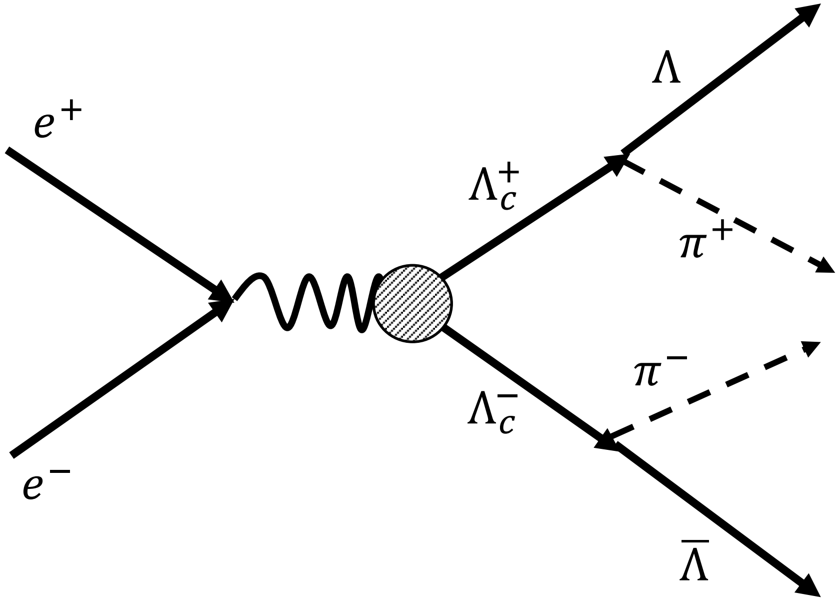
Investigation of the process of electron-positron annihilation into a pair of strange baryons Λ, or charmed baryons Λ_c^+



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Introduction

Year of published	Processes	Number of events near threshold	Links
2008	$e^+e^- \to \Lambda_c^+\Lambda_c^-$	~400	[https://arxiv.org/pdf/0807.4458.pdf]
2018	$e^+e^- \to \Lambda_c^+\Lambda_c^-$	91500	[https://arxiv.org/pdf/1710.00150.pdf]
	$e^+e^- \to \Lambda_c^+\Lambda_c^- \to \Lambda\pi^+\overline{\Lambda}\pi^-$	82	
2018	$e^+e^- \to \Lambda\overline{\Lambda} \to p\pi^-\bar{p}\pi^+$	420600	[https://arxiv.org/pdf/1808.08917.pdf]

here, the following article was used to recalculate the number of events: [https://arxiv.org/pdf/1511.08380.pdf]

Introduction

From [https://arxiv.org/pdf/1808.08917.pdf], we have:

unit momentum vectors $p,\ \bar{p}$

$$\alpha_\psi = \frac{\gamma^2|G_M|^2 - |G_E|^2}{\gamma^2|G_M|^2 + |G_E|^2}$$

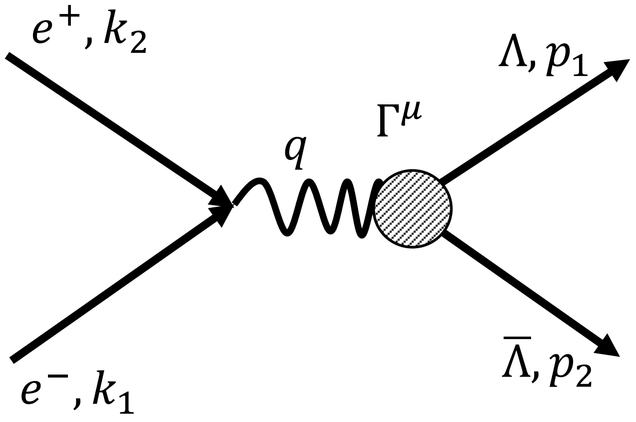
$$\mathcal{W}(\theta, \overrightarrow{n_1}, \overrightarrow{n_2}; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+) = 1 + \alpha_\psi \cos^2\theta + \alpha_-\alpha_+\left[\sin^2\theta\left(n_{1,x}n_{2,x} - \alpha_\psi n_{1,y}n_{2,y}\right) + \left(\alpha_\psi + \cos^2\theta\right)n_{1,z}n_{2,z}\right] +$$
$$\alpha_-\alpha_+\sqrt{1-\alpha_\psi^2}\cos\Delta\Phi\ \sin\theta\ \cos\theta\left(n_{1,x}n_{2,z} + n_{1,z}n_{2.x}\right) + \sqrt{1-\alpha_\psi^2}\sin\Delta\Phi\ \sin\theta\ \cos\theta(\alpha_- n_{1,y} + \alpha_+ n_{2.y})$$

Angle between momentum e^- and momentum Λ

Phase difference between G_M and G_E

α_ψ	$0.461 \pm 0.006 \pm 0.007$
$\Delta\Phi$	$0.740 \pm 0.010 \pm 0.009$
α_-	$0.750 \pm 0.009 \pm 0.004$
α_+	$0.758 \pm 0.010 \pm 0.007$

CP symmetry violation



Matrix element of process:

$$\mathcal{M} = \frac{e^2}{s}\bar{v}(k_2)\gamma_\mu u(k_1)\,\bar{u}(p_1)\left\{G_M\gamma^\mu + \frac{(p_2-p_1)^\mu}{2M}(F_2 - i\gamma_5 F_3)\right\}v(p_2)$$

New term: $i\gamma_5 F_3$

Mass of Λ: M

$$F_2 = \frac{G_M - G_E}{1-\gamma^2}$$

CP-conjugate matrix element of process:

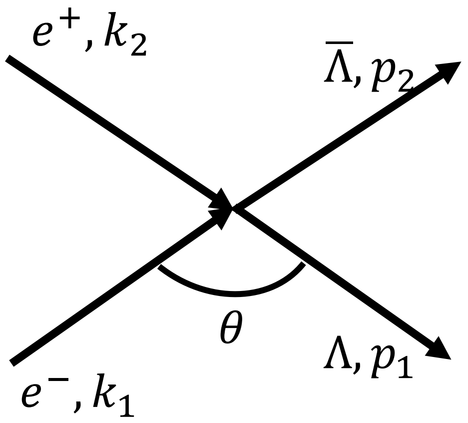
$$\mathcal{M}_{CP} = \frac{e^2}{s}\bar{v}(k_2)\gamma_\mu u(k_1)\,\bar{u}(p_1)\left\{G_M\gamma^\mu + \frac{(p_2-p_1)^\mu}{2M}(F_2 + i\gamma_5 F_3)\right\}v(p_2)$$

Cross section of the annihilation process for unpolarized final particles:

$$\frac{d\sigma}{d\Omega} = \frac{e^4\beta}{256\pi^2M^2\gamma^4}\{|G_E|^2\sin^2\theta + \gamma^2|G_M|^2(1+\cos^2\theta) + \gamma^2(\gamma^2-1)|F_3|^2\sin^2\theta\}$$

Velocity of Λ: β

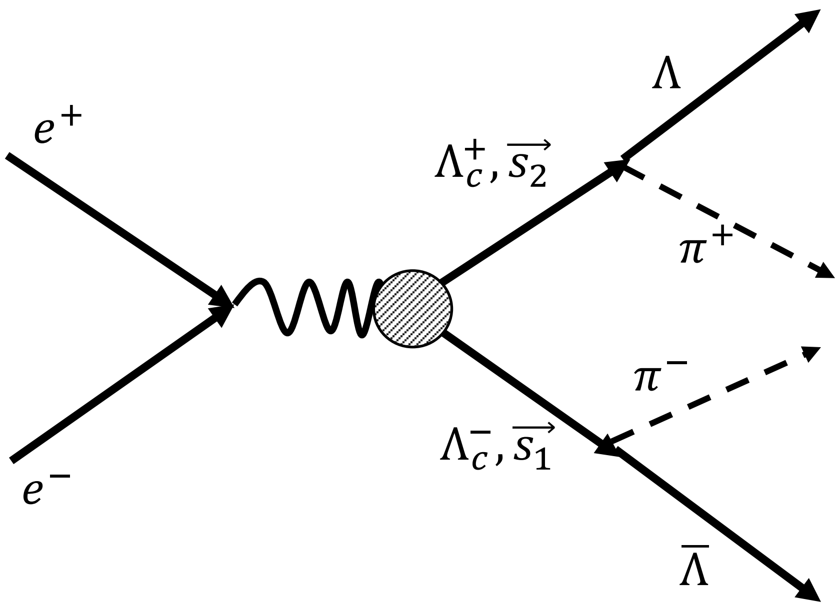
Lorenz factor of Λ: γ



$$F_3(0) = \frac{2M}{e}d$$

Connection between EDM and ED form-factor

Polarized final state



Vector of spin final particles Λ_c^+ and Λ_c^-

$$\left.\frac{d\sigma(\overrightarrow{n_1},\ \overrightarrow{n_2})}{d\Omega}\right|_{e^+e^-\to\Lambda_c^+\Lambda_c^-\to\Lambda\pi^+\overline{\Lambda}\pi^-} = \left.\frac{d\sigma(\overrightarrow{s_1}\to\alpha_-\overrightarrow{n_1},\ \overrightarrow{s_2}\to\alpha_+\overrightarrow{n_2})}{d\Omega}\right|^{(polarized)}_{e^+e^-\to\Lambda_c^+\Lambda_c^-}$$

Unit vector of momentum final particles p and $\bar{p}$

Free parameters of the distribution

Let's introduce the following definitions:

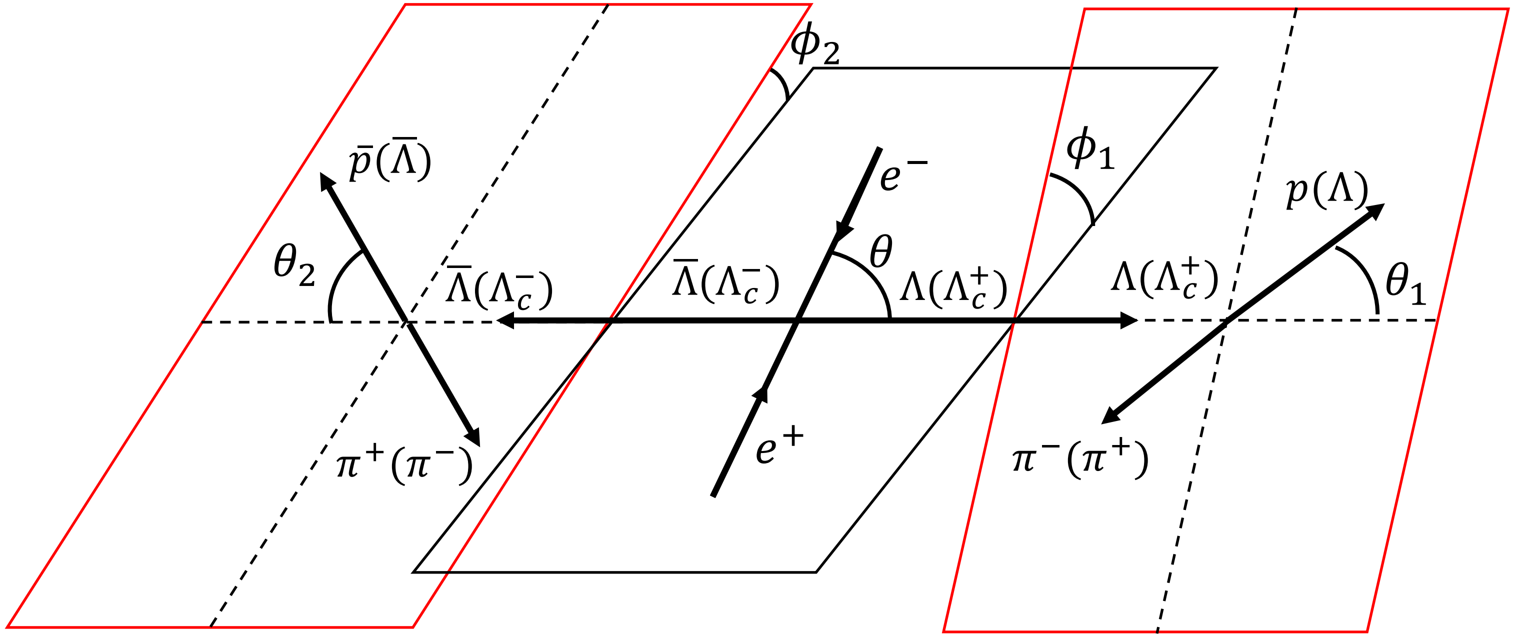
$$\Sigma = \frac{e^4}{4\gamma^2}\left(|G_E|^2 + \gamma^2|G_M|^2\right)$$

$$f_\psi = \frac{\sqrt{2}\,|F_3|\gamma^2\beta}{\sqrt{|G_E|^2+\gamma^2|G_M|^2}}$$

Cross section of pair e^-e^+ annihilation into a polarized pair $\Lambda_c^+\Lambda_c^-$:

$$\frac{d\sigma}{d\Omega} = \frac{\beta\Sigma}{256\pi^2M^2\gamma^2}\Big\{1+\alpha_\psi\cos^2\theta+\sin^2\theta\left(s_{1,x}s_{2,x}-\alpha_\psi s_{1,y}s_{2,y}\right)+\left(\alpha_\psi+\cos^2\theta\right)s_{1,z}s_{2,z}+$$
$$+\sqrt{1-\alpha_\psi^2}\cos\Delta\Phi_{\mathrm{EM}}\sin\theta\cos\theta\left(s_{1,x}s_{2,z}+s_{1,z}s_{2,x}\right)+\sqrt{1-\alpha_\psi^2}\sin\Delta\Phi_{EM}\sin\theta\cos\theta\left(s_{1,y}+s_{2,y}\right)+$$
$$+\sqrt{1-\alpha_\psi}f_\psi\cos\Delta\Phi_{\mathrm{E3}}\sin^2\theta\left(s_{1,x}s_{2,y}-s_{1,y}s_{2,x}\right)+\sqrt{1+\alpha_\psi}f_\psi\cos\Delta\Phi_{M3}\sin\theta\cos\theta\left(s_{1,y}s_{2,z}-s_{1,z}s_{2,y}\right)+$$
$$+\sqrt{1-\alpha_\psi}f_\psi\sin\Delta\Phi_{\mathrm{E3}}\sin^2\theta\left(s_{1,z}-s_{2,z}\right)+\sqrt{1+\alpha_\psi}f_\psi\sin\Delta\Phi_{M3}\sin\theta\cos\theta\left(s_{1,x}-s_{2,x}\right)\Big\}$$

Polarized final state



A schematic representation of the kinematics of the two-step process of annihilation of an electron-positron pair into a pair of heavy baryons decaying into a baryon-meson pair.

Definition of the unit momentum vectors p, $\bar{p}$ in terms of the kinematic angles:

$$\vec{n}_1 = (\sin\theta_1 \cos\phi_1, \sin\theta_1 \sin\phi_1, \cos\theta_1)$$

$$\vec{n}_2 = (\sin\theta_2 \cos\phi_2, \sin\theta_2 \sin\phi_2, \cos\theta_2)$$

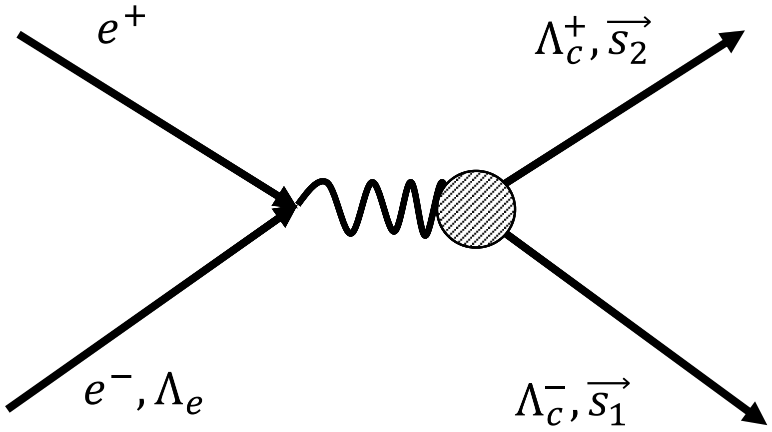
Complex phases of the form-factors

$$G_M = |G_M| e^{i\Phi_M} \qquad G_E = |G_E| e^{i\Phi_E} \qquad F_3 = |F_3| e^{i\Phi_3}$$

Phase difference:

$$\Delta\Phi_{AB} = \Phi_A - \Phi_B$$

Polarized electron in the initial state



The total scattering cross section of the annihilation process of a pair e^-e^+ with a polarized electron in the initial state:

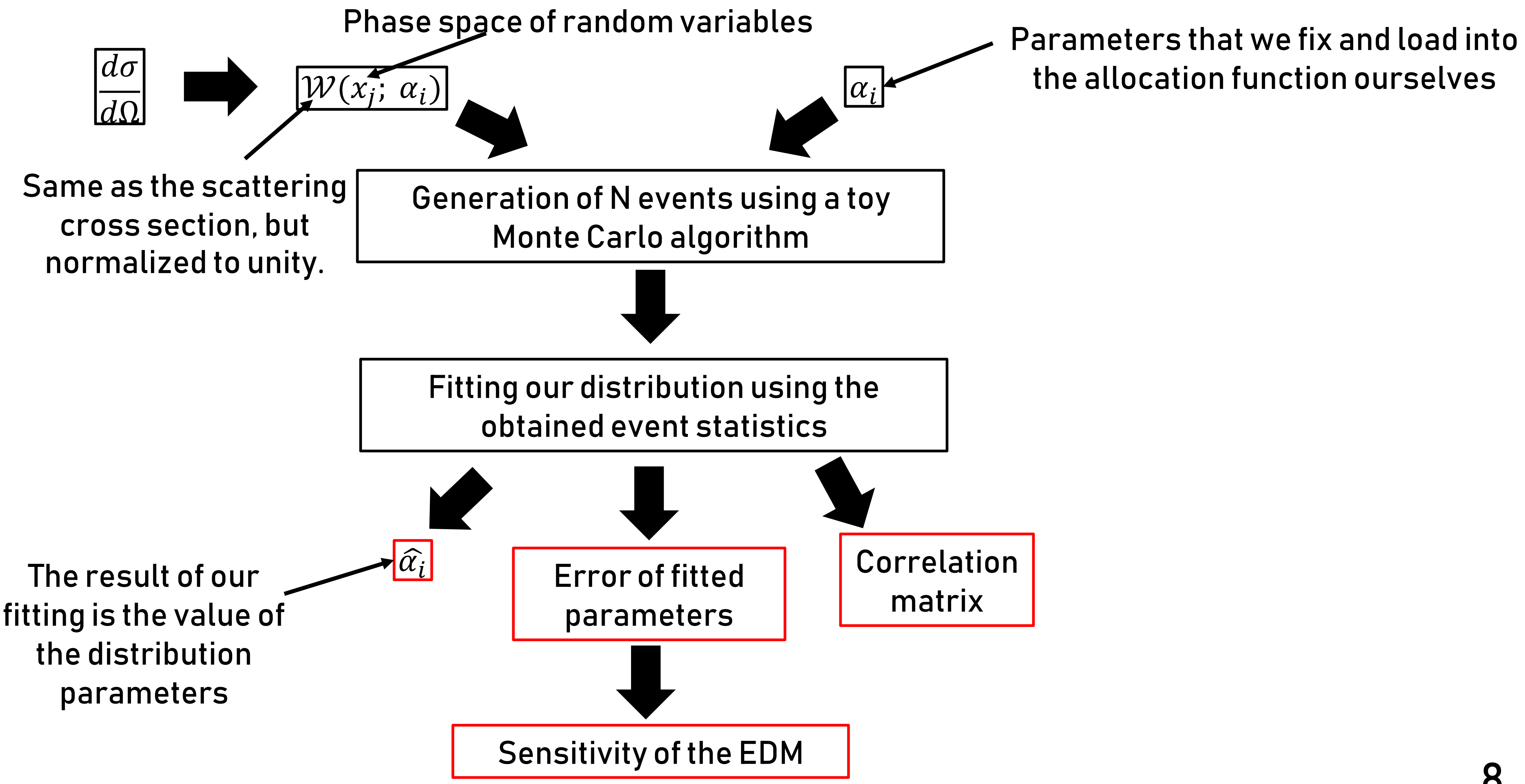
$$\left.\frac{d\sigma}{d\Omega}\right|_{\Lambda_e} = \frac{d\sigma}{d\Omega} + \Delta\left(\frac{d\sigma}{d\Omega}\right)$$

Additional terms in the annihilation cross section at initial electron polarization:

$$\Delta\left(\frac{d\sigma}{d\Omega}\right) = \frac{\beta\Sigma\Lambda_e}{256\pi^2M^2\gamma^2}\left\{\sin\theta\left[\sqrt{1+\alpha_\psi}f_\psi\sin\Delta\Phi_{M3}\left(s_{1,z}s_{2,x} - s_{1,x}s_{2,z}\right) - \sqrt{1+\alpha_\psi}f_\psi\cos\Delta\Phi_{M3}(s_{1,y} - s_{2,y})\right] + \right.$$

$$\left. + \sin\theta\left[\sqrt{1-\alpha_\psi}f_\psi\sin\Delta\Phi_{EM}\left(s_{1,y}s_{2,z} + s_{1,z}s_{2,y}\right) + \sqrt{1-\alpha_\psi}f_\psi\cos\Delta\Phi_{EM}(s_{1,x} + s_{2,x})\right] + \left(1+\alpha_\psi\right)\cos\theta(s_{1,x} + s_{2,x})\right\}$$

Scheme of the Toy Monte-Carlo simulation



Probability density function

Definition of the probability density function:

$$W(\theta_\Lambda, \theta_1, \phi_1, \theta_2, \phi_2; \alpha_\psi, f_\psi, \alpha_+, \alpha_-, \Delta\Phi_{EM}, \Delta\Phi_{M3}) = \frac{1}{\sigma(e^-e^+ \to B\bar{B} \to B_{fin}M\bar{B}_{fin}\bar{M})} \cdot \frac{d\sigma(e^-e^+ \to B\bar{B} \to B_{fin}M\bar{B}_{fin}\bar{M})}{d\cos\theta\, d\Omega_M d\Omega_{\bar{M}}}$$

Definition of the one dimensional probability density function:

$$W(\theta_1) = \frac{1}{2} + \frac{\sqrt{1-\alpha_\psi}}{3+\alpha_\psi} f_\psi \alpha_- \sin(\Delta\Phi_{EM} + \Delta\Phi_{M3}) \cos\theta_1$$

$$W(\theta_2) = \frac{1}{2} - \frac{\sqrt{1-\alpha_\psi}}{3+\alpha_\psi} f_\psi \alpha_+ \sin(\Delta\Phi_{EM} + \Delta\Phi_{M3}) \cos\theta_2$$

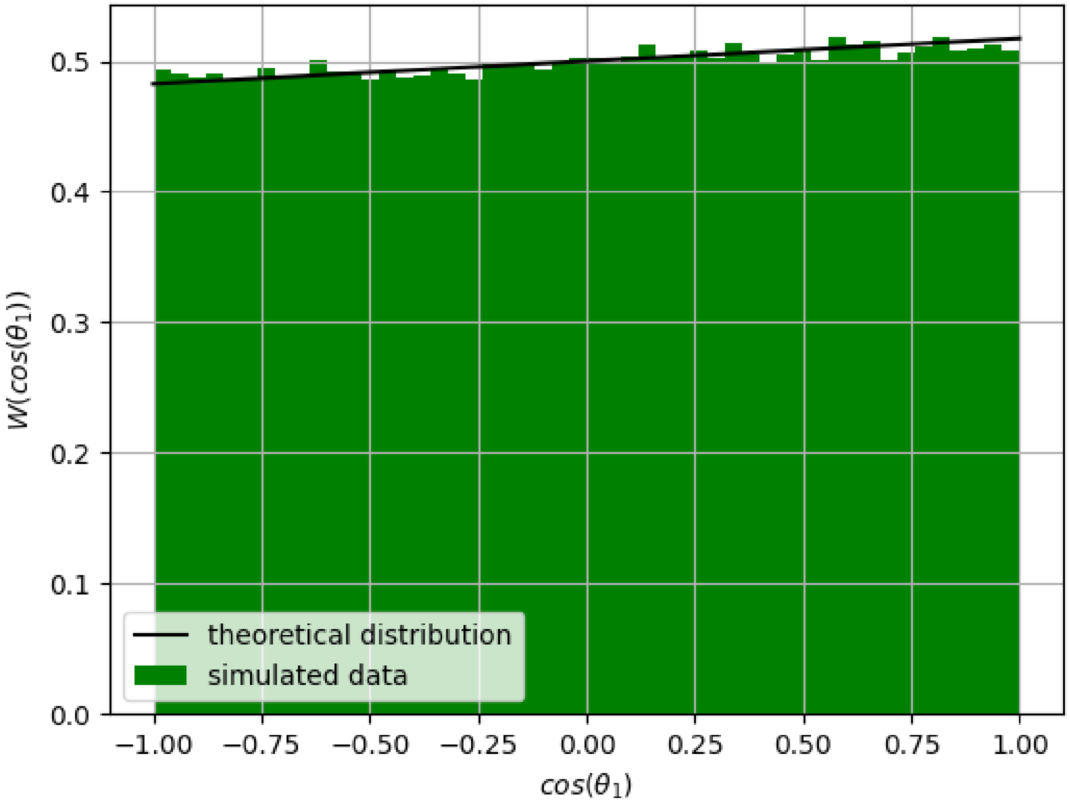
$$W(\phi_1) = \frac{1}{2\pi} + \frac{3\pi\alpha_-\Lambda_e}{32(3+\alpha_\psi)} \left\{ \sqrt{1-\alpha_\psi^2} \cos\Delta\Phi_{EM} \cos\phi_1 - f_\psi \sqrt{1+\alpha_\psi} \cos\Delta\Phi_{M3} \sin\phi_1 \right\}$$

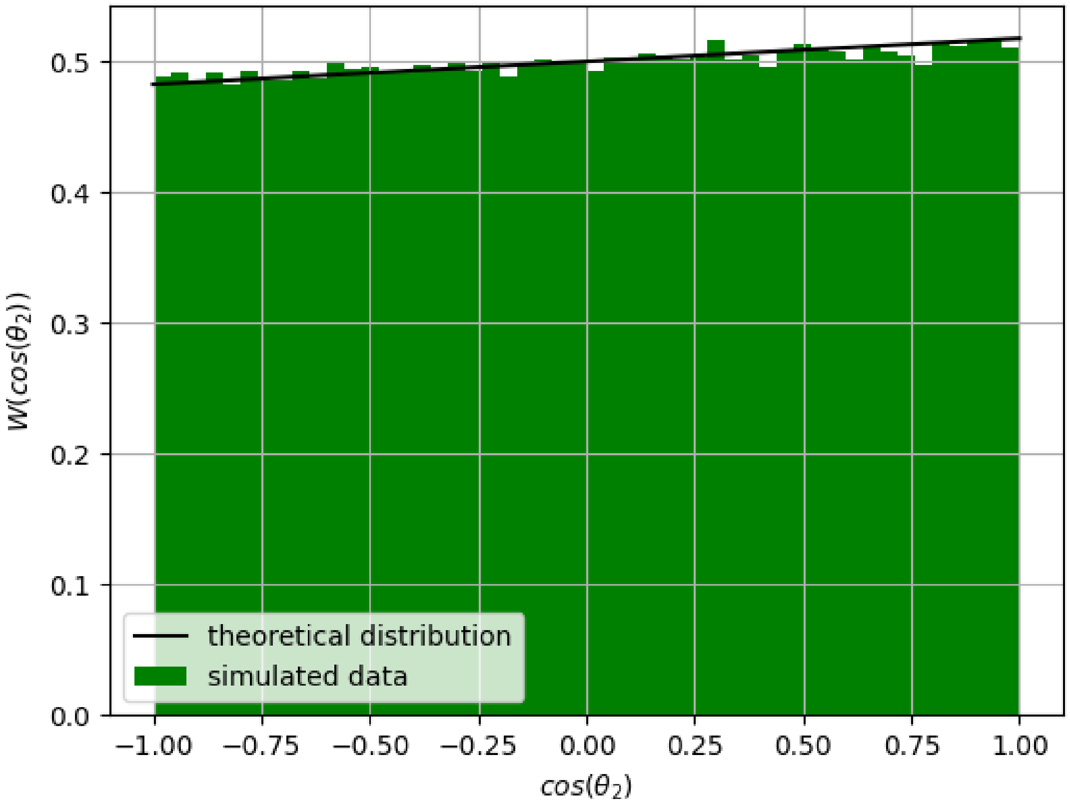
$$W(\phi_2) = \frac{1}{2\pi} + \frac{3\pi\alpha_+\Lambda_e}{32(3+\alpha_\psi)} \left\{ \sqrt{1-\alpha_\psi^2} \cos\Delta\Phi_{EM} \cos\phi_2 + f_\psi \sqrt{1+\alpha_\psi} \cos\Delta\Phi_{M3} \sin\phi_2 \right\}$$

$$W(\theta) = \frac{3(1+\alpha_\psi \cos^2\theta)}{2(3+\alpha_\psi)}$$

Monte-Carlo simulation of the pseudodata

It is for process $e^+e^- \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$





Parameters, which we used:

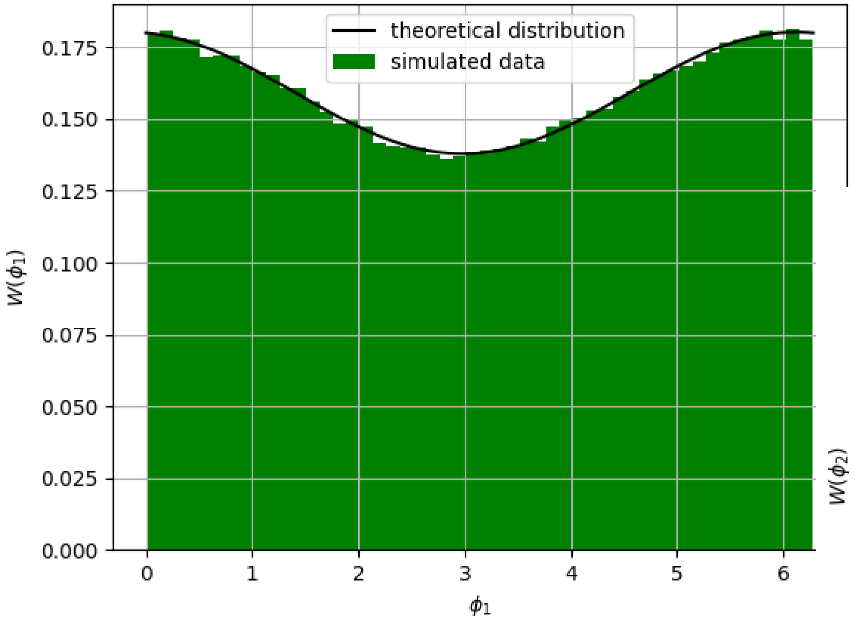
These we know from experiment → $\alpha_\psi = 0.461 \quad \alpha_- = 0.75 \quad \alpha_+ = -0.758 \quad \Delta\Phi_{EM} = 0.74$

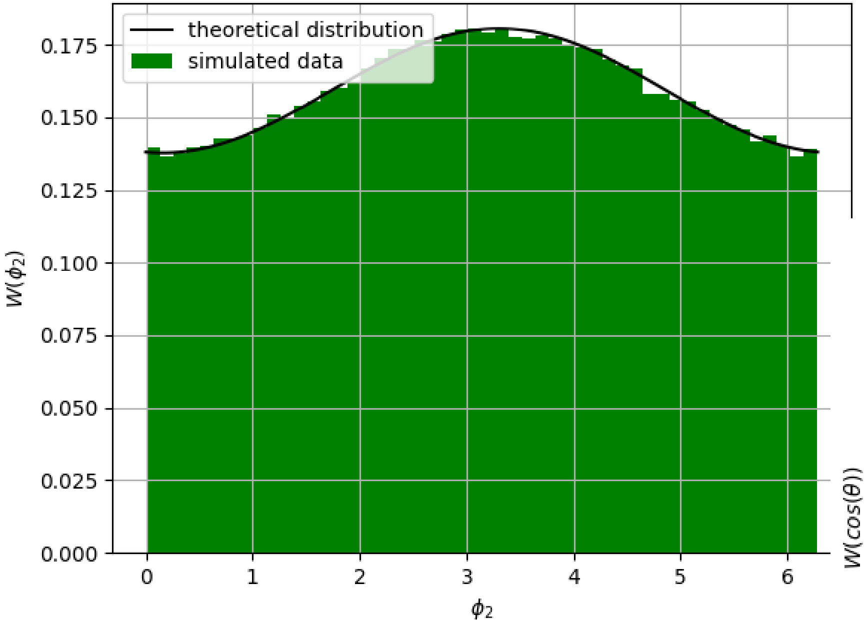
These we don't know → $f_\psi = 0.1 \quad \Delta\Phi_{M3} = 0.5$

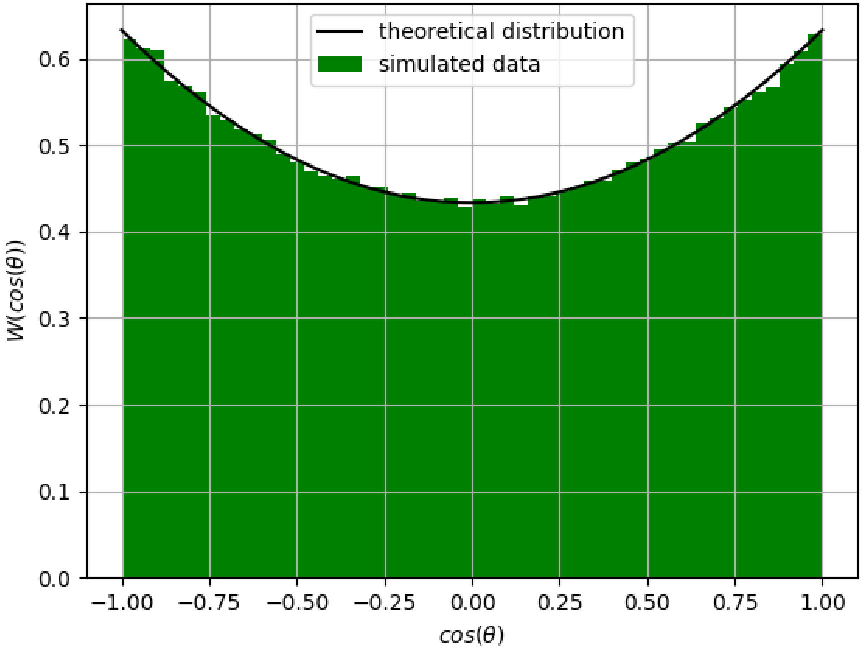
$\Lambda_e = 0.5$ ← This we can vary

Monte-Carlo simulation of the pseudodata

It is for process $e^+e^- \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$







Statistical method of the analysis

Suppose we have the following distribution density function: $f_{\vec{v}}(x_i^j)$

unknown parameters → $\vec{v}$; random variables → x_i^j

$$\mathcal{L}(\vec{v}) = \sum_{j=1}^{N_{MC}} \ln f_{\vec{v}}(x_i^j)$$

maximum likelihood function

$$\left.\frac{\partial \mathcal{L}}{\partial v_a}\right|_{\vec{v}=\vec{v}_{fit}} = 0$$

system of the equations for unknown parameters

covariation matrix

$$V_{ab} = \left(\frac{\partial^2 \mathcal{L}(\vec{v})}{\partial v_a \partial v_b}\right)^{-1}$$

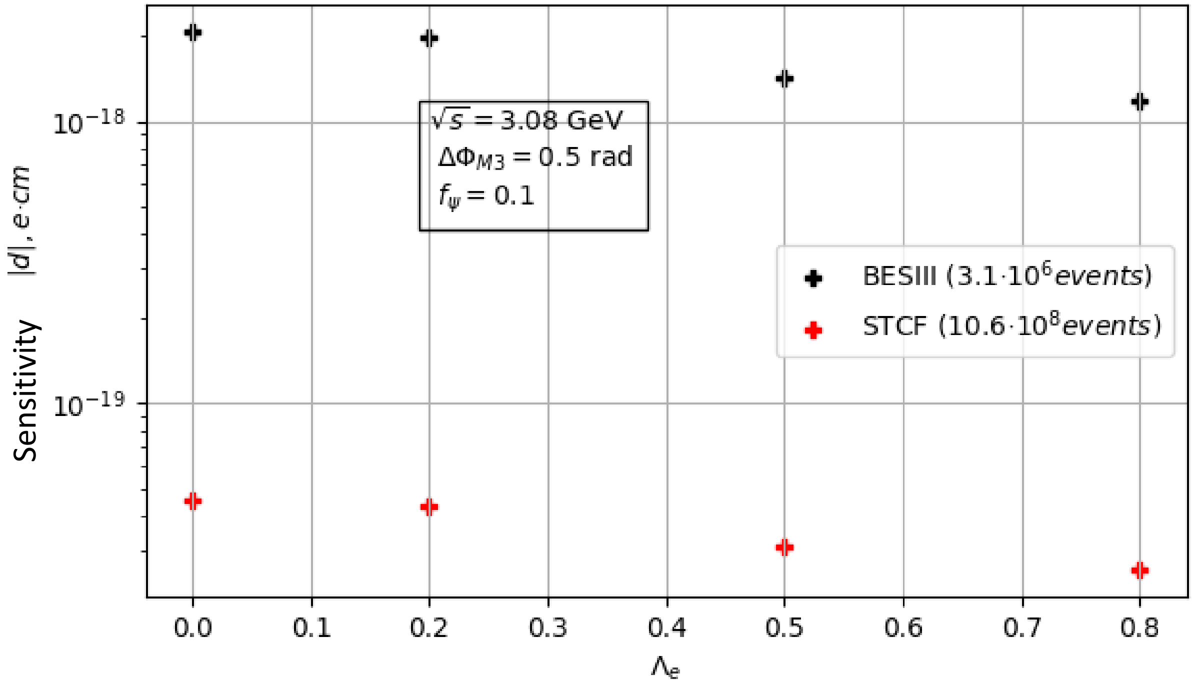
correlation matrix

$$\rho_{ab} = \frac{V_{ab}}{\sqrt{V_{aa}V_{bb}}}$$

standard deviation (error)

$$\sigma_a = \sqrt{V_{aa}}$$

Results ($e^+e^- \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$)



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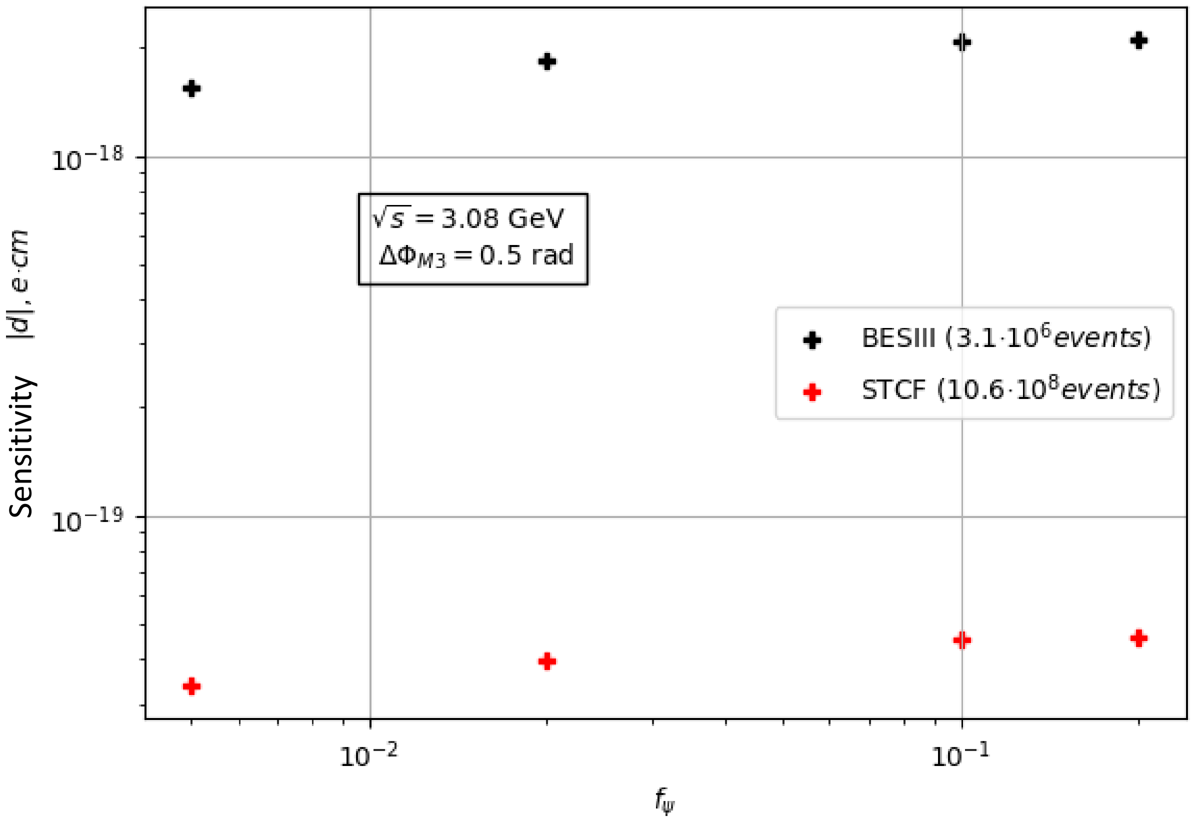
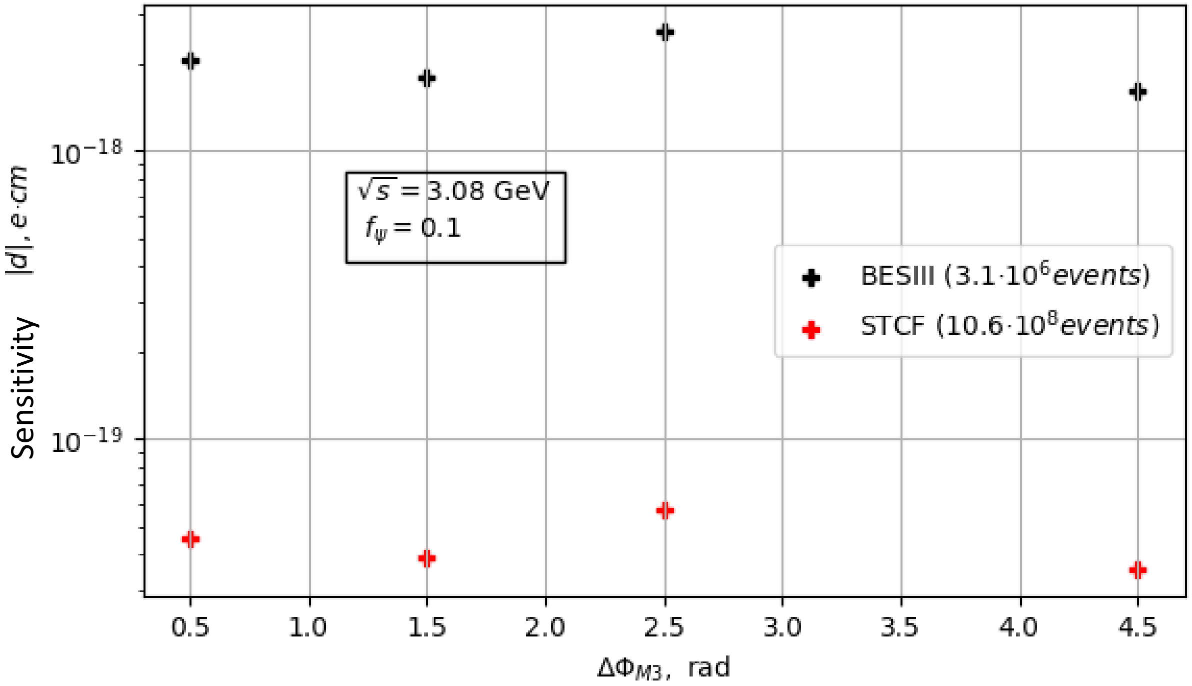
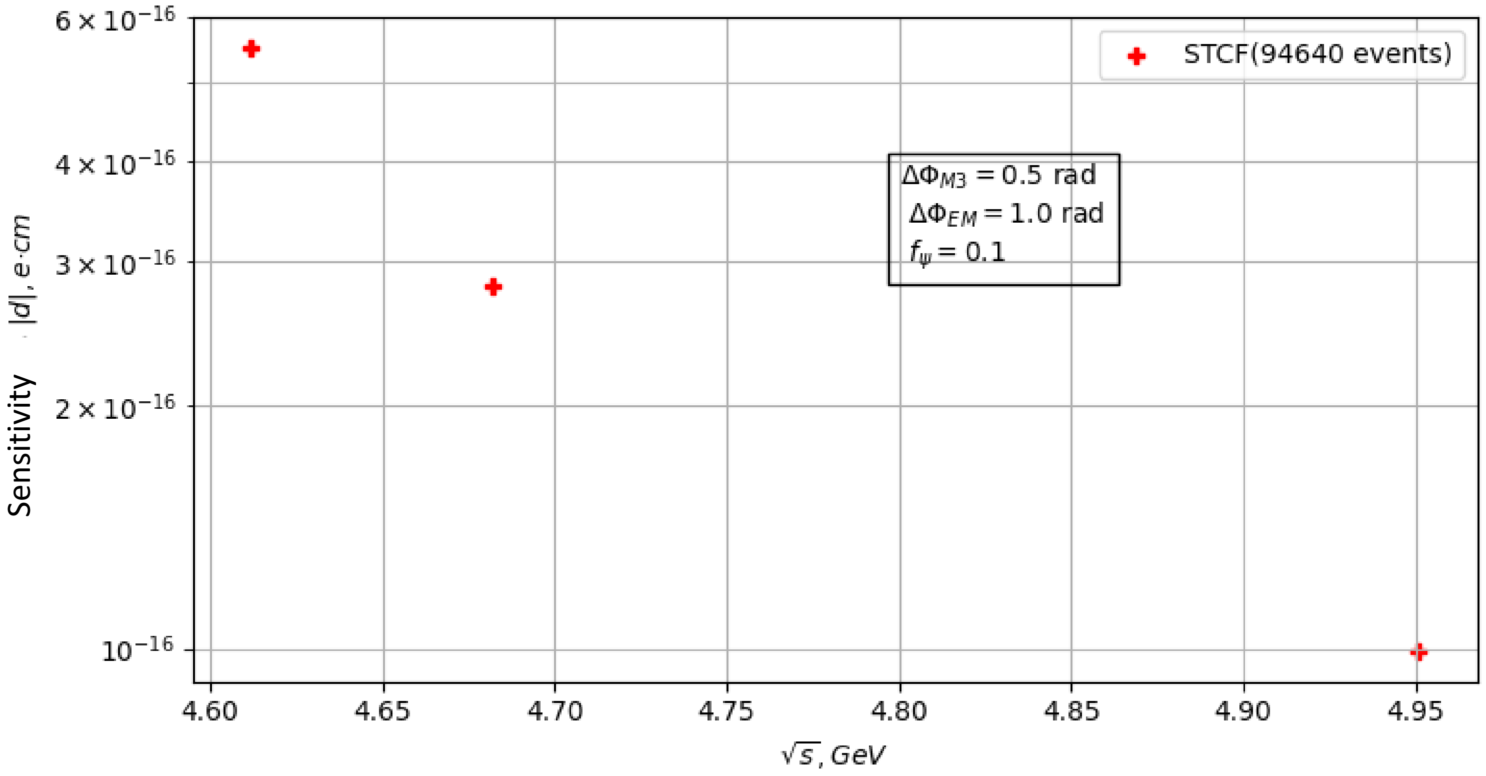
Results ($e^+e^- \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$)





Results ($e^+e^- \to \Lambda_c^+\Lambda_c^- \to \Lambda\pi^+\bar{\Lambda}\pi^-$)



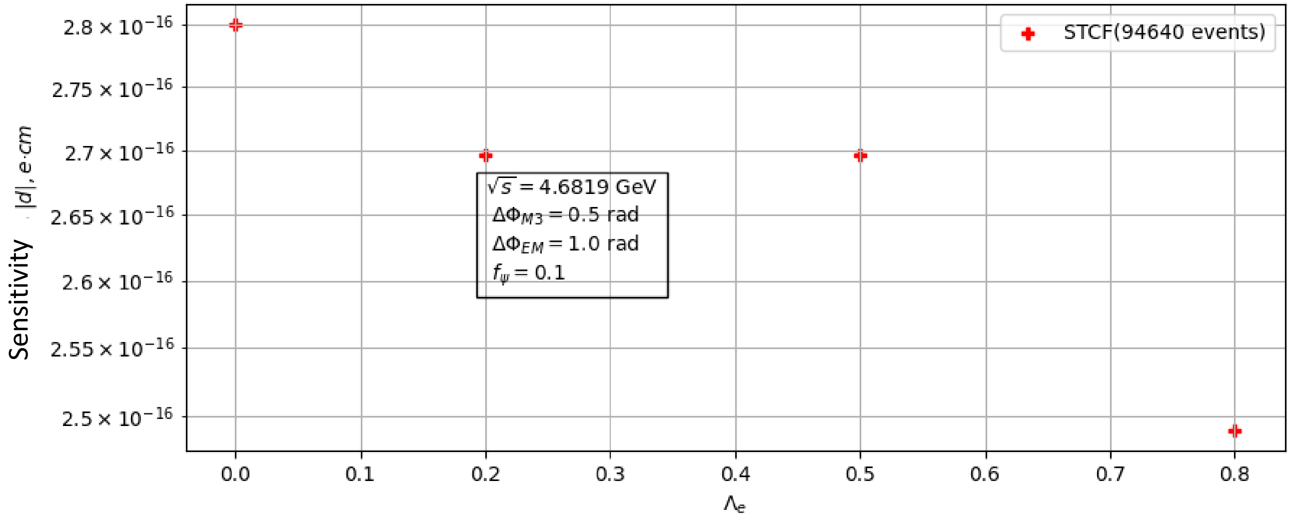
Parameters, which we used:

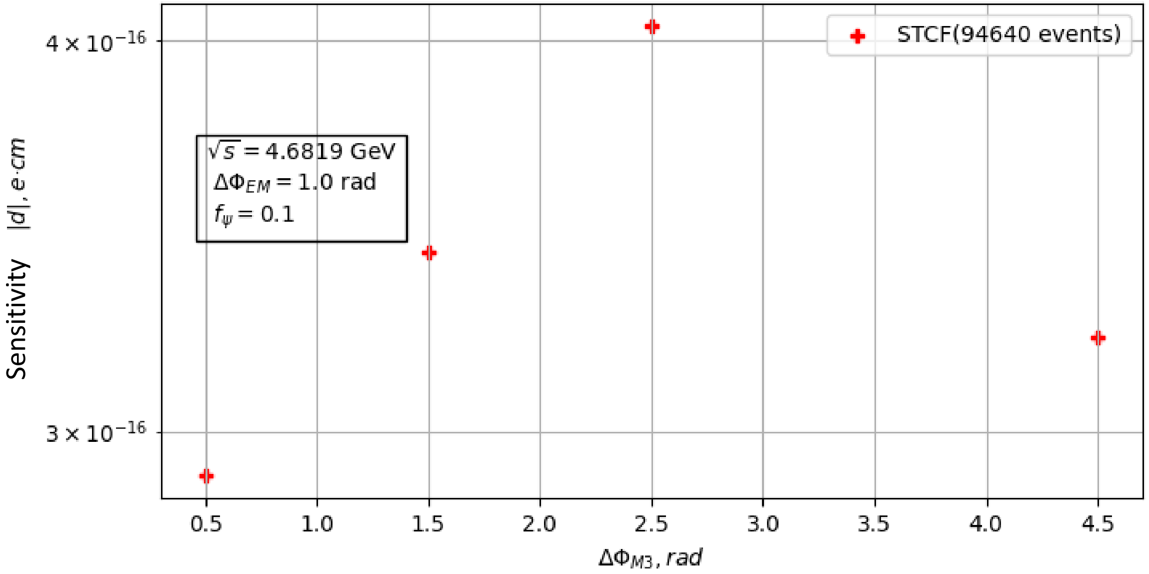
$\alpha_- = 0.75 \quad \alpha_+ = -0.758$

$\sqrt{s}$, GeV	4.6119	4.6819	4.9509
α_ψ	-0.26	0.15	0.63

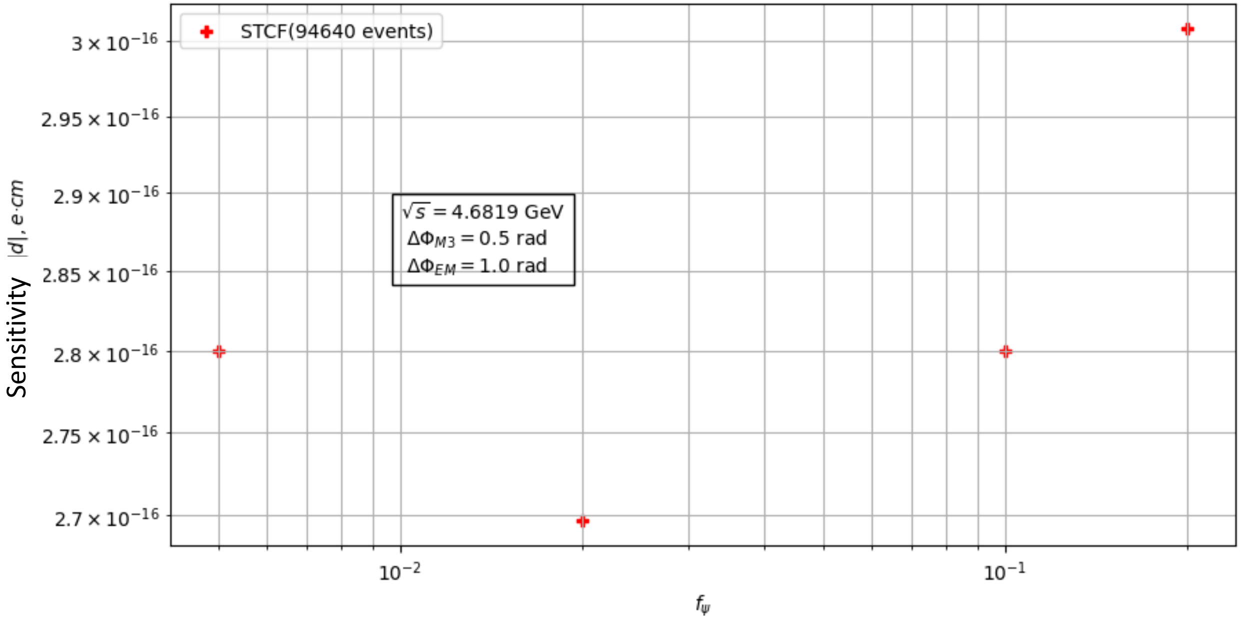
These we know from experiment

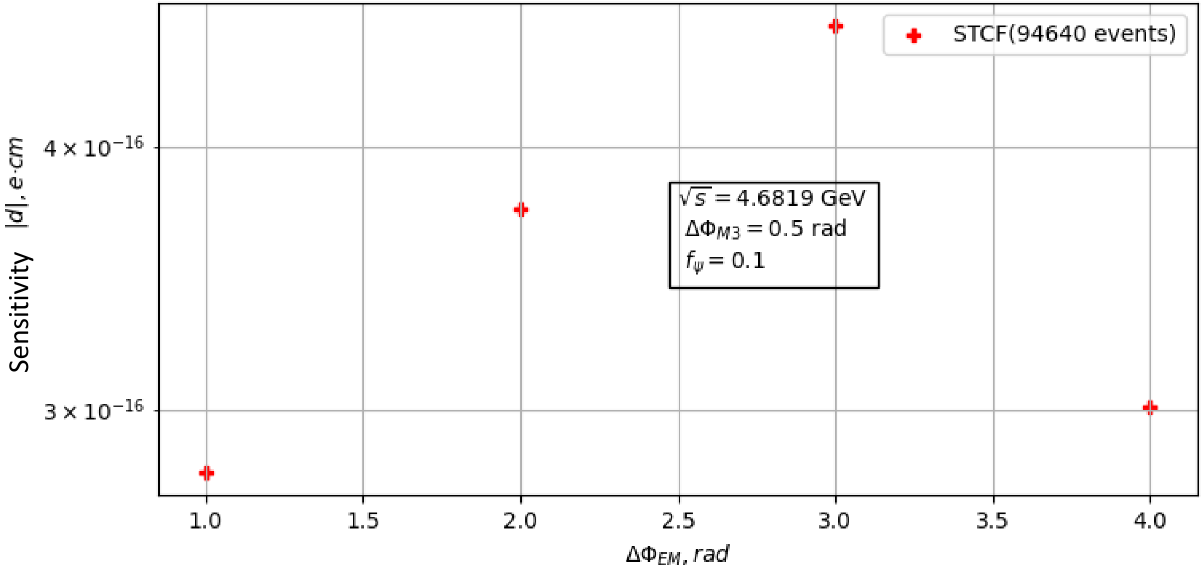
Results ($e^+e^- \to \Lambda_c^+\Lambda_c^- \to \Lambda\pi^+\overline{\Lambda}\pi^-$)





Results $(e^+e^- \to \Lambda_c^+\Lambda_c^- \to \Lambda\pi^+\overline{\Lambda}\pi^-)$





Conclusions

The contribution from the electric dipole moment form factor was added in the consideration of the pairs $\Lambda_c^+\Lambda_c^-$ or $\Lambda\overline{\Lambda}$ birth process.

Also, the initial state with a polarized electron was considered.

With the help of statistical methods the generation of events of decay processes born in the process of annihilation of pairs $\Lambda_c^+\Lambda_c^-$ or $\Lambda\overline{\Lambda}$, and further reconstruction of parameters of the scattering cross section was performed.

This project was realized with the support of a grant from l'Agence Universitaire de la Francophonie in collaboration with IJCLab. Based on the results of this project, the following paper will be published: «Determination of the sensitivity of Λ and Λ_c^+ electric dipole moments using a full angular analysis».