Spin Filtering in Storage Rings: Scattering within the Beam, and the FILTEX results (PAX scrutiny of the filtering process)

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SPIN'05, 27 September - 1 October 2005, Dubna, Russia

Contents:

- Spin filtering & scattering within the beam: a quantum-mechanical evolution of spin-density matrix
- Why the spin-filtering on polarized electrons cancels out?
- Comparison with the kinetic equation approach of Milstein & Strakhovenko
- Interpretation of the FILTEX findings: one minor, but important, conceptual correction to Meyer's analysis
- Implications for spin-filtering of antiprotons inPAX FAIR

What do we (PAX) want (M.Contalbrigo's talk):
harvest top-class physics with double-polarized antiproton-proton collider at FAIR

What do we need: antiprotons of highest possible polarization.

How shall we get them: by spin filtering

Need a scrutiny of the FILTEX spin filtering of protons

⋆ The textbook optics: optical polarizer absorbs the "wrong" polarization.

⋆ Spin filtering of neutrons in polarized He^3 - a popular source of polarized neutrons.

⋆ Spin filtering in storage rings - a unique practical solution for antiprotons.

⋆ Internal atomic polarized $H\uparrow$ and $D\uparrow$ cell targets - a unique choice for a polarizer.

⋆ Polarized atom$\uparrow$ = proton$\uparrow$ (deuteron$\uparrow$) + electron$\uparrow$. Impact of electrons?

⋆ Electron-to-proton polarization transfer (Akhiezer et al, 50's).: QED, the same status as the hyperfine splitting in atoms. Exists, is large and is routinely used at MAMI, Bates, Jlab for precision measurements of G_E/G_M

⋆ H.O.Meyer's question: what scattering within the beam does to filtering?

The transmission and scattering

⋆ Why is the sky that blue? It is exclusively the scattered light!

⋆ Why is the setting sun so reddish? It is exclusively the transmitted light!

N.B. We only see the transmitted light from distant stars!

⋆ Why the sun changes its color? Transmission changes the unscattered light!

⋆ Optical filtering: with rare exceptions one only deals with the transmitted light.

⋆ Unique feature of storage rings: a mixing of the transmitted and scattered beam

⋆ The technical description: the polarization dependent refraction index.

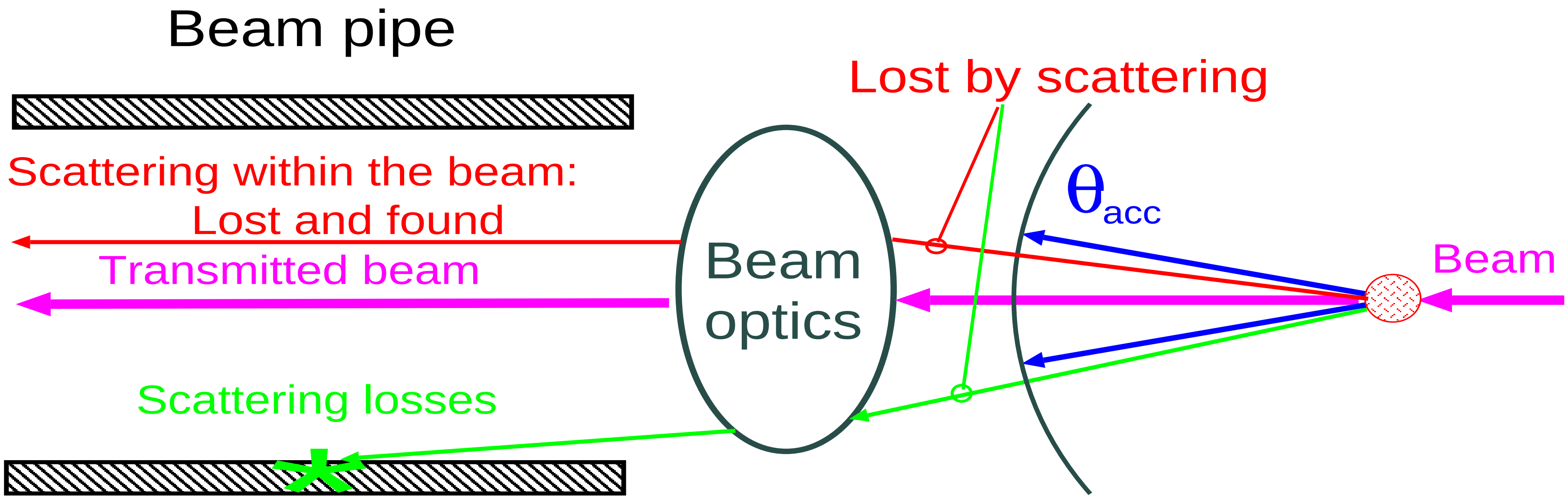
⋆ Fermi-Akhiezer-Pomeranchuk-Lax formula:

$$n = 1 + \frac{2\pi}{p^2} N \hat{f}(o)$$

The forward NN scattering amplitude $\hat{f}(o)$ depends on the beam and target spins

⋆ Polarized target is an optically active medium!

What the internal target does to the beam?
(a poor theorists notion)



Hans Otto Meyer (1994): polarization of the transmitted beam is modified by polarization of particles scattered within the beam

Large effects in the FILTEX experiment (Protons, T=23 MeV, Test Storage Ring, Heidelberg, 1992) ?

The kinematics of p-atom interactions in storage rings

⋆ Screening of $e\&p$ Coulomb fields beyond the Bohr radius a_B: incoherent quasielastic (E) scattering off protons and electrons at

$$\theta \gtrsim \theta_{min} = \frac{\alpha_{em} m_e}{\sqrt{2 m_p T_p}} \Longrightarrow d\sigma_E = d\sigma_{el}^{p} + d\sigma_{el}^{e}$$

⋆ Electron is too light a target to deflect heavy protons (Horowitz& Meyer):

$$\theta \leq \theta_e = m_e/m_p$$

⋆ Dominant Coulomb pp scattering at up to

$$\theta \lesssim \theta_{Coulomb} \approx \sqrt{2\pi\alpha_{em}/m_p T_p \sigma_{tot,nucl}^{pp}} \approx 100\mathrm{mrad}$$

⋆ FILTEX ring acceptance $\theta_{acc} = 4.4$ mrad.

⋆ Strong inequality

$$\theta_{min} \ll \theta_e \ll \theta_{acc} \ll \theta_{Coulomb}$$

The corollaries: (i) pe scattering entirely within the stored beam, (ii) Beam losses dominated by Coulomb pp scattering.

First warning: how do we measure $\sigma^{pp}_{tot,nucl}$ in the liquid hydrogen target?

⋆ Beam attenuation: $\hat{\sigma}_{tot}(p - atom) \equiv \hat{\sigma}^{pp}_{tot} + +\hat{\sigma}^{pe}_{tot}$.

⋆ The pe X-section is gigantic:

$$\hat{\sigma}^{pe}_{tot} = \hat{\sigma}^{e}_{el}(> \theta_{\min}) \approx 4\pi\alpha^2_{em}a^2_B \approx 2 \cdot 10^4 Barn$$

How do we extract $\sigma^{pp}_{tot,nucl} \sim$ 40 mb on top of such a background?

⋆ $\theta \leq \theta_e \ll$ angular divergence of any beam, pe scattering is entirely within the beam and does not cause any attenuation!

⋆ Skrinsky's question (2004, unpublished): shall the spin filtering by $e\uparrow$ be observable?

⋆ Milstein & Strakhovenko (2005): electrons wouldn't work! (independent & simultaneous observation by NNN & F.Pavlov within a very different formalism).

⋆ Getting rid of Coulomb pp scattering in $\sigma^{pp}_{tot,nucl}$:
(i) measure transmitted beam intensity with acceptance $> \theta_{Coulomb}$,
(ii) extrapolate to zero acceptance angle.

Transmission Losses vs. Scattering within the Beam

⋆ Polarization of the transmitted beam: propagates at ZERO scattering angle, gets polarized by absorption & elastic scattering out of the beam

⋆ Lost & found polarization of scattered particles.

⋆ Pertinent features of spin filtering in storage rings (the poor theorists notion):

(i) ultra-thin target,

(ii) $\theta \geq \theta_{acc}$: scattering out of the beam pipe,

(iii) ring optics (betatron oscillations & focusing & defocusing & electron cooling & ...): transverse momentum $\mathbf{p}$ gets randomized between consecutive interactions with the target,

(iv) angular divergence of the beam at the target $\ll \theta_{acc}$.

⋆ The appropriate quantum-mechanical approach: the evolution equation for the spin-density matrix of the stored beam

The In-Medium Hamiltonian and Evolution of Transmitted Beam

⋆ Time = distance z traversed in the medium.

$$\text{Fermi} \quad \text{Hamiltonian} = \hat{H} = \frac{1}{2}N\hat{F}(0) = \frac{1}{2}N[\hat{R}(0) + i\hat{\sigma}_{tot}]$$

N = density of atoms in the target.

⋆ The density matrix of the stored beam

$$\hat{\rho}(\mathbf{p}) = \frac{1}{2}[I_0(\mathbf{p}) + \boldsymbol{\sigma}\mathbf{s}(\mathbf{p})]$$

$I_0(\mathbf{p})$ = particle density, $\mathbf{s}(\mathbf{p})$ = spin density.

⋆ Textbook quantum-mechanical evolution for pure transmission ($\theta_{acc} \to 0$, vanishing scattering within the beam)

$$\frac{d}{dz}\hat{\rho}(\mathbf{p}) = i[\hat{H}, \hat{\rho}(\mathbf{p})] = \underbrace{i\frac{1}{2}N(\hat{R}\hat{\rho}(\mathbf{p}) - \hat{\rho}(\mathbf{p})\hat{R})}_{\text{Real} \quad \text{potential=Pure} \quad \text{refraction}}$$

$$- \underbrace{\frac{1}{2}N(\hat{\sigma}_{tot}\hat{\rho}(\mathbf{p}) + \hat{\rho}(\mathbf{p})\hat{\sigma}_{tot})}_{\text{(Imaginary} \quad \text{potential=Pure} \quad \text{attenuation)}}$$

Evolution of Transmitted Beam Cont'd

$$\hat{\sigma}_{tot} = \sigma_0 + \underbrace{\sigma_1(\boldsymbol{\sigma}\cdot\boldsymbol{Q}) + \sigma_2(\boldsymbol{\sigma}\cdot\mathbf{k})(\boldsymbol{Q}\cdot\mathbf{k})}_{spin-sensitive\ \ loss},$$

$$\hat{R} = R_0 + \underbrace{R_1(\boldsymbol{\sigma}\cdot\boldsymbol{Q}) + R_2(\boldsymbol{\sigma}\cdot\mathbf{k})(\boldsymbol{Q}\cdot\mathbf{k})}_{\boldsymbol{\sigma}\cdot\mathrm{Pseudomagnetic\ \ field}}$$

$\mathbf{k}$ = beam axis, $\boldsymbol{Q}$ = target polarization.

⋆ Evolution of the beam polarization $\boldsymbol{P} = \mathbf{s}/I_0$

$$d\boldsymbol{P}/dz = \underbrace{-N\sigma_1(\boldsymbol{Q} - (\boldsymbol{P}\cdot\boldsymbol{Q})\boldsymbol{P}) - N\sigma_2(\boldsymbol{Q}\mathbf{k})(\mathbf{k} - (\boldsymbol{P}\cdot\mathbf{k})\boldsymbol{P})}_{\mathrm{(Polarization\ buildup\ by\ spin-sensitive\ loss)}}$$
$$+ \underbrace{NR_1(\boldsymbol{P}\times\boldsymbol{Q}) + nR_2(\boldsymbol{Q}\mathbf{k})(\boldsymbol{P}\times\mathbf{k})}_{\mathrm{(Spin\ precession\ in\ pseudomagnetic\ \ field)}}$$

⋆ Precession effects are missed in Milstein-Strakhovenko kinetic equation for spin-state population numbers. Kinetic equation holds only if spin-density matrix is diagonal.

⋆ Kinetic equation is recovered from evolution of the density matrix upon averaging over precessions - the case in storage rings and pure transverse or longitudinal polarizations.

The polarization buildup

⋆ Coupled evolution equations after into-the-beam scattering

$$\frac{d}{dz}\begin{pmatrix} I_0 \\ s \end{pmatrix} = -N \begin{pmatrix} \sigma_0(>\theta_{\min}) & Q\sigma_1(>\theta_{\min}) \\ Q\sigma_1(>\theta_{\min}) & \sigma_0(>\theta_{\mathrm{acc}}) \end{pmatrix} \cdot \begin{pmatrix} I_0 \\ s \end{pmatrix},$$

⋆ Solutions

$$\propto \exp(-\lambda_{1,2} N z)$$

with eigenvalues

$$\lambda_{1,2} = \sigma_0 \pm Q\sigma_1$$

⋆ Reduction to Meyer's equation for pure transverse polarizations:

$$\frac{dP}{dz} = -N\sigma_1 Q(1-\boldsymbol{P}^2)$$

⋆ Polarization buildup

$$P(z) = -\tanh(Q\sigma_1 N z)$$

⋆ Any spin-dependent loss filters spin of the stored beam:

Impact of Scattering within the Beam upon Spin Filtering

⋆ Quasielastic (E) $p + atom \to p'_{scatt} + e + p_{recoil}$, $\mathbf{q}$ = momentum transfer:

$$\frac{d\hat{\sigma}_E}{d^2\mathbf{q}} = \frac{1}{(4\pi)^2}\hat{\mathcal{F}}(\mathbf{q})\hat{\rho}\hat{\mathcal{F}}^\dagger(\mathbf{q}) = \frac{1}{(4\pi)^2}\hat{\mathcal{F}}_e(\mathbf{q})\hat{\rho}\hat{\mathcal{F}}_e{}^\dagger(\mathbf{q}) + \frac{1}{(4\pi)^2}\hat{\mathcal{F}}_p(\mathbf{q})\hat{\rho}\hat{\mathcal{F}}_p{}^\dagger(\mathbf{q})$$

⋆ Lost and found: scattering within the beam at $\theta \leq \theta_{acc}$

⋆ Formal derivation from multiple-scattering theory: unitarity(loss-recovery balance) is satisfied rigorously.

$$\begin{aligned}\frac{d}{dz}\hat{\rho} = i[\hat{H},\hat{\rho}] \;&=\; \underbrace{i\frac{1}{2}N(\hat{R}\hat{\rho}(\mathbf{p}) - \hat{\rho}(\mathbf{p})\hat{R})}_{Ignore\ this\ precession} \\ &-\; \underbrace{\frac{1}{2}N(\hat{\sigma}_{tot}\hat{\rho}(\mathbf{p}) + \hat{\rho}(\mathbf{p})\hat{\sigma}_{tot})}_{Evolution\ by\ loss} \\ &+\; \underbrace{N\int^{\Omega_{acc}}\frac{d^2\mathbf{q}}{(4\pi)^2}\hat{\mathcal{F}}(\mathbf{q})\hat{\rho}(\mathbf{p}-\mathbf{q})\hat{\mathcal{F}}^\dagger(\mathbf{q})}_{\text{Lost and found: scattering within the beam}}\end{aligned}$$

Needle-Sharp Scattering off Electrons: $\theta_e \ll \theta_{acc}$

$\star$ Breit pe interaction (1929): Coulomb (+ unimportant relativistic corrections) + hyperfine + tensor + spin-orbit (negligible small & unimportant to us)

$$U(\mathbf{q}) = \alpha_{em}\{\frac{1}{\mathbf{q}^2} + \mu_p \frac{(\boldsymbol{\sigma}_p\mathbf{q})(\boldsymbol{\sigma}_e\mathbf{q}) - (\boldsymbol{\sigma}_p\boldsymbol{\sigma}_e\mathbf{q}^2}{4m_p m_e \mathbf{q}^2}\}$$

$$\hat{\sigma}^e_{tot} = \underbrace{\sigma^e_0}_{Coulomb} + \underbrace{\sigma^e_1(\boldsymbol{\sigma}_p \cdot \boldsymbol{Q}_e) + \sigma^e_2(\boldsymbol{\sigma}_p \cdot \mathbf{k})(\boldsymbol{Q}_e \cdot \mathbf{k})}_{Coluomb \times (Hyperfine + Tensor)}$$

$\star$ Horowitz-Meyer (1994): substantial transfer of polarization to scattered protons!

$\star$ Stronger transfer of longitudinal polatization: $\sigma^e_2 = 2\sigma^e_1$. (property inherent to Buttimore et al. helicity amplitudes)

$\star$ Polarization of scattered protons $\boldsymbol{P}_f$ (transverse case):

$$\sigma^e_0 \boldsymbol{P}_f = \sigma^e_0 \boldsymbol{P} + \sigma^e_1 \boldsymbol{Q}_e$$

$\star$ one-to-one beam-to-scattered proton spin transfer (Milstein-Strakhovenko)

⋆ Pure electron contribution to the loss of transmitted beam (suppress $\theta >> \theta_{min}$)

$$\frac{1}{2}\frac{d}{dz}I_0(\mathbf{p})(1+\boldsymbol{\sigma}\cdot\boldsymbol{P}(\mathbf{p})) = -\frac{1}{2}NI_0(\mathbf{p})[\underbrace{\sigma_0^e+\sigma_1^e\boldsymbol{P}\boldsymbol{Q}_e}_{particle\ number\ loss} + \boldsymbol{\sigma}\underbrace{(\sigma_0^e\boldsymbol{P}+\sigma_1^e\boldsymbol{Q}_e)}_{selective\ spin\ loss}]$$

⋆ Lost & found (precession-averaged) from scattering within the beam

$$\begin{aligned} & N\int\frac{d^2\mathbf{q}}{(4\pi)^2}\hat{\mathcal{F}}_e(\mathbf{q})\hat{\rho}(\mathbf{p}-\mathbf{q})\hat{\mathcal{F}}_e^\dagger(\mathbf{q}) \\ &= \frac{1}{2}NI_0(\mathbf{p})\int\frac{d^2\mathbf{q}}{(4\pi)^2}\hat{\mathcal{F}}_e(\mathbf{q})\hat{\mathcal{F}}_e^\dagger(\mathbf{q}) + \frac{1}{2}N\boldsymbol{s}(\mathbf{p})\int\frac{d^2\mathbf{q}}{(4\pi)^2}\hat{\mathcal{F}}_e(\mathbf{q})\boldsymbol{\sigma}\hat{\mathcal{F}}_e^\dagger(\mathbf{q}) \\ &= \underbrace{\frac{1}{2}NI_0(\mathbf{p})[\sigma_0^e+\sigma_1^e(\boldsymbol{P}\cdot\boldsymbol{Q})]}_{Lost\&found\ particle\ number} + \underbrace{\frac{1}{2}NI_0(\mathbf{p})\boldsymbol{\sigma}[\sigma_0^e\boldsymbol{P}+\sigma_1^e\boldsymbol{Q}_e]}_{Lost\&found\ spin} \end{aligned}$$

⋆ The net effect:

$$\hat{\sigma}_{tot} \equiv \hat{\sigma}^p_{abs} + \hat{\sigma}^p_{el}(>\theta_{\min}) + \hat{\sigma}^e_{el}(>\theta_{\min}) \Longrightarrow \hat{\sigma}_{tot} - \hat{\sigma}^e_{el}(>\theta_{\min}) = \hat{\sigma}^p_{abs} + \hat{\sigma}^p_{el}(>\theta_{\min}).$$

⋆ Skrinsky' concern was well taken: electrons in the target are invisible, scattering within the beam cancels exactly the transmission losses (also Milstein & Strakhovenko).

⋆ Sad conclusion: Farewell to electromagnetic electron-to-antiproton spin transfer...

Nuclear Spin Filtering: Nulcear pp Scattering within the Beam

⋆ Decompose pure transmission losses (transverse polarization)

$$\begin{aligned}\frac{d}{dz}\hat{\rho} &= -\underbrace{\frac{1}{2}N(\hat{\sigma}_{tot}(>\theta_{\rm acc})\hat{\rho}(\mathbf{p})+\hat{\rho}(\mathbf{p})\hat{\sigma}_{tot}(>\theta_{\rm acc}))}_{Unrecoverable\ transmission\ loss}\\ &- \frac{1}{2}NI_0(\mathbf{p})[\underbrace{\sigma_0^{el}(<\theta_{\rm acc})+\sigma_1^{el}(<\theta_{\rm acc})\boldsymbol{PQ}}_{Potentially\ recoverable\ particle\ loss}\\ &+ \boldsymbol{\sigma}\underbrace{(\sigma_0^{el}(<\theta_{\rm acc})\boldsymbol{P}+\sigma_1^{el}(<\theta_{\rm acc})\boldsymbol{Q})}_{Potentially\ recoverable\ spin\ loss}]\end{aligned}$$

⋆ Angular divergence of the beam at target $\ll \theta_{acc}$: integrate over $\mathbf{p}$

$$\int d^2\mathbf{p}\int^{\Omega_{\rm acc}}\frac{d^2\mathbf{q}}{(4\pi)^2}\hat{\mathcal{F}}(\mathbf{q})\hat{\rho}(\mathbf{p}-\mathbf{q})\hat{\mathcal{F}}^{\dagger}(\mathbf{q}) =$$

$$[\int d^2\mathbf{p}I_0(\mathbf{p})]\cdot\int^{\Omega_{\rm acc}}\frac{d^2\mathbf{q}}{(4\pi)^2}\hat{\mathcal{F}}(\mathbf{q})\frac{1}{2}(1+\boldsymbol{\sigma P})\hat{\rho}(\mathbf{q})\hat{\mathcal{F}}^{\dagger}(\mathbf{q}) = \hat{\sigma}^E(\leq\theta_{\rm acc})\cdot\int d^2\mathbf{p}I_0(\mathbf{p})$$

⋆ The mismatch of potentially recoverable losses and scattering within the beam

$$\Delta\hat{\sigma} = \frac{1}{4}(\hat{\sigma}_{el}(<\theta_{\rm acc})(1+\boldsymbol{\sigma P})+(1+\boldsymbol{\sigma P})\hat{\sigma}_{el}(<\theta_{\rm acc}))-\hat{\sigma}^E(\leq\theta_{\rm acc})$$

⋆ X-section of scattering within the beam (precession averaged)

$$\hat{\sigma}^E(\leq \theta_{\rm acc}) = \underbrace{\sigma_0^{el}(\leq \theta_{\rm acc}) + \sigma_1^{el}(\leq \theta_{\rm acc})(\boldsymbol{P}\cdot\boldsymbol{Q})}_{Lost\ \&\ found\ particles} + \underbrace{\boldsymbol{\sigma}\cdot\left(\sigma_0^E(\leq \theta_{\rm acc})\boldsymbol{P}) + \sigma_1^E(\leq \theta_{\rm acc})\boldsymbol{Q})\right)}_{Lost\ \&\ found\ spin}$$

⋆ The mismatch X-section operator

$$\begin{aligned}\Delta\hat{\sigma} &= \underbrace{\sigma_0^{el}(< \theta_{\rm acc}) + \sigma_1^{el}(< \theta_{\rm acc})\boldsymbol{P}\boldsymbol{Q}_e}_{Potentially\ recoverable\ particle\ loss} \\ &+ \boldsymbol{\sigma}\underbrace{(\sigma_0^{el}(< \theta_{\rm acc})\boldsymbol{P} + \sigma_1^{el}(< \theta_{\rm acc})\boldsymbol{Q}_e)}_{Potentially\ recoverable\ spin\ loss} \\ &- \underbrace{\sigma_0^{el}(\leq \theta_{\rm acc}) + \sigma_1^{el}(\leq \theta_{\rm acc})(\boldsymbol{P}\cdot\boldsymbol{Q})}_{Lost\ \&\ found\ particles} \\ &- \underbrace{\boldsymbol{\sigma}\cdot\left(\sigma_0^E(\leq \theta_{\rm acc})\boldsymbol{P} + \sigma_1^E(\leq \theta_{\rm acc})\boldsymbol{Q}\right)}_{Lost\ \&\ found\ spin} \\ &= \boldsymbol{\sigma}\left(2\Delta\sigma_0\boldsymbol{P} + \Delta\sigma_1\boldsymbol{Q}\right)\end{aligned}$$

⋆ Lost & found corrected coupled evolution equations

$$\frac{d}{dz}\begin{pmatrix} I_0 \\ s \end{pmatrix} = -n\begin{pmatrix} \sigma_0(> \theta_{\rm acc}) & Q\sigma_1(> \theta_{\rm acc}) \\ Q(\sigma_1(> \theta_{\rm acc}) + \Delta\sigma_1) & \sigma_0(> \theta_{\rm acc}) + 2\Delta\sigma_0 \end{pmatrix}\cdot\begin{pmatrix} I_0 \\ s \end{pmatrix},$$

⋆ No corrections to the equation for the particle number.

⋆ $\Delta\sigma_{0,1}$: a mismatch between the spin of the beam taken away by the scattered particle and the lost & found spin put back by after the particle scatteres within the beam. In terms of standard observables (Bystricky et al.):

$$\sigma_1^{el}(>\theta_{\rm acc}) = \frac{1}{2}\int_{\theta_{\rm acc}} d\Omega (d\sigma/d\Omega)(A_{00nn} + A_{00ss})$$

$$\begin{aligned}
\Delta\sigma_0 &= \frac{1}{2}[\sigma_0^{el}(\leq\theta_{\rm acc}) - \sigma_0^{E}(\leq\theta_{\rm acc})] \\
&= \frac{1}{2}\int_{\theta_{\rm min}}^{\theta_{\rm acc}} d\Omega\frac{d\sigma}{d\Omega}(1 - \frac{1}{2}D_{n0n0} - \frac{1}{2}D_{s'0s0}\cos(\theta_{lab})) \\
\Delta\sigma_1 &= \sigma_1^{el}(\leq\theta_{\rm acc}) - \sigma_1^{E}(\leq\theta_{\rm acc}) \\
&= \frac{1}{2}\int_{\theta_{\rm min}}^{\theta_{\rm acc}} d\Omega\frac{d\sigma}{d\Omega}(A_{00nn} + A_{00ss} - K_{n00n} - K_{s'00s}\cos(\theta_{lab}))
\end{aligned}$$

⋆ The SAID menagerie:
$A_{00nn} = A_{yy}$, $A_{00ss} = A_{xx}$, $K_{n00n} = D_t$, $D_{s'0s0} = R$, $D_{n0n0} = D$, $K_{s'00s} = -R'_t$.

⋆ Milstein & Strakhovenko relate $\Delta\sigma_{0,1}$ to spin-flip scattering.

Polarization Buildup with Scattering within the Beam

⋆ Coupled evolution equations after into-the-beam scattering

$$\frac{d}{dz}\begin{pmatrix} I_0 \\ s \end{pmatrix} = -n \begin{pmatrix} \sigma_0(>\theta_{\rm acc}) & Q\sigma_1(>\theta_{\rm acc}) \\ Q(\sigma_1(>\theta_{\rm acc}) + \Delta\sigma_1) & \sigma_0(>\theta_{\rm acc}) + 2\Delta\sigma_0 \end{pmatrix} \cdot \begin{pmatrix} I_0 \\ s \end{pmatrix},$$

⋆ Solutions

$$\propto \exp(-\lambda_{1,2} N z)$$

with eigenvalues

$$\begin{aligned} \lambda_{1,2} &= \sigma_0 + \Delta\sigma_0 \pm \sigma_3 \\ \sigma_3 &= Q\sqrt{\sigma_1(\sigma_1 + \Delta\sigma_1) + \Delta\sigma_0{}^2}, \end{aligned}$$

⋆ The polarization buildup (also Milstein&Strakhovenko)

$$P(z) = -\frac{(\sigma_1 + \Delta\sigma_1)\tanh(\sigma_3 N z)}{\sigma_3 + \Delta\sigma_0 \tanh(\sigma_3 N z)}$$

⋆ The effective small-time polarization cross section

$$\sigma_P \approx -Q(\sigma_1 + \Delta\sigma_1)$$

Pauli principle and Spin Deep under the Coulomb peak

⋆ "Normal" elastic scattering into $\theta \leq \theta_{acc} = 4.4 \cdot 10^{-3}$ is entirely negligible.

⋆ "Abnormal" $\theta_{acc} \ll \theta_{Coulomb}$ - scattering within the beam is deep under the Coulomb peak.

⋆ Entirely inaccessible in scattering experiments, important for storage rings. Need extrapolations of hadronic amplitudes.

⋆ Pauli principle $\Longrightarrow$ double-spin dependence from exchange interaction

$$\begin{aligned}\hat{\mathcal{F}}_{Coulomb} &= \frac{1}{2}\mathcal{F}(\theta) + \frac{1}{4}(1 + \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)\mathcal{F}(\pi - \theta) \\ &= \underbrace{\mathcal{F}_0(\theta)}_{Coulomb\ singularity\ 1/\theta^2} + \underbrace{\mathcal{F}_1(\theta)}_{Constant}\ \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2\end{aligned}$$

⋆ Exchange interaction stronger than Breit interaction of magnetic moments of protons

⋆ Add to $\mathcal{F}_1(\theta)$ similar (and typically larger) two-spin nuclear interaction amplitudes.

⋆ $1/\theta^2$ enhancement makes interference $\propto \mathcal{F}_0(\theta)\mathcal{F}_1(\theta)$ substantial.

⋆ Upon azimuthal integrations spin-flips don't interfere with the dominant $\mathcal{F}_0(\theta)$

Understanding the FILTEX result according to Meyer-Horowitz:

⋆ The FILTEX polarization rate as published in 1993: $\sigma_P = 63 \pm 3(stat.)$ mb, a fantastic 20σ measurement!

⋆ Better understanding of target density & polarization (F.Rathmann, PhD): $\sigma_P = 72.5 \pm 5.8(stat. + sys.)$ (stat.)

⋆ The expectation from filtering by pure nuclear scattering: $\sigma_{P,expected} = 122$ mb.

⋆ H.O. Meyer: correct σ_P for scattering within the beam. Strong effect of Coulomb-nuclear interference $\propto \mathcal{F}_0(\theta)\mathcal{F}_1(\theta)$. Enhanced by $\log(\theta^2_{acc}/\theta^2_{min}) \approx 11$. Meyer's reevaluation $\sigma_1(> \theta_{\rm acc}) = 83$ mb (SAID of 94) instead of 122 mb

⋆ Add scatterinhg within the beam off polarized electrons: $\delta\sigma_1^{ep} = -70$ mb

⋆ Add scattering within the beam off polarized protons: $\delta\sigma_1^{ep} = +52$ mb

⋆ Net result: $\sigma_P = 65$ mb. Good but accidental agreement with FILTEX!

⋆ What went wrong: : Double counting, Meyer should have started with loss from $\theta > \theta_{min}$, and then add scattering within the beam.

Still, Meyer asked right questions and was infinitesimally close to the correct answer!

Understanding the FILTEX result: why negligible small $\Delta\sigma_{1,0}$

⋆ NNN-Pavlov: SAID-SP05 for filtering by loss: $\sigma_1(>\theta_{\rm acc}) = -85.6$ (only marginal changes from SAID to Nijmegen databases).

⋆ Spin deep under the Coulomb peak:

$$\hat{\mathcal{F}} = \underbrace{\mathcal{F}_0(\theta)}_{Coulomb\ \propto\ 1/\theta^2} + \underbrace{\mathcal{F}_1(\theta)}_{Breit+Nuclear} \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + (\mathrm{other\ two-spin\ terms})$$

⋆ Treatment is identical to that of the Breit proton-electron interaction.

⋆ The dominant spin-dependence from the interference $\propto \mathcal{F}_0(\theta)\mathcal{F}_1(\theta)$.

⋆ Scattering within the beam cancels filtering by transmission losses:

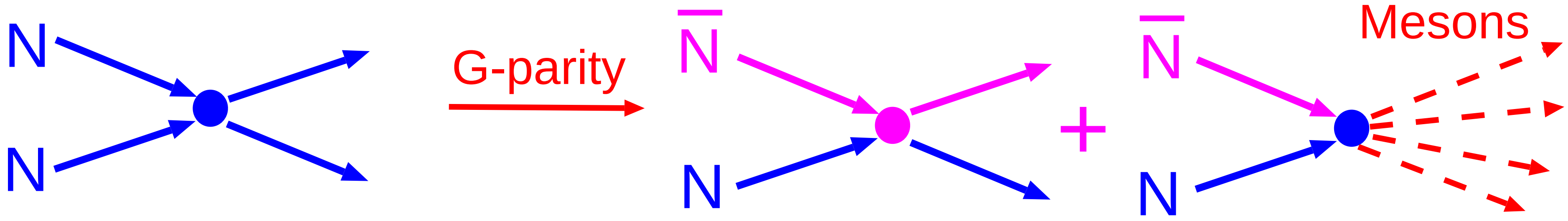
$$\hat{\sigma}_{tot} \equiv \hat{\sigma}^p_{abs} + \hat{\sigma}^p_{el}(>\theta_{\rm min}) \Longrightarrow \hat{\sigma}_{tot} - \hat{\sigma}^p_{el}(\theta_{\rm min} \leq \theta \leq \theta_{\rm acc}) = \hat{\sigma}^p_{abs} + \hat{\sigma}^p_{el}(>\theta_{\rm acc}).$$

⋆ Nonrelativistic heavy particles love retaining their spin: very small mismatch X-section

$$\Delta\sigma_1 \approx -6 \cdot 10^{-3}\ \mathrm{mb}$$

⋆ Full agreement with Milstein & Strakhovenko result in terms of the spin-flip X-section.

Juelich models for antiproton-proton interaction (also Paris, Nijmegen...)

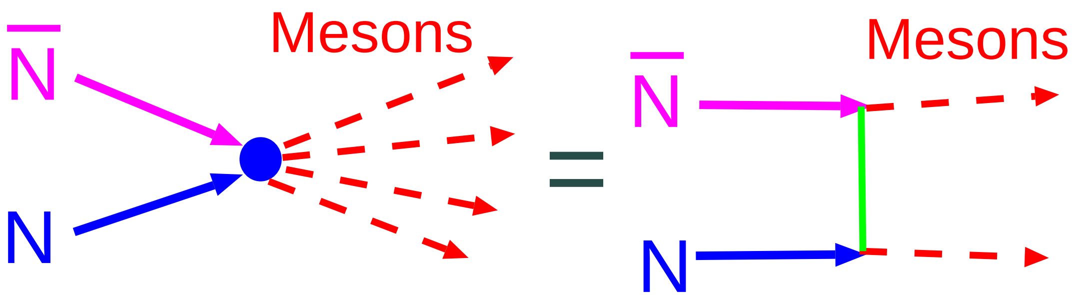


Bonn meson exchange: well defined G-parity is crucial

Annihilation needs extra modelling

* Annihilation: phenomenological optical potential (model A)

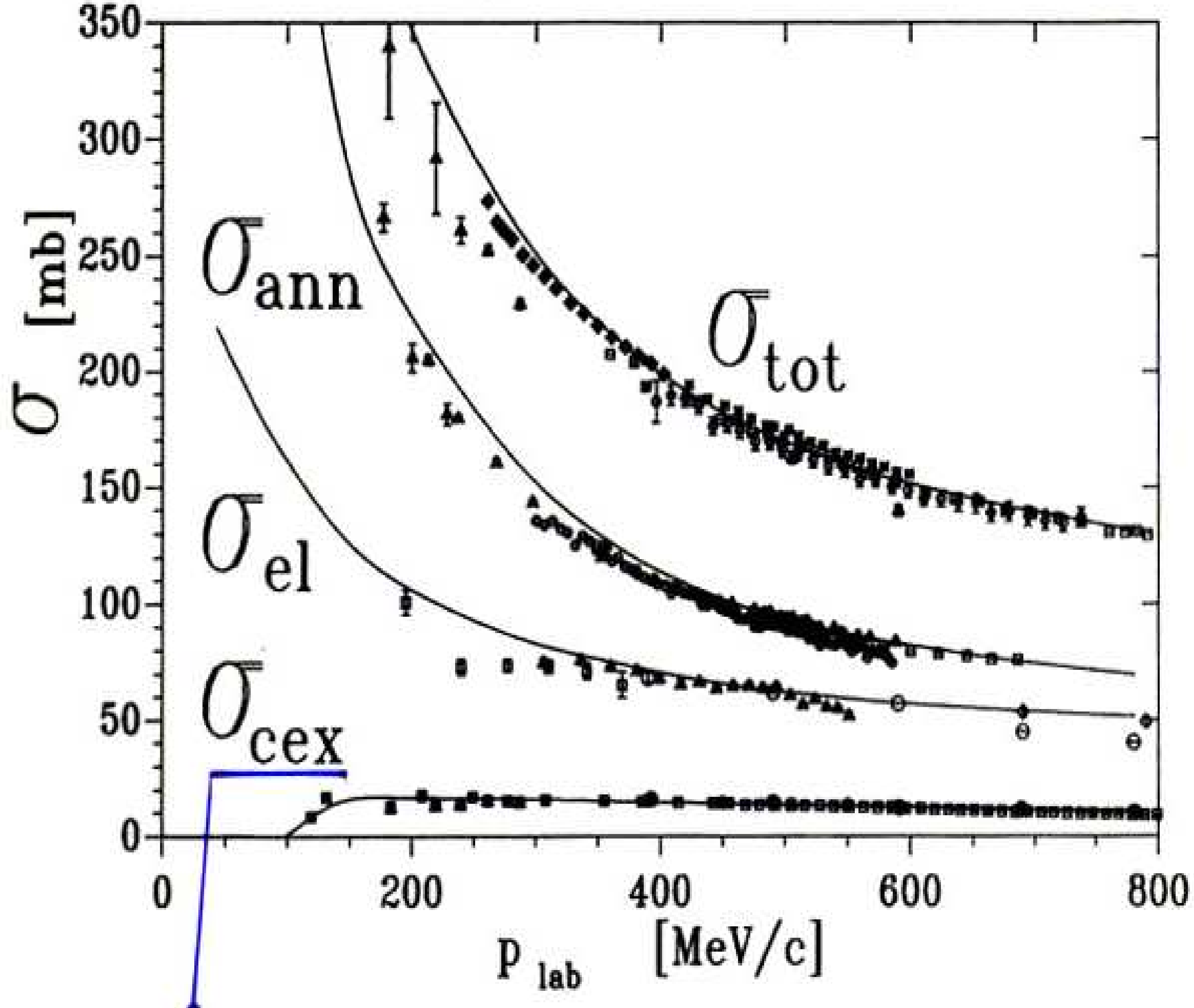
* Annihilation: pure field-theoretic baryon exchange (model C)



Approximation by two-meson channels, not quite realistic strength

* Annihilation: hybrid model: baryon exchange for two-meson channels optical potential for the rest (model D)

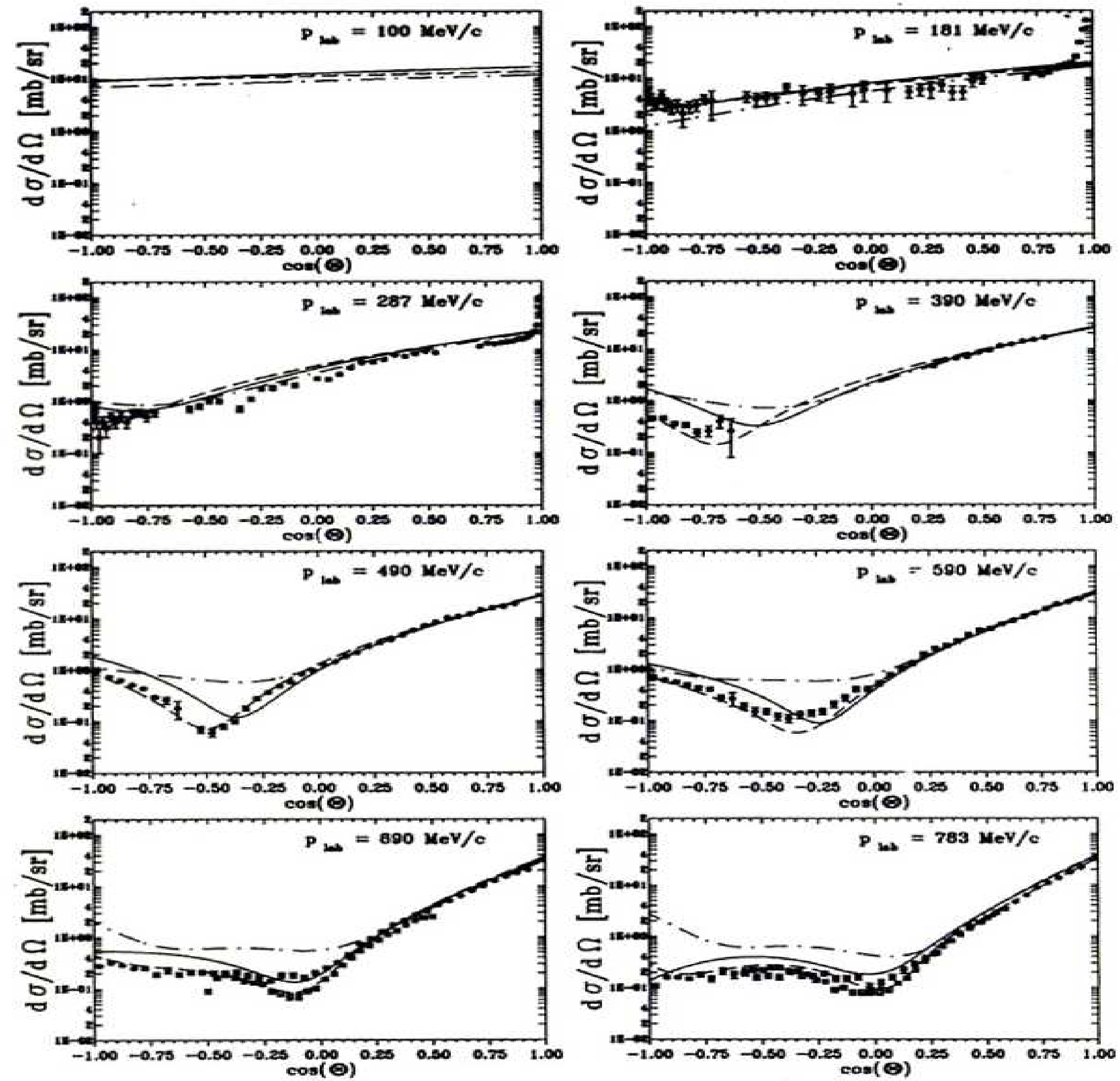
Good degree of success with total, elastic, annihilation X-sections, diifferential $d\sigma$(elastic), analyzing power (model A does best job)



$\bar{p}p \to \bar{n}n$

$\bar{p}p \to \bar{p}p$

differential cross sections

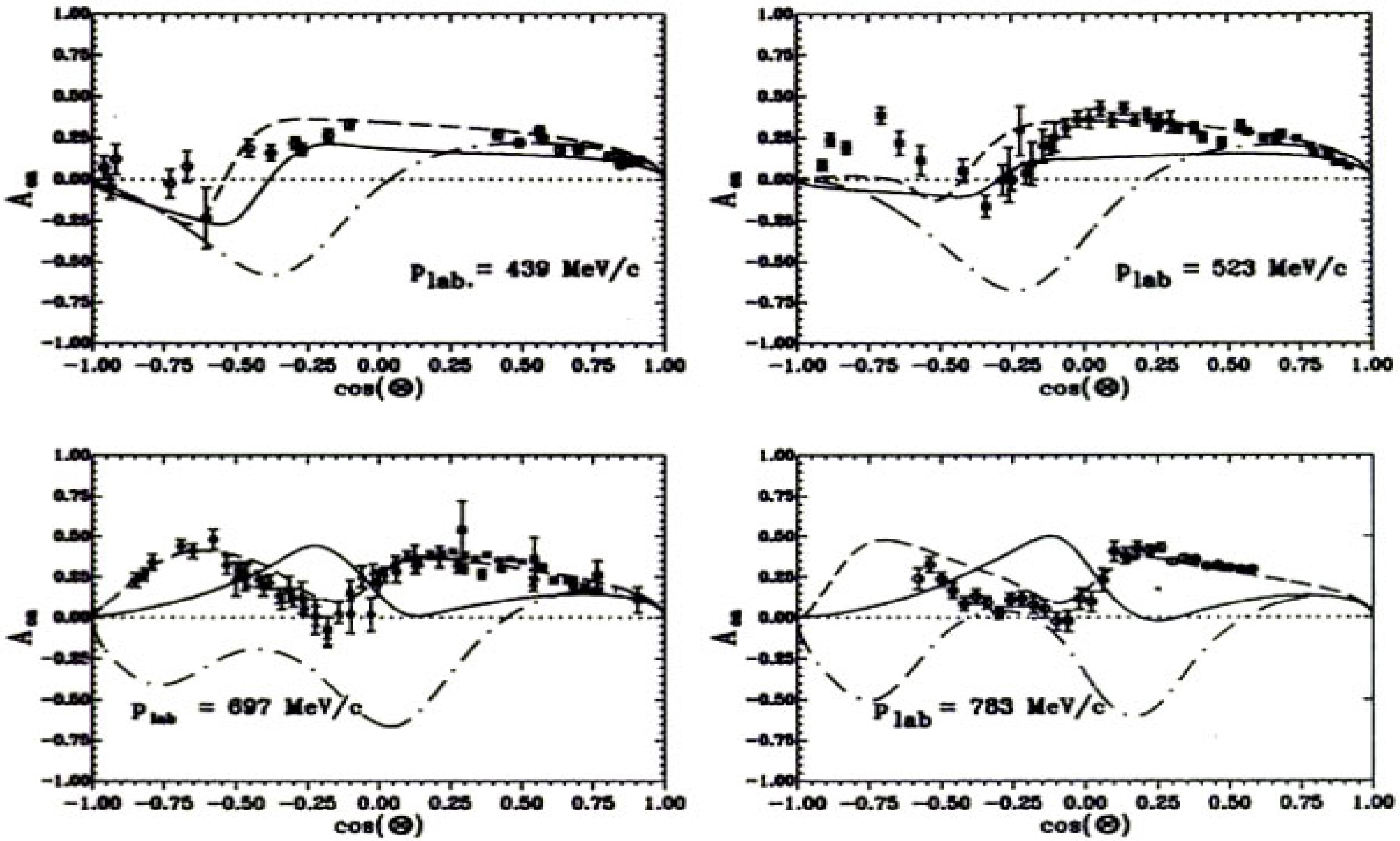


——— model D (microscopic annihilation)

- - - - - model A (phenomenological annihilation)

$\bar{p}p \rightarrow \bar{p}p$

analyzing powers

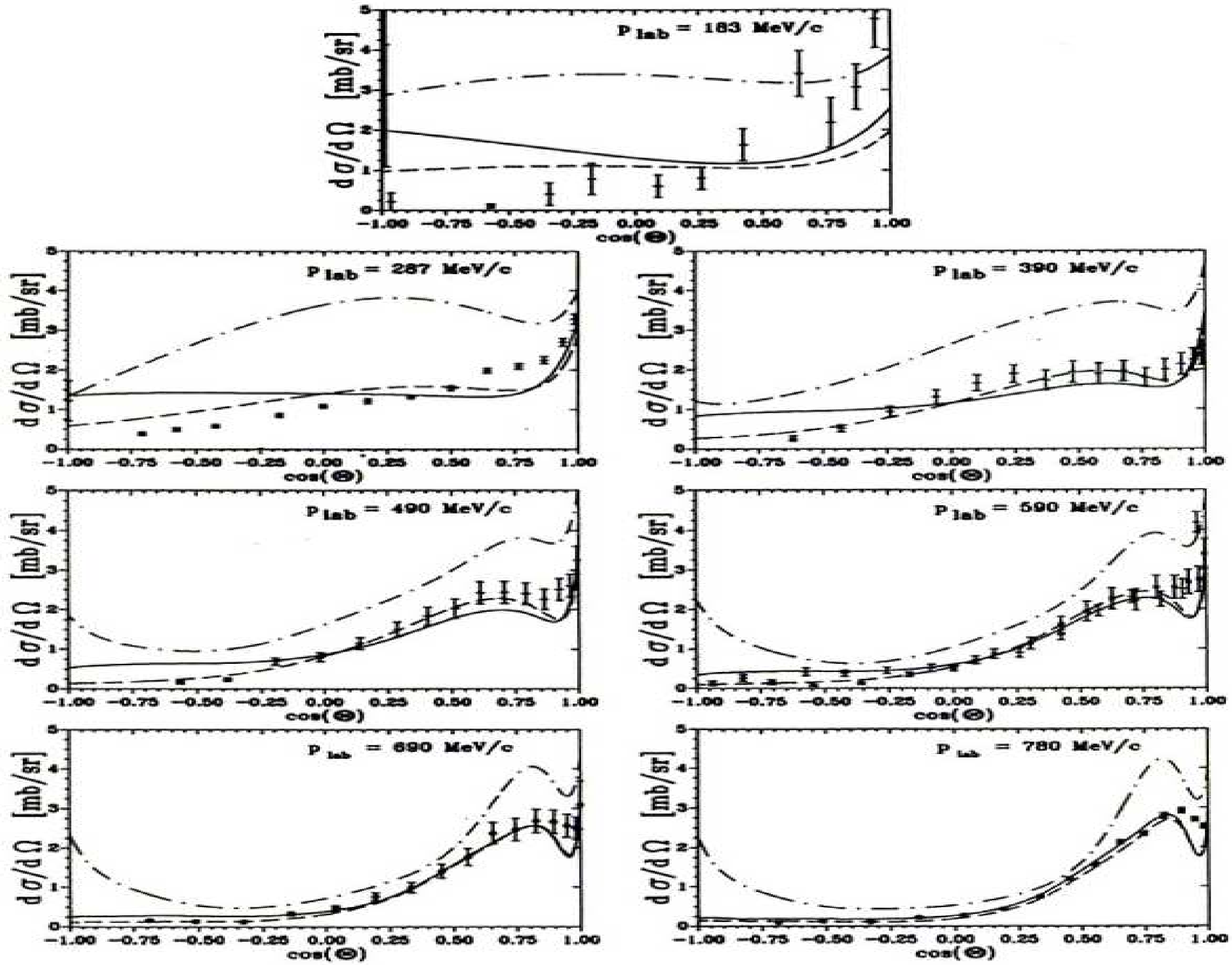


——— D (microscopic annihilation)

– – – – A (phenomenological annihilation)

$\bar{p}p \rightarrow \bar{n}n$

differential cross sections

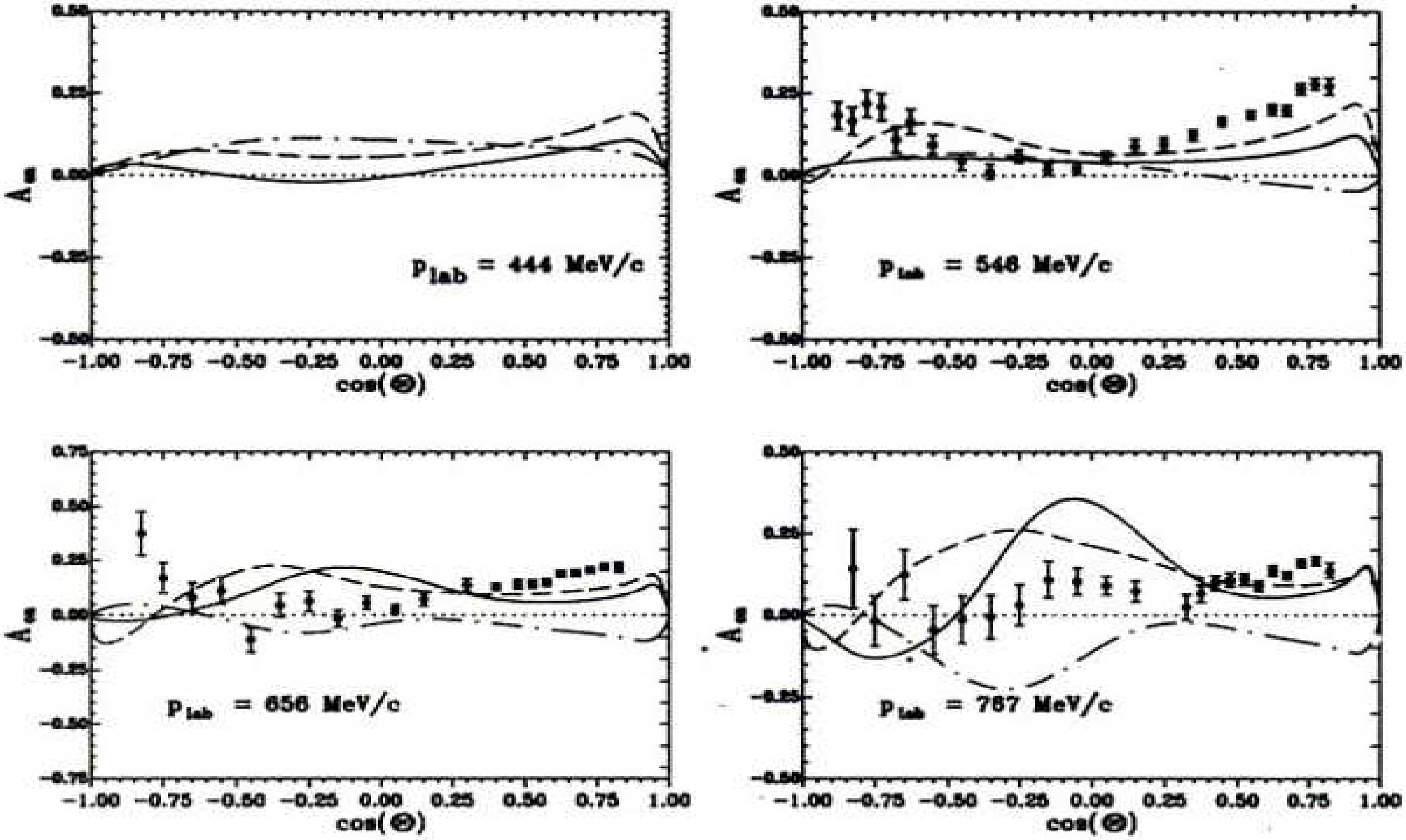


——— D (microscopic annihilation)

- - - - A (phenomenological annihilation)

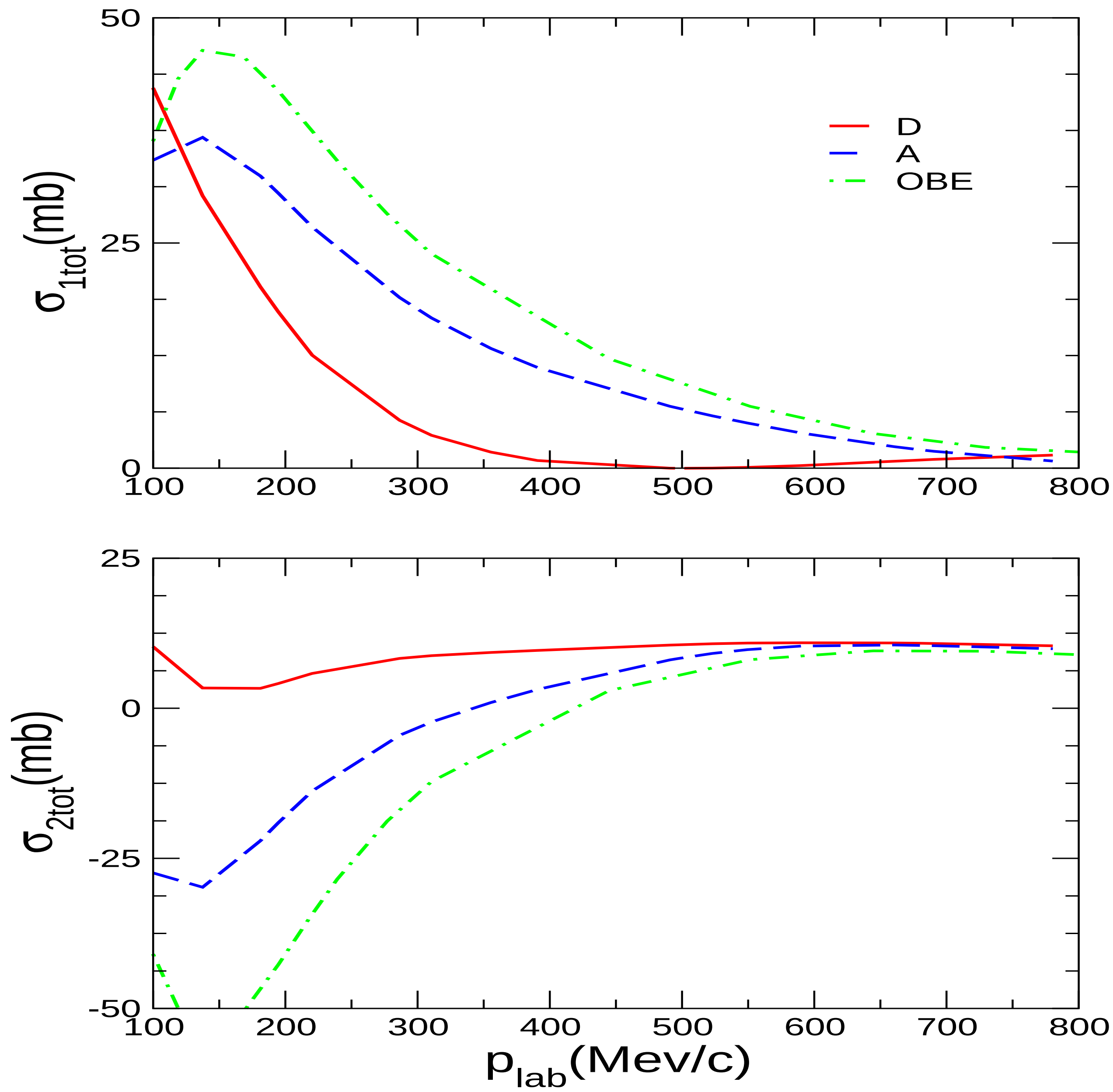
$\bar{p}p \rightarrow \bar{n}n$

analyzing powers



——— D (microscopic annihilation)

- - - - A (phenomenological annihilation)


50
25
0
σ_{1tot}(mb)
D
A
OBE
100
200
300
400
500
600
700
800
25
0
-25
-50
σ_{2tot}(mb)
p_{lab}(Mev/c)

Conclusions: what is the future for PAX?

⋆ FILTEX: an important proof of the principle of spin filtering.

⋆ A consensus between theorists (Budker Institute & IKP FZJ): Polarized electrons in polarized atoms wouldn't polarize antiprotons in storage rings.

⋆ H.O. Meyer: scattering within the beam + Coulomb-nuclear interference reduce the expected $\sigma_P = 122$ mb down to $\sigma_P = 85.6$ mb (SAID-SP05).

⋆ Still slight disagreement between experiment $\sigma_P = 72.5 \pm 5.8(stat. + sys.)$ (FILTEX) and theory, $\sigma_P = 85.6 mb$ (Meyer & Budker Institute & IKP FZJ).

⋆ Solution for PAX: spin filtering by nuclear antiproton-proton interaction .

⋆ Theoretical models are encouraging: substantial filtering of practical interest (Contalbrigo's talk)

⋆ Spin filtering of antiprotons must be optimized experimentally with antiprotons available elsewhere (AD ring at CERN?).