Precision Electroweak Physics at Belle II with a Polarized Electron Beam SuperKEKB Upgrade

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University of Victoria

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

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

April 13, 2022

This talk

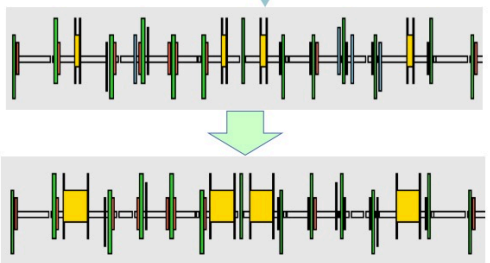
Contents

Upgrading SuperKEKB with polarized electrons

Opens New Windows for Discovery with Belle II

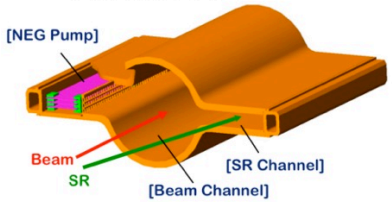
- Extremely rich and unique high precision electroweak program
- Probe of Dark Sector
- τ Magnetic Form factor F_2(10GeV) -> g-2 @ 10^{-5}
- Polarized Beam also provides:
  - Improved precision measurements of τ Michel Parameters, τ electric dipole moment (EDM) and reduces backgrounds in $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ precision leading to significantly improved sensitivities
- hadronic studies

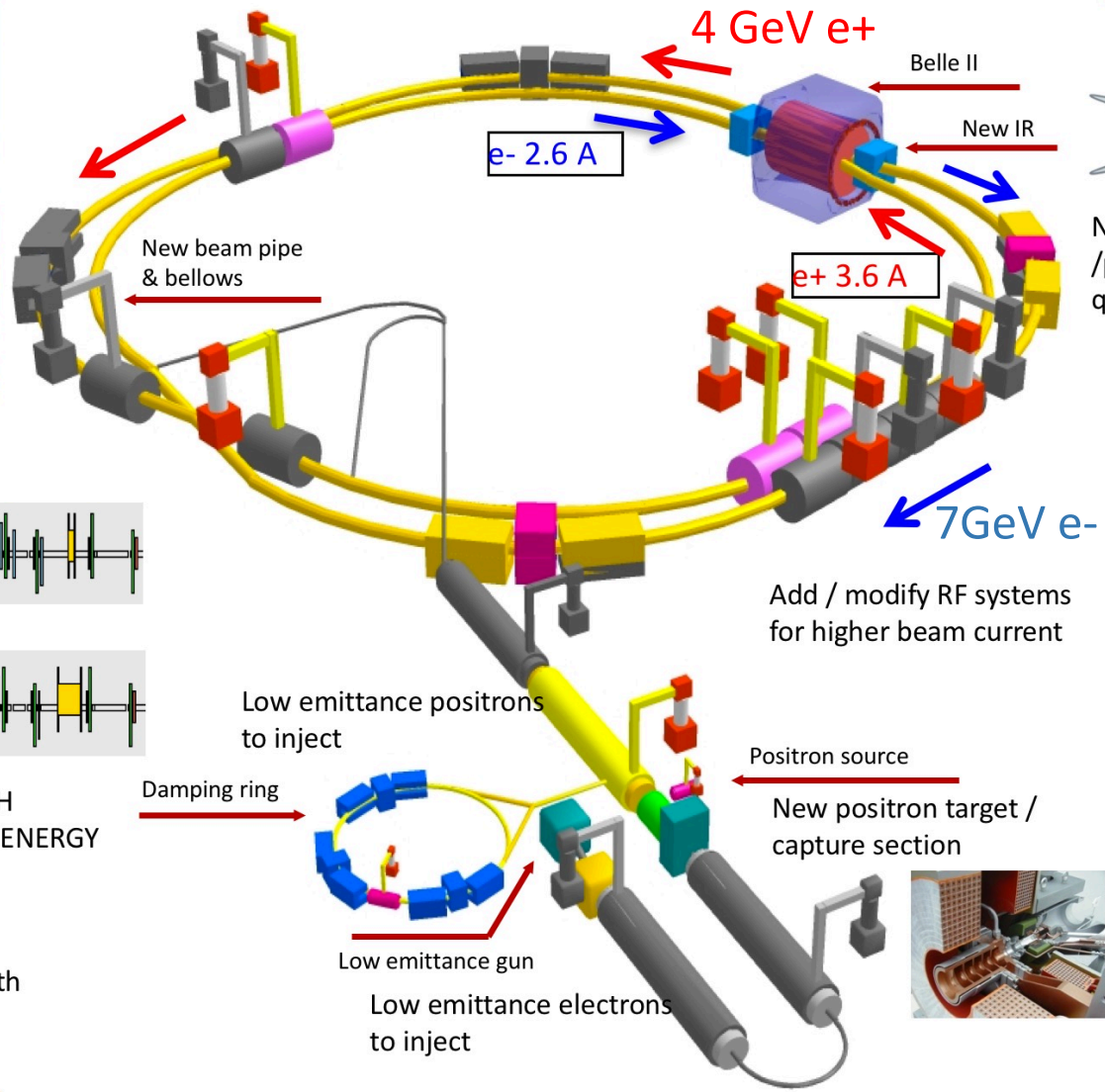
Replace short dipoles with longer ones (LER)



Redesign the lattices of HIGH ENERGY RING (HER) & LOW ENERGY RING (LER) to squeeze the emittance

TiN-coated beam pipe with antechambers

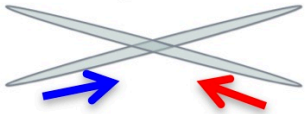




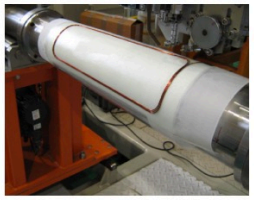
Add / modify RF systems for higher beam current

New positron target / capture section

Colliding bunches



New superconducting /permanent final focusing quads near the IP



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 IP, 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 IP

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

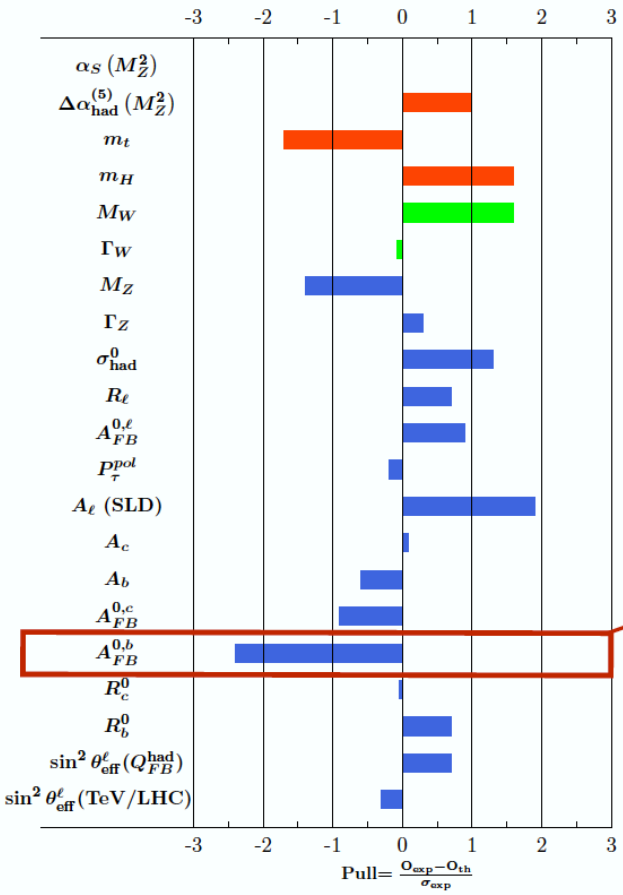
T_3 = -0.5 for charged leptons and D-type quarks
+05 for neutrinos and U-type quarks

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

The Standard Model Electroweak fit

SM fit results: Predictions for EWPO

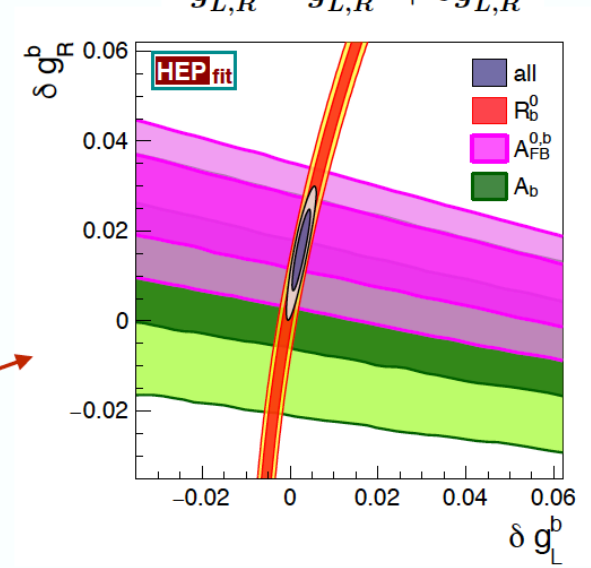
Also good agreement between indirect determination of EWPO and experimental measurements, with one notable exception



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

Requires modifications of (right-handed) Zbb couplings

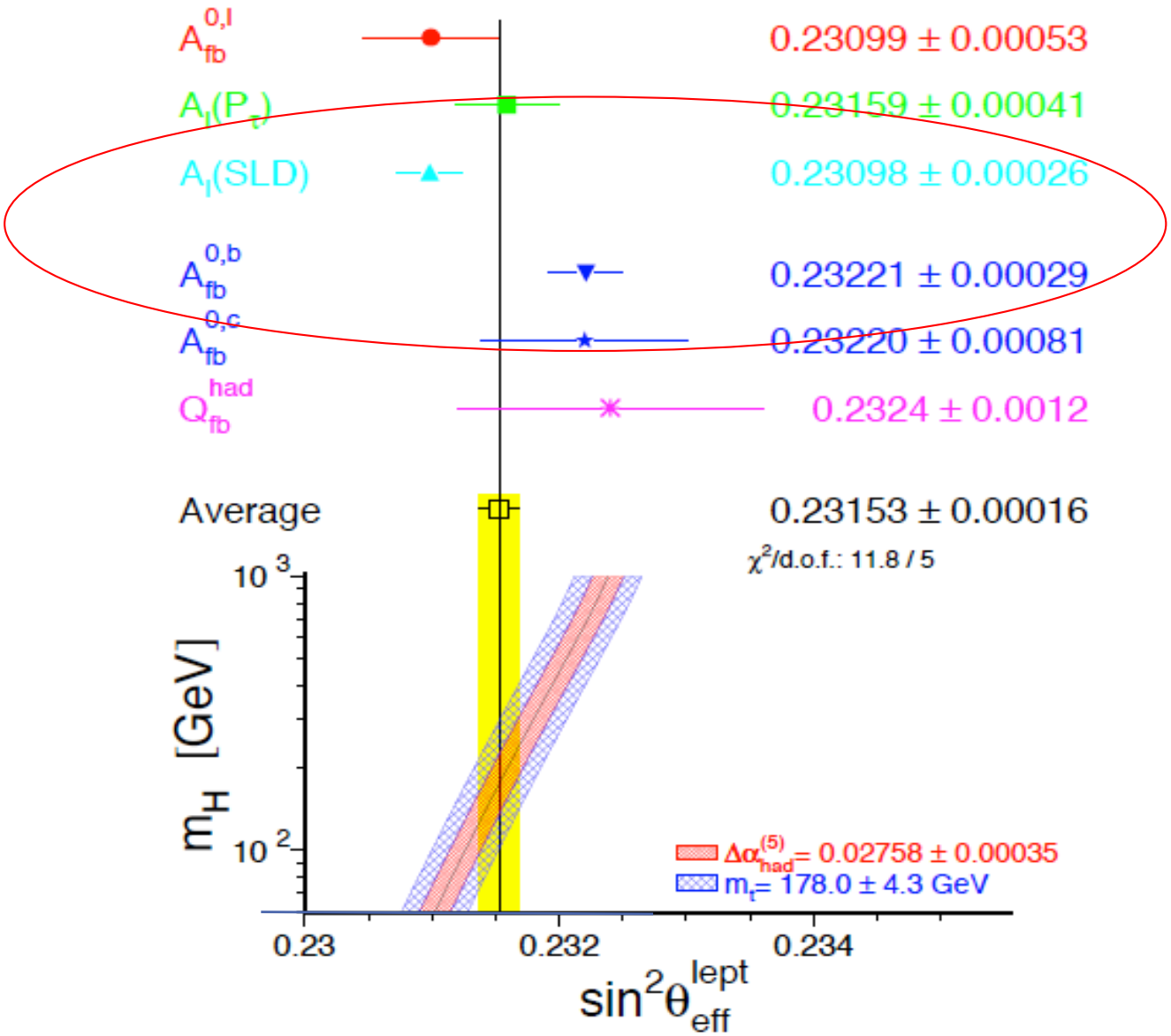
$$g_{L,R}^b = g_{L,R}^{b\,SM} + \delta g_{L,R}^b$$



	Fit result	Correlations	
δg_R^b	0.017±0.007	1.00	
δg_L^b	0.003±0.001	0.89	1.00

29th International Symposium on Lepton Photon Interactions at High Energies
Toronto, August 6, 2019 19 Jorge de Blas
INFN - University of Padova

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)

‘Chiral Belle’ -> Left-Right Asymmetries

- Measure difference between cross-sections with left-handed beam electrons and right-handed beam electrons normalized by their sum
- Same technique as SLD A_{LR} measurement at the Z-pole giving single most precise measurement of :

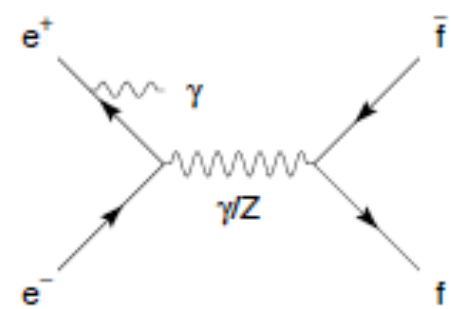
$$\sin^2\theta_{eff}^{lepton} = 0.23098 \pm 0.00026$$

- 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:

(for s-channel Born)

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

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



‘Chiral Belle’ Left-Right Asymmetries

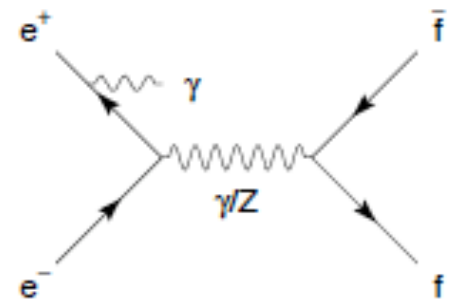
Electron helicity would be chosen randomly pulse-to-pulse by controlling the circular polarization of the source laser illuminating a GaAs photocathode.

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

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

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

(for s-channel Born)



Source generates mainly right-handed electrons

Source generates mainly left-handed electrons

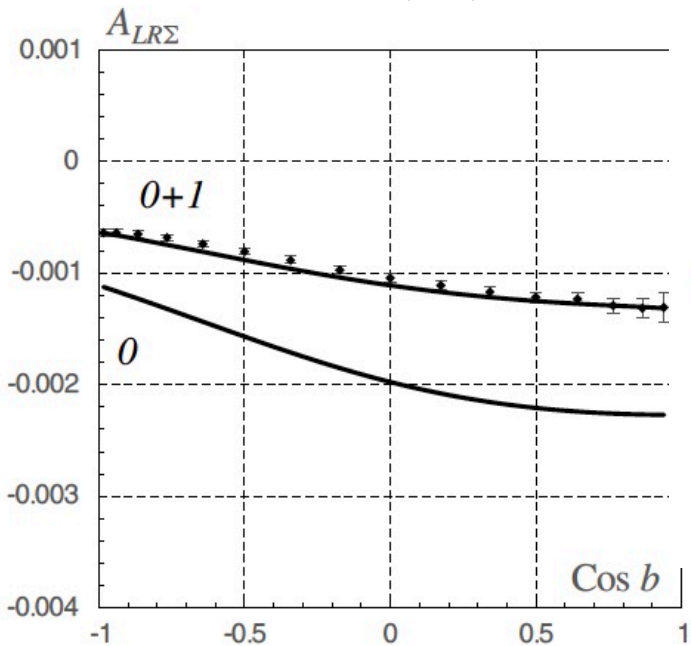
For A_{LR} calculation with NLO corrections for mu-pair final state, see:
Aleksejevs, Barkanova, Roney, Zykunov “NLO radiative corrections for Forward-Backward and Left-Right Asymmetries at a B Factory”, arXiv:1801.08510

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)

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

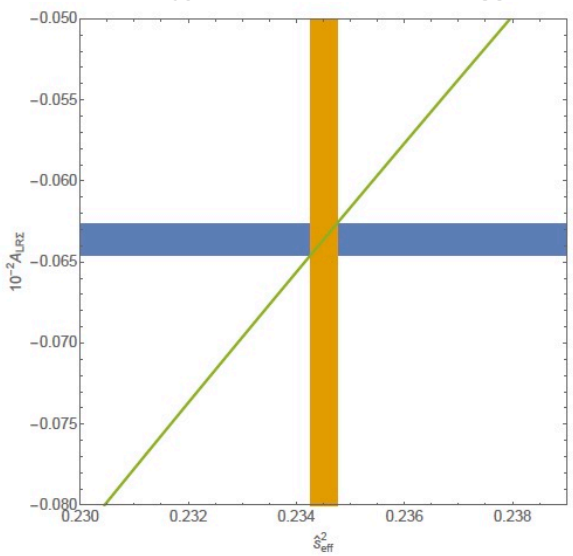


$$\Sigma_L^C = \int_{\cos b}^{\cos a} \sigma_L^C \cdot d(\cos\theta), \quad \Sigma_R^C = \int_{\cos b}^{\cos a} \sigma_R^C \cdot d(\cos\theta)$$

a=10° & energy of photons < 2GeV

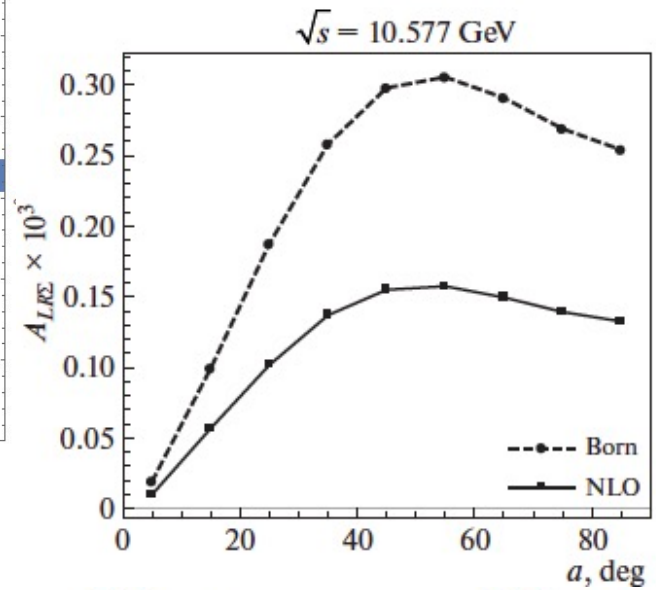
Phys.Rev. D101 (2020) no.5, 053003

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



$$A_{LR\Sigma}^C = A_{LR\Sigma}^C(a) = \frac{\Sigma_L^C - \Sigma_R^C}{\Sigma_L^C + \Sigma_R^C}$$

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



$$\Sigma_L^C = \int_{-\cos a}^{\cos a} \frac{d\sigma_{L0}^C}{dc} \cdot dc, \quad \Sigma_R^C = \int_{-\cos a}^{\cos a} \frac{d\sigma_{R0}^C}{dc} \cdot dc.$$

PHYSICS OF ATOMIC NUCLEI Vol. 83 No. 3 2020

New generator: ReneSANCe

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

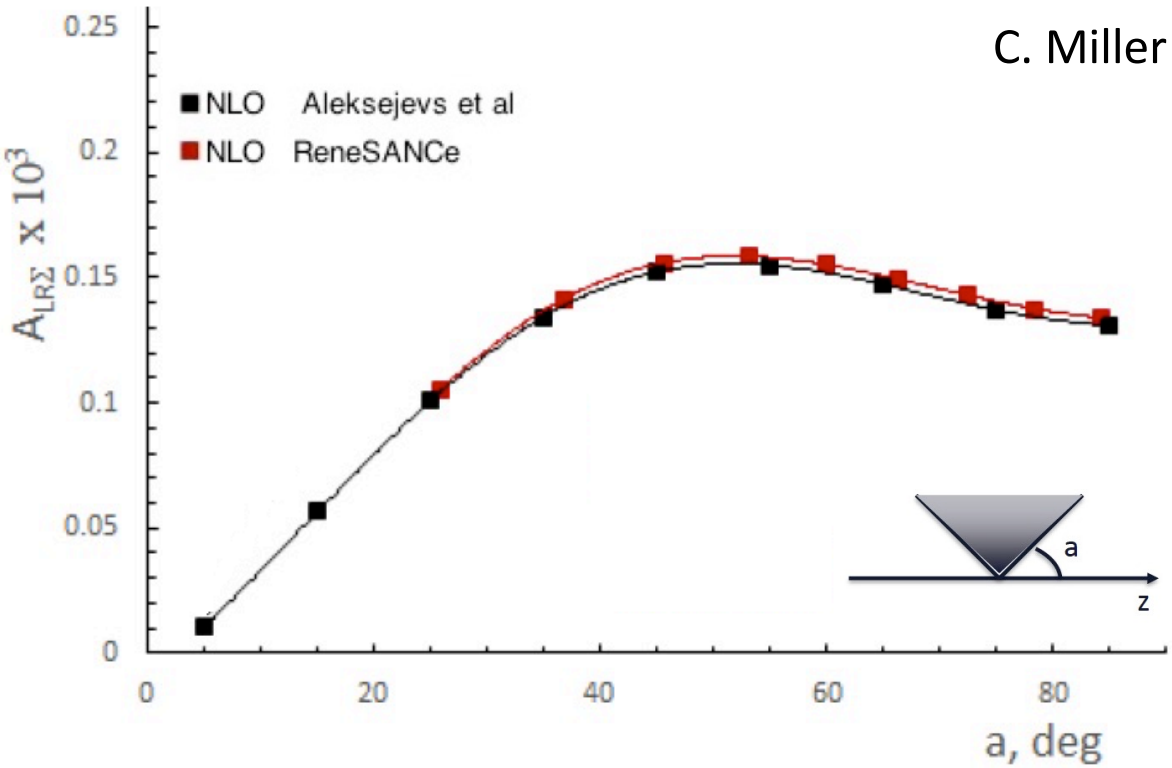
New generator with beam polarization capable of producing Bhabhas.

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

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

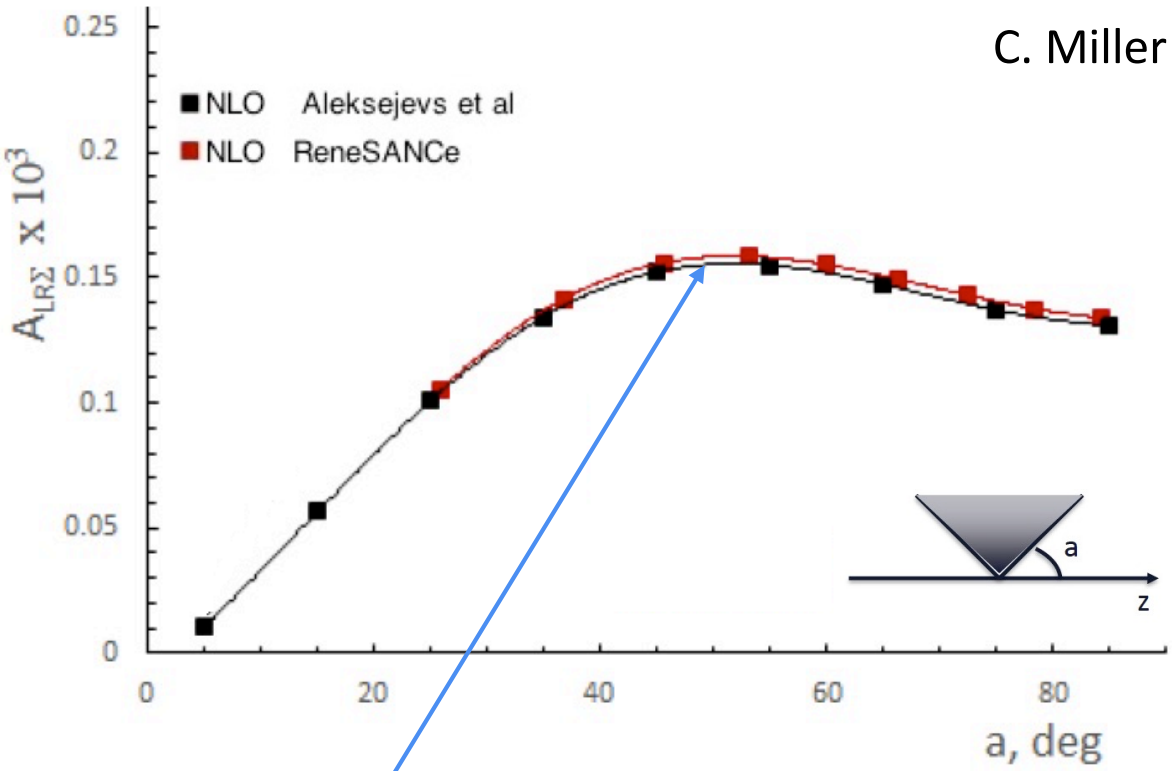
ReneSANCe *cf* Aleksejevs *et al*



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 $\delta\sin^2\theta_W$ / δA_{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. = 0.15)	+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) (17nb, eff. = 0.36)	+0.00015 ±.000003	2.0%

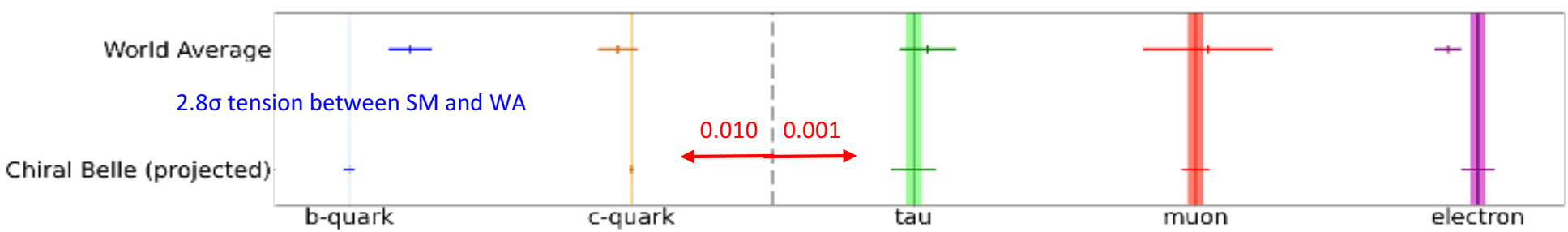
1 - Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

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

High Precision Neutral Current Vector Coupling 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]

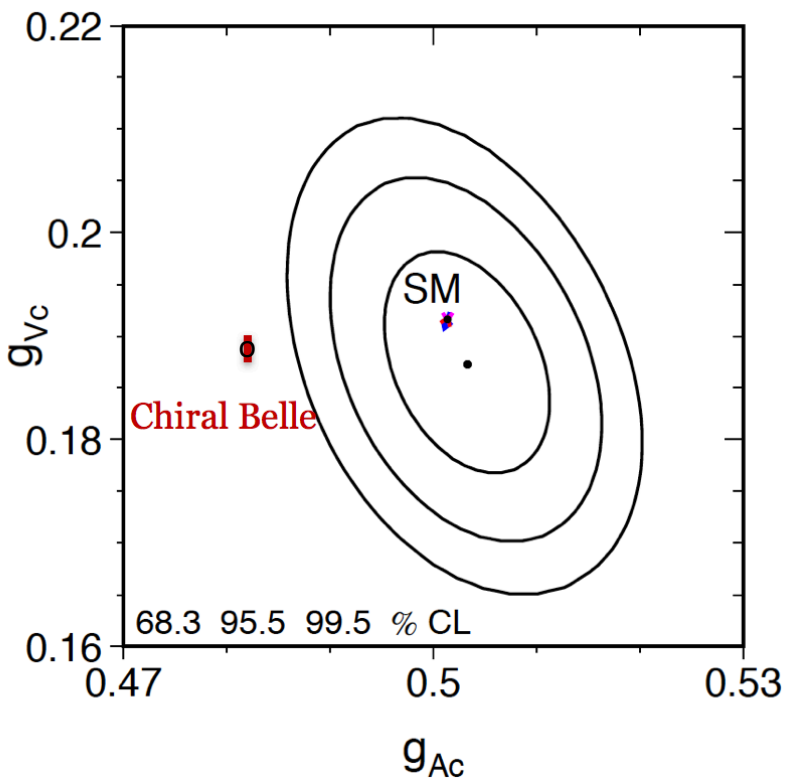


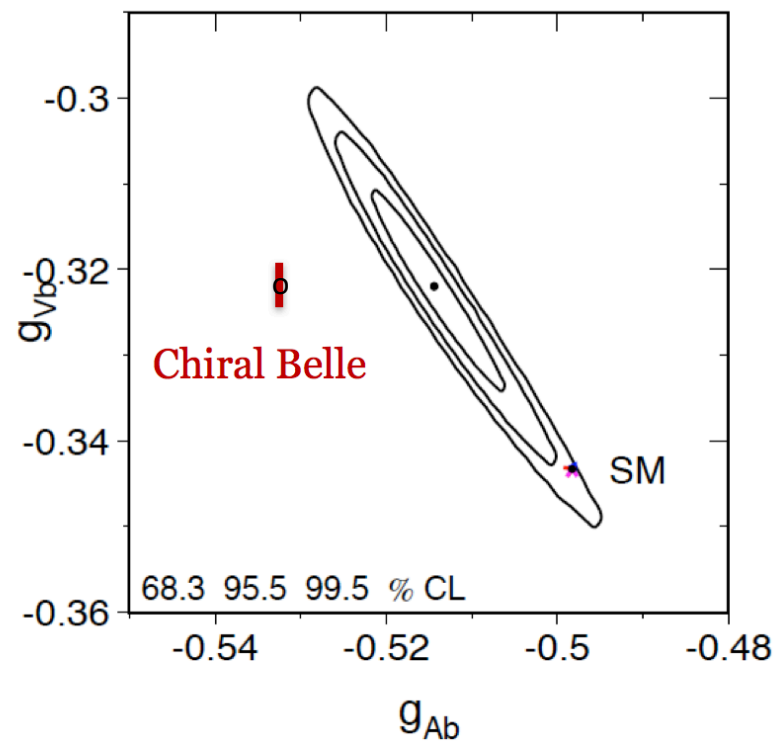
Highest Precision b and c Neutral Current Vector Coupling Measurements

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
with 20 ab^{-1}





b-to-c Neutral Current Vector Coupling Universality Ratio

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

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 determining g_V^b that were significant in extraction from A_{FB}^b at Z-pole

b-c UNIVERSALITY
70% polarized e⁻ beam

	SM	World Average[1]	Chiral Belle 20 ab^{-1}	Chiral Belle 50 ab^{-1}	Chiral Belle 250 ab^{-1}
g_V^b/g_V^c	-1.7901	-1.719	±0.0058 (stat ~ total)	±0.0034 (stat ~ total)	±0.00015 (stat ~ total)
Ratio	± .0005	± .082	Improves x 14	Improves x 24	Improves x 50
Relative error:	0.18%	4.8%	0.32%	0.19%	0.09%

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

Chiral Belle probes both high and low energy scales

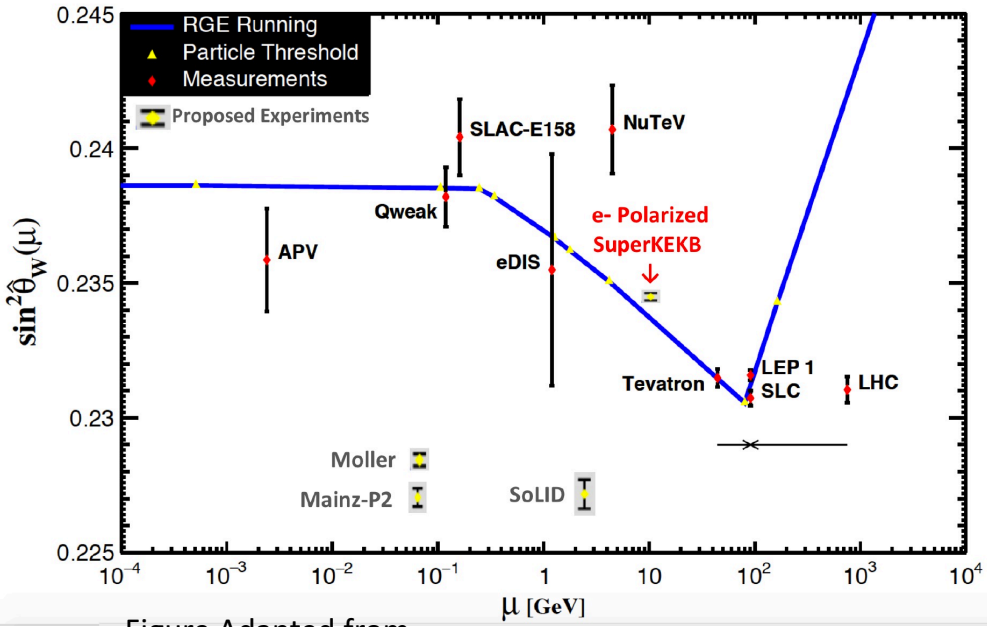


Figure Adapted from
J. Erler and A. Freitas, (PDG) Phys. Rev. D98 , 030001 (2018)

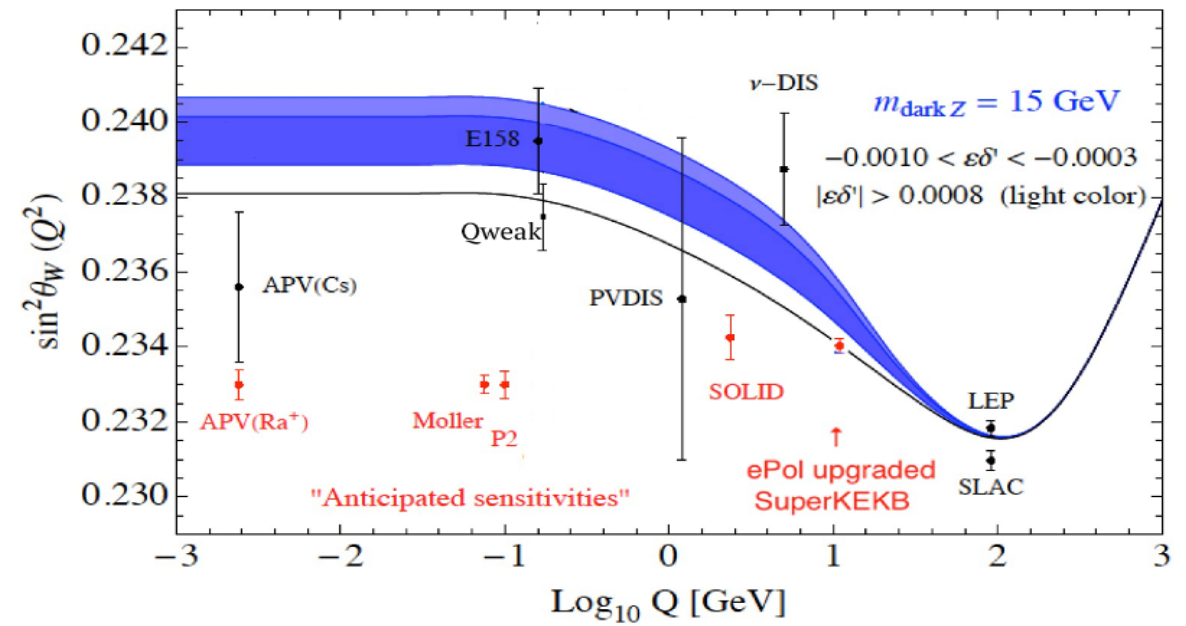
Chiral Belle: $\sigma < 0.0002$ with 40 ab^{-1}
Using only clean leptonic states

- **Precision probe of running of the weak mixing angle**
- **Being away from Z-pole opens NP sensitivities not available at the pole**

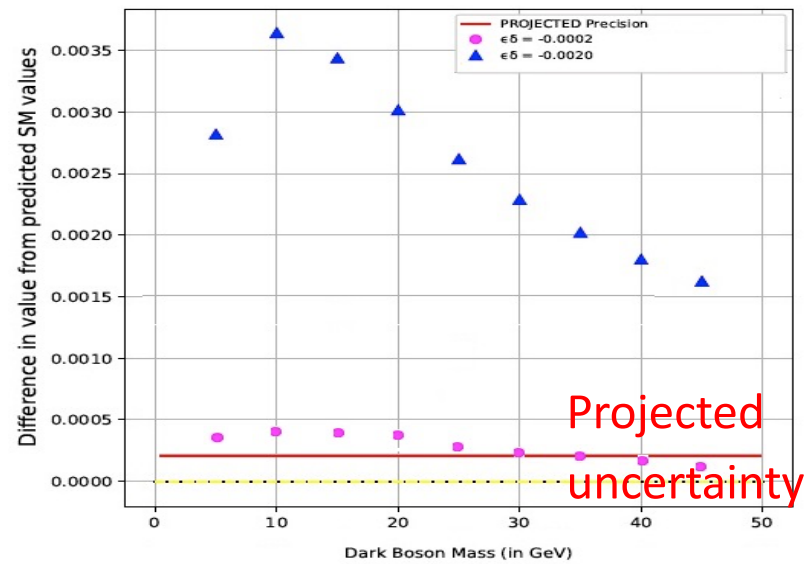
- Measurements of $\sin^2\theta_{eff}^{lepton}$ of using lepton pairs of comparable precision to that obtained by LEP/SLD, except at 10.58GeV
  - sensitive to Z' > TeV scale; can probe purely Z' that only couple to leptons: complementary to direct Z' searches at LHC which couple to both quarks and leptons

Running of $\sin^2\theta_W(Q^2)$: Window on 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].

Chiral Belle probes both high and low energy scales

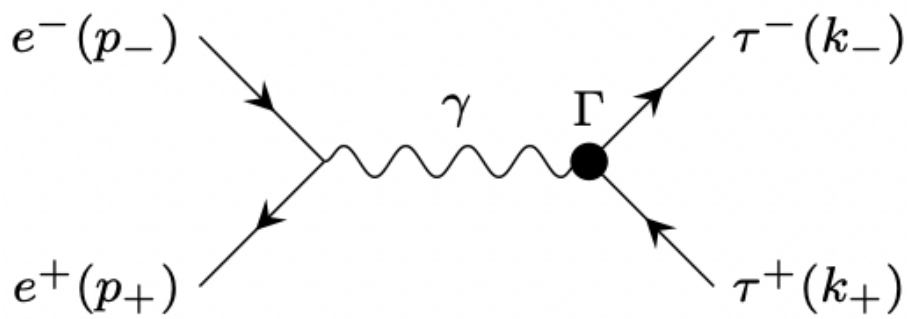
Global interest in this EW physics:

- 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 without accessing mu, tau, charm or beauty
- Next generation high energy e+e- colliders: ILC (where polarization is planned) & FCC-ee

Chiral Belle also provides:

- **Improved precision measurements of electric dipole moment (EDM) and information on the Magnetic Form factor F_2(10GeV)**
  - See J. Bernabéu, G. A. Gonzalez-Sprinberg, and J. Vidal, *"CP violation and electric dipole moment at low energy tau production with polarized electrons"*, Nucl. Phys. B763:283–292, 2007, hep-ph/0610135.
  - J. Bernabéu, G. A. Gonzalez-Sprinberg, and J. Vidal *Nucl.Phys.B* 790 (2008) 160-174, *"Tau anomalous magnetic moment form-factor at Super B/flavor factories"*
  - A. Crivellin, M. Hoefericher, J.M. Roney, arXiv:2111.10378 [hep-ex] *"Towards testing the magnetic momement of the tau at one part per million"*
- **τ Michel Parameters**
  - Denis Epifanov talk at Tau 2021 the Russian Super Tau-Charm Factory (STCF) which will operate with e- polarized beams
- **Reduces backgrounds in $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$** – leading to improved sensitivities; also electron beam polarization and can be used to distinguish Left and Right handed New Physics currents.
  - See: arXiv:1008.1541v1 [hep-ex]
- **Polarized e+e- annihilation into a polarized Λ or a hadron pair experimentally probes dynamical mass generation** in QCD

Electric and Magnetic Moments of the τ Lepton



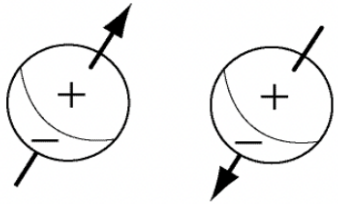
$$\Gamma^\mu = \underbrace{F_1\left(q^2\right)\gamma^\mu}_{\text{radiative corrections}} + \underbrace{F_2\left(q^2\right)\frac{1}{2m_\tau}\mathrm{i}\sigma^{\mu\nu}q_\nu}_{\text{MDM}} + \underbrace{F_3\left(q^2\right)\frac{1}{2m_\tau}\sigma^{\mu\nu}q_\nu\gamma_5}_{\text{EDM}}$$

- $F_1\left(q^2\right)$, $F_2\left(q^2\right)$ are called the Dirac and Pauli; $F_1(0) = 1$; $F_2(0) = a_\tau$
- $g = 2\cdot\left[F_1(0) + F_2(0)\right] = 2 + 2F_2(0)$ $d_\tau^\gamma = \frac{e}{2m_\tau}\cdot F_3(0)$ $\frac{\alpha}{2\pi}$ $\approx 0.001\,161\,4$

Leading 'Schwinger' term

Electric and Magnetic Moments of the 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))

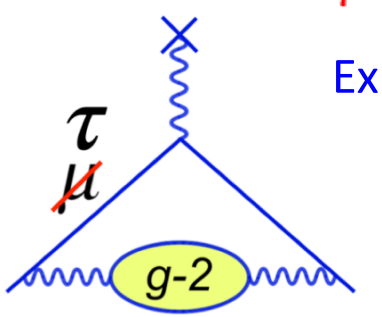
With 40ab^{-1} + 70% Polarization: accesses τ EDM at the 10^{-20} e·cm level (using J. Bernabéu *et al*, Nucl. Phys. B763:283–292, 2007)

For the magnetic moment :

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

Large deviation in anomalous magnetic moment of muon:

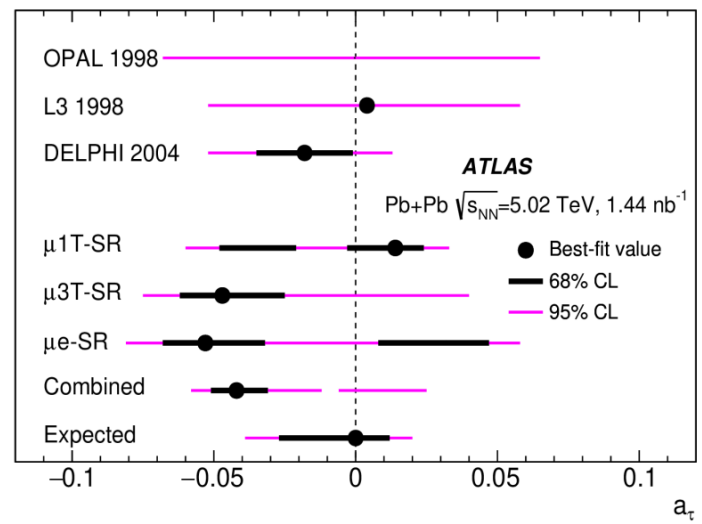
$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (251 \pm 59)\times 10^{-11}[4.2\sigma]$$



Expectation from Minimal Flavour Violation:

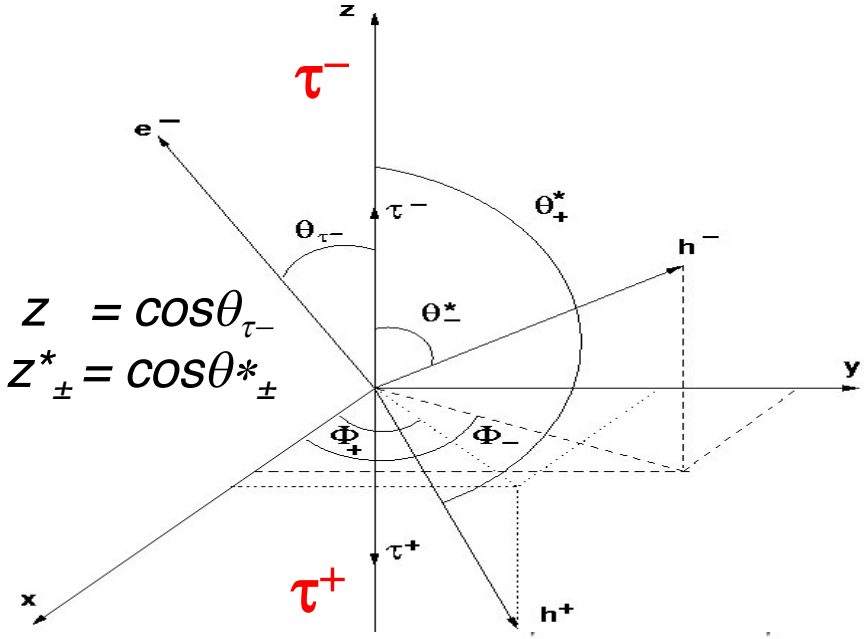
$$a_\tau^{\text{BSM}} \sim a_\mu^{\text{BSM}} \left(\frac{m_\tau}{m_\mu}\right)^2 \sim 10^{-6}$$

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

Magnetic Moment of the τ Lepton with Polarized Beams



$z = \cos\theta_{\tau-}$

$z^*_{\pm} = \cos\theta^*_{\pm}$

Coordinate system for hadronic tau-pair

$e^+e^- \rightarrow \tau^+\tau^-$; $\tau^+ \rightarrow h^+ \bar{\nu}_\tau$ and $\tau^- \rightarrow h^- \nu_\tau$ events

Using z-axis is aligned τ^- momentum, $\theta_{\tau-}$ is production angle of τ^- with respect to the e-beam direction in CM, and the azimuthal and polar angles of the produced hadrons, $h^\pm$, in $\tau^\pm$ rest frame, are $\phi^*_\pm$ and $\theta^*_\pm$.

τ–pair production plane and $\tau^\pm$ direction of flight are fully reconstructed as described in J. H. Kuhn, Phys. Lett. B 313, 458 (1993)

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

$$= \frac{\sigma_R^\pm|_{\rm Pol} - \sigma_L^\pm|_{\rm Pol}}{\sigma}$$

+ $\tau^+ \rightarrow h^+ \bar{\nu}_\tau$
- $\tau^- \rightarrow h^- \nu_\tau$

σ^{Re}: Right Handed beam Xsec

σ^{Le}: Left Handed beam Xsec

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

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

$$= \frac{\sigma_{FB}^\pm(+)|_{\rm Pol} - \sigma_{FB}^\pm(-)|_{\rm Pol}}{\sigma}$$

(J. Bernabéu *et al* *Nucl.Phys.B* 790 (2008) 160-174)

From J. Bernabéu *et al*, *Nucl.Phys.B* 790 (2008) 160-174

Tau anomalous magnetic moment form-factor at Super B/flavor factories

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

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

Then, we define the longitudinal asymmetry as

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

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

$|F_1|^2$ cancels in the difference

$\gamma = E_\tau/m_\tau \quad \alpha = (m_\tau^2 - 2m_h^2)/(m_\tau^2 + 2m_h^2)$

Magnetic Moment of the τ Lepton

A. Crivellin, M. Hoefericher, J.M. Roney, arXiv:2111.10378 [hep-ex] *"Towards testing the magnetic moment of the tau at one part per million"*

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

	$s = 0$	$s = (10\,\mathrm{GeV})^2$
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 70% polarized beam – orders of magnitude improvement.**
  - To achieve $\mathcal{O}(10^{-6})$ requires more precise knowledge of m_τ and $m_{\Upsilon(1S)}$ and more statistics

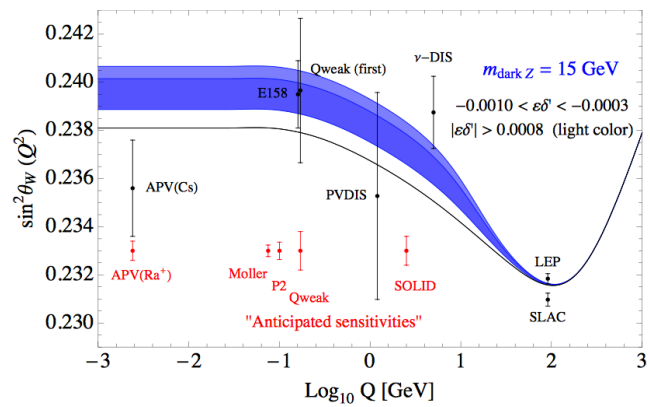
Summary

- e^- polarization upgrade at SuperKEKB would open a unique discovery window with precision electroweak physics
  - Measure the b, charm, tau, muon vector couplings with the highest precision and competitive electron coupling measurement
  - Unique probe of universality at unprecedented precision

- Access tau g-2 at orders of magnitude higher precision than any other method via F_2(10GeV)
- Also get significant improvements to LFV, Michel parameters, LFV, EDM

Summary

- Competitive $\sin^2\theta_W$ with measurements at Z-pole (until FCC) but at 10.58 GeV and complementary to Moller and low energy PV
  - test running of couplings
  - probe new physics at TeV scale complementary to LHC
  - probe 'Dark Sector'

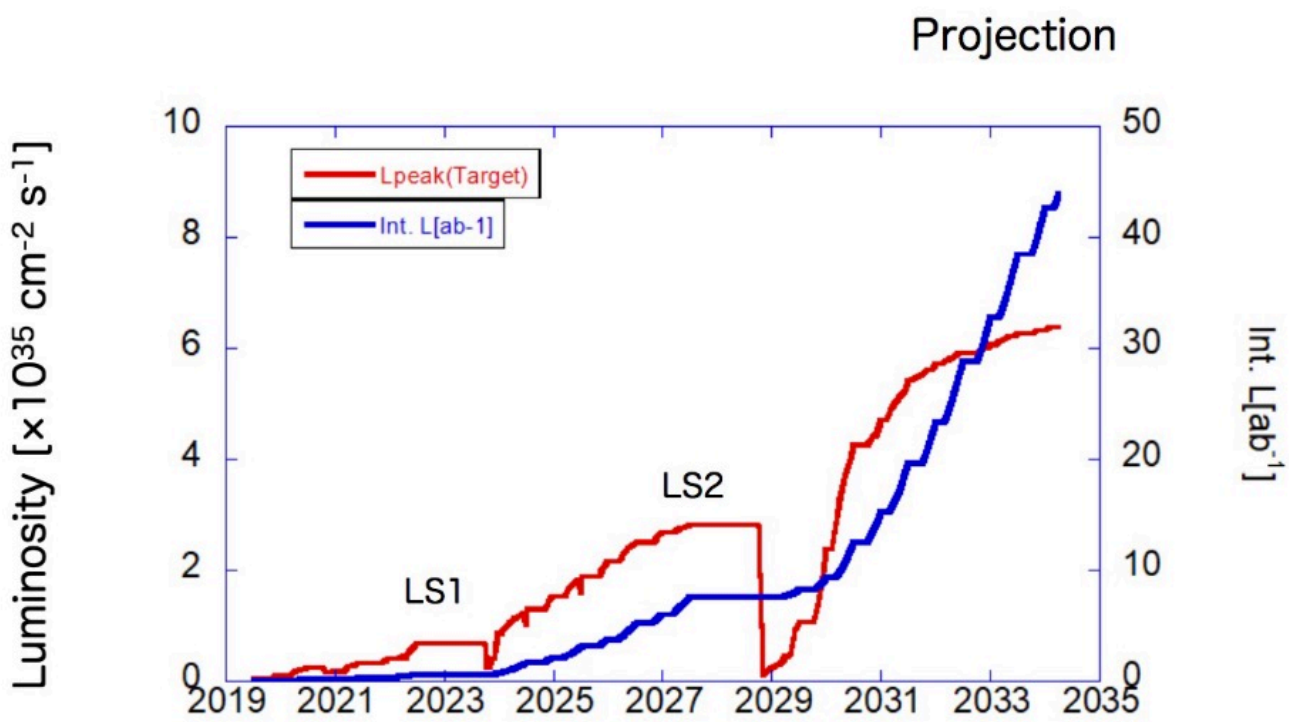


- Applying for US-Japan funds for development of spin rotators at BNL and polarization source
- Build on international partnerships with KEK to create a ***unique*** discovery machine

Additional Information

SuperKEKB polarization upgrade

- Aim to install polarization Long Shutdown 2
- Polarization R&D in MEXT KEK Roadmap 2021-26



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. = 0.15)	+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

From J. Bernabéu *et al*, Nucl. Phys. B763:283–292, 2007

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

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

Angular asymmetries (P_N^τ) are proportional to EDM

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

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

$\not{CP}$: $$A_N^{CP} \equiv \frac{1}{2}(A_N^+ + A_N^-)$$

EDM of the τ Lepton with e- polarized SuperKEKB

Beam polarization substantially improves τ EDM experimental sensitivity by allowing measurements of the polarization of a single τ, rather than measurements of correlations between two τ leptons produced in the same event.

The beam polarization upgrade at SuperKEKB furthers experimental sensitivity since the uncertainties in modeling the forward-backward asymmetry in the detector response are independent of beam polarization and will largely cancel.

Using J. Bernabéu *et al*, Nucl. Phys. B763:283–292, 2007
-> 40ab^{-1} Chiral Belle data with 70% polarization, the sensitivity is

$|d_\tau^\gamma| < O(10^{-20})$(Statistical error only)

World best measurement from Belle - arXiv:2108.11543 -

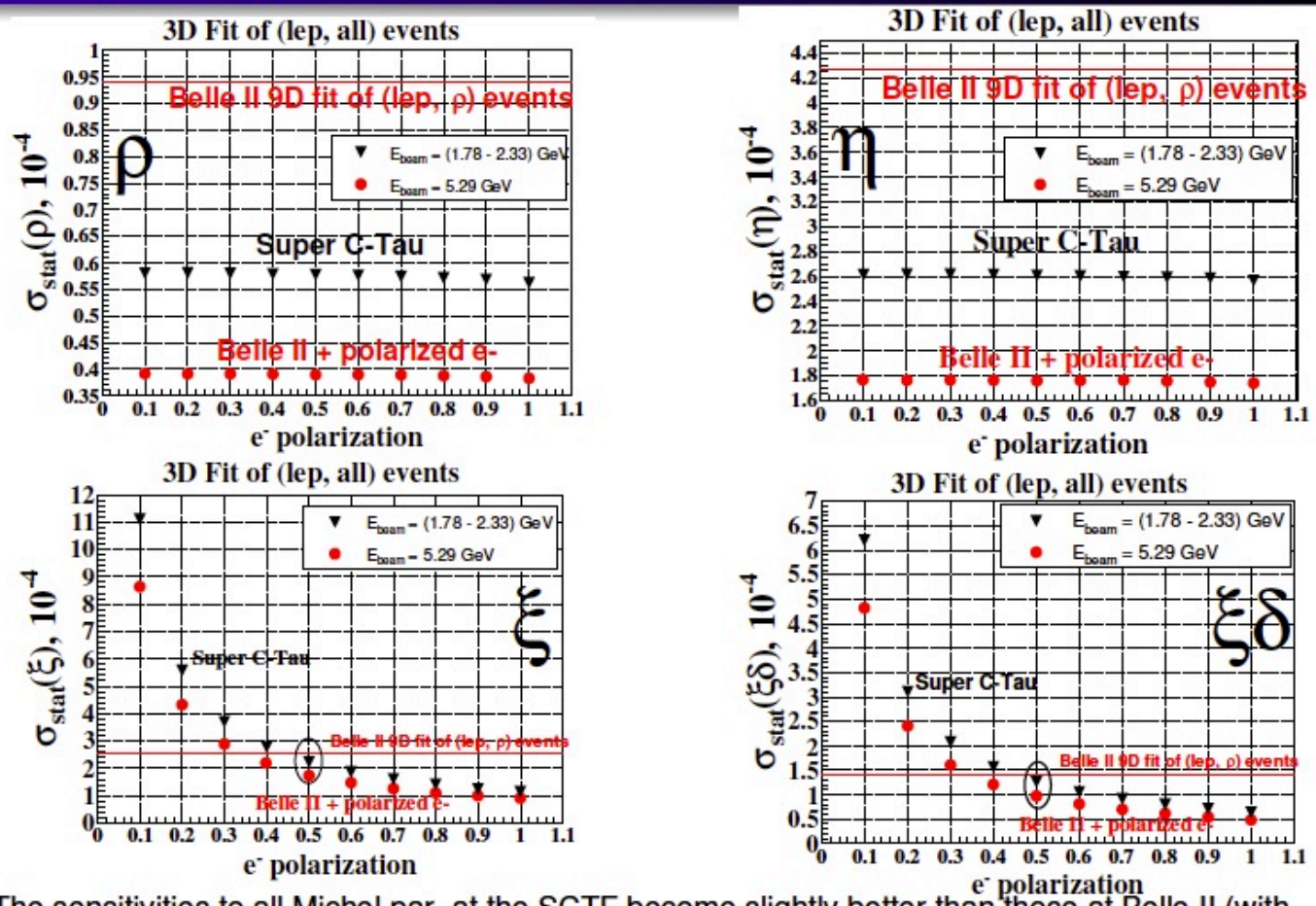
$$-1.85 \times 10^{-17} < \mathcal{R}(\tilde{d}_\tau) < 0.61 \times 10^{-17} ecm \ (95\,\% \, CL)$$

$$-1.03 \times 10^{-17} < \Im(\tilde{d}_\tau) < 0.23 \times 10^{-17} ecm \ (95\,\% \, CL)$$

Note: extrapolating statistical error from recent Belle results would give a limit of ~5x10^{-19} for unpolarized Belle II data with 50ab^{-1}

From Denis Epifanov's talk at Tau2021 on Super Tau Charm Factory: τ Michel Parameter with polarized e- beam

Fit of $(\ell,\ \mathrm{all})$ in 3D at Belle II and SCTF



The sensitivities to all Michel par. at the SCTF become slightly better than those at Belle II (with unpolarized e^- beam) for $\mathcal{P}_e > 0.5$.

Expected MP stat. uncertainties are $\sim 10^{-4}$, to reach the same level systematic uncertainty, the NNLO corrections ($\mathcal{O}(\alpha^4)$) to the differential $e^+e^- \to \tau^+\tau^-$ cross section are mandatory.

TAU2021 1 October 2021 | Super Charm-Tau factory in Russia | Denis Epifanov (BINP) | 13/33

It would be very exciting to have both projects probing tau sector with polarized e- beams

50ab^{-1} of polarized Belle II data assumed in these studies

Tau Polarization as Beam Polarimeter

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

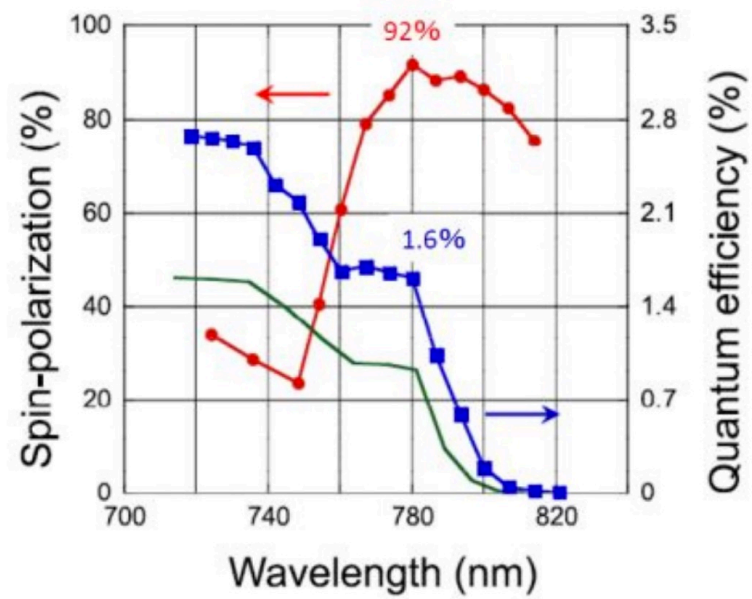
$$+ P_e \frac{\cos\theta}{1+\cos^2\theta}$$

- 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
- Can expect ~1/2 % 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
- Preliminary BaBar results on sensitivity studies are very promising! Systematics < 0.5%

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 GaAs cathode with a thin Negative Electron Affinity (NEA) surface.

KEK and Hiroshima Groups - work on ILC sources leveraged

Polarization in SuperKEKB

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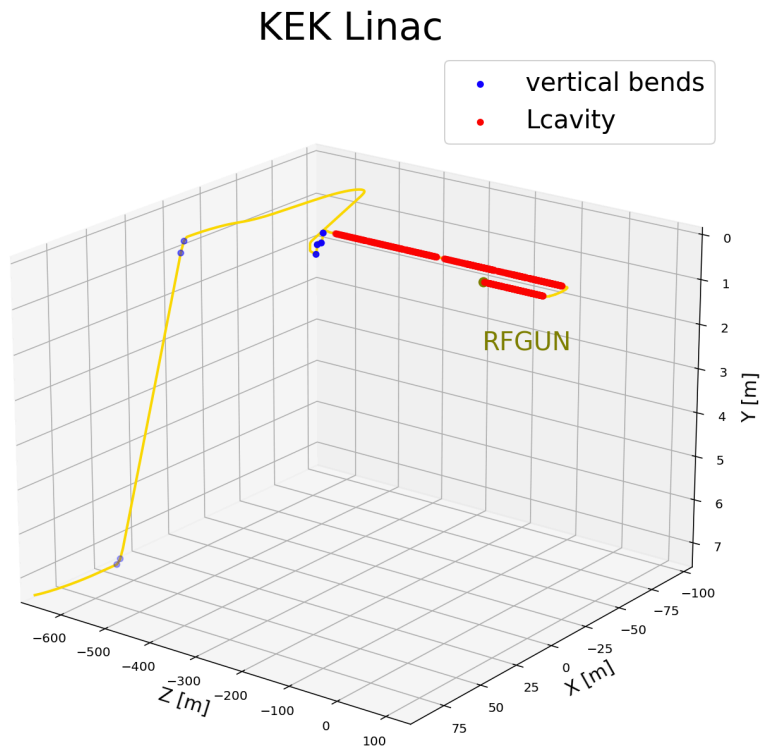

Y. Peng (UVic)

Design source photo-cathode

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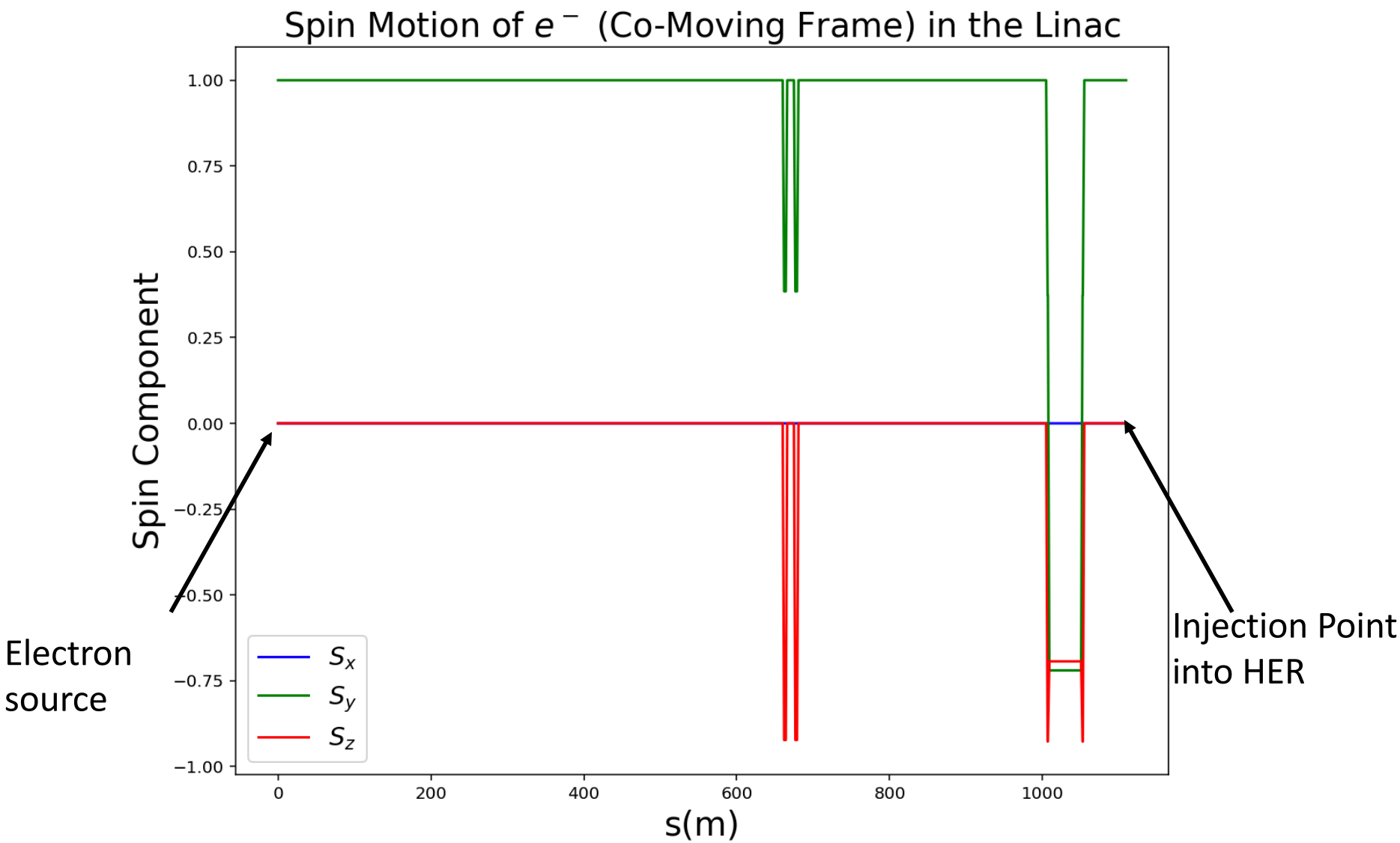
Polarization in SuperKEKB



Polarization in SuperKEKB

Hardware needs

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

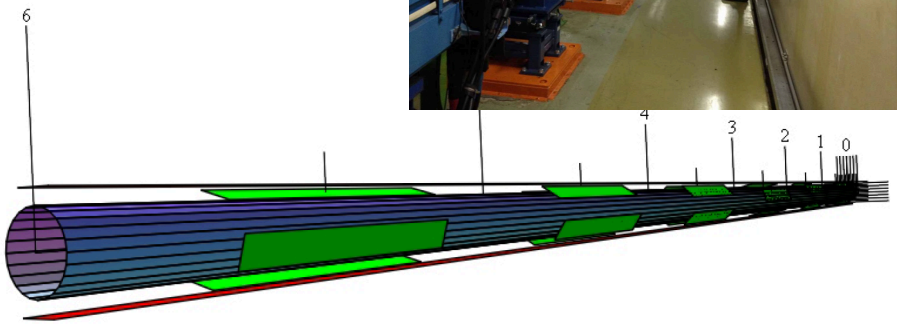
Use of solenoids and dipoles, plus the quadrupoles (needed for decoupling) on either side of interaction point

BINP, ANL, BNL, TRIUMF-Victoria Groups

Polarization in SuperKEKB

Hardware needs

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



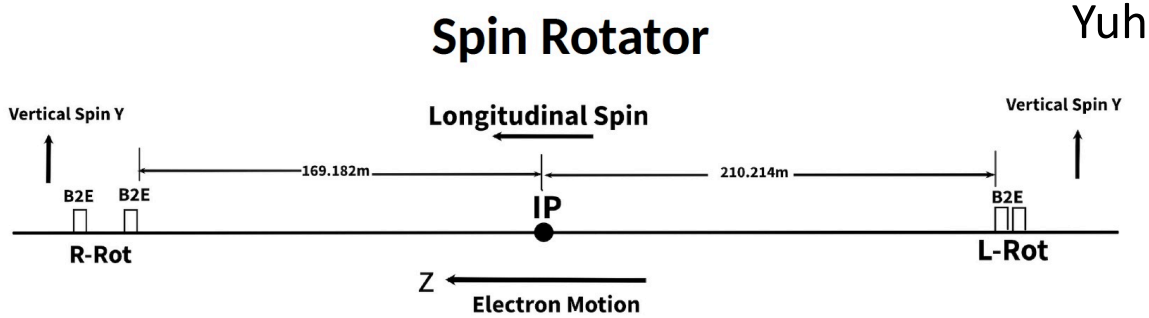
In preliminary studies, one concept (U. Wienands, ANL) is to use overlapping field magnets which would replace existing bending magnets either side of interaction point

BINP, ANL, BNL, TRIUMF-Victoria Groups

Preliminary studies – ANL, TRIUMF, Victoria

Overlapping Field Solenoid-Dipole-Quadrupole Spin Rotator - Uli Wienands, ANL

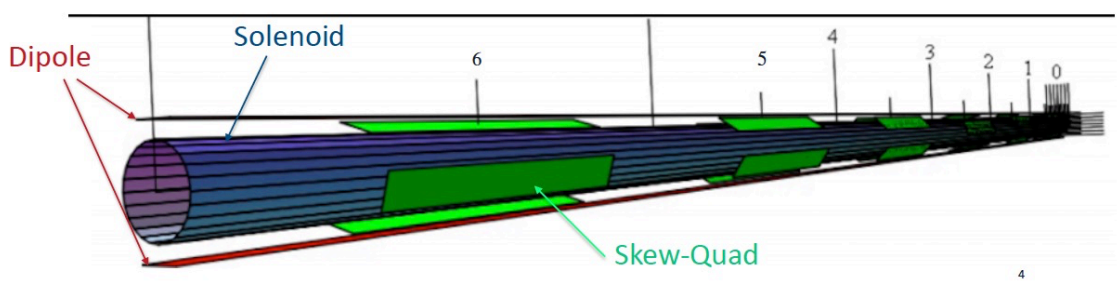
Yuhao Peng, Victoria



Left rotator(L-Rot) is to rotate the vertical spin to the longitudinal direction

Right rotator(R-Rot) is to rotate the longitudinal back to vertical

- replace some existing ring dipoles(send) near the IP with the solenoid-dipole combined function magnets and maintain the original dipole strength to keep the geometry
- Install 6 skew-quadruple on top of each rotator section to compensate for the x-y plane coupling caused by solenoids



U. Wienands, ANL

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

Preliminary studies – ANL, TRIUMF, Victoria

Simulation Tool

- **Bmad** is an open-source software library (aka toolkit)created/maintained by David Sagan at Cornell University for simulating charged particles and X-rays. Étienne Forest's "Polymorphic Tracking Code" (**PTC**) is incorporated into it.
- **Tao** is a user-friendly interface to Bmad which gives general purpose simulation, based upon Bmad.
- **Bmad** via the **Tao** interface is a powerful and user-friendly tool used for viewing lattices, doing Twiss and orbit calculations, and performing nonlinear optimization on lattices

Using SuperKEKB High Energy Ring lattice (Demin Zhou, KEK)

Yuhao Peng (Victoria)

Original Lattice

	X		Y		
	Model	Design	Model	Design	
Q	45.530994	45.530994	43.580709	43.580709	! Tune
Chrom	1.593508	1.591895	1.622865	1.621568	! dQ/(dE/E)
J_damp	1.000064	0.999662	1.000002	1.000002	! Damping Partition
Emittance	4.44061E-09	4.44277E-09	5.65367E-13	5.65331E-13	! Meters

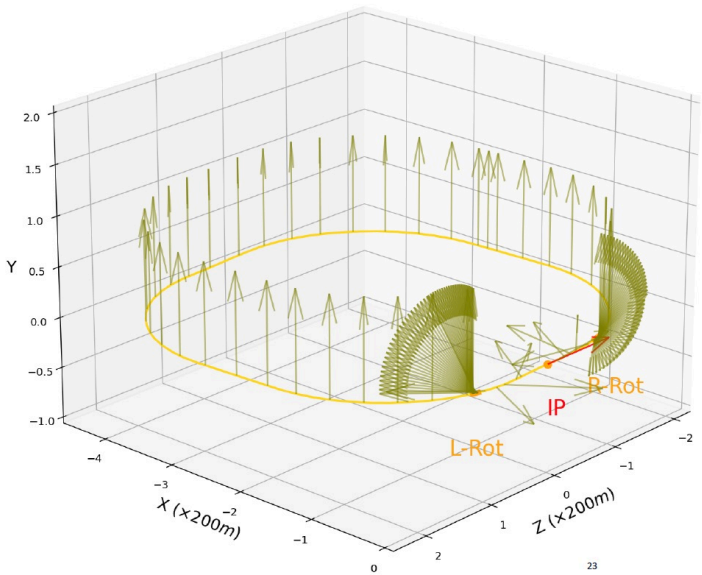
Lattice with Rotators after re-matching chromaticity and tunes

	X		Y		
	Model	Design	Model	Design	
Q	45.530994	45.530994	43.580709	43.580709	! Tune
Chrom	1.593508	1.255194	1.622865	1.622979	! dQ/(dE/E)
J_damp	0.984216	0.983532	1.005266	1.005262	! Damping Partition #
Emittance	4.88967E-09	4.89624E-09	3.96631E-12	3.96983E-12	! Meters

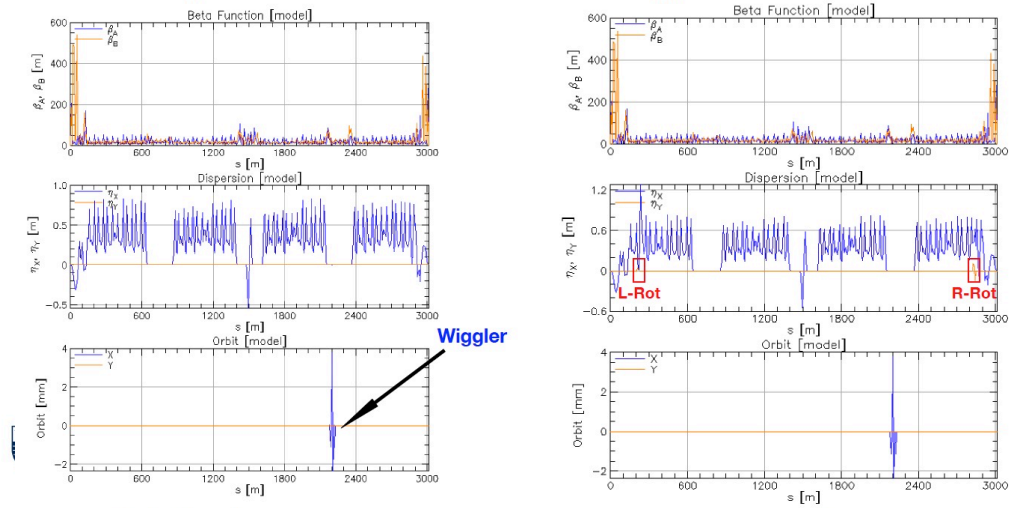
Next steps: now conducting long term tracking studies -> very promising

Preliminary studies – ANL, TRIUMF, Victoria

Spin Motion of e^- (Lab Frame) in the SuperKEKB HER with Spin Rotator Installed



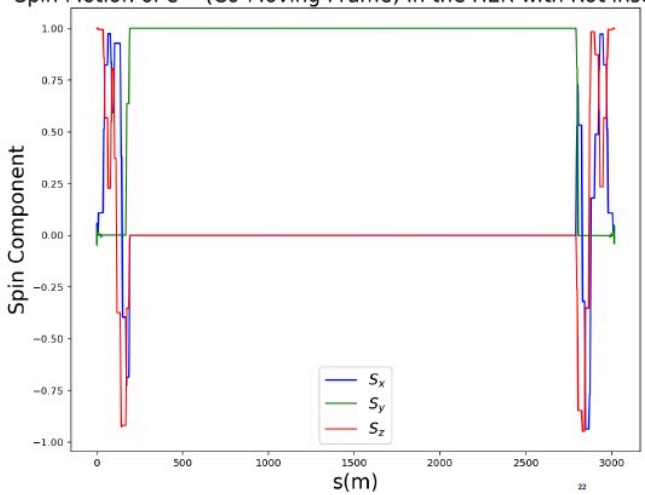
Comparison of Full Lattice



Original

Rot

Spin Motion of e^- (Co-Moving Frame) in the HER with Rot installed

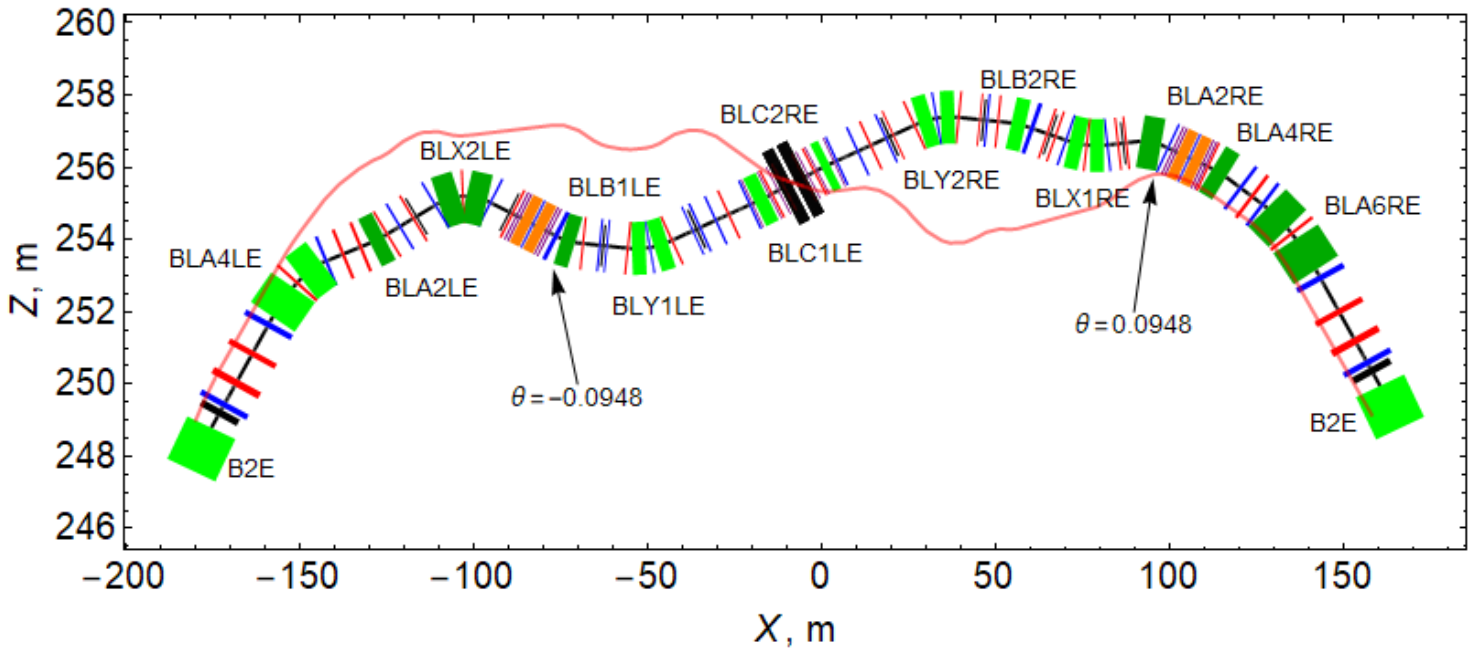


Spin Component	Entrance of Rot	IP	Exit
X	-0.0000032792024300	-0.0000044677361868	-0.0000063748934711
Y	0.9999999999802550	0.0000026796195603	0.9999999999793680
Z	-0.0000053600276775	0.9999999999864290	0.0000007825194459

Yuhao Peng, Victoria

Preliminary studies by BINP group

Another Concept: install spin-rotator magnets in drift regions



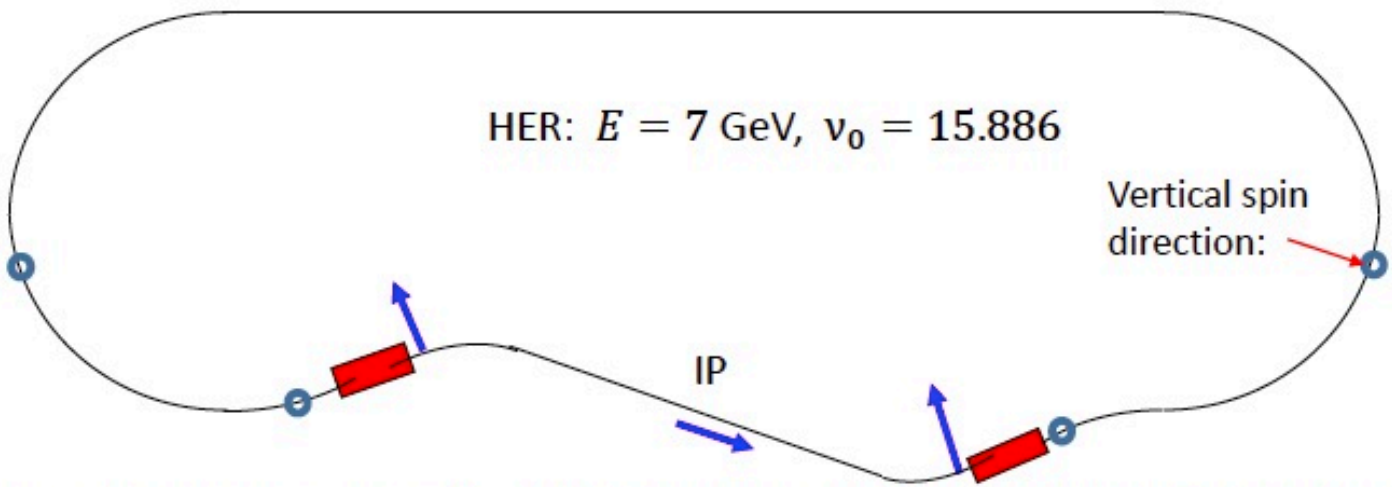
"B2E"	"BLA6RE"	"BLA4RE"	"BLA2RE"	"BLX1RE"	"BLB2RE"	"BLY2RE"	"BLC2RE"
0.0557427	0.0501498	0.0271539	0.0557427	−0.0221788	0.0234696	0.027	0.00591985

"BLC1LE"	"BLY1LE"	"BLB1LE"	"BLX2LE"	"BLA2LE"	"BLA4LE"
−0.00591047	−0.0270414	−0.0387835	0.0532119	−0.0181419	0.0663659

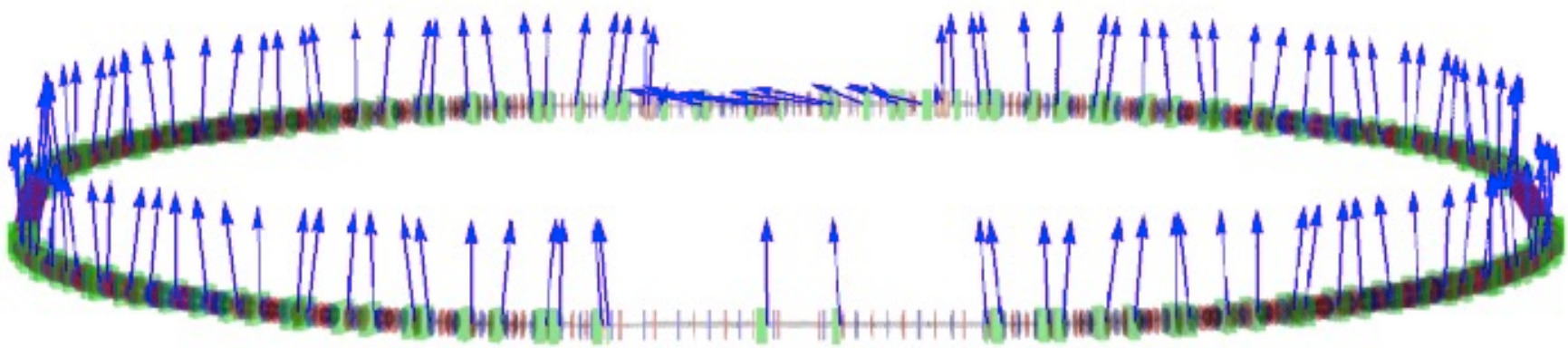
From I. Koop, A.Otboev and Yu.Shatunov, BINP, Novosibirsk preliminary considerations on the longitudinal polarization at SuperKEKB

Preliminary studies by BINP group

A scheme with restoration of the vertical spin direction in main arcs

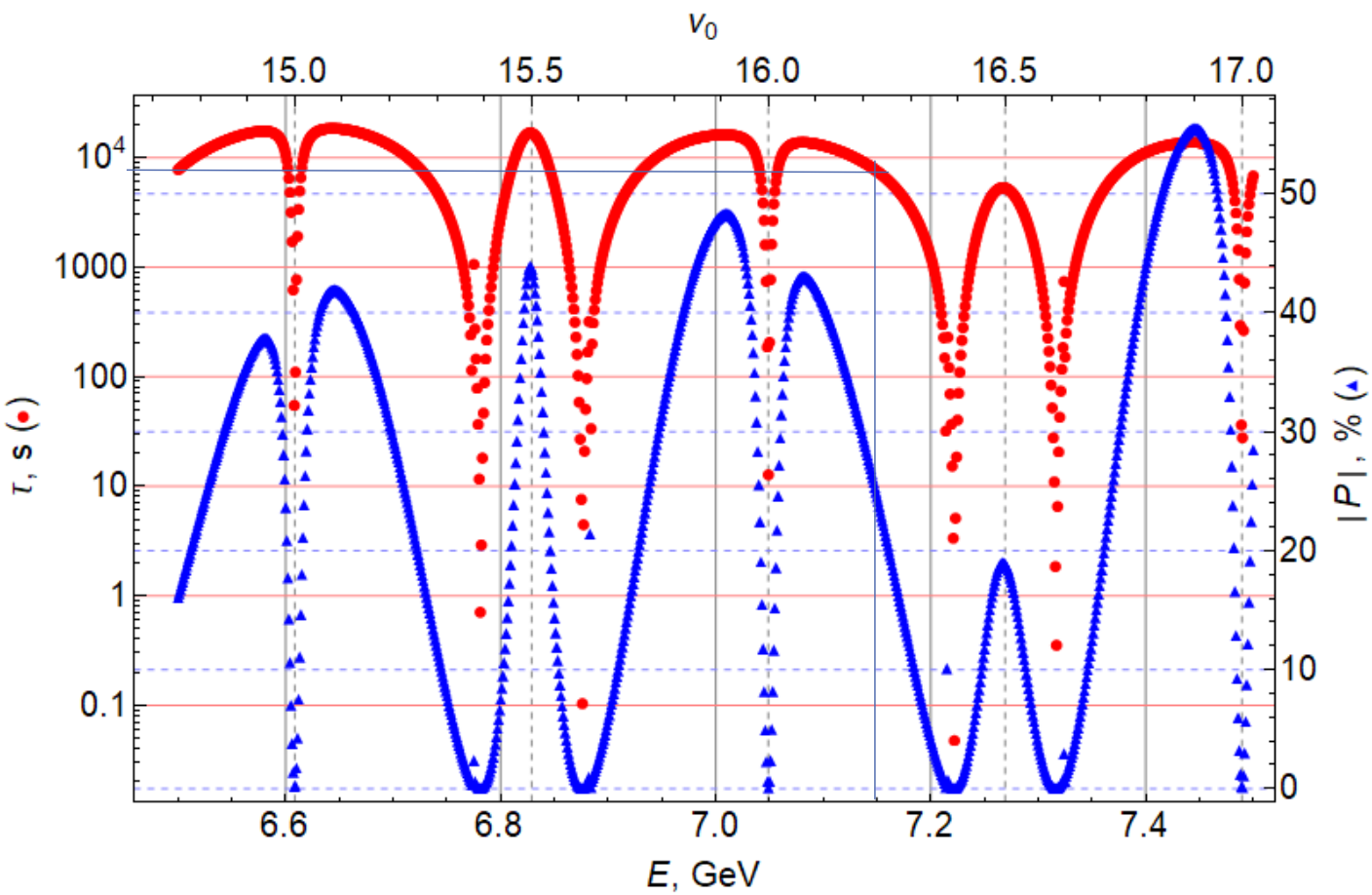


Spin direction is vertical in the main part of HER. Then it is rotated to the horizontal plane by the set of two solenoids, which are comprising the 90^0 spin rotator.



From I. Koop, A.Otboev and Yu.Shatunov, BINP, Novosibirsk preliminary considerations on the longitudinal polarization at SuperKEKB

Preliminary studies by BINP group



Depolarization lifetime at E=7.15GeV is 7500s (~2 hrs)

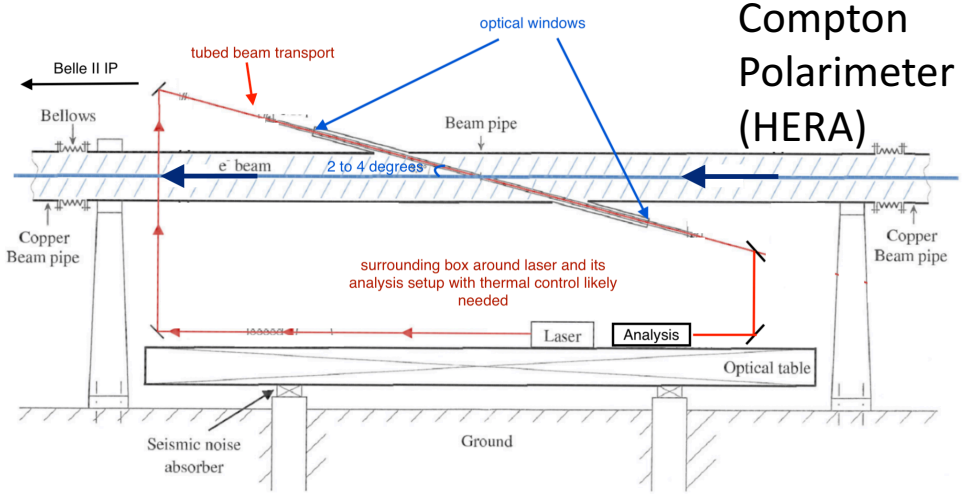
Note: beam is topped-up @ 50Hz continuously (current beam lifetime without top-up ~1hr)

From I. Koop, A.Otboev and Yu.Shatunov, BINP, Novosibirsk preliminary considerations on the longitudinal polarization at SuperKEKB

Polarization in SuperKEKB

Hardware needs

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



Space is available for laser interaction region and scattered electron detector

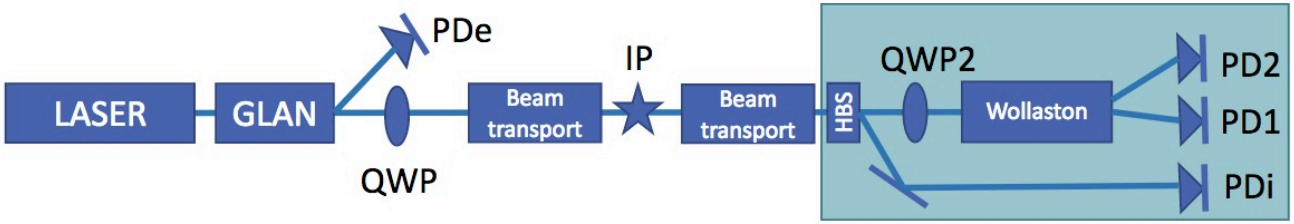
LAL Orsay and U. Manitoba groups

Polarization in SuperKEKB

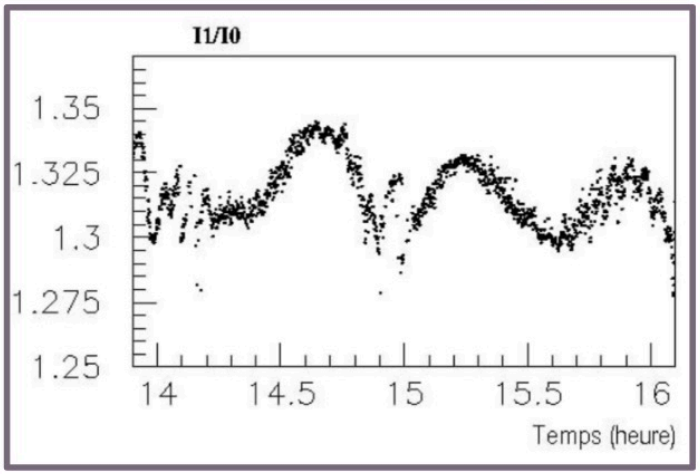
LAL Orsay team (A. Martens, Y. Peinaud,F. Zomer, P. Bambade,F. Le Diberder, K. Trabselsi) **HERA Compton Polarimeter experience**

Brisson JINST 5 P06006 (2010), Zomer HDR (2003), Jacquet HDR (2009), Baudrand PhD thesis (2007)

Laser beam polarization control



- Polarization independent Holographic Beam Sampler
- Careful suppression of laser intensity fluctuations
- Use of balanced photodiodes and differential electronics



Example of time dependent measurement at HERA
- Remaining 0.3% fluctuations

- More frequent measurements ?
- Modulation of circular polarization to avoid DC fluctuations ?

Polarization in SuperKEKB

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

work on Compton polarimeter at JLab - QWeak and MOLLER –

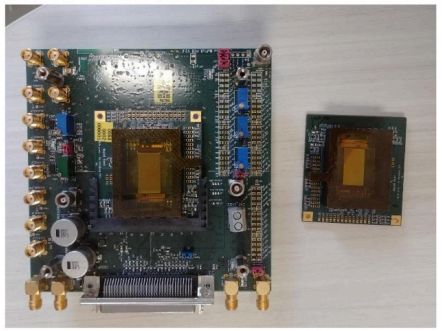
Using HPVMAPs as Compton e- Detector at MOLLER

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

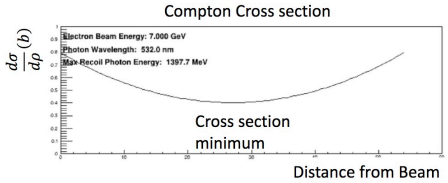
The chip is primarily developed by groups at the U. of Heidelberg and the Karlsruhe Institute of Technology, and intended for various experiments:

- ATLAS
- Mu3e
- PANDA
- P2
- MOLLER

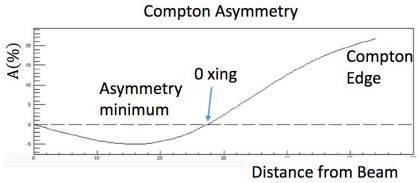
The implementation as a Compton detector is done by the Manitoba group.

Calculations/Simulations

Compton Cross section



Compton Asymmetry



Masanori Satoh, KEK (June 2020)

Linac Beam 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)	