On the near-threshold incoherent ϕ photoproduction on the deuteron: Any trace of a resonance?

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Motivation

- Presence of **a local peak near threshold** at $E_\gamma \sim 2.0$ GeV in the **differential cross-section (DCS) of $\gamma p \to \phi p$ at forward angle** by **Mibe and Chang, et al.** [PRL **95** 182001 (2005)] from the **LEPS Collaboration**.
  $\longrightarrow$ Observed also recently by **JLAB**: **B. Dey et al.** [PRC **89** 055208 (2014)], and **Seraydaryan et al.** [PRC **89** 055206 (2014)].

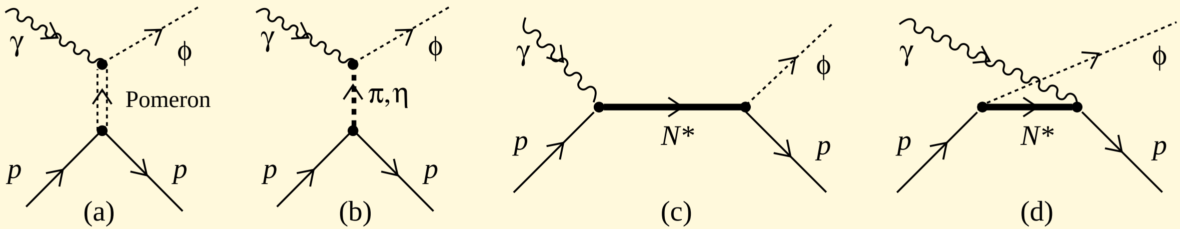
- **Conventional model of Pomeron plus π and η exchanges** usually can only give rise to a **monotonically-increasing** behavior.

- We would like to see whether this **local peak** can be explained as a **resonance**.

- In order to **check** this assumption, we apply the results on $\gamma p \to \phi p$ to $\gamma d \to \phi p n$ to see if we can **describe the latter**.

Reaction model for $\gamma p \to \phi p$

- Here are the **tree-level diagrams** calculated in our model in an **effective Lagrangian** approach.



N^* is the postulated resonance.

- 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 follow the work of **Donnachie, Landshoff, and Nachtmann**
$\longrightarrow$ **Pomeron-isoscalar-photon** analogy

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

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

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

- $\Gamma^{\mu\nu}$ is chosen to maintain **gauge invariance**.
- 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

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

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 $\Lambda_M = 1.2$ **GeV** 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

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

  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 $\gamma N N^*$ **vertices**, simply change $g_{\phi N N^*} \longrightarrow e g_{\gamma N N^*}$ and $\phi_\mu \longrightarrow A_\mu$.

- **Current conservation** fixes $g^{(1)}_{\gamma NN^*} \longrightarrow 0$ for $J^P = 1/2^{\pm}$ and the term **proportional** to $g^{(3)}_{\gamma NN^*}$ **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 $p^2 - M^2_{N^*} \longrightarrow p^2 - M^2_{N^*} + iM_{N^*}\Gamma_{N^*}$.
- The **form factor** for the **vertices** used in the s**-** and u**-channel diagrams** is

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

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

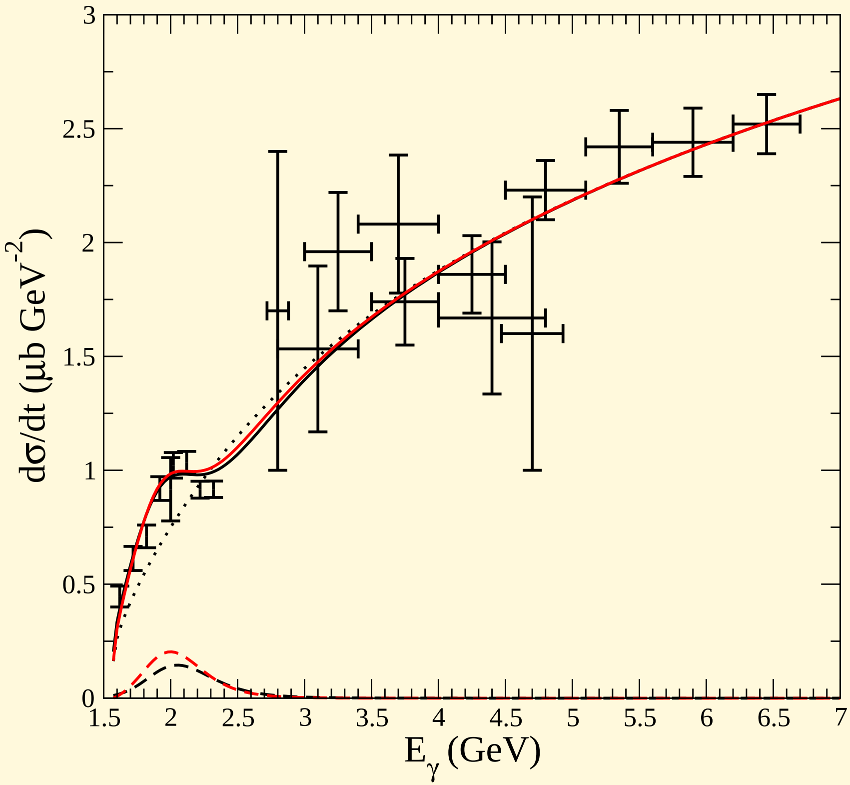
Fitting to $\gamma p \to \phi p$ experimental data

- 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**
  - **DCS as a function of t** at eight incoming photon energy bins
  - **Nine spin-density matrix elements (SDME)** at three incoming photon energy bins

Results for $\gamma p \to \phi p$

- 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.
- **Decay angular distributions**, not used in the fitting procedure, can also be explained well.
- We study the effect of the resonance to the **DCS of $\gamma p \to \omega p$**.
$\longrightarrow$ The resonance seems to have a **considerable amount of strangeness content**.

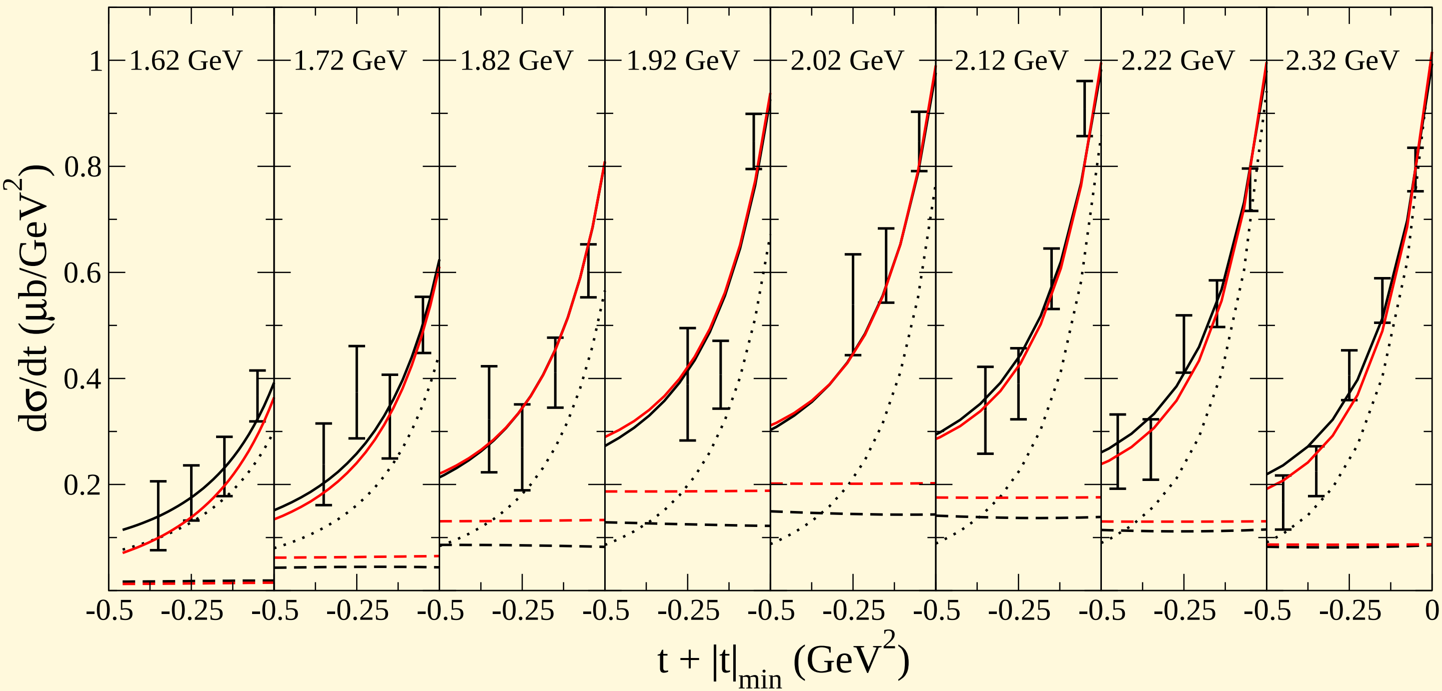
DCS of $\gamma p \to \phi p$ at forward angle



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

Total $\to$ full, Nonresonant $\to$ dotted, Resonant $\to$ dashed

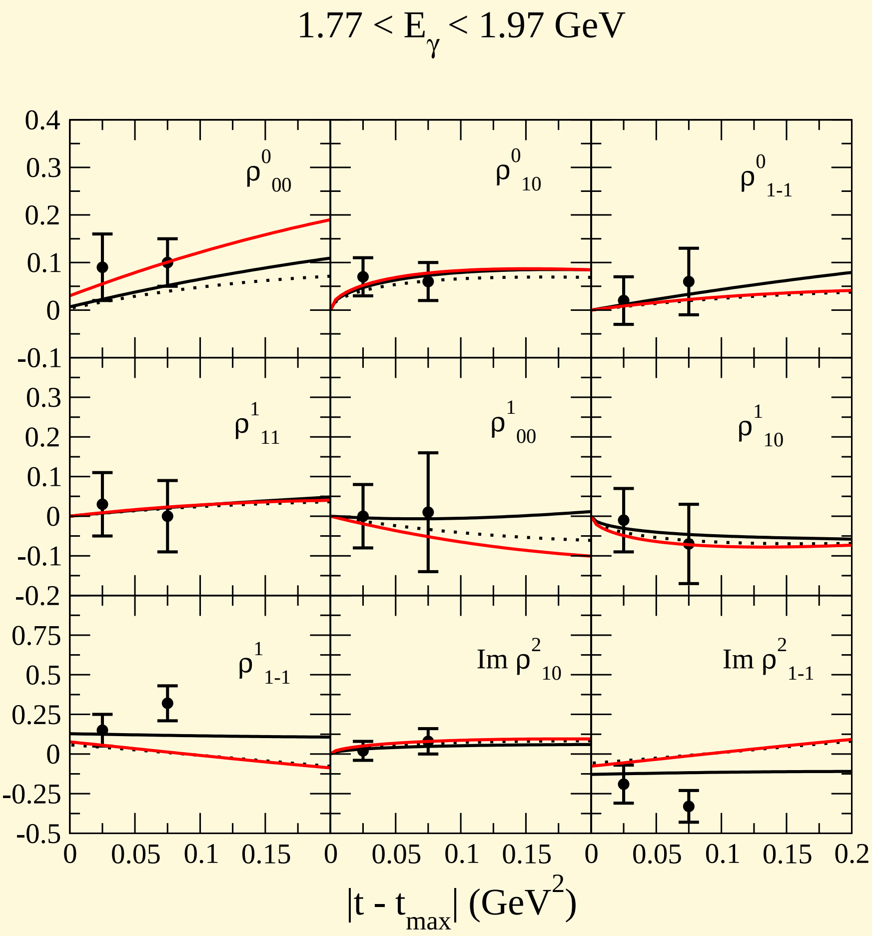
DCS of $\gamma p \to \phi p$ as a function of t



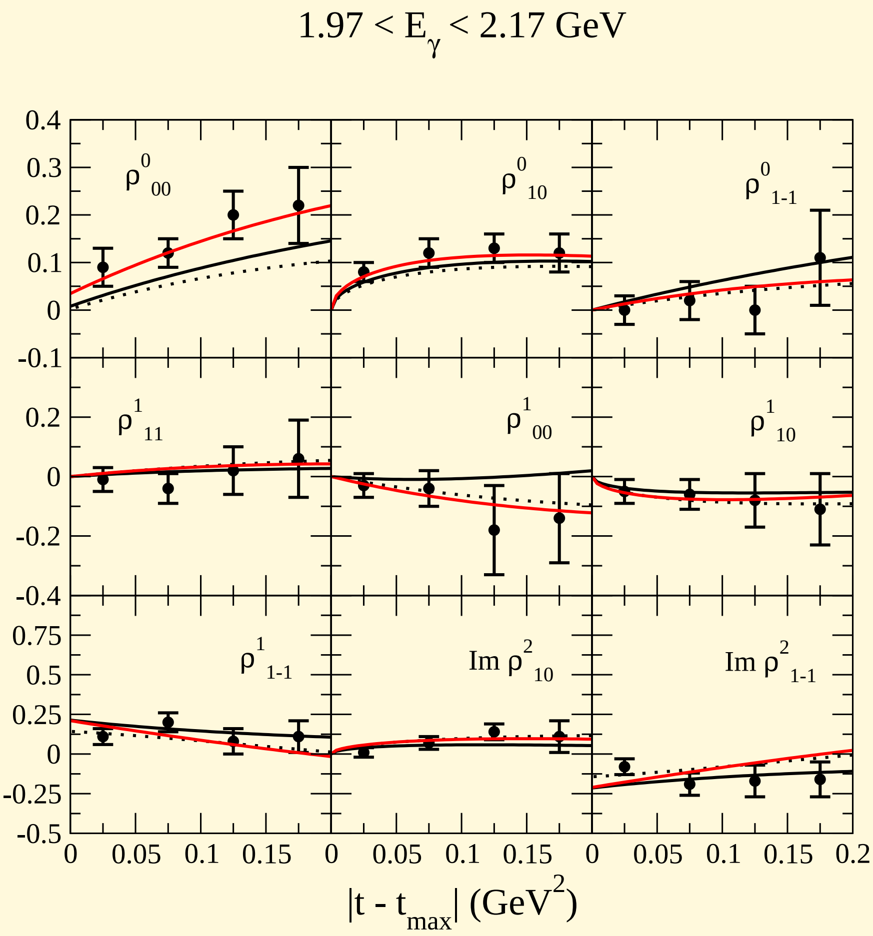
Black$\rightarrow J^P = 3/2^-$ **Red**$\rightarrow J^P = 3/2^+$

Total $\rightarrow$ full, Nonresonant $\rightarrow$ dotted, Resonant $\rightarrow$ dashed

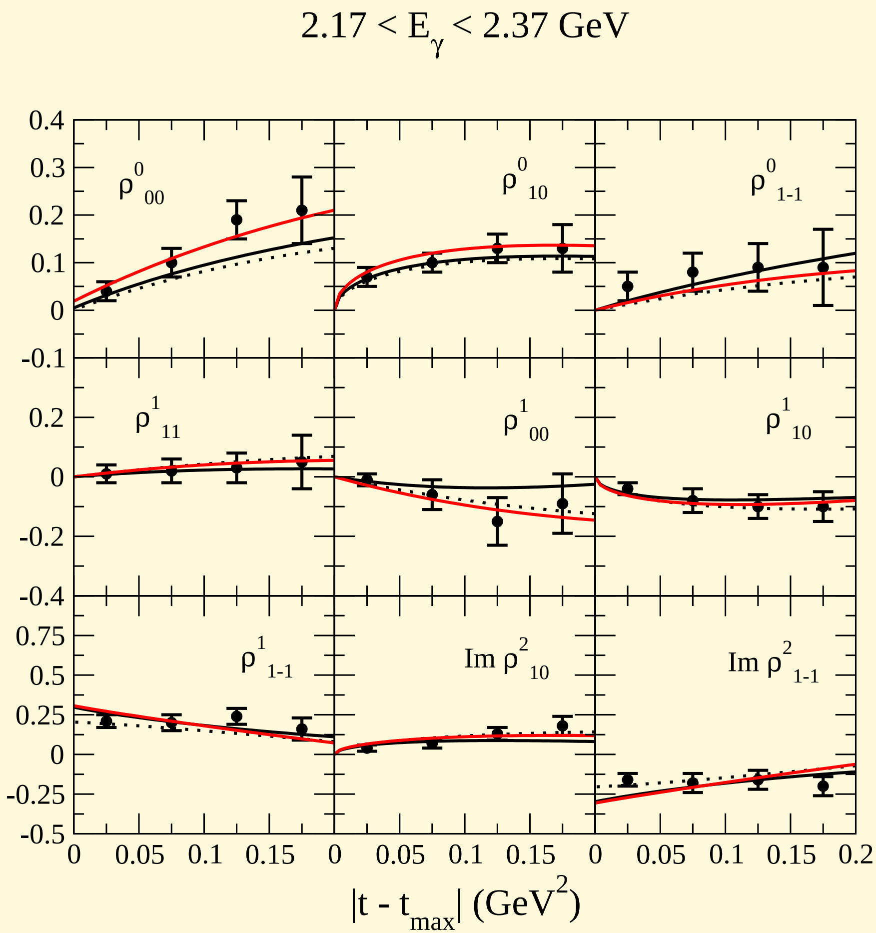
SDME of $\gamma p \to \phi p$ as a function of t



SDME of $\gamma p \to \phi p$ as a function of t



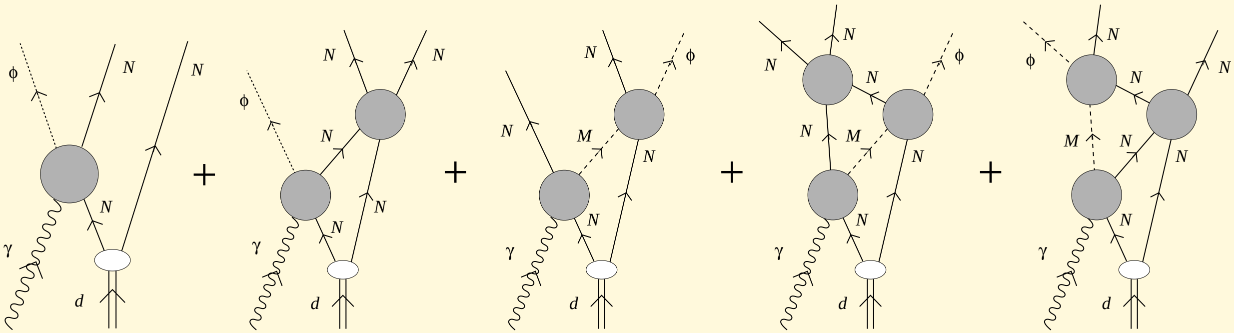
SDME of $\gamma p \to \phi p$ as a function of t



	$J^P = 3/2^+$	$J^P = 3/2^-$
M_{N^*}(GeV)	**2.08 ± 0.04**	**2.08 ± 0.04**
Γ_{N^*}(GeV)	**0.501 ± 0.117**	**0.570 ± 0.159**
$eg^{(1)}_{\gamma NN^*}g^{(1)}_{\phi NN^*}$	0.003 ± 0.009	−0.205 ± 0.083
$eg^{(1)}_{\gamma NN^*}g^{(2)}_{\phi NN^*}$	−0.084 ± 0.057	−0.025 ± 0.017
$eg^{(1)}_{\gamma NN^*}g^{(3)}_{\phi NN^*}$	0.025 ± 0.076	−0.033 ± 0.017
$eg^{(2)}_{\gamma NN^*}g^{(1)}_{\phi NN^*}$	0.002 ± 0.006	−0.266 ± 0.127
$eg^{(2)}_{\gamma NN^*}g^{(2)}_{\phi NN^*}$	−0.048 ± 0.047	−0.033 ± 0.032
$eg^{(2)}_{\gamma NN^*}g^{(3)}_{\phi NN^*}$	0.014 ± 0.040	−0.043 ± 0.032
χ^2/N	0.891	0.821

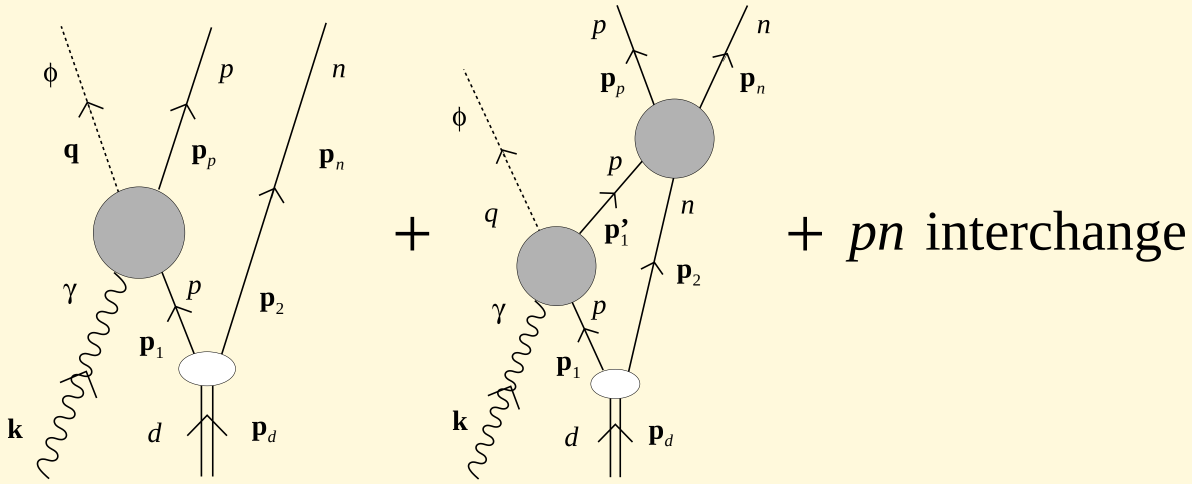
- The ratio $A_{1/2}/A_{3/2} = 1.05$ for the $J^P = 3/2^-$ resonance.
- The ratio $A_{1/2}/A_{3/2} = 0.89$ for the $J^P = 3/2^+$ resonance.

Reaction model for $\gamma d \to \phi p n$



(a) (b) (c) (d) (e)

- We calculate only **(a) and (b)**, as **(c), (d), and (e) are estimated to be small**.
- We want to know if the resonance would manifest itself in **different reaction**.



- **Fermi motion** of the proton and neutron inside the deuteron is included using **deuteron wave function** calculated by **Machleidt** in PRC **63** 024001 (2001).
- **Final-state interactions (FSI) of** *pn* system is included using **Nijmegen** *pn* scattering amplitude.
- **On- and off-shell** parts of the *pn* **propagator** are included.
$\longrightarrow \frac{1}{E_p+E_n-E_1'-E_2+i\epsilon} = \frac{\mathcal{P}}{E_p+E_n-E_1'-E_2} - i\pi\delta(E_p+E_n-E_1'-E_2)$

- The **same model** for the amplitude of $\gamma p \rightarrow \phi p$.
  $\longrightarrow$ **Realistic** model
  $\longrightarrow$ **Correct spin structure** is maintained

- A $J^P = 3/2^-$ **resonance** is also present in the $\gamma n \rightarrow \phi n$ amplitude

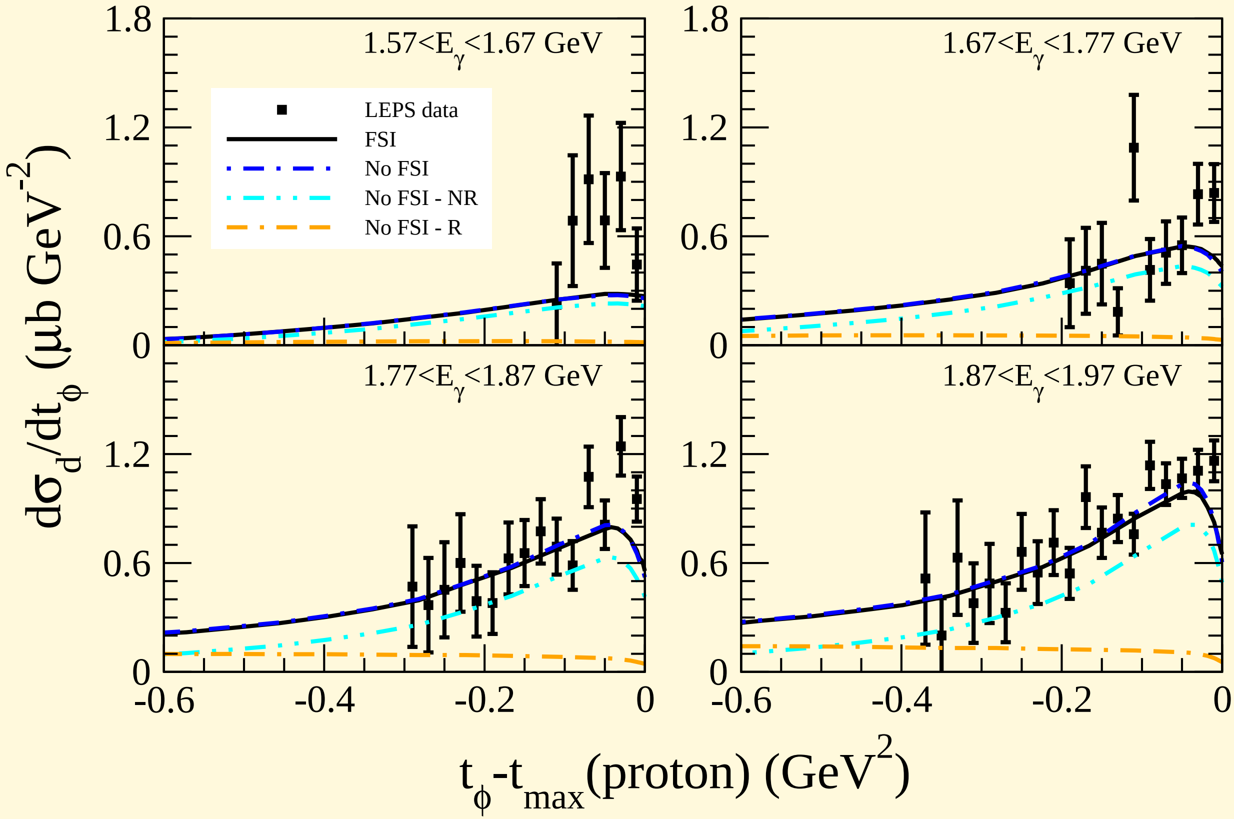
  - **For $\phi n n^*$ vertex**, ϕp and ϕn cases are **the same since ϕ is an $I = 0$ particle**.
  - **For $\gamma n n^*$ vertex**, we assume that the **resonance** would have the **same properties, including its coupling to γn, as a CQM state with the same isospin, J^P, and similar value of $A_{1/2}/A_{3/2}$ for the γp decay**
    $\longrightarrow N\frac{3}{2}^-(2095)[D_{13}]_5$ in **Capstick's work** in PRD **46**, 2864 (1992), the **only one with positive value of $A_{1/2}/A_{3/2}$ for γp in the energy region**.

Results for $\gamma d \to \phi pn$

- Notice that **no fitting is performed** to the LEPS data on DCS [PLB **684** 6-10 (2010)] and SDME [PRC **82** 015205 (2010)] of $\gamma d \to \phi pn$ from **Chang et al.**.
  $\longrightarrow$ We use **directly the parameters resulting from** $\gamma p \to \phi p$.
- We found a **fair agreement** with the LEPS experimental data on both observables.
- **Resonance**, **Fermi motion**, and pn **FSI** effects are found to be **large**.
  $\longrightarrow$ **Without them**, the DCS data **cannot** be described.

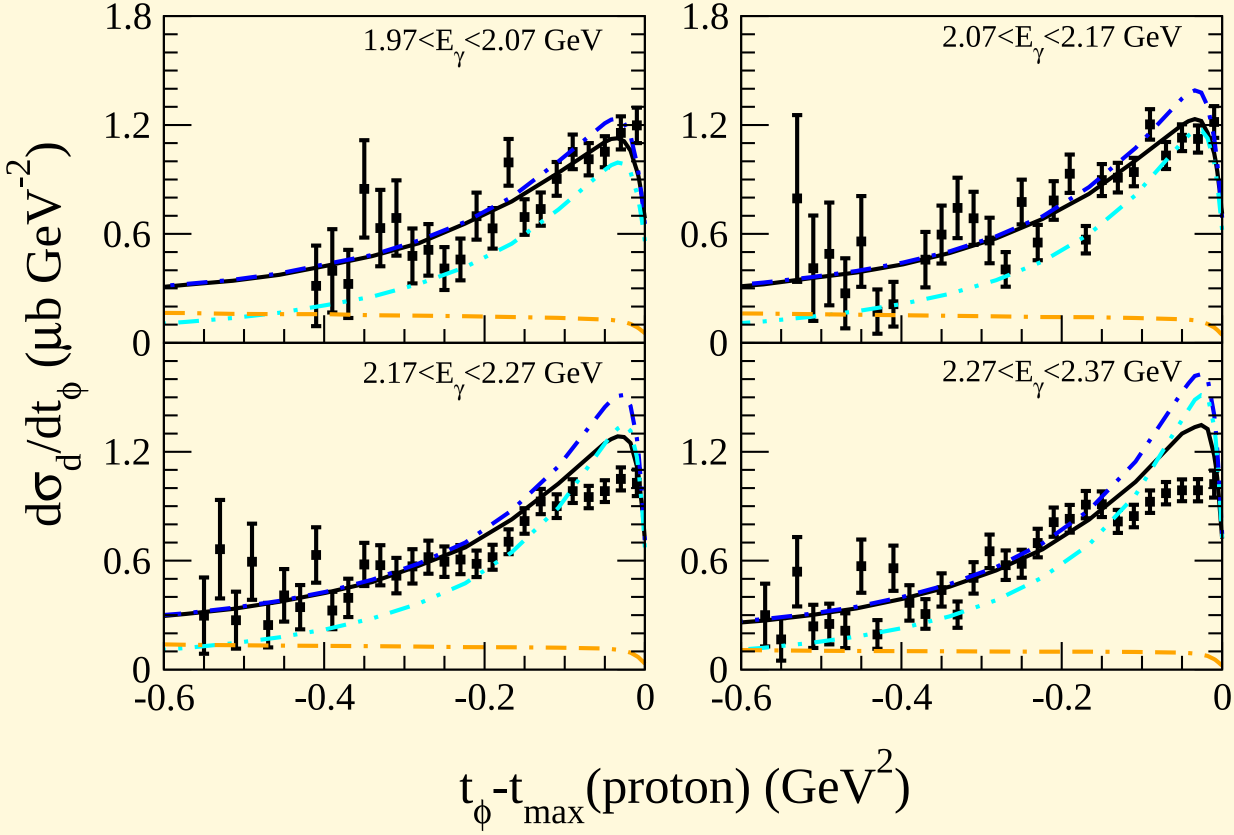
DCS of $\gamma d \to \phi pn$

Not fitted



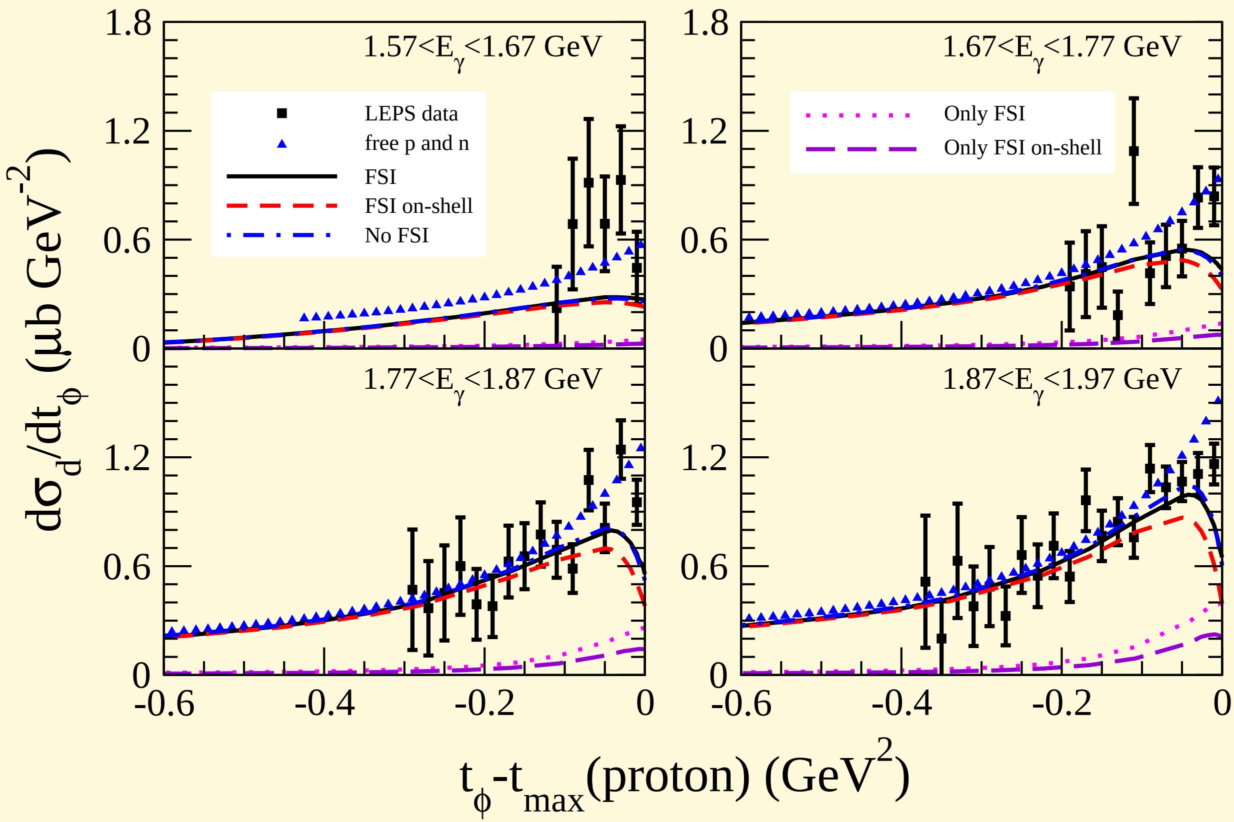
DCS of $\gamma d \to \phi pn$

Not fitted



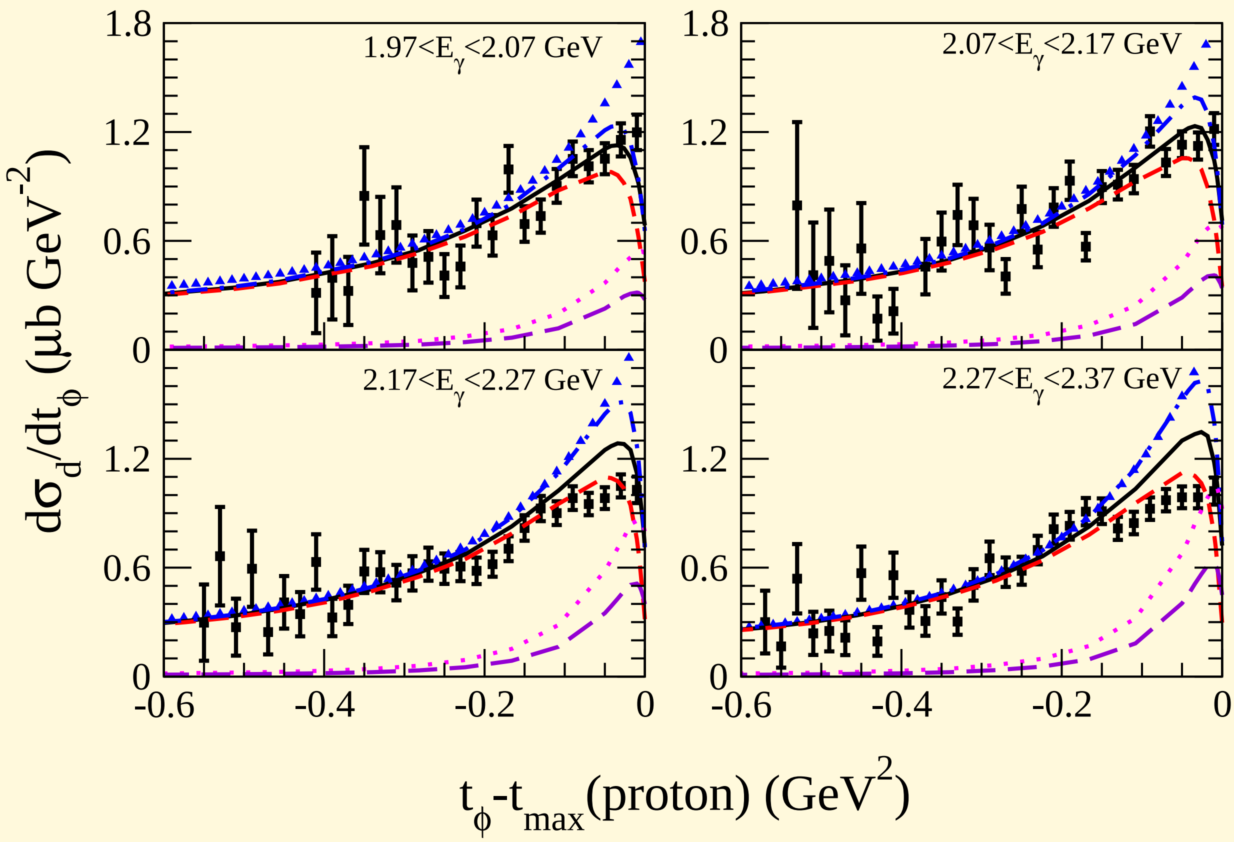
DCS of $\gamma d \to \phi p n$

Not fitted



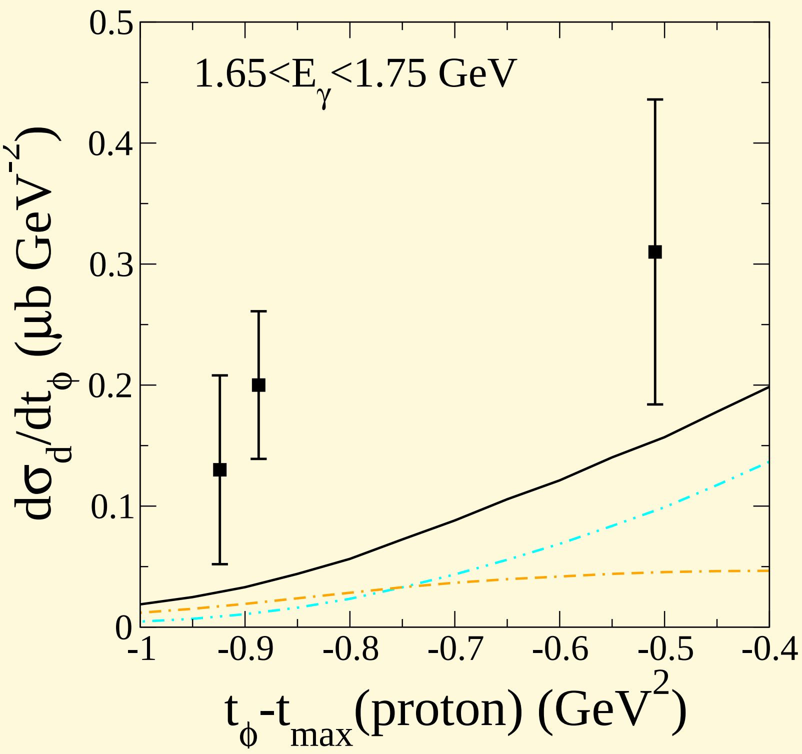
DCS of $\gamma d \to \phi pn$

Not fitted



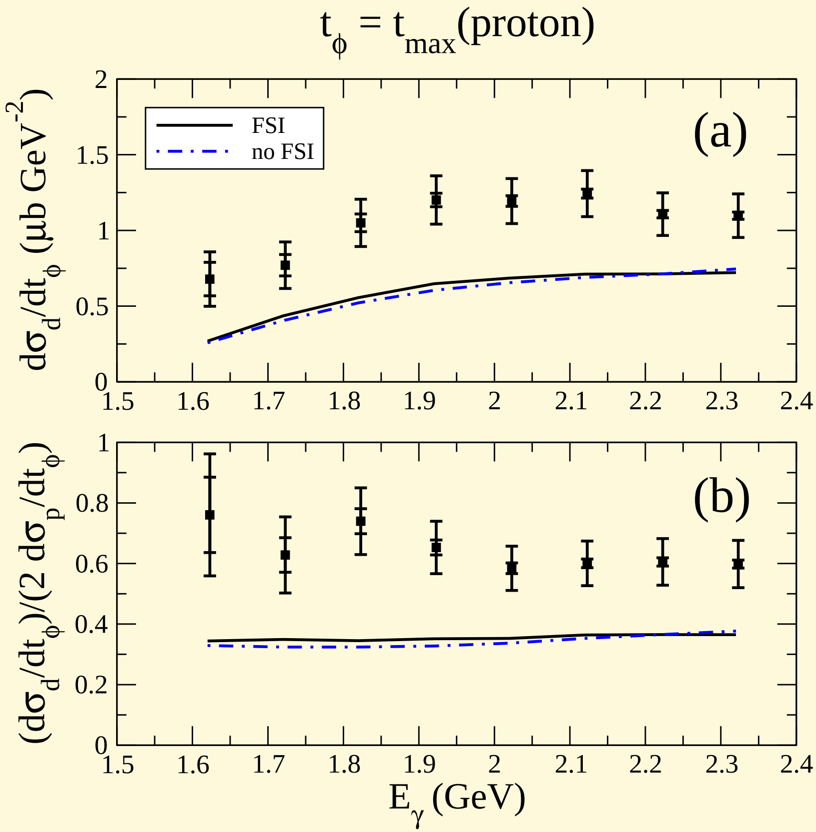
DCS of $\gamma d \to \phi p n$

Not fitted



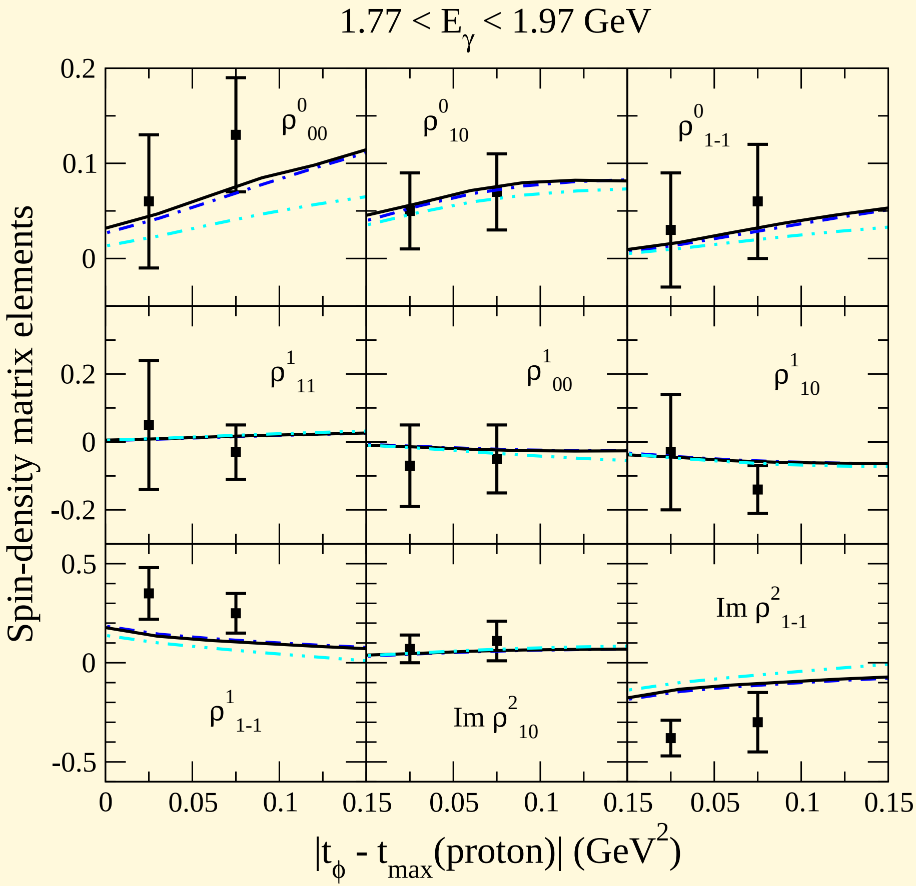
DCS of $\gamma d \to \phi p n$ and its ratio to twice DCS of $\gamma p \to \phi p$ at forward angle

Not fitted



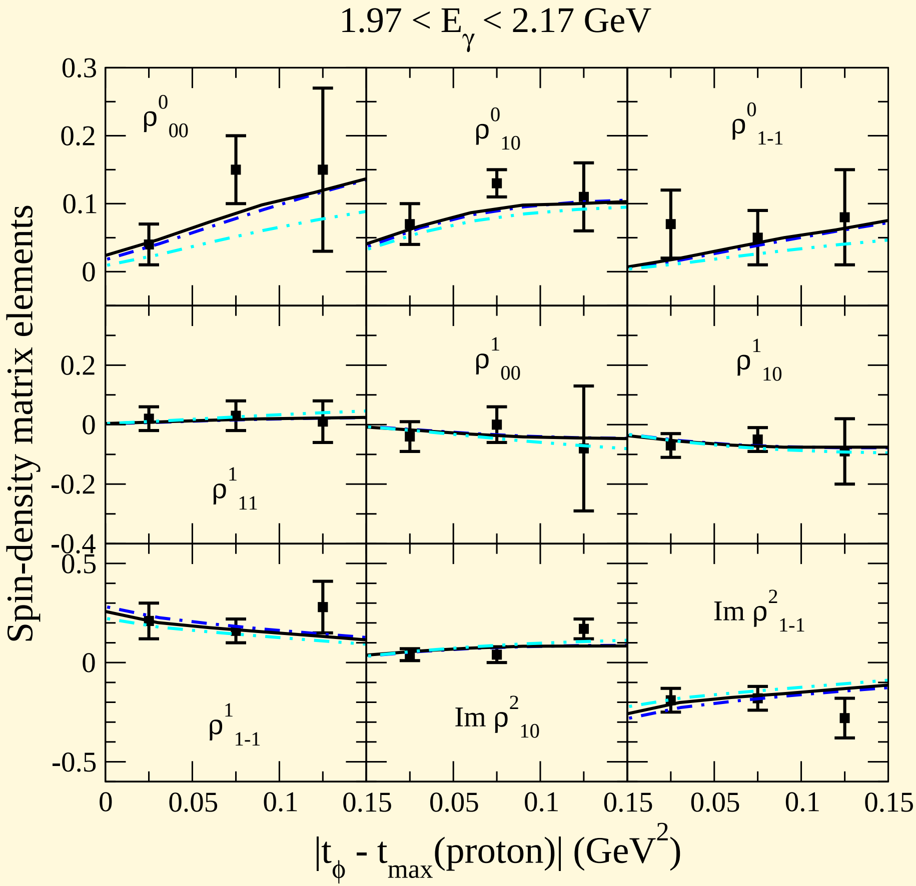
SDME of $\gamma d \to \phi p n$ as a function of t

Not fitted



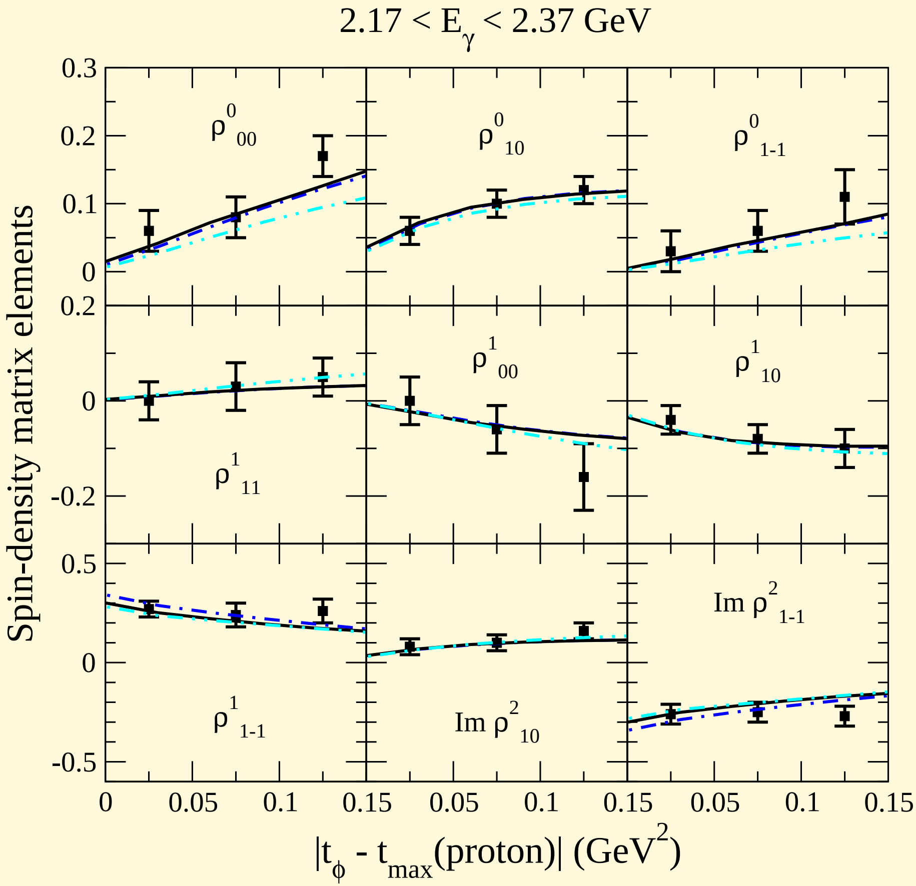
SDME of $\gamma d \rightarrow \phi p n$ as a function of t

Not fitted



SDME of $\gamma d \rightarrow \phi p n$ as a function of t

Not fitted



Summary and conclusions

- **Inclusion of a resonance is needed** to explain the **non-monotonic behavior** in the DCS $\gamma p \to \phi p$ near threshold.
- Resonance with $J = 3/2$ of either parity is preferred for $\gamma p \to \phi p$, while $J^P = 1/2^{\pm}$ cannot fit the data.
- The resonance seems to have a **considerable amount of strangeness content**.
  $\longrightarrow$ Based on a **separate study** on its effect on $\gamma p \to \omega p$.
- Agreement to the experimental data on the DCS and SDME of $\gamma d \to \phi pn$ is only quite reasonable using $J^P = 3/2^-$ resonance.
- **Fermi motion**, **final-state interaction of** pn, and **resonance effects** are found to be **large** and **important** to describe the data.

THANK YOU!

Pomeron exchange

We follow the work of **Donnachie, Landshoff, and Nachtmann**

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

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

with

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

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

A1

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

in which

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

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

$F_1(t) \rightarrow$ **isoscalar EM form-factor of the nucleon**
$F_2(t) \rightarrow$ **form-factor for the ϕ-γ-Pomeron coupling**
Pomeron trajectory $\alpha_P = 1.08 + 0.25t$.

- 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**.

Effects on $\gamma p \to \omega p$

- 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**,

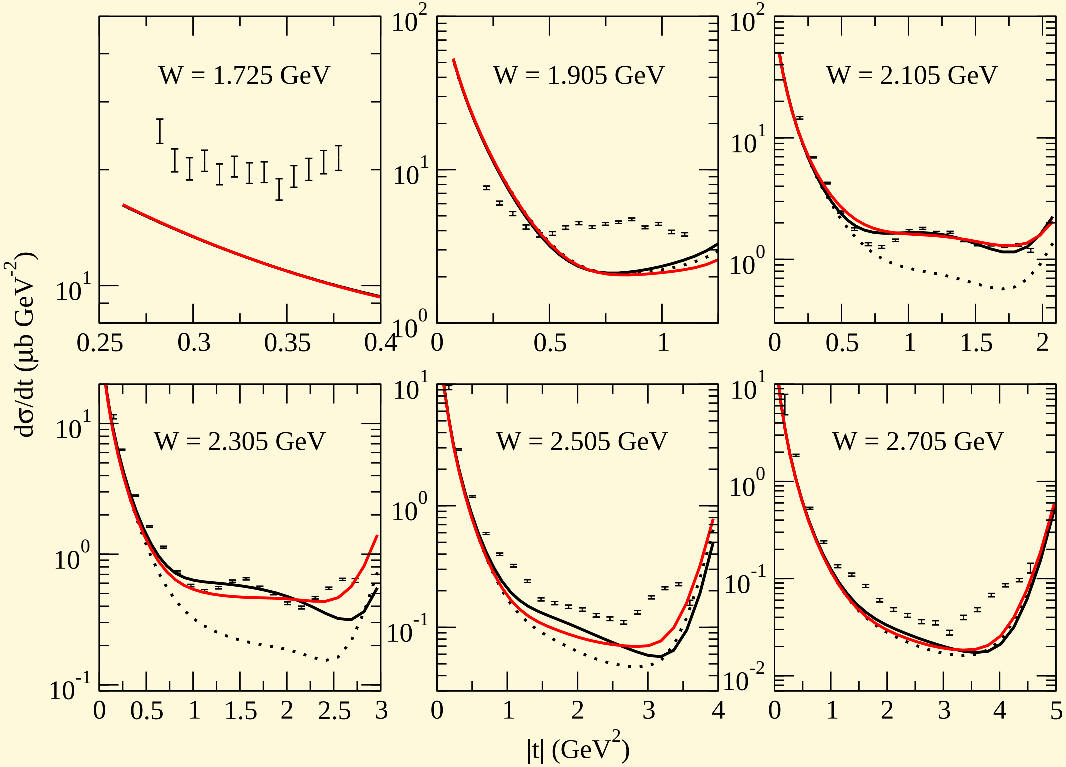
$$g_{\phi NN^*} = -\mathbf{x}_{\rm OZI} \tan\Delta\theta_V g_{\omega NN^*}$$

  where $\mathbf{x}_{\rm OZI} = \mathbf{1}$ is the **ordinary** $\phi - \omega$ **mixing**.

- 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**.
- The **large value of** $x_{\mathbf{OZI}}$ indicates that the resonance has a **considerable amount of strangeness content**.

B1

DCS of $\gamma p \to \omega p$ as a function of t



Data from M. Williams, PRC 80, 065209 (2009)

B2