# What can Regge theory tell us about hadron dynamics and spectroscopy?


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**Rencontres de Physique des Particules 2026**
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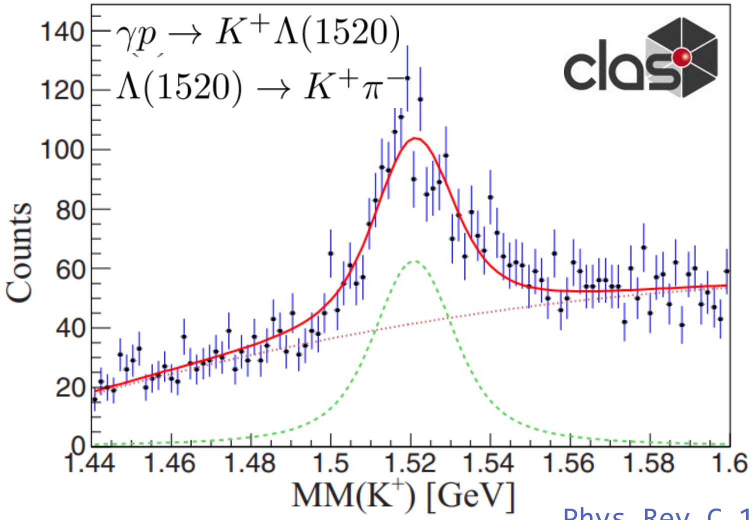
UNIVERSITAT DE BARCELONA ICCUB EXCELENCIA MARÍA DE MAEZTU 04/2025-03/2031 beatriu depinós bp' JPAC EXOHAD EXOTIC HADRONS TOPICAL COLLABORATION

# The hadron spectrum

* Very rich variety of structures observed in hadron reactions and decays




Phys.Rev.C 103, 025206 (2021)

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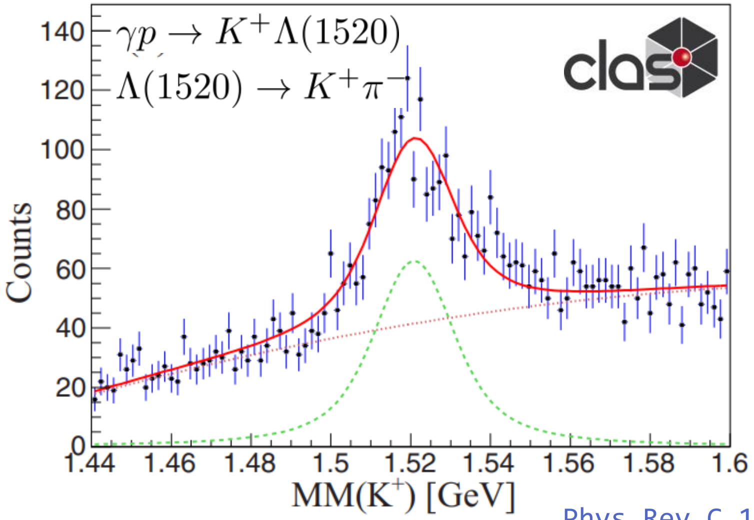


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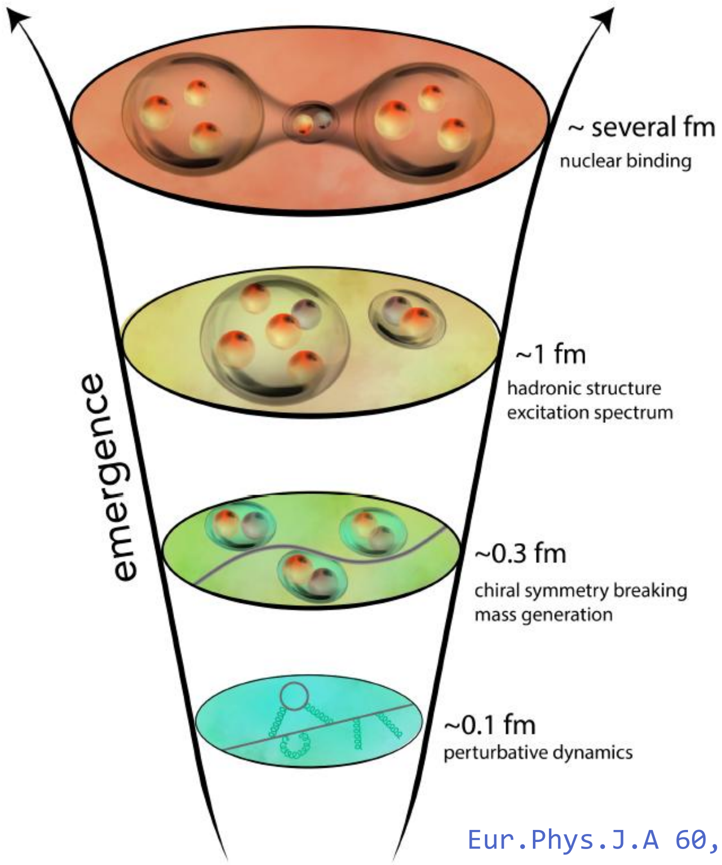
- Emergence phenomenon of QCD




Eur.Phys.J.A 60, 173 (2024)

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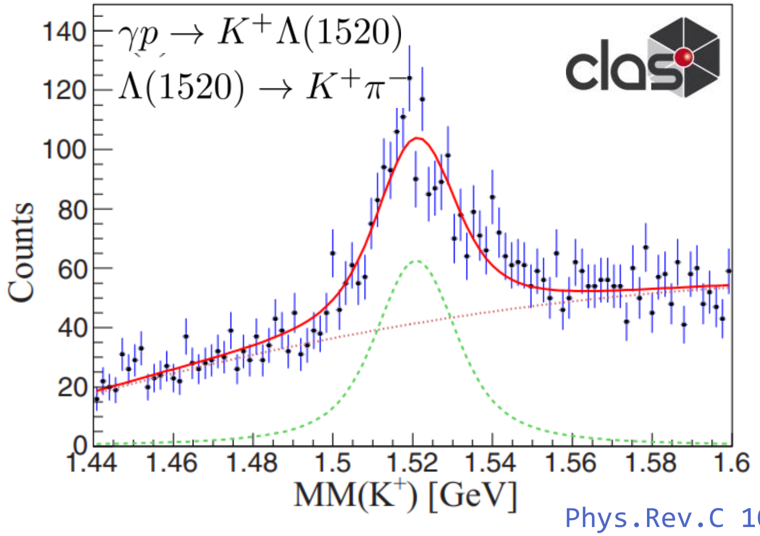


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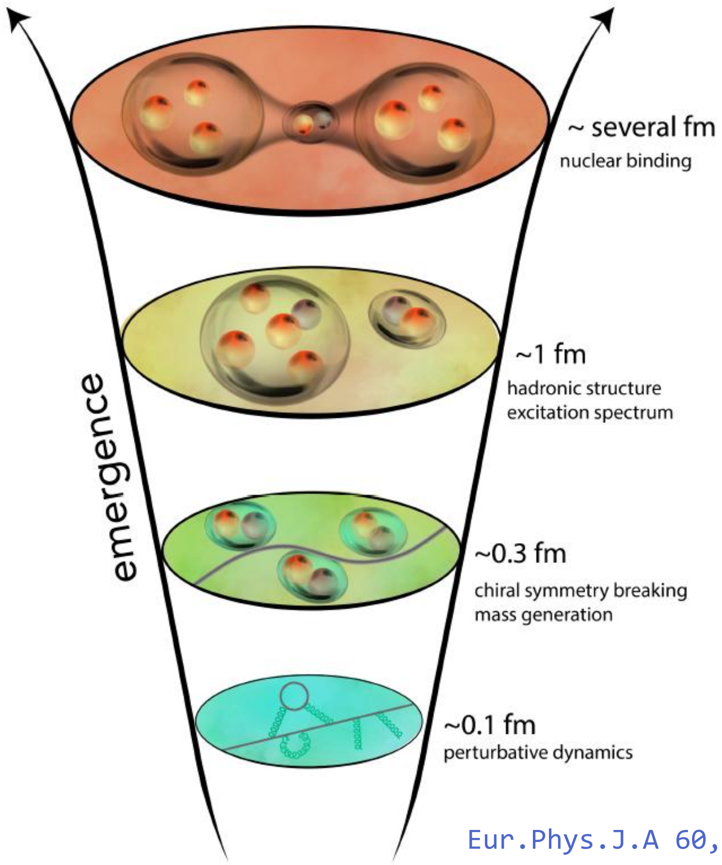
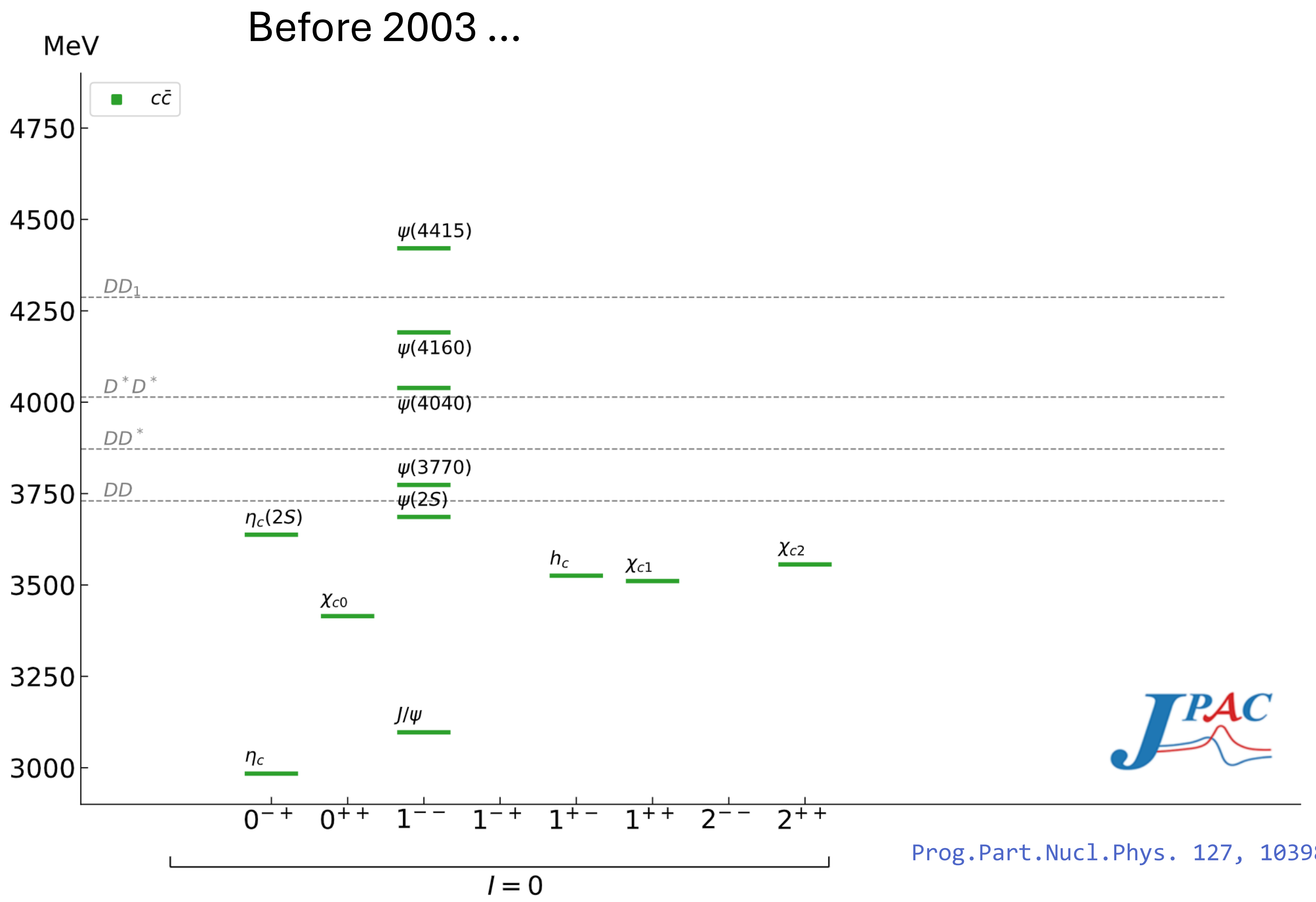


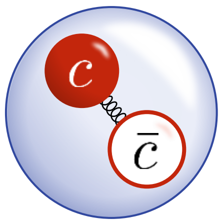

Eur.Phys.J.A 60, 173 (2024)

→ Ultimate goals: Understand in terms of quarks and gluons

Learn about QCD dynamics in the non-perturbative regime

# Heavy hadron spectrum: XYZP$_c$



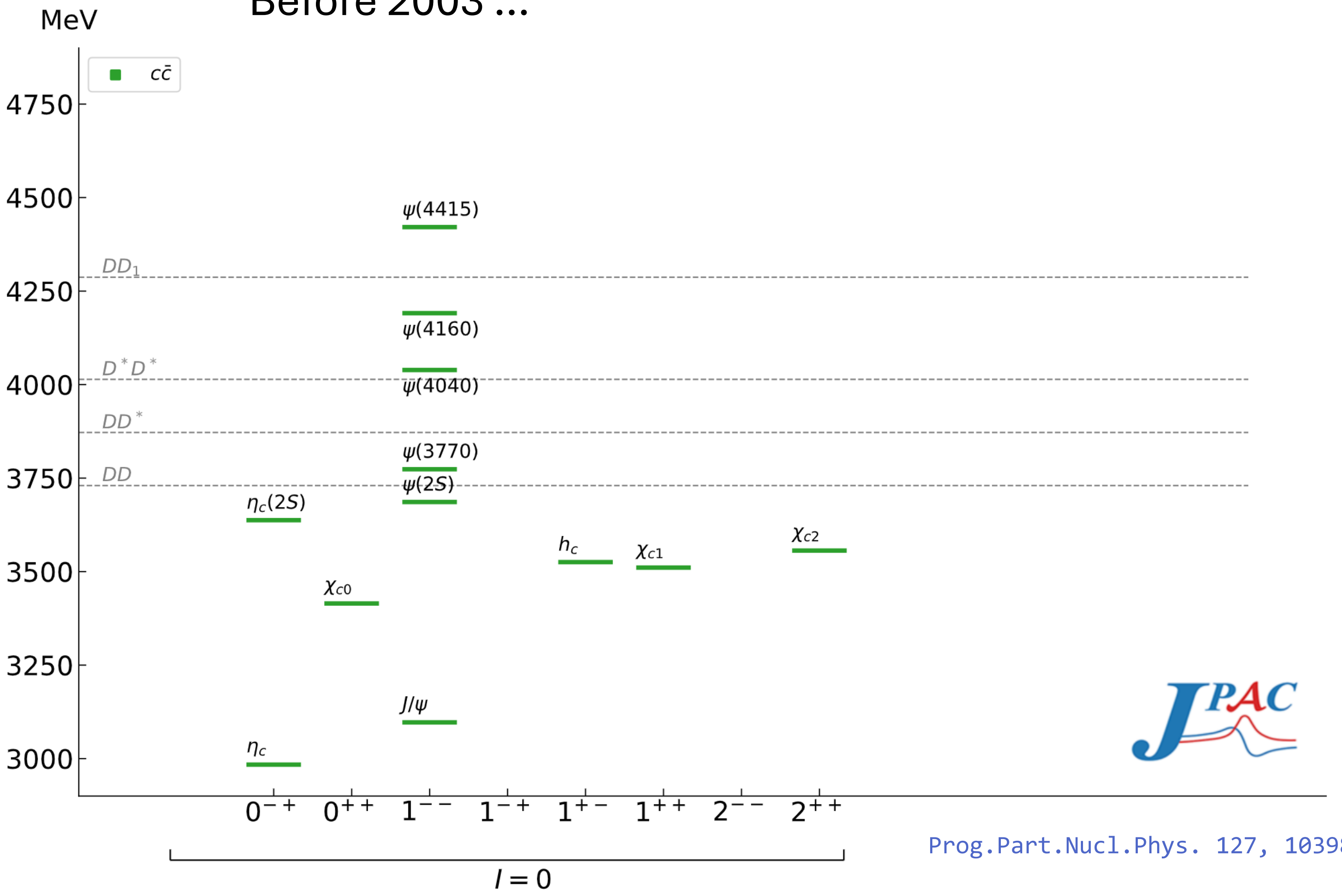



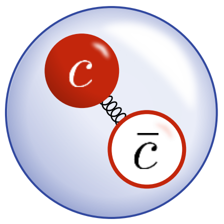

charmonium

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

# Heavy hadron spectrum: XYZP$_c$

Before 2003 ...

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- The quark model organizes the spectrum of "conventional" hadrons

# Heavy hadron spectrum: $XYZP_c$

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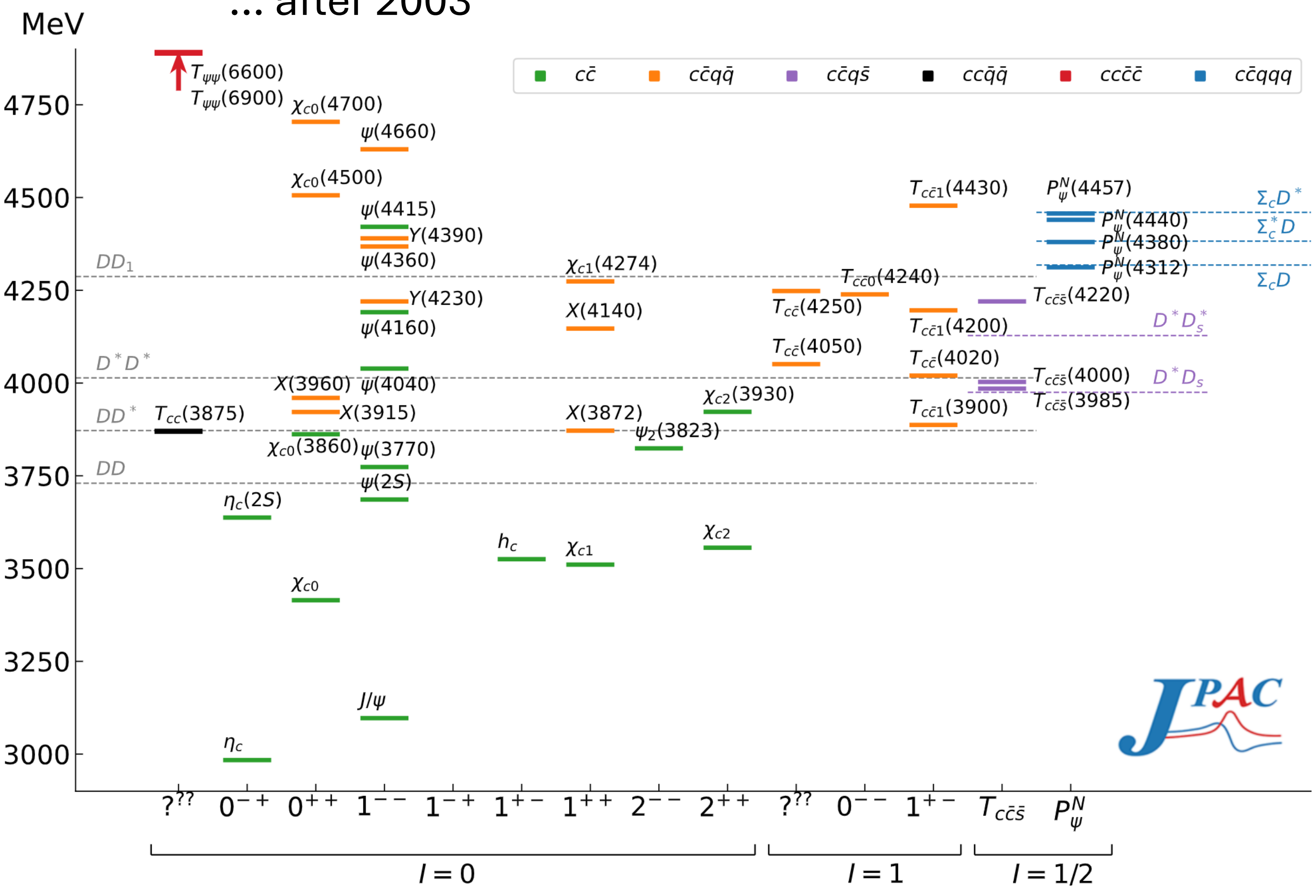


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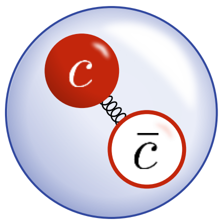
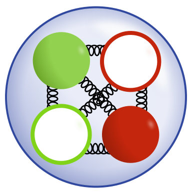
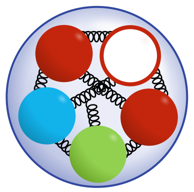



charmonium

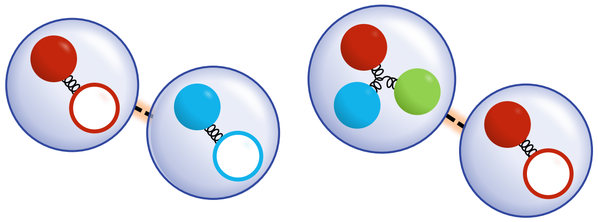
✳ **Exotic hadrons:** don't fit in the "conventional" quark model



tetraquark



pentaquark



hadronic molecules

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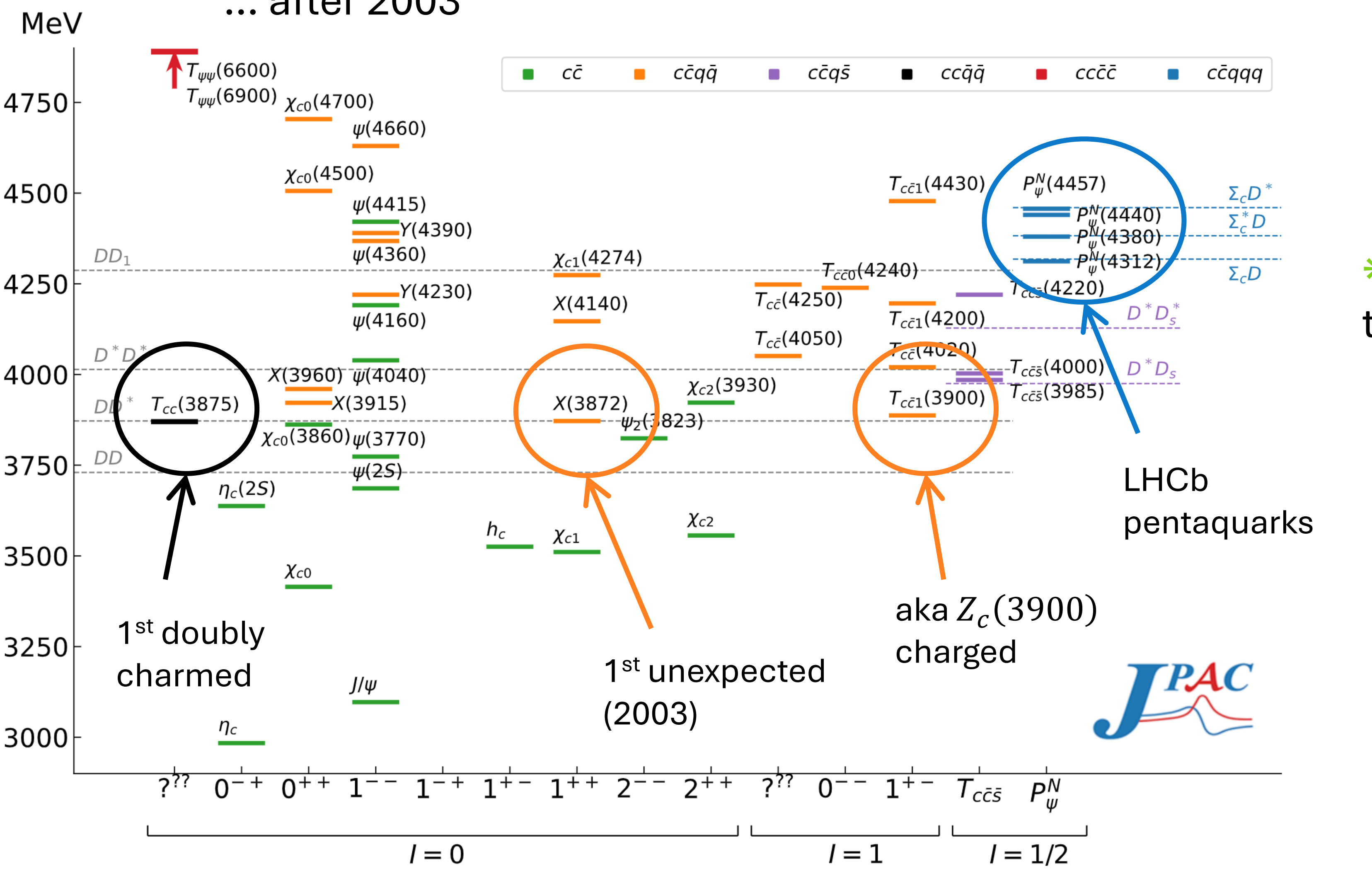


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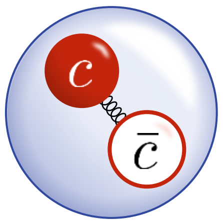


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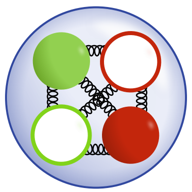

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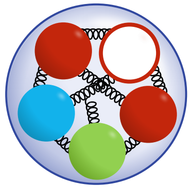

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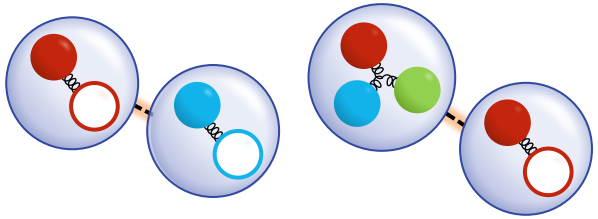
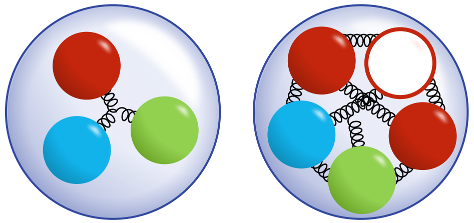


hadronic molecules

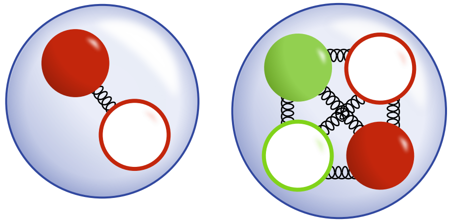
# Exotic hadrons

- In the original 1964 quark model papers, Gell-Mann and Zweig suggested the existence of multiquark states

Baryons



Mesons



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)

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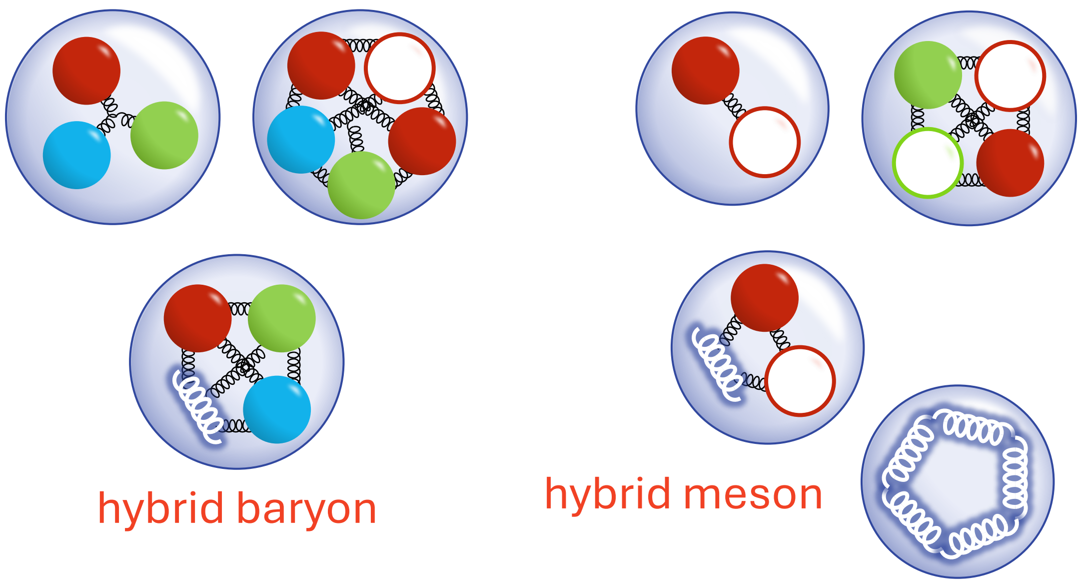

hybrid baryon

hybrid meson

glueball

- QCD allows constituent gluons

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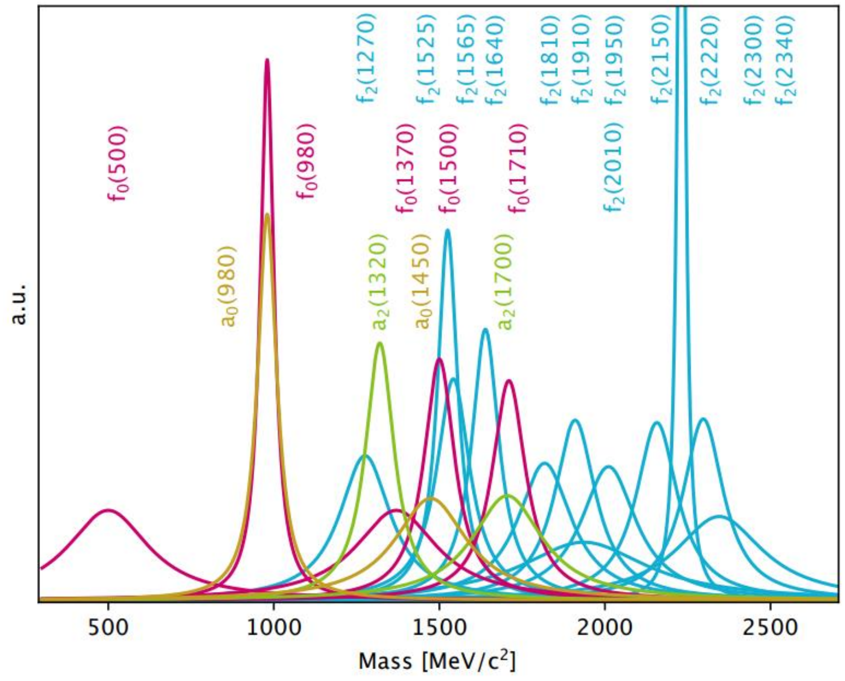
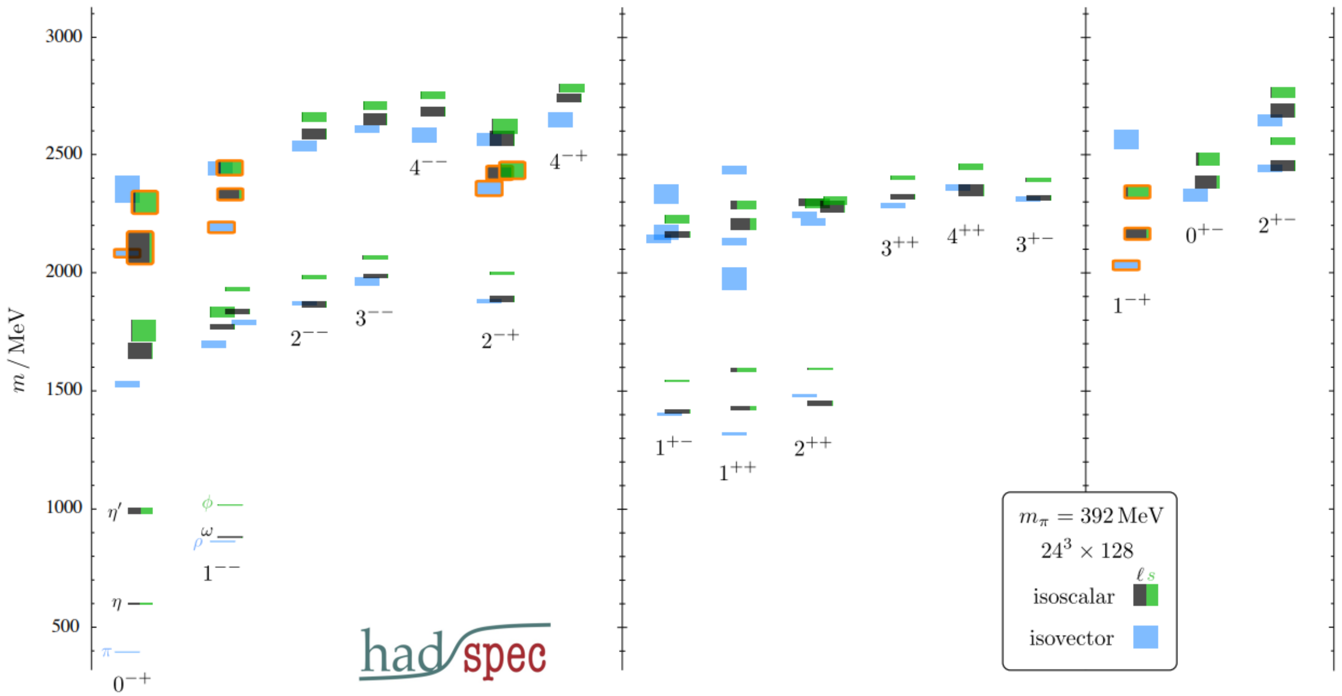
# Challenges in the light meson spectrum



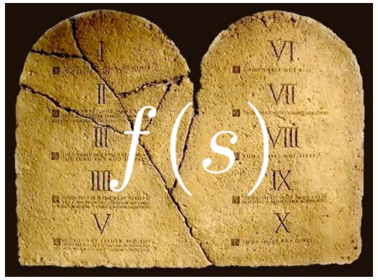

Lattice QCD predictions

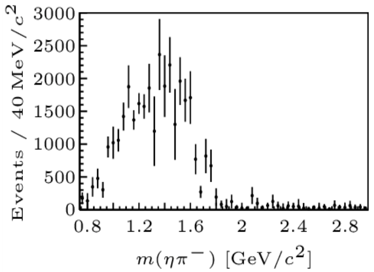



J.Dudek et al., Phys.Rev.D 88, 094505 (2013)

- Wide, overlapping states
- Can't use simplistic resonance extraction techniques (e.g. Breit Wigner fits)
- Need for amplitude level analysis → Collaboration between theorists and experimentalists

# Theorist approaches




**TOP DOWN**

1 You are given a model/theory

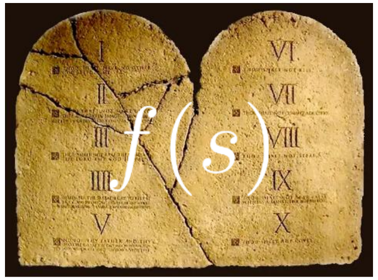
↓

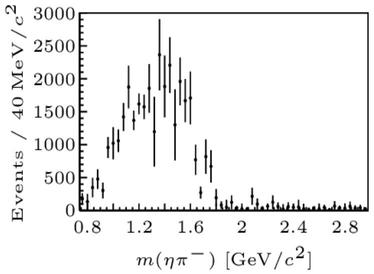
2 You calculate the amplitude

↓

3 You compare with data (or not)

# Theorist approaches

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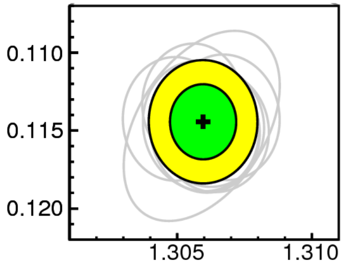
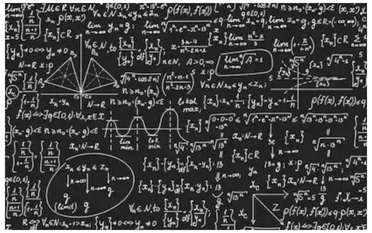
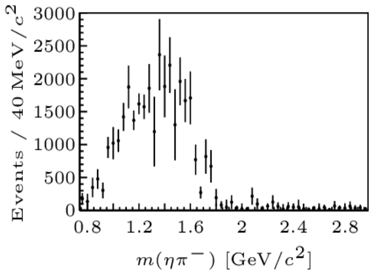





## BOTTOM UP

3 You extract physics

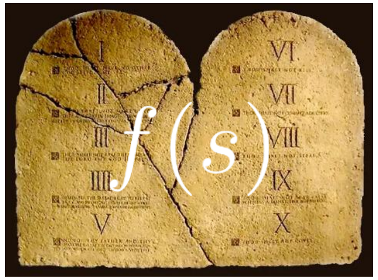
↑

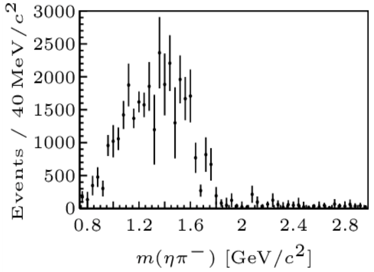
2 You choose a set of generic amplitudes

↑

1 You start with data

# Theorist approaches

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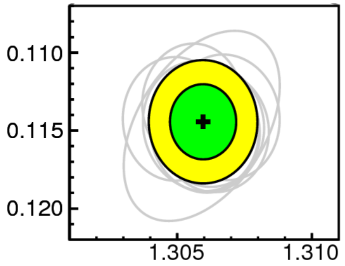


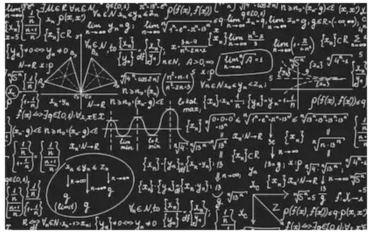

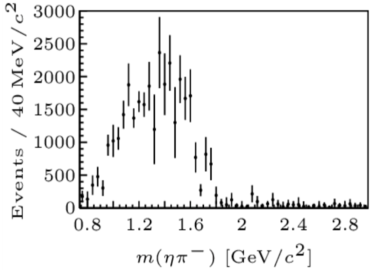


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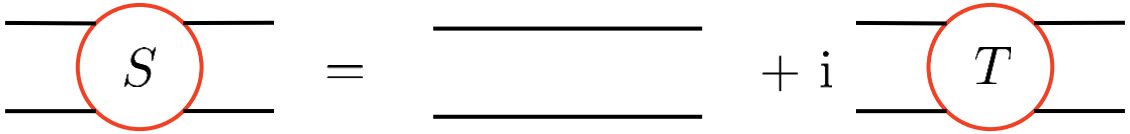
1 You start with data

Predictive power ✓
Physical interpretation ✓ (within the model ✘)
Biased by the input ✘

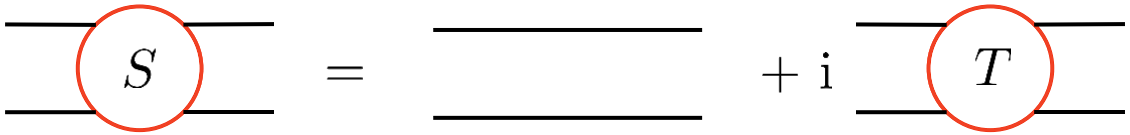
Less predictive power ✘
Some physical interpretation ✘
Minimally biased ✓

# S-matrix theory




Fundamental principles of any quantum theory of scattering

# S-matrix theory

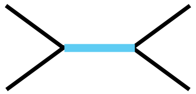



Fundamental principles of any quantum theory of scattering

- Rotational invariance → **Partial wave expansion**

$$\langle \text{out}|T|\text{in}\rangle \equiv A(s,z) = \sum_{\ell=0}^{\infty}(2\ell+1)f_\ell(s)P_\ell(z)$$

$$f_\ell \sim \frac{1}{s-m_R^2}$$



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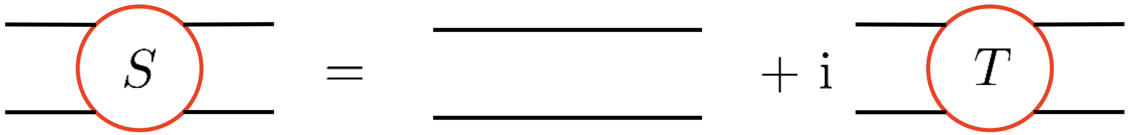


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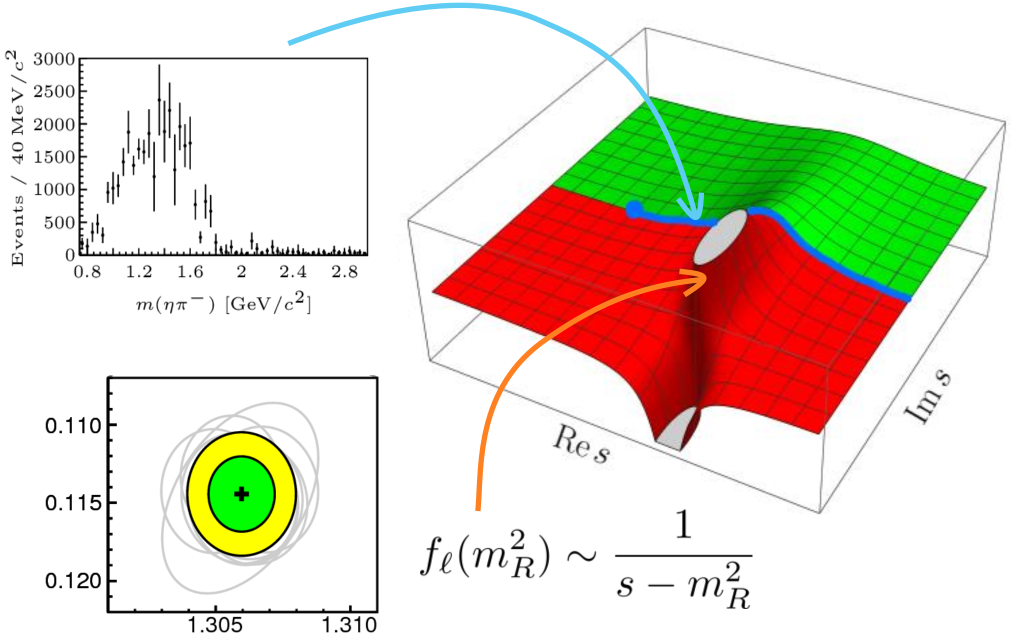
- Causality → **Analyticity**

$$f_\ell(s) = \frac{1}{\pi}\int ds' \frac{\text{Disc}\, f_\ell(s')}{s'-s-i\epsilon}$$

Poles in the complex energy plane characterize resonances




$$f_\ell(m_R^2) \sim \frac{1}{s-m_R^2}$$

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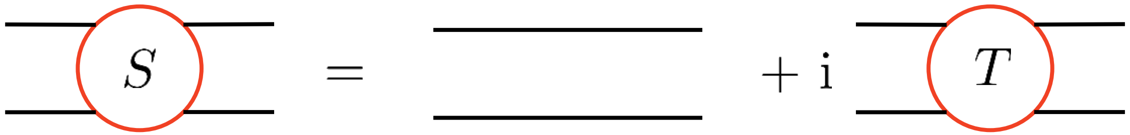


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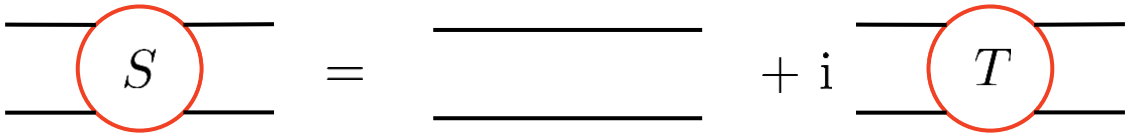


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(in a relativistic QFT)

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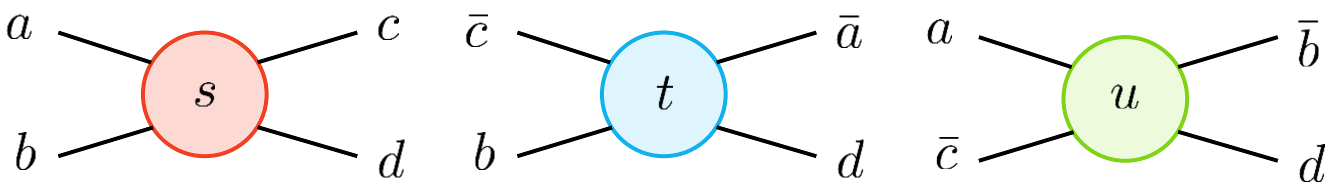
- Existence of antiparticles → **Crossing symmetry**




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

# Regge theory

Expansion in t-channel partial waves

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

- Converges in the t-channel kinematics ( $|z_t|<1$)

  but in the s-channel kinematics $z_t=\cos\theta_t=1+\frac{2s}{t-4m^2}>1$

# Regge theory

Expansion in t-channel partial waves

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

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

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- Analytical continuation to **complex values of angular momentum** T.Regge, *Nuovo Cim.* 18, 947 (1960)

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

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→ For fixed ℓ, in the *s*-plane, partial waves have cuts (unitarity) and poles (particles)

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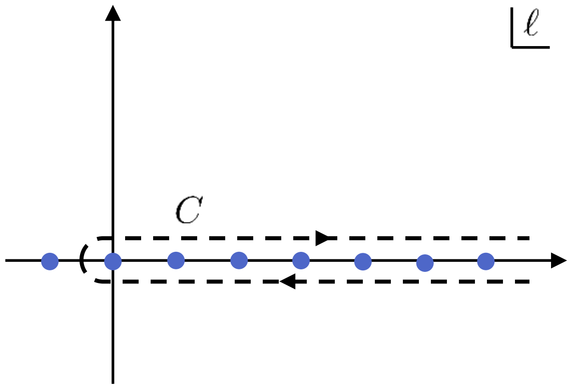
# Regge theory

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

Sommerfeld-Watson transform

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



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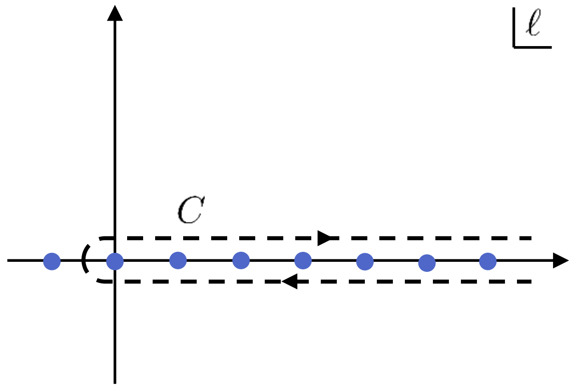
$$A(t,z_t)=\sum_{\ell=0}^{\infty}(2\ell+1)f_\ell(t)P_\ell(z_t)$$

Sommerfeld-Watson transform

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

Deform the contour,
assuming only singularities are poles

$$f_\ell(t)\sim\frac{\beta(t)}{\ell-\alpha(t)}$$



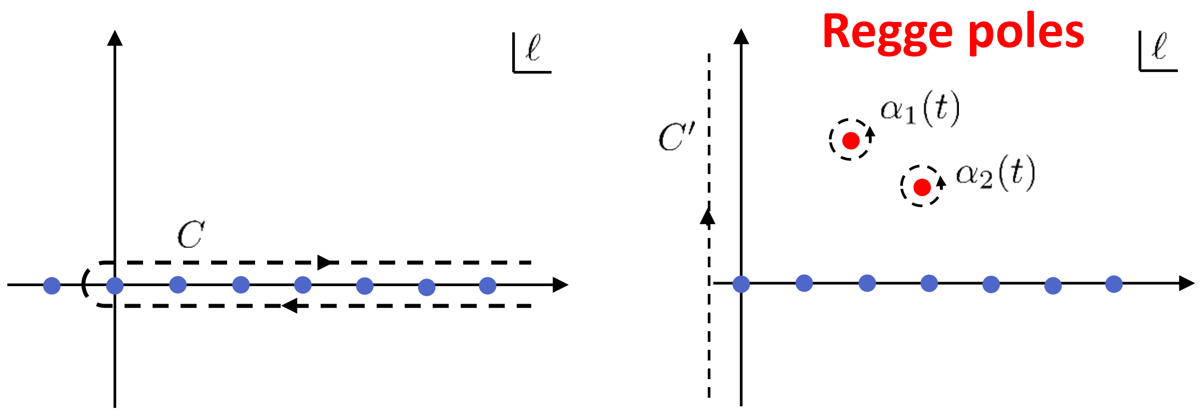
# Regge theory

Sommerfeld-Watson transform

$$A(t,z_t) = \sum_{\ell=0}^{\infty}(2\ell+1)f_\ell(t)P_\ell(z_t) \longrightarrow A(t,z_t) = -\frac{1}{2i}\int_C \mathrm{d}\ell\, \frac{(2\ell+1)\,P_\ell(-z_t)\,f(\ell,t)}{\sin\pi\ell}$$

Deform the contour,
assuming only singularities are poles

$$f_\ell(t) \sim \frac{\beta(t)}{\ell-\alpha(t)}$$



# Regge theory

$$A(t, z_t) = \sum_{\ell=0}^{\infty} (2\ell+1) f_\ell(t) P_\ell(z_t) \xrightarrow{\text{Sommerfeld-Watson transform}} A(t, z_t) = -\frac{1}{2i} \int_C \mathrm{d}\ell \, \frac{(2\ell+1)\, P_\ell(-z_t)\, f(\ell, t)}{\sin \pi \ell}$$

Deform the contour,
assuming only singularities are poles

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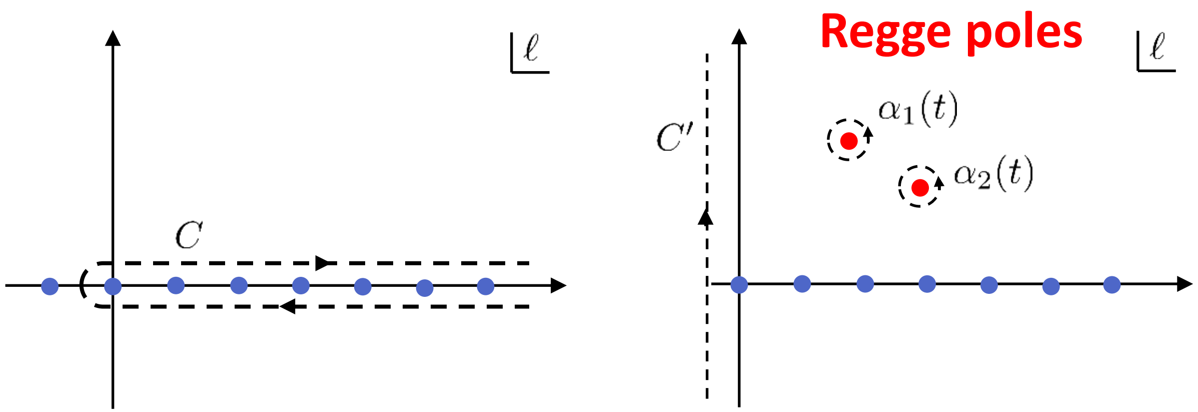


$$A(s,t) = \underbrace{-\frac{1}{2i} \int_{-\frac{1}{2}-i\infty}^{-\frac{1}{2}+i\infty} \mathrm{d}\ell \ldots}_{} \underbrace{- \sum_i \frac{\pi(2\alpha_i(t)+1)\beta_i(t)}{\sin\left(\pi \alpha_i^{\pm}(t)\right)} \frac{1}{2} P_{\alpha_i}(-z_t)}_{}$$

# Regge theory

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

Sommerfeld-Watson transform

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

Deform the contour,
assuming only singularities are poles

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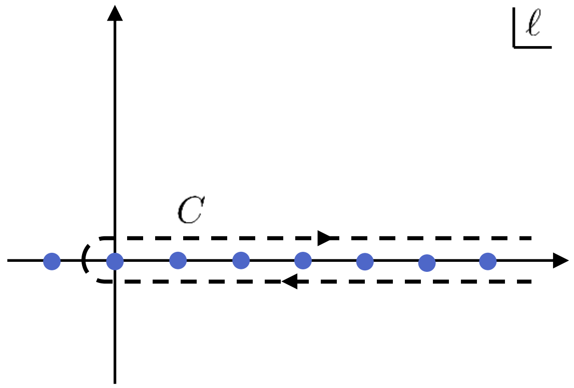


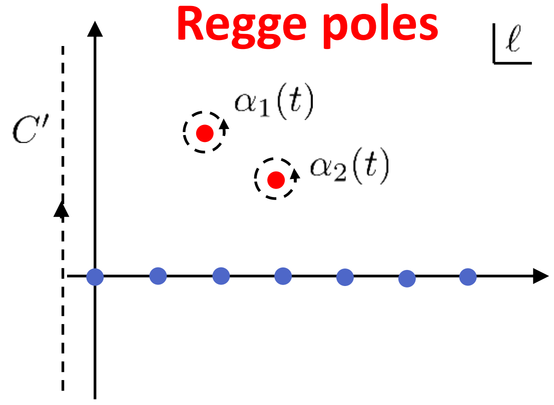


$$A(s,t)=-\frac{1}{2i}\int_{-\frac{1}{2}-i\infty}^{-\frac{1}{2}+i\infty}\mathrm{d}\ell\ldots-\sum_i\frac{\pi(2\alpha_i(t)+1)\beta_i(t)}{\sin\left(\pi\alpha_i^{\pm}(t)\right)}\frac{1}{2}P_{\alpha_i}(-z_t)$$

background $\sim s^{-1/2}$

pole contributions $\sim s^{\alpha(t)}$

# Regge theory

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

Sommerfeld-Watson transform

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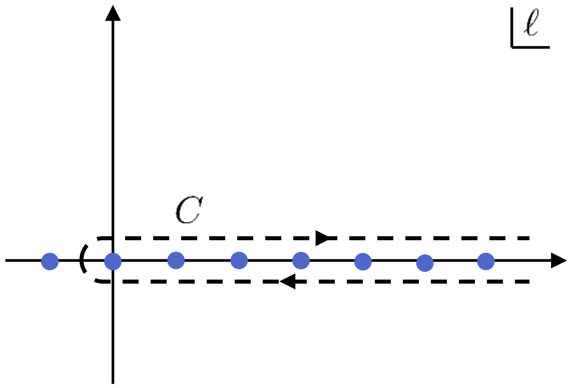
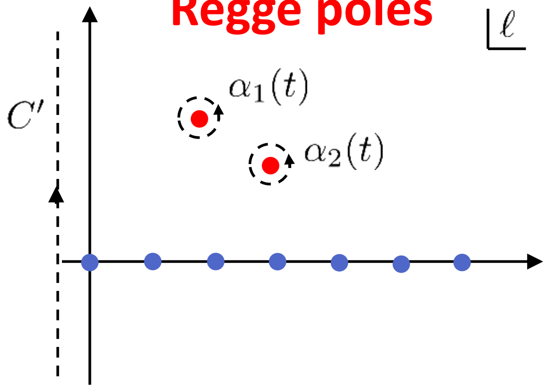


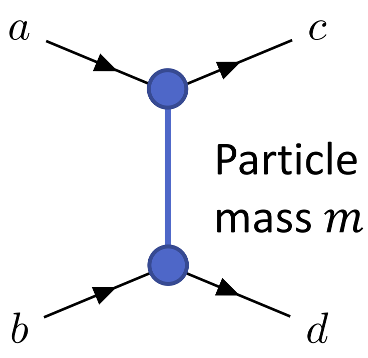

$$A(s,t) = -\frac{1}{2i}\int_{-\frac{1}{2}-i\infty}^{-\frac{1}{2}+i\infty} \mathrm{d}\ell \ldots - \sum_i \frac{\pi(2\alpha_i(t)+1)\beta_i(t)}{\sin\left(\pi\alpha_i^{\pm}(t)\right)}\frac{1}{2}P_{\alpha_i}(-z_t)$$

background $\sim s^{-1/2}$

pole contributions $\sim s^{\alpha(t)}$

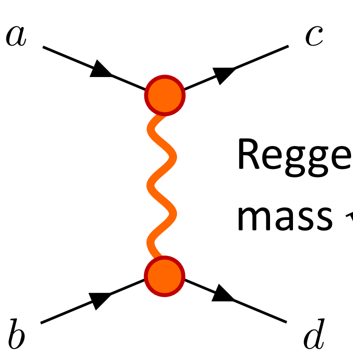
Regge poles dominate at large s

# Fixed vs Regge (moving) poles




Particle with
mass $m$ and spin $J$

$$\frac{1}{t-m^2}$$




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

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

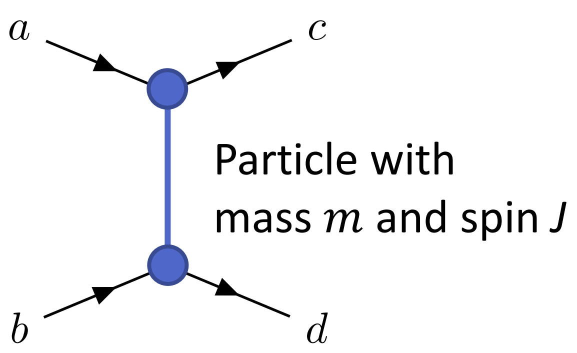
poles for integer $\alpha(t)$

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

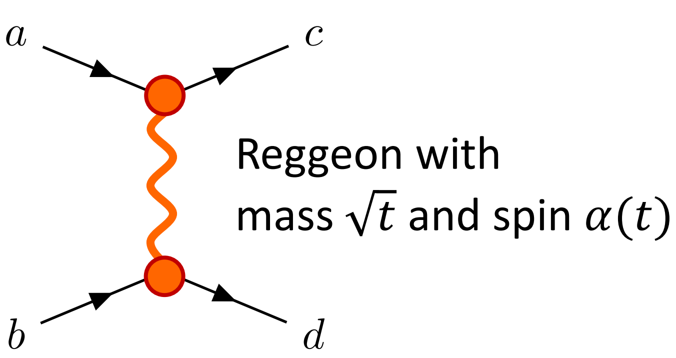
asymptotic behavior

cancel non-physical poles

# Fixed vs Regge (moving) poles




→




$$\frac{1}{t-m^2}$$

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

poles for integer $\alpha(t)$

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

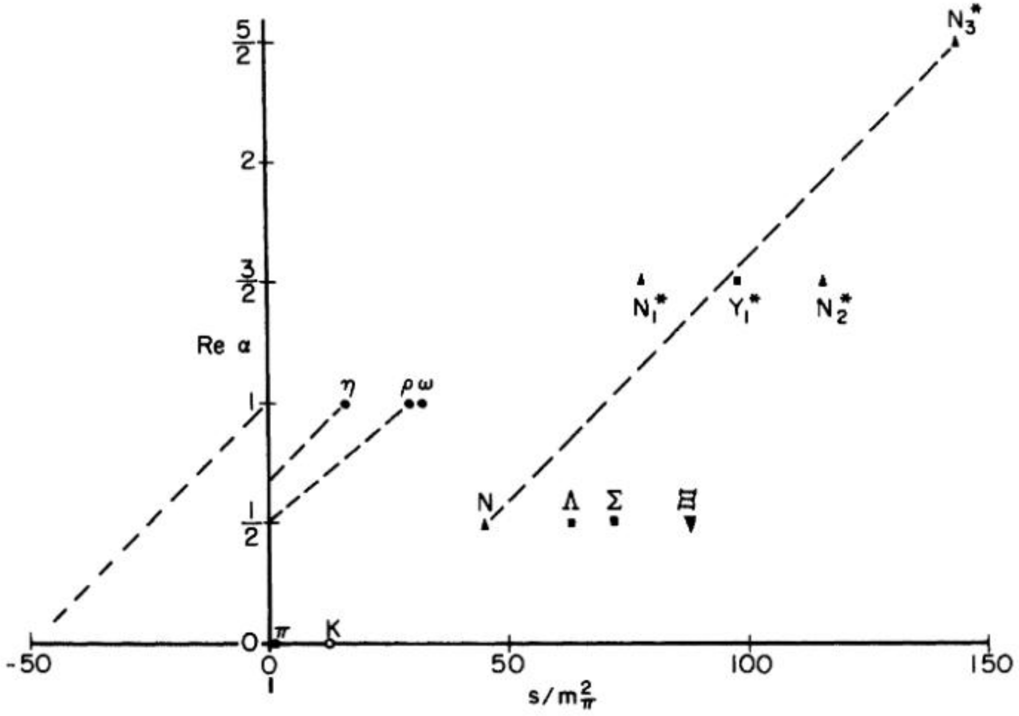
asymptotic behavior

cancel non-physical poles

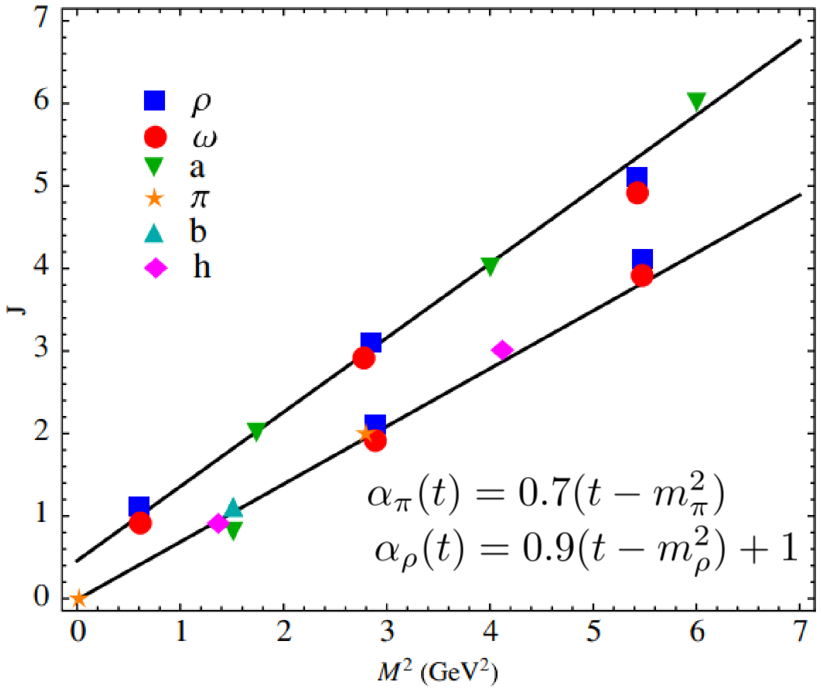
Resonances appear simultaneously as poles in energy and spin!

# Regge trajectories

- Hadron organize into families with same quantum numbers but different spin
- Chew-Frautschi plot: almost straight trajectories




G.F.Chew and S.C.Frautschi, *Phys.Rev.Lett. 8, 41 (1962)*




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

# Regge trajectories

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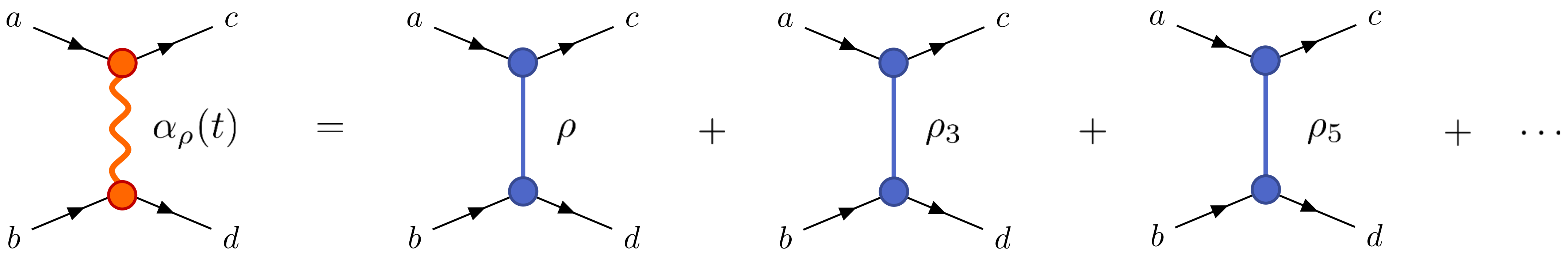
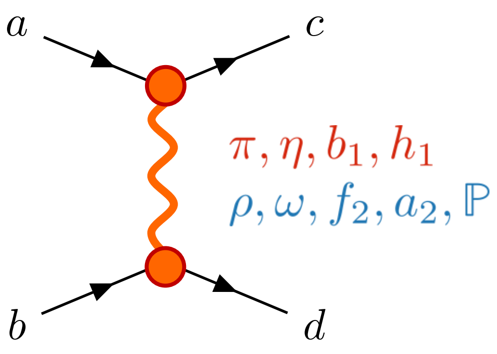


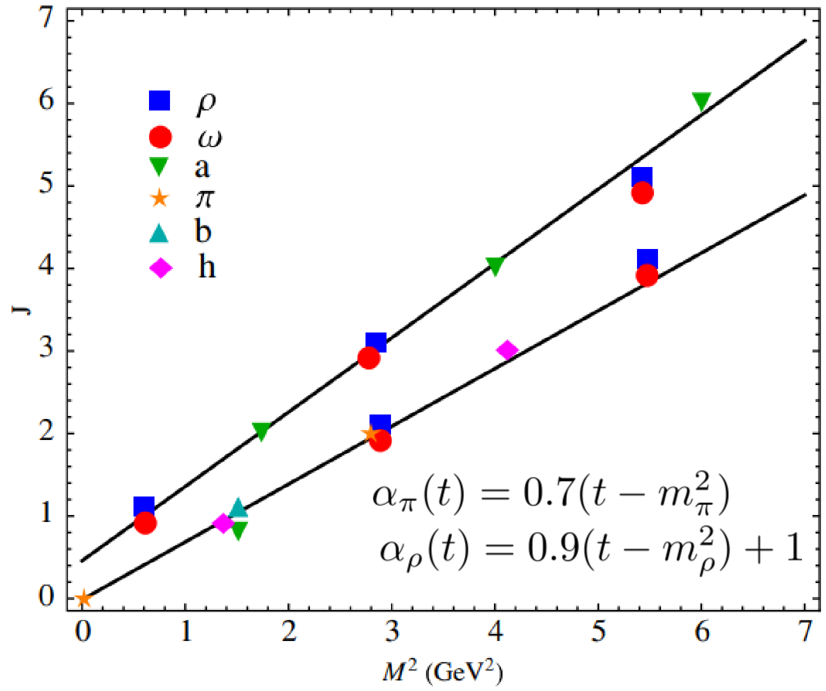
# Regge trajectories

* Hadron organize into families with same quantum numbers but different spin
* Chew-Frautschi plot: almost straight trajectories

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

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

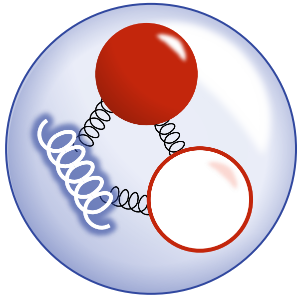


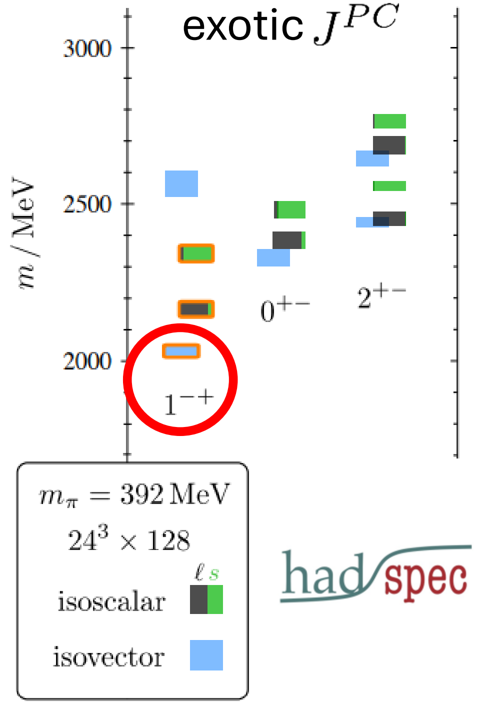




* Natural parity dominates
* Pion exchange important at forward t

# The hybrid meson: $\pi_1(1600)$

- Lightest exotic $1^{-+}$ isovector predicted by lattice QCD

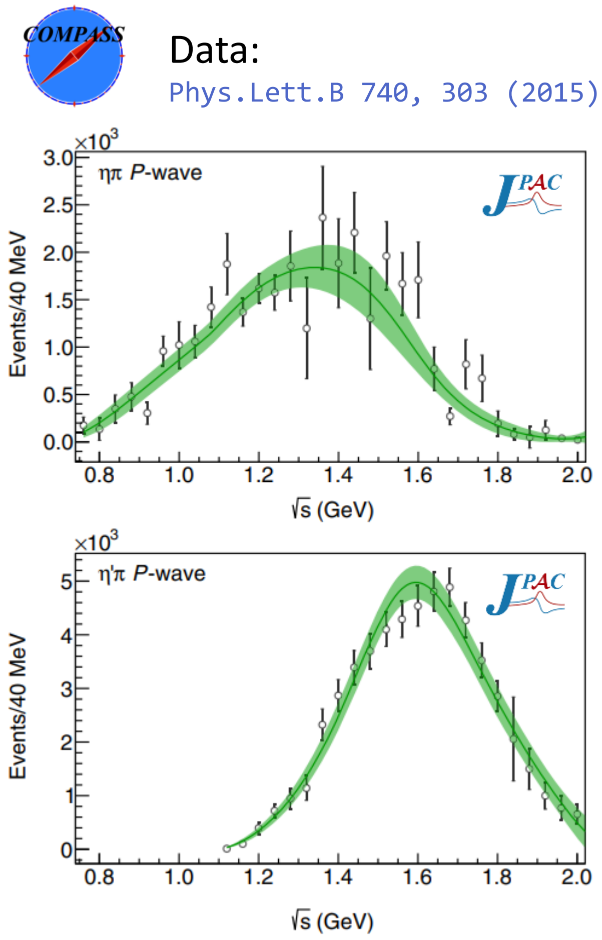





J.Dudek et al., Phys.Rev.D 88, 094505 (2013)

# The hybrid meson: $\pi_1(1600)$

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

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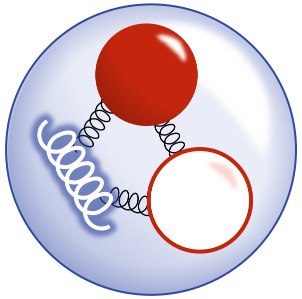
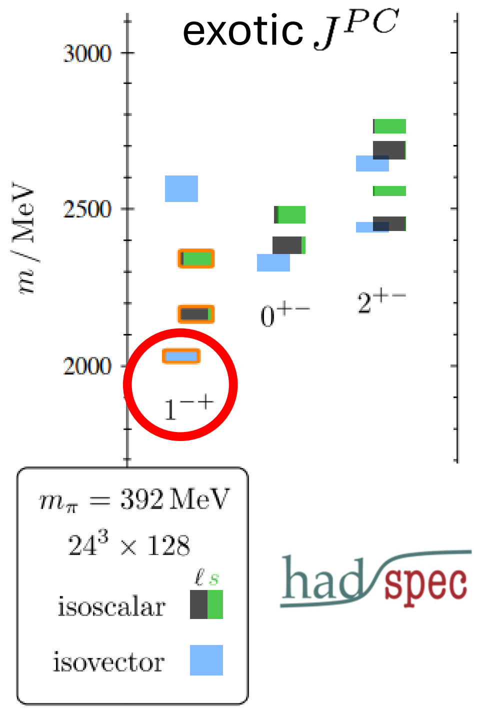




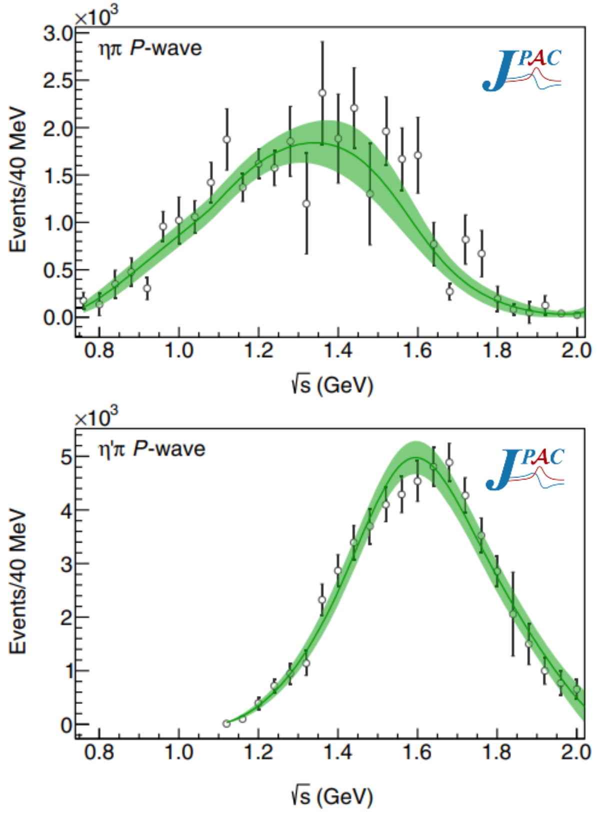

J.Dudek et al., Phys.Rev.D 88, 094505 (2013)

- Best experimental evidence from COMPASS@CERN with a pion beam

- Historically, two candidates: $\pi_1(1400)$ and $\pi_1(1600)$

# The hybrid meson: $\pi_1(1600)$

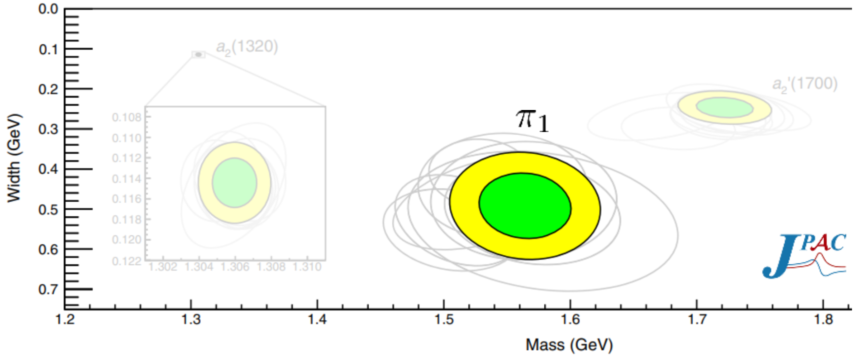
Data:
Phys.Lett.B 740, 303 (2015)




⁎ Coupled-channel analysis by JPAC:

→ Data is consistent with a single resonance pole

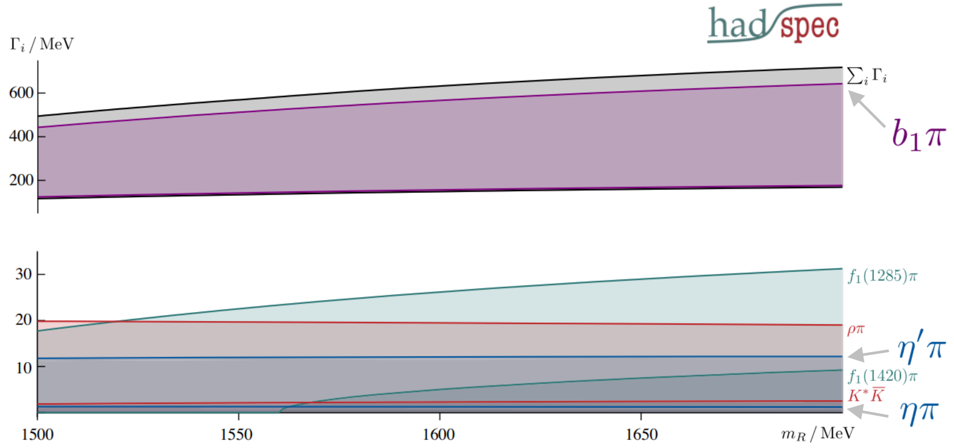
A.Rodas et al., Phys.Rev.Lett. 122, 042002 (2019)




⁎ Confirmed by HadSpec:

→ Also provided decay rates

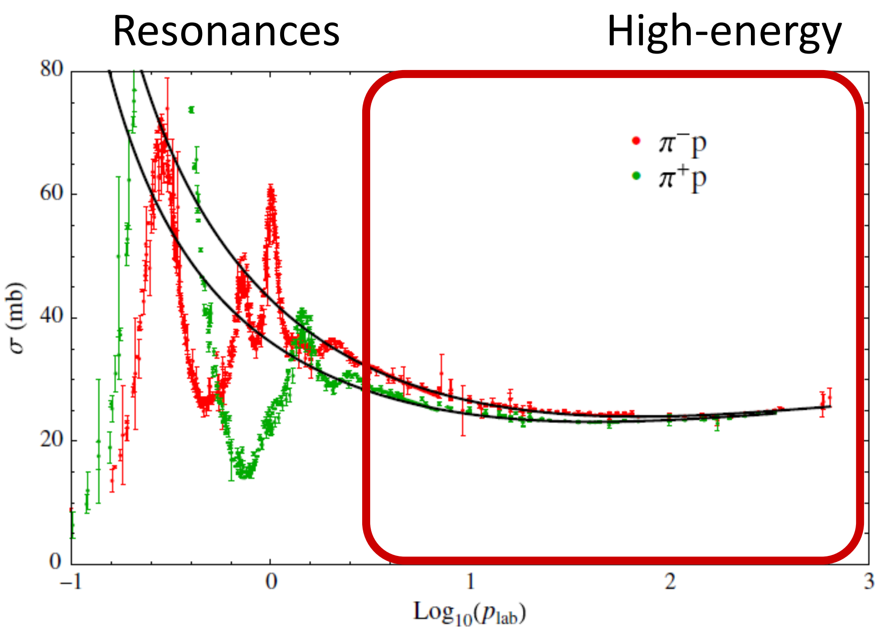
A.Woss et al., Phys.Rev.D 103 5, 054502 (2021)



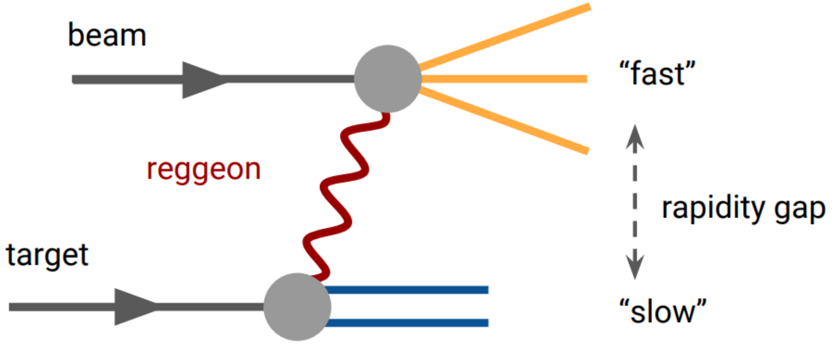

⁎ Experimental confirmation with a photon beam is the main goal of GlueX@Jefferson Lab

# Hadron production at high energies

* Dominated by the exchange of Regge trajectories in the t-channel




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




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 (formally through finite-energy sum rules)

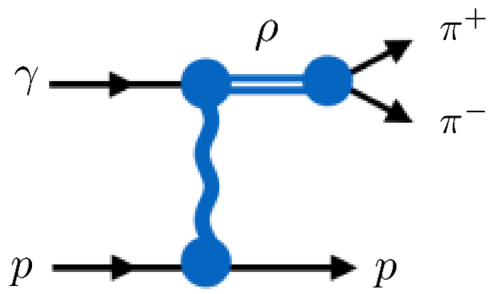
Duality between resonance poles and Regge exchanges

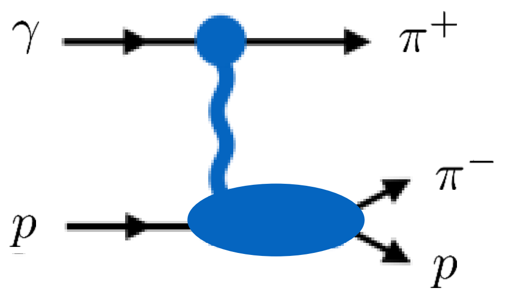
Dolen, Horn, Schmid, Phys.Rev. 166, 1768 (1968)
Veneziano, Nuovo Cim.A 57, 198 (1968)

# Two pion photoproduction in the ρ region

Ł.Bibrzycki, N.Hammoud, V.Mathieu, R.J.Perry, GM, et al. (JPAC), Phys.Rev.D 111, 014002 (2025)

Regge-based model fitted to angular moments from CLAS@Jefferson Lab




- ⁎ 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)

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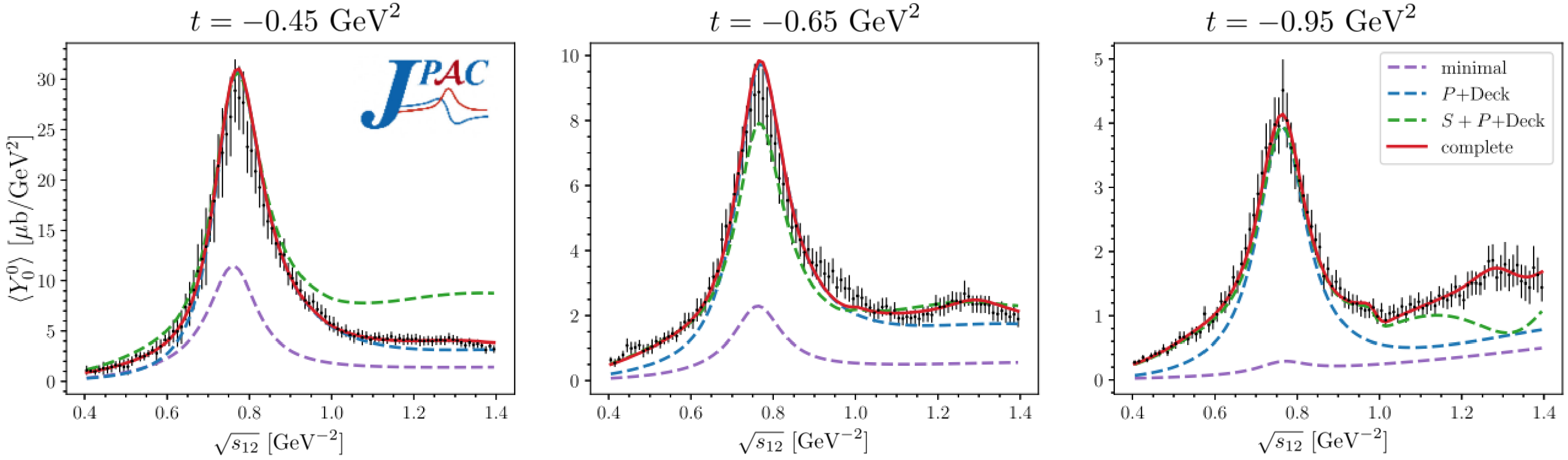
Regge-based model fitted to angular moments from CLAS@Jefferson Lab

$$\langle Y_M^L \rangle = \sqrt{4\pi}\kappa \sum_{lml'm'} A_{Mmm'}^{Ll l'} \sum_{\lambda_\gamma \lambda_1 m' \lambda_2} \mathcal{M}^{l'*}_{\lambda_\gamma \lambda_1 m' \lambda_2 (s,t,s_{12})} \mathcal{M}^{l*}_{\lambda_\gamma \lambda_1 m \lambda_2 (s,t,s_{12})}$$

$$A_{Mmm'}^{Ll l'} = \int d\Omega^H Y_m^l(\Omega^H) Y_{m'}^{l'*}(\Omega^H) \mathrm{Re}\left\{ Y_M^L(\Omega^H) \right\}$$



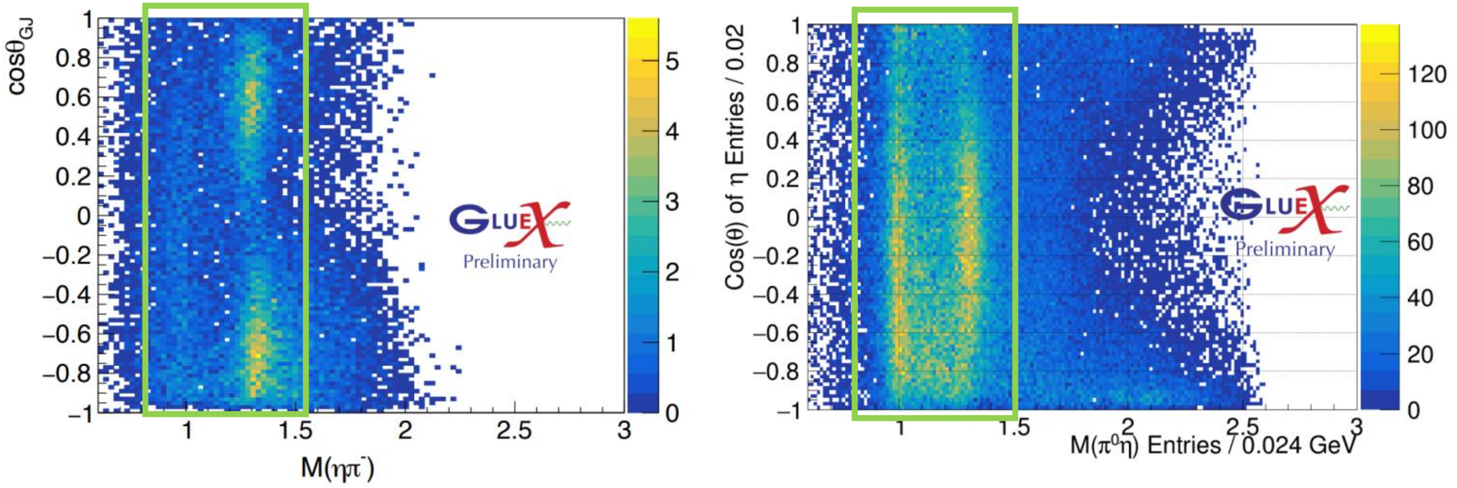

Data:
Phys.Rev.D 80, 072005 (2009)

→ Much more physics than just Pomeron exchange

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

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

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



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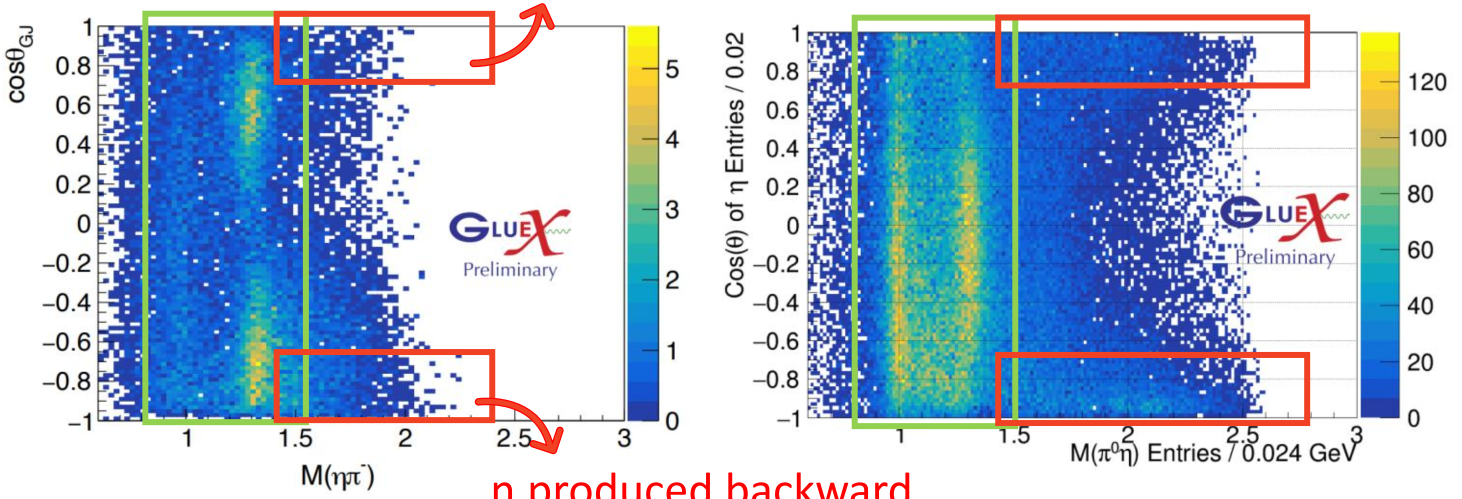
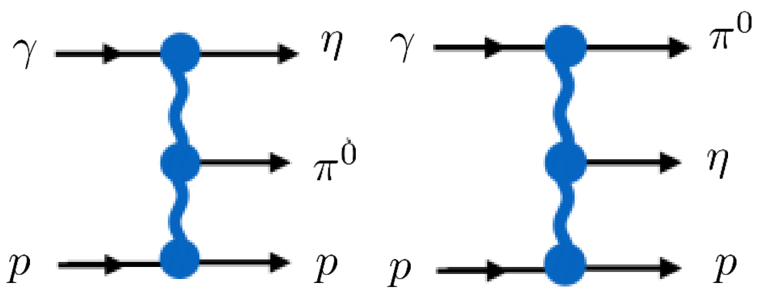



η produced backward

Double Regge production



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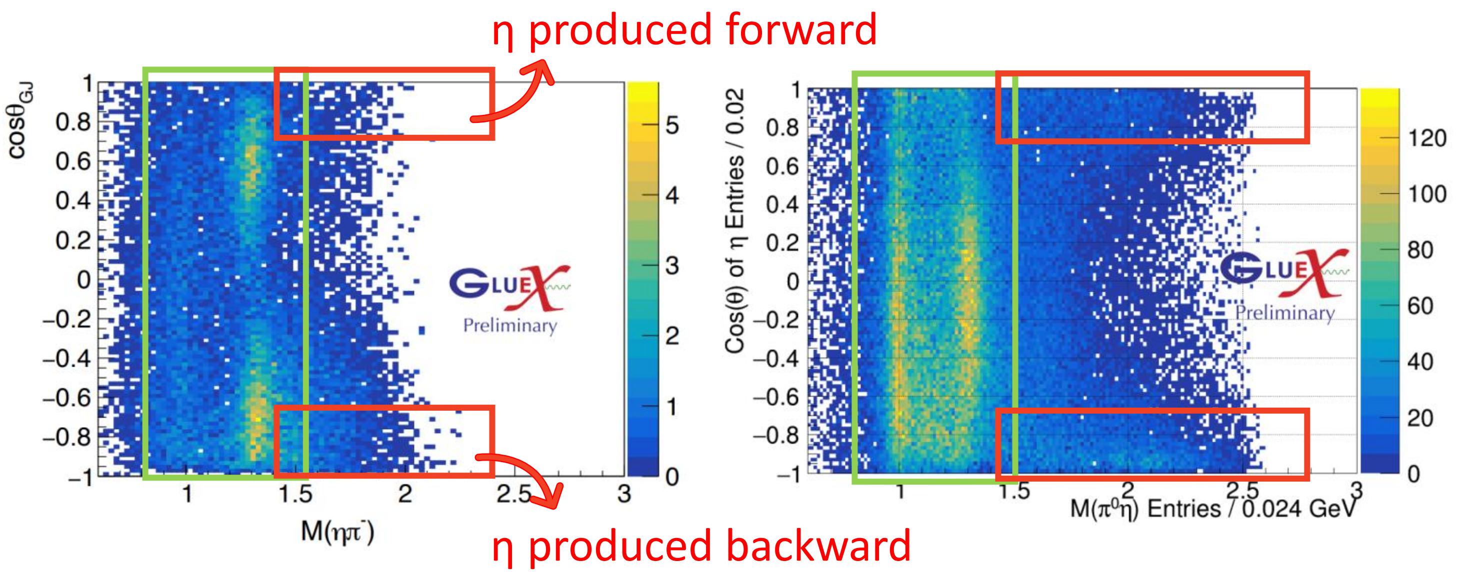
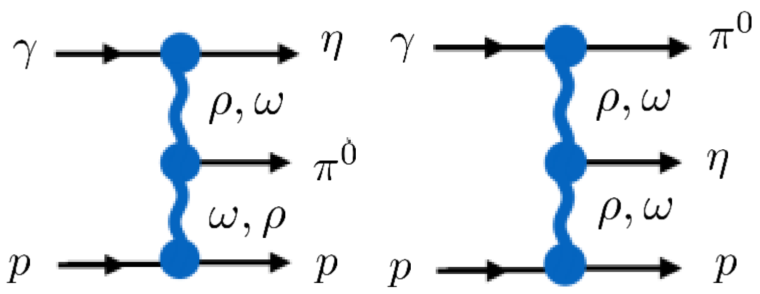



Double Regge production




→ **Vector exchanges**

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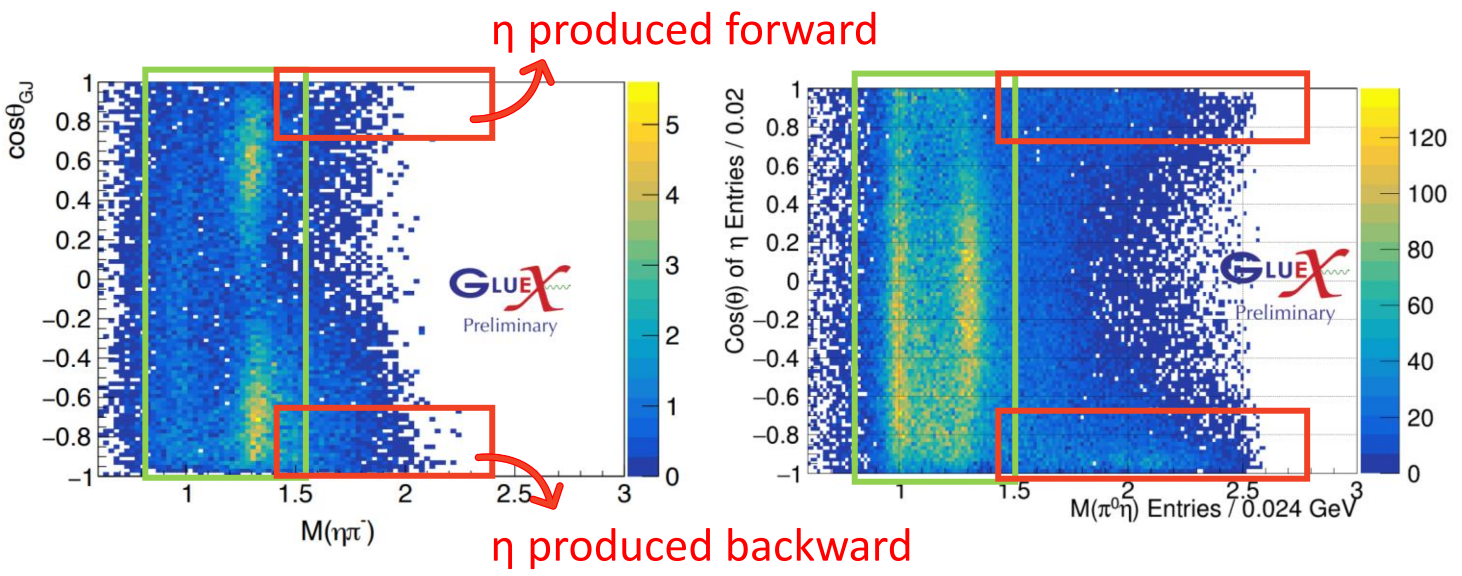
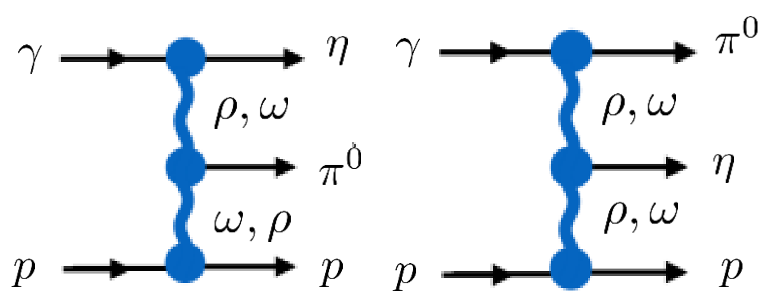



Double Regge production




→ **Vector exchanges**

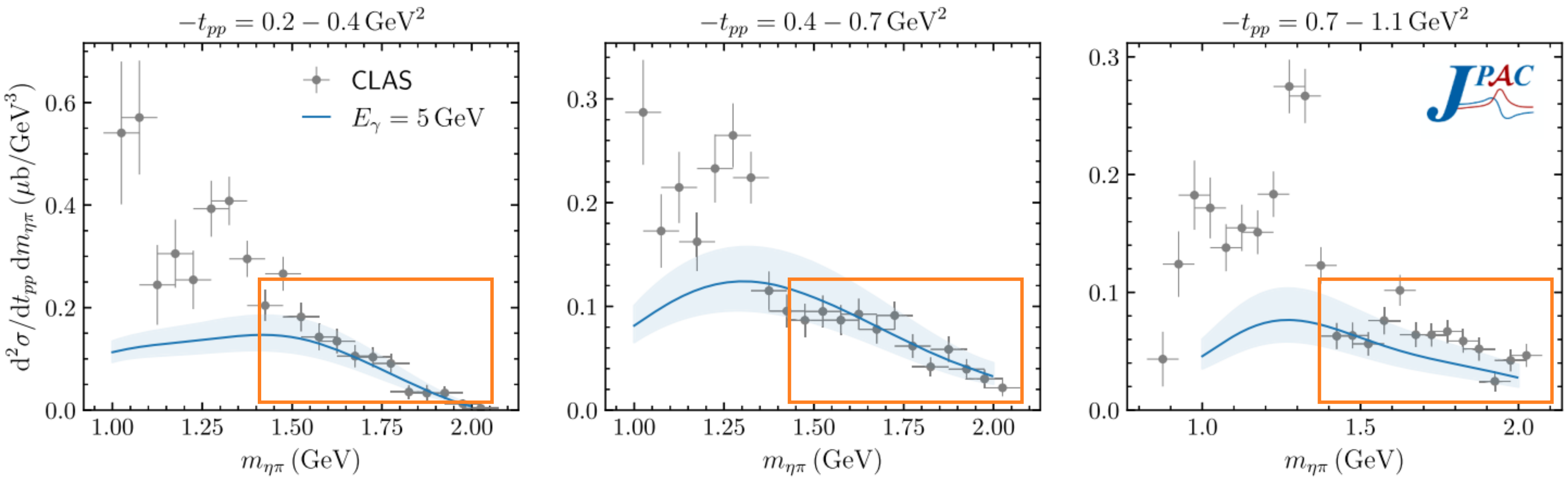
* **Forward-backward asymmetry:**
  - → Interference between even and odd partial waves
  - → Presence of exotic partial waves (also at low energies)

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

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

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

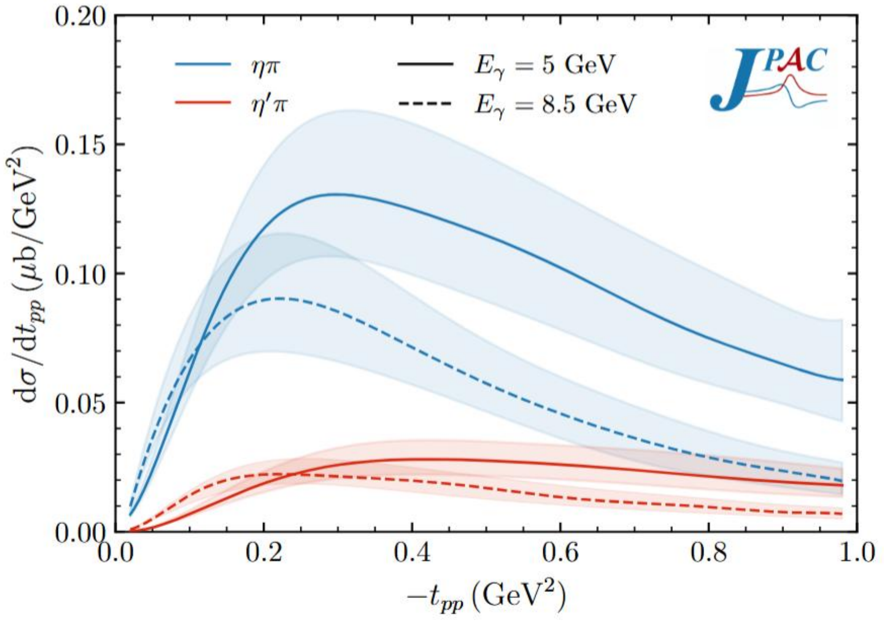
* Comparison with CLAS data (not a fit): Phys.Rev.C 102, 032201 (2020)



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

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

* Predictions for GlueX energy



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

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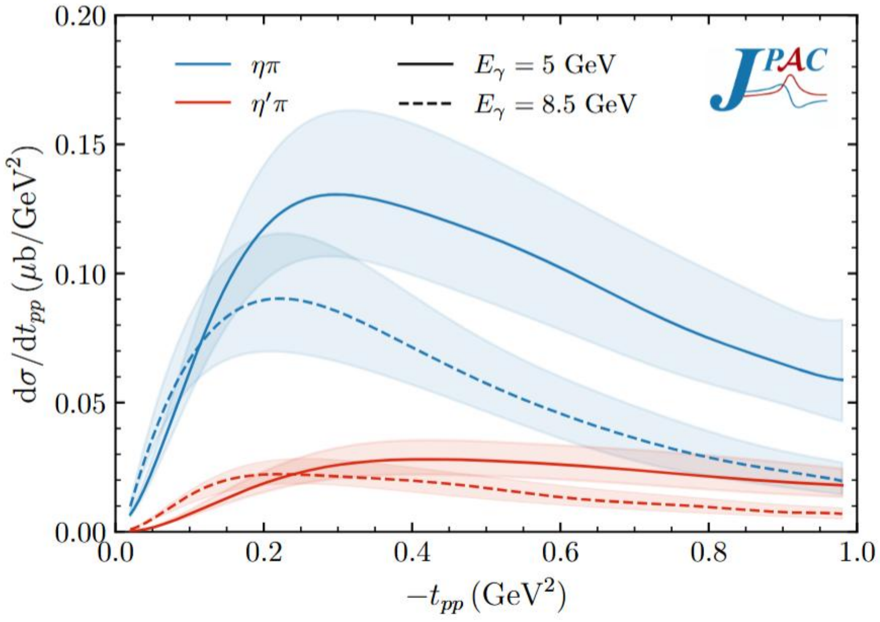
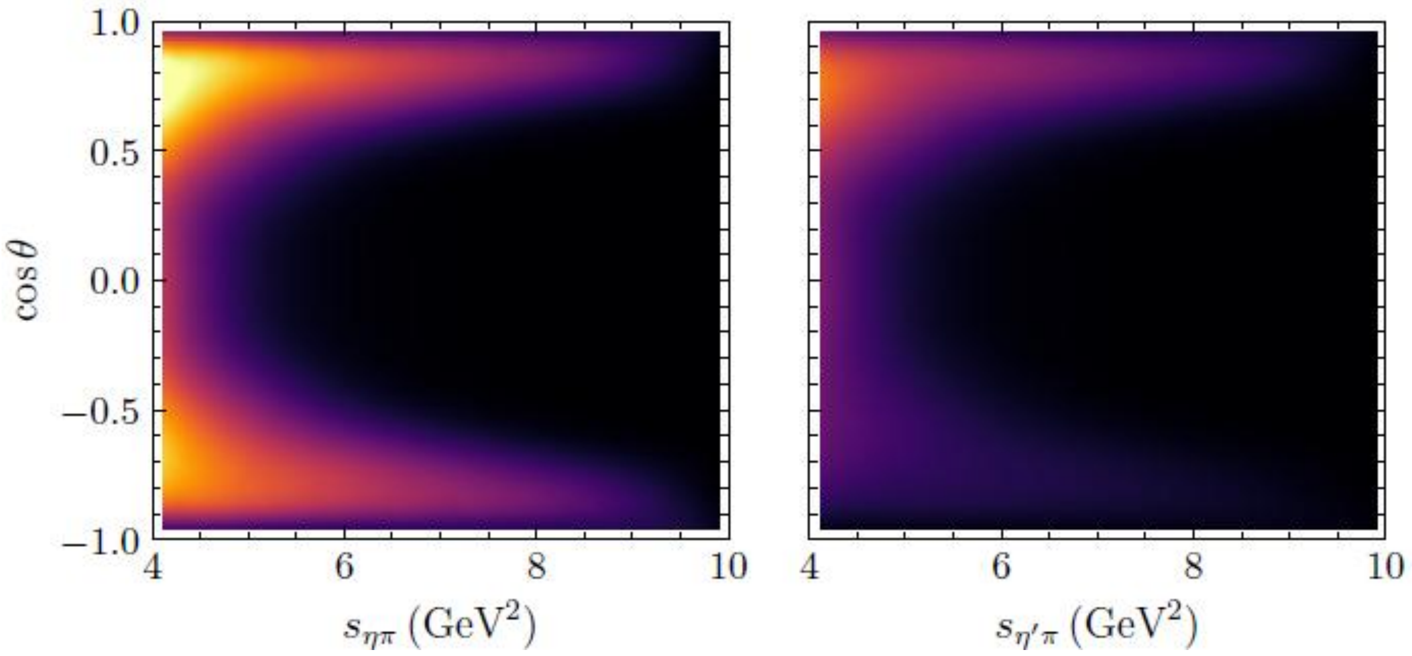
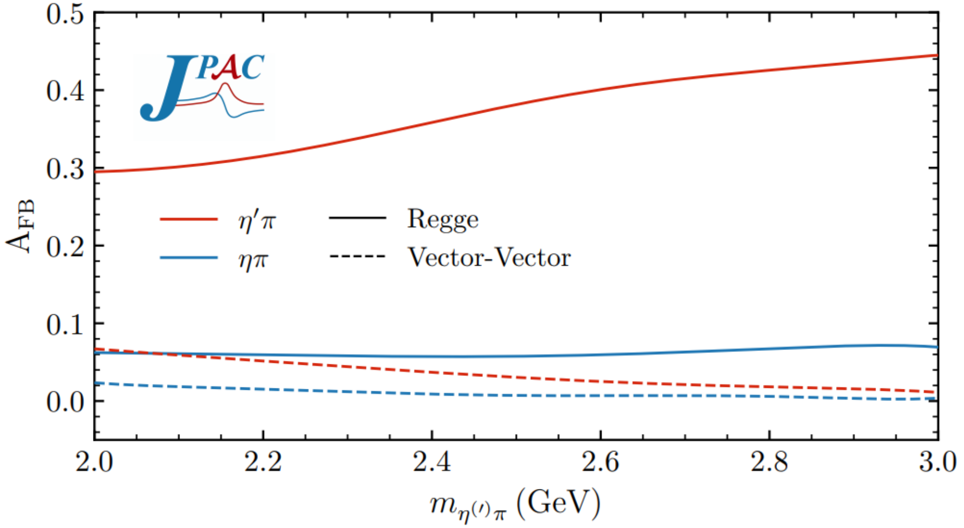


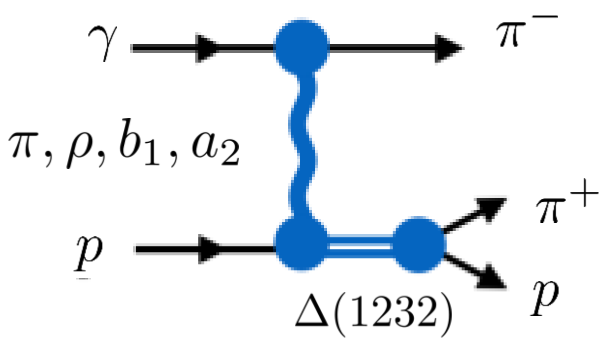

$$A_{\rm FB}(m^2_{\eta\pi}) = \frac{F(m^2_{\eta\pi}) - B(m^2_{\eta\pi})}{F(m^2_{\eta\pi}) + B(m^2_{\eta\pi})}$$

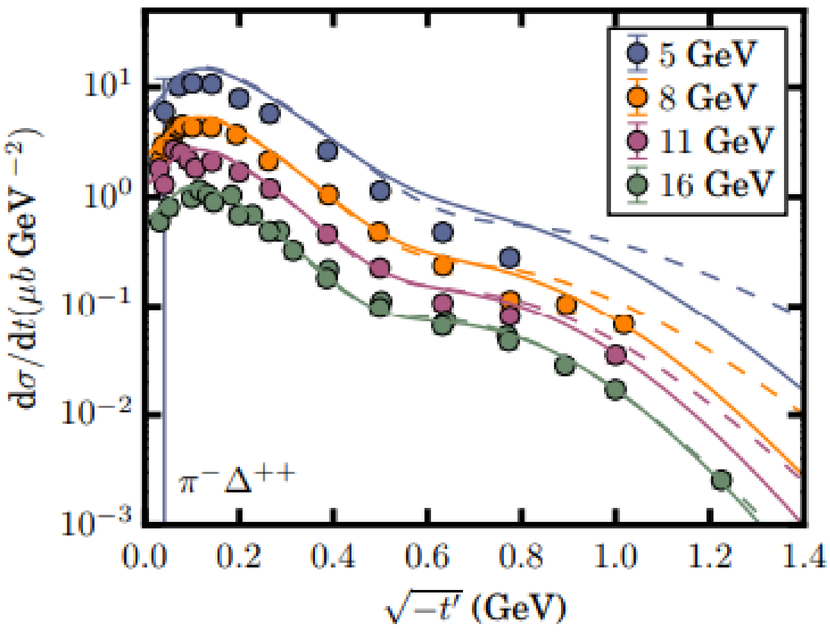


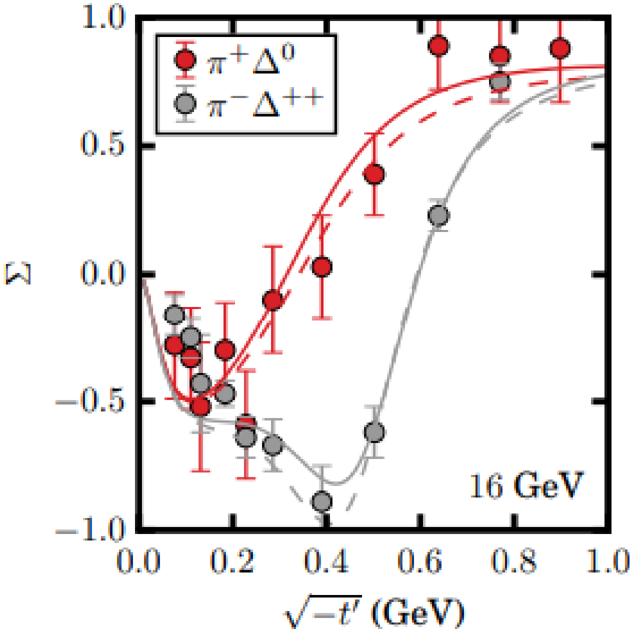
# $\pi\Delta$ photoproduction

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

* 2018 JPAC model fitted to cross section and beam asymmetry data from SLAC (relative phases unconstrained) Phys.Lett.B 779, 77 (2018)



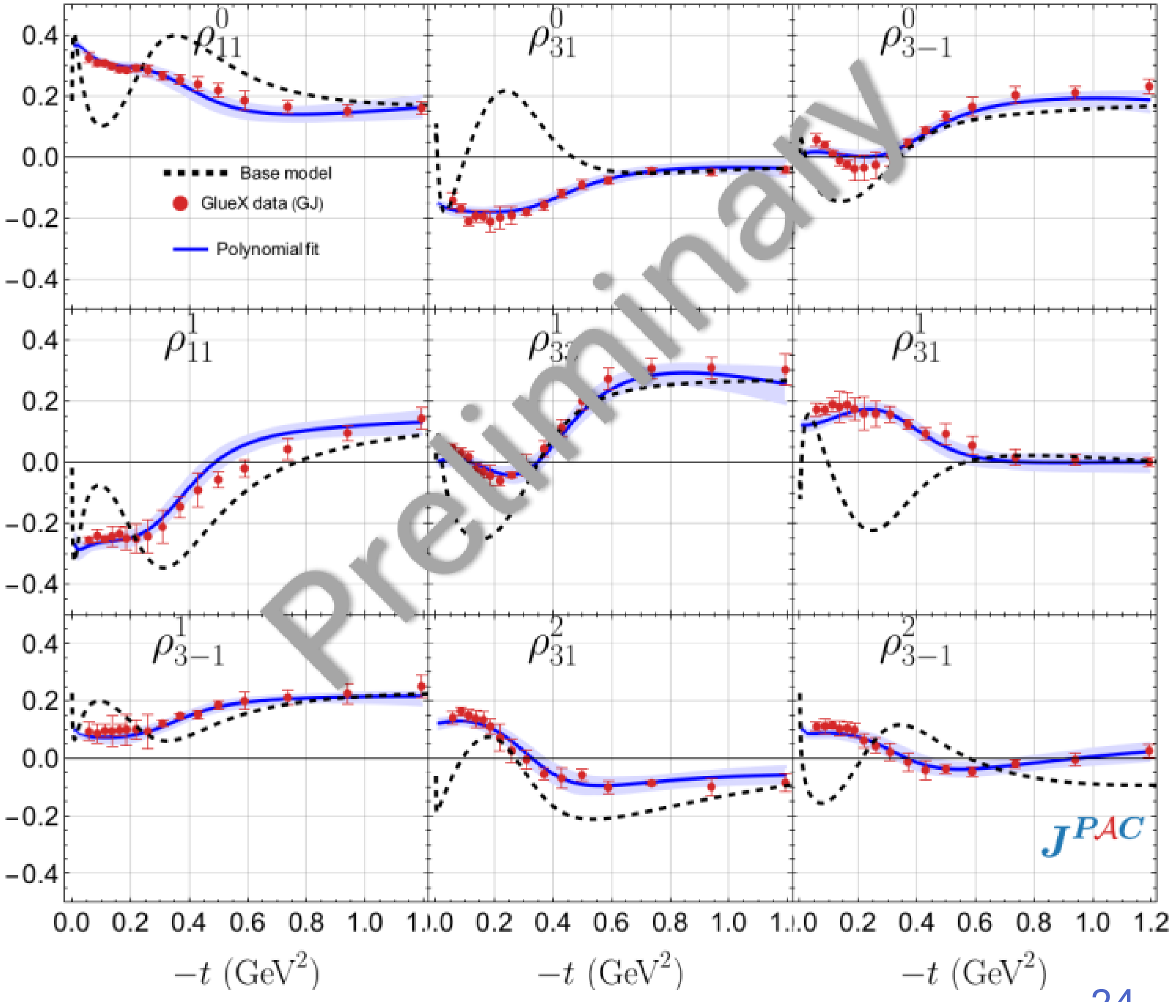



# $\pi\Delta$ photoproduction

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

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

Dashed lines: old JPAC model




- New data for 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

# Summary

- **Hadron spectroscopy** provides us a window to nonperturbative QCD
- Reliable extraction of **resonance parameters** from experimental data needs amplitude analysis
- **S-matrix theory** and **Regge theory** provide us with the framework to do it with minimal model dependence and understand production mechanisms
- Crucial for interpreting GlueX and CLAS experimental data from Jefferson Lab and extracting the **hybrid meson** signal