

Peter Hurck for the GlueX collaboration

Hadron spectroscopy at GlueX



University
of Glasgow

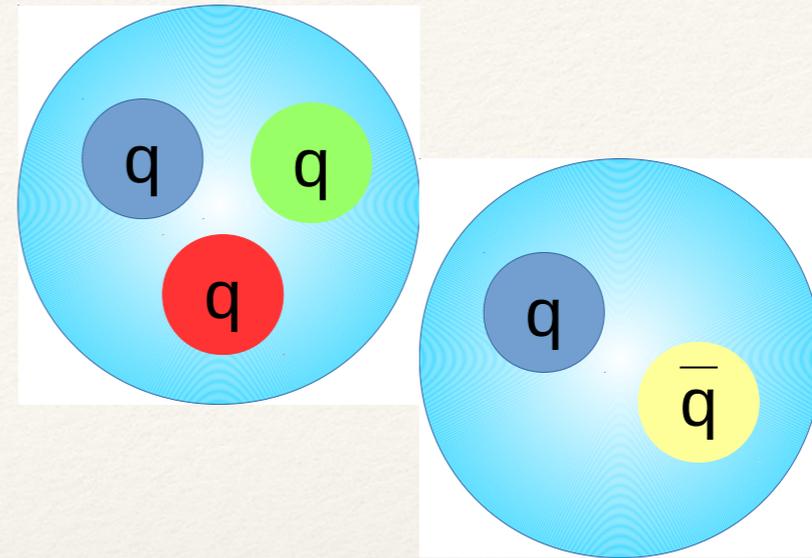
Exotic Hadron Spectroscopy 2023

Institute for Particle Physics Phenomenology (IPPP), Durham University



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!



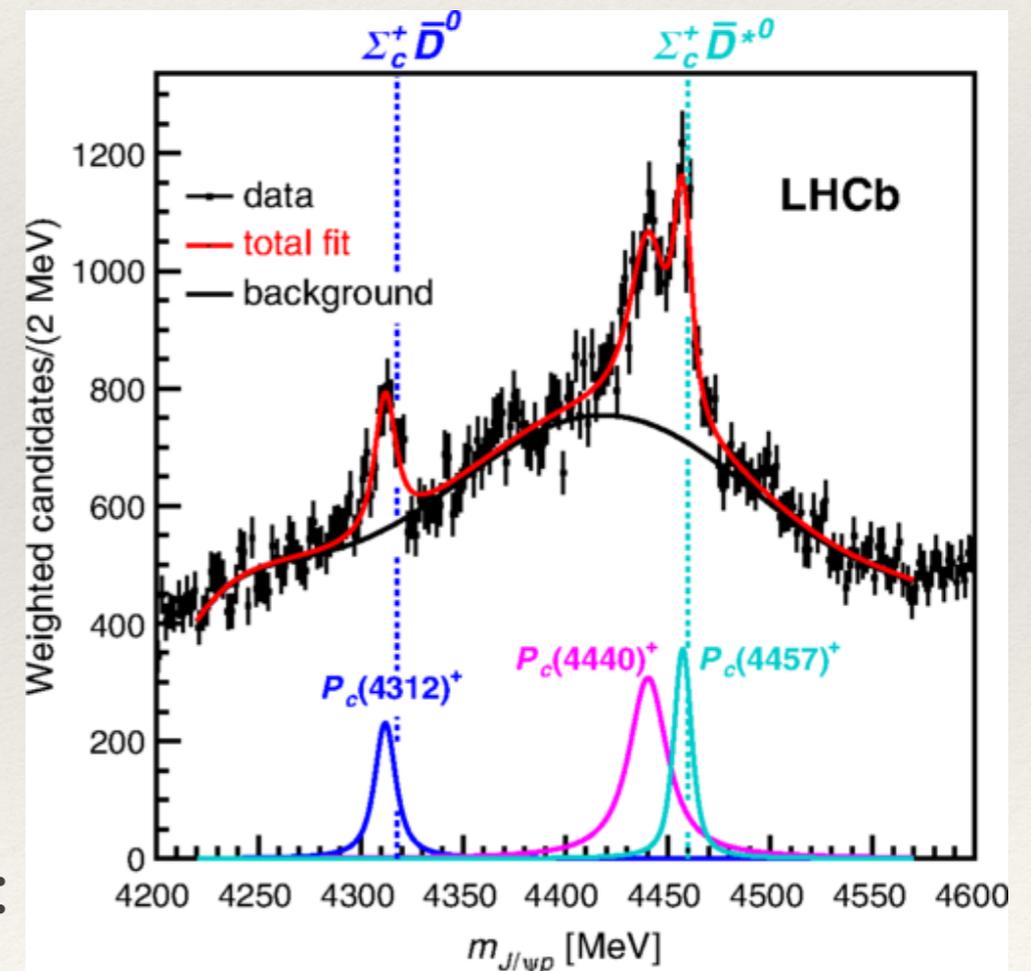
A SCHEMATIC MODEL OF BARYONS AND MESONS *

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



LHCb, *Phys. Rev. Lett.* 122, 222001

Evidence exists for pentaquark states:

Hybrid mesons

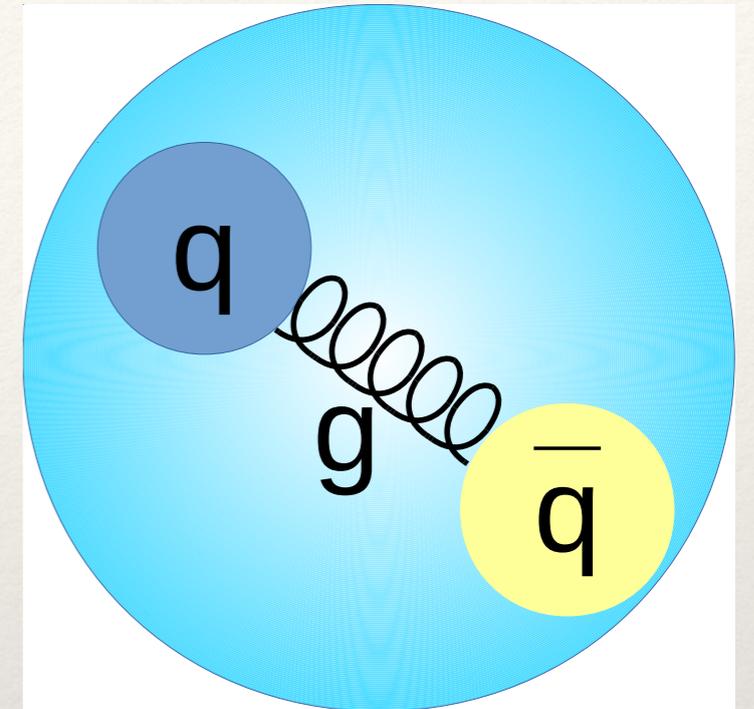
- ❖ main objective for GlueX:
Search and study of hybrid mesons

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

→ not allowed:

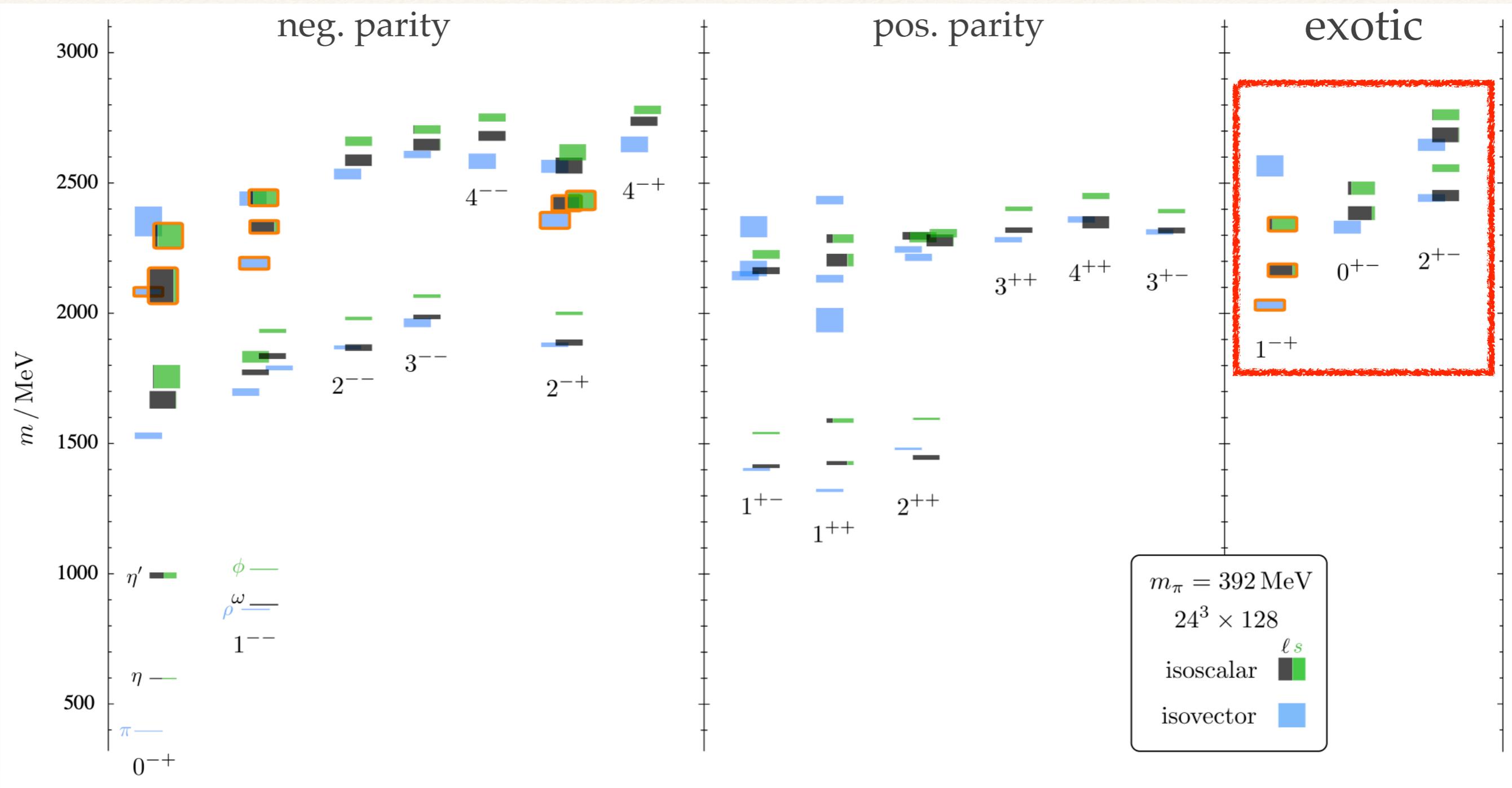
$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \dots$$

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



Light quark mesons from lattice QCD

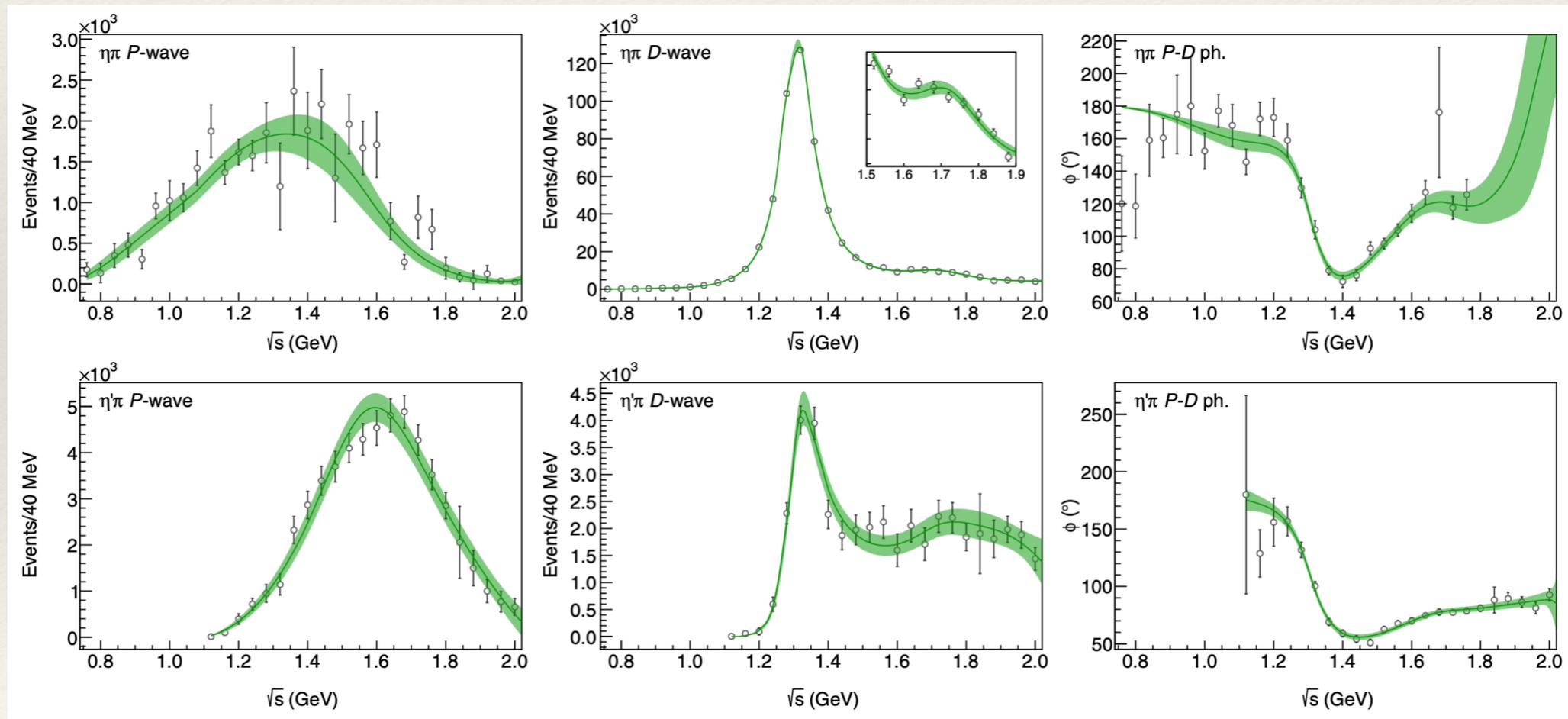
hadspec collaboration



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

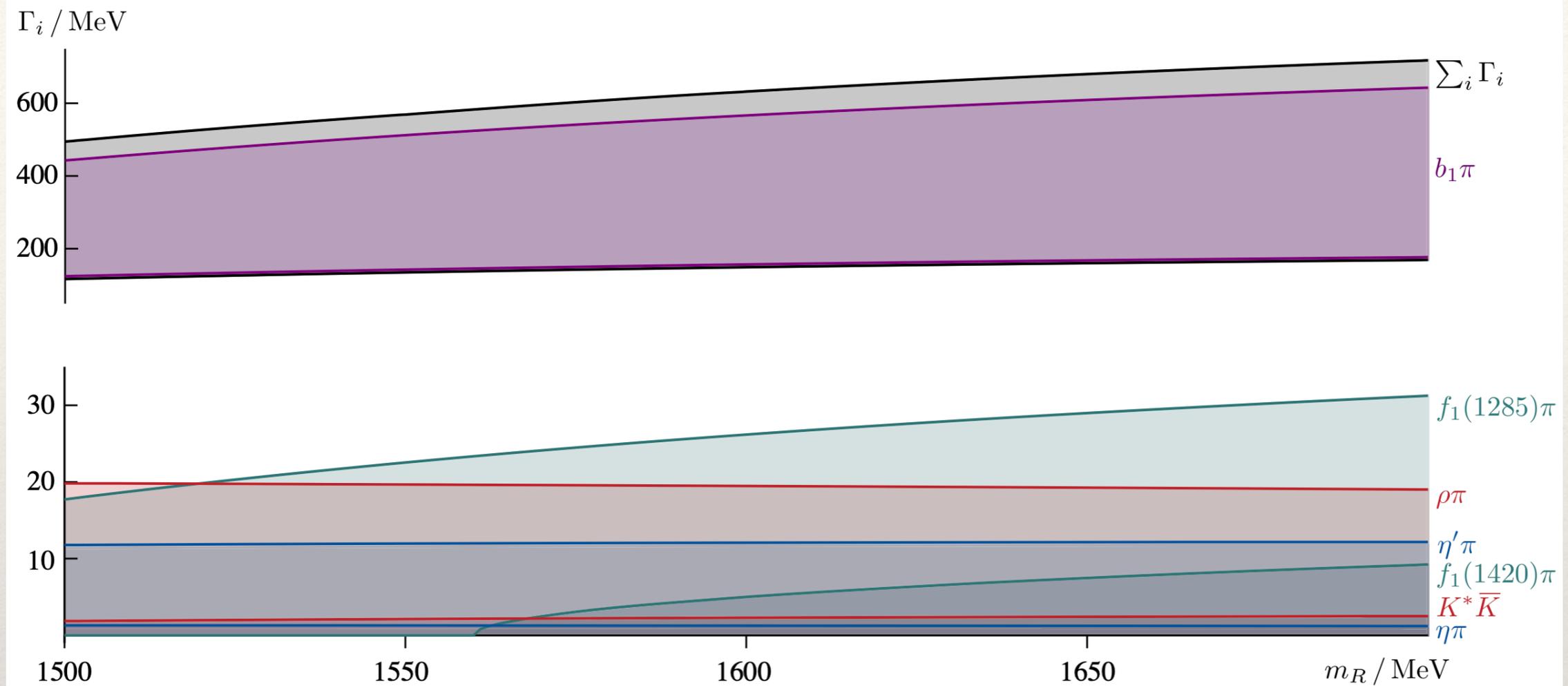


mass = $1564 \pm 24 \pm 86$ MeV width = $492 \pm 54 \pm 102$ MeV

1^{-+} hybrid from lattice QCD

hadspec collaboration

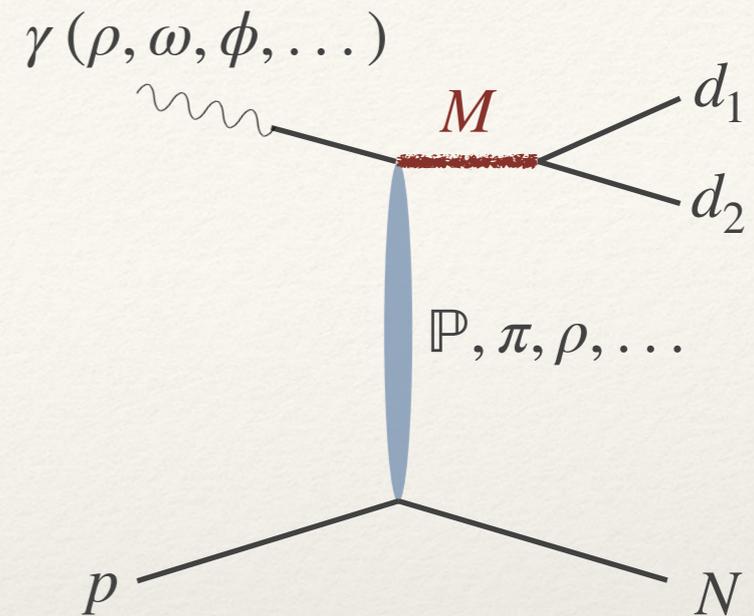
hadspec, Phys. Rev. D 103, 054502



- ❖ 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

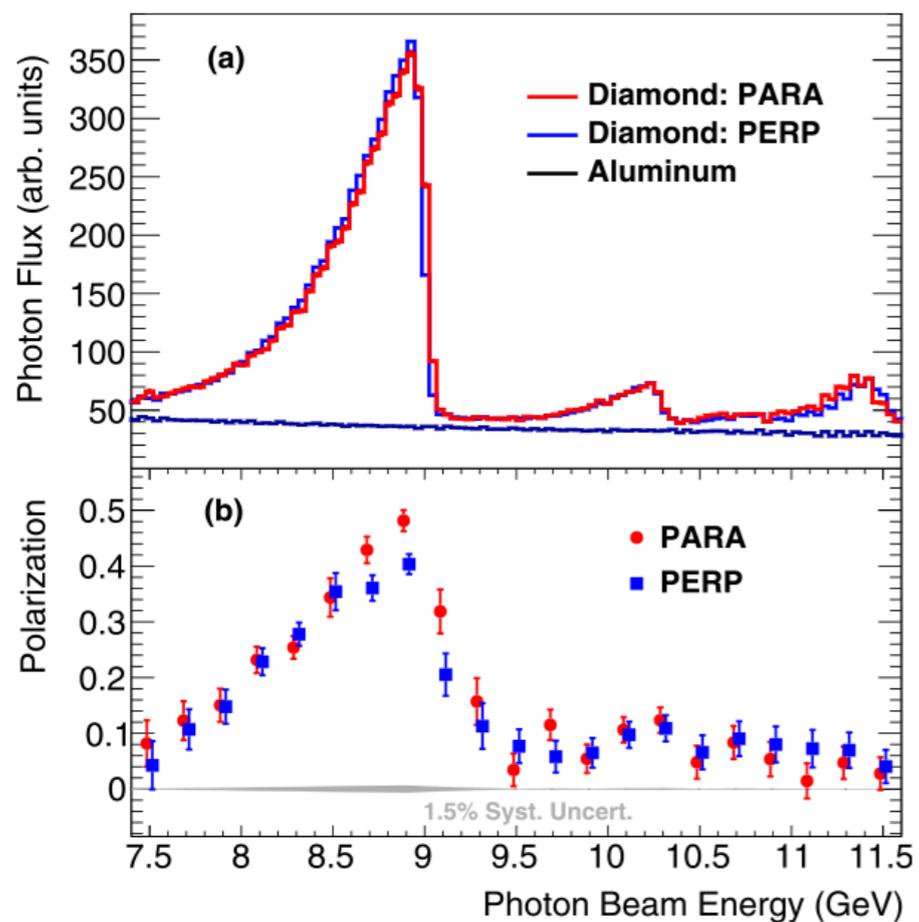
- ❖ Photoproduction complementary to pion production
- ❖ Utilize polarization to understand production mechanisms
- ❖ Study production mechanisms to inform choice of wave sets for PWA (beam asymmetries, spin density matrix elements)
- ❖ Reproduce previous results by COMPASS
 - ❖ Focus on $\eta\pi$ and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



CEBAF at Jefferson Lab

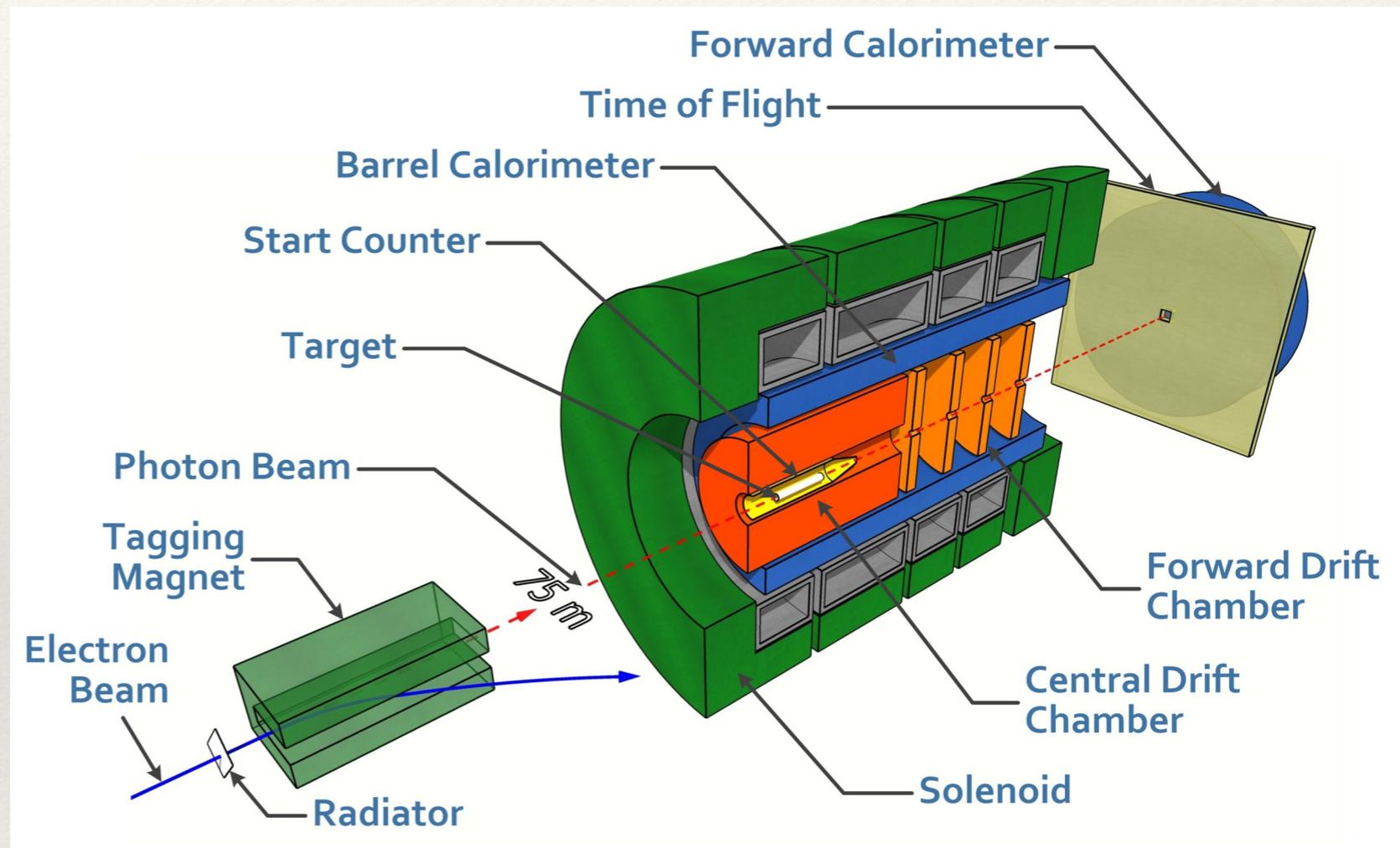


GlueX experiment in Hall D



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

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

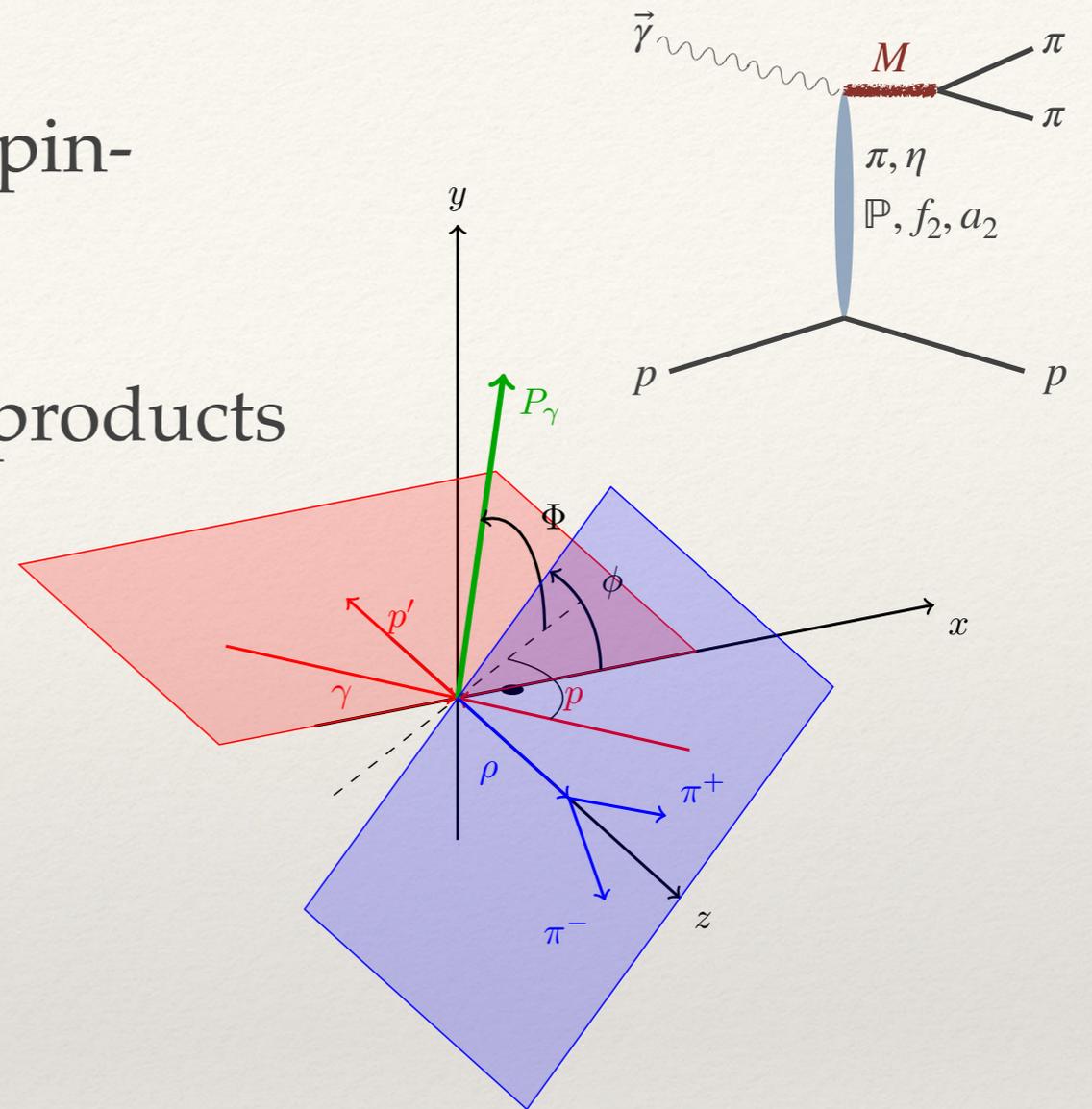


- ❖ tag electrons to determine photon energy

- ❖ 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_{jk}^i 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:

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

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

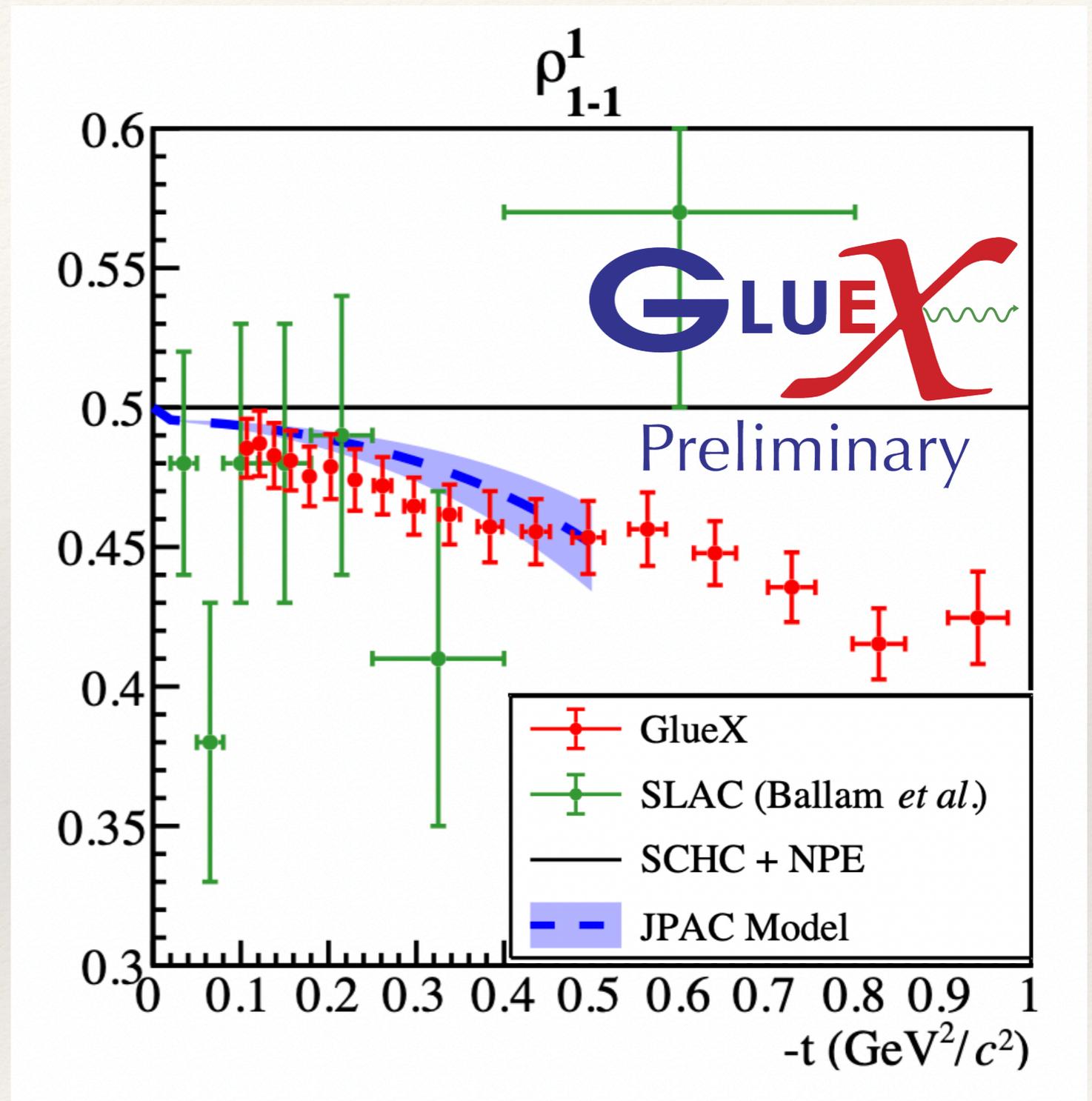
$$W^1(\cos \theta, \phi) = \frac{3}{4\pi} \left(\rho_{11}^1 \sin^2 \theta + \rho_{00}^1 \cos^2 \theta - \sqrt{2}\text{Re}\rho_{10}^1 \sin 2\theta \cos \phi - \rho_{1-1}^1 \sin^2 \theta \cos 2\phi \right)$$

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

$\rho(770)$ SDMEs

- ❖ 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

- ❖ Study combinations of SDMEs which are purely natural or unnatural

$$\rho_{jk}^{N,U} = \frac{1}{2} \left(\rho_{jk}^0 \mp (-1)^i \rho_{-jk}^1 \right)$$

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

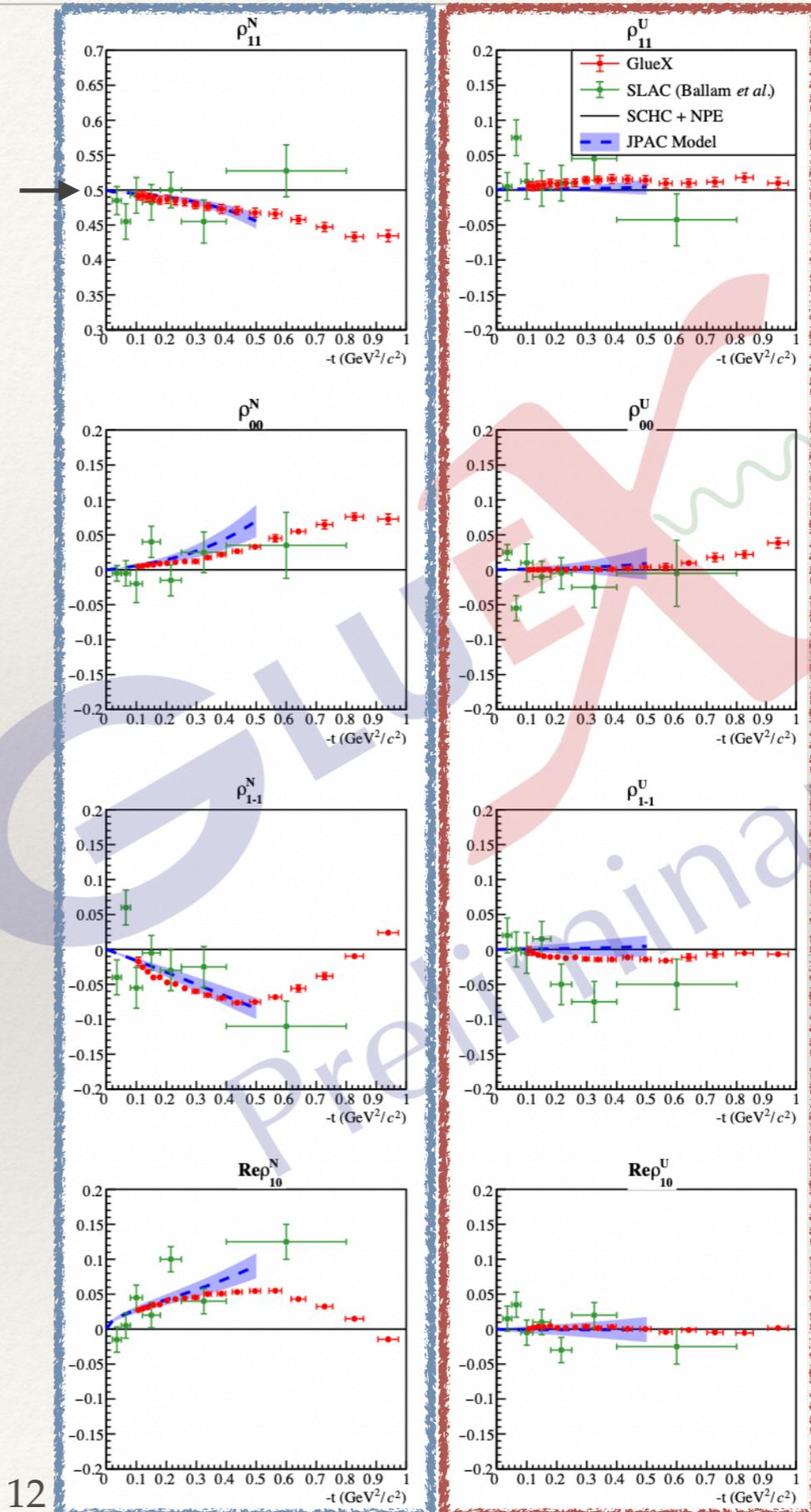
pos. parity exchange / natural:

e.g. f_2, a_2

neg. parity exchange / unnatural:

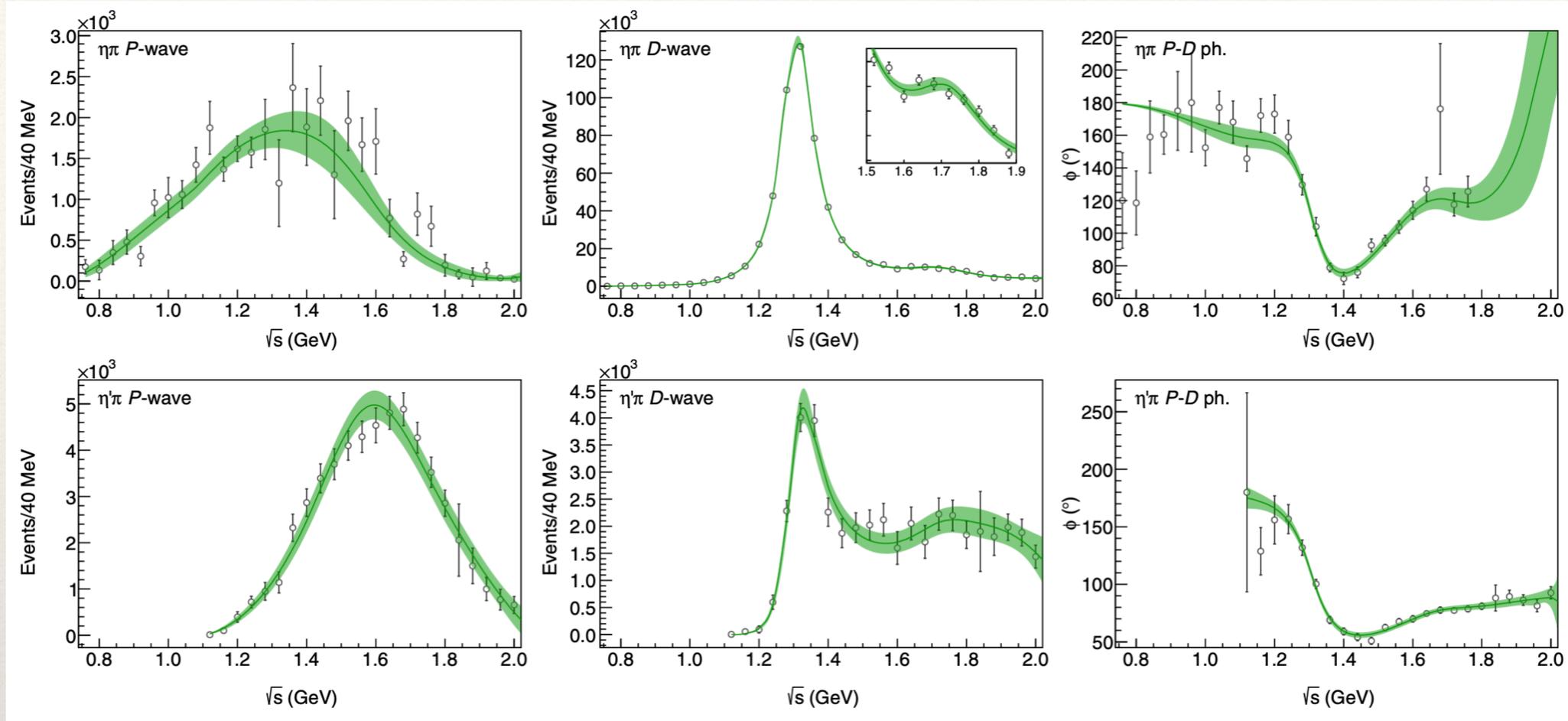
e.g. π, η

- ❖ Dominance of natural amplitudes
- ❖ Publication in preparation
- ❖ In the pipeline: ϕ, ω
- ❖ Already published: $K^+\Lambda(1520)$



Hybrid search in $\eta\pi$

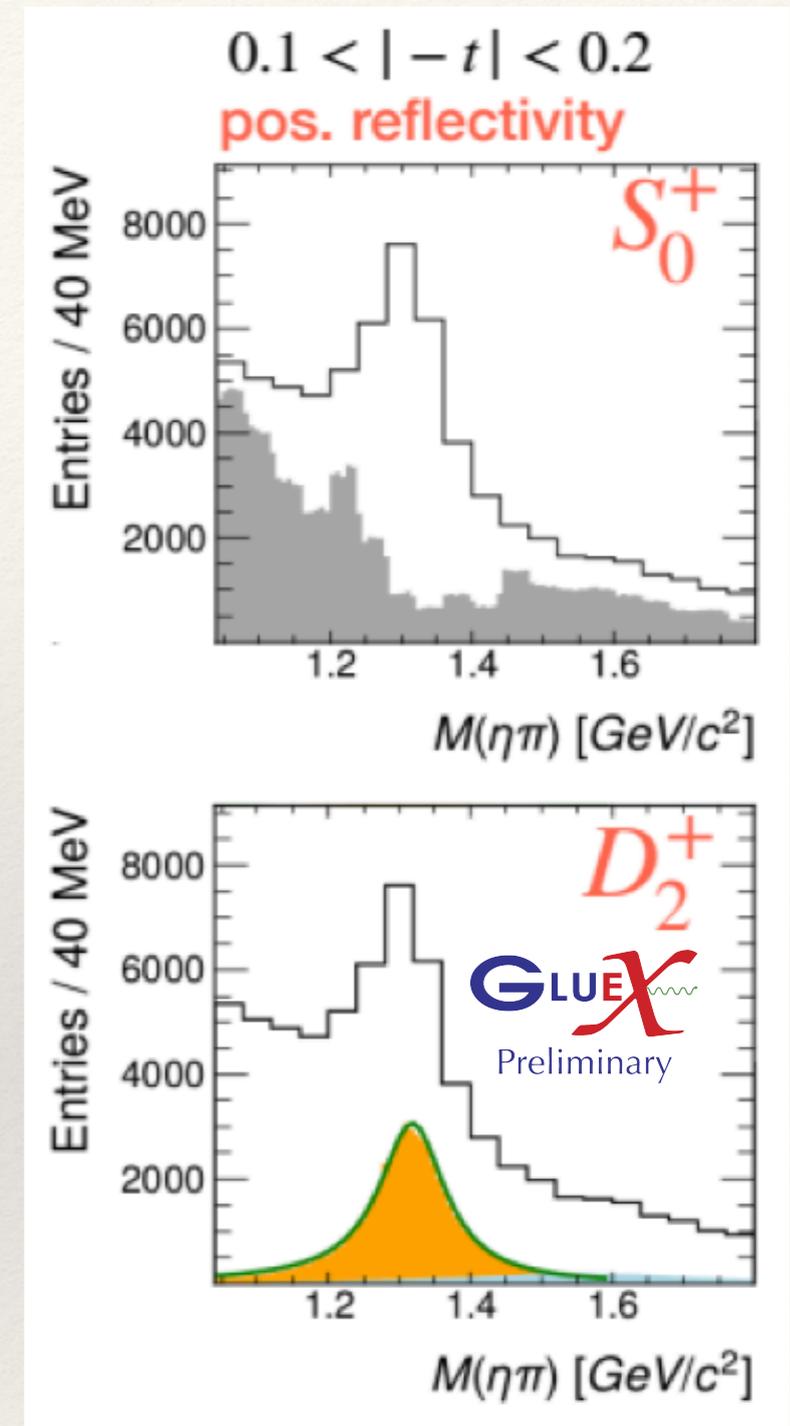
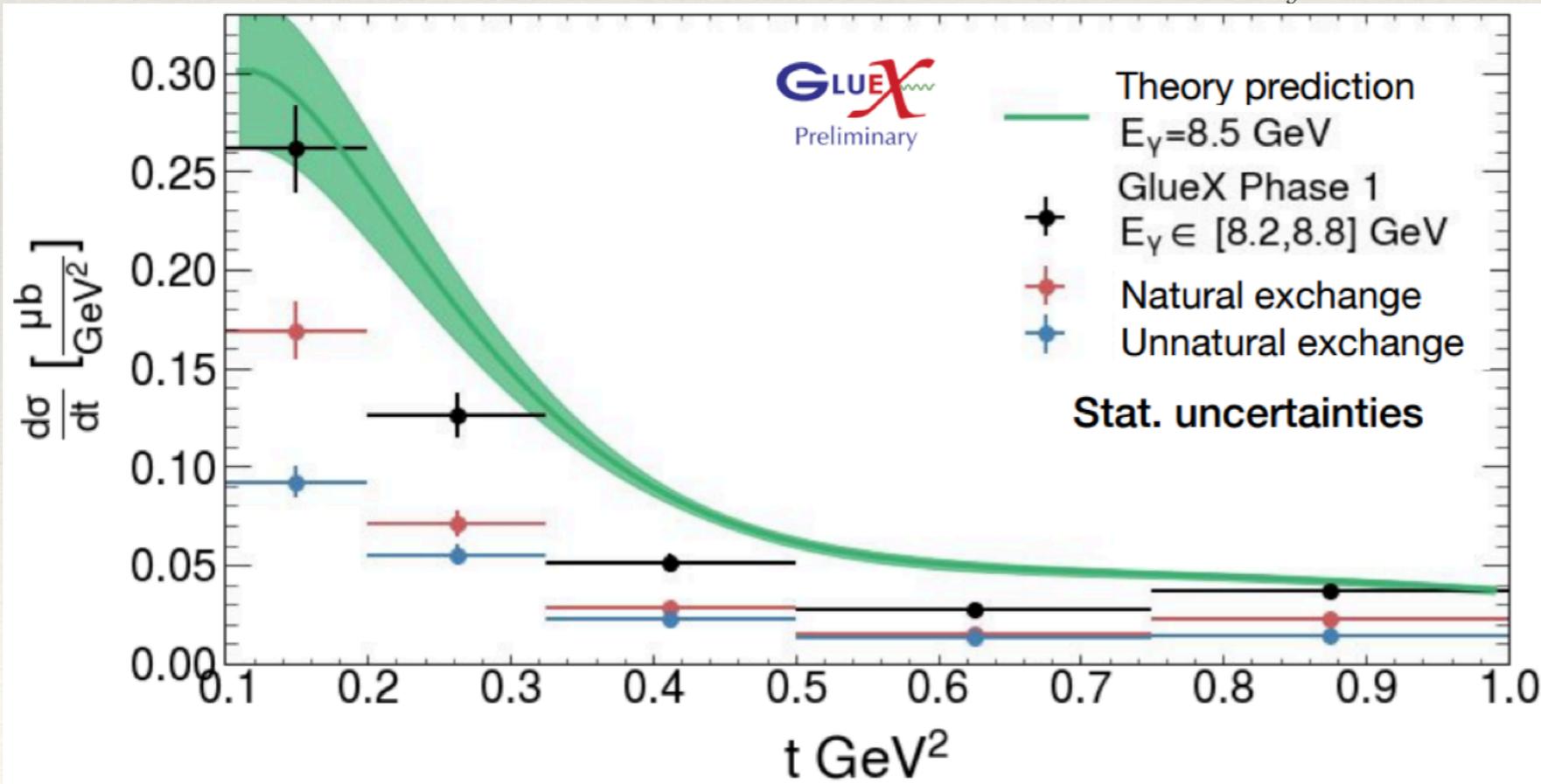
JPAC, *Phys. Rev. Lett.* **122**, 042002



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

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

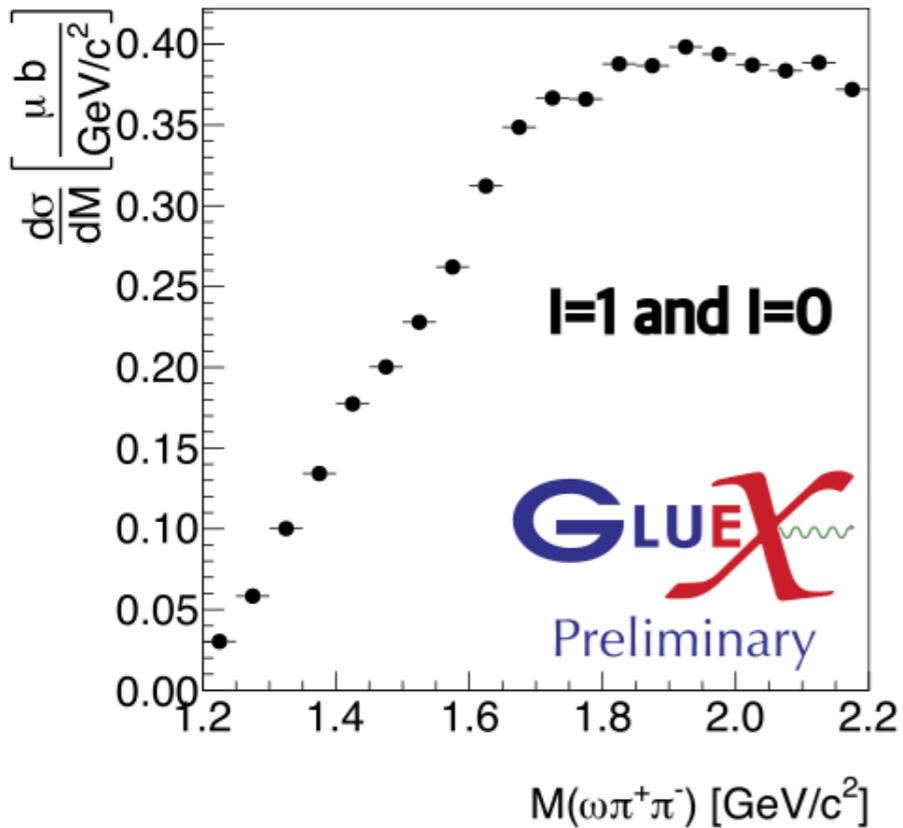
- ❖ First look at PWA in $\eta\pi^0$
- ❖ Study $a_2(1320)$ cross-section
- ❖ Positive helicity (natural exchange, e.g. ρ) dominates
- ❖ a_2 predominantly D_2 wave, consistent with helicity=2 dominance at Belle ($\gamma\gamma \rightarrow \eta\pi^0$)
Belle, Phys. Rev. D 80, 032001



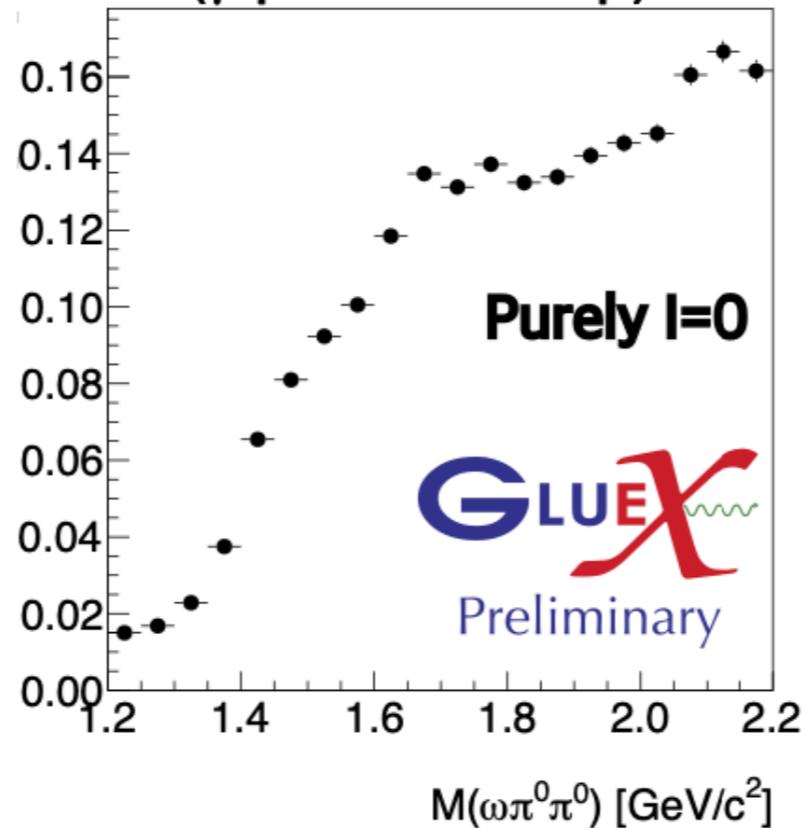
Mixed method: imposing BW shape on a_2 improves fit

$\pi_1(1600)$ upper limits

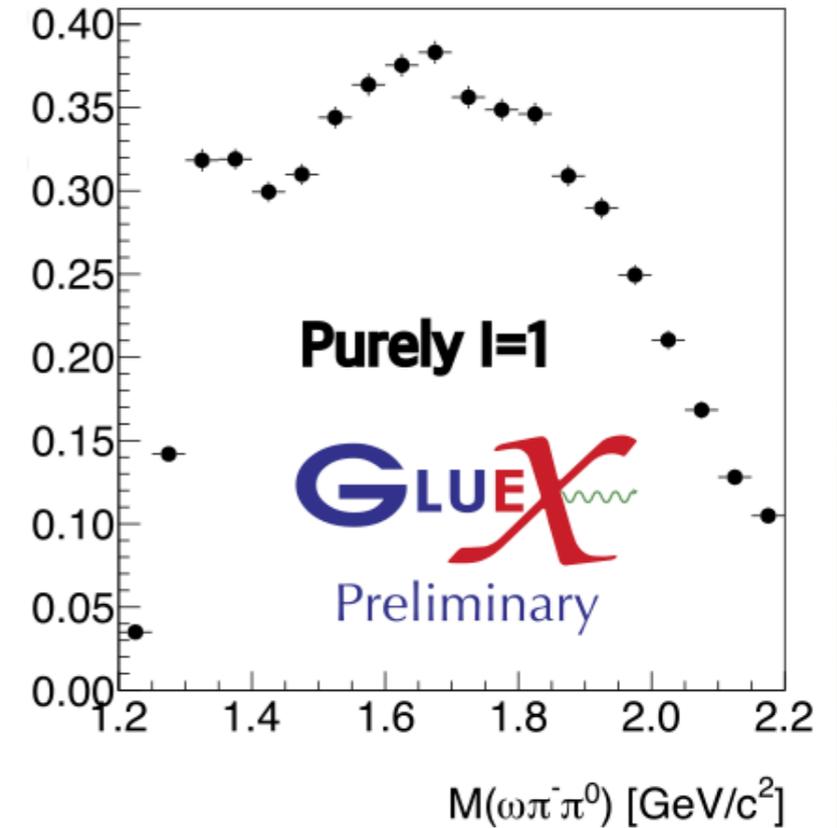
$\sigma(\gamma p \rightarrow \omega \pi^+ \pi^- p)$



$\sigma(\gamma p \rightarrow \omega \pi^0 \pi^0 p)$

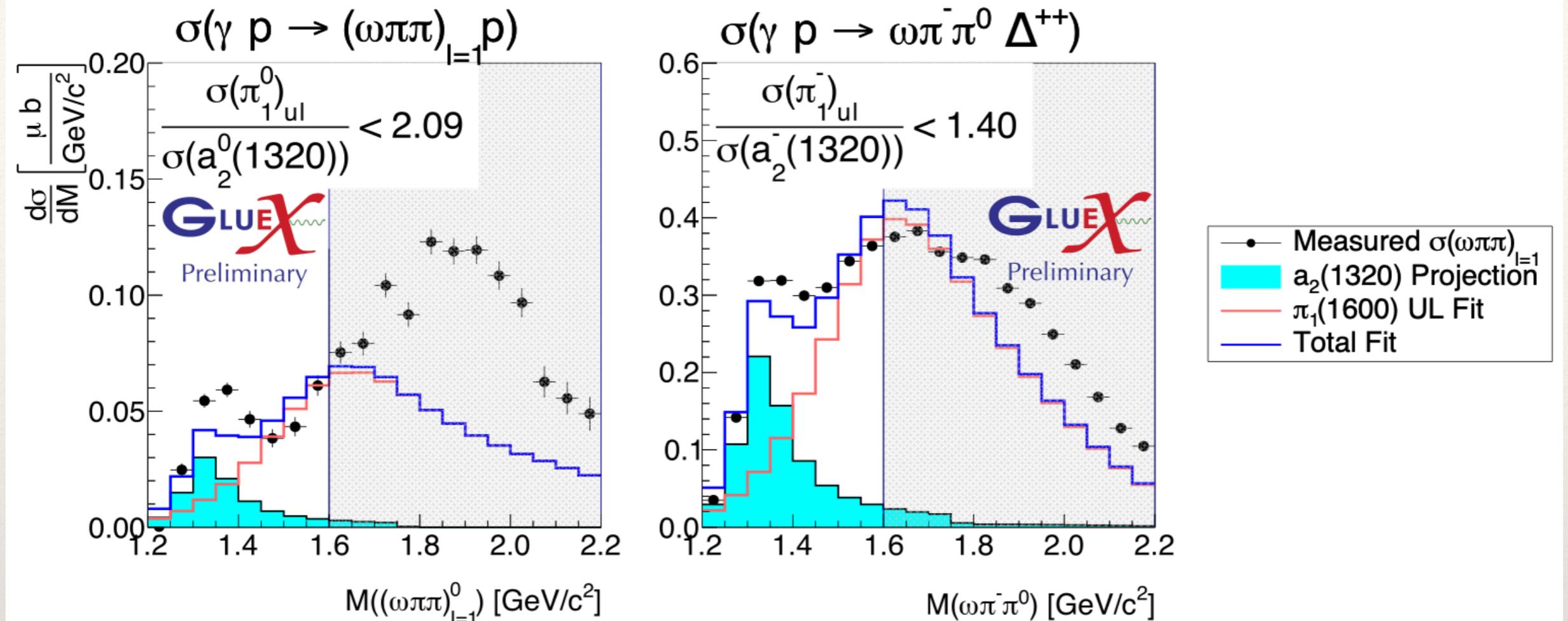


$\sigma(\gamma p \rightarrow \omega \pi^- \pi^0 \Delta^{++})$



- ❖ 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)

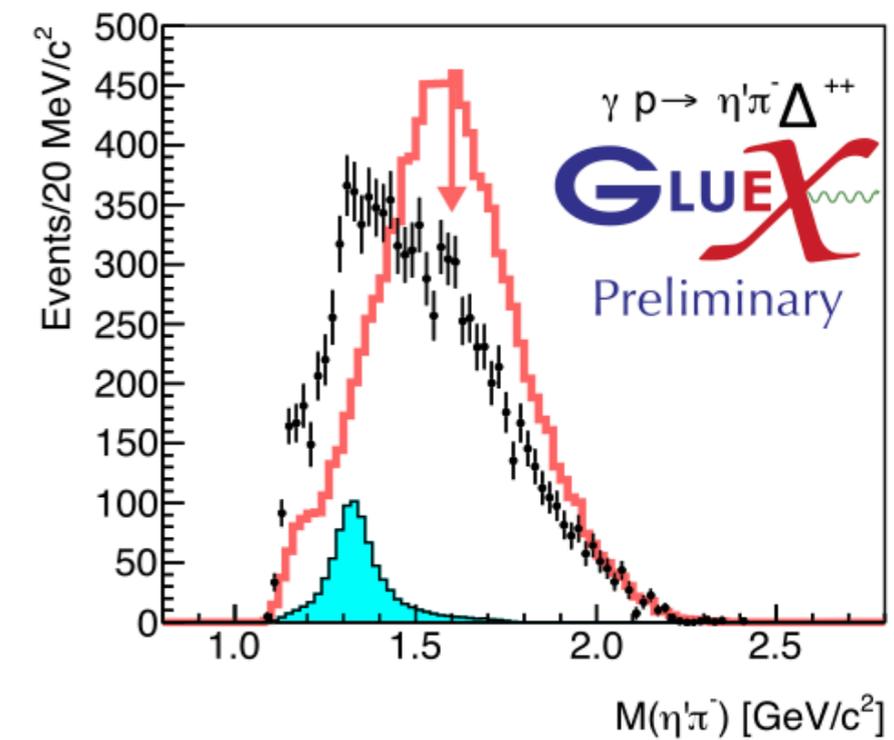
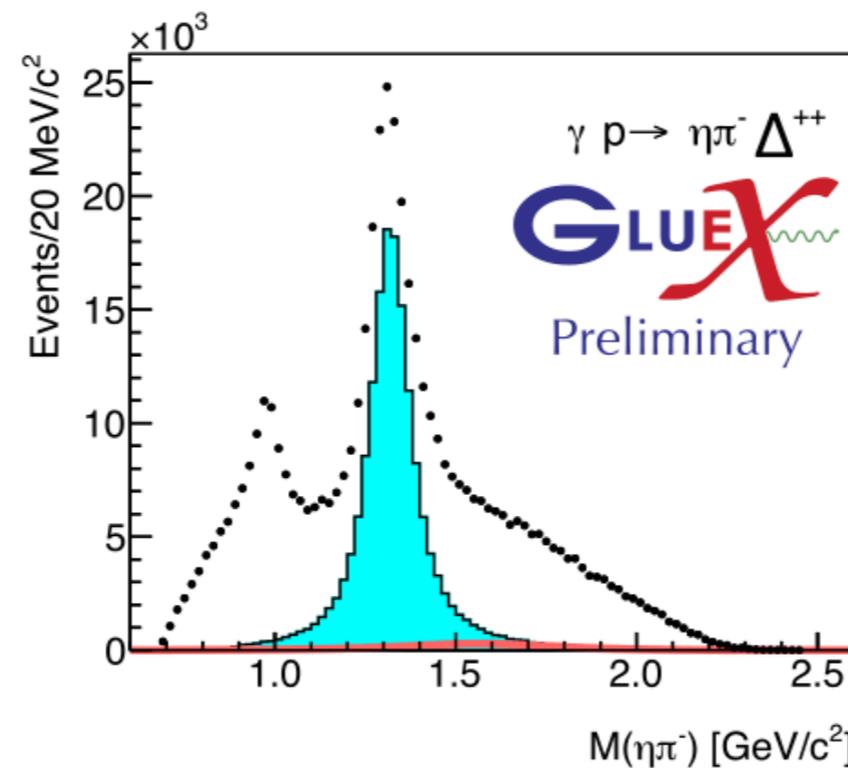
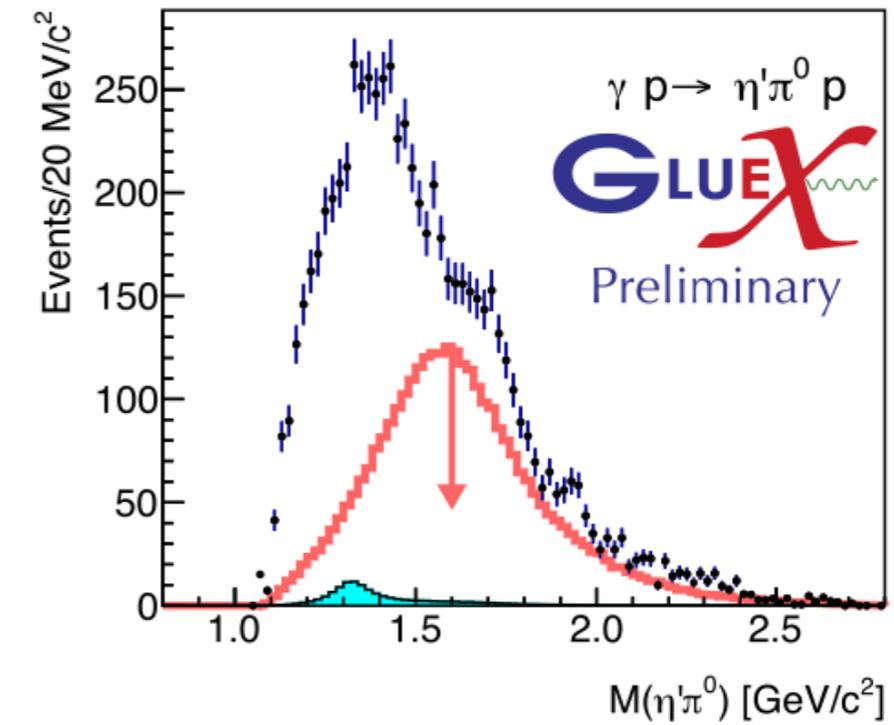
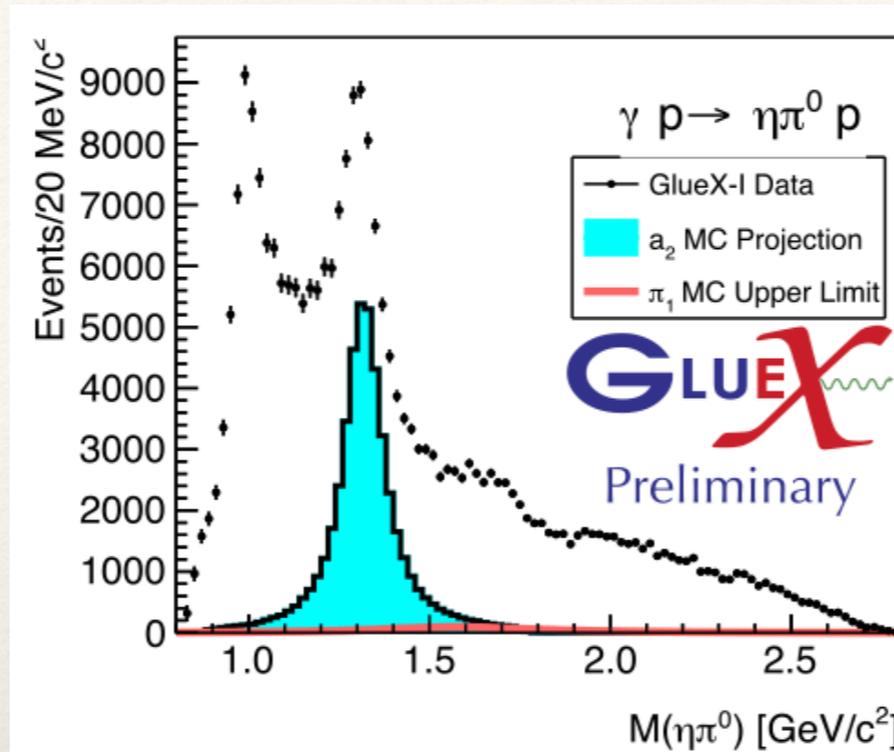
$\pi_1(1600)$ upper limits



- ❖ Fit $M(\omega\pi\pi)_{I=1} < 1.6 \text{ GeV}/c^2$
- ❖ 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 $\eta'\pi$

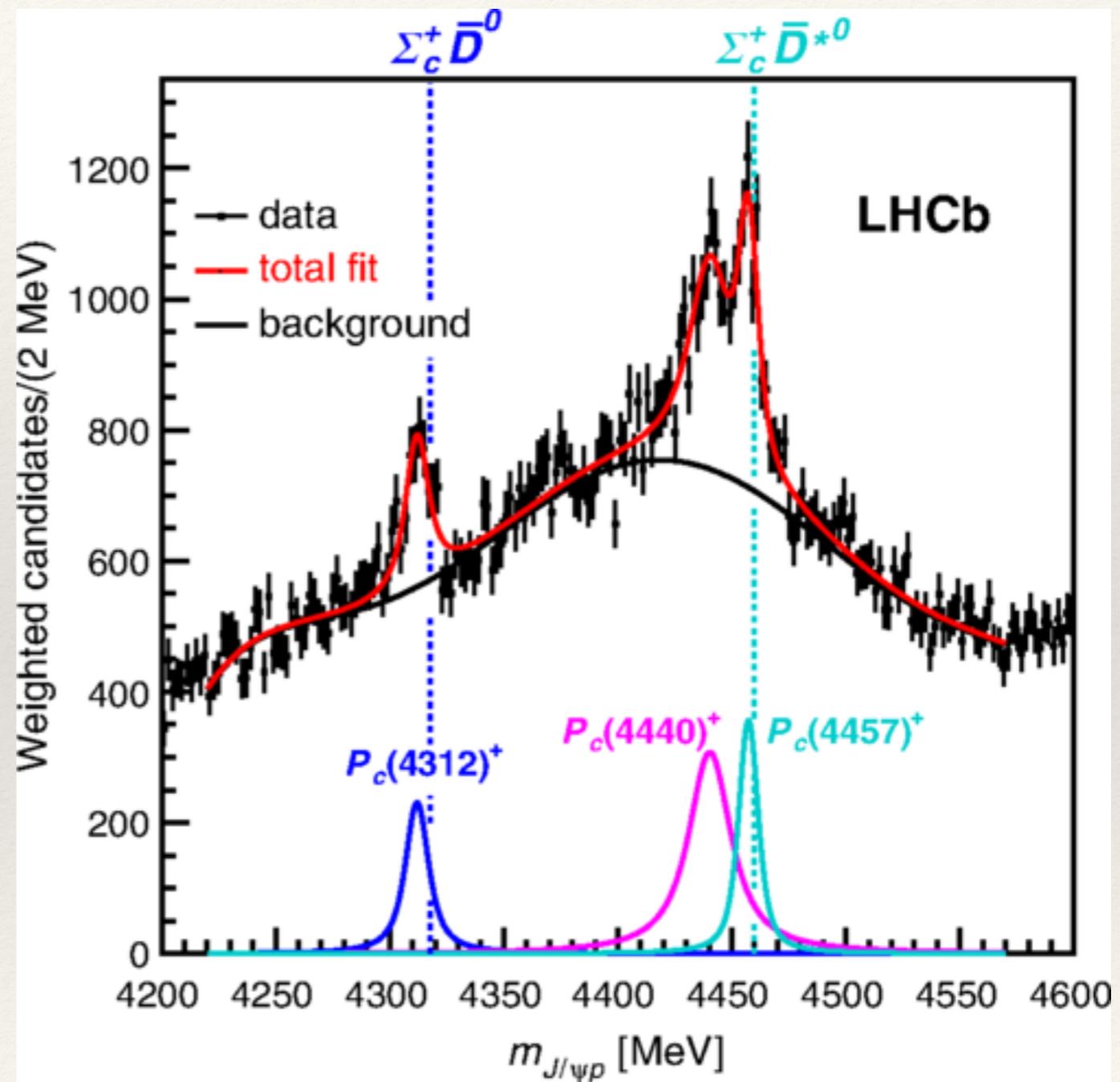
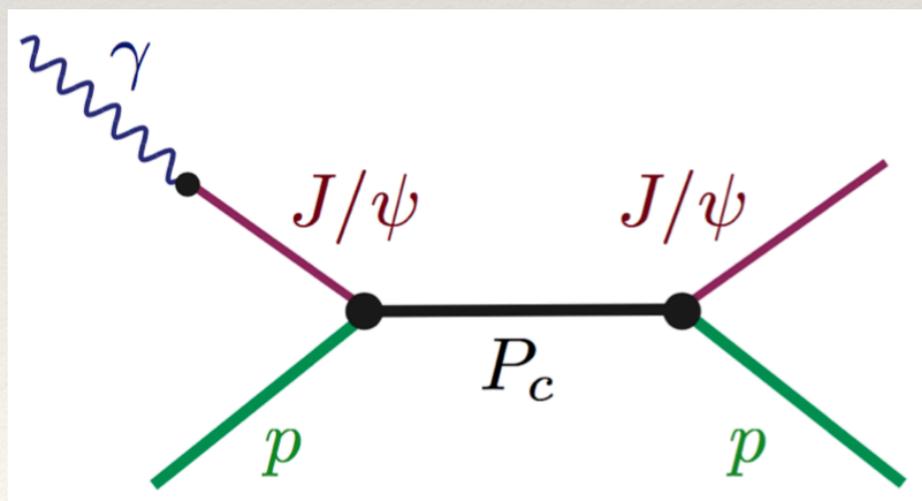
- ❖ $\pi_1 \rightarrow \eta\pi$ expected to be very small
- ❖ $\pi_1 \rightarrow \eta'\pi$ potentially dominating the spectrum
- ❖ First limit on size of photoproduction cross-sections
- ❖ Guidance for amplitude analysis



$J/\psi p$

- ❖ LHCb sees pentaquark signal in $\Lambda_b^0 \rightarrow J/\psi p K^-$
- ❖ GlueX can search for s-channel production

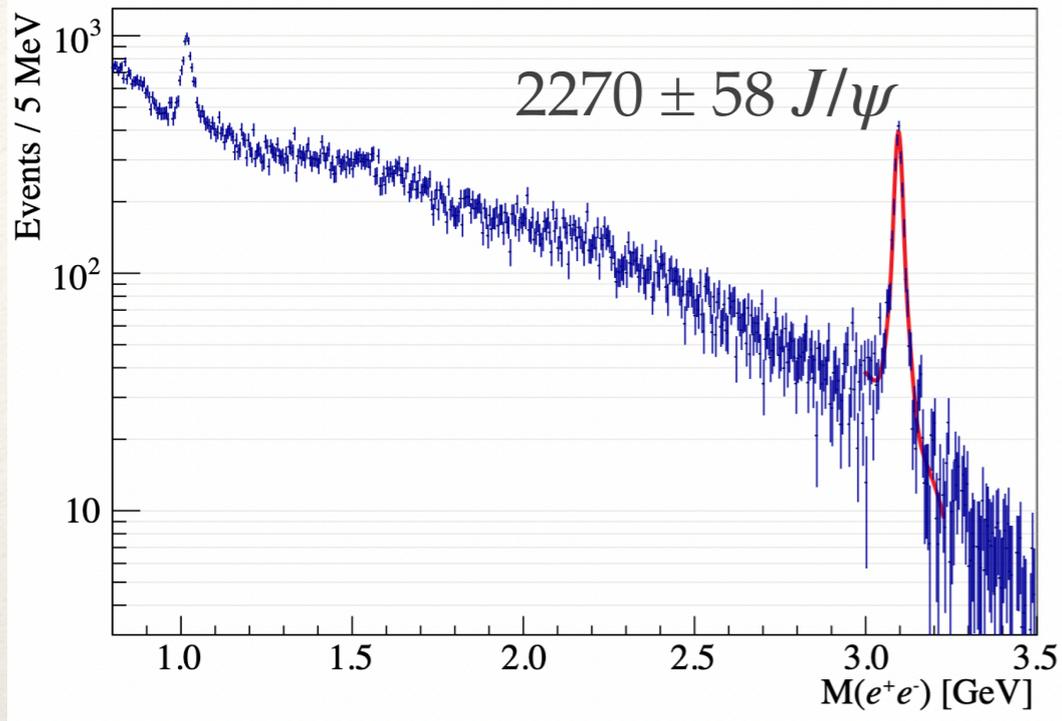
VMD



LHCb, Phys. Rev. Lett. 122, 222001

$J/\psi p$

GlueX, *Phys. Rev. Lett.* **123**, 072001
arXiv:2304.03845



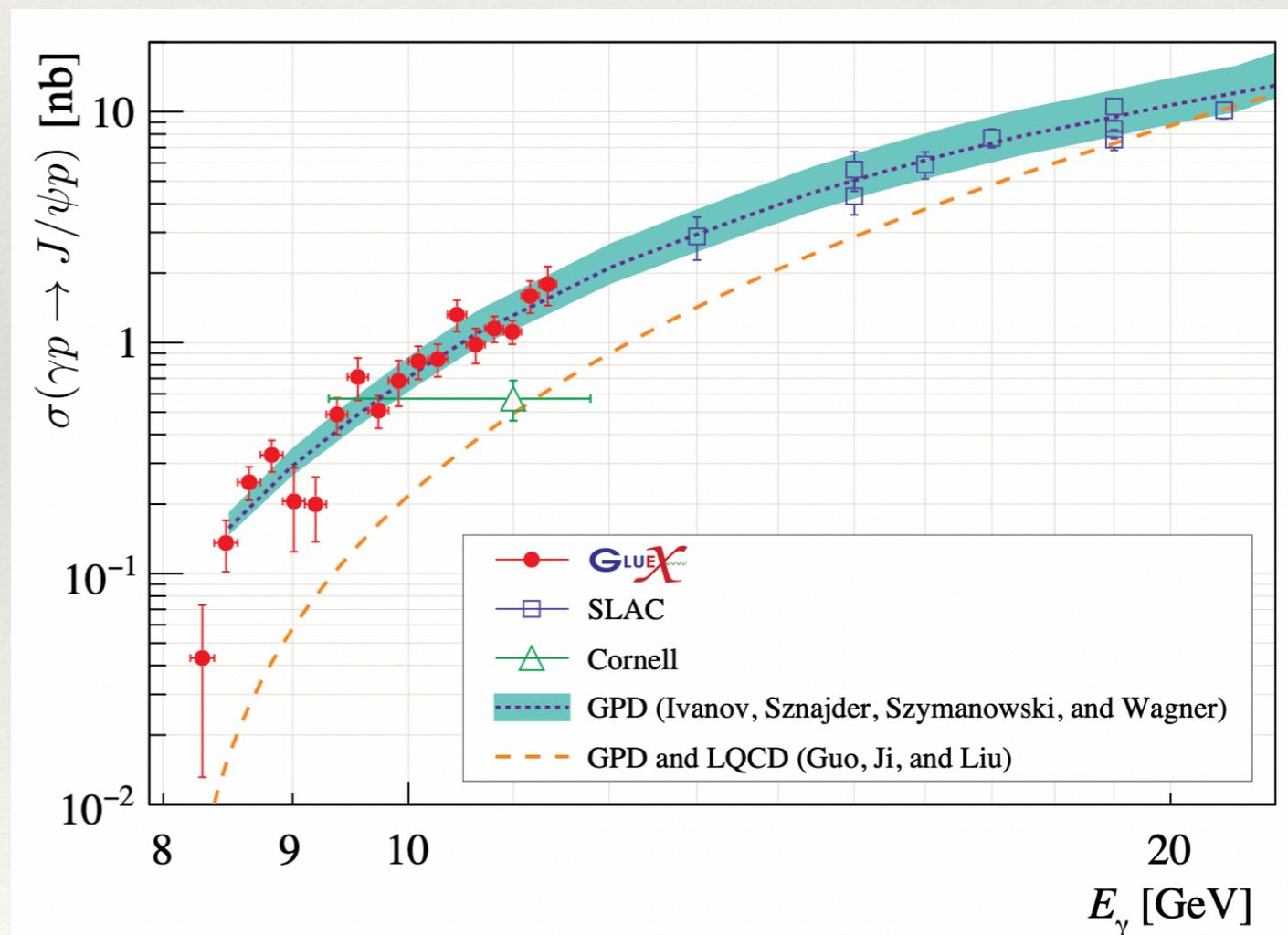
- ❖ measure leptonic decay
 $\gamma p \rightarrow J\psi p \rightarrow e^+ e^- p$
- ❖ exclusive reaction
- ❖ normalise cross-section to non-resonant $e^+ e^-$ production (Bethe-Heitler)

- ❖ Updated measurement:
 4x more stats
- ❖ Dip at ~ 9 GeV has 2.6σ significance
 (with look-elsewhere-effect 1.4σ)
- ❖ Improved model dependent P_c
 upper limits by $\sim 30\%$
 previous:

$$BR(P_c(4312) \rightarrow J/\psi p) < 4.6 \%$$

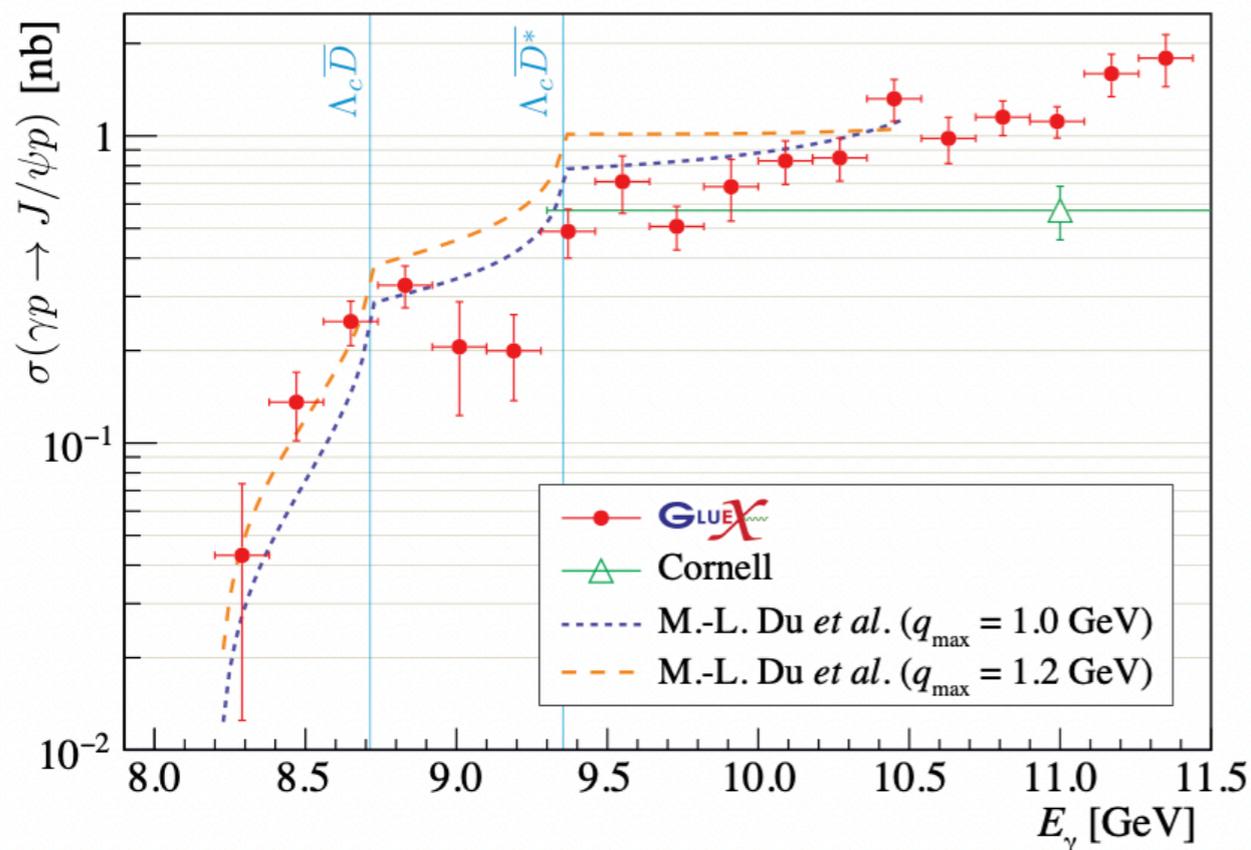
$$BR(P_c(4440) \rightarrow J/\psi p) < 2.3 \%$$

$$BR(P_c(4457) \rightarrow J/\psi p) < 3.8 \%$$



$J/\psi p$

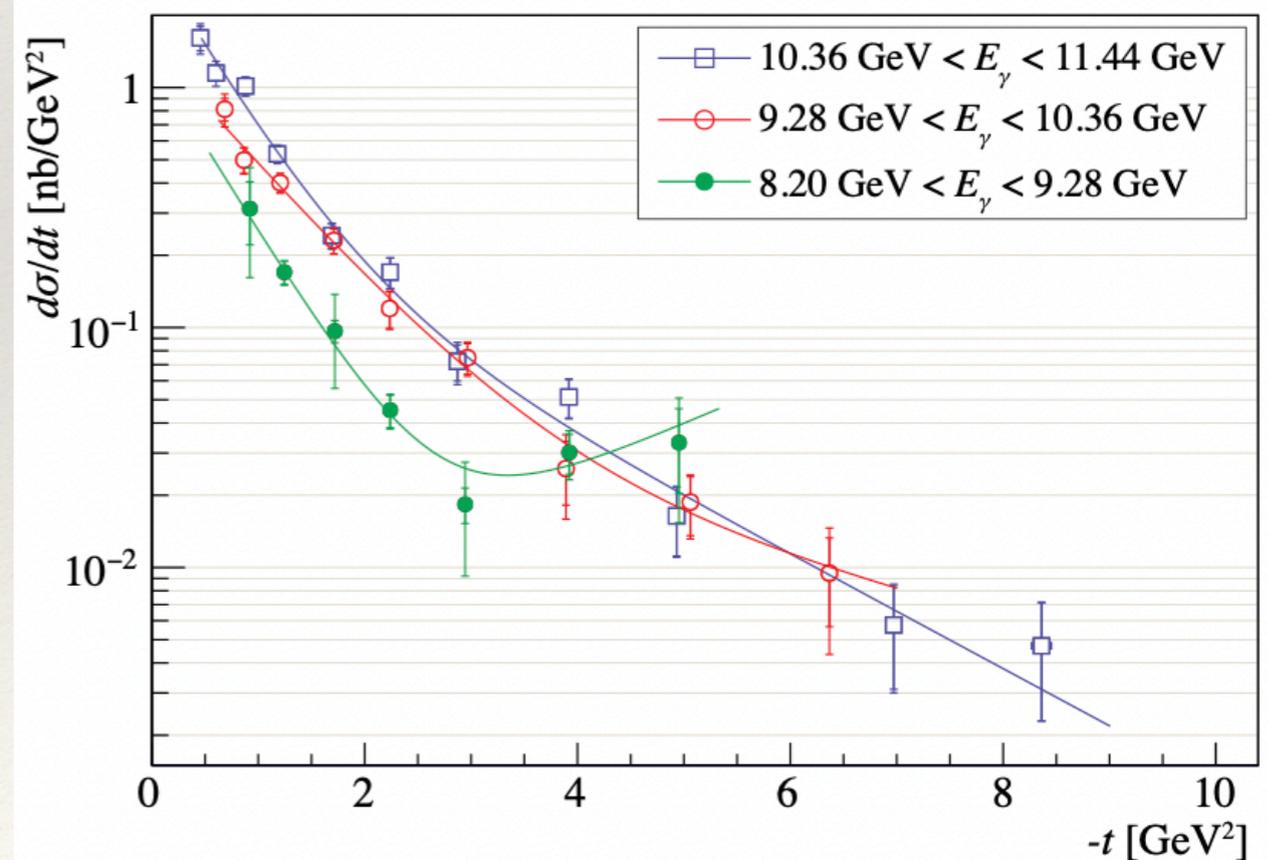
GlueX, Phys. Rev. Lett. 123, 072001
arXiv:2304.03845



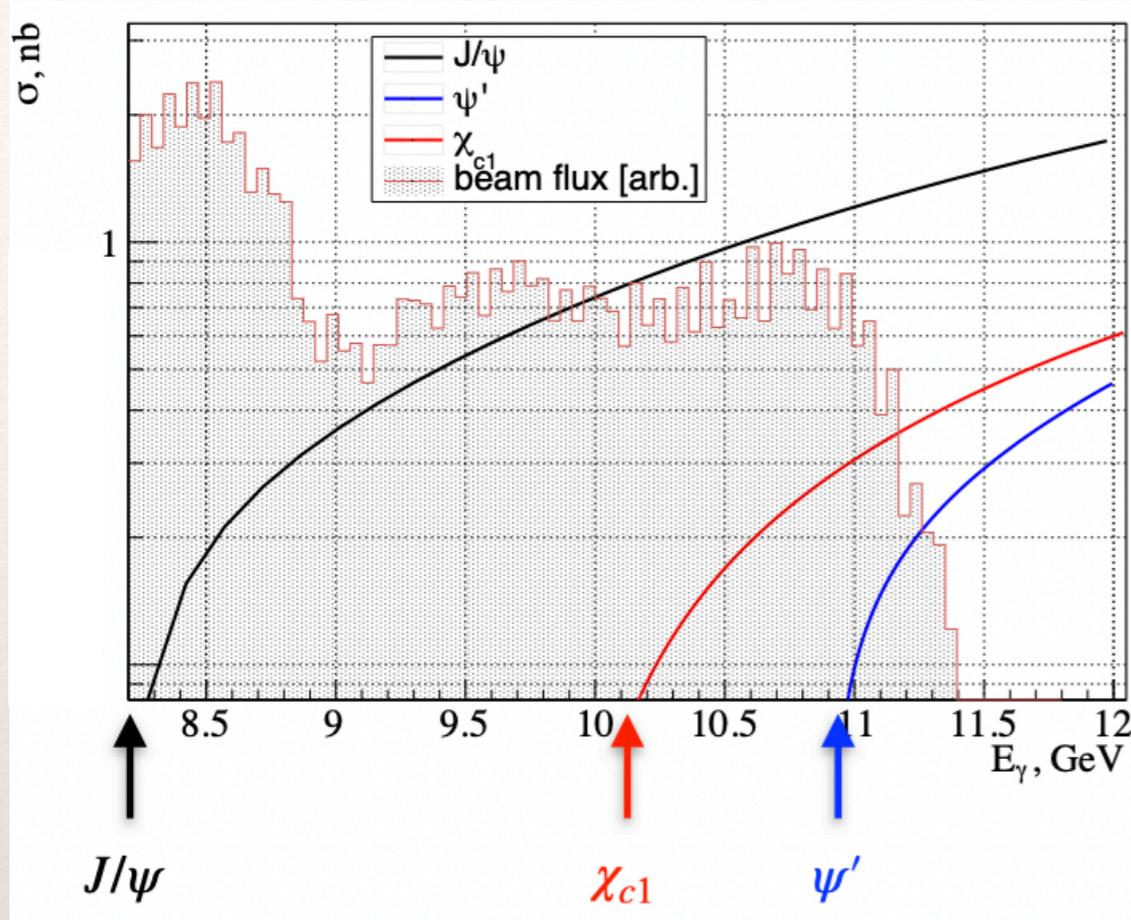
M.-L. Du et al. Deciphering the mechanism of near-threshold J/ψ photoproduction. Eur. Phys. J. C 80, 1053 (2020)

- ❖ Flattening of $d\sigma/dt$ in lowest energy range
- ❖ Indication of s- or u-channel contribution?
- ❖ Need better understanding of production mechanism

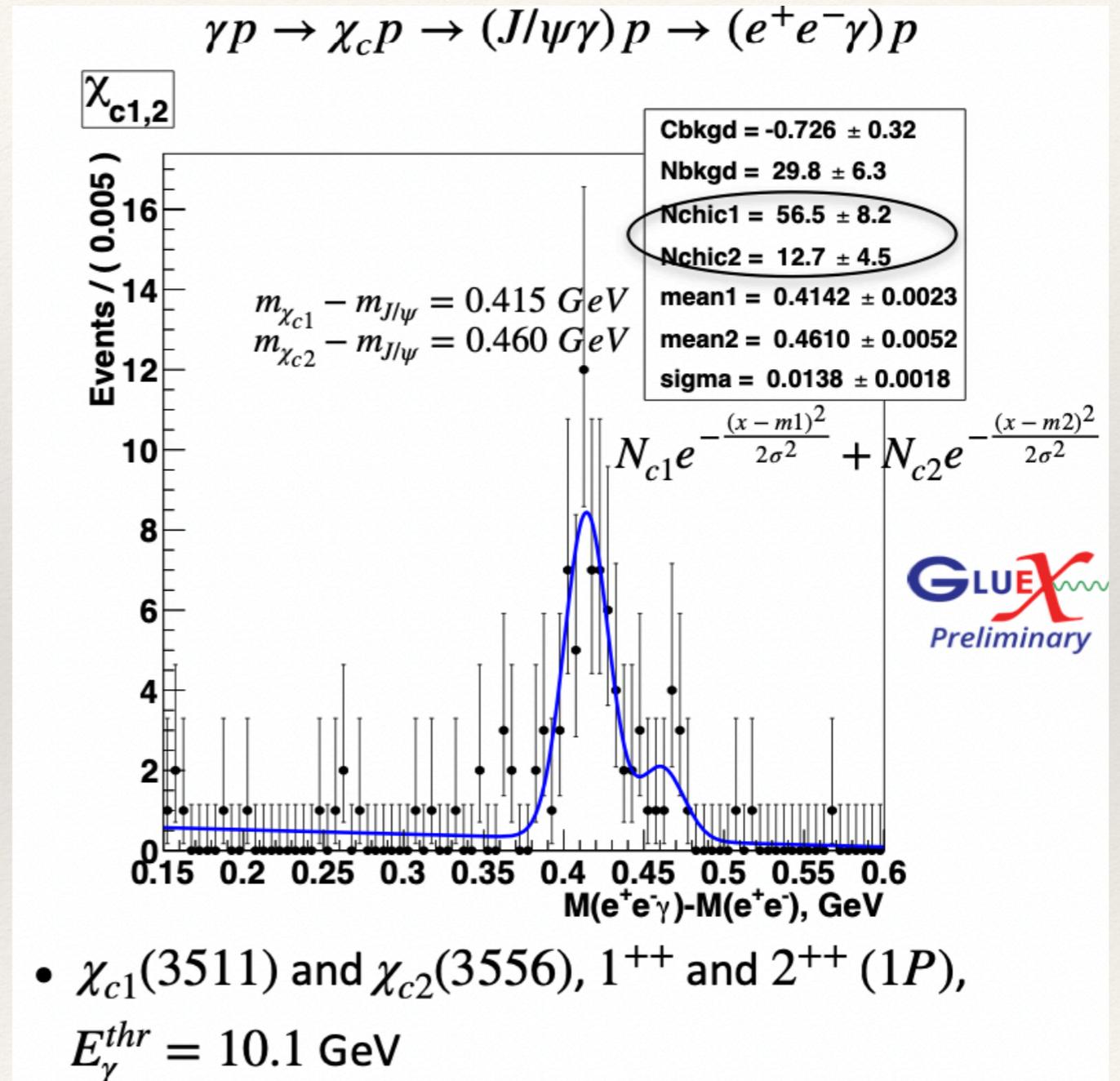
- ❖ Du et al. propose production through $\Lambda_c \bar{D}$ and $\Lambda_c \bar{D}^*$
- ❖ Generate cusp structures



Further Charmonium states

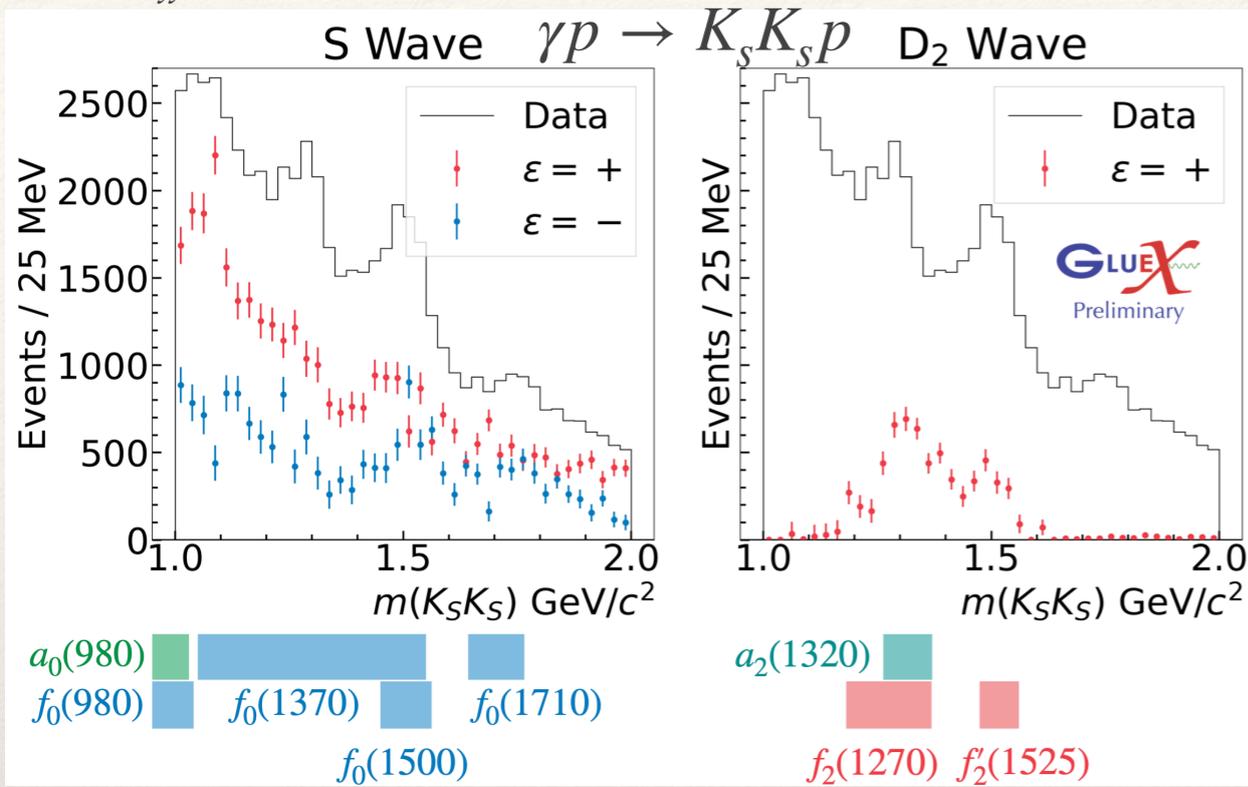


- ❖ Small number of χ_{c1} and χ_{c2}
- ❖ Even a few ψ'

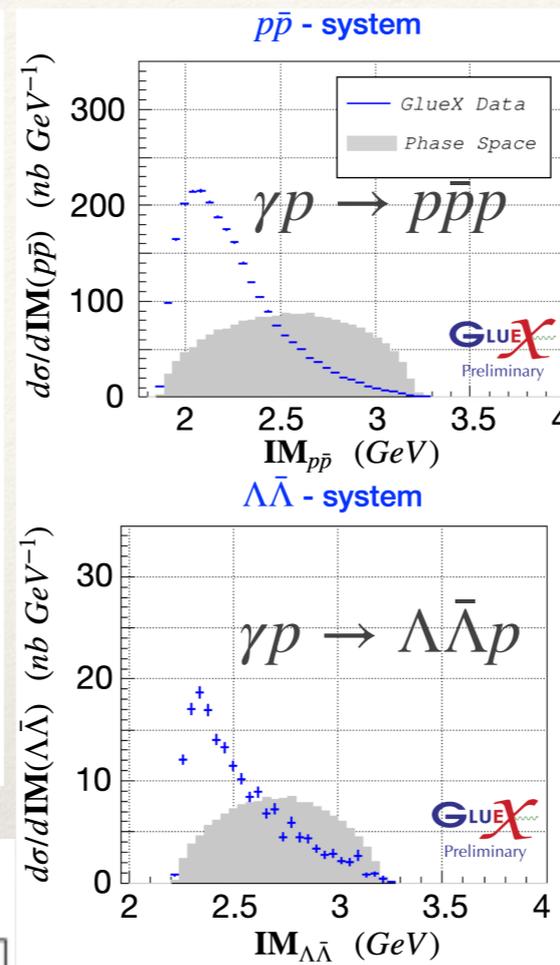


Further analyses

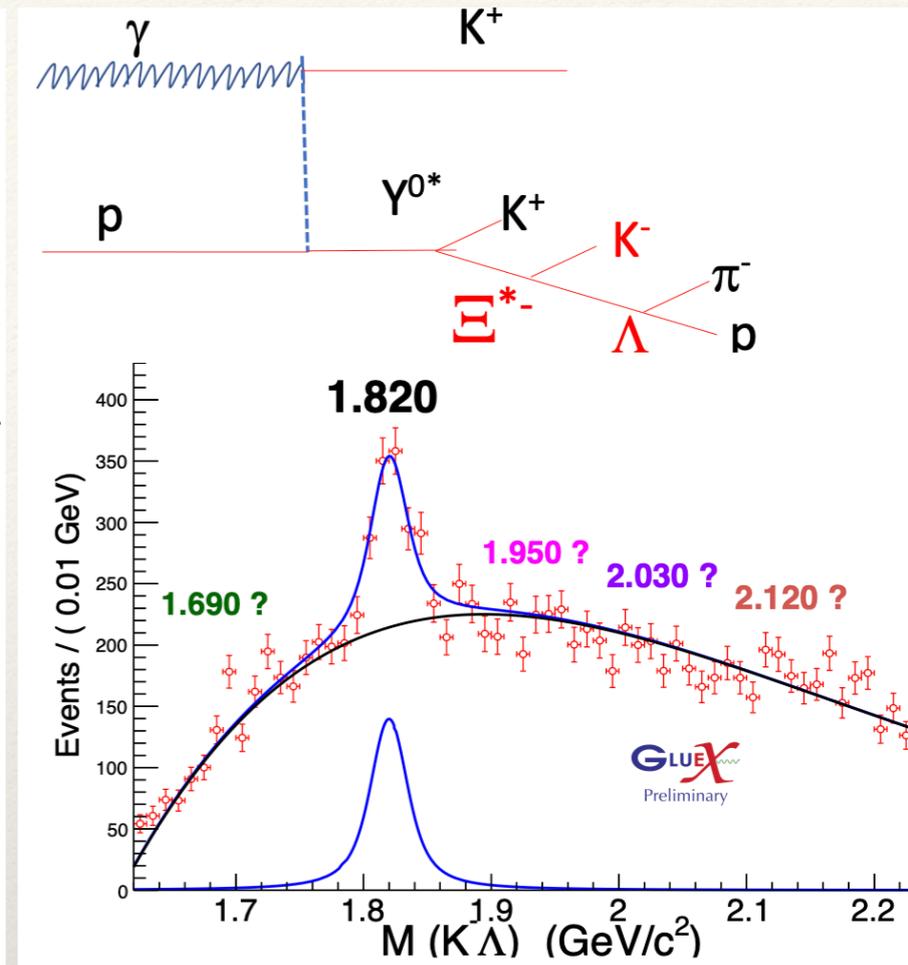
N. D. Hoffman, APS 4/2023



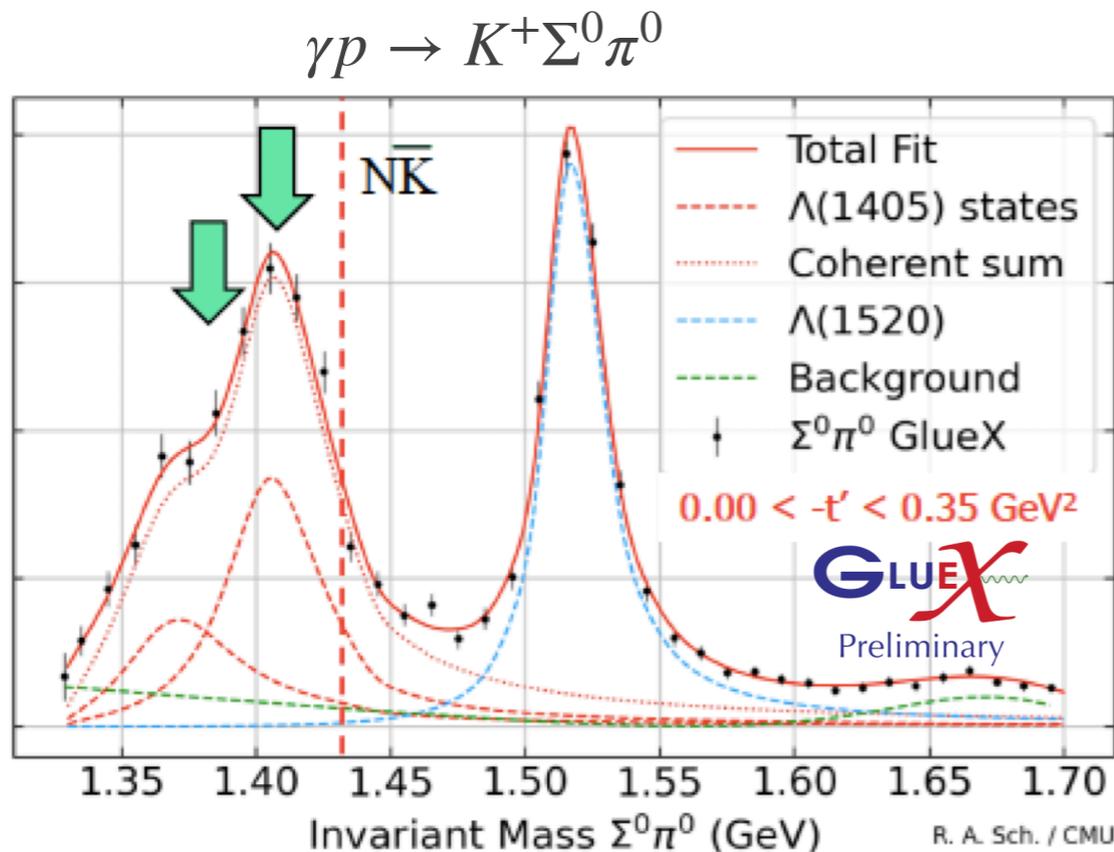
Hao Li, APS-DNP 2021



C. Akondi, GHP 2023

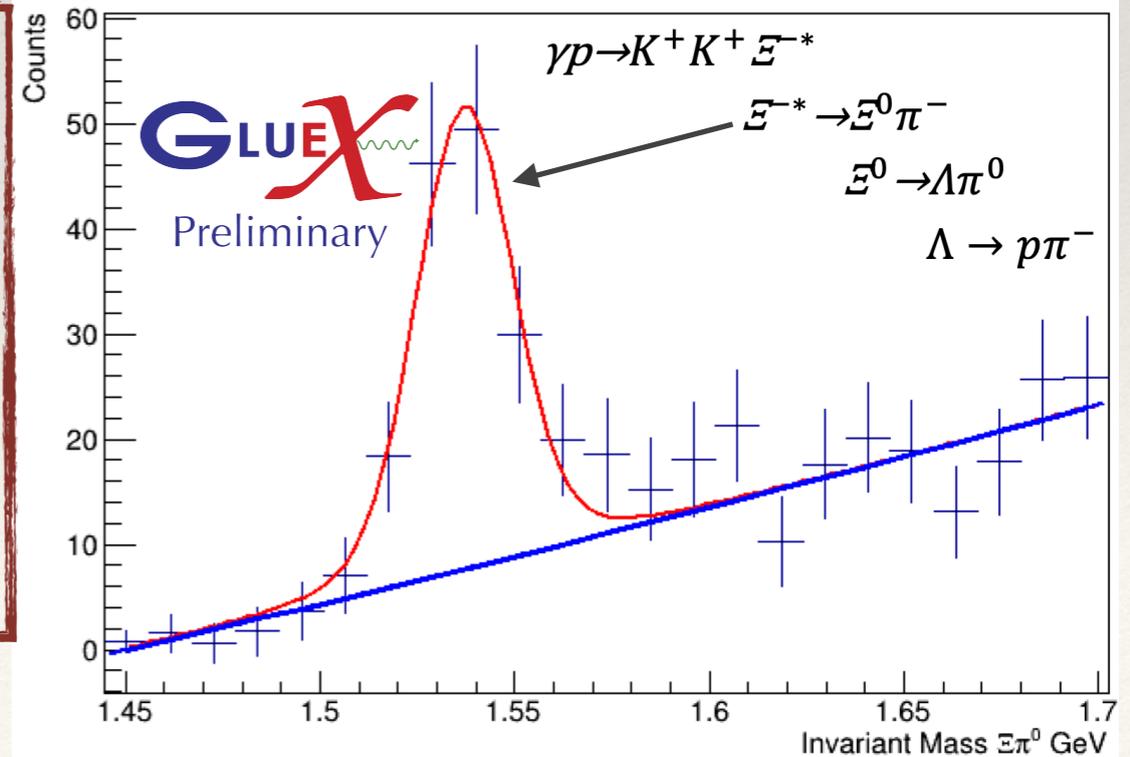


Cross section $d\sigma/dM$ (a.u.)



Just a glimpse of our ongoing physics program

B. Sumner, GHP 2023



N. Wickramaarachchi, HYP2022

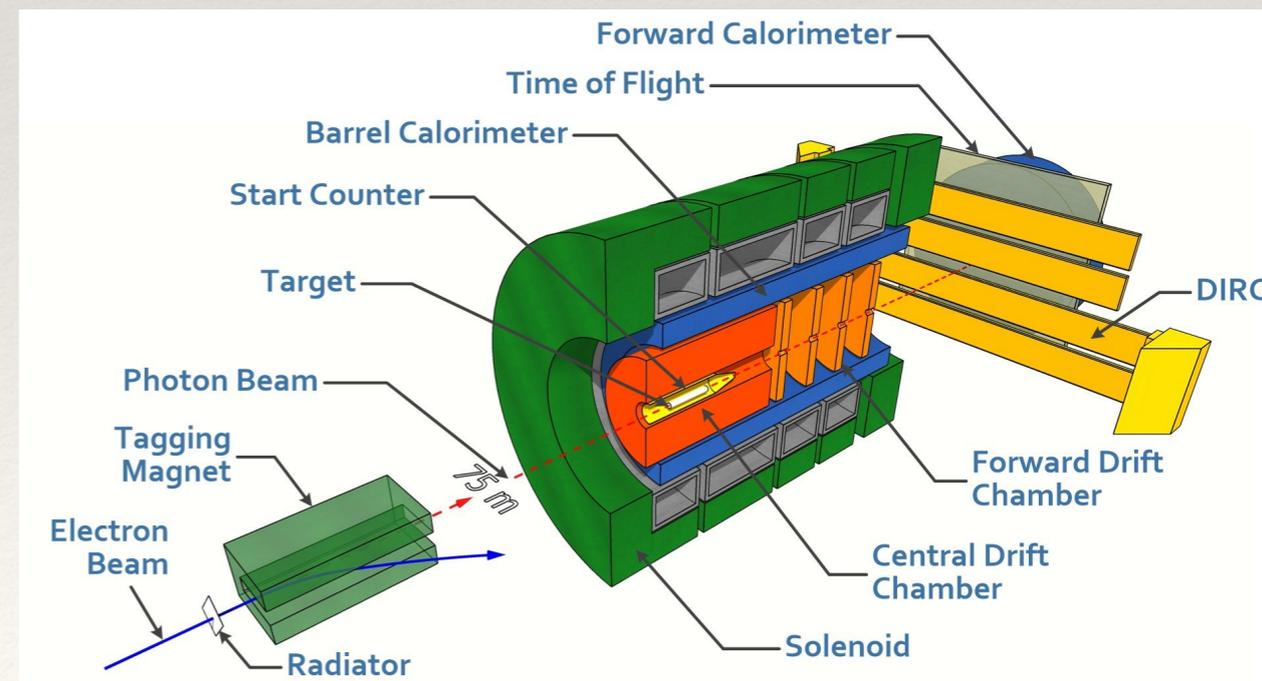
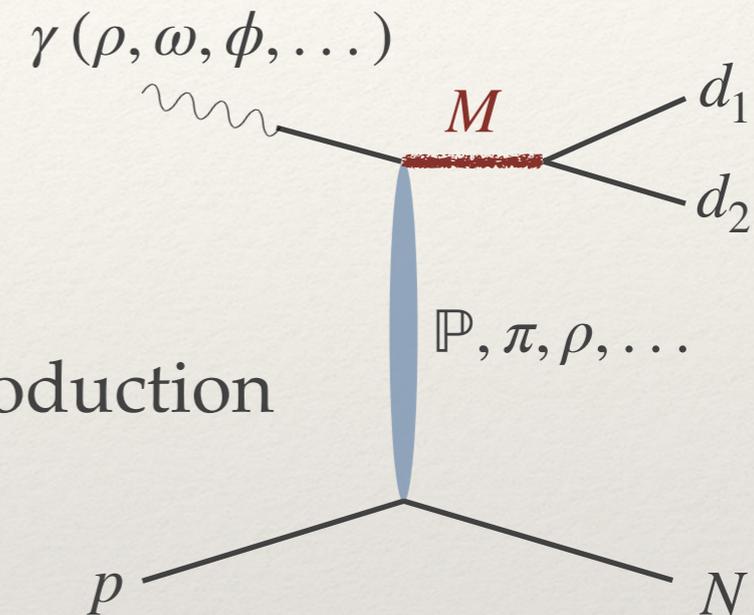
Summary

Acknowledgments:



gluex.org/thanks

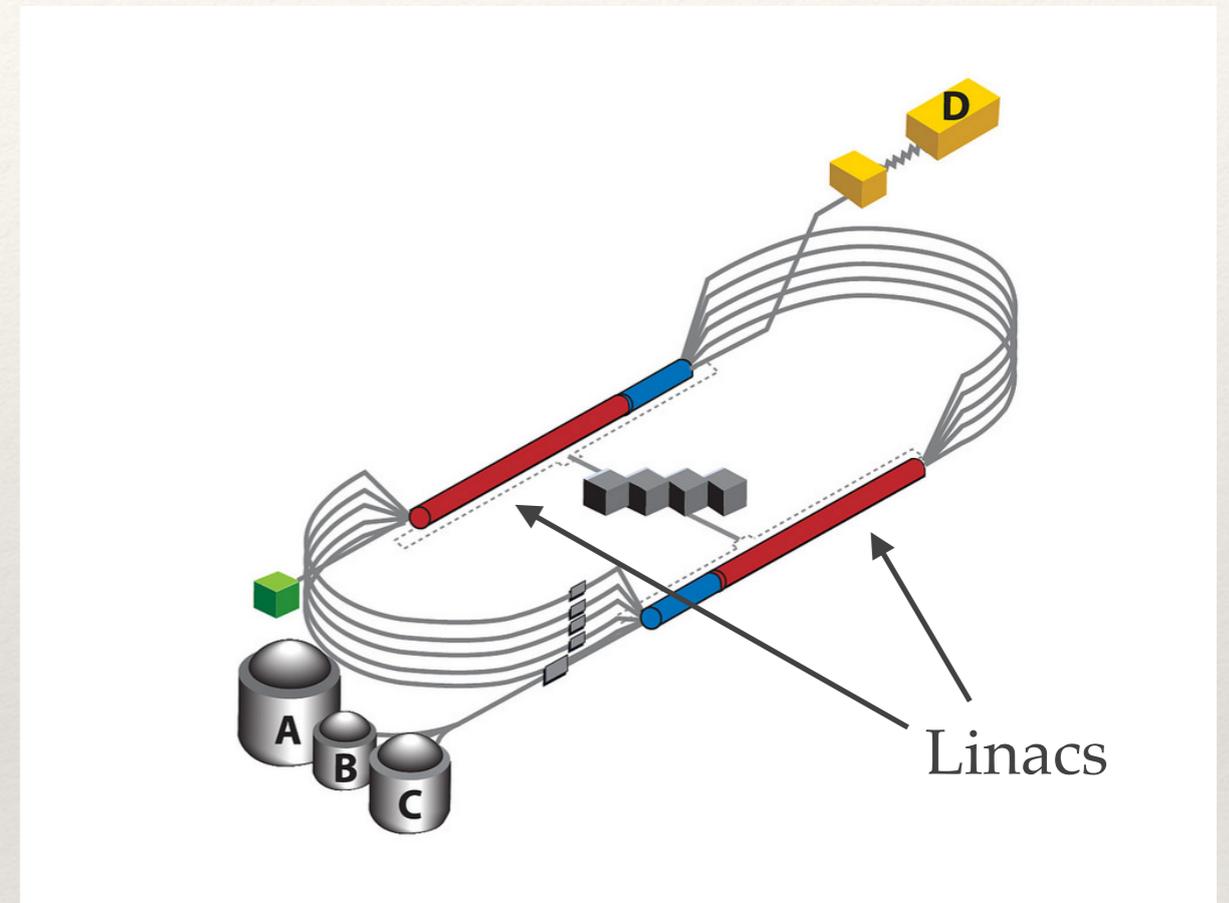
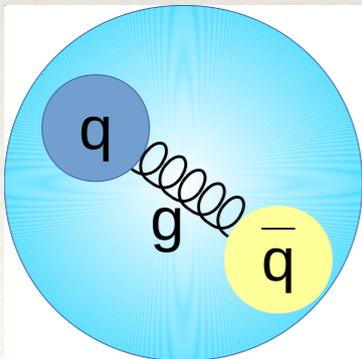
- ❖ GlueX has a unique data set with unprecedented statistical precision in its energy range
- ❖ Start with studying production mechanisms and develop PWA in parallel
- ❖ $\pi_1(1600)$ upper limits, guide for future searches
- ❖ J/Ψ near threshold extends understanding of production mechanism
- ❖ Many more interesting analyses in the pipeline and room for other physics:
 - ❖ $\Lambda(1405)$, cascades, ALPs, ...
- ❖ Future and outlook:
 - ❖ Ongoing GlueX-II
 - ❖ KLong, HI-Gluex, GlueX-24 (?)



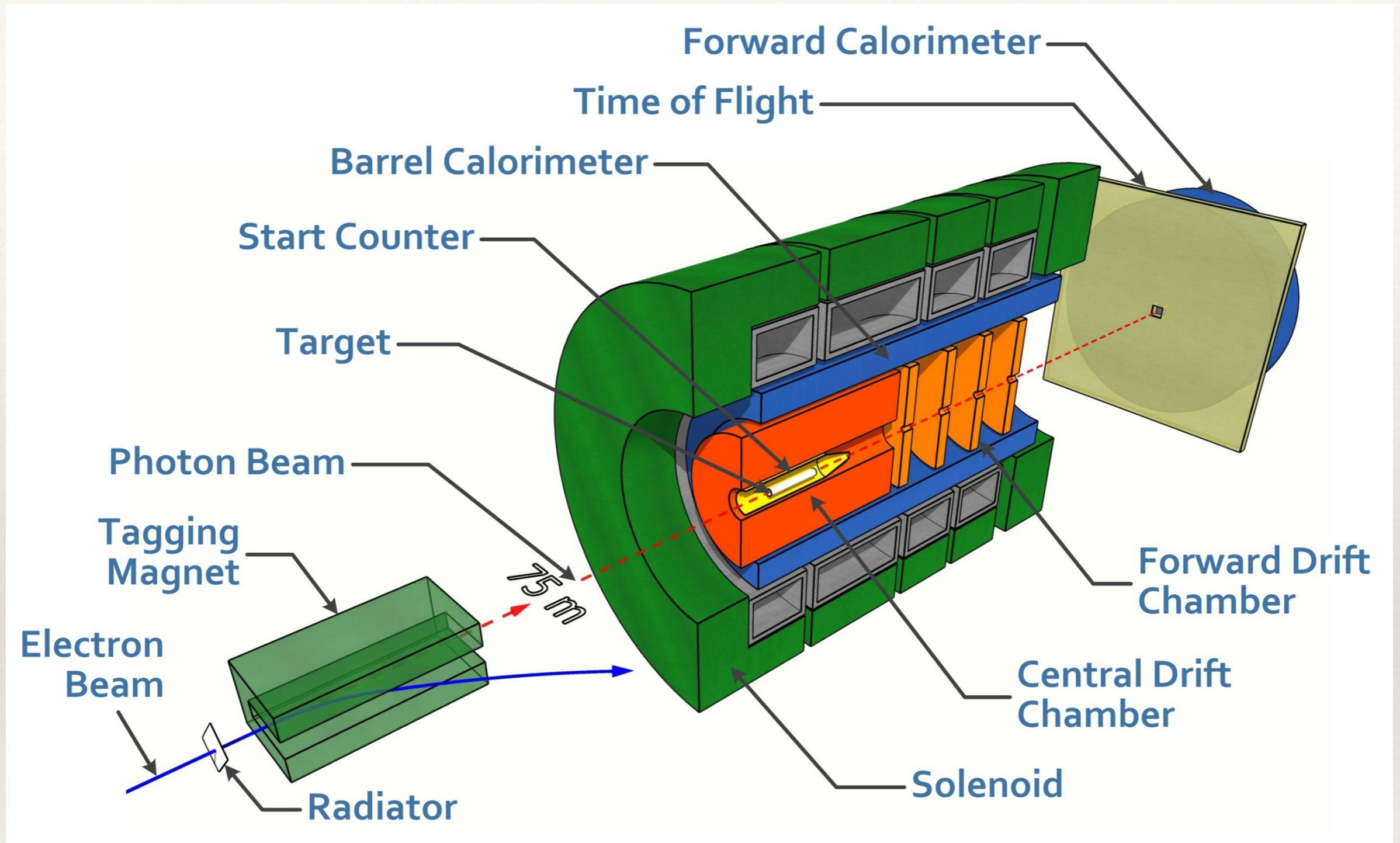
Backup

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



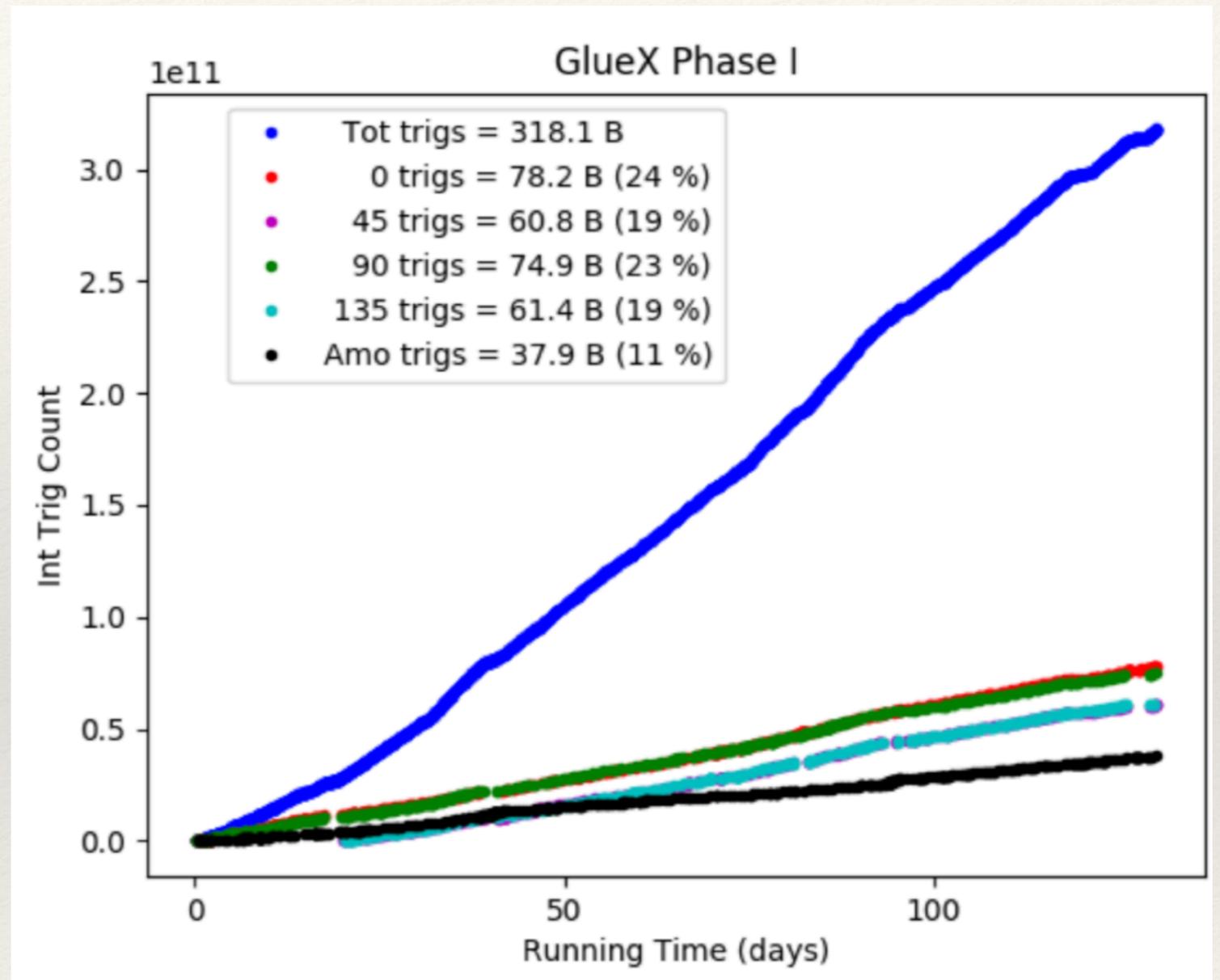
GlueX experiment in Hall D



- ❖ 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



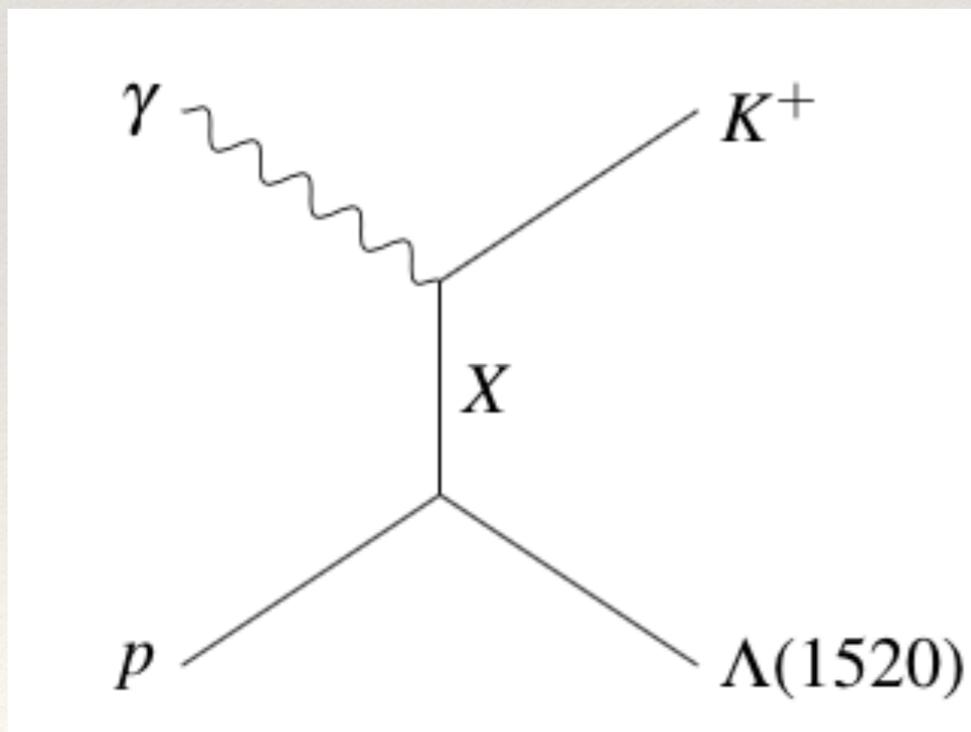
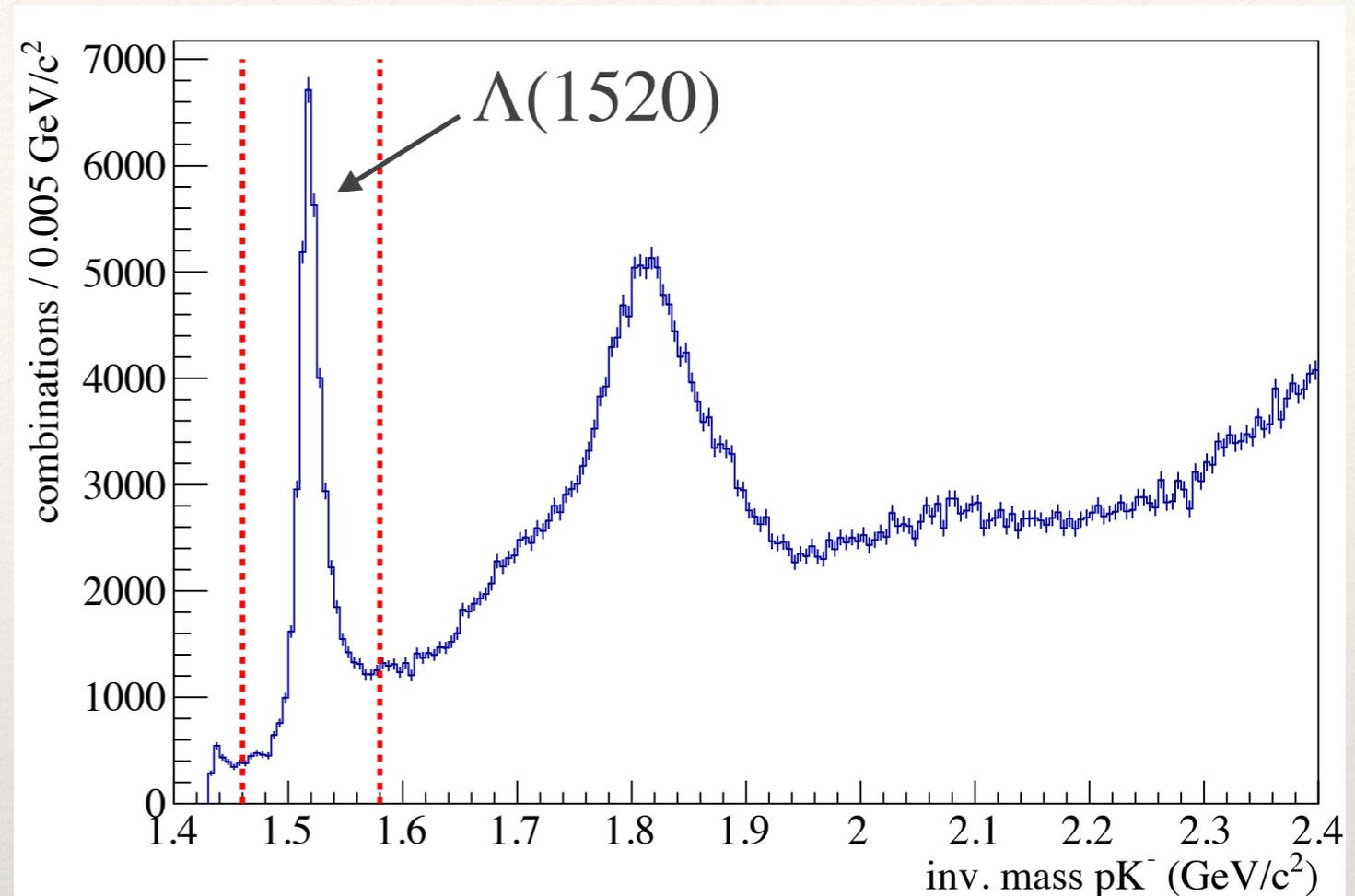
From 2019 onwards:
GlueX-II incl. DIRC

121 pb⁻¹ in coherent peak

$\Lambda(1520)$ SDMEs

Phys.Rev.C 105 (2022) 3, 035201

- ❖ Excited Λ hyperon with $J^P = \frac{3}{2}^-$
- ❖ $\Lambda(1520) \rightarrow K^- p$

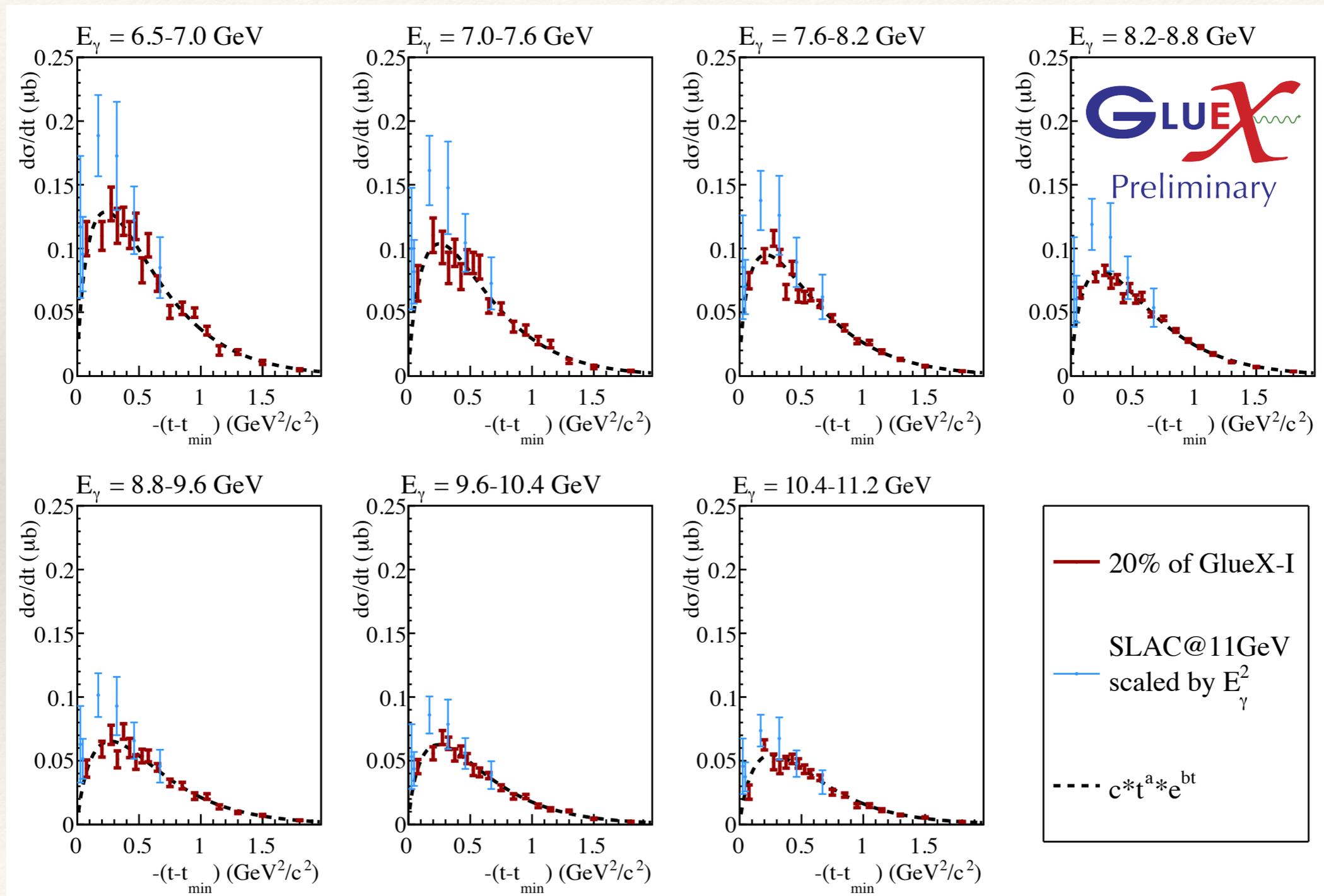


- ❖ Production mechanism via strangeness
- ❖ First measurement of polarised SDMEs for $\Lambda(1520)$

$\Lambda(1520)$ cross-sections

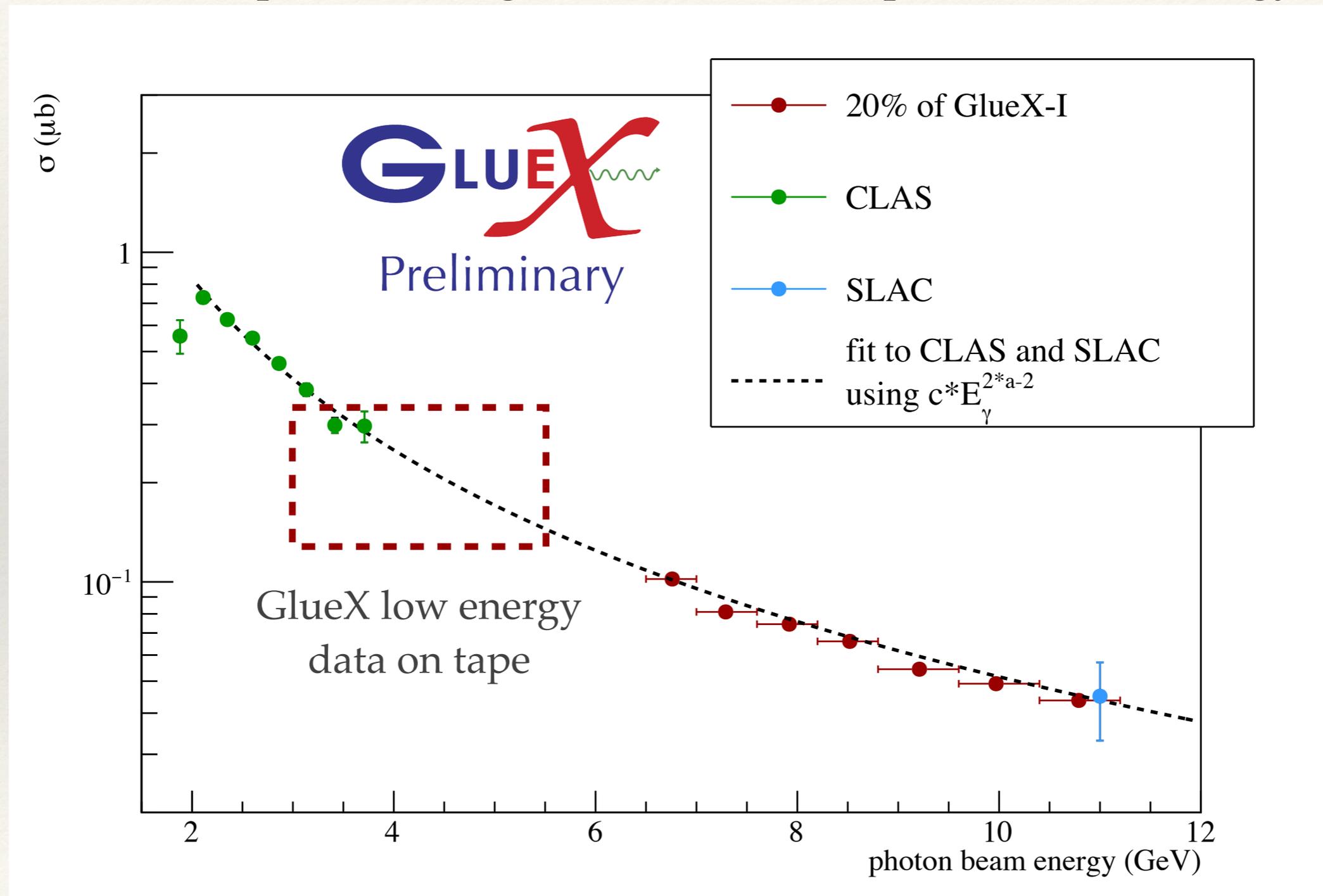
PH (HYP2022)

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



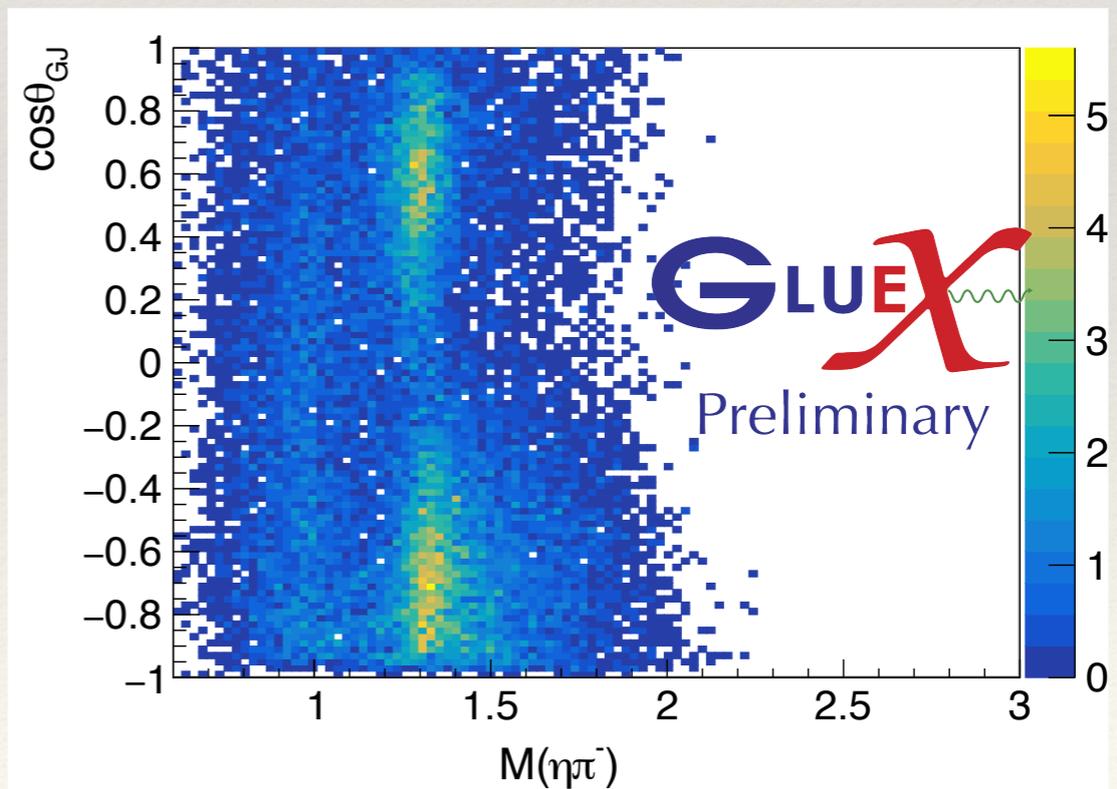
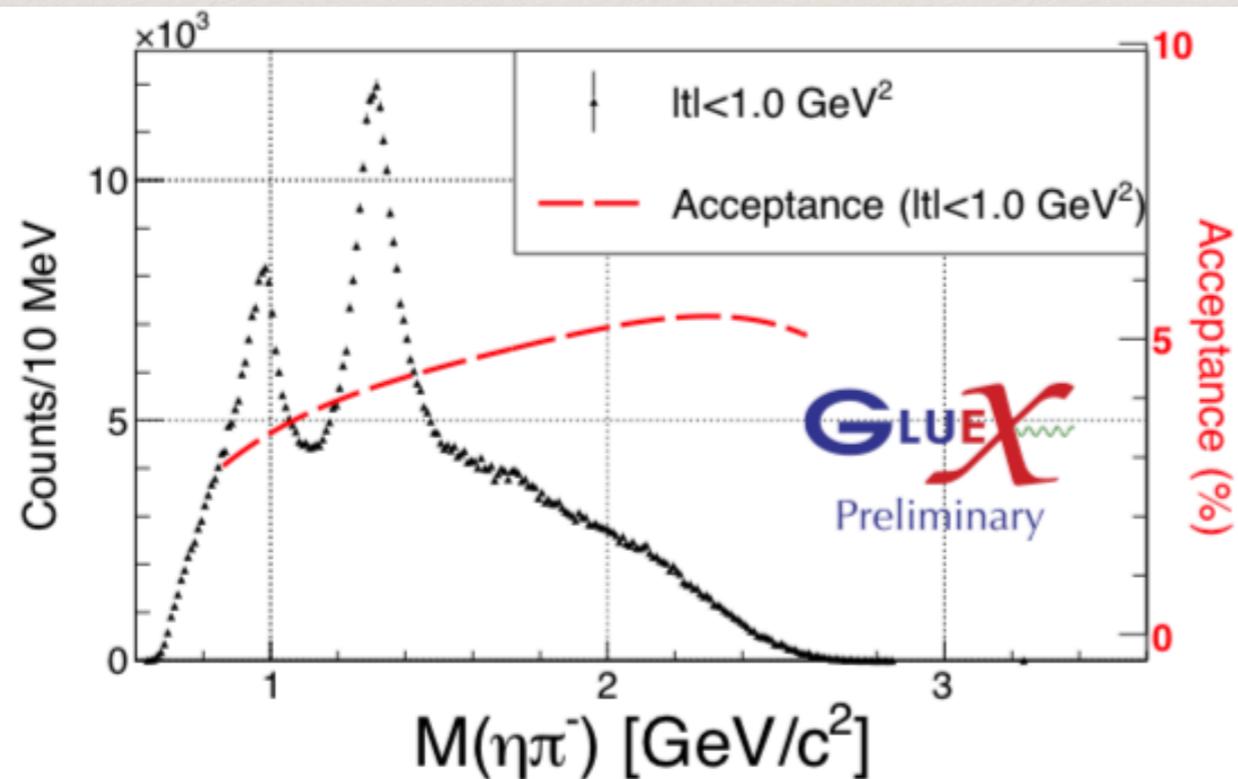
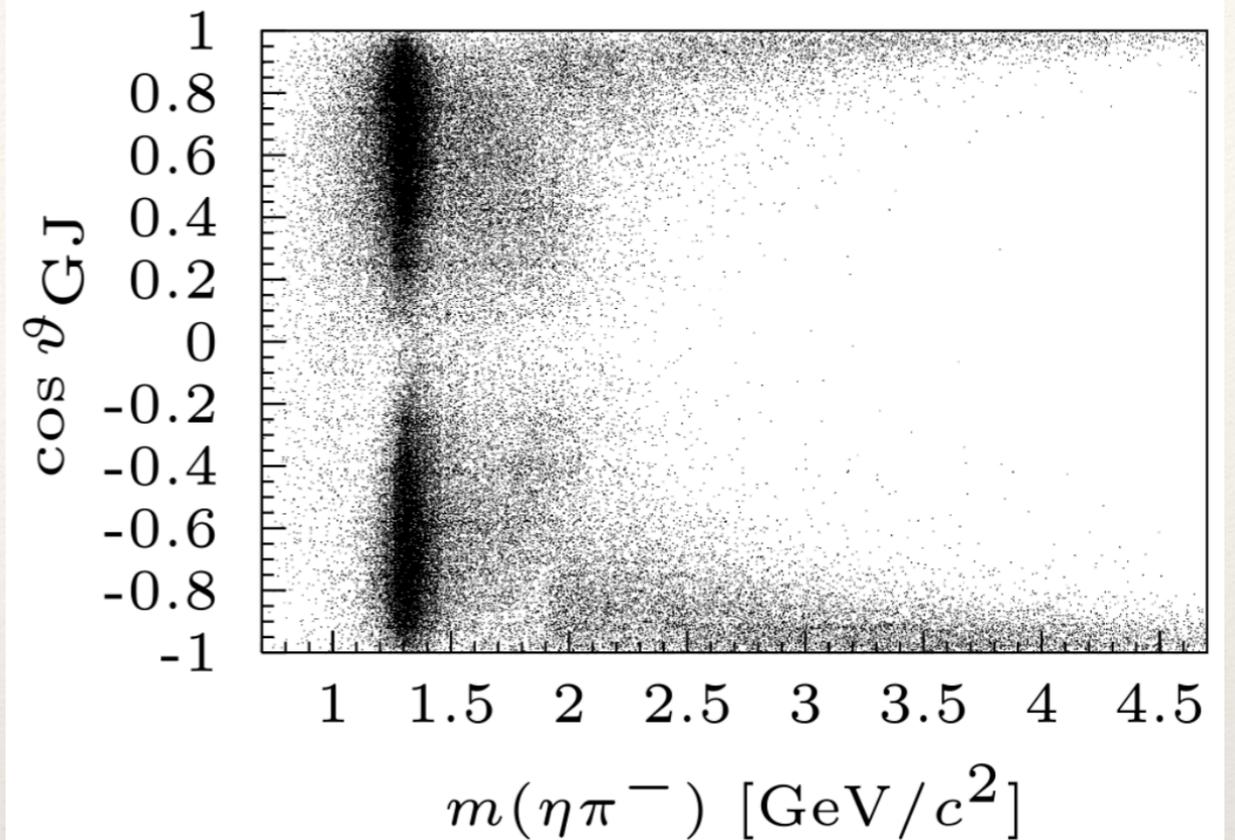
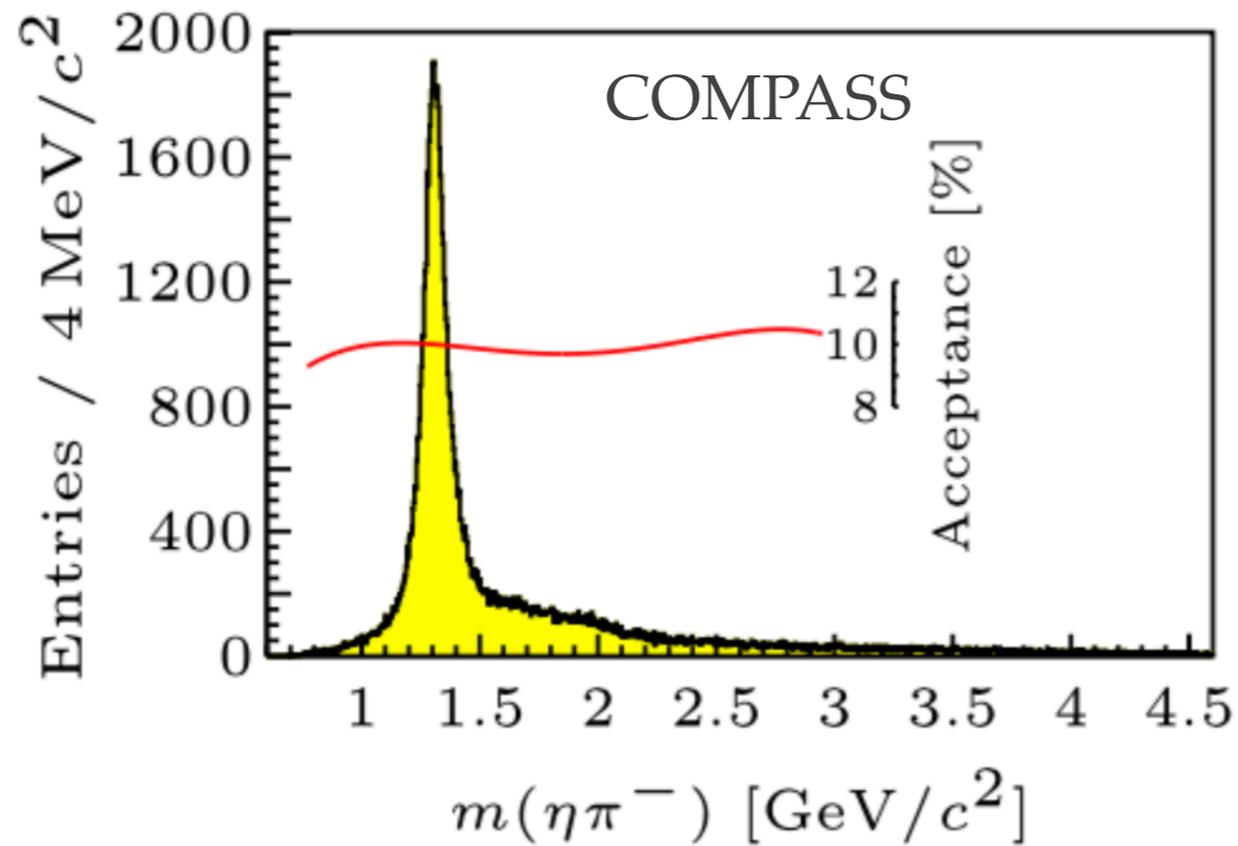
$\Lambda(1520)$ cross-sections

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



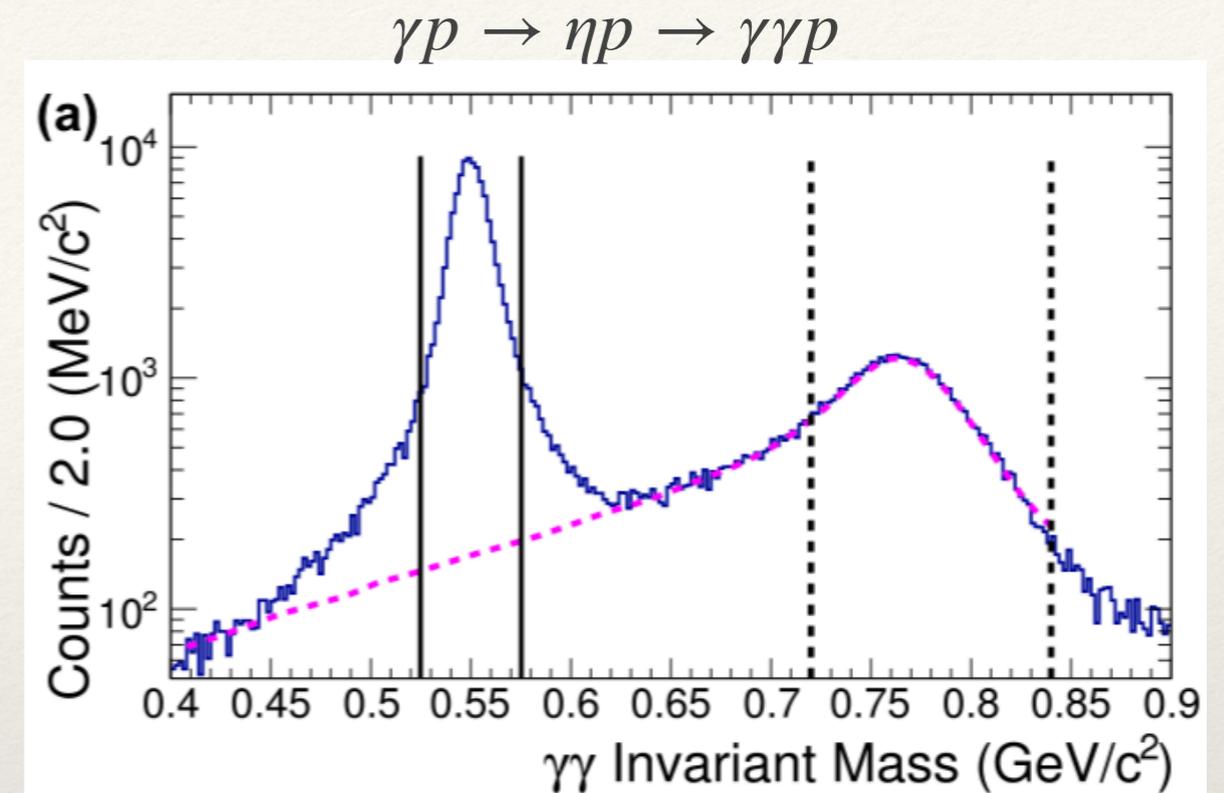
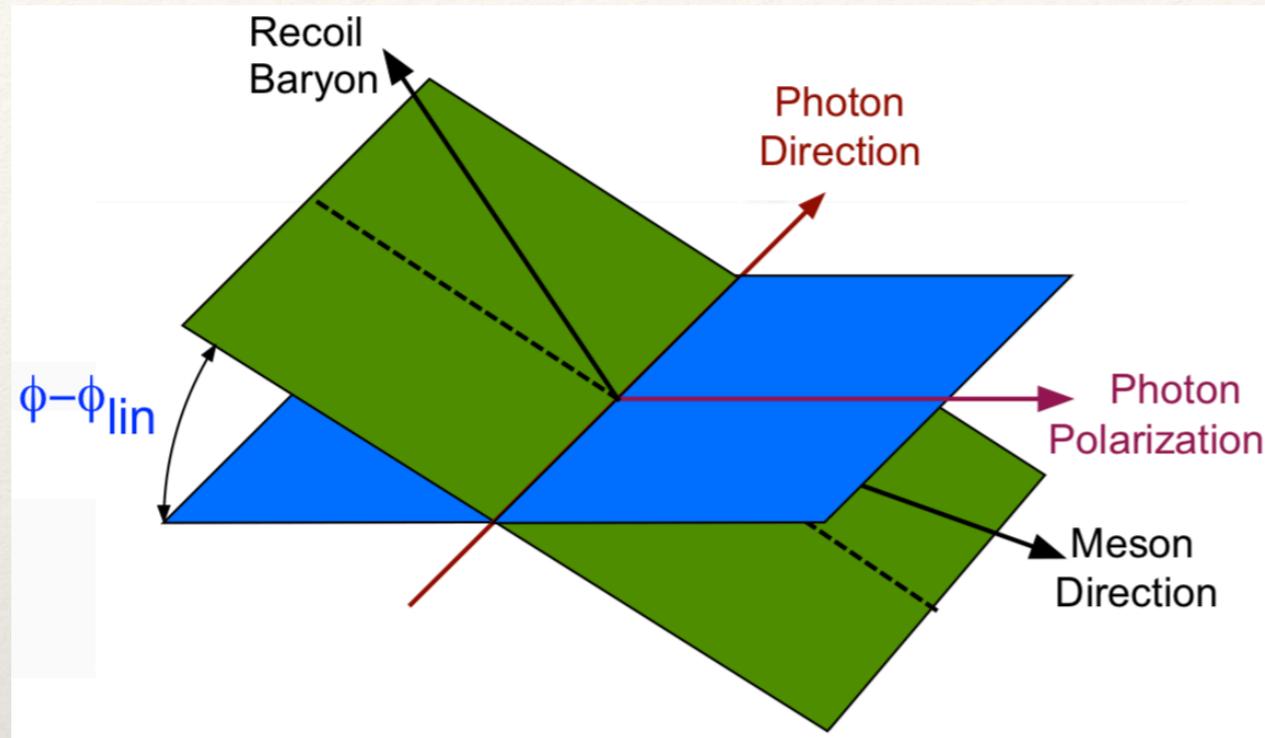
Hybrid search in $\eta\pi^-$

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

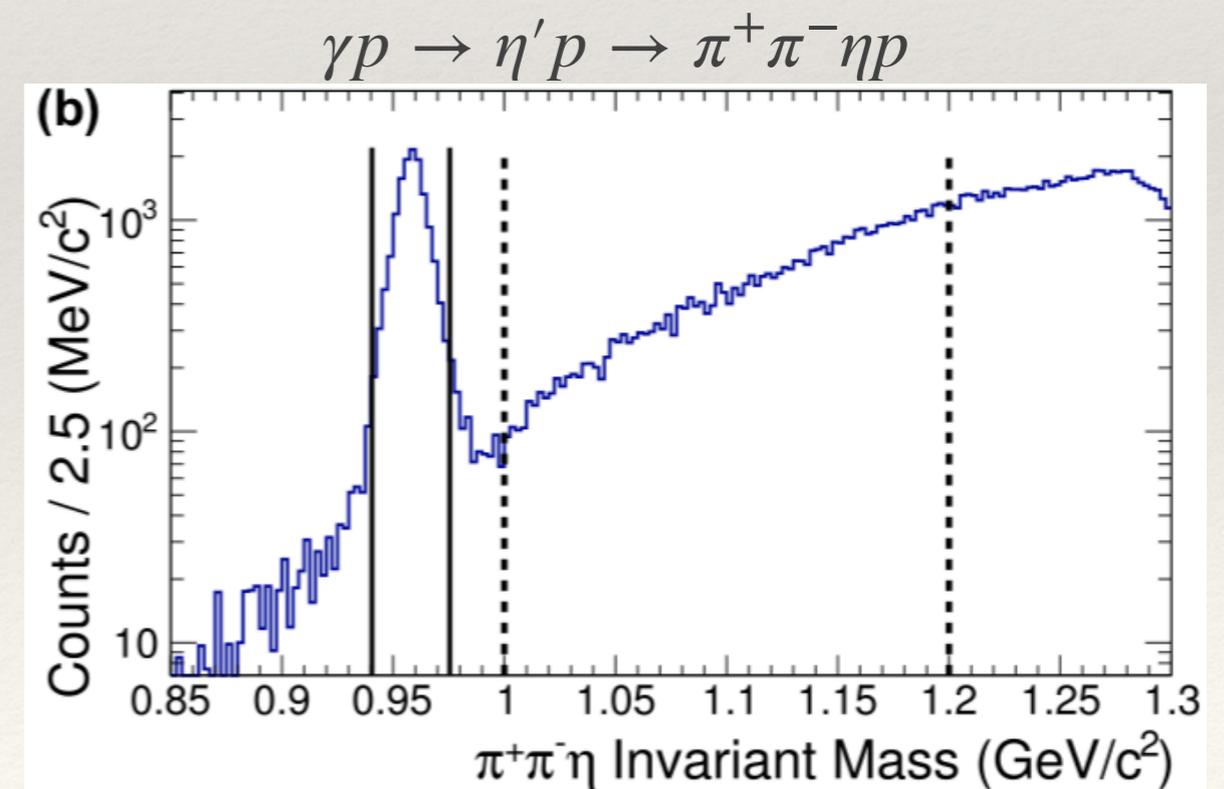


η/η' beam asymmetry

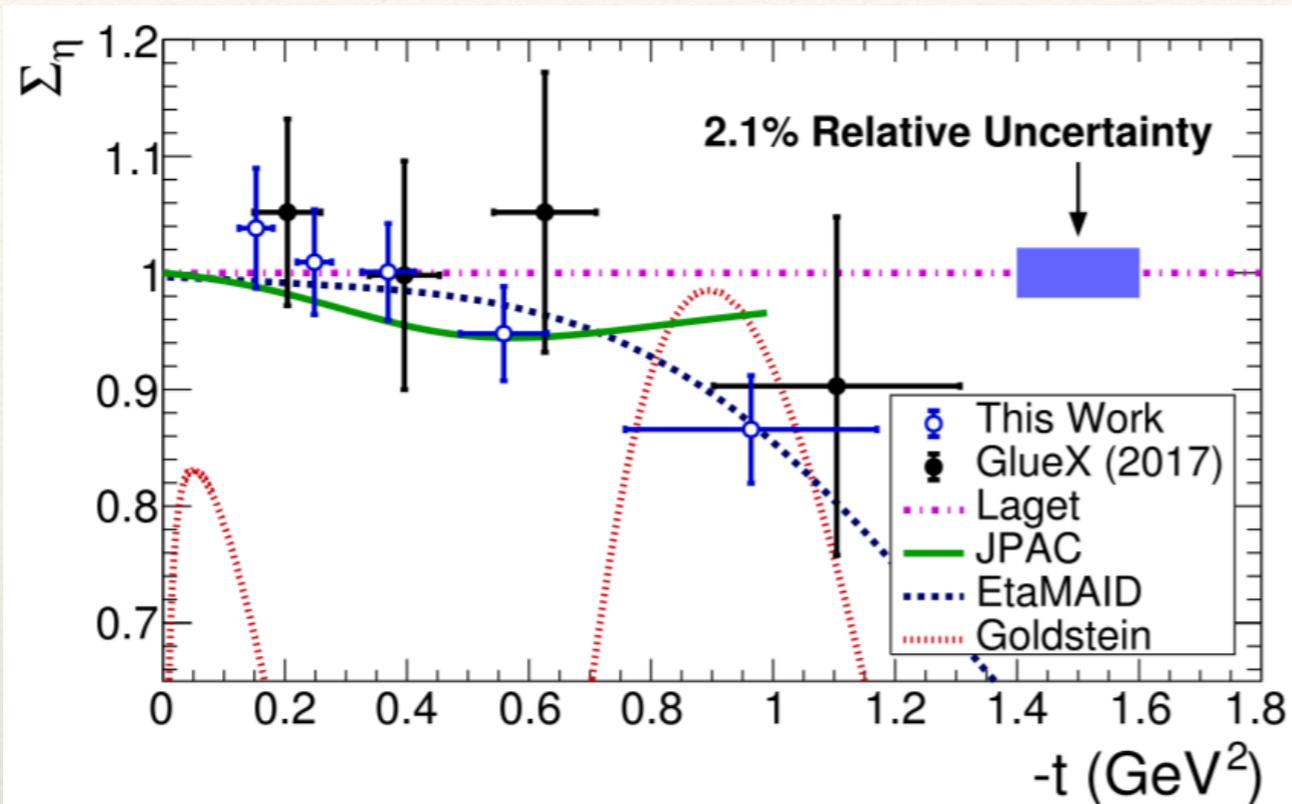
$$\sigma(\phi) \sim 1 - P_\gamma \Sigma \cos 2(\phi - \phi_{lin})$$



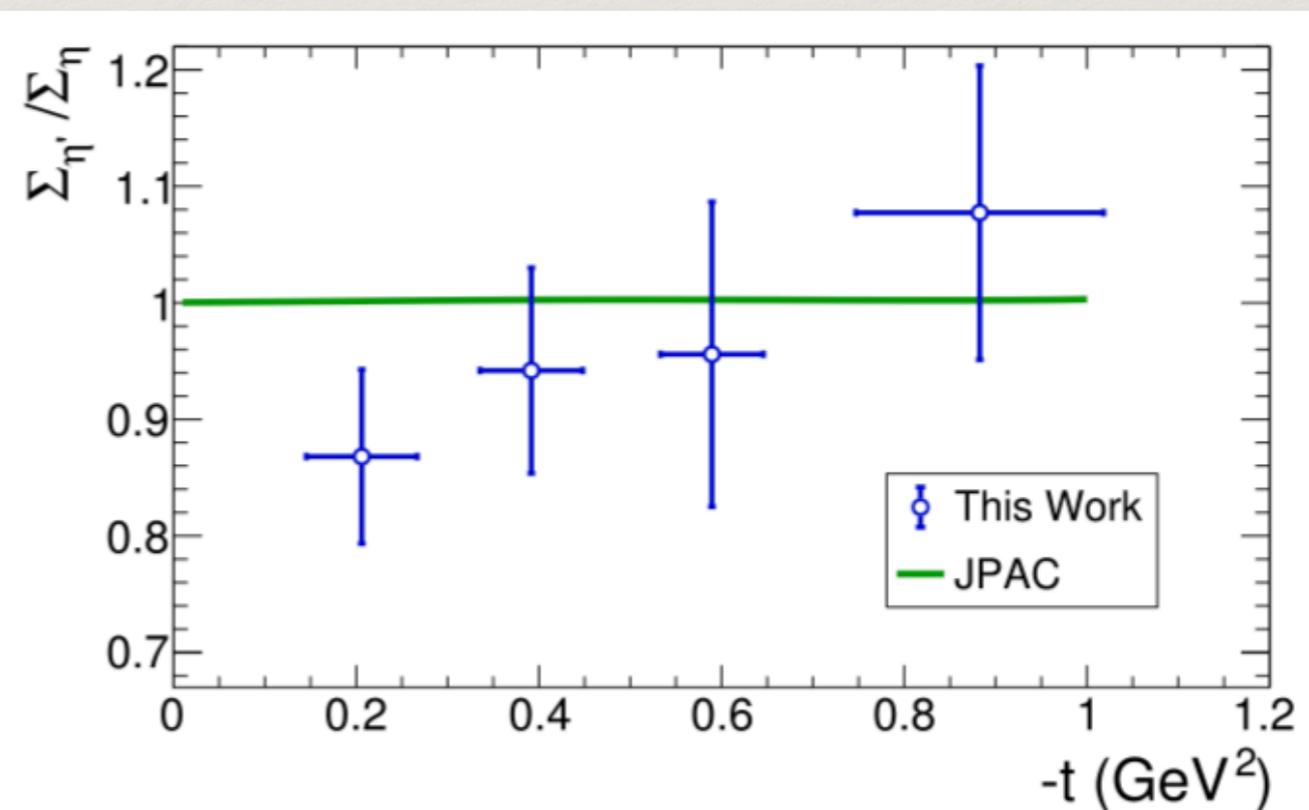
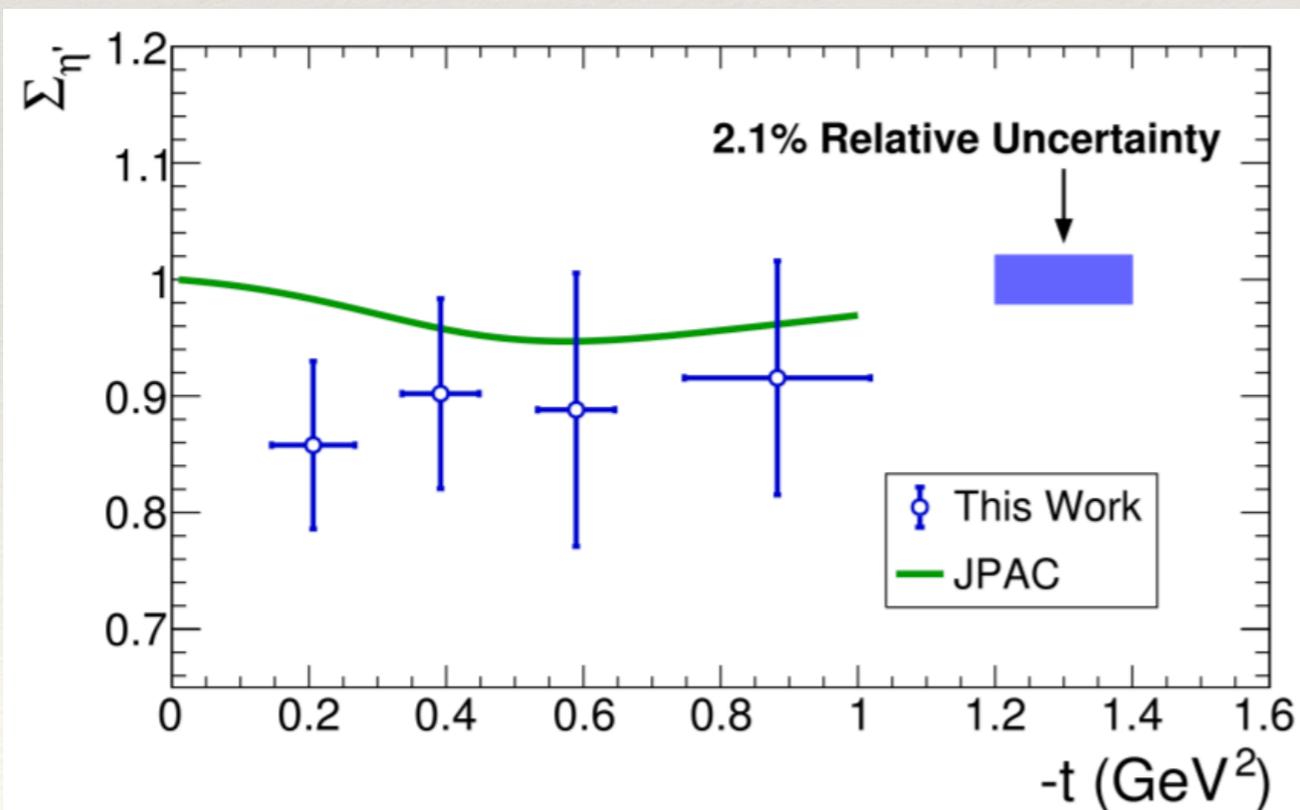
- ❖ measure photon beam asymmetry Σ to learn about t-channel Reggeon exchange
- ❖ ratio of $\Sigma_{\eta'}/\Sigma_{\eta}$ provides information on $s\bar{s}$ exchange



η/η' beam asymmetry

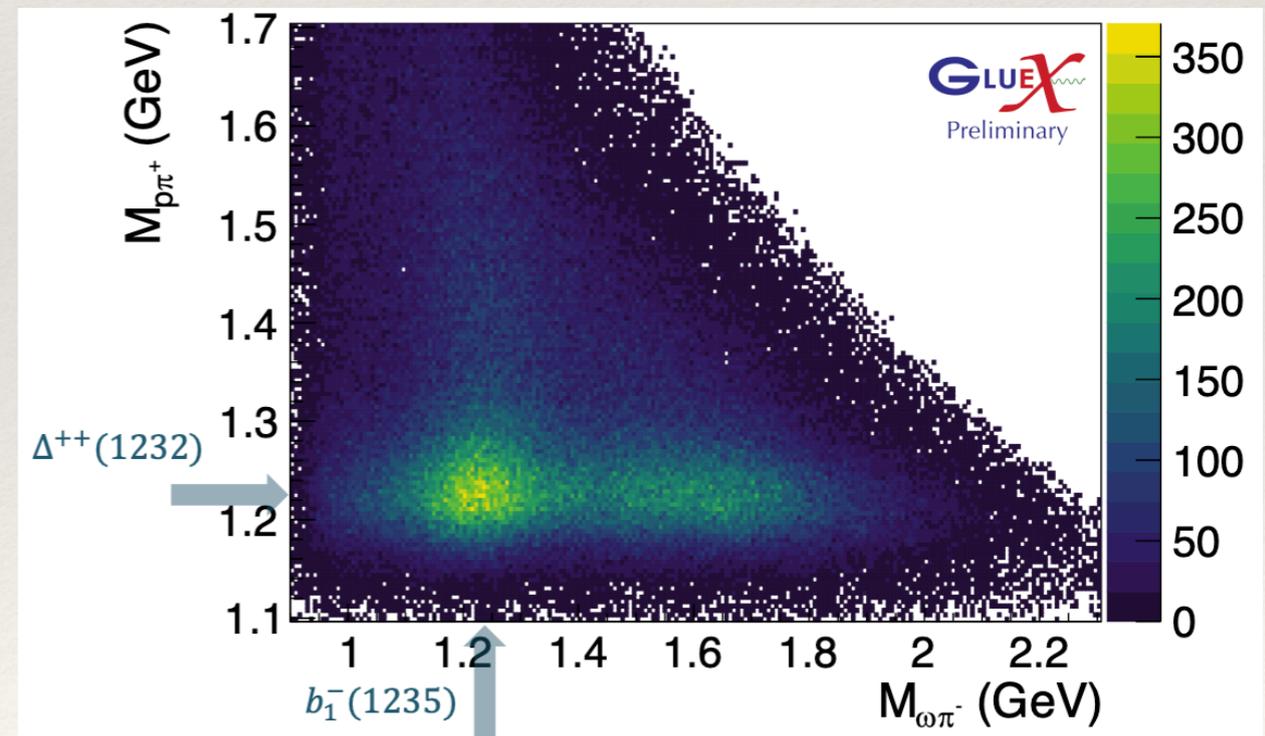
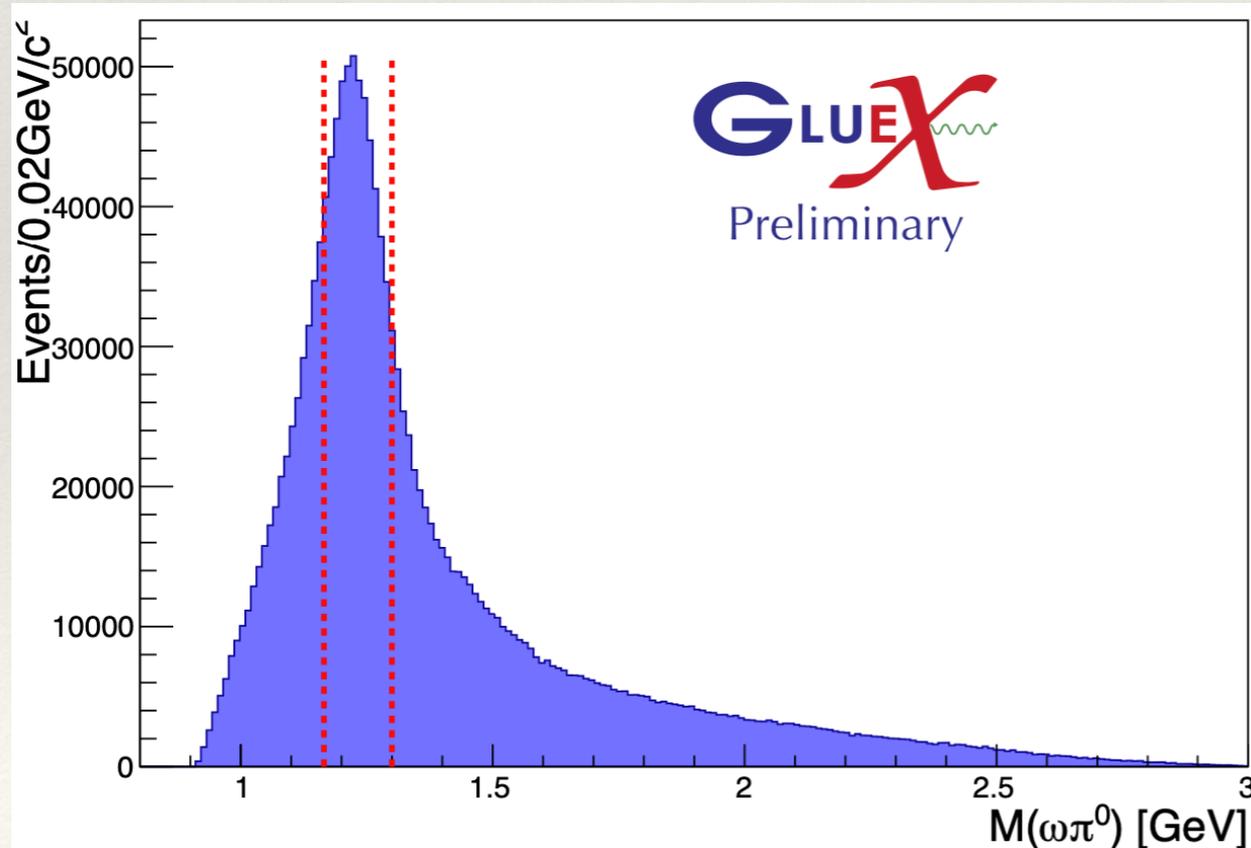


- ❖ vector exchange dominating
- ❖ ratio indicates no substantial $s\bar{s}$ component in exchange



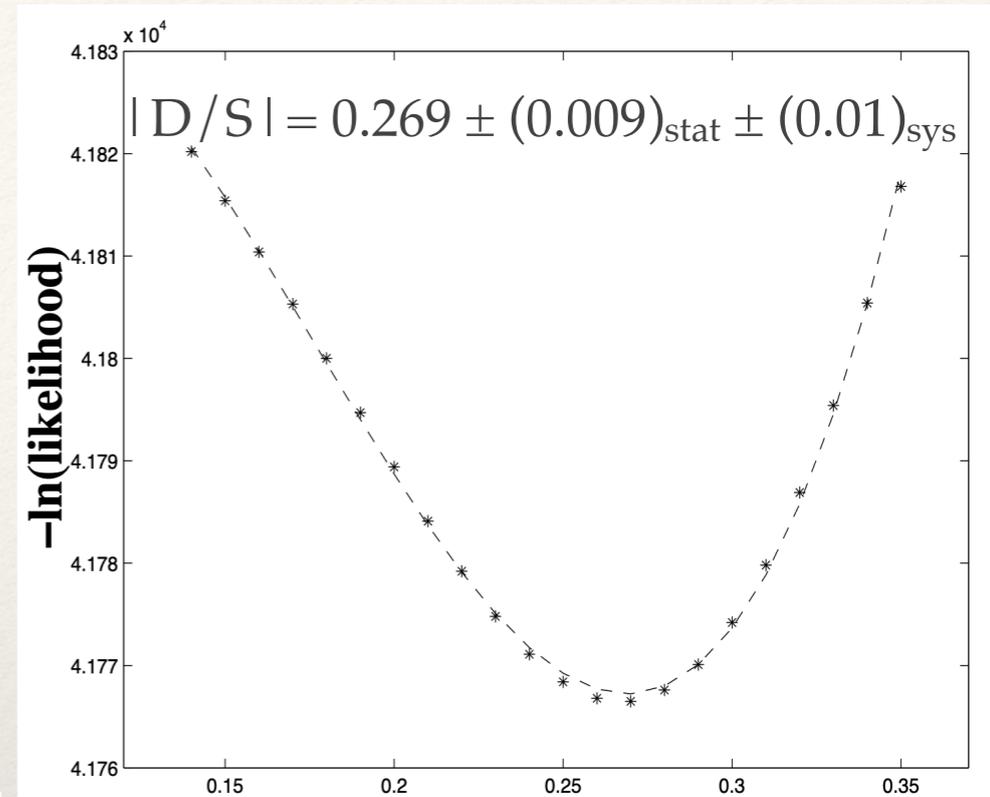
b_1 decay

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

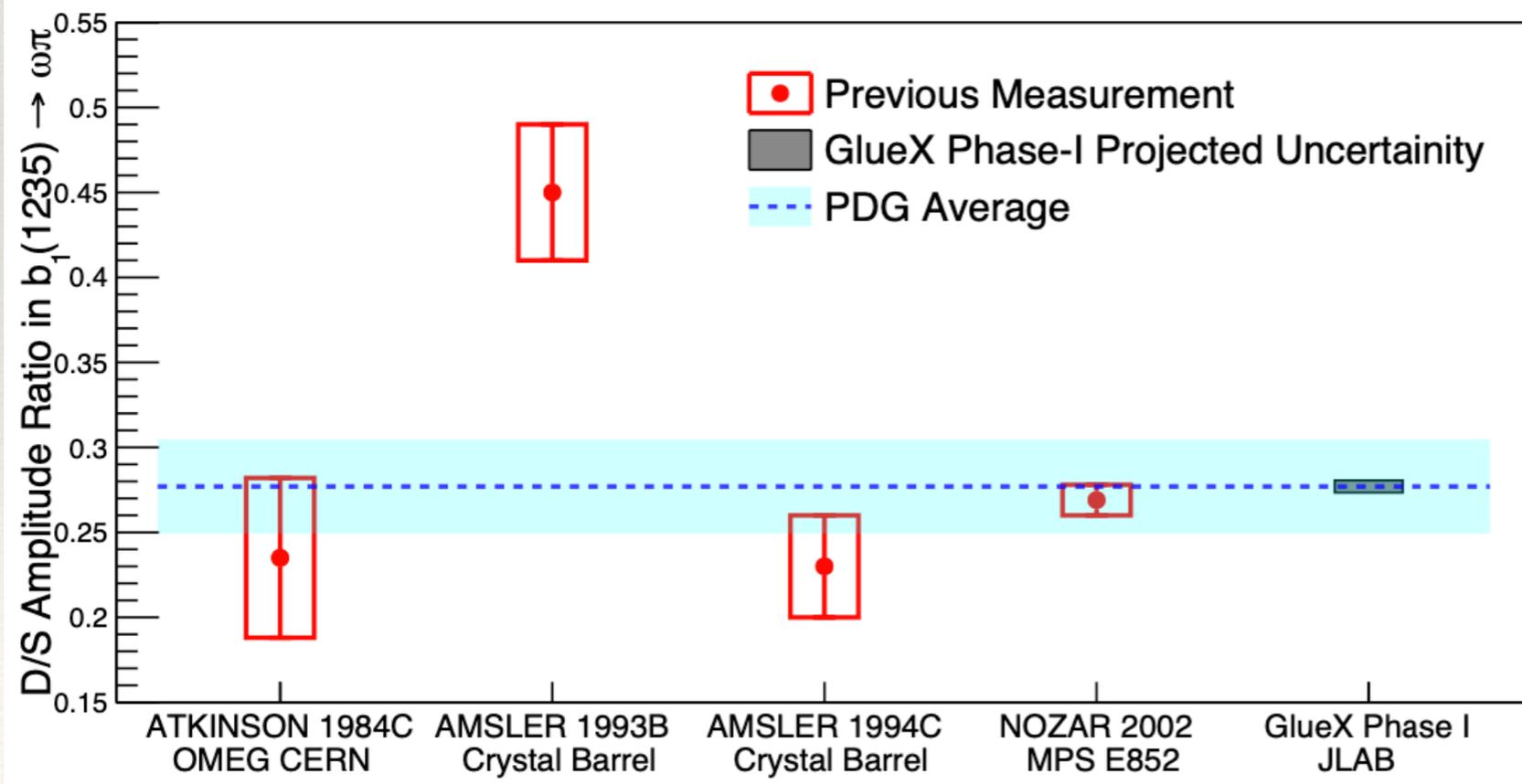


b_1 decay

- ❖ 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 ($\omega\eta, \phi\pi, \phi\eta, \dots$)

$J/\psi\gamma$

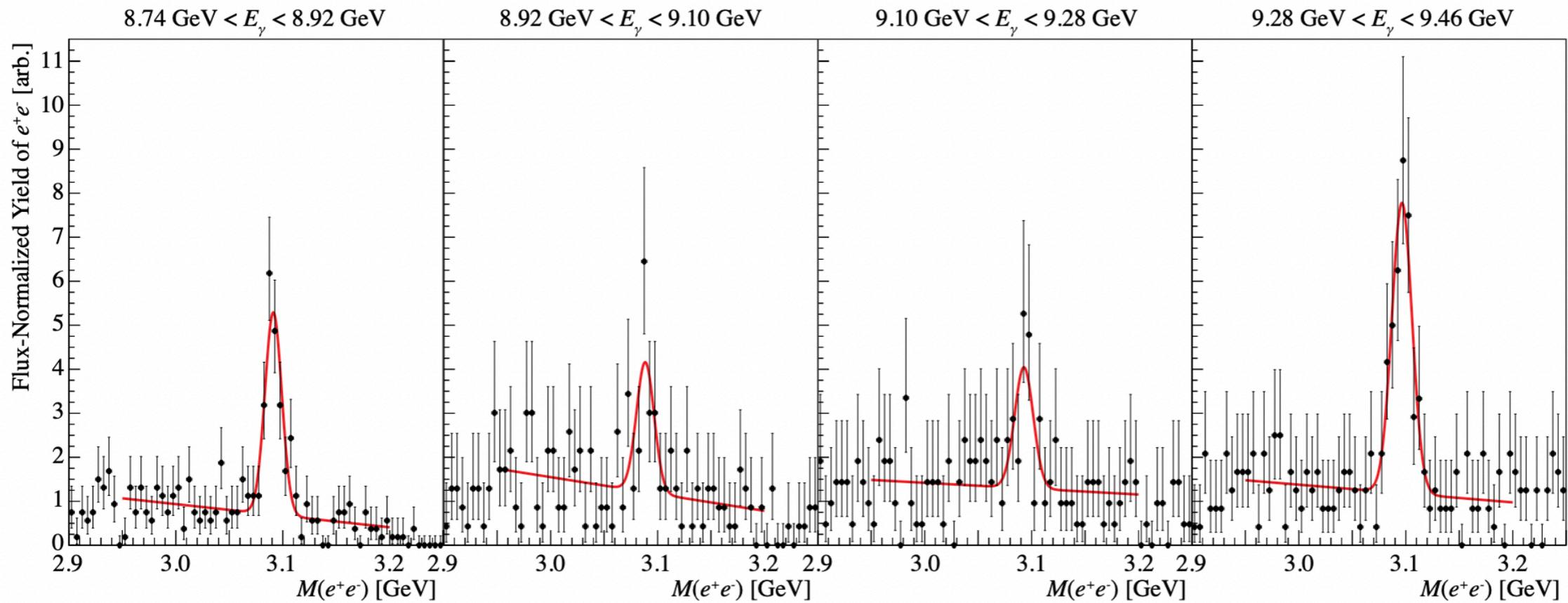
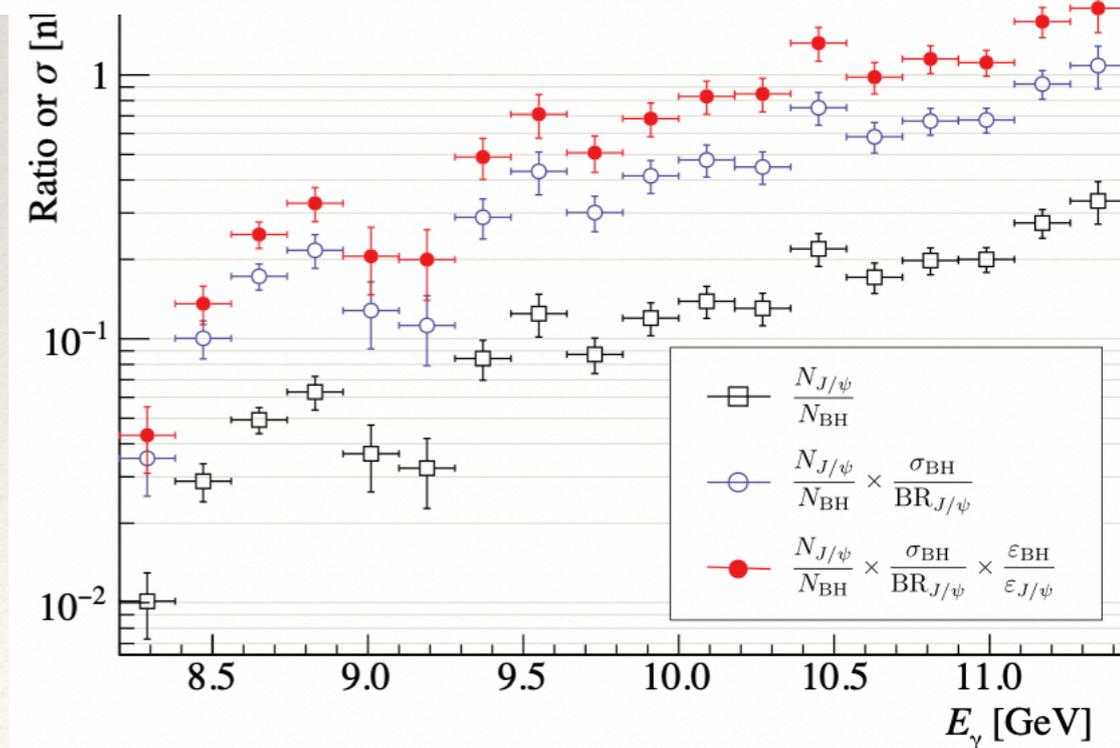
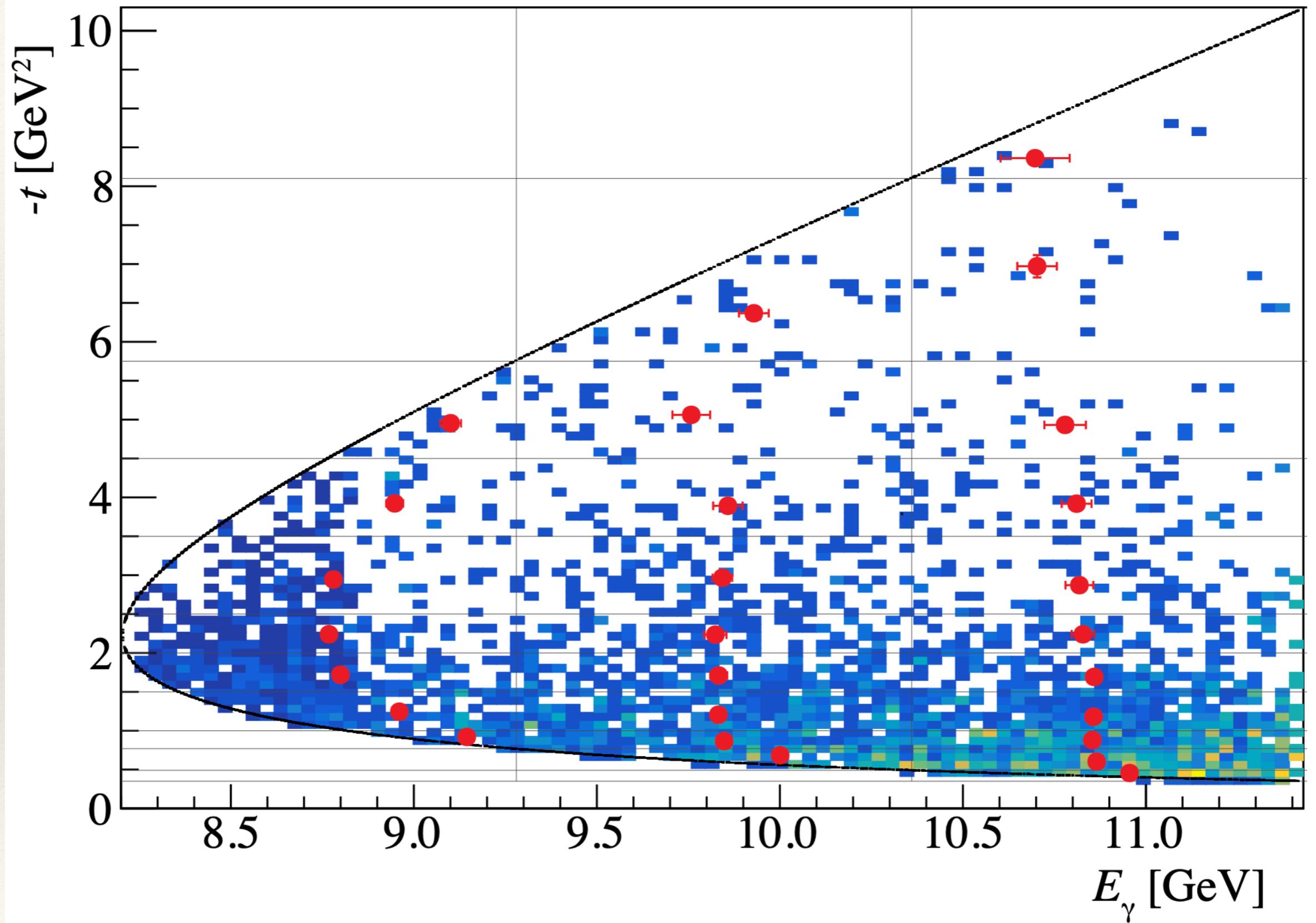


FIG. 8. Distribution of $M(e^+e^-)$ in bins of beam energy E_γ with fits to the J/ψ peak overlaid. The y axis of each histogram is scaled by the flux integrated over the corresponding E_γ bin.

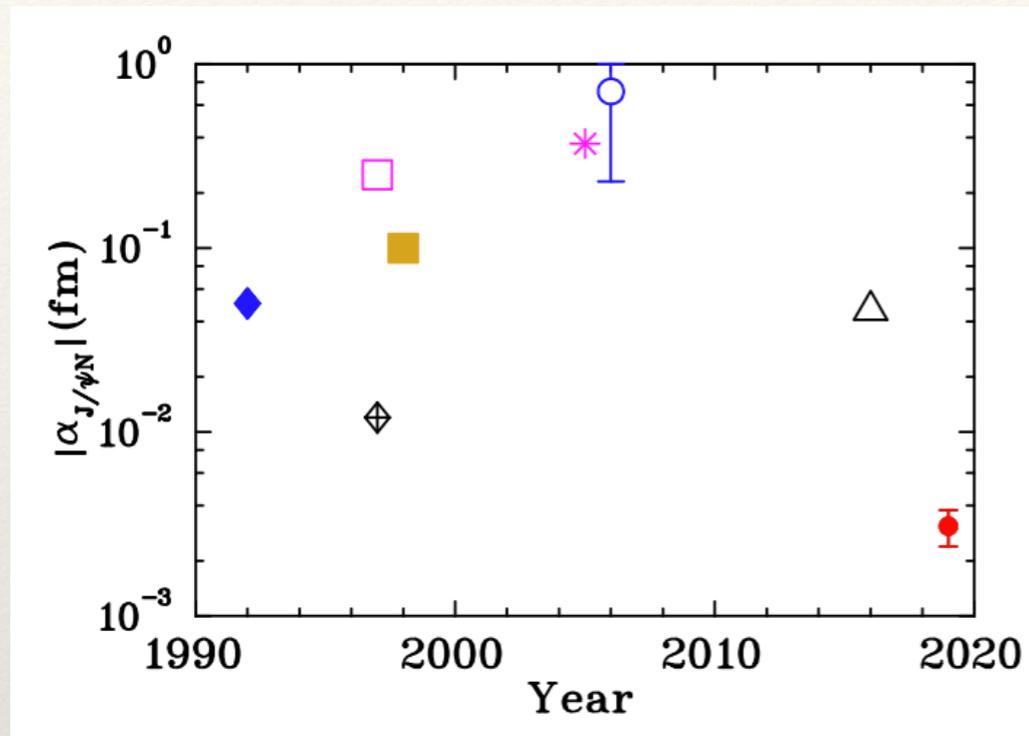
❖ Dip is really due to yields



$J/\psi\rho$ 

J/ψ - further interest

$J/\Psi - p$ scattering length



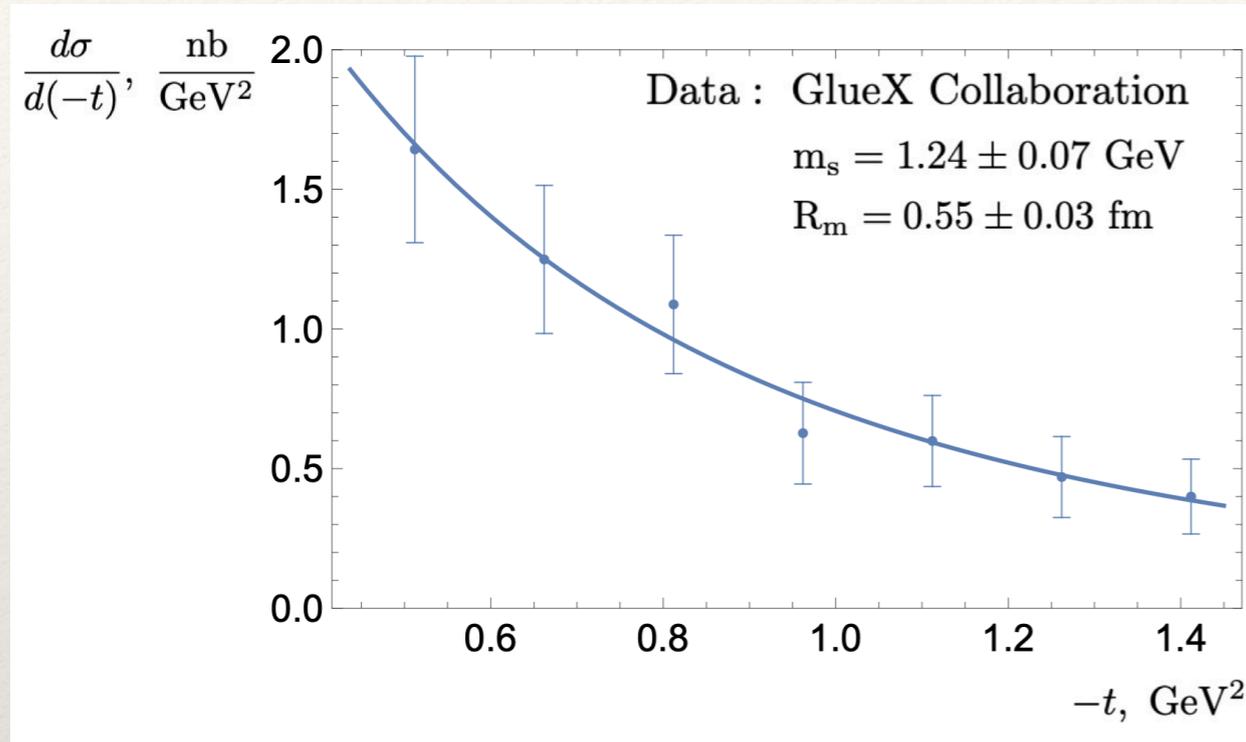
- $\text{Strakovsky, Epifanov, Pentchev, Phys. Rev. C 101, 042201(R) (2020)}$ GlueX data
- ◆ $A. B. Kaidalov \text{ and } P. E. Volkovitsky, Phys. Rev. Lett. 69, 3155 (1992)$
- ◇ $V. I. Shevchenko, Phys. Lett. B 392, 457 (1997)$
- $S. J. Brodsky \text{ and } G. A. Miller, Phys. Lett. B 412, 125 (1997).$
- $A. Hayashigaki, Prog. Theor. Phys. 101, 923 (1999).$
- ✱ $A. Sibirtsev \text{ and } M. B. Voloshin, Phys. Rev. D 71, 076005 (2005)$
- $K. Yokokawa, S. Sasaki, T. Hatsuda, \text{ and } A. Hayashigaki, Phys. Rev. D 74, 034504 (2006)$
- △ $O. Gryniuk \text{ and } M. Vanderhaeghen, Phys. Rev. D 94, 074001 (2016)$

- ❖ Scattering length much smaller than most theoretical calculations
- ❖ Maybe sign of a “young” J/Ψ forming in the proton
Pentchev, Strakovsky, Eur. Phys. J. A 57 (2021) 2, 56

J/ψ - further theoretical interest

Proton mass radius

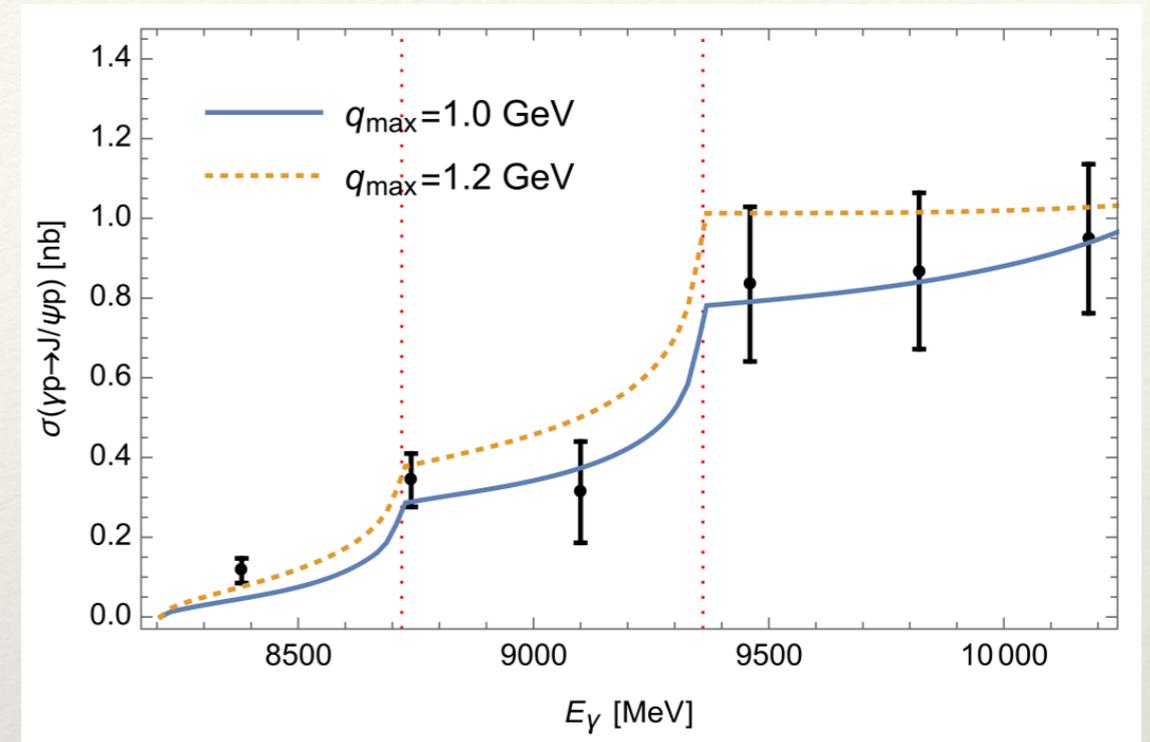
D. Kharzeev, arXiv:2102.00110



- ❖ Use the differential cross-section data to extract the proton mass radius:
 $R_m = 0.55 \pm 0.03$ fm
- ❖ Smaller than charge radius
- ❖ Need more data at $t \rightarrow 0$

Open charm cusps

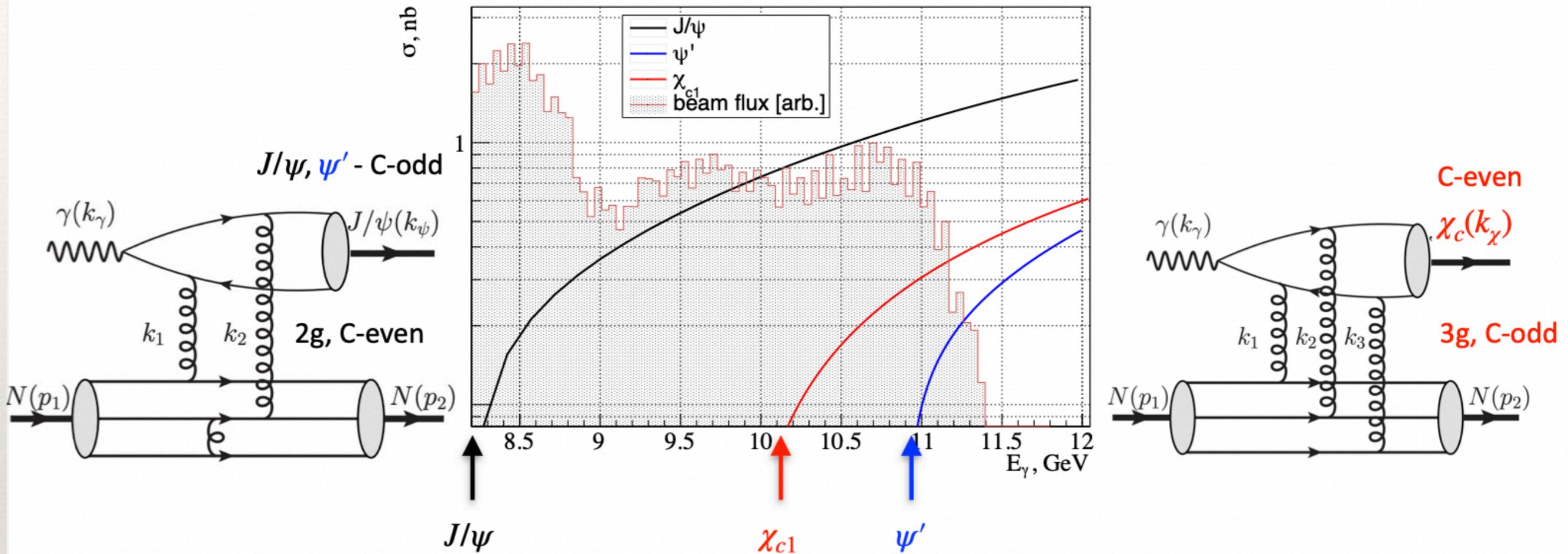
Du et al., Eur. Phys. J. C (2020) 80:1053



- ❖ Influence of loops with open charm hadrons near threshold
- ❖ Data not precise enough yet for definitive statements but does not disagree with model

Further Charmonium states

C-odd ($J/\psi, \psi'$) vs C-even (χ_c) production



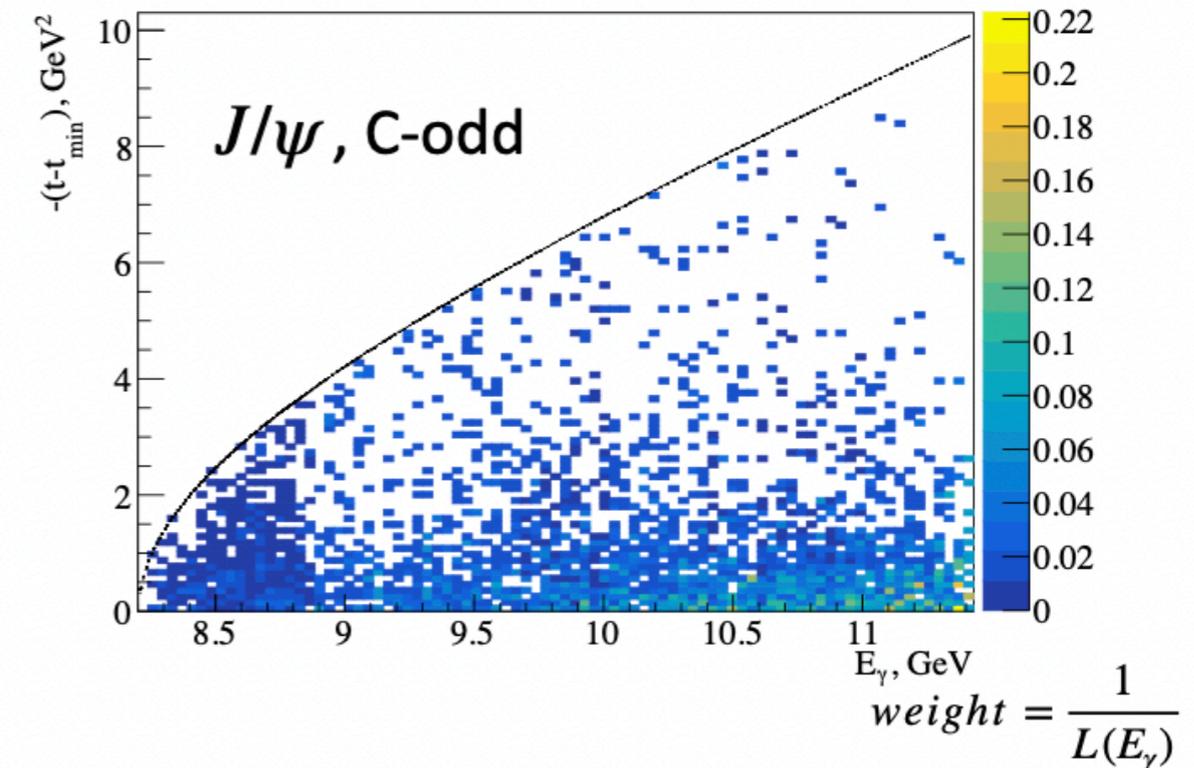
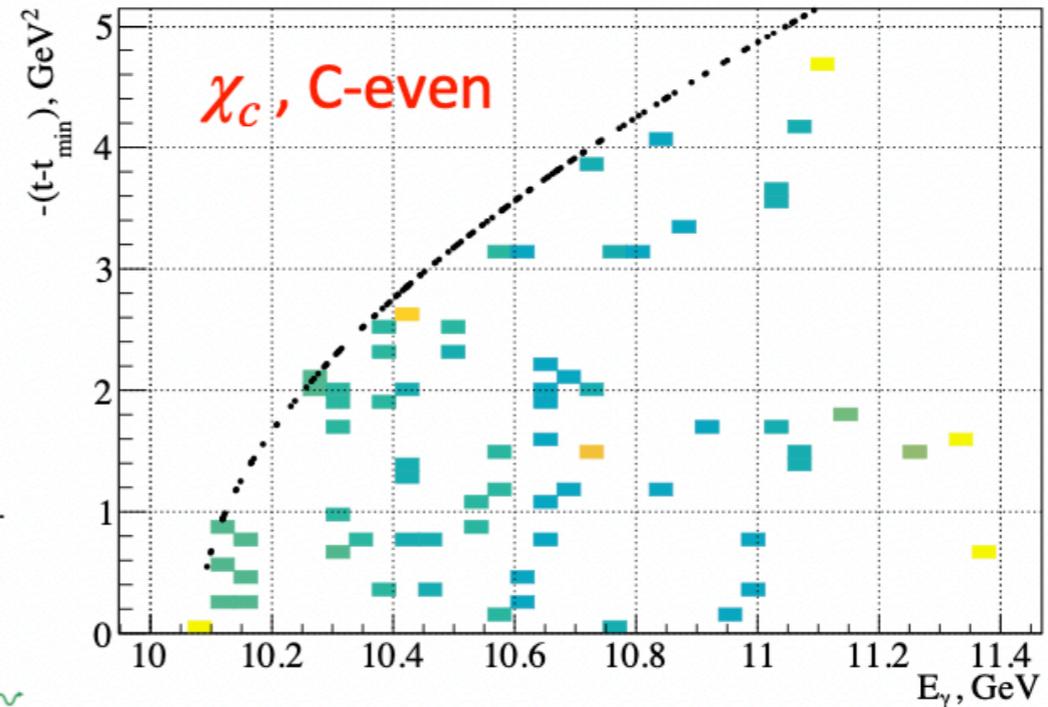
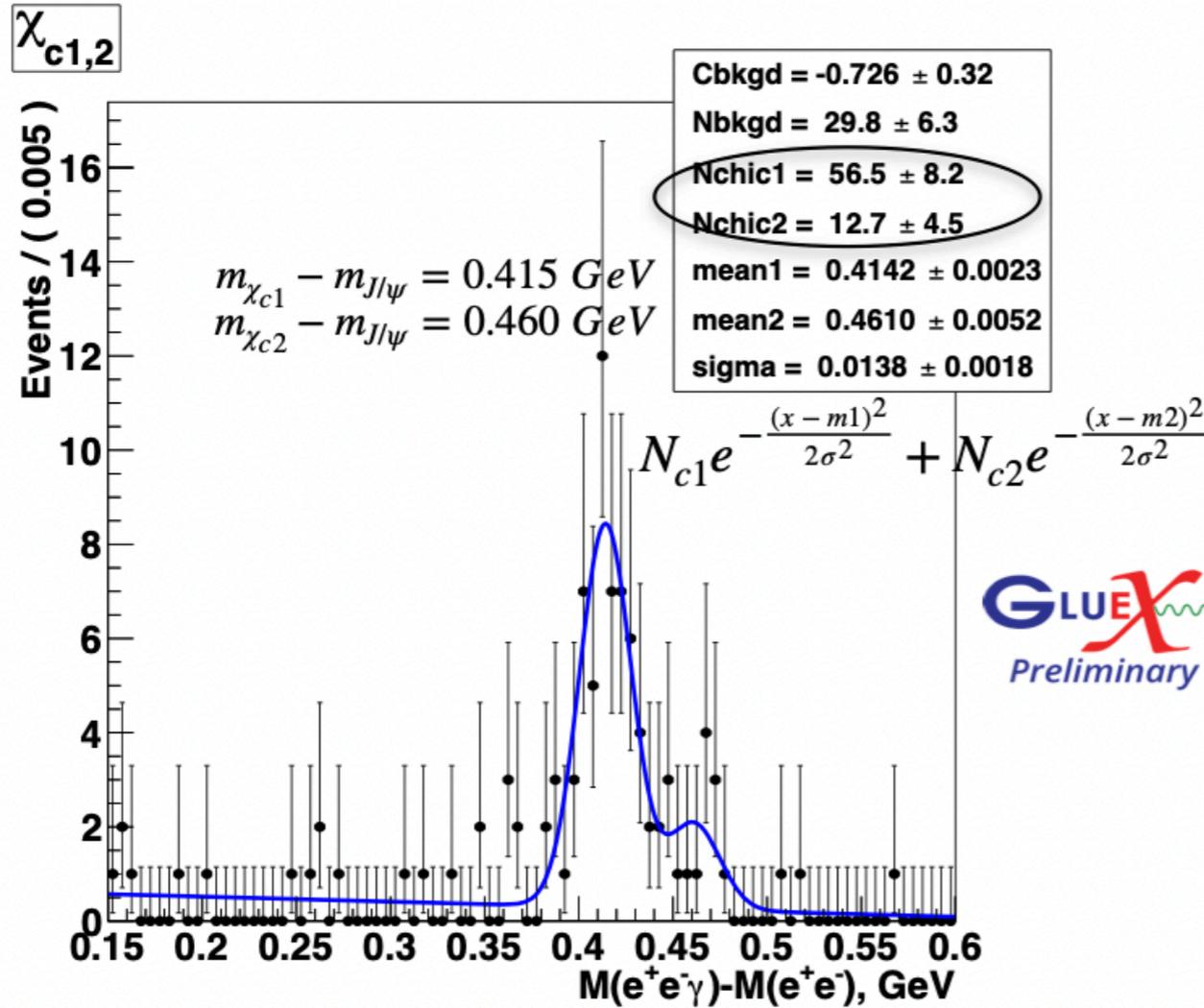
- $\chi_{c1}(3511)$ and $\chi_{c2}(3556)$, 1^{++} and 2^{++} ($1P$), $E_\gamma^{thr} = 10.1$ GeV
- C-even charmonium states require 3g-exchange

- GlueX has observed also a small number of $\psi'(3686)$ ($2S$) states in $\gamma p \rightarrow \psi' p \rightarrow (e^+e^-) p$, $E_\gamma^{thr} = 10.9$ GeV

Further Charmonium states

C-odd ($J/\psi, \psi'$) vs C-even (χ_c) production

$$\gamma p \rightarrow \chi_c p \rightarrow (J/\psi \gamma) p \rightarrow (e^+ e^- \gamma) p$$



- $\chi_{c1}(3511)$ and $\chi_{c2}(3556)$, 1^{++} and 2^{++} ($1P$),
 $E_\gamma^{thr} = 10.1 \text{ GeV}$
- C-even charmonium states require 3g-exchange
- Dramatic difference in (E_γ, t) distribution w.r.t J/ψ