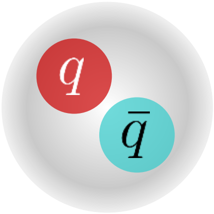
Light meson photoproduction with Regge theory: advancing hybrid meson searches at GlueX

Glòria Montaña

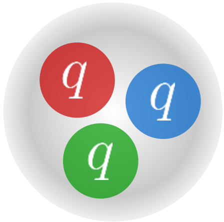
IJCLab PHE Seminar
March 2, 2026

Exotic hadrons

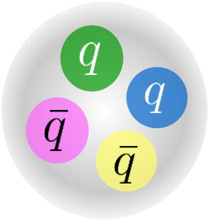
Mesons and baryons aren't the only states allowed by QCD



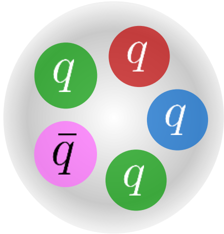
meson



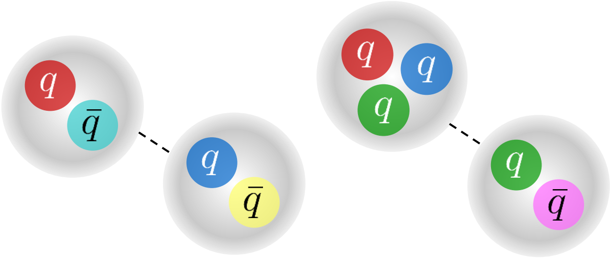
baryon



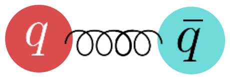
tetraquark



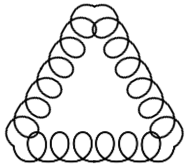
pentaquark

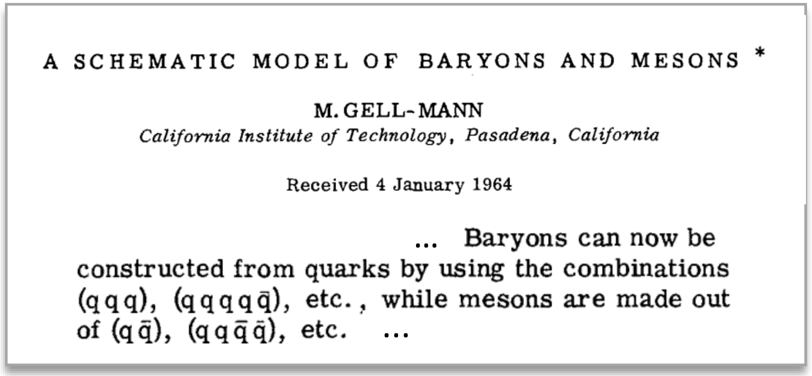


hadronic molecules



hybrid meson


glueball

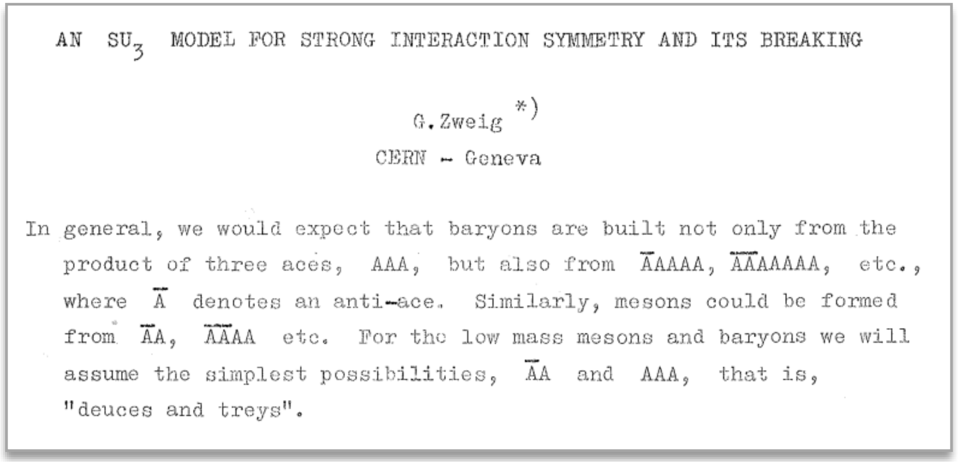

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

... Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. ...

Phys.Lett. 8, 214 (1964)


AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

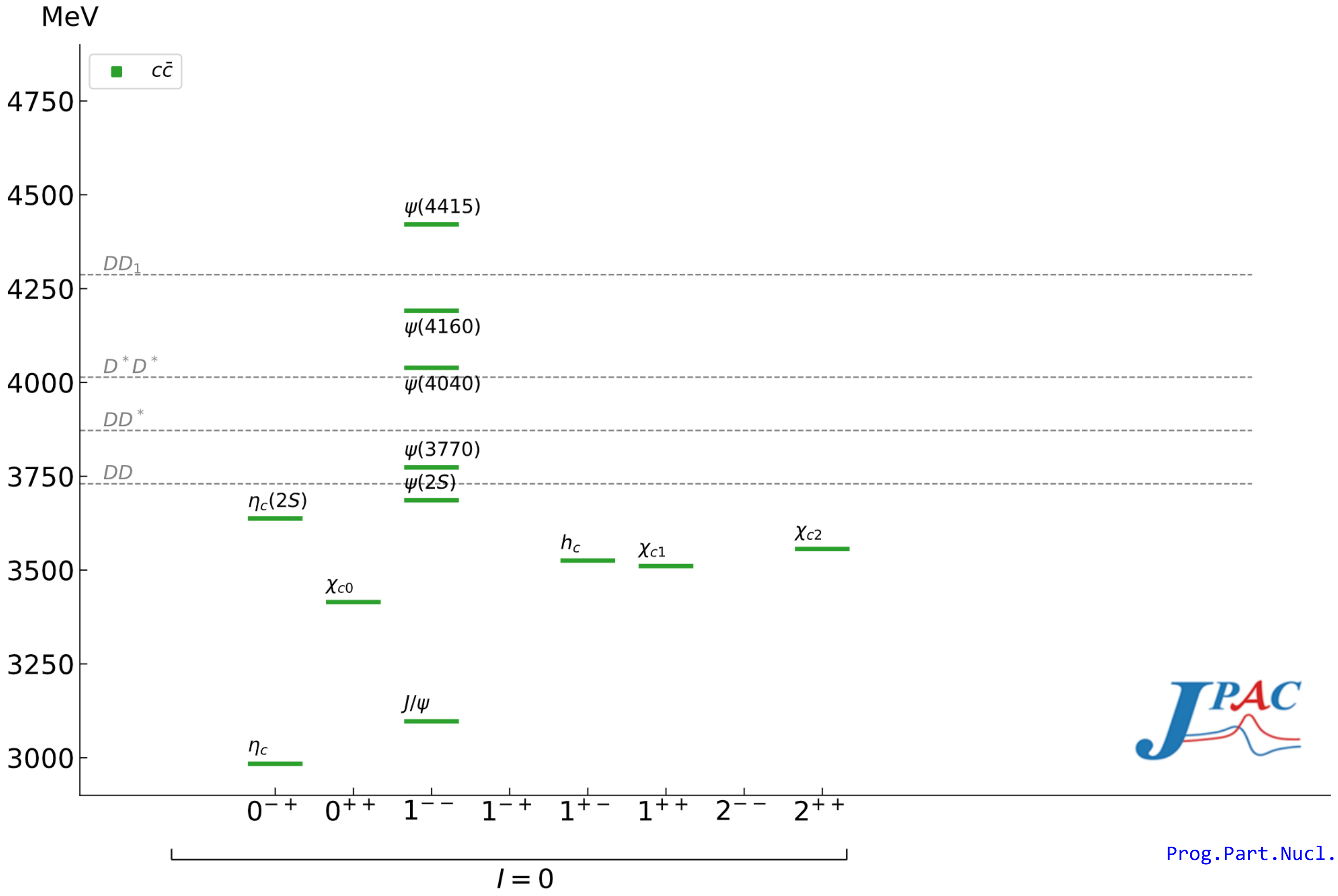
In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

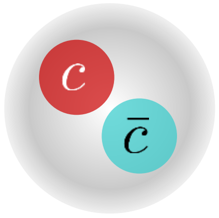
CERN-TH-401 (1964)

Hybrid mesons (with valence gluons) ➜ insight into the gluon dynamics in the nonperturbative regime

Heavy hadron spectroscopy: XYZP$_c$

Before 2003 …





charmonia states

Prog.Part.Nucl.Phys. 127, 103981 (2022)

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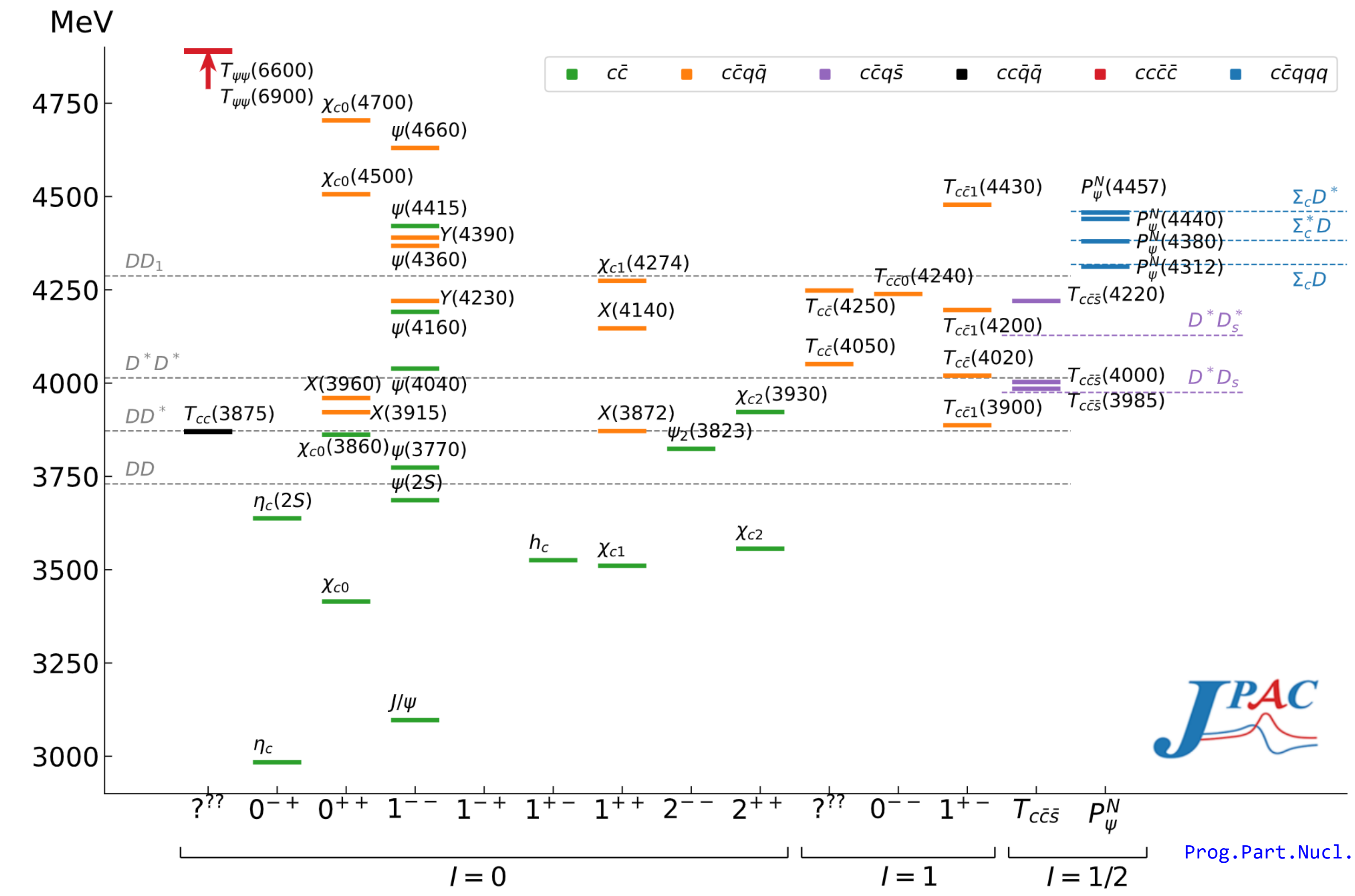

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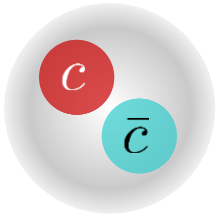

charmonia states

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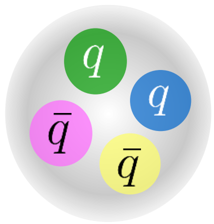

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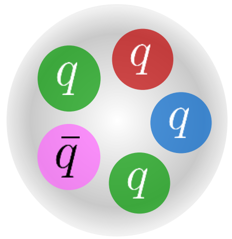

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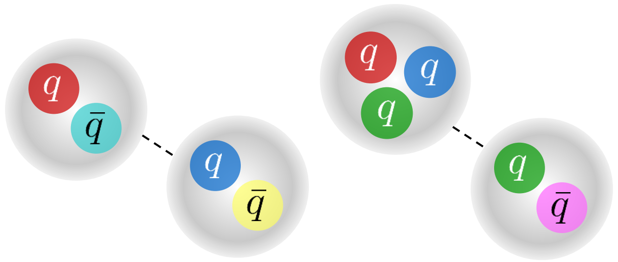

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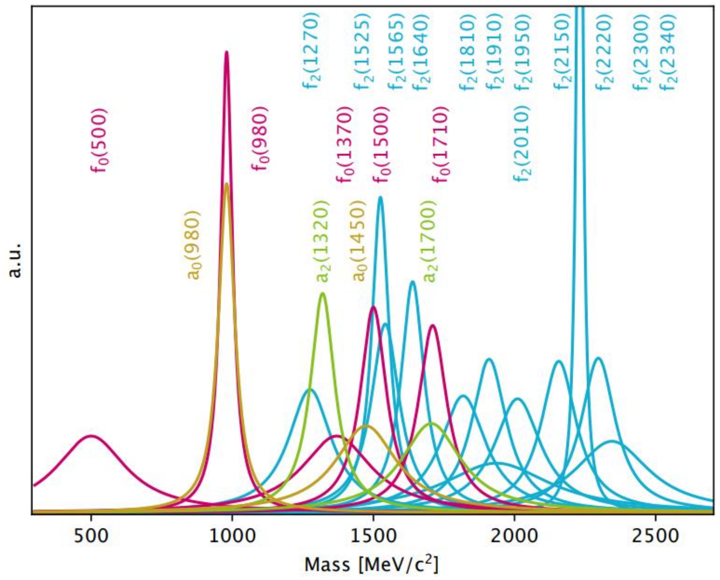
Light meson spectroscopy

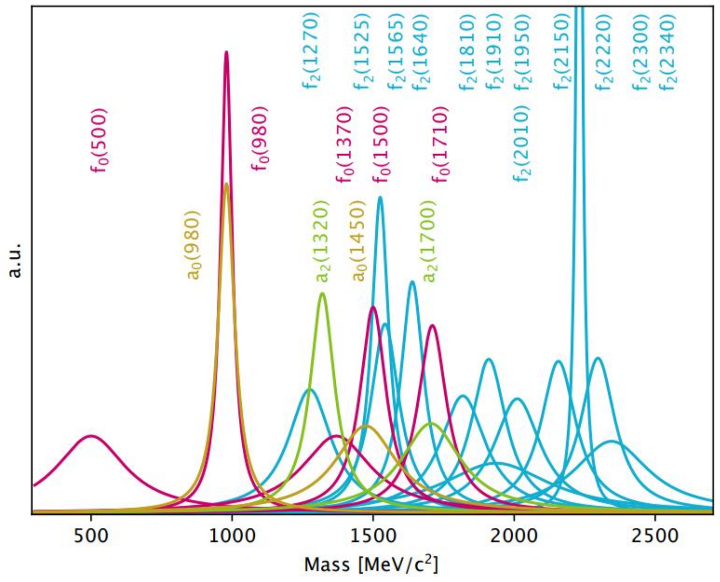


Experimental challenges:

✳ Many wide and overlapping states

✳ Need complicated partial wave analysis (PWA) techniques

Light meson spectroscopy



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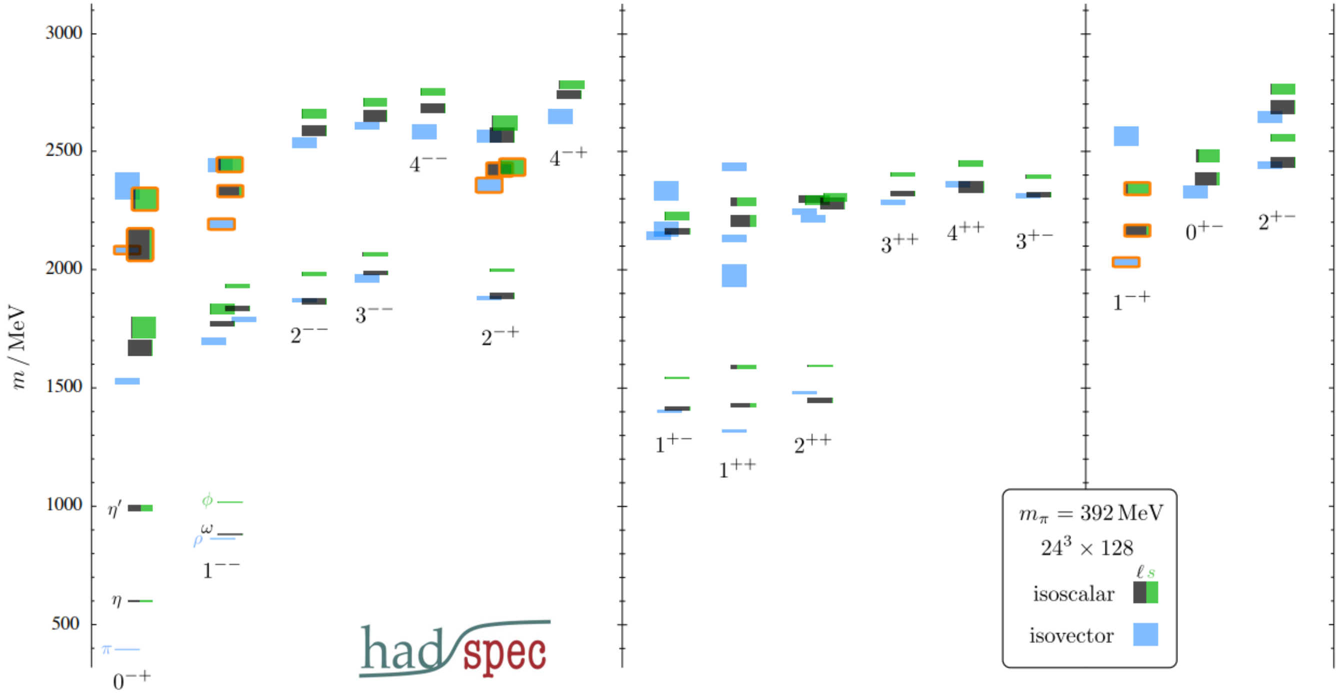
Lattice QCD predictions:

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



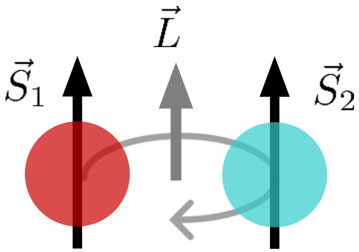
Exotic quantum numbers

Quantum numbers:

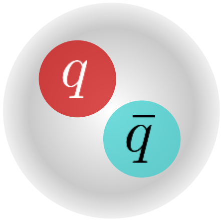
$$\vec{J} = \vec{L} \otimes \vec{S} \quad , \qquad \vec{S} = \vec{S}_1 \otimes \vec{S}_2$$

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

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



Conventional $q\bar{q}$ mesons:



$$J^{PC} \quad \left\{ \begin{array}{cccc} & 0^{++} & 0^{-+} & \\ 1^{--} & 1^{++} & & 1^{+-} \\ 2^{--} & 2^{++} & 2^{-+} & \\ 3^{--} & 3^{++} & & 3^{+-} \\ \vdots & \vdots & \vdots & \vdots \end{array} \right.$$

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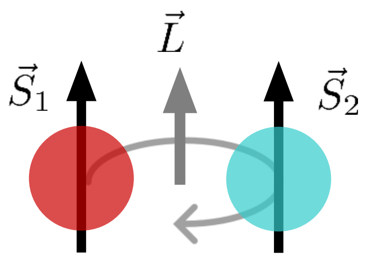

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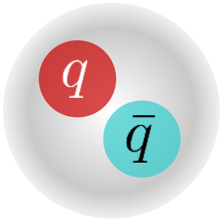
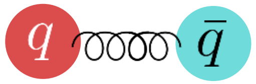


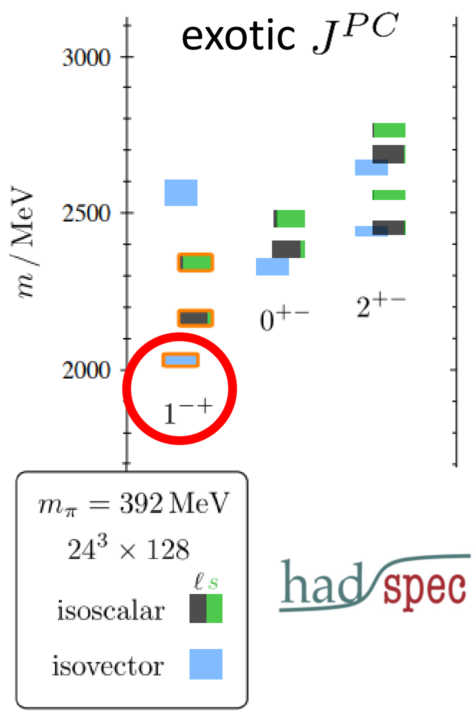
J^{PC}

0^{--}	0^{++}	0^{-+}	0^{+-}
1^{--}	1^{++}	1^{-+}	1^{+-}
2^{--}	2^{++}	2^{-+}	2^{+-}
3^{--}	3^{++}	3^{-+}	3^{+-}
$\vdots$	$\vdots$	$\vdots$	$\vdots$

Hybrid mesons



∗ Predictions from lattice QCD:



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

∗ Gluonic fields in hybrid mesons give rise to states with **"exotic" quantum numbers** (not allowed for $q\bar{q}$)

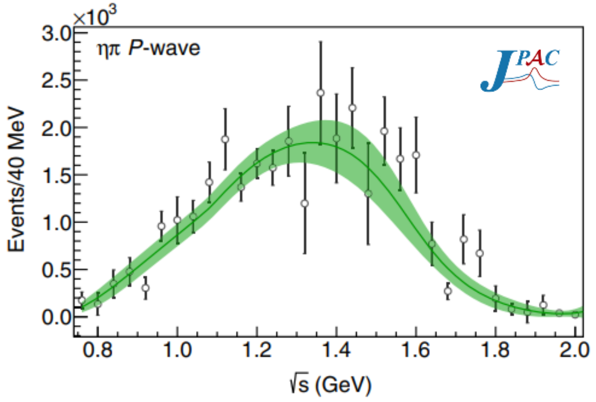
→ "Smoking gun" to find exotic mesons!

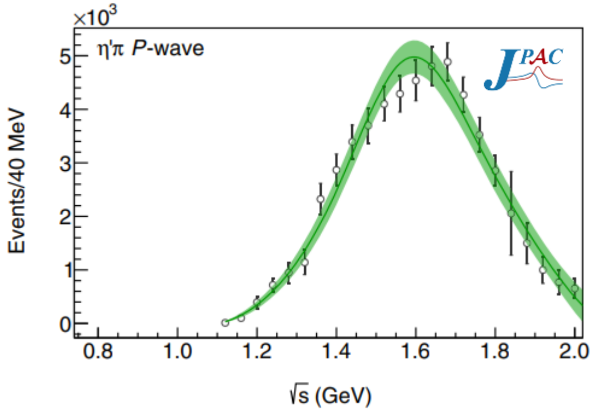
The $\pi_1(1600)$

Best experimental evidence from COMPASS with a pion beam

Historically, two 1^{-+} isovector candidates: $\pi_1(1400)$ and $\pi_1(1600)$

Data:
Phys.Lett.B 740, 303 (2015)





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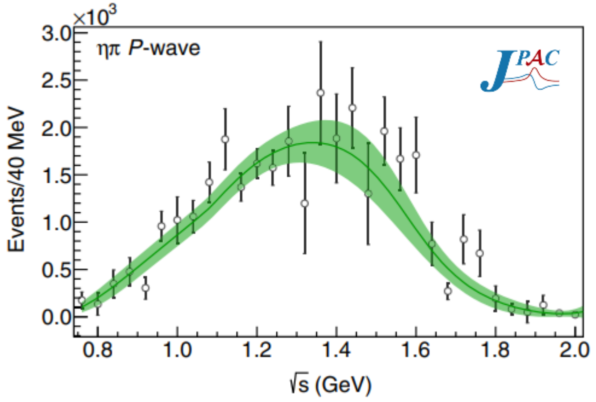
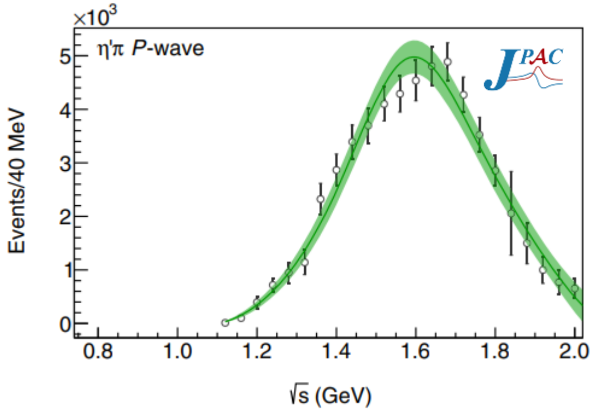
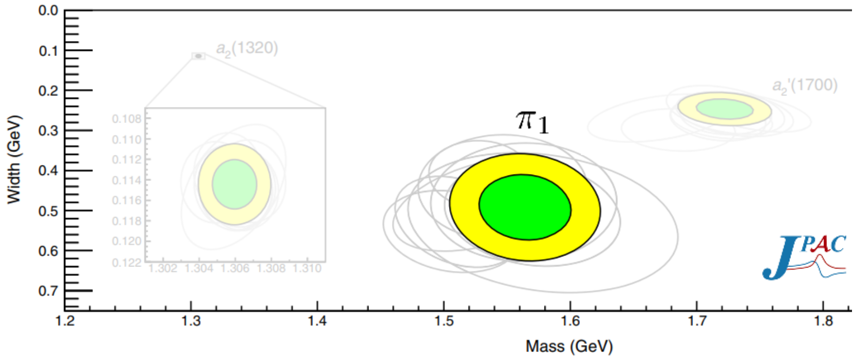




✳ Coupled-channel analysis by JPAC:

→ Data is consistent with **a single resonance pole**

A.Rodas et al., Phys.Rev.Lett. 122, 042002 (2019)



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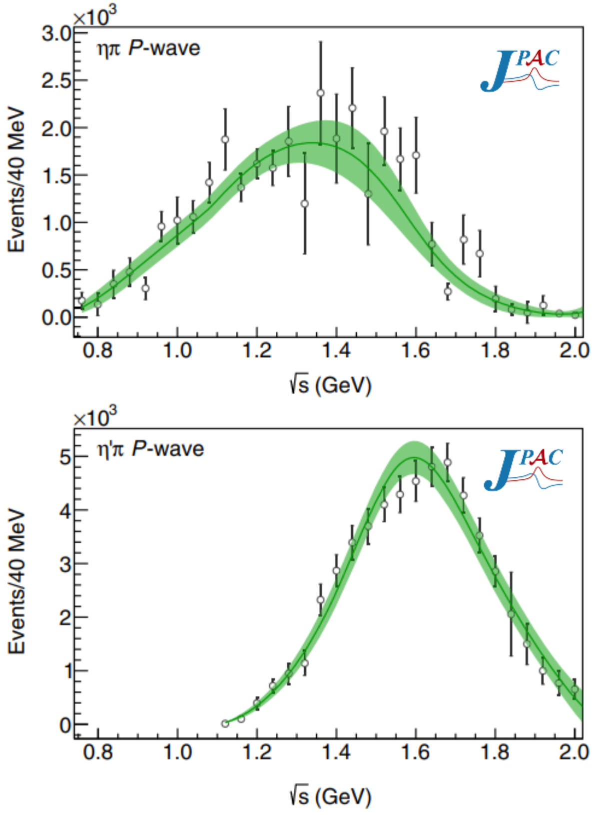

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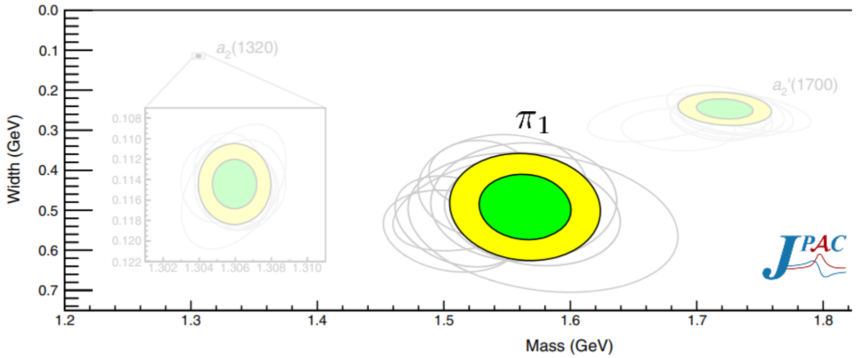
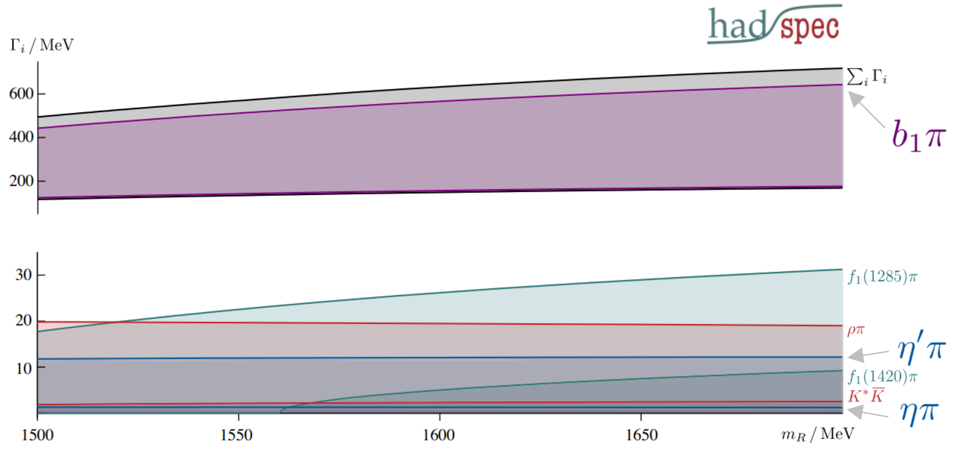


✳ Confirmed by HadSpec:

→ Also provided decay rates

A.Woss et al., Phys.Rev.D 103 5, 054502 (2021)



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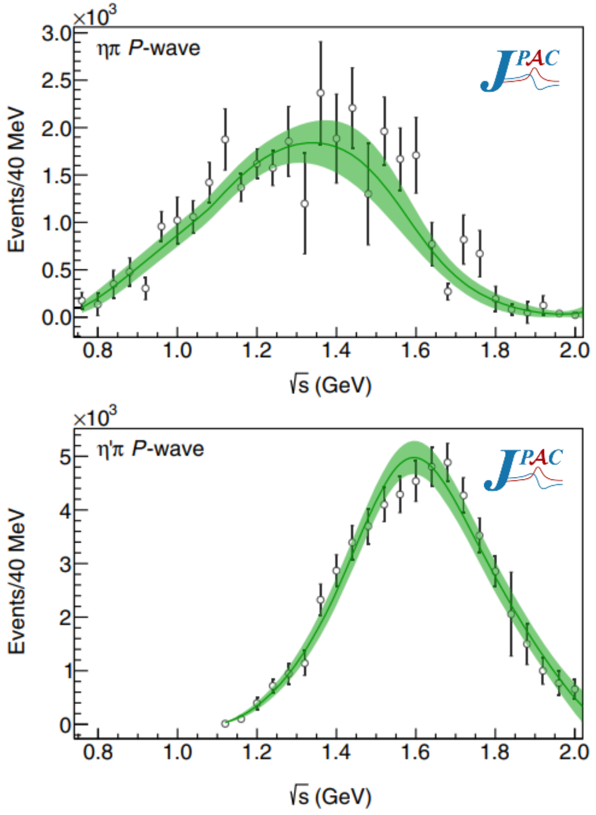

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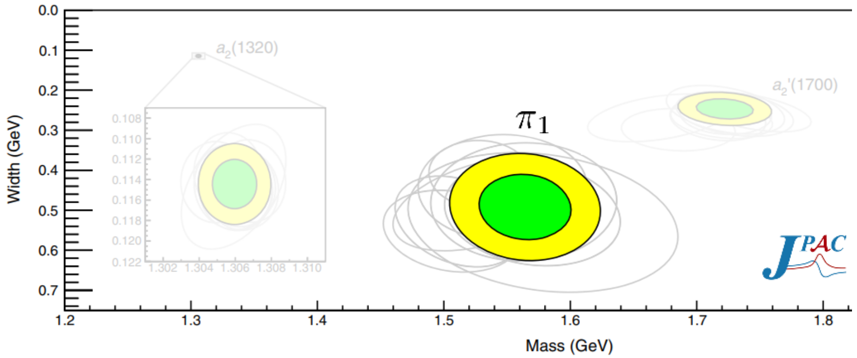

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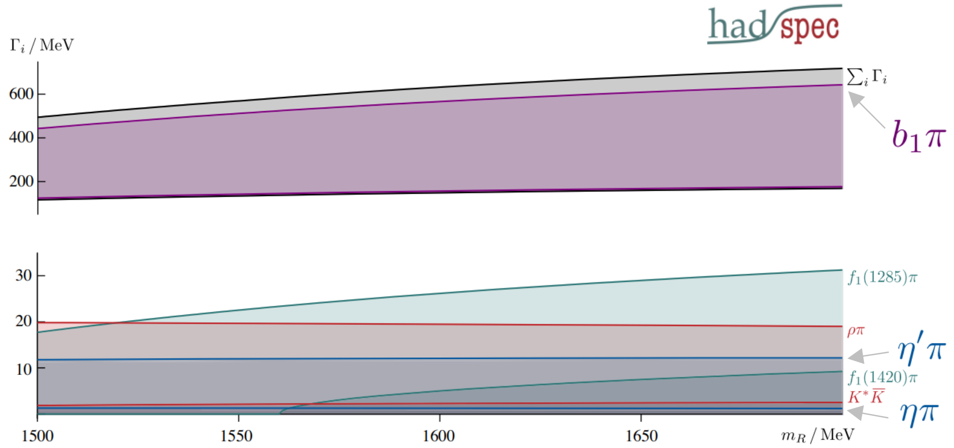


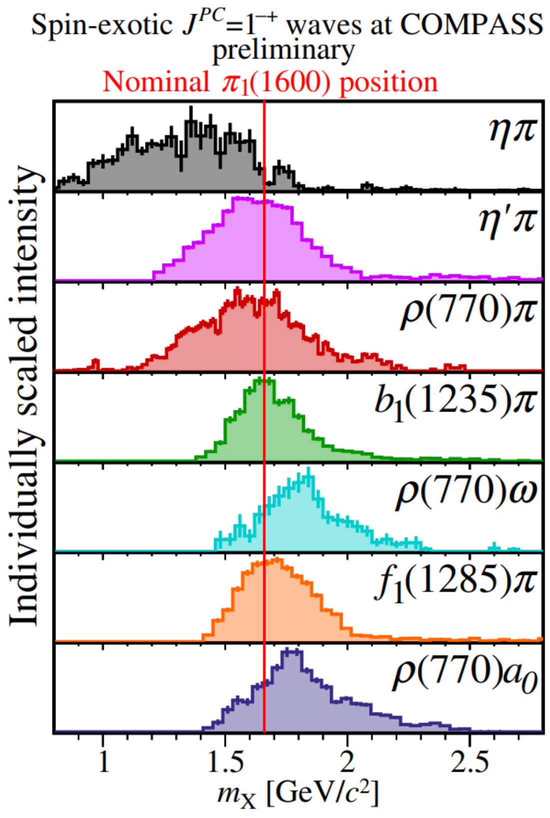
⁕ Experimental confirmation with a photon beam is the main goal of GlueX

The $\pi_1(1600)$

More recently…

- Multiple decay channels with high statistics data from COMPASS

Talk by D.Spuelbeck at HADRON2025 (2508.18908)



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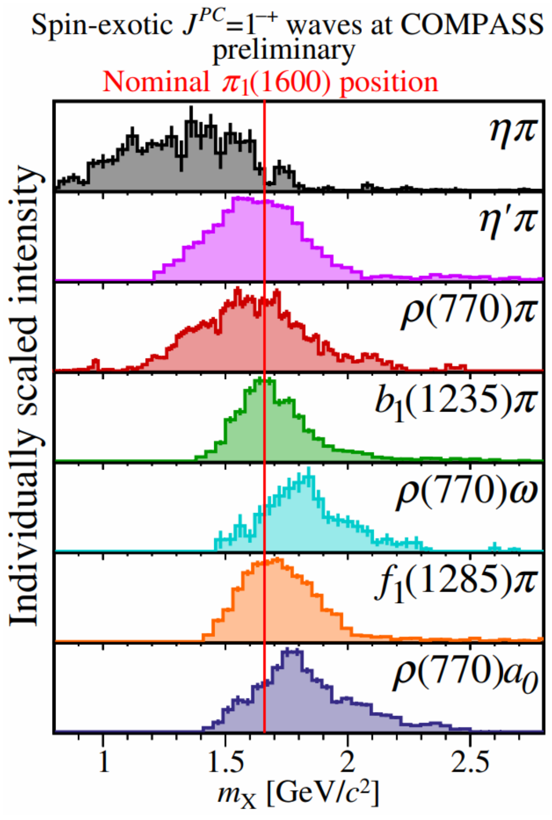
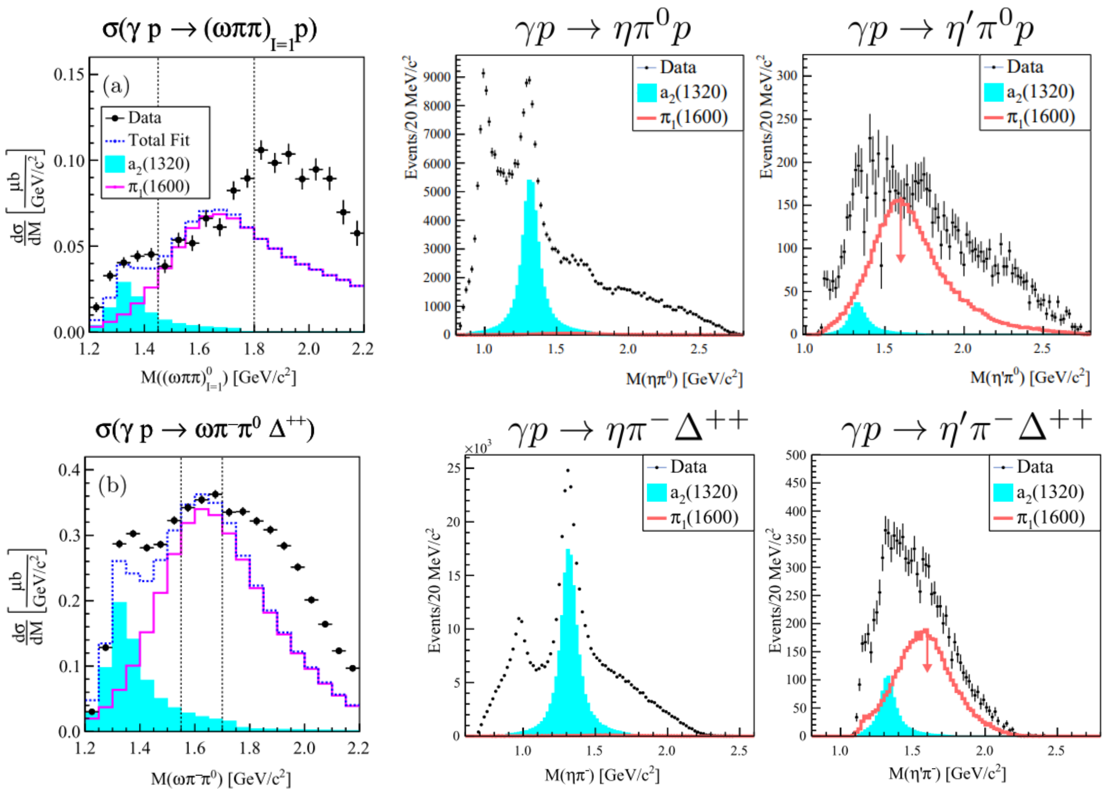


✳ Upper limit for photoproduction cross sections from GlueX

Phys.Rev.Lett. 133 261903 (2024)



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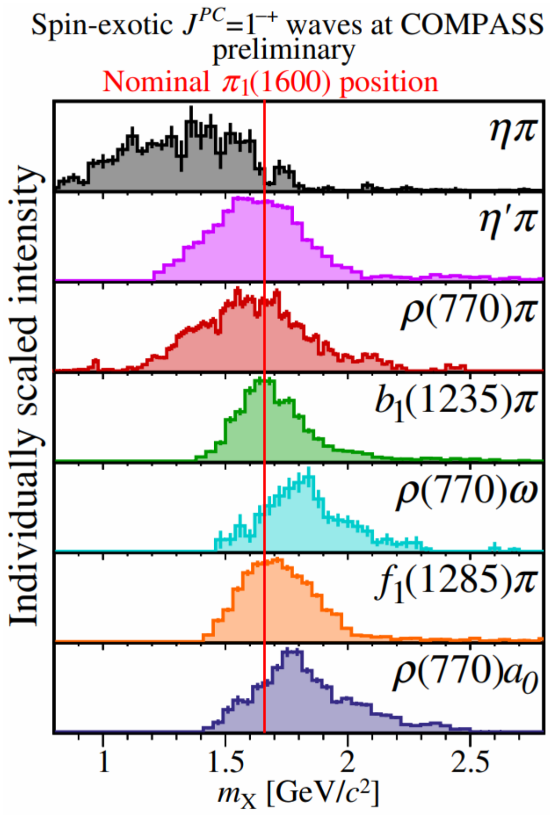

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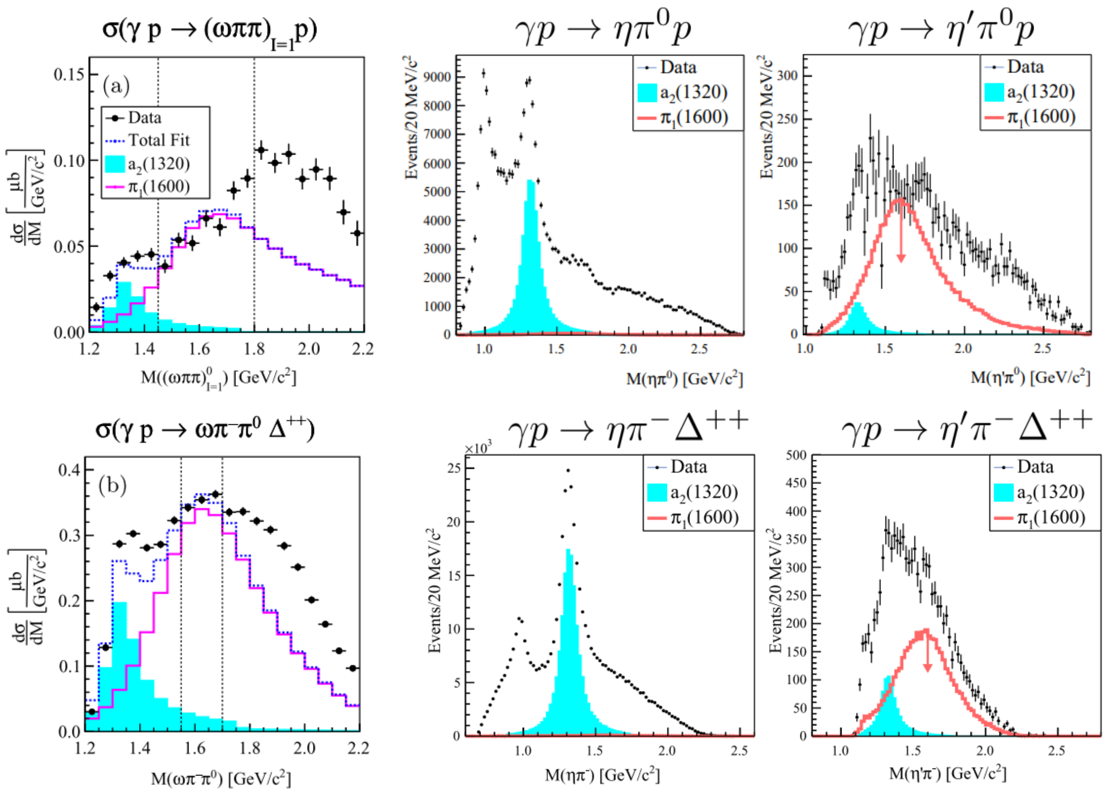

∗ Observation of isospin partner $\eta_1(1855)$ by BES-III Phys.Rev.Lett. 129, 192002 (2022)

00 Motivation

01 Remarks on Scattering and Regge Theory

02 Pion exchange in pion photoproduction

03 Photoproduction of $\eta^{(\prime)}\pi$ in the double-Regge region

04 Other studies

05 Conclusions

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Principles of Scattering Theory

Probability conservation

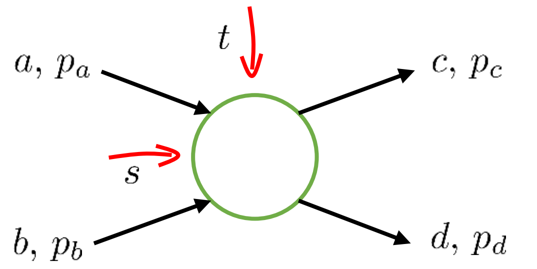
Unitarity $SS^\dagger = 1$

if $S = 1 + iA$ then $-i(A - A^\dagger) = 2\mathrm{Im}\, A = AA^\dagger$

Causality

Analyticity

$A(s)$ has singularities (poles and branch cuts) in the complex s plane.



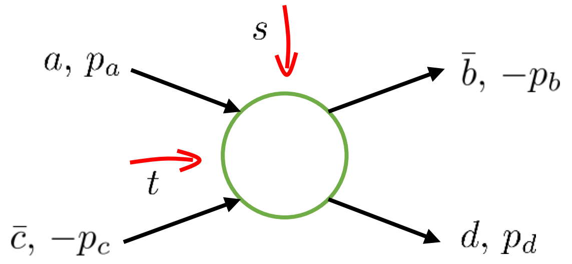
Existence of antiparticles

Crossing symmetry $A_{ab\to cd}(s,t,u) = A_{a\bar{c}\to\bar{b}d}(t,s,u)$

Physical regions (in the case of equal mass particles):

s - channel: $a + b \to c + d$ $\quad s \geq 4m^2,\ t \leq 0,\ u \leq 0$

t - channel: $a + \bar{c} \to \bar{b} + d$ $\quad t \geq 4m^2,\ s \leq 0,\ u \leq 0$



Conservation of orbital angular momentum

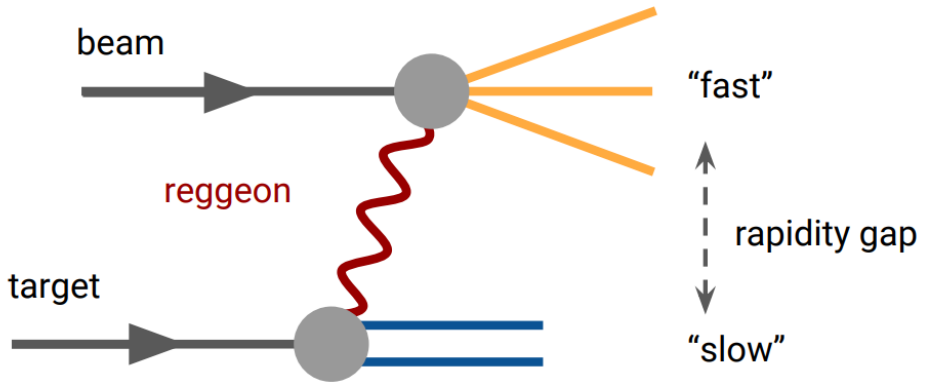
Partial wave expansion

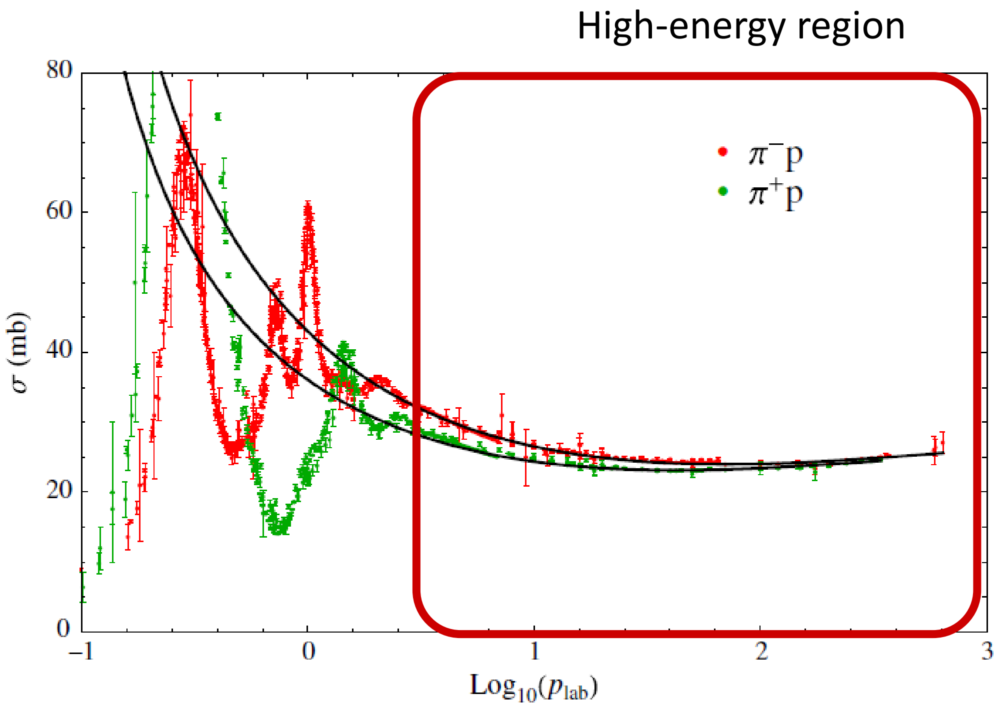
$$A(s,t) = \sum_{\ell=0}^{\infty}(2\ell+1) f_\ell(s) P_\ell(z)$$

$f_\ell(s)$: s - channel partial wave amplitudes
$P_\ell(z)$: Legendre polynomials

Meson photoproduction at high energies

At high energies, meson photoproduction is dominated by the **exchange of Regge trajectories** in the t-channel





V.Mathieu et al., Phys.Rev.D 92, 074004 (2015)

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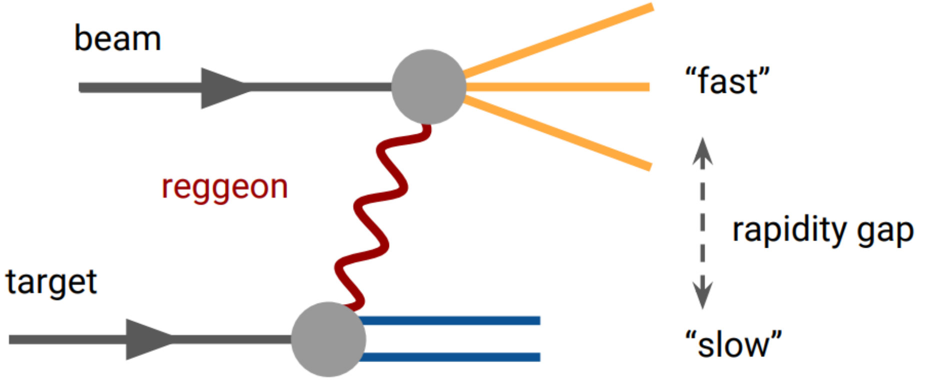
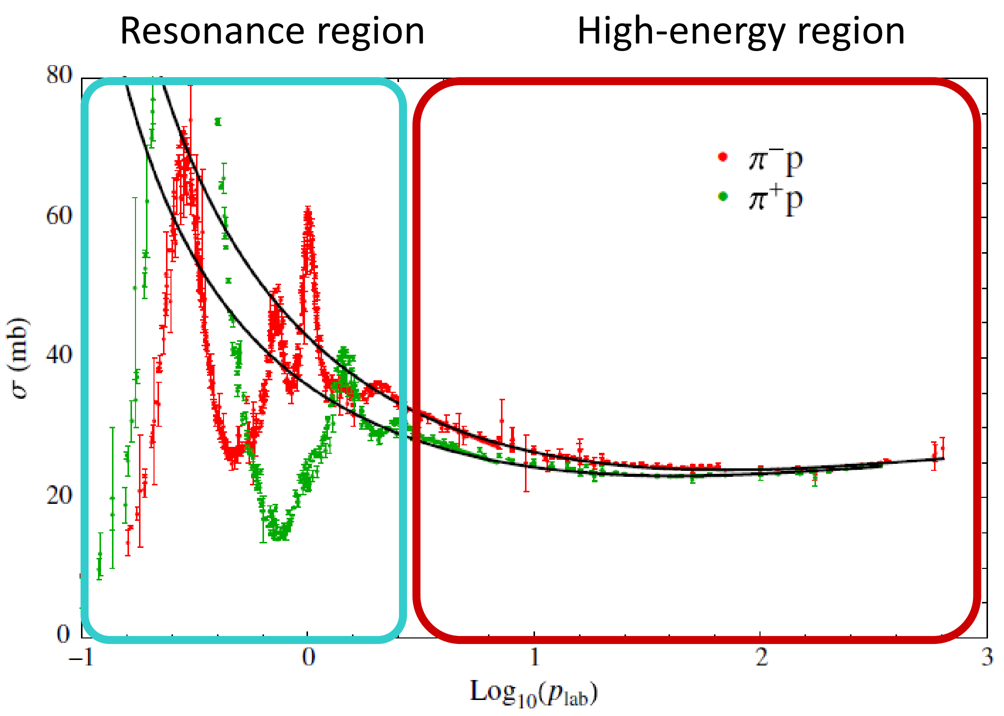


✳ **Duality** between resonance poles and Regge exchanges

Dolen, Horn, Schmid, Phys.Rev. 166, 1768 (1968), Veneziano, Nuovo Cim.A 57, 198 (1968)



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Low-energy: resonances

$$A(s,t) \sim \sum_r \frac{g_r}{s - s_r}$$

High energy: Regge exchanges

$$A(s,t) \sim \sum_i \frac{g_i}{t - t_i}$$

Analytically connected

Introduction to Regge Theory

T.Regge, *Nuovo Cim.* 18, 947 (1960)

At high energy, the scattering amplitude in the physical region of the s-channel is related to t-channel exchanges

Regge limit

$$A(s,t) = \sum_{\ell=0}^{\infty} (2\ell+1) f_\ell(t) P_\ell(z_t) \xrightarrow{s \gg -t, m^2} A(s,t) \sim s^{\ell_{\text{eff}}}$$

t-channel partial wave amplitudes

$$z_t = \cos\theta_t = 1 + \frac{2s}{t-4m^2}$$

$$\lim_{z\to\infty} P_\ell(z) \sim z^\ell$$

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The concept of partial-wave amplitude can be extended to complex values of angular momentum

$\{f_\ell(t)\} \longrightarrow f(\ell,t)$ with $f(\ell,t) \to f_\ell(t),\ \ell \in \{0,1,2,\ldots\}$

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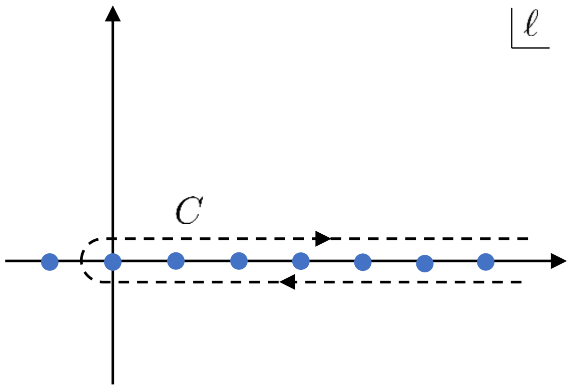
$\{f_\ell(t)\} \longrightarrow f(\ell,t)$ with $f(\ell,t) \to f_\ell(t),\ \ell \in \{0,1,2,\ldots\}$

Do the sum: Sommerfeld-Watson transform

$$A(s,t) = -\frac{1}{2i}\int_C \mathrm{d}\ell \, \frac{(2\ell+1)\,P_\ell(-z_t)\,f(\ell,t)}{\sin \pi\ell}$$



Introduction to Regge Theory

Sommerfeld-Watson transform

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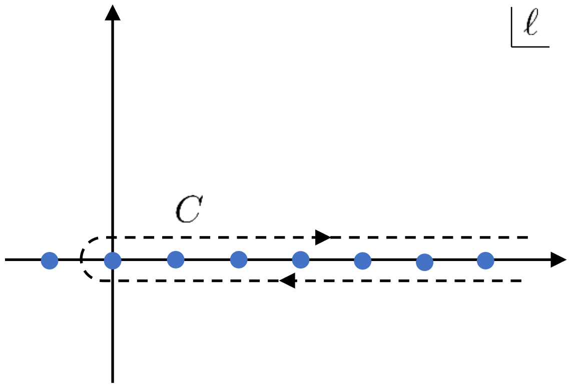

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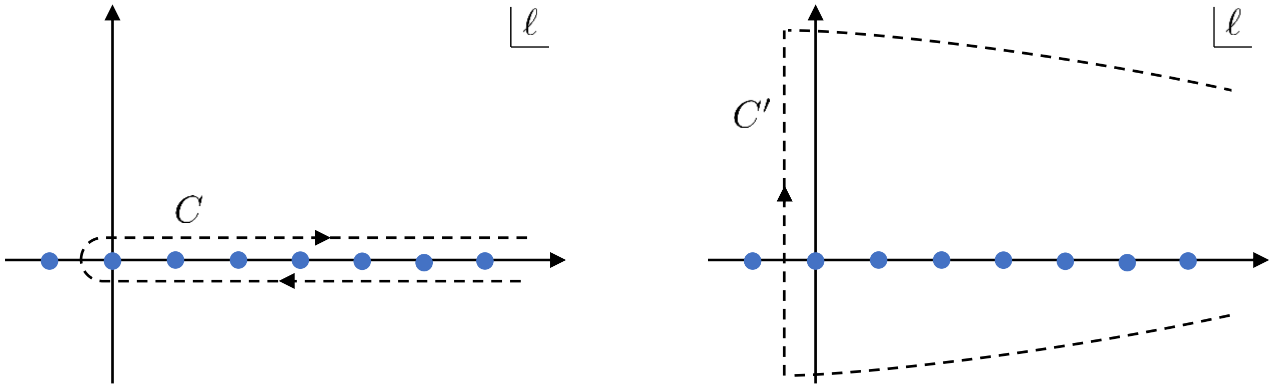
⁎ Deform the contour



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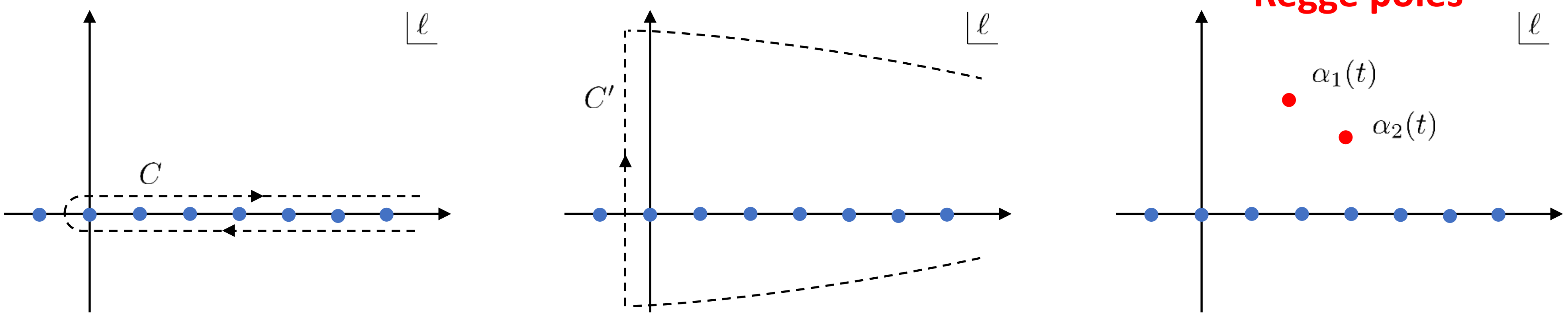
→ Assuming the partial waves are analytic ℓ, the only singularities are poles $f_\ell(t) \sim \dfrac{\beta(t)}{\ell - \alpha(t)}$

Regge poles



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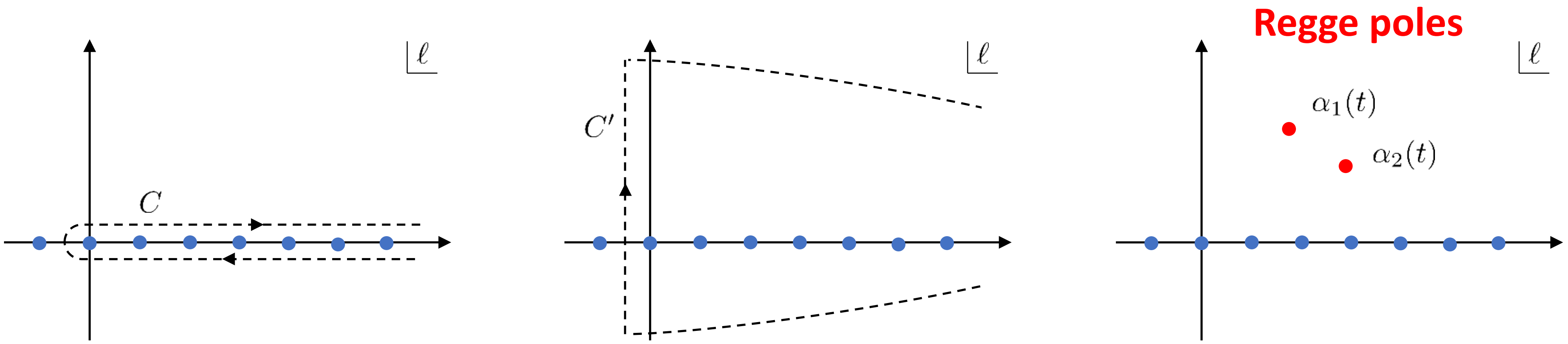
$$A(s,t) = \underbrace{-\frac{1}{2i}\int_{-\frac{1}{2}-i\infty}^{-\frac{1}{2}+i\infty} \mathrm{d}\ell \ldots}_{\text{background } \sim\, s^{-1/2}} \underbrace{- \sum_i \frac{\pi(2\alpha_i(t)+1)\beta_i(t)}{\sin\left(\pi\alpha_i^{\pm}(t)\right)} \frac{1}{2} P_{\alpha_i}(-z_t)}_{\text{pole contributions } \sim\, s^{\alpha(t)}}$$



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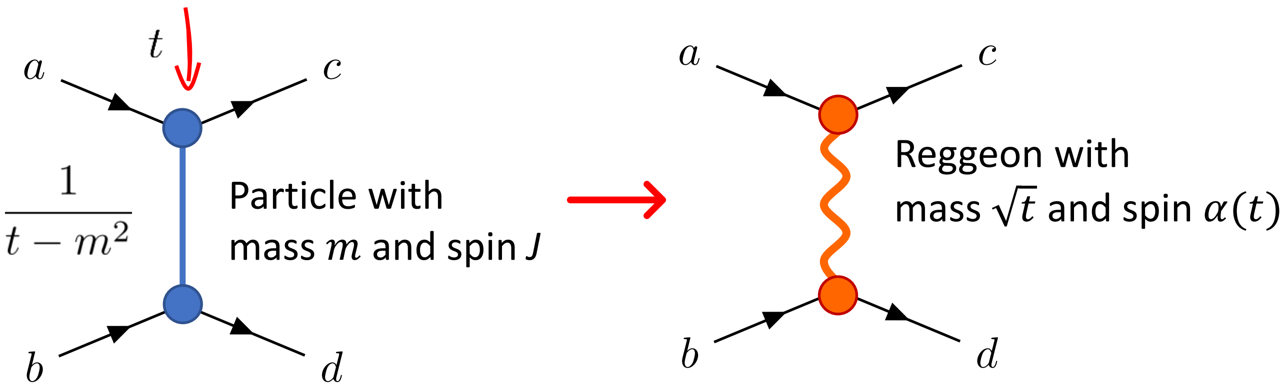


$$\mathcal{P}_{\text{Regge}} = \frac{\pi\alpha'}{\sin\left(\pi\alpha(t)\right)} \frac{1+\eta e^{-i\pi\alpha(t)}}{2} \left(\frac{s}{s_0}\right)^{\alpha(t)} \frac{1}{\Gamma\left(1+\alpha(t)\right)}$$

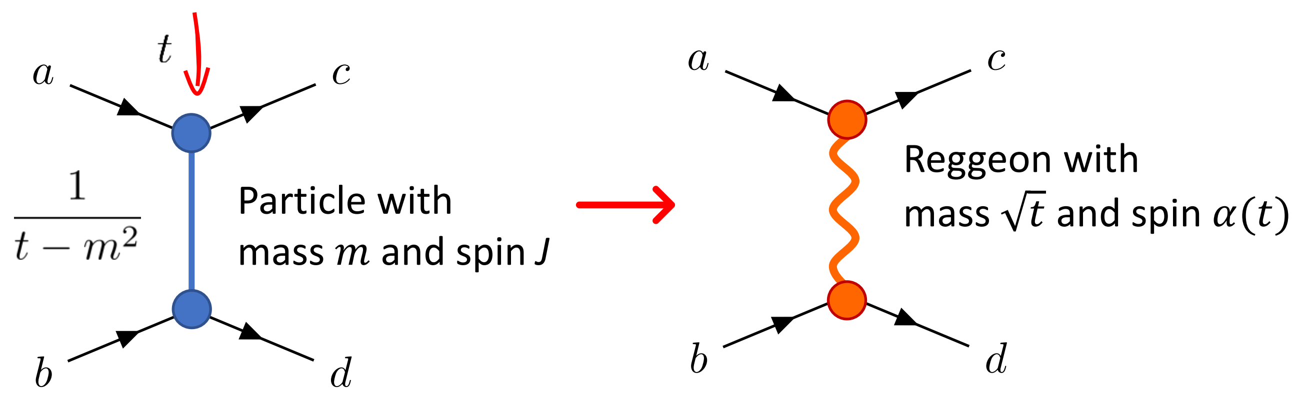
poles for integer $\alpha(t)$

signature factor $\eta = (-1)^J$

asymptotic behavior

cancel non-physical poles

Introduction to Regge Theory



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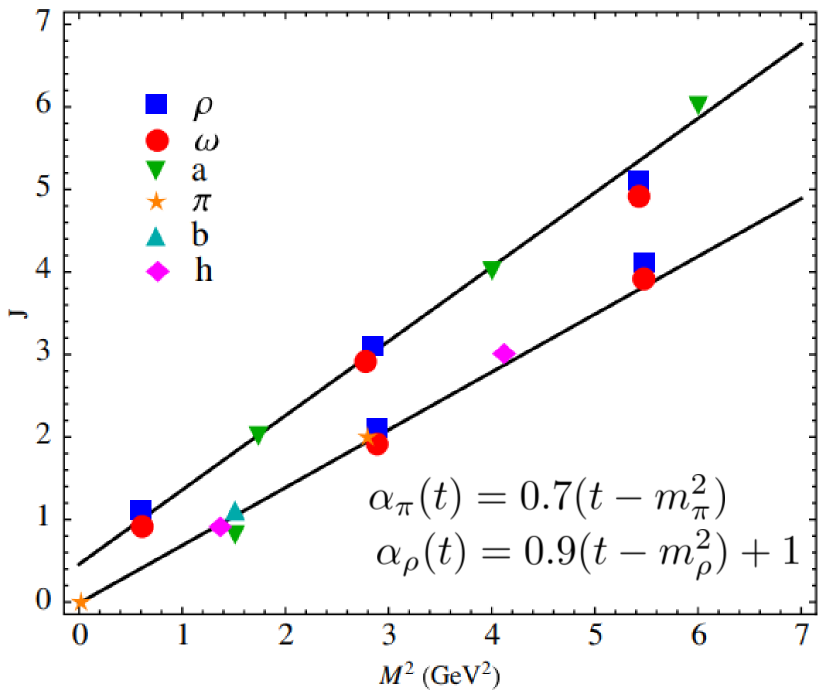
Resonances appear simultaneously as poles in energy and spin!

∗ **Regge trajectories:** families with same quantum numbers but different spin

∗ Almost straight lines (Chew-Frautschi plot)

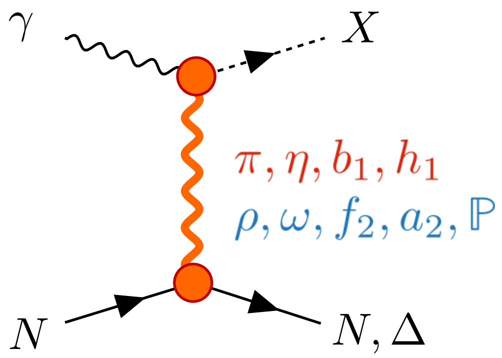
∗ In standard Regge theory parameterized by: $\alpha(t) = \alpha' t + \alpha_0$



V.Mathieu et al., *Phys.Rev.D* 98, 014041 (2018)

Model for meson photoproduction

We "only" need to know the (dominant) crossed-channel exchanges



→ **Unnatural** parity $(P(-1)^J = -1)$: $0^-, 1^+, 2^-, 3^+, \ldots$

→ **Natural** parity $(P(-1)^J = +1)$: $0^+, 1^-, 2^+, 3^-, \ldots$

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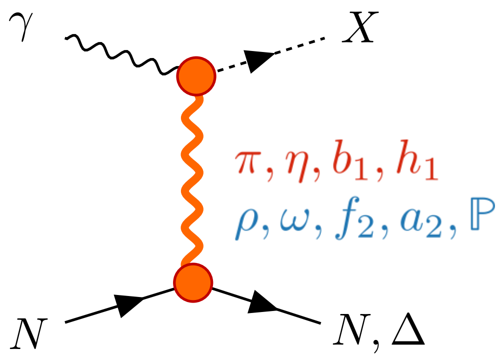

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⁎ Neutral-exchange reactions:

$\gamma p \to \pi_1^0 p$

$\gamma p \to b_1^0 p$, $\gamma p \to a_0^0 p$, $\gamma p \to a_2^0 p$,

$\gamma p \to \eta^{(\prime)} \pi^0 p \ldots$

→ Natural parity exchanges dominate

⁎ Charge-exchange reactions:

$\gamma p \to \pi_1^- \Delta^{++}$

$\gamma p \to b_1^- \Delta^{++}$, $\gamma p \to \pi^- \Delta^{++}$, $\gamma p \to a_0^- \Delta^{++}$, $\gamma \Delta^{++} \to a_2^- p$,

$\gamma p \to \eta^{(\prime)} \pi^- \Delta^{++} \ldots$

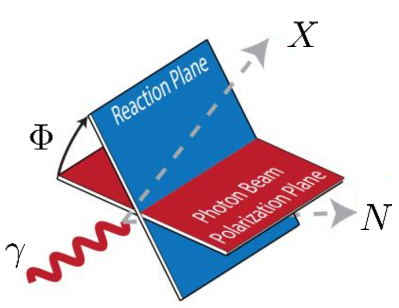
→ Small -t: unnatural (pion) exchanges favored

→ Larger -t: natural exchanges favored

Model for meson photoproduction

Linearly polarized photon beam at GlueX helps disentangle the production mechanisms

- Beam asymmetry



$$\Sigma = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel} \approx \frac{d\sigma_N - d\sigma_U}{d\sigma_N + d\sigma_U}$$

V.Mathieu et al., Phys.Rev.D 92, 074013 (2015)

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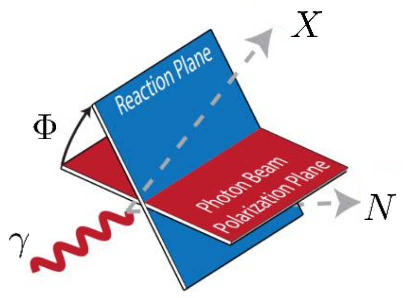

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→ Neutral- vs charge-exchange reactions:

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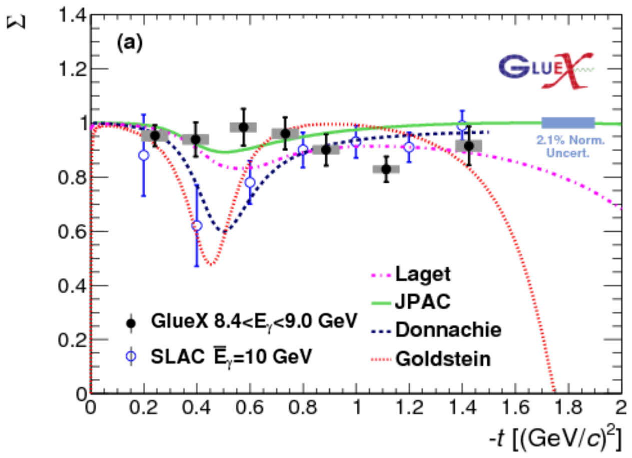
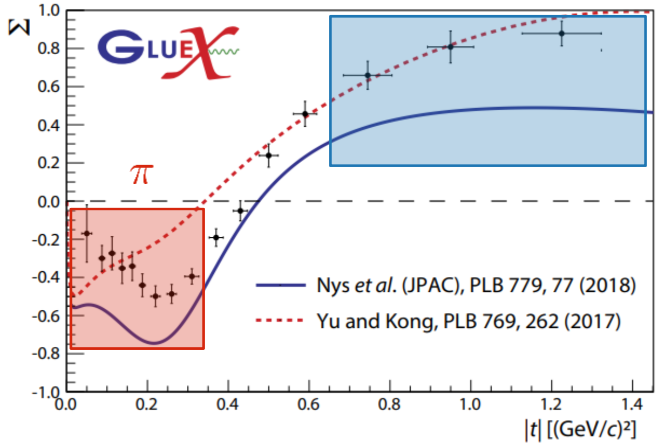


GlueX Collaboration, Phys.Rev.C 95, 042201 (2017)

$\gamma p \to \pi^- \Delta^{++}$ ρ, a_2



GlueX Collaboration, Phys.Rev.C 103, L022201 (2021)

00 Motivation

01 Remarks on Scattering and Regge Theory

02 Pion exchange in pion photoproduction

03 Photoproduction of $\eta^{(\prime)}\pi$ in the double-Regge region

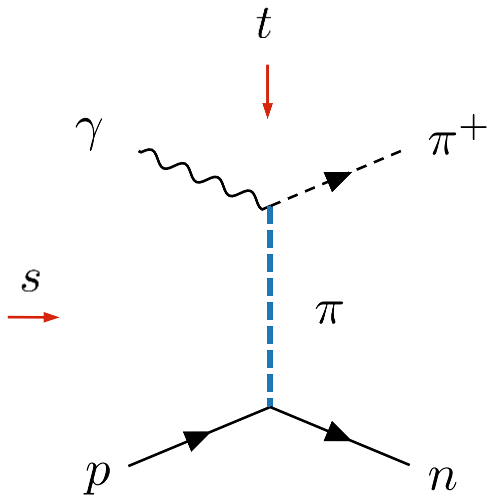
04 Other studies

05 Conclusions

Understanding pion exchange

What do we know?

- Dominates in charge exchange reactions at small momentum transfer
- Low energies: constrained by effective Lagrangians of QCD
- High energies: Regge theory



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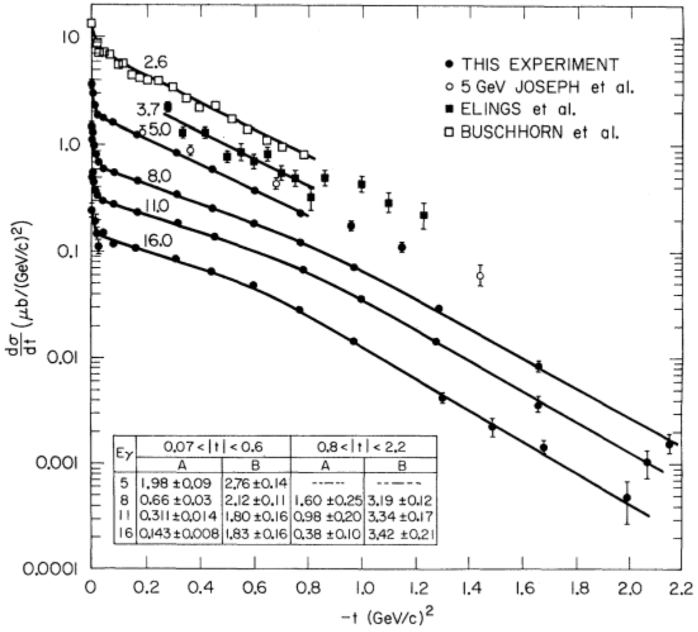
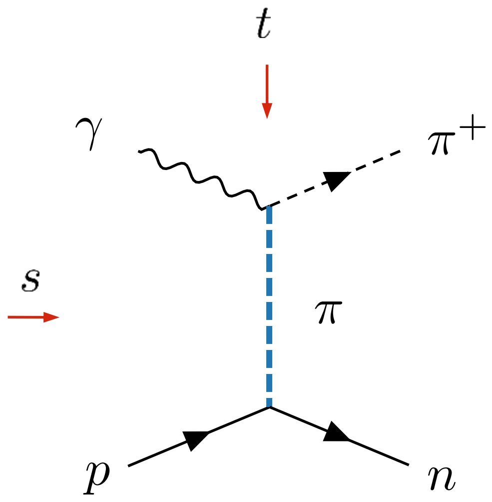
Simplest charge-exchange process is pion photoproduction

Boyarski et al., *Phys.Rev.Lett.* 20, 300 (1968)



E_γ	$0.07 < \lvert t \rvert < 0.6$		$0.8 < \lvert t \rvert < 2.2$	
	A	B	A	B
5	1.98 ±0.09	2.76 ±0.14	------	------
8	0.66 ±0.03	2.12 ±0.11	1.60 ±0.25	3.19 ±0.12
11	0.311 ±0.014	1.80 ±0.16	0.98 ±0.20	3.34 ±0.17
16	0.143 ±0.008	1.83 ±0.16	0.38 ±0.10	3.42 ±0.21



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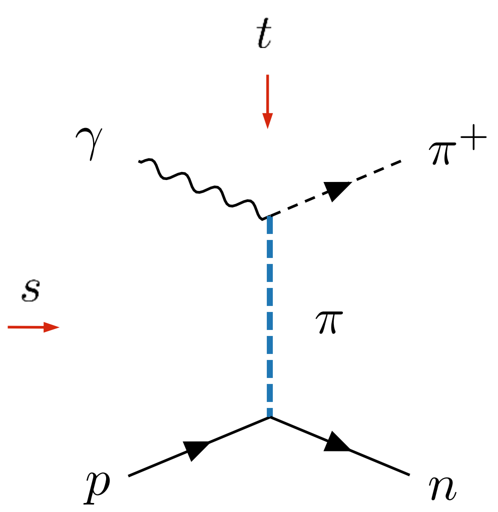

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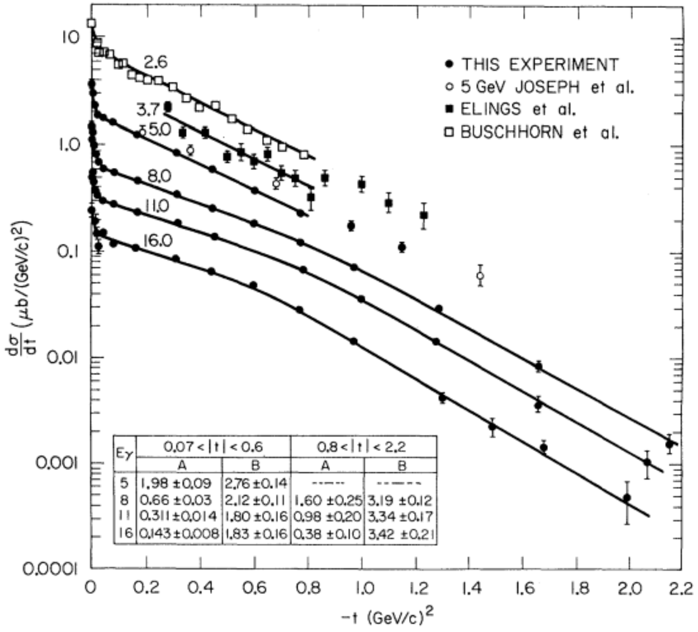

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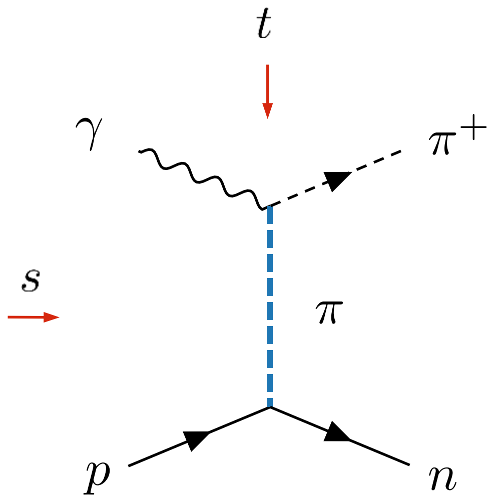

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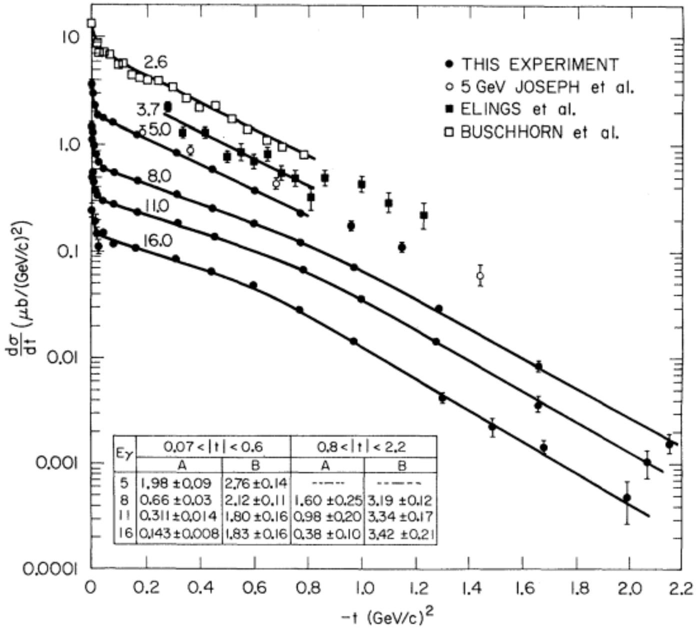

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Early solutions:

☒ Parity-doublet conspirator of the pion

Ball, Frazer and Jacob, *Phys.Rev.Lett.* 20, 518 (1968)

? Regge cuts and absorption (final state interactions)

Henyey, Kane, Pumplin, *Phys.Rev.* 182, 1579 (1969)

☑ Nucleon Born terms

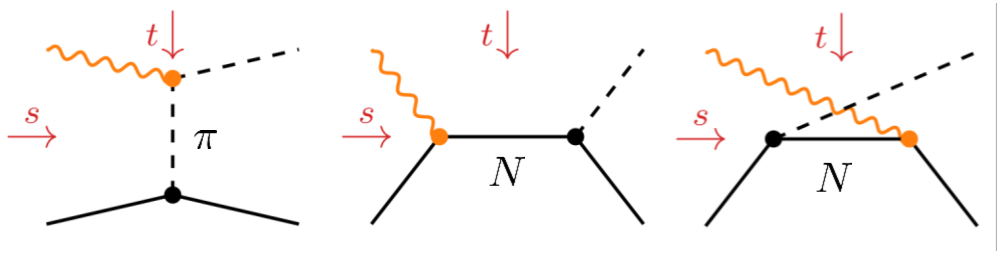
Jones, *Rev.Mod.Phys.* 52, 545 (1980) 545

Born amplitudes

In terms of Born diagrams, **current conservation** relates t-channel diagram (pion exchange) and s-, u-channel diagrams (nucleon exchanges)

$$A_{\mu_\gamma \mu_i \mu_f} = \epsilon_{\mu_\gamma}(k) \cdot J_{\mu_i \mu_f}$$

$$J^{\mu}_{\mu_i \lambda_f} = J^{\mu}_{\mu_i \mu_f, t} + J^{\mu}_{\mu_i \mu_f, s} + J^{\mu}_{\mu_i \mu_f, u}$$



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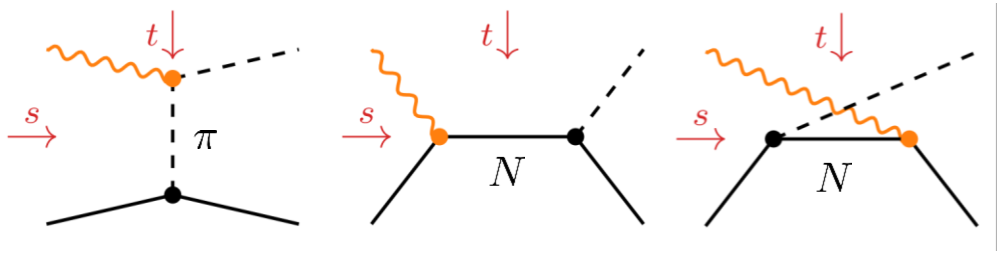

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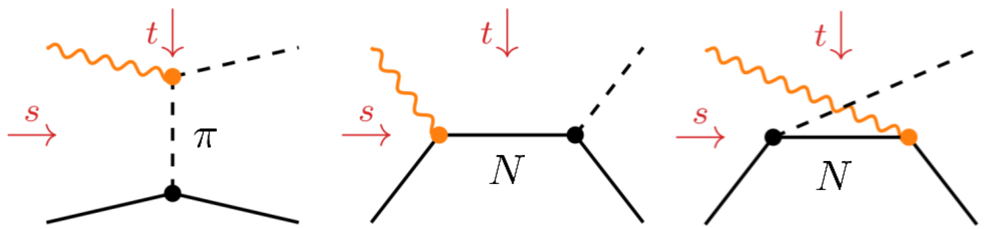

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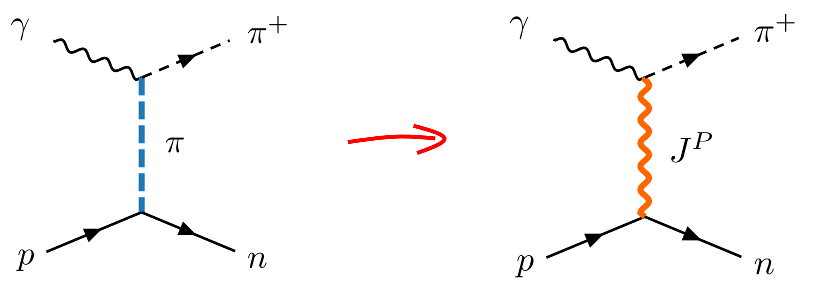
Reggeization of pion exchange

In the Regge-pole approximation:



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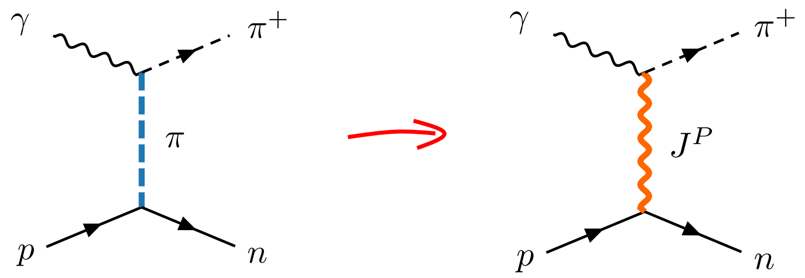

⁕ Empirical prescription by Vanderhaegen, Guidal and Laget

- Preserves gauge invariance and describes forward peak)

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Nucl.Phys.A 627, 645 (1997)

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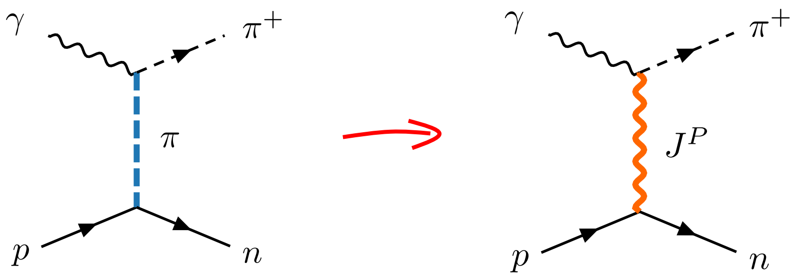

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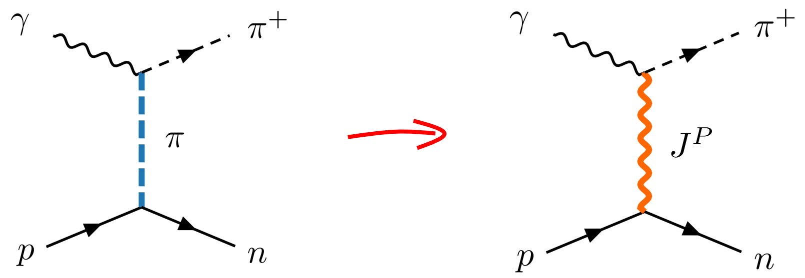

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⁎ Sum partial-wave expansion in the t-channel:

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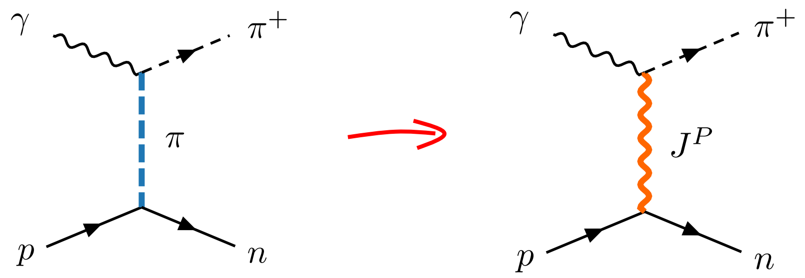
Reggeization of pion exchange

In the Regge-pole approximation:



✳ Empirical prescription by Vanderhaegen, Guidal and Laget

- Preserves gauge invariance and describes forward peak)

$$A^{\mathrm{VGL}}_{\lambda_\gamma\lambda_i\lambda_f}(s,t) = A^{\mathrm{Born}}_{\lambda_\gamma\lambda_i\lambda_f}(s,t)(t-m_\pi^2)\,\alpha'\frac{1+e^{-i\pi\alpha(t)}}{2}\Gamma(-\alpha(t))\left(\frac{s}{s_0}\right)^{\alpha(t)}$$

Nucl.Phys.A 627, 645 (1997)

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No pion pole?

Reggeization of pion exchange

GM, D.Winney, et al. (JPAC), Phys.Rev.D 110, 114012 (2024)

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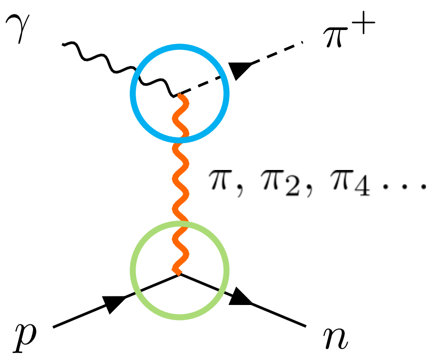

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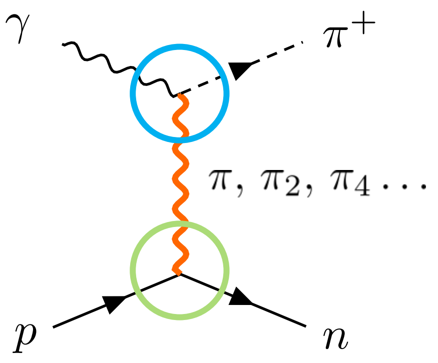

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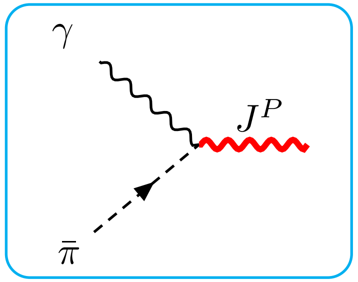

$$1^- \otimes 0^- = 1^+ \left\{ \begin{array}{ll} L = 1 & J = 0 \\ L = \{J-1, J+1\} & J \geq 2 \end{array} \right\}$$ one L vs two L's

$$V^J_{\lambda_\gamma}(\sigma_J) = 2\sqrt{2}\, g_{\gamma\pi}\, \epsilon^*_{\nu_1\cdots\nu_J}(\sigma_J)\, \epsilon_\mu(k,\lambda_\gamma)\, (k^{\nu_1}\cdots k^{\nu_{J-1}}) \left[k^{\nu_J} p^\mu_\pi - g^{\nu_J\mu}(k\cdot p_\pi) \right]$$

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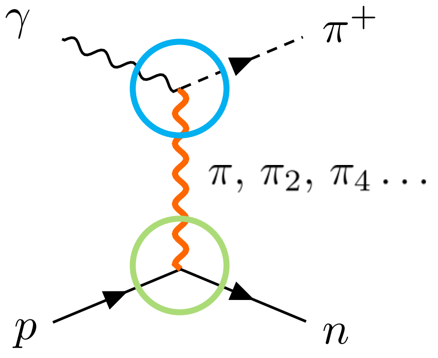

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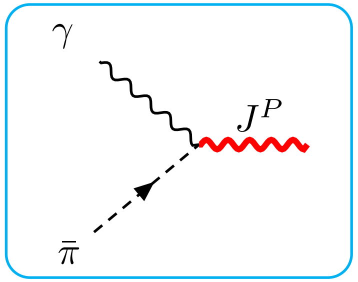

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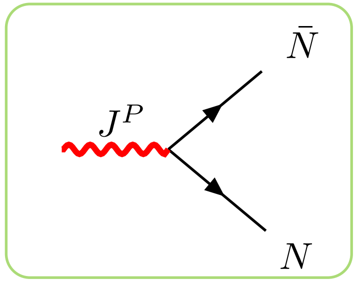

$$\frac{1}{2}^+ \otimes \frac{1}{2}^- = 0^- \oplus 1^- \rightarrow \quad L = J$$

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$$(P^\nu = p^\nu_i + p^\nu_f)$$

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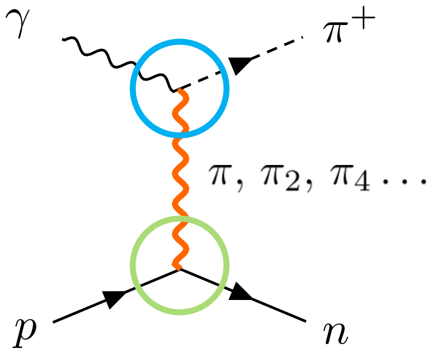

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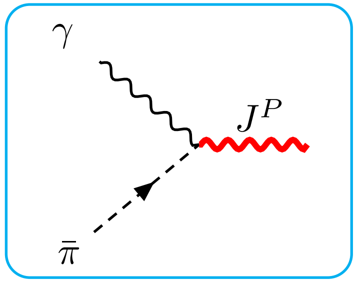

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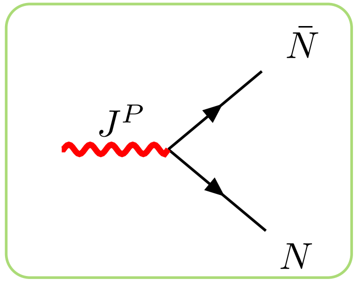

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→ spin-J amplitude:

$$a^J_{\lambda_\gamma\lambda_i\lambda_f}(t) \equiv \frac{2e_\pi g_J t}{J-\alpha_\pi(t)}(2\lambda_i\delta_{\lambda_i\lambda_f})c^2_J\sqrt{\frac{J+1}{J}}(-2p_t k_t)^J$$ **for $J > 0$**

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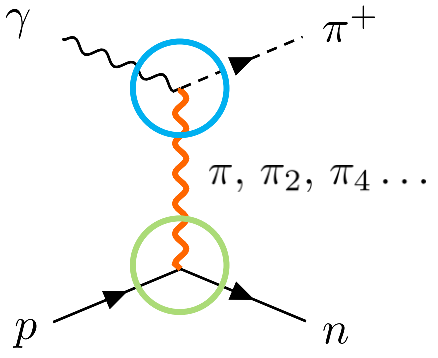

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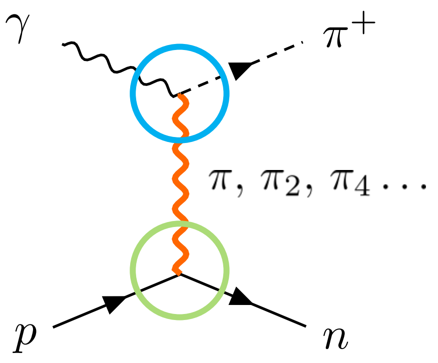

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$$P^{11}_{J-1}(z_t) = J\ {}_2\tilde{F}_1\left(1-J, J+2; 2; \frac{1-z_t}{2}\right)$$

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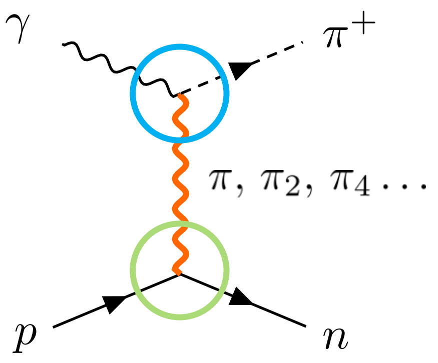

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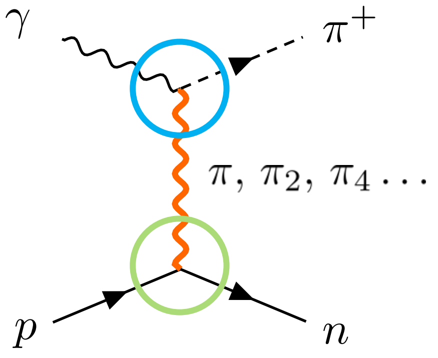

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The $J \to 0$ amplitude is finite!

3. Sum the tower of exchanges (e.g. Sommerfeld-Watson, or generating function for Jacobi polynomials)

$$A_{\lambda_\gamma \lambda_i \lambda_f}(s,t) = A^{J\to 0}_{\lambda_\gamma \lambda_i \lambda_f}(s,t) + \sum_{J=1} (2J+1)\, a^J_{\lambda_\gamma \lambda_i \lambda_f}(t)\, d^J_{\lambda_\gamma \lambda_i - \lambda_f}(\theta_t)$$

$$\propto \alpha' \tau \frac{2}{\sqrt{\pi}} \Gamma\left(\alpha(t) + \frac{3}{2}\right) \Gamma(-\alpha(t))\, (sR^2)^{\alpha(t)}$$

vs $\quad \mathcal{P}^{\text{Regge}}_\pi \propto \alpha' \tau\, \Gamma(-\alpha(t)) \left(\frac{s}{s_0}\right)^{\alpha(t)}$

Interpretation in terms of Born diagrams

* In the s-channel CM frame

$$A^{\mathrm{e}}_{\mu_\gamma \mu_i \mu_f} = 2\sqrt{2} g_{\pi NN} \left[e_\pi \frac{(\epsilon_{\mu_\gamma} \cdot p_\pi)}{t-\mu^2} + \underbrace{e_{N_i} \cancel{\frac{(\epsilon_{\mu_\gamma} \cdot p_i)}{s-M^2}} + e_{N_f} \frac{(\epsilon_{\mu_\gamma} \cdot p_f)}{u-M^2}}_{1/s} \right] \bar{u}_{\mu_f}(p_f) \gamma_5 u_{\mu_i}(p_i)$$

$$\sim \sqrt{t}$$

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Re-write as 3 gauge-invariant terms proportional to the mass of the exchanged particle

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$$\left. + \frac{1}{2} e_{N_i} \left(\frac{\epsilon \cdot p_\pi}{s - m_N^2} + \frac{\epsilon \cdot P}{s - u} \frac{t - m_\pi^2 - k^2}{s - m_N^2} \right) - \frac{1}{2} e_{N_f} \left(\frac{\epsilon \cdot p_\pi}{u - m_N^2} + \frac{\epsilon \cdot P}{s - u} \frac{t - m_\pi^2 - k^2}{u - m_N^2} \right) \right] \bar{u}_{\mu_f}(p_f) \gamma_5 u_{\mu_i}(p_i)$$

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vanishes in t-channel CM

only contribution s-channel CM, subleading in the t-channel CM

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→ At large s, this is the *J=0* partial wave (π + *N* contributions)

vanishes in t-channel CM

only contribution s-channel CM, subleading in the t-channel CM

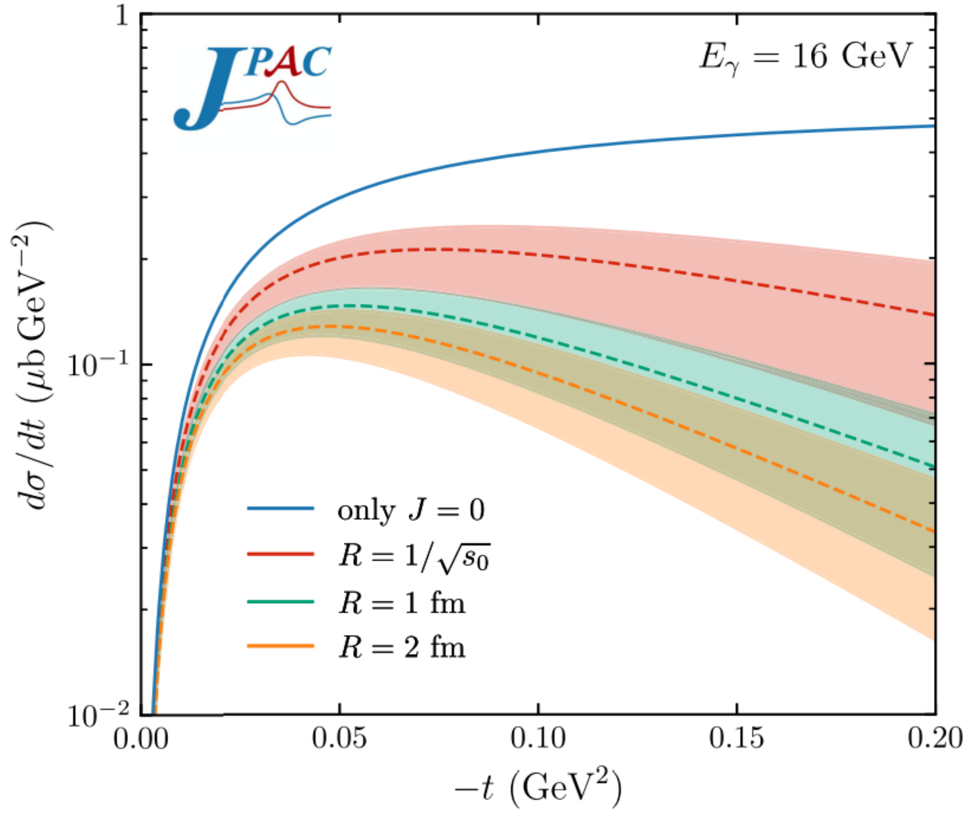
$$\left. + \frac{1}{2} e_{N_i} \left(\frac{\epsilon \cdot p_\pi}{s - m_N^2} + \frac{\epsilon \cdot P}{s-u} \frac{t - m_\pi^2 - k^2}{s - m_N^2} \right) - \frac{1}{2} e_{N_f} \left(\frac{\epsilon \cdot p_\pi}{u - m_N^2} + \frac{\epsilon \cdot P}{s-u} \frac{t - m_\pi^2 - k^2}{u - m_N^2} \right) \right] \bar{u}_{\mu_f}(p_f) \gamma_5 u_{\mu_i}(p_i)$$

Results for pion photoproduction

GM, D.Winney, et al. (JPAC), Phys.Rev.D 110, 114012 (2024)

* Reggeized pion exchange

$$A^{\text{Regge}}_{\lambda_\gamma\lambda_i\lambda_f}(s,t) \propto t(sR^2)^{\alpha(t)}$$



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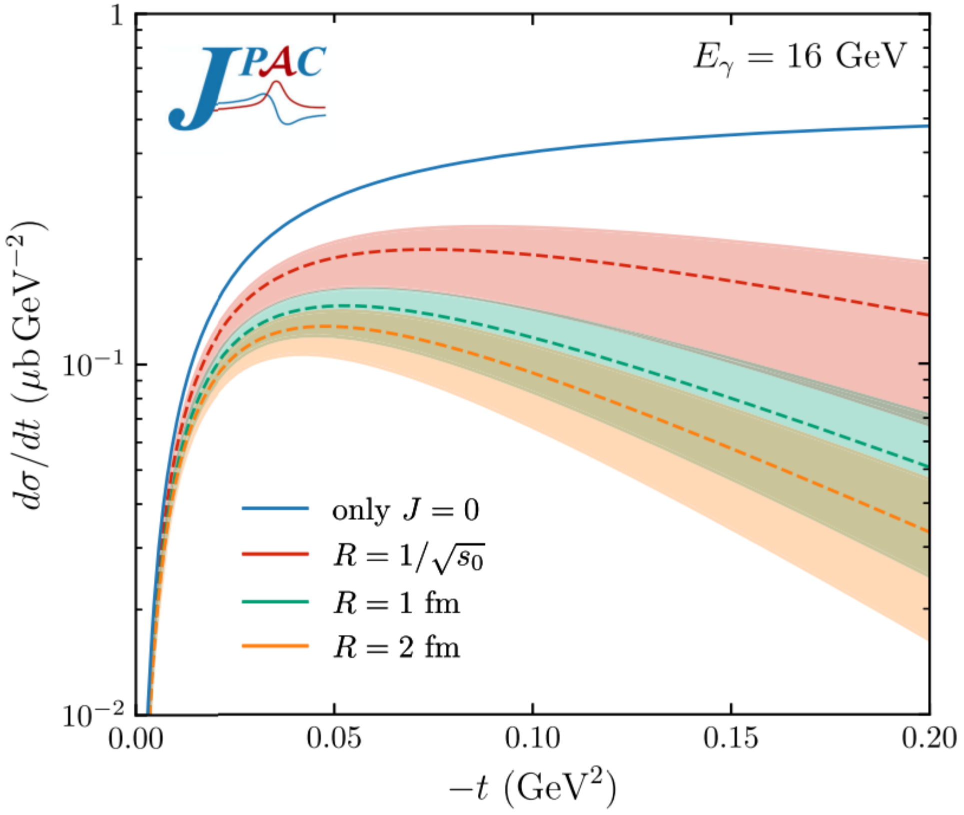
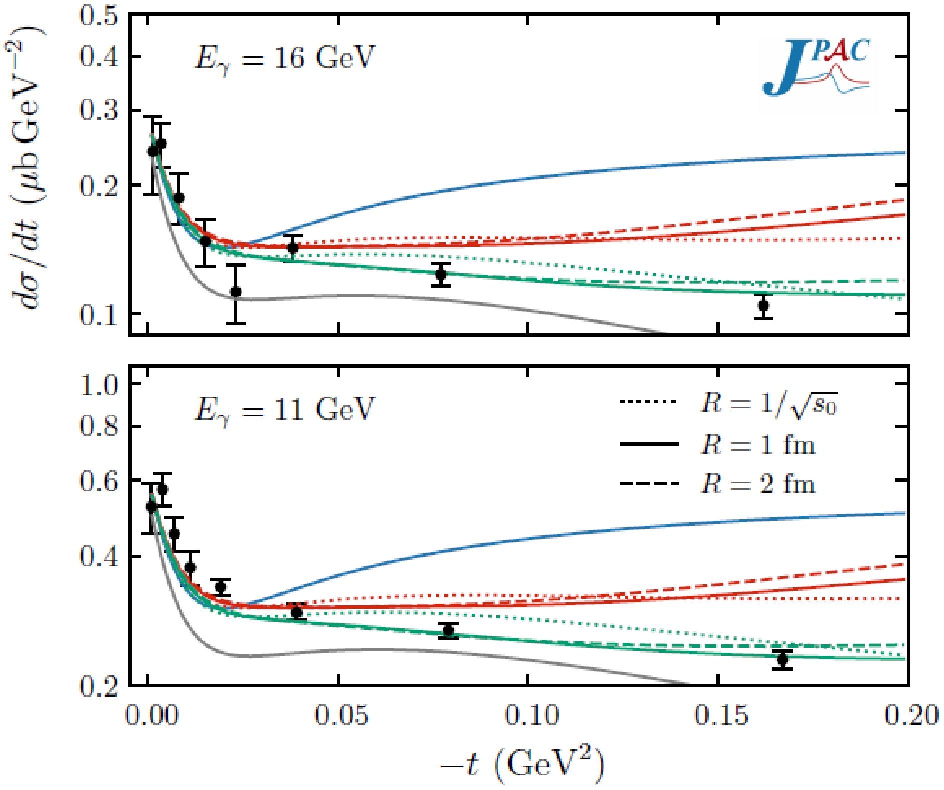


⁎ Adding the nucleon magnetic term

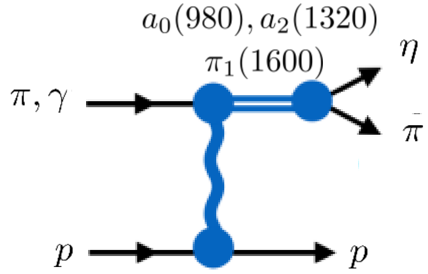
- With a form factor (missing Regge exchanges)

Comparison with VGL approach (grey line)

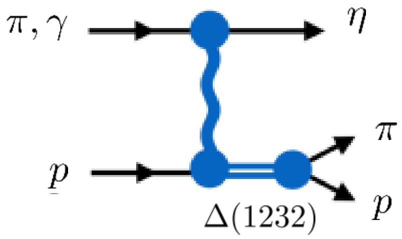


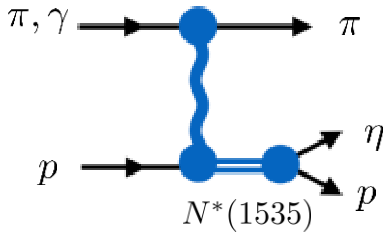
$\eta^{(\prime)}\pi$ final state

✳ Meson resonances

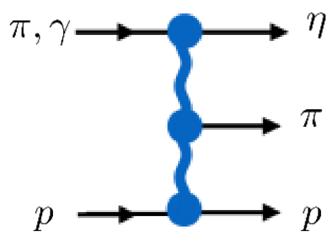


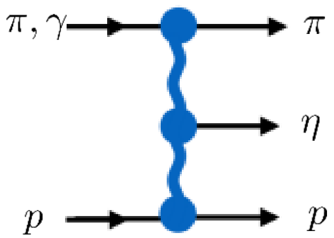
✳ Baryon resonances



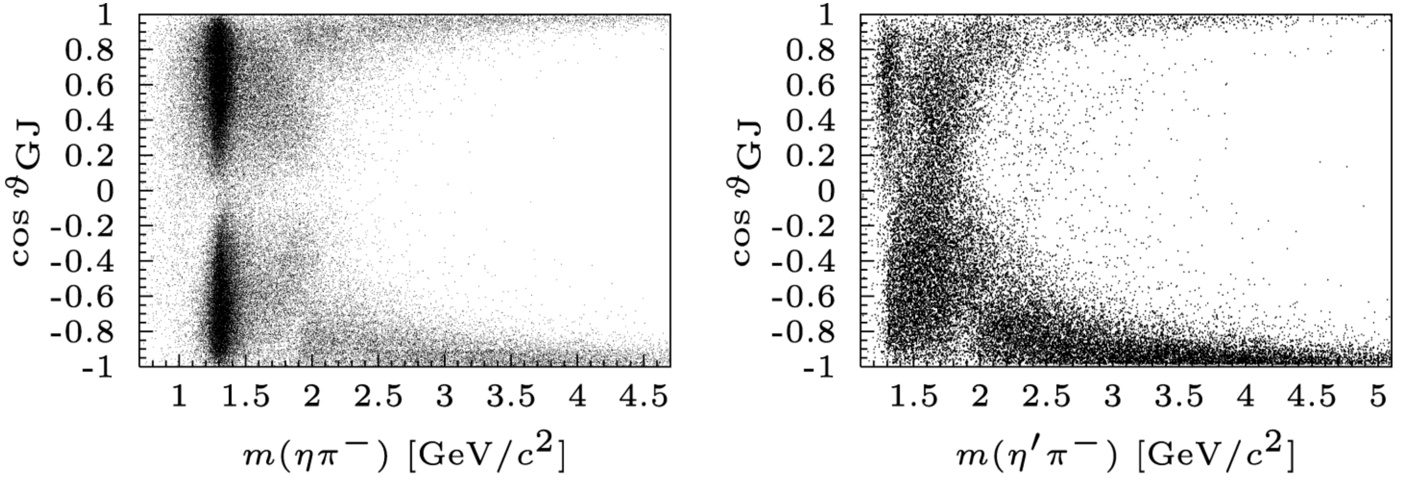


✳ Double Regge production





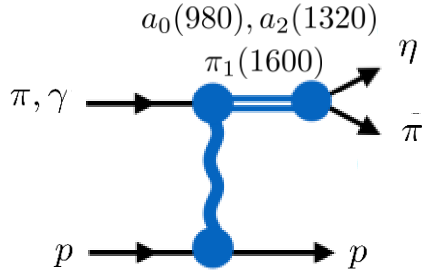
Pion beam



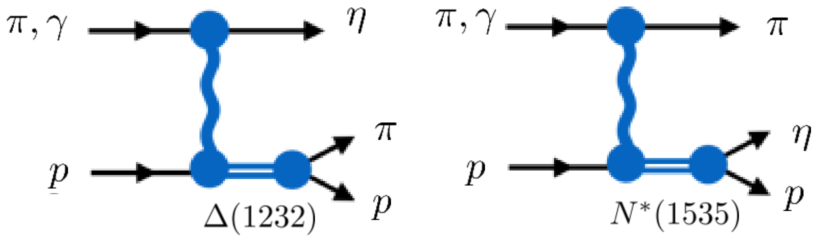
COMPASS, *Phys.Lett.B* 740, 303 (2015)

$\eta^{(\prime)}\pi$ final state

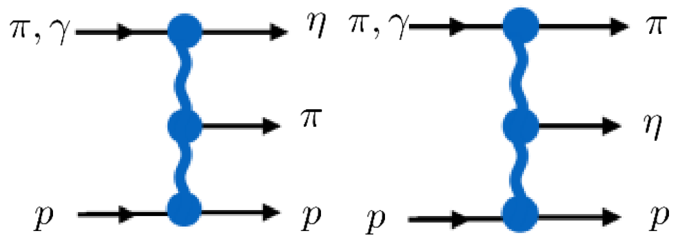
- Meson resonances



- Baryon resonances



- Double Regge production



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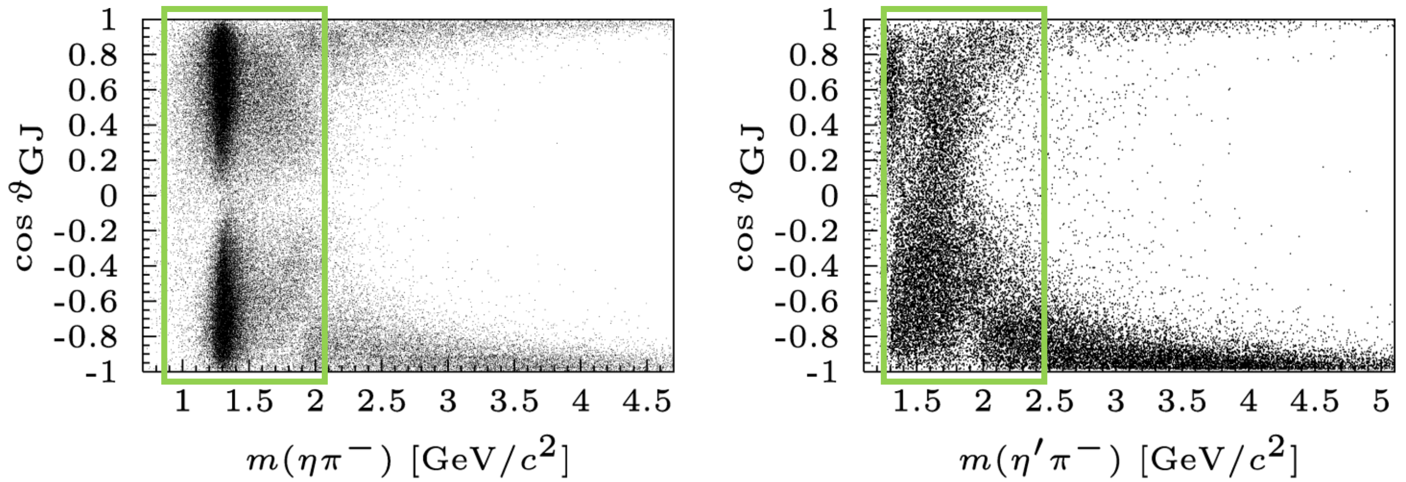

COMPASS, *Phys.Lett.B* 740, 303 (2015)

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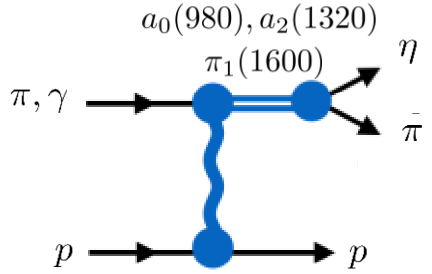

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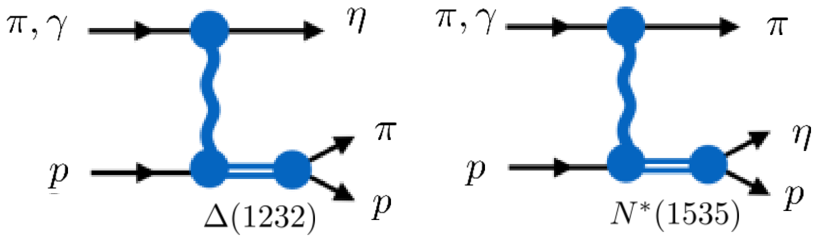

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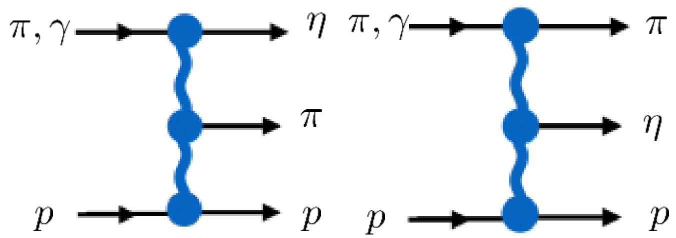

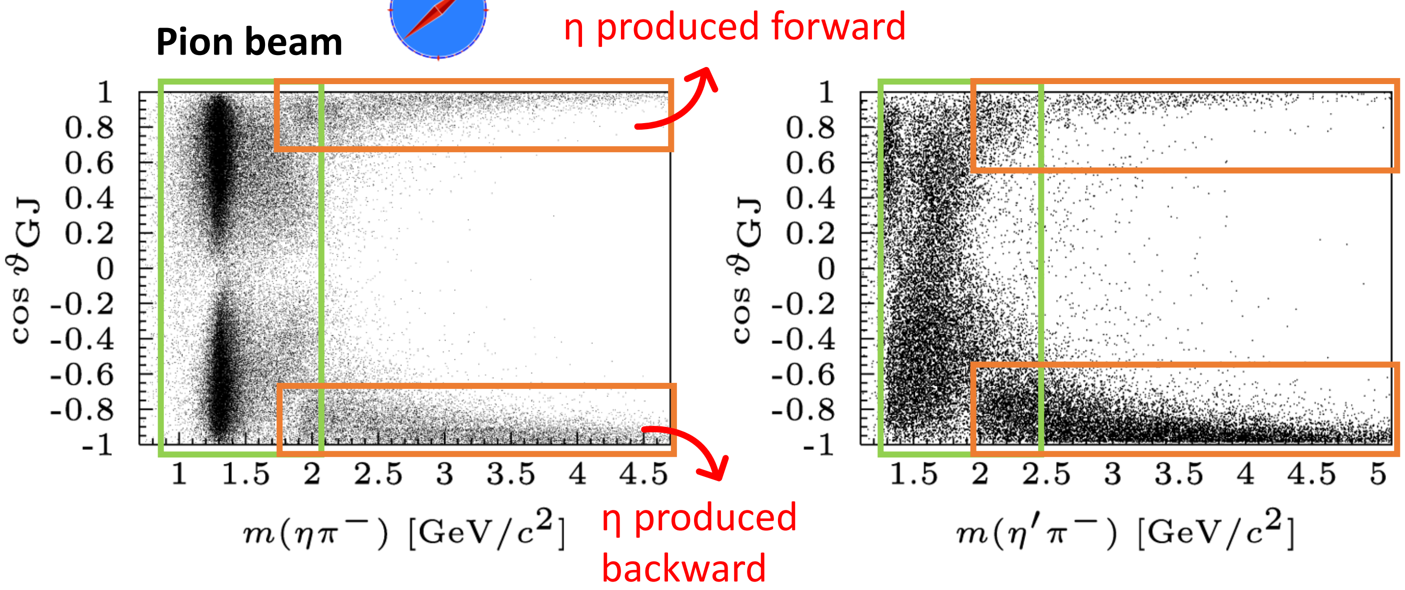

COMPASS, *Phys.Lett.B* 740, 303 (2015)

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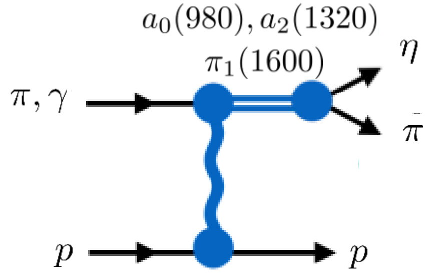

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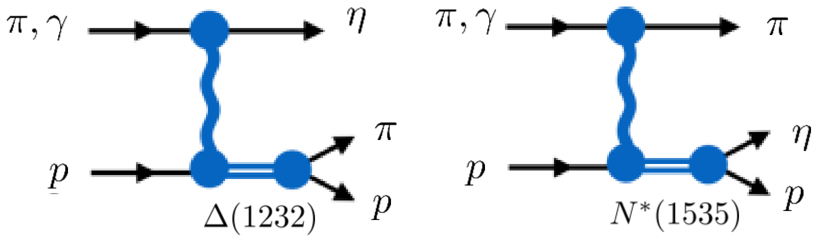

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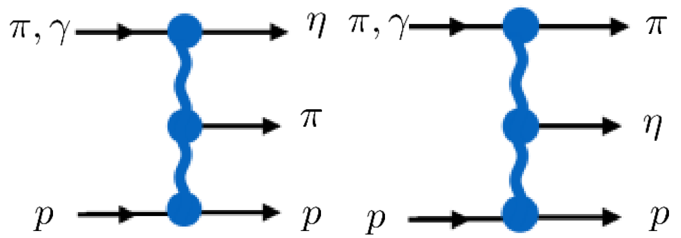
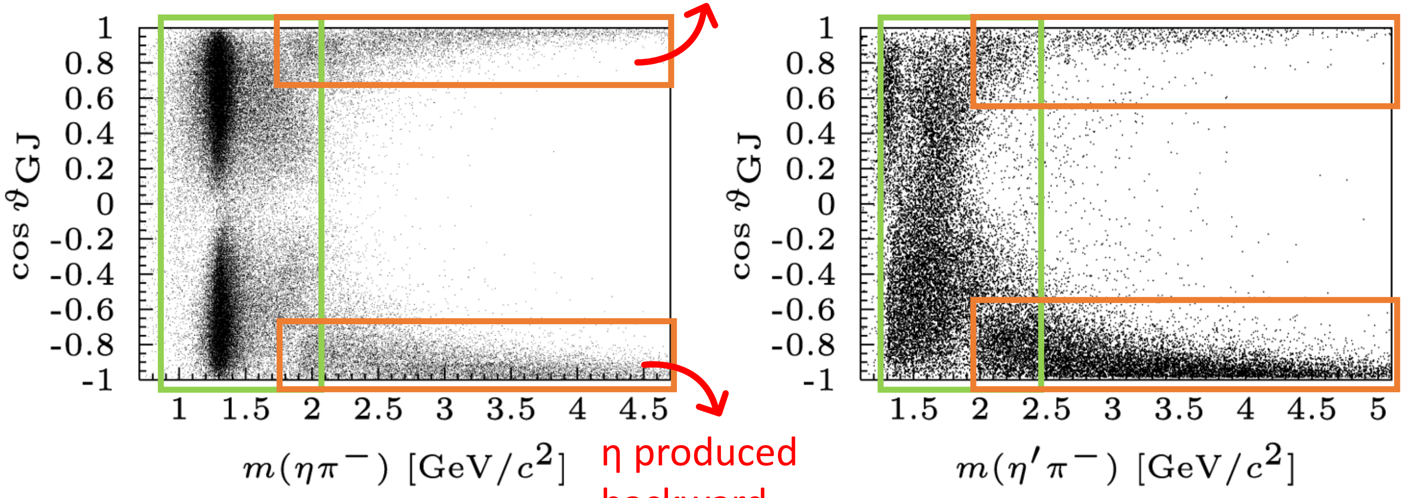


Pion beam

η produced forward



η produced backward

COMPASS, *Phys.Lett.B* 740, 303 (2015)

✳ **Forward-backward asymmetry:**

$$A_{\mathrm{FB}}(m^2_{\eta\pi}) = \frac{F(m^2_{\eta\pi}) - B(m^2_{\eta\pi})}{F(m^2_{\eta\pi}) + B(m^2_{\eta\pi})}$$

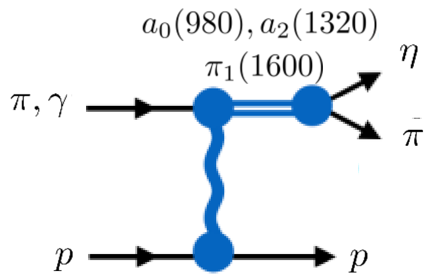
Interference between even and odd partial waves

→ Odd partial waves are exotic (e.g. 1^{-+})

Presence of exotic partial waves (also at low energies)

$\eta^{(\prime)}\pi$ final state

* Meson resonances



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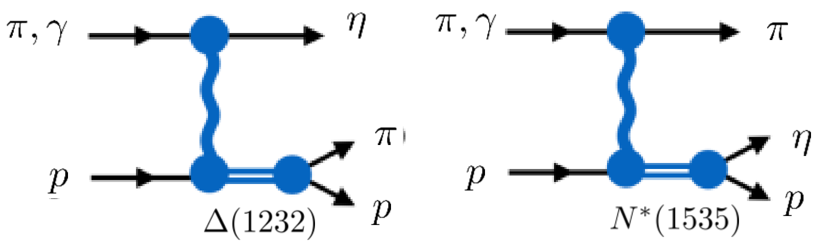

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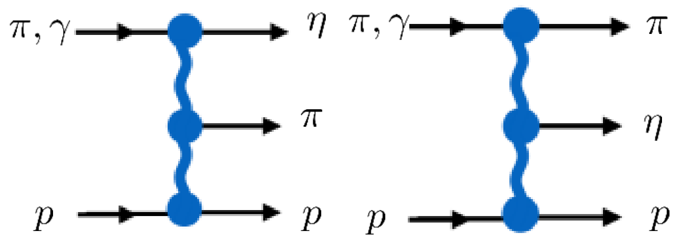

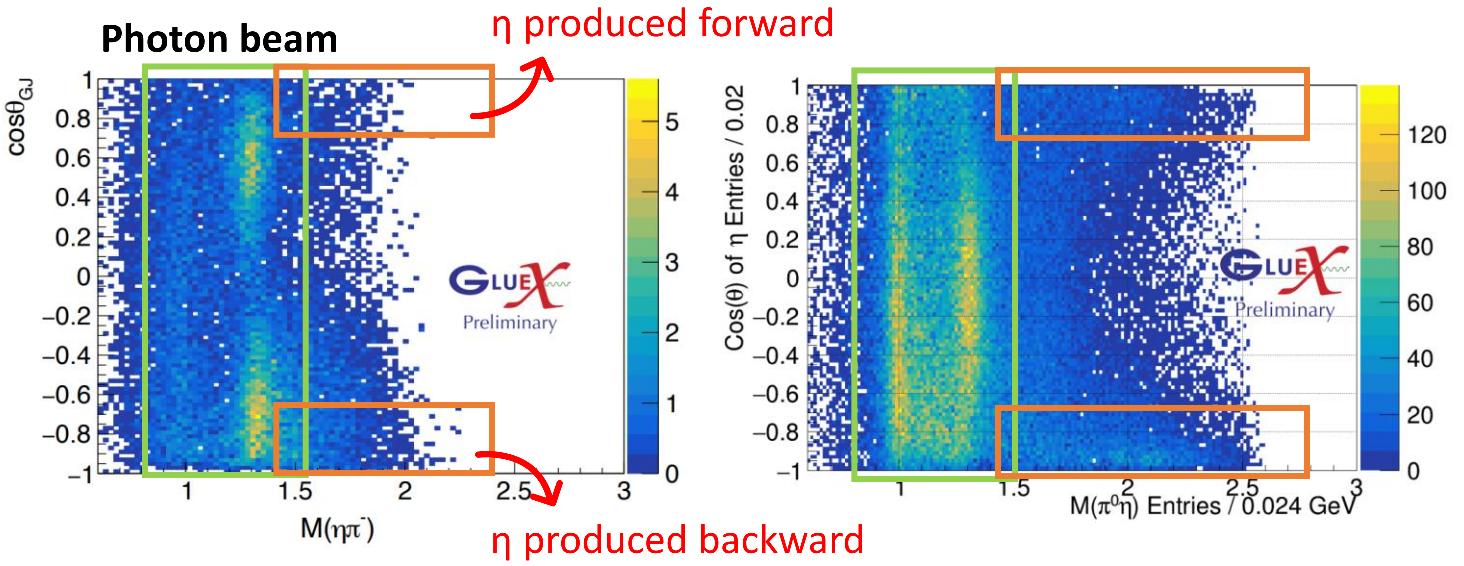

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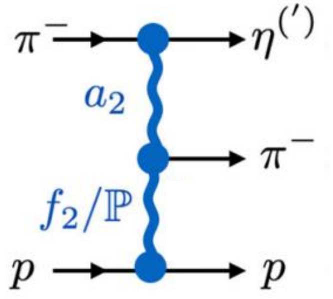
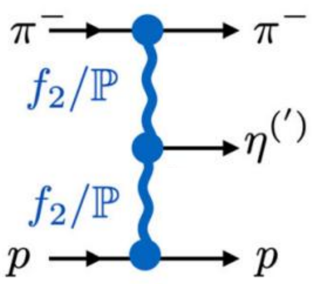
Double Regge production of $\eta^{(\prime)}\pi$ at COMPASS

* ✳ Dominant exchanges:

Fast η cos θ ≈ +1



Fast π cos θ ≈ -1



Double Regge production of $\eta^{(\prime)}\pi$ at COMPASS

∗ Dominant exchanges:

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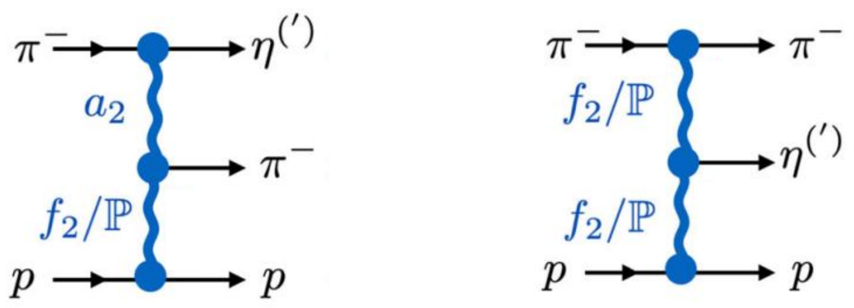
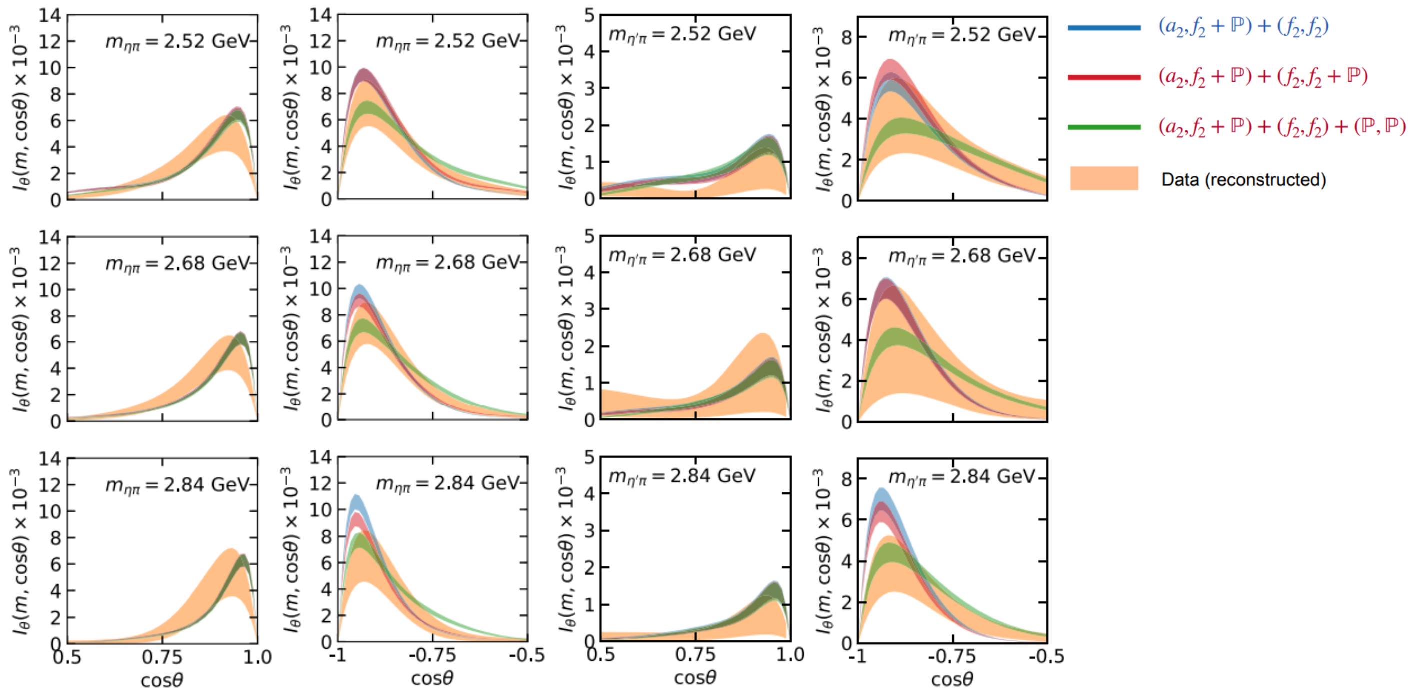


L.Bibrzycki, et al. (JPAC), Eur.Phys.J.C 81, 647 (2021)



∗ Pomeron exchange needed to describe the data

∗ $(\mathbb{P}, \mathbb{P})$ more important for $\eta'\pi$

Double Regge production of $\eta^{(\prime)}\pi$ at COMPASS

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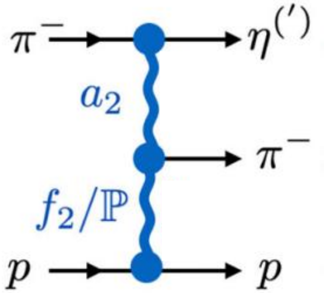

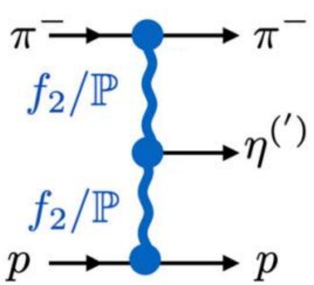

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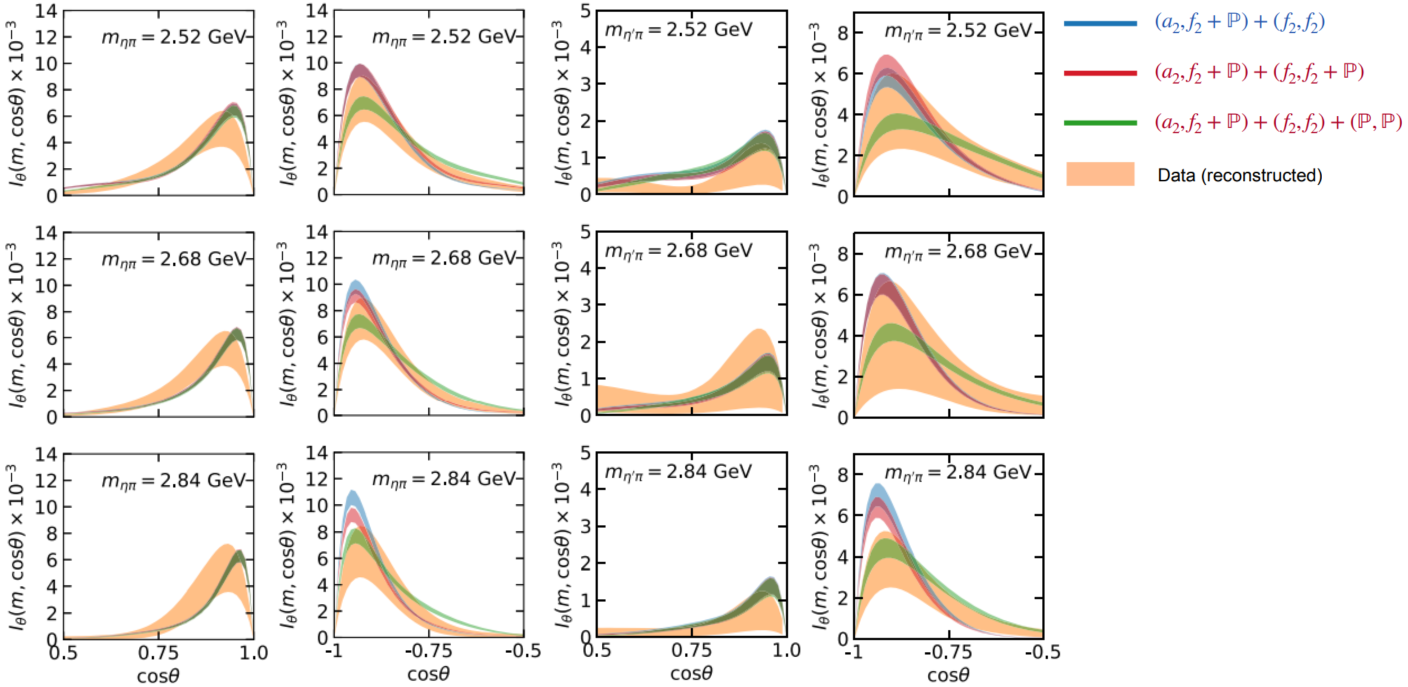
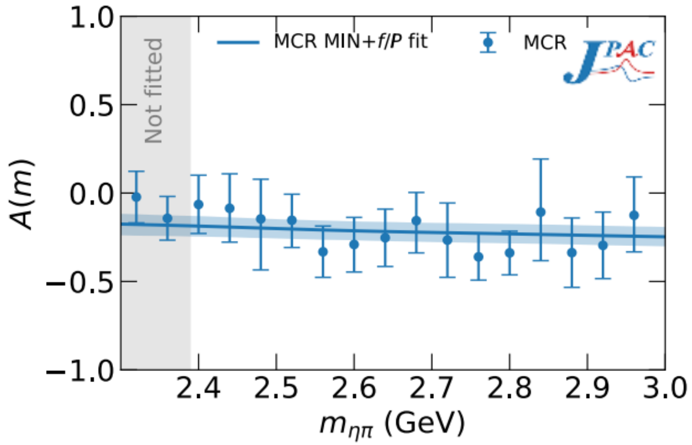
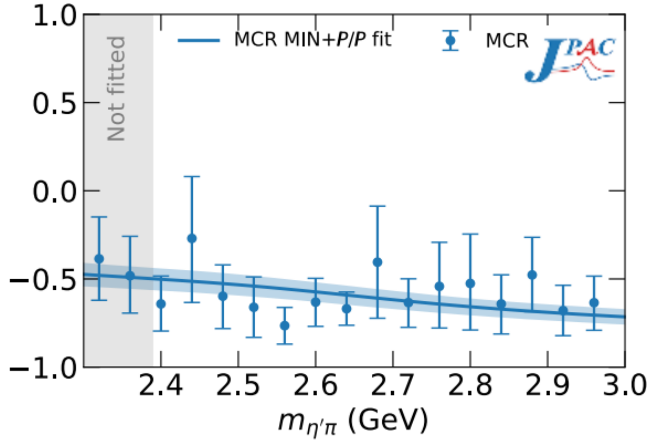
L.Bibrzycki, et al. (JPAC), Eur.Phys.J.C 81, 647 (2021)



∗ Asymmetry originating mainly from $(a_2, f_2 + \mathbb{P}) \neq (f_2, f_2 + \mathbb{P})$, and also $(\mathbb{P},\mathbb{P})$, specially for $\eta'\pi$

∗ Pomeron couples more strongly to η'





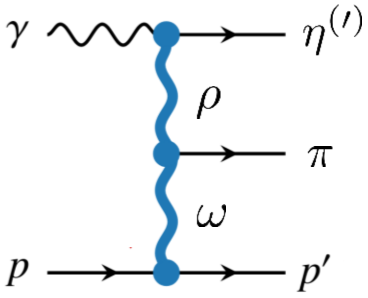
Double Regge photoproduction of $\eta^{(\prime)}\pi$

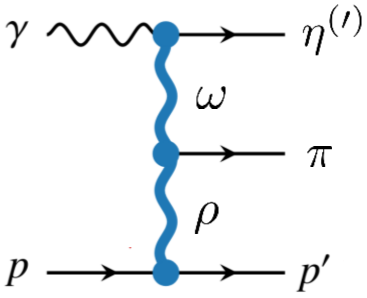
GM, V.Mathieu, et al. (JPAC), Phys.Lett.B 872, 140101 (2026)

* Vector (natural parity) exchanges are dominant

Fast η

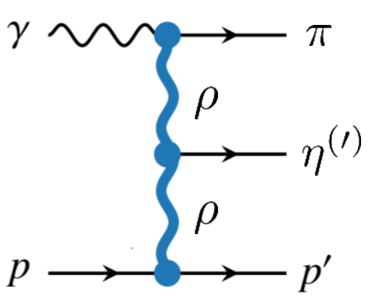
$\cos\theta \approx +1$

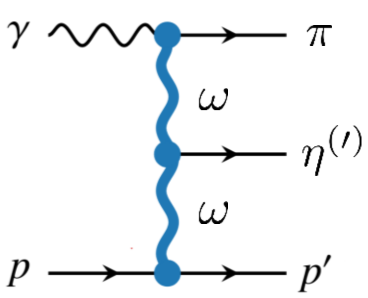




Fast π

$\cos\theta \approx -1$





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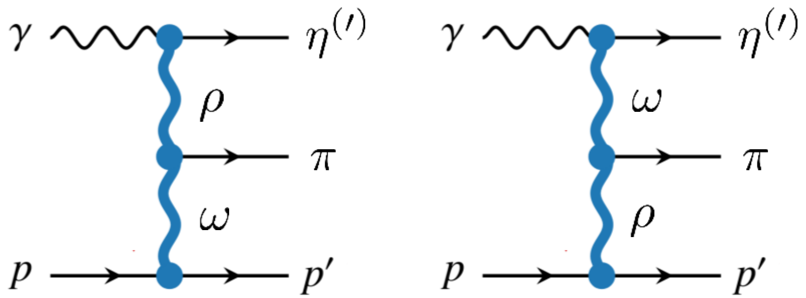

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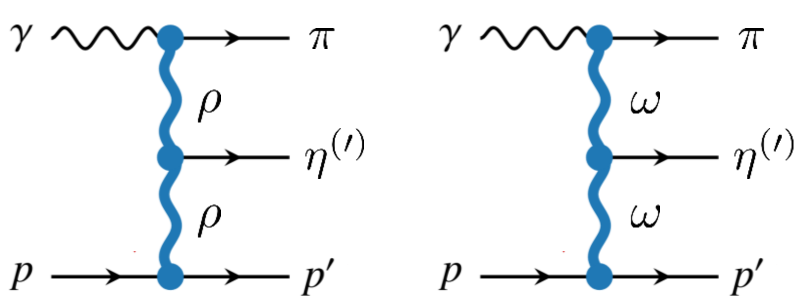
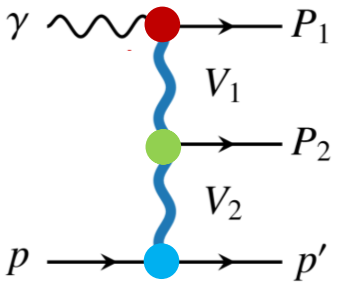


* Lorentz structure of the vertices:



Top vertex: $\langle V_1|\gamma P_1\rangle = \frac{g_{\gamma V_1 P_1}}{m_0} i\epsilon_{\alpha\beta\mu\nu}\varepsilon_\gamma^{\alpha *} q_\gamma^\beta q_{V_1}^\mu \varepsilon_{V_1}^\nu$

Middle vertex: $\langle V_2|V_1 P_2\rangle = \frac{g_{V_1 V_2 P_2}}{m_0} i\epsilon_{\alpha\beta\mu\nu}\varepsilon_{V_1}^{\alpha *} q_{V_1}^\beta q_{V_2}^\mu \varepsilon_{V_2}^\nu$

Bottom vertex: $\langle N'|V_2 N\rangle = \bar{u}(\vec{q}_{p'},\mu')\left[(g_1^{V_2}+g_2^{V_2})\gamma_\nu - g_2^{V_2}\frac{(q_p+q_{p'})_\nu}{2m_p}\right]u(\vec{q}_p,\mu)$

All couplings are known

Double Regge photoproduction of $\eta^{(\prime)}\pi$

GM, V.Mathieu, et al. (JPAC), Phys.Lett.B 872, 140101 (2026)

* Identify the kinematical factor $$K_{\lambda_\gamma \lambda\lambda'} = 2 m_p t_1 |\vec{p}_1||\vec{p}_2| \lambda_\gamma \sum_{\xi=-1}^{1} (-\xi) e^{-i\xi\omega} d^1_{\lambda_\gamma \xi}(\theta_1)\, d^1_{\xi\Lambda}(\theta_2)$$

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* **Reggeization** → sum over spins J_1 and J_2

$$K_{\lambda_\gamma \lambda\lambda'} \to K_{\lambda_\gamma \lambda\lambda'} \times R\,(\alpha_1(t_1), \alpha_2(t_2), s_1, s_2, \kappa)$$

with $$\kappa^{-1} \equiv \frac{s}{\alpha' s_1 s_2}$$

Double Regge photoproduction of $\eta^{(\prime)}\pi$

GM, V.Mathieu, et al. (JPAC), Phys.Lett.B 872, 140101 (2026)

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based on the model of Shimada, Martin, and Irving

Shimada, Martin, Irving, Nucl. Phys. B 142 (1978)

poles for integer $\alpha_i(t)$

$$R(\alpha_1, \alpha_2, s_1, s_2, \kappa) = [(\alpha_1 - 1)\Gamma(1-\alpha_1)]\,[(\alpha_2 - 1)\Gamma(1-\alpha_2)]$$
$$\times \left[\xi_1\xi_{21}\kappa^{1-\alpha_1} V(\alpha_1, \alpha_2, \kappa) + \xi_2\xi_{12}\kappa^{1-\alpha_2} V(\alpha_2, \alpha_1, \kappa)\right] \underbrace{\left(\frac{s_1}{s_0}\right)^{\alpha_1 - 1} \left(\frac{s_2}{s_0}\right)^{\alpha_2 - 1}}_{\text{asymptotic behavior}}$$

signature factors

vertex function

$$V(\alpha_1, \alpha_2, \kappa) = \frac{\Gamma(\alpha_1 - \alpha_2)}{\Gamma(1-\alpha_2)}\, {}_1F_1(1-\alpha_1, 1-\alpha_1+\alpha_2, -\kappa)$$

Results for $\eta^{(\prime)}\pi$ photoproduction

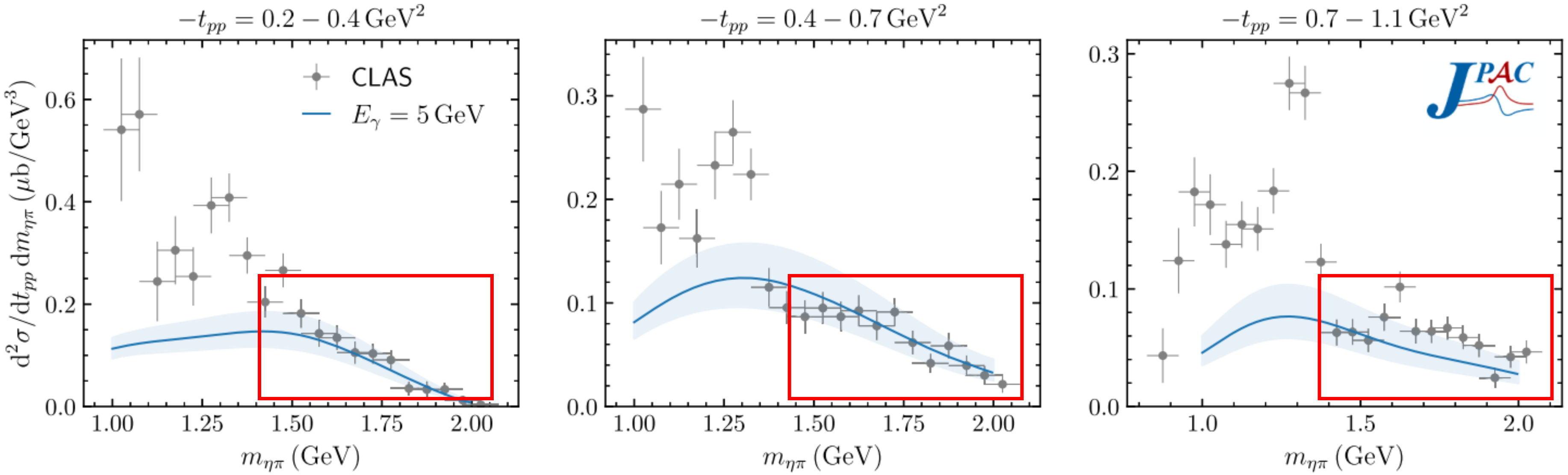
GM, V.Mathieu, et al. (JPAC), Phys.Lett.B 872, 140101 (2026)

Use linear Regge trajectories: $\alpha_i(t_i) = 1 + \alpha'(t_i - m_{V_i}^2)$, with α'=0.9 GeV^{-2}

All parameters of the model completely fixed $(s_0 = 1\ \mathrm{GeV}^2)$

✳ Comparison with CLAS data (not a fit): Phys.Rev.C 102, 032201 (2020)

Shaded bands:
$0.95\ \mathrm{GeV}^2 < s_0 < 1.05\ \mathrm{GeV}^2$

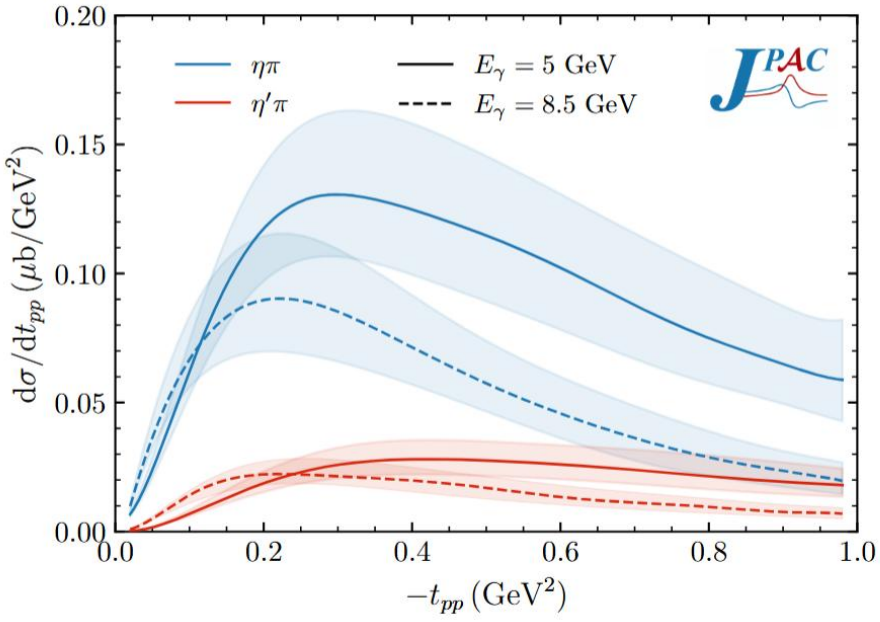


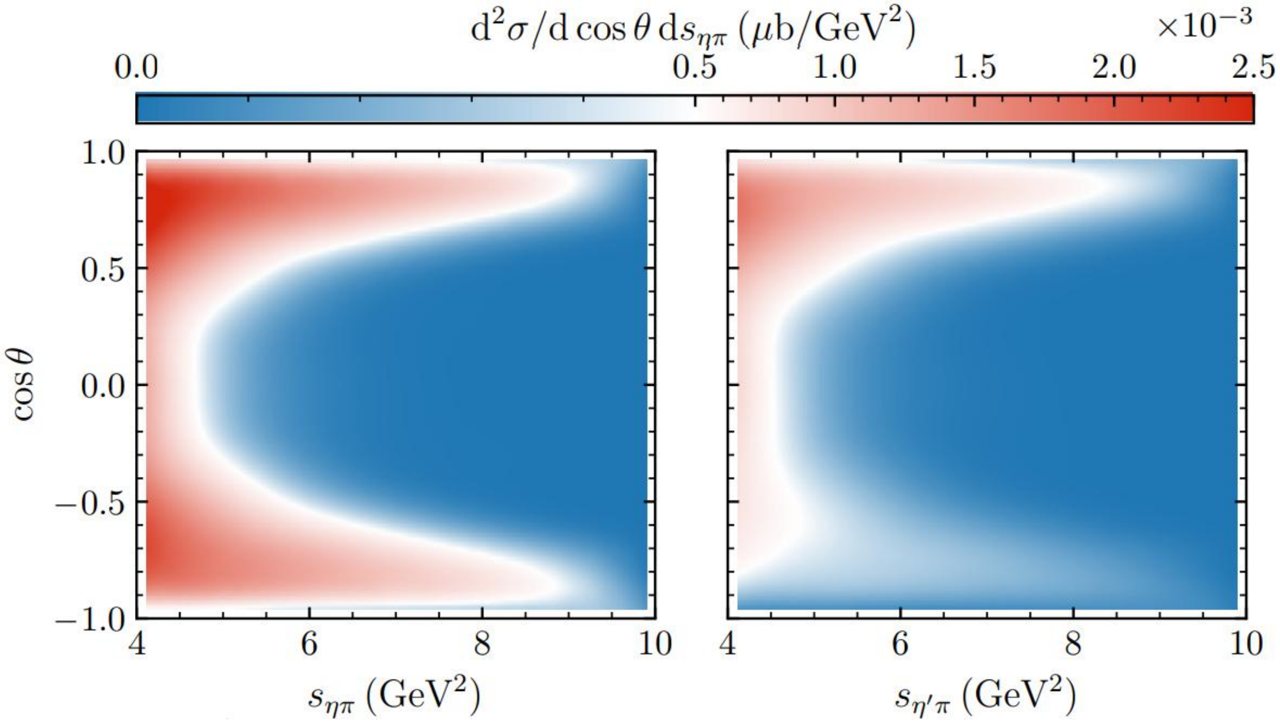
→ Good description of the data above the resonance region

Results for $\eta^{(\prime)}\pi$ photoproduction

GM, V.Mathieu, et al. (JPAC), Phys.Lett.B 872, 140101 (2026)

* Predictions for GlueX energy $E_\gamma = 8.5$ GeV





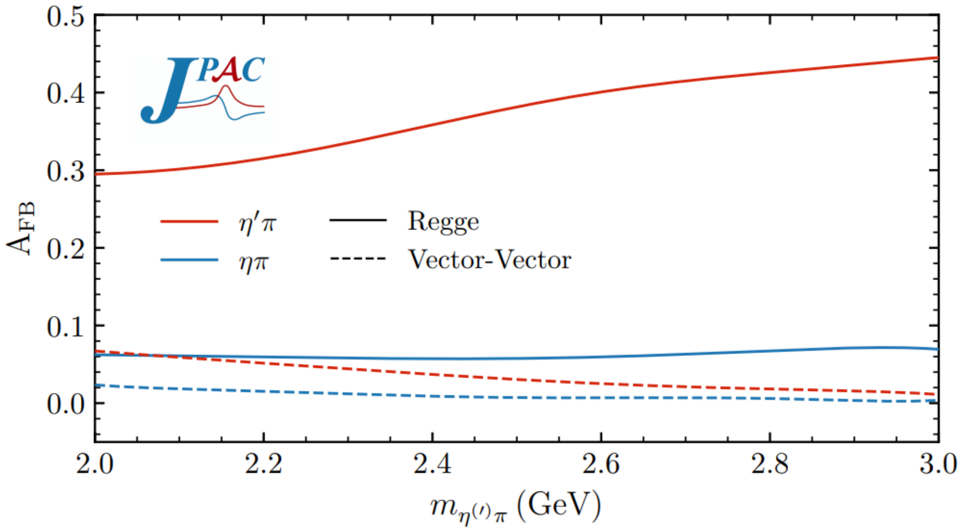
→ Clear forward and backward peaks

Results for $\eta^{(\prime)}\pi$ photoproduction

GM, V.Mathieu, et al. (JPAC), Phys.Lett.B 872, 140101 (2026)

✳ **Forward-backward asymmetry**

$$A_{\mathrm{FB}}(m_{\eta\pi}^2) = \frac{F(m_{\eta\pi}^2) - B(m_{\eta\pi}^2)}{F(m_{\eta\pi}^2) + B(m_{\eta\pi}^2)}$$



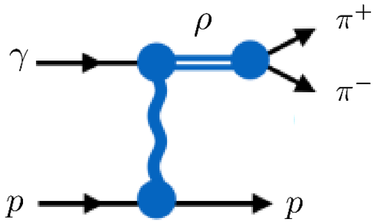
→ Larger for $\eta'\pi$ (but no Pomeron here)

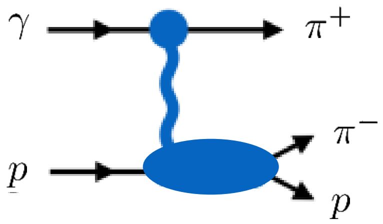
→ Stronger exotic partial waves in $\eta'\pi$

Two pion photoproduction in the ρ region

JPAC, Phys.Rev.D 111, 014002 (2025)

Regge-based model fitted to angular moments from CLAS

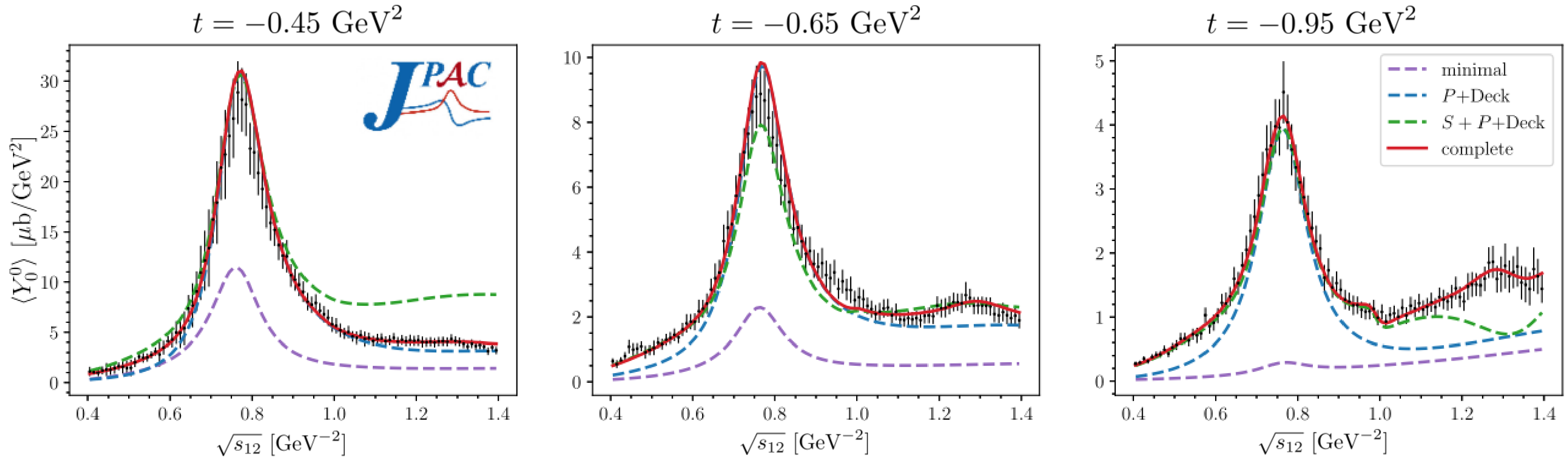




- ⁎ Resonant component: $f_0(500)$, $\rho(770)$, $f_0(980)$, $f_2(1270)$, $f_0(1370)$ produced through Pomeron and natural parity Regge exchanges
- ⁎ Non-resonant component (Deck mechanism)

$$\langle Y_M^L \rangle = \sqrt{4\pi} \int d\Omega^H \frac{d\sigma}{dtd\sqrt{s_1 2}d\Omega^H} \mathrm{Re}\{\mathrm{Y}_\mathrm{M}^\mathrm{L}(\Omega^\mathrm{H})\}$$

→ Much more physics than just Pomeron exchange

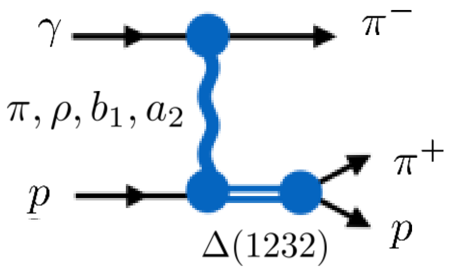


Data:
Phys.Rev.D 80, 072005 (2009)

$\pi\Delta$ photoproduction

V.Shastry et al. (JPAC): arXiv:2026.XXXX

Regge-based model fitted to spin-density matrix elements (SDMEs) from GlueX



- ✳ 2018 JPAC model fitted to cross section and beam asymmetry data from SLAC (relative phases unconstrained) Phys.Lett.B 779, 77(2018)
- ✳ SDMEs allow for a revisited model (more flexible)

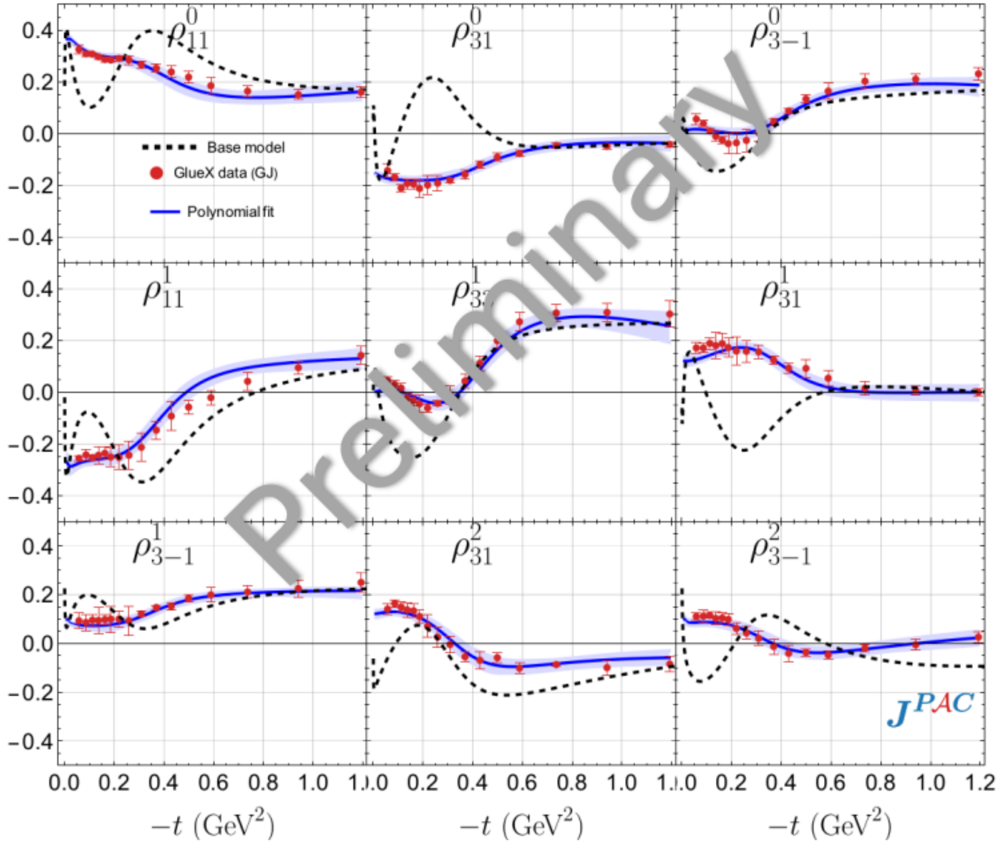
$$W(\Omega_{\pi^+}, \Phi) = 2N \left\{ \rho^0_{33} \sin^2\theta + \rho^0_{11} \left(\frac{1}{3} + \cos^2\theta \right) + \cdots \right\}$$

$$\rho^0_{\lambda_\Delta \lambda'_\Delta} = \frac{1}{2N} \sum_{\lambda_\gamma \lambda_N} T_{\lambda_\gamma \lambda_N \lambda_\Delta}(s,t) T^*_{\lambda_\gamma \lambda_N \lambda'_\Delta}(s,t)$$

$$\vdots$$

→ Better understanding of the production amplitudes

→ Extraction of (universal) Regge couplings



Data:
Phys.Lett.B 863, 139639 (2025)

Dashed lines: old JPAC model

00 Motivation

01 Remarks on Scattering and Regge Theory

02 Pion exchange in pion photoproduction

03 Photoproduction of $\eta^{(\prime)}\pi$ in the double-Regge region

04 Other studies

05 Conclusions

Conclusions

- ✳ A precise understanding of the production mechanisms is crucial for the light hybrid meson searches
- ✳ Regge theory and amplitude analysis describe data and provide predictions with minimal model assumptions

Conclusions

- A precise understanding of the production mechanisms is crucial for the light hybrid meson searches
- Regge theory and amplitude analysis describe data and provide predictions with minimal model assumptions
- **Pion exchange**:
  - → Crucial to describe charge exchange reactions at GlueX/CLAS12 at small momentum transfer
  - → Our approach reconciles gauge invariance and Regge theory
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- **Many more ongoing studies:**
  - → More complicated final states: $\pi^+\pi^-$, K^+K^-, $\pi\Delta$, $b_1 p$, $b_1\Delta$, $\rho\Delta$, …
  - → In parallel with GlueX/CLAS12 experimental analyses

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