Physics Prospects of Beam Polarization at Belle II:

Upgrading SuperKEKB with polarized e^- Beams

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1 October 2021

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

University of Victoria

30 years of Tau Lepton International Workshops

The 16th International Workshop on Tau Lepton Physics (TAU2021) (Virtual Edition)

September 27, 2021 to October 1, 2021
Indiana University

Dedication

In Memoriam

The 16th International Workshop on Tau Lepton Physics (TAU2021) is dedicated to **Simon Eidelman and Olga Igonkina**, colleagues, friends and brilliant physicists who both made major contributions to physics, and in particular to the field of tau lepton physics research.

Simon Eidelman (1948 - 2021), chief researcher of the Budker Institute of Nuclear Physics and of the faculty at the Physics Department of Novosibirsk State University is remembered and honored for his early ground breaking work on electric-positron colliders, and his later work with the CMD-2 and CMD-3 groups at Novosibirsk, Belle and Belle-2 in Japan, and LHCb at CERN. He was among the pioneers in terms of evaluating the hadronic contribution to the anomalous magnetic moment of the muon, based on measurements taken at e+e– colliders. For many years Simon was an active member of the Particle Data Group. He was a member of the International Advisory Committee of the TAU Workshop Series

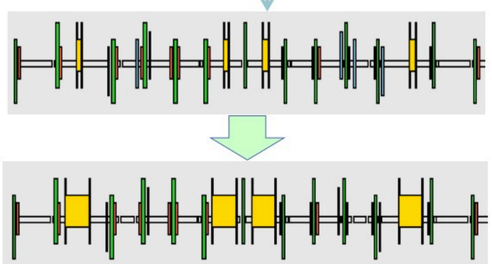
Olga Igonkina (1973 - 2019) was Senior Researcher at Nikhef, and professor by extraordinary appointment at Radboud University Nijmegen. She joined the ATLAS collaboration in 2006 and was a key member, pursuing her research with enthusiasm and passion. She organized the 15th International Workshop on Tau Lepton Physics in Amsterdam in 2018. She was a dedicated scientist, teacher and mentor, and is greatly missed by colleagues, friends and all who knew her.

Upgrading SuperKEKB with polarized electrons

Opens New Windows for Discovery with Belle II

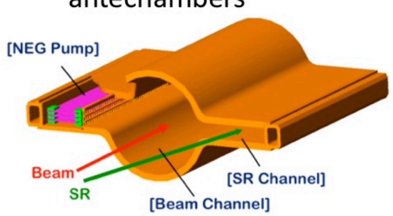
- Extremely rich and unique high precision electroweak program
- Probe of Dark Sector
- Polarized Beam also provides:
  - Improved precision measurements of τ Michel Parameters, electric dipole moment (EDM) and information on Magnetic Form factor F_2
  - Reduces backgrounds in $\tau \rightarrow \mu\gamma$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

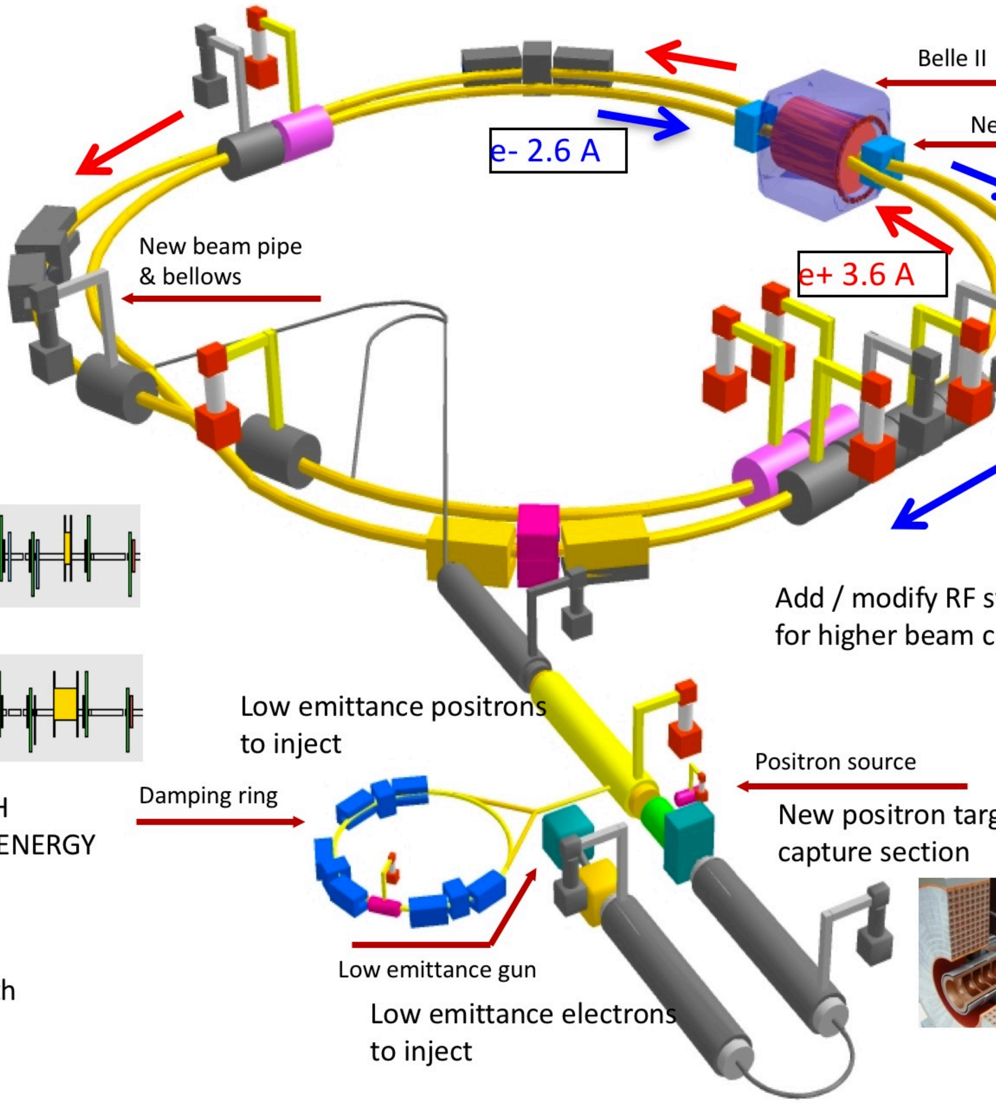
Replace short dipoles with longer ones (LER)



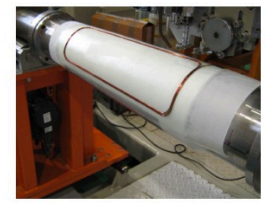
Redesign the lattices of HIGH ENERGY RING (HER) & LOW ENERGY RING (LER) to squeeze the emittance

TiN-coated beam pipe with antechambers



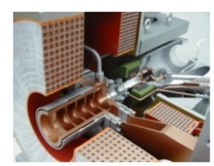


New superconducting /permanent final focusing quads near the IP



Add / modify RF systems for higher beam current

New positron target / capture section



To obtain x40 higher luminosity

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

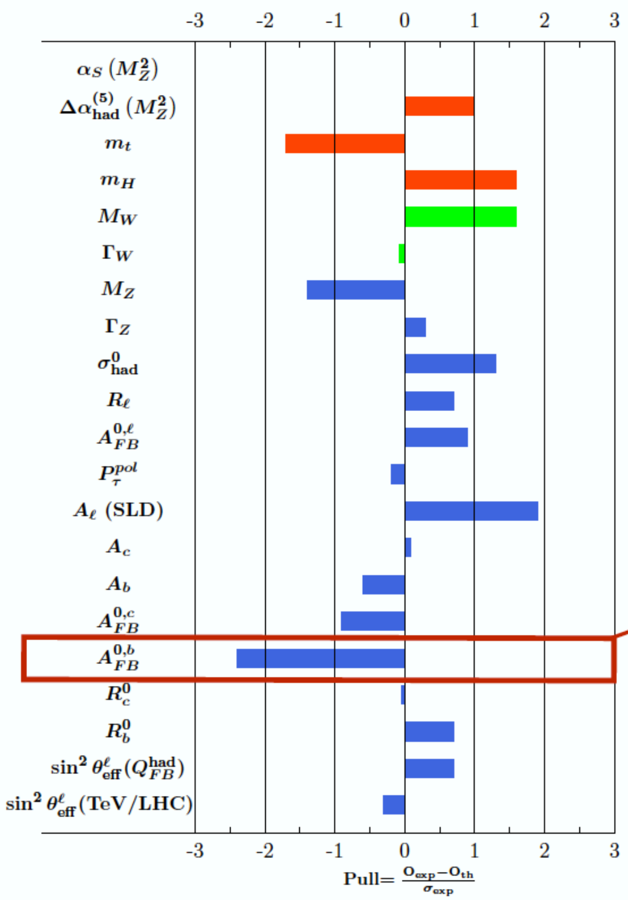
T_3 = -0.5 for charged leptons and D-type quarks
+05 for neutrinos and U-type quarks

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

The Standard Model Electroweak fit

SM fit results: Predictions for EWPO

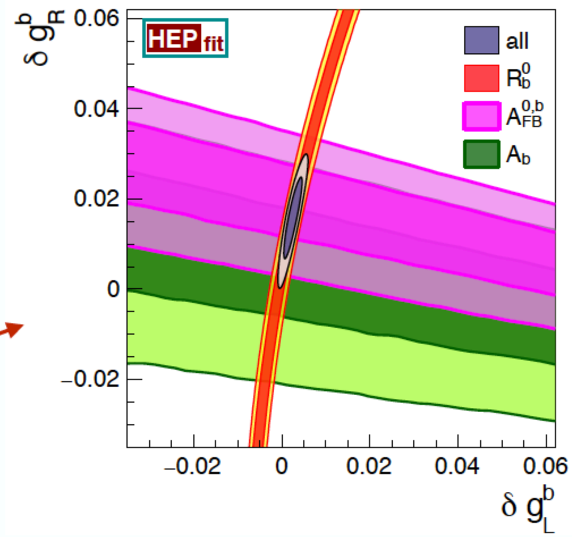
Also good agreement between indirect determination of EWPO and experimental measurements, with one notable exception



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

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

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



	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

‘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 :

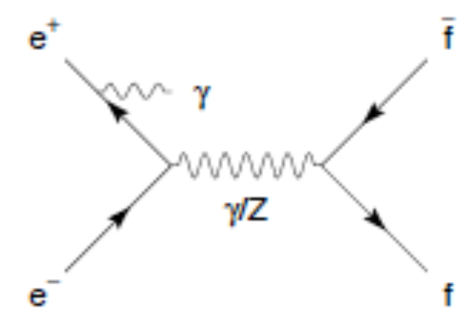
$$\sin^2\theta_{eff}^{lepton} = 0.23098 \pm 0.00026$$

- 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

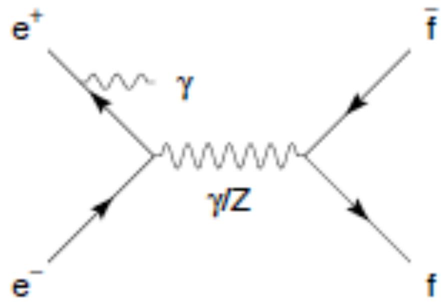
Electron helicity would be chosen randomly pulse-to-pulse by controlling the circular polarization of the source laser illuminating a GaAs photocathode.

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

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

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

(for s-channel Born)

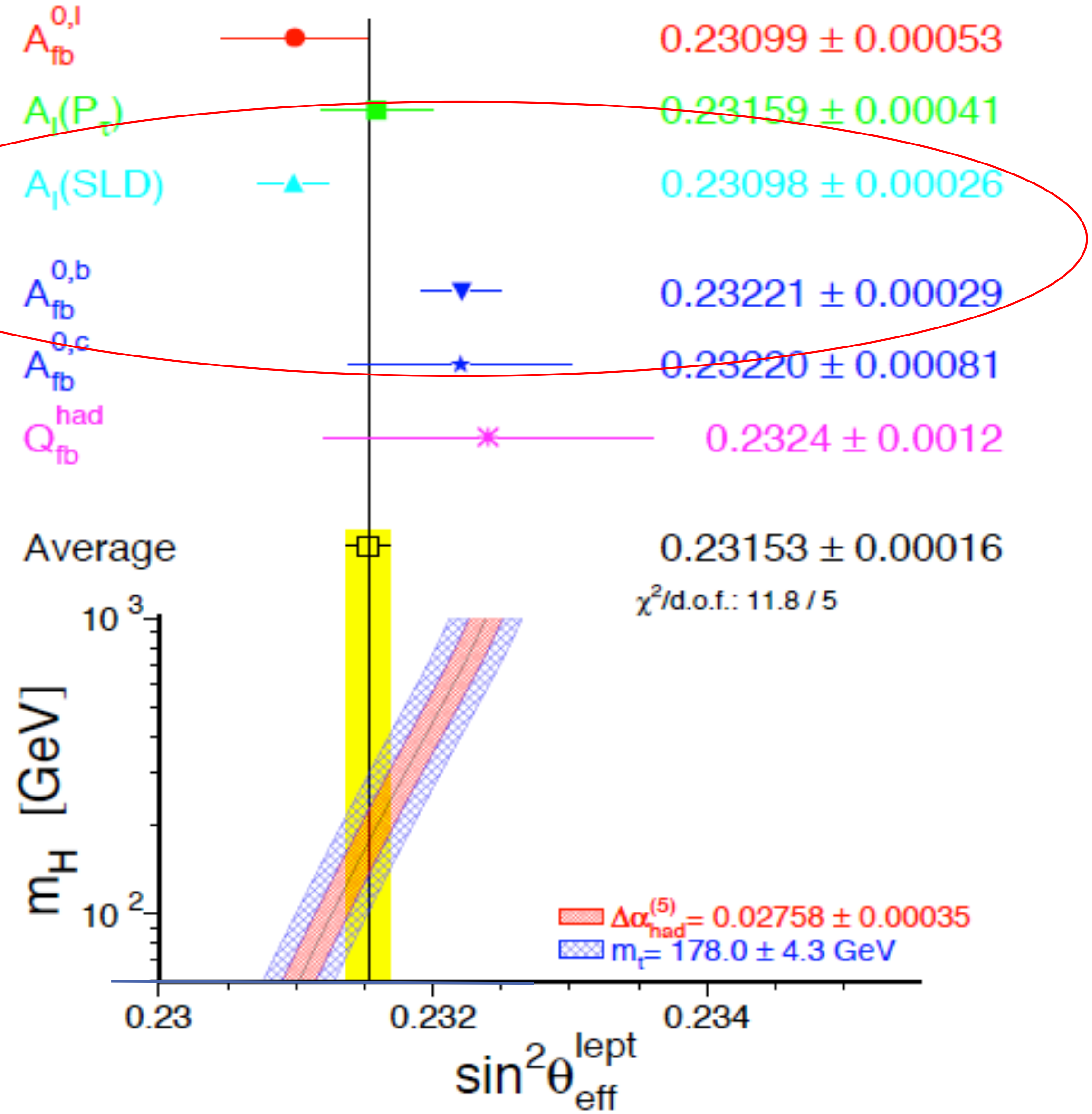


Source generates mainly right-handed electrons

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

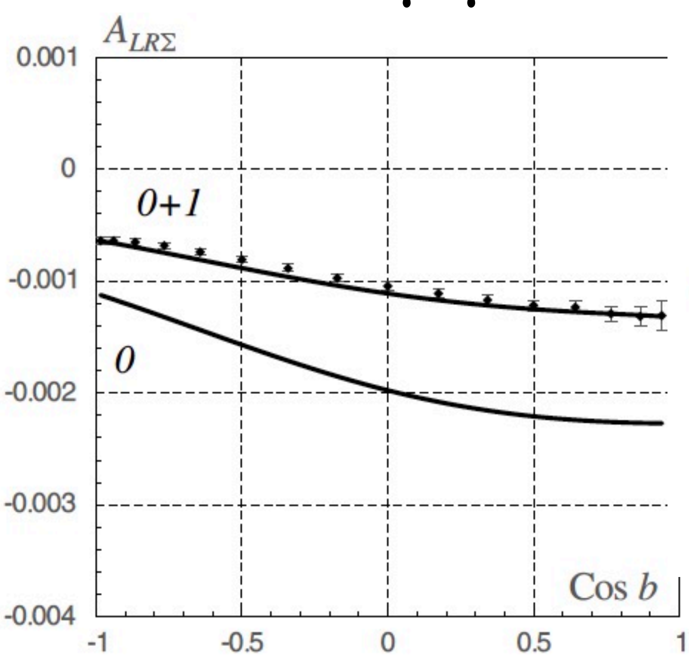
3.2σ comparing only A_{LR} (SLC) and $A^{0,b}_{fb}$(LEP)

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) **(see Ruban Sandapen's talk)**

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

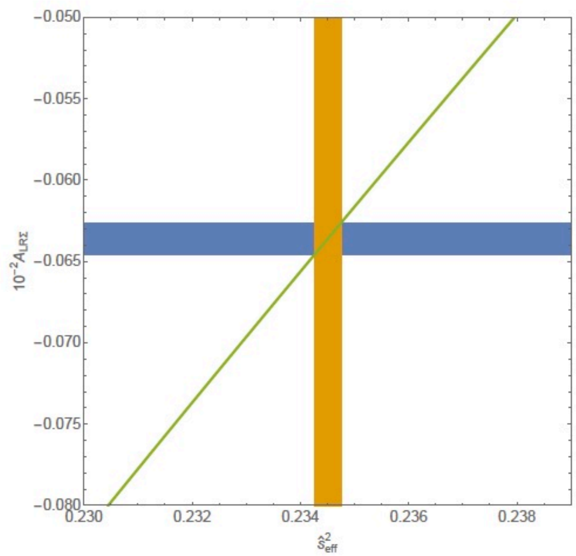


$$\Sigma_L^C = \int_{\cos b}^{\cos a} \sigma_L^C \cdot d(\cos\theta), \quad \Sigma_R^C = \int_{\cos b}^{\cos a} \sigma_R^C \cdot d(\cos\theta)$$

a=10° & energy of photons < 2GeV

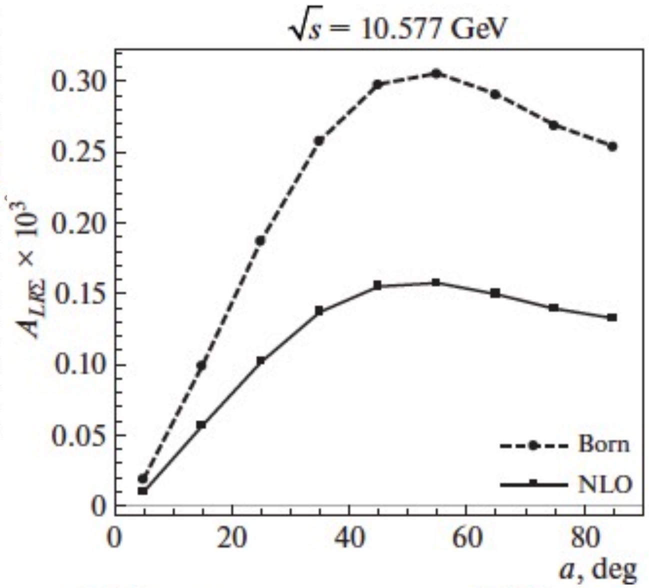
Phys.Rev. D101 (2020) no.5, 053003

$A_{LR}^{\mu\mu}$ 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.

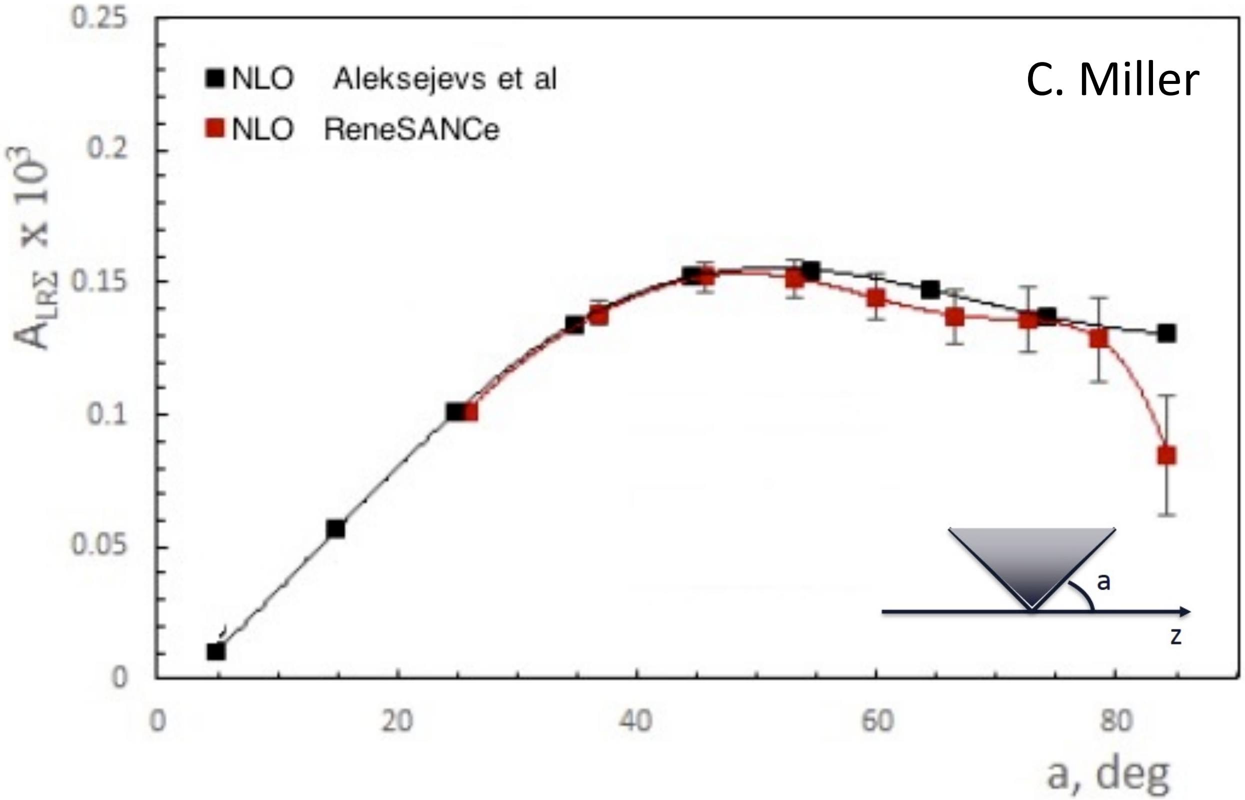
Polarization in each beam and special mode to efficiently calculate A_{LR} without event generation output.

Caleb Miller (Victoria) has been working 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

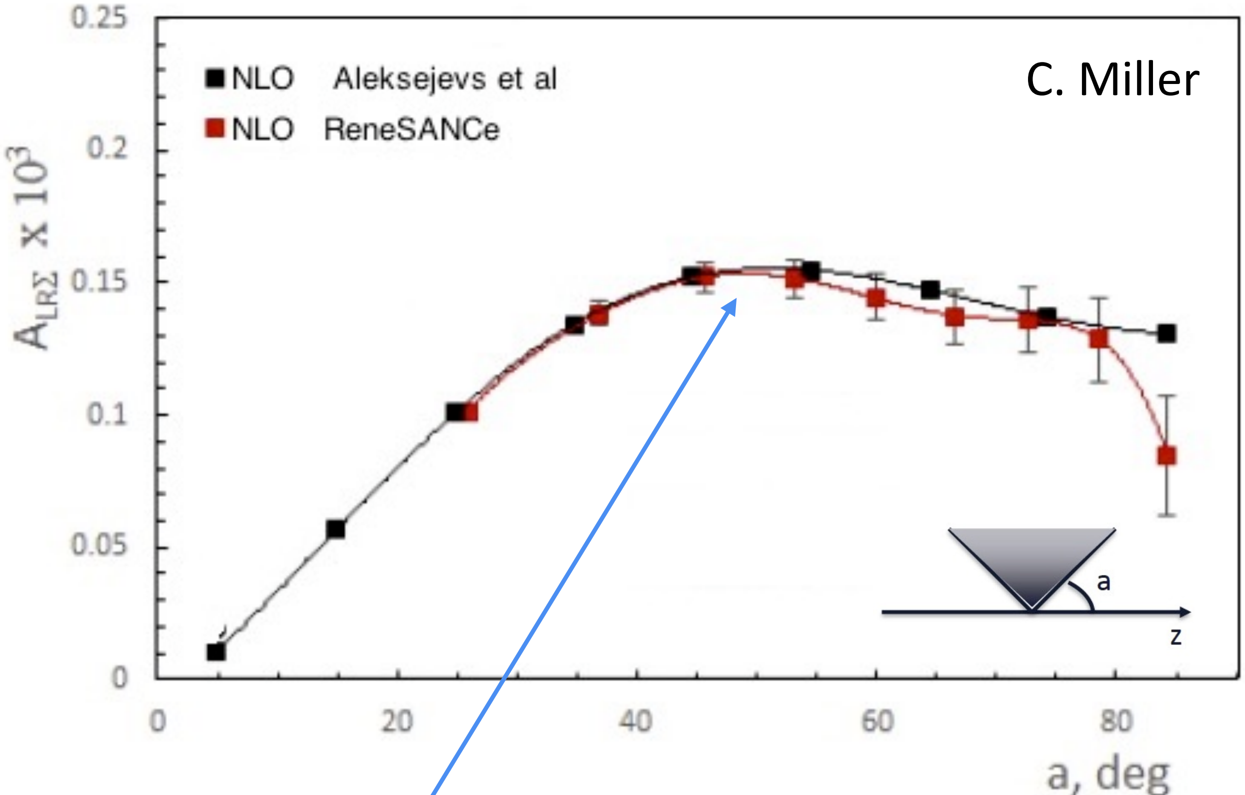
ReneSANCe *cf* Aleksejevs *et al*



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 $\delta \sin^2 \theta_W$ / 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 $\delta \sin^2 \theta_W \ / \ \delta A_{LR}$

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

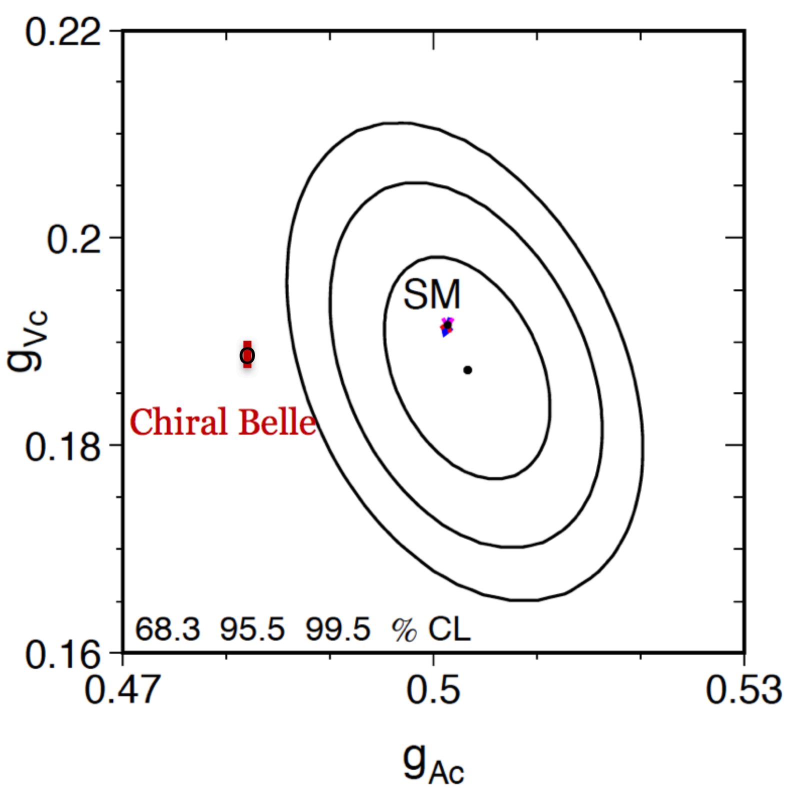
$\sin^2\Theta_W$ - all LEP+SLD measurements combined WA = 0.23153 ± 0.00016

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

Chiral Belle probes both high and low energy scales

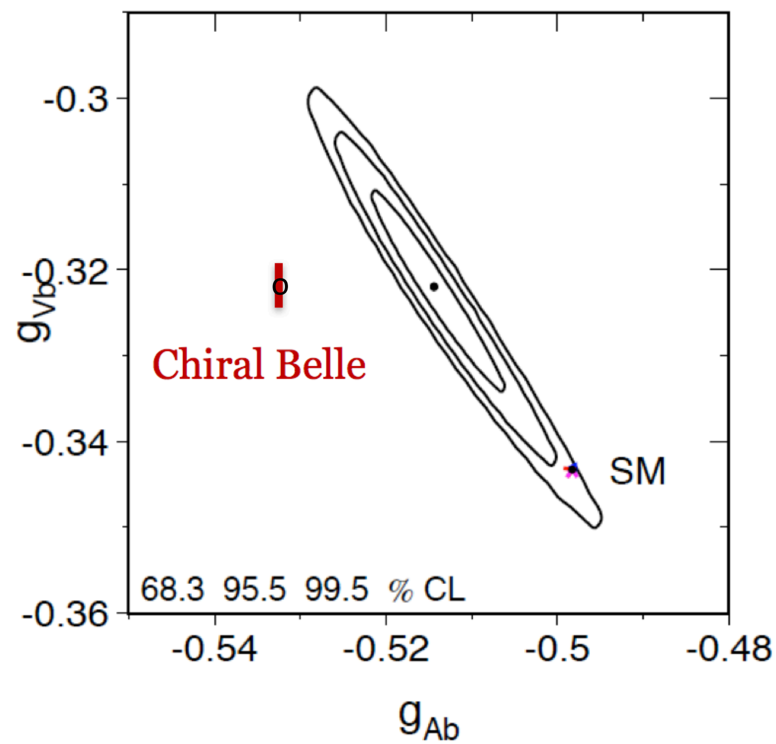
Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

c-quark:
Chiral Belle ~7 times more precise



b-quark:
Chiral Belle ~4 times more precise

with 20 ab^{-1}



Chiral Belle probes both high and low energy scales

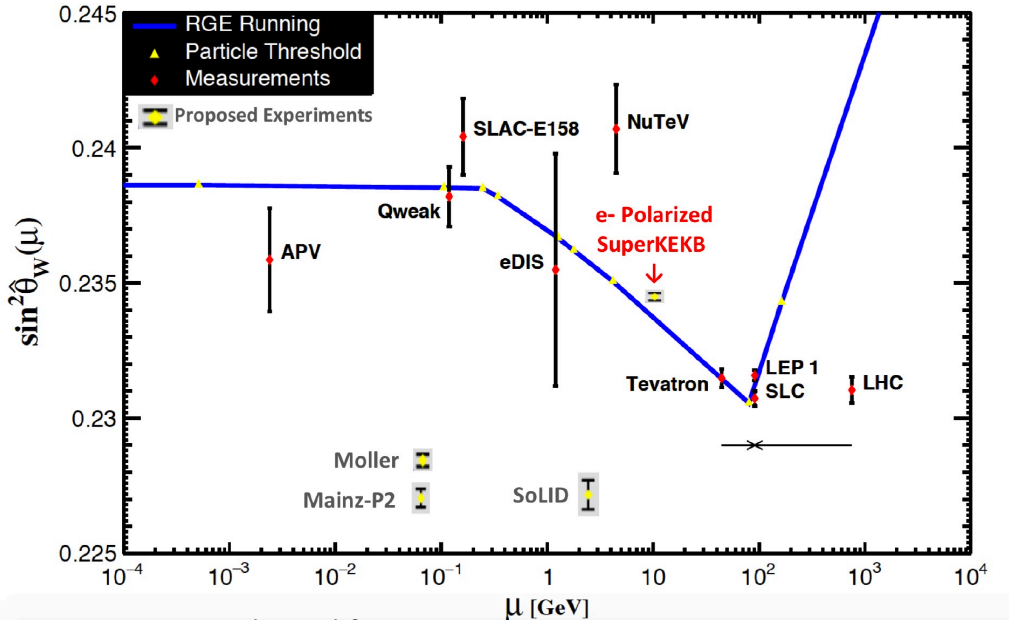


Figure Adapted from
J. Erler and A. Freitas, (PDG) Phys. Rev. D98 , 030001 (2018)

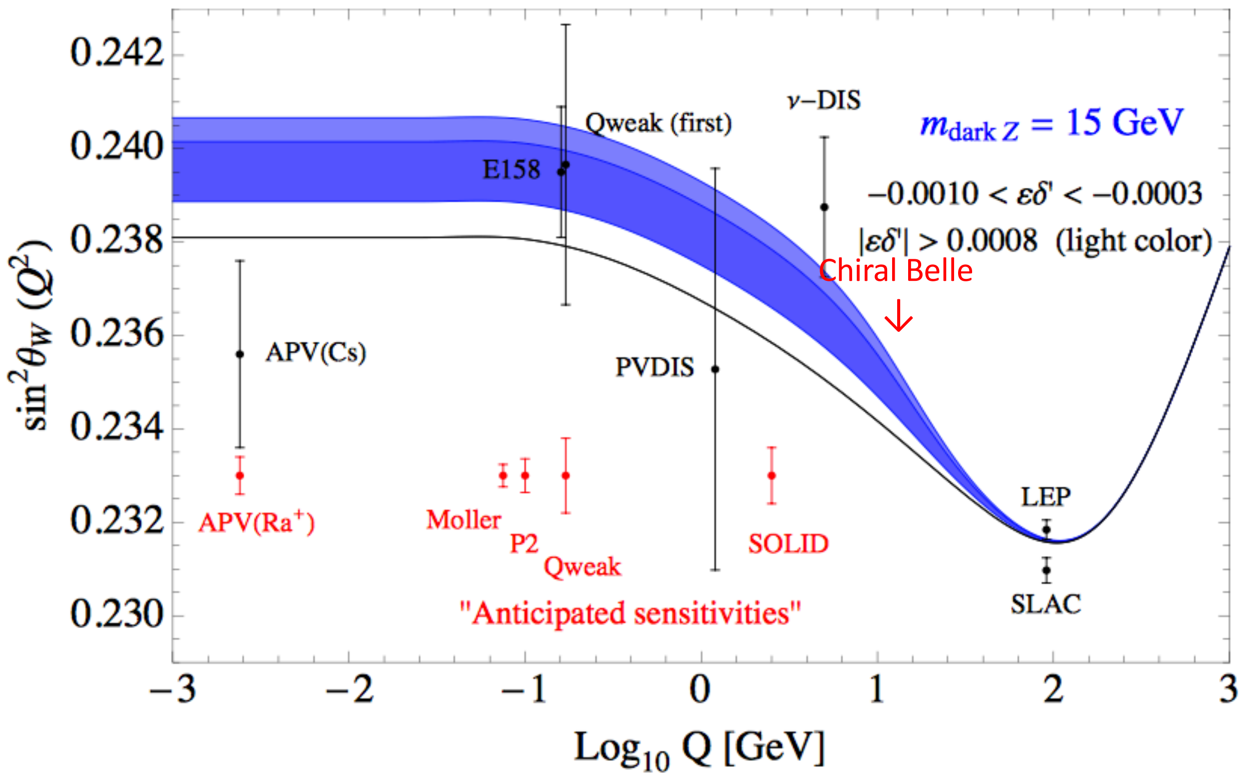
Chiral Belle: σ < 0.0002 with 40 ab^{-1}
Using only clean leptonic states

- **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
- highest precision test neutral current vector coupling universality where beam polarization error cancels (< 0.3% relative error for b-to-c, *cf* 4% now)
- Most precise measurements for charm and beauty
  - probes both heavy quark phenomenology and Up vs Down

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)



Chiral Belle probes both high and low energy scales

Global interest in this EW physics:

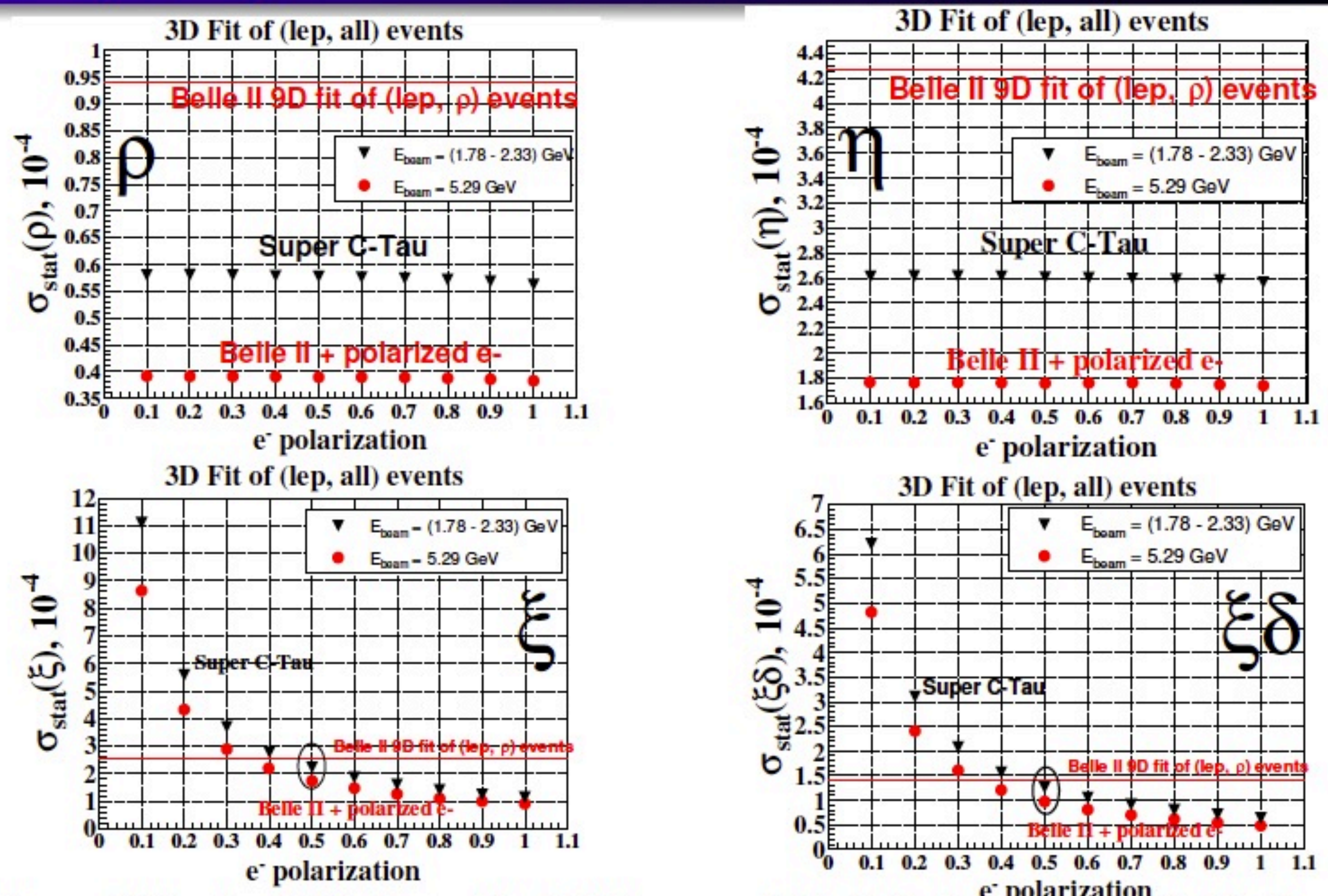
- LHC experiments
- APV measurements at lower energy scales
- Moller Experiment at Jefferson Lab which will measure $\sin^2\theta_{eff}^{electron}$ below 100MeV with similar precision (note: Moller is only sensitive to electron couplings.)
- EIC can measure $\sin^2\theta_{eff}$ in similar kinematic region,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

Chiral Belle also provides

- Improved precision measurements of τ Michel Parameters, electric dipole moment (EDM) and information on Magnetic Form factor F_2
  - 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”*
  - See Denis Epifanov talk this morning on the Russian Super Tau-Charm Factory (STCF) which will operate with e- polarized beams
- e^- beam polarization can be used to reduce 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

From Denis Epifanov's talk this morning on STCF: τ Michel Parameter with polarized e- beam

Fit of $(\ell,\ \text{all})$ 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

50/ab of polarized Belle II data assumed in these studies

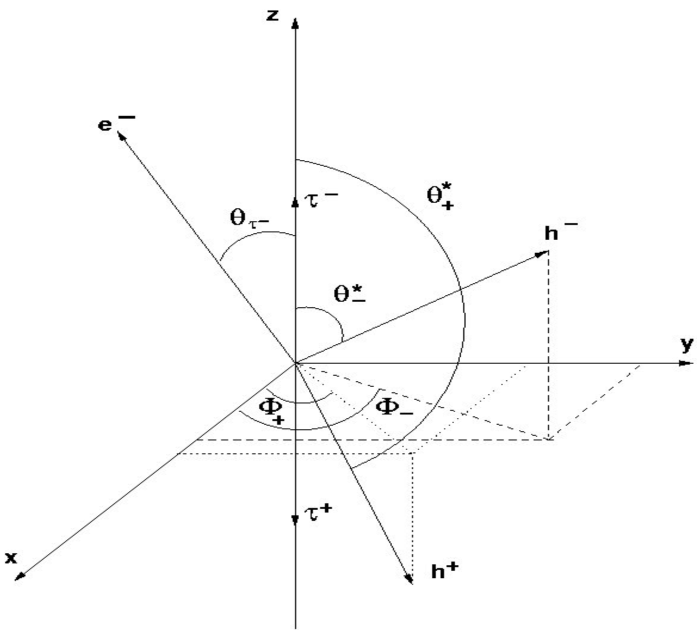
From J. Bernabéu *et al*, Nucl. Phys. B763:283–292, 2007

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

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

With beam polarization λ :

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



Now, to be sensitive only to the EDM we can define the azimuthal asymmetry as:

$$A_N^{\mp} = \frac{\sigma_L^{\mp} - \sigma_R^{\mp}}{\sigma} = \alpha_{\mp}\frac{3\pi\gamma\beta}{8(3-\beta^2)}\frac{2m_\tau}{e}d_\tau^\gamma \tag{14}$$

where

$$\sigma_L^{\mp} = \int_0^{2\pi} d\phi_{\pm}\left[\int_0^{\pi} d\phi_{\mp}\left.\frac{d^2\sigma^S}{d\phi_- d\phi_+}\right|_{Pol(e^-)}\right] = Br(\tau^+ \to h^+\bar{\nu}_\tau)Br(\tau^- \to h^-\nu_\tau)\,\alpha_{\mp}\frac{(\pi\alpha\beta)^2\gamma}{8s}\frac{2m_\tau}{e}d_\tau^\gamma \tag{15}$$

$$\sigma_R^{\mp} = \int_0^{2\pi} d\phi_{\pm}\left[\int_{\pi}^{2\pi} d\phi_{\mp}\left.\frac{d^2\sigma^S}{d\phi_- d\phi_+}\right|_{Pol(e^-)}\right] = -Br(\tau^+ \to h^+\bar{\nu}_\tau)Br(\tau^- \to h^-\nu_\tau)\,\alpha_{\mp}\frac{(\pi\alpha\beta)^2\gamma}{8s}\frac{2m_\tau}{e}d_\tau^\gamma \tag{16}$$

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^-

$\not{CP}$:

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

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

They conclude:

$$|d_\tau^\gamma| \leq 1.6\ 10^{-19}\ ecm \quad \text{Super B/Flavor factory, 1 yr running, } 15ab^{-1}$$
$$|d_\tau^\gamma| \leq 7.2\ 10^{-20}\ ecm \quad \text{Super B/Flavor factory, 5 yrs running, } 75ab^{-1}$$

Using Bernabéu *et al* from this study one can calculate for $40ab^{-1}$ Chiral Belle data with 70% polarization:

$|d_\tau^{\gamma}| < 1.4 \times 10^{-20}$ (Statistical error only)

World best measurement from Belle - arXiv:2108.11543 -

$$-1.85\times10^{-17} < \mathcal{R}(\tilde{d}_\tau) < 0.61\times10^{-17} ecm\ (95\%\ \text{CL})$$
$$-1.03\times10^{-17} < \mathfrak{I}(\tilde{d}_\tau) < 0.23\times10^{-17} ecm\ (95\%\ \text{CL})$$

Note: extrapolating statistical error from Belle results shown by Kenji Inami on Tuesday would give a limit of $\sim5\text{x}10^{-19}$ for unpolarized Belle II data with $50ab^{-1}$

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

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

In EFT interactions between τ and photon

$$\Gamma^{\mu}(q^2) = F_1(q^2)\gamma^{\mu} + F_2(q^2)\frac{i\sigma^{\mu\nu}q_{\nu}}{2m_{\tau}} + F_3(q^2)\frac{\sigma^{\mu\nu}q_{\nu}\gamma_5}{2m_{\tau}}$$

$F_1(q^2)$: Dirac form factor $F_1(0) = 1$

$F_2(q^2)$: Pauli form factor $F_2(0) = a_{\tau}$

$F_3(q^2)$: $F_3(0) = d_{\tau} \cdot 2m_{\tau} / eQ_{\tau}$

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

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

Then, we define the longitudinal asymmetry as

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

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

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

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

Table 1
Sensitivity of the F_2 measurement at the Υ energy (ab = attobarn = $10^{-18}b$)

EXPERIMENT ⇓	OBSERVABLE		
	Cross Section	Normal Asymmetry	Transverse and Longitudinal Asymmetry combined*
	$Re\{F_2\}$	$Im\{F_2\}$	$Re\{F_2\}$
Babar+Belle $2ab^{-1}$	4.6×10^{-6}	2.1×10^{-5}	1.0×10^{-5}
Super B/Flavor Factory (1 yr. running) $15ab^{-1}$	1.7×10^{-6}	7.8×10^{-6}	3.7×10^{-6}
Super B/Flavor Factory (5 yrs. running) $75ab^{-1}$	7.5×10^{-7}	3.5×10^{-6}	1.7×10^{-6}

*Polarized electrons required

Using Bernabéu *et al* from this study one can calculate for $40ab^{-1}$ Chiral Belle data with 100% polarization:

$Re\{F_2(10GeV)\}$ ~ 2×10^{-6} (Statistical error only)

Note: extrapolating statistical error for unpolarized Belle II data with $50ab^{-1}$ would give a sensitivity of $\sim 4 \times 10^{-6}$

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

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
- Gives ~0.5% absolute precision of the polarization at the interaction point – includes transport effects, lumi-weighting, stray e^+ polarizationIt
- 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
- Experience from OPAL (at LEP) indicates a 0.2% on systematic error on the A^{pol}_{FB} is achievable, translates into 0.5% error on the beam polarization
- C. Miller is deploying this with BaBar data at UVic – very promising! BaBar dataset (530fb^{-1}) expected to yield 0.5% statistical error from only $\tau \rightarrow \pi\,\nu$ with $\tau \rightarrow \rho\,\nu$ tag

Tau Polarization as Beam Polarimeter

Tau decay Polarization Sensitivity

- Using KKMC to generate $\tau \to \pi\nu$

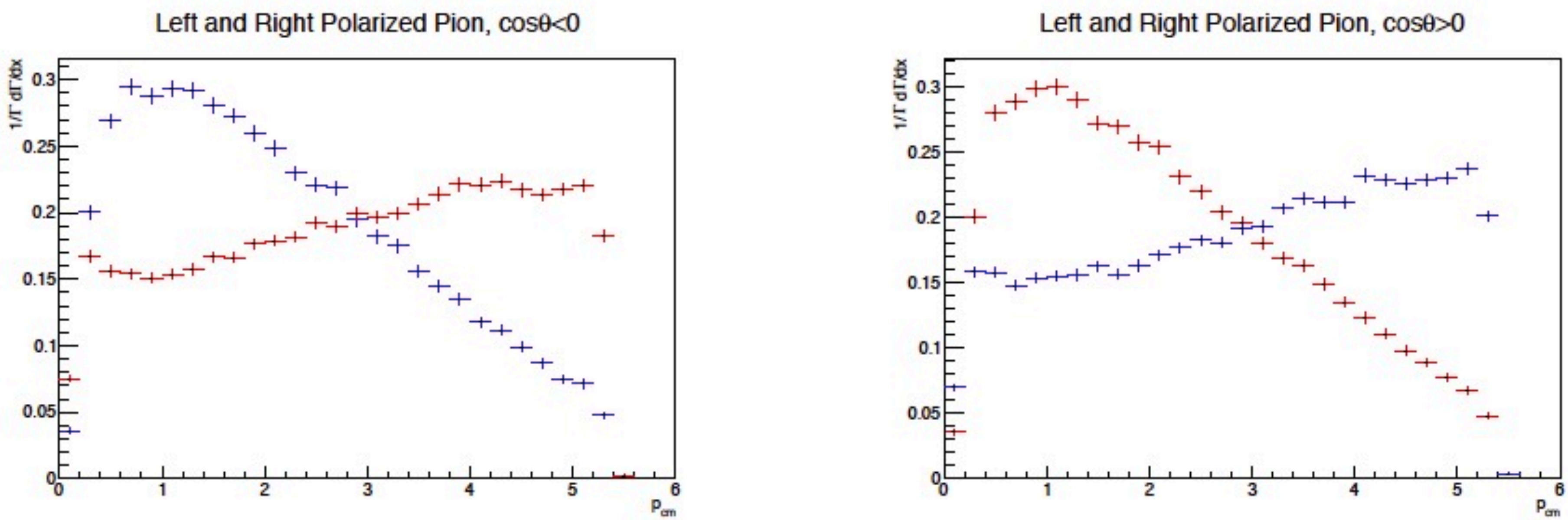


Figure: Pion momentum distribution in the backward direction from a polarized beam. Blue: left handed e^- beam, Red: right handed e^- beam

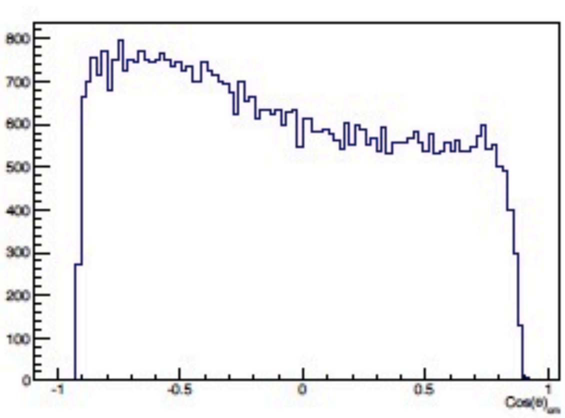
Figure: Pion momentum distribution in the forward direction from a polarized beam. Blue: left handed e^- beam, Red: right handed e^- beam

Tau Polarization as Beam Polarimeter

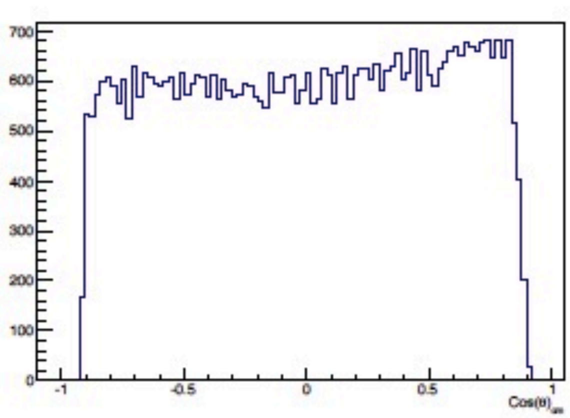
Pion Angular Distributions with Polarization

$\pi^- \cos\theta$ distributions

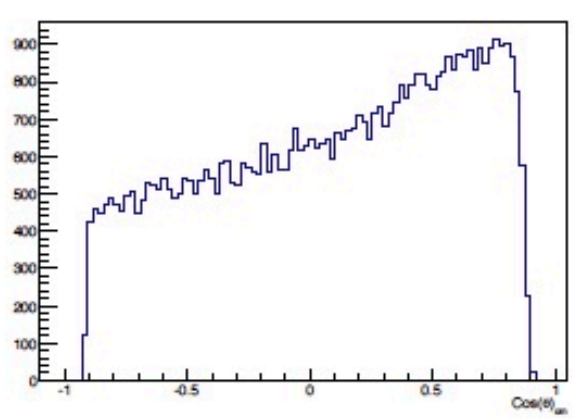
Left Polarization



No Polarization



Right Polarization



BaBar dataset (530fb^{-1}) expected to yield 0.5% statistical error
from only $\tau \to \pi\, \nu$ with $\tau \to \rho\, \nu$ tag

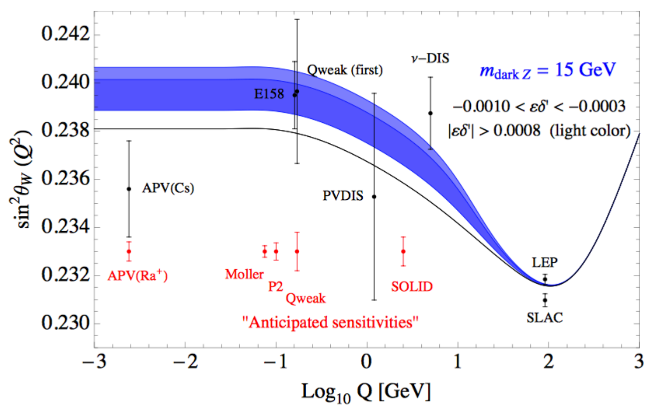
Summary

- 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

- Also get significant improvements to tau LFV, Michel parameters, LFV, EDM, and F_2(10GeV)

Summary

- competitive 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'



- Build on international partnerships with KEK to create a unique discovery machine

Summary

By opening this ***unique*** window on New Physics …
we could find something REALLY exciting

Thankyou for your attention…

…and consider taking the plunge and join the SuperKEKB electron beam polarization project!

Many areas where new people can have an impact! Additional accelerator physicists, experimentalist and theorists very welcome as we move through the White Paper stage

- Beam dynamics and spin tracking
- Spin rotator design
- Compton polarimetry – detector expertise
- Polarized low emittance source
- Tau decay polarimetry – use as many decay channels as possible
- Tau Michel parameter, EDM and F_2 studies
- Detailed physics MC studies with final-state fermion selection optimizing signal to background: b, c, tau, mu and e, as well as light quarks
- Precision EW theoretical calculations
- Bhabha MC generator with polarized beams -> now have ReneSANCe

Additional Information

Masanori Satoh, KEK (June 2020)

Linac Beam Parameters for KEKB/SuperKEKB

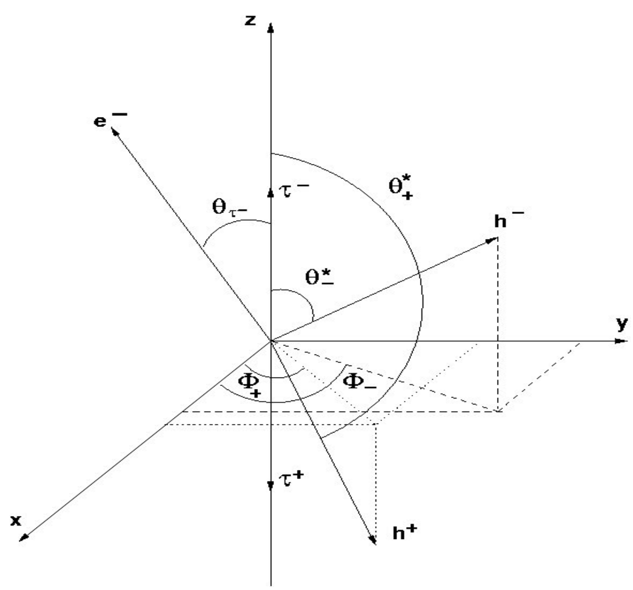
Stage	KEKB (final)		Phase-I		Phase-II		Phase-III (interim)		Phase-III (final)	
Beam	e+	e–	e+	e–	e+	e–	e+	e–	e+	e–
Energy	3.5 GeV	8.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV
Stored current	1.6 A	1.1 A	1.0 A	1.0 A	–	–	1.8 A	1.3 A	3.6 A	2.6 A
Life time (min.)	150	200	100	100	–	–	–	–	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) (μrad)	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)	

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

Normal polarization:

EDM and polarized beams can produce a P-even observable



$$\left.\frac{d\sigma^S}{d\Omega_{\tau^-}}\right|_\lambda = \frac{\alpha^2}{16s}\beta\{\lambda[(s_- + s_+)_x X_+ + (s_- + s_+)_z Z_+ + (s_- - s_+)_y Y_-] + (s_- - s_+)_x X_- + (s_- - s_+)_z Z_-\},$$

where

$$X_+ = \frac{1}{\gamma}\sin\theta_{\tau^-}, \qquad X_- = -\frac{1}{2}\sin(2\theta)\frac{2m_\tau}{e}\mathrm{Im}\{d_\tau^\gamma\},$$

$$Z_+ = -\cos\theta_{\tau^-}, \qquad Z_- = -\frac{1}{\gamma}\sin^2\theta\frac{2m_\tau}{e}\mathrm{Im}\{d_\tau^\gamma\},$$

$$Y_- = \gamma\beta^2\cos\theta_{\tau^-}\sin\theta_{\tau^-}\frac{2m_\tau}{e}\mathrm{Re}\{d_\tau^\gamma\}$$

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

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

The most general Lorentz invariant structure describing the interaction of a vector boson V with two on-shell fermions $f\bar{f}$ can be written in terms of six form factors:

$$\langle f(p_-)\bar{f}(p_+)|\, J^\mu(0)\,|0\rangle = e\,\bar{u}(p_-)\Big[(F_1 + F_4\gamma_5)\gamma^\mu + \frac{1}{2m_f}(i\,F_2 + F_3\gamma_5)\sigma^{\mu\nu}q_\nu + \frac{1}{2m_f}(i\,F_5 + F_6\gamma_5)q^\mu\Big]v(p_+) \quad (6)$$

where $q = p_+ + p_-$. Since the two fermions are on-shell the form factors F_i appearing in Eq. (6) are functions of q^2 and m_f^2 only.

In addition, if the current J^μ is conserved, we must have

$$i\frac{q^2}{2m_f}F_5 + \left(\frac{q^2}{2m_f}F_6 - 2m_f\,F_4\right)\gamma_5 = 0 \quad \Rightarrow \begin{cases} F_5 = 0 \\ F_6 = \dfrac{4m_f^2}{q^2}F_4 \end{cases} \quad (7)$$

so that the final expression for the gauge invariant $f\bar{f}\gamma$ vertex reduces to:

$$\langle f(p_-)\bar{f}(p_+)|\, J^\mu(0)\,|0\rangle = e\,\bar{u}(p_-)\left[\gamma^\mu\,F_1 + \frac{1}{2m_f}(i\,F_2 + F_3\gamma_5)\sigma^{\mu\nu}q_\nu + \left(q^2\gamma^\mu - q^\mu\,\not{q}\right)\gamma_5 F_A\right]v(p_+) \quad (8)$$

In this expression, F_1 parametrizes the vectorial part of the electromagnetic current ($F_1(0) = 1$), $F_A = -F_4/q^2$ is the so-called anapole moment, while F_2 and F_3 parametrize the usual magnetic and electric dipole moments, respectively, i.e.

$$F_2(0) = a_f, \quad d_f = \frac{e}{2m_f}F_3(0). \quad (9)$$

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

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

The direct text-book computation of the magnetic part of the standard one-loop QED vertex yields [16]

$$F_2(s) = \left(\frac{\alpha}{2\pi}\right)\frac{2m_\tau^2}{s}\frac{1}{\beta}\left(\log\frac{1+\beta}{1-\beta} - i\,\pi\right), \quad \text{for} \quad q^2 = s > 4m_\tau^2, \tag{10}$$

where α is the fine structure constant and $\beta = (1 - 4m_\tau^2/s)^{1/2}$ is the velocity of the τ. For $M_\Upsilon \sim 10\,\text{GeV}$,

$$F_2(M_\Upsilon^2) = (2.65 - 2.45\,i) \times 10^{-4}. \tag{11}$$

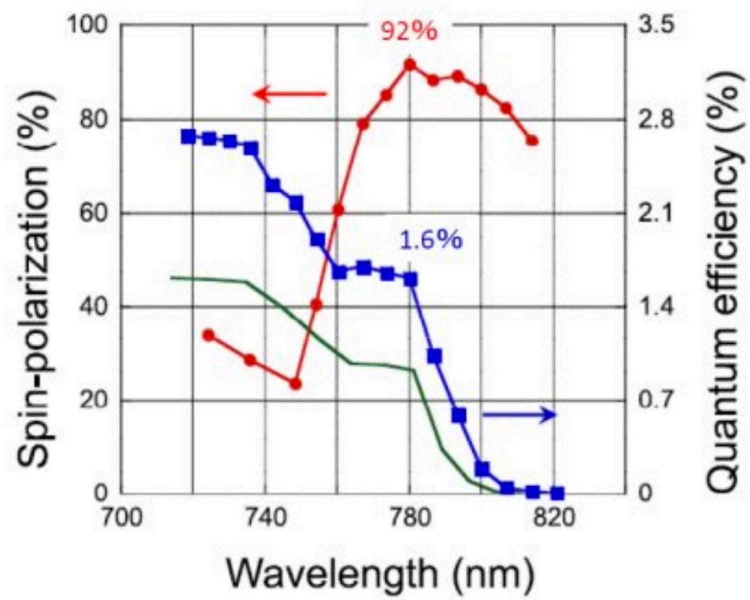
Polarization in SuperKEKB

- 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

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

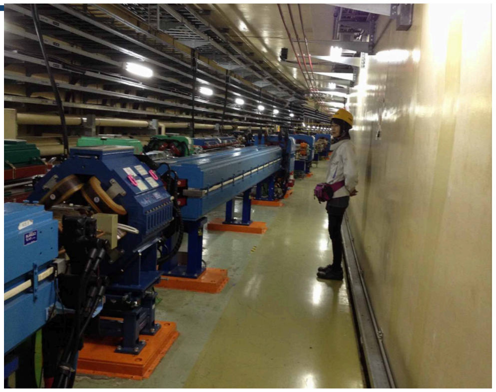
20 mm-mrad vertical emittance

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



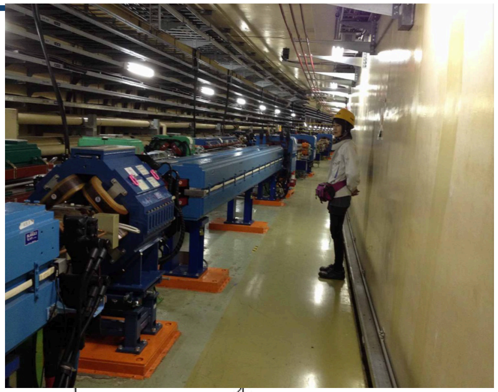
Hardware needs

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

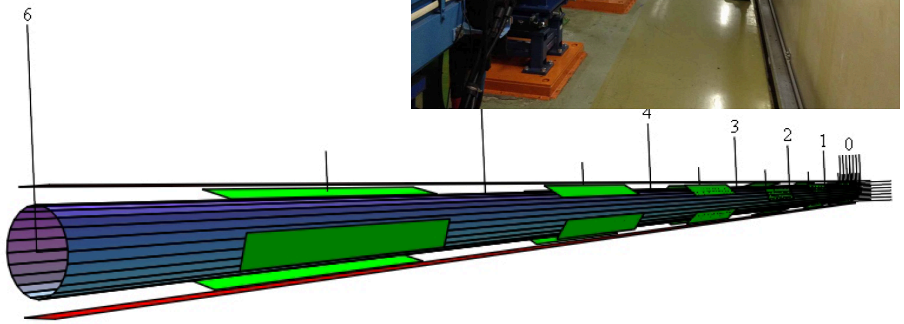
BINP, ANL, BNL, TRIUMF-Victoria Groups

Polarization in SuperKEKB



Hardware needs

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



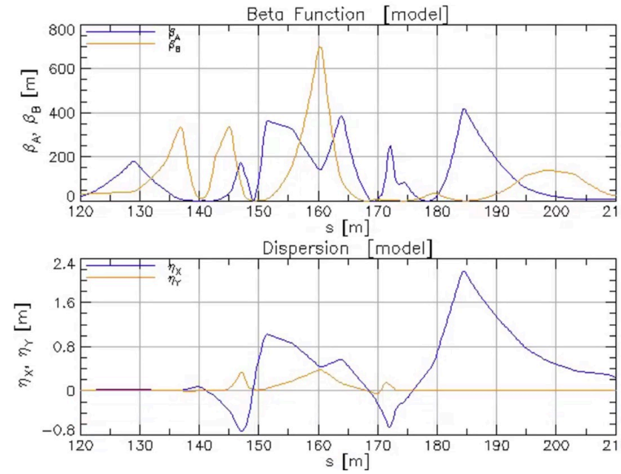
In preliminary studies, one concept (U. Wienands, ANL) is to used combined-function magnets which would replace three existing bending magnets. 5.9m long, 150m on either side of interaction point.

BINP, ANL, BNL, TRIUMF, Victoria Groups

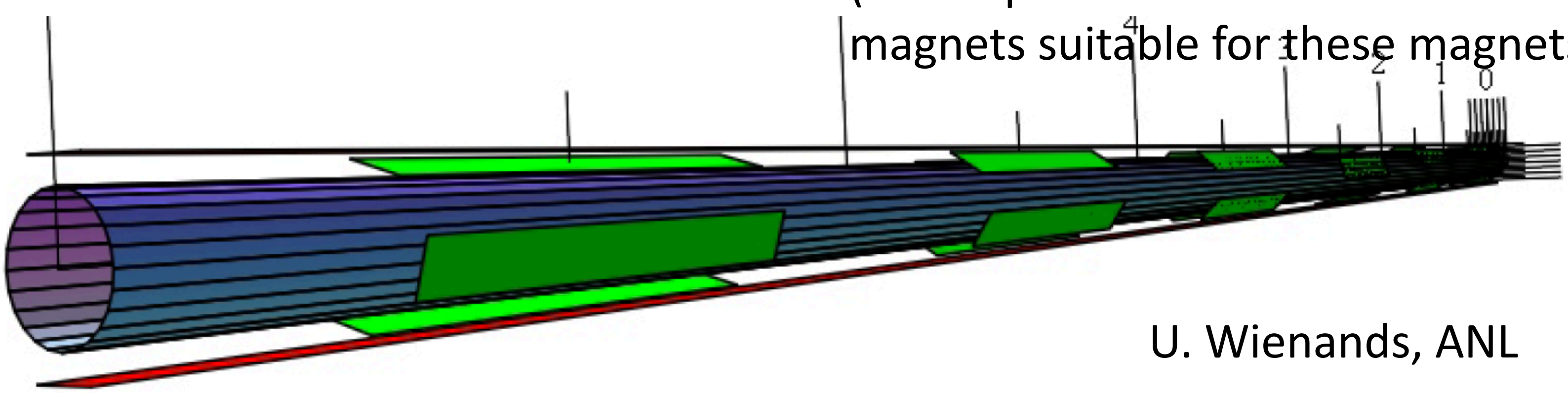
Compact Spin Rotator

- Combined-Function Solenoid-Dipole-Quadrupole Rotator
  - ≈ 6 m long, 3 magnets, replace SKEKB BLA4{L,R}E and B2E magr
    - no change in geometry of the machine
    - with solenoid & quadrupoles off, present optics is restored.
  - We have a first optical match in Bmad on the L side of SKEKB.
    - existence proof, optimization needed
- Using three magnets allows the rotator to be tuned to alig spin direction at IP
- Rotator parameters:
  - 4.45 T solenoid (2 magnets); 0.798 T (1 magnet)
  - same dipole magnetic fields as the dipoles they replace (≈ 0.2, 0.3 T)
  - ≤ 35 T/m quadrupole gradient; ≤ 2.8 T field @ r = 8 cm
    - 6 quadrupoles at various skew angles

Bmad Match



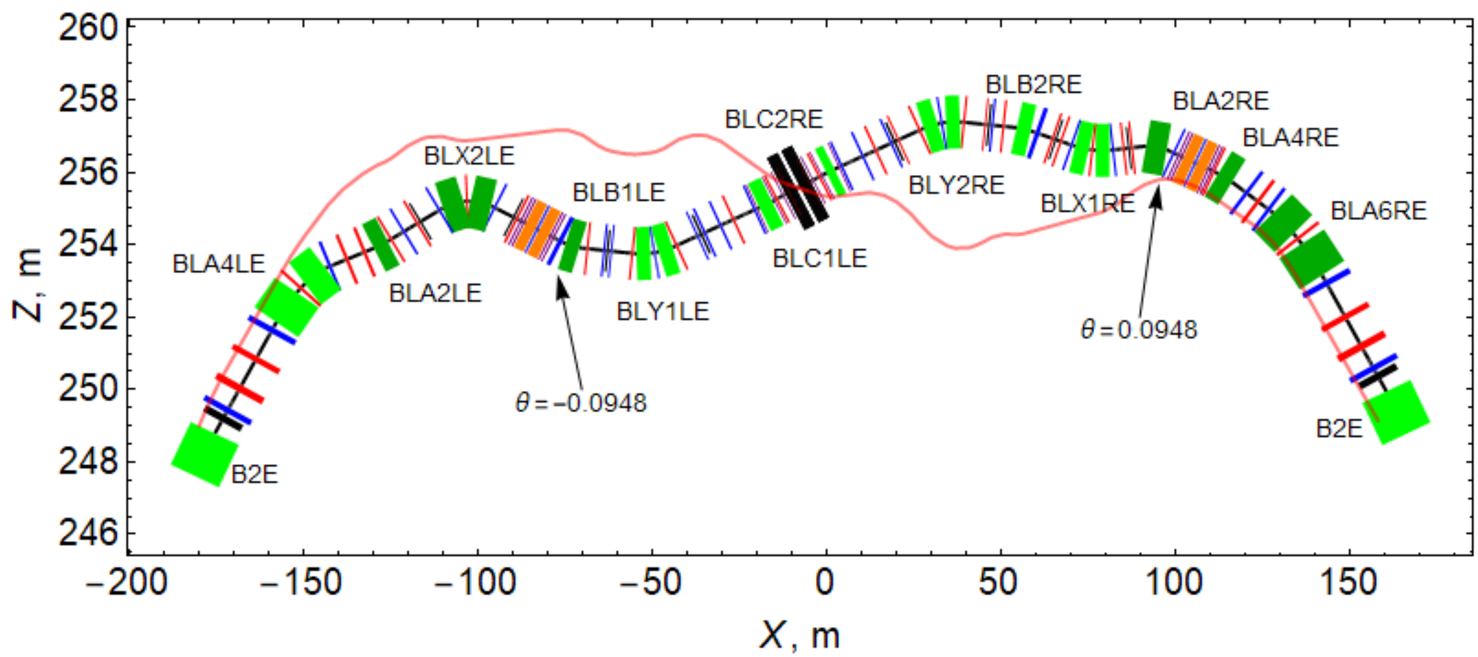
(BNL expertise in construction of direct wind magnets suitable for these magnets)



U. Wienands, ANL

Preliminary studies by BINP group

Another Concept: install spin-rotator magnets in drift regions

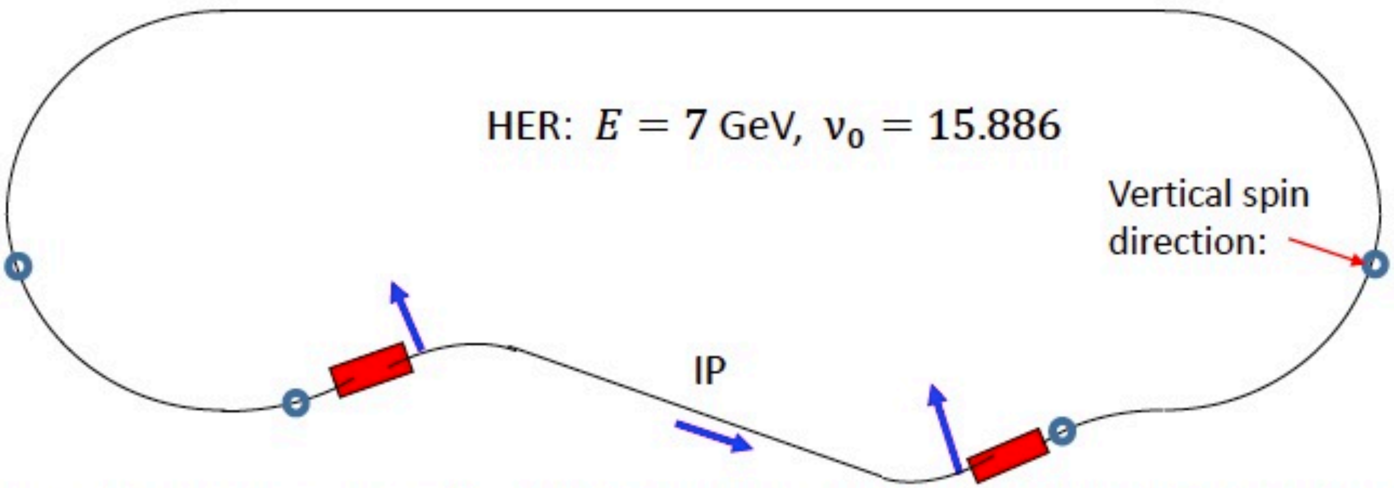


"B2E"	"BLA6RE"	"BLA4RE"	"BLA2RE"	"BLX1RE"	"BLB2RE"	"BLY2RE"	"BLC2RE"
0.0557427	0.0501498	0.0271539	0.0557427	−0.0221788	0.0234696	0.027	0.00591985
"BLC1LE"	"BLY1LE"	"BLB1LE"	"BLX2LE"	"BLA2LE"	"BLA4LE"		
−0.00591047	−0.0270414	−0.0387835	0.0532119	−0.0181419	0.0663659		

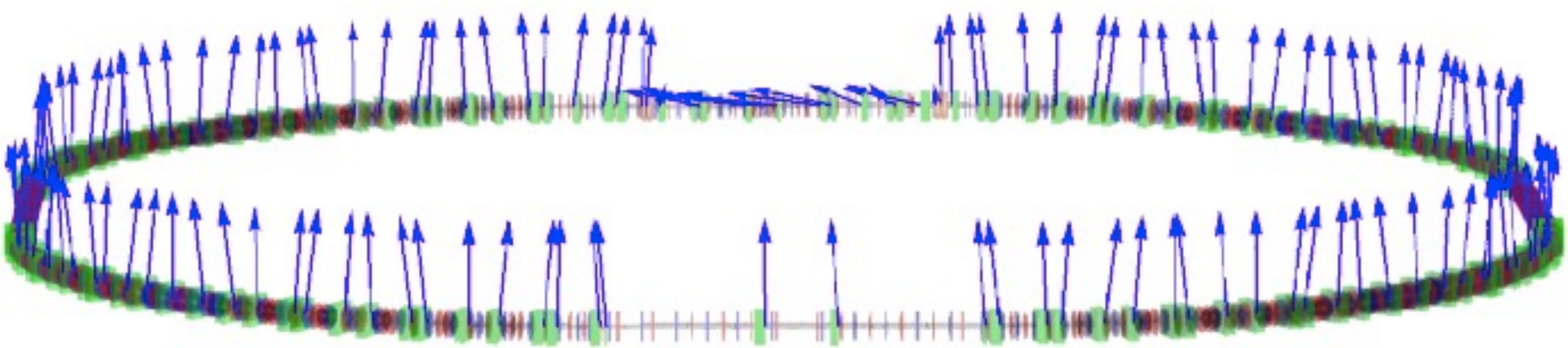
From I. Koop, A.Otboev and Yu.Shatunov, BINP, Novosibirsk preliminary considerations on the longitudinal polarization at SuperKEKB

Spin Rotator

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

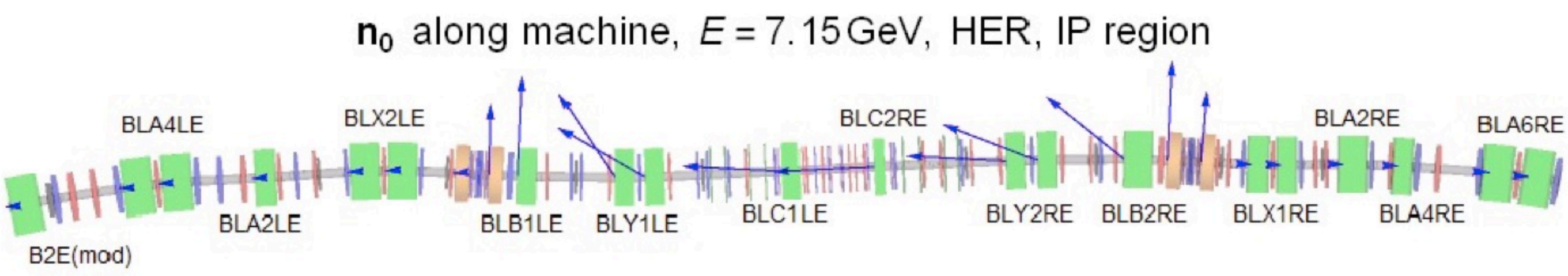


Spin direction is vertical in the main part of HER. Then it is rotated to the horizontal plane by the set of two solenoids, which are comprising the 90^0 spin rotator.



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

Preliminary studies by BINP group

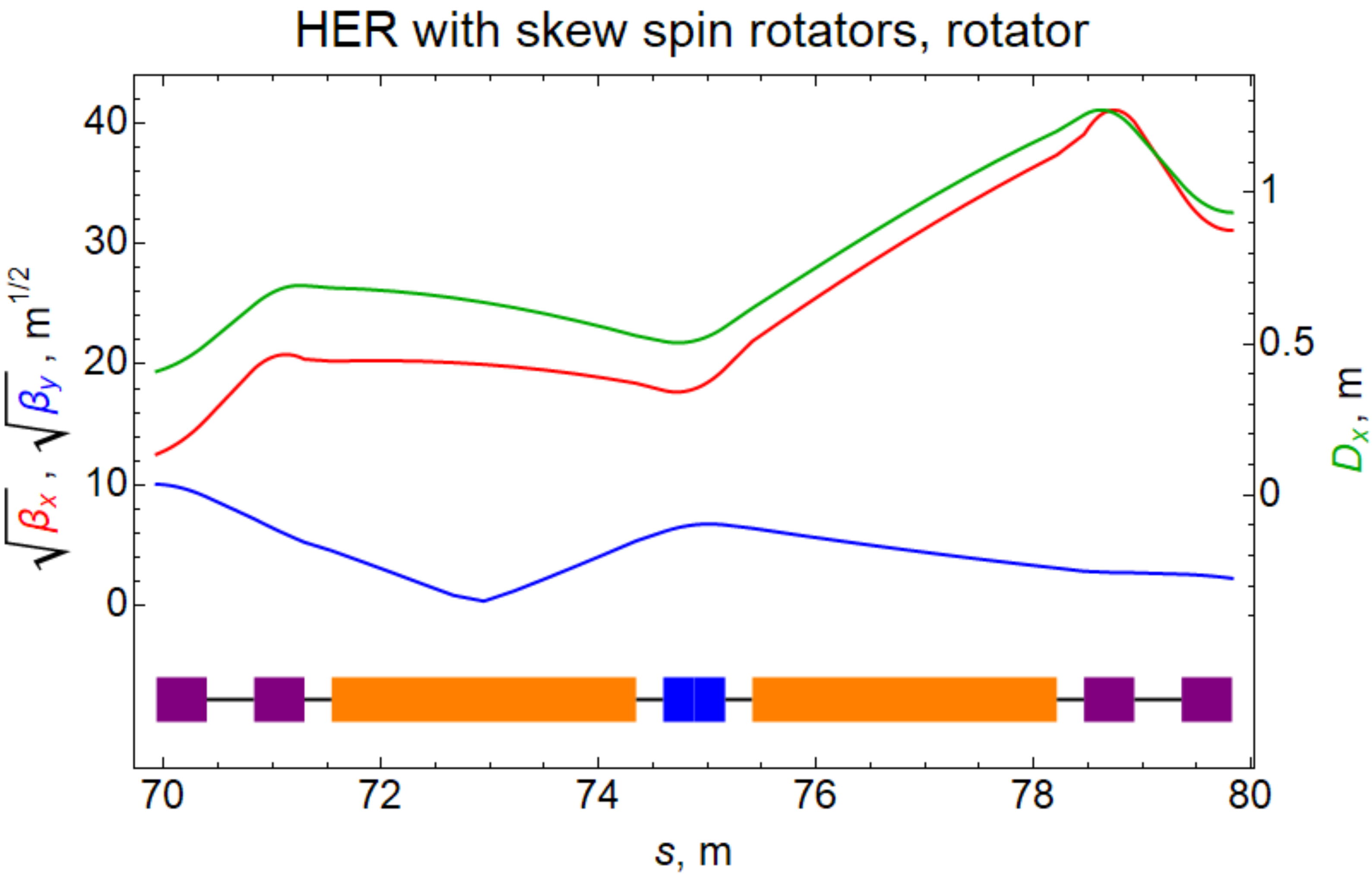


"B2E(mod)"	"BLA2LE"	"BLA2RE"	"BLA4LE"	"BLA4RE"	"BLA6RE"	"BLB1LE"
0.0745895	−0.0181419	0.0591537	0.0520765	0.0280687	0.0501498	−0.0368136
"BLB2RE"	"BLC1LE"	"BLC2RE"	"BLX1RE"	"BLX2LE"	"BLY1LE"	"BLY2RE"
0.0548871	−0.00591049	0.0059199	−0.0310501	0.0570931	−0.0270415	0.018

In arcs spin is directed purely vertically, while at IP longitudinally.

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

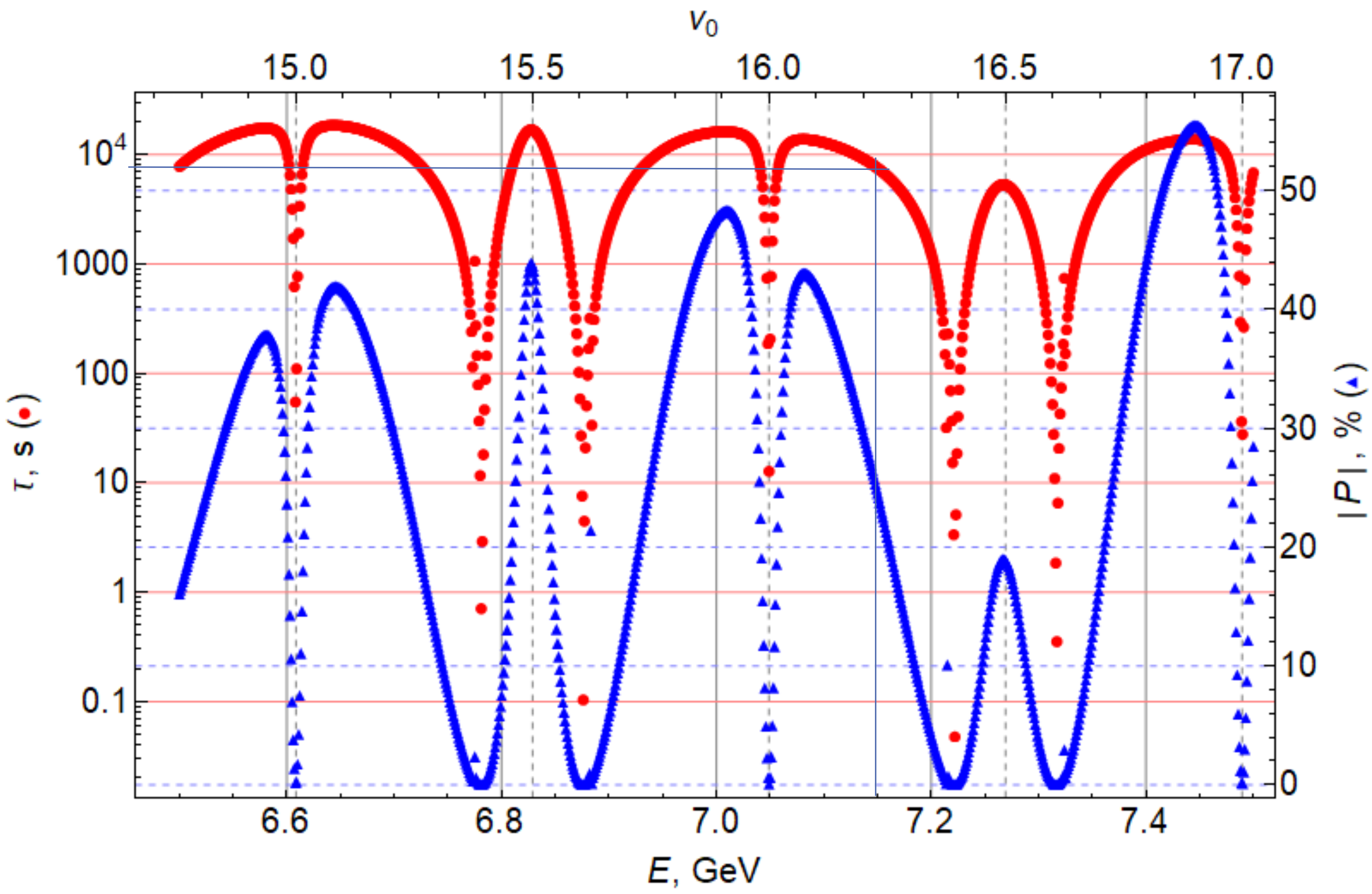
Preliminary studies by BINP group



e.g. Lattice functions for left-side spin rotator. Solenoids orange, central quad is normal, while doublets are rolled anti-symmetrically by $\varphi = \pm 22.474^0$.

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

Recent preliminary studies by BINP group



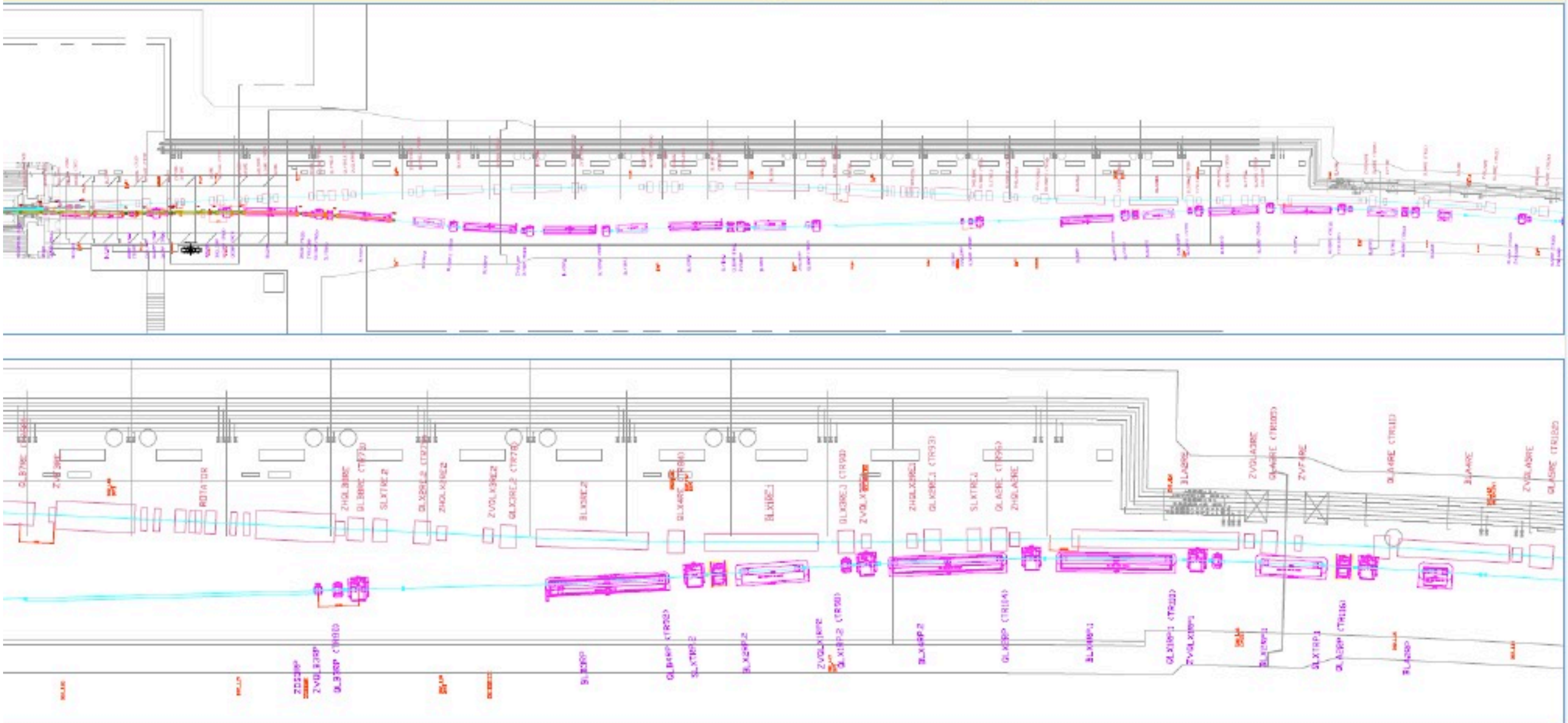
Depolarization lifetime at E=7.15GeV is 7500s (~2 hrs)

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

Recent studies by BINP group

Version 3 of the FF region geometry: Right half from IP



Koop, Long. Pol. 11

Polarization in SuperKEKB

Hardware needs

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

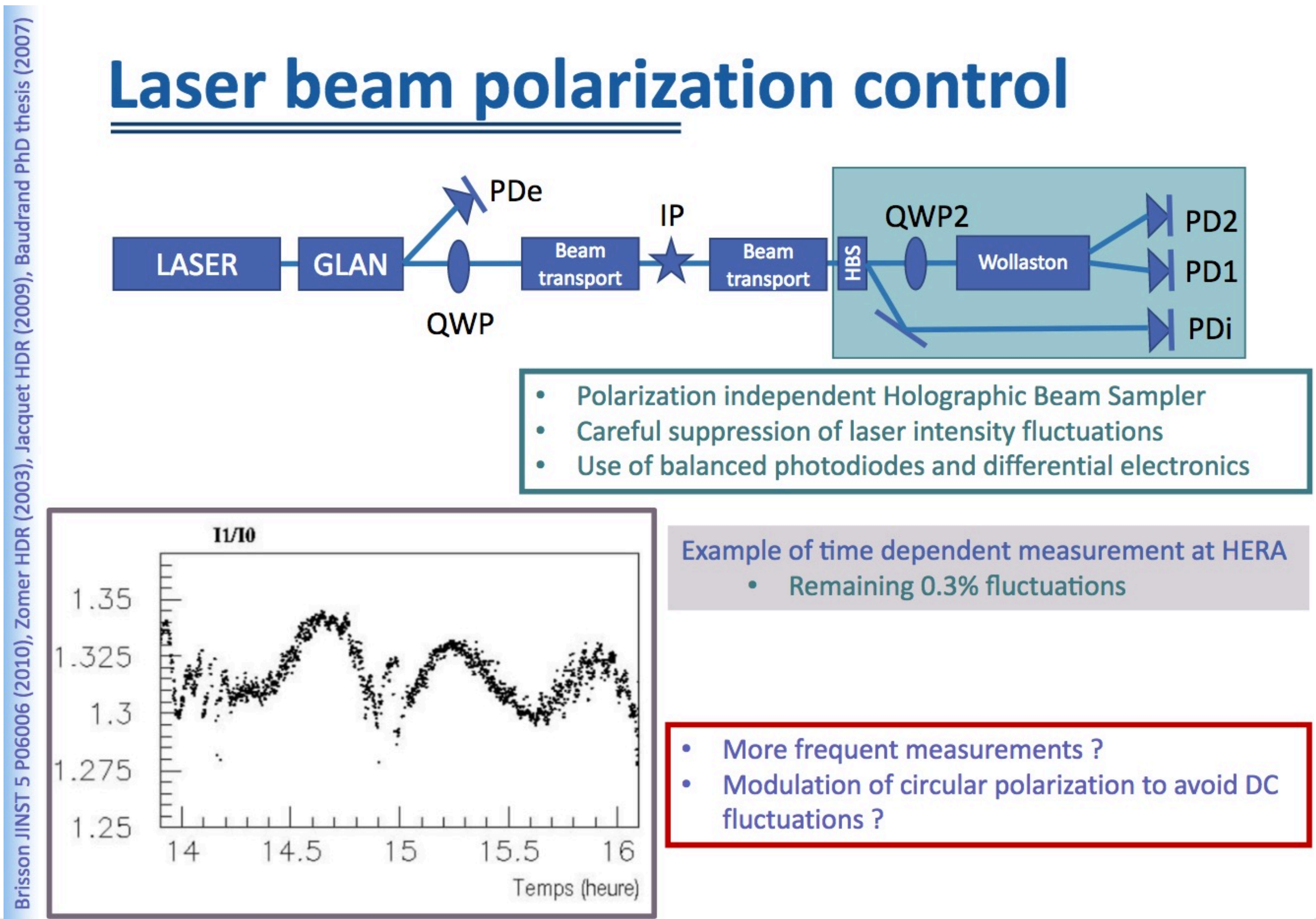
Figure 1: SuperKEKB left side cryostat at KEK.

Space is available outside
Cryostats for the final focusing quads

LAL Orsay and U. Manitoba groups

Polarization in SuperKEKB

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



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

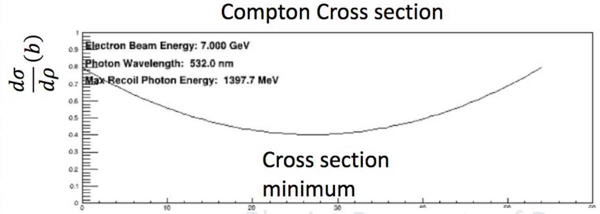
The chip is primarily developed by groups at the U. of Heidelberg and the Karlsruhe Institute of Technology, and intended for various experiments:

- ATLAS
- Mu3e
- PANDA
- P2
- MOLLER

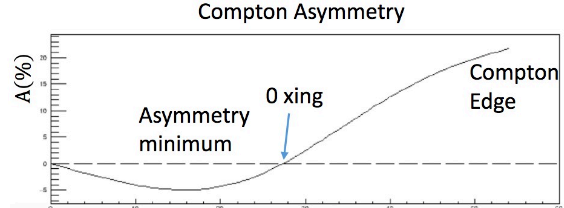
The implementation as a Compton detector is done by the Manitoba group.

Calculations/Simulations

Compton Cross section



Compton Asymmetry



Growing international collaboration of Accelerator and Particle Physicists ~ half from outside Belle II

- Canada: TRIUMF, UVic, Manitoba, UBC/IPP
- France: LAL/Orsay
- KEK & Hiroshima Univ. + Oide-san (CERN)
- Russia: BINP
- USA: ANL, BLN, Louisville, Duke

Theorists in Canada, Italy, Russia & U.S. published recently on physics enabled by this project

Preparing White Paper as basis for LOI, followed by CDR & TDR, then construction.

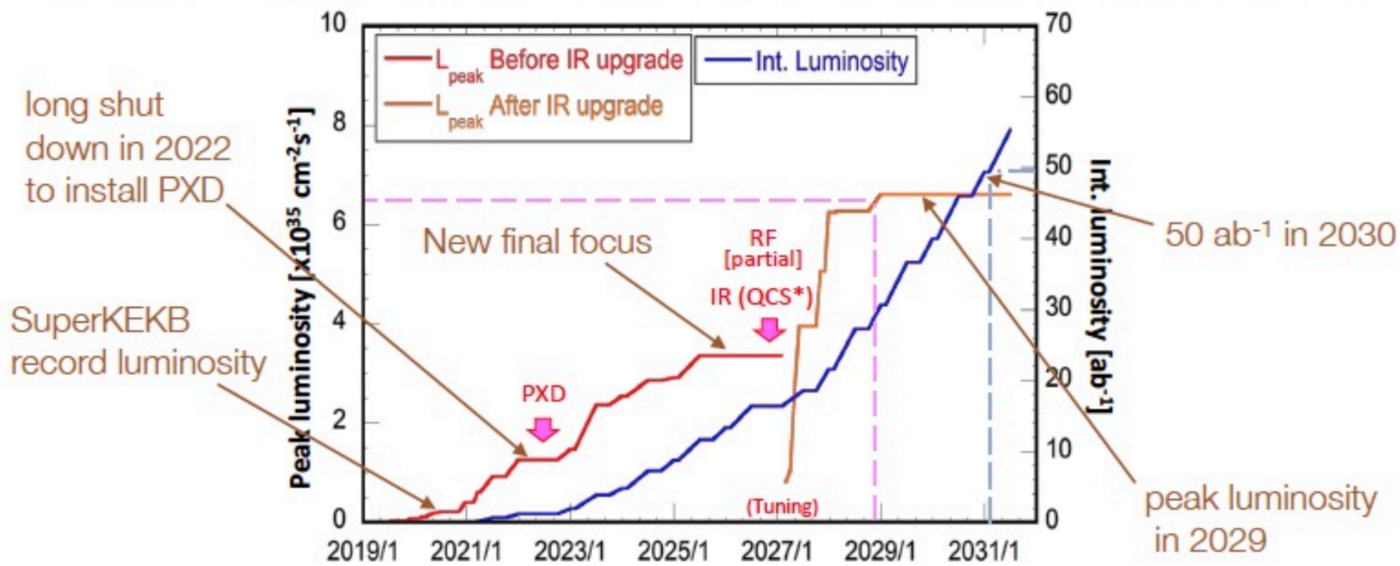
Additional Attraction: **Opportunity not just for physics, but serves as real-world project to develop technologies for learning and training for future e+e- polarization projects**

SuperKEKB polarization upgrade

- Would aim to install polarization in shutdown for new final focus ~2027 – Pol. R&D in MEXT KEK Roadmap 2021-26

Longer term Belle II run plan

- Run through 2030 to get full data set.
- New 2-layer pixel detector in 2022; new final focus 2026.



From S. Banerjee

Proceedings of SuperB Workshop VI (https://arxiv.org/pdf/0810.1312.pdf)

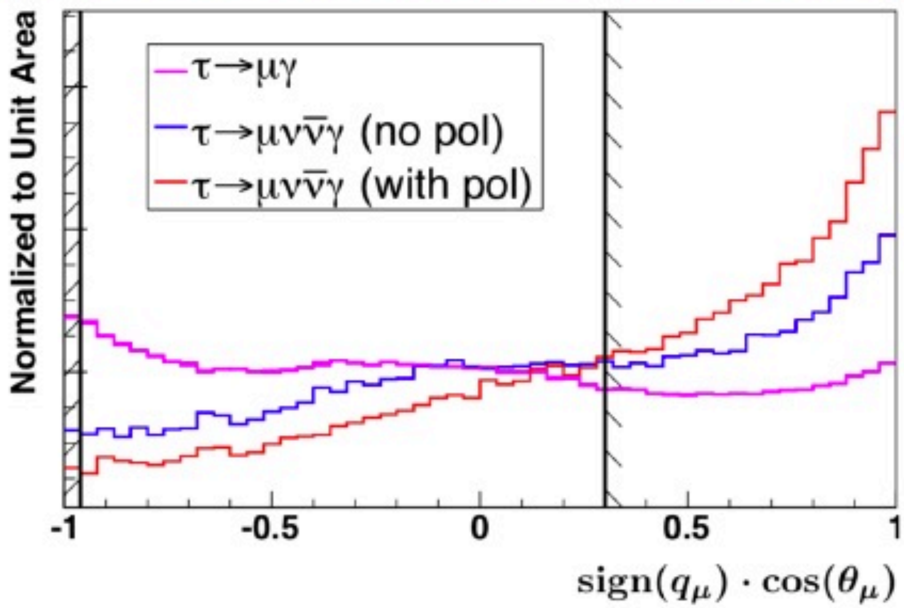


FIG. 15: Distribution of the cosine of the signal-side muon multiplied by the muon charge for signal and background events with and without electron beam polarization in the $\tau^\pm \to \mu^\pm\gamma$ search analysis at Super$B$.

The "irreducible background" would be cut by 70% for a 39% loss in signal efficiency. This would result in approximately a 10% improvement in the sensitivity.

Helicity structure of LFV coupling (https://arxiv.org/pdf/1609.04617.pdf)

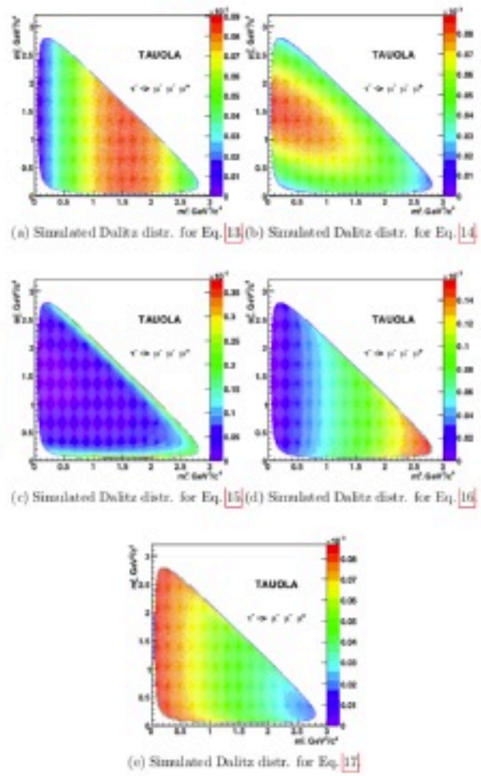
Four left-handed leptons (O1 operator)

Two left-handed, two right-handed leptons (O4 operator)

Radiative right-handed leptons (R1 operator)

Interference between O1 and R1 operators

Interference between O4 and R1 operators



(a) Simulated Dalitz distr. for Eq. 13 (b) Simulated Dalitz distr. for Eq. 14

(c) Simulated Dalitz distr. for Eq. 15 (d) Simulated Dalitz distr. for Eq. 16

(e) Simulated Dalitz distr. for Eq. 17

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Figure 1: Dalitz distributions simulated in the effective field approach for the five different BSM operators corresponding to different lepton chirality structures [25]. The normalized to unit area distributions, implemented in the TAUOLA package.

The most important aspect of having the polarization is the possibility to determine the helicity structure of the LFV coupling from the final state momenta distributions.