Photoproduction of 1 and 2 Mesons

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JPAC Collaboration Workshop
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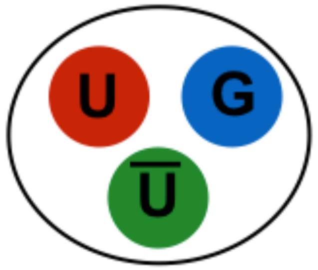
The Factorization Hypothesis

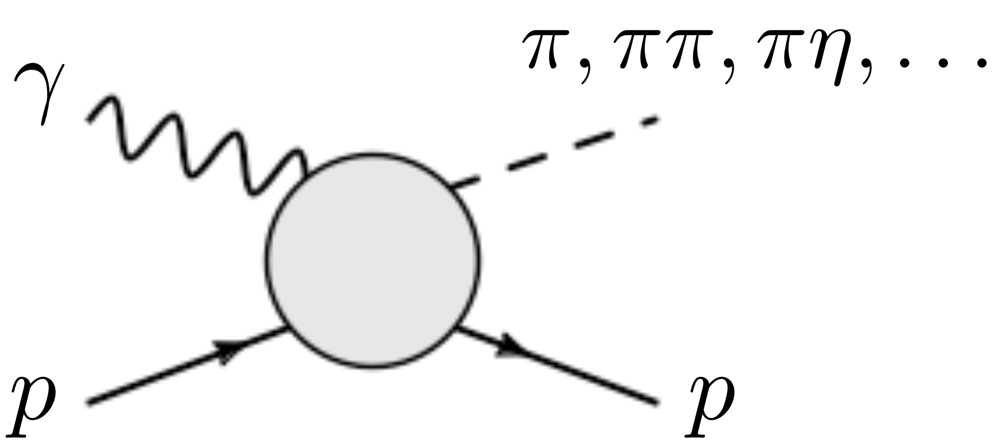
Photoproduction of mesons at $E_\gamma = 6 - 12\ \mathrm{GeV}$

Study photoproduction of mesons

Search for exotic resonances



Special interest in mesons:



The Factorization Hypothesis

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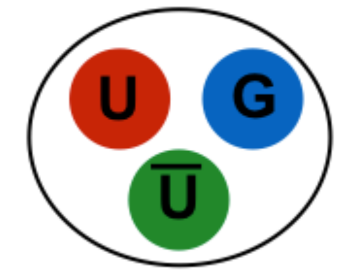
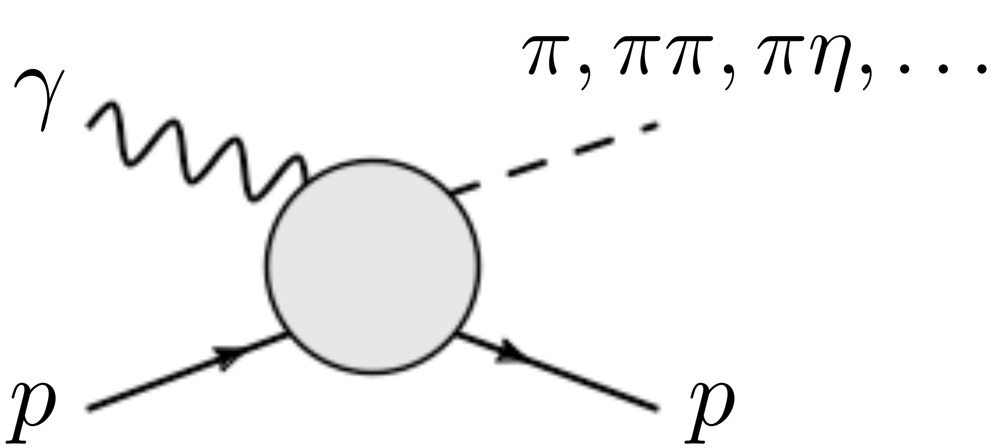
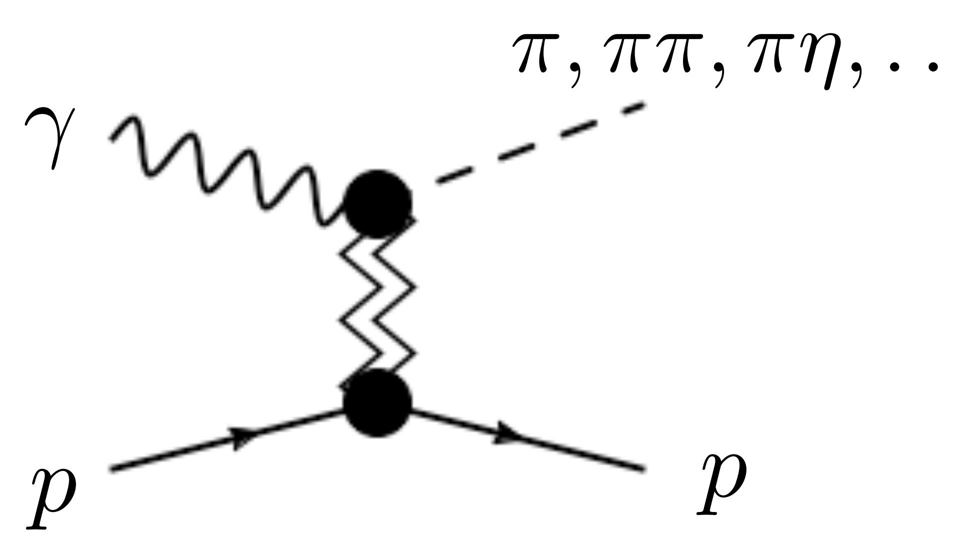


Special interest in mesons:

Does the target decouple at JLab energies ?



Factorization ?



JPAC publications on JLab physics

Single Meson Photoproduction:

$\vec{\gamma} p \to \pi N$ Mathieu et al **PRD92 074013 (2015)**
Mathieu et al **PRD98 014041 (2018)**

$\vec{\gamma} p \to \eta p$ Nys et al **PRD95 034014 (2017)**
Mathieu et al **EPL122 41001 (2018)**

$\vec{\gamma} p \to \pi \Delta$ Nys et al **PLB779 77 (2018)**

$\vec{\gamma} p \to \eta' p$ Mathieu et al **PLB774 362 (2017)**

Vector Meson Photoproduction:

$\vec{\gamma} p \to \rho^0 p$
$\vec{\gamma} p \to \omega p$
$\vec{\gamma} p \to \phi p$
} Mathieu et al **PRD97 094003 (2018)**

$\vec{\gamma} p \to J/\psi p$ Hiller Blin et al **PRD94 034002 (2016)**
Winney et al **PRD100 034019 (2019)**

Double Mesons Photoproduction:

$\vec{\gamma} p \to \pi^0 \eta p$ Mathieu et al **PRC100 0540 (172019)**

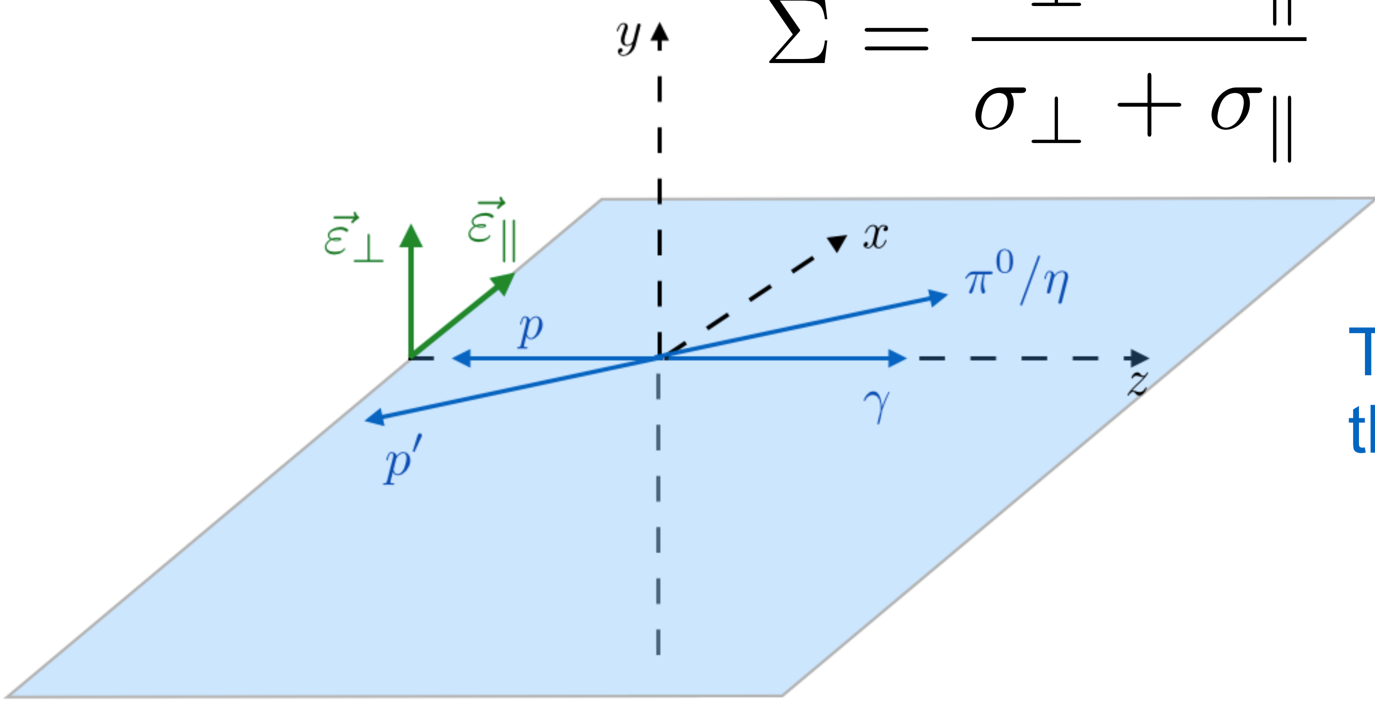
Inclusive Electroproduction:

$e^- p \to e^- X$ Hiller Blin et al **PRC100 035201 (2019)**

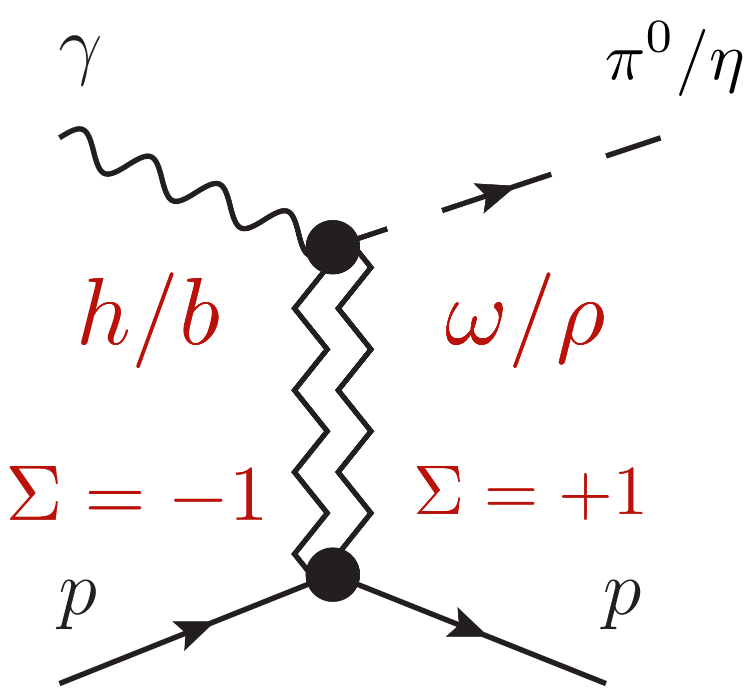
Simulations and codes available: http://www.ceem.indiana.edu/~jpac/

Single Meson Photoproduction

$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel}$$



The beam asymmetry Σ is related to the reflection through the reaction plane



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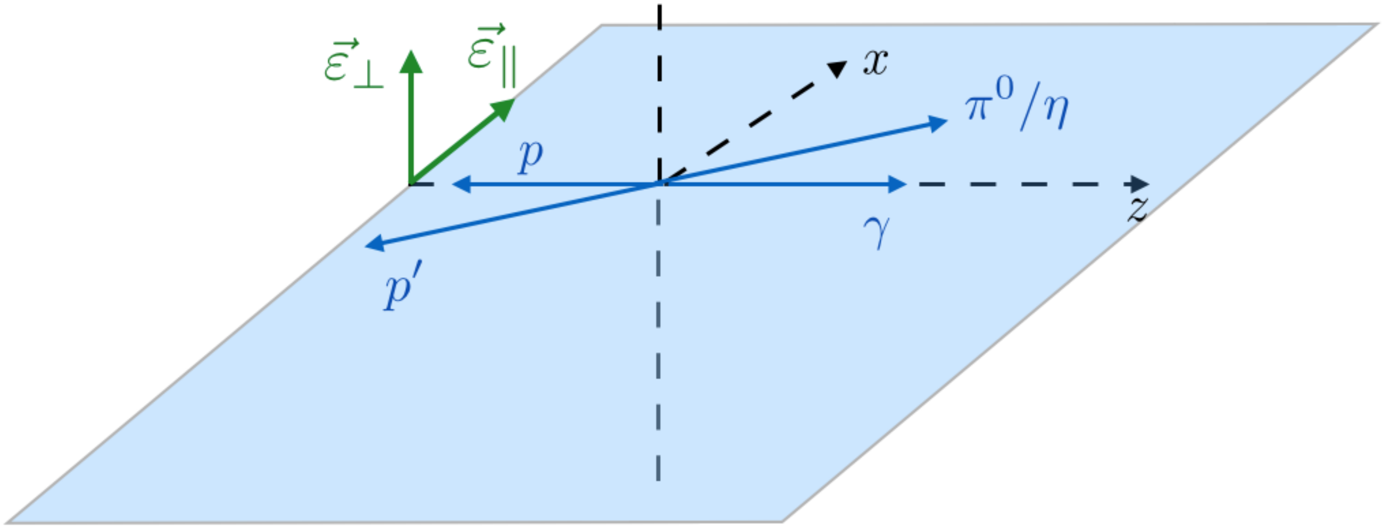
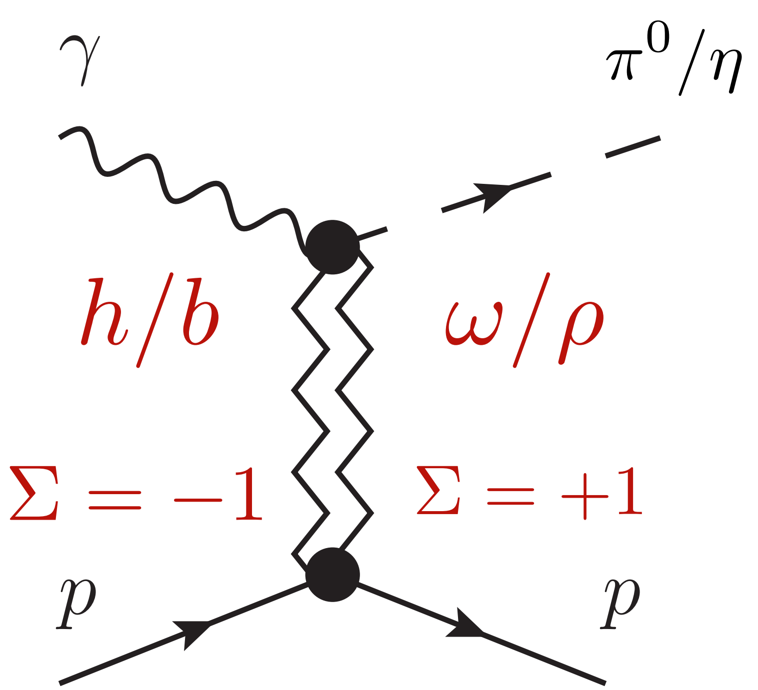
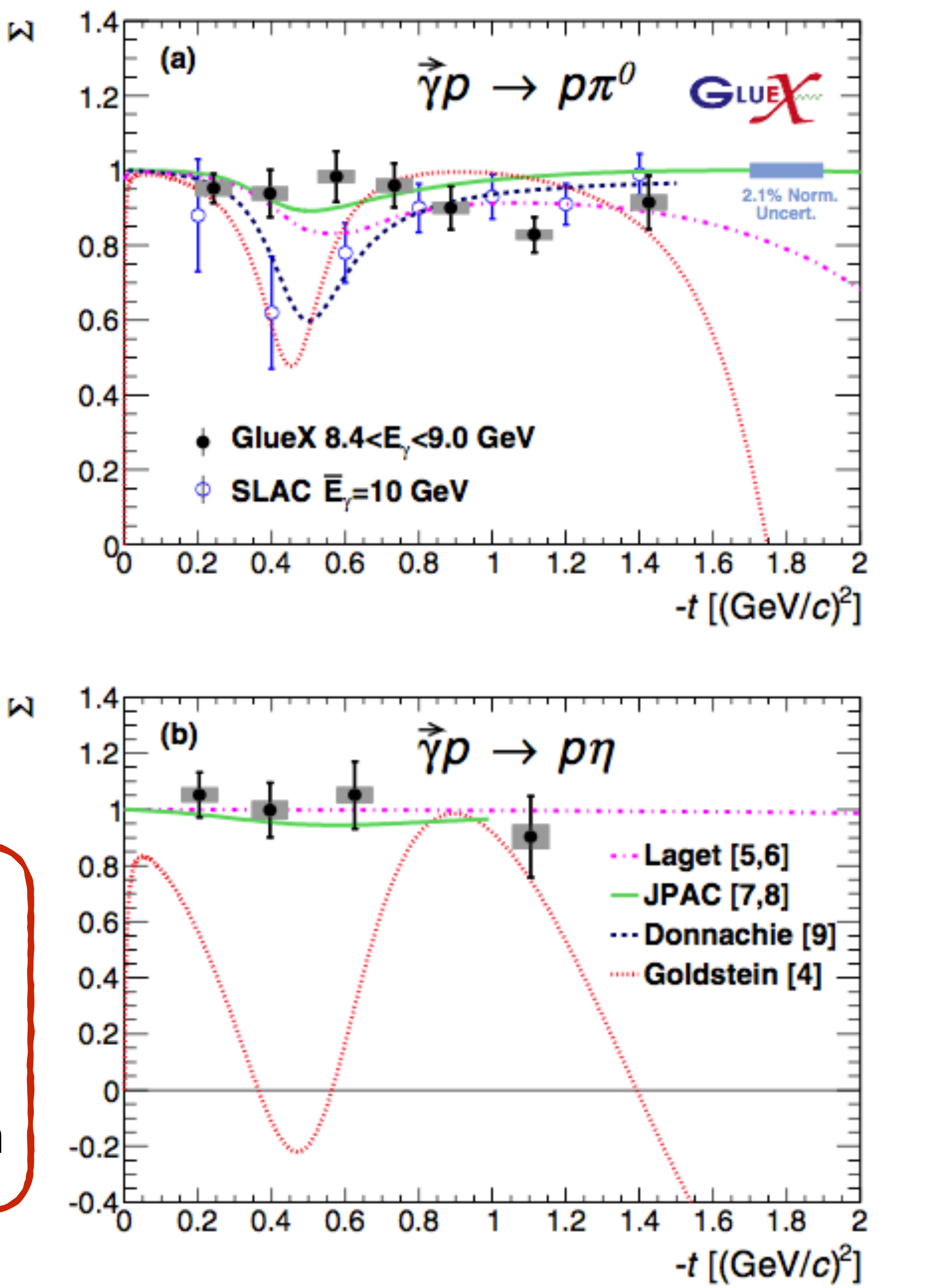




Dominance of vector meson exchange in both π^0/η photoproduction

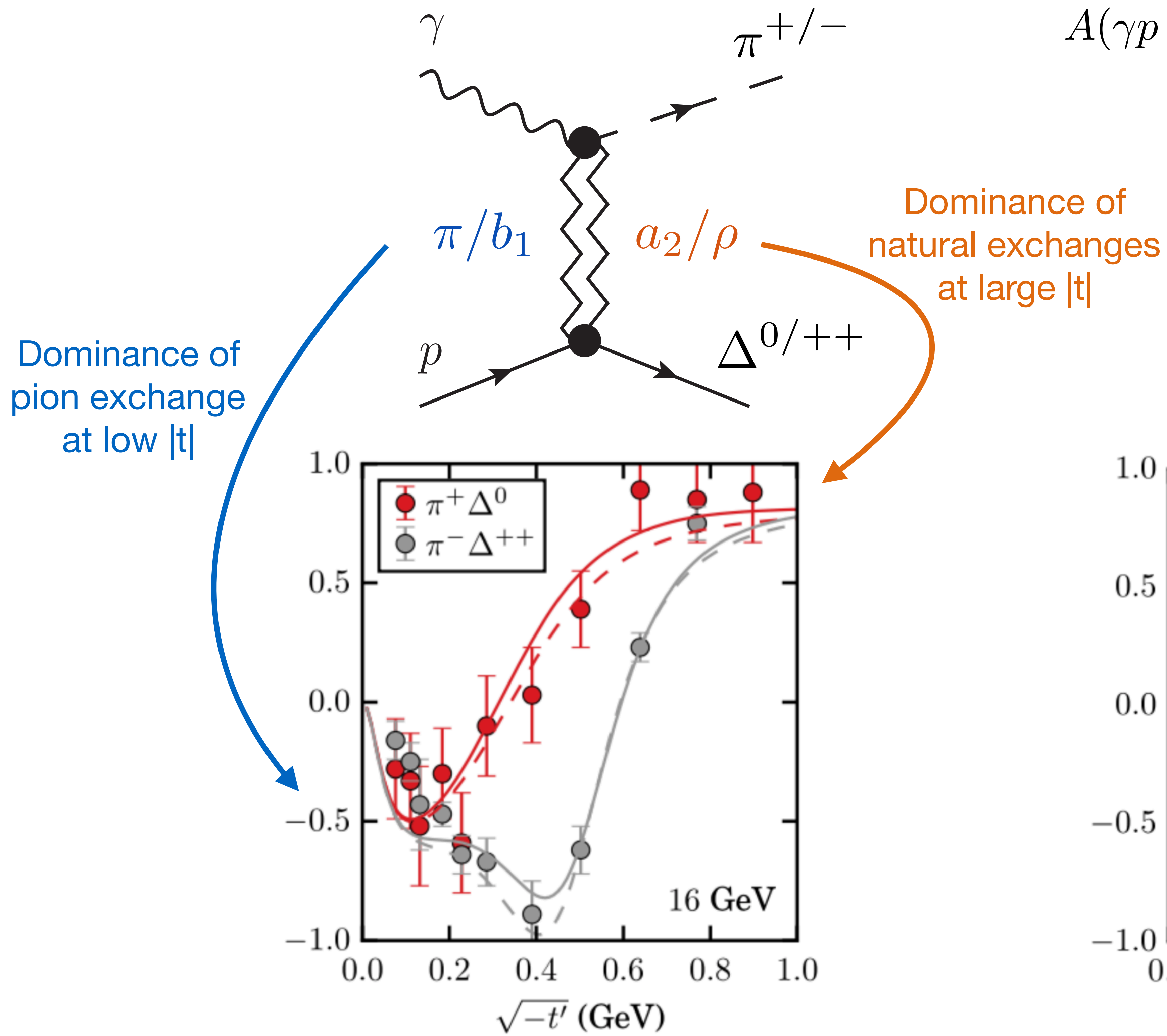


GlueX, VM and Nys PRC95 (2017)

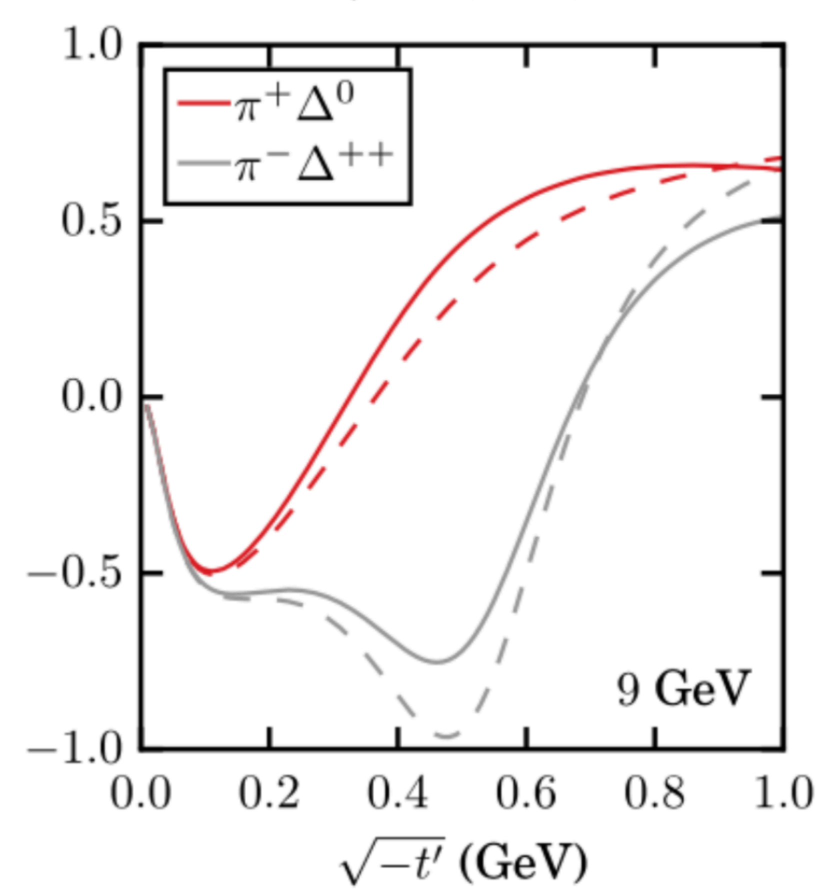
Single Meson Photoproduction

$$\sqrt{3}A(\gamma p \to \pi^+\Delta^0) = A^{\rho+b_1} + A^{a_2+\pi}$$

$$A(\gamma p \to \pi^-\Delta^{++}) = A^{\rho+b_1} - A^{a_2+\pi}$$



Prediction for GlueX



Nys et al **PLB779 77 (2018)**

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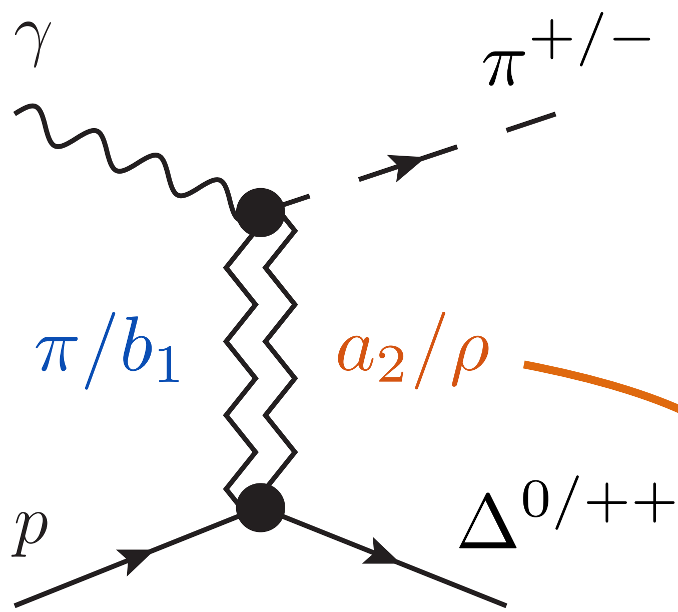
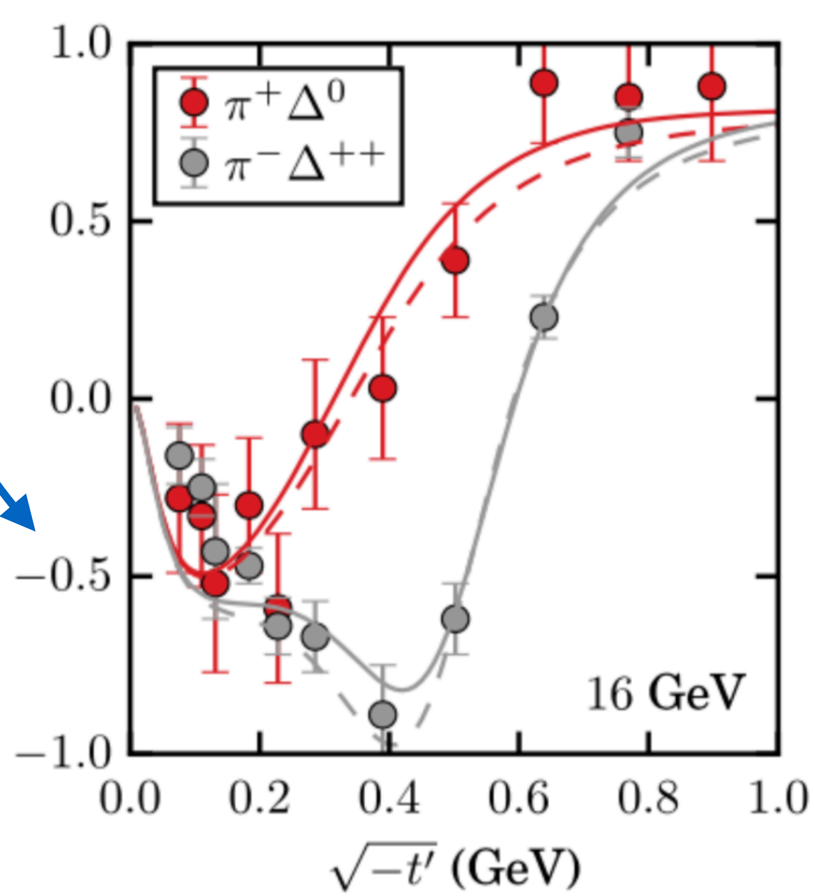
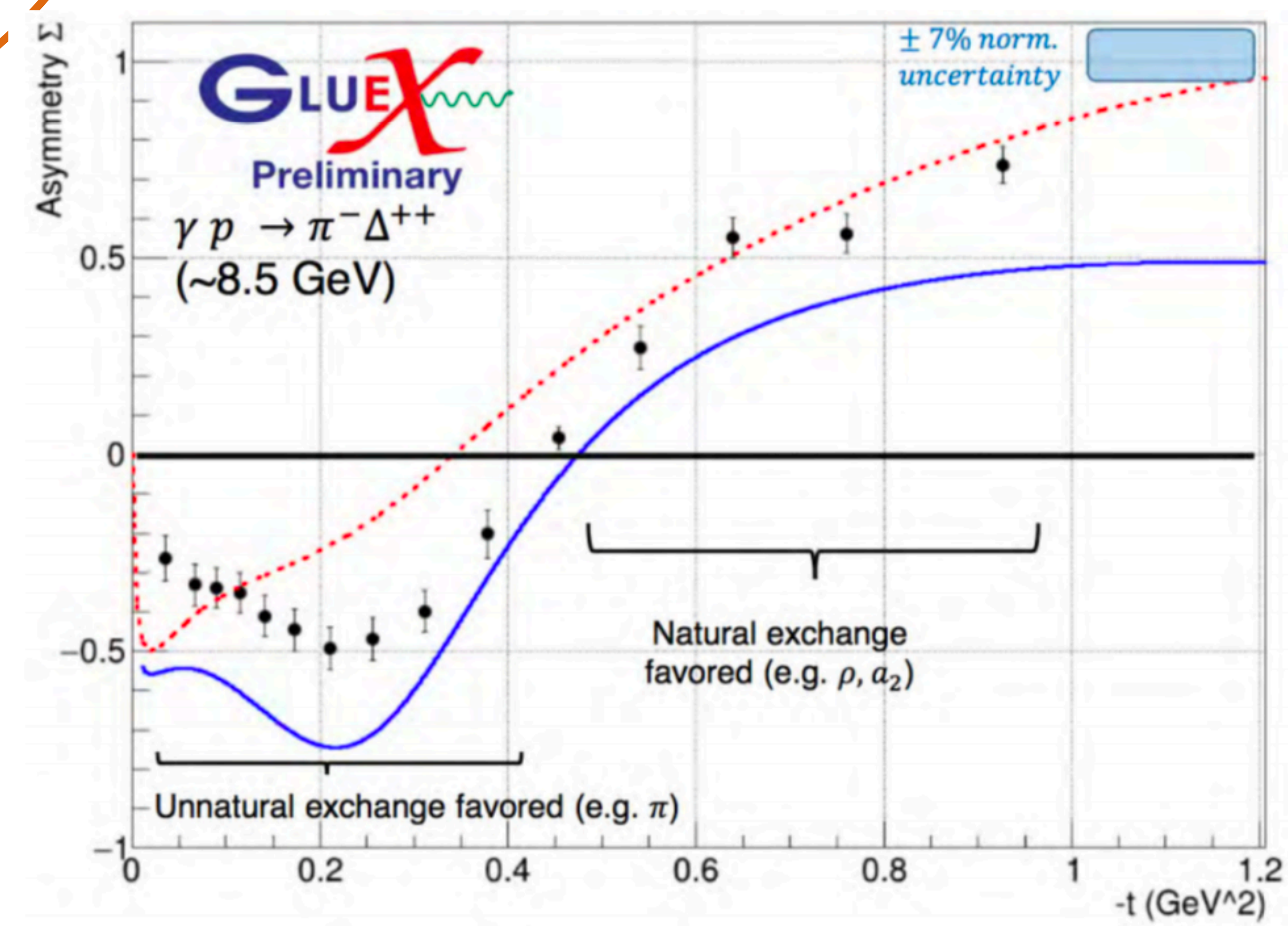


Dominance of pion exchange at low |t|

Dominance of natural exchanges at large |t|

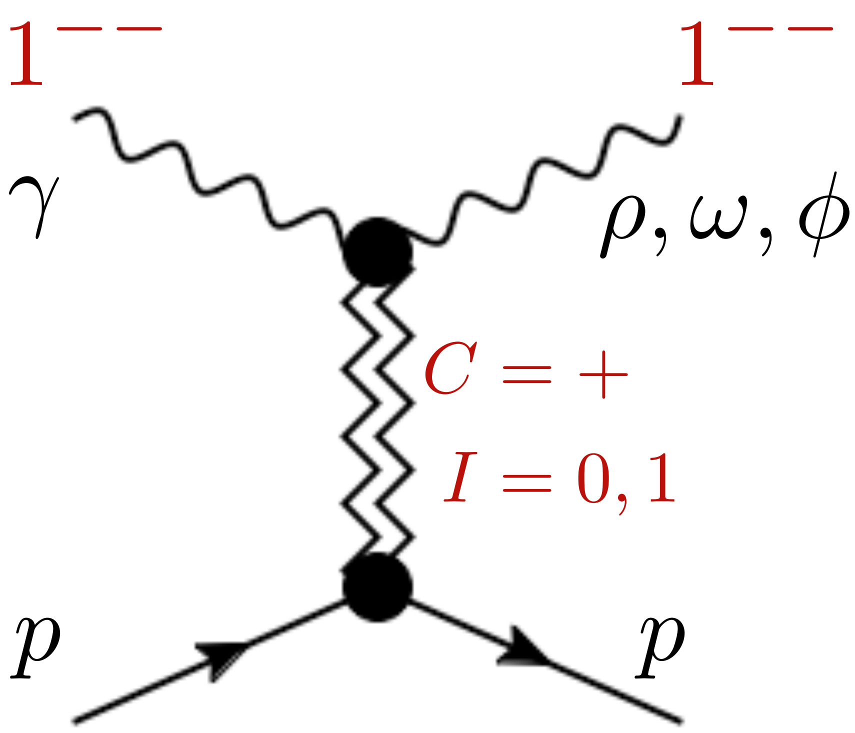


Prediction for GlueX



Nys et al **PLB779 77 (2018)**

Vector Meson Photoproduction



Probe different exchanges by combined analysis of ρ, ω, ϕ

Pomeron dominates at high energies

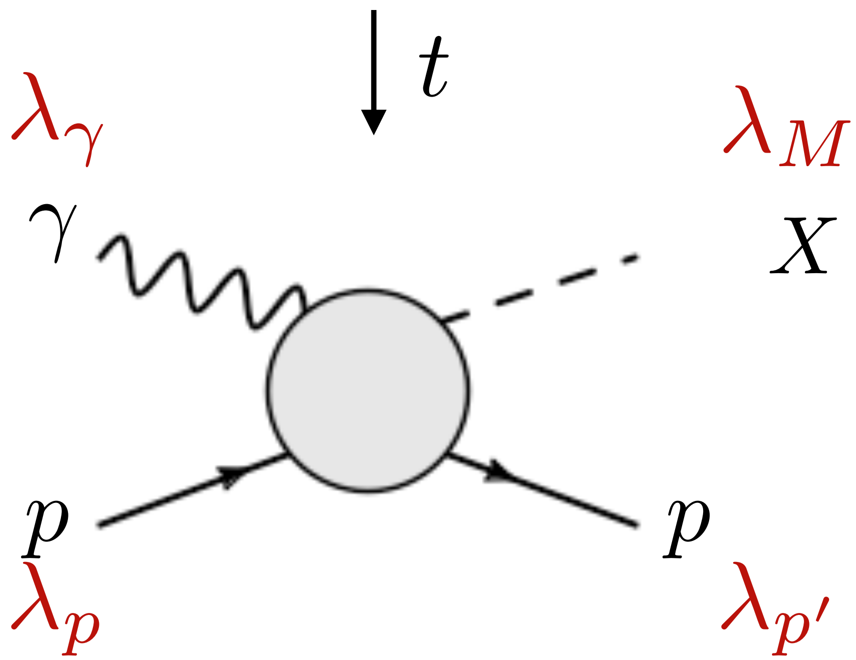
Use the angular distribution of the vector to extract spin density matrix elements

$$\frac{8\pi}{3}\frac{d\sigma}{d\Omega} = 1 - \rho^0_{00} + \left(3\rho^0_{00} - 1\right)\cos^2\theta - 2\sqrt{2}\mathrm{Re}\ \rho^0_{10}\sin 2\theta\cos\phi - 2\rho^0_{1-1}\sin^2\theta\cos 2\phi$$

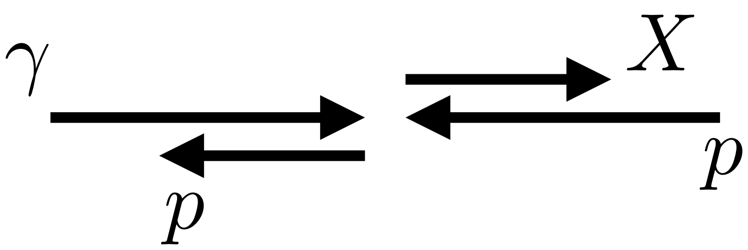
9 SDME accessible with linearly polarized beam

ρ^0_{00}	$\mathrm{Re}\ \rho^0_{10}$	ρ^0_{1-1}
ρ^1_{11}	$\mathrm{Re}\ \rho^1_{10}$	ρ^0_{11}
ρ^1_{1-1}	$\mathrm{Im}\ \rho^2_{10}$	$\mathrm{Im}\ \rho^2_{1-1}$

Factorization



Angular mom. conservation in forward direction:



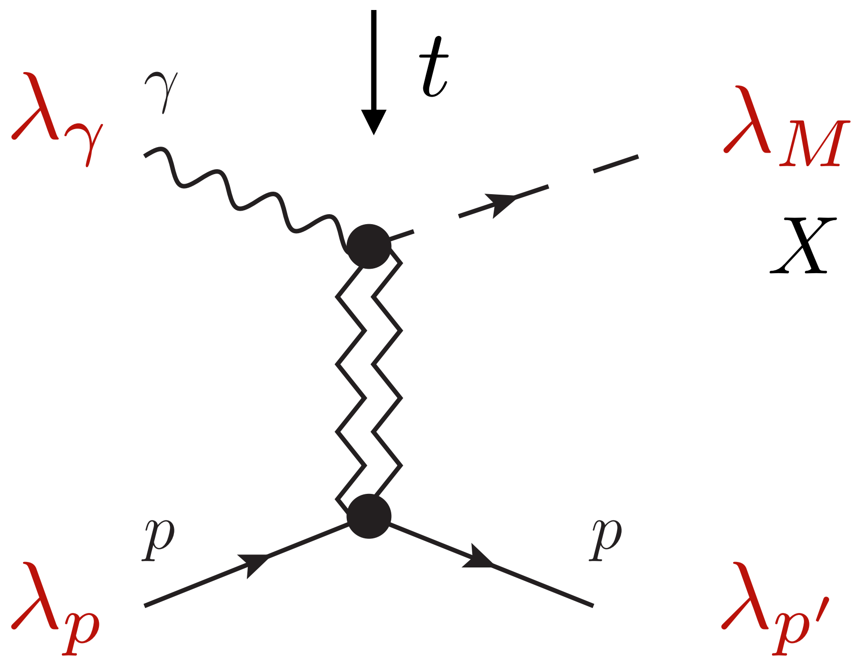
$$A^{\lambda_\gamma \lambda_M}_{\lambda_p \lambda_{p'}} \propto (\sin\theta/2)^{|\lambda_\gamma - \lambda_p + \lambda_{p'} - \lambda_M|}$$

$\sqrt{-t}$

Leading order in the energy :

$$A^{\lambda_\gamma \lambda_M}_{\lambda_p \lambda_{p'}} \propto \gamma(t)(\sqrt{-t})^{|(\lambda_\gamma - \lambda_M)-(\lambda_p - \lambda_{p'})|}$$

Factorization



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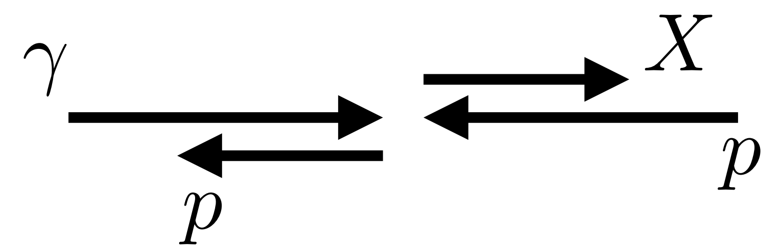


$$A^{\lambda_\gamma \lambda_M}_{\lambda_p \lambda_{p'}} \propto (\sin\theta/2)^{|\lambda_\gamma - \lambda_p + \lambda_{p'} - \lambda_M|}$$

$\sqrt{-t}$

Leading order in the energy :

$$A^{\lambda_\gamma \lambda_M}_{\lambda_p \lambda_{p'}} \propto \gamma(t)(\sqrt{-t})^{|(\lambda_\gamma - \lambda_M) - (\lambda_p - \lambda_{p'})|}$$

Factorization implies angular mom, conservation at each vertex:

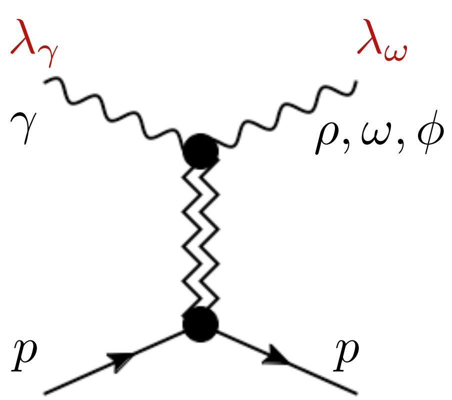
$$A^{\lambda_\gamma \lambda_M}_{\lambda_p \lambda_{p'}} \propto \gamma(t)(\sqrt{-t})^{|\lambda_\gamma - \lambda_M|} \times (\sqrt{-t})^{|\lambda_p - \lambda_{p'}|}$$

top vertex   bottom vertex

Spin Density Matrix Elements

Use the angular distribution of the vector
to extract spin density matrix elements

$$\frac{8\pi}{3}\frac{d\sigma}{d\Omega} = 1 - \rho^0_{00} + \left(3\rho^0_{00} - 1\right)\cos^2\theta - 2\sqrt{2}\mathrm{Re}\ \rho^0_{10}\sin 2\theta\cos\phi - 2\rho^0_{1-1}\sin^2\theta\cos 2\phi$$



Structure at the top vertex:

$$T_{\lambda_\gamma \lambda_\omega} = \beta_0 \left(\delta^{\lambda_\omega}_{\lambda_\gamma} + \beta_1 \frac{\sqrt{-t}}{m_\omega} \delta^{\lambda_\omega}_0 + \beta_2 \frac{-t}{m^2_\omega} \delta^{\lambda_\omega}_{-\lambda_\gamma} \right)$$

Spin Density Matrix Elements

Use the angular distribution of the vector to extract spin density matrix elements

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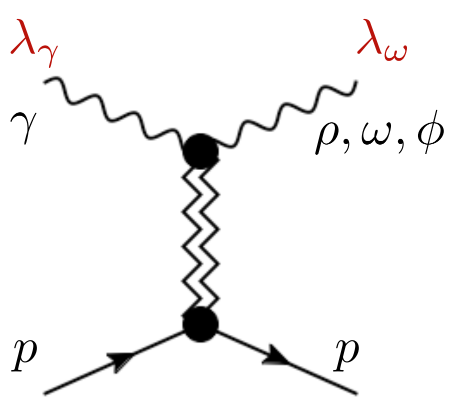


Structure at the top vertex:

$$T_{\lambda_\gamma\lambda_\omega} = \beta_0\left(\delta^{\lambda_\omega}_{\lambda_\gamma} + \beta_1\frac{\sqrt{-t}}{m_\omega}\delta^{\lambda_\omega}_0 + \beta_2\frac{-t}{m^2_\omega}\delta^{\lambda_\omega}_{-\lambda_\gamma}\right)$$

$$\rho^0_{00} = \frac{2}{N}\sum_{\lambda,\lambda'}\left|T_{\substack{1,0\\ \lambda,\lambda'}}\right|^2$$

$$\mathrm{Re}\ \rho^0_{10} = \frac{1}{N}\mathrm{Re}\sum_{\lambda,\lambda'}\left(T_{\substack{1,1\\ \lambda,\lambda'}} - T_{\substack{1,-1\\ \lambda,\lambda'}}\right)T^*_{\substack{1,0\\ \lambda,\lambda'}}$$

$$\rho^0_{1-1} = \frac{2}{N}\mathrm{Re}\sum_{\lambda\lambda'}T_{\substack{1,1\\ \lambda,\lambda'}}T^*_{\substack{1,-1\\ \lambda,\lambda'}}$$

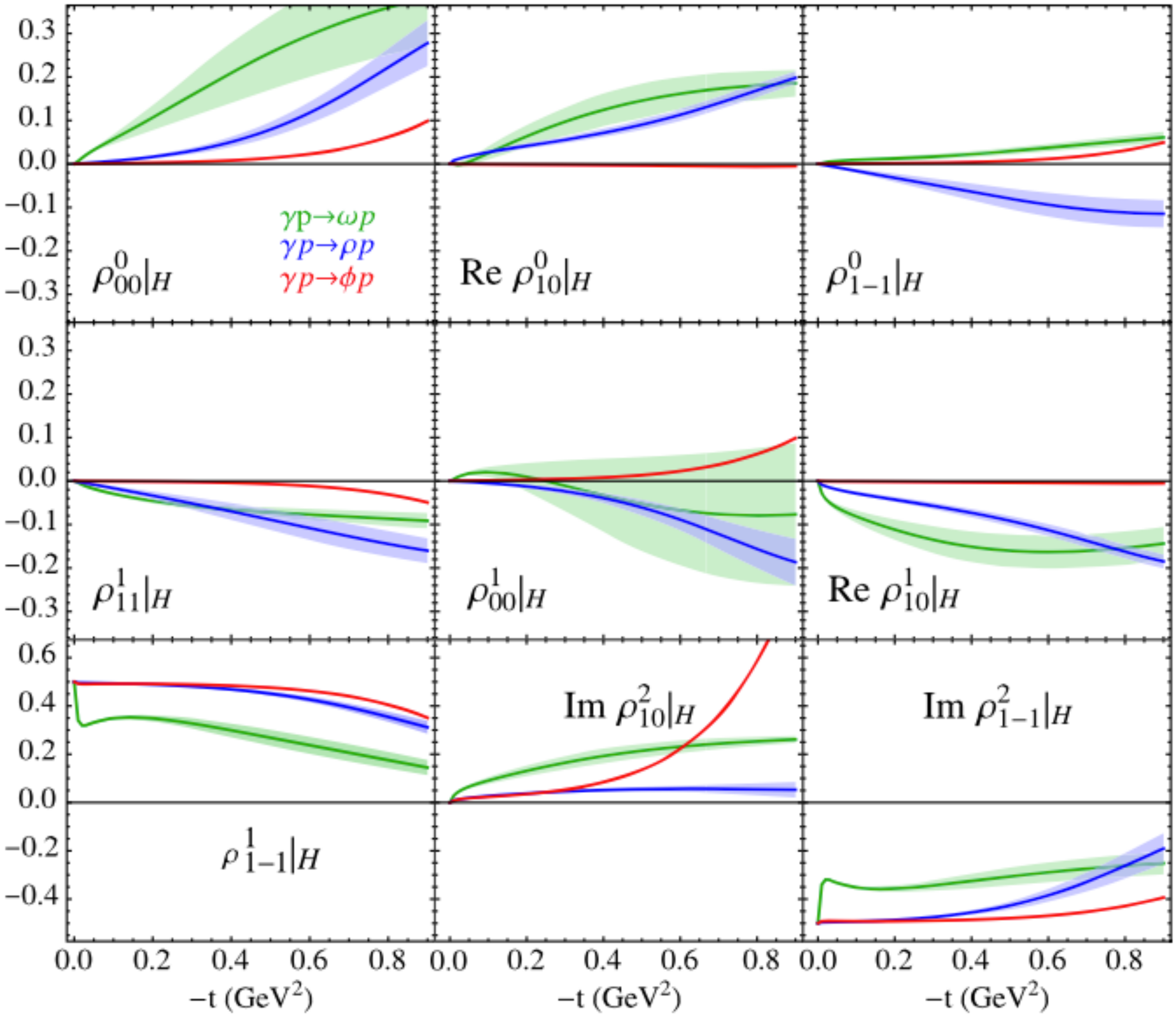
$$\rho^0_{00} \propto \beta_1^2\frac{-t}{m^2_\omega}$$

$$\mathrm{Re}\ \rho^0_{10} \propto \frac{1}{2}\beta_1\frac{\sqrt{-t}}{m_\omega}$$

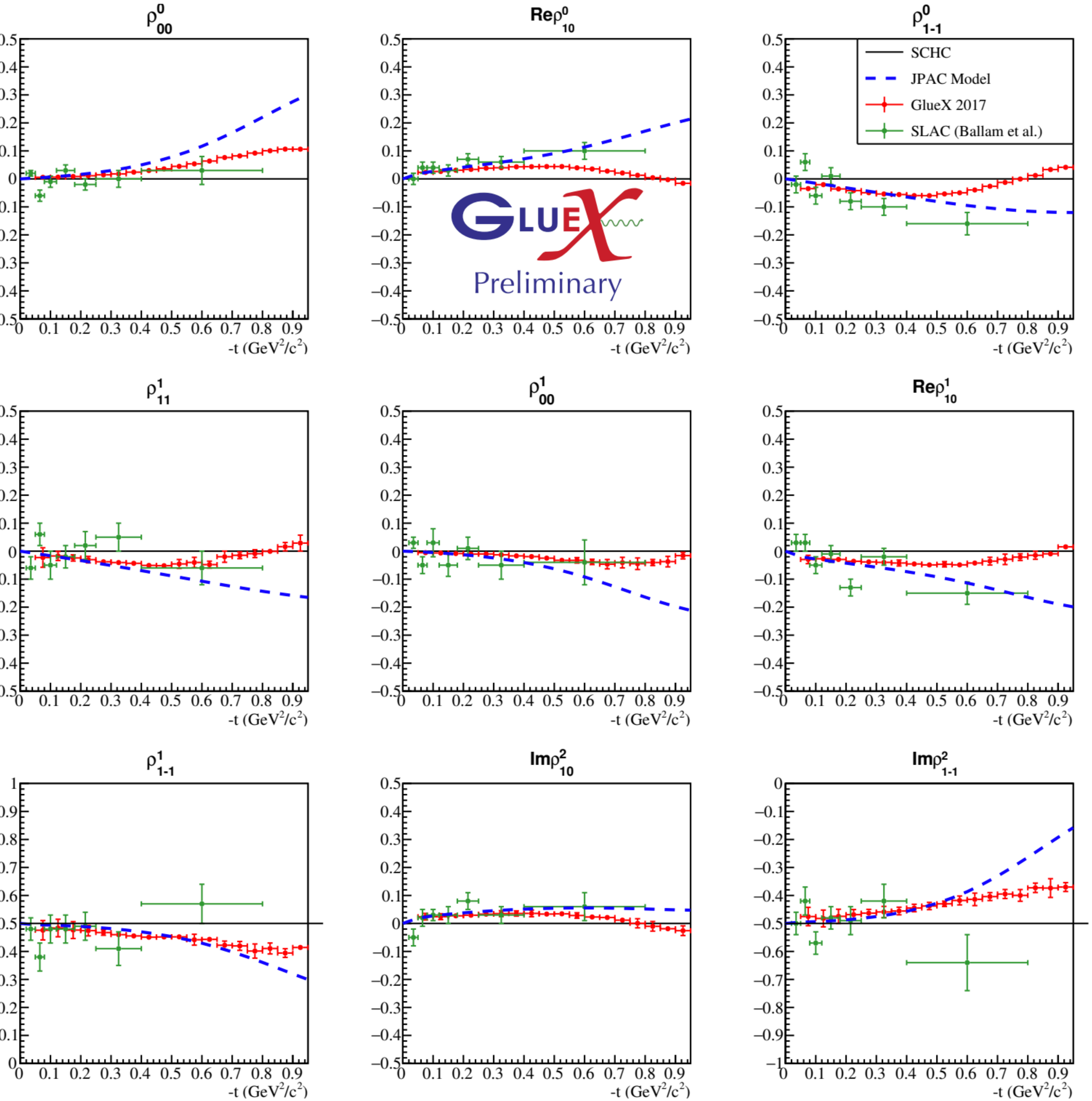
$$\rho^0_{1-1} \propto \beta_2\frac{-t}{m^2_\omega}$$

Predictions for Vector Meson SDME

VM et al (JPAC), PRD97 (2018)



$\vec{\gamma} p \to \rho^0 p$



Preliminary

A. Austregesilo 1908.07275

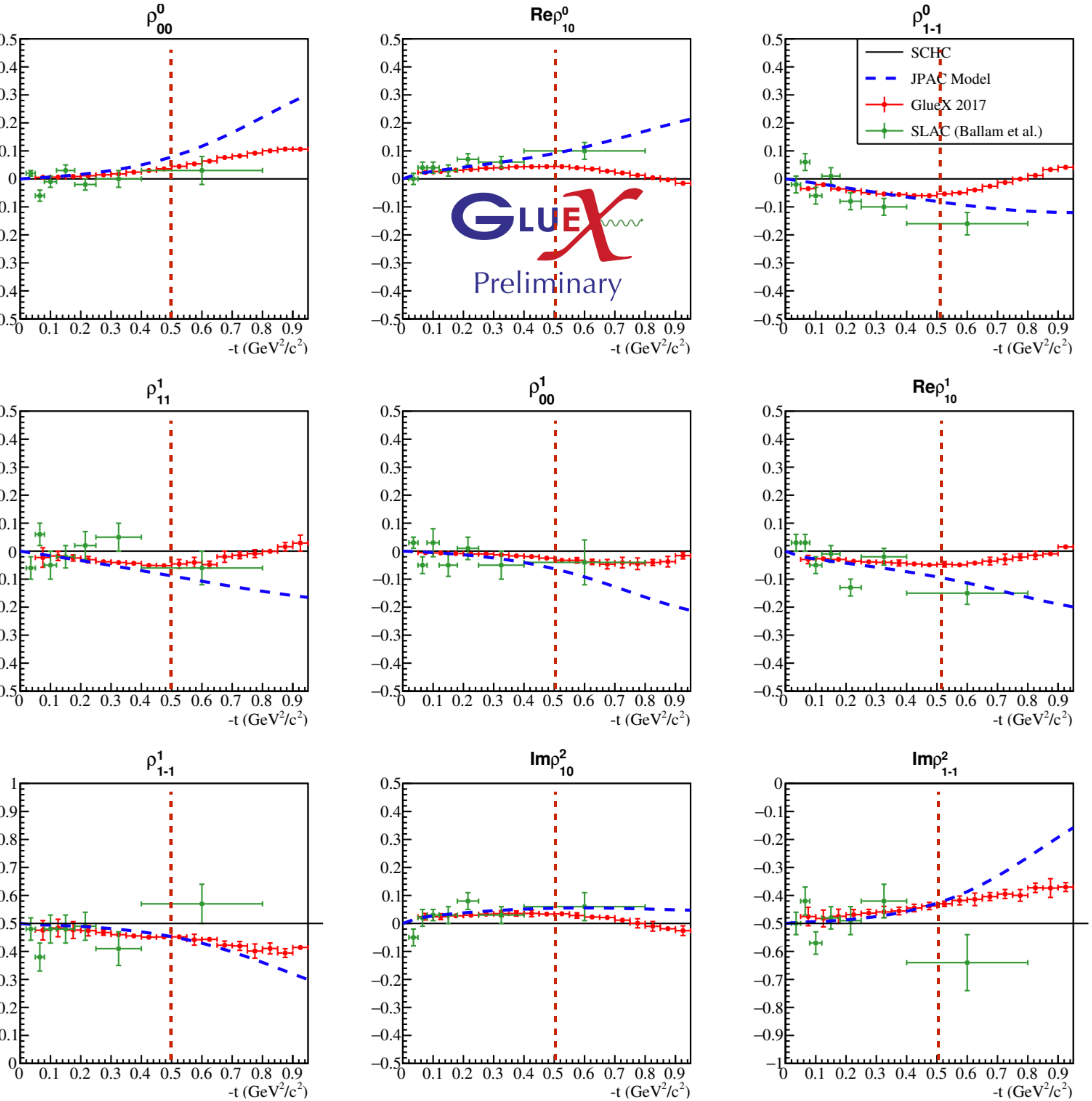
kinematics expanded

in power of $\dfrac{-t}{m_\rho^2}$

$$\rho^1_{1-1} = \pm\frac{1}{2} + \mathcal{O}(t^2)$$

$$\mathrm{Im}\ \rho^2_{1-1} = \mp\frac{1}{2} + \mathcal{O}(t^2)$$

top sign for natural exchange
bottom sign for unnatural exch.



GlueX

Preliminary

A. Austregesilo 1908.07275

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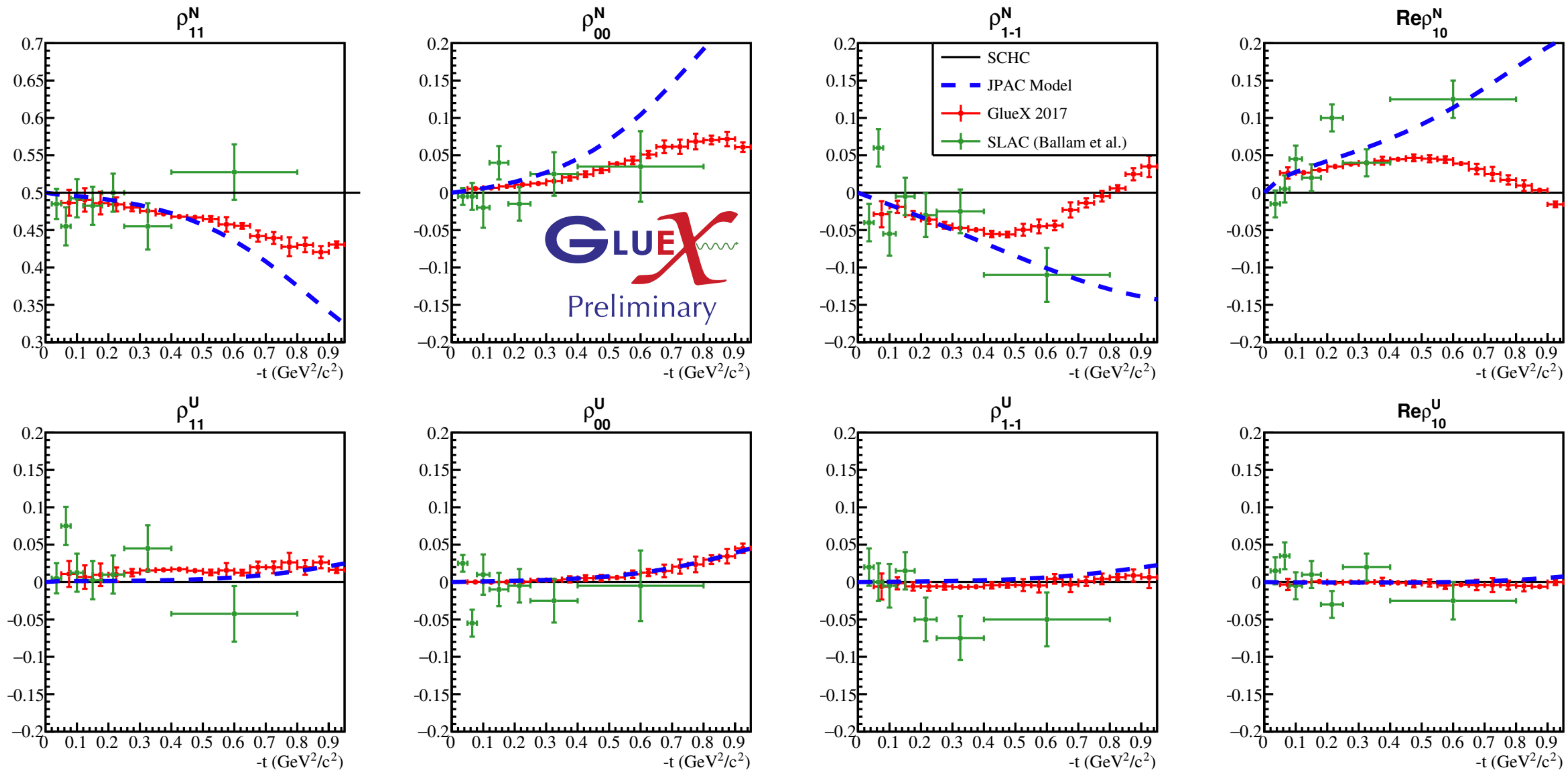
$$\rho^1_{1-1} = \pm\frac{1}{2} + \mathcal{O}(t^2)$$

$$\mathrm{Im}\ \rho^2_{1-1} = \mp\frac{1}{2} + \mathcal{O}(t^2)$$

top sign for natural exchange
bottom sign for unnatural exch.

$\vec{\gamma}p \rightarrow \rho^0 p$ SDME: Natural- and Unnatural-exchange



Clear domination of natural (Pomeron and tensor 2++) exchanges over unnatural (pseudo-scalar 0-+ and 1++) ones

GlueX Preliminary

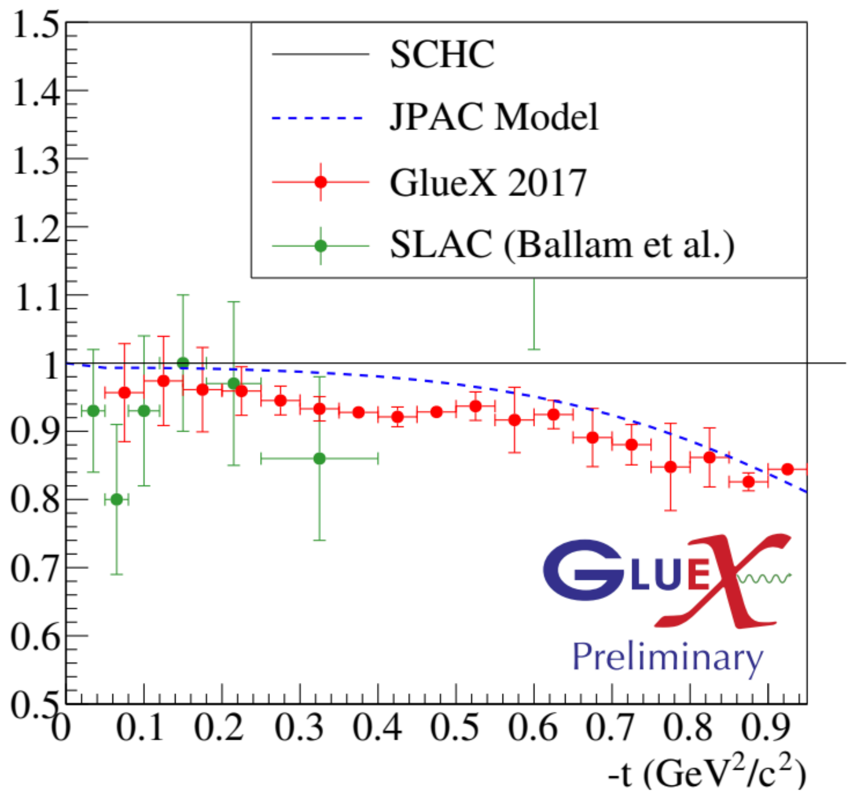
VM et al (JPAC), PRD97 (2018)

A. Austregesilo 1908.07275

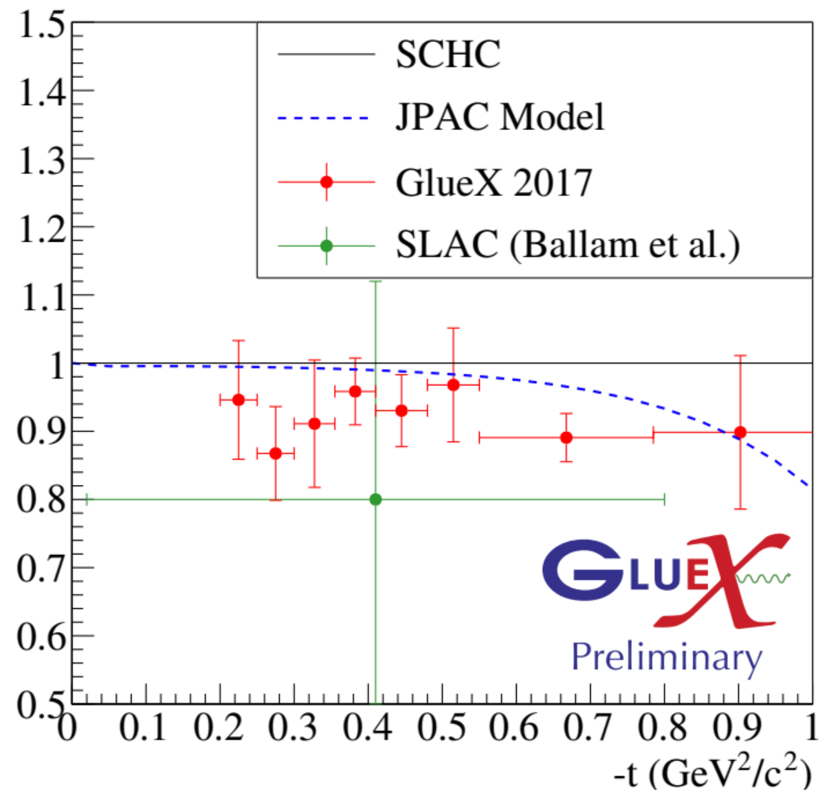
Vector Meson SDME: Parity Asymmetry

$$P_\sigma = 2\rho^1_{1-1} - \rho^1_{00} = \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U}$$

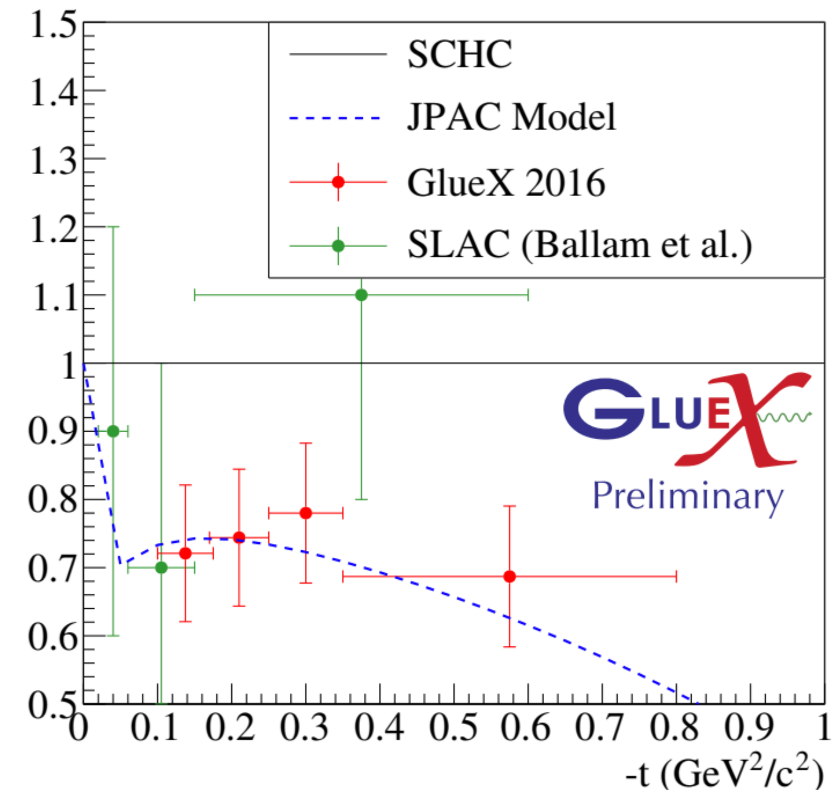
$\rho(770)$



$\phi(1020)$



$\omega(782)$



Clear domination of natural (Pomeron and tensor 2++) exchanges over unnatural (pseudo-scalar 0-+ and 1++) ones

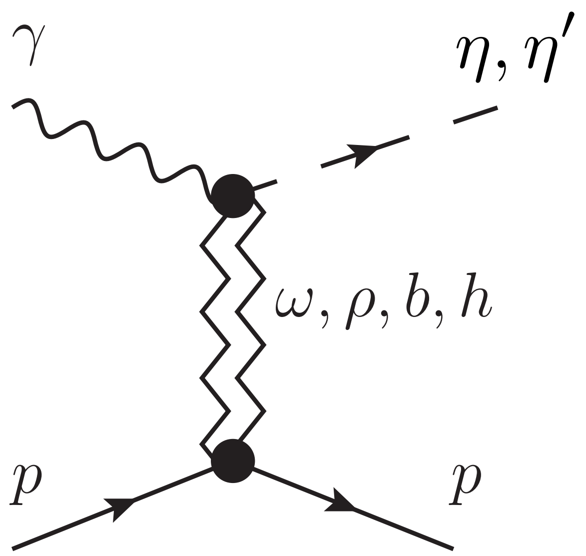
Except at low |t| for the Omega (pion exchange)

GlueX Preliminary

VM et al (JPAC), PRD97 (2018)

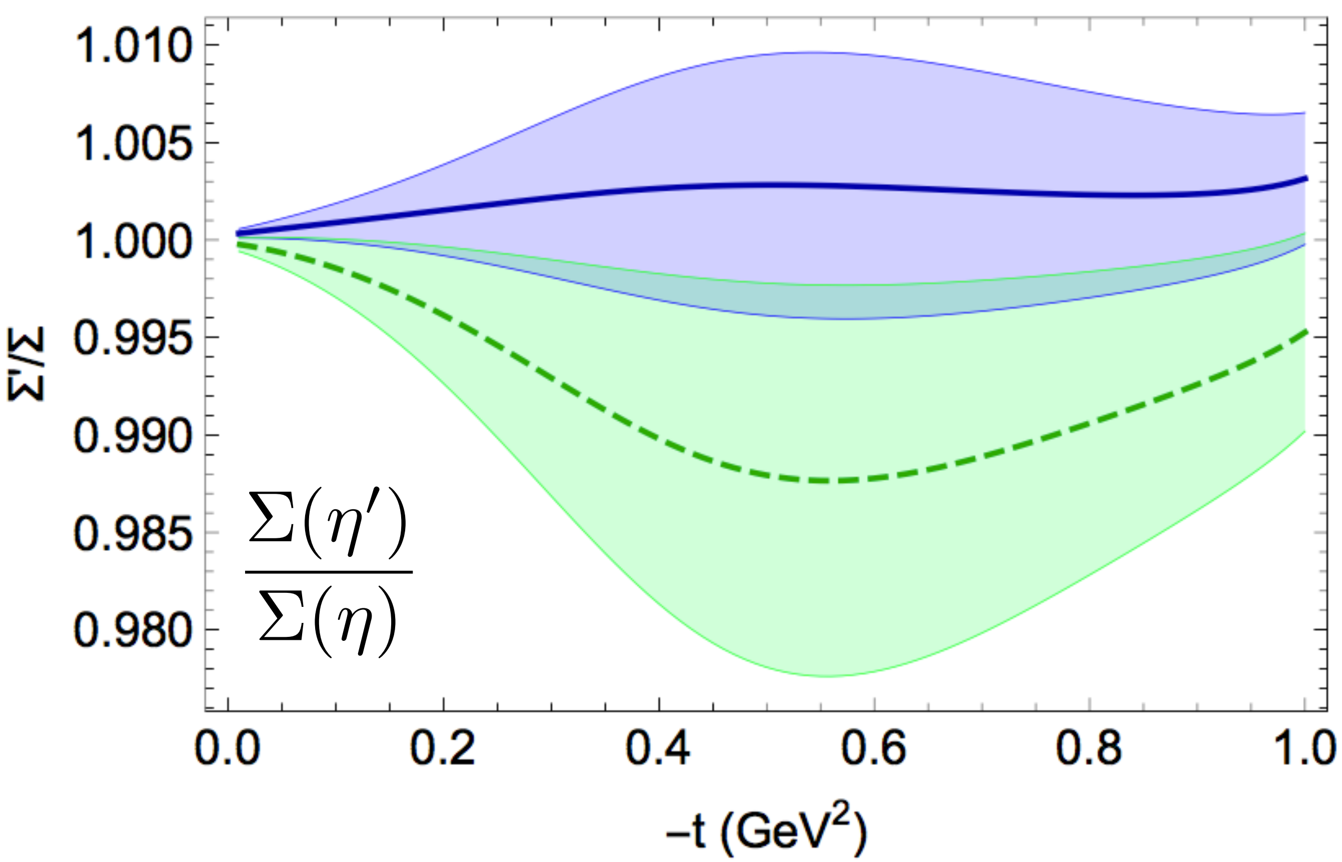
A. Austregesilo 1908.07275

Pseudoscalar Meson Beam Asymmetry



$$\Sigma(\eta) = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 + |b+h|^2}$$
$$= \Sigma(\eta')$$

$b_1 \to \gamma\eta^{(\prime)}$ not known

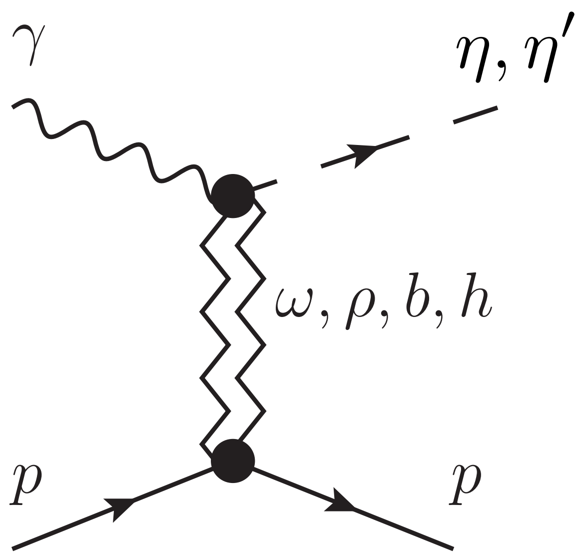


Beam asymmetry Difference probes strange exchanges contribution and deviation from quark model

blue and green models represent the estimation of systematic errors

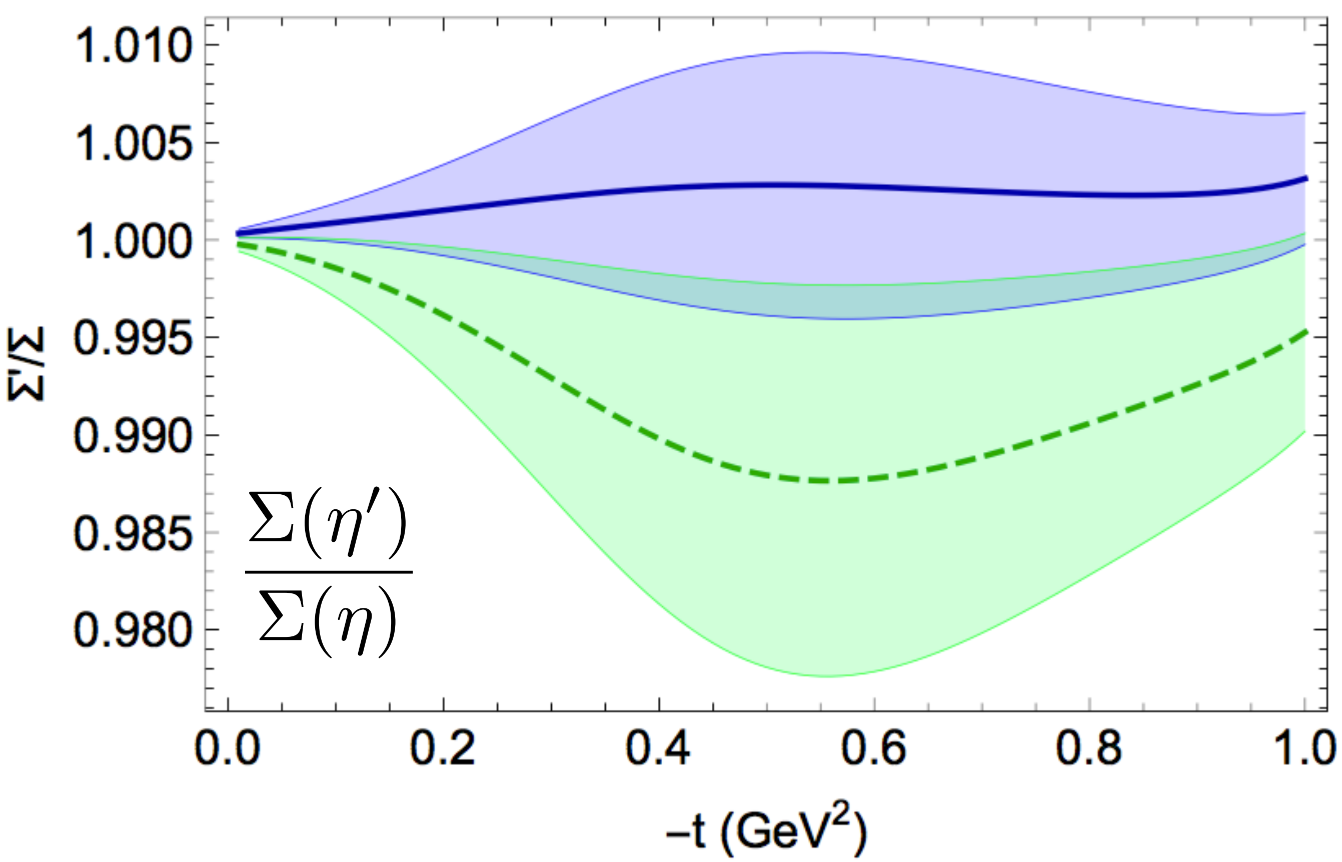
VM et al. (JPAC) PLB774 (2017) 362

Pseudoscalar Meson Beam Asymmetry



$$\Sigma(\eta) = \frac{|\rho + \omega + \phi|^2 - |b + h + h'|^2}{|\rho + \omega + \phi|^2 + |b + h + h'|^2}$$
$$\neq \Sigma(\eta')$$

$b_1 \to \gamma\eta^{(\prime)}$ not known



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Beam asymmetry Difference probes strange exchanges contribution and deviation from quark model

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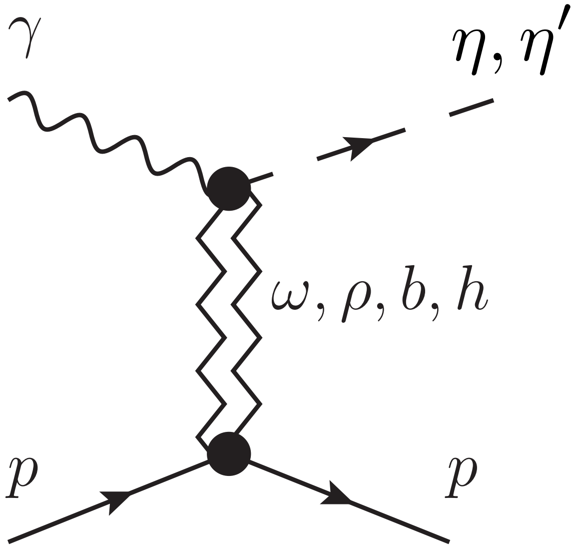
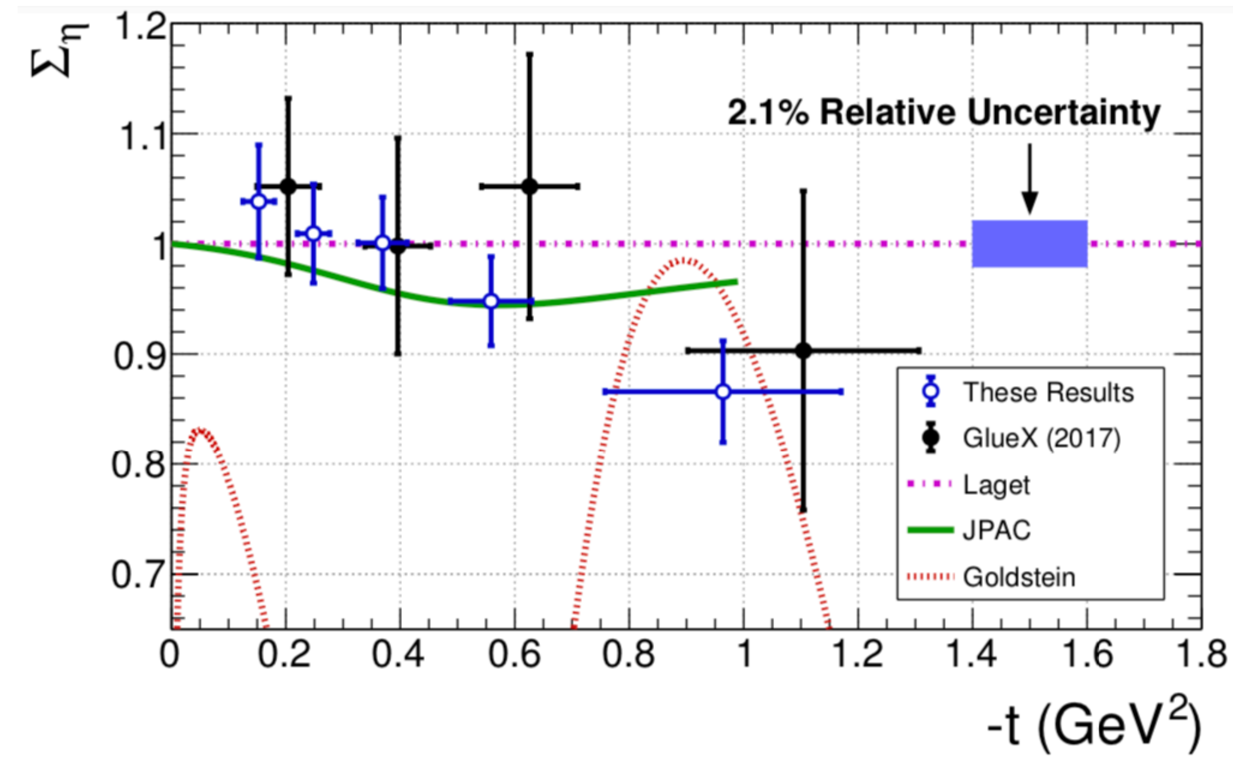
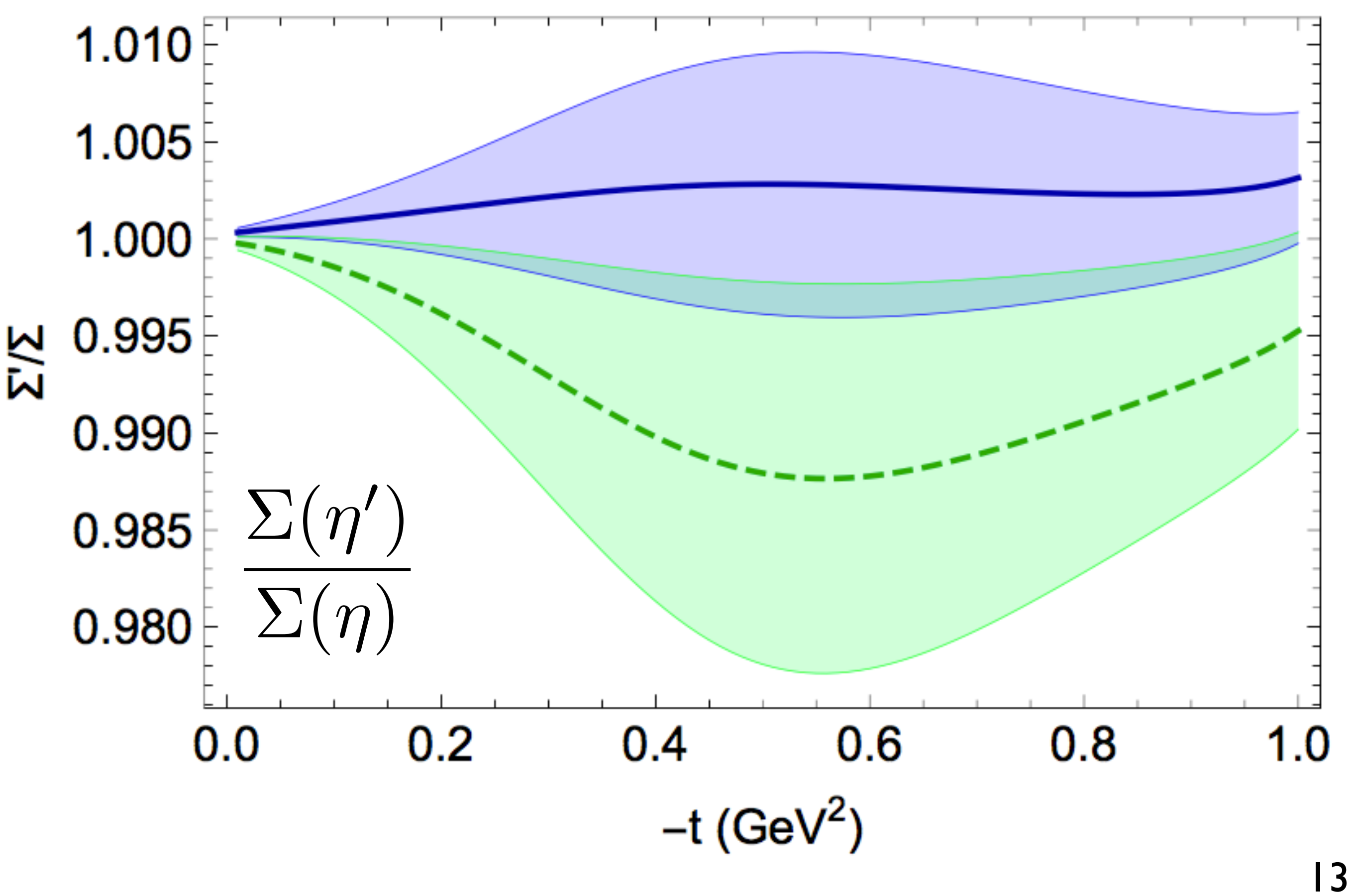
VM et al. (JPAC) PLB774 (2017) 362

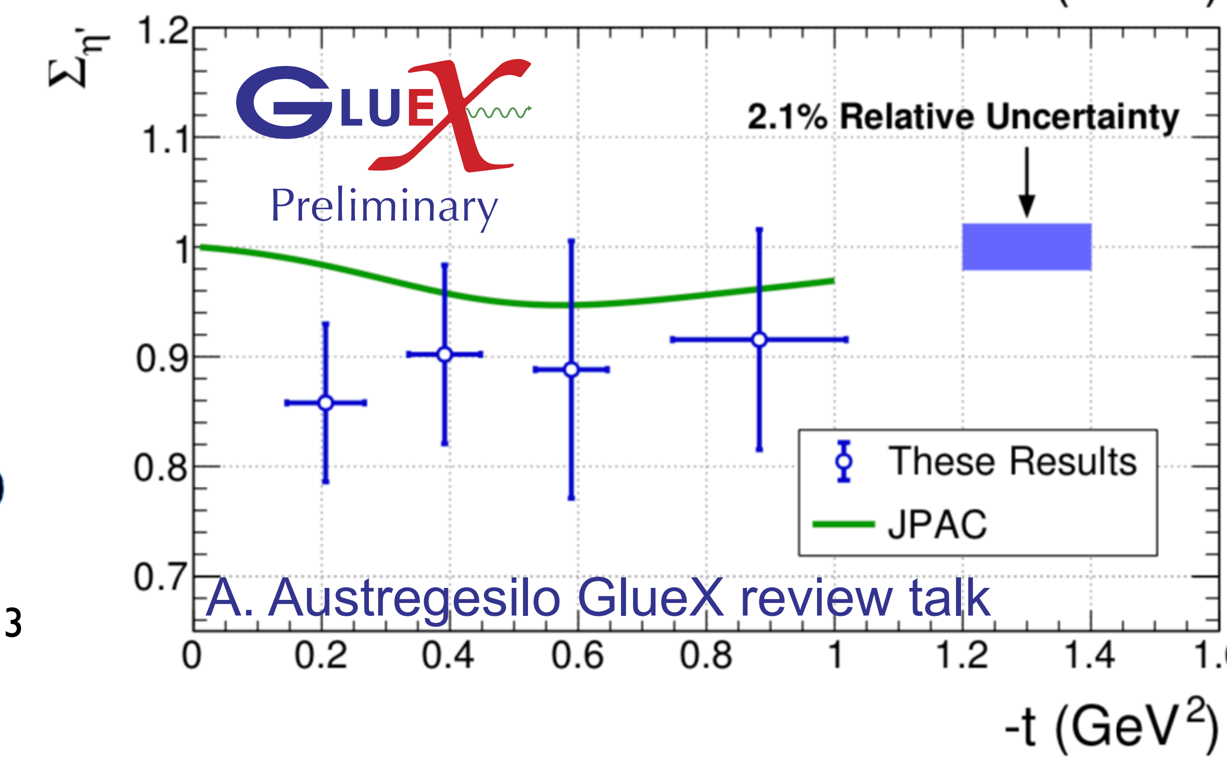
Pseudoscalar Meson Beam Asymmetry



$$\Sigma(\eta) = \frac{|\rho + \omega + \phi|^2 - |b + h + h'|^2}{|\rho + \omega + \phi|^2 + |b + h + h'|^2}$$







VM et al. (JPAC) PLB774 (2017) 362

Conclusion

Single Meson Photoproduction:

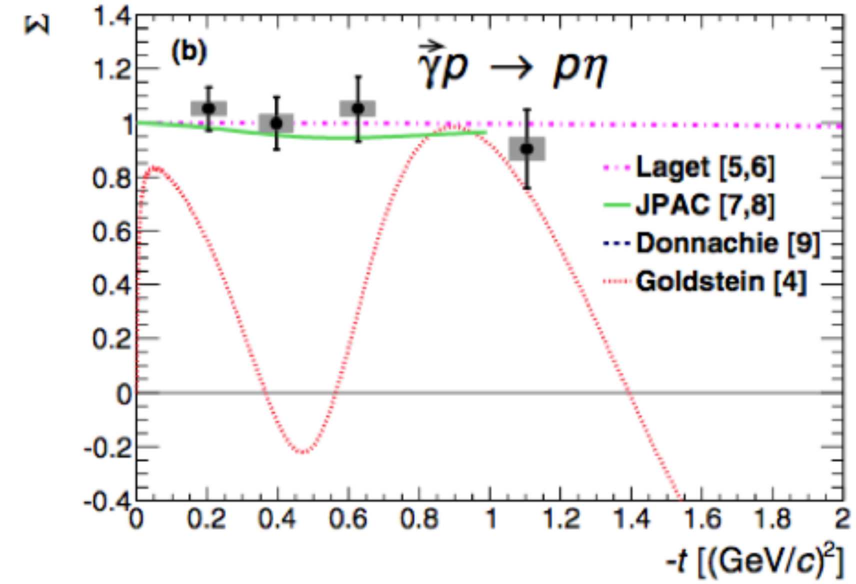
$$\vec{\gamma}p \to \pi^0 p$$

$$\vec{\gamma}p \to \eta p$$

$$\vec{\gamma}p \to \pi\Delta$$

Dominance of natural exch. in both π^0/η photoproduction

Significant $\pi^{\pm}$ exch. at low t



$$\rho(770)$$

Vector Meson Photoproduction:

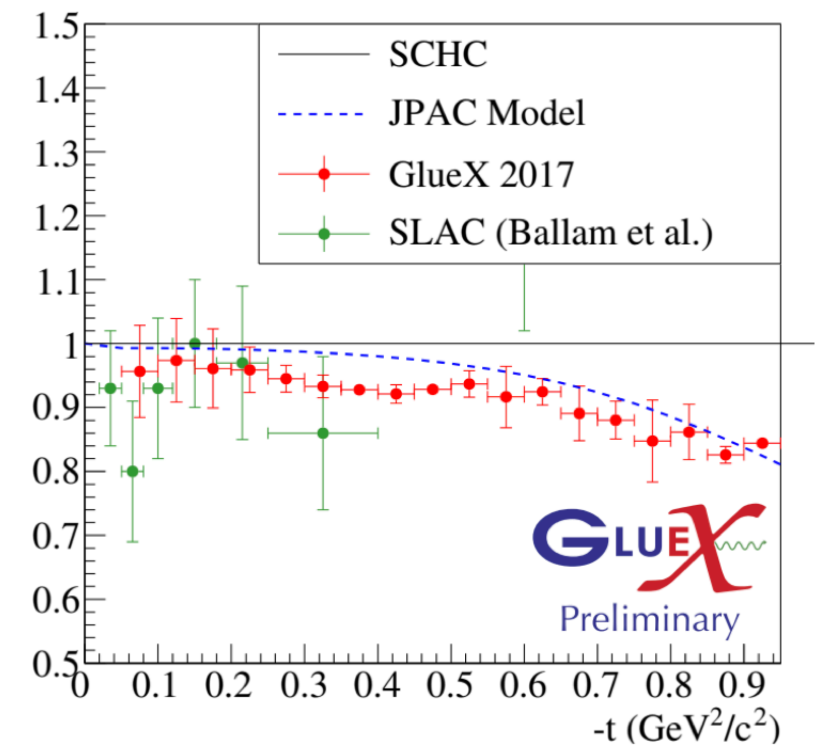
$$\vec{\gamma}p \to \rho^0 p$$

$$\vec{\gamma}p \to \omega p$$

$$\vec{\gamma}p \to \phi p$$

Consistent with factorization

Dominance of natural exchanges



Double Mesons Photoproduction:

$$\vec{\gamma}p \to \pi^0 \eta p$$

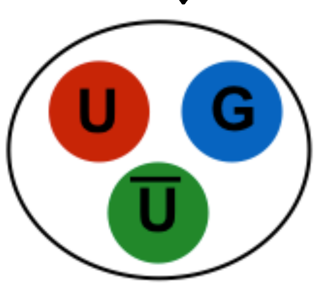
Observables: Moments of Angular distribution

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

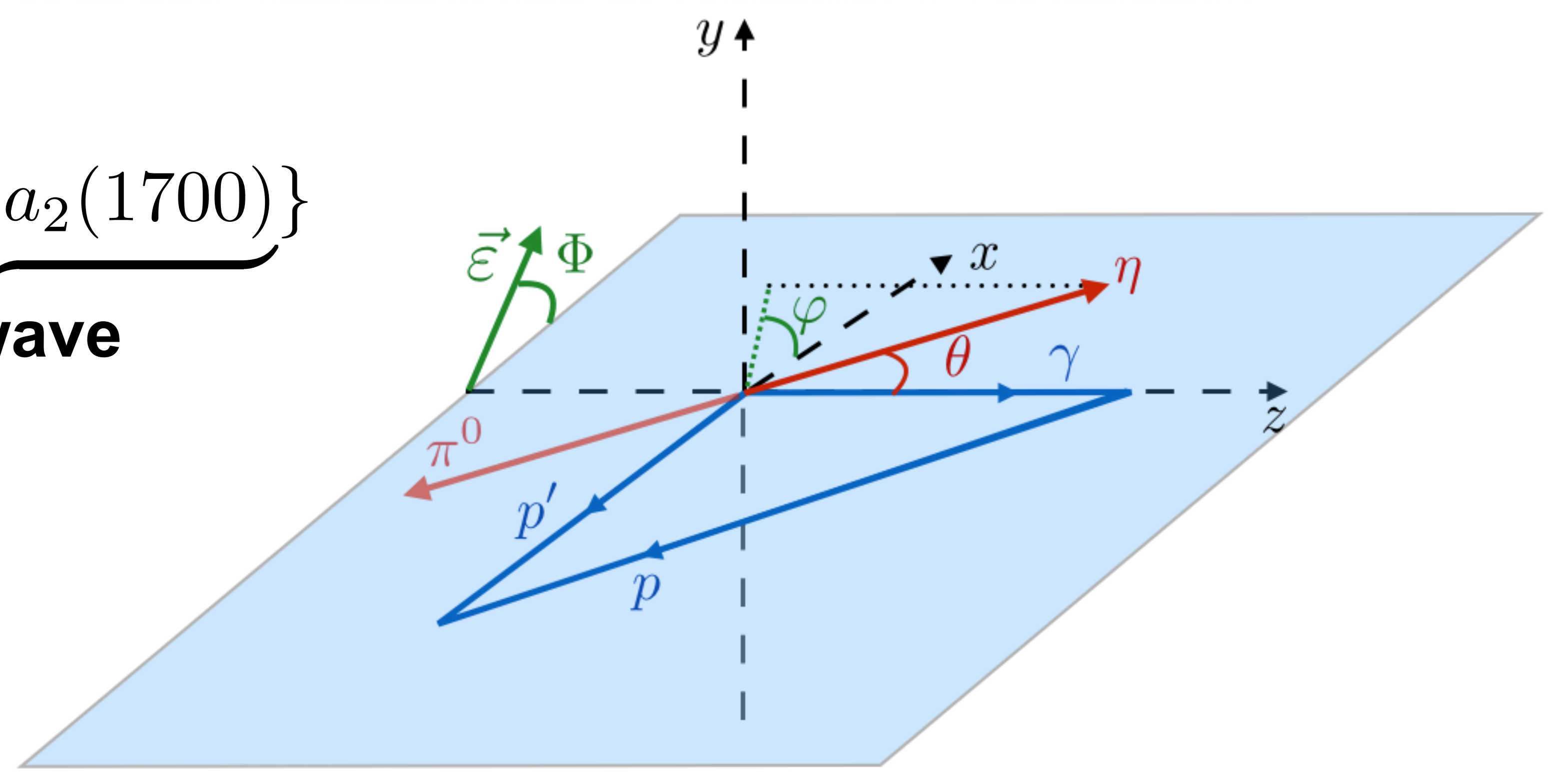
$$H^0(LM) = \frac{1}{2\pi}\int I(\Omega, \Phi)\, d^L_{M0}(\theta)\cos M\phi\, \mathrm{d}\Omega\mathrm{d}\Phi$$

$$R = \{\underbrace{a_0(980)}_{\text{S-wave}}, \underbrace{\pi_1(1600)}, \underbrace{a_2(1320), a_2(1700)}_{\text{D-wave}}\}$$

S-wave **D-wave**



exotic P-wave



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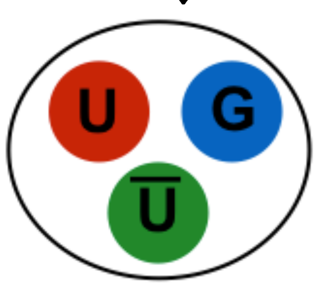
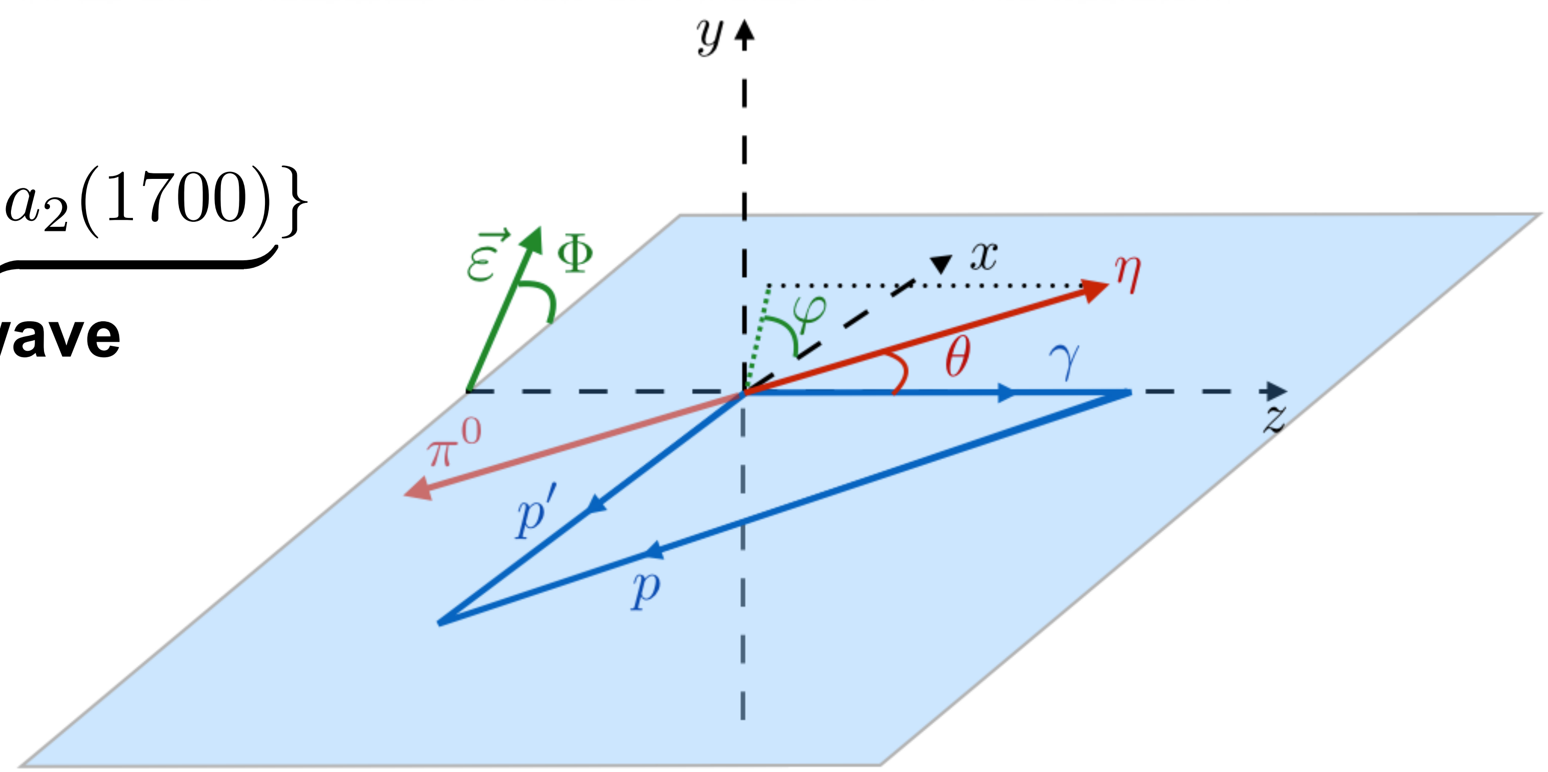
$$H^1(LM) = \frac{-1}{\pi P_\gamma}\int I(\Omega,\Phi) \boxed{\cos 2\Phi}\, d^L_{M0}(\theta)\cos M\phi\, \mathrm{d}\Omega \mathrm{d}\Phi$$

$$\mathrm{Im}\, H^2(LM) = \frac{1}{\pi P_\gamma}\int I(\Omega,\Phi) \boxed{\sin 2\Phi}\, d^L_{M0}(\theta)\sin M\phi\, \mathrm{d}\Omega \mathrm{d}\Phi$$

$$R = \{\underbrace{a_0(980)}_{\text{S-wave}}, \underbrace{\pi_1(1600)}, \underbrace{a_2(1320), a_2(1700)}_{\text{D-wave}}\}$$



exotic P-wave



Observables: Moments of Angular distribution

$$H^0(LM) = \frac{1}{2\pi}\int I(\Omega,\Phi)\, d^L_{M0}(\theta)\cos M\phi\, \mathrm{d}\Omega\mathrm{d}\Phi$$

$$H^1(LM) = \frac{-1}{\pi P_\gamma}\int I(\Omega,\Phi)\cos 2\Phi\, d^L_{M0}(\theta)\cos M\phi\, \mathrm{d}\Omega\mathrm{d}\Phi$$

$$\mathrm{Im}\, H^2(LM) = \frac{1}{\pi P_\gamma}\int I(\Omega,\Phi)\sin 2\Phi\, d^L_{M0}(\theta)\sin M\phi\, \mathrm{d}\Omega\mathrm{d}\Phi$$

Moments are unambiguously extracted and are related to partial waves (interferences)

$$^{(+)}H^0(00) = 2\left[|S_0^{(+)}|^2 + |P_{-1}^{(+)}|^2 + |P_0^{(+)}|^2 + |P_1^{(+)}|^2 + |D_{-2}^{(+)}|^2 + |D_{-1}^{(+)}|^2 + |D_0^{(+)}|^2 + |D_1^{(+)}|^2 + |D_2^{(+)}|^2\right]$$

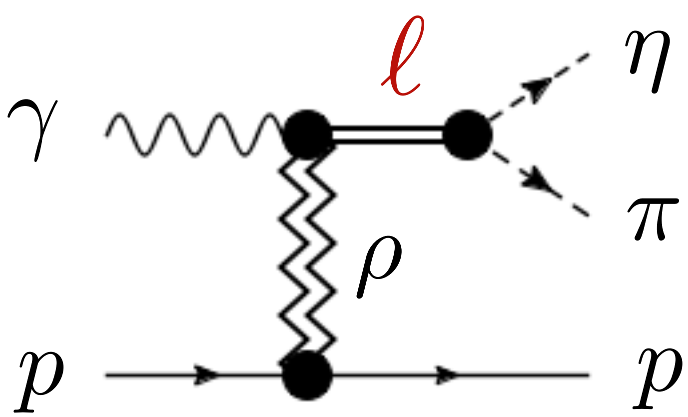
$$^{(+)}H^0(10) = \frac{4}{\sqrt{3}}\mathrm{Re}\left(S_0^{(+)}P_0^{(+)*}\right) + \frac{8}{\sqrt{15}}\mathrm{Re}\left(P_0^{(+)}D_0^{(+)*}\right) + \frac{4}{\sqrt{5}}\mathrm{Re}\left(P_1^{(+)}D_1^{(+)*}\right) + \frac{4}{\sqrt{5}}\mathrm{Re}\left(P_{-1}^{(+)}D_{-1}^{(+)*}\right)$$

$$^{(+)}H^0(20) = \frac{4}{5}|P_0^{(+)}|^2 - \frac{2}{5}\left(|P_1^{(+)}|^2 + |P_{-1}^{(+)}|^2\right) + \frac{4}{7}|D_0^{(+)}|^2 + \frac{2}{7}\left(|D_1^{(+)}|^2 + |D_{-1}^{(+)}|^2\right) - \frac{4}{7}\left(|D_2^{(+)}|^2 + |D_{-2}^{(+)}|^2\right) + \frac{4}{\sqrt{5}}\mathrm{Re}\left(S_0^{(+)}D_0^{(+)*}\right)$$

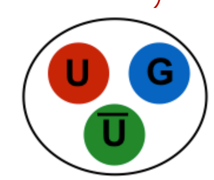
$$^{(+)}H^0(30) = \frac{12}{7\sqrt{5}}\mathrm{Re}\left(\sqrt{3}P_0^{(+)}D_0^{(+)*} - P_1^{(+)}D_1^{(+)*} - P_{-1}^{(+)}D_{-1}^{(+)*}\right)$$

Model

VM et al (JPAC), PRD100 (2019) 054017



$$R = \{\underbrace{a_0(980)}_{S_0^{(+)}}, \underbrace{\pi_1(1600)}_{P_{0,1}^{(+)}}, \underbrace{a_2(1320), a_2(1700)}_{D_{0,1,2}^{(+)}}\}$$

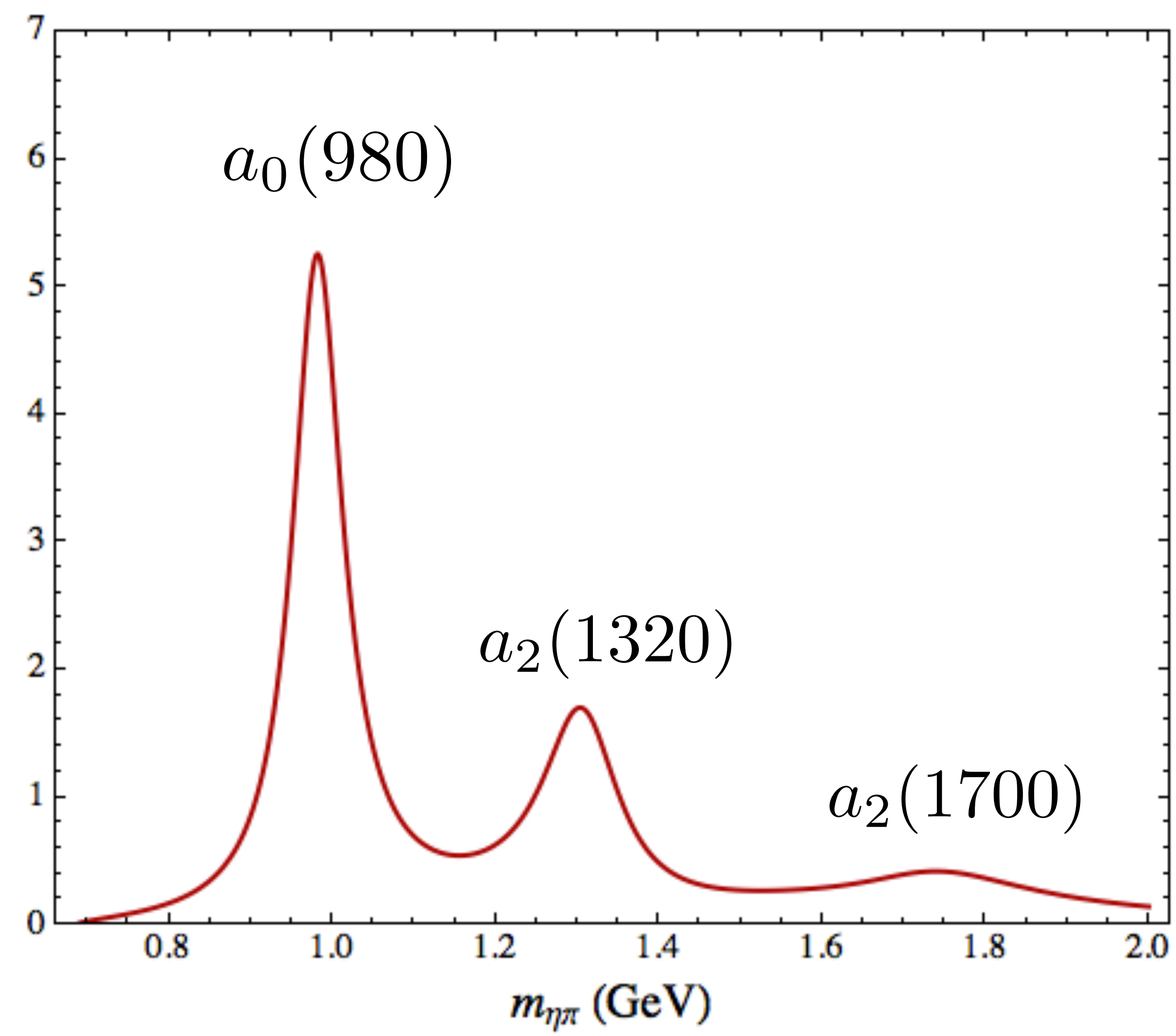


production: **natural exchanges**

line shape: **Breit-Wigner form**

parameters: **arbitrary**

Small exotic wave,
not apparent in the diff. cross. section

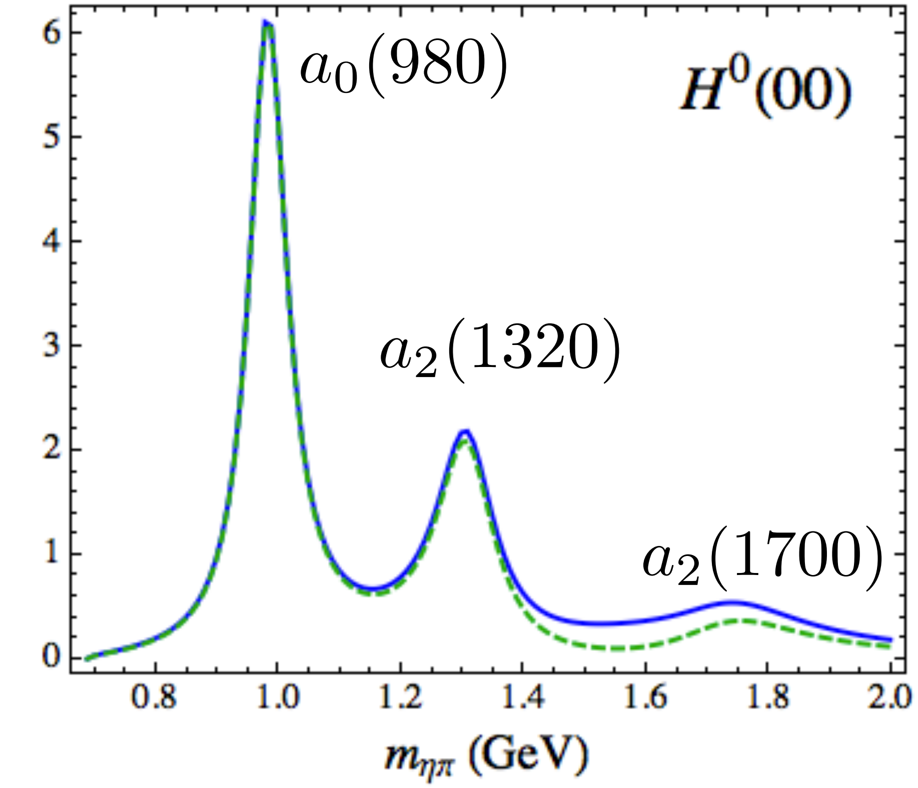


Moments

VM et al (JPAC), PRD100 (2019) 054017

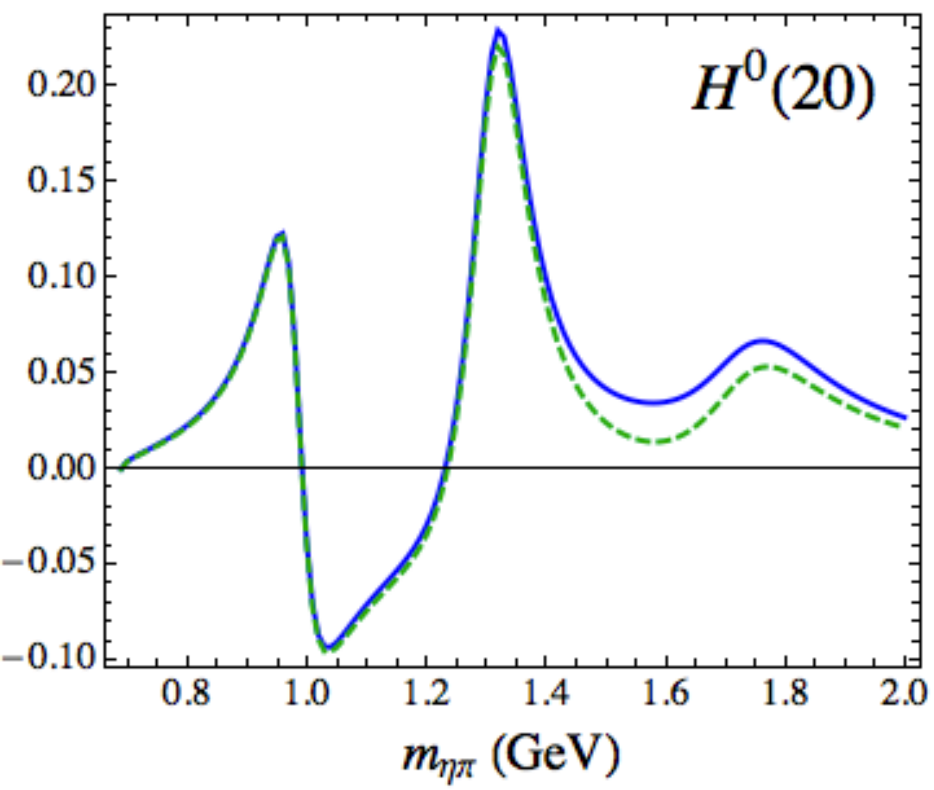
solid lines: *S* + *P* + *D* waves

dashed lines: *S* + *D* waves



$$|S|^2 \quad |D|^2 \quad |P|^2$$

$$(S+D)(S+D)^*$$

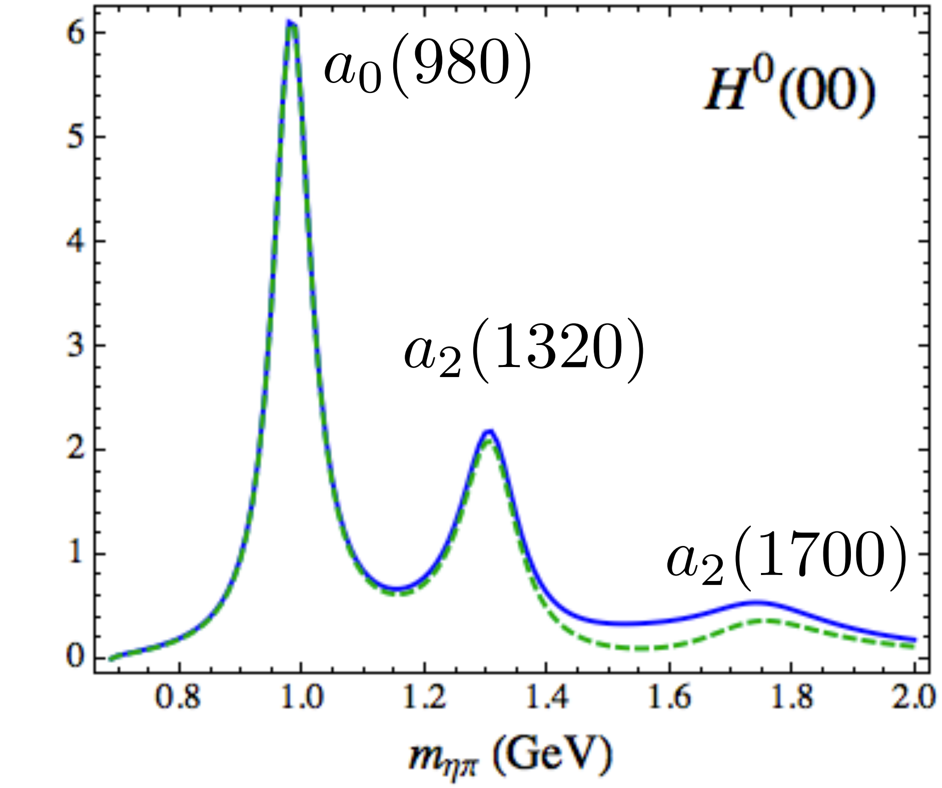


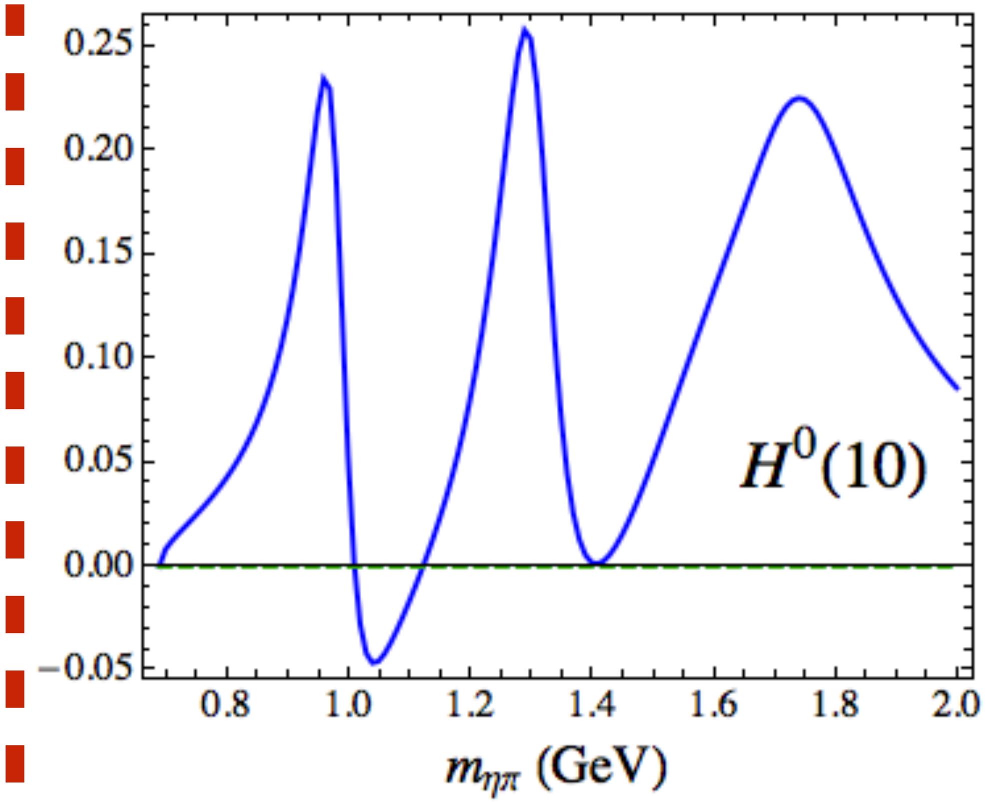
Moments

VM et al (JPAC), PRD100 (2019) 054017

solid lines: *S* + *P* + *D* waves

dashed lines: *S* + *D* waves

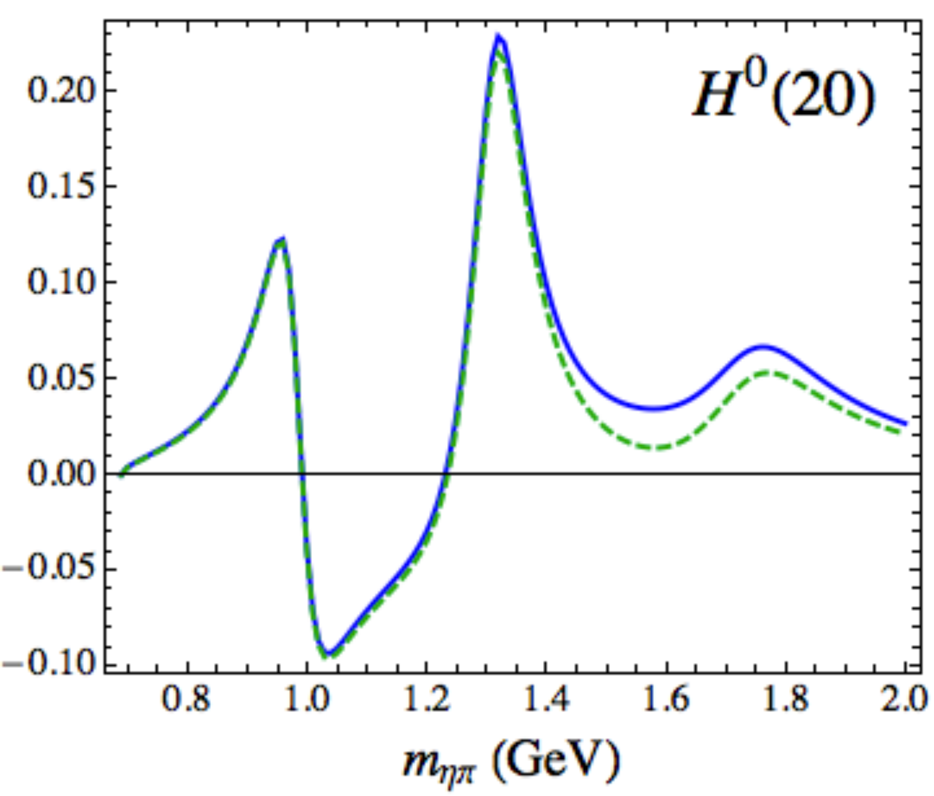


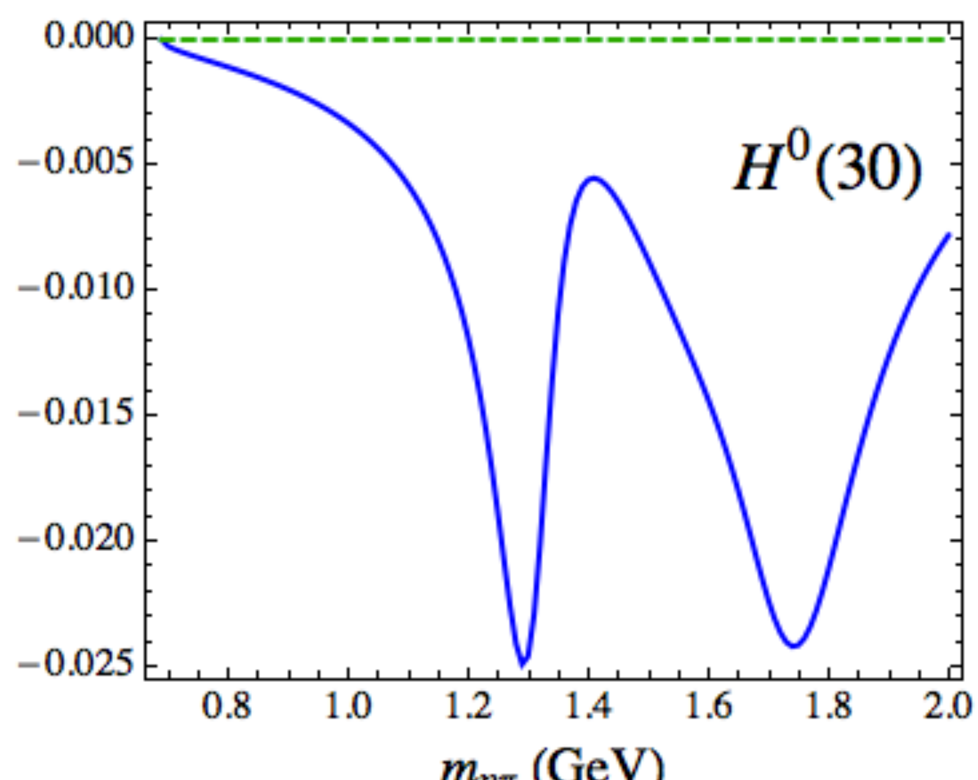


$$|S|^2 \quad |D|^2 \quad |P|^2$$
$$(S+D)(S+D)^*$$

$$(S+D)P^*$$

P- wave apparent as an interference in odd moments but not in even moments



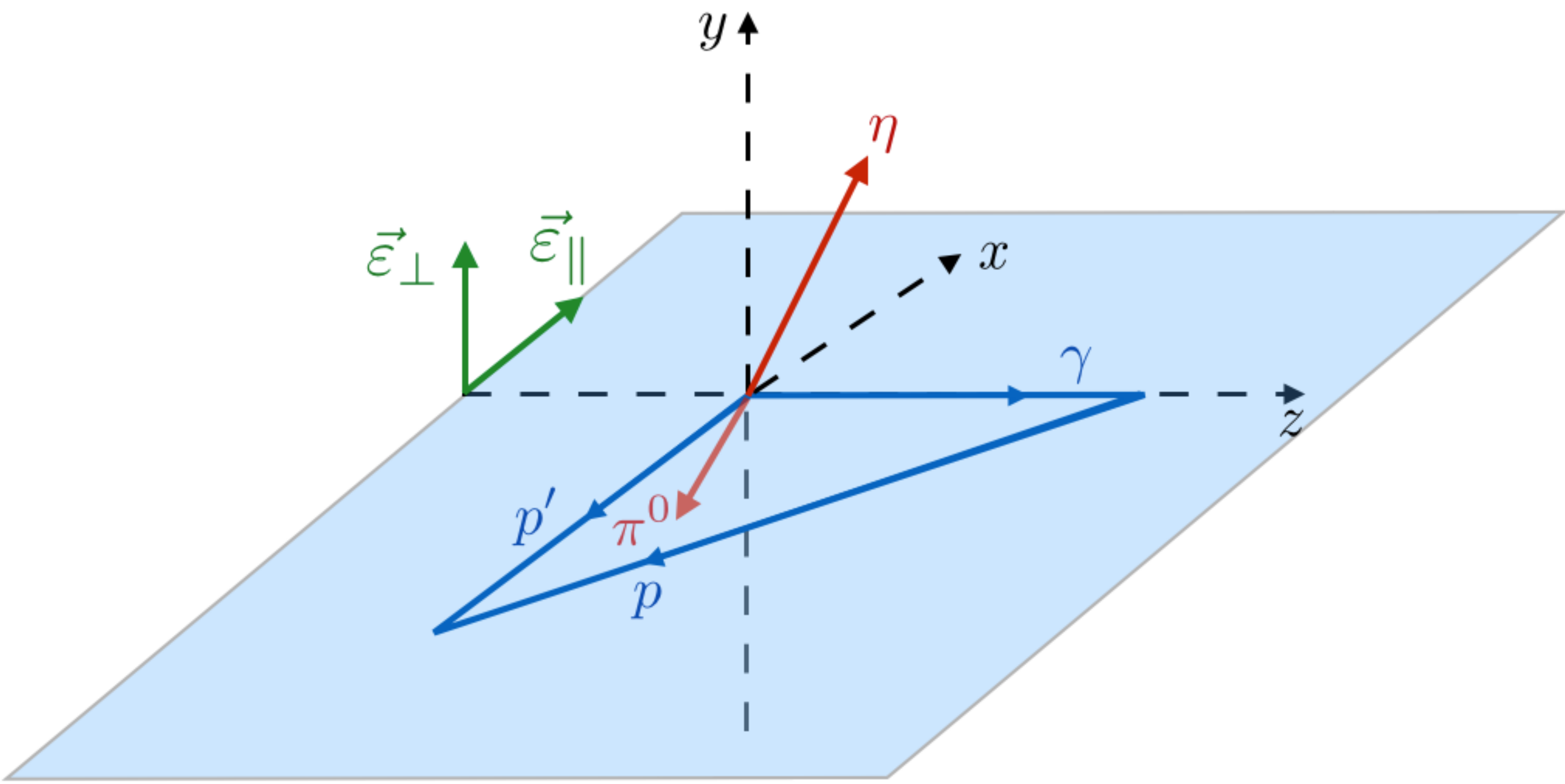


Beam Asymmetries

VM et al (JPAC), PRD100 (2019) 054017

$$\Sigma_{\mathcal{D}} = \frac{1}{P_\gamma} \frac{\int_{\mathcal{D}} I^{\parallel}(\Omega) - I^{\perp}(\Omega) \mathrm{d}\Omega}{\int_{\mathcal{D}} I^{\parallel}(\Omega) + I^{\perp}(\Omega) \mathrm{d}\Omega}$$

$\Sigma_{4\pi} =$ fully integrated

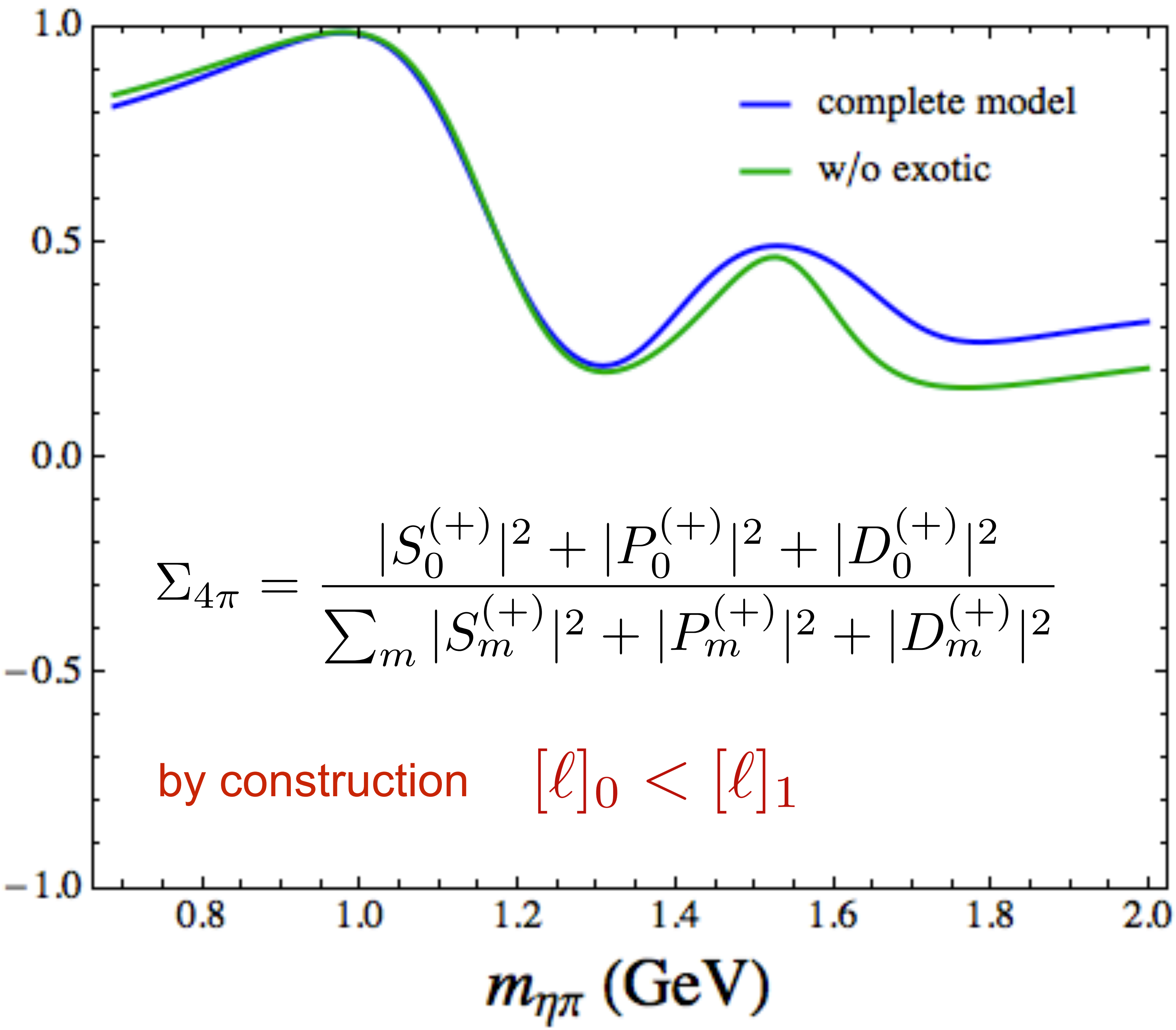


Beam Asymmetries

VM et al (JPAC), PRD100 (2019) 054017

$$\Sigma_{\mathcal{D}} = \frac{1}{P_\gamma} \frac{\int_{\mathcal{D}} I^{\|}(\Omega) - I^{\perp}(\Omega) \mathrm{d}\Omega}{\int_{\mathcal{D}} I^{\|}(\Omega) + I^{\perp}(\Omega) \mathrm{d}\Omega}$$

$\Sigma_{4\pi} =$ fully integrated



Beam Asymmetries

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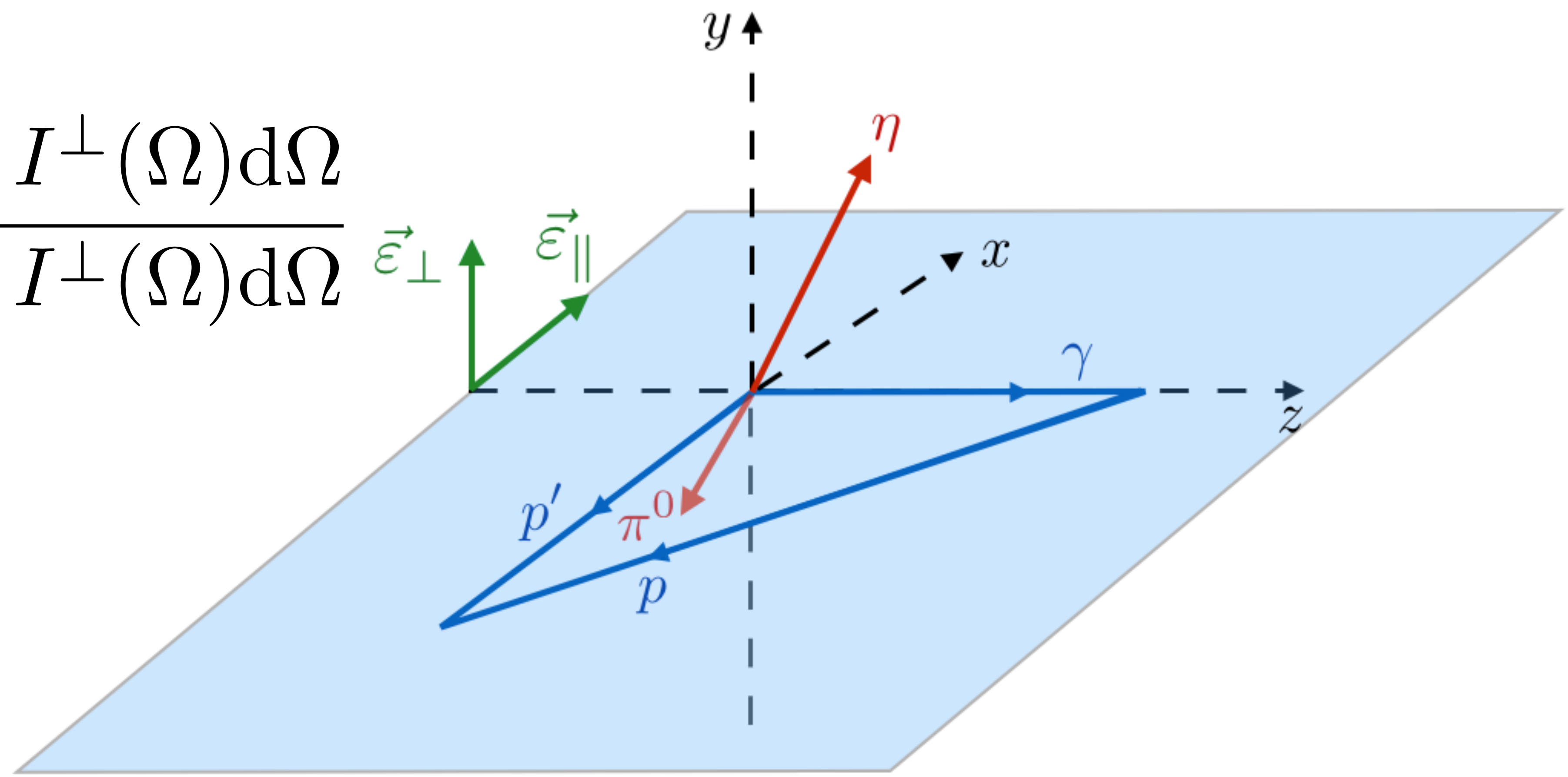
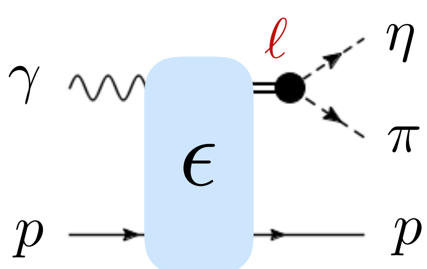


amplitude:
production x decay



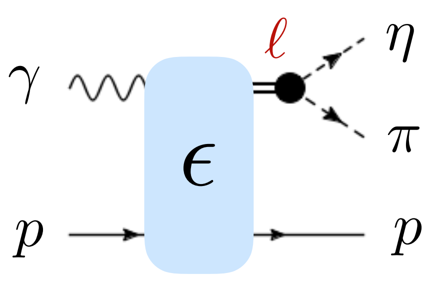
Beam asymmetry sensitive to reflection through the reaction plane

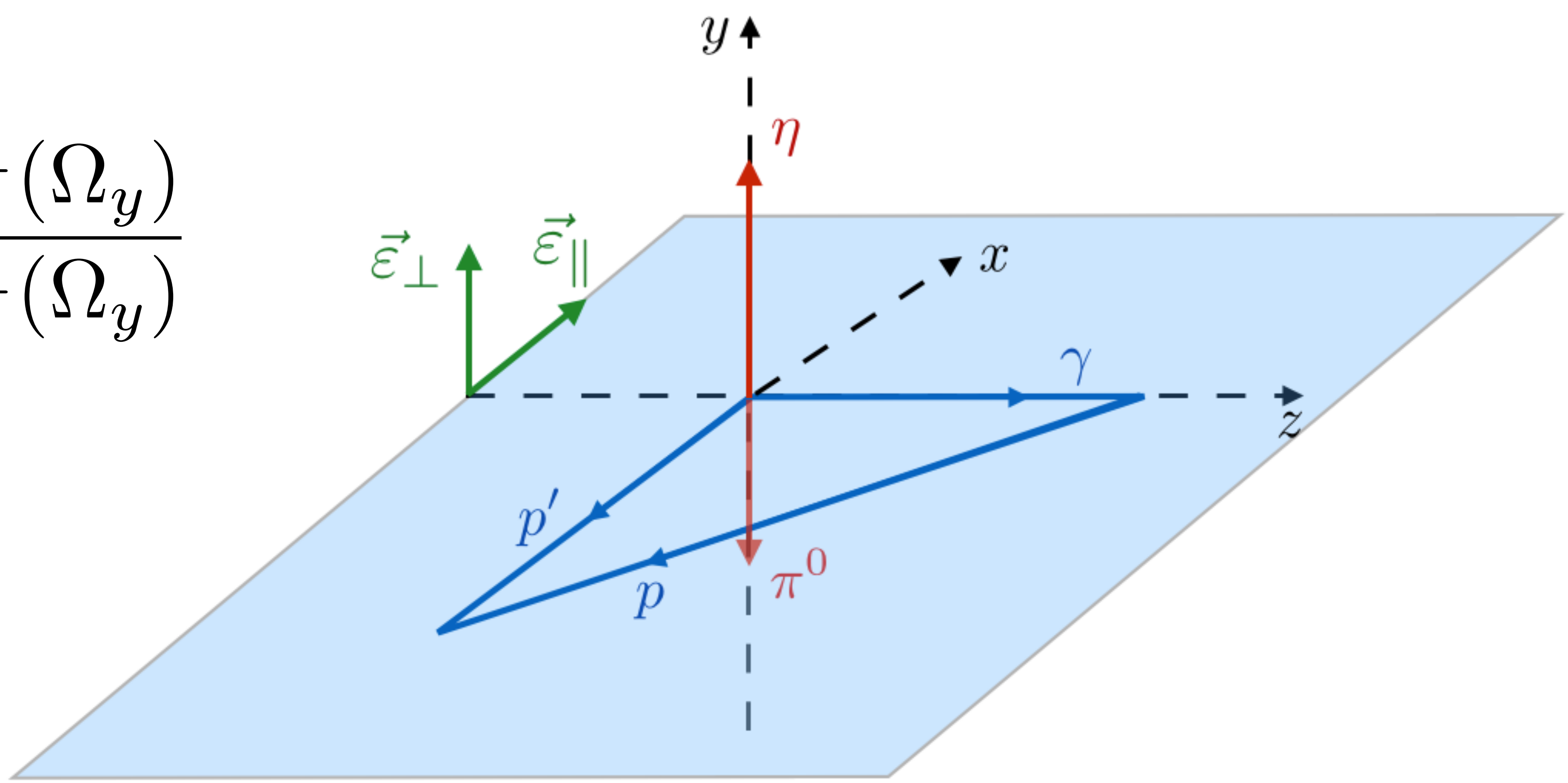
use reflection operator = parity followed by 180° rotation around Y-axis

Beam Asymmetries

$$\Sigma_y = \frac{1}{P_\gamma} \frac{I^{\parallel}(\Omega_y) - I^{\perp}(\Omega_y)}{I^{\parallel}(\Omega_y) + I^{\perp}(\Omega_y)}$$

amplitude:
production x decay





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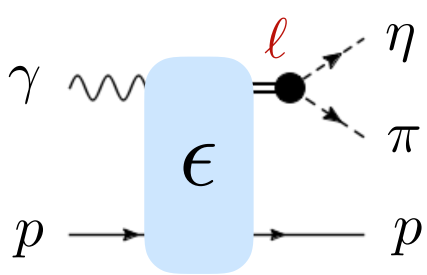
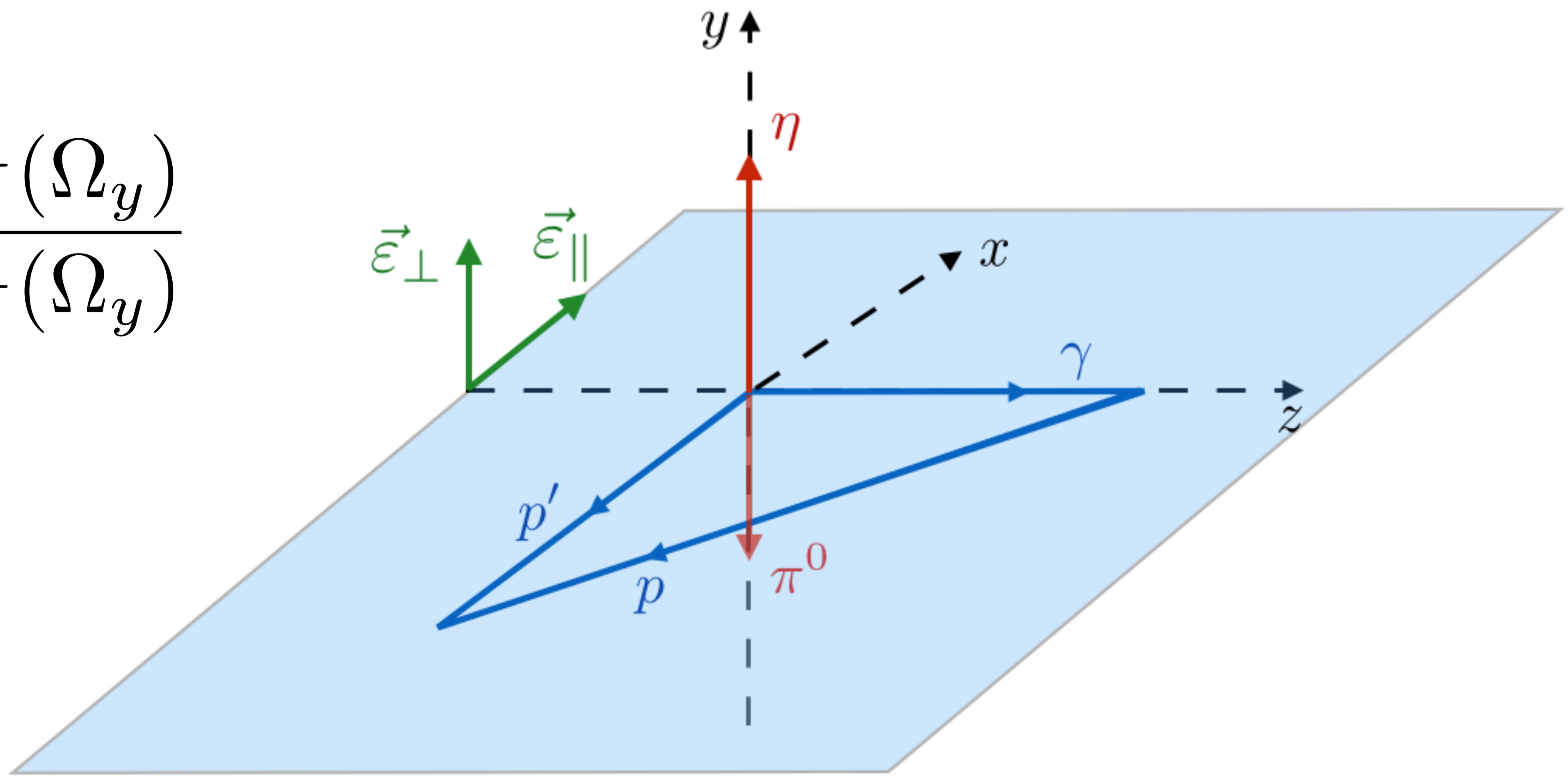
Beam Asymmetries

$$\Sigma_y = \frac{1}{P_\gamma} \frac{I^{\parallel}(\Omega_y) - I^{\perp}(\Omega_y)}{I^{\parallel}(\Omega_y) + I^{\perp}(\Omega_y)}$$

amplitude:
production x decay





Beam asymmetry sensitive to reflection through the reaction plane

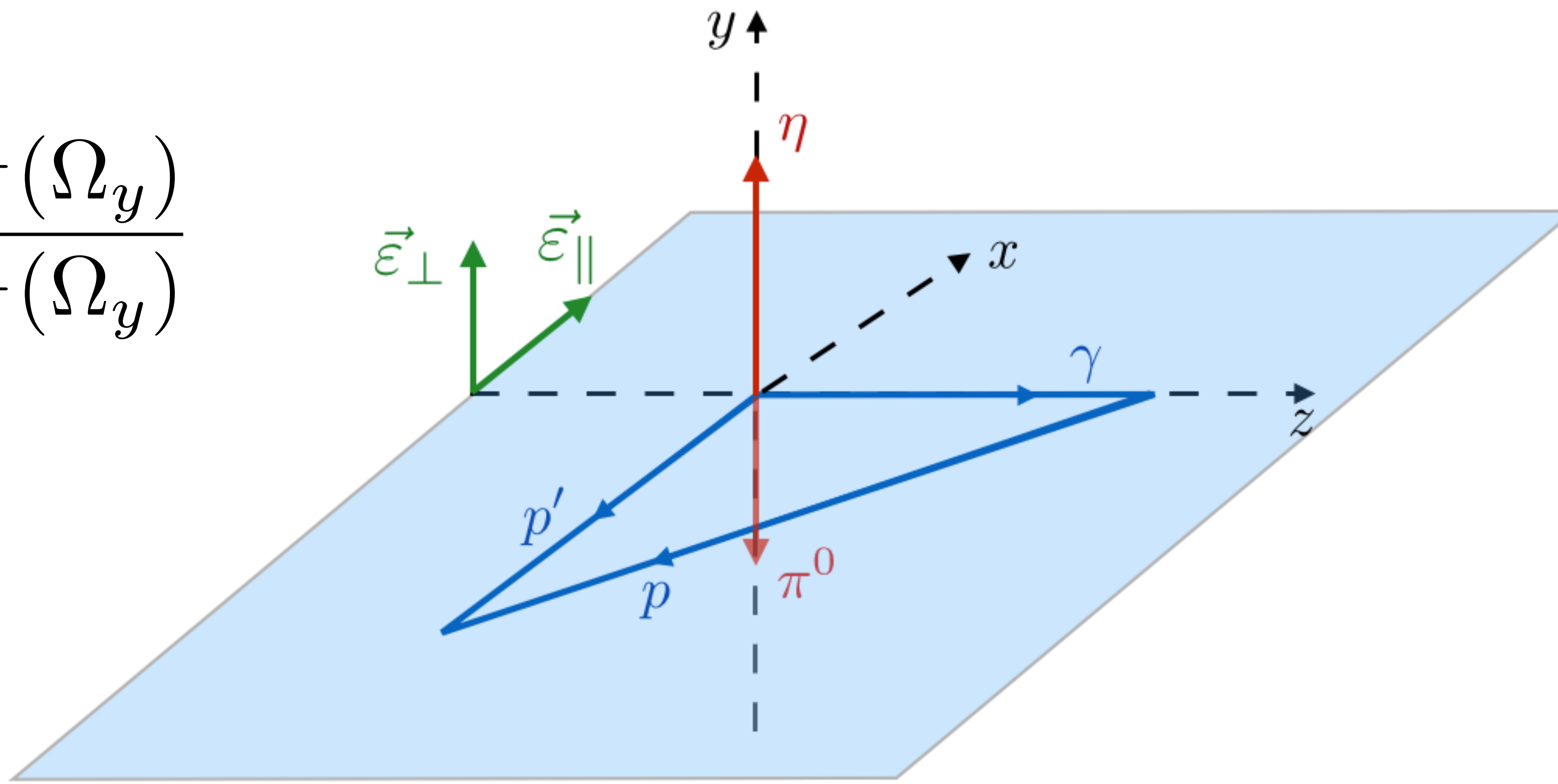
use reflection operator = parity followed by 180° rotation around Y-axis

$$[\ell]_m^{(\epsilon)} \longrightarrow \Sigma_y = \epsilon(-1)^\ell$$

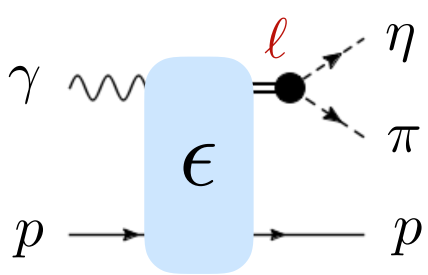
Odd waves change sign!!!

Beam Asymmetries

$$\Sigma_y = \frac{1}{P_\gamma} \frac{I^{\parallel}(\Omega_y) - I^{\perp}(\Omega_y)}{I^{\parallel}(\Omega_y) + I^{\perp}(\Omega_y)}$$



amplitude:
production x decay



Beam asymmetry sensitive to reflection through the reaction plane

use reflection operator = parity followed by 180° rotation around Y-axis

$$[\ell]_m^{(\epsilon)} \longrightarrow \Sigma_y = \epsilon(-1)^\ell$$

Odd waves change sign!!!

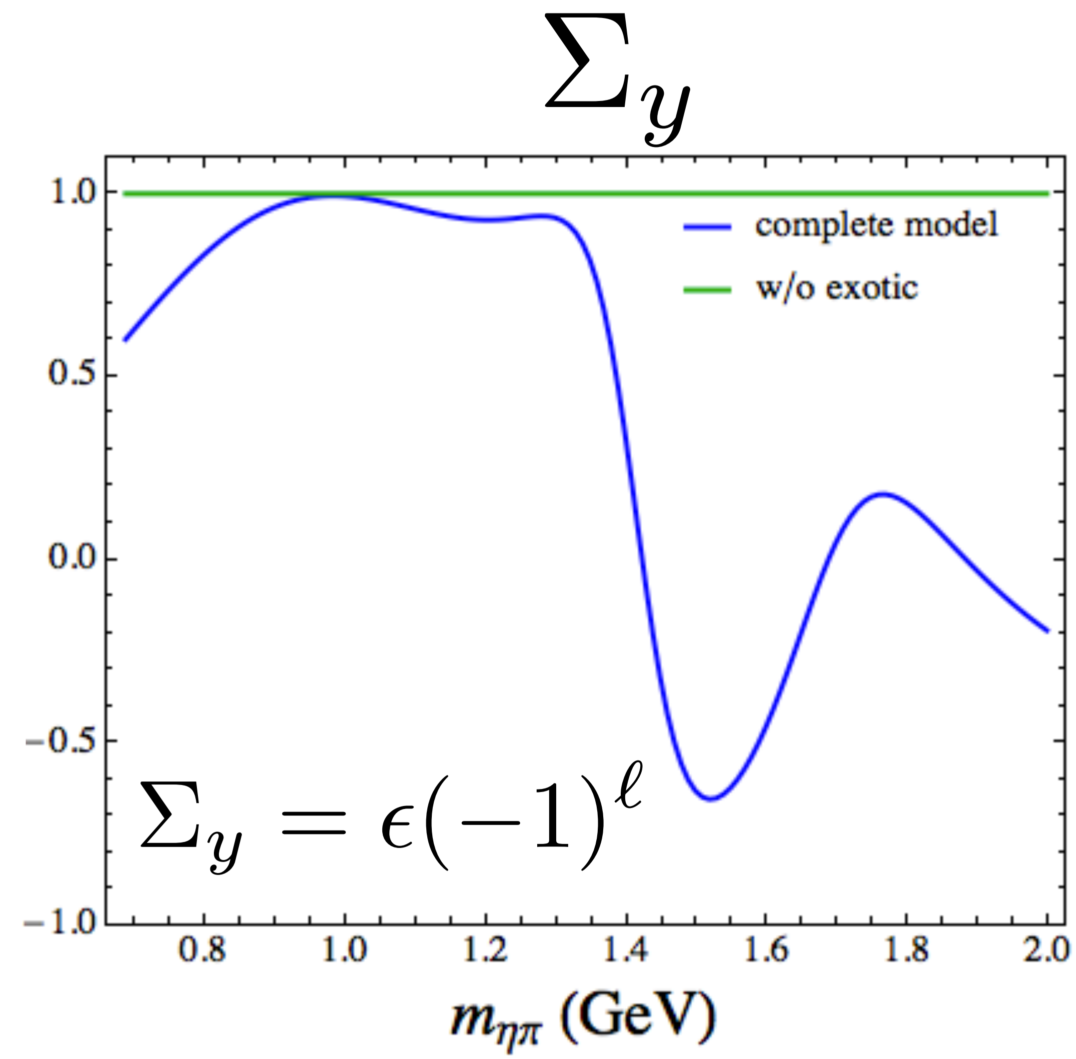
For $\pi^0\pi^0, \eta\eta$ **Only even waves** $\longrightarrow \Sigma_y = \epsilon$

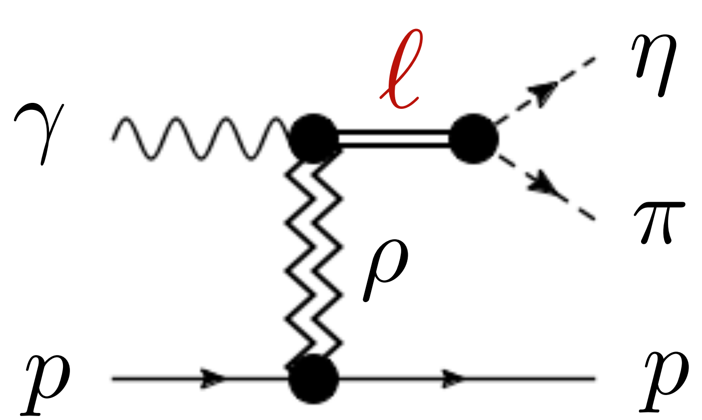
Beam Asymmetries

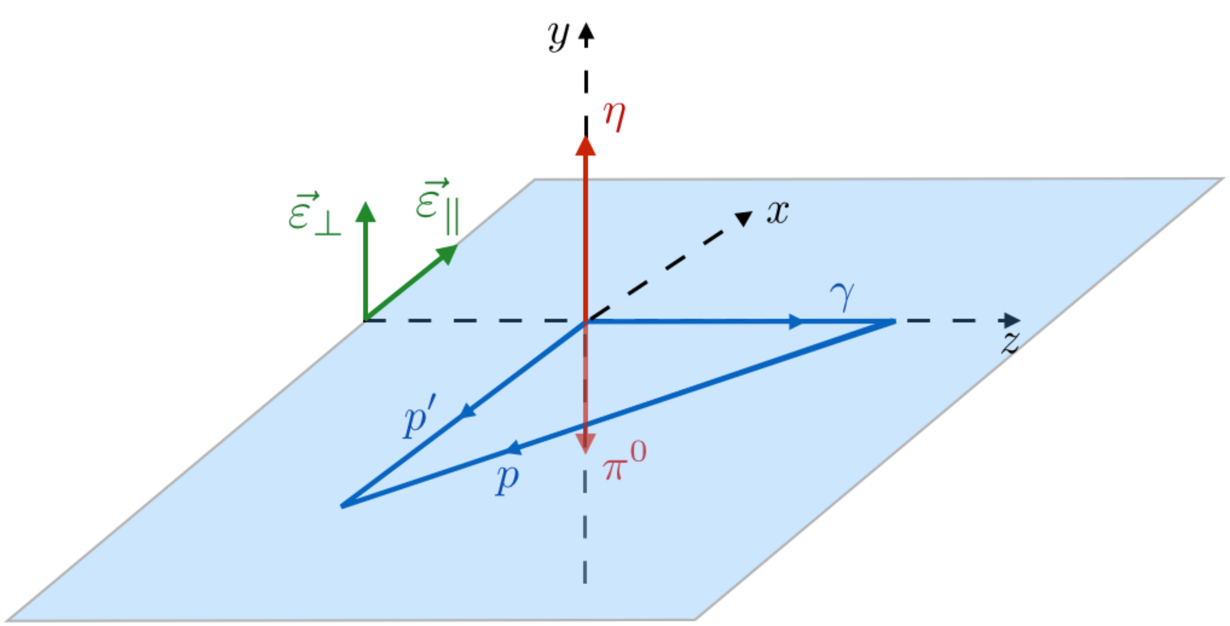
$$\Sigma_y = \frac{1}{P_\gamma} \frac{I(\Omega_y, 0) - I(\Omega_y, \frac{\pi}{2})}{I(\Omega_y, 0) + I(\Omega_y, \frac{\pi}{2})} = -\frac{I^1(\Omega_y)}{I^0(\Omega_y)}$$

Intensities can be computed from moments:

$$I^0(\Omega_y) = H^0(00) - \frac{5}{2} H^0(20) - 5\sqrt{\frac{3}{2}} H^0(22) + \frac{27}{8} H^0(40) + \frac{9}{2}\sqrt{\frac{5}{2}} H^0(42) + \frac{9}{4}\sqrt{\frac{35}{2}} H^0(44)$$





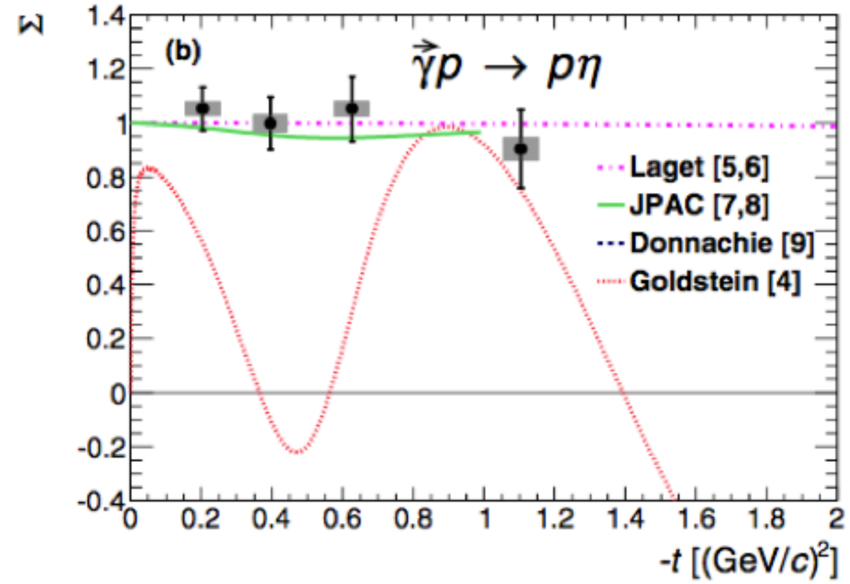


Conclusion

Single Meson Photoproduction:

$$\vec{\gamma}p \to \pi^0 p$$
$$\vec{\gamma}p \to \eta p$$

Dominance of natural exchanges in both π^0/η photoproduction

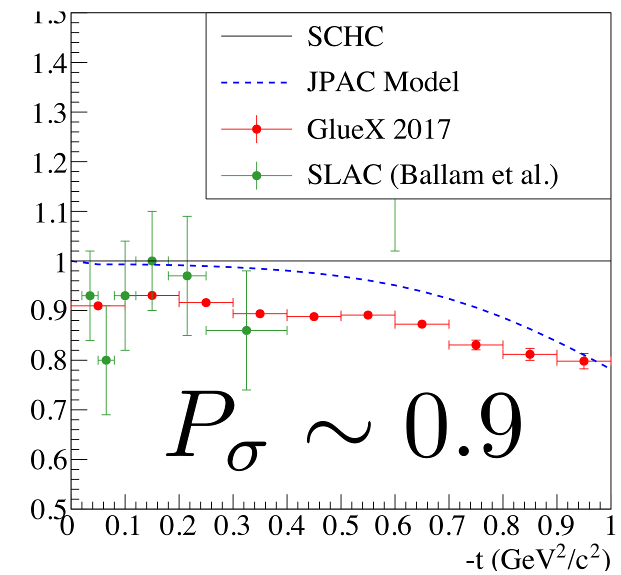


Vector Meson Photoproduction:

$$\vec{\gamma}p \to \rho^0 p$$
$$\vec{\gamma}p \to \omega p$$
$$\vec{\gamma}p \to \phi p$$

Consistent with factorization

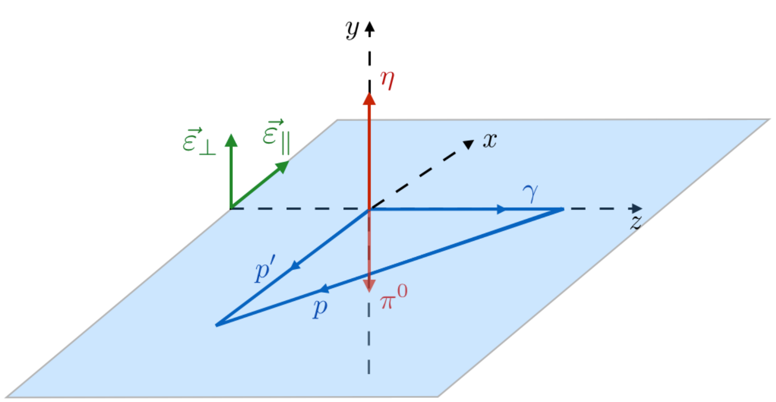
Dominance of natural exchanges

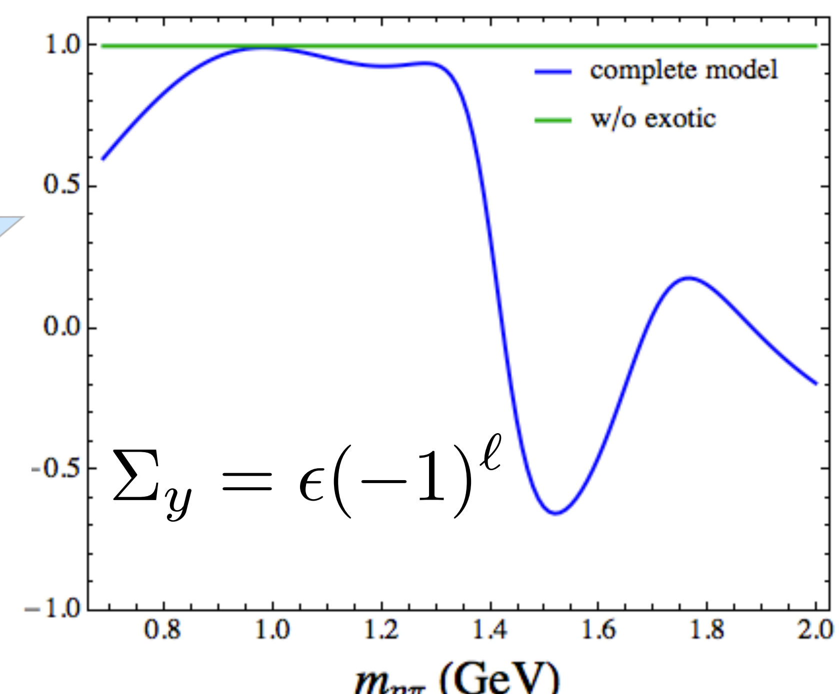


Double Mesons Photoproduction:

$$\vec{\gamma}p \to \pi^0 \eta p$$

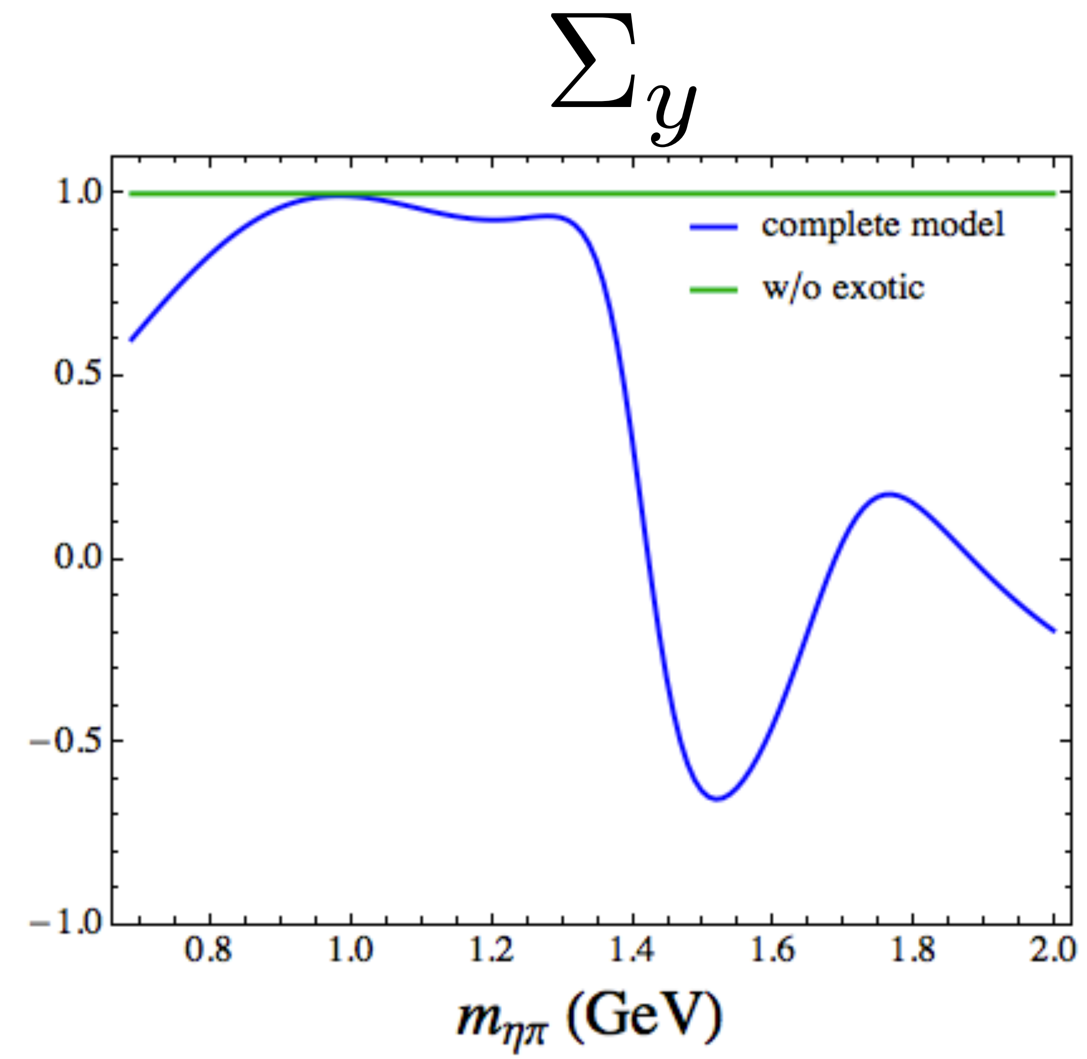
New observable sensitive to exotic production

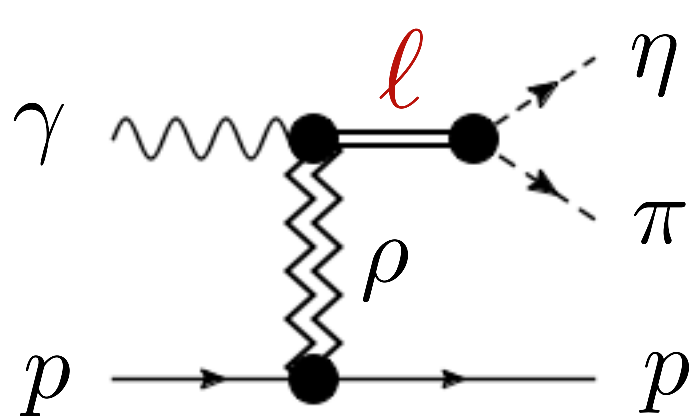


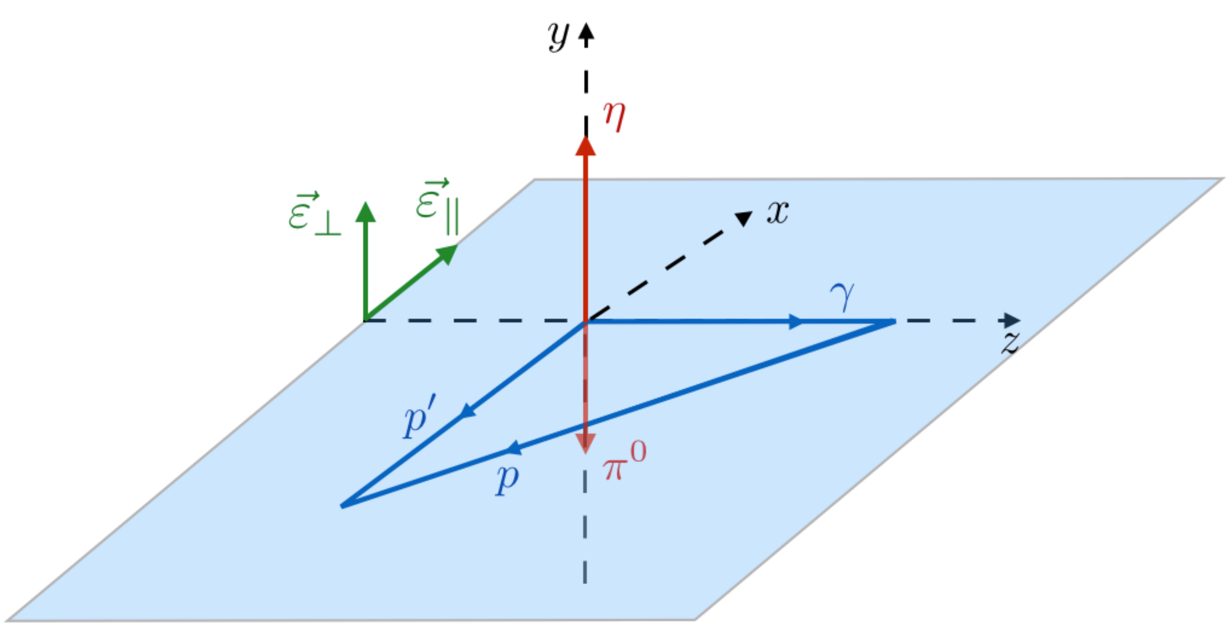


Backup Slides

Beam Asymmetries

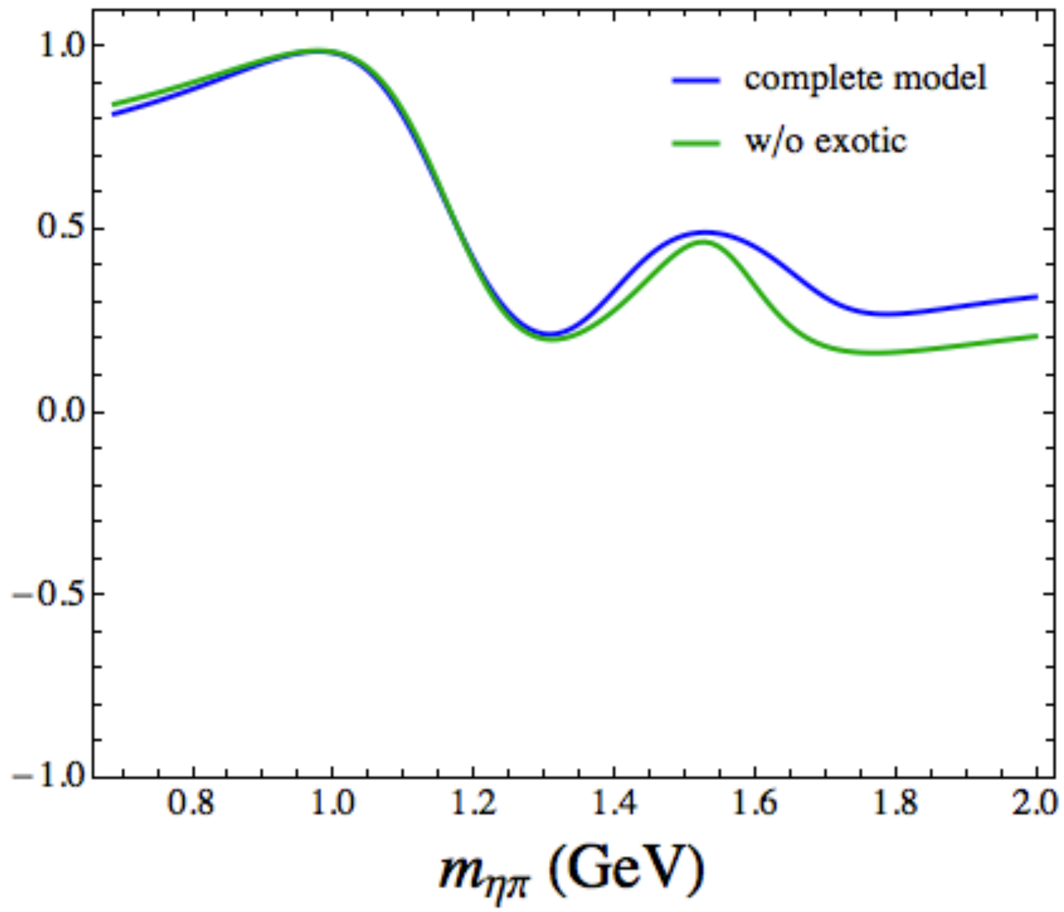




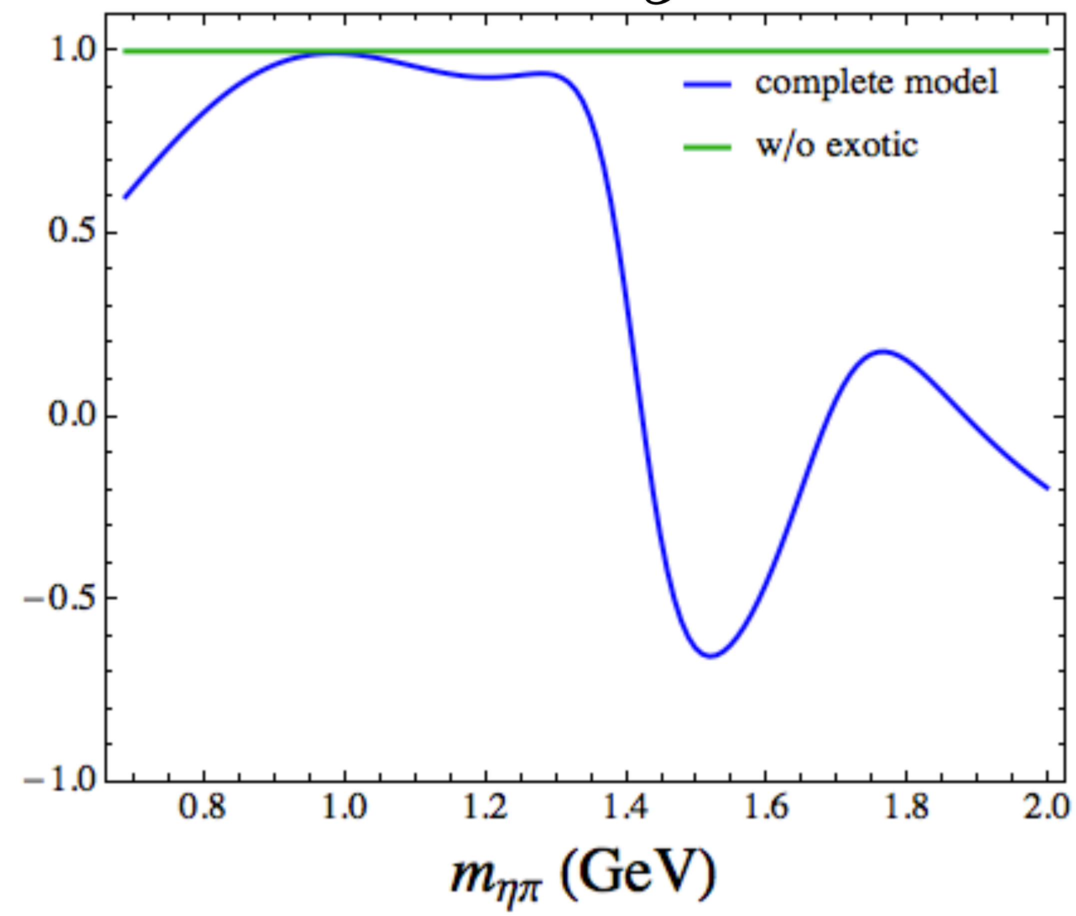


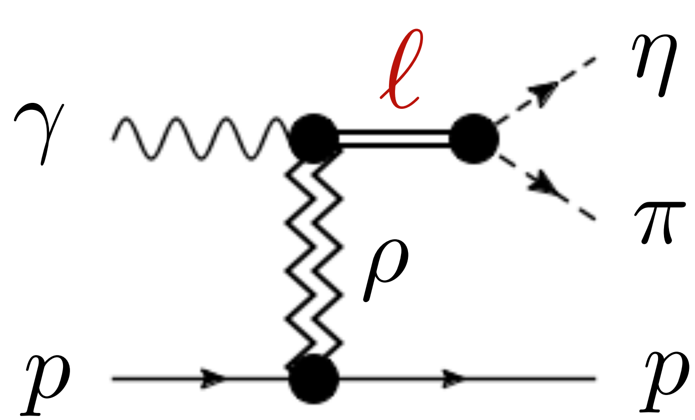
Beam Asymmetries

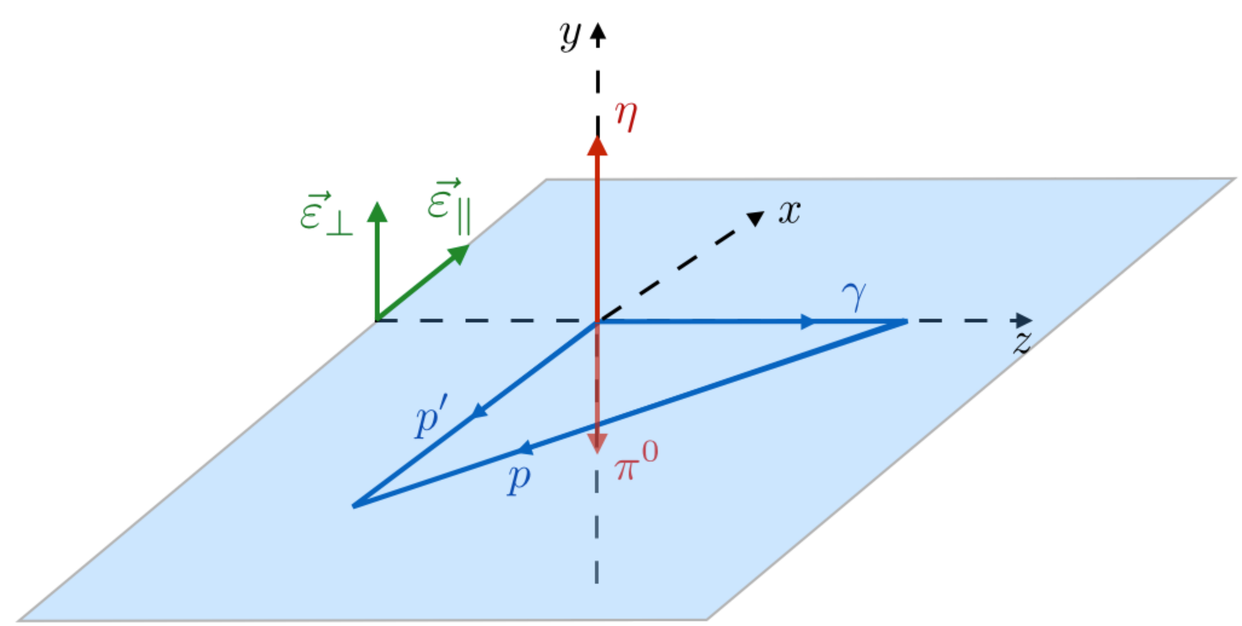
$\Sigma_{4\pi}$



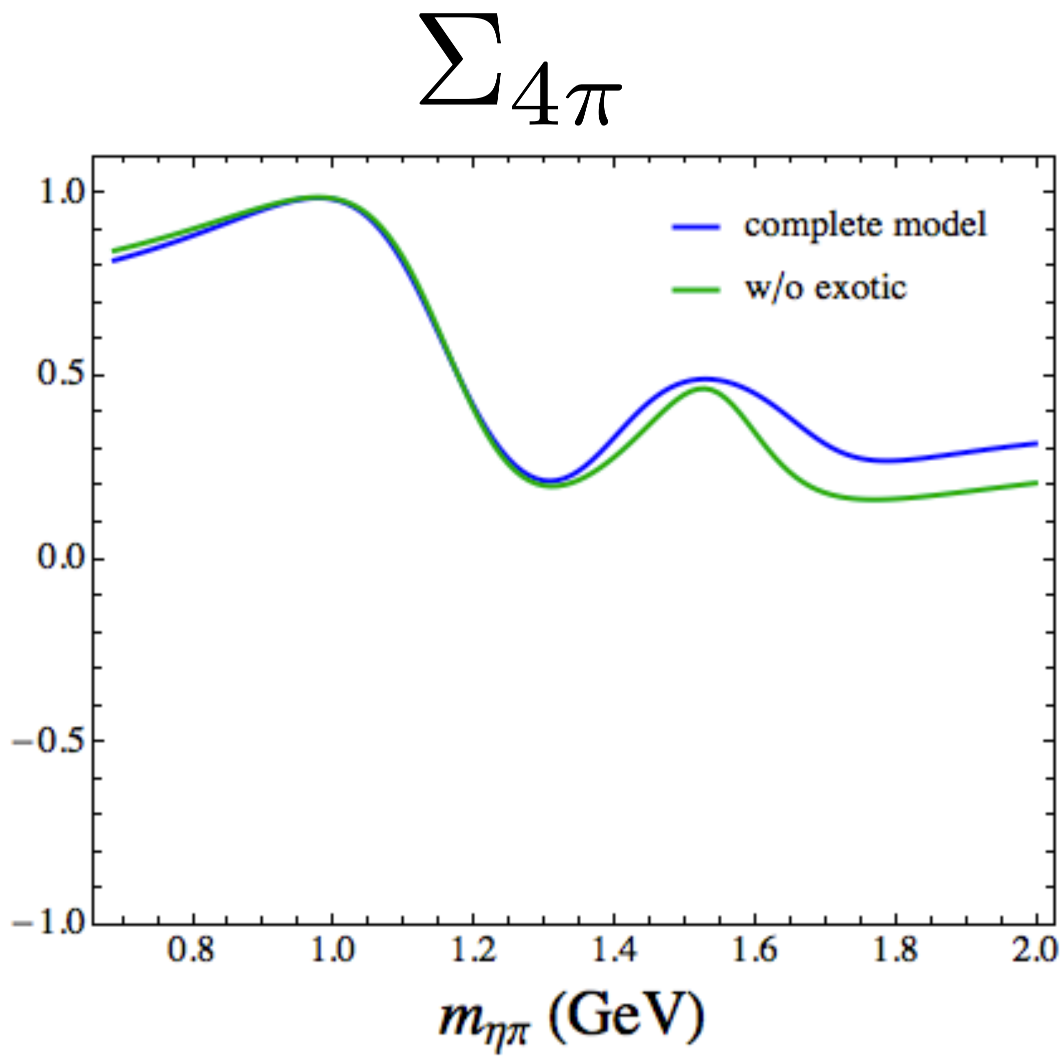
Σ_y

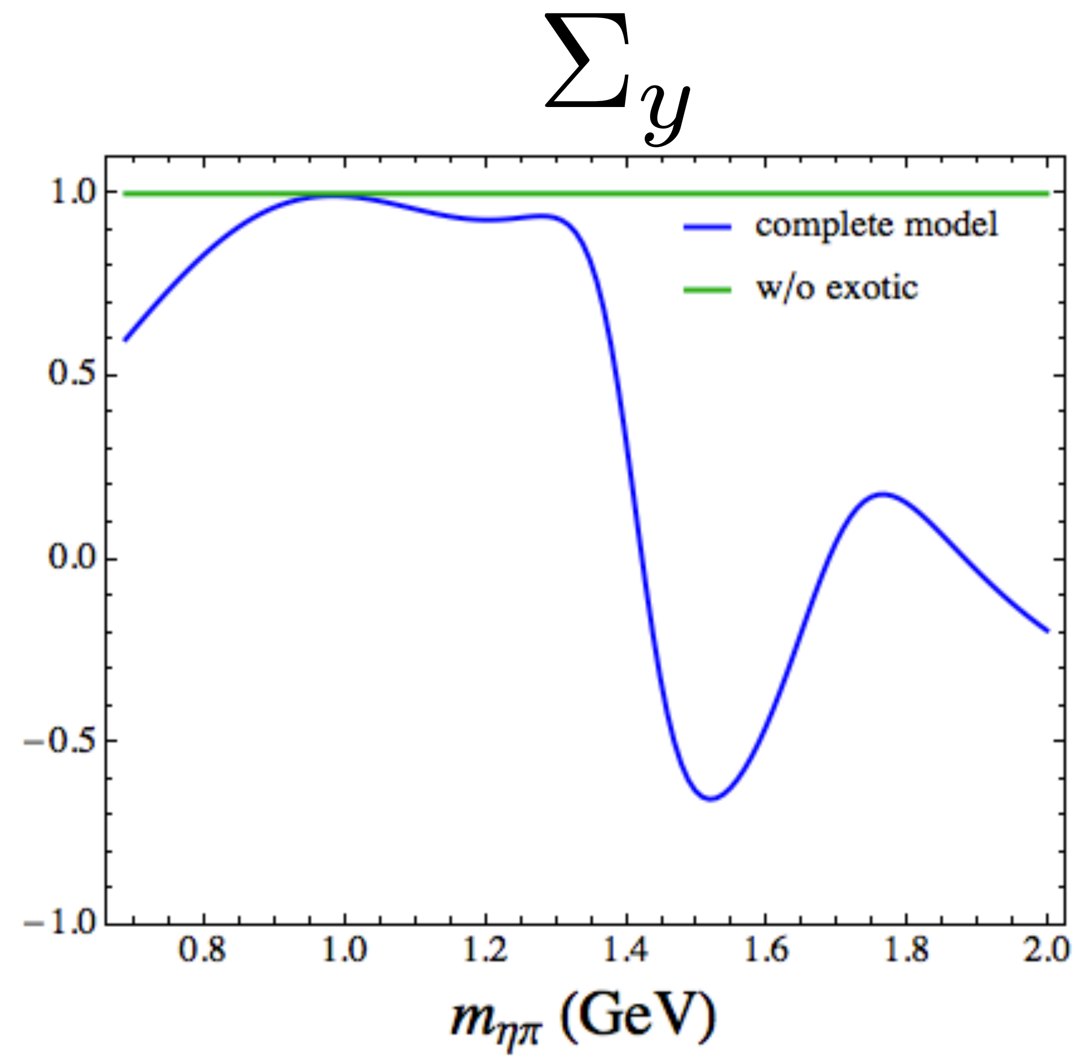


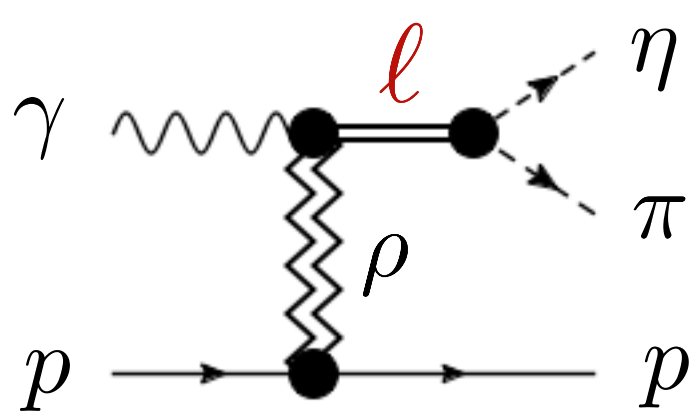




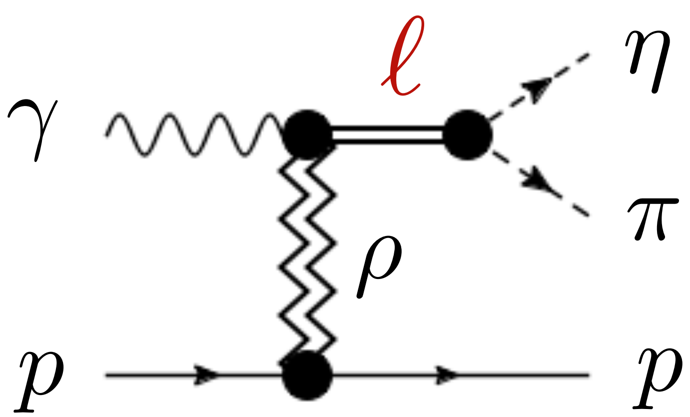
Beam Asymmetries







Model



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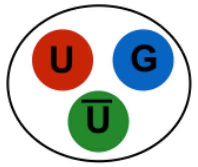

production: natural exchanges

line shape: Breit-Wigner form

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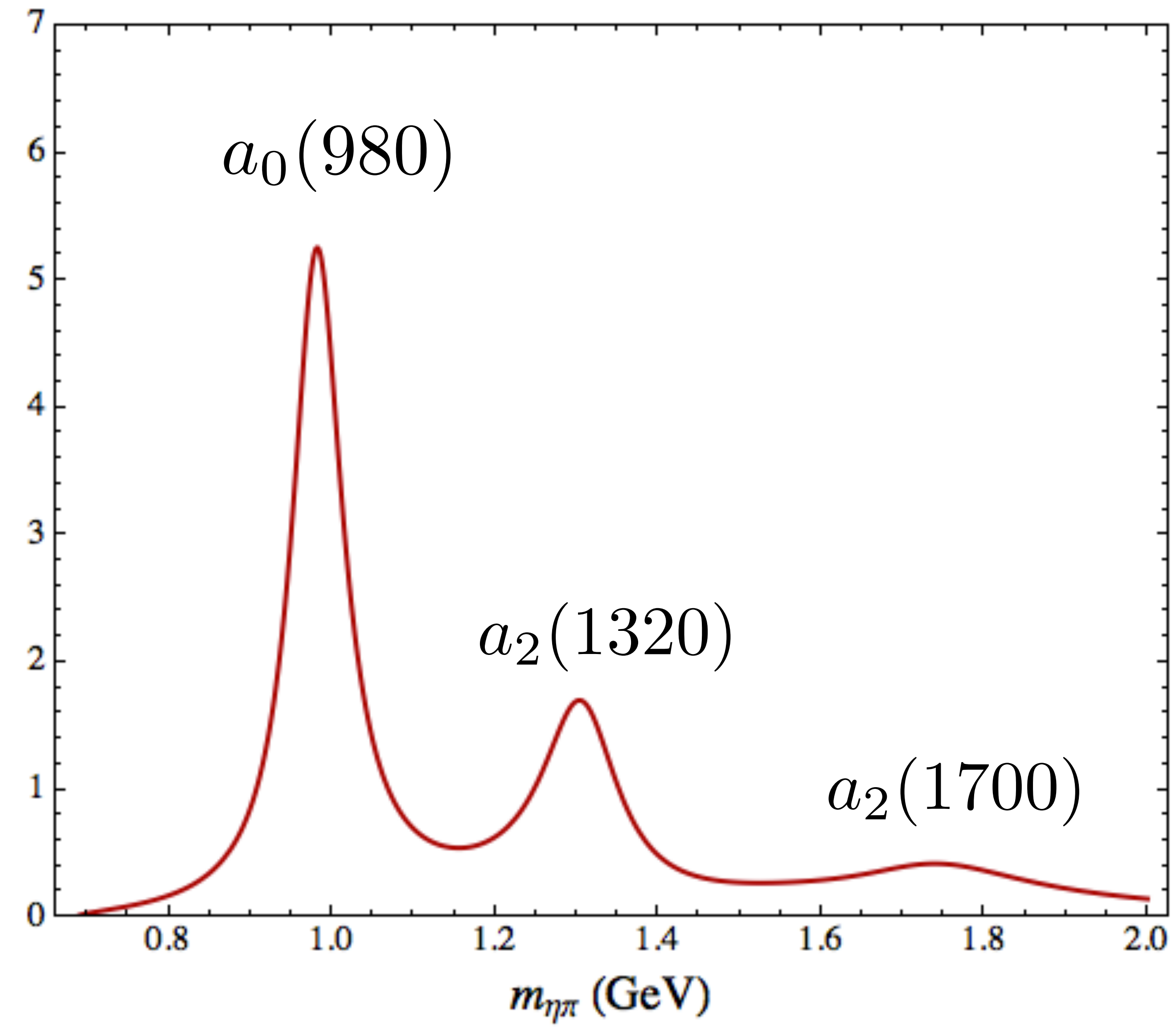
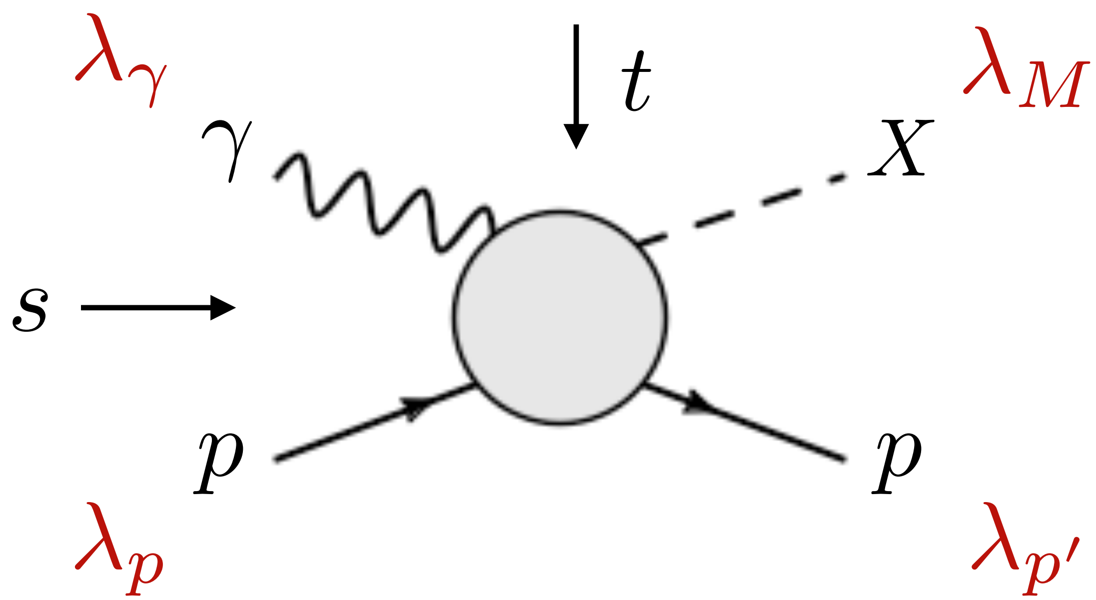
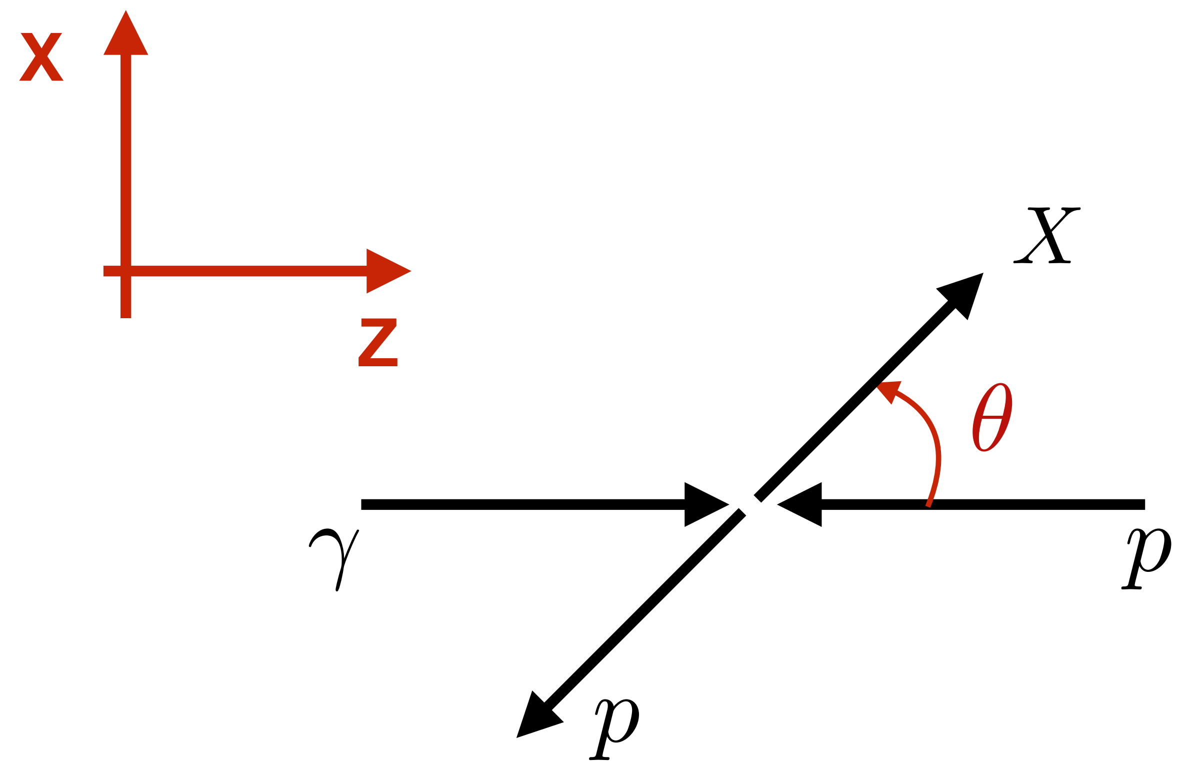


VM et al (JPAC), in preparation

Kinematics





$$A^{\lambda_\gamma \lambda_M}_{\lambda_p \lambda_{p'}}(s,t)$$

$\lambda_i =$ **s-channel helicity of particle i**

$t =$ **momentum transfered squared**

$s =$ **center of mass energy squared**

High energy approximation

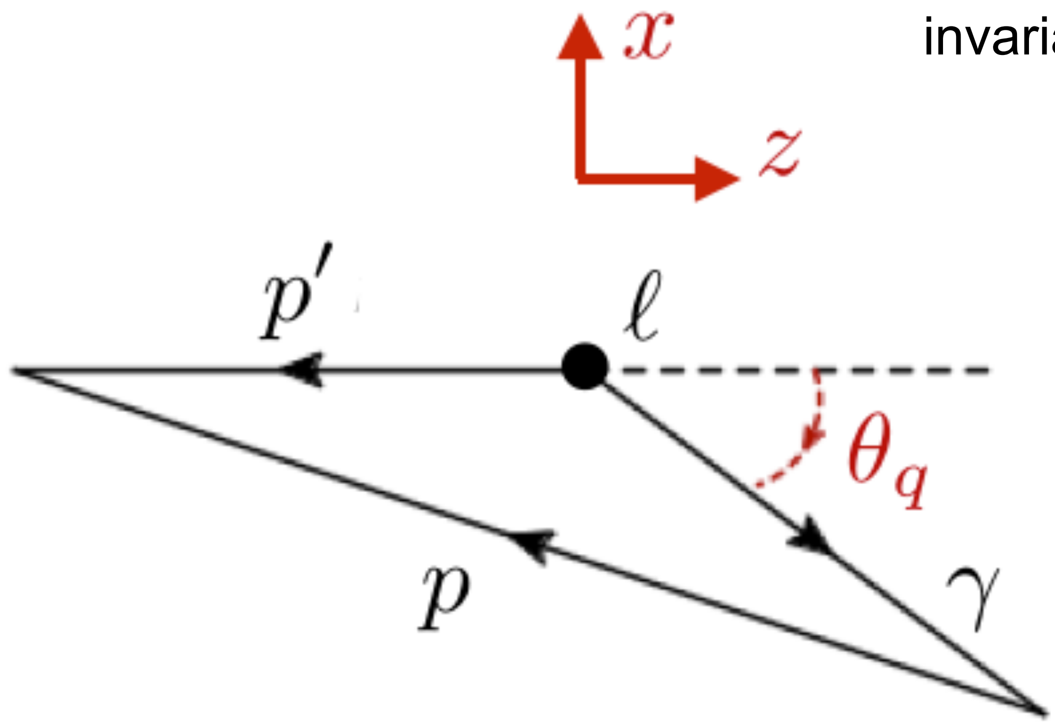
$$\cos\theta \to 1 + \frac{2t}{s}$$

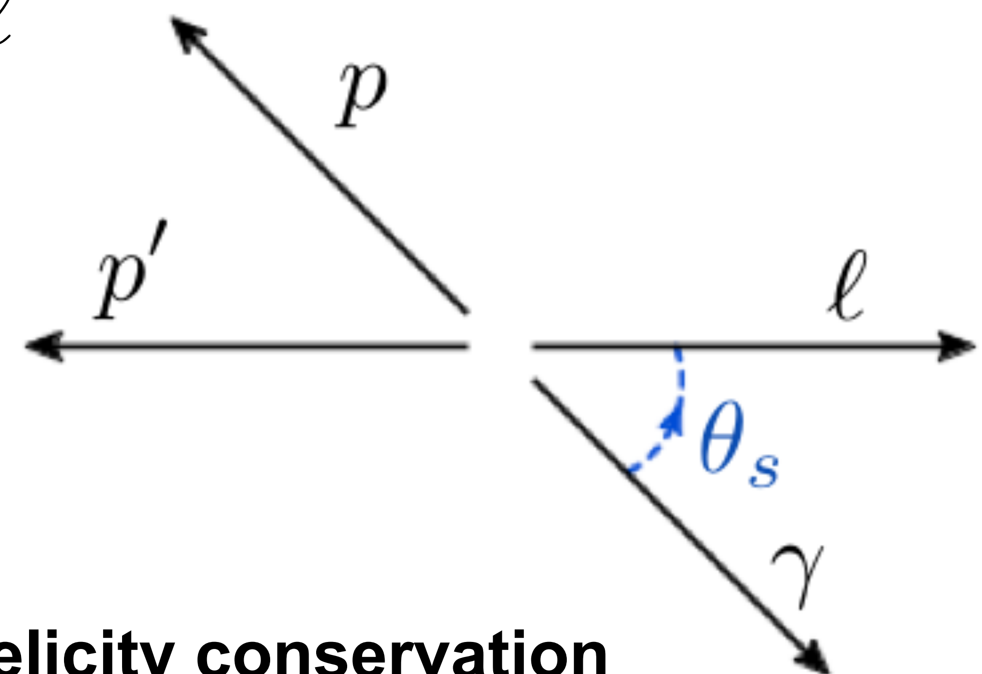
$$\sin\theta \to 2\sqrt{-t/s}$$

$$\sin\theta/2 \to \sqrt{-t/s}$$

Frame

Helicity frame — **boost** → invariant helicity ℓ — **s-channel**

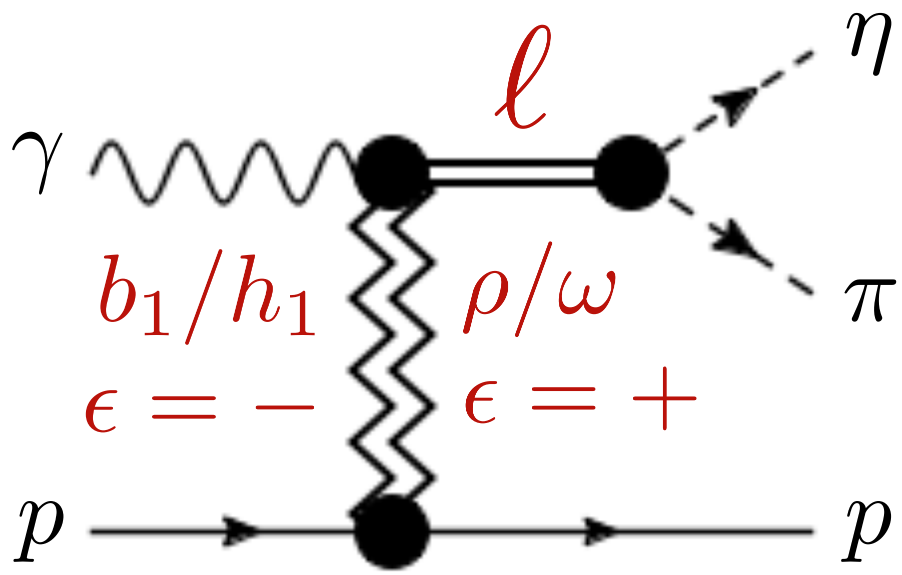




helicity conservation

between γ **and** ℓ

$$T_{\lambda_\gamma m} \simeq \delta_{\lambda_\gamma, m} T_{\lambda_\gamma m} + \dots$$

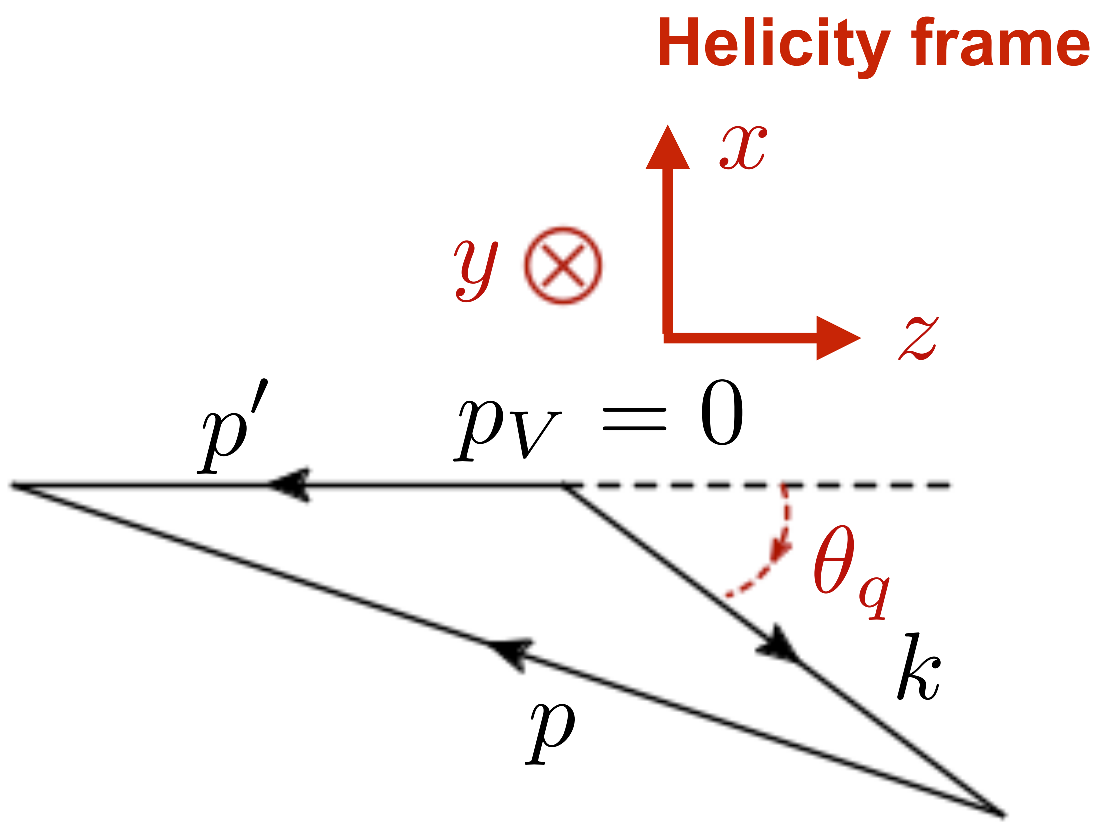


Reflectivity basis:

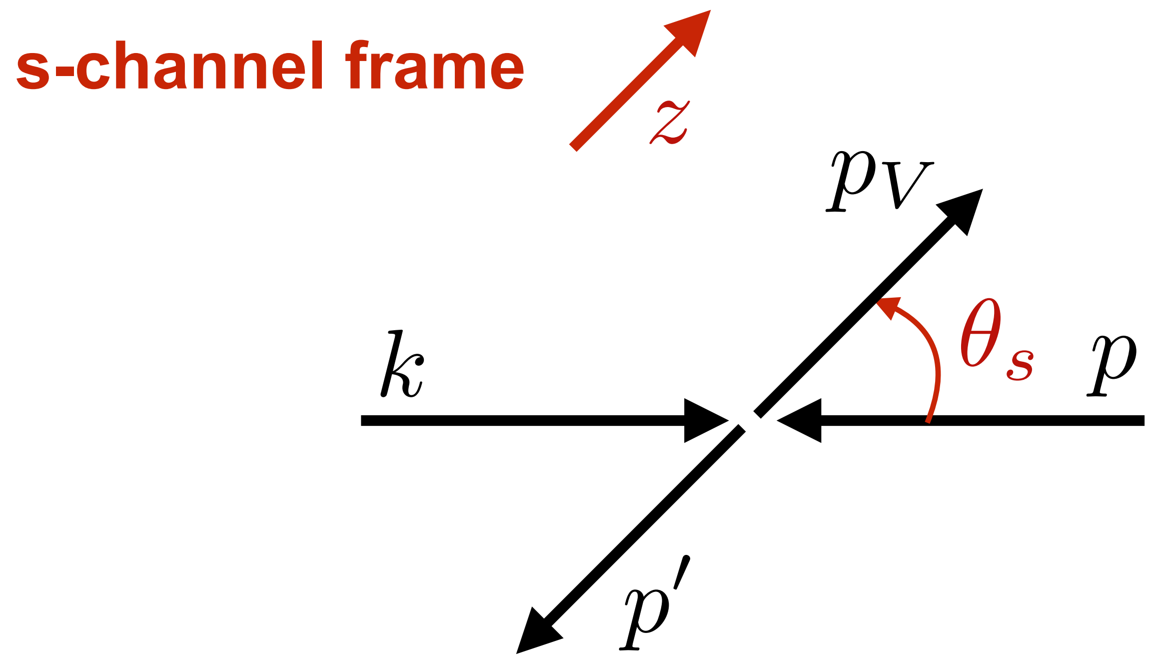
$$[\ell]_m^{(\epsilon)} = T_{1m} - \epsilon\, T_{-1-m}$$

Dominant: $(\epsilon = +, m = 1)$

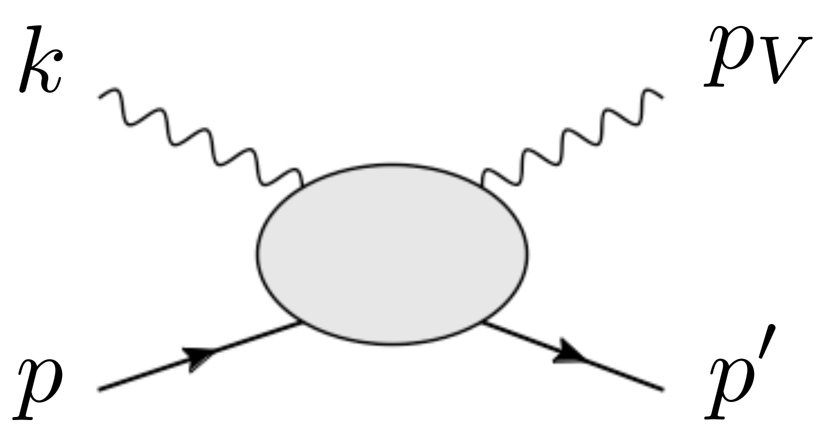
Frames



Helicity frame
x
y
z
p′
p_V = 0
θ_q
k
p

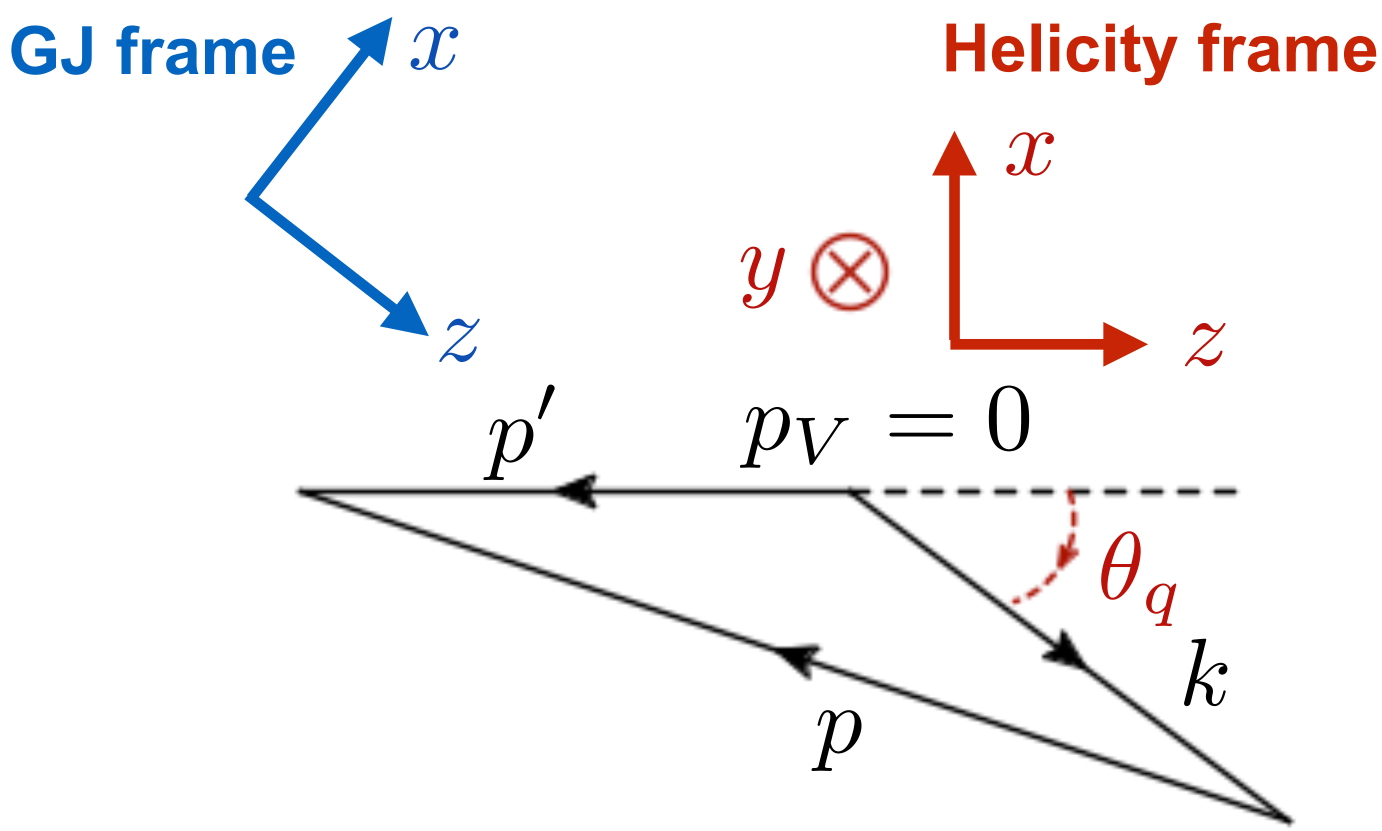


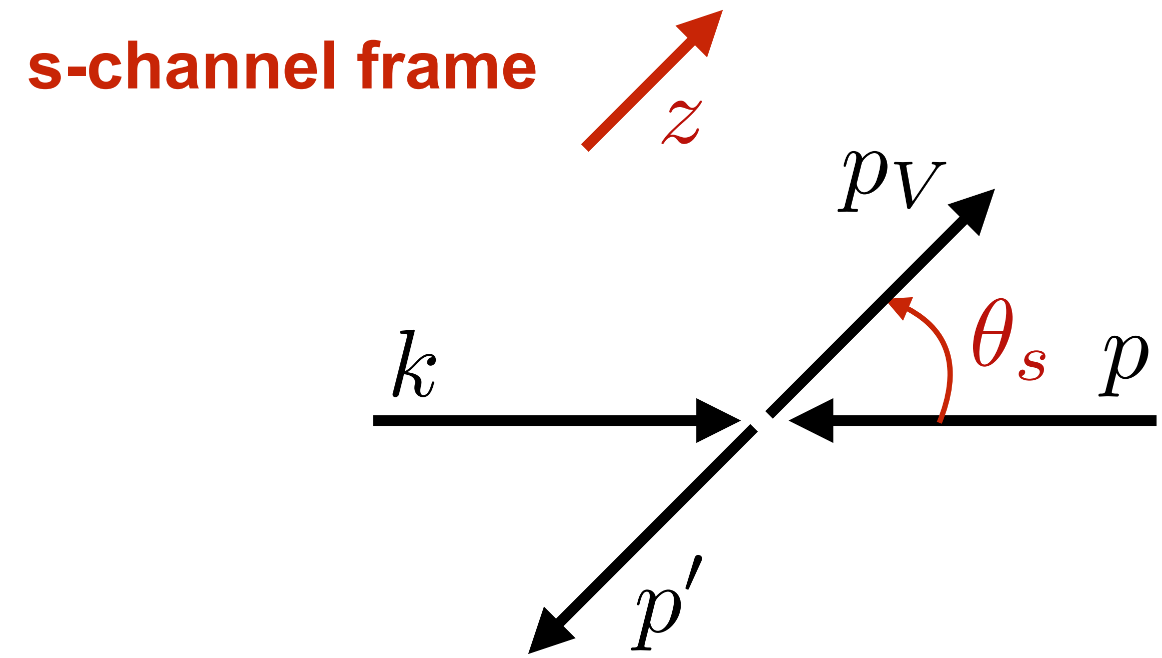
s-channel frame
z
p_V
θ_s
k
p
p′

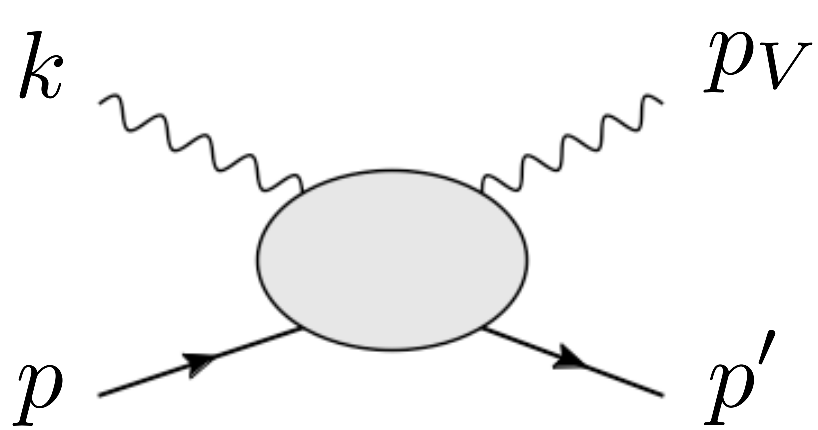


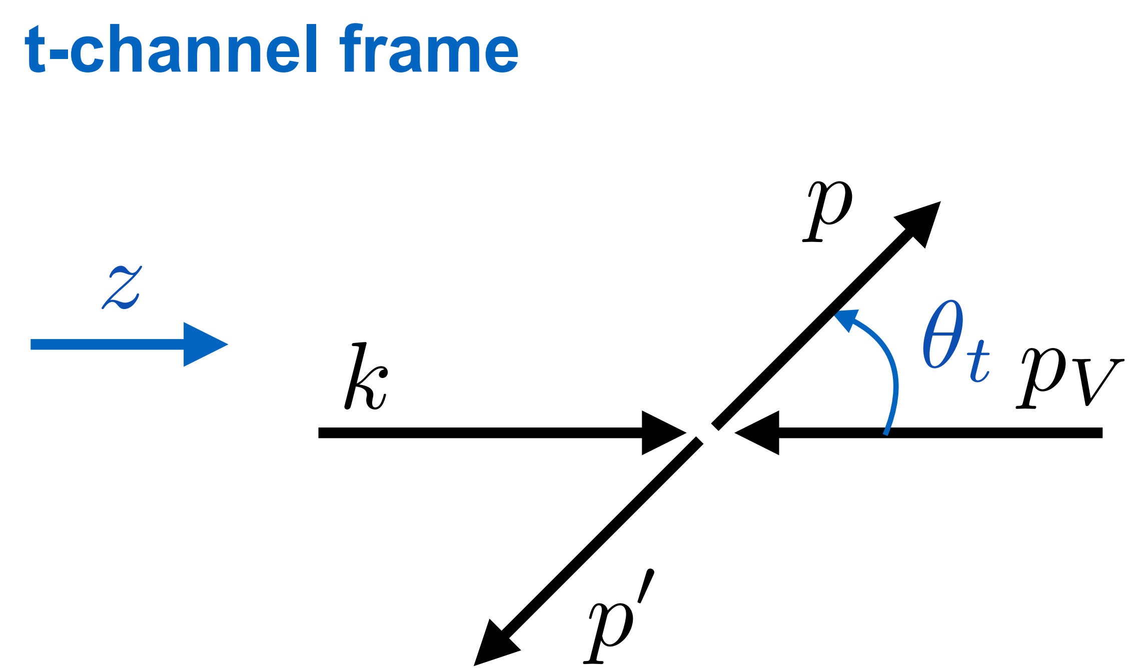
k
p_V
p
p′

Frames

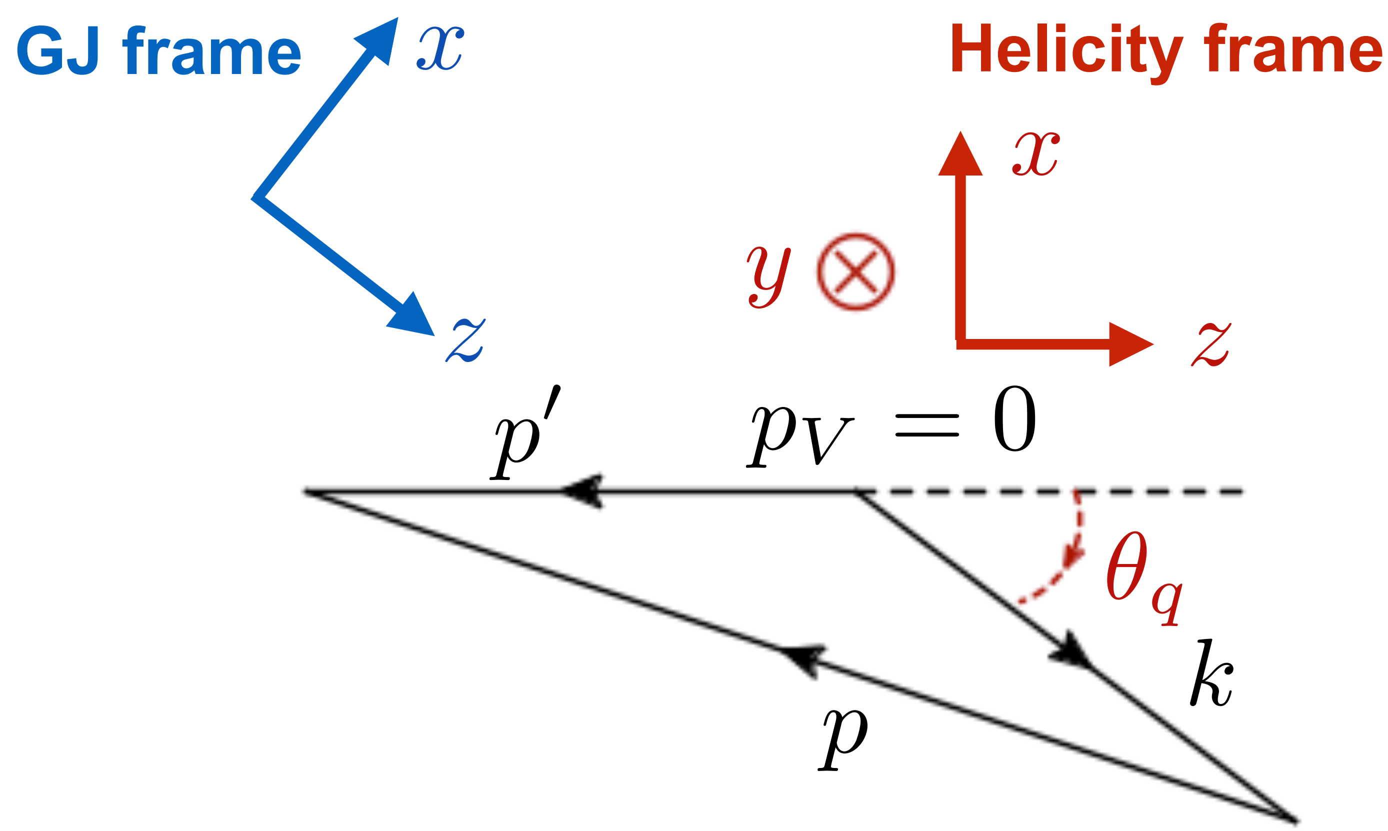

GJ frame
x
z
Helicity frame
x
y
z
p′
$p_V = 0$
θ_q
k
p

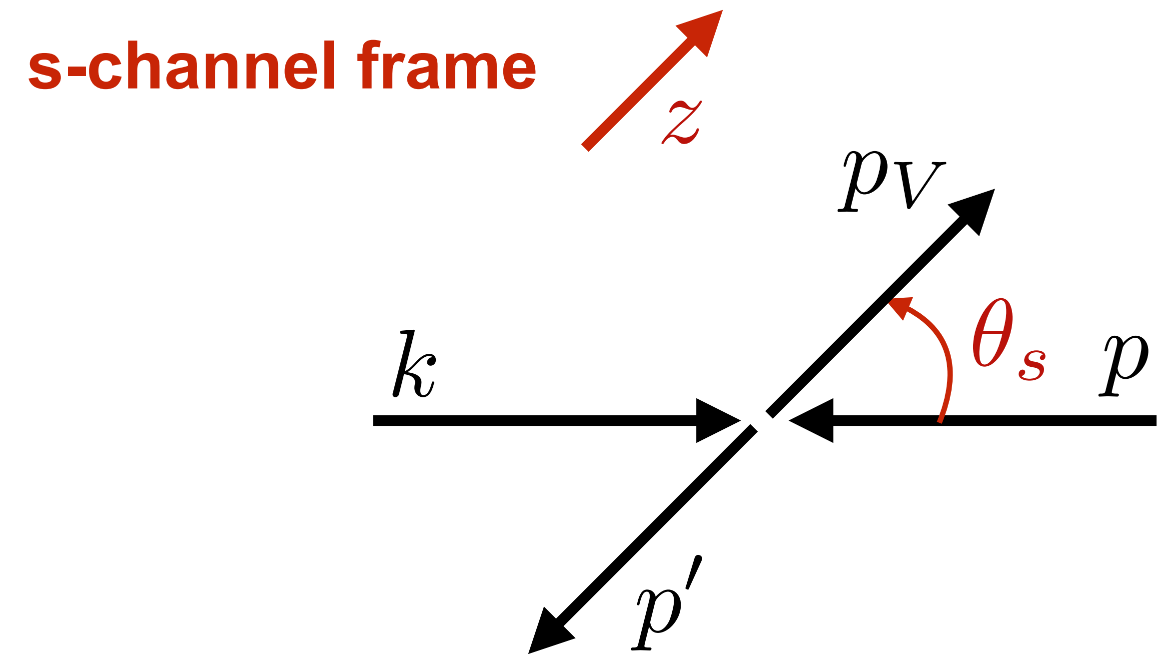

s-channel frame
z
p_V
k
θ_s
p
p′


k
p_V
p
p′


t-channel frame
z
p
k
θ_t
p_V
p′

Frames

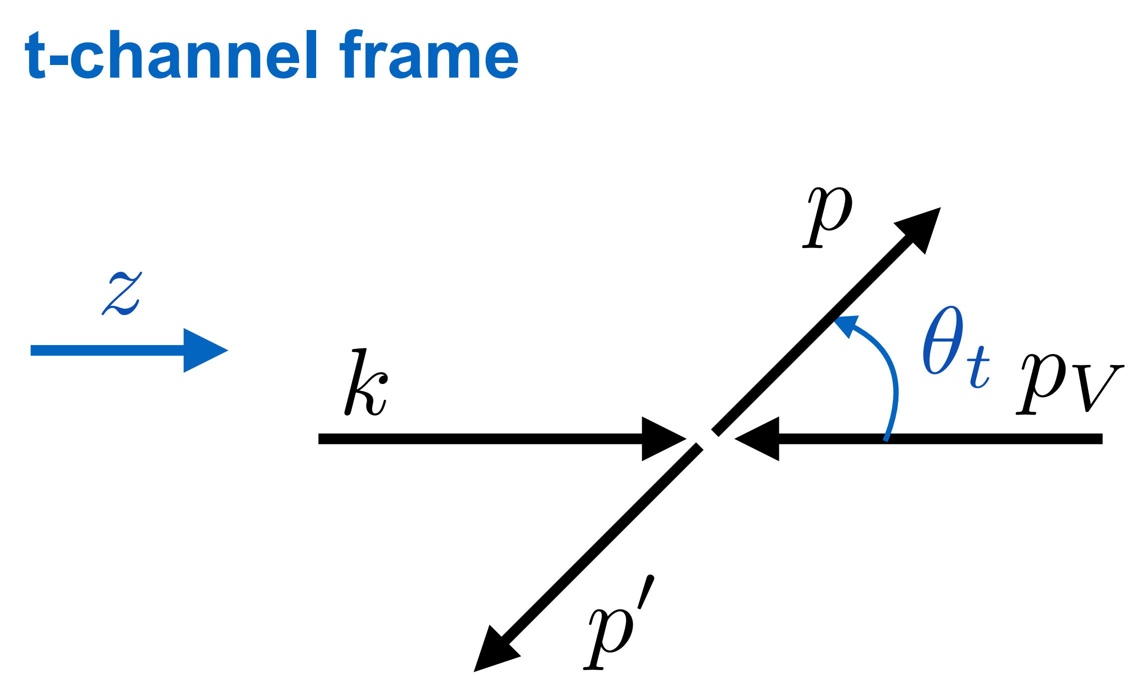




$$\rho_{MM'}\big|_H = \rho_{MM'}\big|_{s\text{-chan}}$$

rotation

$$\rho_{MM'}\big|_{GJ} = \rho_{MM'}\big|_{t\text{-chan}}$$



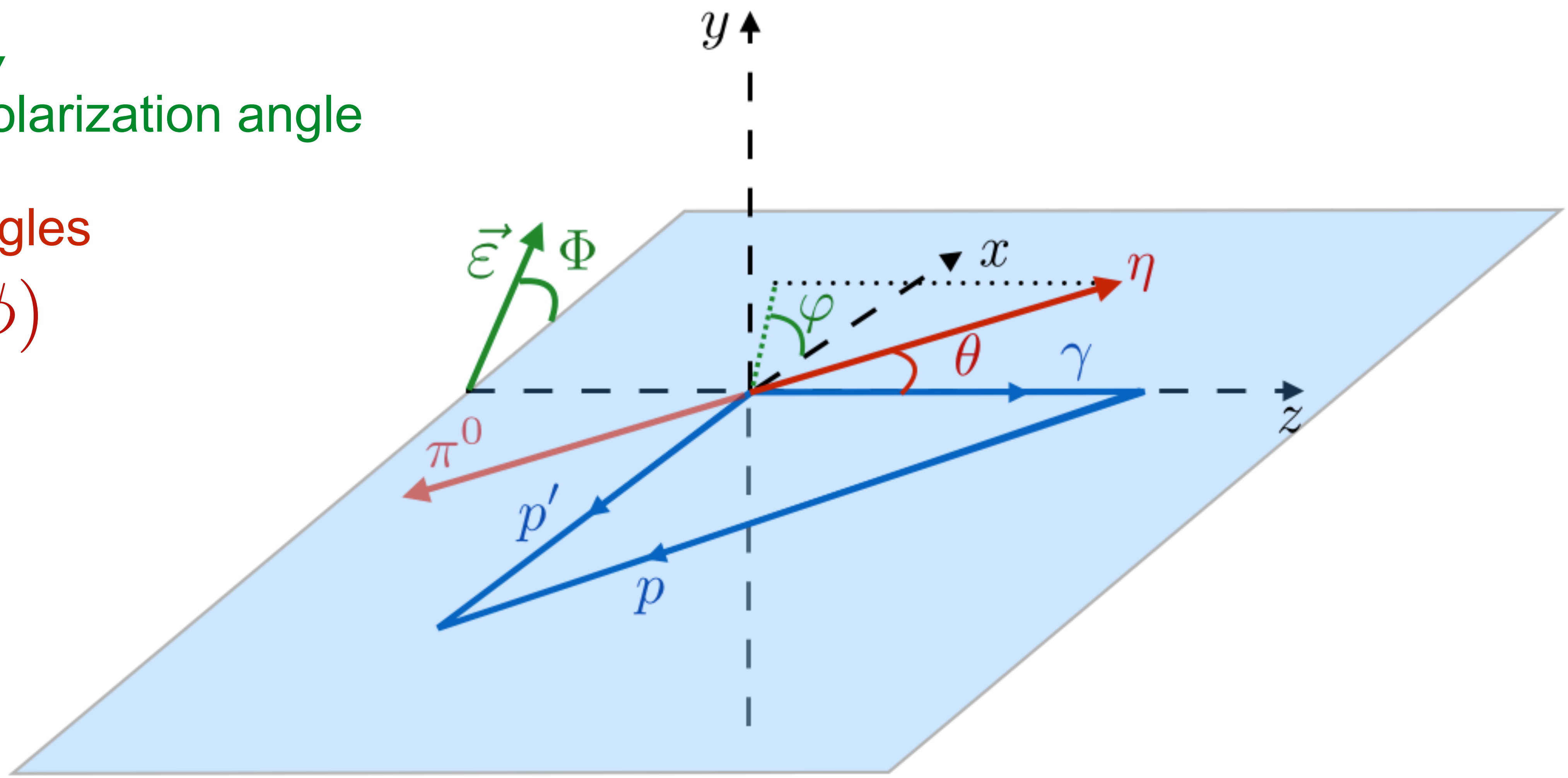
Measured Intensities

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

polarization angle

η decay angles

$\Omega = (\theta, \phi)$

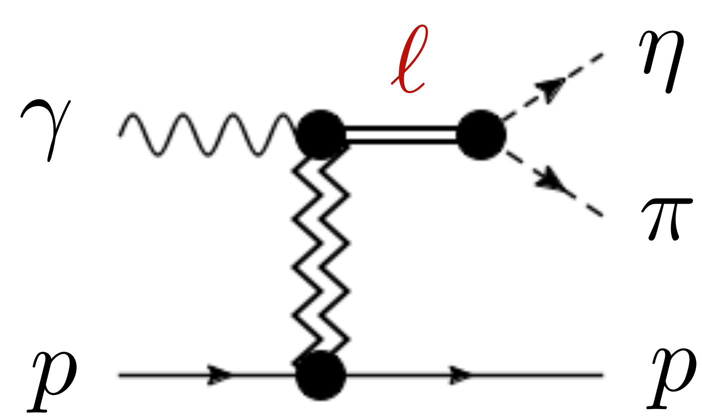


Implicit variables

Beam energy (fixed)

momentum transfer (integrated)

$\eta\pi$ invariant mass (binned)



Spin Density Matrix Elements

$$\rho^0_{00} = \frac{2}{N} \sum_{\lambda,\lambda'} \left| T_{\substack{1,0 \\ \lambda,\lambda'}} \right|^2$$

$$N = \sum_{\lambda,\lambda',\lambda_\gamma,\lambda_V} \left| T_{\substack{\lambda_\gamma,\lambda_V \\ \lambda,\lambda'}} \right|^2$$

$$\text{Re } \rho^0_{10} = \frac{1}{N} \text{Re } \sum_{\lambda,\lambda'} \left(T_{\substack{1,1 \\ \lambda,\lambda'}} - T_{\substack{1,-1 \\ \lambda,\lambda'}} \right) T^*_{\substack{1,0 \\ \lambda,\lambda'}}$$

$$\rho^1_{11} = \frac{2}{N} \text{Re } \sum_{\lambda,\lambda'} T_{\substack{-1,1 \\ \lambda,\lambda'}} T^*_{\substack{1,1 \\ \lambda,\lambda'}}$$

$$\rho^0_{1-1} = \frac{2}{N} \text{Re} \sum_{\lambda\lambda'} T_{\substack{1,1 \\ \lambda,\lambda'}} T^*_{\substack{1,-1 \\ \lambda,\lambda'}}$$

$$\rho^1_{00} = \frac{2}{N} \text{Re } \sum_{\lambda,\lambda'} T_{\substack{-1,0 \\ \lambda,\lambda'}} T^*_{\substack{1,0 \\ \lambda,\lambda'}}$$

$$\rho^1_{1-1} + \text{Im } \rho^2_{1-1} = \frac{2}{N} \sum_{\lambda,\lambda'} T_{\substack{-1,1 \\ \lambda,\lambda'}} T^*_{\substack{1,-1 \\ \lambda,\lambda'}}$$

$$\text{Re } \rho^1_{10} + \text{Im } \rho^2_{10} = \frac{1}{N} \text{Re } \sum_{\lambda,\lambda'} \mathcal{M}_{\substack{-1,1 \\ \lambda,\lambda'}} \mathcal{M}^*_{\substack{1,0 \\ \lambda,\lambda'}}$$

$$\rho^1_{1-1} - \text{Im } \rho^2_{1-1} = \frac{2}{N} \sum_{\lambda,\lambda'} T_{\substack{1,1 \\ \lambda,\lambda'}} T^*_{\substack{-1,-1 \\ \lambda,\lambda'}}$$

$$\text{Re } \rho^1_{10} - \text{Im } \rho^2_{10} = \frac{1}{N} \text{Re } \sum_{\lambda_\gamma,\lambda,\lambda'} \mathcal{M}_{\substack{1,1 \\ \lambda,\lambda'}} \mathcal{M}^*_{\substack{-1,0 \\ \lambda,\lambda'}}$$

Observables: Moments of Angular distribution

$$H^0(LM) = \frac{1}{2\pi} \int I(\Omega, \Phi)\, d^L_{M0}(\theta) \cos M\phi \, \mathrm{d}\Omega \mathrm{d}\Phi$$

$$H^1(LM) = \frac{-1}{\pi P_\gamma} \int I(\Omega, \Phi) \cos 2\Phi \, d^L_{M0}(\theta) \cos M\phi \, \mathrm{d}\Omega \mathrm{d}\Phi$$

$$\mathrm{Im}\, H^2(LM) = \frac{1}{\pi P_\gamma} \int I(\Omega, \Phi) \sin 2\Phi \, d^L_{M0}(\theta) \sin M\phi \, \mathrm{d}\Omega \mathrm{d}\Phi$$

$m' = m - M$

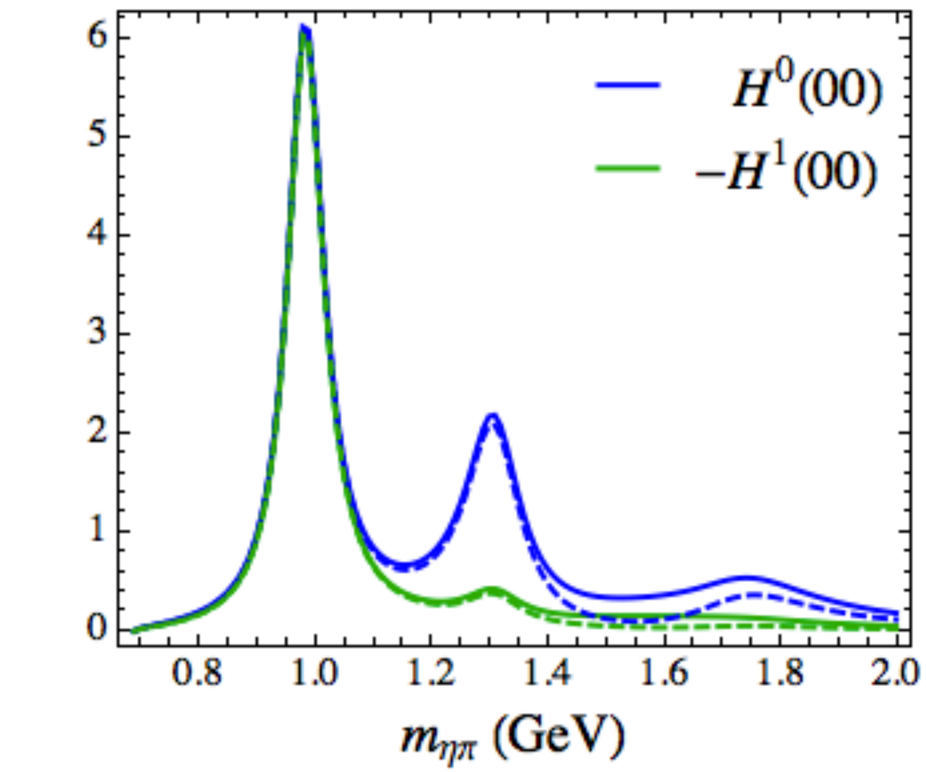
$$H^1(LM) + \mathrm{Im}\ H^2(LM) \propto \sum_{\epsilon, \substack{\ell\ell' \\ mm'}} \left(\frac{2\ell' + 1}{2\ell + 1}\right)^{1/2} \epsilon(-1)^m C^{\ell 0}_{\ell' 0 L 0} C^{\ell m}_{\ell' m' L M} [\ell]^{(\epsilon)}_{-m} [\ell']^{(\epsilon)*}_{m'}$$

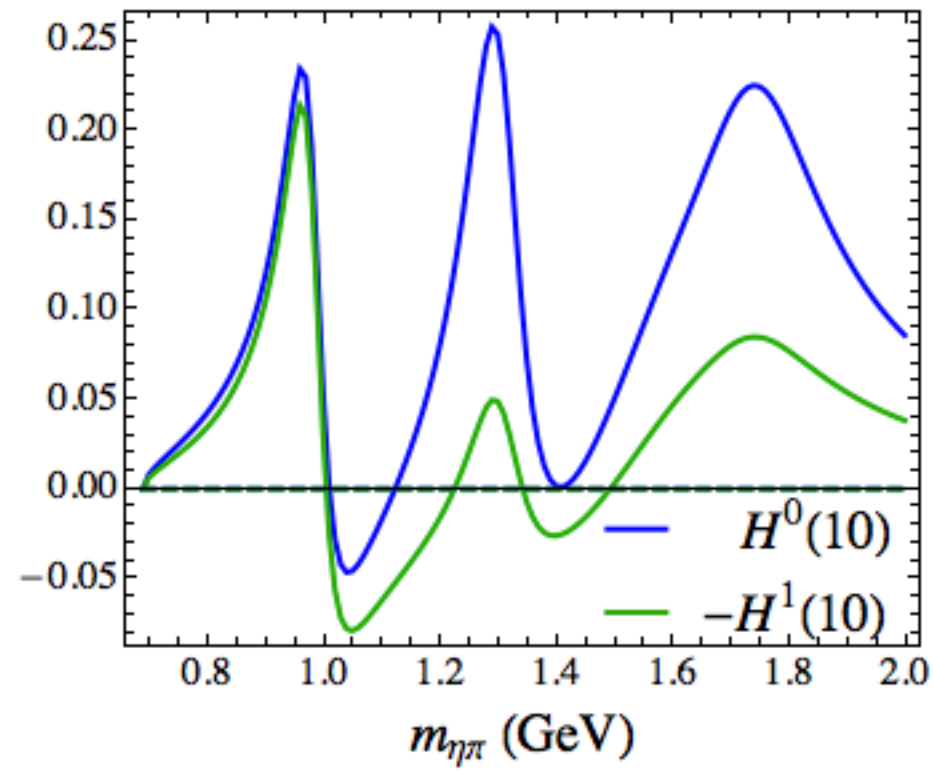
$0 \leqslant -m \;;\; 0 \leqslant m'$

The model features only positive projections

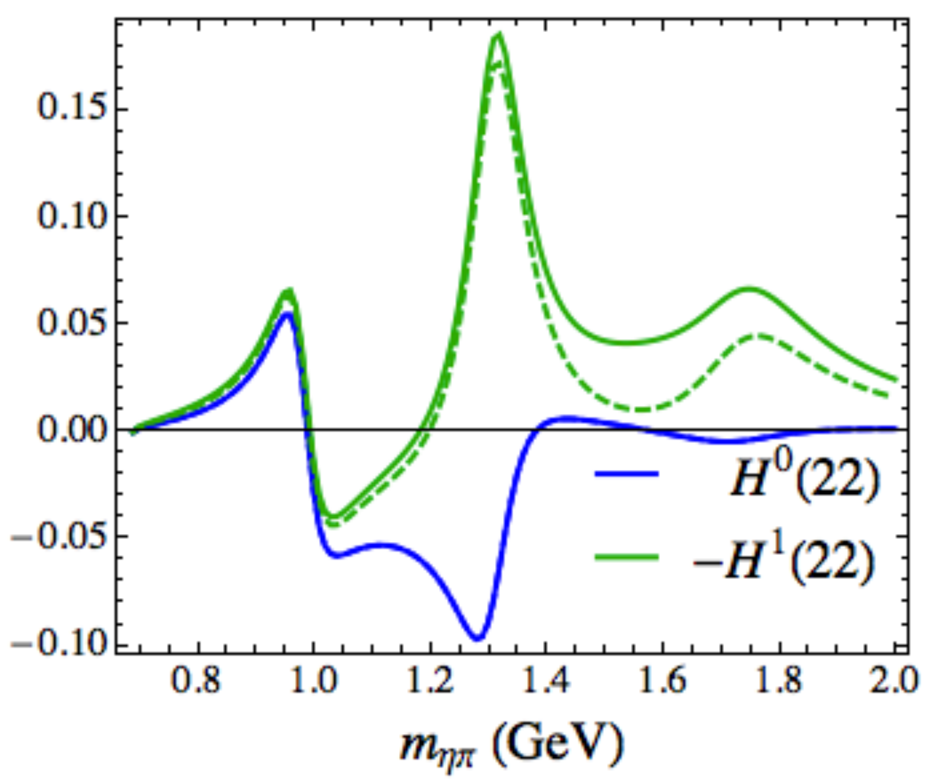
$$H^1(LM) + \mathrm{Im}\ H^2(LM) = 0 \qquad M \geqslant 1$$

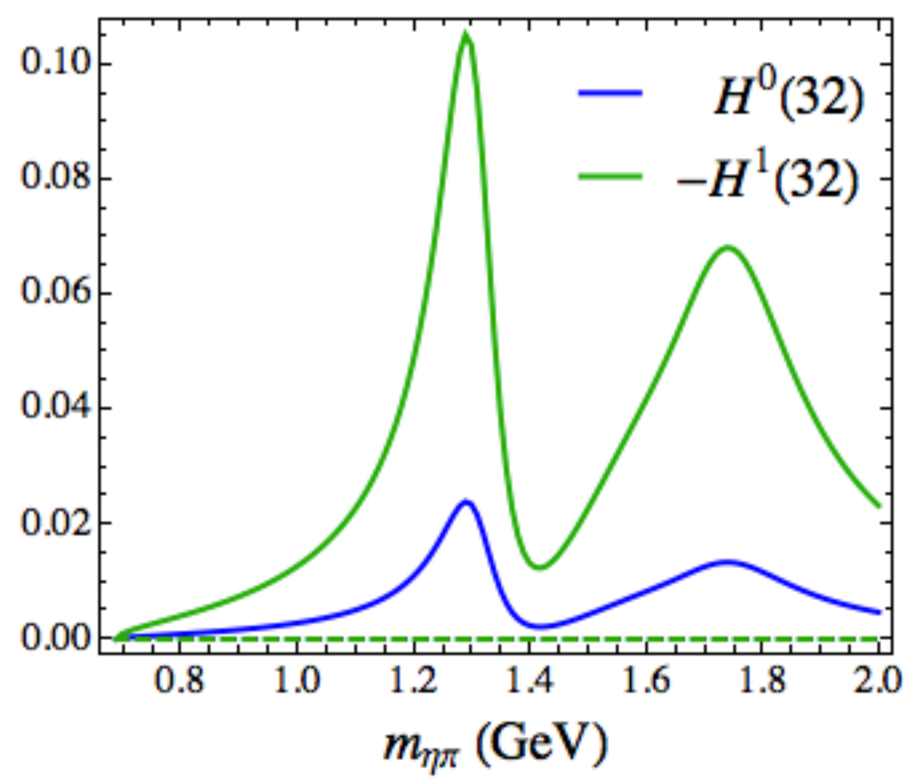
Moments





P- wave apparent in odd moments but not in even moments

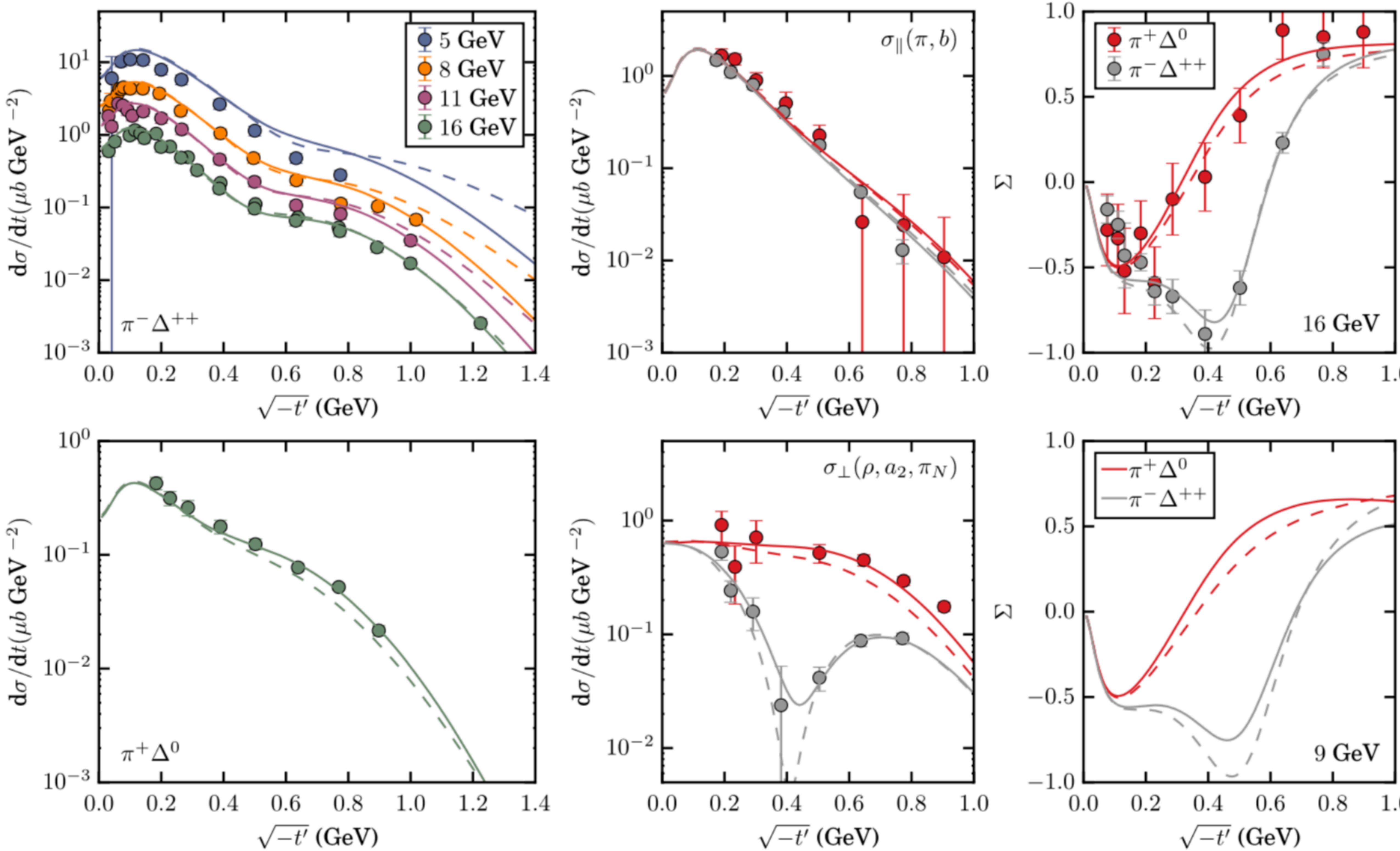




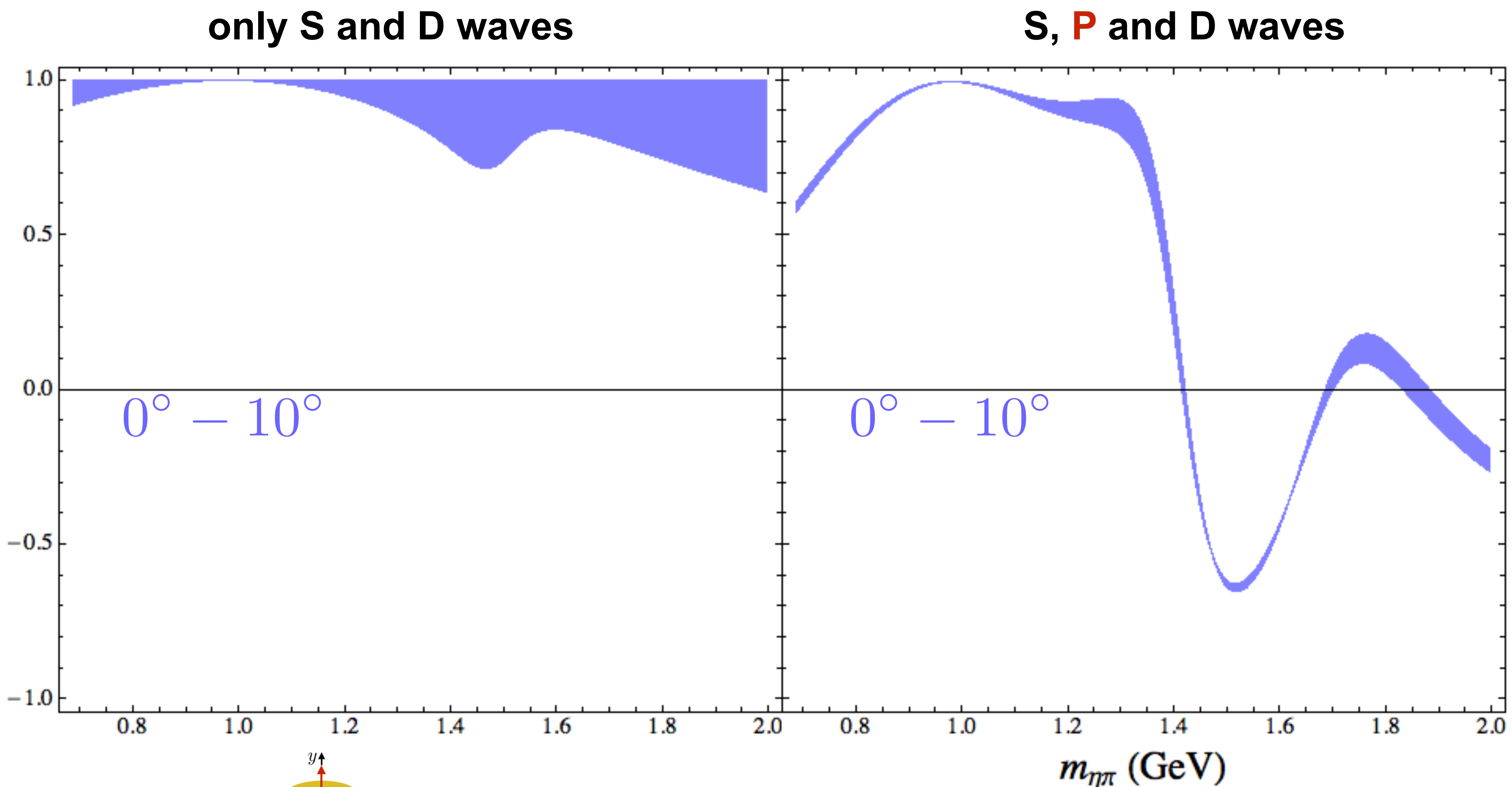
$a_2(1700)$ **more apparent in odd moments than in even moments**

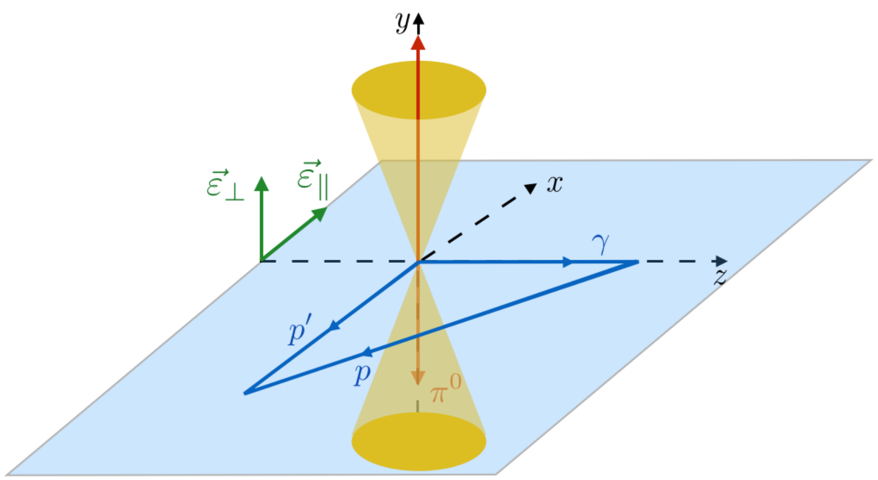
solid lines: *S* + *P* + *D* waves

dashed lines: *S* + *D* waves


5 GeV
8 GeV
11 GeV
16 GeV
$\pi^-\Delta^{++}$
$\sigma_\parallel(\pi, b)$
$\pi^+\Delta^0$
$\pi^-\Delta^{++}$
16 GeV
$\pi^+\Delta^0$
$\sigma_\perp(\rho, a_2, \pi_N)$
$\pi^+\Delta^0$
$\pi^-\Delta^{++}$
9 GeV
$d\sigma/dt(\mu b\ GeV^{-2})$
Σ
$\sqrt{-t'}$ (GeV)

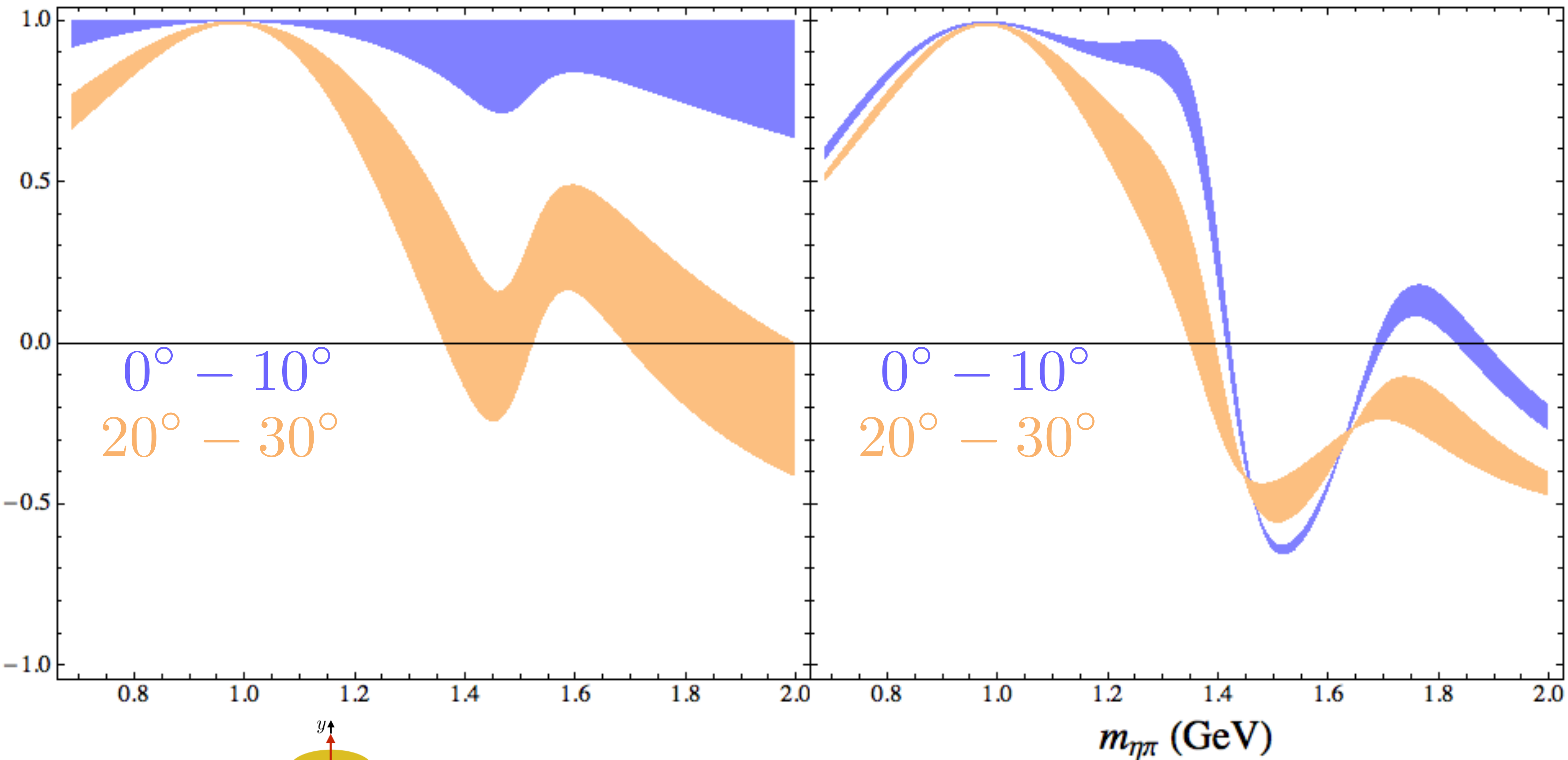
Beam Asymmetries: $\Sigma_{y\pm\delta^\circ}$

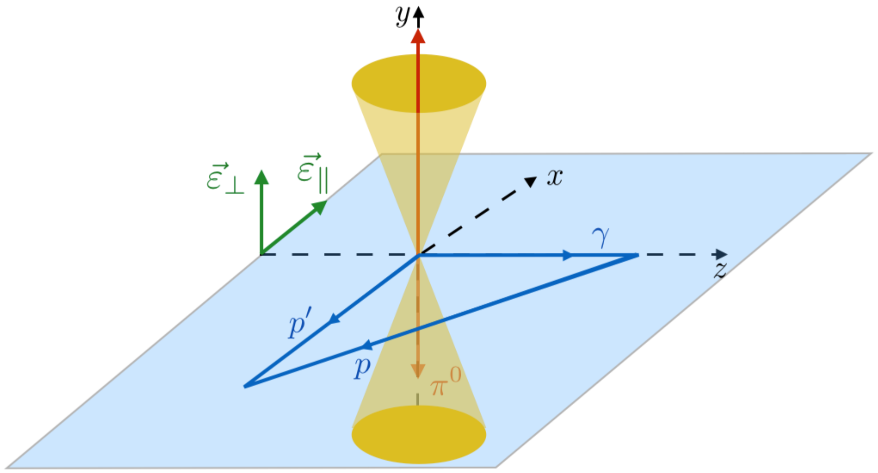




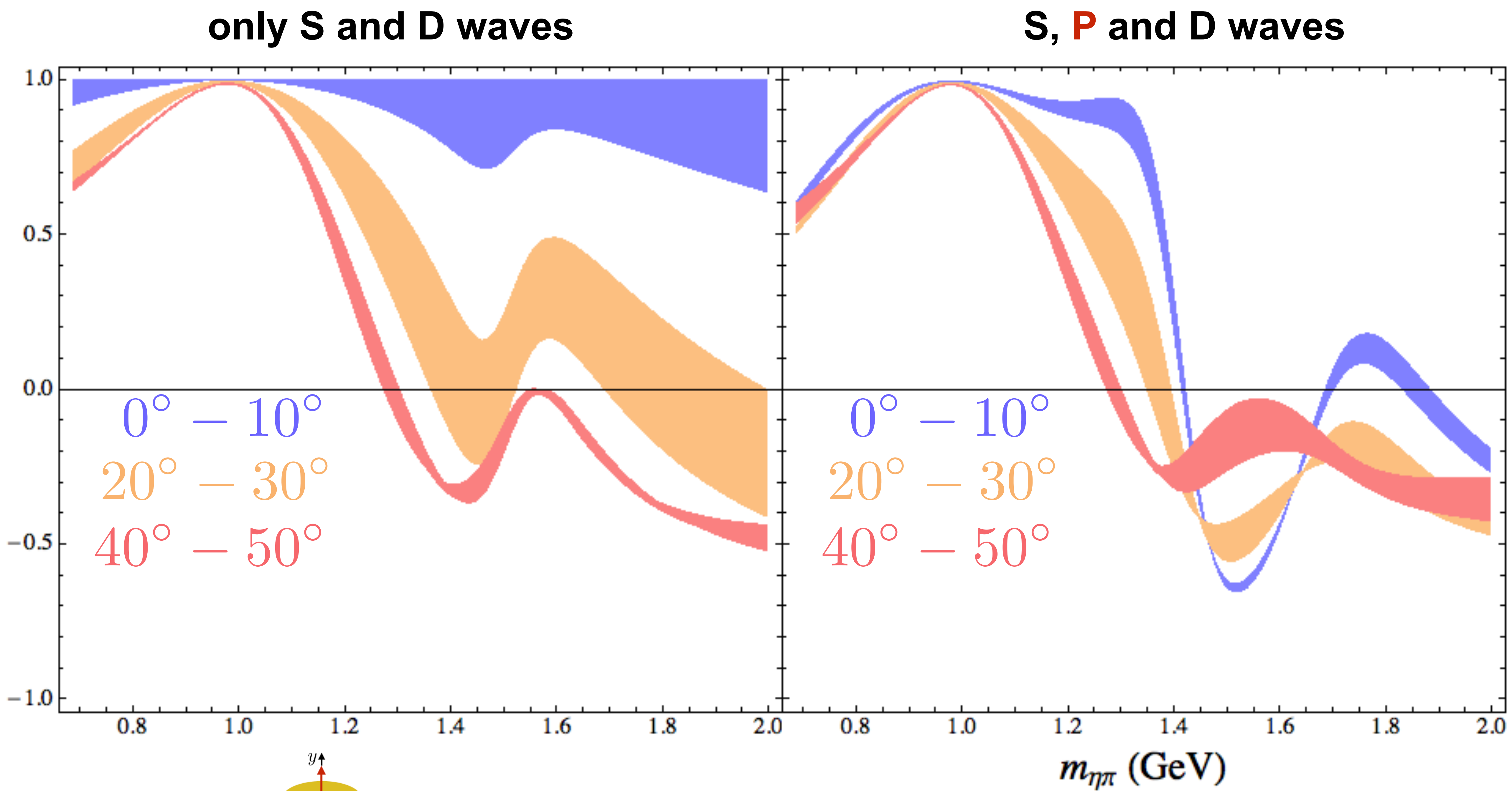
Beam Asymmetries: $\Sigma_{y\pm\delta^\circ}$

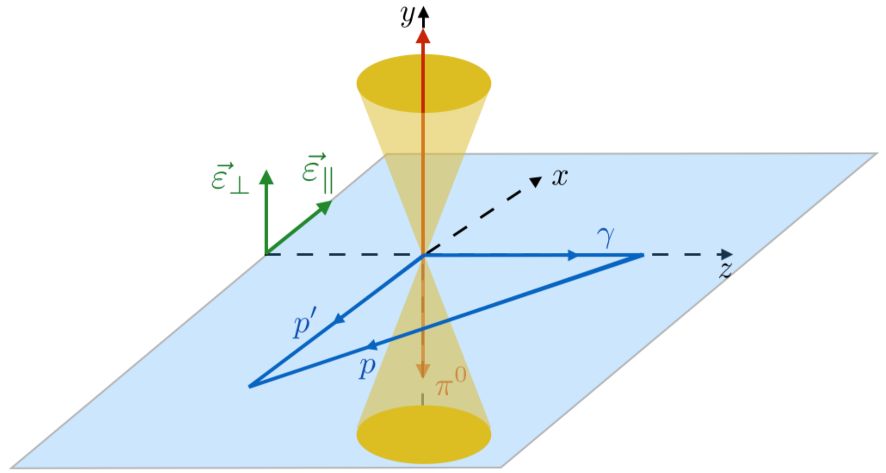
only S and D waves | **S, P and D waves**





Beam Asymmetries: $\Sigma_{y\pm\delta^\circ}$

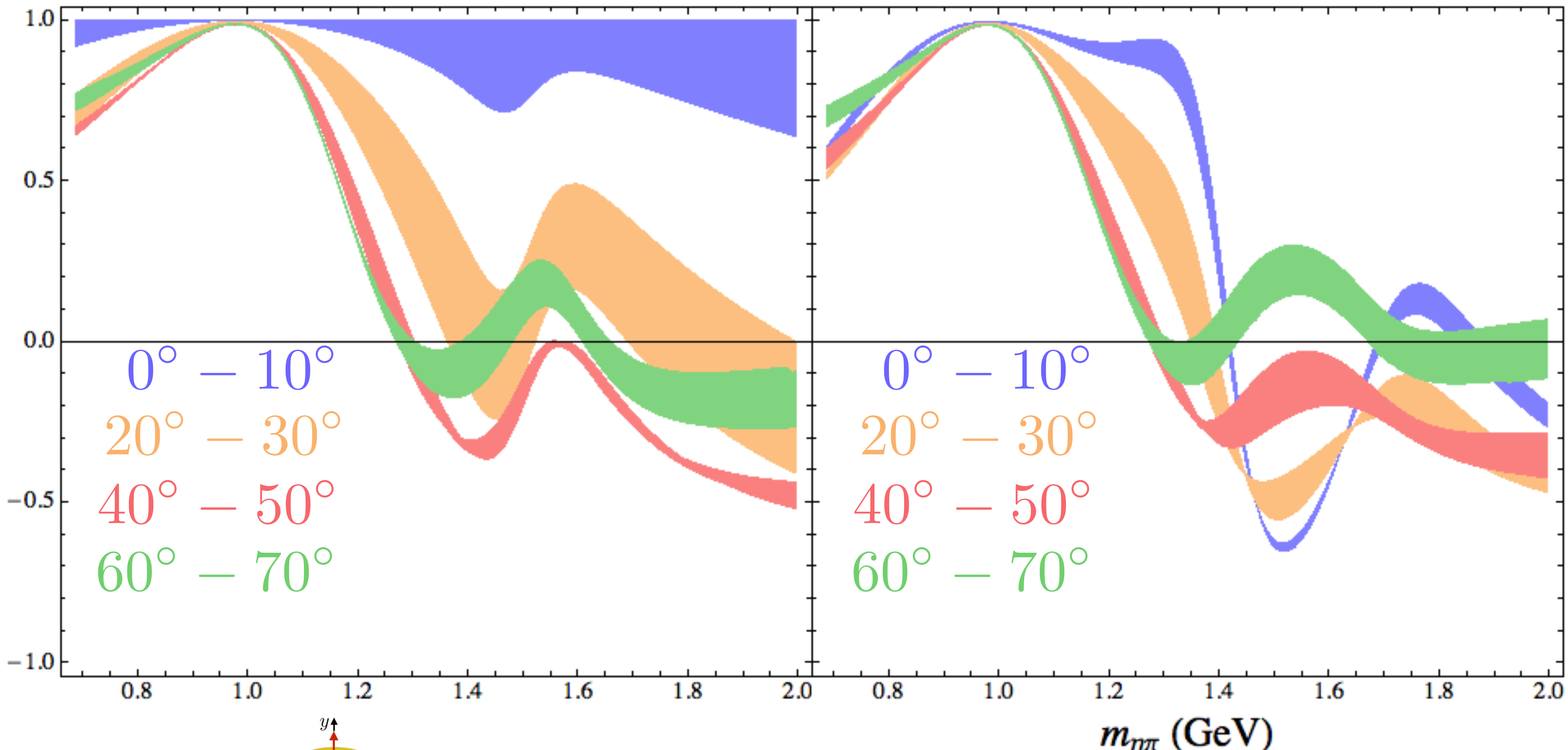


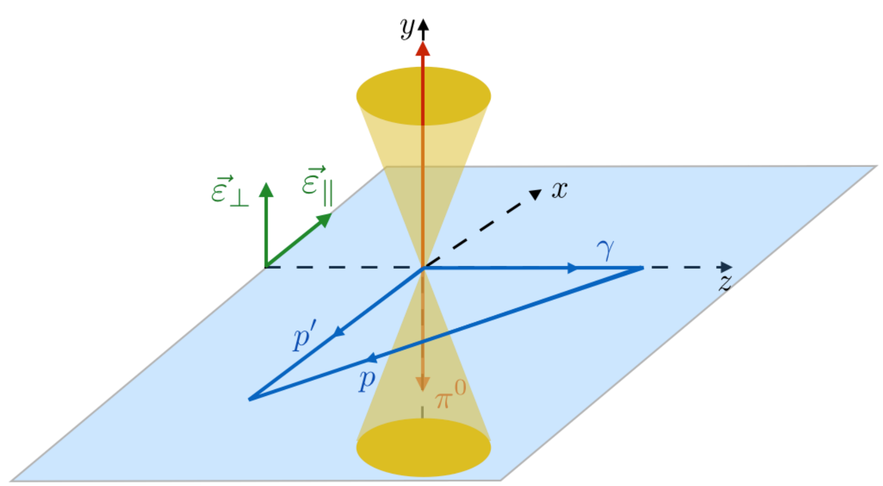


with an opening angle greater than 30° the observables is not sensitive to the P-wave (with our model)

Beam Asymmetries: $\Sigma_{y\pm\delta^\circ}$

only S and D waves **S, P and D waves**

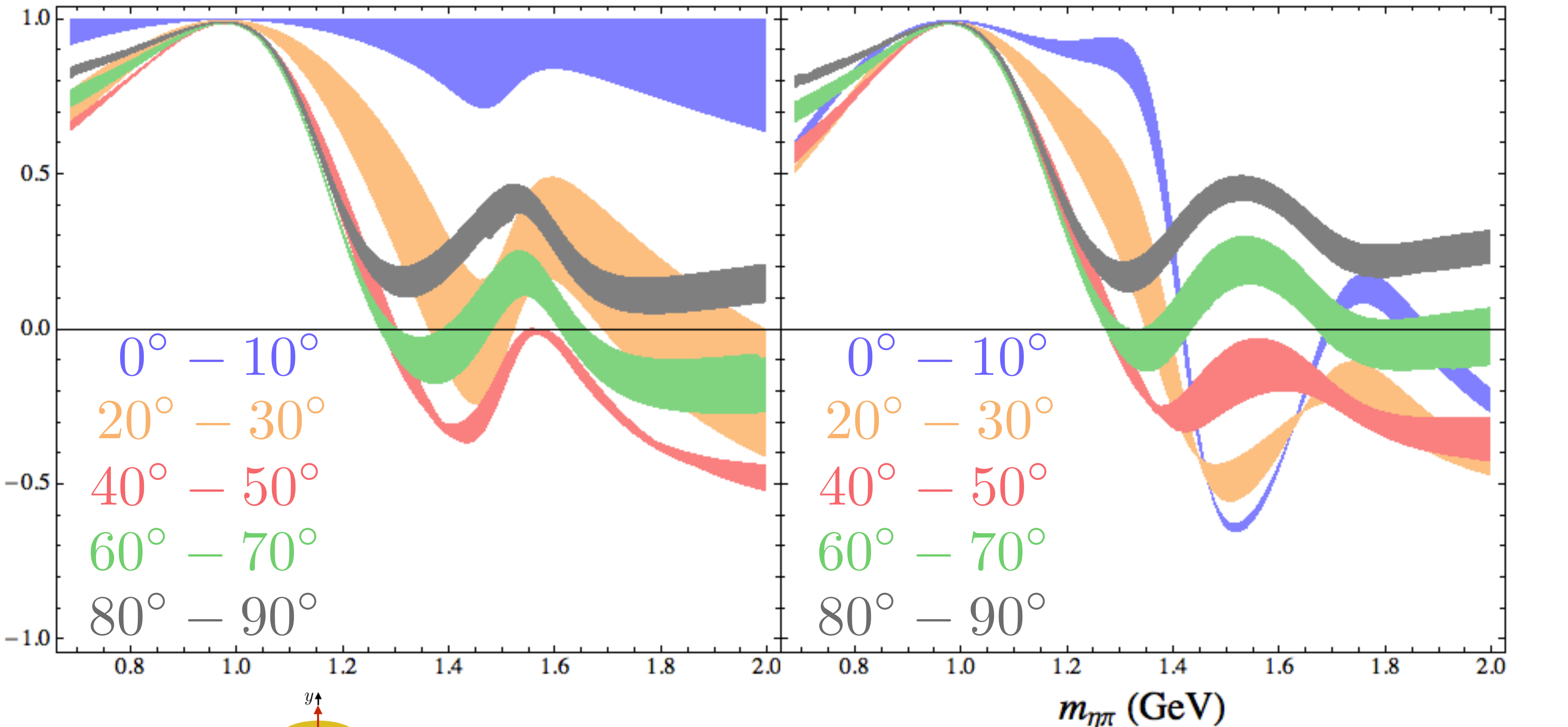


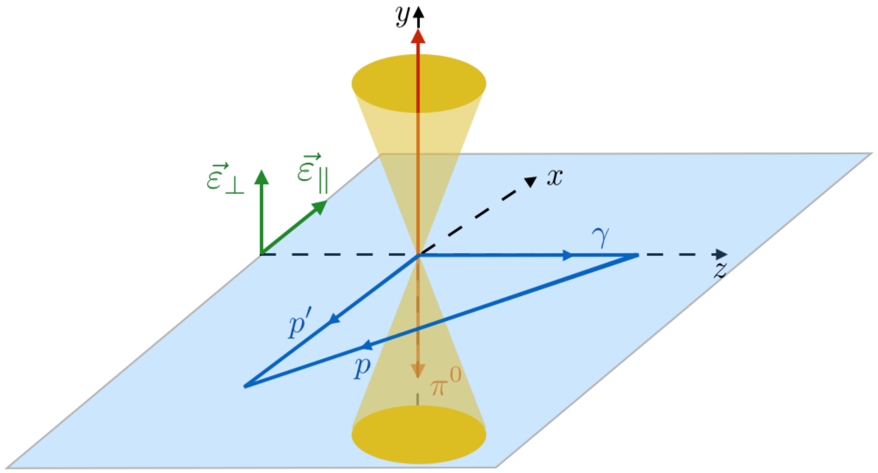


with an opening angle greater than 30°
the observables is not sensitive to the P-wave
(with our model)

Beam Asymmetries: $\Sigma_{y \pm \delta^\circ}$

only S and D waves | **S, P and D waves**





with an opening angle greater than 30° the observables is not sensitive to the P-wave (with our model)

Observables: Moments of Angular distribution

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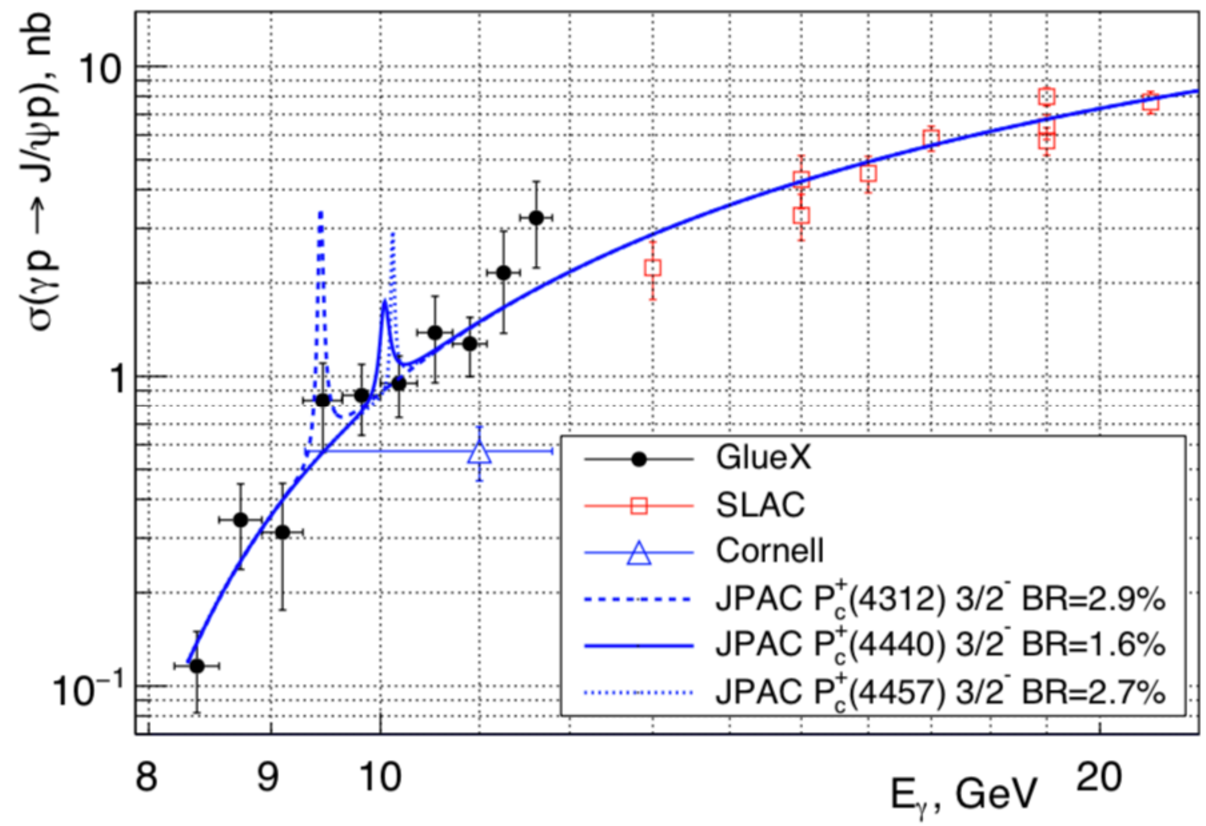
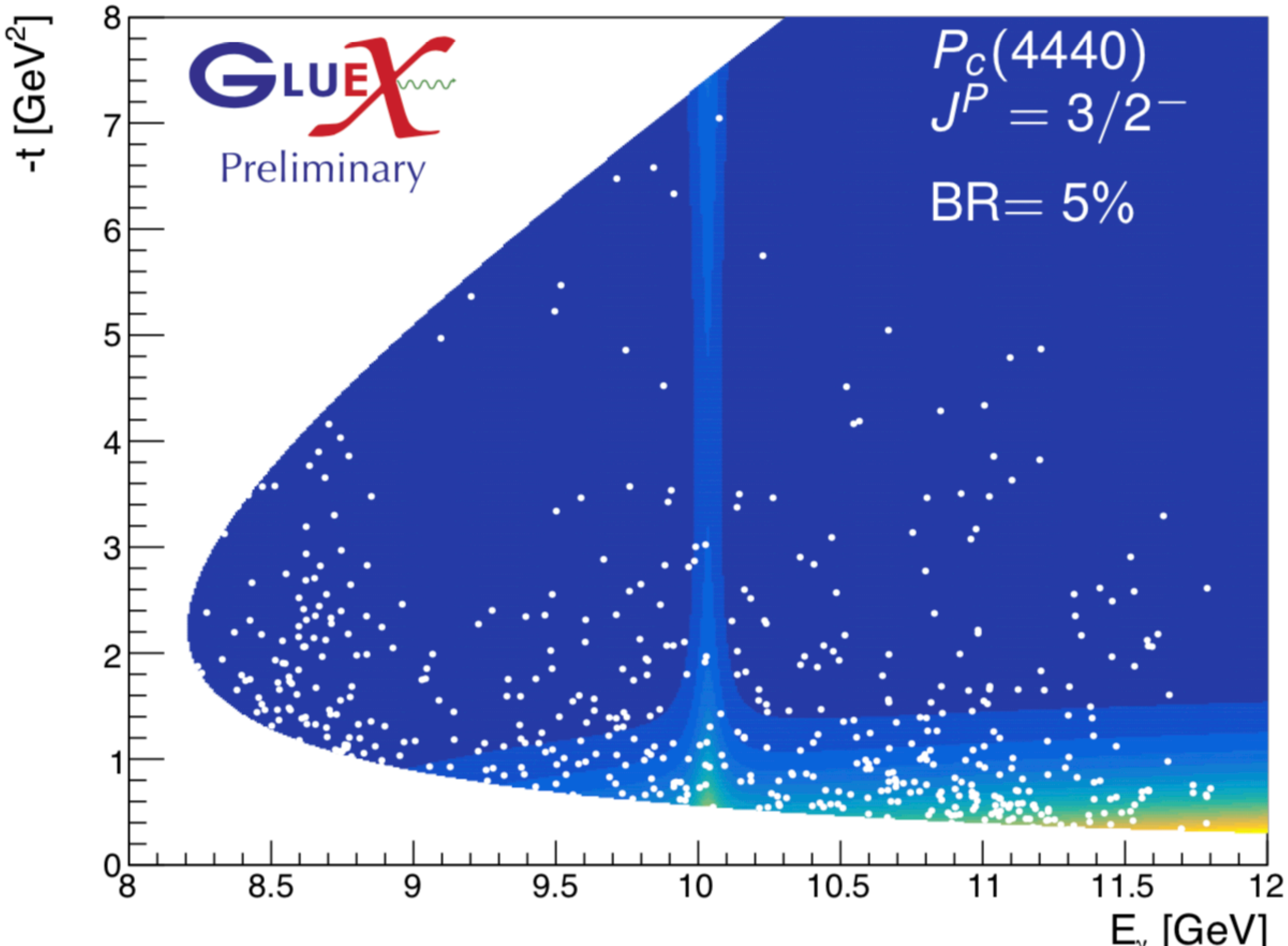
$$H^1(LM) = \frac{-1}{\pi P_\gamma}\int I(\Omega,\Phi)\cos 2\Phi\, d^L_{M0}(\theta)\cos M\phi\, \mathrm{d}\Omega\mathrm{d}\Phi$$

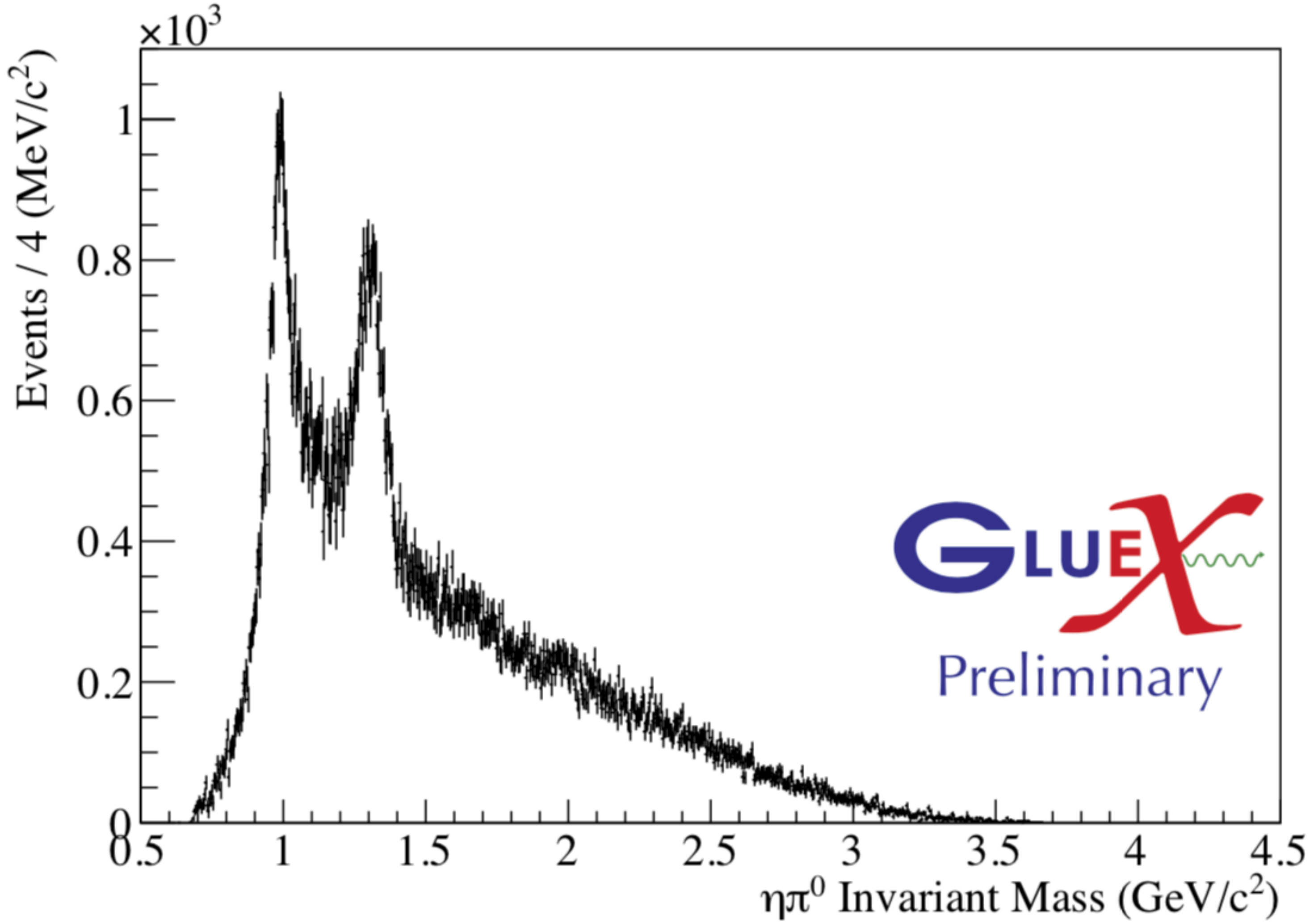
$$\mathrm{Im}\, H^2(LM) = \frac{1}{\pi P_\gamma}\int I(\Omega,\Phi)\sin 2\Phi\, d^L_{M0}(\theta)\sin M\phi\, \mathrm{d}\Omega\mathrm{d}\Phi$$

Moments are unambiguously extracted and are related to partial waves (interferences)

$$\begin{aligned}
{}^{(+)}H^0(21) &= 2\mathrm{Re}\left[\left(\frac{S_0^{(+)}}{\sqrt{5}} + \frac{D_0^{(+)}}{7}\right)\left(D_1^{(+)*} - D_{-1}^{(+)*}\right)\right] + 2\frac{\sqrt{3}}{5}\mathrm{Re}\left[P_0^{(+)}\left(P_1^{(+)*} - P_{-1}^{(+)*}\right)\right] \\
&+ 2\frac{\sqrt{6}}{7}\mathrm{Re}\left[D_1^{(+)}D_2^{(+)*} - D_{-1}^{(+)}D_{-2}^{(+)*}\right] \\
{}^{(+)}H^1(21) &= 2\mathrm{Re}\left[\left(\frac{S_0^{(+)}}{\sqrt{5}} + \frac{D_0^{(+)}}{7}\right)\left(D_1^{(+)*} - D_{-1}^{(+)*}\right)\right] + 2\frac{\sqrt{3}}{5}\mathrm{Re}\left[P_0^{(+)}\left(P_1^{(+)*} - P_{-1}^{(+)*}\right)\right] \\
&+ 2\frac{\sqrt{6}}{7}\mathrm{Re}\left[D_1^{(+)}D_{-2}^{(+)*} + D_{-1}^{(+)}D_2^{(+)*}\right] \\
{}^{(+)}H^2(21) &= -2\mathrm{Re}\left[\left(\frac{S_0^{(+)}}{\sqrt{5}} + \frac{D_0^{(+)}}{7}\right)\left(D_1^{(+)*} + D_{-1}^{(+)*}\right)\right] - 2\frac{\sqrt{3}}{5}\mathrm{Re}\left[P_0^{(+)}\left(P_1^{(+)*} + P_{-1}^{(+)*}\right)\right] \\
&+ 2\frac{\sqrt{6}}{7}\mathrm{Re}\left[D_1^{(+)}D_{-2}^{(+)*} + D_{-1}^{(+)}D_2^{(+)*}\right]
\end{aligned}$$


σ(γp → J/ψp), nb
10
1
10^{-1}
8
9
10
20
E$_\gamma$, GeV
GlueX
SLAC
Cornell
JPAC P_c^+(4312) 3/2$^-$ BR=2.9%
JPAC P_c^+(4440) 3/2$^-$ BR=1.6%
JPAC P_c^+(4457) 3/2$^-$ BR=2.7%

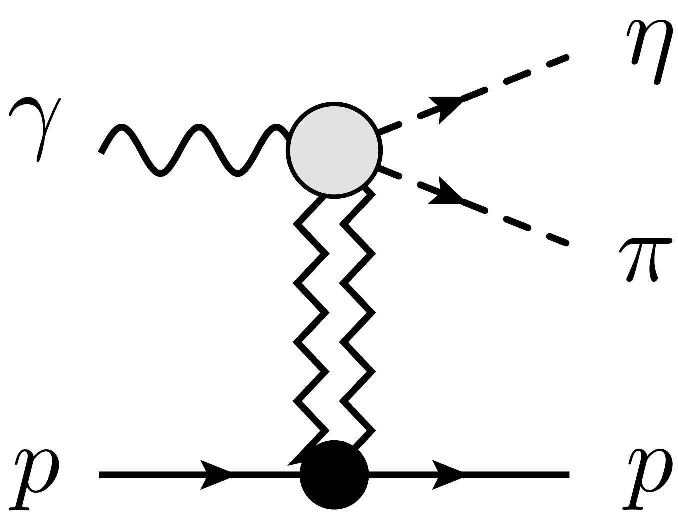

-t [GeV^2]
GlueX
Preliminary
$P_c(4440)$
$J^P = 3/2^-$
BR= 5%
E$_\gamma$ [GeV]
0
1
2
3
4
5
6
7
8
8.5
9
9.5
10
10.5
11
11.5
12

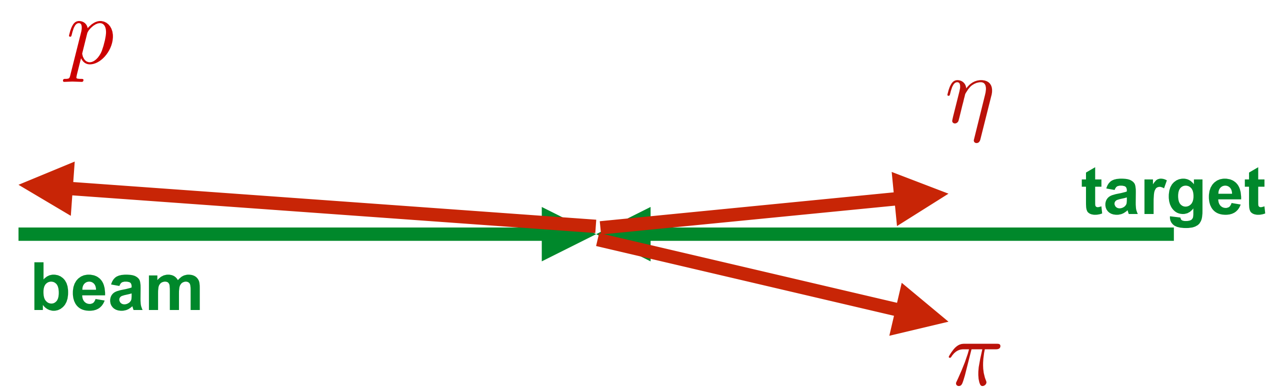


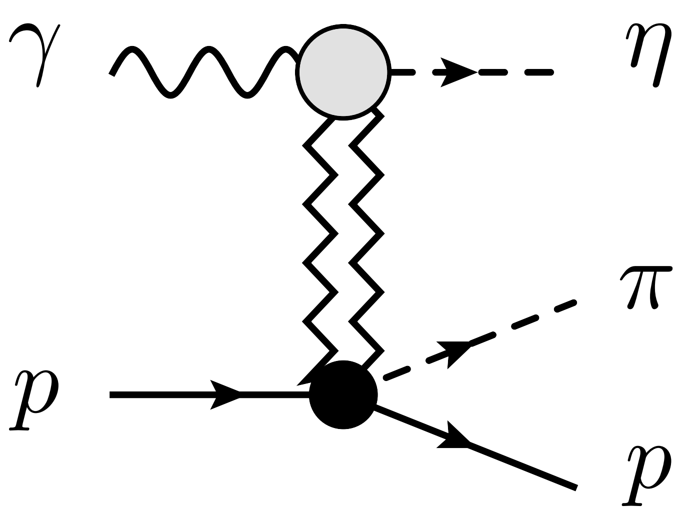
×10^3
Events / 4 (MeV/c^2)
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
ηπ^0 Invariant Mass (GeV/c^2)
GlueX
Preliminary

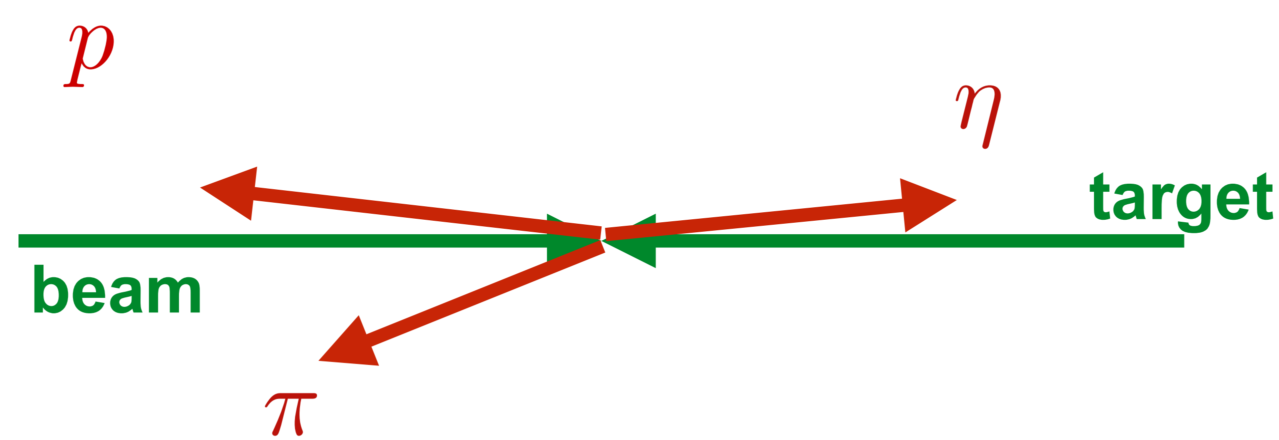
Longitudinal Plot

How do we select beam fragmentation ? → **Boost in the rest frame**







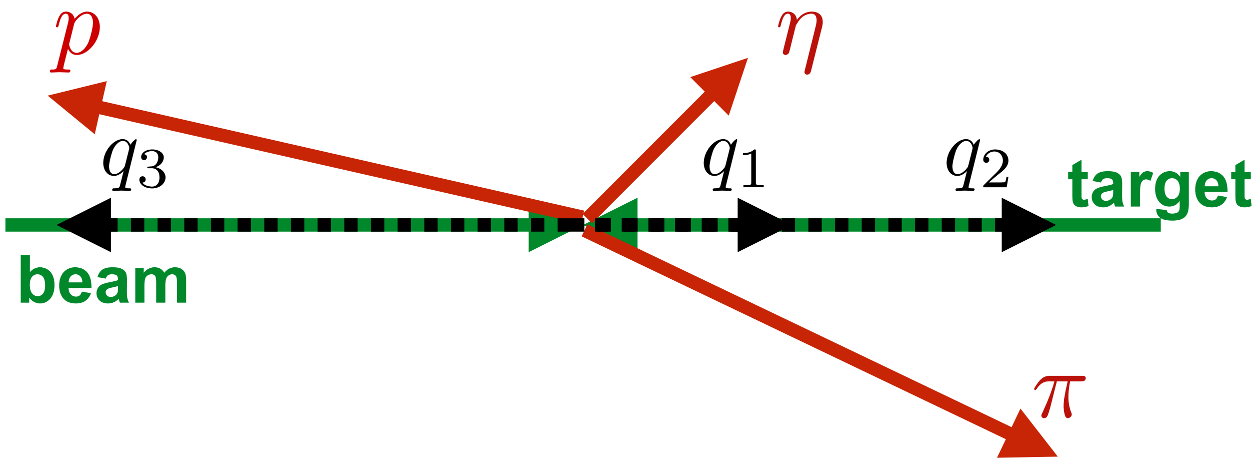


Van Hove NPB9 (1969) 331

Shi et al (JPAC) PRD91 (2015) 034007

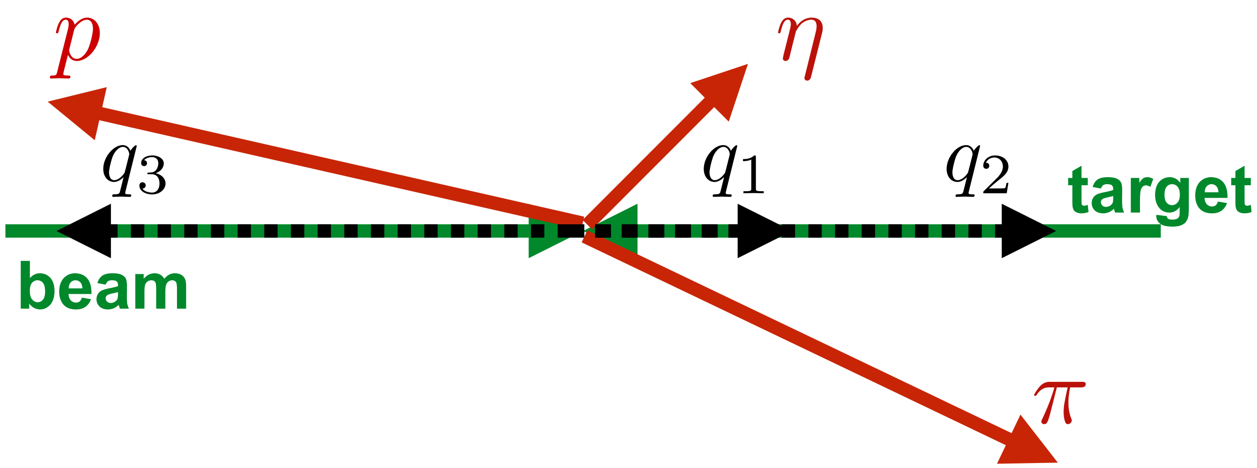
Pauli et al PRD98 (2018) 065201

Longitudinal Plot



only 2 variables since $q_1 + q_2 + q_3 = 0$

Longitudinal Plot



only 2 variables since $q_1 + q_2 + q_3 = 0$

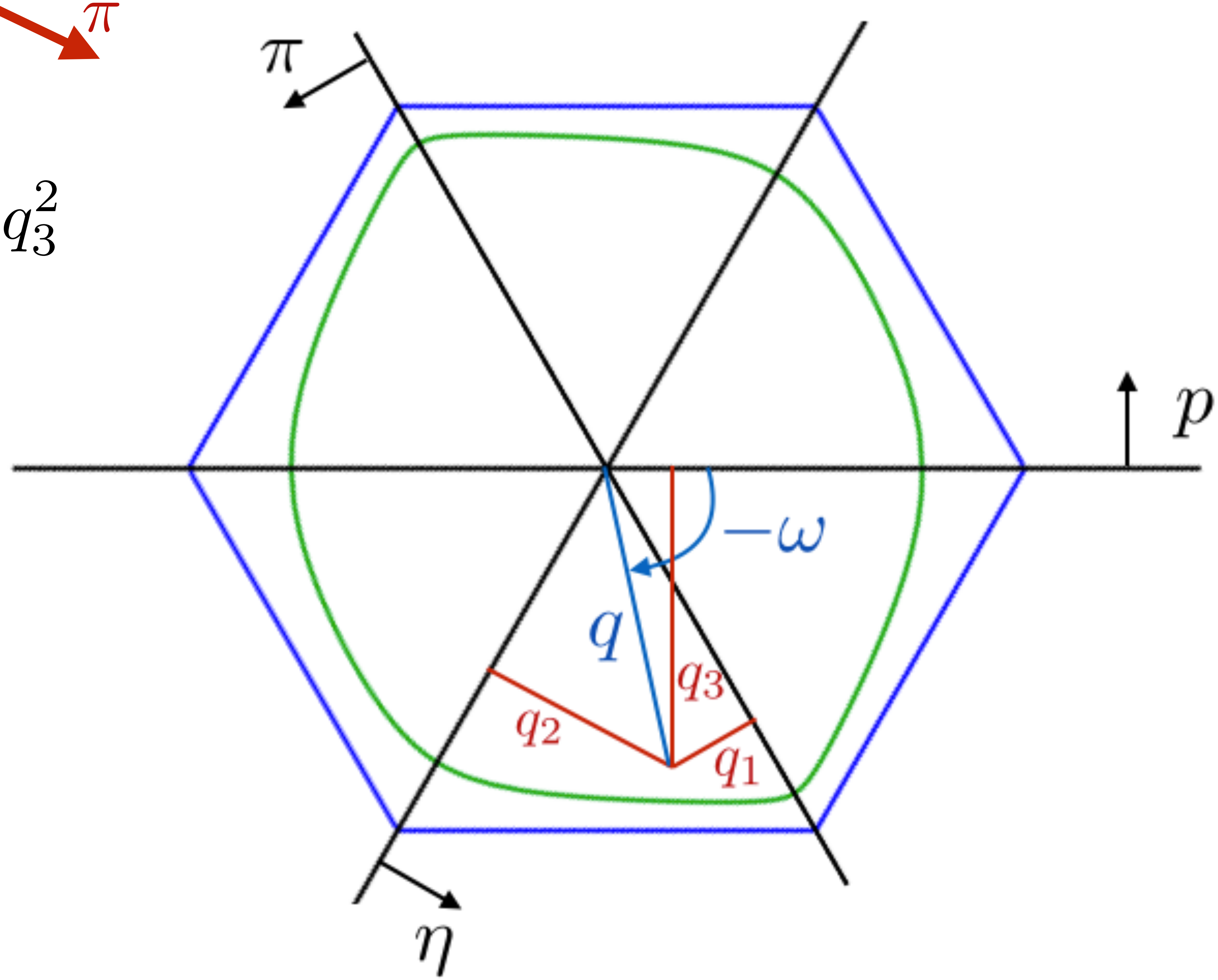
radius: $q^2 = q_1^2 + q_2^2 + q_3^2$

longitudinal angle: ω

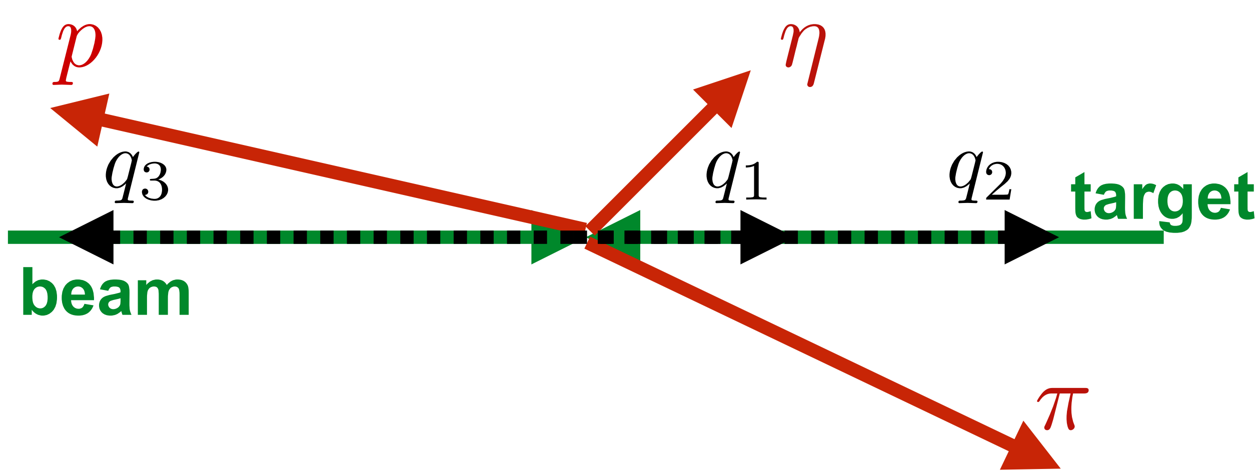
$$q_3 = \sqrt{\frac{2}{3}} q \sin \omega$$

$$q_2 = \sqrt{\frac{2}{3}} q \sin \left(\omega + \frac{2\pi}{3} \right)$$

$$q_1 = \sqrt{\frac{2}{3}} q \sin \left(\omega + \frac{4\pi}{3} \right)$$



Longitudinal Plot



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$$q_3 = \sqrt{\frac{2}{3}} q \sin \omega$$

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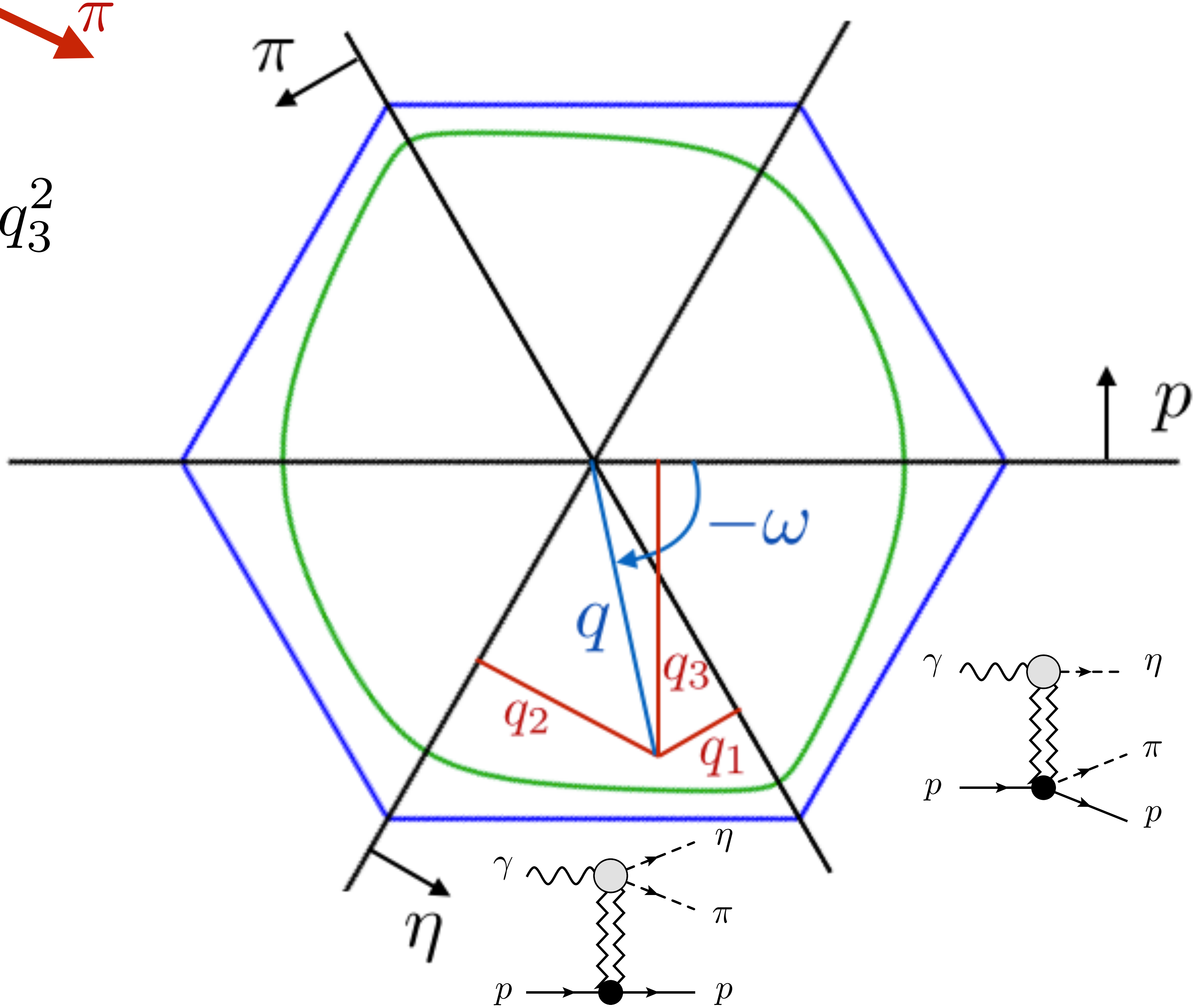
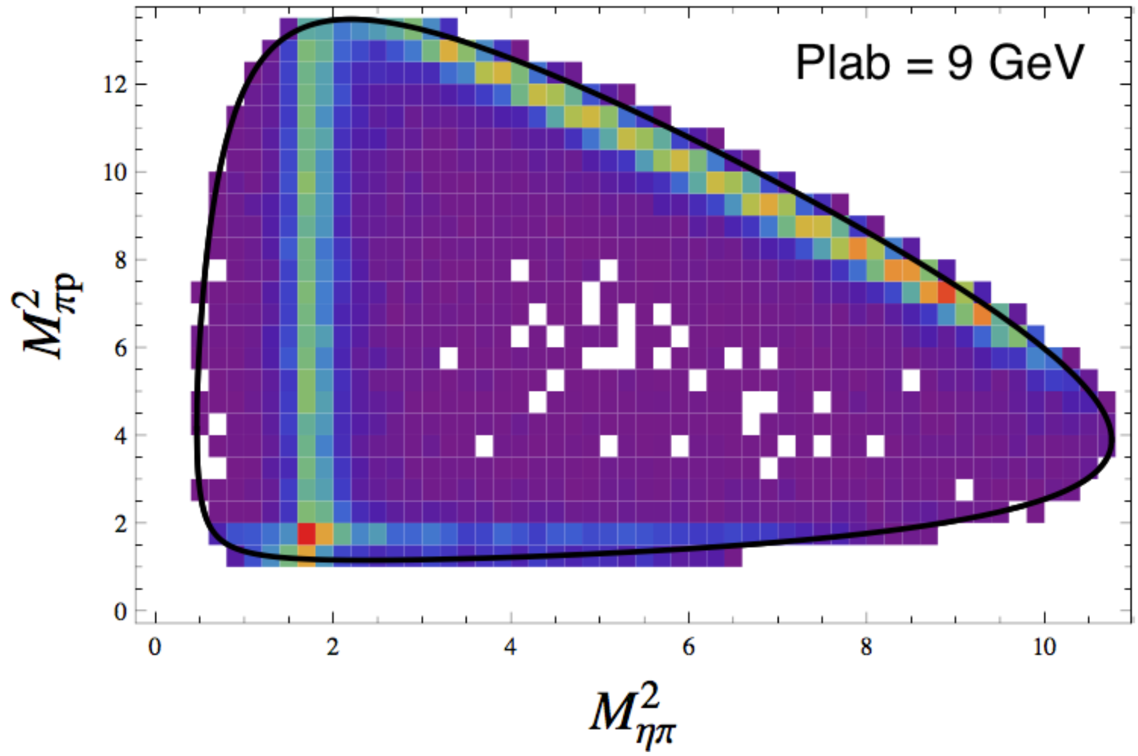
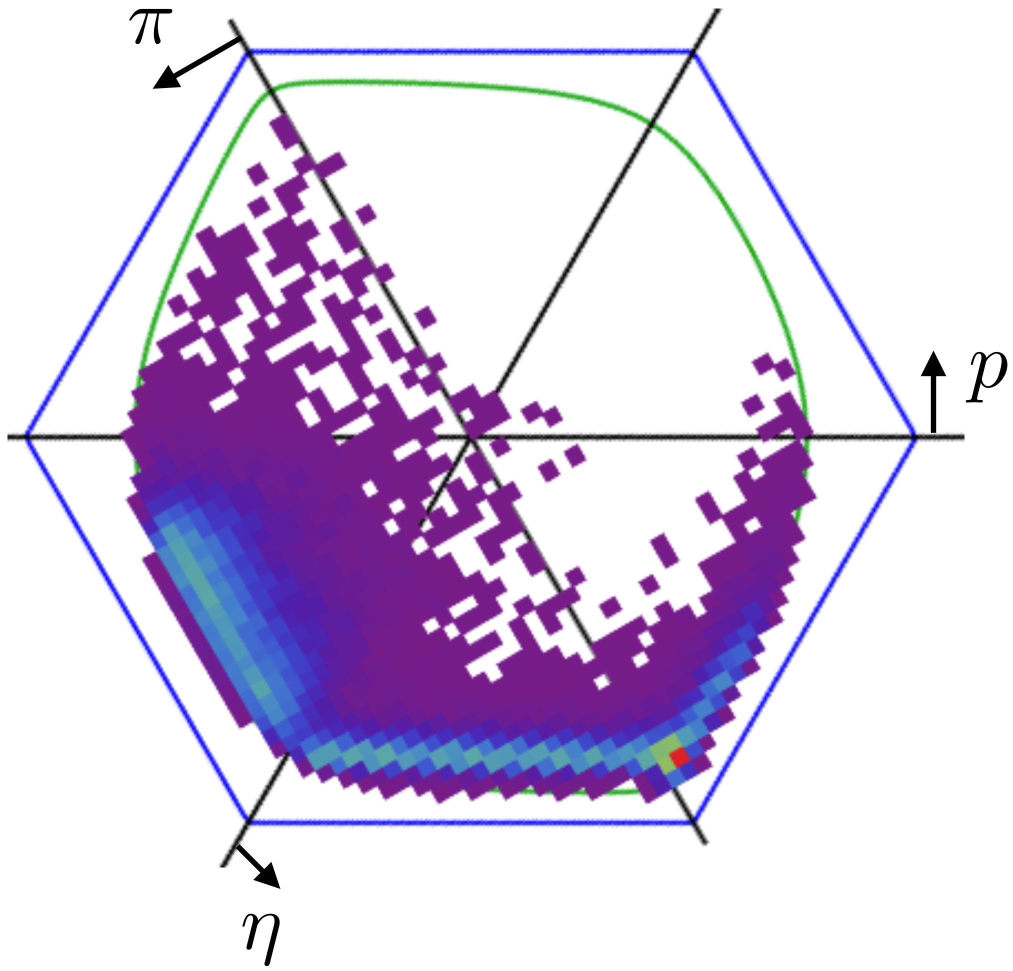
$$q_1 = \sqrt{\frac{2}{3}} q \sin \left(\omega + \frac{4\pi}{3} \right)$$

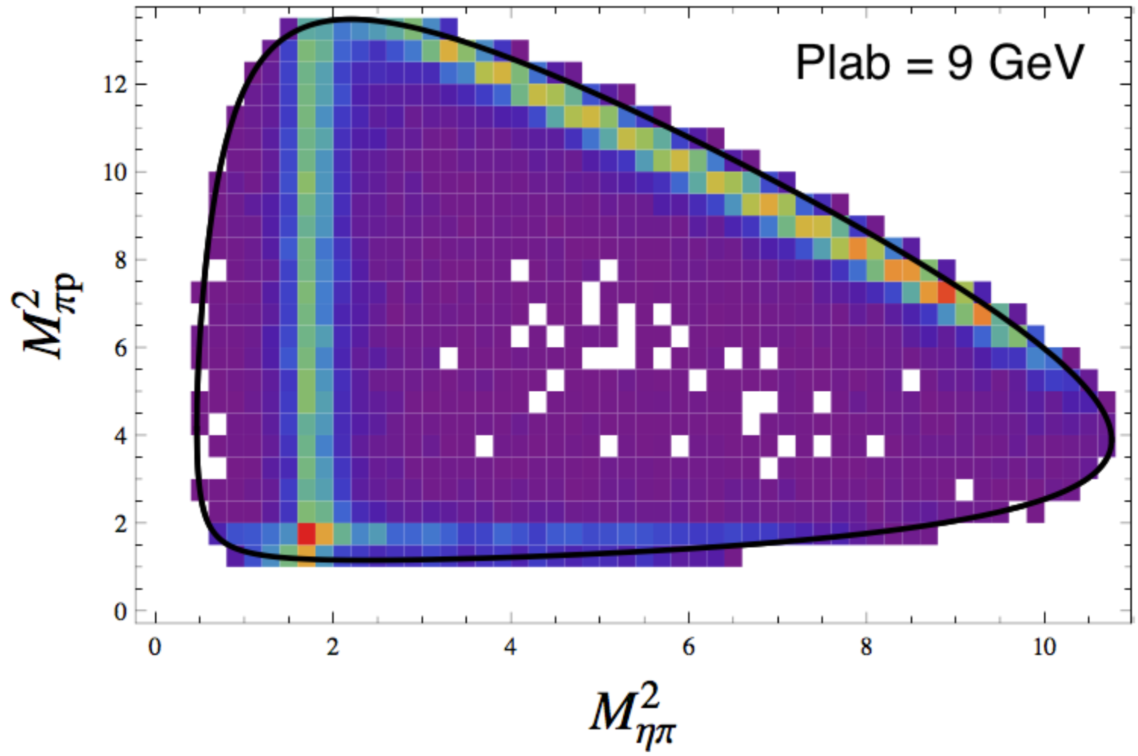


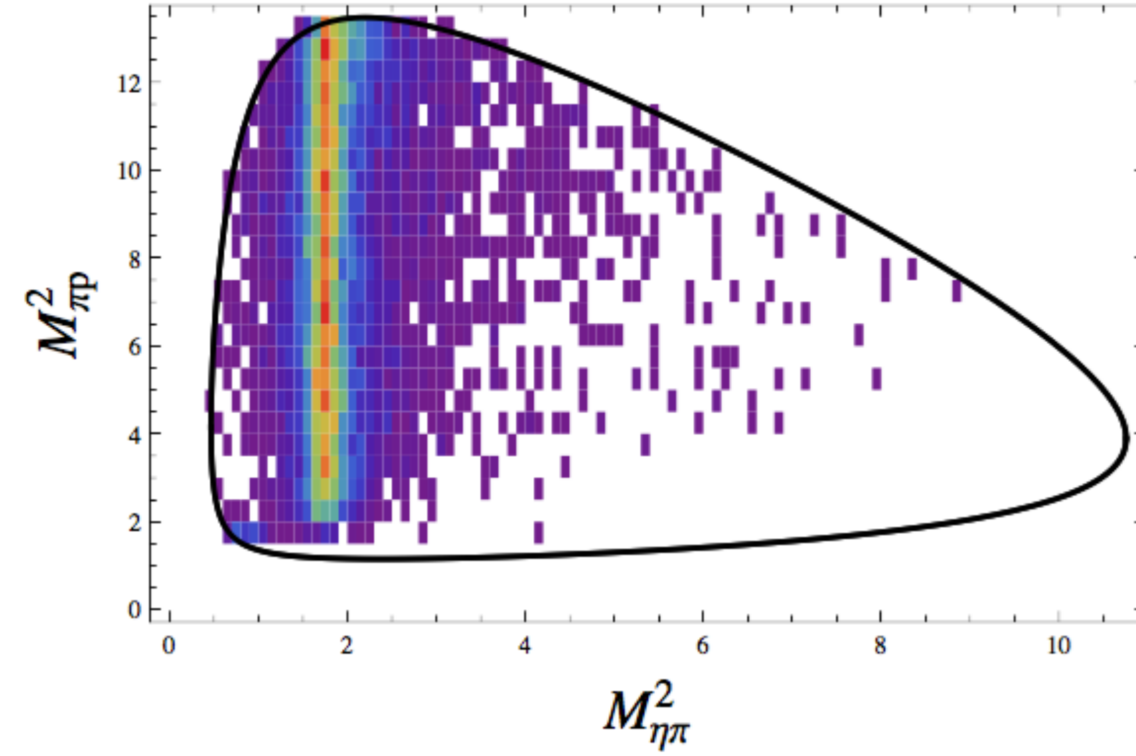
Cut in Longitudinal Angle

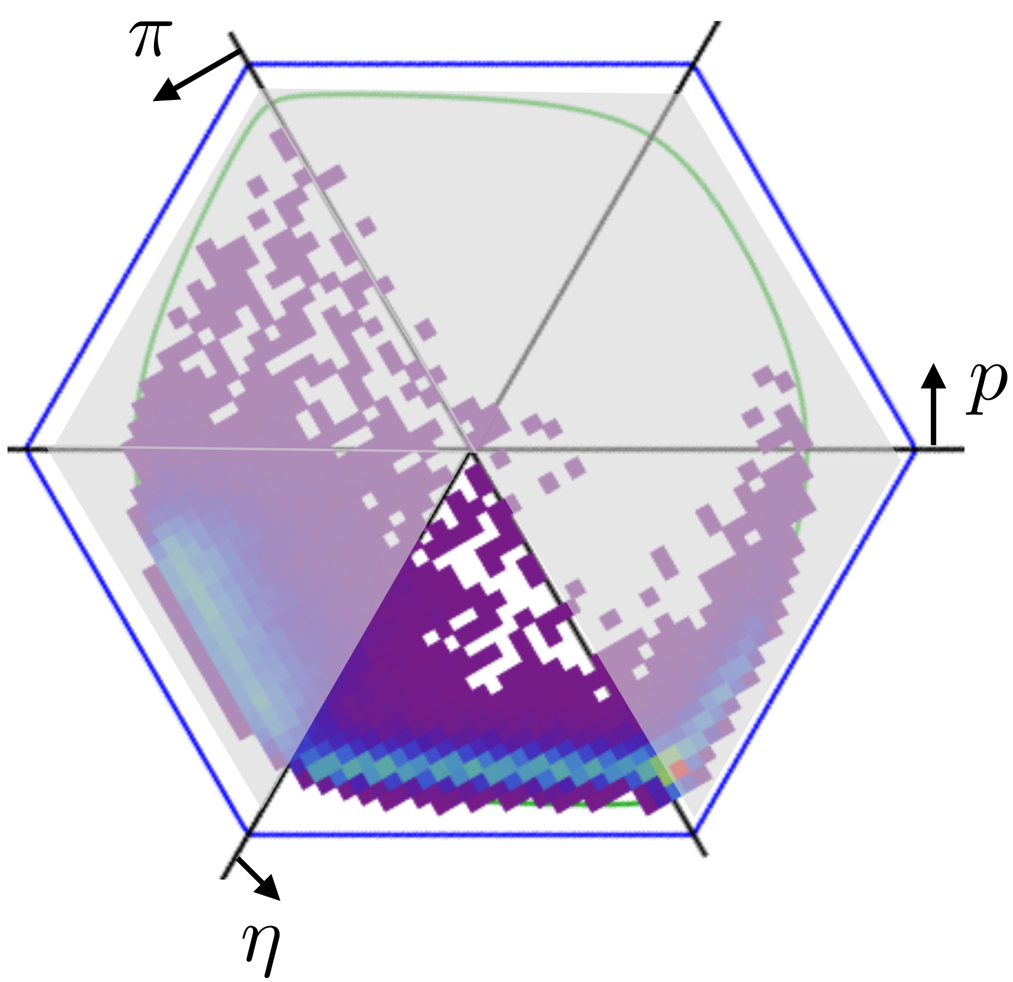


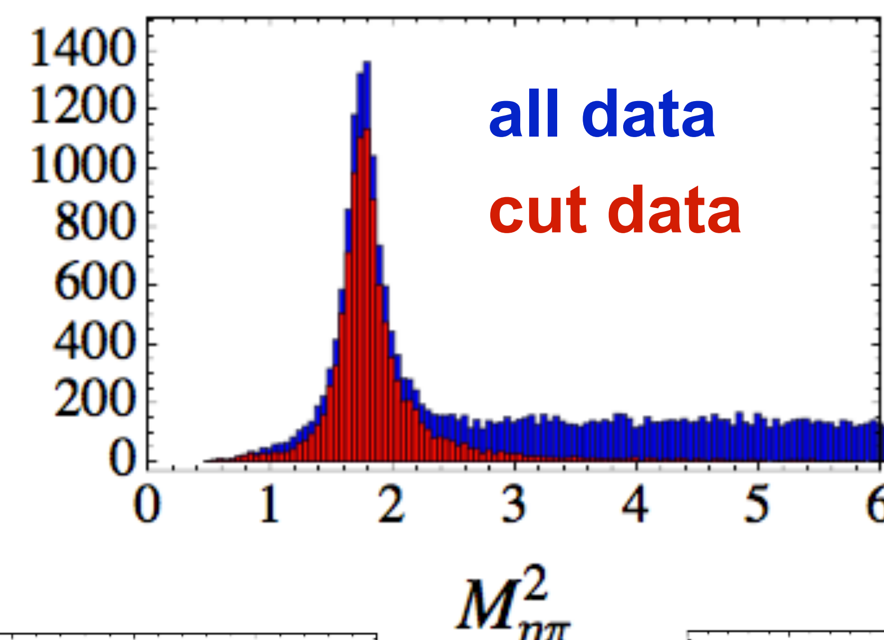


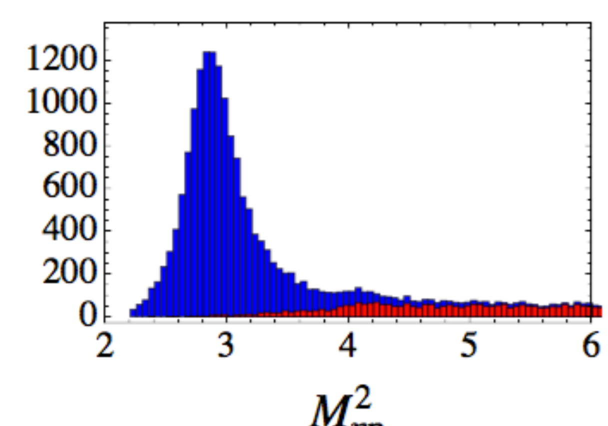
Cut in Longitudinal Angle

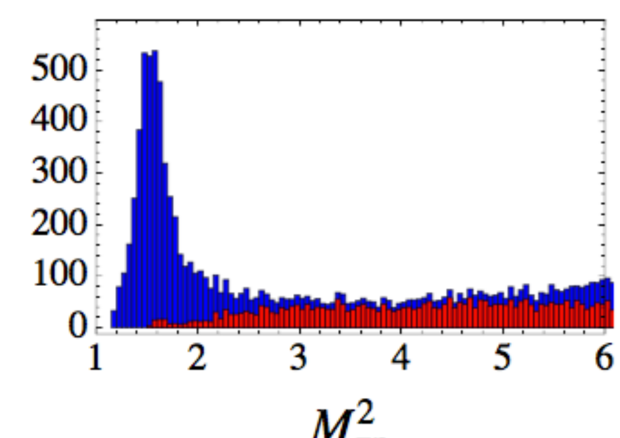




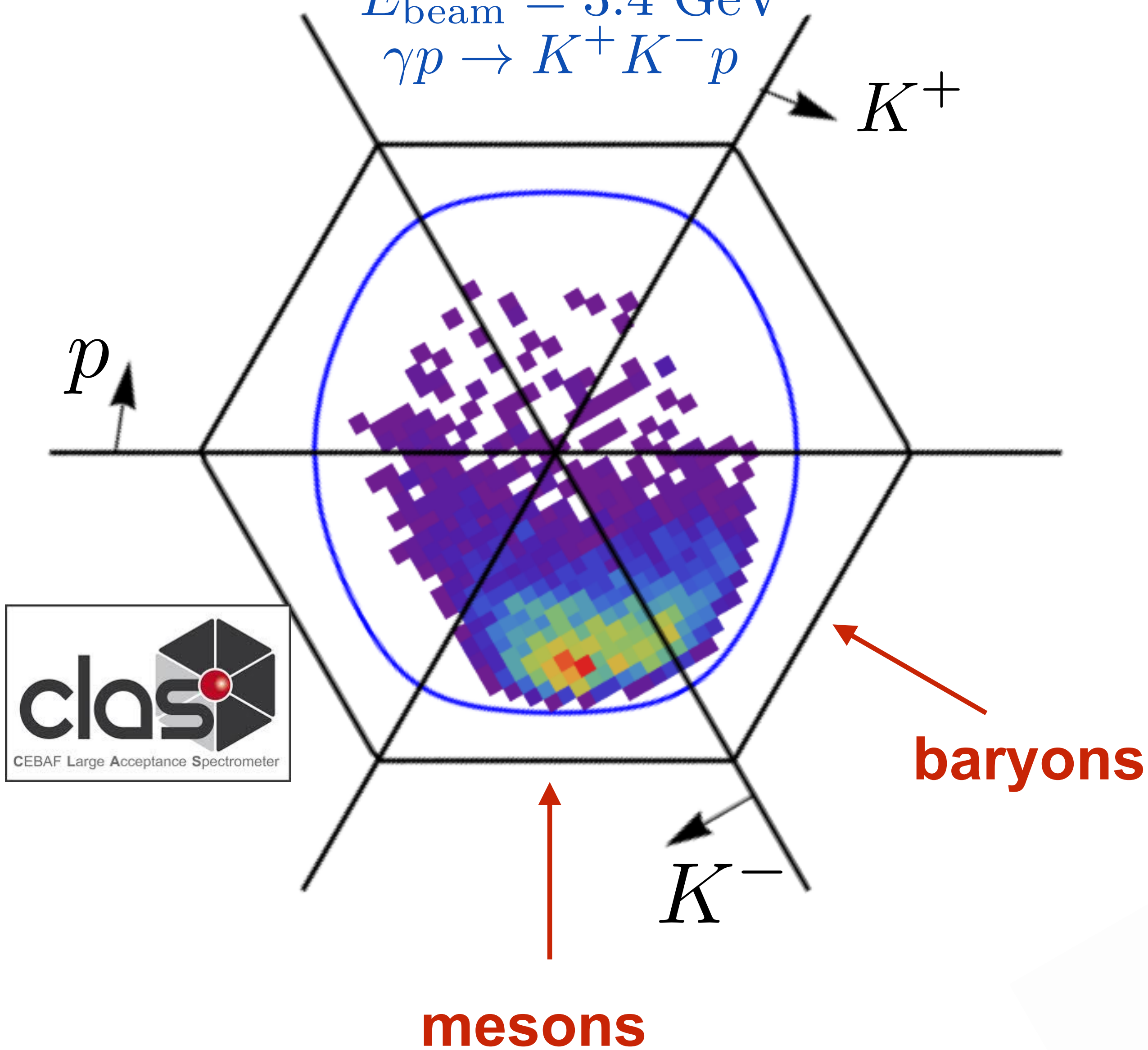




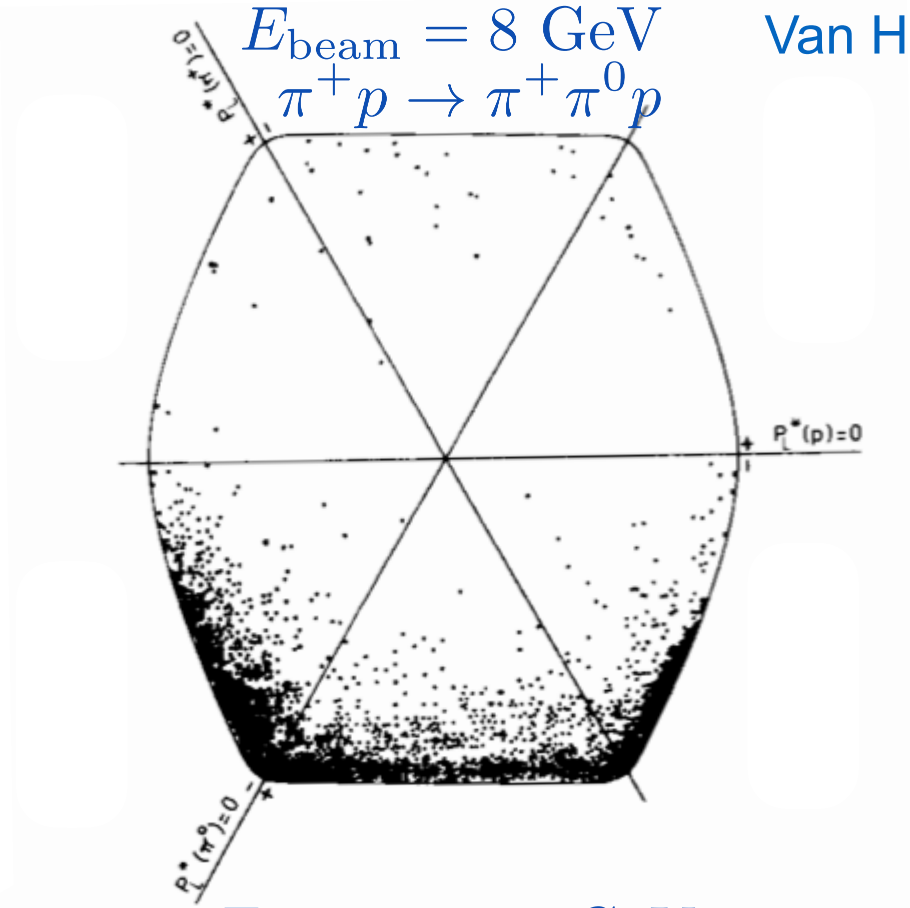


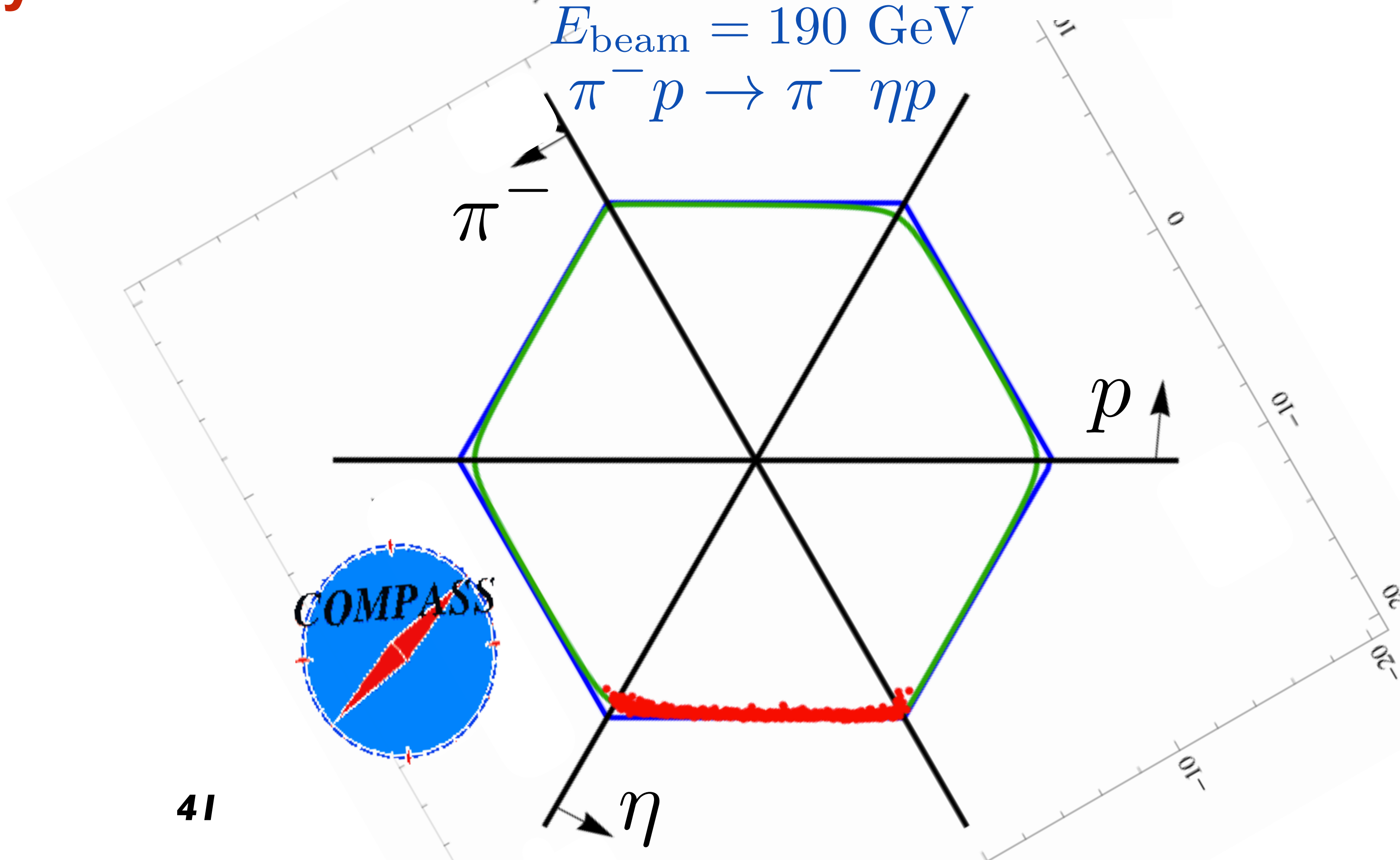


Longitudinal Plot: Energy Evolution



Van Hove (1969)

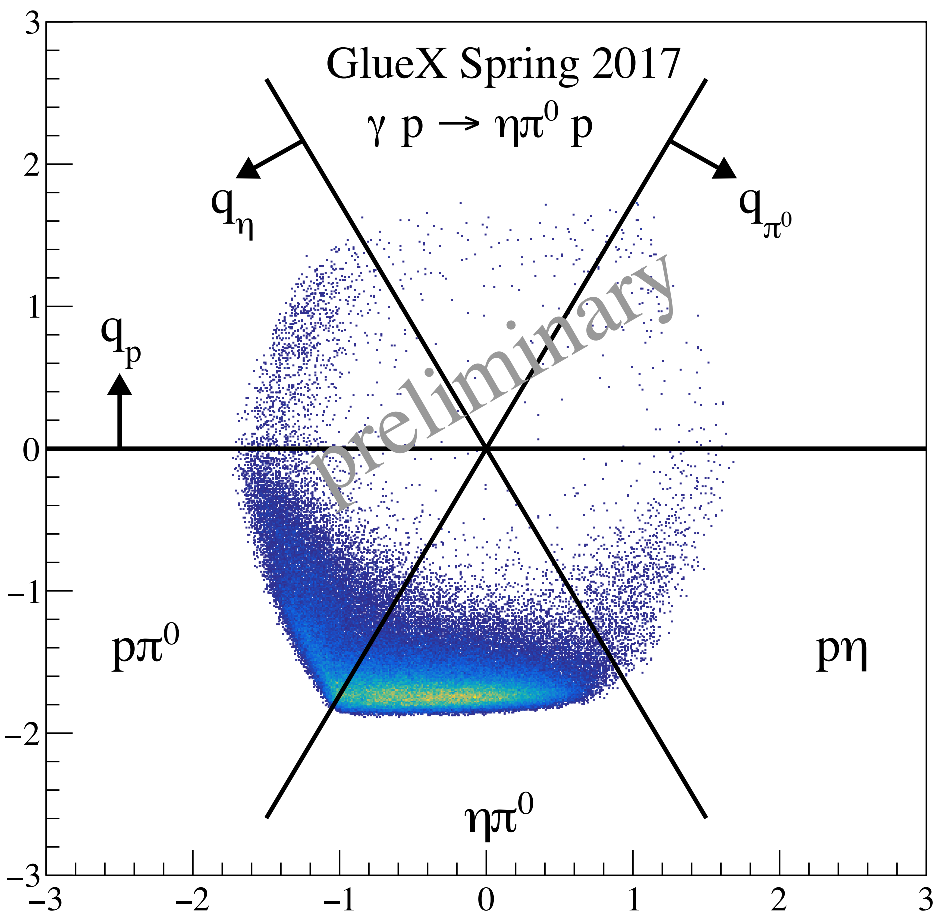




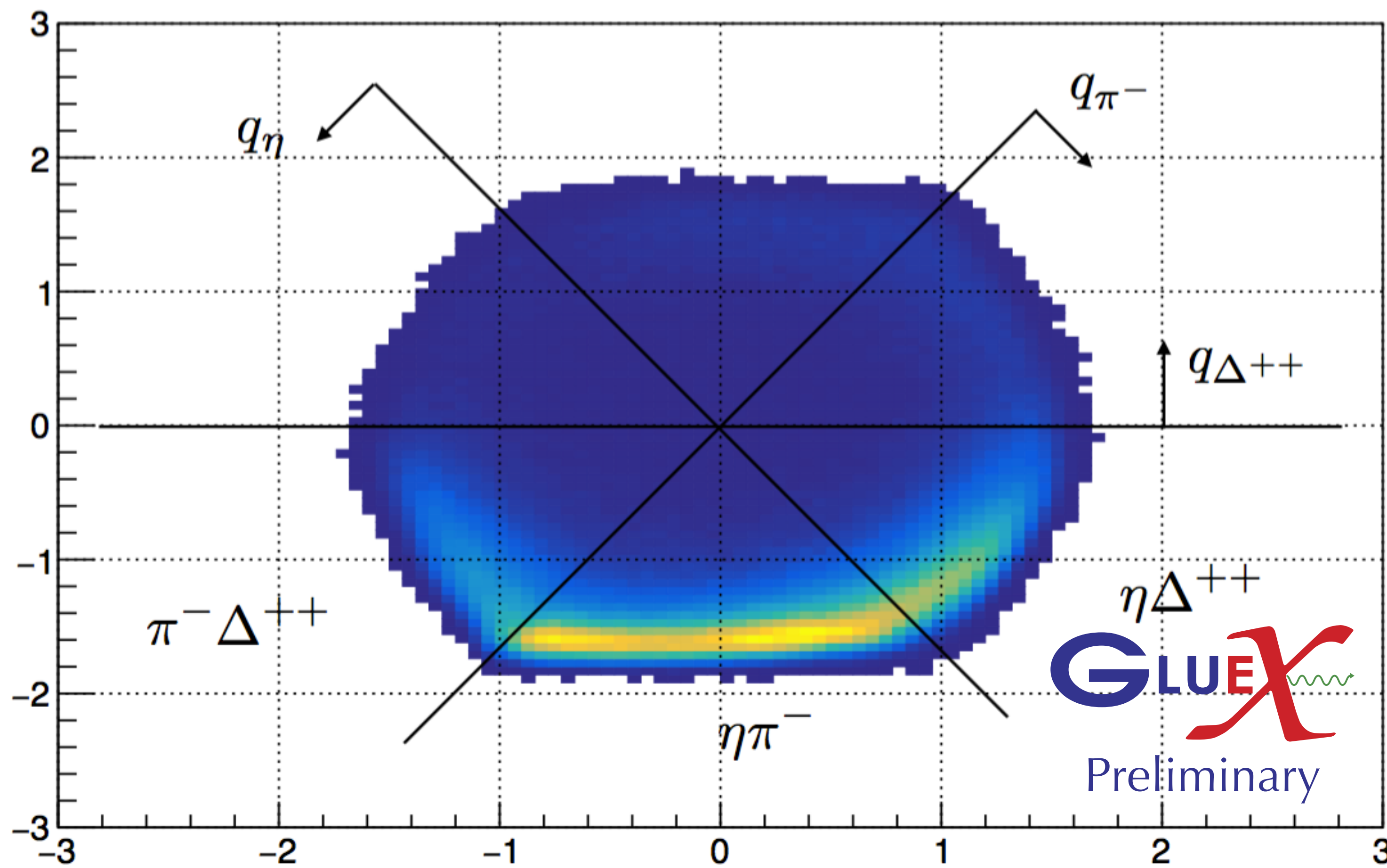
GlueX Preliminary Results

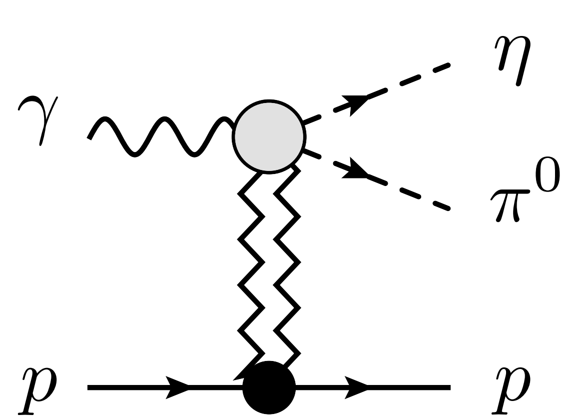
not corrected for acceptance

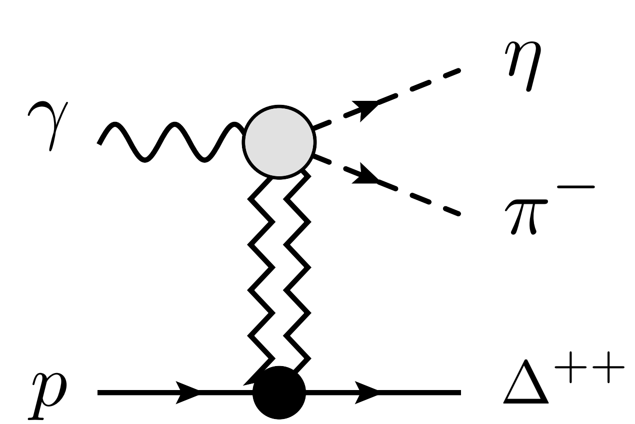
$\gamma p \to \eta\pi^0 p$



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







Courtesy of A. Austregesilo and C. Gleason

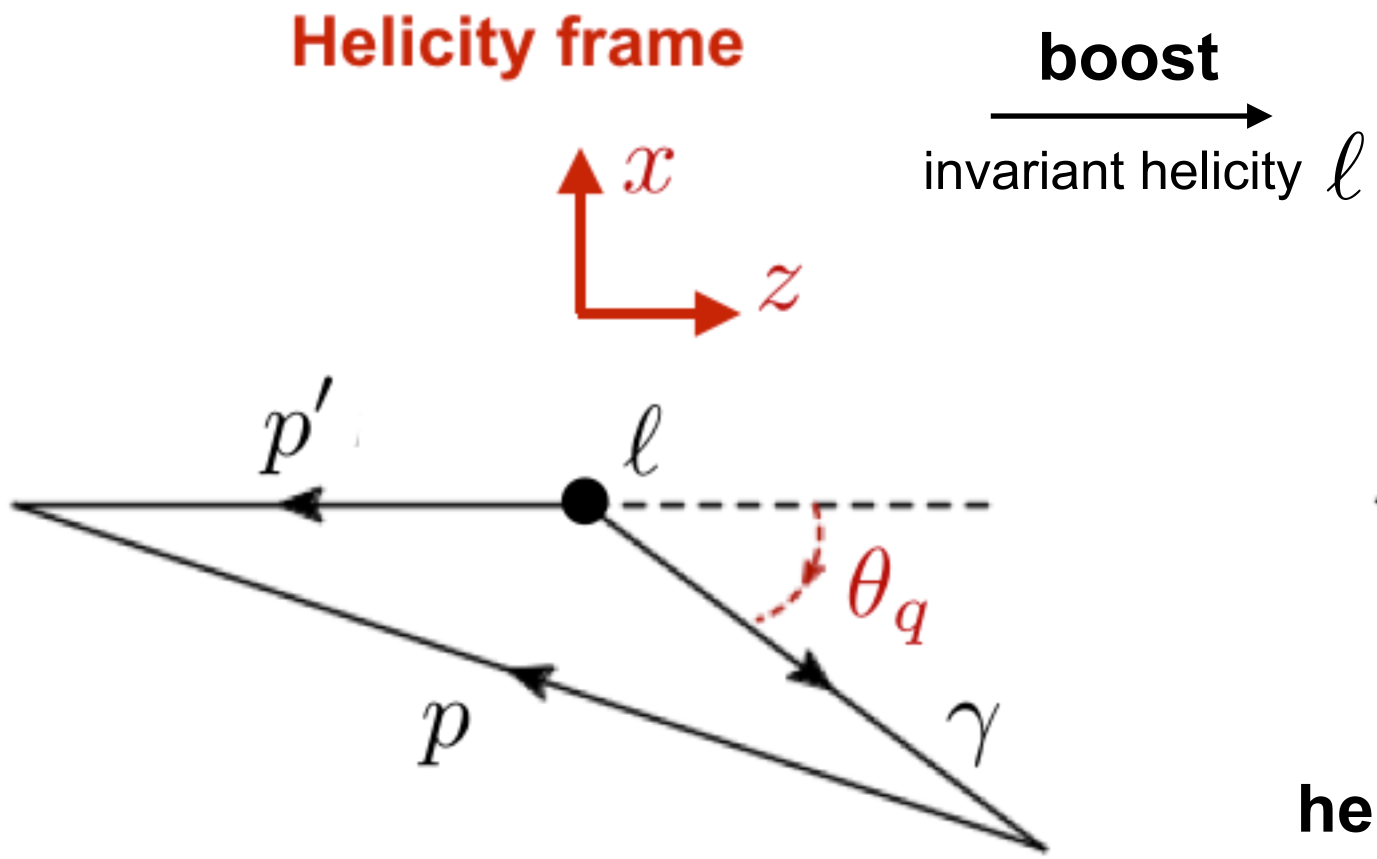
The resulting photon spin density matrix reads

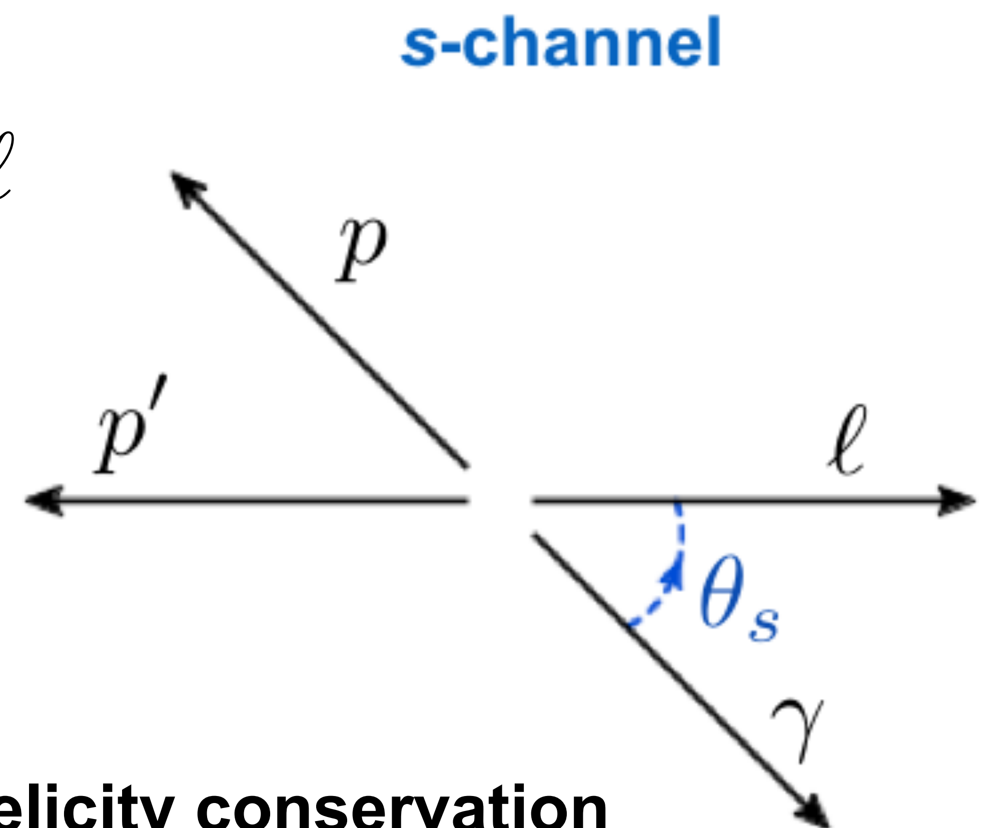
$$L_{\lambda\lambda'} = \frac{Q^2}{2(1-\epsilon)} \begin{pmatrix} 1 & \sqrt{\epsilon(1+\epsilon+2\delta)}\,e^{-i\Phi} & -\epsilon e^{-2i\Phi} \\ \sqrt{\epsilon(1+\epsilon+2\delta)}\,e^{i\Phi} & 2(\epsilon+\delta) & -\sqrt{\epsilon(1+\epsilon+2\delta)}\,e^{-i\Phi} \\ -\epsilon e^{2i\Phi} & -\sqrt{\epsilon(1+\epsilon+2\delta)}\,e^{i\Phi} & 1 \end{pmatrix} \quad (44)$$

$$\frac{Q^2\epsilon}{2(1-\epsilon)} = l_x^2$$

Schilling and Wolf NPB61 (1973) 381

Frame

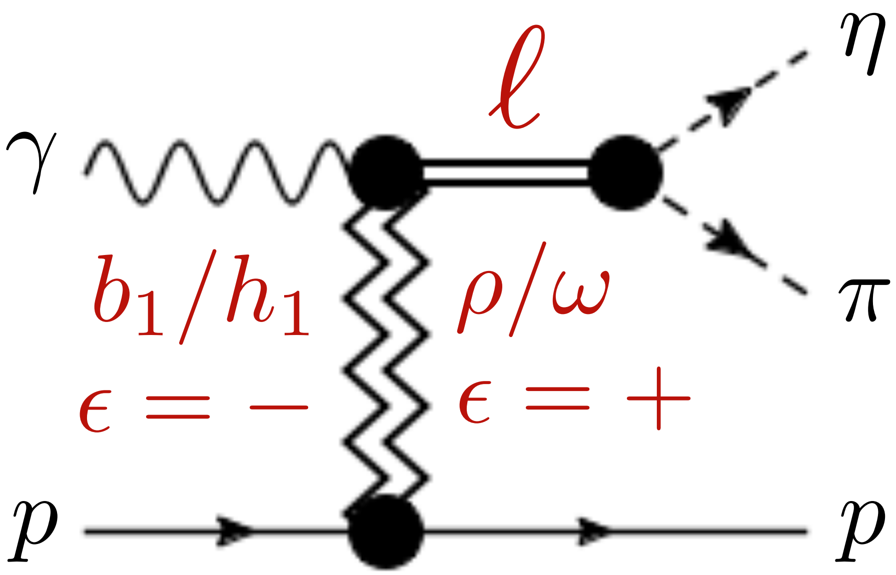




helicity conservation

between γ **and** ℓ

$$T_{\lambda_\gamma m} \simeq \delta_{\lambda_\gamma, m} T_{\lambda_\gamma m} + \dots$$



Reflectivity basis:

$$[\ell]_m^{(\epsilon)} = T_{1m} - \epsilon T_{-1-m}$$

Dominant: $(\epsilon = +, m = 1)$

Observables: Moments of Angular distribution

$$H^0(LM) = \frac{1}{2\pi}\int I(\Omega,\Phi)\, d^L_{M0}(\theta)\cos M\phi\, \mathrm{d}\Omega\mathrm{d}\Phi$$

$$H^1(LM) = \frac{-1}{\pi P_\gamma}\int I(\Omega,\Phi)\cos 2\Phi\, d^L_{M0}(\theta)\cos M\phi\, \mathrm{d}\Omega\mathrm{d}\Phi$$

$$\mathrm{Im}\, H^2(LM) = \frac{1}{\pi P_\gamma}\int I(\Omega,\Phi)\sin 2\Phi\, d^L_{M0}(\theta)\sin M\phi\, \mathrm{d}\Omega\mathrm{d}\Phi$$

$m' = m - M$

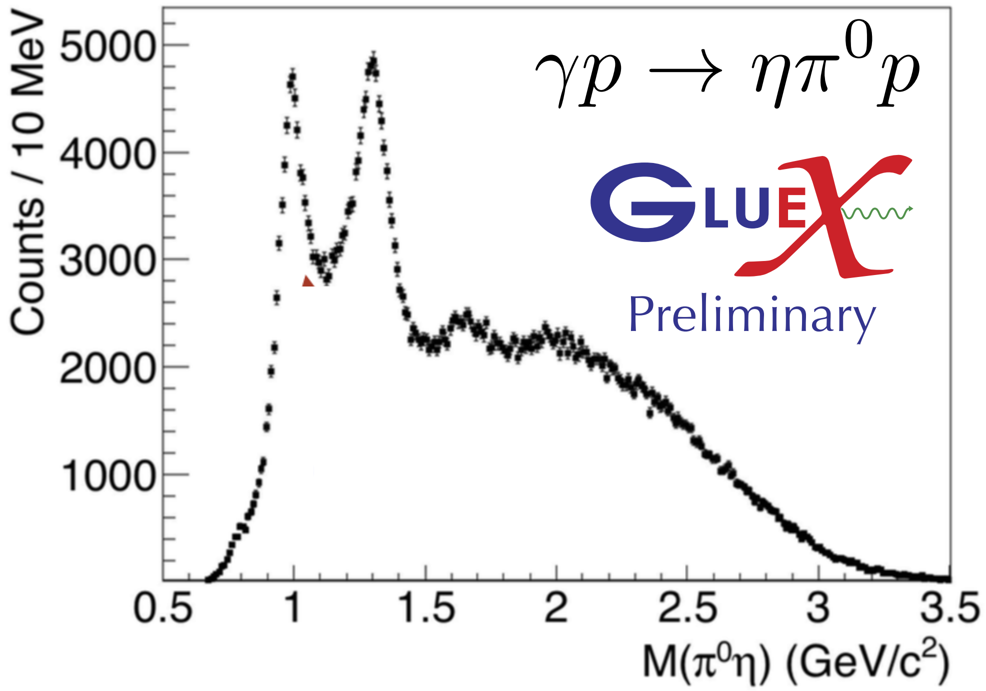
$$H^1(LM) + \mathrm{Im}\ H^2(LM) \propto \sum_{\substack{\epsilon,\ \ell\ell' \\ mm'}} \left(\frac{2\ell'+1}{2\ell+1}\right)^{1/2} \epsilon(-1)^m C^{\ell 0}_{\ell' 0 L 0} C^{\ell m}_{\ell' m' L M}\, [\ell]^{(\epsilon)}_{-m} [\ell']^{(\epsilon)*}_{m'}$$

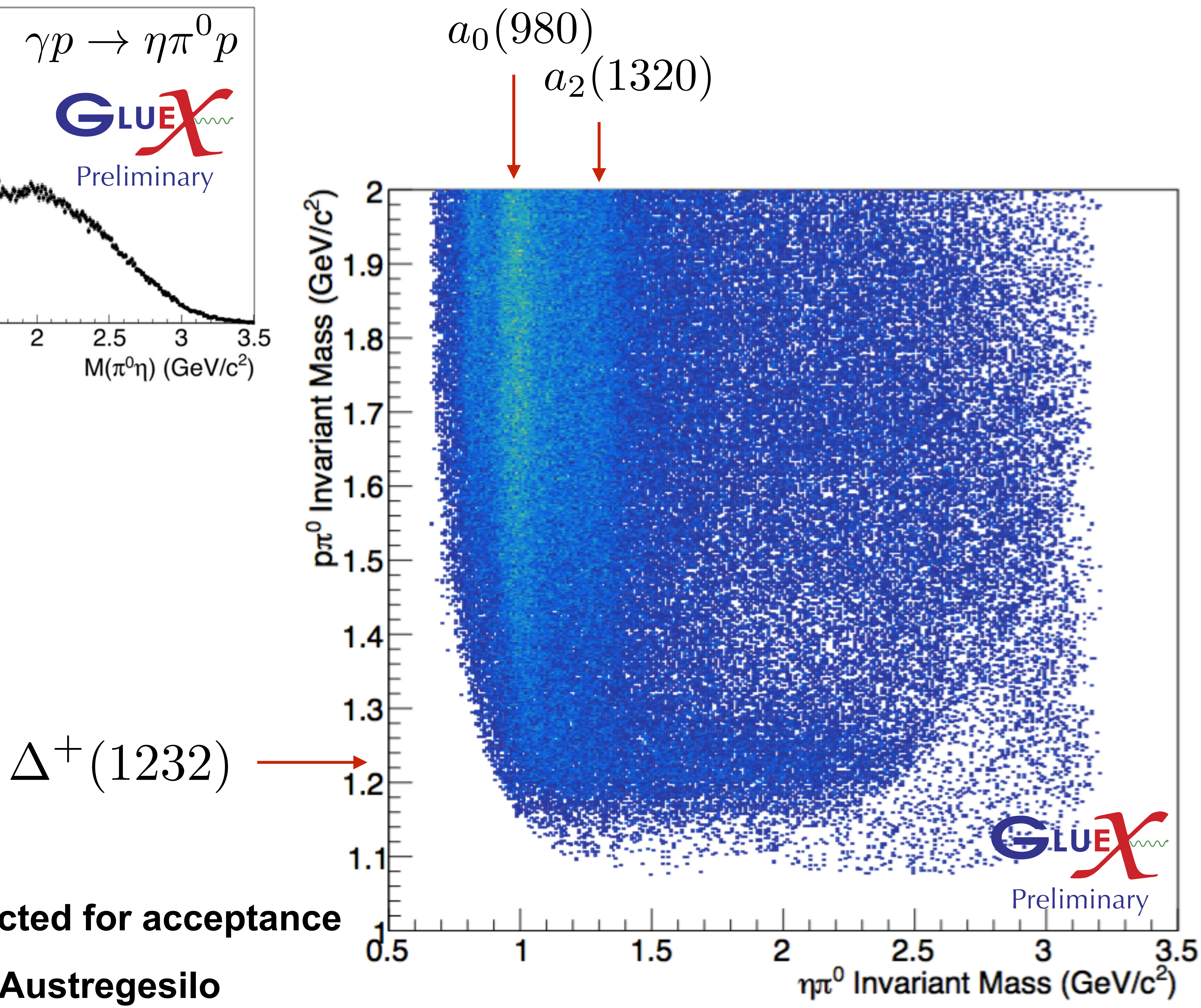
$0 \leqslant -m\ ;\ 0 \leqslant m'$

The model features only positive projections

$$H^1(LM) + \mathrm{Im}\ H^2(LM) = 0 \qquad M \geqslant 1$$

Eta-Pi Production@GlueX

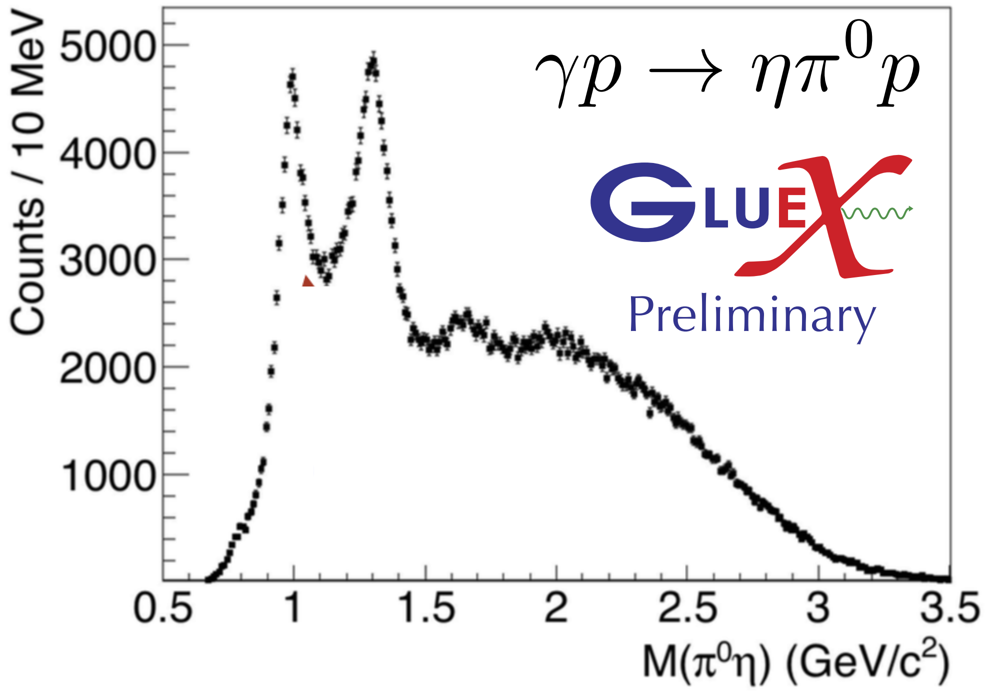


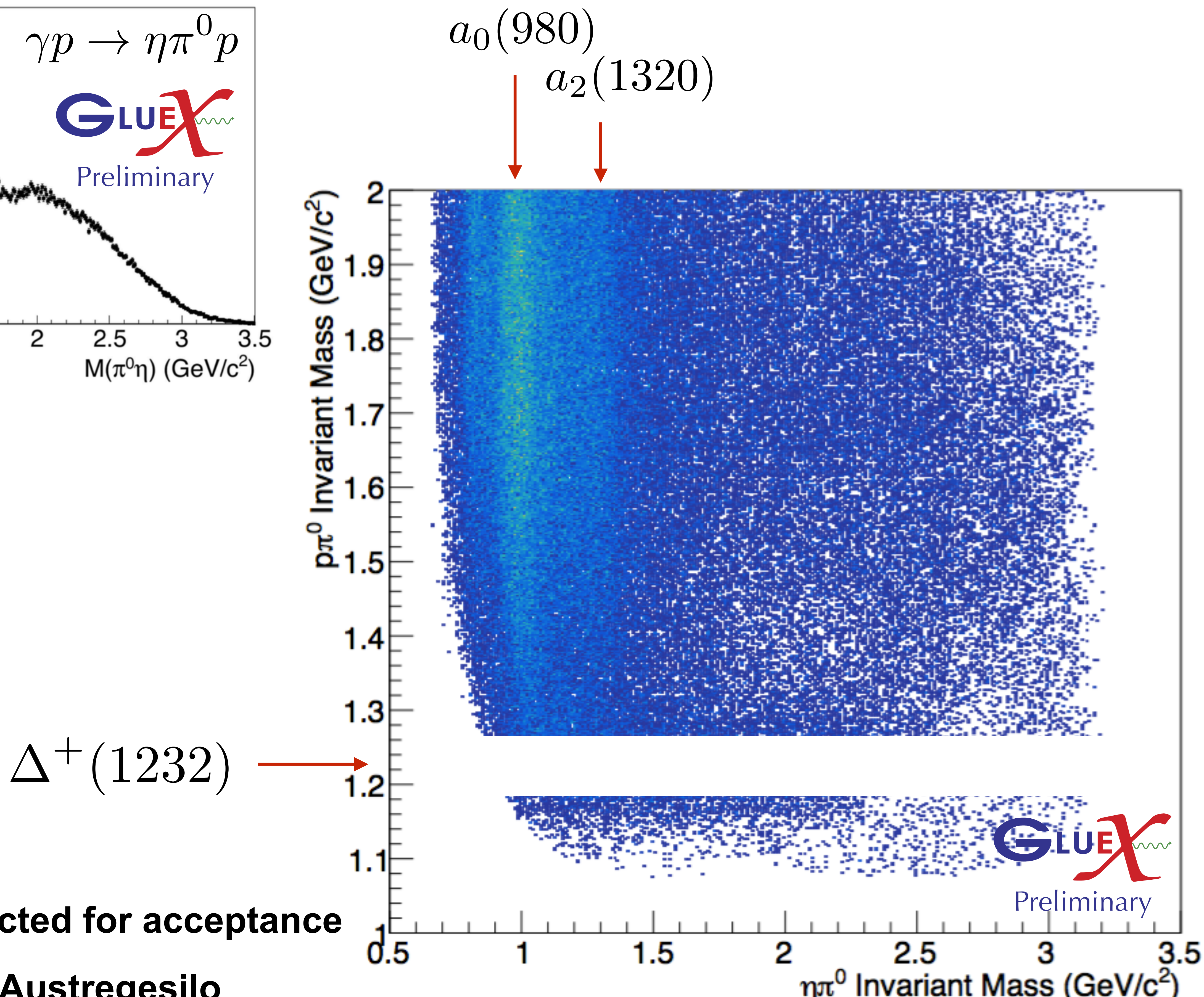


data non-corrected for acceptance

Courtesy of A. Austregesilo

Eta-Pi Production@GlueX

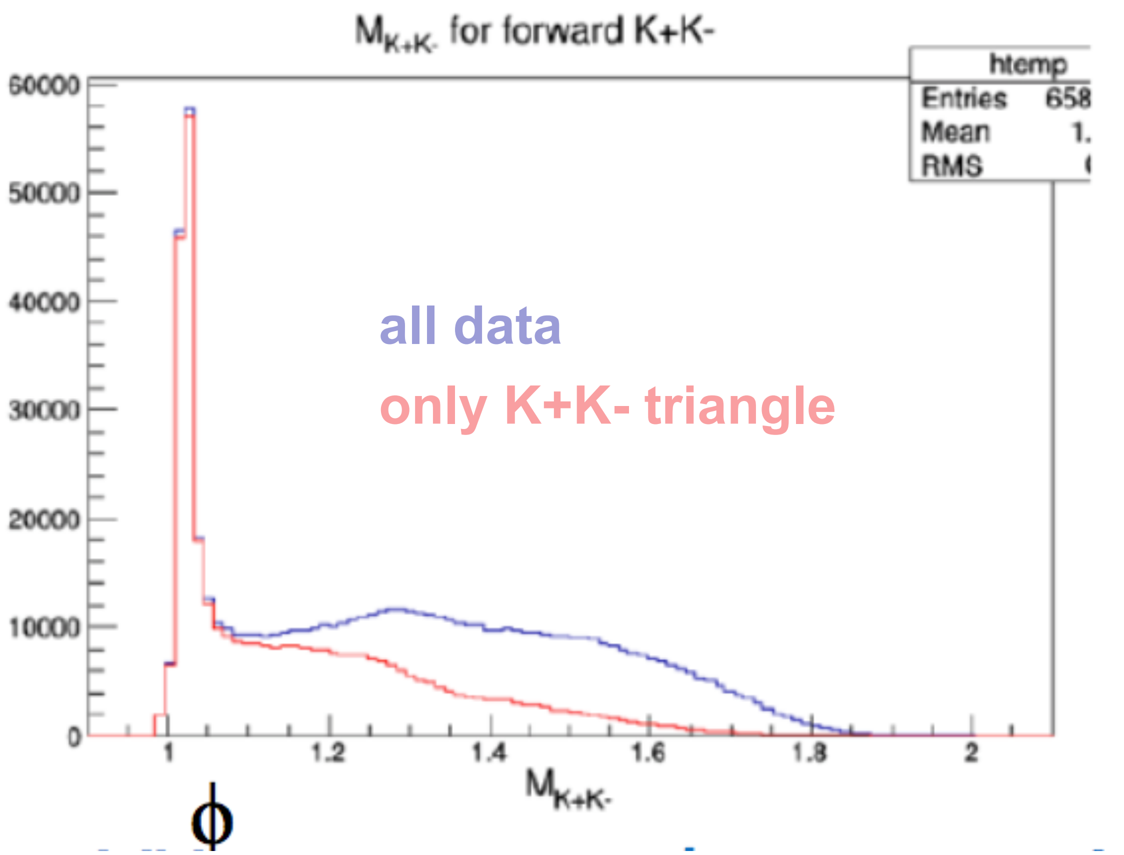


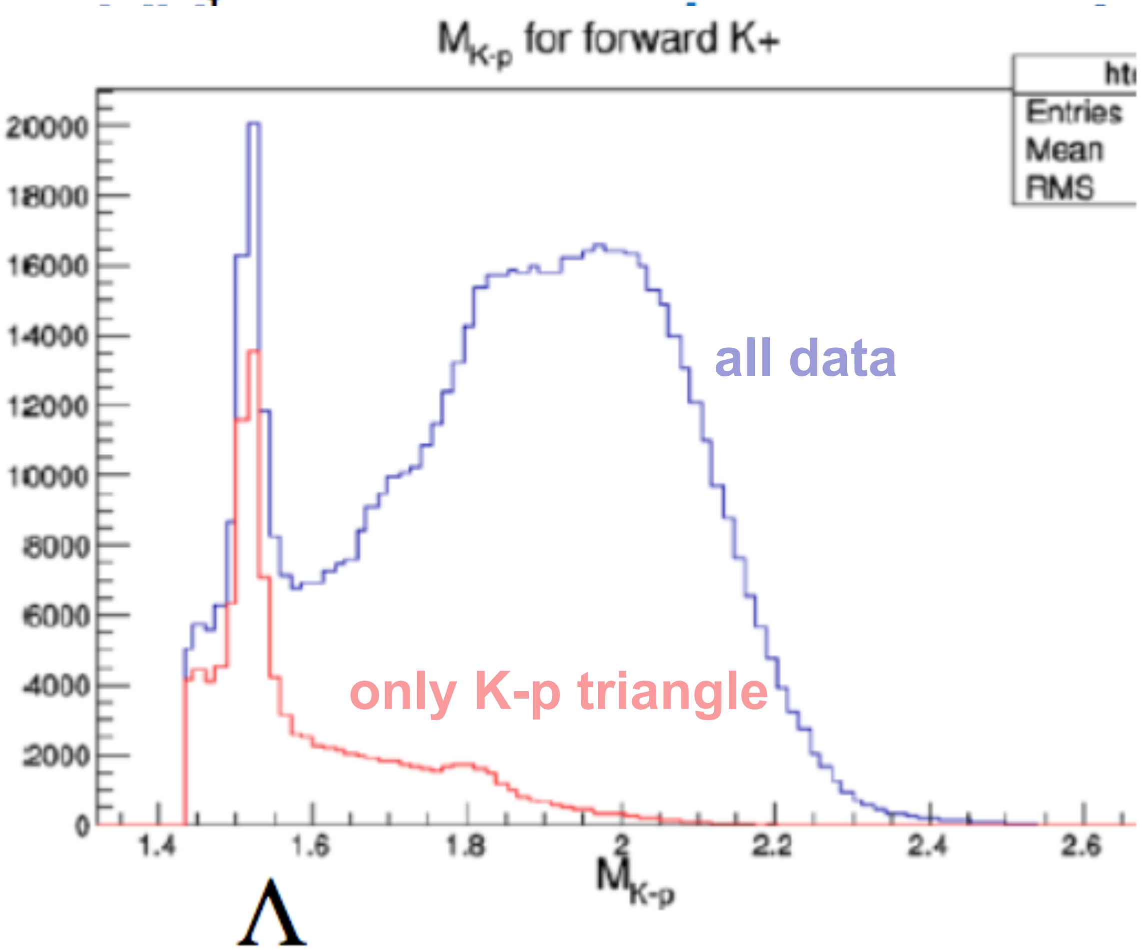


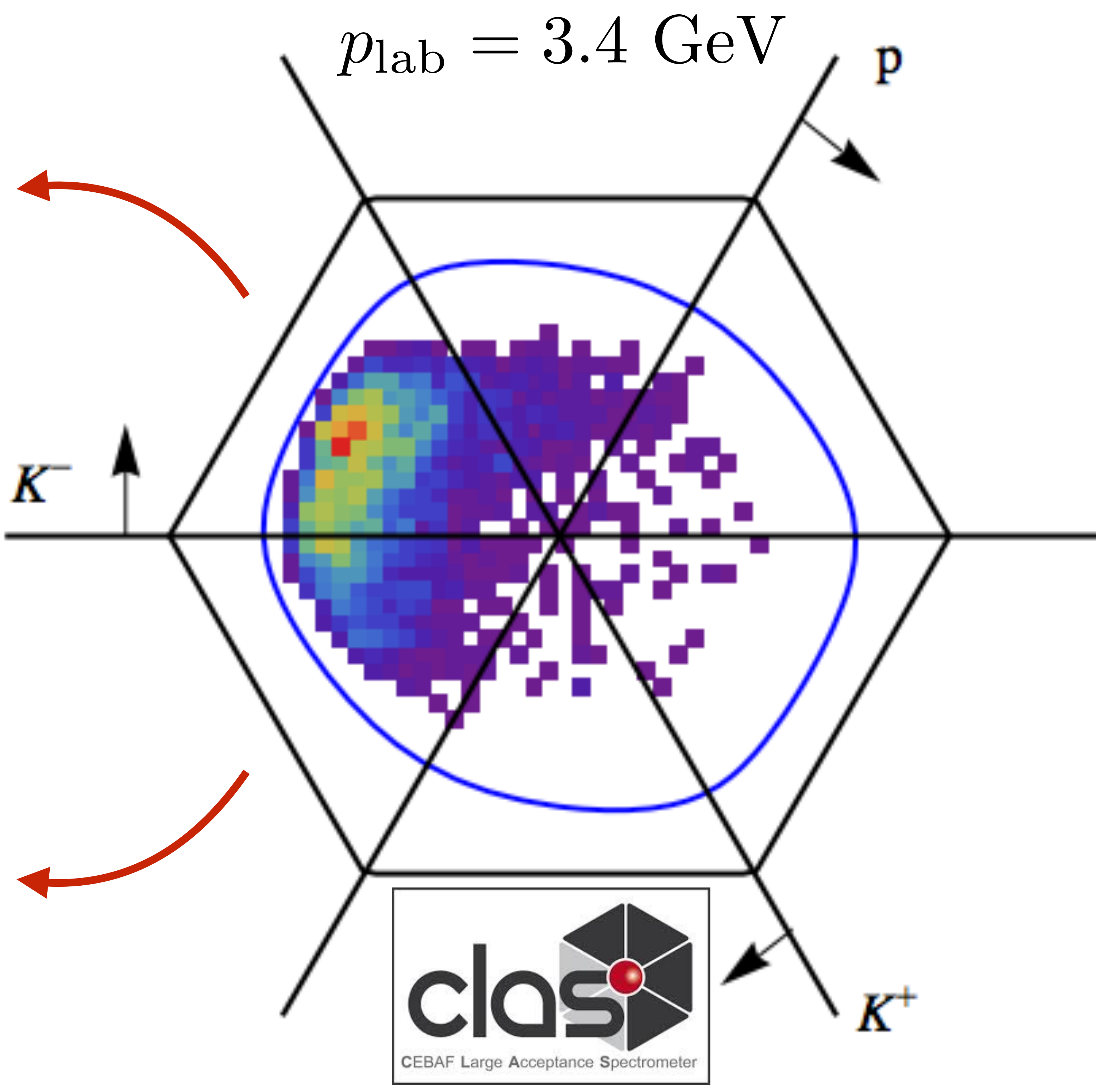
data non-corrected for acceptance

Courtesy of A. Austregesilo

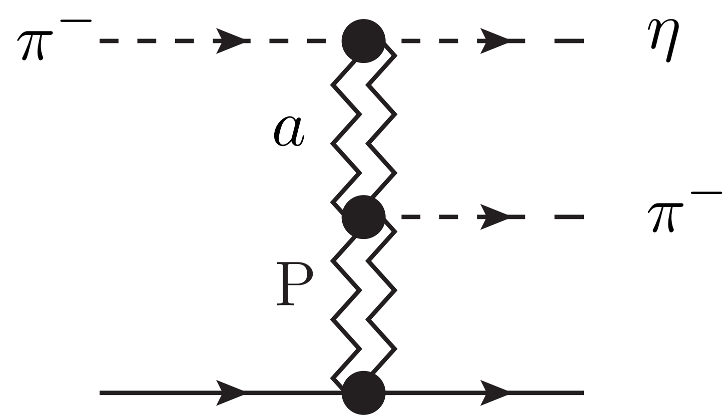
Longitudinal Plot





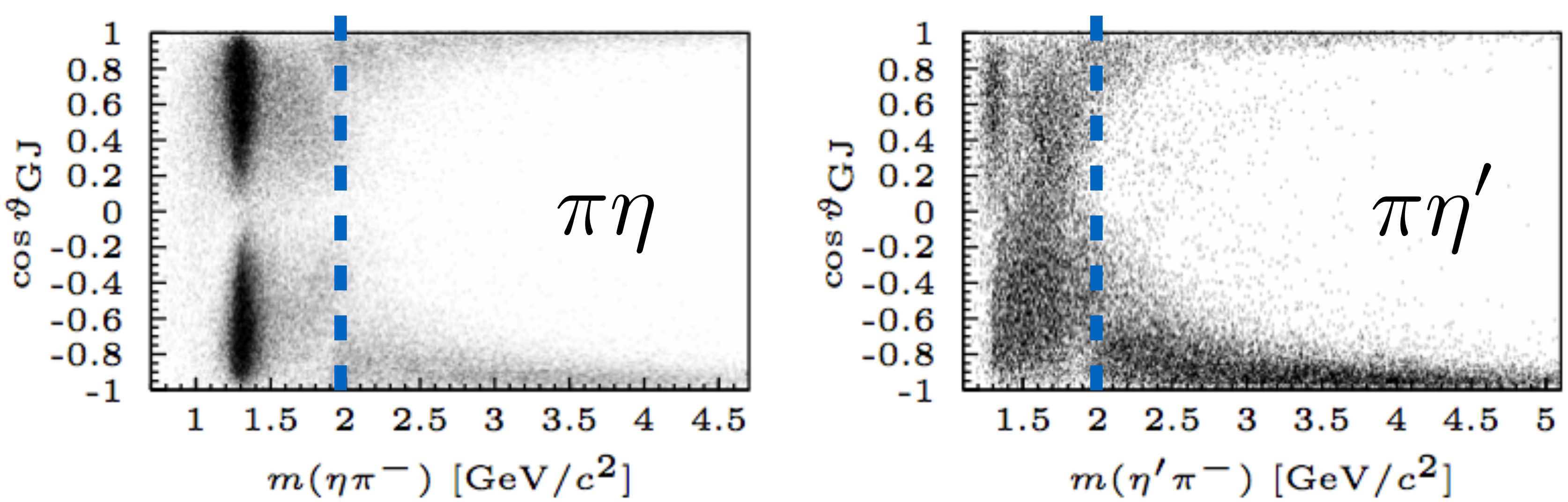


High Mass Region

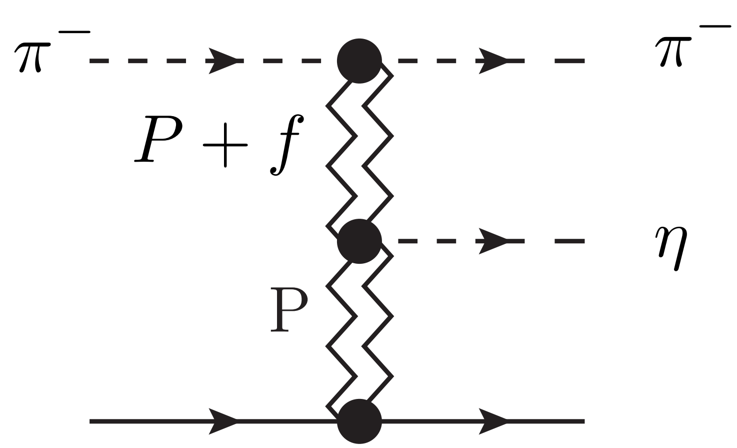


$a : I^G J^{PC} = 1^-(0, 2, 4, 6, \ldots)^{++}$

$\cos\theta_{GF} \sim 1 \rightarrow \eta$ forward

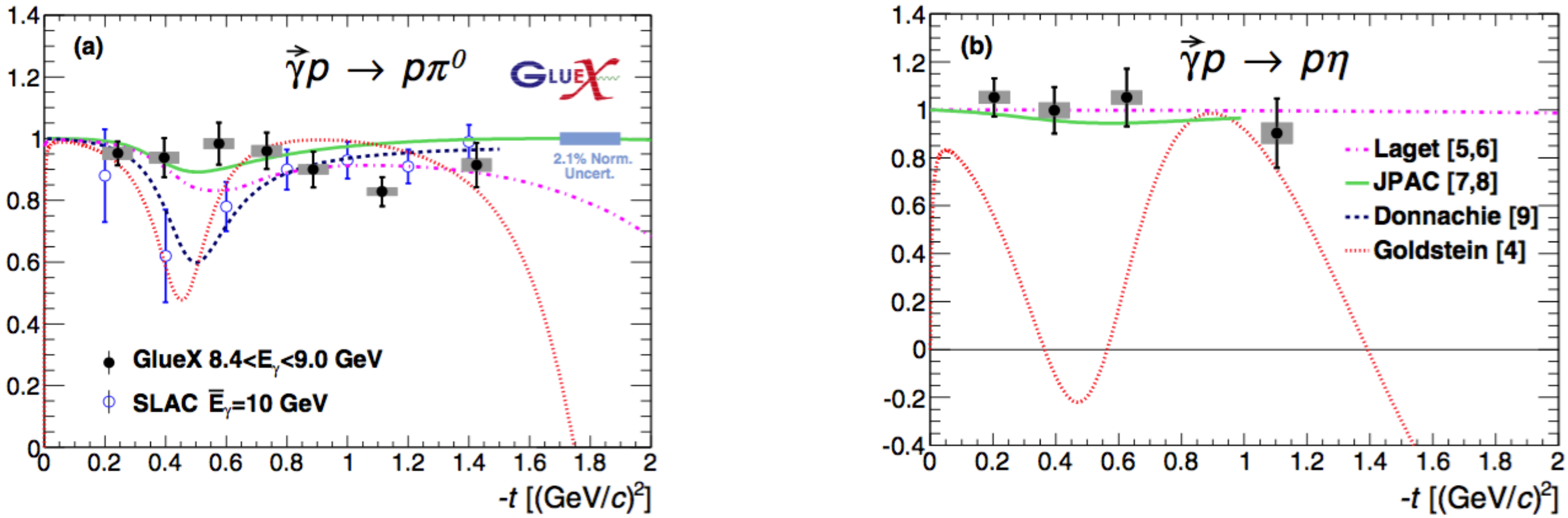


$\cos\theta_{GF} \sim -1 \rightarrow \eta$ backward



$f : I^G J^{PC} = 0^+(0, 2, 4, 6, \ldots)^{++}$

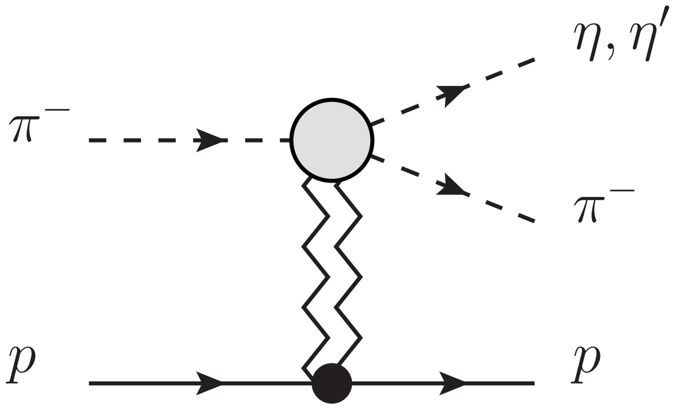
GlueX Results

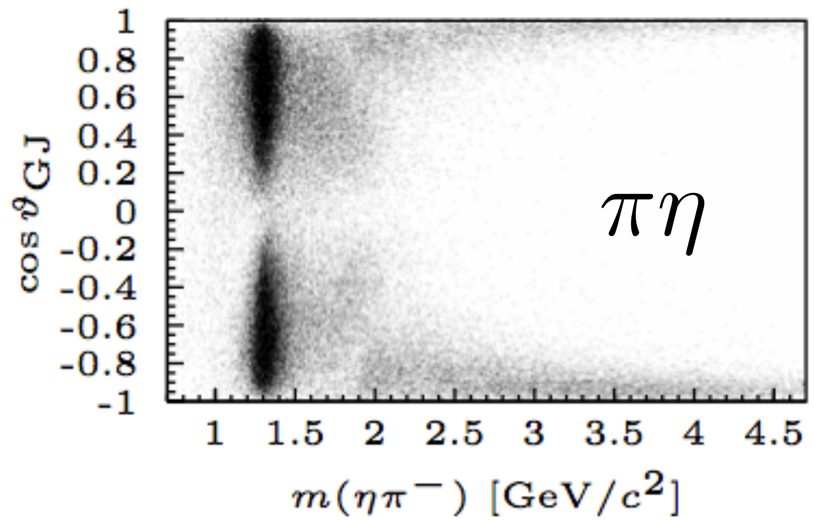


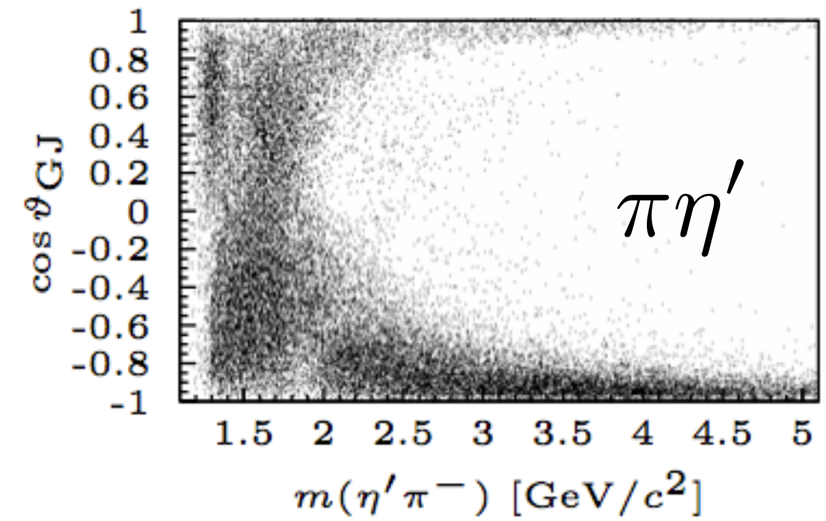
GlueX, VM and J. Nys PRC95 (2017)

Eta-Pi @COMPASS

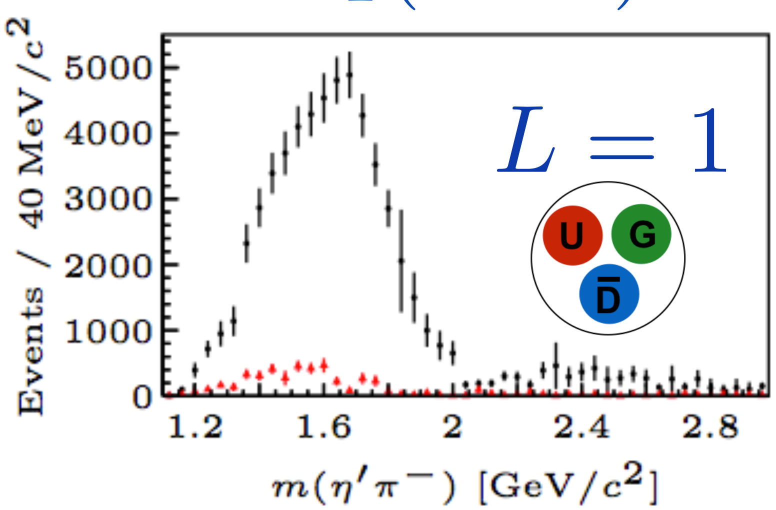
COMPASS Phys. Lett. B740 (2015)



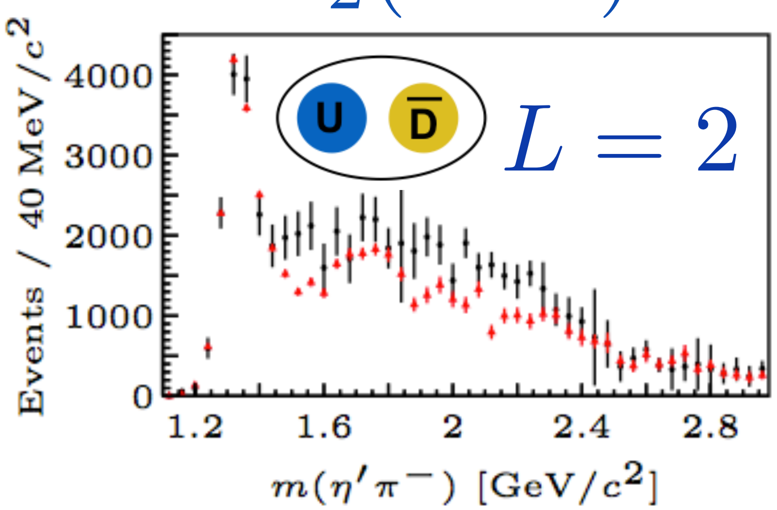




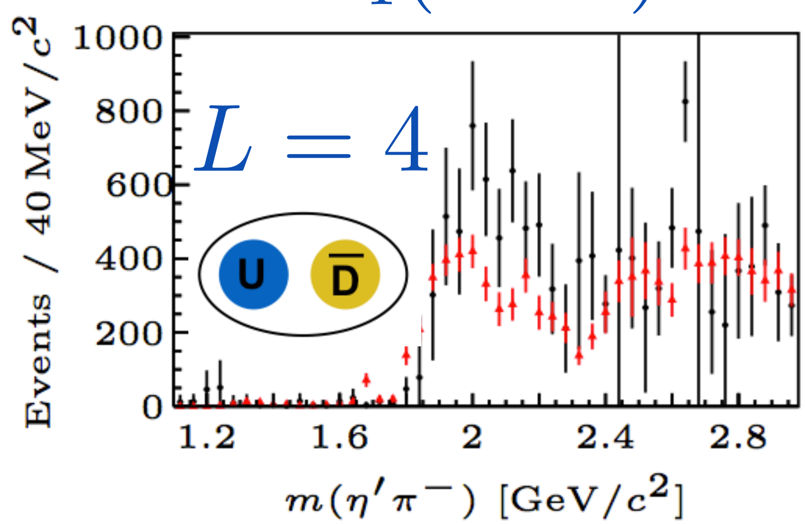
$\pi_1(1600)$?

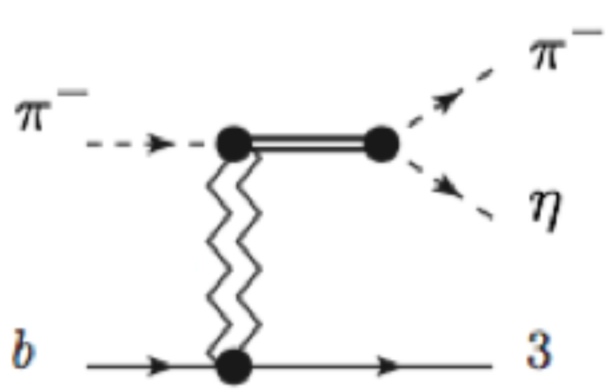


$a_2(1320)$



$a_4(2040)$

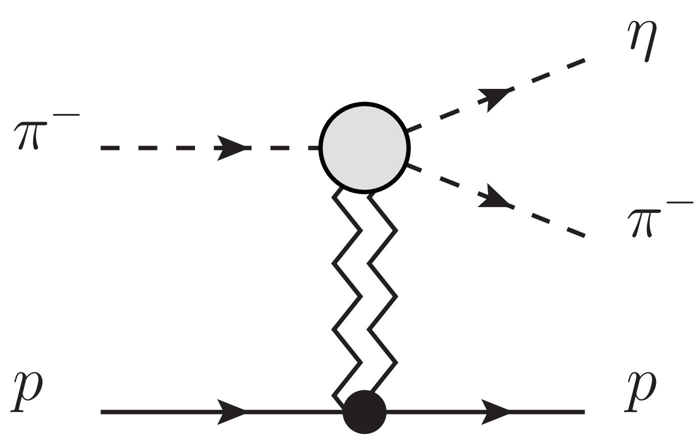


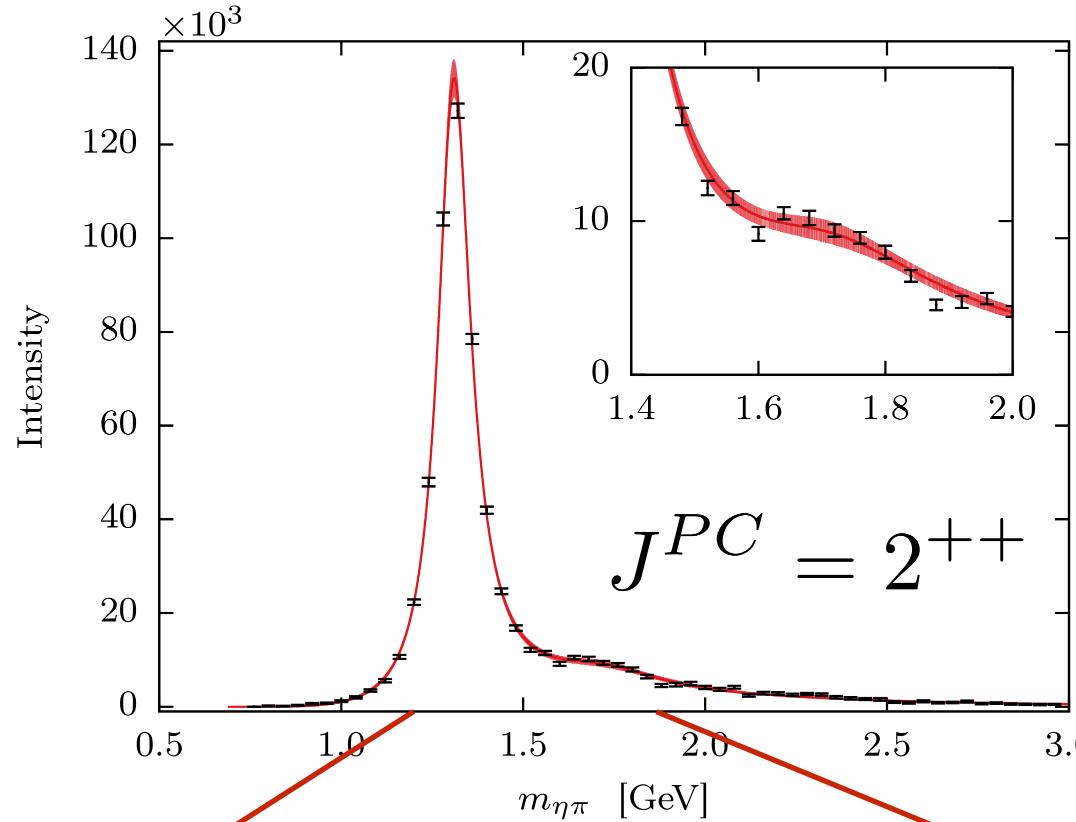


black: $\pi\eta'$

red: $\pi\eta$ **(scaled)**

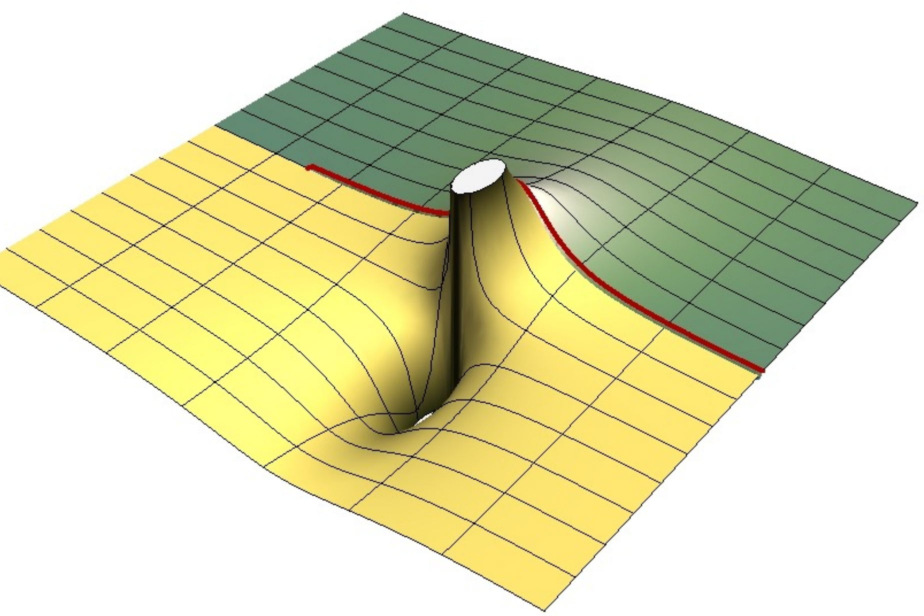
Resonance in angular mom. L = 1 ?

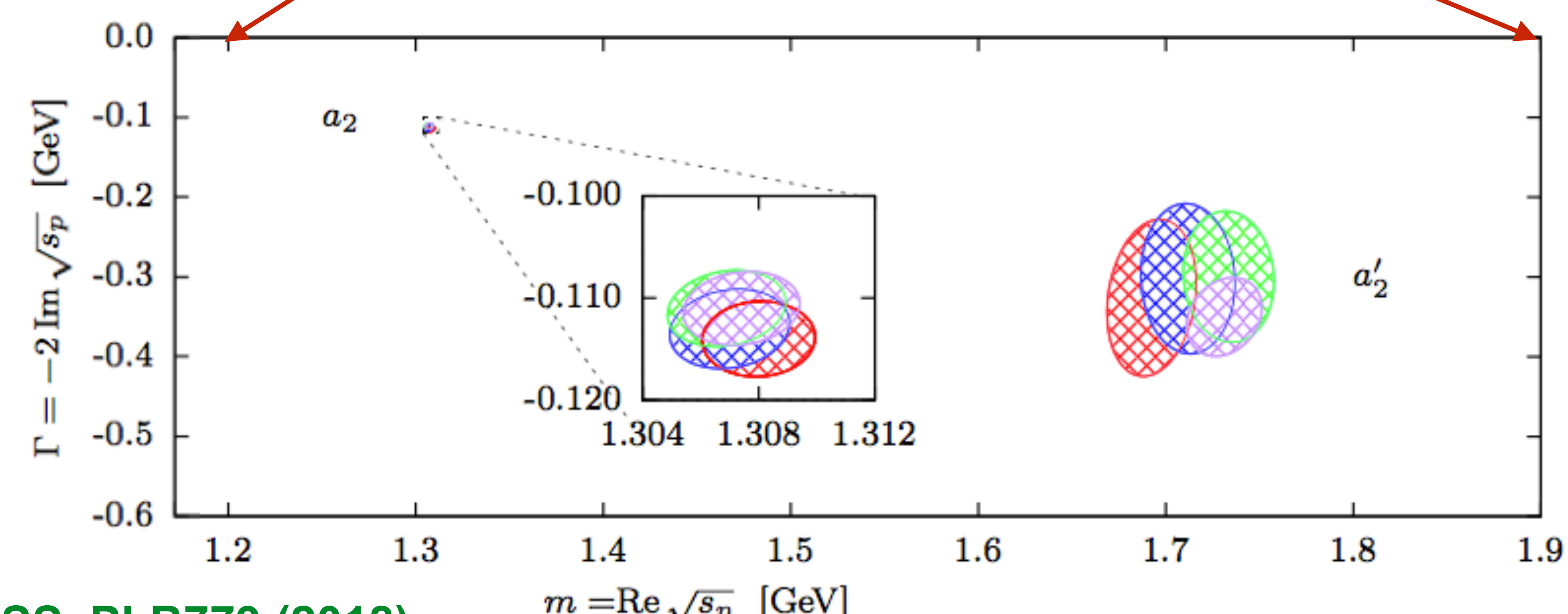




first precise determination of

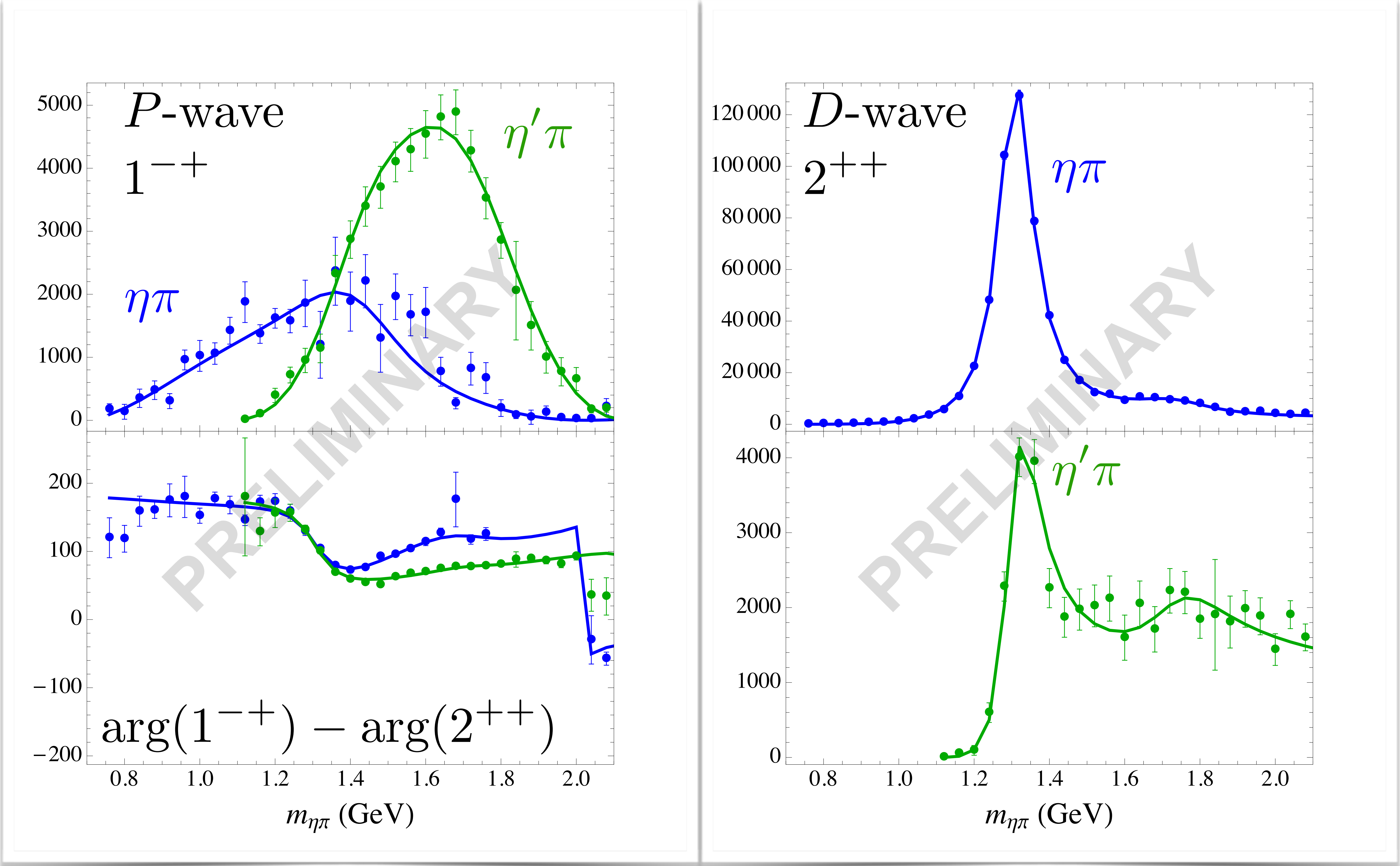
$a_2(1700)$ **pole location**





A. Jackura et al (JPAC) and COMPASS, PLB779 (2018)

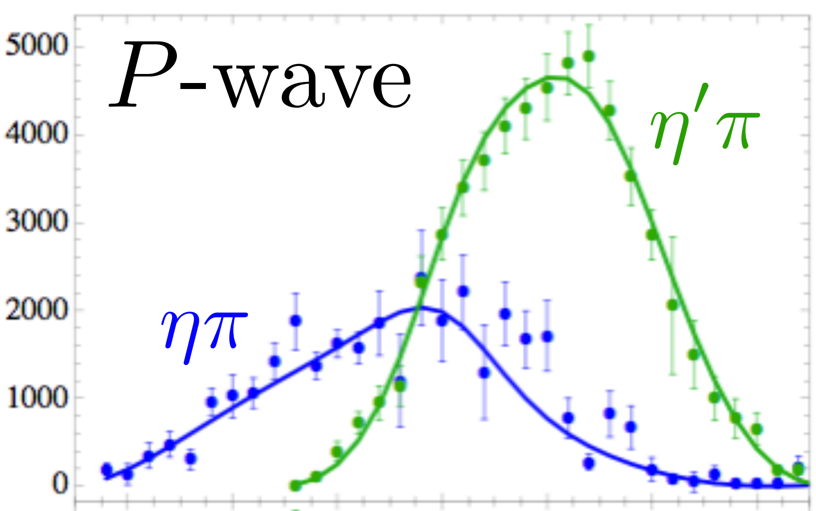
Exotic wave @COMPASS

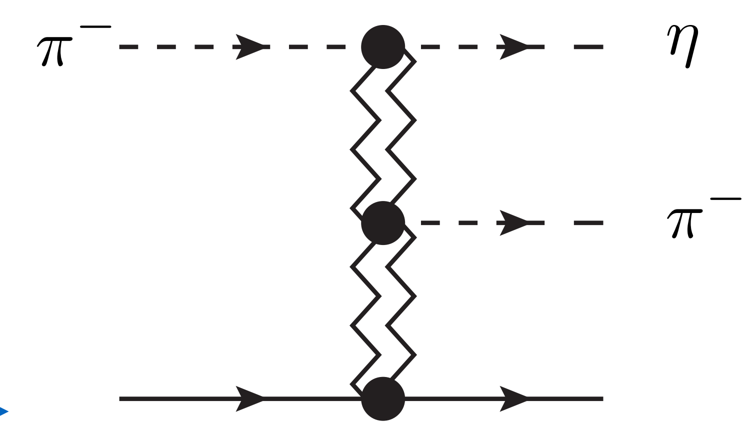


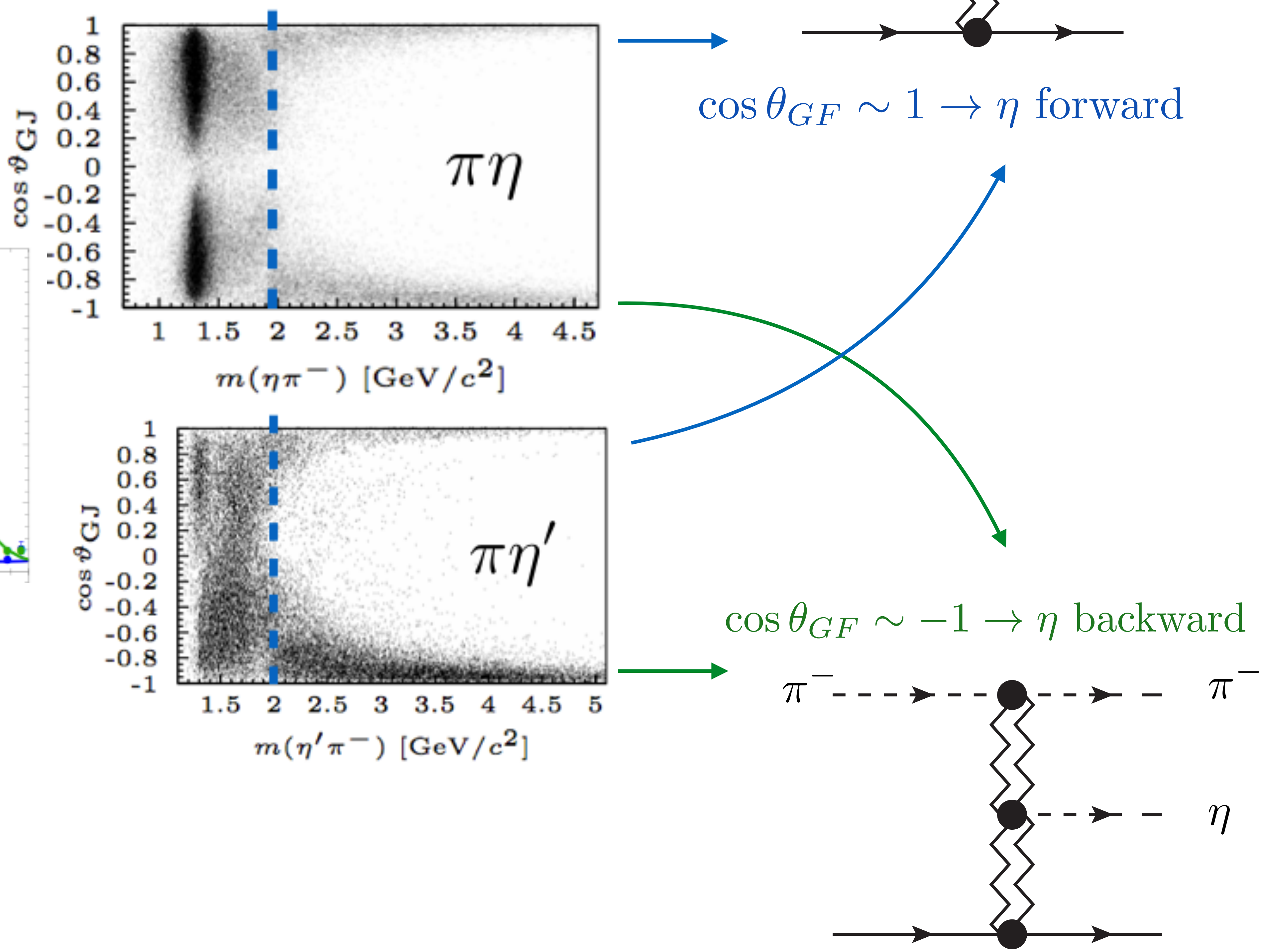
On-going analysis: Systematic studies and exploration of the complex plane

Exotic wave @COMPASS

Dispersion relation relates the high (exchanges) and the low (resonances) regions

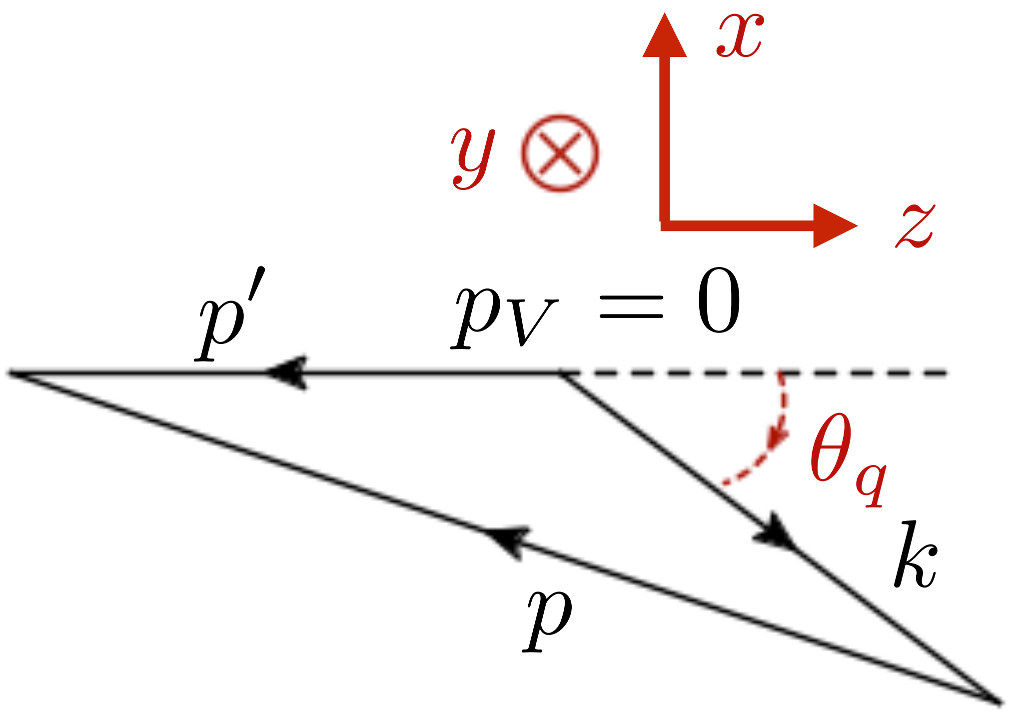




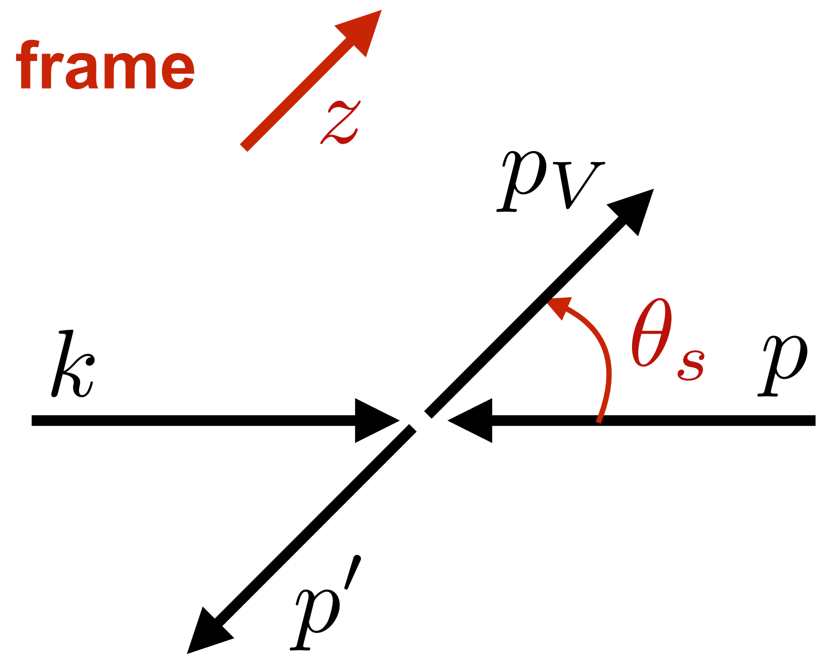


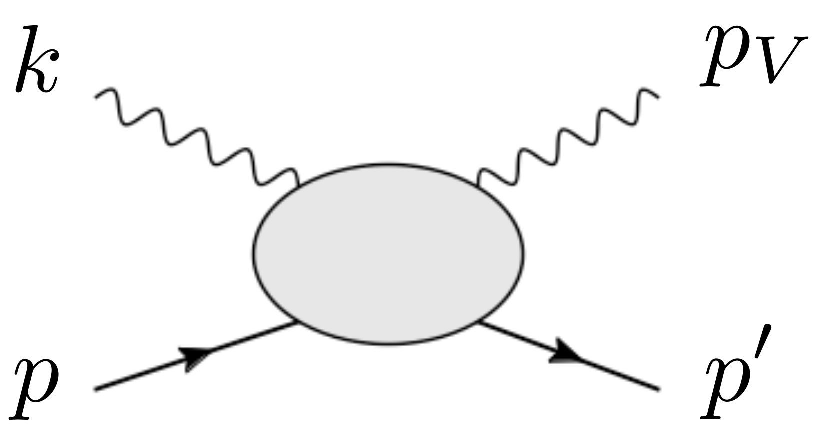
Frames

Helicity frame

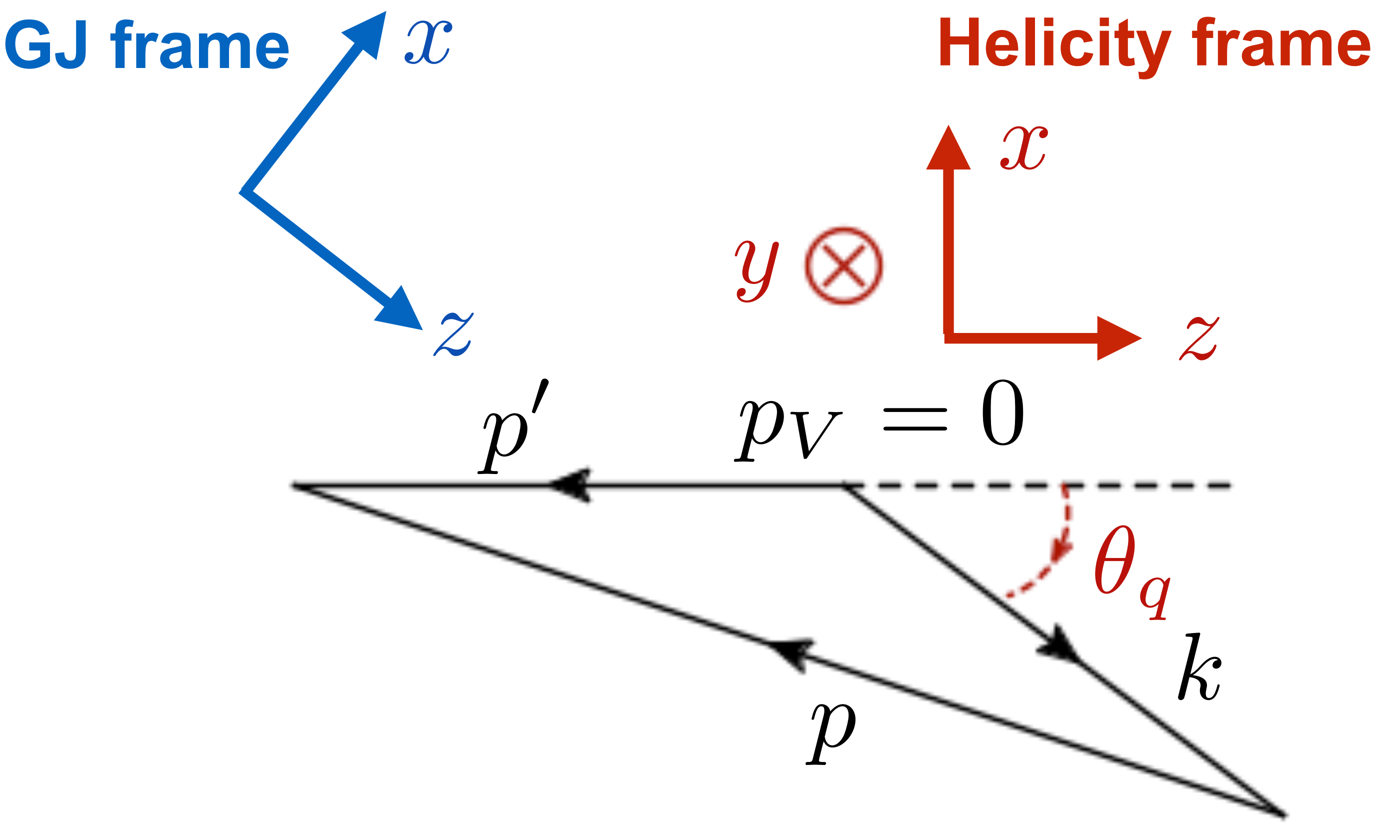


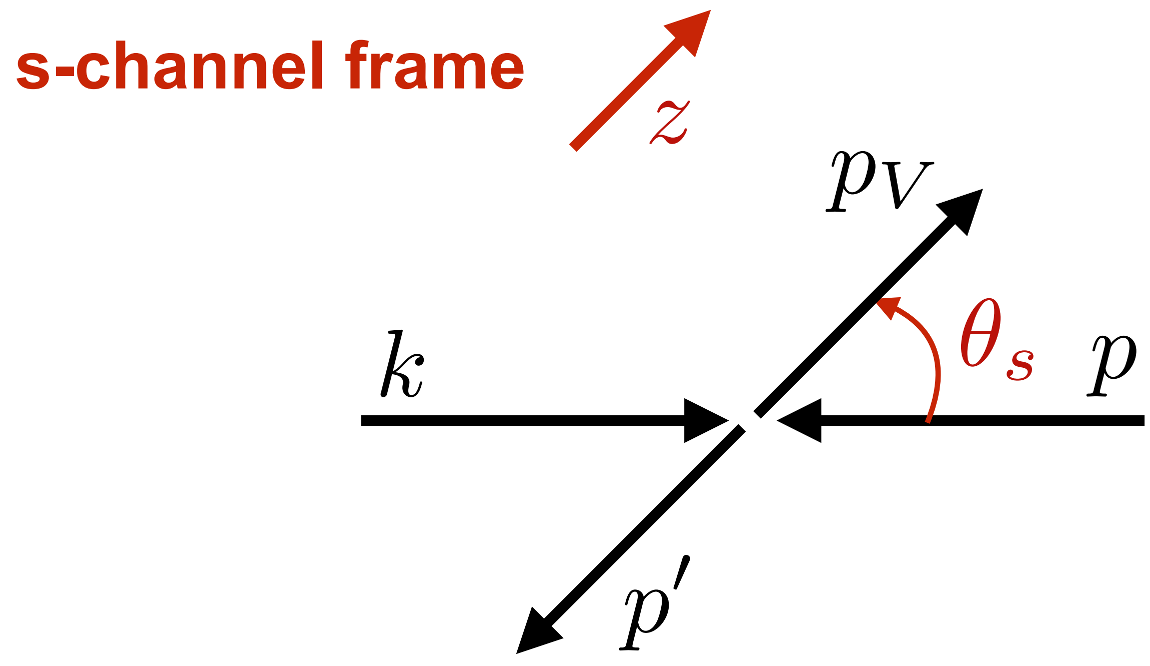
s-channel frame

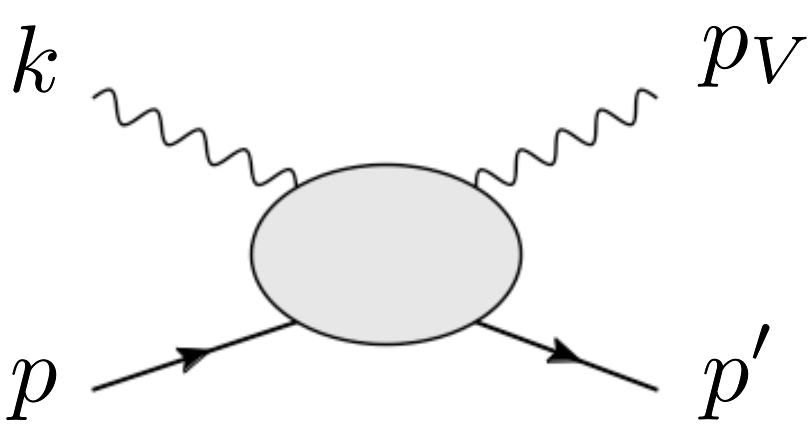


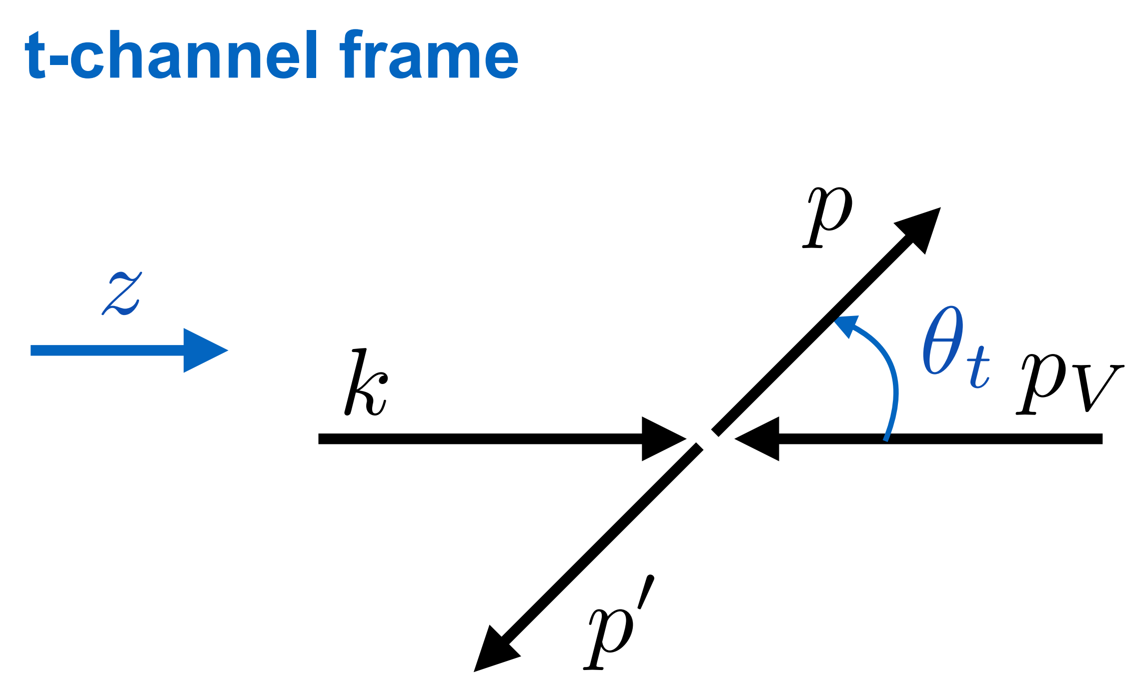


Frames

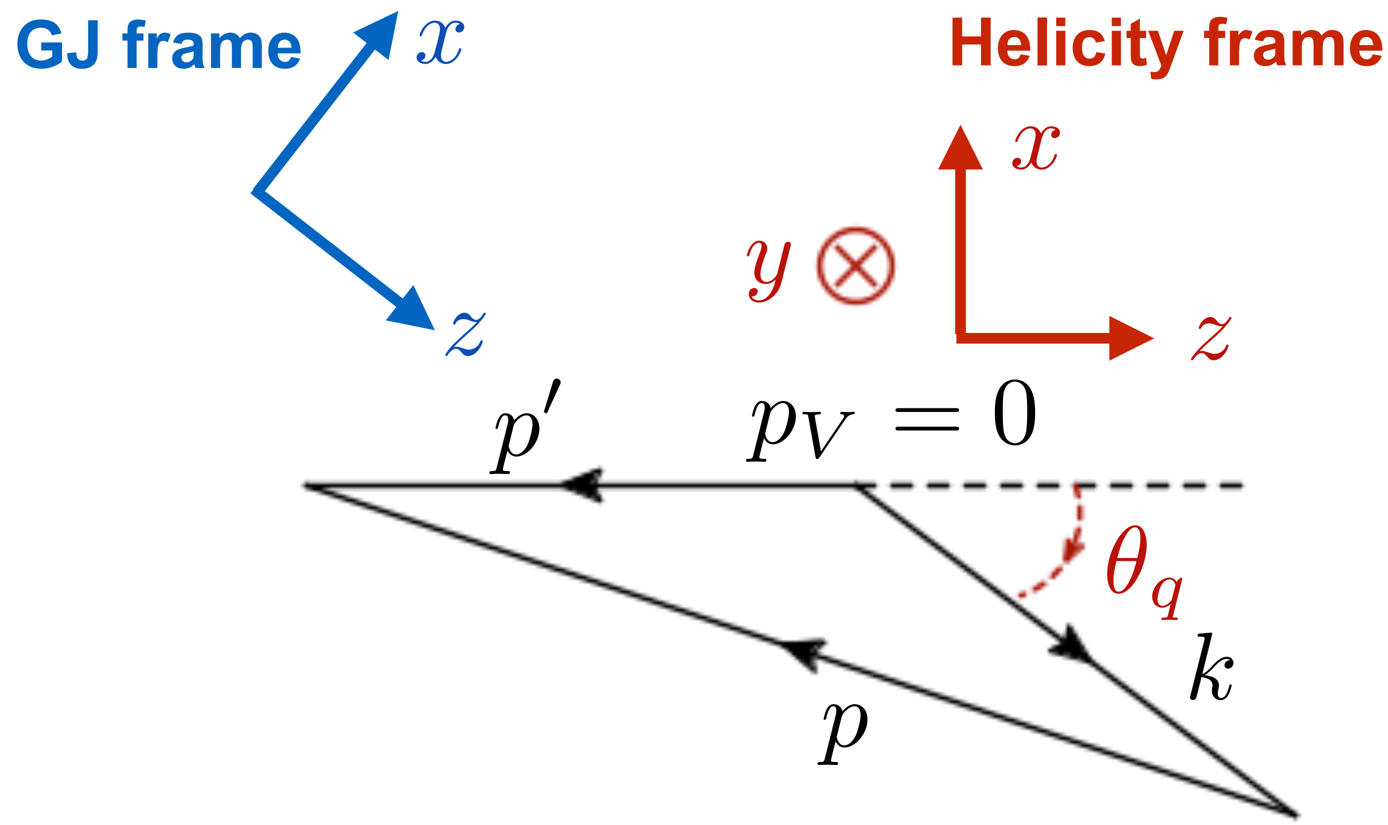

GJ frame
Helicity frame
x
z
y
p'
$p_V = 0$
θ_q
k
p

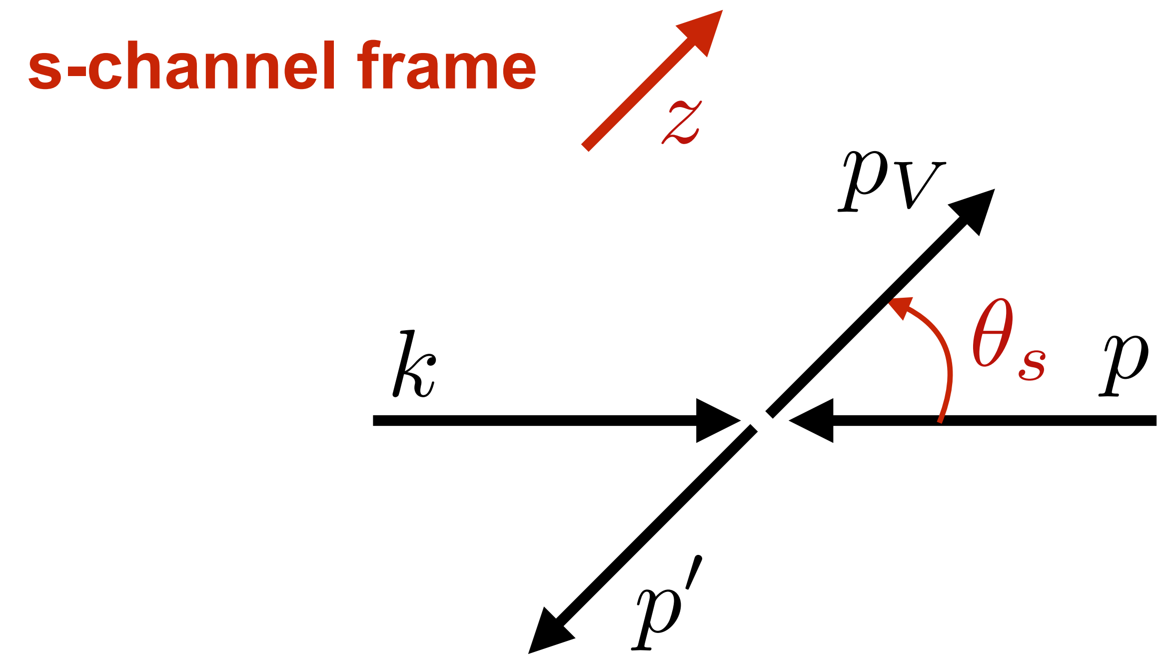

s-channel frame
z
p_V
θ_s
k
p
p'

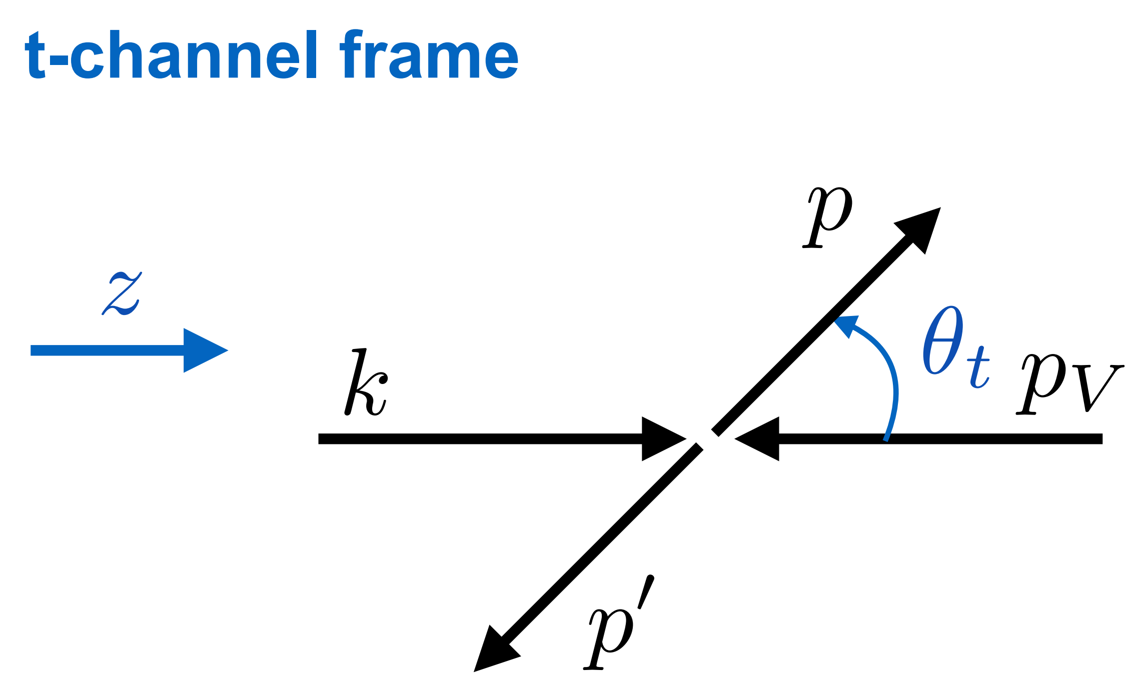

k
p_V
p
p'


t-channel frame
z
p
θ_t
p_V
k
p'

Frames







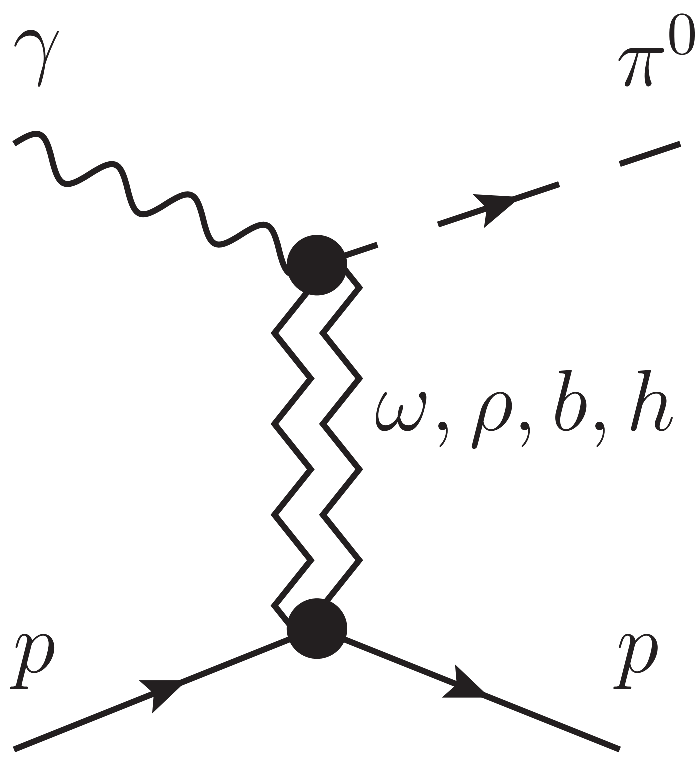
$$\rho_{MM'}\big|_H = \rho_{MM'}\big|_{s\text{-chan}}$$

rotation

$$\rho_{MM'}\big|_{GJ} = \rho_{MM'}\big|_{t\text{-chan}}$$

4. Parametrize Reactions: $\gamma p \to \pi^0 p$

At high energy, particles are produced via the exchange of a force



4. Parametrize Reactions: $\gamma p \to \pi^0 p$

Blue line: Model from VM et al arXiv:1505.02321 **Red points: Data from CLAS (in preparation)**