Analyzing Light Resonances in Two-Pion Photoproduction through a Regge Formalism Approach

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Joint Physics Analysis Center

Outline

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  - Model description:
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    - Non-resonant Production
      - Deck Mechanism
      - NRS- and NRP-waves
    - Model Refinement and Free Parameter Introduction
  - Results
- Conclusions

Motivation for Double Pion Photoproduction Study

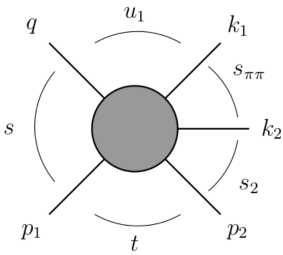
- **Exploring Diverse Production Mechanisms:**
  It's crucial to conduct a comprehensive investigation of various production methods to understand the intricate processes involved in the production and decay of exotic particles.
- **Leveraging New CLAS12 and GleuX Data:**
  The analysis of previously unexplored data from CLAS12 and GlueX offers a unique opportunity for a comprehensive study. This analysis aims to reveal valuable insights into production mechanisms, including pion exchange, final state interactions, and reggeization.
- **Overcoming Model Limitations:**
  Addressing constraints in earlier models, particularly those related to high momentum transfer, is essential for advancing our understanding of double pion photoproduction.

Process:

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

Kinematic Variables:

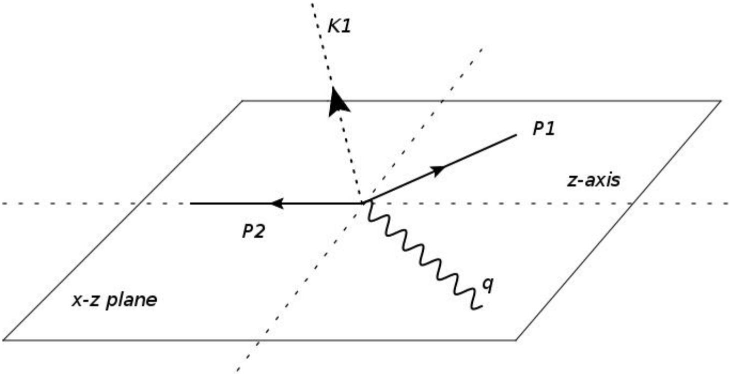
$$s = (p_1 + q)^2$$
$$s_i = (k_i + p_2)^2$$
$$t = (p_1 - p_2)^2$$
$$s_{\pi\pi} = (k_1 + k_2)^2 = m_{\pi\pi}^2$$



Two-Pion Photoproduction: Helicity Frame

Helicity Frame: $\Omega^H(\theta^H, \phi^H)$

$$\boldsymbol{p_1^H} = |\vec{p_1}|(\sin\theta_1, 0, \cos\theta_1)$$
$$\boldsymbol{p_2^H} = |\vec{p_2}|(0, 0, -1)$$
$$\boldsymbol{q^H} = |\vec{q}|(-\sin\theta_q, 0, \cos\theta_q)$$
$$\boldsymbol{k_1^H} = |\vec{k_1}|(\sin\theta^H\cos\phi^H, \sin\theta^H\sin\phi^H, \cos\theta^H) = -\boldsymbol{k_2^H}$$

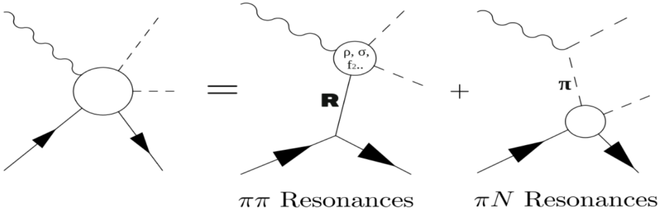


Model Description

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

$2 \to 3$ Dynamics

Built from known dynamics in $2 \to 2$ subchannels:



- $\pi\pi$ resonances are directly implemented in our model.
- πN resonances are embedded in the Deck mechanism.

Meson Resonances Below 1 GeV

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

also known as σ; was $f_0(600)$

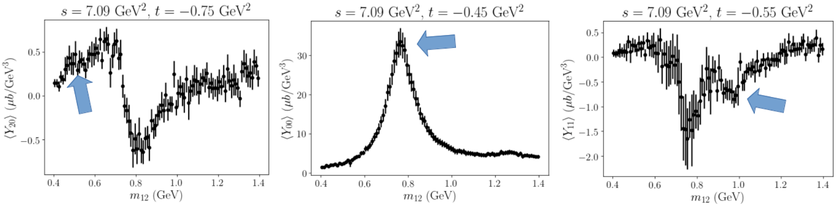
See the review on "Scalar Mesons below 1 GeV."

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

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

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 ± 20 MeV [h]
Full width (Breit-Wigner) = 10 to 100 MeV [h]



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

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 ± 0.23 MeV
Full width (Breit-Wigner) = 149.1 ± 0.8 MeV

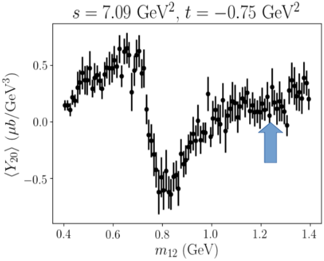
R.L. Workman et al. (Particle Data Group), Prog.Theor.Exp.Phys. 2022, 083C01 (2022)

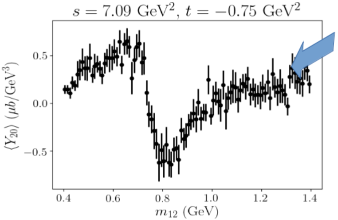
$f_2(1270)$ $I^G(J^{PC}) = 0^+(2^{++})$

Mass (T-Matrix Pole$\sqrt{s}$) = (1260–1283) – i(90–110) MeV

Mass (Breit-Wigner) = 1275.4 ± 0.8 MeV

Full Width (Breit-Wigner) = 186.6 ± 2.3 MeV





$f_0(1370)$ $I^G(J^{PC}) = 0^+(0^{++})$

See the review on "Spectroscopy of Light Meson Resonances" and a note on "Non-$q\bar{q}$ Candidates" in PDG 06, Journal of Physics **G33** 1 (2006).

Mass (T-Matrix Pole$\sqrt{s}$) = (1250–1440) – i(60–300) MeV

Mass (Breit-Wigner) = 1200 to 1500 MeV

Full Width (Breit-Wigner) = 200 to 500 MeV

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

Resonant Production

- Utilizing an Effective Lagrangian: Employing a one-particle exchange model.
- "Reggeize" Transformation: Employing the Reggeization process, represented by

$$R_N(s,t) = \frac{1+e^{i\pi\alpha_N(t)}}{\sin(\pi\alpha(t))}\left(\frac{s}{s_0}\right)^{\alpha_N(t)}$$

- "Breit-Wignerize" Approach: Adopting the Breit-Wignerization method as described in [Phys. Rev. D 98, 030001 (2018)],

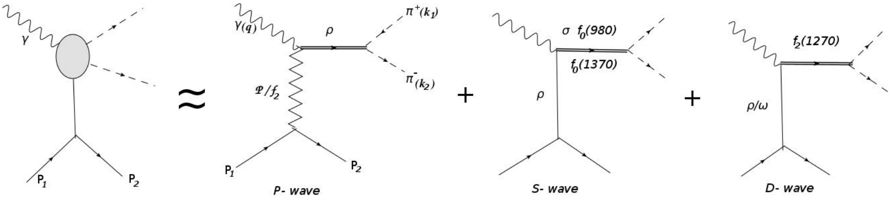
$$\mathrm{BW}^{\mathrm{dep}}(s,l) = \frac{n(s)}{m_{\mathrm{BW}}^2 - s - i m_{\mathrm{BW}}\Gamma_{\mathrm{tot}}(s)}, \text{ where } n(s) = \left(\frac{q}{q_0}\right)^l F_l(q,q_0)$$

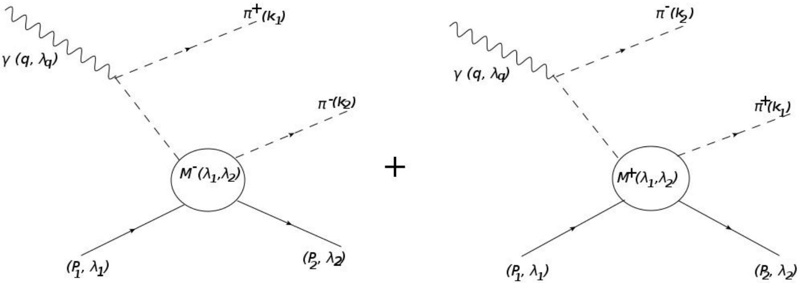
Resonant Production

Thus, the partial wave amplitude is expressed as:

$$\mathcal{M}_{\lambda_1,\lambda_2,\lambda_q}(s,t,s_{\pi\pi},\Omega_H) = \sum_{lm} \mathcal{M}^{lm}_{\lambda_1,\lambda_2,\lambda_q}(s,t,s_{\pi\pi},\Omega_H) Y_{lm}(\Omega_H)$$

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





The Deck Mechanism describes non-resonant production with the following equation:

$$\mathcal{M}^{\text{Deck,GI}}_{\lambda_1\lambda_2\lambda_q}(s,t,s_{\pi\pi},\Omega) = \sqrt{4\pi\alpha} \times \left[\left(\frac{\epsilon(q,\lambda_q)\cdot k_1}{q\cdot k_1} - \frac{\epsilon(q,\lambda_q)\cdot(p_1+p_2)}{q\cdot(p_1+p_2)}\right)\beta(t_{\pi_1})\mathcal{M}^{-}_{\lambda_1\lambda_2}(s_2,t) - \left(\frac{\epsilon(q,\lambda_q)\cdot k_2}{q\cdot k_2} - \frac{\epsilon(q,\lambda_q)\cdot(p_1+p_2)}{q\cdot(p_1+p_2)}\right)\beta(t_{\pi_2})\mathcal{M}^{+}_{\lambda_1\lambda_2}(s_1,t)\right],$$

Non Resonant Production: NRP- NRS- Waves

$$F_{bkg}(s_{\pi\pi}) \equiv [(s_{\pi\pi}^{\text{th}} - s_{\pi\pi})(s_{\pi\pi}^{\text{max}} - s_{\pi\pi})]\,,$$

where

$$s_{\pi\pi}^{\text{th}} = 4m_\pi^2$$

$$s_{\pi\pi}^{\text{max}} = s + m_p^2 - \frac{1}{2m_p^2}\Big[(s+m_p^2)(2m_p^2 - t) - \lambda^{1/2}(s, m_p^2, 0)\lambda^{1/2}(t, m_p^2, m_p^2)\Big]\,.$$

Thus

$$\mathcal{M}_P^{\text{nr}} = R_{f_2}(s,t)\frac{1}{s}F_{bkg}(s_{\pi\pi})\bar{u}(p_2,\lambda_2)\not{\epsilon}'(\lambda_\gamma)u(p_1,\lambda_1)\,,$$

$$\mathcal{M}_S^{\text{nr}} = \frac{1}{s}g_{s_j}^{\text{nr}}R(s,t)[(s_{\pi\pi}^{\text{th}} - s_{\pi\pi})(s_{\pi\pi}^{\text{max}} - s_{\pi\pi})]\bar{u}(p_2,\lambda_2)\gamma^\mu u(p_1,\lambda_1)\epsilon_\mu(\lambda_\gamma)\,.$$

Model Refinement and Free Parameter Introduction

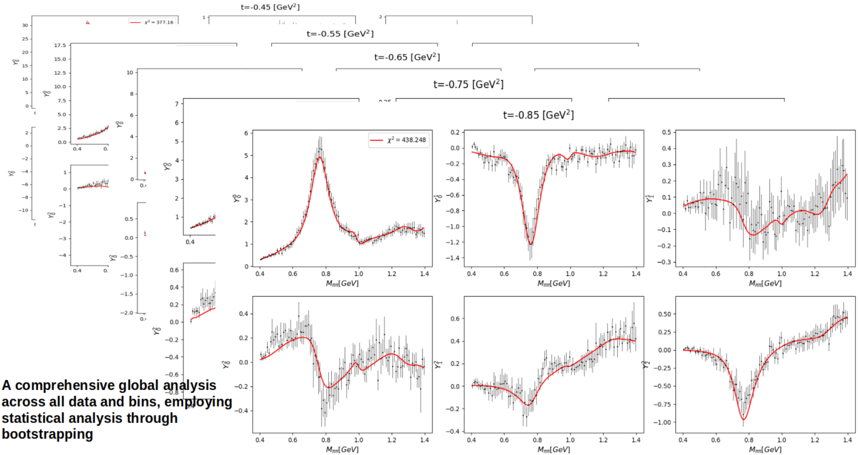
- Model limitations addressed by introducing free parameters to redefine t-dependence (g^{lm}) in resonant and non-resonant components.
- Modified model equation:

$$\tilde{\mathcal{M}}_{\lambda_1,\lambda_2,\lambda_q}(s,t,s_{\pi\pi},\Omega_H) = \sum_{lm} g^{lm}\mathcal{M}^{lm}_{\lambda_1,\lambda_2,\lambda_q}(s,t,s_{\pi\pi},\Omega_H)Y_{lm}(\Omega_H)$$

- A total of 30 free parameters: 2 each for $f_0(500)$, $f_0(980)$, $f_0(1375)$, and background; 6 for ρ via f_2 and background; and 10 for $f_2(1270)$.

Results- Preliminary

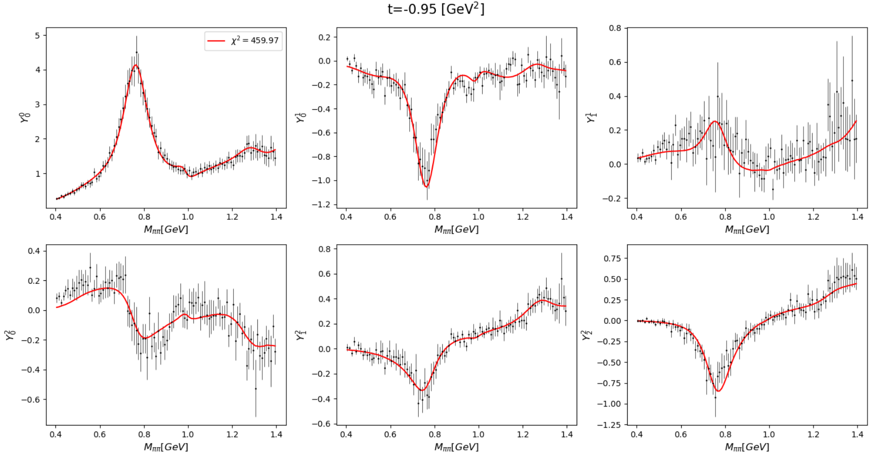
E_γ=3.7 GeV, $< Y_{LM} >= \sqrt{4\pi} \int d\Omega^H \frac{d\sigma}{dtdm_{\pi\pi}d\Omega^H} \text{Re}\, Y_{LM}(\Omega^H)$ [Phys.Rev.D 80 (2009) 072005]



A comprehensive global analysis across all data and bins, employing statistical analysis through bootstrapping

Results- Preliminary

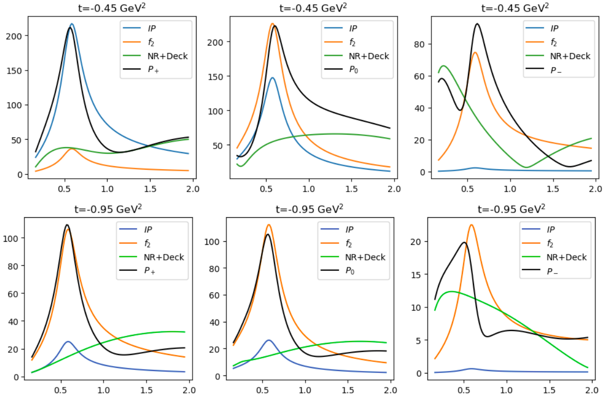
E_γ=3.7 GeV:



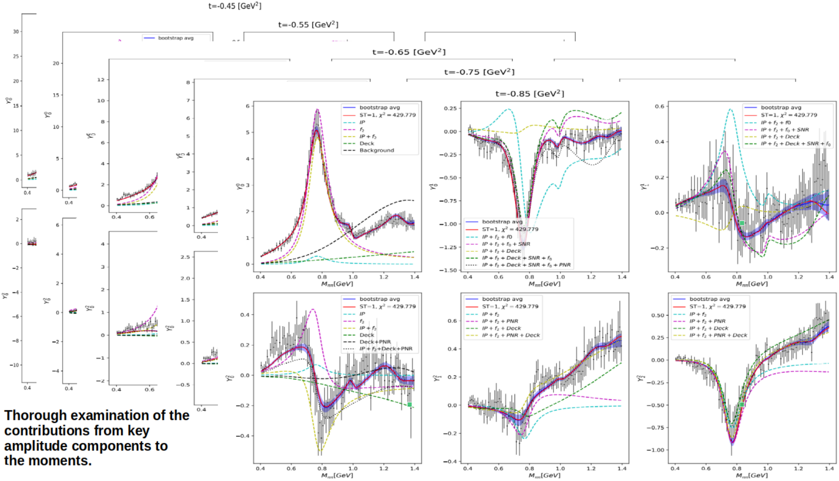
Results- Preliminary

Partial Wave Analysis of P-Wave Contributions:

- At $t = -0.45$, both P^+ and P^0 reach maxima at the ρ peak.
- Surprisingly, P^0 appears slightly larger than P^+, contrary to the expectation based on s-channel helicity conservation (SCHC) i.e. $|P^+| > |P^-|, |P^0|$ near $t \approx 0$.

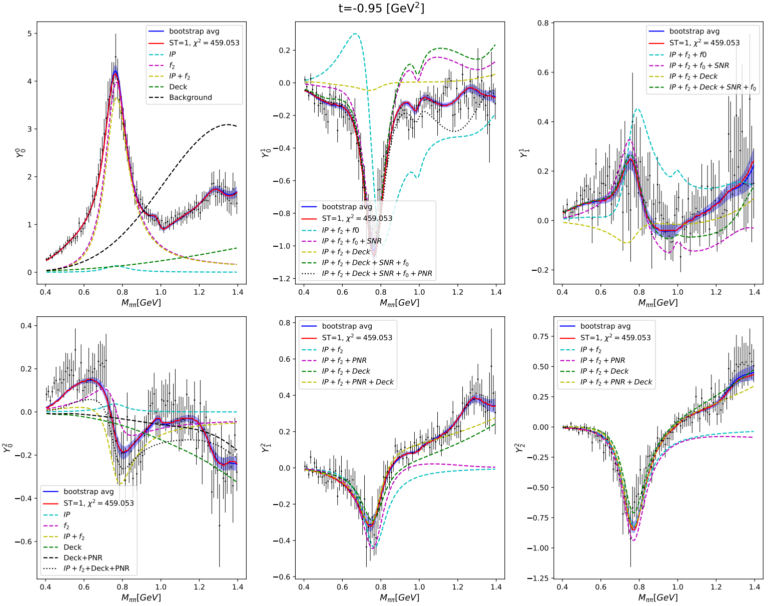


Results- Preliminary



Thorough examination of the contributions from key amplitude components to the moments.

Results- Preliminary



Conclusion

- **Innovative Theoretical Framework:**
  Developed a new theoretical framework to improve accuracy.
- **Integrated Resonance Effects:**
  Integrated resonance effects for a comprehensive model.
- **Diverse Methodology:**
  Applied various methods to enhance flexibility and accuracy.
- **Empirical Validation:**
  Empirically validated the model with experimental data fitting.


Thank
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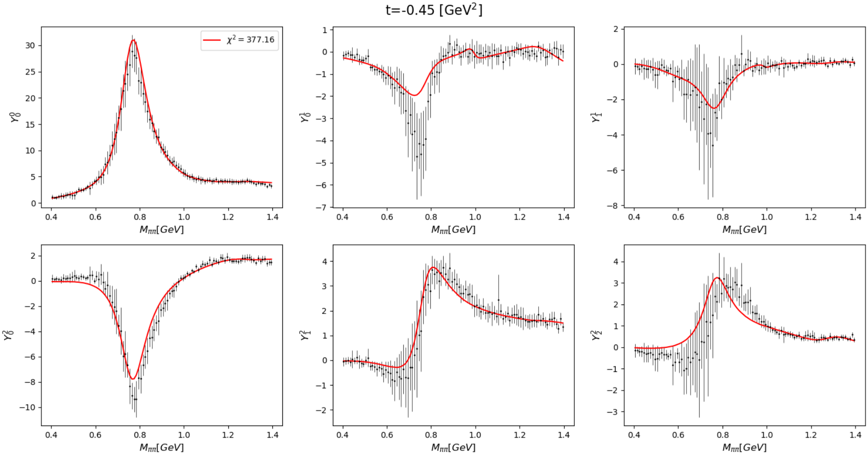
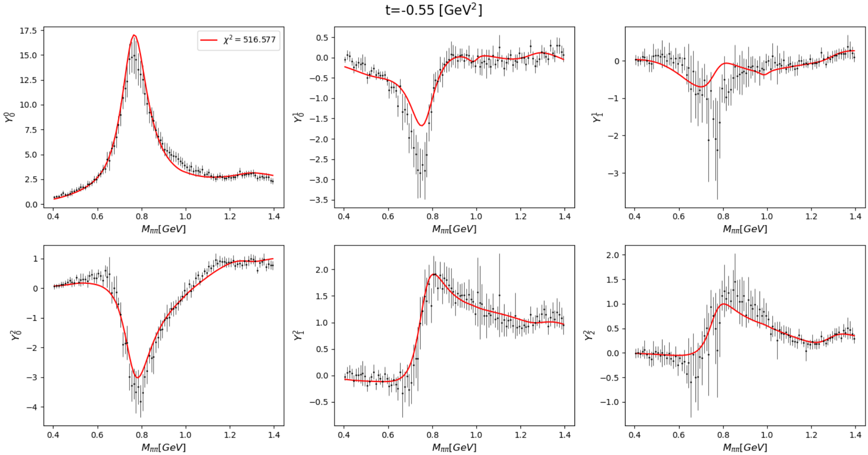
Back-Up Slides- Preliminary Results



Back-Up Slides- Preliminary Results



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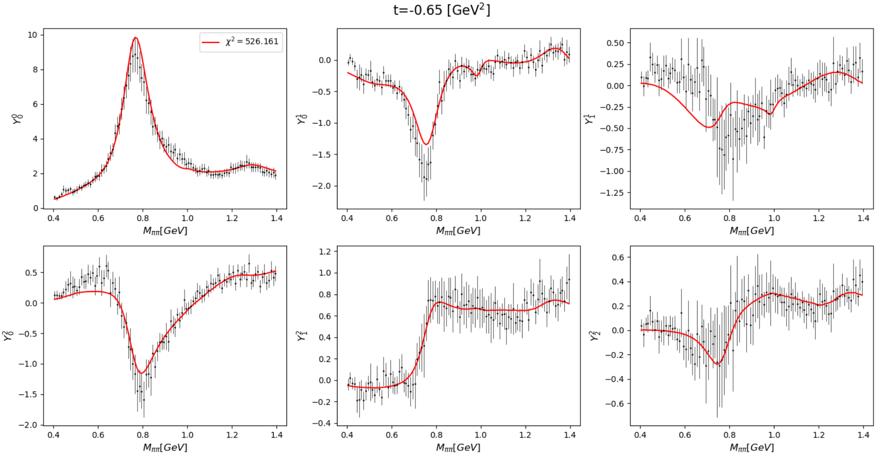

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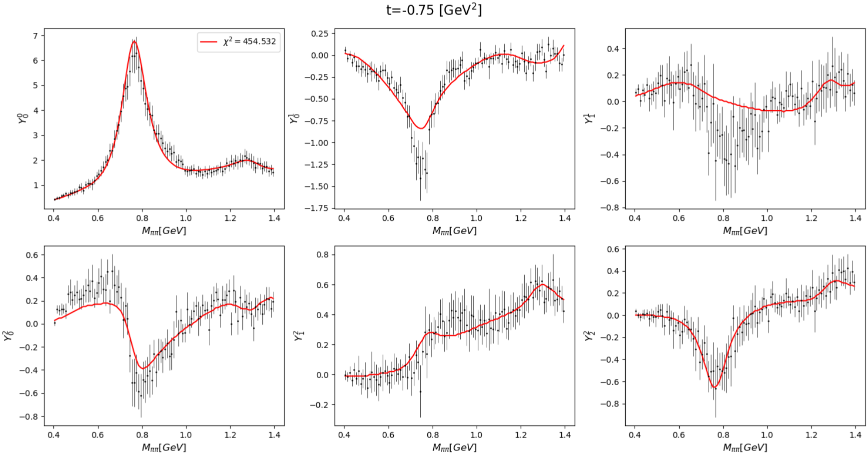

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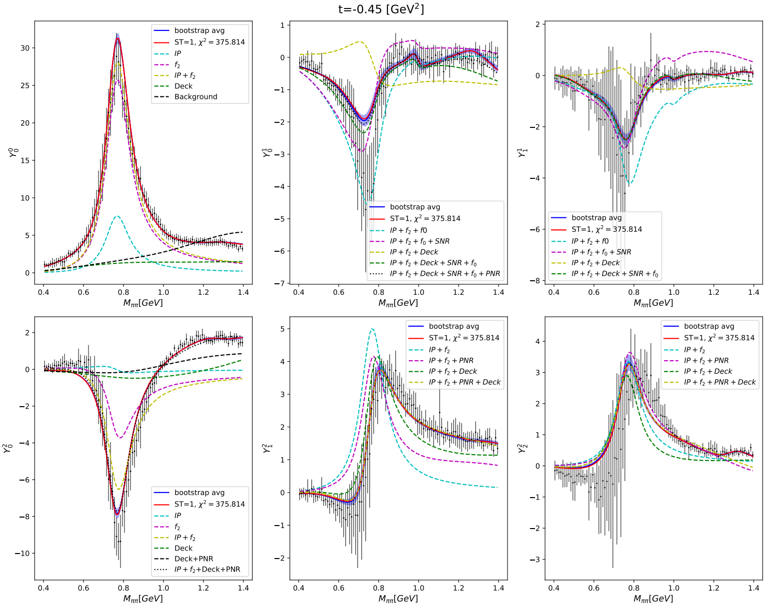

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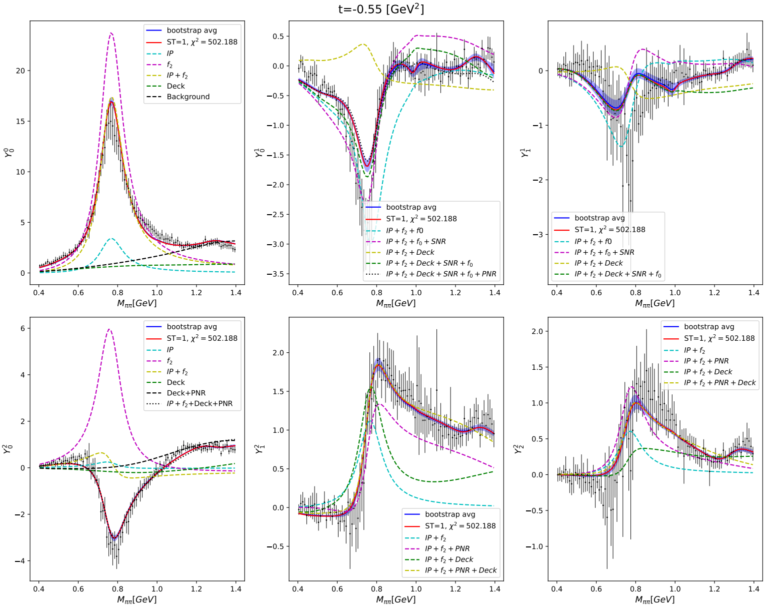

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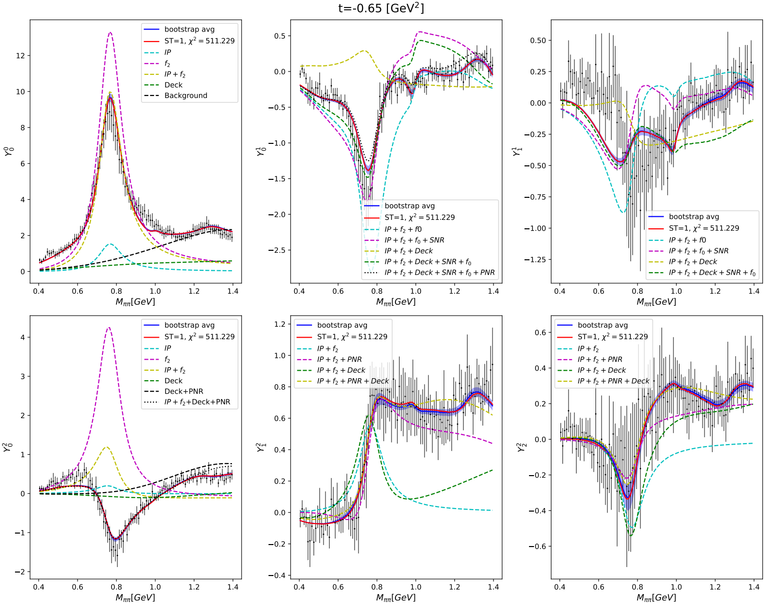

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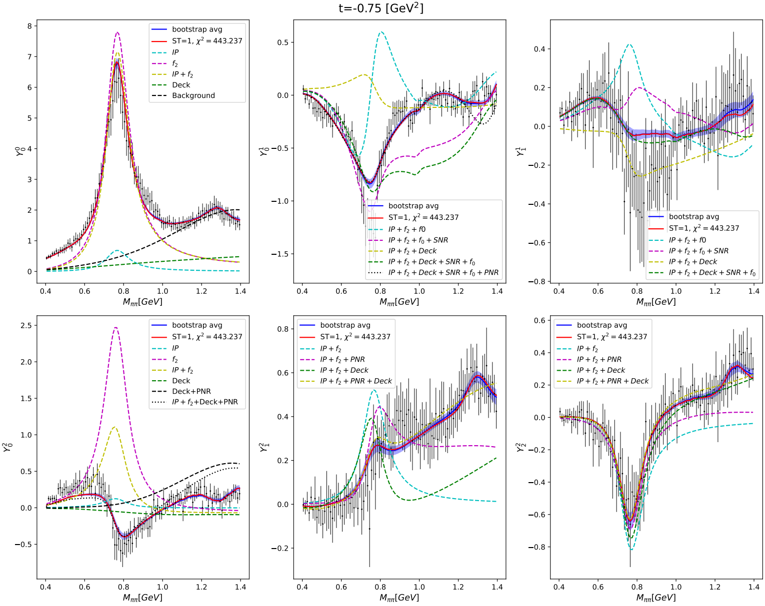
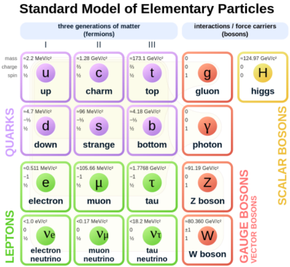
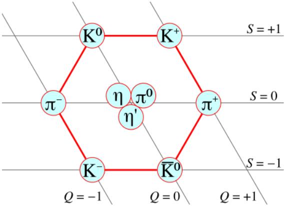
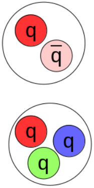


Light Meson Spectroscopy

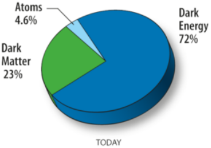


Standard (Quark) Model





Beyond the Standard Model



Beyond the Standard (Quark) Model