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

MIN16, Kyoto University

July 2016

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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)].

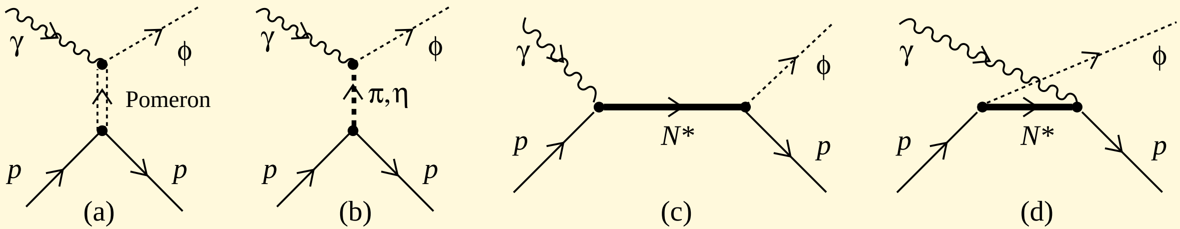
- **Conventional model of Pomeron plus π and η exchanges** usually can only give rise to a **monotonically-increasing** behavior.

- 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 $\gamma d \to \phi pn$ 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

- π **and** η **exchanges**
  For t**-channel exchange involving** π **and** η, we use **effective Lagrangian approach**.

- **Resonances**
  Only **spin** $1/2$ or $3/2$ because the **resonance is close to the threshold**.
  $\longrightarrow$ **Effective Lagrangian approach** for the **vertices**, and **Breit-Wigner** form for the **propagators**.

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

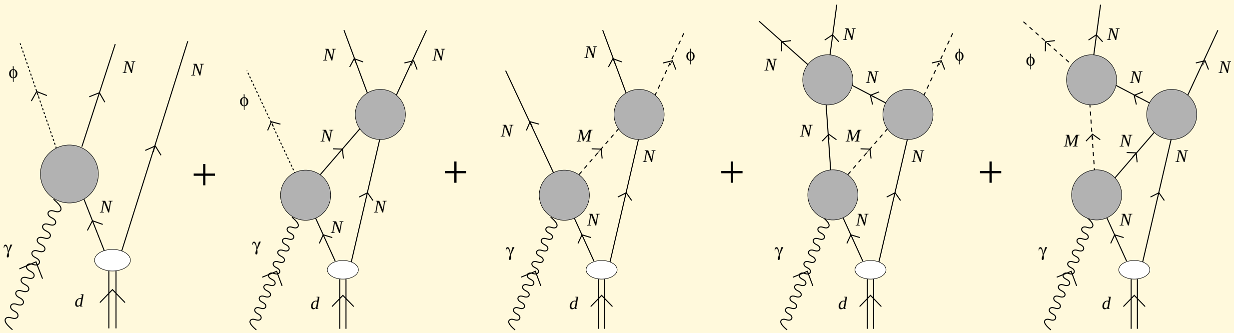
Results for $\gamma p \to \phi p$

- 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**.

	$J^P = 3/2^+$	$J^P = 3/2^-$
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

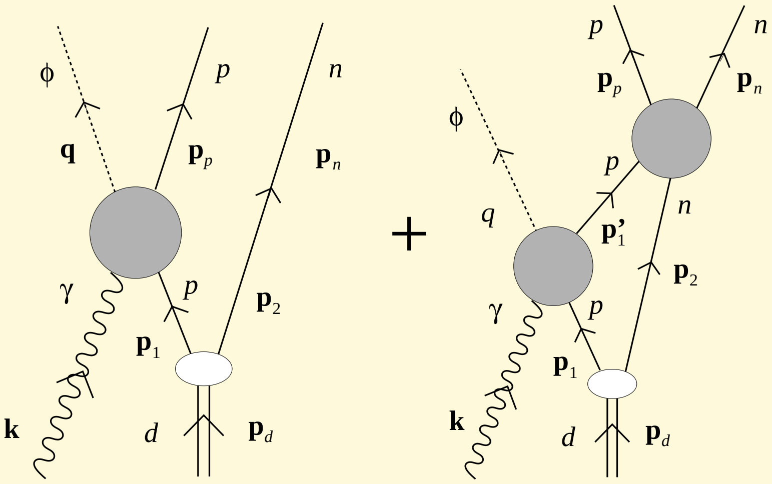
- The ratio $A_{1/2}/A_{3/2} = 1.05$ for the $J^P = 3/2^-$ resonance.
- The ratio $A_{1/2}/A_{3/2} = 0.89$ for the $J^P = 3/2^+$ resonance.

Reaction model for $\gamma d \to \phi pn$



(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**.



+ *pn* interchange

- **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.
$\longrightarrow \frac{1}{E_p+E_n-E_1'-E_2+i\epsilon} = \frac{\mathcal{P}}{E_p+E_n-E_1'-E_2} - i\pi\delta(E_p+E_n-E_1'-E_2)$

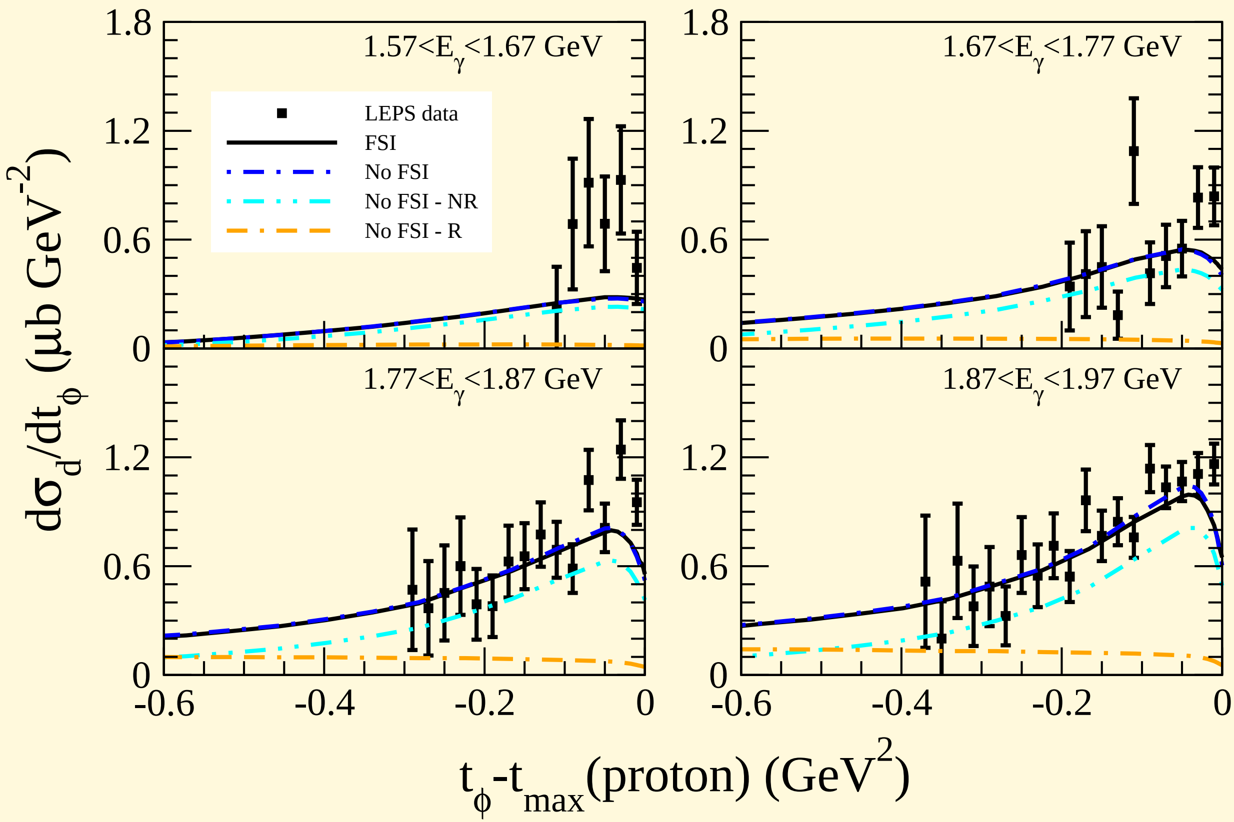
- The **same model** for the amplitude of $\gamma p \to \phi p$.
  $\longrightarrow$ **Realistic** model
  $\longrightarrow$ **Correct spin structure** is maintained
- A $J^P = 3/2^-$ **resonance** is also present in the $\gamma n \to \phi n$ amplitude
  - **For $\phi n n^*$ vertex**, ϕp and ϕn cases 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.

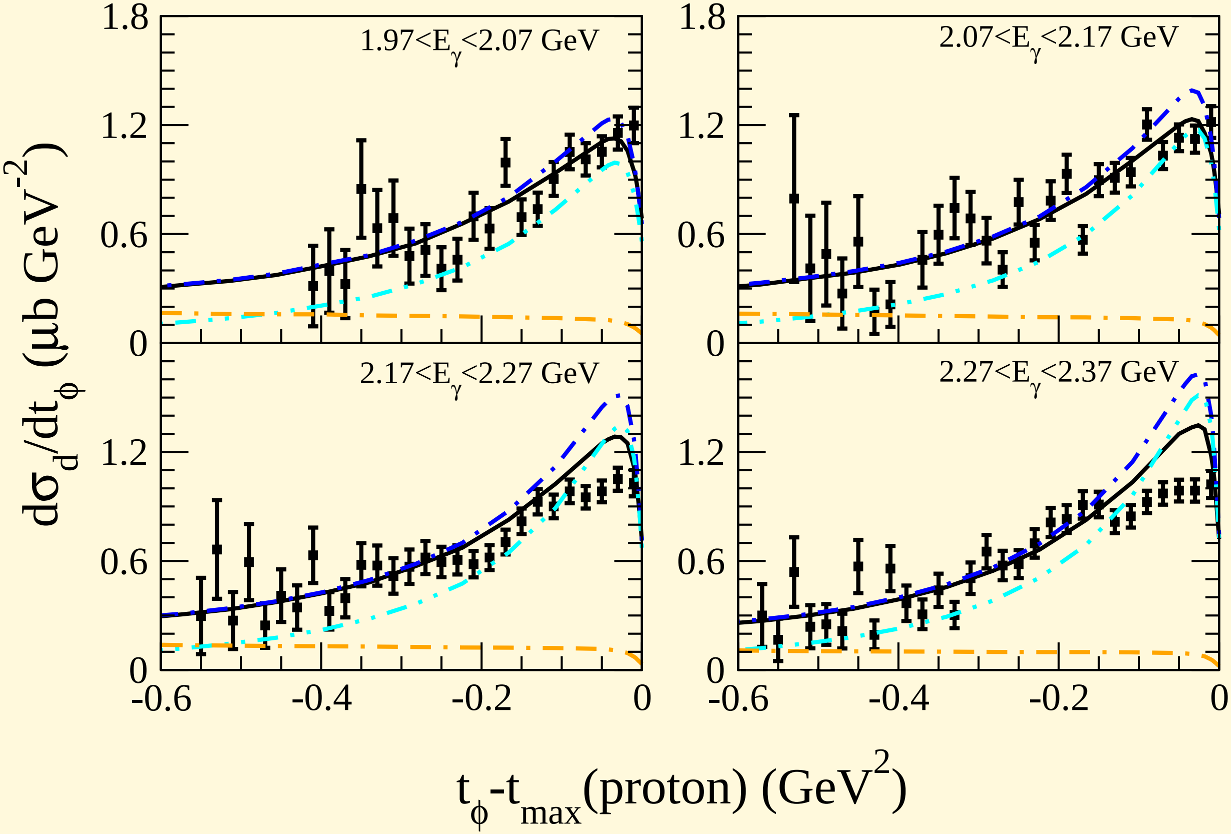
DCS of $\gamma d \to \phi pn$

Not fitted



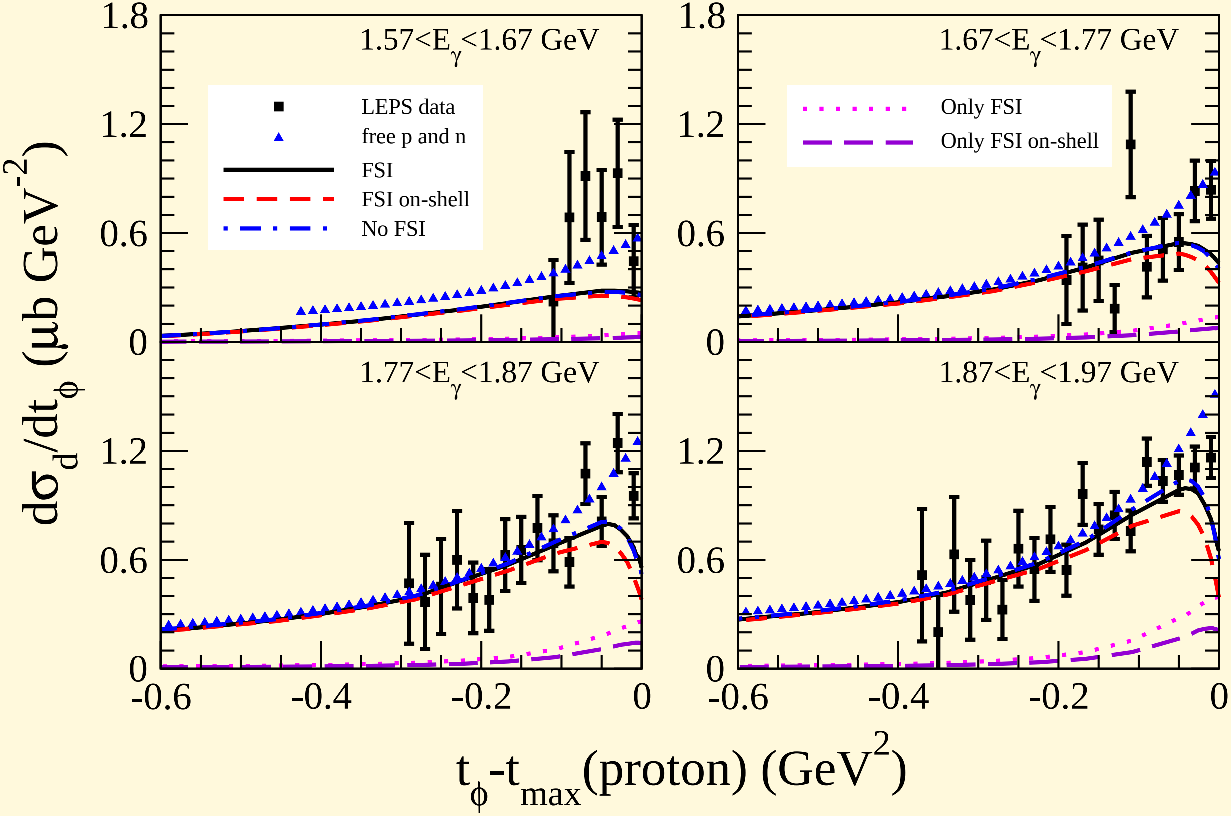
DCS of $\gamma d \to \phi pn$

Not fitted



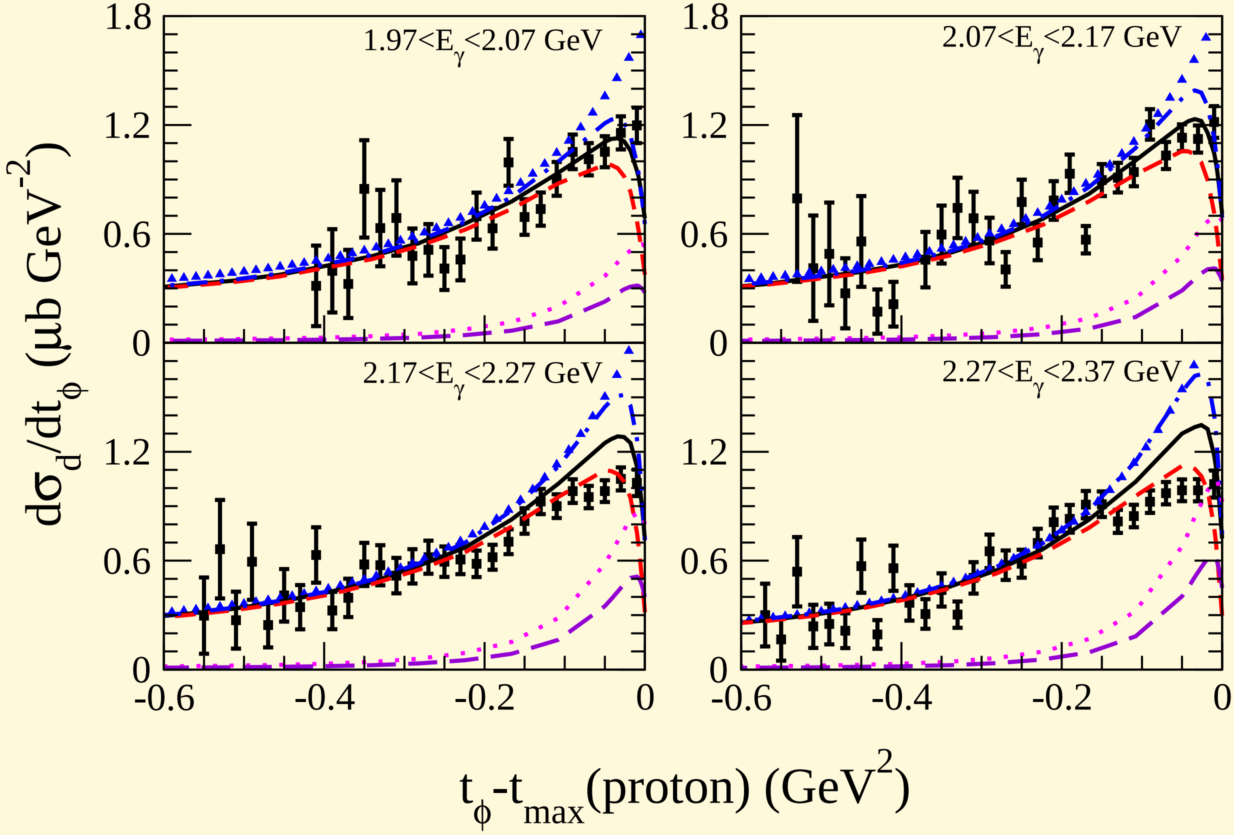
DCS of $\gamma d \to \phi p n$

Not fitted



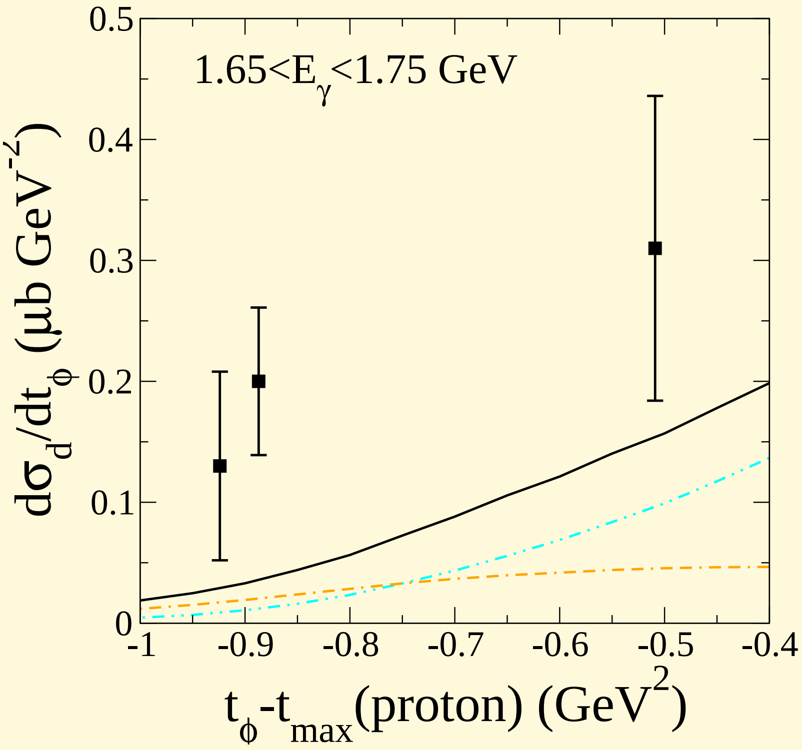
DCS of $\gamma d \to \phi pn$

Not fitted



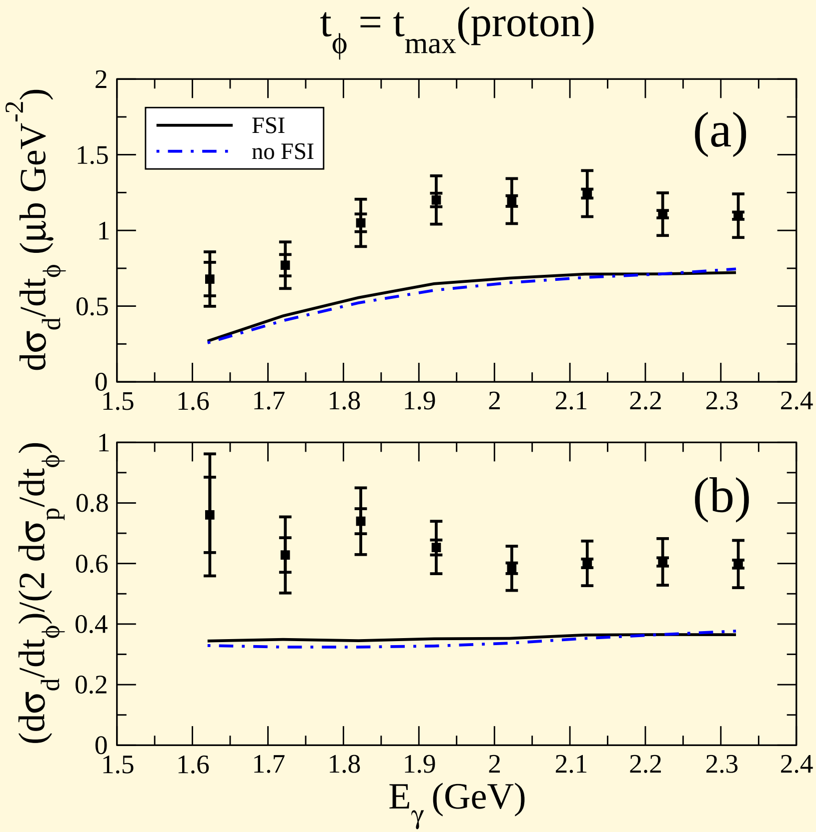
DCS of $\gamma d \to \phi p n$

Not fitted



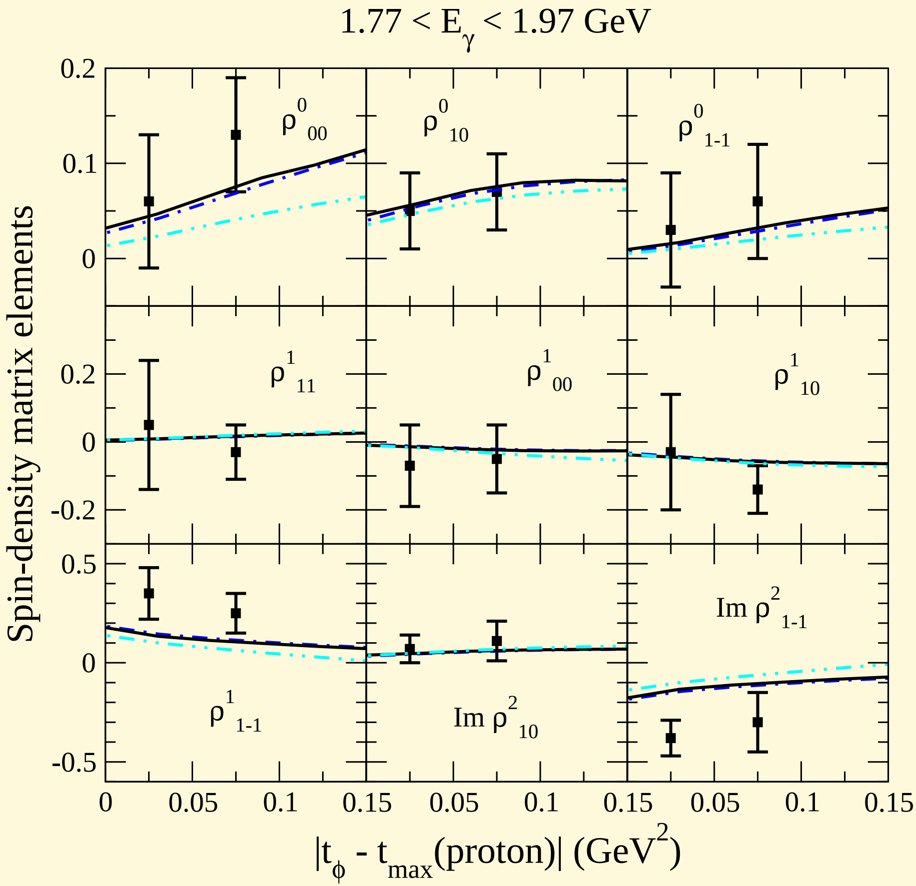
DCS of $\gamma d \to \phi p n$ and its ratio to twice DCS of $\gamma p \to \phi p$ at forward angle

Not fitted



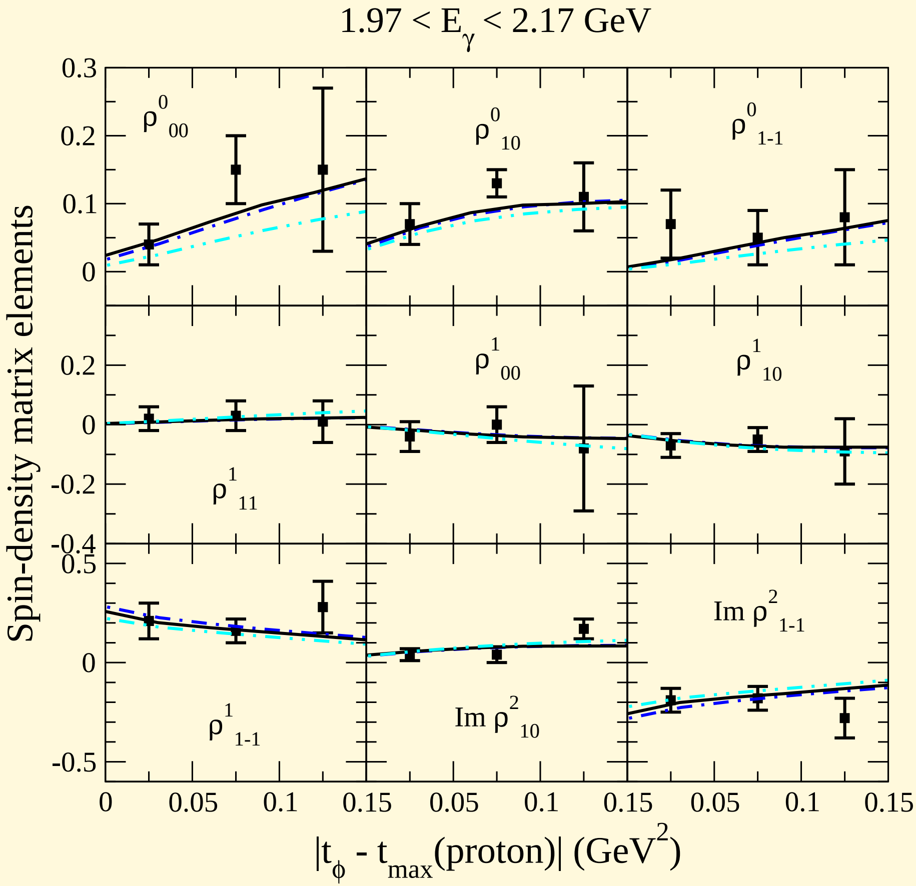
SDME of $\gamma d \to \phi p n$ as a function of t

Not fitted



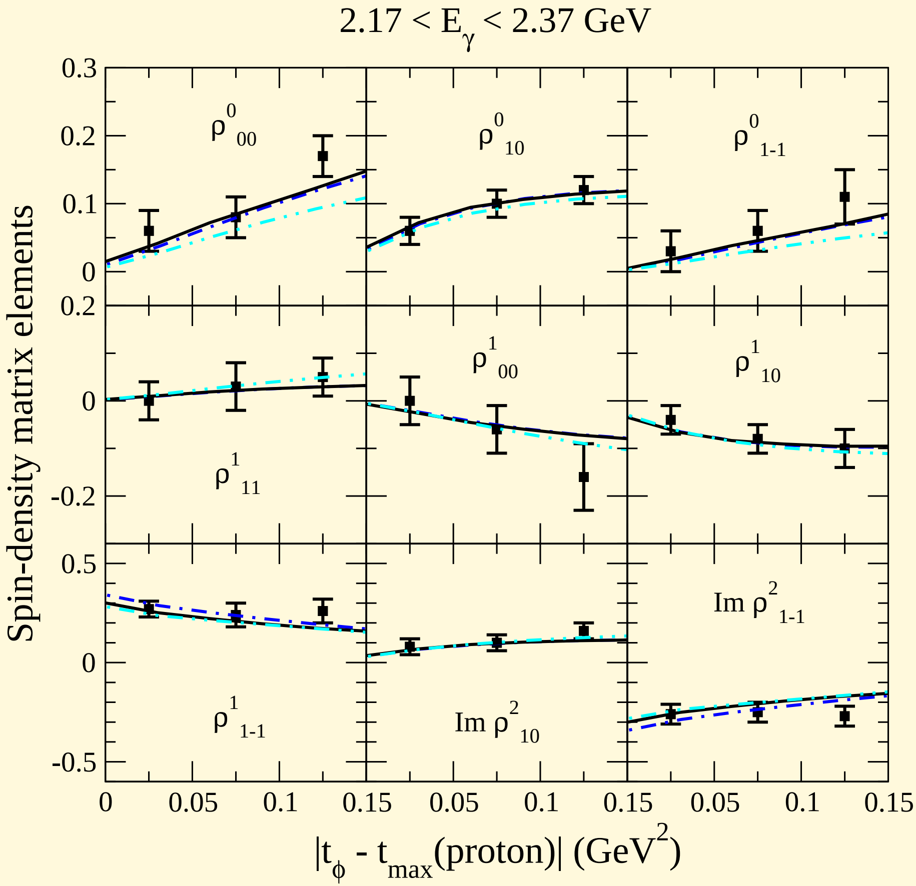
SDME of $\gamma d \to \phi p n$ as a function of t

Not fitted



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

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

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

$F_1(t) \to$ **isoscalar EM form-factor of the nucleon**
$F_2(t) \to$ **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**.

A2

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

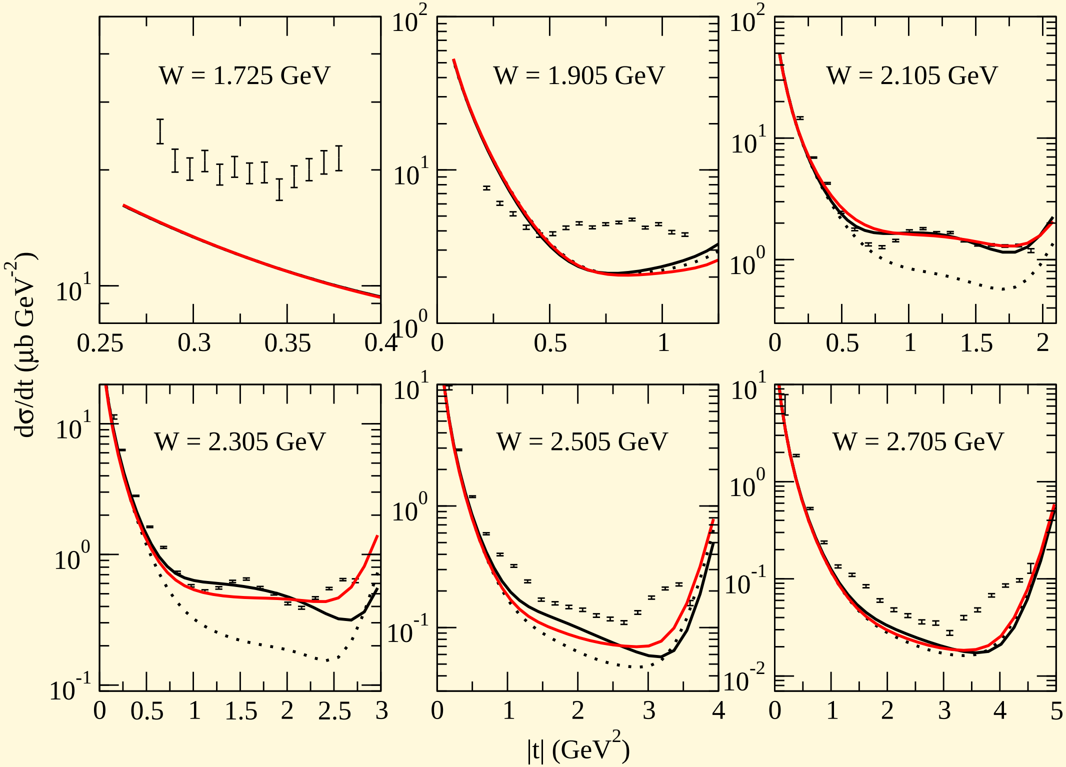
- From the $\phi - \omega$ **mixing**, we expect the resonance to also contribute to ω **photoproduction**.
- The coupling constants $g_{\phi NN^*}$ and $g_{\omega NN^*}$ are **related**, and in our study we choose to use the so-called **"minimal" parametrization**,

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

  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