η' N 束縛状態の光生成

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in collaboration with

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1. Introduction
2. Formulation of the photoproduction
3. Results and discussions
4. Summary

[1] T. S. , D. Jido and S. Sakai, in preparation

1. Introduction

1. Introduction

++ The properties of the η' meson ++

η'(958) $I^G(J^{PC}) = 0^+(0^{-+})$

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

η'

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.**

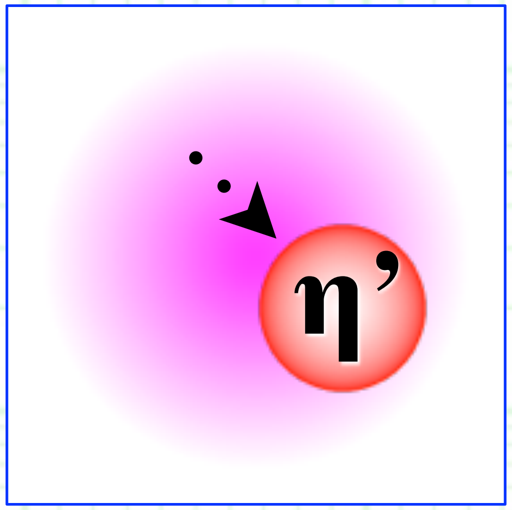
’t Hooft ()1976).

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

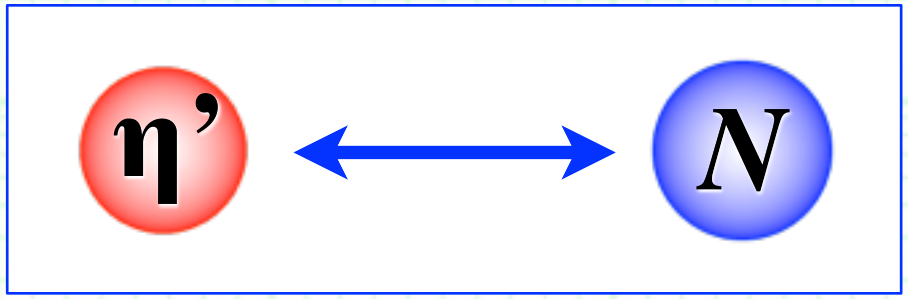
1. Introduction

++ 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.

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.

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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

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

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

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

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

1. Introduction

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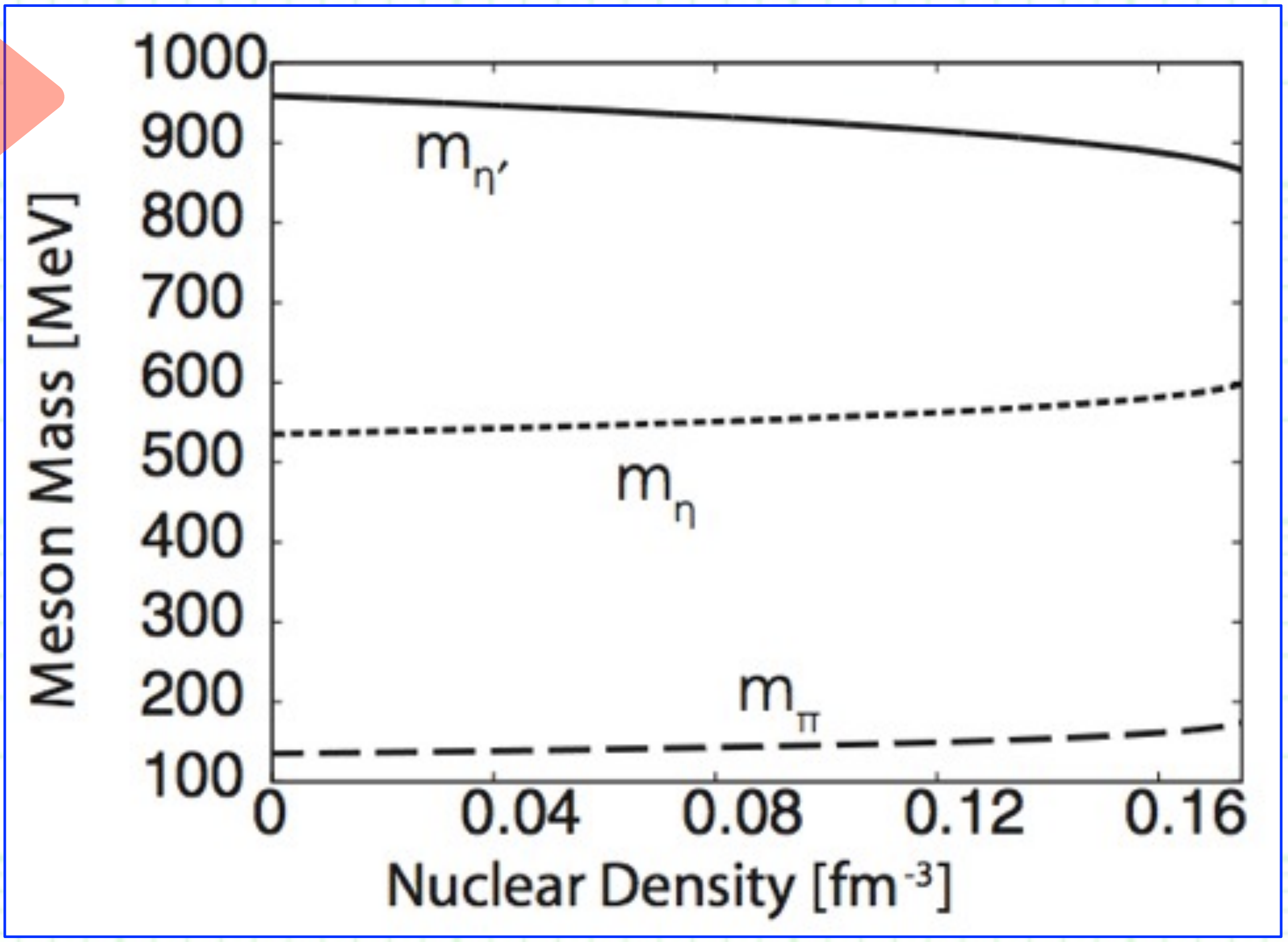

- Since the mass is generated by the spontaneous breaking of the chiral symmetry, the mass is reduced in nuclear matter, where the chiral symmetry is partially restored:

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

1. Introduction

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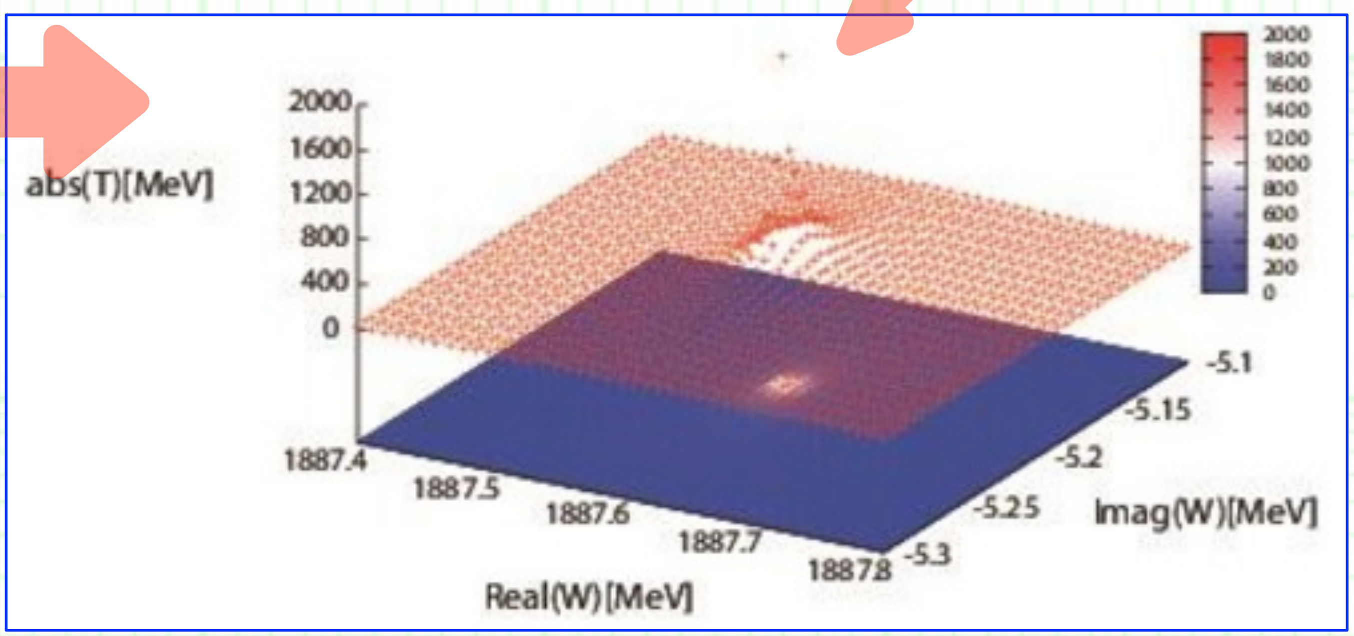


Taken from talk in ELPH workshop C008 given by S. Sakai.

□ 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).

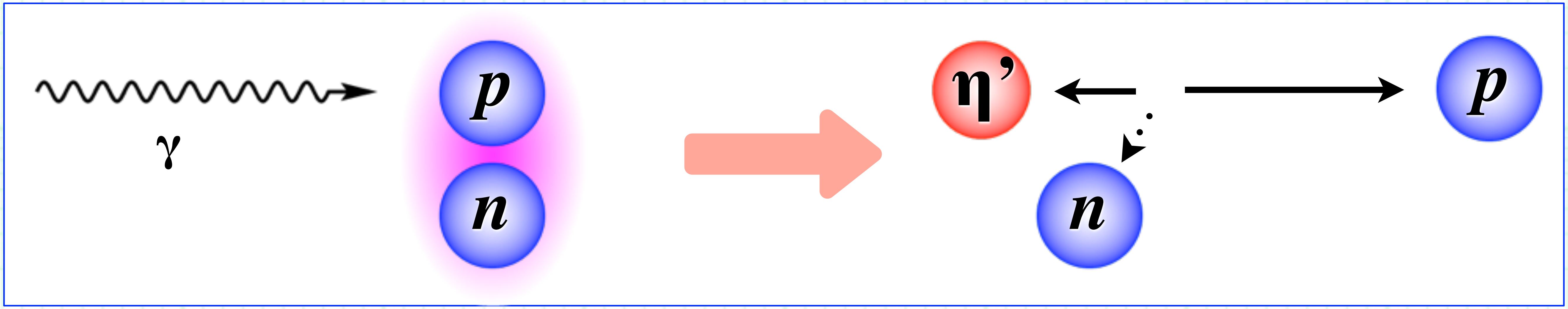
1. Introduction

++ Motivation ++

- Such an η' *N* bound state should 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) and ELPH experiments.
- □ It may also contain some clue to the η' *N* interaction.

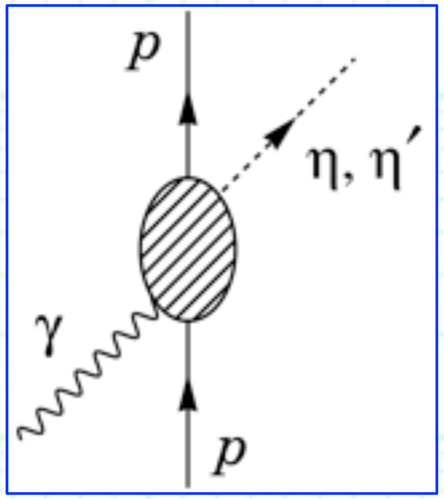
--> Against the quasi-free η' , can we really observe the signal ?

2. Formulation of the photoproduction

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.



□ The cross section can be expressed as:

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

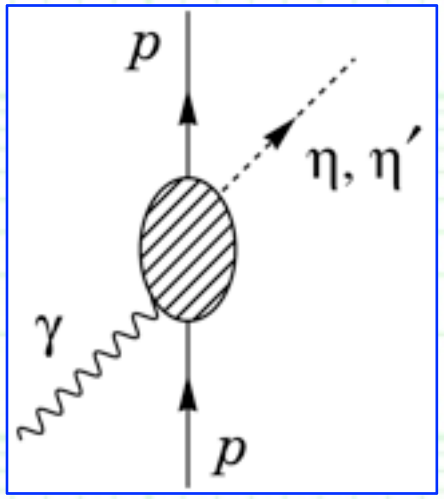
--- $E_\gamma^{\rm lab}$: Initial photon energy in the Lab. frame,
Ω: CM solid angle for the final proton momentum,
$p_{\rm cm}'$: CM momentum of the final proton,
W_2: CM energy of the system,
$T_{\gamma\, p \to m\, p}$: The $\gamma\, p$ --> $m\, p$ ($m = \eta, \eta'$) scattering amplitude.

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

2. Formulation

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

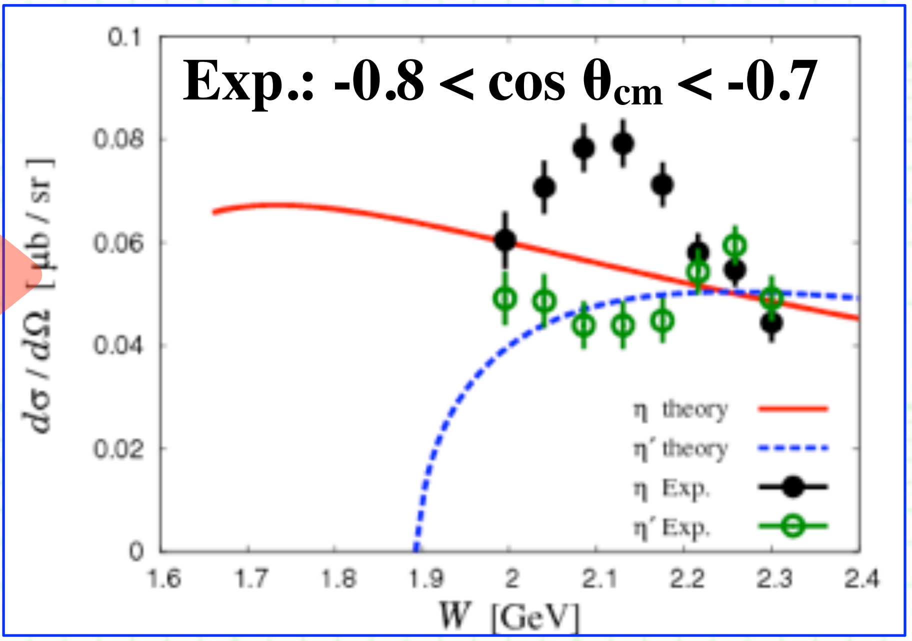
- We first consider **the free proton $\gamma\, p$ --> $\eta\, p$ and $\eta'\, p$ reactions** as an elementary part of the photoproduction on a deuteron target.



□ 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.

Sumihama *et al.* (2009).



□ We employ the constant amplitude

$$T_{\gamma p \to \eta p} = 0.362\ \mathrm{GeV}^{-1}, \quad T_{\gamma p \to \eta' p} = 0.425\ \mathrm{GeV}^{-1}$$

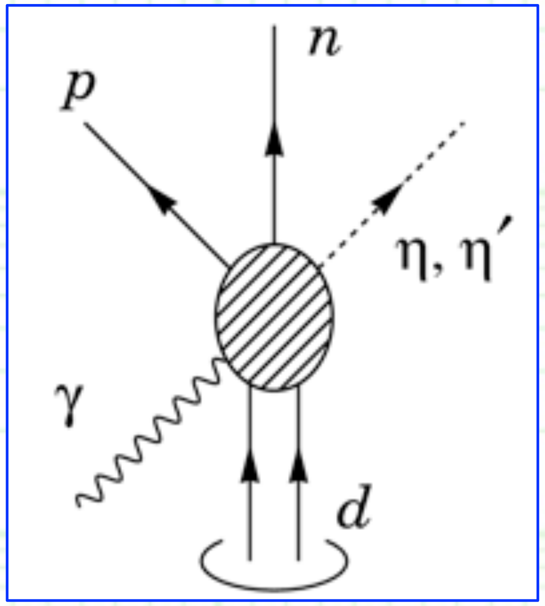
to reproduce roughly the LEPS data.

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

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.



  - The cross section can be expressed as:

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

--- 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 $\gamma\ d$ --> $p\ X$ ($X = \eta\ n, \eta'\ n$) scattering amplitude.

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

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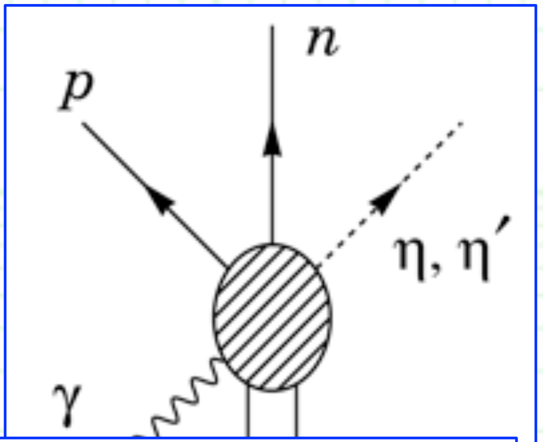
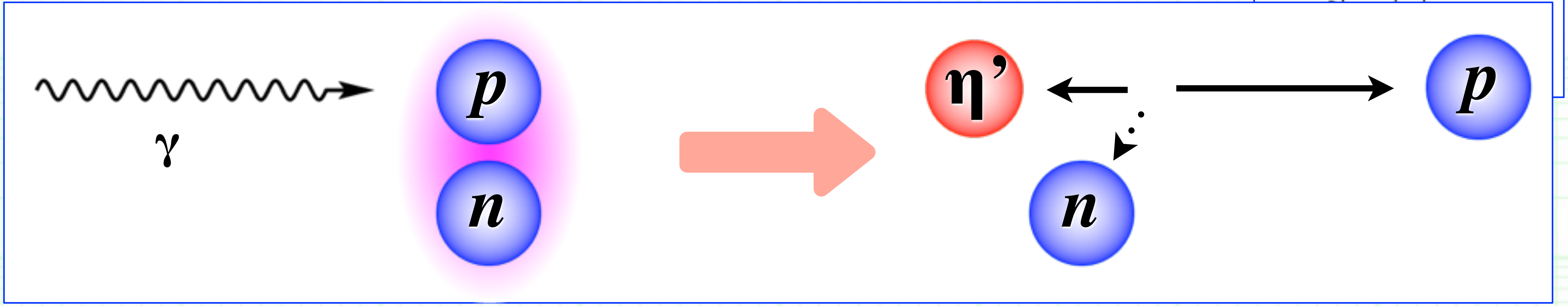
- Next we consider **the $\gamma\ d$ --> $p\ X$ reaction** with $X = \eta\ n, \eta'\ n$ on a deuteron target.



  - In this study we calculate the $\gamma\ d$ --> $p\ X$ amp. from **diagrams favored by the kinematics** of <u>the forward fast proton emission</u>.



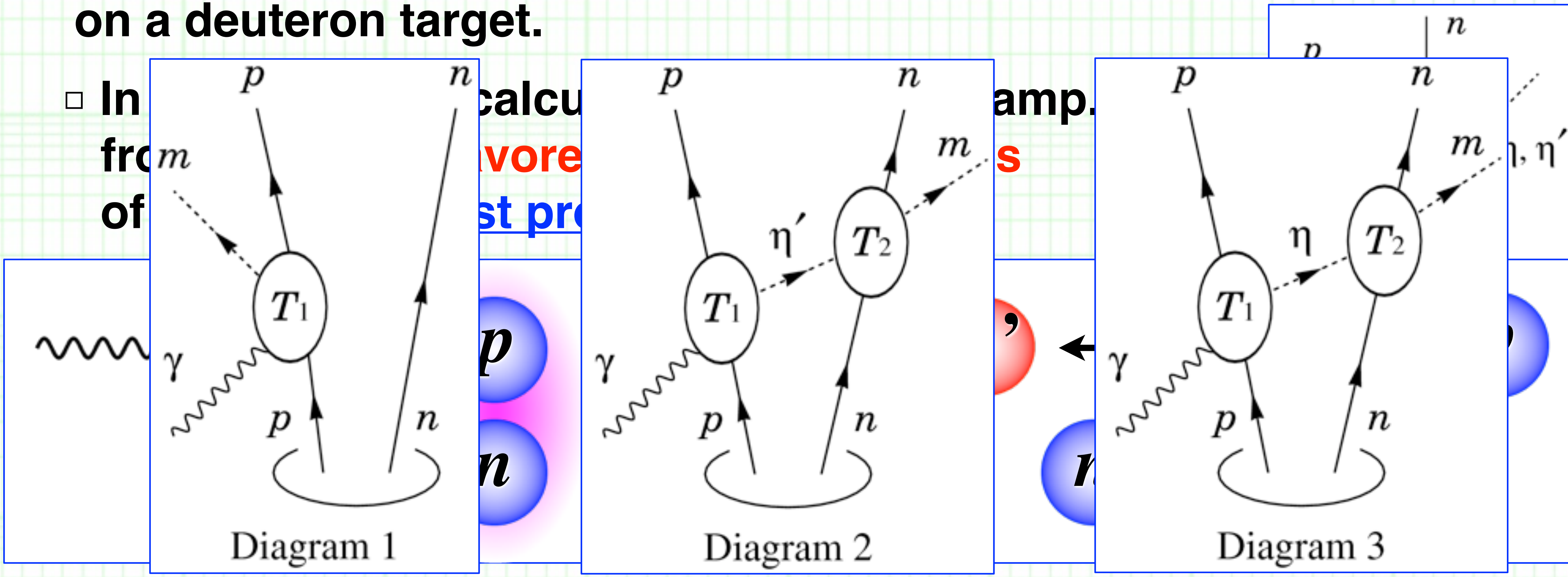
--- 1. Single scattering on a bound proton.
2. Double scattering with $\eta'\ n$ --> X transition --- <u>η' exchange</u>.
3. Double scattering with $\eta\ n$ --> X transition --- η exchange.

2. Formulation

++ γ *d* --> *p X* reaction with *X* = η *n*, η’ *n* ++

- Next we consider **the γ *d* --> *p X* reaction** with ***X* = η *n*, η’ *n*** on a deuteron target.

  - In … calcu … amp.
    fro … vore … s
    of … st pro …



--- 1. Single scattering on a bound proton.
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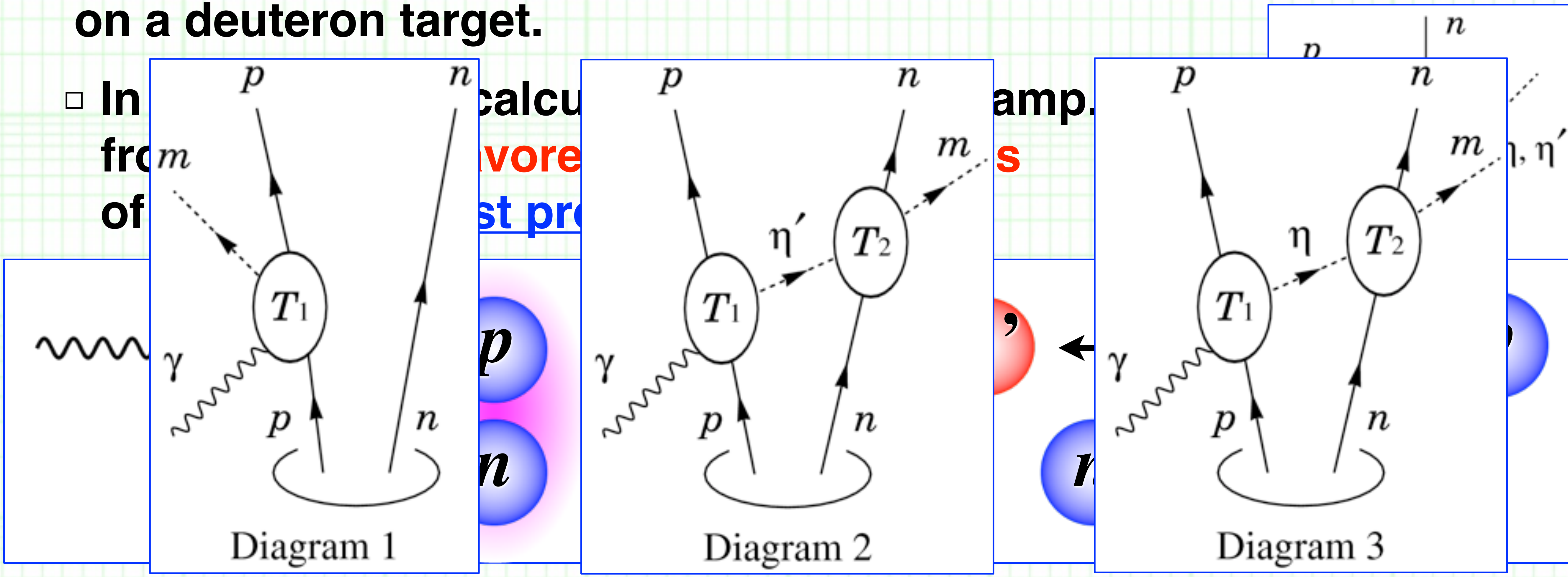
3. Double scattering with η *n* --> *X* transition --- η exchange.

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. fr … vore … s of … st pr …



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

2. Formulation

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- 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).

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

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

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

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

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

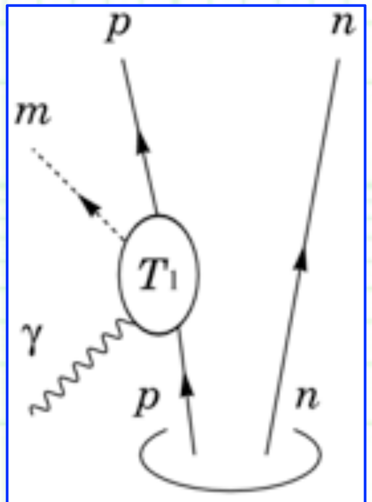

Diagram 1

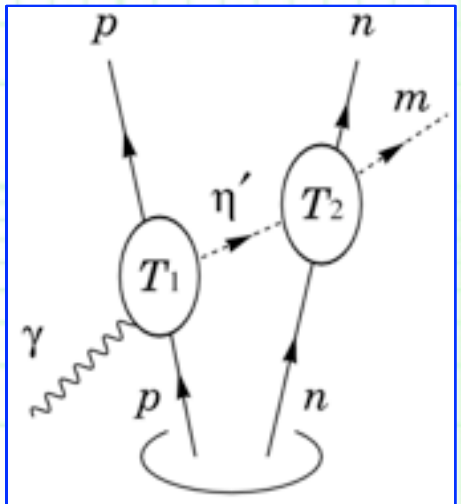

Diagram 2

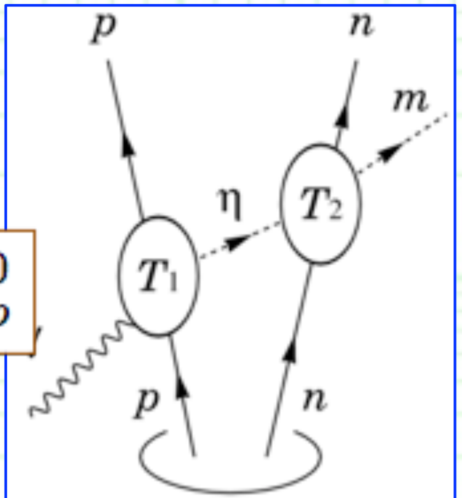

Diagram 3

2. Formulation

++ γ *d* --> *p X* reaction with *X* = η *n*, η' *n* ++

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

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

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

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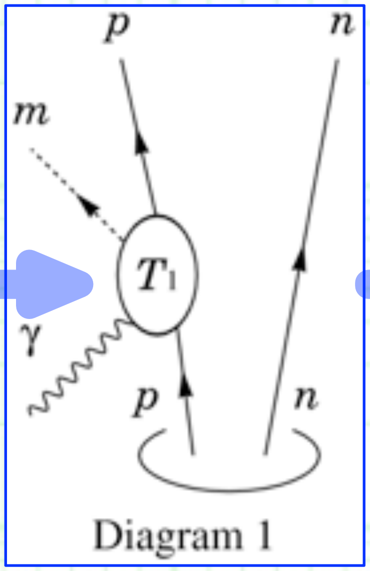
$$q^0 = M_p + E_\gamma^{\text{lab}} - p_p^0$$

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



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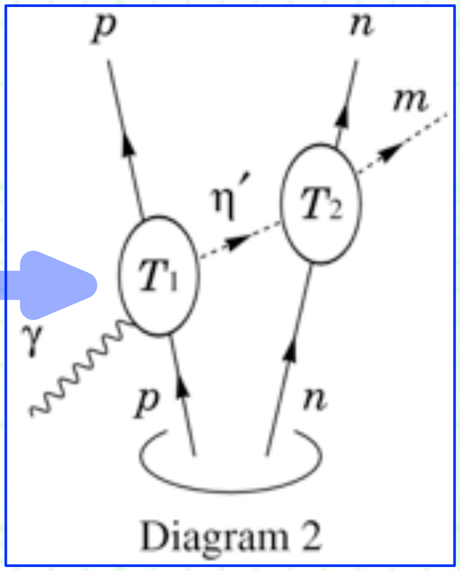

Diagram 2

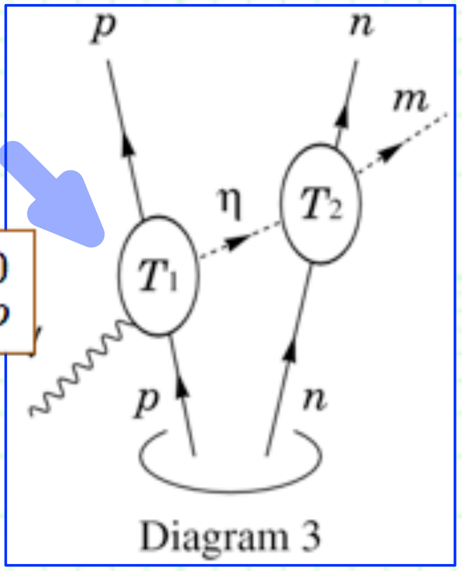

Diagram 3

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

++ γ *d* --> *p X* reaction with *X* = η *n*, η' *n* ++

- Next we consider **the γ *d* --> *p X* reaction** with ***X* = η *n*, η' *n*** on a deuteron target.
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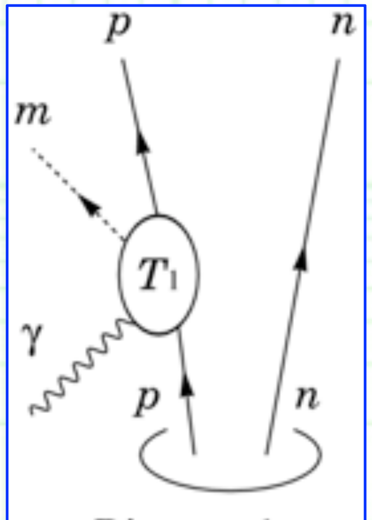

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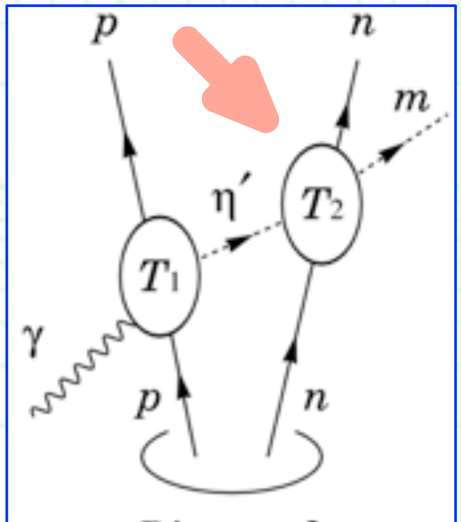

Diagram 2

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

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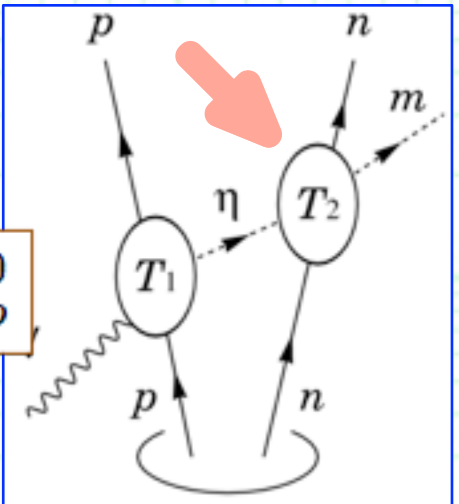

Diagram 3

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

2. Formulation

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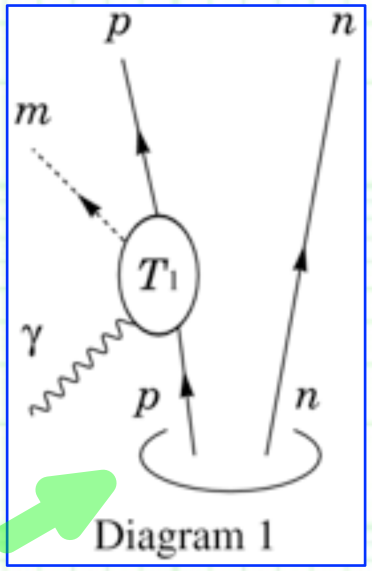

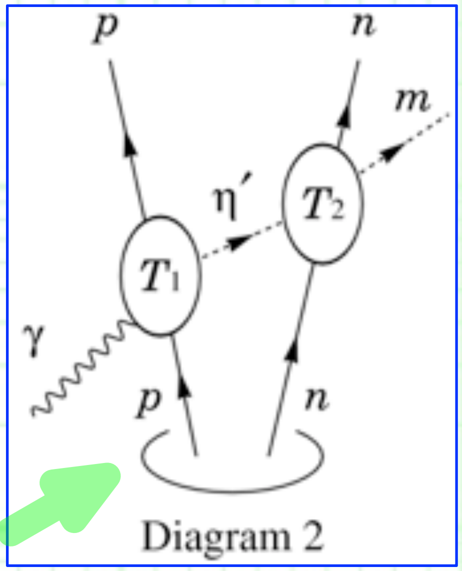

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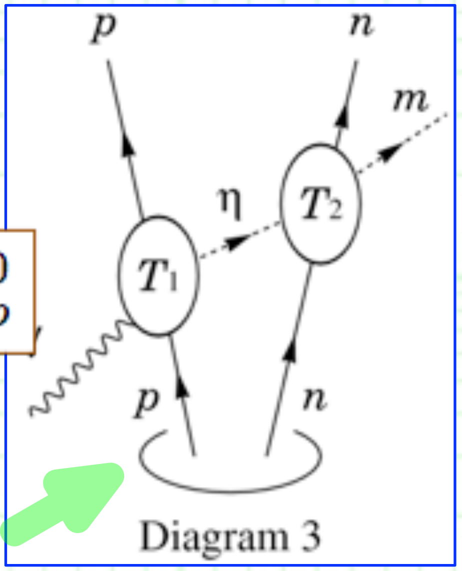


3. Deuteron wave function is an analytic form taken from the Bonn potential with s wave only:

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

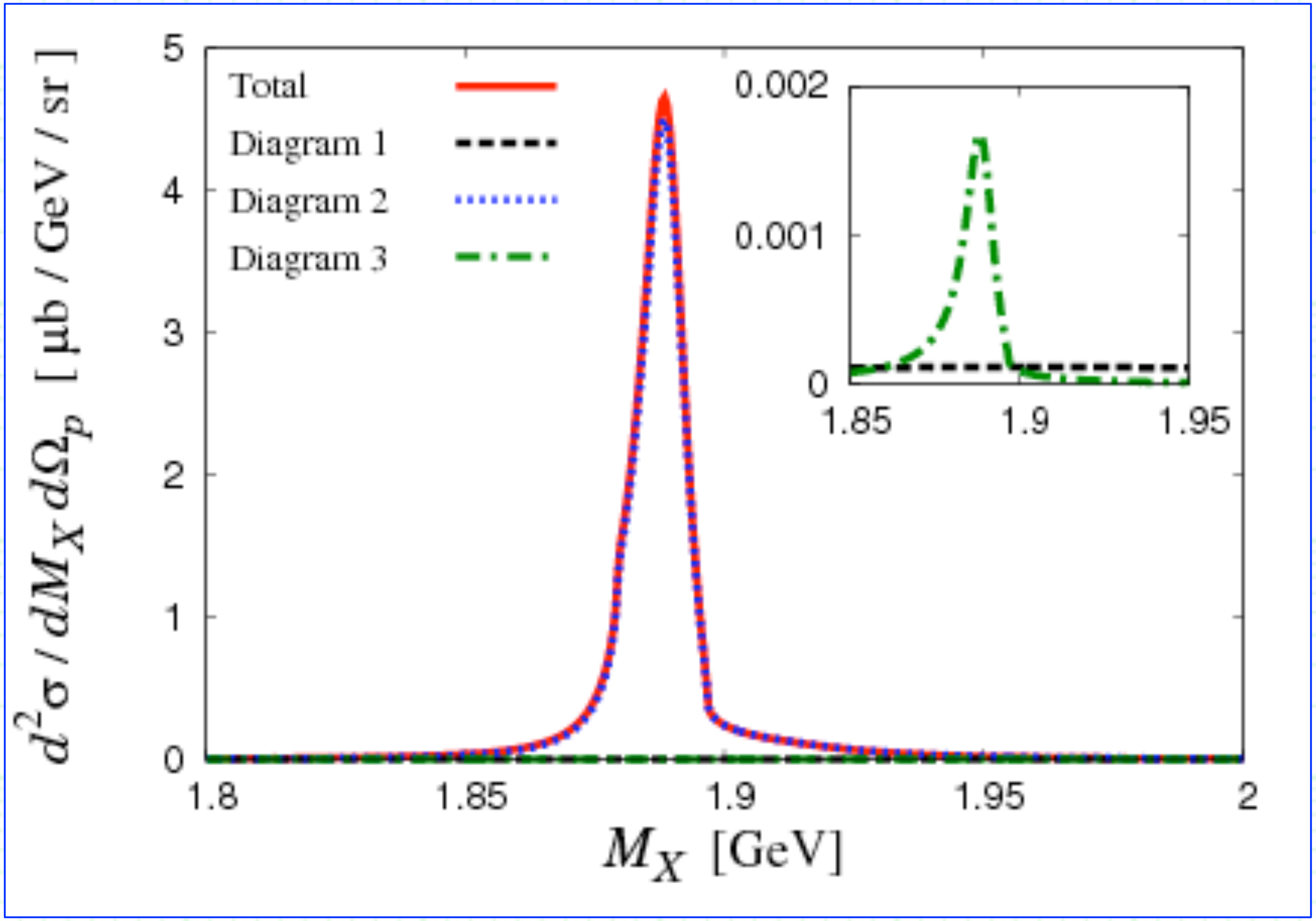
Machleidt, *Phys. Rev.* C63 (2001) 024001.

3. Results and discussions

3. Results and discussions

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

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



3. Results and discussions

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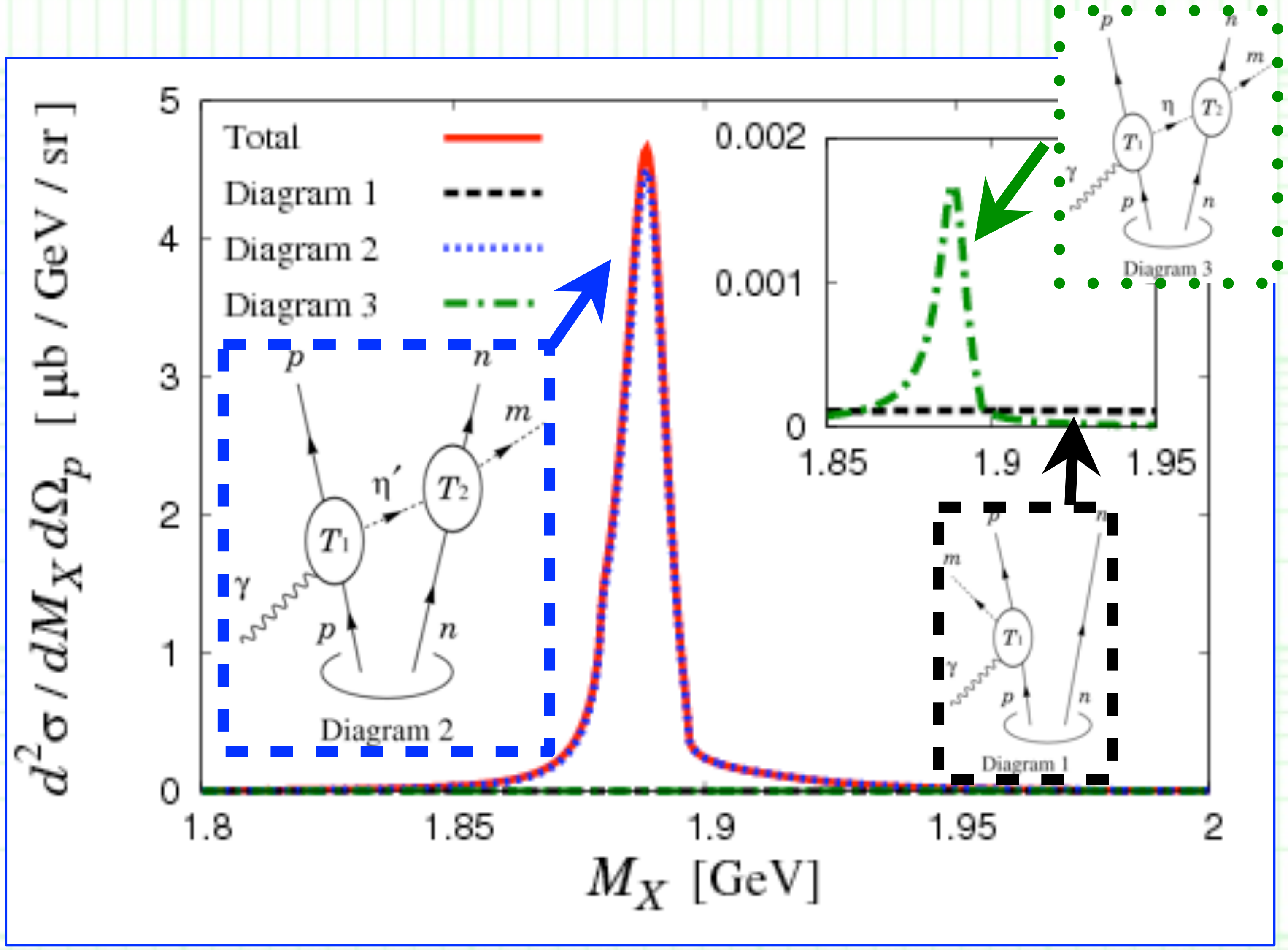
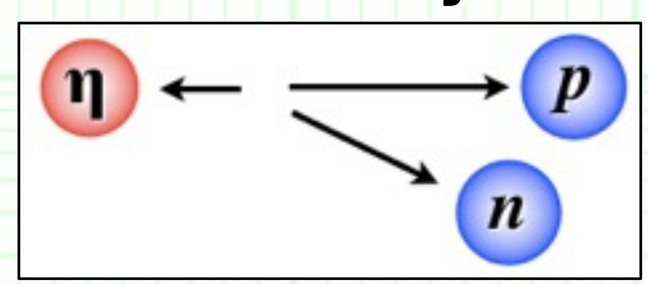


- The signal of the η' n bound state is dominated by Diag. 2 (η' exchange).

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

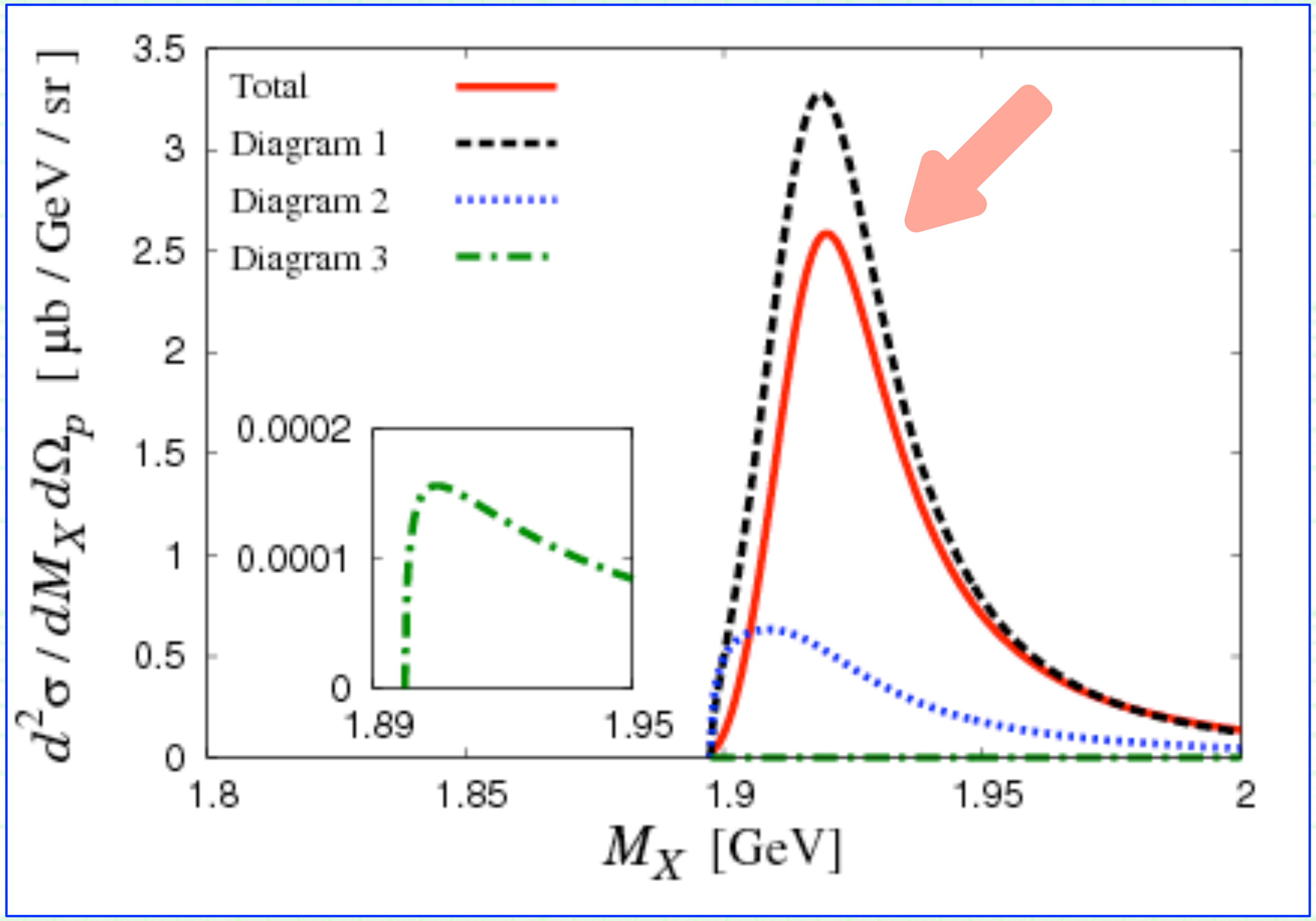
- Diag. 1 is negligible since large Fermi motion is necessary:



3. Results and discussions

++ $\gamma\ d$ --> $p\ \eta'\ n$ 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 $\eta'\ n$ bound state.

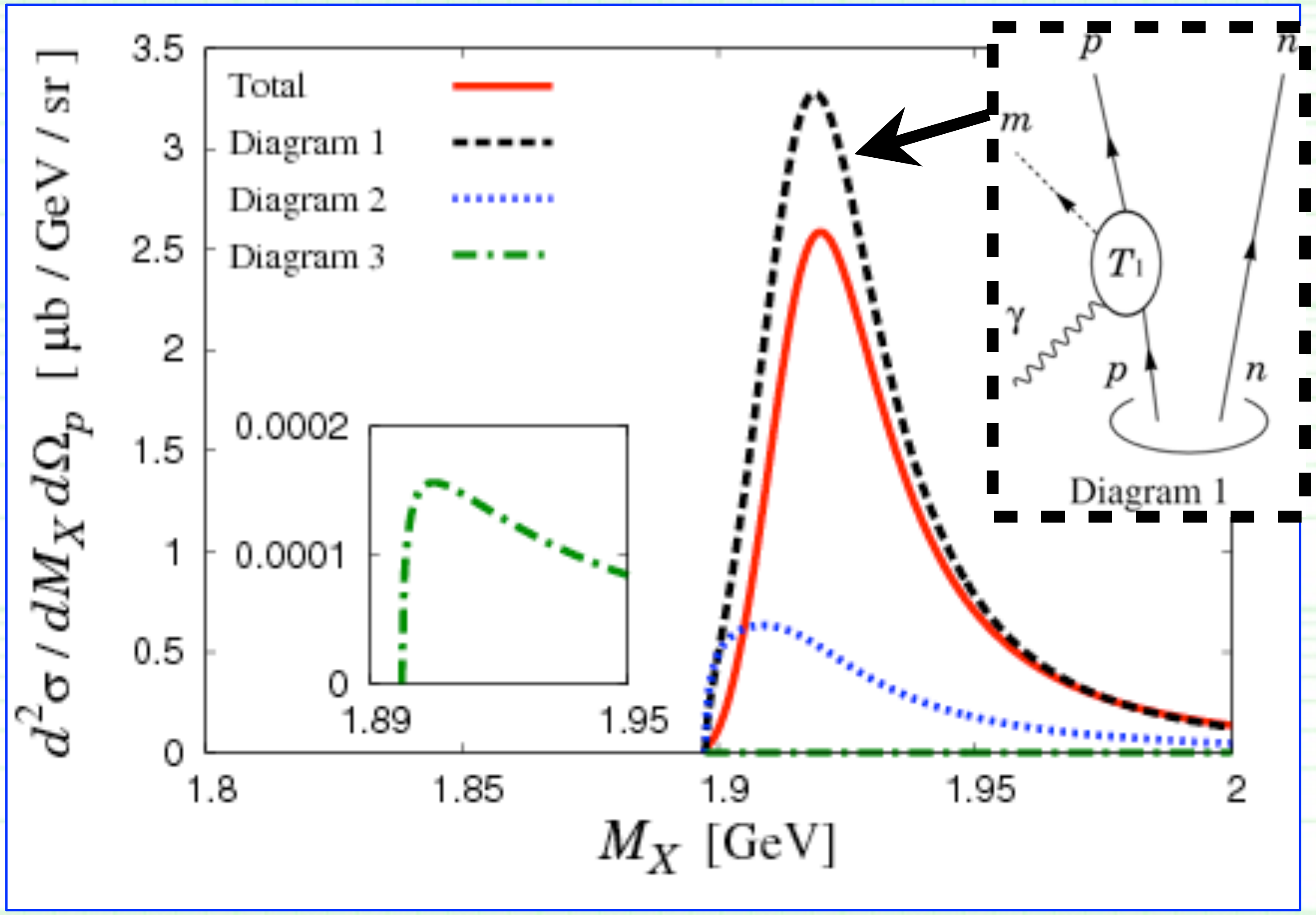


- We find quasi-free η' production peak just above the $\eta'\ n$ threshold.

3. Results and discussions

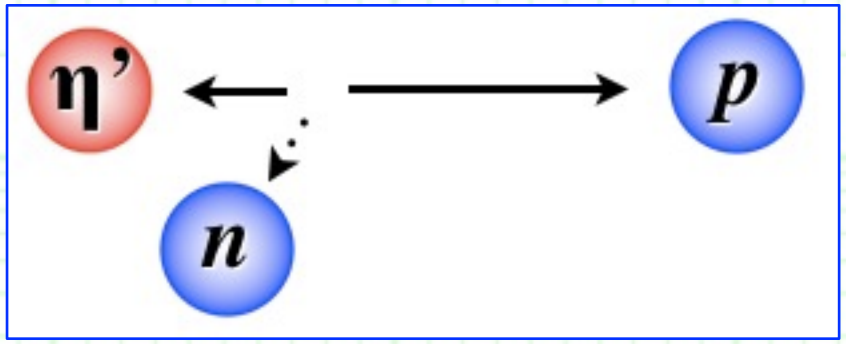
++ $\gamma\, d \to p\, \eta'\, n$ reaction ++

- 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.

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

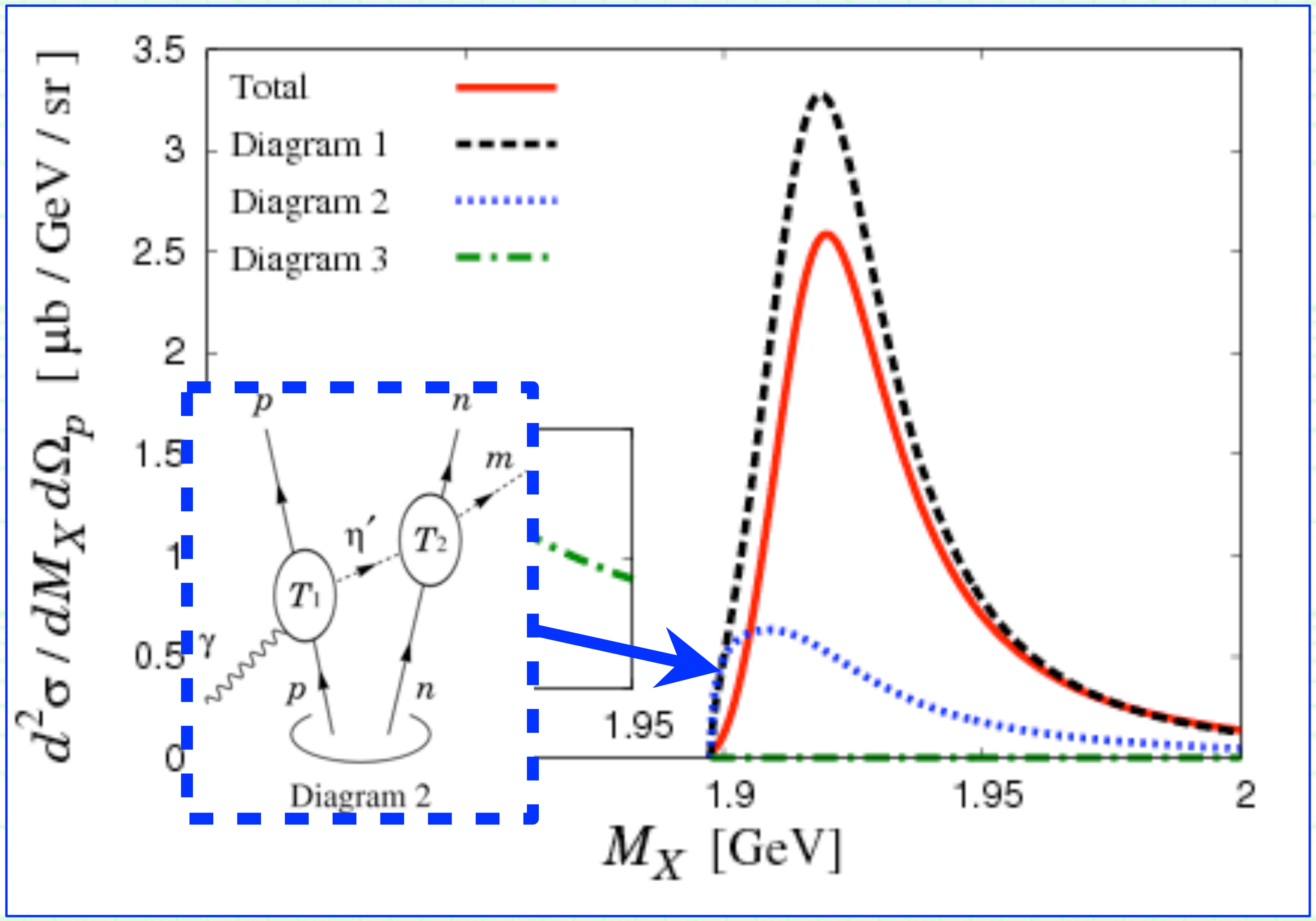


--- The invariant mass $M_X = M_{\eta' n}$ becomes small for forward proton emission.

3. Results and discussions

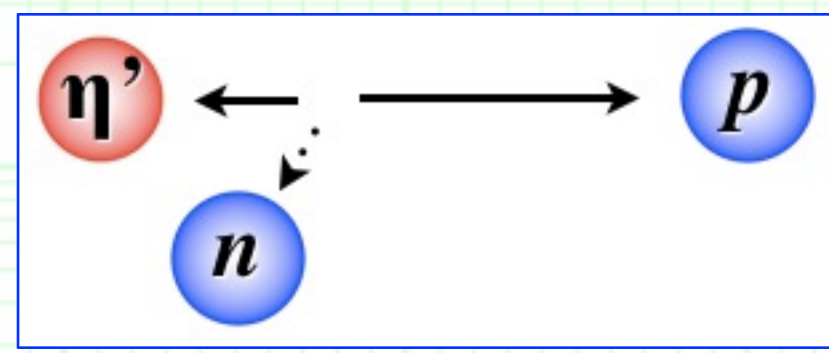
++ $\gamma\, d \to p\, \eta'\, n$ reaction ++

- We next consider $\gamma\, d \to p\, \eta'\, n$ reaction with $E_\gamma^{\rm lab} = 2.1$ GeV, $\theta_p = 0^{\rm o}$ 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.

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



□ However, the η'-exchange double scattering is non-negligible.

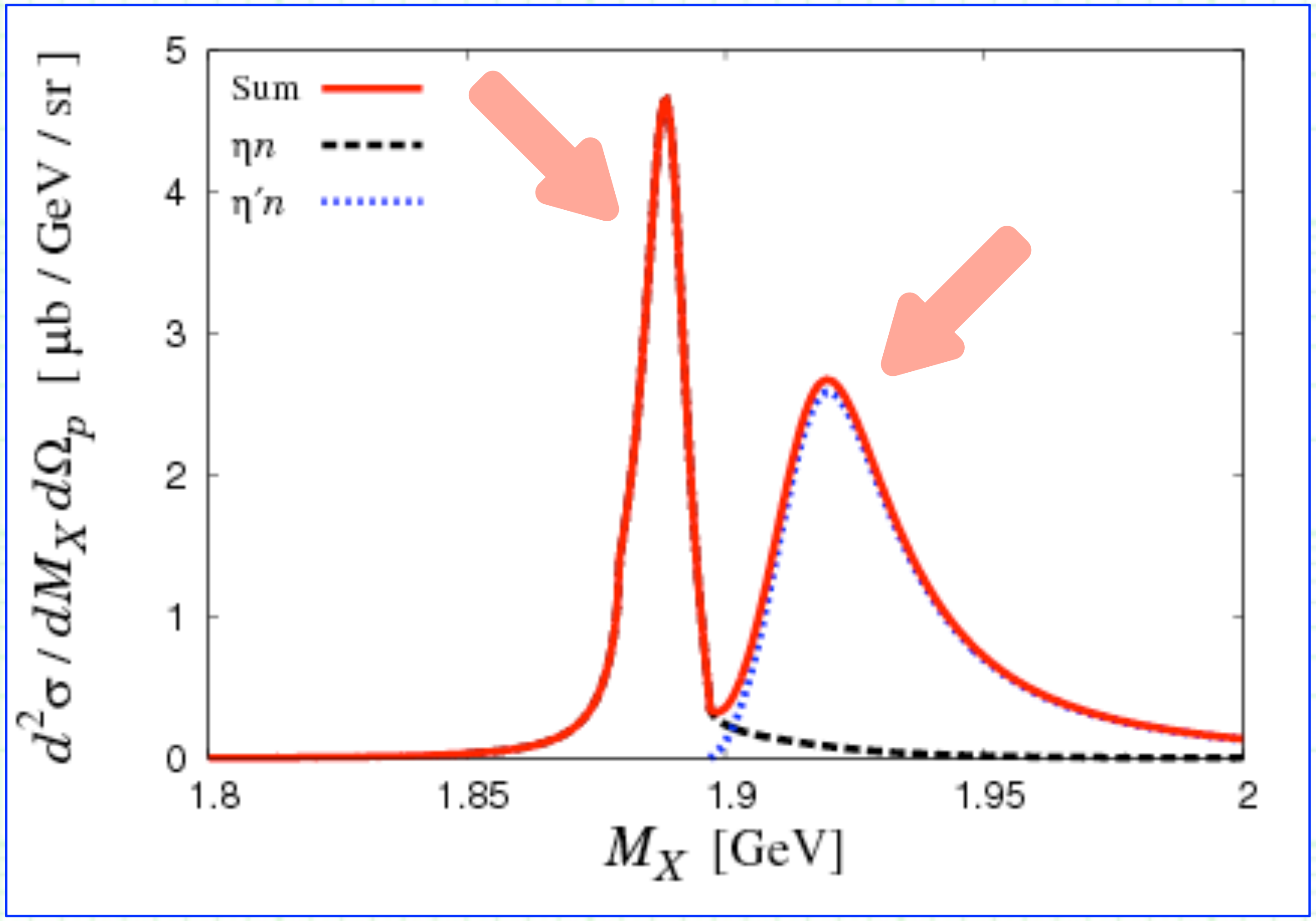
--- Almost on-shell η' and large magnitude of the amplitude $T_{\eta' n \to \eta' n}$

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 $E_{\gamma}^{\rm lab} = 2.1$ GeV, $\theta p = 0^{\circ}$.



- 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**.

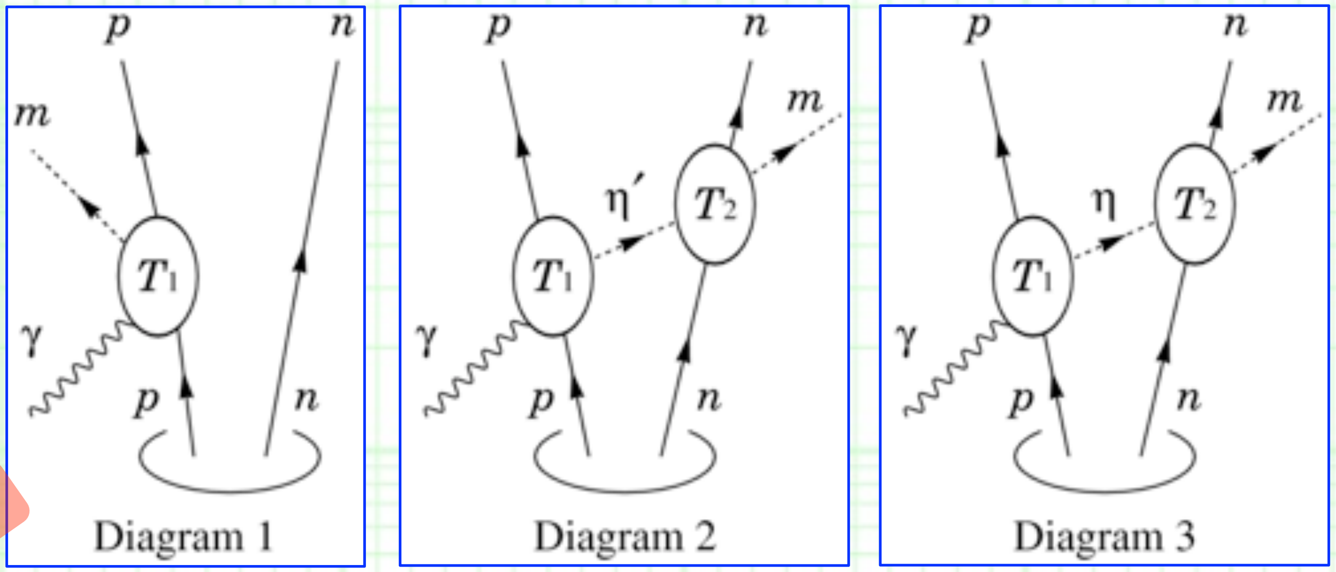
--> In our model we **can observe the signal** of the $\eta'\, n$ bound state.

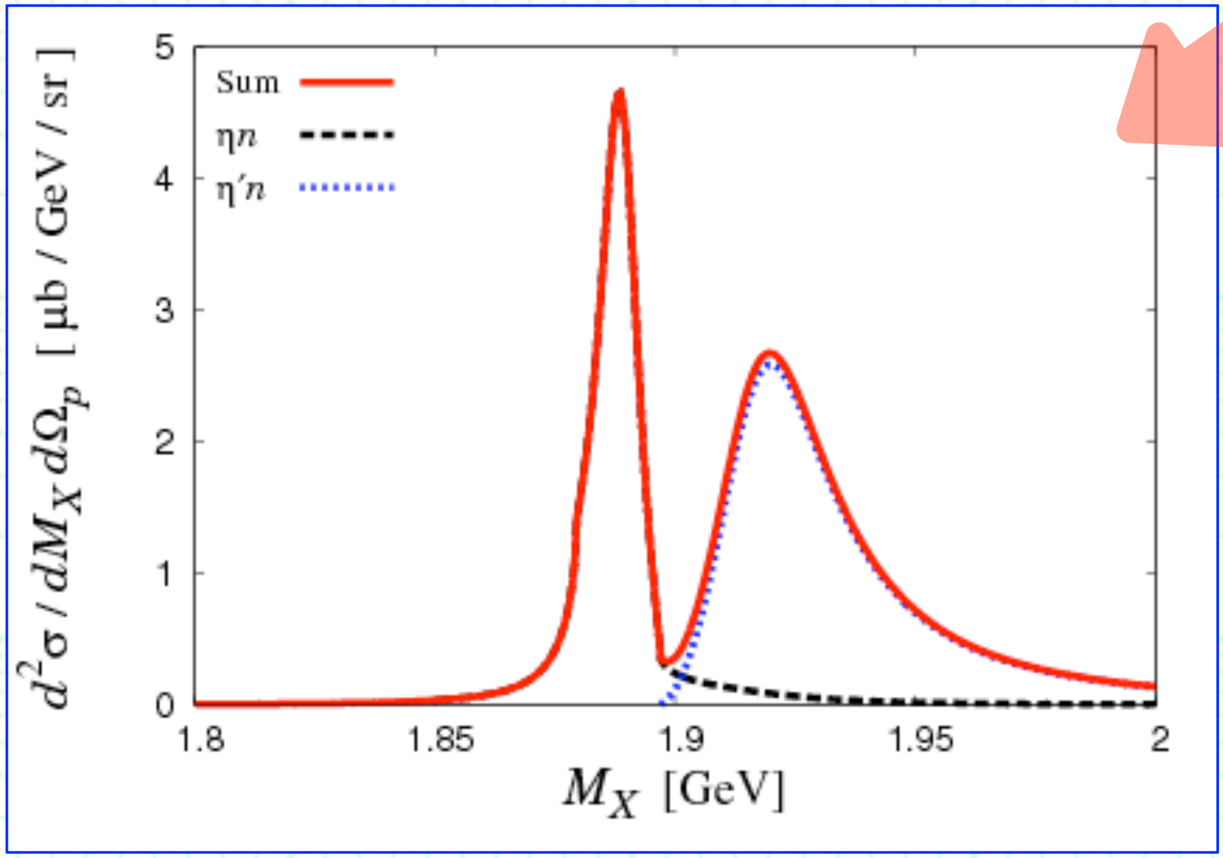
3. Results and discussions

++ From numerical results ... ++

- Taking into account three diagrams, which are relevant to our kinematics of the forward proton emission, we can calculate the differential cross section.

--> The η' n bound state can be produced by the η'-exchange double scatt., and quasi-free η' by the single scatt.





- From the numerical results of the differential cross section, the signal of the η' n bound state is comparable to the quasi-free η'.

--> In our model we can observe the signal of the η' n bound state.

3. Results and discussions

++ Model dependence ++

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

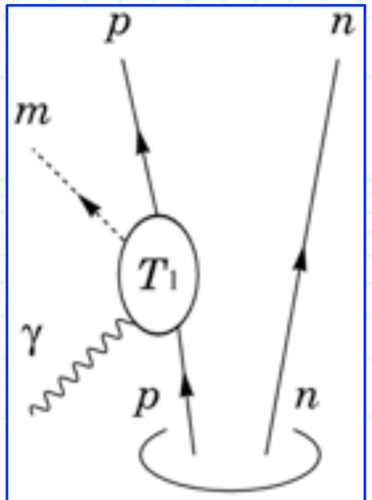


Diagram 1

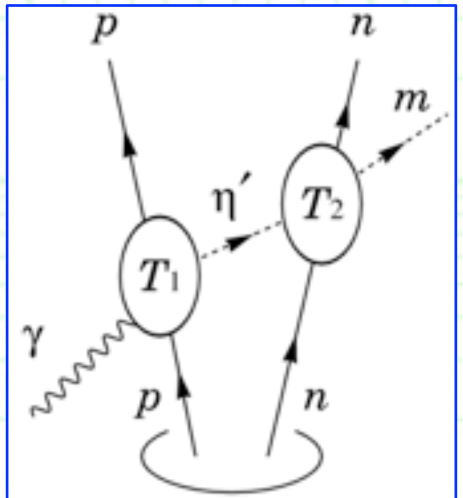


Diagram 2

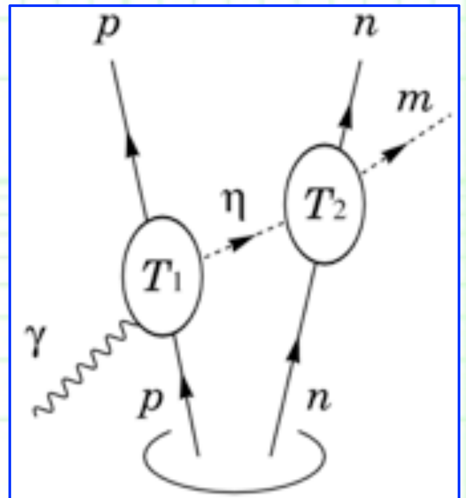
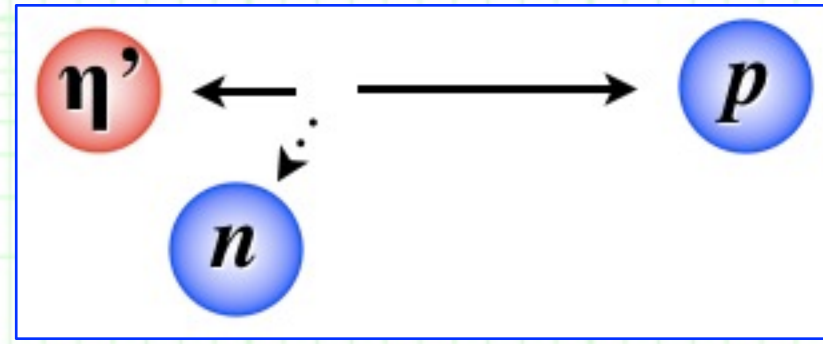


Diagram 3



□ Other diagrams ?

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

□ Improvement of amplitudes $T_{\gamma p \to \eta p, \eta' p}$ (T_1) and $T_{\eta p, \eta' p \to X}$ (T_2).

□ Other prescription to calculate double scattering (Diags. 2, 3) ?

--- Discuss the prescription dependence in the next pages.

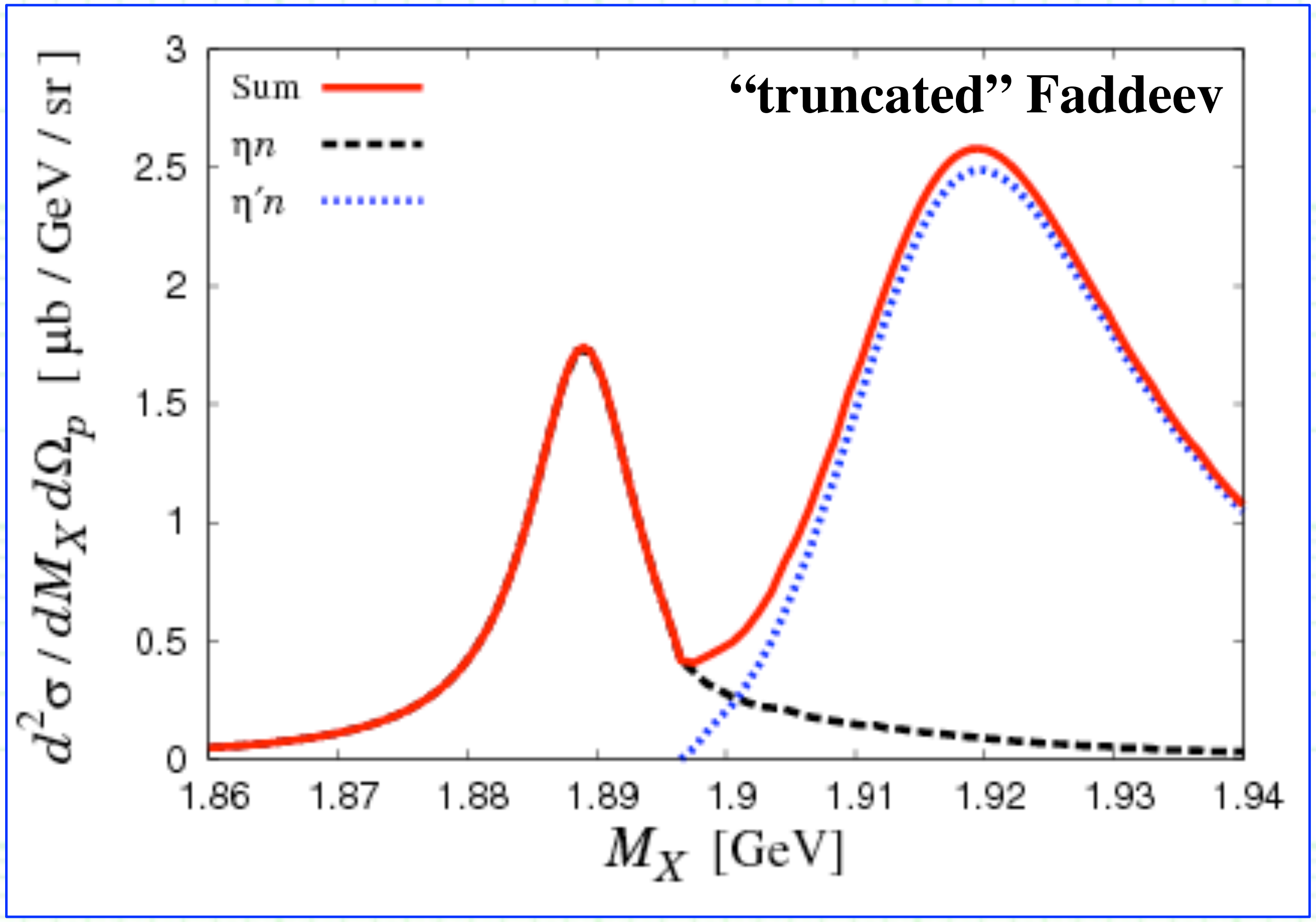
3. Results and discussions

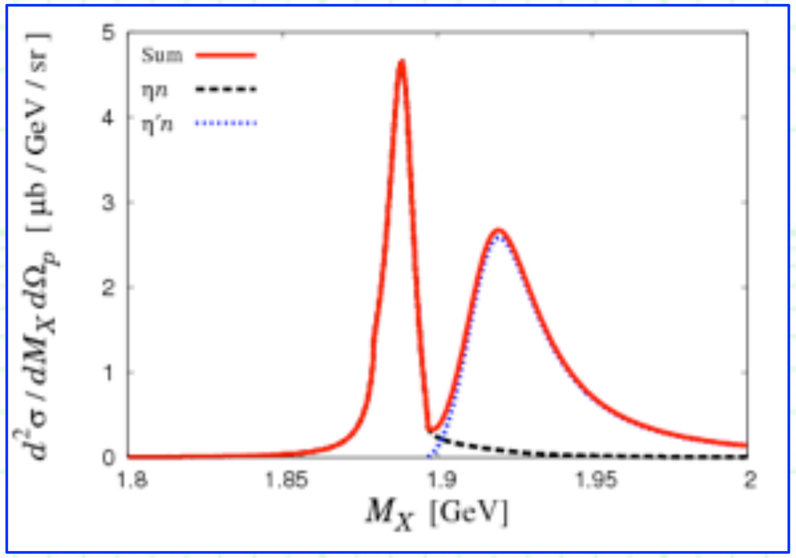
++ Model dependence ++

- Calculate the differential cross section in a different prescription of double scattering (the “truncated” Faddeev approach), in which exchanged η(’) energy is:

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

Miyagawa and Haidenbauer (2012).





- We find the signal of the η’ *n* bound state also in the “truncated” Faddeev approach. (But the signal becomes weak)

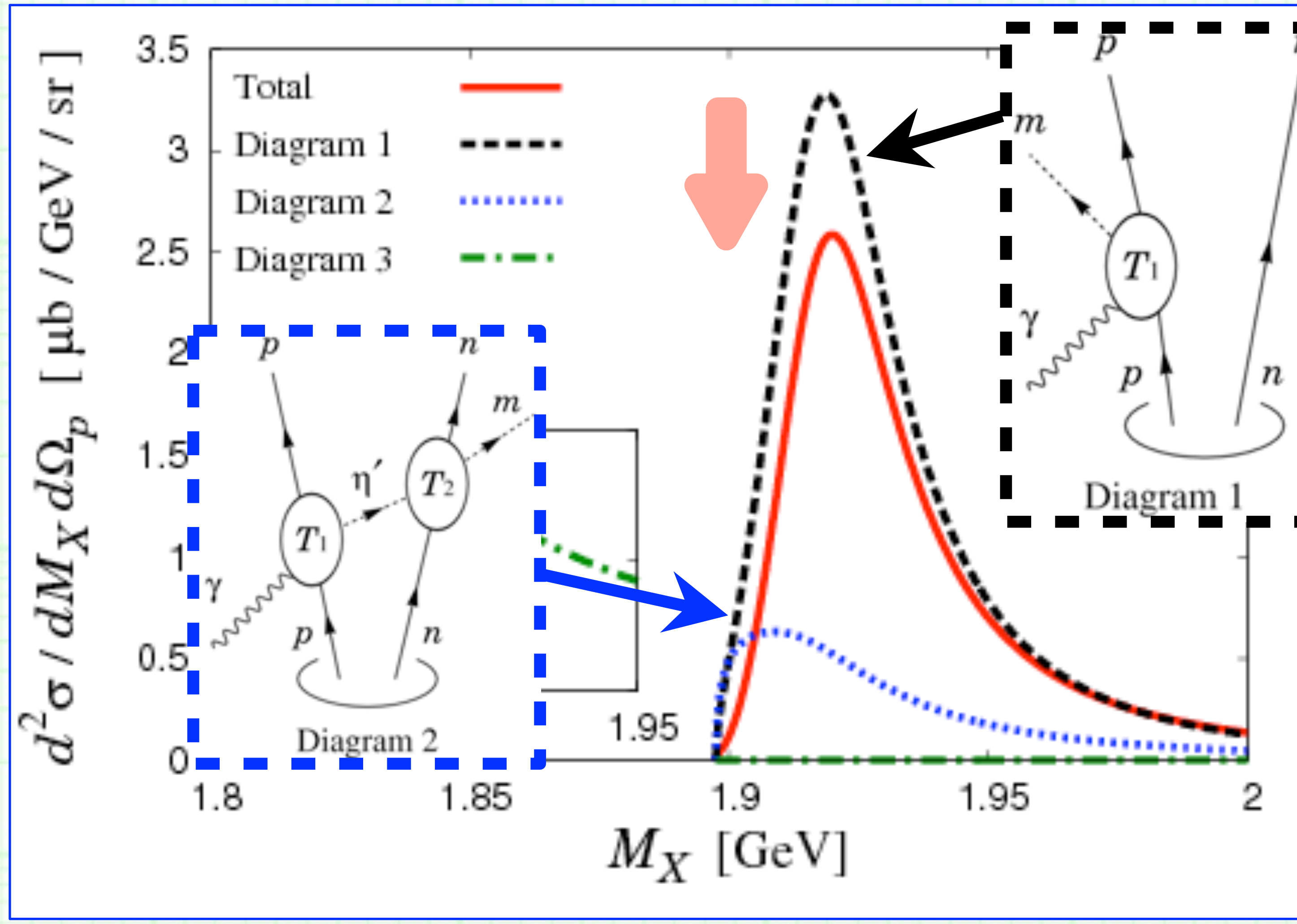
--> The prescription does not contaminate the bound-state signal.

3. Results and discussions

++ Quasi-free η’ production yield ++

- We have found that in
  the $\gamma\ d$ --> $p\ \eta'\ n$ reaction
  the quasi-free η’ production is slightly suppressed
  (~ 80 -- 90 %)
  due to the η’-exchange double scattering.

--- Absorption of η’
    with large Im[$T_{\eta' n \to \eta' n}$].



- Is there any possibility
  to observe the suppression of the production yield in Exp. ?

--- Reference: Free-proton cross section.

--> Calculate the total cross section of the quasi-free η’ production on a deuteron with forward angular cut in Lab. frame (cf. LEPS), and compare it with that on a free proton target.

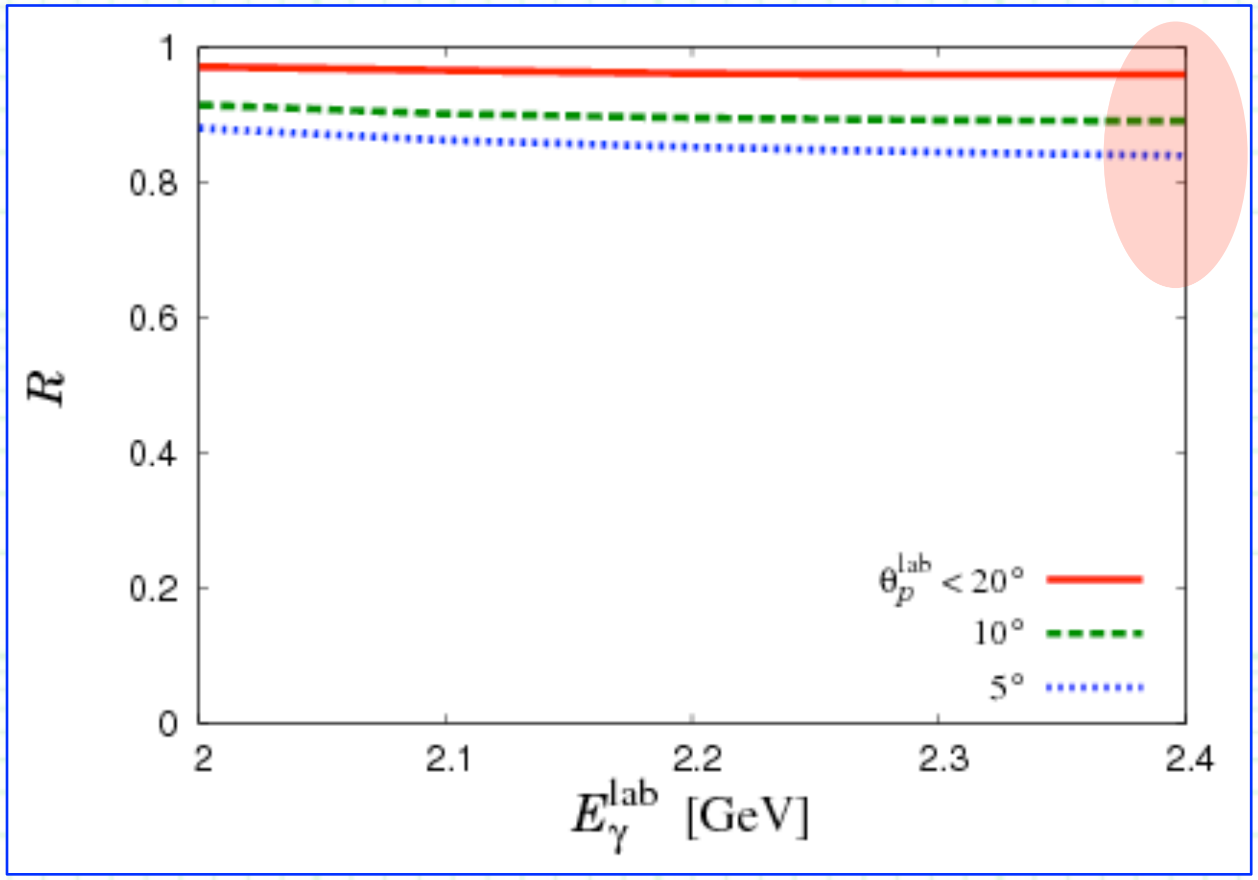
3. Results and discussions

++ Quasi-free η' production yield ++

- We **define the ratio R of the two total cross sections**:

$$R \equiv \left[\frac{\sigma_{\gamma d \to p\eta' n}}{\sigma_{\gamma p \to p\eta'}} \right]_{\theta_p^{\rm lab} < \theta_{\rm upper\ limit}}$$

--- Since a bound proton is nearly on-shell and at rest in a deuteron, the ratio R is almost unity if the double scattering is negligible. (cf. similar ratio for the quasi-free η (not η') production is > 0.98.)



- The ratio becomes smaller as the angular cut decreases, since the momentum matching between η' and n becomes better.
- **The ratio is $R \sim 0.84$ at $E_\gamma^{\rm lab} = 2.4$ GeV, $\theta_p^{\rm lab} < 5^{\rm o}$.**

3. Results and discussions

++ Quasi-free η’ production yield ++

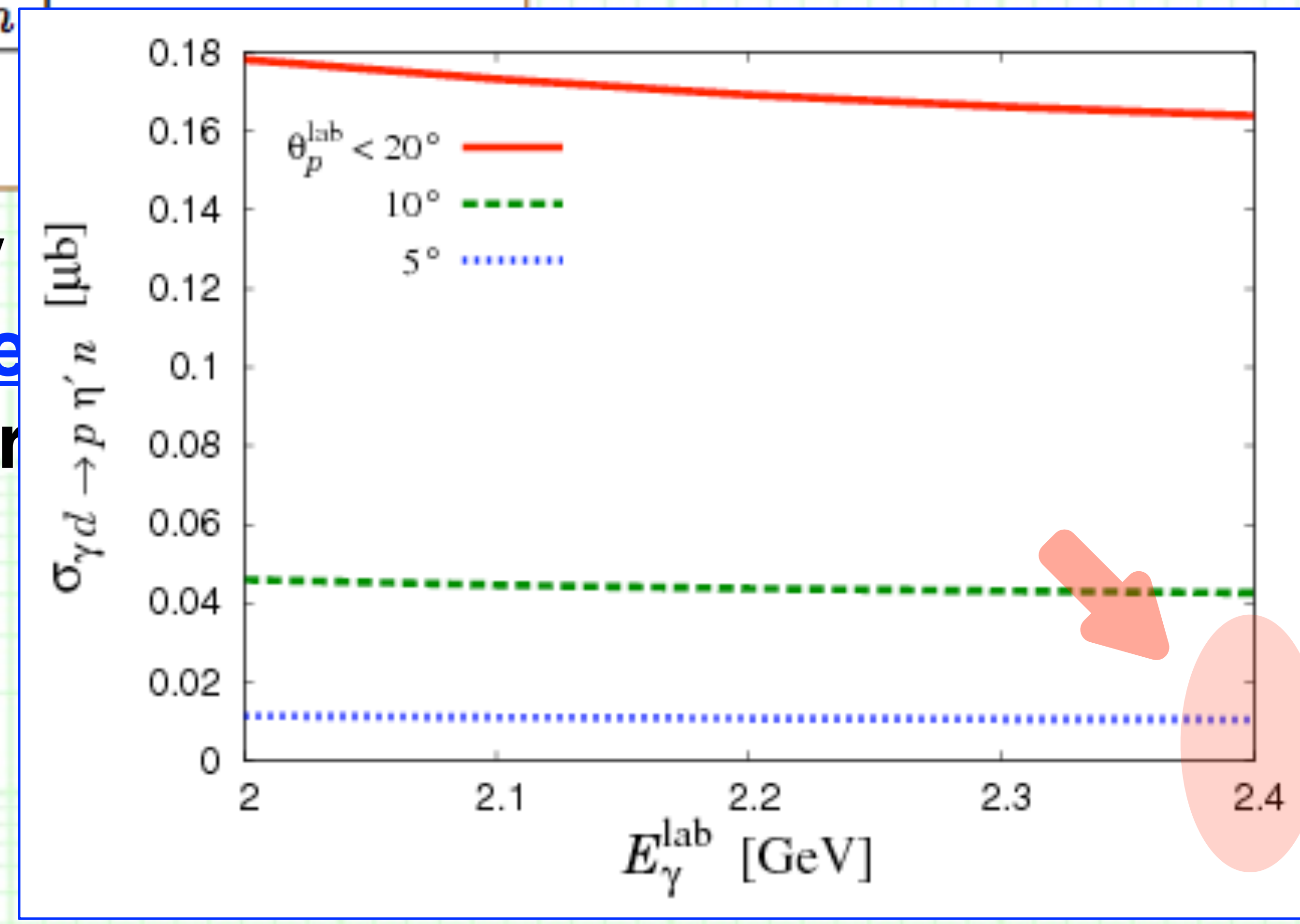
- We **define the ratio R of the two total cross sections**:

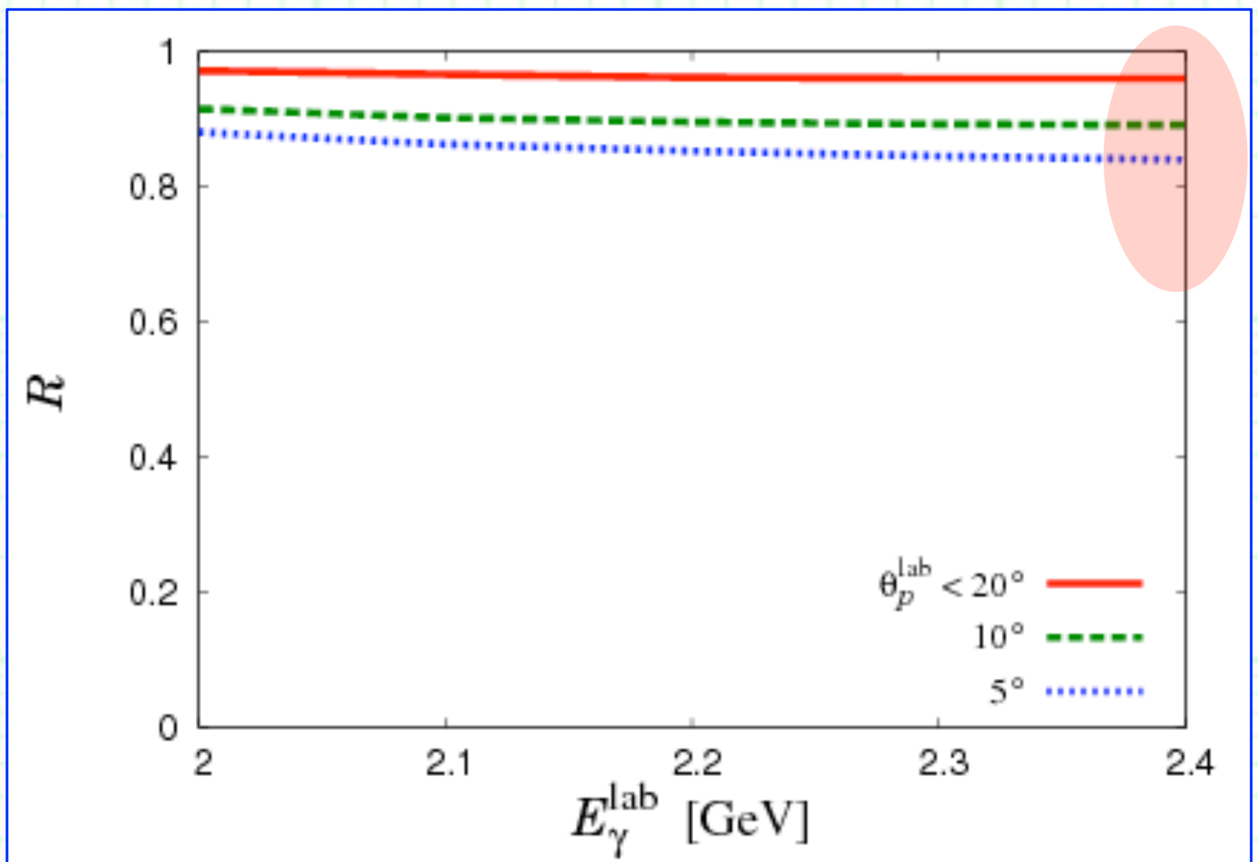
$$R \equiv \left[\frac{\sigma_{\gamma d \to p\eta' n}}{\sigma_{\gamma p \to p\eta'}} \right.$$

--- Since a bound proton is nearly

the ratio R is almost unity if the

(cf. similar ratio for the quasi-fr





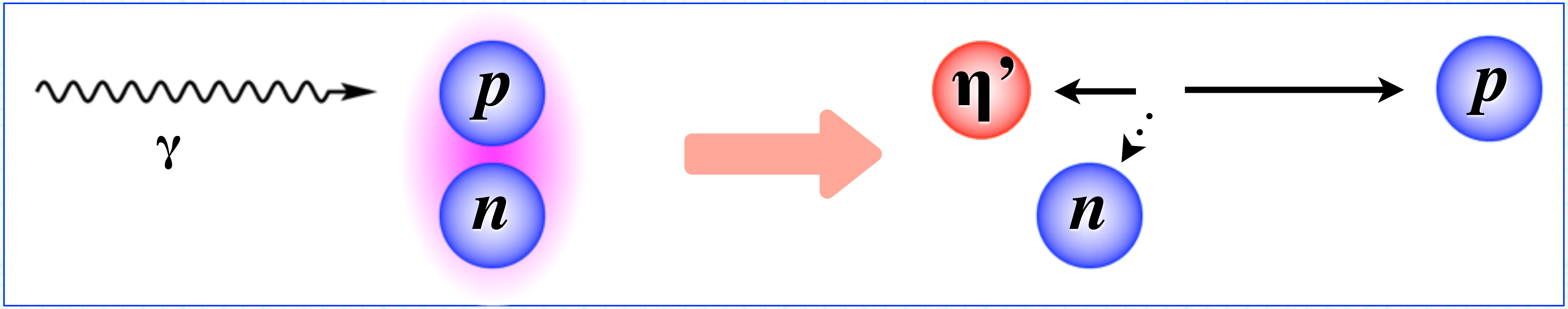
- However, at E_γ^{lab} = 2.4 GeV, $\theta_p^{lab} < 5^o$ **the total cross section is small** (~ 10 nb).

4. Summary

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 **observe the bound-state signal against the quasi-free η'**.

- 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

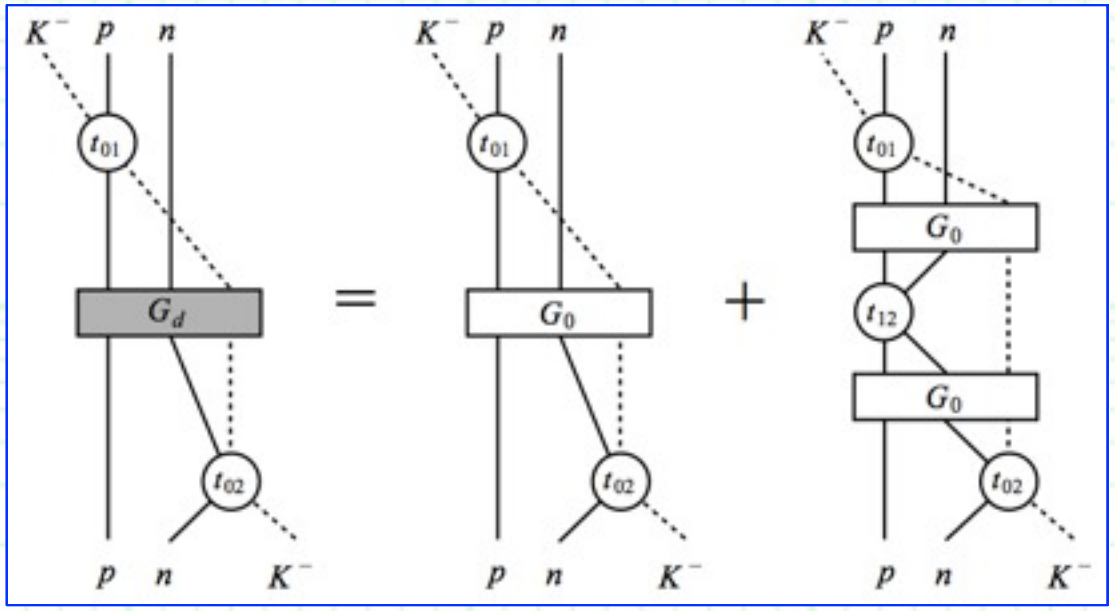
3. Results and discussions

++ 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**.

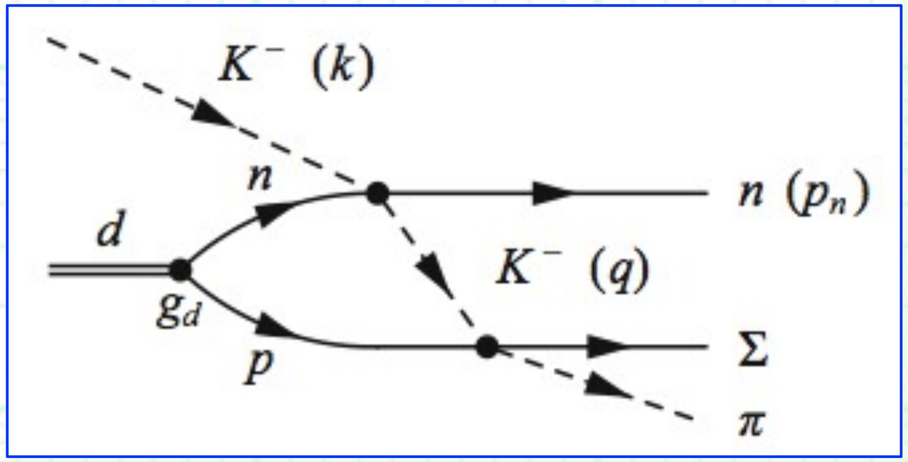


D. Jido, E. Oset and T. S. (2013).

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

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 ?