Regge approach to light meson photoproduction

Glòria Montaña

Theory Center, Thomas Jefferson National Accelerator Facility

Multi-Particle Reactions Workshop 2025, UC Berkeley, July 28, 2025

Jefferson Lab JSA A SURA Company JPAC EXOHAD EXOTIC HADRONS TOPICAL COLLABORATION

Joint Physics Analysis Center

JPAC

Spectroscopy analyses

⟶ Understand production mechanisms

- **Reggeization of pion exchange**
- **Double Regge exchange**


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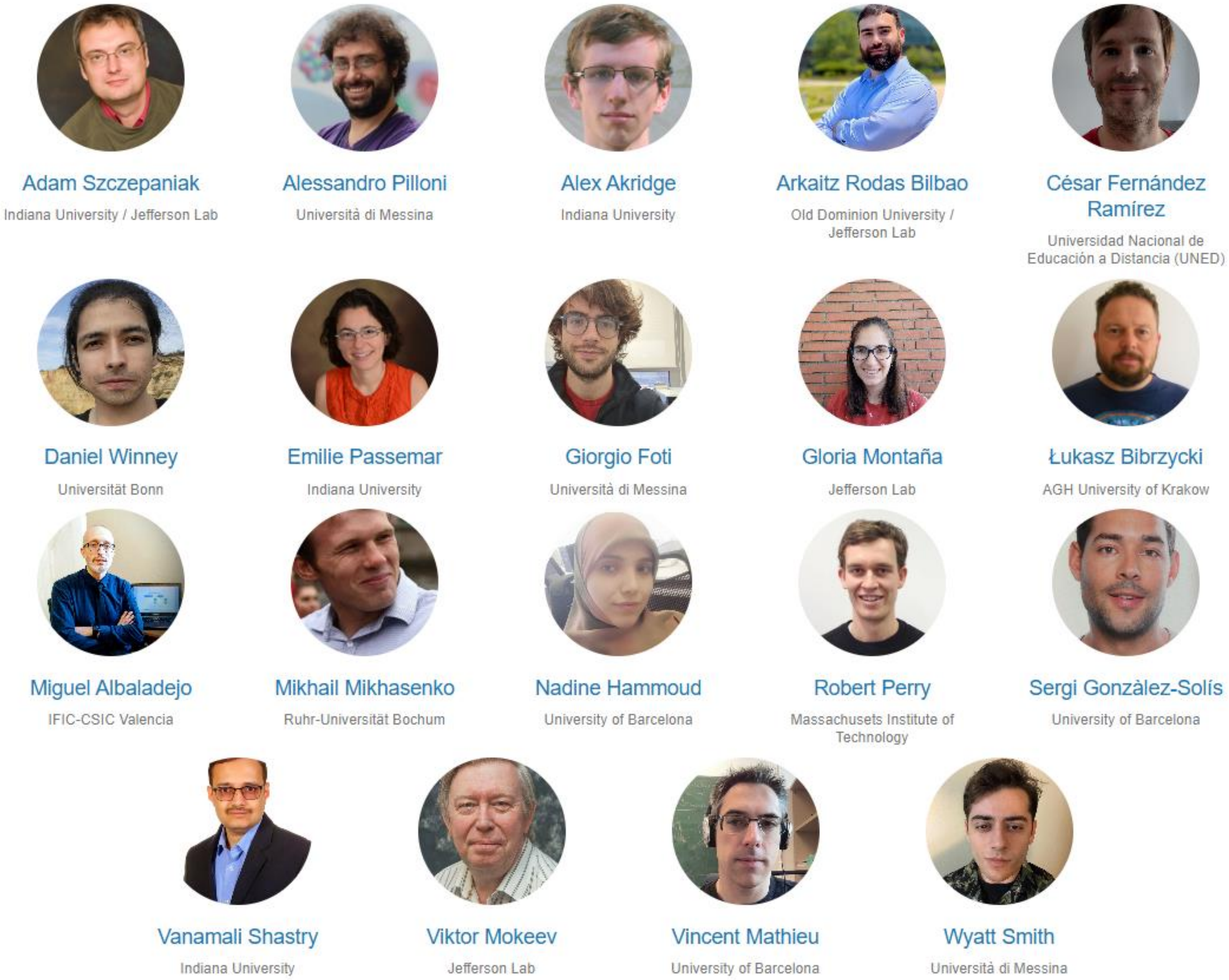
This talk



Regge theory 101

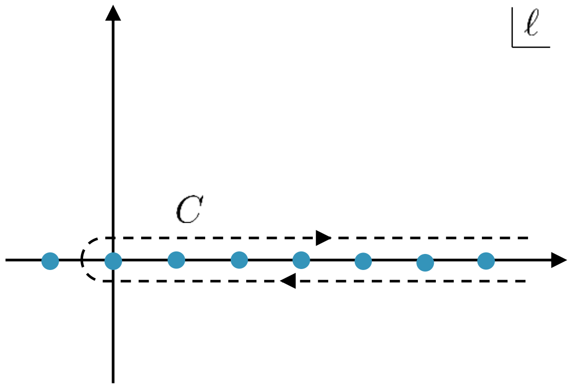
[T. Regge, *Nuovo Cim*. 18 (1960) 947-956]

Partial wave expansion

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

Sommerfeld-Watson transform

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



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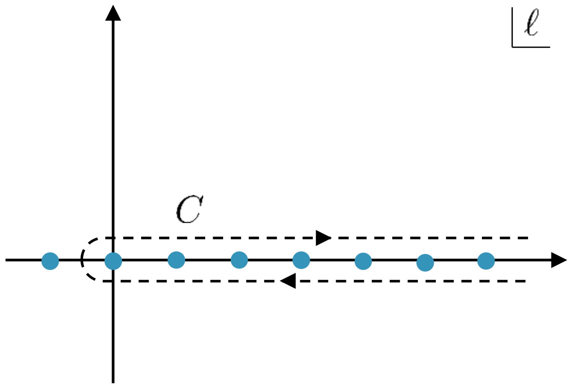

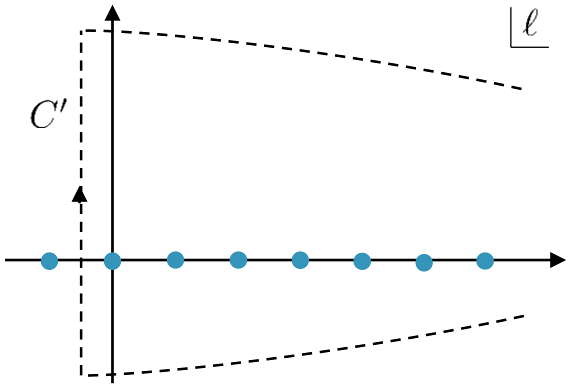

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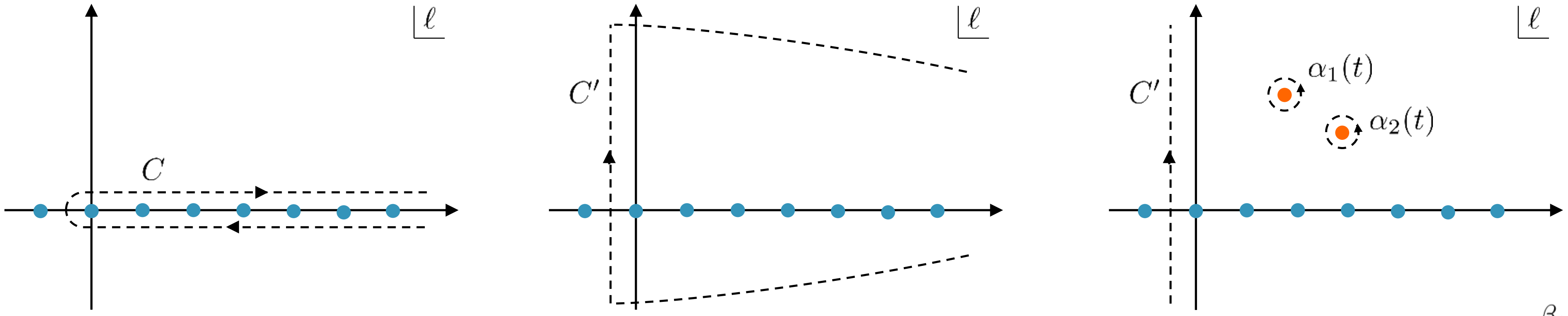
$$\longrightarrow \quad A(s,t) = \underbrace{-\frac{1}{2i}\int_{-\frac{1}{2}-i\infty}^{-\frac{1}{2}+i\infty} d\ell \ldots}_{\text{background } \sim s^{-1/2}} \underbrace{- \sum_i \frac{\pi(2\alpha_i(t)+1)\beta_i(t)}{\sin\left(\pi\alpha_i^{\pm}(t)\right)}\frac{1}{2} P_{\alpha_i}(-z_t)}_{\text{pole contributions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

Regge poles



$$\beta_i(t) = \mathrm{Res} f_{\ell\to\alpha_i(t)}(t)$$

Regge theory 101

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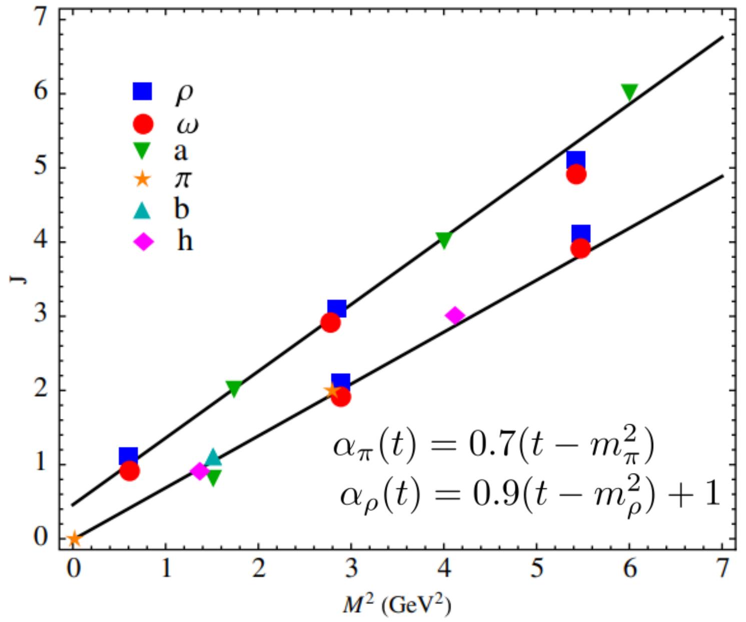
Scattering amplitudes are analytic in *s* and *t* ⟶ Partial waves must be analytic in angular momentum

$$f_\ell(t) = \int \frac{\mathrm{d}z}{2} P_\ell(z) A(z,t) \sim \frac{\beta(t)}{\ell - \alpha(t)}$$

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 (2018) 1, 014041]

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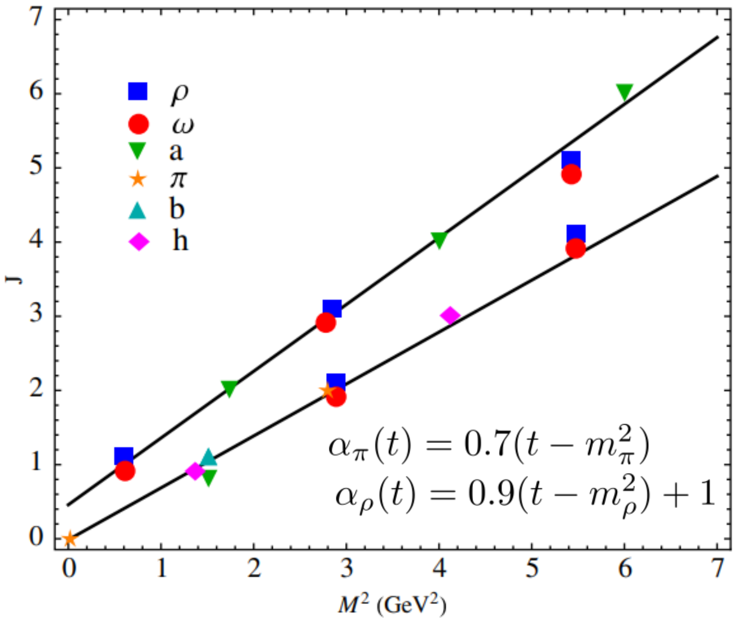

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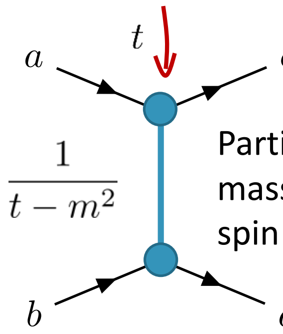
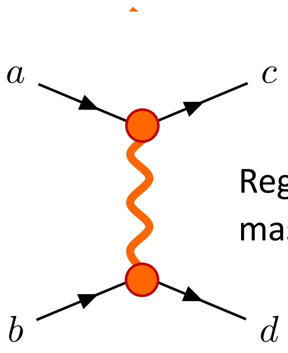


Particle with mass m and spin J

→

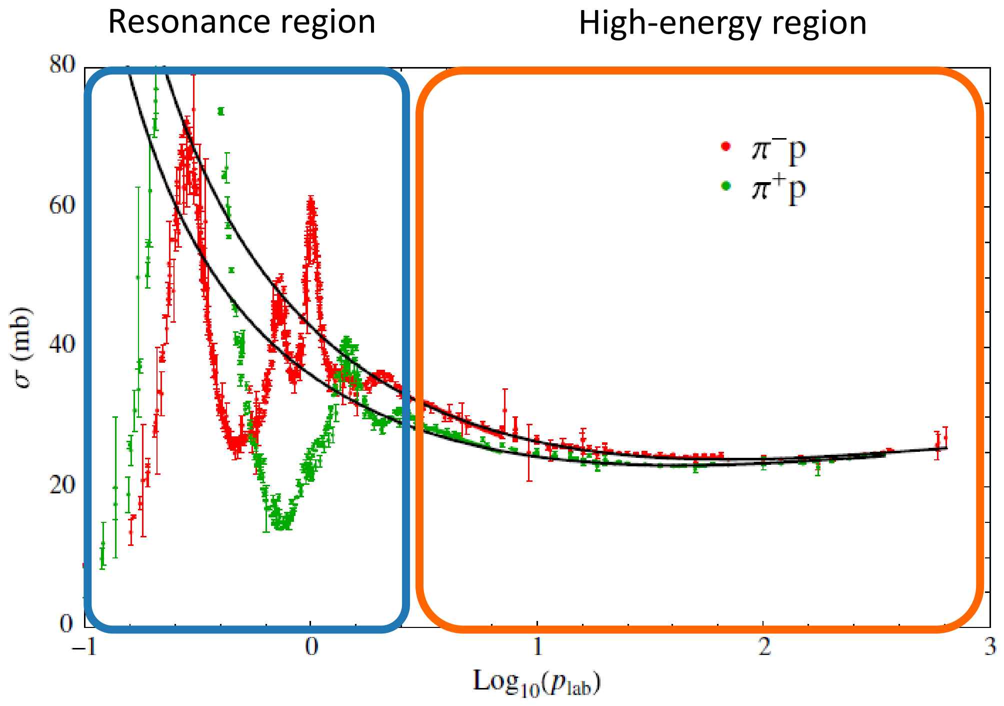


Reggeon with mass $\sqrt{t}$ and spin $\alpha(t)$

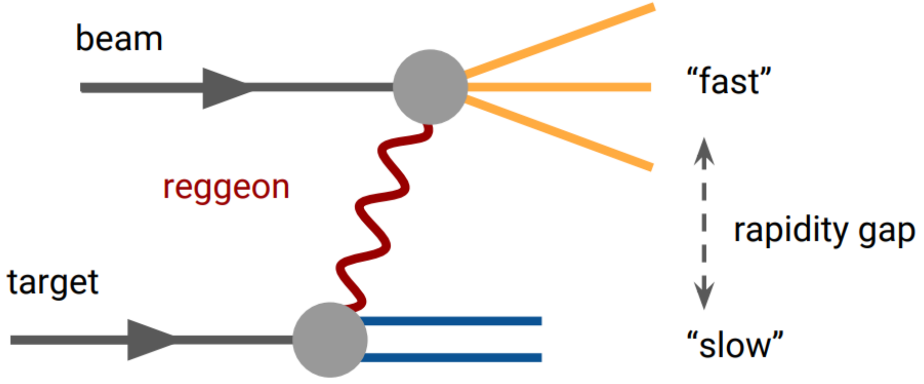
$$\mathcal{P}_{\text{Regge}} = \frac{\pi\alpha'}{\sin(\pi\alpha(t))} \frac{1 + \eta e^{-i\pi\alpha(t)}}{2} \left(\frac{s}{s_0}\right)^{\alpha(t)} \frac{1}{\Gamma(1+\alpha(t))}$$

poles for integer $\alpha(t)$ — signature factor — asymptotic behavior — cancel non-physical poles

When do we use Regge theory?



[V.Mathieu et al., *Phys.Rev.D* 92 (2015) 7]



Low-energy: resonances

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

High energy: Regge exchanges

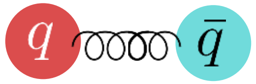
$$A(s,t) \sim \sum_i \frac{g_i}{t - t_i}$$

Analytically connected

Model for diffractive production

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

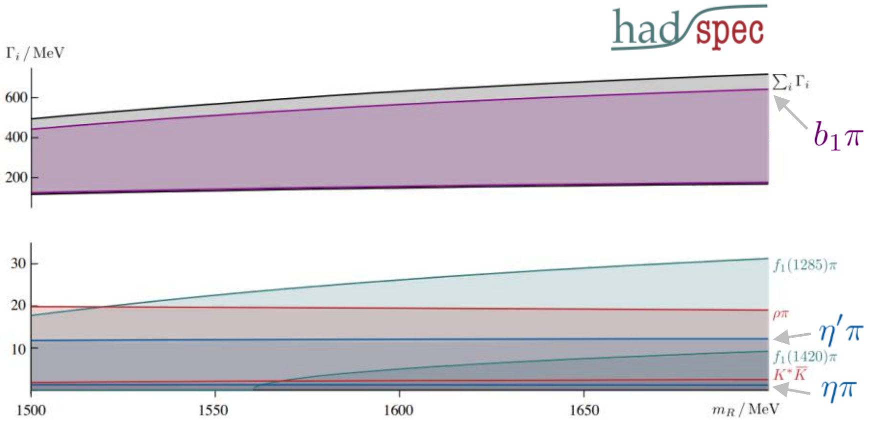
Photoproduction of the hybrid $\pi_1(1600)$



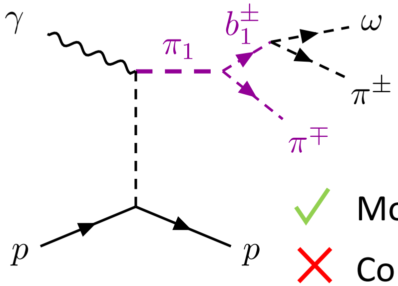
Lightest isoscalar with $J^{PC} = 1^{-+}$

Predicted by lattice QCD

Experimental evidence from COMPASS)

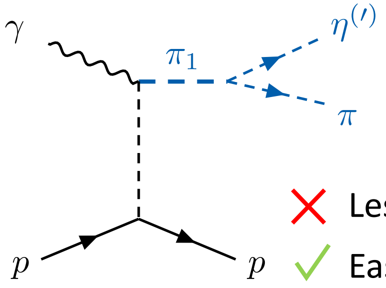


[Woss et al., *Phys.Rev.D* 103 5, 054502 (2021)]



✓ More statistics

✗ Complicated final state



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✓ Easier (less particles)

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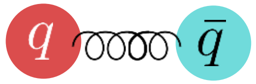

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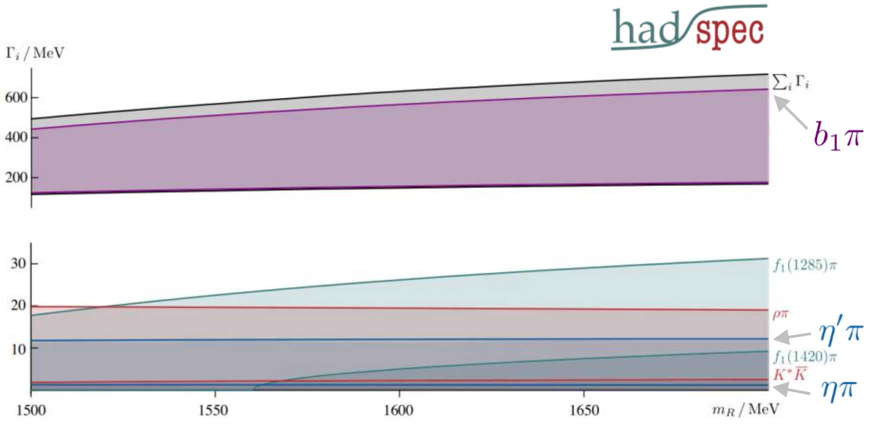

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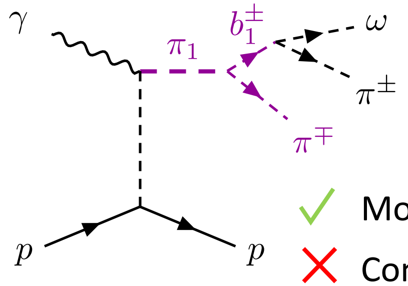

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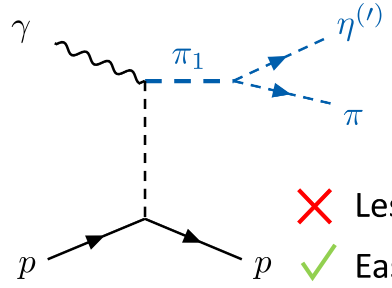

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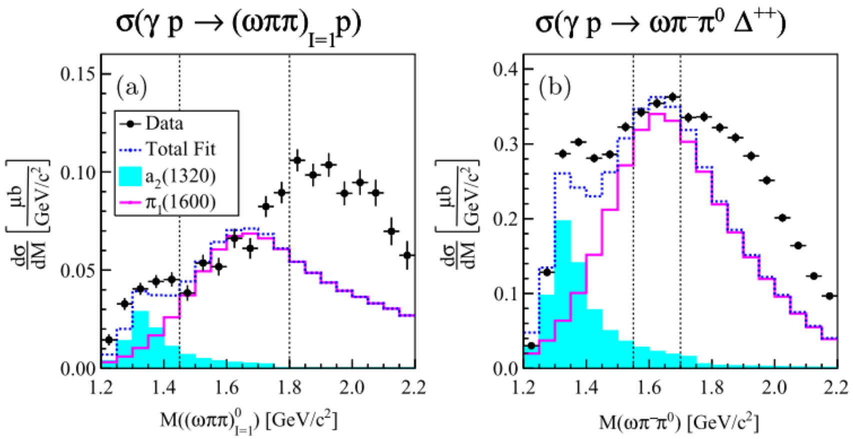
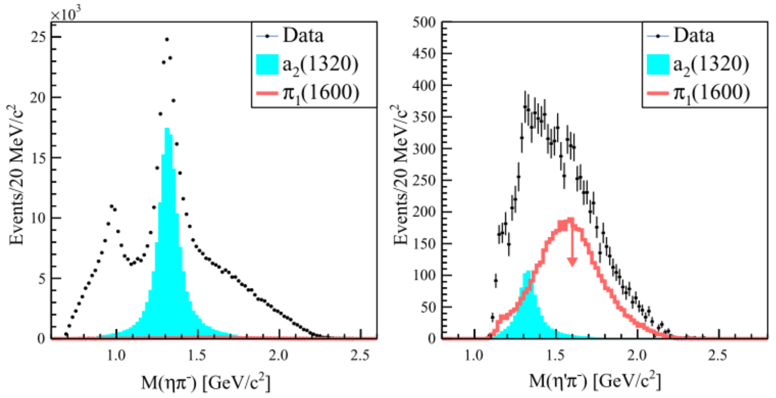
GLUEX



[Afzal et al., *Phys.Rev. Lett.* 133 261903 (2024)]



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Need a better understanding of production mechanisms!

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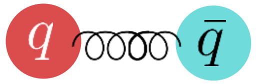

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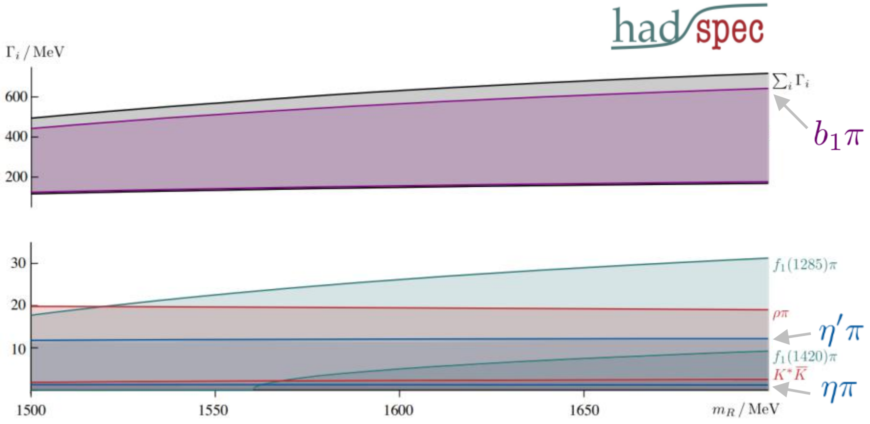

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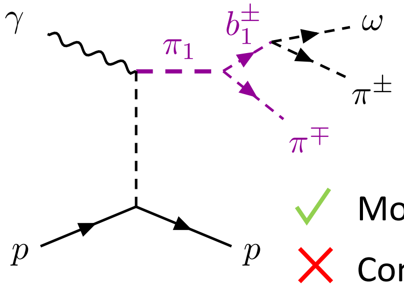

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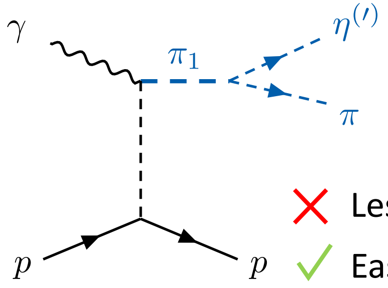

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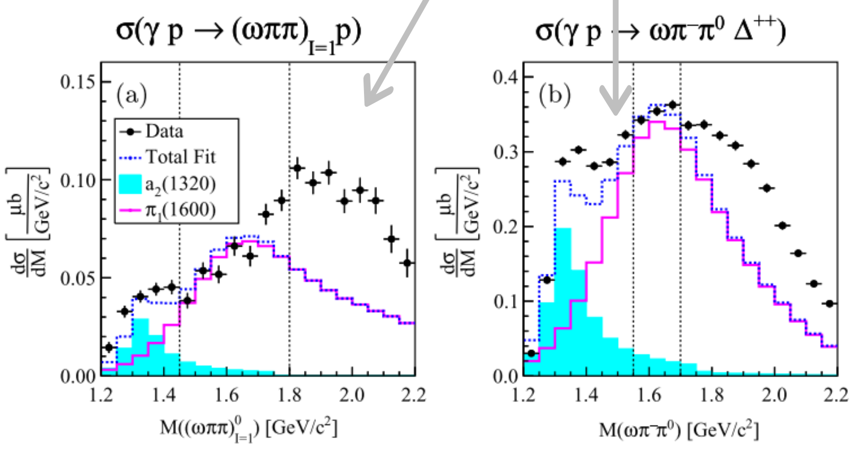
(neutral) pomeron exchange < (charged) pion exchange



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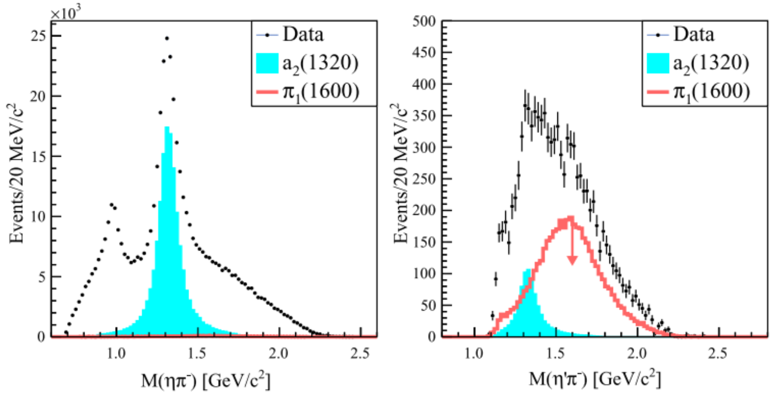

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Need a better understanding of production mechanisms!

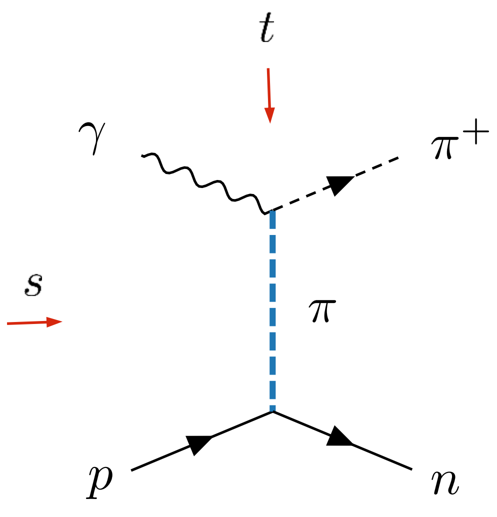
Understanding pion exchange

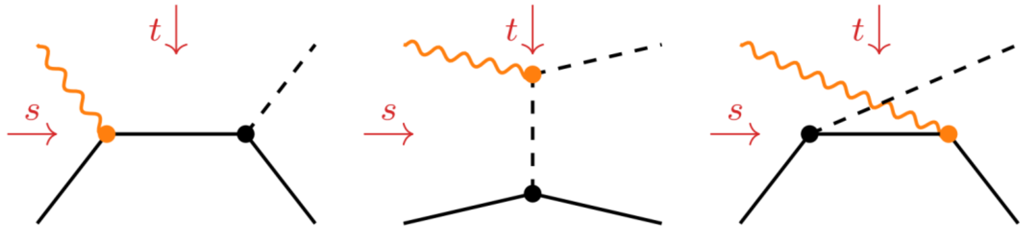
[GM, Daniel Winney, et al. (JPAC), *Phys.Rev.D* 110 (2024) 11, 114012]

Simplest charge-exchange process is pion photoproduction

Pion exchange diagram vanishes in the *t*-channel CM frame

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





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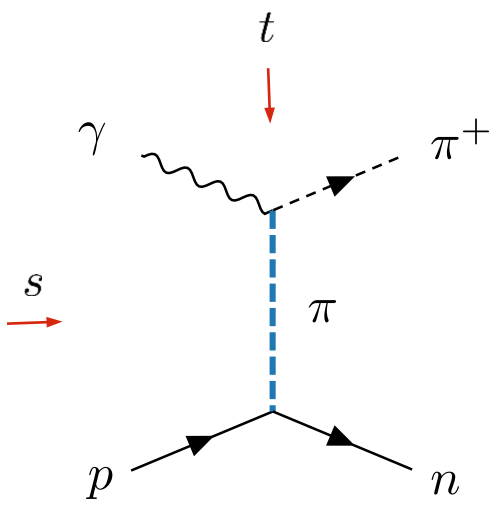

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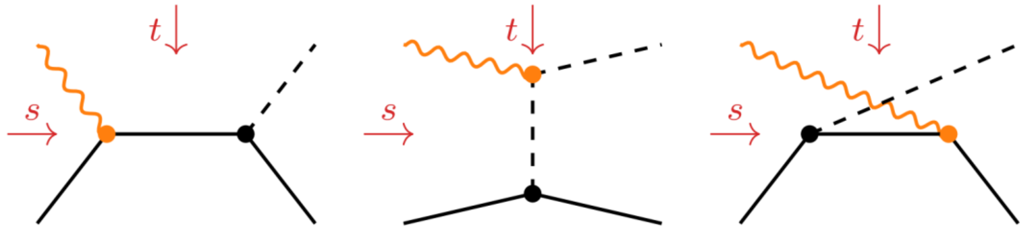
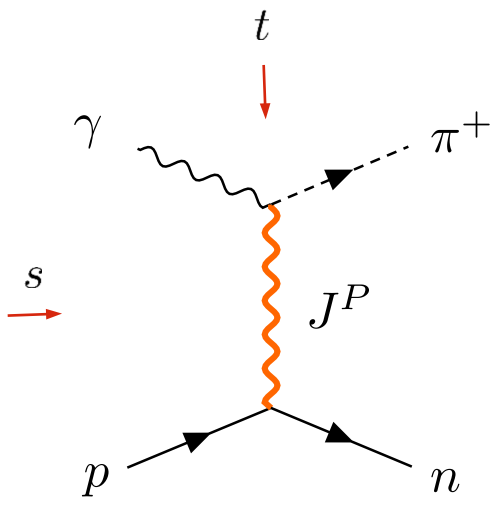


What about the Reggeized pion?

$$A_{\lambda_\gamma \lambda_i \lambda_f}(s,t) = \sum_J (2J+1)\, a^J_{\lambda_\gamma \lambda_i \lambda_f}(t)\, \underbrace{d^J_{\lambda_\gamma \lambda_i - \lambda_f}(\theta_t)}_{J \geq |\lambda_\gamma| = 1}$$

No pion pole?

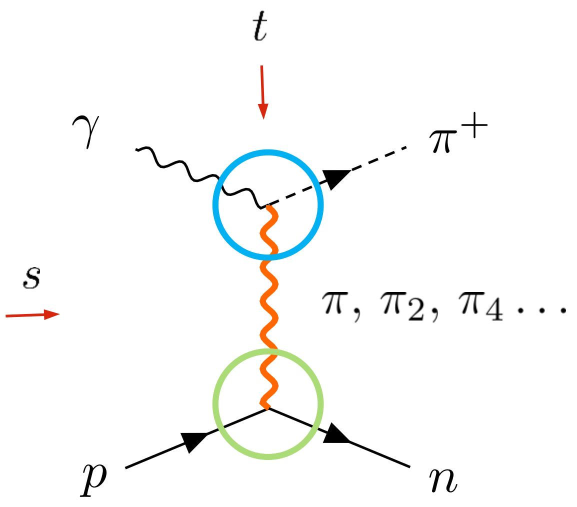


Reggeization of pion exchange

[GM, Daniel Winney, et al. (JPAC), *Phys.Rev.D* 110 (2024) 11, 114012]

1. Build an amplitude for the exchange of a particle of arbitrary spin $J > 0$ (gauge invariant by construction)

$$A^J_{\lambda_\gamma\lambda_i\lambda_f}(s,t) = \sum_{\sigma_J} \frac{V^J_{\lambda_\gamma}(\sigma_J) V^J_{\lambda_i\lambda_f}(\sigma_J)}{J-\alpha(t)} = \underbrace{a^J_{\lambda_\gamma\lambda_i\lambda_f}(t)}_{\propto \frac{1}{\sqrt{J}}} d^J_{\lambda_\gamma\lambda_i-\lambda_f}(\theta_t)$$



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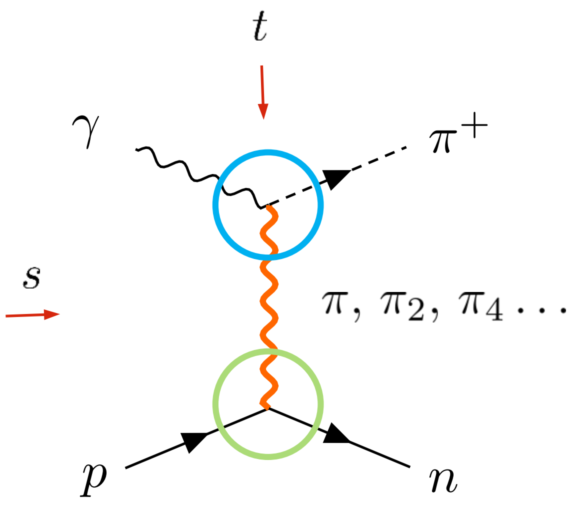

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2. Analytically continue to *J* = 0
   - Use the hypergeometric function

$$d^J_{\lambda_\gamma,0}(\theta_t) \propto \sqrt{J}$$

$$A^{J\to 0}_{\lambda_\gamma \lambda_i \lambda_f}(s,t) \propto \frac{t}{-\alpha(t)} (2\lambda_i \lambda_\gamma \delta_{\lambda_i \lambda_f}) \frac{z_t}{\sqrt{1 - z_t}} \approx i \frac{t}{m_\pi^2 - t} (2\lambda_i \lambda_\gamma \delta_{\lambda_i \lambda_f})$$

The spin *J* → 0 amplitude is finite!

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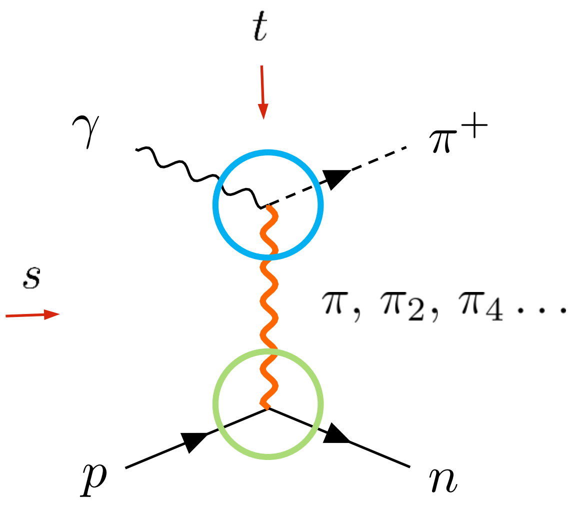

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The spin $J \to 0$ amplitude is finite!

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

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

Results for pion photoproduction

[GM, Daniel Winney, et al. (JPAC), *Phys.Rev.D* 110 (2024) 11, 114012]

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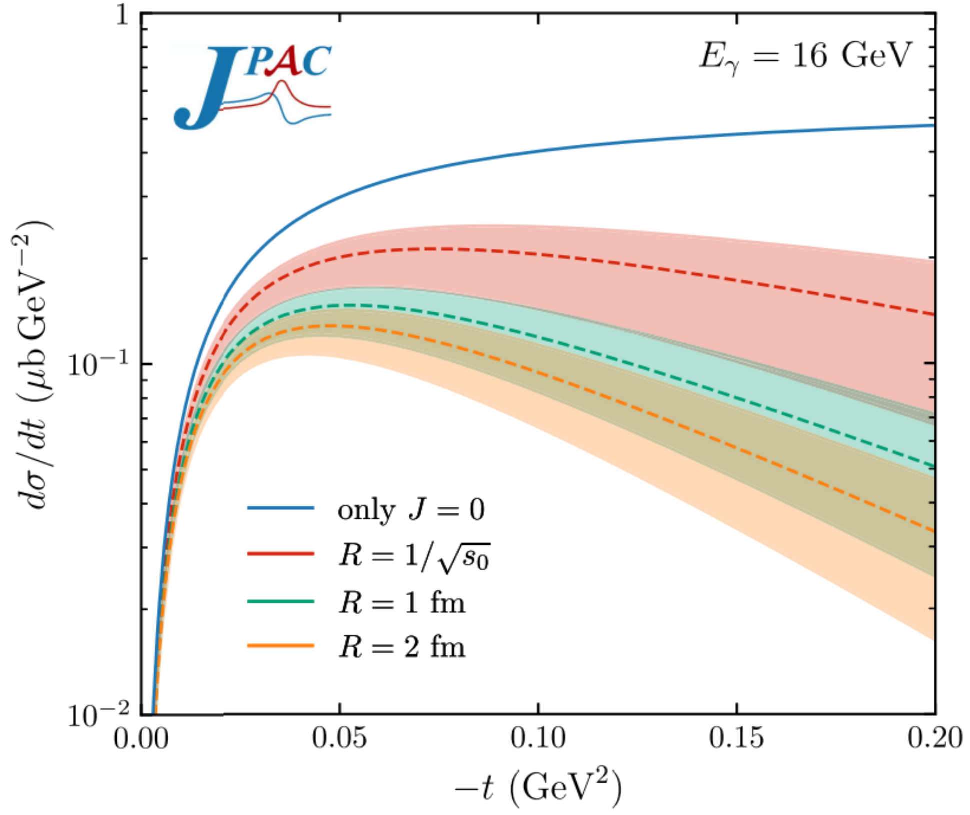

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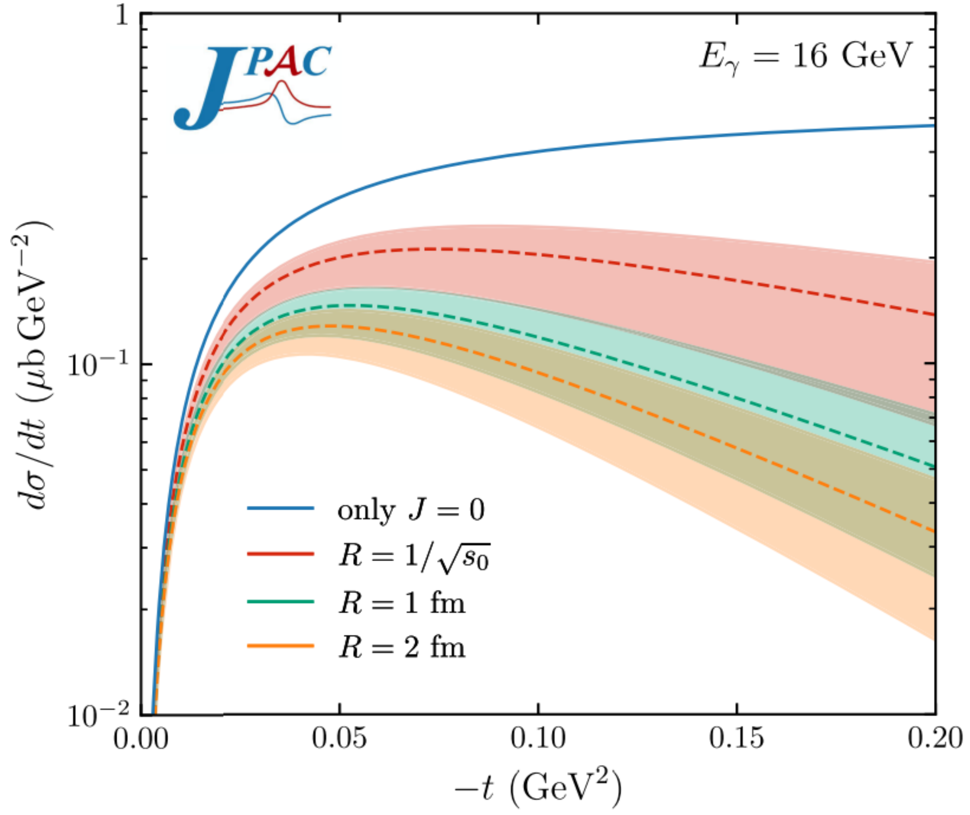
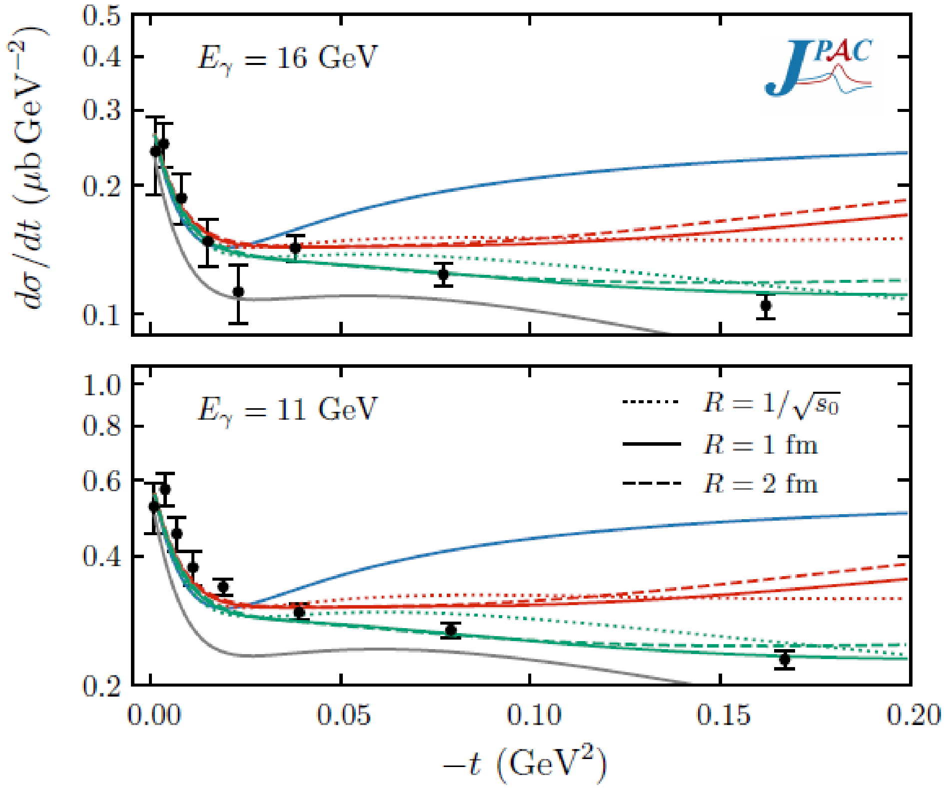


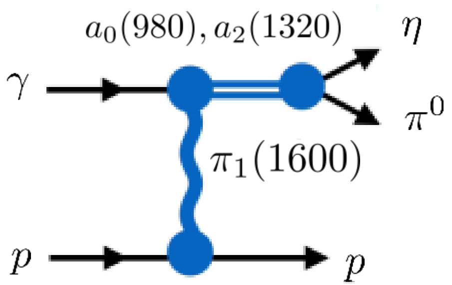
Adding the nucleon magnetic term

- Gauge invariant by itself

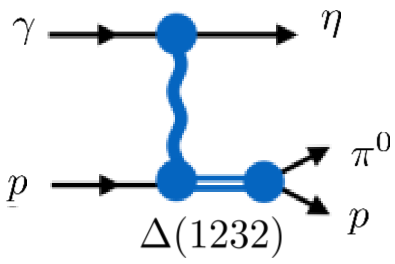


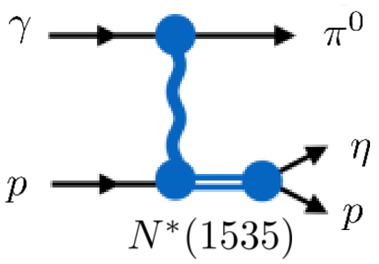
Photoproduction of ηπ and η'π

Meson resonances

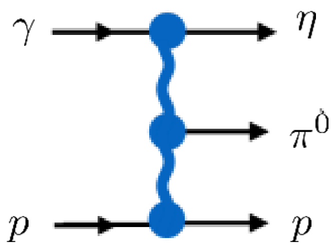


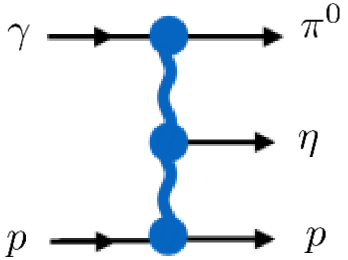
Baryon resonances





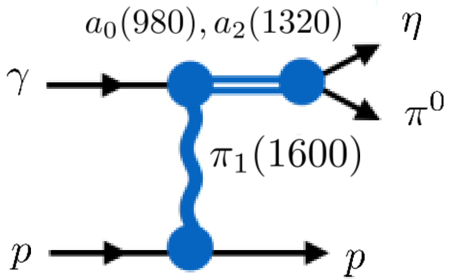
Double Regge production



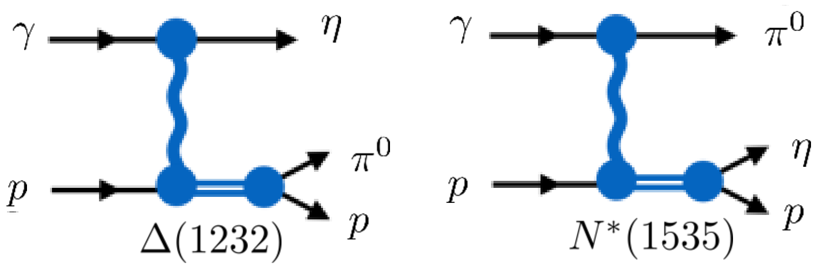


Photoproduction of ηπ and η'π

Meson resonances



Baryon resonances



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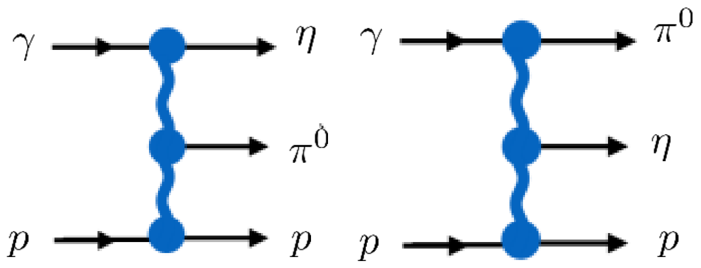
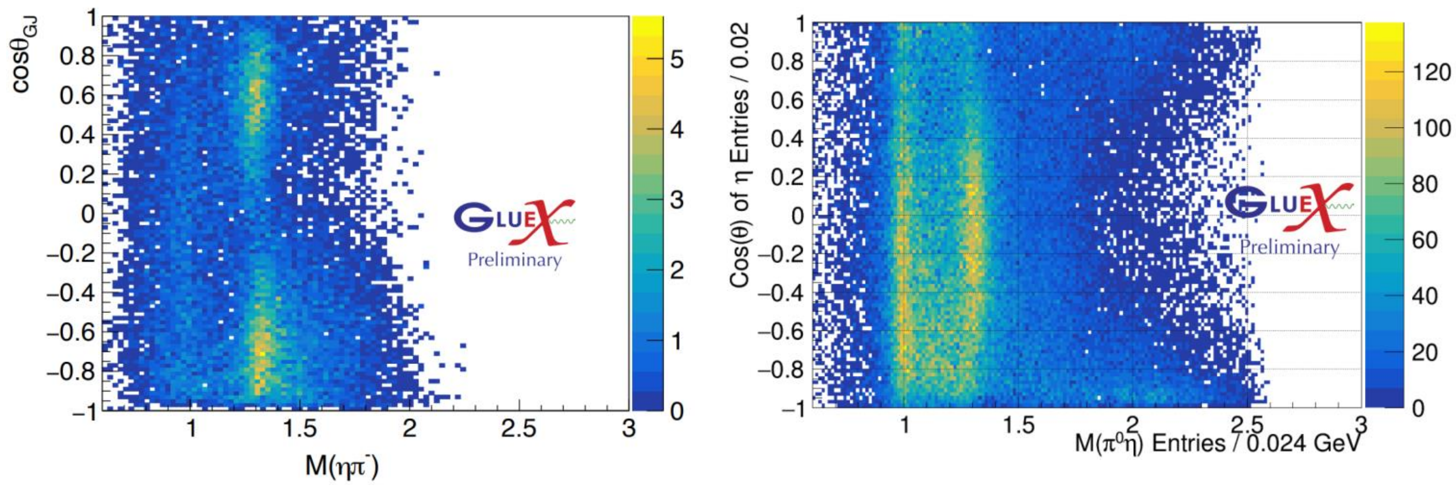
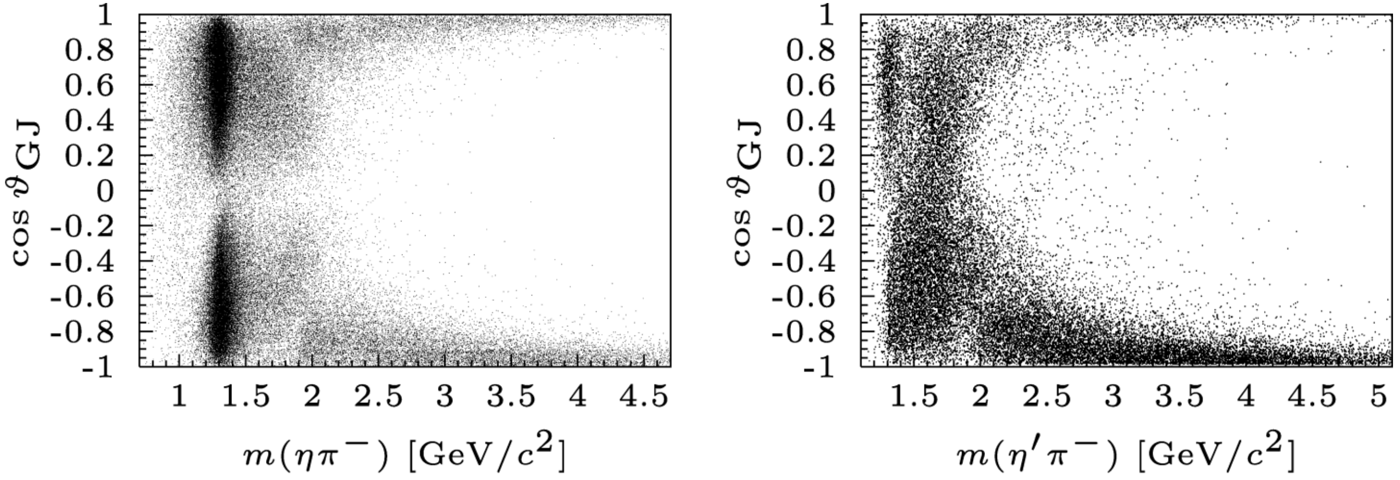


With photon beam



With pion beam

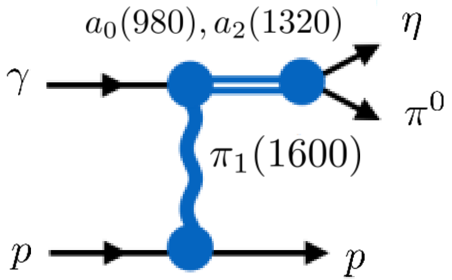


[COMPASS, *Phys.Lett.B* 740 (2015) 303-311]

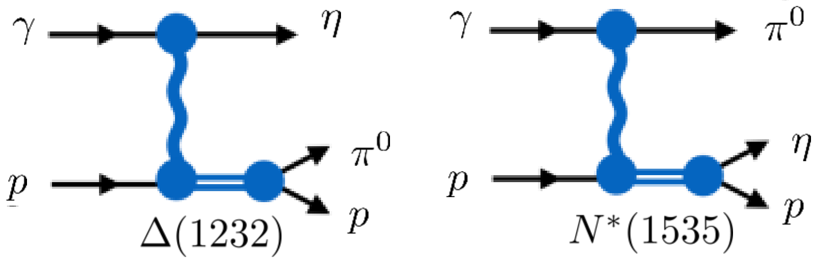
Photoproduction of ηπ and η’π

- Clear signals of the a0(980) and a2(1320)

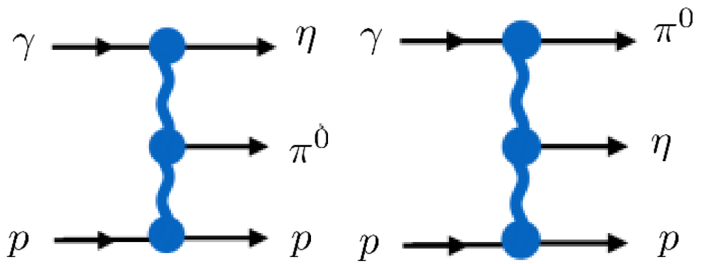
Meson resonances



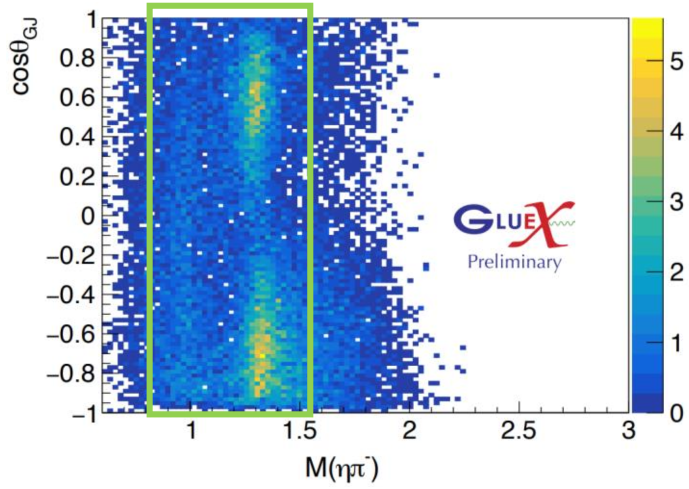
Baryon resonances

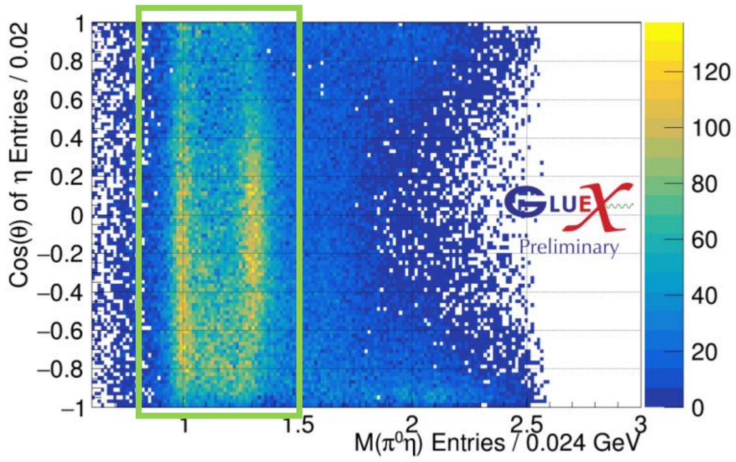


Double Regge production

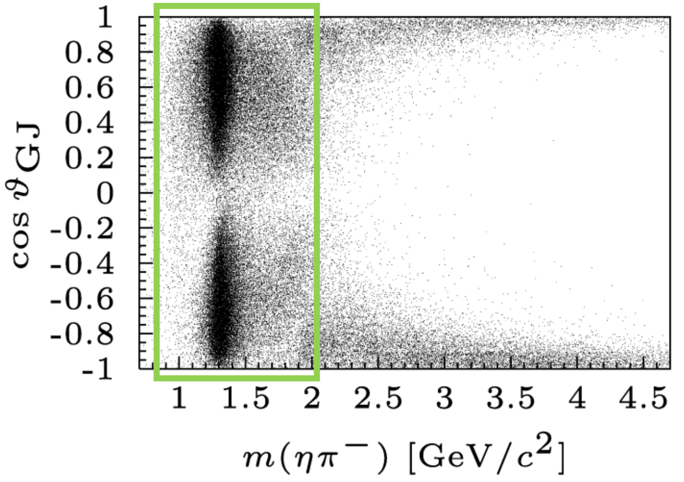


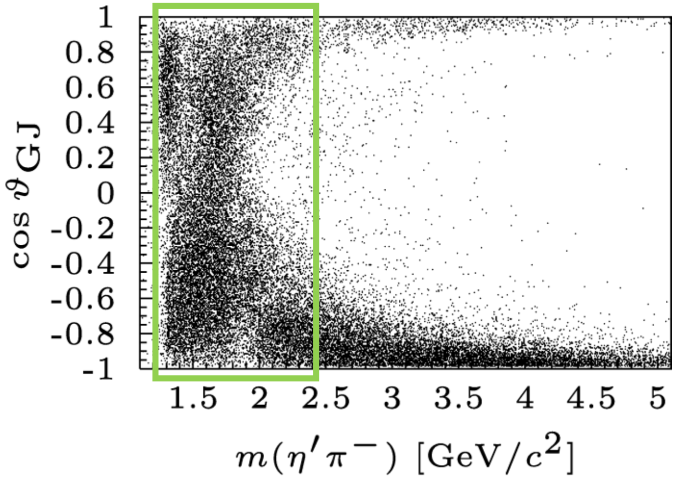
With photon beam





With pion beam



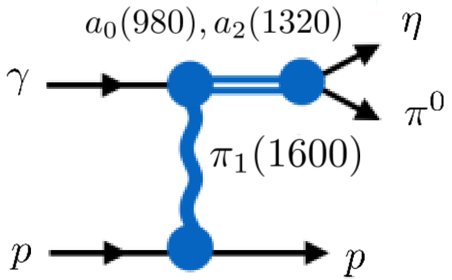


[COMPASS, *Phys.Lett.B* 740 (2015) 303-311]

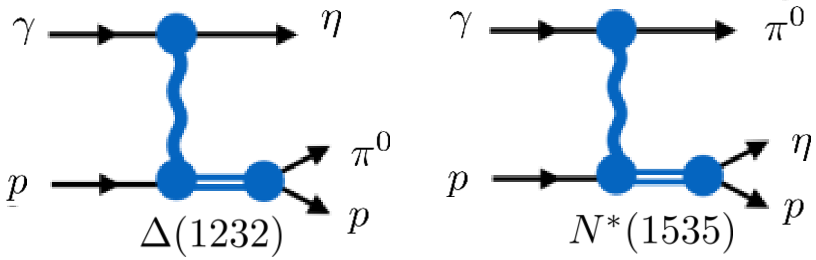
Photoproduction of ηπ and η’π

- Clear signals of the a0(980) and a2(1320)
- Forward-backward asymmetry at high energies

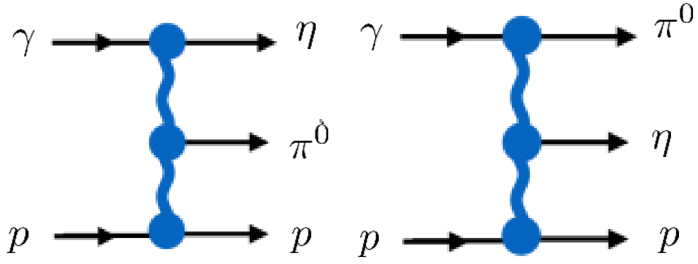
Meson resonances



Baryon resonances

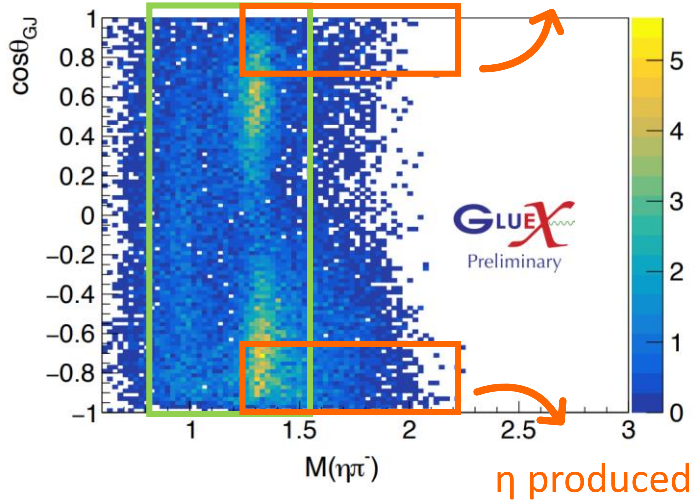


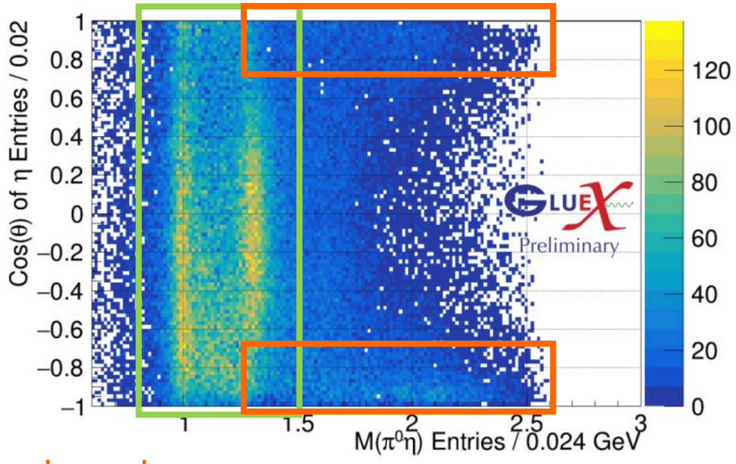
Double Regge production



With photon beam

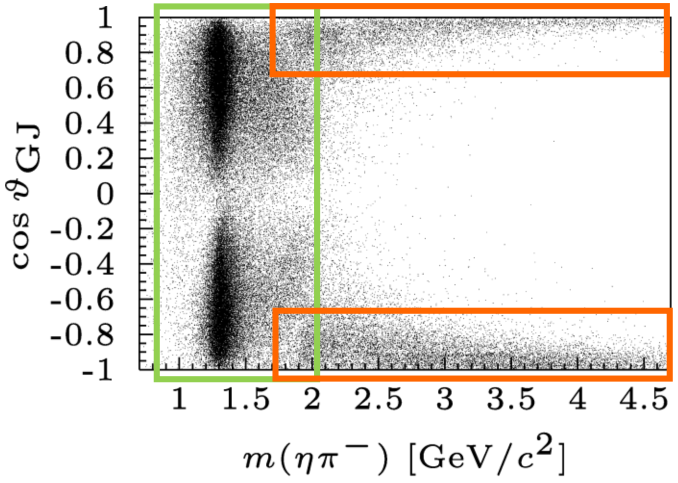
η produced forward

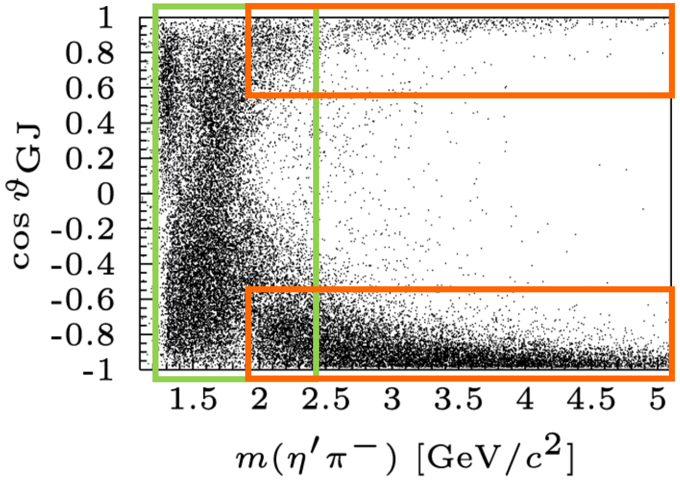




η produced backward

With pion beam



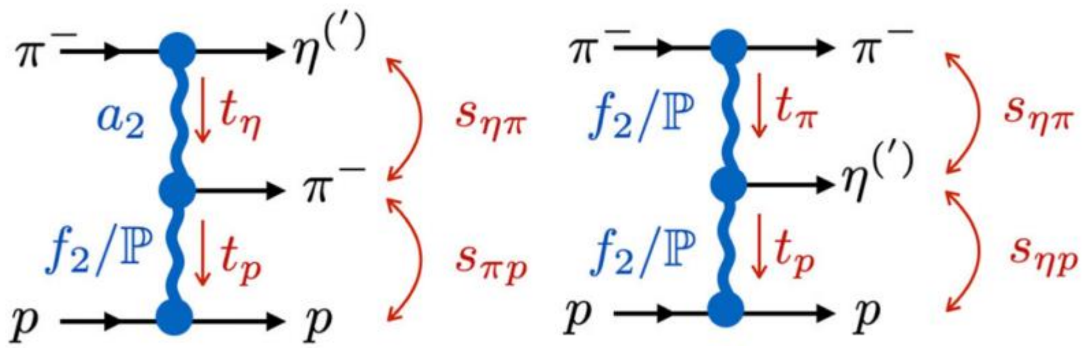


[COMPASS, *Phys.Lett.B* 740 (2015) 303-311]

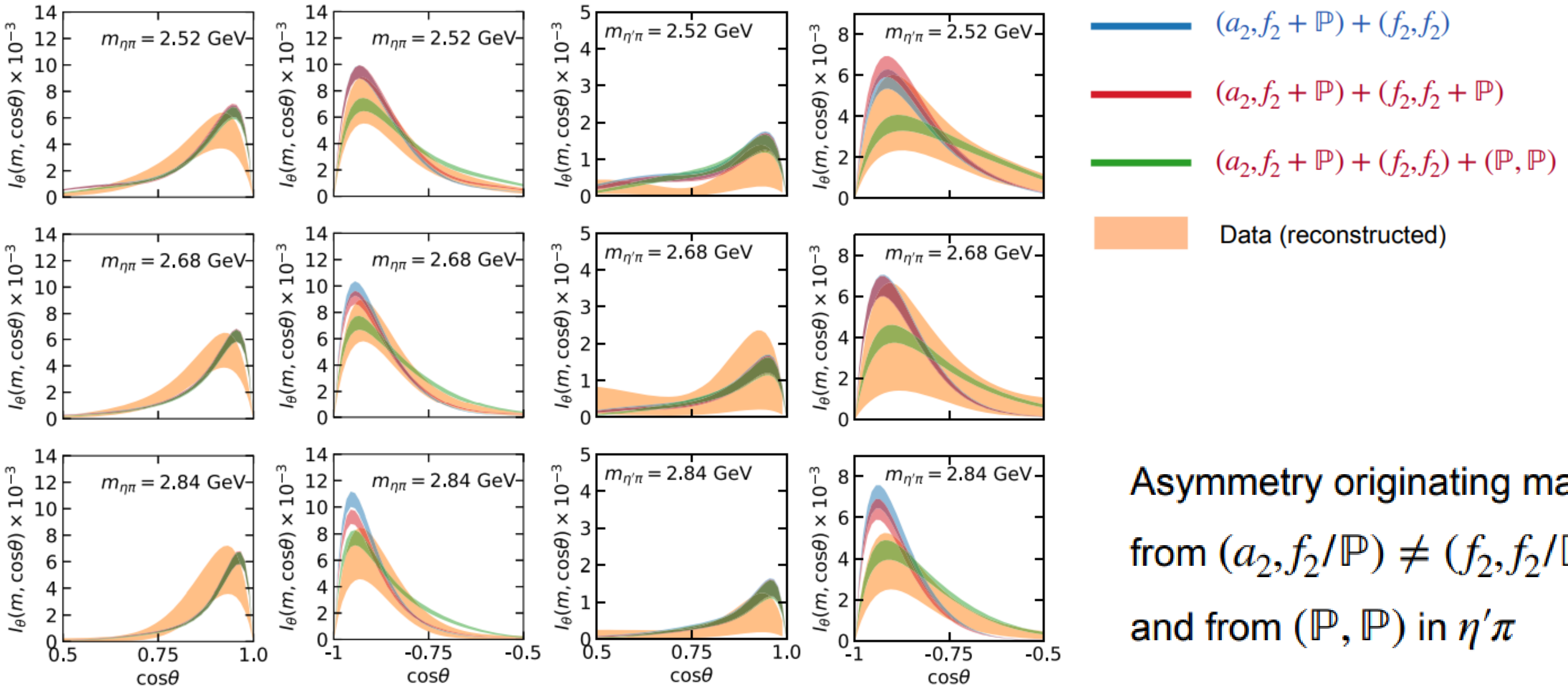
Double Regge $\eta^{(\prime)}\pi$ at COMPASS

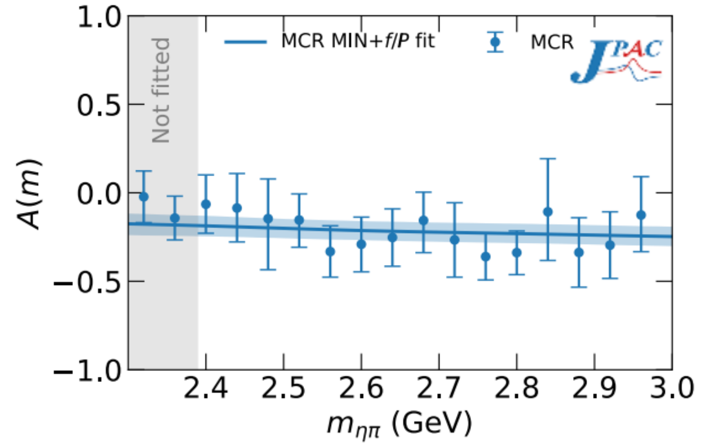
[L. Bibrzycki, C. Fernandez-Ramirez et al. (JPAC), *Eur.Phys.J.C* 81 (2021) 647]

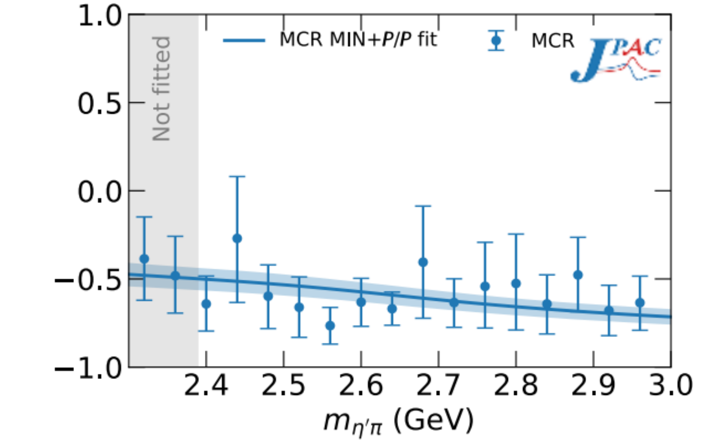
Fast $\eta^{(\prime)}$ Fast π



$$\text{Asymmetry} = \frac{\text{Forward} - \text{Backward}}{\text{Forward} + \text{Backward}}$$



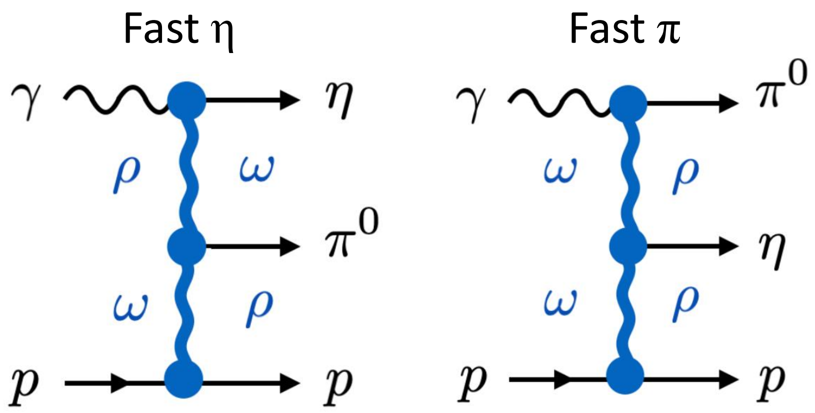




Asymmetry originating mainly from $(a_2,f_2/\mathbb{P}) \neq (f_2,f_2/\mathbb{P})$ and from $(\mathbb{P},\mathbb{P})$ in $\eta'\pi$

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

[GM, Vincent Mathieu, et al. (JPAC), arXiv:2008.XXXX]



1. Start from a vector-vector exchange model

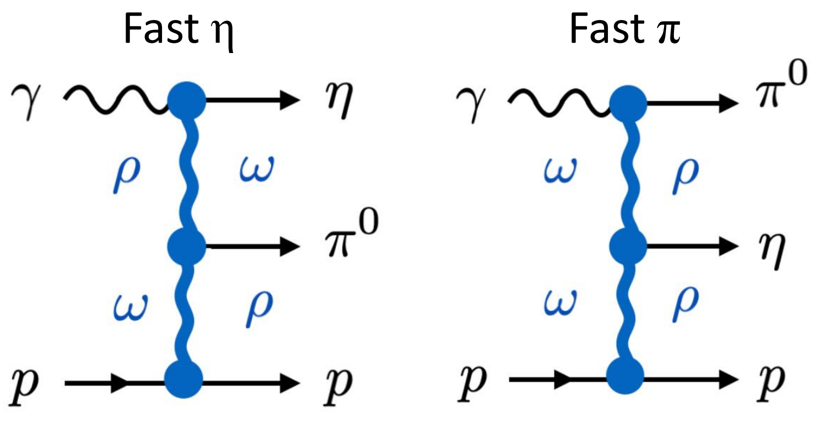
$$A_{\lambda_\gamma\lambda\lambda'} = \sum_{\text{diagrams}} \left(\frac{g_{\gamma V_1 P_1}}{m_0} \frac{g_{V_1 V_2 P_2}}{m_0} \right) \frac{g_{\lambda_\gamma,\lambda'-\lambda} K_{\lambda_\gamma\lambda\lambda'}}{(m_{V_1}^2 - i m_{V_1}\Gamma_{V_1} - t_1)(m_{V_2}^2 - i m_{V_2}\Gamma_{V_2} - t_p)}$$

2. Reggeize

$$K_{\lambda_\gamma\lambda\lambda'} \to K_{\lambda_\gamma\lambda\lambda'} \times R\left(\alpha_1(t_\pi), \alpha_2(t_p), s_{\eta\pi}, s_{\eta p}, \frac{s}{\alpha' s_{\eta\pi} s_{\eta p}}\right)$$

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

[GM, Vincent Mathieu, et al. (JPAC), arXiv:2008.XXXX]



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[Shimada, Martin and Irving, *Nucl. Phys. B* 142 (1978)]

vertex function

$$R(\alpha_1, \alpha_2, s_1, s_2, \eta) = [\xi_1 \xi_{21} \eta^{\alpha_1 - 1} V(\alpha_1, \alpha_2, \eta) + \xi_2 \xi_{12} \eta^{\alpha_2 - 1} V(\alpha_2, \alpha_1, \eta)] (\alpha' s_1)^{\alpha_1 - 1} (\alpha' s_2)^{\alpha_2 - 1} [(\alpha_1 - 1)\Gamma(1 - \alpha_1)] [(\alpha_2 - 1)\Gamma(1 - \alpha_2)]$$

signature factors

$$\eta = \frac{s}{\alpha' s_1 s_2}$$

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

[GM, Vincent Mathieu, et al. (JPAC), arXiv:2008.XXXX]

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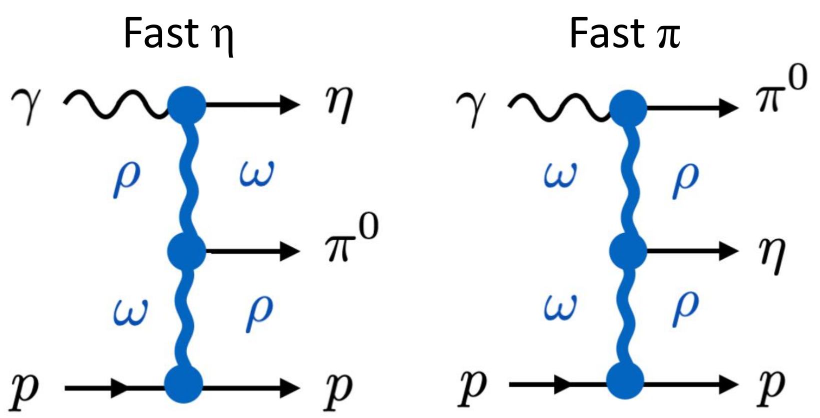

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signature factors

$$\eta = \frac{s}{\alpha' s_1 s_2}$$

In the double Regge limit $(s, s_{\eta,\pi}, s_p \to \infty,\ \eta \sim \text{ct.},\ s_{\eta\pi}/s_{\eta p} \sim \text{ct.})$

$K_{\lambda_\gamma \lambda\lambda'} \sim s_{\eta\pi} s_{\eta p}$ and $K_{\lambda_\gamma \lambda\lambda'} R \sim C_1 s^{\alpha_1(t_\pi)} s_{\eta p}^{\alpha_2(t_p) - \alpha_1(t_\pi)} + C_2 s_{\eta\pi}^{\alpha_1(t_\pi) - \alpha_2(t_p)} s^{\alpha_2(t_p)}$

Forward-Backward asymmetry

[GM, Vincent Mathieu, et al. (JPAC), arXiv:2008.XXXX]

(Preliminary results)

The asymmetry is defined as $(M = \sqrt{s_{\eta\pi}})$

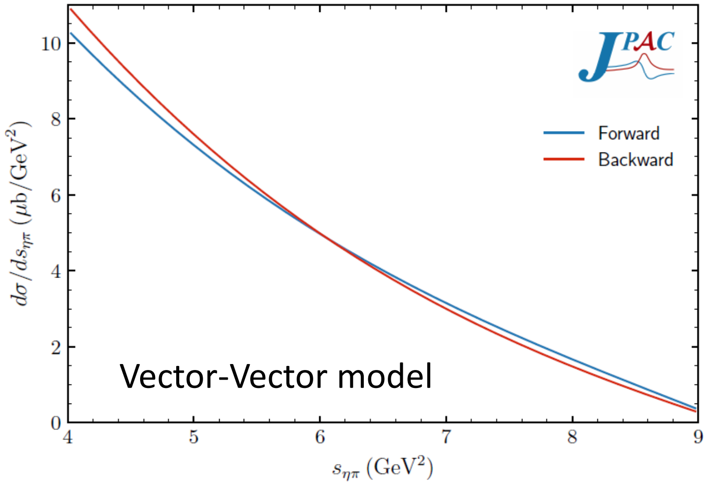
$$A(M) = \frac{F(M) - B(M)}{F(M) + B(M)}$$

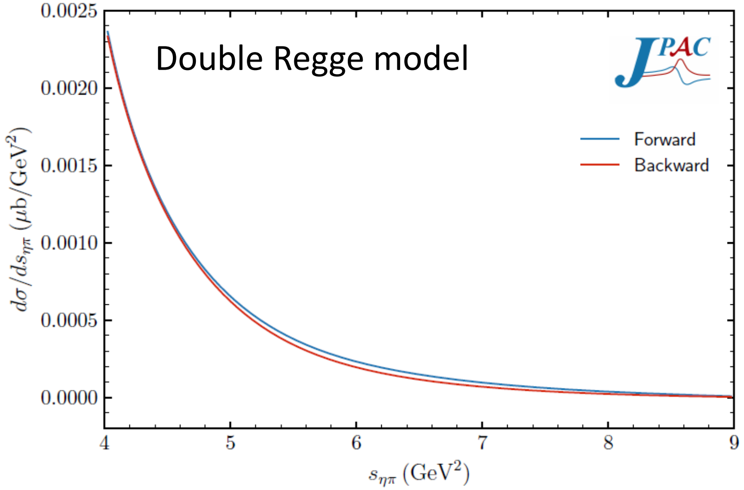
The forward and backward intensities contain cuts in kinematic variables

$$F(M) = \int d^2\Omega_{GJ} dz_{cm} \frac{d\sigma}{d\Omega_{GJ} dz_{cm} dM^2_{\eta\pi}} \theta(t_\eta > -2)\theta(t_p > -2)\theta(s_{\eta\pi} > 4)\theta(s_{\pi p} > 4)\theta(s_{\eta p} > 4.75)$$

$$B(M) = \int d^2\Omega_{GJ} dz_{cm} \frac{d\sigma}{d\Omega_{GJ} dz_{cm} dM^2_{\eta\pi}} \theta(t_\pi > -2)\theta(t_p > -2)\theta(s_{\eta\pi} > 4)\theta(s_{\pi p} > 4)\theta(s_{\eta p} > 4.75)$$

and the physics model is captured in $\frac{d\sigma}{d\Omega_{\mathrm{GJ}} dz_{\mathrm{cm}} ds_{\eta\pi}} \propto |A_{\lambda_\gamma \lambda\lambda'}|^2$





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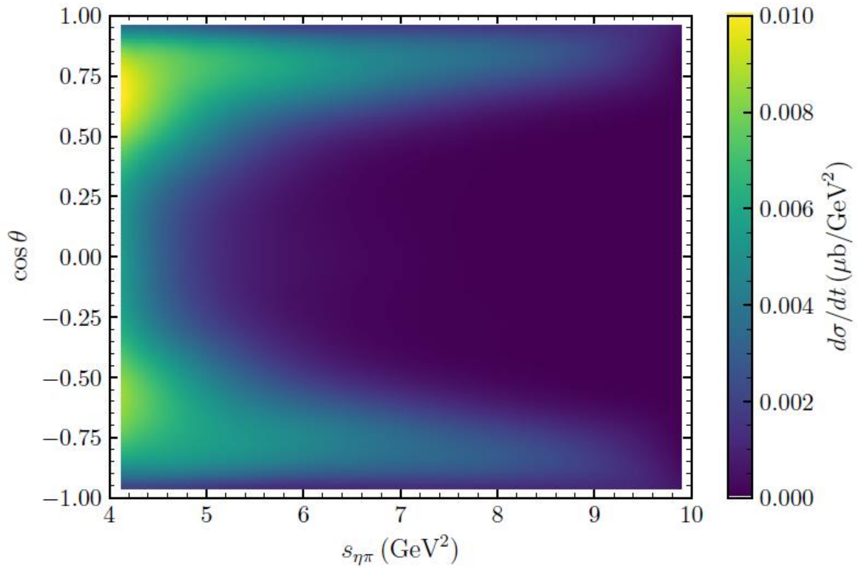

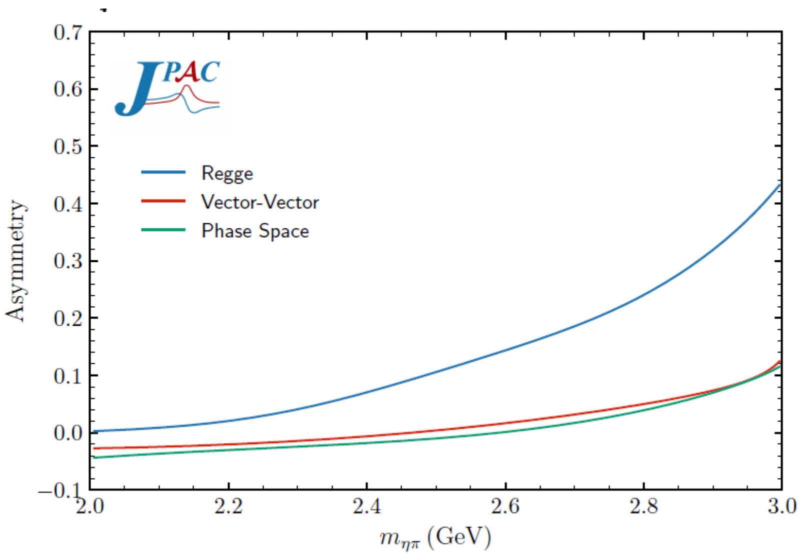

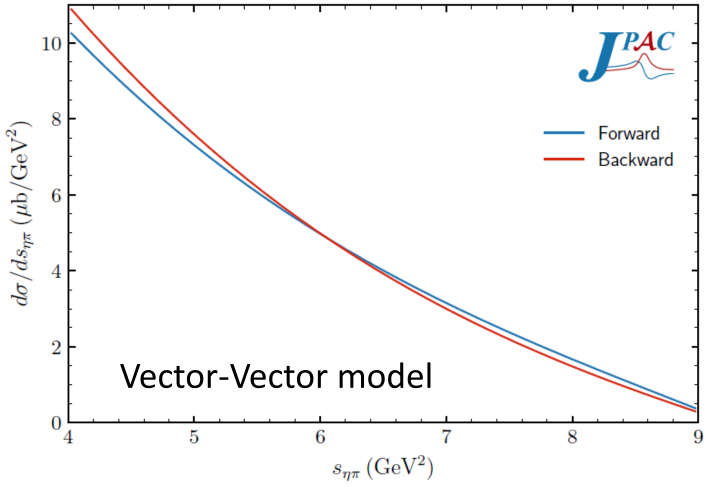

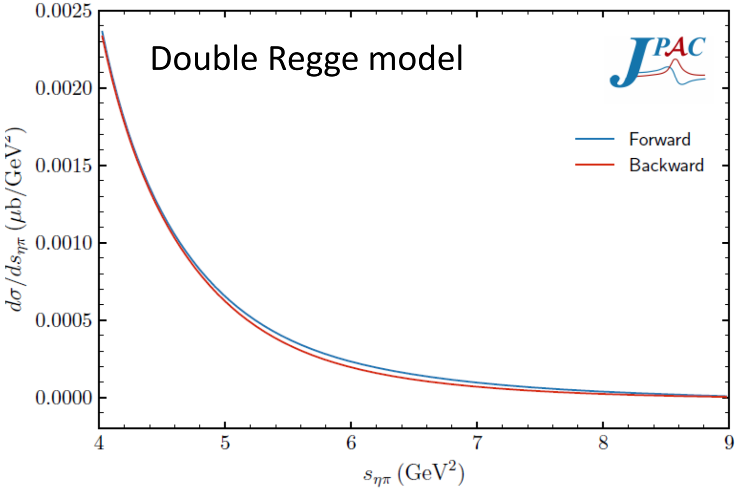

Summary

Regge theory is a practical tool to model and understand meson production at **high energies**

- Step forward in understanding pion exchange in pion photoproduction (gauge invariance)
- Interesting physics in $\eta^{(\prime)}\pi$, in the resonance region (hybrid meson) but also in the double Regge region

Strong effort from JPAC to **provide theory support to experimental analyses** (GlueX, but also CLAS, COMPASS…)

- Understand the data
- Provide predictions
- Close collaboration with experimentalists