Discovering Exotic Mesons @CLAS12

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Jefferson Lab
Joint Physics Analysis Center

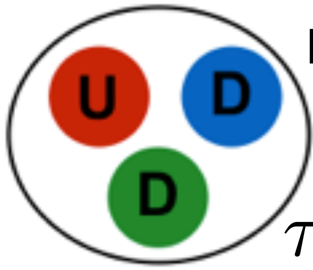
CLAS collaboration meeting
JLab, March 2019

Jefferson Lab
Thomas Jefferson National Accelerator Facility

JPAC Joint Physics Analysis Center

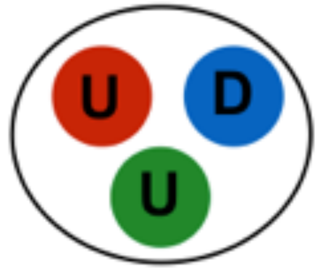
Ordinary and Exotic Hadrons

Ordinary baryons:



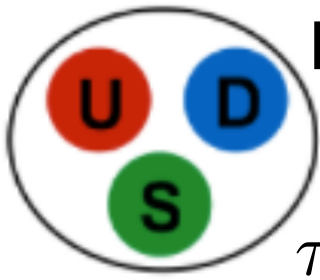
neutron

$\tau \sim 10^3 s$



proton

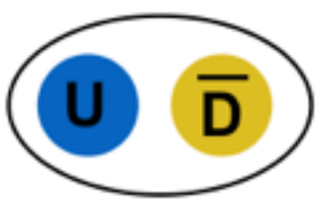
stable



baryon Λ

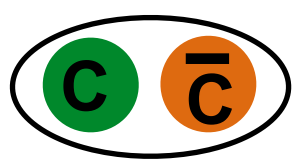
$\tau \sim 10^{-10} s$

Ordinary mesons



pion

$\tau \sim 10^{-8} s$



J/ψ

$\tau \sim 10^{-20} s$

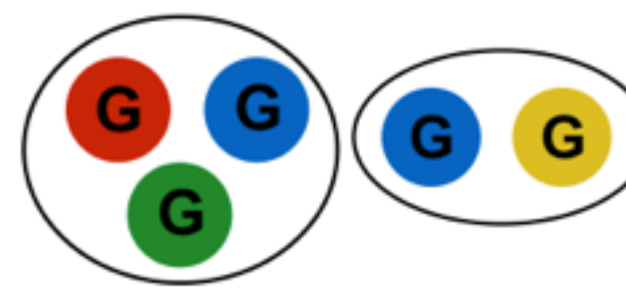
kaon

$\tau \sim 10^{-8} s$

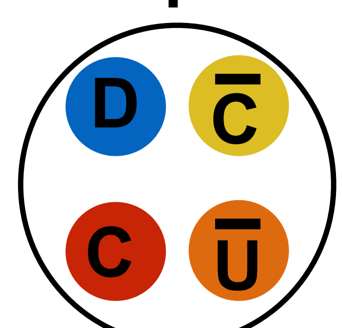
Exotic matter

hybrid mesons

glueballs



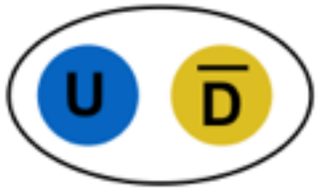
tetraquarks



pentaquarks

Hybrid Mesons Production

Ordinary mesons



$$\vec{J} = \vec{L} \oplus \vec{S}$$

$$P = -(-1)^L$$

$$C = (-1)^{L+S}$$

Examples of quantum numbers

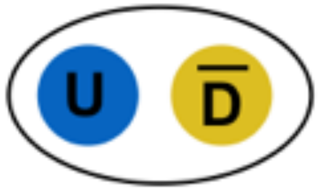
QNs J^{PC}	(I^G)	Names	(I^G)		
1^{++}	(1^-)	a_1	(0^+)	f_1	f_1'
1^{--}	(1^+)	ρ_1	(0^-)	ω_1	ϕ_1
0^{-+}	(1^-)	π_0	(0^+)	η_0	η_0'
$\mathbf{1^{-+}}$	$\mathbf{(1^-)}$	$\boldsymbol{\pi_1}$	$\mathbf{(0^+)}$	$\boldsymbol{\eta_1}$	$\boldsymbol{\eta_1'}$
2^{-+}	(1^-)	π_2	(0^+)	η_2	η_2'
$\mathbf{0^{+-}}$	$\mathbf{(1^+)}$	$\mathbf{b_0}$	$\mathbf{(0^-)}$	$\mathbf{h_0}$	$\mathbf{h_0'}$
1^{+-}	(1^+)	b_1	(0^-)	h_1	h_1'
$\mathbf{2^{+-}}$	$\mathbf{(1^+)}$	$\mathbf{b_2}$	$\mathbf{(0^-)}$	$\mathbf{h_2}$	$\mathbf{h_2'}$

Meyer and Van Harleem (2010)

hybrid mesons

Hybrid Mesons Production

Ordinary mesons



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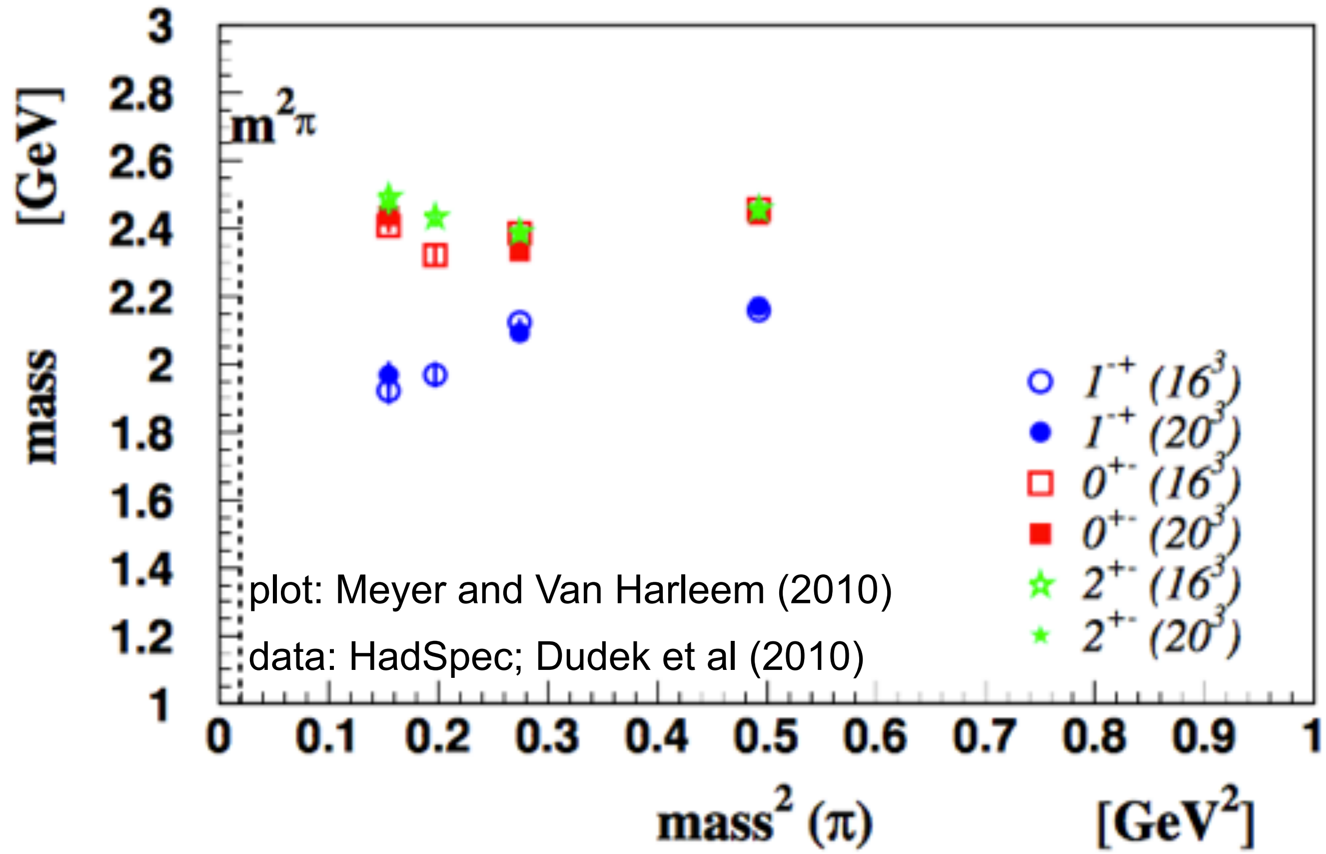

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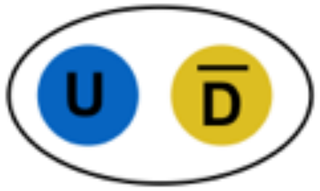

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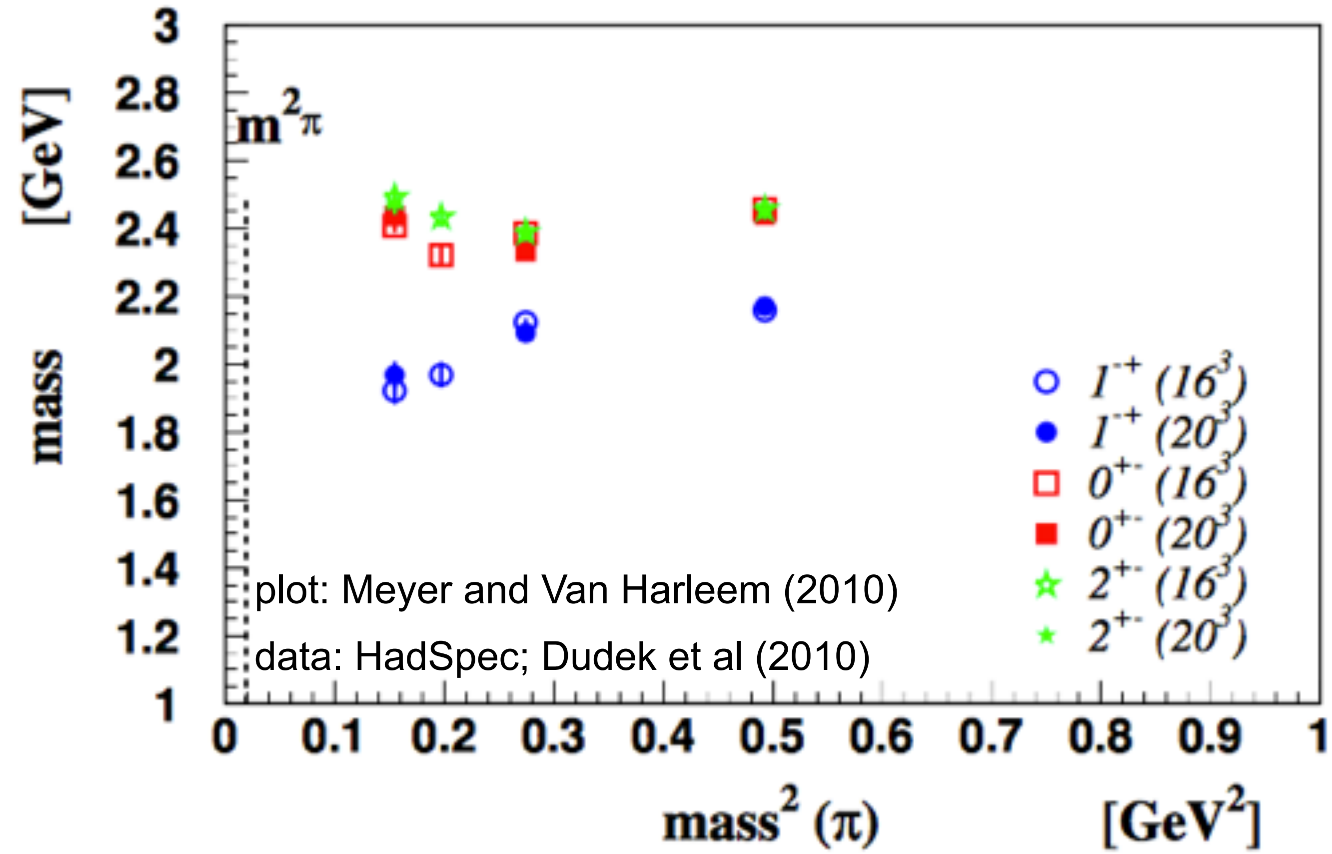

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Meyer and Van Harleem (2010)

hybrid mesons

$$\eta_1 \to \eta\eta', a_2\pi, K_1 K, \ldots$$

$$\pi_1 \to \eta\pi, \eta'\pi, \rho\pi, b_1\pi, \ldots$$

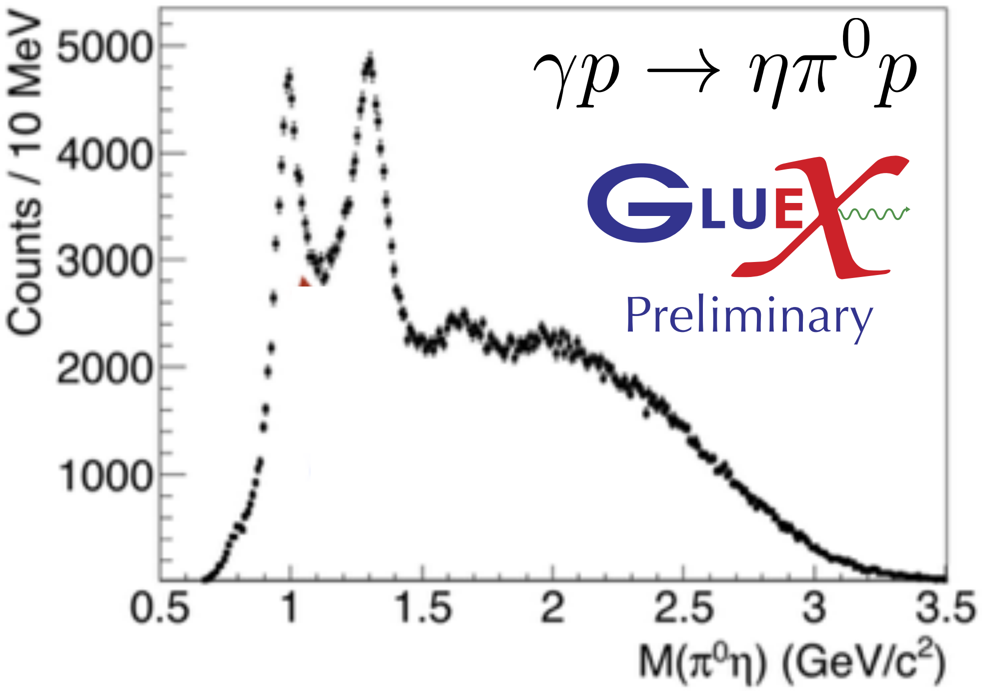
$$\gamma p \to \eta\pi^0 p$$

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

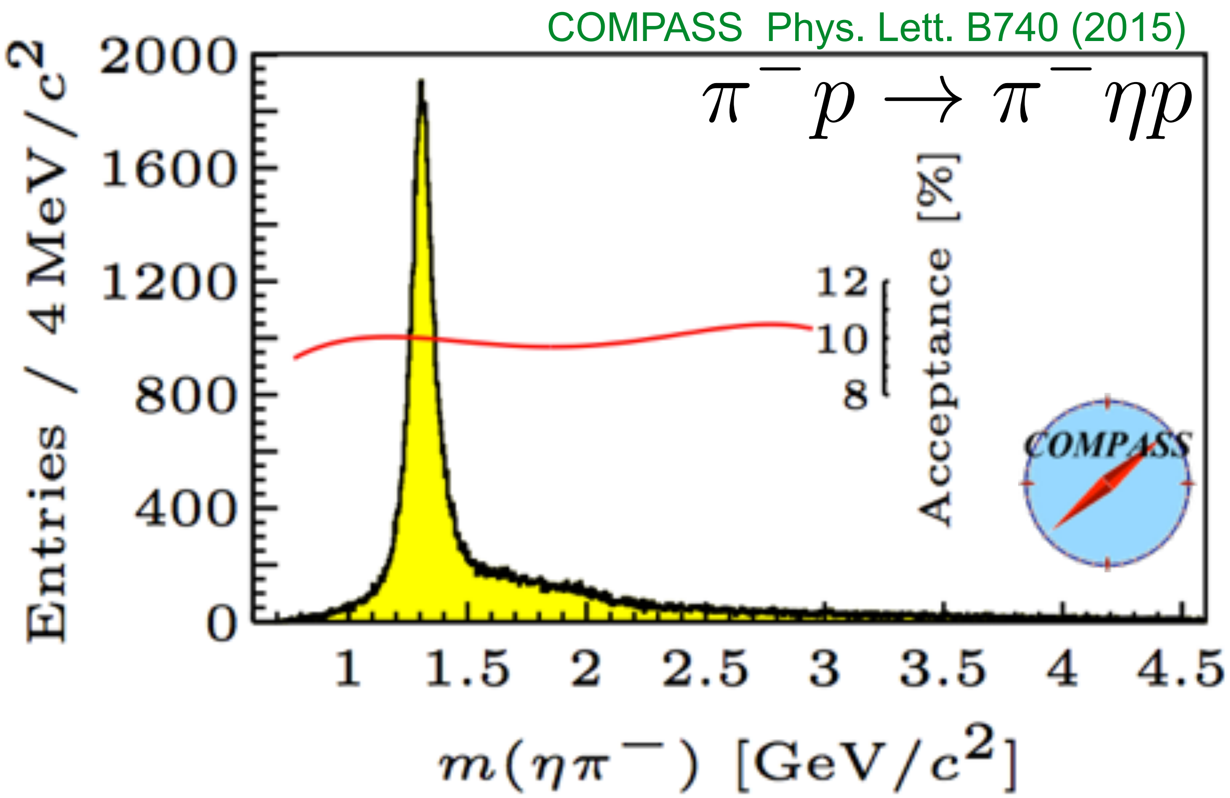
in P-wave

Eta-Pi Production

$E_{\mathrm{beam}} = 9\ \mathrm{GeV}$



$E_{\mathrm{beam}} = 190\ \mathrm{GeV}$



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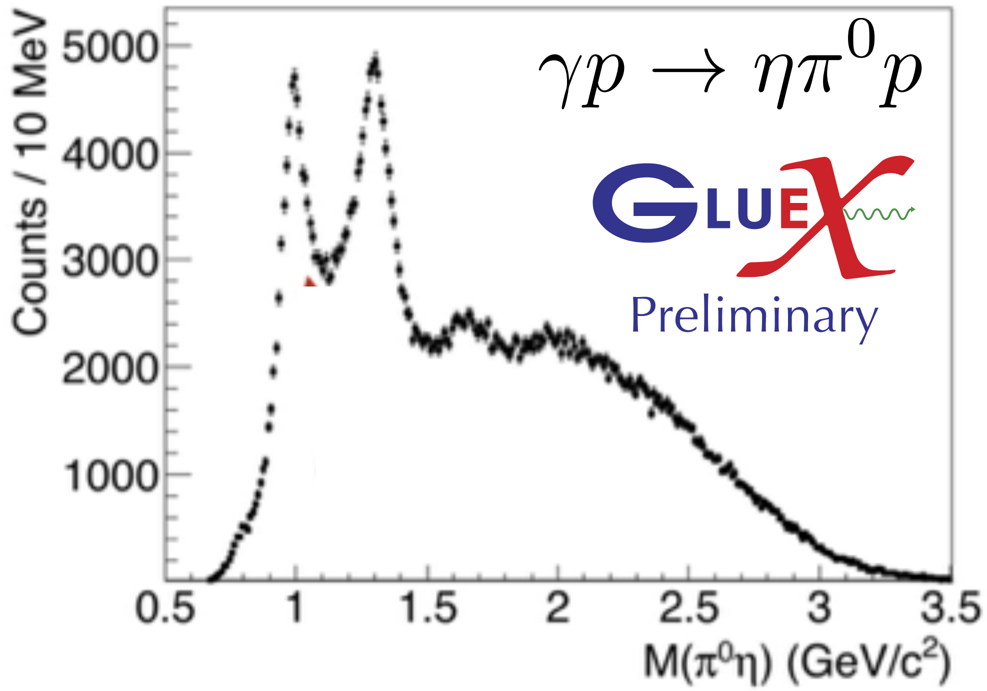

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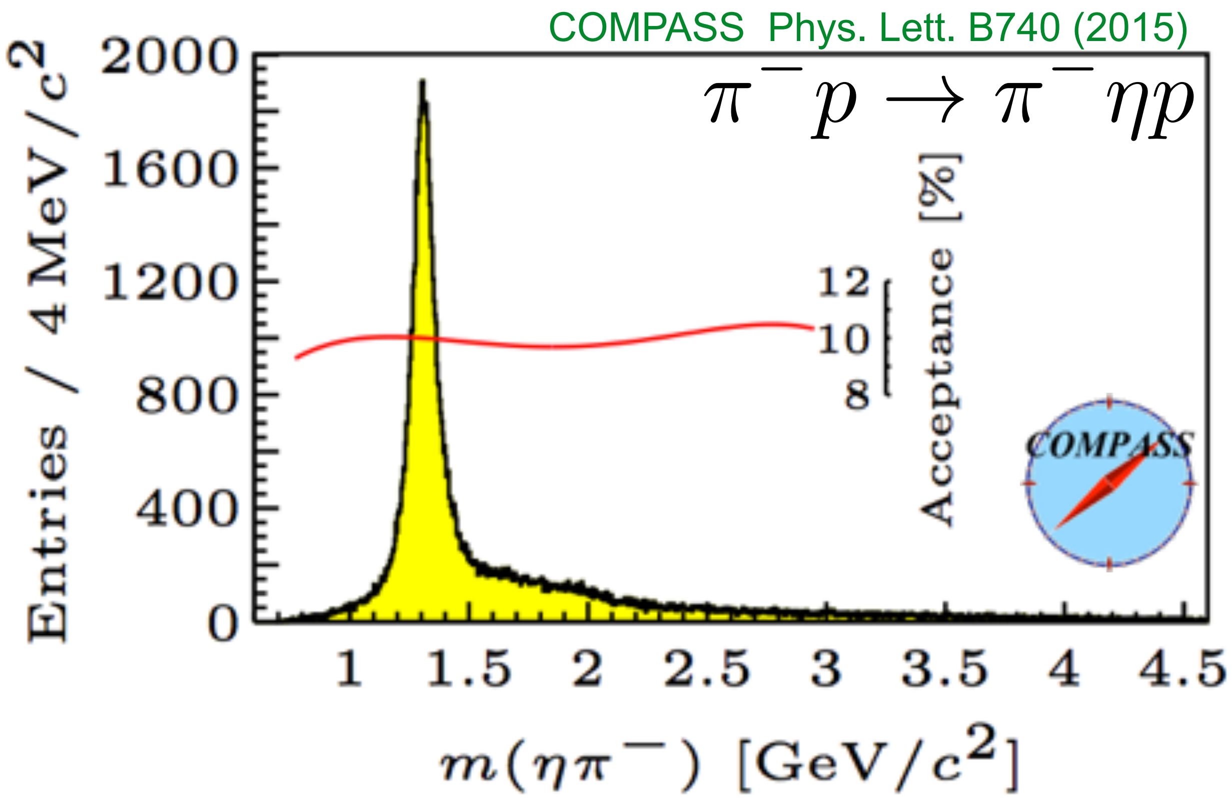
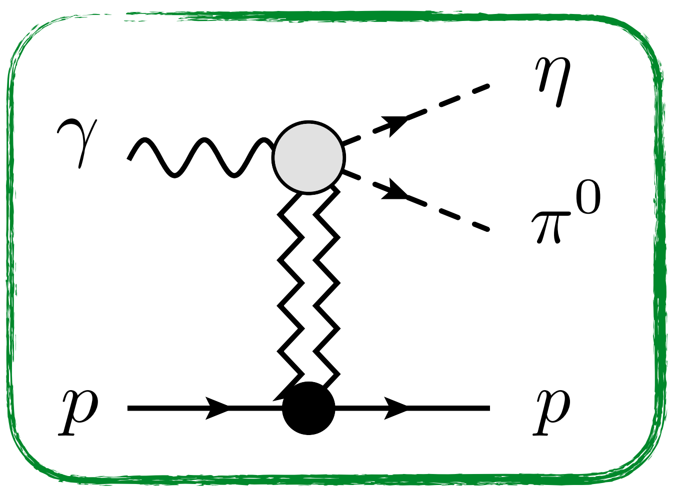
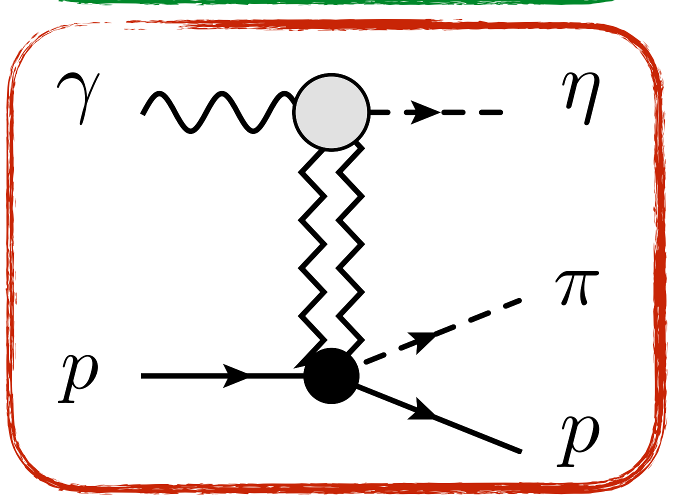
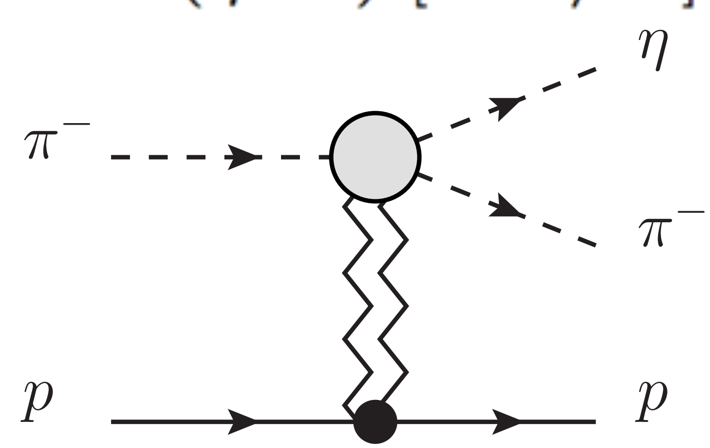




"signal"



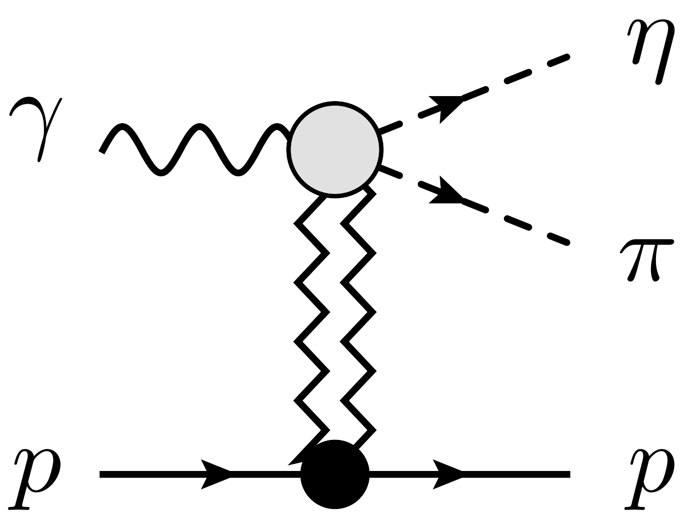
"background"

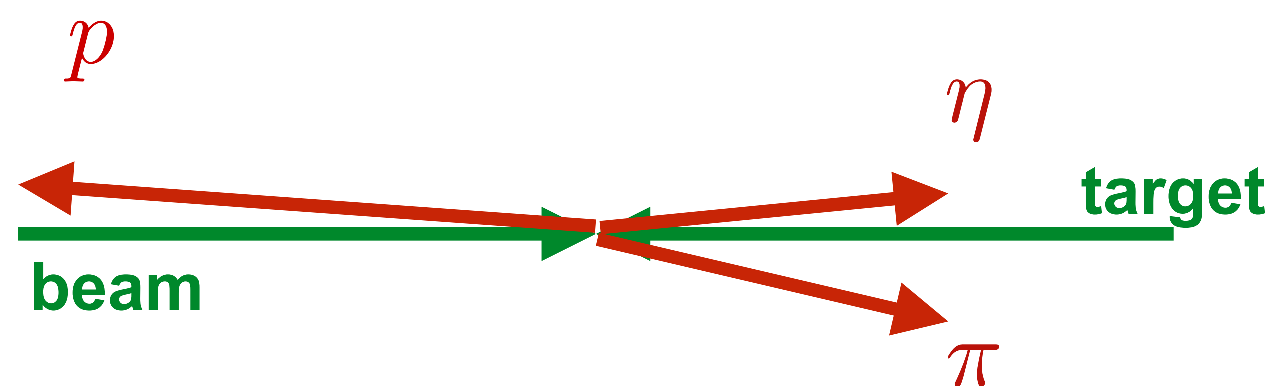


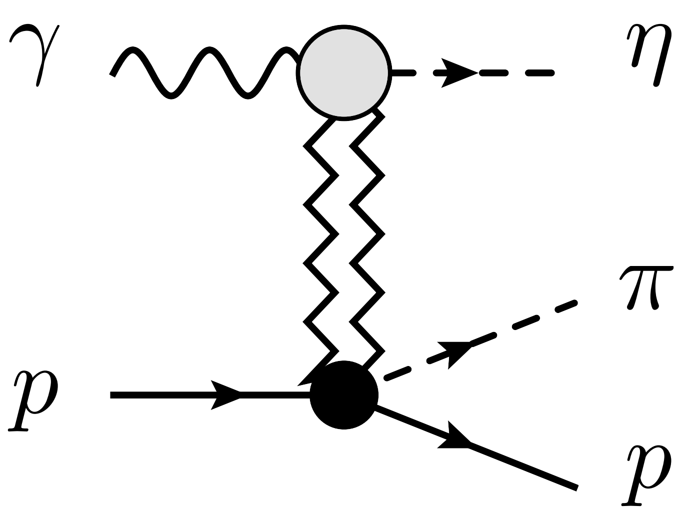
only "signal" at high energy

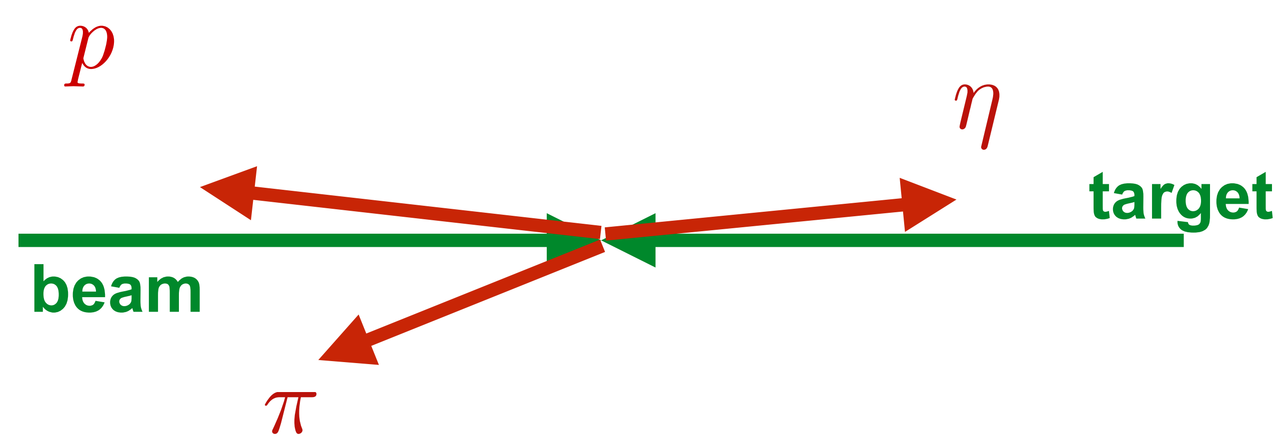
Longitudinal Plot

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







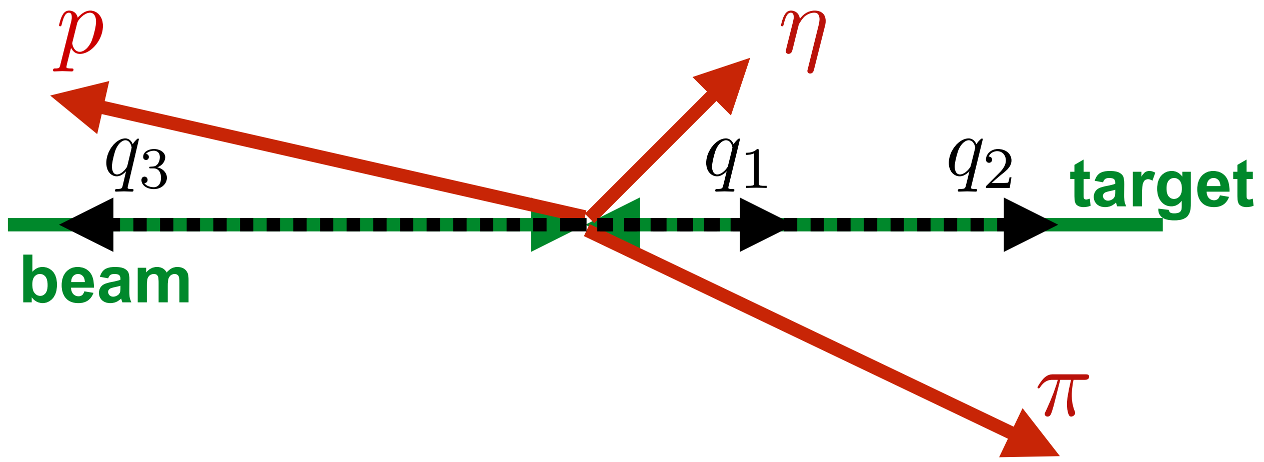


Van Hove NPB9 (1969) 331

Shi et al (JPAC) PRD91 (2015) 034007

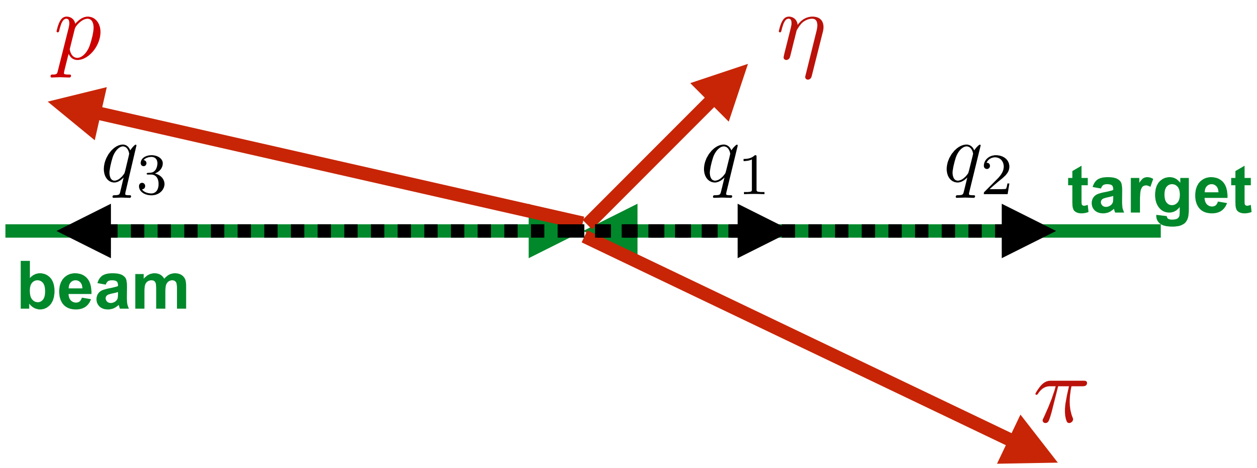
Pauli et al PRD98 (2018) 065201

Longitudinal Plot



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

Longitudinal Plot



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

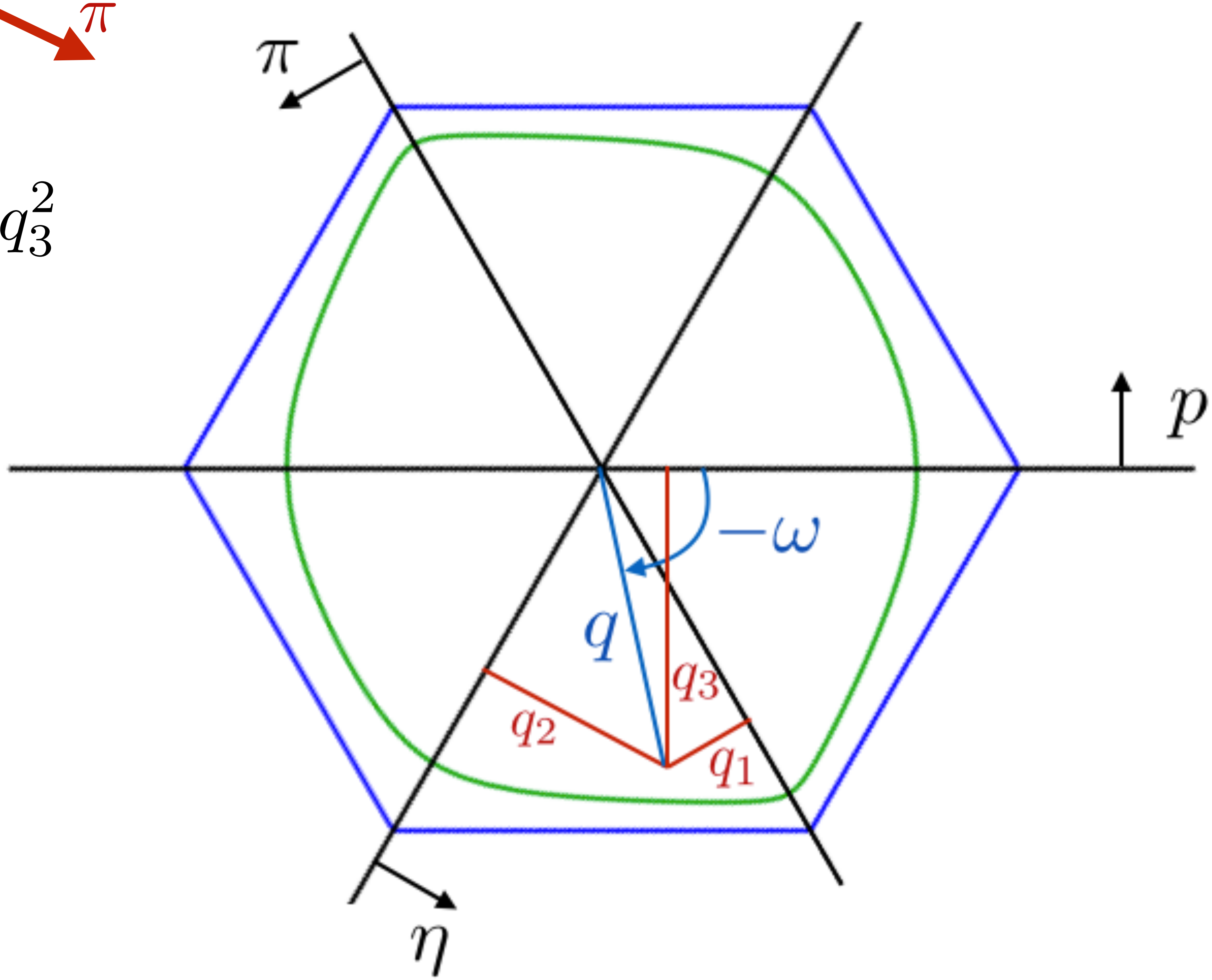
radius: $q^2 = q_1^2 + q_2^2 + q_3^2$

longitudinal angle: ω

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

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

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



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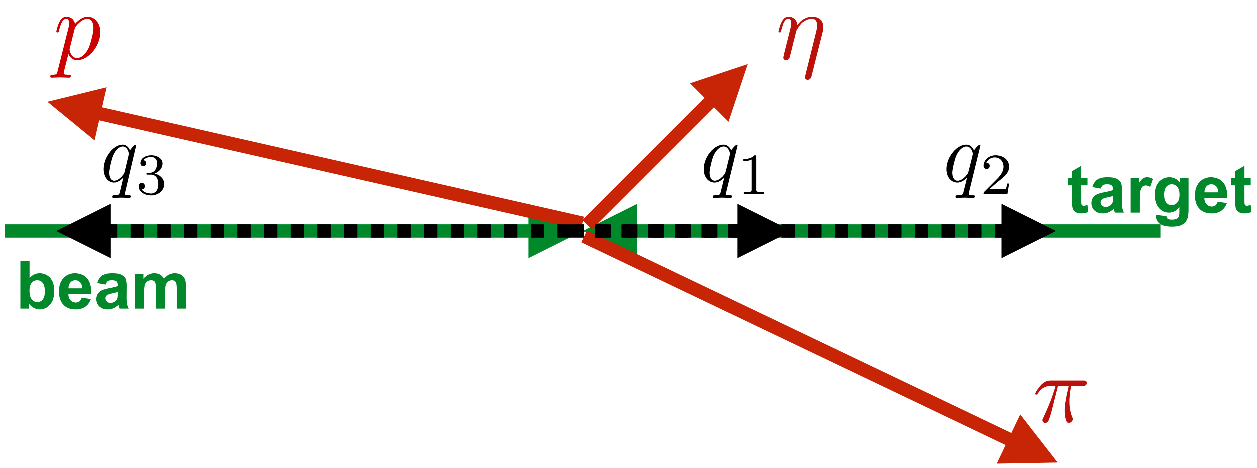

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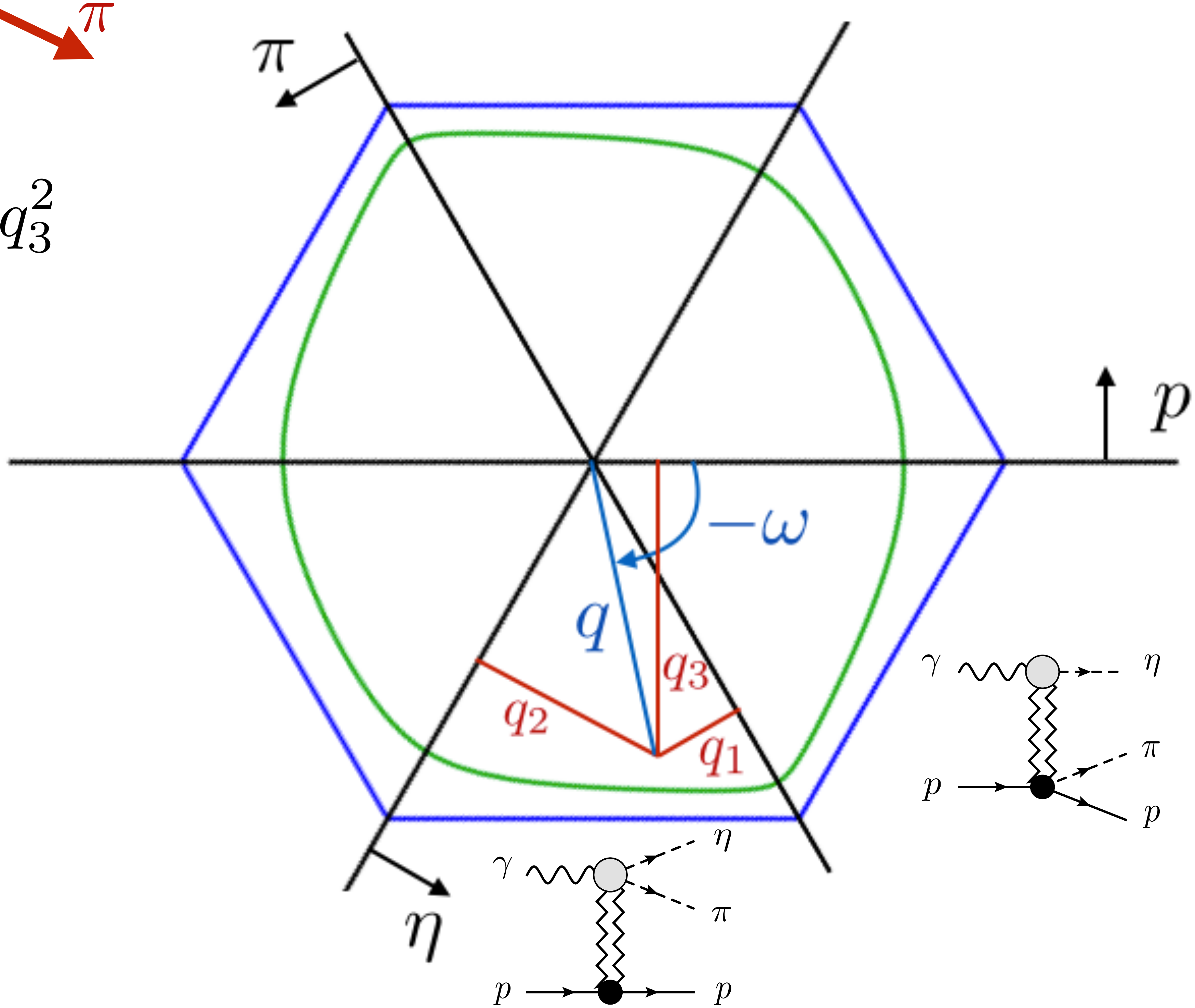
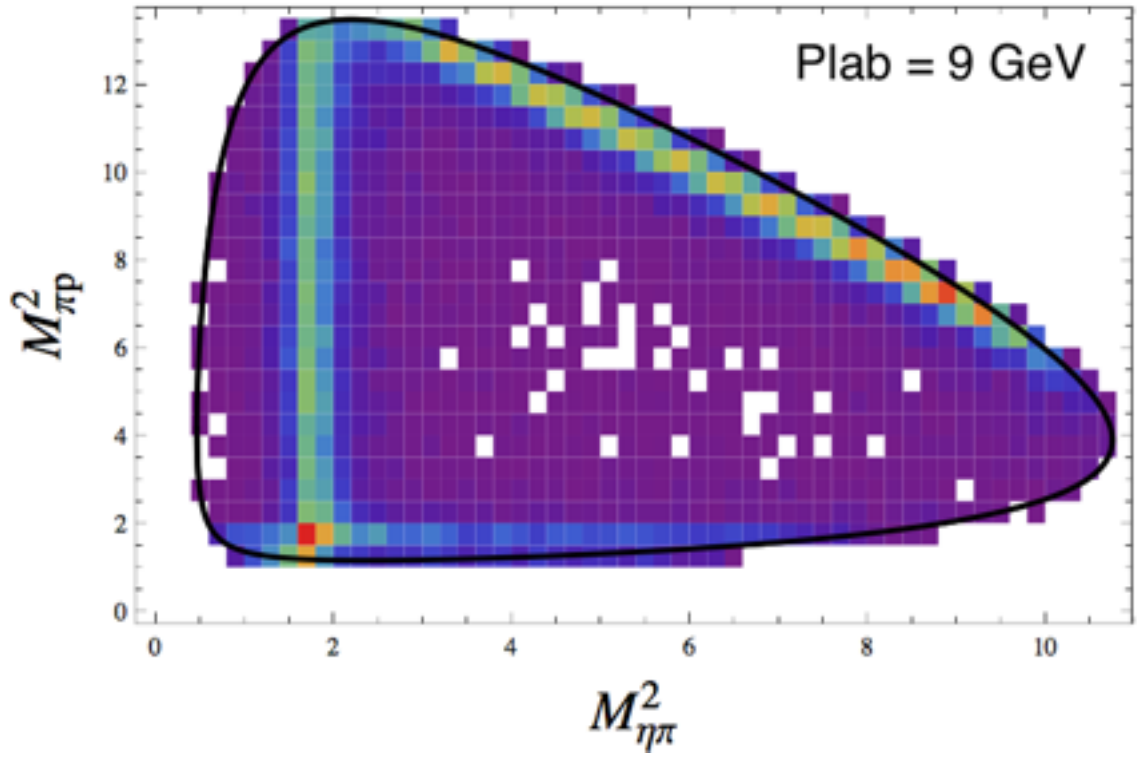
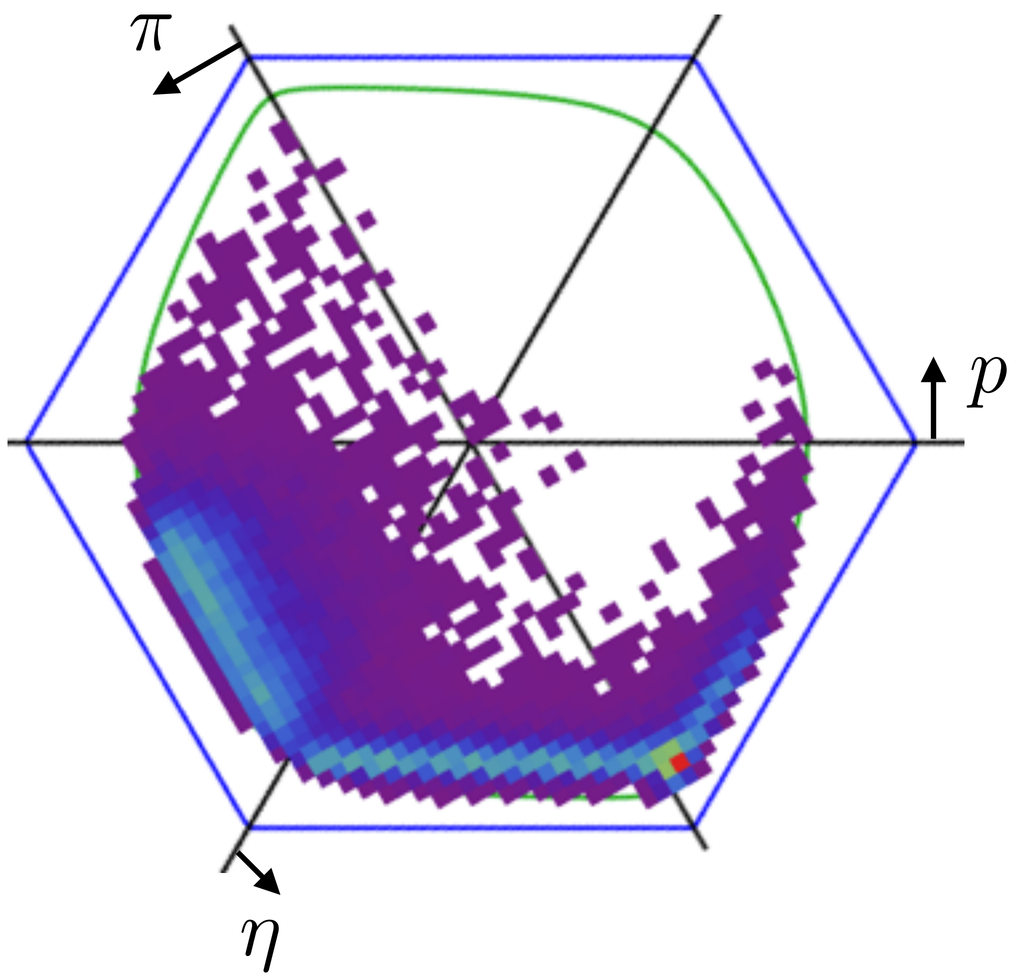


Cut in Longitudinal Angle





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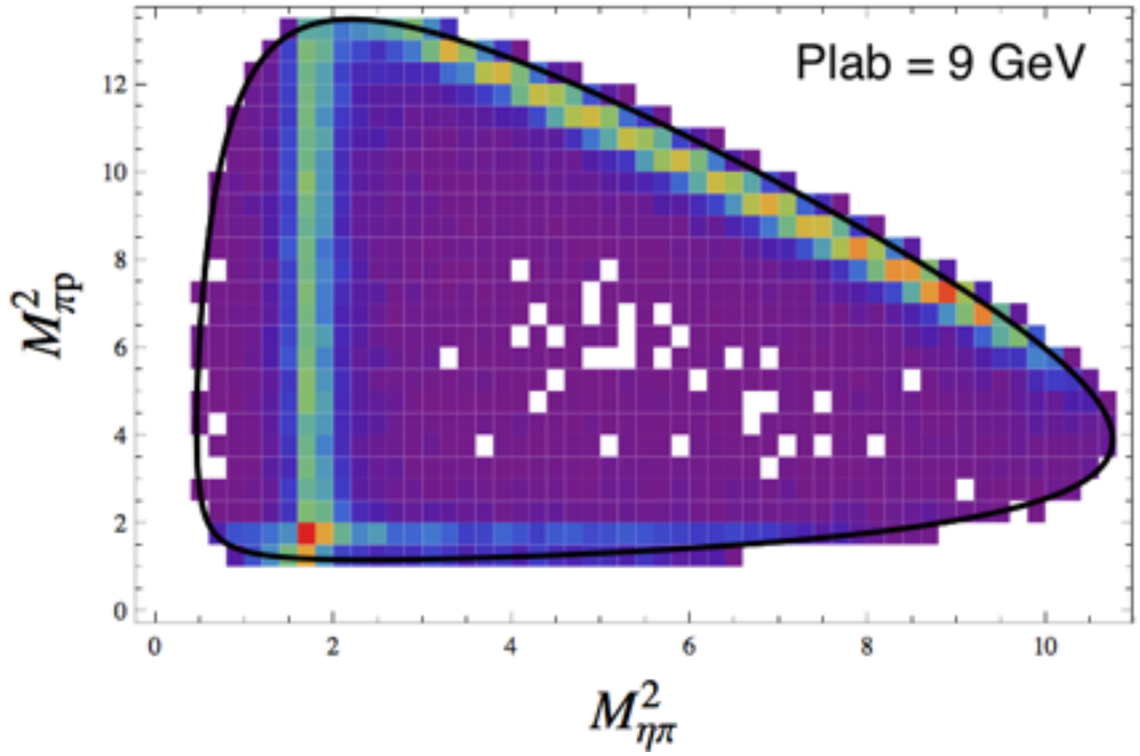
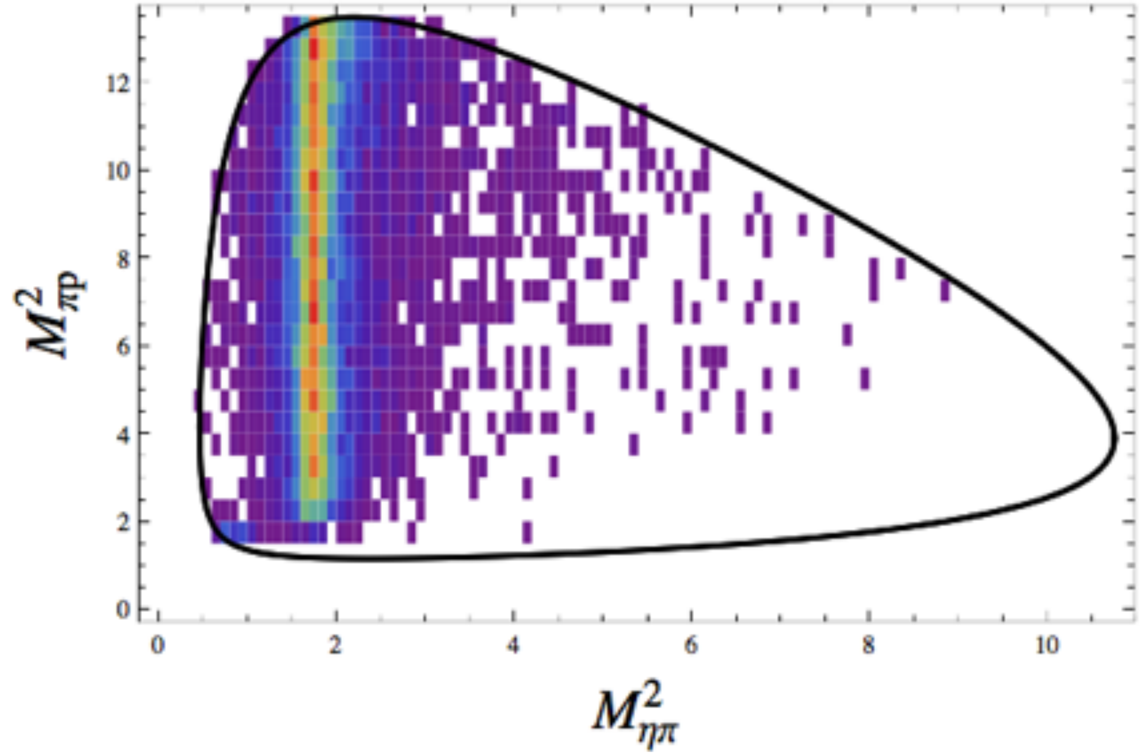
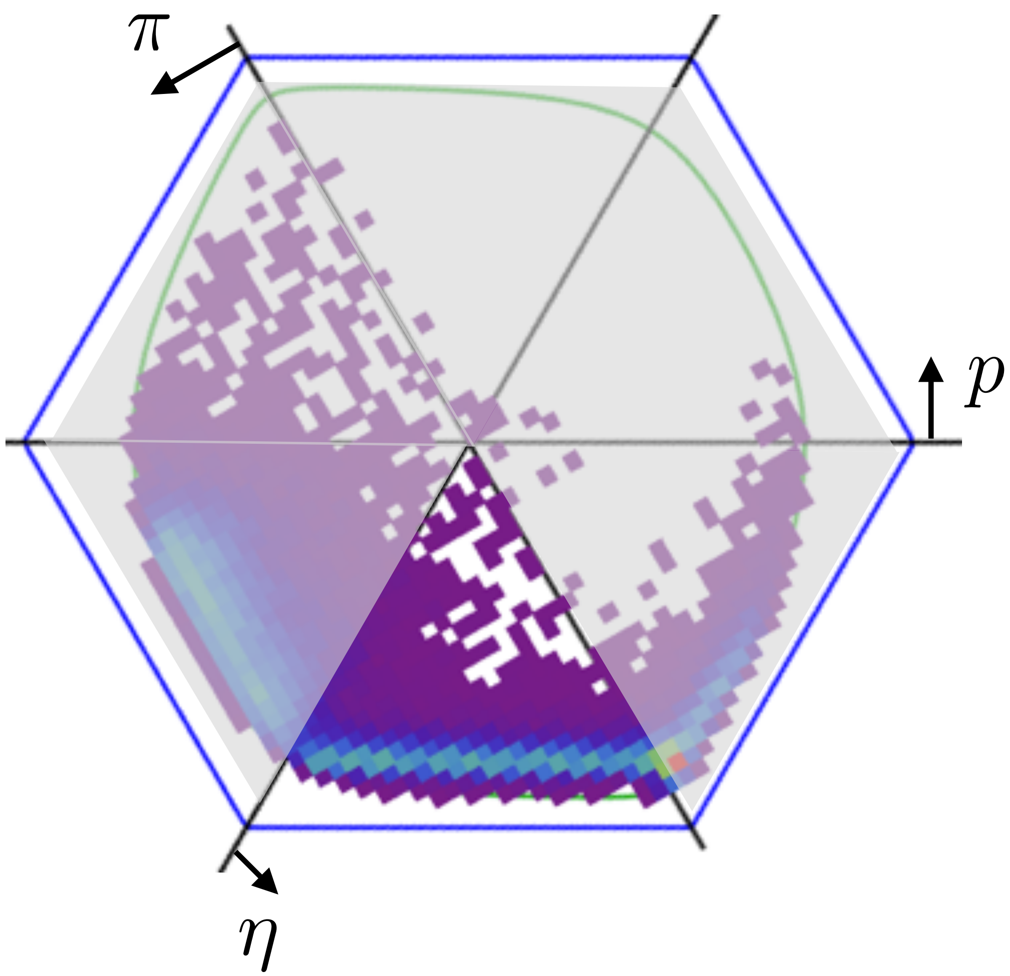
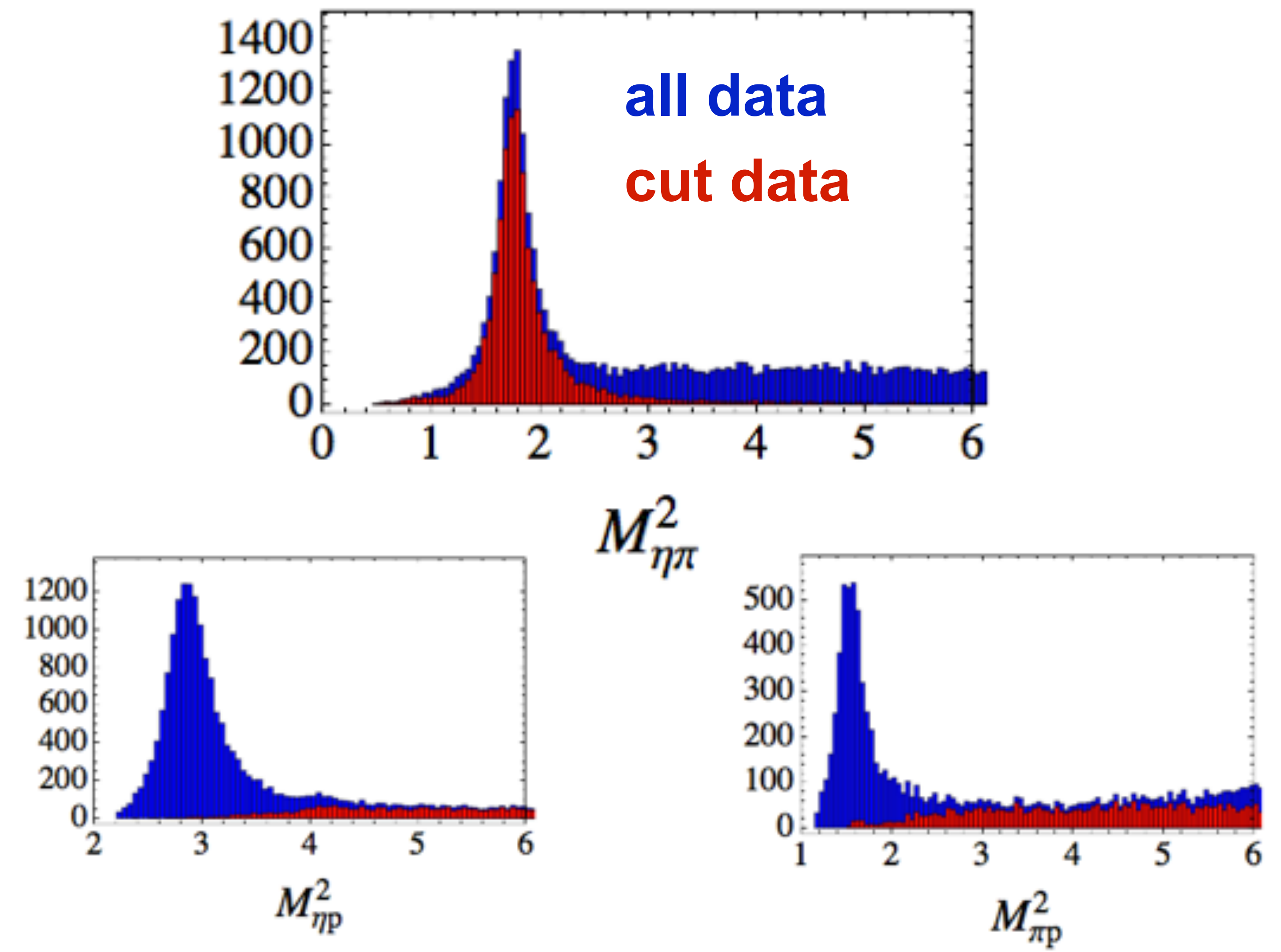
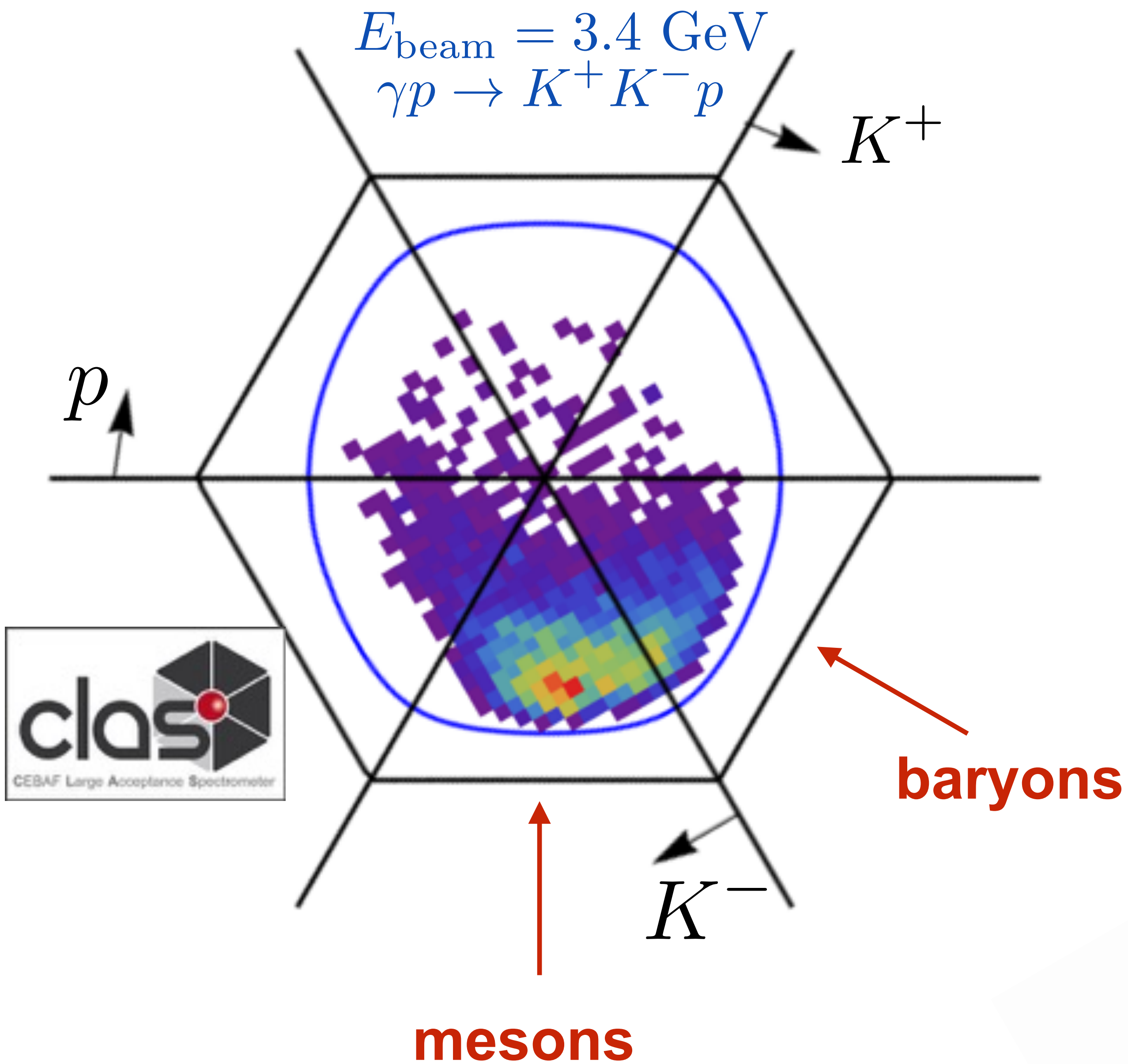


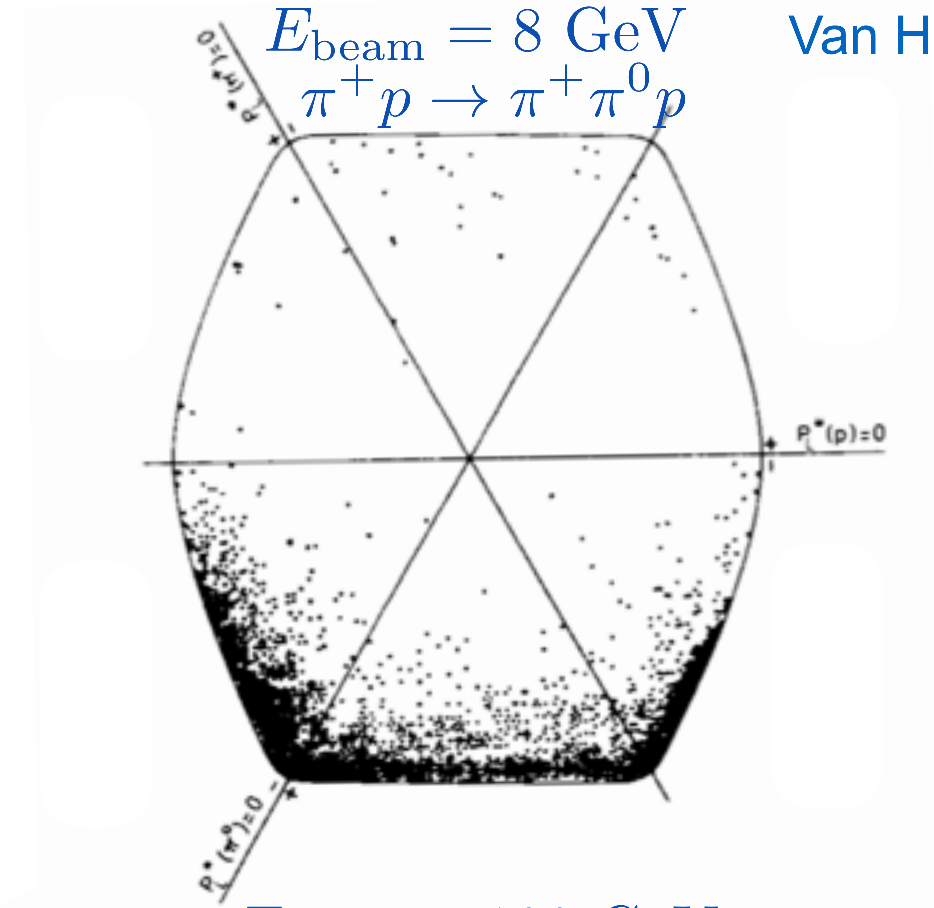




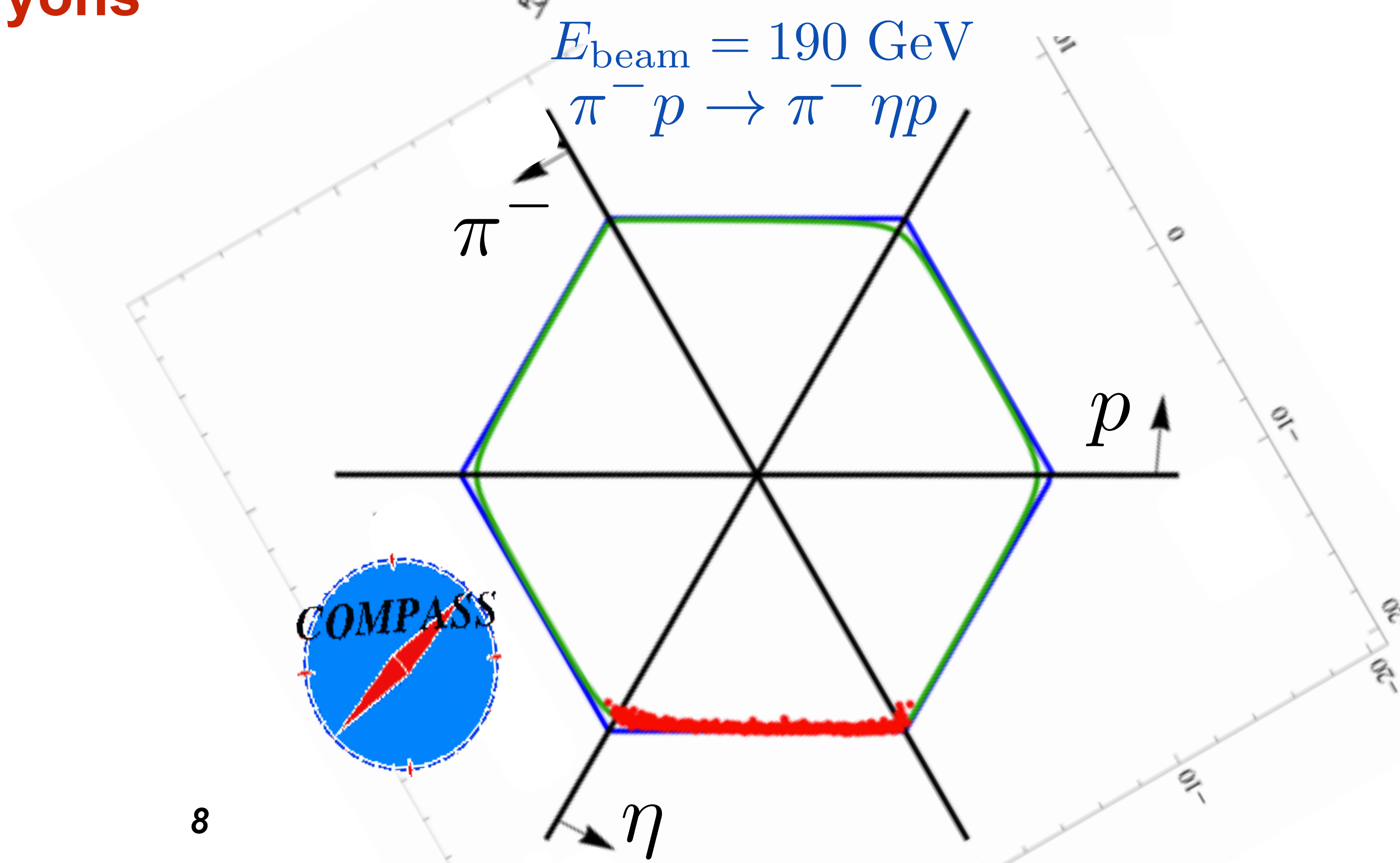


Longitudinal Plot: Energy Evolution





Van Hove (1969)

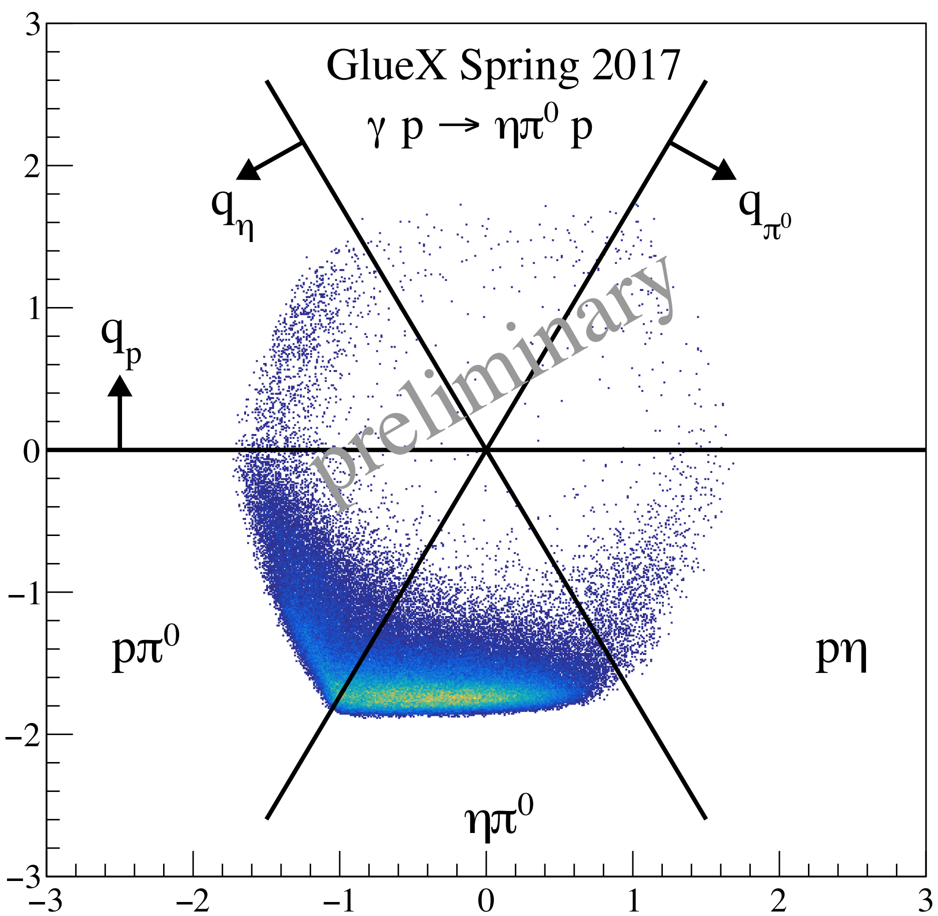


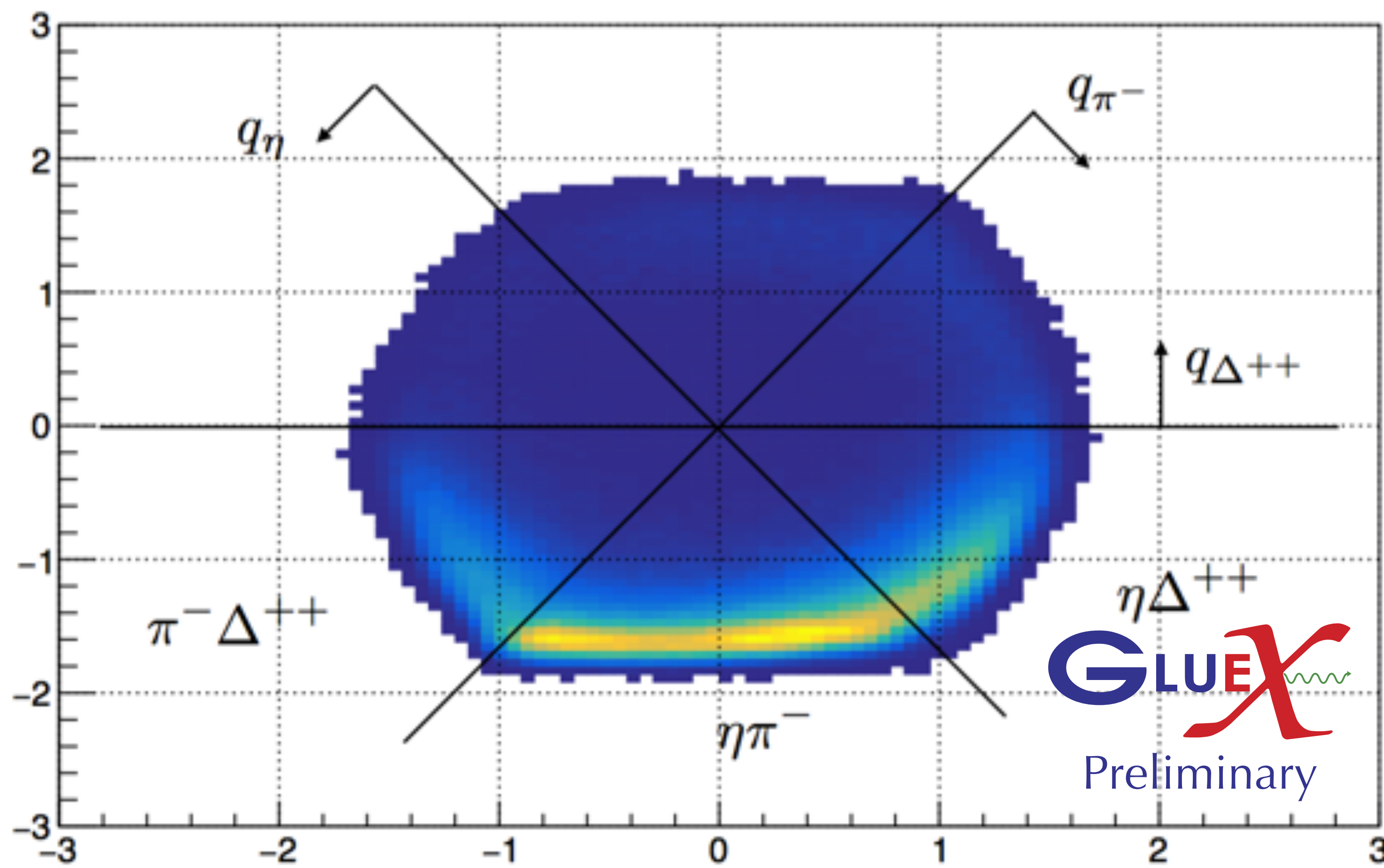
GlueX Preliminary Results

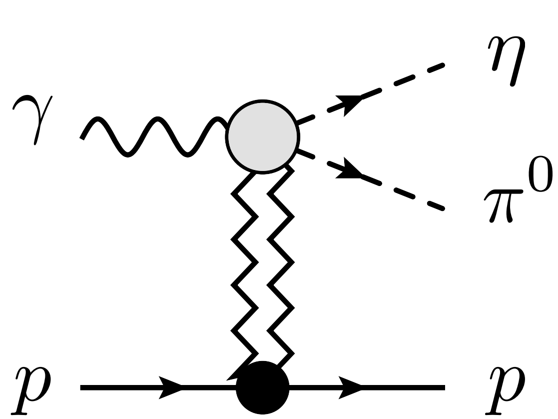
not corrected for acceptance

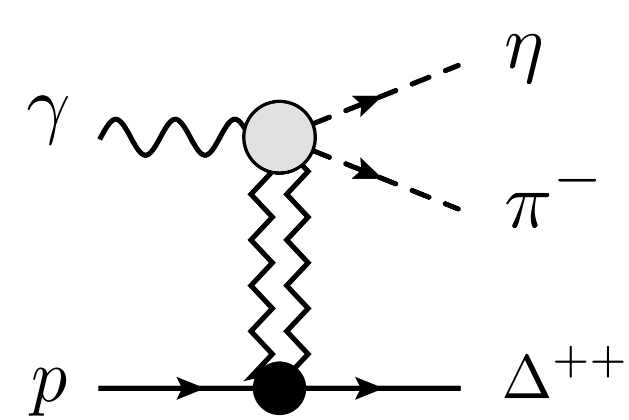
$$\gamma p \rightarrow \eta \pi^0 p$$

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









Courtesy of A. Austregesilo and C. Gleason

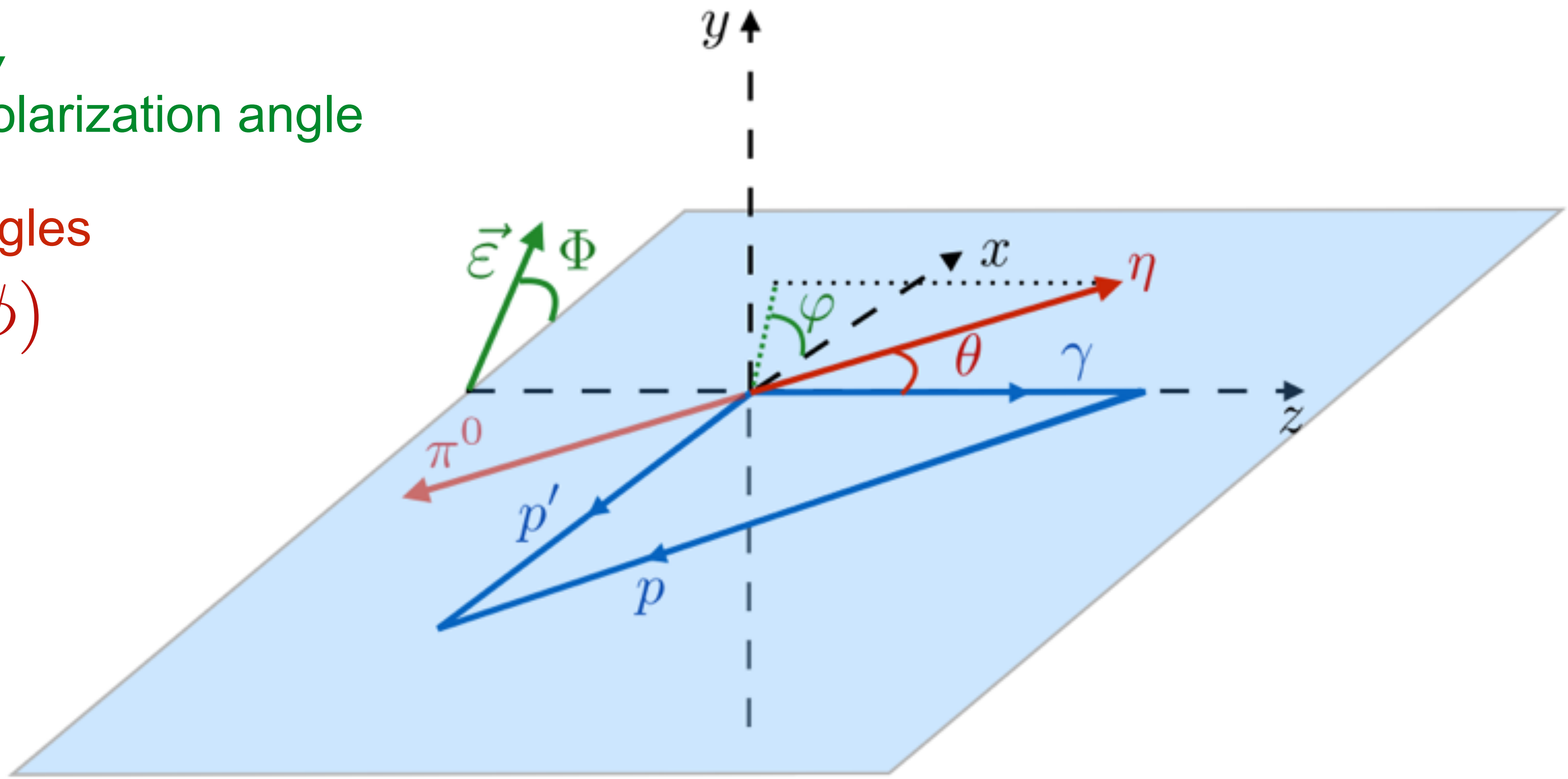
Measured Intensities

$$I(\Omega, \Phi) = I^0(\Omega) - P_\gamma I^1(\Omega)\cos 2\Phi - P_\gamma I^2(\Omega)\sin 2\Phi + \mathcal{O}(Q^2)$$

polarization angle

η decay angles

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

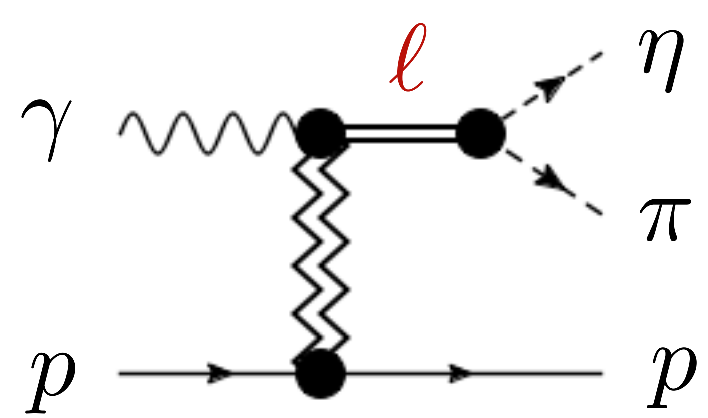


Implicit variables

Beam energy (fixed)

momentum transfer (integrated)

$\eta\pi$ invariant mass (binned)



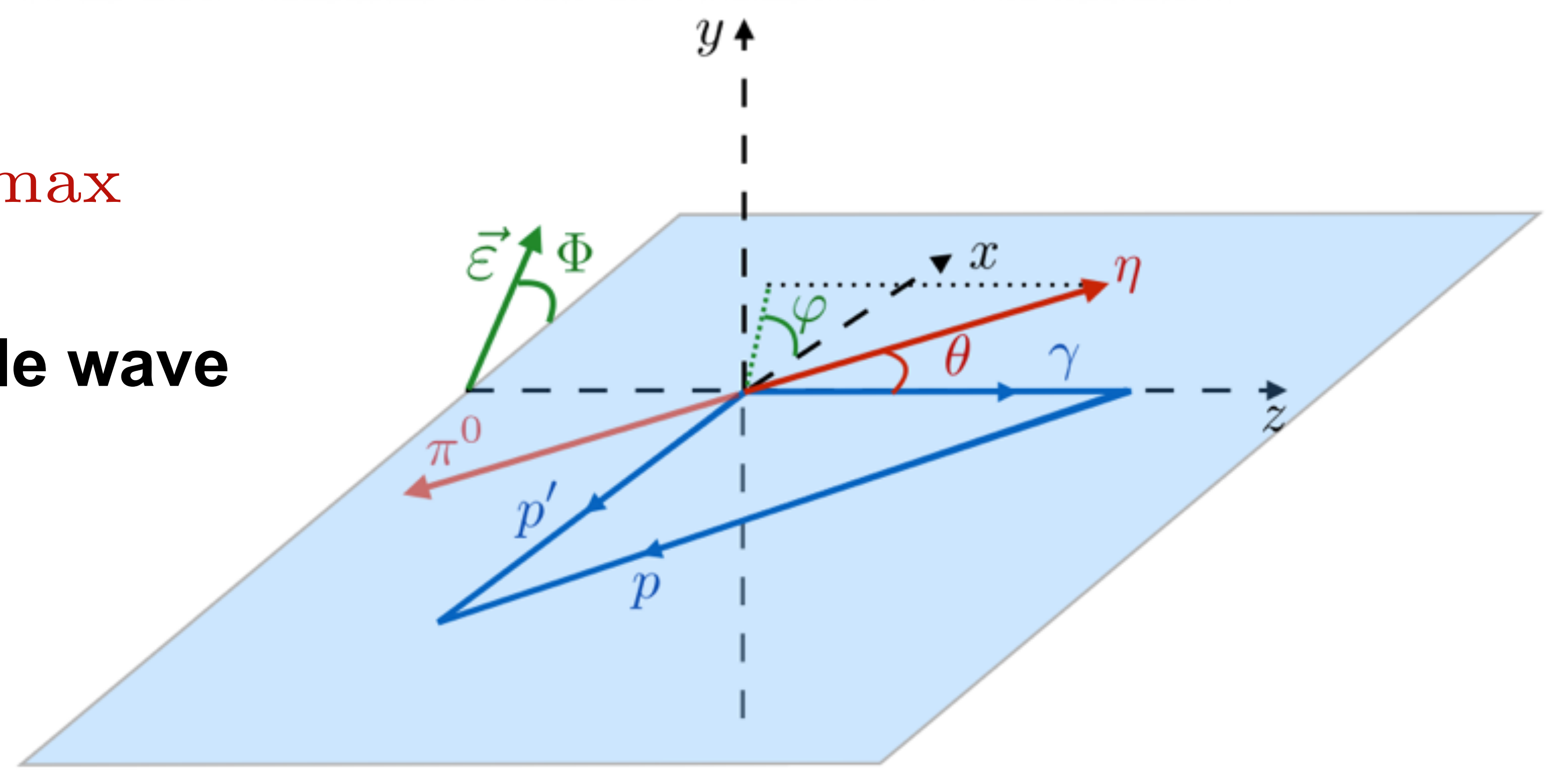
Observables: Moments of Angular distribution

$$I(\Omega,\Phi) = I^0(\Omega) - P_\gamma I^1(\Omega)\cos 2\Phi - P_\gamma I^2(\Omega)\sin 2\Phi + \mathcal{O}(Q^2)$$

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

Extract moments up to $L \leq 2\ell_{\mathrm{max}}$

ℓ_{max} **is the highest non-negligible wave**



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

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

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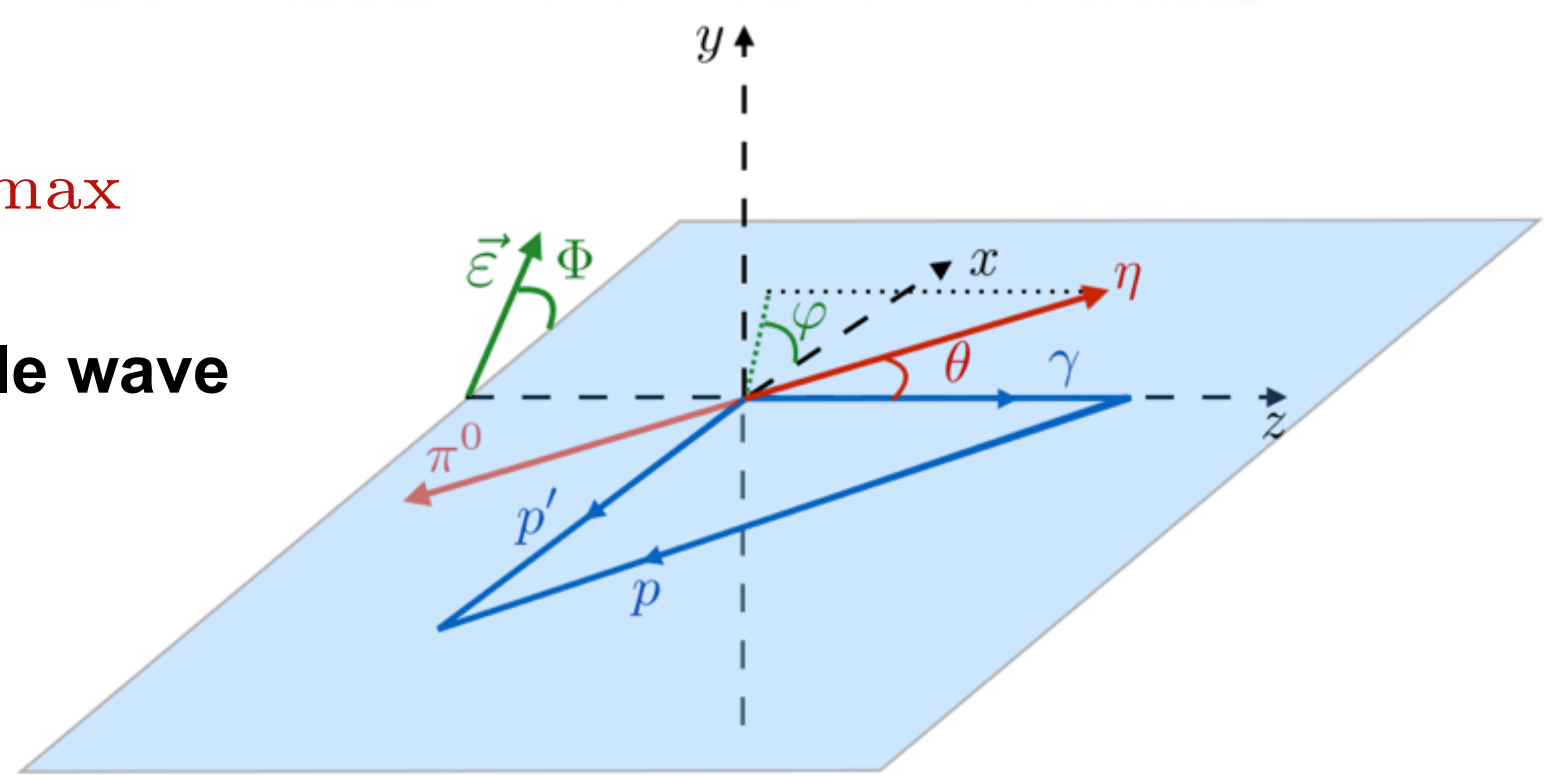
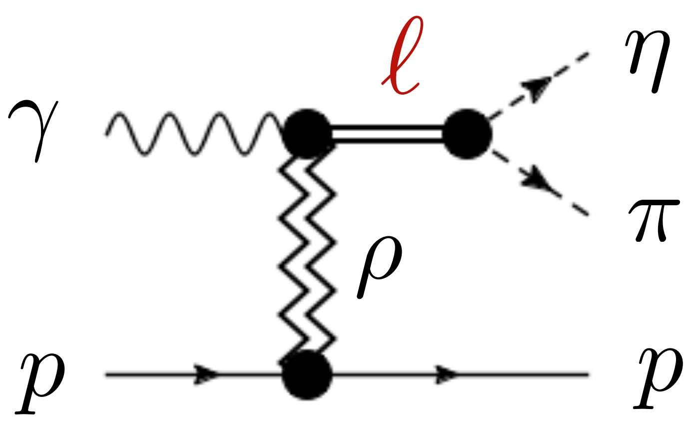


Model



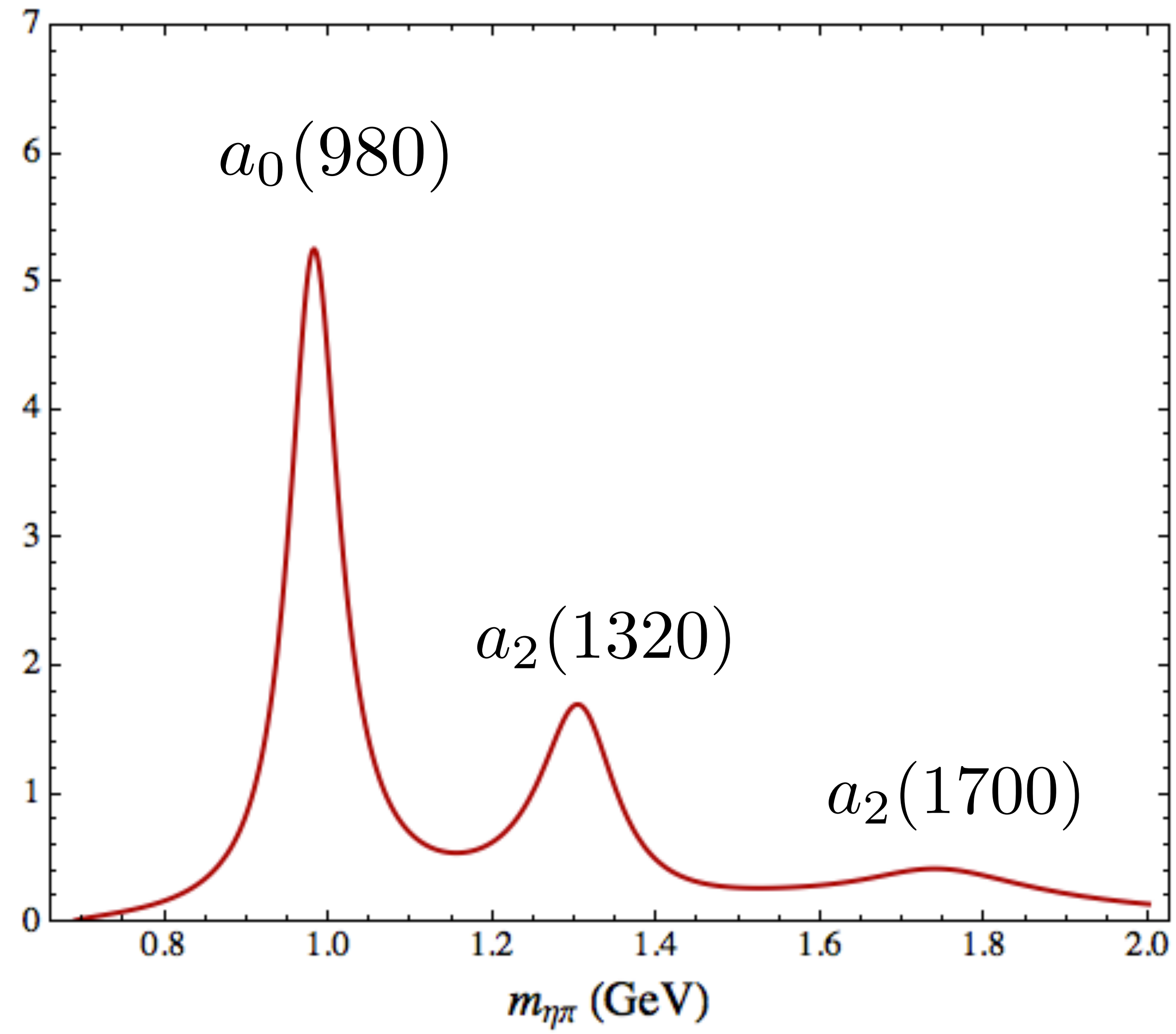
$$R = \{\underbrace{a_0(980)}_{S_0^{(+)}}, \underbrace{\pi_1(1600)}_{P_{0,1}^{(+)}}, \underbrace{a_2(1320), a_2(1700)}_{D_{0,1,2}^{(+)}}\}$$

production: natural exchanges

line shape: Breit-Wigner form

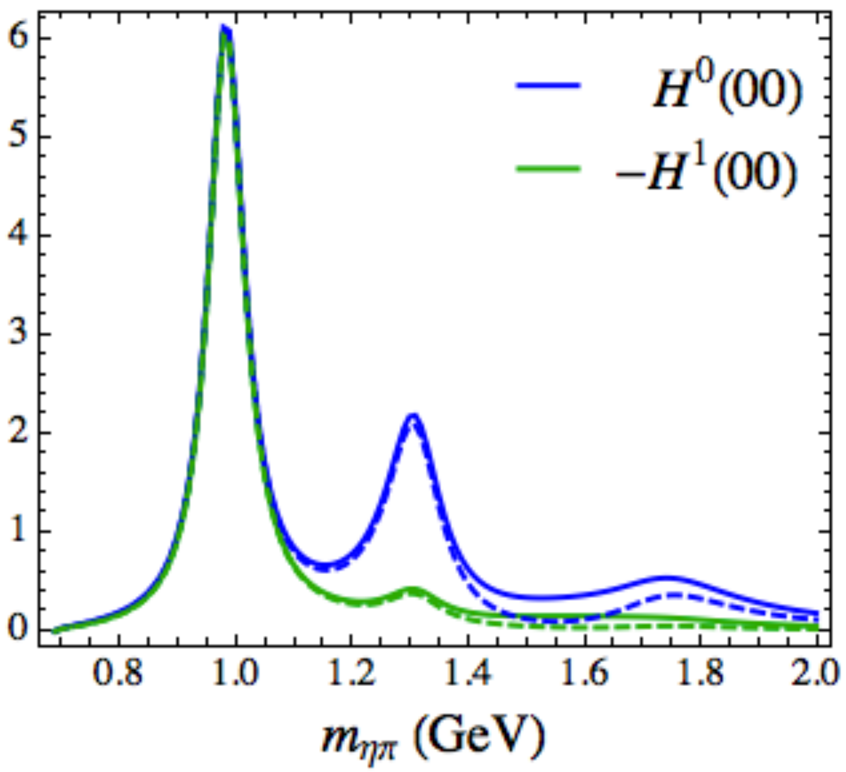
parameters: arbitrary

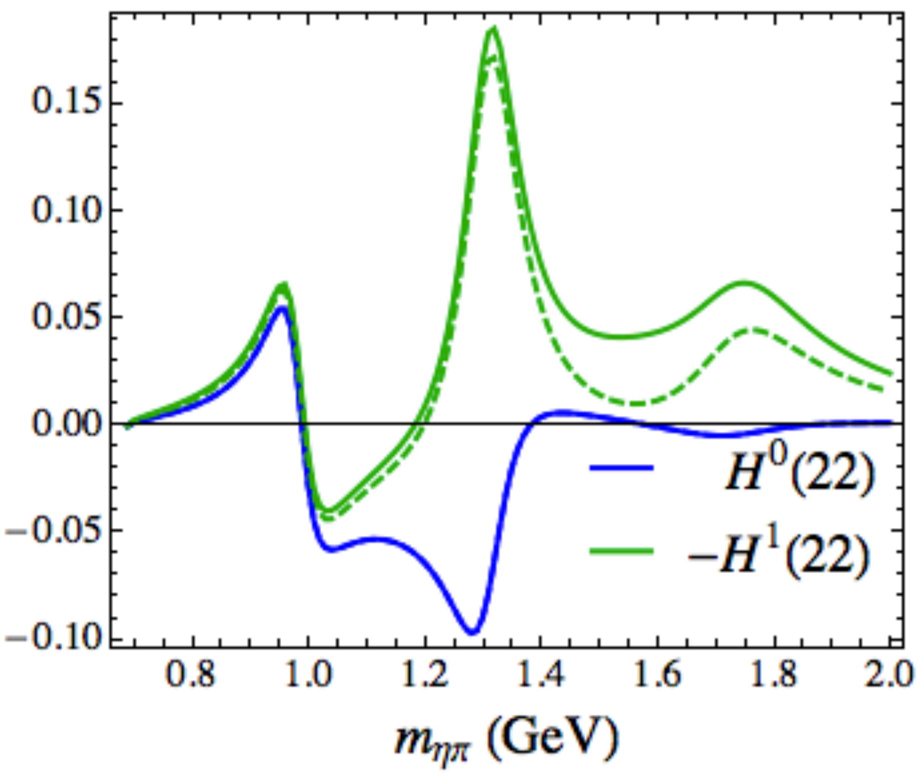
Small exotic wave,
not apparent in the diff. cross. section



VM et al (JPAC), in preparation

Moments

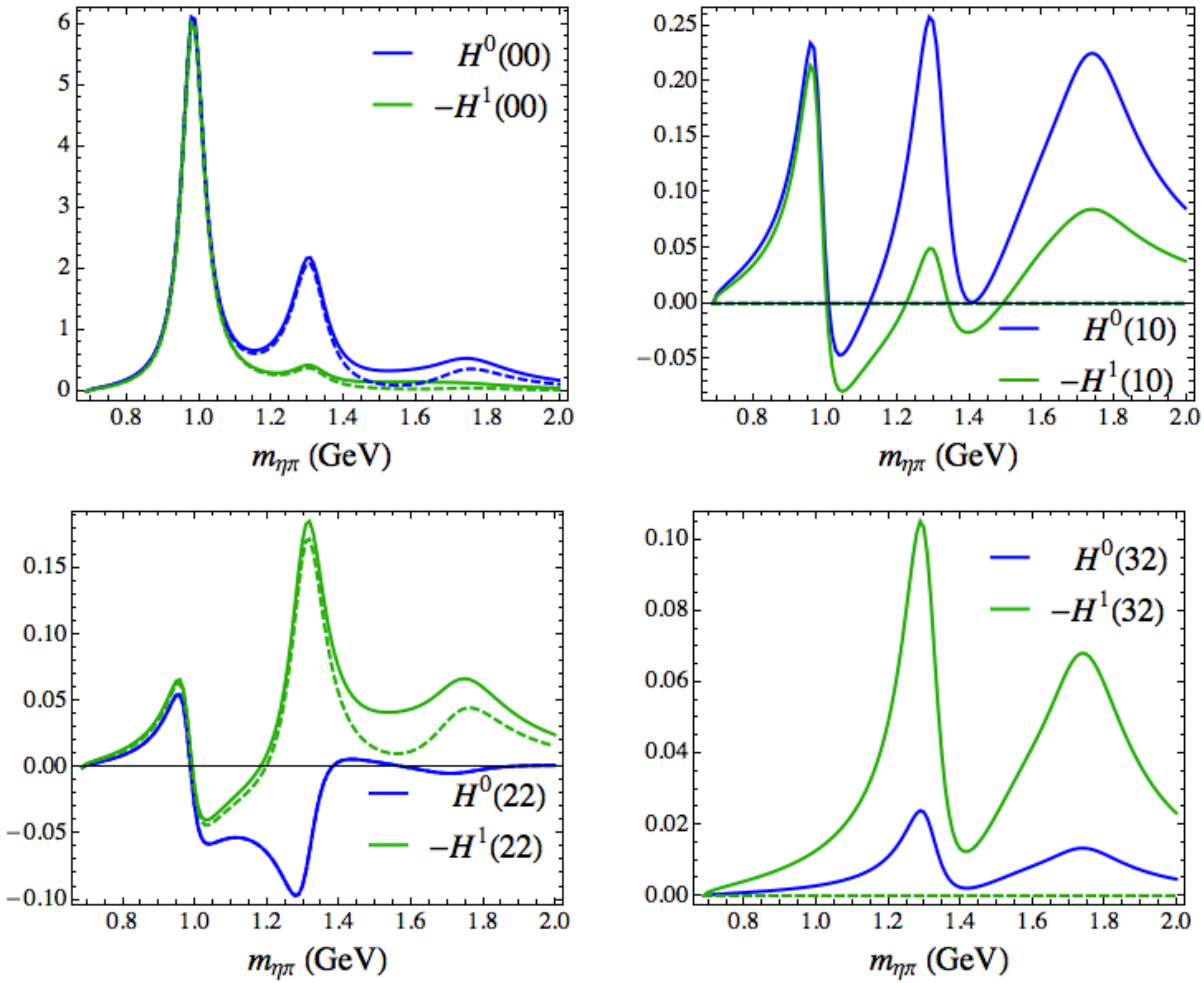




solid lines: *S* + *P* + *D* waves

dashed lines: *S* + *D* waves

Moments



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

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

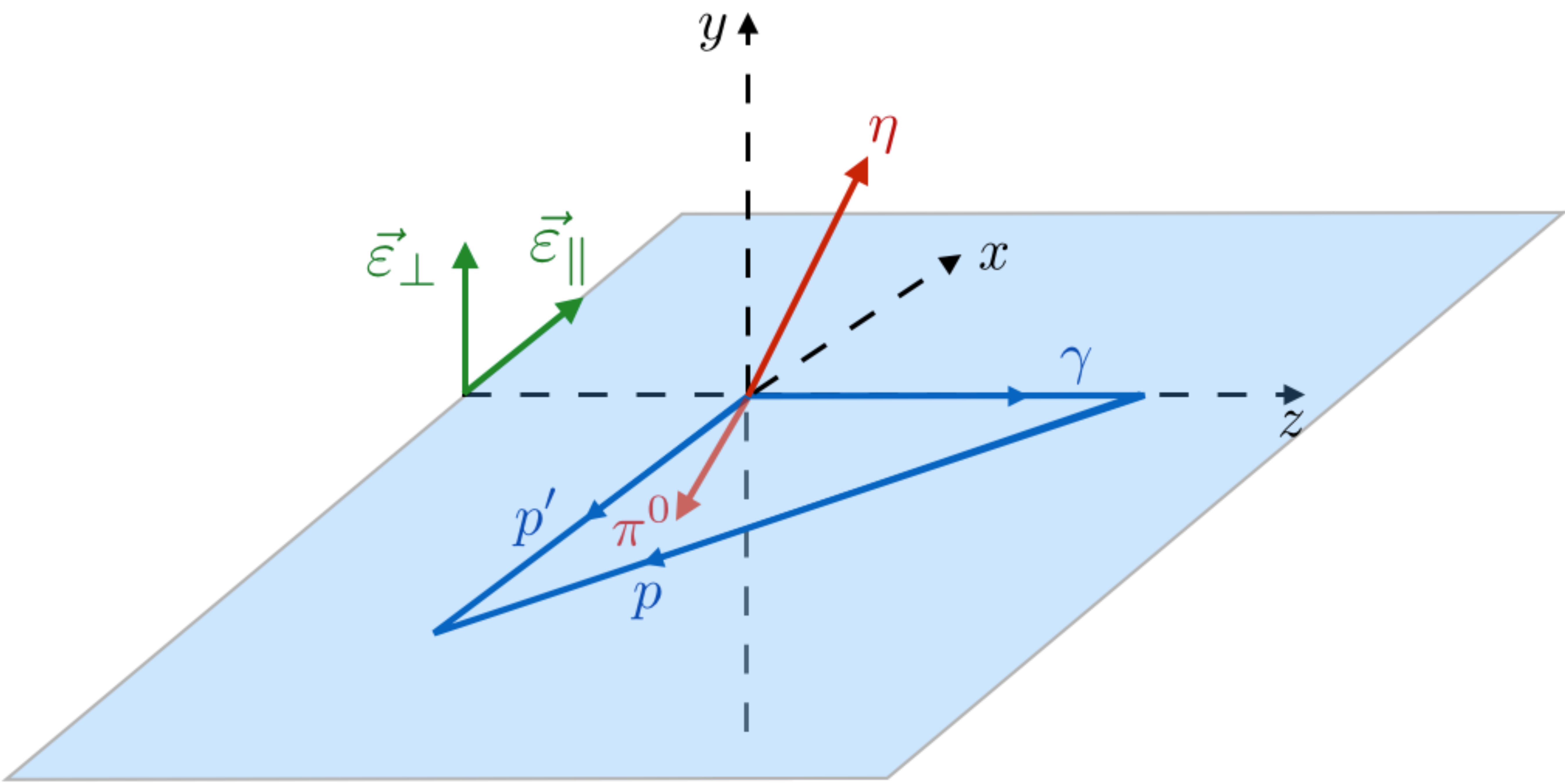
solid lines: *S* + *P* + *D* waves

dashed lines: *S* + *D* waves

Beam Asymmetries

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

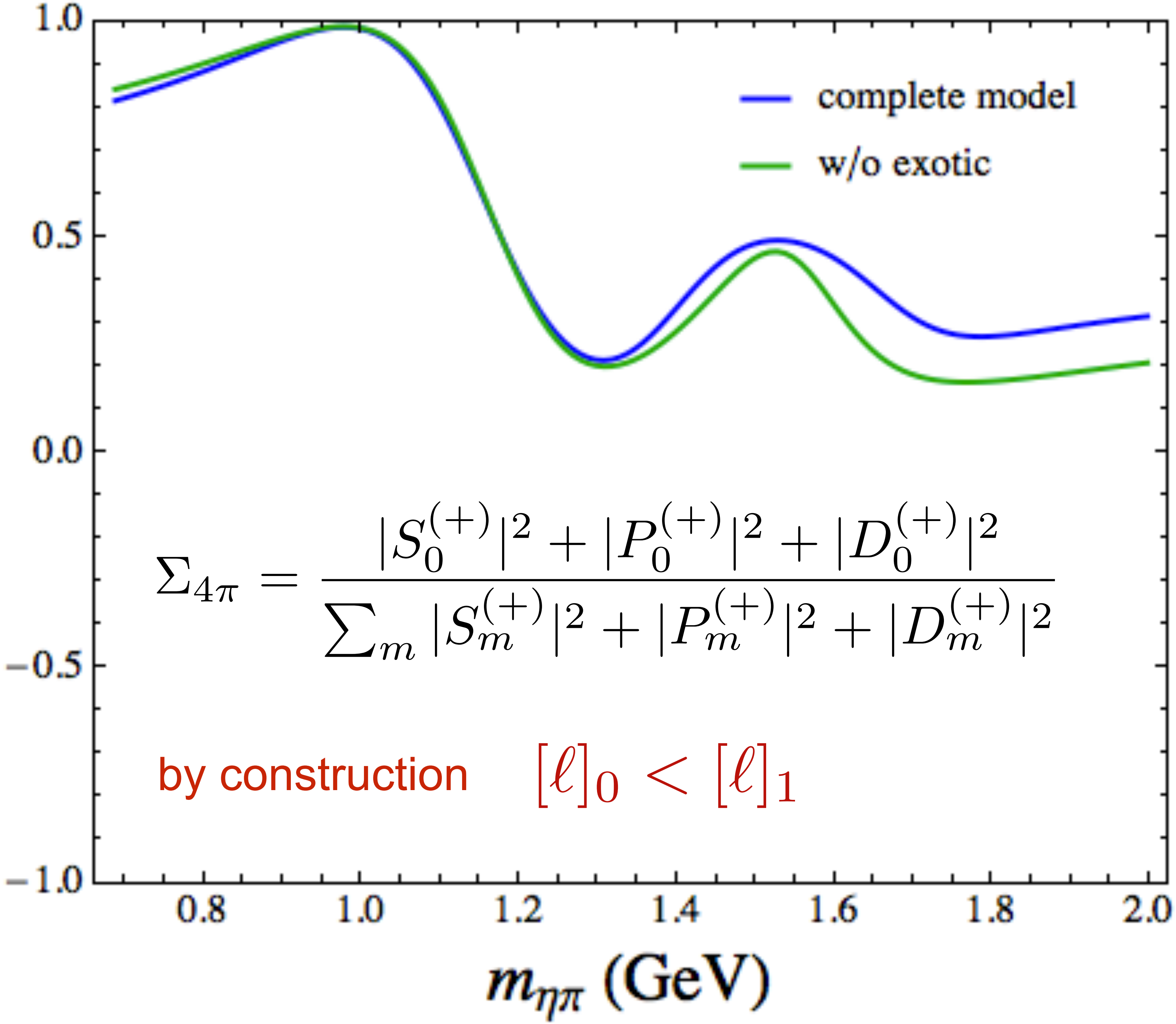
$\Sigma_{4\pi} =$ fully integrated



Beam Asymmetries

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

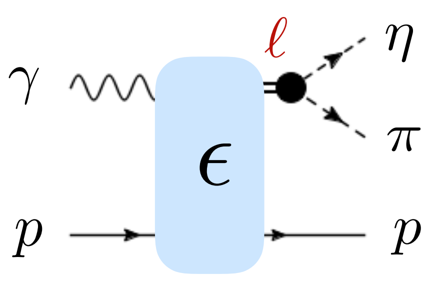
$\Sigma_{4\pi} =$ fully integrated

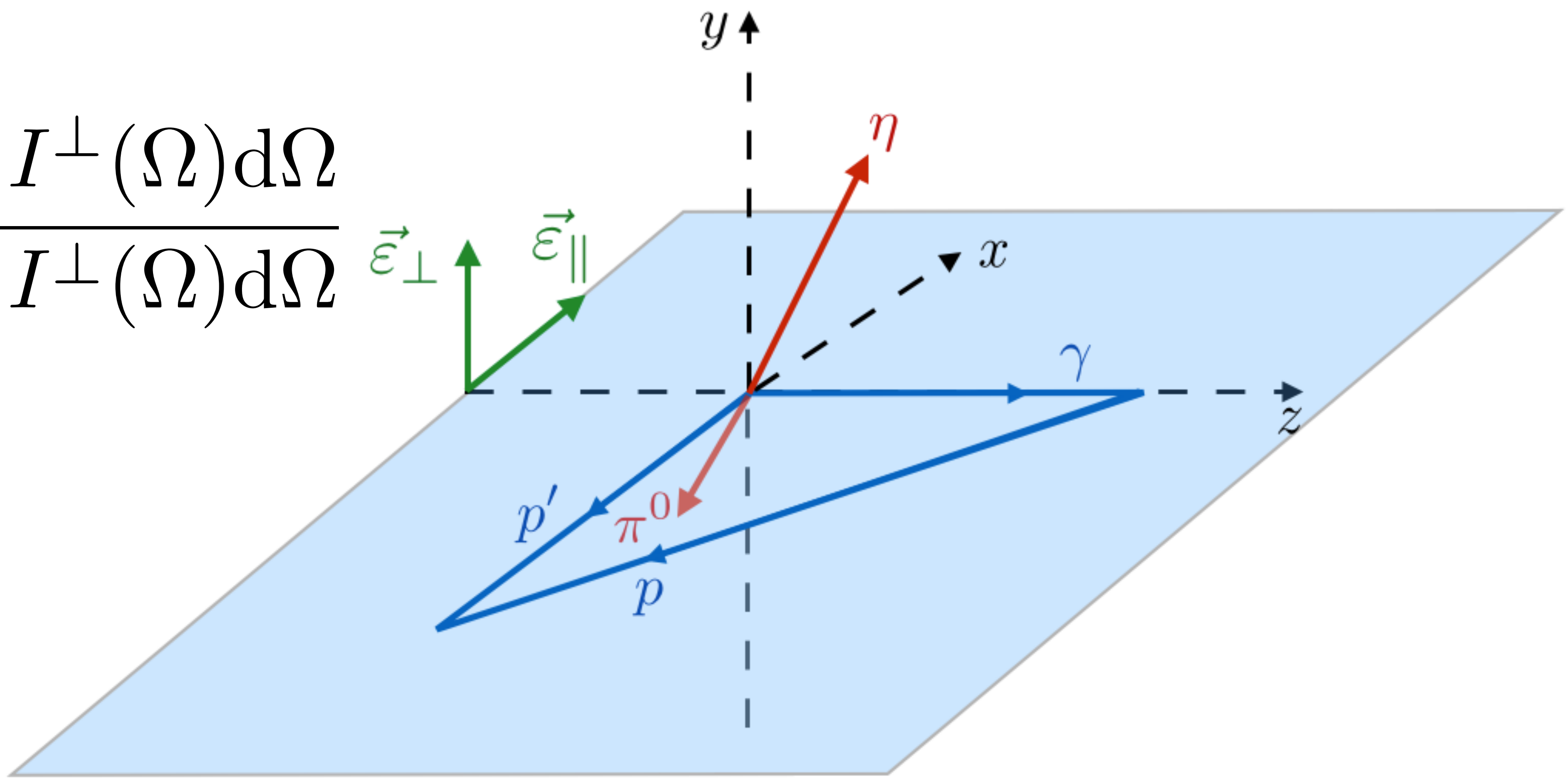


Beam Asymmetries

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

amplitude:
production x decay





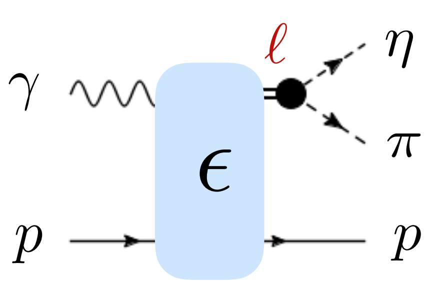
Beam asymmetry sensitive to reflection through the reaction plane

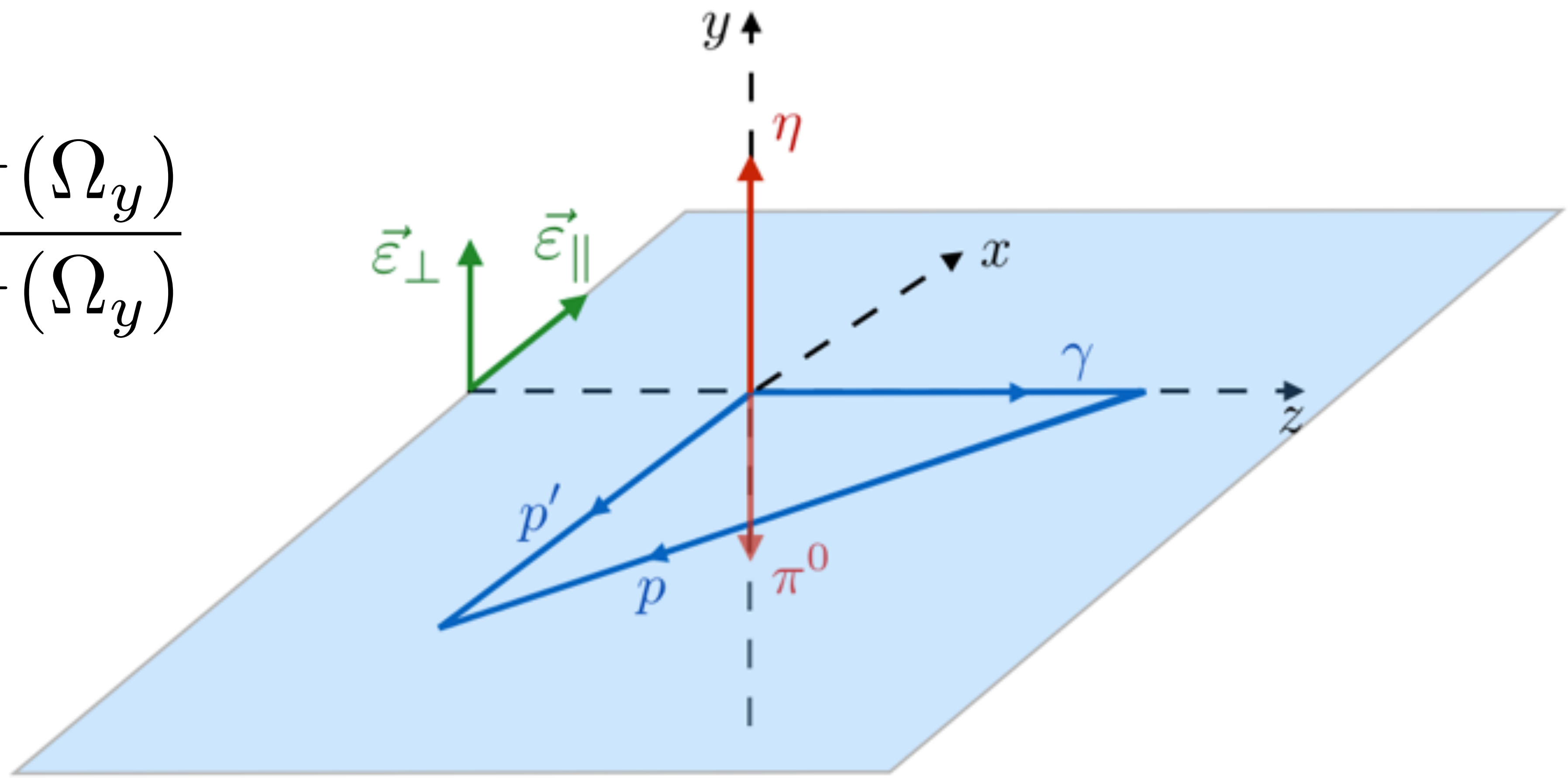
use reflection operator = parity followed by 180° rotation around Y-axis

Beam Asymmetries

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

amplitude:
production x decay





Beam asymmetry sensitive to reflection through the reaction plane

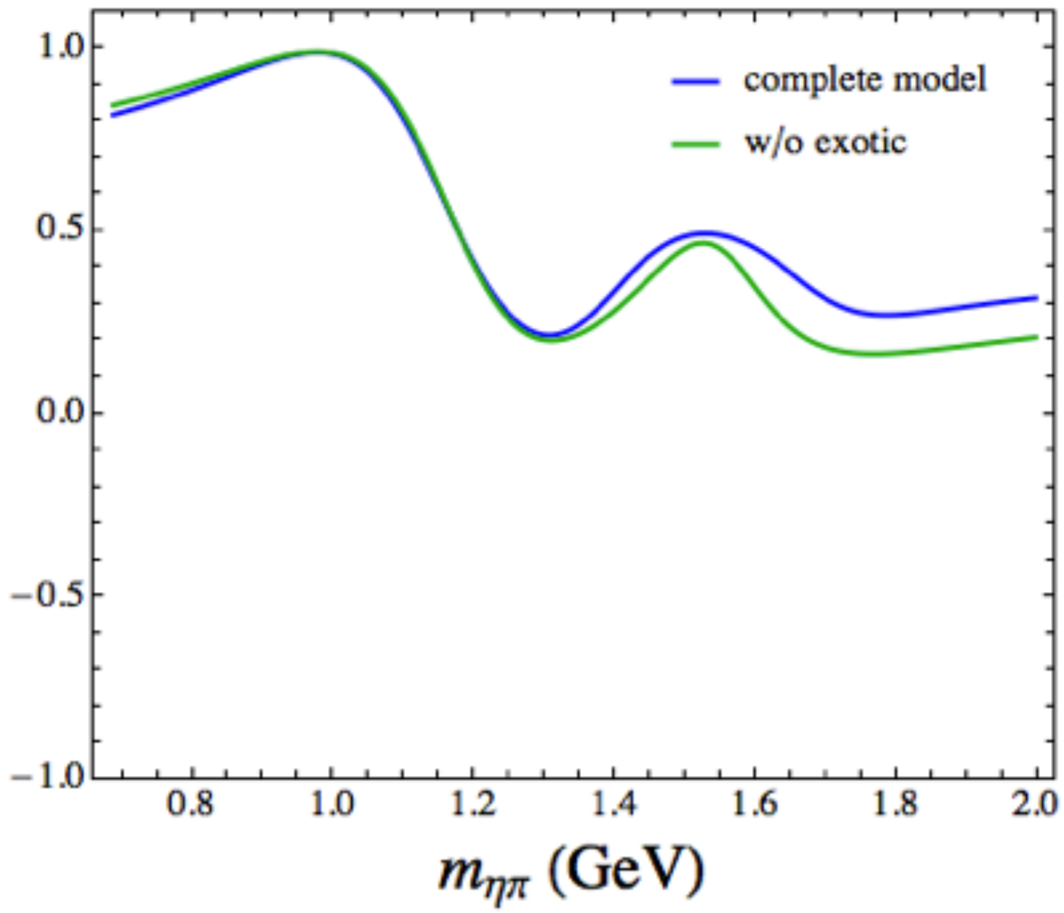
use reflection operator = parity followed by 180° rotation around Y-axis

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

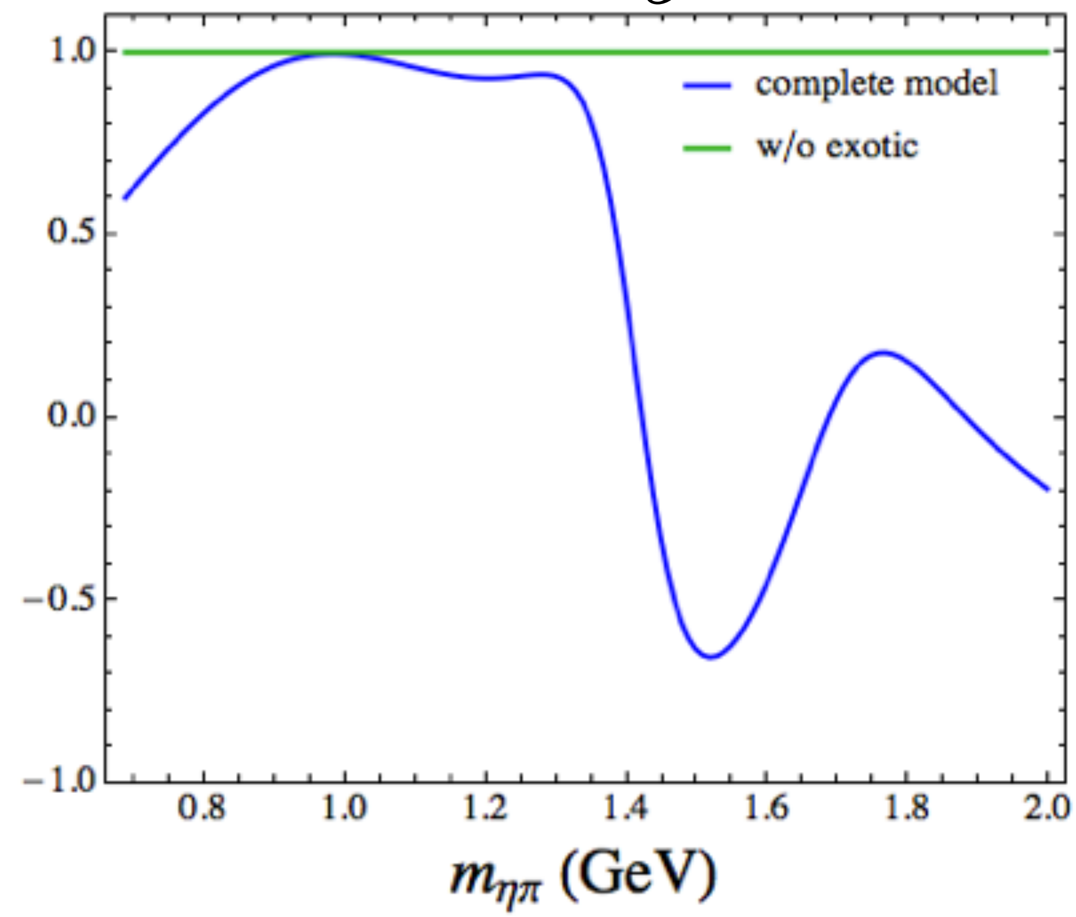
Odd waves change sign!!!

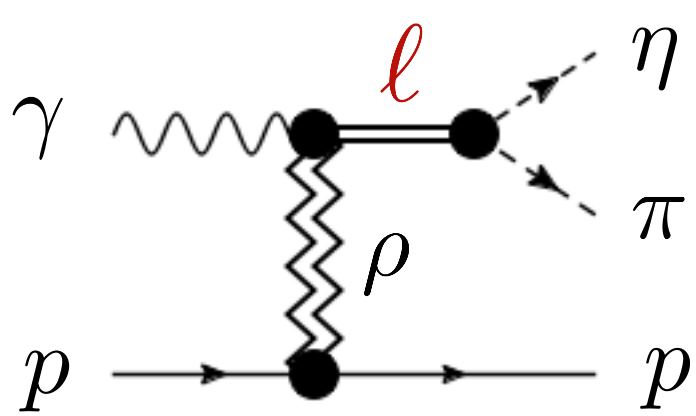
Beam Asymmetries

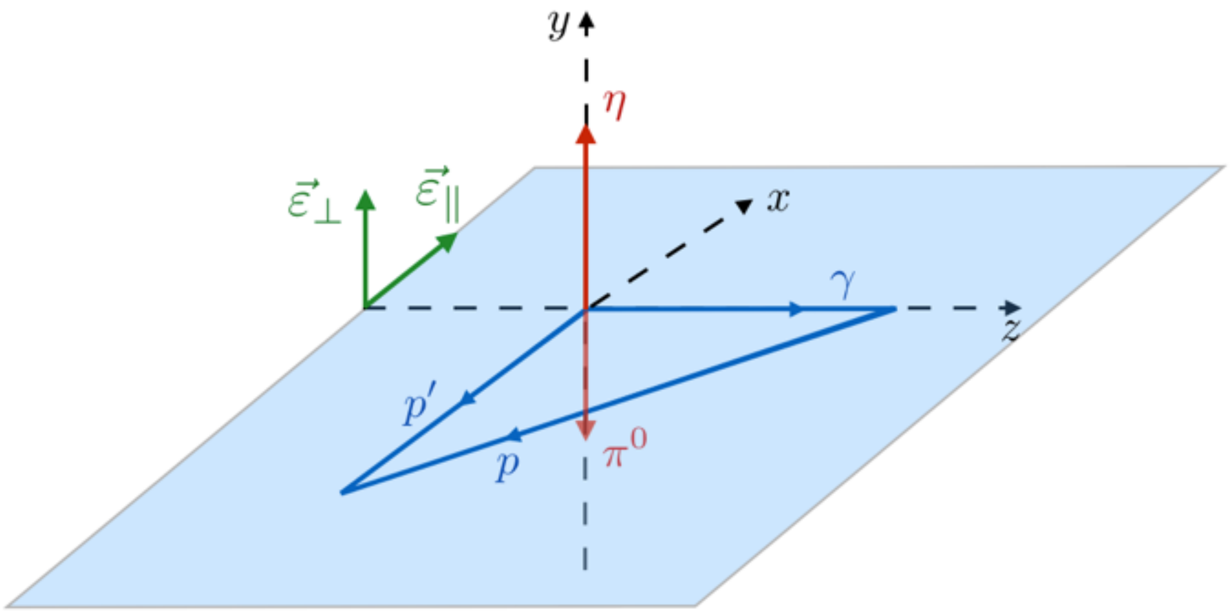
$\Sigma_{4\pi}$



Σ_y

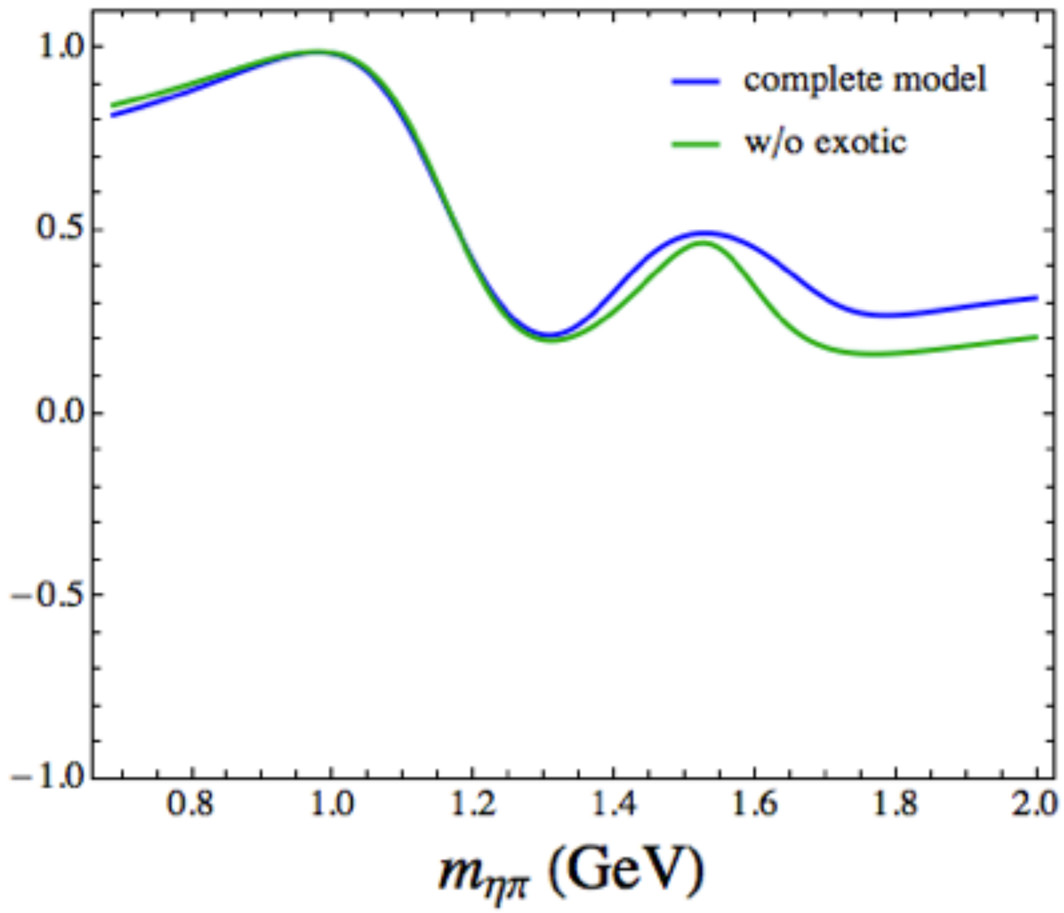




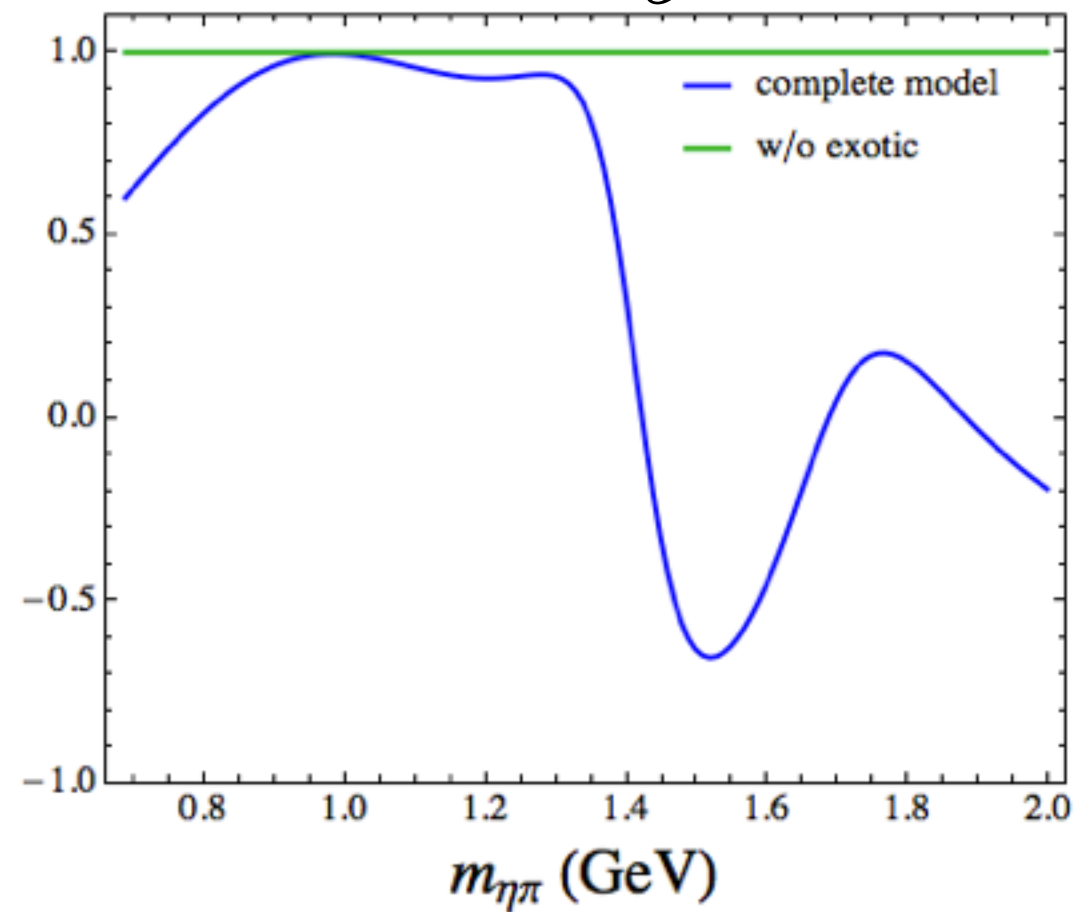


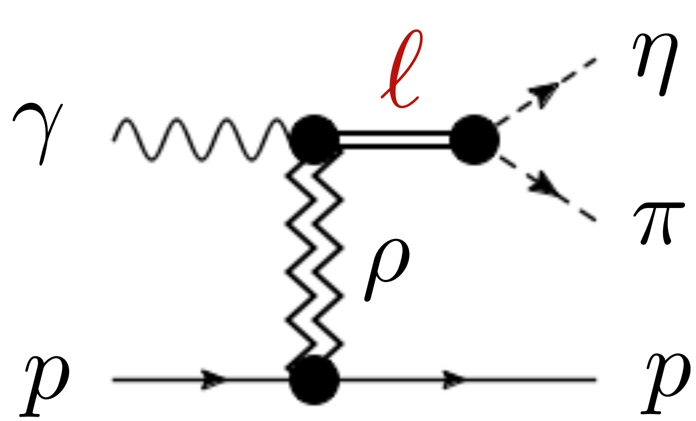
Beam Asymmetries

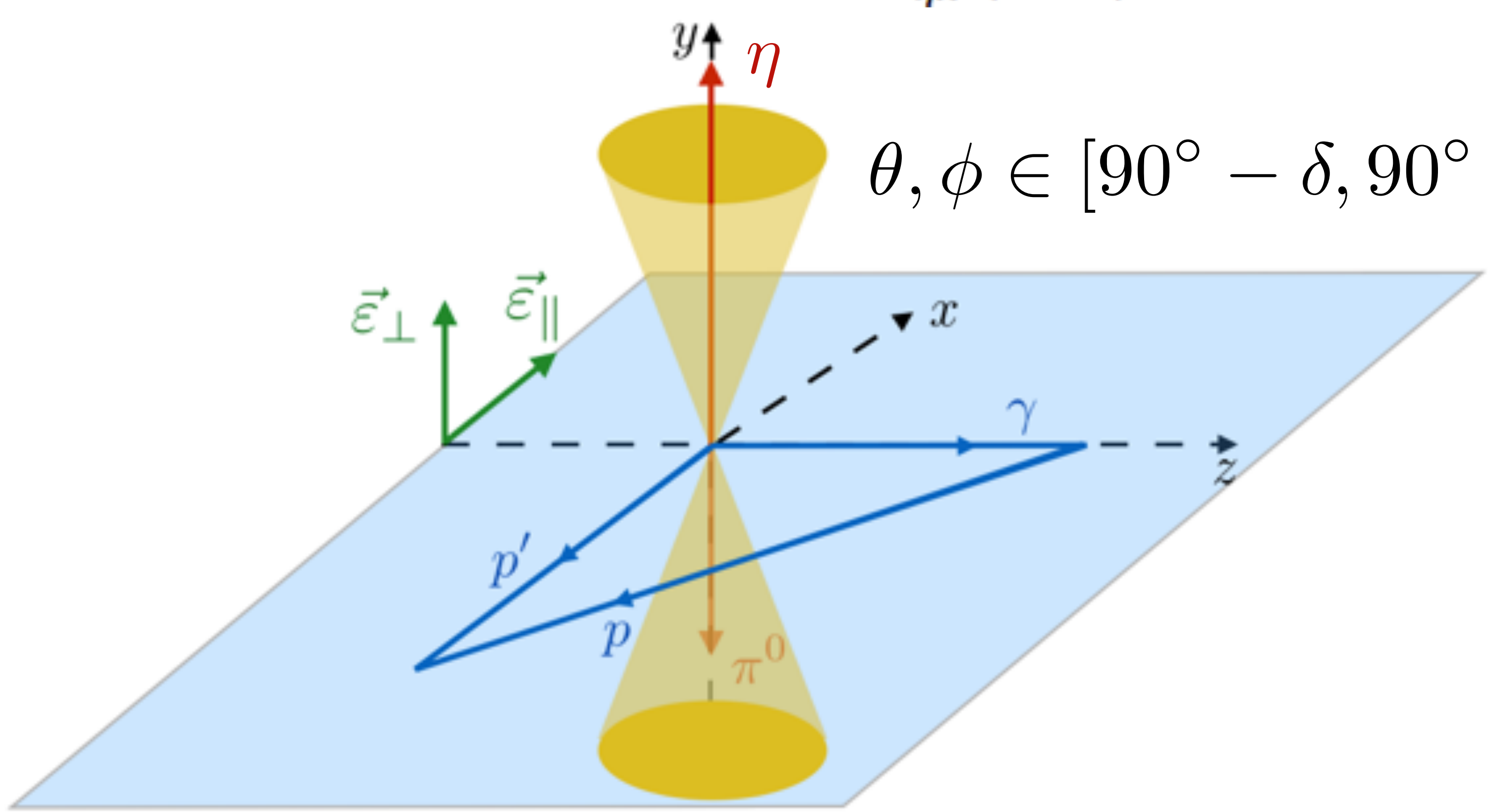
$$\Sigma_{4\pi}$$



$$\Sigma_y$$



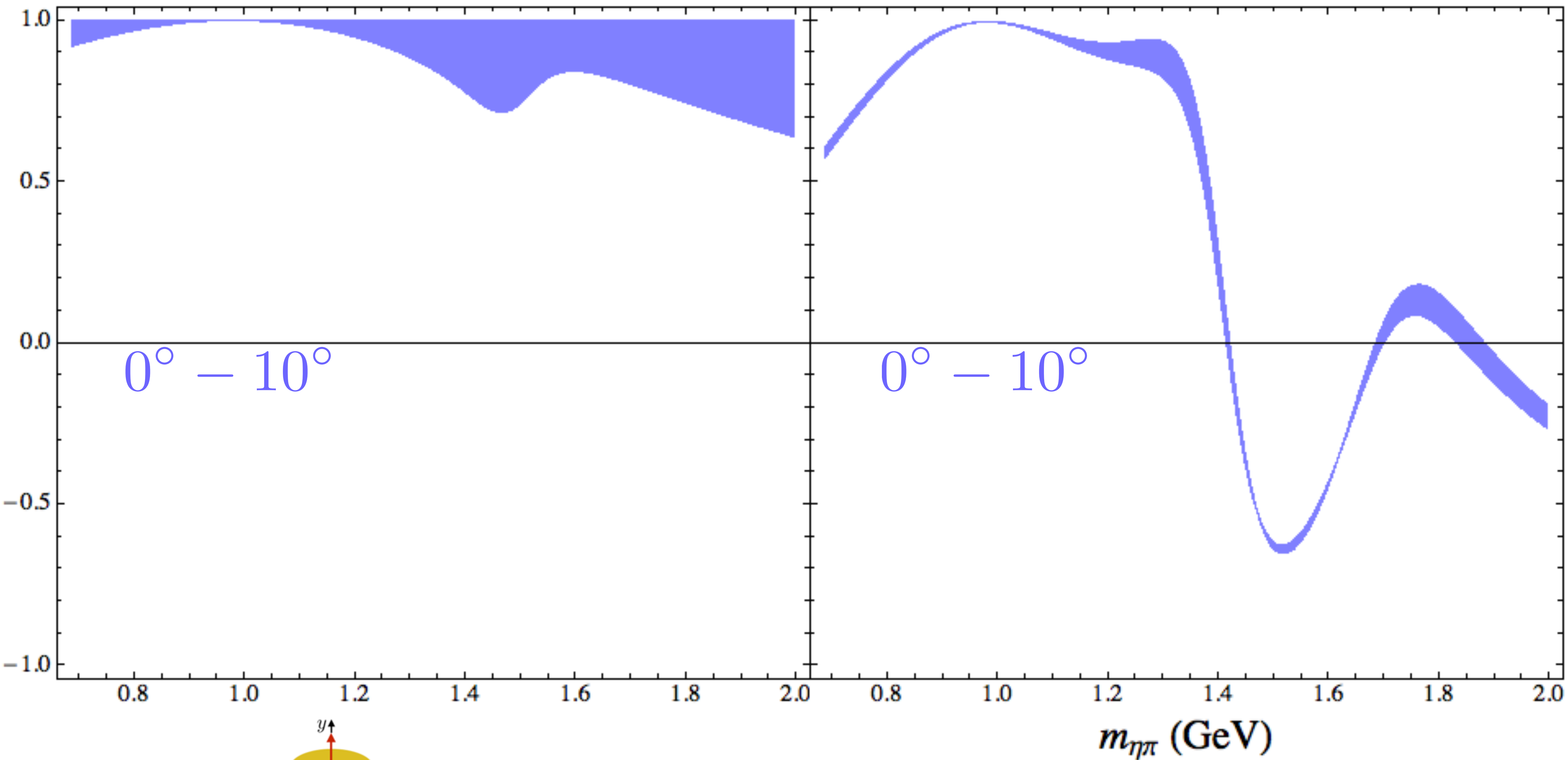


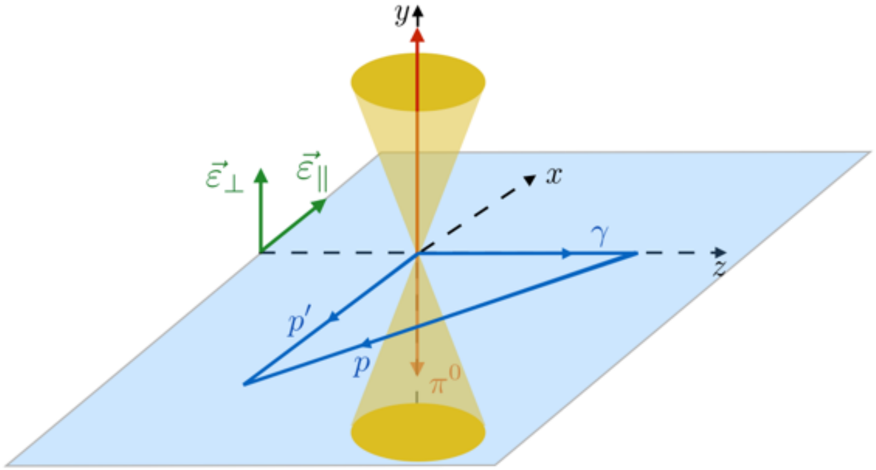


$$\theta, \phi \in [90^\circ - \delta, 90^\circ + \delta]$$

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

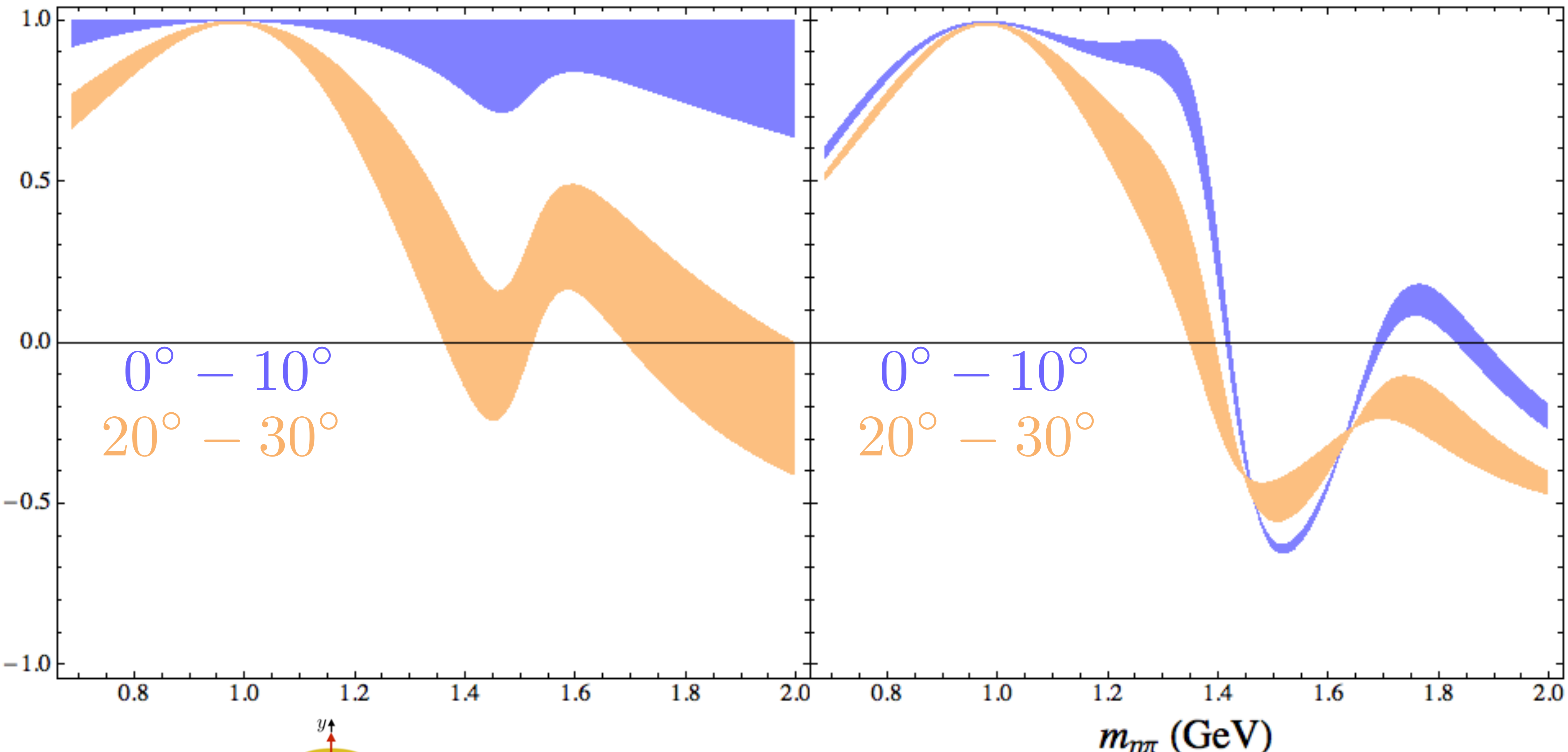
only S and D waves **S, P and D waves**

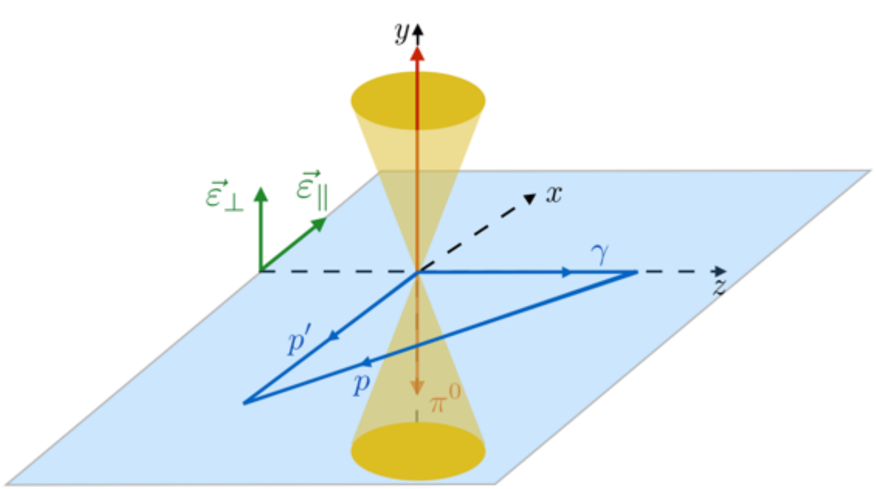




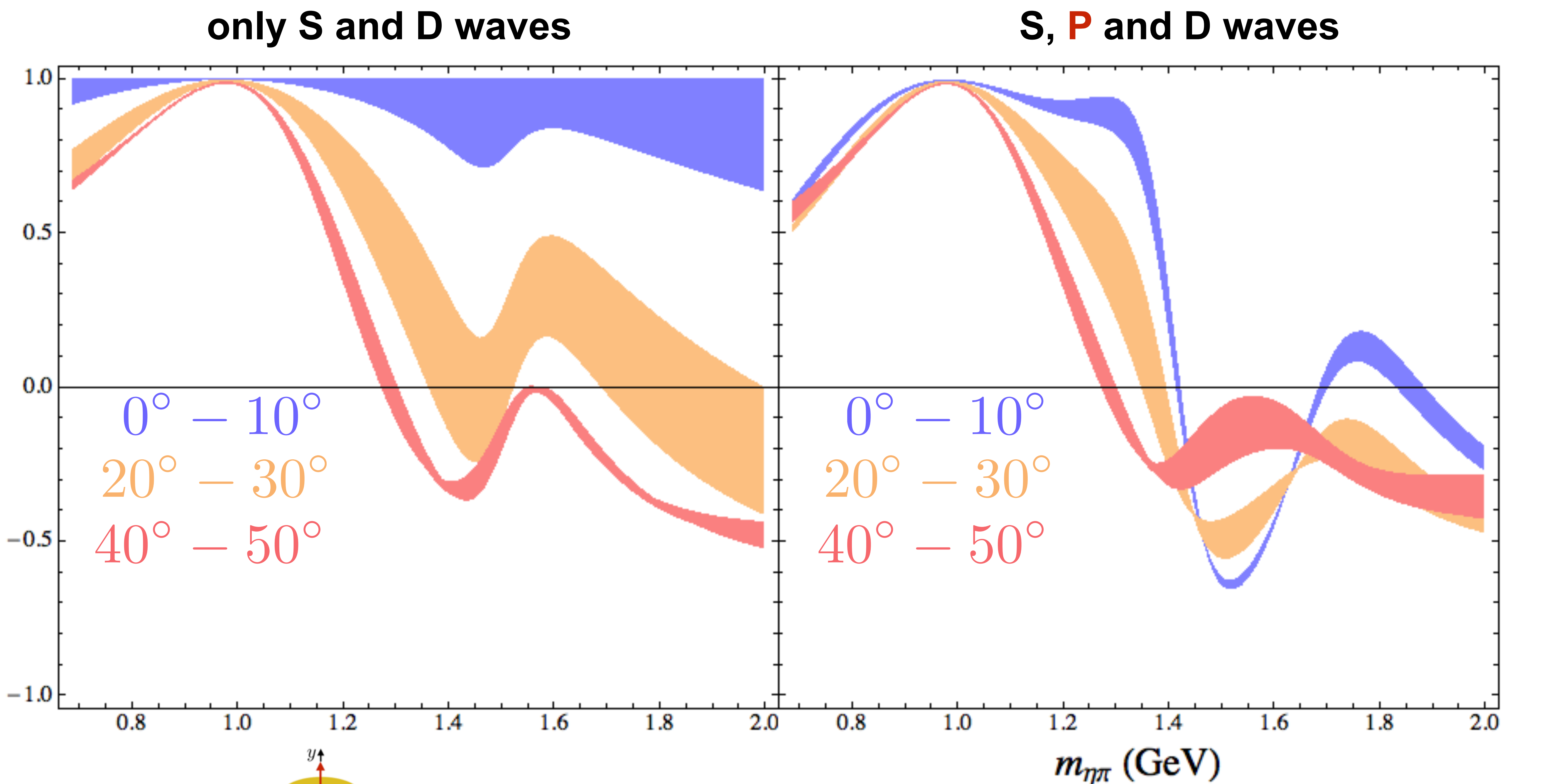
Beam Asymmetries: $\Sigma_{y\pm\delta^\circ}$

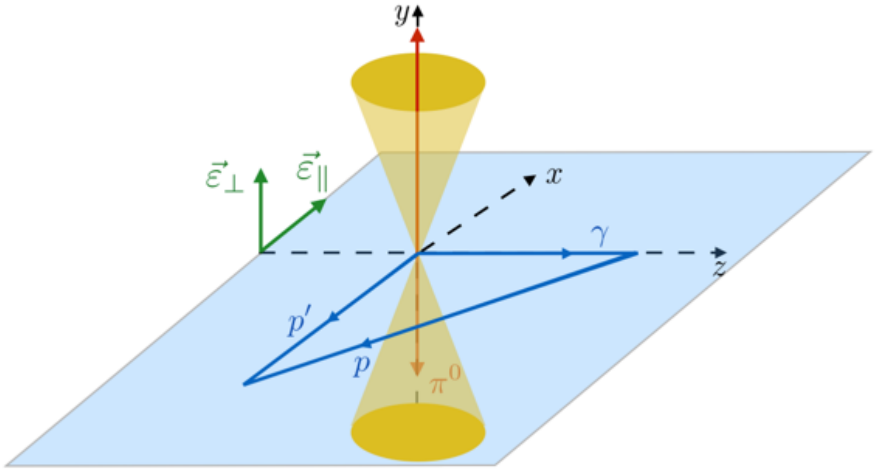
only S and D waves | **S, P and D waves**





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

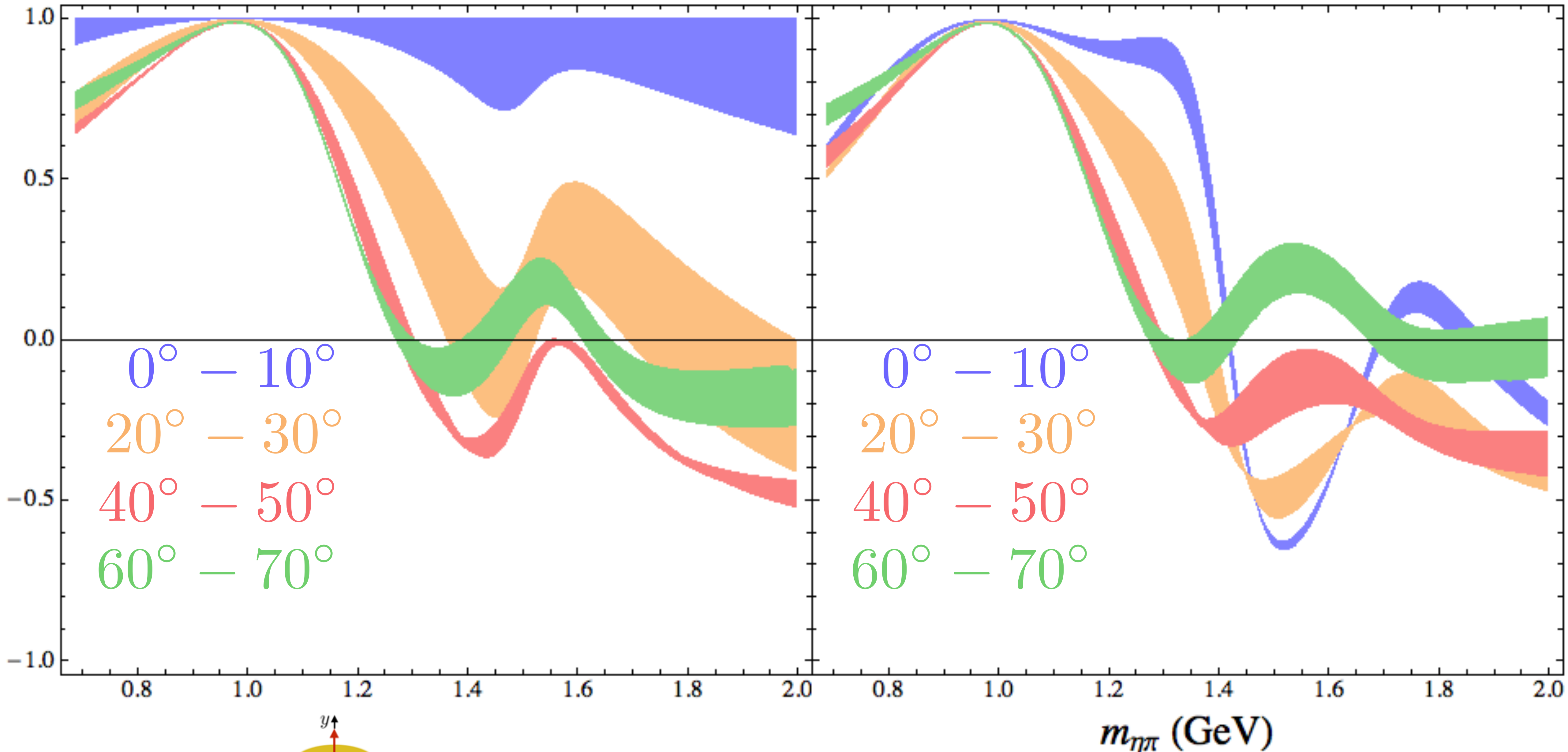


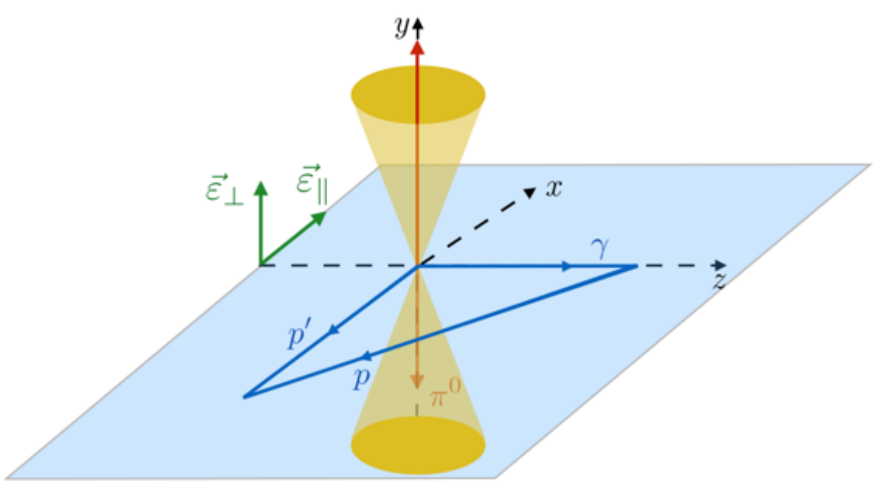


with an opening angle greater than 30°
the observables is not sensitive to the P-wave
(with our model)

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

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

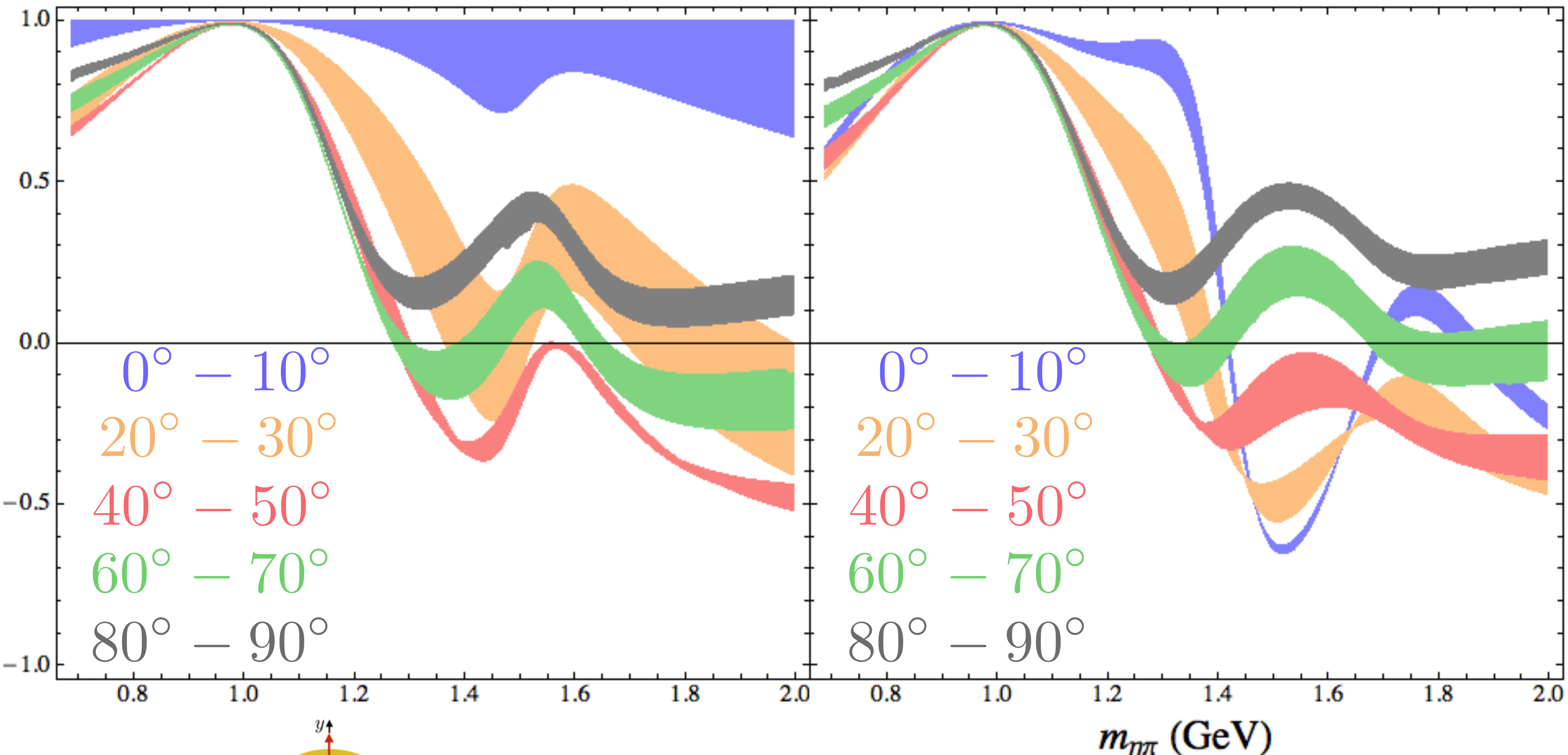


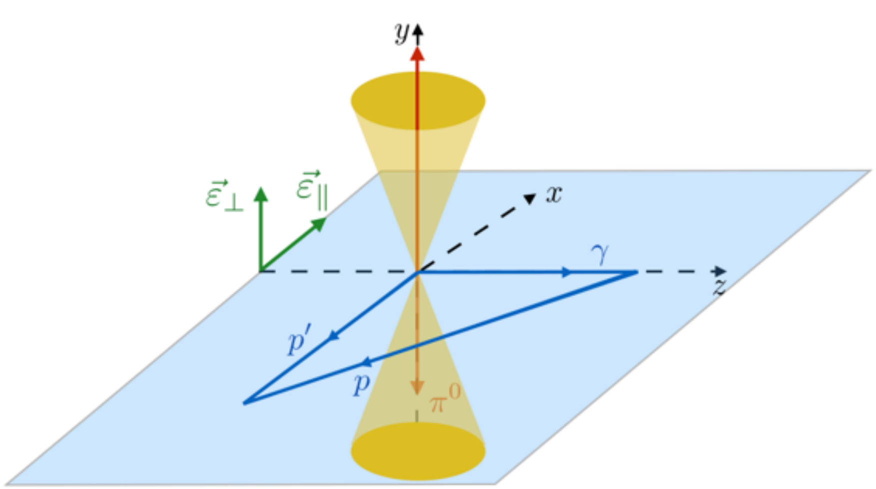


with an opening angle greater than 30°
the observables is not sensitive to the P-wave
(with our model)

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

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

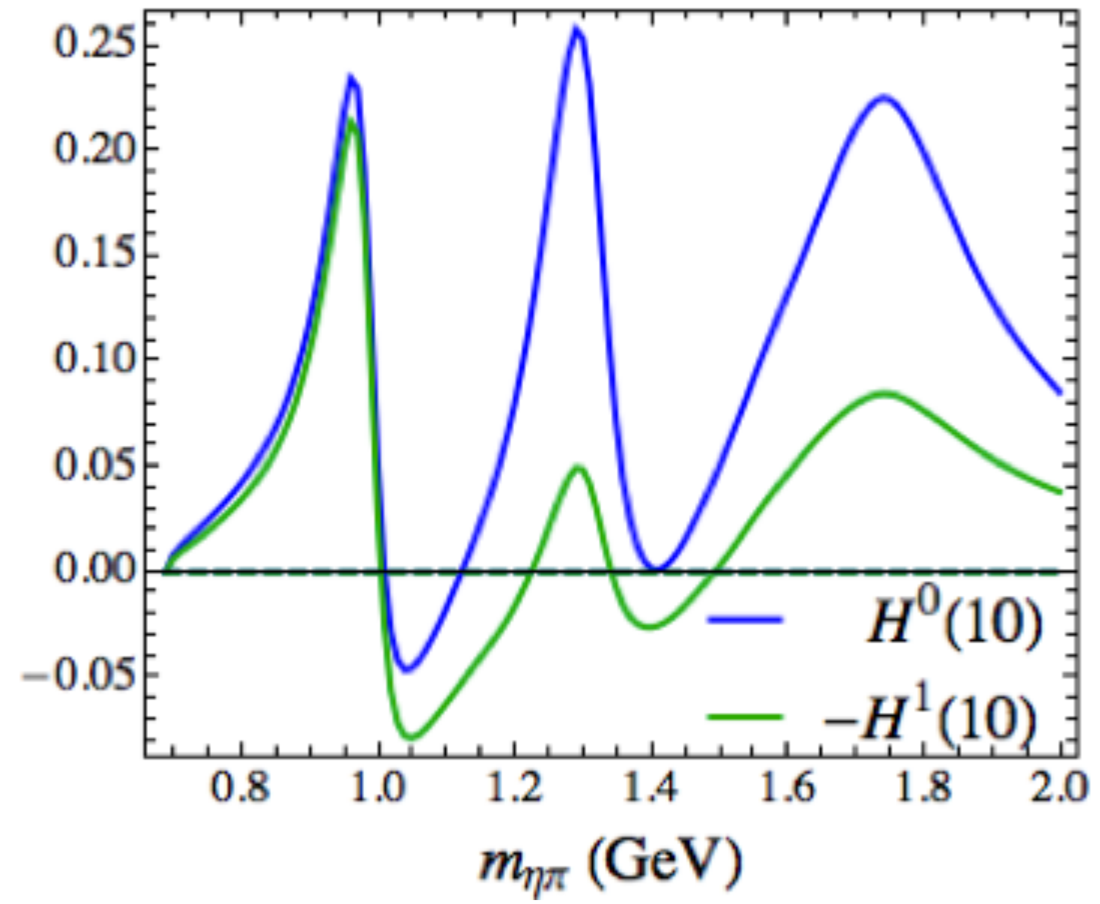




with an opening angle greater than 30° the observables is not sensitive to the P-wave (with our model)

Conclusions

Moments of angular distribution and beam asymmetries provides info on wave content and production mechanism



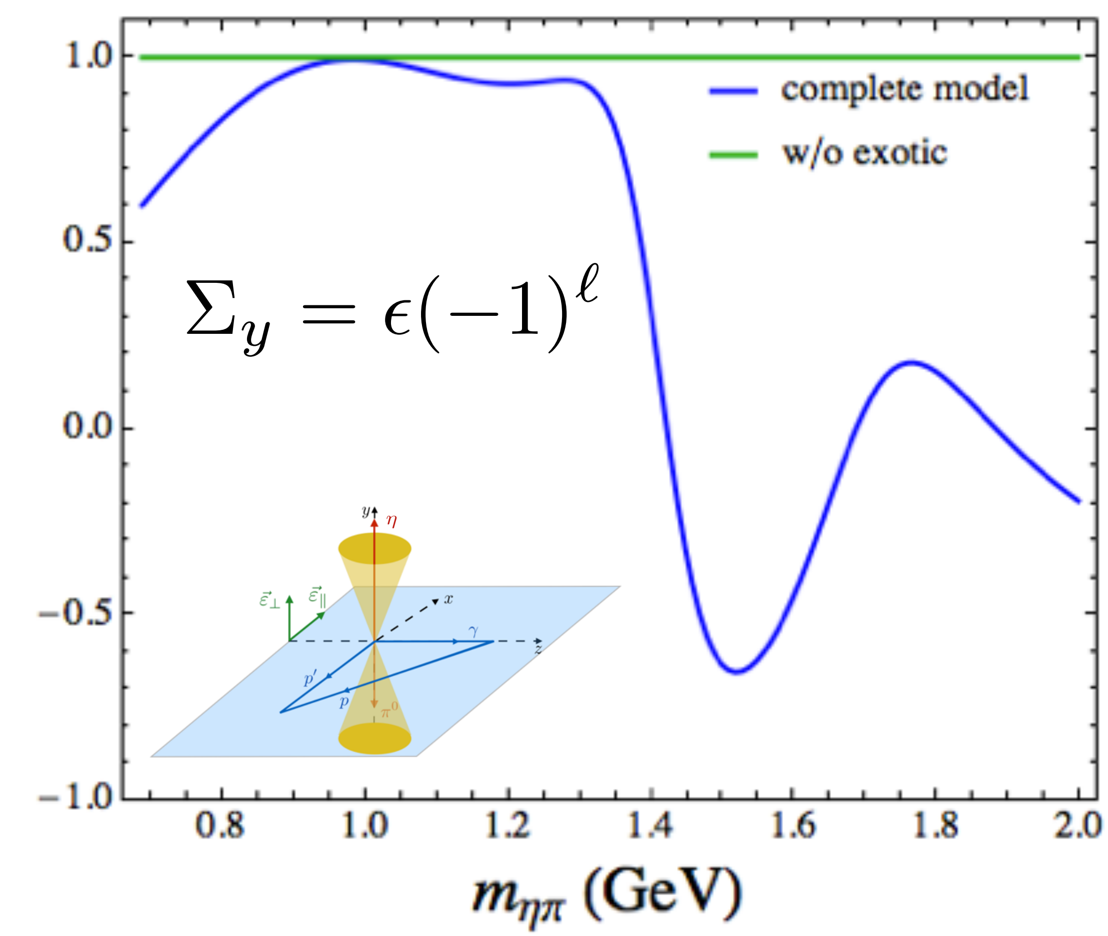
Current/future applications @GlueX:

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

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

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

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



Future plan: partial wave analysis

Backup Slides

The resulting photon spin density matrix reads

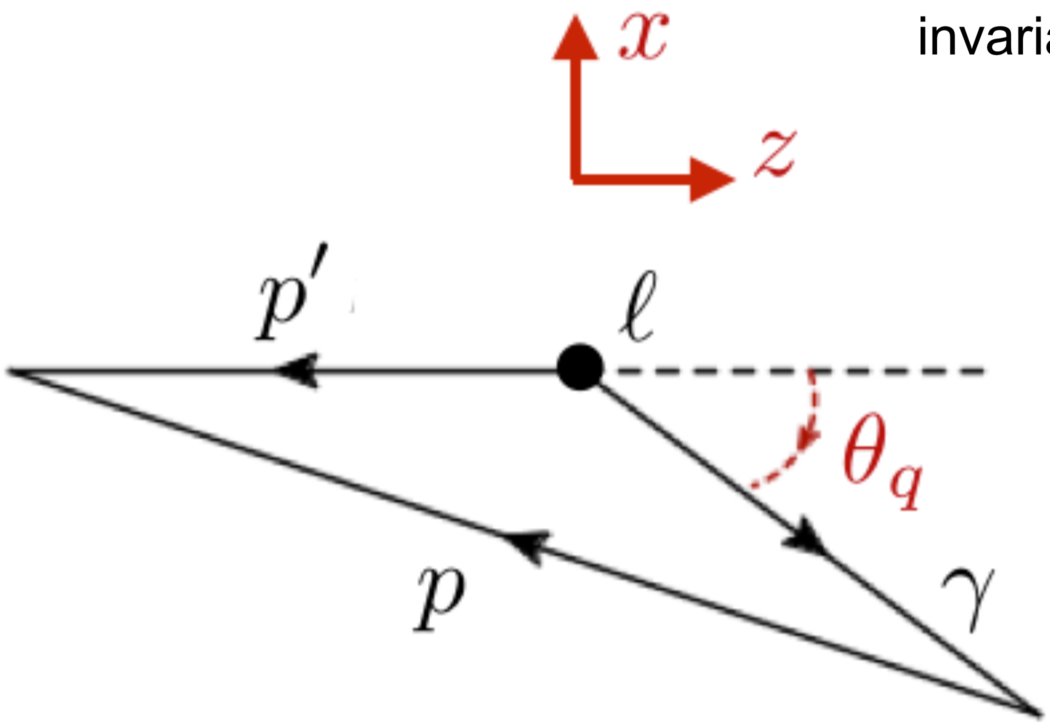
$$L_{\lambda\lambda'} = \frac{Q^2}{2(1-\epsilon)} \begin{pmatrix} 1 & \sqrt{\epsilon(1+\epsilon+2\delta)}\,e^{-i\Phi} & -\epsilon e^{-2i\Phi} \\ \sqrt{\epsilon(1+\epsilon+2\delta)}\,e^{i\Phi} & 2(\epsilon+\delta) & -\sqrt{\epsilon(1+\epsilon+2\delta)}\,e^{-i\Phi} \\ -\epsilon e^{2i\Phi} & -\sqrt{\epsilon(1+\epsilon+2\delta)}\,e^{i\Phi}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

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

Schilling and Wolf NPB61 (1973) 381

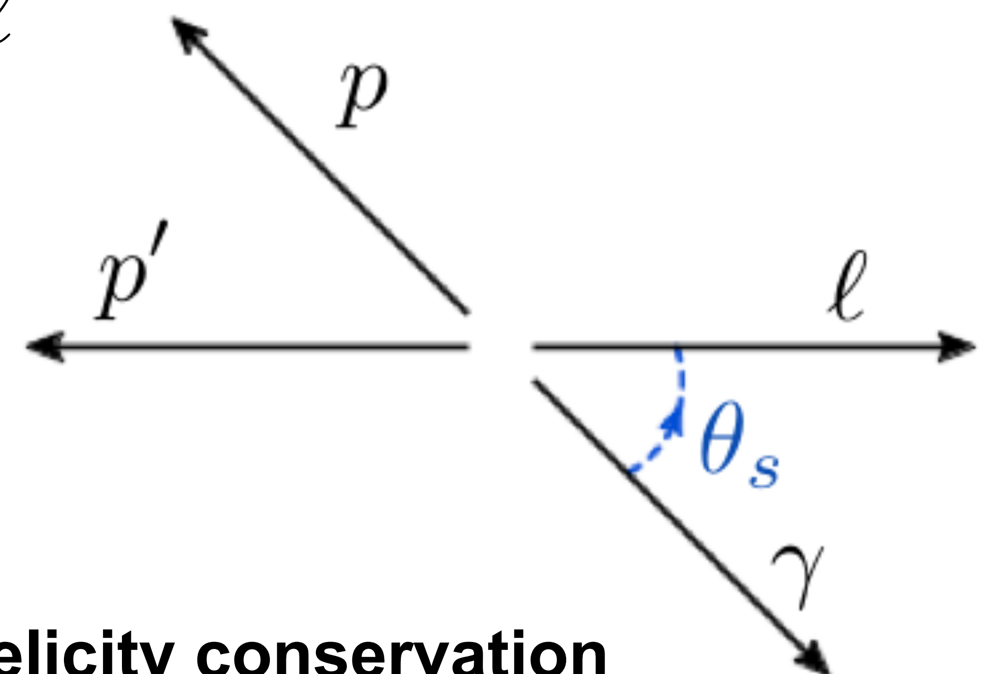
Frame

Helicity frame



boost →
invariant helicity ℓ

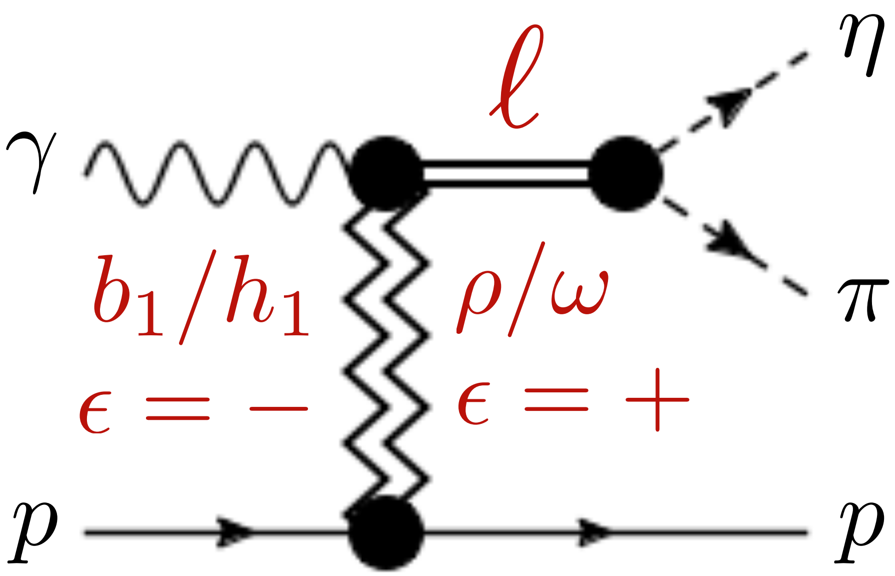
s-channel



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

Observables: Moments of Angular distribution

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

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

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

$m' = m - M$

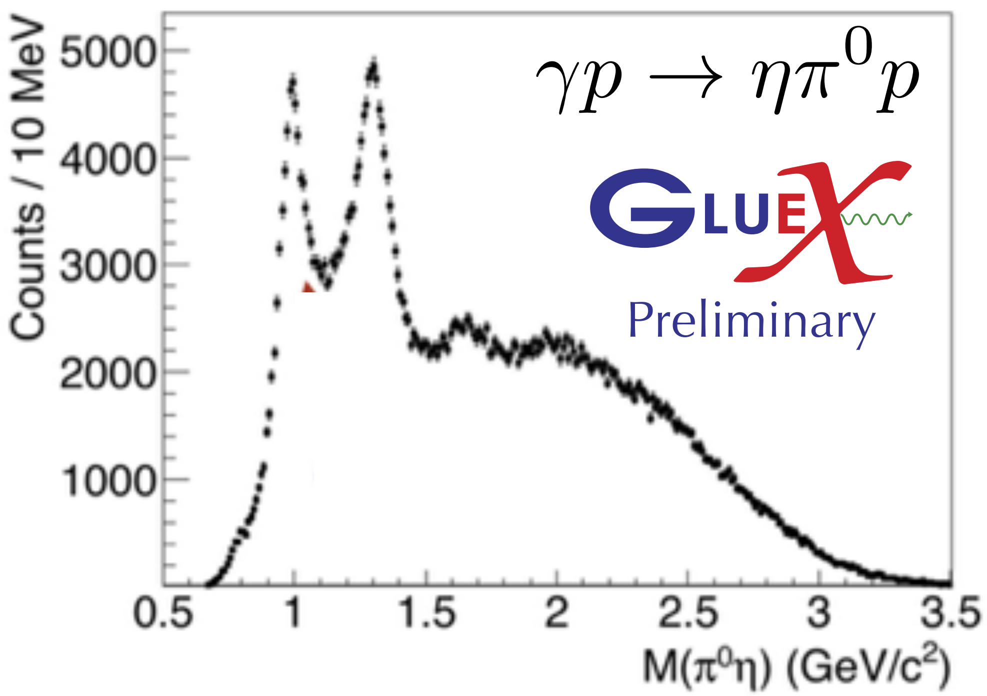
$$H^1(LM) + \mathrm{Im}\ H^2(LM) \propto \sum_{\epsilon, \substack{\ell\ell' \\ mm'}} \left(\frac{2\ell' + 1}{2\ell + 1} \right)^{1/2} \epsilon (-1)^m C^{\ell 0}_{\ell' 0 L 0} C^{\ell m}_{\ell' m' L M} [\ell]^{(\epsilon)}_{-m} [\ell']^{(\epsilon)*}_{m'}$$

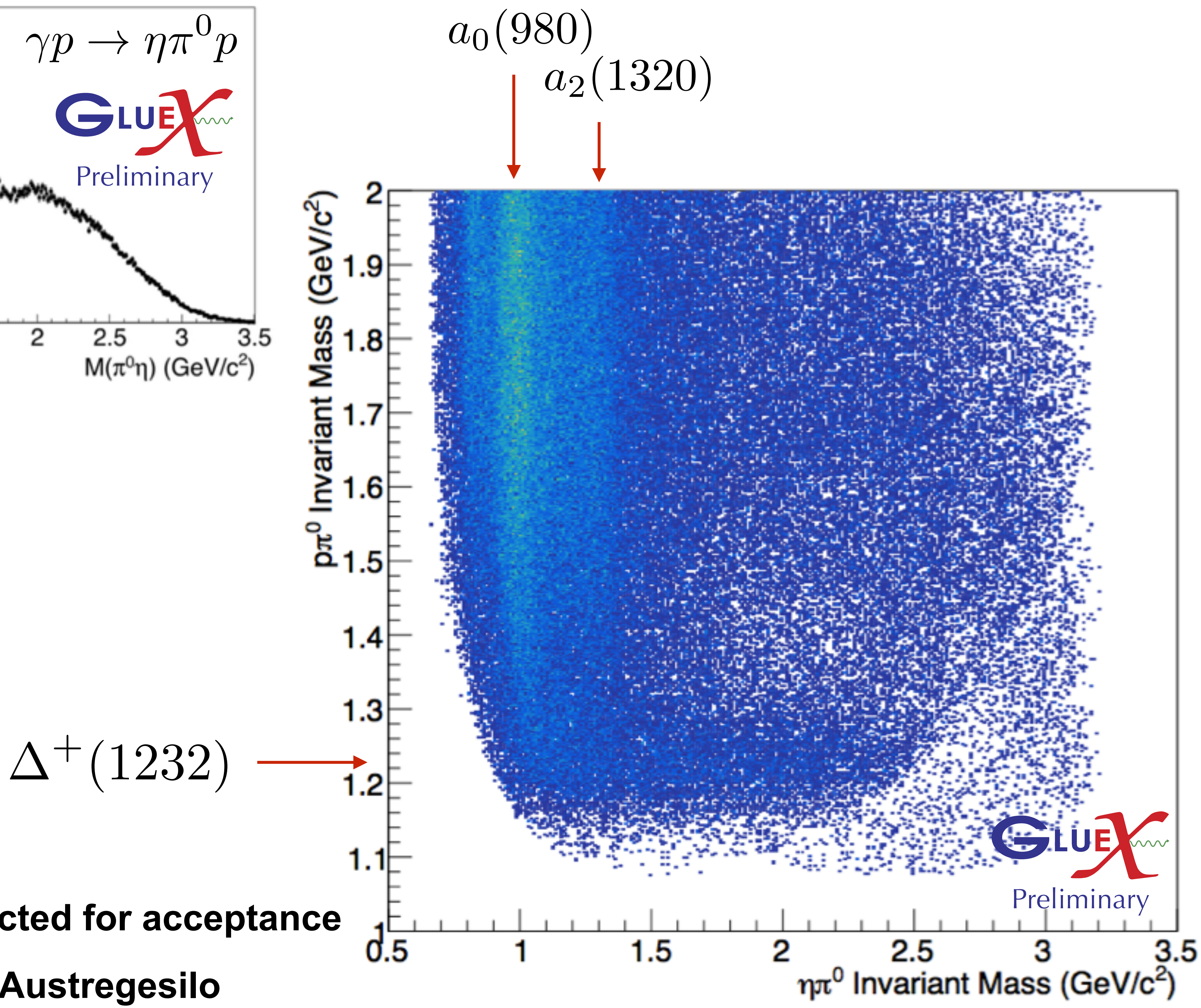
$0 \leqslant -m \; ; \; 0 \leqslant m'$

The model features only positive projections

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

Eta-Pi Production@GlueX

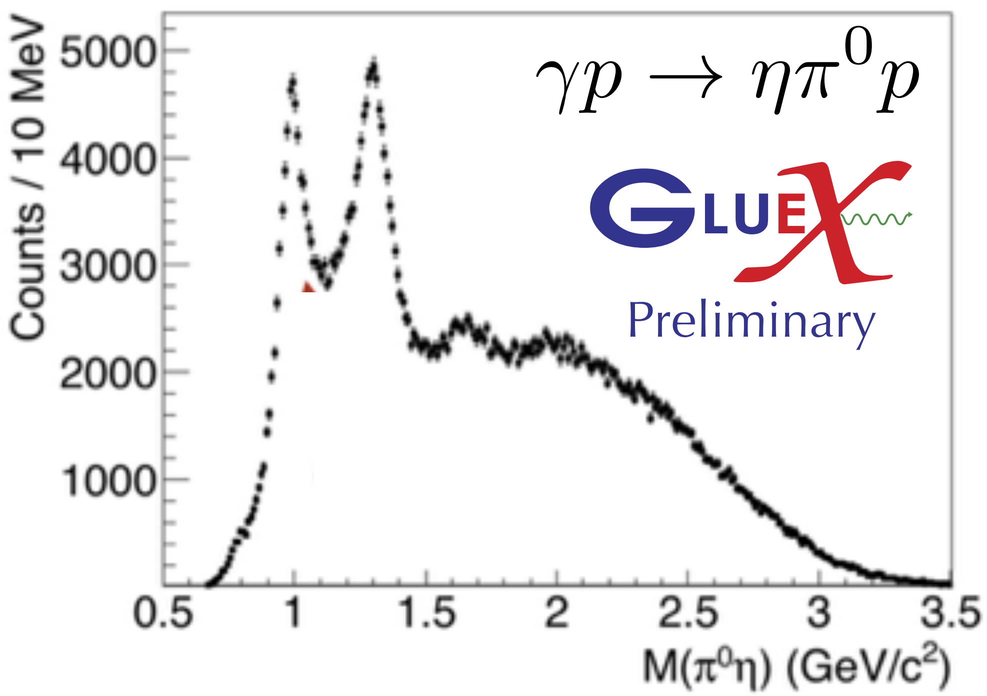


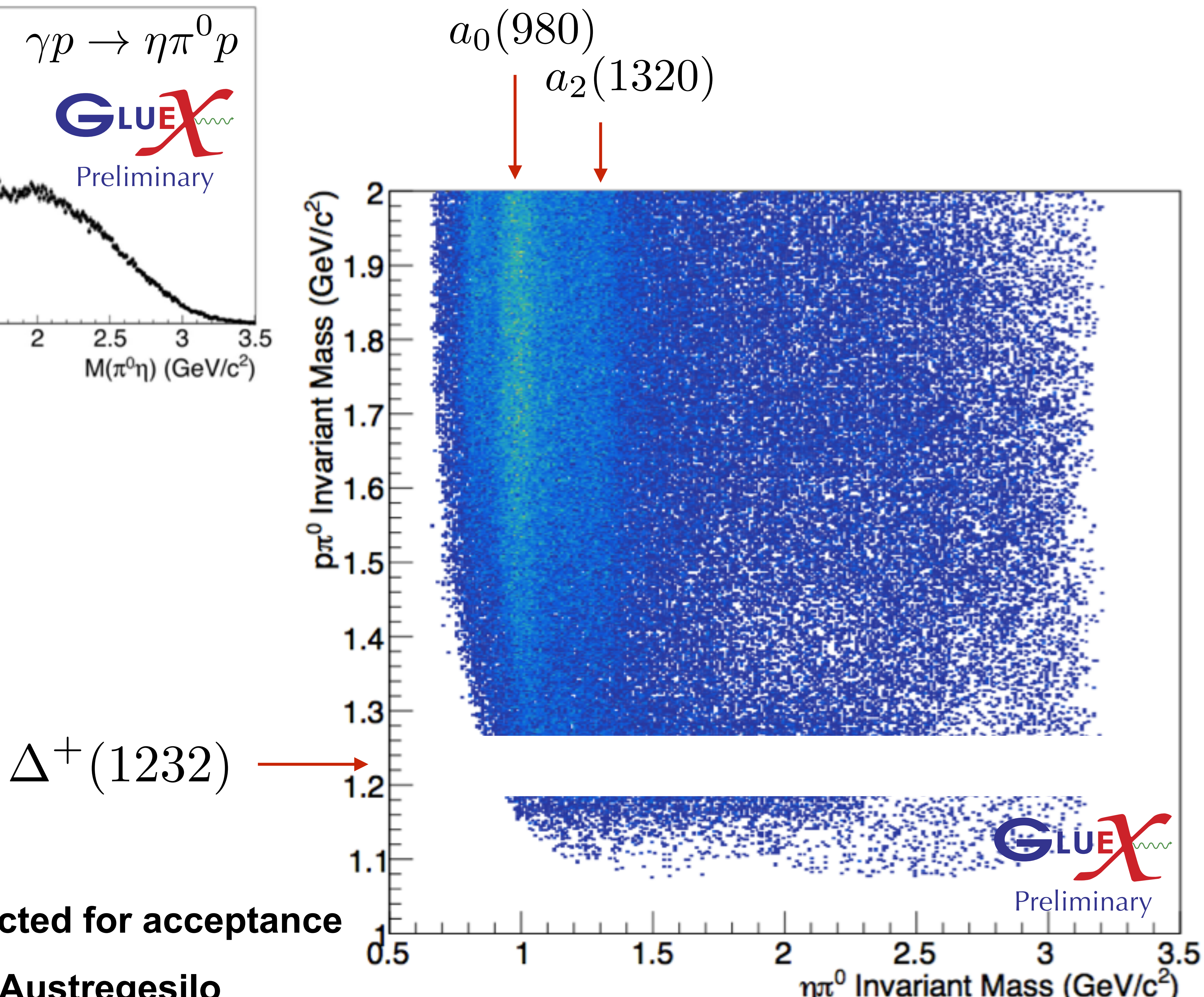


data non-corrected for acceptance

Courtesy of A. Austregesilo

Eta-Pi Production@GlueX

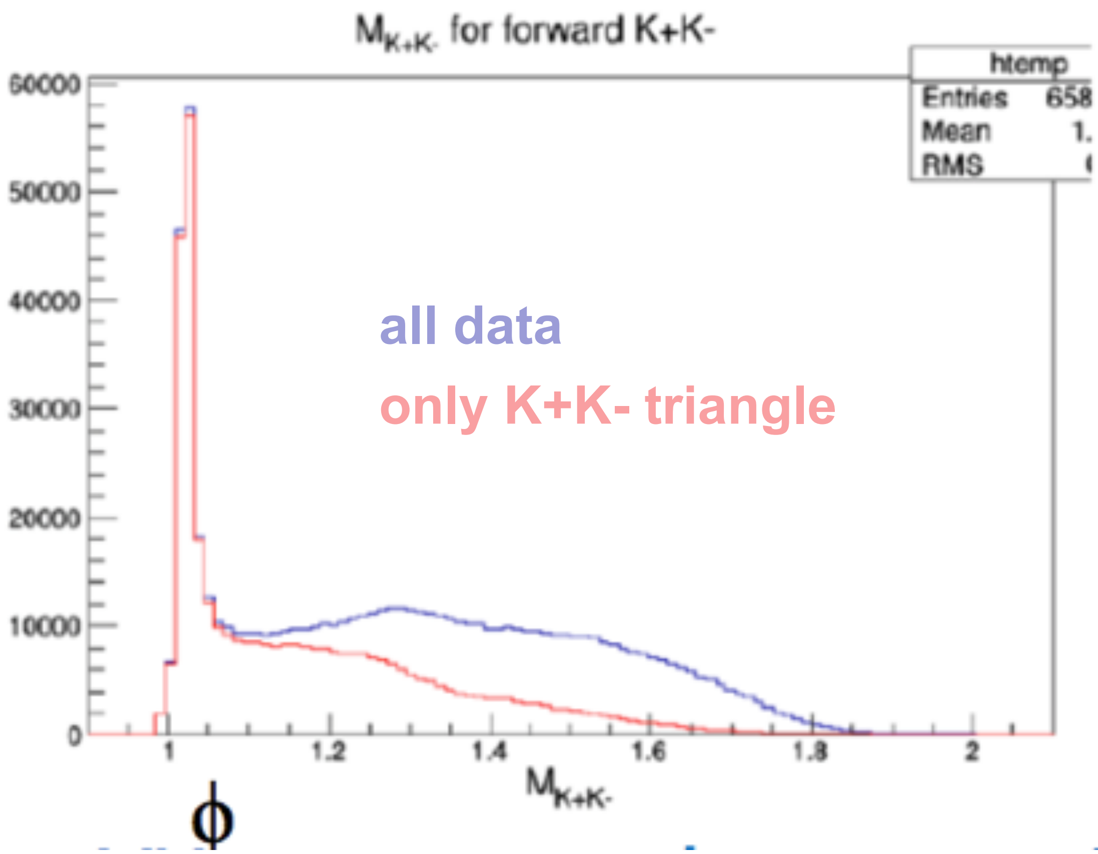


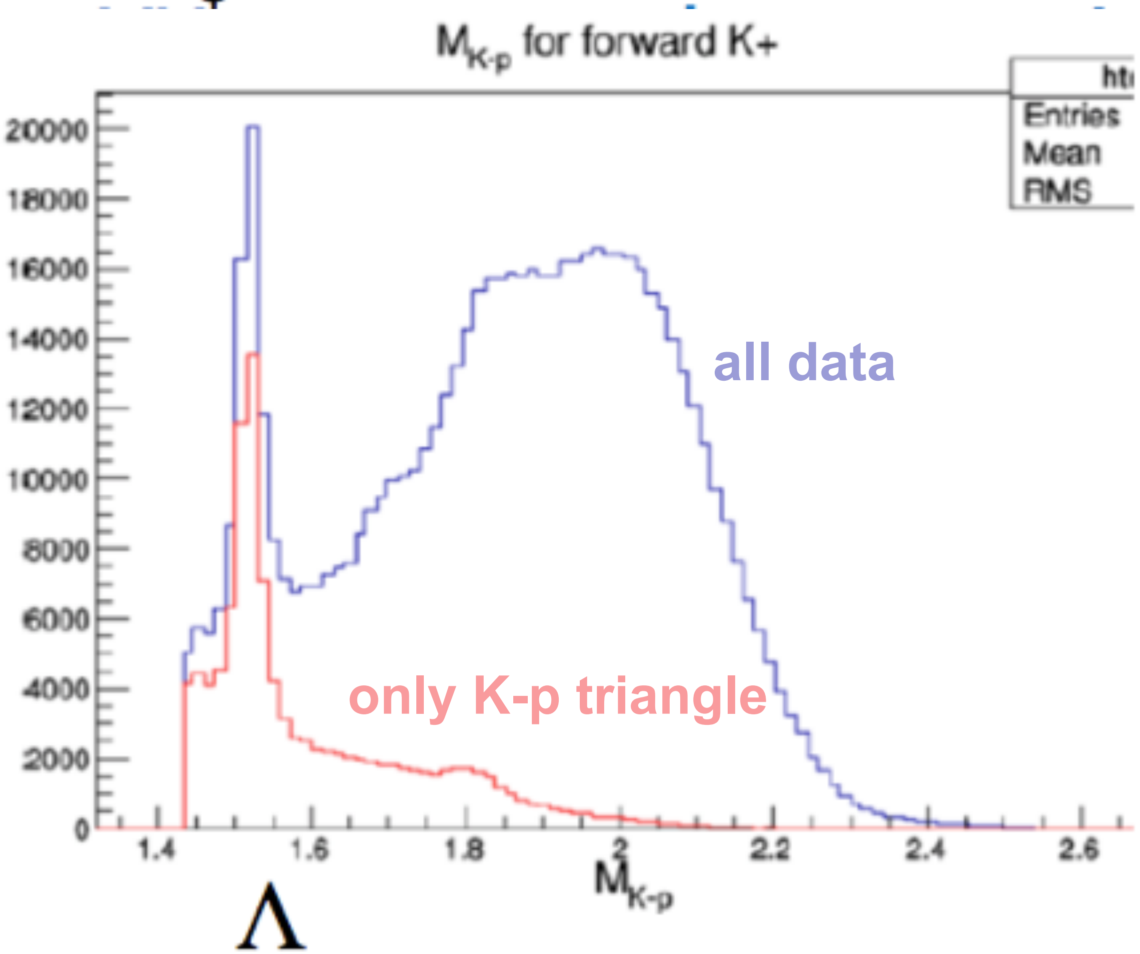


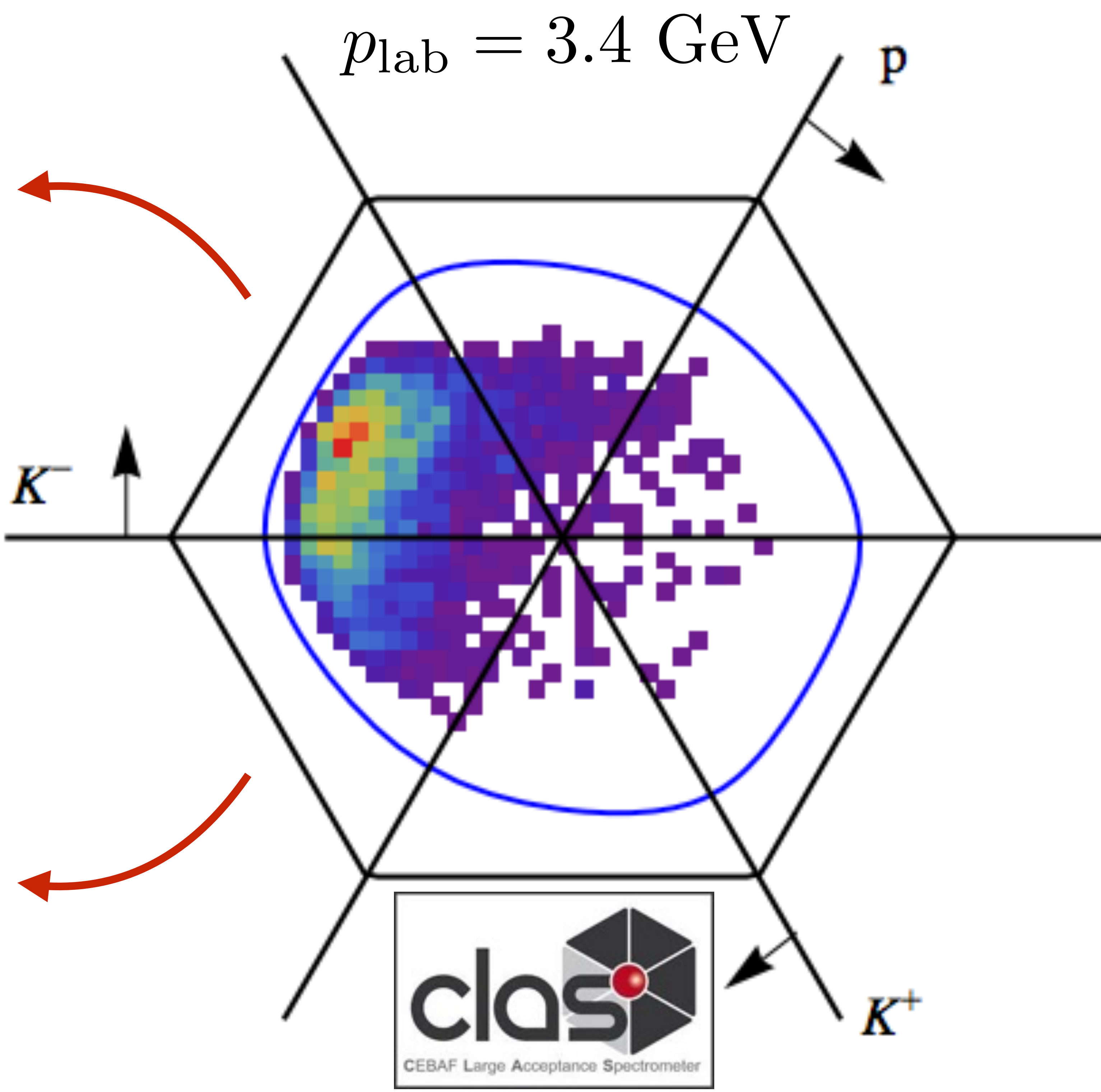
data non-corrected for acceptance

Courtesy of A. Austregesilo

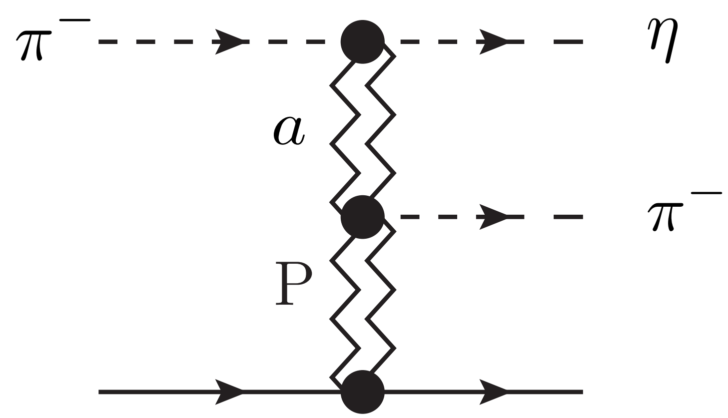
Longitudinal Plot





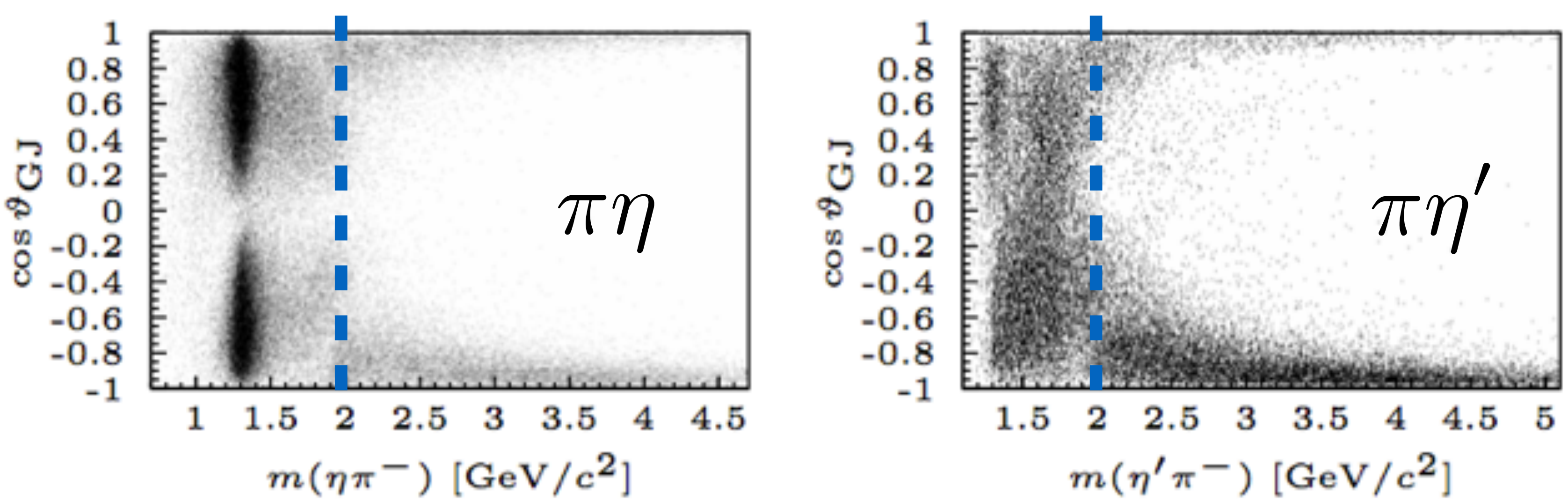


High Mass Region

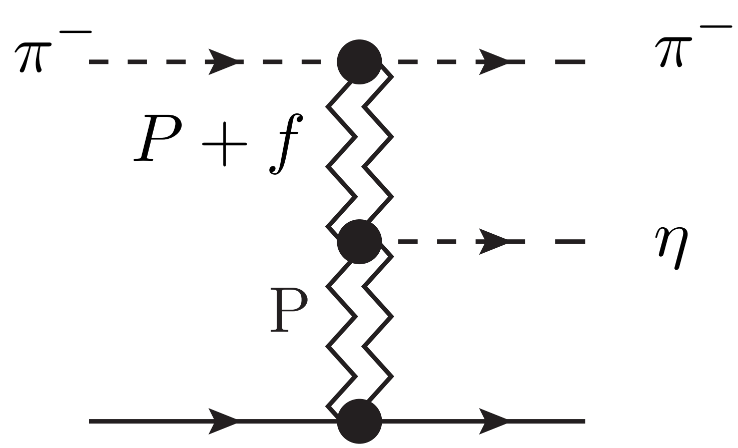


$a: I^G J^{PC} = 1^-(0,2,4,6,\ldots)^{++}$

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

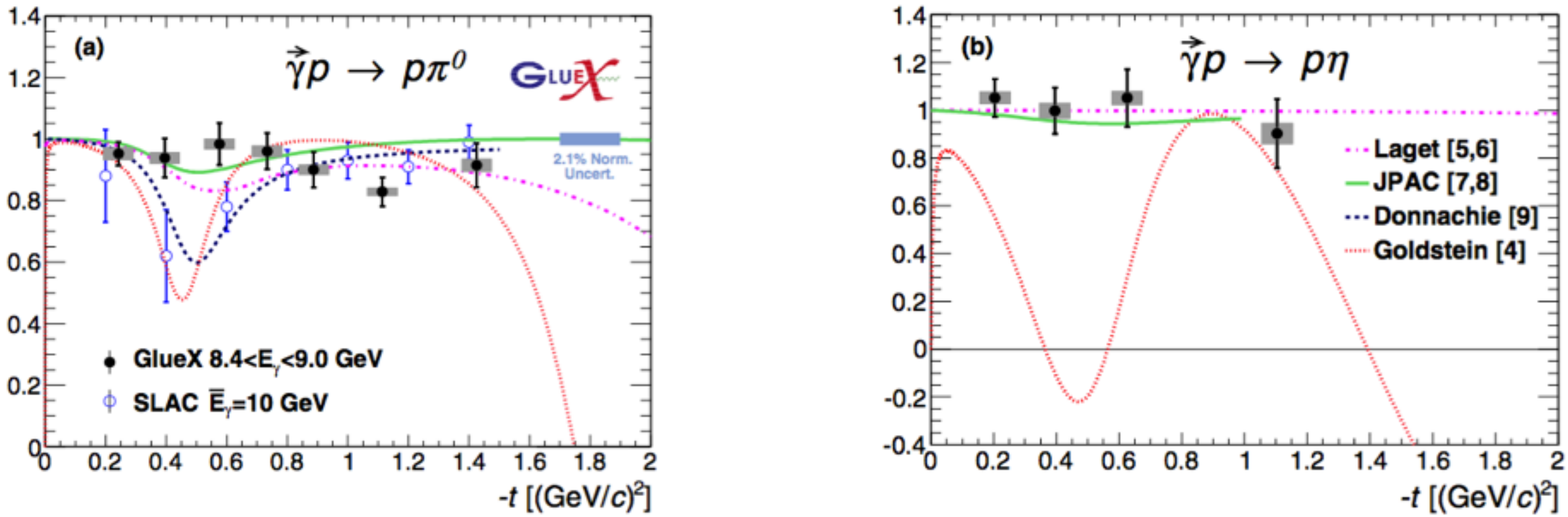


$\cos\theta_{GF} \sim -1 \rightarrow \eta$ backward



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

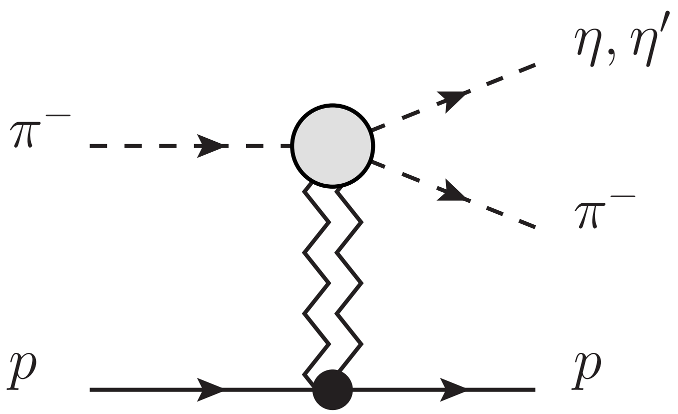
GlueX Results

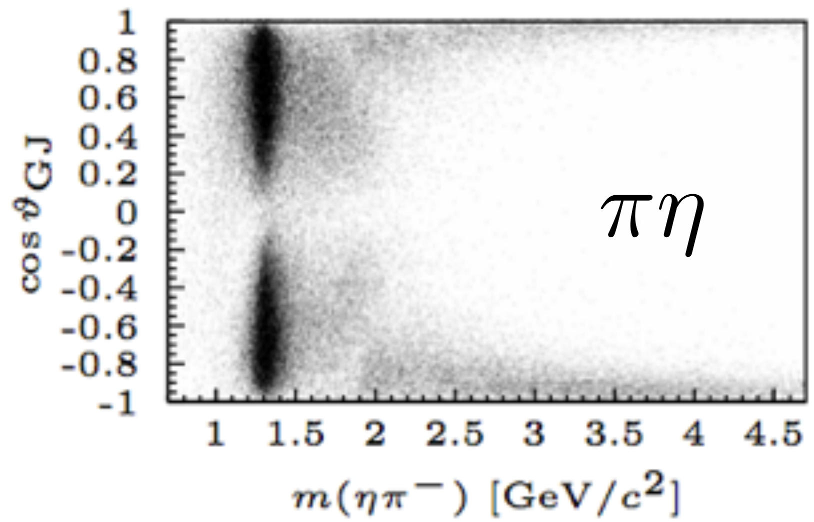


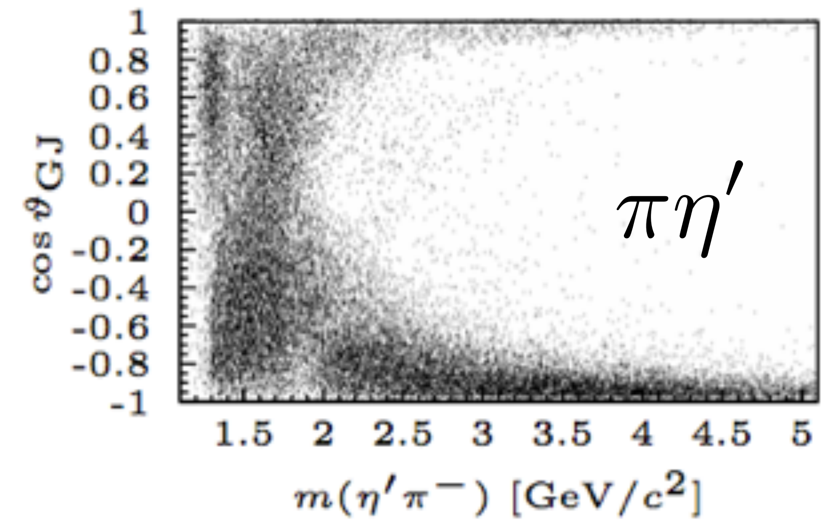
GlueX, VM and J. Nys PRC95 (2017)

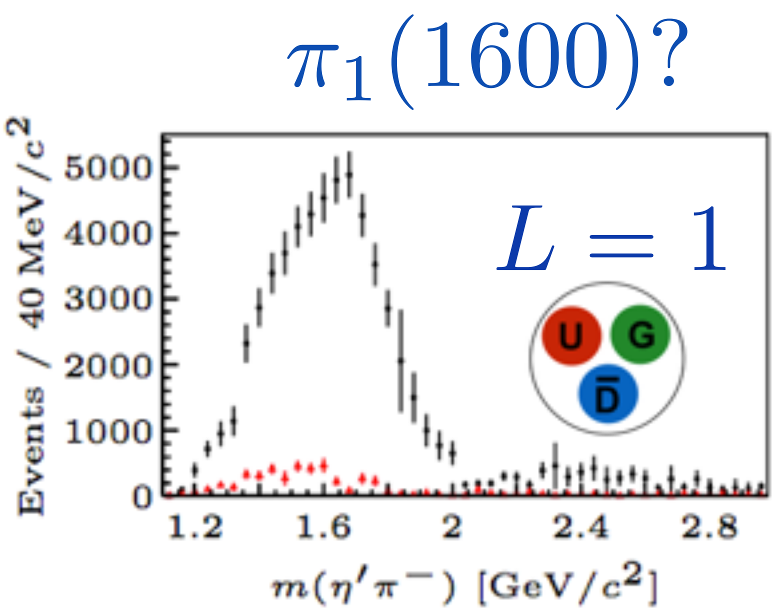
Eta-Pi @COMPASS

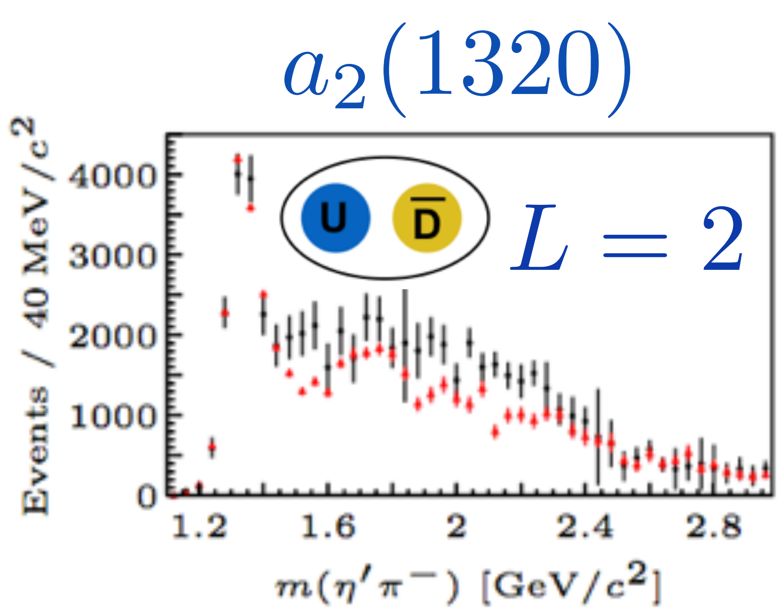
COMPASS Phys. Lett. B740 (2015)

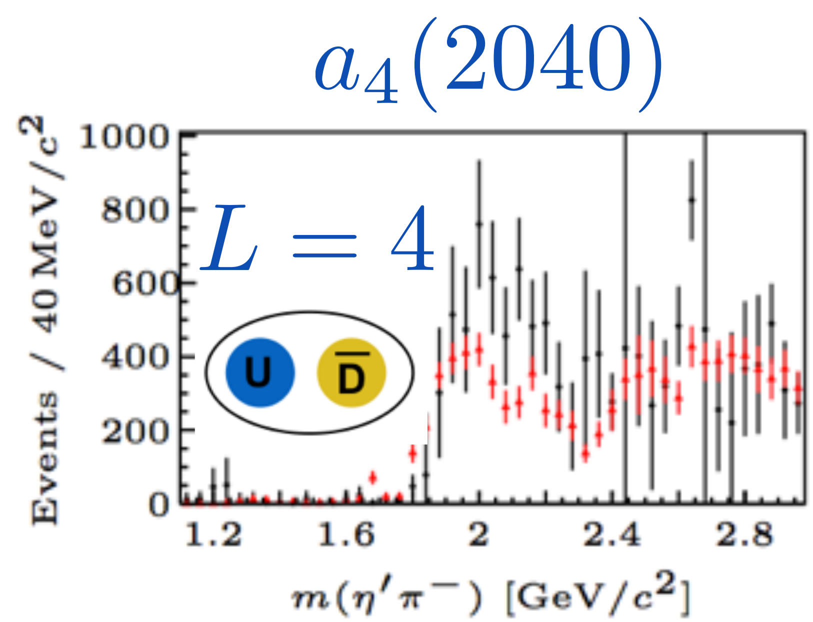


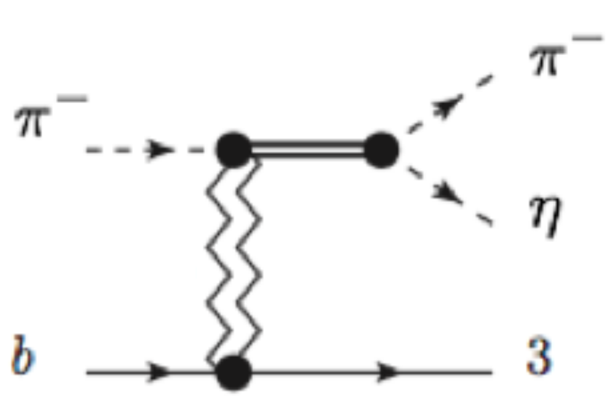










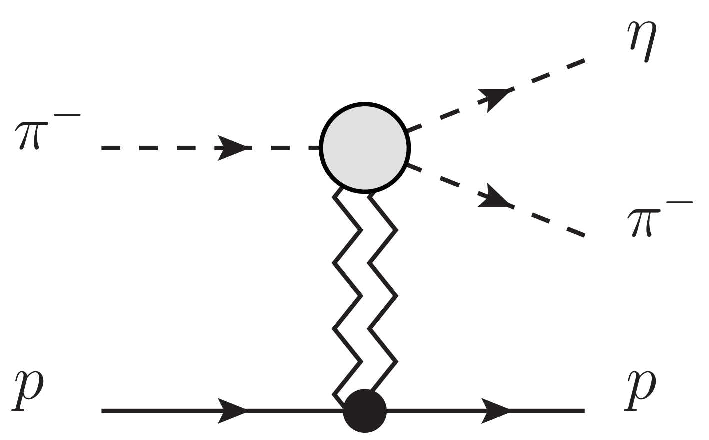


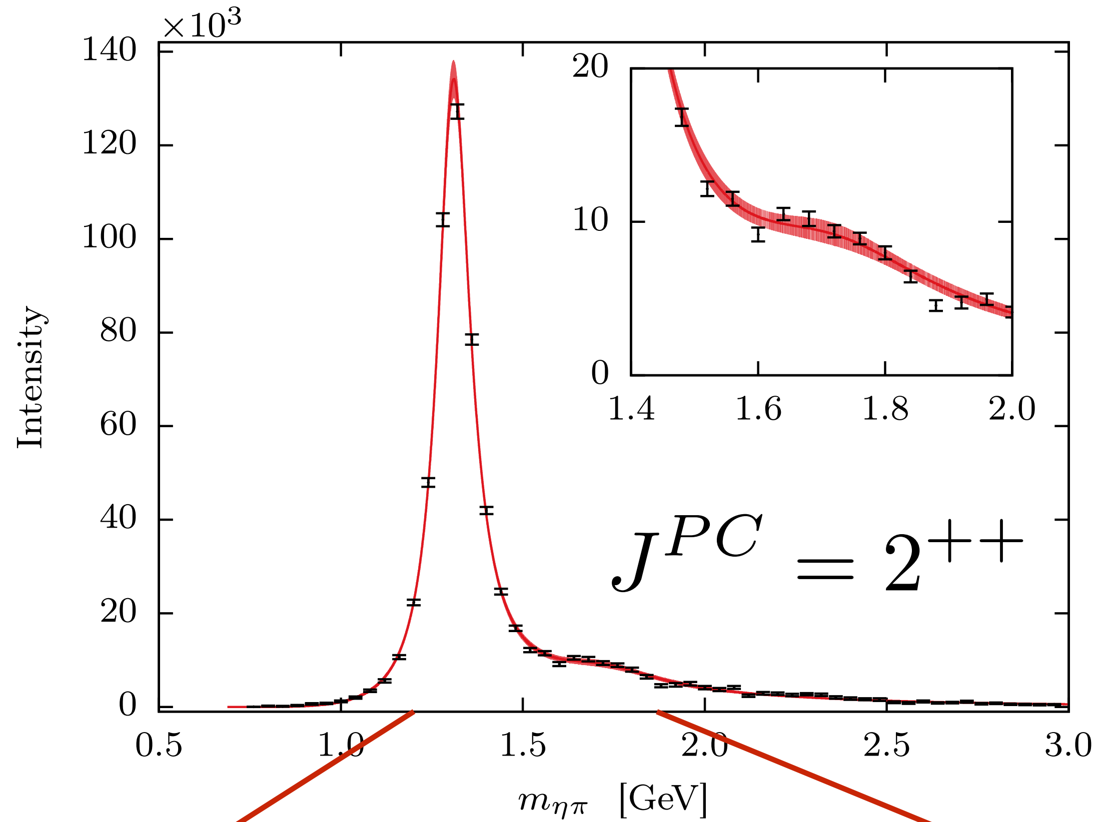
black: $\pi\eta'$

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

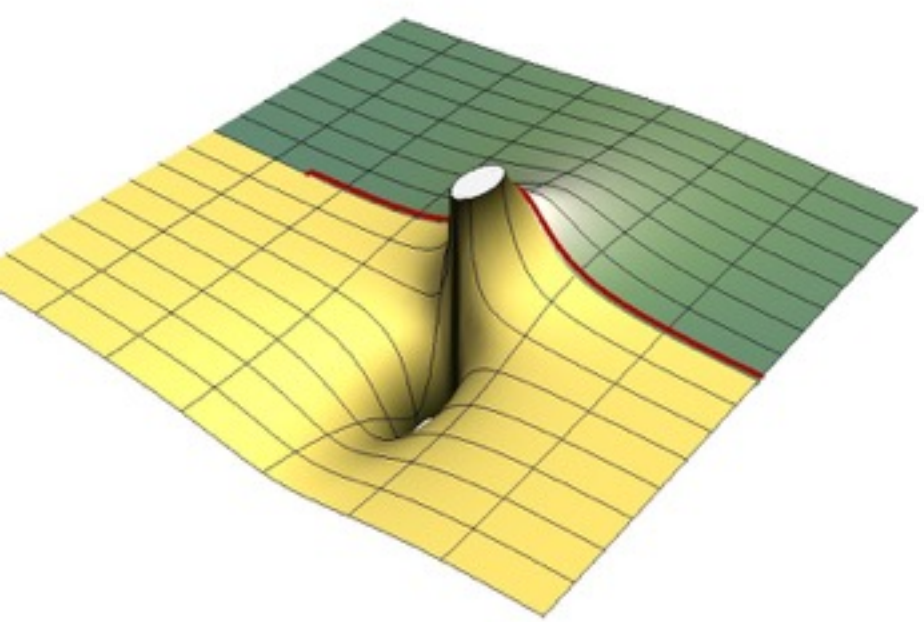
Resonance in angular mom. L = 1 ?

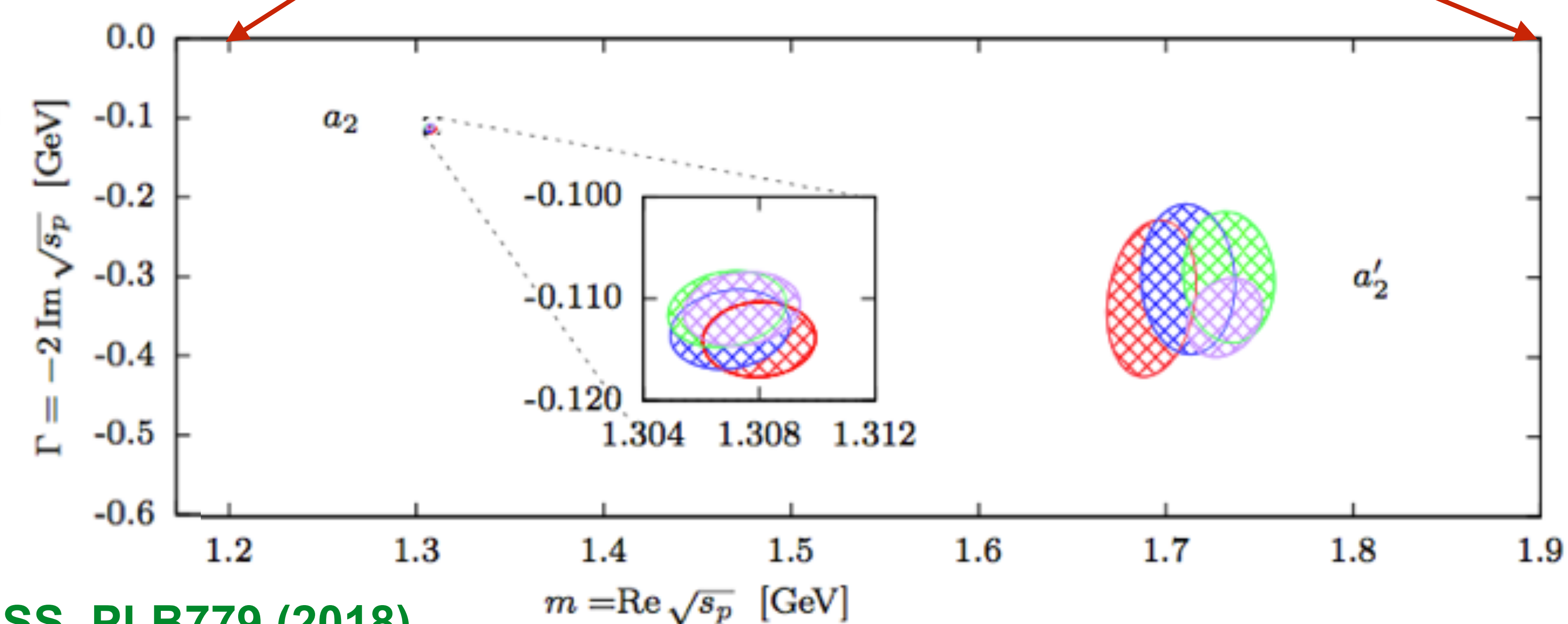
Eta-Pi@COMPASS





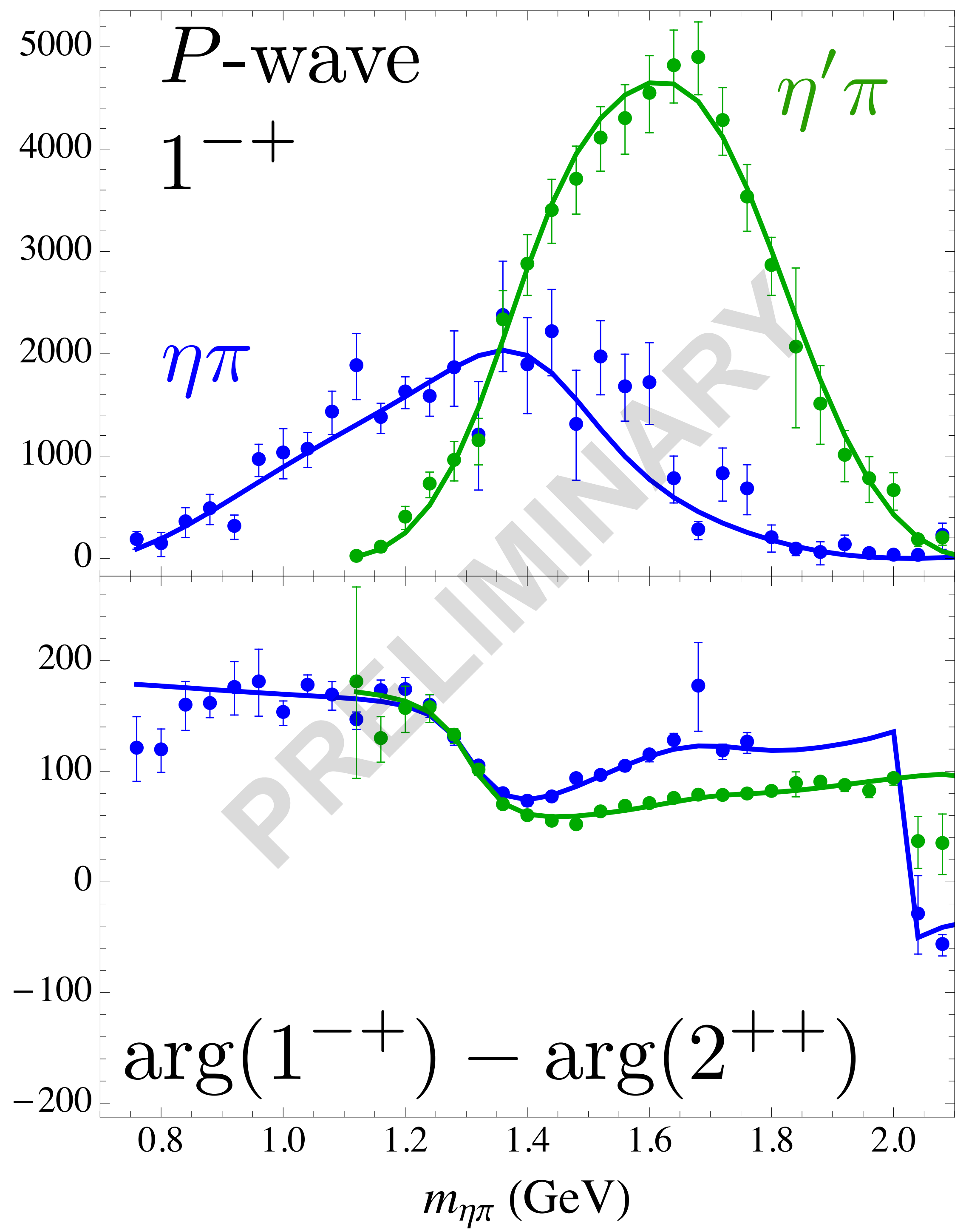
first precise determination of $a_2(1700)$ pole location

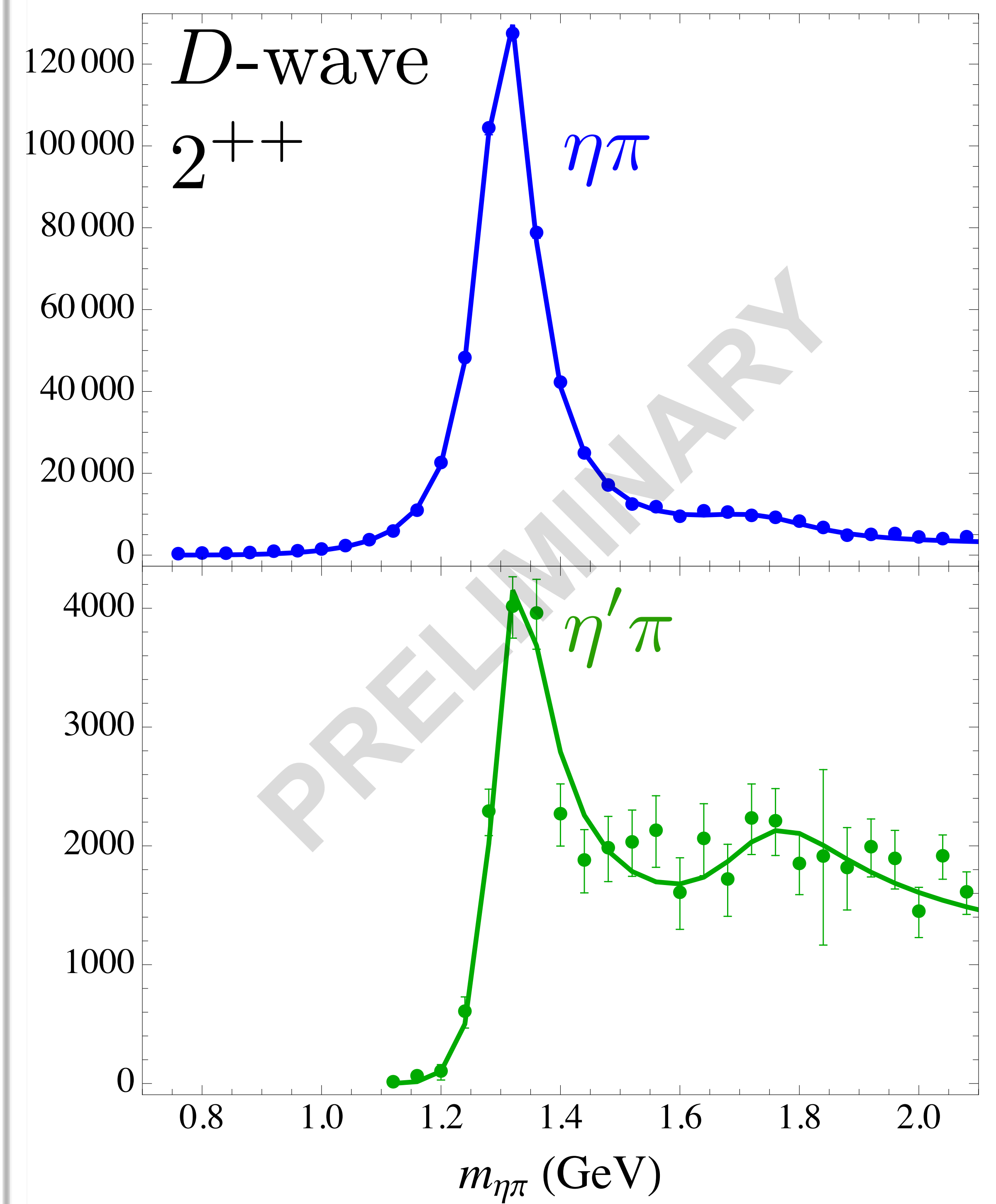




A. Jackura et al (JPAC) and COMPASS, PLB779 (2018)

Exotic wave @COMPASS

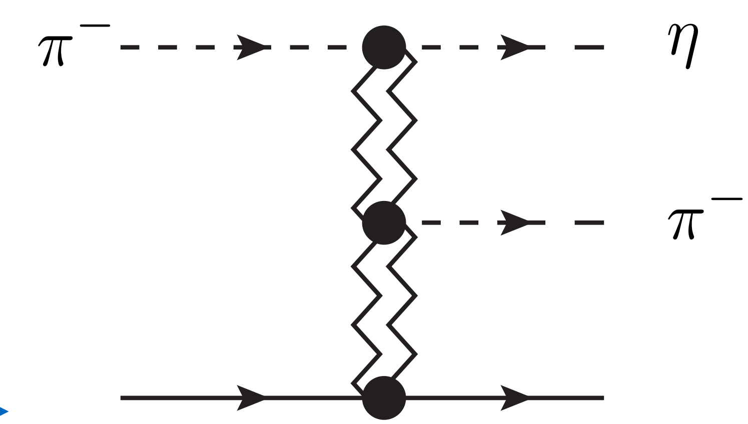


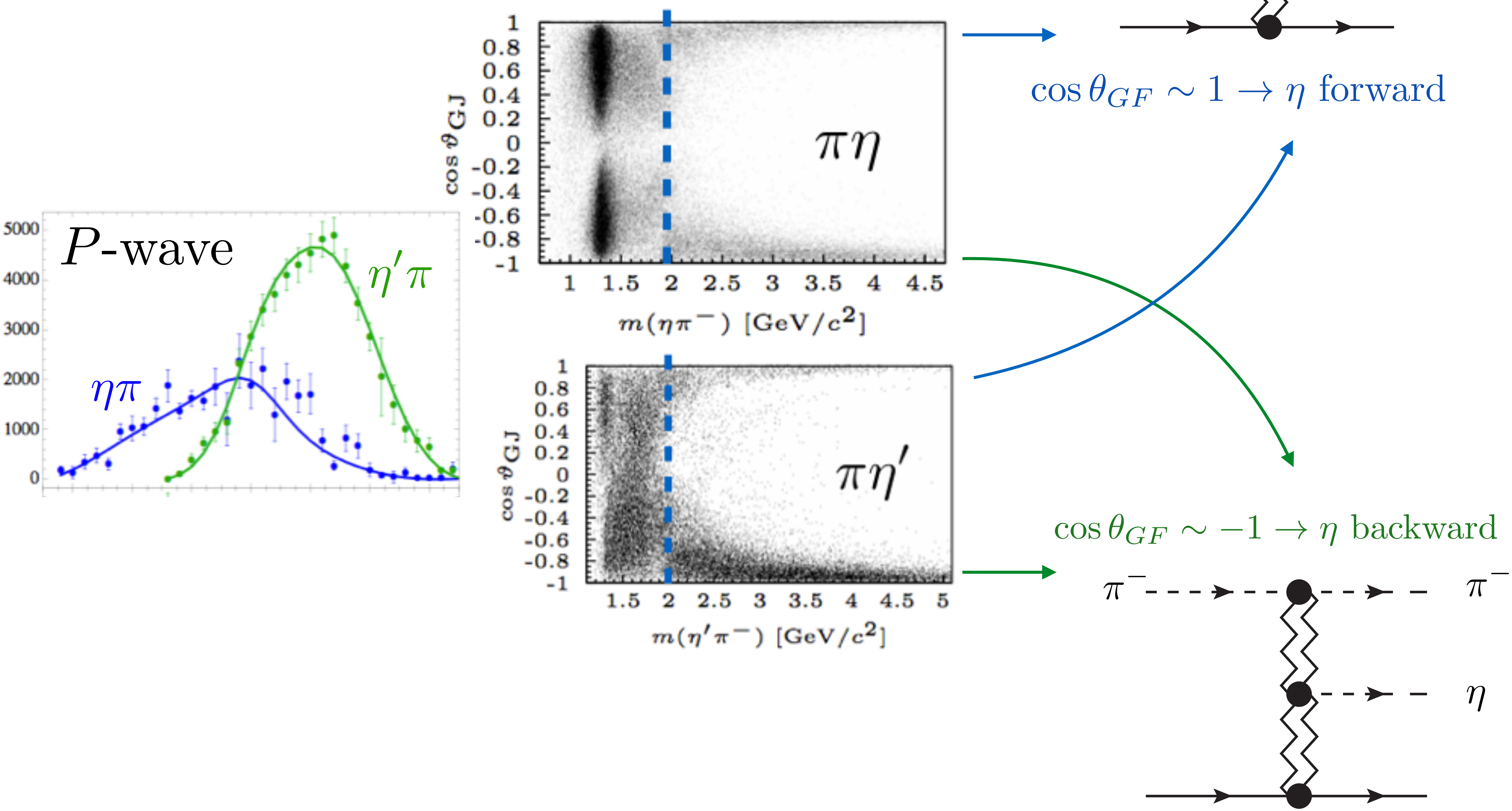


On-going analysis: Systematic studies and exploration of the complex plane

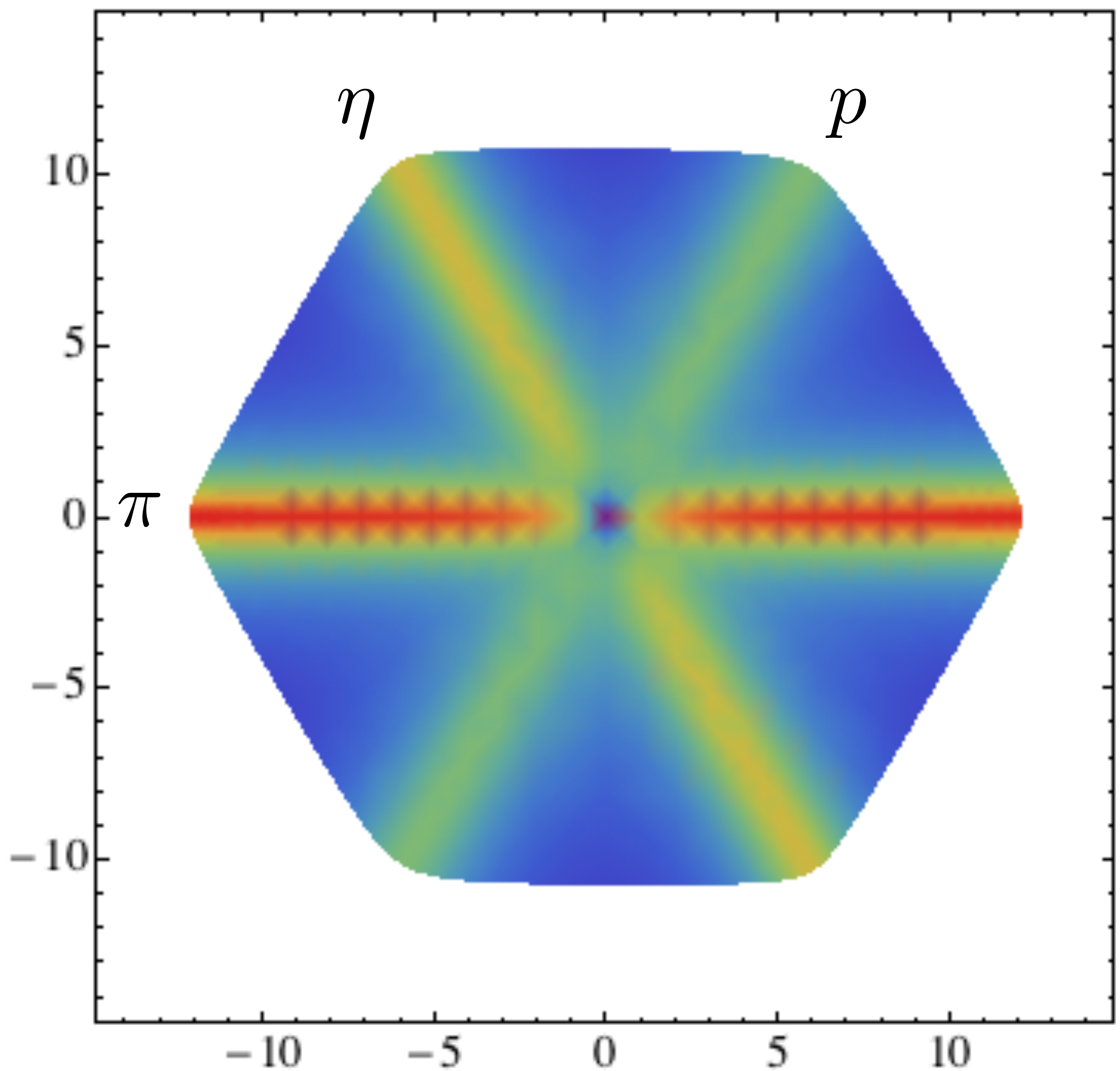
Exotic wave @COMPASS

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





Phase space at Eg = 9 GeV



$AB \to 1234$

$$q_1 + q_2 + q_3 + q_4 = 0$$

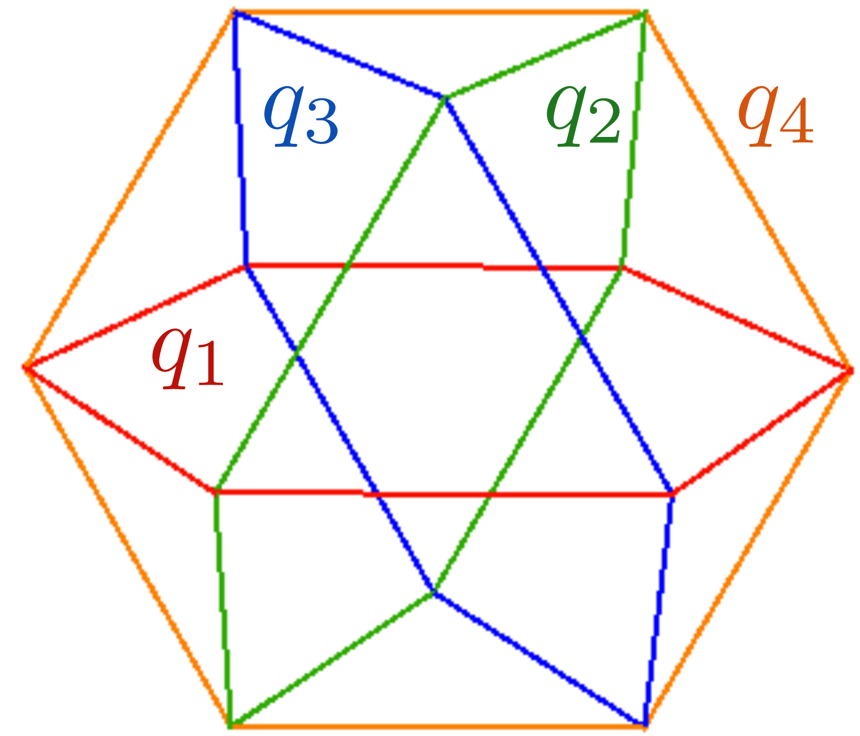
$$X = \sqrt{\frac{3}{8}}(q_1 + q_2 + 2q_3)$$

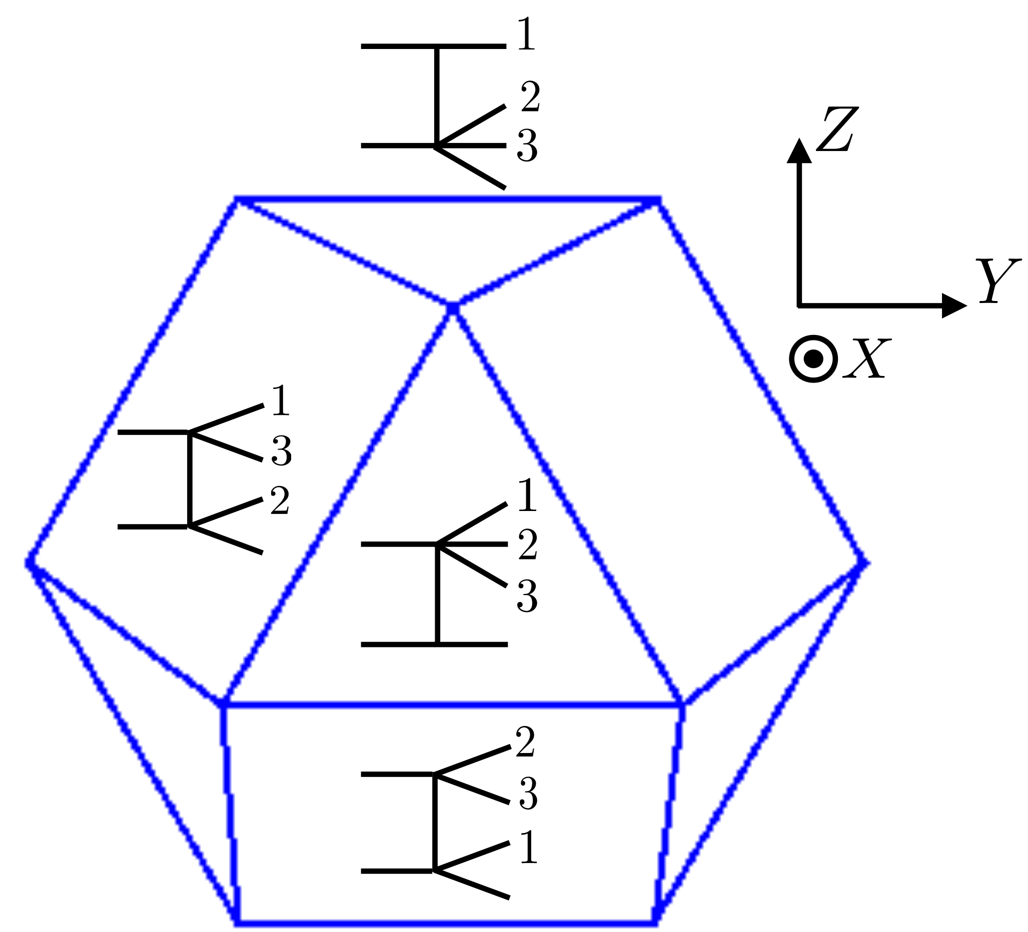
$$Y = \sqrt{\frac{1}{8}}(q_1 + 3q_2)$$

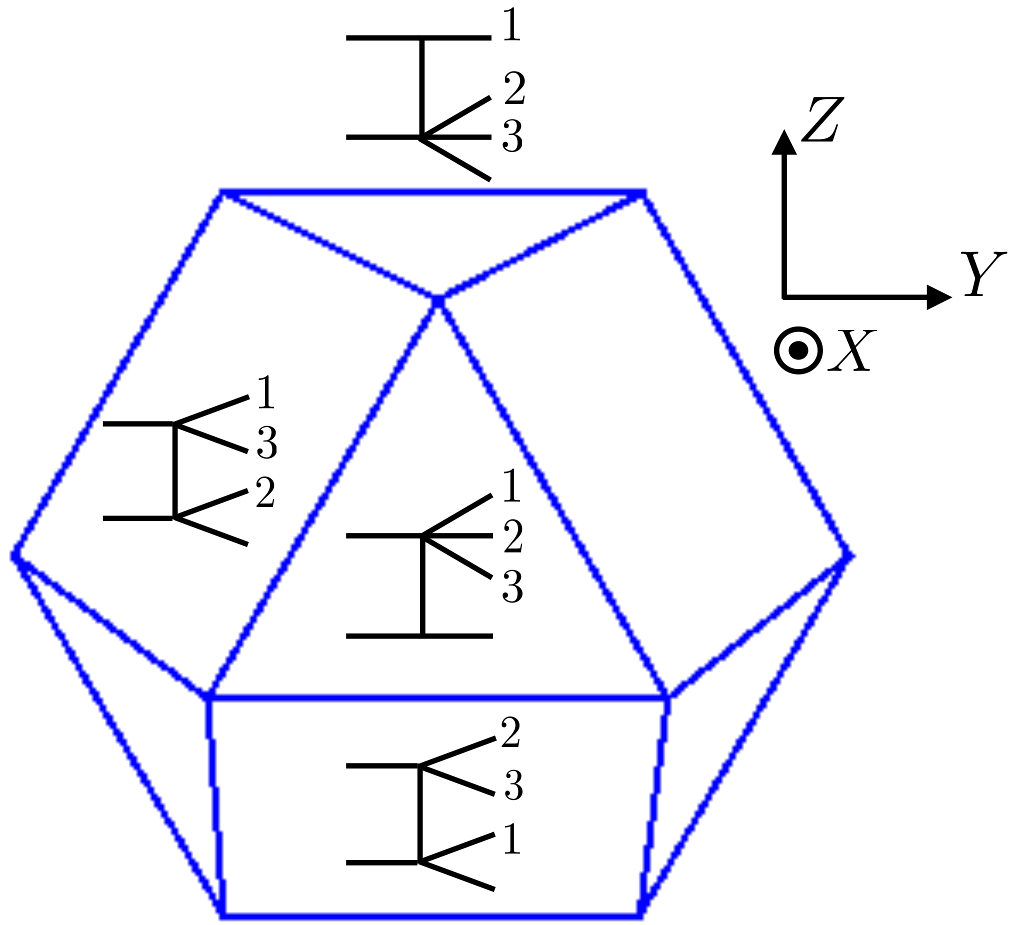
$$Z = q_1$$

triangle = 3 q > 0 or 3 q < 0

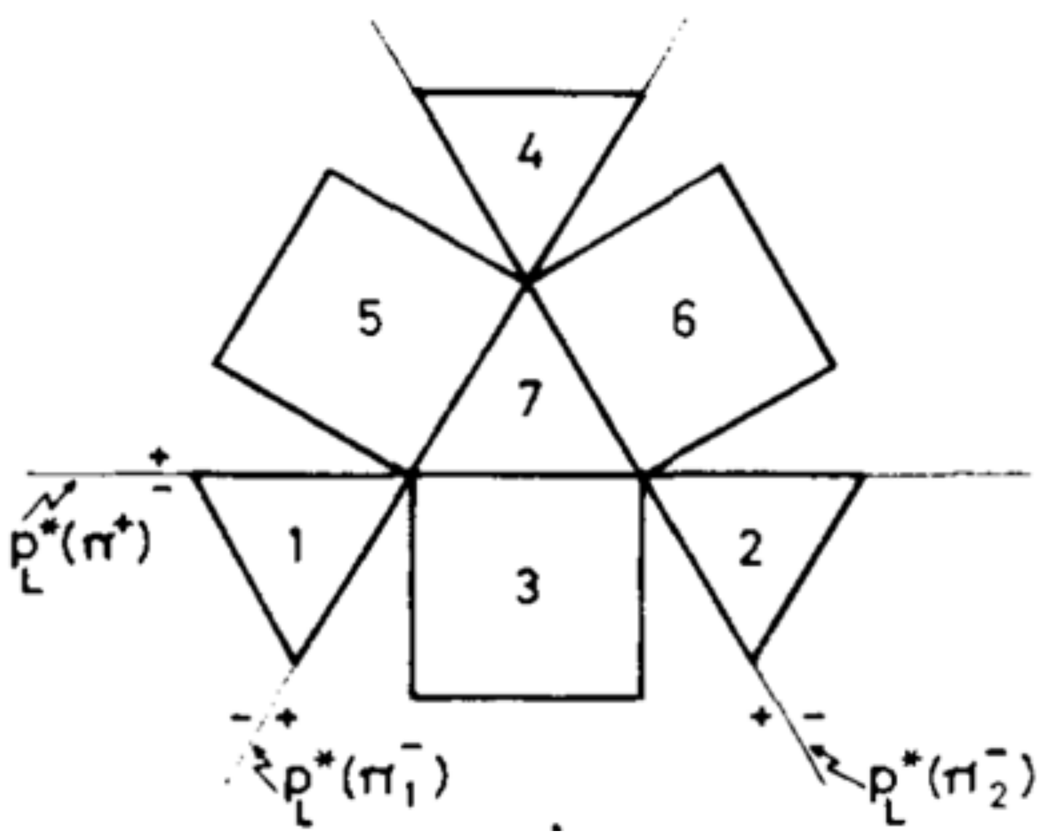
square = 2 q > 0

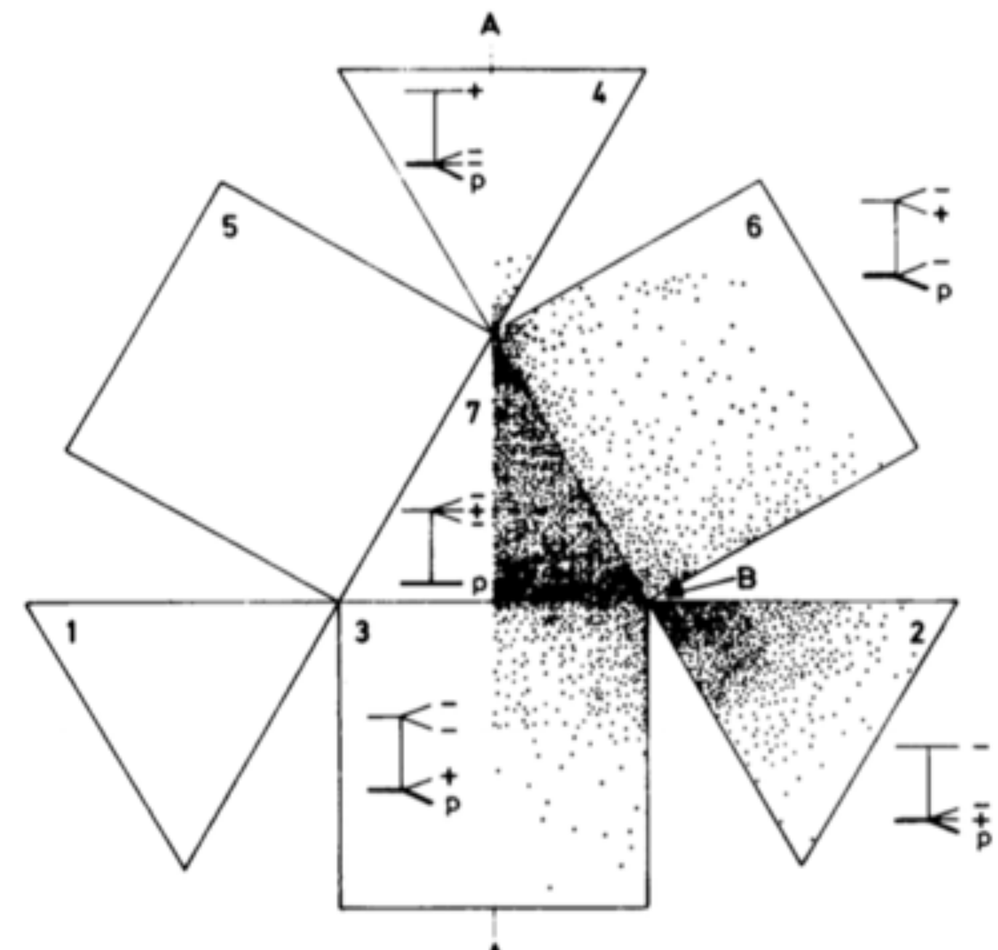






$$\pi^- p \to \pi^+ \pi^- \pi^- p$$ **at 16 GeV**





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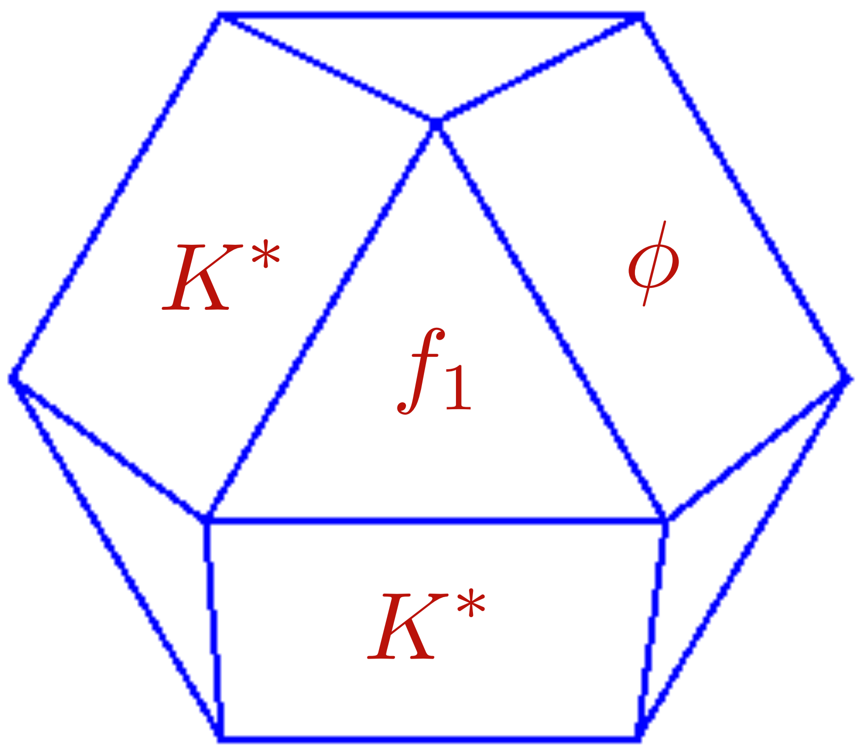
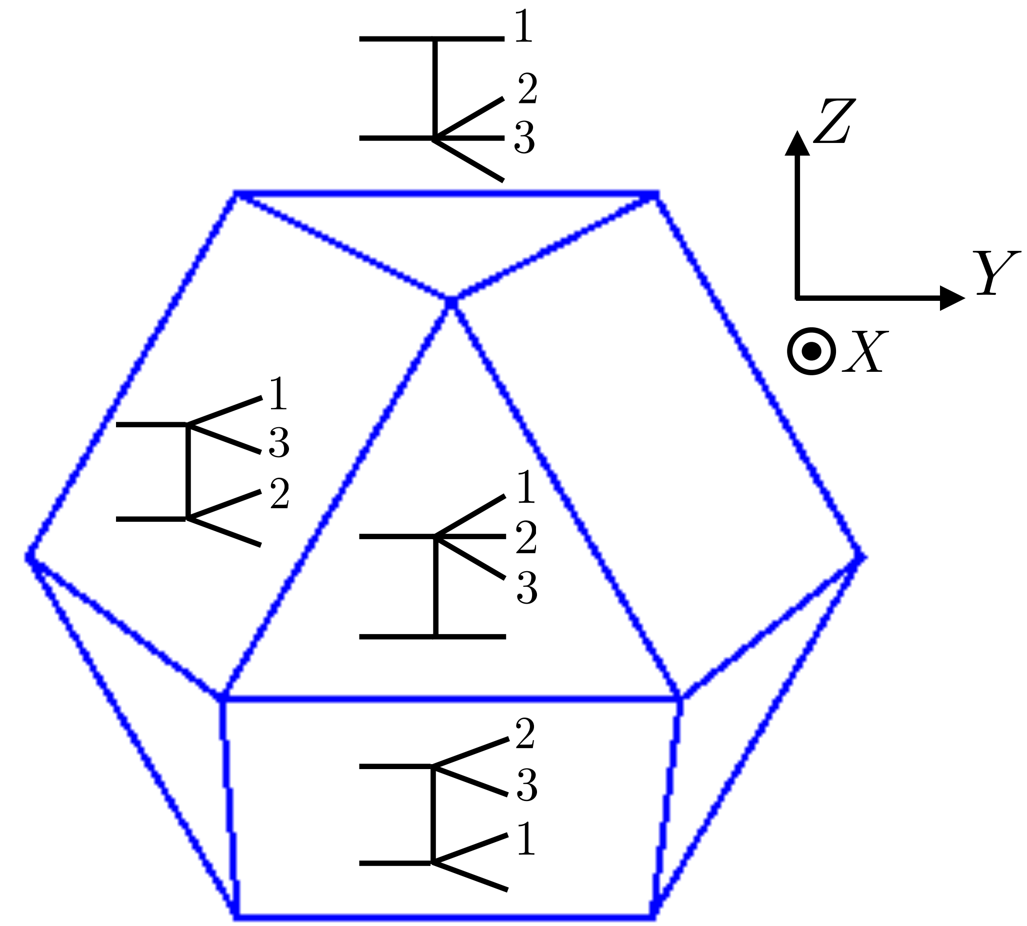
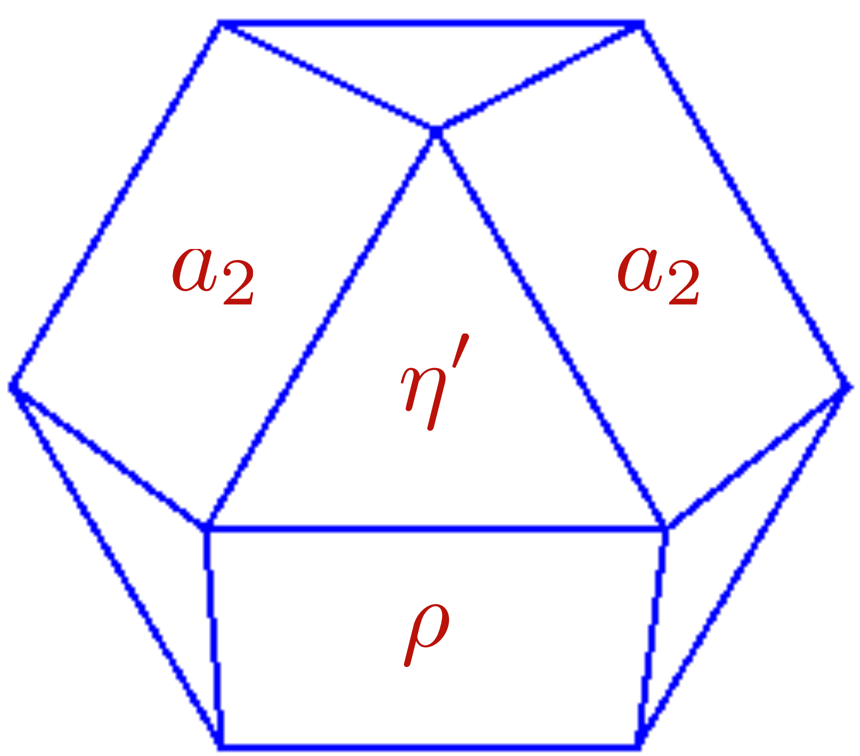
$$\gamma p \to K^+ K^- \pi^0 p$$





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



$$\gamma p \to \omega \pi^+ \pi^- p$$