Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation

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On behalf of Belle II & SuperKEKB e- Polarization Upgrade Working Group

Snowmass 2021

Snowmass Rare Processes and Precision Measurements Frontier Spring Meeting

University of Cincinnati, Cincinnati, Ohio, USA (May 16 - May 19, 2022)

Snowmass 2021 White Paper
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April 13, 2022

pdf available here

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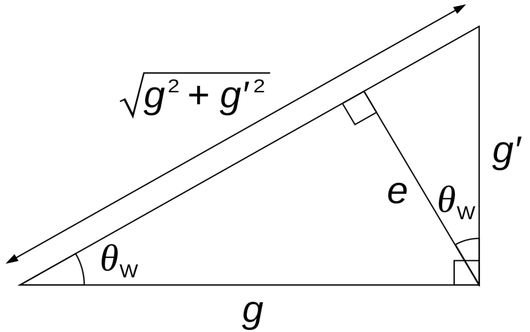
This talk

The electroweak mixing angle (θ_W)

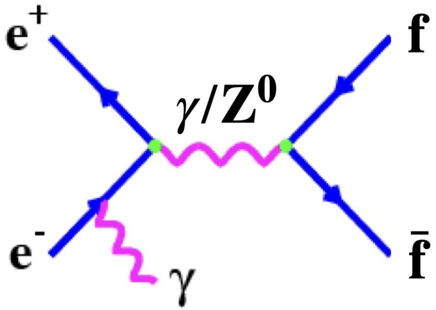


$$e = g \sin \theta_W = g' \cos \theta_W$$

$$\sin \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

Mixing in terms of the weak isospin g and weak hypercharge g'

SuperKEKB/Belle Upgrade: Polarized e- Beam



$\langle Pol \rangle$ is the average electron beam polarization for the sample under consideration:

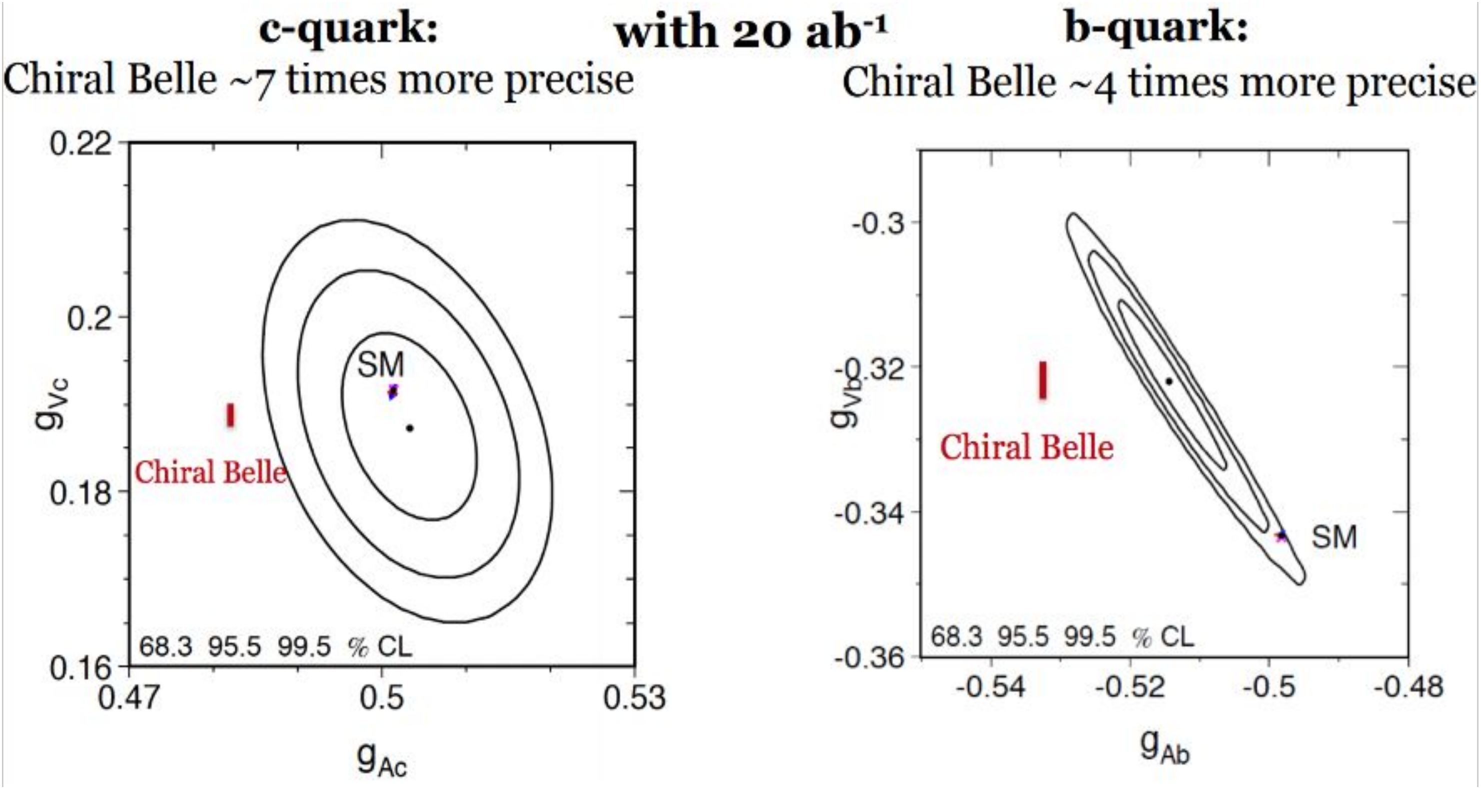
$$\langle Pol \rangle = \frac{1}{2}\left[\left(\frac{N_{eR} - N_{eL}}{N_{eR} + N_{eL}}\right)_{\mathbf{R}} - \left(\frac{N_{eR} - N_{eL}}{N_{eR} + N_{eL}}\right)_{\mathbf{L}}\right]$$

Measure:

(for Born-level s-channel process)

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

Precision electroweak measurements

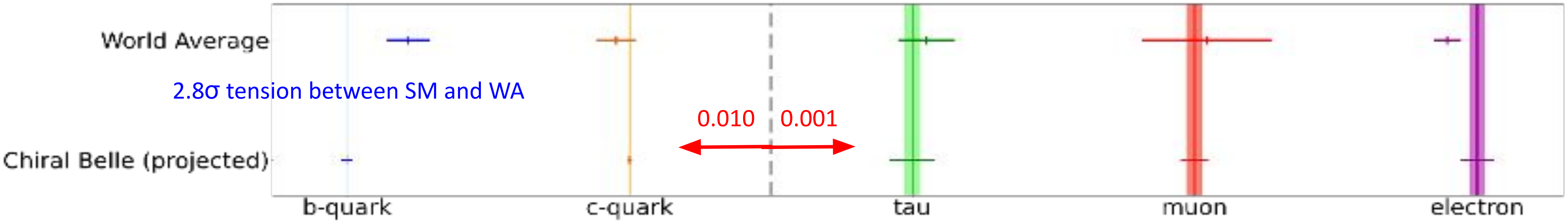


- Adapted from Fig. 7.4 of *Precision electroweak measurements on the Z resonance*, Phy.Rep.427 (5), 2006 (LEP/SLD).
- Red bars show expected ±1 sigma uncertainty with 20 ab^{-1} of data at Chiral Belle [placed at arbitrary positions].

Precision electroweak measurements

Fermion	g_V^f (Standard Model)	g_V^f (World Average)	$\sigma(g_V^f)$ (Chiral Belle 40ab^{-1})
b-quark	-0.3437 ± 0.0001	-0.3220 ± 0.0077	0.0020 (4 x improvement)
c-quark	0.1920 ± 0.0002	0.1873 ± 0.0070	0.0010 (7 x improvement)
Tau	-0.0371 ± 0.0003	-0.0366 ± 0.0010	0.0008
Muon	-0.0371 ± 0.0003	-0.03667 ± 0.0023	0.0005 (4 x improvement)
Electron	-0.0371 ± 0.0003	-0.03816 ± 0.00047	0.0006

Combined analysis (assuming universality) : $\sigma(g_V^f) = 0.00033_{stat} \pm 0.00018_{sys}$ [*cf.* SM error of ±0.0003]



Neutral current vector coupling universality

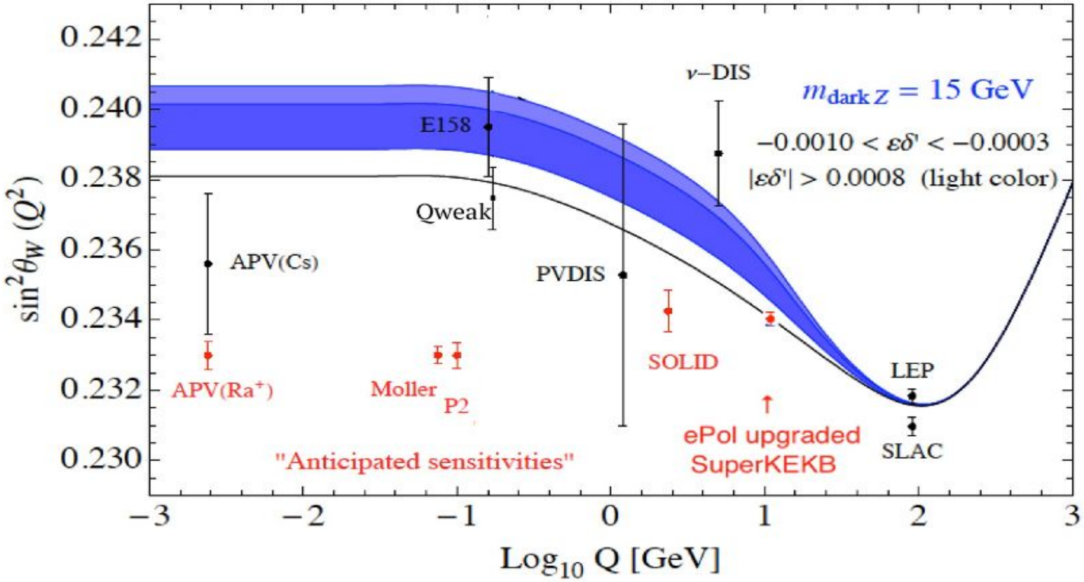
$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_F s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle P \rangle \propto T_3^f - 2Q_f \sin^2\theta_W$$

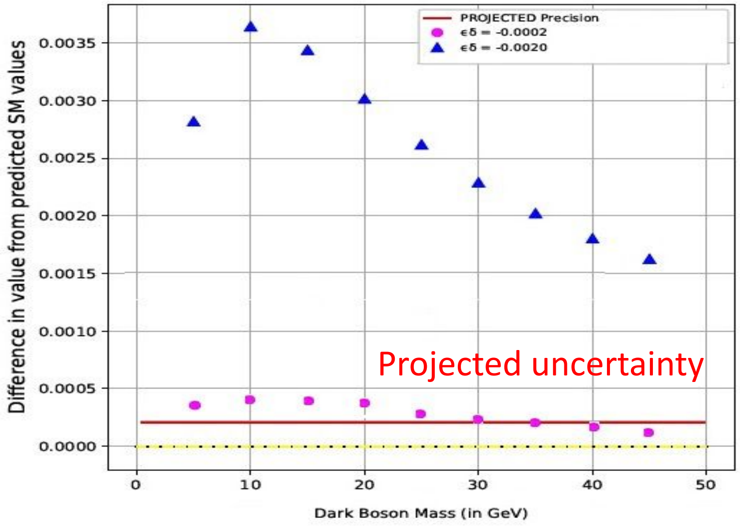
- The ratio $A_{LR}^{f_1}/A_{LR}^{f_2}$ provides a measurement of $g_V^{f_1}/g_V^{f_2}$
  - <P> cancels in ratio: uncertainty dominated by statistics
  - Avoid hadronization uncertainties in measurement of g_V^b which was significant in extraction from A_{FB}^b at Z-pole
- g_V^b/g_V^c can be measured with stats-limited relative error of 0.3% (with 20ab^{-1}) → 14 x more precise than world average
- Most precise tests of universality for all fermions.

Running of $\sin^2\theta_W(Q^2)$: window to the Dark Sector

Dark blue band shows Q^2-dependent shift in $\sin^2\theta_W$ due to 15 GeV parity-violating dark Z

Differences between SM and 2 benchmark scenarios of dark Z

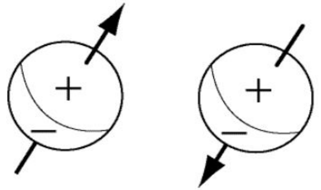




- Adapted from Fig. 3 of H. Davoudiasl, H.S. Lee and W.J. Marciano, Phys.Rev.D 92(5),2015.
- Red bars shows expected ±1 sigma uncertainty = 0.0002 with 40 ab^{-1} at Chiral Belle [placed at arbitrary positions].
- Also sensitive to parity violation induced by exchange of heavy particles e.g. a hypothetical TeV-scale Z' boson, which if couples only to lepton will be uniquely produced @ Belle II and not in pp collisions.

Electric and magnetic moments of τ lepton

Charge asymmetry along spin direction: EDM $\neq 0 \Rightarrow$ CP violation
SM expectation $\mathcal{O}(10^{-37})$ e.cm far below experimental sensitivity
New physics in loops can enhance EDM of τ lepton ~ $\mathcal{O}(10^{-19})$ e.cm

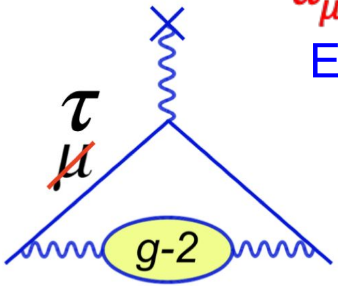


W. Bernreuther et. al. Phys. Lett. B 391, 413 (1997); T. Huang et. al. Phys. Rev. D 55, 1643 (1997).

$$a_\ell = (g_\ell - 2)/2$$

Large deviation in anomalous magnetic moment of muon

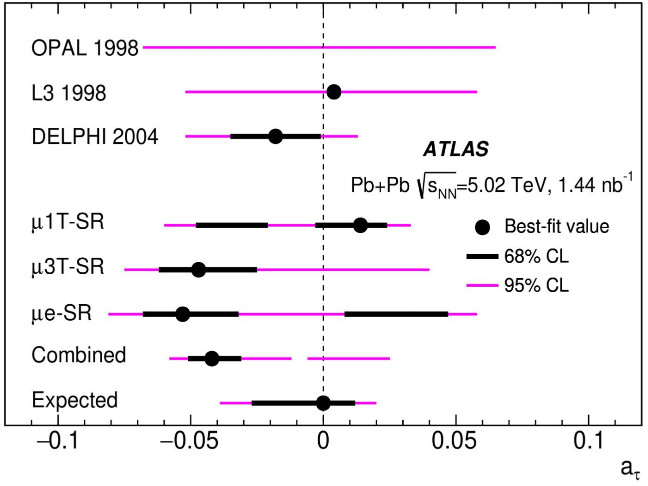
$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (251 \pm 59)\times 10^{-11}[4.2\sigma]$$



Expectation from Minimal flavor violation:

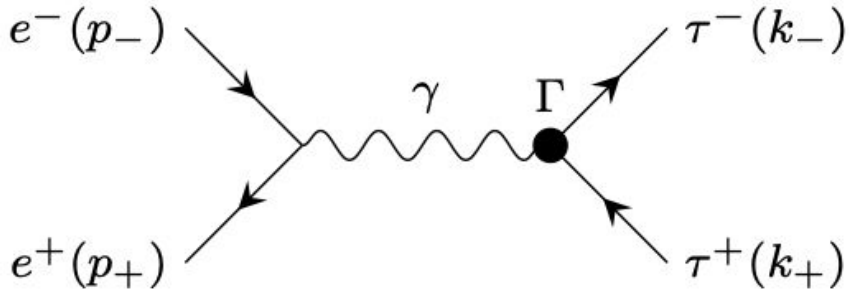
$$a_\tau^{\text{BSM}} \sim a_\mu^{\text{BSM}} \left(\frac{m_\tau}{m_\mu}\right)^2 \sim 10^{-6}$$

Current bound in tau ~ $\mathcal{O}(10^{-2})$
Chiral Belle reach ~ $\mathcal{O}(10^{-5})$ with 50ab^{-1}



e-Print: 2204.13478 [hep-ex]
ATLAS Collaboration

Effective field theory approach to τ-pair production



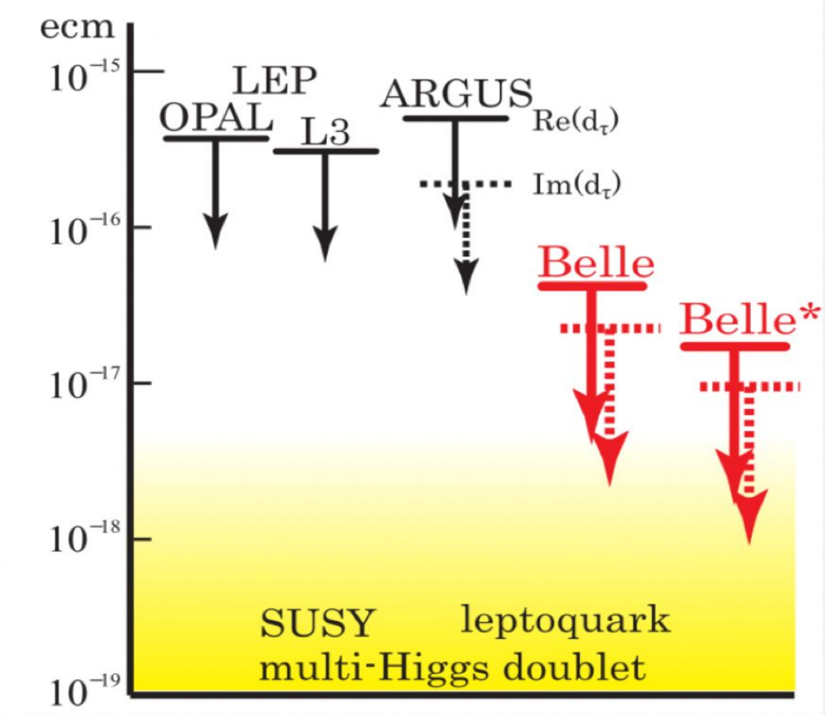
$$\Gamma^\mu = \underbrace{F_1\left(q^2\right)\gamma^\mu}_{\text{radiative corrections}} + \underbrace{F_2\left(q^2\right)\frac{1}{2m_\tau}\mathrm{i}\sigma^{\mu\nu}q_\nu}_{\text{MDM}} + \underbrace{F_3\left(q^2\right)\frac{1}{2m_\tau}\sigma^{\mu\nu}q_\nu\gamma_5}_{\text{EDM}}$$

- $F_1\left(q^2\right)$, $F_2\left(q^2\right)$ are called the Dirac and Pauli; $F_1(0) = 1;$ $F_2(0) = a_\tau$
- $g = 2 \cdot [F_1(0) + F_2(0)] = 2 + 2F_2(0)$ $d_\tau^\gamma = \frac{e}{2m_\tau} \cdot F_3(0)$

Leading term

$\approx 0.001\ 161\ 4$

Electric dipole moments of τ lepton



Belle; 833 fb-1 data (arXiv:2108.11543 [hep-ex])

$$\mathrm{Re}(d_\tau) = (-0.62 \pm 0.63) \times 10^{-17}\ \mathrm{ecm},$$
$$\mathrm{Im}(d_\tau) = (-0.40 \pm 0.32) \times 10^{-17}\ \mathrm{ecm}.$$

– 95% confidence intervals

$$-1.85 \times 10^{-17} < \mathrm{Re}(d_\tau) < 0.61 \times 10^{-17}\ \mathrm{ecm},$$
$$-1.03 \times 10^{-17} < \mathrm{Im}(d_\tau) < 0.23 \times 10^{-17}\ \mathrm{ecm}.$$

- Consistent with zero EDM
- Systematic errors similar to statistical
- Dominant systematics: Data-MC mismatch in momentum/angular distributions

➢ Preliminary studies at Belle II show much better control in agreement between Data-MC

➢ After improved control of systematics, extrapolation based on statistical errors only

➢ **With 50 ab^{-1} data at Belle II: Re(d$_\tau$) ~ 8 x 10 $^{-19}$, Im(d$_\tau$) ~ 4 x 10 $^{-19}$**

➢ Further improvement expected from proposed upgrade of polarized e- beams.

Electric dipole moments of τ lepton

CP violation and electric-dipole-moment at low energy τ production with polarized electrons

J. Bernabeu G.A. Gonzalez-Sprinberg J. Vidal

Nucl.Phys.B763:283-292,2007, hep-ph/0610135

P_N^τ :polarization of one of the τ's normal to the scattering plane.

With beam polarization λ :

$$P_N^\tau \propto \lambda\gamma\beta^2 \cos\theta_\tau \sin\theta_\tau \frac{m_\tau}{e} \mathrm{Re}(d_\tau^\gamma)$$

Angular asymmetries (P_N^τ) are proportional to EDM

$$A_N^\mp = \frac{\sigma_L^\mp - \sigma_R^\mp}{\sigma_L^\mp + \sigma_R^\mp} = \alpha_\mp \frac{3\pi\gamma\beta}{8(3-\beta^2)} \frac{2m_\tau}{e} \mathrm{Re}(d_\tau^\gamma)$$

One can also measure A for τ^+ and/or τ^-

$\not{CP}$:

$$A_N^{CP} \equiv \frac{1}{2}(A_N^+ + A_N^-)$$

Magnetic dipole moments of τ lepton

Tau anomalous magnetic moment form factor at super B/flavor factories

J. Bernabéu [a,b], G.A. González-Sprinberg [c], J. Papavassiliou [a,b], J. Vidal [a,b,*]

Nucl.Phys.B790:160-174,2008

4.1. Transverse asymmetry

To get an observable sensitive to the relevant signal define the azimuthal transverse asymmetry as

$$A_T^{\pm} = \frac{\sigma_R^{\pm}|_{\mathrm{Pol}} - \sigma_L^{\pm}|_{\mathrm{Pol}}}{\sigma} = \mp\alpha_{\pm}\frac{3\pi}{8(3-\beta^2)\gamma}\left[|F_1|^2 + (2-\beta^2)\gamma^2\,\mathrm{Re}\{F_2\}\right], \tag{29}$$

where

$$\begin{aligned}\sigma_L^{\pm}|_{\mathrm{Pol}} &\equiv \int_{\pi/2}^{3\pi/2} d\phi_{\pm}\left[\frac{d\sigma^S}{d\phi_{\pm}}\bigg|_{\mathrm{Pol}(e^-)}\right] \\ &= \pm\mathrm{Br}(\tau^+\to h^+\bar{\nu}_\tau)\,\mathrm{Br}(\tau^-\to h^-\nu_\tau) \\ &\quad\times\alpha_{\pm}\frac{(\pi\alpha)^2\beta}{8s}\frac{1}{\gamma}\left[|F_1|^2 + (2-\beta^2)\gamma^2\,\mathrm{Re}\{F_2\}\right],\end{aligned} \tag{30}$$

$$\sigma_R^{\pm}|_{\mathrm{Pol}} \equiv \int_{-\pi/2}^{\pi/2} d\phi_{\pm}\left[\frac{d\sigma^S}{d\phi_{\pm}}\bigg|_{\mathrm{Pol}(e^-)}\right] = -\sigma_L^{\pm}|_{\mathrm{Pol}}. \tag{31}$$

4.2. Longitudinal asymmetry

Then, we define the longitudinal asymmetry as

$$A_L^{\pm} = \frac{\sigma_{\mathrm{FB}}^{\pm}(+)|_{\mathrm{Pol}} - \sigma_{\mathrm{FB}}^{\pm}(-)|_{\mathrm{Pol}}}{\sigma} = \mp\alpha_{\pm}\frac{3}{4(3-\beta^2)}\left[|F_1|^2 + 2\,\mathrm{Re}\{F_2\}\right], \tag{34}$$

where

$$\begin{aligned}\sigma_{\mathrm{FB}}^{\pm}(+)\big|_{\mathrm{Pol}} &\equiv \int_0^1 d(\cos\theta_{\pm}^*)\frac{d\sigma_{\mathrm{FB}}^S}{d(\cos\theta_{\pm}^*)}\bigg|_{\mathrm{Pol}(e^-)} \\ &= \mp\alpha_{\pm}\,\mathrm{Br}(\tau^+\to h^+\bar{\nu}_\tau)\,\mathrm{Br}(\tau^-\to h^-\nu_\tau)\frac{\pi\alpha^2}{4s}\beta\left[|F_1|^2 + 2\,\mathrm{Re}\{F_2\}\right],\end{aligned} \tag{35}$$

$$\sigma_{\mathrm{FB}}^{\pm}(-)\big|_{\mathrm{Pol}} \equiv \int_{-1}^0 d(\cos\theta_{\pm}^*)\frac{d\sigma_{\mathrm{FB}}^S}{d(\cos\theta_{\pm}^*)}\bigg|_{\mathrm{Pol}(e^-)} = -\sigma_{\mathrm{FB}}^{\pm}(+)\big|_{\mathrm{Pol}}. \tag{36}$$

Combining Eq. (29) and Eq. (34) one can determine the real part of $F_2(s)$.

$$\mathrm{Re}\{F_2(s)\} = \mp\frac{8(3-\beta^2)}{3\pi\gamma\beta^2}\frac{1}{\alpha_{\pm}}\left(A_T^{\pm} - \frac{\pi}{2\gamma}A_L^{\pm}\right).$$

Magnetic dipole moments of τ lepton

Andreas Crivellin, Martin Hoferichter, J. Michael Roney arXiv:2111.10378 **[hep-ph]**

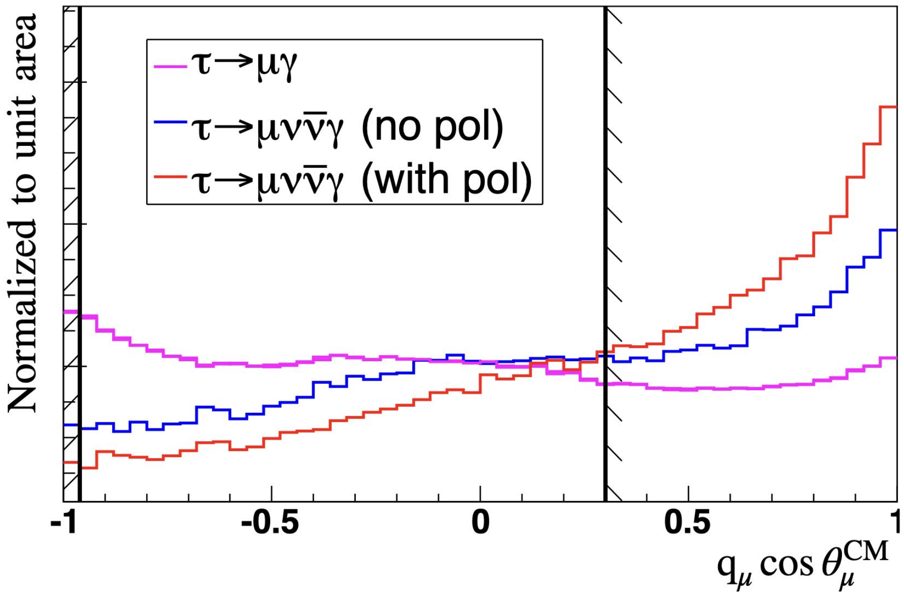
Contributions to $F_2(s)$ in units of 10^{-6}.

	$s = 0$	$s = (10\,\text{GeV})^2$
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

- Detector level systematics cancels in asymmetries between left (right) beams.
- Precision ≃ $\mathcal{O}(10^{-5})$ or better expected with 50 ab^{-1} of data with polarized beam.

Search for lepton flavor violation in τ decays

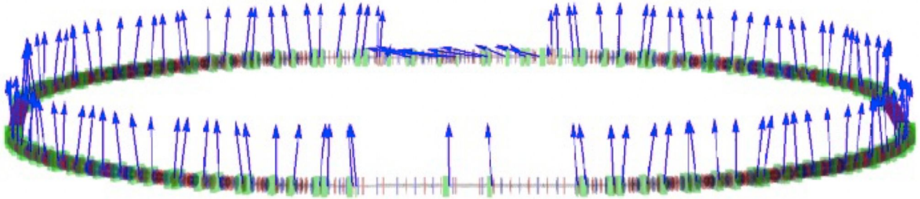
- Belle II to probe LFV in several channels ≃ $\mathcal{O}(10^{-10})$ to $\mathcal{O}(10^{-9})$ with 50 ab^{-1}
- With beam polarization, helicity distributions can suppress backgrounds
- Optimization study shows at least 10% improvement in $\tau\to\ell\gamma$ sensitivity



- Possible to disentangle helicity structure of LFV in $\tau\to\ell\ell\ell$ from Dalitz plots

Many more interesting physics explorations

- Left-right beam asymmetry in production of Λ hadron probes mechanism of dynamical mass generation schemes in QCD
- Novel and feasible accelerator hardware developments:



1. Low emittance polarized source
2. Spin rotators
3. Compton Polarimeters

- Tau polarization measures beam polarization with 0.5% accuracy

$$P_{\tau^-} = P_e \frac{\cos\theta}{1+\cos^2\theta} - \frac{8G_F s g_V^\tau}{4\sqrt{2}\pi\alpha}\left(g_A^\tau \frac{\overrightarrow{|p|}}{p^0} + 2g_A^e \frac{\cos\theta}{1+\cos^2\theta}\right)$$

Summary and Outlook

- Open up a unique window of Electroweak precision measurements
  - Detector systematics cancels in left-right beam asymmetry
- Neutral current vector coupling universality
  - No other experiment (running or planned) matches sensitivity
- Chiral Belle probes parity violation both at low & high energy:
  - When Dark Z is off-shell and couples more to 3rd generation
  - TeV-scale Z' which couples only to leptons
- Unambiguous signatures of new physics if moments of $\tau \neq 0$
  - Probe EDM to $\mathcal{O}(10^{-19})$ & $(g-2)_\tau$ to $\mathcal{O}(10^{-5})$ or better
- Boost sensitivity of searches of LFV in τ decays
  - disentangle helicity structure of LFV
- Proposed upgrade: Chiral Belle with 70% polarized electron beams
  - Compton polarimeters complemented with τ polarization studies