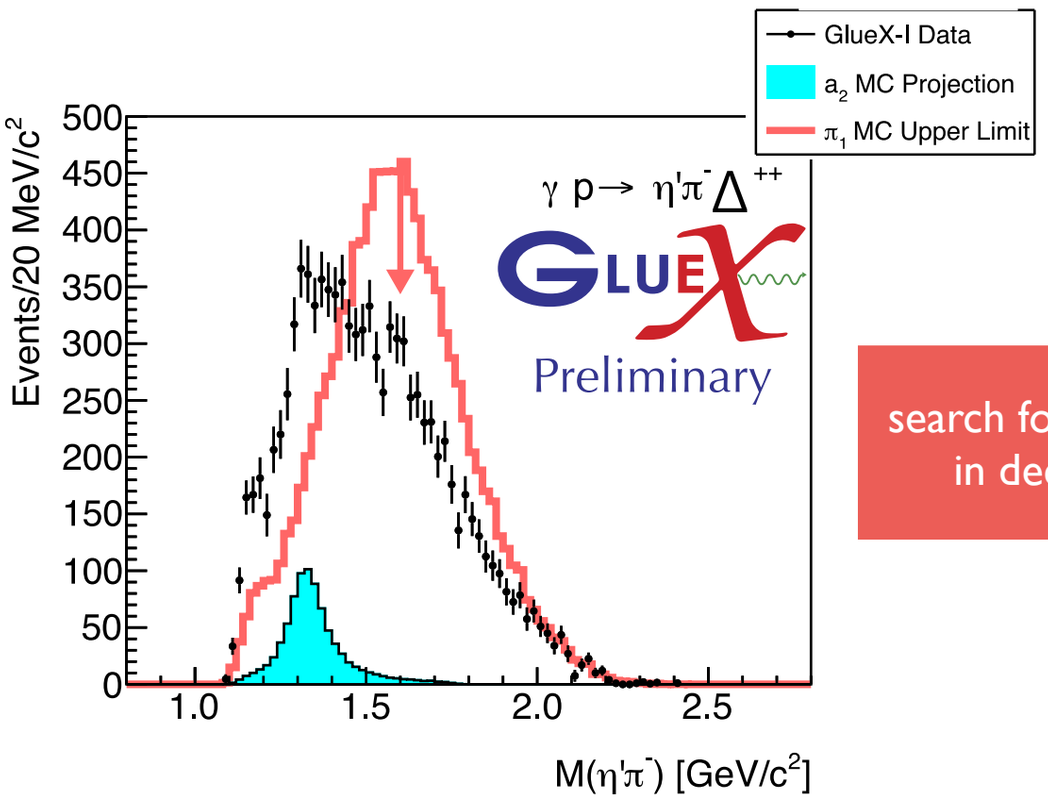
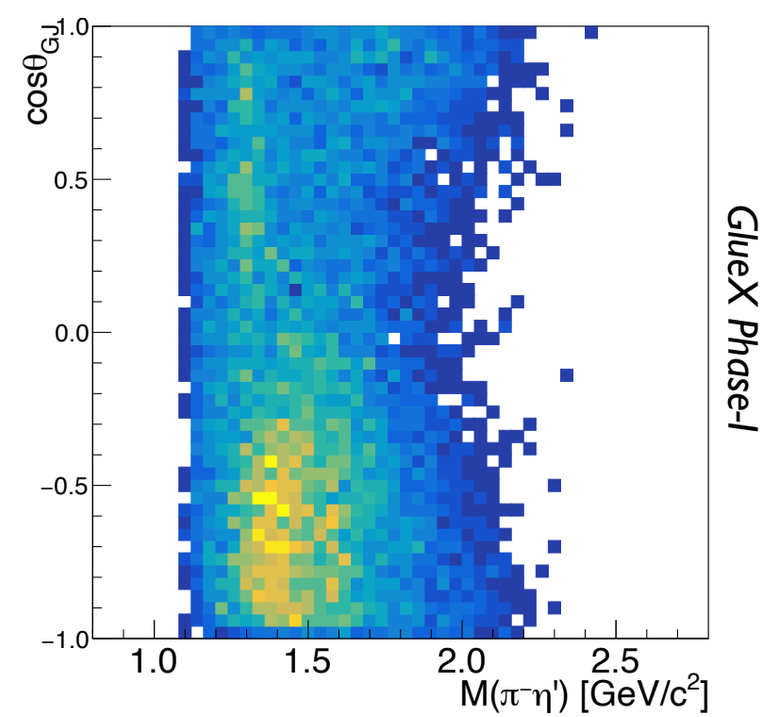
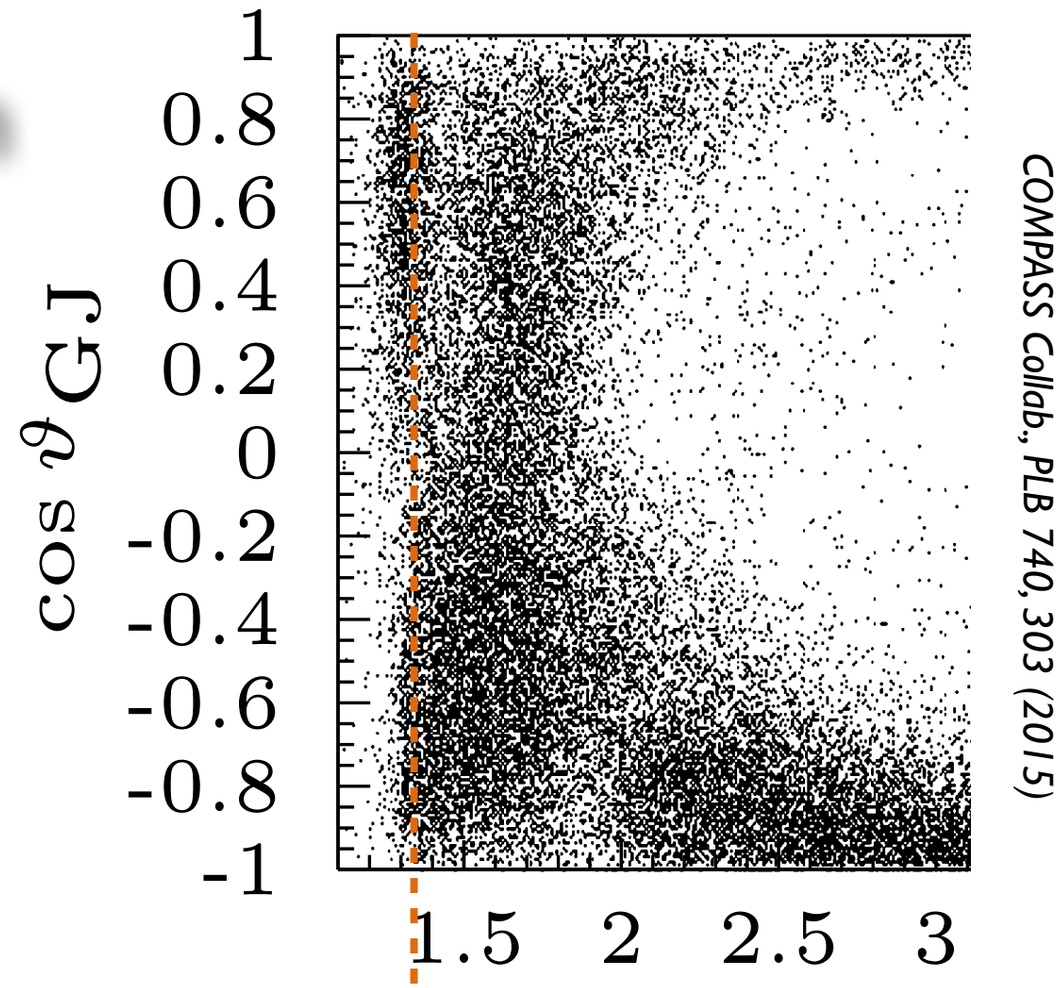


search for resonances in decay angles

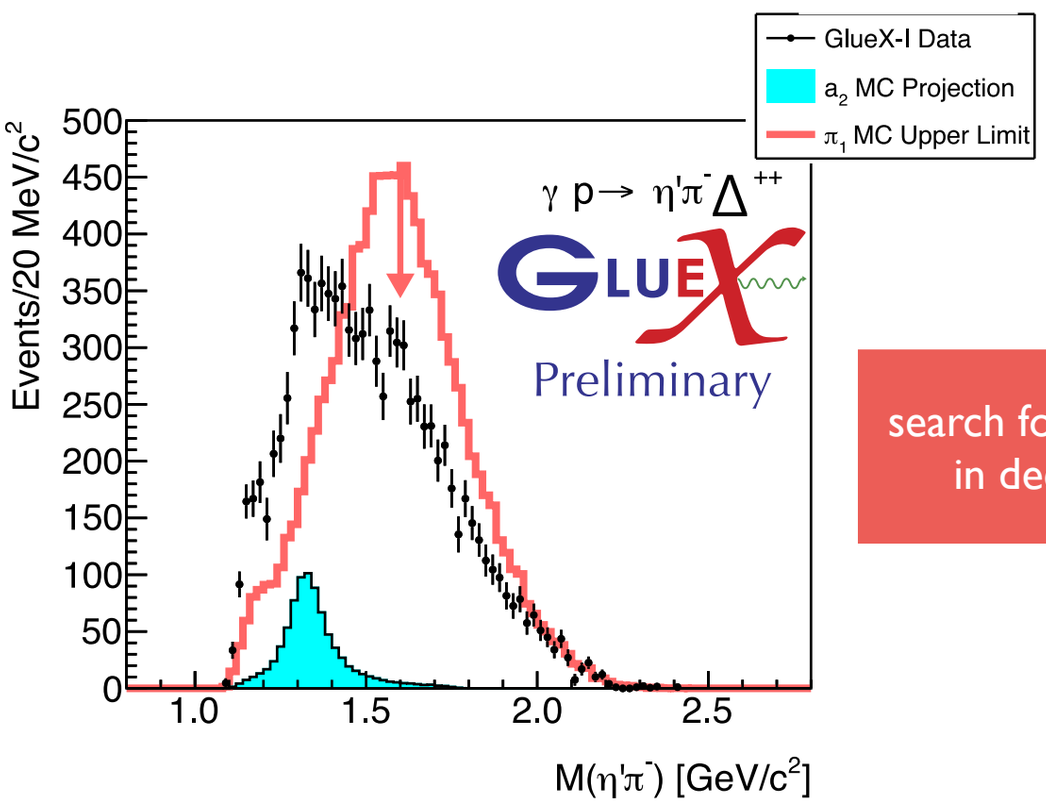


Current Status of π_1 Search

- Lattice QCD calculations from hadSpec combined with data confirm that $\gamma p \to \eta' \pi^- \Delta^{++}$ is the most promising reaction to search
- Distribution of $\eta' \pi^-$ decay is consistent with COMPASS data
  - interpreted by JPAC as interference between a_2 and exotic π_1 resonances
  - forward/backward asymmetry indicates interference between even and odd (exotic) partial waves
- Further analysis is needed to draw quantitative conclusions
  - phenomenology of a_2 production is a key ingredient



COMPASS Collab., PLB 740, 303 (2015)



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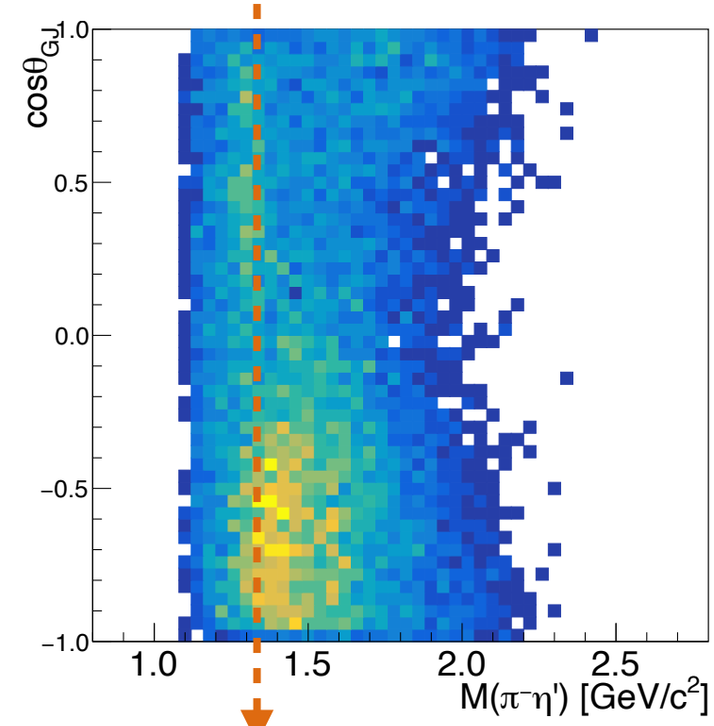


GlueX Phase-I

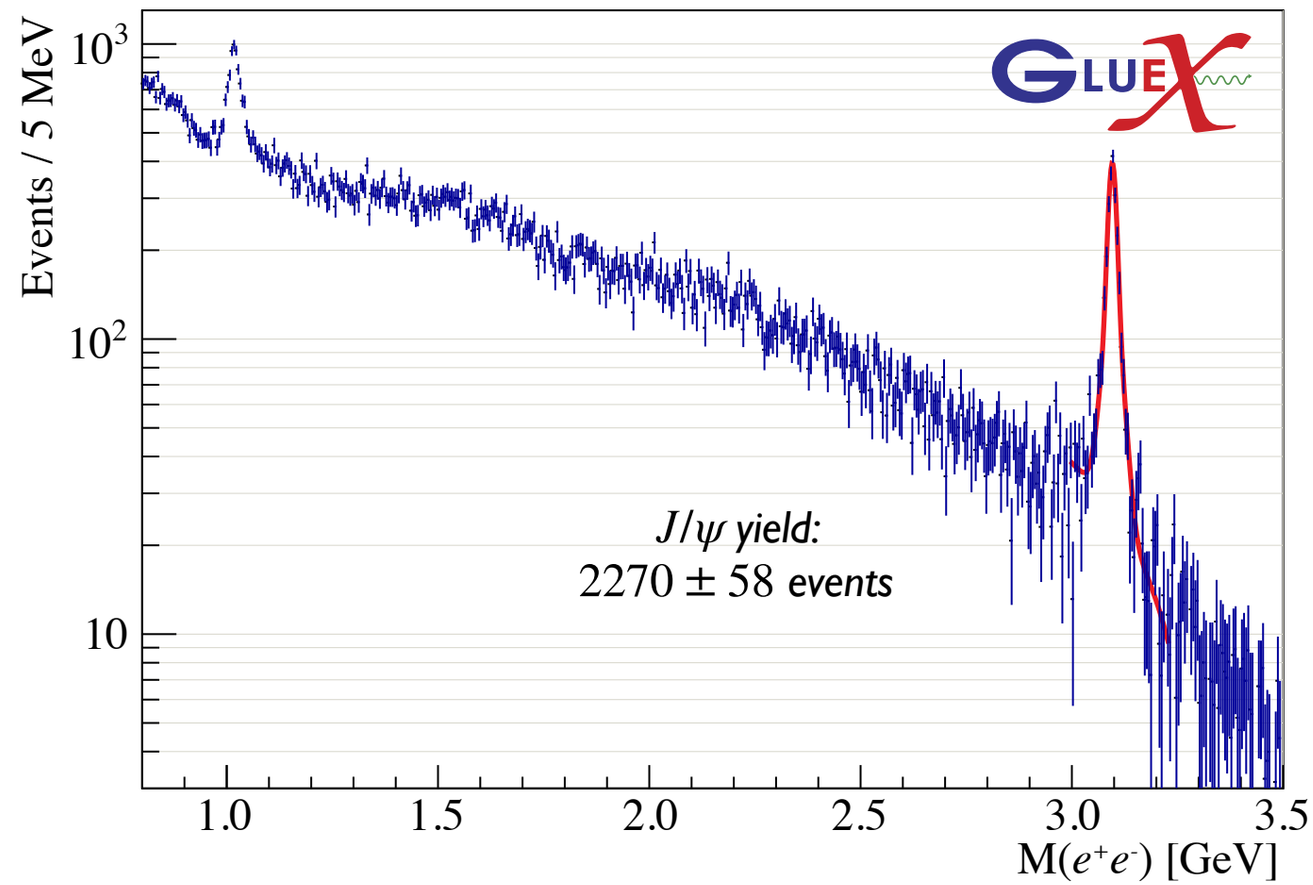
$a_2(1320)$

Outline

- A brief introduction to the GlueX experiment
- Production of conventional mesons
  - Beam asymmetries for π^0, π^-, η production
  - Spin-density matrix elements for ρ production
- Status of the search for hybrid mesons
  - Upper limit on the exotic π_1 cross section
  - Opportunities for π_1 discovery in photoproduction
  - A standard candle: a_2 production properties
- Production of J/ψ at threshold

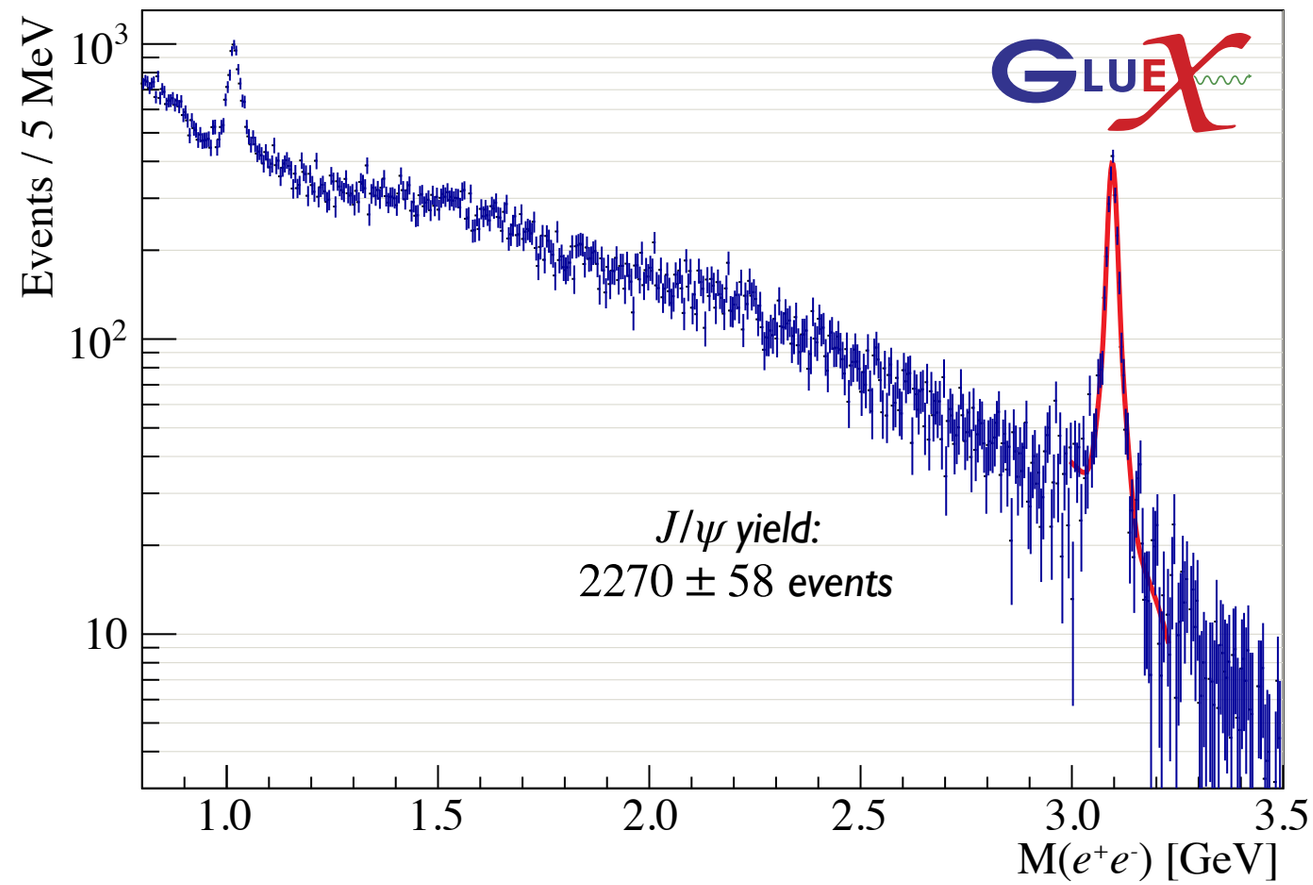
Photoproduction of J/ψ

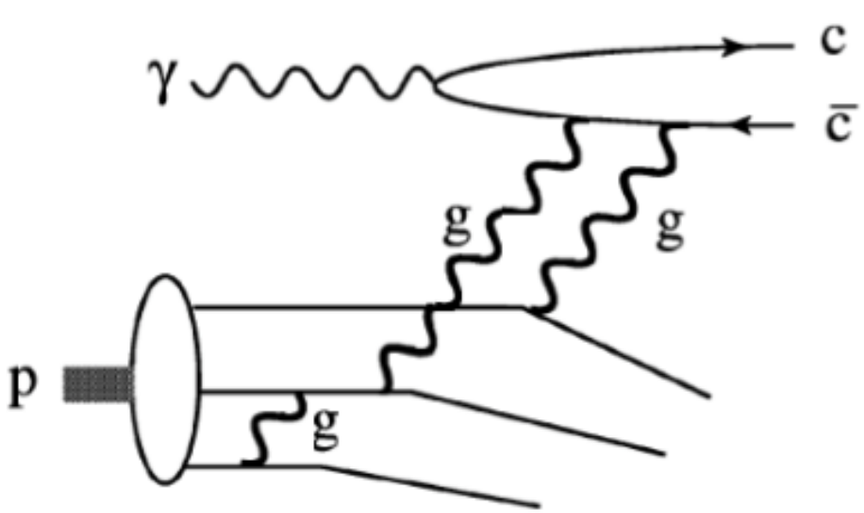
- Threshold: $E_\gamma = 8.3$ GeV

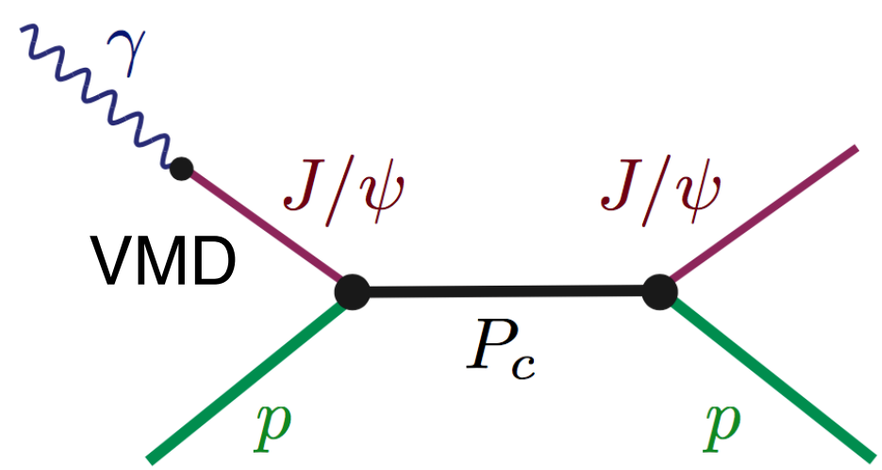


Photoproduction of J/ψ

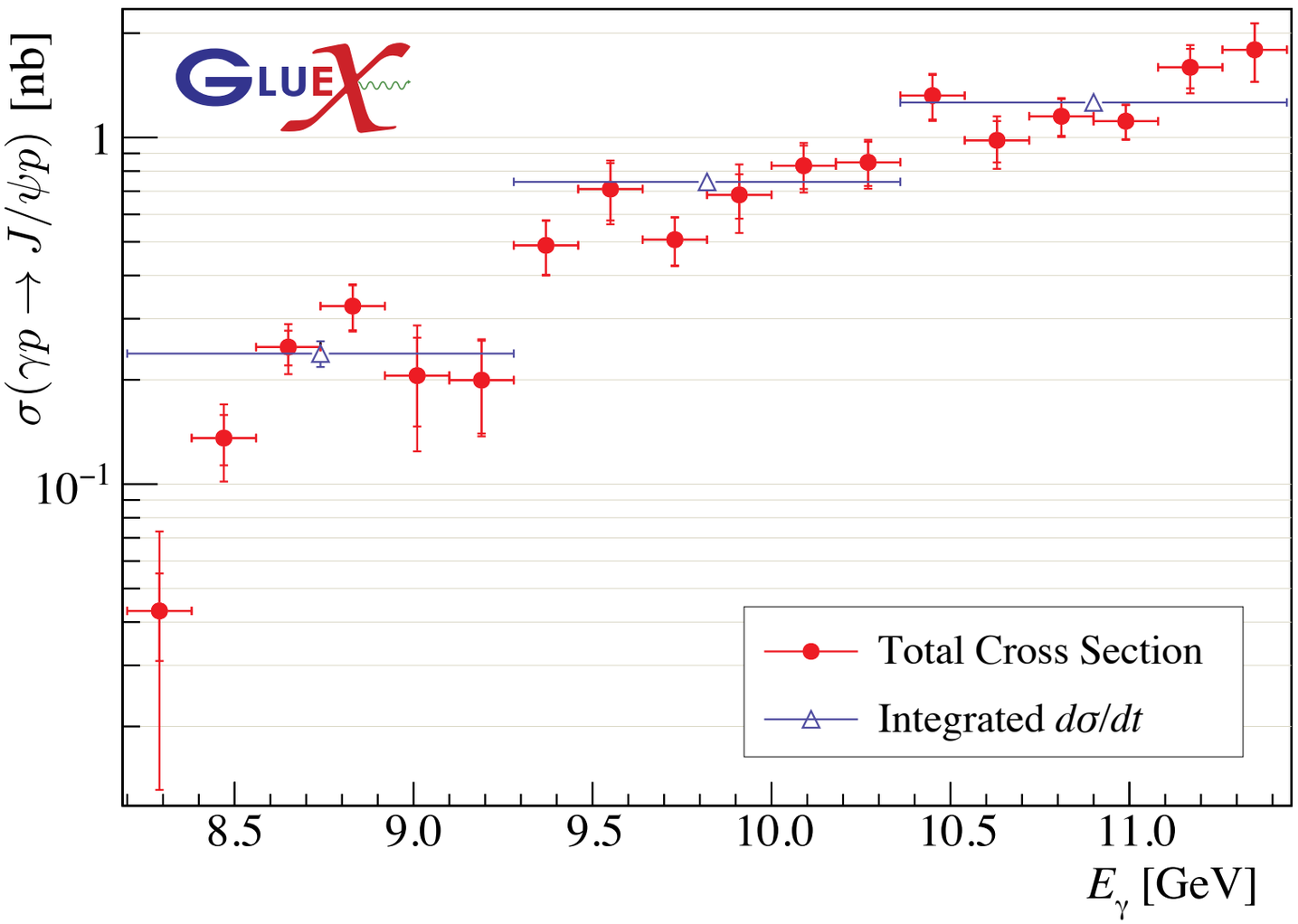
- Threshold: $E_\gamma = 8.3\ \mathrm{GeV}$
- Multiple physics interests:
  - gluon exchange as a probe of proton structure
  - search for pentaquark resonances
- Understanding production mechanism is critical







Total and Differential Cross Section



- Structure in σ vs. E_γ

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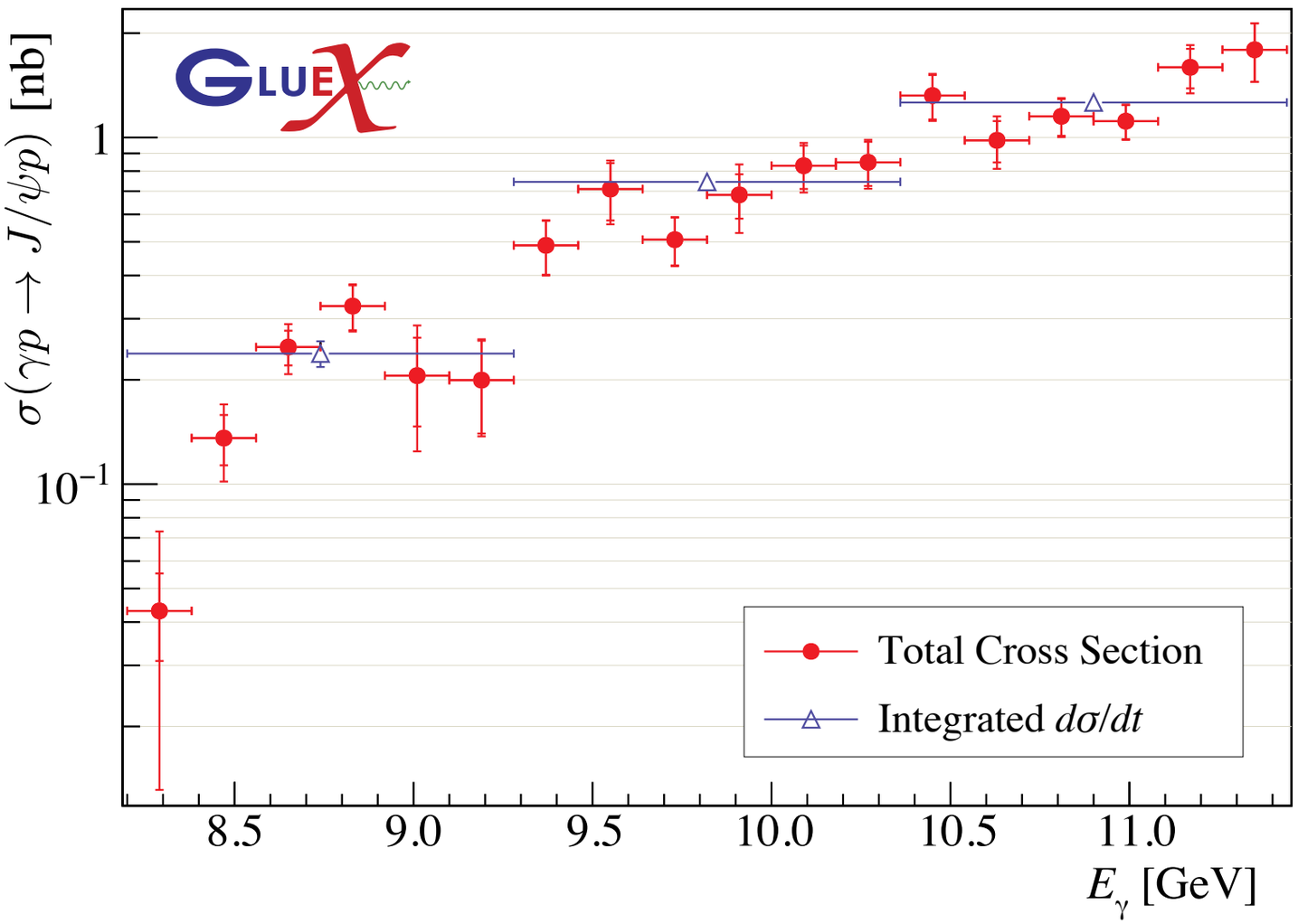
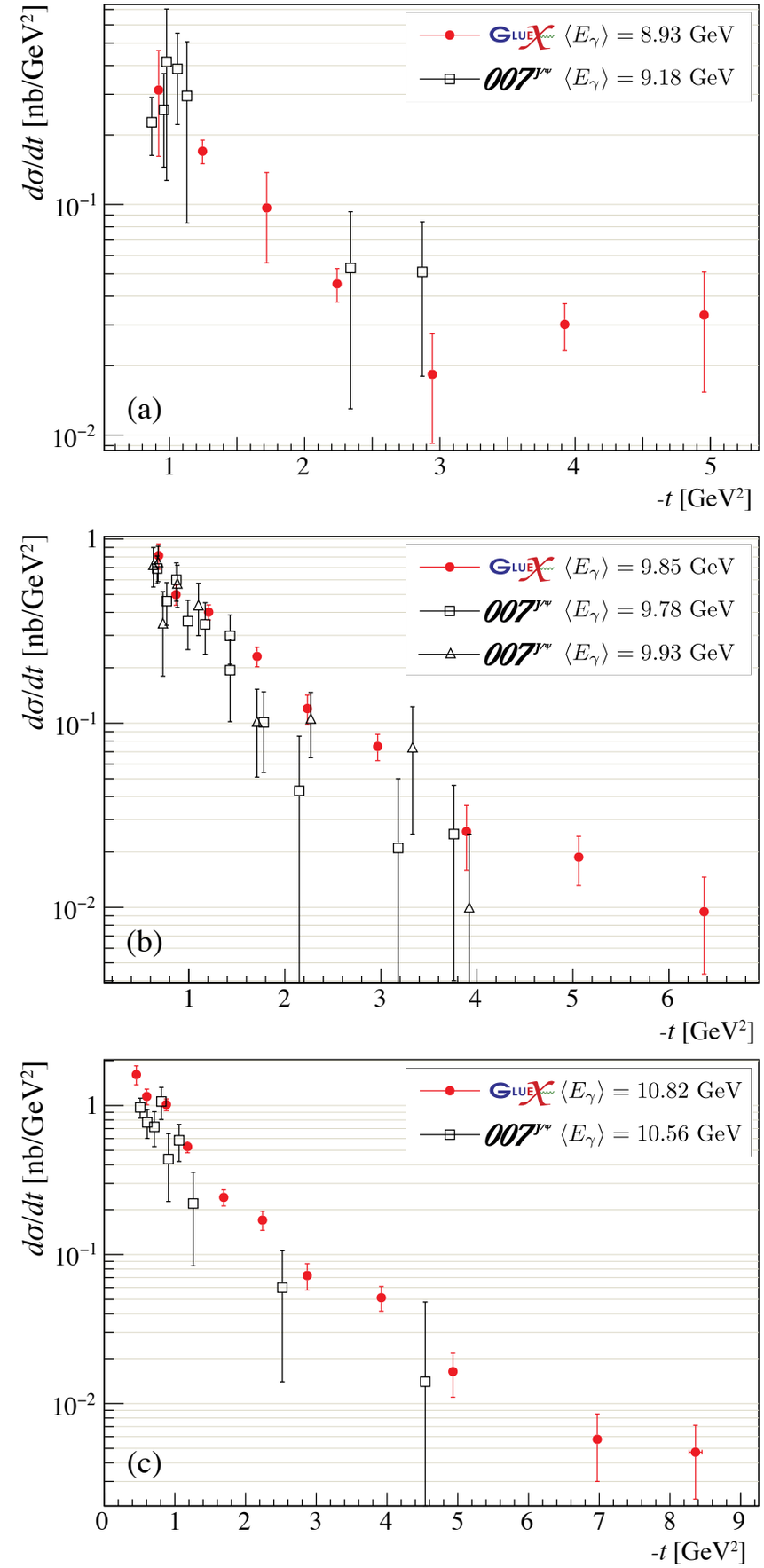
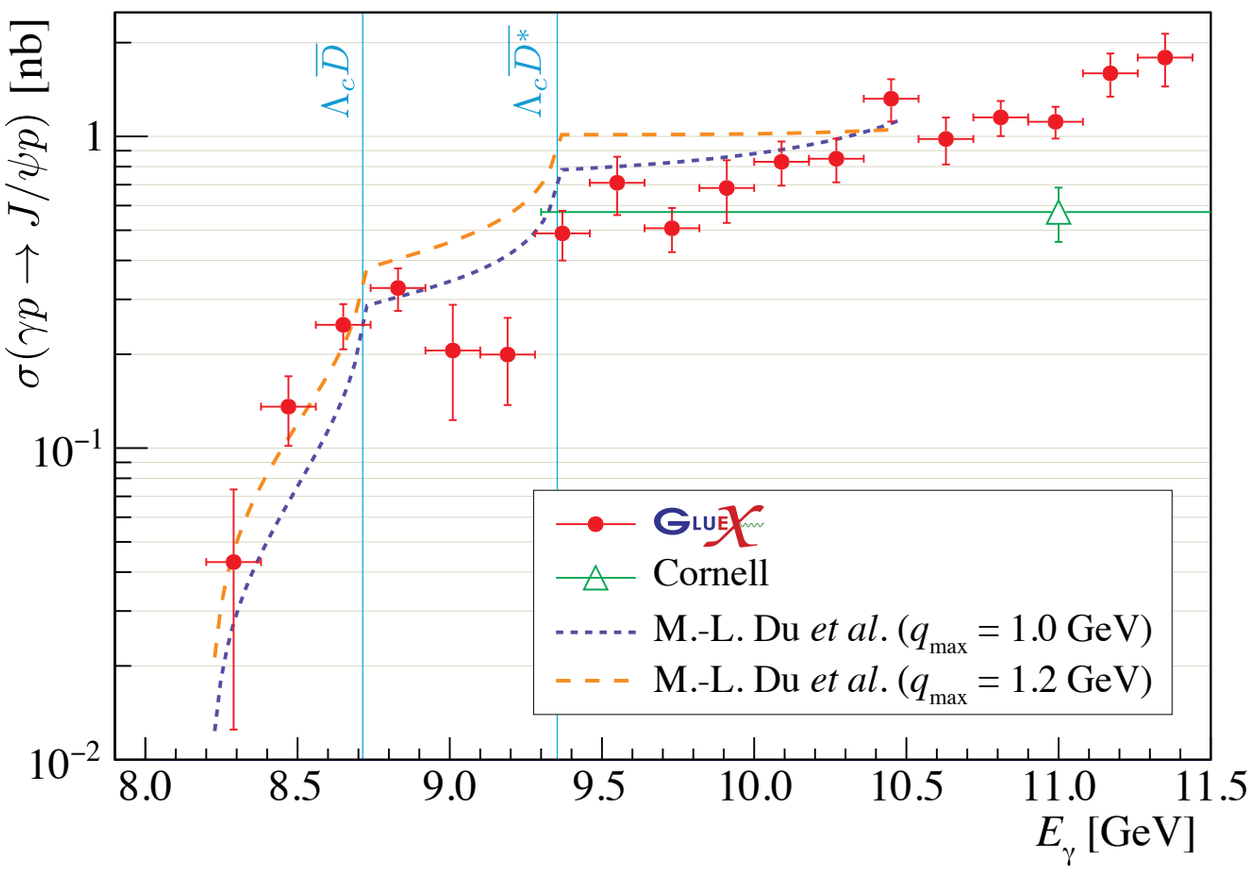




- Structure in σ vs. E_γ
- Interesting $d\sigma/dt$ at low E_γ
- Consistent with J/ψ – 007 (Hall C)

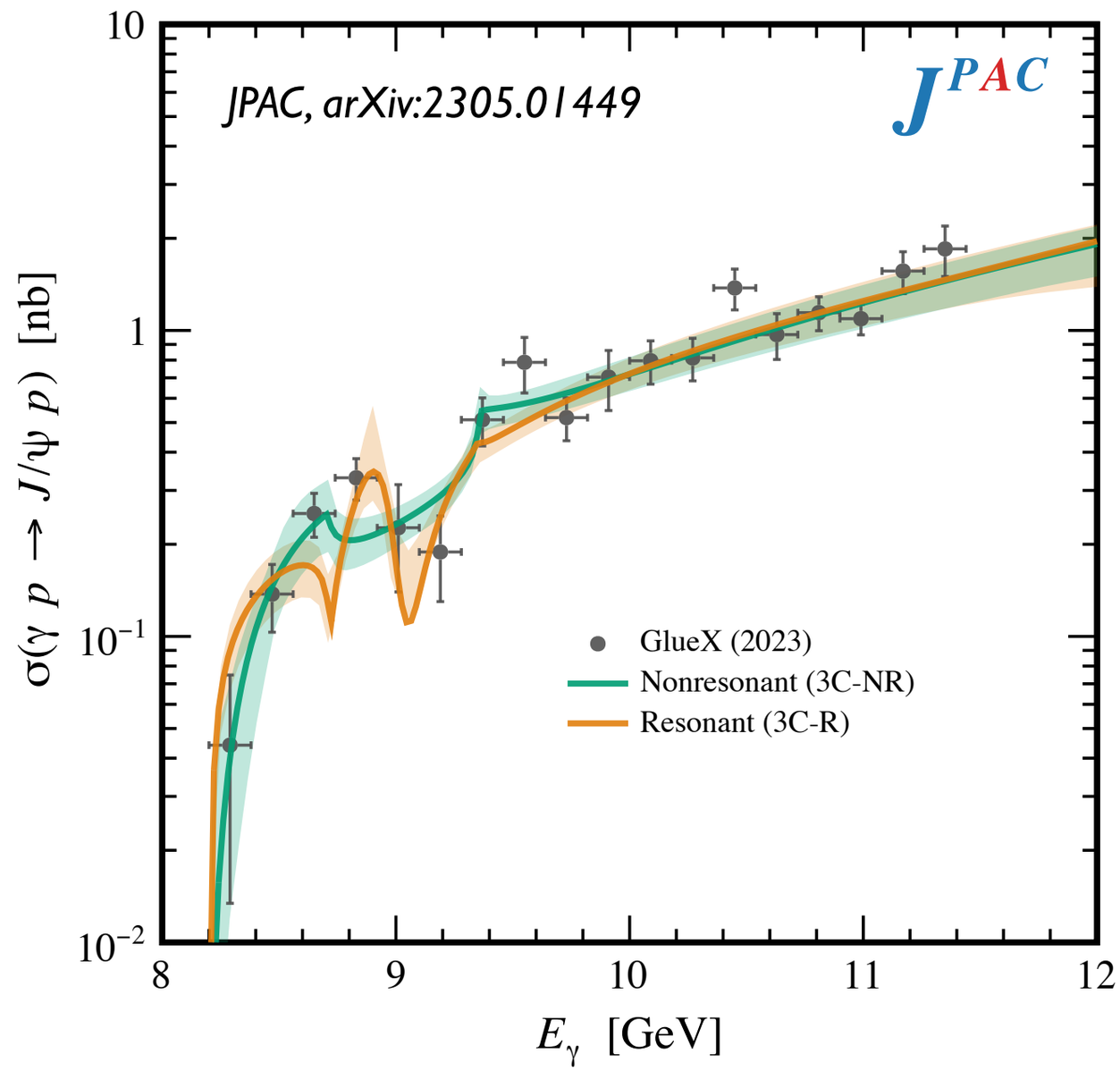
Thresholds and Pentaquark Resonances

- Conspicuous structure at open charm thresholds
- Production mechanism must be understood to interpret data
- More precision and polarization observables would be desirable



GlueX Collab., arXiv:2304.03845
to be published in Phys. Rev. C

see talk by A. Szczepaniak on Tuesday



Summary and Outlook

- The GlueX experiment is pursuing a broad program in hadron physics using polarized photoproduction (see also the talk by Volker Crede on Friday evening)

acknowledgement: gluex.org/thanks

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- Initial results provide detailed information about the production mechanisms of conventional mesons: motivates theoretical descriptions
- Using Lattice QCD and previous experimental data we can limit π_1 cross section in photoproduction <u>and</u> identify most promising discovery opportunities in photoproduction
  - stay tuned -- anticipate more results in the future
  - first step in a broader hybrid search in photoproduction (see also talk by Frank Nerling on Saturday afternoon)
- Photoproduction of J/ψ at threshold has interesting implications on spectroscopy and proton structure -- more data and polarization observables is desirable

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- Photoproduction of J/ψ at threshold has interesting implications on spectroscopy and proton structure -- more data and polarization observables is desirable
- GlueX will resume data taking in 2024 after a calorimeter upgrade; plenty of topics to work on -- new collaborators are welcome!

acknowledgement: gluex.org/thanks