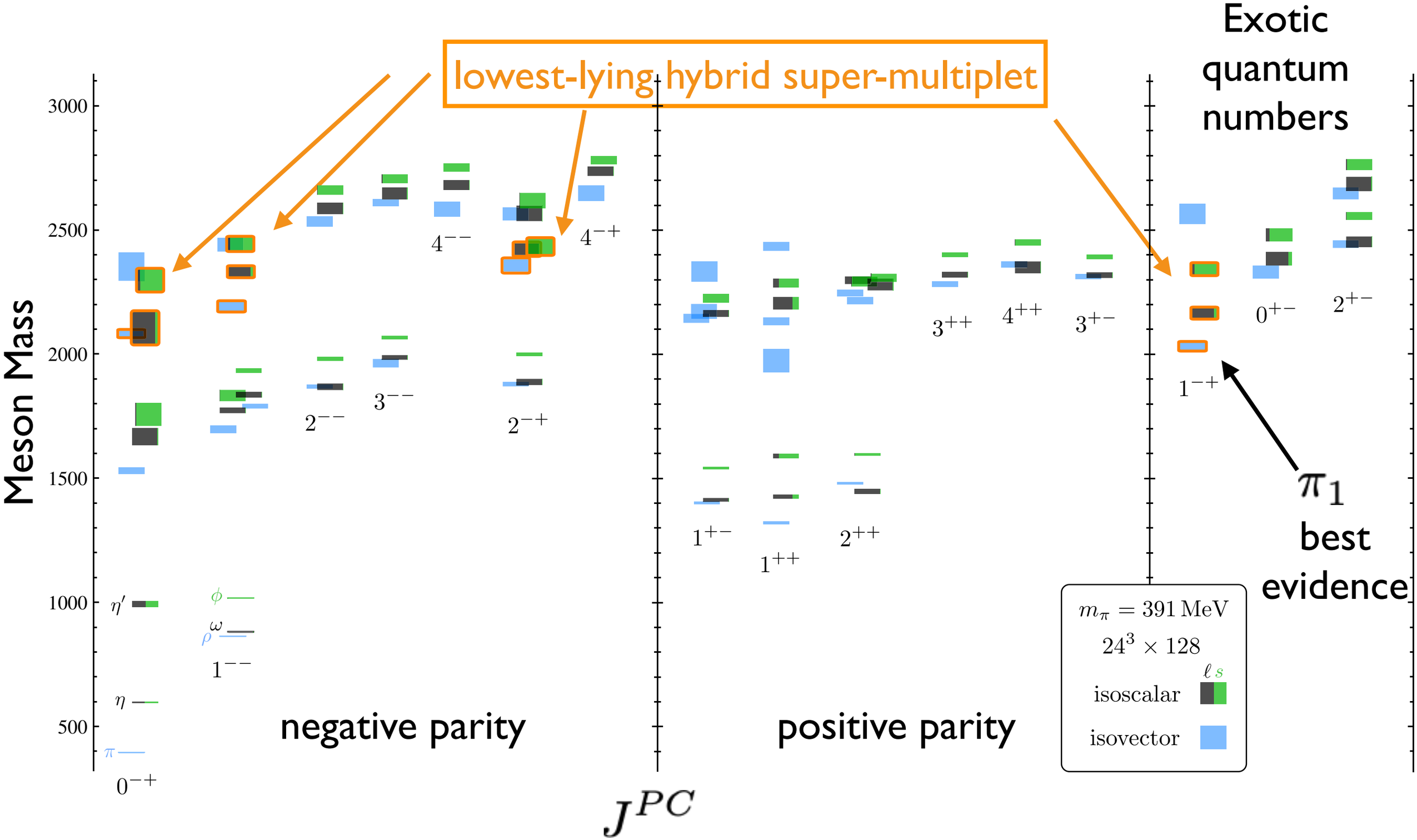
Probing meson photoproduction mechanisms with observables in exclusive vector-meson photoproduction

Mark Dalton for the GlueX Collaboration

GlueX Acknowledgements: gluex.org/thanks

Light quark mesons from lattice QCD



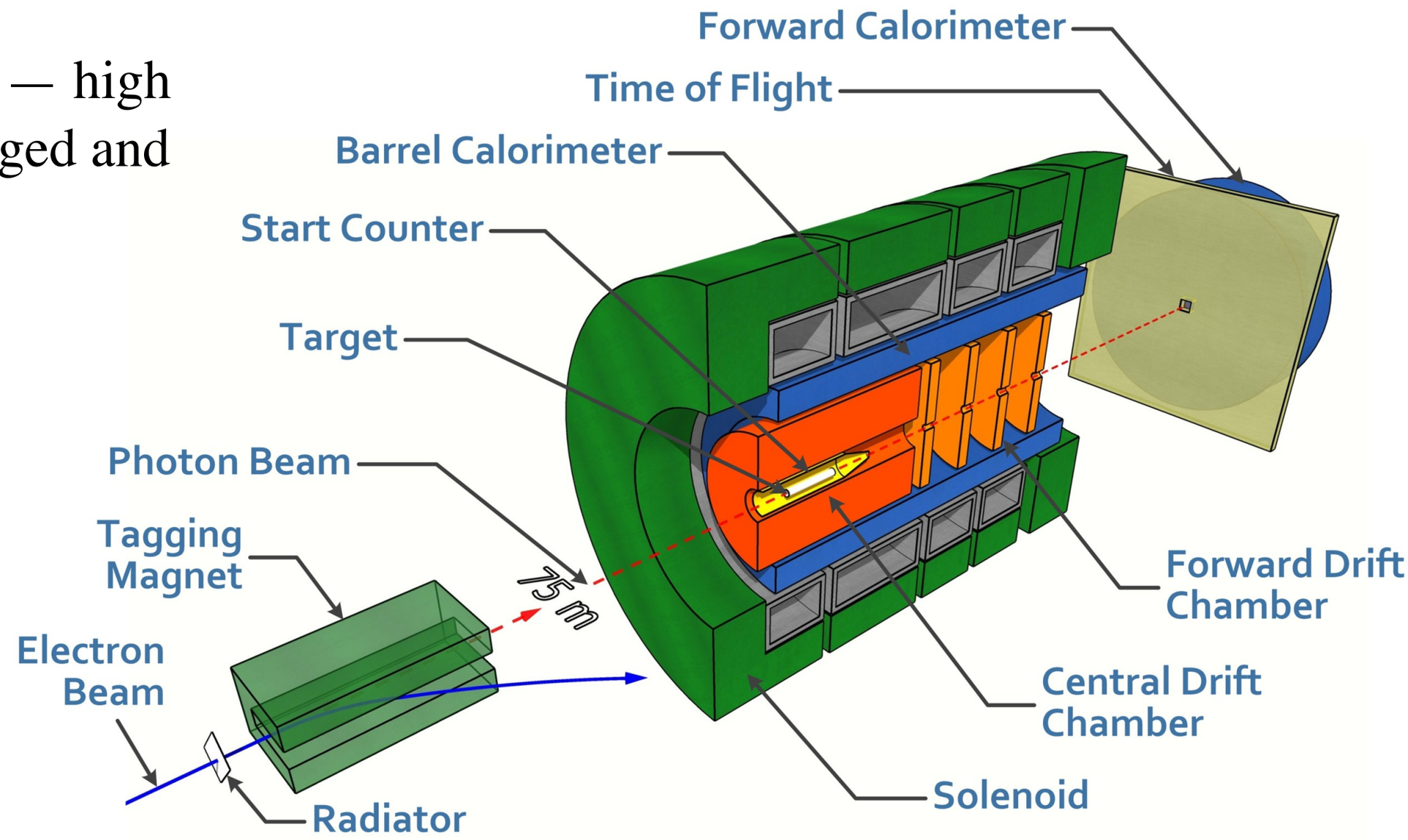
Pattern suggests 1^{+-} constituent gluon

PRD 88 (2013) 094505 Dudek et al.

Experiment and Detector

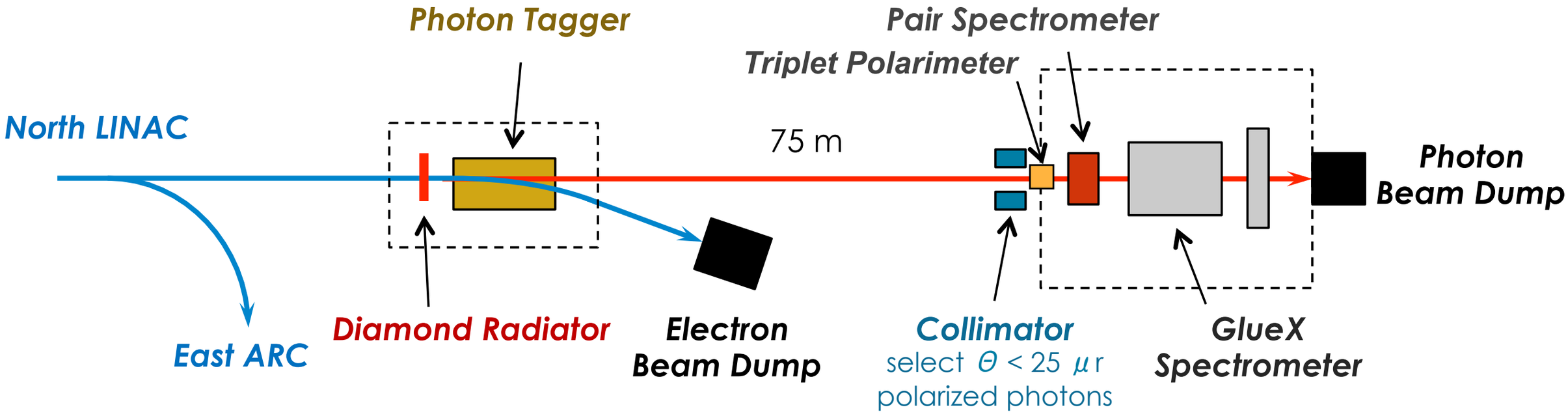
Hall D at Jefferson Lab

Linearly polarized photon beam
Proton target
Hermetic detector — high efficiency for charged and neutral particles



Nucl. Instrum. & Meth. A987, 164807 (2021)

Photon Beamline



~12 GeV electrons from CEBAF

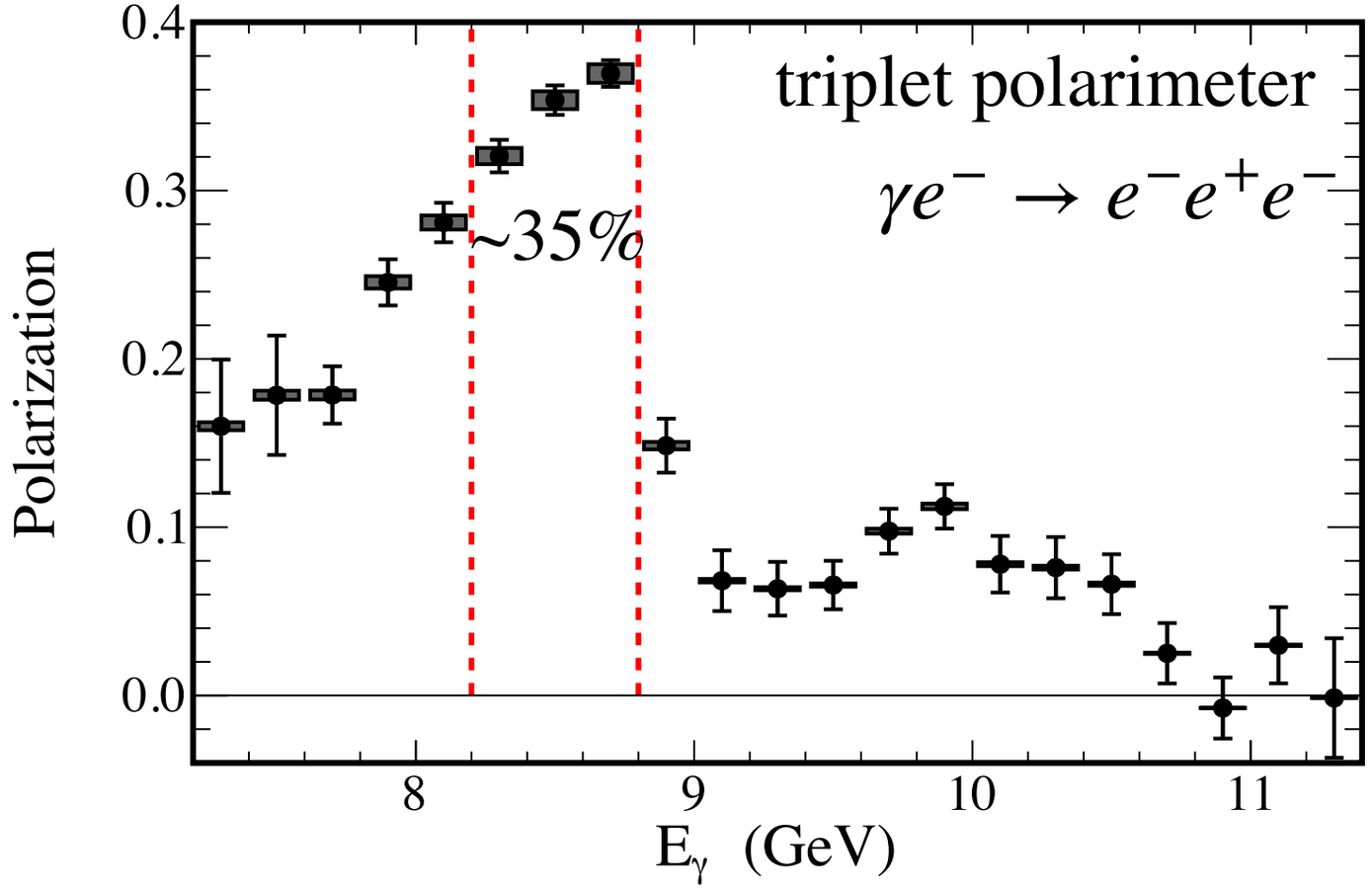
Coherent bremsstrahlung on thin diamond wafer

Linearly polarized in coherent peak ~35%

Tagged photon energy

GlueX phase 1 tagged luminosity

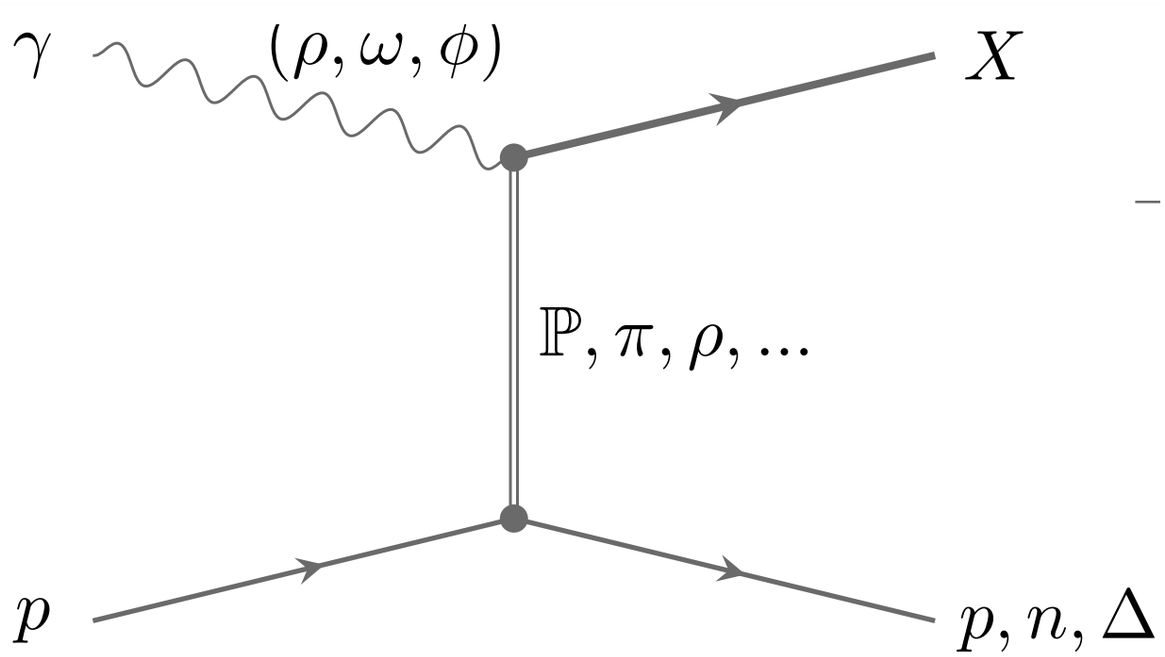
8.2 - 8.8 GeV	125 pb^{-1}
6.0 - 11.6 GeV	440 pb^{-1}



Meson Photoproduction

Vector Meson Dominance — exchange a hadron with the target.
Photon polarization helps determine quantum numbers of produced mesons

Exchange		Exotic Final States	
$\mathbb{P}$	0^{++}	b, h, h'	$2^{+-}, 0^{+-}$
π^0	0^{-+}	b_2, h_2, h_2'	2^{+-}
$\pi^{\pm}$	0^{-+}	$\pi_1^{\pm}$	1^{-+}
ω	1^{--}	π_1, η_1, η_1'	1^{-+}



Interpretation of final states requires understanding of production

Prior photoproduction data at this energy is sparse.

	SLAC	GlueX 1	
$\gamma p \to \rho p$	~3.5 k events	~200 M events	
$\gamma p \to \omega p$	~1.0 k events	~9 M events	$\omega \to \pi^+\pi^-\pi^0$
$\gamma p \to \phi p$	~150 events	~1.8 M events	$\varphi \to K^+K^-$

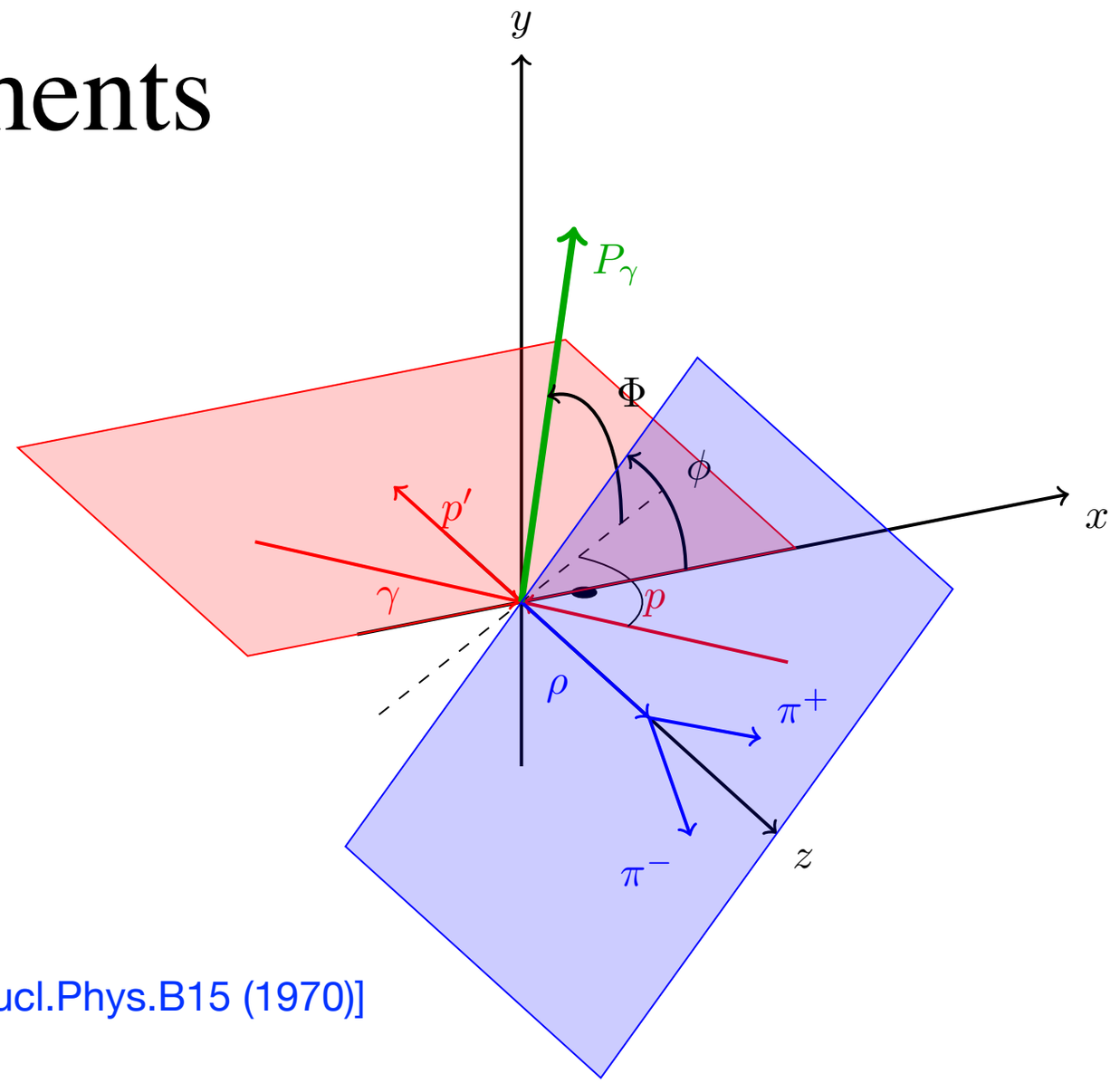
Spin Density Matrix Elements

Angular distribution of vector meson decay products gives access to production mechanism.

Linear beam polarization provides access to 9 SDMEs

Measured Intensity

$I(\Omega) \propto W(\cos\theta, \phi, \Phi)$



Schilling [Nucl.Phys.B15 (1970)]

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

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

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

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

Model

Joint Physics Analysis Center

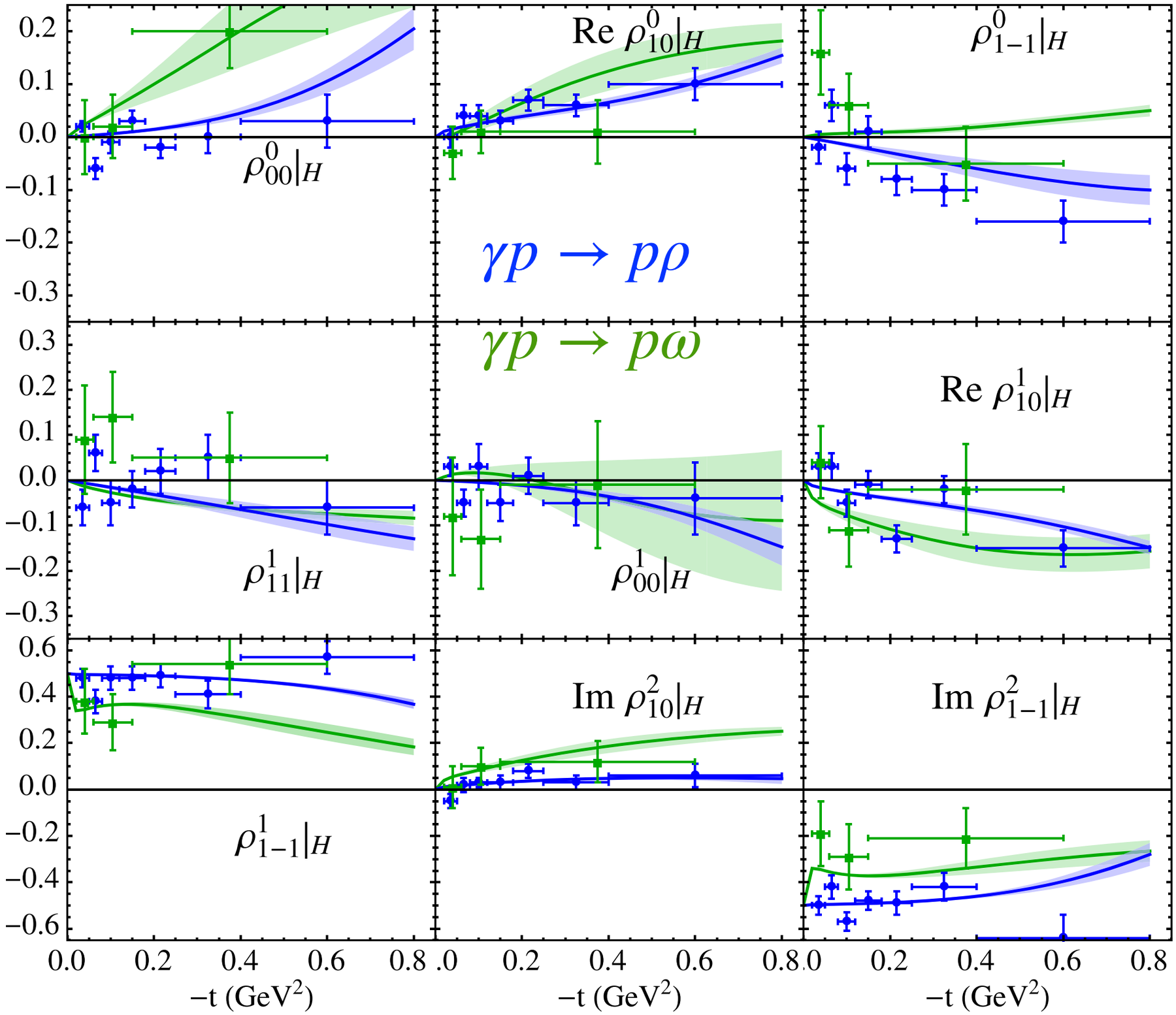
Mathieu [Phys.Rev.D, 97 (2018) 094003]

Regge model fit to cross section and SDME data from SLAC.

s channel helicity conservation SCHC $\rho^1_{1-1} = -\,\mathrm{Im}\rho^2_{1-1} = 0.5$ at $t \to 0$

ω has largest uncertainties

ω deviates from SCHC due to π exchange

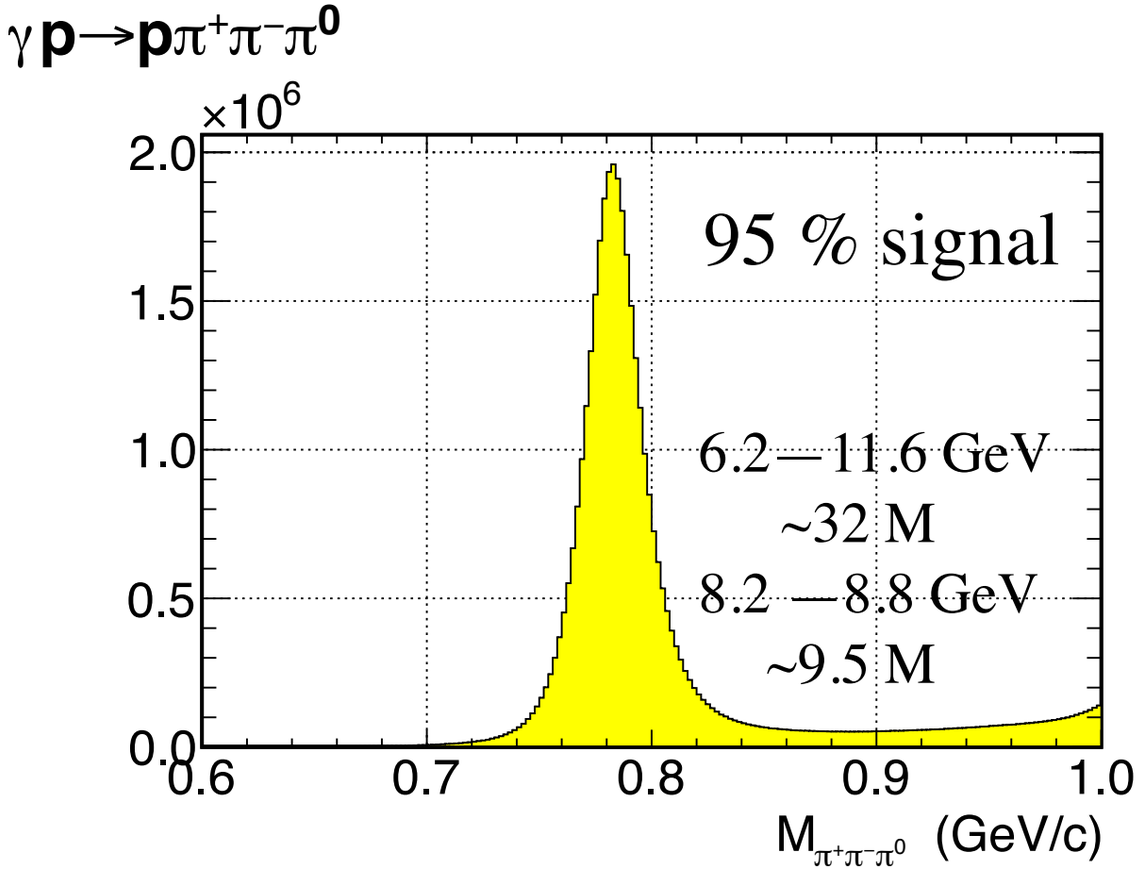


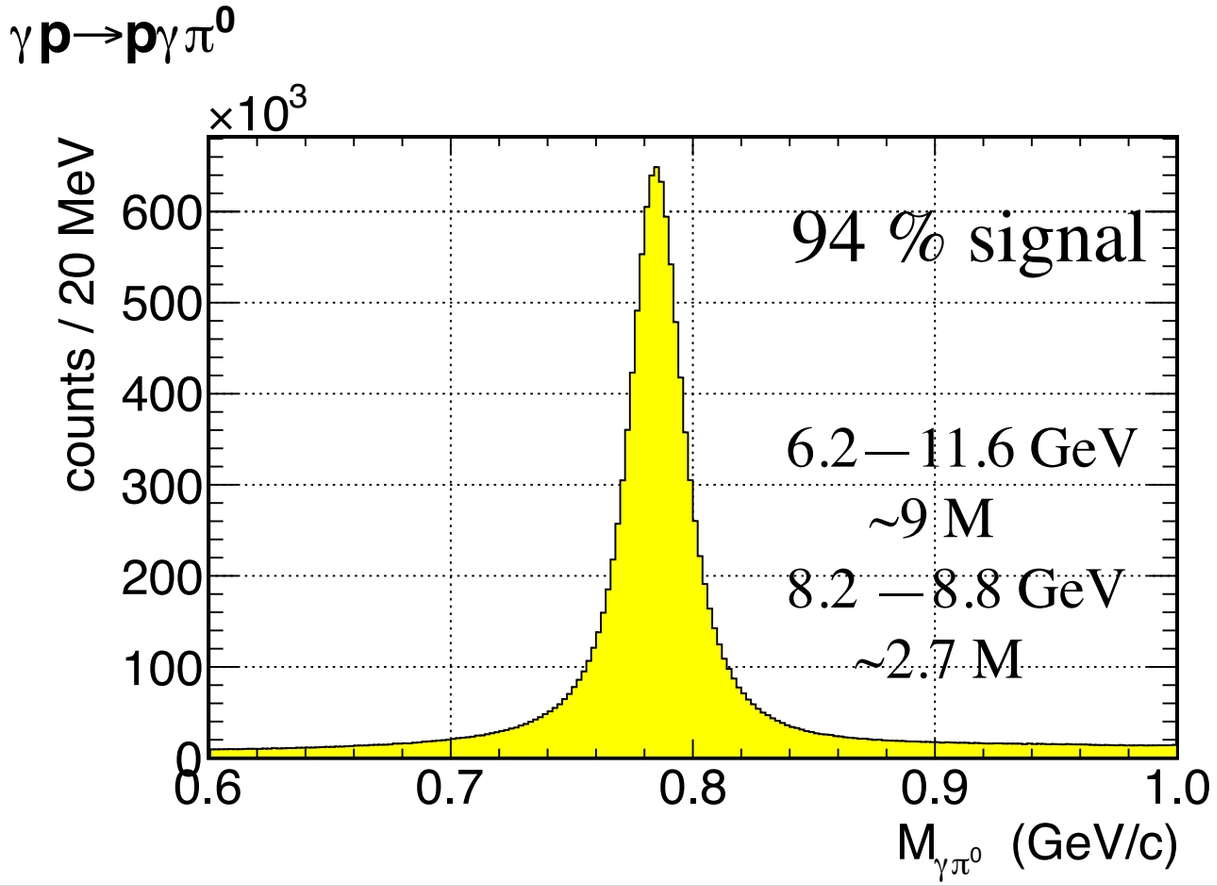
$\gamma p \rightarrow \omega p$

Will focus on $\gamma p \rightarrow \omega p$, other vector mesons also under analysis.

Backgrounds are small in the forward region subtracted using sidebands.

SDMEs extracted with unbinned extended maximum likelihood fits in 3D space in each bin of -t





ω SDMEs

$\gamma p \to \omega p$

$\omega \to \pi^+\pi^-\pi^0$

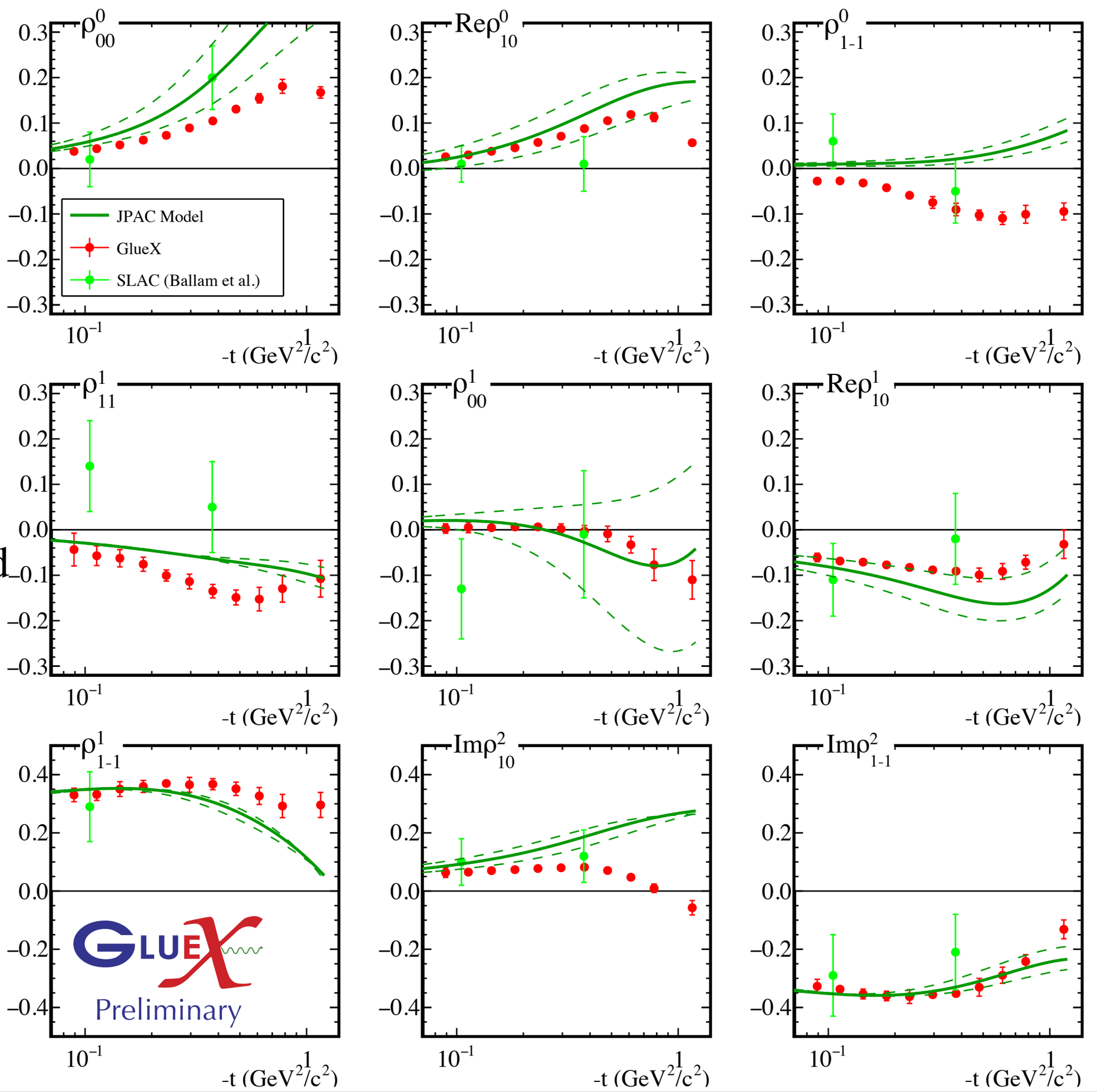
Logarithmic in t

All GlueX 1 data

Uncertainty dominated by systematics

Agree with JPAC for most SDMEs at moderate t (consistent with factorization of Regge residues)

DNP 2020



ρ SDMEs

$\gamma p \rightarrow \rho p$

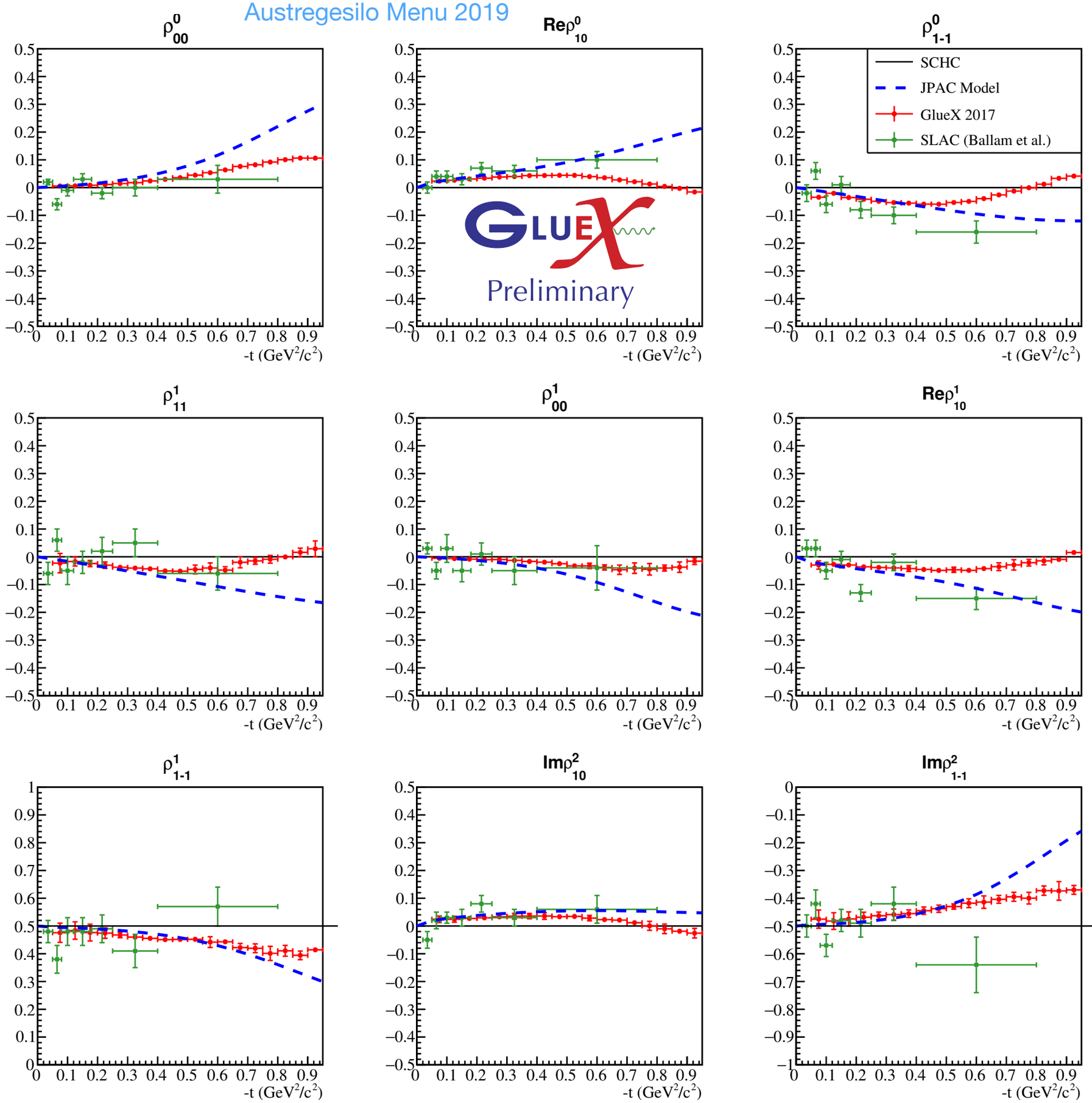
Released MENU 2019
~20% of GlueX 1 data

Uncertainty dominated by systematics

Agree with JPAC and SCHC at low t (consistent with factorization of Regge residues)

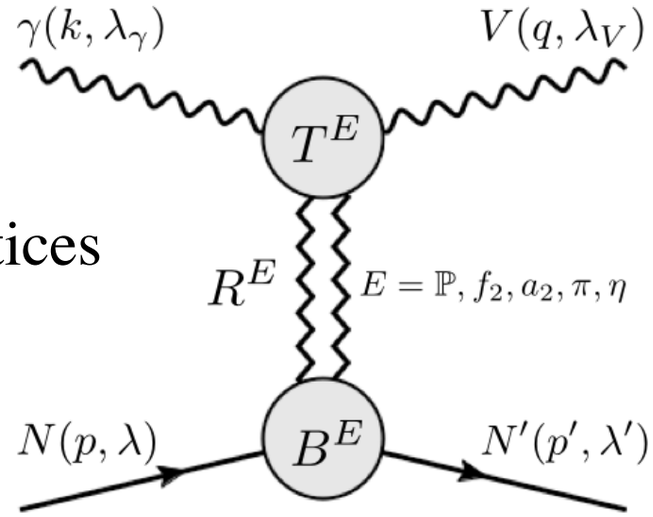
Publication in preparation

Austregesilo Menu 2019



Lessons from SDMEs

helicity transfer: 0, 1 or 2



Factorizes in to 2 vertices and a Regge factor

natural-parity exchanges are predominantly helicity conserving

ω production unnatural-parity consistent with a one-pion exchange

t dependence less important for SDMEs since it largely cancels in the ratio
Statistics limit SDME measurements to low t

[PhysRevD.97.094003 Mathieu]

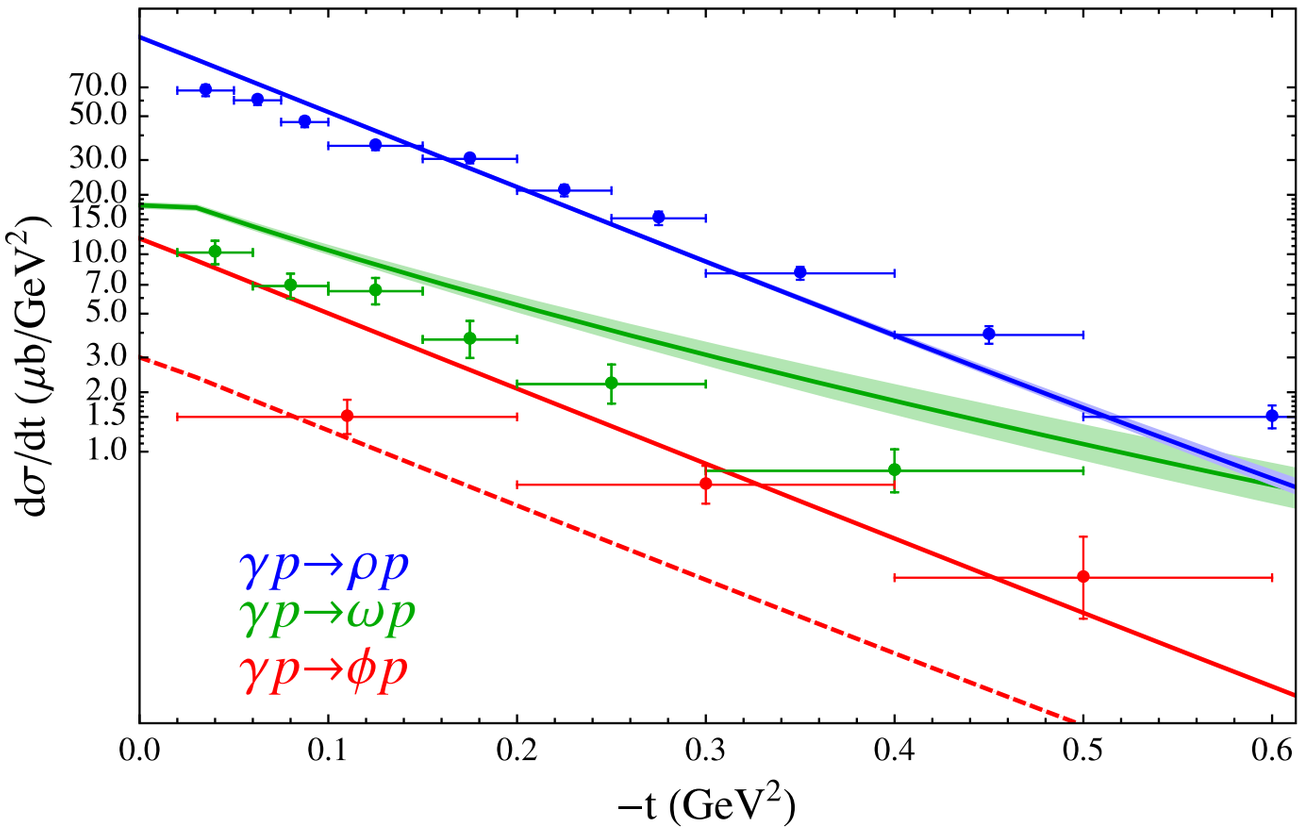


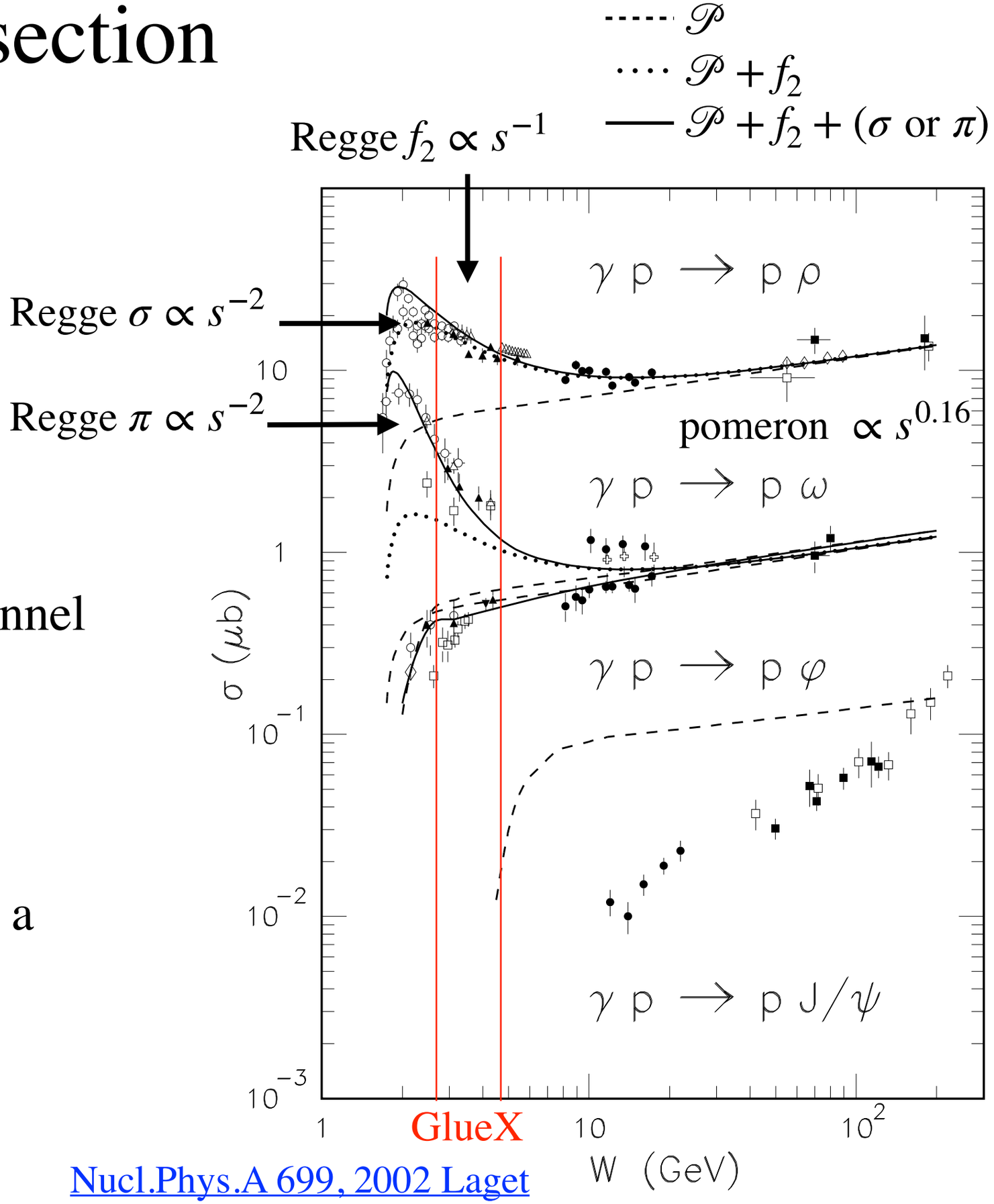
FIG. 10. $\gamma p \to (\rho^0, \omega, \phi) p$ differential cross section at 9.3 GeV

Vector meson cross section

Describing the cross section energy and momentum dependence requires good understanding of production mechanisms

Small angle, Pomeron and t-channel Reggeons

Large angle, exclusive meson production can be understood in a perturbative way at the level of effective parton degrees of freedom

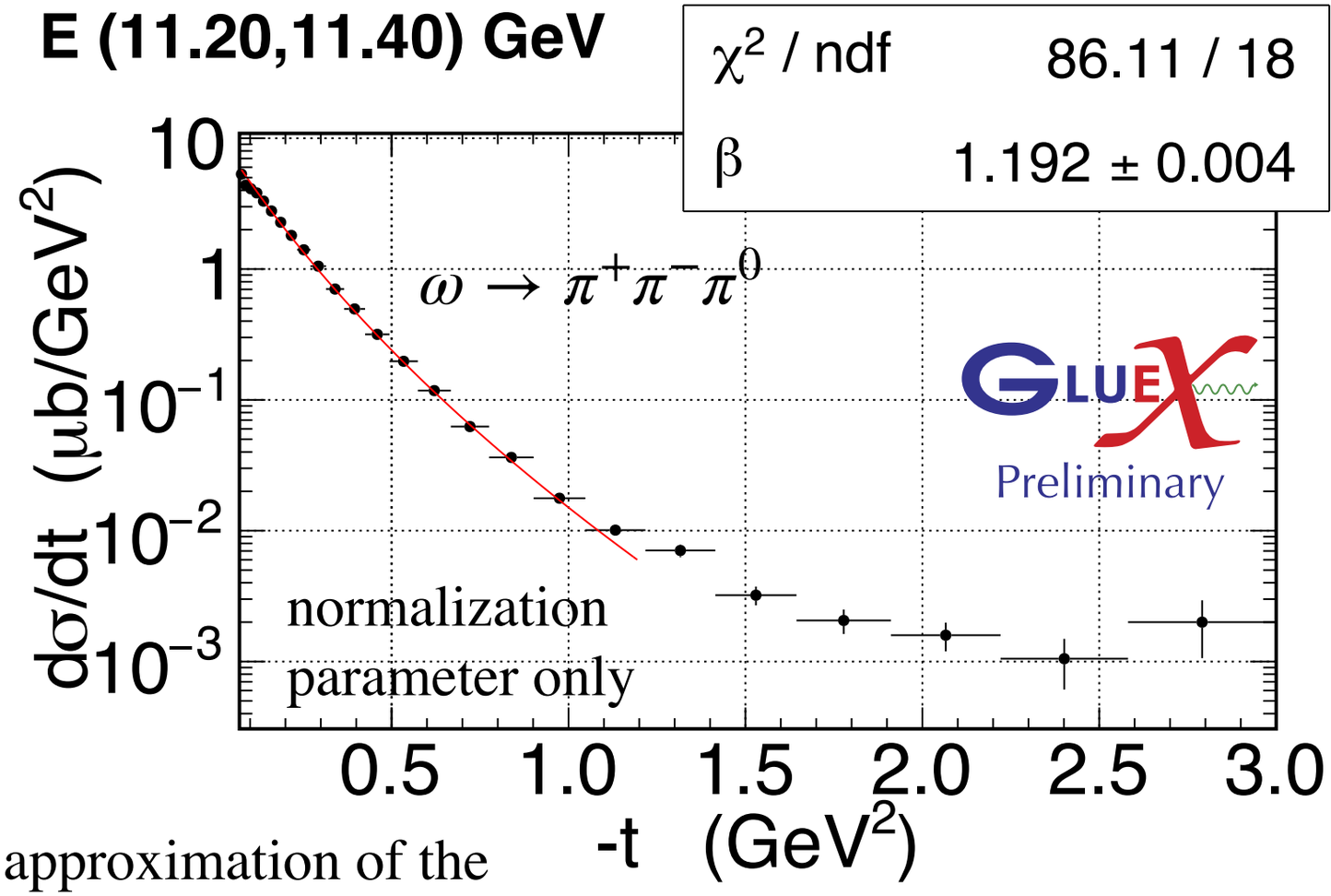


Nucl.Phys.A 699, 2002 Laget

Scattering picture, -t dependence

low t: diffractive scattering of the hadronic contents of the photon (wide energy range, threshold to HERA energies)
high t: partonic description of hard scattering mechanisms

GlueX energy: pomeron only exchange, good description of low t dependence but not of energy dependence.



$$\frac{d\sigma}{dt} \propto |F_1(t)F_V(t)|^2$$

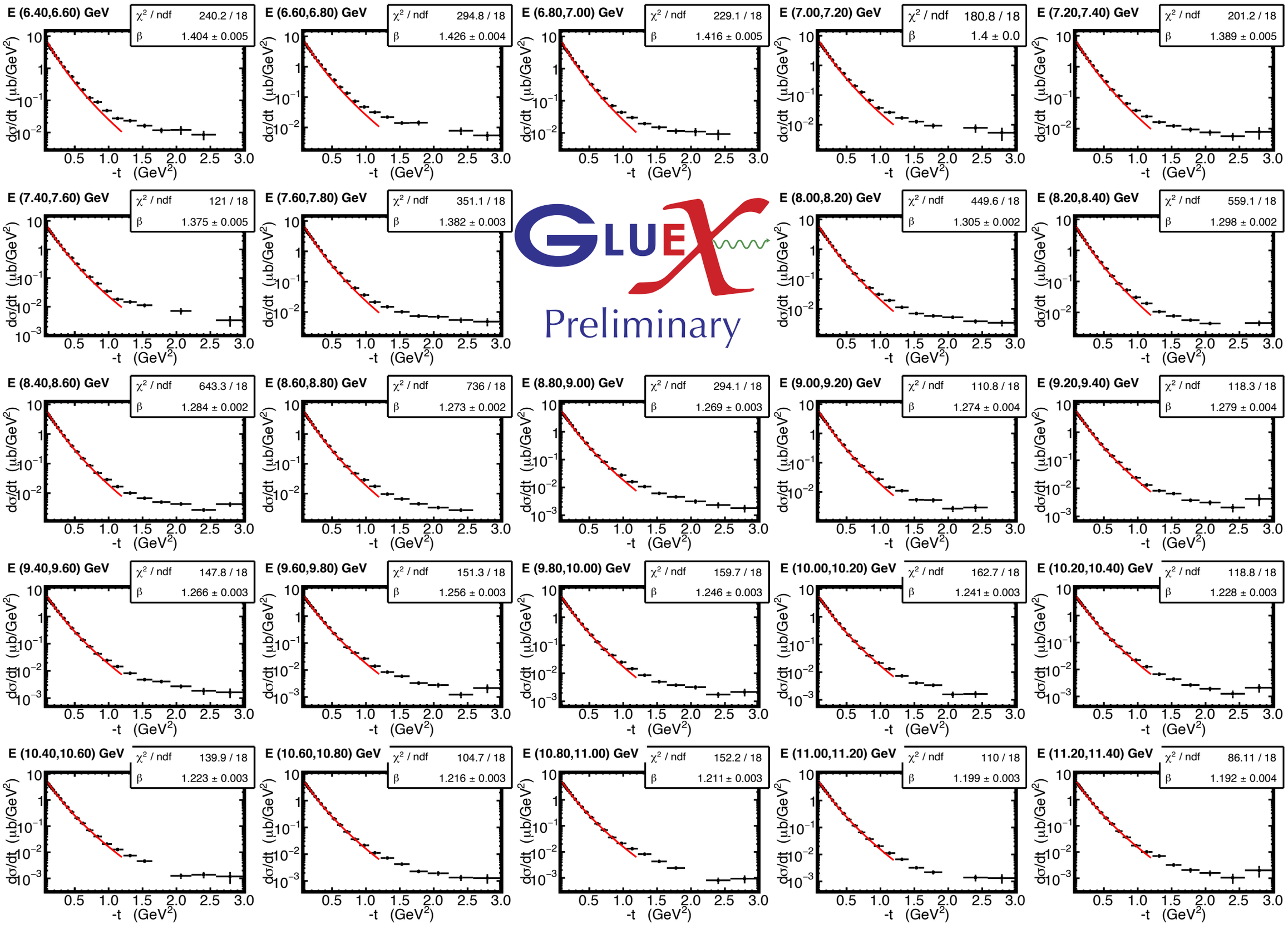
$$F_1(t) = \frac{4m_p^2 - 2.8t}{4m_p^2 - t}\frac{1}{(1 - t/t_0)^2}$$

dipole approximation of the nucleon Dirac form factor

$$F_V(t) = \frac{1}{1 - t/m_\omega^2}\frac{2\mu_0^2 + m_\omega^2}{2\mu_0^2 + m_\omega^2 - t}$$

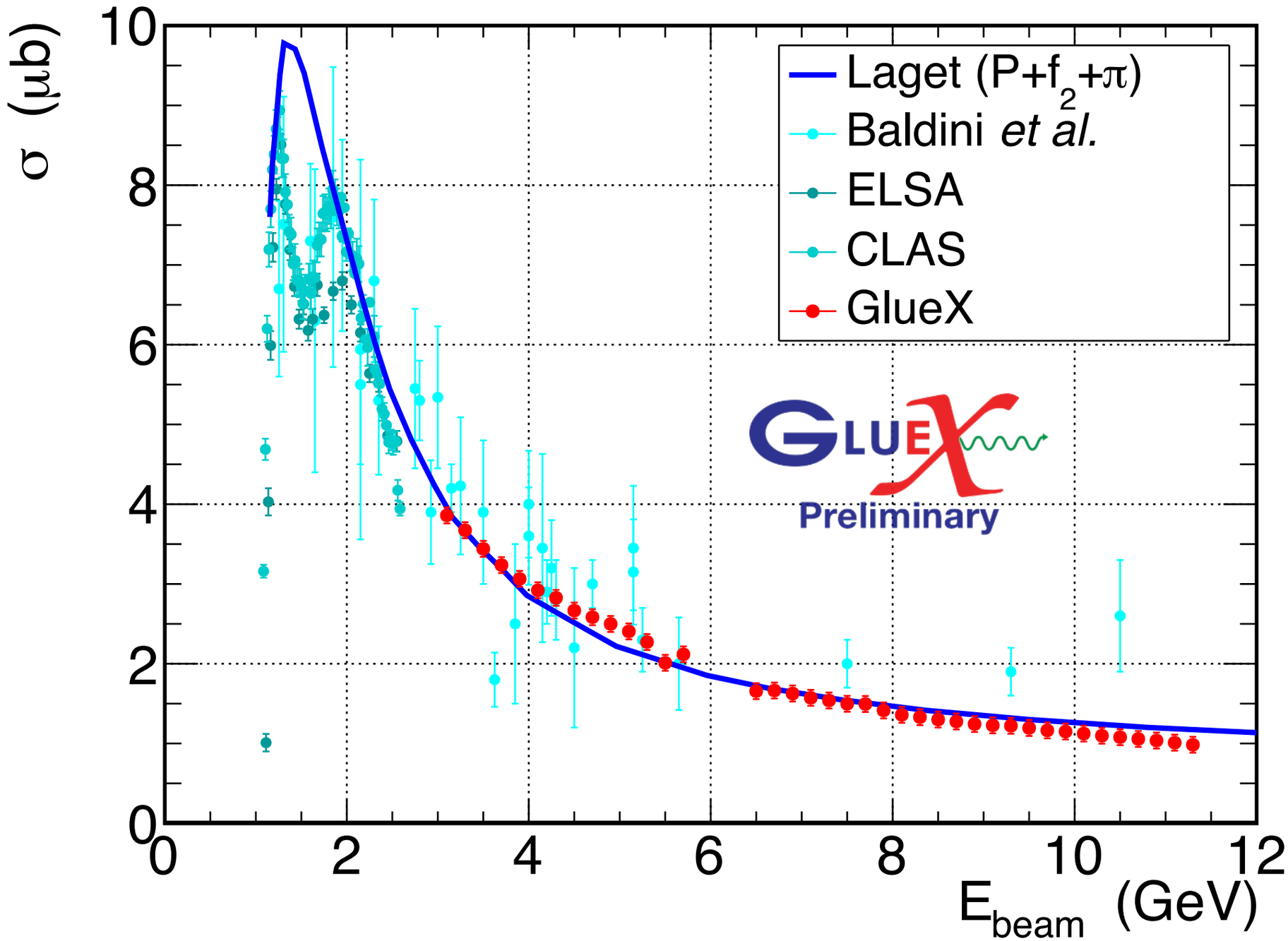
empirical form factor at the photon vertex

Stamp plots, $\omega \to \pi^+\pi^-\pi^0$, 50% of GlueX phase 1



Total Cross Section

Obtained using model extrapolations of $-t \to 0$



Uncertainties systematics dominated (preliminary)

Shows good agreement with model by Laget ($\mathscr{P} + f_2 + \pi$ exchange)

Constituent Counting Rules

High energy at fixed $\cos\theta_{\rm cm}$ and $s, t \gg M_p^2$

$$\frac{d\sigma}{dt} \propto s^{-(n-2)}$$

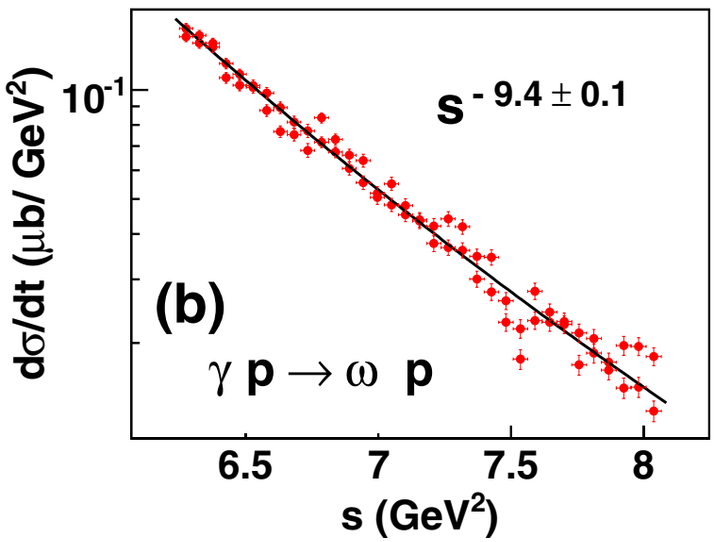
$n_e = 1$ elementary
$n_m = 2$ meson
$n_B = 3$ baryon

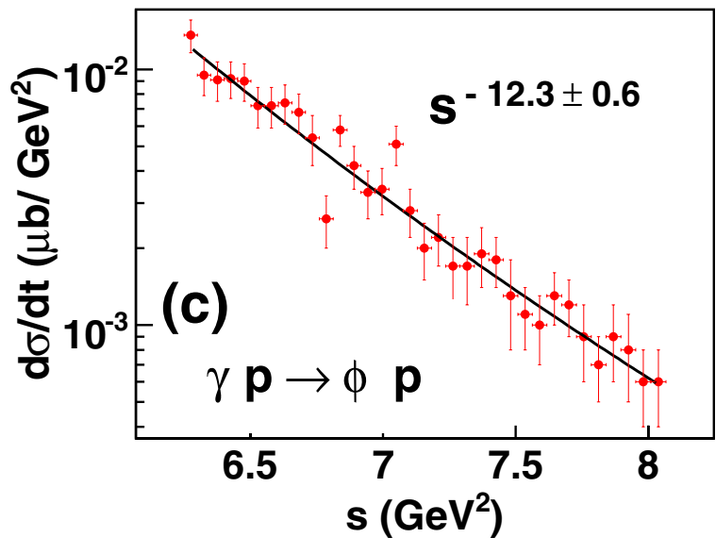
$n_\gamma = 1$ point like
$n_\gamma = 2$ $q\bar{q}$ configuration

n is the minimal number of constituents involved

$n_{\rm tot}$ = 3+3+2+1 = 9
$n_{\rm tot}$ = 3+3+2+2 = 10

Fits of CLAS data $\omega \to \pi^+\pi^-\pi^0$ PhysRevD.90.014013 Dey

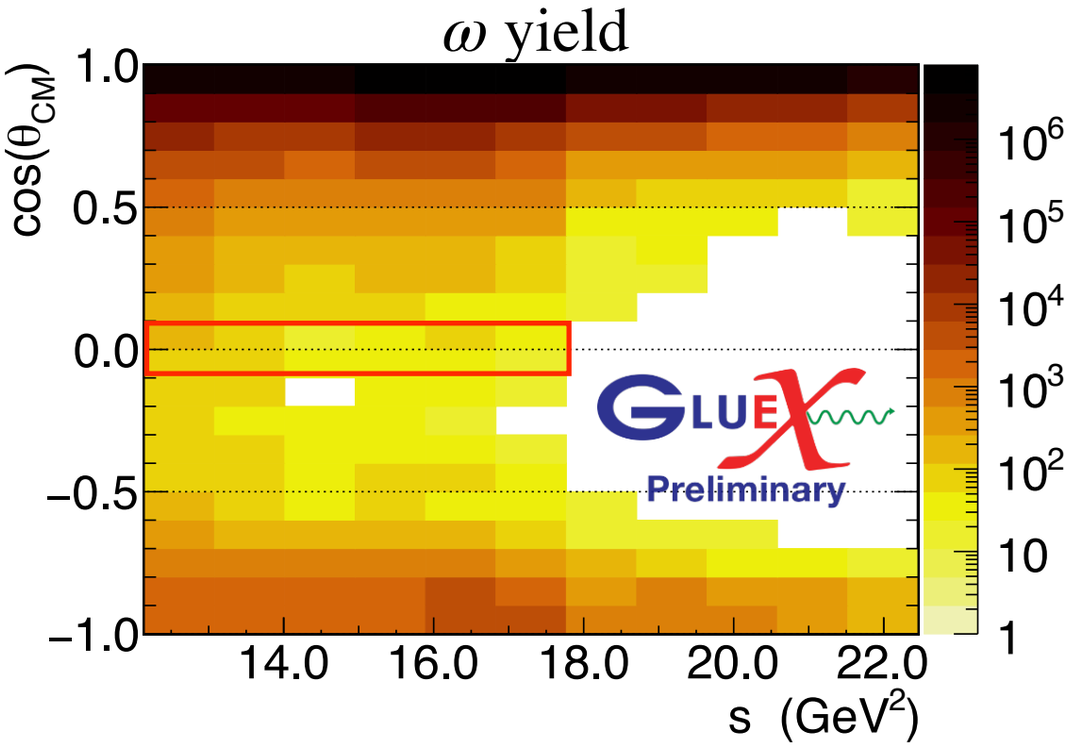




Could be explained by additional gluon exchanges

arxiv:2005.13067 Reed obtain $s^{-9.08 \pm 0.11}$

GlueX will produce cross sections at $\cos\theta = 0$ up to $s \approx 17\,\text{GeV}^2$



Conclusion

Vector meson photoproduction is a fruitful place to study QCD and understand reaction mechanisms.

GlueX: precise, high statistics data to study energy and t dependence.
statistical precision increased by orders of magnitude over existing data.

Work with JPAC to refine model using both cross section and polarization (SDME) data.

Access to hard scattering cross sections up to $s \approx 17\,\mathrm{GeV}^2$

GlueX Acknowledgements: gluex.org/thanks