Normal Spin Asymmetries:

Resonance Region

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Outline

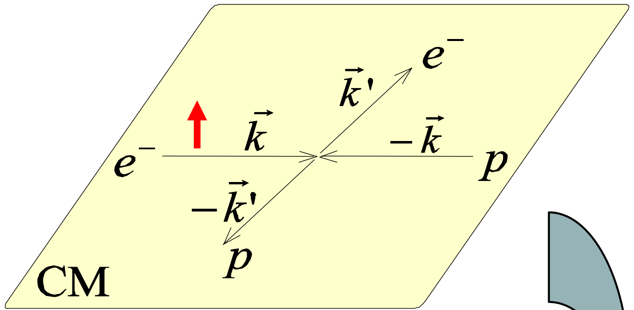
- Normal spin asymmetries related to T-odd effects in elastic electron-nucleon scattering ⟶ direct measurement of the absorptive part of 2-γ exchange box diagram

- Unitarity to relate the absorptive part of 2-γ exchange amplitude to pion electroproduction amplitudes

- Estimates of resonance contribution to Beam and Target Normal asymmetries

Pasquini, Vanderhaeghen, Phys. Rev. C70 (2004)

Transverse beam spin asymmetry



$\uparrow \equiv (\hat{k} \times \hat{k}')$

$$T_{f\,i} \equiv T_{\uparrow}(\vec{k}, \vec{k}')$$

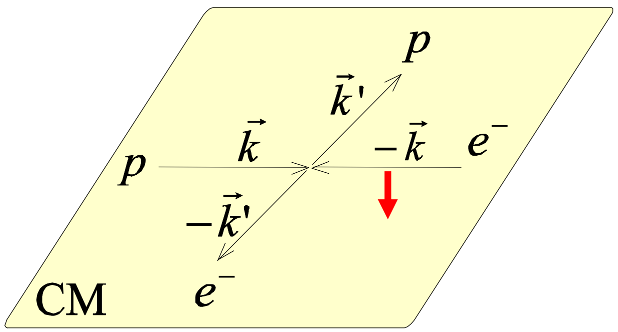
$$|T_{f\,i}|^2 \sim \sigma_{\uparrow}$$

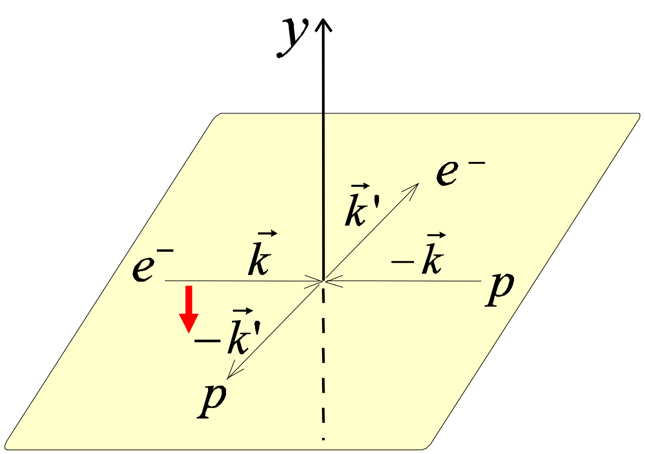
time reversed states

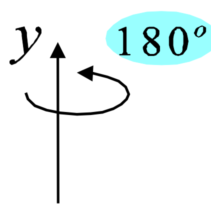
$$i \rightarrow \tilde{i}$$
$$f \rightarrow \tilde{f}$$

momenta and spins reversed

$$T_{\tilde{f}\,\tilde{i}} \equiv T_{\downarrow}(-\vec{k}, -\vec{k}')$$







rotation over 180° around axis ⊥ to plane

$$T_{\downarrow}(-\vec{k}, -\vec{k}') = \eta\, T_{\downarrow}(\vec{k}, \vec{k}')$$

phase (↑ η)

$$|T_{\tilde{f}\,\tilde{i}}|^2 = |T_{\downarrow}(\vec{k}, \vec{k}')|^2 \sim \sigma_{\downarrow}$$

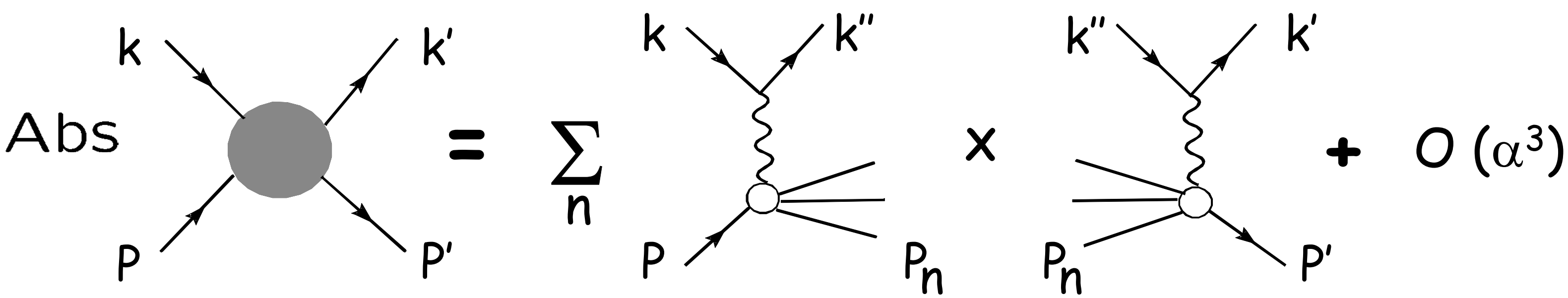
De Rujula et al., NPB35 (1971)

$$A = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = \frac{|T_{f\,i}|^2 - |T_{\tilde f\,\tilde i}|^2}{|T_{f\,i}|^2 + |T_{\tilde f\,\tilde i}|^2} \propto \text{ T-odd effects}$$

- Unitarity

$$S\,S^\dagger = S^\dagger\,S = \mathcal{I} \quad \text{with} \quad S_{f\,i} = \delta_{f\,i} - iT_{f\,i}$$

$$\Rightarrow \quad i(T_{f\,i} - T^\dagger_{f\,i}) = \Sigma_n T^\dagger_{f\,n} T_{n\,i} \equiv \mathrm{Abs}\,T_{f\,i}$$



on-shell intermediate states

- Time reversal invariance: $|T_{f\,i}|^2 \equiv |T_{\tilde i\,\tilde f}|^2$

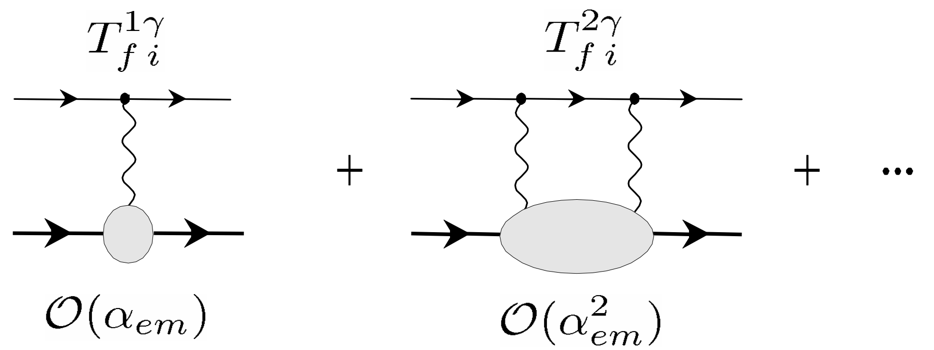
$$\begin{cases} |\mathrm{Abs}\,T_{f\,i}|^2 = |T_{f\,i}|^2 + |T_{\tilde f\,\tilde i}|^2 - 2\,\mathrm{Re}(T_{f\,i}\,T_{i\,f}) \\ 2\,\mathrm{Im}\,(T^*_{f\,i}\mathrm{Abs}\,T_{f\,i}) = 2\,\mathrm{Re}\,(|T_{f\,i}|^2 - T^*_{f\,i}T^*_{i\,f}) \end{cases}$$

$$\boxed{2\,\mathrm{Im}\,(T^*_{f\,i}\mathrm{Abs}\,T_{f\,i}) - |\mathrm{Abs}\,T_{f\,i}|^2 = |T_{f\,i}|^2 - |T_{\tilde f\,\tilde i}|^2 \sim A}$$

$$A \sim 2\,\mathrm{Im}\,(T^{*}_{f\,i}\mathrm{Abs}\,T_{f\,i}) - |\mathrm{Abs}\,T_{f\,i}|^2 = |T_{f\,i}|^2 - |T_{\tilde{f}\,\tilde{i}}|^2$$

- Perturbation theory in α_{em}

$T_{f\,i} =$



➡ to $\mathcal{O}(\alpha^2_{em})$ $\quad |T^{1\,\gamma}_{f\,i}|^2 - |T^{1\,\gamma}_{\tilde{f}\,\tilde{i}}|^2 = 0$

1 γ exchange gives no contribution to spin asymmetries

➡ to $\mathcal{O}(\alpha^3_{em})$

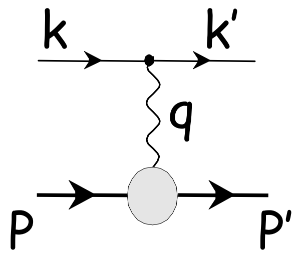
$$|T_{f\,i}|^2 - |T_{\tilde{f}\,\tilde{i}}|^2 = 2\,\mathrm{Im}\,(T^{*\,1\gamma}_{f\,i}\ \mathrm{Abs}\,T^{2\,\gamma}_{f\,i})$$

spin asymmetries arise from interference of
1γ exchange and absorptive part of 2γ exchange

→ to $\mathcal{O}(\alpha_{em})$

$$A = \frac{\mathrm{Im}\,(T^{*\,1\gamma}_{f\,i}\,\mathrm{Abs}\,T^{2\gamma}_{f\,i})}{|T^{1\gamma}_{f\,i}|^2}$$

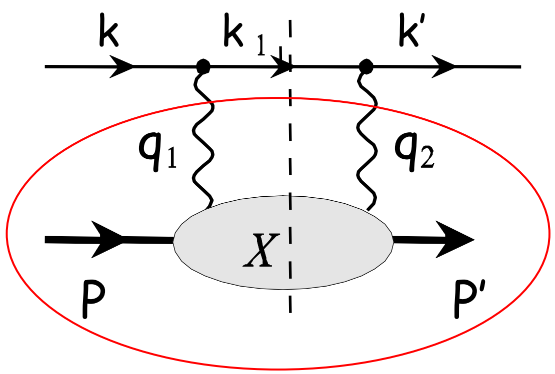
→ 1γ exchange



$$\Sigma_{\mathrm{spin}}\,|T^{1\gamma}_{f\,i}|^2 = \frac{e^4}{Q^4}\,D(s,Q^2)$$

functions of elastic nucleon form factors

→ 2γ exchange

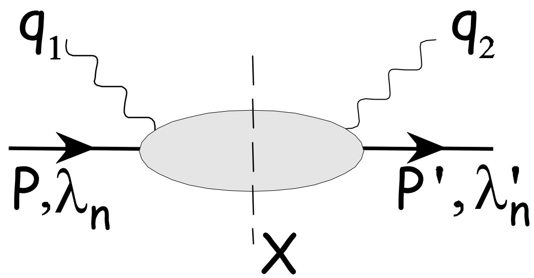


absorptive part of doubly virtual Compton scattering

$$\mathrm{Abs}\,T^{2\gamma} = e^4 \int \frac{d^3\vec{k}_1}{(2\pi)^3 2E_{k_1}}\bar{u}(k',h')\gamma_\mu(\gamma\cdot k_1 + m_e)\gamma_\nu u(k,h)$$
$$\times \frac{1}{Q_1^2 Q_2^2} W^{\mu\nu}(p',\lambda'_N;p,\lambda_N)$$

Hadronic Tensor: Absorptive part of Doubly Virtual Compton Tensor

$$W^{\mu\nu} = \sum_X (2\pi)^4 \delta^4(p + q_1 - p_X) \, \langle p' \lambda'_N | J^\mu(0) | X \rangle \, \langle X | J^\nu(0) | p \lambda_N \rangle$$



on-shell intermediate states ($M_X^{\,2} = W^2$)

Transverse spin asymmetries

$$A = -\frac{1}{(2\pi)^3} \frac{e^2 Q^2}{D(s,Q^2)} \int_{M^2}^{(\sqrt{s}-m_e)^2} dW^2 \, \frac{|\vec{k}_1|}{4\sqrt{s}} \int d\Omega_{k_1} \frac{1}{Q_1^2 \, Q_2^2} \, \mathrm{Im} \left\{ L_{\alpha\mu\nu} H^{\alpha\mu\nu} \right\}$$

lepton $\quad L_{\alpha\mu\nu} = \bar{u}(k',h')\gamma_\mu(\gamma \cdot k_1 + m_e)\gamma_\nu u(k,h) \cdot [\bar{u}(k',h')\gamma_\alpha u(k,h)]^*$

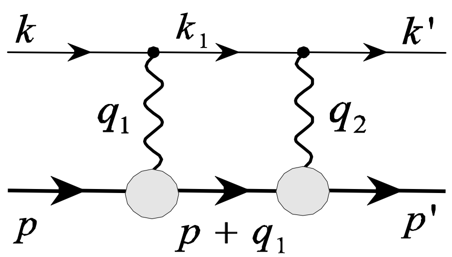
hadron $\quad H^{\alpha\mu\nu} = W^{\mu\nu} \cdot \left[\bar{u}(p',\lambda'_N) \left(G_M \gamma^\alpha - F_2 \frac{P^\alpha}{M} \right) u(p,\lambda_N) \right]^*$

- Beam normal spin asymm. $\quad h \, // \, (\hat{k} \times \hat{k}')$
- Target normal spin asymm. $\quad \lambda_N \, // \, (\hat{k} \times \hat{k}')$

sum over spins unpolarized particles

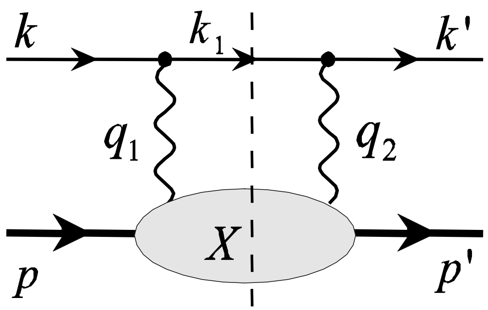
Model for the hadronic tensor

- Elastic contribution



on-shell nucleon intermediate states

- Inelastic contribution

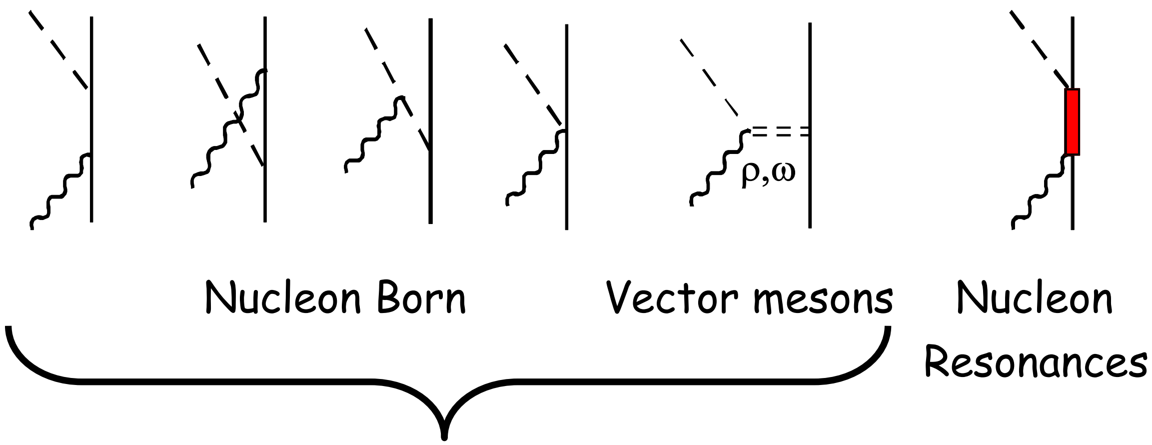


X= π N

resonant and non-resonant π N intermediate states
calculated with MAID2000

MAID

The Mainz-Dubna Unitary Isobar Model



✓ Background and resonance separately unitarized

✓ Pion cloud is absorbed in the dressed resonances

✓ Vector meson and Resonance parameters fitted to $\gamma^* + N \rightarrow \pi N$ experimental data

Nucleon resonance included
(all 13 **** below 2 GeV)

Resonance	Partial Wave	Multipoles
Δ(1232)	P_{33}	M_{1+}, E_{1+}, L_{1+}
N*(1440)	P_{11}	M_{1-}, L_{1-}
N*(1520)	D_{13}	M_{2-}, E_{2-}, L_{2-}
N*(1535)	S_{11}	E_{0+}, L_{0+}
Δ(1620)	S_{31}	E_{0+}, L_{0+}
N*(1650)	S_{11}	E_{0+}, L_{0+}
N*(1680)	F_{15}	M_{3-}, E_{3-}, L_{3-}
Δ(1700)	D_{33}	M_{2-}, E_{2-}, L_{2-}
N*(1675)	D_{15}	M_{2+}, E_{2+}, L_{2+}
N*(1720)	P_{13}	M_{1+}, E_{1+}, L_{1+}
Δ(1910)	P_{31}	M_{1-}, L_{1-}
Δ(1905)	F_{35}	M_{3-}, E_{3-}, L_{3-}
Δ(1950)	F_{37}	M_{3+}, E_{3+}, L_{3+}

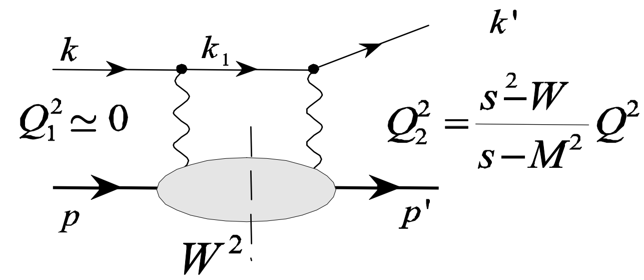
Drechsel, Hanstein, Kamalov, Tiator, NPA645 (1999)

Kinematical limits

$Q^2{}_1 \simeq 0,\ Q^2{}_2 \neq 0$

↓

$k \mathbin{/\!/} k_1$

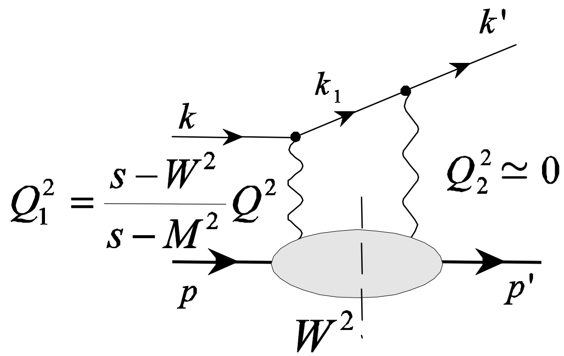


Quasi - VCS

$Q^2{}_1 \neq 0,\ Q^2{}_2 \simeq 0$

↓

$k_1 \mathbin{/\!/} k'$

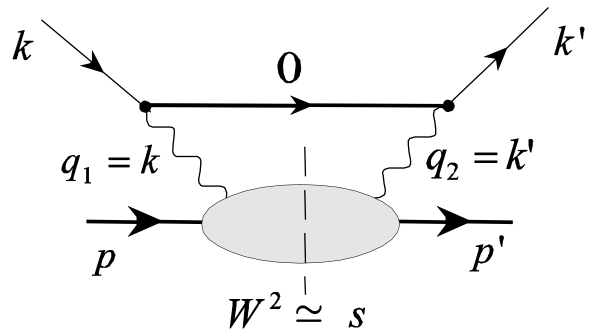


Quasi - VCS

$Q^2{}_1 \simeq 0,\ Q^2{}_2 \simeq 0$

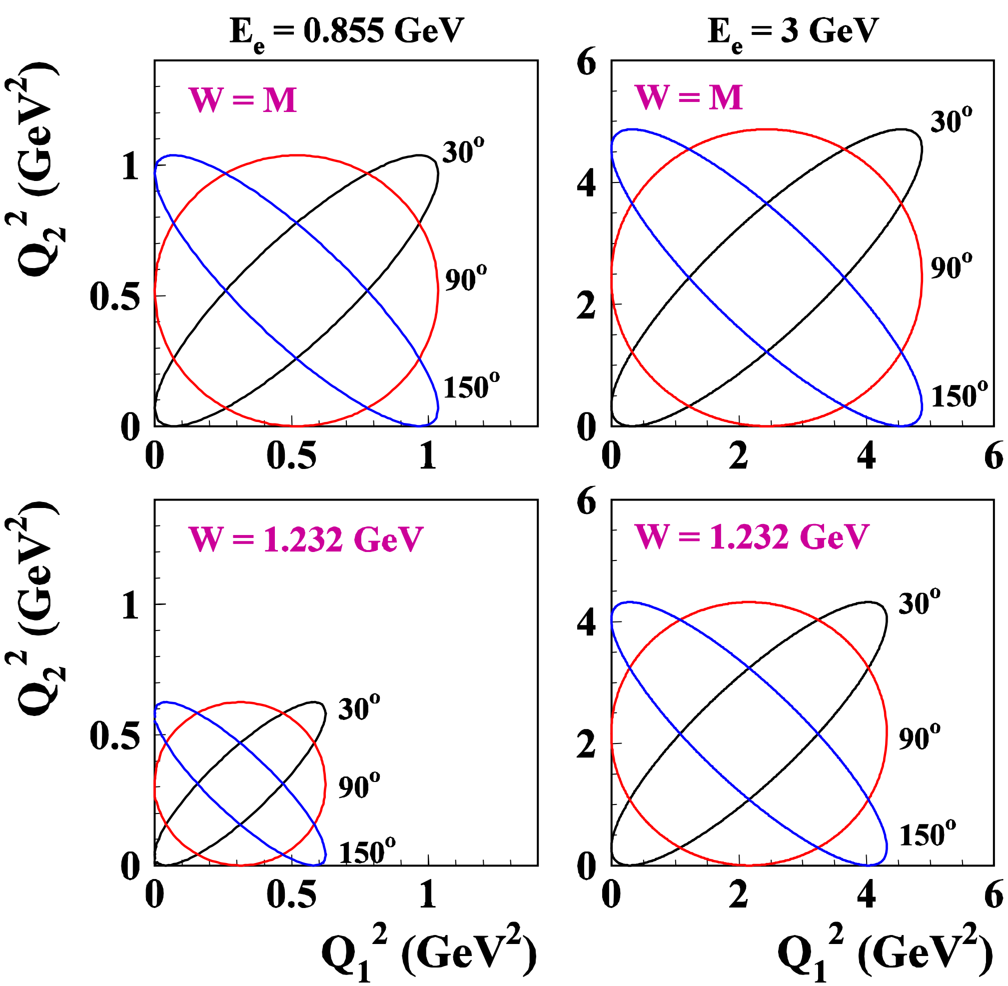
↓

$k_1 = 0,\ W = \sqrt{s} - m_e$



Quasi - RCS

Kinematical bounds for Q^2_1 and Q^2_2

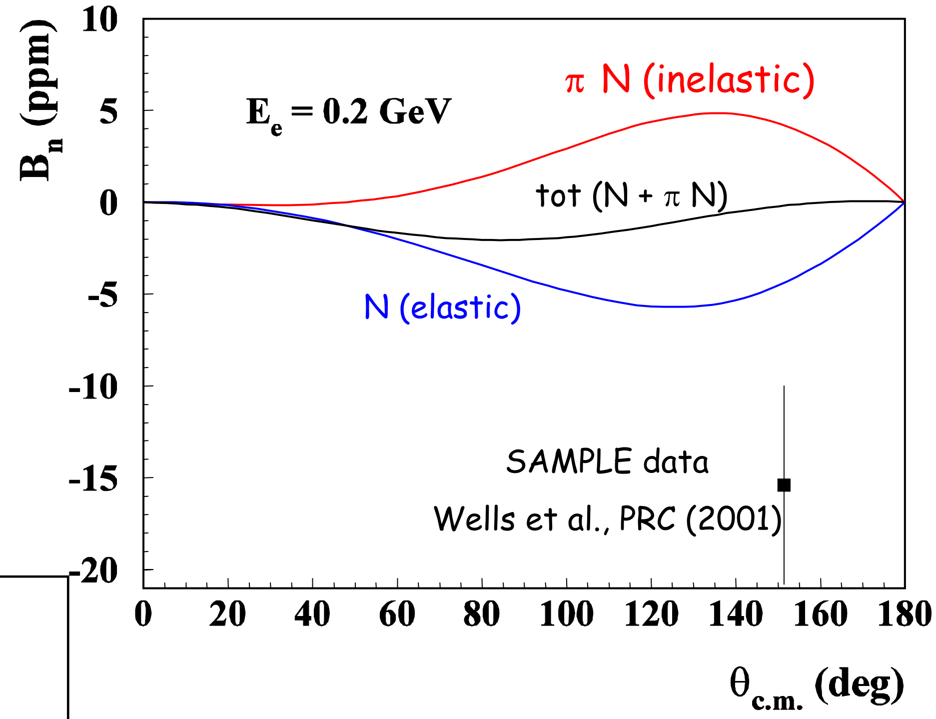


Elastic contribution

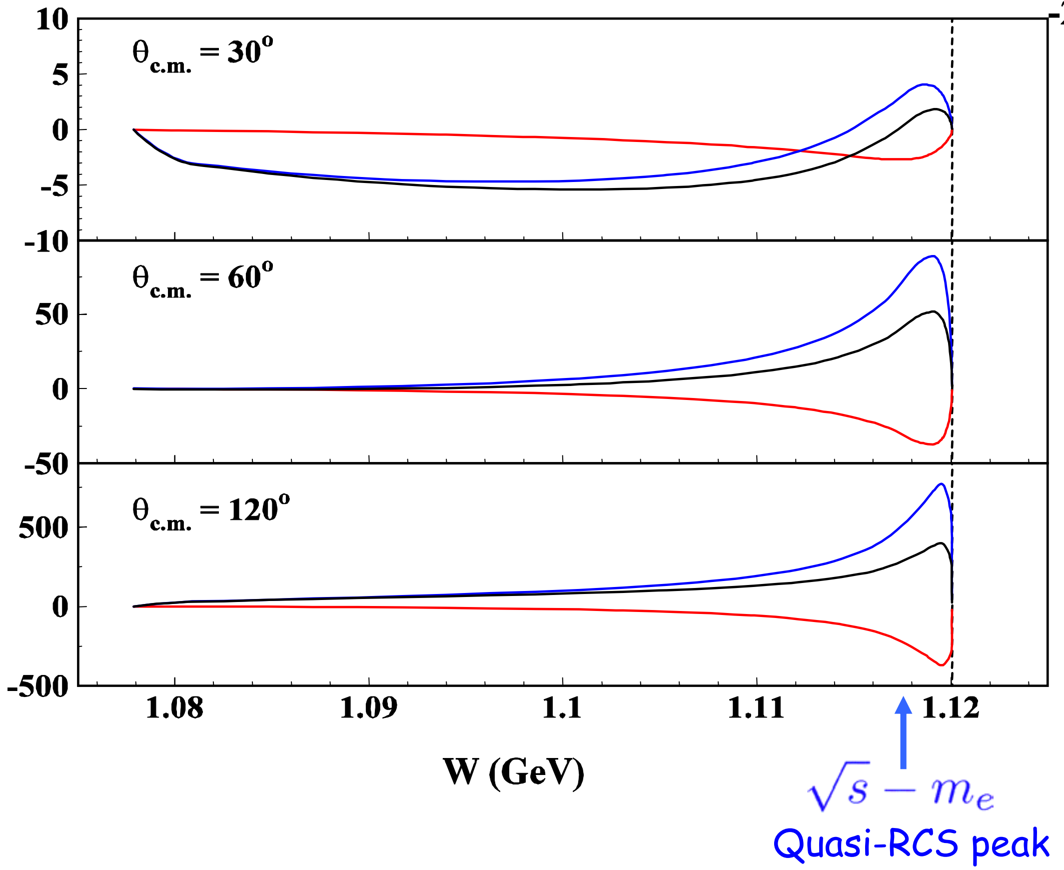
Inelastic contribution

Beam normal spin asymmetry

Ee =0.2 GeV



Integrand [ppm GeV^{-1}]



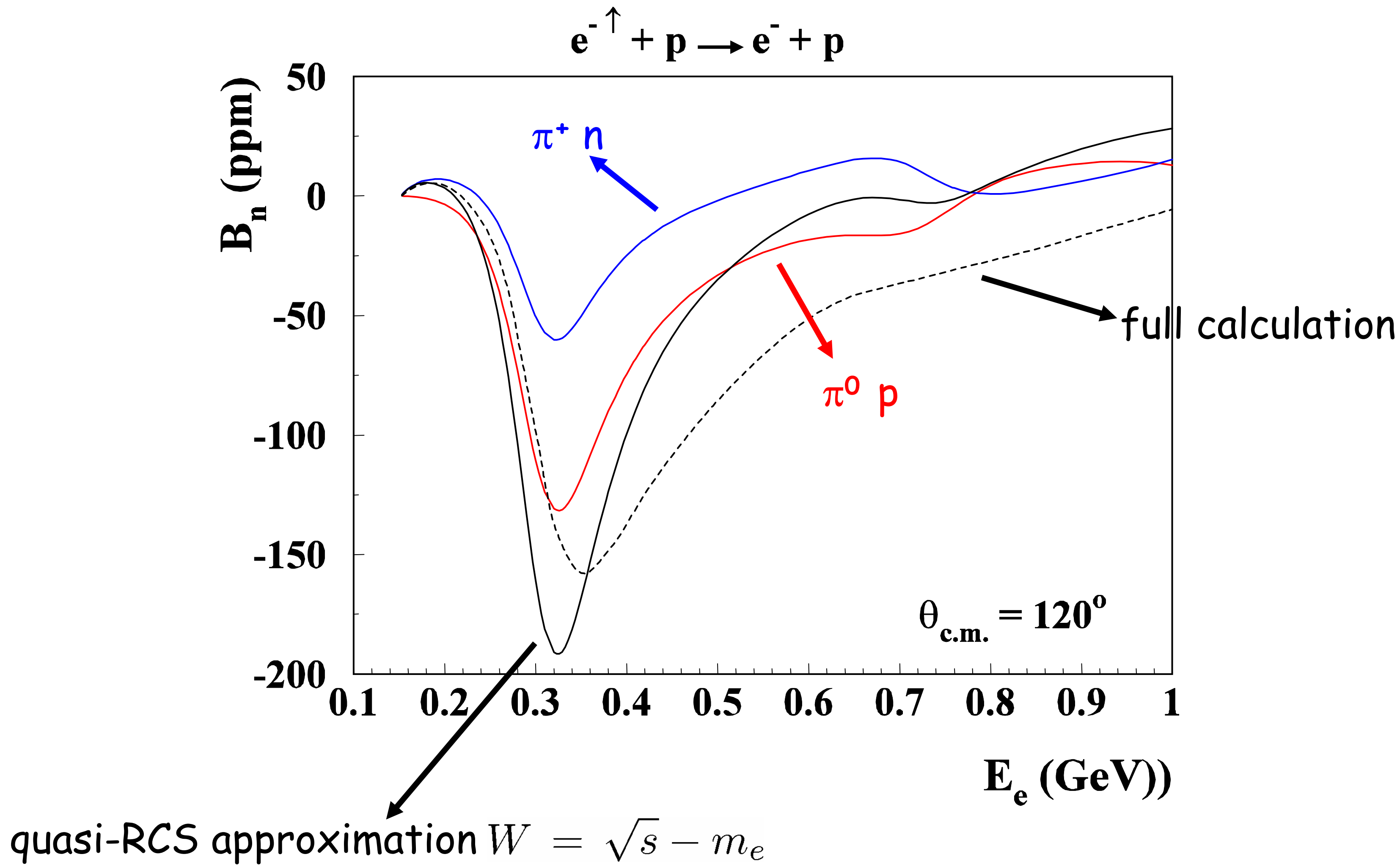
✓ inelastic contribution dominated by the region of threshold pion production

✓ MAID in the threshold region is consistent with chiral predictions

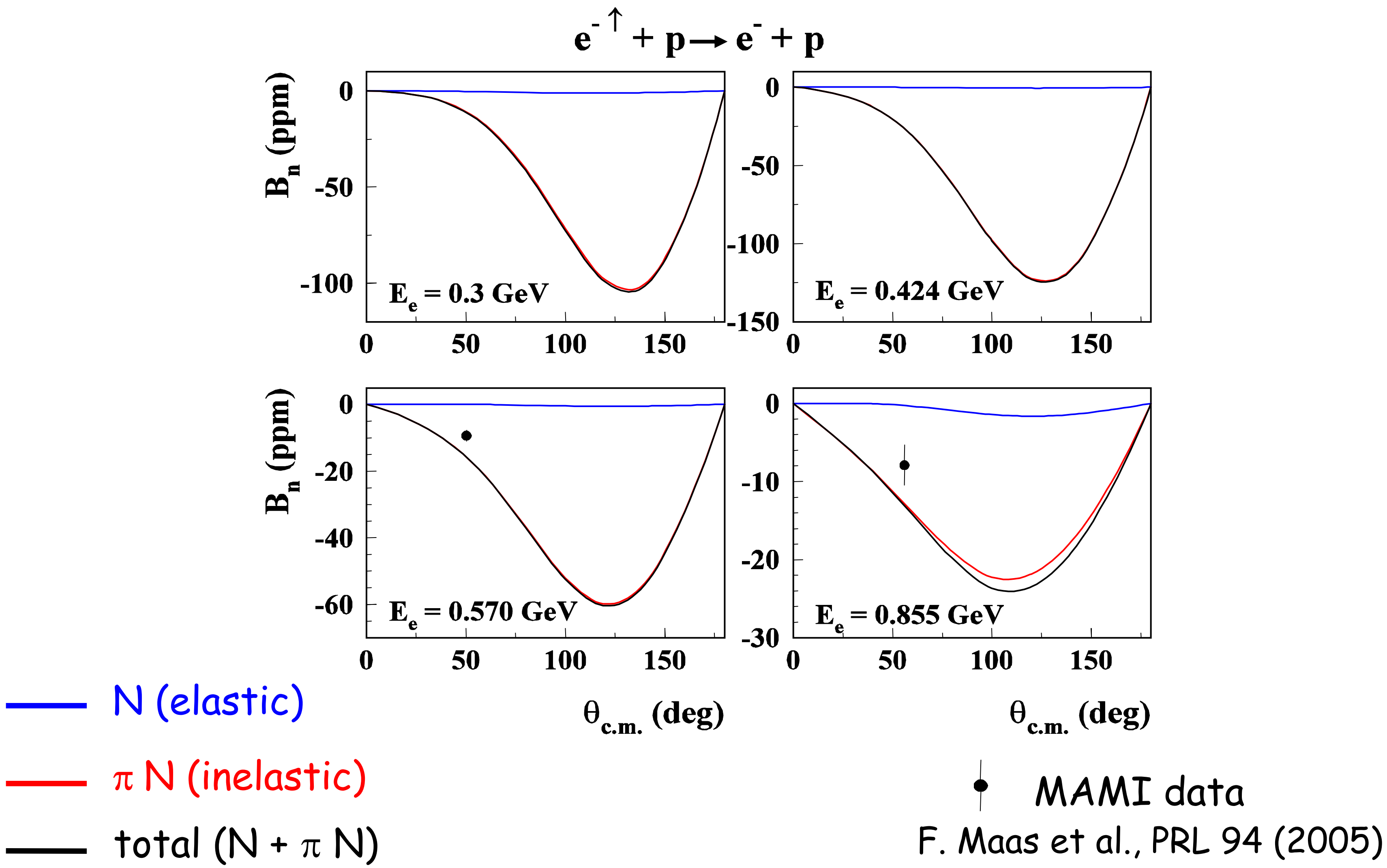
➥ Model Indipendent Estimate

Beam normal spin asymmetry:

energy dependence at fixed θ_{cm}=120°



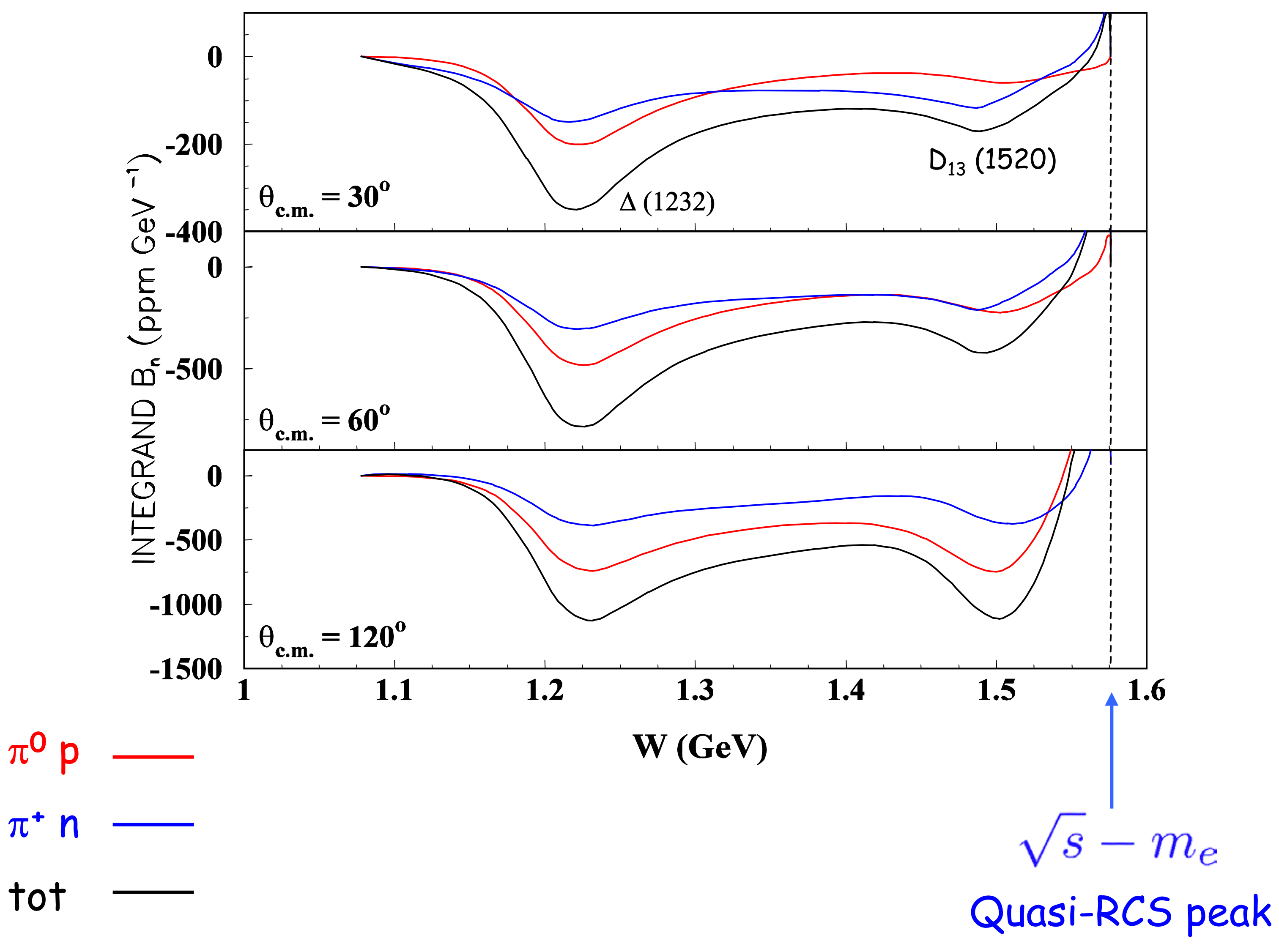
Beam normal spin asymmetry



New measurements at MAMI and at JLab in the forward and backward regions

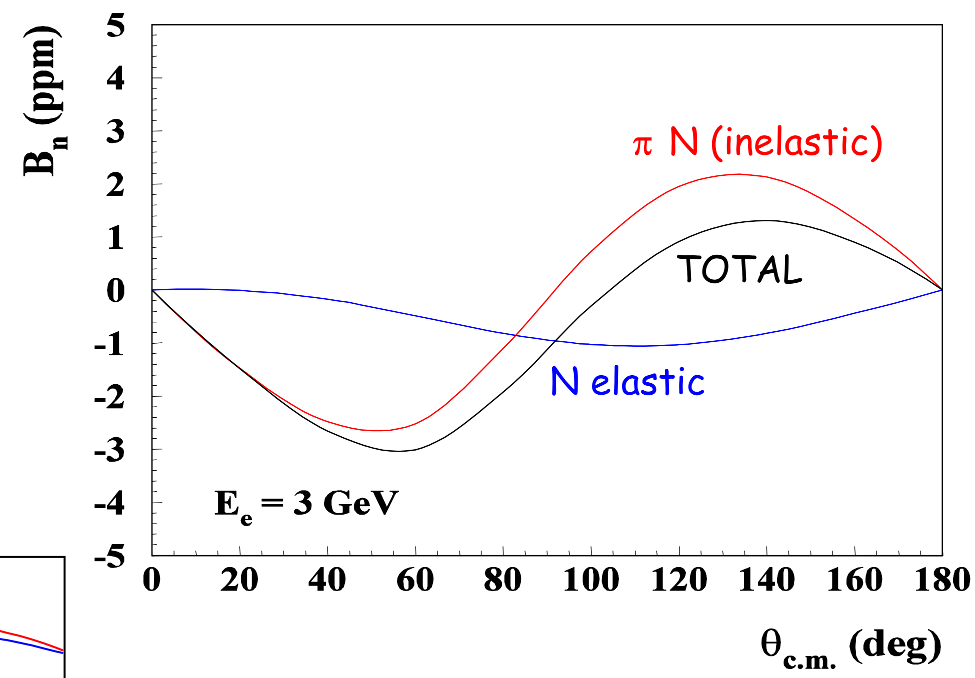
Integrand : beam normal spin asymmetry

Ee = 0.855 GeV

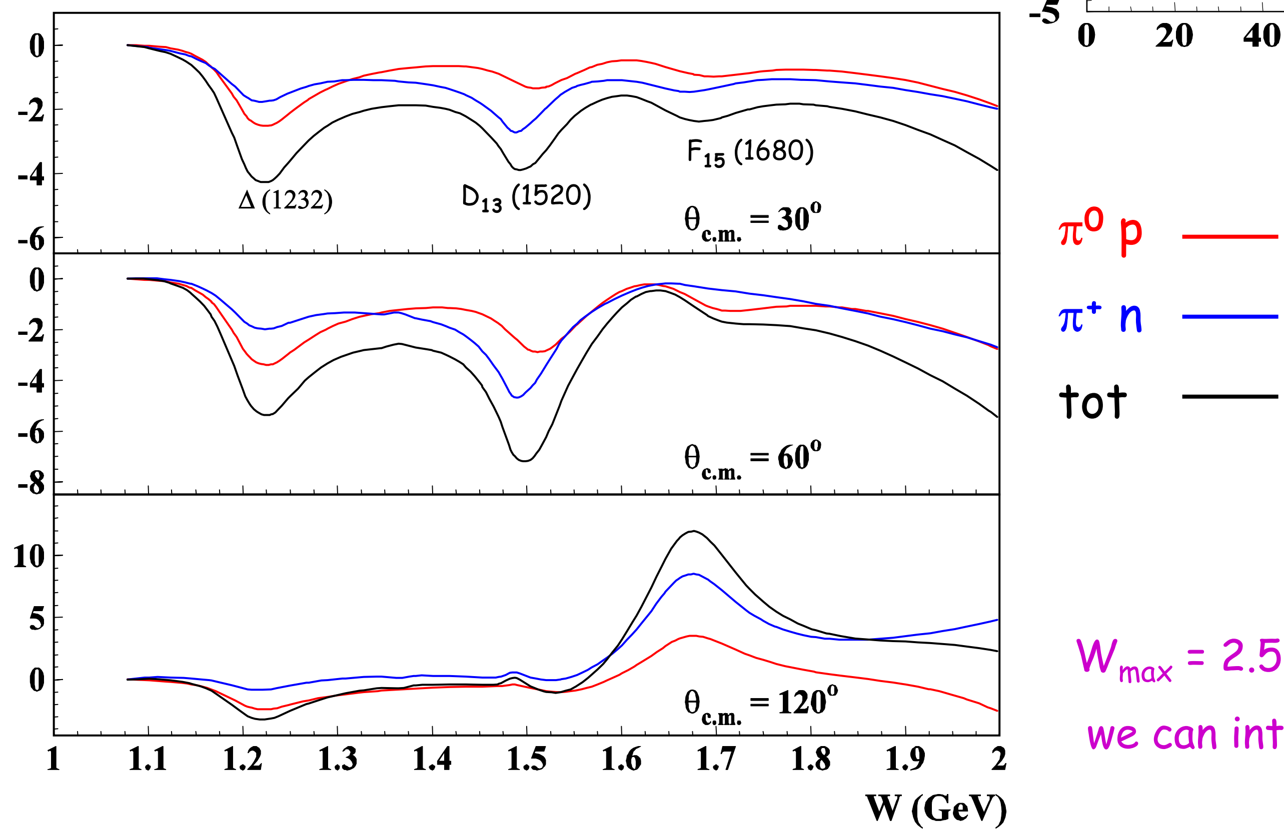


Beam normal spin asymmetry

E_e = 3 GeV



Integrand [ppm GeV^{-1}]

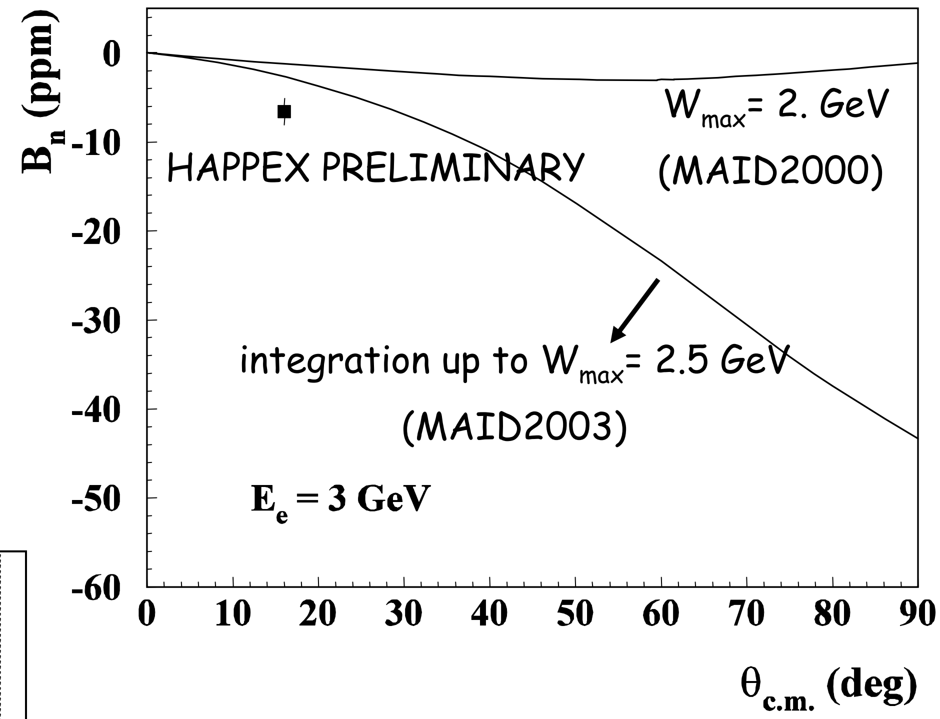


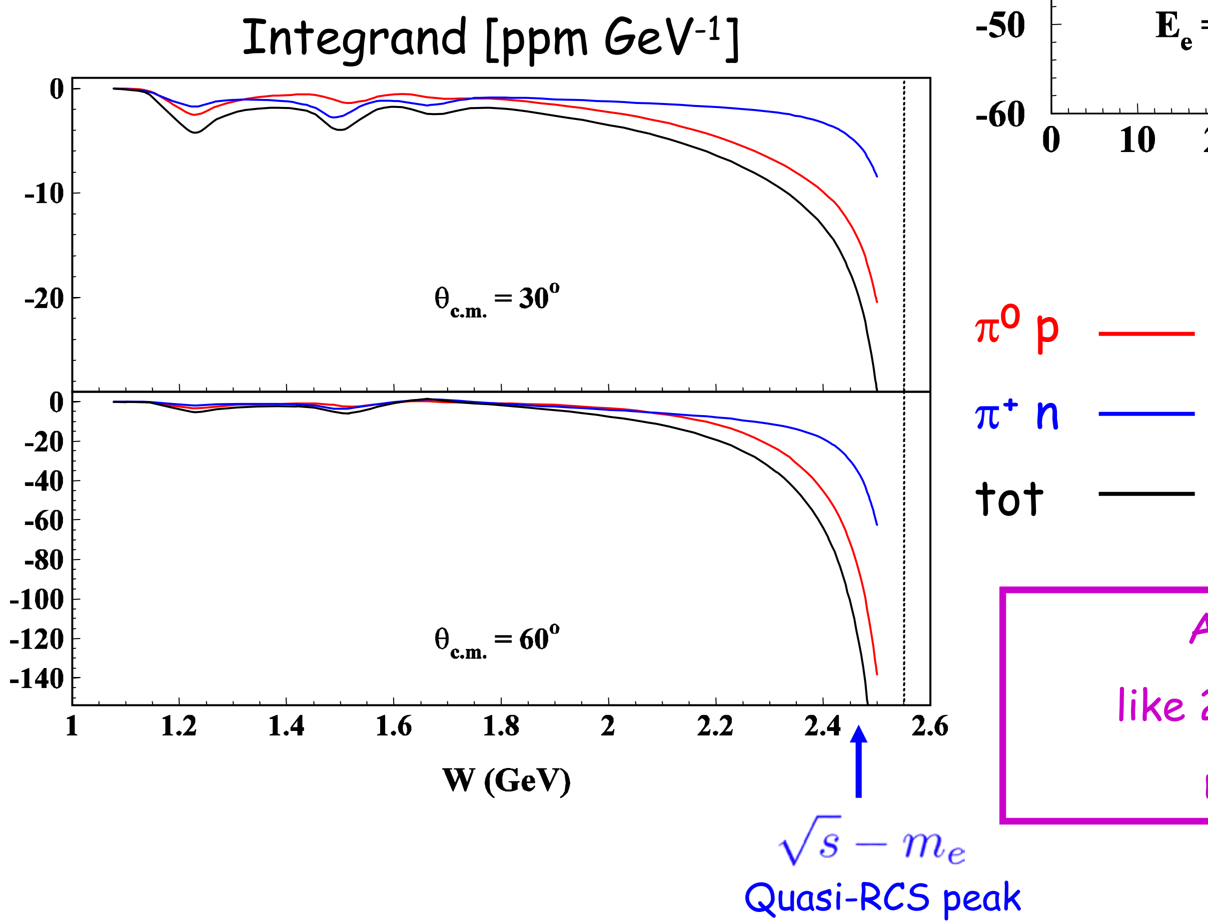
WARNING

W_{max} = 2.55 GeV, but with MAID2000 we can integrate only up to W = 2 GeV

Beam normal spin asymmetry

E_e = 3 GeV





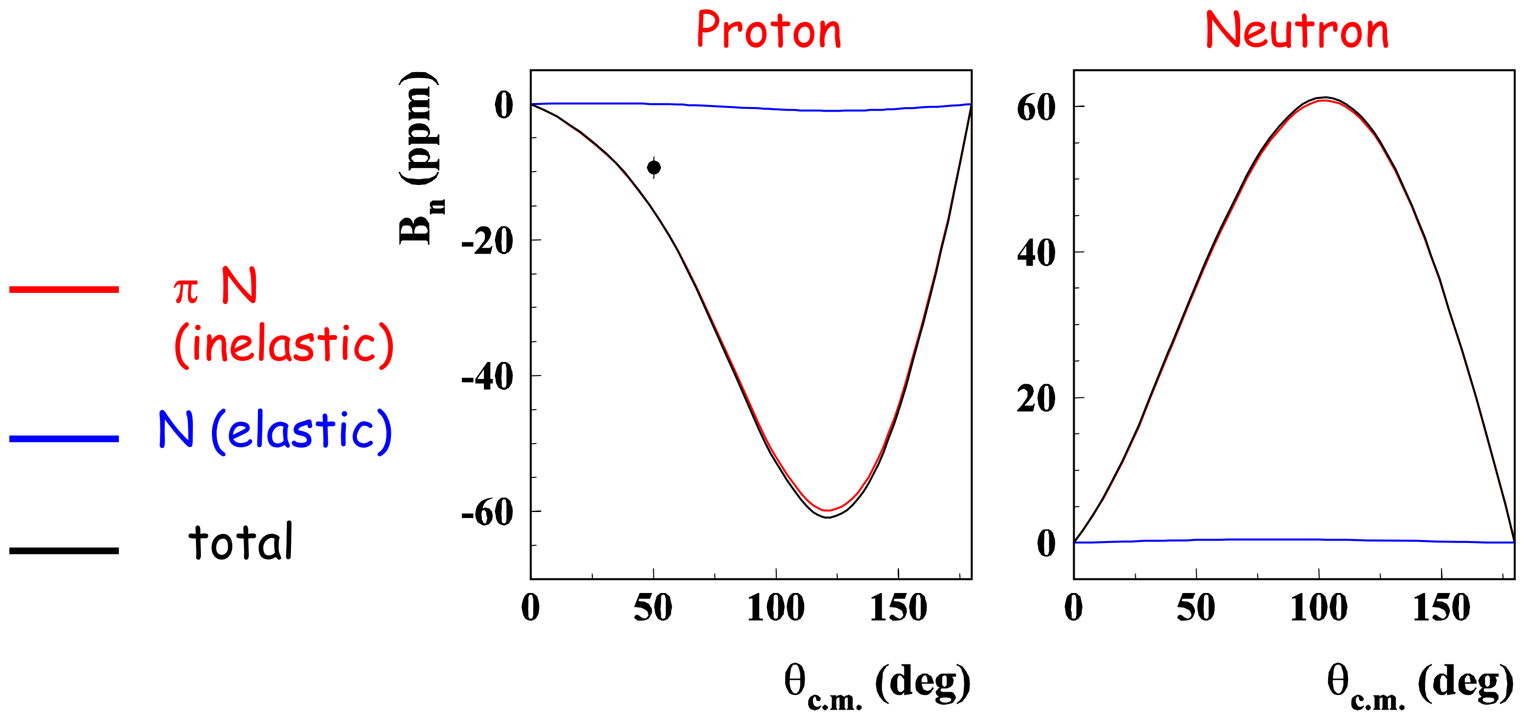
Additional contributions

like 2-pion intermediates states

may become important

Beam normal spin asymmetry

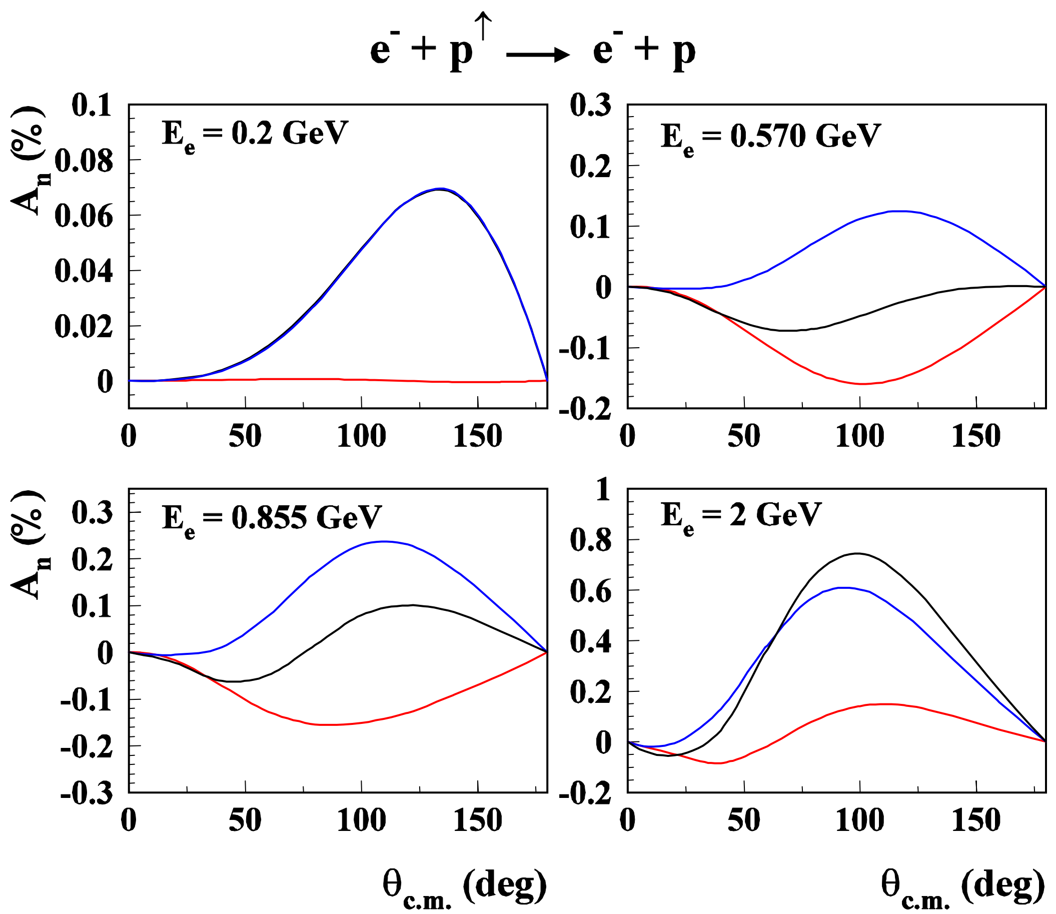
Ee = 0.570 GeV

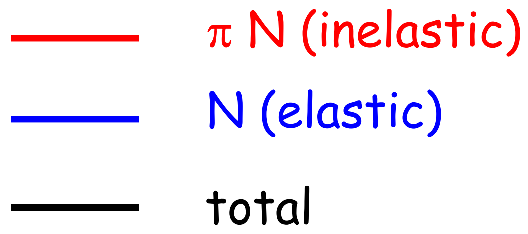


$$B_n = \frac{2\,m_e}{Q}\sqrt{2\,\varepsilon\,(1-\varepsilon)}\sqrt{1+\frac{1}{\tau}}\left(G_M^2 + \frac{\varepsilon}{\tau}G_E^2\right)^{-1}$$

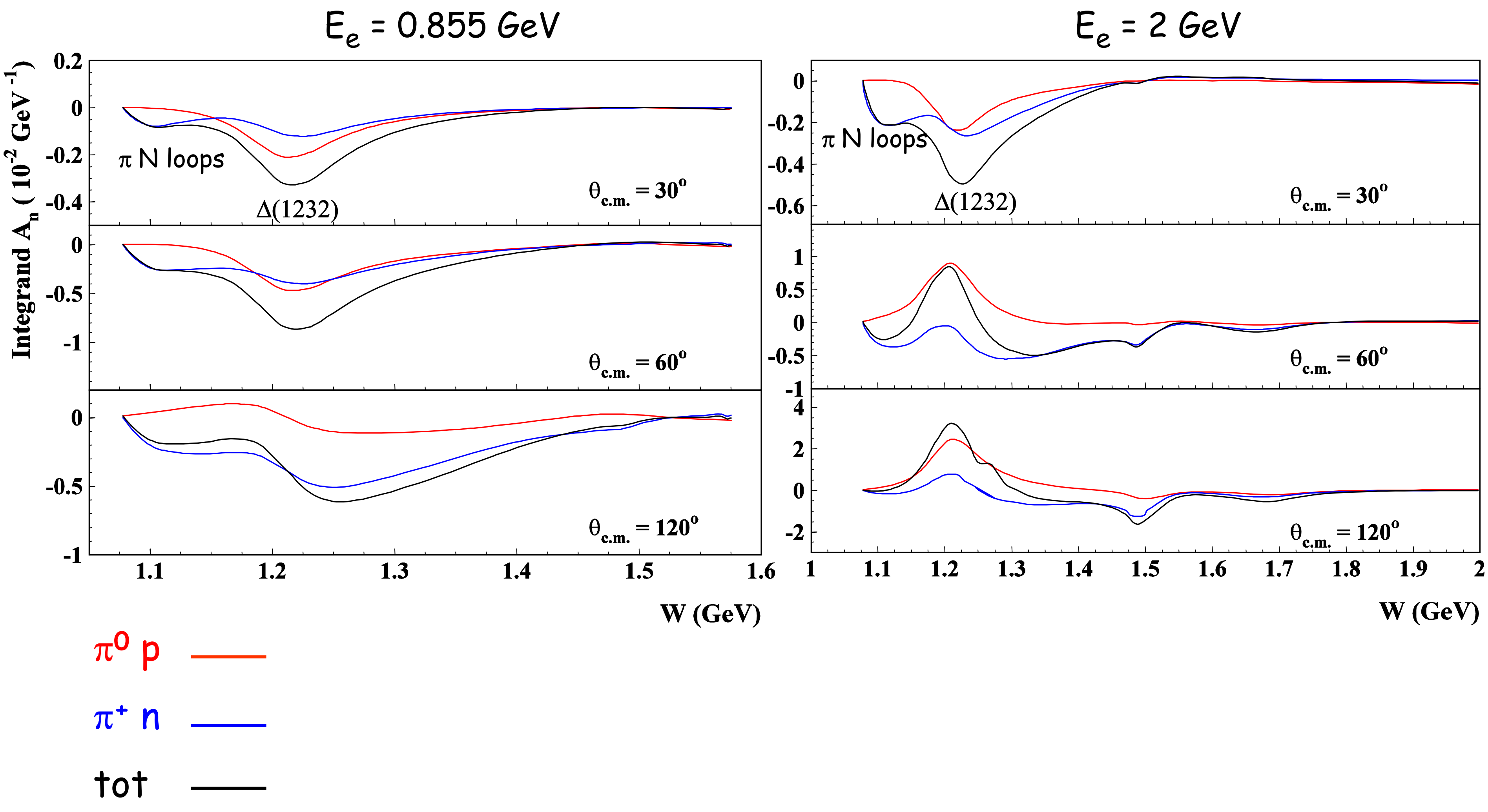
$$\times \quad \left\{-\tau\,G_M\,\mathcal{I}m\left(\tilde{F}_3 + \frac{1}{1+\tau}\frac{\nu}{M^2}\tilde{F}_5\right) - G_E\,\mathcal{I}m\left(\tilde{F}_4 + \frac{1}{1+\tau}\frac{\nu}{M^2}\tilde{F}_5\right)\right\}$$

Target normal spin asymmetry



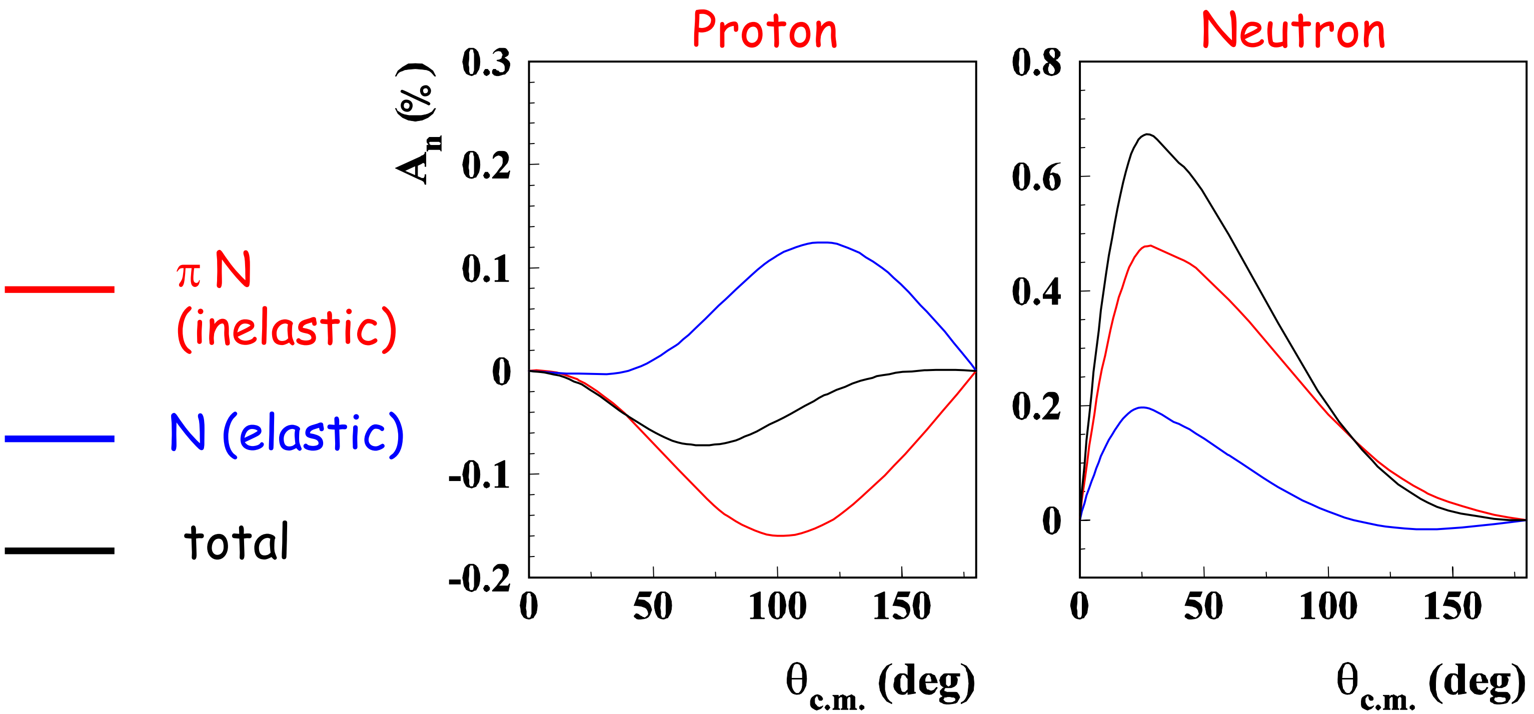


Integrand : target normal spin asymmetry



Target normal spin asymmetry

Ee = 0.570 GeV



$$A_n = \sqrt{\frac{2\,\varepsilon\,(1+\varepsilon)}{\tau}}\;\left(G_M^2 + \frac{\varepsilon}{\tau}\,G_E^2\right)^{-1}$$

$$\times\;\left\{-G_M\,\mathcal{I}m\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + G_E\,\mathcal{I}m\left(\delta\tilde{G}_M + \left(\frac{2\varepsilon}{1+\varepsilon}\right)\frac{\nu}{M^2}\tilde{F}_3\right)\right\}$$

Conclusions

- TSA in elastic electron-nucleon scattering : unique new tool to access the imaginary part of 2γ exchange amplitudes

- Imaginary part of 2γ amplitude

  ➡ absorptive part of non-forward doubly VCS tensor

- Unitarity to relate the absorptive part of doubly VCS tensor to pion-electroproduction amplitudes

  ➡ TSA in the resonance region as a new tool to extract information on resonance transition form factors

- Outlook: to access the real part of the 2-γ exchange amplitudes through a dispersion relation formalism

  ➡ a precise knowledge of the imaginary part 2-γ exchange amplitudes is a necessary prerequisite