Theoretical study of photoproduction of an $\eta' N$ bound state on a deuteron target with forward proton emission

Takayasu SEKIHARA (JAEA)

in collaboration with

Daisuke JIDO (Tokyo Metropolitan Univ.)

Shuntaro SAKAI (RCNP, Osaka Univ.)

---

1. Introduction
2. Formulation
3. Results and discussions
4. Summary

---

[1] T. S. , D. Jido and S. Sakai, *Phys. Rev.* C (2016), in press [arXiv:1604.03634 [nucl-th]].

1. Introduction

++ The properties of the η' meson ++

η'(958) $I^G(J^{PC}) = 0^+(0^{-+})$

η'

Mass $m = 957.78 \pm 0.06$ MeV
Full width $\Gamma = 0.198 \pm 0.009$ MeV

η'(958) DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi^+\pi^-\eta$	(42.9 ±0.7) %		232
$\rho^0\gamma$ (including non-resonant $\pi^+\pi^-\gamma$)	(29.1 ±0.5) %		165
$\pi^0\pi^0\eta$	(22.2 ±0.8) %		239
$\omega\gamma$	(2.75±0.23) %		159
$\gamma\gamma$	(2.20±0.08) %		479
$3\pi^0$	(2.14±0.20) × 10^{-3}		430

Particle Data Group.

- **Large mass** compared to the lowest pseudo-scalar meson octet, (π, *K*, η).

--- ***U***

--- $U_A(1)$ **problem**: Where has the 9th NG boson gone ?

Weinberg (1975).

- The $U_A(1)$ problem can be solved by **instantons** (non-trivial classical solutions of EOM) through the $U_A(1)$ anomaly.

't Hooft (1976); Witten (1979); Veneziano (1979).

- The η' meson has **a direct connection to the dynamics of QCD**.

1. Introduction

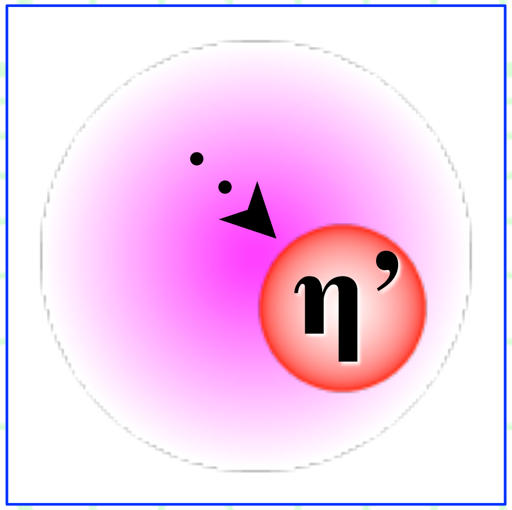
++ The properties of the η' meson ++

- There are **several approaches** to investigate the η' properties.
  - ◻ Behavior of the η' meson **in vacuum**.

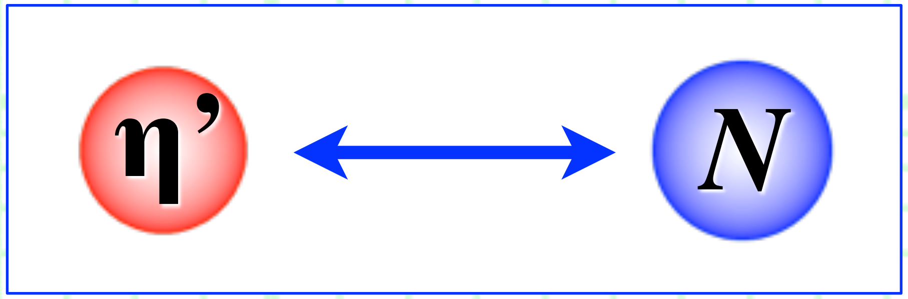
  --- Decay modes, mixings, ...

  - ◻ Behavior of the η' meson **in medium**.

  --- Finite temperatures, **finite nuclear densities**.



  - ◻ **The interaction between η' and *N*.**



  - ◻ "Numerical experiments" for the η' meson on a lattice.

1. Introduction

++ The η' N interaction ++

- So far, **the interaction between η' and N is not well known**.

--- We do not know even whether it is attractive or repulsive.

- Recently, based on the linear sigma model, the η' N interaction was studied. Sakai and Jido, *Phys. Rev.* C88 (2013) 064906; arXiv:1607.07116 [nucl-th].

9

Lagrangian of linear sigma model

J.Schechter,Y.Ueda,Phys.Rev.D3,168(1971).
J.T.Renaghan, et al. PRD62,085008(2000).

$$\mathcal{L} = \frac{1}{2}\mathrm{tr}(\partial_\mu M \partial^\mu M^\dagger) - \frac{\mu^2}{2}\mathrm{tr}(MM^\dagger) - \frac{\lambda}{4}\mathrm{tr}\left[(MM^\dagger)^2\right] - \frac{\lambda'}{4}\left[\mathrm{tr}(MM^\dagger)\right]^2 + A\mathrm{tr}\chi M^\dagger + \sqrt{3}B\det M + \mathrm{h.c.}$$

The effect from the current quark mass

$U_A(1)$ anomaly effect

$$+\bar{N}i\partial\!\!\!/ N - g\bar{N}\left(\frac{1}{\sqrt{3}}\sigma_0 + \frac{1}{\sqrt{6}}\sigma_8 + i\gamma_5\frac{\vec{\tau}\cdot\vec{\pi}}{\sqrt{2}} + i\gamma_5\frac{1}{\sqrt{3}}\eta_0 + i\gamma_5\frac{1}{\sqrt{6}}\eta_8\right)N$$

Contribution from nucleon

$$M = \sum_{a=0}^{8}\frac{\sigma_a\lambda_a}{\sqrt{2}} + i\sum_{a=0}^{8}\frac{\pi_a\lambda_a}{\sqrt{2}} \qquad N = \begin{pmatrix} p \\ n \end{pmatrix} \qquad \chi = \sqrt{3}\begin{pmatrix} m_u & & \\ & m_d & \\ & & m_s \end{pmatrix} = \begin{pmatrix} m_q & & \\ & m_q & \\ & & m_s \end{pmatrix}$$

(λ_a:Gell-Mann matrix, τ_i:Pauli matrix)

Taken from talk in ELPH workshop C008 given by S. Sakai.

- A large part of the η' mass is **generated by the spontaneous breaking of chiral symmetry** through the $U_A(1)$ anomaly.

S. H. Lee and T. Hatsuda (1996); T. D. Cohen (1996).

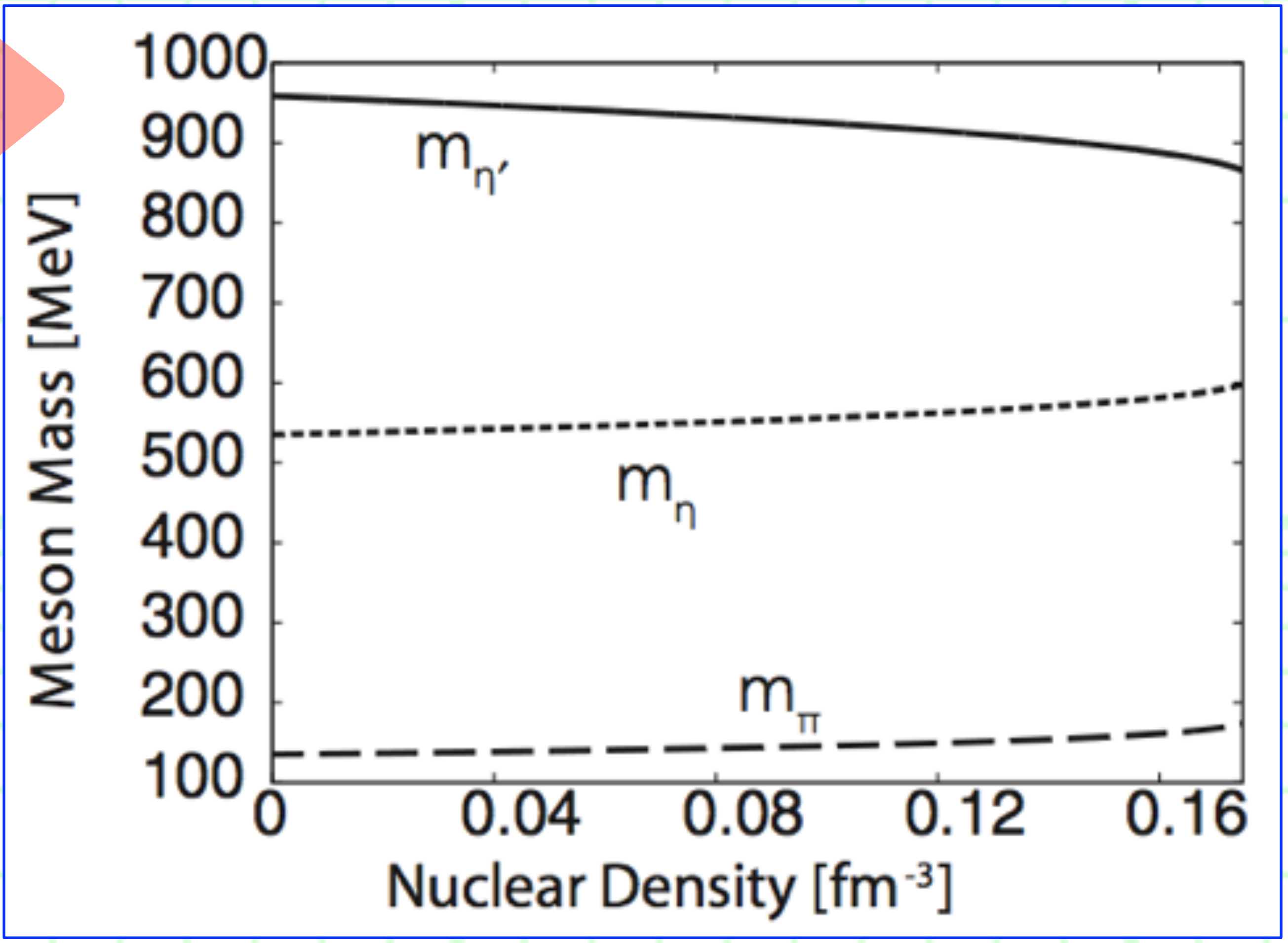
1. Introduction

++ The η' *N* interaction ++

- So far, the interaction between η' and *N* is not well known.

--- We do not know even whether it is attractive or repulsive.

- Recently, based on the linear sigma model, the η' *N* interaction was studied. Sakai and Jido, *Phys. Rev.* C88 (2013) 064906; arXiv:1607.07116 [nucl-th].



- Since the mass is generated by the spontaneous breaking of the chiral symmetry, the mass is reduced in nuclear matter, where the chiral symmetry is partially restored:

$\Delta m_{\eta'} \sim$ -- 80 MeV at $\rho = \rho_0$.

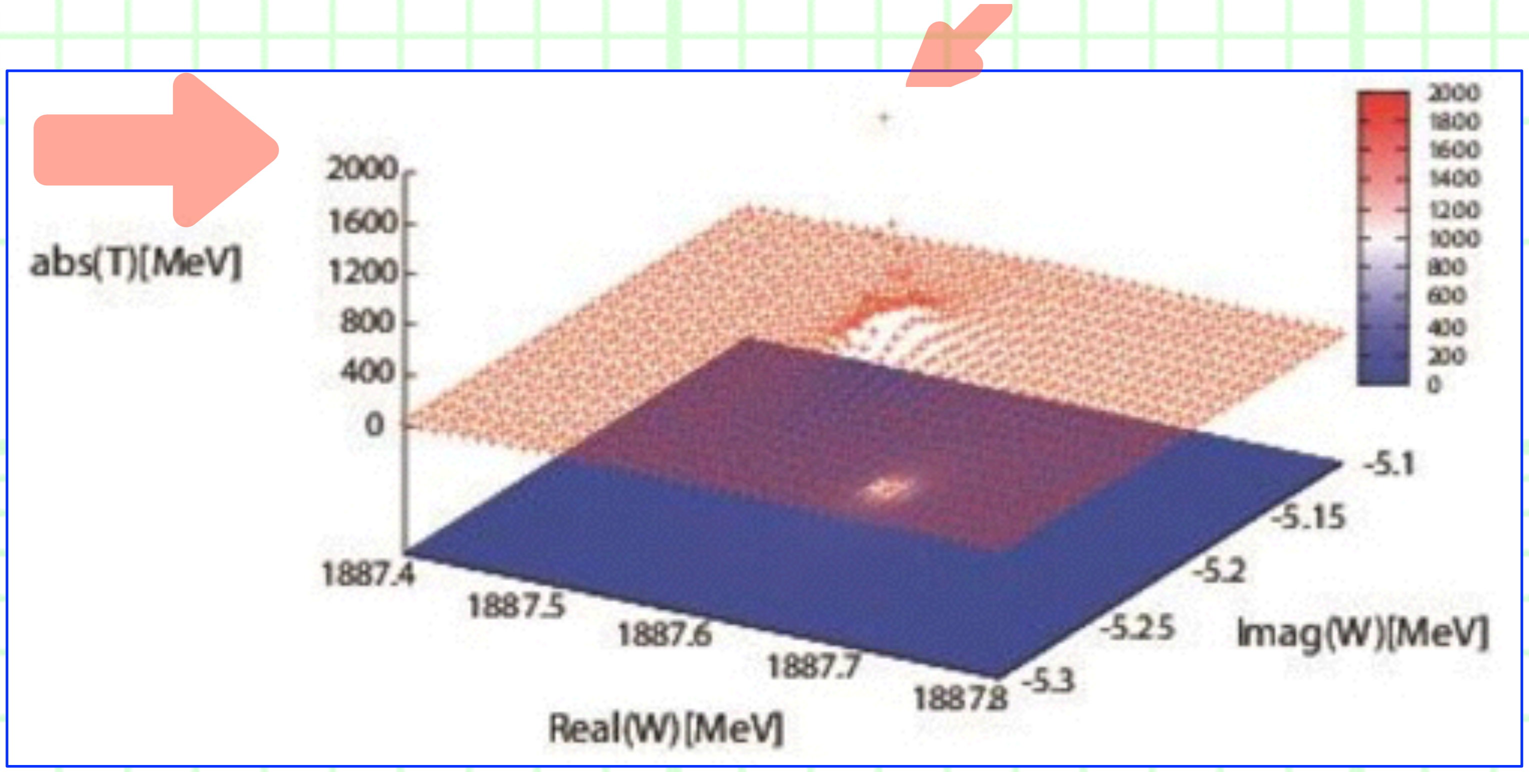
1. Introduction

++ The η’ *N* interaction ++

- So far, the interaction between η’ and *N* is not well known.

--- We do not know even whether it is attractive or repulsive.

- Recently, based on the linear sigma model, the η’ *N* interaction was studied. Sakai and Jido, *Phys. Rev.* C88 (2013) 064906; arXiv:1607.07116 [nucl-th].



Taken from talk in ELPH workshop C008 given by S. Sakai.

- Mass modification is represented by self-energy, which can be translated into a potential between two particles.

--- Indeed, in this model, the attraction between η’ *N* is sufficiently attractive to generate an η’ *N* bound state ($B_E \sim 10$ MeV).

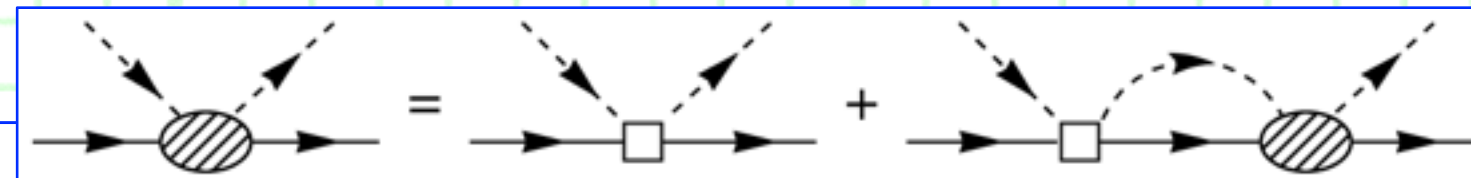
1. Introduction

++ The η' N interaction ++

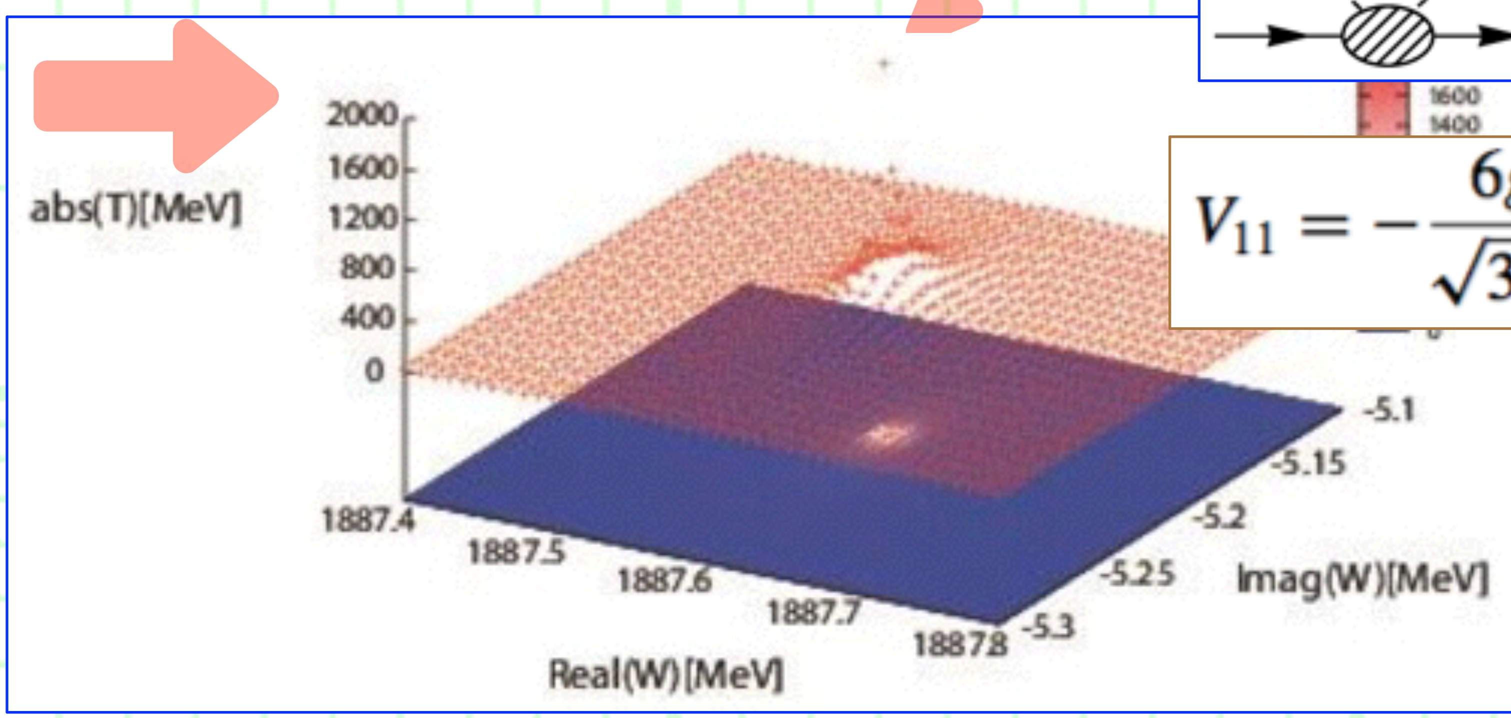
- So far, **the interaction between η' and N is not well known**.

--- We do not know even whether it is attractive or repulsive.

- Recently, based on the linear sigma model, the η' N interaction was studied. Sakai and Jido, *Phys. Rev.* C88 (2013) 064906; arXiv:1607.07116 [nucl-th].



$$V_{11} = -\frac{6gB}{\sqrt{3}m_{\sigma 0}^2}, \quad V_{12} = V_{21} = +\frac{6gB}{\sqrt{6}m_{\sigma 8}^2}, \quad V_{22} = 0,$$



Taken from talk in ELPH workshop C008 given by S. Sakai.

- The present formulation gives **the pole position: 1889.5 -- 6.3 i MeV**. ($B_E \sim 8$ MeV, $\Gamma \sim 13$ MeV).

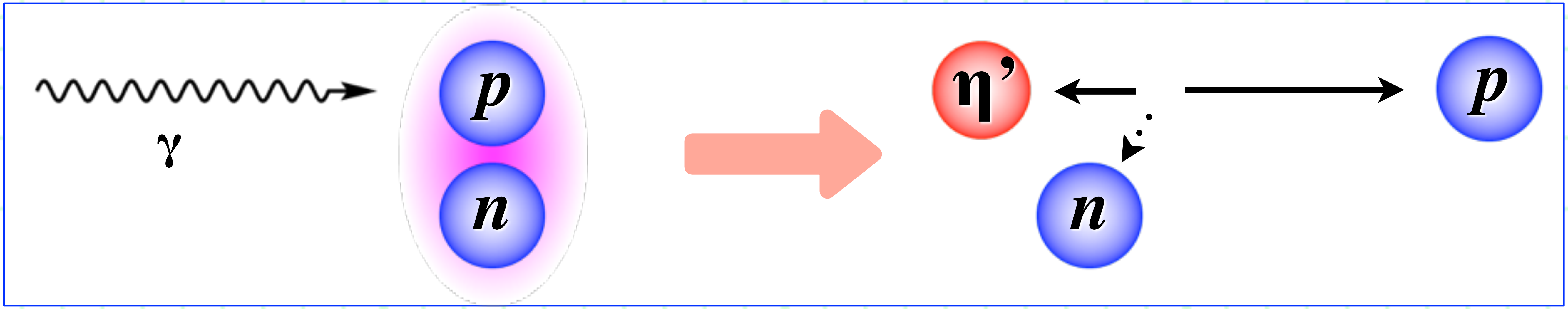
1. Introduction

++ Motivation ++

- Such an η' *N* bound state, if it exists, may be observed in Exps.

--- Which reactions ?

- The photoproduction of η(') on a deuteron with forward proton emission will be suited for the observation.



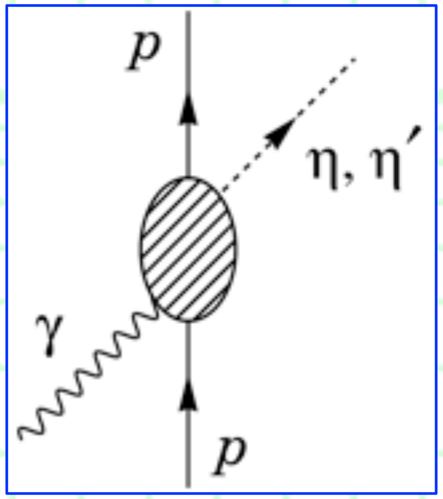
- □ The forward proton emission gives a good kinematical condition for the production of the η' *N* bound system.
- □ This reaction can be observed in LEPS(2) experiments.
- □ It may also contain some clue to the η' *N* interaction.

--> Against the quasi-free η' , can we really observe the signal ?

2. Formulation

++ $\gamma\, p \to \eta\, p$ and $\eta'\, p$ reactions ++

- We first consider the free proton $\gamma\, p \to \eta\, p$ and $\eta'\, p$ reactions as an elementary part of the photoproduction on a deuteron target.



□ The cross section can be expressed as:

$$\frac{d\sigma_{\gamma p \to mp}}{d\Omega} = \frac{p'_{\rm cm} M_p}{16\pi^2 E_\gamma^{\rm lab} W_2} |T_{\gamma p \to mp}|^2, \quad m = \eta,\ \eta'$$

--- $E_\gamma^{\rm lab}$: Initial photon energy in the Lab. frame,
Ω: CM solid angle for the final proton momentum,
$p_{\rm cm}'$: CM momentum of the final proton,
W_2: CM energy of the system,
$T_{\gamma p \to m p}$: The $\gamma\, p \to m\, p$ ($m = \eta, \eta'$) scattering amplitude.

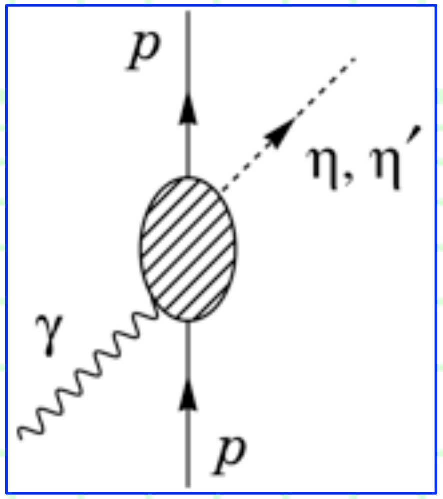
□ Only the $\gamma\, p \to m\, p$ scattering amplitude $T_{\gamma p \to m p}$ is unknown.

2. Formulation

++ $\gamma\, p$ --> $\eta\, p$ and $\eta'\, p$ reactions ++

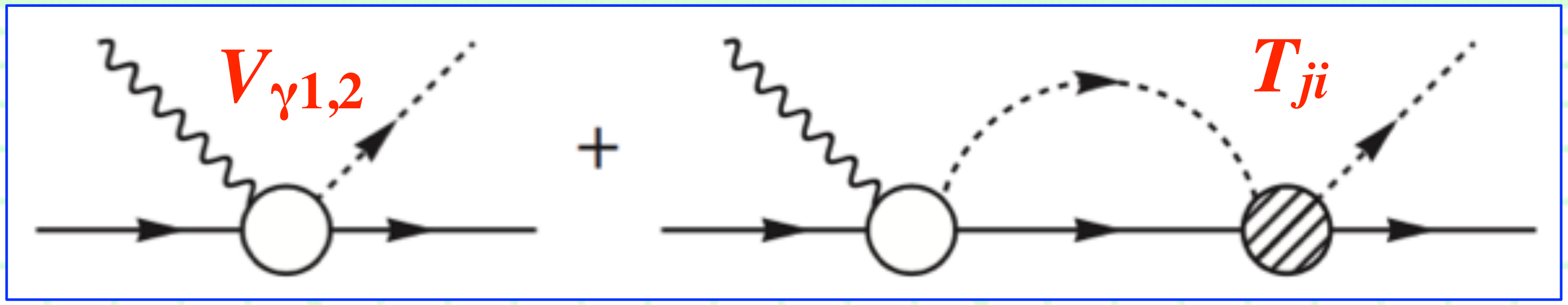
- We first consider the free proton $\gamma\, p$ --> $\eta\, p$ and $\eta'\, p$ reactions as an elementary part of the photoproduction on a deuteron target.

  - In this study we are interested in the ratio of the signal of the $\eta'\, n$ bound state to the quasi-free η' production contribution.



--> We need only a "rough" scattering amplitude for the $\gamma\, p$ --> $m\, p$ reaction, $T_{\gamma p \to m p}$, since the magnitude of the amplitude is irrelevant to the ratio of signal to quasi-free.

$$T_{\gamma p \to i} = V_{\gamma i} + \sum_{j=1}^{2} V_{\gamma j} G_j T_{ji}$$



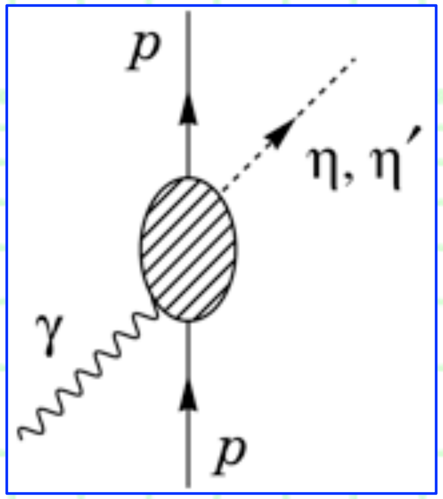
- $V_{\gamma 1,2}$: constants as model parameters to reproduce data.
- T_{ji} : $\eta^{(\prime)}\, p$ --> $\eta^{(\prime)}\, p$ Amp. taken from linear sigma model.

Sakai and Jido, *Phys. Rev.* C88 (2013).

2. Formulation

++ $\gamma\, p$ --> $\eta\, p$ and $\eta'\, p$ reactions ++

- We first consider **the free proton $\gamma\, p \to \eta\, p$ and $\eta'\, p$ reactions** as an elementary part of the photoproduction on a deuteron target.

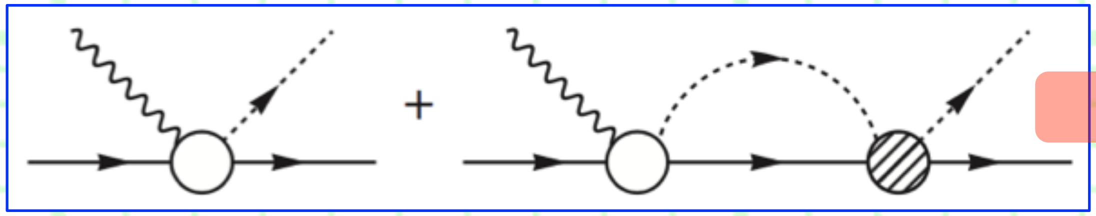


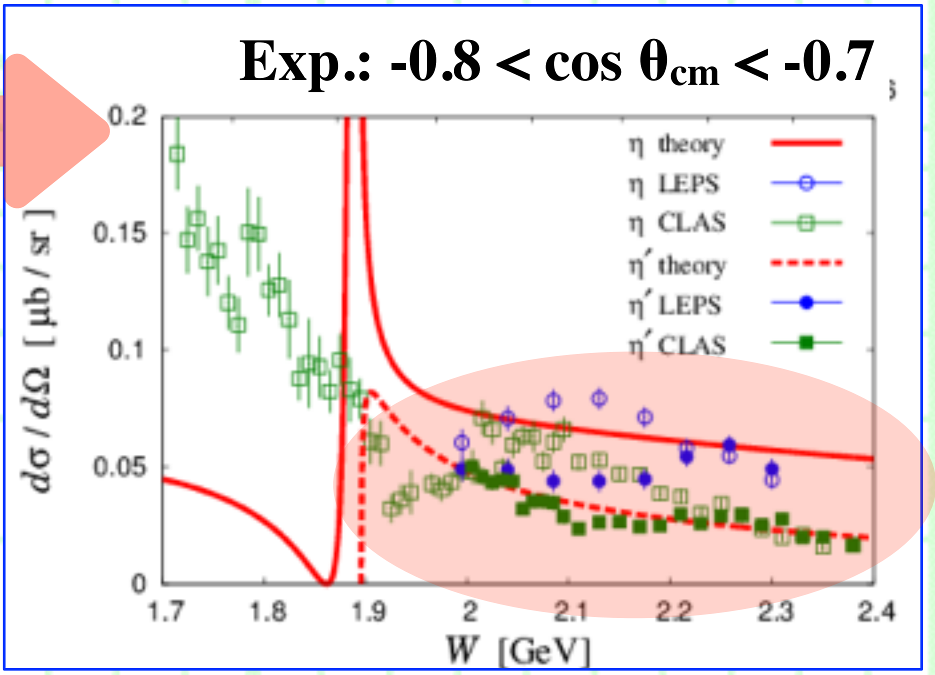
- □ In this study we are interested in **the ratio** of **the signal of the $\eta'\, n$ bound state** to the quasi-free η' production contribution.

--> We need only **a "rough" scattering amplitude** for the $\gamma\, p \to m\, p$ reaction, $T_{\gamma p \to m p}$, since the magnitude of the amplitude is irrelevant to the ratio of signal to quasi-free.

Williams *et al.* (2009); Sumihama *et al.* (2009).

$$T_{\gamma p \to i} = V_{\gamma i} + \sum_{j=1}^{2} V_{\gamma j} G_j T_{ji}$$





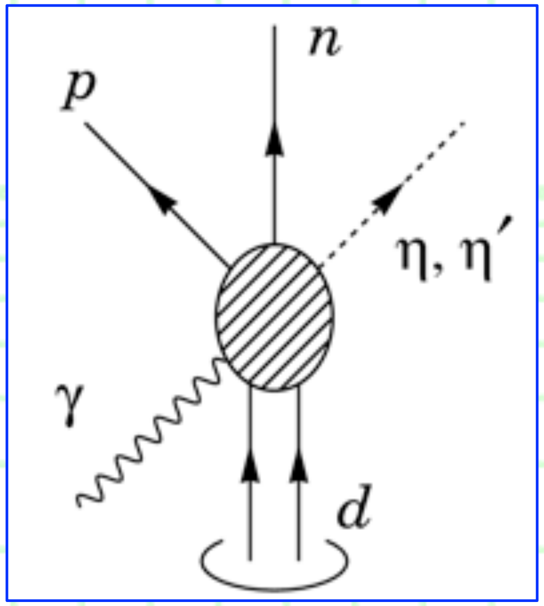
- □ We fix **two constants $V_{\gamma 1,2}$** to reproduce roughly the LEPS & CLAS data.

--- We also neglect angular dependence since we take forward proton emission.

2. Formulation

++ $\gamma\, d \to p\, X$ reaction with $X = \eta\, n, \eta'\, n$ ++

- Next we consider **the $\gamma\, d \to p\, X$ reaction** with $X = \eta\, n, \eta'\, n$ on a deuteron target.



- The cross section can be expressed as:

$$\frac{d^2\sigma_{\gamma d \to pX}}{dM_X d\Omega_p} = \frac{p_p p_m^* M_p M_n}{4E_\gamma^{\text{lab}} W_3} \frac{1}{(2\pi)^5} \int d\Omega_n^* |T_{\gamma d \to pX}|^2$$

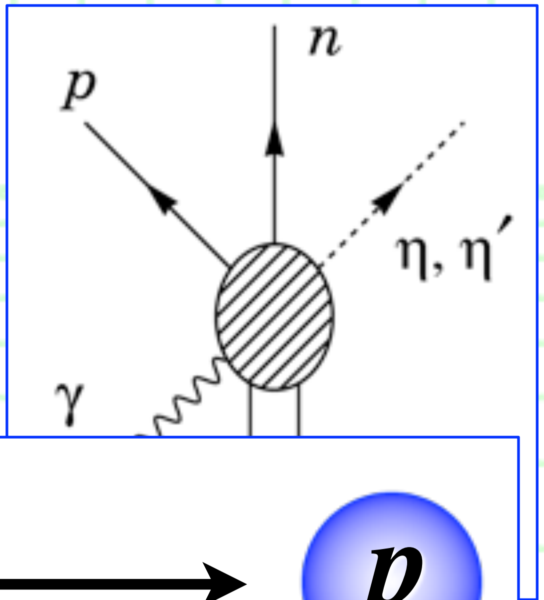
--- M_X: Invariant mass of the final $X = m$-n system,
Ωp: Total-CM solid angle for the final proton,
p_p: Total-CM momentum of the final proton,
Ωn^*: Solid angle for the final neutron in the m-n CM frame,
p_m^*: Momentum of the final neutron in the m-n CM frame,
W_3: Total-CM energy of the system,
$T_{\gamma d \to p X}$: the $\gamma\, d \to p\, X$ ($X = \eta\, n, \eta'\, n$) scattering amplitude.

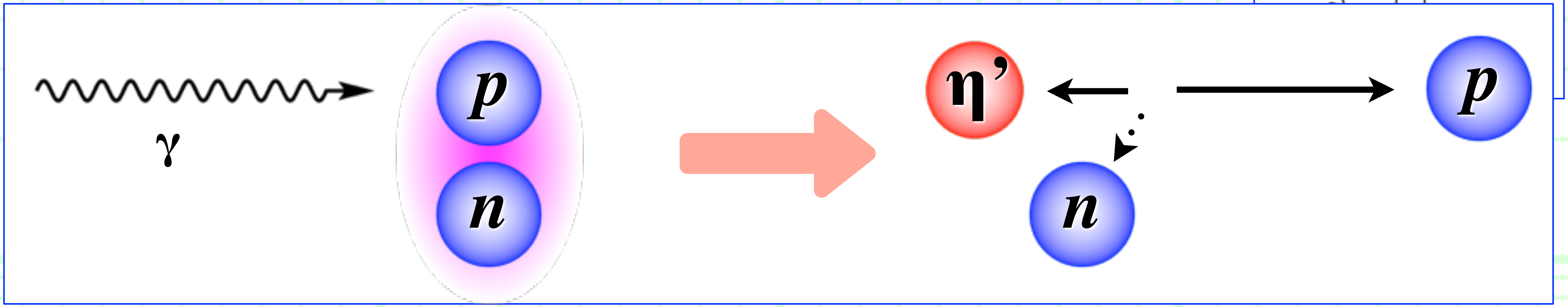
- Again only the $\gamma\, d \to p\, X$ scattering amp. $T_{\gamma d \to p X}$ is unknown.

2. Formulation

++ $\gamma\ d$ --> $p\ X$ reaction with $X = \eta\ n, \eta'\ n$ ++

- Next we consider **the $\gamma\ d$ --> $p\ X$ reaction** with $X = \eta\ n, \eta'\ n$ on a deuteron target.
  - In this study we calculate the $\gamma\ d$ --> $p\ X$ amp. from **diagrams favored by the kinematics** of **the forward fast proton emission**.



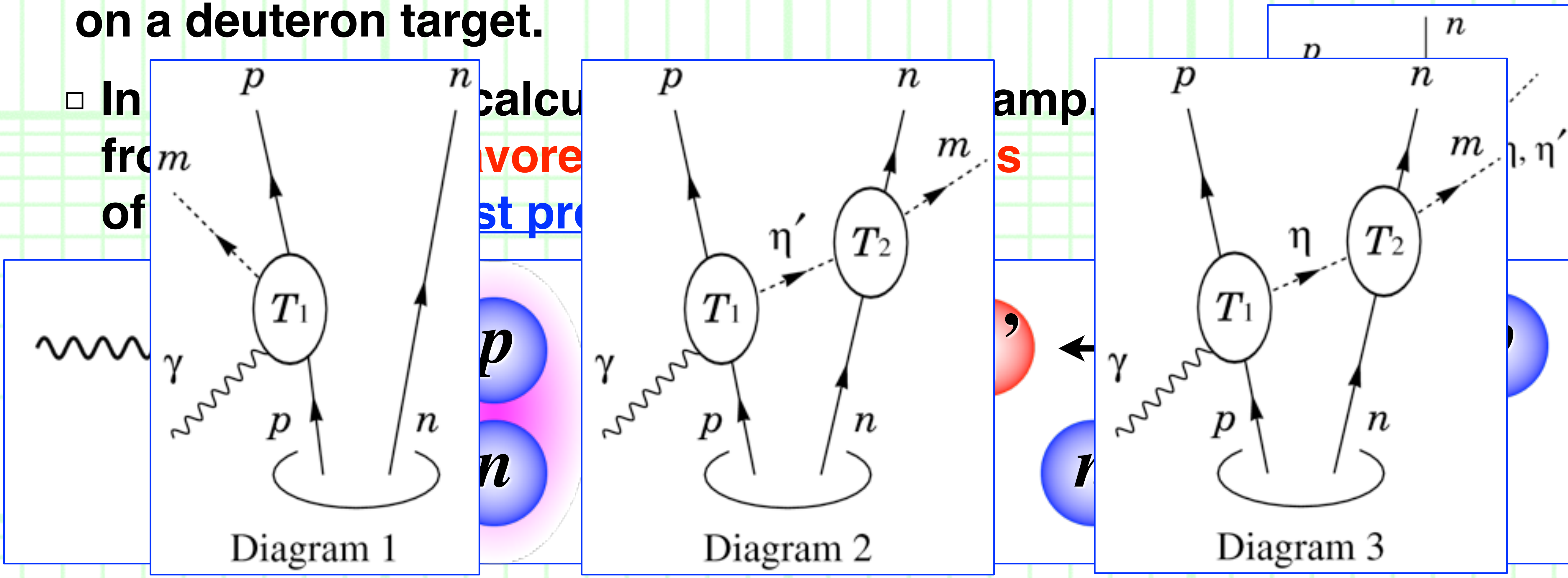


--- 1. **Single scattering on a bound proton.**
2. **Double scattering with $\eta'\ n$ --> X transition** --- η' exchange.
3. Double scattering with $\eta\ n$ --> X transition --- η exchange.

2. Formulation

++ $\gamma\, d$ --> $p\, X$ reaction with $X = \eta\, n, \eta'\, n$ ++

- Next we consider **the $\gamma\, d$ --> $p\, X$ reaction** with $X = \eta\, n, \eta'\, n$ on a deuteron target.
  - In ... calcu ... amp. fro ... vore ... s of ... st pr ...

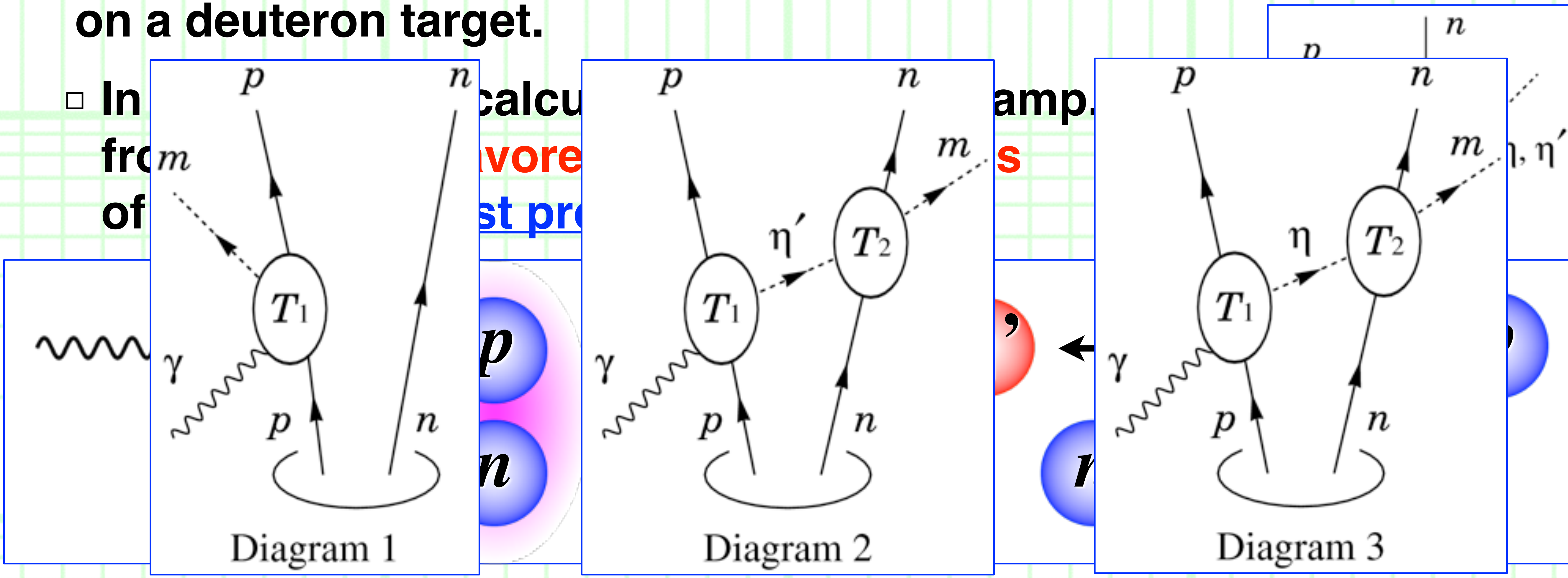


--- 1. **Single scattering on a bound proton.**
2. **Double scattering with $\eta'\, n$ --> X transition** --- η' exchange.
3. Double scattering with $\eta\, n$ --> X transition --- η exchange.

2. Formulation

++ $\gamma\, d$ --> $p\, X$ reaction with $X = \eta\, n, \eta'\, n$ ++

- Next we consider **the $\gamma\, d$ --> $p\, X$ reaction** with $X = \eta\, n, \eta'\, n$ on a deuteron target.
  - In ... calcu ... amp. fro ... vore ... s of ... st pro



× We do **not consider scatterings on a bound neutron**, which will lead to forward fast neutron in the final state and gives only small momentum to the final proton.

2. Formulation

++ $\gamma\, d$ --> $p\, X$ reaction with $X = \eta\, n, \eta'\, n$ ++

- Next we consider **the $\gamma\, d$ --> $p\, X$ reaction** with $X = \eta\, n, \eta'\, n$ on a deuteron target.
  - **Scattering amplitudes from these diagrams** are obtained as: D. Jido, E. Oset and T. S. (2009); (2013).

$$T_{\gamma d \to pX} = \mathcal{T}_1^{(m)} + \mathcal{T}_2^{(m)} + \mathcal{T}_3^{(m)}$$

$$\mathcal{T}_1^{(m)} = T_{\gamma p \to mp} \times \tilde{\varphi}(\vec{p}_n)$$

$$\mathcal{T}_2^{(m)} = T_{\gamma p \to \eta' p} T_{\eta' n \to X}(M_X) \int \frac{d^3 q}{(2\pi)^3} \frac{\tilde{\varphi}(\vec{q} + \vec{p}_p - \vec{k})}{q^2 - M_{\eta'}^2 + i\epsilon}$$

$$q^0 = M_d + E_\gamma^{\rm lab} - p_p^0 - M_n - \frac{|\vec{q} + \vec{p}_p - \vec{k}|^2}{2M_n}$$

$$\mathcal{T}_3^{(m)} = T_{\gamma p \to \eta p} T_{\eta n \to X}(M_X) \int \frac{d^3 q}{(2\pi)^3} \frac{\tilde{\varphi}(\vec{q} + \vec{p}_p - \vec{k})}{q^2 - M_{\eta}^2 + i\epsilon}$$

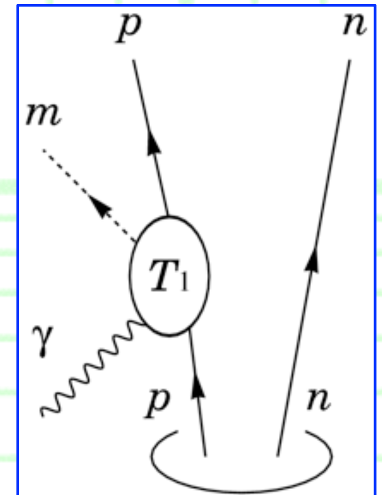


Diagram 1

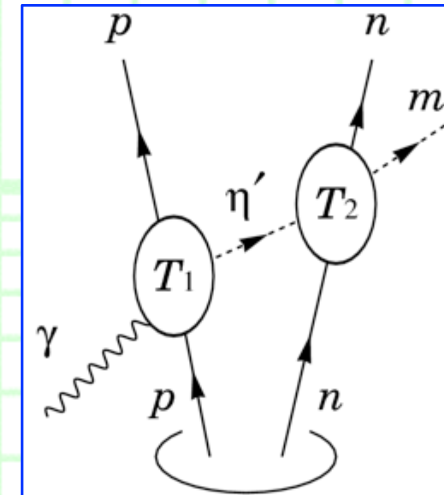


Diagram 2

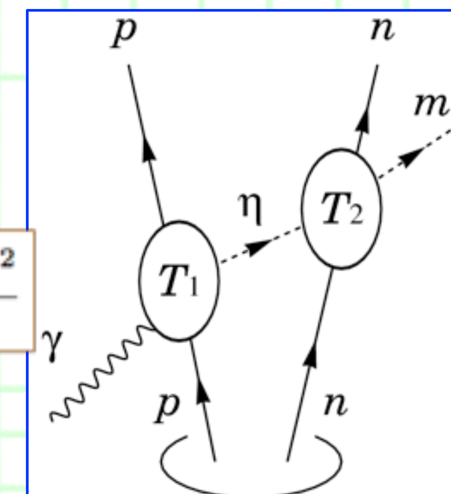


Diagram 3

2. Formulation

++ γ d --> p X reaction with $X = \eta\ n, \eta'\ n$ ++

- Next we consider **the γ d --> p X reaction** with **$X = \eta\ n, \eta'\ n$** on a deuteron target.
  - **Scattering amplitudes from these diagrams** are obtained as: D. Jido, E. Oset and T. S. (2009); (2013).

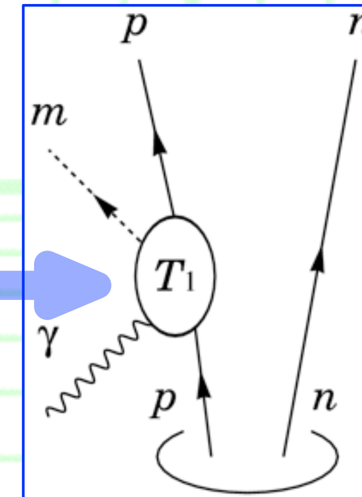


Diagram 1

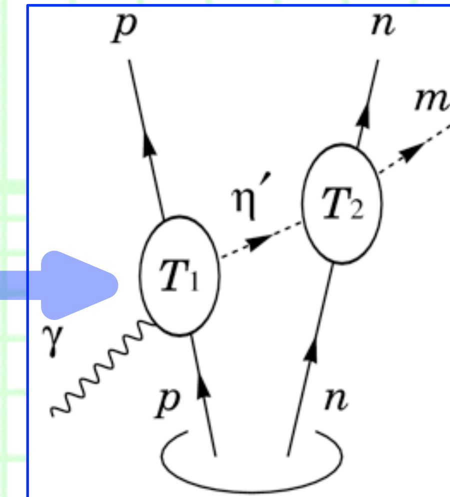


Diagram 2

$$T_{\gamma d \to p X} = T_1^{(m)} + T_2^{(m)} + T_3^{(m)}$$

$$T_1^{(m)} = T_{\gamma p \to m p} \times \tilde{\varphi}(\vec{p}_n)$$

$$T_2^{(m)} = T_{\gamma p \to \eta' p} T_{\eta' n \to X}(M_X) \int \frac{d^3 q}{(2\pi)^3} \frac{\tilde{\varphi}(\vec{q} + \vec{p}_p - \vec{k})}{q^2 - M_{\eta'}^2 + i\epsilon}$$

$$q^0 = M_d + E_\gamma^{\rm lab} - p_p^0 - M_n - \frac{|\vec{q} + \vec{p}_p - \vec{k}|^2}{2M_n}$$

$$T_3^{(m)} = T_{\gamma p \to \eta p} T_{\eta n \to X}(M_X) \int \frac{d^3 q}{(2\pi)^3} \frac{\tilde{\varphi}(\vec{q} + \vec{p}_p - \vec{k})}{q^2 - M_{\eta}^2 + i\epsilon}$$

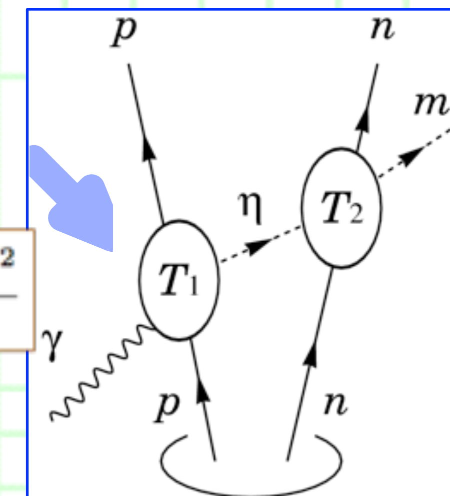


Diagram 3

1. The γ p --> η p, η' p amplitude $T_{\gamma p \to \eta p, \eta' p}$ is already fixed from the free proton reaction.

2. Formulation

++ $\gamma\ d$ --> $p\ X$ reaction with $X = \eta\ n, \eta'\ n$ ++

- Next we consider **the $\gamma\ d$ --> $p\ X$ reaction** with $X = \eta\ n, \eta'\ n$ on a deuteron target.
  - **Scattering amplitudes from these diagrams** are obtained as: D. Jido, E. Oset and T. S. (2009); (2013).

$$T_{\gamma d \to pX} = T_1^{(m)} + T_2^{(m)} + T_3^{(m)}$$

$$T_1^{(m)} = T_{\gamma p \to mp} \times \tilde{\varphi}(\vec{p}_n)$$

$$T_2^{(m)} = T_{\gamma p \to \eta' p} T_{\eta' n \to X}(M_X) \int \frac{d^3 q}{(2\pi)^3} \frac{\tilde{\varphi}(\vec{q} + \vec{p}_p - \vec{k})}{q^2 - M_{\eta'}^2 + i\epsilon}$$

$$q^0 = M_d + E_\gamma^{\rm lab} - p_p^0 - M_n - \frac{|\vec{q} + \vec{p}_p - \vec{k}|^2}{2M_n}$$

$$T_3^{(m)} = T_{\gamma p \to \eta p} T_{\eta n \to X}(M_X) \int \frac{d^3 q}{(2\pi)^3} \frac{\tilde{\varphi}(\vec{q} + \vec{p}_p - \vec{k})}{q^2 - M_\eta^2 + i\epsilon}$$

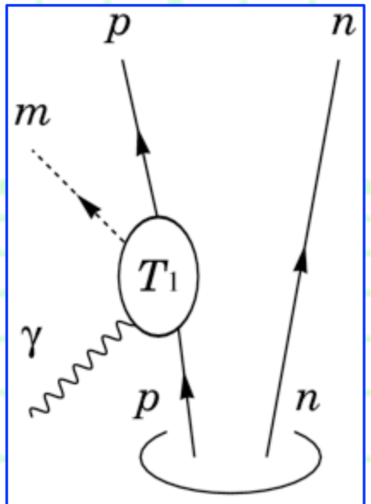


Diagram 1

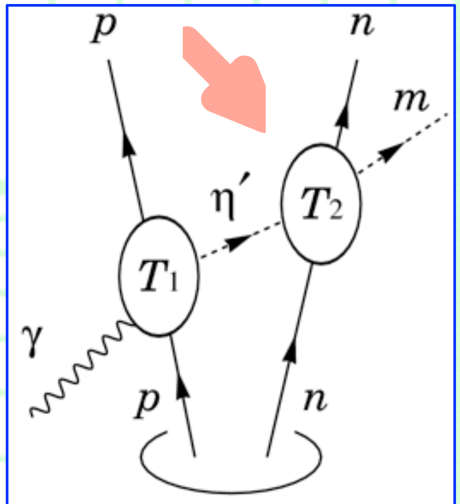


Diagram 2

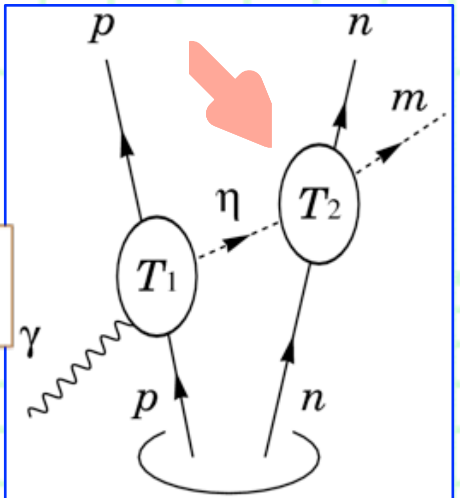


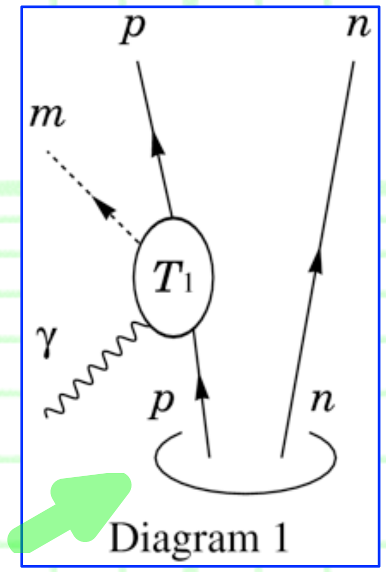
Diagram 3

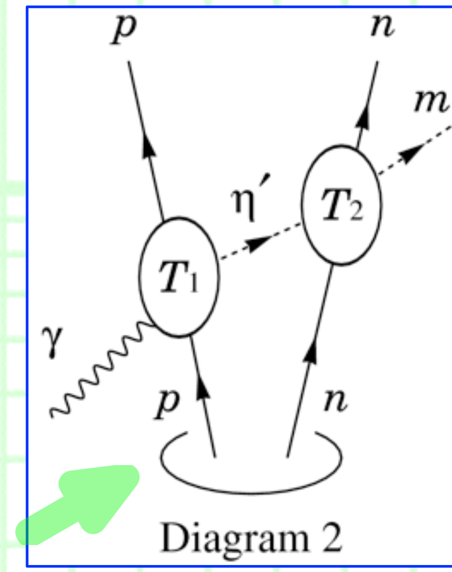
2. **The $\eta\ n, \eta'\ n$ --> X amplitude $T_{\eta n, \eta' n \to X}$** is **taken from the linear sigma model** (already discussed in Intro.).

2. Formulation

++ $\gamma\, d$ --> $p\, X$ reaction with $X = \eta\, n, \eta'\, n$ ++

- Next we consider **the $\gamma\, d$ --> $p\, X$ reaction** with $X = \eta\, n, \eta'\, n$ on a deuteron target.
  - Scattering amplitudes from these diagrams are obtained as: D. Jido, E. Oset and T. S. (2009); (2013).





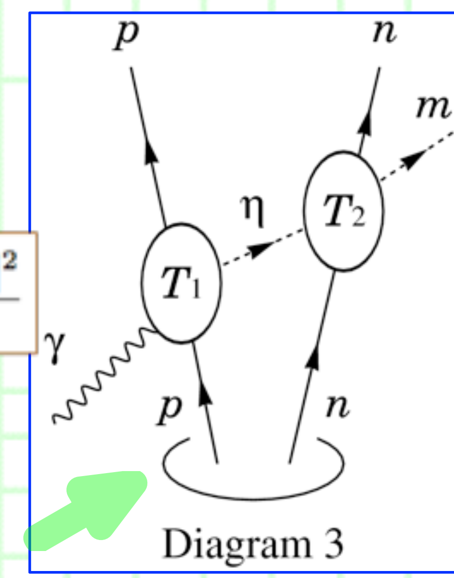
$$T_{\gamma d \to pX} = \mathcal{T}_1^{(m)} + \mathcal{T}_2^{(m)} + \mathcal{T}_3^{(m)}$$

$$\mathcal{T}_1^{(m)} = T_{\gamma p \to mp} \times \tilde{\varphi}(\vec{p}_n)$$

$$\mathcal{T}_2^{(m)} = T_{\gamma p \to \eta' p} T_{\eta' n \to X}(M_X) \int \frac{d^3 q}{(2\pi)^3} \frac{\tilde{\varphi}(\vec{q} + \vec{p}_p - \vec{k})}{q^2 - M_{\eta'}^2 + i\epsilon}$$

$$q^0 = M_d + E_\gamma^{\rm lab} - p_p^0 - M_n - \frac{|\vec{q} + \vec{p}_p - \vec{k}|^2}{2M_n}$$

$$\mathcal{T}_3^{(m)} = T_{\gamma p \to \eta p} T_{\eta n \to X}(M_X) \int \frac{d^3 q}{(2\pi)^3} \frac{\tilde{\varphi}(\vec{q} + \vec{p}_p - \vec{k})}{q^2 - M_\eta^2 + i\epsilon}$$



3. Deuteron wave function is **an analytic form** taken from the Bonn potential with s wave only:

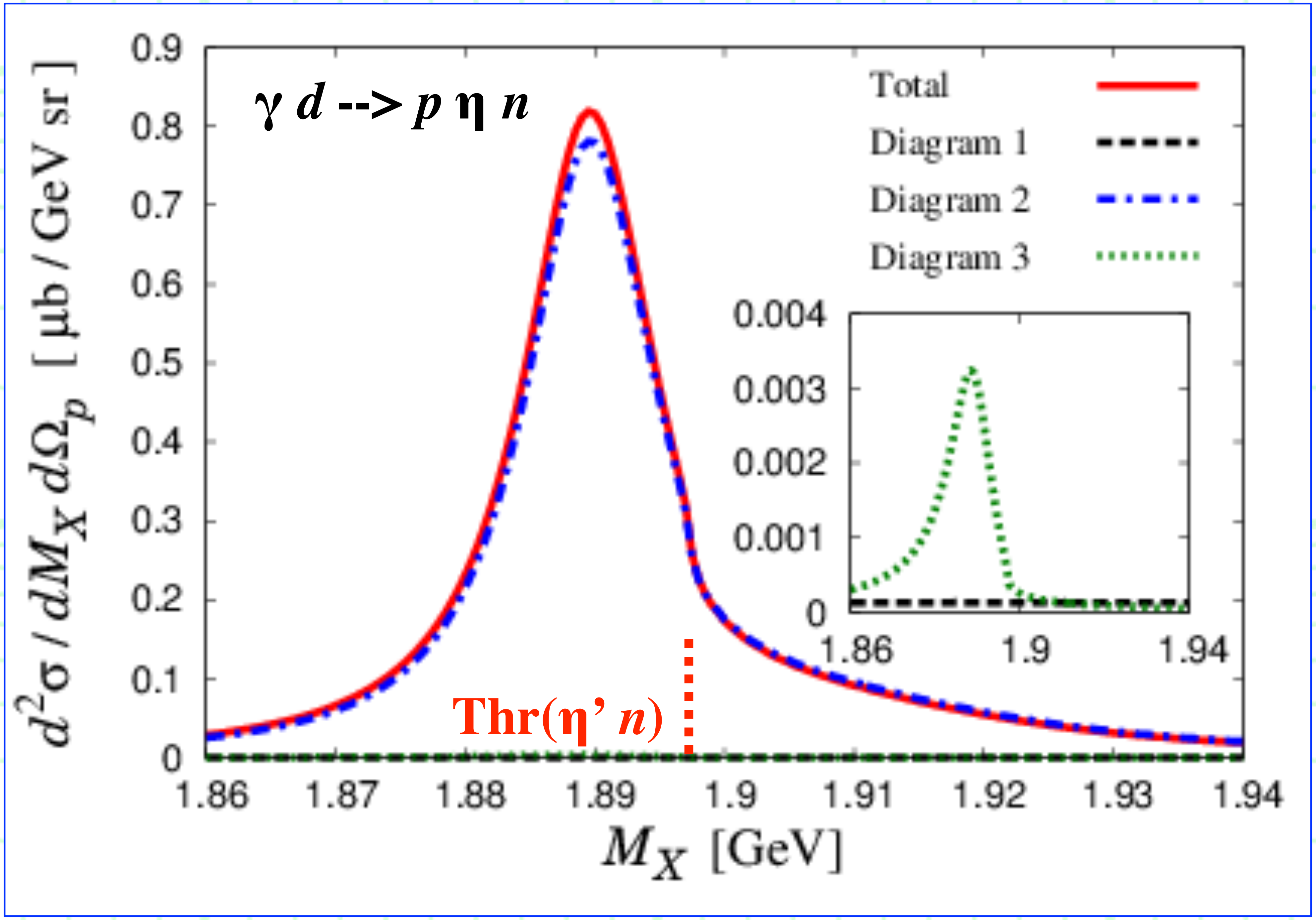
$$\tilde{\varphi}(\vec{q}) = \sum_{j=1}^{11} \frac{C_j}{\vec{q}^{\,2} + m_j^2}$$

Machleidt, *Phys. Rev.* C63 (2001) 024001.

3. Results and discussions

++ $\gamma\, d \to p\, \eta\, n$ reaction ++

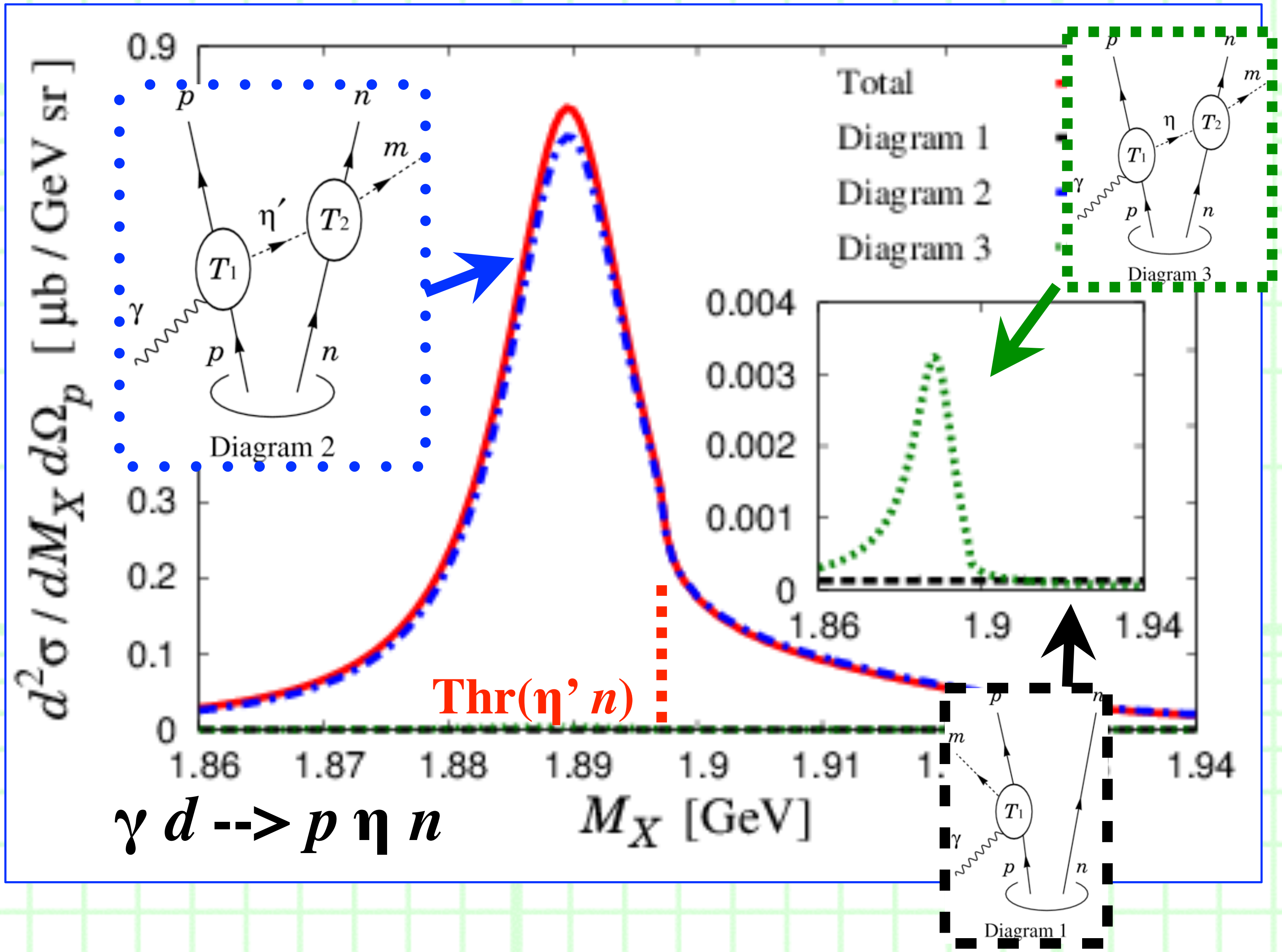
- We first consider $\gamma\, d \to p\, \eta\, n$ reaction with $E_\gamma^{lab} = 2.1$ GeV, $\theta p = 0^o$ and calculate the differential cross section.



3. Results and discussions

++ $\gamma\, d \rightarrow p\, \eta\, n$ reaction ++

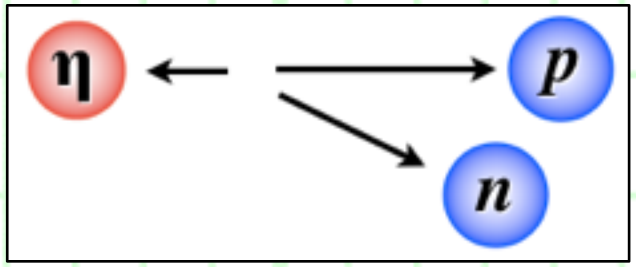
- We first consider $\gamma\, d \rightarrow p\, \eta\, n$ reaction with $E_\gamma^{lab} = 2.1$ GeV, $\theta p = 0^o$ and calculate the differential cross section.



□ The signal of the η' n bound state is dominated by Diag. 2 (η' exchange).

--- Almost on-shell η' and large η' n --> η n Amp.

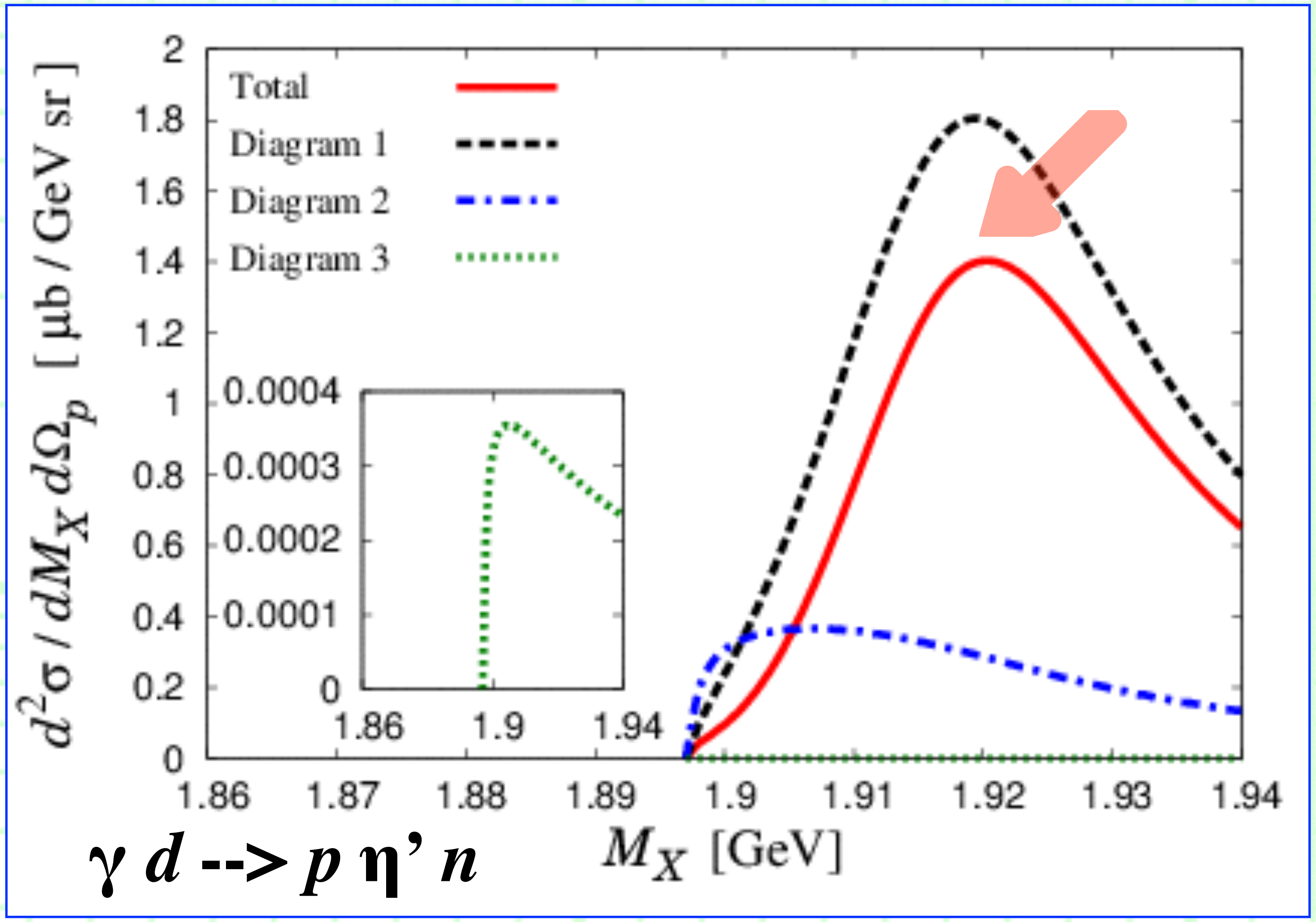
□ Diag. 1 is negligible since large Fermi motion is necessary:



3. Results and discussions

++ $\gamma\, d \to p\, \eta'\, n$ reaction ++

- We next consider $\gamma\, d \to p\, \eta'\, n$ reaction with $E_\gamma^{lab} = 2.1$ GeV, $\theta p = 0^o$ and calculate the differential cross section so as to compare quasi-free η' production with the signal of the η' n bound state.

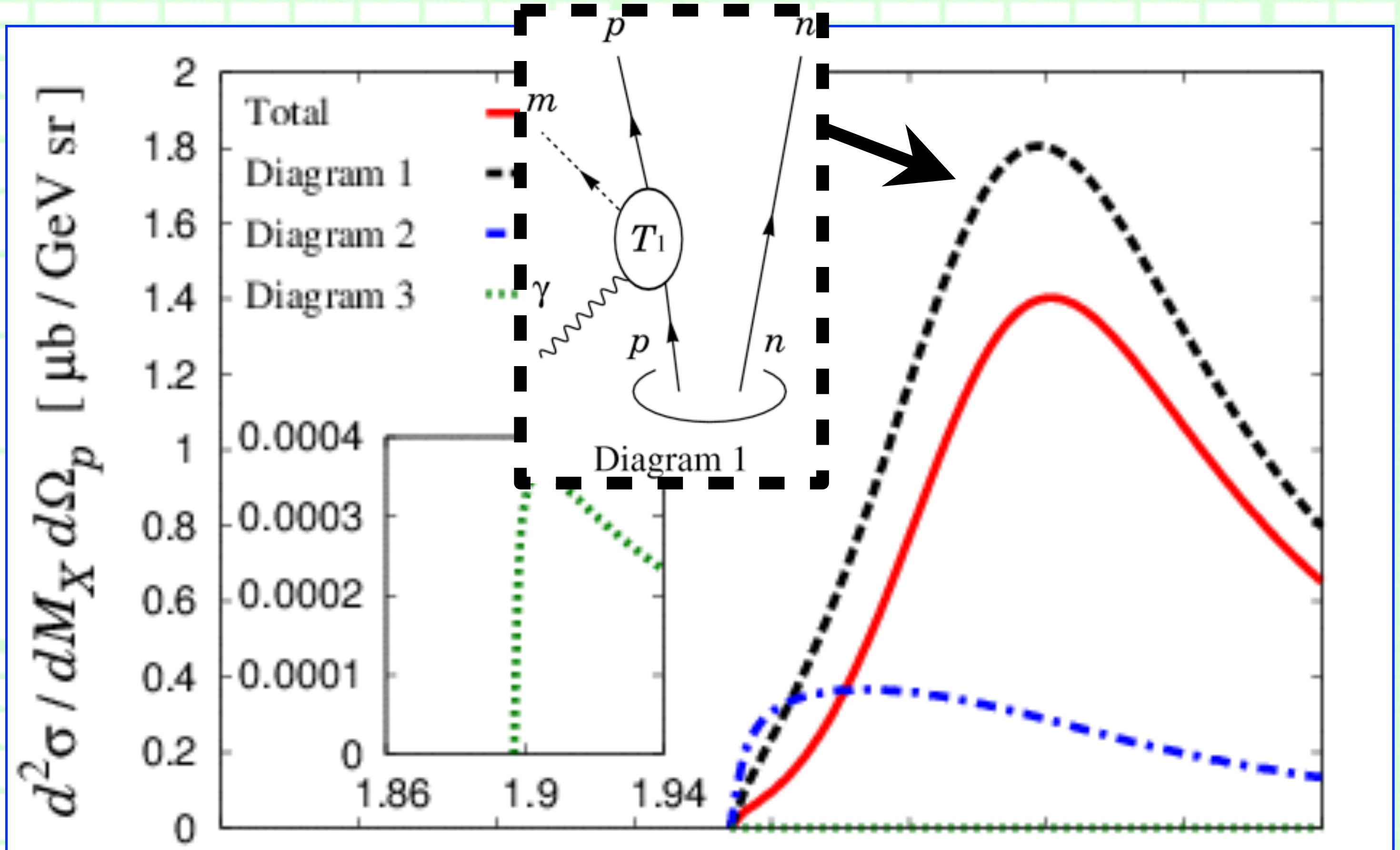


- □ We find quasi-free η' production peak just above the η' n threshold.

3. Results and discussions

++ $\gamma\ d$ --> $p\ \eta'\ n$ reaction ++

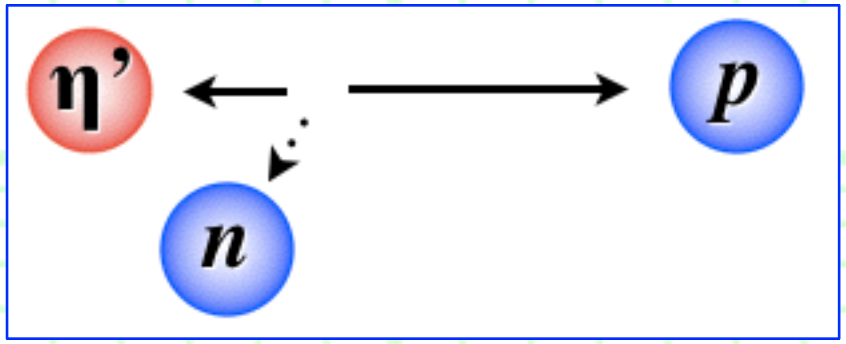
- We next consider $\gamma\ d$ --> $p\ \eta'\ n$ reaction with $E_\gamma^{lab} = 2.1$ GeV, $\theta p = 0^o$ and calculate the differential cross section so as to compare quasi-free η' production with the signal of the η' n bound state.



$\gamma\ d$ --> $p\ \eta'\ n$

□ We find quasi-free η' production peak just above the η' n threshold.

--- Large single-scattering η' production part.

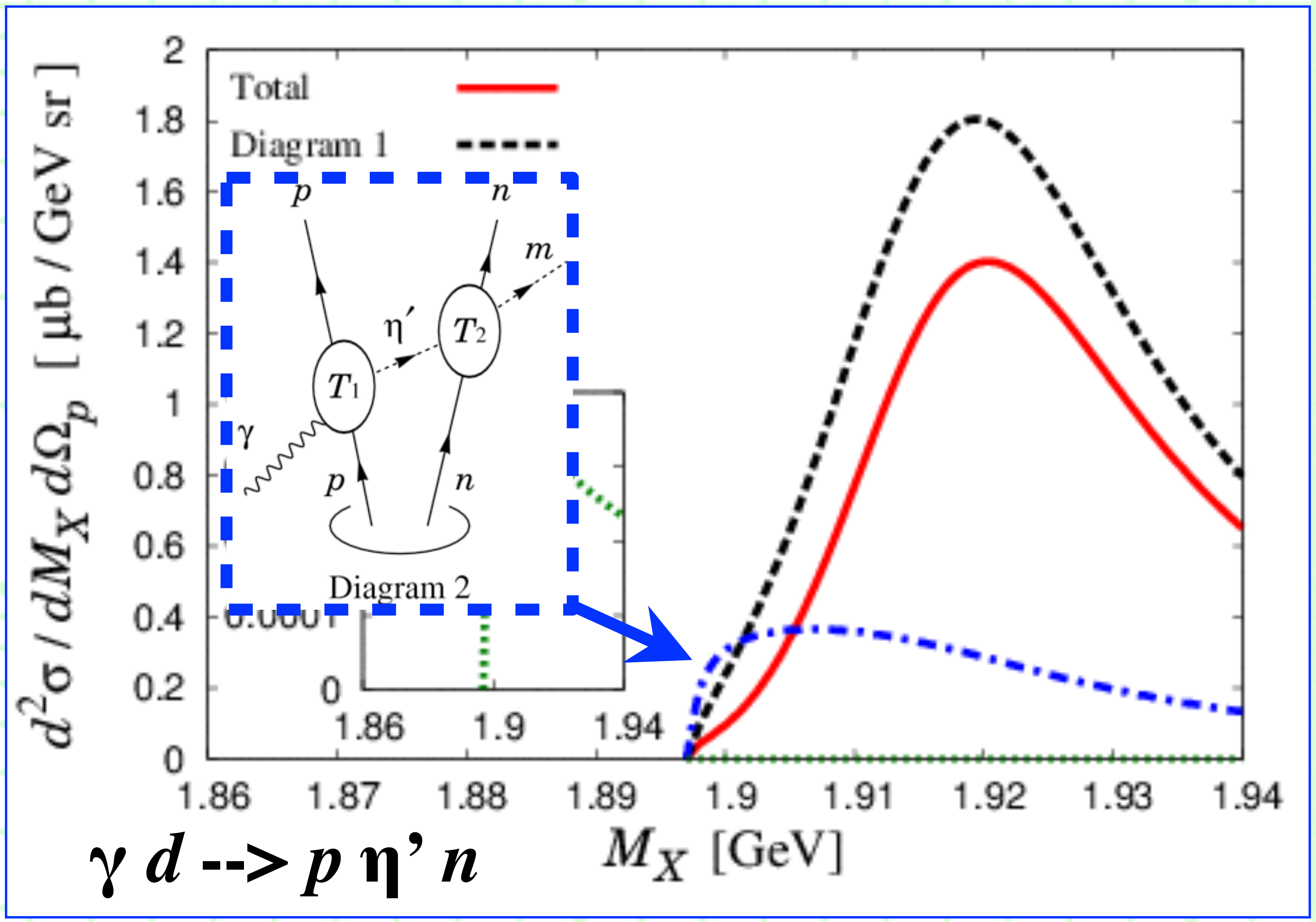


--- The invariant mass $M_X = M_{\eta' n}$ becomes small for forward proton emission.

3. Results and discussions

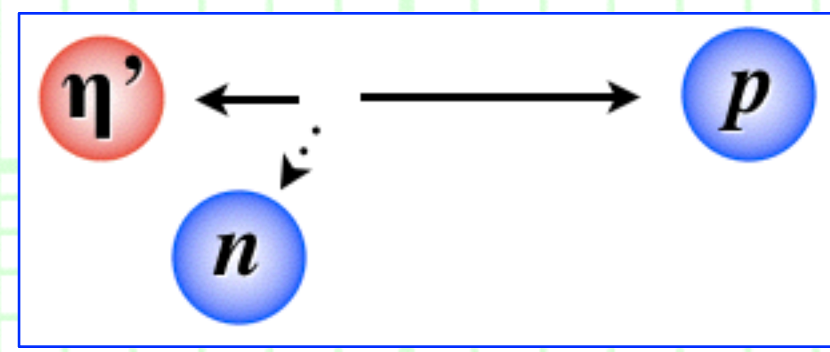
++ $\gamma\ d \to p\ \eta'\ n$ reaction ++

- We next consider $\gamma\ d \to p\ \eta'\ n$ **reaction with** $E_\gamma^{lab} = 2.1$ **GeV,** $\theta p = 0^o$ and calculate <u>the differential cross section</u> so as to compare quasi-free η' production with the signal of the η' *n* bound state.



□ We find **quasi-free η' production peak** just above the η' *n* threshold.

--- <u>Large single-scattering</u> η' production part.



□ However, <u>the η'-exchange double scattering</u> is **non-negligible**.

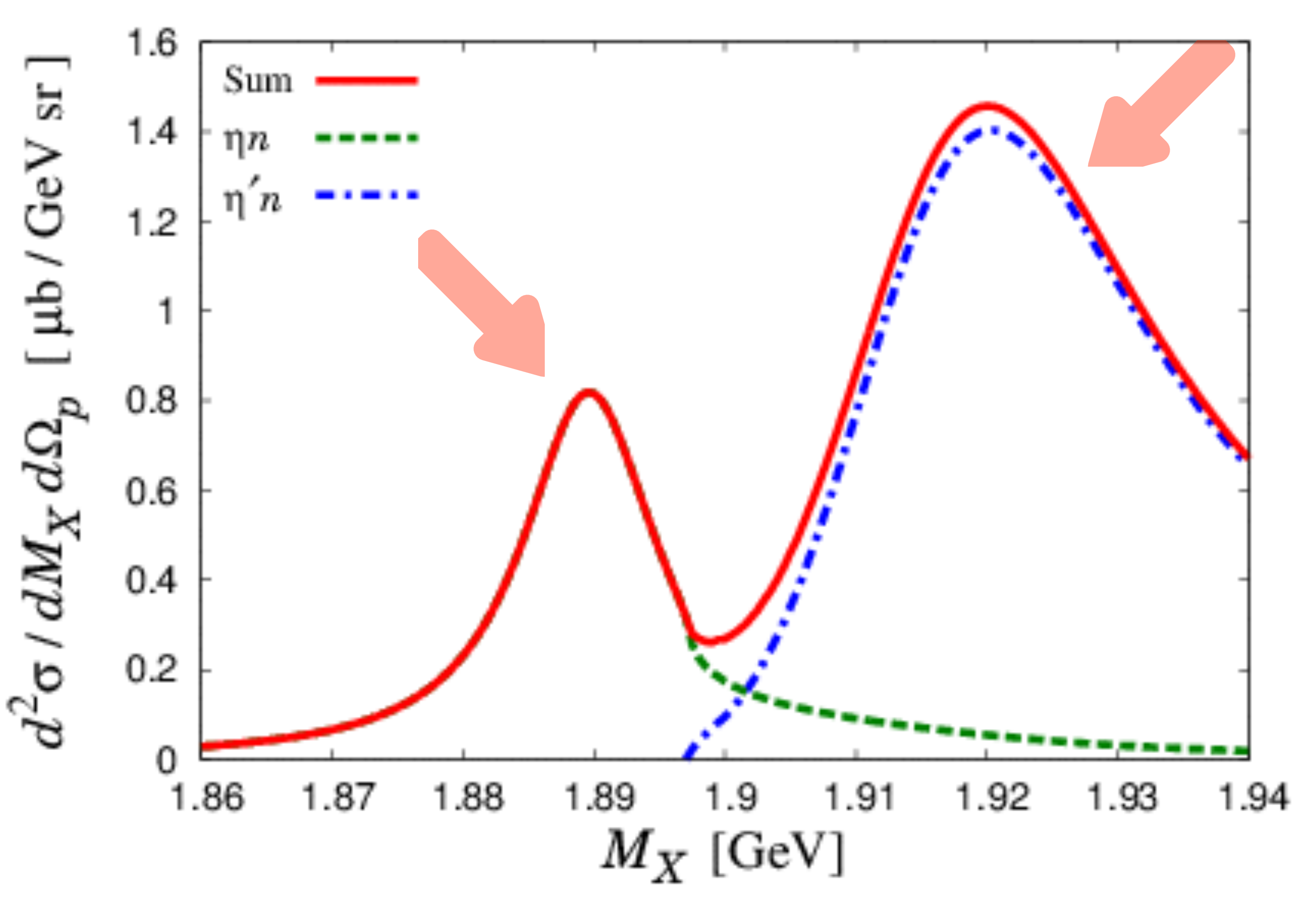
--- Almost on-shell η' and large magnitude of the amplitude $T_{\eta' n \to \eta' n}$

3. Results and discussions

++ $\gamma\, d$ --> $p\, X$ ($X = \eta\, n, \eta'\, n$) reaction from the sum ++

- For observation of the signal of the $\eta'\, n$ bound state in real Exps., the signal should be comparable to the quasi-free η' contribution.

--> We plot sum of two differential cross sections for $\gamma\, d$ --> $p\, \eta'\, n$ and $\gamma\, d$ --> $p\, \eta'\, n$ reactions with $E_\gamma^{lab} = 2.1$ GeV, $\theta p = 0^o$.



□ We clearly find two peaks around the $\eta'\, n$ threshold.

--- The lower is the bound state signal, and the higher is the quasi-free η' part.

□ Both the contributions are comparable with each other.

--> In our model we can observe the signal of the $\eta'\, n$ bound state.

3. Results and discussions

++ Model dependence ++

- We want to study **model dependence** of our results.

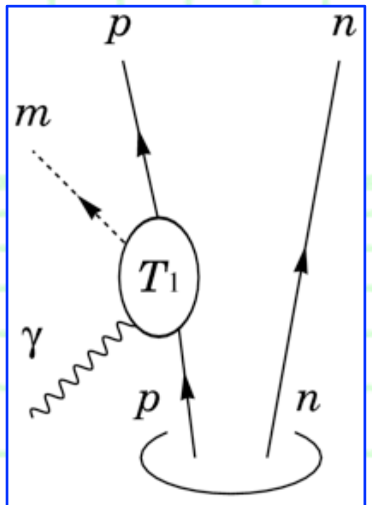


Diagram 1

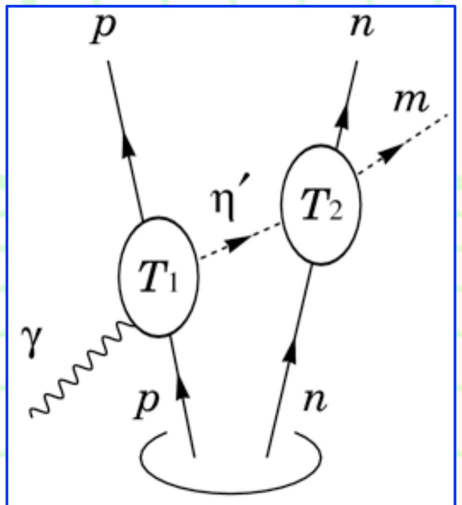


Diagram 2

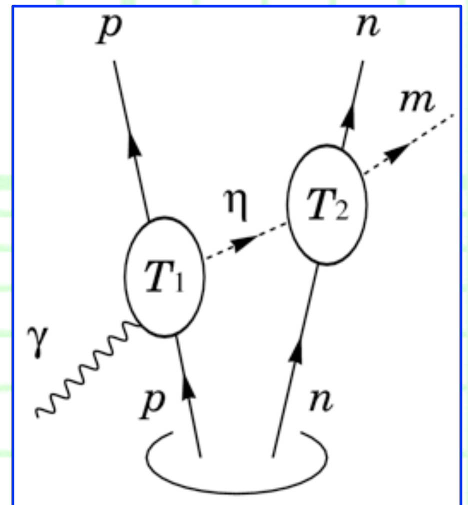
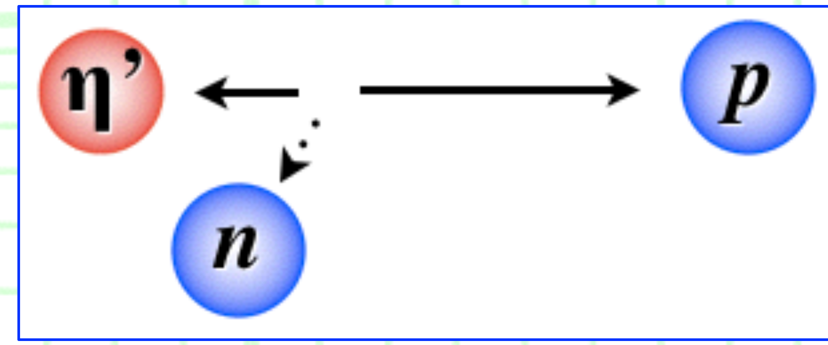


Diagram 3



□ Other diagrams ?

<-- Other diagrams will be **kinematically unfavored**, or give only background. --- The forward emission of a fast proton.

□ Changing the $\eta' N$ interaction in $T_{\eta p, \eta' p \to X}$ (T_2).

<-- **We now examine this !**

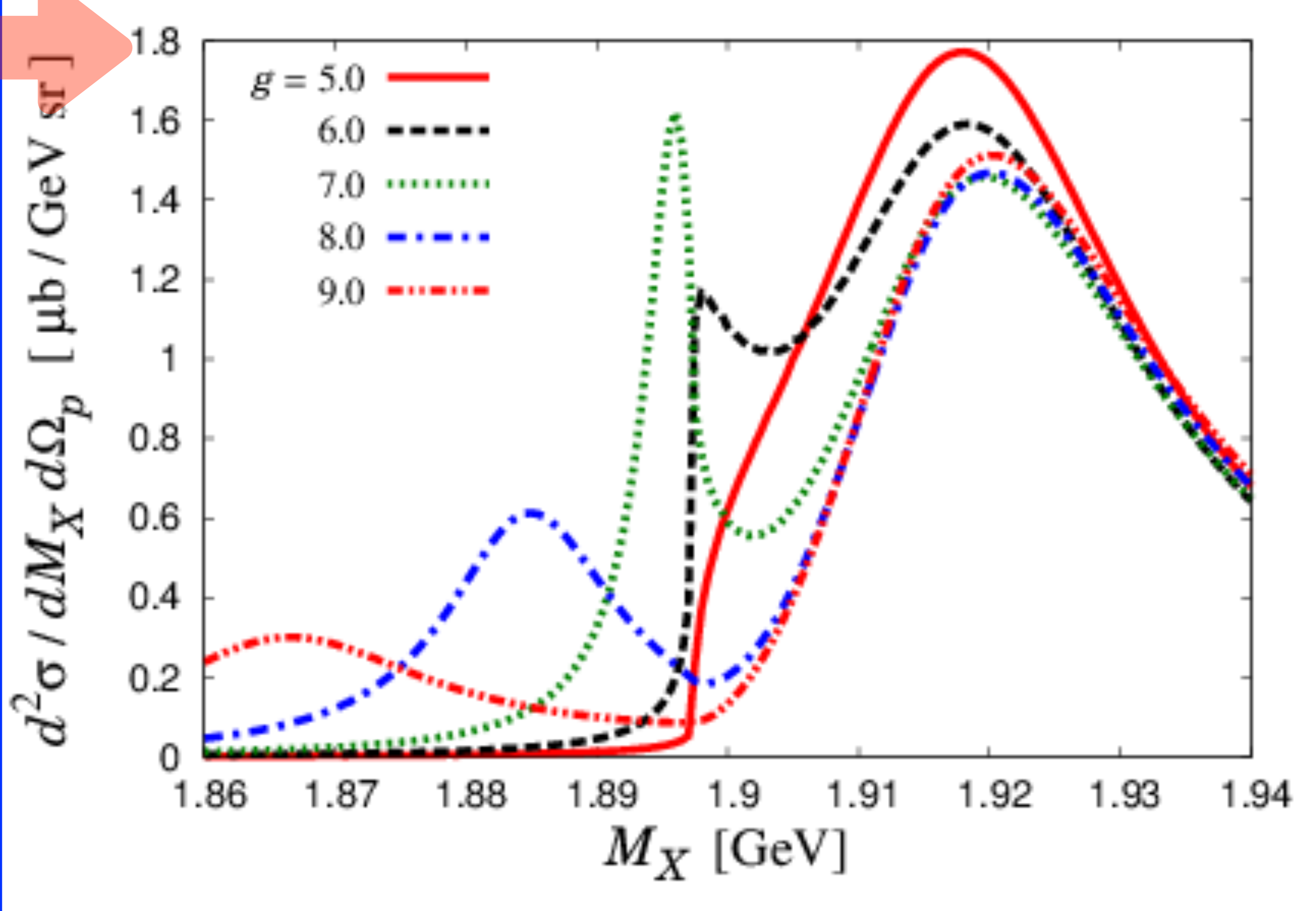
3. Results and discussions

++ Model dependence ++

- **Change the η'N interaction** and **check the interaction dependence**.

g	$g_{\eta' n}$	B_E (MeV)	Γ (MeV)
	Shift parameter g		
5.0	No structure		
6.0	Cusp only		
7.0	$1.63+0.56i$	0.9	5.4
8.0	$2.71+0.43i$	12.8	16.0
9.0	$3.49+0.40i$	31.8	26.0
	Shift parameter $m_{\sigma 8}$		
$m_{\sigma 8}$ (GeV)	$g_{\eta' n}$	B_E (MeV)	Γ (MeV
0.9	$3.19+1.25i$	9.5	60.9
1.0	$2.79+0.91i$	8.8	34.4
1.1	$2.57+0.67i$	8.4	21.2
1.2	$2.43+0.49i$	8.0	14.1
1.3	$2.34+0.37i$	7.7	9.8
	Introduce πN channel		
	$g_{\eta' n}$	B_E (MeV)	Γ (MeV
	$4.10+0.15i$	57.0	14.5

$$V_{11} = -\frac{6gB}{\sqrt{3m_{\sigma 0}^2}}, \quad V_{12} = V_{21} = +\frac{6gB}{\sqrt{6m_{\sigma 8}^2}}, \quad V_{22} = 0,$$



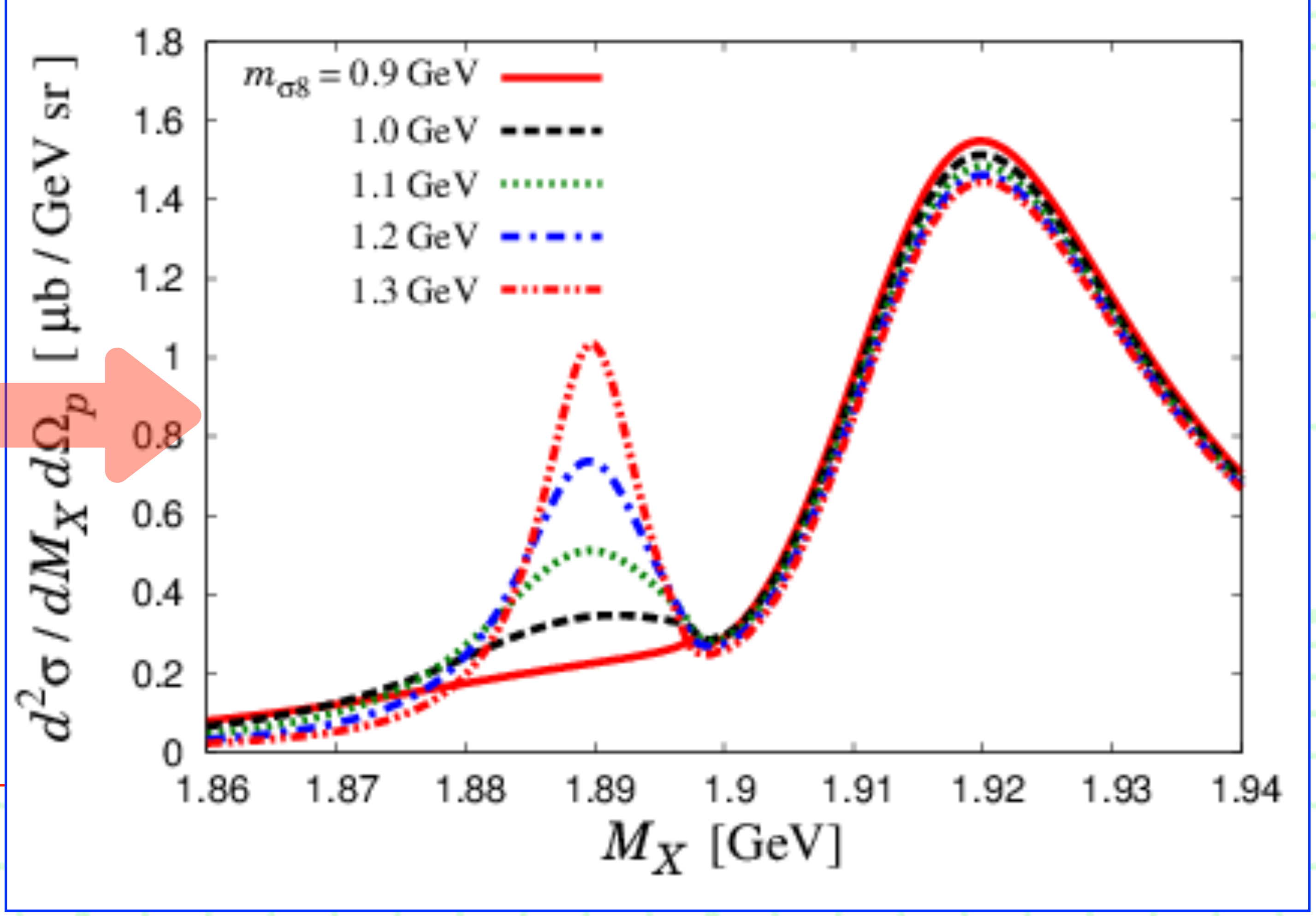
3. Results and discussions

++ Model dependence ++

- **Change the η'N interaction** and **check the interaction dependence**.

g	$g_{\eta' n}$	B_E (MeV)	Γ (MeV)
	Shift parameter g		
5.0	No structure		
6.0	Cusp only		
7.0	$1.63 + 0.56i$	0.9	5.4
8.0	$2.71 + 0.43i$	12.8	16.0
9.0	$3.49 + 0.40i$	31.8	26.0
	Shift parameter $m_{\sigma 8}$		
$m_{\sigma 8}$ (GeV)	$g_{\eta' n}$	B_E (MeV)	Γ (MeV)
0.9	$3.19 + 1.25i$	9.5	60.9
1.0	$2.79 + 0.91i$	8.8	34.4
1.1	$2.57 + 0.67i$	8.4	21.2
1.2	$2.43 + 0.49i$	8.0	14.1
1.3	$2.34 + 0.37i$	7.7	9.8
	Introduce πN channel		
	$g_{\eta' n}$	B_E (MeV)	Γ (MeV)
	$4.10 + 0.15i$	57.0	14.5

$$V_{11} = -\frac{6gB}{\sqrt{3m_{\sigma 0}^2}}, \quad V_{12} = V_{21} = +\frac{6gB}{\sqrt{6m_{\sigma 8}^2}}, \quad V_{22} = 0,$$



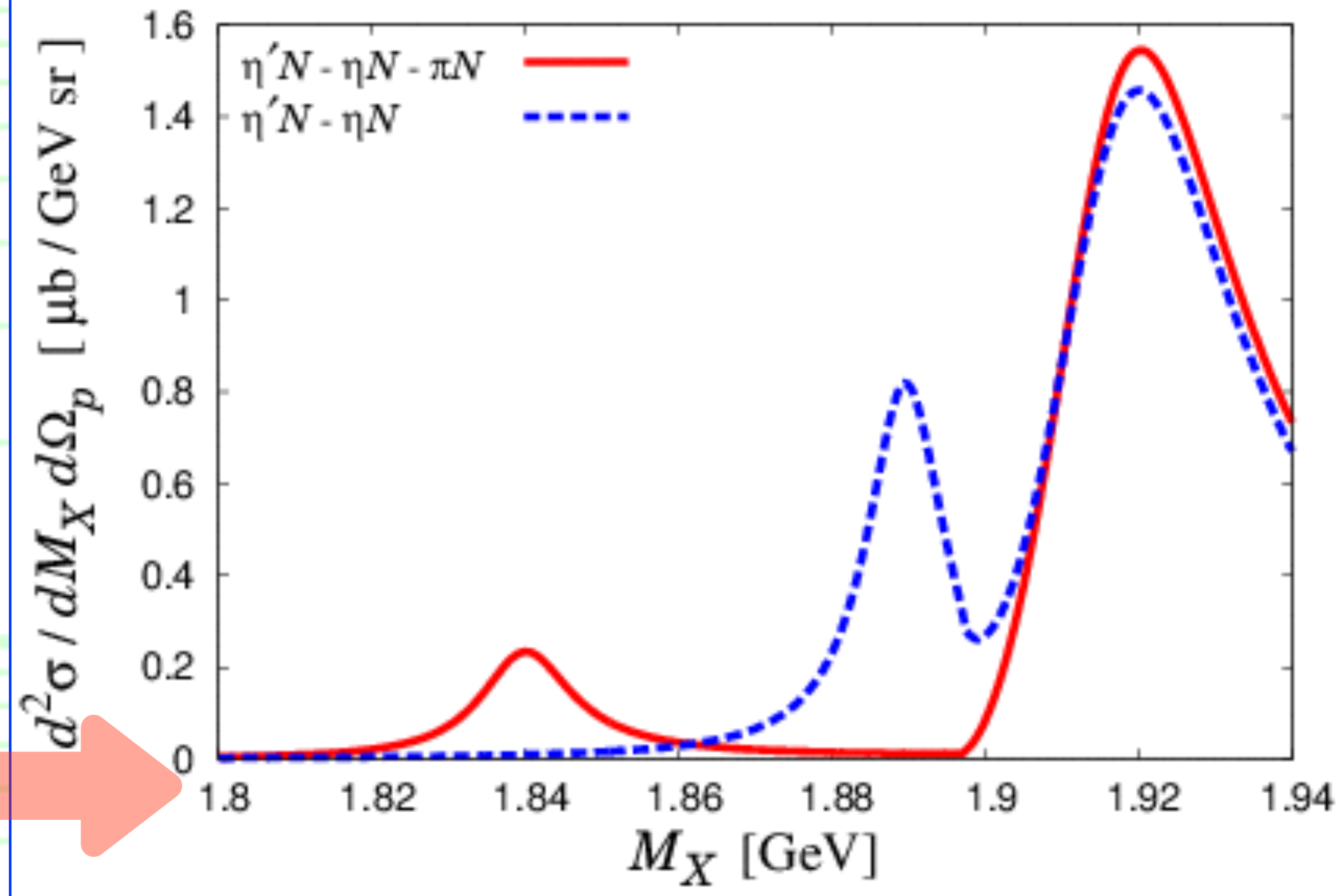
3. Results and discussions

++ Model dependence ++

- **Change the η'N interaction** and **check the interaction dependence**.

g	$g_{\eta' n}$	B_E (MeV)	Γ (MeV)
	Shift parameter g		
5.0	No structure		
6.0	Cusp only		
7.0	$1.63 + 0.56i$	0.9	5.4
8.0	$2.71 + 0.43i$	12.8	16.0
9.0	$3.49 + 0.40i$	31.8	26.0
	Shift parameter $m_{\sigma 8}$		
$m_{\sigma 8}$ (GeV)	$g_{\eta' n}$	B_E (MeV)	Γ (MeV)
0.9	$3.19 + 1.25i$	9.5	60.9
1.0	$2.79 + 0.91i$	8.8	34.4
1.1	$2.57 + 0.67i$	8.4	21.2
1.2	$2.43 + 0.49i$	8.0	14.1
1.3	$2.34 + 0.37i$	7.7	9.8
	Introduce πN channel		
	$g_{\eta' n}$	B_E (MeV)	Γ (MeV)
	$4.10 + 0.15i$	57.0	14.5

$$V_{11} = -\frac{6gB}{\sqrt{3m_{\sigma 0}^2}}, \quad V_{12} = V_{21} = +\frac{6gB}{\sqrt{6m_{\sigma 8}^2}}, \quad V_{22} = 0,$$



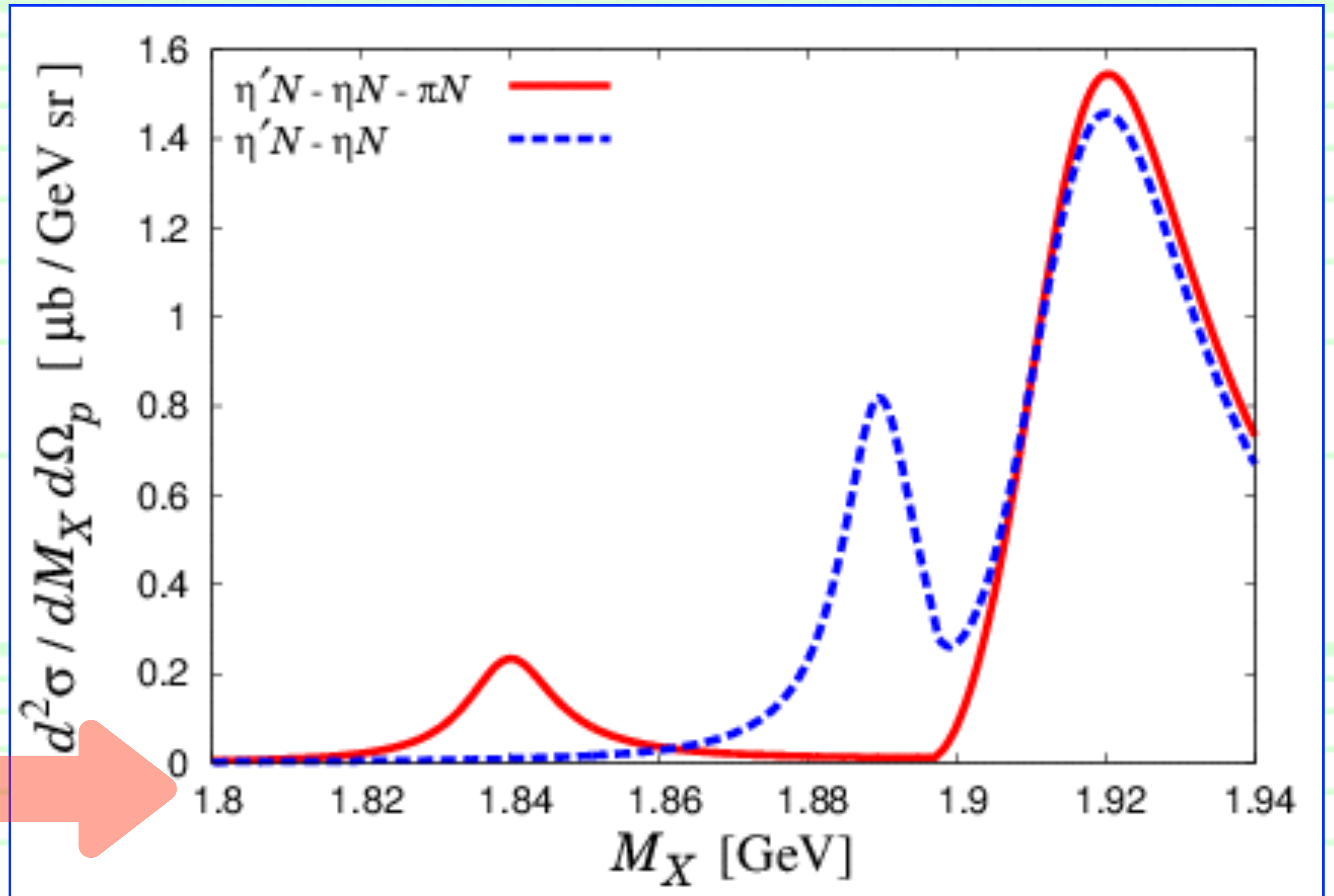
3. Results and discussions

++ Model dependence ++

- **Change the η'N interaction** and **check the interaction dependence**.

	Shift parameter g		
g	$g_{\eta' n}$	B_E (MeV)	Γ (MeV)
5.0	No structure		
6.0	Cusp only		
7.0	$1.63 + 0.56i$	0.9	5.4
8.0	$2.71 + 0.43i$	12.8	16.0
9.0	$3.49 + 0.40i$	31.8	26.0
	Shift parameter $m_{\sigma 8}$		
$m_{\sigma 8}$ (GeV)	$g_{\eta' n}$	B_E (MeV)	Γ (MeV)
0.9	$3.19 + 1.25i$	9.5	60.9
1.0	$2.79 + 0.91i$	8.8	34.4
1.1	$2.57 + 0.67i$	8.4	21.2
1.2	$2.43 + 0.49i$	8.0	14.1
1.3	$2.34 + 0.37i$	7.7	9.8
	Introduce πN channel		
	$g_{\eta' n}$	B_E (MeV)	Γ (MeV)
	$4.10 + 0.15i$	57.0	14.5

$$V_{11} = -\frac{6gB}{\sqrt{3}m_{\sigma 0}^2}, \quad V_{12} = V_{21} = +\frac{6gB}{\sqrt{6}m_{\sigma 8}^2}, \quad V_{22} = 0,$$

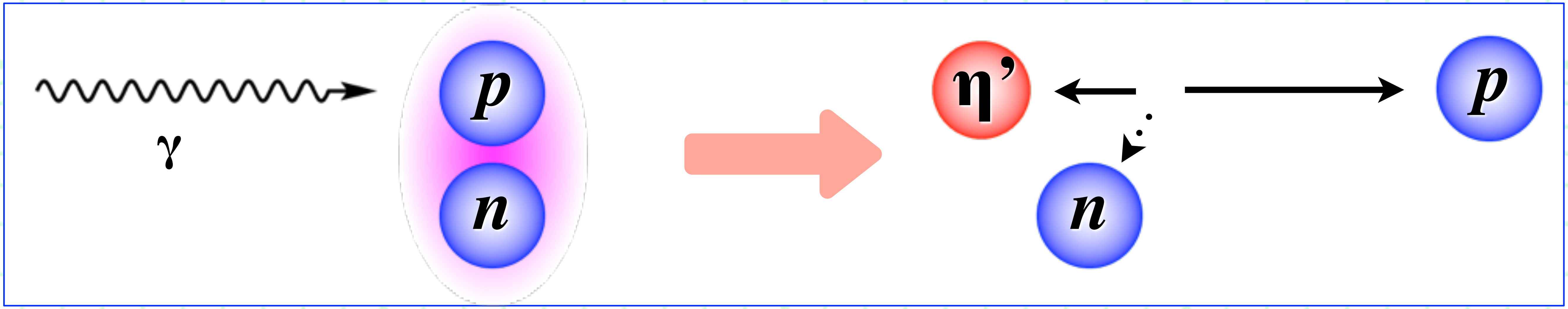


--- We can **observe the signal of the η'N bound state in experiments** if the bound state exists at **more than several MeV below the η'N threshold with a small decay width**.

4. Summary

++ Summary ++

- We investigate photoproduction of an η' *n* bound state in the γ *d* --> *p X* reaction with *X* = η *n*, η' *n*.



--- The forward proton emission allows us to consider selectively the η' *N* photoproduction.

- Using the η' *n* interaction based on the linear sigma model, we can observe the bound-state signal against the quasi-free η', if the bound state is more than several MeV below the η'*N* threshold with a small decay width.

- The quasi-free η' production yield compared to free-proton case may be a clue to the η' *N* interaction.

Thank you very much for your kind attention !

Appendix

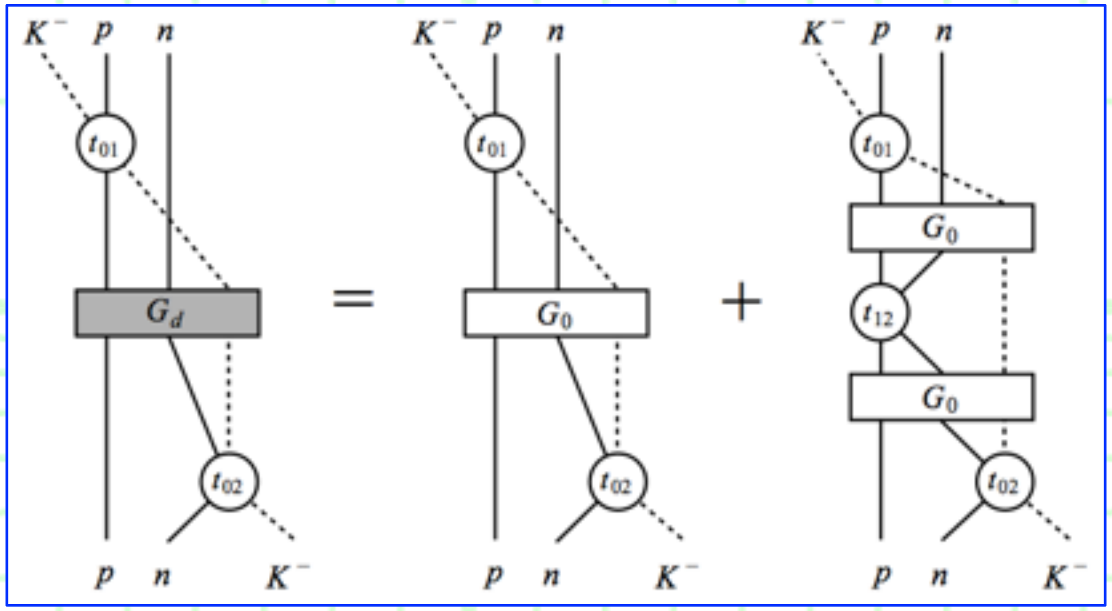
3. Results and discussions

++ Model dependence ++

- We have used the following form for **the exchanged η(') meson energy**:

$$q^0 = M_p + E_\gamma^{\rm lab} - p_p^0$$

--- Based on **the Watson formalism**, in which **the Green's function contains effect of *NN* interaction**.



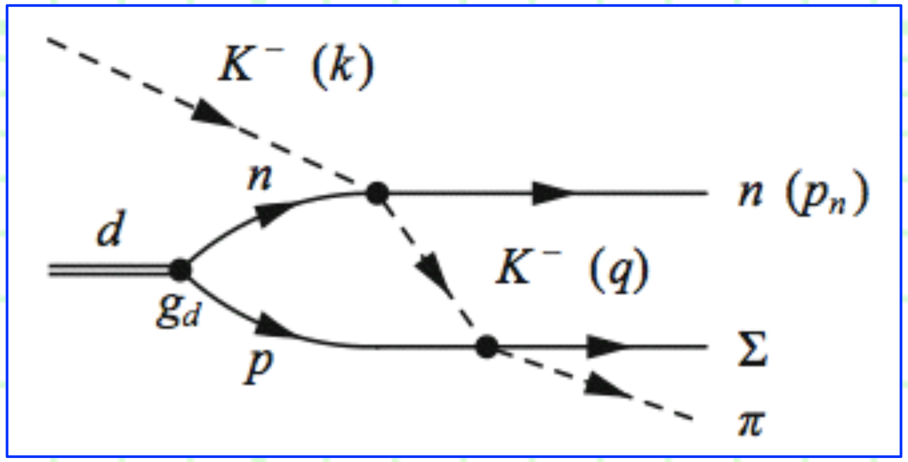
D. Jido, E. Oset and T. S. (2013).

- On the other hand, when we take **"truncated" Faddeev approach**, the energy of exchanged η(') meson is:

Miyagawa and Haidenbauer (2012);
D. Jido, E. Oset and T. S. (2013).

$$q^0 = M_d + E_\gamma^{\rm lab} - p_p^0 - M_n - \frac{|\vec{q} + \vec{p}_p - \vec{k}|^2}{2M_n}$$

--- This contains **less diagrams** concerned with *NN* interaction, but we can calculate **correct two-body threshold** in loops.

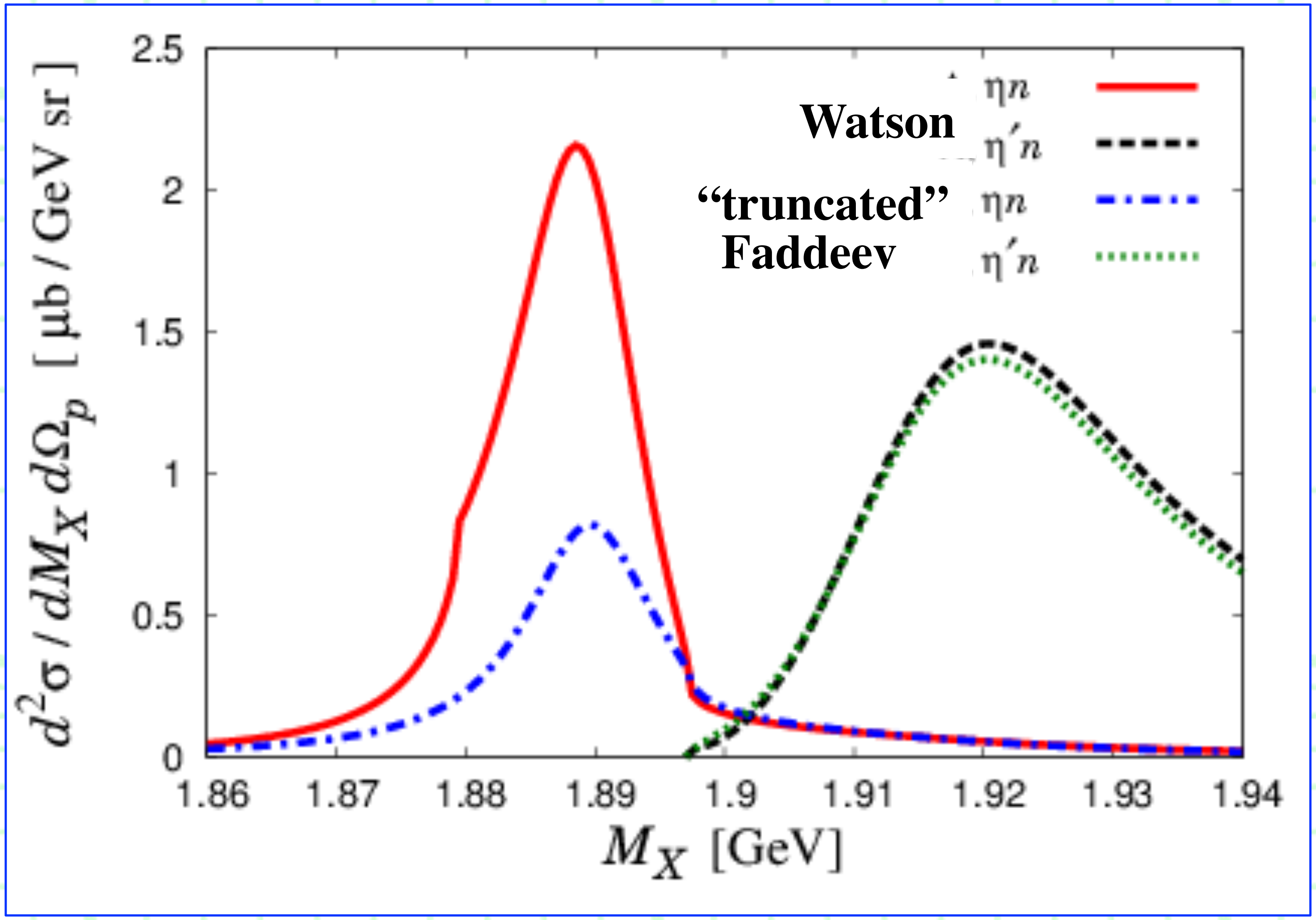


--> How is **the dependence** with respect to the prescription ?

3. Results and discussions

++ Model dependence ++

- Calculate **the differential cross section in two prescriptions of double scattering** (the Watson and "truncated" Faddeev).



- We find **the signal of the η' *n* bound state** in two approaches

--> The prescription does not contaminate the bound-state signal, although the strength is weak for "truncated" Faddeev.