Slepton Production in e^-e^--Collisions

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- Motivation

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- Process

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- Neutralino Sector

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- LR-Mixing

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- Threshold Behaviour

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- Summary

Motivation

$$e^- e^- \longrightarrow \tilde{l}_i \tilde{l}_j$$

- high cross sections

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- high cross sections
- distinctive threshold

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$$e^- e^- \longrightarrow \tilde{l}_i \tilde{l}_j$$

- high cross sections
- distinctive threshold
- high beam polarisation

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- special polarisation dependence

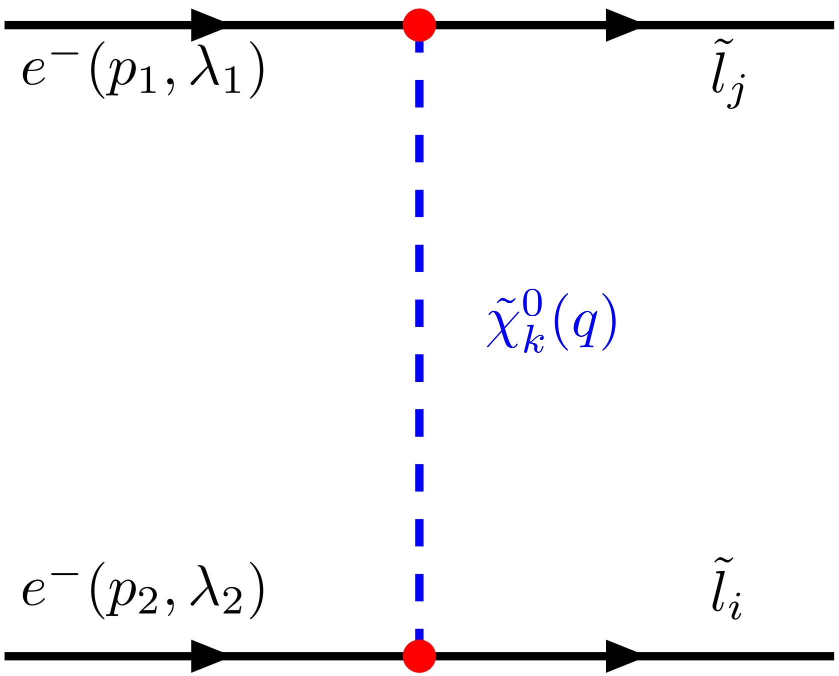
Motivation

$$e^-e^- \longrightarrow \tilde{l}_i \tilde{l}_j$$

- high cross sections
- distinctive threshold
- high beam polarisation
- special polarisation dependence
- low background

} **high sensitivity to $\tilde{l}$- and $\tilde{\chi}^0$-properties**

Process



$+ \, \tilde{l}_i \longleftrightarrow \tilde{l}_j$

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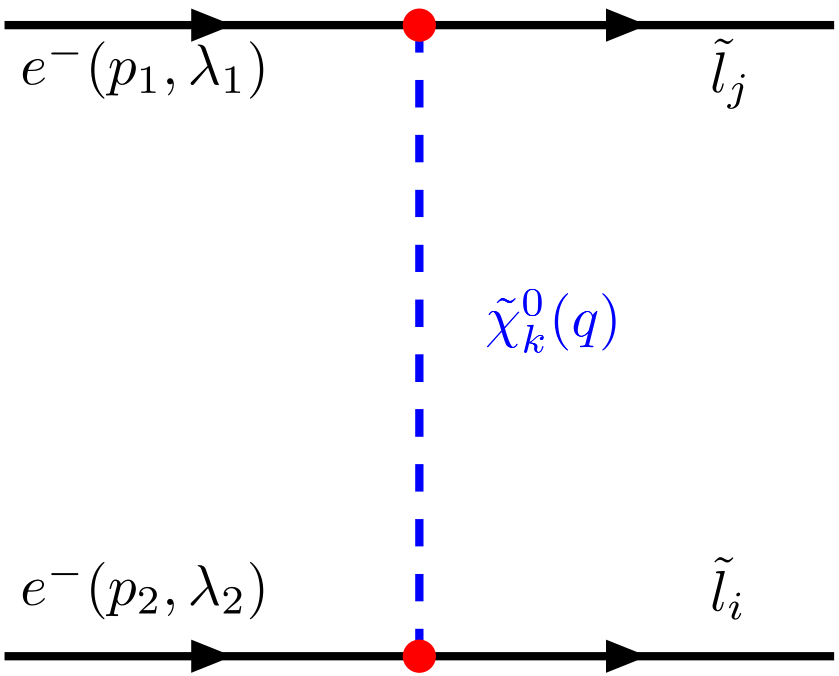

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Amplitude (t-Channel)

$$T^{\lambda_1\lambda_2}_{i,j}(\tilde{\chi}^0_k) = g^2 \bar{v}(p_2,\lambda_2)$$
$$(a^{mi^*}_k P_L + b^{mi^*}_k P_R)$$
$$\Delta^k_t(\not{q} + m_{\tilde{\chi}^0_k})$$
$$(a^{mj^*}_k P_L + b^{mj^*}_k P_R)$$
$$u(p_1,\lambda_1)$$

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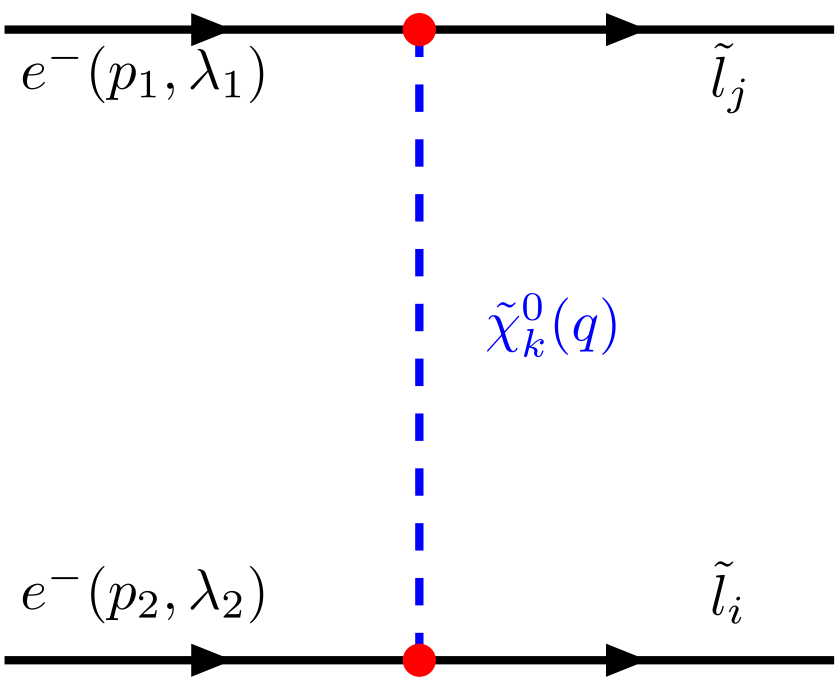

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& u(p_1, \lambda_1)
\end{aligned}
$$

- neutralino exchange ⇒ massive fermion propagator
- Including LR and Flavour Mixing

(Hikasa, 1986; Blöchinger et.al., 2002; Arkani-Hamed et al. hep-ph/9704205)

Neutralino Mass Matrix

$$Y = \begin{pmatrix} M_2 s_W^2 + M_1 c_W^2 & (M_2 - M_1) s_W c_W & 0 & 0 \\ (M_2 - M_1) s_W c_W & M_2 c_W^2 s_W^2 & m_Z & 0 \\ 0 & m_Z & \mu s_{2\beta} & -\mu c_{2\beta} \\ 0 & 0 & -\mu c_{2\beta} & -\mu s_{2\beta} \end{pmatrix}$$

Basis: $\tilde{\gamma}$, $\tilde{Z}$, $\tilde{H}_a^0$, $\tilde{H}_b^0$; GUT: $M_1 = \frac{5}{3} \tan^2 \theta_W M_2$

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Diagonalisation with matrix N : $N^* Y N^{-1} = M_D$
gives Down-Lepton-Slepton-Neutralino-Couplings

$$f_k^L = \sqrt{2} \left[\frac{1}{\cos \theta_W} \left(\frac{1}{2} - \sin^2 \theta_W \right) N_{k2} + \sin \theta_W \right]$$

$$f_k^R = \sqrt{2} \sin \theta_W (\tan \theta_W N_{k2} - N_{k1})$$

Mixing LR

Slepton mass matrix (in MSSM):

$$\mathcal{M}^2_{\tilde{l}} = \begin{pmatrix} M_L^2 + m_l^2 + D_L & m_l(A_l - \mu \tan\beta) \\ m_l(A_l - \mu \tan\beta) & M_E^2 + m_l^2 + D_R \end{pmatrix} = \begin{pmatrix} m^2_{LL} & m^2_{LR} \\ m^2_{LR} & m^2_{RR} \end{pmatrix}$$

where $D_L = (-\frac{1}{2} + \sin^2\theta_W)\cos(2\beta)m_Z^2$ and $D_R = -\sin^2\theta_W \cos(2\beta)m_Z^2$

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Slepton LR-Mixing:

$$\begin{pmatrix} \tilde{l}_1 \\ \tilde{l}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{l}} & \sin\theta_{\tilde{l}} \\ -\sin\theta_{\tilde{l}} & \cos\theta_{\tilde{l}} \end{pmatrix} \begin{pmatrix} \tilde{l}_L \\ \tilde{l}_R \end{pmatrix}$$

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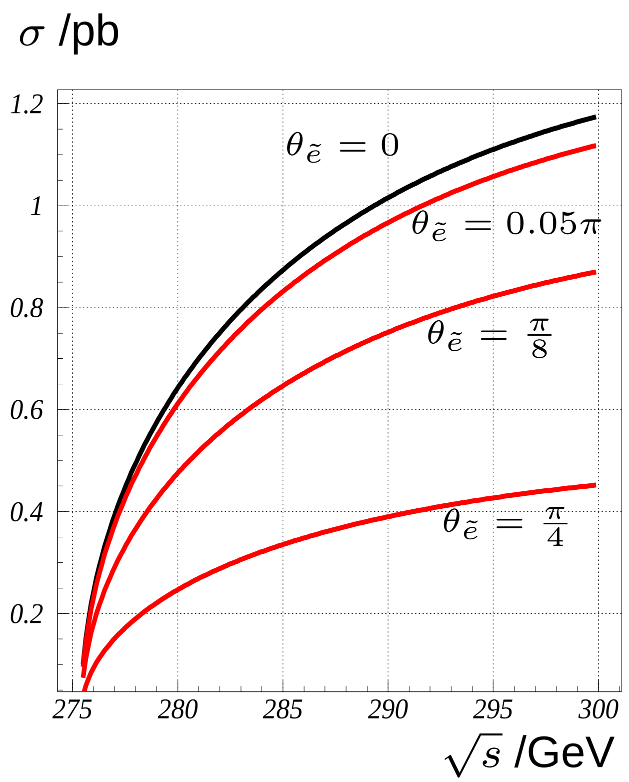
The couplings are given by

$$a_k^{e2} = f_k^L \cos\theta_{\tilde{l}} \qquad a_k^{e1} = -f_k^L \sin\theta_{\tilde{l}}$$
$$b_k^{e2} = f_k^R \sin\theta_{\tilde{l}} \qquad b_k^{e1} = f_k^R \cos\theta_{\tilde{l}}$$

Threshold Behaviour

Production of $\tilde{l}_R\tilde{l}_R$
(similar for $\tilde{l}_L\tilde{l}_L$)
$\Rightarrow$ Threshold: $\propto \beta$



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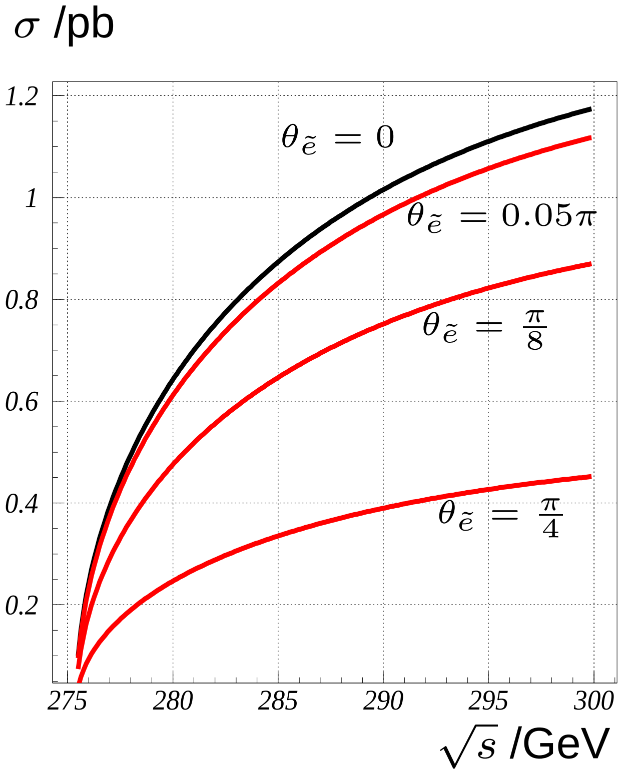
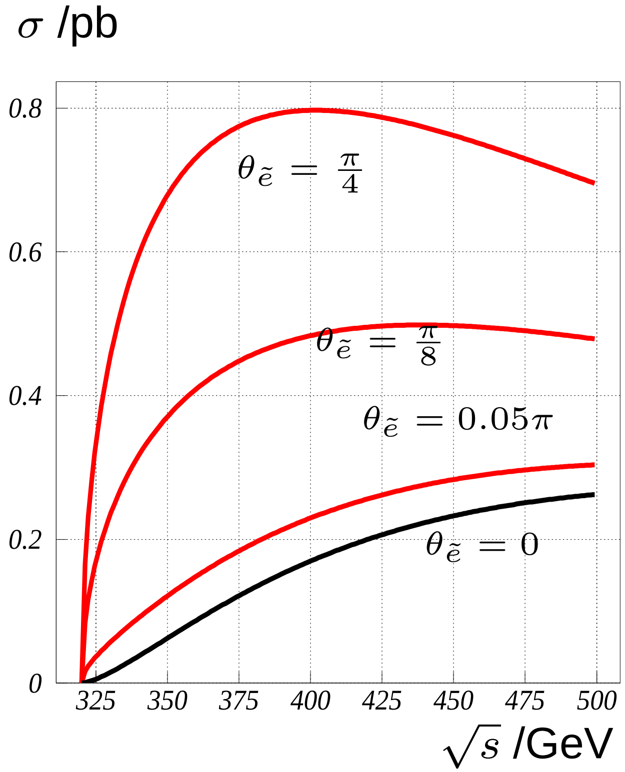


Production of $\tilde{l}_L \tilde{l}_R$
$\Rightarrow$ Threshold: $\propto \beta^3$
BUT: $\propto \beta$ with LR-Mixing



No beam polarisation necessary!

Mixing Flavour

Most general form of Flavour Mixing Matrix:

$$W_i = \begin{pmatrix} c_{\phi^i_{12}} c_{\phi^i_{13}} & s_{\phi^i_{12}} c_{\phi^i_{13}} & s_{\phi^i_{13}} e^{-i\delta} \\ -s_{\phi^i_{12}} c_{\phi^i_{23}} - c_{\phi^i_{12}} s_{\phi^i_{23}} s_{\phi^i_{13}} e^{i\delta} & c_{\phi^i_{12}} c_{\phi^i_{23}} - s_{\phi^i_{12}} s_{\phi^i_{23}} s_{\phi^i_{13}} e^{i\delta} & s_{\phi^i_{13}} c_{\phi^i_{13}} \\ s_{\phi^i_{12}} s_{\phi^i_{23}} - c_{\phi^i_{12}} c_{\phi^i_{23}} s_{\phi^i_{13}} e^{i\delta} & -c_{\phi^i_{12}} s_{\phi^i_{23}} - s_{\phi^i_{12}} c_{\phi^i_{23}} s_{\phi^i_{13}} e^{i\delta} & c_{\phi^i_{23}} c_{\phi^i_{12}} \end{pmatrix}$$

i: L or R, ϕ^i_{12}, ϕ^i_{23}, ϕ^i_{13}: Mixing angles, δ: CP-phase (Arkani-Hamed et al. hep-ph/9704205)

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Full mixing matrix for all three generations left and right:

$$W = \begin{pmatrix} W_L & 0 \\ 0 & W_R \end{pmatrix}$$

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Note: Does not include LR-Mixing

Mixing Everything

To incorporate both Flavour- and LR-Mixing:

$$
\begin{aligned}
M^2 &= L W M_D^2 W^\dagger L^\dagger \\
&= \begin{pmatrix} 0 & L_L \\ L_R & 0 \end{pmatrix} \begin{pmatrix} W_L & 0 \\ 0 & W_R \end{pmatrix} \begin{pmatrix} M_L & 0 \\ 0 & M_R \end{pmatrix}^2 \begin{pmatrix} W_L^\dagger & 0 \\ 0 & W_R^\dagger \end{pmatrix} \begin{pmatrix} 0 & {L_R}^\dagger \\ {L_L}^\dagger & 0 \end{pmatrix}
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Affects the couplings: $\alpha = 1..3$: Lepton, $m = 1..3$: Slepton, $k = 1..4$: Neutralino

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f^L_{\alpha k} \to f^L_{\alpha k} W^{m\alpha} \qquad f^R_{\alpha k} \to f^R_{\alpha k} W^{(m+3)\alpha}
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$$f^L_{\alpha k} \to f^L_{\alpha k} W^{m\alpha} \qquad f^R_{\alpha k} \to f^R_{\alpha k} W^{(m+3)\alpha}$$

- LR-Mixing (including Flavour Mixing):

$$\begin{aligned} a_k^{m2} &= \cos\theta_{\tilde{l}} f^L_{\alpha k} W^{\alpha m}; & a_k^{m1} &= -\sin\theta_{\tilde{l}} f^L_{\alpha k} W^{\alpha(m+3)} \\ b_k^{m2} &= \sin\theta_{\tilde{l}} f^R_{\alpha k} W^{\alpha m}; & b_k^{m1} &= \cos\theta_{\tilde{l}} f^R_{\alpha k} W^{\alpha(m+3)} \end{aligned}$$

Polarisation Dependence

- Density Matrix Formalism (Bouchiat-Michel-Formulae)

(Nucl. Phys. B **5** (1958) p. 416)

$$u(p,\lambda')\,\bar{u}(p,\lambda) = \frac{1}{2}(1+2\lambda\gamma_5)\,\delta_{\lambda\lambda'}\cdot \not{p} + \frac{1}{2}\gamma_5\left(\not{s}^1\sigma^1_{\lambda\lambda'} + \not{s}^2\sigma^2_{\lambda\lambda'}\right)\cdot\not{p}$$

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⇒ Contributions in transverse polarisation?

Polarisation Dependence

Squared amplitude:

$$\propto \ \mathrm{Tr}\left\{[u(p_1,\lambda_1')\bar{u}(p_1,\lambda_1)](\not{q}+m_{\tilde{\chi}_k^0})[v(p_2,\lambda_2')\bar{v}(p_2,\lambda_2)](\not{q}+m_{\tilde{\chi}_l^0})\right\}$$

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Bouchiat-Michel-Formulae yield e.g.:

$$\underbrace{\cdots \delta_{\lambda_1,\lambda_1'} \ \not{p}_1 \cdots}_{\text{long. and unpol. contrib.}} \ (\not{q} + m_{\tilde{\chi}^0_k}) \underbrace{\cdots \not{s}^a \sigma^a_{\lambda_2,\lambda_2'} \ \not{p}_2 \cdots}_{\text{transverse contrib.}} (\not{q} + m_{\tilde{\chi}^0_k})$$

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$\Rightarrow$ Contributions linear in the transverse polarisation

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Contributions of all polarisation combinations,
transverse as well as longitudinal.

Overall Structure

- $\propto (1 \pm P_1^L)(1 \pm P_2^L) \cdot a_k^{mi*} b_k^{mj*} a_l^{mi} b_l^{mj} \cdot [(p_1, p_2, q) \cdots]$

($k, l = 1..4$: Neutralinos; $i, j = 1, 2$ (“L,R”): Slepton, $m = 1..3$: Slepton flavour)

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- $\propto \pm P_{1,2}^T (1 \pm P_{2,1}^L) \cdot a_k^{mi\,*} b_k^{mj\,*} a_l^{mj} a_l^{mi} \cdot [(\cdot, \cdot) + \varepsilon_{\mu\nu\rho\sigma} \cdots]$

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- $\propto P_1^T P_2^T \cdot (a_k^{mi*} b_k^{mj*} b_l^{mi} a_l^{mj} \pm a_k^{mj*} b_k^{mi*} b_l^{mj} a_l^{mi}) \cdot [\cdots]$

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($k, l = 1..4$: Neutralinos; $i, j = 1, 2$ (“L,R”): Slepton, $m = 1..3$: Slepton flavour)

Overall Structure

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Overall Structure

	$\tilde{l}_i\tilde{l}_i$		$\tilde{l}_i\tilde{l}_j$	
	$\lvert T\rvert^2$	TU^*	$\lvert T\rvert^2$	TU^*
$(1+P_1^L)(1-P_2^L)$	c^2s^2	c^2s^2	c^4	$-c^2s^2$
$(1-P_1^L)(1+P_2^L)$	c^2s^2	c^2s^2	s^4	$-c^2s^2$
$(1-P_1^L)(1-P_2^L)$	c^4	c^4	c^2s^2	c^2s^2
$(1+P_1^L)(1+P_2^L)$	s^4	s^4	s^2c^2	s^2c^2
$P_{1,2}^T(1-P_{2,1}^L)m_{\tilde{\chi}_l^0}$	c^3s CP	c^3s CP	$-c^2s^2$ CP	$-c^3s$ CP
$P_{1,2}^T(1+P_{2,1}^L)m_{\tilde{\chi}_l^0}$	s^3c CP	s^3c CP	$-c^2s^2$ CP	$-c^2s^2$ CP
$P_{1,2}^T(1-P_{2,1}^L)m_{\tilde{\chi}_k^0}$	c^3s CP	c^3s CP	$-c^3s$ CP	$-c^3s$ CP
$P_{1,2}^T(1+P_{2,1}^L)m_{\tilde{\chi}_k^0}$	$-s^3c$ CP	$-s^3c$ CP	$-s^2c^2$ CP	$-s^2c^2$ CP
$P_1^TP_2^T$	$\pm c^2s^2$ CP	$\pm c^2s^2$ CP	$\pm c^2s^2$ CP	$c^4\pm s^4$ CP c^2s^2 CP

$c=\cos\theta_{\tilde{l}}$ and $s=\sin\theta_{\tilde{l}}$

$\lvert U\rvert^2$ and UT^* analogous; “CP” marks CP sensitive contributions

Flavour Mixing

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- $e^- e^- \longrightarrow \tilde{\tau}_i \tilde{\tau}_j$ 2 flavour mixing vertices $\Rightarrow$ low cross section

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Access to Contributions $\propto P^T(1 \pm P^L)$

- **LR-Mixing:** $\theta_{\tilde{\tau}}$
- **Flavour Mixing:** ϕ_{12}, ϕ_{13}
- **Asymmetries**

σ : ϕ_{13}-Dependence

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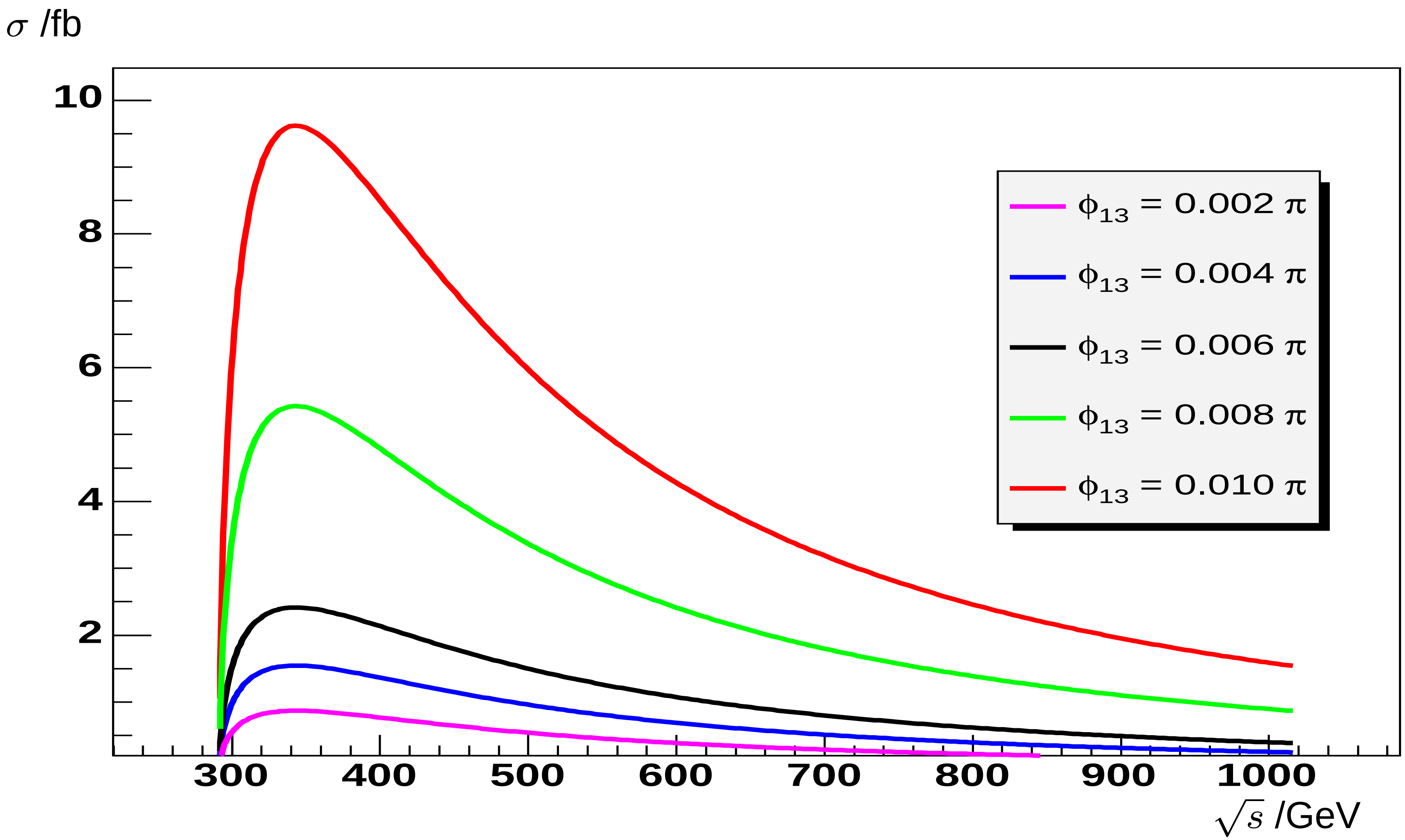
$e^- e^- \longrightarrow \tilde{\tau}_1 \tilde{e}_R$: **SPS1a**-like Scenario, $P_1^T = P_2^L = 80\%$

$\phi_{12} = 0, \ \phi_{23} = 0$



σ : ϕ_{13}-Dependence

From the Flavour Mixing Matrix W assuming $\phi_{12} = \phi_{23} = 0$

$$W^i = \begin{pmatrix} \cos\phi^i_{13} & 0 & \sin\phi^i_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\phi^i_{13} e^{i\delta} & 0 & 1 \end{pmatrix}$$

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$\Rightarrow$ Expect only low sensitivity of asymmetries to ϕ^i_{13} for small values as $\sigma \propto \sin^2\phi^i_{13}$

But: strong dependence of σ on ϕ_{13}

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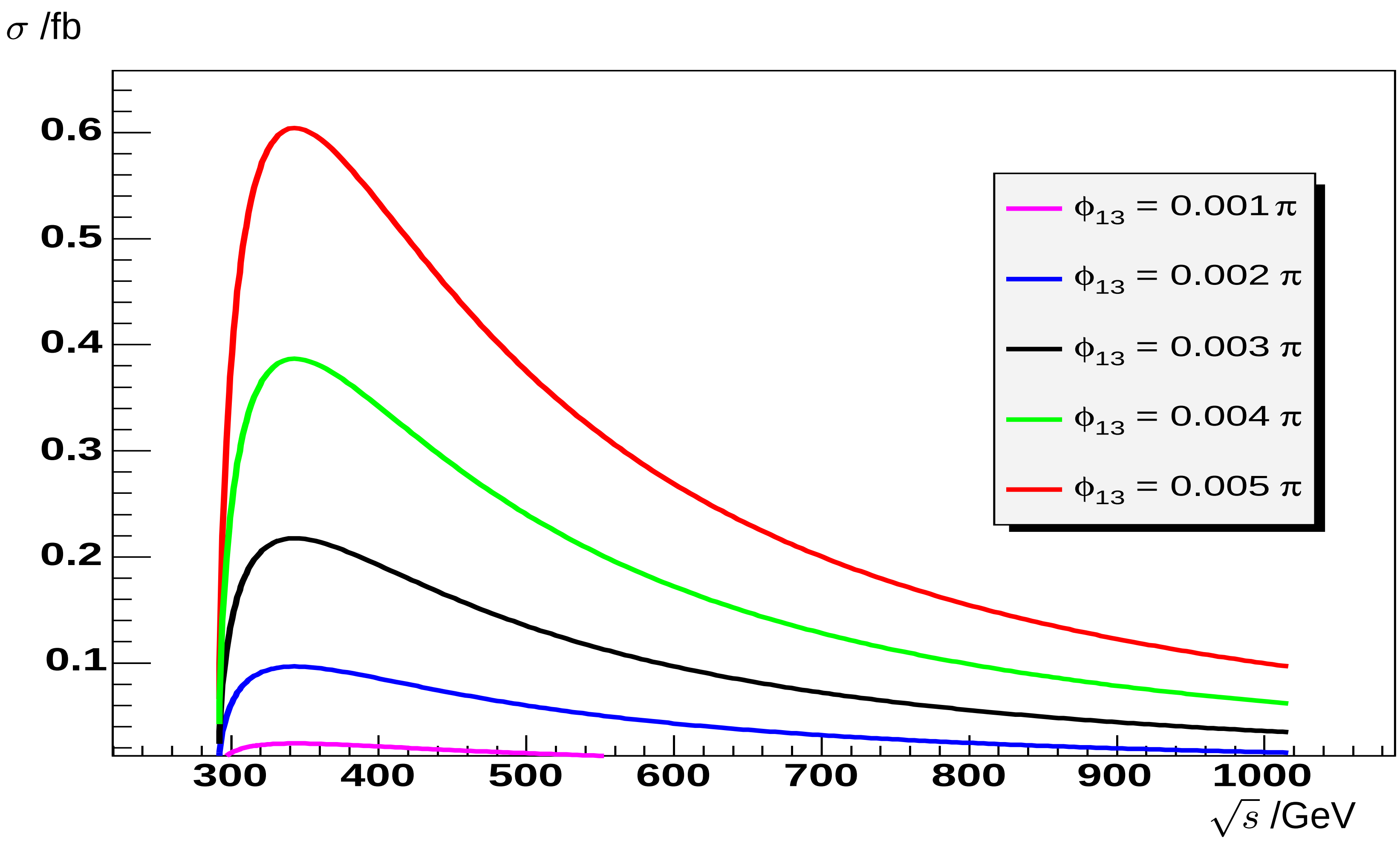

Asymmetries

Polarisation asymmetry:

$$A_\sigma = \frac{\sigma(P_1^A, P_1^B) - \sigma(P_2^A, P_2^B)}{\sigma(P_1^A, P_1^B) + \sigma(P_2^A, P_2^B)}$$

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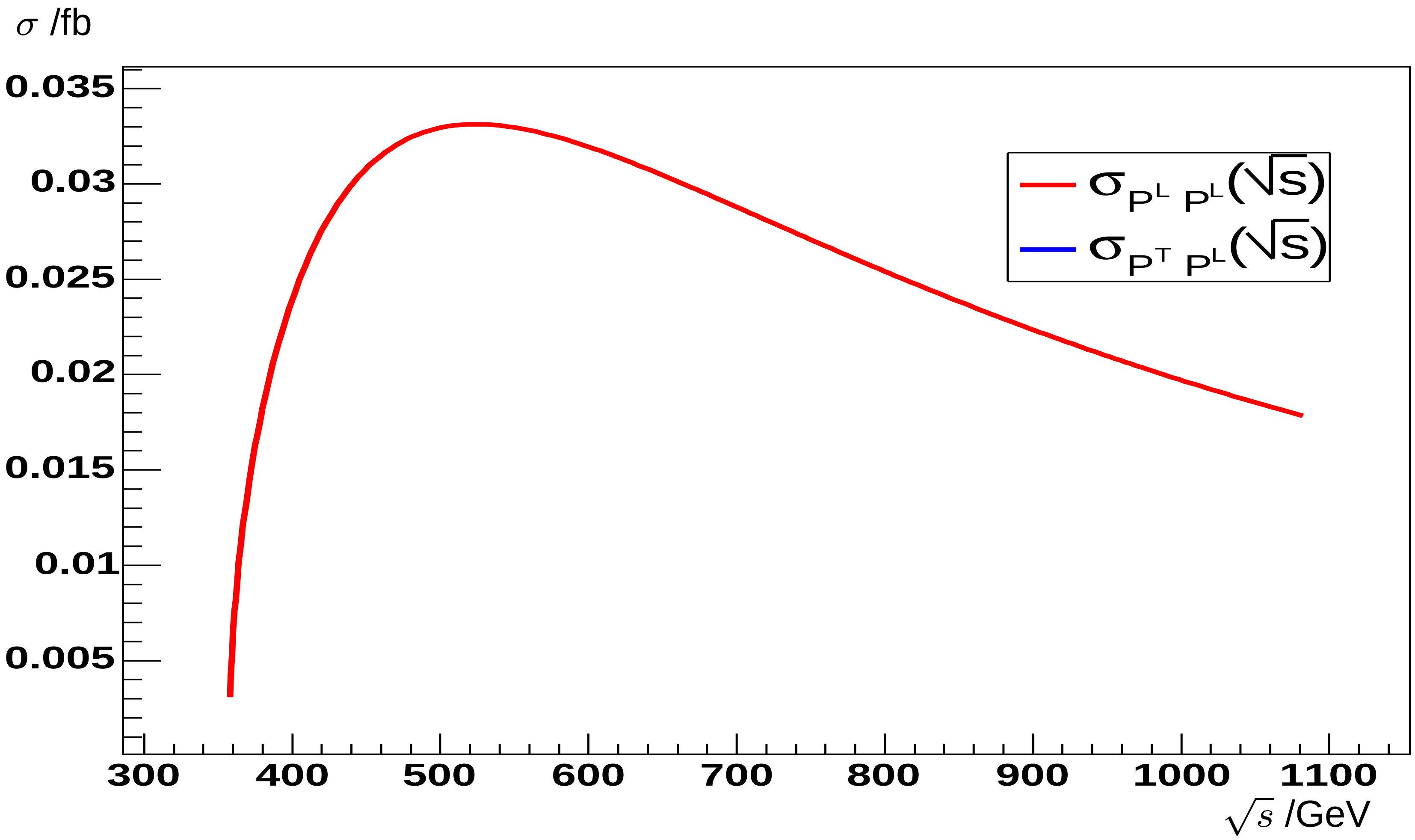
$e^- e^- \longrightarrow \tilde{\tau}_1 \tilde{e}_L$

SPS1a-like Scenario, $P_1^T = P_2^L = 80\%$

$\phi_{12} = \phi_{23} = 0, \phi_{13} = 0.008, \ \theta_{\tilde{\tau}} = \frac{\pi}{4}$



Polarisation Asymmetries

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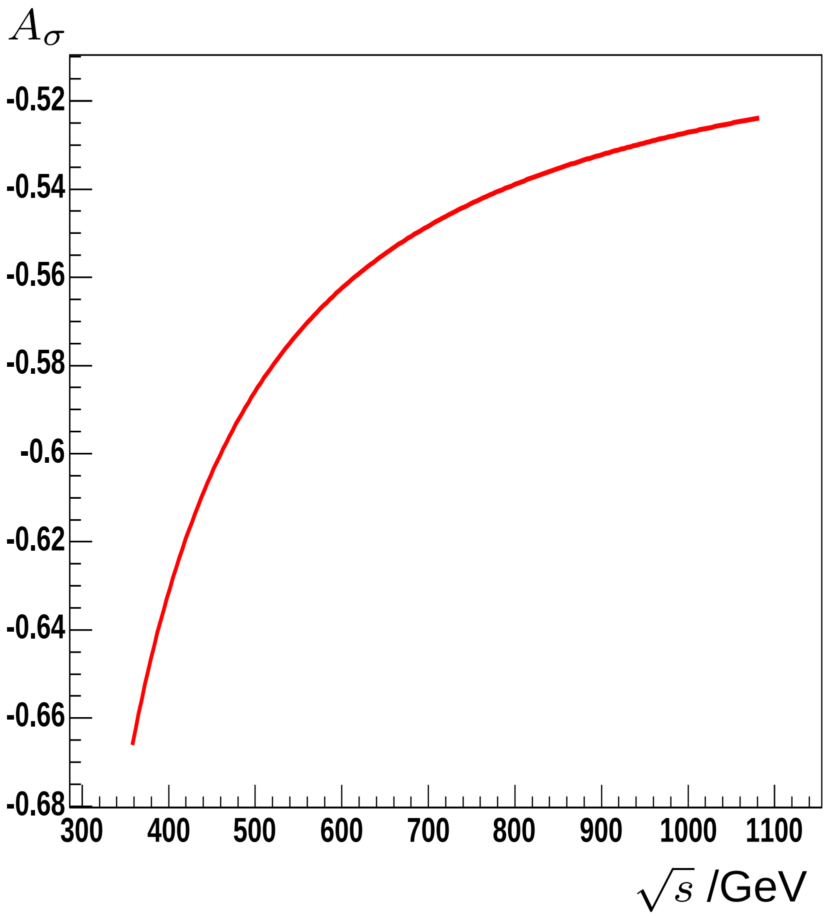

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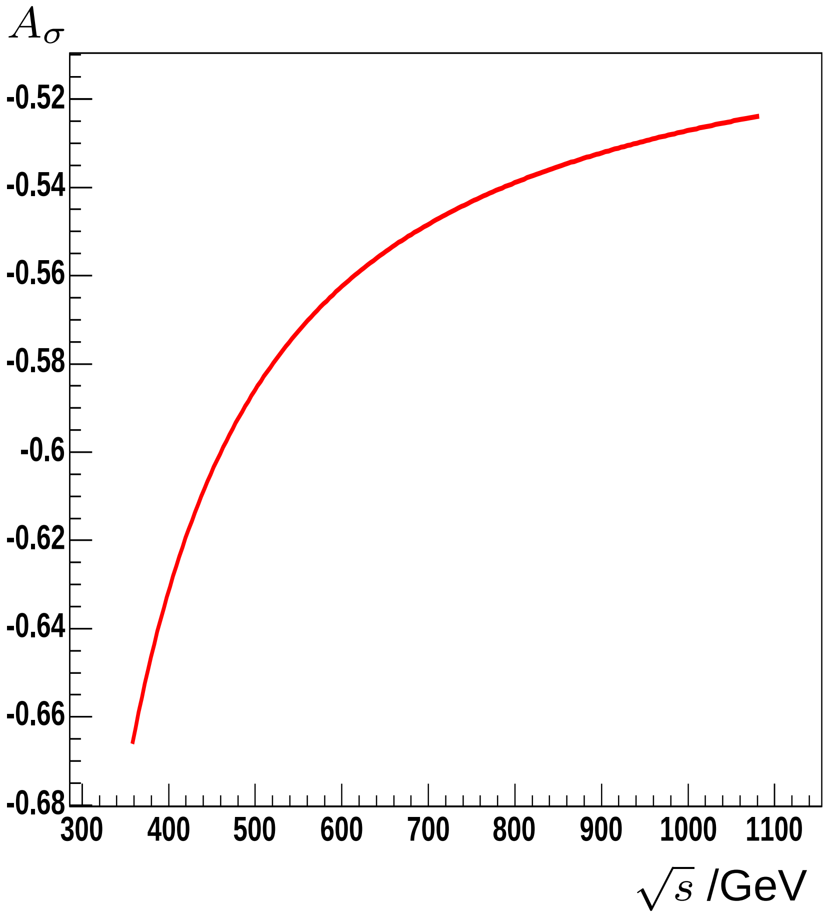

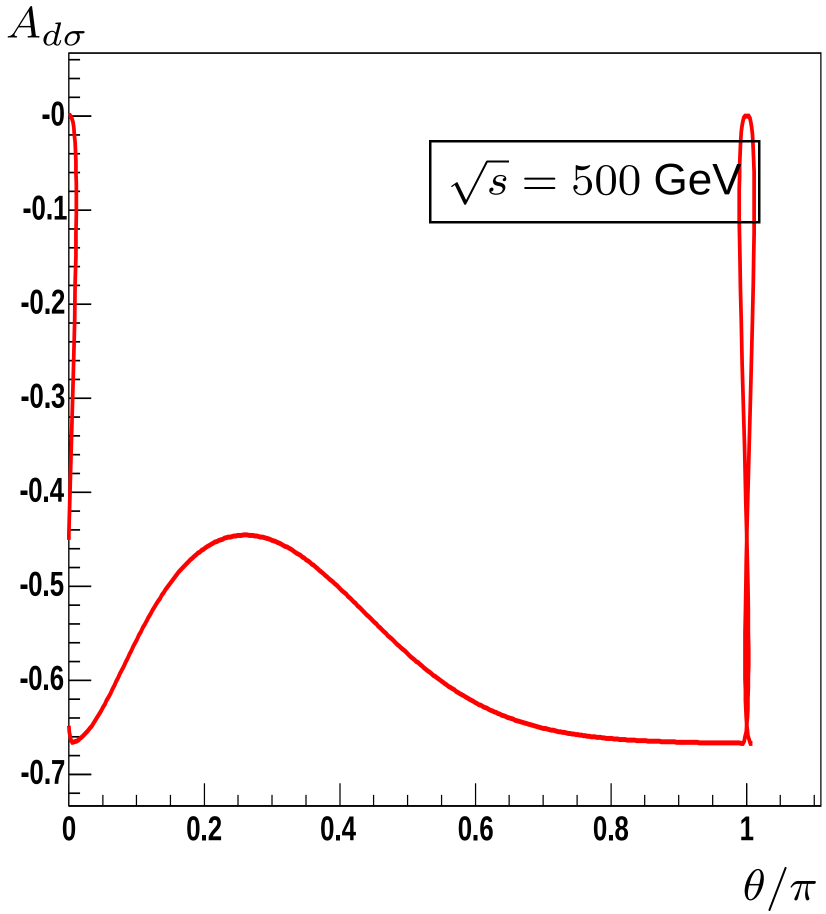

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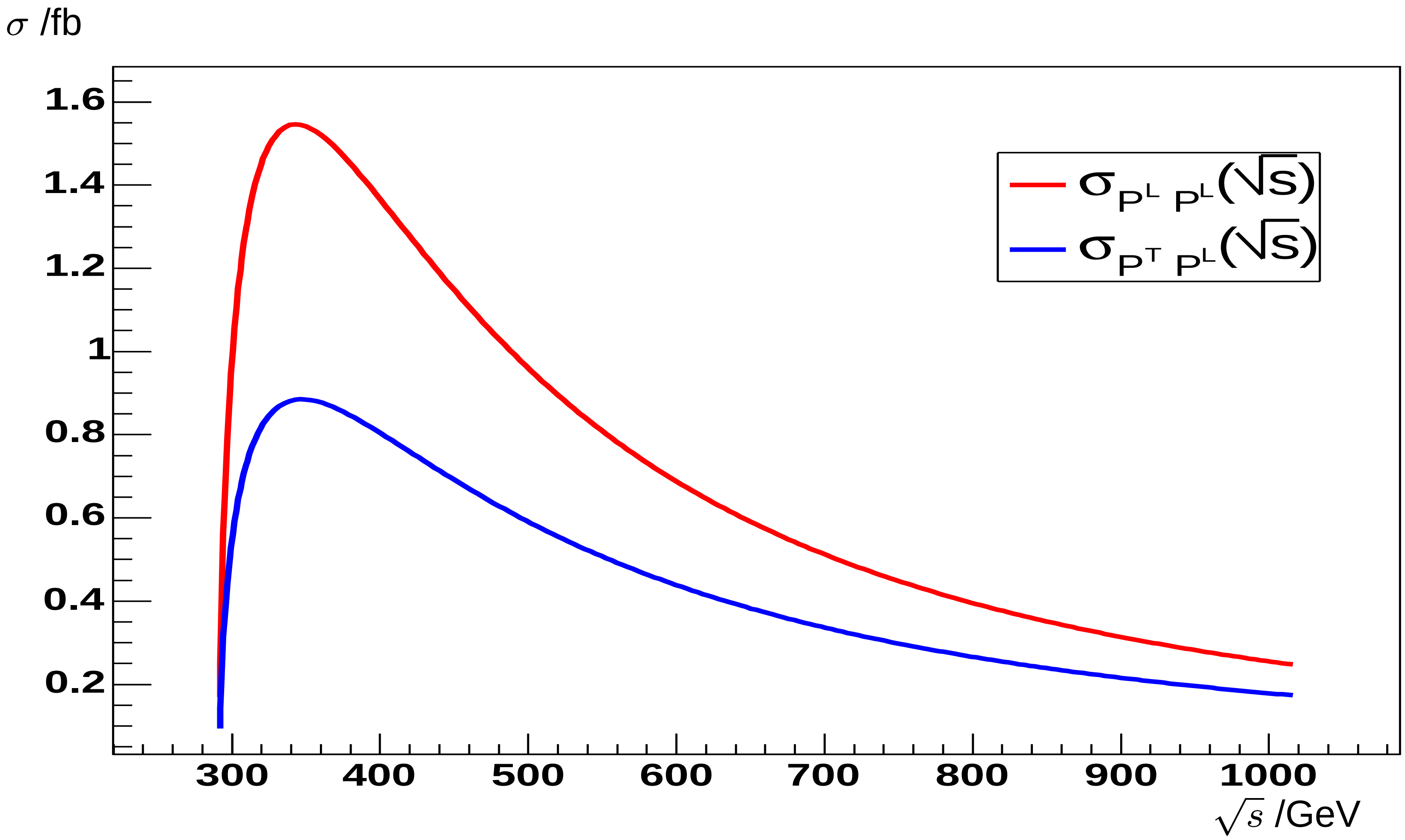

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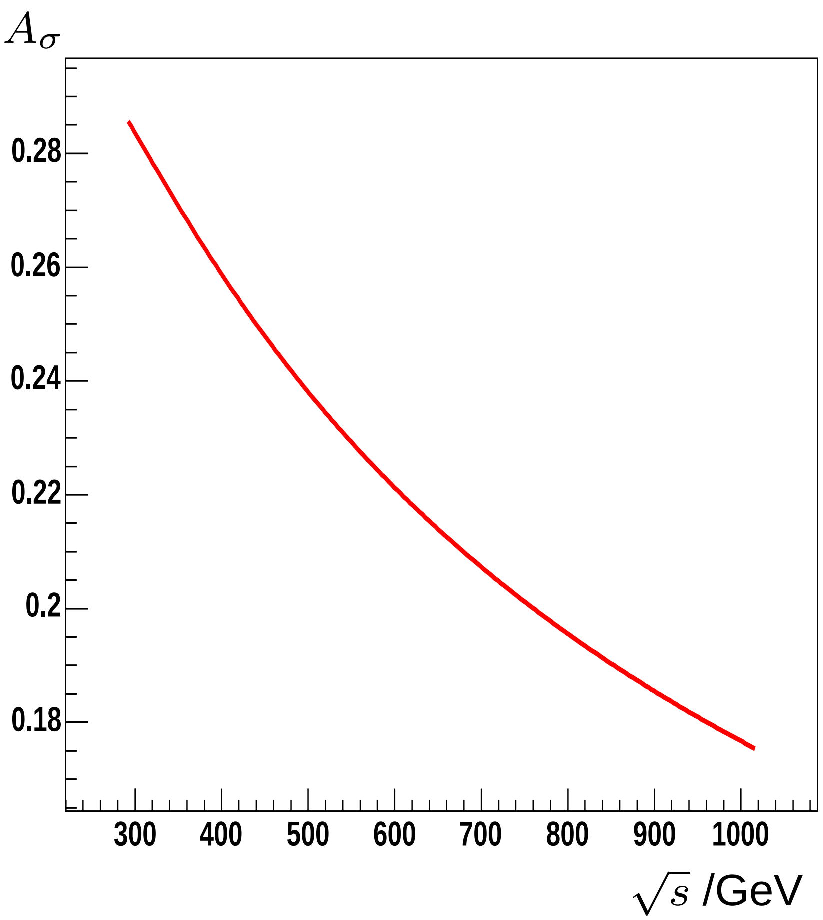

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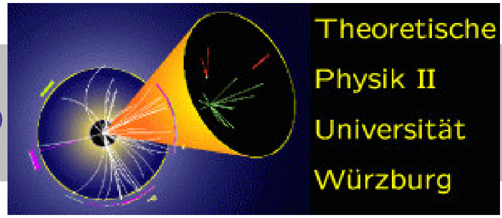

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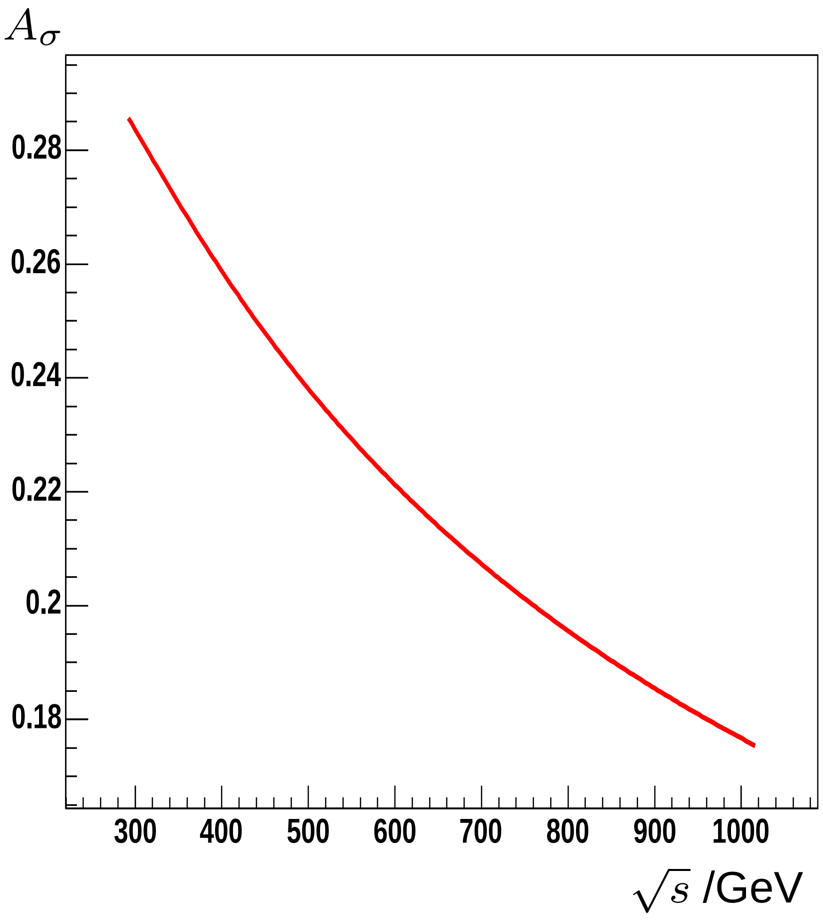

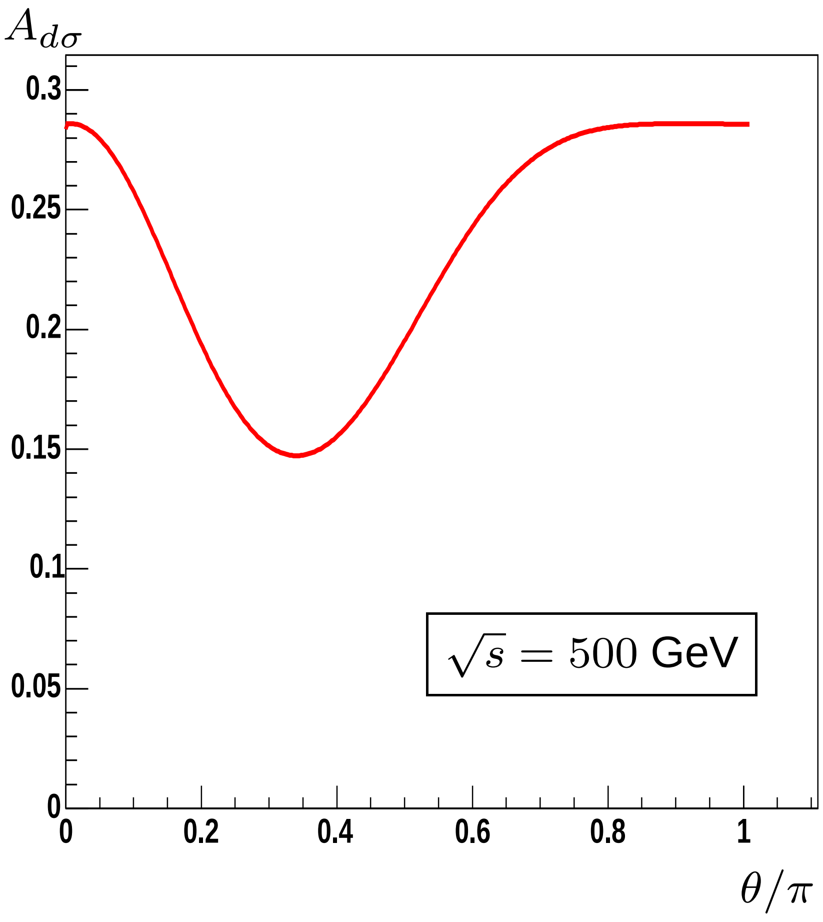

$\sigma : \theta_{\tilde{\tau}}$-Dependence

From the couplings:

$$a_k^{m2} = \cos\theta_{\tilde{l}} f_{\alpha k}^L W^{\alpha m}; \qquad a_k^{m1} = -\sin\theta_{\tilde{l}} f_{\alpha k}^L W^{\alpha(m+3)}$$

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as $\theta_{\tilde{\tau}}$ maximal, i. e. $\approx \pi/4$
$\Rightarrow$ strong dependence on $\theta_{\tilde{\tau}}$

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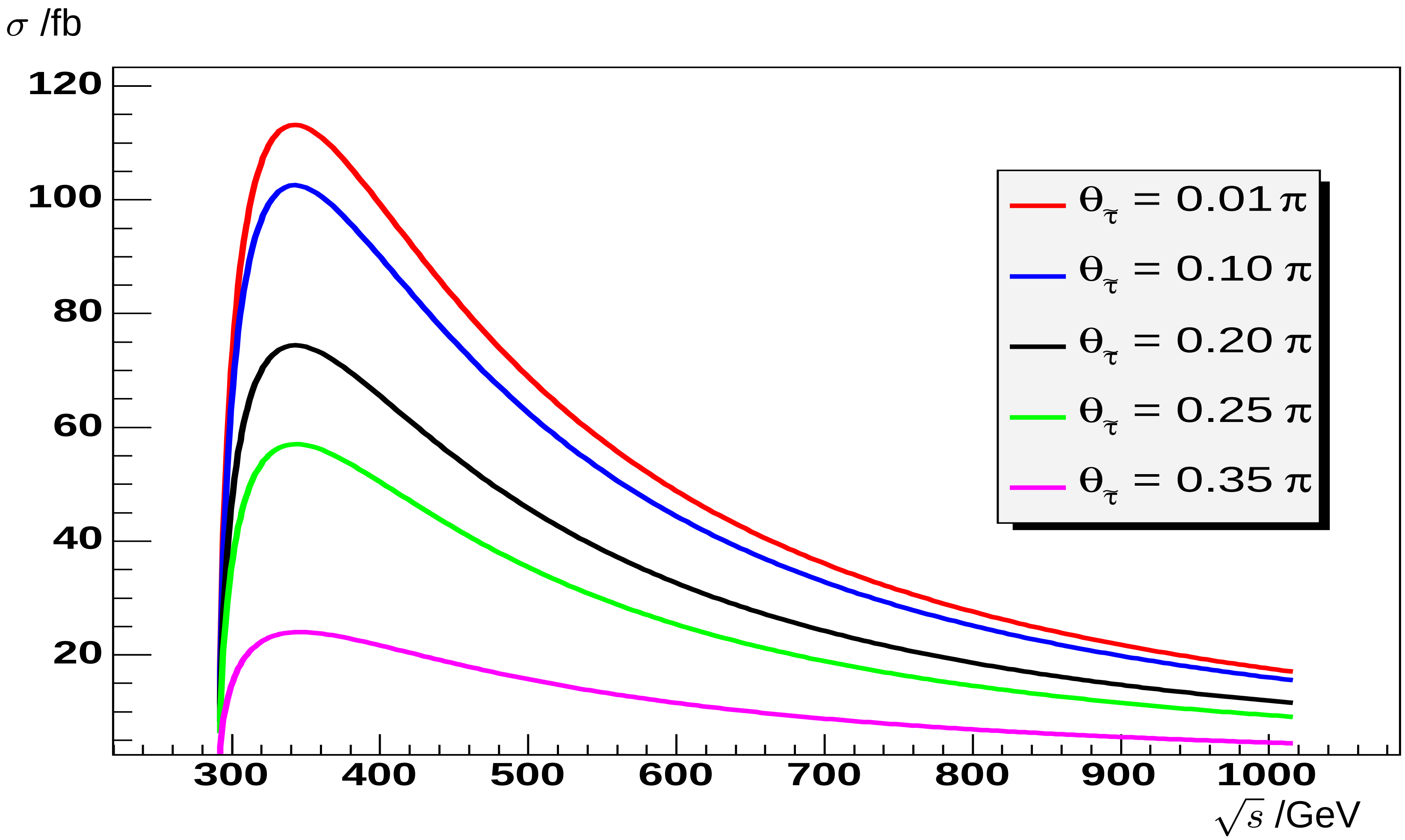

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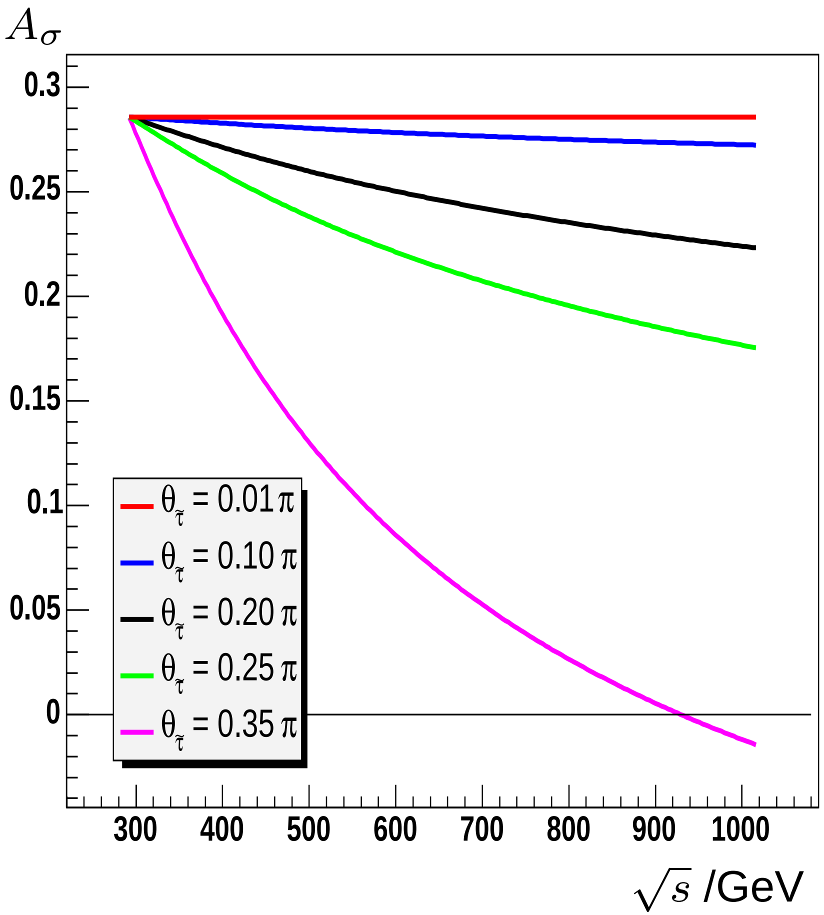

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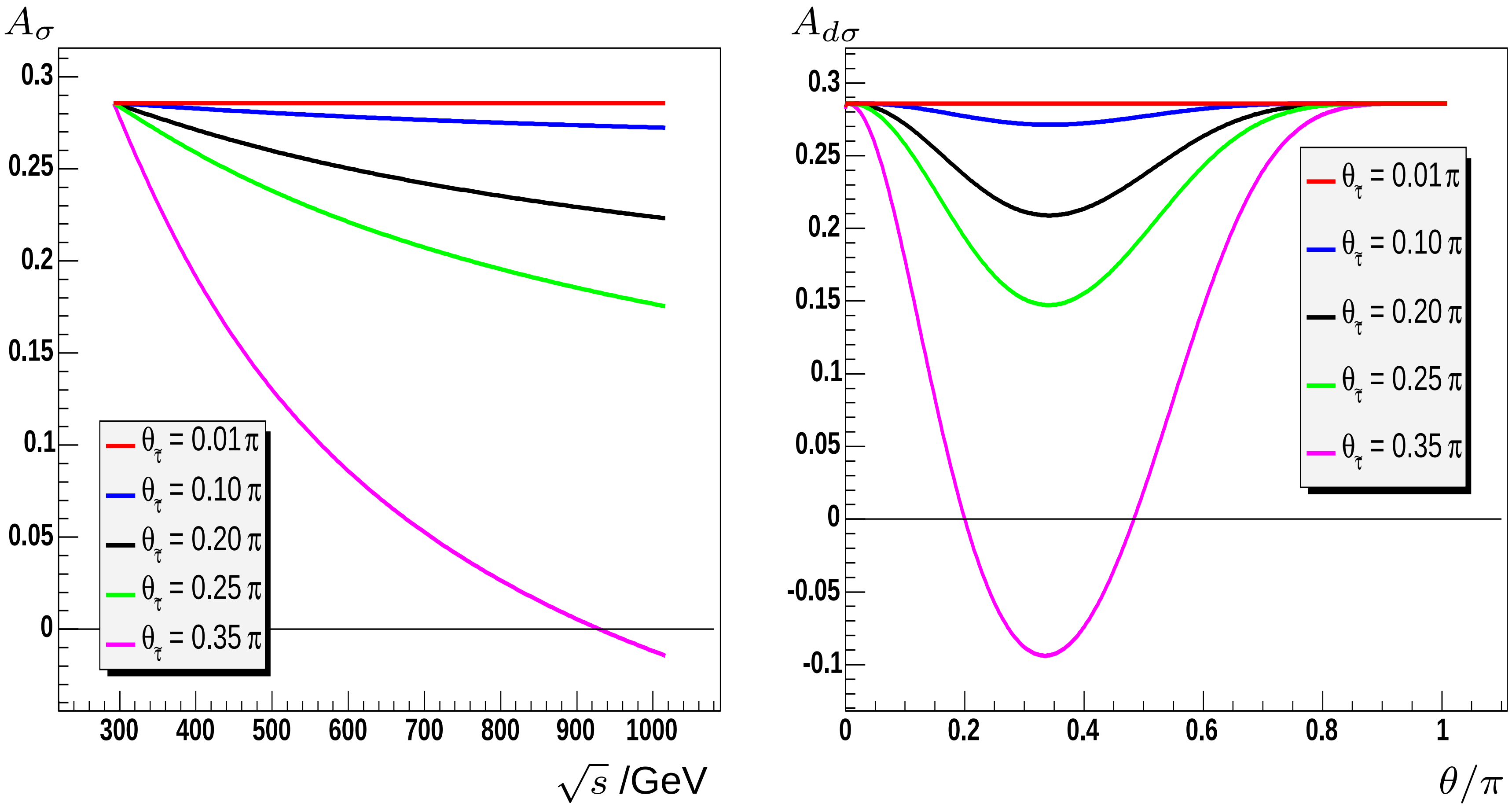

CP-Violation

Source: Triple Products

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$$\mathrm{Tr}\,\{\gamma_5\,\not{a}\,\not{b}\,\not{c}\,\not{d}\} = 4\,i\,\varepsilon_{\mu\nu\rho\sigma}a^\mu b^\nu c^\rho d^\sigma \;=\; < abcd >$$

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Here probably accessible via

- transverse polarisation
- perpendicular to the production plane

i.e. contributions of the form:

$$< p_2 s^a p_1 q >$$

CP-Violation

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$\Rightarrow$ Future investigations necessary

Summary

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- √ Very sensitive to Slepton LR-Mixing at threshold
- √ Massive Fermion propagator
- √ Linear contributions in transverse polarisation
- √ Sensitivity to Flavour Mixing
- √ High polarisation asymmetries for $\tilde{\tau}\tilde{e}$ production $\Rightarrow \theta_{\tilde{\tau}}$

Summary

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$$e^- e^- \longrightarrow \tilde{l}_i \tilde{l}_j$$

- √ High cross sections in slepton production
- √ Very sensitive to Slepton LR-Mixing at threshold
- √ Massive Fermion propagator
- √ Linear contributions in transverse polarisation
- √ Sensitivity to Flavour Mixing
- √ High polarisation asymmetries for $\tilde{\tau}\tilde{e}$ production $\Rightarrow \theta_{\tilde{\tau}}$
- √ CP-sensitivity depending on transverse polarisation

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To do

- Detailed scenario analysis
- CP-Violation