On the low energy structure of the ϕ-photoproduction reaction

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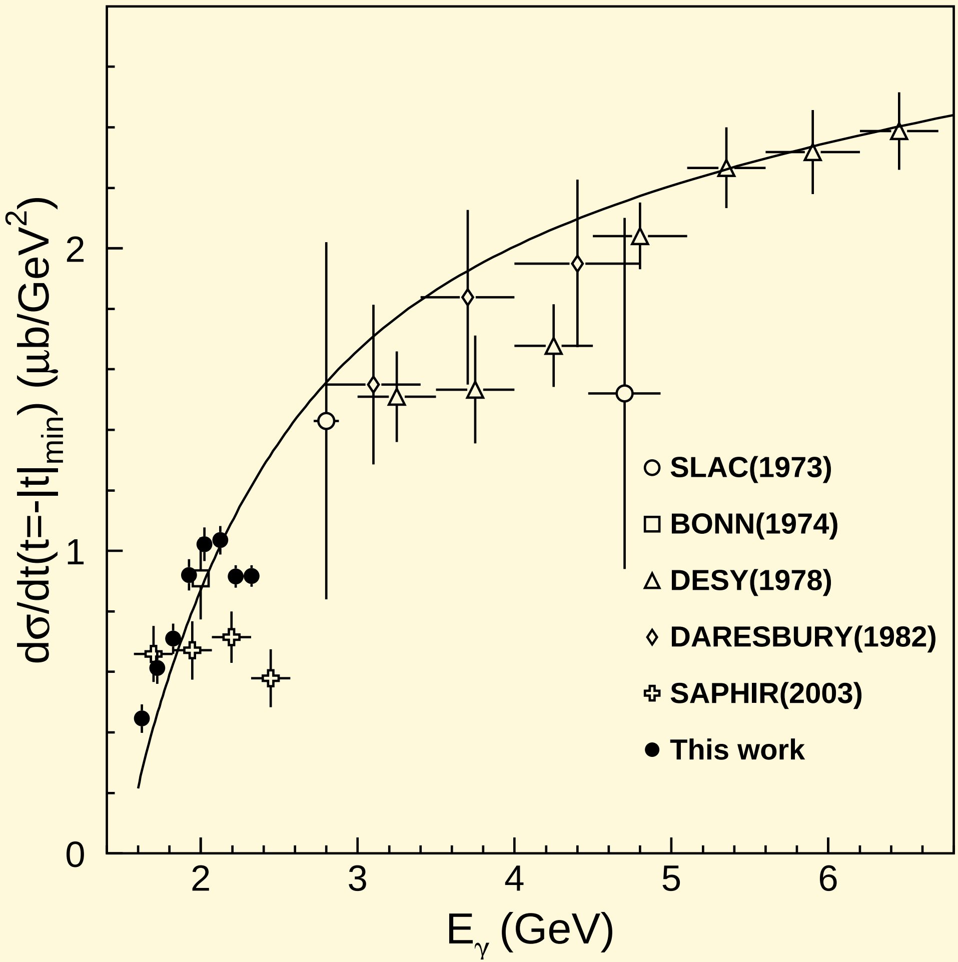
Reaction and conventions

- We study the reaction $\gamma p \to \phi p$.
- We are working in **LAB frame** where the **initial proton is at rest**.
  - p_i is the 4-momentum of the **proton** in the **initial** state,
  - k is the 4-momentum of the **photon** in the **initial** state,
  - p_f is the 4-momentum of the **proton** in the **final** state,
  - q is the 4-momentum of the ϕ in the **final** state.

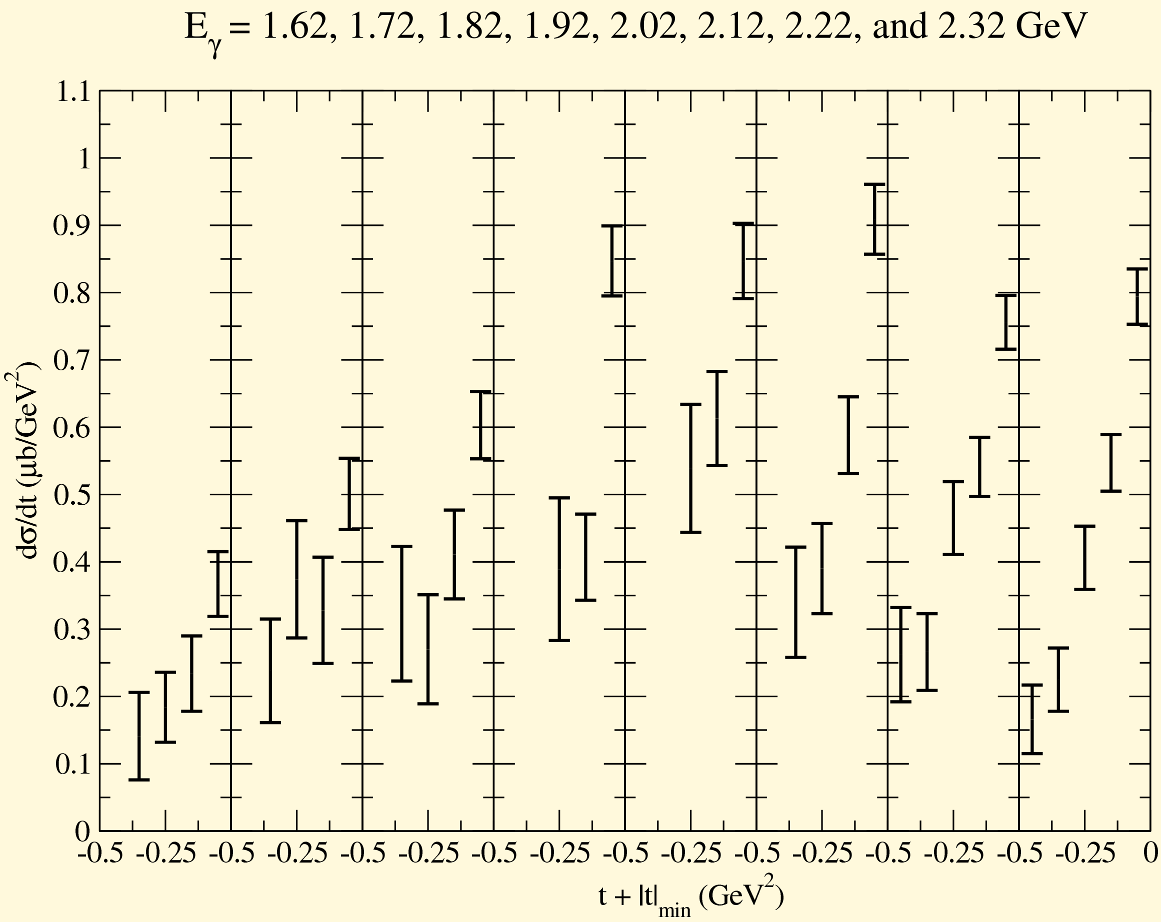
Motivation

- Studying the strangeness content of nucleon resonances and OZI violation.
  $\longrightarrow$ $\phi(1020)$ is composed of $s\bar{s}$
- Analysis of differential cross-section (DCS) of phi photoproduction at forward angle by Mibe and Chang, et.al. (Phys. Rev. Lett. **95** 182001 (2005)) shows the presence of a structure ("bump") near threshold (E_γ around 2.0 GeV).
  $\longrightarrow$ Seen also by Tedeschi et.al.: unpublished, but shown in some talks.
- Efforts to explain structure without involving resonance has been failed so far.
  $\longrightarrow$ Recently, Ozaki and Hosaka et.al. also show the need to include a resonance to explain the structure.
- The structure is not seen in other channels so far.
  $\longrightarrow$ Could it be a "missing" resonance?

DCS of ϕ-photoproduction at forward angle



DCS of ϕ-photoproduction as a function of $t + |t|_{min}$



Previous Studies

Ingredients of ϕ-photoproduction near threshold

- Mostly pomeron and also t-channel π and η exchange.
- Pomeron exchange dominates over t-channel π and η exchange, even from energy close to threshold.

What is in the structure?

- We must not spontaneously jump into conclusion that the structure is caused by a resonance.
- Mibe and Chang et.al. conclude that the structure is **not likely** due to **unnatural parity** processes like t-channel π and η exchange.
  $\longrightarrow$ Analysis of decay angular distribution of $\phi \rightarrow K\bar{K}$.
- But, natural parity process like pomeron exchange cannot possibly reproduce the structure either.

Reaction Model

- We mostly follow Titov and Lee (Phys.Rev.C **67**, 065205 (2003)) and also Titov and Kämpfer (Phys.Rev.C **76**, 035202 (2007)).
- For pomeron, we use **two-gluon exchange** model

$$i\mathcal{M} = i\bar{u}_f(p_f)\epsilon_\phi^{*\mu} M_{\mu\nu} u_i(p_i)\epsilon_\gamma^\nu$$

$$M_{\mu\nu} = M(s,t)\Gamma_{\mu\nu}$$

with

$$M(s,t) = C_p F_1(t) F_\phi(t) \frac{1}{s}\left(\frac{s-a_p}{s_p}\right)^{\alpha_P(t)} \exp\left[-\frac{i\pi}{2}\alpha_P(t)\right]$$

$$\begin{aligned}\Gamma_{\mu\nu} &= \not{k}\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right) - \gamma_\nu\left(k_\mu - q_\mu \frac{k\cdot q}{q^2}\right) \\ &- \left(q_\nu - \bar{p}_\nu \frac{k\cdot q}{p\cdot k}\right)\left(\gamma_\mu - \not{q}\frac{q_\mu}{q^2}\right) \quad ; \quad \bar{p} = \frac{1}{2}(p_f + p_i)\end{aligned}$$

Here

$$F_1(t) = \frac{4m_N^2 - 2.8t}{(4m_N^2 - t)(1 - t/0.7)^2}$$

$$F_\phi(t) = \frac{2\mu_0^2}{(1 - t/M_\phi^2)(2\mu_0^2 + M_\phi^2 - t)}; \quad \mu_0^2 = 1.1 \text{ GeV}^2$$

$F_1(t)$ is the **isoscalar EM form-factor of the nucleon**, and $F_\phi(t)$ is the **form-factor for the ϕ-γ-Pomeron coupling**, and the **pomeron trajectory** is

$$\alpha_P = 1.08 + 0.25t$$

- For s- and u-channels, we use these **phenomenological Lagrangian densities** to calculate the reaction amplitudes

$$\mathcal{L}_{N^*N\gamma} = -\frac{eg_\gamma}{2(m_N + M_{N^*})}\bar{\psi}_{N^*}\Gamma\sigma_{\mu\nu}\psi_N F^{\mu\nu} + \text{h.c.}$$

$$\mathcal{L}_{N^*N\phi} = g_\phi^{(1)}\bar{\psi}_{N^*}\Gamma\gamma_\mu\psi_N\phi^\mu - \frac{g_\phi^{(2)}}{2(m_N + M_{N^*})}\bar{\psi}_{N^*}\Gamma\sigma_{\mu\nu}\psi_N G^{\mu\nu} + \text{h.c.}$$

with

$$\begin{aligned}\Gamma &= \gamma_5 \quad \text{for} \quad J^P = \tfrac{1}{2}^- \\ &= 1 \quad \text{for} \quad J^P = \tfrac{1}{2}^+\end{aligned}$$

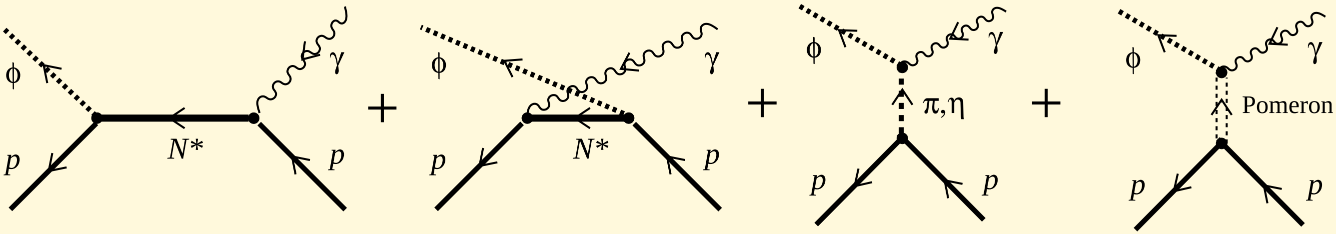
- For t-channels involving π and η exchange, we use

$$\mathcal{L}_{NNM} = -ig_{NNM}\bar{\psi}_N\gamma_5\tau_3\psi_N\varphi_M$$

$$\mathcal{L}_{\gamma\phi M} = \frac{eg_{\gamma\phi M}}{M_\phi}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\phi_\nu\partial_\alpha A_\beta\varphi_M$$

  with M denotes pseudoscalar mesons like π and η. We use $g^2_{\pi NN}/4\pi = 14.00$, $g^2_{\eta NN}/4\pi = 0.10$, $g_{\gamma\phi\pi} = 0.14$, and $g_{\gamma\phi\eta} = 0.71$, **fixed during fitting**.

- Here are the **tree-level diagrams** calculated in our model



- Propagator in the s-channel diagram is chosen to be

$$G(s) = \frac{i\left(\not{q}_s + M_{N^*}\right)}{q_s^2 - M_{N^*}^2 + iM_{N^*}\Gamma_{N^*}}$$

- Form-factors in the s- and u-channel diagram is

$$F_{N^*}(q^2) = \frac{\Lambda_{N^*}^4}{\Lambda_{N^*}^4 + (q^2 - M_{N^*}^2)^2}$$

  where q is the 4-momentum flowing in the resonance N^*.

- Form-factor in the t-channel diagram is

$$F_M(t) = \left(\frac{\Lambda_M^2 - m_M^2}{\Lambda_M^2 - t}\right)^2$$

- We choose $\Lambda_{N^*} = \Lambda_M = 1.2$, fixed during fitting.

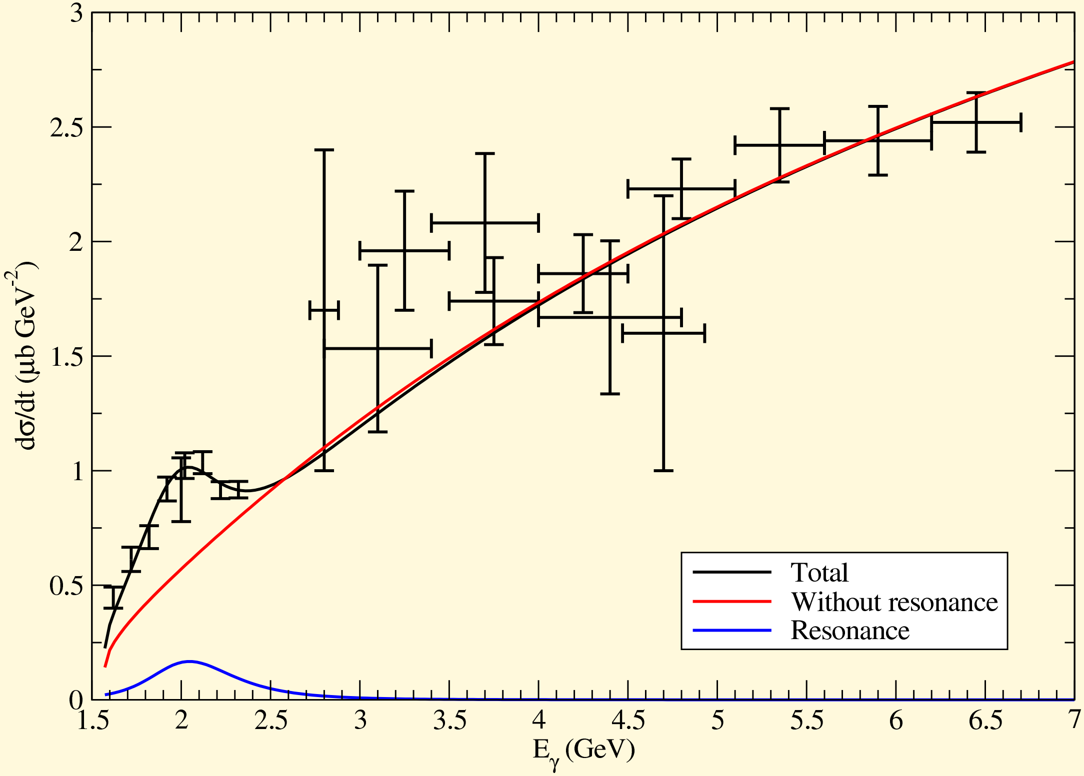
Some remarks

- We focus on the tree-level diagrams since their effects are dominant.
  $\longrightarrow$ Need to be known before including higher-order effects.
- We try $J^P = \frac{1}{2}^+$ and $J^P = \frac{1}{2}^-$ resonances, **one at a time**, in our model.
- We do not include effects of other resonances included in Titov and Lee analysis.
  $\longrightarrow$ They show that the effects are small for small scattering angles.
- Our model are gauge-invariant.

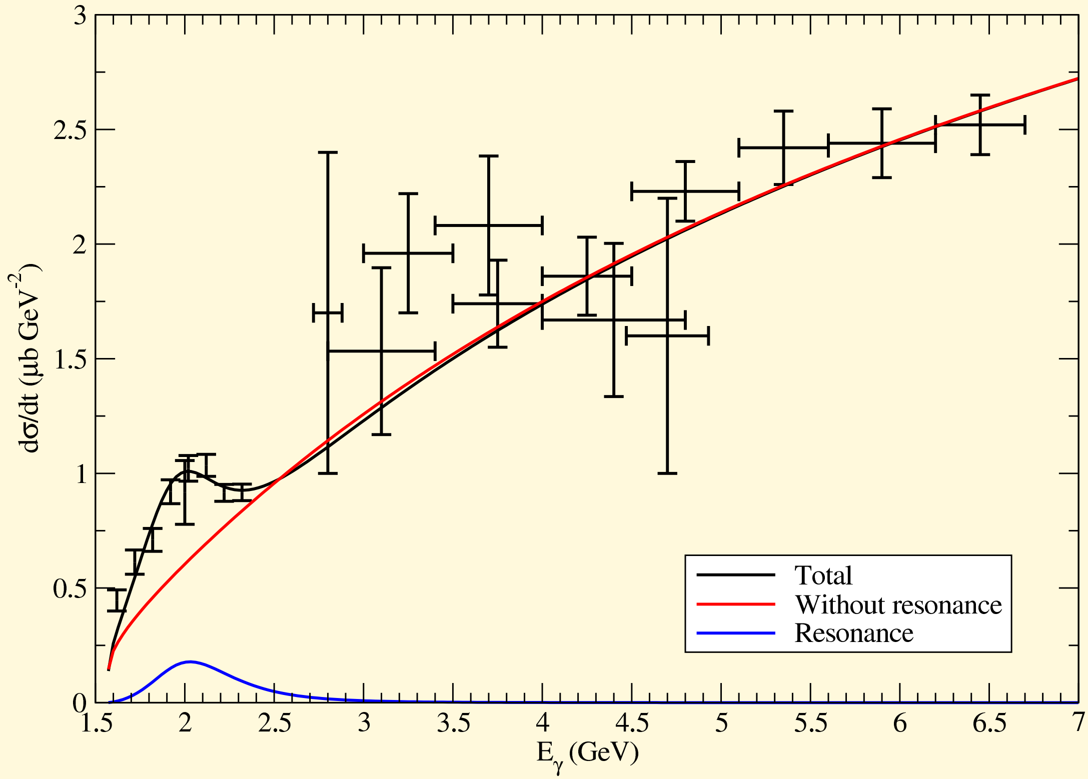
Results

- We fit our model to **DCS at forward angle as a function of E_γ**, **DCS as a function of t**, and **decay angular distribution** in the **Gottfried-Jackson (GJ)** frame (outgoing ϕ is at rest).
- We have **six fit parameters** M_{N^*}, Γ_{N^*}, $g_\gamma g_\phi^{(1)}$, $g_\gamma g_\phi^{(2)}$, C_p, and a_p.
- We need to modify the pomeron contribution at the energies near threshold ($a_p \neq 0$).
  $\longrightarrow$ Reasonable because model for pomeron exchange works better at high energy.

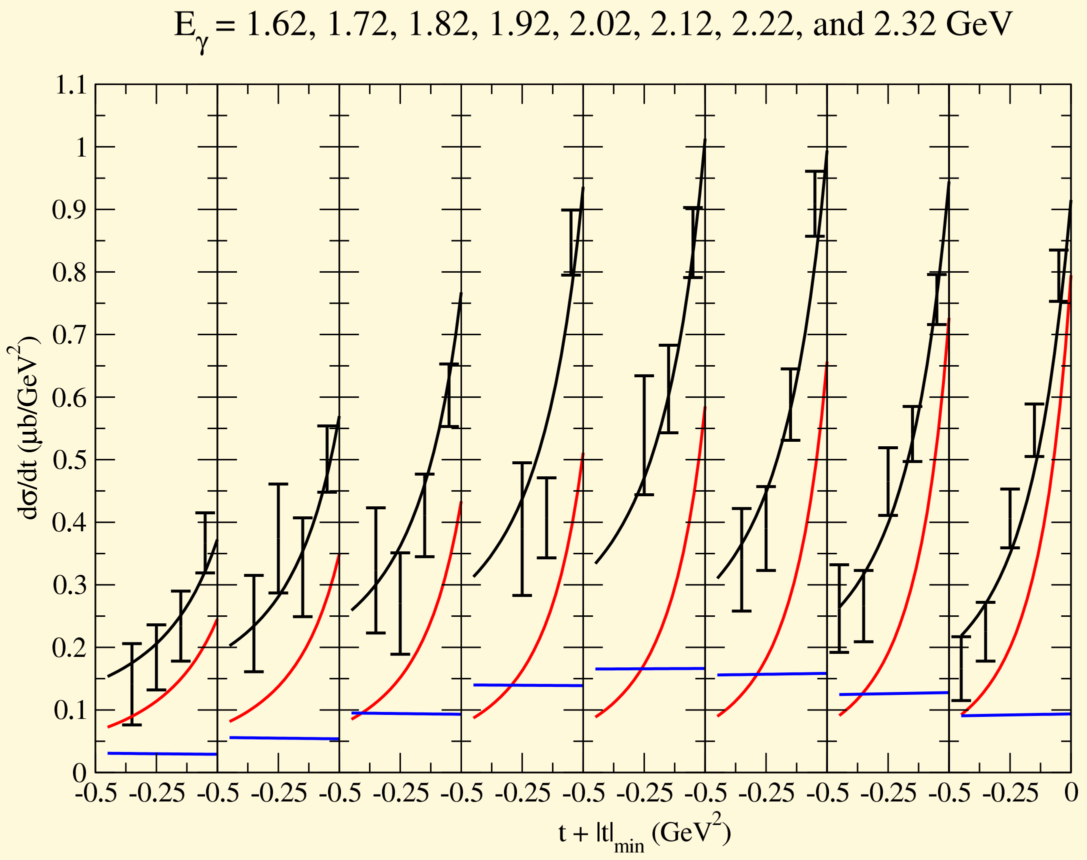
DCS at forward angle for $J^P = \frac{1}{2}^-$



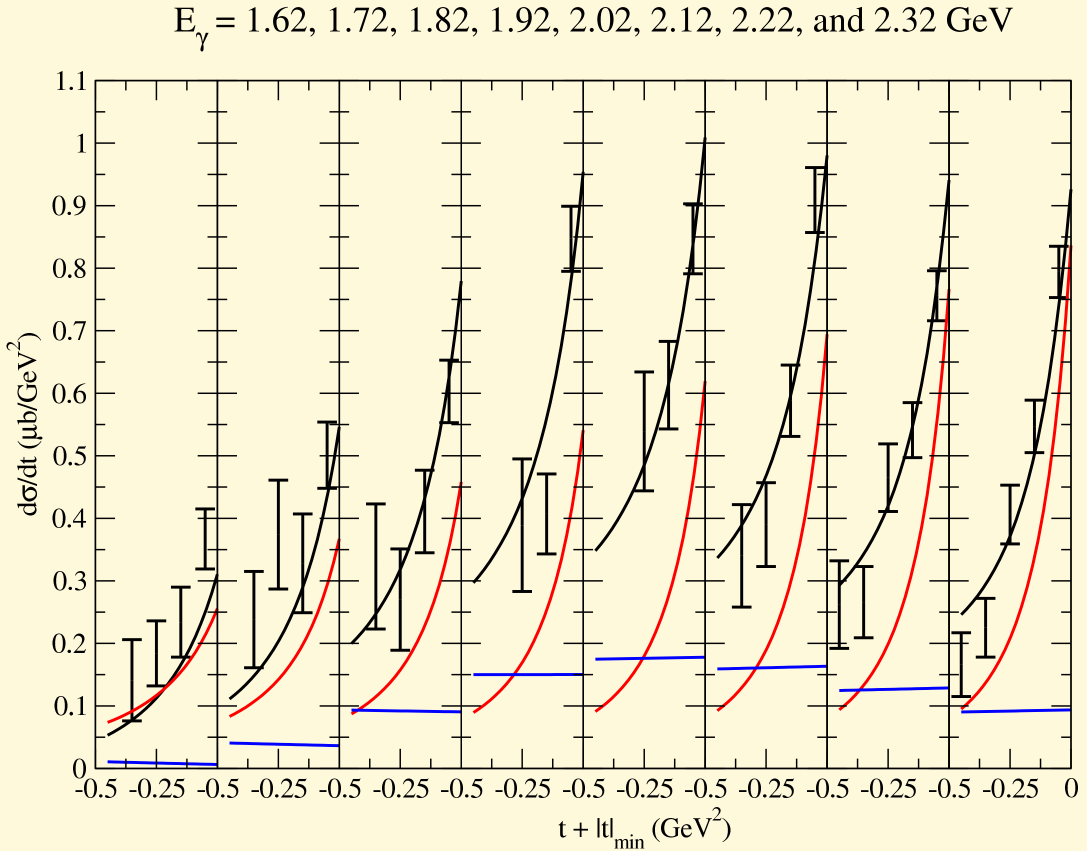
DCS at forward angle for $J^P = \frac{1}{2}^+$



DCS as a function of $t + |t|_{min}$ for $J^P = \frac{1}{2}^-$



DCS as a function of $t + |t|_{min}$ for $J^P = \frac{1}{2}^+$



Decay angular distribution

We choose to work in **Gottfried-Jackson (GJ)** frame, where ϕ **is in its rest frame**:

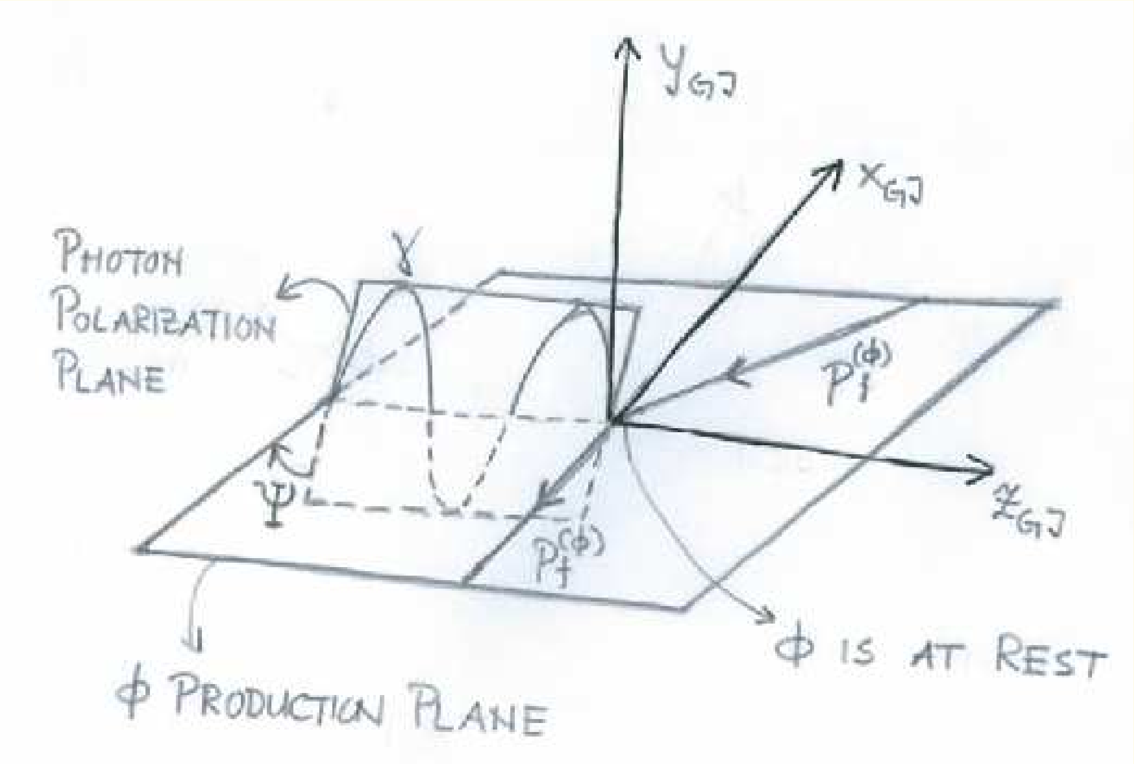
- z-axis is chosen along the direction of the incoming photon $\mathbf{k}^{(\phi)}$,
- y-axis is chosen along the direction of $\mathbf{p}_i^{(\phi)} \times \mathbf{p}_f^{(\phi)}$

For **linearly polarized photon**:

$$
\begin{aligned}
W(\cos\theta) &= \frac{3}{2}\left(\frac{1}{2}(1-\rho^0_{00})\sin^2\theta + \rho^0_{00}\cos^2\theta\right) \\
W(\Phi) &= \frac{1}{2\pi}(1 - 2\mathrm{Re}\rho^0_{1-1}\cos 2\Phi) \\
W(\Phi-\Psi) &= \frac{1}{2\pi}\left(1 + 2P_\gamma(\rho^1_{1-1} - \mathrm{Im}\rho^2_{1-1})\cos(\Phi-\Psi)\right) \\
W(\Phi+\Psi) &= \frac{1}{2\pi}\left(1 + 2P_\gamma(\rho^1_{1-1} + \mathrm{Im}\rho^2_{1-1})\cos(\Phi+\Psi)\right) \\
W(\Psi) &= \frac{1}{2\pi}\left(1 - P_\gamma(2\rho^1_{11} + \rho^1_{00}\cos 2\Psi)\right)
\end{aligned}
$$

P_γ is the **polarization strength**, in this work is **unity**. The ρ's are the **density matrix elements**.

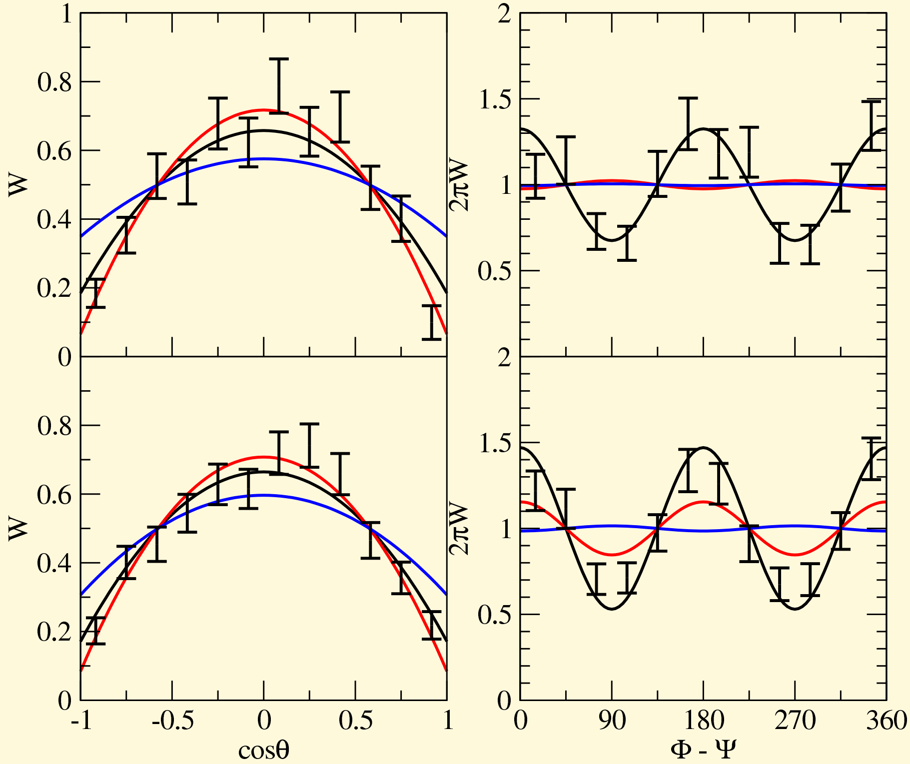
Gottfried-Jackson frame



The angles θ and Φ in the next slides are defined in the (x_{GJ}, y_{GJ}, z_{GJ}).

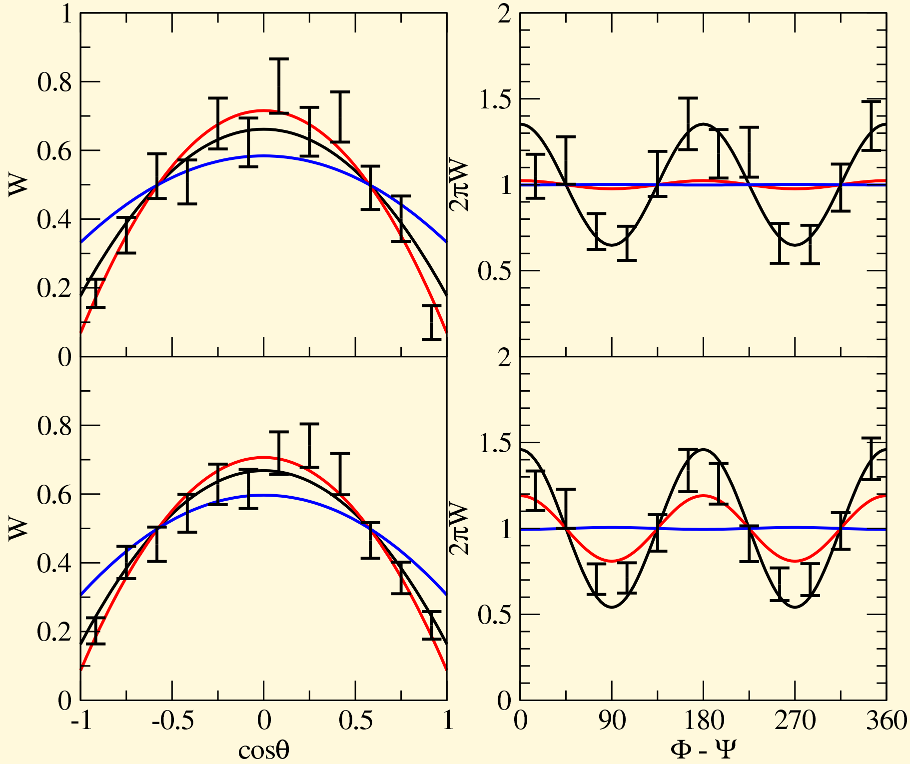
The angle Ψ is the angle between **photon polarization** and **ϕ production** plane.

Decay angular distribution $W(\theta)$ and $W(\Phi - \Psi)$ for $J^P = \frac{1}{2}^-$



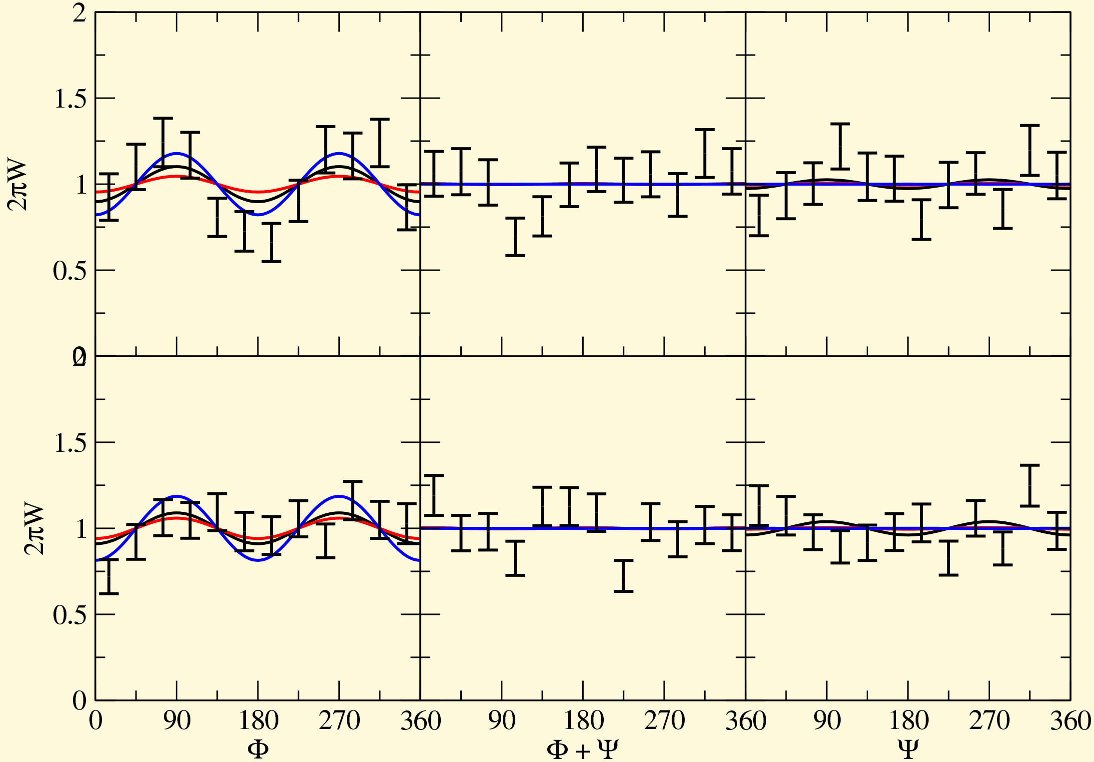
$E_\gamma = 2.07$ GeV (upper panels), $E_\gamma = 2.27$ GeV (lower panels)

Decay angular distribution $W(\theta)$ and $W(\Phi - \Psi)$ for $J^P = \frac{1}{2}^+$



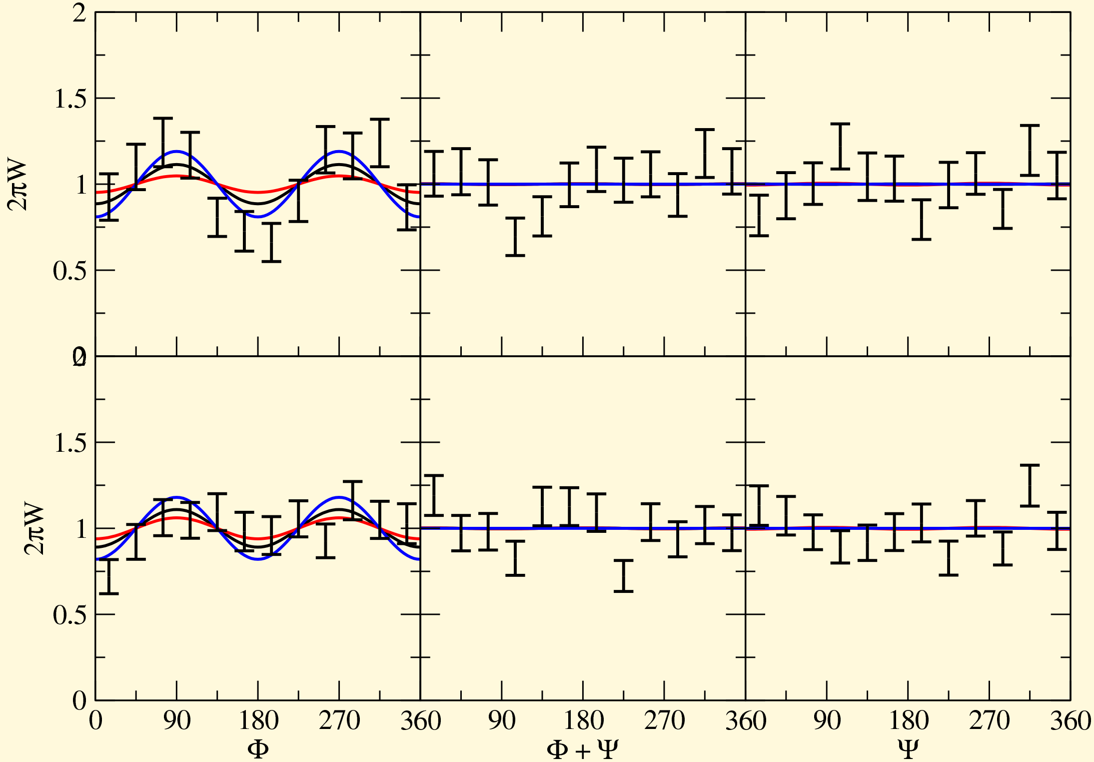
$E_\gamma = 2.07$ GeV (upper panels), $E_\gamma = 2.27$ GeV (lower panels)

Decay angular distribution $W(\Phi)$, $W(\Phi + \Psi)$, and $W(\Psi)$ for $J^P = \frac{1}{2}^-$



$E_\gamma = 2.07$ GeV (upper panels), $E_\gamma = 2.27$ GeV (lower panels)

Decay angular distribution $W(\Phi)$, $W(\Phi + \Psi)$, and $W(\Psi)$ for $J^P = \frac{1}{2}^+$



$E_\gamma = 2.07$ GeV (upper panels), $E_\gamma = 2.27$ GeV (lower panels)

Comparison between $J^P = \frac{1}{2}^+$ and $J^P = \frac{1}{2}^-$

- We found that both a $J^P = \frac{1}{2}^+$ and a $J^P = \frac{1}{2}^-$ resonance **can explain** the nonmonotonic behavior, **individually**, as well as DCS as a function of t and decay angular distributions.
- **DCS in forward direction**: both produce very similar results.
- **DCS as a function of t**: $J^P = \frac{1}{2}^+$ at lower photon lab energies (E_γ) is less in agreement with data than $J^P = \frac{1}{2}^-$.
- **Decay angular distributions**:
  - Results from both resonances are similarly in good agreement with data, especially $W(\theta)$ and $W(\Phi - \Psi)$.
  - However, in $W(\Phi)$ at $E_\gamma = 2.07$ GeV both resonances fails to produce the adequate strength. At $E_\gamma = 2.27$ GeV, the agreement is again very good.
  - $W(\Phi + \Psi)$ and $W(\Psi)$ shows only very small oscillation.
- The following table shows the comparison of fitted parameters.

Fitted parameters	$J^P = \frac{1}{2}^-$	$J^P = \frac{1}{2}^+$
M_{N^*}(MeV)	2140 ± 20	2120 ± 30
Γ_{N^*}(MeV)	297 ± 64	294 ± 86
$g_\gamma g_\phi^{(1)}$	0.27 ± 0.22	-0.018 ± 0.164
$g_\gamma g_\phi^{(2)}$	1.24 ± 0.68	-2.075 ± 1.046
C_p	4.11 ± 0.29	3.98 ± 0.32
$\sqrt{a_p}$ (MeV)	1.50 ± 0.11	1.44 ± 0.12

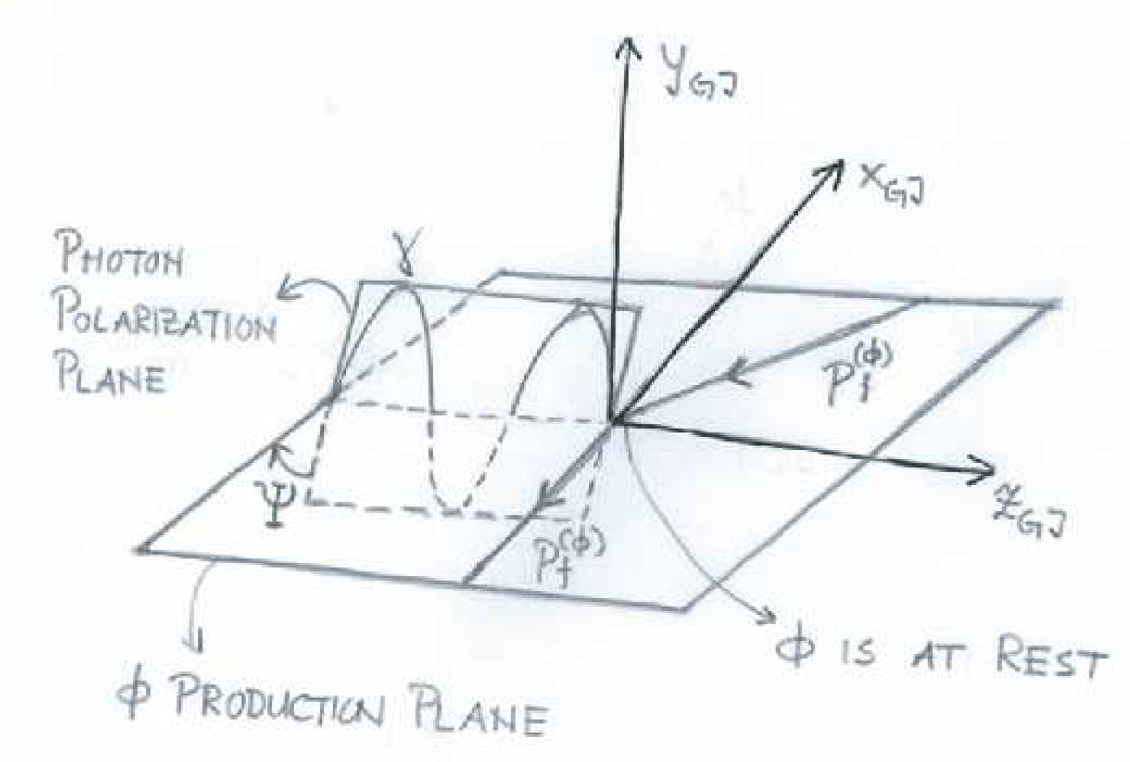
All errors are estimated using **MINUIT**.

- The fitted parameters are all found to be of reasonable values.
- The **masses and total widths** of both resonances are found to be the **same** within their respective error ranges.
- Close ties between the two resonances make it hard for us to decide which one is actually responsible for the structure.
- Or, it could be that we need to test **higher spin** resonances. $\longrightarrow$ The $J^P = \frac{3}{2}^+$ and $J^P = \frac{3}{2}^-$ are still in progress.
- More observables will also help to distinguish between resonances.

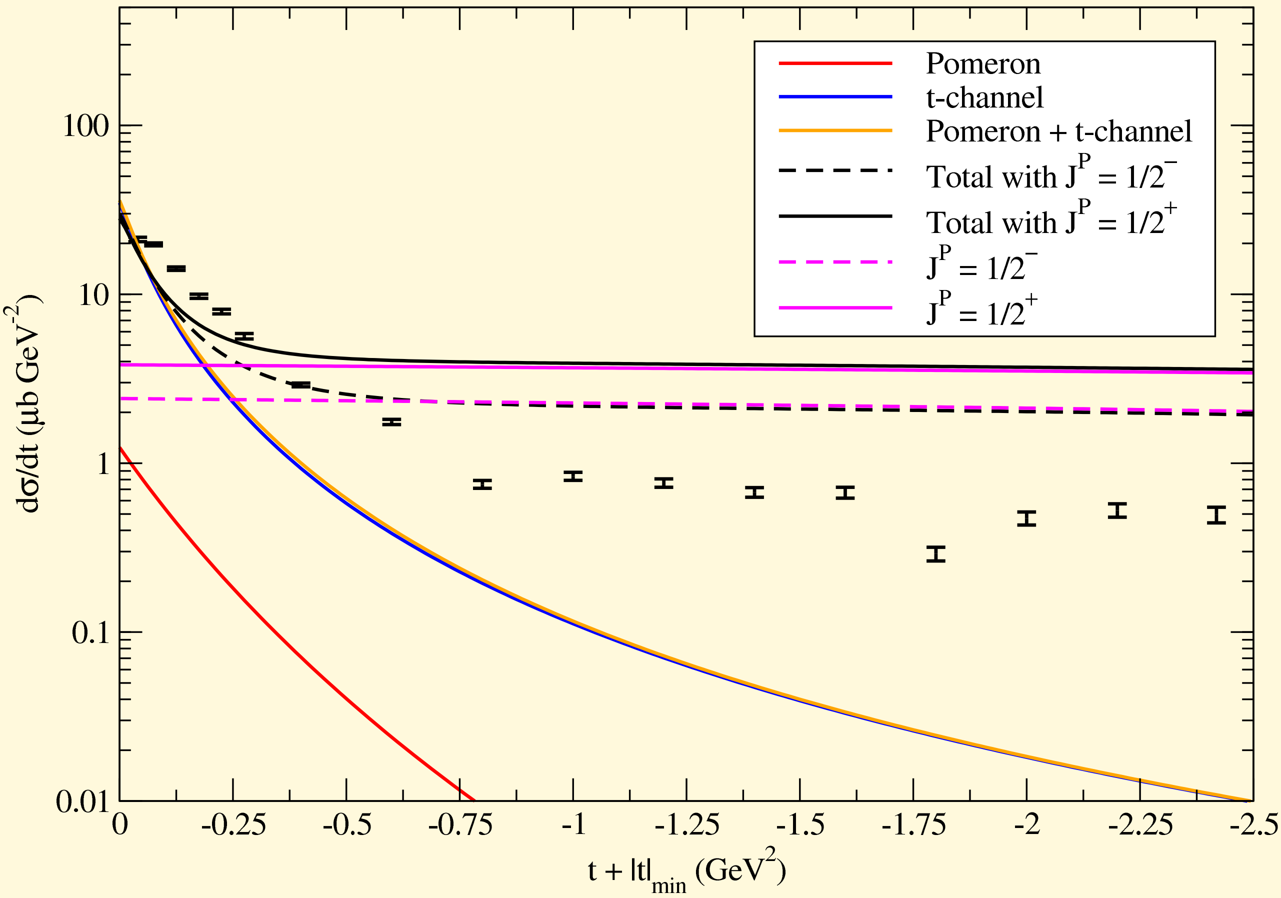
Conclusion and Outlook

- The **nonmonotonic structure** in the DCS of ϕ-photoproduction at forward angle can be explained by **including a resonance**.
- Other observables like **DCS as a function of t**, and **decay angular distribution**, can also be **explained** by the resonance.
- **Both** $J^P = \frac{1}{2}^+$ and $J^P = \frac{1}{2}^-$ resonances can explain the data very well and give out **very similar** resonance masses and widths.
- Given already how close the fit results of $J^P = \frac{1}{2}^+$ and $J^P = \frac{1}{2}^-$ resonances to the data, we might also need **more observables** to resolve the situation.
- We also proceed to test other resonances as well (in progress).

THANK YOU!



y_{GJ}
x_{GJ}
z_{GJ}
PHOTON
POLARIZATION
PLANE
γ
Ψ
$P_i^{(\phi)}$
$P_f^{(\phi)}$
φ IS AT REST
φ PRODUCTION PLANE


Pomeron
t-channel
Pomeron + t-channel
Total with J^P = 1/2^−
Total with J^P = 1/2^+
J^P = 1/2^−
J^P = 1/2^+
dσ/dt (μb GeV^-2)
t + |t|_min (GeV^2)
100
10
1
0.1
0.01
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
-2.25
-2.5