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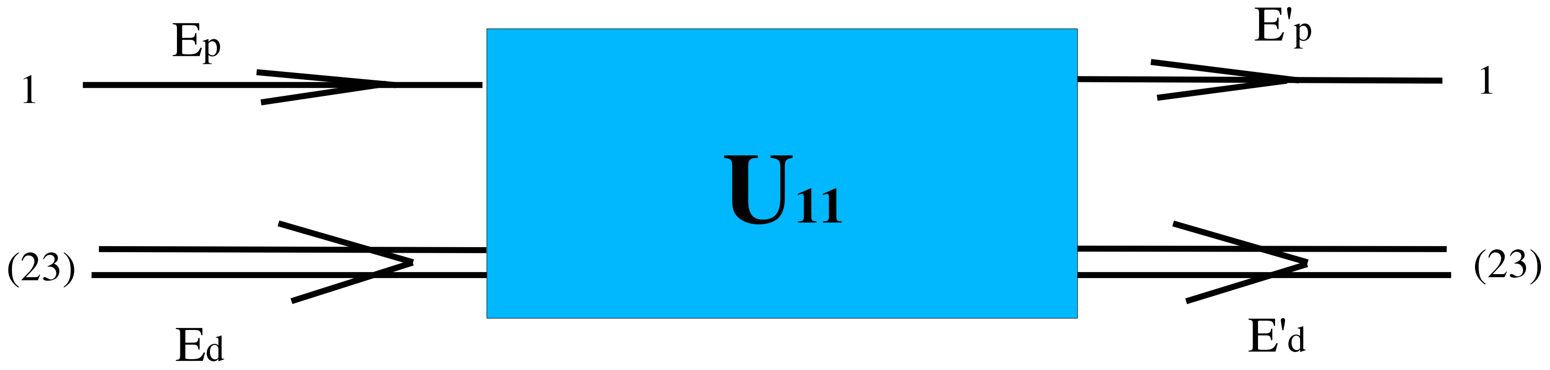
Role of reaction mechanisms in deuteron-proton elastic scattering at GeV energies

- The theoretical model is suggested for description of $dp \to dp$ reaction in the full angular range
- The model allows calculating both differential cross section and polarization observables in the deuteron energy range between 500 and 2000 MeV.
- The results are presented in comparison with the data.

$dp \to dp$



The matrix element of the transition operator U_{11} defines reaction amplitude

$$U_{dp\to dp} = \delta(E_d + E_p - E'_d - E'_p)\mathcal{J} =< 1(23)|[1 - P_{12} - P_{13}]U_{11}|1(23) >$$

Alt-Grassberger-Sandhas equations for rearrangement operators: Nucl.Phys. B2, 167 (1967)
E.Schmid, H.Ziegelmann The Quantum Mechanical Three-Body Problem

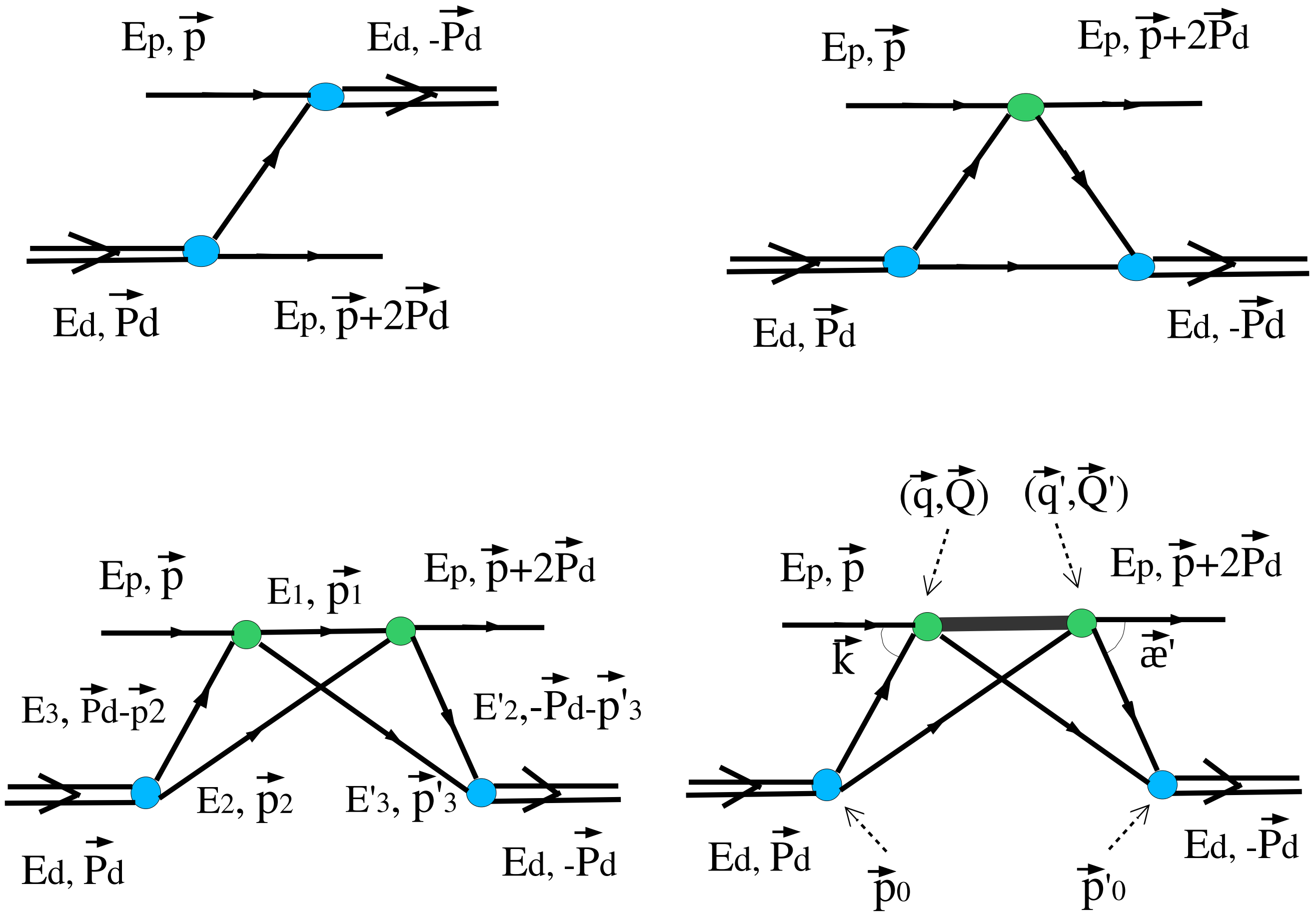
$$
\begin{aligned}
U_{11} &= t_{13} g_0 U_{21} + t_{12} g_0 U_{31} \\
U_{21} &= g_0^{-1} + t_{23} g_0 U_{11} + t_{12} g_0 U_{31} \\
U_{31} &= g_0^{-1} + t_{23} g_0 U_{11} + t_{13} g_0 U_{21}
\end{aligned}
$$

$t_1 = t(2,3)$, **etc., is the t-matrix of the two-particle interaction**
g_0 **is the free three-particle propagator**
Iterating AGS-equations up to second order terms over t one obtains

$$
U_{11} = -2 P_{12} g_0^{-1} + 2 t_{12}^{sym} + 2 t_{12}^{sym} g_0 t_{13}^{sym}
$$

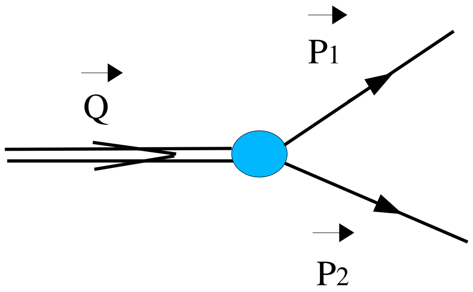
$t_{ij}^{sym} = [1 - P_{ij}] t_{ij}$– **antisymmetrized t-matrix**

Diagrams



Ep, p
Ed, -Pd
Ed, Pd
Ep, p+2Pd
Ep, p
Ep, p+2Pd
Ed, Pd
Ed, -Pd
Ep, p
E1, p1
Ep, p+2Pd
E3, Pd-p2
E'2,-Pd-p'3
E2, p2
E'3, p'3
Ed, Pd
Ed, -Pd
(q,Q)
(q',Q')
Ep, p
Ep, p+2Pd
k
æ'
Ed, Pd
p0
p'0
Ed, -Pd

Lorenz transformation



$$L(\vec{u})p_1 = (E^*, \vec{p})$$
$$L(\vec{u})p_2 = (E^*, -\vec{p})$$

with velocity

$$\vec{u} = \frac{\vec{p}_1 + \vec{p}_2}{E_1 + E_2}$$

The c.m. energy of one of the nucleons E^* is related with Mandelstam variable s by

$$E^* = \sqrt{s}/2 \quad .$$

Let's introduce new variables $\vec{Q}$ and $\vec{k}$ which can be expressed through $\vec{p}_1$ and $\vec{p}_2$

$$\vec{Q} = \vec{p}_1 + \vec{p}_2$$
$$\vec{k} = \frac{(E_2 + E^*)\vec{p}_1 - (E_1 + E^*)\vec{p}_2}{E_1 + E_2 + 2E^*} \quad .$$

Deuteron wave function

The deuteron wave function in the rest has the standard form

$$< m_p m_n, \vec{p} | \Omega_d | \vec{0}, \mathcal{M}_d >=$$
$$\frac{1}{\sqrt{4\pi}} < m_p m_n, \vec{p} | \left\{ u(p) + \frac{w(p)}{\sqrt{8}} [3(\vec{\sigma}_1 \hat{p})(\vec{\sigma}_2 \hat{p}) - (\vec{\sigma}_1 \vec{\sigma}_2)] \right\} | \vec{0} \mathcal{M}_d >$$

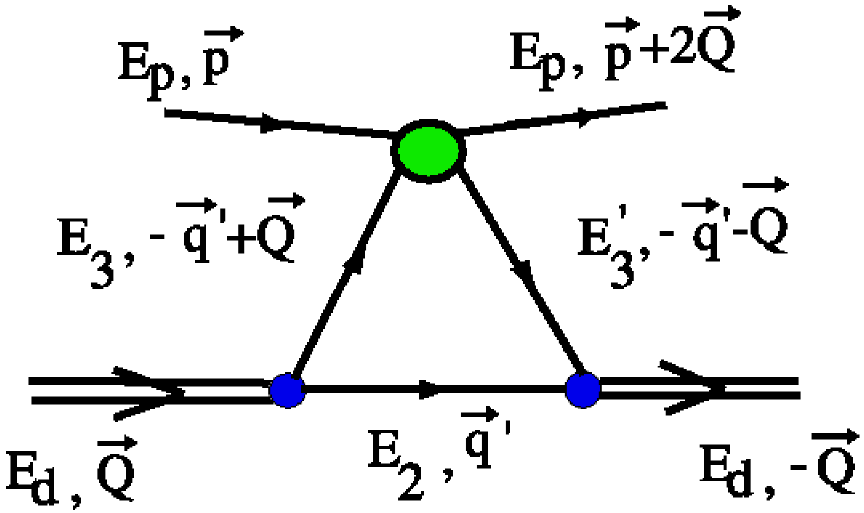
$u(p)$ **and** $w(p)$ **-** $S-$ **and** $D-$ **components of the deuteron.**
Then the deuteron wave function in the moving frame is

$$< \vec{p}_1 \ \vec{p}_2, m_1 m_2 | \Omega_d | \vec{Q}, \mathcal{M}_d > \quad \sim \quad < \vec{p}, m_1' m_2' | W^{\dagger}_{1/2}(\vec{p}_1, \vec{u}) W^{\dagger}_{1/2}(\vec{p}_2, \vec{u}) \Omega_d | \vec{0}, \mathcal{M}_d >$$

where $W_{1/2}$ **is Wigner rotation operator**

$$W_{1/2}(\vec{p}_i, \vec{u}) \quad = \quad exp\left\{-i\omega_i(\vec{n}_i \vec{\sigma}_i)/2\right\} = cos(\omega_i/2)[1 - i(\vec{n}_i \vec{\sigma}_i) tg(\omega_i/2)]$$
$$\vec{n}_i \quad = \quad \frac{\vec{p}_i \times \vec{u}}{|\vec{p}_i \times \vec{u}|}$$

Single Scattering contribution



$$\mathcal{J}_{SS} =_{1(23)}< \vec{p}' m'; -\vec{Q}\mathcal{M}'_d|\Omega^{\dagger}_d(23)|[1 - P_{12}]|t_{NN}\Omega_d(23)|\vec{Q}\mathcal{M}_d; \vec{p}m >_{1(23)}$$

Nucleon-Nucleon t-matrix

W.G.Love, M.A.Franey, Phys.Rev.C24, 1073 (1981)
N.B.Ladygina,nucl-th/0805.3021

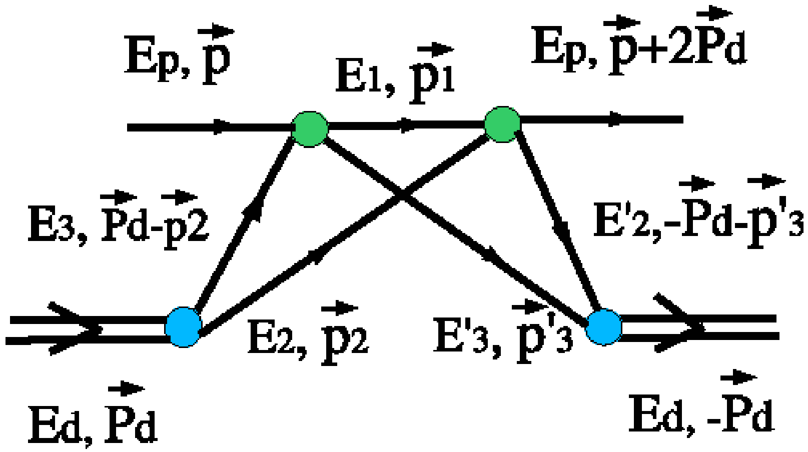
$$\begin{aligned} < \kappa' m_1' m_2' | t | \kappa m_1 m_2 > \quad = \quad & < \vec{\kappa}' m_1' m_2' | A + B(\vec{\sigma}_1 \hat{N}^*)(\vec{\sigma}_2 \hat{N}^*) + C(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \hat{N}^* + \\ & D(\vec{\sigma}_1 \hat{q}^*)(\vec{\sigma}_2 \hat{q}^*) + F(\vec{\sigma}_1 \hat{Q}^*)(\vec{\sigma}_2 \hat{Q}^*) | \vec{\kappa} m_1 m_2 > \end{aligned}$$

where the orthonormal basis is combinations of the nucleons relative momenta in the initial $\vec{\kappa}$ and final $\vec{\kappa}'$ states

$$\hat{q}^* = \frac{\vec{\kappa} - \vec{\kappa}'}{|\vec{\kappa} - \vec{\kappa}'|} \quad , \quad \hat{Q}^* = \frac{\vec{\kappa} + \vec{\kappa}'}{|\vec{\kappa} + \vec{\kappa}'|} \quad , \quad \hat{N}^* = \frac{\vec{\kappa} \times \vec{\kappa}'}{|\vec{\kappa} \times \vec{\kappa}'|}$$

The amplitudes A, B, C, D, F are the functions of the center-of-mass energy and scattering angle. The radial parts of these amplitudes are taken as a sum of Yukawa terms.

Double scattering contribution

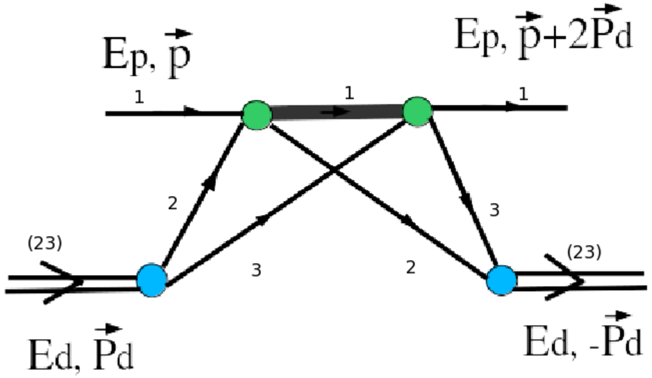


$$\mathcal{J}_{DS} = \quad < 1(23)|[1 - P_{12}]|t_{NN}|N(1)N(2) > |N(3) > g_0$$
$$< N(2)| < N(1)N(3)|t_{NN}[1 - P_{13}]|(23)1 >$$

g_0 is a free three-particle propagator:

$$g_0 = \frac{1}{E_d + E_p - E_1 - E_2 - E_3' + i\varepsilon} =$$
$$= \mathcal{P}\frac{1}{E_d + E_p - E_1 - E_2 - E_3'} - i\pi\delta(E_d + E_p - E_1 - E_2 - E_3')$$

Δ-contribution



$$\mu^2 = E_\Delta^2 - \vec{p}_\Delta^{\,2}$$

Δ-contribution is defined by two $N\Delta$ matrices

$$\mathcal{J}_\Delta = \quad < 1(23)|[1 - P_{12}]|t_{N\Delta}|\Delta(1)N(2) > |N(3) > g_0$$
$$< N(2)| < \Delta(1)N(3)|t_{\Delta N}[1 - P_{13}]|(23)1 >$$

g_0–a free three-particle propagator:

$$g_0 = \frac{1}{E_d + E_p - E_2' - E_3 - E(m_\Delta) + i\Gamma(E_\Delta)/2}$$

the distribution function of Δ-energy:

$$\rho(\mu) = \frac{1}{2\pi}\frac{\Gamma(\mu)}{(E_\Delta(\mu) - E_\Delta(m_\Delta))^2 + \Gamma^2(\mu)/4},$$

and wave functions of the initial and final deuterons.

Δ-isobar definition

The potential for the $NN \to N\Delta$ transition is based on the $\pi-$ and $\rho-$ exchanges:

$$t^{(\pi)}_{N\Delta} = -\frac{f_\pi f^*_\pi}{m^2_\pi} F^2_\pi(t) \frac{q^2}{m^2_\pi - t} (\vec{\sigma} \cdot \hat{q})(\vec{S} \cdot \hat{q})(\vec{\tau} \cdot \vec{T})$$

$$t^{(\rho)}_{N\Delta} = -\frac{f_\rho f^*_\rho}{m^2_\rho} F^2_\rho(t) \frac{q^2}{m^2_\rho - t} \{(\vec{\sigma}\vec{S}) - (\vec{\sigma} \cdot \hat{q})(\vec{S} \cdot \hat{q})\}(\vec{\tau} \cdot \vec{T})$$

with coupling constants:

$$f_\pi = 1.008 \qquad f^*_\pi = 2.156$$

$$f_\rho = 7.8 \qquad f^*_\rho = 1.85 f_\rho$$

The hadronic form factor has a pole form:

$$F_x(t) = (\Lambda^2_x - m^2_x)/(\Lambda^2_x - t)^n, \qquad n = 1 \quad for\ \pi - meson$$

$$n = 2 \quad for\ \rho - meson$$

The reaction amplitude is defined through 12 terms:

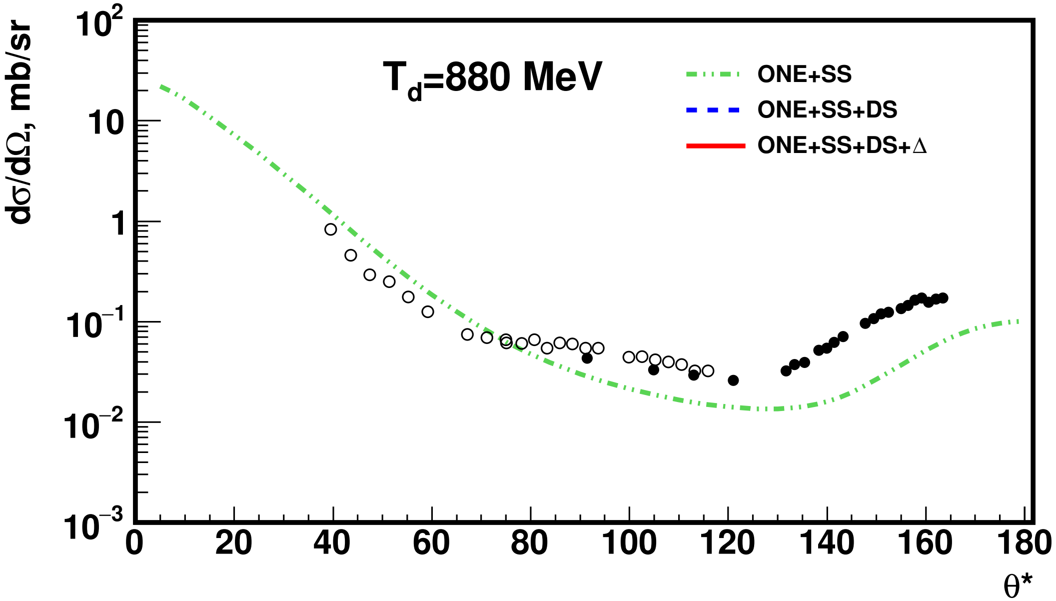
$$\mathcal{J}_{dp\to dp} =< 1M'_d| < \frac{1}{2}m'|F_1 + F_2(\vec{S}\vec{y}) + F_3 Q_{xx} + F_4 Q_{yy} +$$
$$F_5(\vec{\sigma}\vec{x})(\vec{S}\vec{x}) + F_6(\vec{\sigma}\vec{x})Q_{xx} + F_7(\vec{\sigma}\vec{y}) + F_8(\vec{\sigma}\vec{y})(\vec{S}\vec{y}) + F_9(\vec{\sigma}\vec{y})Q_{xx} +$$
$$F_{10}(\vec{\sigma}\vec{y})Q_{yy} + F_{11}(\vec{\sigma}\vec{z})(\vec{S}\vec{z}) + F_{12}(\vec{\sigma}\vec{z})Q_{yz}|\frac{1}{2}m > |1M_d >$$

σ_i, S_i **are the spin operators for** $s = 1/2$ **(Pauli matrices) and** $S = 1$
Q_{ij} **is the quadrupole tenzor:**

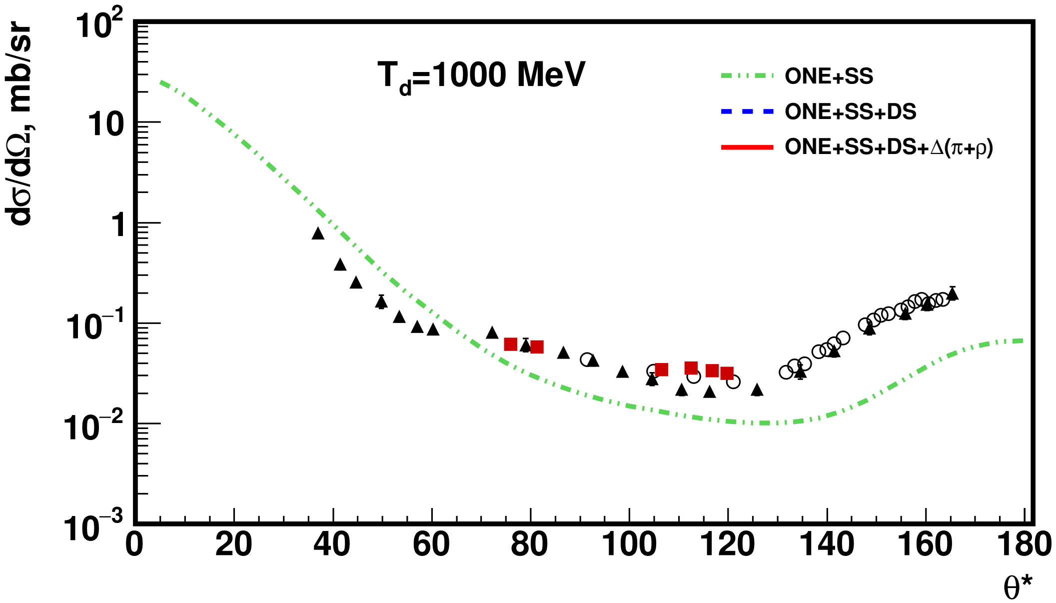
$$Q_{ij} = \frac{1}{2}(S_i S_j + S_j S_i) - \frac{2}{3}\delta_{ij}$$

$$\boxed{C_{i,j,k,l} = \frac{Tr(\mathcal{J}\sigma_i S_j \mathcal{J}^\dagger \sigma_k S_l)}{Tr(\mathcal{J}\mathcal{J}^\dagger)}} \qquad (1)$$

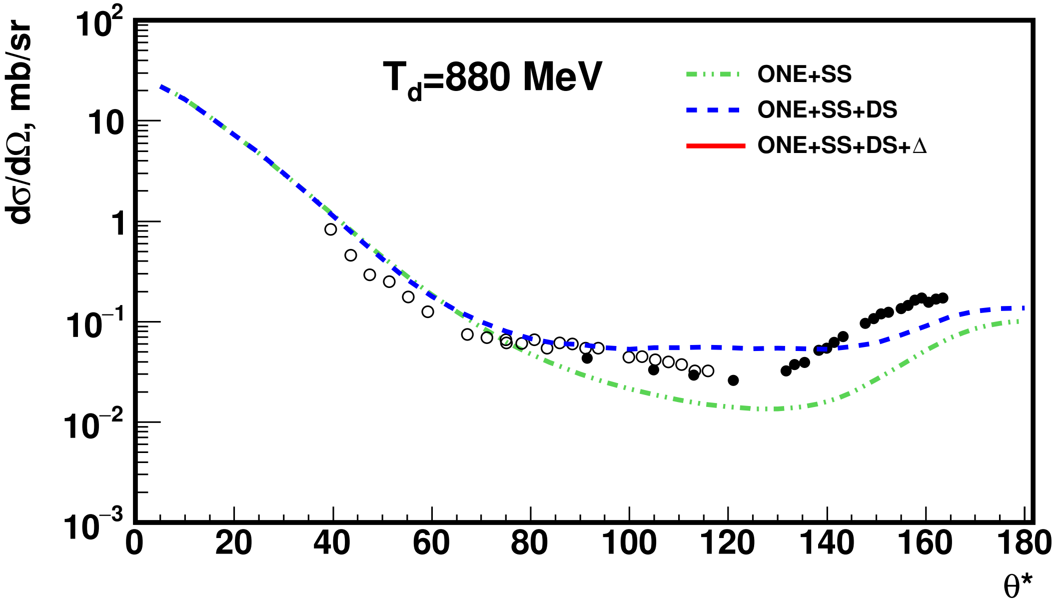
$$\sigma \sim Tr(\mathcal{J}\mathcal{J}^\dagger), \quad A_y = \frac{Tr(\mathcal{J}S_y\mathcal{J}^\dagger)}{Tr(\mathcal{J}\mathcal{J}^\dagger)}, \quad A_{yy} = \frac{Tr(\mathcal{J}Q_{yy}\mathcal{J}^\dagger)}{Tr(\mathcal{J}\mathcal{J}^\dagger)}$$



● - N.E.Booth et al., Phys.Rev.D4, p.1261 (1971), $T_d = 850 MeV$
○- J.C.Alder et al., Phys.Rev.C6, p.2010 (1972), $T_d = 940 MeV$



▲-J.S. Vincent et al., Phys. Rev. Lett. 24, 236 (1970), $T_d = 1160 MeV$
■ - A.A. Terekhin, et al., Eur. Phys. J. A55, 129(2019)



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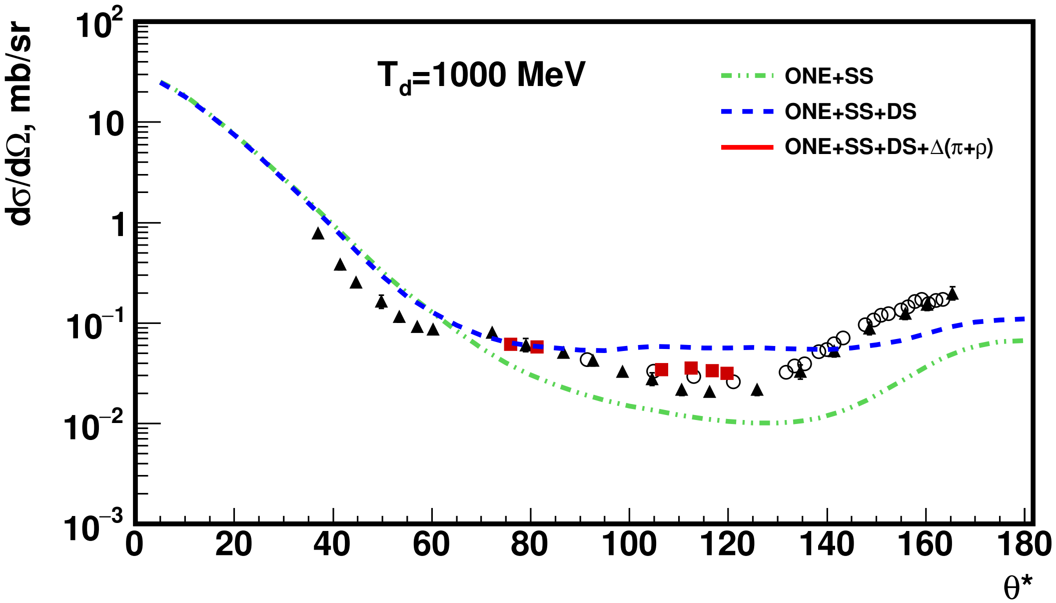

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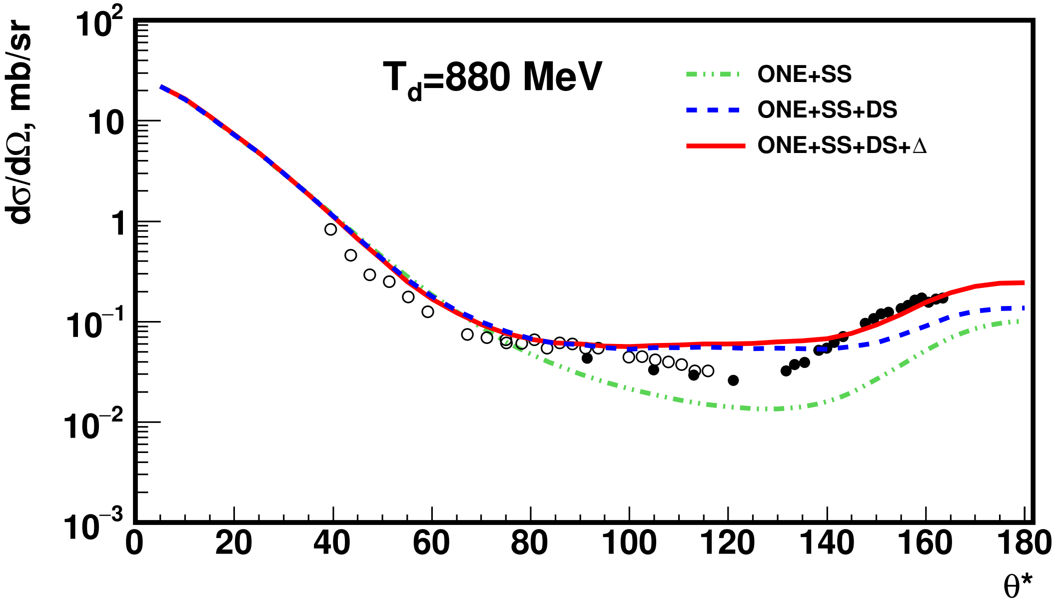

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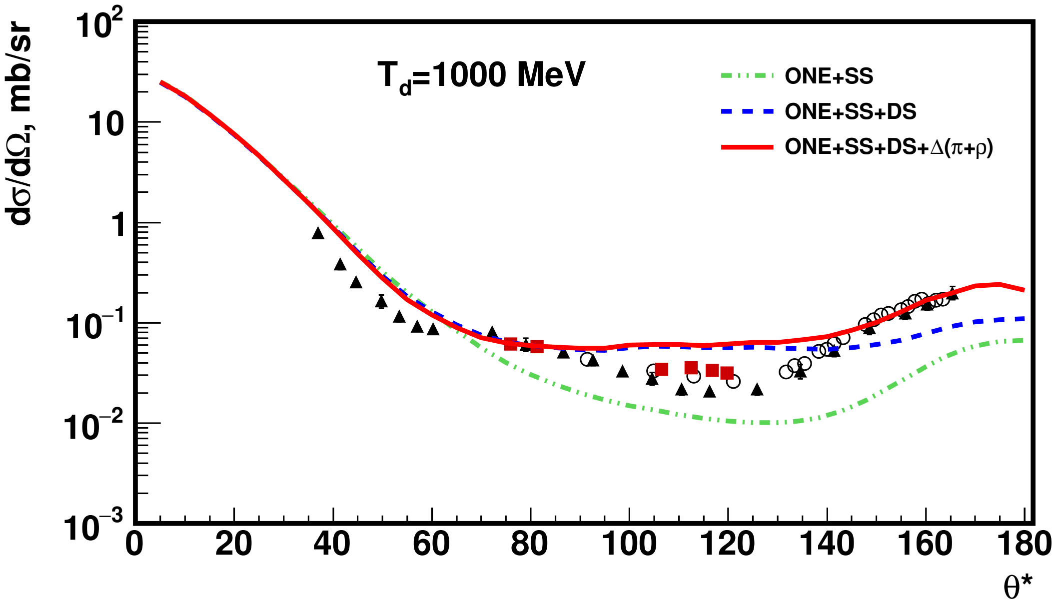

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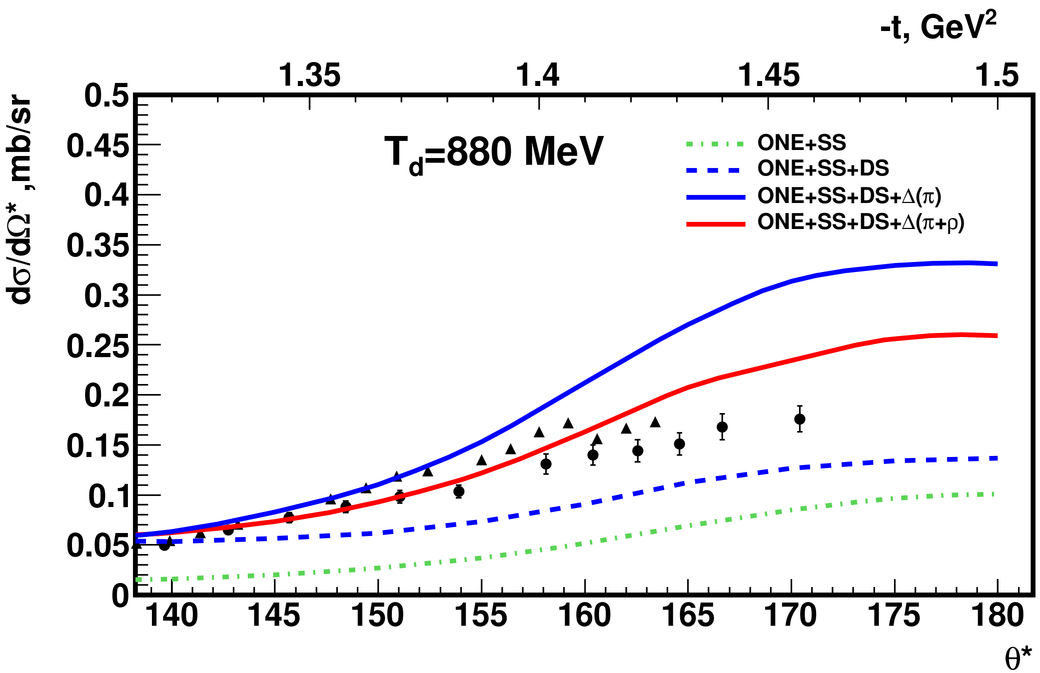

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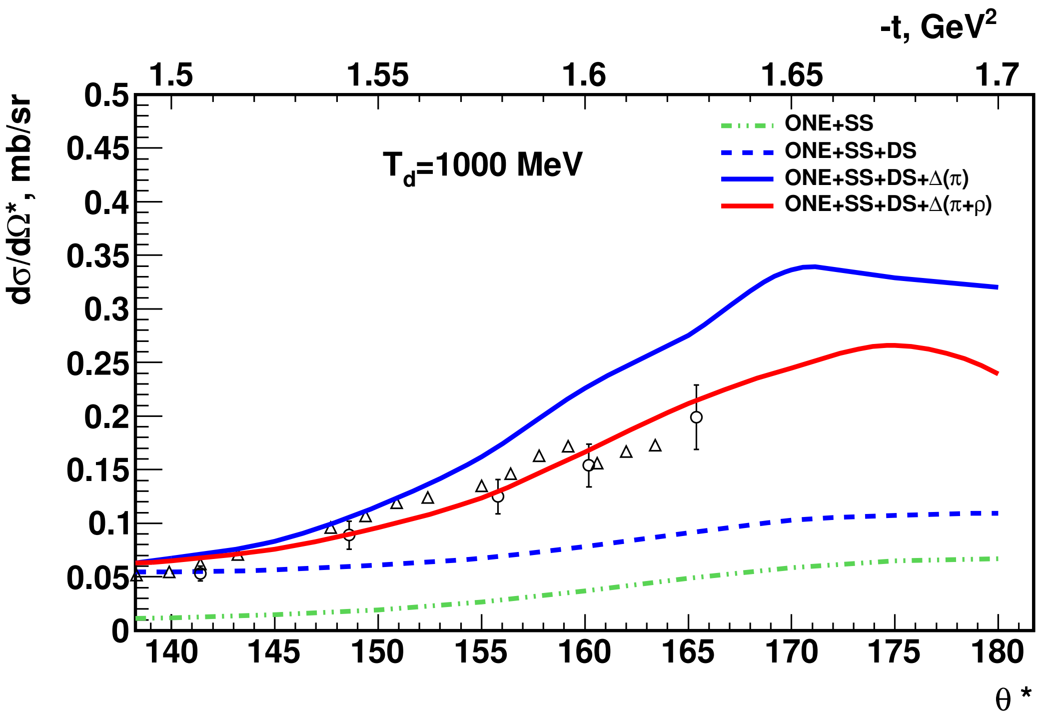

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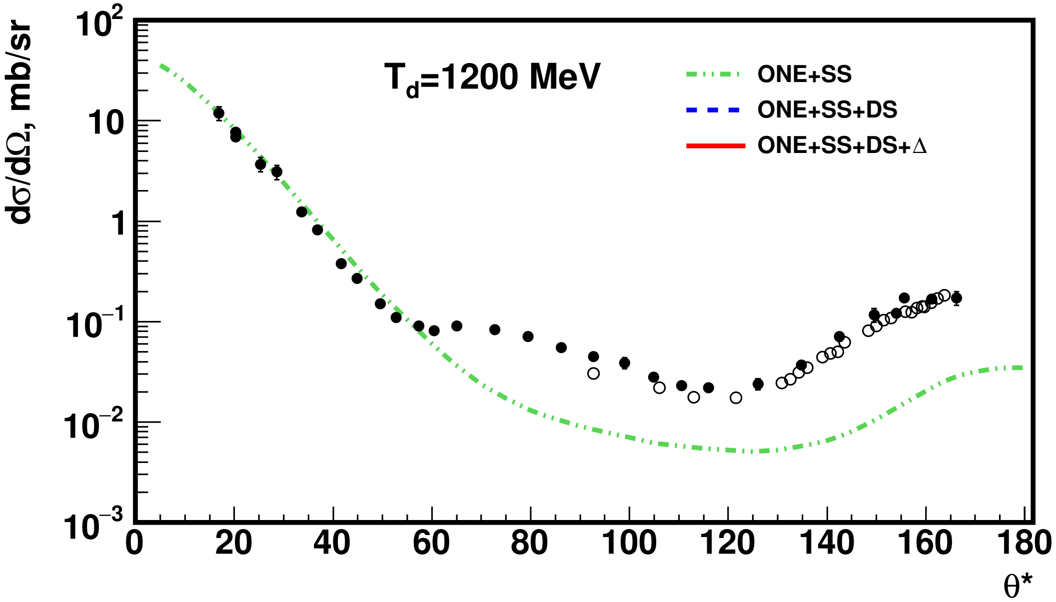

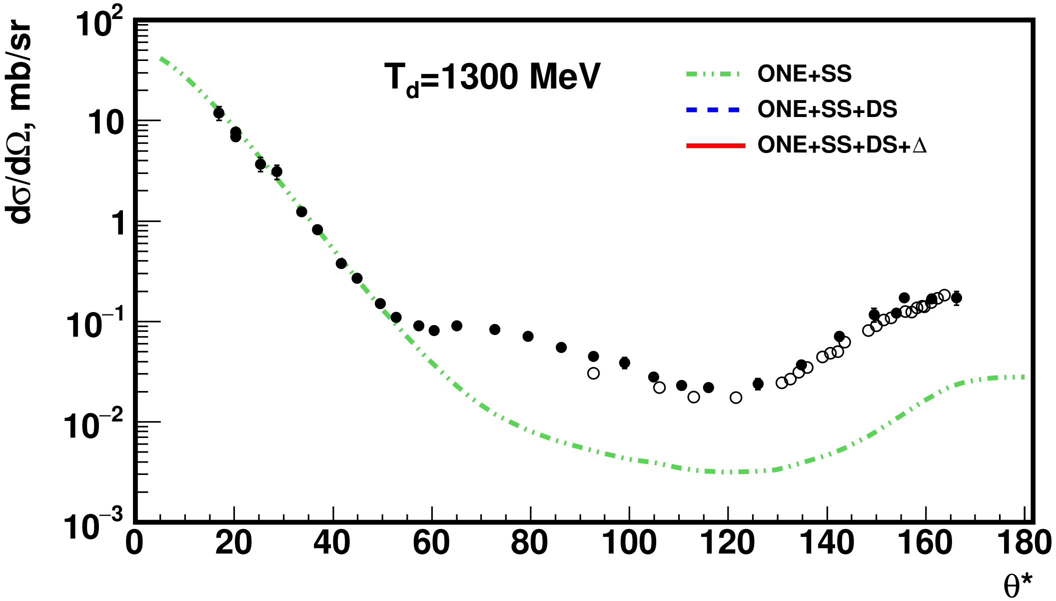

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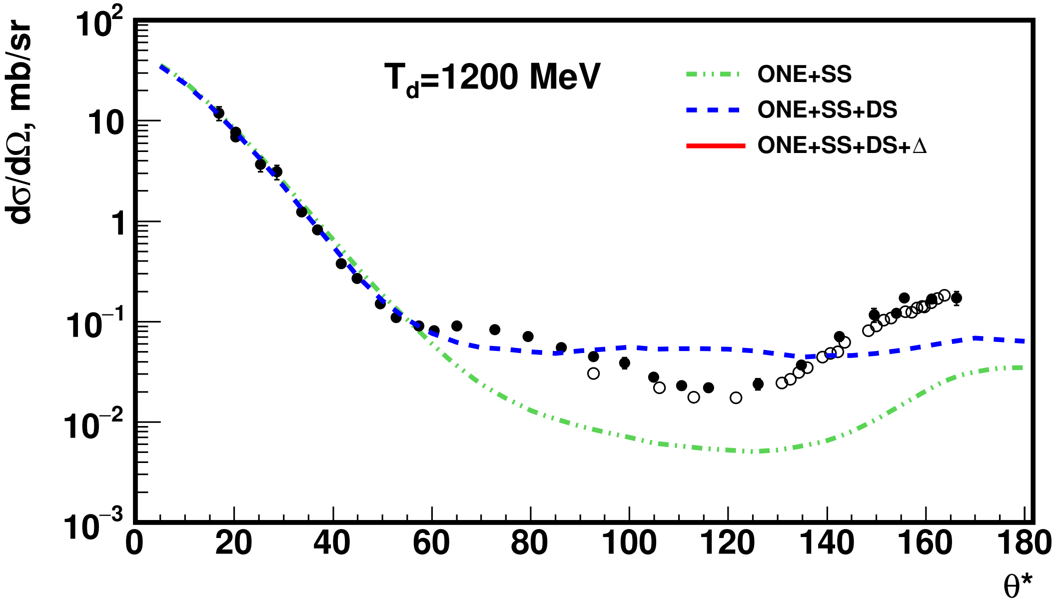

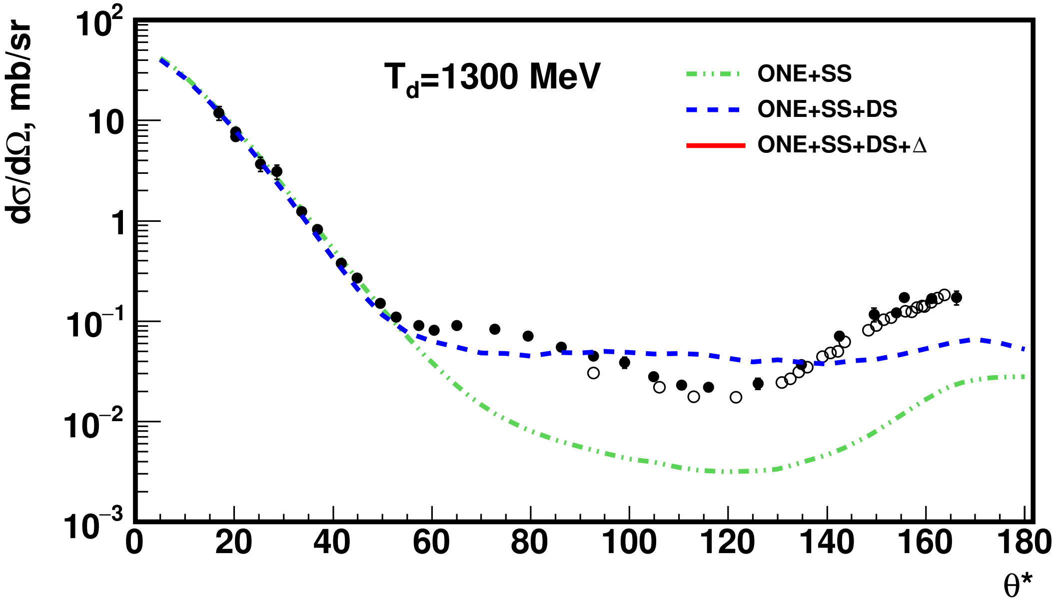

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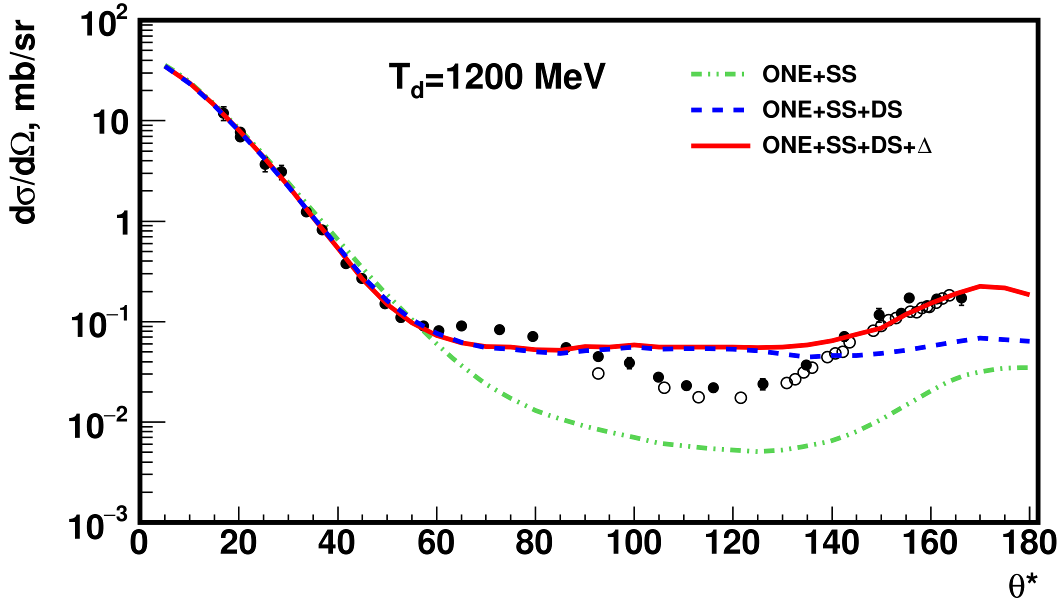

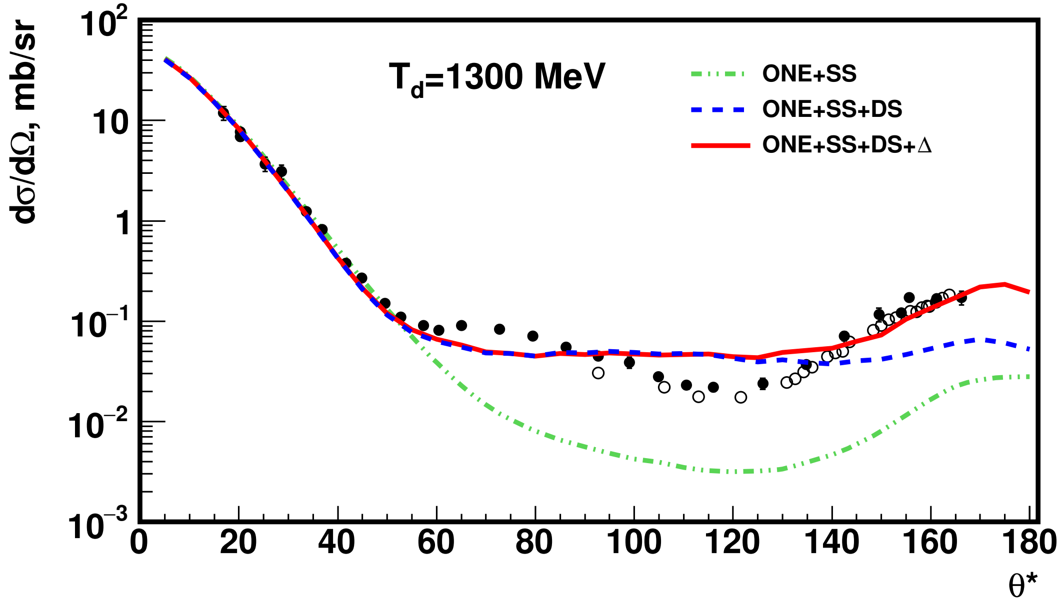

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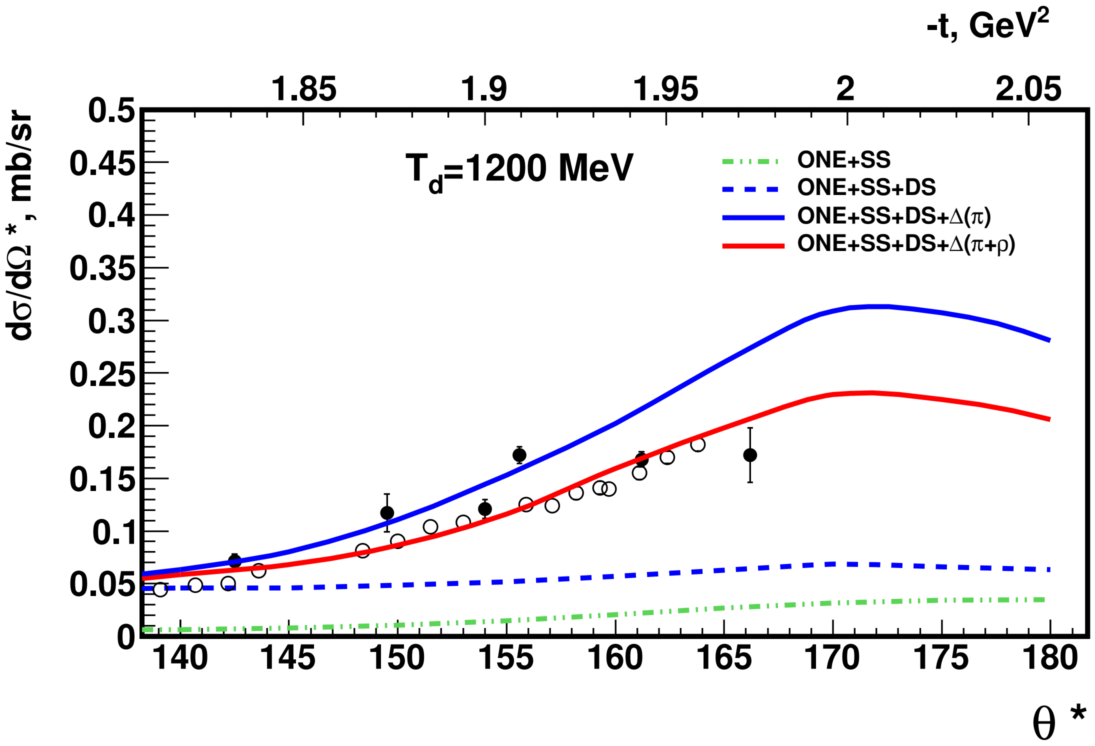

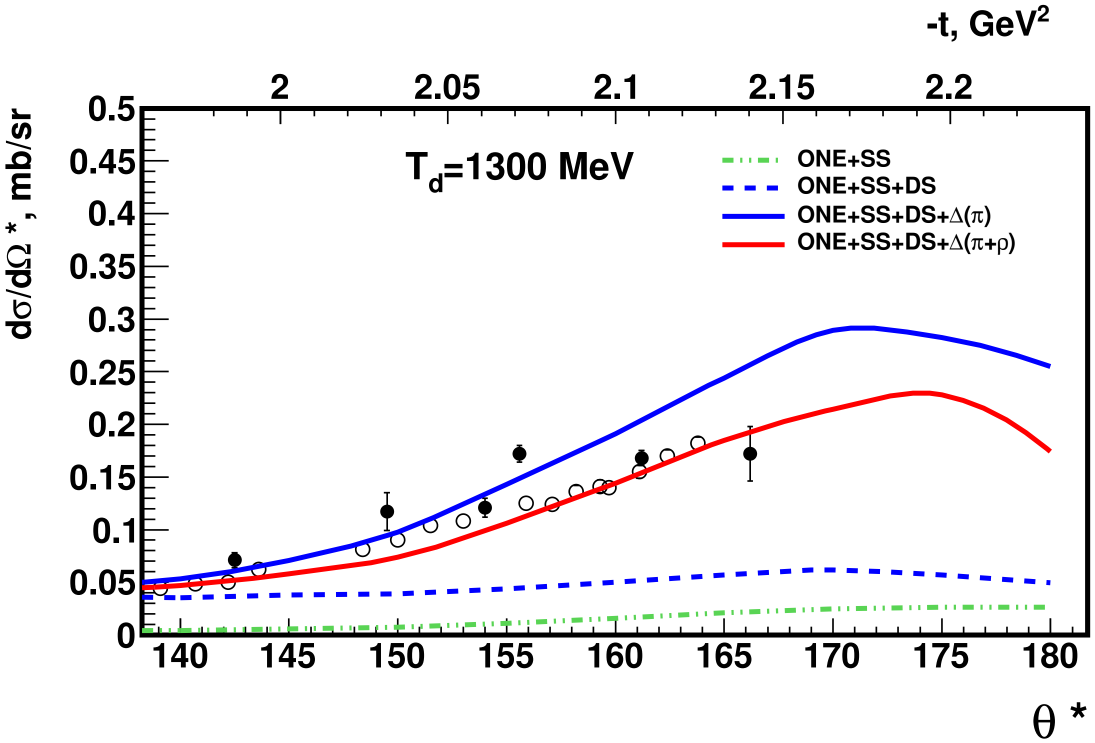

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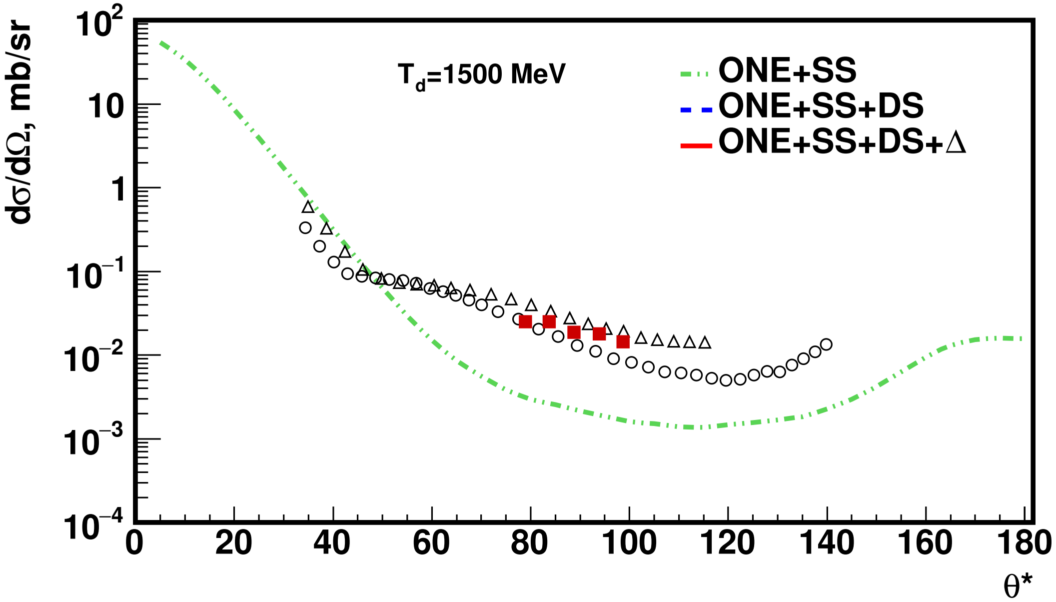

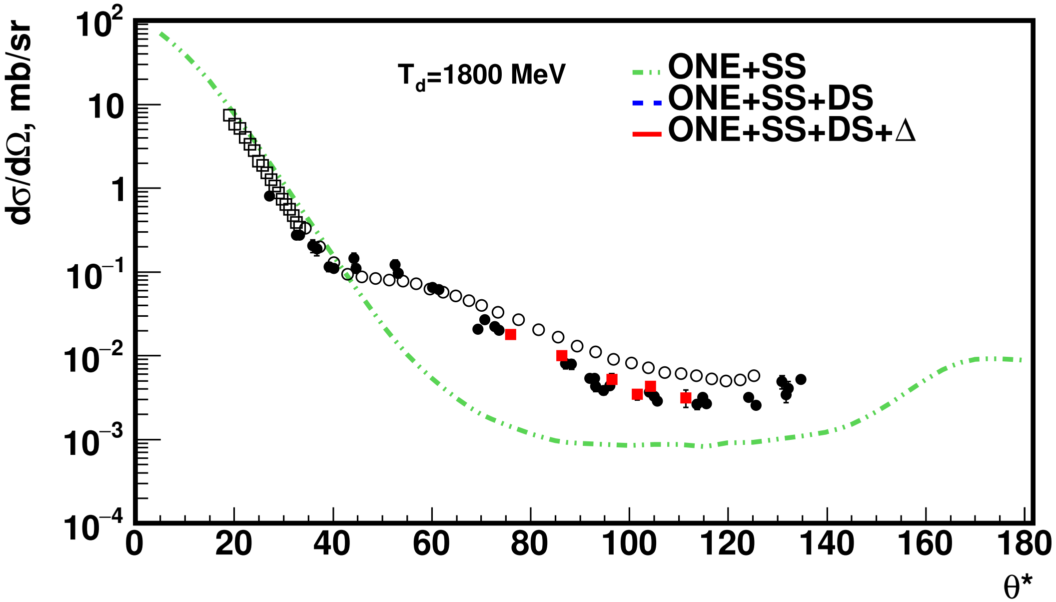

○ - E.Gülmez et al., Phys.Rev.C42, p.2067, 1991, $T_d = 1.585\,GeV$

△ - E.Gülmez et al., Phys.Rev.C42, p.2067, 1991, $T_d = 1.286\,GeV$

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□ - C. Fritzsch et al., Phys.Lett.B 784, 277 (2018), $T_d = 1.8\,GeV$

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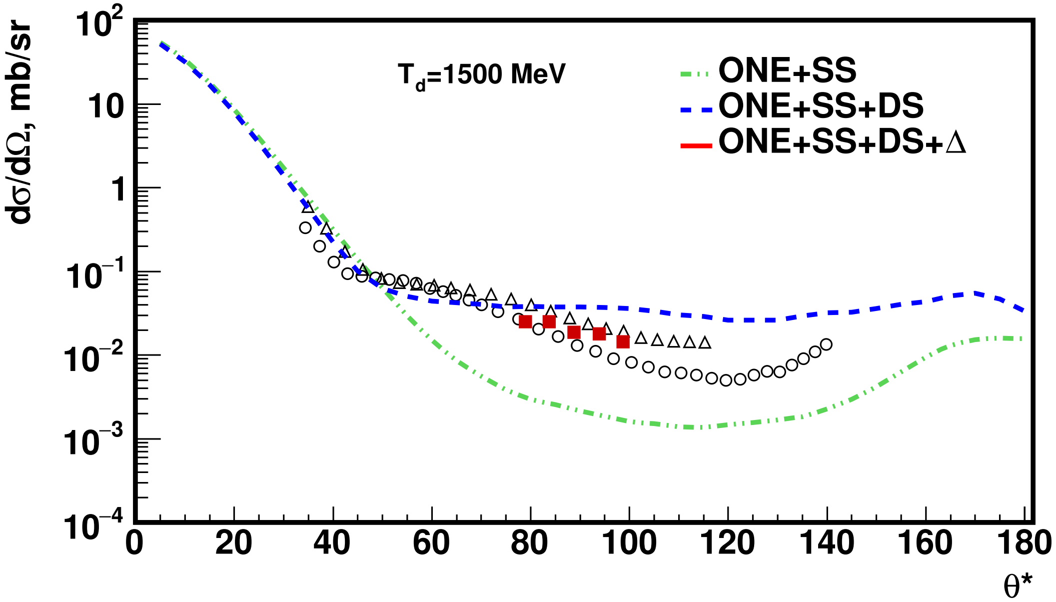

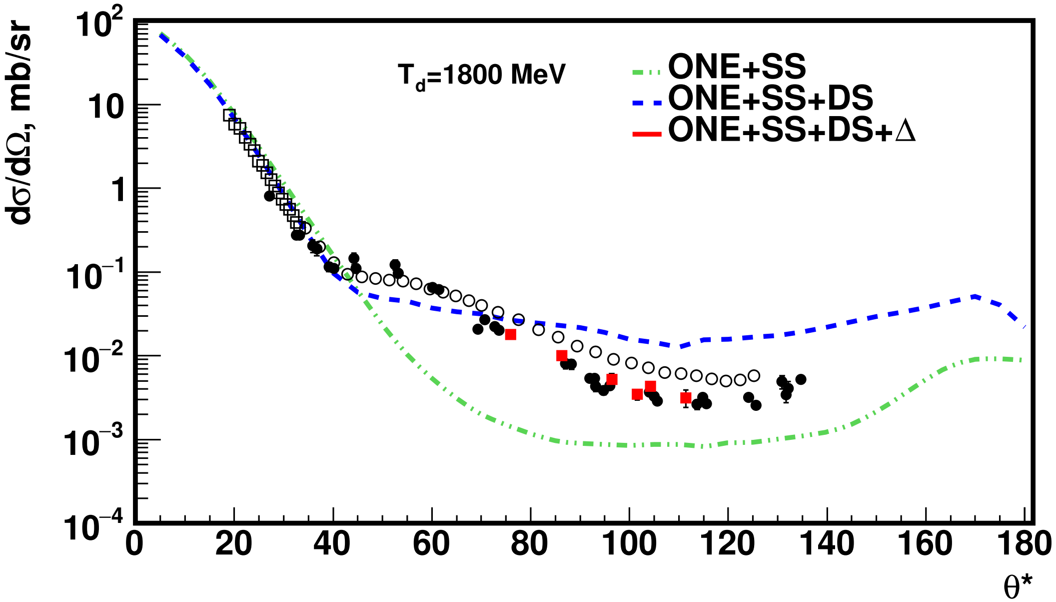

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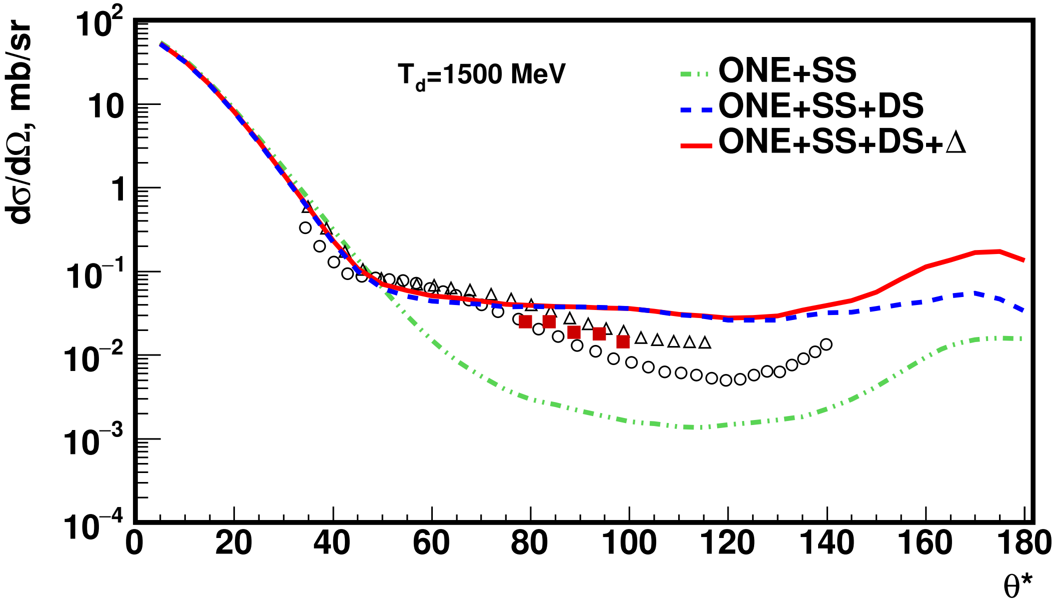

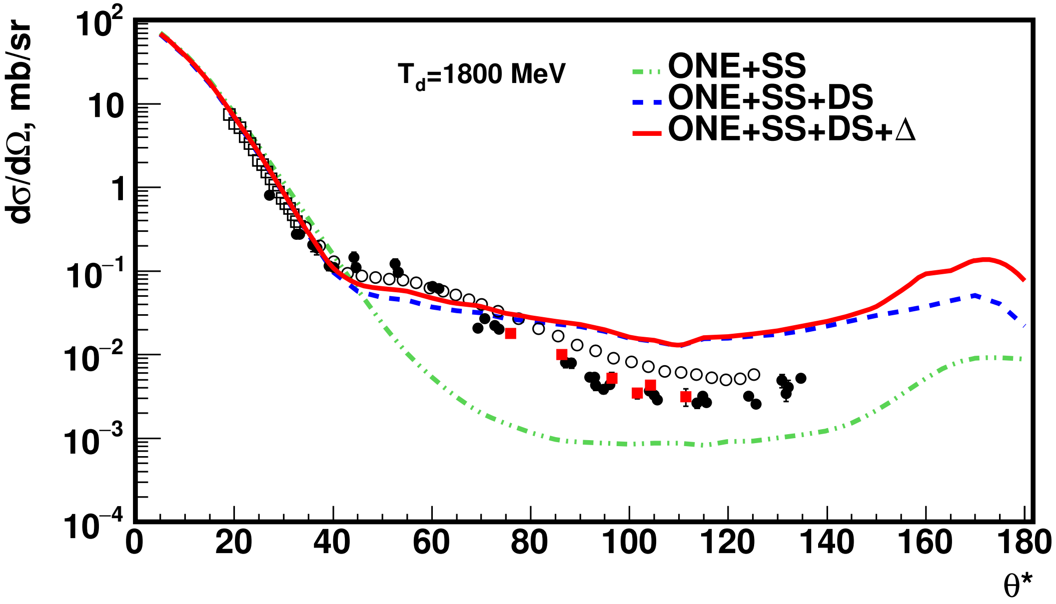

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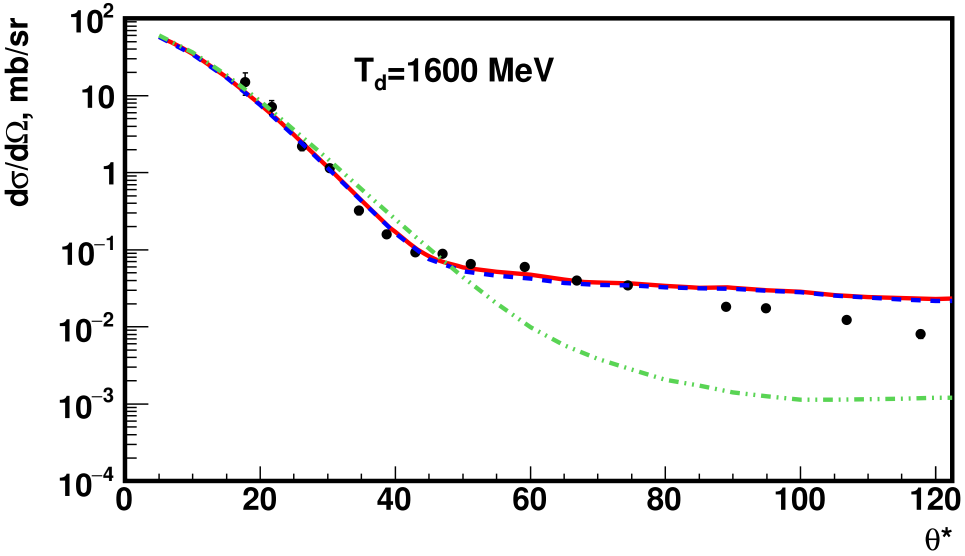
$T_d = 1600$ MeV

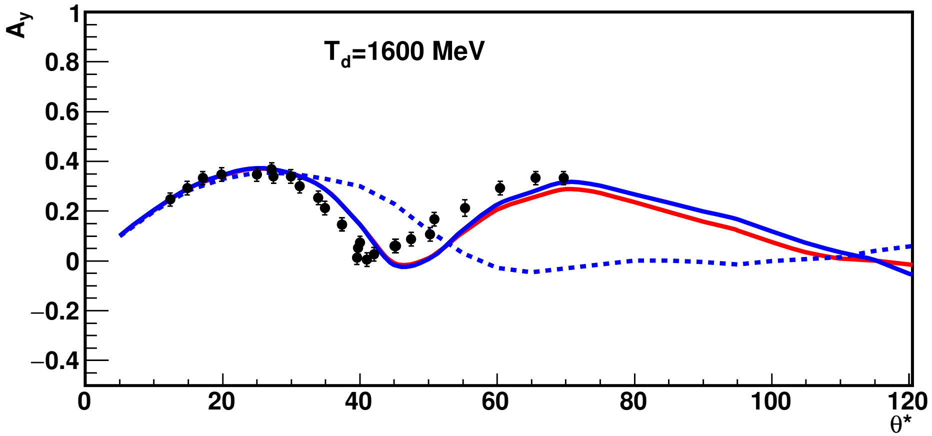


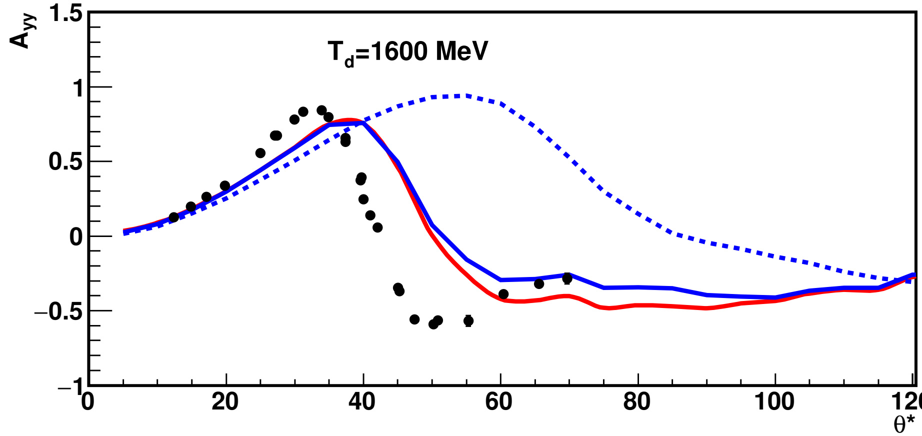
V.Ghazikhanian et al., Phys.Rev.C43,p.1532(1991)

ONE+SS

ONE+SS+DS

ONE+SS+DS+Δ





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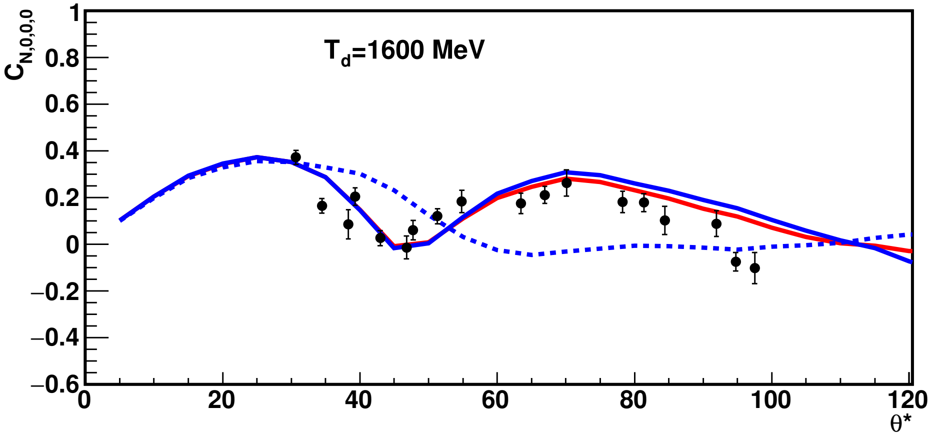

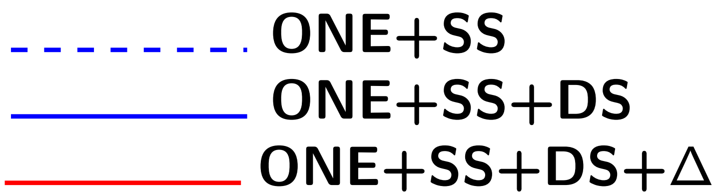

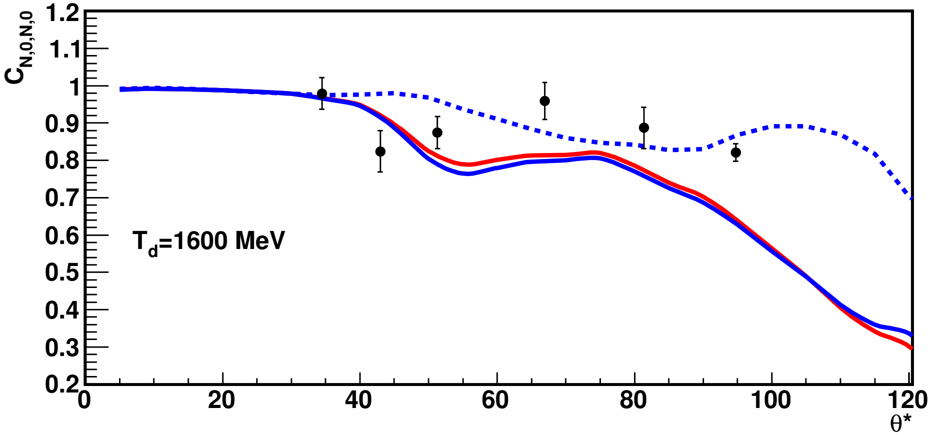

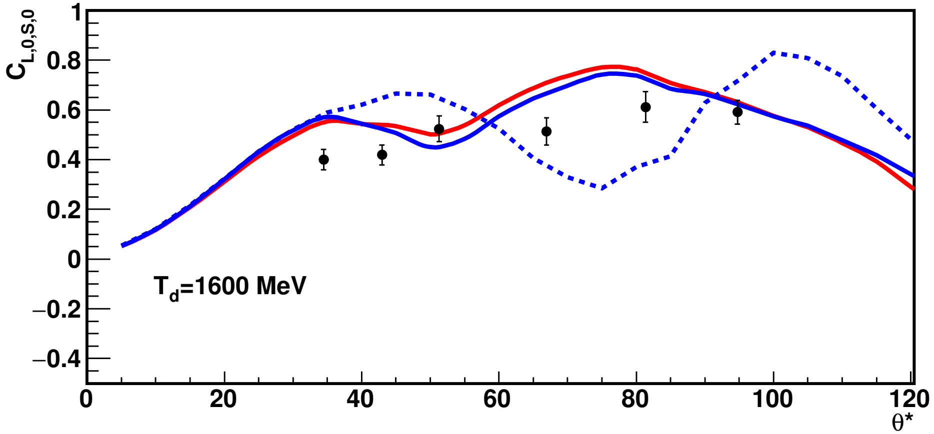

Conclusion

- dp elastic scattering has been considered taking into account four contributions: one-nucleon-exchange, single-scattering, double-scattering, and Δ-excitation in an intermediate state.
- A good description of the differential cross section has been obtained at the scattering angle $\theta^* \leq 100^\circ$ and $\theta^* \geq 130^\circ$ in the energy range between 880 and 1800 MeV.
- The description of the growth of the differential cross section at $\theta^* \geq 140^\circ$ became possible due to the inclusion of the Δ-isobar term in the consideration.
- A quite good description of the polarisation data at the deuteron energies T_d=1600 MeV on the deuteron vector A_y and tensor A_{yy} analysing powers, and on the proton analyzing power $C_{N,0,0,0}$ and proton polarization transfer $C_{N,0,N,0}$ $C_{L,0,S,0}$ has been obtained at the scattering angle $\theta^* \leq 100^\circ$
- Nevertheless, there are problems with the description of the differential cross section at the scattering angles $100^\circ < \theta^* \leq 130^\circ$