

Discovering Exotic Mesons @GlueX

Vincent MATHIEU

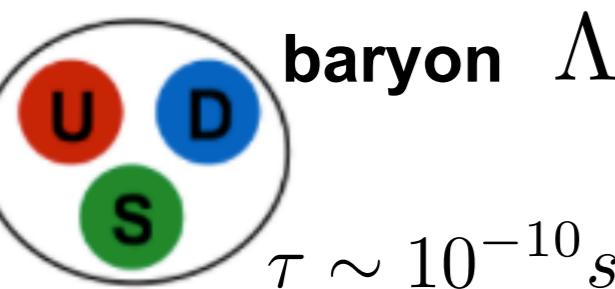
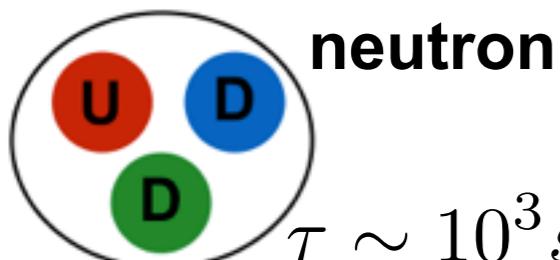
Jefferson Lab
Joint Physics Analysis Center

Cake Seminar
JLab, February 2019



Ordinary and Exotic Hadrons

Ordinary baryons:



Ordinary mesons



proton

stable

QUARKS

UP
mass $2,3 \text{ MeV}/c^2$
charge $\frac{2}{3}$
spin $\frac{1}{2}$



CHARM
 $1,275 \text{ GeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$



TOP
 $173,07 \text{ GeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$



DOWN
 $4,8 \text{ MeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$



STRANGE
 $95 \text{ MeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$

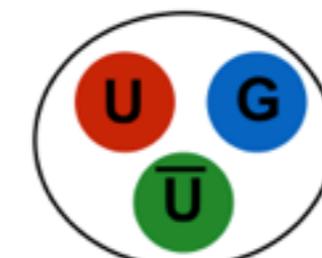


BOTTOM
 $4,18 \text{ GeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$

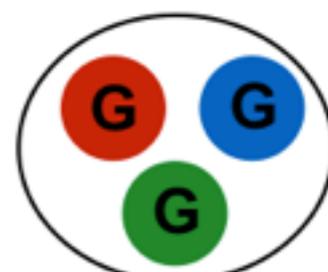


Exotic matter

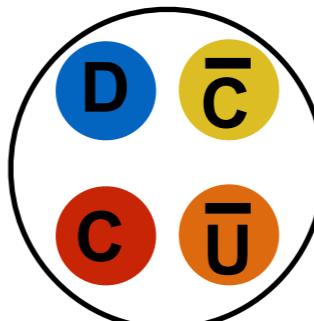
hybrid mesons



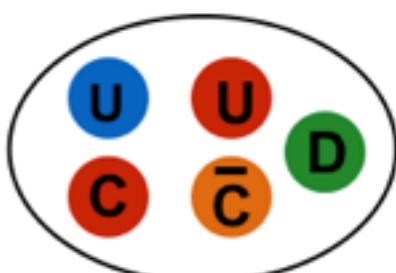
glueballs



tetraquarks

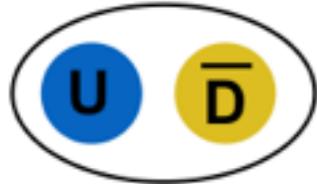


pentaquarks



Hybrid Mesons Production

Ordinary mesons



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

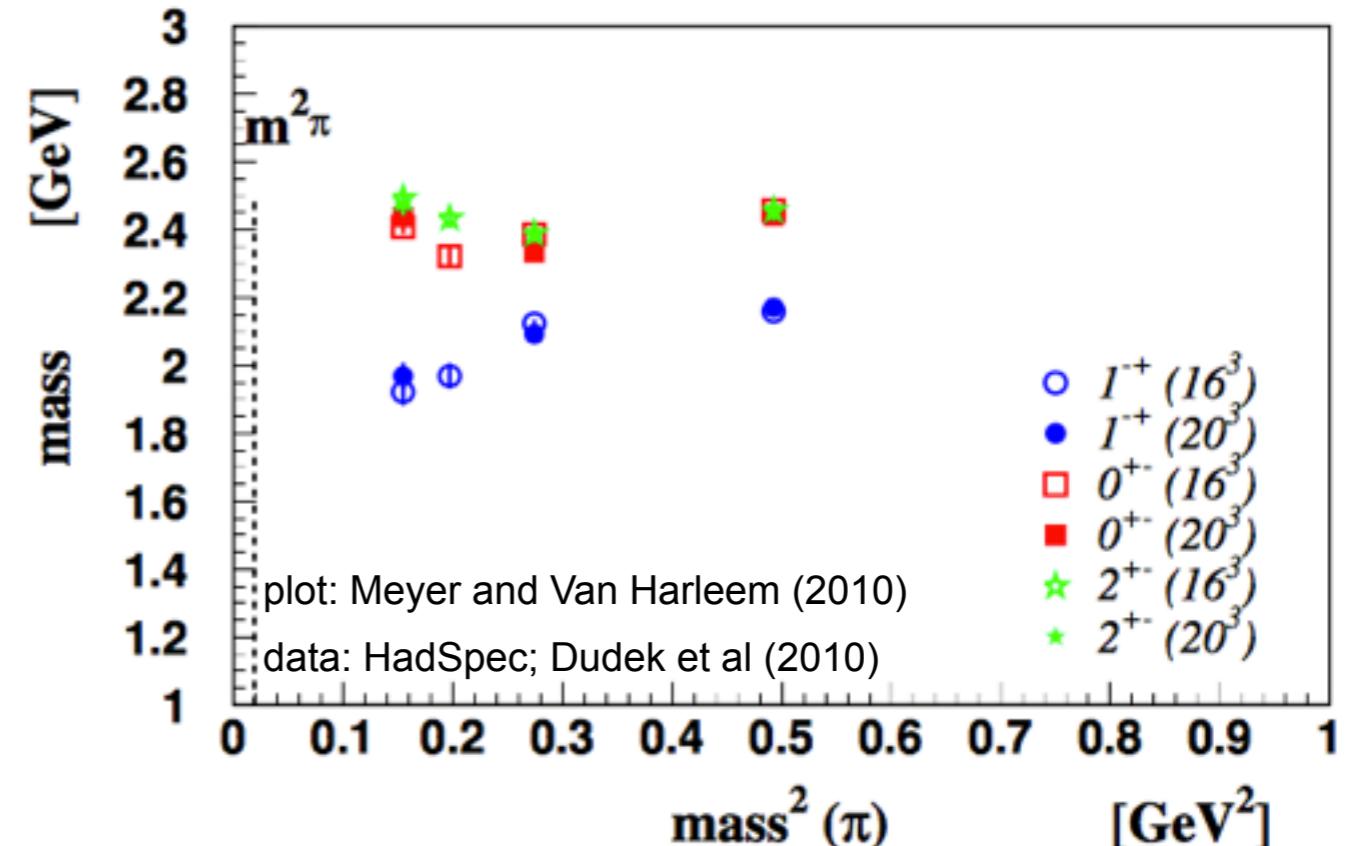
$$P = -(-1)^L$$

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

Examples of quantum numbers

QNs J^{PC}	(I^G)	Names
1^{++}	(1^-)	a_1
1^{--}	(1^+)	ρ_1
0^{-+}	(1^-)	π_0
1^{-+}	(1^-)	π_1
2^{-+}	(1^-)	π_2
0^{+-}	(1^+)	b_0
1^{+-}	(1^+)	b_1
2^{+-}	(1^+)	b_2
	(I^G)	
	f_1	
	ω_1	
	η_0	
	η_1	
	η_2	
	h_0	
	h_1	
	h_2	

Meyer and Van Harleem (2010)



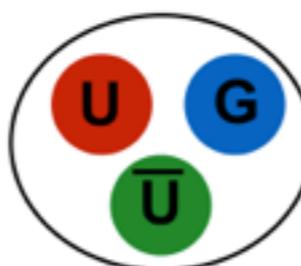
$$\eta_1 \rightarrow \eta\eta', a_2\pi, K_1K, \dots$$

$$\pi_1 \rightarrow \eta\pi, \eta'\pi, \rho\pi, b_1\pi, \dots$$

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

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

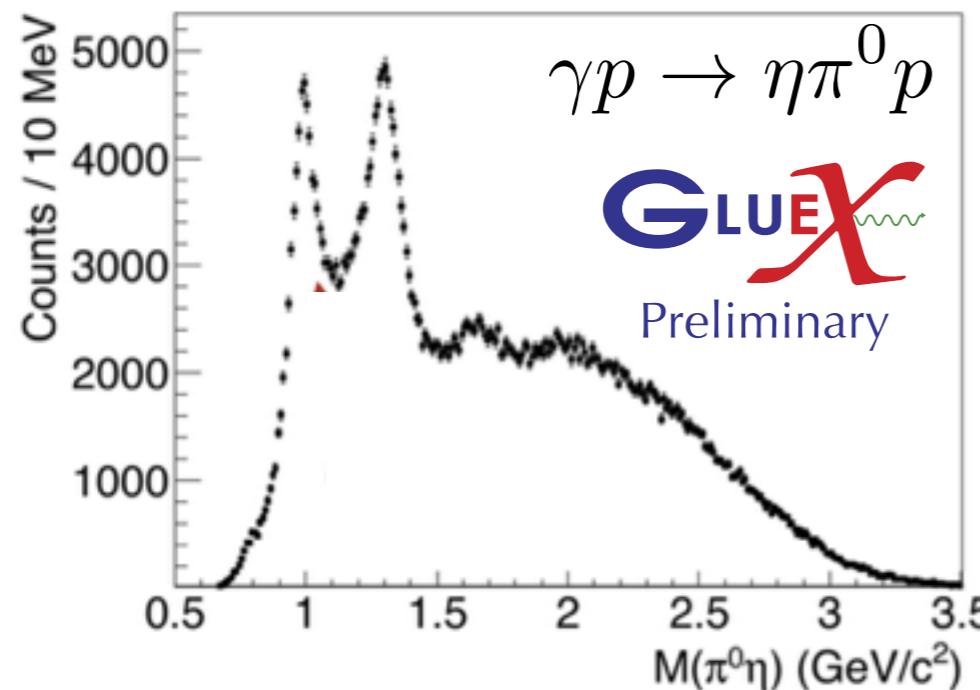
hybrid mesons



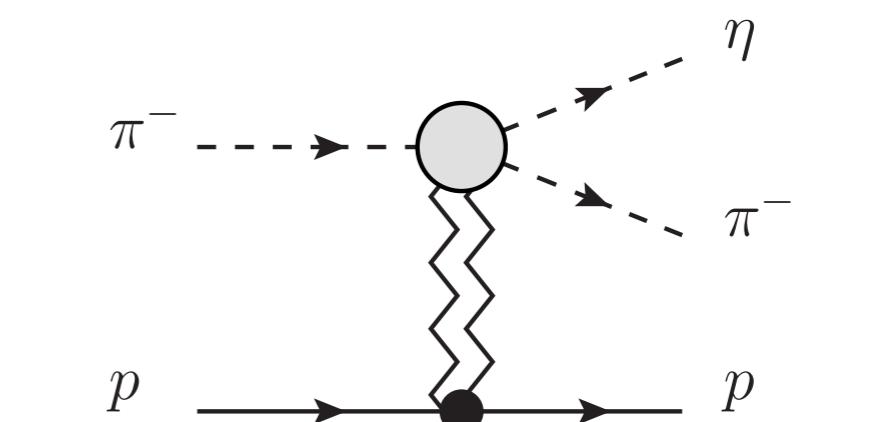
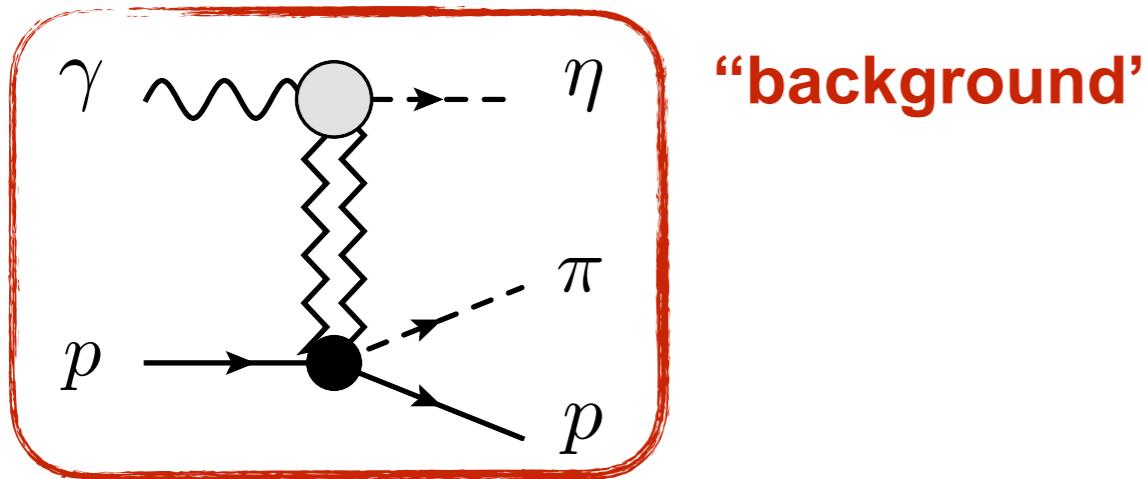
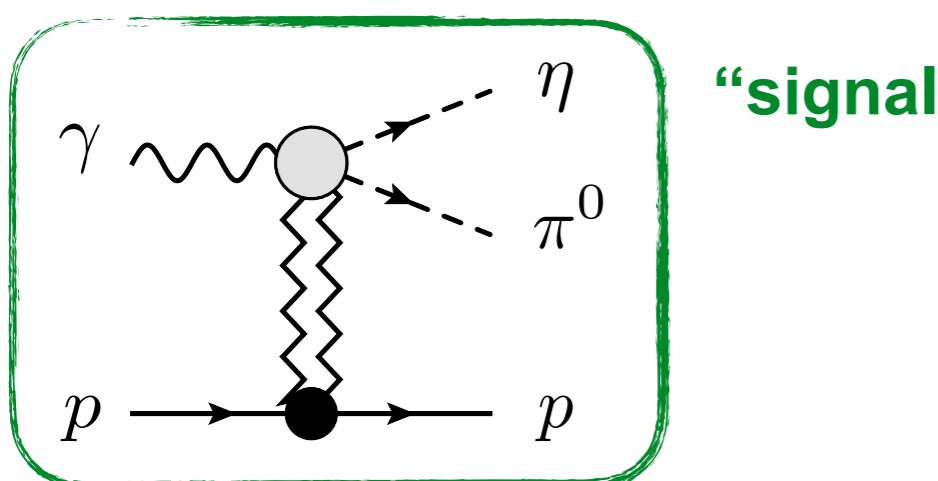
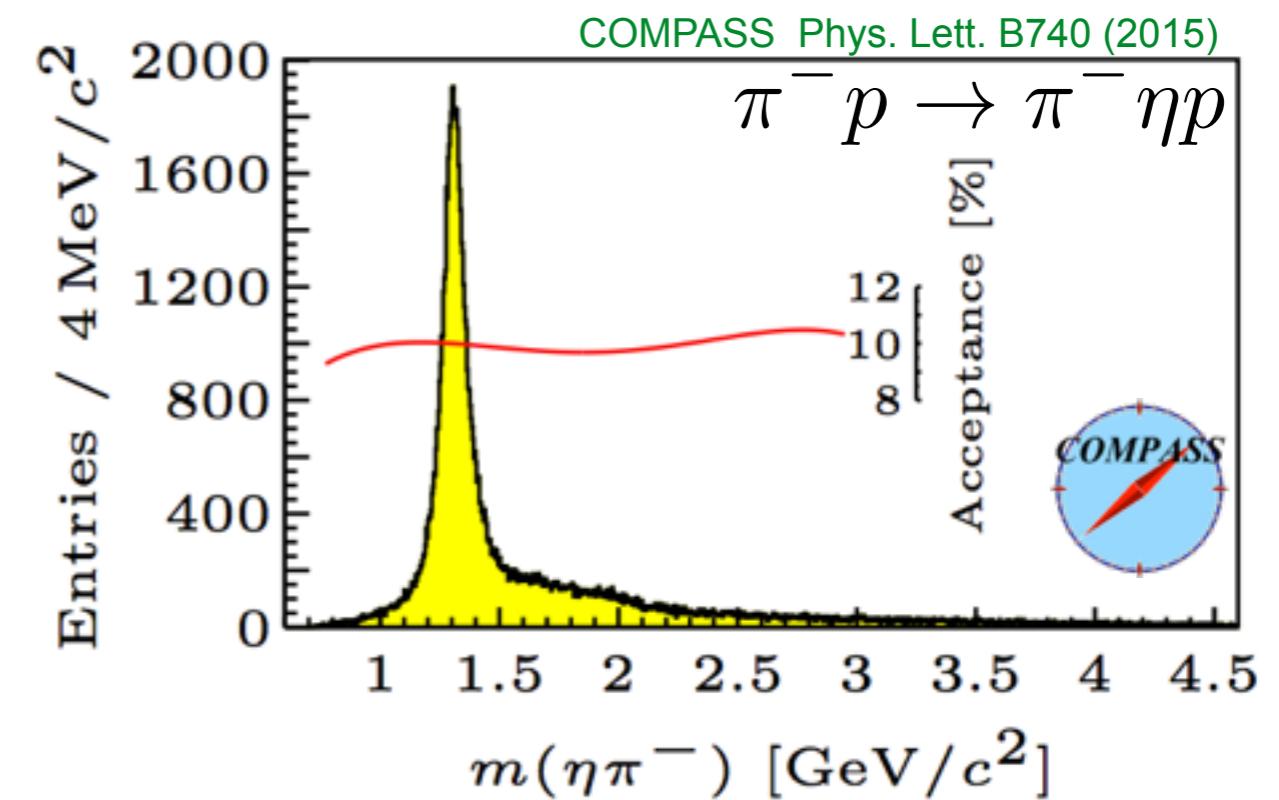
Eta-Pi Production

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

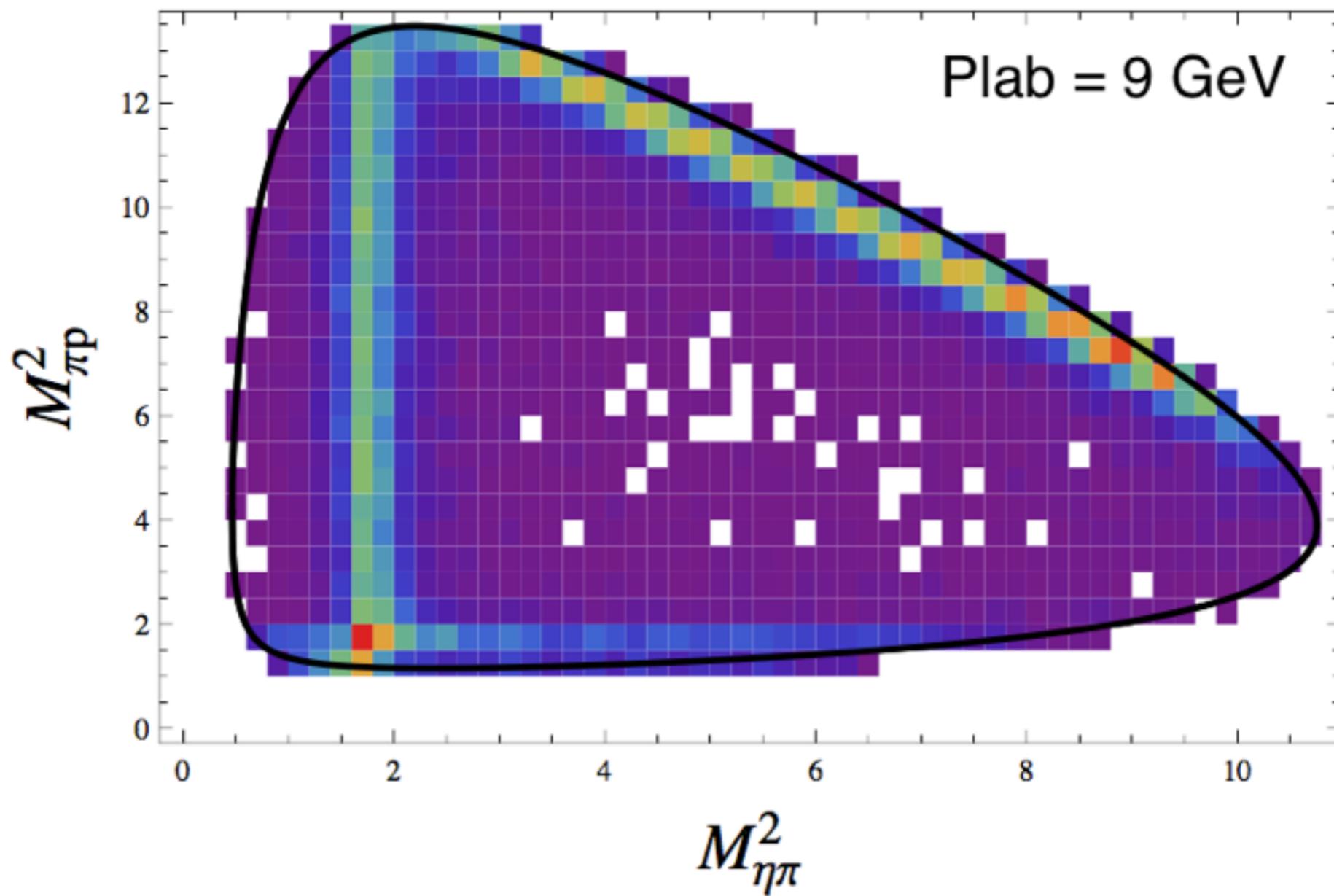
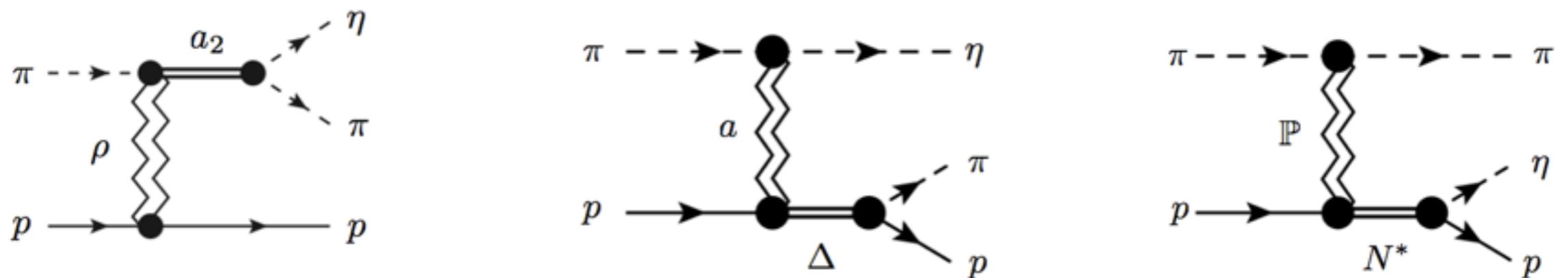


$E_{\text{beam}} = 190 \text{ GeV}$



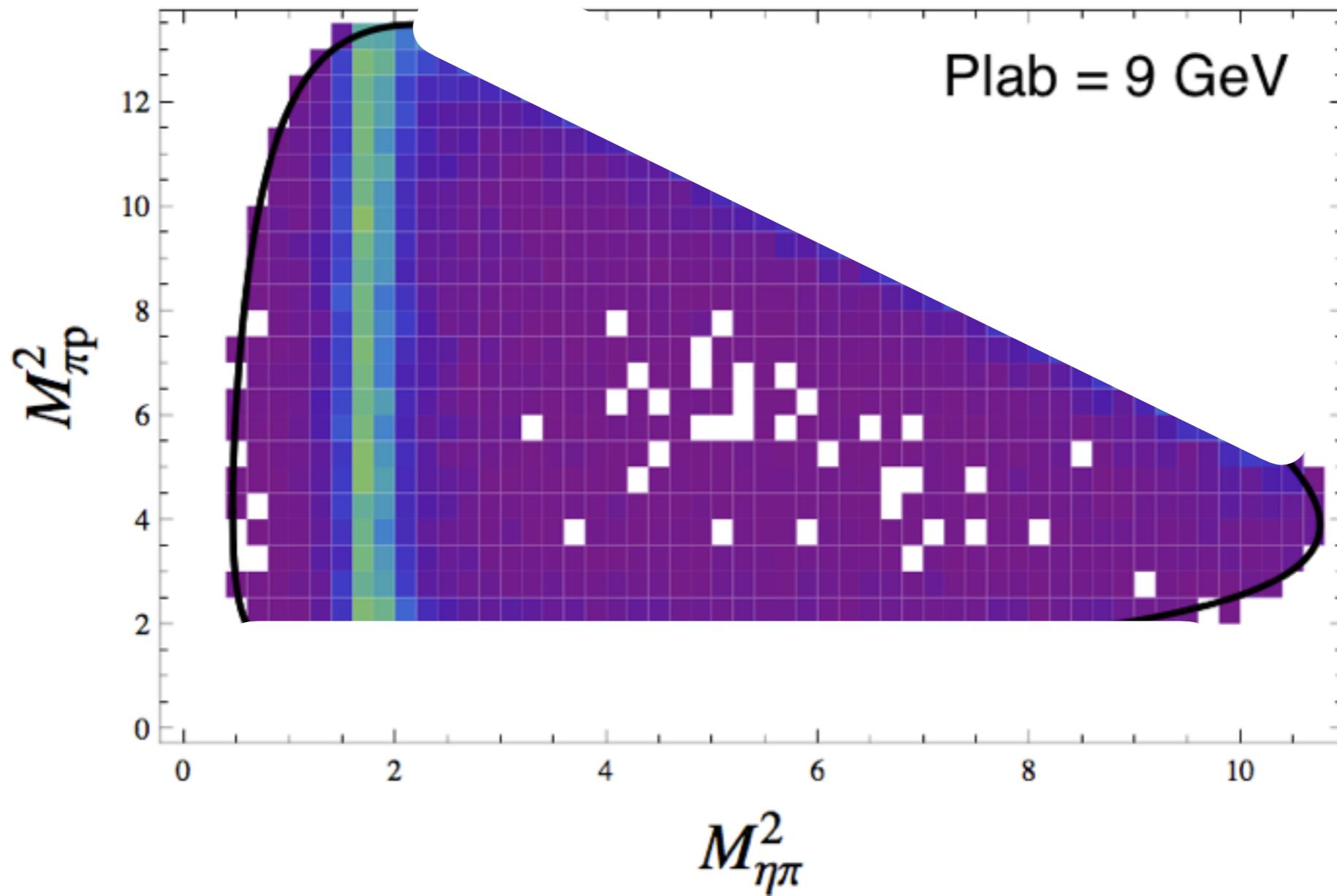
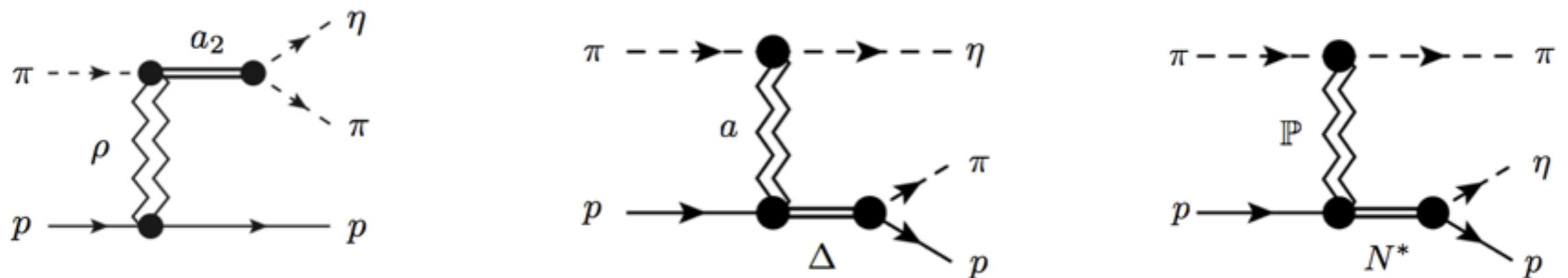
Eta-Pi Production: toy model

5



Eta-Pi Production: toy model

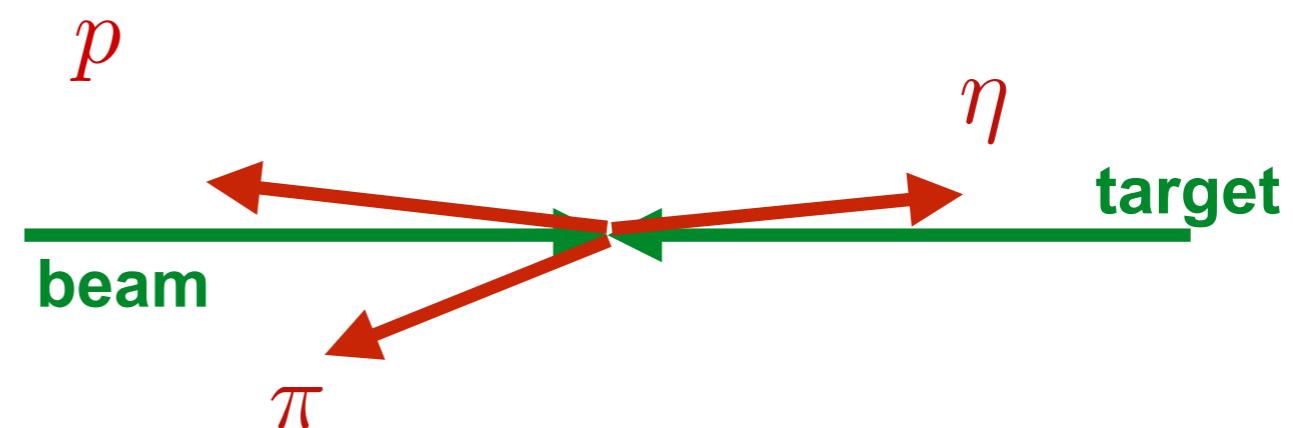
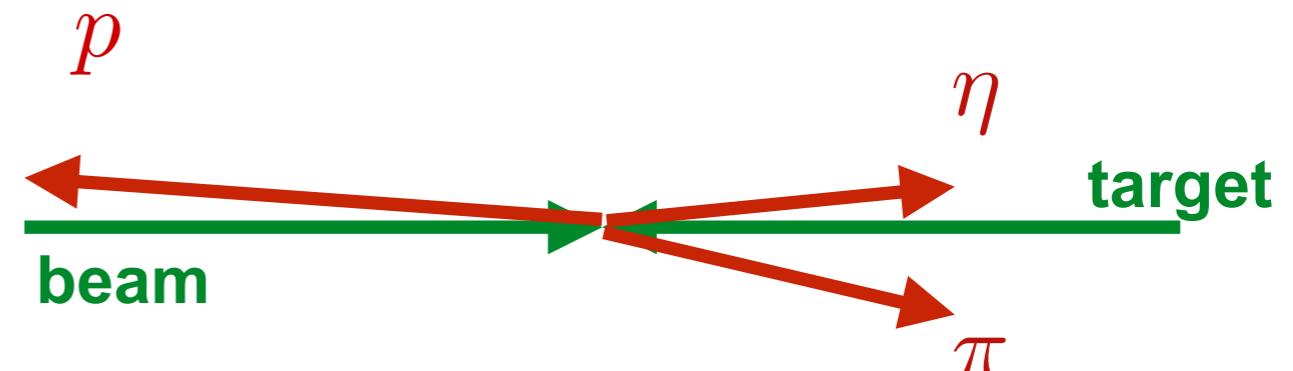
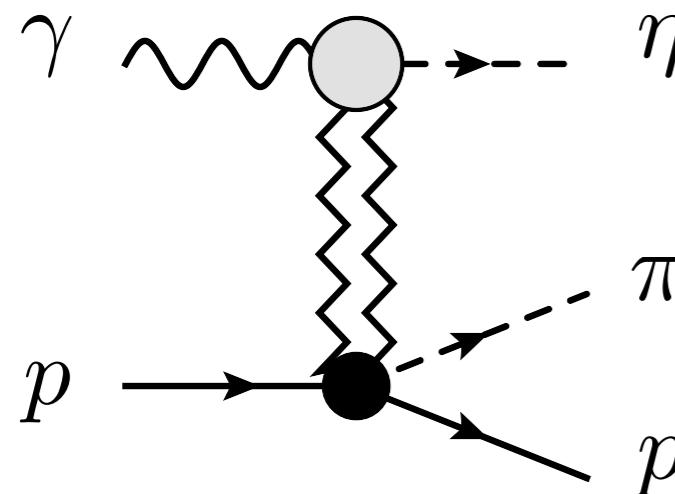
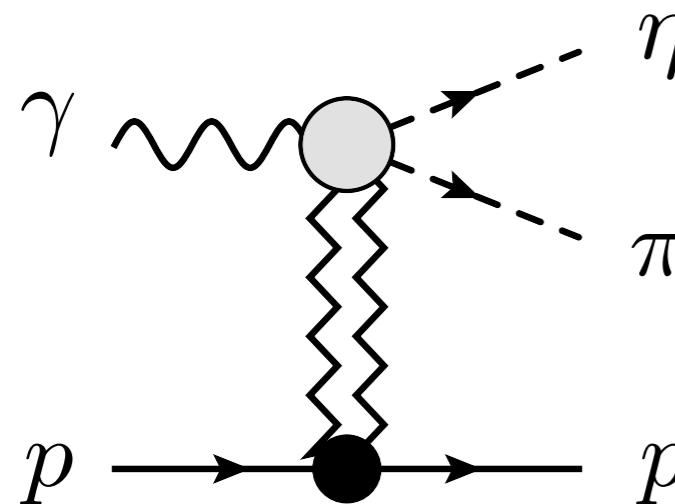
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Longitudinal Plot

How do we select beam fragmentation ?

→ Boost in the rest frame

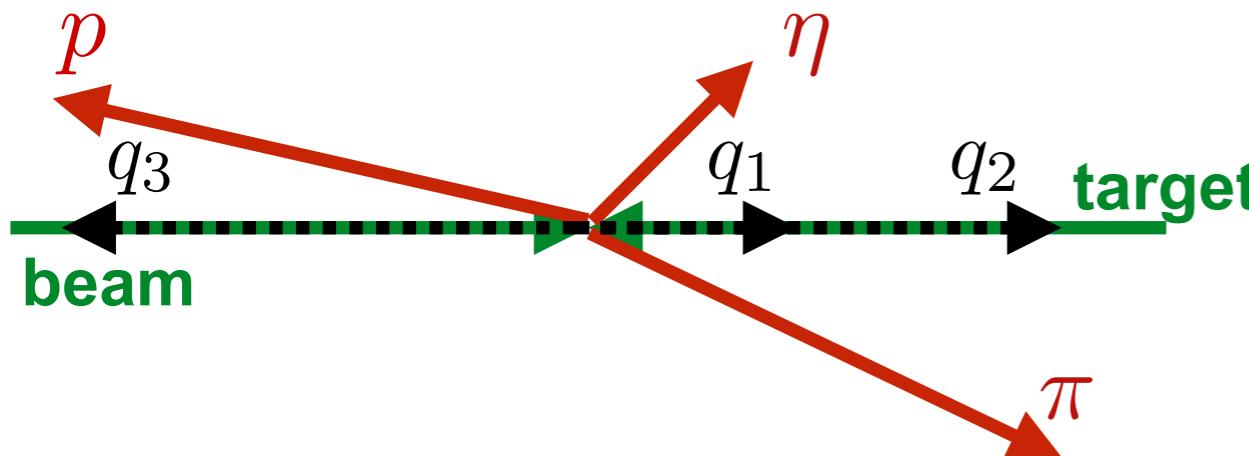


Van Hove NPB9 (1969) 331

Shi et al (JPAC) PRD91 (2015) 034007

Pauli et al PRD98 (2018) 065201

Longitudinal Plot



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

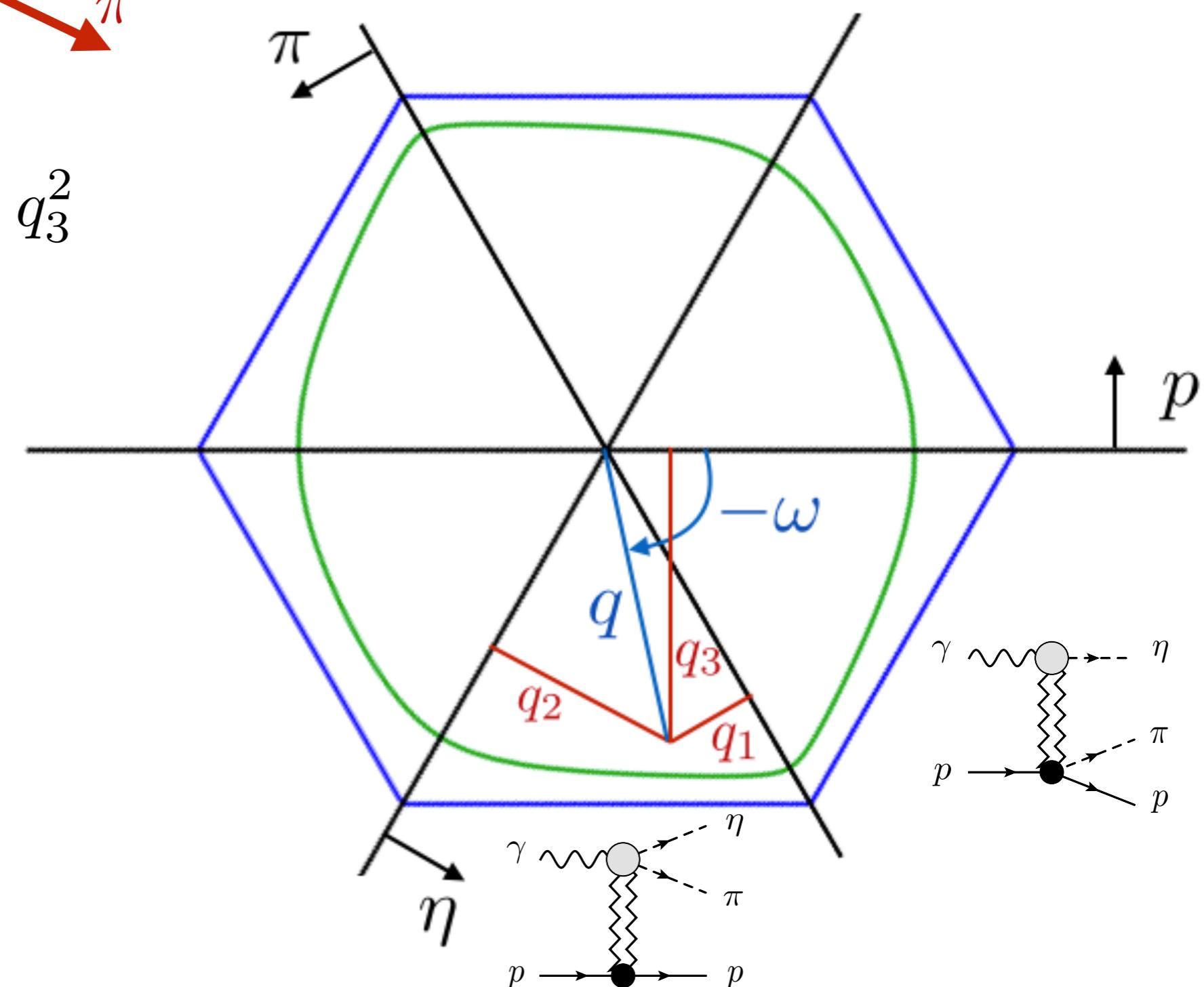
$$\text{radius: } q^2 = q_1^2 + q_2^2 + q_3^2$$

longitudinal angle: ω

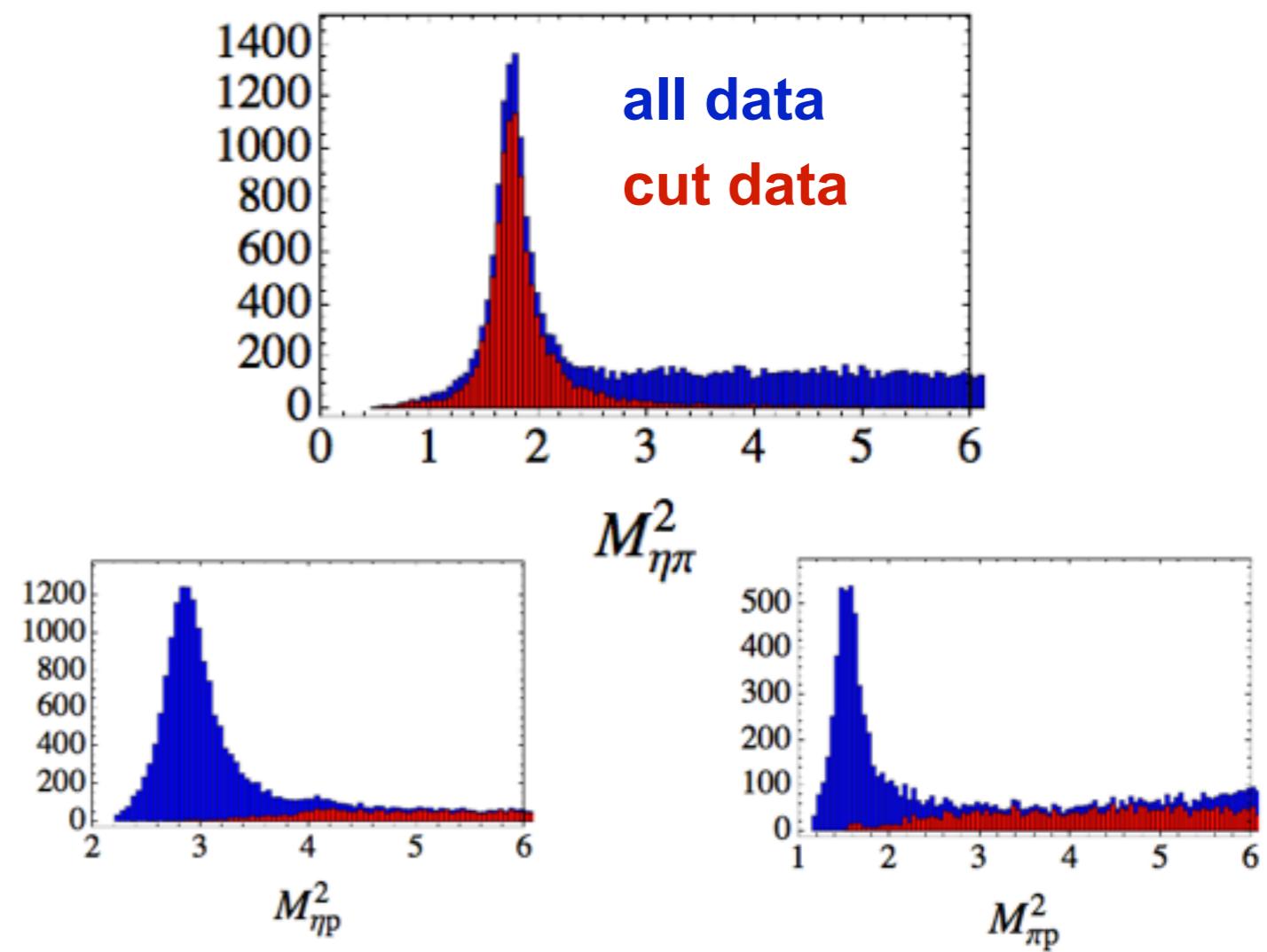
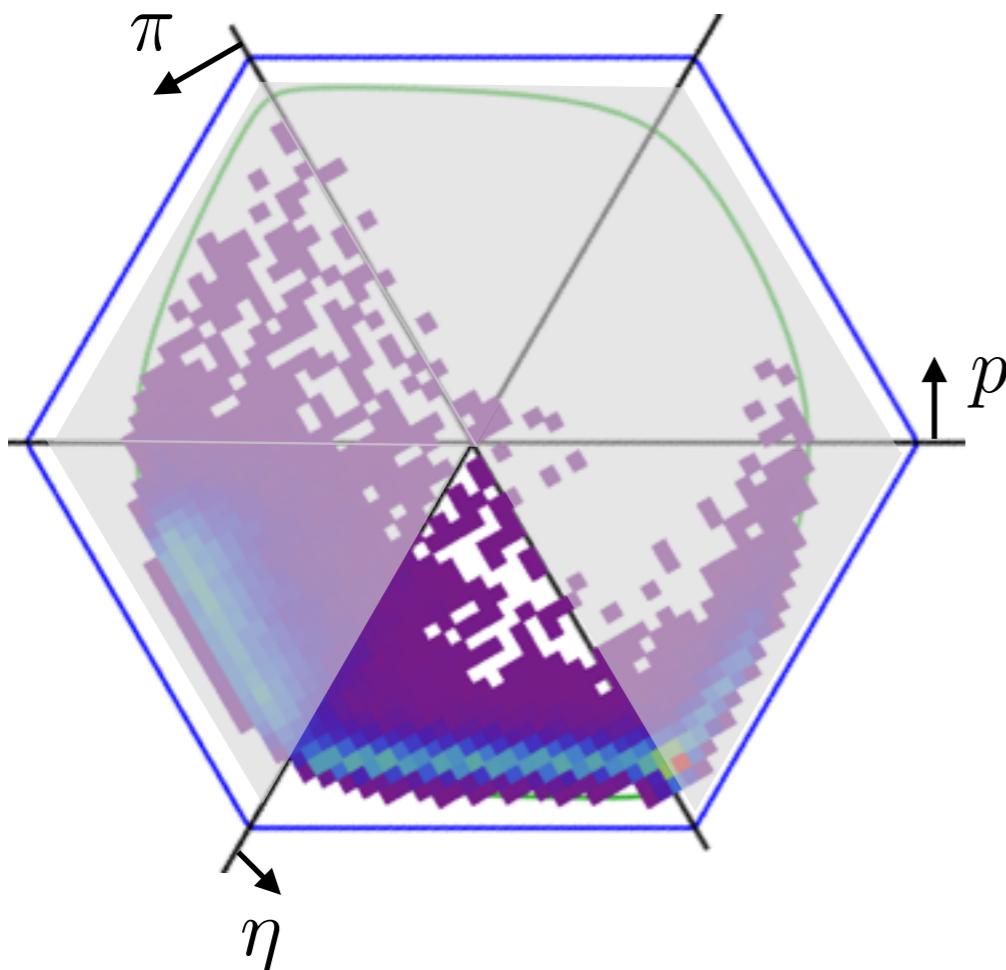
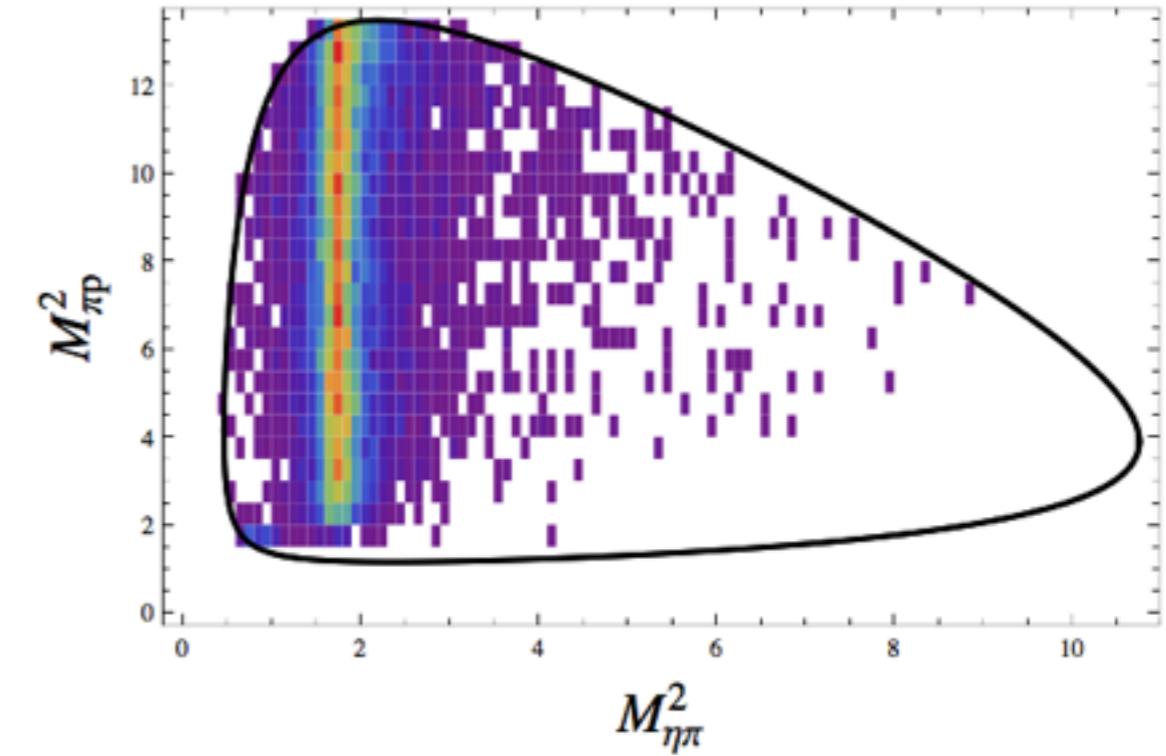
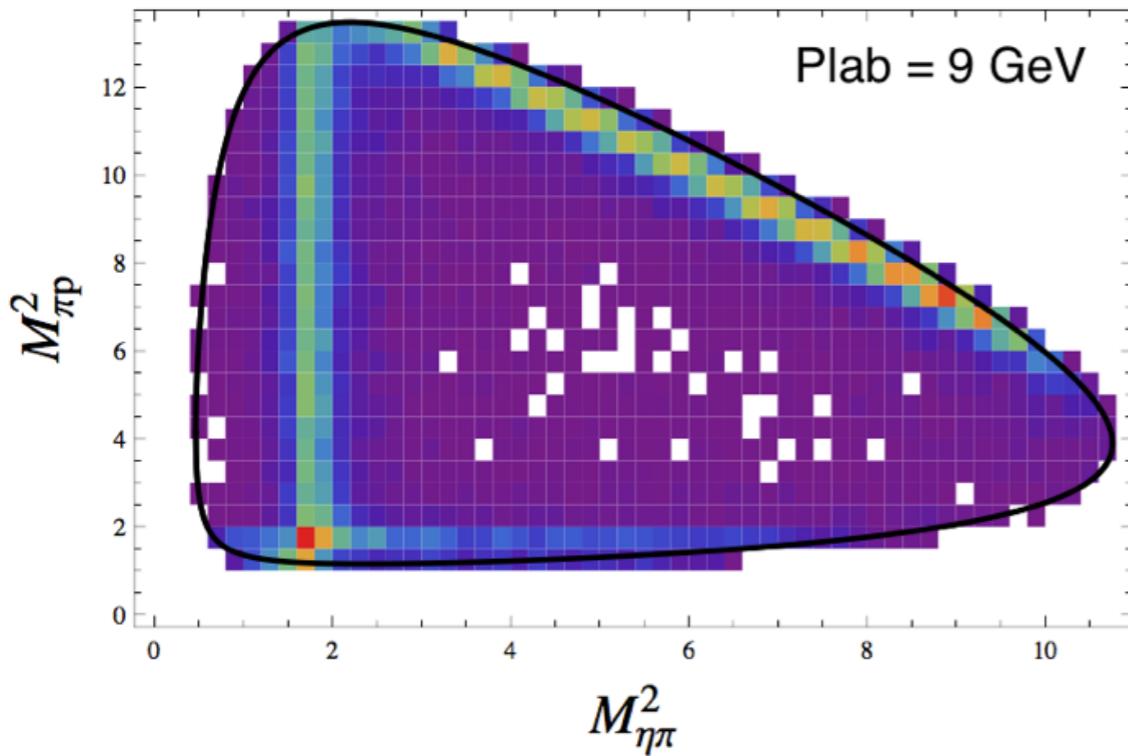
$$q_3 = \sqrt{\frac{2}{3}}q \sin \omega$$

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

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

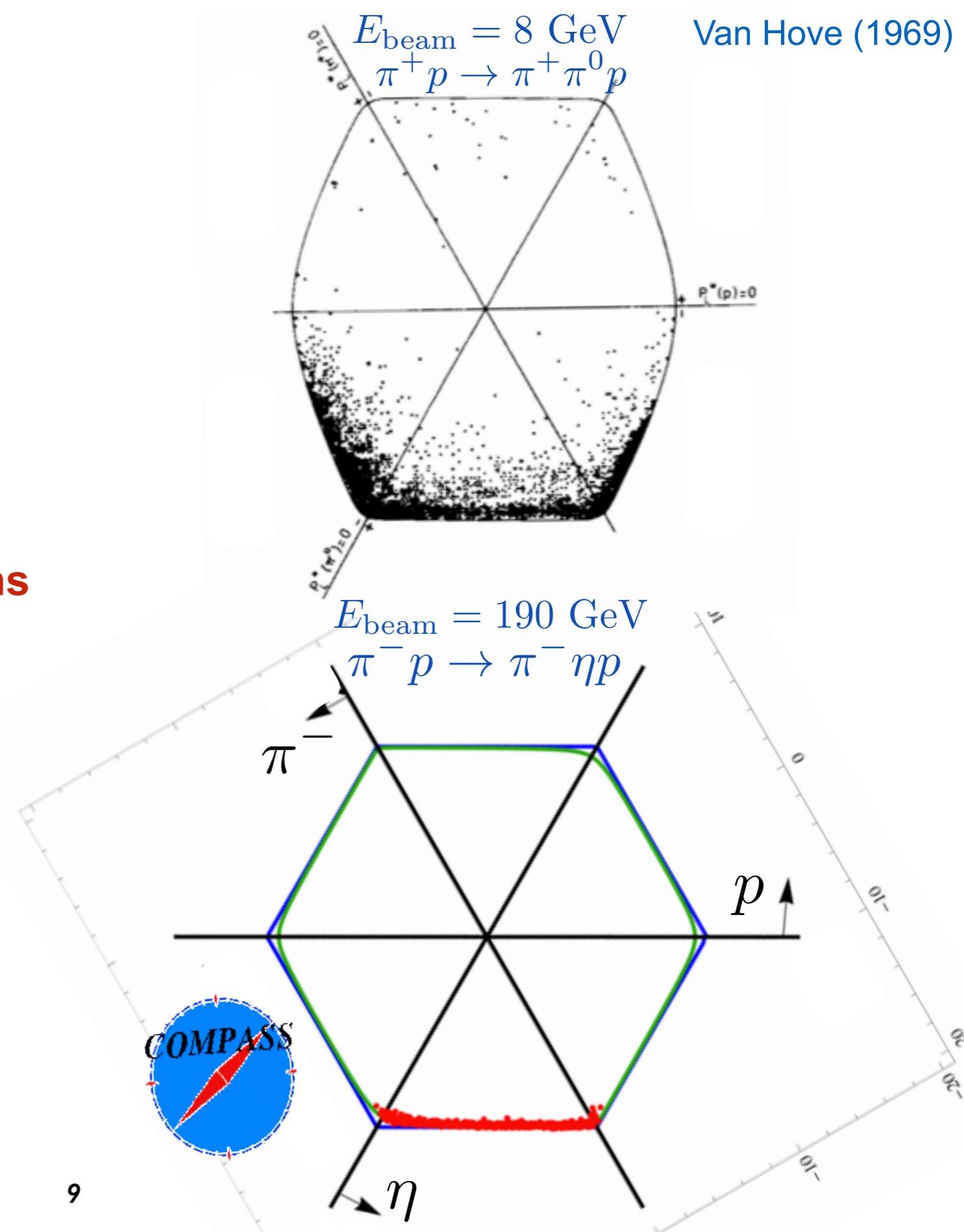
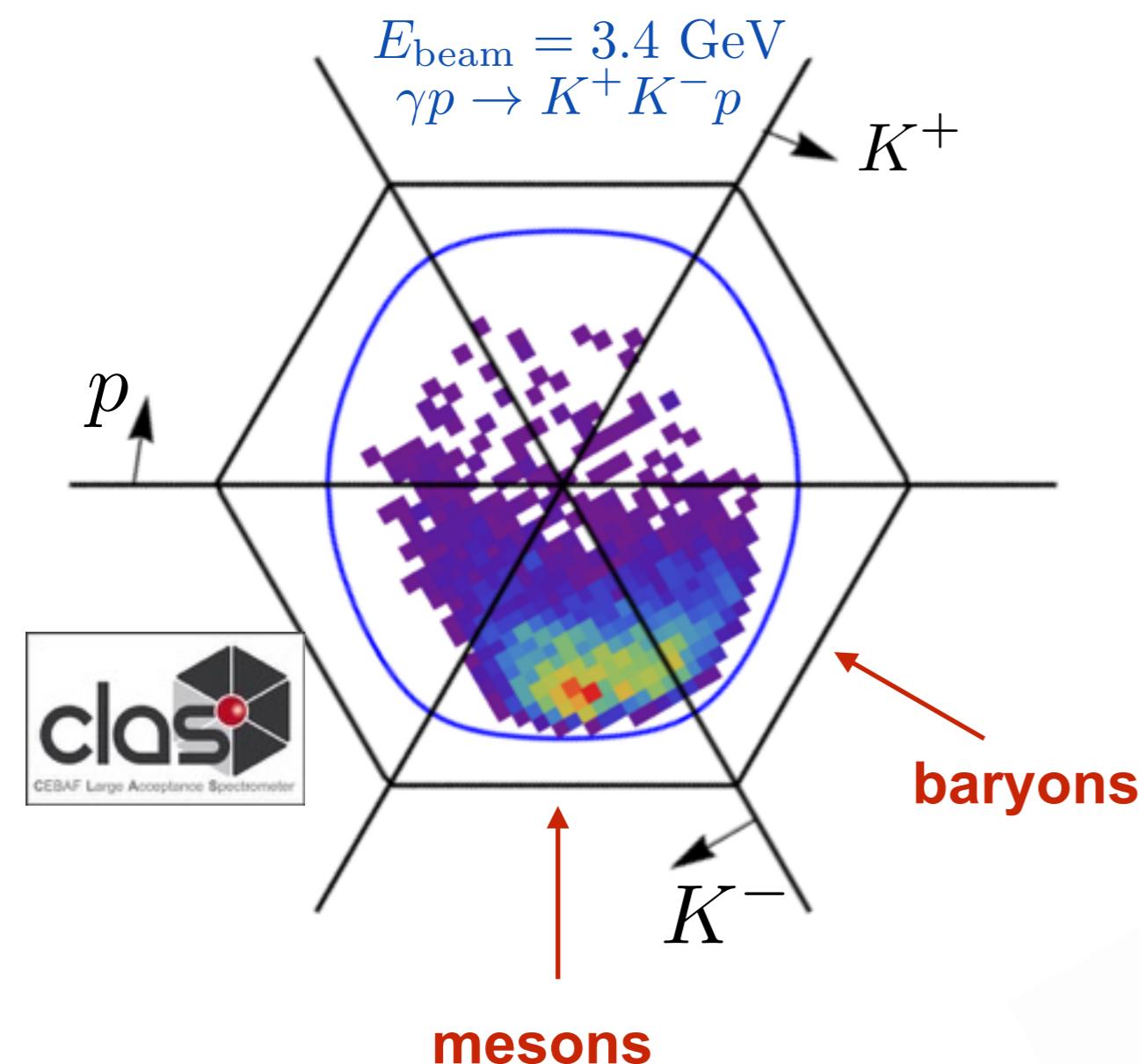


Cut in Longitudinal Angle



Longitudinal Plot: Energy Evolution

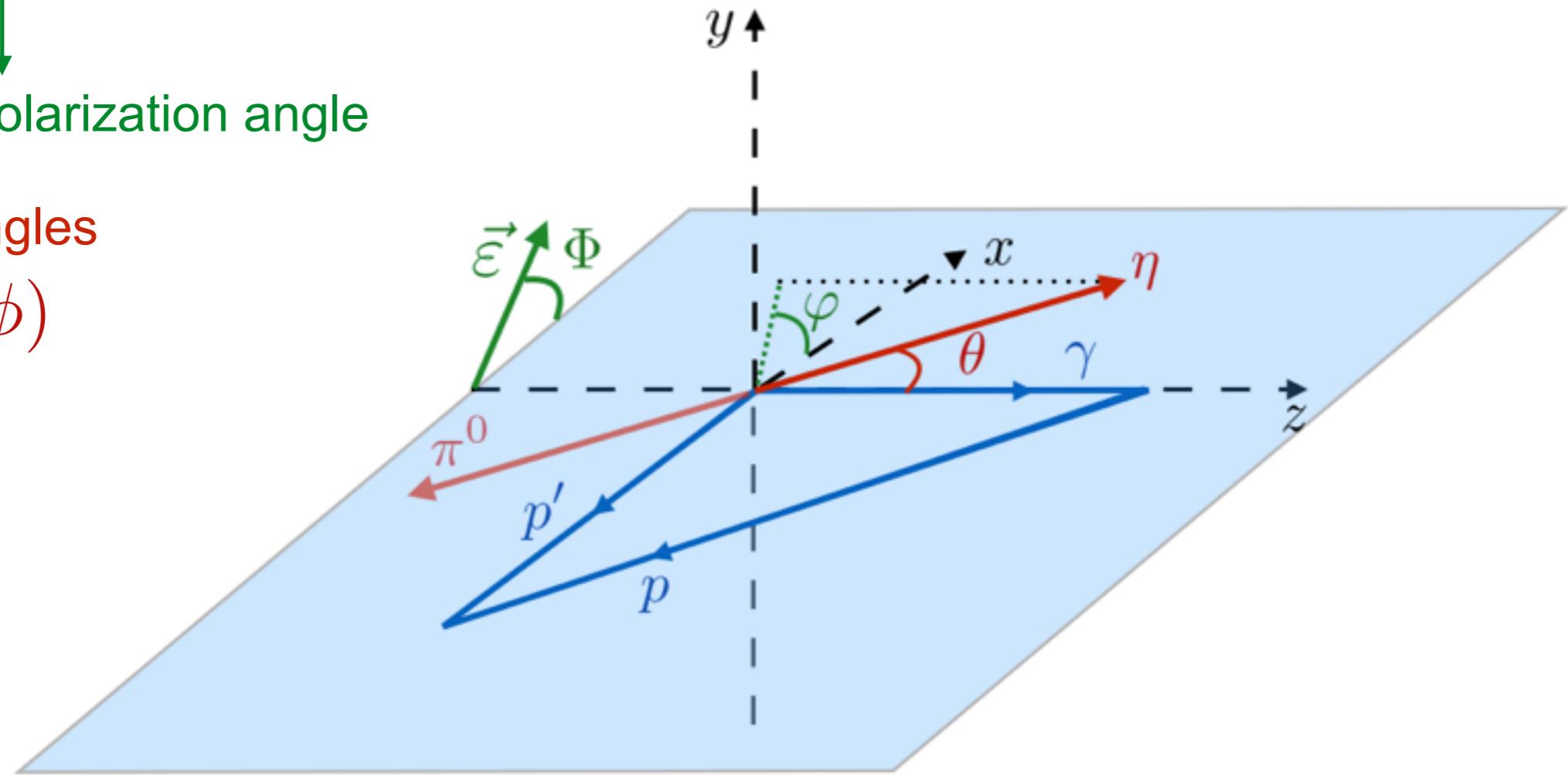
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Measured Intensities

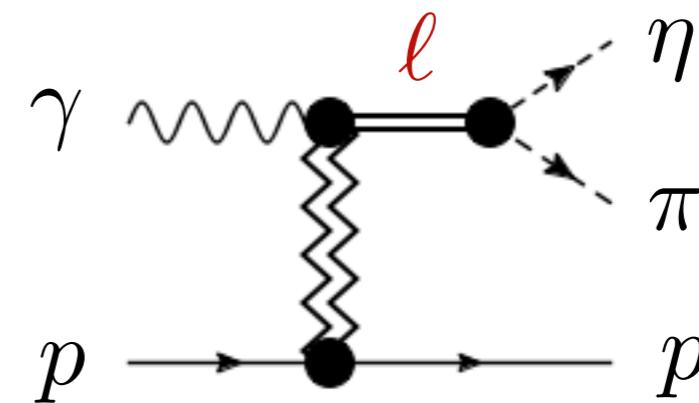
$$I(\Omega, \Phi) = I^0(\Omega) - P_\gamma I^1(\Omega) \cos 2\Phi - P_\gamma I^2(\Omega) \sin 2\Phi$$


 polarization angle
 η decay angles
 $\Omega = (\theta, \phi)$



Implicit variables

- Beam energy (fixed)
- momentum transfer (integrated)
- $\eta\pi$ invariant mass (binned)



Observables: Moments of Angular distribution

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

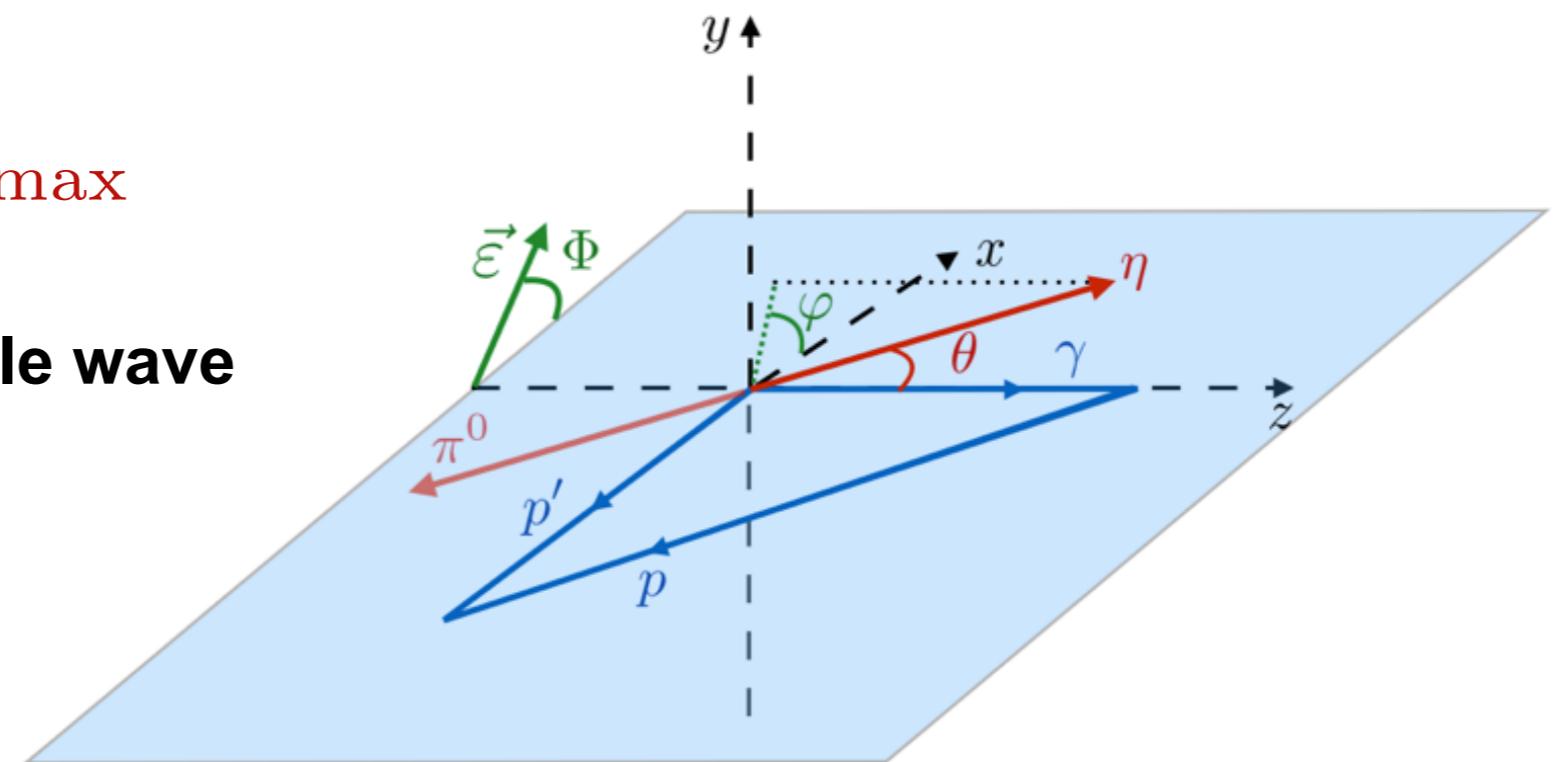
$$H^0(LM) = \frac{1}{2\pi} \int I(\Omega, \Phi) d_{M0}^L(\theta) \cos M\phi \, d\Omega d\Phi$$

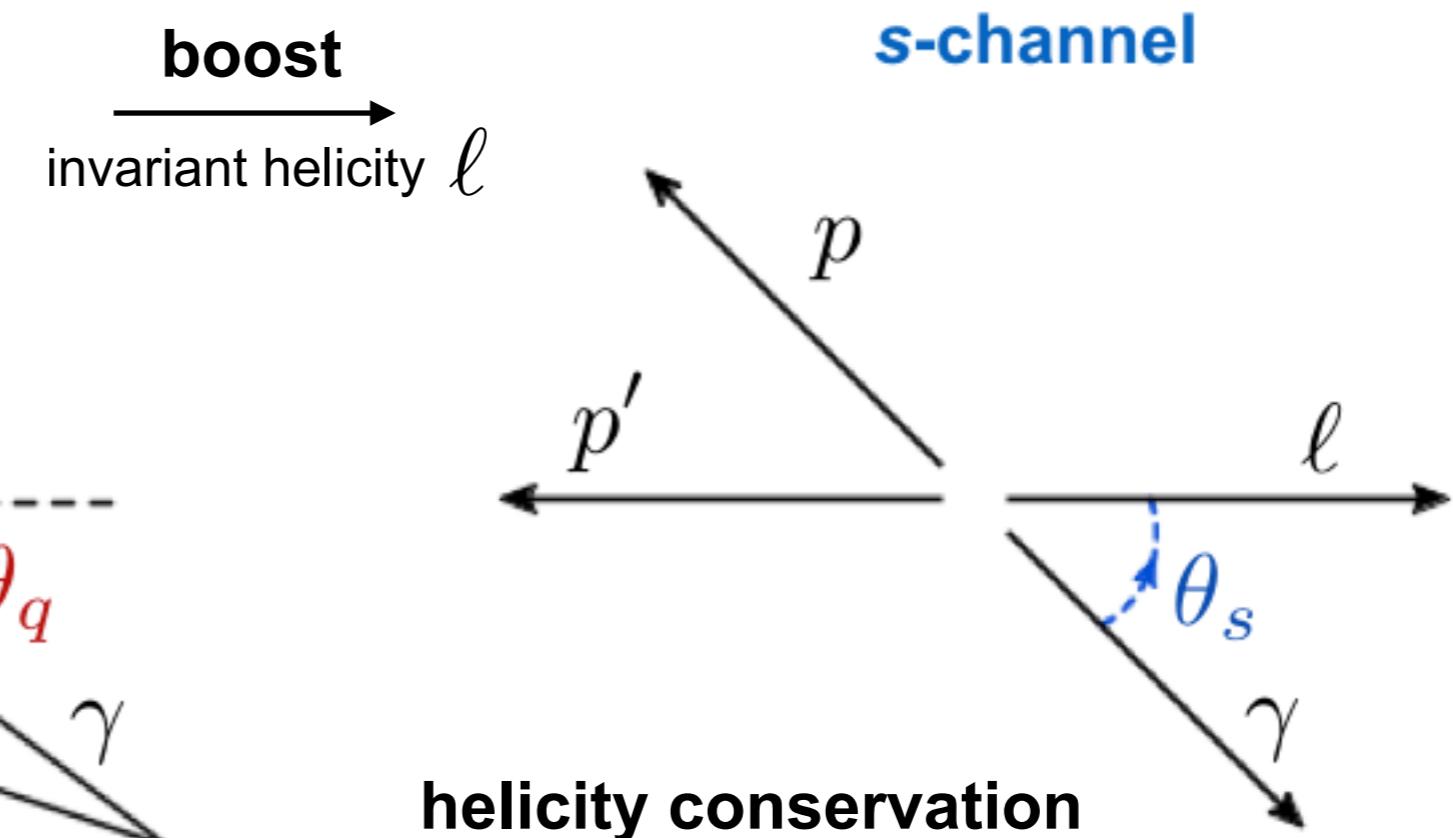
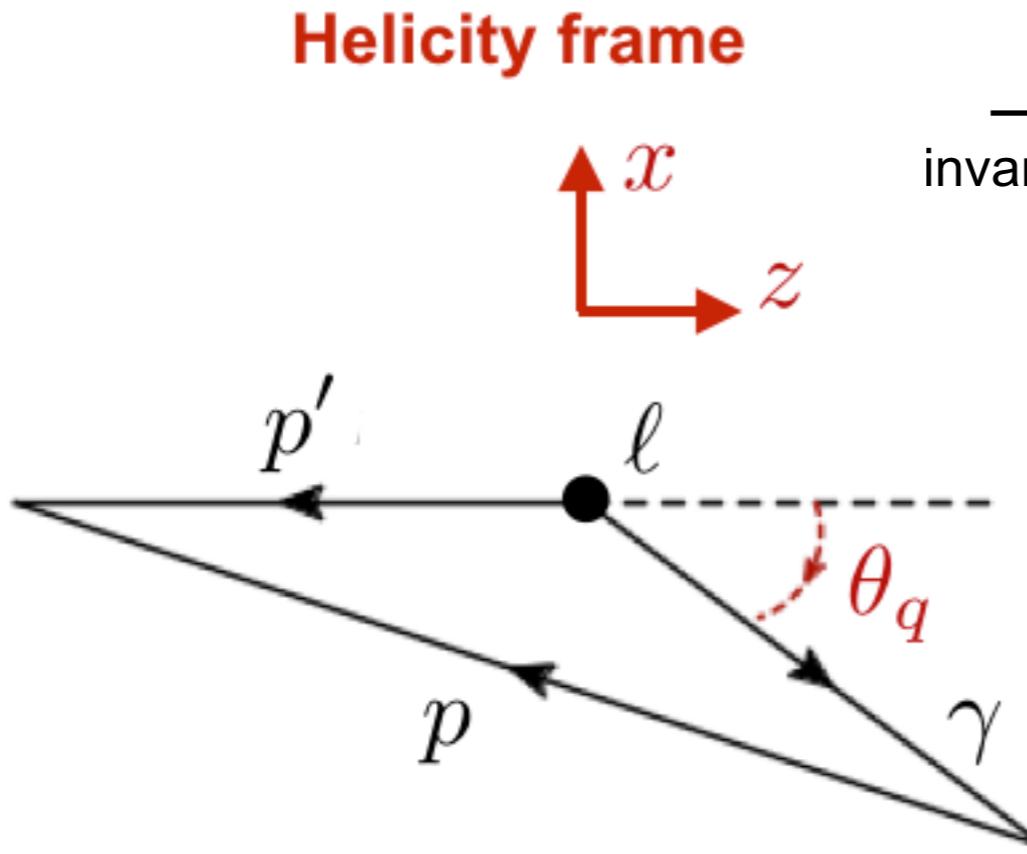
$$H^1(LM) = \frac{-1}{\pi P_\gamma} \int I(\Omega, \Phi) \boxed{\cos 2\Phi} d_{M0}^L(\theta) \cos M\phi \, d\Omega d\Phi$$

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

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

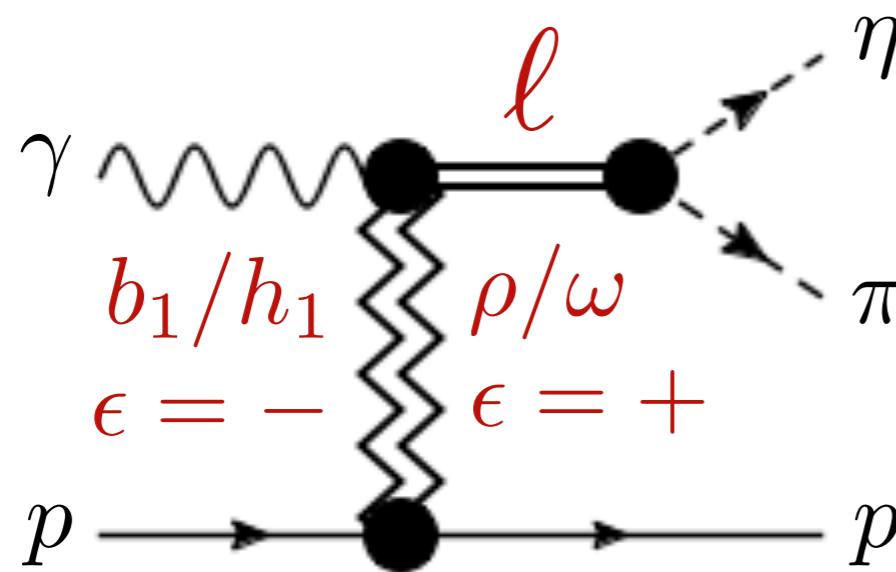
ℓ_{\max} is the highest non-negligible wave





between γ and ℓ

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

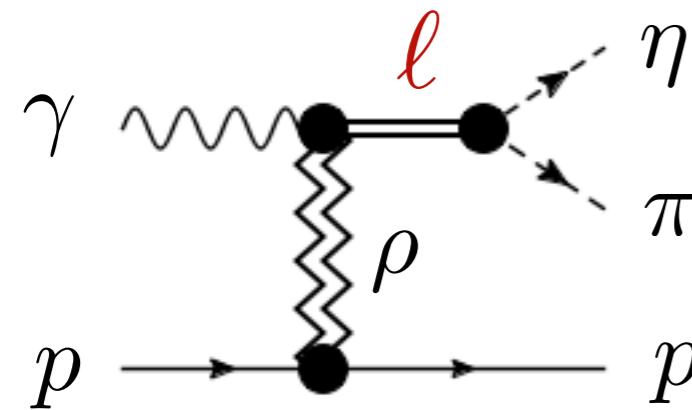


Reflectivity basis:

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

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

Model



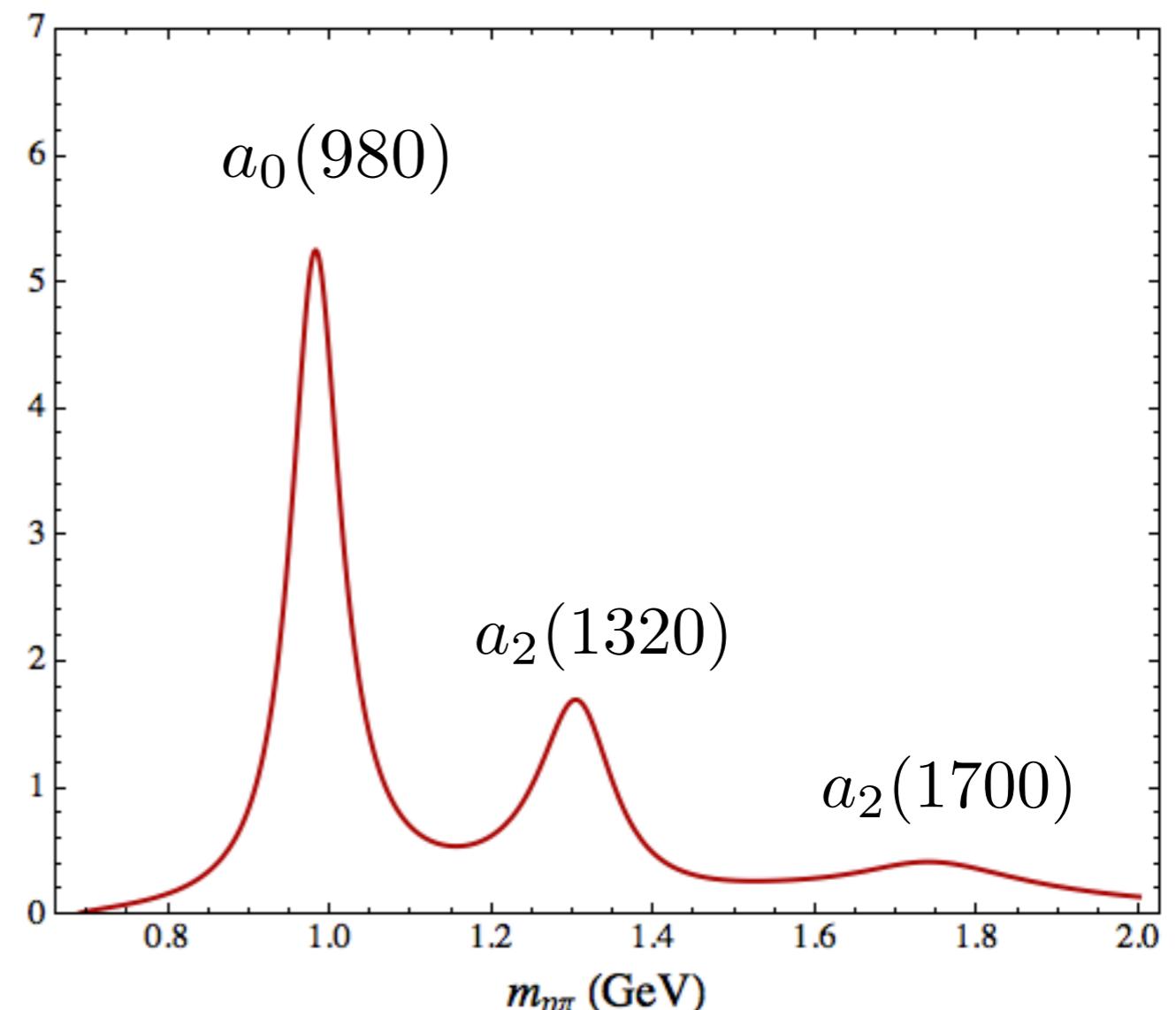
$$R = \underbrace{\{a_0(980), \pi_1(1600)\}}_{S_0^{(+)}} \cup \underbrace{\{a_2(1320)\}}_{P_{0,1}^{(+)}} \cup \underbrace{\{a_2(1700)\}}_{D_{0,1,2}^{(+)}}$$

production: natural exchanges

line shape: Breit-Wigner form

parameters: arbitrary

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



Observables: Moments of Angular distribution

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

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

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

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

$m' = m - M$

\uparrow

\downarrow

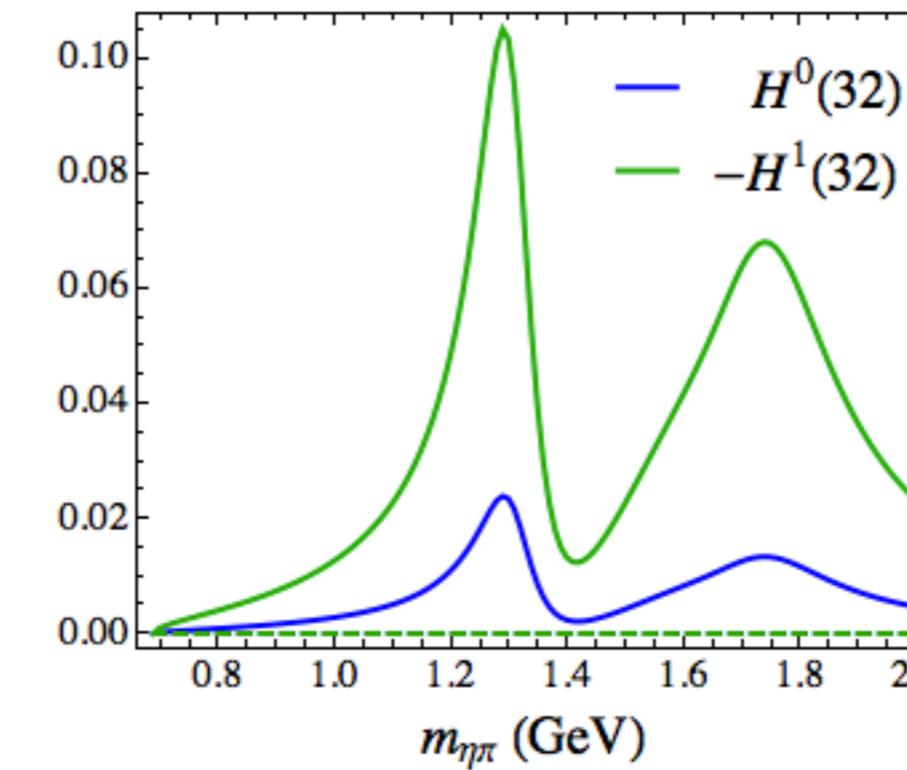
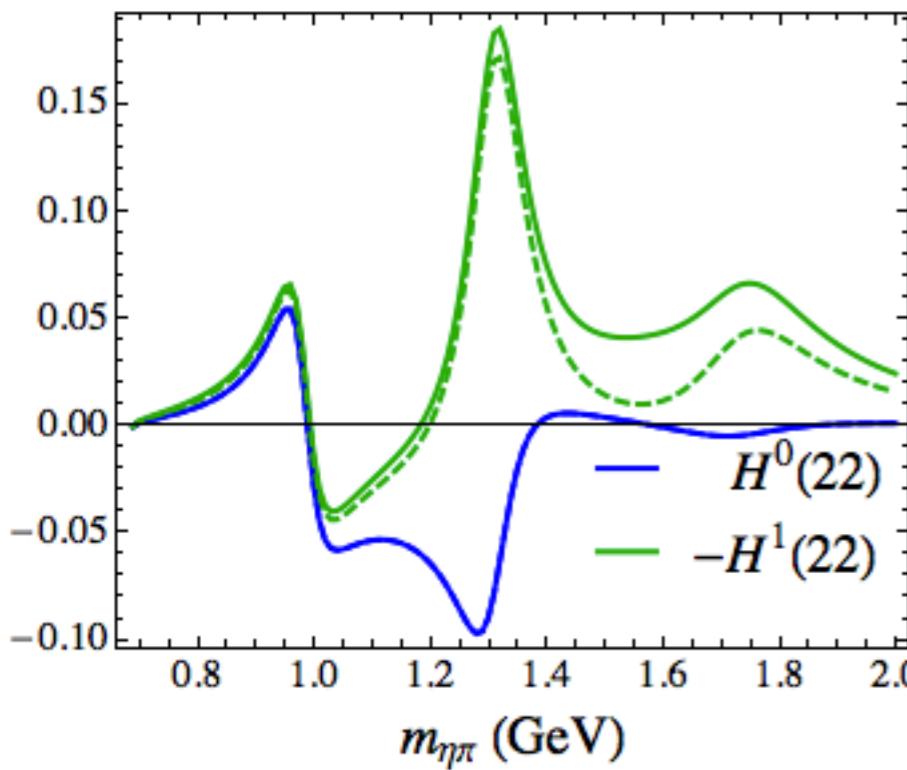
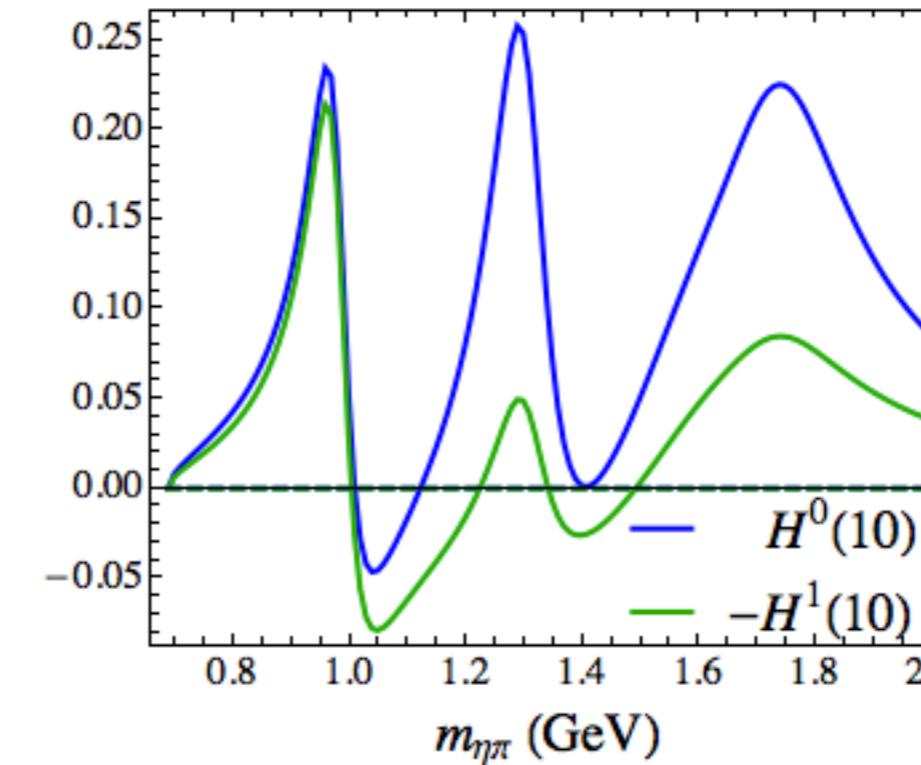
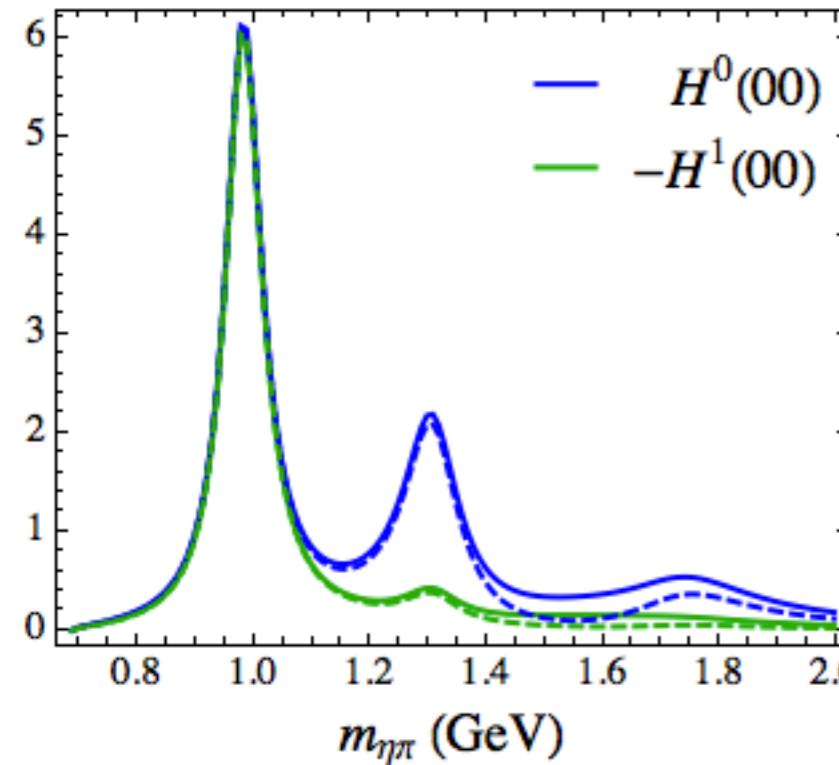
\downarrow

$0 \leq -m ; 0 \leq m'$

The model features
only positive projections

$$H^1(LM) + \text{Im } H^2(LM) = 0 \quad M \geq 1$$

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

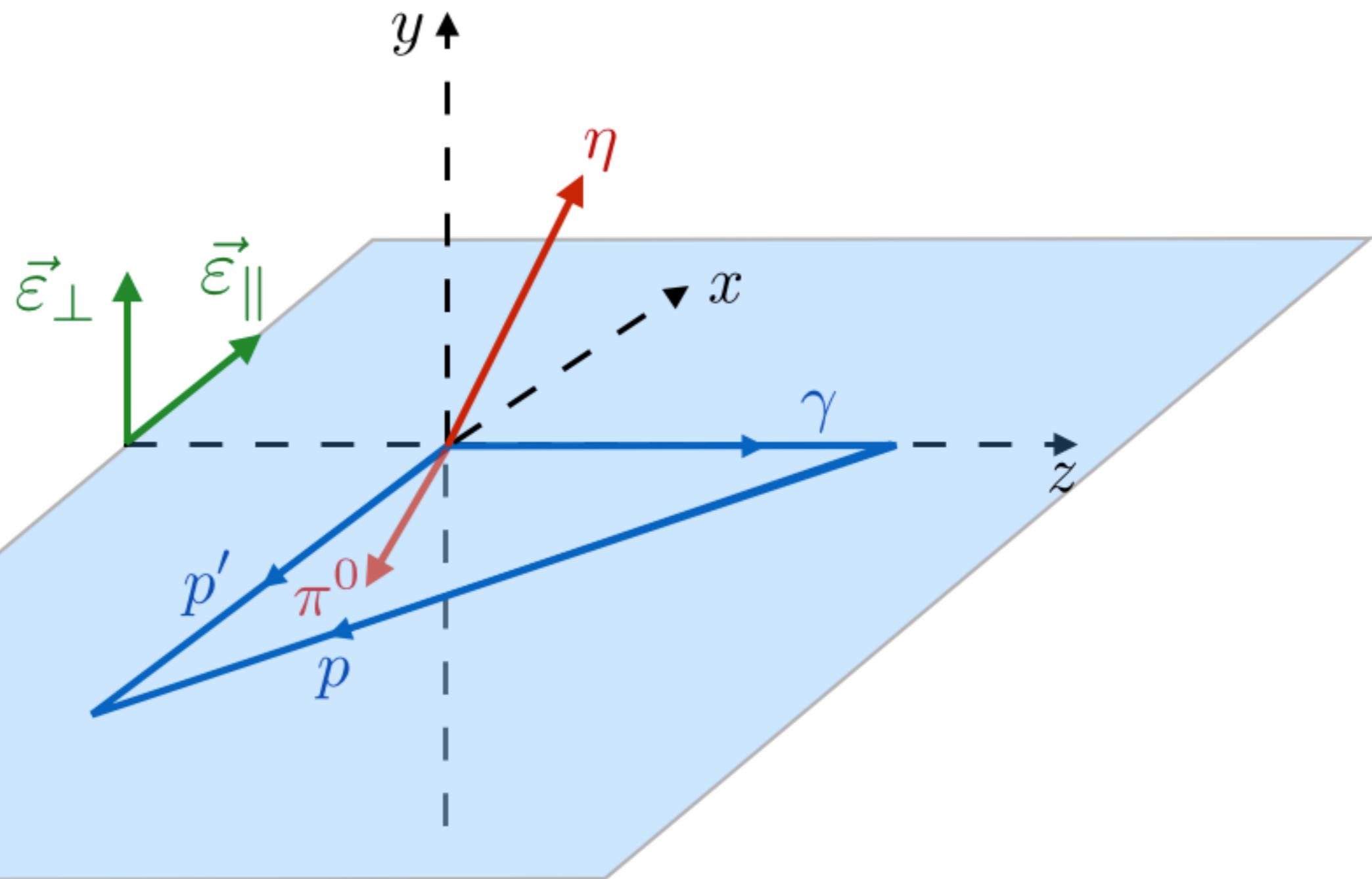
dashed lines: $S + D$ waves

Beam Asymmetries

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

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

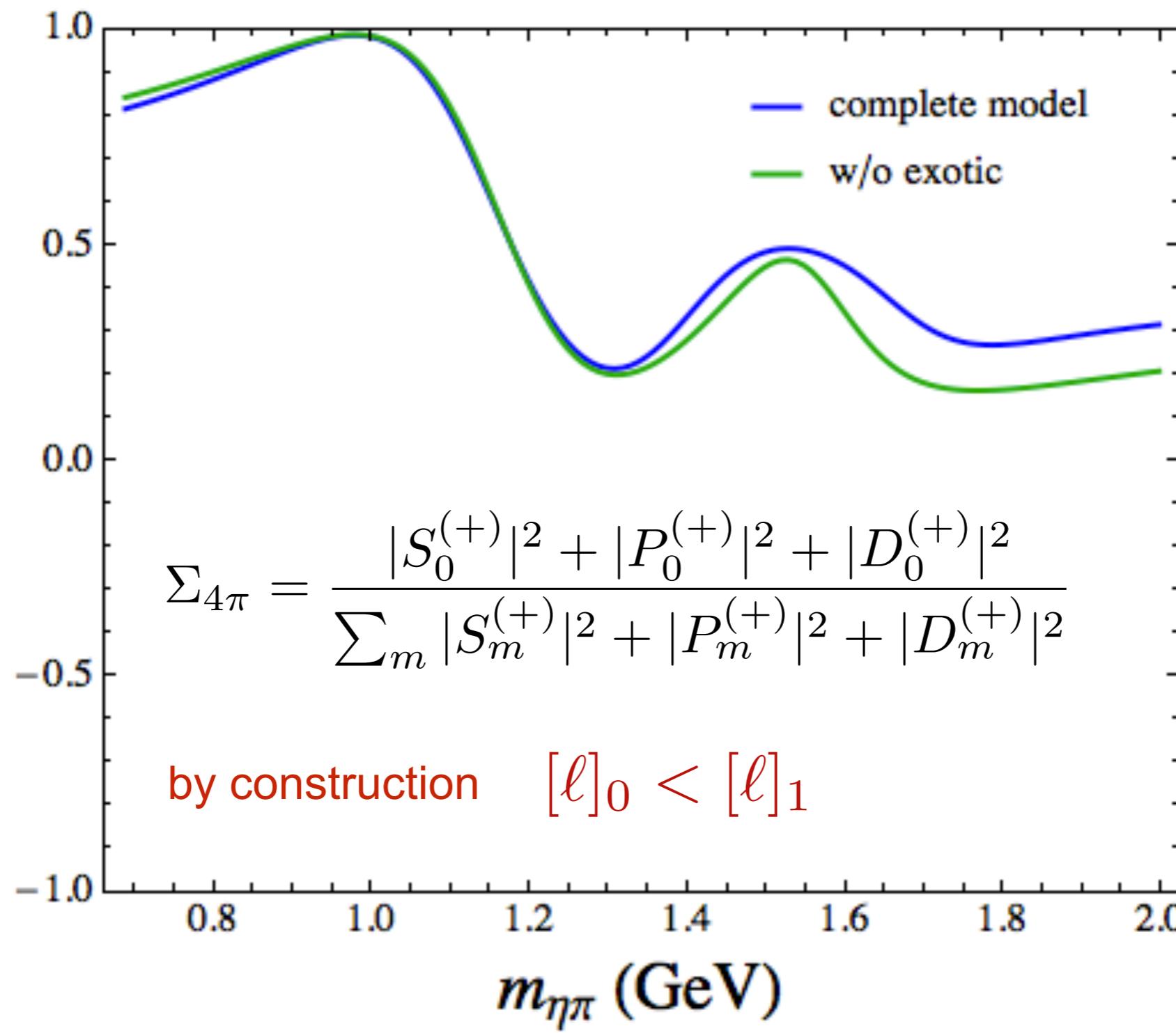


Beam Asymmetries

17

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

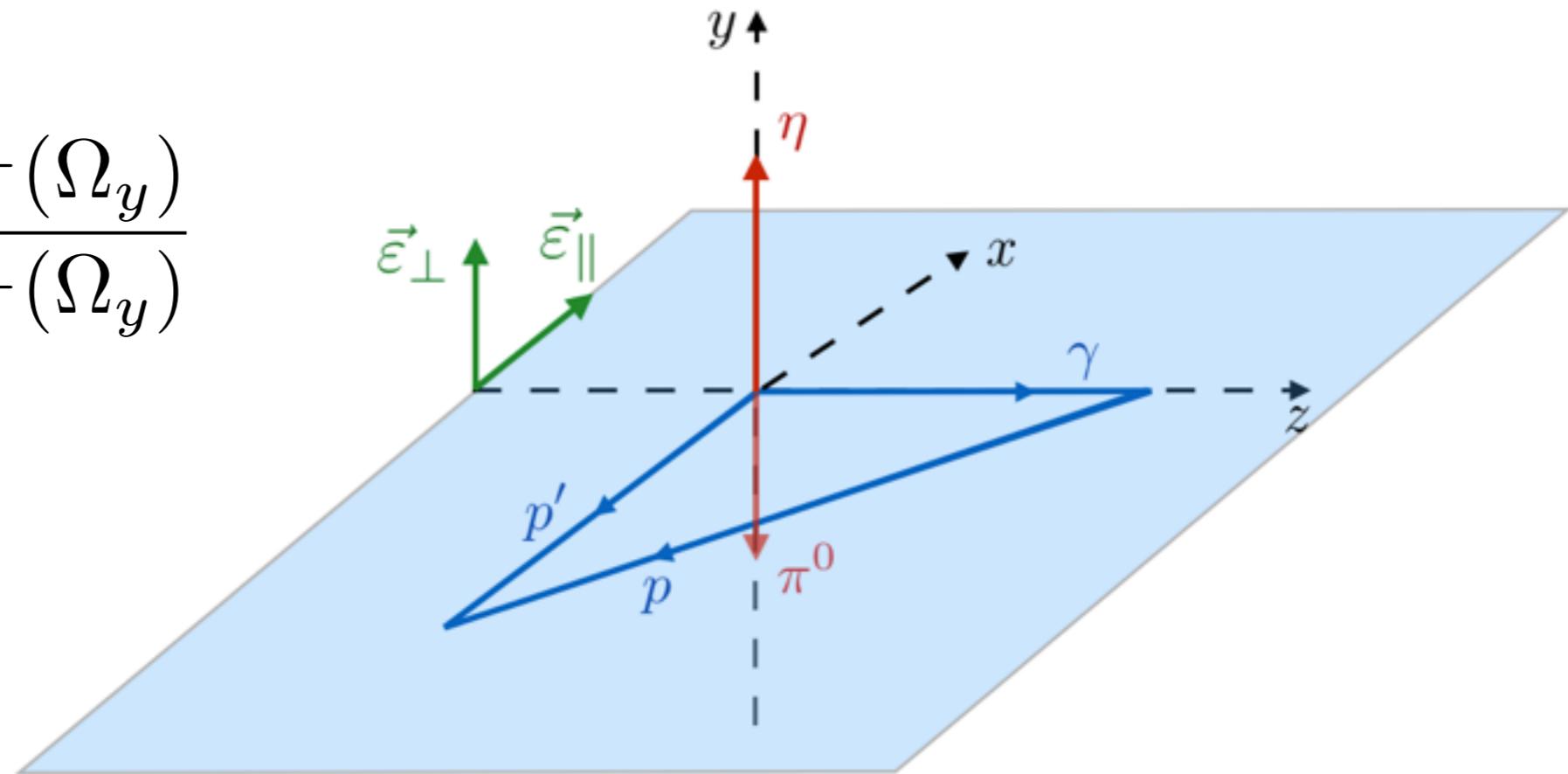
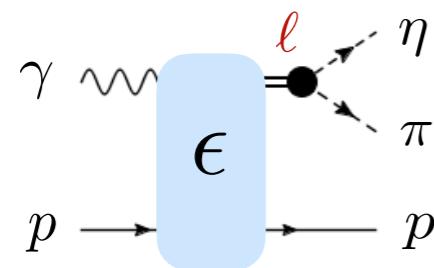
$\Sigma_{4\pi}$ = fully integrated



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

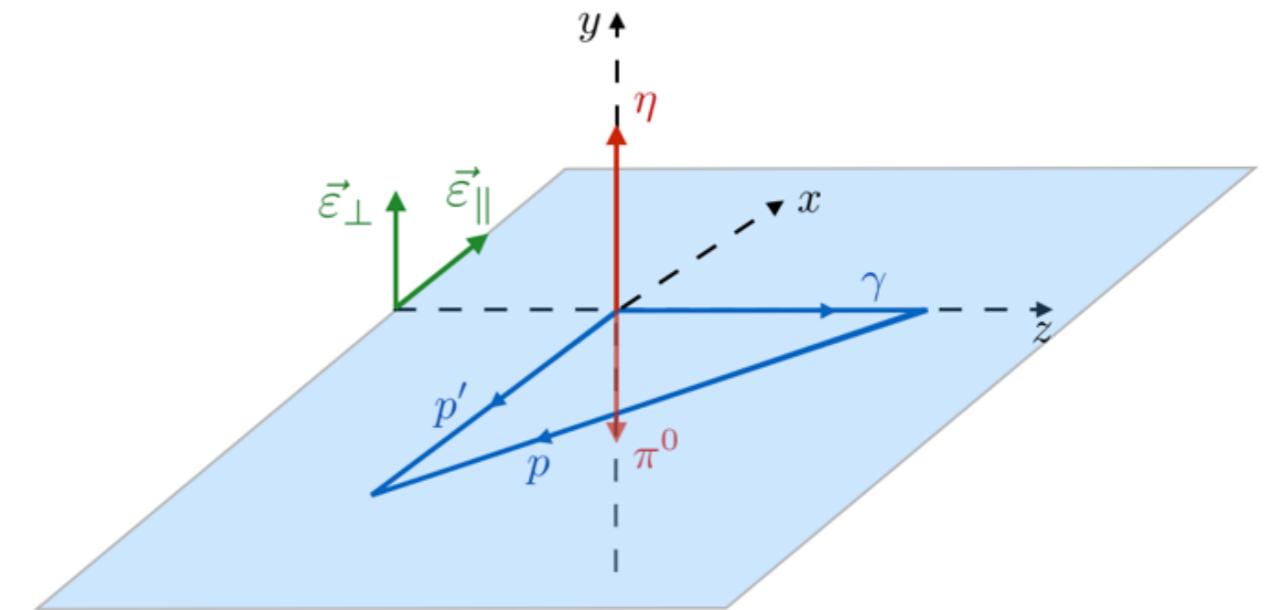
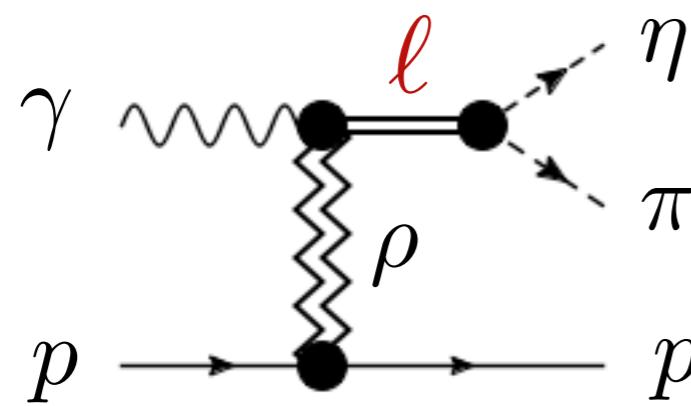
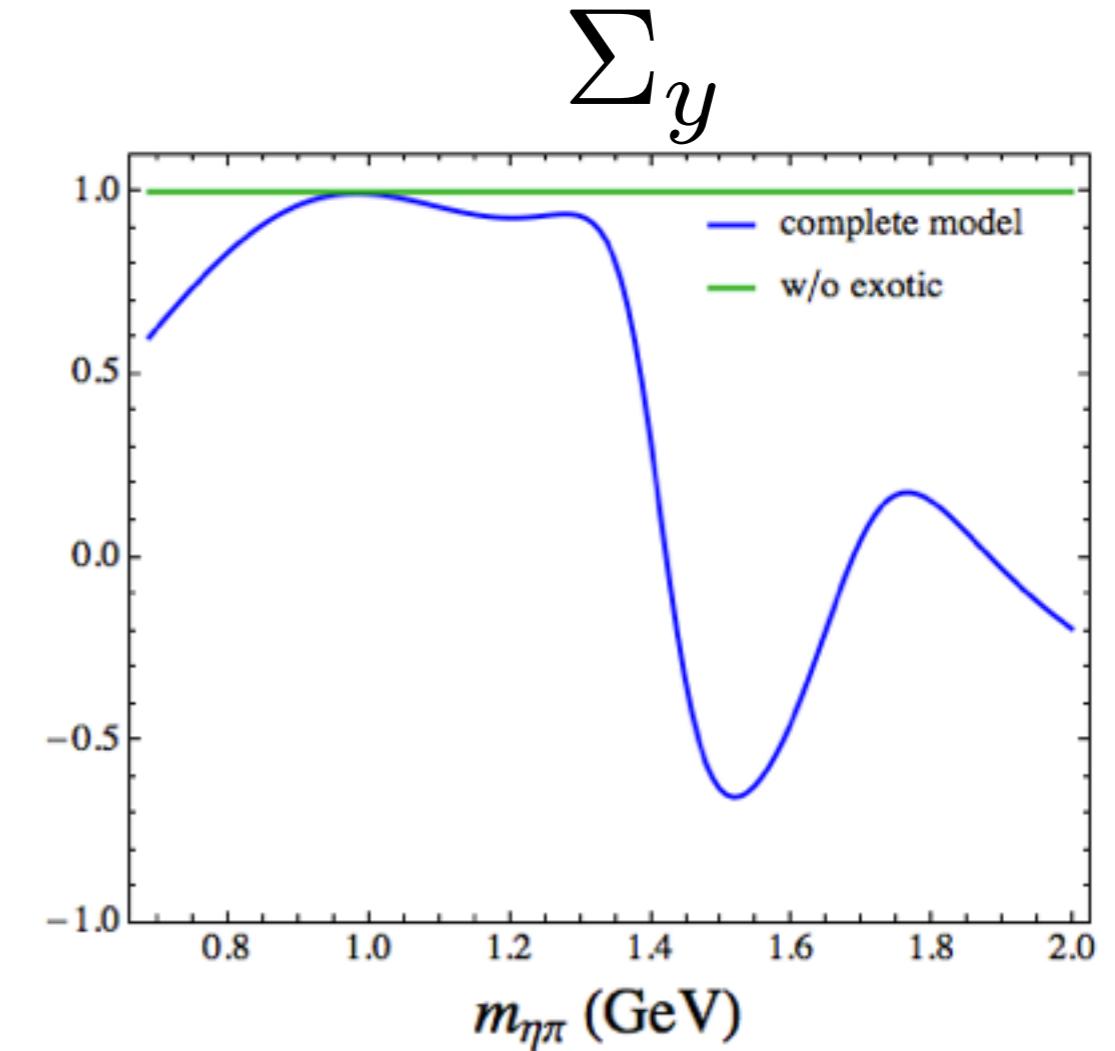
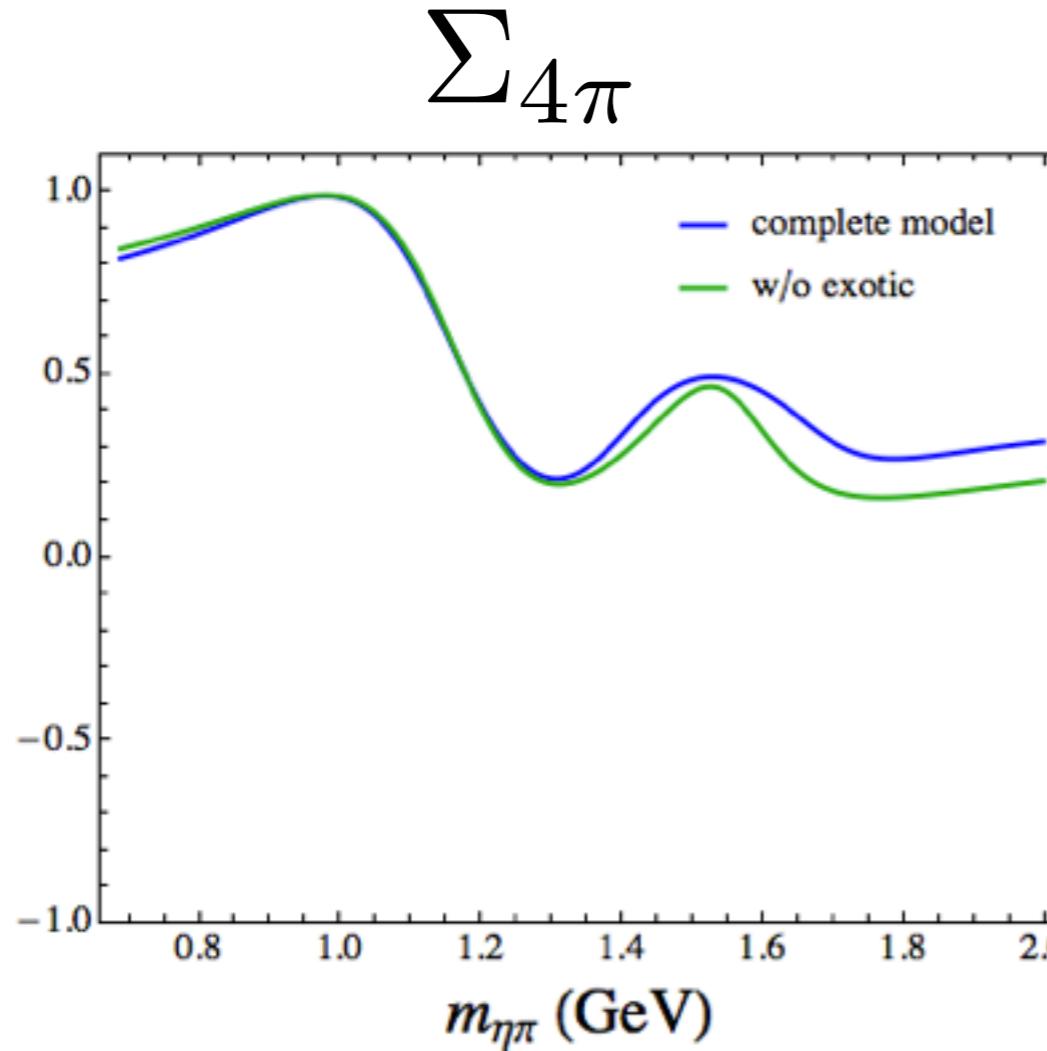
use reflection operator = parity followed by 180° rotation around Y-axis

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

Odd waves change sign!!!

Beam Asymmetries

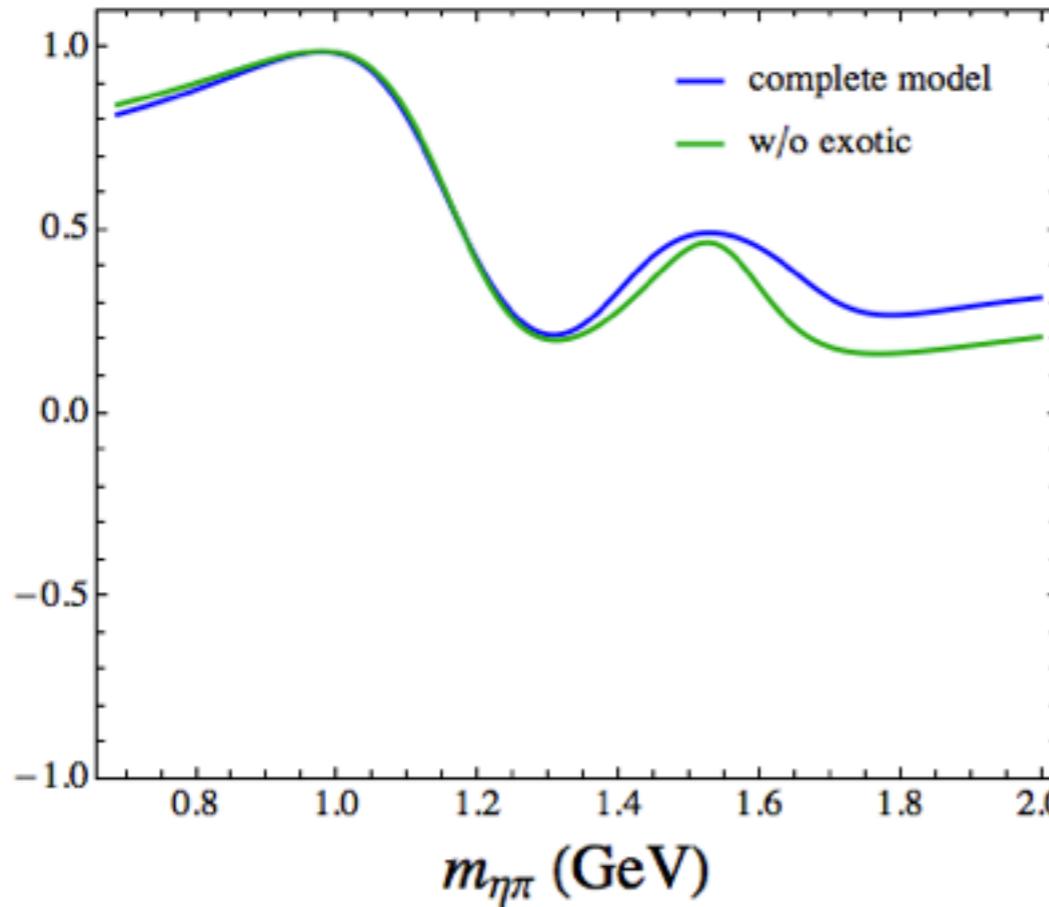
19



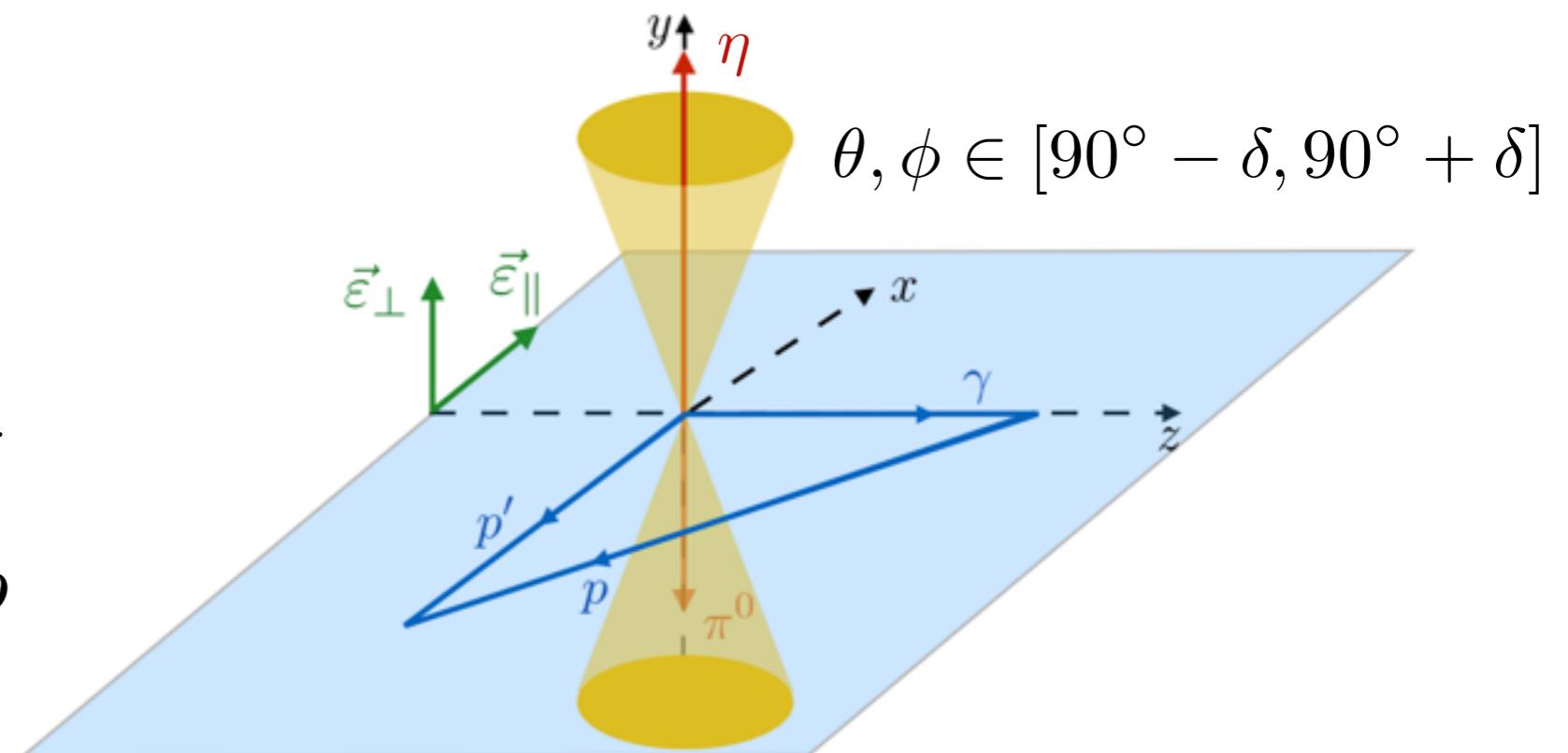
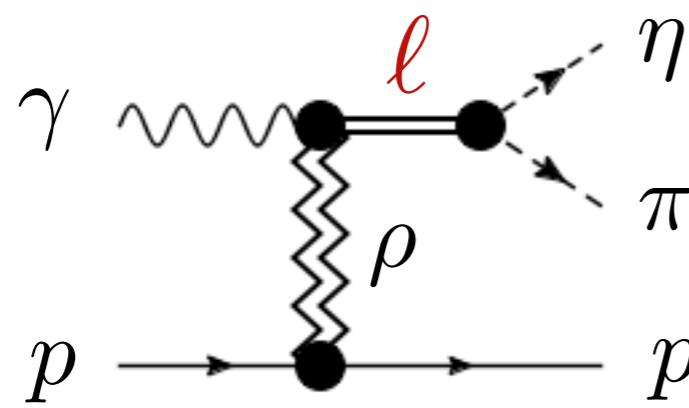
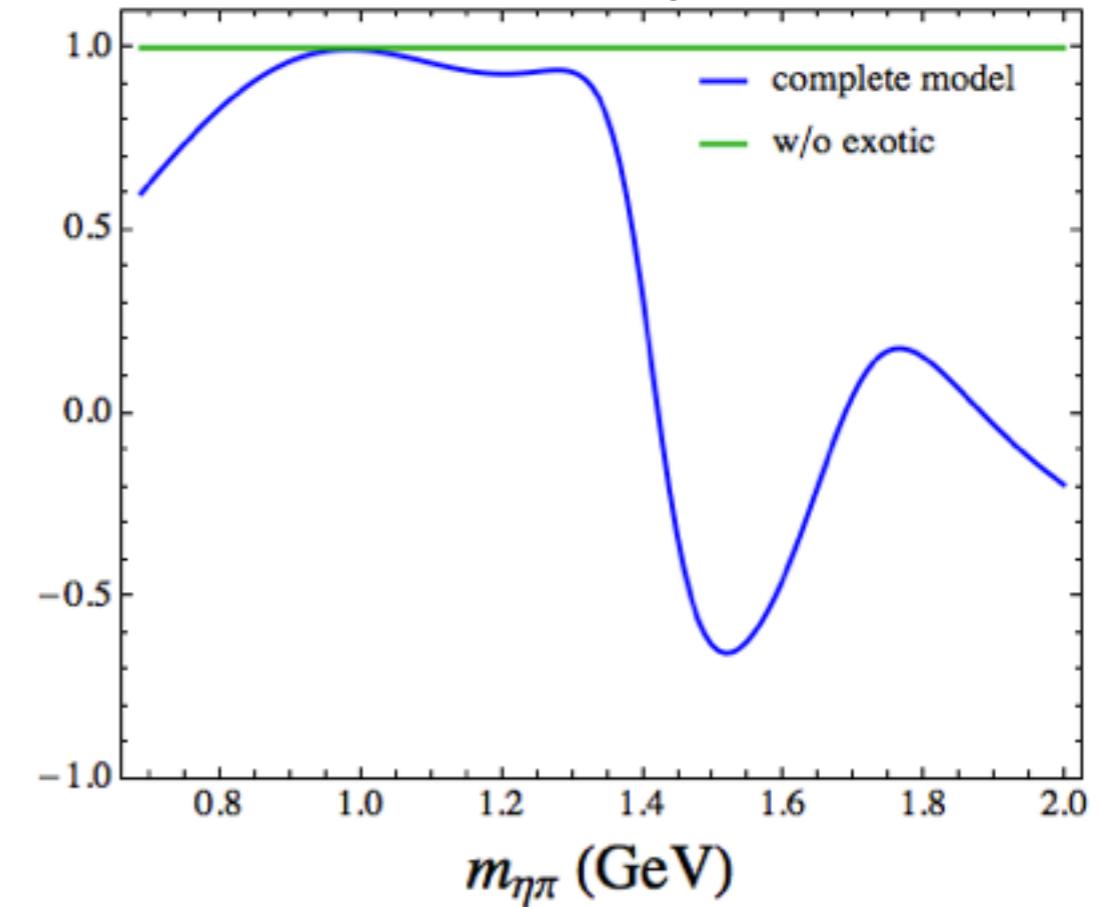
Beam Asymmetries

19

$$\Sigma_{4\pi}$$

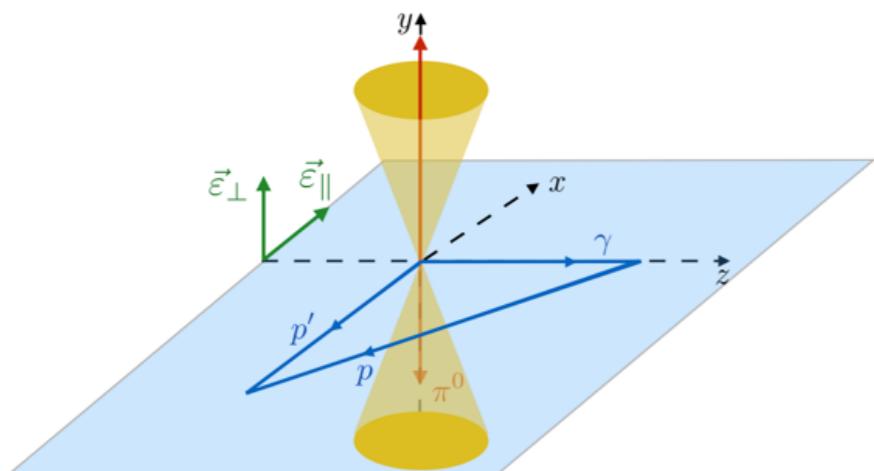
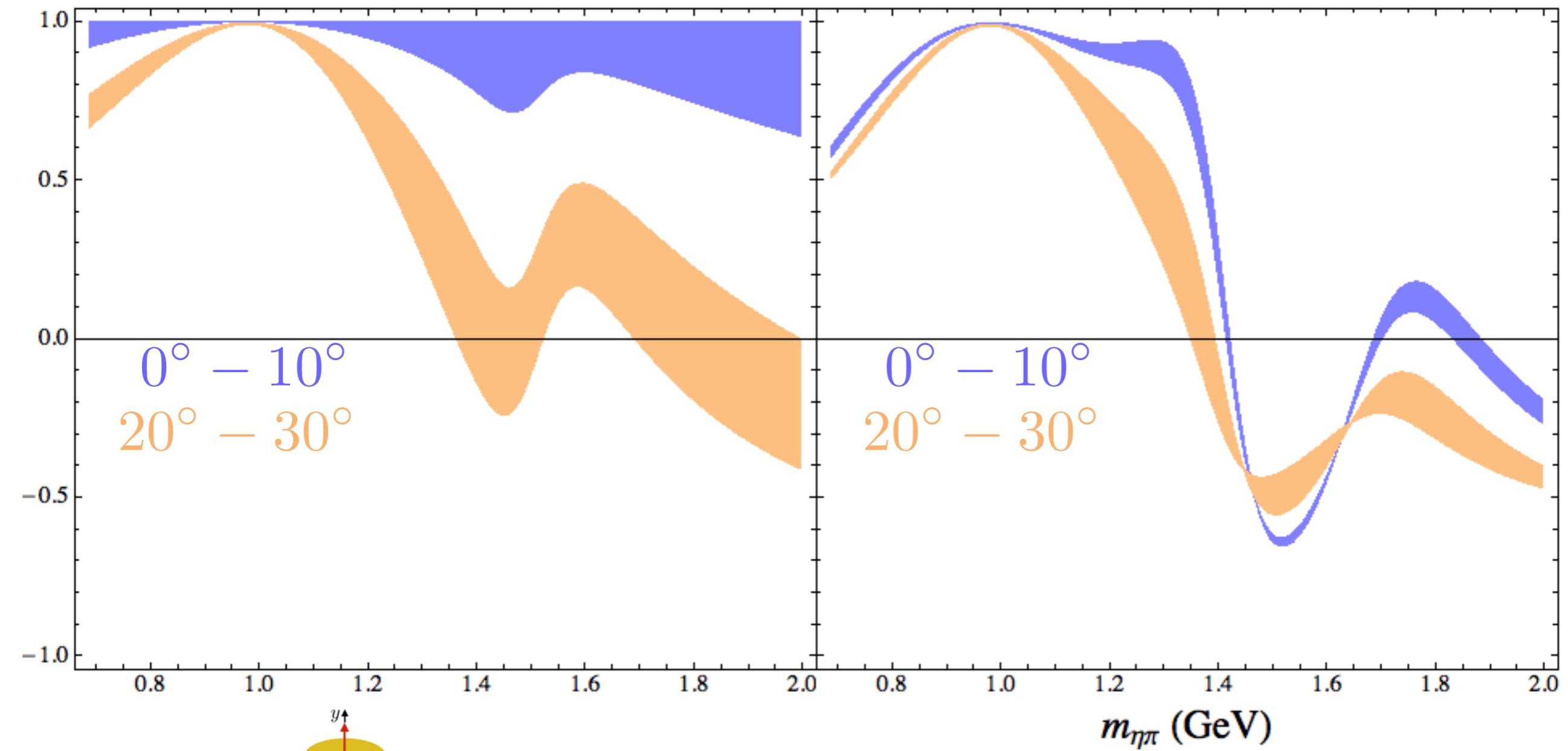


$$\Sigma_y$$



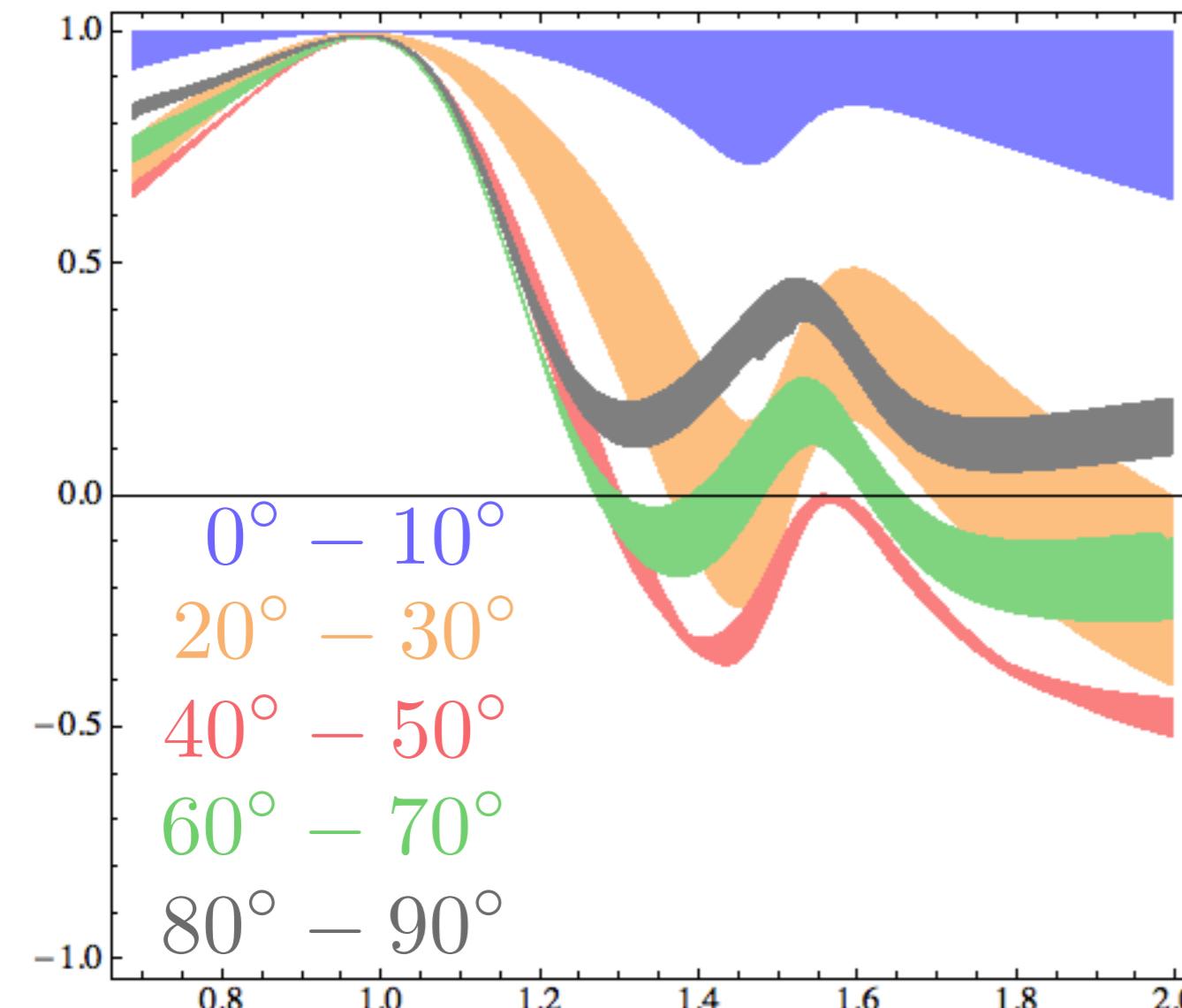
Beam Asymmetries: $\Sigma_{y \pm \delta^\circ}$

only S and D waves

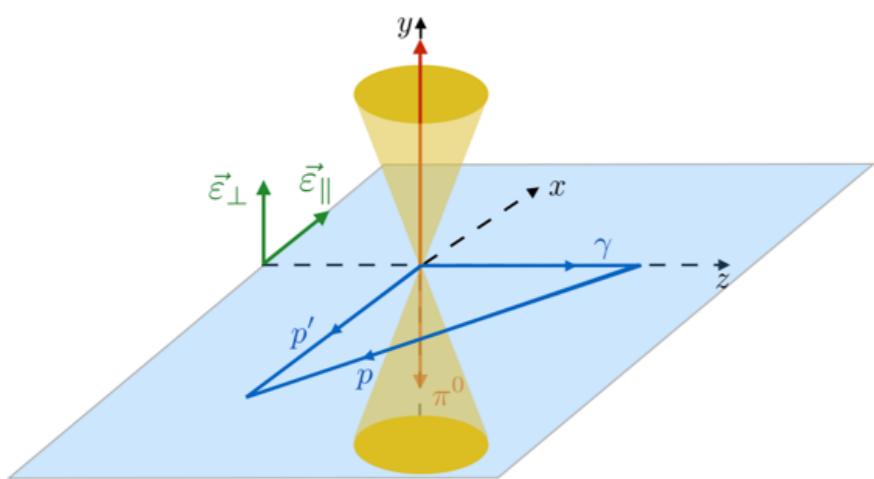
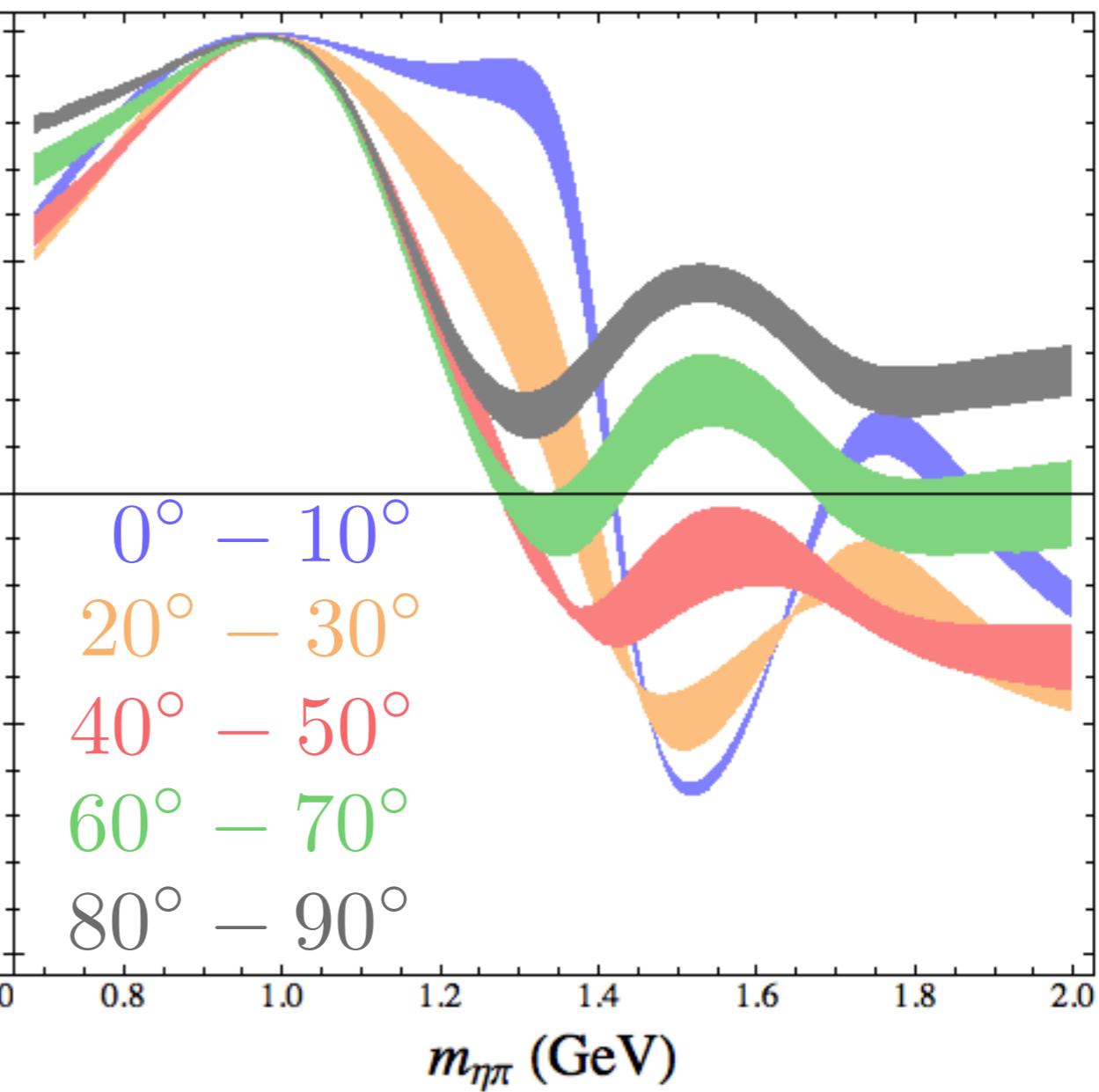


Beam Asymmetries: $\Sigma_{y \pm \delta^\circ}$

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:

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

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

$$\gamma p \rightarrow \eta \eta p$$

$$\gamma p \rightarrow \eta \eta' p$$

Future plan: partial wave analysis

