Resonance interpretation of the nonmonotonic behavior in the cross section of ϕ photoproduction near threshold

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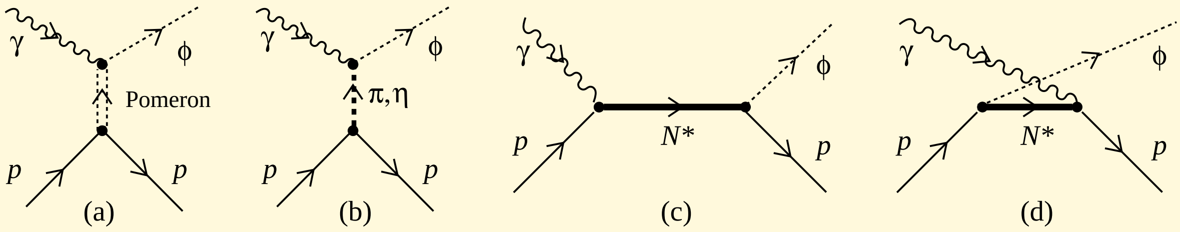
Motivation

- 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 local peak near threshold** (E_γ around 2.0 GeV).
  $\longrightarrow$ Seen also by Tedeschi et.al.: unpublished, but shown in some talks.
- We would like to see whether the local peak in the differential cross section (DCS) of ϕ photoproduction at forward angle can be **explained as a resonance** since the **conventional model of Pomeron plus π and η exchanges** usually can only give rise to a **monotonically-increasing** behavior.

Reaction model

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



- Throughout this presentation,
  - 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.

Pomeron exchange

- We use **Donnachie-Landshoff 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

$$M(s,t) = C_P F_1(t) F_2(t) \frac{1}{s}\left(\frac{s - s_{th}}{4}\right)^{\alpha_P(t)} \exp\left[-i\pi\alpha_P(t)/2\right]$$

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

Here, $\Gamma^{\mu\nu}$ is chosen to maintain **gauge invariance**

- Here

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

$$F_2(t) = \frac{2\mu_0^2}{(1 - t/M_\phi^2)(2\mu_0^2 + M_\phi^2 - t)}; \quad \mu_0^2 = 1.1 \text{ GeV}^2$$

$F_1(t)$ is the **isoscalar EM form-factor of the nucleon**, and $F_2(t)$ is the **form-factor for the ϕ-γ-Pomeron coupling**, and the **pomeron trajectory** is

$$\alpha_P = 1.08 + 0.25t$$

- The **strength factor** $C_P = 3.65$ is chosen to **fit** the **total cross sections** data at **high energy**.
- The **threshold factor** $s_{th} = 1.3$ **GeV**^{2} is chosen to **match** the **forward differential cross sections** data at around $E_\gamma = 6$ **GeV**.

π and η exchanges

- For **t-channel exchange involving π and η**, we use

$$
\begin{aligned}
\mathcal{L}_{\gamma\phi M} &= \frac{e g_{\gamma\phi M}}{m_\phi} \epsilon^{\mu\nu\alpha\beta} \partial_\mu \phi_\nu \partial_\alpha A_\beta \varphi_M \\
\mathcal{L}_{MNN} &= \frac{g_{MNN}}{2M_N} \bar{\psi} \gamma^\mu \gamma^5 \psi \partial_\mu \varphi_M
\end{aligned}
$$

  with $M = (\pi, \eta)$.

- We choose $g_{\pi NN} = 13.26$, $g_{\eta NN} = 1.12$, $g_{\gamma\phi\pi} = -0.14$, and $g_{\gamma\phi\eta} = -0.71$.

- Form factor at **each vertex** in the t-channel diagram is

$$
F_{MNN}(t) = F_{\gamma\phi M}(t) = \frac{\Lambda_M^2 - m_M^2}{\Lambda_M^2 - t}
$$

- The value $\Lambda_M = 1.2$ is taken for **both** $M = (\pi, \eta)$.

Resonances

- Only **spin** $1/2$ or $3/2$ because the **resonance is close to the threshold**.

- **Lagrangian densities** that couple **spin-**$1/2$ and $3/2$ particles to γN or ϕN channels are

$$\begin{aligned}
\mathcal{L}^{1/2^\pm}_{\phi NN^*} &= g^{(1)}_{\phi NN^*}\bar{\psi}_N\Gamma^\pm\gamma^\mu\psi_{N^*}\phi_\mu + g^{(2)}_{\phi NN^*}\bar{\psi}_N\Gamma^\pm\sigma_{\mu\nu}G^{\mu\nu}\psi_{N^*}, \\
\mathcal{L}^{3/2^\pm}_{\phi NN^*} &= ig^{(1)}_{\phi NN^*}\bar{\psi}_N\Gamma^\pm\left(\partial^\mu\psi^\nu_{N^*}\right)\tilde{G}_{\mu\nu} + g^{(2)}_{\phi NN^*}\bar{\psi}_N\Gamma^\pm\gamma^5\left(\partial^\mu\psi^\nu_{N^*}\right)G_{\mu\nu} \\
&+ ig^{(3)}_{\phi NN^*}\bar{\psi}_N\Gamma^\pm\gamma^5\gamma_\alpha\left(\partial^\alpha\psi^\nu_{N^*} - \partial^\nu\psi^\alpha_{N^*}\right)\left(\partial^\mu G_{\mu\nu}\right),
\end{aligned}$$

  where $G_{\mu\nu} = \partial_\mu\phi_\nu - \partial_\nu\phi_\mu$ and $\tilde{G}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}G^{\alpha\beta}$. The operator $\Gamma^\pm$ are given by $\Gamma^+ = 1$ and $\Gamma^- = \gamma_5$, depending on the parity of the resonance N^*.

- For the γNN^* **vertices**, simply change $g_{\phi NN^*} \longrightarrow eg_{\gamma NN^*}$ and $\phi_\mu \longrightarrow A_\mu$.

- **Current conservation** fixes $g^{(1)}_{\gamma N N^*} \to 0$ for $J^P = 1/2^\pm$ and the term **proportional** to $g^{(3)}_{\gamma N N^*}$ **vanishes** in the case of **real photon**.
- The **effect of the width** is taken into account in a **Breit-Wigner** form by replacing the usual denominator $p^2 - M^2_{N^*} \to p^2 - M^2_{N^*} + iM_{N^*}\Gamma_{N^*}$.
- The **form factor** for the **vertices** used in the s**-** and u**-channel diagrams** is

$$F_{N^*}(p^2) = \frac{\Lambda^4}{\Lambda^4 + (p^2 - M^2_{N^*})^2} \tag{1}$$

with $\Lambda = 1.2$ **GeV** for **all resonances**.

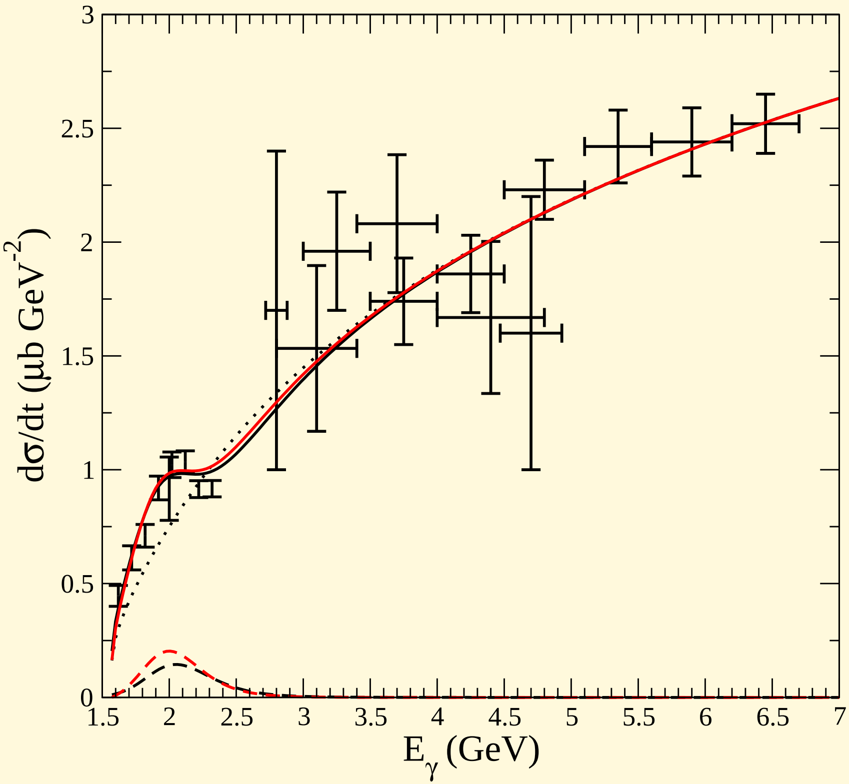
Fitting to experimental data

- We include only **one resonance at a time**.
- We fit only **masses**, **widths**, and **coupling constants** of the resonances to the experimental data, while **other parameters are fixed** during fitting.
- Experimental data to fit
  - **Differential cross sections** (DCS) at **forward angle** (LEPS 2005)
  - **DCS as a function of t** at eight incoming photon energy bins (LEPS 2005)
  - **Nine spin-density matrix elements (SDME)** at **three** incoming photon energy bins (New LEPS 2010)
- In our previous work **[PLB 691 (2010) 214-218]**, instead of the new 2010 SDME data, we used **five decay angular distributions** of K^+K^- pair at **two** incoming photon energy bins.
- Note that **decay angular distributions are functions of SDME**.

Results

- Both $J^P = 1/2^{\pm}$ resonances **cannot fit the data**.
- **DCS at forward angle and as a function of t** are markedly **improved** by the inclusion of the $J^P = 3/2^{\pm}$ resonances.
- In general, **SDME are also improved** by both $J^P = 3/2^{\pm}$ resonances.

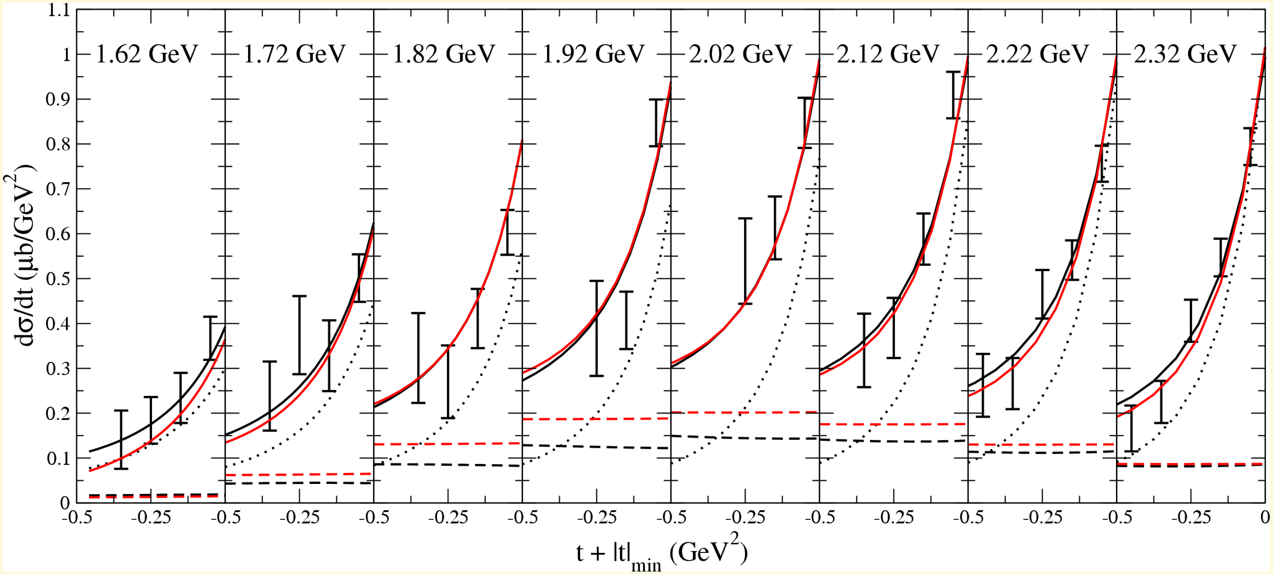
DCS at forward angle



Black$\rightarrow J^P = 3/2^-$ **Red**$\rightarrow$ $J^P = 3/2^+$

Full $\rightarrow$ total, Nonresonant $\rightarrow$ dotted, Resonant $\rightarrow$ dashed

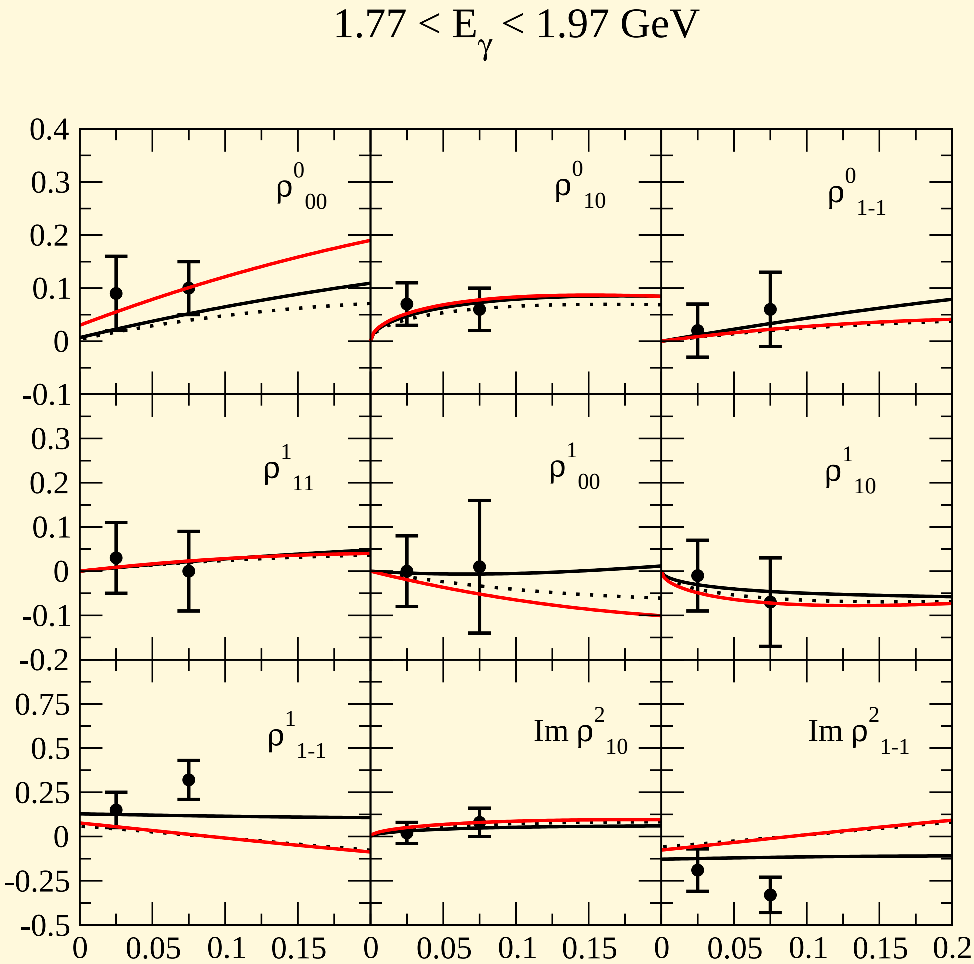
DCS as a function of t



Black$\rightarrow J^P = 3/2^-$ **Red**$\rightarrow$ $J^P = 3/2^+$

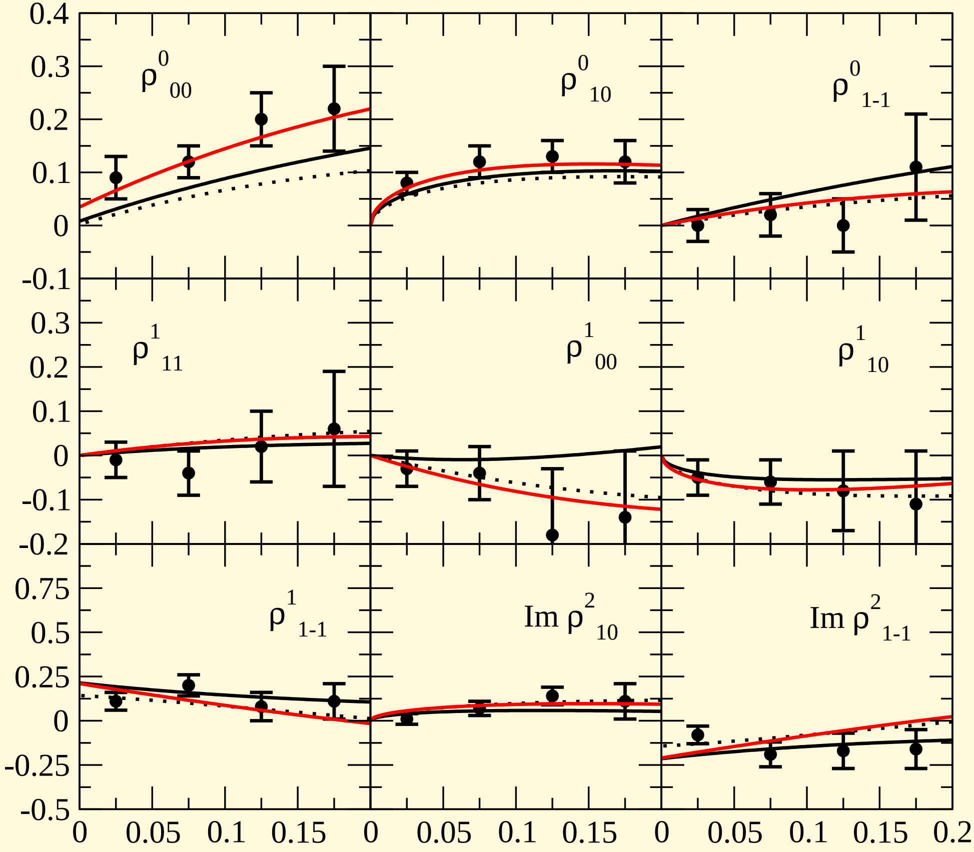
Full $\longrightarrow$ total, Nonresonant $\longrightarrow$ dotted, Resonant $\longrightarrow$ dashed

SDME as a function of t



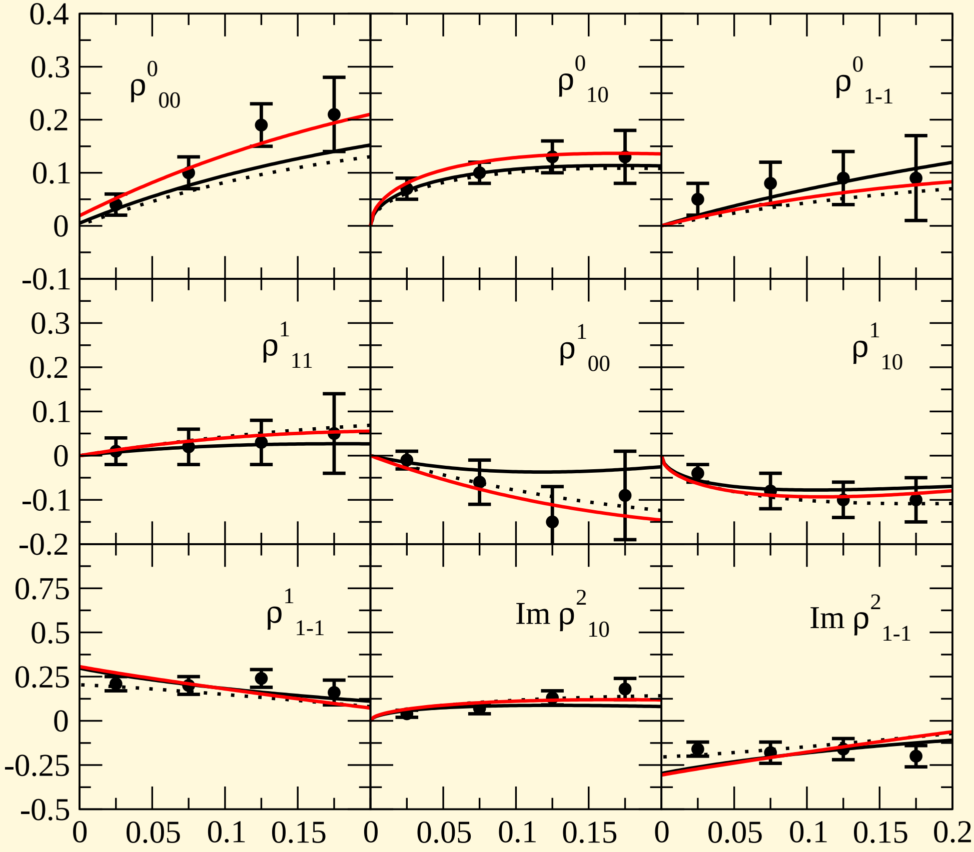
SDME as a function of t

$1.97 < E_\gamma < 2.17$ GeV



SDME as a function of t

$2.17 < E_\gamma < 2.37$ GeV



	$J^P = 3/2^+$		$J^P = 3/2^-$	
	This work	Previous work	This work	Previous work
M_{N^*}(GeV)	2.08 ± 0.032	2.05 ± 0.06	2.08 ± 0.048	2.10 ± 0.03
Γ_{N^*}(GeV)	0.501 ± 0.111	0.450 ± 0.111	0.570 ± 0.169	0.465 ± 0.141
$eg^{(1)}_{\gamma NN^*} g^{(1)}_{\phi NN^*}$	0.003 ± 0.009	0.000 ± 0.008	-0.205 ± 0.095	-0.186 ± 0.079
$eg^{(1)}_{\gamma NN^*} g^{(2)}_{\phi NN^*}$	-0.084 ± 0.057	-0.410 ± 0.185	-0.025 ± 0.017	-0.015 ± 0.030
$eg^{(1)}_{\gamma NN^*} g^{(3)}_{\phi NN^*}$	0.025 ± 0.071	-0.318 ± 0.156	-0.033 ± 0.018	-0.02 ± 0.032
$eg^{(2)}_{\gamma NN^*} g^{(1)}_{\phi NN^*}$	0.002	0.000 ± 0.002	-0.266	-0.212 ± 0.076
$eg^{(2)}_{\gamma NN^*} g^{(2)}_{\phi NN^*}$	-0.048	-0.100 ± 0.037	-0.033	-0.017 ± 0.035
$eg^{(2)}_{\gamma NN^*} g^{(3)}_{\phi NN^*}$	0.014	-0.078 ± 0.031	-0.043	-0.025 ± 0.037
χ^2/N	0.955	1.066	0.881	0.983

- The ratio $A_{1/2}/A_{3/2} = 1.05$ (previous work 1.16) for the $J^P = 3/2^-$ resonance.
- The ratio $A_{1/2}/A_{3/2} = 0.89$ (previous work 0.69) for the $J^P = 3/2^+$ resonance.

- We found that $J^P = 3/2^-$ resonance parameters are **very close** to our previous work.
- On the other hand, $J^P = 3/2^+$ resonance parameters are mostly **different**, especially the coupling constants.
- We prefer $J^P = 3/2^-$ based on the **stability of the extracted resonance parameters** across **different sets of experimental data**. $\longrightarrow$ cannot be identified with $D_{13}(2080)$ (PDG lists $A_{1/2}/A_{3/2} = -1.18$)

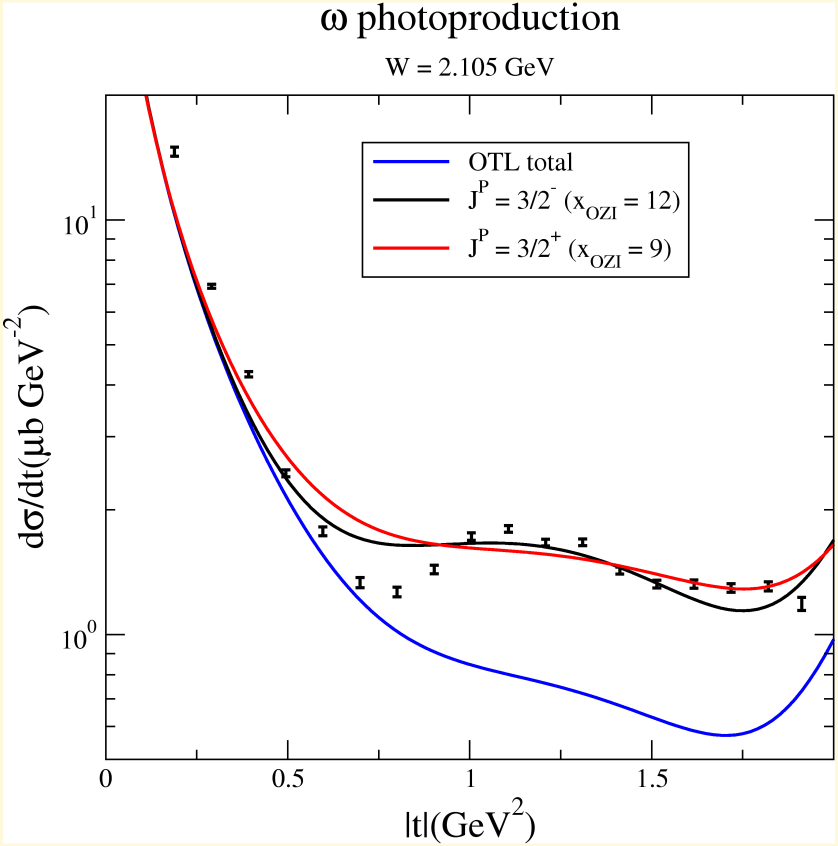
Effects on ω photoproduction

- From the $\phi - \omega$ **mixing**, we expect the resonance to also contribute to ω **photoproduction**.
- The coupling constants $g_{\phi NN^*}$ and $g_{\omega NN^*}$ are **related**, and in our study we choose to use the so-called **"minimal" parametrization**,

$$g_{\phi NN^*} = -\tan\Delta\theta_V x_{\text{OZI}} g_{\omega NN^*}$$

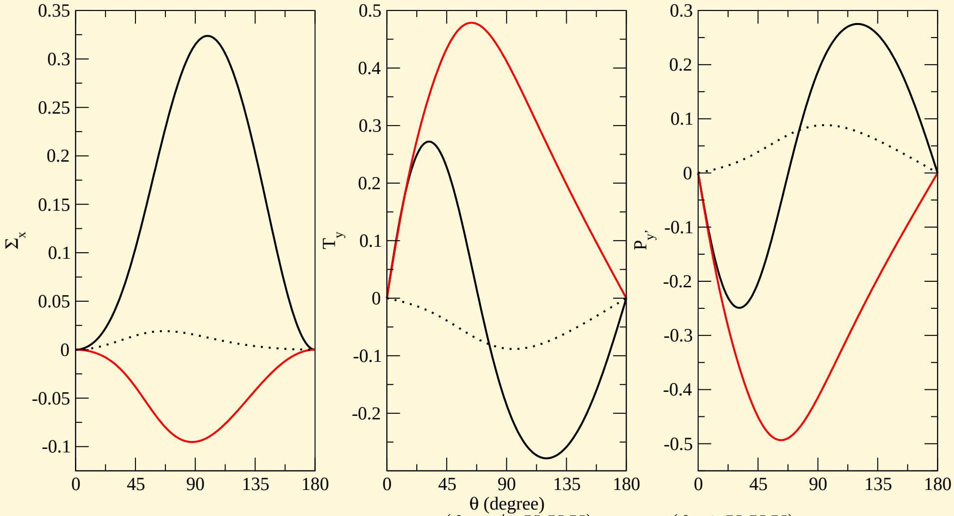
- By using $x_{\mathbf{OZI}} = 12$ for the $J^P = 3/2^-$ resonance and $x_{\mathbf{OZI}} = 9$ for the $J^P = 3/2^+$ resonance, we found that we can **explain quite well** the **DCS of ω photoproduction at $W = 2.015$ GeV**.
- The **large value of $x_{\mathbf{OZI}}$** indicates that the resonance has a **considerable amount of strangeness content**.

DCS of ω photoproduction as a function of t



Data from M. Williams, Phys.Rev.C.80, 065209 (2009)

Predictions for single polarization observables

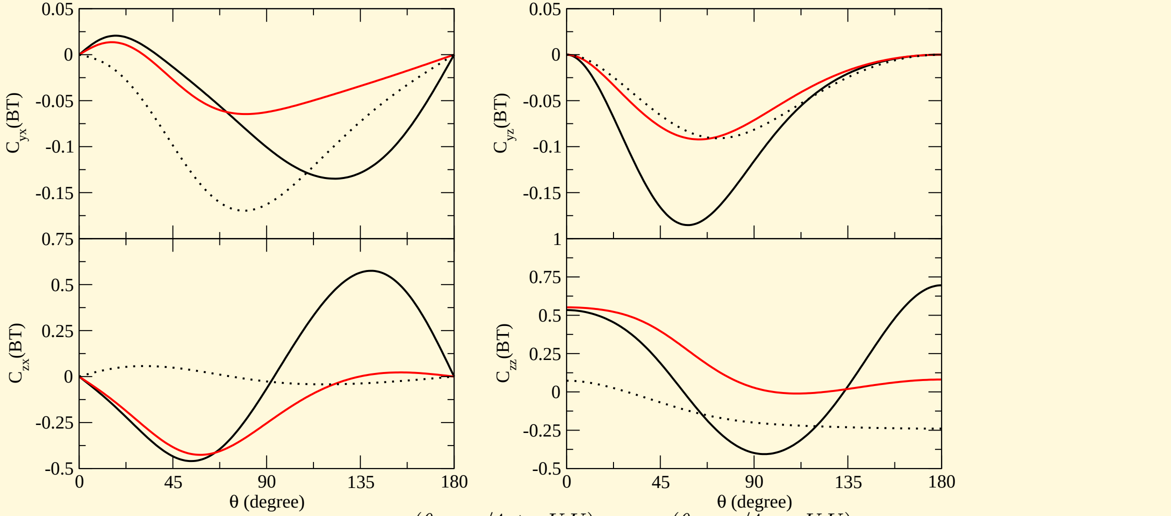


$$\Sigma_x = \frac{d\sigma^{(\theta=\pi/2,U;U,U)} - d\sigma^{(\theta=0,U;U,U)}}{d\sigma^{(\theta=\pi/2,U;U,U)} + d\sigma^{(\theta=0,U;U,U)}}$$

$$T_y = \frac{d\sigma^{(U,+y;U,U)} - d\sigma^{(U,-y;U,U)}}{d\sigma^{(U,+y;U,U)} + d\sigma^{(U,-y;U,U)}}$$

$$P_{y'} = \frac{d\sigma^{(U,U;+y',U)} - d\sigma^{(U,U;-y',U)}}{d\sigma^{(U,U;+y',U)} + d\sigma^{(U,U;-y',U)}}$$

Predictions for double polarization observables



$$C_{yx}^{BT} = \frac{d\sigma^{(\theta=-\pi/4,+x;U,U)} - d\sigma^{(\theta=-\pi/4,-x;U,U)}}{d\sigma^{(\theta=-\pi/4,+x;U,U)} + d\sigma^{(\theta=-\pi/4,-x;U,U)}}$$

$$C_{yz}^{BT} = \frac{d\sigma^{(\theta=-\pi/4,+z;U,U)} - d\sigma^{(\theta=-\pi/4,-z;U,U)}}{d\sigma^{(\theta=-\pi/4,+z;U,U)} + d\sigma^{(\theta=-\pi/4,-z;U,U)}}$$

$$C_{zx}^{BT} = \frac{d\sigma^{(+z,\theta=\pi/2;U,U)} - d\sigma^{(+z,\theta=0;U,U)}}{d\sigma^{(+z,\theta=\pi/2;U,U)} + d\sigma^{(+z,\theta=0;U,U)}}$$

$$C_{zz}^{BT} = \frac{d\sigma^{(+z,+z;U,U)} - d\sigma^{(+z,-z;U,U)}}{d\sigma^{(+z,+z;U,U)} + d\sigma^{(+z,-z;U,U)}}$$

Summary and conclusions

- **Inclusion of a resonance is needed** to explain the **non-monotonic behavior** in the DCS of ϕ-meson photoproduction near threshold.
- Resonance with $J^P = 3/2^-$ is preferred in this study.
- The resonance seems to have a **considerable amount of strangeness content**.
- $D_{13}(2080)$ **is ruled out** based on the different sign of $A_{1/2}/A_{3/2}$.
- Further experiments, e.g. measurement of **single and double polarizations**, would be helpful to check our predictions.

THANK YOU!