Peter Hurck for the GlueX collaboration

Hadron spectroscopy at GlueX

NSTAR 2024
Hilton Hotel York

Introduction

- QCD gives rise to spectrum of hadrons
  - Many $q\bar{q}$ and qqq states have been observed
  - $q\bar{q}q\bar{q}$, $qqqq\bar{q}$, … are not forbidden!

A SCHEMATIC MODEL OF BARYONS AND MESONS *

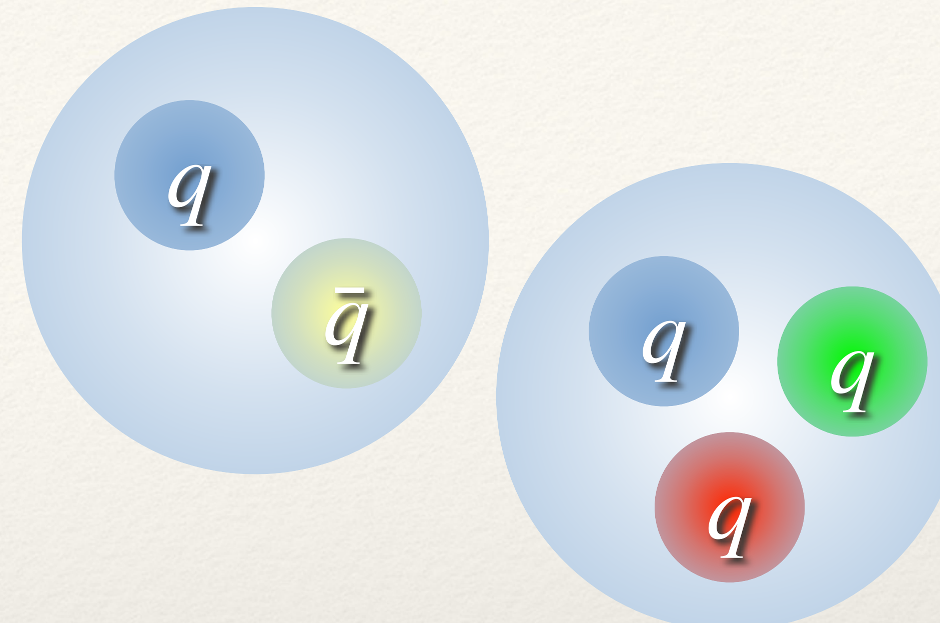
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

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

Phys. Lett. 8 (1964) 214

  - $q\bar{q}g$ are also allowed!
  - so are g-only states



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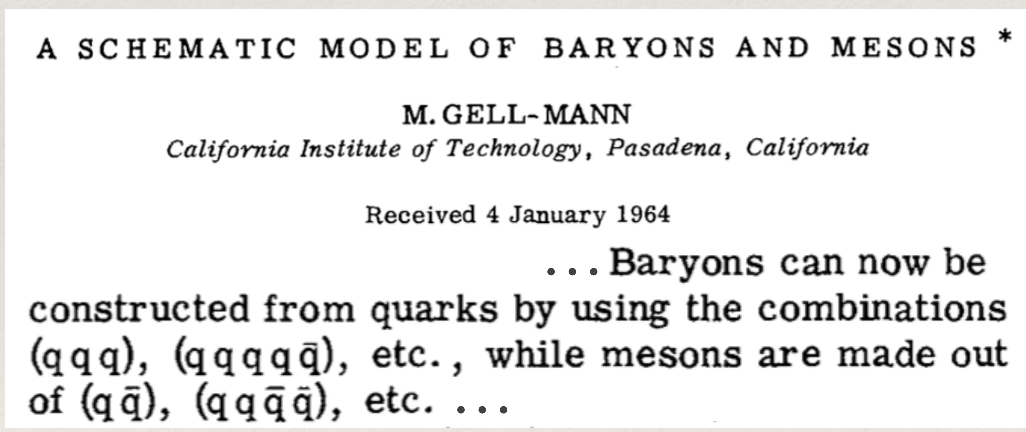

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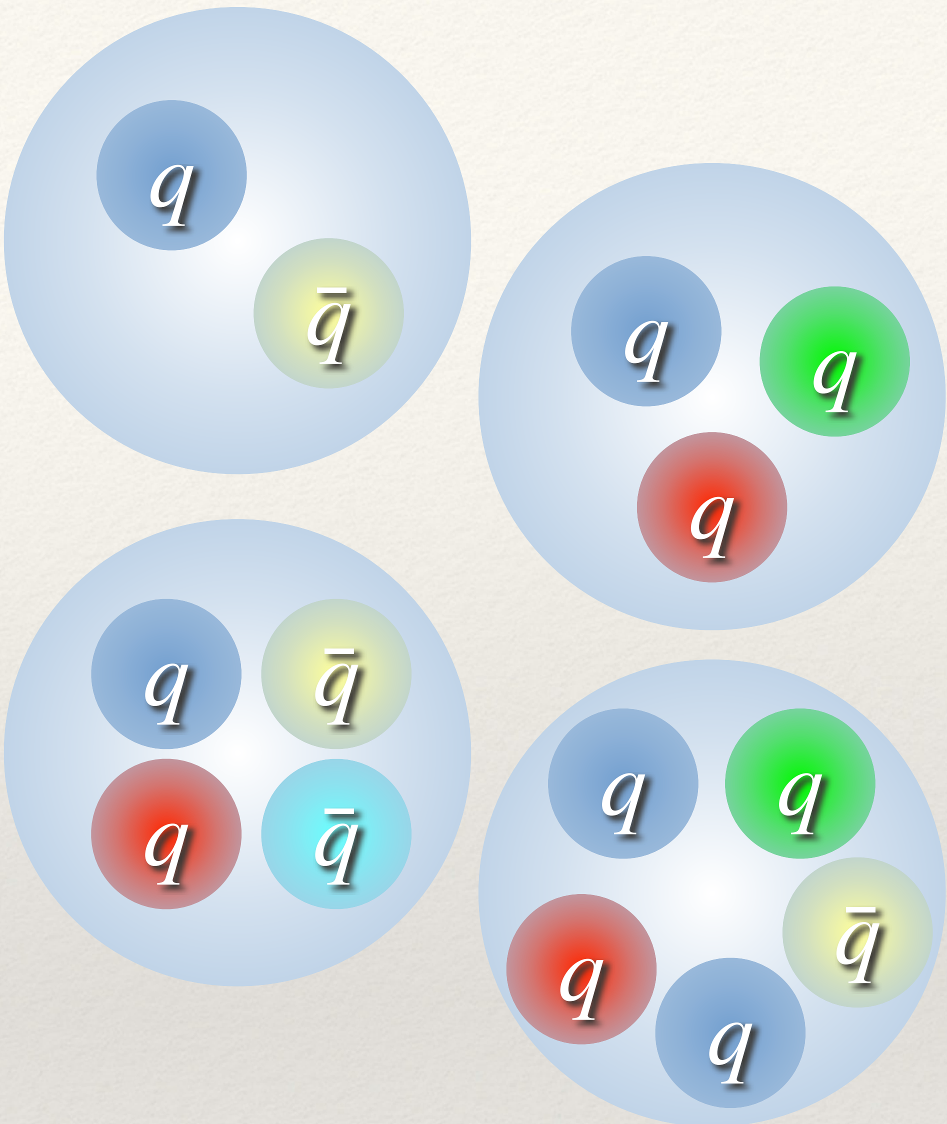

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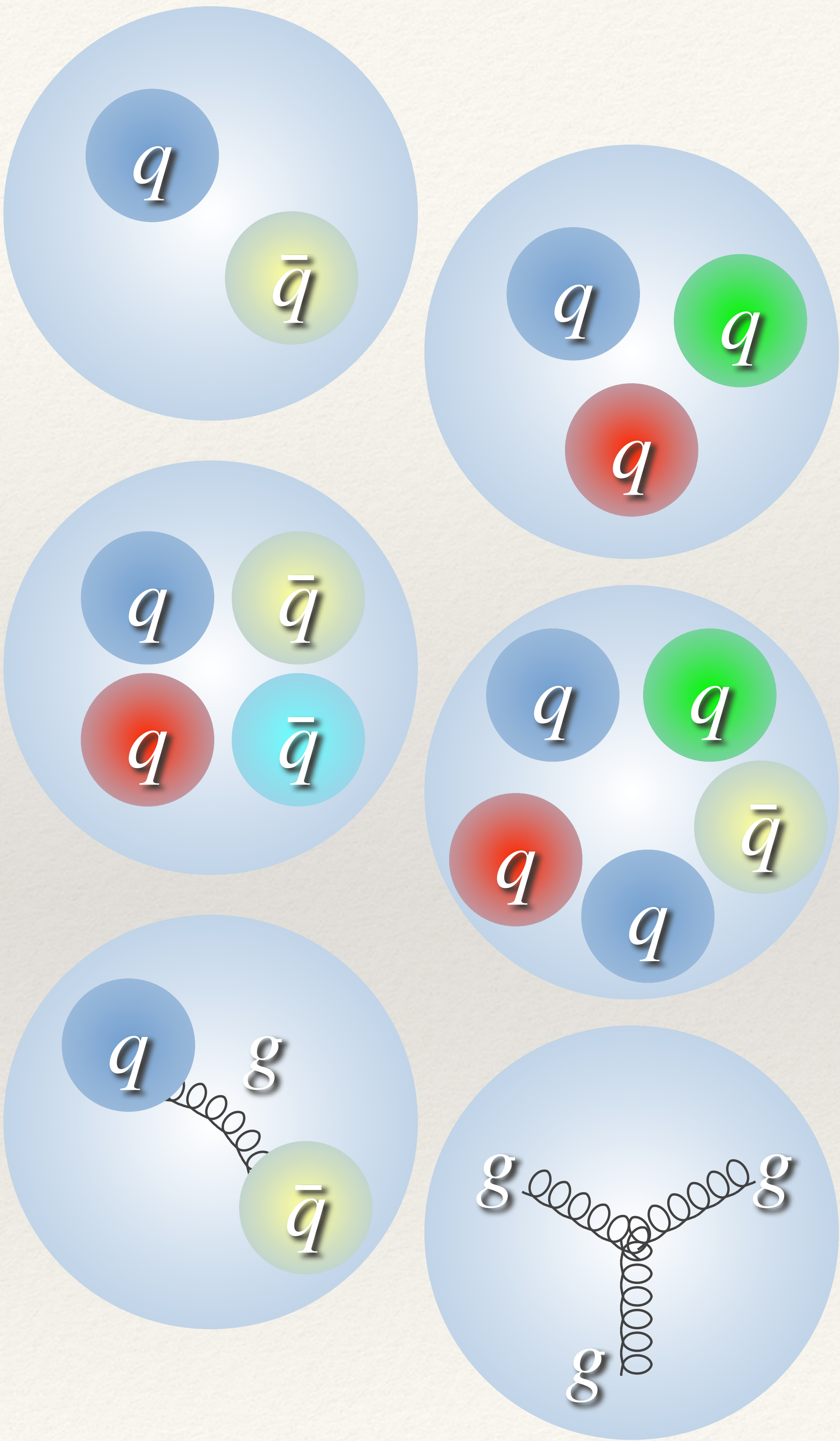
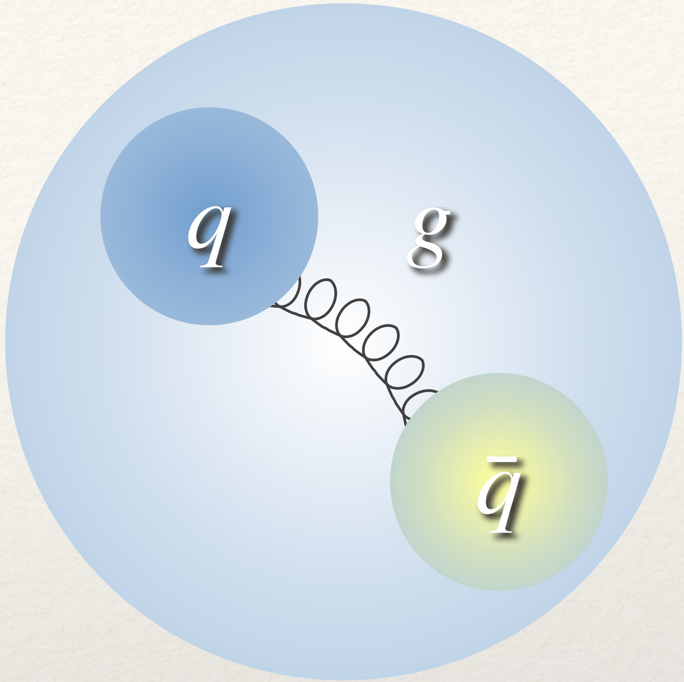


Hybrid mesons



- main objective for GlueX:
  Search and study of hybrid mesons

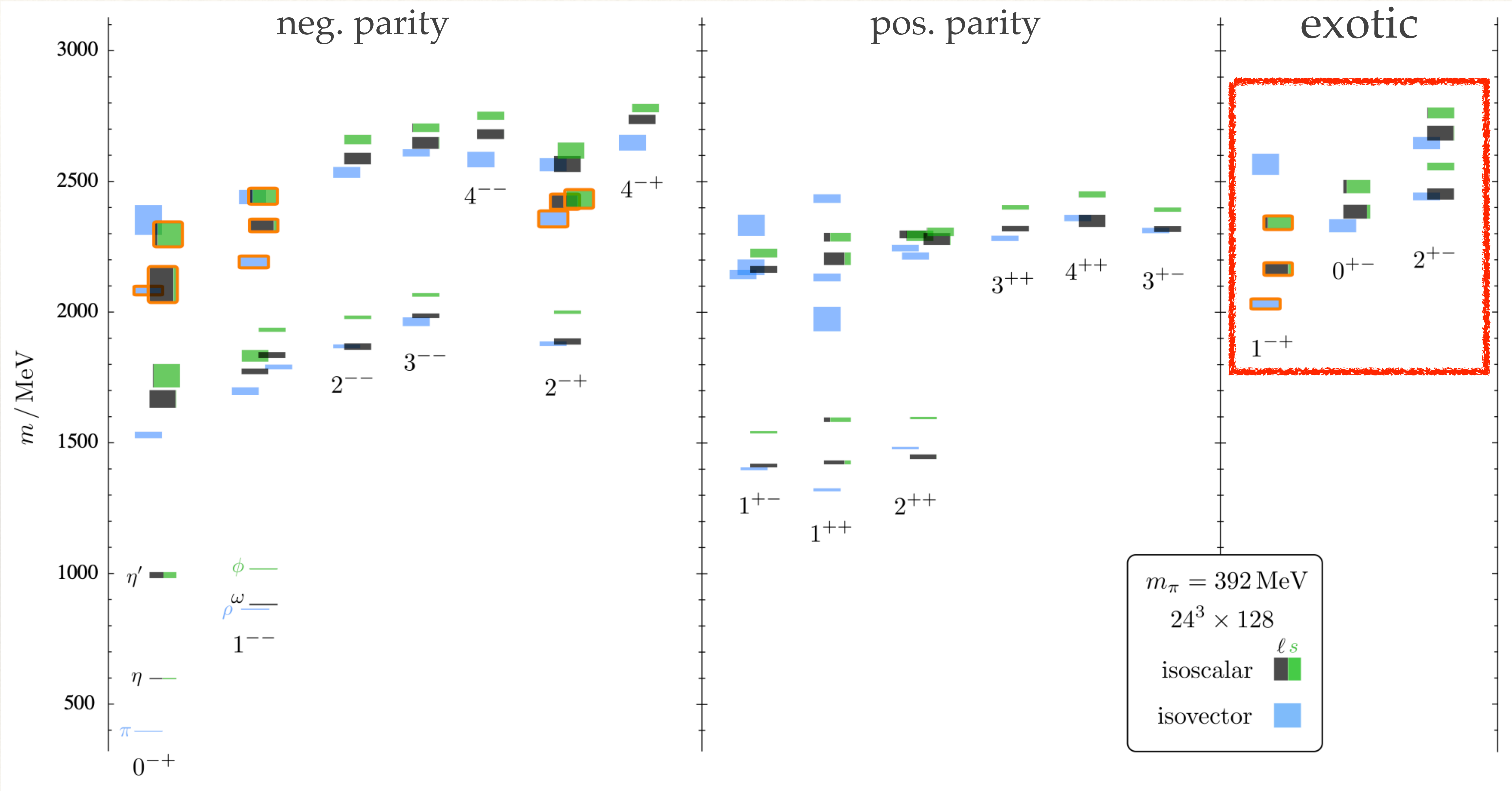
- In quark model:
  $\vec{J} = \overrightarrow{L} + \vec{S}$, $P = (-1)^{L+1}$, $C = (-1)^{L+S}$

  $\rightarrow$ not allowed:
  $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

- "Exotic" quantum numbers are "smoking gun" for something not being pure $q\bar{q}$

Light quark mesons from lattice QCD

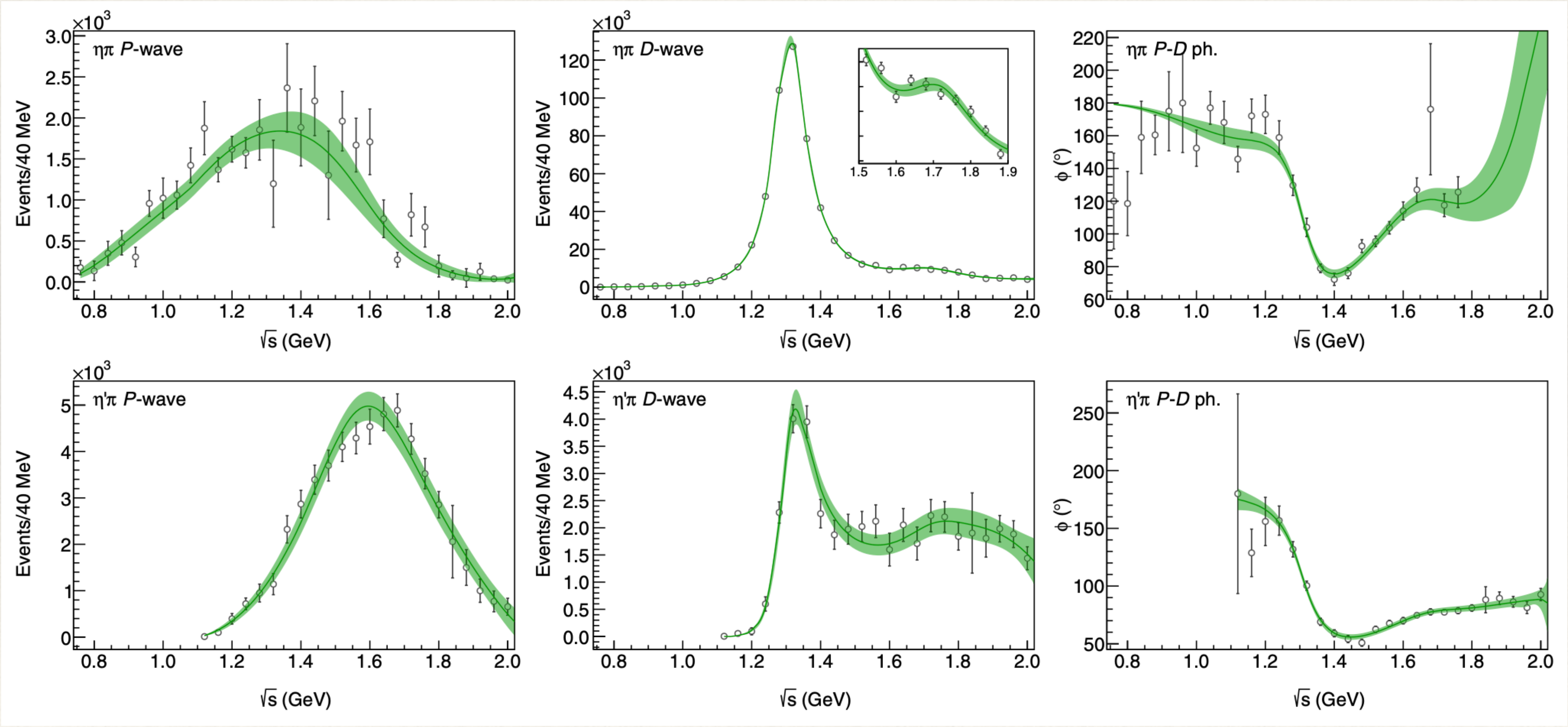
hadspec collaboration



hadspec, Phys. Rev. D ***88****, 094505*

Hybrid mesons - evidence

- Experimental evidence for a 1^{-+}:
  - $\pi_1(1400)$: GAMS, VES, E852, CBAR, COMPASS
  - $\pi_1(1600)$: VES, E852, COMPASS
- JPAC coupled channel fit to $\eta\pi$ and $\eta'\pi$ data from COMPASS



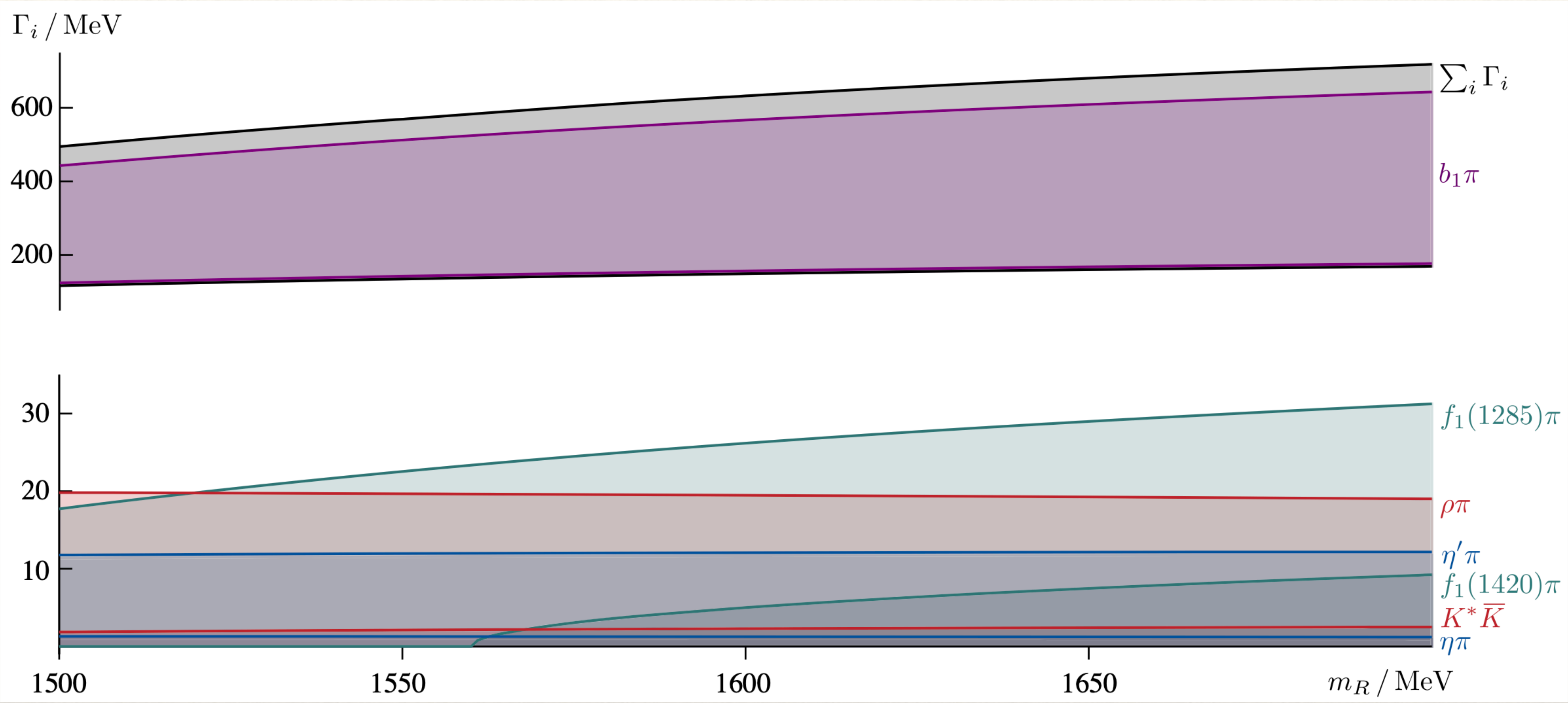
mass = 1564 ± 24 ± 86 MeV   width = 492 ± 54 ± 102 MeV

JPAC, Phys. Rev. Lett. ***122***, *042002*

1^{-+} hybrid from lattice QCD

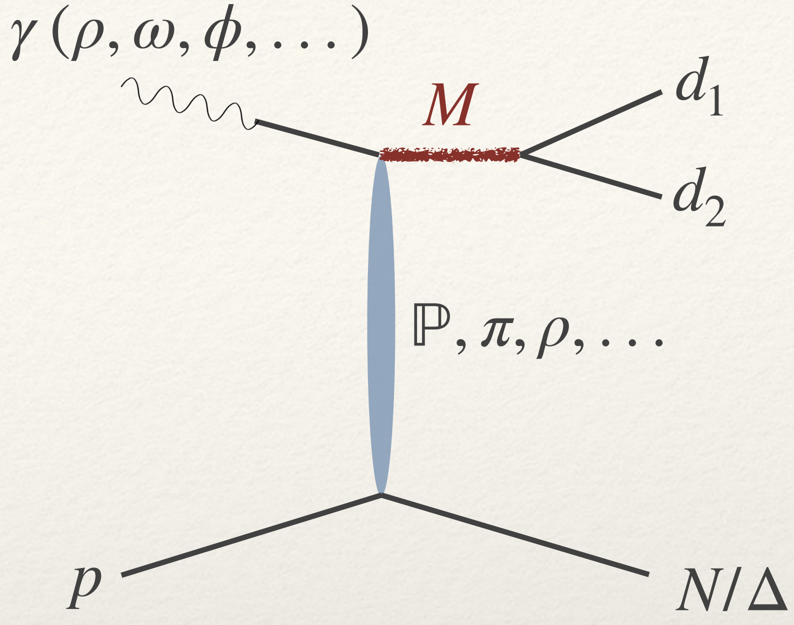
hadspec collaboration

hadspec, Phys. Rev. D ***103****, 054502*



- LQCD indicates that $b_1\pi$ is the dominant decay mode
  - Experimentally challenging
- Start with $\eta\pi$, $\eta'\pi$
  - Smaller expected branching ratio but large statistics
  - Narrow peaks and pseudo scalars

Towards hybrids at GlueX

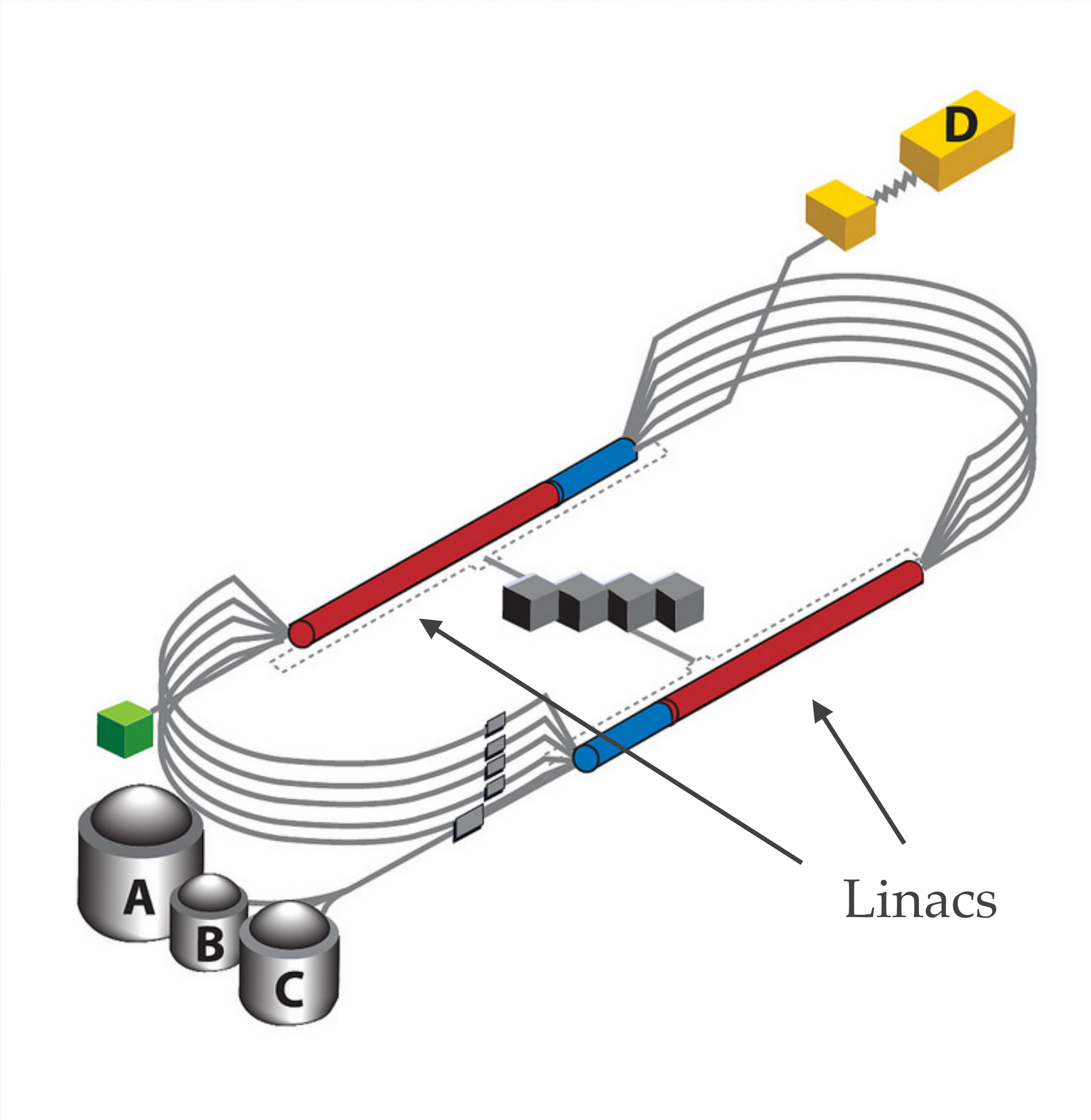


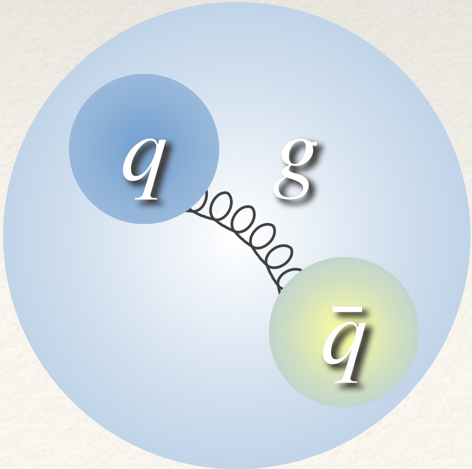
- Photoproduction complementary to pion production
  - Utilize polarization to understand production mechanisms
- Study production mechanisms to inform choice of wave sets for PWA (beam asymmetries, spin density matrix elements)
- Focus on $\eta\pi$ and $\eta'\pi$
  - Look at different production and decay mechanisms
- Work closely with theory colleagues to tackle model complexity

CEBAF at Jefferson Lab

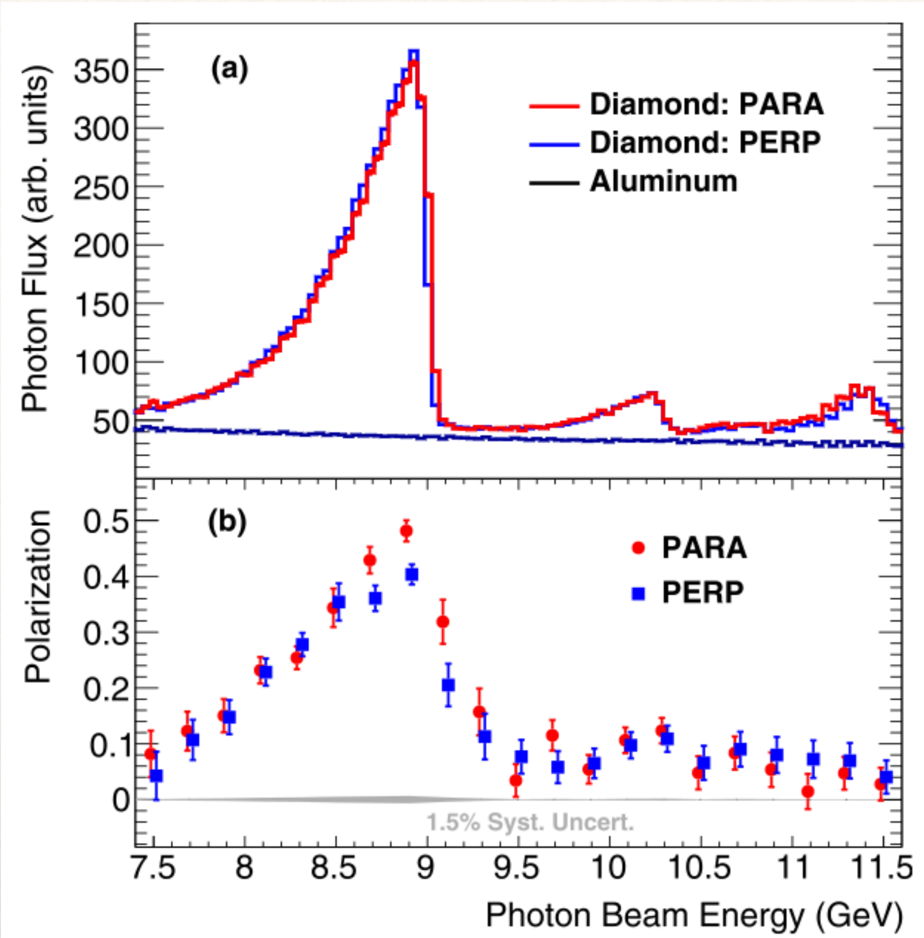
CEBAF at Jefferson Lab

- up to 12 GeV electron beam
- high luminosities for Hall A/C (high resolution spectrometer)
- CLAS12 in Hall B
- GlueX in Hall D
  - Focus on exotic hybrid mesons
    BUT:
    Large data set available to study wide range of reactions



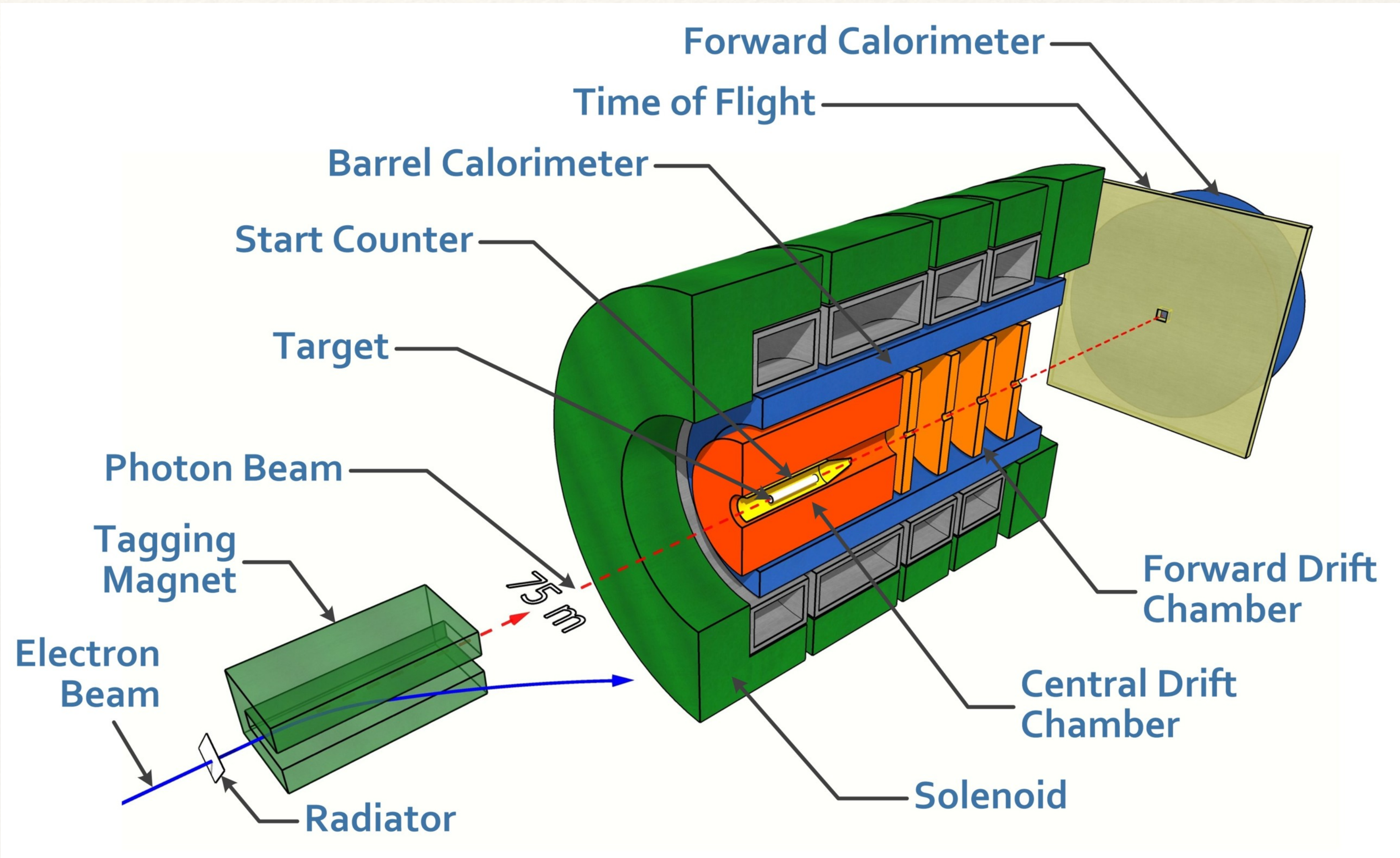


GlueX experiment in Hall D



GlueX, *Nucl. Instrum. Meth. A* 987 (2021) 164807

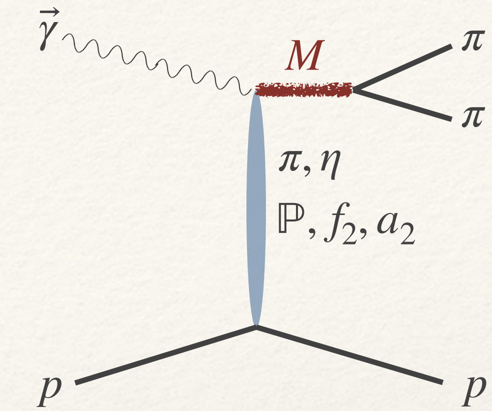
- produce linearly polarized photon beam via coherent bremsstrahlung on thin diamond



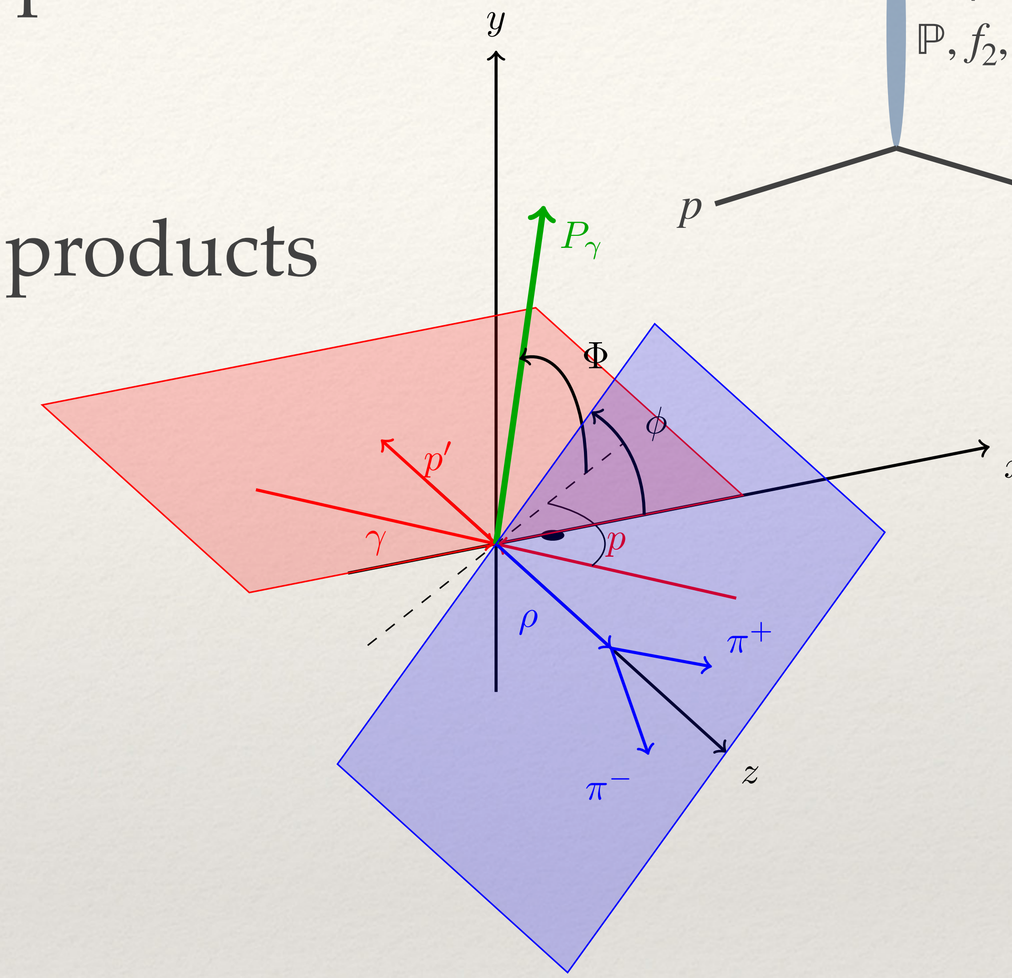
- tag electrons to determine photon energy

- Acceptance: $\theta_{lab} \approx 1^\circ - 120^\circ$
- Charged particles: $\sigma_p/p \approx 1\% - 3\,\%$ ($8\% - 9\,\%$ very-forward high-momentum tracks)
- Photons: $\sigma_E/E = 6\,\%/\sqrt{E} \oplus 2\,\%$

Spin density matrix elements



- SDMEs ρ^{i}_{jk} contain information on the spin-polarization of the produced state
- Measure angular distribution of decay products
- Learn about production mechanism
    - Study the naturality $\eta = P(-1)^J$ of the exchanged particle X



For vector meson to pseudo-scalar decays:

$$W(\cos\theta, \phi, \Phi) = W^0(\cos\theta, \phi, \Phi) + P_\gamma \cos(2\Phi) W^1(\cos\theta, \phi, \Phi) + P_\gamma \sin(2\Phi) W^2(\cos\theta, \phi, \Phi)$$

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

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

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

*Schilling et. al., Nucl. Phys. B **15** (1970) 397-412*

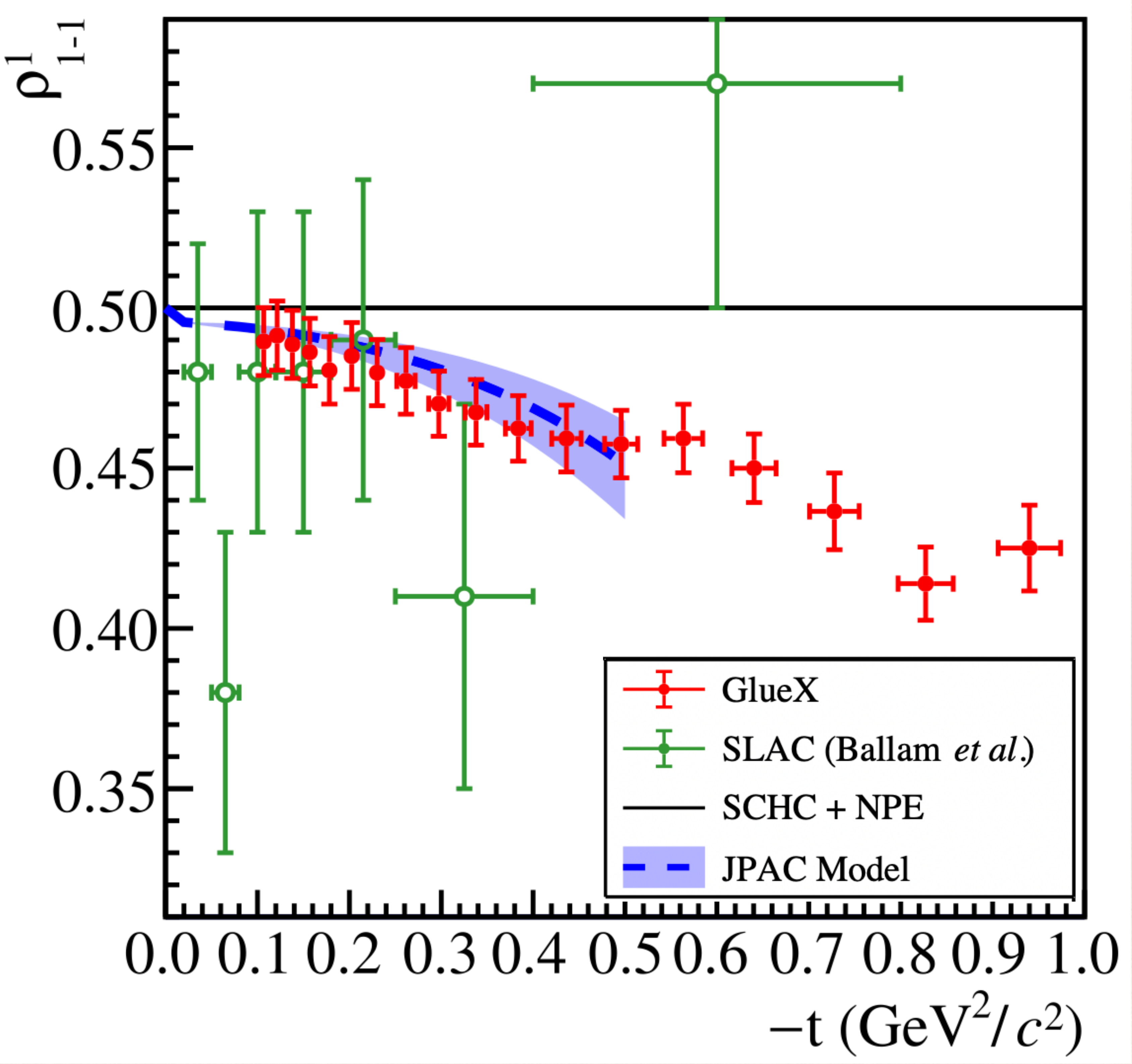
$\rho(770)$ SDMEs

Phys. Rev. C 108, 055204 (2023)

$\gamma p \rightarrow \rho(770)\, p \rightarrow \pi^+\pi^-\ p$

- Uncertainties dominated by systematics
- s-channel helicity conservation: $\rho^1_{1-1} = 0.5$ valid for very small $-t$
- JPAC: Regge model (fit to SLAC data) →good agreement at low $-t$

JPAC, Phys. Rev. D ***97****, 094003 (2018)*



$\rho(770)$ SDMEs

Phys. Rev. C 108, 055204 (2023)

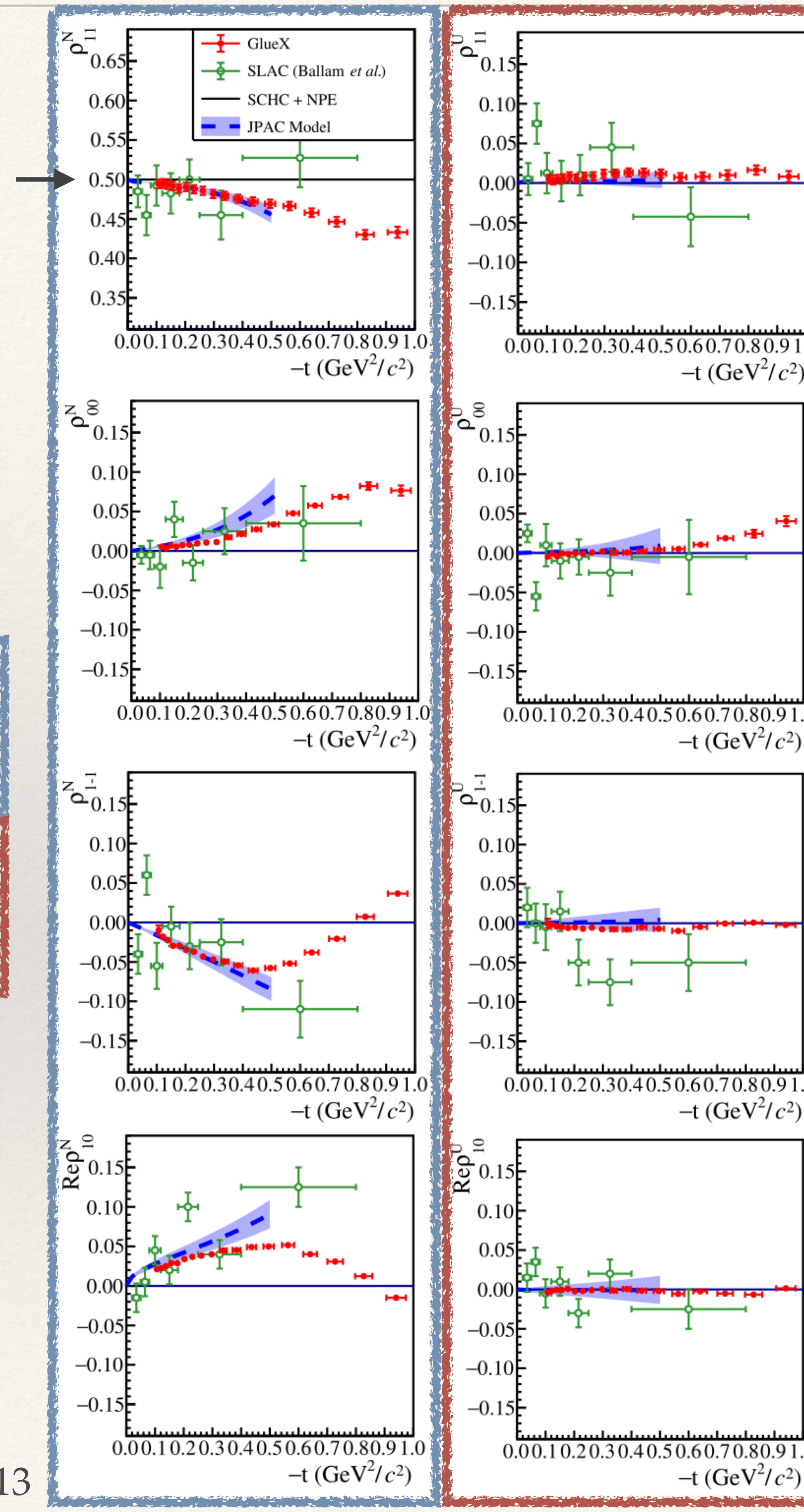
- Study combinations of SDMEs which are purely natural or unnatural
  - $$\rho^{N,U}_{jk} = \frac{1}{2}\left(\rho^{0}_{jk} \mp (-1)^{i}\rho^{1}_{-jk}\right)$$

*Schilling et. al., Nucl. Phys. B **15** (1970) 397-412*

pos. parity exchange / natural:
e.g. f_2, a_2

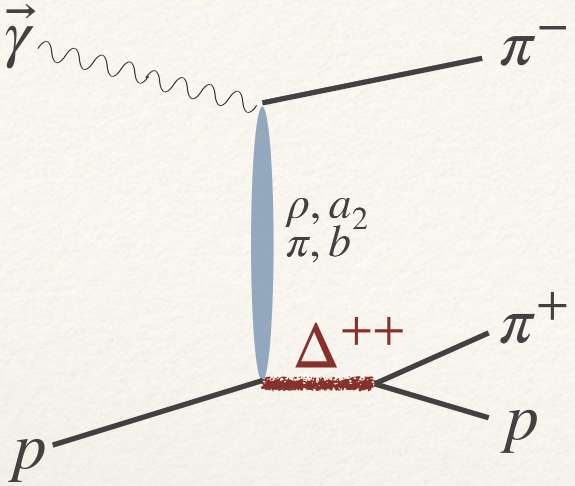
neg. parity exchange / unnatural:
e.g. π, η

- Dominance of natural amplitudes
- In the pipeline: ϕ, ω



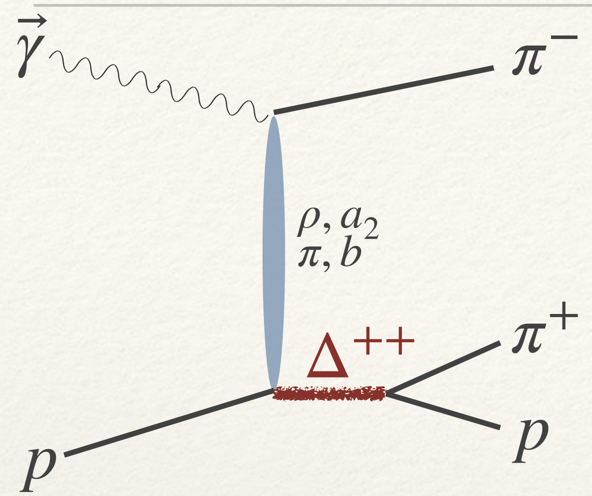
*JPAC, Phys. Rev. D **97**, 094003 (2018)*

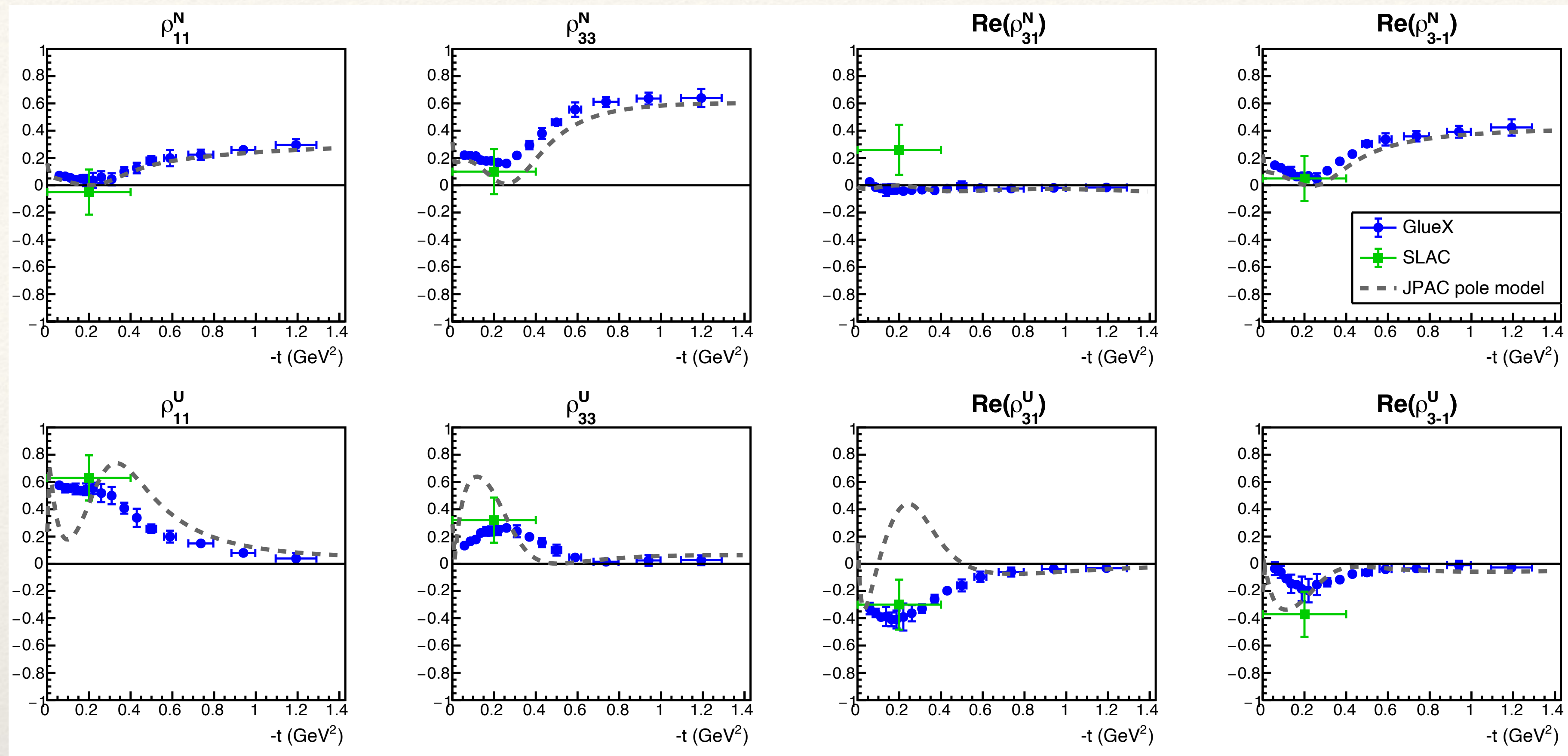
$\Delta^{++}(1232)$ SDMEs



$\Delta^{++}(1232)$ SDMEs

F. Afzal





- Orders of magnitude improvement over previous data

JPAC, Physics Letters B 779 (2018) 77–81

- Data will be used to describe bottom vertex of reaction (couplings)
  - Important for hybrid search
- Good description of natural exchange by JPAC model

Publication in preparation

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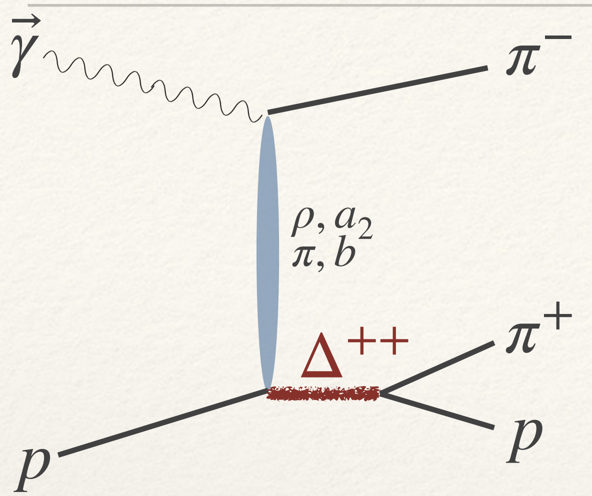

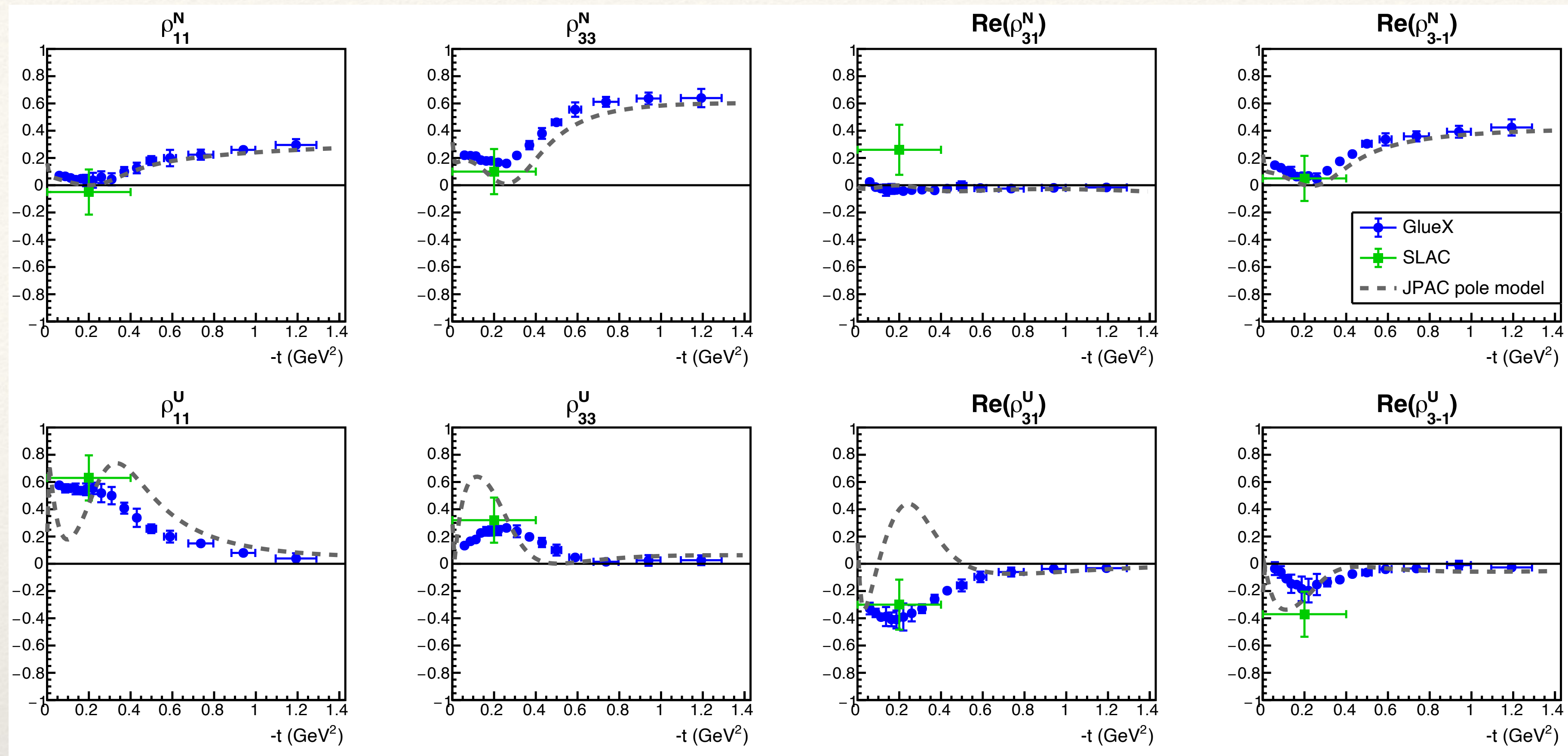

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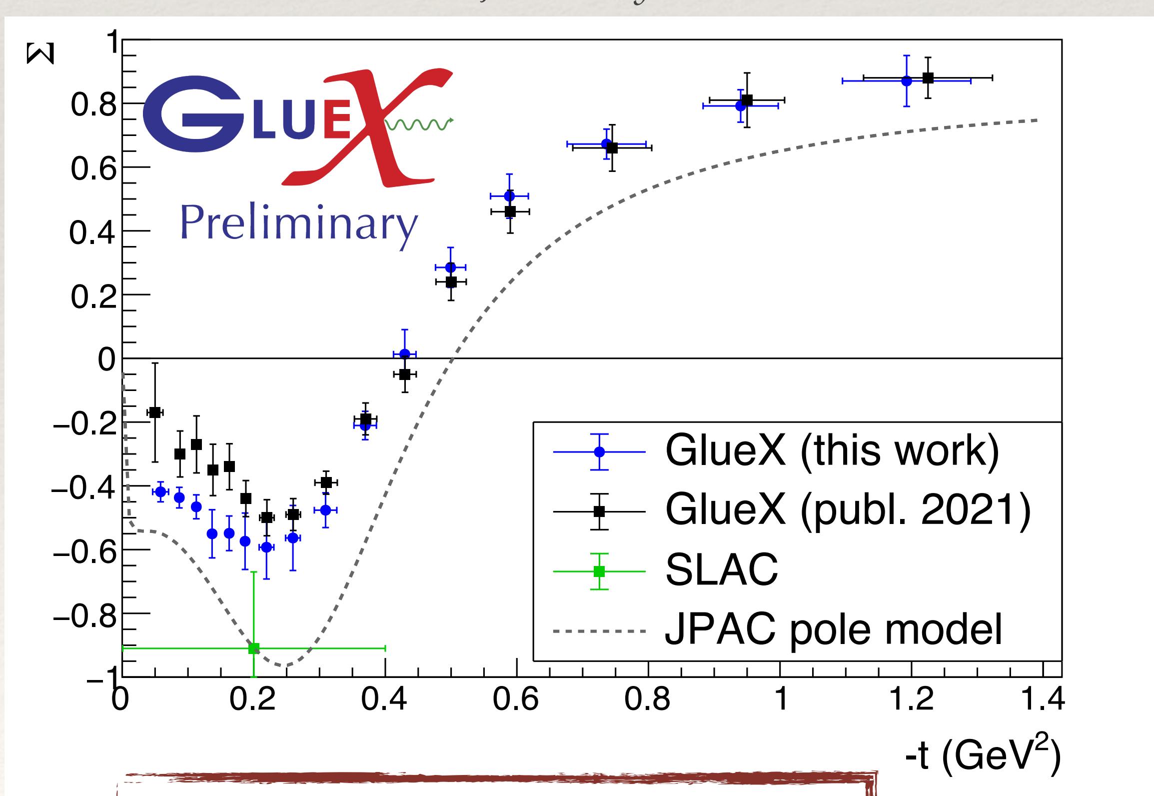
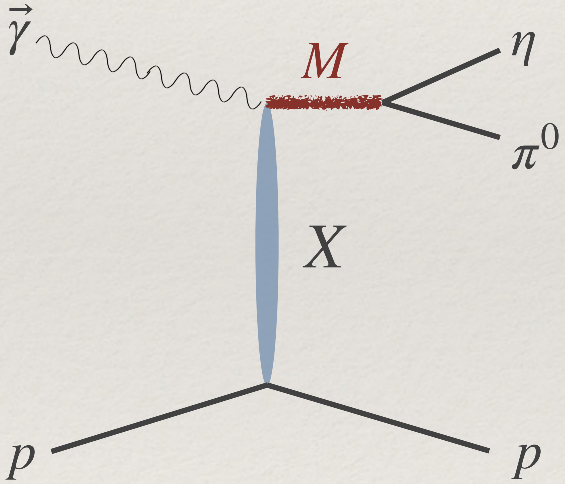
- Orders of magnitude improvement over previous data
- Data will be used to describe bottom vertex of reaction (couplings)
  - Important for hybrid search
- Good description of natural exchange by JPAC model
- More reliable than "simple" beam asymmetry

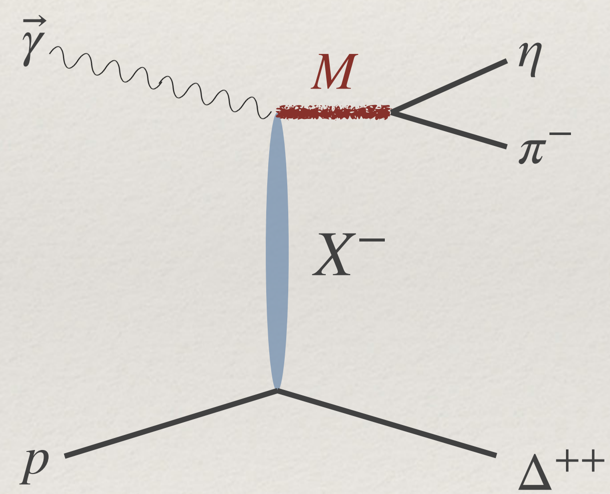


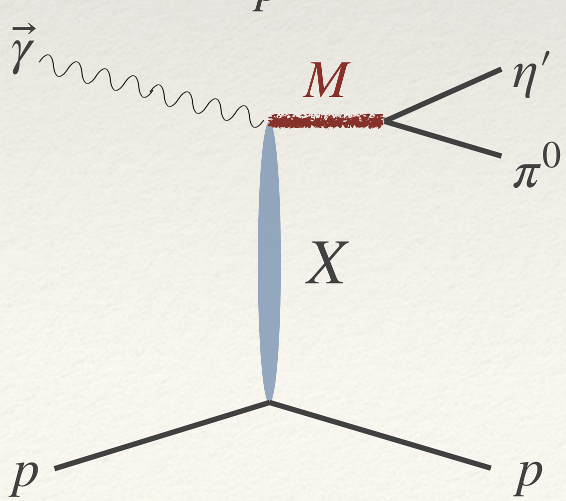
Publication in preparation

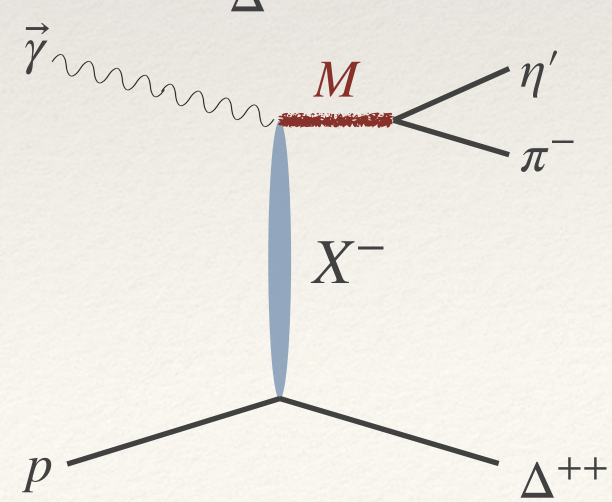
Hybrid search in $\eta\pi$

- JPAC coupled channel fit to $\eta\pi$ and $\eta'\pi$ data from COMPASS
- GlueX has access to different decay modes in multiple final states
- $\gamma p \to \eta\pi^0 p,\ \eta \to \gamma\gamma$
- $\gamma p \to \eta\pi^0 p,\ \eta \to \pi^+\pi^-\pi^0$
- $\gamma p \to \eta'\pi^0 p,\ \eta' \to \pi^+\pi^-\eta,\ \eta \to \gamma\gamma$
- $\gamma p \to \eta\pi^-\Delta^{++},\ \eta \to \pi^+\pi^-\pi^0$
- $\gamma p \to \eta\pi^-\Delta^{++},\ \eta \to \gamma\gamma$
- $\gamma p \to \eta'\pi^-\Delta^{++},\ \eta' \to \pi^+\pi^-\eta,\ \eta \to \gamma\gamma$







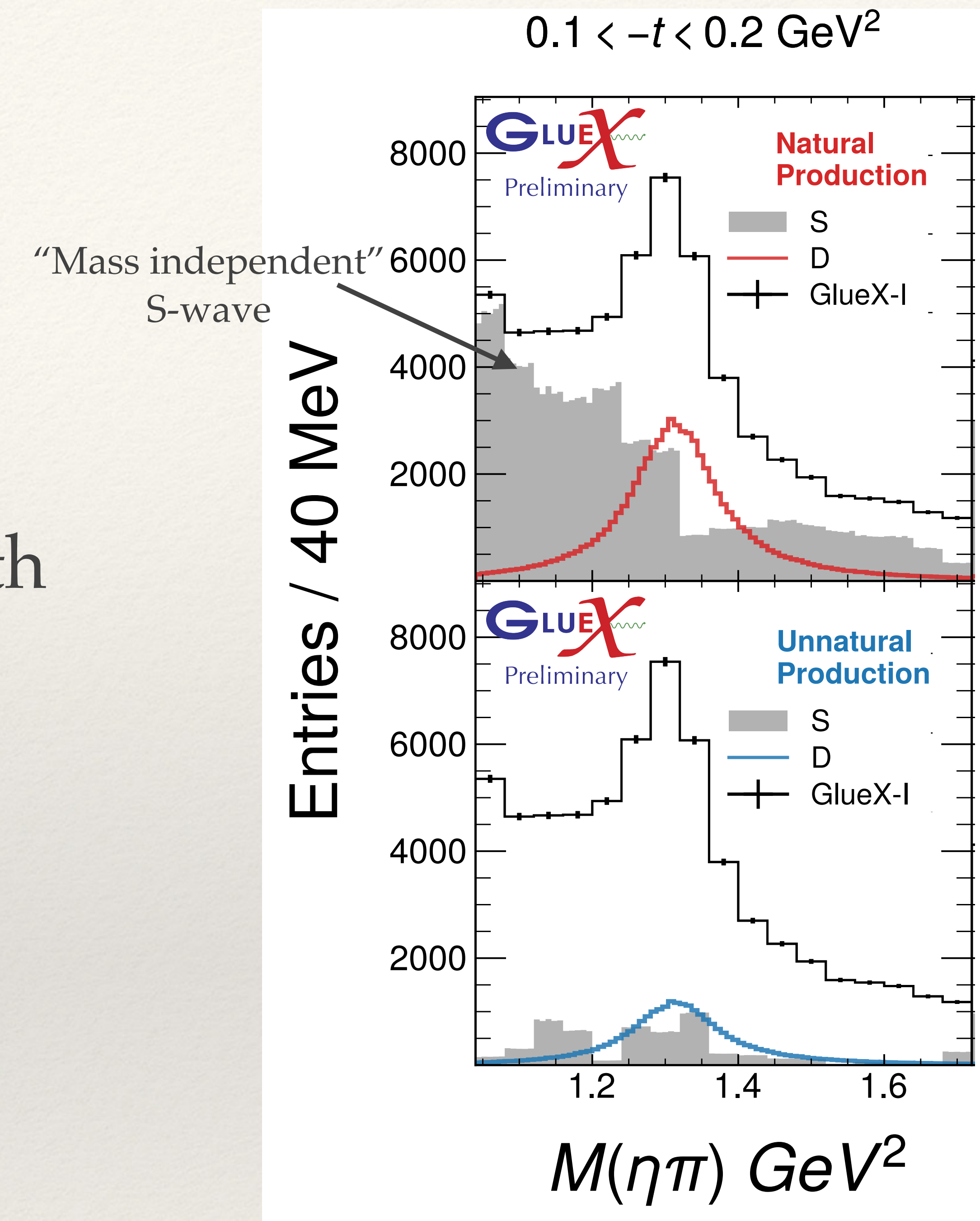


Towards a PWA in $\eta\pi^0$ - $a_2(1320)$ cross-section

- First look at PWA in $\gamma p \rightarrow \eta\pi^0\, p$
- Study $a_2(1320)$ cross-section
- Positive helicity (natural exchange, e.g. ρ) dominates
- a_2 predominantly D_2 wave, consistent with helicity=2 dominance at Belle ($\gamma\gamma \rightarrow \eta\pi^0$)

Belle, Phys. Rev. D ***80****, 032001*

L. Ng, M. Albrecht



Mixed method: imposing BW shape on a_2 improves fit

Publication in preparation

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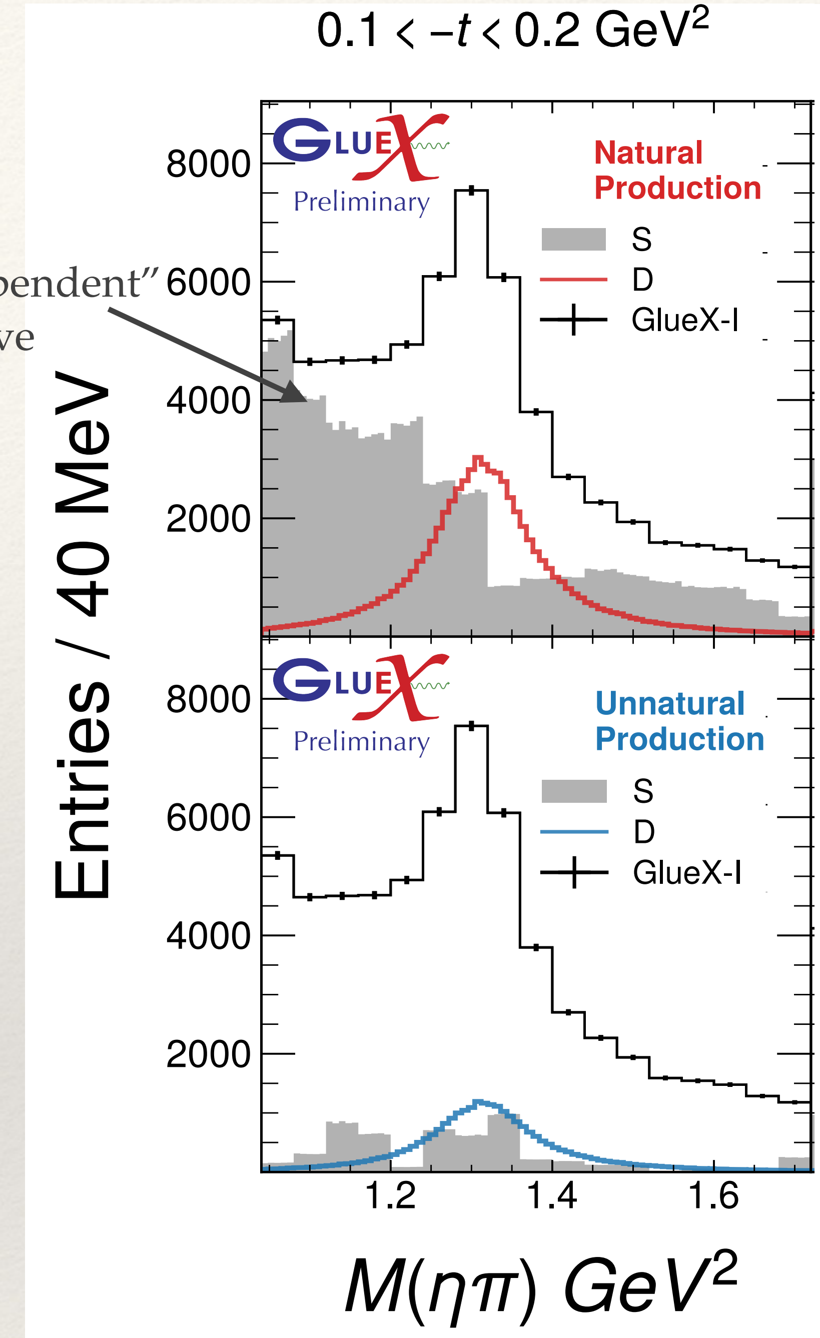
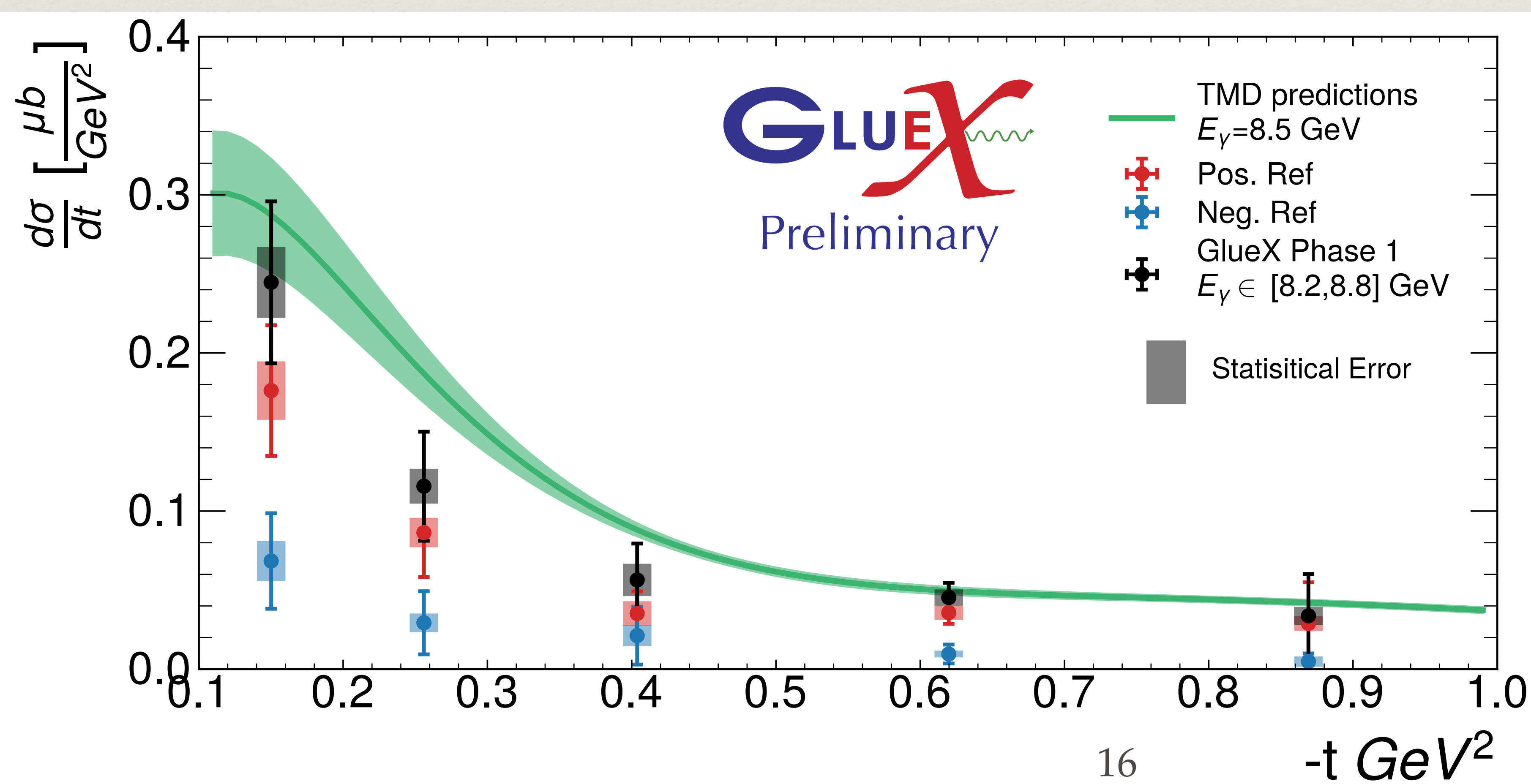
"Mass independent" S-wave



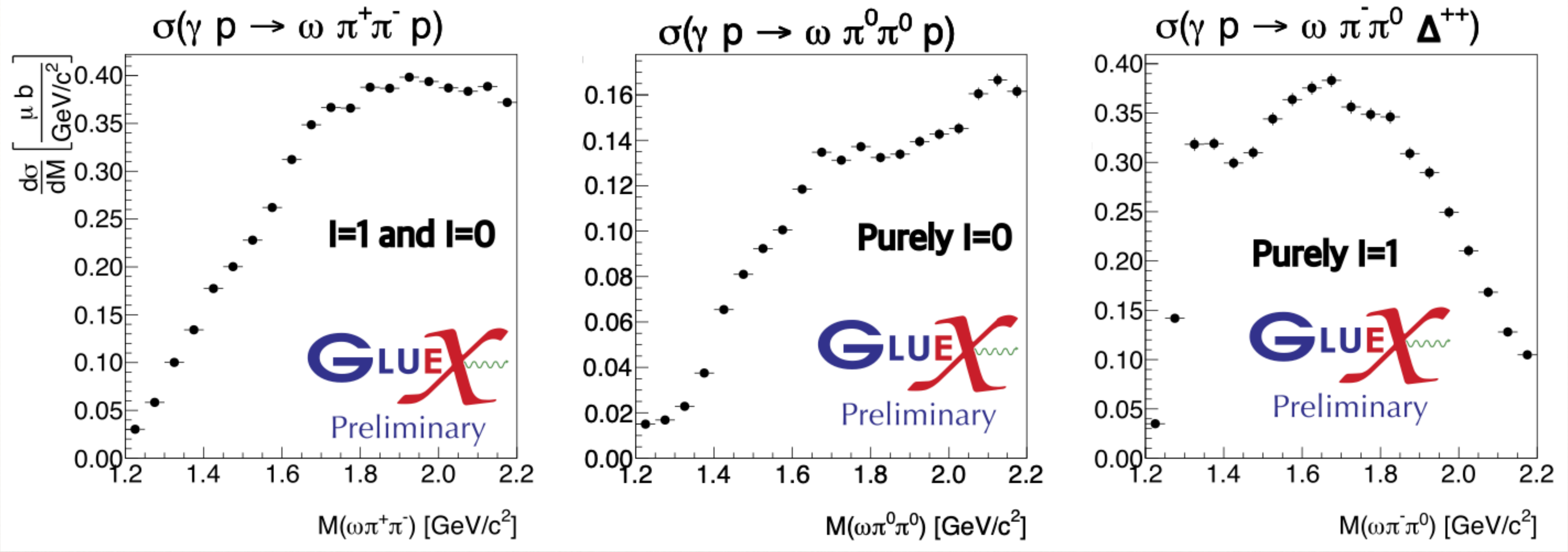


Mixed method: imposing BW shape on a_2 improves fit

Publication in preparation

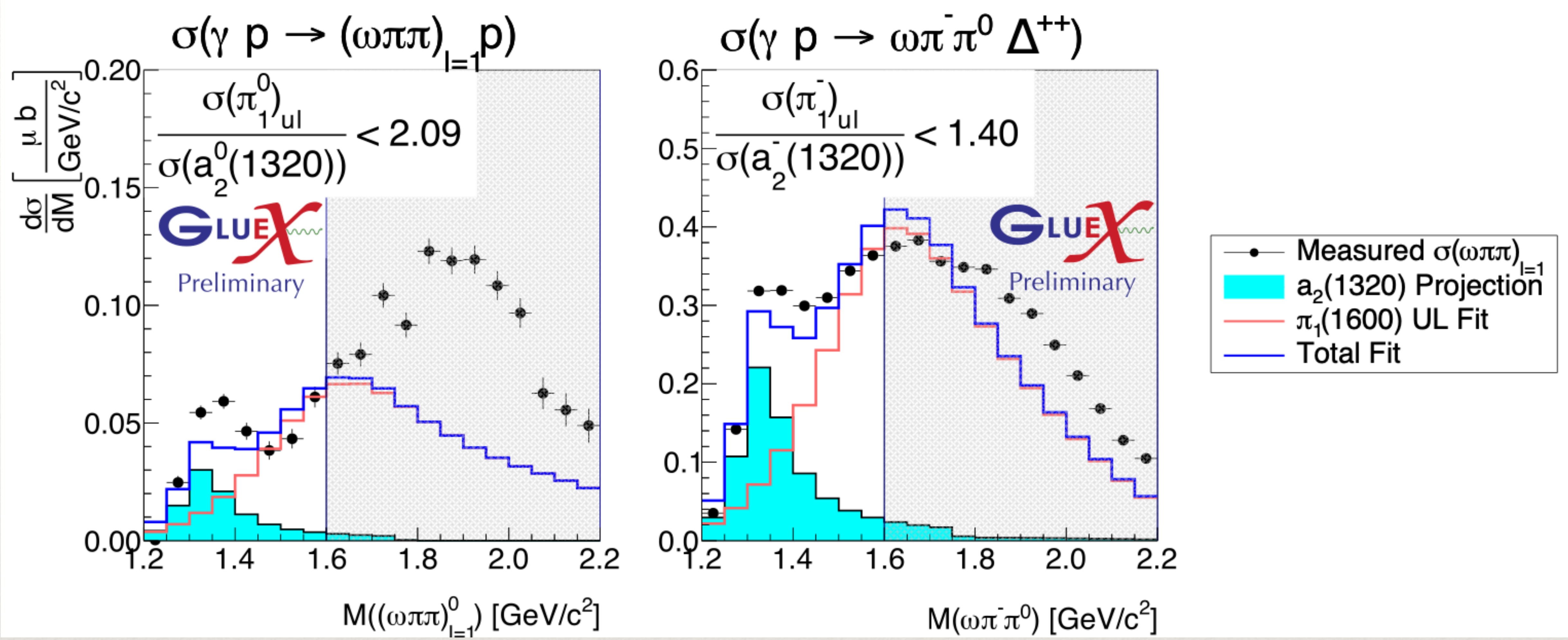
$\pi_1(1600)$ upper limits

W. Imoehl



- Set upper limit on $\pi_1(1600)$ using isospin separation, assume no $I = 2$
  - $\sigma((\omega\pi\pi)^0)_{I=1} = \sigma(\omega\pi^+\pi^-) - 2\sigma(\omega\pi^0\pi^0)$
  - $\sigma((\omega\pi\pi)^-)_{I=1} = \sigma(\omega\pi^-\pi^0)$
- Fit $\sigma(\omega\pi\pi)_{I=1}$ using known shapes for a_2 (PDG) and π_1 (JPAC)

$\pi_1(1600)$ upper limits

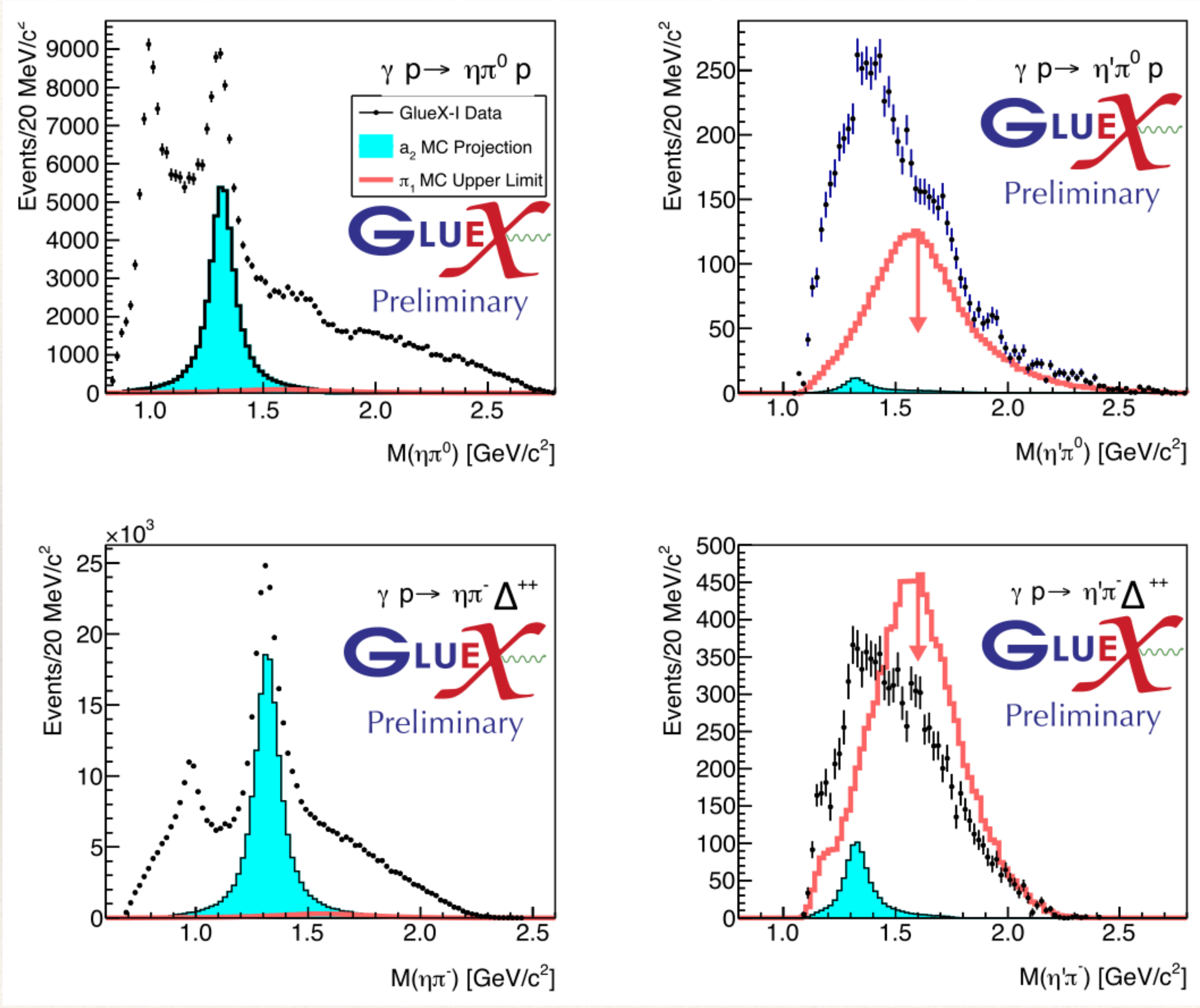


- Fit $M(\omega\pi\pi)_{I=1} < 1.6\,\mathrm{GeV}/c^2$
- Fix a_2 size to measured cross-section adjusted with known BR
- π_1 BR from lattice
- Only free parameter is π_1 normalisation!
- π_1 upper limits similar in size to a_2 cross-sections

π_1 projections to $\eta\pi$ and $\eta'\pi$

W. Imoehl

- $\pi_1 \rightarrow \eta\pi$ expected to be very small
- $\pi_1 \rightarrow \eta'\pi$ potentially dominating the spectrum
- First limit on size of photoproduction cross-sections
- Guidance for amplitude analysis



Publication in preparation

Hyperons at GlueX

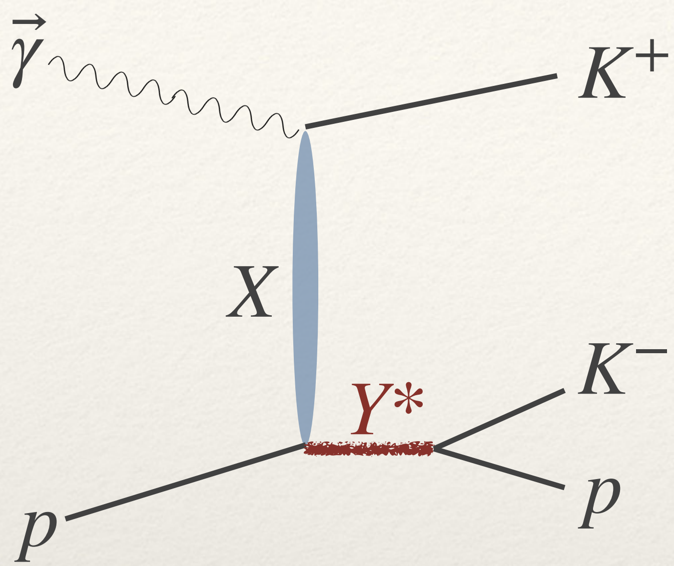
"For several decades, there has been very little new experimental data bearing on the properties of Λ and Σ resonances. [...] the ***field is starved for data****. Recent analyses (see below) have improved what we know about the properties of the known Λ and Σ resonances, but the* ***established resonances are the same ones that were listed in our 1984 edition*** *[...]"*

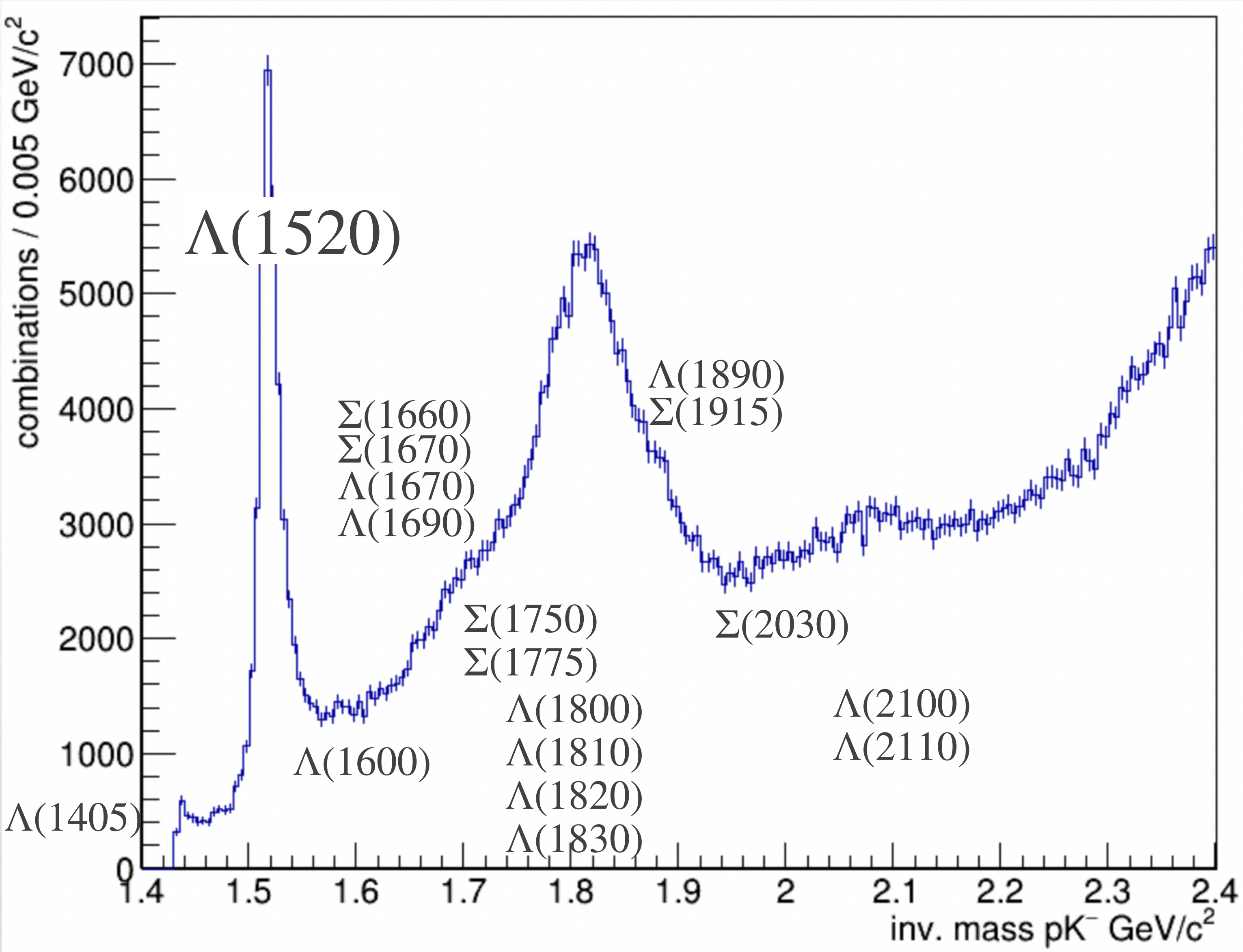
— Λ and Σ resonances, PDG (2021)

Excited hyperons

Phys. Rev. C **105**, 035201

$\gamma p \rightarrow K^+ Y^* \rightarrow K^+ K^- p$



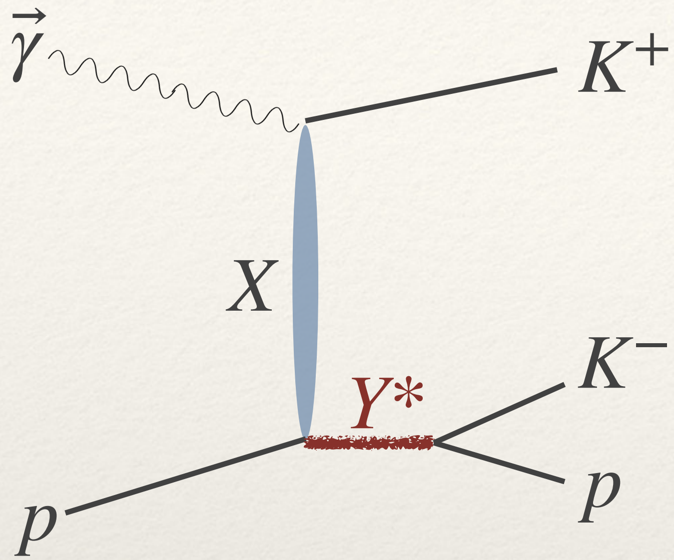


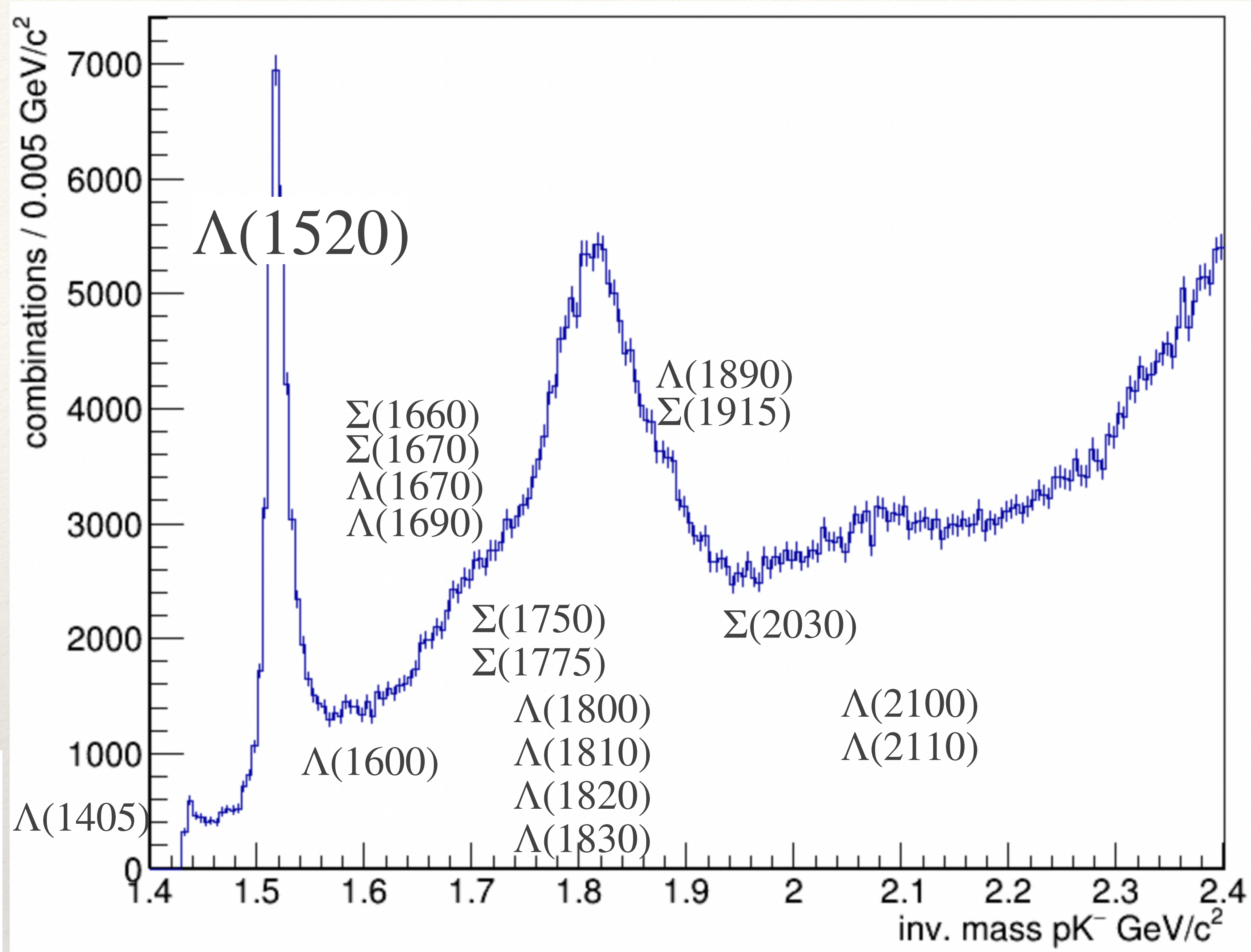
- Many excited Λ^* and Σ^* expected in spectrum
- Most prominent: $\Lambda(1520)$ hyperon with $J^P = 3/2^-$

Excited hyperons

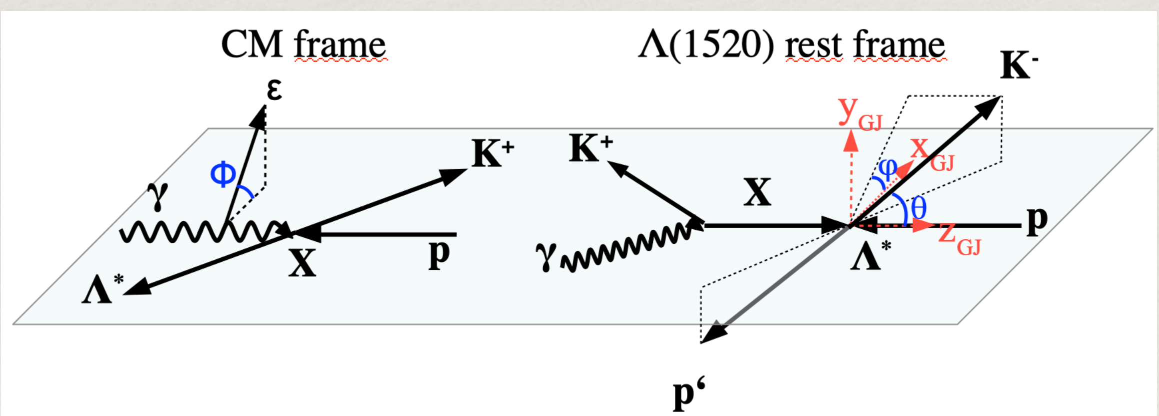
Phys. Rev. C **105**, 035201

$\gamma p \to K^+ Y^* \to K^+ \, K^- p$





Λ(1520) SDMEs



$$W_0 = \frac{1}{4\pi}\left[3\left(\frac{1}{2}-\rho^0_{11}\right)\sin^2(\theta)+\rho^0_{11}\left(1+3\cos^2(\theta)\right)-2\sqrt{3}\left(\mathrm{Re}(\rho^0_{31})\cos(\varphi)\sin(2\theta)+\mathrm{Re}(\rho^0_{3-1})\cos(2\varphi)\sin^2(\theta)\right)\right]$$

$$W_1 = \frac{1}{4\pi}\left[3\rho^1_{33}\sin^2(\theta)+\rho^1_{11}(1+3\cos^2(\theta))-2\sqrt{3}\left(\mathrm{Re}(\rho^1_{31})\cos(\varphi)\sin(2\theta)+\mathrm{Re}(\rho^1_{3-1})\cos(2\varphi)\sin^2(\theta)\right)\right]$$

$$W_2 = \frac{1}{4\pi}\left[2\sqrt{3}\left(\mathrm{Im}(\rho^2_{31})\sin(\varphi)\sin(2\theta)+\mathrm{Im}(\rho^2_{3-1})\sin(2\varphi)\sin^2(\theta)\right)\right]$$

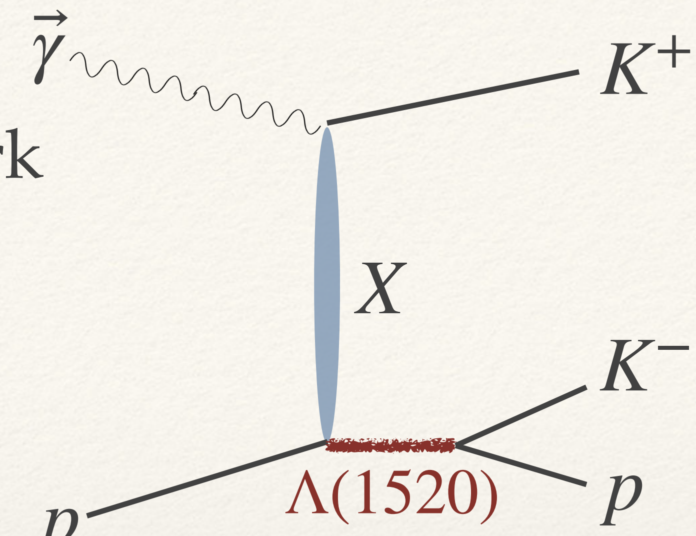
$$W = W_0 - P_\gamma \cos(2\Phi) W_1 - P_\gamma \sin(2\Phi) W_2$$

- Many excited Λ^* and Σ^* expected in spectrum
- Most prominent: Λ(1520) hyperon with $J^P = 3/2^-$

Λ(1520) SDME combinations

Phys. Rev. C **105**, 035201

- red and blue show model predictions in Reggeized framework (priv. comm. based on [1])
- natural amplitudes dominate
- More work needed to model the reaction accurately

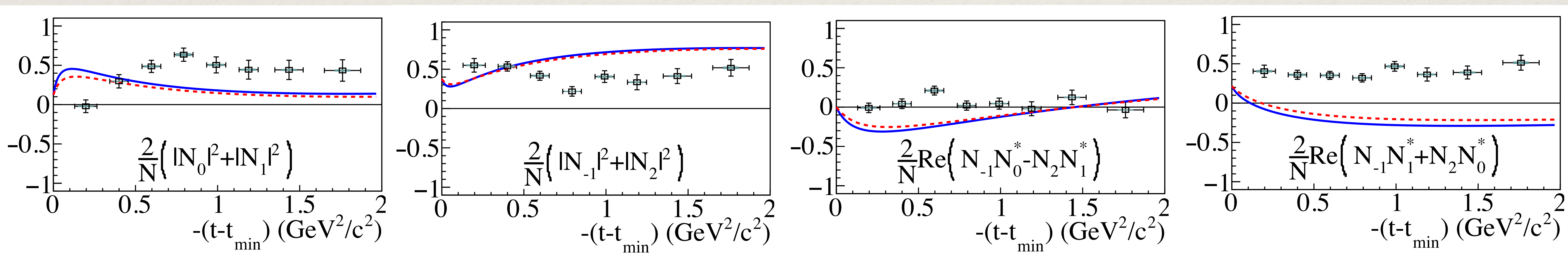


X is exchange particle with spin-parity quantum number J^P and naturality $\eta = P(-1)^J$

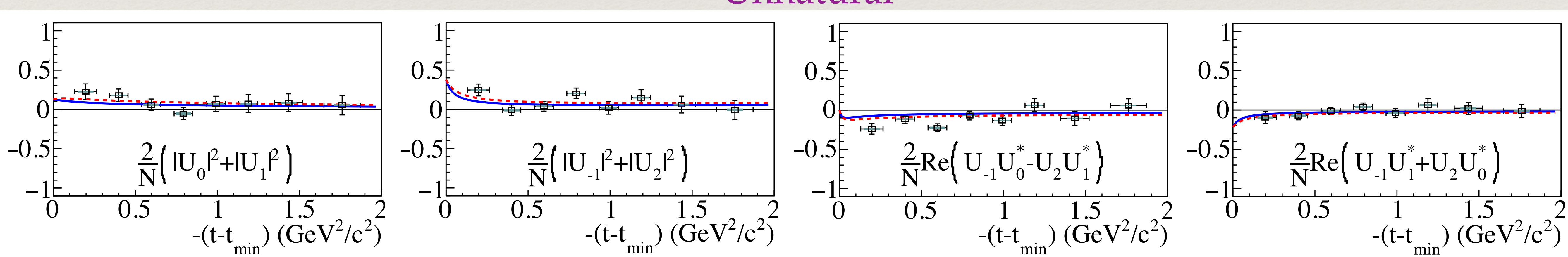
Natural: e.g. $K^*(892)$, $K_2^*(1430)$

Unnatural: e.g. $K(492)$, $K_1(1270)$

Natural



Unnatural



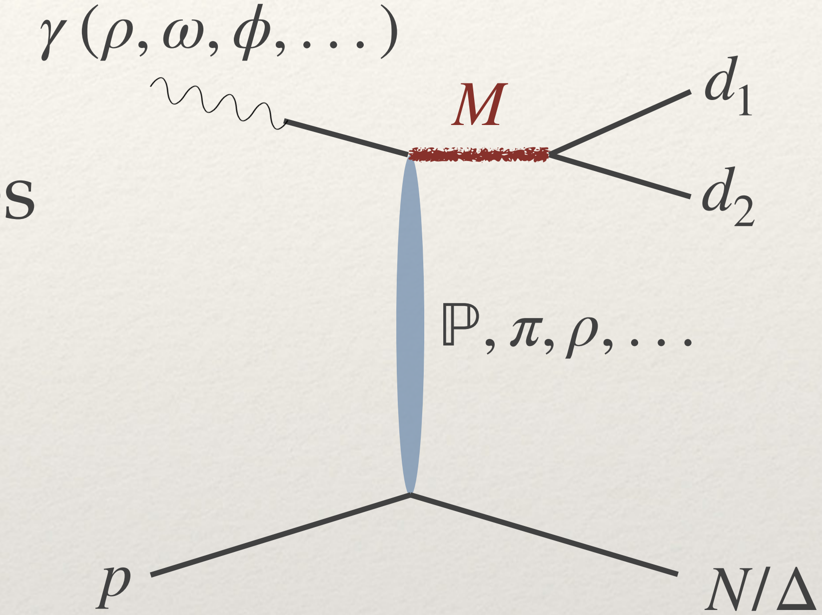
[1] *Byung-Geel Yu and Kook-Jin Kong, Phys. Rev. C* ***96****, 025208 (2017)*

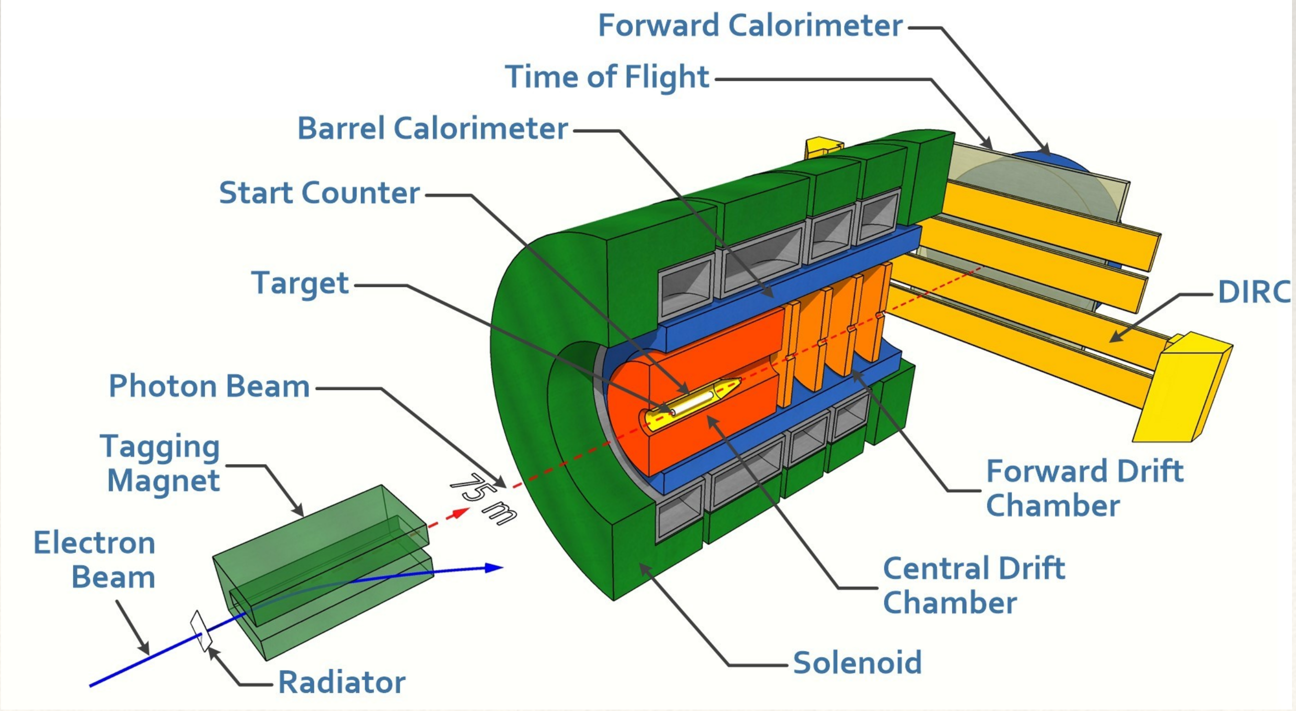
Summary

Acknowledgments:

gluex.org/thanks

- GlueX has a unique data set with unprecedented statistical precision in its energy range
- Start with studying production mechanisms (SDMEs) and develop PWA in parallel
- $\pi_1(1600)$ upper limits, guide for future searches
- Many more interesting analyses in the pipeline and room for other physics
  - Rich hyperon spectrum visible in photoproduction
  - $\Lambda(1405)$ (R. Schumacher, **Tue 14.00h, parallel III B**)
  - Cascades and charmonium (S. Dobbs, **Fri 11.15h, plenary X**)

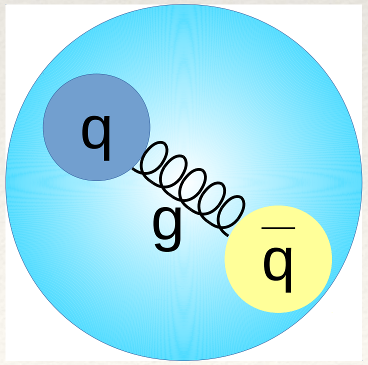


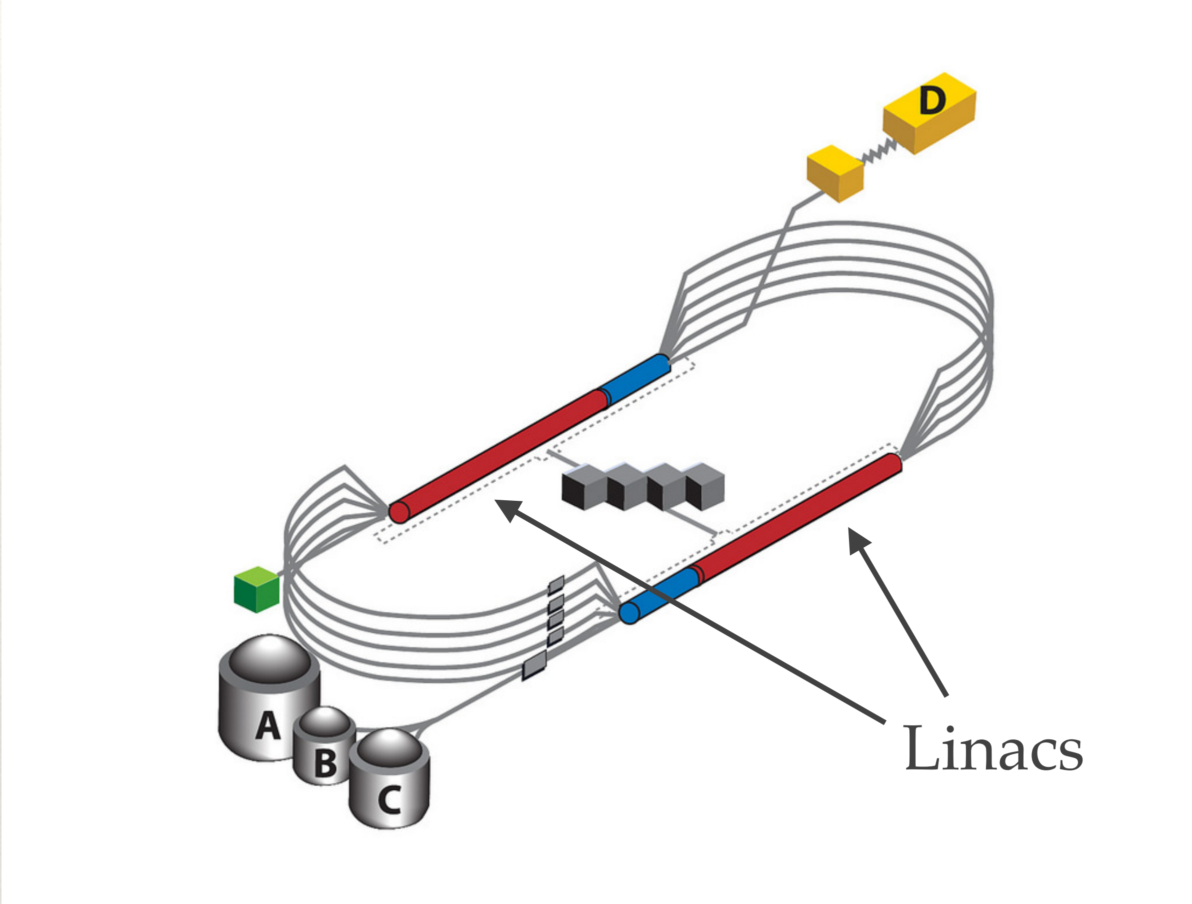


Backup

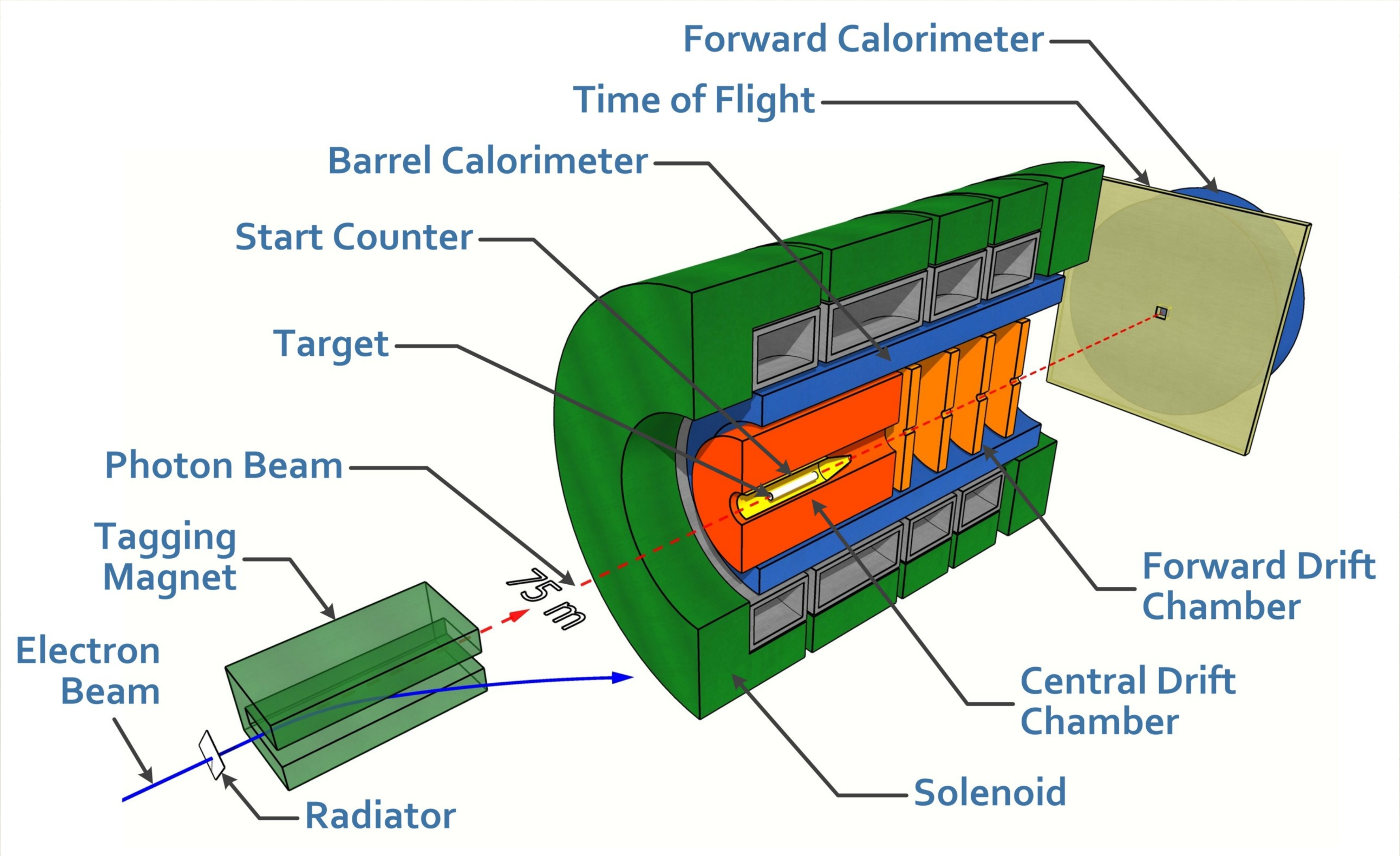
CEBAF at Jefferson Lab

- up to 12 GeV electron beam
- high luminosities for Hall A/C
- CLAS12 in Hall B
- GlueX in Hall D
  main objective:
  Search and study of hybrid mesons





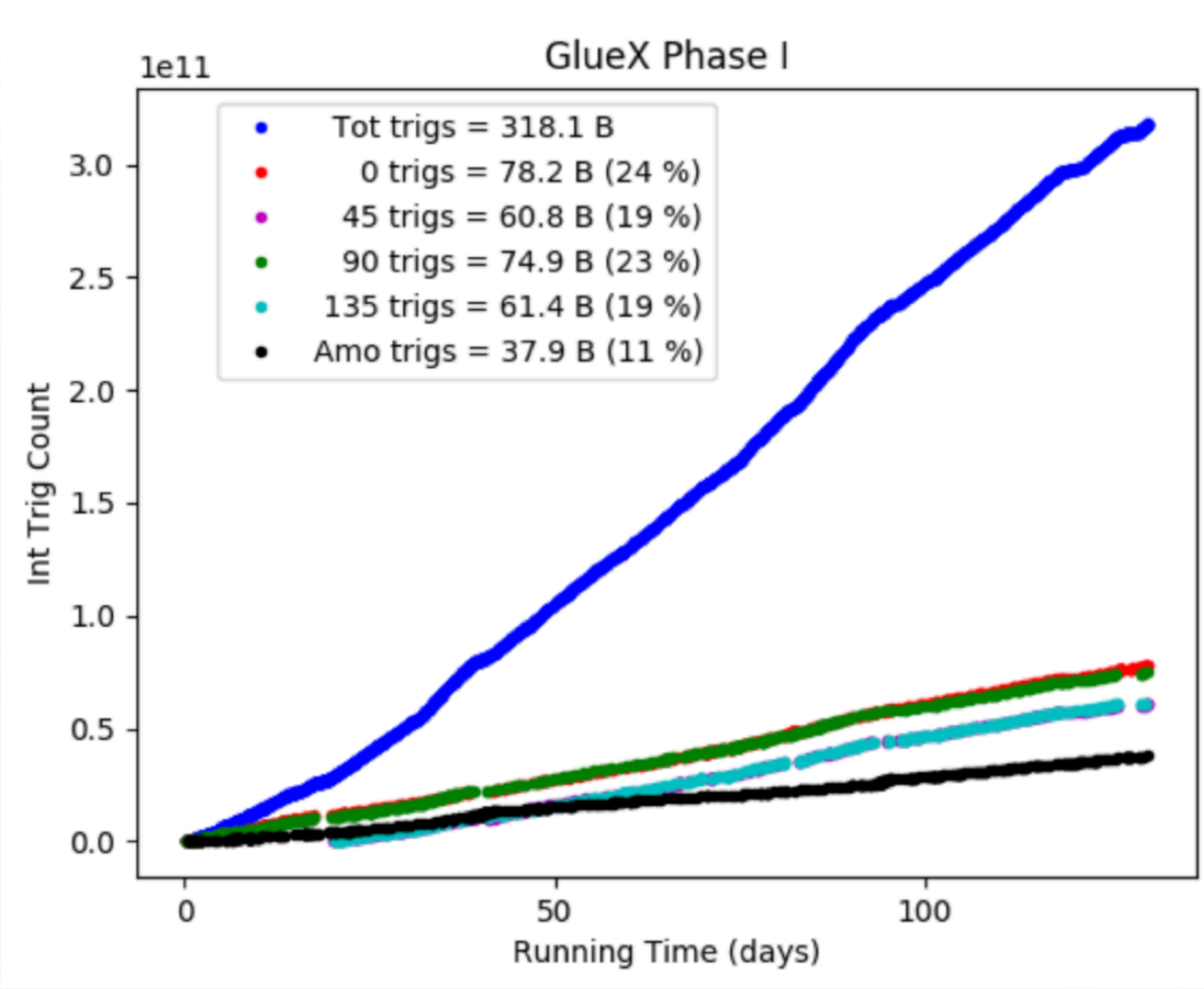
GlueX experiment in Hall D



- Acceptance: $\theta_{lab} \approx 1^{\circ} - 120^{\circ}$
- Charged particles: $\sigma_p/p \approx 1\% - 3\,\%$ ($8\% - 9\,\%$ very-forward high-momentum tracks)
- Photons: $\sigma_E/E = 6\,\%/\sqrt{E} \oplus 2\,\%$

GlueX experiment

- Spring 2016
  - Engineering run
- Spring 2017
  - 20% of GlueX-I
- Spring 2018
  - 50% of GlueX-I
- Fall 2018
  - 30% of GlueX-I



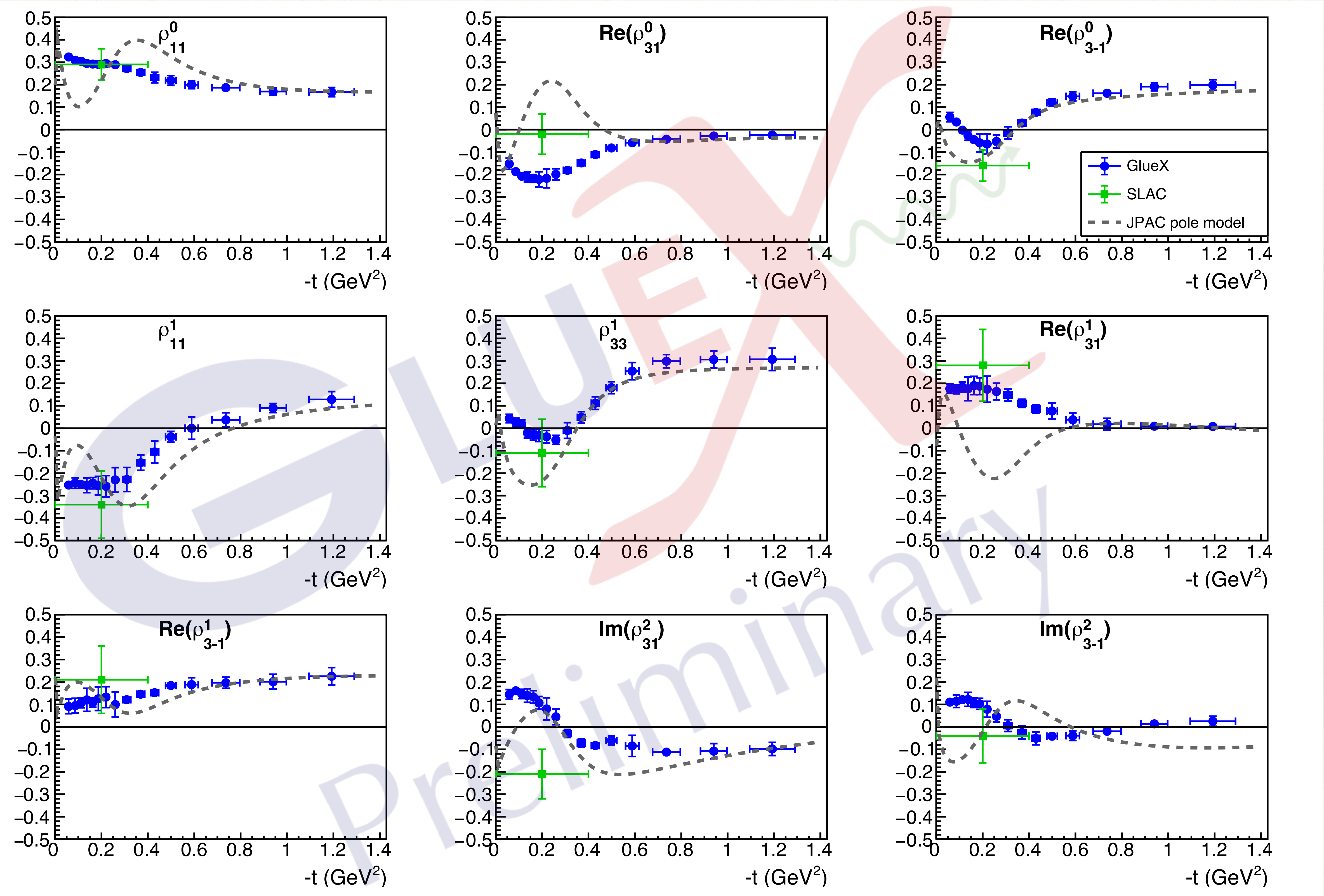
From 2019 onwards:
GlueX-II incl. DIRC

121 pb^{-1} in coherent peak

$\Delta^{++}(1232)$ SDMEs

F. Afzal

$\gamma p \to \pi^- \Delta^{++}(1232) \to \pi^- \pi^+ p$

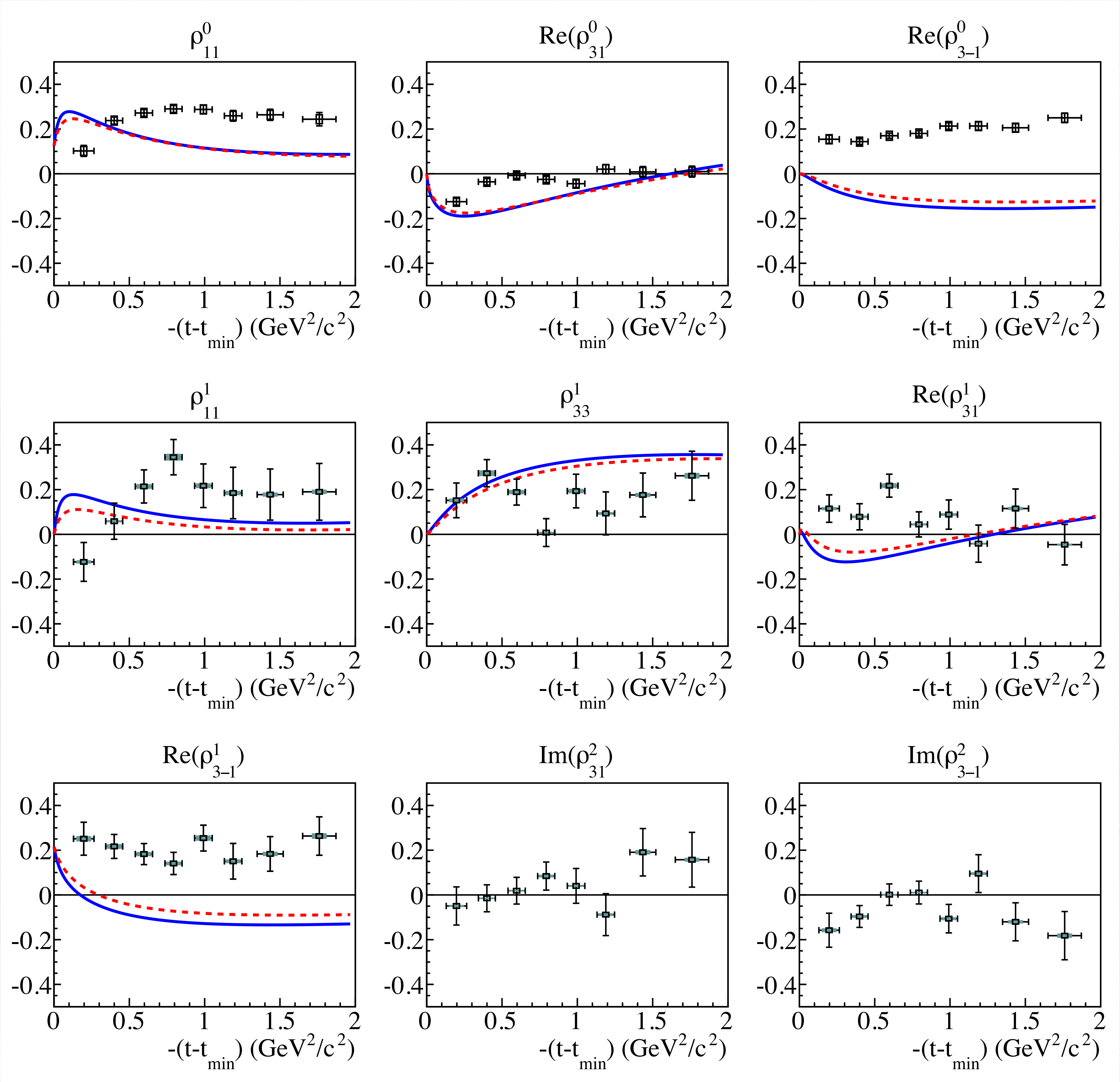


JPAC, Physics Letters B 779 (2018) 77–81

Λ(1520) SDMEs

PH (Phys. Rev. C **105**, 035201)

- So far, sparse data at high energies
- red and blue show model predictions in Reggeized framework (priv. comm. based on [1])
- these measurements constrain models in the future

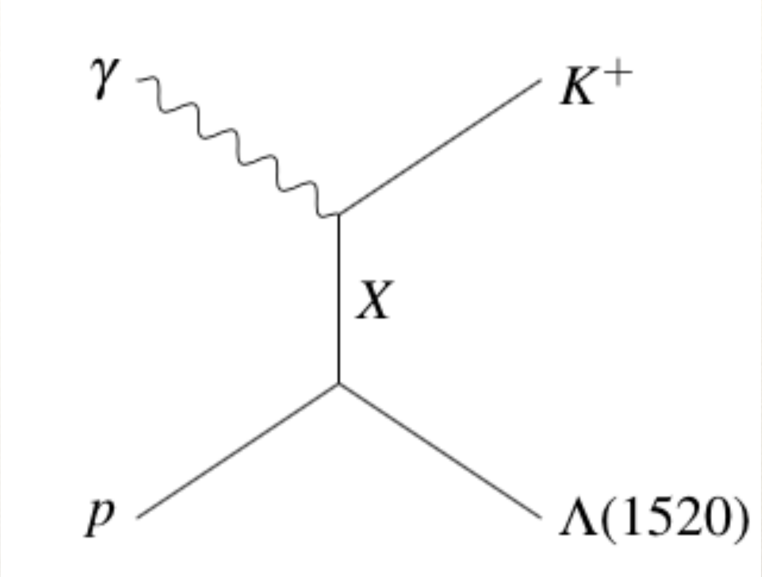


[1] *Byung-Geel Yu and Kook-Jin Kong, Phys. Rev. C* ***96****, 025208 (2017)*

$\Lambda(1520)$ SDME Interpretation

PH (Phys. Rev. C **105**, 035201)

- to help with interpretation form combinations of SDMEs which correspond to purely natural (N) and purely unnatural (U) exchange amplitudes



X is exchange particle with spin-parity quantum number J^P and naturality $\eta = P(-1)^J$

Natural: e.g. $K^*(892)$, $K_2^*(1430)$

Unnatural: e.g. $K(492)$, $K_1(1270)$

$$\rho^0_{11} + \rho^1_{11} = \frac{2}{N}(|N_0|^2 + |N_1|^2) \qquad \mathrm{Re}(\rho^0_{31} + \rho^1_{31}) = \frac{2}{N}(N_{-1}N_0^* - N_2N_1^*)$$

$$\rho^0_{11} - \rho^1_{11} = \frac{2}{N}(|U_0|^2 + |U_1|^2) \qquad \mathrm{Re}(\rho^0_{31} - \rho^1_{31}) = \frac{2}{N}(U_{-1}U_0^* - U_2U_1^*)$$

$$\rho^0_{33} + \rho^1_{33} = \frac{2}{N}(|N_{-1}|^2 + |N_2|^2) \qquad \mathrm{Re}(\rho^0_{3-1} + \rho^1_{3-1}) = \frac{2}{N}(N_{-1}N_1^* + N_2N_0^*)$$

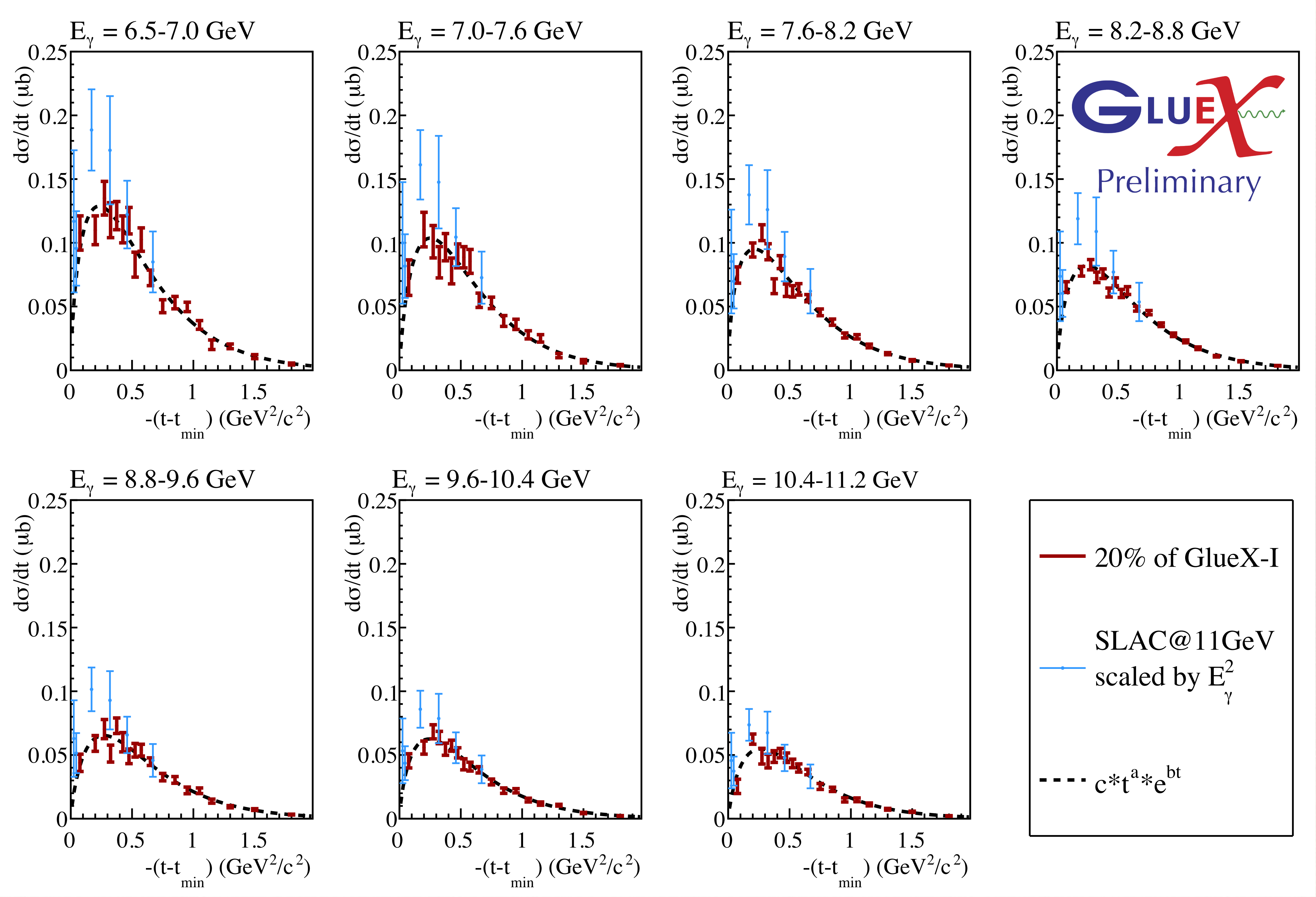
$$\rho^0_{33} - \rho^1_{33} = \frac{2}{N}(|U_{-1}|^2 + |U_2|^2) \qquad \mathrm{Re}(\rho^0_{3-1} - \rho^1_{3-1}) = \frac{2}{N}(U_{-1}U_1^* + U_2U_0^*)$$

$$N = 2(|N_{-1}|^2 + |N_0|^2 + |N_1|^2 + |N_2|^2 + |U_{-1}|^2 + |U_0|^2 + |U_1|^2 + |U_2|^2)$$

work by V. Mathieu (JPAC)

Λ(1520) cross-sections

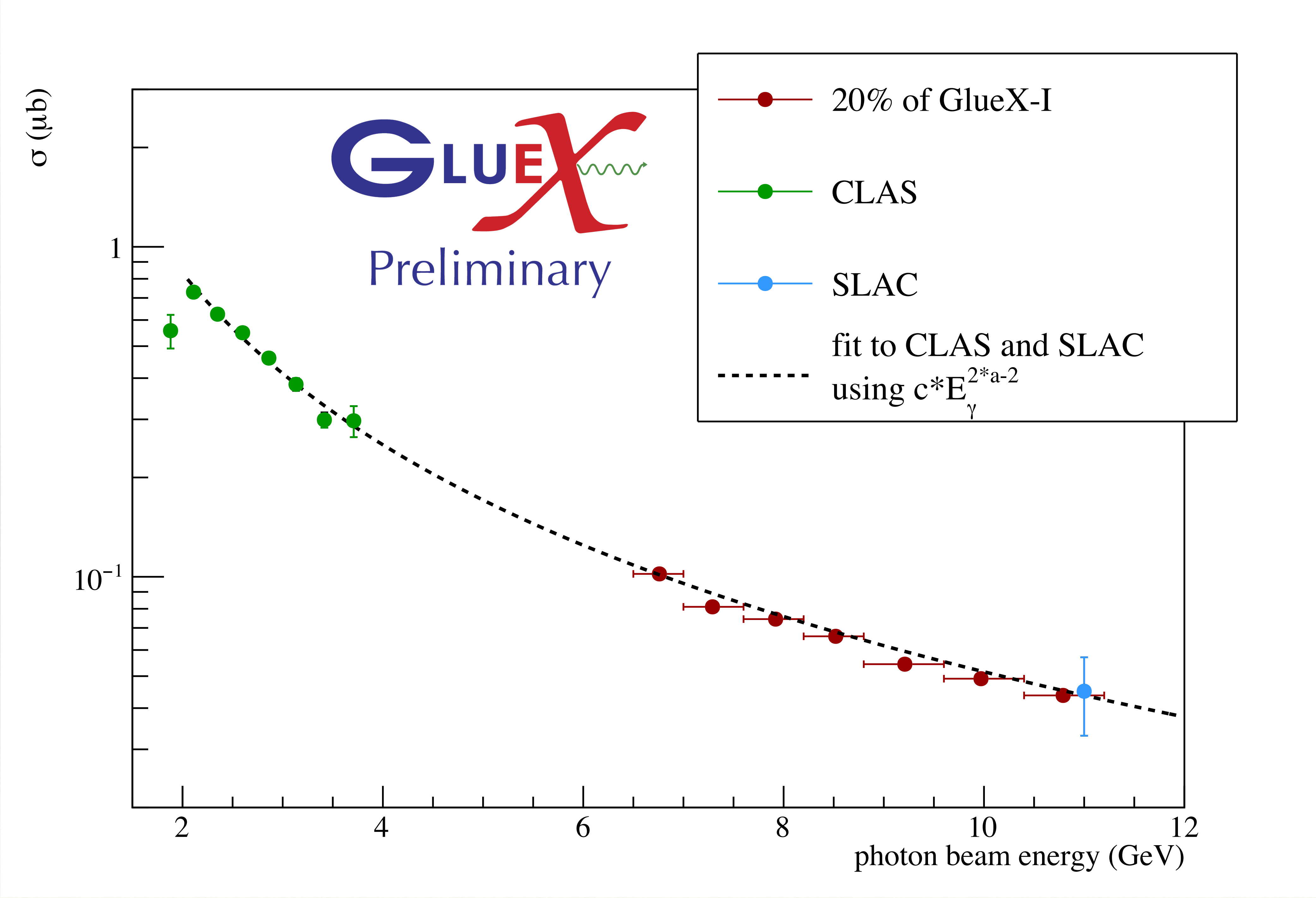
- To get full picture of production we need couplings: measure cross-sections
- Fit t-distribution and integrate to get "total cross-section"



SLAC, *Phys. Lett. B* **34** (1971) 547-550

Λ(1520) cross-sections

- Good agreement with previous data by SLAC
- More data on tape, including some with lower photon beam energy



CLAS, *Phys. Rev. C* **88** (2013) 045201

SLAC, *Phys. Lett. B* **34** (1971) 547-550

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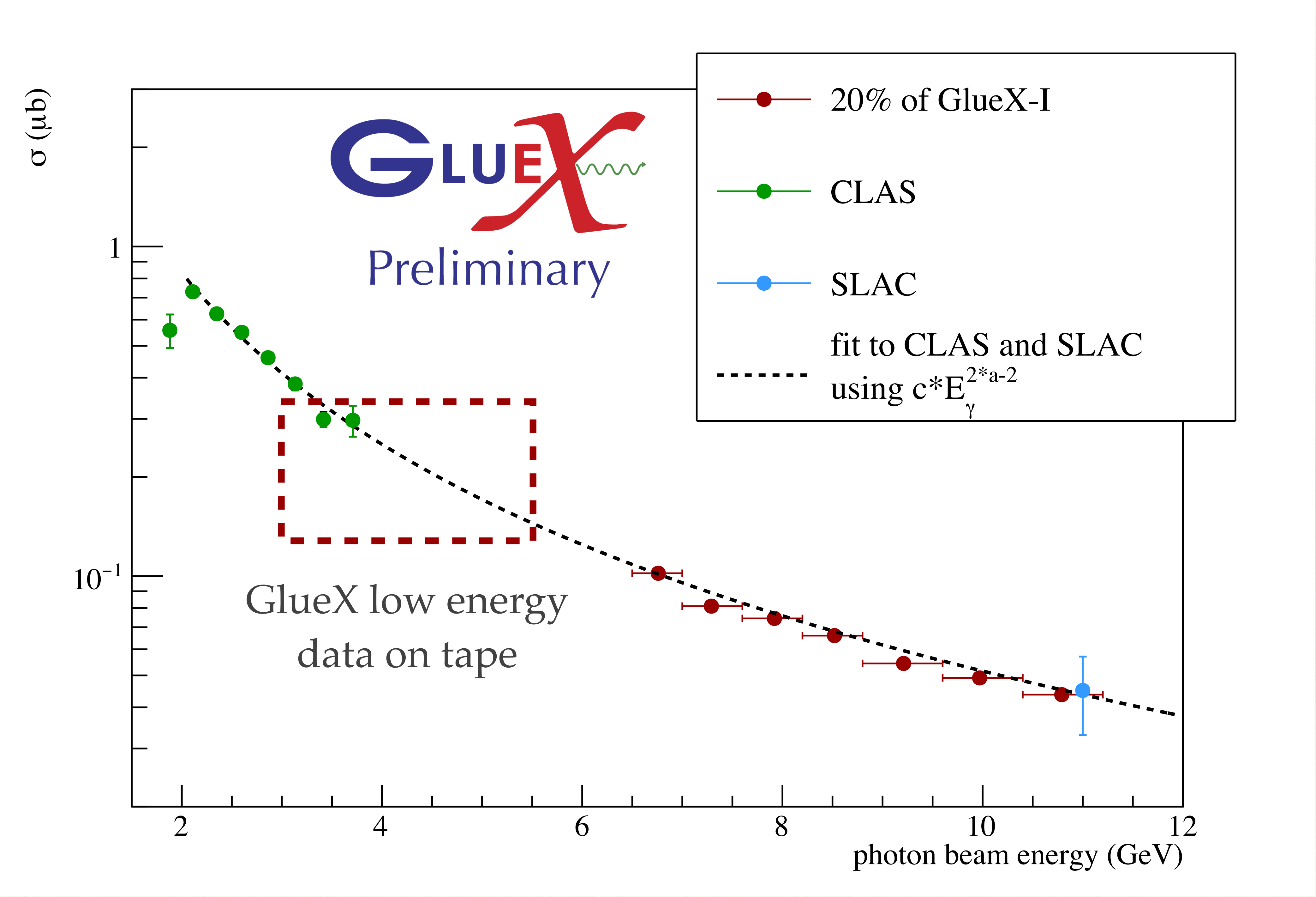
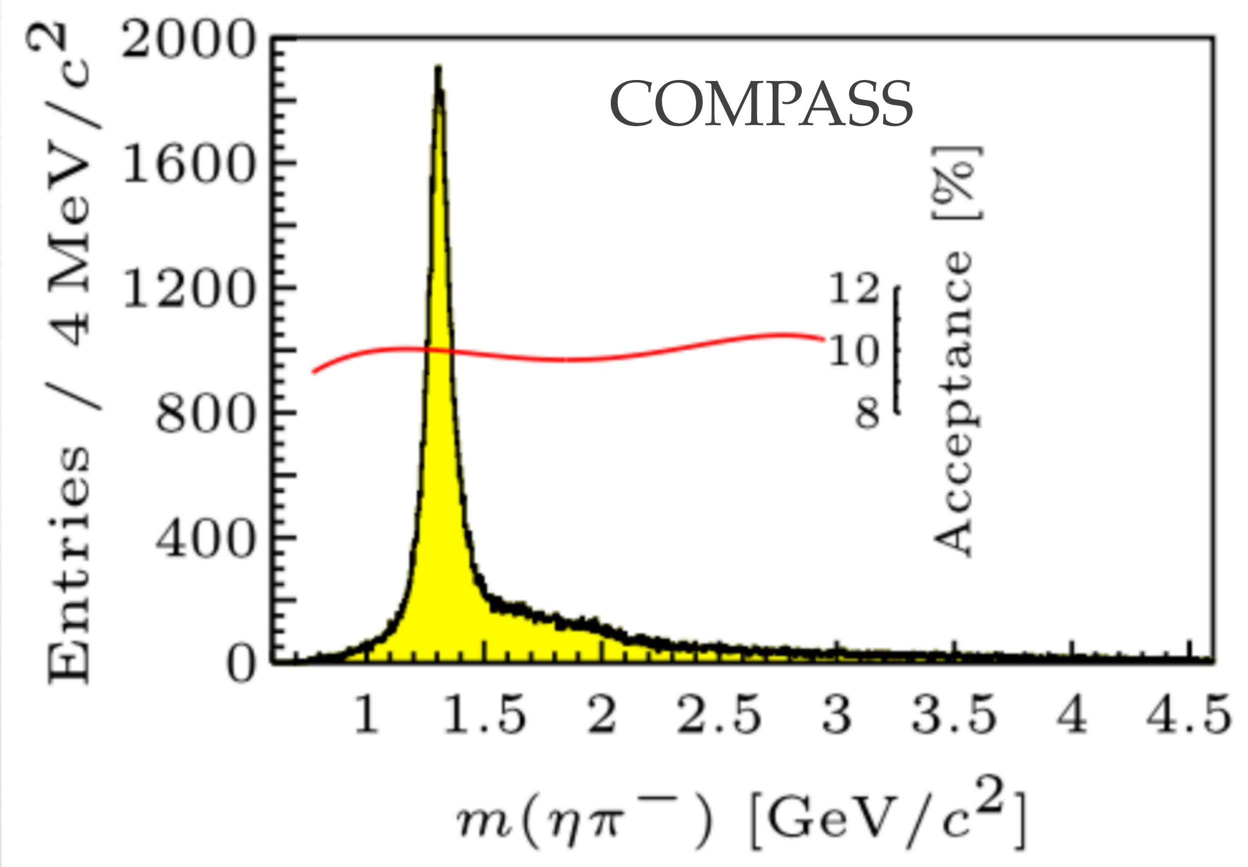


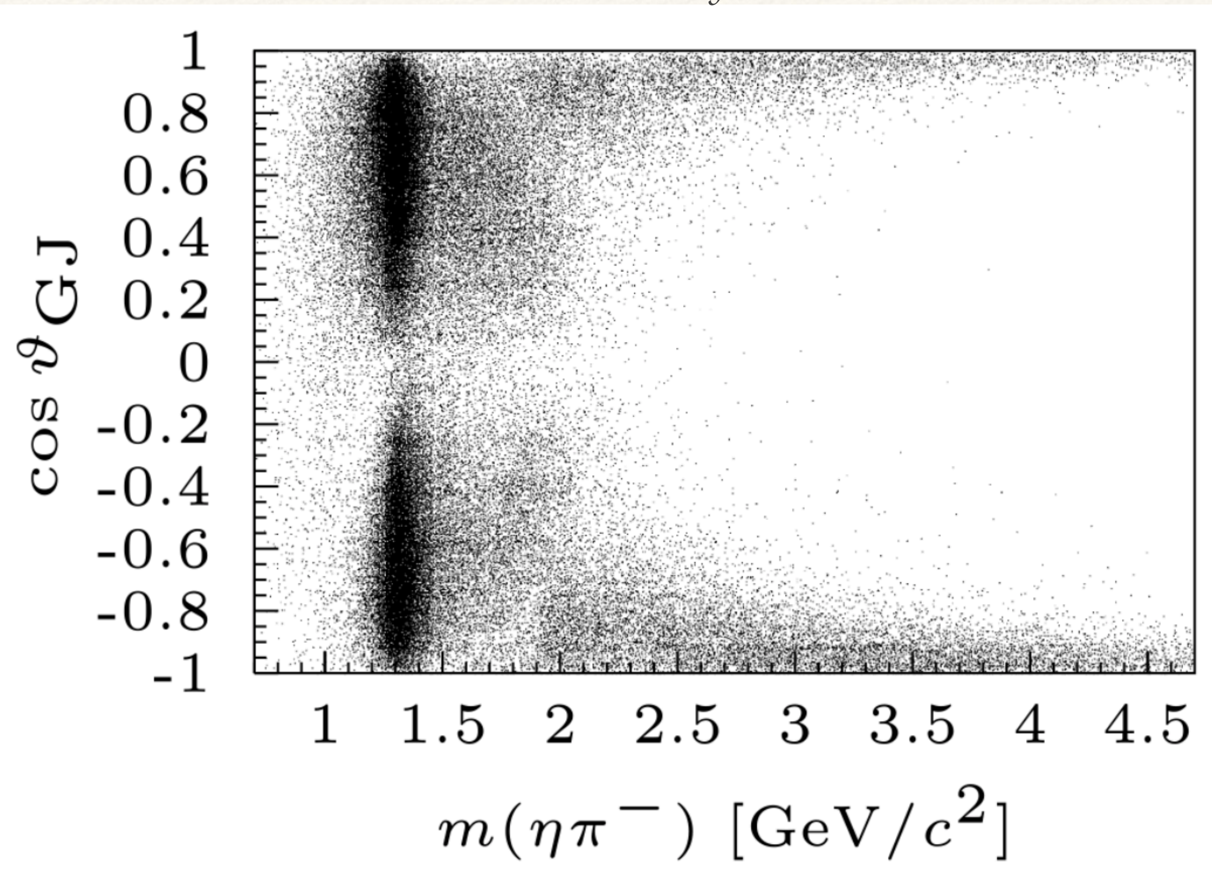
CLAS, *Phys. Rev. C* **88** (2013) 045201

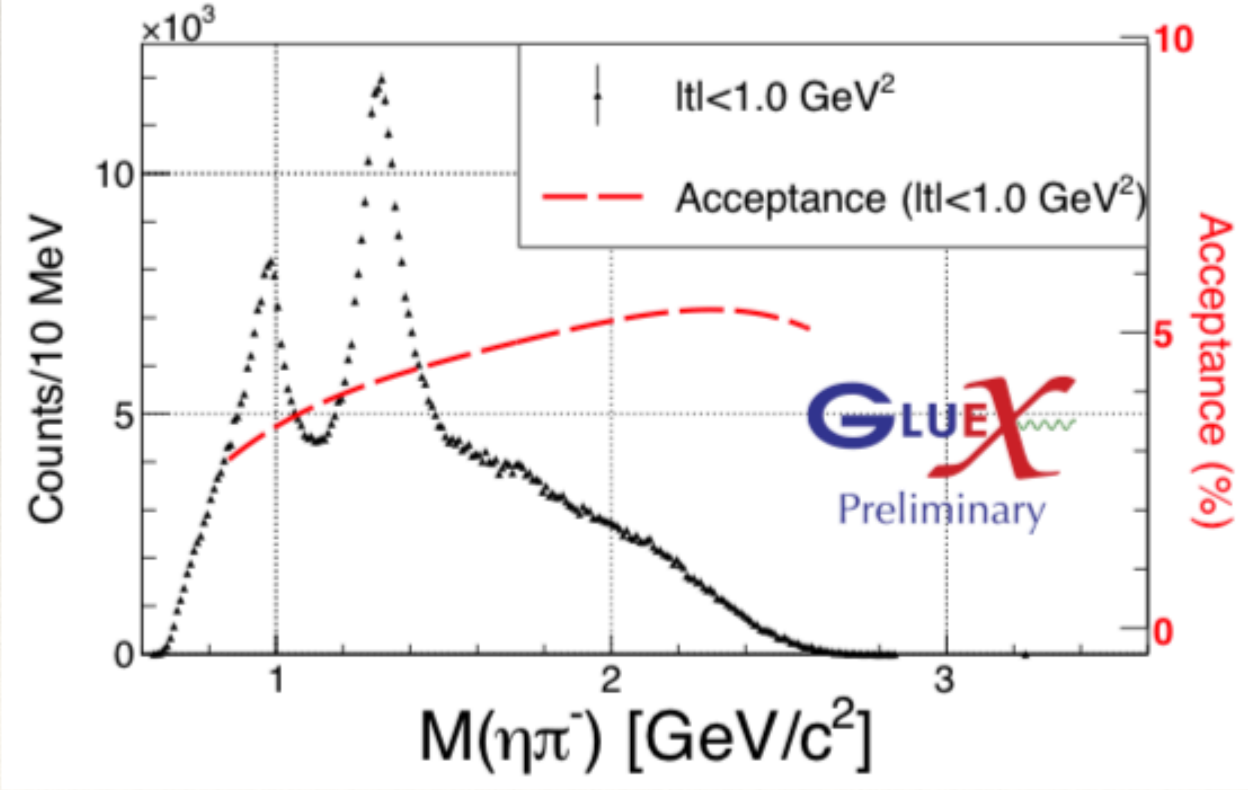
SLAC, *Phys. Lett. B* **34** (1971) 547-550

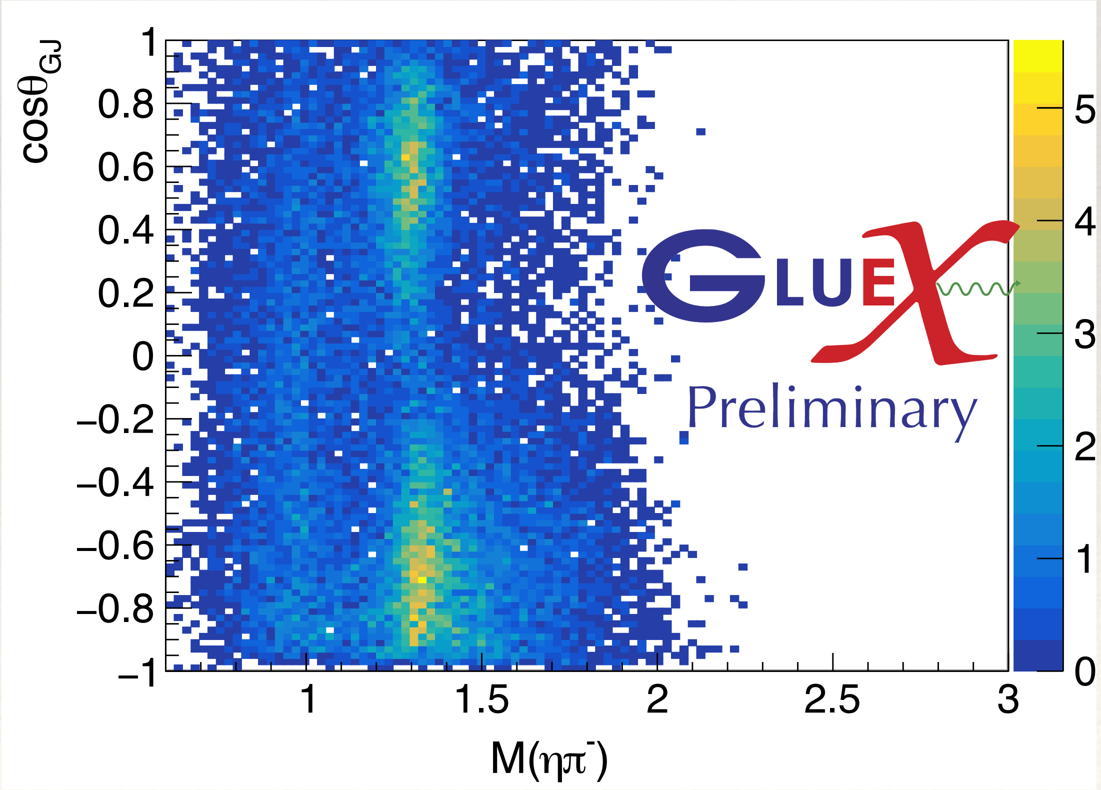
Hybrid search in $\eta\pi^-$

COMPASS, Phys. Lett. B 740 (2015) 303–311



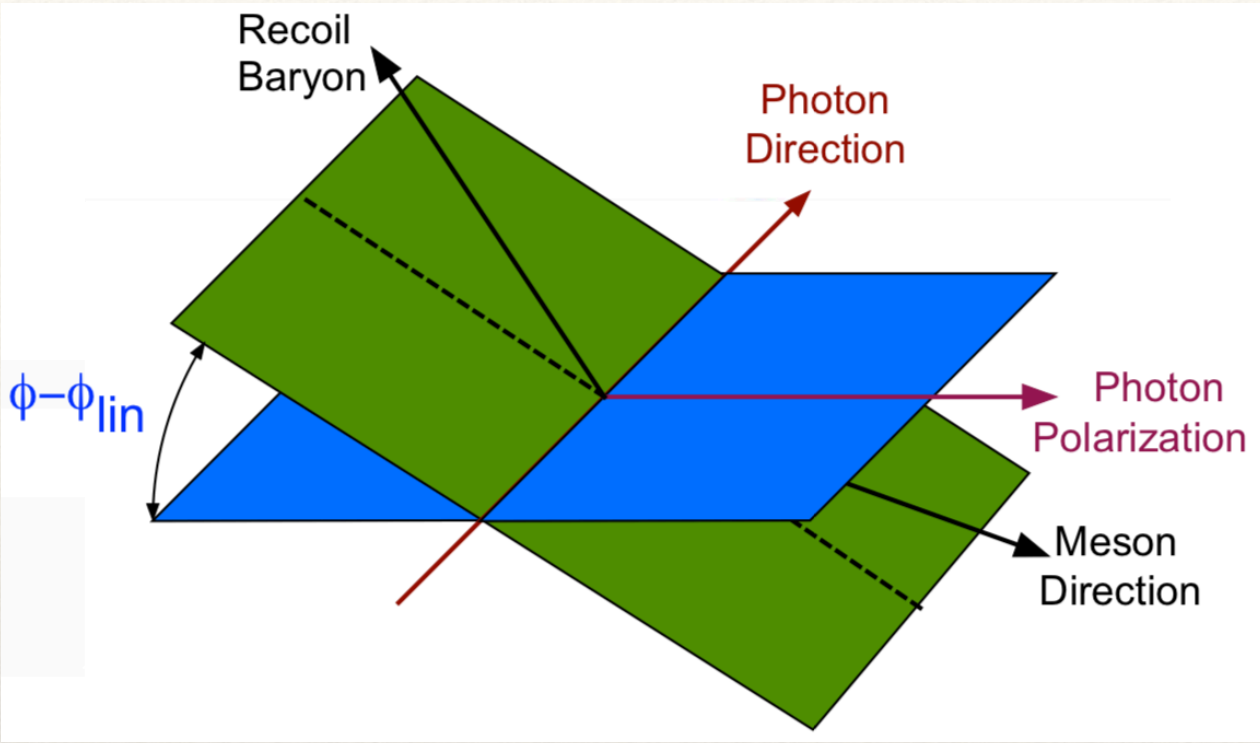




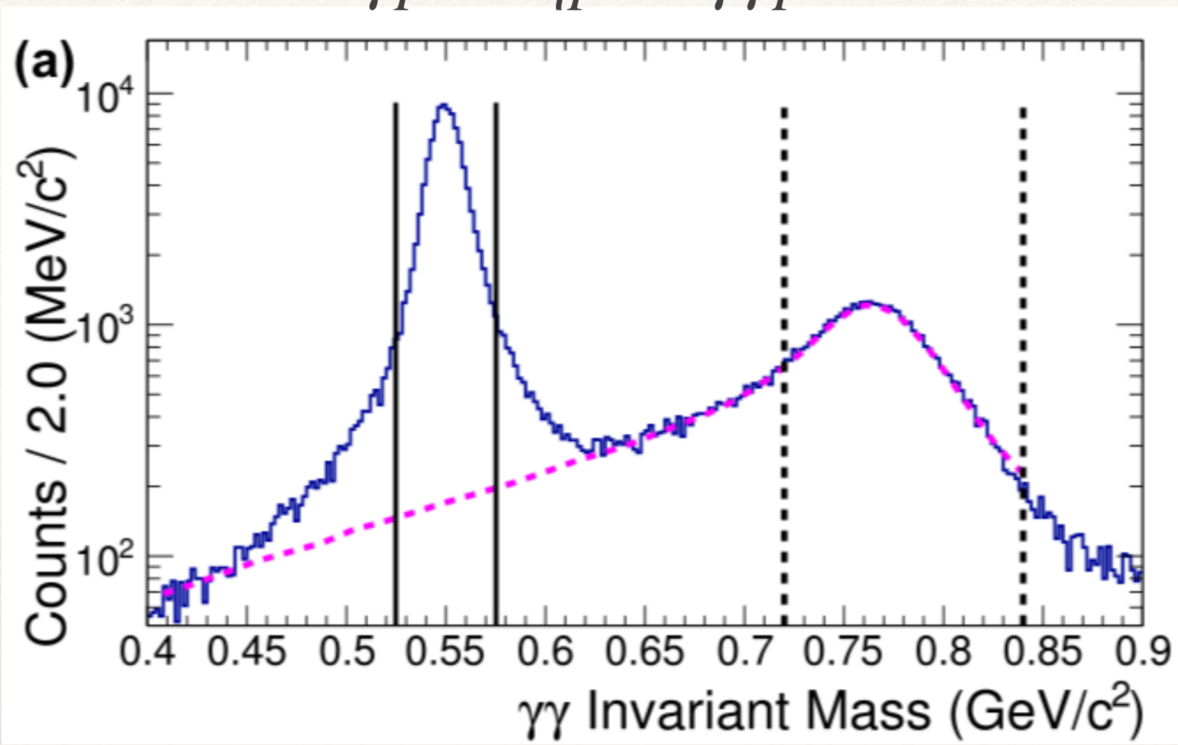


η/η' beam asymmetry

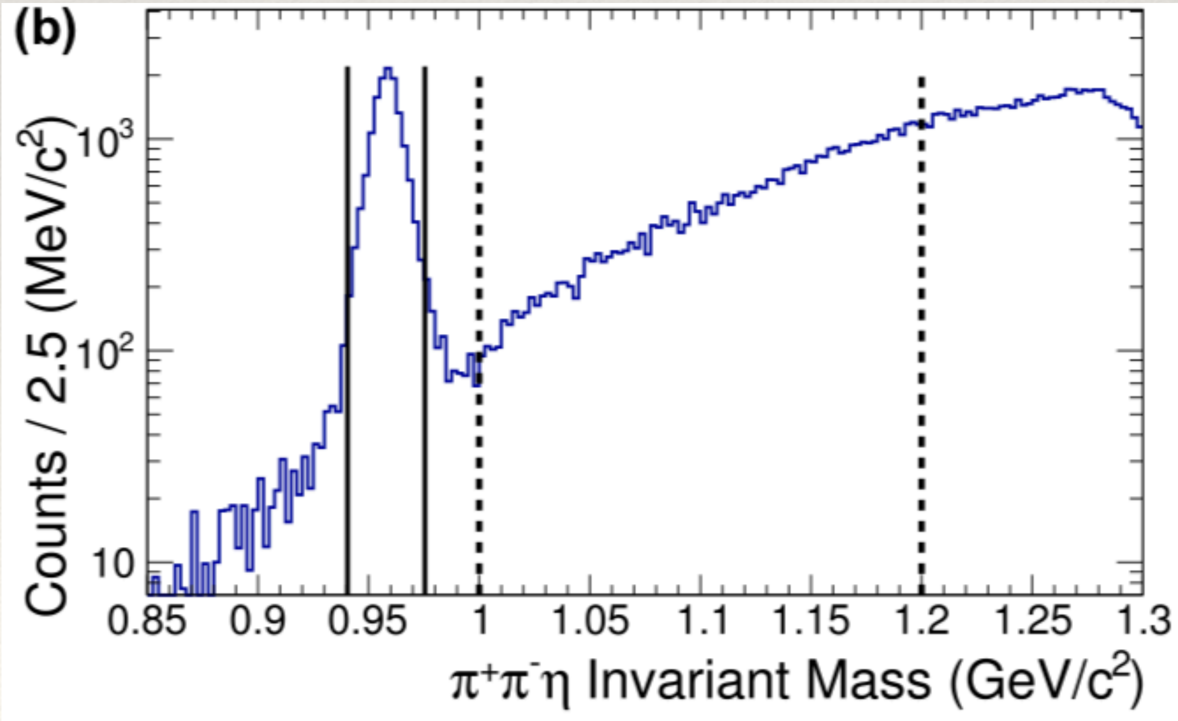
$$\sigma(\phi) \sim 1 - P_\gamma \Sigma \cos 2(\phi - \phi_{lin})$$



$\gamma p \to \eta p \to \gamma\gamma p$



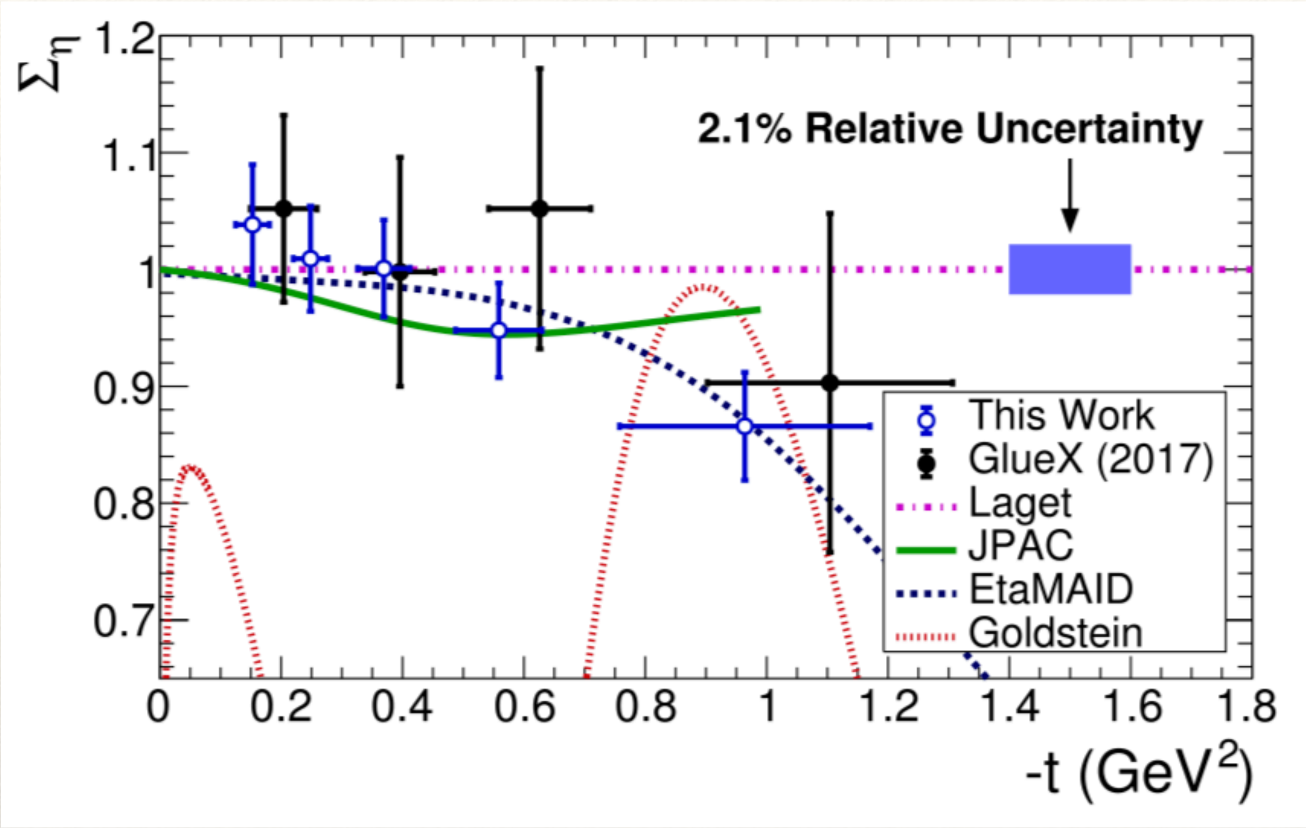
$\gamma p \to \eta' p \to \pi^+\pi^-\eta p$



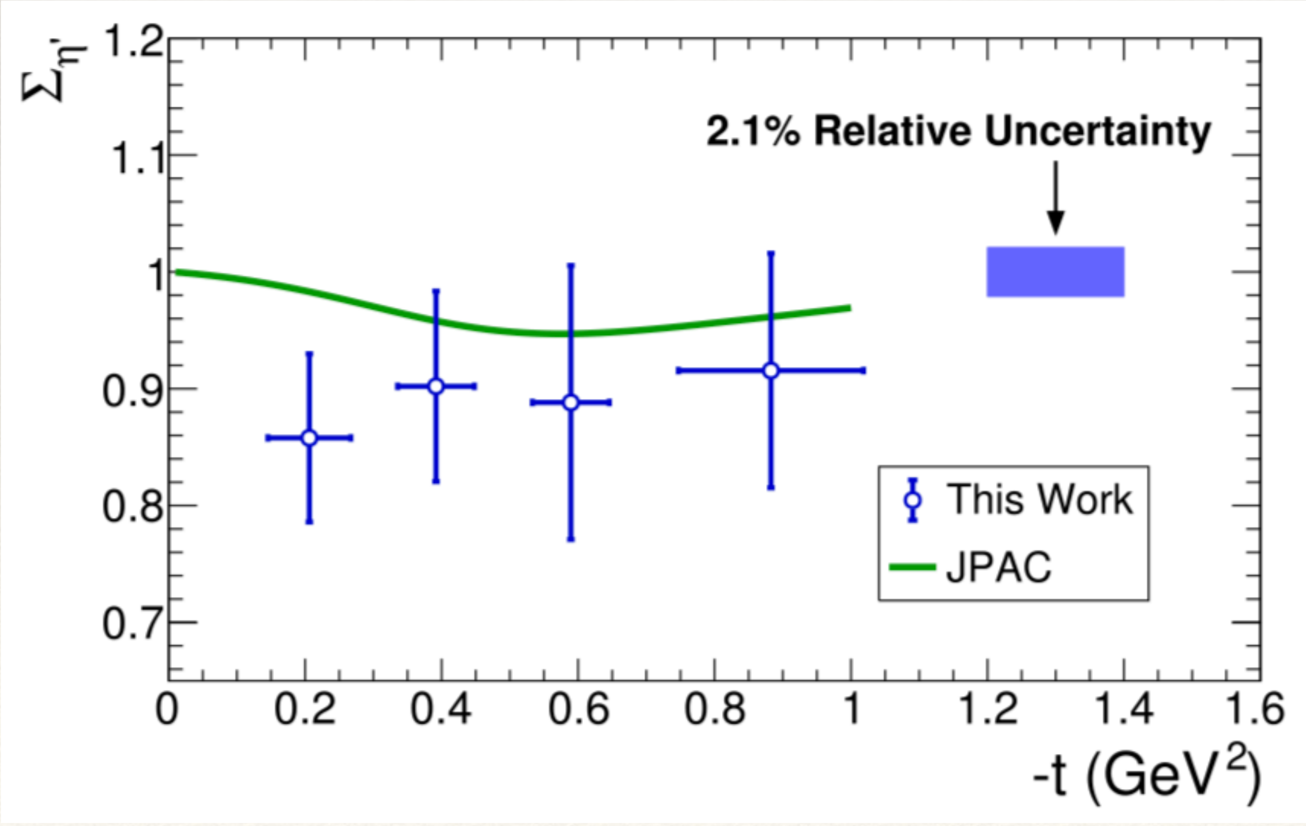
- measure photon beam asymmetry Σ to learn about t-channel Reggeon exchange
- ratio of $\Sigma_{\eta'}/\Sigma_\eta$ provides information on $s\bar{s}$ exchange

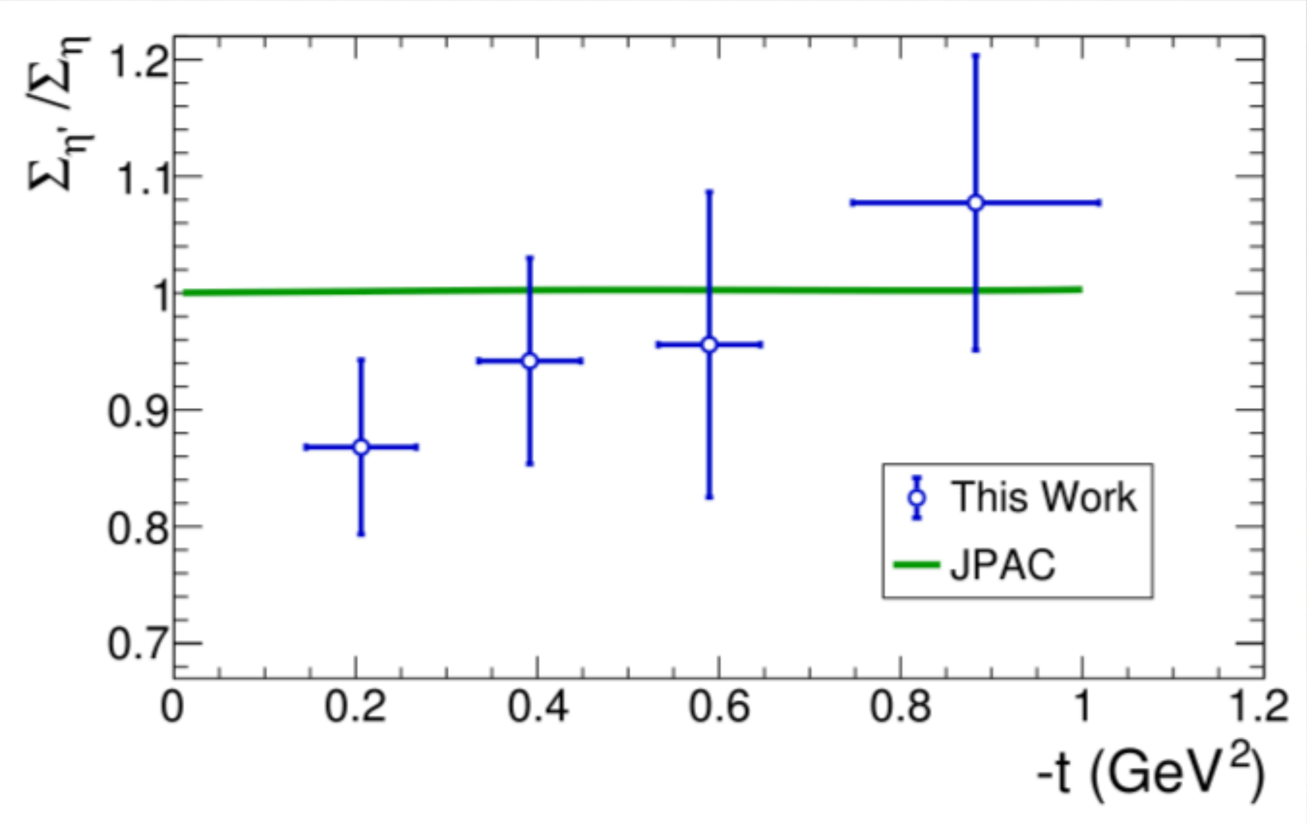
Phys. Rev. C 100, 052201(R) (2019)

η/η' beam asymmetry



- vector exchange dominating
- ratio indicates no substantial $s\bar{s}$ component in exchange

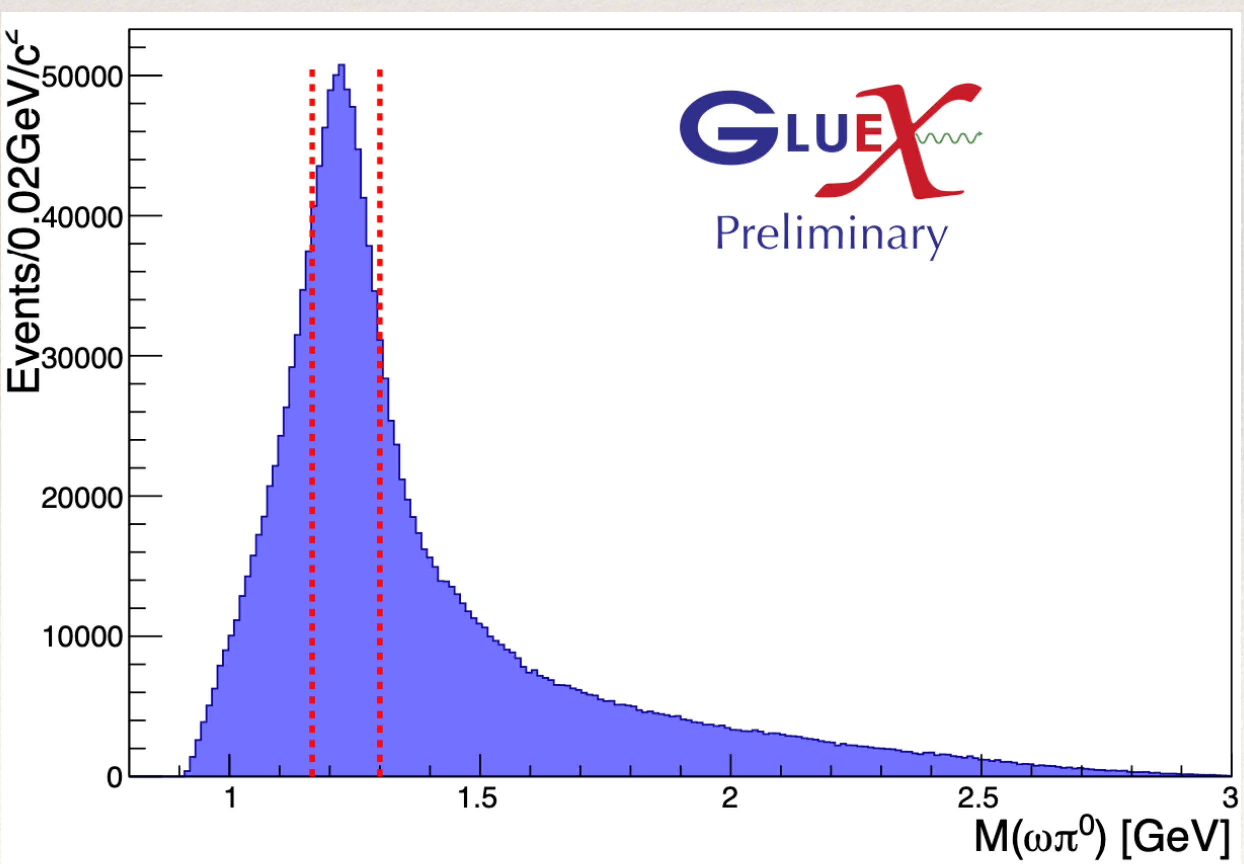


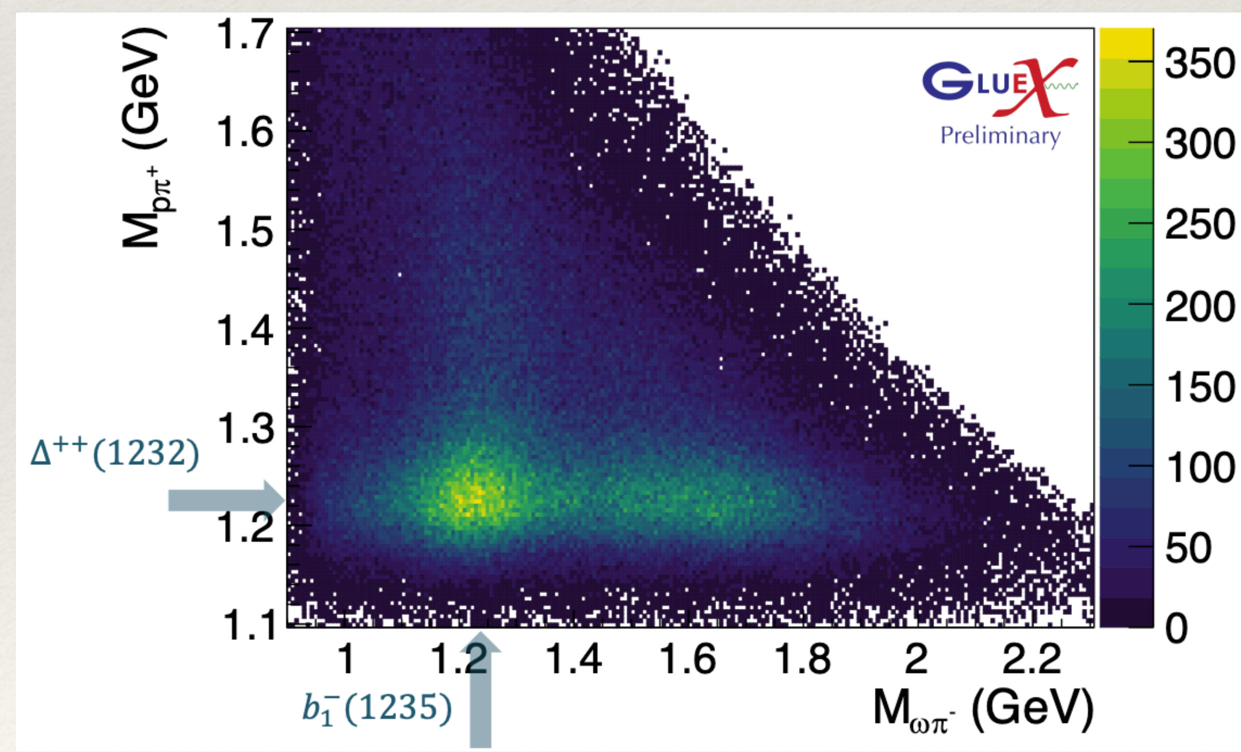


Phys. Rev. C 100, 052201(R) (2019)

b_1 decay

- LQCD: $b_1\pi$ is dominating decay mode of 1^{-+} exotic
- First step: study b_1
  - $\gamma p \rightarrow b_1 p \rightarrow \omega\pi^0 p \rightarrow \pi^+\pi^-\pi^0\pi^0 p$
  - $\gamma p \rightarrow b_1^- \Delta^{++} \rightarrow \omega\pi^- \Delta^{++} \rightarrow \pi^+\pi^-\pi^0\pi^-\pi^+ p$

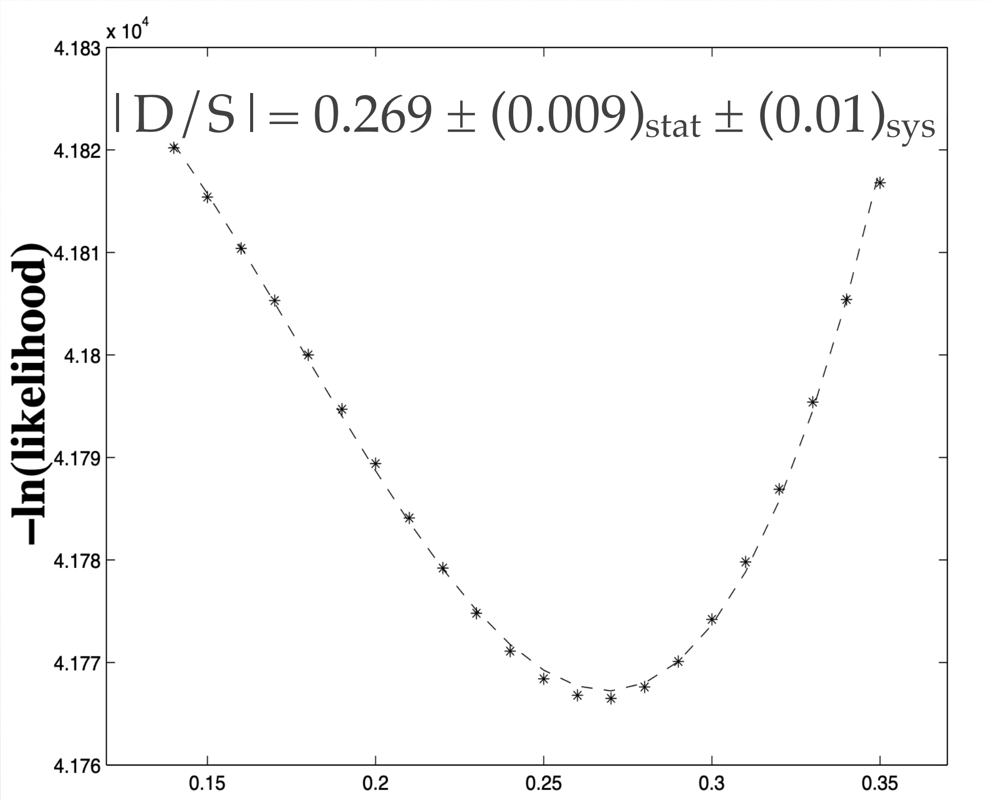




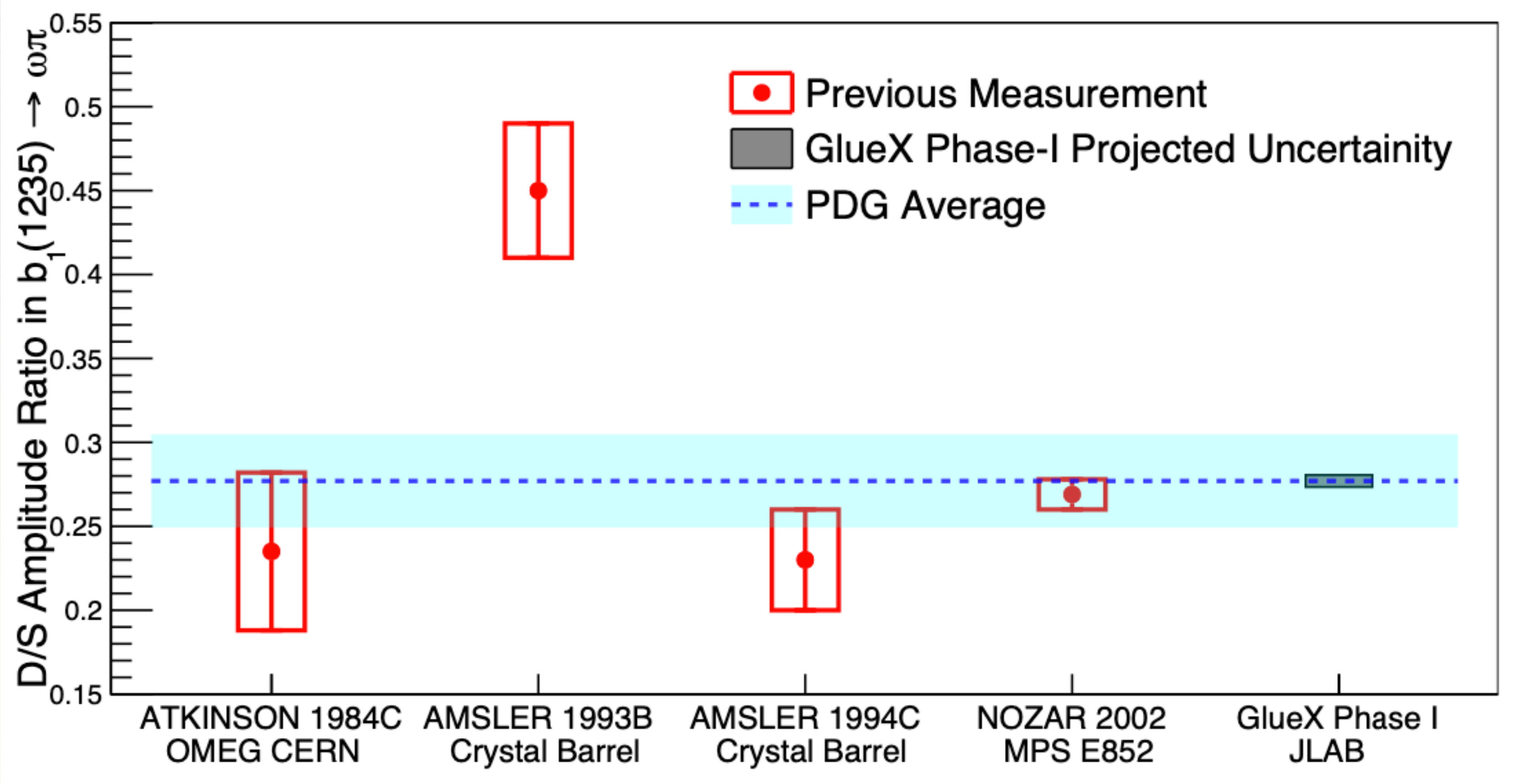
b_1 decay

- Start by measuring D/S amplitude ratio
- LQCD prediction by hadspec of $|D/S| = 0.27(20)$

hadspec, Phys. Rev. D 100, 054506 (2019)



E852, Phys. Lett. B 541, 35 (2002)



- Good first test of amplitude model
- Can be expanded to all vector-pseudoscalar systems ($\omega\eta$, $\phi\pi$, $\phi\eta$,…)