$\eta' - \pi$ production and search for exotic mesons at COMPASS and JLab12

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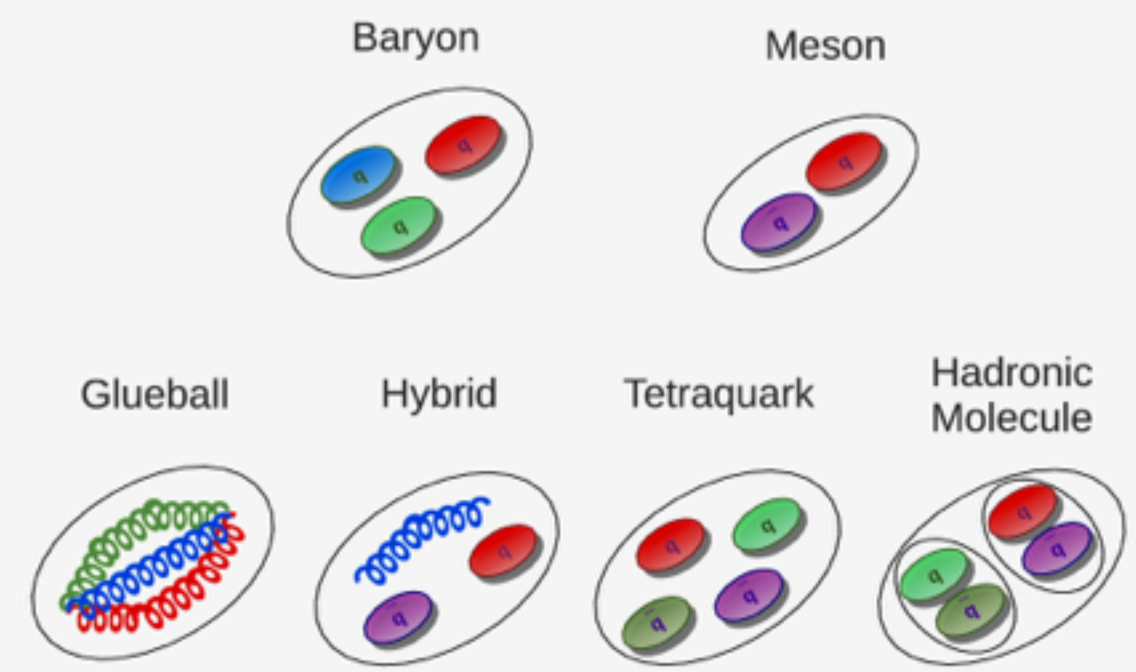
OUTLINE

- motivation and context: exotic states of *QCD spectrum*
- phenomenology and formalism: *peripheral meson production* @ GlueX & COMPASS
- data analysis: ηπ production @ COMPASS
- model and theoretical analysis: Regge *formalism* and *finite-energy sum rules* (FESR)
- *summary and outlook:* GlueX and *expectations*

QCD SPECTRUM AND EXOTIC HADRONS

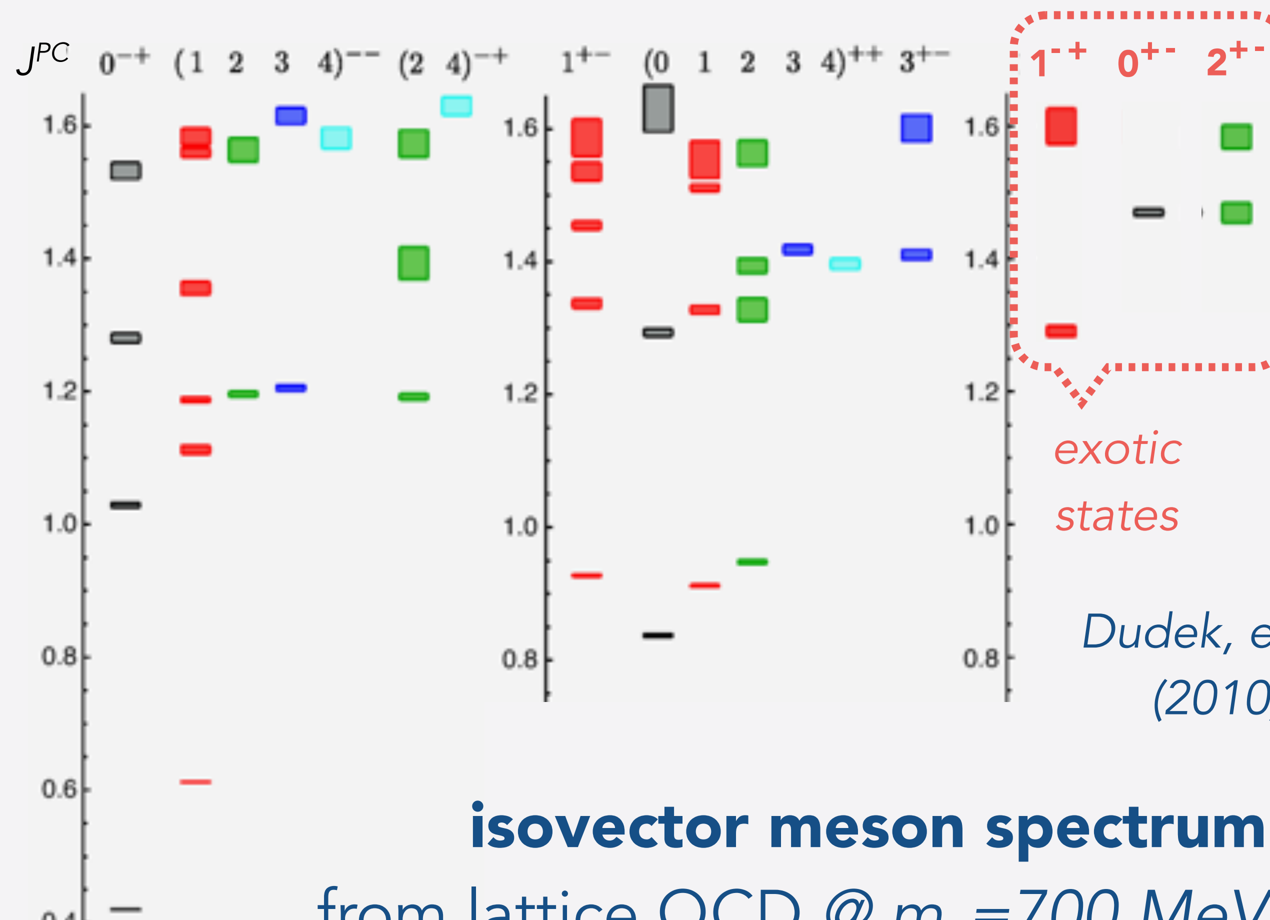


ordinary hadrons

color singlets

exotic hadrons

~300 states
only few
well-established



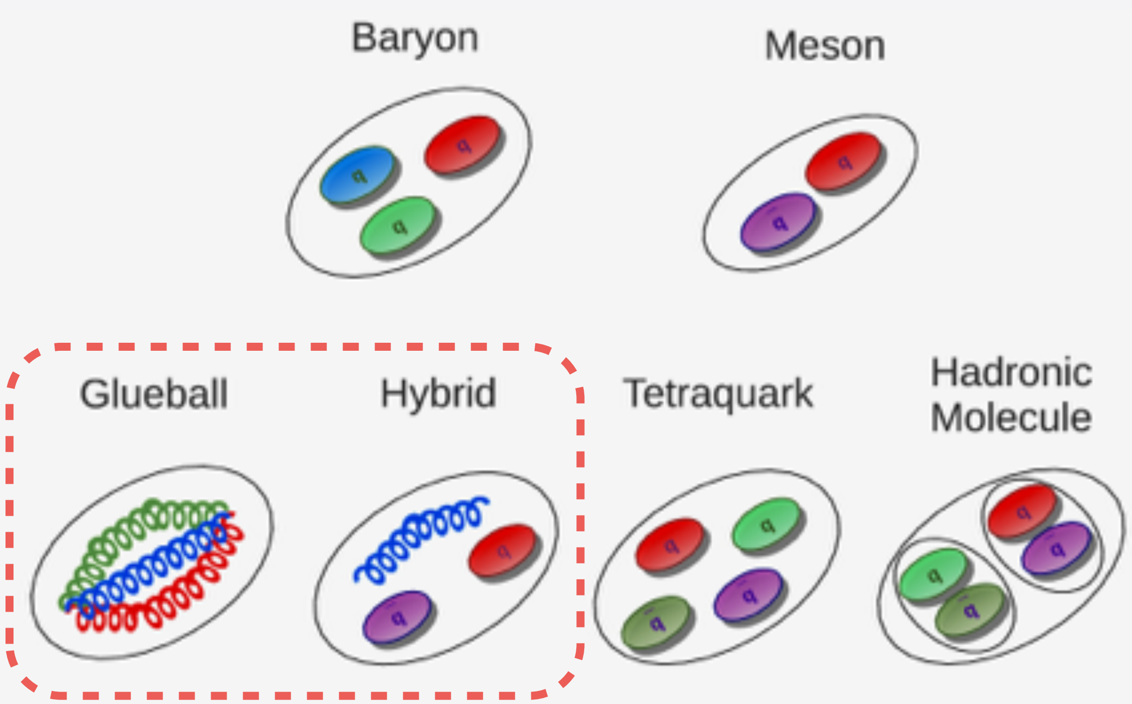
exotic states

Dudek, et al. (2010)

isovector meson spectrum

from lattice QCD @ m_π=700 MeV

QCD SPECTRUM AND EXOTIC HADRONS



gluon excitations

information about soft gluonic modes of QCD

expected *ground state*

exotic meson: $J^{PC} = 1^{-+}$

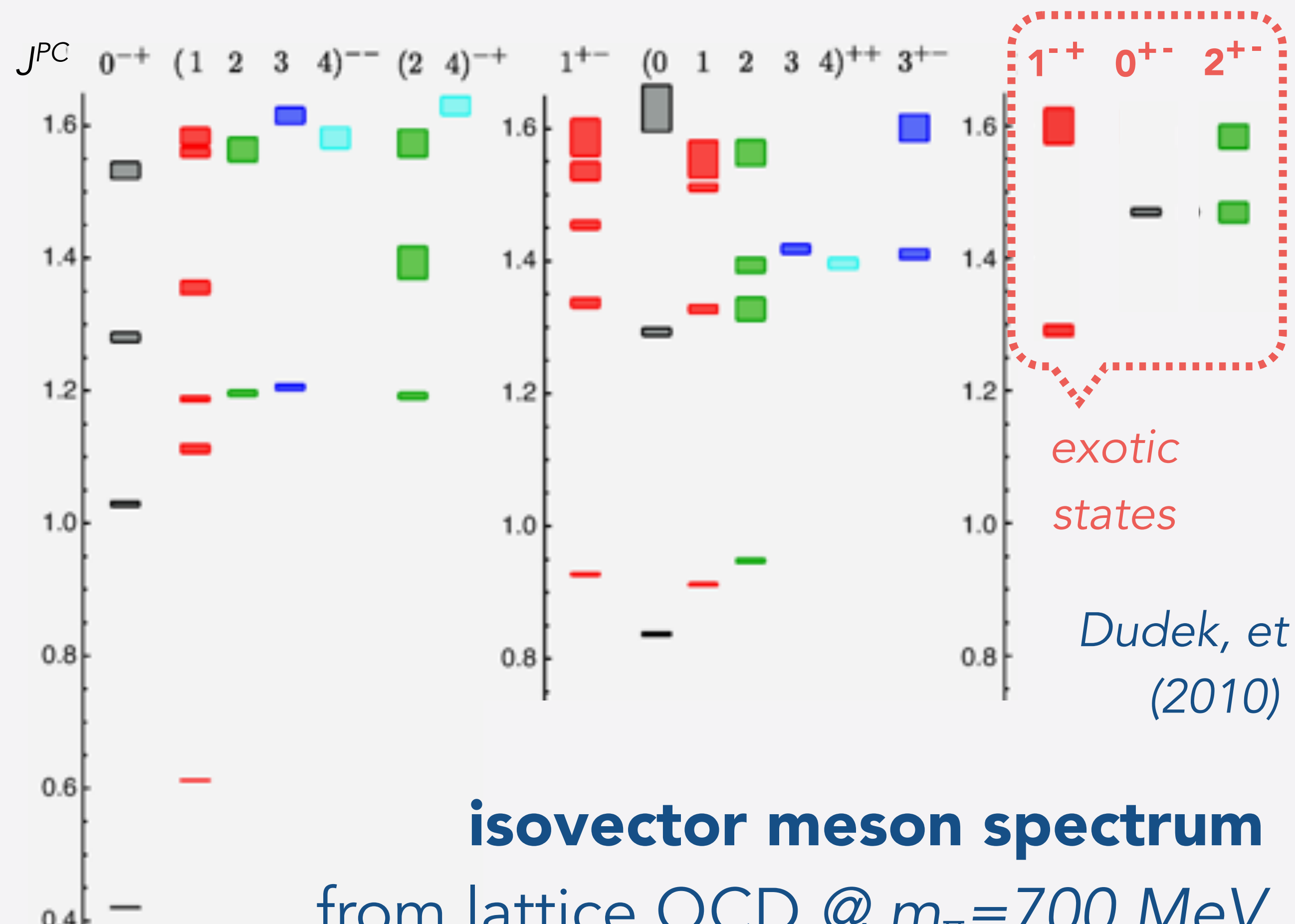
ordinary hadrons

~300 states

only few well-established

color singlets

exotic hadrons



Dudek, et al. (2010)

isovector meson spectrum

from lattice QCD @ m_π=700 MeV

$I^G J^{PC} = 1^- 1^{-+}$

decay modes

$\pi\eta, \pi\eta', \pi\rho, \pi a_1, \pi b_1, \pi f_1$

SEARCHES FOR HYBRIDS IN PERIPHERAL PRODUCTION -3-

$I^G J^{PC} = 1^- 1^{-+}$ $\xrightarrow{\text{decay modes}}$ $\pi\eta,\ \pi\eta',\ \pi\rho,\ \pi a_1,\ \pi b_1,\ \pi f_1$

$\pi_1(1400)$ $\xrightarrow{\text{decay}}$ $\pi\eta$
- $\pi^- p \to \pi^- \eta p$ — **E852**, GAMS, KEK, VES
- $\bar{p} n \to \eta \pi^- \pi^0$ — **Crystal Barrel**

$\pi_1(1600)$ $\xrightarrow{\text{decay}}$ $\pi\eta',\ \pi\rho$
- $\pi^- p \to \pi^- \eta' p$ — **E852**
- $\pi^- p \to \pi^- \rho^0 p$ — **VES, E852** controversial!

$\pi_1(2015)$ $\xrightarrow{\text{decay}}$ $\pi b_1,\ \pi f_1$
- $\pi^- p \to \pi^- b_1 p$ — **E852**

SEARCHES FOR HYBRIDS IN PERIPHERAL PRODUCTION -3-

$I^G J^{PC} = 1^- 1^{-+}$ $\xrightarrow{\text{decay modes}}$ $\pi\eta$, $\pi\eta'$, $\pi\rho$, πa_1, πb_1, πf_1

$\pi_1(1400) \xrightarrow{\text{decay}} \pi\eta$

- $\pi^- p \to \pi^- \eta p$ — **E852**, GAMS, KEK, VES
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$\pi_1(2015) \xrightarrow{\text{decay}} \pi b_1, \pi f_1$

- $\pi^- p \to \pi^- b_1 p$ — **E852**

$\pi_1(1400)$?
$\pi_1(1600)$

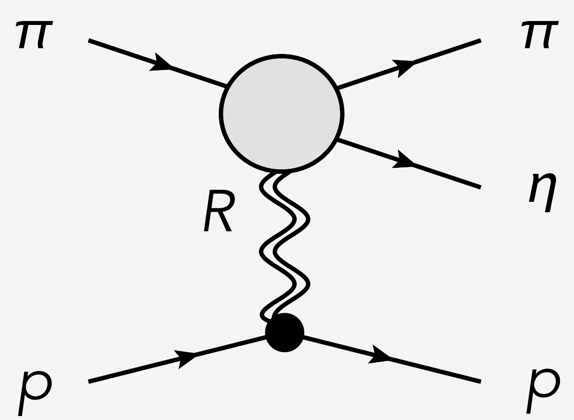
$\pi p \to X p \to \eta^{(\prime)} \pi p$ — **COMPASS** on 191 GeV pion beam @ CERN

NEW data

Forthcoming data

$\gamma p \to X p \to \eta^{(\prime)} \pi p$ — **GlueX** on 12 GeV electron beam @ JLab

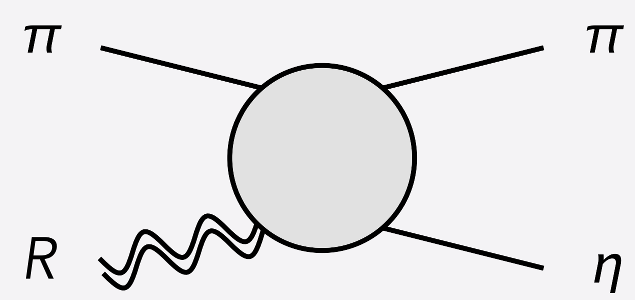
@ large energy



Regge exchange

$$A_{\pi p \to \pi \eta p} = R\, A_{\pi R \to \pi \eta}$$

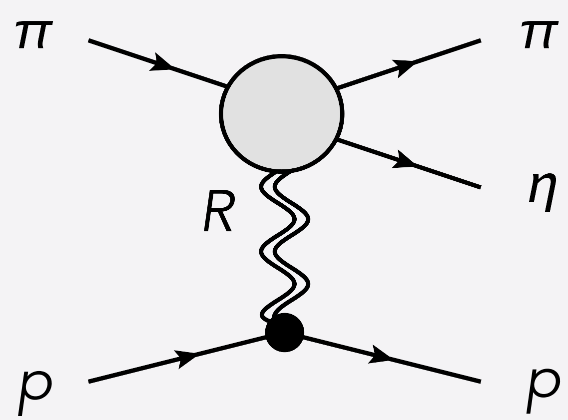
factorization



Reggeon-particle amplitude

PERIPHERAL PRODUCTION IN REGGE MODEL

@ large energy



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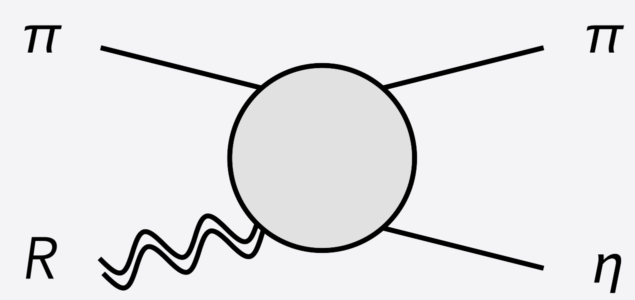


Reggeon-particle amplitude

well-defined quantum numbers for each *Regge exchange*

discontinuity **only**
in the ***s-channel invariant mass***

↓

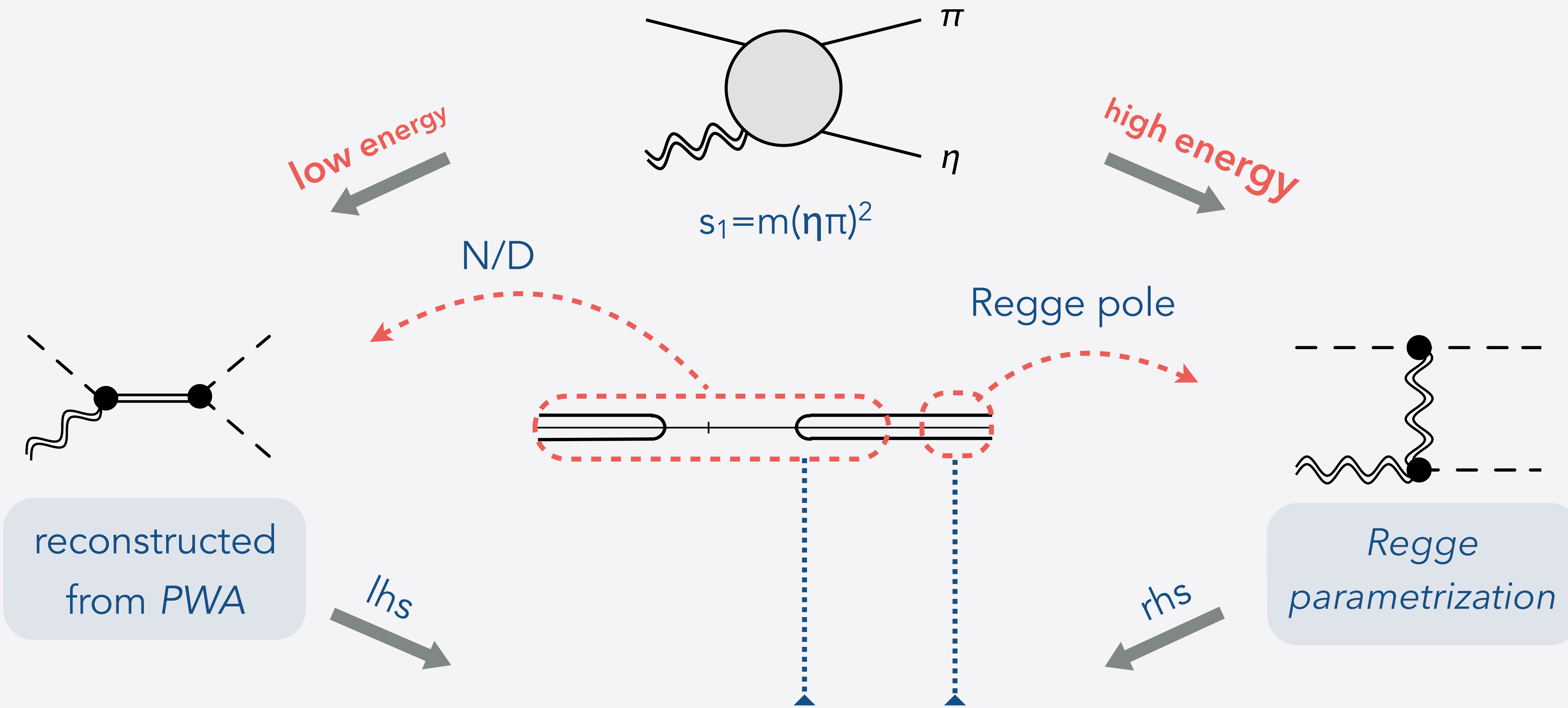
dispersion relation at fixed t

no *overlapping discontinuities*
in invariant masses

↓

Reggeization

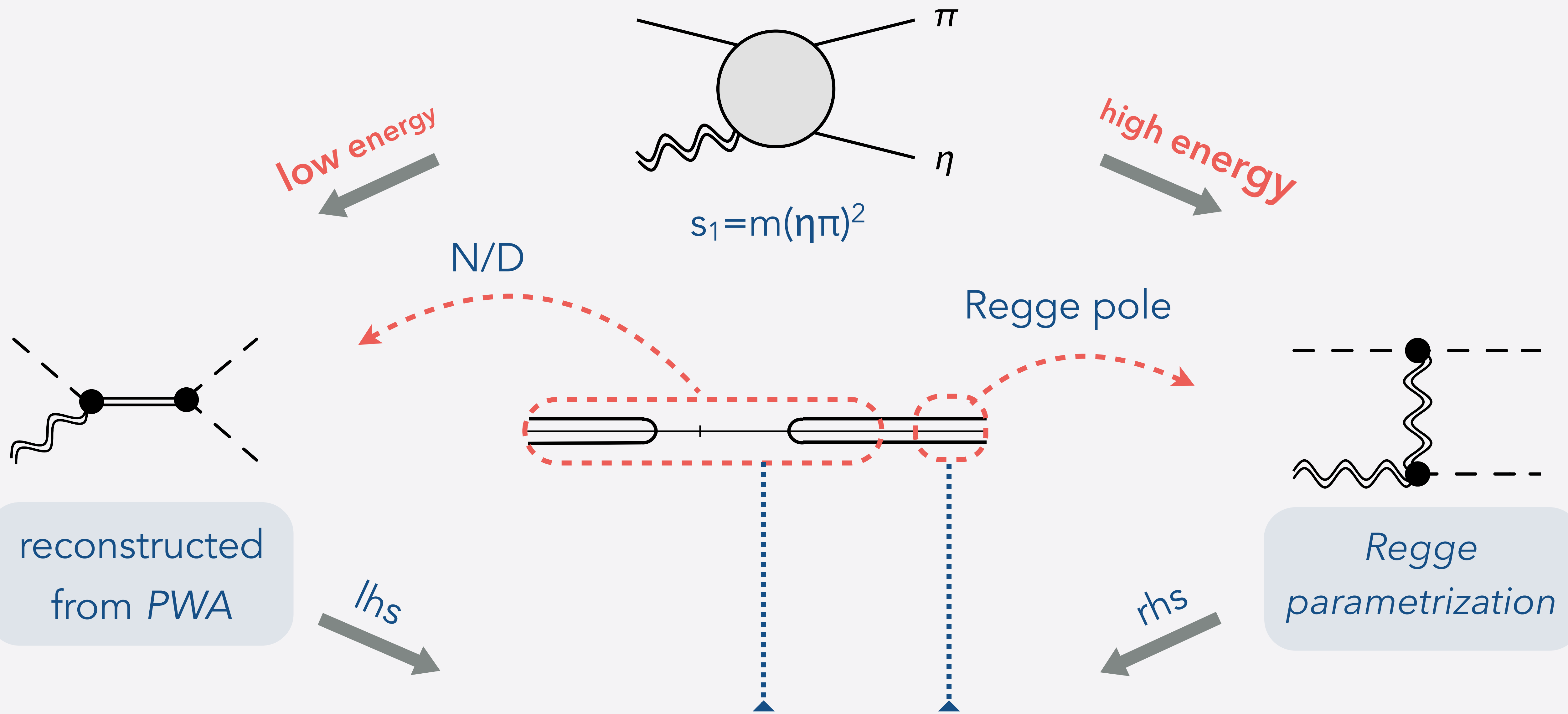
FINITE ENERGY SUM RULES



$$0 = \oint \mathrm{d}s\, A(s) - A^R(s)$$

Cauchy integral theorem

FINITE ENERGY SUM RULES

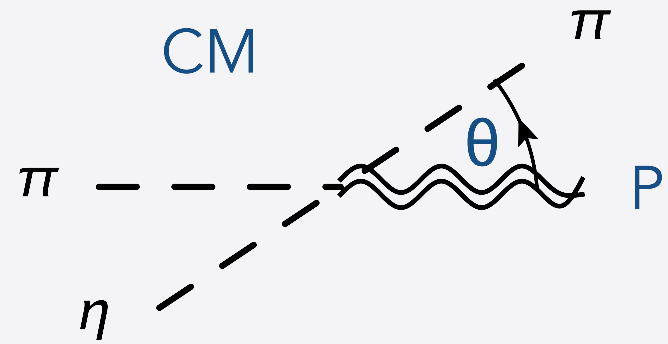


$$\int_0^N \mathrm{d}s\,\mathrm{Im}\,A(s) = N^{\alpha+1}V$$

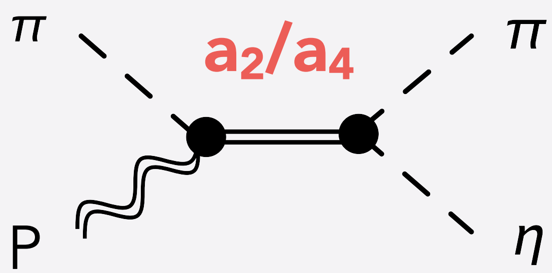
<u>aim</u>: *first systematic analysis of* ***peripheral production*** *using* ***FESR***

PHENOMENOLOGY OF $\eta\pi$ PRODUCTION AT COMPASS

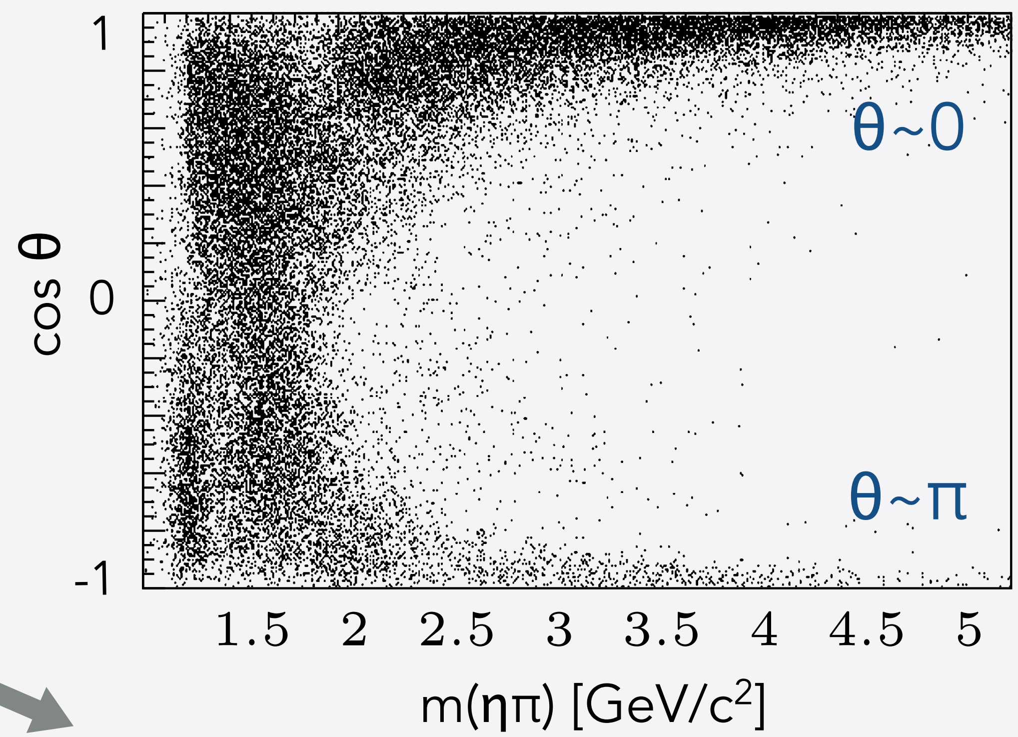
CM



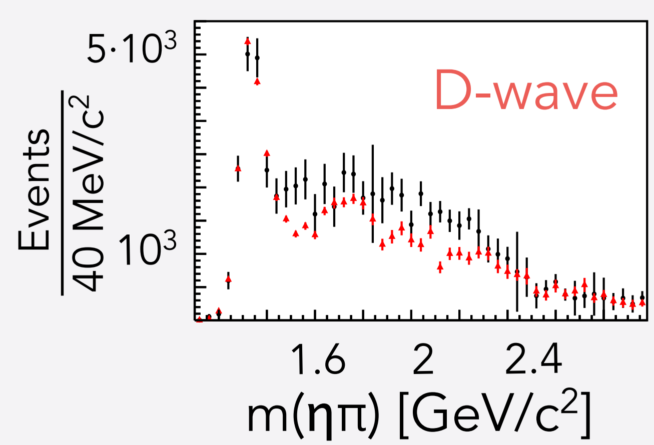
$m(\eta\pi) < 3\ (GeV/c^2)^2$



PWA



ηπ vs η′π



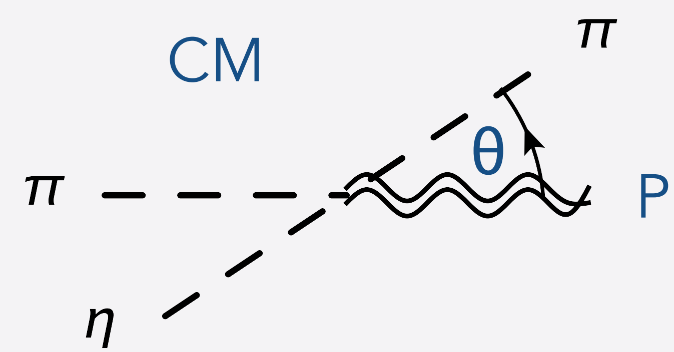
COMPASS coll. (2015)

a_2 (1320)

a_4 (2040)

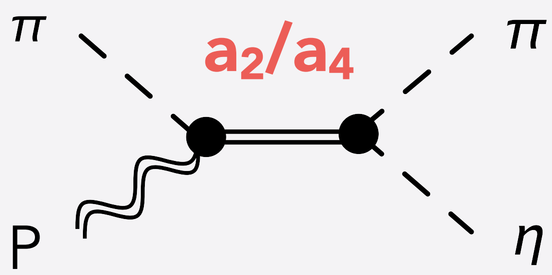
PHENOMENOLOGY OF $\eta\pi$ PRODUCTION AT COMPASS

CM

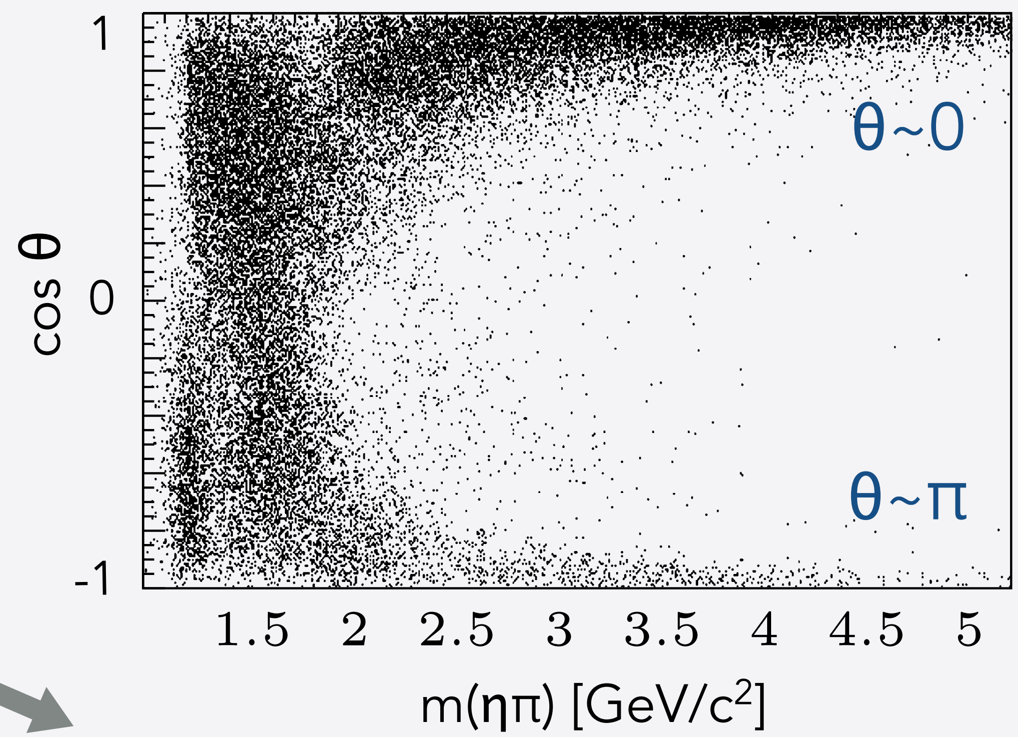


$m(\eta\pi) < 3\ (GeV/c^2)^2$

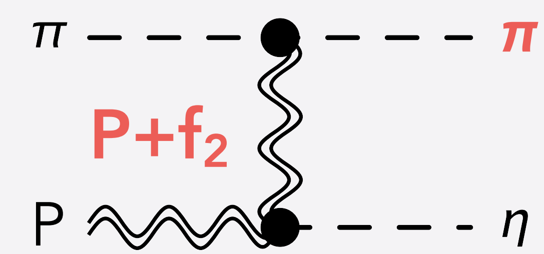
$m(\eta\pi) \in [5\text{-}6]\ (GeV/c^2)^2$



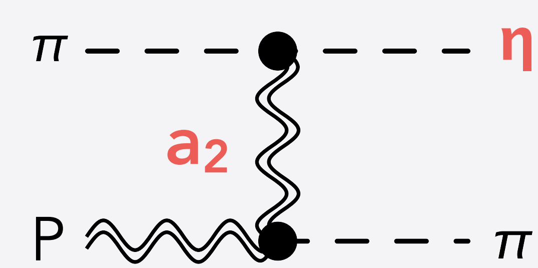
PWA



fwd π

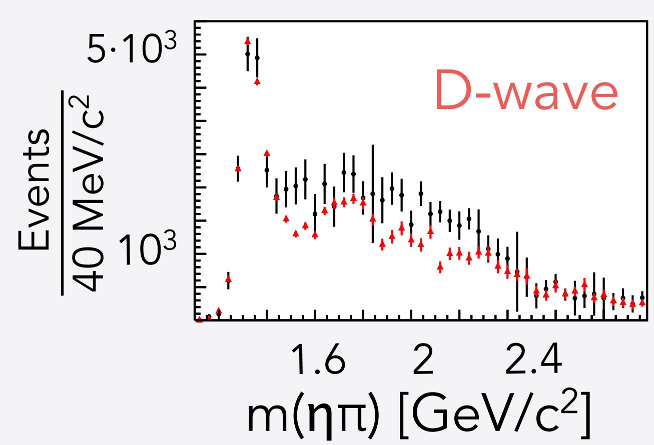


fwd η



$\eta\pi$ vs $\eta'\pi$

COMPASS coll.
(2015)

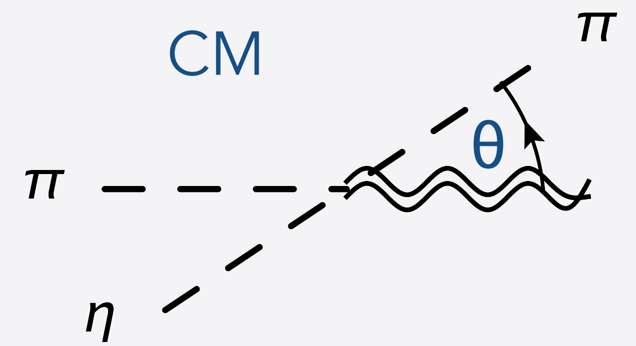


a_2 (1320)

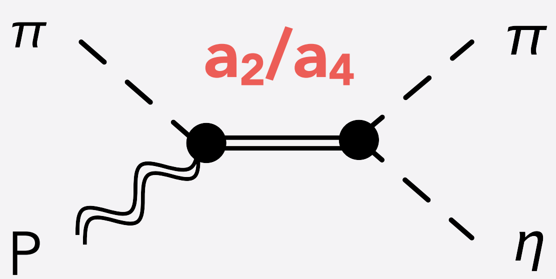
a_4 (2040)

$m(\eta\pi) < 3\ (\mathrm{GeV}/c^2)^2$

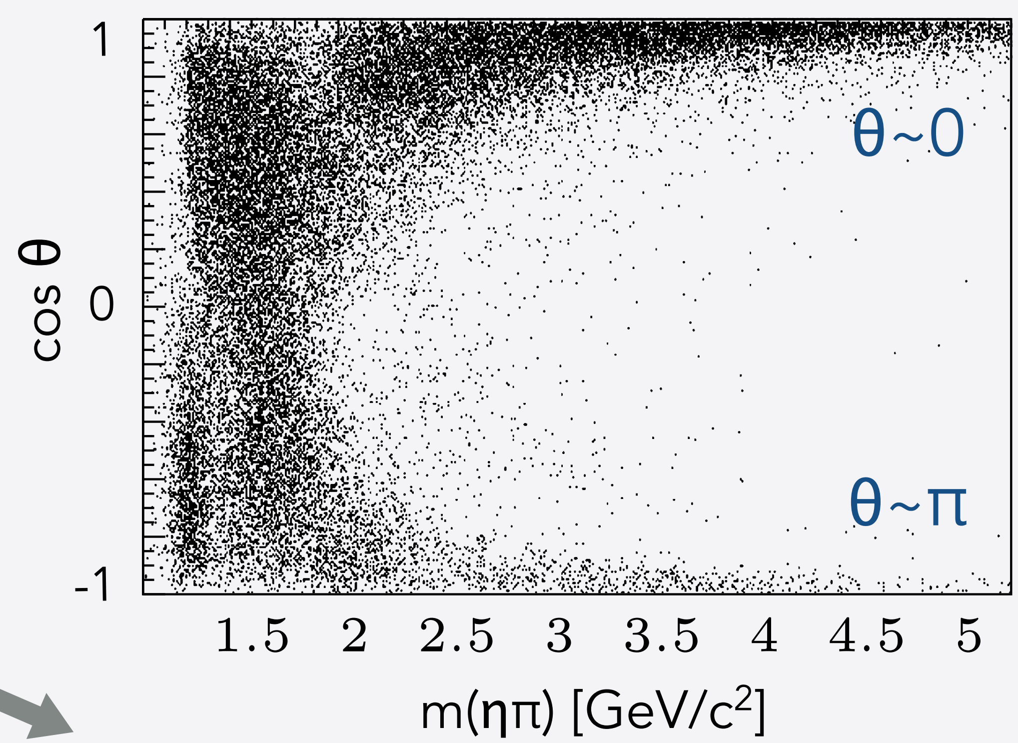
CM



$m(\eta\pi) \in [5\text{-}6]\ (\mathrm{GeV}/c^2)^2$

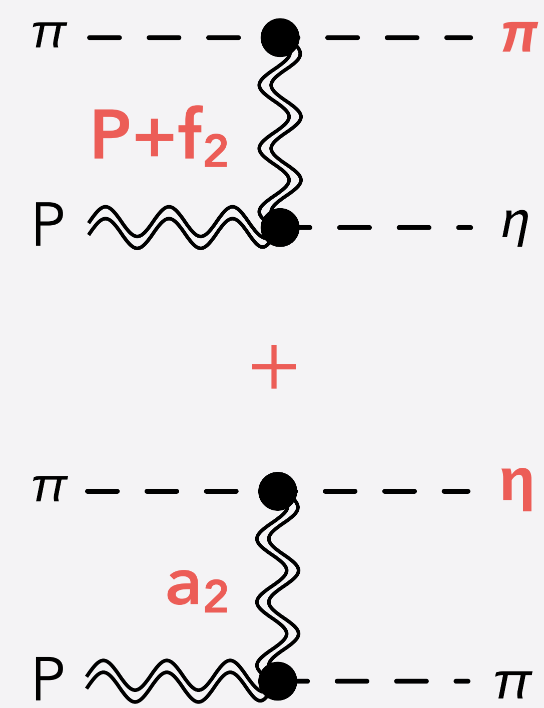


PWA



fwd π

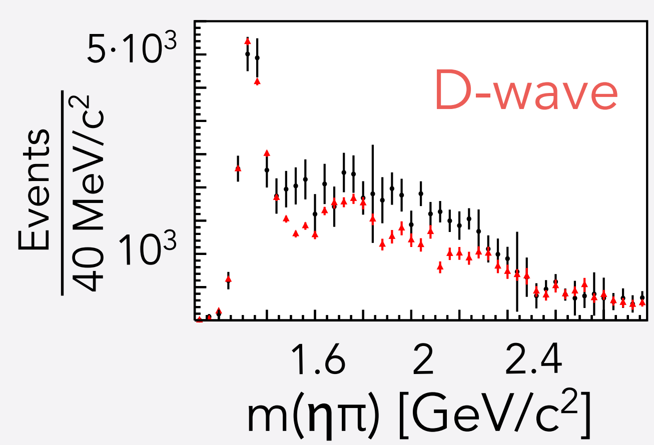
fwd η



$= \Sigma$ even waves

(D+G-waves)

ηπ vs η'π

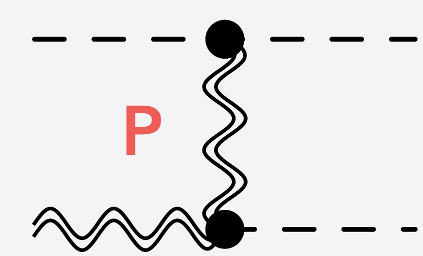


COMPASS coll.
(2015)

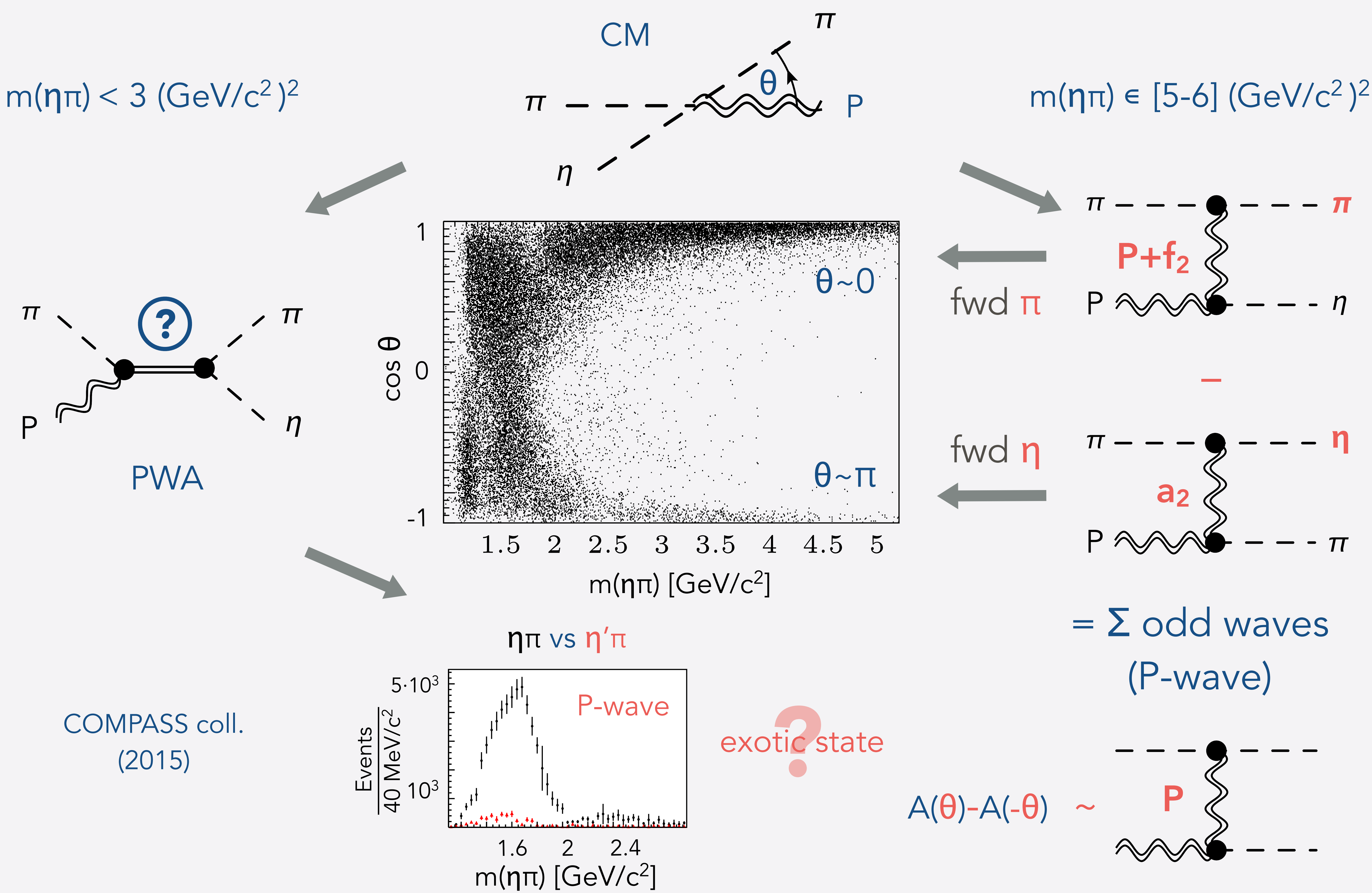
a_2 (1320)

a_4 (2040)

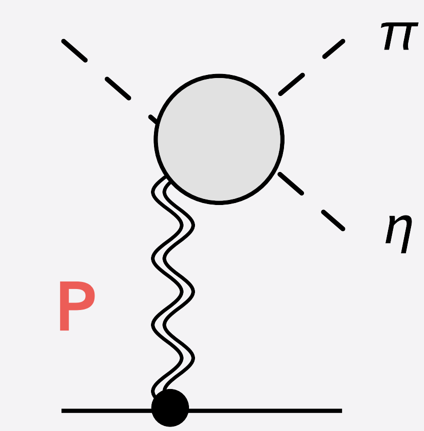
$A(\theta)+A(-\theta)$ ~



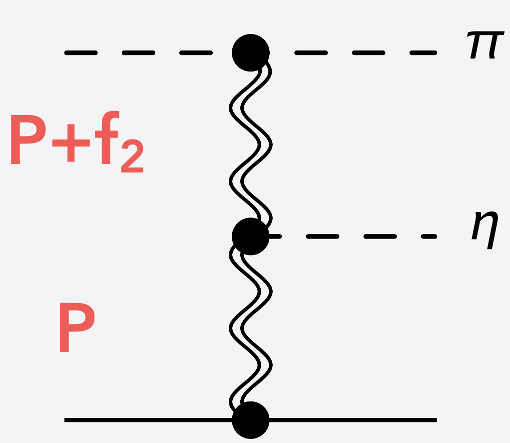
PHENOMENOLOGY OF $\eta\pi$ PRODUCTION AT COMPASS



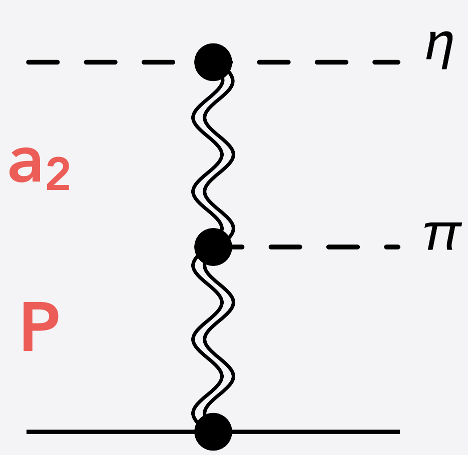
SINGLE AND DOUBLE REGGE LIMITS

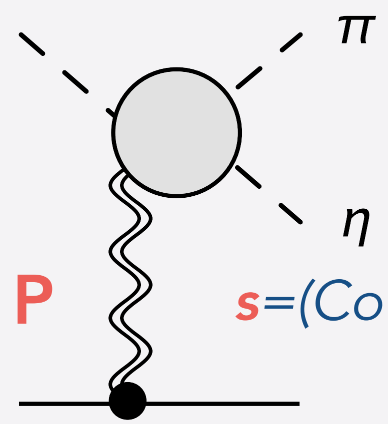


Single-Regge limit



Double-Regge limit





$s_1 = m(\eta\pi)^2$

s=(CoM energy)^2

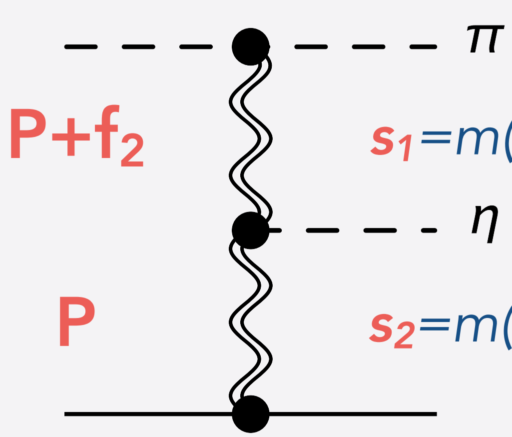
Single-Regge limit

$$A = K\,R(s) \sum_{J,\lambda} \frac{N_J(s_1)}{D_J(s_1)}\, d^J_{\lambda 0}(\theta) e^{i\lambda\phi}$$

Gottfried-Jackson angles

$$\cos\theta = a' + b' t_1 + c t_1^2$$
$$\cos\phi = a + b\frac{s_2}{s}$$

t_1 - (beam mom. transfer)^2



$s_1 = m(\eta\pi)^2$

$s_2 = m(p\eta)^2$

Double-Regge limit

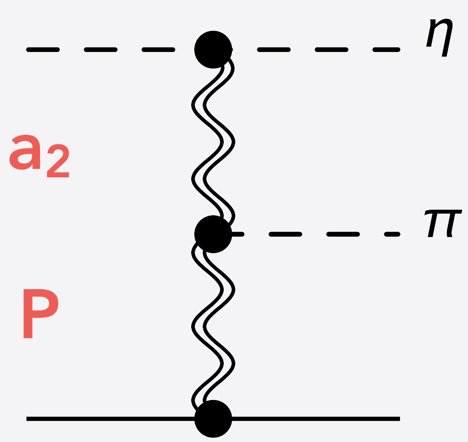
forward π amplitude

$$A^R_t = K\,R(s_1, t_1) R(s_2) V(\omega)$$

Toller angle

$$\cos\omega \approx \frac{s_1 s_2}{s}$$

u_1 - (beam mom. transfer)^2



forward η amplitude

$$A^R_u = K\,R(s_1, u_1) R(s_2) V(\omega)$$

CONSTRAINTS AND EXPECTATIONS

conservation of parity and angular momentum

$$A_L \to K_L A_L$$

threshold behavior

$$K_L \sim q^L$$

$$q = \sqrt{(s_1 - (m_\pi + m_\eta)^2)(s_1 - (m_\pi - m_\eta)^2)}$$

partial-wave amplitudes

$$A_L = \int A(\Omega)\, Y_L(\Omega)\, \mathrm{d}\Omega$$

L - *orbital angular momentum*

Pomeron exchange contribution

$$A \sim s_1 e^{\alpha' t \log s_1}$$

asymptotic behavior of the *P-wave*

$$A_1 \sim \frac{1}{\log s_1}$$

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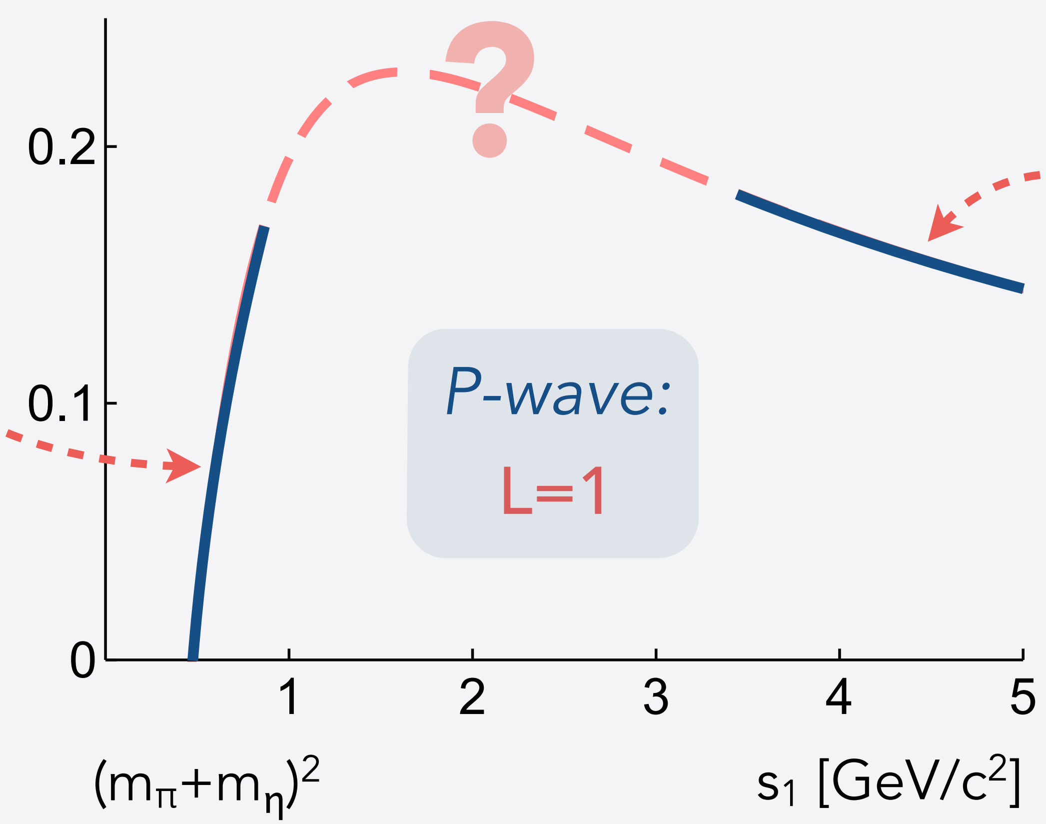

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asymptotic behavior of the *P-wave*

$$A_1 \sim \frac{1}{\log s_1}$$

normalization constrained by ***sum rules***

FINITE-ENERGY SUM RULE

FESR for ***forward-backward asymmetry***

$$\int_0^N \mathrm{d}s_1 \, \mathrm{Im}\, A_{even/odd}(s_1) = \sum_R N^{\alpha_R} V_R$$

symmetric combination:
non-exotic
even partial waves
exchanges: **$P+f_2+a_2$**

antisymmetric combination:
exotic
odd partial waves
exchanges: **$P+f_2-a_2$**

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symmetric combination:
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antisymmetric combination:
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odd partial waves
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expansion in powers of **s_2/s**

$$V(\omega) = \sum_i V^{(i)} \left(\frac{s_2}{s}\right)^i \longrightarrow \int_0^N \mathrm{d}s_1 \, \mathrm{Im}\, A_L(s_1) = \sum_{R,i} C_L^{(i)}(N) V_R^{(i)}$$

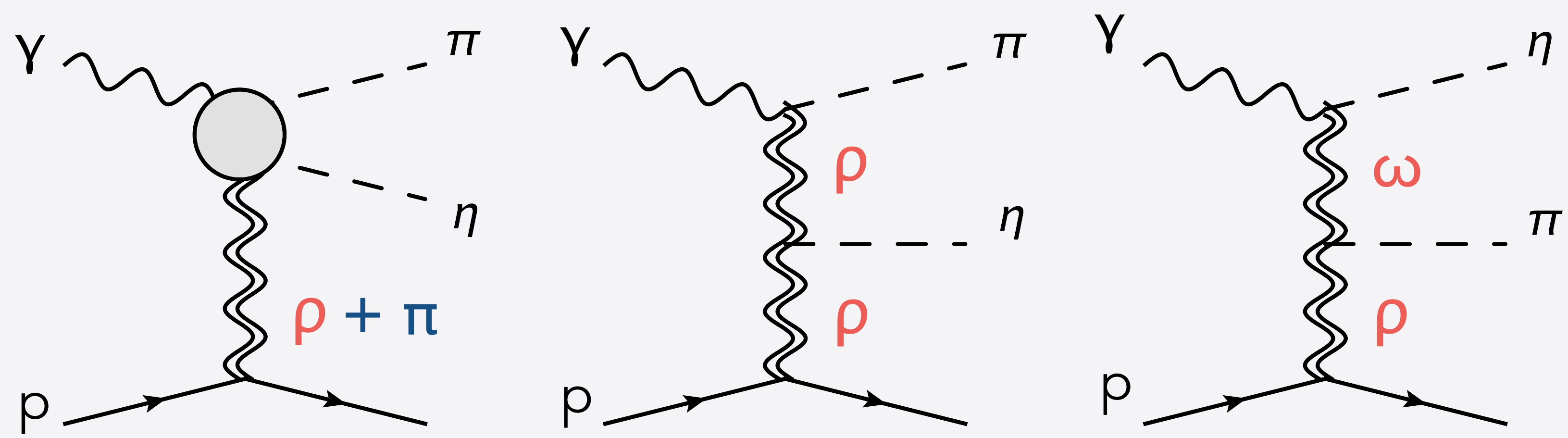
coherent contributions from ***larger angular momenta*** $\xrightarrow{\textit{stabilize}}$ truncated ***PW series***

SUMMARY & OUTLOOK

photoproduction

@ GlueX

γp→Xp→πηp



SUMMARY & OUTLOOK

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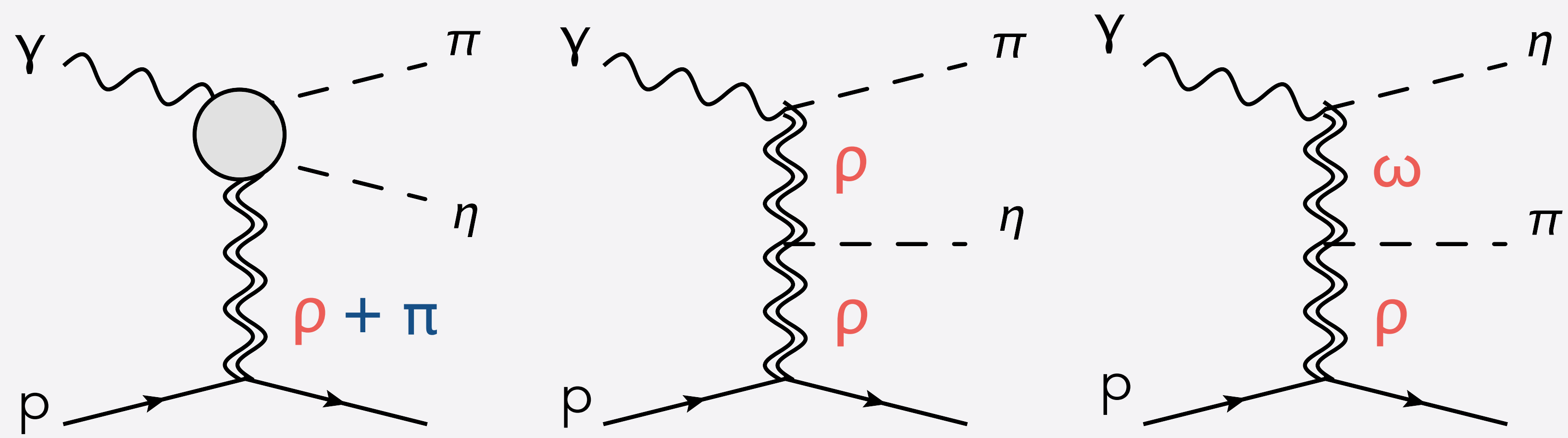
$\gamma p \to X p \to \pi\eta p$

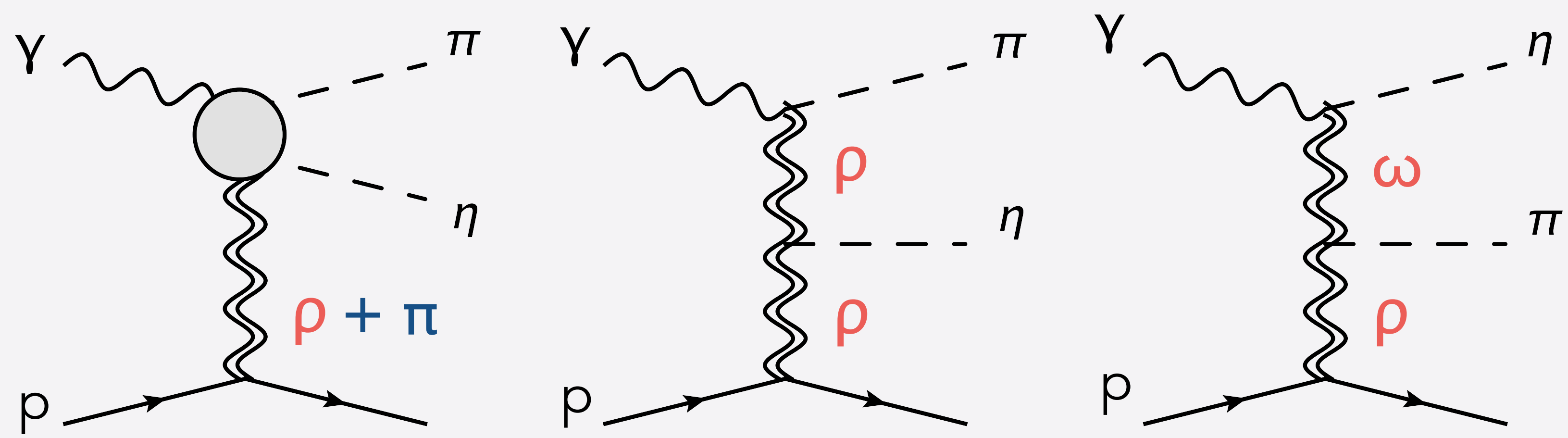


- construct *fitting functions* for the ***single-*** *and* ***double-diffractive*** regime using ***Regge formalism***; parametrize the *low-energy* amplitude within ***N/D formalism***
- extract the *parameters* of the ***reggeon-particle amplitude***
- analyze *correlation* between ***low-*** *and* ***high-energy*** regions using ***FESR***

SUMMARY & OUTLOOK

photoproduction
@ GlueX

$\gamma p \rightarrow Xp \rightarrow \pi\eta p$



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expectations

- non-trivial *correlation* between *production* of ***exotic states*** and violation of ***exchange degeneracy***
- *sensitivity* to the ***gluon component of*** η'