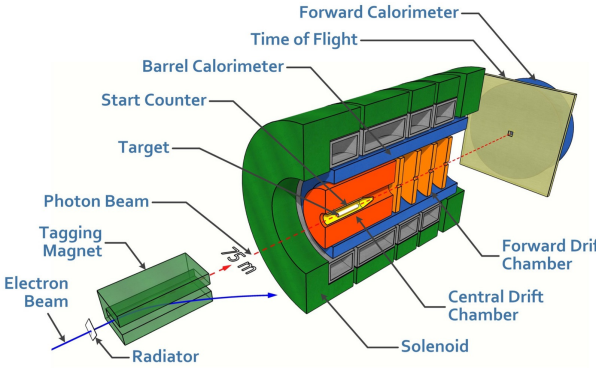
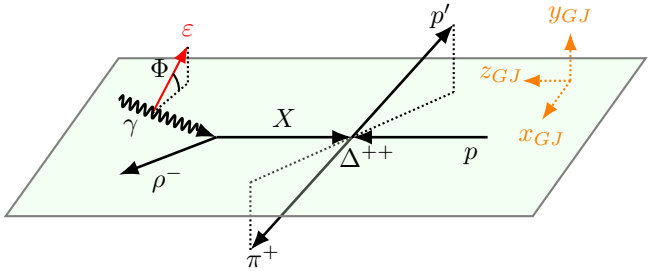
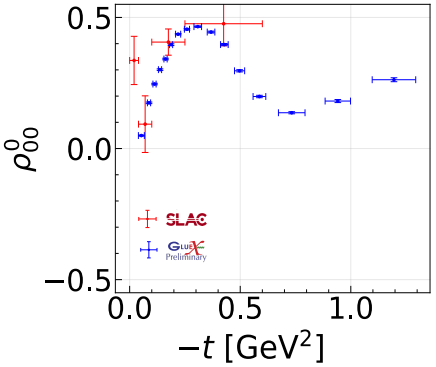






Spin-Density Matrix Elements in the reaction $\gamma p \longrightarrow \rho^- \Delta^{++}$ at GlueX

Niklas Herrmann for the GlueX collaboration

Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

RUB

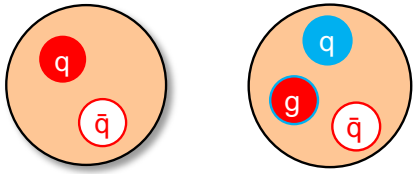
MESON Kraków - B6

June 29, 2026

Jefferson Lab

GlueX

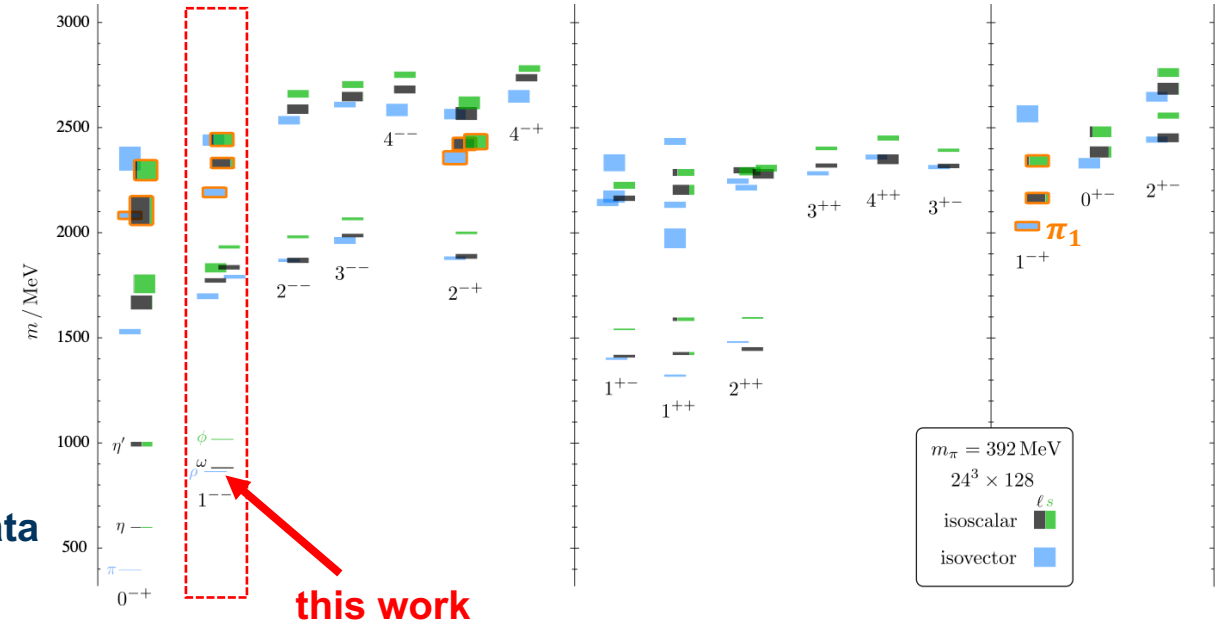
Lattice QCD



- **Goal of GlueX: map the full spectrum of light-quark mesons with an emphasis on hybrid mesons by using photoproduction**
- **Best evidence for gluonic excitations is for $\pi_1(1600)$ in COMPASS pion-production data**

Alexeev et al. (2022), *Phys. Rev. D* 105, 012005

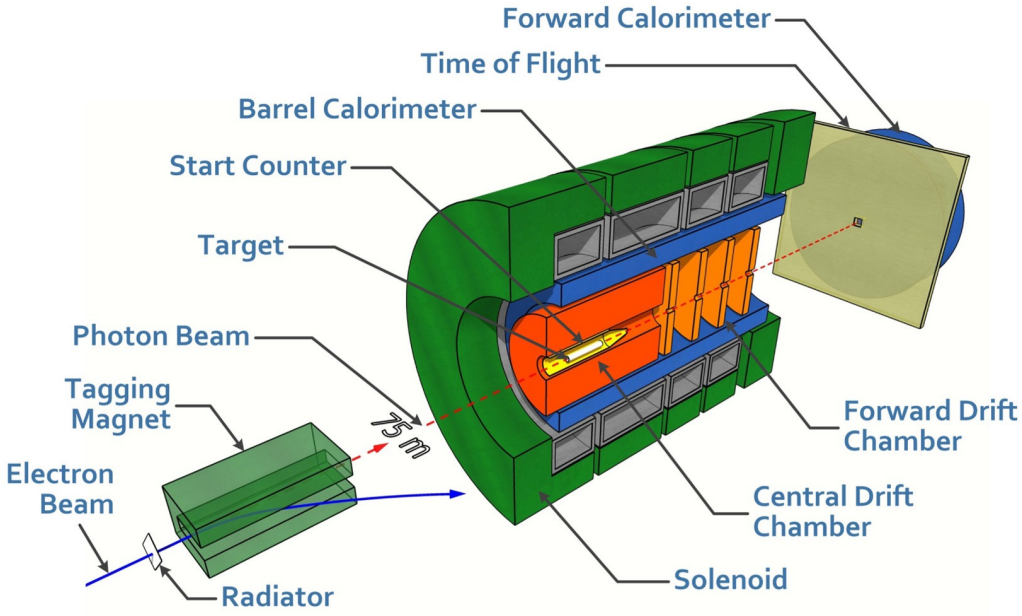
Dudek et al. (2013), *Phys. Rev. D*, 88, 094505



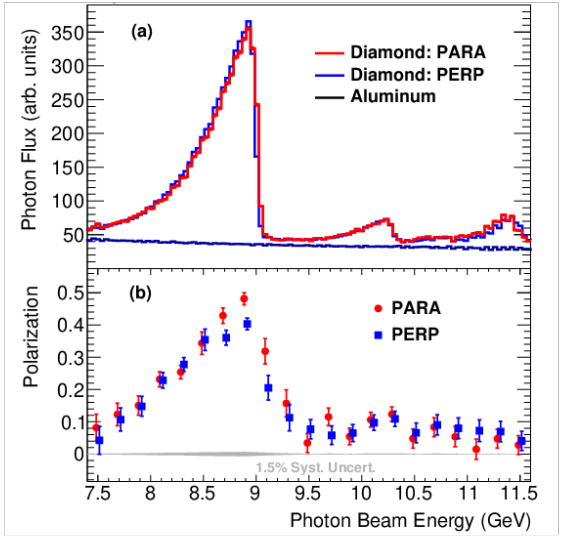
GlueX experiment

F. Nerling (Thu, A2)
H. Li (Fr, B3)
I. Belov (Sat, A5)
F. Afzal (Mo, plenary)
M. Scott (Mo, B6)

MESON 2026



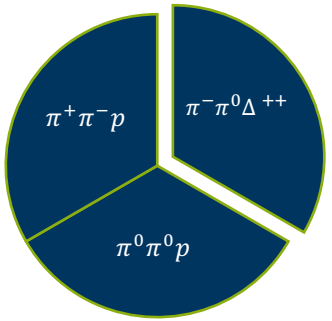
GlueX: NIMA 987 (2021) 164807

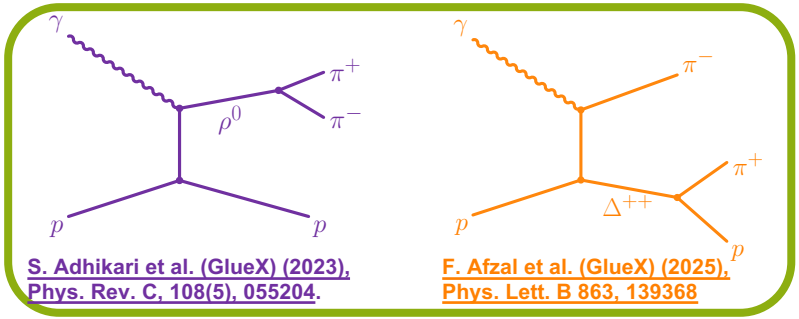


→ **Experimental setup for light-quark meson spectroscopy providing nearly complete acceptance for charged and neutral particles in the final state**

Motivation for the reaction $\gamma p \rightarrow \rho^- \Delta^{++}$

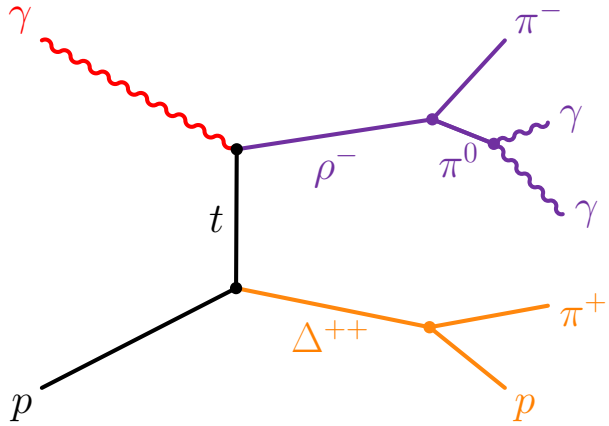
- $\pi^+\pi^- p$ and $\pi^0\pi^0 p$ states (neutral exchange) currently being analyzed by other collaborators
- $\pi^-\pi^0\Delta^{++}$ (charge exchange, no isoscalar contribution) not studied yet
- Spin-Density Matrix describes the polarization of the produced Meson-Baryon system
- Goal: Determination of Spin-Density Matrix of Δ^{++} and ρ^-





S. Adhikari et al. (GlueX) (2023), Phys. Rev. C, 108(5), 055204.

F. Afzal et al. (GlueX) (2025), Phys. Lett. B 863, 139368

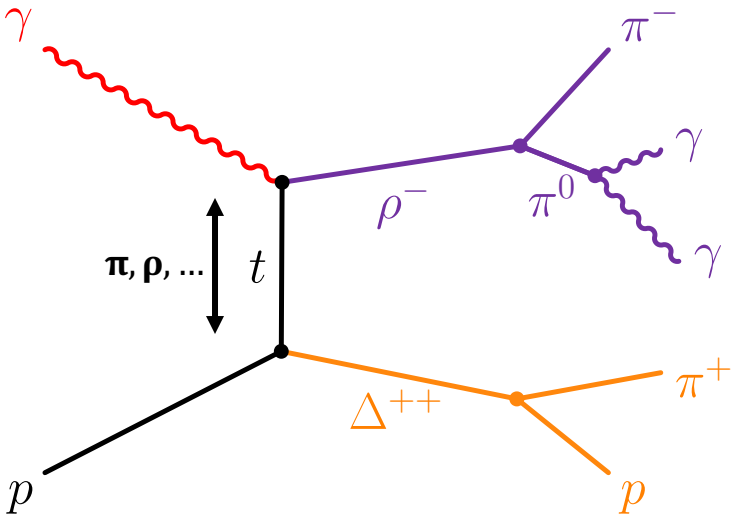


SDMEs

- **SDMEs sensitive to the production mechanism**
- **Knowledge of the photon polarization enables the decomposition of the meson-baryon system spin–density matrix into its unpolarized and polarized components :**

  $\hat{\rho}^0$ **(unpol),** $\hat{\rho}^1$ **(linear)** $\hat{\rho}^2$ **(linear)**

- **SLAC determined the unpolarized SDMEs in the 1970s**



$$\vec{P}_\gamma = P_\gamma\,(-\cos(2\Phi), -\sin(2\Phi), 0)$$

SDMEs

$$\hat{\rho}_\gamma = \frac{1}{2} I + \vec{P}_\gamma \cdot \vec{\sigma}$$

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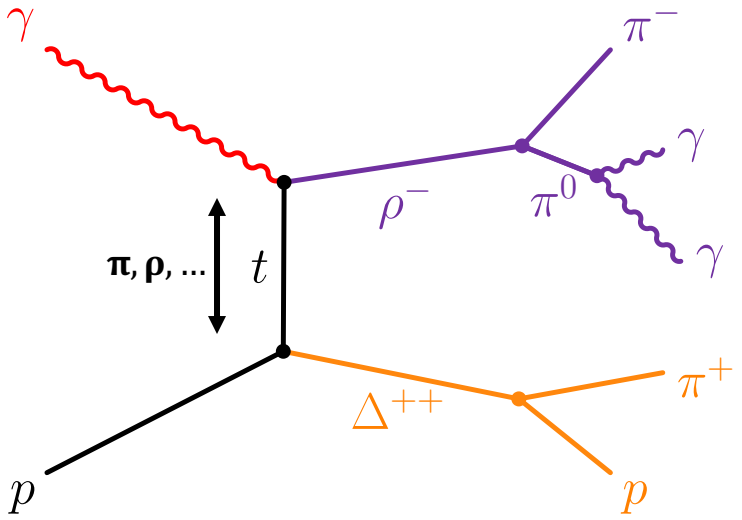

$$\vec{P}_\gamma = P_\gamma\,(-\cos(2\Phi), -\sin(2\Phi), 0)$$

$$\hat{\rho}_{\rho^-\Delta^{++}} = \hat{\rho}^0 + \sum_{\alpha=1}^{3} P_\gamma^\alpha \hat{\rho}^\alpha$$

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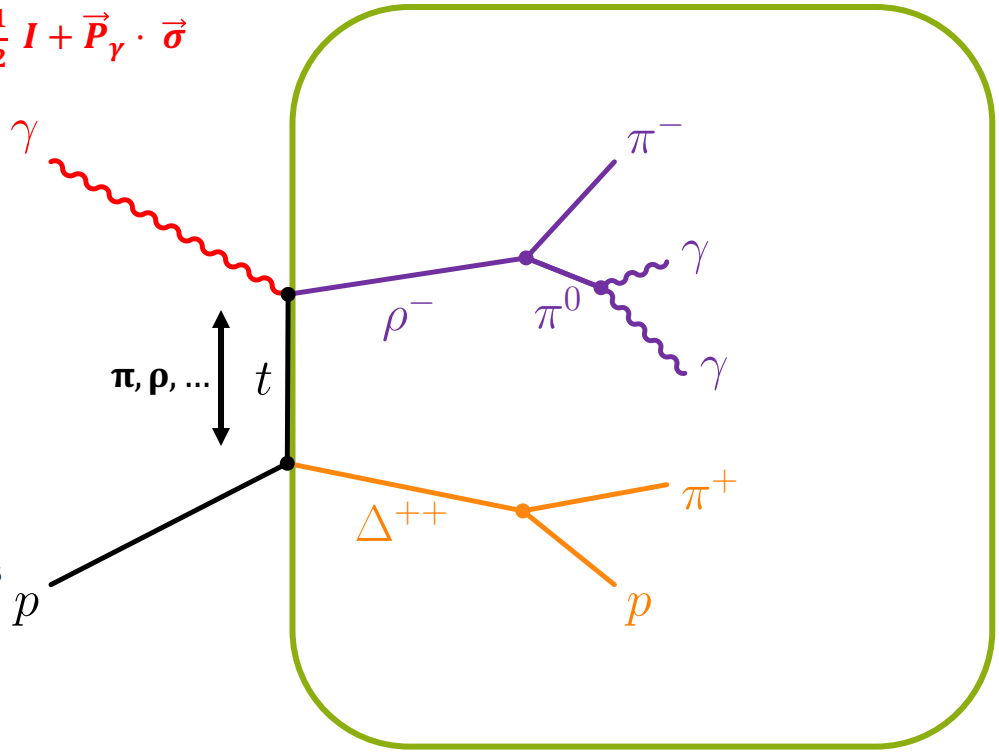

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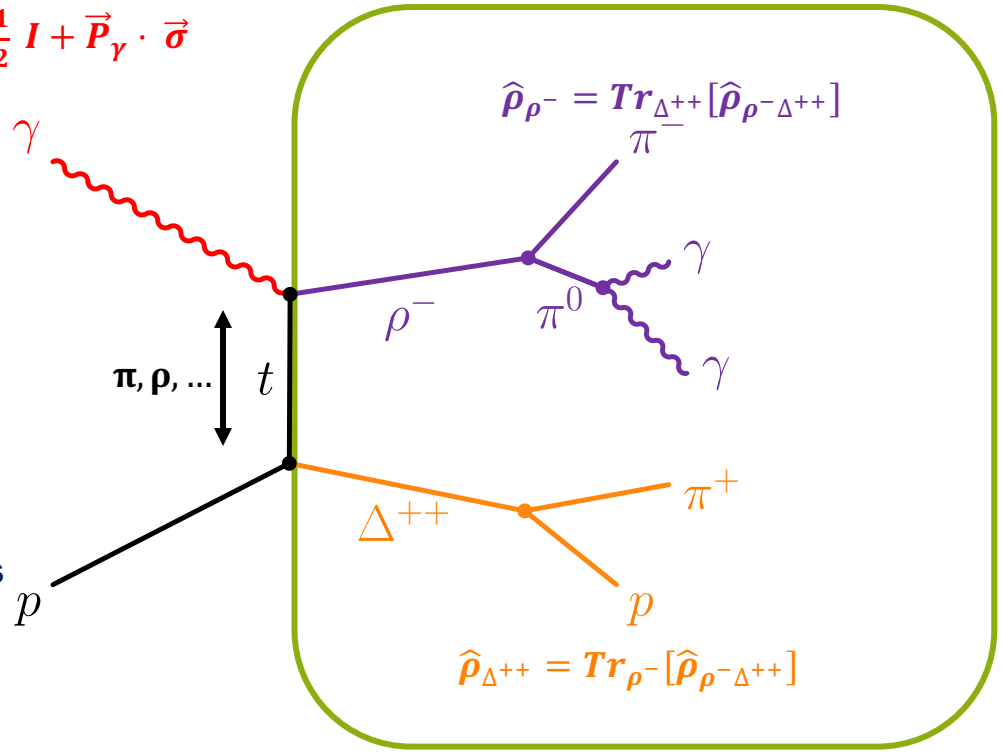


$$\vec{P}_\gamma = P_\gamma\,(-\cos(2\Phi), -\sin(2\Phi), 0)$$

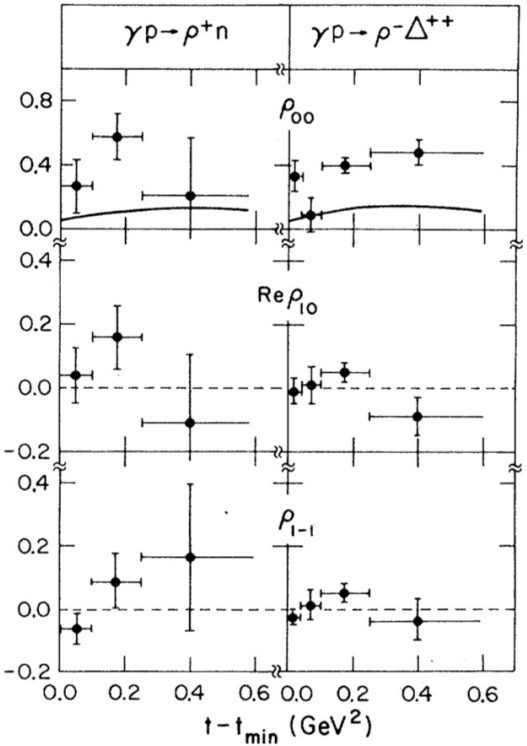
$$\hat{\rho}_{\rho^-\Delta^{++}} = \hat{\rho}^0 + \sum_{\alpha=1}^{3} P_\gamma^\alpha \hat{\rho}^\alpha$$

SDMEs

- SDMEs sensitive to mechanism
- Knowledge of the p enables the decom of the meson-baryo system spin–densi unpolarized and po

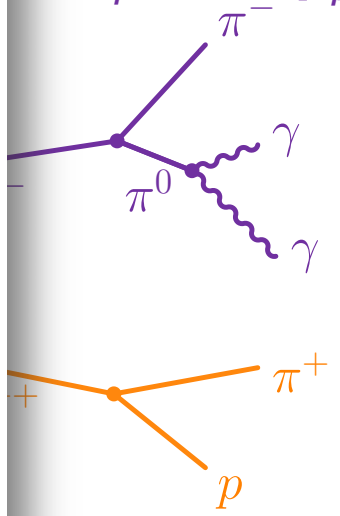
  $\hat{\rho}^0$ (unpol), $\hat{\rho}^1$ (lin
- SLAC determined t in the 1970s

J. Abramson et al. (1976), Phys. Rev. Lett., 36(24), 1432–1434.



SLAC

$$\hat{\rho}_{\rho^-} = Tr_{\Delta^{++}}[\hat{\rho}_{\rho^-\Delta^{++}}]$$



$$\hat{\rho}_{\Delta^{++}} = Tr_{\rho^-}[\hat{\rho}_{\rho^-\Delta^{++}}]$$

Event selection

Mass windows

$0.62\ \text{GeV} < M(\pi^-\pi^0) < 0.93\ \text{GeV}$

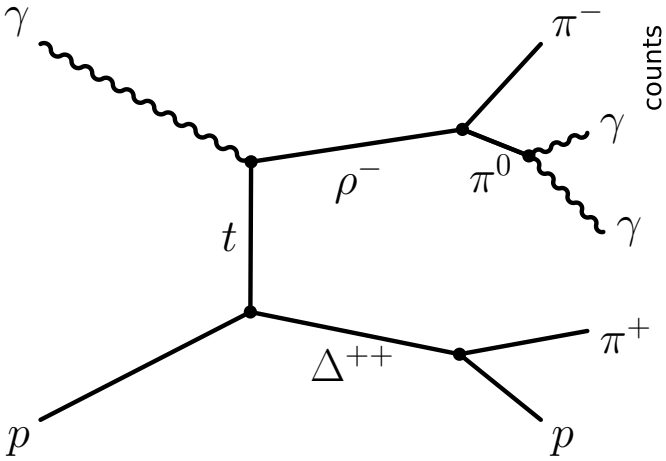
$1.10\ \text{GeV} < M(\pi^+ p) < 1.35\ \text{GeV}$

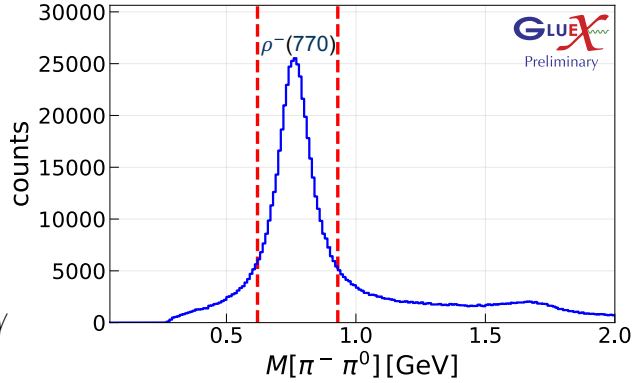
$0.12\ \text{GeV} < M(\gamma\gamma) < 0.15\ \text{GeV}$

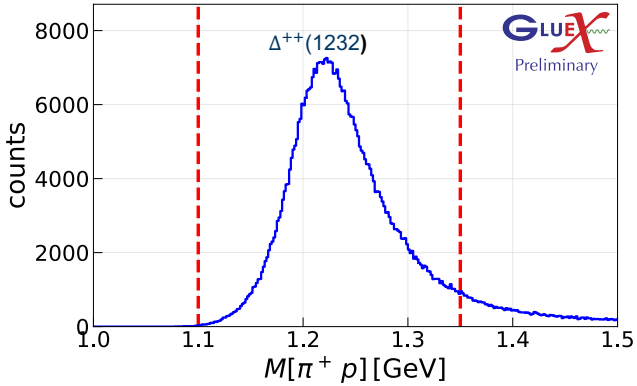
$0.9\ \text{GeV} < M(\pi^-\pi^0\pi^+)$

$2.0\ \text{GeV} < M(\pi^0 p)$

$0.025\ \text{GeV}^2 < -t < 1.4\ \text{GeV}^2$
(16 bins in range)



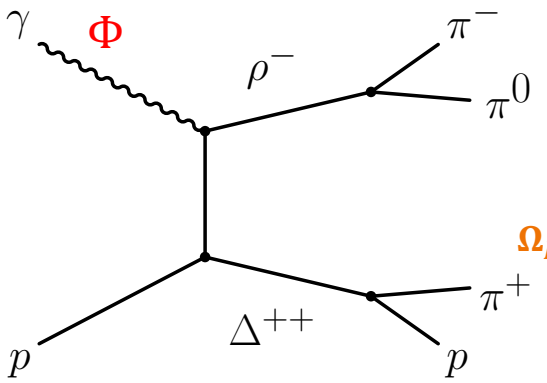




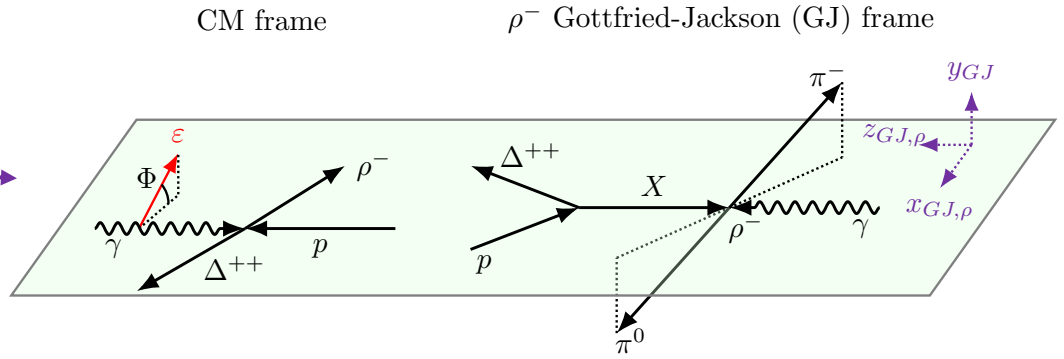
→ **After the selection, a total of 1.8 million events remains for GlueX-I**
→ **Background from different final states ~ 1.4 %**
→ **Combinatorial background < 1% to 14 % depending on –t**

Fit to extract SDMEs

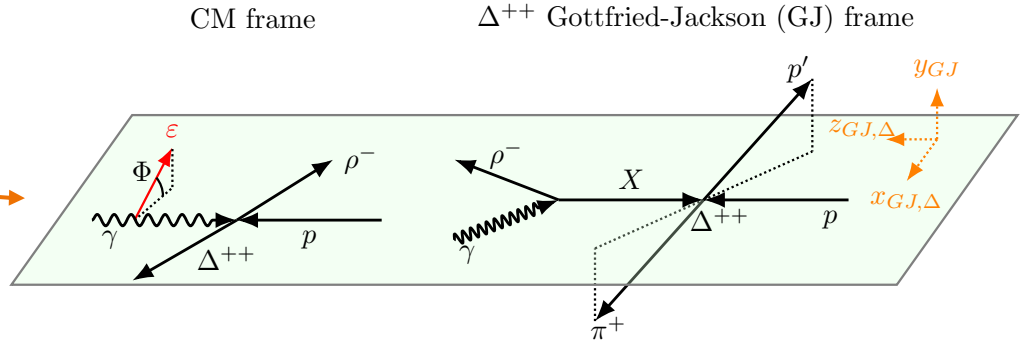
Frames



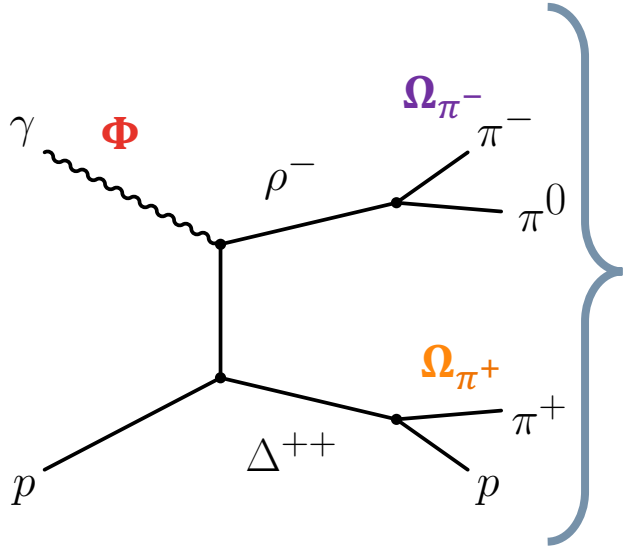
$\Omega_{Decay\ Meson}$
$(\vartheta_{\pi^-}, \varphi_{\pi^-})$



$\Omega_{Decay\ Baryon}$
$(\vartheta_{\pi^+}, \varphi_{\pi^+})$



Full fit model - Double SDMEs



$$I^{\alpha} = \frac{2\kappa}{\pi} \sum_{l,l'} \sum_{\lambda_\Delta,\lambda_\Delta'} \sum_{m,m'} \left|\widetilde{F}\ (m^2_{\pi p})\right|^2 c_{\lambda_\Delta\lambda_\Delta'}(\Omega_{\pi^+})\ \rho^{\alpha,l,l'}_{mm',\lambda_\Delta\lambda_\Delta'}(s,t) c^{l,l'}_{mm'}\ (\Omega_{\pi^-})\ |\ F(m^2_{\pi\pi})|^2$$

Fitparameter $r^{\alpha}_{mm'\lambda_\Delta\lambda'_\Delta}$, $\tilde{r}^{\alpha}_{mm'\lambda_\Delta\lambda'_\Delta}$ **is a linear combination of one to four** $\rho^{\alpha}_{mm'\lambda_\Delta\lambda'_\Delta}$

↓

Parity, hermicity, normalisation, linear combination

↓

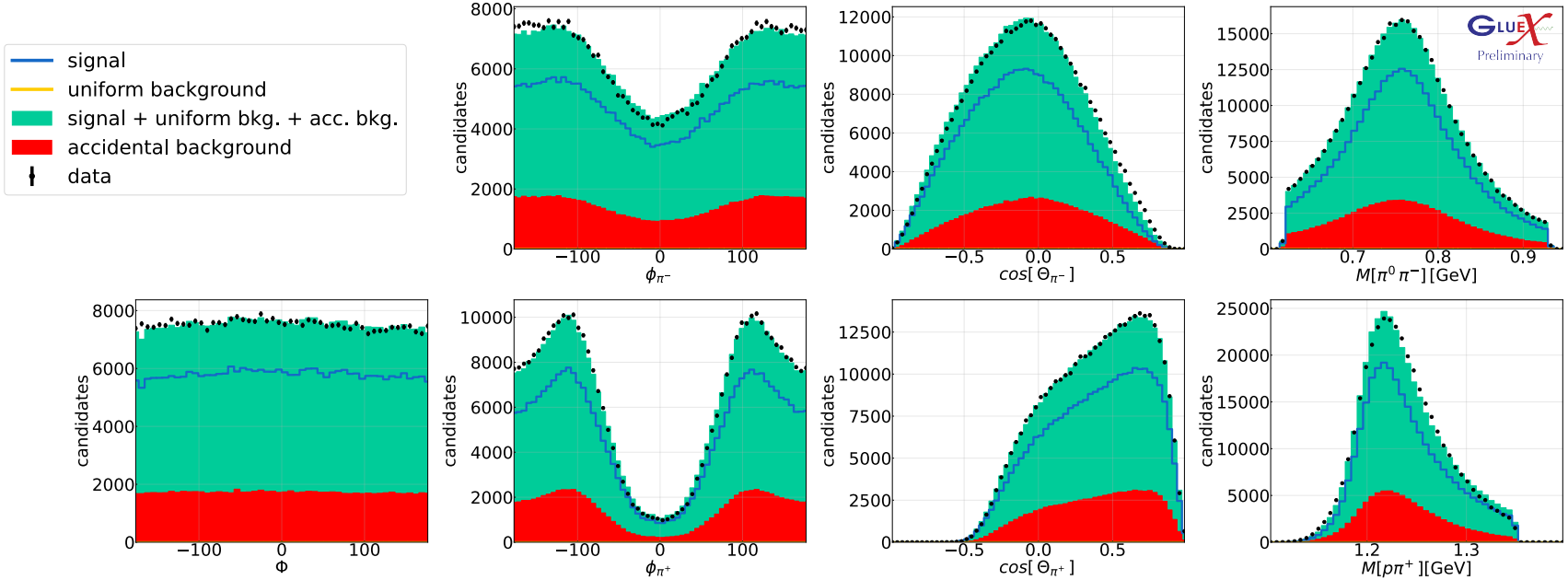
$\alpha = 0$: 19 fit parameters
$\alpha = 1$: 20 fit parameters
$\alpha = 2$: 16 fit parameters

Open question: do the upper and lower vertex factorize?

Factorization $\Longrightarrow$ $\tilde{r}^{\alpha}_{mm'\lambda_\Delta\lambda'_\Delta}$ **vanishes**

Fit Evaluation

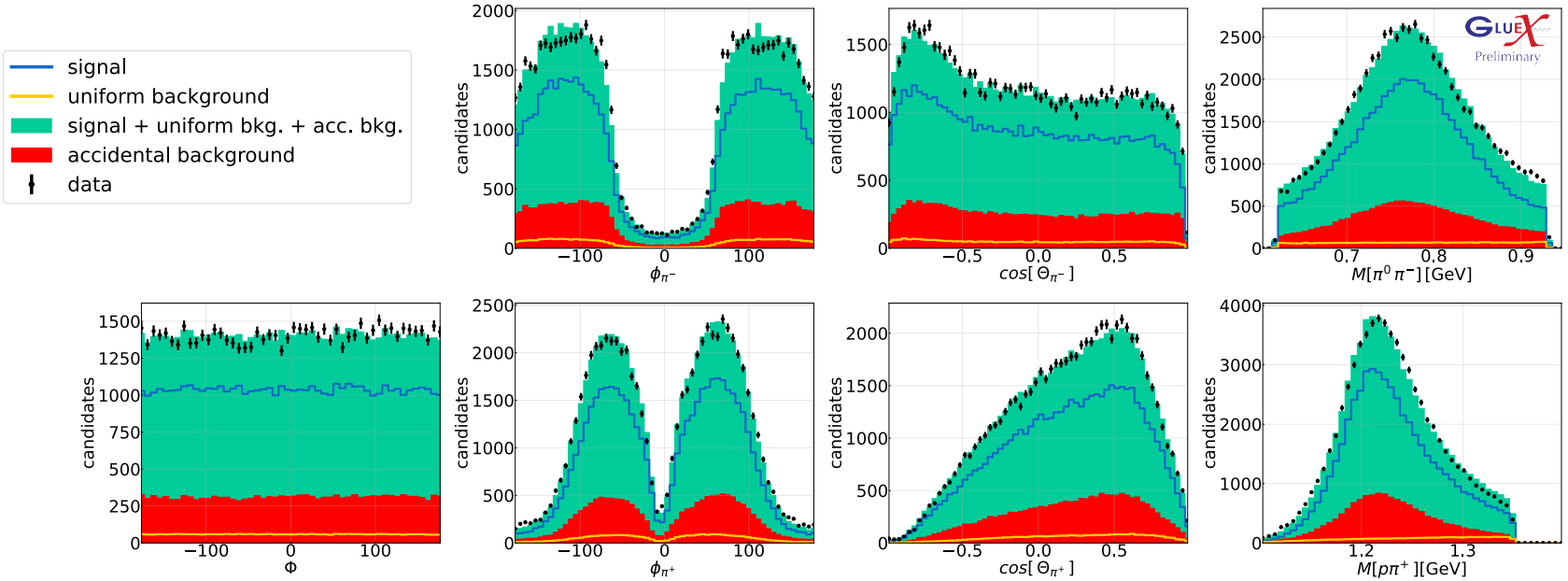
$0.025\,\mathrm{GeV}^2 < |t| < 0.075\,\mathrm{GeV}^2$



→ **Overall very good agreement between data and fit**

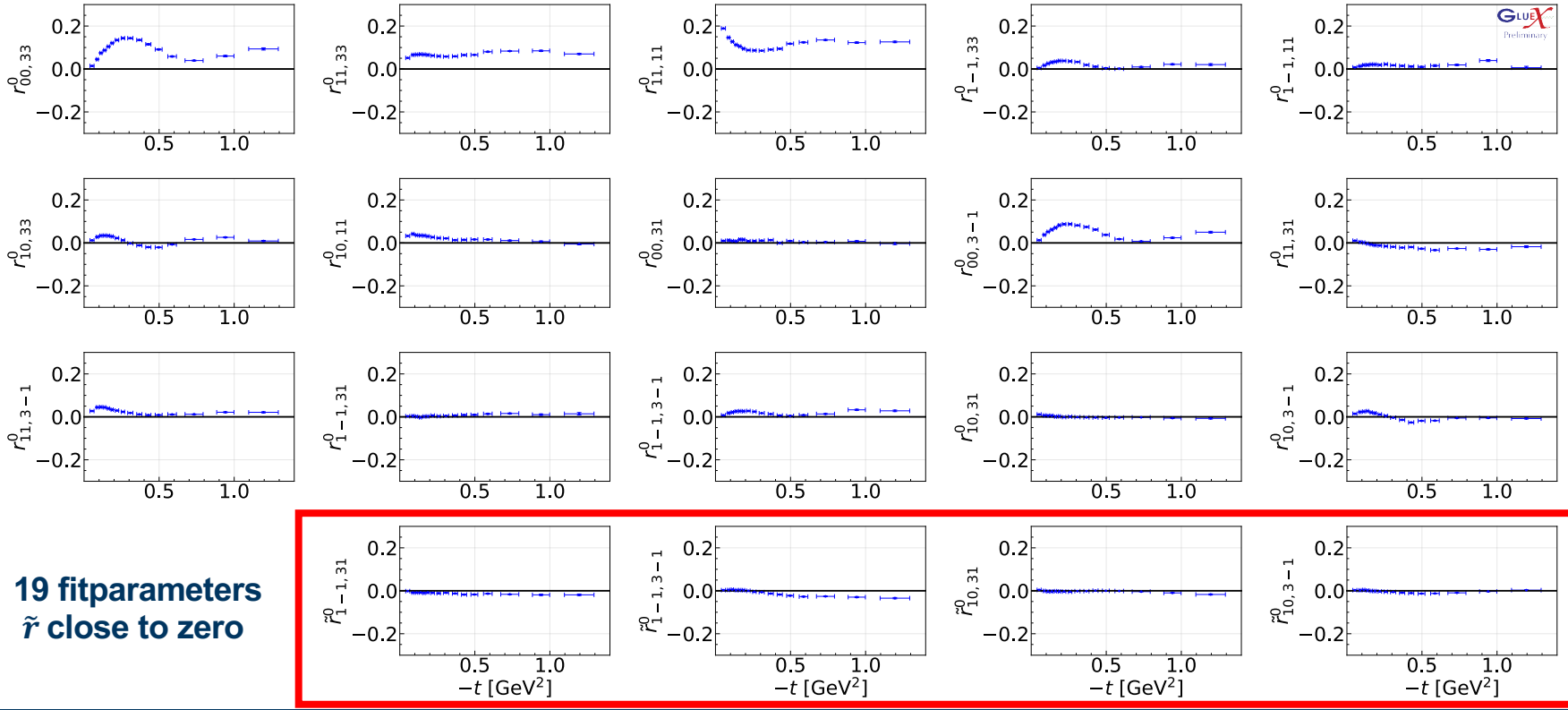
Fit Evaluation

$0.460\,\text{GeV}^2 < |t| < 0.540\,\text{GeV}^2$



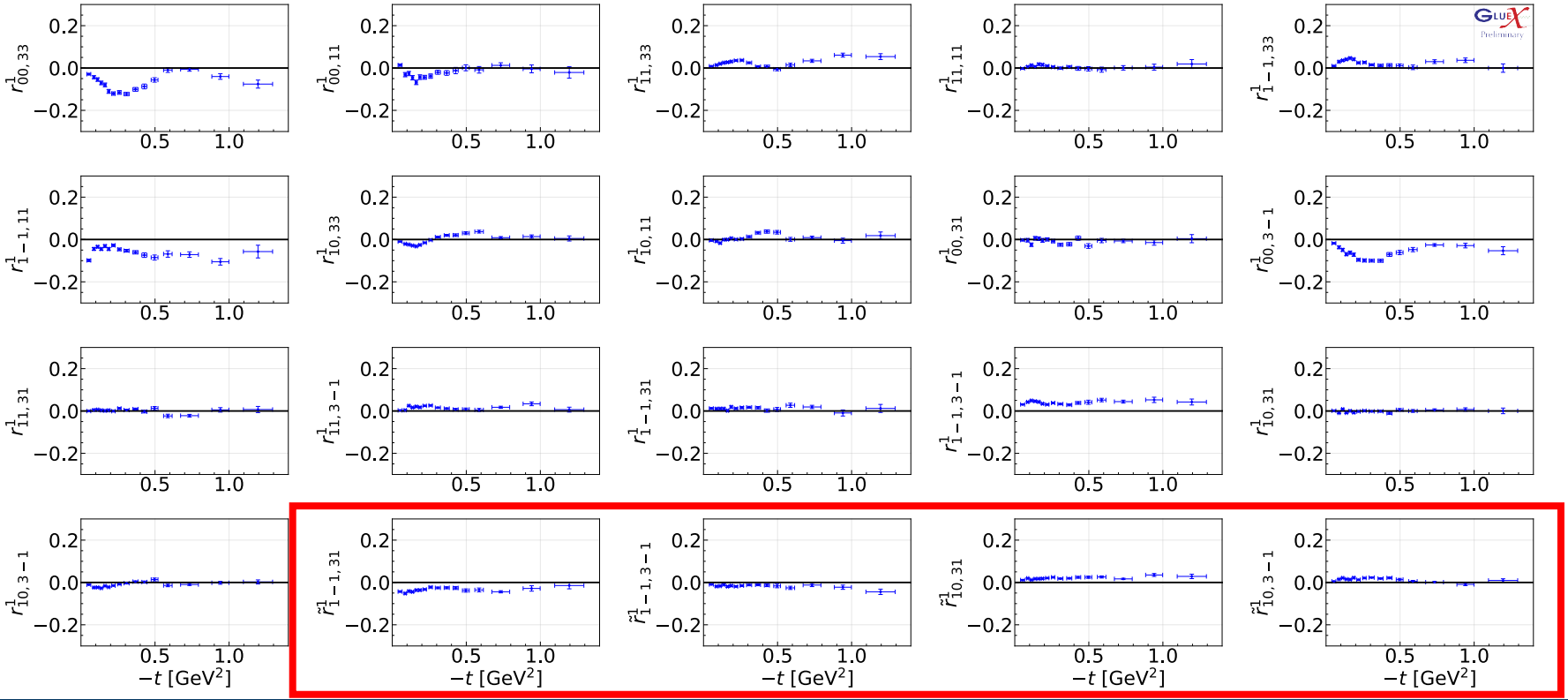
→ **Overall very good agreement between data and fit (even for higher t-bins)**

Full model - unpolarized Double SDMEs

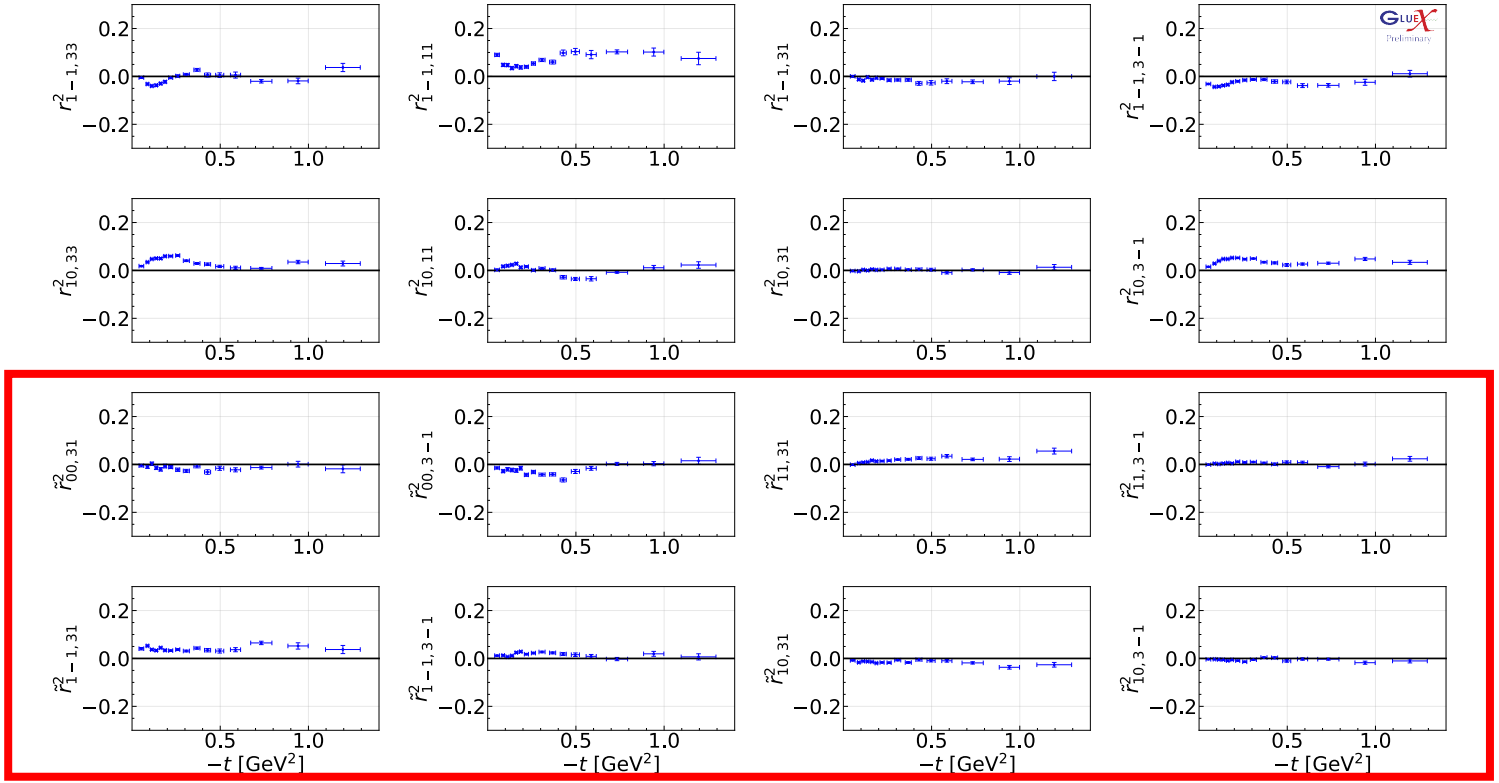


→ **19 fitparameters**
→ **$\tilde{r}$ close to zero**

Full model - polarized Double SDMEs (α = 1)



Full model - polarized Double SDMEs (α = 2)



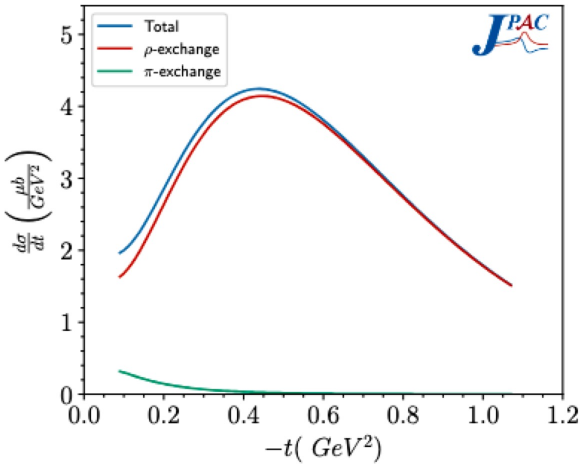
Naturality

- **Naturality is given by the quantum numbers J^P of the exchanged particle:**

$$\eta = P(-1)^J$$

- **Certain linear combinations of SDMEs allow separation of natural ($\eta = 1$) and unnatural ($\eta = -1$) exchange amplitudes**

V. Shastry, V. Mathieu

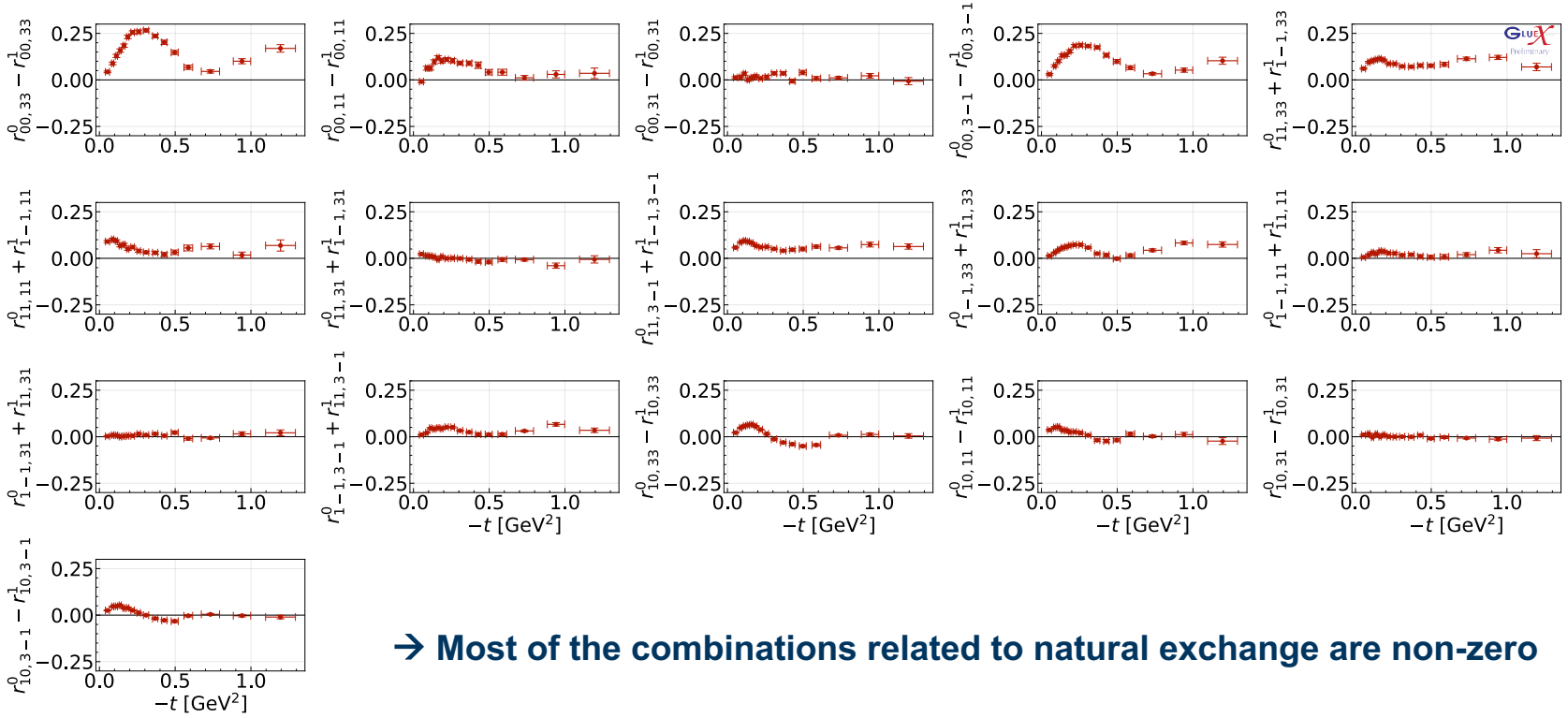


$r^0_{1-1,33} + r^1_{11,33} = 2\,\mathrm{Re}(N_{1,-3}N^*_{-1,-3} + N_{1,3}N^*_{-1,3})$ **(purely natural exchange amplitudes)**

$r^0_{00,33} + r^1_{00,33} = 2(|U_{0,3}|^2 + |U_{0,-3}|^2)$ **(purely unnatural exchange)**

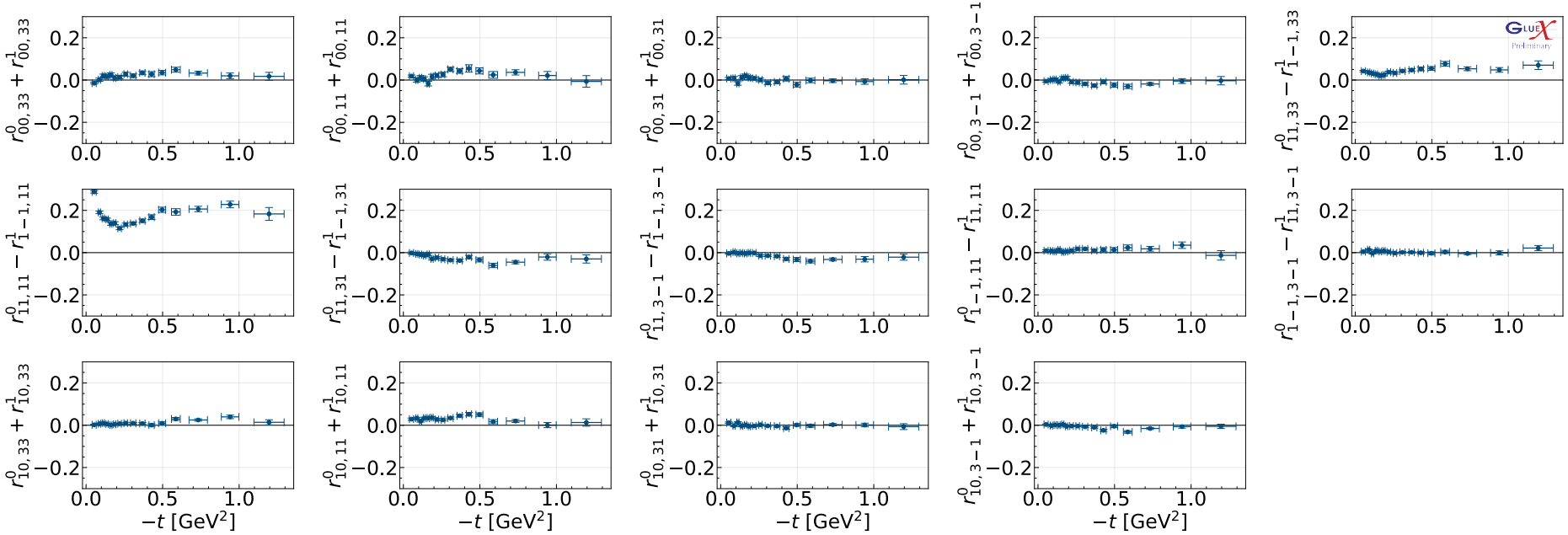
$\tilde{r}^0_{10,31} + \tilde{r}^1_{10,31} = \frac{1}{2}[(N_{1,-3} + N^*_{-1,-3})U^*_{0,-1} - (N_{1,-1} + N_{-1,-1})U^*_{0,-3}]$ **(interference)**

Natural exchange



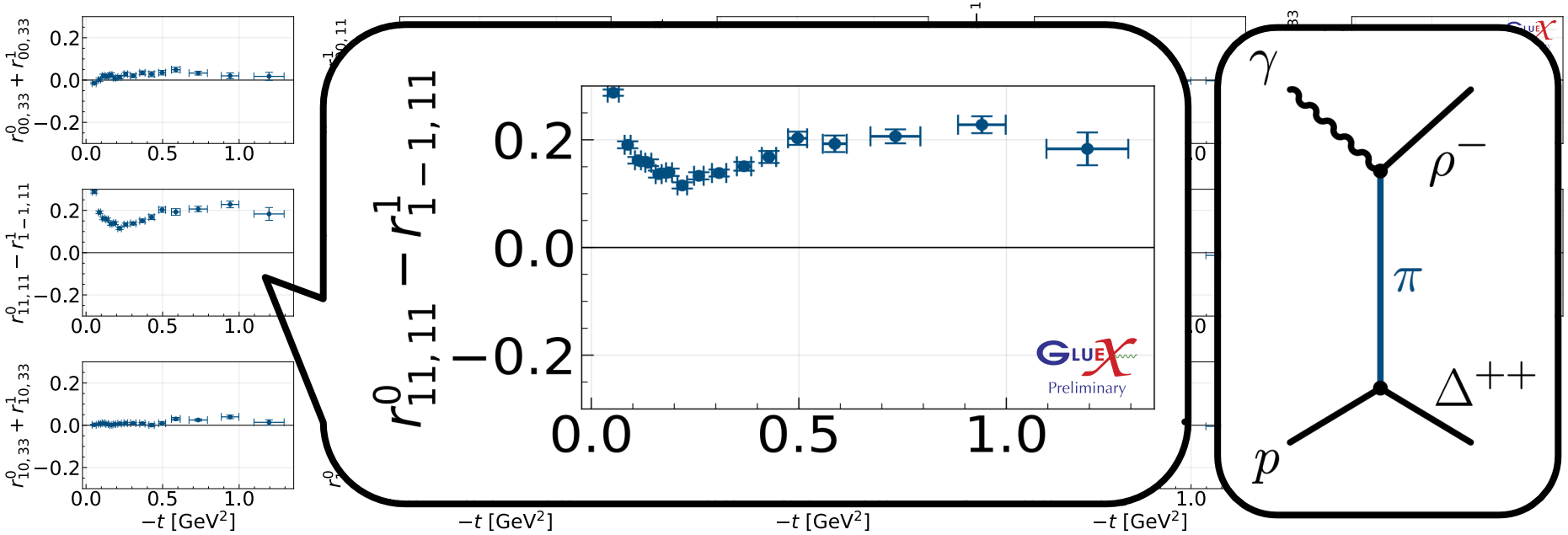
→ **Most of the combinations related to natural exchange are non-zero**

Unnatural exchange



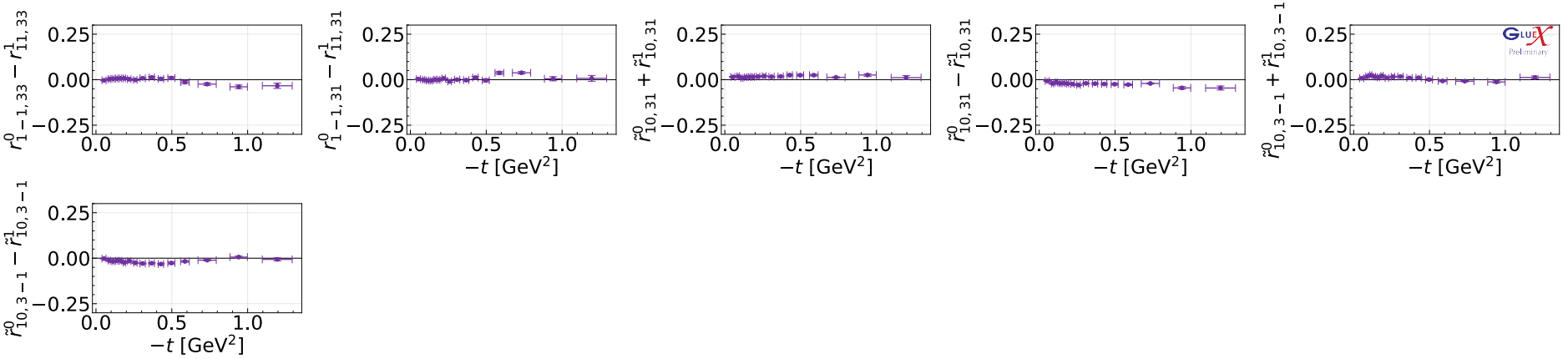
→ **Small unnatural exchange contributions**

Unnatural exchange



→ **Small unnatural exchange contributions**

Interference



→ **No strong interference between natural and unnatural exchange**

→ **This also confirms that only one exchange dominates**

→ **In this case, we can try to fit a simplified factorized model**

Factorized Model

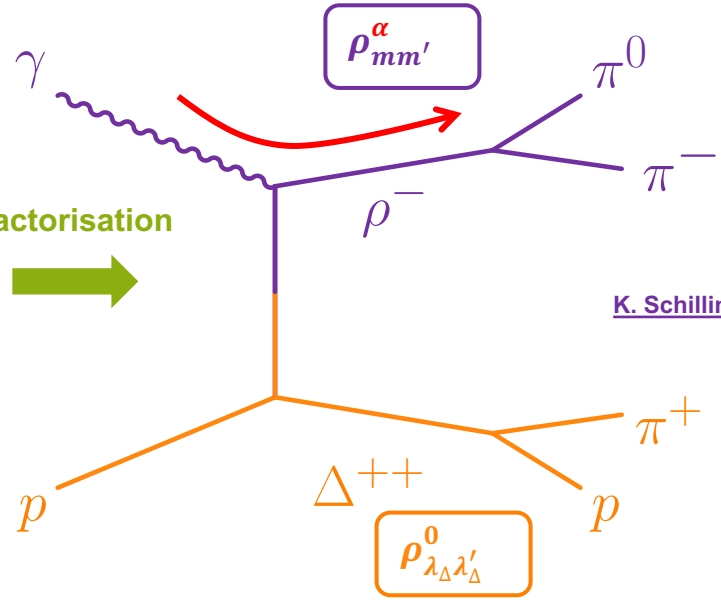
Factorized fit model

In case of factorization photon talks only to meson!

55 fit parameters

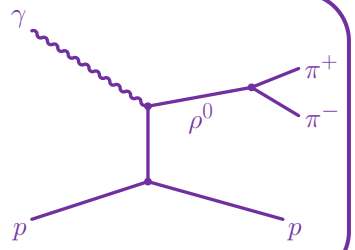
$r^0_{00,33}, r^0_{11,33}, r^0_{11,11}, r^0_{1-1,33}$
$r^0_{1-1,33}, r^0_{1-1,11}, \cdots$
$r^1_{00,33}\ r^0_{00,11}\ r^0_{11,33}\ r^1_{11,11}, r^1_{1-1,33}$
$r^1_{1-1,11}\ r^1_{10,33}\ r^1_{10,11}, \cdots$
$r^2_{1-1,33}\ r^2_{1-1,11}\ r^2_{1-1,31}\ r^2_{1-1,3-1},$
$r^2_{10,33}, r^2_{00,31}\ r^2_{00,3-1}\ r^2_{11,31}, \cdots$

factorisation



9 fit parameters

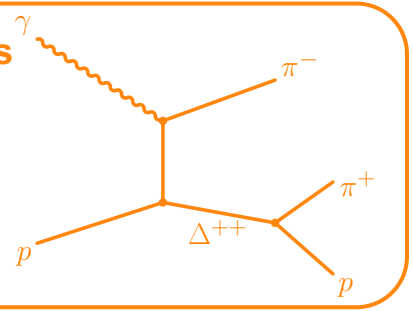
$\rho^0_{00}\ \rho^0_{10}\ \rho^0_{1-1}$
$\rho^1_{11}\ \rho^1_{00}\ \rho^1_{10}\ \rho^1_{1-1}$
$\rho^2_{10}\ \rho^2_{1-1}$



K. Schilling, P. Seyboth & G. Wolf (1970), Nuclear Physics B, 15(2), 397–412.

3 fit parameters

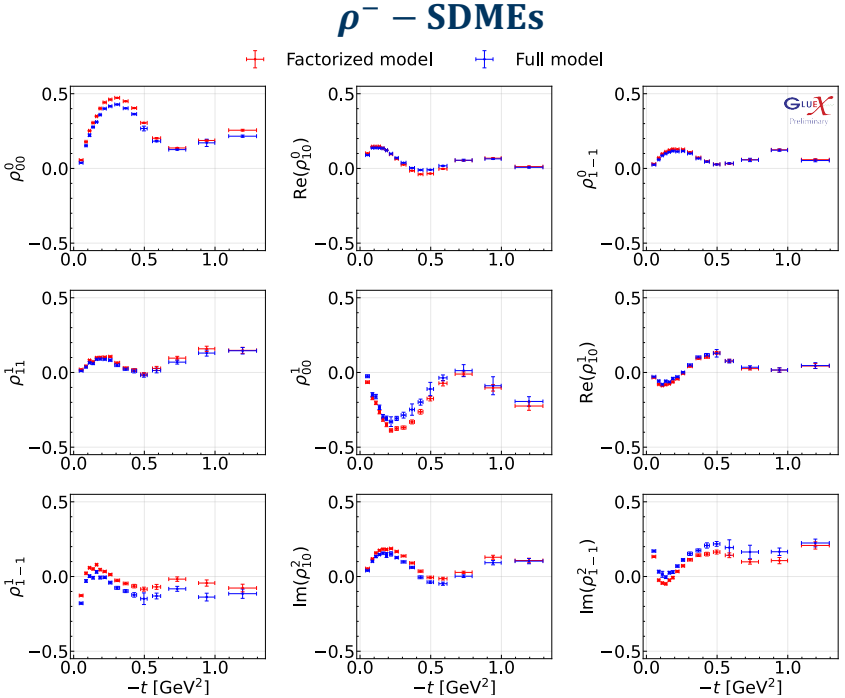
$\rho^0_{\frac{1}{2}\frac{1}{2}}\ \rho^0_{\frac{3}{2}\frac{1}{2}}\ \rho^0_{\frac{3}{2}\frac{-1}{2}}$

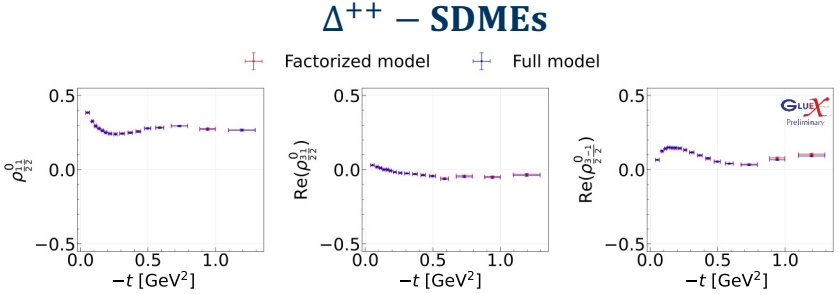


F. Afzal et al. (2025), *Phys. Lett. B, 863*, 139368.

$$I_{tot} = (I_{0,\rho} + \sum_{\alpha=1,2} P_\alpha\ I_{\alpha,\rho}) I_{0,\Delta}$$

Comparison between factorized and full model





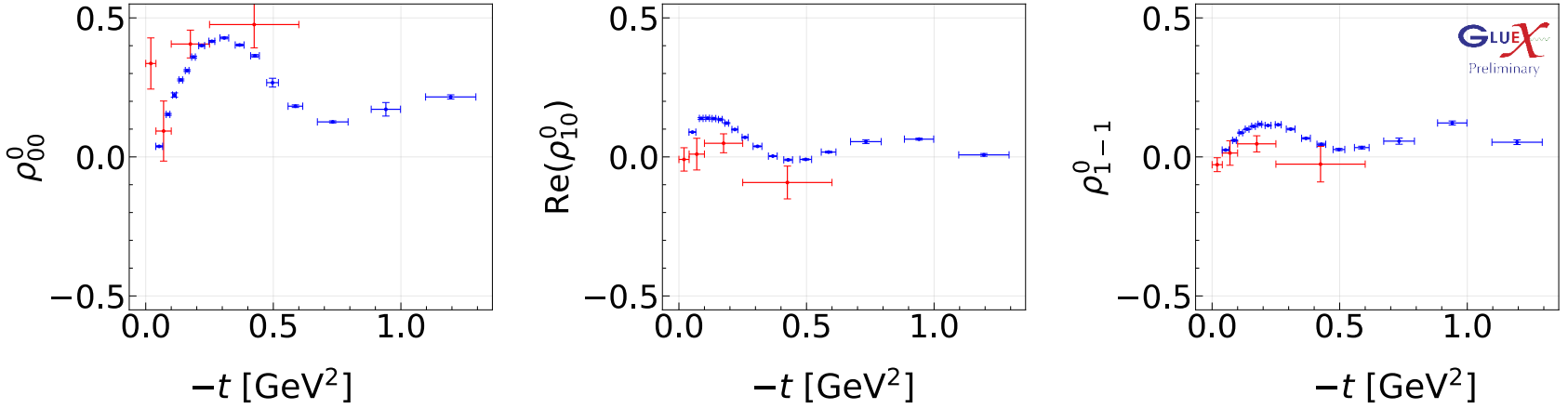
→Overall good agreement between full model and factorized model

Results for ρ^- compared to SLAC

J. Abramson et al. (1976) Phys. Rev. Lett., 36(24),1432–1434.

SLAC

GlueX Preliminary



→ Within the errors, our results agree with the previous measurement for unpolarized SDMEs (visible systematic trend)

Acknowledgements

Conclusion

- **Photoproduction is an alternative mechanism to search for hybrid mesons**

→ **Polarized SDMEs are an important tool to understand the production mechanism**

- **First results of the SDMEs of the reaction $\gamma + p \rightarrow \rho^- \Delta^{++}$ in GlueX-I data**
- **Within uncertainties, the results are consistent with previous measurements for unpolarized SDMEs from SLAC**
- **Full model (55 fit parameters) and factorized model (12 fit parameters) in good agreement**
- **Factorized model Ansatz is reasonable**
- **Results could also be used for other studies ($\Delta^{++}\eta\pi$, $\Delta^{++}\eta'\pi$, $\Delta^{++}\pi\,\pi\,\pi$)**

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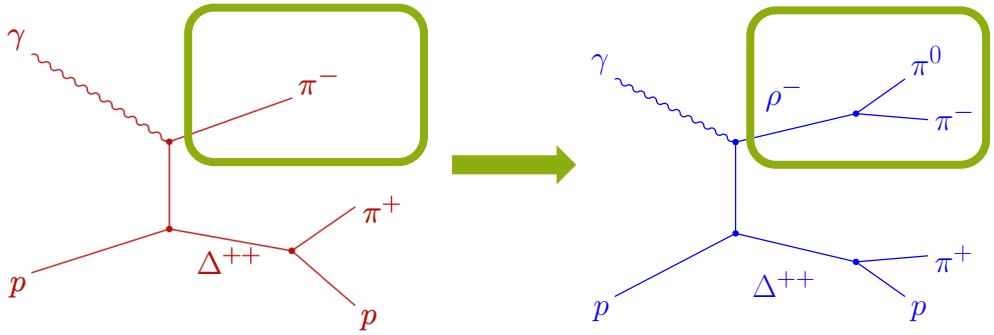
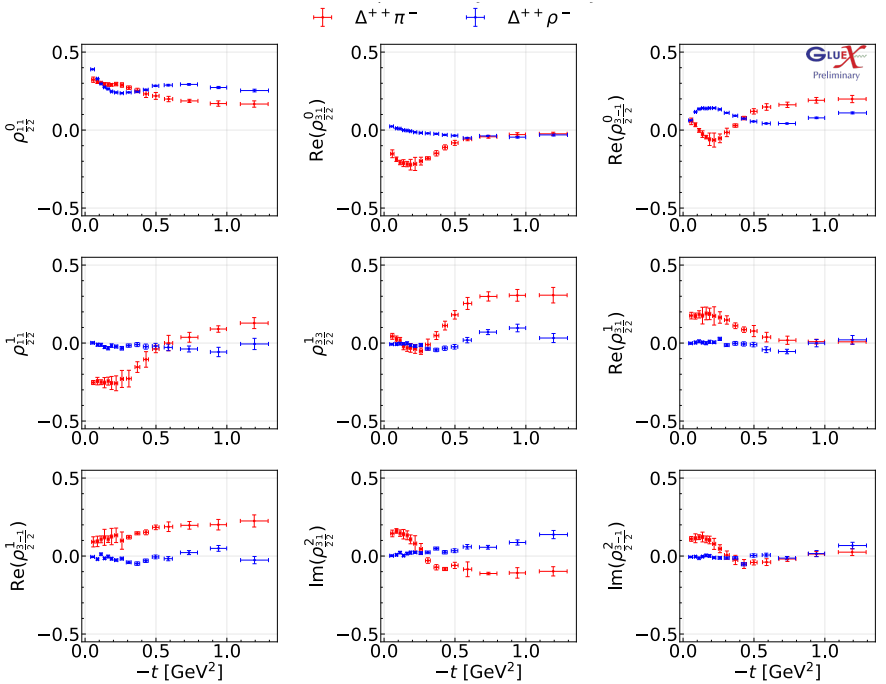
GlueX

Appendix

Comparison between $\Delta^{++}\pi^-$ and $\Delta^{++}\rho^-$

F. Afzal et al. (GLUEX)
(2025), *Phys. Lett. B*, *863*, 139368.





→Different production mechanisms result in different SDME dependences on $-t$

Reduced Spin Density Matrix

- **Given a joint system $\Delta^{++}\rho^{-}$ the reduced density matrix for subsystem Δ^{++} is:**

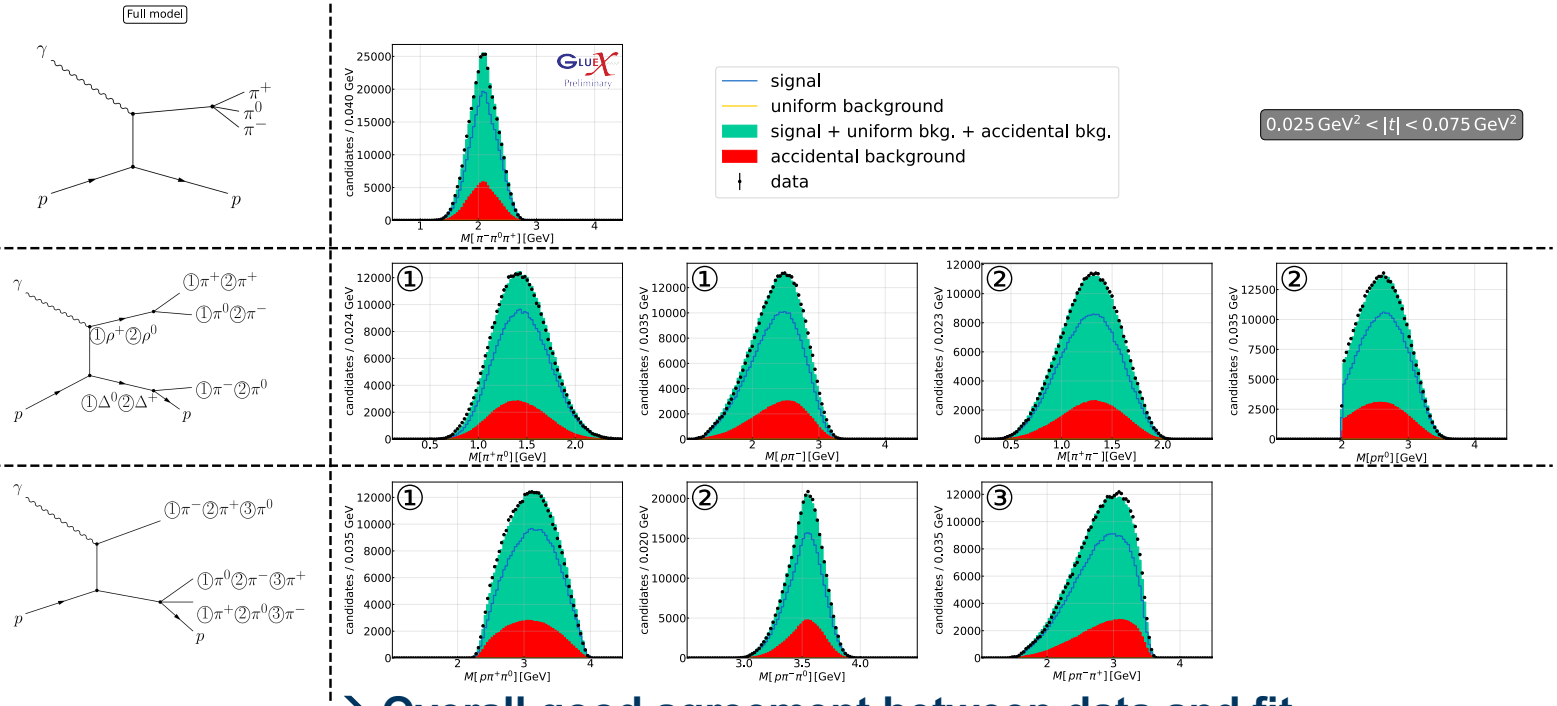
$$\rho_{\Delta^{++}} = Tr_{\rho^-}\left(\rho_{\Delta^{++}\rho^-}\right) = \sum_m \rho_{mm\,,\lambda_\Delta \lambda'_\Delta}$$

- $\rho_{\Delta^{++}}$ **allows calculation of expectation values for observables acting only on subsystem Δ^{++}, yielding the same results as using the total density matrix**

- **Example:** $\rho^{0,\rho^-}_{00} = \sum_\lambda \rho^0_{00,\lambda\lambda} = \left(\rho^0_{00,-3-3} + \rho^0_{00,-1-1} + \rho^0_{00,11} + \rho^0_{00,33}\right) = \left(2r^0_{00,11} + 2r^0_{00,33}\right)$
- **One can also show with the parity relation that:** $Tr\left(\rho_{\rho^-}{}^0\right) = Tr\left(\rho_{\Delta^{++}}{}^0\right)$, $Tr\left(\rho_{\rho^-}{}^1\right) = Tr\left(\rho_{\Delta^{++}}{}^1\right)$

$$\Longrightarrow \rho^1_{00} = 2\left(\rho^1_{\frac{1}{2}\frac{1}{2}} + \rho^1_{\frac{3}{2}\frac{3}{2}} - \rho^1_{11}\right)$$

Fit evaluation



→ **Overall good agreement between data and fit**

Event selection

Vertex and Quality:

Cut on vertex position

$QF_{shower} > 0.5$

$N_{unused\ tracks} \leq 1$

$N_{unused\ shower} \leq 3$

Kinematics:

χ^2/NDF < 5

$8.2\ \text{GeV} < E_{beam} < 8.8\ \text{GeV}$

$-0.01\ \text{GeV}^2 < {M_{miss}}^2 < 0.01\ \text{GeV}^2$

$p_{\pi^+,z} < 0.2\ \text{GeV}$

$0.025\ \text{GeV}^2 < -t < 1.4\ \text{GeV}^2$

Mass windows:

$0.62\ \text{GeV} < M(\pi^-\pi^0) < 0.93\ \text{GeV}$

$1.10\ \text{GeV} < M(\pi^+p) < 1.35\ \text{GeV}$

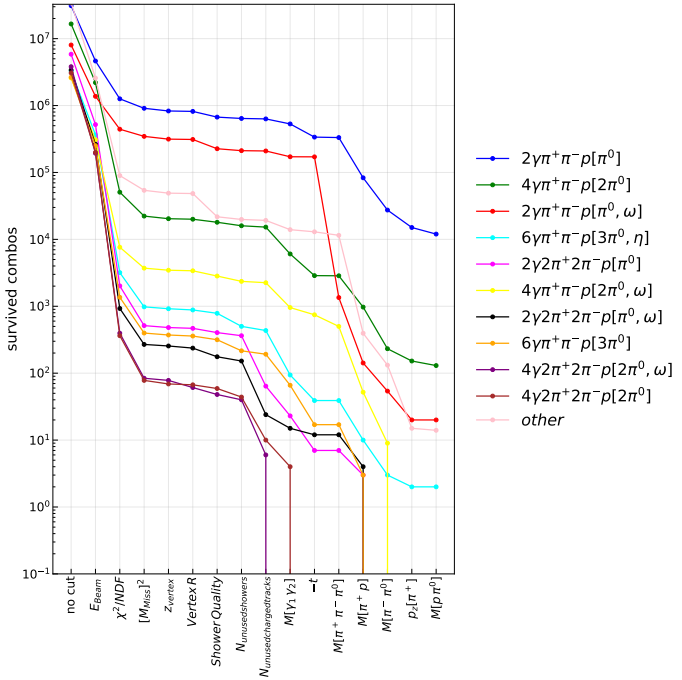
$0.12\ \text{GeV} < M(\gamma\gamma) < 0.15\ \text{GeV}$

$0.9\ \text{GeV} < M(\pi^-\pi^0\pi^+)$

$2.0\ \text{GeV} < M(\pi^0p)$

Effectivness of event selection

$N_t / \sum_t N_t$ [%]	Topology
98.644	$2\gamma\pi^+\pi^- p[\pi^0]$
0.847	$4\gamma\pi^+\pi^- p[2\pi^0]$
0.149	$2\gamma\pi^+\pi^- p[\pi^0, \omega]$
0.009	$6\gamma\pi^+\pi^- p[3\pi^0, \eta]$
0.000	$2\gamma 2\pi^+ 2\pi^- p[\pi^0]$
0.027	$4\gamma\pi^+\pi^- p[2\pi^0, \omega]$
0.000	$2\gamma 2\pi^+ 2\pi^- p[\pi^0, \omega]$
0.000	$6\gamma\pi^+\pi^- p[3\pi^0]$
0.000	$4\gamma 2\pi^+ 2\pi^- p[2\pi^0, \omega]$
0.000	$4\gamma 2\pi^+ 2\pi^- p[2\pi^0]$
0.324	other



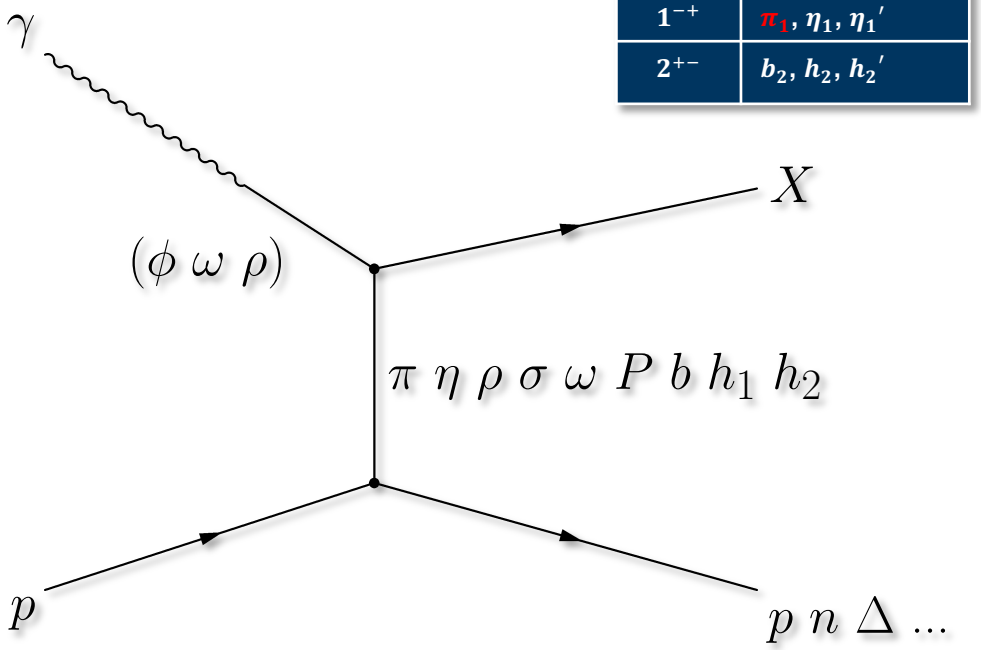
→The event selection is effective: background processes not corresponding to $\pi^+\pi^-\pi^0 p$ final states are significantly suppressed by the applied cuts (background < 1.4 %)

Photoproduction

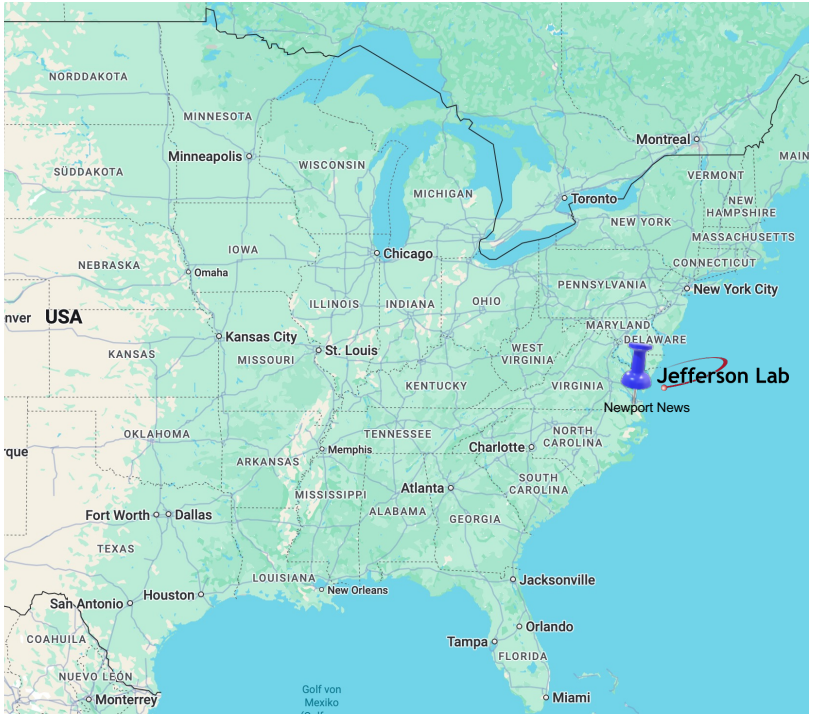
- **Photoproduction is a complementary production process to search for hybrid mesons compared to ongoing searches at other facilities**
- **Different reggeons with different quantum numbers are exchanged in t-channel process**

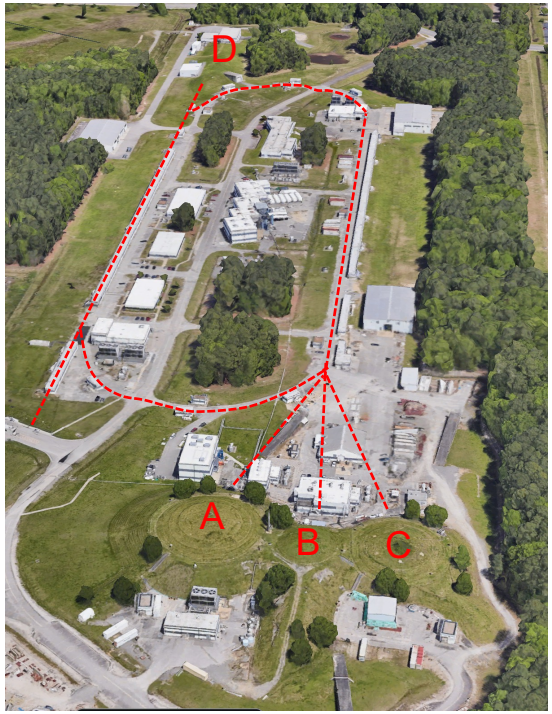
  → Can produce mesons of any J^{PC}
- **Photon Polarization → constrain on production processes, studying of hadron properties**

J^{PC}	Exotic Meson
0^{+-}	b_0, h_0, h_0'
1^{-+}	π_1, η_1, η_1'
2^{+-}	b_2, h_2, h_2'

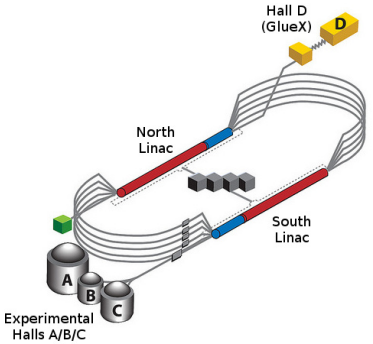


CEBAF at Jefferson Lab



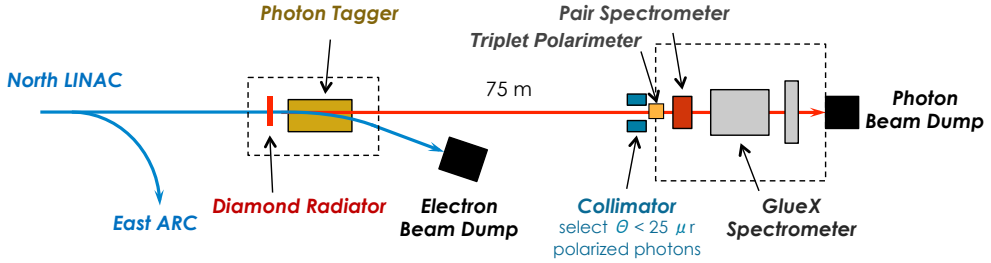


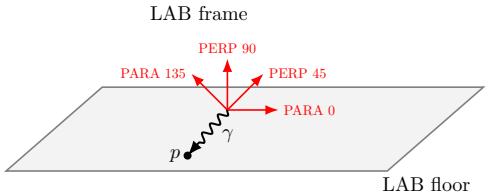
- E_e< 12 GeV electron beam
- I_e up to 2μA
- GlueX in Hall D
- CLAS in Hall B

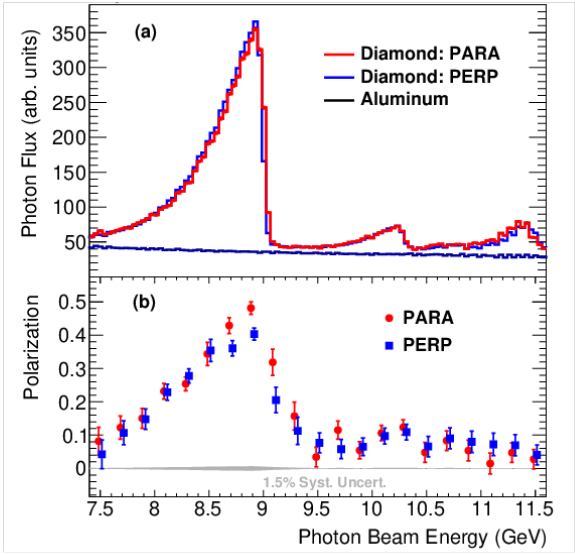


Photon Beam Line

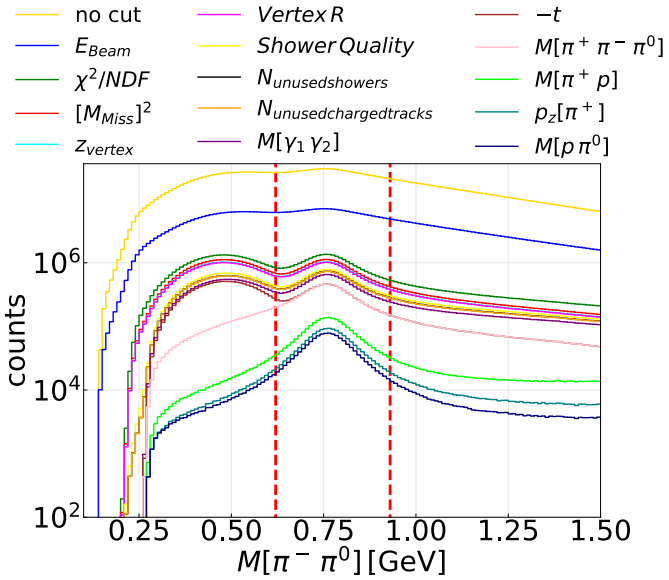
- **Coherent Bremsstrahlung on thin diamond radiator**
- **Collimator to suppress incoherent part**
- **Linear polarization in peak ($P \sim 35\%$) measured by Triplet polarimeter**
- **Beam energy is tagged, photon flux measured close to spectrometer**
- **Polarization rotated into 4 different orientations (parallel and perpendicular)**
- **$I_\gamma \sim 1 - 5 \cdot 10^7 \frac{\gamma}{s}$ (in peak)**

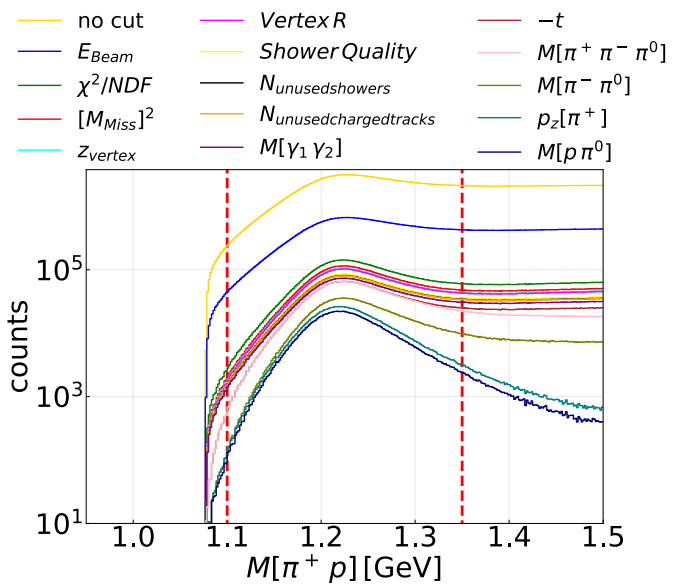


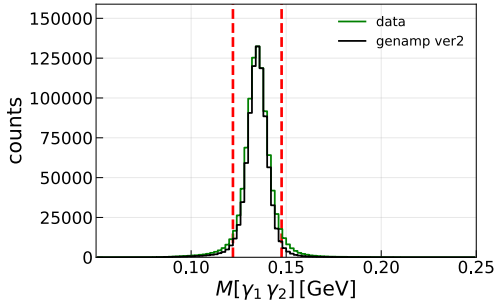




Invariant mass cuts





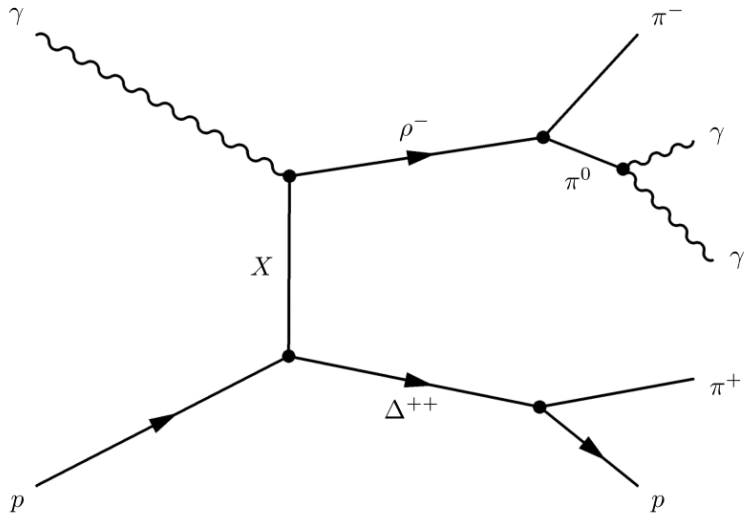


Process of interest

- **Study of exclusive photoproduction of $\Delta^{++}\rho^{-}$**
- **Data from GlueX-I (2017+2018)**

<u>Dataset contains:</u>

- **Applied kinematic fit (momentum, vertex)**
- **No mass constraint on π^0**
- **Event topology: p, π^+, π^- and 2 neutral showers**
- **up to 3 additional charged tracks allowed**
- **$\pm$4 beam bunches at each side**



Intensities

$$W(\Omega_\pi, \Omega_p, \Phi) = \frac{3}{4\pi}\left(W^0(\Omega_\pi, \Omega_p) - P_\gamma \cos(2\Phi)\, W^1(\Omega_\pi, \Omega_p, \Phi) - P_\gamma \sin(2\Phi)\, W^2(\Omega_\pi, \Omega_p, \Phi)\right)$$

Full model – Double SDME

$$W^0(\Omega_\pi, \Omega_p) = \cos^2(\vartheta_\pi)\left[W^0_{00}(\Omega_p) - \overline{W}^0_{00}(\Omega_p)\right] + \sin^2(\vartheta_\pi)\left[W^0_{11}(\Omega_p) - \overline{W}^0_{11}(\Omega_p)\right]$$
$$-\sin^2(\vartheta_\pi)\left(\cos(2\phi_\pi)\left[W^0_{1-1}(\Omega_p) - \overline{W}^0_{1-1}(\Omega_p)\right] + \sin(2\phi_\pi)\,\widetilde{W}^0_{1-1}(\Omega_p)\right)$$
$$-\sqrt{2}\sin(2\vartheta_\pi)\left(\cos(\phi_\pi)\left[W^0_{10}(\Omega_p) - \overline{W}^0_{10}(\Omega_p)\right] + \sin(\phi_\pi)\,\widetilde{W}^0_{10}(\Omega_p)\right)$$

$W^1(\Omega_\pi, \Omega_p)$ has same form as $W^0(\Omega_\pi, \Omega_p)$ due to the same parity relations

$$W^2(\Omega_\pi, \Omega_p) = \cos^2(\vartheta_\pi)\widetilde{W}^2_{00}(\Omega_p) + \sin^2(\vartheta_\pi)\widetilde{W}^2_{11}(\Omega_p)$$
$$+\sin^2(\vartheta_\pi)\left(\sin(2\phi_\pi)\left[W^2_{1-1}(\Omega_p) - \overline{W}^2_{1-1}(\Omega_p)\right] - \cos(2\phi_\pi)\,\widetilde{W}^2_{1-1}(\Omega_p)\right)$$
$$+\sqrt{2}\sin(2\vartheta_\pi)\left(\sin(\phi_\pi)\left[W^2_{10}(\Omega_p) - \overline{W}^2_{10}(\Omega_p)\right] + \cos(\phi_\pi)\,\widetilde{W}^0_{10}(\Omega_p)\right)$$

$$W^\alpha_{mm'}(\Omega_p) = r^\alpha_{mm'3}\sin^2(\vartheta_p) + r^\alpha_{mm'11}\left(\frac{1}{3} + \cos^2(\vartheta_p)\right)$$

$$\overline{W}^\alpha_{mm'}(\Omega_p) = \frac{2}{\sqrt{3}}\left[r^\alpha_{mm'3}\cos(\varphi_p)\sin(2\vartheta_p) + r^\alpha_{mm'3-1}\cos(2\varphi_p)\sin^2(\vartheta_p)\right]$$

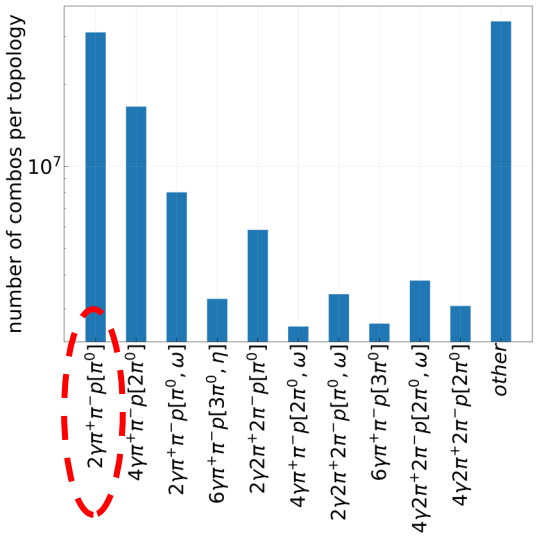
$$\widetilde{W}^\alpha_{mm'}(\Omega_p) = \frac{2}{\sqrt{3}}\left[\tilde{r}^\alpha_{mm'31}\sin(\varphi_p)\sin(2\vartheta_p) + \tilde{r}^\alpha_{mm'3-1}\sin(2\varphi_p)\sin^2(\vartheta_p)\right]$$

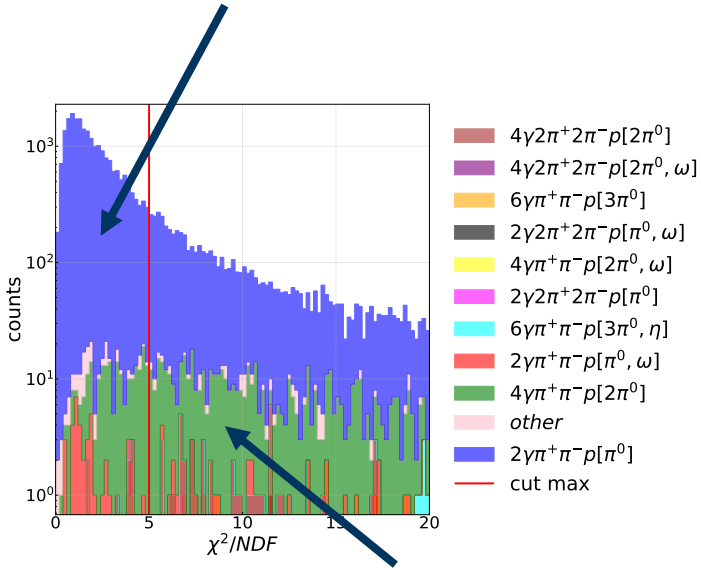
→ $r^\alpha_{mm'\lambda_\Delta\lambda'_\Delta}$ is a linear combination of one to four $\rho^\alpha_{mm'\lambda_\Delta\lambda'_\Delta}$

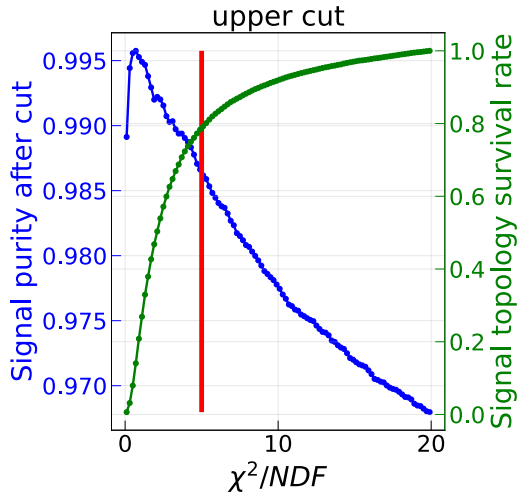
Bggen study

Only the correctly reconstructed channel peaks at low χ^2/ndf

Before any cuts

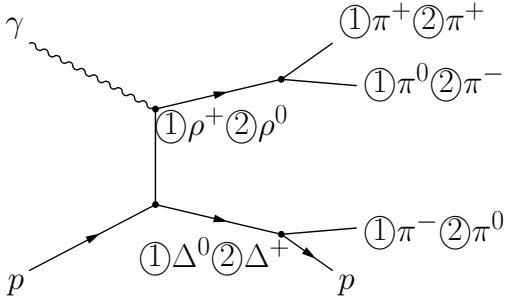


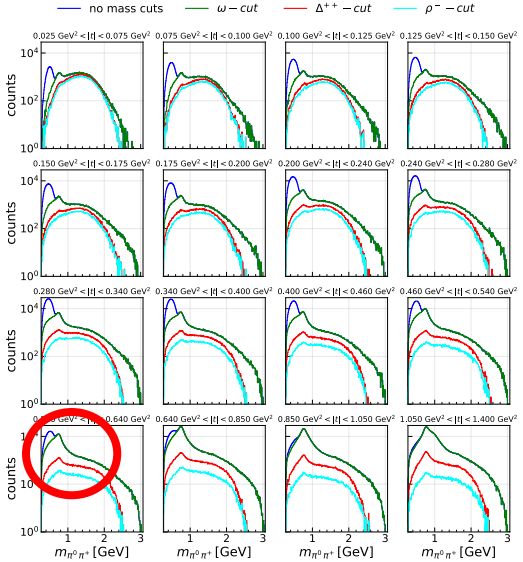


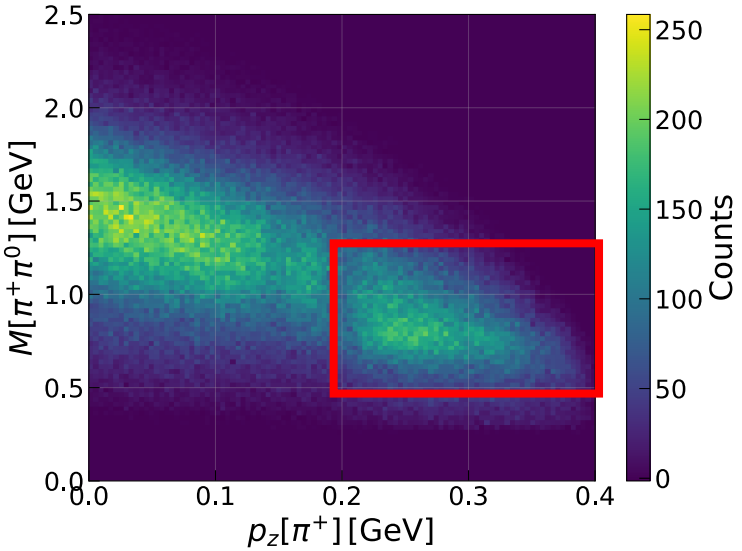


other channels appear flat due to poor fit under wrong hypotheses

ρ^0/ρ^+ background

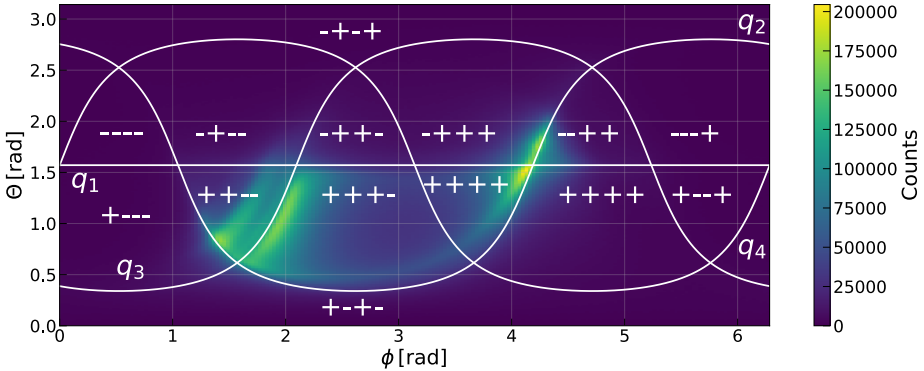






→ **Cut on $p_{\pi^+,z} < 0.2$ GeV**

Great-circle Plot



$$r = \sqrt{x^2 + y^2 + z^2}$$

$$\theta = \tan^{-1}\frac{\sqrt{x^2 + y^2}}{z}$$

$$\phi = \tan^{-1}\frac{y}{x}$$

Event selection