Prospects on the magnetic/electric dipole moment of the tau and polarized beams

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Martin Hoferichter

Albert Einstein Center for Fundamental Physics,
Institute for Theoretical Physics, University of Bern

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2024 Belle II Physics Week, KEK, Tsukuba

Talk by J. Michael Roney at 2024 US Belle II Summer Workshop
https://indico.belle2.org/event/11190/contributions/76575/

The Belle II Detector Upgrades Framework Conceptual Design Report, arXiv:2406.19421

Snowmass 2021 White Paper, Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation, arXiv:2205.12847

Crivellin, MH, Roney PRD 106 (2022) 093007

Gogniat, MH, Ulrich work in progress

Why do we need a polarized electron beam?

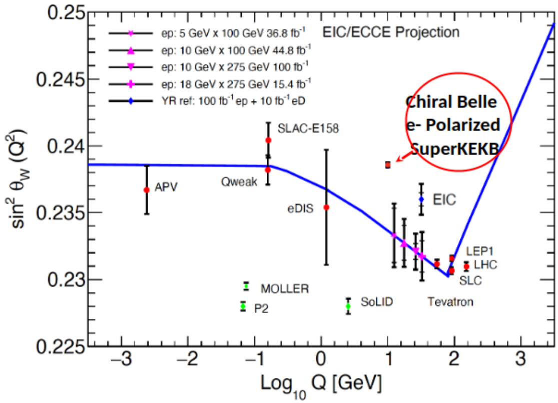


Figure adapted from Boughezal et al. 2022, used in EIC Snowmass paper 2203.13199

- Main motivation: **precision neutral-current electroweak program**
  - With 40 ab^{-1}, $\Delta\sin^2\theta_W = 0.00018$ (combined leptons)
    $\hookrightarrow$ same precision as Z-pole measurements, but at $s \simeq (10\,\text{GeV})^2$!
  - Precision probe of running of $\sin^2\theta_W$, complementary to MOLLER, P2, ...
  - Probes e, μ, τ, c, b couplings, not "just" first generation

Left-right asymmetries

	SM	LEP+SLAC	Chiral Belle Δg_V^f			$\Delta \sin^2\theta_W$
f	$g_V^f(M_Z)$	g_V^f	1 ab^{-1}	20 ab^{-1}	40 ab^{-1}	40 ab^{-1}
b	$-0.3437(1)$	$-0.3220(77)$	0.0022	0.002	0.002	0.003
c	0.1920(2)	0.1873(70)	0.0036	0.001	0.001	0.0008
τ	$-0.0371(3)$	$-0.0366(10)$	0.0049	0.001	0.0008	0.0004
μ	$-0.0371(3)$	$-0.03667(23)$	0.0031	0.0007	0.0005	0.0003
e	$-0.0371(3)$	$-0.03816(47)$	0.0039	0.0009	0.0006	0.0003

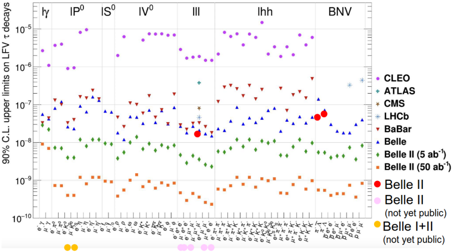
ICHEP talk by Roney

- **Vector couplings** from Z–γ interference

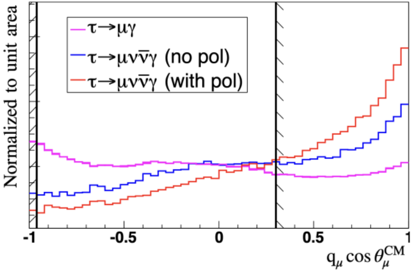
$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_F s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle \text{Pol} \rangle \qquad g_V^f = T_3^f - 2Q_f \sin^2\theta_W$$

- Major improvements for 2nd and 3rd generation, by factors $\{4,6,3\}$ for $\{b,c,\mu\}$
- Average of $\{e,\mu,\tau\}$ for $\sin^2\theta_W$ same precision as Z-pole measurements
- Universality of g_V^f even better tested because dominant $\langle\text{Pol}\rangle$ uncertainty cancels

Polarization upgrade: broader physics program



talk by S. Prell



2205.12847

- Improved sensitivity to **lepton-flavor-violating decays**: $\tau \to \mu\gamma$ and $\tau \to e\gamma$

  $\hookrightarrow$ e^- beam polarization helps reduce backgrounds

- Improved precision measurements of **τ Michel parameters**
- Precision QCD studies
- **Dipole moments of the τ**
  - Anomalous magnetic moment a_τ via Pauli form factor $F_2(s)$ at $s \simeq (10\,\text{GeV})^2$
  - EDM d_τ via $F_3(s)$ at $s \simeq (10\,\text{GeV})^2$

  $\hookrightarrow$ focus of this talk

Definition of dipole moments and form factors

EFT definition

$$\mathcal{L}_{\text{dipole}} = -c_R^{\ell\ell}\bar{\ell}\sigma^{\mu\nu}P_R\ell F_{\mu\nu} + \text{h.c.} \qquad P_R = \frac{\mathbb{1}+\gamma_5}{2} \qquad \ell \in \{e,\mu,\tau\}$$

$$a_\ell = -\frac{4m_\ell}{e}\text{Re}\, c_R^{\ell\ell} \qquad d_\ell = -2\,\text{Im}\, c_R^{\ell\ell}$$

- **Hermiticity** leaves only two dipole structures

  $\hookrightarrow$ a_ℓ, d_ℓ real quantities by definition

- But PDG lists limits Belle 2022

$$\text{Re}\, d_\tau = -0.62(63)\times 10^{-17}\, e\,\text{cm} \qquad \text{Im}\, d_\tau = -0.40(32)\times 10^{-17}\, e\,\text{cm}$$

$\hookrightarrow$ to understand what's going on need to look at **form factors**

Electromagnetic form factors

Form factors

$$\langle p'|j^\mu_{\text{em}}|p\rangle = e\,\bar{u}(p')\left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m_\ell}F_2(q^2) + \frac{\sigma^{\mu\nu}q_\nu\gamma_5}{2m_\ell}F_3(q^2) + \left(\gamma^\mu - \frac{2m_\ell q^\mu}{q^2}\right)\gamma_5 F_4(q^2)\right]u(p)$$

$$F_1(0) = 1 \qquad F_2(0) = a_\ell \qquad F_3(0) = \frac{2m_\ell}{e}d_\ell \qquad F_4(0) = \text{anapole moment} \qquad q = p' - p$$

- At $e^+e^- \to \tau^+\tau^-$, don't measure $F_i(0)$, but $F_i(s)$ with $s \simeq (10\,\text{GeV})^2$

  $\hookrightarrow$ $F_i(s)$ can develop an imaginary part!

- Limits should read (strictly speaking)

$$\frac{e}{2m_\tau}\text{Re}\,F_3(s) = -0.62(63)\times 10^{-17}\,e\,\text{cm} \qquad \frac{e}{2m_\tau}\text{Im}\,F_3(s) = -0.40(32)\times 10^{-17}\,e\,\text{cm}$$

- Still interesting because of EFT: heavy new physics decouples

  $\hookrightarrow$ $\text{Re}\,F_3(s) \simeq d_\tau$ if $M^2_{\text{BSM}} \gg s$

- Imaginary part not related to EDM

Current limits for τ EDM

- Idea: write $e^+e^- \to \tau^+\tau^-$ matrix element as

$$\mathcal{M}^2 = \mathcal{M}^2_{\text{SM}} + \text{Re}\, d_\tau \mathcal{M}^2_{\text{Re}} + \text{Im}\, d_\tau \mathcal{M}^2_{\text{Im}} + \cancel{|d_\tau|^2 \mathcal{M}^2_{d^2}}$$

- ***CP*-odd terms**

$$\mathcal{M}^2_{\text{Re}} \propto (\mathbf{S}_+ \times \mathbf{S}_-) \cdot \hat{\mathbf{k}}, \quad (\mathbf{S}_+ \times \mathbf{S}_-) \cdot \hat{\mathbf{p}}$$
$$\mathcal{M}^2_{\text{Im}} \propto (\mathbf{S}_+ - \mathbf{S}_-) \cdot \hat{\mathbf{k}}, \quad (\mathbf{S}_+ - \mathbf{S}_-) \cdot \hat{\mathbf{p}}$$

  with $\tau^\pm$ spin vectors $\mathbf{S}_\pm$ and CMS momenta $\hat{\mathbf{k}}$ (τ^-), $\hat{\mathbf{p}}$ (e^-)

- Problem: cannot reconstruct $\mathbf{S}_\pm$ and $\hat{\mathbf{k}}$ exactly due to neutrinos

  $\hookrightarrow$ method of optimal observables, need to vary $m_{\nu\nu}$

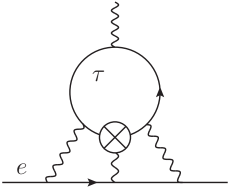
- Includes average over $e\mu$, $e\pi$, $\mu\pi$, $e\rho$, $\mu\rho$, $\pi\rho$, $\rho\rho$, $\pi\pi$ channels

Indirect limits for τ EDM and future improvements

- Another EFT argument: d_τ generates contribution to d_e
  - ThO: $d_e \leq 1.1 \times 10^{-29}\, e\,\text{cm}$ Andreev et al. 2018
  - HfF$^+$: $d_e \leq 4.1 \times 10^{-30}\, e\,\text{cm}$ Roussy et al. 2023

  via 3-loop diagram Grozin, Khriplovich, Rudenko 2009

$$d_\tau \leq \left[\left(\frac{15}{4}\zeta(3) - \frac{31}{12}\right)\frac{m_e}{m_\tau}\left(\frac{\alpha}{\pi}\right)^3\right]^{-1} d_e$$
$$= \{1.6 \times 10^{-18}, 5.9 \times 10^{-19}\}\, e\,\text{cm}$$



- For d_τ, no changes due to d_e vs. d_e^{equiv} in ThO (and likely HfF) molecule due to $1/m_\tau^3$ scaling Ema, Gao, Pospelov 2022
- Limit can be evaded by cancellation with other d_τ source

  $\hookrightarrow$ need to check explicitly
- Projections for Belle II:
  - $50\,\text{ab}^{-1}$, no polarization: $d_\tau \simeq 10^{-19}\, e\,\text{cm}$
  - With polarization: $d_\tau \simeq 10^{-20}\, e\,\text{cm}$, **how?**

What about the magnetic dipole moment?

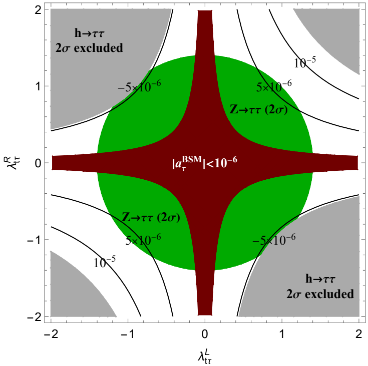
- Current status:

$-0.052 < a_\tau < 0.013$ 95% CL DELPHI 2004

$-0.057 < a_\tau < 0.024$ 95% CL ATLAS 2023

$-0.088 < a_\tau < 0.056$ 68% CL CMS 2023

- Points of comparison:
  - SM prediction Keshavarzi et al. 2020:
    $a_\tau^{\text{SM}} = 1{,}177.171(39) \times 10^{-6}$
  - Schwinger term:
    $a_\tau^{\text{1-loop QED}} = \frac{\alpha}{2\pi} = 1.16141\ldots \times 10^{-3}$
  - Electroweak contribution: $a_\tau^{\text{EW}} \simeq 0.5 \times 10^{-6}$
  - Concrete models: S_1 leptoquark model promising due to **chiral enhancement** with $\frac{m_t}{m_\tau}$
    $\hookrightarrow$ can get $a_\tau^{\text{BSM}} \simeq (\text{few}) \times 10^{-6}$ without violating $h \to \tau\tau$ and $Z \to \tau\tau$



Crivellin, MH, Roney 2021

- Can one probe the interesting range at Belle II?

Why do we care about tau dipole moments?

- **Interplay with electron and muon**:
  - Already stringent limits on d_e from atomic systems
    $\hookrightarrow$ will further improve in the future
  - Current limit on $d_\mu < 1.8 \times 10^{-19} e\,\text{cm}$ BNL 2009
    $\hookrightarrow$ will improve in the next years with new experiments Fermilab, J-PARC, PSI
  - a_e to be probed at 10^{-13}, limited by tension in $\alpha(\text{Cs})$ and $\alpha(\text{Rb})$
    $\hookrightarrow$ improved atom interferometry experiments ongoing
  - a_μ to be probed at 10^{-10} Fermilab 2025, J-PARC 2028–, limited by tensions in HVP
    $\hookrightarrow$ theory effort ongoing to resolve this
- Comparing a_ℓ, d_ℓ, for all $\ell = \{e, \mu, \tau\}$ reveals hints about **flavor structure**
  $\hookrightarrow$ scaling with lepton masses, complex phases, lepton flavor universality
- Rest of the talk: how would polarization at Belle II help in constraining d_τ, a_τ?
  $\hookrightarrow$ look at cross section and asymmetries for **general $\gamma^*\tau\tau$ vertex**

First attempt: total cross section

Differential cross section for $e^+e^- \to \tau^+\tau^-$ with general $\gamma^*\tau\tau$ vertex

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta}{4s}\Big[(2-\beta^2\sin^2\theta)\Big(|F_1|^2-\gamma^2|F_2|^2\Big)+4\text{Re}\,(F_1F_2^*)+2(1+\gamma^2)|F_2|^2+\beta^2\gamma^2\sin^2\theta|F_3|^2\Big]$$

with scattering angle θ, $\beta=\sqrt{1-4m_\tau^2/s}$, $\gamma=\sqrt{s}/(2m_\tau)$

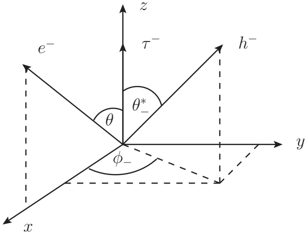
- Interference term $4\text{Re}\,(F_1F_2^*)$ in principle provides sensitivity to $F_2(s)$
- Same EFT argument as for d_τ: $\text{Re}\,F_2(s)=\text{Re}\,F_2^{\text{SM}}(s)+a_\tau^{\text{BSM}}$ if $M_{\text{BSM}}^2 \gg s$
- Could be determined by fit to θ dependence
- But: need to measure total cross section at 10^{-5} (at least)

  $\hookrightarrow$ **can we use asymmetries instead**?
- Usual forward–backward asymmetry ($z=\cos\theta$)

$$\sigma_{\text{FB}} = 2\pi\bigg[\int_0^1 dz\frac{d\sigma}{d\Omega}-\int_{-1}^0 dz\frac{d\sigma}{d\Omega}\bigg]$$

  alone does not help

Second attempt: τ polarization



- Idea: use **polarization information of the $\tau^\pm$**

  $\hookrightarrow$ semileptonic decays $\tau^\pm \to h^\pm \overset{(-)}{\nu}_\tau$, $h = \pi, \rho, a_1, \ldots$

  Bernabéu et al. 2007–2009

- Polarization characterized by

$$\mathbf{n}^*_\pm = \mp\alpha_\pm \begin{pmatrix} \sin\theta^*_\pm \cos\phi_\pm \\ \sin\theta^*_\pm \sin\phi_\pm \\ \cos\theta^*_\pm \end{pmatrix} \qquad \alpha_\pm \equiv \begin{cases} 1 & h^\pm = \pi^\pm \\ \frac{m_\tau^2 - 2m_{h^\pm}^2}{m_\tau^2 + 2m_{h^\pm}^2} = \begin{cases} 0.45 & h^\pm = \rho^\pm \\ 0.02 & h^\pm = a_1^\pm \end{cases} \end{cases}$$

  $\hookrightarrow$ angles in $\tau^\pm$ rest frame

- Can get additional information when separating L, T components of ρ, a_1

- Construct asymmetries from **spin-dependent cross section**

Second attempt: normal asymmetry

Spin-dependent cross section for $e^+e^- \to \tau^+\tau^-$ with general $\gamma^*\tau\tau$ vertex

$$\frac{d\sigma^S}{d\Omega} = \frac{\alpha^2\beta}{8s}\Big[(s_- - s_+)_x X_- + (s_- + s_+)_y Y_+ + (s_- - s_+)_z Z_-\Big]$$

$$X_- = \beta\gamma\sin\theta\cos\theta\Big[\text{Im}\,(F_3F_1^*) + \text{Im}\,(F_3F_2^*)\Big] \qquad Z_- = -\beta\sin^2\theta\Big[\text{Im}\,(F_3F_1^*) + \gamma^2\text{Im}\,(F_3F_2^*)\Big]$$

$$Y_+ = \beta^2\gamma\cos\theta\sin\theta\,\text{Im}\,(F_2F_1^*)$$

- **Normal asymmetry**

$$A_N^\pm = \frac{\sigma_L^\pm - \sigma_R^\pm}{\sigma_{\text{tot}}} = \pm\alpha_\pm\frac{\pi\alpha^2\beta^3\gamma}{3s\sigma_{\text{tot}}}\text{Im}\,(F_2F_1^*) \qquad \sigma_L^\pm = \int_\pi^{2\pi} d\phi_\pm\frac{d\sigma_{\text{FB}}}{d\phi_\pm} \quad \sigma_R^\pm = \int_0^\pi d\phi_\pm\frac{d\sigma_{\text{FB}}}{d\phi_\pm}$$

  ↪ only get access to Im F_2

- Can also project out Im F_3, but neither one tests a_τ or d_τ (in the EFT sense above)

  ↪ need **electron polarization**

Third attempt: electron polarization

Polarized cross section for $e^+e^- \to \tau^+\tau^-$ with general $\gamma^*\tau\tau$ vertex

$$\frac{d\sigma^{S\lambda}}{d\Omega} = \frac{\alpha^2\beta\lambda}{16s}\Big[(s_- + s_+)_x X_+ + (s_- - s_+)_y Y_- + (s_- + s_+)_z Z_+\Big]$$

$$X_+ = \frac{\sin\theta}{\gamma}\Big[|F_1|^2 + (1+\gamma^2)\mathrm{Re}\,(F_2F_1^*) + \gamma^2|F_2|^2\Big] \qquad Z_+ = \cos\theta\,|F_1 + F_2|^2$$

$$Y_+ = -\beta\gamma\sin\theta\Big[\mathrm{Re}\,(F_3F_1^*) + \mathrm{Re}\,(F_3F_2^*)\Big]$$

- Can now construct helicity difference

$$d\sigma^S_{\text{pol}} = \frac{1}{2}\Big(d\sigma^{S\lambda}\big|_{\lambda=1} - d\sigma^{S\lambda}\big|_{\lambda=-1}\Big)$$

- The normal asymmetry with $d\sigma_{\text{FB}} \to d\sigma^S_{\text{pol}}$ in $\sigma^\pm_L$, $\sigma^\pm_R$ gives

$$A_N^\pm = \frac{\sigma_L^\pm - \sigma_R^\pm}{\sigma_{\text{tot}}} = \alpha_\pm\frac{\pi^2\alpha^2\beta^2\gamma}{4s\sigma_{\text{tot}}}\Big[\mathrm{Re}\,(F_3F_1^*) + \mathrm{Re}\,(F_3F_2^*)\Big]$$

$\hookrightarrow$ provides access to d_τ!

Third attempt: electron polarization

- To isolate a_τ, consider **transverse and longitudinal asymmetries** Bernabéu et al. 2007

$$A_T^\pm = \frac{\sigma_R^\pm - \sigma_L^\pm}{\sigma_{\text{tot}}} \qquad A_L^\pm = \frac{\sigma_{\text{FB},\,R}^\pm - \sigma_{\text{FB},\,L}^\pm}{\sigma_{\text{tot}}}$$

  defined via

$$\sigma_R^\pm = \int_{-\pi/2}^{\pi/2} d\phi_\pm \frac{d\sigma_{\text{pol}}^S}{d\phi_\pm} \qquad \sigma_L^\pm = \int_{\pi/2}^{3\pi/2} d\phi_\pm \frac{d\sigma_{\text{pol}}^S}{d\phi_\pm} \qquad \sigma_{\text{FB},\,R}^\pm = \int_0^1 dz_\pm^* \frac{d\sigma_{\text{FB, pol}}^S}{dz_\pm^*} \qquad \sigma_{\text{FB},\,L}^\pm = \int_{-1}^0 dz_\pm^* \frac{d\sigma_{\text{FB, pol}}^S}{dz_\pm^*}$$

- Linear combination

$$A_T^\pm - \frac{\pi}{2\gamma} A_L^\pm = \mp\alpha_\pm \frac{\pi^2\alpha^2\beta^3\gamma}{4s\sigma_{\text{tot}}}\Big[\text{Re}\,(F_2 F_1^*) + |F_2|^2\Big]$$

  gives access to a_τ

How to make use of this in practice?

Contributions to $\text{Re}\, F_2^{\text{eff}}(s) \times 10^6$	$s=0$	$s=(10\,\text{GeV})^2$
1-loop QED	1161.41	−265.90
e loop	10.92	−2.43
μ loop	1.95	−0.34
2-loop QED (mass independent)	−0.42	−0.24
HVP	3.33	−0.33
EW	0.47	0.47
total	1177.66	−268.77

$$\text{Re}\, F_2^{\text{eff}}((10\,\text{GeV})^2) \simeq \mp \frac{0.73}{\alpha_\pm}\Big(A_T^\pm - 0.56 A_L^\pm\Big)$$

- **Strategy**:
  - Measure effective $F_2(s)$

$$\text{Re}\, F_2^{\text{eff}} = \mp \frac{8(3-\beta^2)}{3\pi\gamma\beta^2\alpha_\pm}\Big(A_T^\pm - \frac{\pi}{2\gamma}A_L^\pm\Big) \qquad \sigma_{\text{tot}} \simeq \frac{2\pi\alpha^2\beta(3-\beta^2)}{3s}$$

  - Compare measurement to SM prediction for $\text{Re}\, F_2^{\text{eff}}$, difference gives constraint on a_τ^{BSM}
  - A measurement of $A_T^\pm - \frac{\pi}{2\gamma}A_L^\pm$ at $\lesssim 1\%$ would already be competitive with current limits
  - Detector systematics cancel in asymmetries

    $\hookrightarrow$ polarization largest uncertainty, but $\lesssim 0.5\% \times \text{Re}\, F_2^{\text{eff}}(s) \simeq 1 \times 10^{-6}$

How to make use of this in practice?

- **Challenges (experiment)**:
  - Cancellation in $A_T^\pm - \frac{\pi}{2\gamma} A_L^\pm$: $A_{T,L}^\pm = \mathcal{O}(1)$, difference $\mathcal{O}(\alpha)$
    $\hookrightarrow$ need m_τ and $M_{\Upsilon(1S)}$ at same level as target precision for a_τ
  - With 40 ab^{-1} and 60% selection efficiency, 10^{-5} for Re F_2^{eff} realistic
    $\hookrightarrow$ Snowmass 2205.12847 also gives a formulation of Re F_2^{eff} in terms of count rates
  - Beyond 10^{-5}, need more statistics and m_τ, $M_{\Upsilon(1S)}$
- **Challenges (theory)**:
  - Form factor only dominates for resonant $\tau^+\tau^-$ pairs

$$|H(M_\Upsilon)|^2 = \left(\frac{3}{\alpha}\text{Br}(\Upsilon \to e^+e^-)\right)^2 \simeq 100$$

  - However: continuum pairs dominate even at $\Upsilon(nS)$, $n = 1, 2, 3$, due to energy spread
  - Need to consider $A_T^\pm$, $A_L^\pm$ also for nonresonant $\tau^+\tau^-$, requires full calculation of $e^+e^- \to \tau^+\tau^-$ including box diagrams
  - Ultimately, need two-loop accuracy
- Next slides: first results for implementation in MC integrator McMule

What is McMule?

McMule

Fixed-order NNLO QED framework Monte Carlo for MUons and other LEptons

- Provided: matrix elements by McMule or others
- Output: **physical cross section** for any physical observable
- McMule: phase space generation, subtraction, stabilization, integration, event generation, etc.
- All leptonic $2 \to 2$ processes in QED at NNLO (+ a few others)
- Stable public version is an integrator
- Generator on development branch

McMule

Get the code here: `https://mule-tools.gitlab.io`

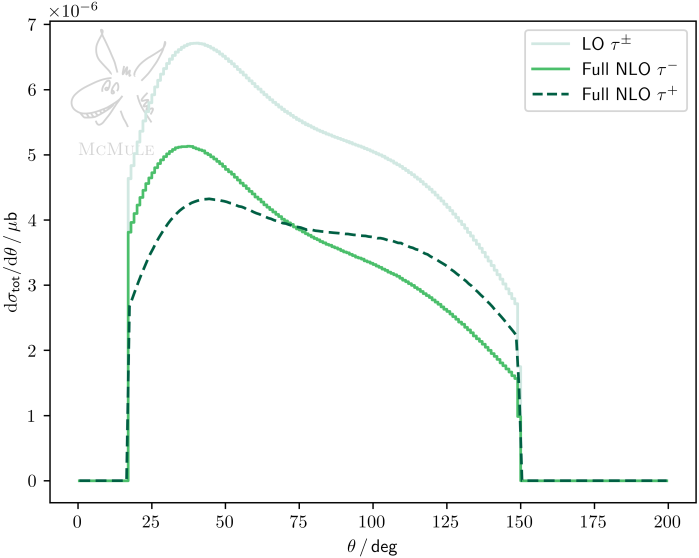
Read the docs here: `https://mcmule.readthedocs.io`

Further reading: 1811.06461, 1909.10244, 2007.01654, 2112.07570, 2212.06481

Processes in McMule

Process	Experiment	Physics motivation	Order
$e\mu \to e\mu$	MUonE	HVP to $(g-2)_\mu$	NNLO+
$\ell p \to \ell p$	P2, MUSE, PRad, QWeak, ...	proton radius and weak charge	NNLO
$eN \to eN$	PRad, ULQ2	background	NNLO−
$e^-e^- \to e^-e^-$	PRad 2	normalization	NNLO
	MOLLER, ...	$\sin^2\theta_W$ at low Q^2	
$e^+e^- \to e^+e^-$	any e^+e^- collider	luminosity measurement	NNLO
$\boldsymbol{ee \to \ell\ell}$	VEPP, BES, DAΦNE, ...	R-ratio	NNLO+
	Belle II	**τ properties**	
$ee \to \gamma\gamma$	DAΦNE	dark searches	NNLO−
	any e^+e^- collider	luminosity measurement	
$e\nu \to e\nu$	DUNE	flux & $\sin^2\theta_W$	NNLO−
$\mu \to \nu\bar{\nu}e$	MEG	ALP searches	NNLO+
	DUNE	beam-line profiling	
$\mu \to \nu\bar{\nu}e\gamma$	MEG, Mu3e, PIONEER	background	NLO
$\mu \to \nu\bar{\nu}eee$	MEG, Mu3e	background	NLO
$ee \to \pi\pi$	VEPP, BES, DAΦNE, ...	R-ratio	NLO+
$ee \to \ell\ell\gamma$	VEPP, BES, DAΦNE, ...	R-ratio	NLO+

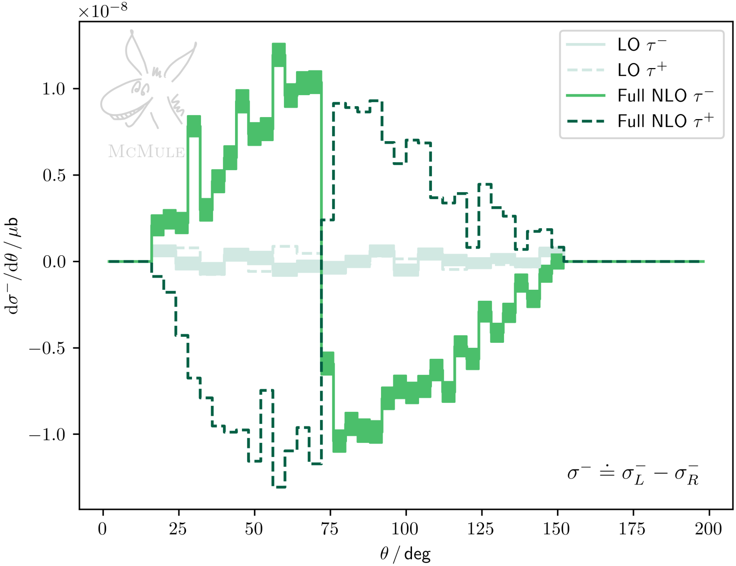
Some first results for $e^+e^- \to \tau^+\tau^-$ (w/o polarization): σ_{tot}



Cuts (lab frame):

- Scattering angle $\theta \in [17^\circ, 150^\circ]$
- Photon energy $E < 50\,\text{MeV}$

Some first results for $e^+e^- \to \tau^+\tau^-$ (w/o polarization): $\sigma_L - \sigma_R$



McMule: getting started

McMule

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Yannick Ulrich [1], Pulak Banerjee [2], Antonio Coutinho [3], Tim Engel [4], Andrea Gurgone [5, 6], Franziska Hagelstein [7, 8], Sophie Kollatzsch [8, 9], Luca Naterop [8, 9], Marco Rocco [8], Nicolas Schalch [1], Vladyslava Sharkovska [8, 9], Adrian Signer [8, 9]

[1] (1, 2) Albert Einstein Center for Fundamental Physics, Universität Bern, CH-3012 Bern, Switzerland

[2] Department of Physics, Indian Institute of Technology Guwahati, Guwahati-781039, Assam, India

[3] IFIC, Universitat de València - CSIC, Parc Científic, Catedrático José Beltrán, 2, E-46980 Paterna, Spain

[4] Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany

[5] Dipartimento di Fisica, Università di Pavia, I-27100 Pavia, Italy

[6] INFN, Sezione di Pavia, I-27100 Pavia, Italy

[7] Institut für Kernphysik & PRISMA$^+$ Cluster of Excellence, Johannes Gutenberg Universität Mainz, D-55099 Mainz, Germany

[8] (1, 2, 3, 4, 5, 6) Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

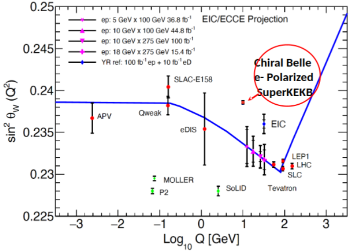
[9] (1, 2, 3, 4) Physik-Institut, Universität Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland

Contents:

- McMule manual at `https://mule-tools.gitlab.io/manual/`
- For general questions contact Yannick Ulrich yannick.ulrich@liverpool.ac.uk
- For $e^+e^- \to \tau^+\tau^-$ contact Joël Gogniat gogniat@itp.unibe.ch

Conclusions

- Exciting physics program at **Chiral Belle**
  - Unprecedented precision for neutral-current vector couplings: **$\sin^2\theta_W$, universality**
  - Highly complementary to low- and high-energy probes of parity violation
  - Improved precision of τ Michel parameters
  - Improved sensitivity to $\tau\to\mu\gamma$, $\tau\to e\gamma$



- **Dipole moments of the τ**
  - EDM: could probe $d_\tau\simeq 10^{-20}\,e\,\text{cm}$
  - $(g-2)_\tau$: could probe $a_\tau^{\text{BSM}}\simeq 10^{-5}$ (assuming current projections for statistics and m_τ, $M_{\Upsilon(1S)}$)
  - Program for a_τ requires theory development up to two-loop level, being implemented into McMule
  - Important especially in view of ongoing developments for $\ell=\{e,\mu\}$