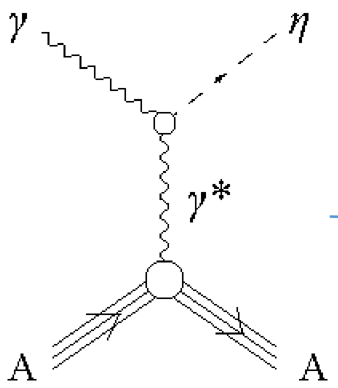
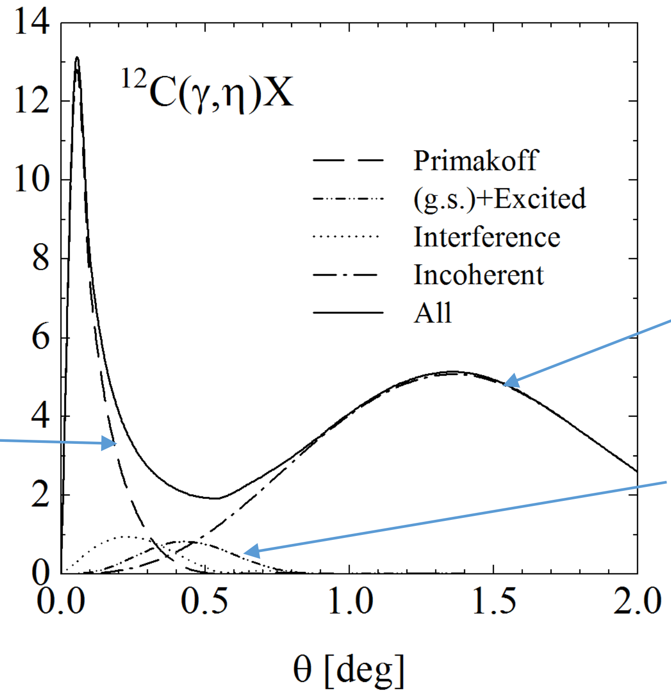
Photoproduction of π^0, η, η' on $d, {}^4He, {}^{12}C, {}^{208}Pb$

at $\theta \longrightarrow 0,\ E_\gamma > 10$ GeV

Primakoff mechanism



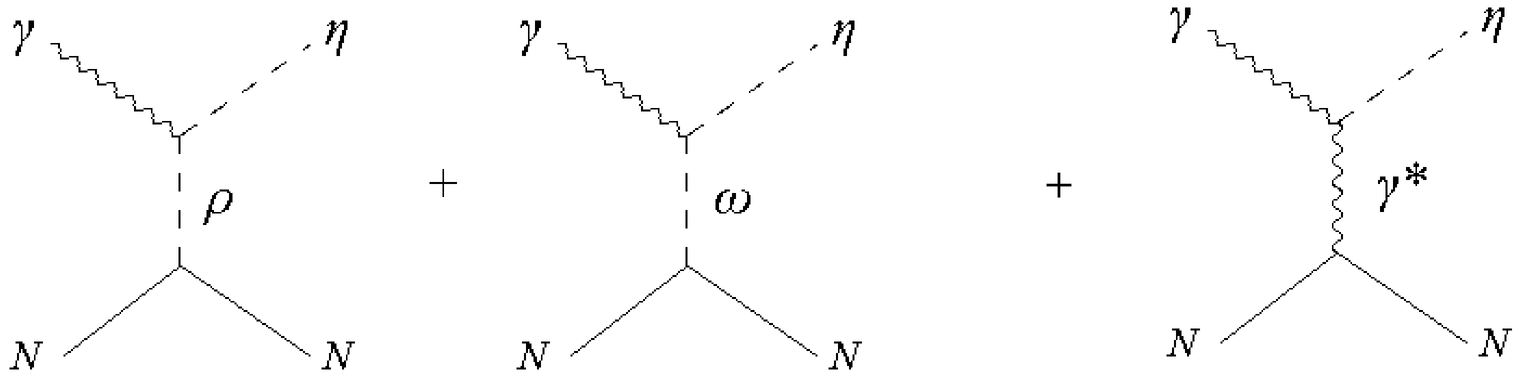


Background

- $\gamma + A \rightarrow \eta + N + (A-1)$
- $\gamma + A \rightarrow \eta + A$
- $\gamma + A \rightarrow \eta + A^*$

Elementary (single-nucleon) amplitude

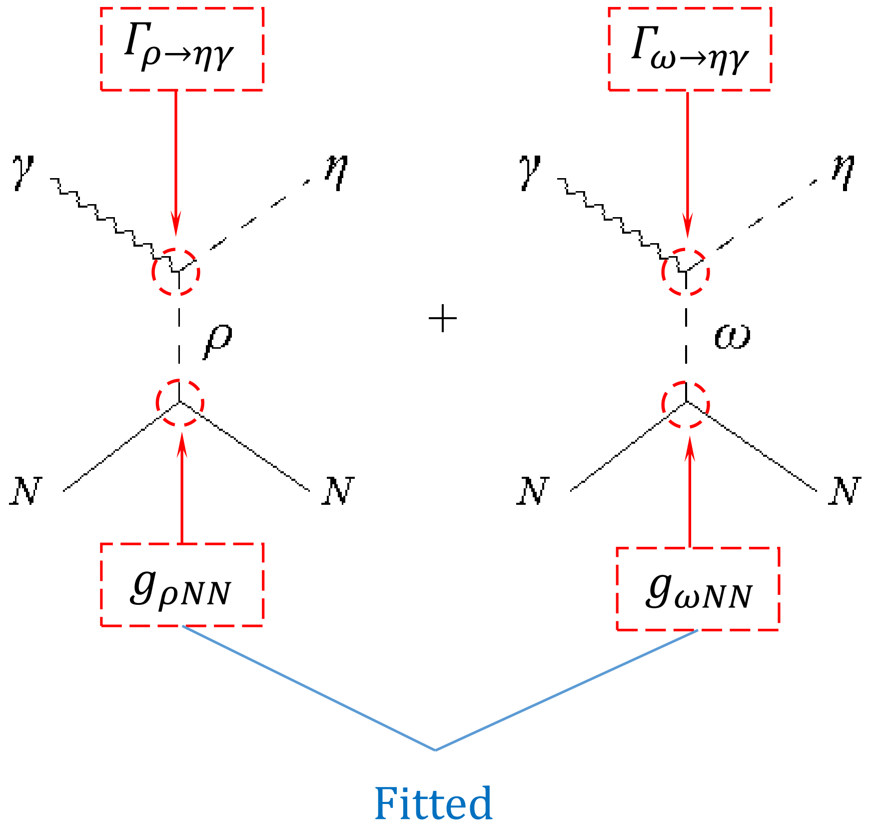
$t_N =$



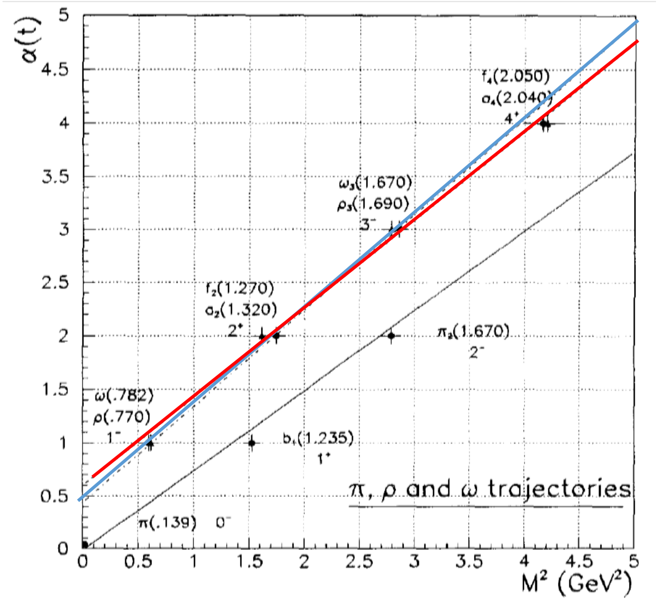
Vector meson exchange
(Regge model)

Primakoff mechanism

Parameters



ρ- and ω- trajectories



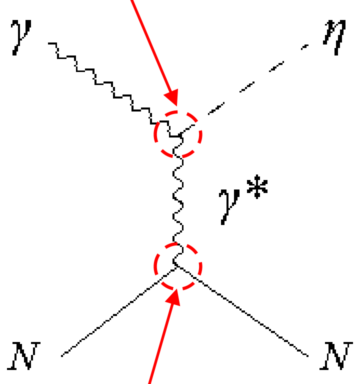
$$\alpha_\rho(t) = 0.55 + 0.8\,t$$

$$\alpha_\omega(t) = 0.44 + 0.9\,t$$

Parameters

Primakoff mechanism

$$H_{\eta\gamma\gamma} = -e\frac{\lambda}{4m_\eta}\varepsilon^{\mu\nu\lambda\sigma}F_{\mu\nu}F_{\lambda\sigma}\varphi_\eta$$



$$H_{\gamma NN} = e\bar{\psi}\gamma^\mu\psi A_\mu + \frac{\kappa_N}{4M_N}\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}$$

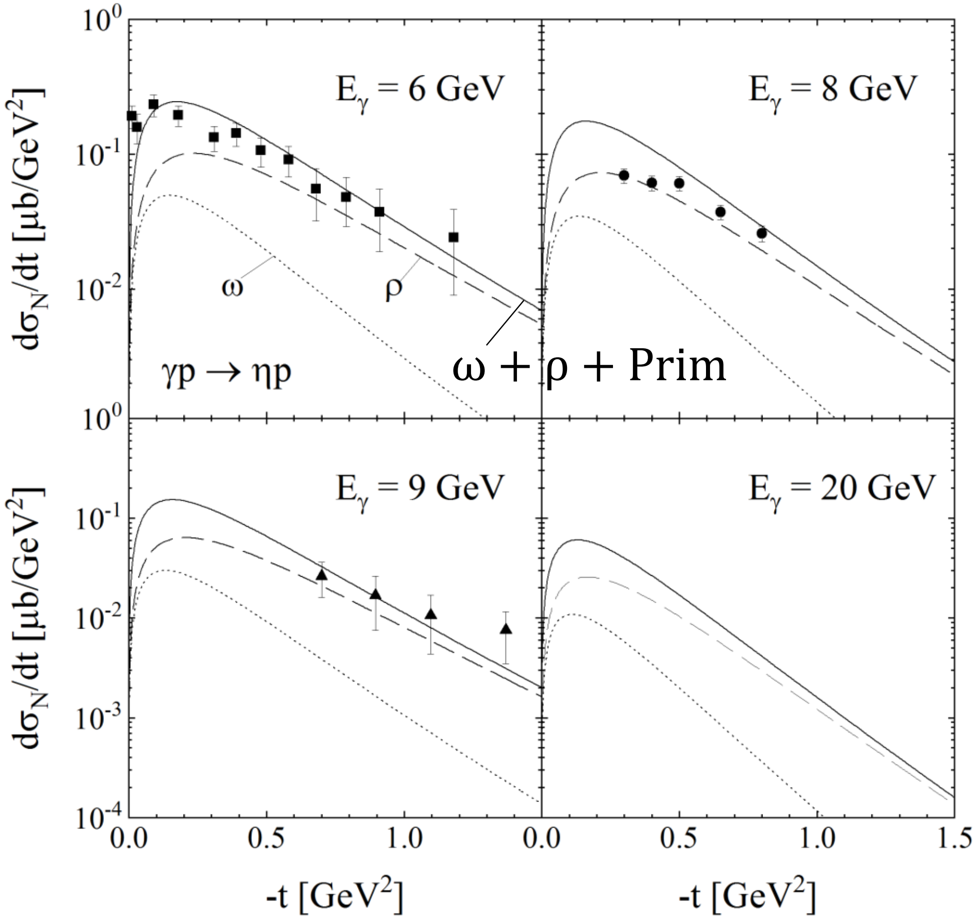
γ^* Propagator :

$$\frac{g^{\mu\nu} - \frac{k^\mu k^\nu}{k^2}}{t} \rightarrow \frac{g^{\mu\nu}}{t}$$ (pole at $t \rightarrow 0$)

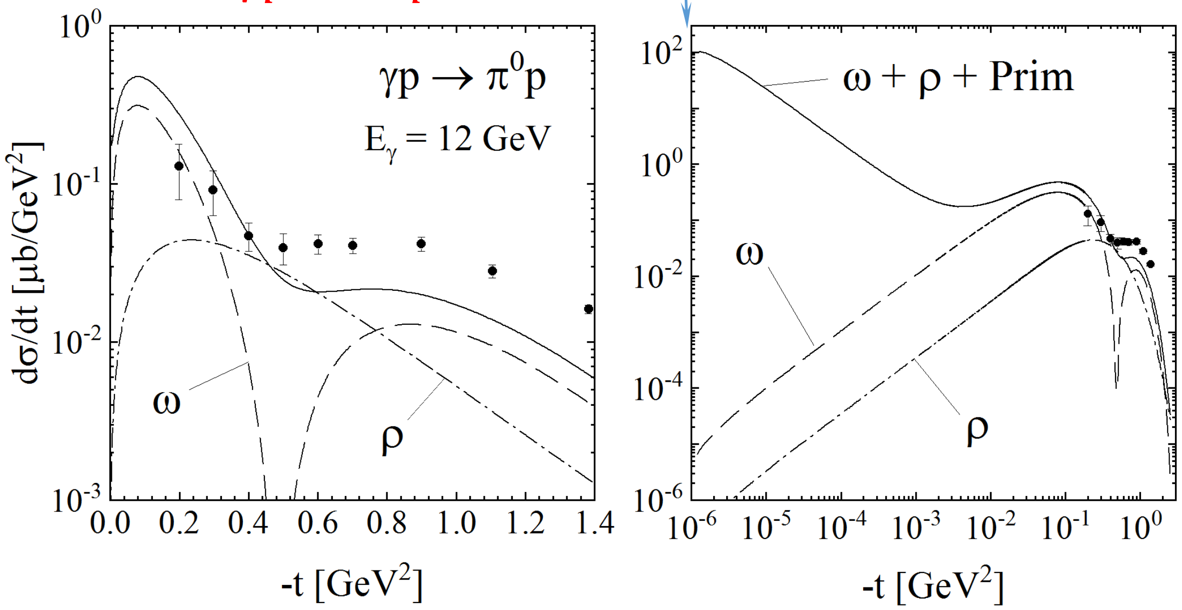
does not contribute

Results for $\gamma p \to \eta p$ and $\gamma p \to \pi^0 p$

$\gamma p \to \eta p$



$\gamma p \to \pi^0 p$ pole at $t \to 0$

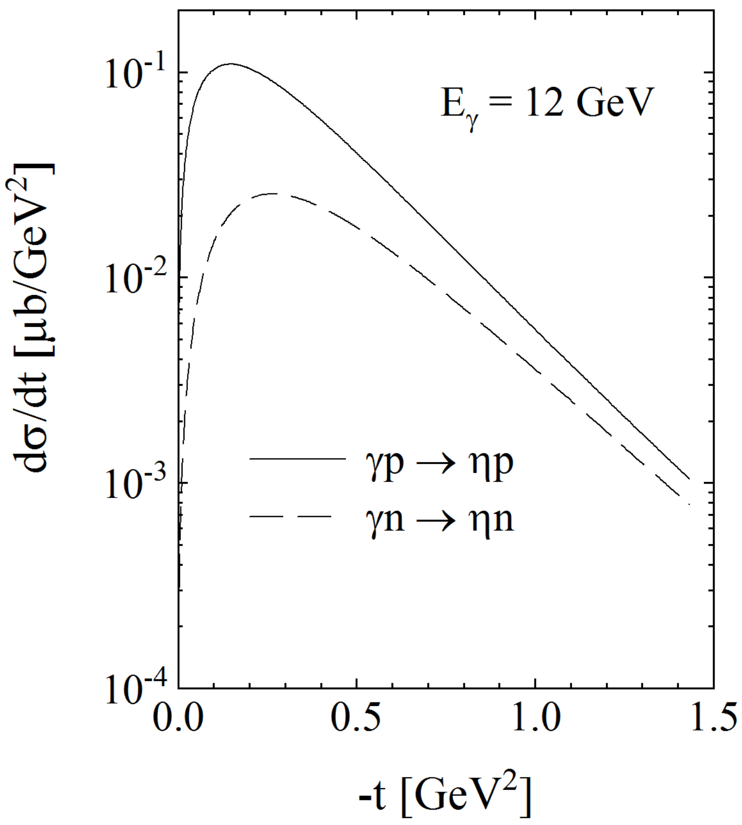


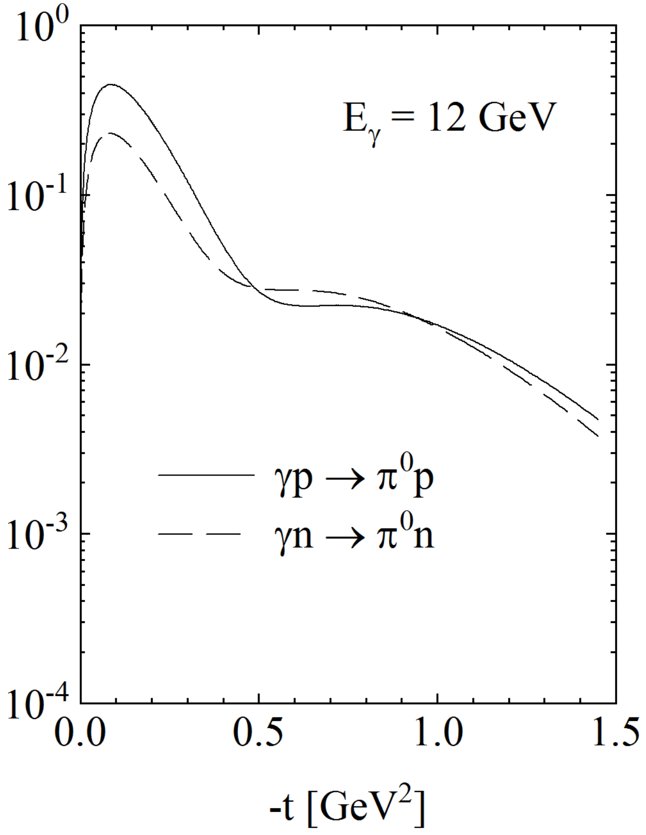
$t_p = t_s + t_v$ fitted

$t_n = t_s - t_v$ model

$\Rightarrow T_{\gamma\, ^4He \to \eta\, ^4He} \sim t_s$ model-dependent

Results for $\gamma N \to \eta N$ and $\gamma N \to \pi^0 N$





Photoproduction on nuclei

3 channels:

- Coherent $\gamma + A \rightarrow \eta + A,$
- Transitions to discrete states $\gamma + A \rightarrow \eta + A^*,$
- Direct reaction (nucleon knock-out) $\gamma + A \rightarrow \eta + N + (A-1)$

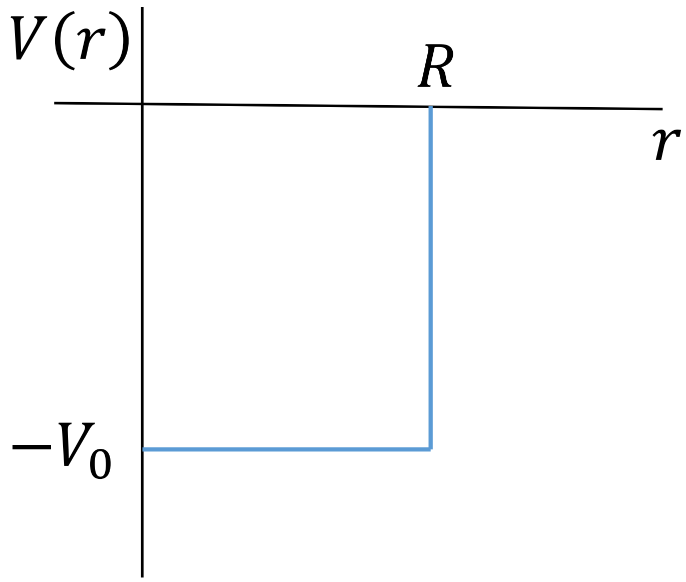
Model: Impulse Approximation

$$T(\gamma A \rightarrow \eta A^*) = \langle A^* | \sum_i t_N(i) | A \rangle$$

Photoproduction on nuclei

Model: ηA Final State Interaction

Square well: $V(r) = \begin{cases} -iV_0, & r < R \\ 0, & r \geq R \end{cases}$



$$V_0 = \frac{3\beta_\eta}{8\pi R^3}\sigma_{\eta N}, \quad \sigma_{\eta N} \approx \sigma_{\eta' N} \approx \sigma_{\pi^0 N} \approx 23\, mb$$

Eikonal w.f. $\phi_\eta^{(-)}(\vec{r}) = \exp[i\vec{q}\vec{r} + i\beta_\eta^{-1} \int_0^\infty V(\vec{r} + \hat{q}s)ds]$

$^{12}C(\gamma,\eta)^{12}C$ and $^{12}C(\gamma,\eta)^{12}C^*$

- $0\hbar\omega$ $(1p \rightarrow 1p)$ excitations : Shell model with intermediate coupling
- $1\hbar\omega, 2\hbar\omega, \ldots$ excitations : Helm model ($eA \rightarrow e'A^*$ matrix elements)

Levels of ^{12}C included:

$0\hbar\omega$

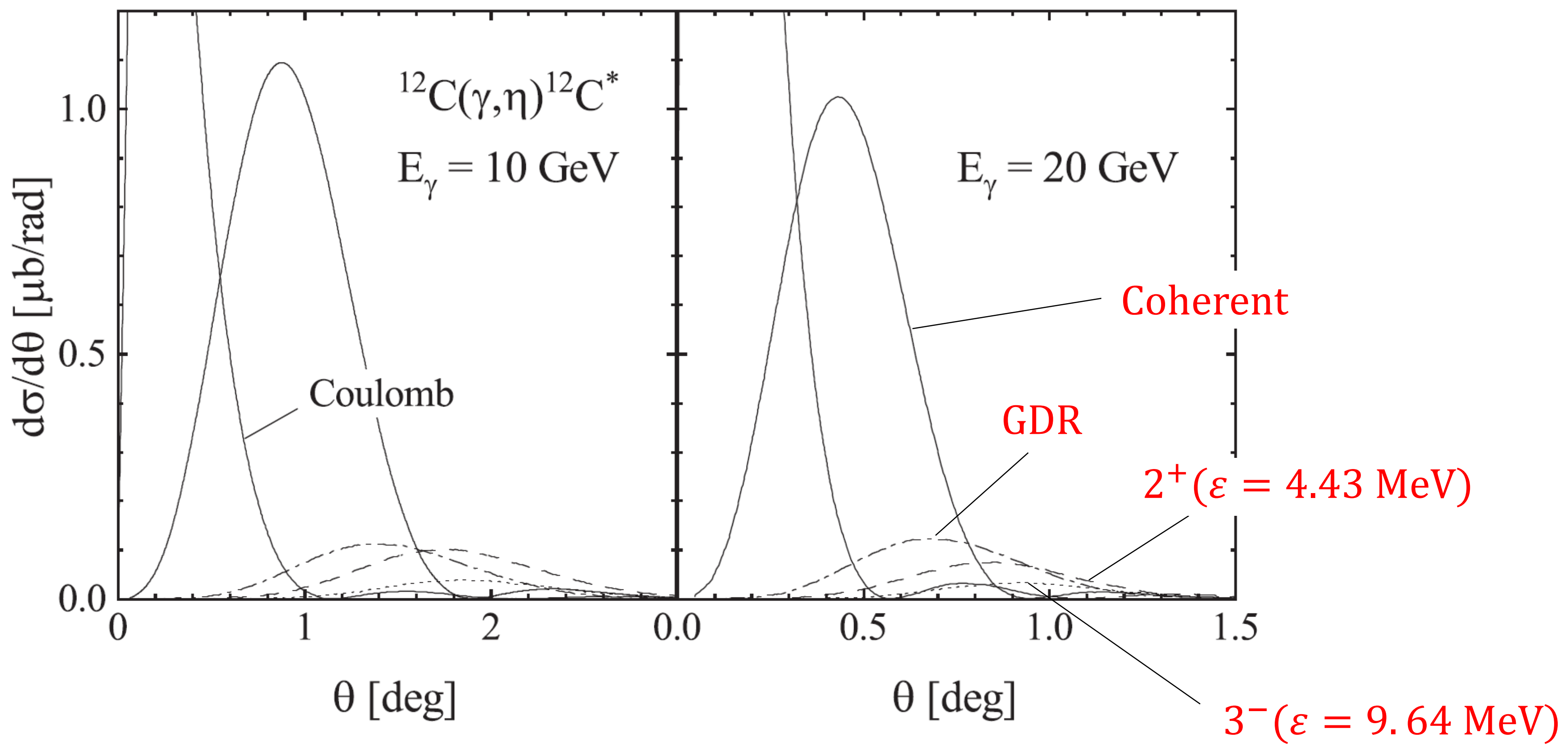
Level No.	J^π	T	ϵ [MeV]
1	0^+	0	0.00
2	2^+	0	4.43
3	1^+	0	12.73
4	1^+	1	15.11
5	2^+	1	16.11

$1\hbar\omega, 2\hbar\omega, \ldots$

Level No.	J^π	T	ϵ [MeV]
1	2^-	1	16.58
2	1^-	1	17.23
3	1^-	1	18.15
4	3^-	1	18.72
5	2^+	1	18.81
6	1^-	1	19.20
7	2^-	1	19.40
8	4^-	1	19.60
9	2^+	1	20.00
10	3^+	1	20.60
11	3^-	1	21.60
12	1^-	1	21–26

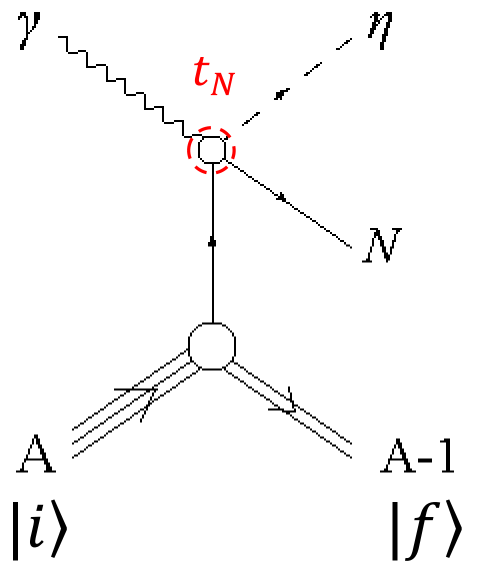
GDR

$^{12}C(\gamma,\eta)^{12}C$ and $^{12}C(\gamma,\eta)^{12}C^*(\varepsilon)$



[A. Fix, Phys. Rev. C **108**, 044607 (2023)]

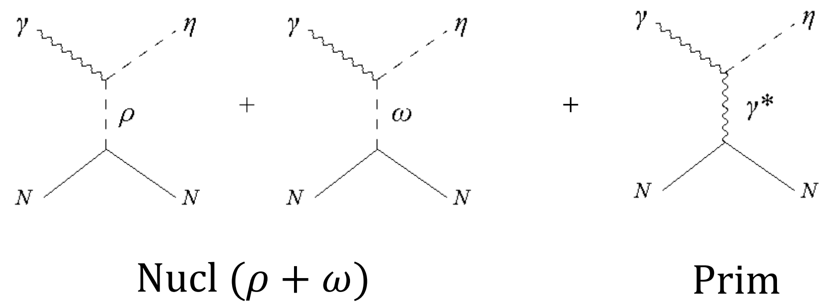
$$\gamma + {}^{12}C \to \eta + {}^{11}C^* + n, \qquad \gamma + {}^{12}C \to \eta + {}^{11}B^* + p$$

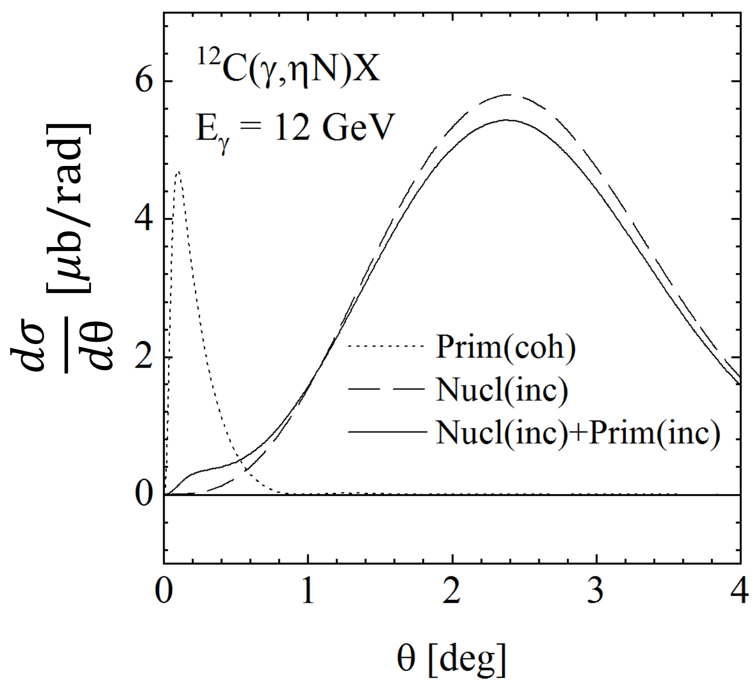


Closure for ${}^{11}C^*$ and ${}^{11}B^*$ states:

$$|T_A|^2 = \sum_f \langle i|\hat{O}|f\rangle \langle i|\hat{O}|f\rangle^* = \langle i|\hat{O}^+\hat{O}|i\rangle \sim F(p)|t_N(p)|^2$$

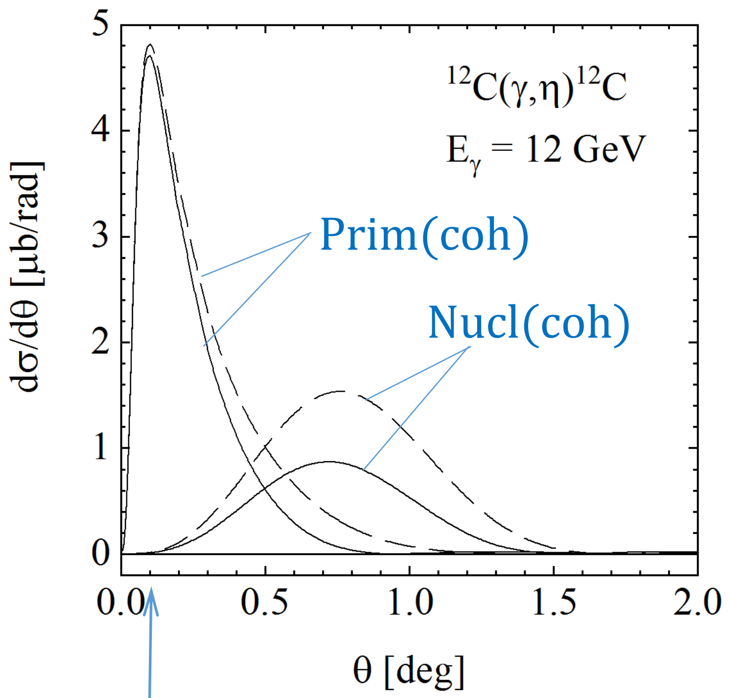
$t_N =$





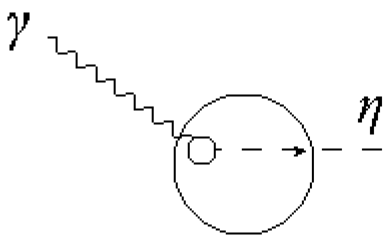
$$\frac{d\sigma}{d\Omega} \sim p_{N(A-1)}$$

Final State Interaction (FSI)

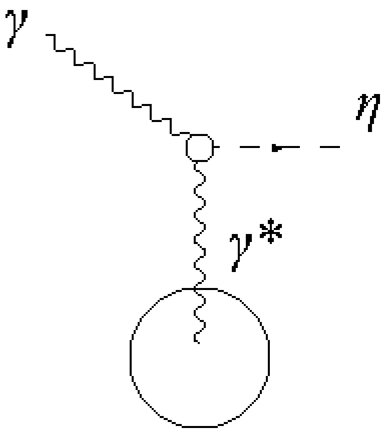


$$\theta_{max} \approx \frac{m_\eta^2}{2E_\gamma}$$

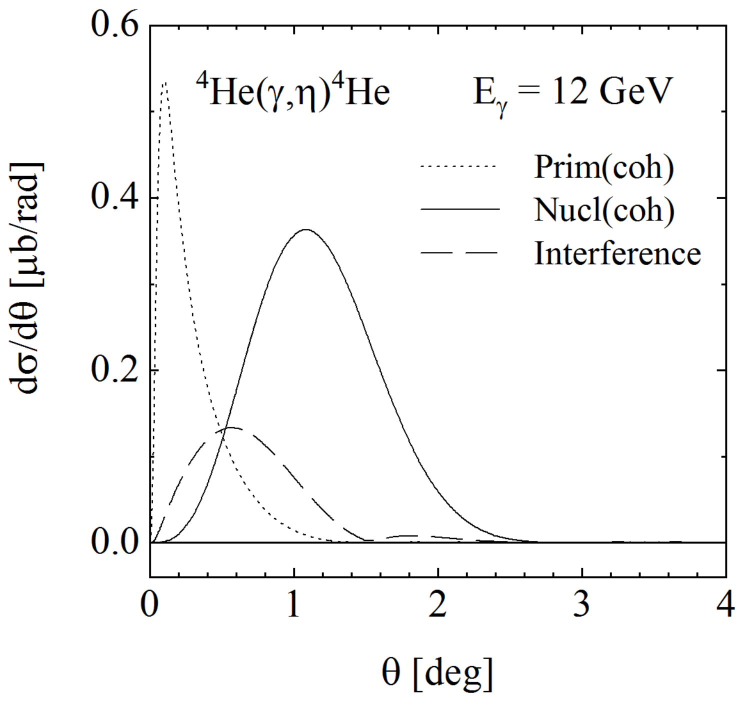
Nucl(coh)

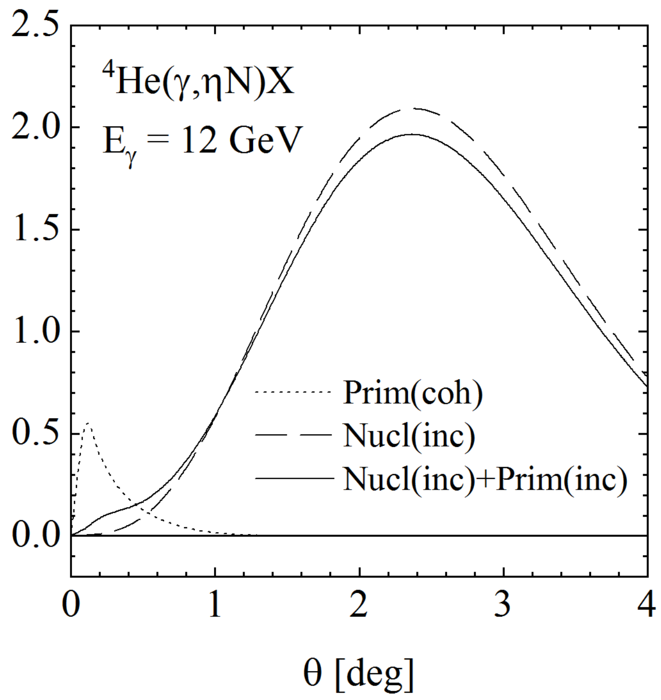


Prim(coh)

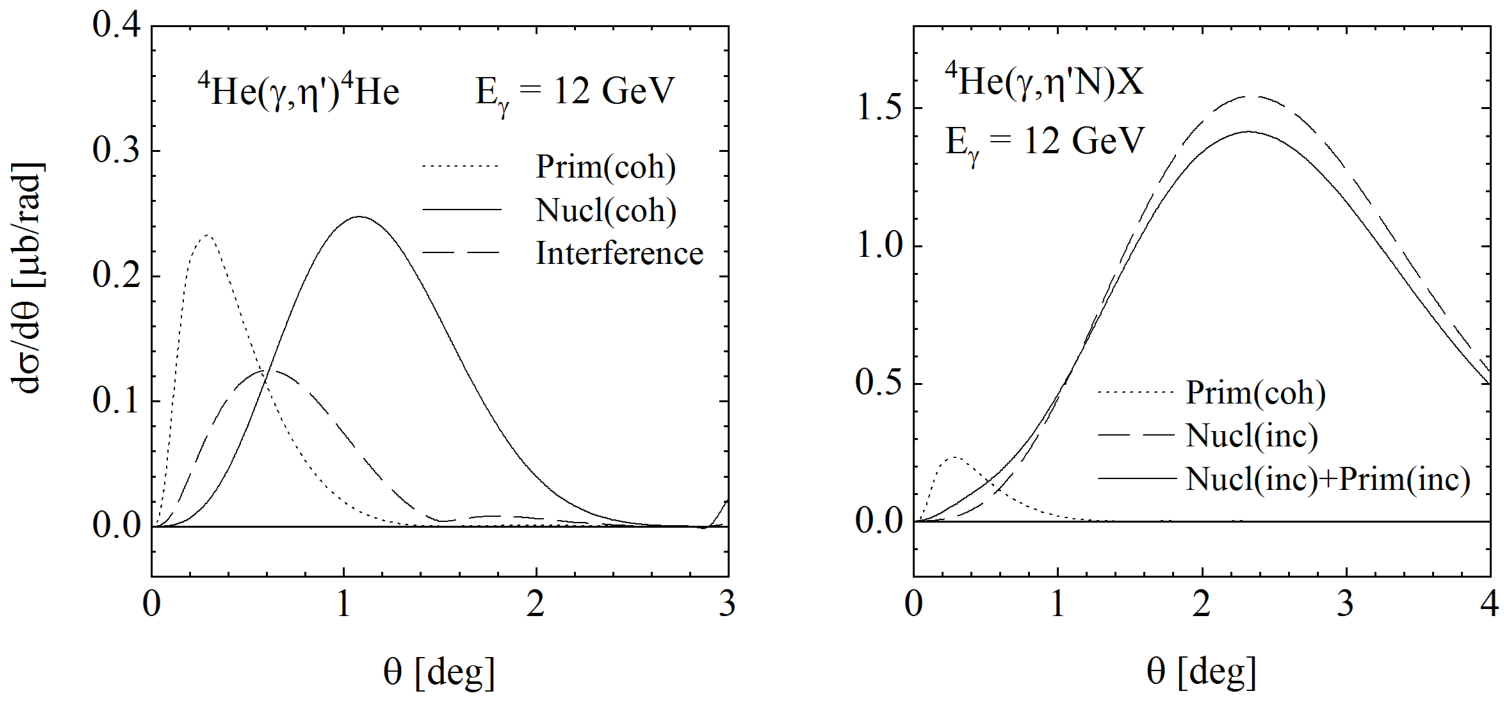


Other nuclei and other mesons

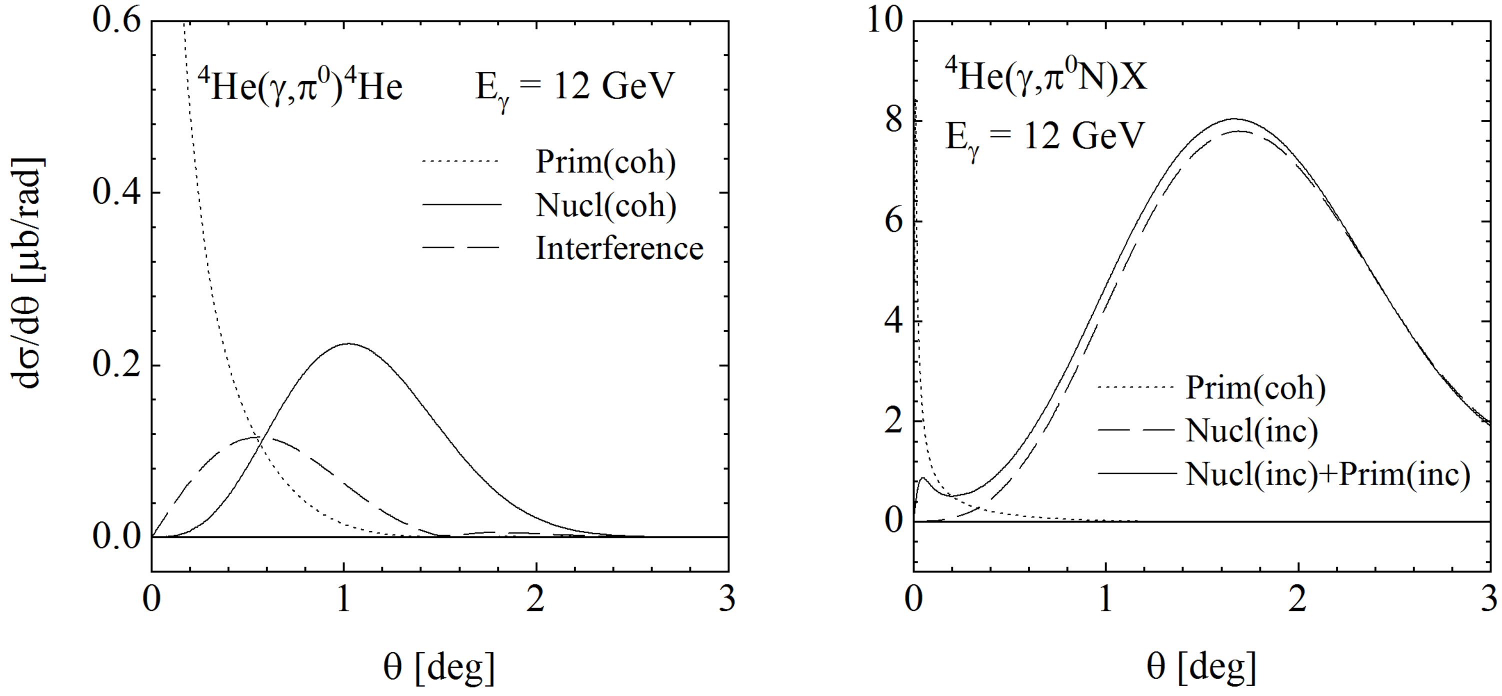




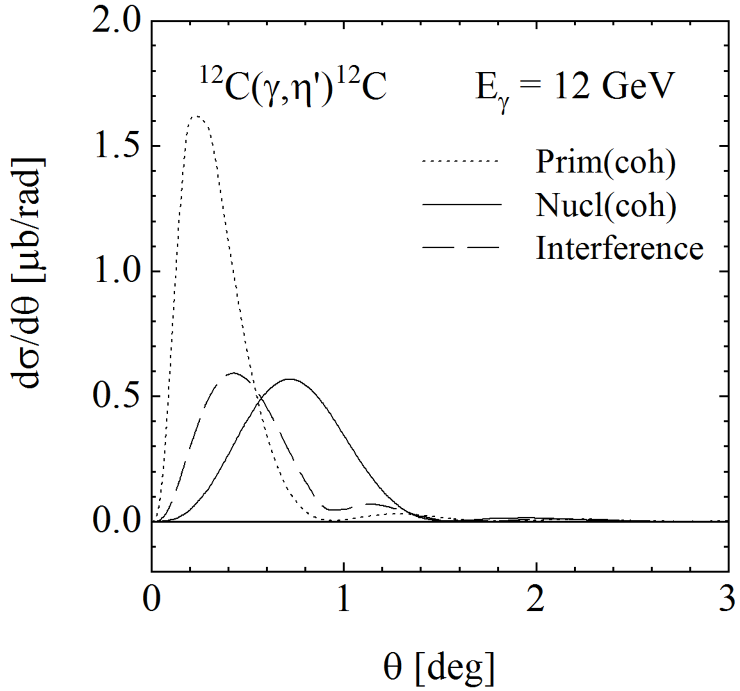
$^4He(\gamma,\eta')$

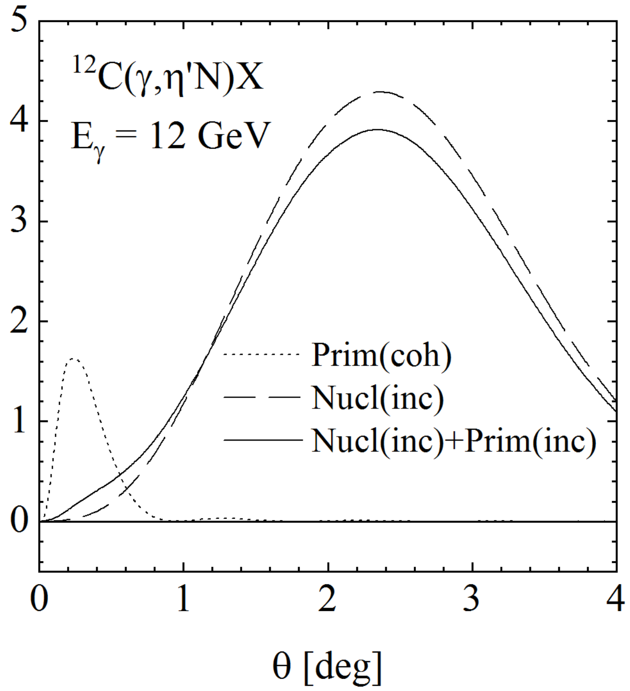


$^4He(\gamma,\pi^0)$

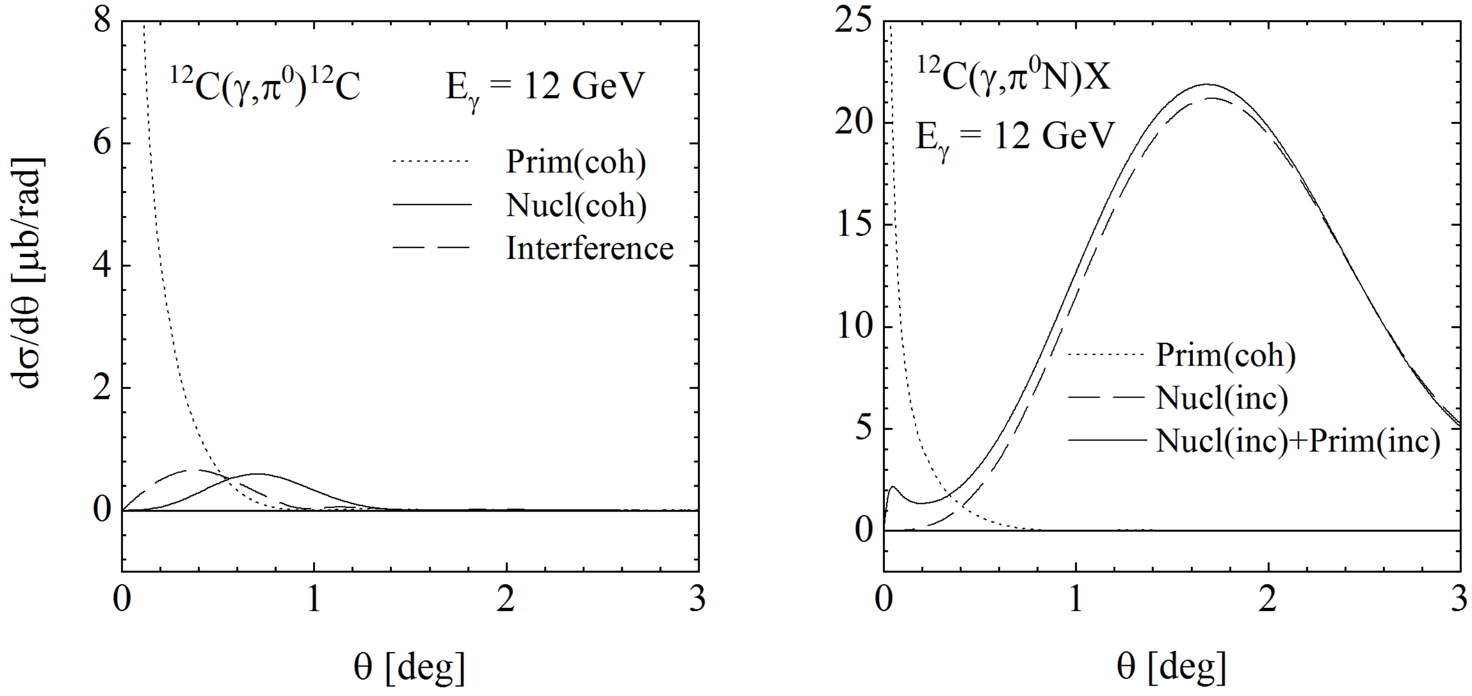


$^{12}C(\gamma, \eta')$

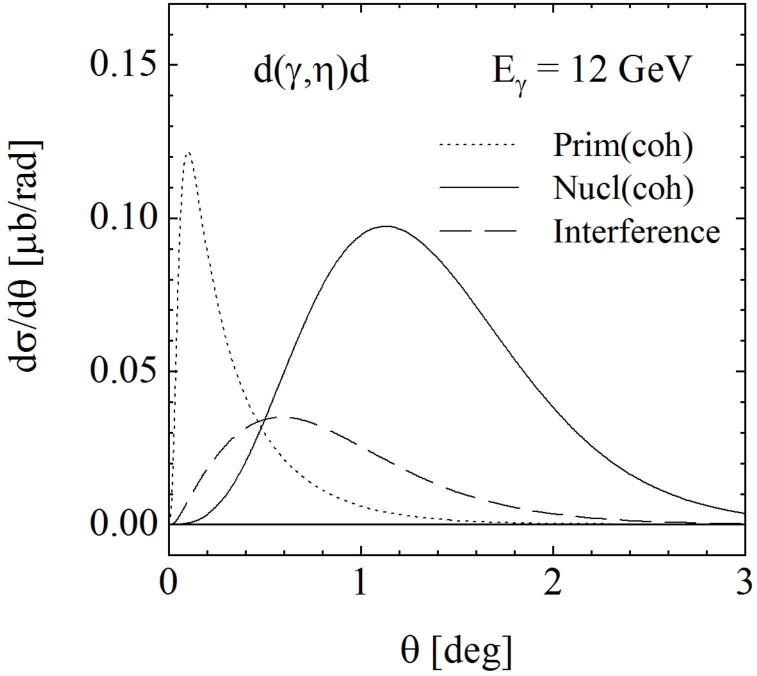




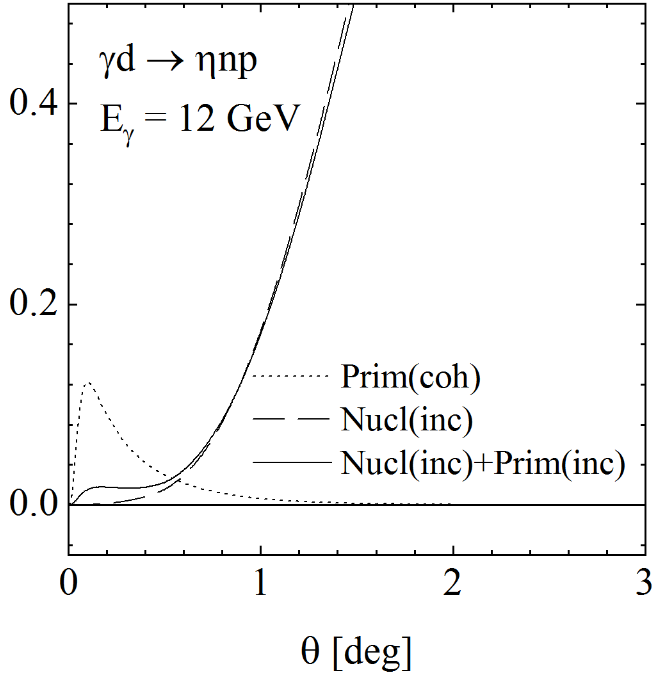
$^{12}C(\gamma,\pi^0)$



$^{2}H(\gamma,\eta)$

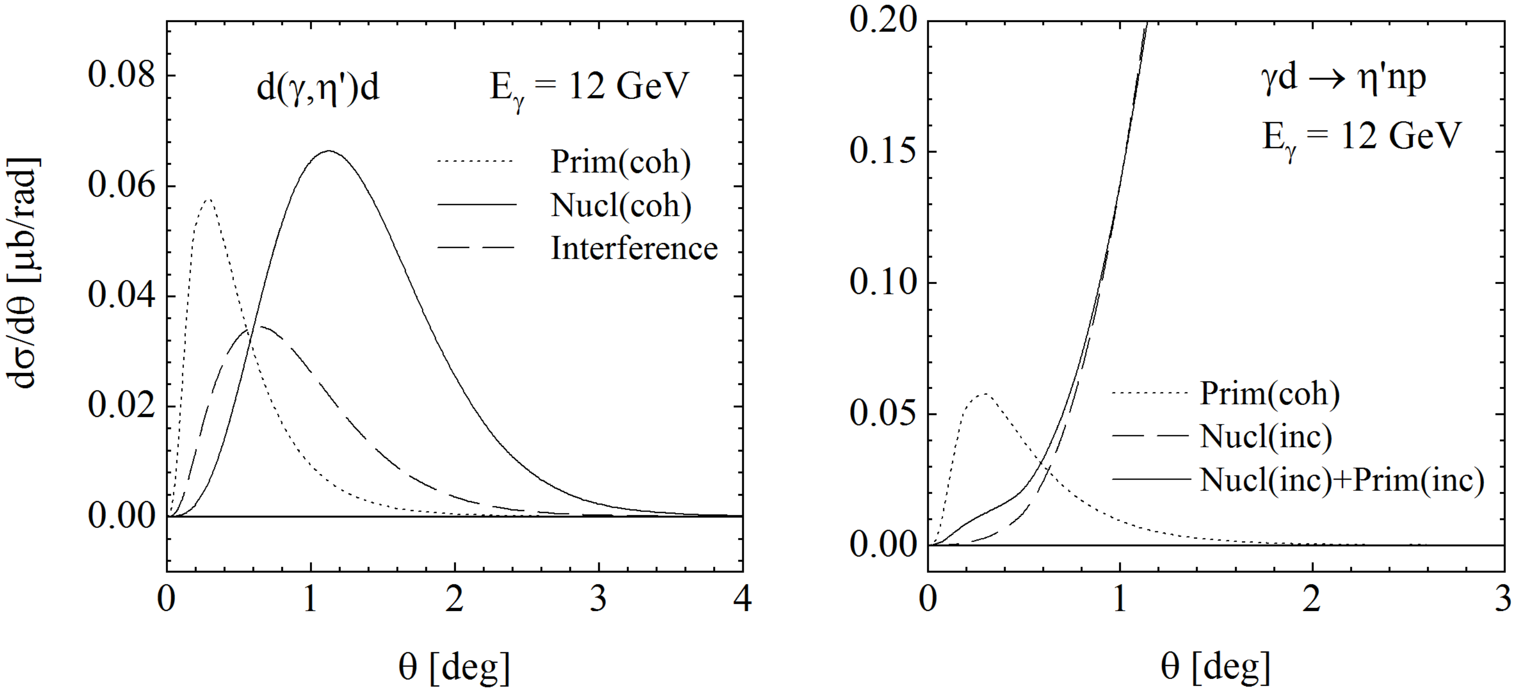


dσ/dθ [μb/rad]
0.15
0.10
0.05
0.00
d(γ,η)d
Eγ = 12 GeV
Prim(coh)
Nucl(coh)
Interference
0
1
2
3
θ [deg]



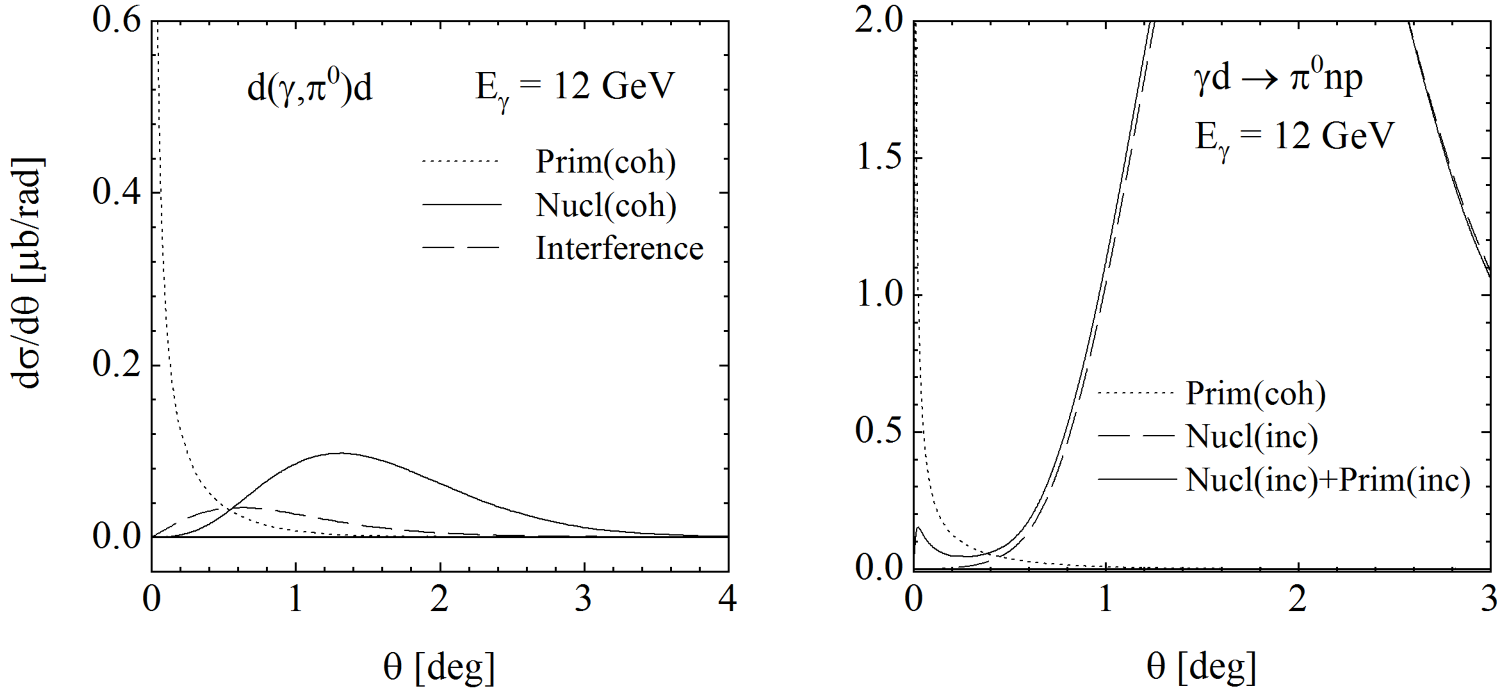
γd → ηnp
Eγ = 12 GeV
0.4
0.2
0.0
Prim(coh)
Nucl(inc)
Nucl(inc)+Prim(inc)
0
1
2
3
θ [deg]

$^{2}H(\gamma,\eta')$



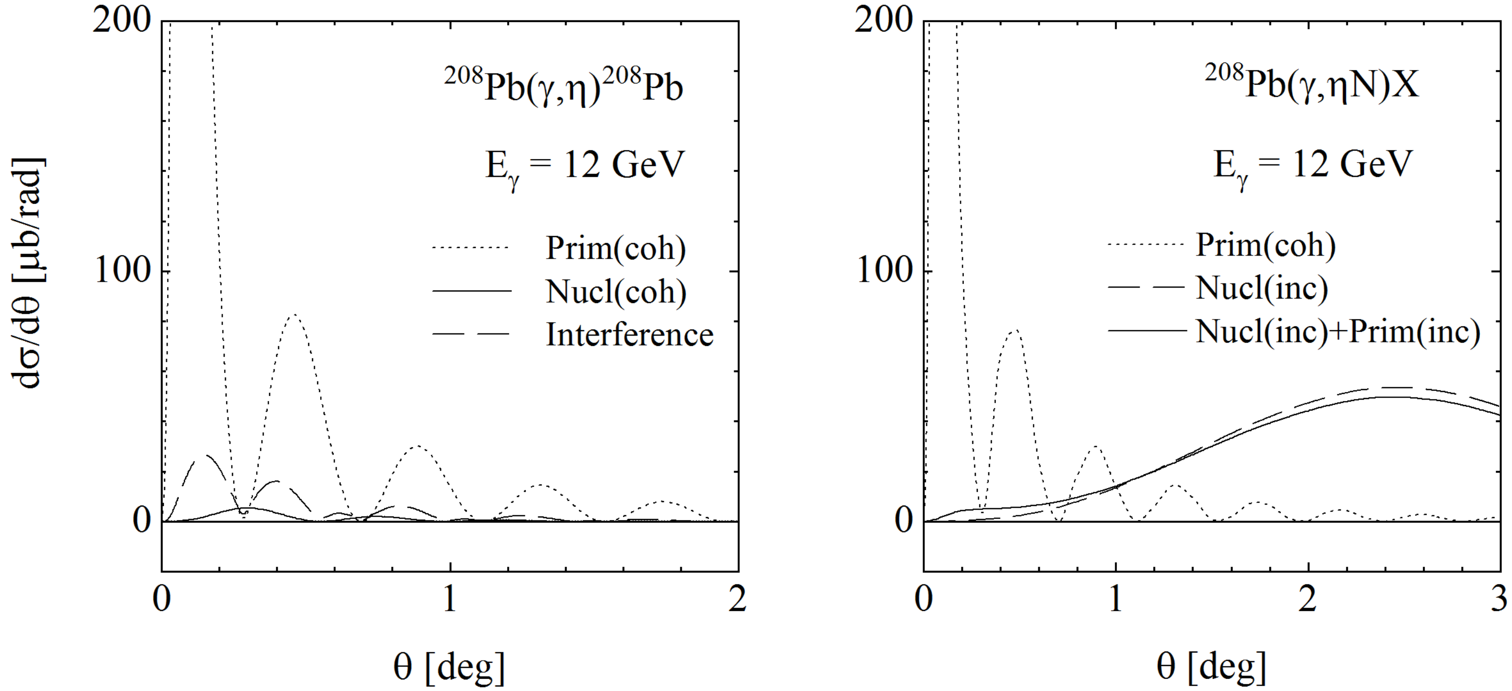
d(γ,η')d
E_γ = 12 GeV
Prim(coh)
Nucl(coh)
Interference
dσ/dθ [μb/rad]
0.08
0.06
0.04
0.02
0.00
0
1
2
3
4
θ [deg]
γd → η'np
E_γ = 12 GeV
Prim(coh)
Nucl(inc)
Nucl(inc)+Prim(inc)
0.20
0.15
0.10
0.05
0.00
0
1
2
3
θ [deg]

$^2H(\gamma,\pi^0)$

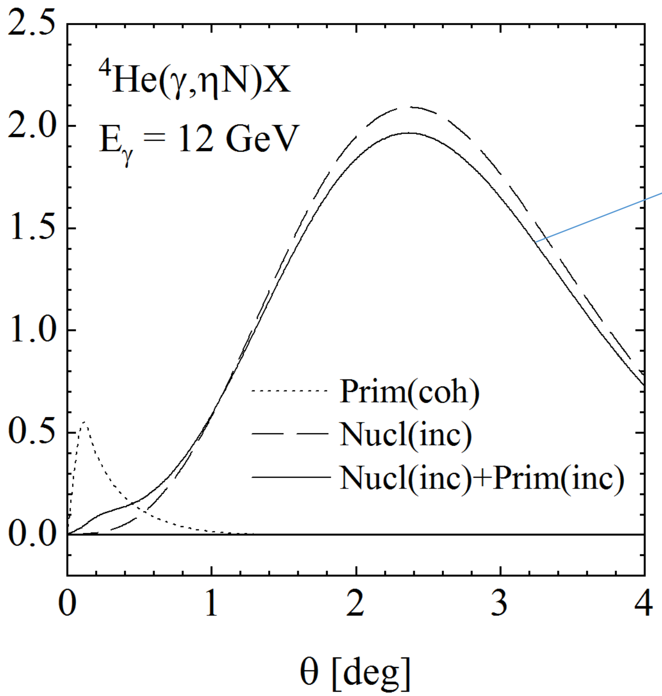


d(γ,π⁰)d
Eγ = 12 GeV
Prim(coh)
Nucl(coh)
Interference
dσ/dθ [μb/rad]
θ [deg]
0.0
0.2
0.4
0.6
0
1
2
3
4
γd → π⁰np
Eγ = 12 GeV
Prim(coh)
Nucl(inc)
Nucl(inc)+Prim(inc)
θ [deg]
0.0
0.5
1.0
1.5
2.0
0
1
2
3

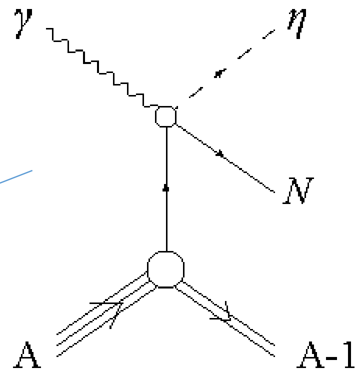
$^{208}Pb(\gamma,\eta)$



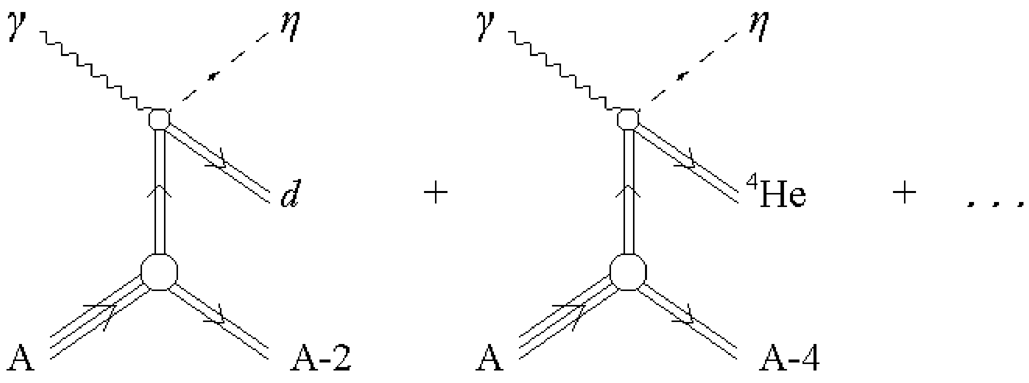
Comments



^{4}He(γ,ηN)X
E_γ = 12 GeV
Prim(coh)
Nucl(inc)
Nucl(inc)+Prim(inc)
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
θ [deg]



γ
η
N
A
A-1



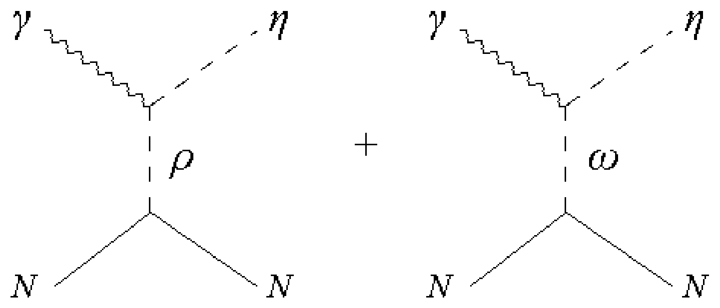
γ
η
d
A
A-2
+
γ
η
^{4}He
A
A-4
+ . . .

?

Elementary amplitude

$$F = \overline{u}_f(p', m_s')\left[\sum_{j=1}^{4} A_j(s,t)\hat{M}_j\right]u_i(p, m_s)$$

$\widehat{M}_j$ – Lorents and gauge invariant forms



$$A_1 = \frac{e\lambda_V}{M_\eta}\left[2M_N g^v_{VNN} + \frac{g^t_{VNN}}{2M_N}t\right]G_V(t),$$

$$A_2 = \frac{e\lambda_V}{M_\eta}\frac{g^t_{VNN}}{2M_N}G_V(t),$$

$$A_3 = \frac{e\lambda_V}{M_\eta}g^v_{VNN}G_V(t),$$

$$A_4 = A_3$$

Regge propagator:

$$G_V(t) = \left(\frac{s}{s_0}\right)^{\alpha_V(t)-1}\frac{\pi\alpha'_V}{\sin[\pi\alpha_V(t)]}\frac{e^{-i\pi\alpha_V(t)}}{\Gamma(\alpha_V(t))}$$

$V = \rho, \omega$

Shell model with intermediate coupling

$$\Psi(JM;TM_T)$$

Mixing coefficients

$$= \sum_{[\lambda]LS} \alpha^{JT}_{[\lambda]LS} \sum_{M_L M_S} C^{JM}_{LM_L\, SM_S}\, \Phi([\lambda]LM_L\, SM_S;TM_T)$$

pure configurations:

$$\Phi([\lambda]LM_L\, SM_S;TM_T)$$

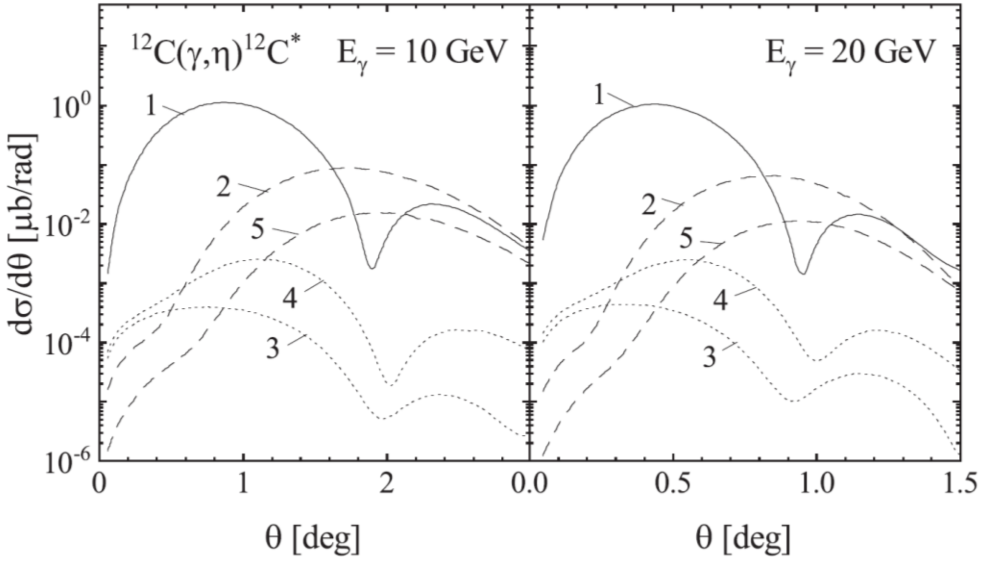
$(1p)^{A-5}$ 1p single nucleon

$$= \sum_{[\lambda']L'S'T'} \langle (1p)^{A-4}\,[\lambda]\,LST\,|\}\,(1p)^{A-5}\,[\lambda']L'S'T'\rangle\, [\,\psi([\lambda']L'S'T')\otimes \phi_{1p}\,]^{LST}_{M_L M_S M_T}$$

fractional parentage coeff.

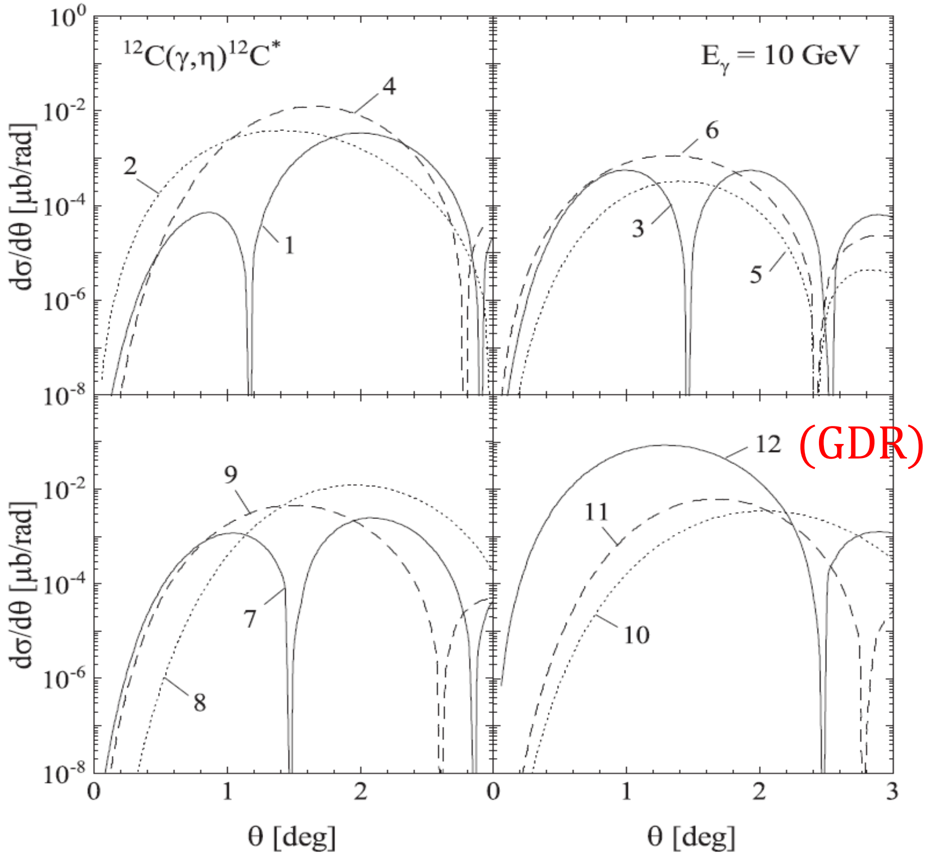
$^{12}C(\gamma,\eta)^{12}C$ and $^{12}C(\gamma,\eta)^{12}C^*(\varepsilon)$

$0\hbar\omega$

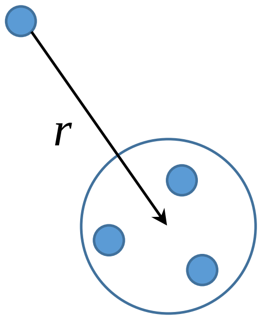


1 – Coherent
2 – 4.43 MeV

$1\hbar\omega, 2\hbar\omega, \ldots$



^4He Wave function



$$\psi(r) = N\frac{e^{-\alpha r}}{r}\sum_{j=1}^{5} a_j e^{-\beta_j r}$$

α_j and β_j are fitted to ^4He charge FF up to $Q = 6\ \text{fm}^{-1}$

j	a_j [fm^{-1}]	β_j [fm^{-1}]
1	1.305	0.0
2	−5.222	1.42
3	7.832	2.84
4	−5.222	4.26
5	1.305	5.68

^{2}H Wave function

$$\phi_{M_d}(\vec{p}) = \sum_{L=0,2} \sum_{M} u_L(p) Y_{LM}(\hat{p})\, \chi_{M_S} (LM\ 1M_S|1M_d)$$

$u_0(p)$ and $u_2(p)$ from Bonn NN model [R.Machleidt *et al,* Phys.Rep. 149, 1 (1987)]

$$u_0(p) = \sqrt{\frac{2}{\pi}} \sum_{i=1}^{11} \frac{C_i}{p^2 + m_i^2}, \qquad u_2(p) = \sqrt{\frac{2}{\pi}} \sum_{i=1}^{11} \frac{D_i}{p^2 + m_i^2}$$

^{208}Pb Wave function

Symmetrized Fermi density:

$$\rho(r) = \rho_0 \left[\frac{1}{1 + \exp\left(\frac{R-r}{a}\right)} + \frac{1}{1 + \exp\left(\frac{R+r}{a}\right)} \right] = \rho_0 \frac{\sinh(R/a)}{\cosh(R/a) + \cosh(r/a)}$$

Parameters: R (radius) , a (diffuseness) $R = 6.654$ fm, $a = 0.475$ fm,

If $R \gg a$,

$$\rho(r) \approx \rho_0 \frac{1}{1 + \exp\left(\frac{R-r}{a}\right)}$$