25TH INTERNATIONAL
SPIN PHYSICS
SYMPOSIUM

September 24 – 29, 2023
Durham Convention Center
Durham, NC, USA

Towards Testing the Magnetic Moment of the tau at One Part per Million

J. Michael Roney

University of Victoria

27 September 2023

On behalf of Andreas Crivellin, Martin Hoferichter and the Belle II/SuperKEKB e- Polarization Upgrade Working Group

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One of the physics goals of the e- polarization-upgraded SuperKEKB e+e- Collider

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Based on
Phys.Rev.D 106 (2022) 9, 093007
and
Snowmass 2021 White Paper
Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation
arXiv:2205.12847

Towards Testing the Magnetic Moment of the tau at One Part per Million

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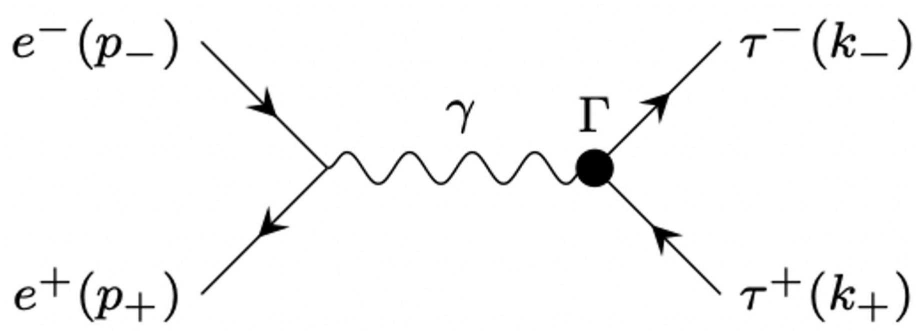
Effective field theory interaction between τ-lepton and photon

Use in 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; $F_1(0) = 1$; $F_2(0) = a_\tau$
- $g = 2\cdot\left[F_1(0) + F_2(0)\right] = 2 + 2F_2(0)$ $d_\tau^\gamma = \frac{e}{2m_\tau}\cdot F_3(0)$

Leading term

$$F_2(0) = a_\tau = (g-2)_\tau/2 \sim \alpha/(2\pi) = 1.1614\times 10^{-3}$$

Electron g-2

$$a_e^{\rm exp} - a_e^{\rm SM}[{\rm Cs}] = -0.88(28)(23)[36] \times 10^{-12}$$
$$a_e^{\rm exp} - a_e^{\rm SM}[{\rm Rb}] = +0.48(28)(9)[30] \times 10^{-12},$$

depending on whether the fine-structure constant is from Cs or Rb atom interferometry. This > 5 σ tension currently the biggest uncertainty.

Theory-side: 4-loop QED contributions are known semi-analytically [1] and a 4.8 σ tension between the numerical evaluations [2, 3] of the 5-loop coefficient amounts to 6 x 10^{-14}

Hadronic uncertainties enter at 1 x 10^{-14} level [4]

[1] S. Laporta, Phys. Lett. B 772, 232 (2017)
[2] T. Aoyama, T. Kinoshita, and M. Nio, Atoms 7, 28 (2019)
[3] S. Volkov, Phys. Rev. D 100, 096004 (2019)
[4] A. Keshavarzi, D. Nomura, and T. Teubner, Phys. Rev. D101, 014029 (2020)

Muon g-2

See Dinko Počanić′s talk in this session for the details of the most recent experimental results from FNAL E989.

New combined world average [Aguillard et al., arXiv 2308.06230, soon in PRL]:

$a_\mu(\mathrm{EXP}) = 116\,592\,059(22) \times 10^{-11}$ (0.19 ppm)

$a_\mu(\mathrm{SM}) = 116\,591\,810(1)(40)(18) \times 10^{-11}$ (0.37 ppm)

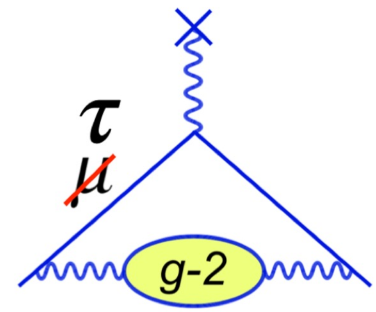
from PDG August 2021 article by A. Höcker and W.J. Marciano
(SM errors are due to the electroweak, lowest-order hadronic, and
higher-order hadronic contributions, respectively)

$a_\mu(\mathrm{SM})$ includes BMW 2021 Lattice QCD calculations but does not include new input to HVP from the 2023 CMD-3 $e^+e^- \to \pi^+\pi^-$ measurement

$$a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = 249(49) \times 10^{-11} \quad (5.1\,\sigma)$$

Await new evaluation of $a_\mu(\mathrm{SM})$ that includes latest input, expect significance to drop

Tau g-2

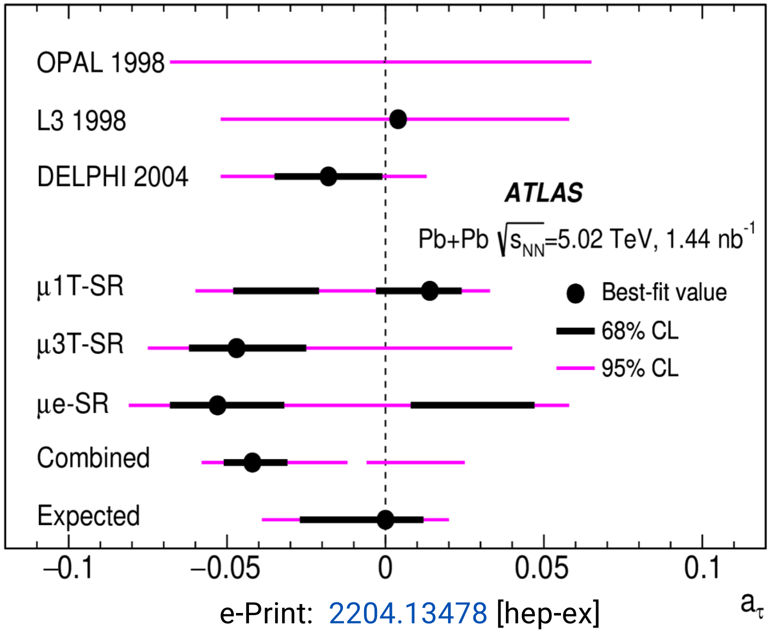


From LEP2 $e^+e^- \rightarrow e^+e^- \tau^+\tau^-$:

$$-0.052 < a_\tau < 0.013 \quad \text{[range: } 2\sigma]$$

From global analysis of LEP and SLD data in effective field theory [Gonzalez-Sprinberg, Santamaria. Vidal. Nucl. Phys. B 582, 3 (2000)]:

$$-0.007 < a_\tau < 0.005 \quad \text{[range: } 2\sigma]$$



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

Limit is still many factors above Schwinger's 1-loop QED term:

$$\alpha/(2\pi) = 1.1614 \times 10^{-3}$$

Tau g-2

Expectation from Minimal flavor violation:

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

Since this is of the order of the SM electroweak (EW) contribution, $a^{EW}{}_{\tau} \sim 0.5 \times 10^{-6}$ [Eidelman and Passera, Mod. Phys. Lett. A 22,159 (2007)] this also sets the scale at which BSM effects might be expect to reasonably arise

… motivates us targeting measurements of a_τ at 10^{-6} level

Tau g-2

Example of BSM model:
In an $SU(2)_L$ Singlet S_1 leptoquark model …

using the bounds on the LHC branching fraction for $h \to \tau^+\tau^-$ and on the Z^0 axial-vector coupling g^τ_A from LEP

(from Crivellin, Hoferichter, Roney *Phys.Rev.D 106 (2022) 9, 093007*)

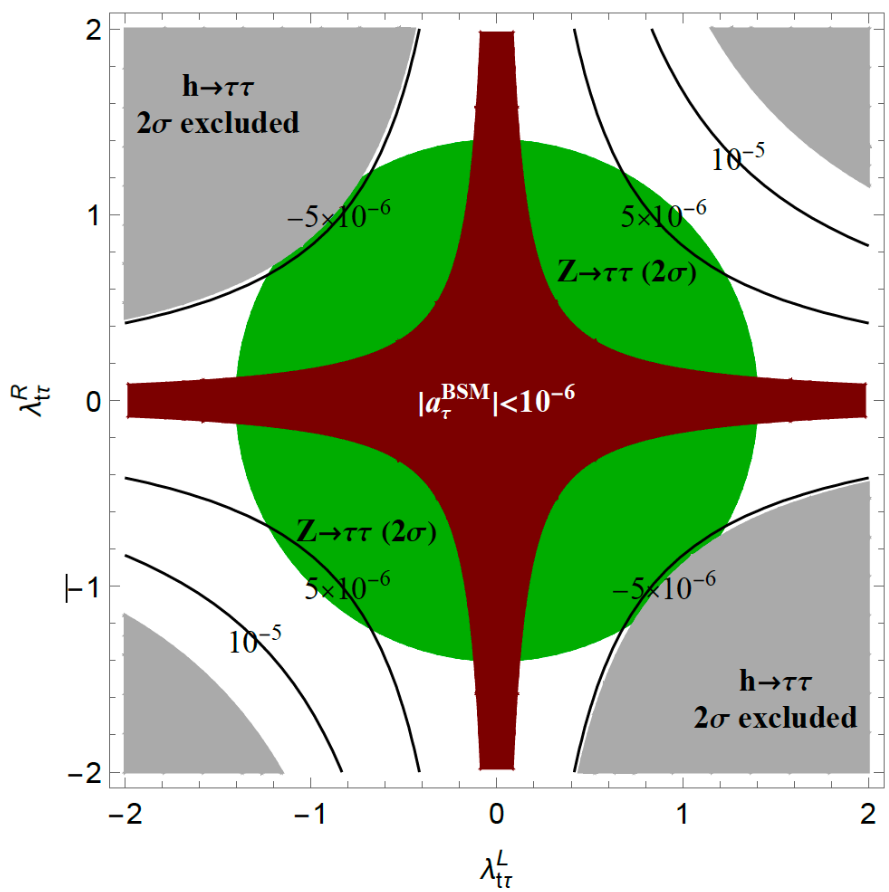


FIG. 2: Illustration of the discovery potential of a_τ in the S_1 LQ model, taking into account the constraints from $h \to \tau^+\tau^-$ (gray, excluded) and $Z \to \tau^+\tau^-$ (green, allowed), with contour lines indicating the respective value of $a_\tau^{\rm BSM}$. The asymmetry in the $h \to \tau\tau$ constructive and destructive exclusion regions originates from the current 1σ upward fluctuation in the data. The LQ mass is set to $M = 2\,\text{TeV}$.

Tau g-2

Various methods to measure a_τ have been proposed:

- radiative τ decays [1]
- channeling [2] in a bent crystal [3, 4]
- γp [5, 6] and heavy-ion [70, 71] reactions at the LHC

but these do not reach that level of precision

[1] Eidelman, Epifanov, Fael, Mercolli, and Passera, JHEP 03, 140 (2016)
[2] I. J. Kim, Nucl. Phys. B 229, 251 (1983)
[3] M. A. Samuel, G.-w. Li, and R. Mendel, Phys. Rev. Lett. 67, 668 (1991), [Erratum: Phys. Rev. Lett. 69, 995 (1992)].
[4] A. S. Fomin, A. Y. Korchin, A. Stocchi, S. Barsuk, and P. Robbe, JHEP 03, 156 (2019)
[5] Koksal, Inan, Billur, Ozguven, and Bahar, Phys. Lett. B 783, 375 (2018)
[6] Gutierrez-Rodrguez, M. Koksal, A. A. Billur, and M. A. Hernandez-Ruez (2019), 1903.04135.
[70] L. Beresford and J. Liu, Phys. Rev. D 102, 113008 (2020)
[71] Dyndal, Klusek-Gawenda, Schott, and Szczurek, Phys. Lett. B 809, 135682 (2020)

Tau g-2

This goal is potentially achievable at a SuperKEKB upgraded with polarized electrons in precision study of $e^+e^- \rightarrow \tau^+\tau^-$ at or around the Υ resonances as pointed out in
J. Bernabeu, G. A. Gonzalez-Sprinberg, J. Papavassiliou, and J. Vidal, Nucl. Phys. B 790, 160 (2008)
and Bernabeu, Gonzalez-Sprinberg, and Vidal, JHEP 01, 062 (2009)

Such measurements at s ~(10 GeV)^2 give the Pauli form factor F_2(~100GeV^2) and deviations from its SM prediction would reveal a BSM contribution.

Although not a measurement of $a_\tau = F_2(0)$ it probes same BSM physics: If associated BSM scale lies beyond the electroweak scale, a mismatch in Re (F_2) can be directly interpreted as a^{BSM}_τ, while bounds for light BSM degrees of freedom become model dependent

Tau g-2

Cross section of $e^+e^- \rightarrow \tau^+\tau^-$

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

Extracting constraints on $a^{BSM}_{\tau.}$ from $e^+e^- \rightarrow \tau^+\tau^-$ proceeds via the term $\mathrm{Re}(F_1F^*_2)$, which is the only one sensitive to 2-loop effects in F_2

Tau g-2

Cross section of $e^+e^- \rightarrow \tau^+\tau^-$

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

Disentangling Re $(F_1F^*_2)$ from dominant $|F_1|^2$ term by means of the angular dependence is possible using semileptonic decays of the τ [1]

… but determining F_2 at 10^{-6} level requires an absolute cross-section measurement at that accuracy

[1] J. Bernabeu, G. A. Gonzalez-Sprinberg, J. Papavassiliou, and J. Vidal, Nucl. Phys. B 790, 160 (2008) using Y.-S. Tsai, Phys. Rev. D 4, 2821 (1971) and J. H. Kuhn, Phys. Lett. B 313, 458 (1993).

Tau g-2

To get there, we need large statistical sample AND control over systematic uncertainties

→ so use observables where systematic effects cancel

i.e. *asymmetries*

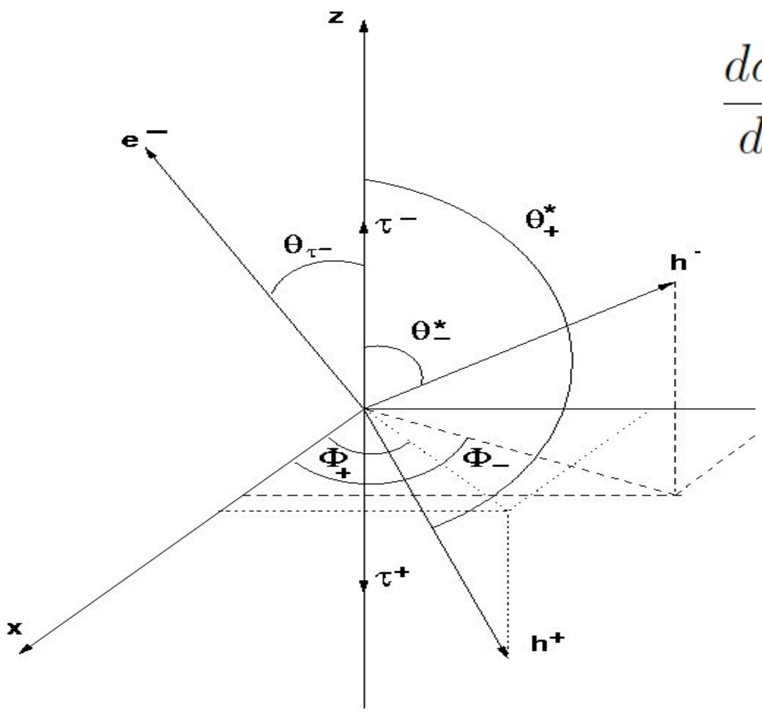
Without polarized beams, one uses 'Normal Asymmetry' defined by

$$A_N^{\pm} = \frac{\sigma_L^{\pm} - \sigma_R^{\pm}}{\sigma} = \pm\,\alpha_{\pm}\,\frac{1}{2(3-\beta^2)}\,\beta^2\,\gamma\,\mathrm{I}m\,\{F_2(s)\}$$

$$\alpha_{\pm} \equiv (m_\tau^2 - 2m_{h\pm}^2)/(m_\tau^2 + 2m_{h\pm}^2)$$

Tau g-2

$$\sigma_{FB}(\vec{s}_+, \vec{s}_-) \equiv 2\pi \left\{ \int_0^1 d(\cos\theta_{\tau^-}) \left[\frac{d\sigma}{d\Omega_{\tau^-}}\right] - \int_{-1}^0 d(\cos\theta_{\tau^-}) \left[\frac{d\sigma}{d\Omega_{\tau^-}}\right] \right\}$$
$$= \frac{\pi\,\alpha^2}{6\,s}\,\beta^3\,\gamma\,(s_- + s_+)_y\,\mathrm{I}m\,\{F_2(s)\}\ ,$$



$$\frac{d\sigma_{FB}}{d\phi_\pm} = \mp\frac{\pi\,\alpha^2}{12s}\,Br(\tau^+ \to h^+\bar{\nu}_\tau)Br(\tau^- \to h^-\nu_\tau)$$
$$\times(\alpha_\pm)\beta^3\,\gamma\,\mathrm{I}m\,\{F_2(s)\}\,\sin\phi_\pm\,.$$
$$\alpha_\pm \equiv (m_\tau^2 - 2m_{h^\pm}^2)/(m_\tau^2 + 2m_{h^\pm}^2)$$

$$\sigma_L^\pm \equiv \int_\pi^{2\pi} d\phi_\pm \left[\frac{d\sigma_{FB}}{d\phi_\pm}\right], \quad \sigma_R^\pm \equiv \int_0^\pi d\phi_\pm \left[\frac{d\sigma_{FB}}{d\phi_\pm}\right] = -\sigma_L^\pm$$

$$A_N^\pm = \frac{\sigma_L^\pm - \sigma_R^\pm}{\sigma} = \pm\,\alpha_\pm\,\frac{1}{2(3-\beta^2)}\,\beta^2\,\gamma\,\mathrm{I}m\,\{F_2(s)\}$$

BUT systematic uncertainties on angular acceptances make it challenging to get to 10^{-6}

Control Systematic Uncertainties using e^- Beam polarization asymmetries

Proposed in J. Bernabeu, G. A. Gonzalez-Sprinberg, J. Papavassiliou, and J. Vidal, Nucl. Phys. B 790, 160 (2008) and J. Bernabeu, G. A. Gonzalez-Sprinberg, and J. Vidal, JHEP 01, 062 (2009), define "effective F_2 "

$$\mathrm{Re}\, F_2^{\mathrm{eff}} = \frac{\alpha}{\pi}\mathrm{Re}\, F_2^{(1)} + \left(\frac{\alpha}{\pi}\right)^2 \Big[\mathrm{Re}\, F_2^{(2)} - \mathrm{Re}\, F_2^{(1)}\mathrm{Re}\, F_1^{(1)} + \mathrm{Im}\, F_2^{(1)}\left(\mathrm{Im}\, F_1^{(1)} + \mathrm{Im}\, F_2^{(1)}\right) - \frac{3+\beta^2}{3-\beta^2}\left(\mathrm{Re}\, F_2^{(1)}\right)^2\Big] + \mathcal{O}(\alpha^3).$$

$$F_i = F_i^{(0)} + \frac{\alpha}{\pi} F_i^{(1)} + \left(\frac{\alpha}{\pi}\right)^2 F_i^{(2)} + \mathcal{O}(\alpha^3)$$

Control Systematic Uncertainties using e^- Beam polarization asymmetries

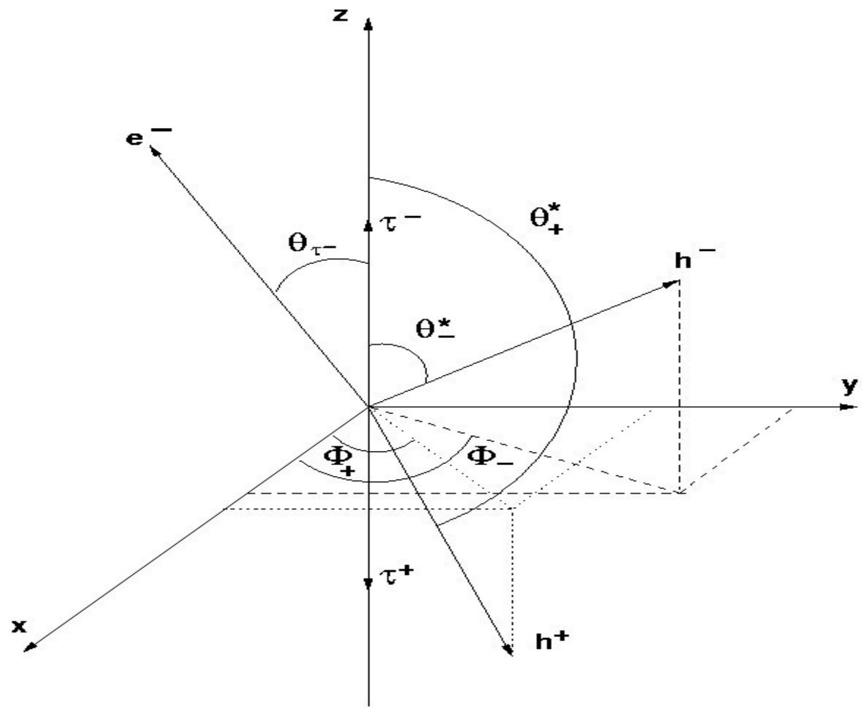
Two left-right beam polarization asymmetries are used, a transverse (A_T) and a longitudinal. (A_L) asymmetry.

A particular linear combination of A_T and A_L cancels large contributions from F_1 and is proportional to the effective Re (F_2):

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

Control Systematic Uncertainties using e^- Beam polarization asymmetries

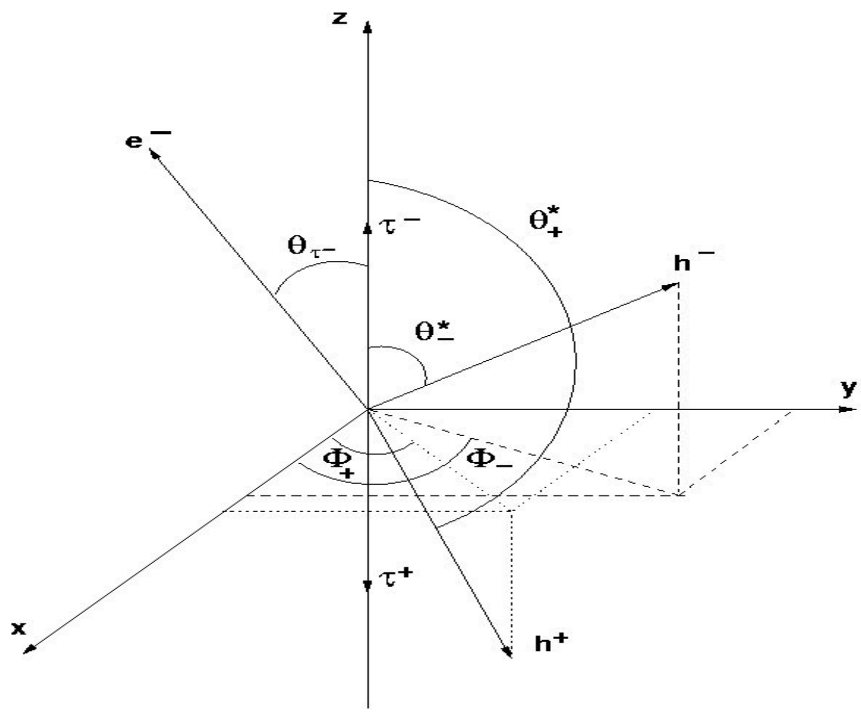
A_T : measured for the τ+ (and separately for the τ+) by counting events with $\pi/2 < \phi_\pm < 3\pi/2$ when beam is right-polarized (Re) and also when the beam is left-polarized (Le) and, taking their difference, then doing the same for events with $-\pi/2 < \phi_\pm < \pi/2$



$$A_T^{\pm} = \frac{1}{2\sigma}\left[\int_{-\pi/2}^{\pi/2}\left(\left(\frac{d\sigma^{R_e}}{d\phi_\pm}\right) - \left(\frac{d\sigma^{L_e}}{d\phi_\pm}\right)\right)d\phi_\pm - \int_{\pi/2}^{3\pi/2}\left(\left(\frac{d\sigma^{R_e}}{d\phi_\pm}\right) - \left(\frac{d\sigma^{L_e}}{d\phi_\pm}\right)\right)d\phi_\pm\right]$$

Control Systematic Uncertainties using e^- Beam polarization asymmetries

A_L: *involves the Re - Le asymmetries as well, along with the asymmetries associated with two angular observables: $z = \cos\theta_{\tau^-}$ and $z^*_{\pm} = \cos\theta^*_{\pm}$* after integrating over all other angles



Define: $$A_{RL} = \frac{d^2\sigma^{R_e}}{dz^*_{\pm}dz} - \frac{d^2\sigma^{L_e}}{dz^*_{\pm}dz},$$

$$A_L^{\pm} = \frac{1}{2\sigma}\left[\int_0^1 dz^*_{\pm}\left(\int_0^1 dz\,(A_{RL}) - \int_{-1}^0 dz\,(A_{RL})\right) - \int_{-1}^0 dz^*_{\pm}\left(\int_0^1 dz\,(A_{RL}) - \int_{-1}^0 dz\,(A_{RL})\right)\right]$$

Control Systematic Uncertainties using e^- Beam polarization asymmetries

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

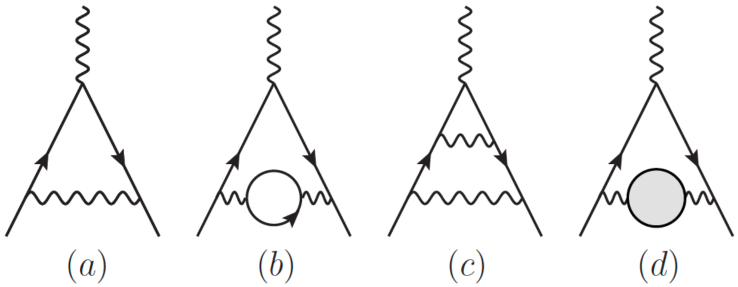


FIG. 1: Representative diagrams contributing to the QED form factors: (a) 1-loop QED, (b) lepton loops, (c) 2-loop QED, (d) HVP; the gray blob denotes the hadronic 2-point function.

(from Crivellin, Hoferichter, Roney *Phys.Rev.D 106 (2022) 9, 093007*)

SM Calculation of contributions to $Re(F^{eff}_2(s))$ in units of 10^{-6}. Total uncertainty: 0.5×10^{-6}

Values for s = 0 are given for illustration only

Note: $Re(F^{eff}_2(s))$ is defined in terms of cross sections, so values below $s = 4m_\tau^2$ are not physical.

Control Systematic Uncertainties using e^- Beam polarization asymmetries

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

Re F^{eff}_2 (100GeV^2) = -268.77 (50) x 10^{-6}

To reach 10^{-6} precision:

- factor in front needed to 0.5% level – not an issue
- average beam polarization needed at same level – can do this with tau beam polarimetry (2308.00774)
- $\pi/2\gamma$ is needed to be well controlled to get the cancellation of the large contribution from F_1

$\gamma = E_\tau/m_\tau = E_{cm}/(2m_\tau)$ precision given by precision on M(Y(1S)) (which gives E_{beam} calibration) and m_τ

- precisions on these currently limit us to 1 x 10^{-5}

Control Systematic Uncertainties using e^- Beam polarization asymmetries

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

As both A_T and A_L involve differences in the polarization state of the beam, the dominant detector systematic uncertainties cancel and one is left only having to address any detector related systematic uncertainties in the residual differences

Control Systematic Uncertainties using e^- Beam polarization asymmetries

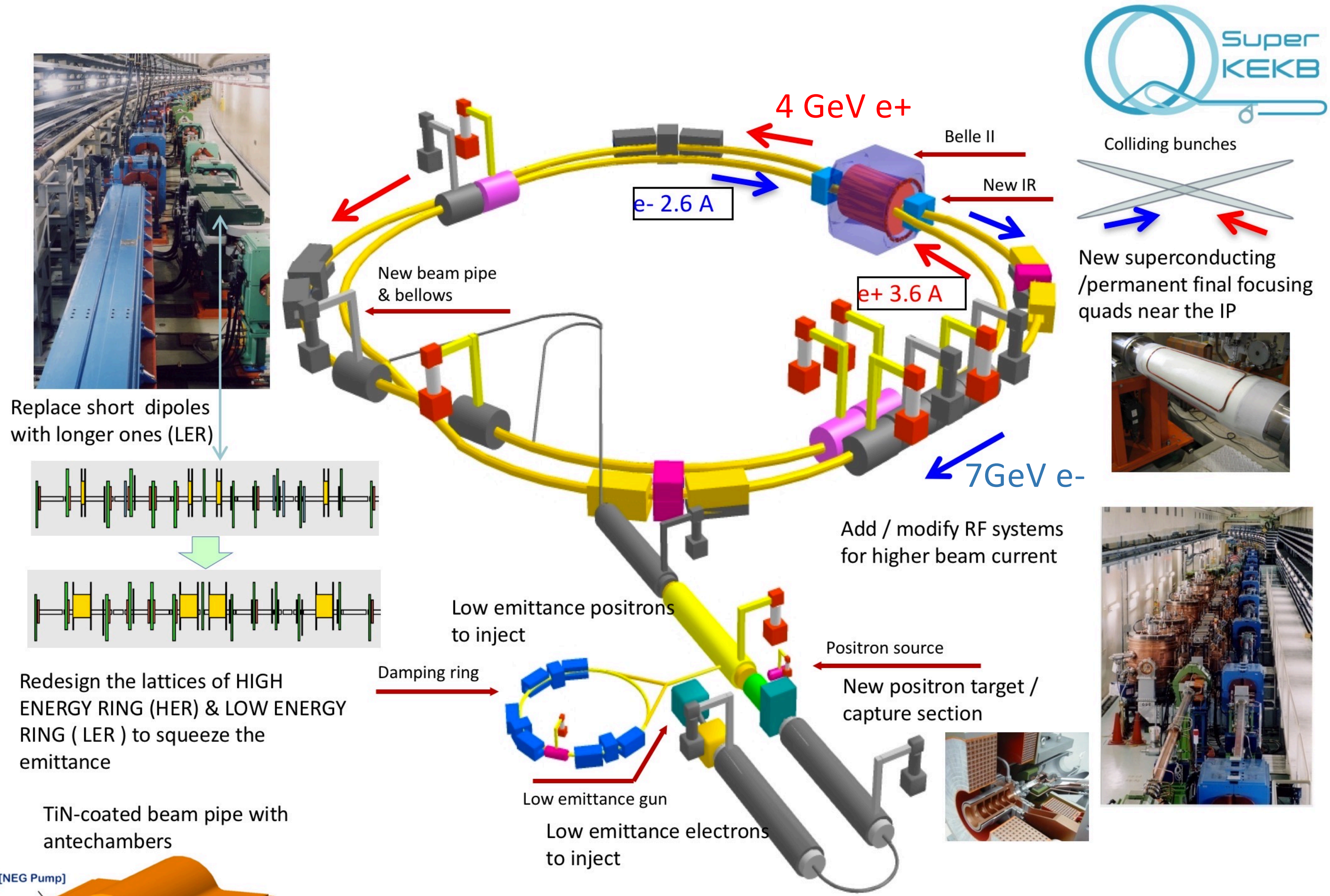
$$\mathrm{Re}(F_2^{\mathrm{eff}}) = \mp \frac{8(3-\beta^2)}{3\pi\gamma\beta^2\alpha_\pm}\left(A_T^\pm - \frac{\pi}{2\gamma}A_L^\pm\right)$$

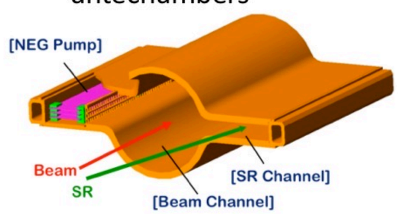
With 40 ab^{-1} of polarized beam data, and 60% efficiency for selecting semileptonic tau decays, the statistical uncertainty would be ~1 x 10^{-5}

1000 x more precise than current limits

So to get to 1 x 10^{-6} would require more statistics as well as higher precisions on M(Υ(1S)) and m_τ

We would also run on the Υ(4S), so we will need two-loop calculations of Re F^{eff}_2 (100GeV^2)





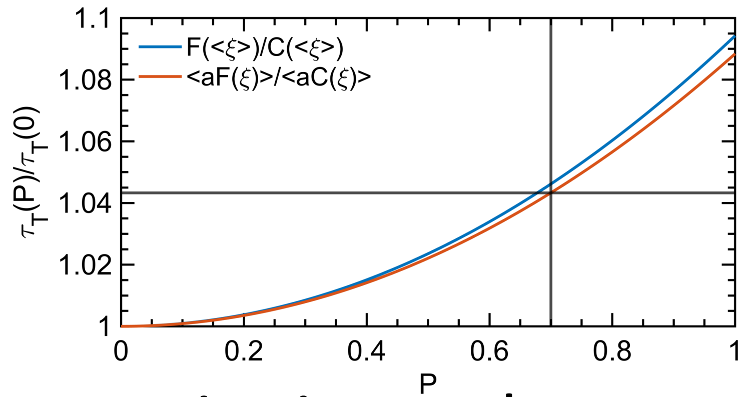
To obtain x40 higher luminosity

Polarization in SuperKEKB

- Goal is ~70% polarization with 80% polarized source (SLC had 75% polarization at the experiment)
- Electron helicity would be chosen randomly pulse-to-pulse by controlling the circular polarization of the source laser illuminating a GaAs photocathode (similar to SLC source)
- Inject vertically polarized electrons into the High Energy Ring (HER) - needs low enough emittance source to be able to inject.
- Rotate spin to longitudinal before Interaction Point, and then back to vertical after IP using solenoidal and dipole fields
- Use Compton polarimeter to monitor longitudinal polarization with <1% absolute precision, higher for relative measurements (arXiv:1009.6178) - needed for real time polarimetry
- Use tau decays to get absolute average polarization at Interaction Point 2308.00774 (*BABAR* analysis accepted for publication in PRD)

Proposal for Stage 1 of Chiral Belle: Dedicated Study of Transverse Polarization Lifetime

Touschek (i.e. intrabeam scattering) lifetimes increase with transverse polarization. In SuperKEKB e- HER transverse spin lifetime ~4% effect



Inject both polarized and unpolarized beams in ring and measure bunch/bunch intensity with time to minimize systematics (feasbile according to KEK experts)

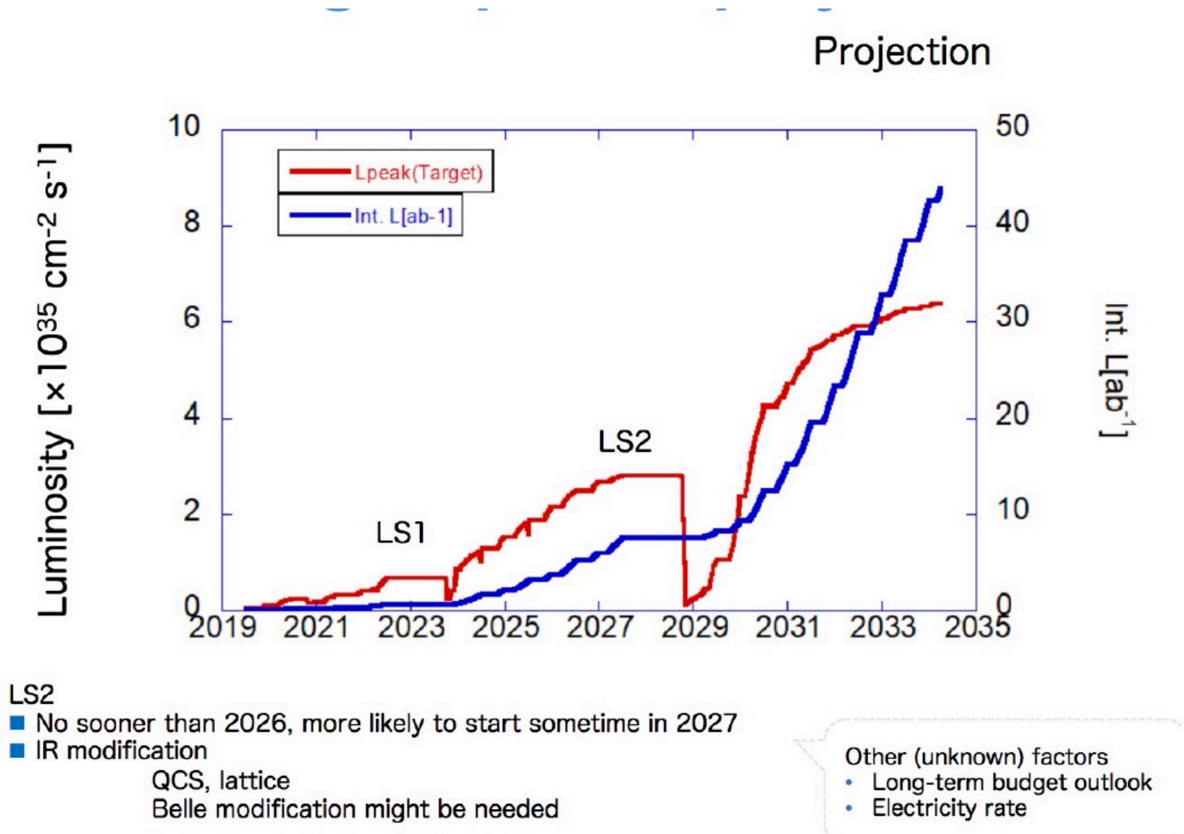
Proposing a ~1-2 day dedicated run with transverse polarized beam injection to measure correlation between polarization and Touschek lifetime and measure the spin lifetime

Goal: validate that transverse spin lifetime is many hours, as BINP and UVic/Argonne studies have independently predicted

Requires installation of polarized source with Wien Filter to send polarized beam into HER (note: no need for long lifetime source). Proposal will have Tousheck lifetime studies with existing data

SuperKEKB polarization upgrade

- Would aim to start to install polarization in Long Shutdown 2 (LS2) for new final focus ~2027, or later
- Polarization upgrade R&D in MEXT KEK Roadmap 2021-26



June 2022 projections

Summary

e^- polarization upgrade at SuperKEKB, aka Chiral Belle, opens a unique means of measuring the tau magnetic moment at a precision that starts to reach the equivalent of the muon g-2 tension scaled by the ratio of masses squared, as motivated in Minimal Flavour Violation

With 40 ab^{-1} ~10^{-5} can be reached

To get below that requires more data and new measurements of the tau mass and Y(1S) mass

Additional Information

Masanori Satoh, KEK (June 2020)

Machine Parameters for KEKB/SuperKEKB

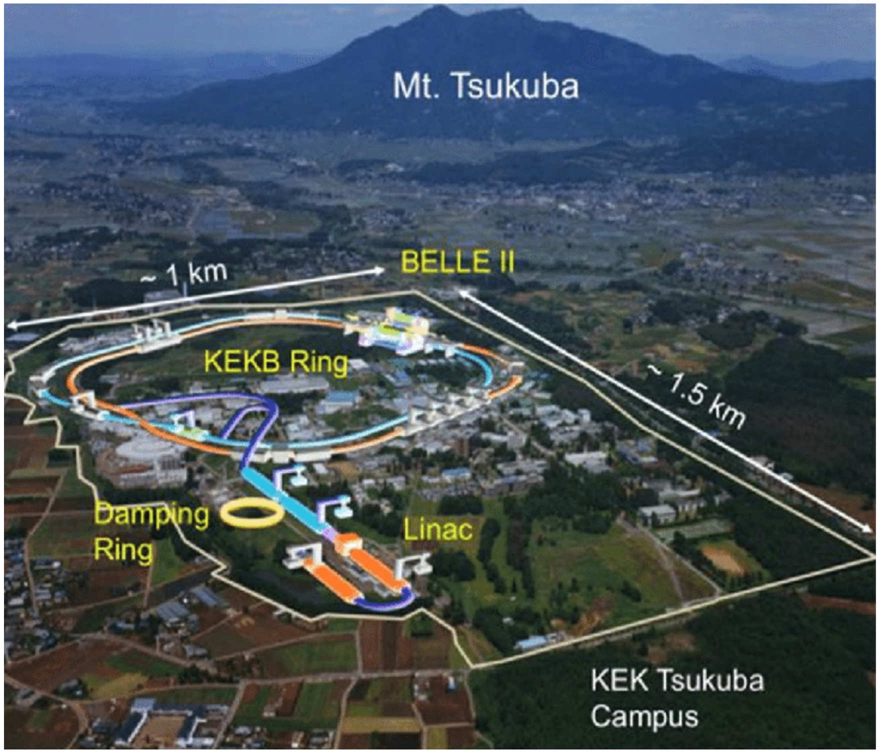
Stage	KEKB (final)		Phase-I		Phase-II		Phase-III (interim)		Phase-III (final)	
Beam	e+	e–	e+	e–	e+	e–	e+	e–	e+	e–
Energy	3.5 GeV	8.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV
Stored current	1.6 A	1.1 A	1.0 A	1.0 A	–	–	1.8 A	1.3 A	3.6 A	2.6 A
Life time (min.)	150	200	100	100	–	–	–	–	6	6
Bunch charge (nC)	primary e- 10 → 1	1	primary e- 8 → 0.4	1	0.5	1	2	2	primary e- 10 → **4**	**4**
Norm. Emittance (γβε) (μmrad)	1400	310	1000	130	200/40 (Hor./Ver.)	150	150/30 (Hor./Ver.)	100/40 (Hor./Ver.)	**100/15** (Hor./Ver.)	**40/20** (Hor./Ver.)
Energy spread	0.13%	0.13%	0.50%	0.50%	0.16%	0.10%	0.16%	0.10%	0.16%	0.07%
Bunch / Pulse	2	2	2	2	2	2	2	2	2	2
Repetition rate	50 Hz		25 Hz		25 Hz		50 Hz		50 Hz	
Simultaneous top-up injection (PPM)	3 rings (LER, HER, PF)		No top-up		Partially		4+1 rings (LER, HER, DR, PF PF-AR)		4+1 rings (LER, HER, DR, PF, PF-AR)	

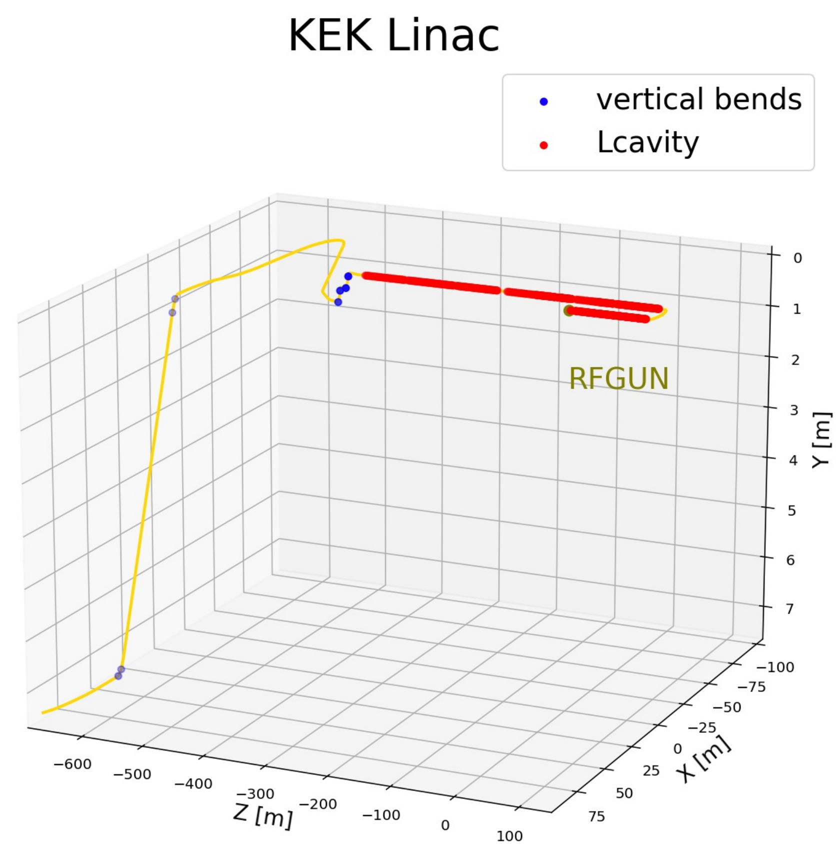
Polarization in SuperKEKB

- These electroweak measurements require highest luminosity possible
- Polarized source not expected to reduce luminosity
- Spin rotators might affect luminosity if not carefully designed to minimize couplings between vertical and horizontal planes
    - Higher order and chromatic effects have to be considered in the design to ensure luminosity is not degraded

KEK Injection Linac polarization BMAD studies

Y. Peng (UVic)

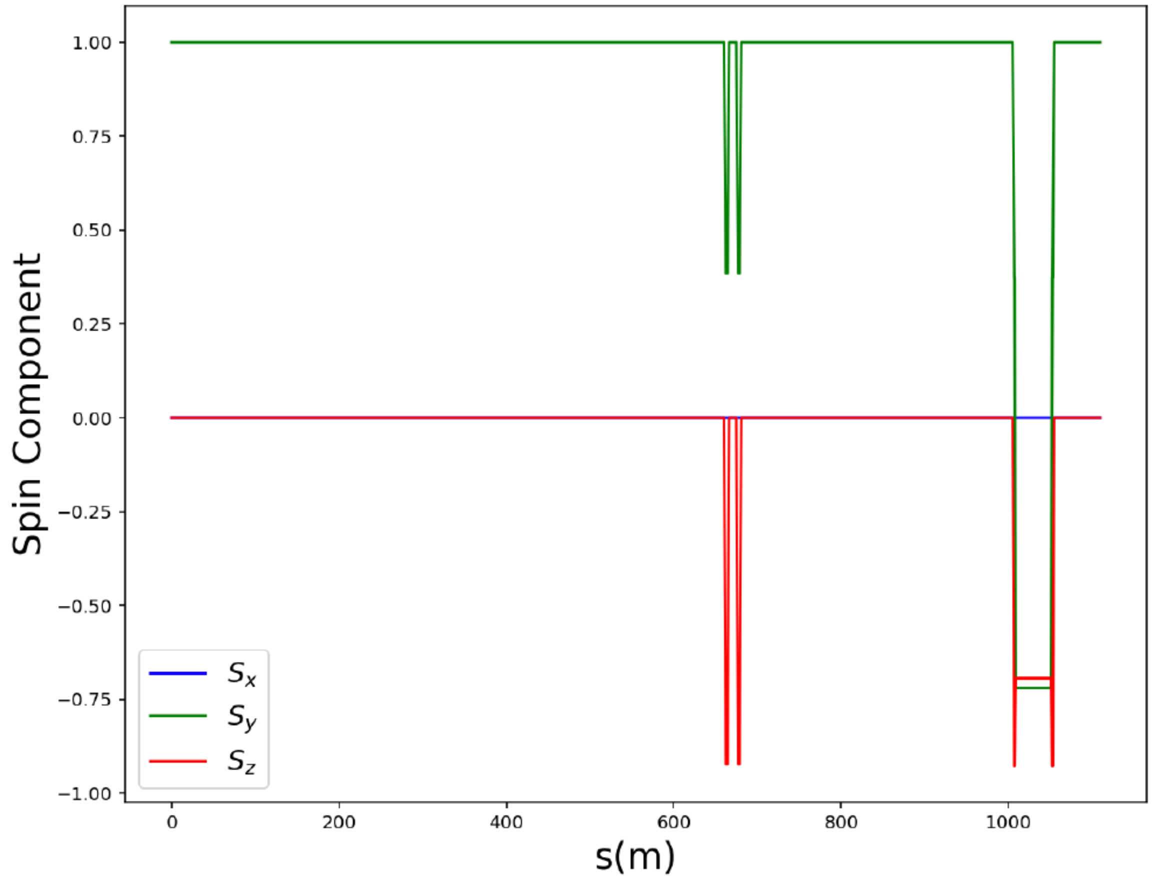




Need transversely polarized beam at the injection point of the e- storage ring (High Energy Ring -HER)

Spin motion in the KEK Injection Linac

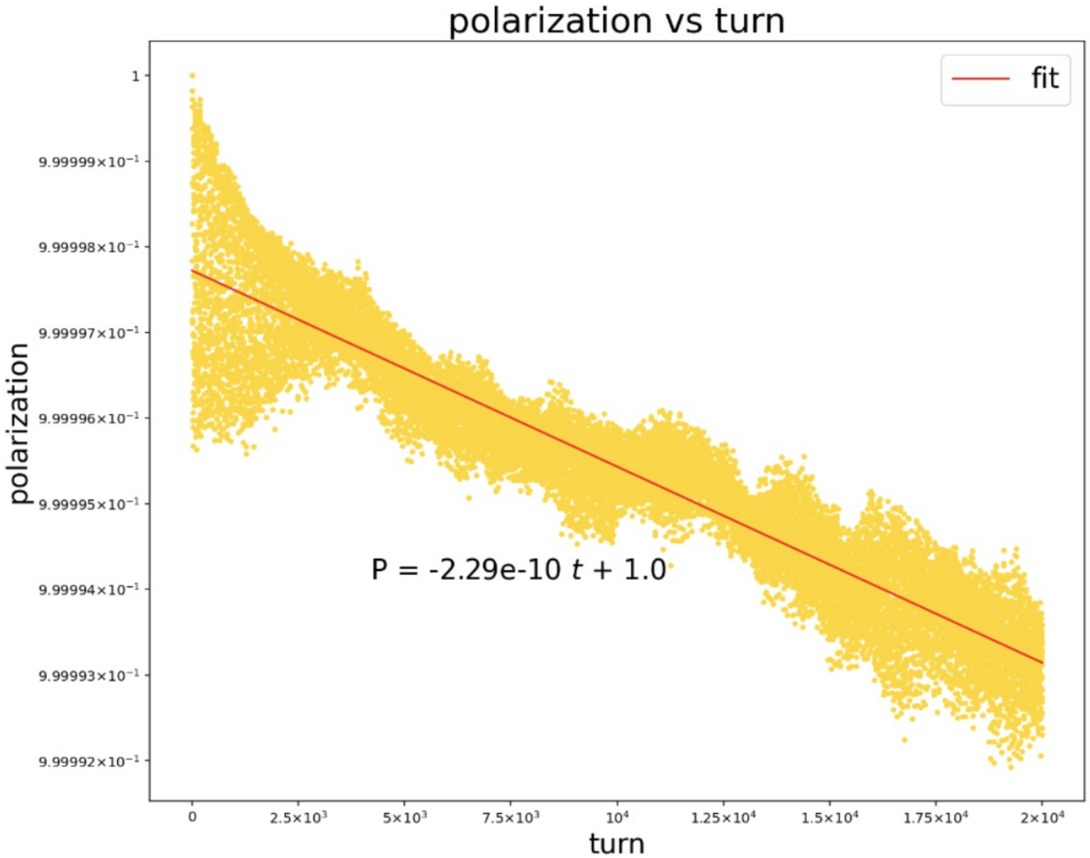
Y. Peng (UVic)



These spin tracking using BMAD show if the electron starts with vertical spin (0,1,0) at the source, after all the vertical beam motion, it will end up with a vertical spin at the injection point, as desired.

Transverse polarization survival rate in HER

Y. Peng (UVic)

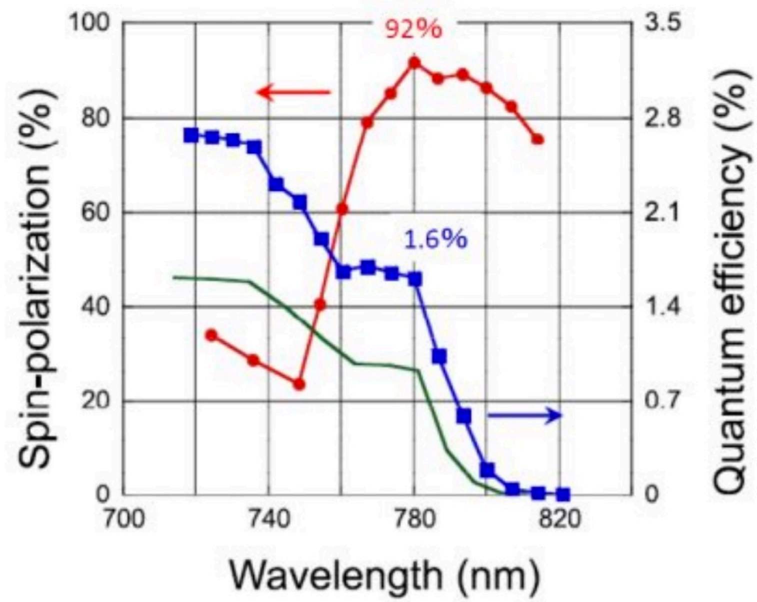


- Tracking 100 particles for 20000 turns in the HER with BMAD
- This study estimates polarization lifetime > 10 hours

Polarization in SuperKEKB

Hardware needs

1. **Low emittance polarized Source**
2. Spin rotators
3. Compton polarimeter



Z. Liptak and M. Kuriki (Hiroshima)

Design source photo-cathode

With 4 nC/bunch

20 mm-mrad vertical emittance

50 mm-mrad horizontal emittance

Current focus is on developing GaAs cathode with a thin Negative Electron Affinity (NEA) surface.

KEK and Hiroshima Groups - work on ILC sources leveraged

Polarization in SuperKEKB

Hardware needs

1. Low emittance Source
2. **Spin rotators**
3. Compton polarimeter

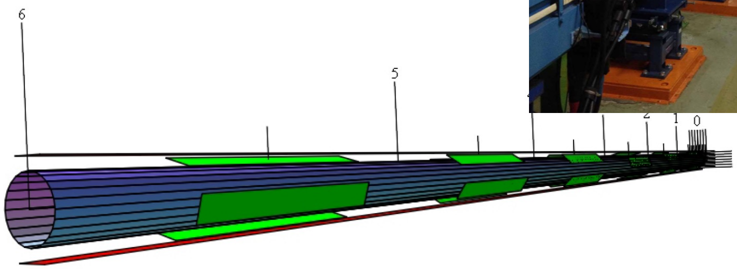
Use of solenoids and dipoles, plus the skew-quadrupoles (needed for decoupling) on either side of interaction point

BINP, ANL, BNL, TRIUMF-Victoria Groups

Polarization in SuperKEKB

Hardware needs

1. Low emittance Source
2. **Spin rotators**
3. Compton polarimeter

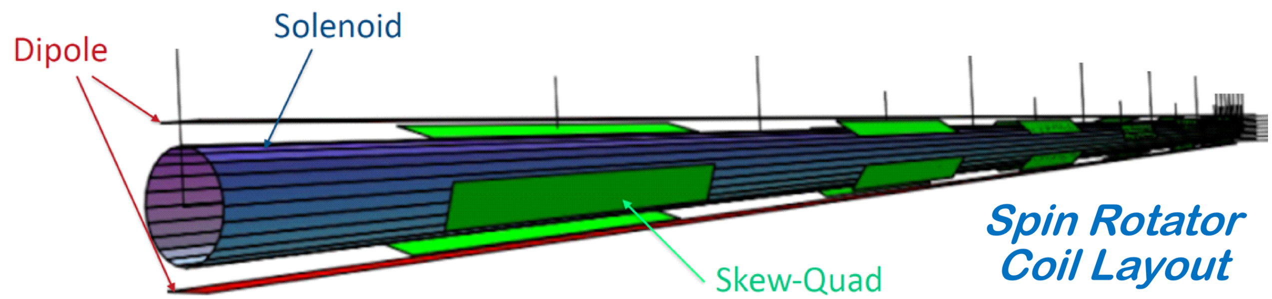


Preliminary studies of two concepts being considered:

1) BINP Concepts: Install Spin-rotator magnets in drift regions, requires repositioning of some magnets in ring
2) Compact Spin Rotator Concept: Combined-function magnets, which would replace two existing dipole magnets on either side of interaction point.

BINP, ANL, BNL, TRIUMF-Victoria Groups

Novel concept: Compact spin rotator



Follows Uli Wienands's (Argonne National Laboratory) idea and direction:

- Replace some existing ring dipoles on both sides of the IP with the dipole-solenoid combined function magnets and keep the original dipole strength to preserve the machine geometry
- Avoids repositioning of other magnets in the ring
- Install 6 skew-quadruple on top of each rotator section to compensate for the x-y plane coupling caused by solenoids
- **Original machine can be recovered by turning off solenoid and skew-quadrupole fields + retune with only the dipoles**

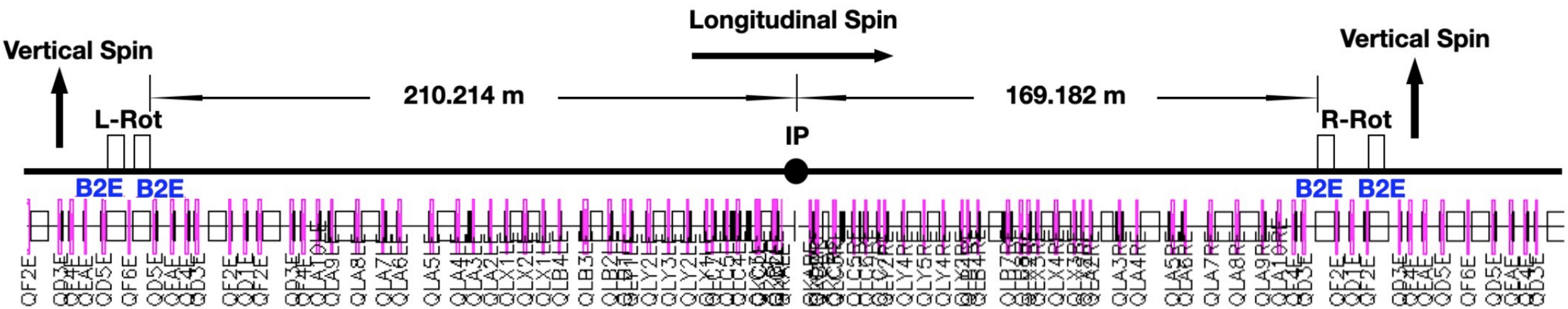
(BNL expertise in construction of direct wind magnets suitable for these magnets)

Compact spin rotator

Working Constraints for the Design

- **Transparency**: Need to maintain the original **beam dynamics,** make the spin rotator transparent to the ring as much as possible (the spin rotator is for the polarization purpose only)
- **Physical constraints**: All new magnets must be manufacturable and installable. Brett Parker (BNL) provided these preliminary physical constraints
  - Solenoid strength can not exceed **5** T
  - Skew-quad can not exceed **30** T/m (~ 3T at the coil)
- Yuhao Peng (UVic) used BMAD, working with Uli Wienands (ANL) & Demin Zhou(KEK) and consulting with David Sagan (Cornell), found a solution under these constraints
  - Demin Zhou provided SAD lattice files for HER translated for BMAD

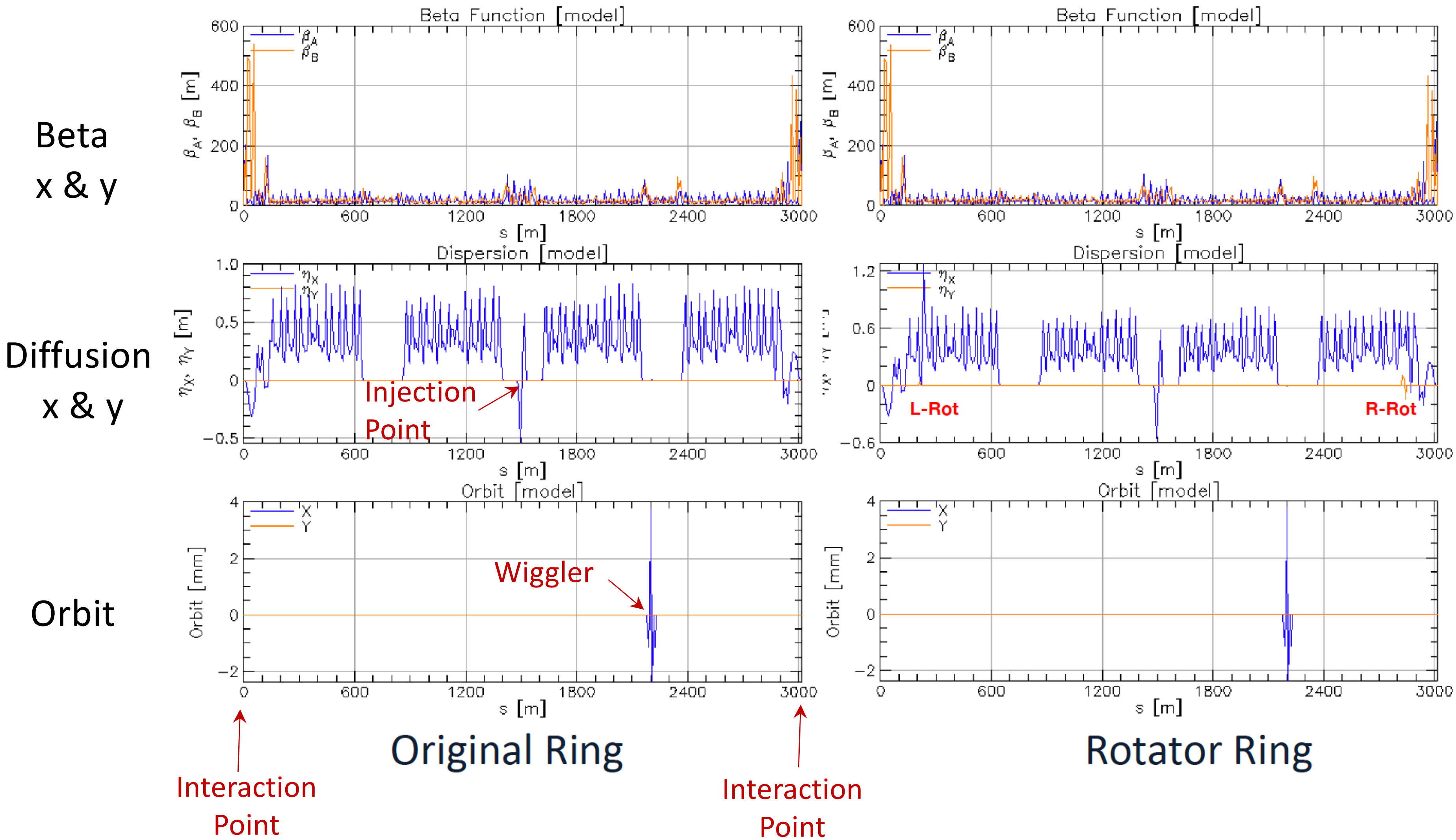
Compact spin rotator



- Left Rotator (L-Rot) rotates the spin from the vertical to the horizontal plane
- Right Rotator (R-Rot) rotates the spin back to the vertical direction
- 4 **B2E** dipoles (using SAD lattice naming convention for HER) shown above to be replaced with the spin rotator magnets

Compact spin rotator

Full lattice Comparison with L/R-Rot installed & matched in the HER ring



Compact spin rotator

Y. Peng (UVic)

Ring parameter comparisons with BMAD following closed-geometry optimization and after matching tune and chromaticity to the original HER

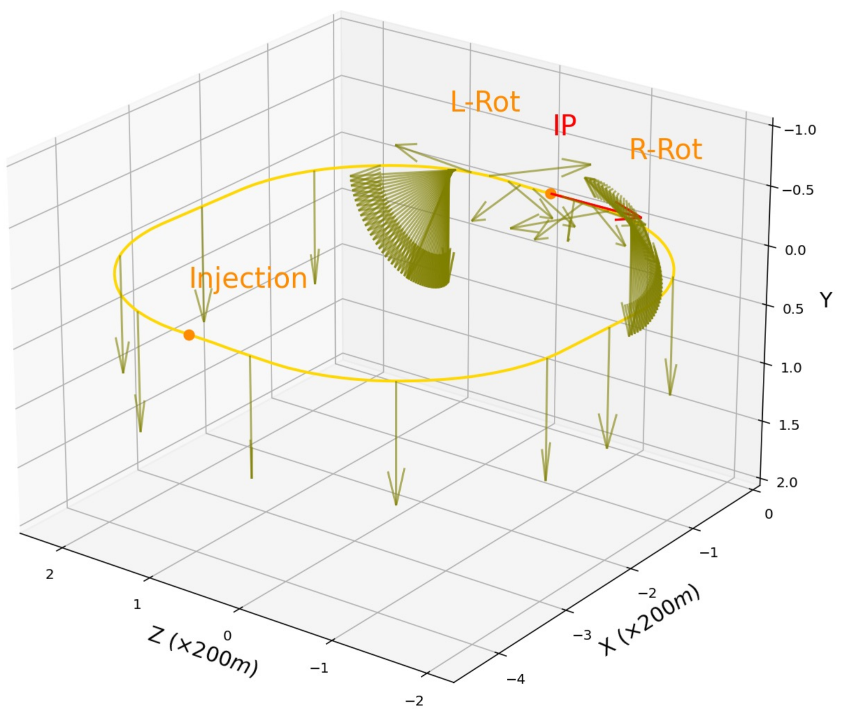
Machine Parameter	Original Ring	Rot Installed
Tune Q_x	45.530994	45.530994
Tune Q_y	43.580709	43.580709
Chromaticity ξ_x	1.593508	1.593508
Chromaticity ξ_y	1.622865	1.622865
Damping partition J_x	1.000064	0.984216
Damping partition J_y	1.000002	1.005266
Emittance ε_x (m)	4.44061×10^{-9}	4.89628×10^{-9}
Emittance ε_y (m)	5.65367×10^{-13}	3.96631×10^{-12}

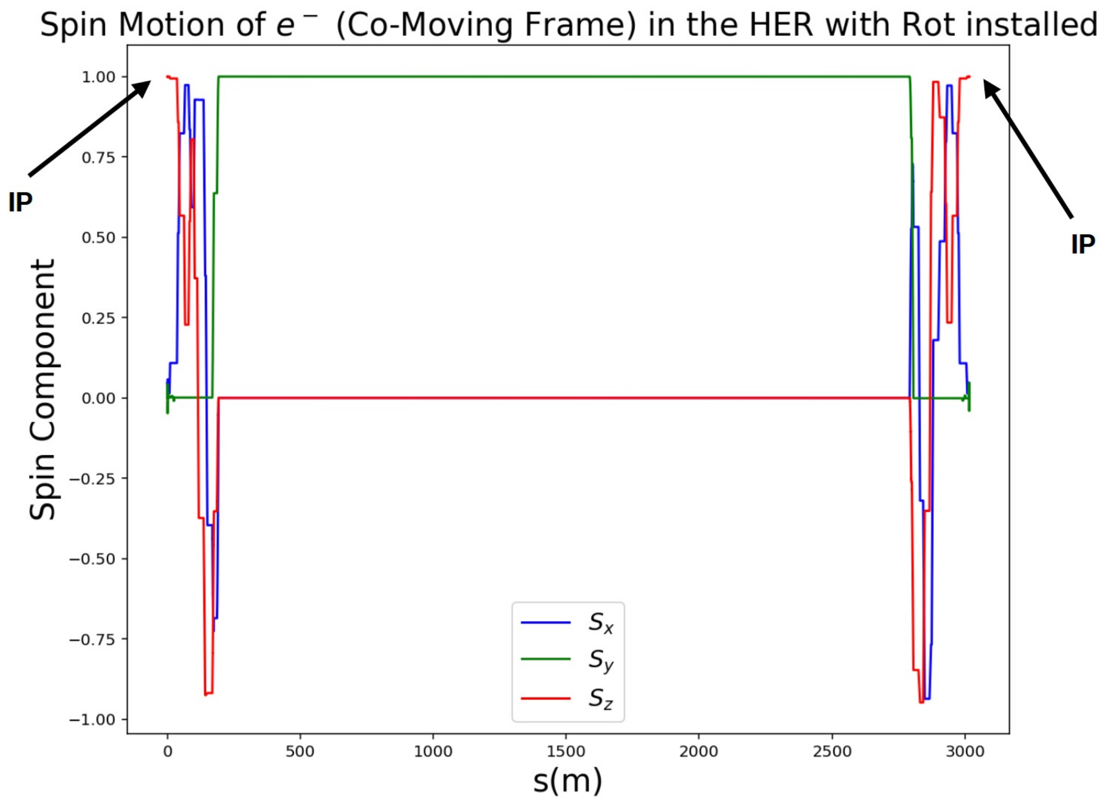
Compact spin rotator

Y. Peng (UVic)

Single Particle Spin Tracking Result

Spin Component	Entrance of the L-Rot	IP	Exit of the R-Rot
X	-0.0000450734	0.0000066698	0.0000538792
Y	0.9999999959	0.0000926945	0.9999999959
Z	-0.0000788085	0.9999999957	-0.0000728110





Compact spin rotator

Y. Peng (UVic)

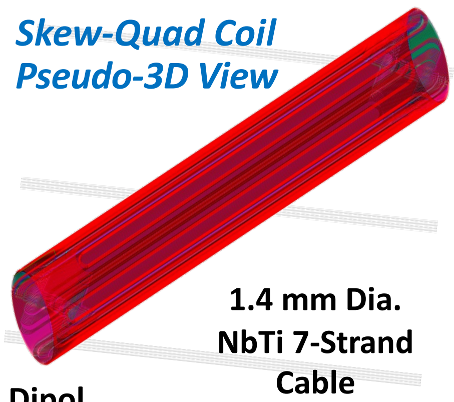
	Solenoid	Field (T)
L-Rot	B2EALSQ	-4.8431
	B2EBLSQ	-2.5774
R-Rot	B2EARSQ	-3.6084
	B2EBRSQ	-3.9420

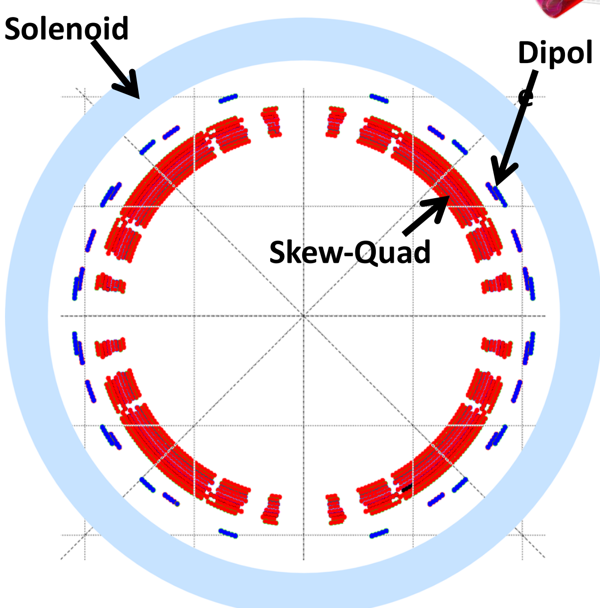
- Solenoid fields below 5 T limit on existing technology
- Maximum skew-quad strength is ~20 T/m, below 30T/m limit on existing technology
- Maximum Ring quad is ~ 14 T/m, which is achievable

Compact Spin Rotator – Coil Feasibility

Brett Parker (BNL)

Skew-Quad Coil Pseudo-3D View





Coil Cross Section at Skew-Quad Center

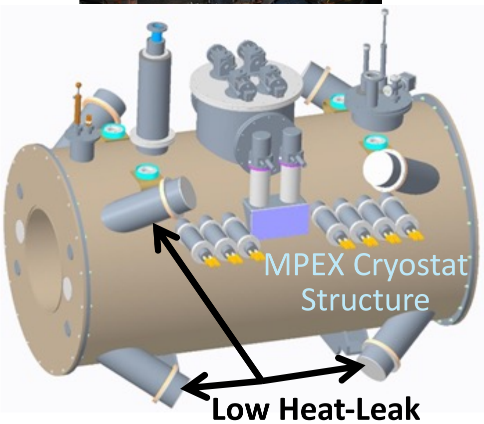
Solenoid Field 4.85 T
Skew Gradient 24 T/m
Dipole Field 0.2 T

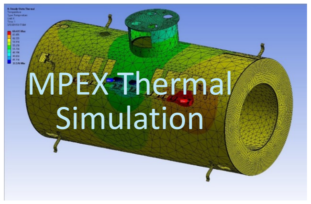
Combined Field @ Skew-Quad is 6.15 T
I_{op} = 729 A
I_q = 1050 A
for 69% Short Sample

- **We plan to use BNL Direct Wind coil production technique to fabricate the nested coil structure.**
- **Results from first pass NbTi coil structure shown here yield desired operating margin at 4.22 K.**
- **Final coil layout requires careful optimization balancing warm-bore, intermediate heat shield, support structure and current lead designs to allow standalone cryocooler operation in tunnel.**
- **Our R&D results will then be used as a basis for a formal request to appropriate funding agency(ies) for the spin rotator component of a future Belle II based Spin Physics upgrade of SuperKEKB.**

Compact Spin Rotator – Cryostat System Feasibility

Brett Parker (BNL)





BNL Design Work: Snake magnet in AGS tunnel and conceptual Oak Ridge MPEX cryostat showing warm bore, low heat-leak support structure, current leads and integrated cooling via cryocoolers.

- **Basic consideration: enough warm bore to accommodate HER beam pipe with water cooling and vacuum features.**
- **Also need some radial space for inner cryostat heat shield.**
- **But skew-quad inner radius should be as small as possible in order to limit peak field (we want to use NbTi cable!).**
- **We are far from any cryogenic supply; so, use cryocoolers.**
- **Cryocooler capacity depends upon heat leak: e.g., the heat shield, support structure and current lead requirements.**
- **For redundancy/rapid maintenance use closed "wet system."**
- **We need a self-consistent pre-conceptual design to find out basic info' such as helium structure (cryogenic safety input).**
- **Feedback from mechanical design used to adjust coil design and ultimately validate magnetic strengths for HER optics.**

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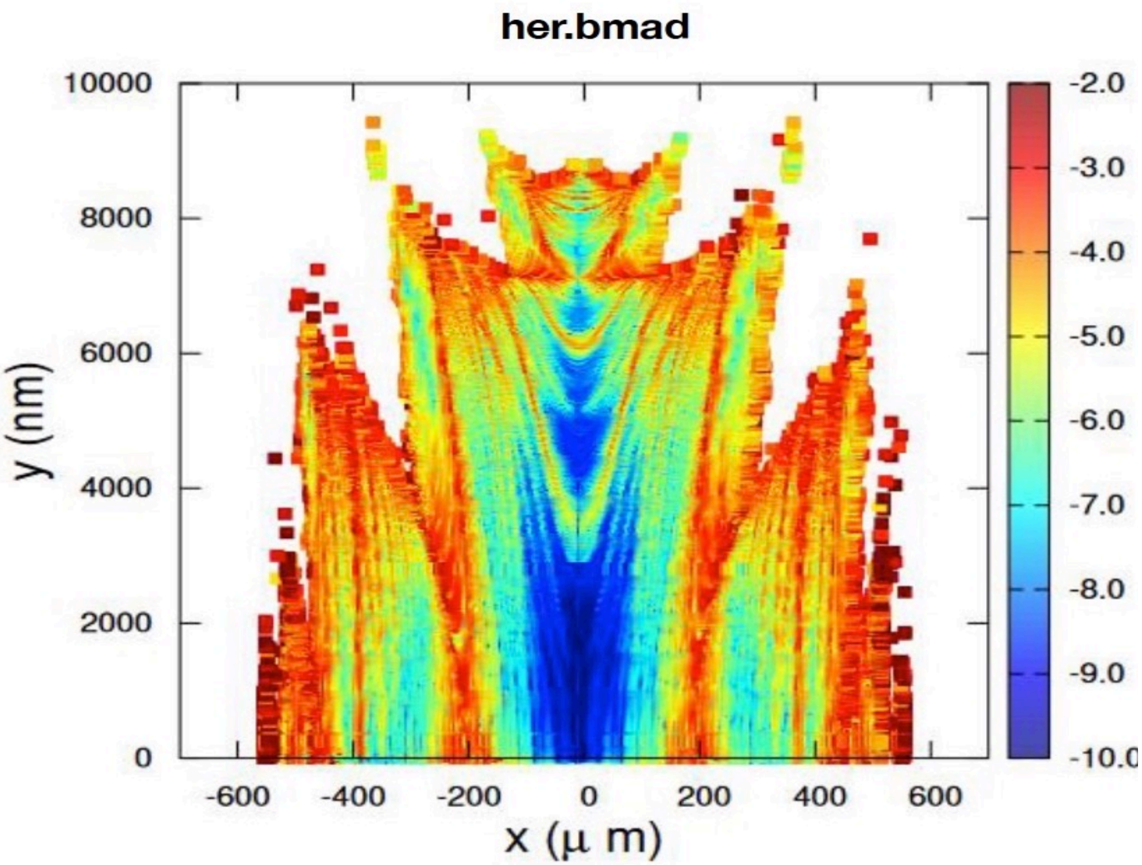
Compact spin rotator

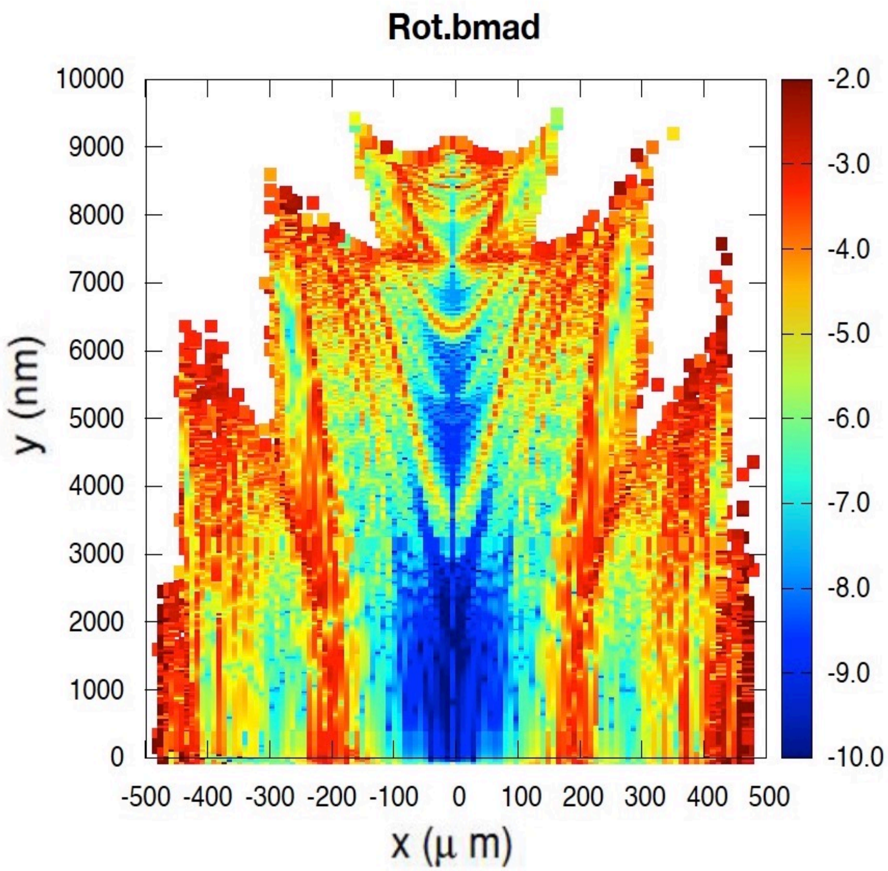
Initial preliminary Frequency Map Analysis (FMA) dynamic aperture studies using BMAD – show no large changes

work by Noah Tessema (UVic)

Original HER Lattice



HER Lattice with spin rotator



Compact spin rotator

Initial preliminary Frequency Map Analysis (FMA) dynamic aperture studies using BMAD – show no large changes

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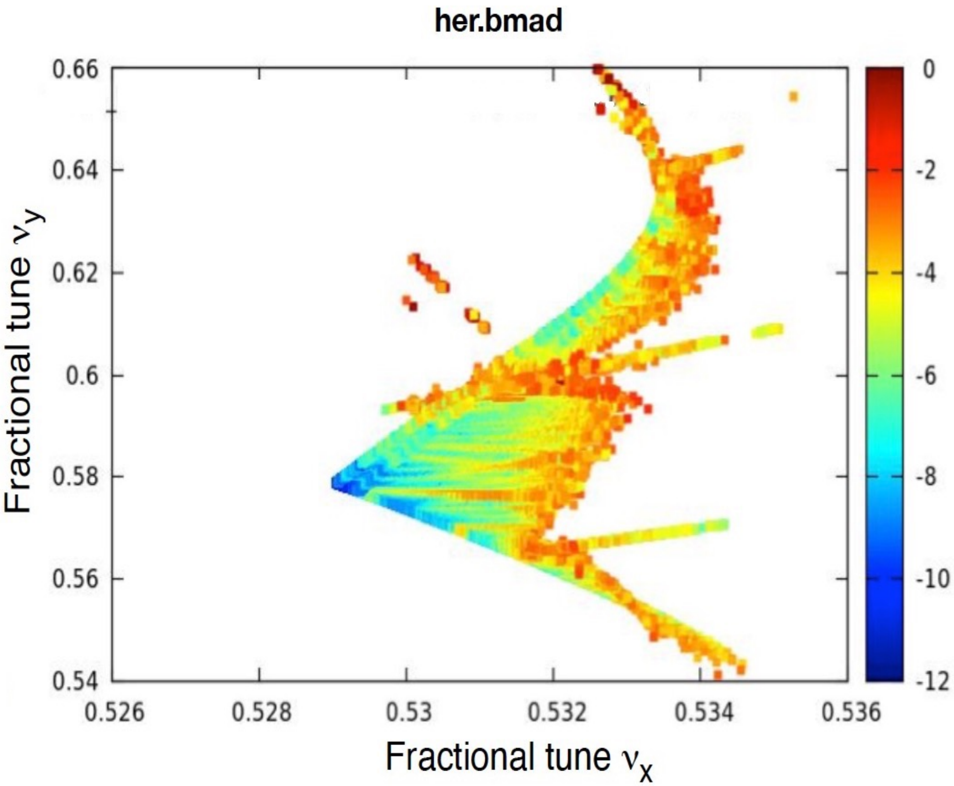
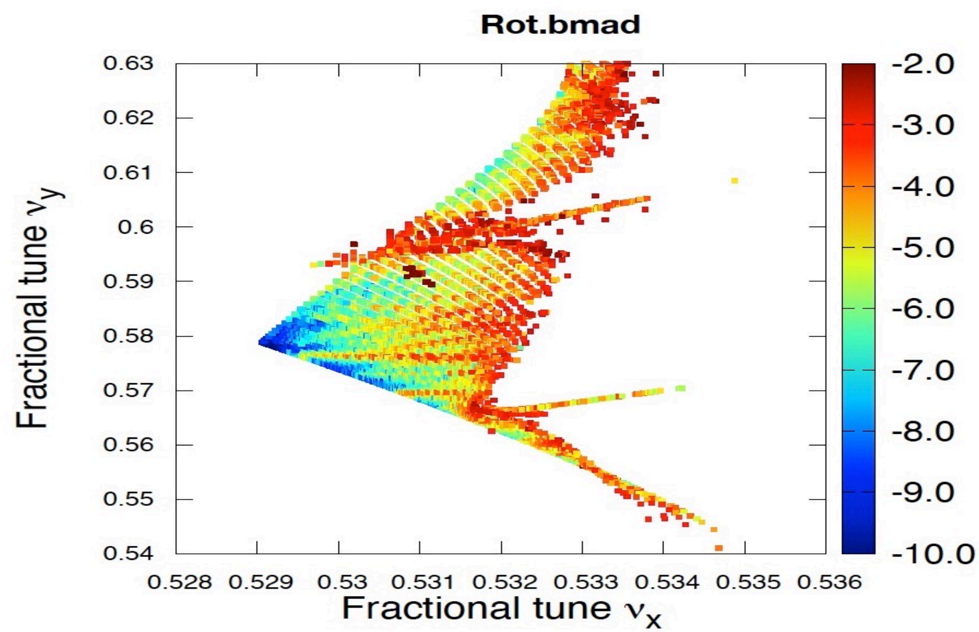
Original HER Lattice



HER Lattice with spin rotator



Next steps: Long Term Tracking studies with radiation damping and radiation fluctuations/quantum excitation

Polarization in SuperKEKB

Hardware needs

1. Low emittance Source
2. Spin rotators
3. **Compton polarimeter**

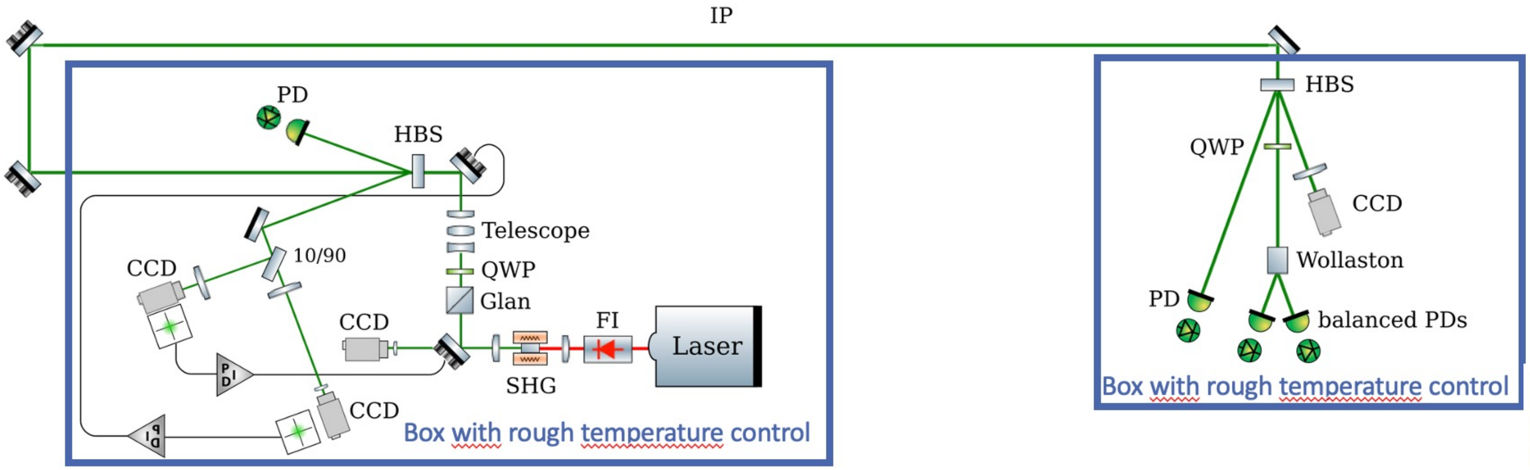
Figure 1: SuperKEKB left side cryostat at KEK.

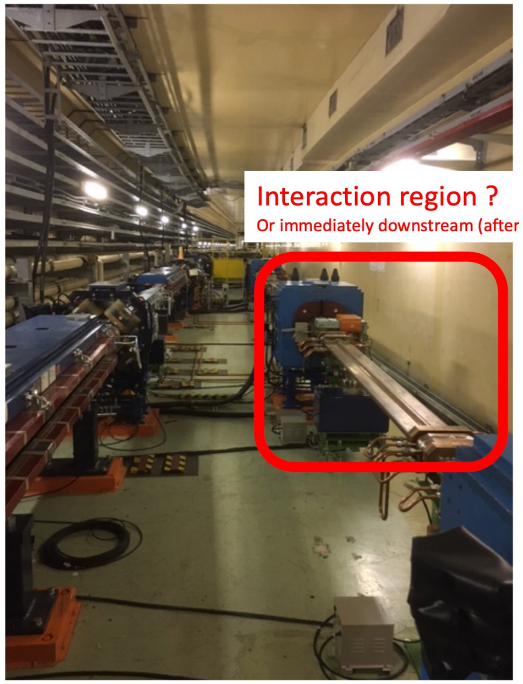
Space is available outside
Cryostats for the final focusing quads

LAL Orsay and U. Manitoba groups

Polarization in SuperKEKB: Compton polarimeter

IJCLab IN2P3 team (A. Martens, Y. Peinaud, F. Zomer, P. Bambade, F. Le Diberder, K. Trabselsi) **HERA Compton Polarimeter experience**





Main challenges related to laser integration in a pre-defined environment
High rep-rate (250MHz) laser considered --> detection capabilities
Polarization control and accurate monitoring is being worked on at IJCLab

Compton Polarimeter Studies of Location – A. Martens(IJCLab)

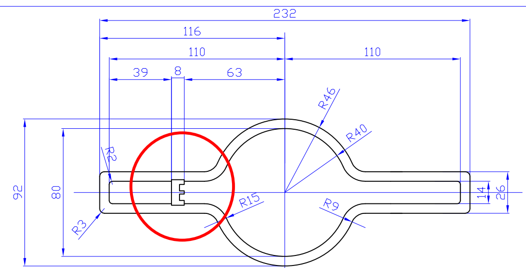
‘minor’ modifications of BLA2LE region

→ actually no modification of magnet needed (contrary to initial suspicion)

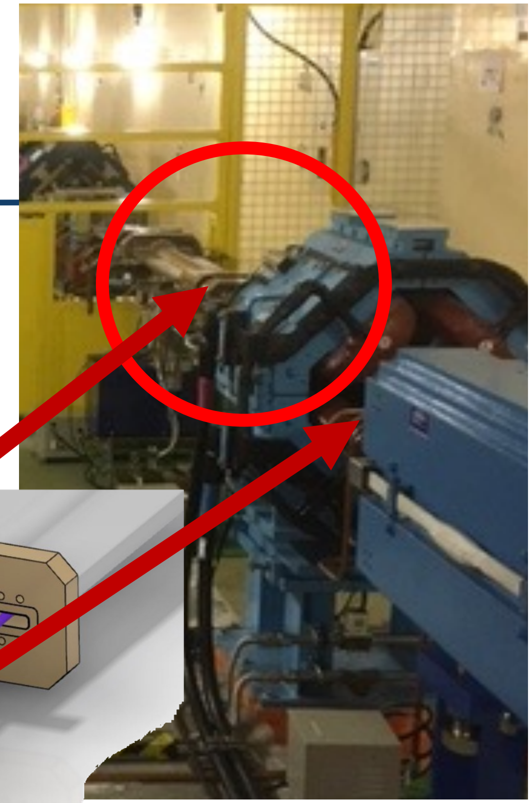
→ NEG pumping not on the ‘right’ side either

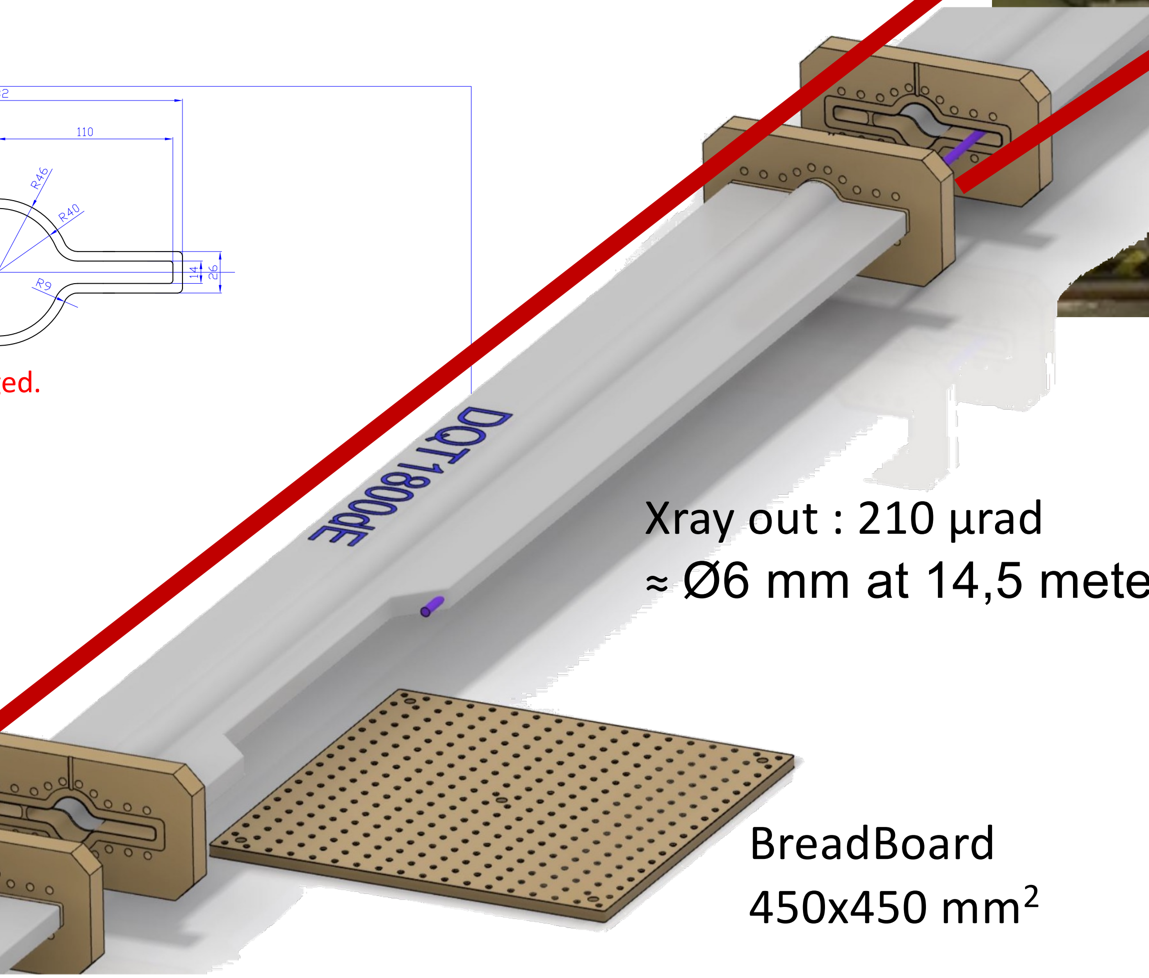
Requires modification of a pipe to let photon beam out

→ proposed pipe modification (validated by T. Ishibashi and D. Zhou)



Pumping port side need to be changed.





Photon detector integration

Xray out : 210 µrad
≈ Ø6 mm at 14,5 meters

BreadBoard
450x450 mm^2

Polarization in SuperKEKB: Compton polarimeter

U. Manitoba team (J. Mammei, M. Gericke, W. Deconinck)

work on Compton polarimeter at JLab - QWeak and MOLLER –

Using HPVMAPs as Compton e- Detector at MOLLER

HVMAPS Beam Test, Fall 2019, DESY

We recently had a beam test of the 8th (2x1 cm^2) and 9th generation chip at DESY.

Version 10 will be submitted for production by the end of this year (full 2x2 cm^2).

If it performs well, version 11 (2020 submission) will be the production chip we use for MOLLER.

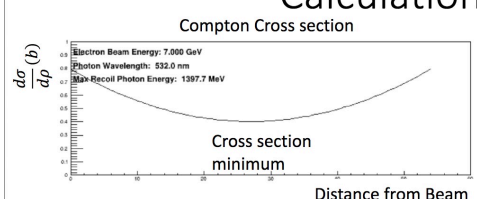
Version 8 at UofM

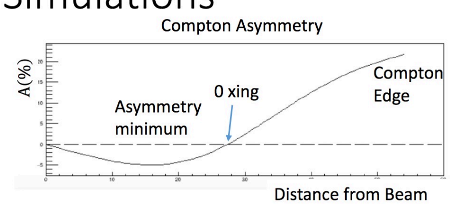
The chip is primarily developed by groups at the U. of Heidelberg and the Karlsruhe Institute of Technology, and intended for various experiments:

- ATLAS
- Mu3e
- PANDA
- P2
- MOLLER

The implementation as a Compton detector is done by the Manitoba group.

Calculations/Simulations





Tau Polarization as Beam Polarimeter

$$P_{z'}^{(\tau-)}(\theta,P_e) = -\frac{8G_F s}{4\sqrt{2}\pi\alpha}\mathrm{Re}\left\{\frac{g_V^l - Q_b g_V^b \Upsilon_{1S,2S,3S}(s)}{1+Q_b^2\Upsilon_{1S,2S,3S}(s)}\right\}\left(g_A^\tau \frac{|\vec{p}|}{p^0} + 2g_A^e \frac{\cos\theta}{1+\cos^2\theta}\right)$$

$$+ P_e \frac{\cos\theta}{1+\cos^2\theta}$$

- Dominant term is the polarization forward-backward asymmetry (A^{pol}_{FB}) whose coefficient is the beam polarization
- Measure tau polarization as a function of θ for the separately tagged beam polarization states
- Expect ~0.5% absolute precision of the polarization at the interaction point – includes transport effects, lumi-weighting, stray e^+ polarization
- Method assumes tau neutrino is 100% left handed – motivates validation of this

Tau Polarization as Beam Polarimeter

- Advantages:
  - Measures beam polarization at the IP: biggest uncertainty in Compton polarimeter measurement is likely the uncertainty in the transport of the polarization from the polarimeter to the IP.
  - It automatically incorporates a luminosity-weighted polarization measurement
  - If positron beam has stray polarization, its effect is automatically included
- C. Miller (UVic) deployed this with *BABAR* data Preliminary (soon to be published) results with *BABAR* Υ(4S) dataset (432fb^{-1}) yield 0.3% combined statistical $\oplus$ systematic uncertainty from only $\tau \to \rho\, \nu$ with $\tau \to (e/\mu)\nu\nu$ tag

Upgrading SuperKEKB with polarized electrons

Opens New Windows for Discovery with Belle II

- Extremely rich and unique high precision electroweak program
- Probe of Dark Sector
- Tau Lepton Magnetic Form factor F_2(10GeV) → τ g-2
- Polarized Beam also provides:
  - Improved precision measurements of τ Michel Parameters, electric dipole moment (EDM)
  - Reduces backgrounds in $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ precision leading to significantly improved sensitivities
- hadronic studies

CHIRAL BELLE PHYSICS PROGRAM

A New Path for Discovery in a Precision Neutral Current Electroweak Program

- Left-Right Asymmetries (A_{LR}) yield high precision measurements of the neutral current vector couplings (g_V) to each of five fermion flavours, *f* :
  - beauty (D-type)
  - charm (U-type)
  - tau
  - muon
  - electron

$$\text{Recall: } g_V^f \text{ gives } \theta_W \text{ in SM} \begin{cases} g_A^f = T_3^f \\ g_V^f = T_3^f - 2Q_f \sin^2\theta_W \end{cases}$$

as well as light quarks

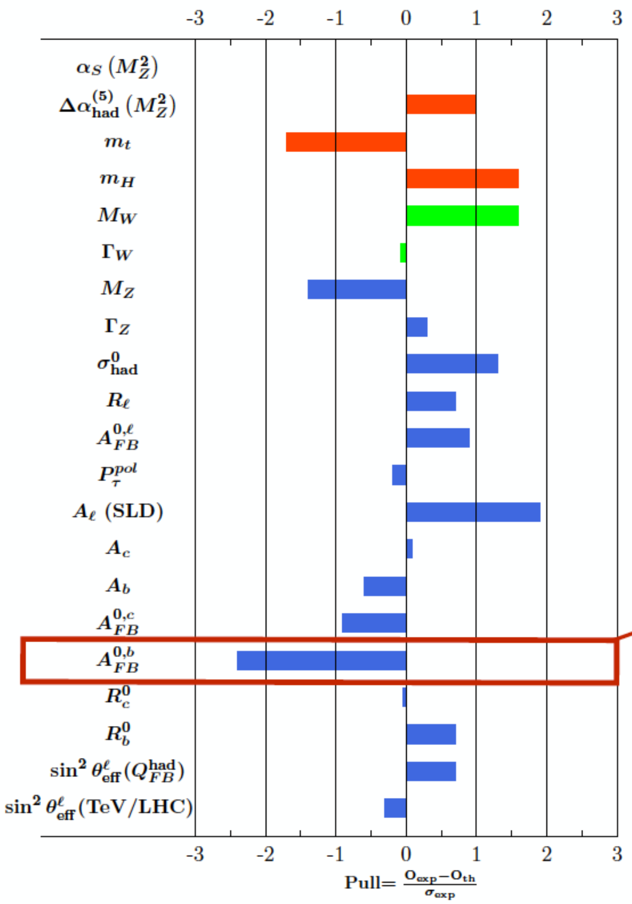
T_3 = -0.5 for charged leptons and D-type quarks
+05 for neutrinos and U-type quarks

From Jorge de Blas's talk this morning on EW Parameter Fits:

The Standard Model Electroweak fit

SM fit results: Predictions for EWPO

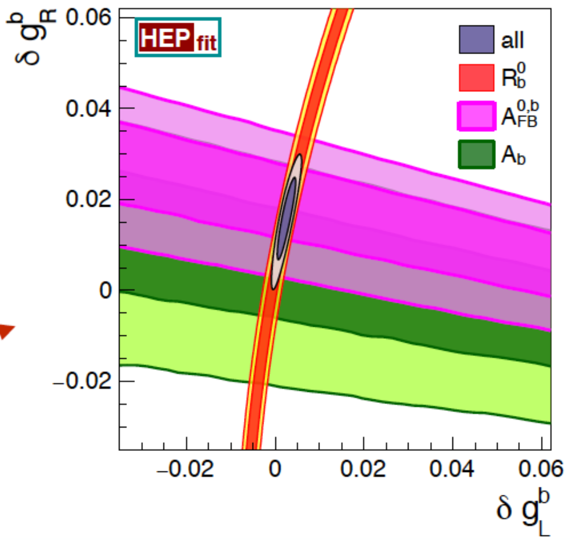
Also good agreement between indirect determination of EWPO and experimental measurements, with one notable exception



~2.5 σ discrepancy in forward-fackward asymmetry of the b quark

Requires modifications of (right-handed) *Zbb* couplings

$$g^b_{L,R} = g^{b\,\mathrm{SM}}_{L,R} + \delta g^b_{L,R}$$



	Fit result	Correlations	
δg^b_R	0.017 ± 0.007	1.00	
δg^b_L	0.003 ± 0.001	0.89	1.00

‘Chiral Belle’ -> Left-Right Asymmetries

•Measure difference between cross-sections with left-handed beam electrons and right-handed beam electrons

•Same technique as SLD A_{LR} measurement at the Z-pole giving single most precise measurement of :

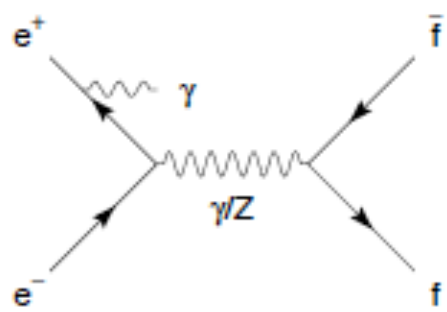
$$\sin^2\theta_{eff}^{lepton} = 0.23098 \pm 0.00026$$

•At 10.58 GeV, polarized e^- beam yields product of the neutral axial-vector coupling of the electron and vector coupling of the final-state fermion via Z-γ interference:

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

$$\propto T_3^f - 2Q_f \sin^2\theta_W$$

(for s-channel Born)



‘Chiral Belle’ Left-Right Asymmetries

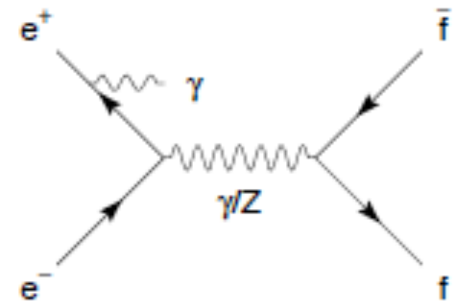
Electron helicity would be chosen randomly pulse-to-pulse by controlling the circular polarization of the source laser illuminating a GaAs photocathode.

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

$$\propto T_3^f - 2Q_f \sin^2\theta_W$$

$$\langle Pol \rangle = 0.5\left\{\left(\frac{N_R^{e-} - N_L^{e-}}{N_R^{e-} + N_L^{e-}}\right)_R - \left(\frac{N_R^{e-} - N_L^{e-}}{N_R^{e-} + N_L^{e-}}\right)_L\right\}$$

(for s-channel Born)

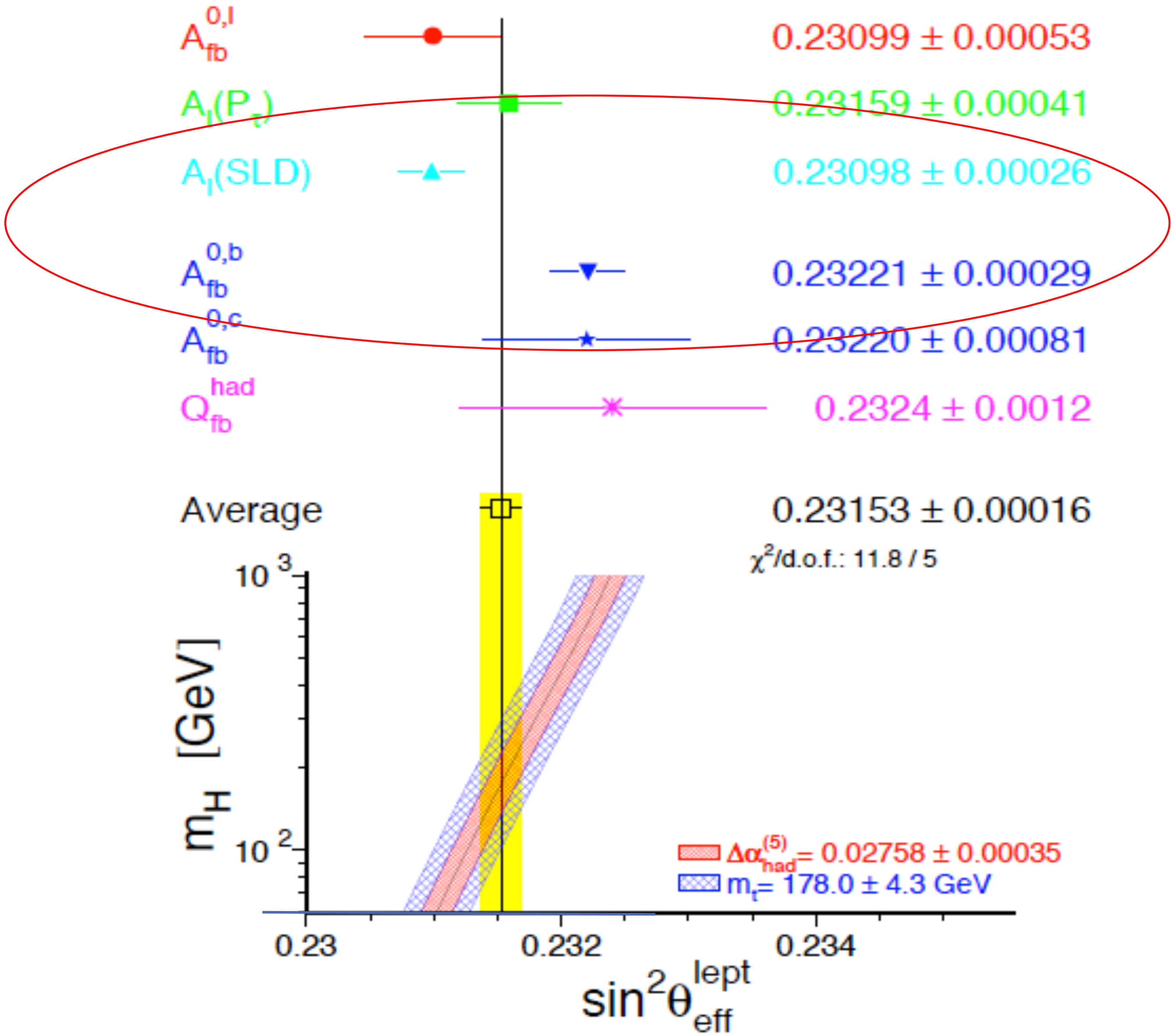


Source generates mainly right-handed electrons

Source generates mainly left-handed electrons

For A_{LR} calculation with NLO corrections for mu-pair final state, see:
Aleksejevs, Barkanova, Roney, Zykunov “NLO radiative corrections for Forward-Backward and Left-Right Asymmetries at a B Factory”, arXiv:1801.08510

Existing tension in data on the Z-Pole:



Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

3.2σ comparing only A_{LR} (SLC) and $A^{0,b}_{fb}$(LEP)

International collaboration of Accelerator and Particle Physicists

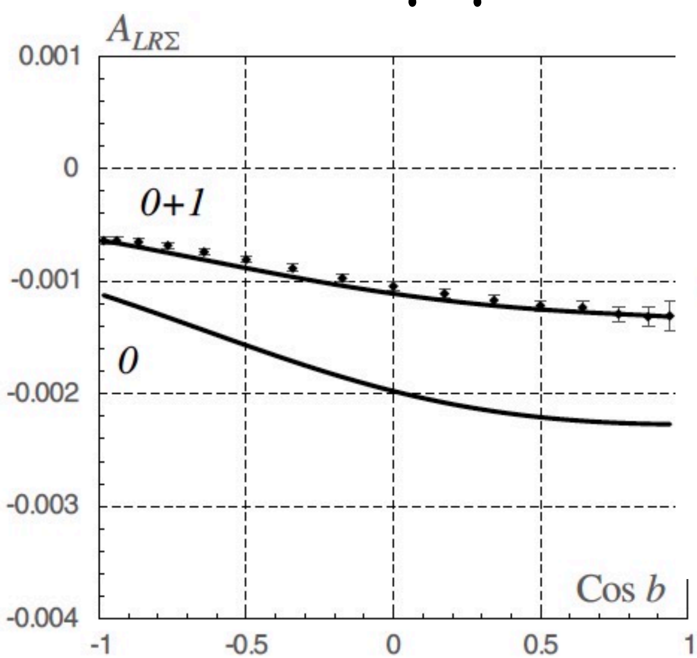
➤ **Theorists currently working on SM Electroweak calculations:**

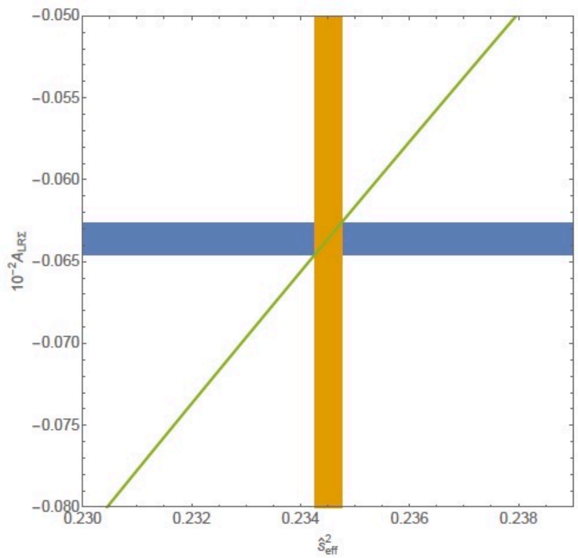
Aleks Aleksejevs & Svetlana Barkanova, (Memorial U Newfoundland),
Vladimir Zykunov & Yu.M.Bystritskiy (DUBNA)

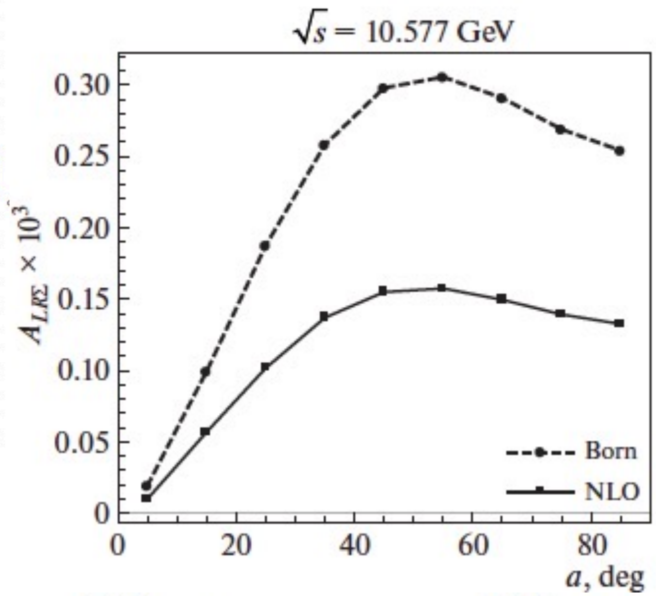
$e^+e^- \rightarrow \mu^+\mu^-$

$A_{LR}^{\mu\mu}$ vs $\sin^2\theta_W^{eff}$

$e^+e^- \rightarrow e^+e^-$







$$A^C_{LR\Sigma} = A^C_{LR\Sigma}(a) = \frac{\Sigma^C_L - \Sigma^C_R}{\Sigma^C_L + \Sigma^C_R}$$

$$\Sigma^C_L = \int_{\cos b}^{\cos a} \sigma^C_L \cdot d(\cos\theta), \quad \Sigma^C_R = \int_{\cos b}^{\cos a} \sigma^C_R \cdot d(\cos\theta)$$

$$\Sigma^C_L = \int_{-\cos a}^{\cos a} \frac{d\sigma^C_{L0}}{dc} \cdot dc, \quad \Sigma^C_R = \int_{-\cos a}^{\cos a} \frac{d\sigma^C_{R0}}{dc} \cdot dc.$$

a=10° & energy of photons < 2GeV

Phys.Rev. D101 (2020) no.5, 053003

PHYSICS OF ATOMIC NUCLEI Vol. 83 No. 3 2020

Recent generator: ReneSANCe

Renat Sadykov (JINR,Dubna) and Vitaly Yermolchyk (JINR Dubna&INP,Misnk), "Polarized NLO EW e+e− -> e+e− cross section calculations with ReneSANCe-v1.0.0", *Comput.Phys.Commun.* 256 (2020) 107445; 2001.10755 [hep-ph]

New generator with beam polarization capable of producing Bhabhas.

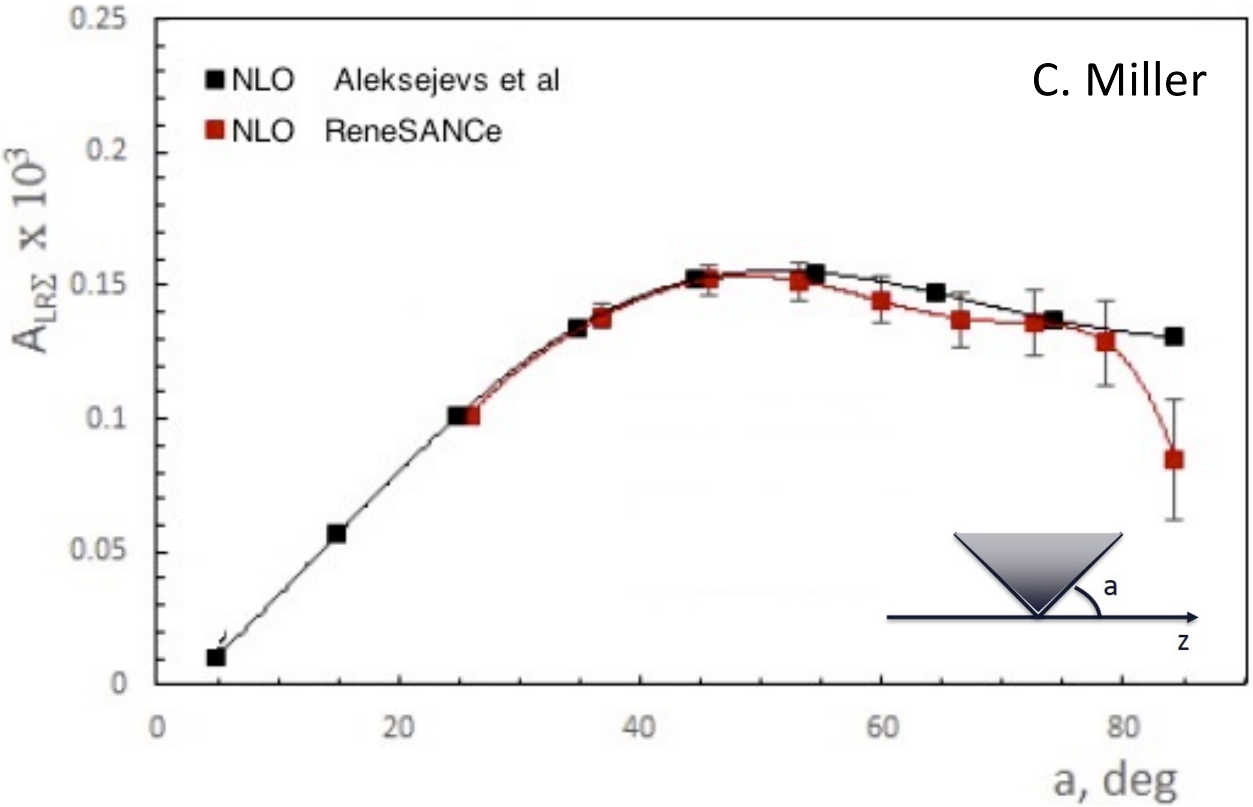
Polarization in each beam and special mode to efficiently calculate A_{LR} without event generation output.

Caleb Miller (Victoria) has worked with authors on use of ReneSANCe for 10.58GeV SuperKEKB polarization application. Now has single beam polarization.

Comparing ReneSANCe with results published in:

A. G. Aleksejevs (Memorial U, Canada), S.G.Barkanova (Memorial U, Canada), Yu.M.Bystritskiy (JINR, Dubna), and V. A. Zykunov (JINR, Dubna& Gomel), "Electroweak Corrections with Allowance for Hard Bremsstrahlung in Polarized Bhabha Scattering", Physics of Atomic Nuclei, 2020, Vol. 83, No. 3, pp. 463–479

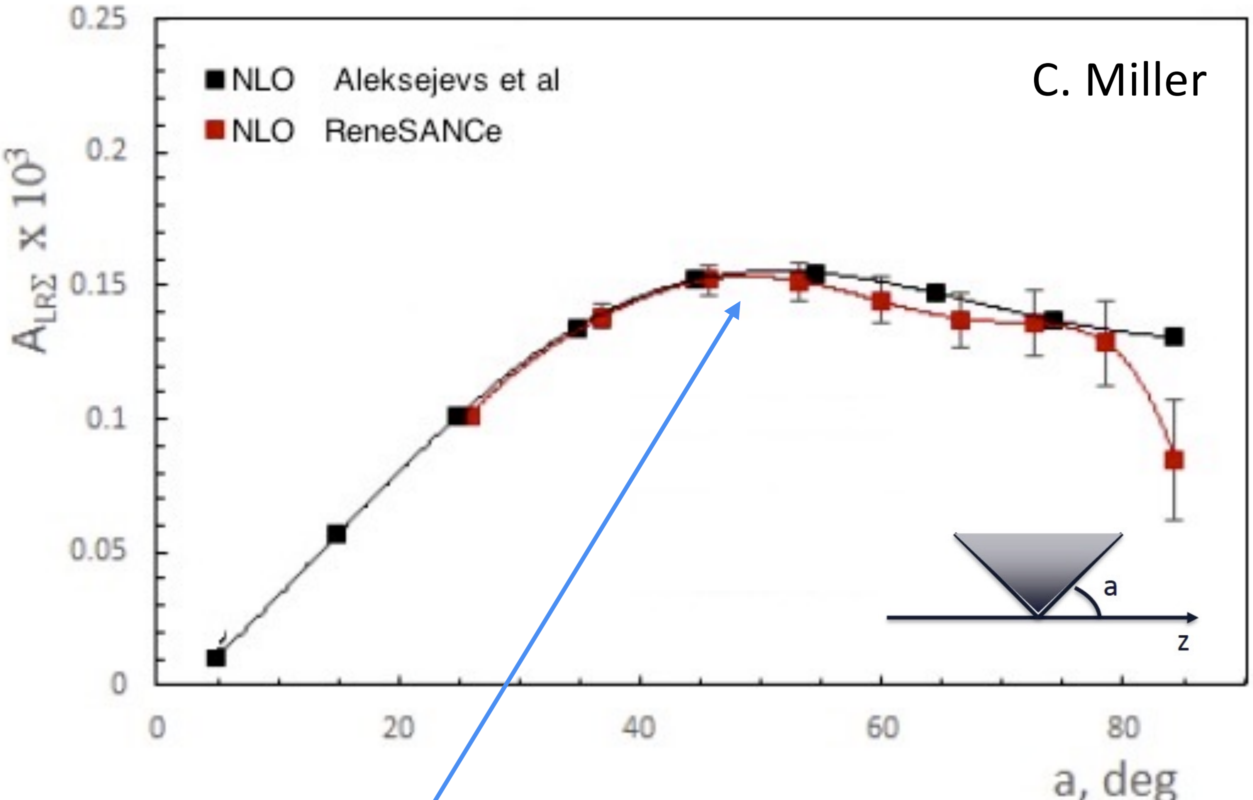
ReneSANCe *cf* Aleksejevs *et al*



A_{LR} as a function of acceptance angle where z is e- direction in centre-of-mass

Using M_W variations with ReneSANCe, can find $\delta \sin^2 \theta_W \ / \ \delta A_{LR}$

ReneSANCe *cf* Aleksejevs *et al*



A_{LR} as a function of acceptance angle where z is e- direction in centre-of-mass

Using M_W variations with ReneSANCe, can find $\delta \sin^2 \theta_W$ / δA_{LR}

Belle II has published a luminosity paper with Bhabha acceptance in the central part of the detector:

F. Abudinén et al, Belle II Collaboration, Chin.Phys.C 44 (2020) 2, 021001

Reports: Cross-section = 17.4nb, efficiency=36%

With 70% polarized electron beam get unprecedented precision for neutral current vector couplings

Final State Fermion	SM A_{LR} (statistical error & sys from 0.5% P_e) For 40/ab	Relative Error
b-quark (selection eff.=0.3)	-0.0200 ±0.0001	0.5%
c-quark (eff. = 0.3)	+0.00546 ±0.00003	0.5%
tau (eff. = 0.25)	-0.00064 ±.000015	2.4%
muon (eff. = 0.5)	-0.00064 ±.000009	1.5%
Electron (barrel) (eff. = 0.36)	+0.00015 ±.000003	2.0%

1 - Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

$\sin^2 \Theta_W$ - all LEP+SLD measurements combined WA = 0.23153 ± 0.00016

With 70% polarized electron beam get unprecedented precision for neutral current vector couplings

Final State Fermion	SM g_V^f (M_Z)	World Average[1] g_V^f	Chiral Belle σ 20 ab^{-1}	Chiral Belle σ 40 ab^{-1}	Chiral Belle σ $\sin^2\Theta_W$ 40 ab^{-1}
b-quark (eff.=0.3)	-0.3437 ± .0001	-0.3220 ±0.0077 (high by 2.8σ)	0.002 Improve x4	0.002	0.003
c-quark (eff. = 0.3)	+0.1920 ±.0002	+0.1873 ± 0.0070	0.001 Improve x7	0.001	0.0008
Tau (eff. = 0.25)	-0.0371 ±.0003	-0.0366 ± 0.0010	0.001 (similar)	0.0008	0.0004
Muon (eff. = 0.5)	-0.0371 ±.0003	-0.03667±0.0023	0.0007 Improve x 3	0.0005	0.0003
Electron (17nb, eff=0.36)	-0.0371 ±.0003	-0.03816 ±0.00047	0.0009	0.0006	0.0003

1 - Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

$\sin^2\Theta_W$ - all LEP+SLD measurements combined WA = 0.23153 ± 0.00016

$\sin^2\Theta_W$ - Chiral Belle combined leptons with 40 ab^{-1} have error ~current WA

Upgrading SuperKEKB with e- Polarized Beams: Chiral Belle → unique probe of New Physics

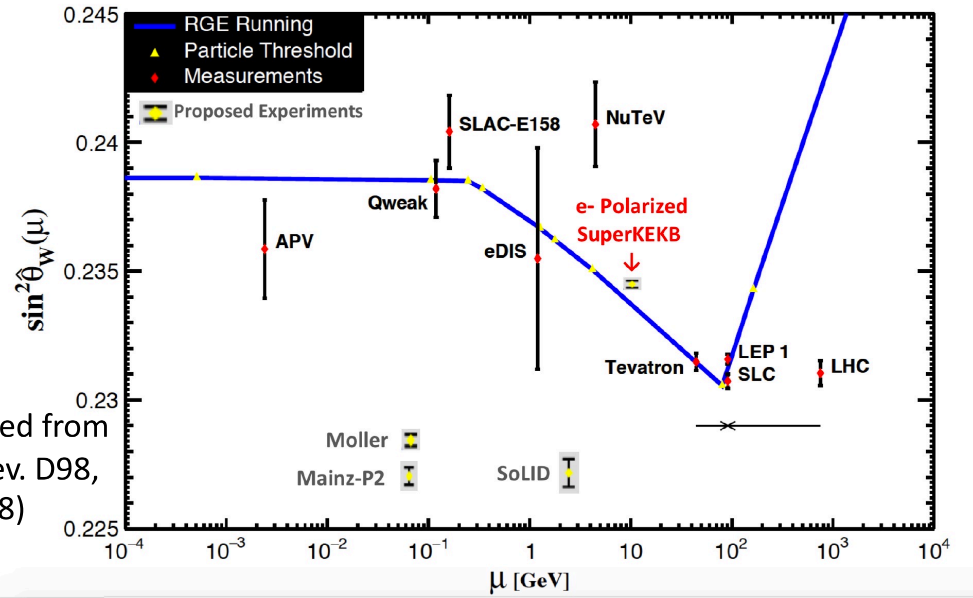


Figure Adapted from PDG Phys. Rev. D98, 030001 (2018)

Chiral Belle: σ = 0.00018 (40ab^{-1}) with only leptonic states
Precision probe of running of the weak mixing angle

Being away from Z-pole opens NP sensitivities not available at the pole, including Z_{dark}

Most precise measurements at any energy for

- **beauty (4x better than World Average, 20ab^{-1})**
- **charm (7x better than World Average, 20ab^{-1})**
- **muons (4 x better than than WA)** (tau and electrons comparable precision as WA)

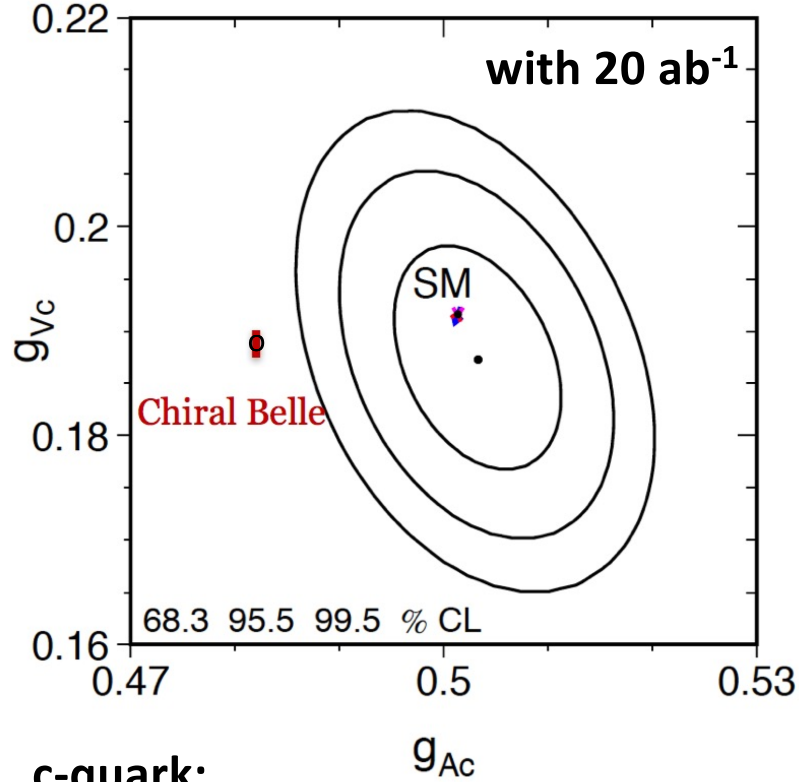
***Uniquely Probes Neutral Current Universality vector coupling of b to that of c*:**
σ (g^b_V/ g^c_V)< 0.3%,
order of magnitude lower than WA

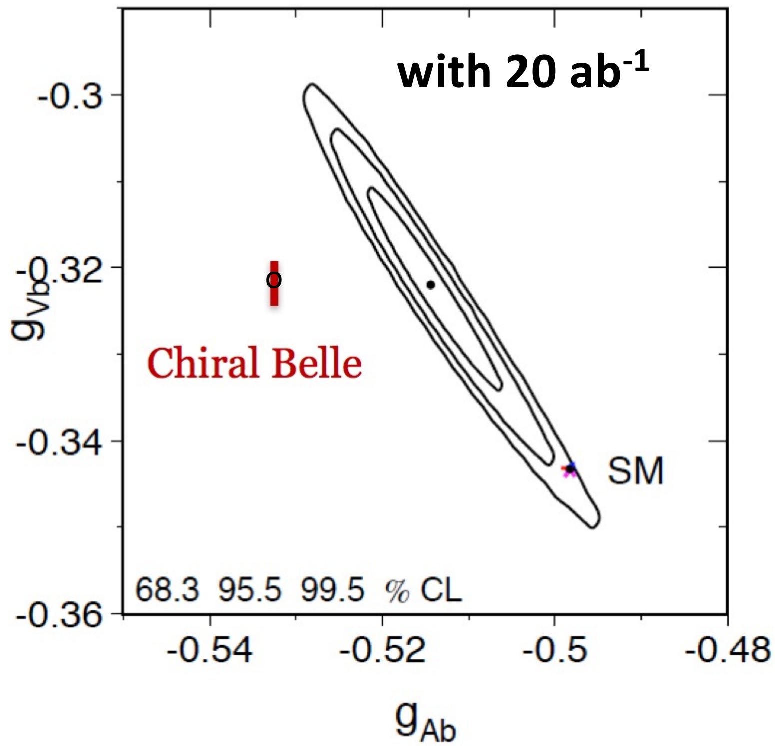
Measurements of $\sin^2\theta_{eff}^{lepton}$ of using lepton pairs of comparable precision to that obtained by LEP/SLD, except at 10.58GeV

Probes both lower mass Z_{dark} and Z' > TeV scale

Unique probe when Z_{dark} and Z' only couples to leptons, including taus

Upgrading SuperKEKB with e- Polarized Beams: Chiral Belle → unique probe of New Physics





Adapted from Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

c-quark:
Chiral Belle ~7 times more precise

b-quark:
Chiral Belle ~4 times more precise

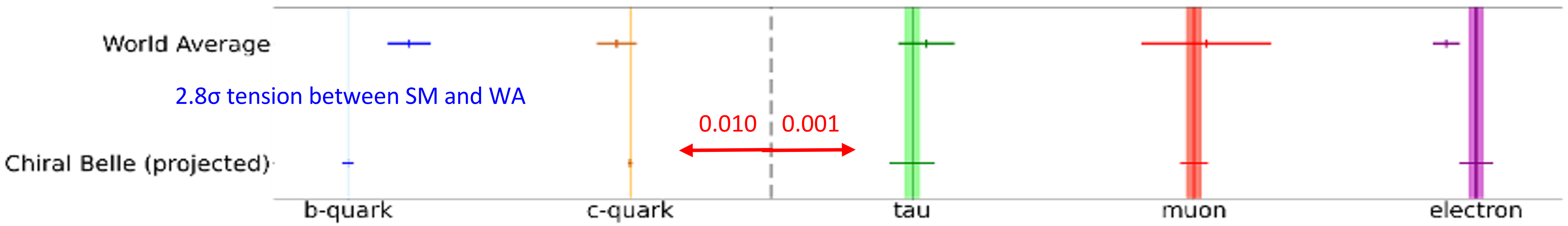
***Probes Neutral Current Universality vector coupling of b to that of c*:**

$\sigma(g^b_V/g^c_V) < 0.3\%$ (40 ab^{-1}) → order of magnitude lower than WA

Precision electroweak measurements

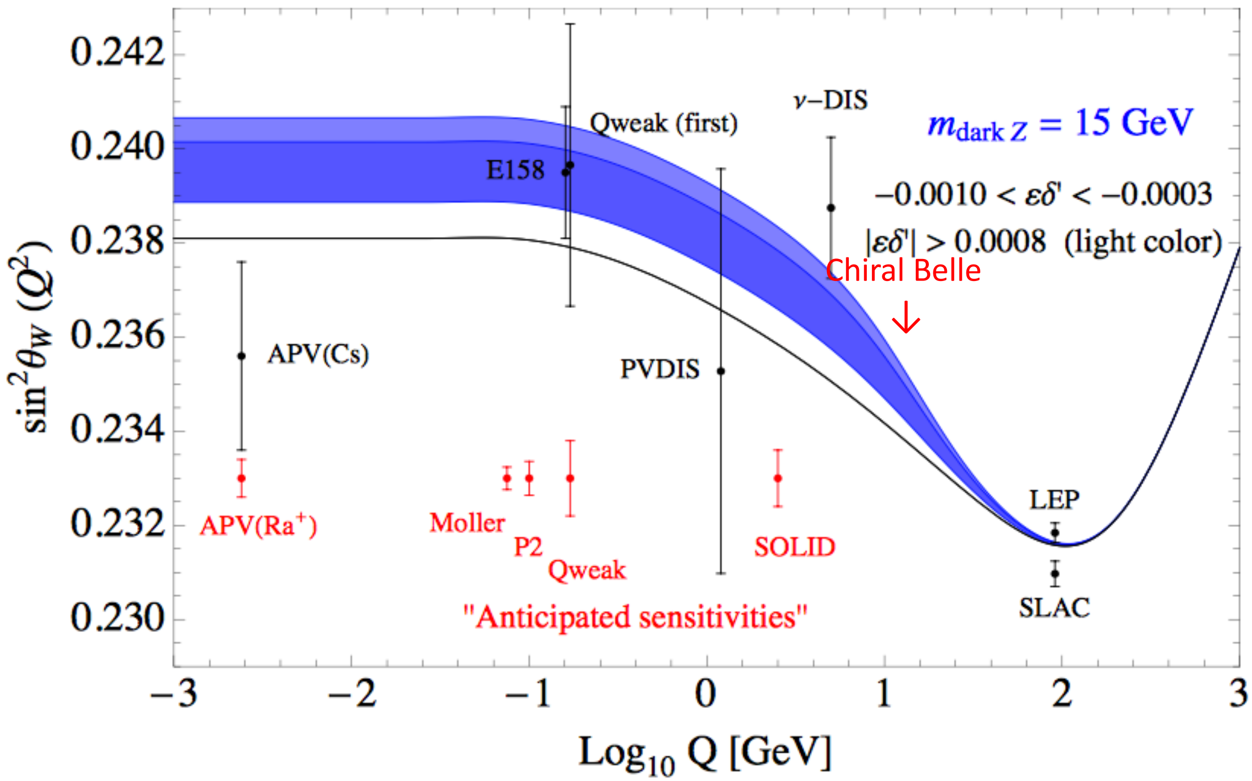
Fermion	g_V^f (Standard Model)	g_V^f (World Average)	$\sigma(g_V^f)$ (Chiral Belle 40ab^{-1})
b-quark	-0.3437 ± 0.0001	-0.3220 ± 0.0077	0.0020 (4 x improvement)
c-quark	0.1920 ± 0.0002	0.1873 ± 0.0070	0.0010 (7 x improvement)
Tau	-0.0371 ± 0.0003	-0.0366 ± 0.0010	0.0008
Muon	-0.0371 ± 0.0003	-0.03667 ± 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} ± 0.00018_{sys} [*cf.* SM error of ±0.0003]



Chiral Belle probes both high and low energy scales

- Unique sensitivity to Dark Sector parity violating light neutral gauge bosons – especially when Z_{dark} is off-shell or couples more to 3rd generation
  - Because couplings are small, this sector would have been hidden
  - See e.g. H. Davoudiasl, H. S. Lee and W. J. Marciano, Phys.Rev. D 92, no. 5, 055005 (2015)

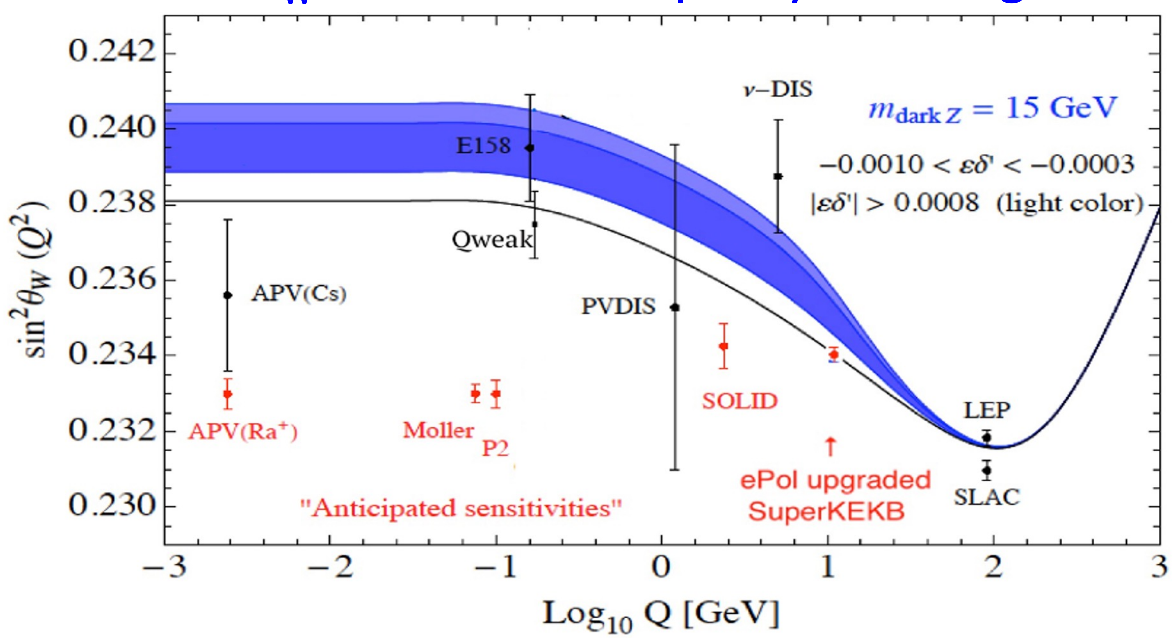


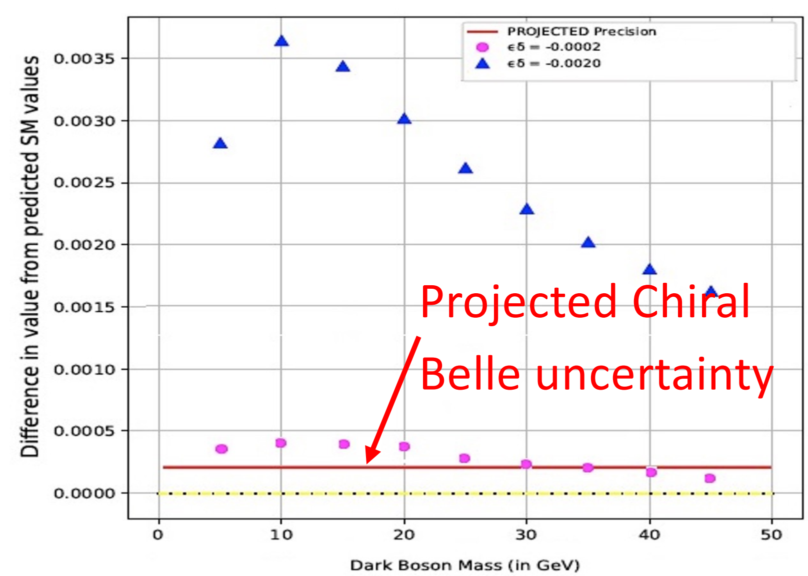
Upgrading SuperKEKB with e- Polarized Beams: Chiral Belle → unique probe of Dark Sector

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 two 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.

Chiral Belle probes both high and low energy scales

Global interest in this EW physics:

- LHC experiments
- APV measurements at lower energy scales
- Moller Experiment at Jefferson Lab which will measure $\sin^2\theta_{eff}^{electron}$ below 100MeV with similar precision (note: Moller is only sensitive to electron couplings.)
- EIC can measure $\sin^2\theta_{eff}$ in similar kinematic region, but with less precision and little sensitivity to heavy flavours
- Next generation high energy e+e- colliders: ILC (where polarization is planned) & FCC-ee

Chiral Belle physics program includes:

- Tau Lepton Magnetic Form factor F_2(10GeV) → τ g-2
  - **Approaches the precision regime in tau that would be sensitive to Minimal Flavour Violation equivalent of muon g-2 anomaly**
- τ electric dipole moment (EDM)
- Improved precision measurements of τ Michel Parameters
- e^- beam polarization can be used to reduce backgrounds in $\tau \to \mu\gamma$ and $\tau \to e\gamma$ – leading to improved sensitivities; also electron beam polarization and can be used to distinguish Left and Right handed New Physics currents.
- Polarized e+e- annihilation into a polarized Λ or a hadron pair experimentally probes dynamical mass generation in QCD