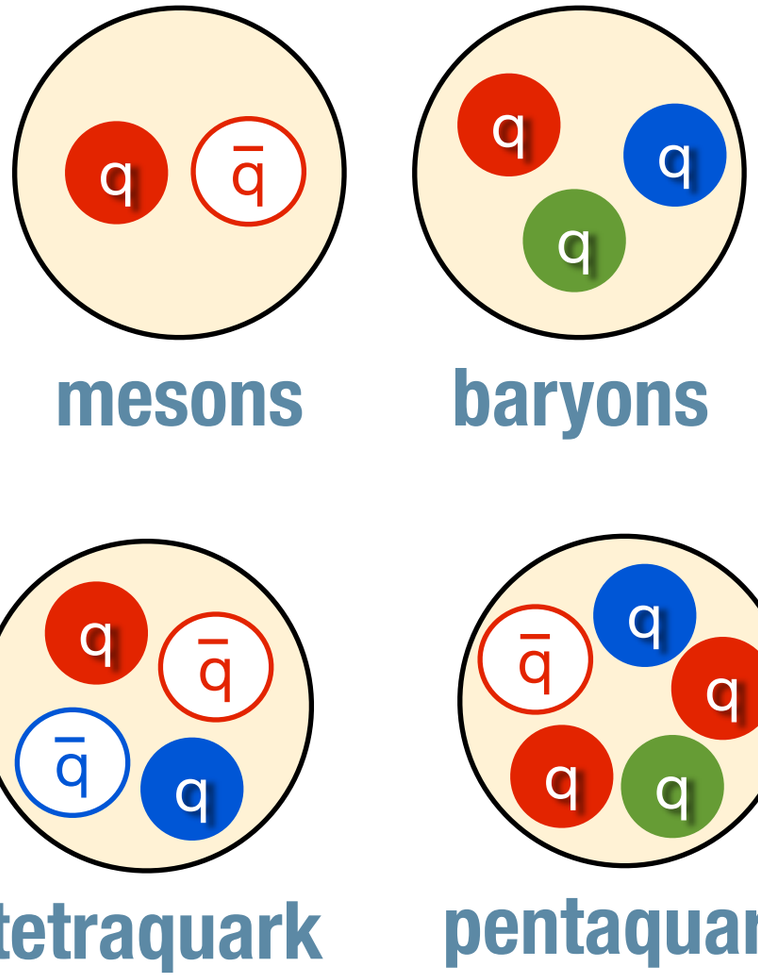
Hadron Spectroscopy with GlueX

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

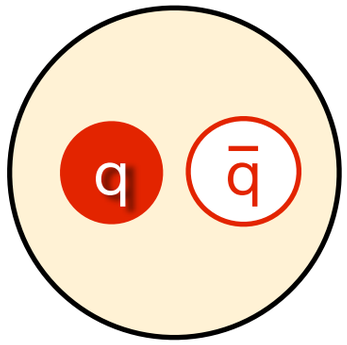
A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

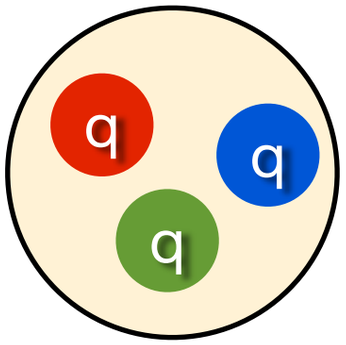
... Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. ...

Phys. Lett. 8 (1964) 214

Confined states of quarks and gluons



mesons



baryons

Observed mesons and baryons well described by 1st principles QCD

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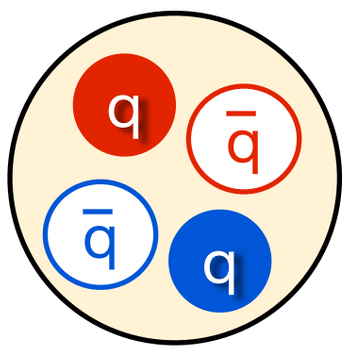
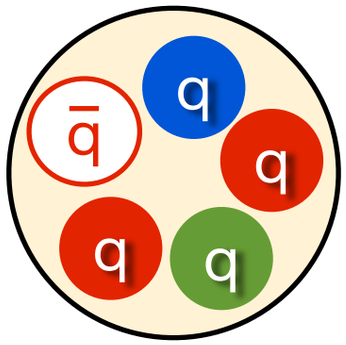
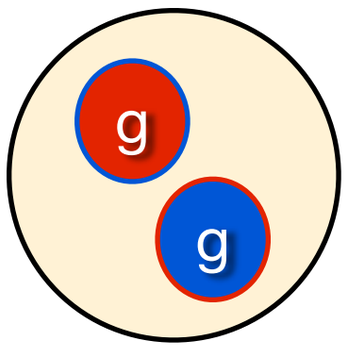


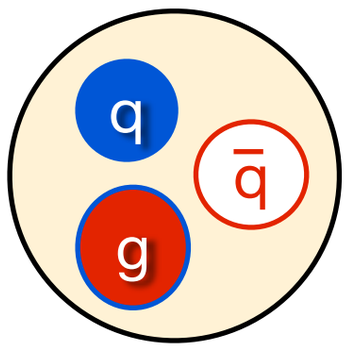
tetraquark



pentaquark



glueball

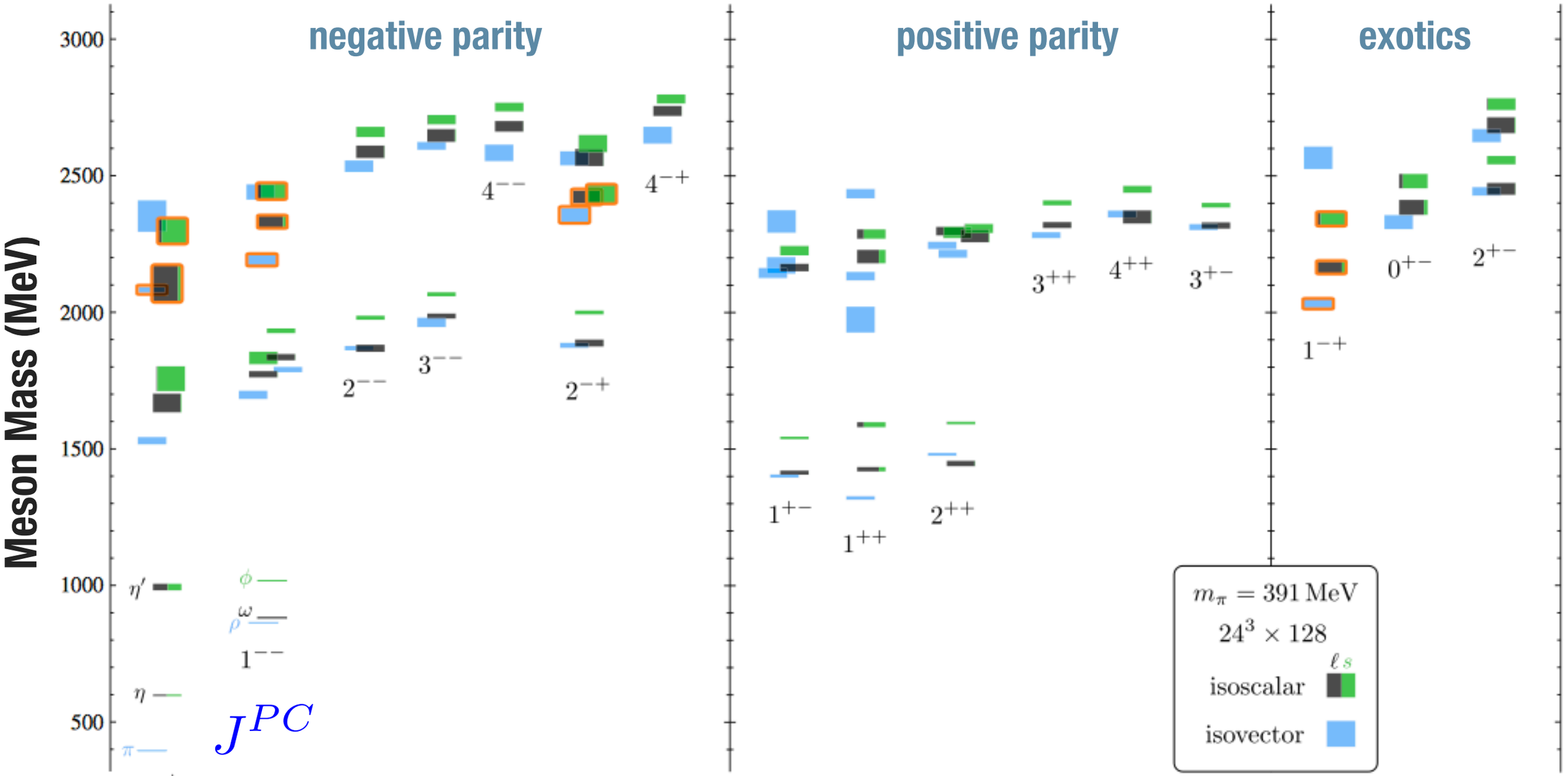


hybrid meson

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

Lattice QCD

had spec **Dudek et al. PRD 88 (2013) 094505**



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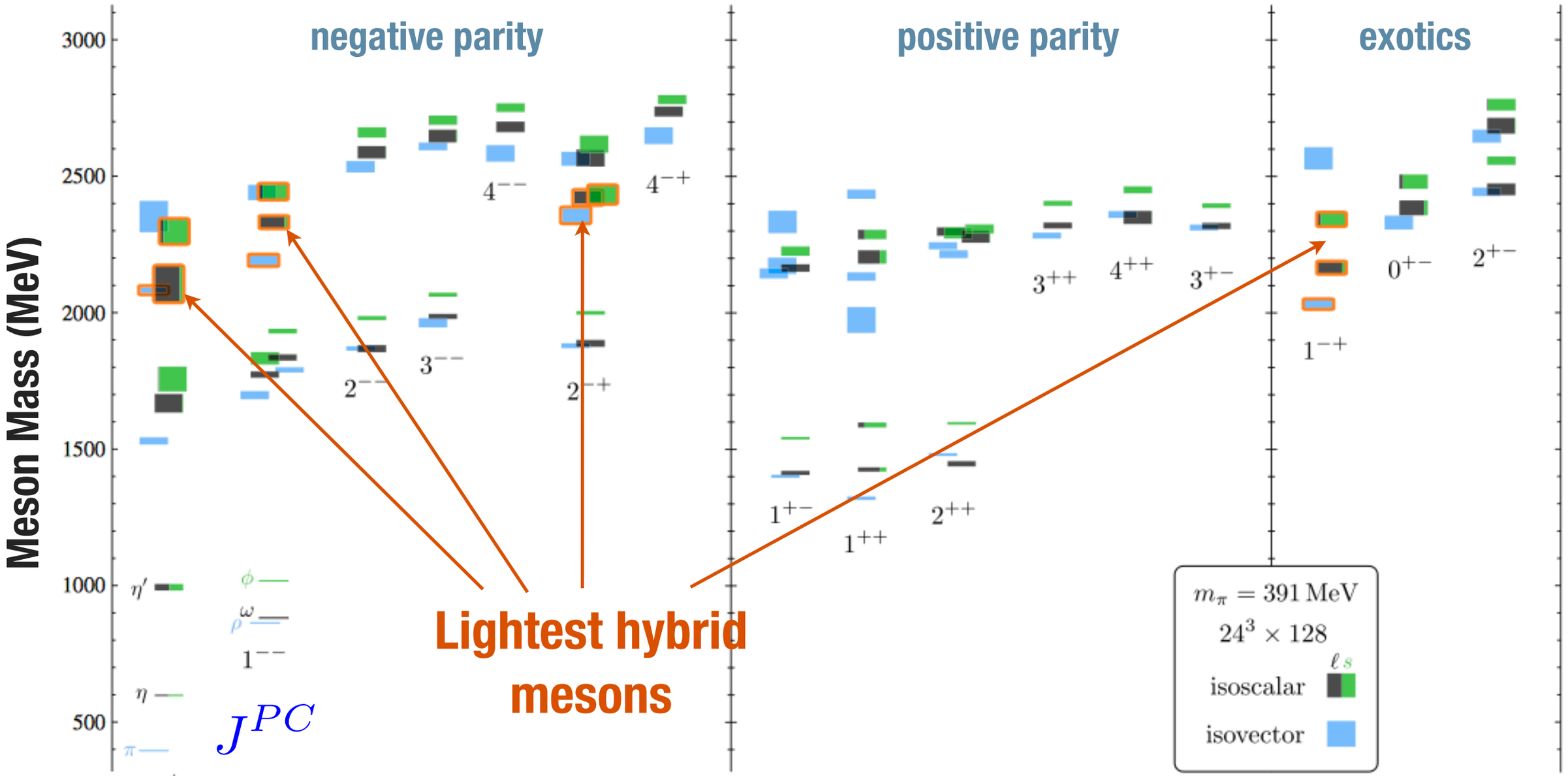
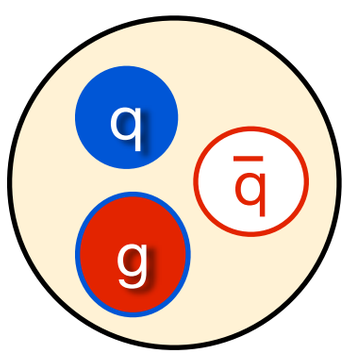


Lightest hybrid mesons



- Hybrid meson: excited gluonic field coupled to $q\bar{q}$ pair
- "Exotic" J^{PC}: not simple $q\bar{q}$ from the non-rel. quark model

$$J^{PC} = 0^{+-}, 1^{-+}, 2^{+-} \ldots$$

Lattice QCD

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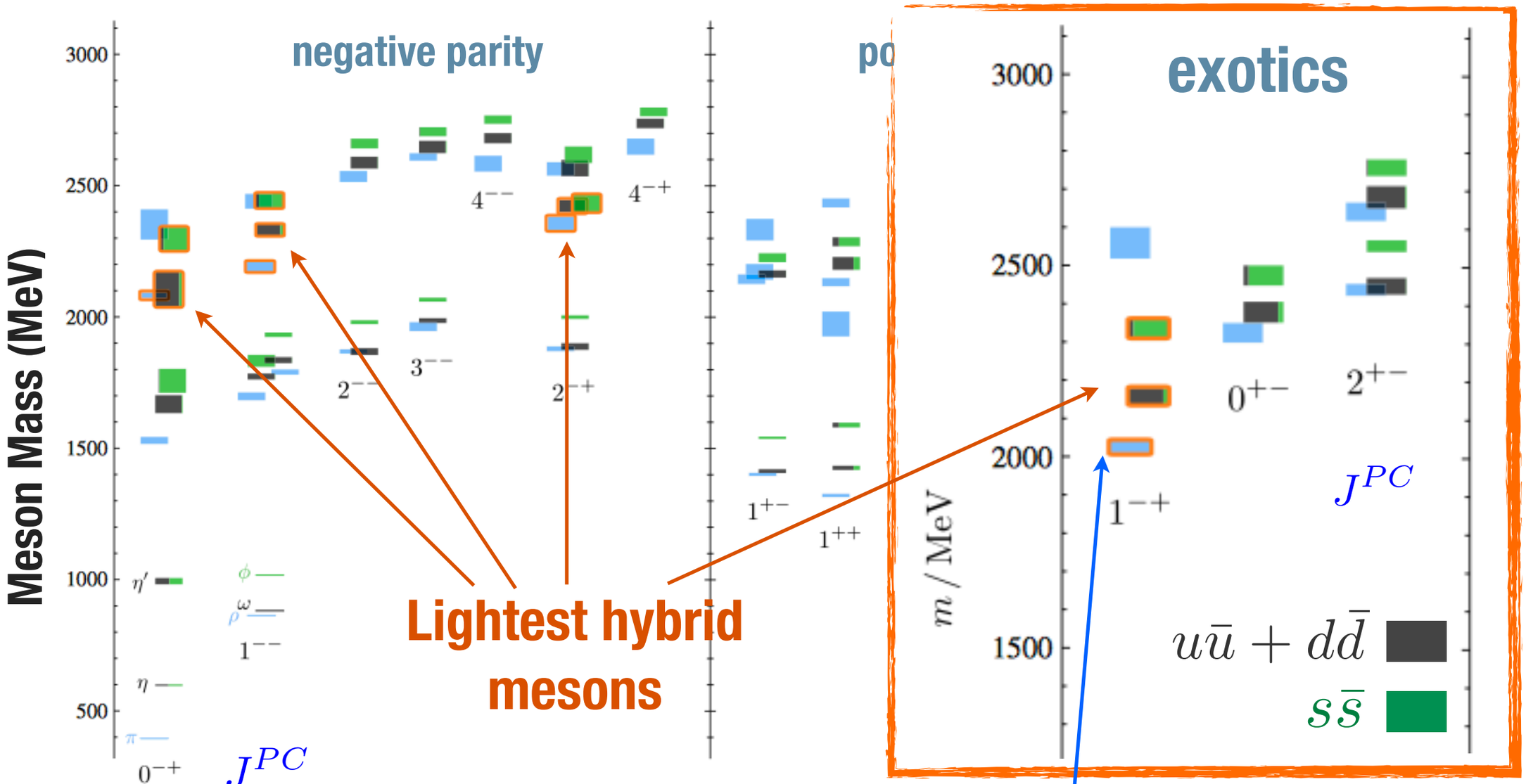

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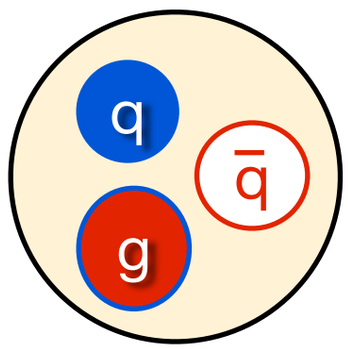
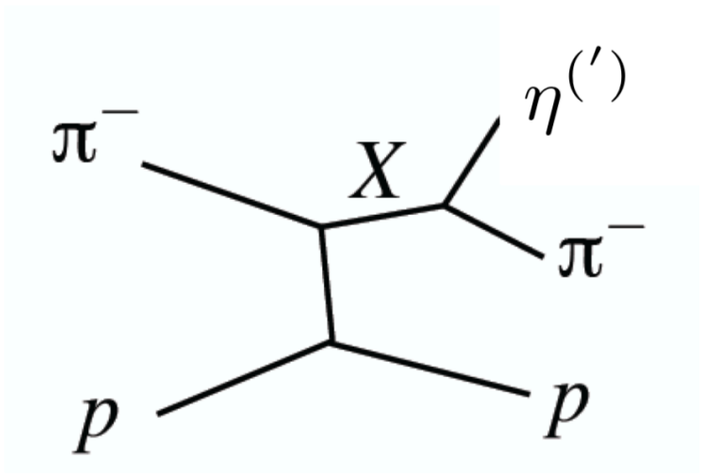
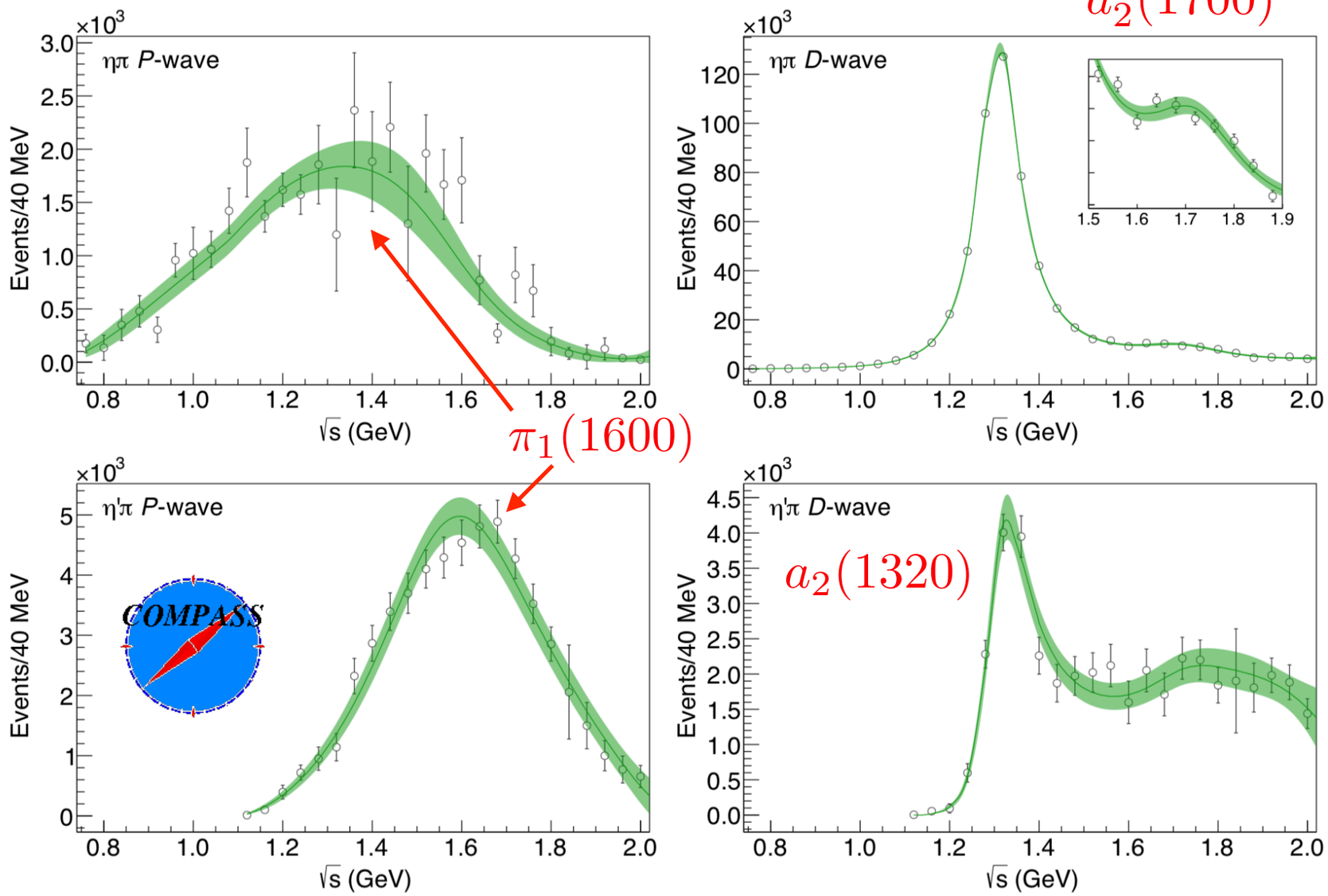


Most experimental searches for hybrids limited to the **π_1 state**

Experimental evidence for $\pi_1(1600)$





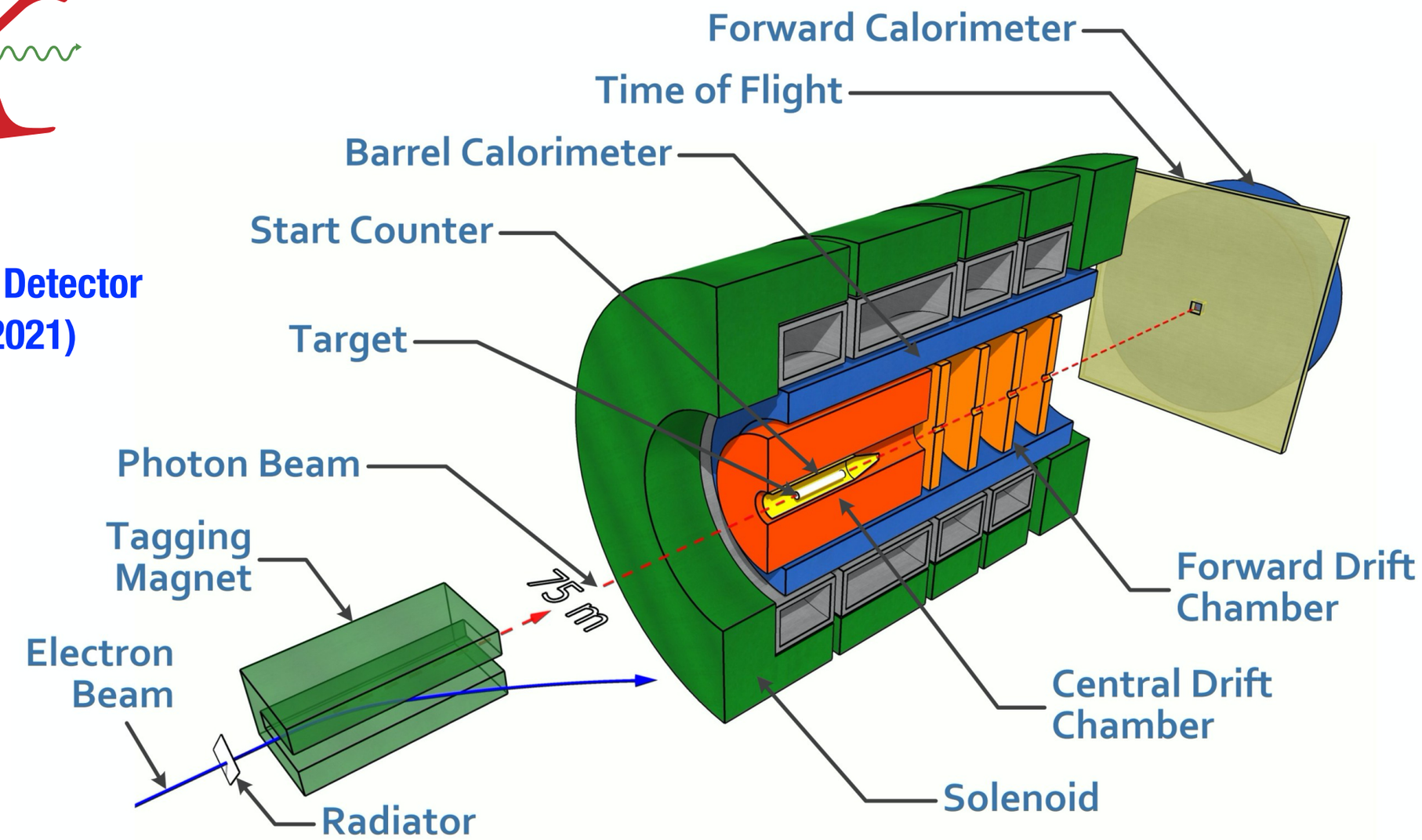
JPAC coupled channel fit to $\eta\pi$ and $\eta'\pi$ determine pole positions for a_2, a_2' and single exotic $\pi_1(1600)$

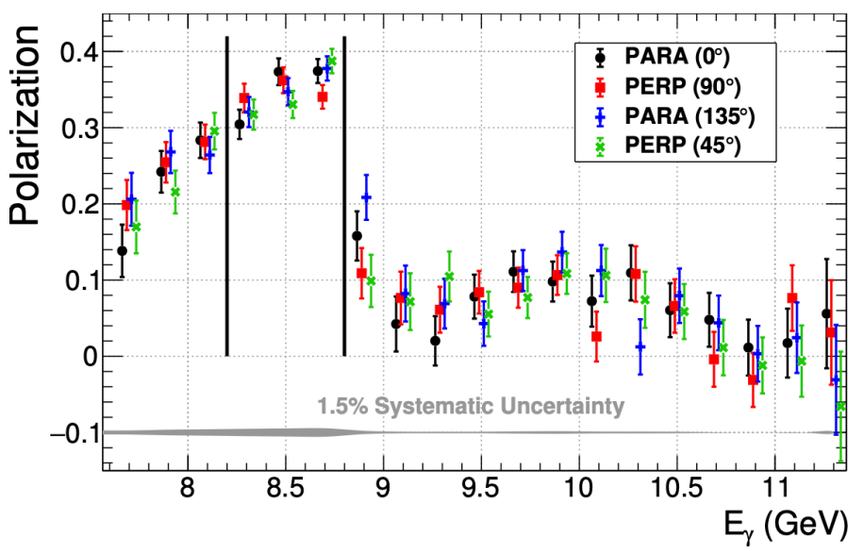
COMPASS: PLB 740 (2015) 303
JPAC: PRL 122 (2019) 042002

GlueX path to hybrid mesons

- Primary goal of GlueX is to search for and ultimately map out the spectrum of light quark hybrid mesons
  - High statistics polarized photoproduction dataset
  - Understand polarized production of isolated hadrons
  - Identifying conventional mesons through PWA
  - Initial search for exotic and conventional J^{PC} hybrids

The GlueX Beamline and Detector
NIM A 987, 164807 (2021)



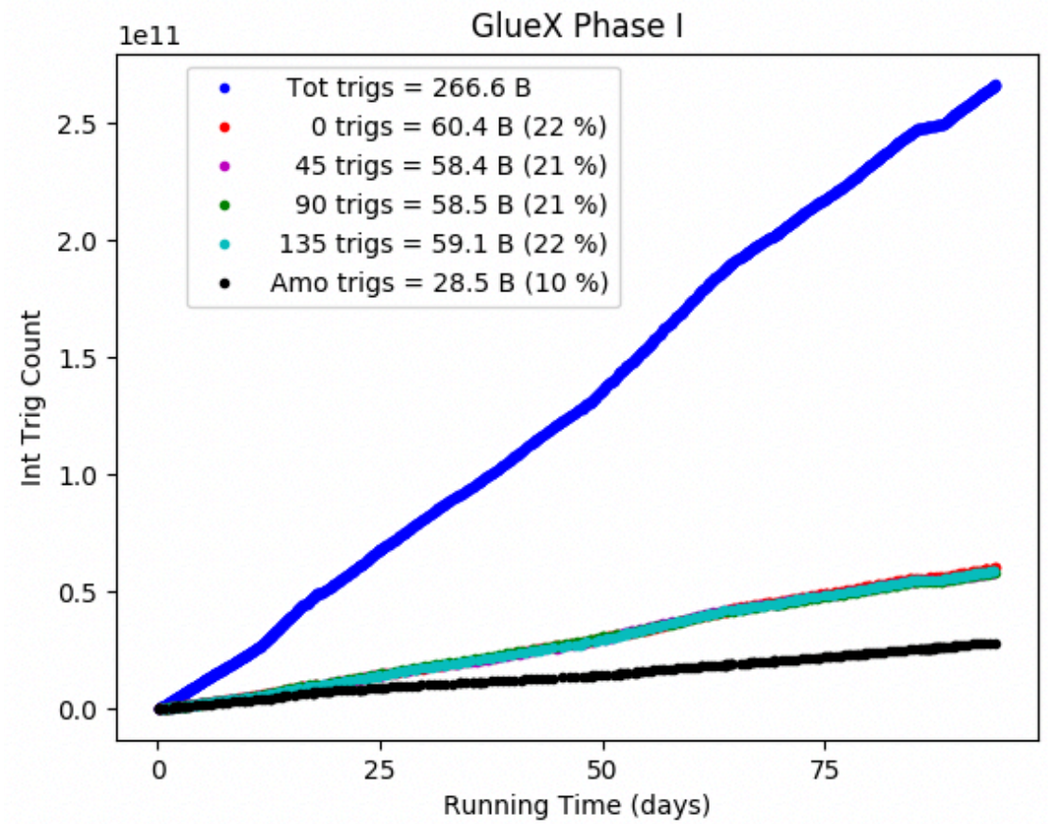


- Large acceptance detector for charged and neutral particles: orders of magnitude higher statistics than previous photoproduction experiments
- Linear polarization ~35% in “coherent” peak with two pairs of orthogonal orientations for systematics evaluation

GlueX datasets

- **GlueX-I:** completed in 2018, full dataset under analysis
- **GlueX-II:** doubled beam intensity
  - π/K identification added in 2020 with DIRC detector
  - $PbWO_4$ calorimeter upgrade underway ready for 2024
- Completed Primakoff expts.: PrimEx-η, Pion Polarizability
- Future program with increased intensity, polarized target, etc.

GlueX-I dataset: 2017-2018
250 B events and ~3 PB of data



Approximate GlueX-I Yields

$\rho(770)$	200M	$\eta\pi$	2M
$\omega(782)$	40M	$\omega\pi$	10M
$\phi(1020)$	2M	J/ψ	2k

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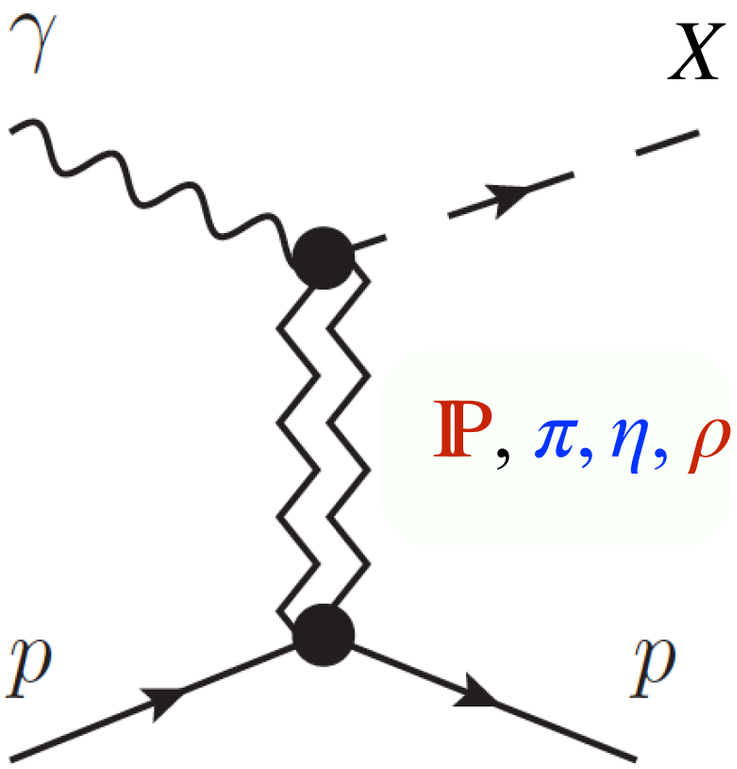


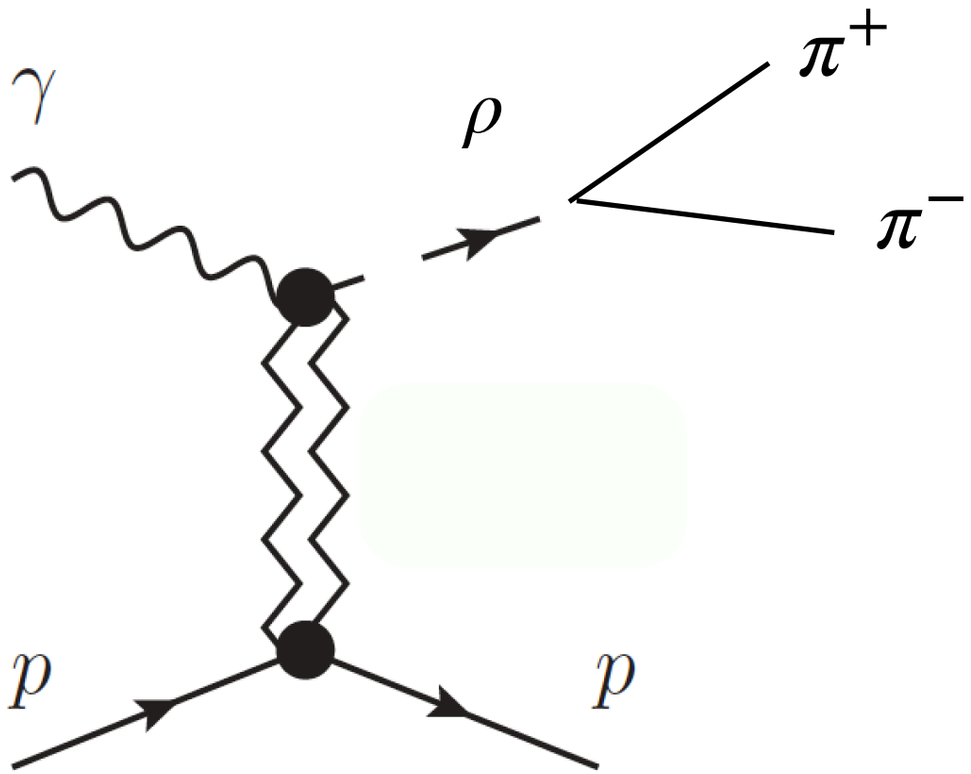
$\mathbb{P}, \pi, \eta, \rho, \omega, b_1, h_1, f_2, a_2$

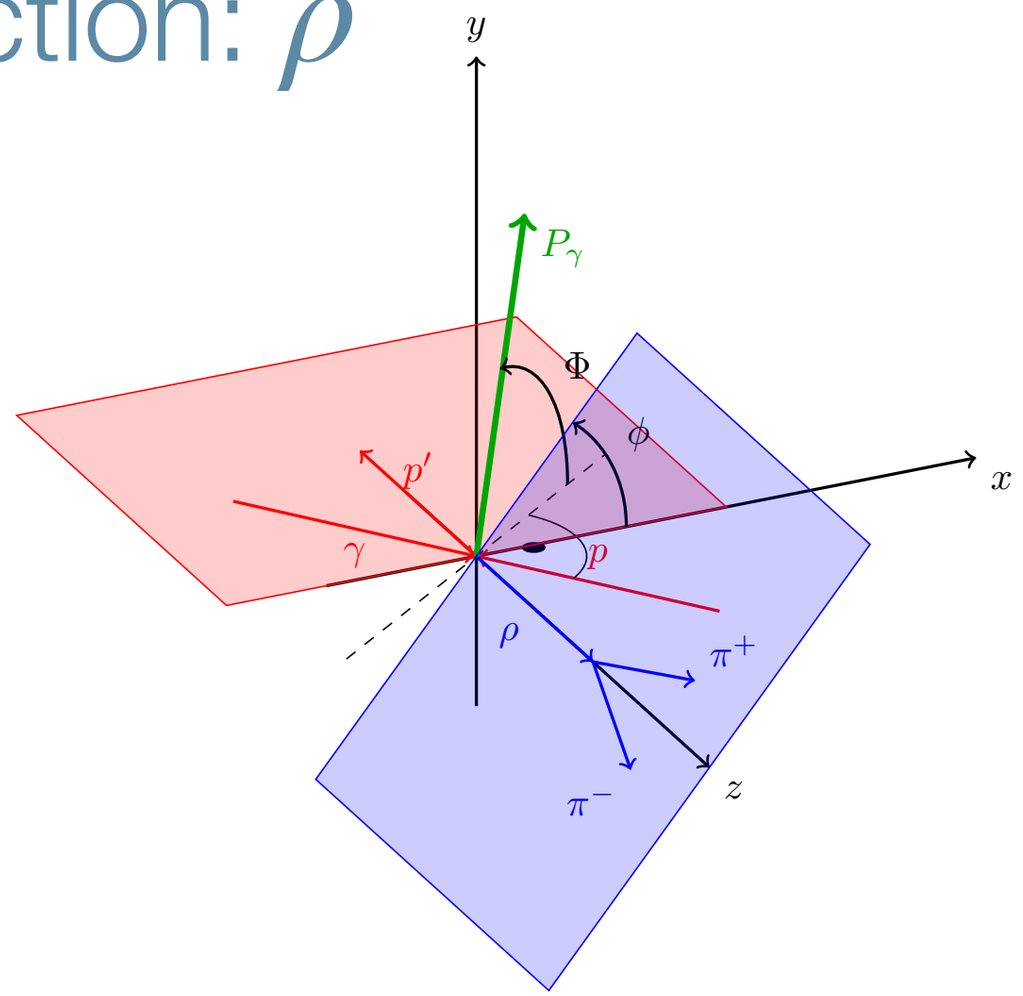
Model through t-channel exchange of Reggeons

Natural $P(-1)^J = +1$: $J^P = 0^+, 1^-, 2^+, 3^- \ldots$

Unnatural $P(-1)^J = -1$: $J^P = 0^-, 1^+, 2^-, 3^+ \ldots$

Polarized photoproduction: ρ





- Vector decay requires three angles to describe intensity: beam polarization Φ and decay θ, ϕ

- Exercise amplitude analysis machinery to extract 9 independent parameters: SDMEs

$$I(\Omega) \propto W(\cos\theta, \phi, \Phi) = W^0(\cos\theta, \phi) - P_\gamma \cos(2\Phi) W^1(\cos\theta, \phi) - P_\gamma \sin(2\Phi) W^2(\cos\theta, \phi)$$

Spin Density Matrix Elements (SDMEs)

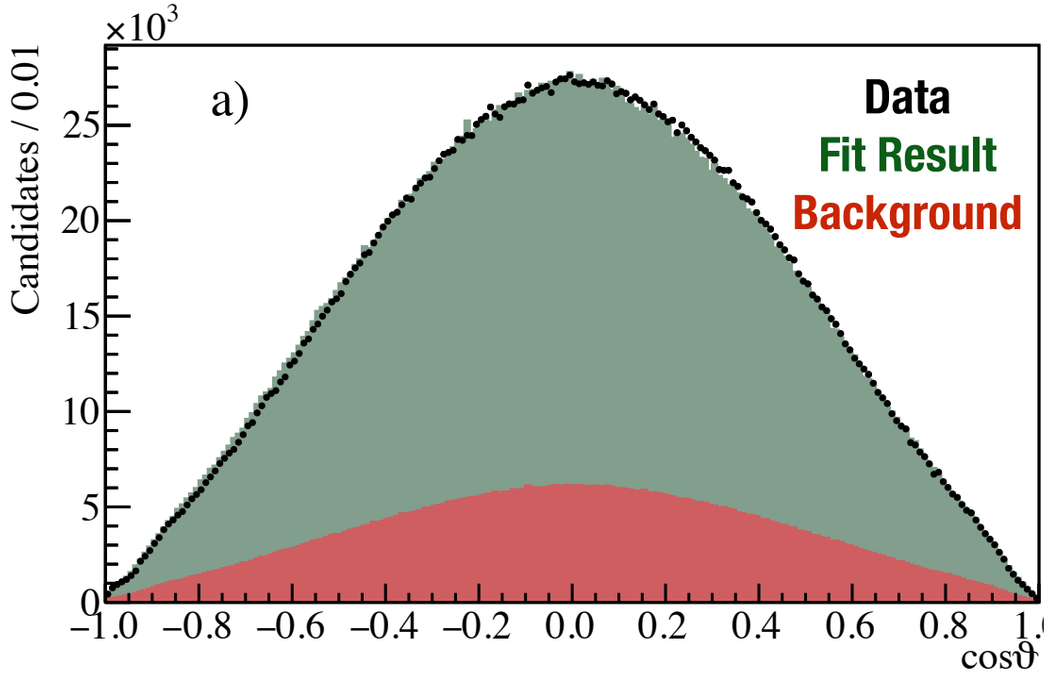
- Intensity expressed as function of production and decay angles for vector mesons: $\gamma p \to \rho p$

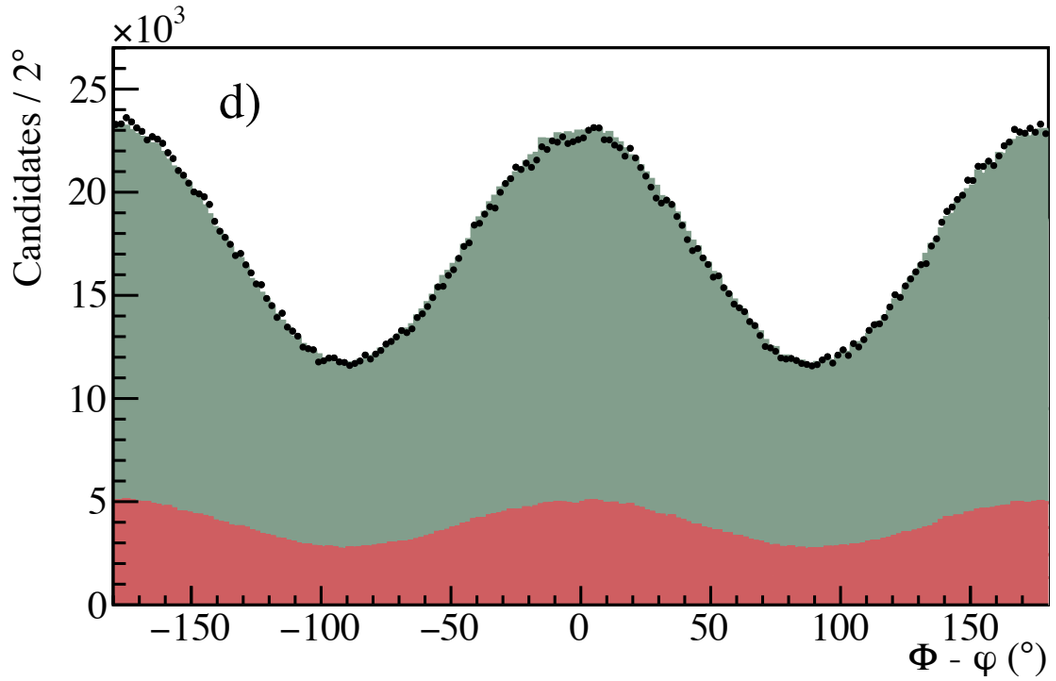
$$I(\Omega) \propto W(\cos\theta, \phi, \Phi) = W^0(\cos\theta, \phi) - P_\gamma \cos(2\Phi) W^1(\cos\theta, \phi) - P_\gamma \sin(2\Phi) W^2(\cos\theta, \phi)$$

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

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

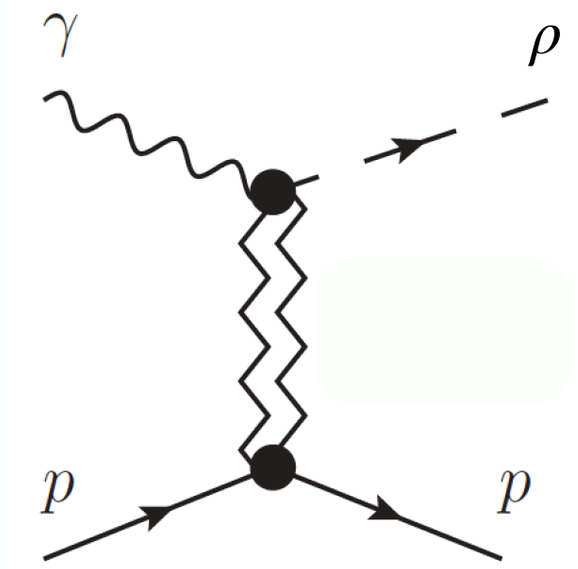
$$W^2(\cos\theta, \phi) = \frac{4}{3\pi}\left(\sqrt{2}\mathrm{Im}\rho^2_{10}\sin 2\theta\sin\phi + \mathrm{Im}\rho^2_{1-1}\sin^2\theta\sin 2\phi\right)$$



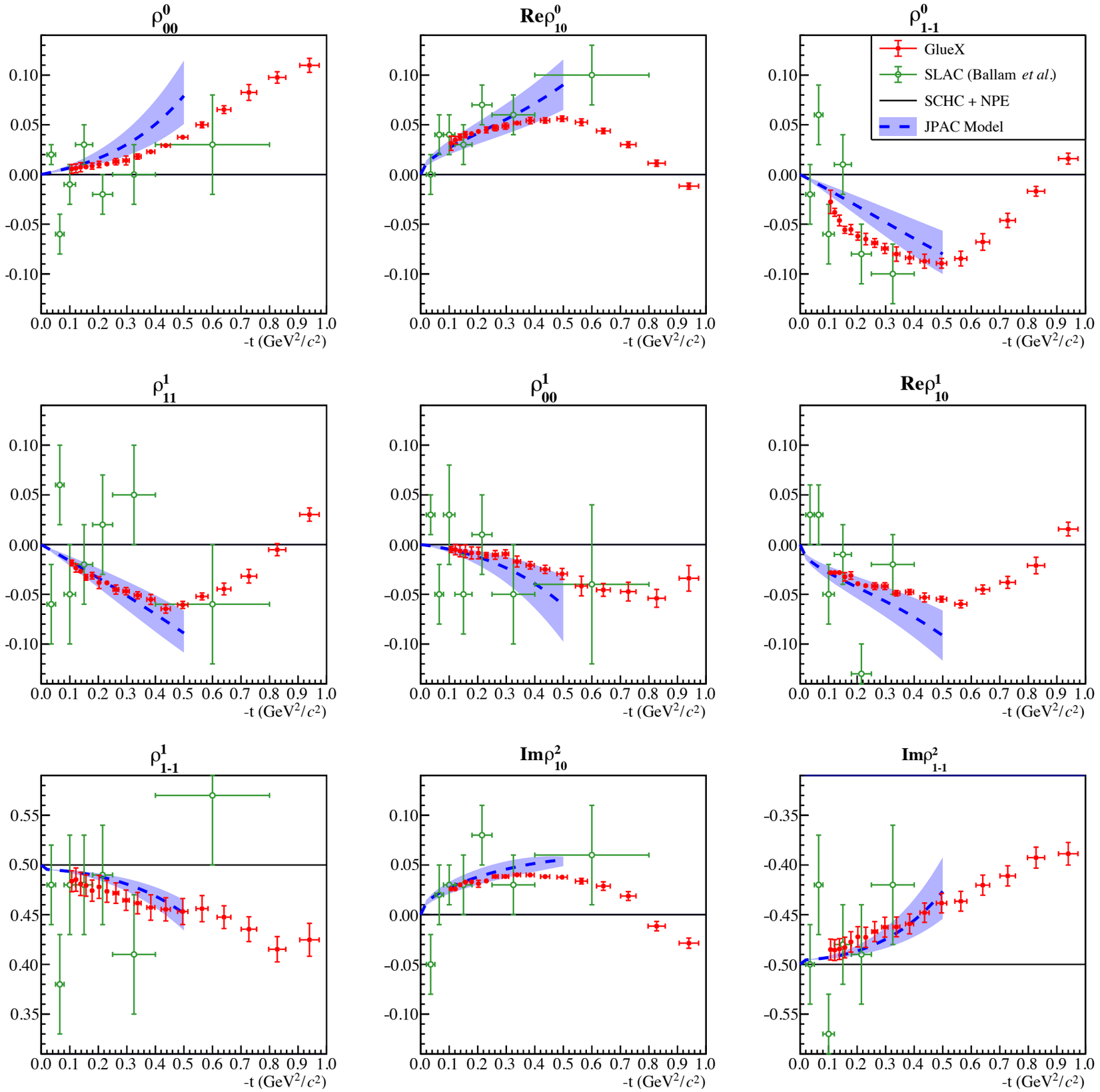


Accepted by PRC, arXiv:2305.09047

ρ SDMEs



- Good agreement with JPAC model for $-t < 0.5$ GeV



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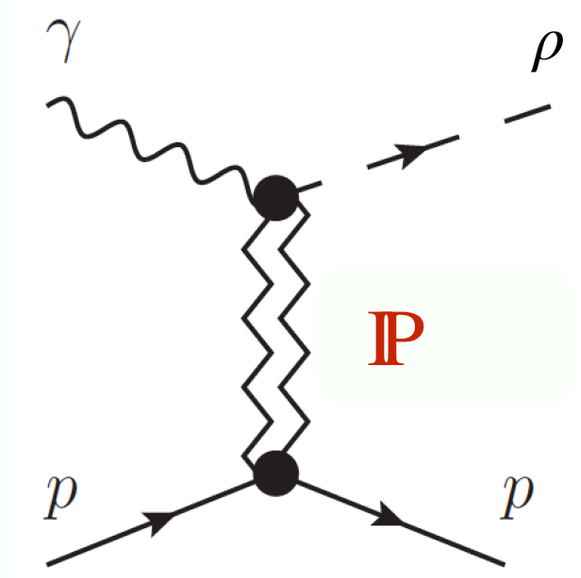
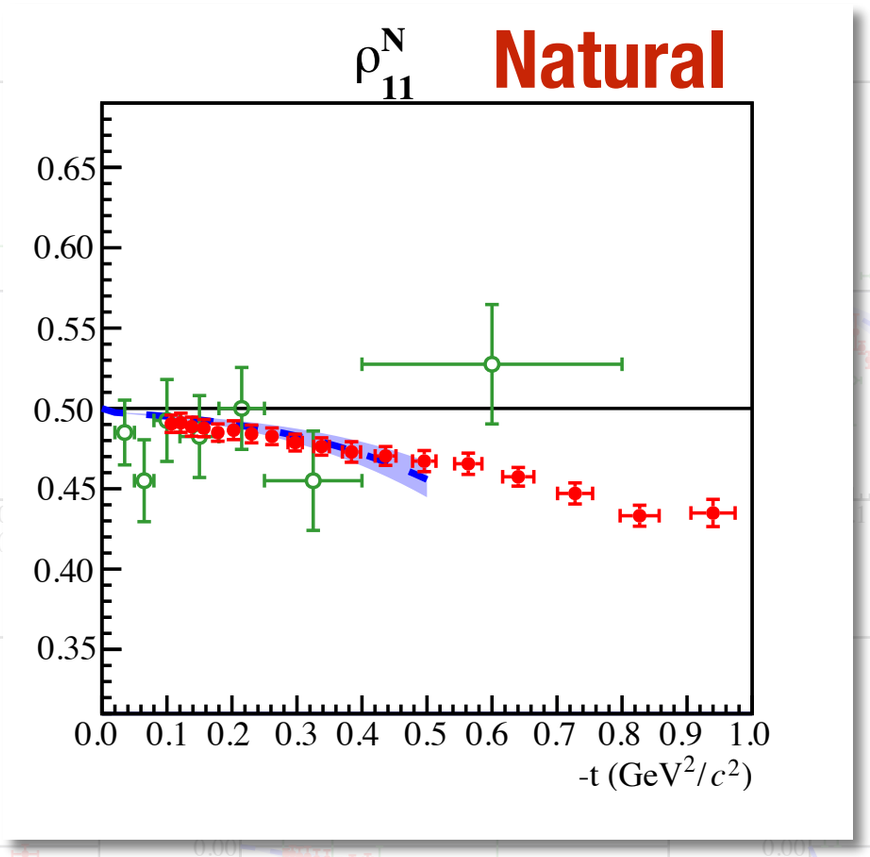
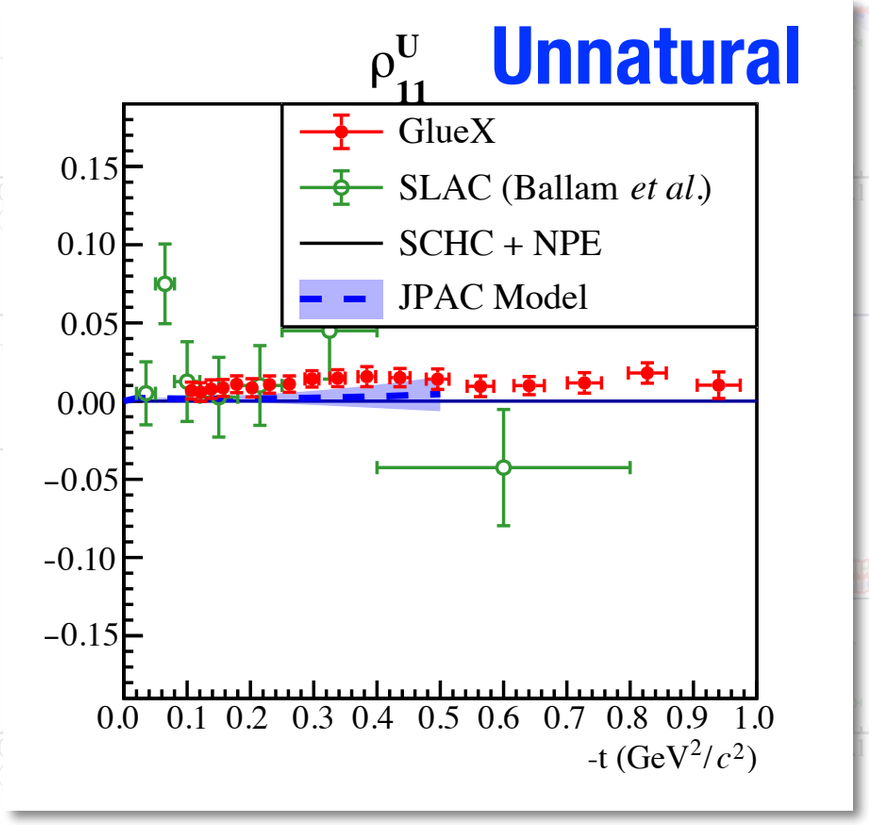


- Good agreement with JPAC model for $-t < 0.5$ GeV
- Natural (ℙ) pomeron exchange dominant for ρ





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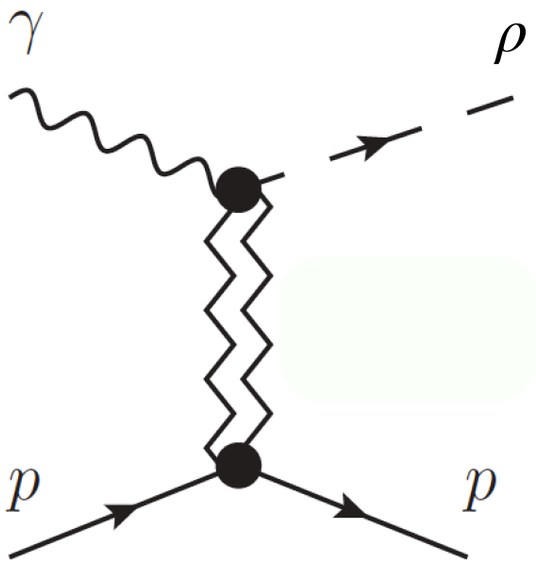
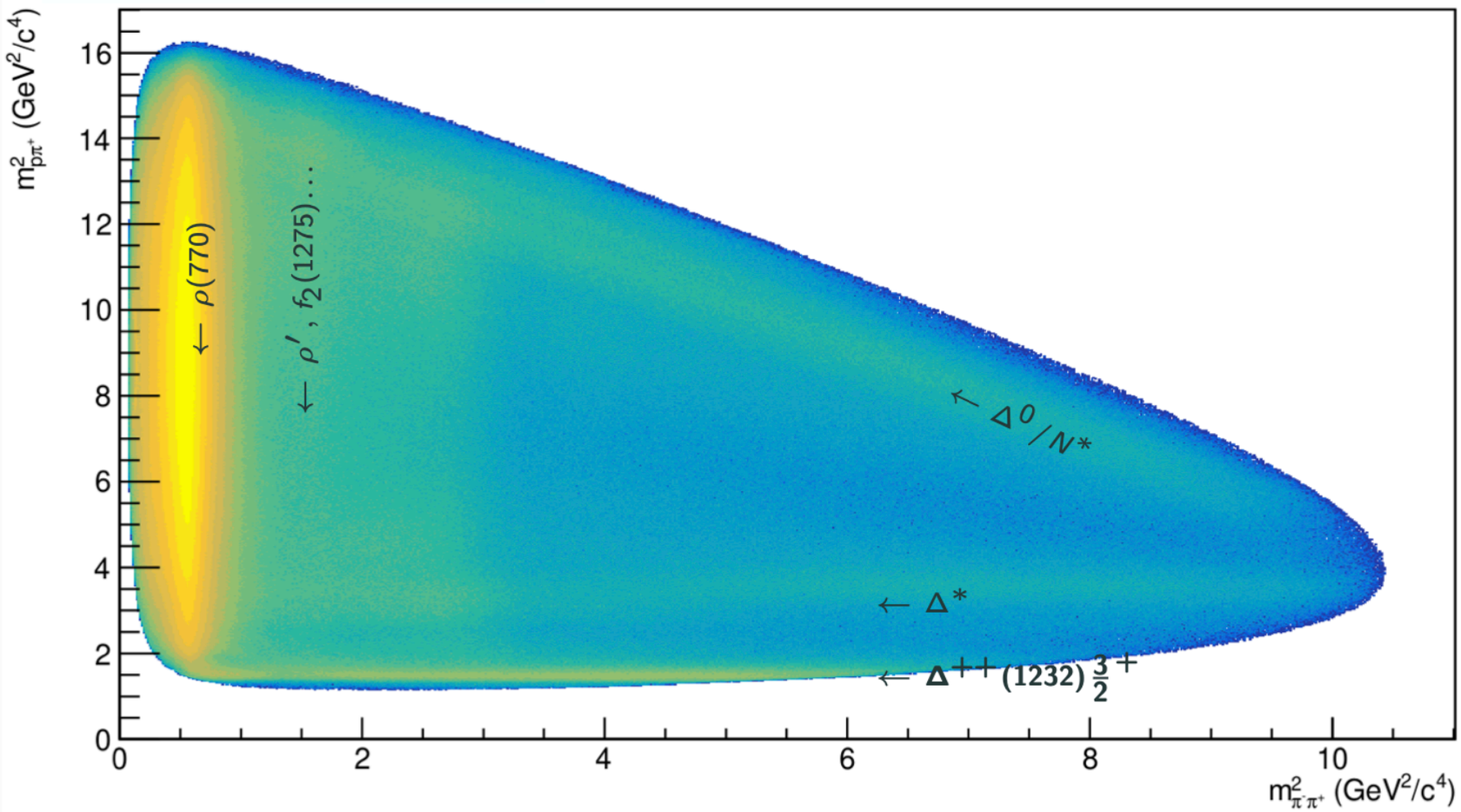
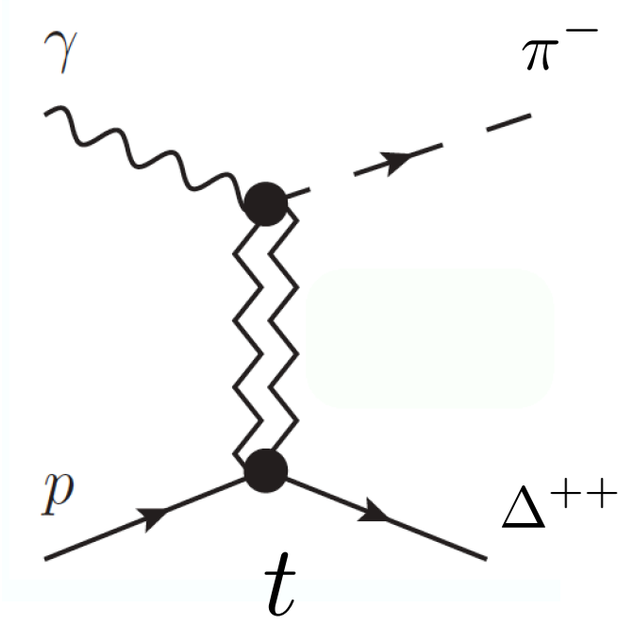
$\gamma p \to p\pi^+\pi^-$: beyond the ρ

Farah Afzal (Thursday 17:30)



- f_0, f_2 and ρ' relevant for larger $M_{\pi\pi}$
- Δ^{++} produced in charge exchange
- Access to charged meson systems





Δ^{++} SDMEs

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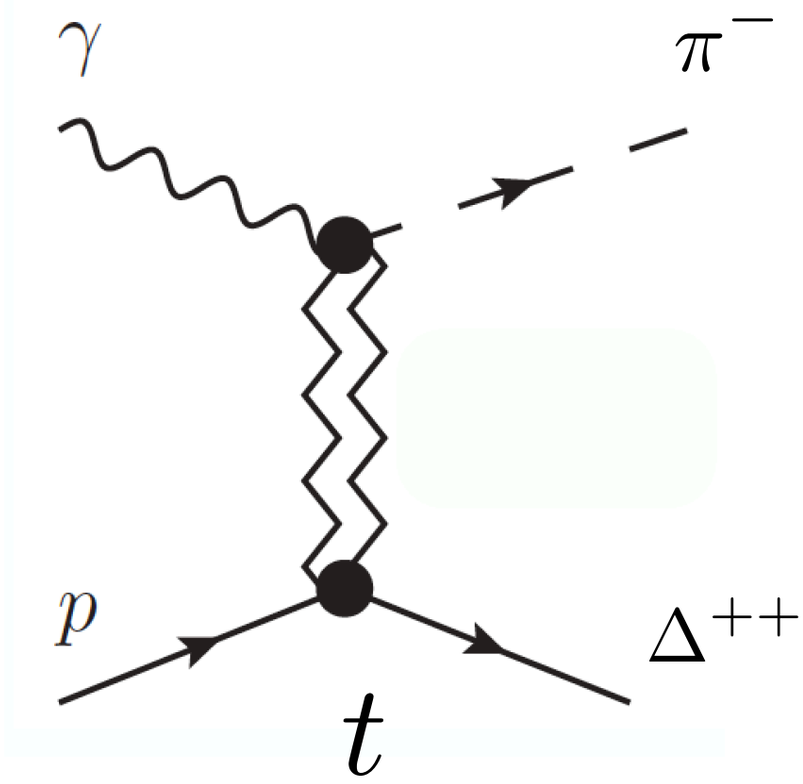

- Study charge exchange production mechanism through SDMEs
- Similar to vector decay requires three angles to describe intensity: beam polarization Φ and Δ^{++} decay θ, ϕ

$$W(\theta,\varphi,\Phi) = \frac{3}{4\pi}\left(\boldsymbol{\rho^0_{33}}\sin^2\theta + \boldsymbol{\rho^0_{11}}\left(\frac{1}{3}+\cos^2\theta\right) - \frac{2}{\sqrt{3}}Re[\boldsymbol{\rho^0_{31}}\cos\varphi\sin 2\theta + \boldsymbol{\rho^0_{3-1}}\cos 2\varphi\sin^2\theta]\right.$$
$$- P_\gamma\cos 2\Phi\left[\boldsymbol{\rho^1_{33}}\sin^2\theta + \boldsymbol{\rho^1_{11}}\left(\frac{1}{3}+\cos^2\theta\right) - \frac{2}{\sqrt{3}}Re[\boldsymbol{\rho^1_{31}}\cos\varphi\sin 2\theta + \boldsymbol{\rho^1_{3-1}}\cos 2\varphi\sin^2\theta]\right]$$
$$\left. - P_\gamma\sin 2\Phi\frac{2}{\sqrt{3}}Im[\boldsymbol{\rho^2_{31}}\sin\varphi\sin 2\theta + \boldsymbol{\rho^2_{3-1}}\sin 2\varphi\sin^2\theta)]\right)$$

Δ^{++} SDMEs

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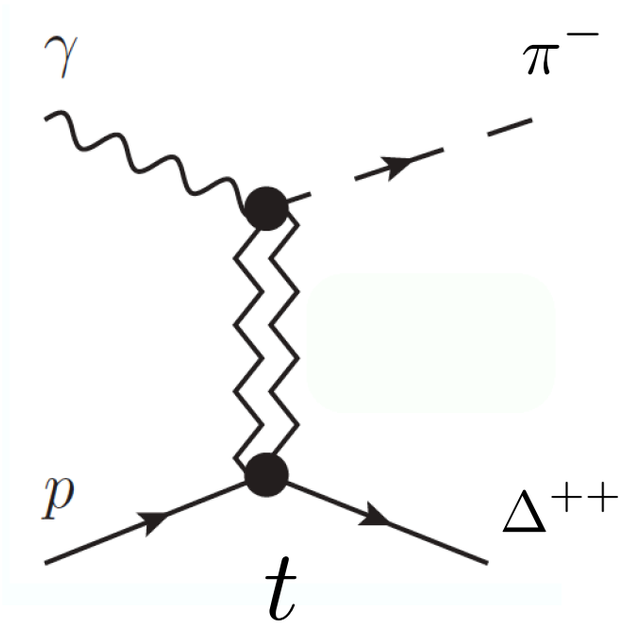
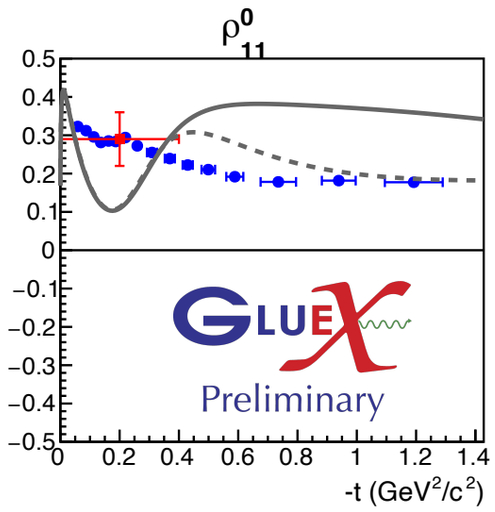
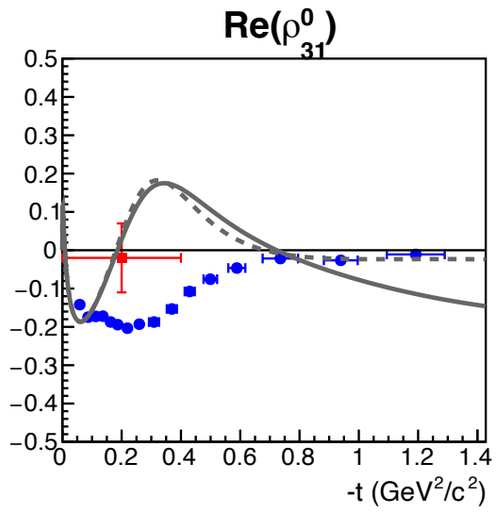
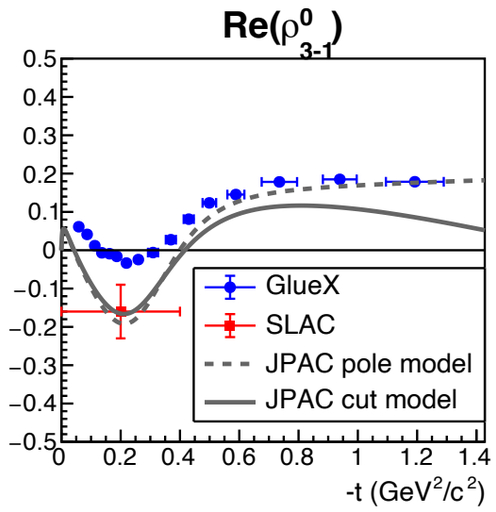
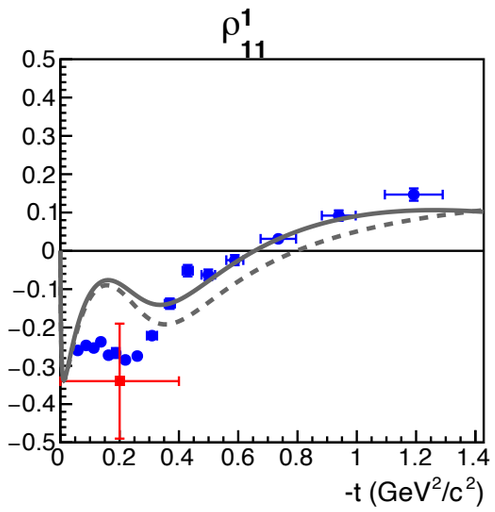


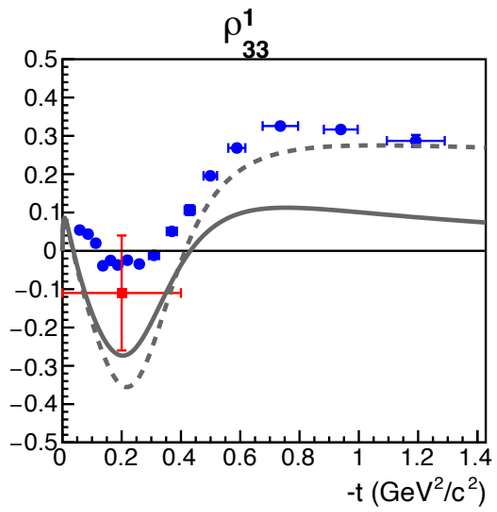
- JPAC model agrees reasonably well for $-t > 0.5$ GeV

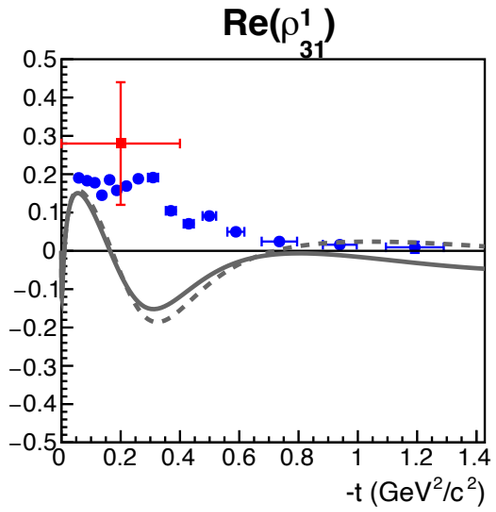


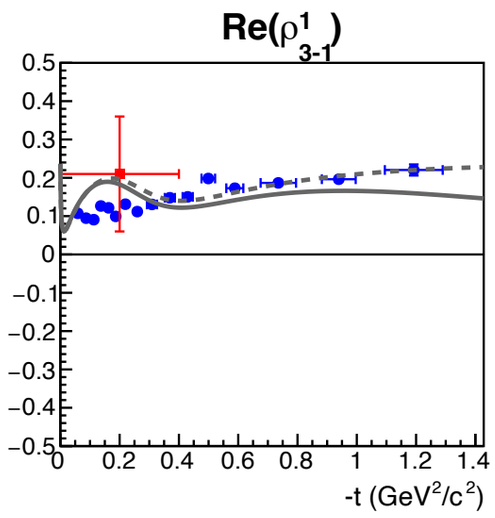


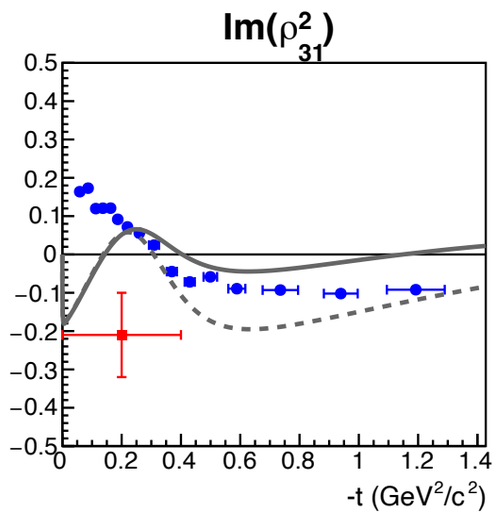


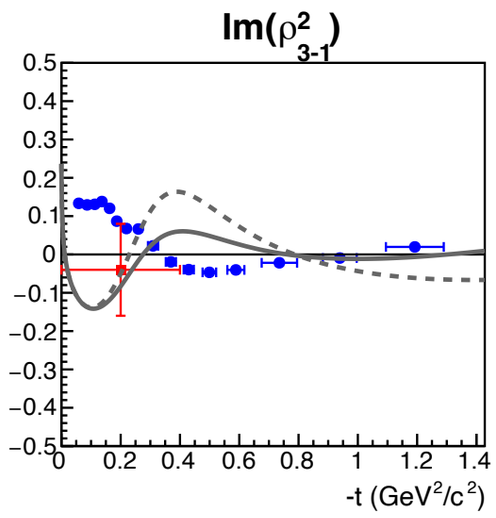




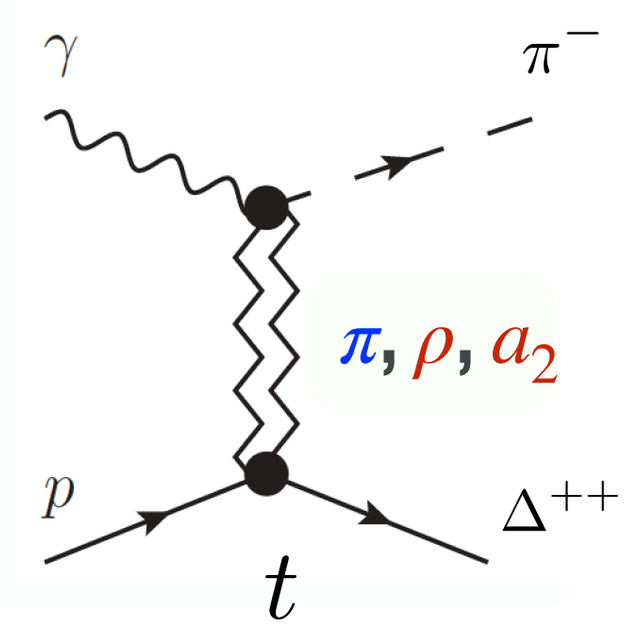




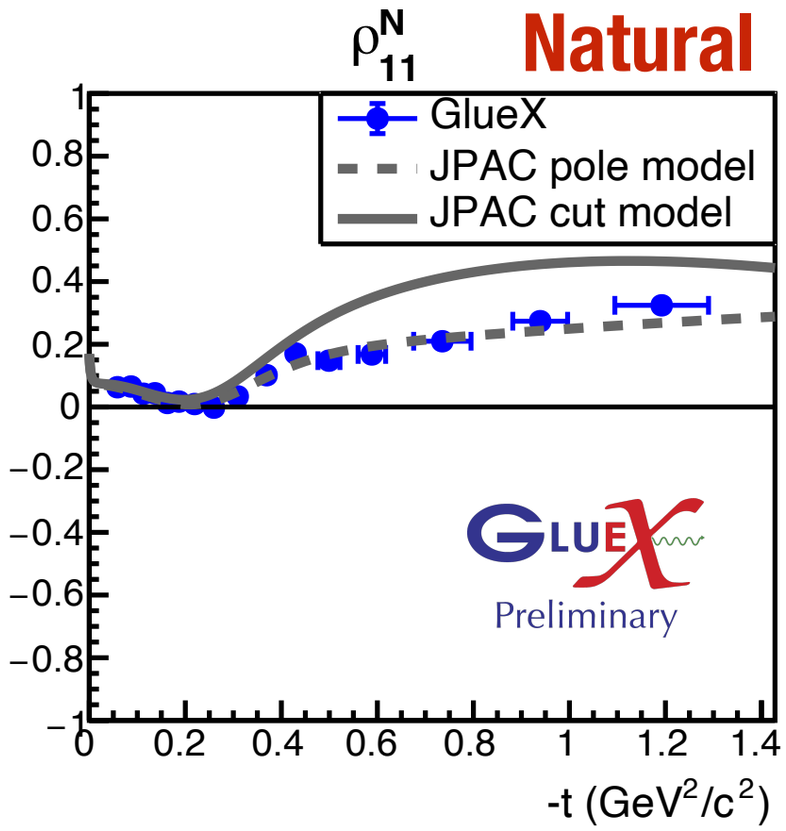


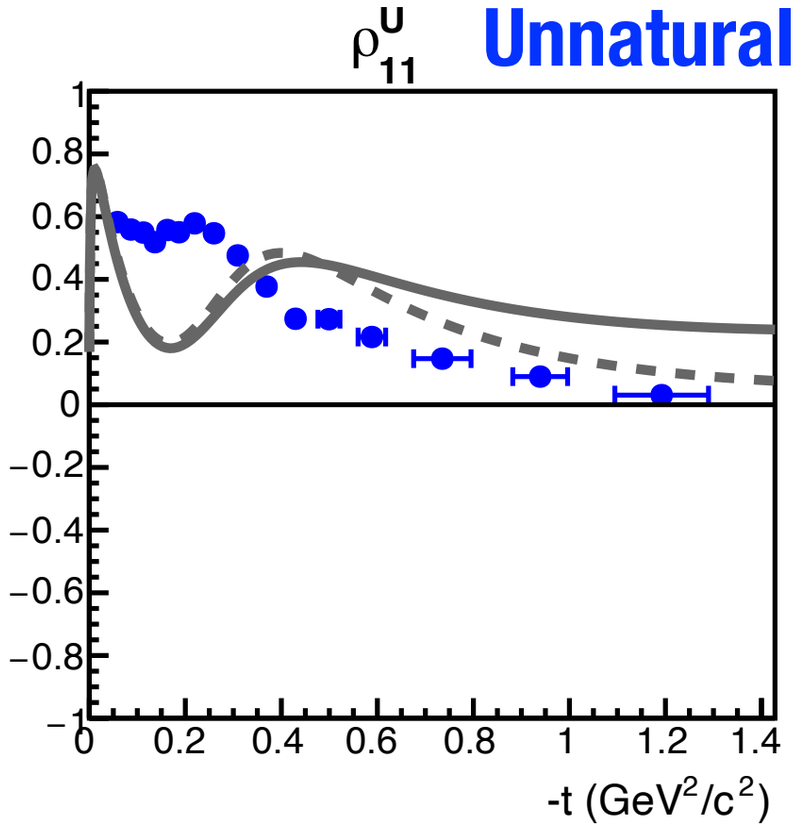


Δ^{++} SDMEs



- JPAC model agrees reasonably well for $-t > 0.5$ GeV
- Better agreement in natural exchange, but contributions from both required





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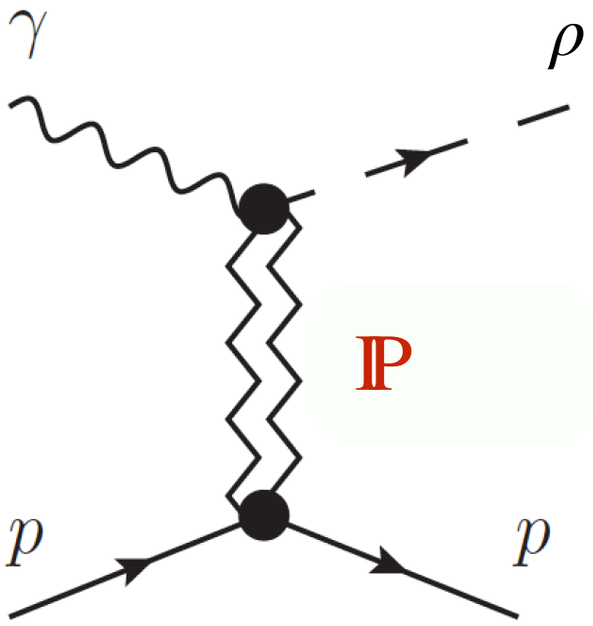
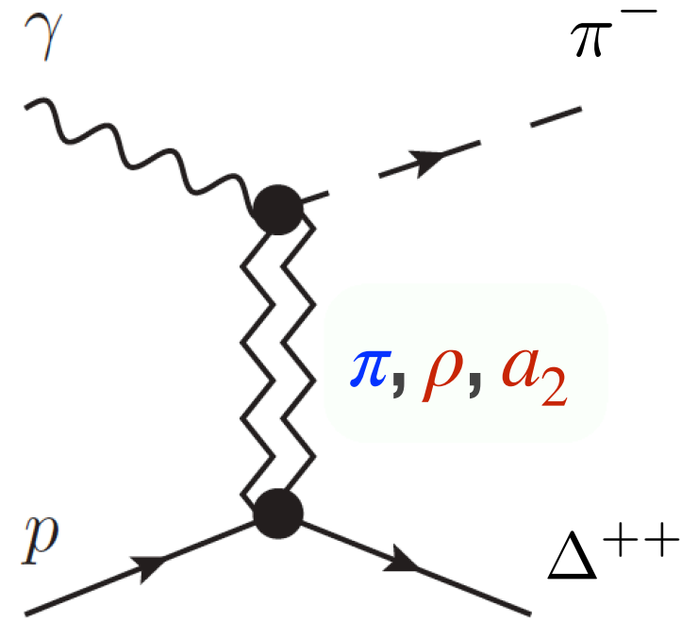
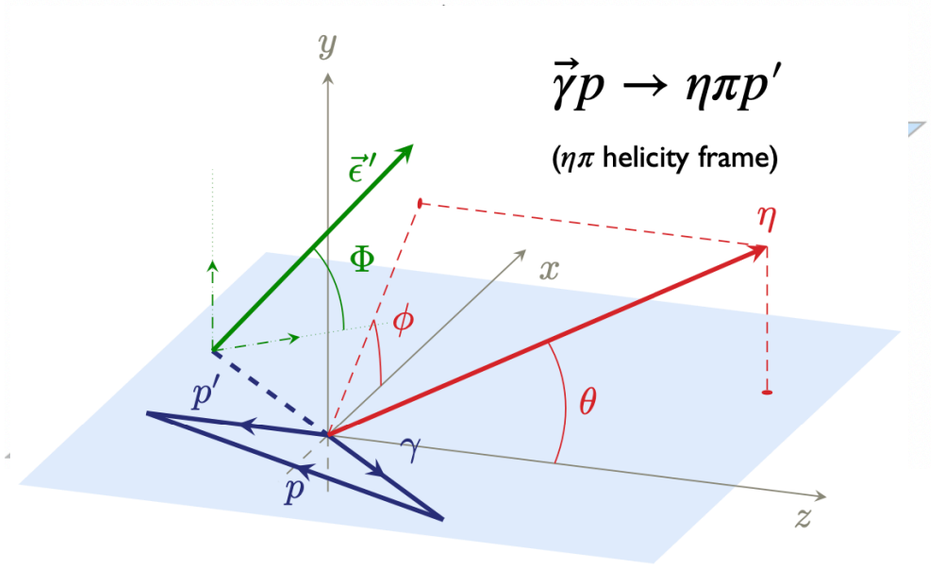


Two examples of modeling charged and neutral t-channel exchange

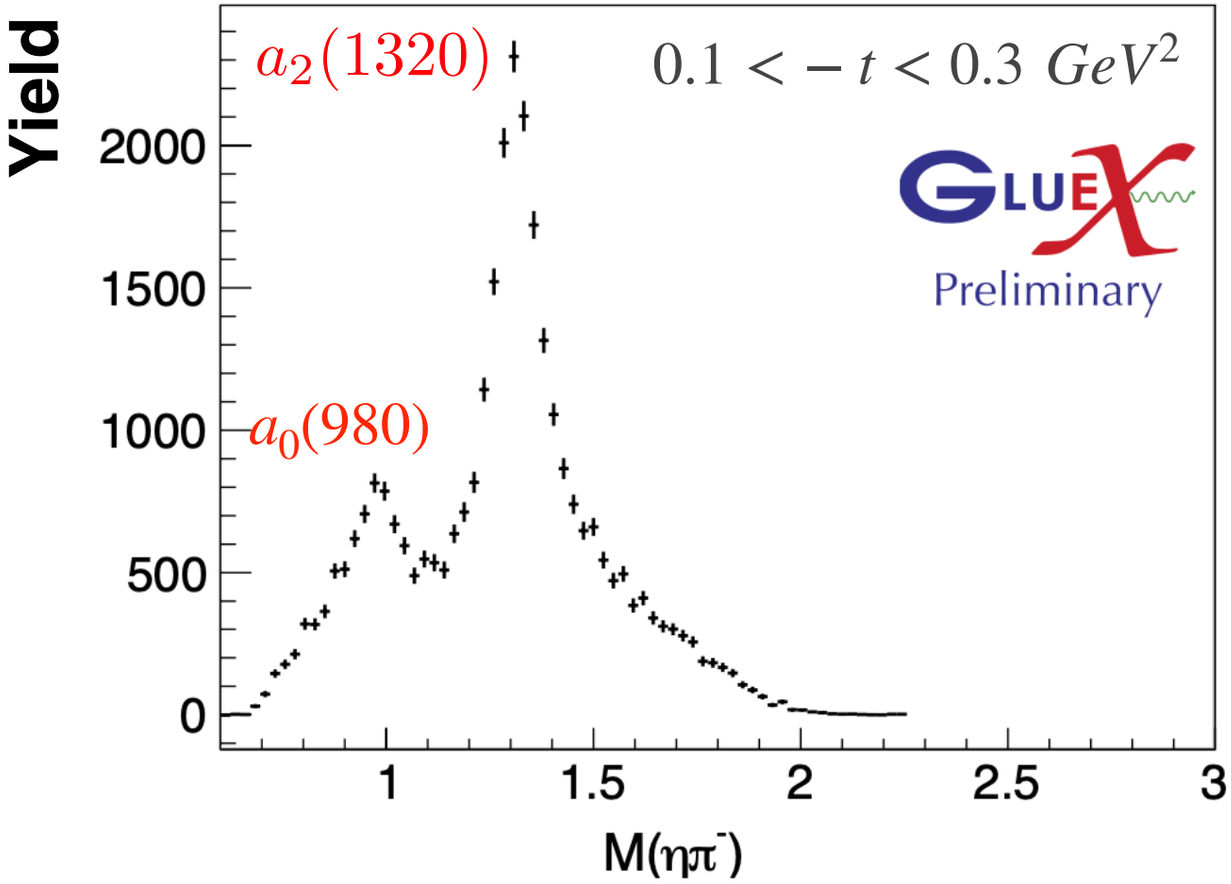


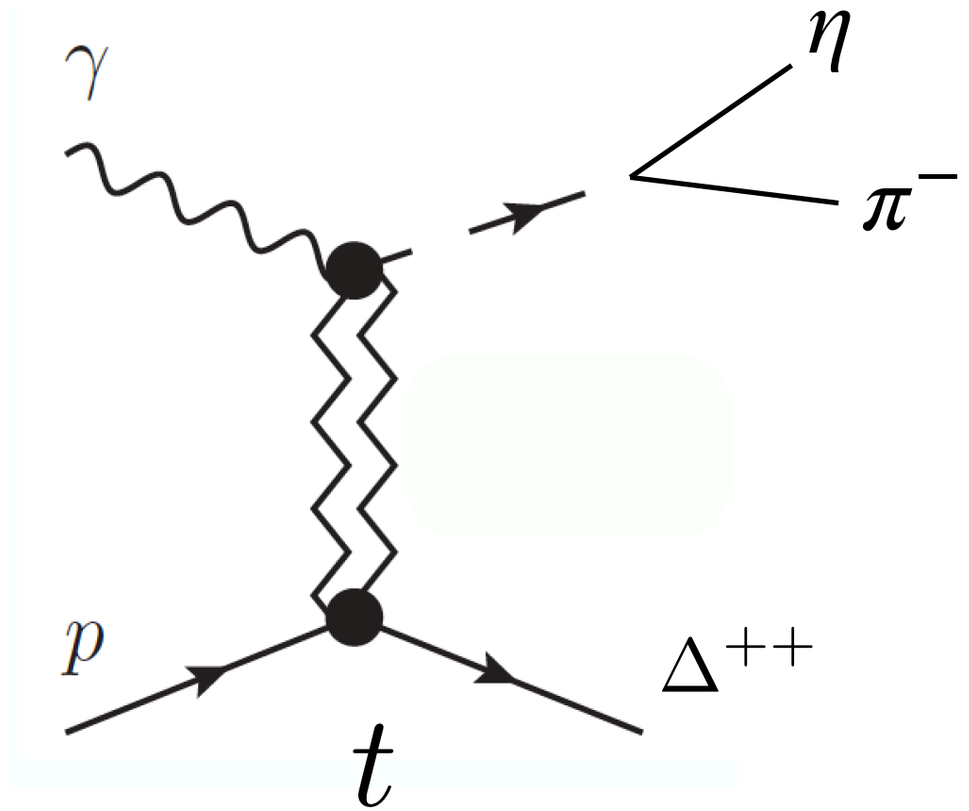
$\eta\pi$ spectroscopy at GlueX

- 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



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





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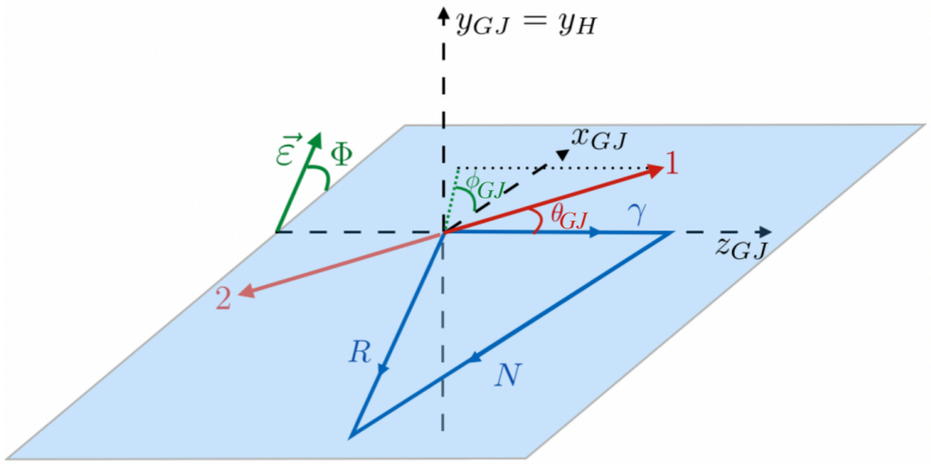
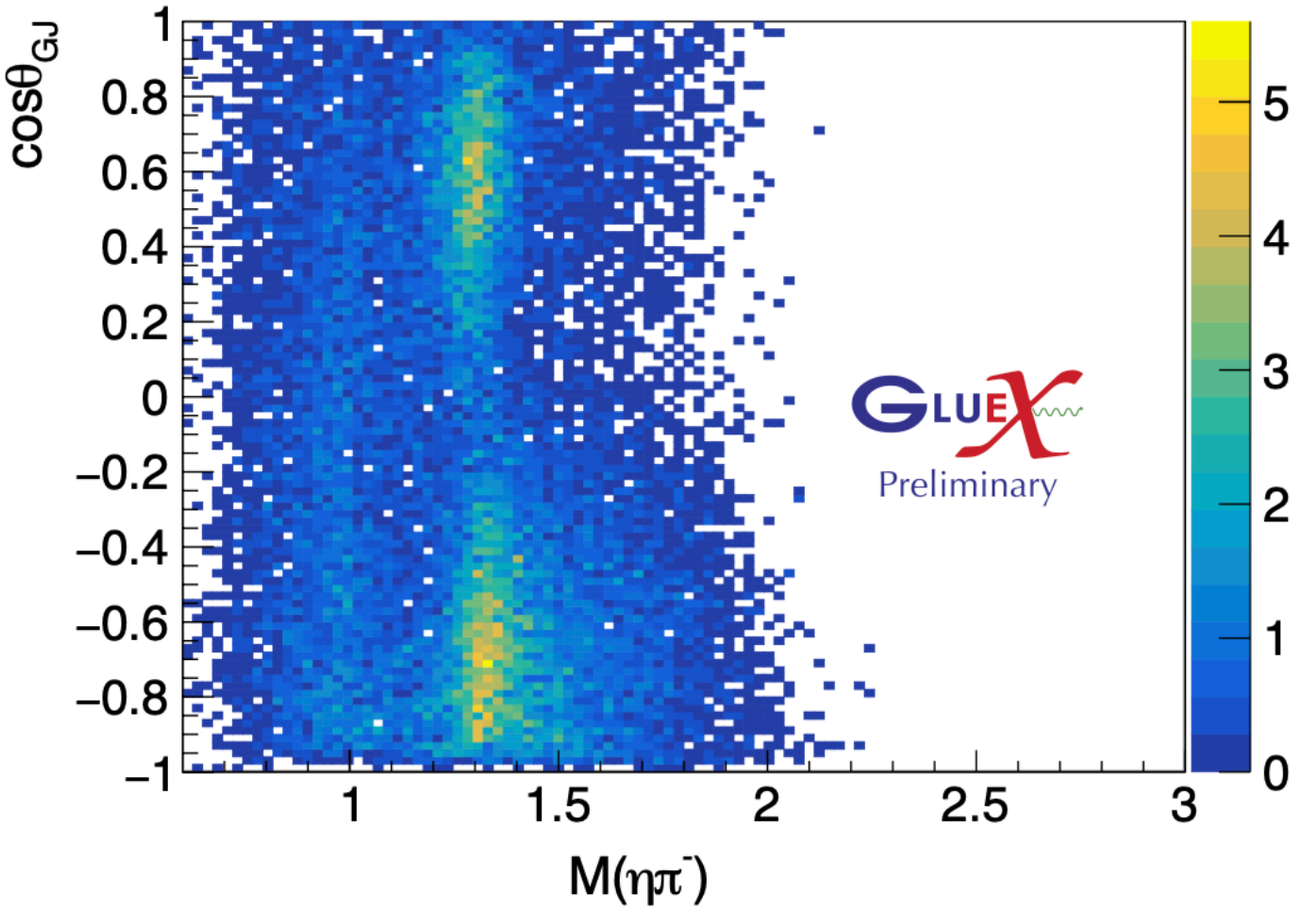
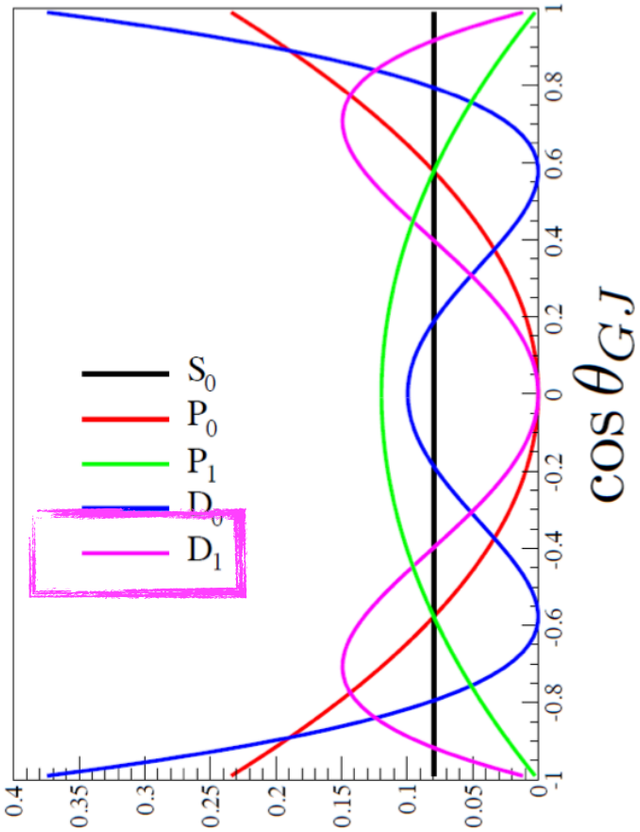


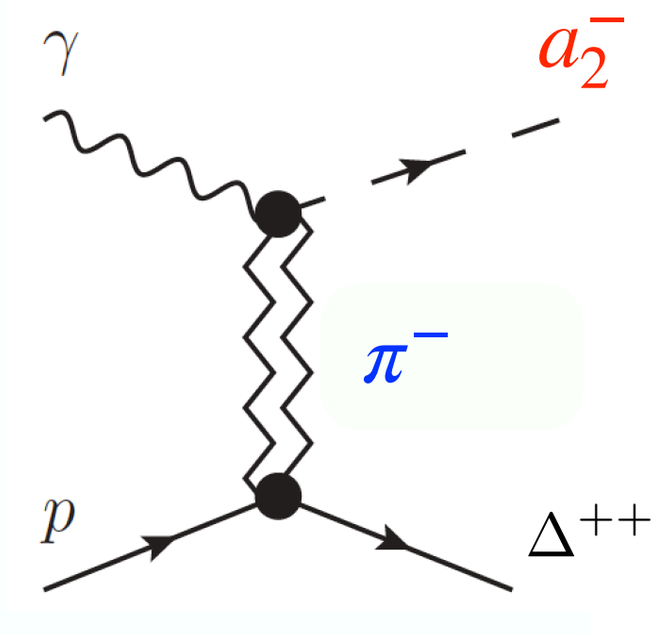
a_0 a_2 $\gamma p \to \eta\pi^-\Delta^{++}$

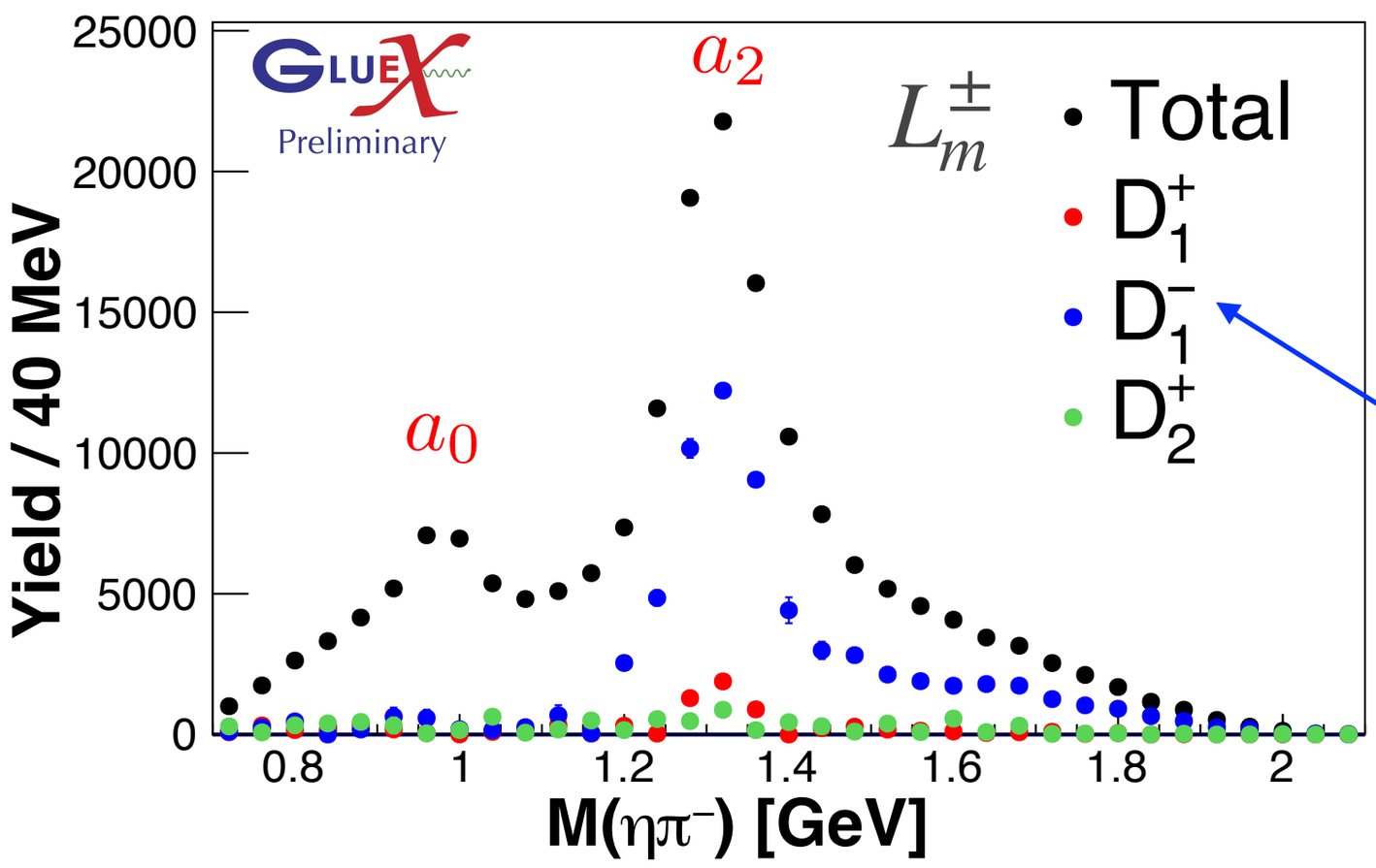




$\eta\pi$ spectroscopy at GlueX

- 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





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

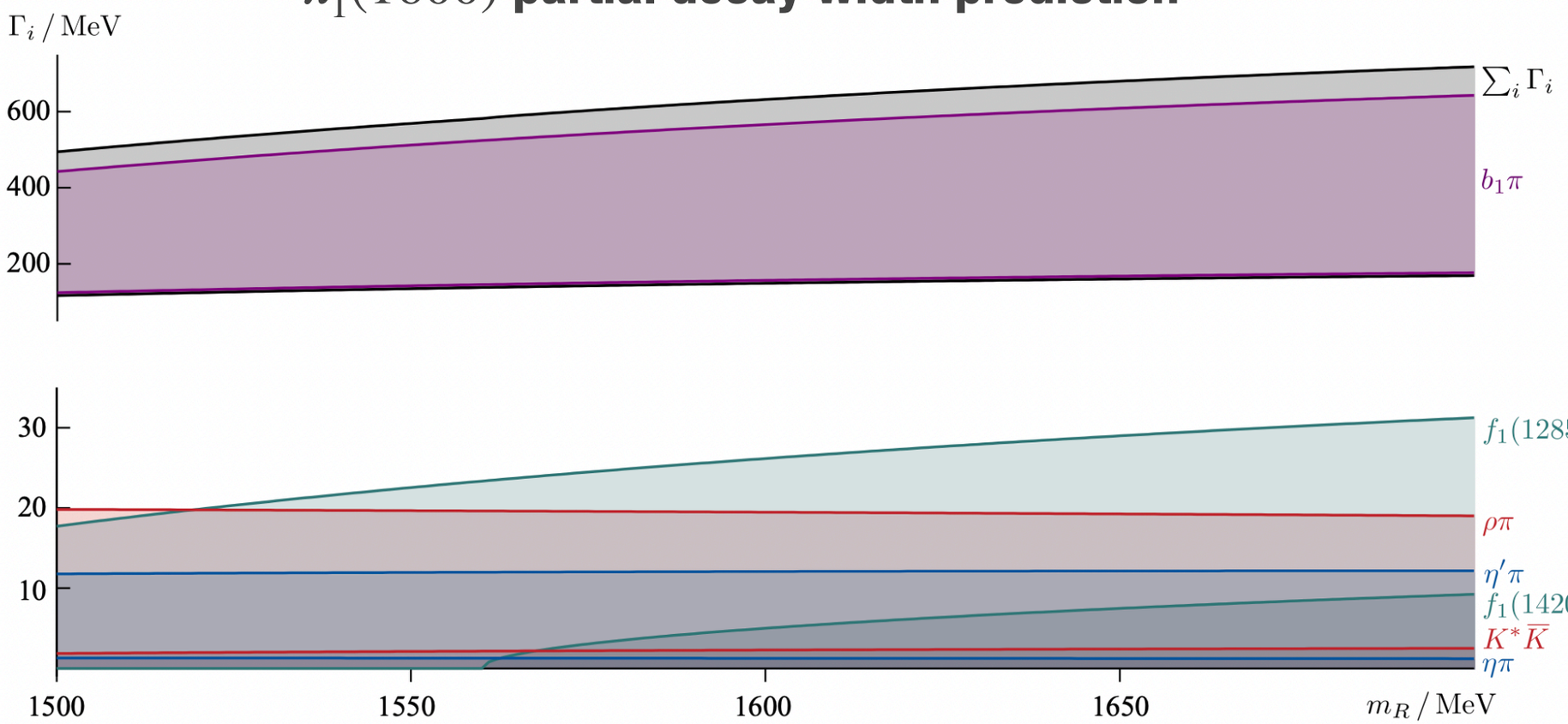
path to hybrid mesons

- Primary goal of GlueX is to search for and ultimately map out the spectrum of light quark hybrid mesons
  - ☑ High statistics polarized photoproduction dataset
  - ☑ Understand polarized production of isolated hadrons
  - ☑ Identifying conventional mesons through PWA
  - ☐ Initial search for exotic and conventional J^{PC} hybrids

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

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

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

Will Imoehl (Thursday 15:10)

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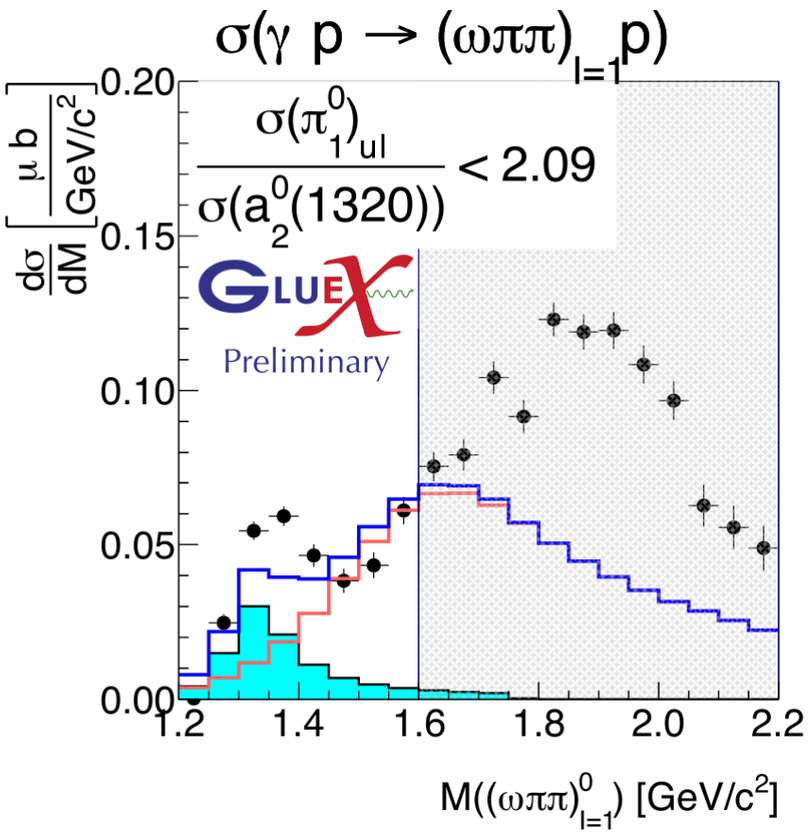
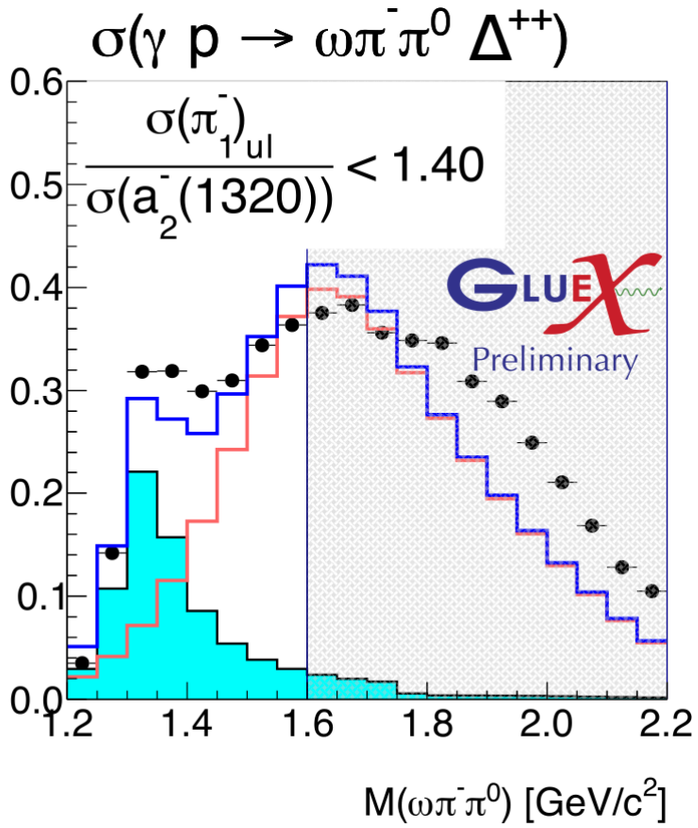
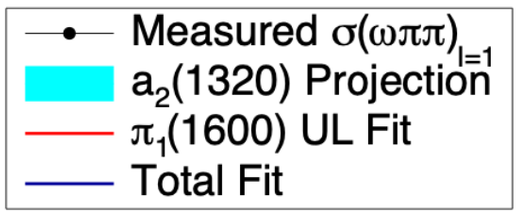
- No clear $\pi_1 \to b_1\pi \to \omega\pi\pi$ signal in I=1 → set upper limit





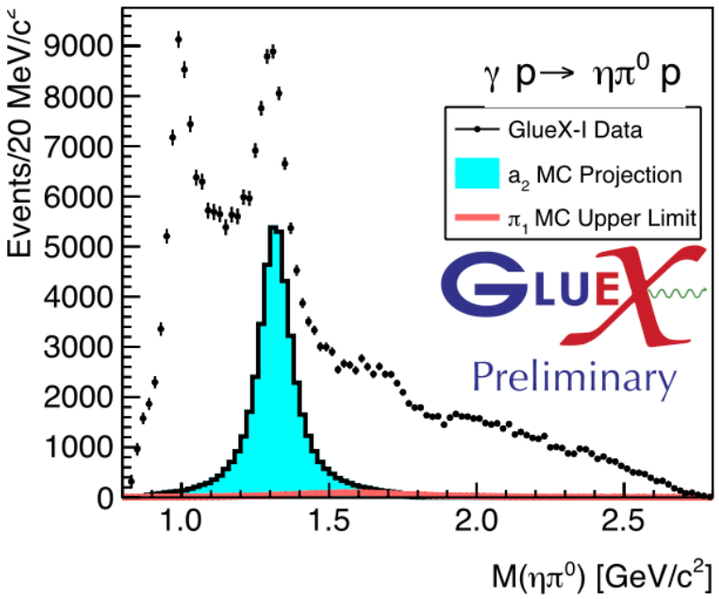


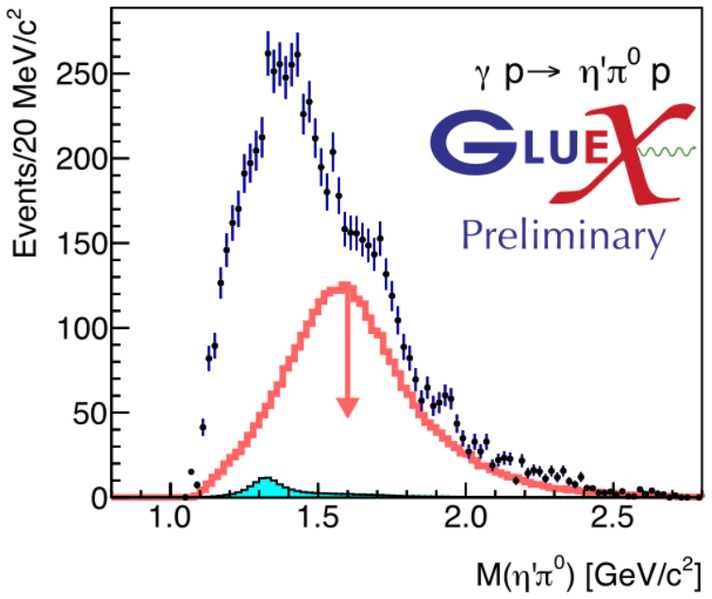
- Fixed BW shapes for a_2 and π_1
- Upper limit on photoproduction cross section ratio $\sigma(\pi_1)_{ul}/\sigma(a_2)$

Upper limit projections to $\eta^{(\prime)}\pi$

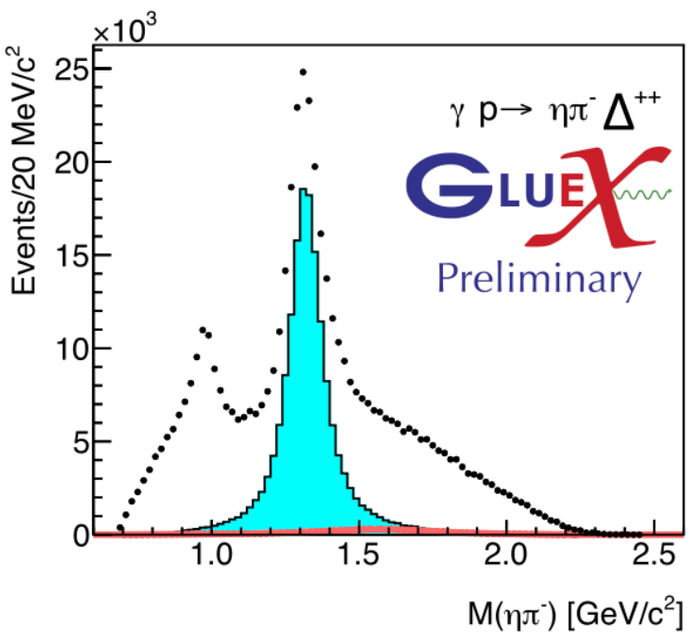
Will Imoehl (Thursday 15:10)

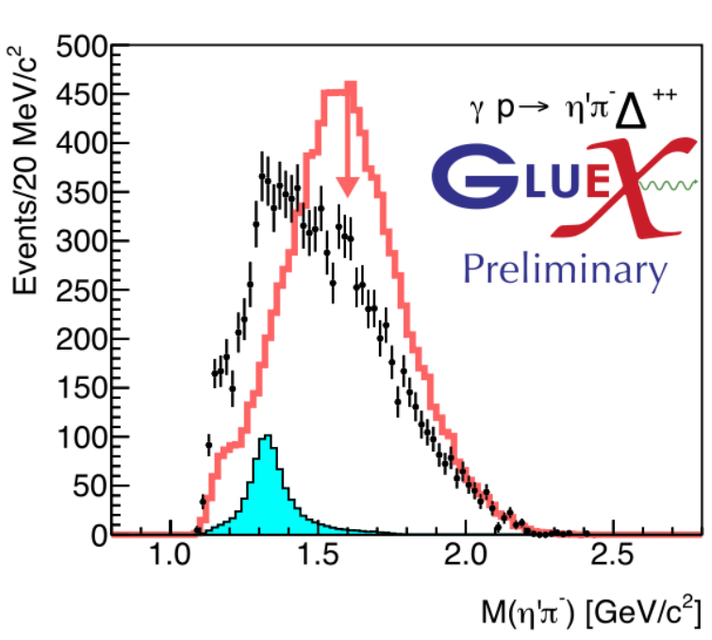
Large π_1 excluded from $\eta\pi$





π_1 could be significant in $\eta'\pi$ relative to a_2 and a_2'

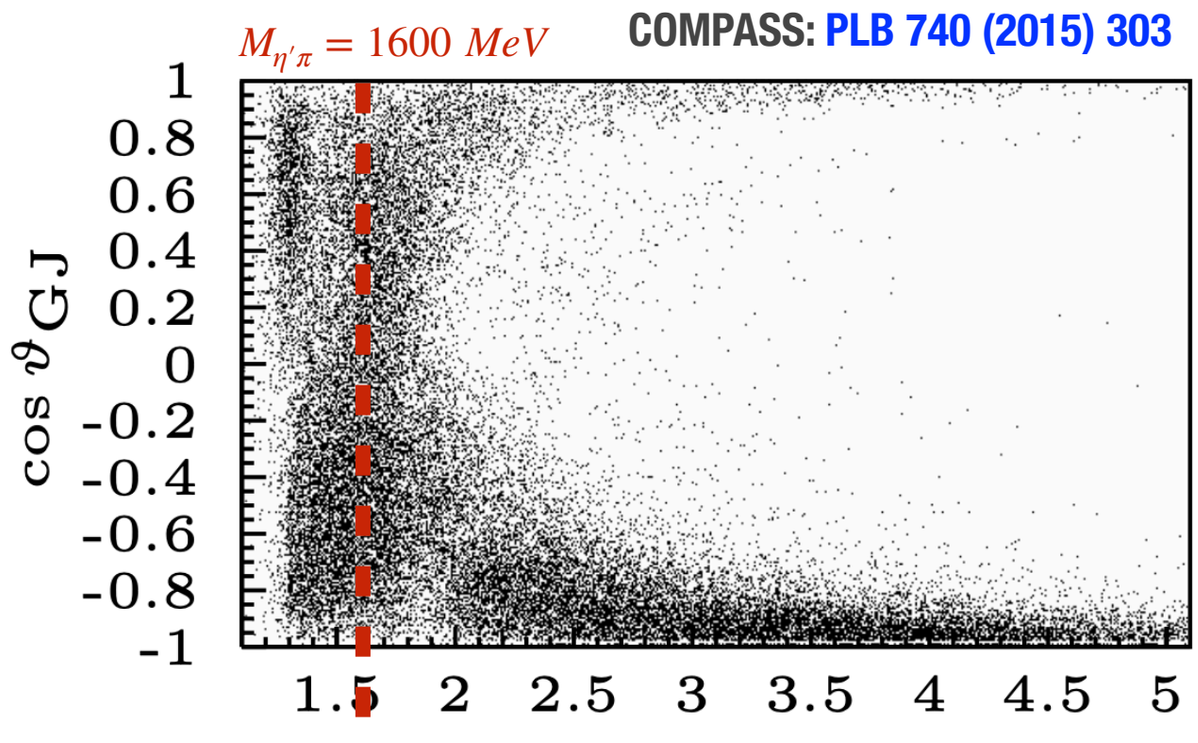


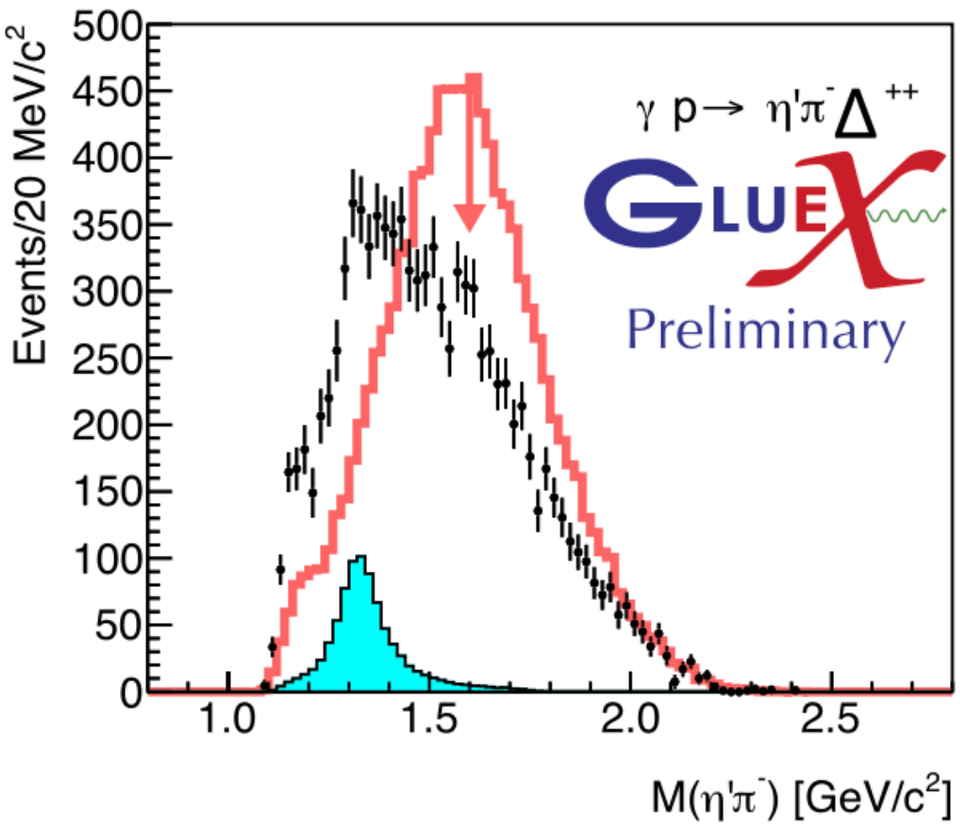


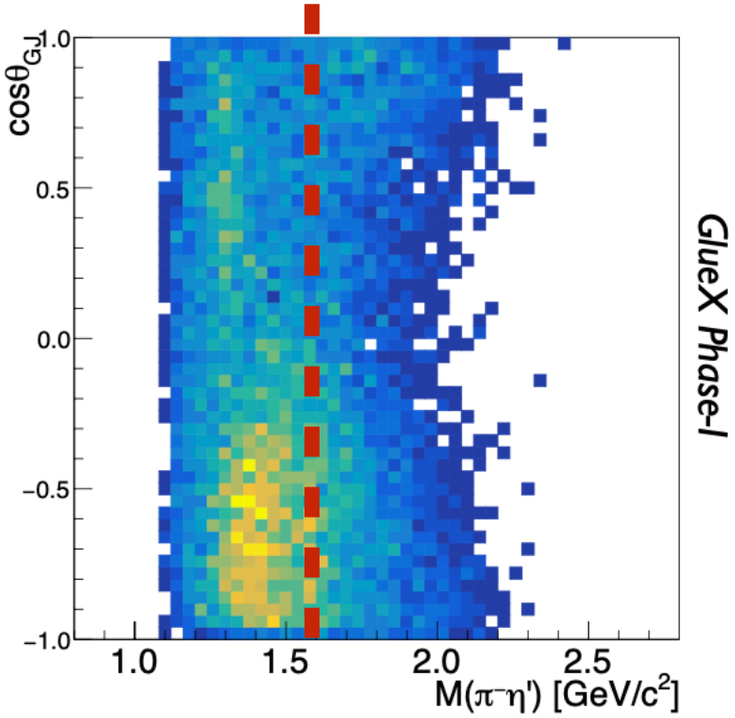
- Upper limit on $\sigma(\pi_1)$ used with lattice QCD limits on $BR(\pi_1 \to \eta^{(\prime)}\pi)$ to project upper limits in these decay modes

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

- 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







path to hybrid mesons

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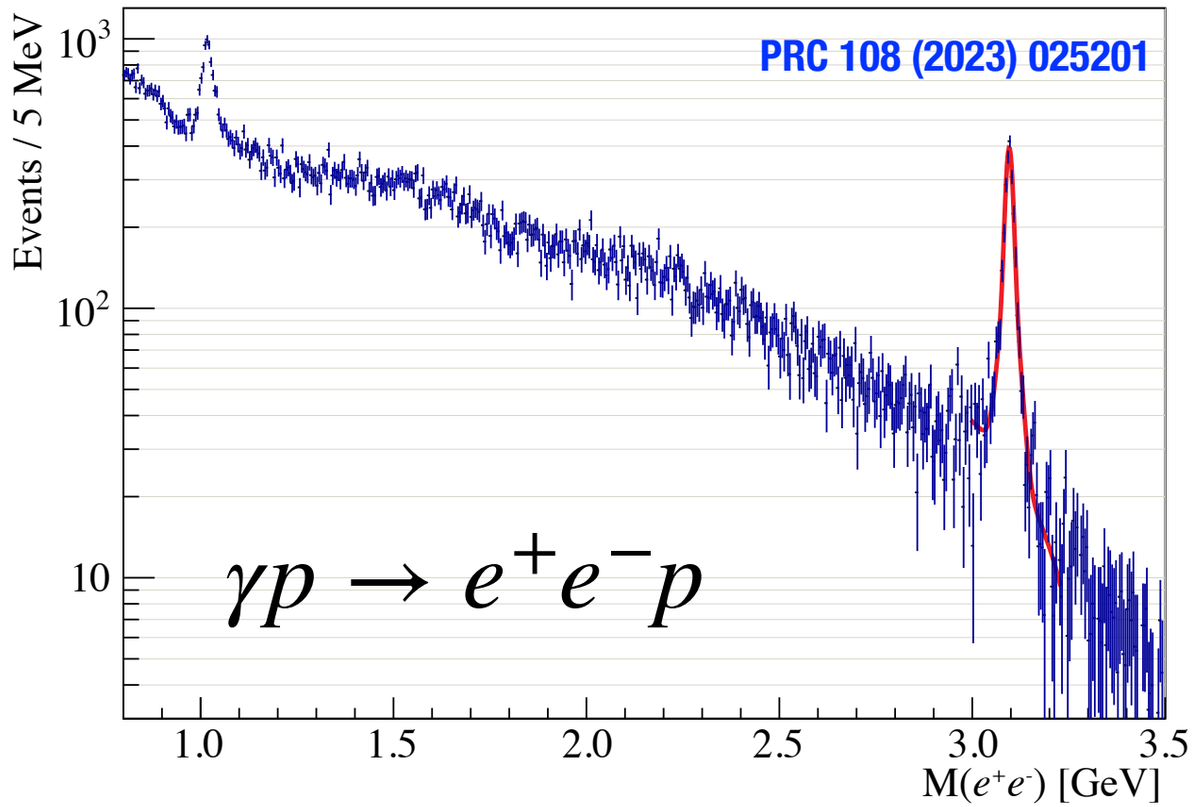
  - ☑ High statistics polarized photoproduction dataset
  - ☑ Understand polarized production of isolated hadrons
  - ☑ Identifying conventional mesons through PWA
  - ☑ Initial search for exotic and conventional J^{PC} hybrids
- Opportunities for a unique photoproduction dataset with a large-acceptance, general-purpose detector
  - J/ψ, baryon-antibaryon, hyperons (V. Crede's talk)

Reinhard Schumacher (Thursday 17:30)

J/ψ photoproduction at GlueX

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



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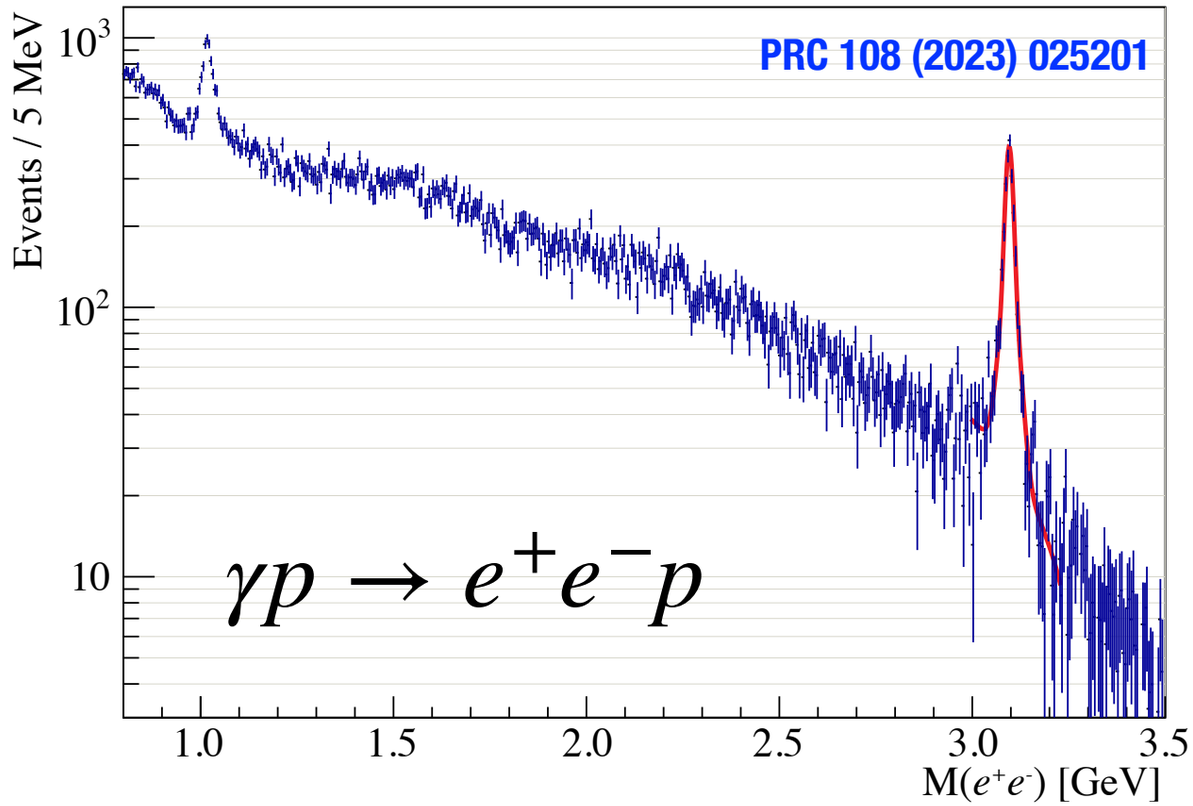
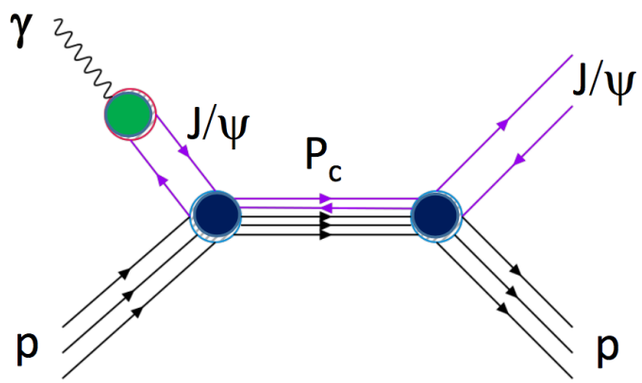
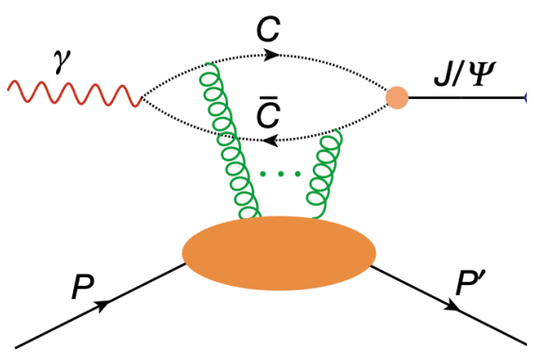


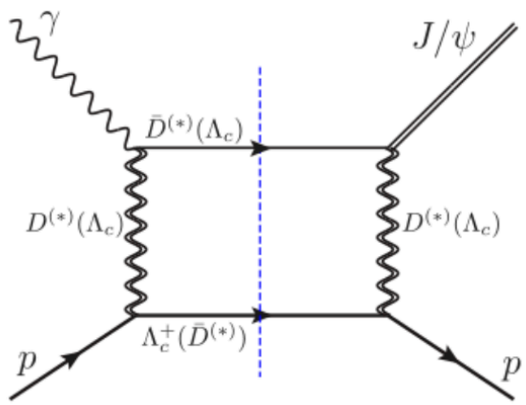
s-channel: pentaquarks



t-channel: gluon GPDs, mass radius



open charm



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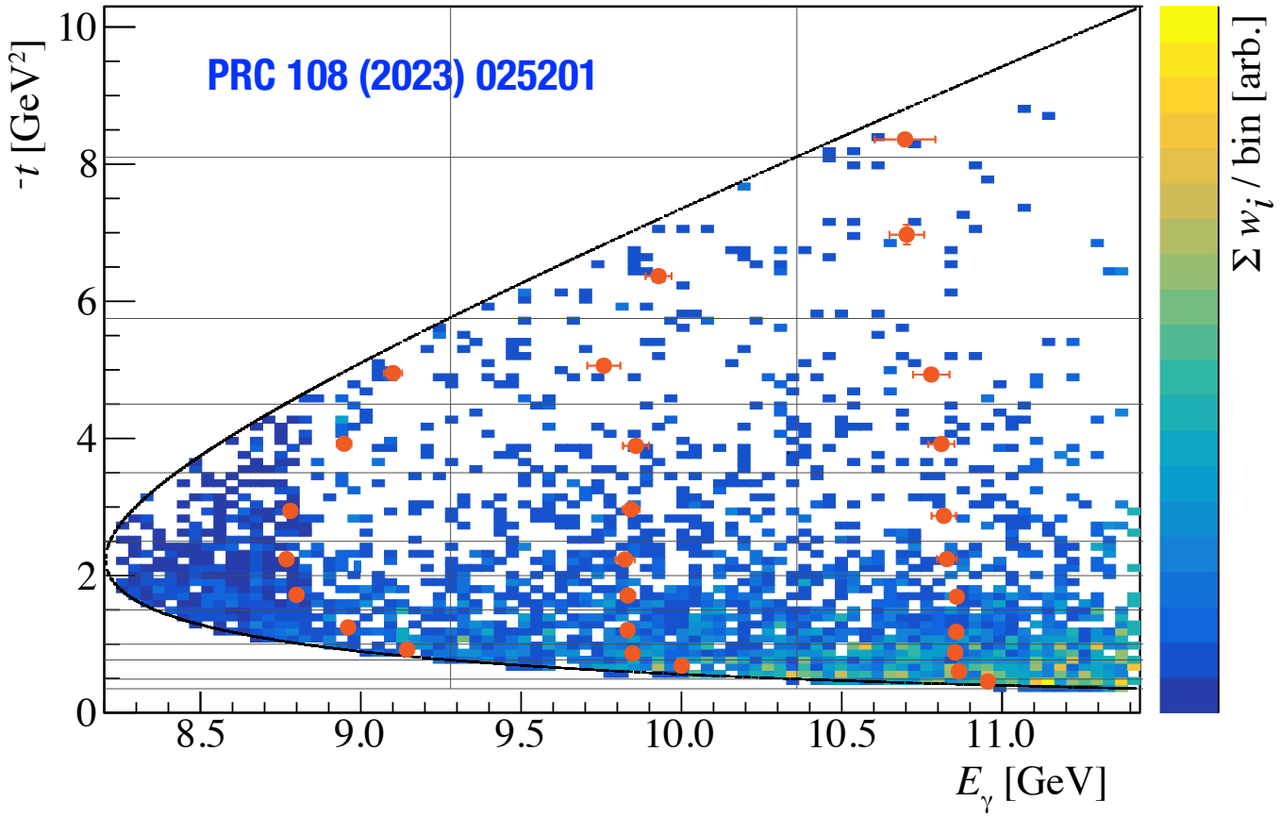

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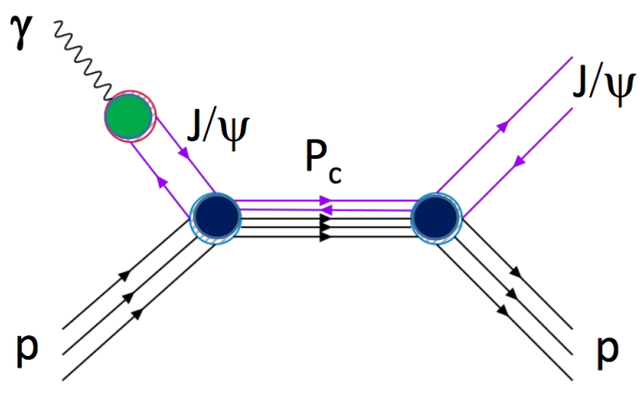

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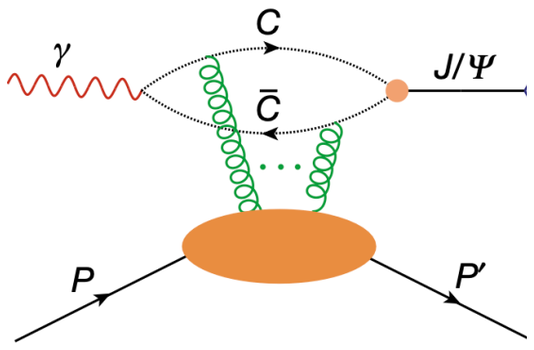
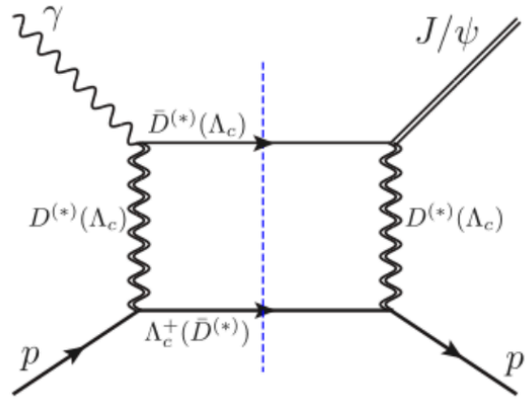
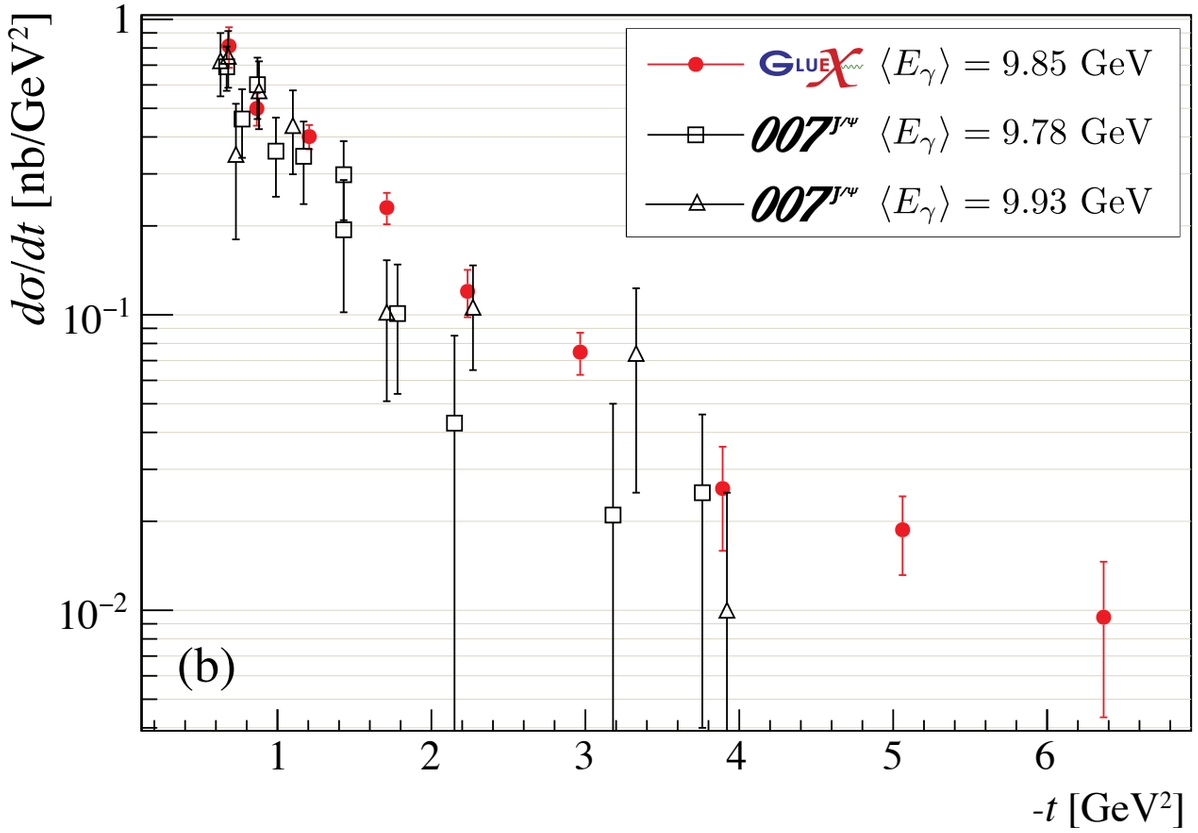


open charm

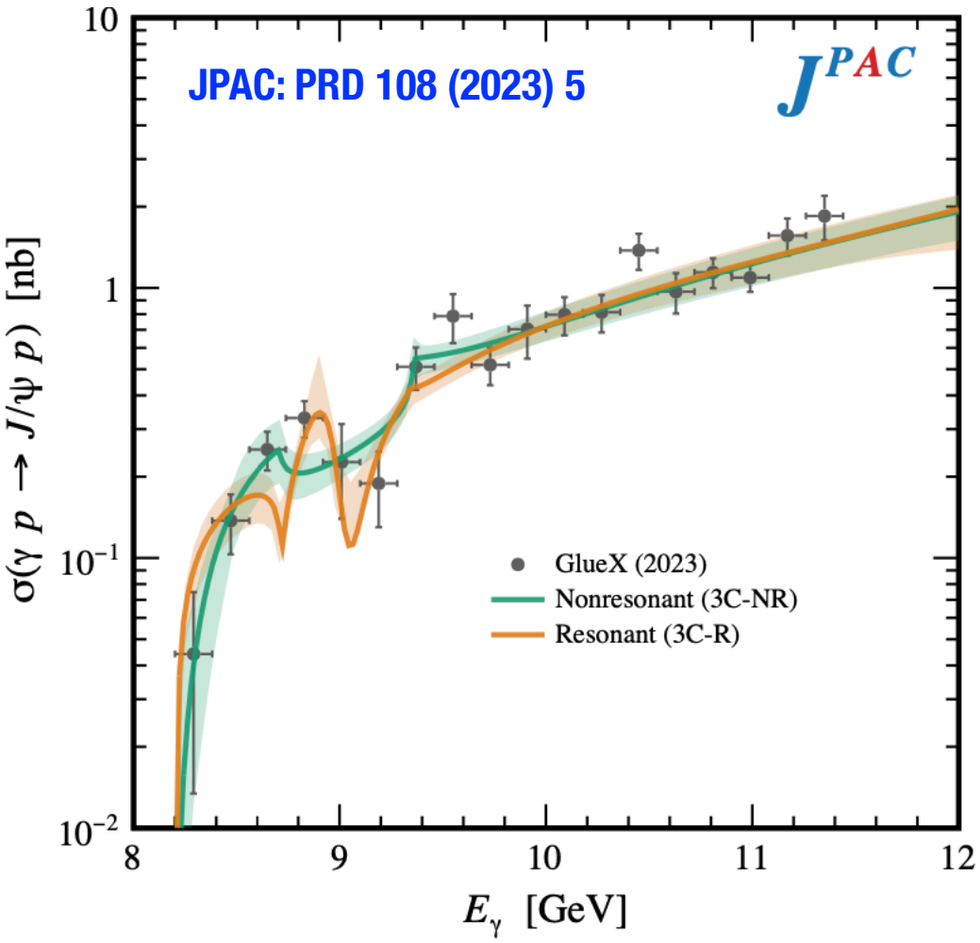


J/ψ cross sections

PRC 108 (2023) 025201



JPAC: PRD 108 (2023) 5



- 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

Summary

- The GlueX experiment has acquired an unprecedented polarized photoproduction dataset and the meson spectroscopy program is well underway

- Polarized photoproduction sensitive to production mechanism, used to study conventional mesons such as $a_2(1320)$ in amplitude analysis of $\eta\pi$

- Upper limits set on photoproduction of $\pi_1(1600)$ using BR prediction from lattice QCD, guides search in $\eta'\pi$

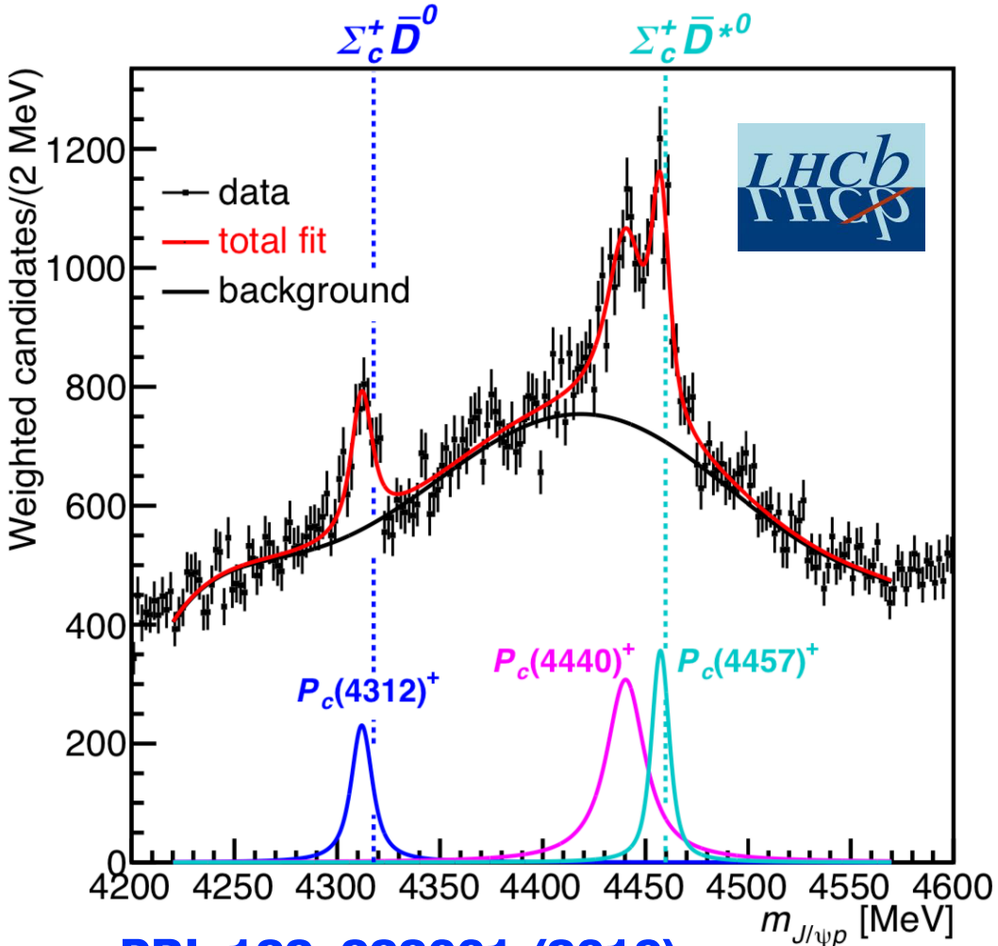
- Broad interest in threshold J/ψ production for both spectroscopy and structure, but more data needed

GlueX acknowledgements: gluex.org/thanks

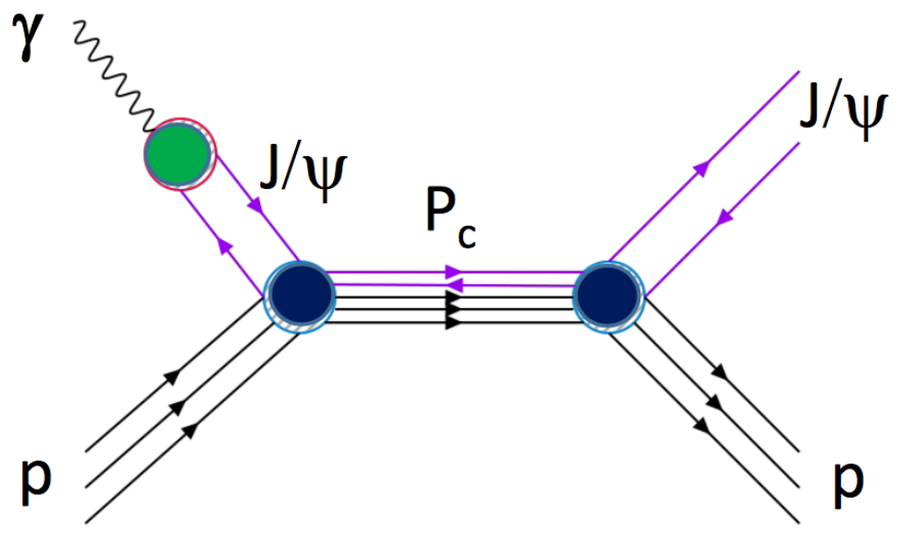
JRS supported by DE-SC0023978 U.S. DEPARTMENT OF ENERGY | Office of Science

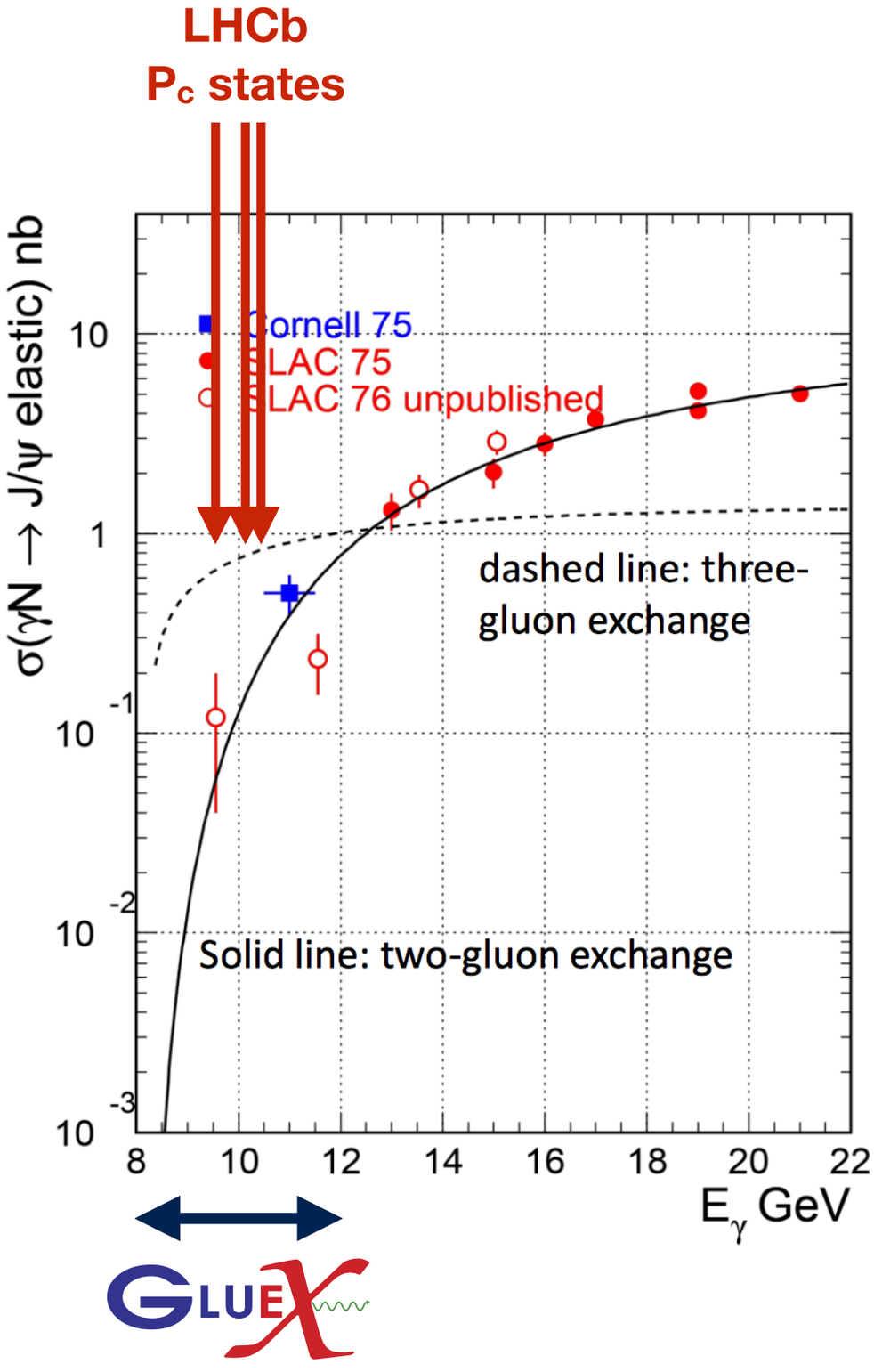
Backup

Charmonium at JLab

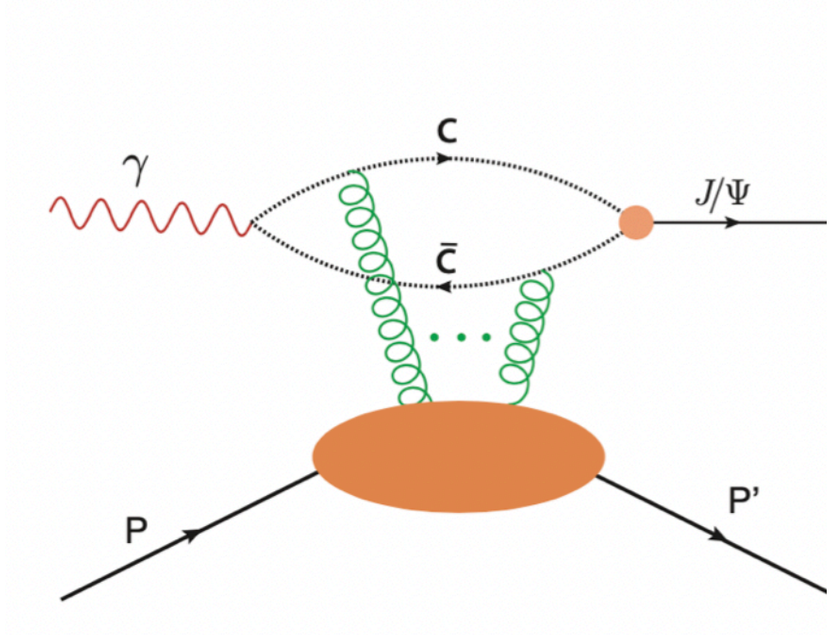


PRL 122, 222001 (2019)



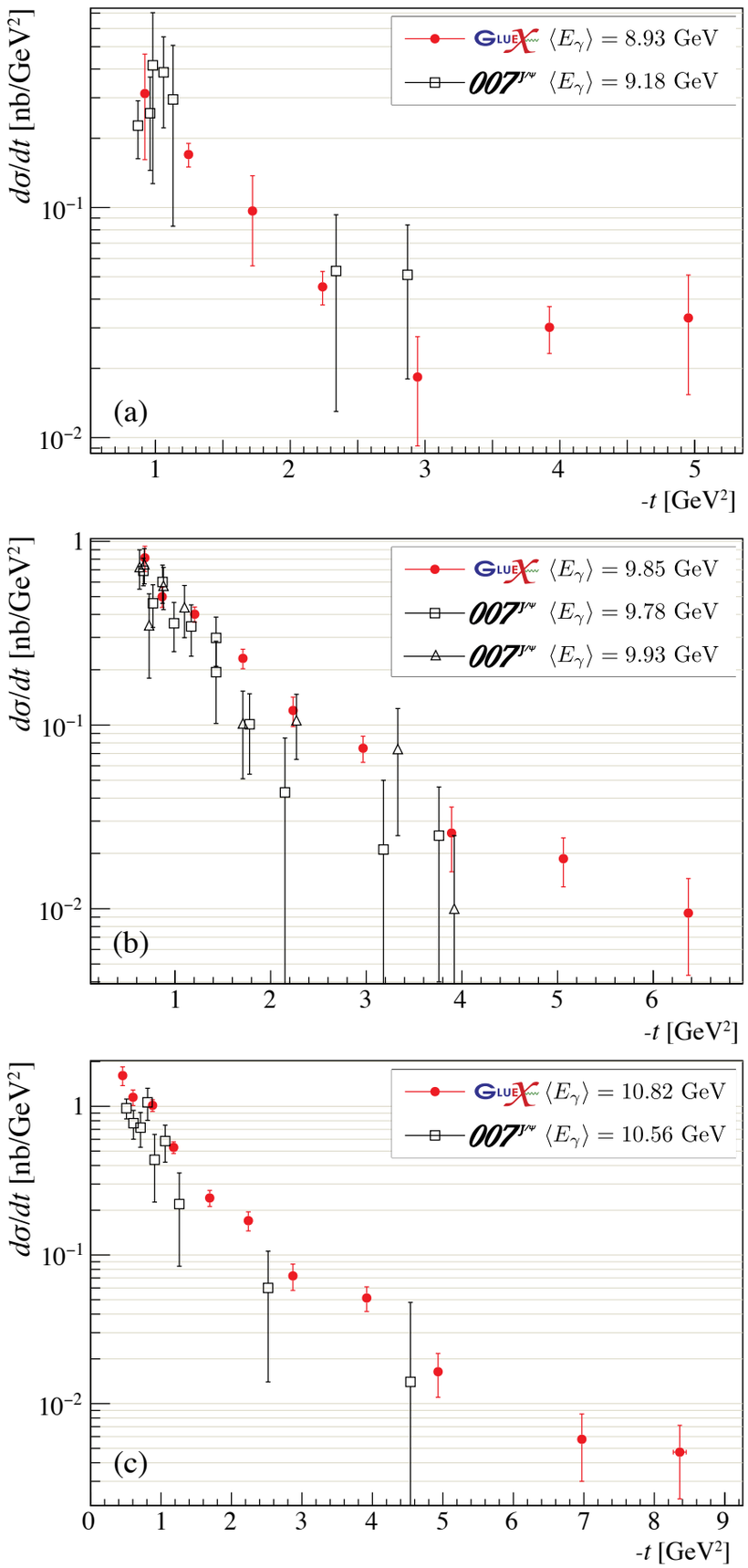


Differential cross section



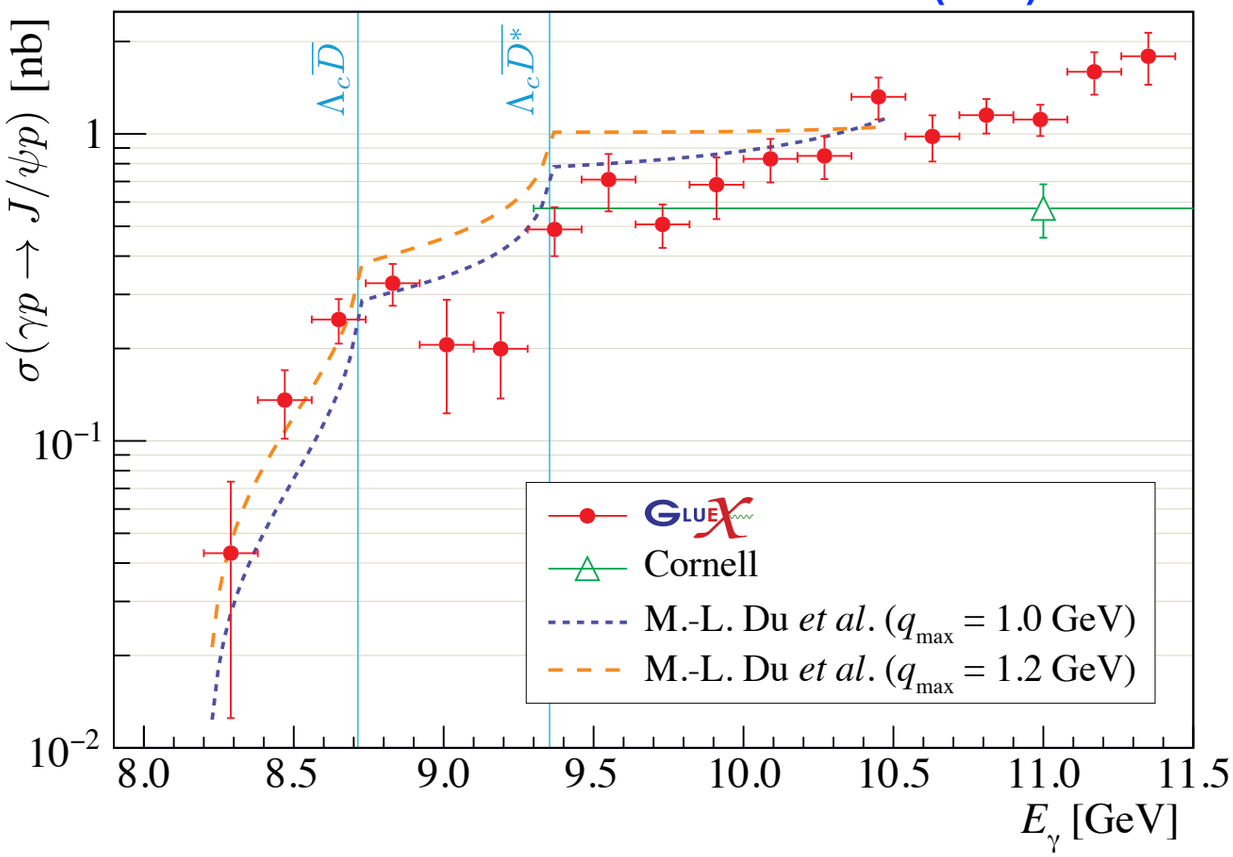
- Potentially sensitive to $J/\psi - p$ scattering: proton “mass radius”, GPDs, etc.
- Consistent results between GlueX and $J/\psi - 007$ (Hall C)
- Interesting enhancement at large -t for low energy

PRC 108 (2023) 025201

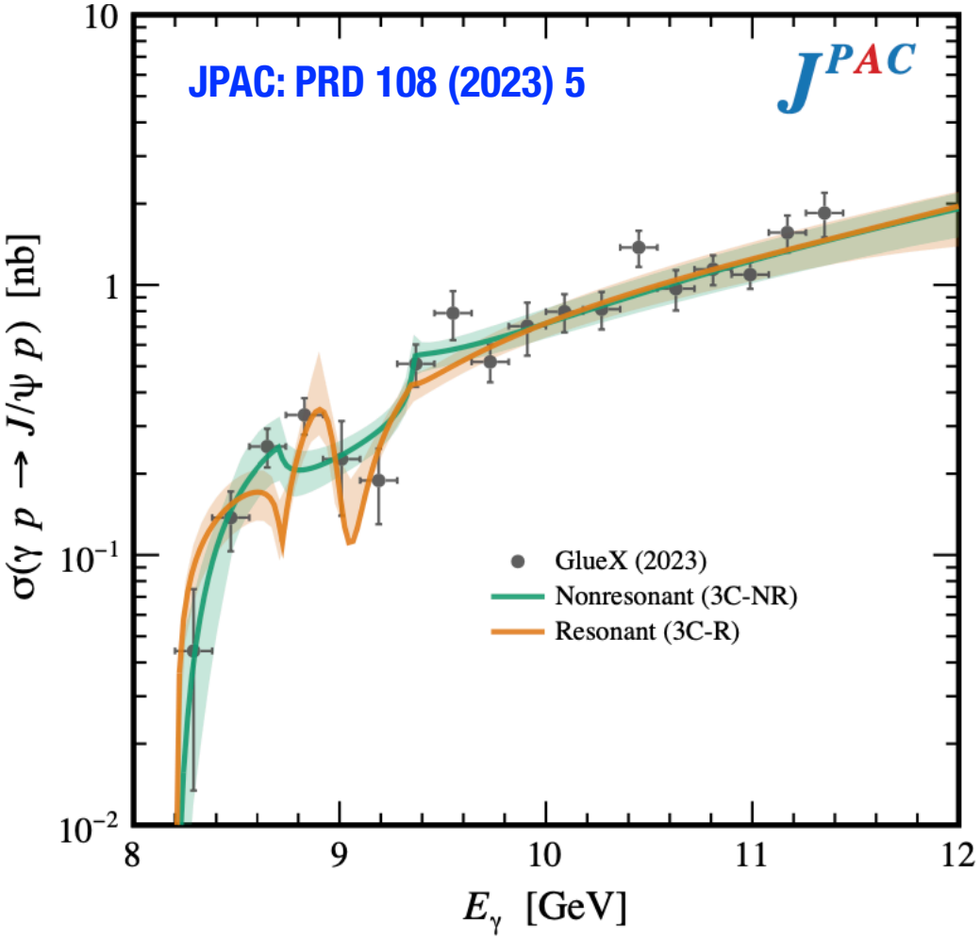


Total cross section

PRC 108 (2023) 025201



JPAC: PRD 108 (2023) 5



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