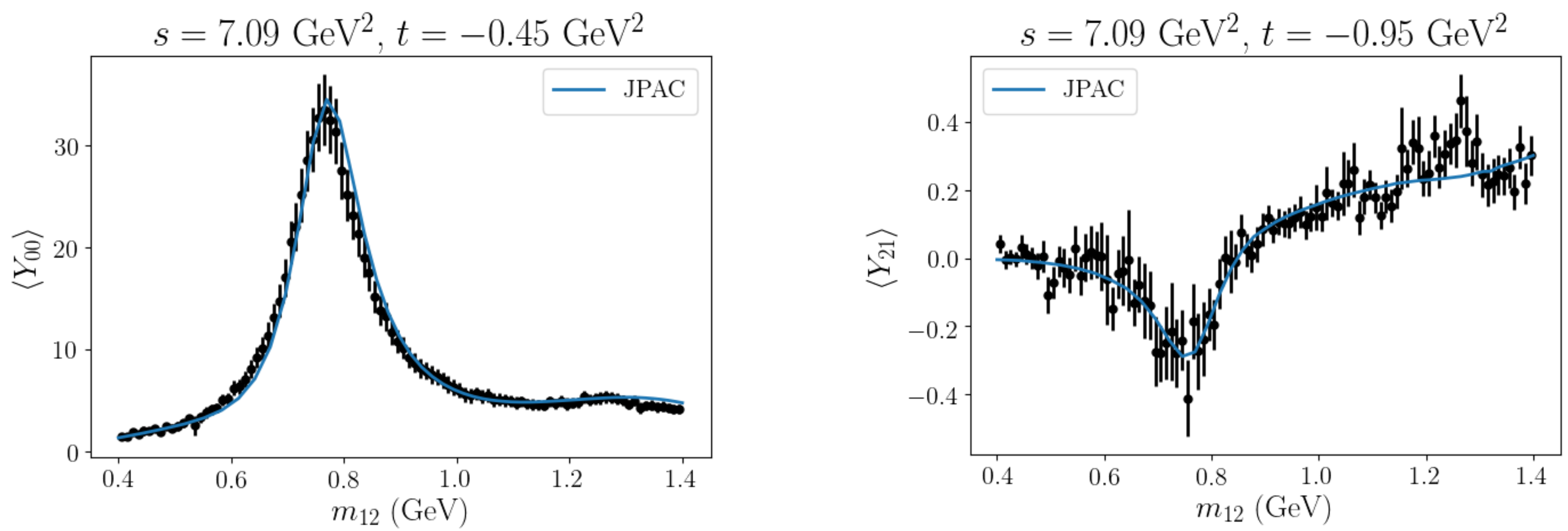
Production mechanisms of light meson resonances in two-pion photoproduction



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with

Lukasz Bibrzycki, Nadine Hammoud, Vincent Mathieu, Adam P. Szczepaniak

Outline

- Why two-pion photoproduction?
- CLAS Measurements
- Theoretical Model:
  - Resonant production
  - Non-resonant production: Deck
- Results
- Further work and conclusions

Why Two-Pion Photoproduction?

- Have previous measurements from CLAS6
- Measurements at CLAS12, GlueX
- Deck piece has applications to exotic 'golden channel': $\pi^-\eta\Delta^{++}$
- Two-pion electroproduction?
- Extraction of pion electromagnetic form factor?

Two-Pion Photoproduction

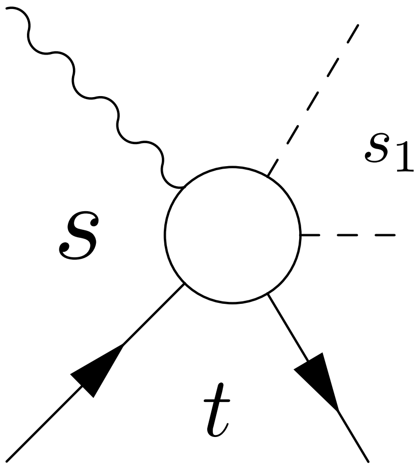
$$\gamma(q, \lambda_\gamma) + p(p_1, \lambda_1) \to \pi^+(k_1) + \pi^-(k_2) + p(p_2, \lambda_2)$$

$$s = (p_1 + q)^2$$

$$t = (p_1 - p_2)^2$$

$$s_{12} = (k_1 + k_2)^2 = m_{12}^2$$

$$\Omega^{\mathrm{H}} = (\theta^{\mathrm{H}}, \phi^{\mathrm{H}})$$



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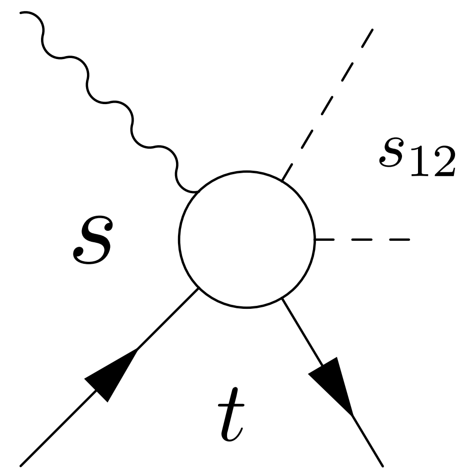
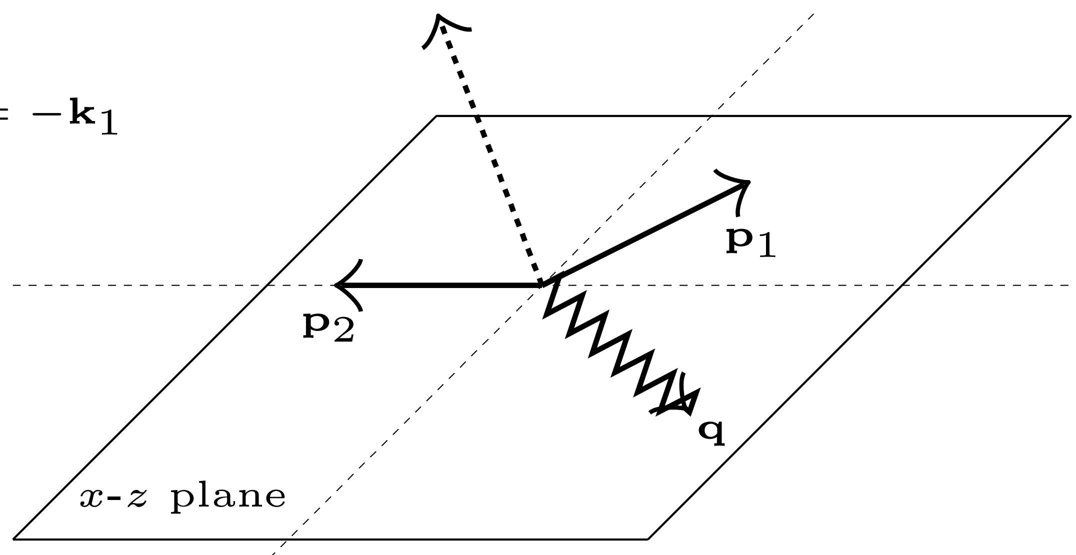


$$\mathbf{k}_1 = |\mathbf{k}_1^{\mathrm{H}}|(\sin\theta_{\mathrm{H}}\cos\phi_{\mathrm{H}}, \sin\theta_{\mathrm{H}}\sin\phi_{\mathrm{H}}, \cos\theta_{\mathrm{H}})$$

$$\mathbf{k}_2 = -\mathbf{k}_1$$



CLAS Measurement: Two-Pion Photoproduction

$$E_\gamma \in [3.0, 3.8]\ \mathrm{GeV}, \quad t \in [-0.4, 1.0]\ \mathrm{GeV}^2$$

$$\langle Y_{LM} \rangle = \sqrt{4\pi} \int d\Omega^{\mathrm{H}} \frac{d\sigma}{dt\,dm_{12}\,d\Omega^{\mathrm{H}}} \mathrm{Re} Y_{LM}(\Omega^{\mathrm{H}}), \qquad \langle Y_{00} \rangle = \frac{d\sigma}{dt\,dm_{12}}$$

Phys.Rev.D 80 (2009) 072005

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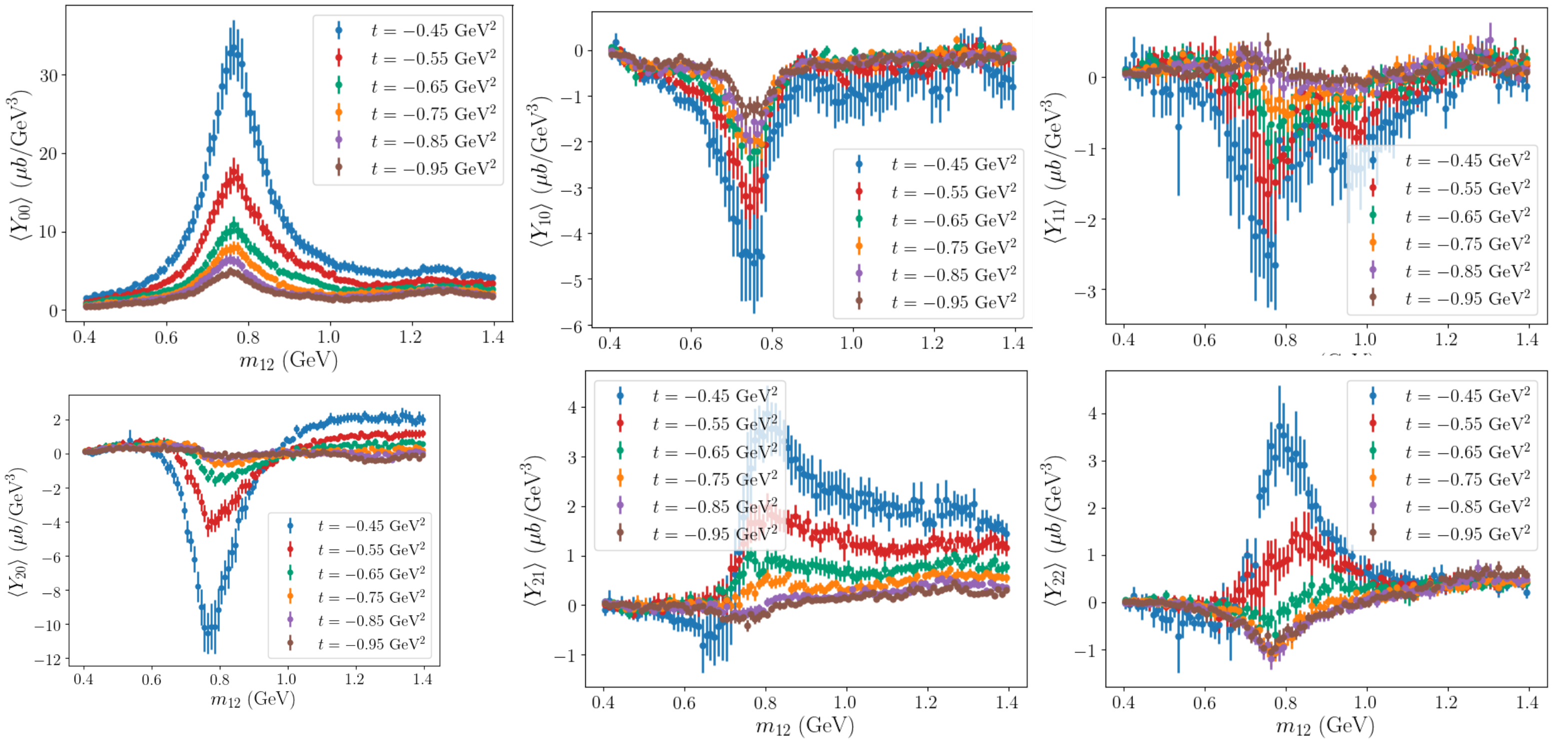
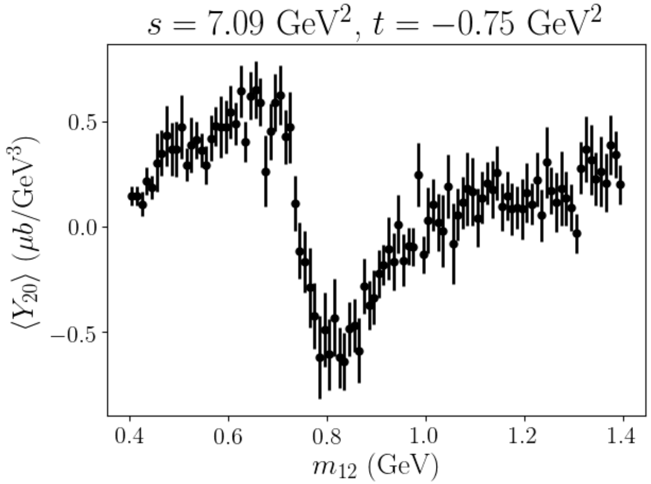
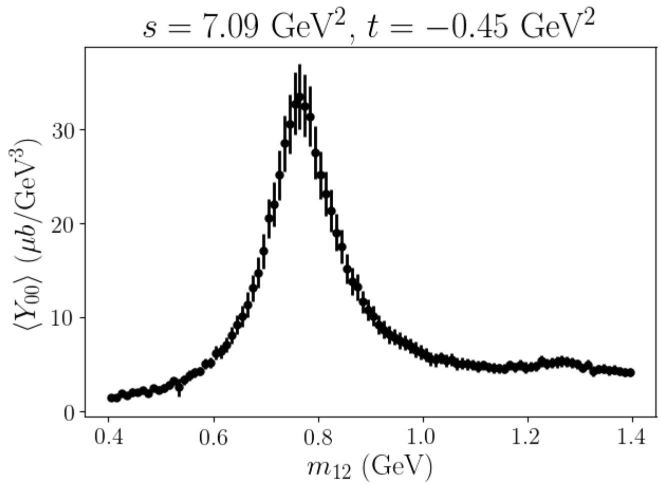
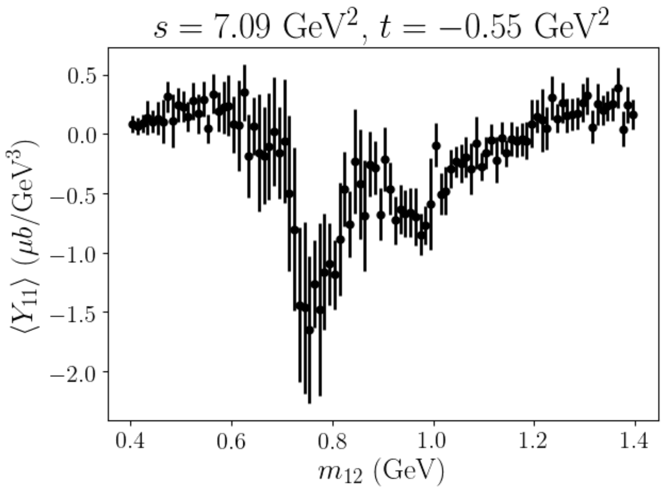


Phys.Rev.D 80 (2009) 072005

Meson Resonances < 1 GeV







R.L. Workman et al. (Particle Data Group), Prog.Theor.Exp.Phys. 2022, 083C01 (2022)

Meson Resonances < 1 GeV

$f_0(500)$ $I^G(J^{PC}) = 0^+(0^{++})$

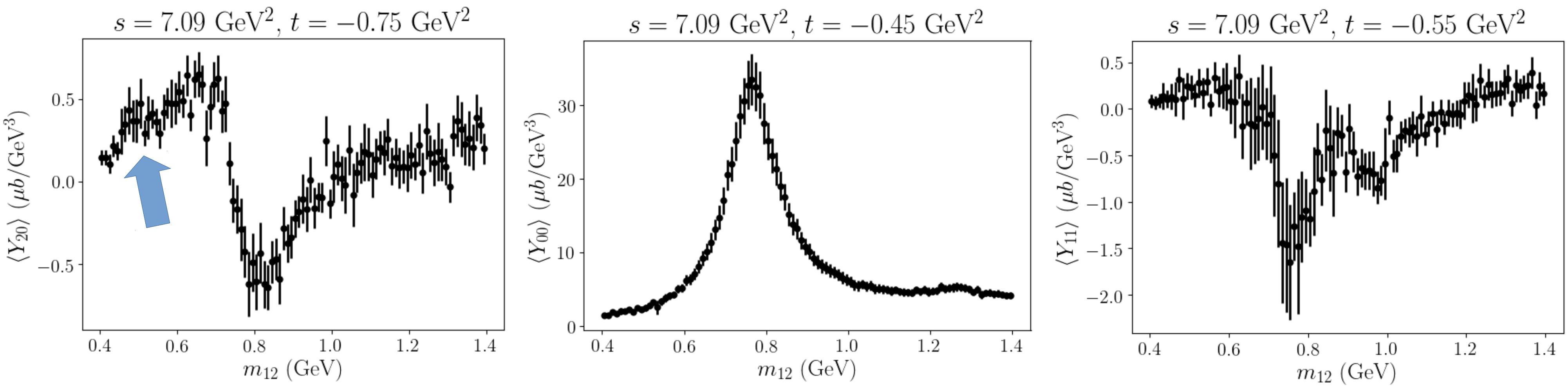
also known as σ; was $f_0(600)$

See the review on "Scalar Mesons below 1 GeV."

Mass (T-Matrix Pole $\sqrt{s}$) = (400–550)$-i$(200–350) MeV

Mass (Breit-Wigner) = 400 to 800 MeV

Full width (Breit-Wigner) = 100 to 800 MeV



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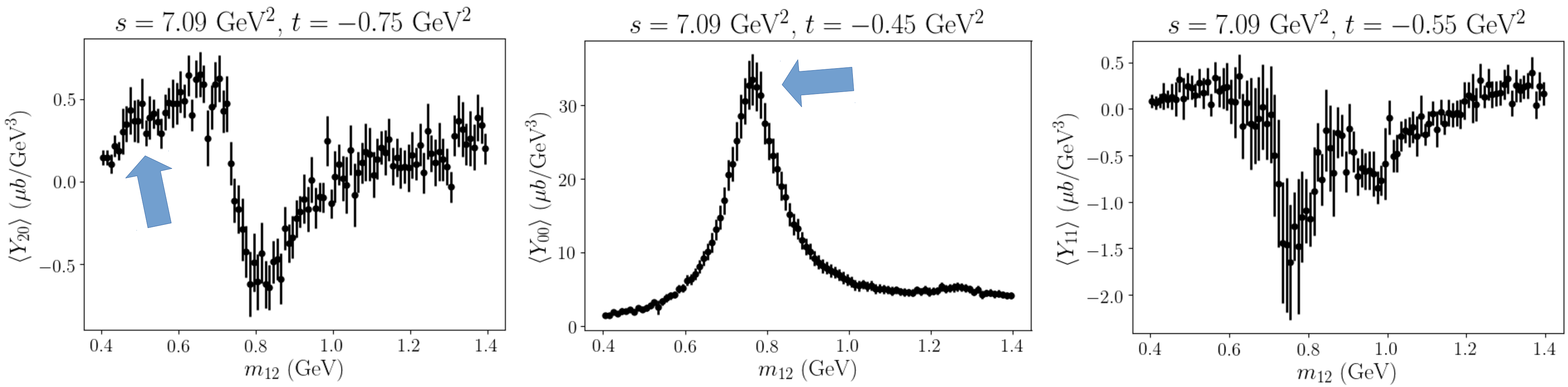

$\rho(770)$ $I^G(J^{PC}) = 1^+(1^{--})$

See the review on "Spectroscopy of Light Meson Resonances."

T-Matrix Pole $\sqrt{s}$ = (761–765) $-$ i (71–74) MeV
Mass (Breit-Wigner) = 775.26 $\pm$ 0.23 MeV
Full width (Breit-Wigner) = 149.1 $\pm$ 0.8 MeV

R.L. Workman et al. (Particle Data Group), Prog.Theor.Exp.Phys. 2022, 083C01 (2022)

MESON RESONANCES < 1 GEV

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See the review on "Scalar Mesons below 1 GeV."

Mass (T-Matrix Pole $\sqrt{s}$) = (400–550)$-i$(200–350) MeV

Mass (Breit-Wigner) = 400 to 800 MeV

Full width (Breit-Wigner) = 100 to 800 MeV

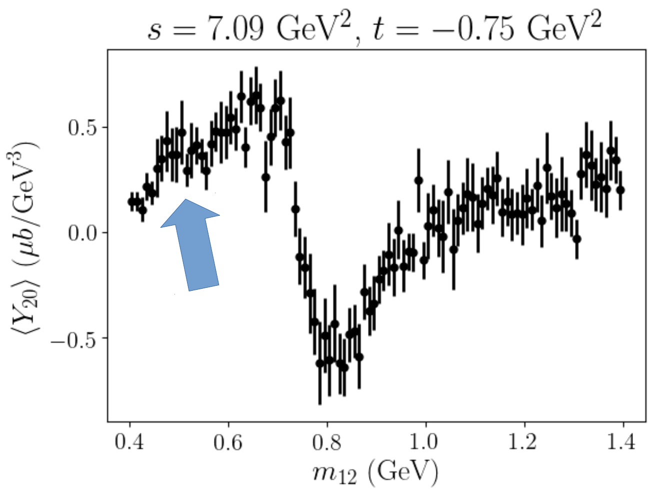
$f_0(980)$ $\quad I^G(J^{PC}) = 0^+(0^{++})$

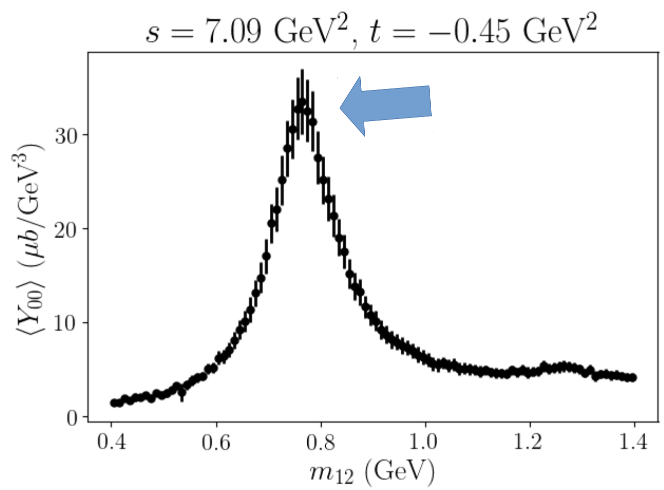
See the review on "Scalar Mesons below 1 GeV."

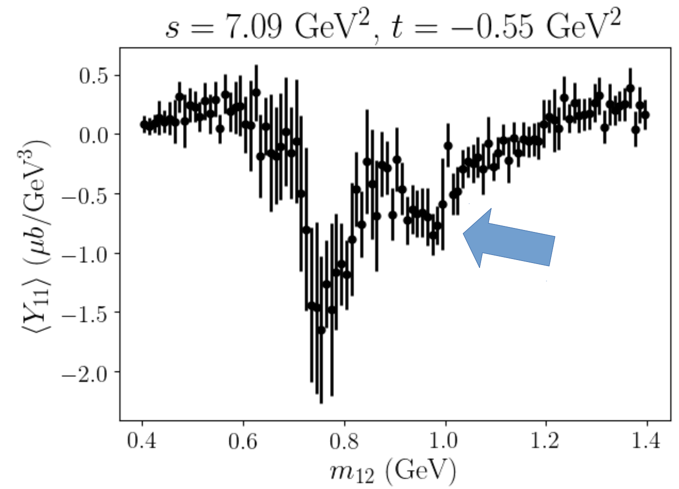
T-matrix pole $\sqrt{s}$ = (980–1010) $-$ i (20–35) MeV [h]

Mass (Breit-Wigner) = 990 $\pm$ 20 MeV [h]

Full width (Breit-Wigner) = 10 to 100 MeV [h]







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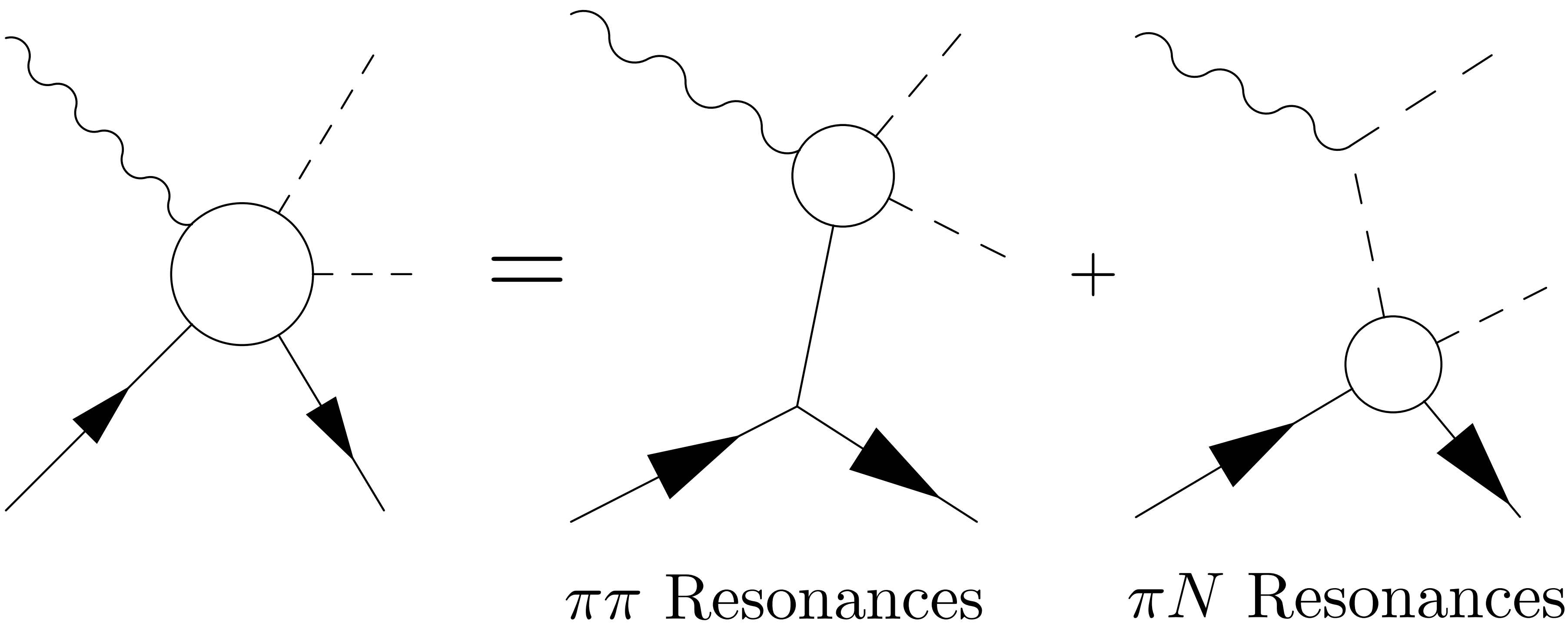
Model Overview

- $2 \to 3$ dynamics built from known dynamics in $2 \to 2$ subchannels.



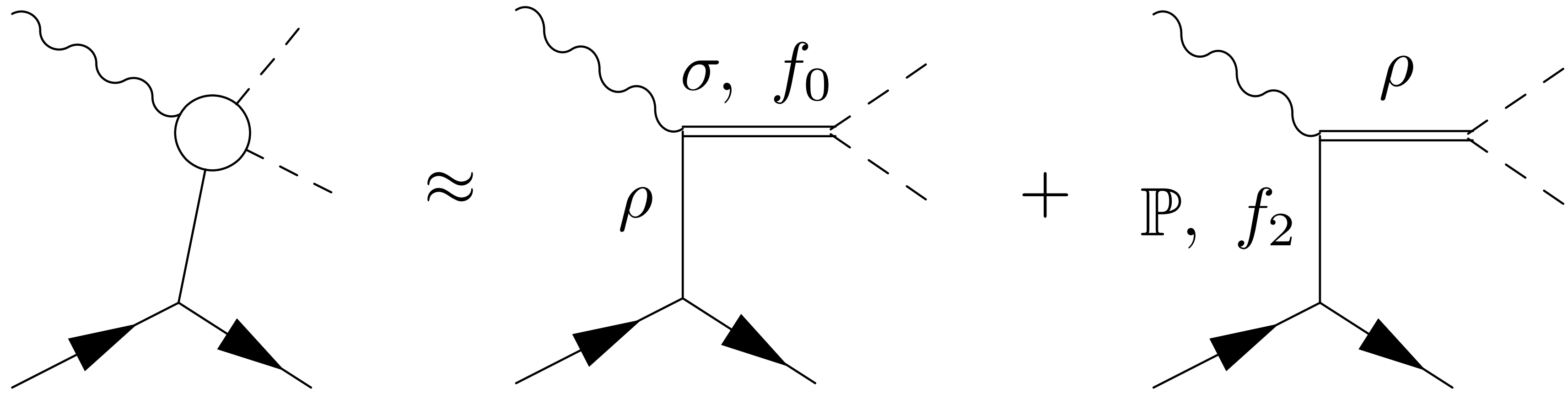
Resonant Production

- Effective Lagrangian: One particle exchange model
- Reggeize:

$$\frac{1}{t - m_{\mathrm{E}}^2} \to R_{\mathrm{E}}(s,t) = \frac{1 + e^{-i\pi\alpha^E(t)}}{\sin \pi\alpha^E(t)} \left(\frac{s}{s_0}\right)^{\alpha^E(t)}$$

- "Breit-Wignerize":

$$\frac{1}{s_{12} - m_{\mathrm{R}}^2} \to S_{\mathrm{BW}}^{\mathrm{dep}}(s_{12}, l) + \mathrm{poly}(s_{12}) = \frac{n(s_{12})}{m^2 - s - im\Gamma_{\mathrm{tot}}(s_{12})} + \mathrm{poly}(s_{12})$$



Partial Wave Amplitudes

$$\mathcal{M}_{\lambda_1\lambda_2\lambda_\gamma}(s,t,s_{12},\Omega_{\rm H}) = \sum_{lm} \mathcal{M}^{lm}_{\lambda_1\lambda_2\lambda_\gamma}(s,t,s_{12}) Y_{lm}(\Omega^{\rm H})$$

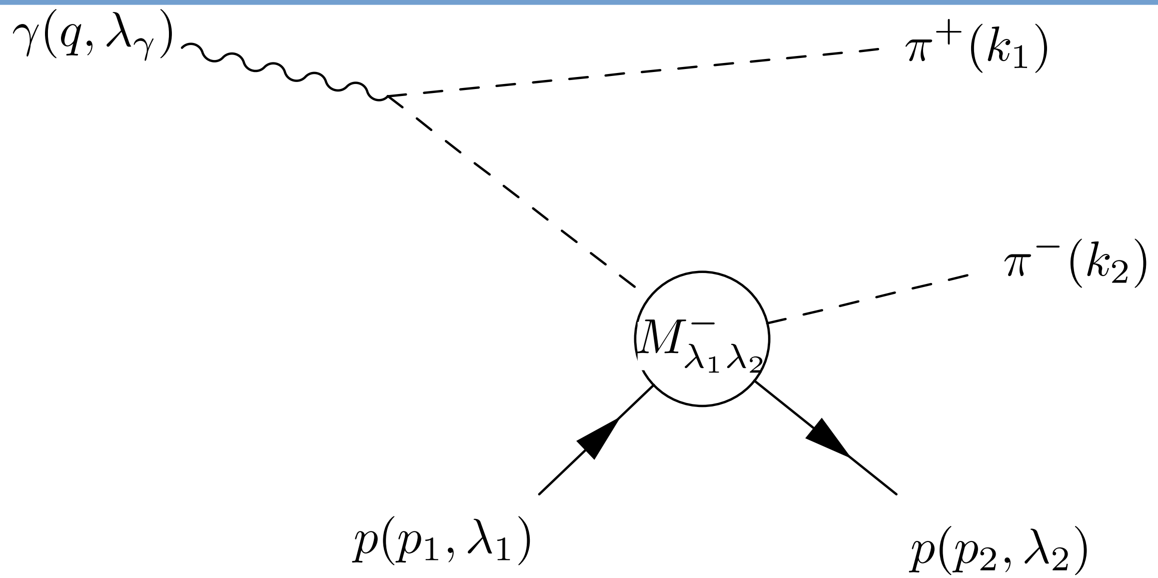
$$\mathcal{M}^{l-m}_{-\lambda_1,-\lambda_2,-\lambda_\gamma} = (-1)^{m-\lambda_2-\lambda_\gamma+\lambda_1} \mathcal{M}^{lm}_{\lambda_1,\lambda_2,\lambda_\gamma}$$

- Model is too rigid to describe data.
- Introduce free parameters g^{lm} for resonant pieces (keep Deck fixed)

$$\tilde{\mathcal{M}}_{\lambda_1\lambda_2\lambda_\gamma}(s,t,s_{12},\Omega_{\rm H}) = \sum_{lm} g^{lm} \mathcal{M}^{lm}_{\lambda_1\lambda_2\lambda_\gamma}(s,t,s_{12}) Y_{lm}(\Omega^{\rm H})$$

- $2+2+2$ ($f_0(500)$, $f_0(980)$, background) $+ 6 + 6$ (ρ, background) $= 18$ free parameters.

Non-Resonant Production: Deck Mechanism

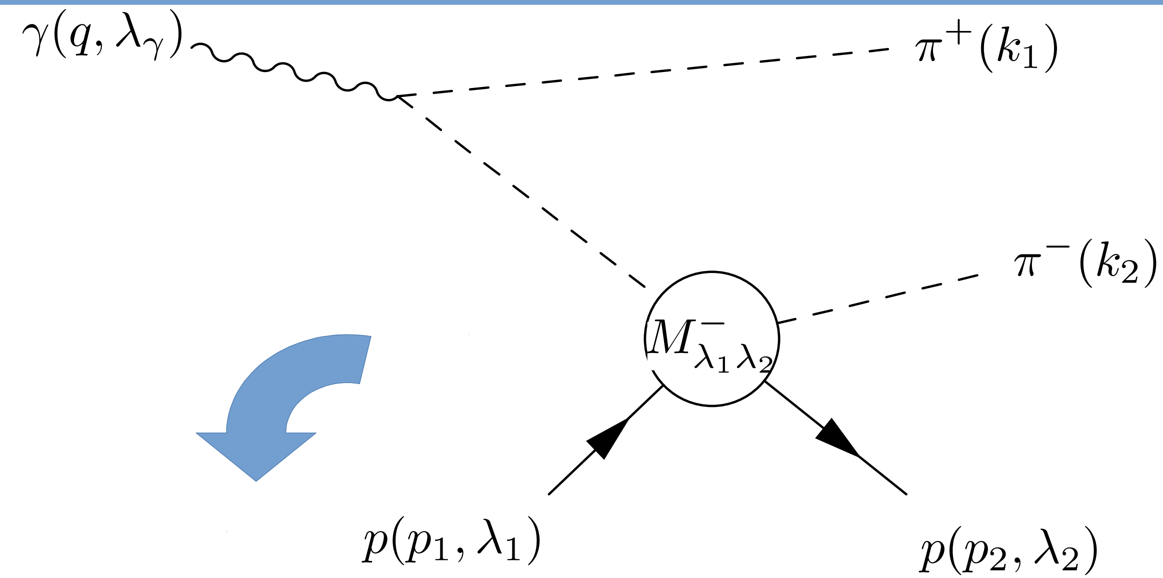


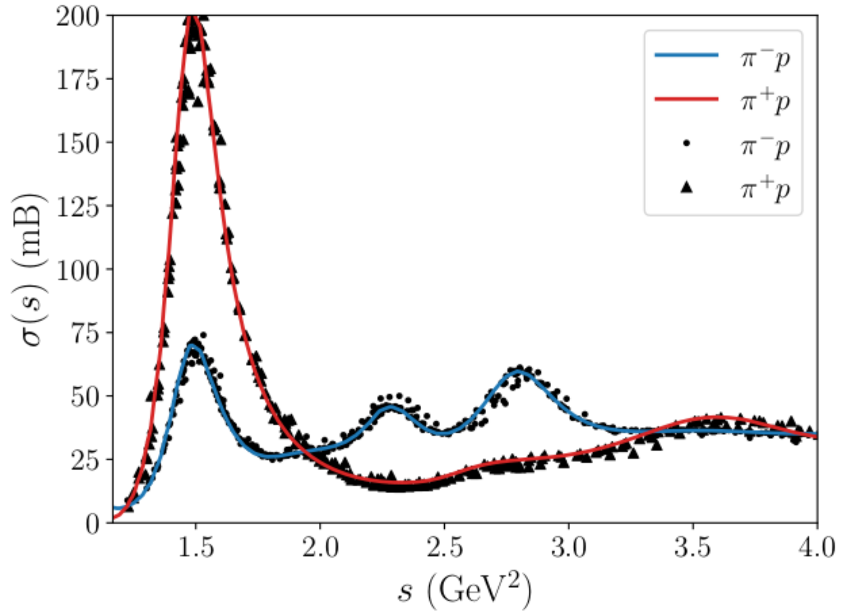
Phys.Rev.D 92 (2015) 7, 074004

SAID

Regge

Non-Resonant Production: Deck Mechanism





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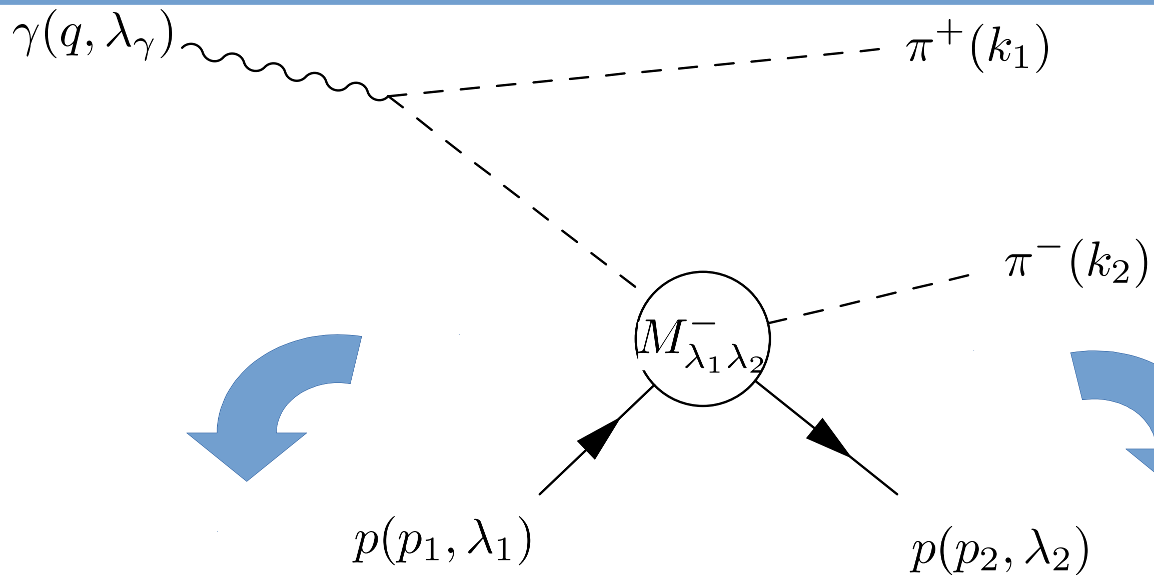

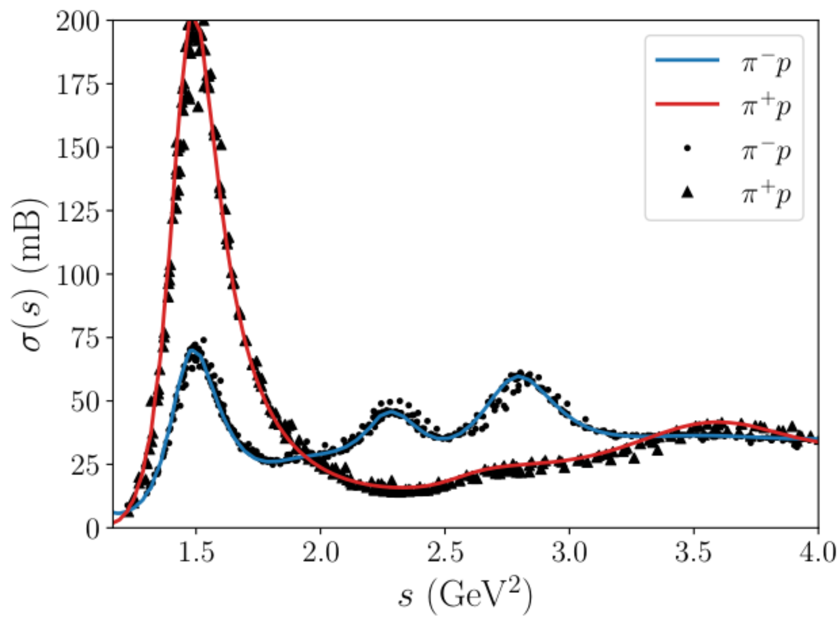

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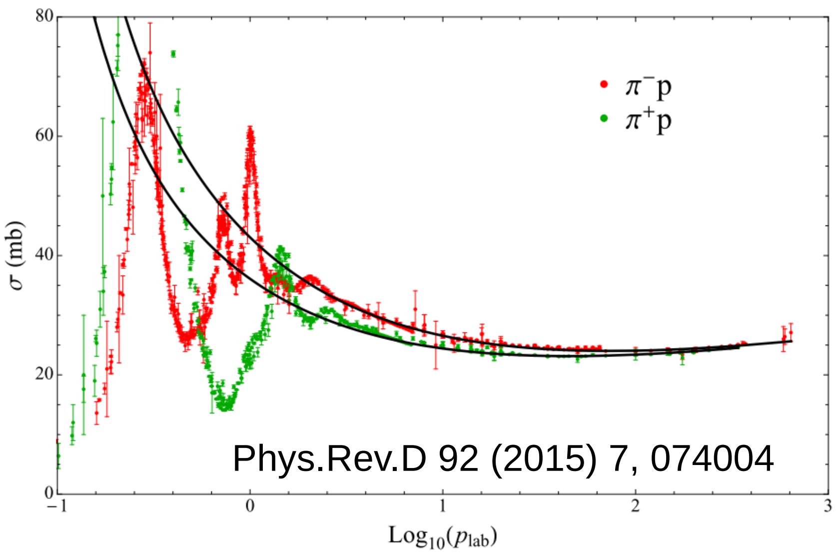
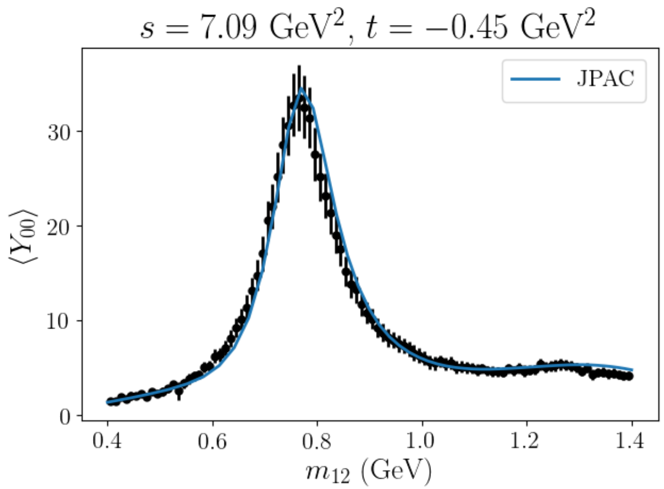


Regge

Results (Preliminary)



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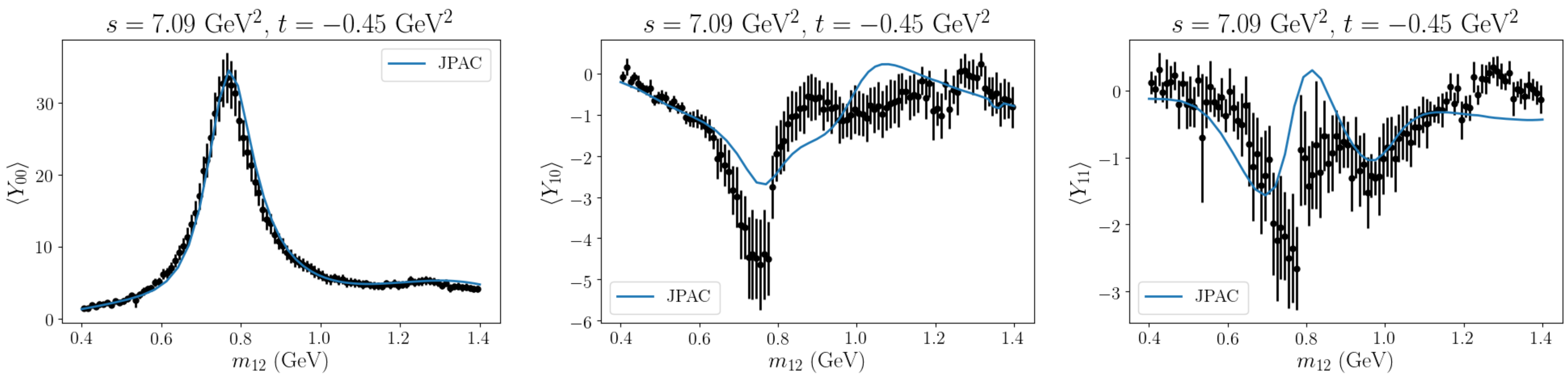
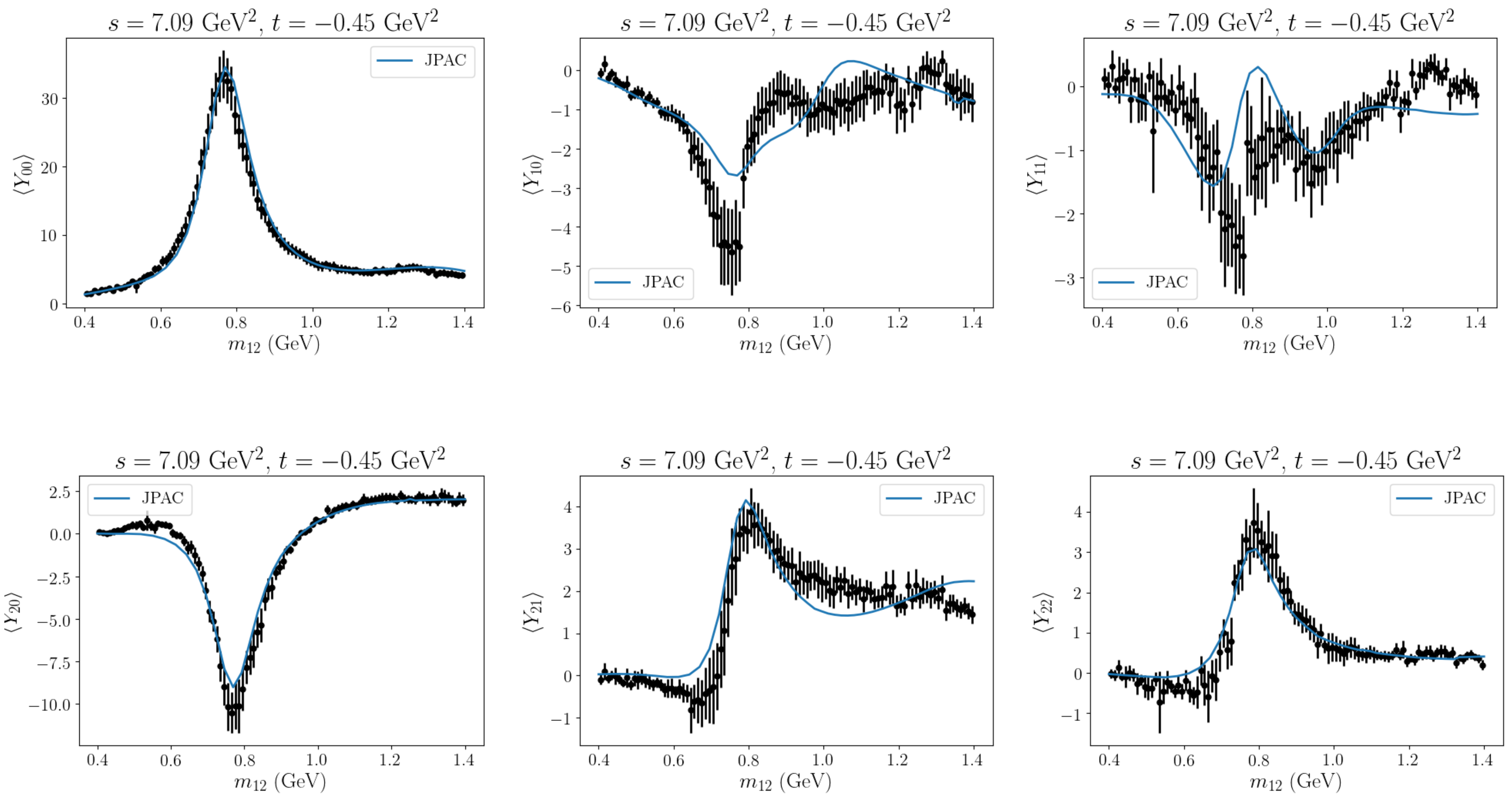


RESULTS (PRELIMINARY)



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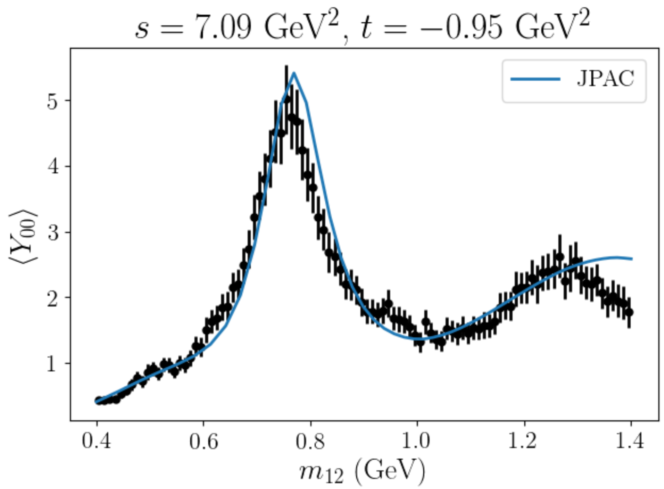

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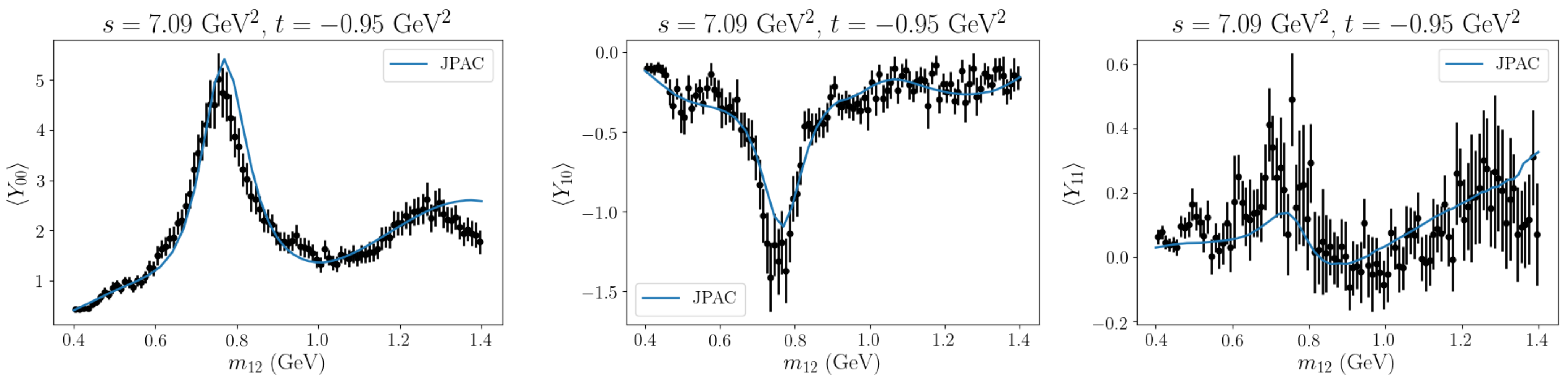

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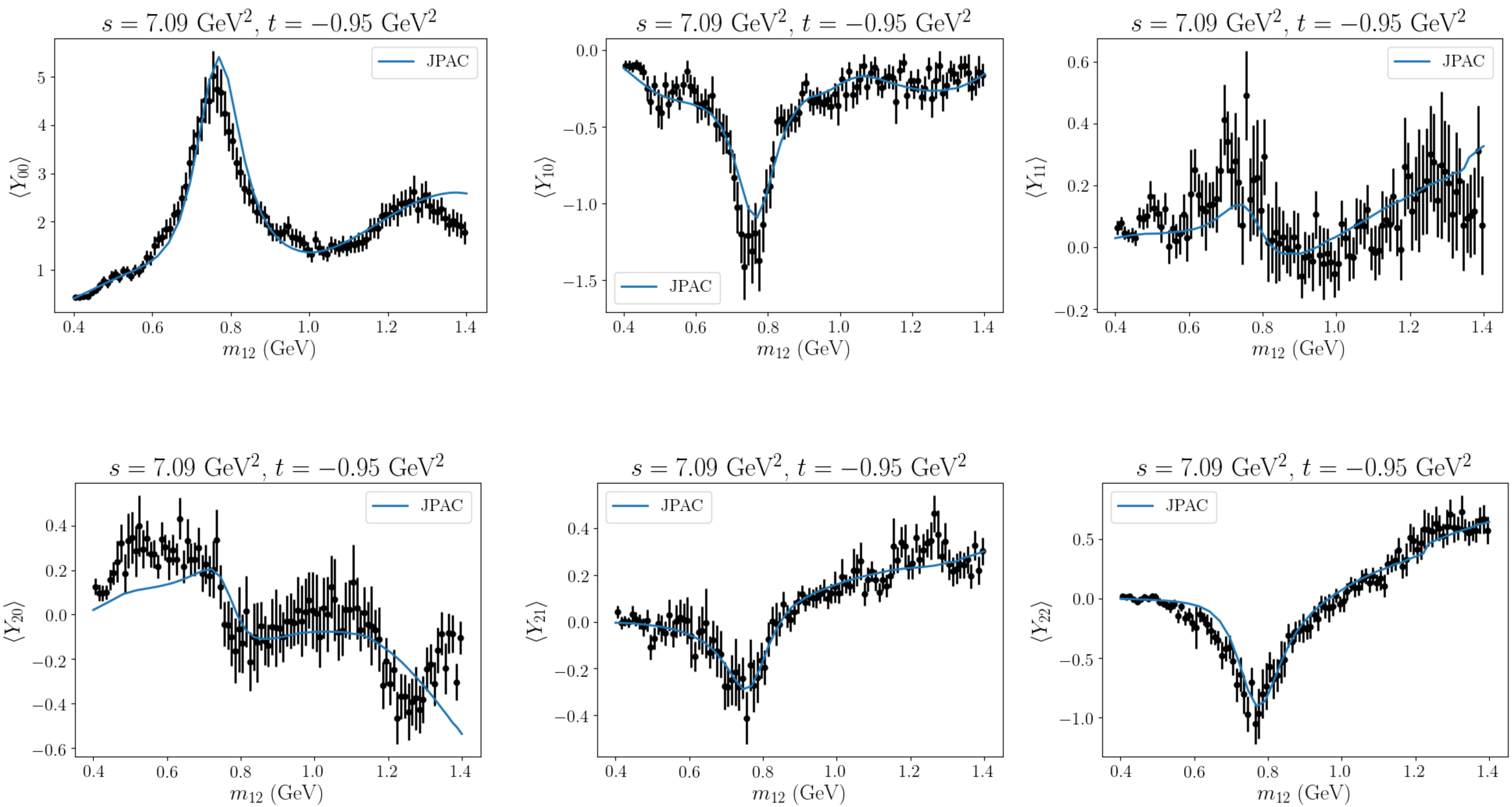
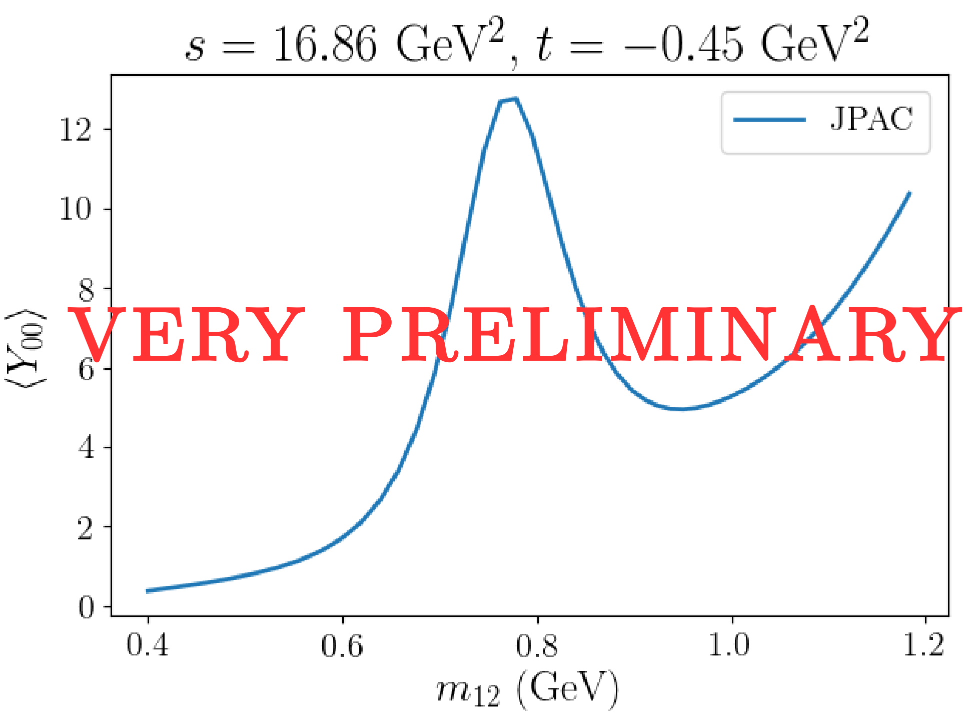
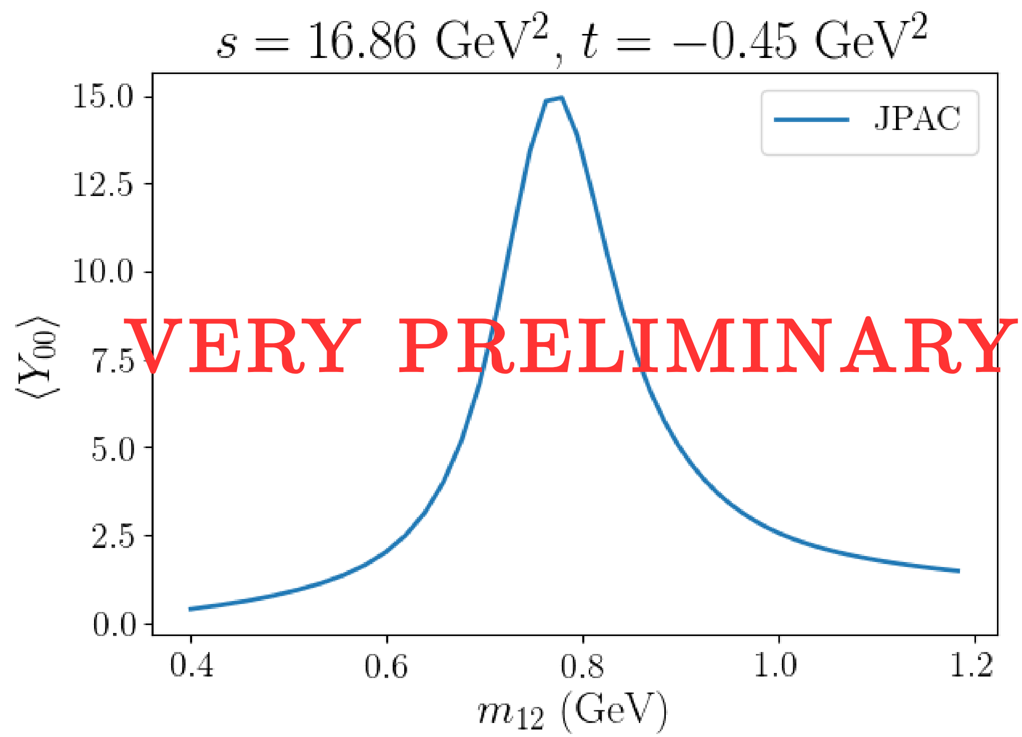


PHOTOPRODUCTION @ s=17 GeV^2



With polynomial background



Without polynomial background

$$\left.\frac{d\sigma}{dt\,dm_{12}}\right|_{s_{12}=m_\rho^2} \sim 10 - 20\ \mu\text{b}/\text{GeV}^3$$

Further work and Conclusions

- Results for other E_γ bins: results qualitatively the same
- Can we provide an empirical parameterization of couplings?
- Polarization observables
- Angular moments in $m_{\pi N}$
- Deck for other final states: $\pi^-\eta\Delta^{++}$ etc
- SDMEs for ρ, Δ
- Two-pion electroproduction for $F_\pi(Q^2)$ determination?

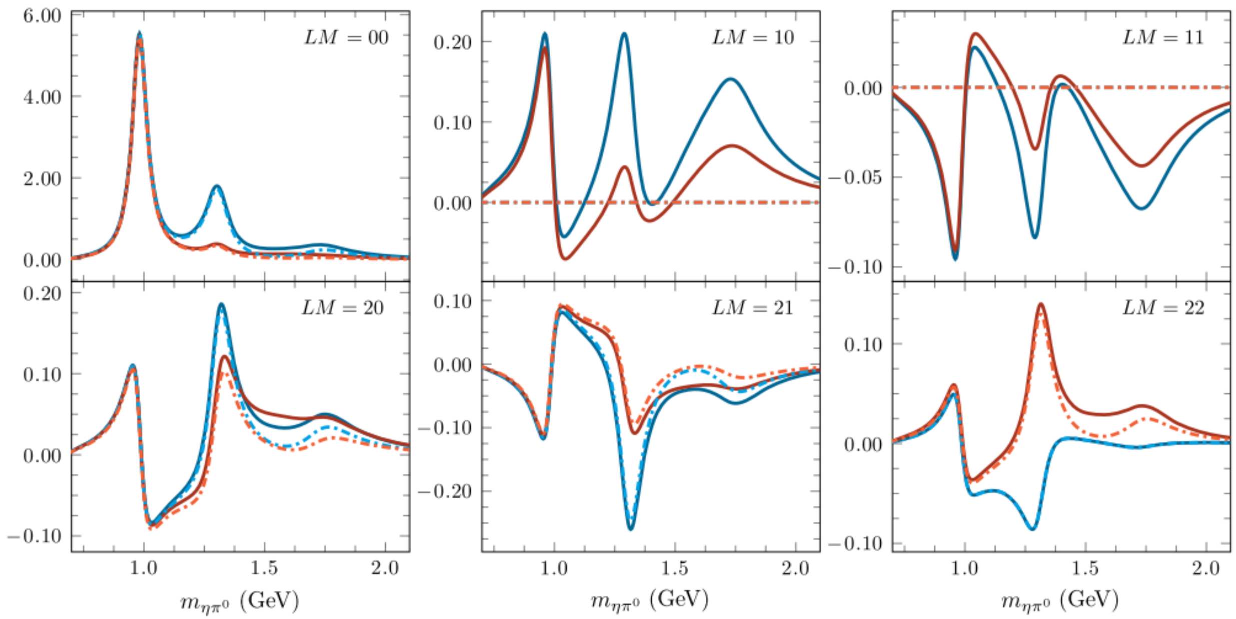
Angular Moments

PHYSICAL REVIEW D **100**, 054017 (2019)

Moments of angular distribution and beam asymmetries in $\eta\pi^0$ photoproduction at GlueX

V. Mathieu,[1,2,*] M. Albaladejo,[1,†] C. Fernández-Ramírez,[3] A. W. Jackura,[4,5] M. Mikhasenko,[6] A. Pilloni,[7,8] and A. P. Szczepaniak[1,4,5]

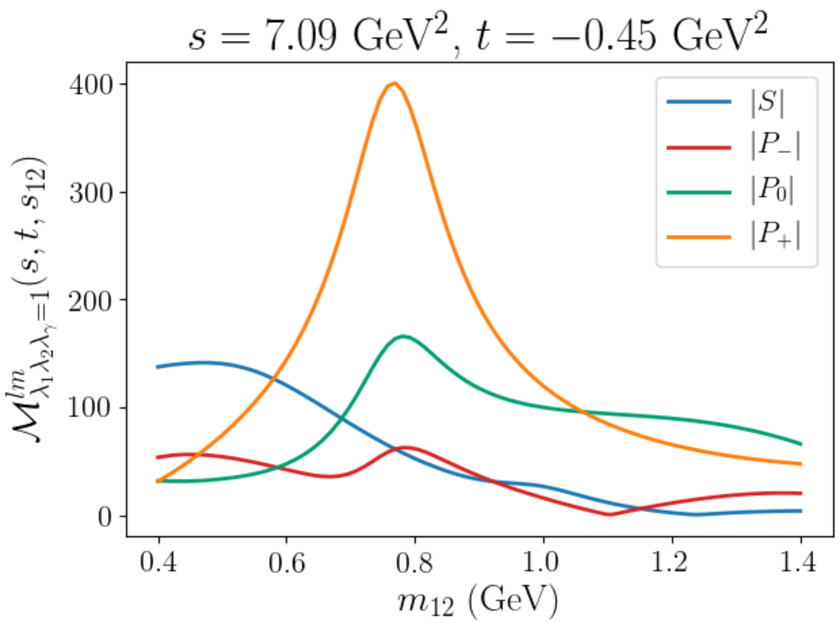
(Joint Physics Analysis Center Collaboration)



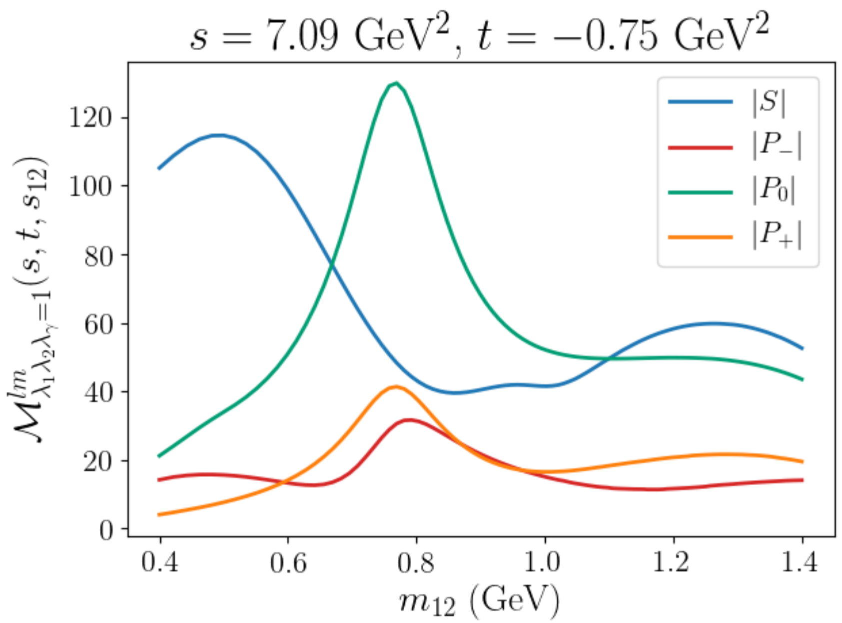
$$\langle Y_{LM} \rangle = \sqrt{4\pi} \int d\Omega^{\mathrm{H}} \frac{d\sigma}{dt\, dm_{12}\, d\Omega^{\mathrm{H}}} \mathrm{Re} Y_{LM}(\Omega^{\mathrm{H}}), \qquad \langle Y_{00} \rangle = \frac{d\sigma}{dt\, dm_{12}}$$

S-Channel Helicty Conservation

$$\tilde{\mathcal{M}}^{lm}_{\lambda_1\lambda_2\lambda_\gamma}(s,t,s_{12}) = \int d\Omega^{\mathrm{H}} Y^*_{lm}(\Omega^{\mathrm{H}})\tilde{\mathcal{M}}_{\lambda_1\lambda_2\lambda_\gamma}(s,t,s_{12},\Omega_{\mathrm{H}})$$



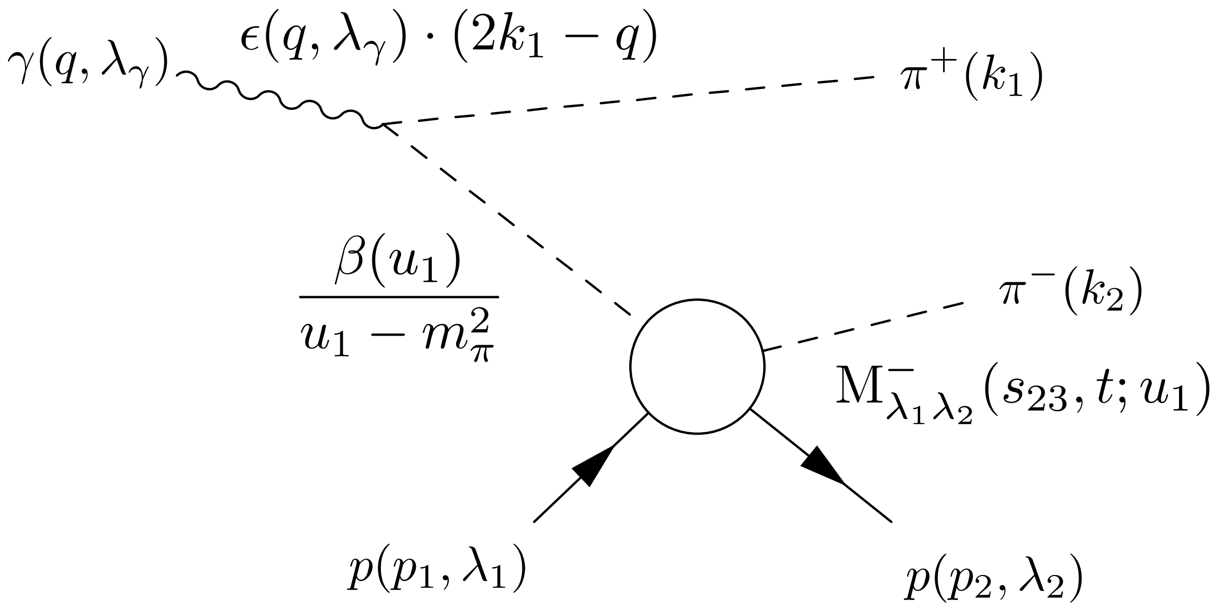
$|P_+| > |P_0|, \ |P_-|$



$|P_0| > |P_+|, \ |P_-|$

Gauge Invariance

$$\mathrm{M}^{\mathrm{Deck}}_{\lambda_1\lambda_2\lambda_\gamma}(s,t,s_{12},\Omega^{\mathrm{H}}) = \epsilon(q,\lambda_\gamma)\cdot(2k_1-q)\,\frac{\beta(u_1)}{u_1-m_\pi^2}\,\mathcal{M}^{-}_{\lambda_1\lambda_2}(s_{23},t;u_1)$$



$$\mathrm{M}^{\mathrm{Deck,GI}}_{\lambda_1\lambda_2\lambda_\gamma}(s,t,s_{12},\Omega^{\mathrm{H}}) = \mathcal{M}^{\mathrm{Deck}}_{\lambda_1\lambda_2\lambda_\gamma}(s,t,s_{12},\Omega^{\mathrm{H}}) + \epsilon(q,\lambda_\gamma)\cdot V_{\mathrm{contact}}$$

Model Parameters

Model parameters not fit from data.

$$m_\sigma = 0.5 \text{ GeV}$$

$$\Gamma_\sigma = 0.5 \text{ GeV}$$

$$m_\rho = 0.775 \text{ GeV}$$

$$\Gamma_\rho = 0.149 \text{ GeV}$$

$$m_{f_0} = 0.99 \text{ GeV}$$

$$\Gamma_{f_0} = 0.2 \text{ GeV}$$

$$\alpha_0^{\mathbb{P}} = 1.08$$

$$\alpha_1^{\mathbb{P}} = 0.2 \text{ GeV}^{-2}$$

$$\alpha_0^{f_2} = 0.5$$

$$\alpha_1^{f_2} = 0.9 \text{ GeV}^{-2}$$

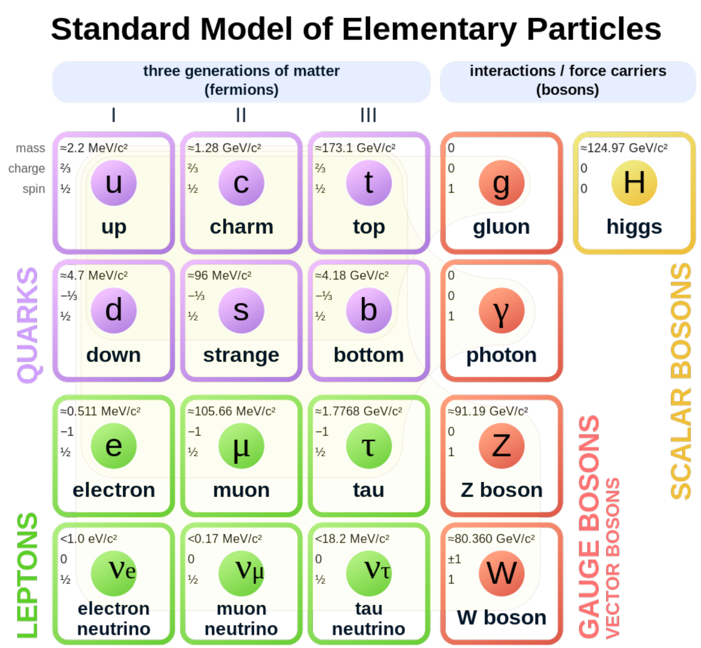
$$\alpha_0^{\rho} = 0.55$$

$$\alpha_1^{\rho} = 0.8 \text{ GeV}^{-2}$$

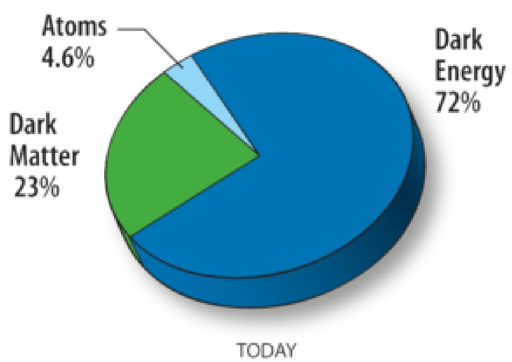
Angular Moments and Partial Waves

$$\begin{aligned}
\langle Y_{00}\rangle &= |S|^2+|P_-|^2+|P_0|^2+|P_+|^2+|D_-|^2+|D_0|^2+|D_+|^2+|F_-|^2+|F_0|^2+|F_+|^2 \\
\langle Y_{10}\rangle &= SP_0^*+P_0S^*+\sqrt{\frac{3}{5}}\left(P_-D_-^*+P_-^*D_-+P_+D_+^*+D_+P_+^*\right)+\sqrt{\frac{4}{5}}\left(P_0D_0^*+D_0P_0^*\right) \\
&+ \sqrt{\frac{24}{35}}\left(D_-F_-^*+F_-D_-^*+D_+F_+^*+F_+D_+^*\right)+\sqrt{\frac{216}{280}}\left(D_0F_0^*+F_0D_0^*\right) \\
\langle Y_{11}\rangle &= \left(-P_-S^*-SP_-^*+P_+S^*+SP_+^*\right)+\sqrt{\frac{1}{20}}\left(P_-D_0^*+D_0P_-^*-P_+D_0^*-D_0P_+^*\right) \\
&+ \sqrt{\frac{3}{20}}\left(-P_0D_-^*-D_-P_0^*+P_0D_+^*+D_+P_0^*\right)+\sqrt{\frac{9}{140}}\left(D_-F_0^*+F_0D_-^*-D_+F_0^*-F_0D_+^*\right) \\
&+ \sqrt{\frac{9}{70}}\left(-D_0F_-^*-F_-D_0^*+D_0F_+^*+F_+D_0^*\right) \\
\langle Y_{20}\rangle &= SD_0^*+D_0S^*+\sqrt{\frac{1}{5}}\left(2|P_0|^2-|P_-|^2-|P_+|^2+|F_-|^2+|F_+|^2\right)+\sqrt{\frac{18}{35}}\left(P_-F_-^*+F_-P_-^*+P_+F_+^*+F_+P_+^*\right) \\
&+ \sqrt{\frac{27}{35}}\left(P_0F_0^*+F_0P_0^*\right)+\sqrt{\frac{5}{49}}\left(|D_-|^2+|D_+|^2\right)+\sqrt{\frac{20}{49}}|D_0|^2+\sqrt{\frac{16}{45}}|F_0|^2 \\
\langle Y_{21}\rangle &= \frac{1}{2}\left(SD_+^*+D_+S^*-SD_-^*-D_-S^*\right)+\sqrt{\frac{3}{20}}\left(P_0P_+^*+P_+P_0^*-P_-P_0^*-P_0P_-^*\right) \\
&+ \sqrt{\frac{9}{140}}\left(P_-F_0^*+F_0P_-^*-P_+F_0^*-F_0P_+^*\right)+\sqrt{\frac{6}{35}}\left(P_0F_+^*+F_+P_0^*-P_0F_-^*-F_-P_0^*\right) \\
&+ \sqrt{\frac{5}{196}}\left(D_0D_+^*+D_+D_0^*-D_0D_-^*-D_-D_0^*\right)+\sqrt{\frac{1}{90}}\left(F_0F_+^*+F_+F_0^*-F_0F_-^*-F_-F_0^*\right) \\
\langle Y_{22}\rangle &= \sqrt{\frac{3}{10}}\left(P_-P_+^*+P_+P_-^*\right)+\sqrt{\frac{3}{140}}\left(P_-F_+^*+F_+P_-^*+P_+F_-^*+F_-P_+^*\right) \\
&+ \sqrt{\frac{4}{30}}\left(-F_+F_-^*-F_-F_+^*\right)+\sqrt{\frac{3}{196}}\left(-D_-D_+^*-D_+D_-^*\right)
\end{aligned}$$

Light Meson Spectroscopy

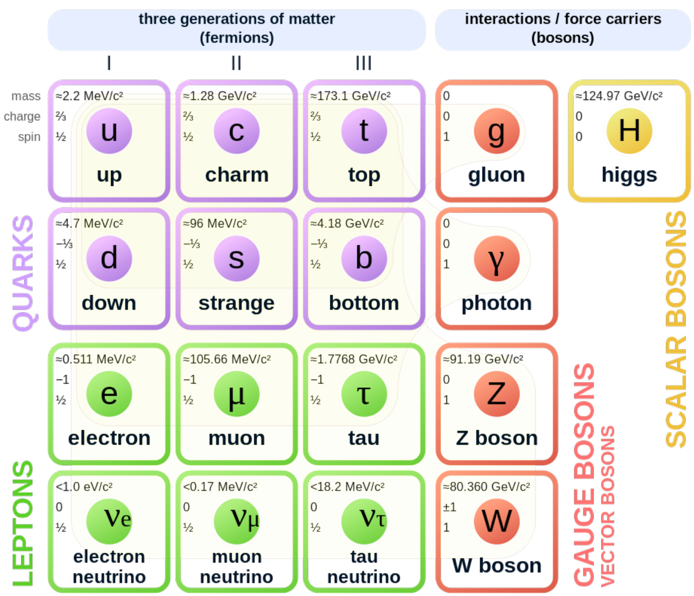


Beyond the Standard Model

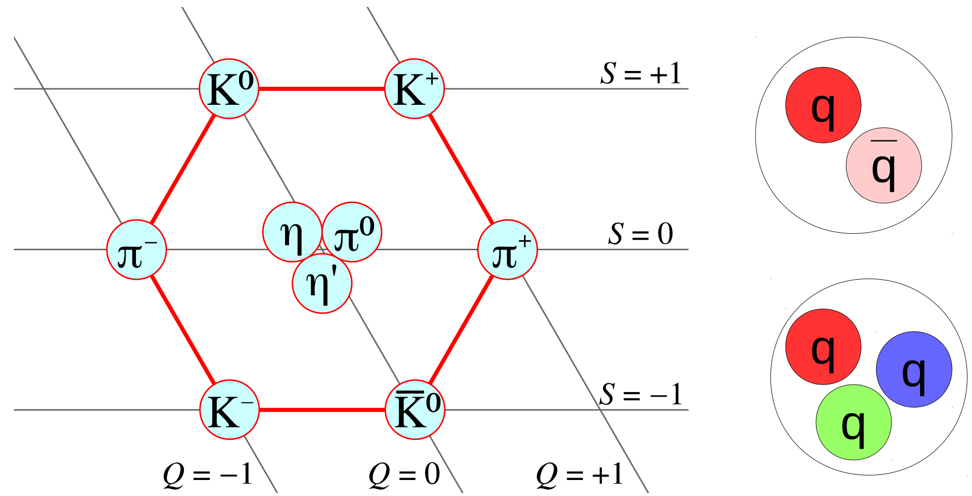


Light Meson Spectroscopy

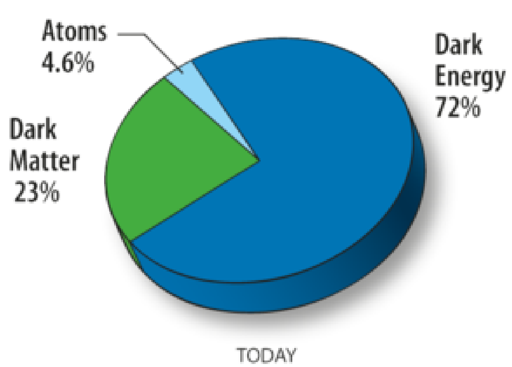
Standard Model of Elementary Particles



Standard (Quark) Model



Beyond the Standard Model



Beyond the Standard (Quark) Model