Electroweak precision at Belle II

Chiral Belle: SuperKEKB with polarized e- beams

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J. Michael Roney (University of Victoria)

5 November 2021
SNOWMASS EF04 Topical Group Community Meeting

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

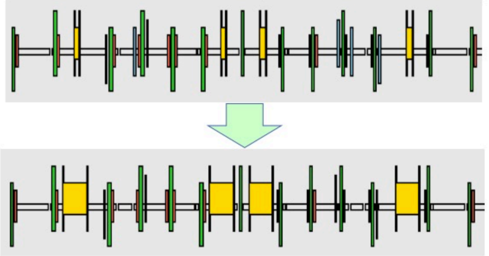
Upgrading SuperKEKB with polarized electrons

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
- Polarized e+e- annihilation into a polarized Λ or a hadron pair experimentally probes dynamical mass generation in QCD

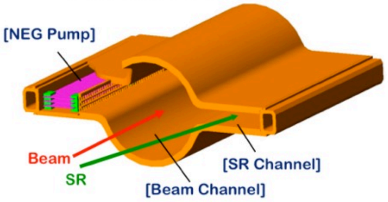
Super KEKB

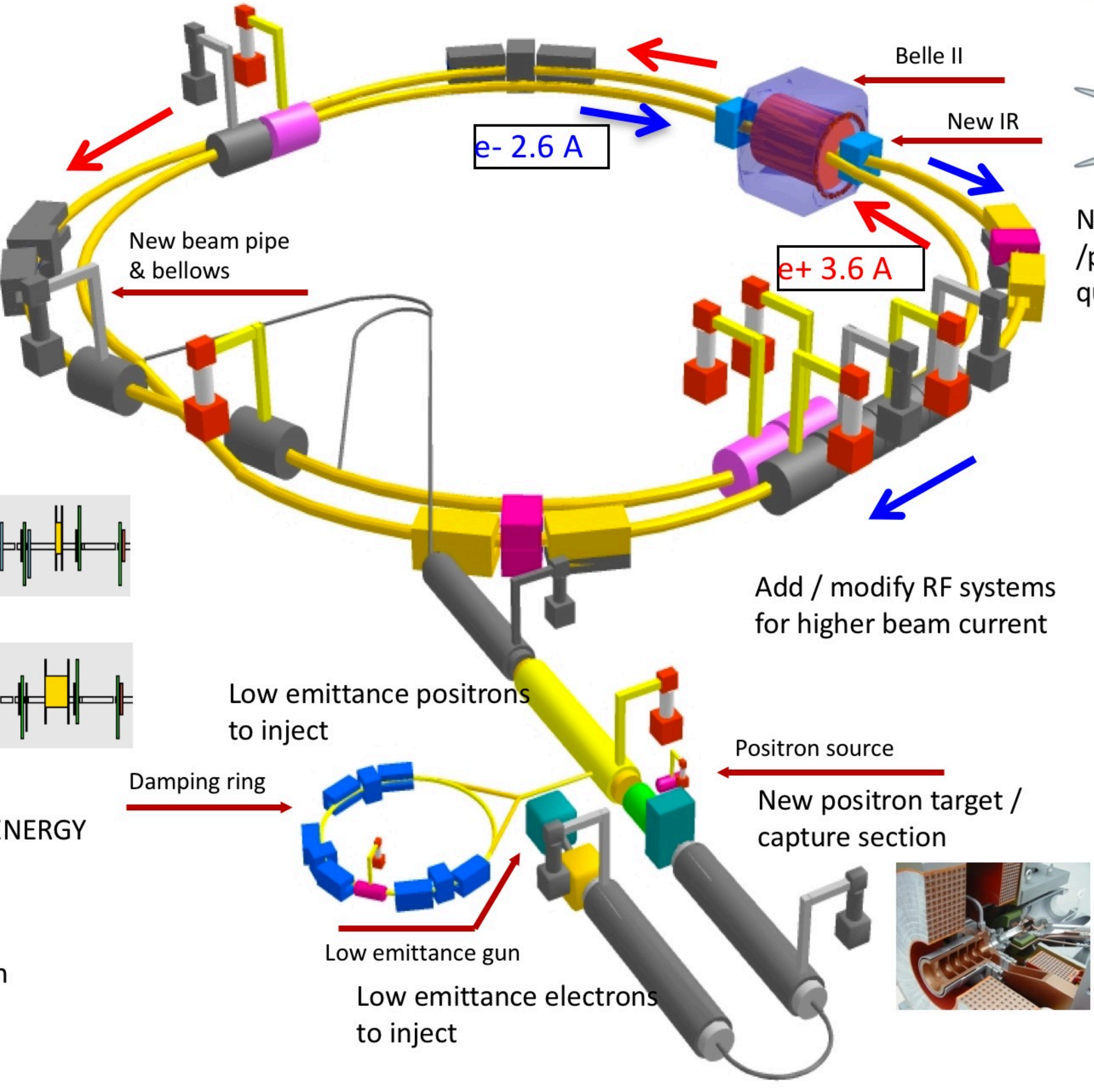
Replace short dipoles with longer ones (LER)



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

TiN-coated beam pipe with antechambers





Belle II

New IR

New beam pipe & bellows

Low emittance positrons to inject

Damping ring

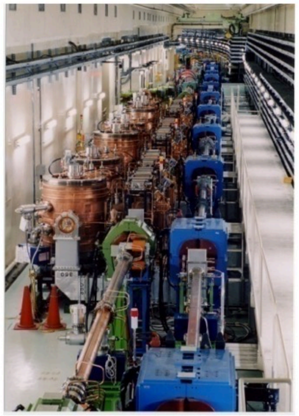
Low emittance gun

Low emittance electrons to inject

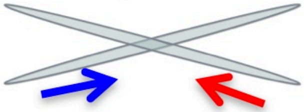
Positron source

New positron target / capture section

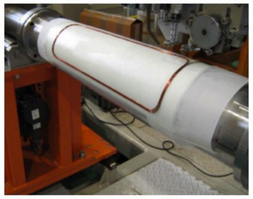
Add / modify RF systems for higher beam current



Colliding bunches



New superconducting /permanent final focusing quads near the IP



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

‘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 :

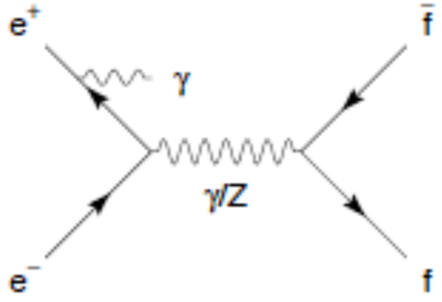
$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lepton}} = 0.23098 \pm 0.00026$$

- 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:

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

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

(for s-channel Born)



‘Chiral Belle’ Left-Right Asymmetries

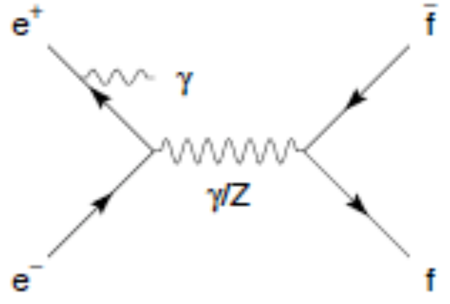
Electron helicity would be chosen randomly pulse-to-pulse by controlling the circular polarization of the source laser illuminating a GaAs photocathode.

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

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

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

(for s-channel Born)

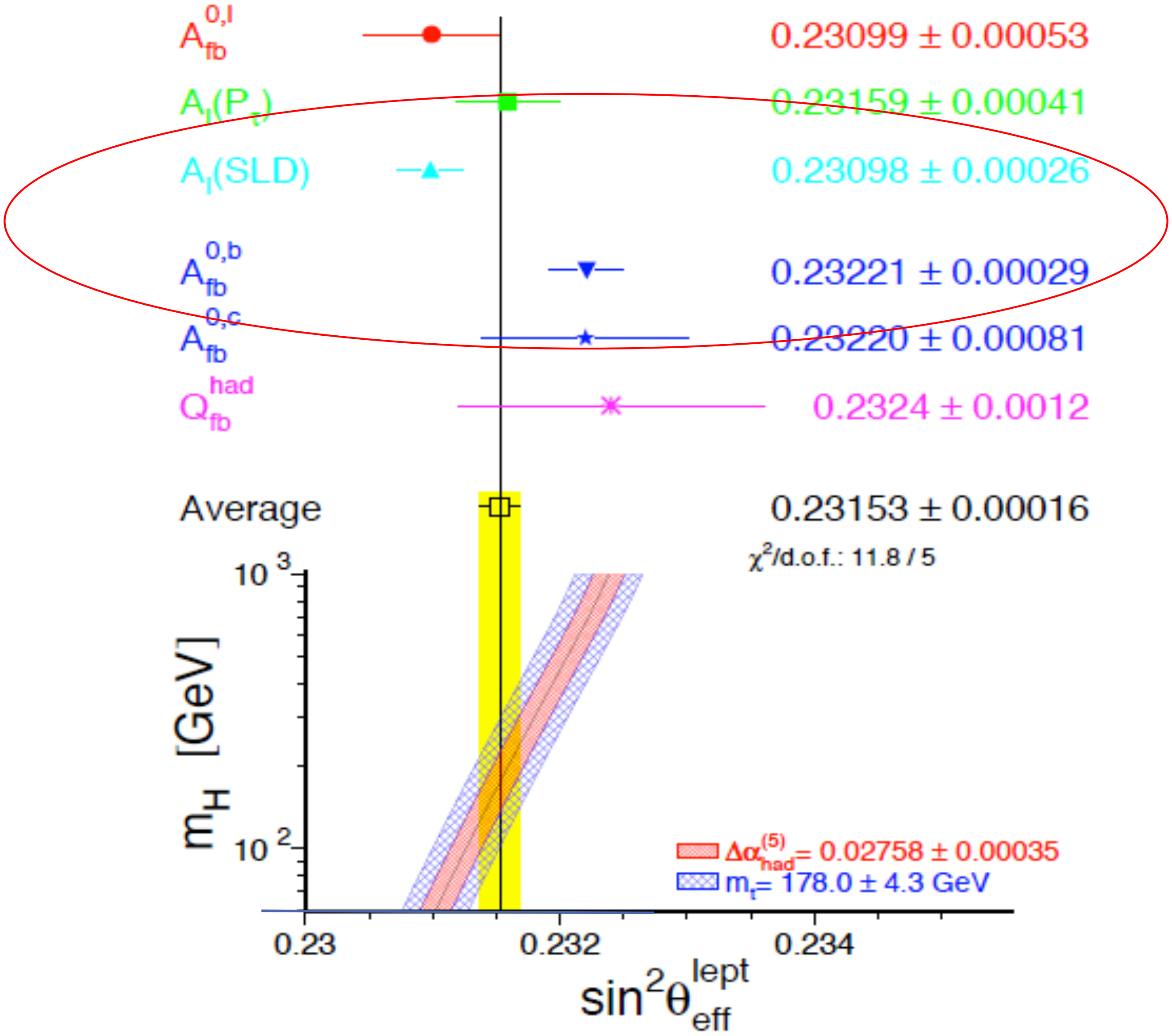


Source generates mainly right-handed electrons

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

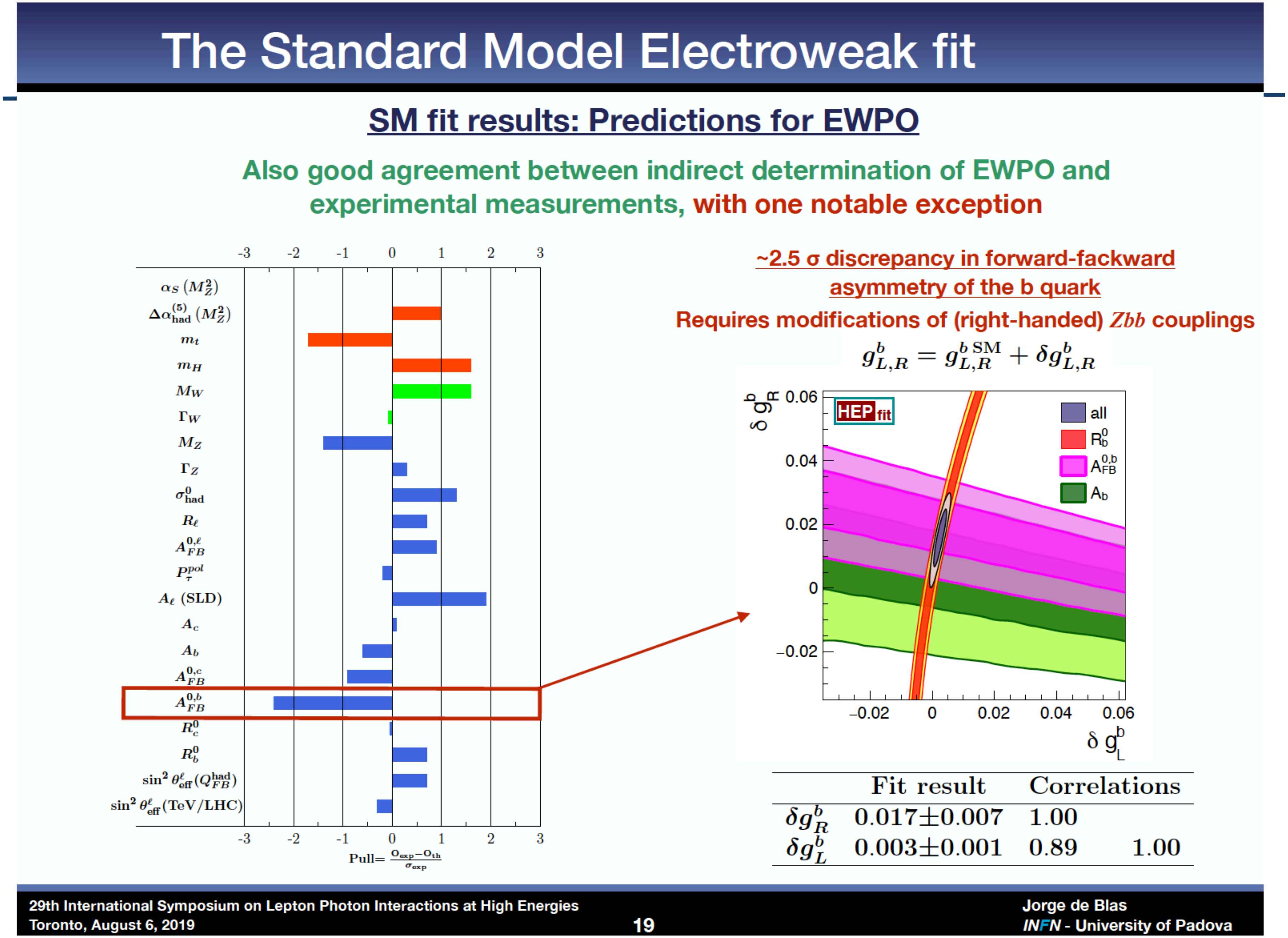
Existing tension in data on the Z-Pole:



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)

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

29th International Symposium on Lepton Photon Interactions at High Energies
Toronto, August 6, 2019

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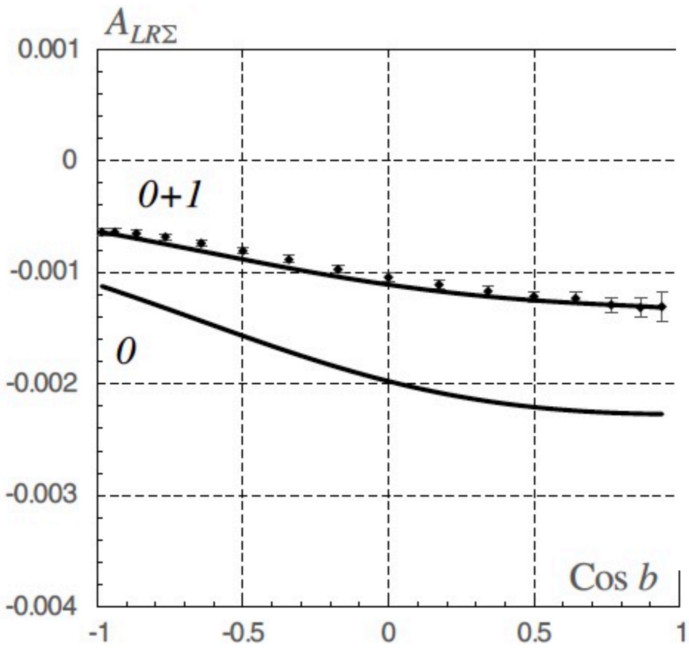
Jorge de Blas
INFN - University of Padova

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)**

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

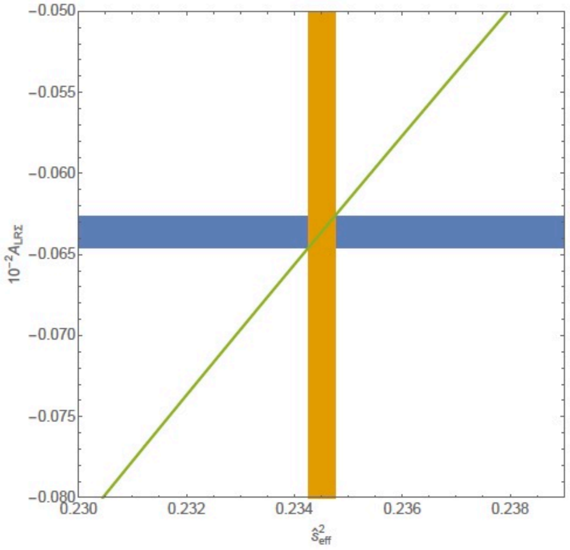


$$\Sigma_L^C = \int_{\cos b}^{\cos a} \sigma_L^C \cdot d(\cos\theta), \quad \Sigma_R^C = \int_{\cos b}^{\cos a} \sigma_R^C \cdot d(\cos\theta)$$

a=10° & energy of photons < 2GeV

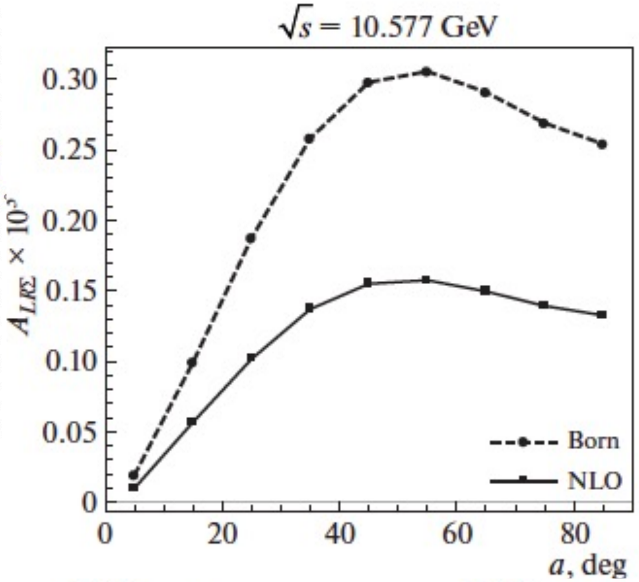
Phys.Rev. D101 (2020) no.5, 053003

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



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

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



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

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.

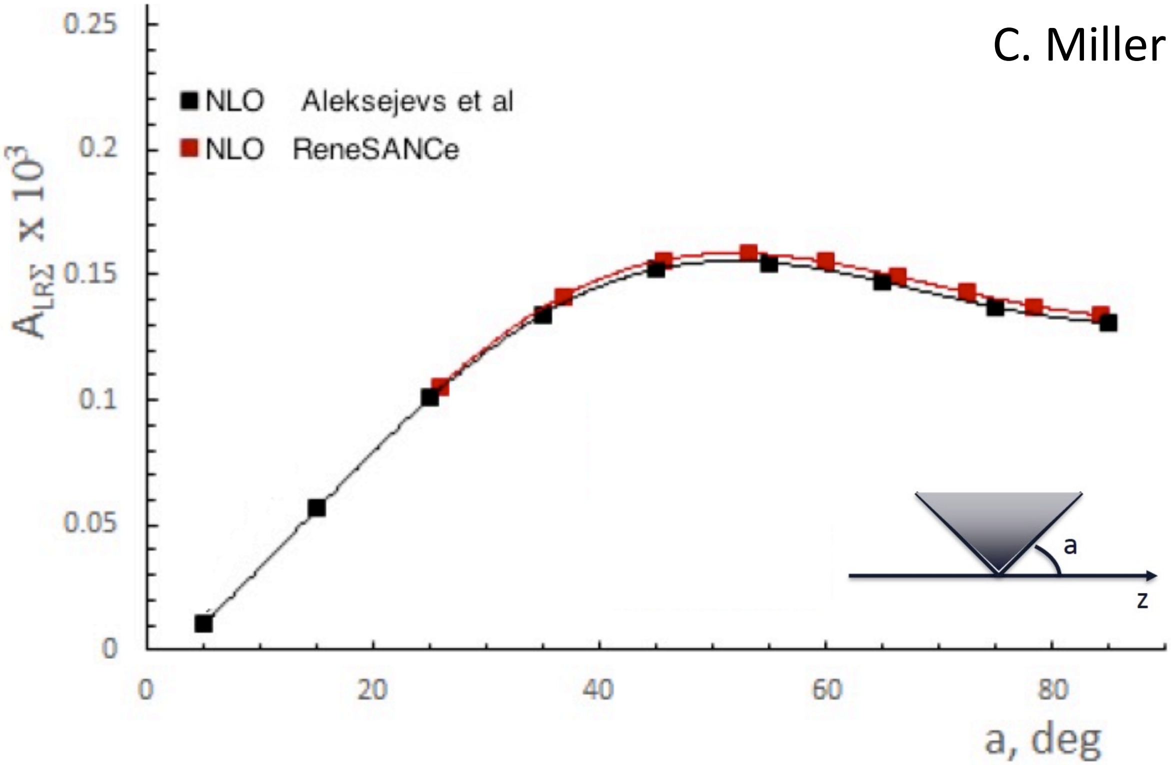
Polarization in each beam and special mode to efficiently calculate A_{LR} without event generation output.

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*

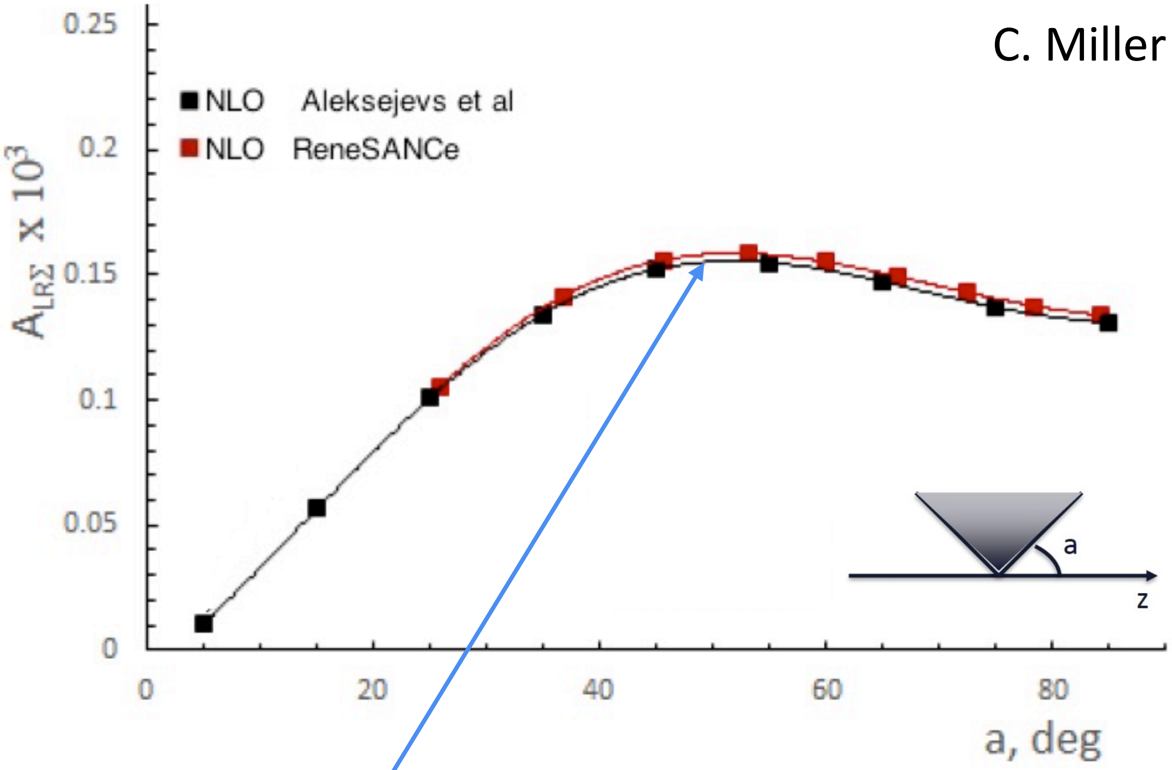


C. Miller

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*



C. Miller

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

Will probe both high and low energy scales

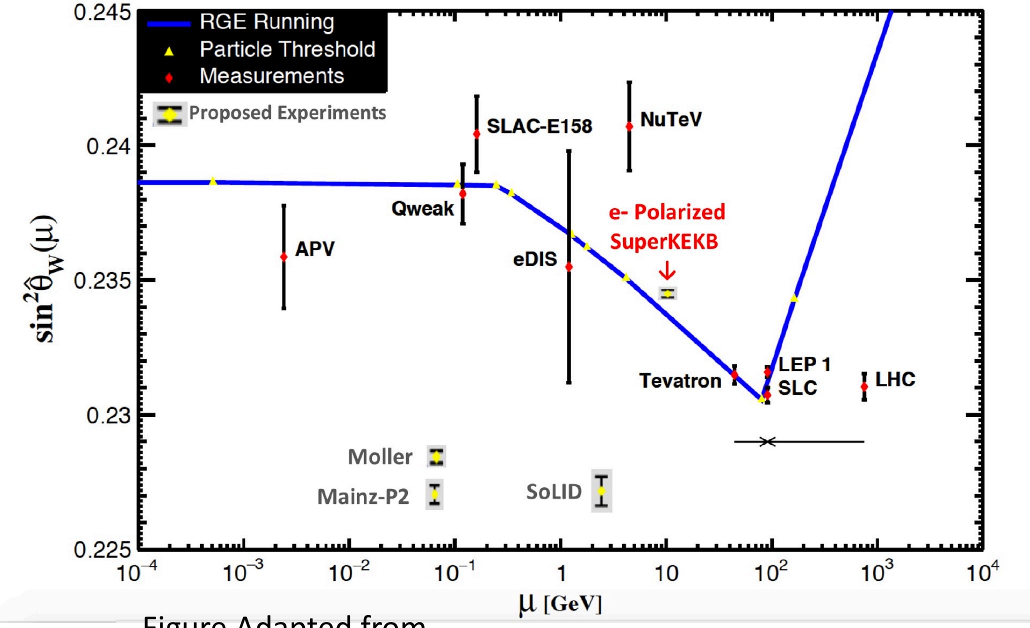


Figure Adapted from
J. Erler and A. Freitas, (PDG) Phys. Rev. D98 , 030001 (2018)

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

- **Precision probe of running of the weak mixing angle**
- **Being away from Z-pole is open to New Physics sensitivities not available at the pole**

More information at arxiv.org/abs/1907.03503

- **Highest precision test or neutral current vector coupling universality as beam polarization error cancels: e.g. < 0.3% relative error for ratio: g^v_b/g^v_c, *cf* 4% now**
- **Most precise measurements for muons, charm and beauty by many factors**
  - probes both heavy quark phenomenology and Up vs Down
- Measurements of $\sin^2\theta_{eff}^{lepton}$ of using lepton pairs of comparable precision WA obtained by LEP/SLD, except at 10.58GeV and in single measurement
  - **Sensitive to Z' > TeV scale; can probe purely Z' that only couple to leptons**

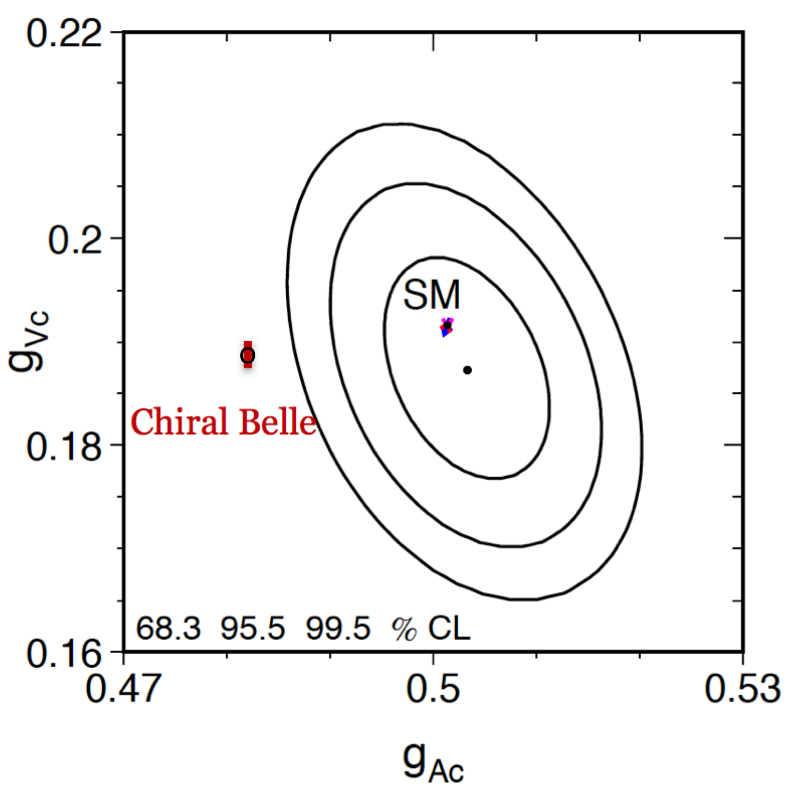
    complementary to direct Z' searches at LHC which couple to both quarks and leptons

Chiral Belle probes both high and low energy scales

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

c-quark:

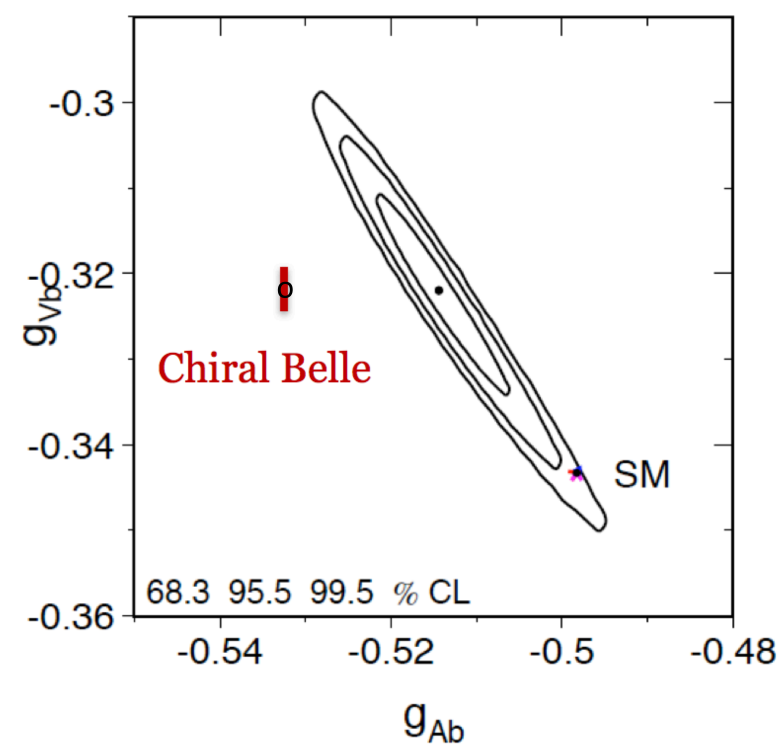
Chiral Belle ~7 times more precise



b-quark:

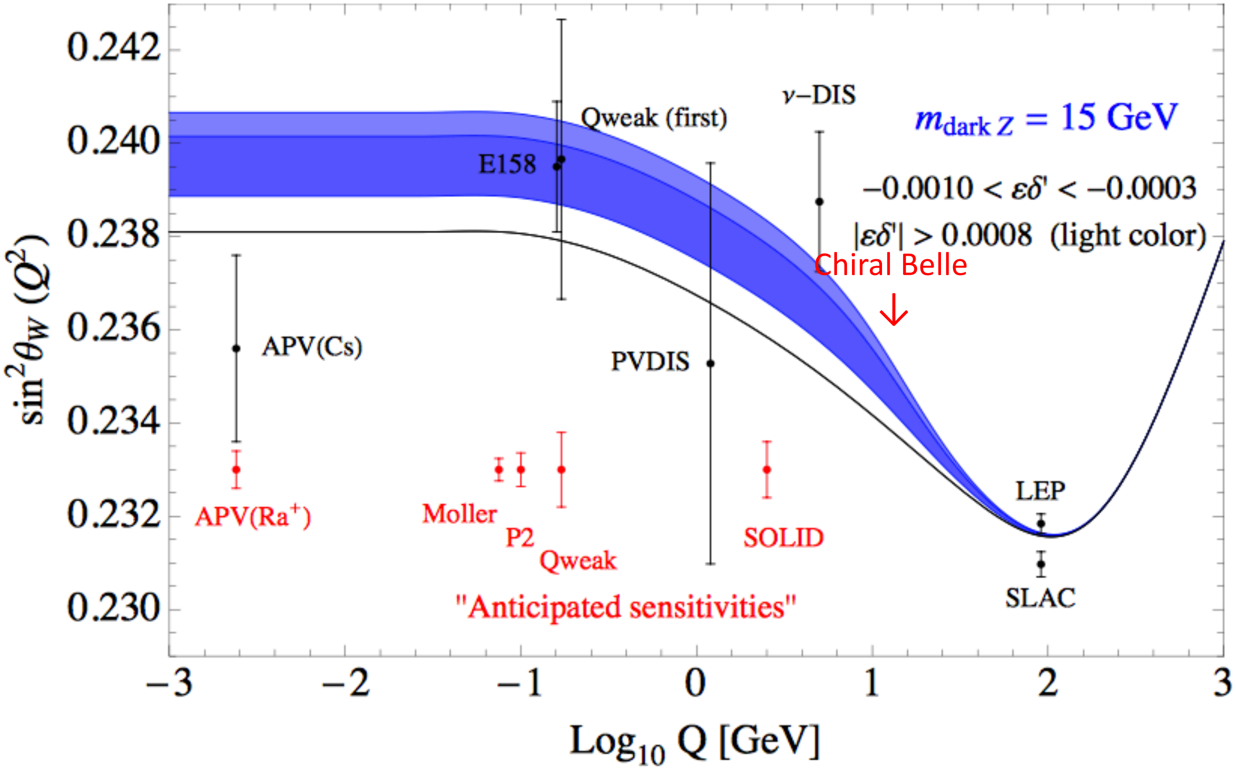
Chiral Belle ~4 times more precise

with 20 ab^{-1}



Chiral Belle probes both high and low energy scales

- 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:

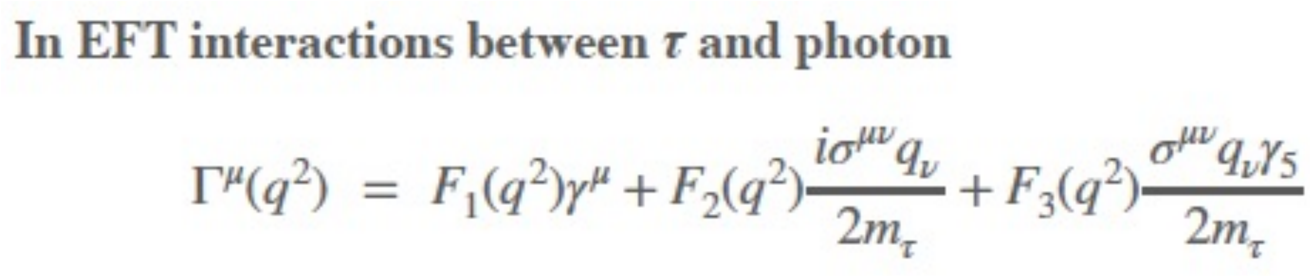
- LHC experiments
- APV measurements at lower energy scales
- Moller Experiment at Jefferson Lab which will measure $\sin^2\theta_{eff}^{electron}$ below 100MeV with similar precision (note: Moller is only sensitive to electron couplings.)
- EIC can measure $\sin^2\theta_{eff}$ in similar kinematic region, 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"*
  - Denis Epifanov talk at Tau 2021 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

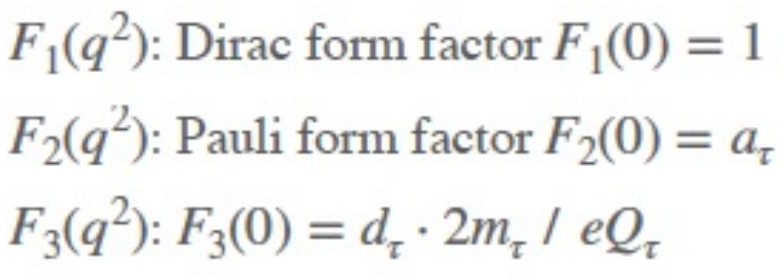
From J. Bernabéu *et al*, *Nucl.Phys.B* 790 (2008) 160-174

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 $F_2(0) = a_{\tau}$

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

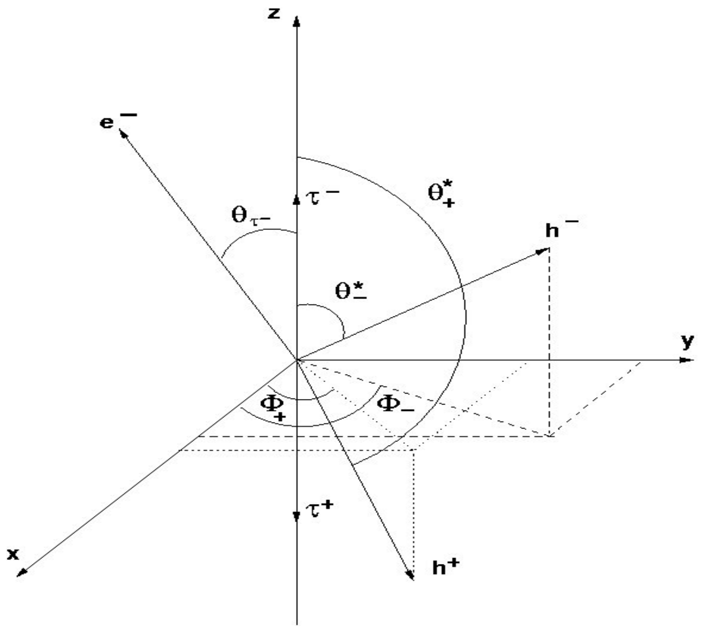
From J. Bernabéu *et al*, Nucl. Phys. B763:283–292, 2007

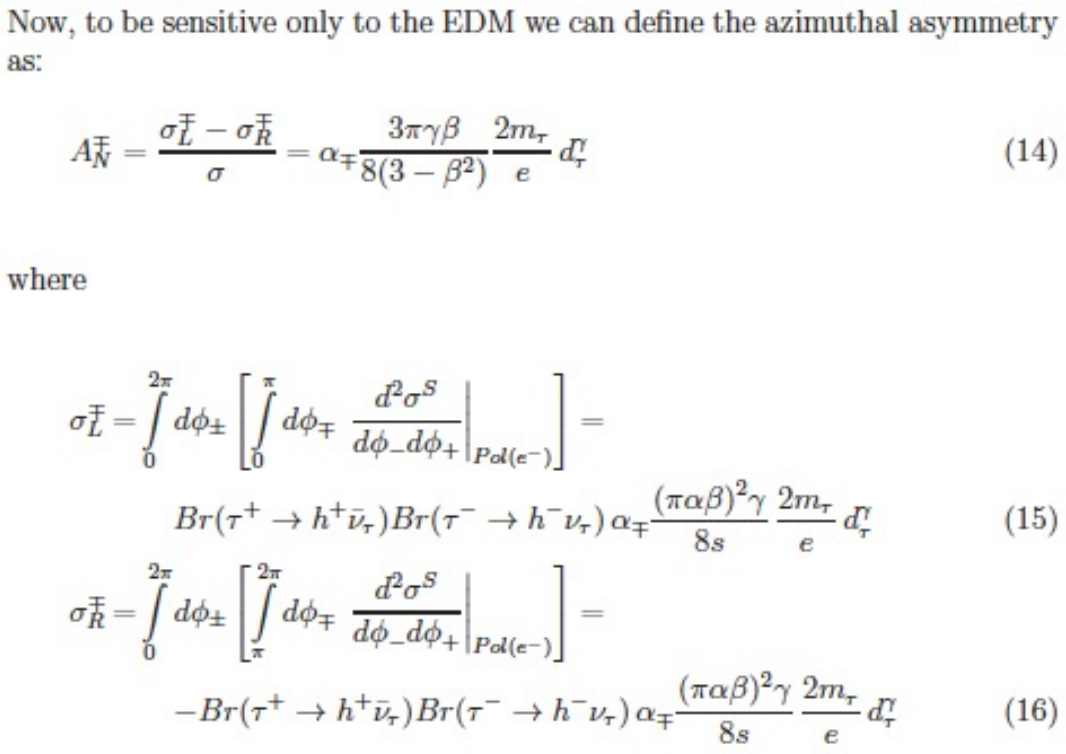
CP violation and electric dipole moment at low energy tau production with polarized electrons

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:

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

where

$$\sigma_L^\mp = \int_0^{2\pi} d\phi_\pm \left[\int_0^{\pi} d\phi_\mp \left. \frac{d^2\sigma^S}{d\phi_- d\phi_+} \right|_{Pol(e^-)} \right] =$$

$$Br(\tau^+ \to h^+ \bar{\nu}_\tau) Br(\tau^- \to h^- \nu_\tau)\, \alpha_\mp \frac{(\pi\alpha\beta)^2\gamma}{8s} \frac{2m_\tau}{e} d_\tau^\gamma \qquad (15)$$

$$\sigma_R^\mp = \int_0^{2\pi} d\phi_\pm \left[\int_\pi^{2\pi} d\phi_\mp \left. \frac{d^2\sigma^S}{d\phi_- d\phi_+} \right|_{Pol(e^-)} \right] =$$

$$-Br(\tau^+ \to h^+ \bar{\nu}_\tau) Br(\tau^- \to h^- \nu_\tau)\, \alpha_\mp \frac{(\pi\alpha\beta)^2\gamma}{8s} \frac{2m_\tau}{e} d_\tau^\gamma \qquad (16)$$

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^-

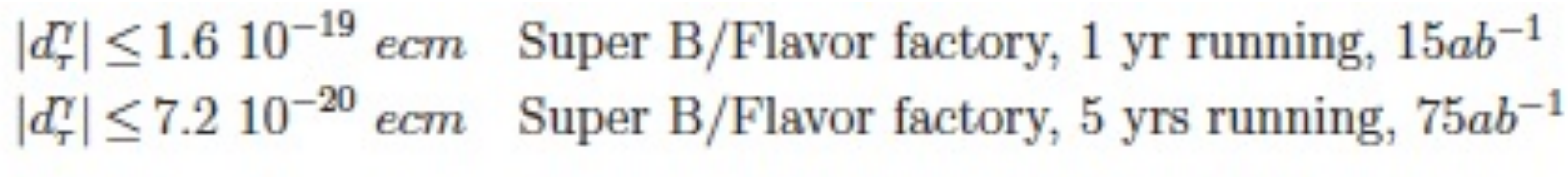
$\cancel{CP}$:

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

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

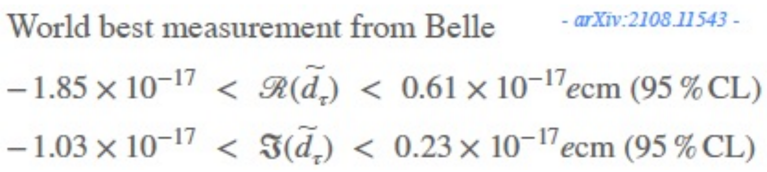
They conclude:



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

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)



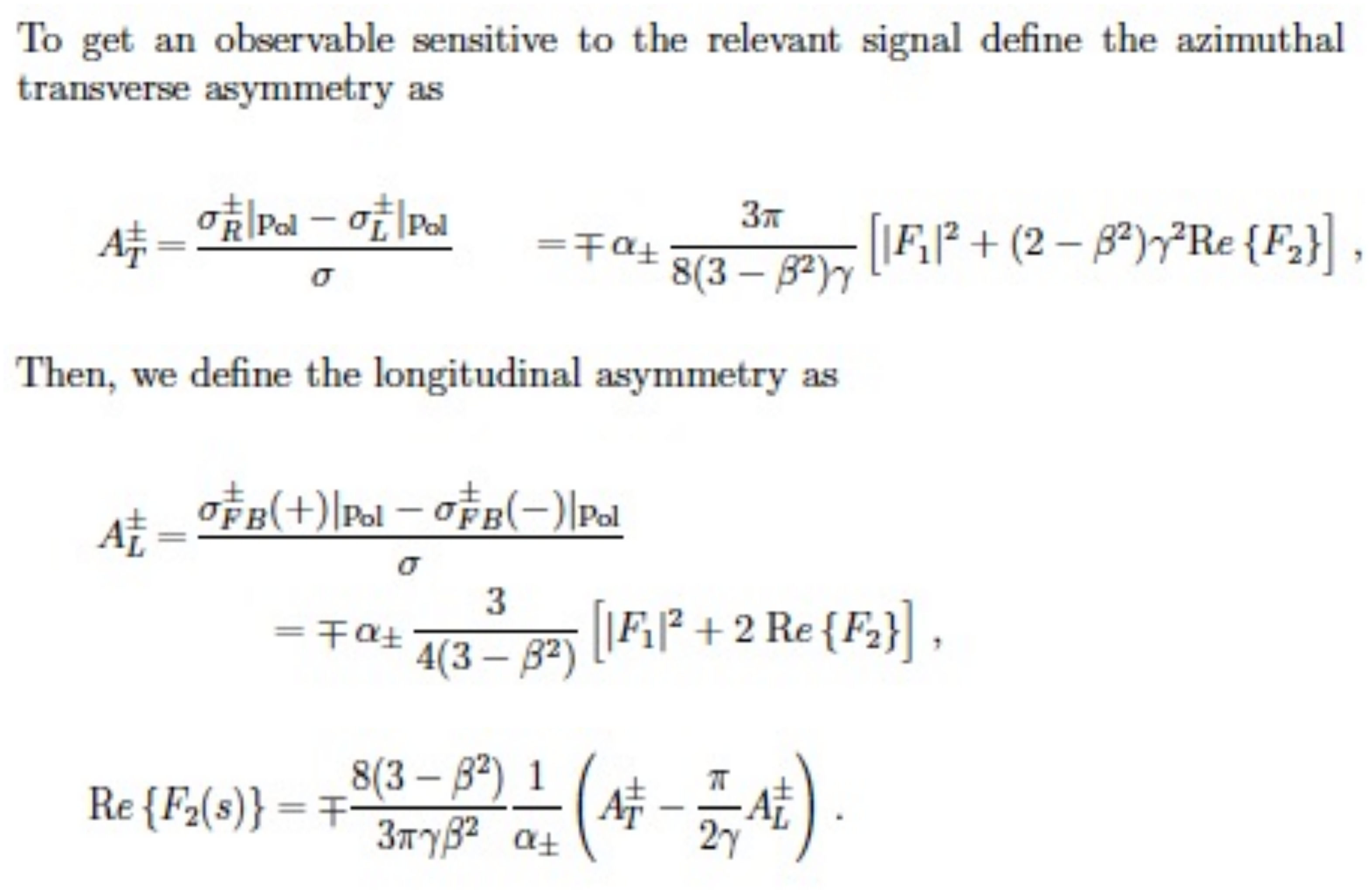
World best measurement from Belle - arXiv:2108.11543 -

$$-1.85 \times 10^{-17} < \mathscr{R}(\tilde{d}_\tau) < 0.61 \times 10^{-17} ecm\ (95\,\%\,\mathrm{CL})$$
$$-1.03 \times 10^{-17} < \mathfrak{I}(\tilde{d}_\tau) < 0.23 \times 10^{-17} ecm\ (95\,\%\,\mathrm{CL})$$

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

From 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

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

Then, we define the longitudinal asymmetry as

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

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

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

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

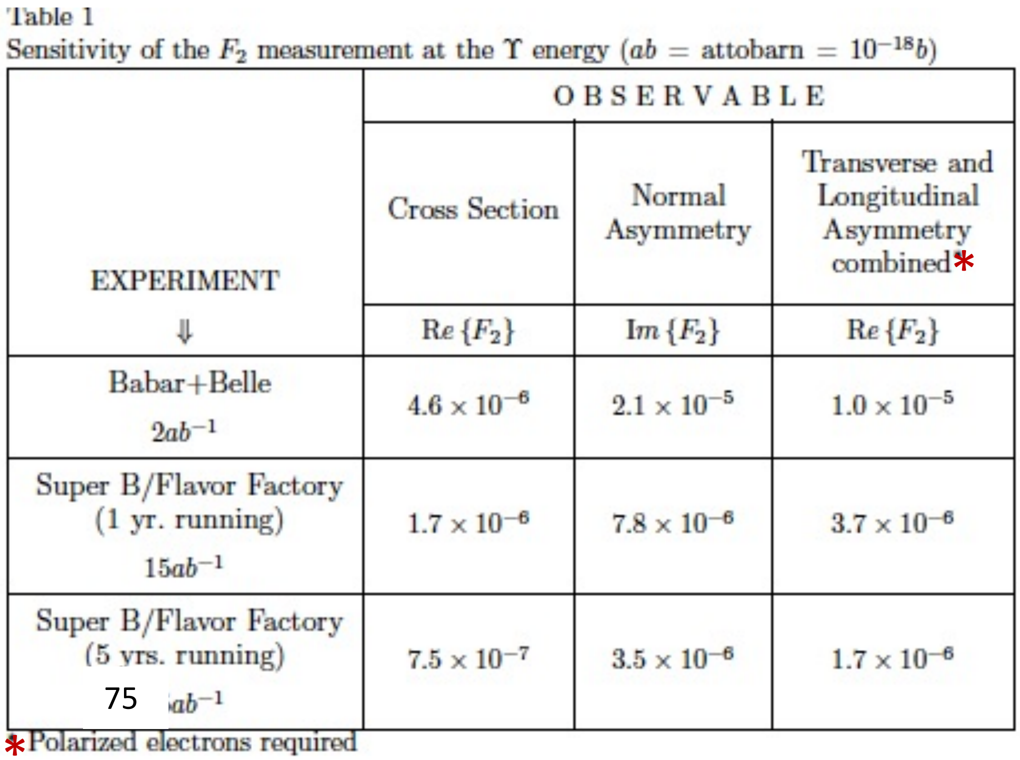


Table 1
Sensitivity of the F_2 measurement at the Υ energy (ab = attobarn = $10^{-18}b$)

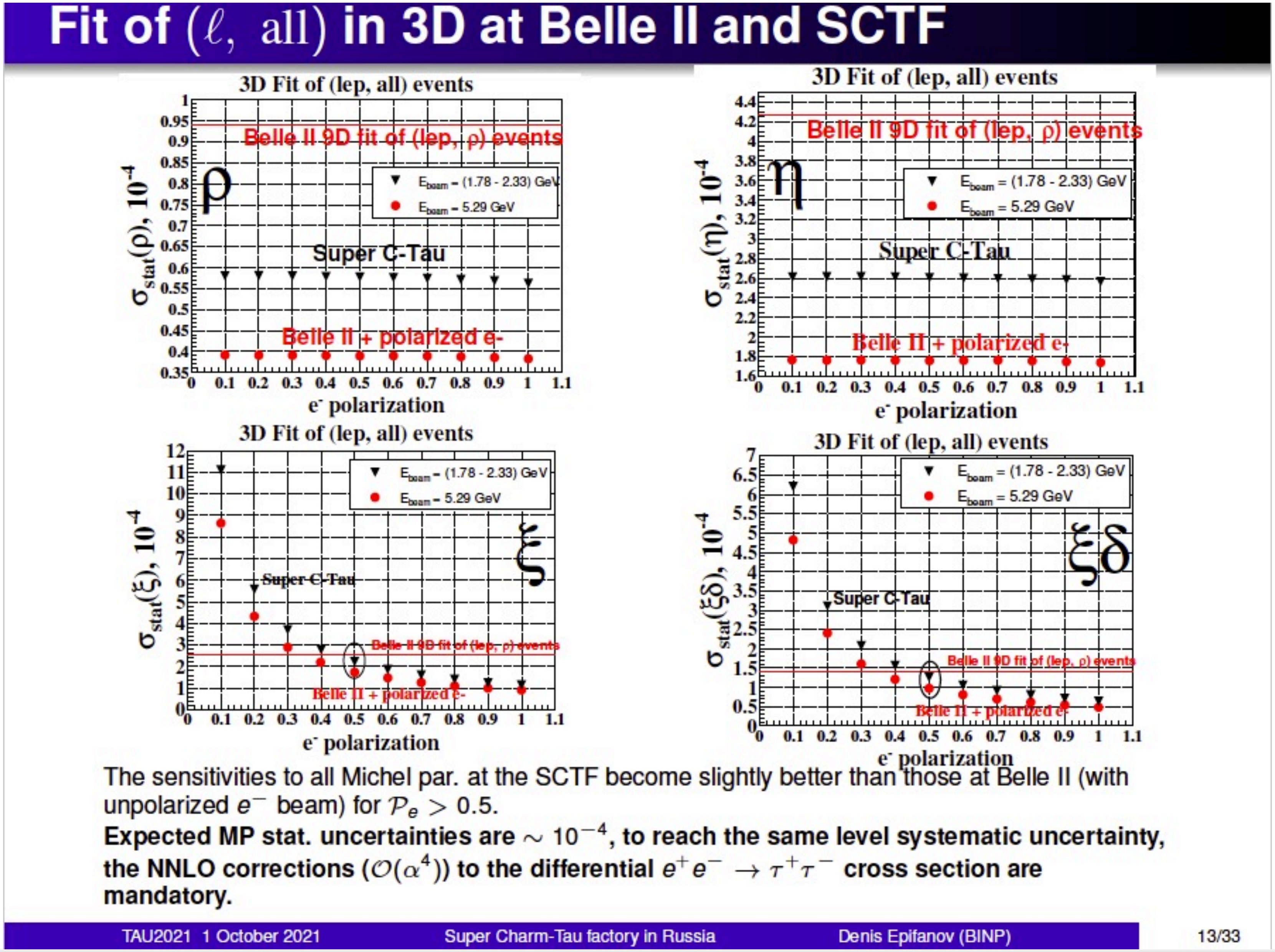
	OBSERVABLE		
	Cross Section	Normal Asymmetry	Transverse and Longitudinal Asymmetry combined*
EXPERIMENT ⇓	$Re\{F_2\}$	$Im\{F_2\}$	$Re\{F_2\}$
Babar+Belle $2ab^{-1}$	4.6×10^{-6}	2.1×10^{-5}	1.0×10^{-5}
Super B/Flavor Factory (1 yr. running) $15ab^{-1}$	1.7×10^{-6}	7.8×10^{-6}	3.7×10^{-6}
Super B/Flavor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

Note: extrapolating statistical error for unpolarized Belle II data with 50ab^{-1}
would give a sensitivity of ~4x10^{-6} (Cross section method would be systematics limited before 15ab^{-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

Will probe both high and low energy scales

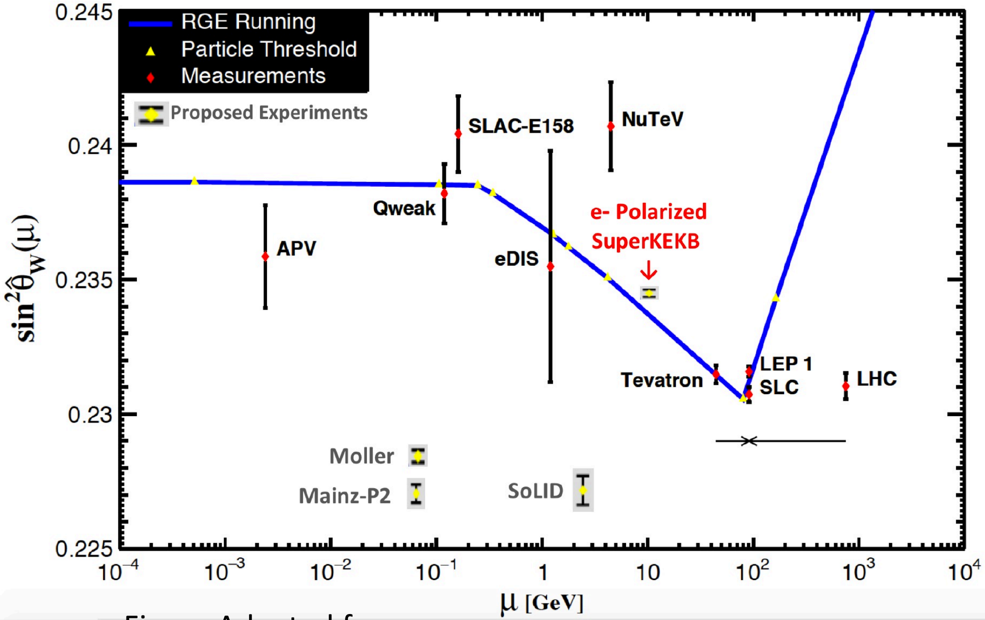


Figure Adapted from
J. Erler and A. Freitas, (PDG) Phys. Rev. D98 , 030001 (2018)

Chiral Belle: σ ~ 0.0002 with 20 ab^{-1}
Using only clean leptonic states

- **Precision probe of running of the weak mixing angle**
- **Being away from Z-pole is open to New Physics sensitivities not available at the pole**

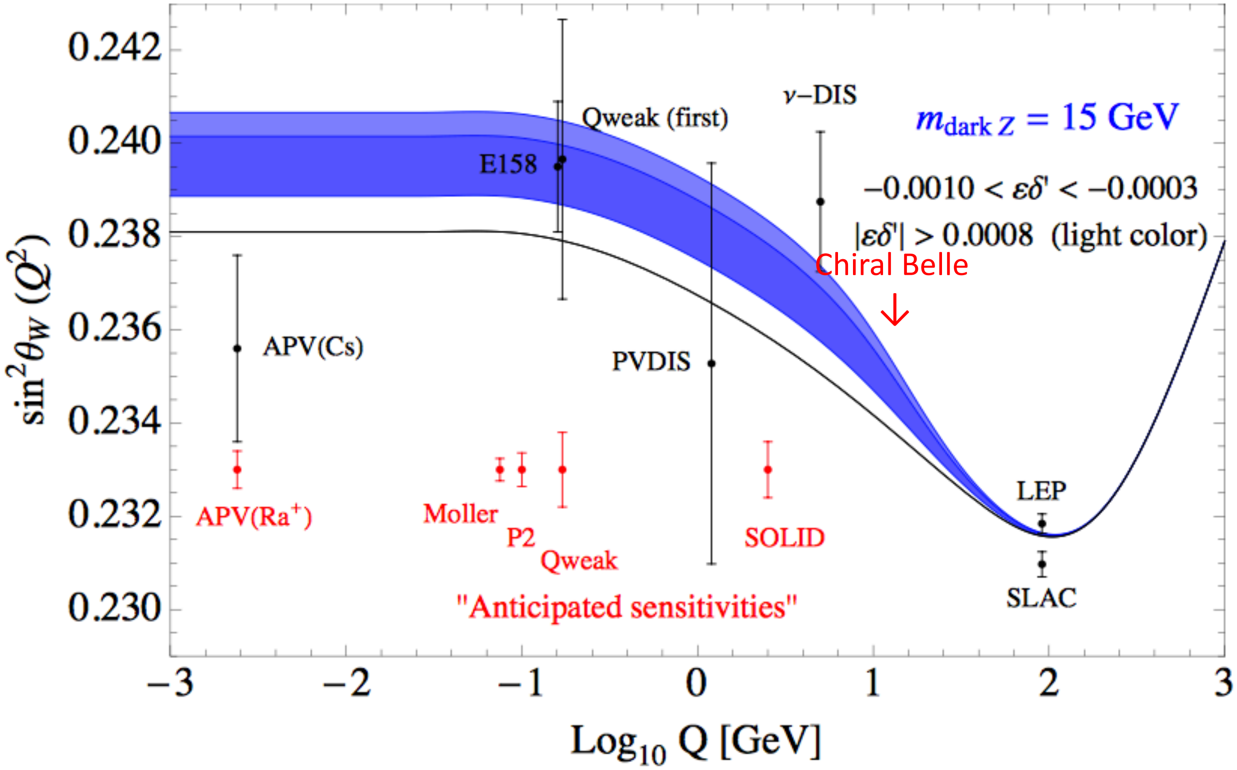
More information at arxiv.org/abs/1907.03503

- **Highest precision test or neutral current vector coupling universality as beam polarization error cancels: e.g. < 0.3% relative error for ratio: g^v_b/g^v_c, *cf* 4% now**
- **Most precise measurements for muons, charm and beauty by many factors**
  - probes both heavy quark phenomenology and Up vs Down
- Measurements of $\sin^2\theta_{eff}^{lepton}$ of using lepton pairs of comparable precision WA obtained by LEP/SLD, except at 10.58GeV and in single measurement
  - **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

Will probe both high and low energy scales

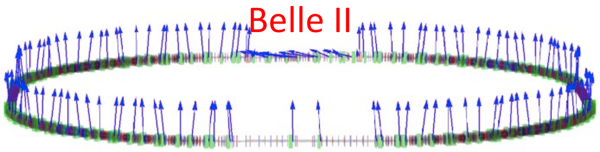
- Unique sensitivity to Dark Sector parity violating light neutral gauge bosons – especially when Z_{dark} is off-shell or couples more to 3rd generation
  - Because couplings are small, this sector would have been hidden
  - See e.g. H. Davoudiasl, H. S. Lee and W. J. Marciano, Phys.Rev. D 92, no. 5,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



Upgrading SuperKEKB with Polarized e- Beam

NEW HARDWARE FOR POLARIZATION UPGRADE:

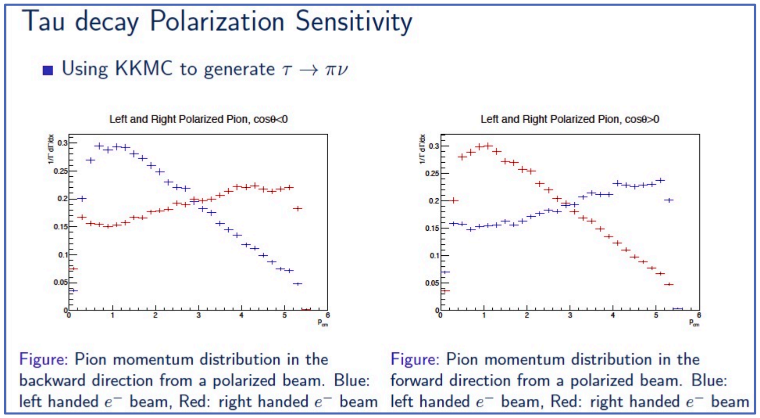
- **Low emittance polarized Source:** electron helicity can be flipped bunch-to-bunch by controlling circular polarization of source laser illuminating a GaAs photocathode (à la SLC). Inject vertically polarized electrons into the 7GeV e- Ring. Needs low enough emittance source to be able to inject. Leverage ILC work; R&D in Japan on photocathodes
- **Spin rotators:** Rotate spin to longitudinal before Interaction Point (IP) in Belle II, and then back to vertical after IP using solenoidal and dipole fields. R&D in Russia & N.A., considering direct-wind combined function magnets (BNL)



e- spin vector around ring

- **Compton polarimeter:** monitors longitudinal polarization with <1% absolute precision, higher for relative measurements - provides real time polarimetry. R&D in Europe& N.A.

→ Use tau decays from $e^+e^- \to \tau^+\tau^-$ measured in Belle II to provide high precision absolute average polarization at IP

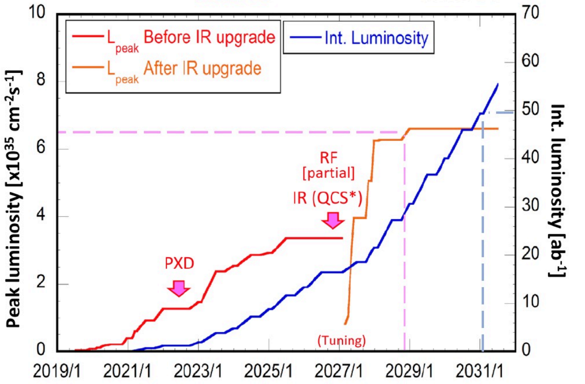

Tau decay Polarization Sensitivity

- 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

Planning to implement ~2027 in mid-decade upgrade window for new final focus;
R&D for this upgrade proposal included in KEK Roadmap for MEXT submitted in 2021



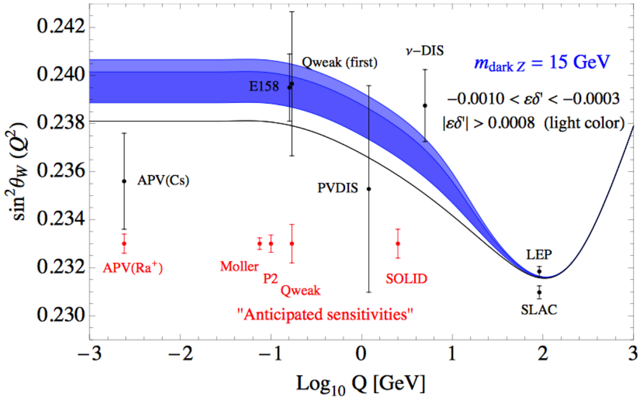
Summary

- 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

Additional Material

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

- 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

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

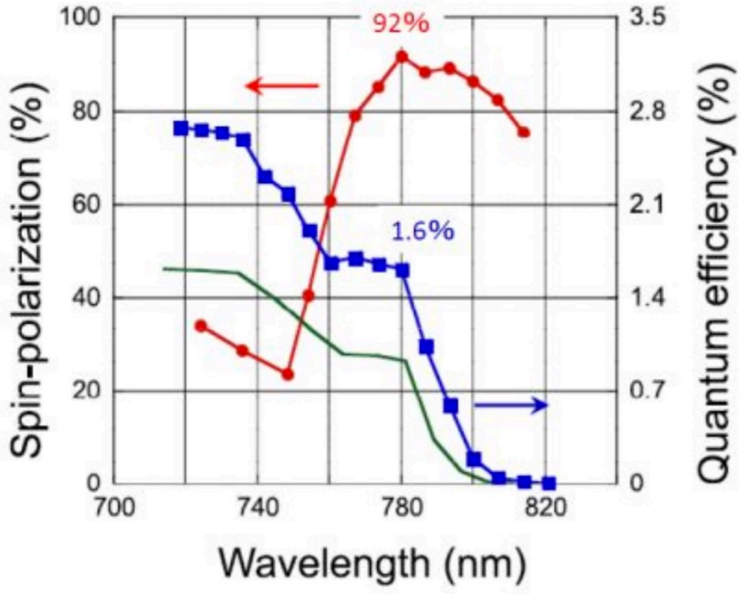
$$+\boxed{P_e}\frac{\cos\theta}{1+\cos^2\theta}$$

- 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
- See Caleb Miller's Talk tomorrow for details on current status of sensitivity studies – very promising!

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

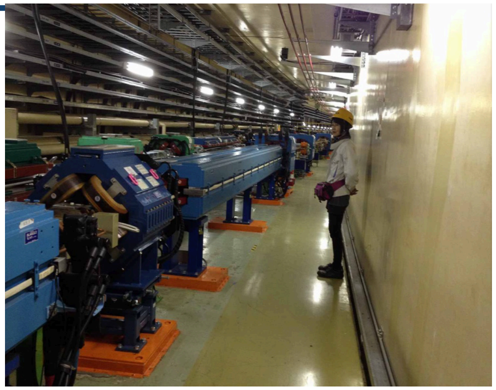
20 mm-mrad vertical emittance

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

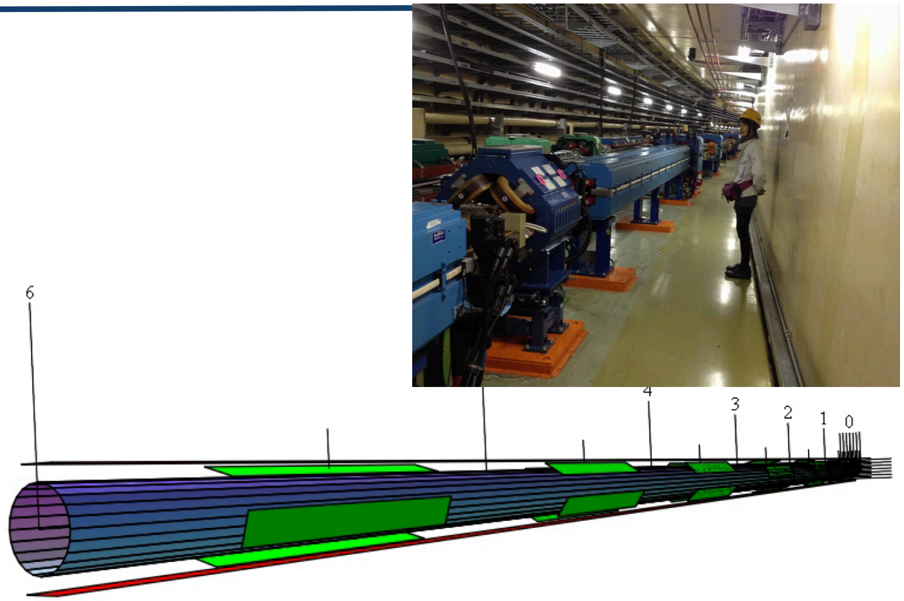
Use of solenoids and dipoles, plus the quadrupoles (needed for decoupling) on either side of interaction point

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 use overlapping field magnets which would replace existing bending magnets either side of interaction point

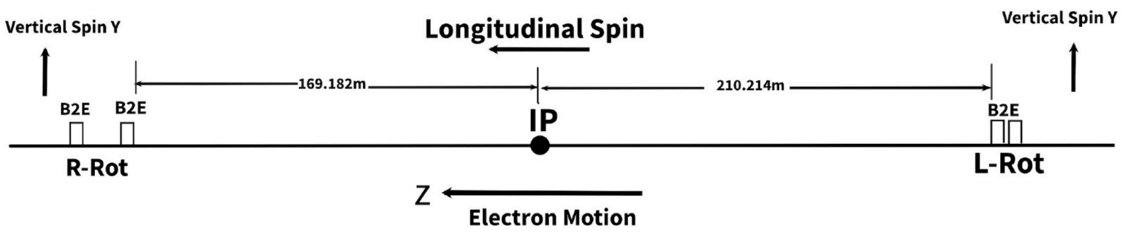
BINP, ANL, BNL, TRIUMF-Victoria Groups

Preliminary studies – ANL, TRIUMF, Victoria

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

Yuhao Peng, Victoria

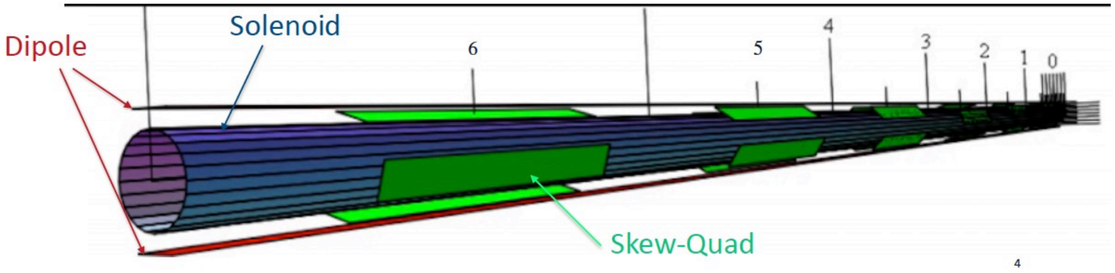
Spin Rotator



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

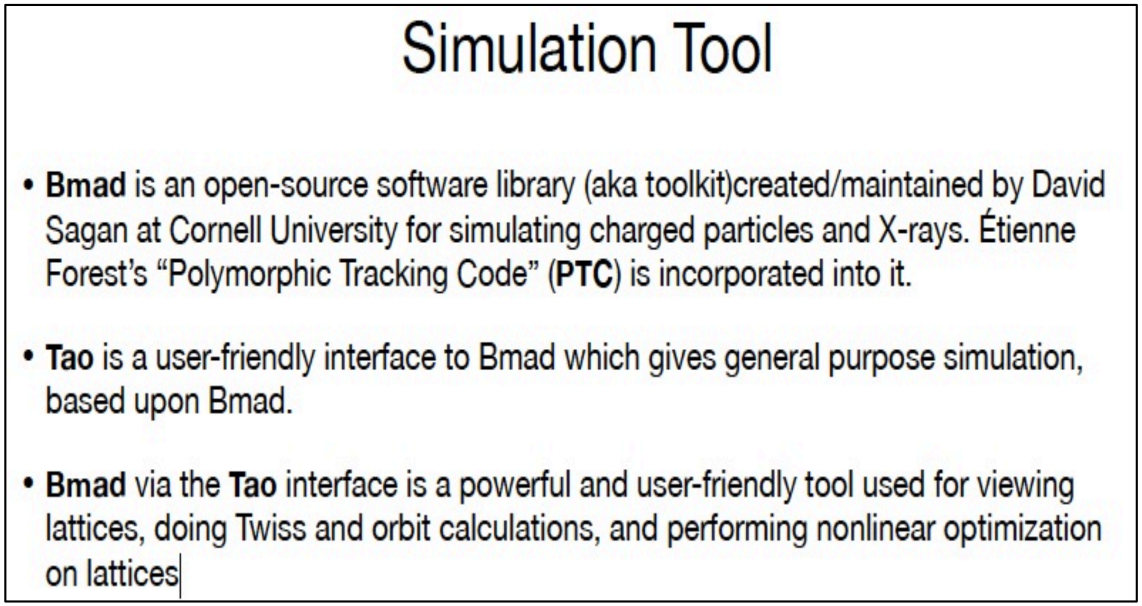
- replace some existing ring dipoles(send) near the IP with the solenoid-dipole combined function magnets and maintain the original dipole strength to keep the geometry
- Install 6 skew-quadruple on top of each rotator section to compensate for the x-y plane coupling caused by solenoids



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

U. Wienands, ANL

Preliminary studies – ANL, TRIUMF, Victoria

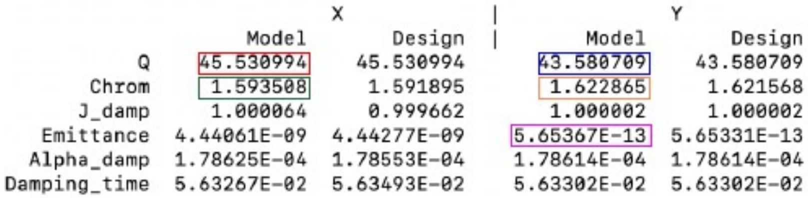


Simulation Tool

- **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

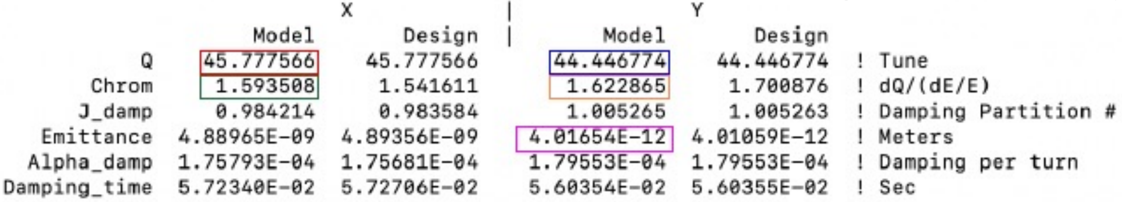
Using SuperKEKB High Energy Ring lattice (Demin Zhou, KEK)

Original Lattice with Rotators



```
                         X             |               Y
                Model         Design   |         Model         Design
           Q  45.530994     45.530994         43.580709     43.580709
       Chrom   1.593508      1.591895          1.622865      1.621568
      J_damp   1.000064      0.999662          1.000002      1.000002
   Emittance 4.44061E-09   4.44277E-09       5.65367E-13   5.65331E-13
  Alpha_damp 1.78625E-04   1.78553E-04       1.78614E-04   1.78614E-04
Damping_time 5.63267E-02   5.63493E-02       5.63302E-02   5.63302E-02
```

Lattice with Rotators after re-matching chromaticity



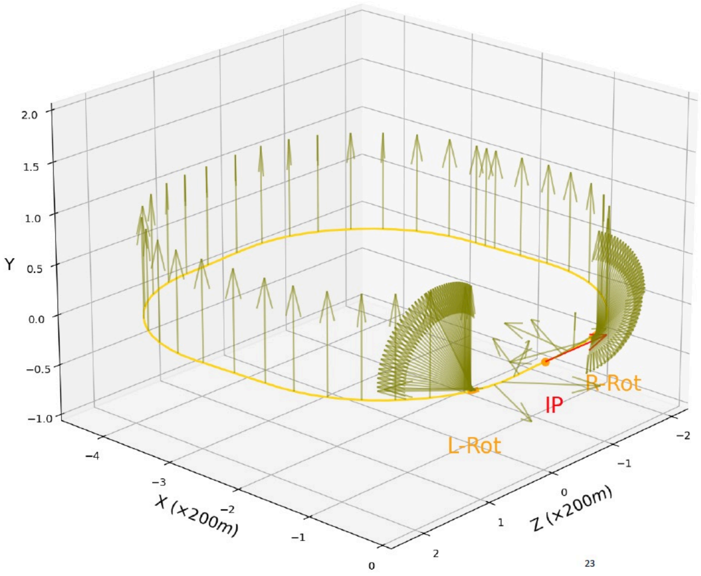
```
                         X             |               Y
                Model         Design   |         Model         Design
           Q  45.777566     45.777566         44.446774     44.446774   ! Tune
       Chrom   1.593508      1.541611          1.622865      1.700876   ! dQ/(dE/E)
      J_damp   0.984214      0.983584          1.005265      1.005263   ! Damping Partition #
   Emittance 4.88965E-09   4.89356E-09       4.01654E-12   4.01059E-12  ! Meters
  Alpha_damp 1.75793E-04   1.75681E-04       1.79553E-04   1.79553E-04  ! Damping per turn
Damping_time 5.72340E-02   5.72706E-02       5.60354E-02   5.60355E-02  ! Sec
```

Yuhao Peng (Victoria)

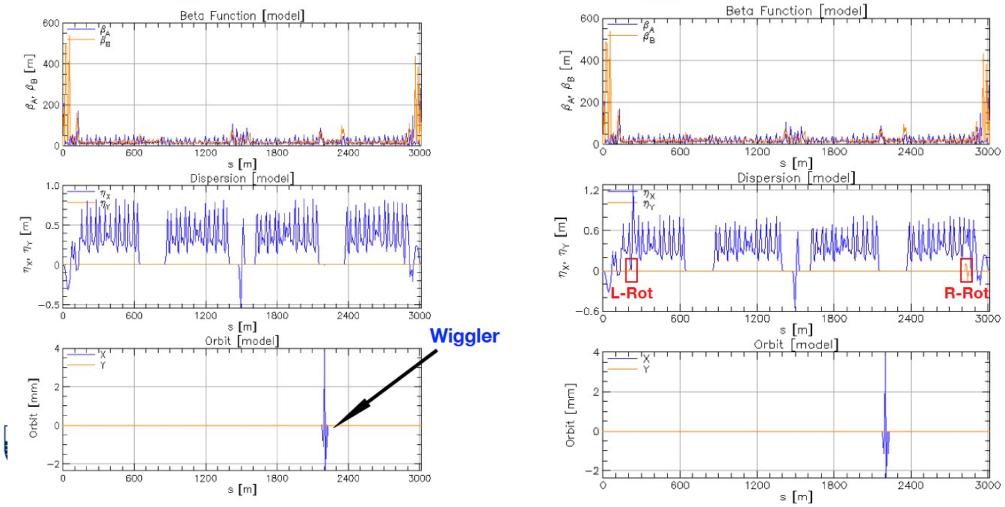
Next steps: re-match tunes and conduct long term tracking studies

Preliminary studies – ANL, TRIUMF, ANL

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



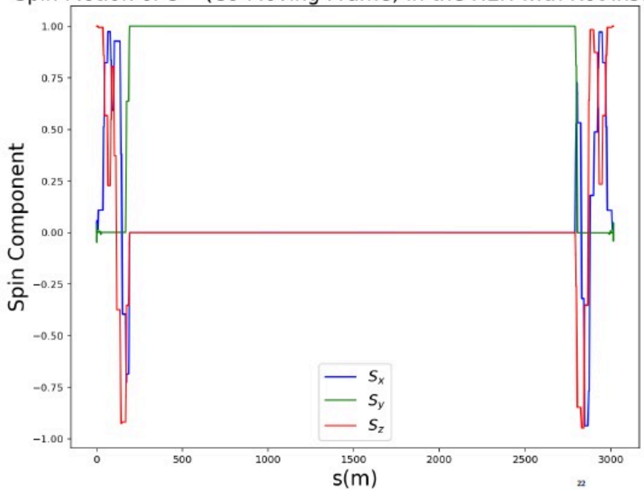
Comparison of Full Lattice



Original

Rot

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

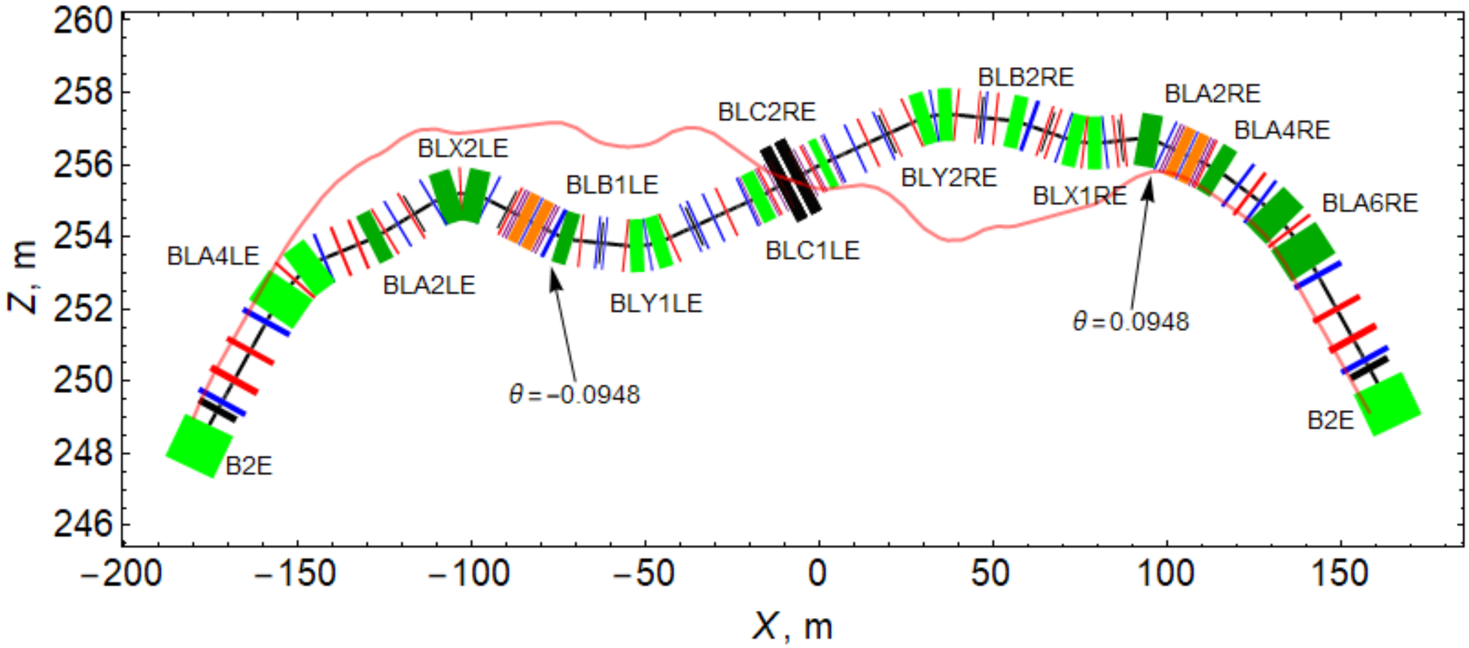


Spin Component	Entrance of Rot	IP	Exit
X	−0.0000032792024300	−0.0000044677361868	−0.0000063748934711
Y	0.9999999999802550	0.0000026796195603	0.9999999999793680
Z	−0.0000053600276775	0.9999999999864290	0.0000007825194459

Yuhao Peng, Victoria

Preliminary studies by BINP group

Another Concept: install spin-rotator magnets in drift regions

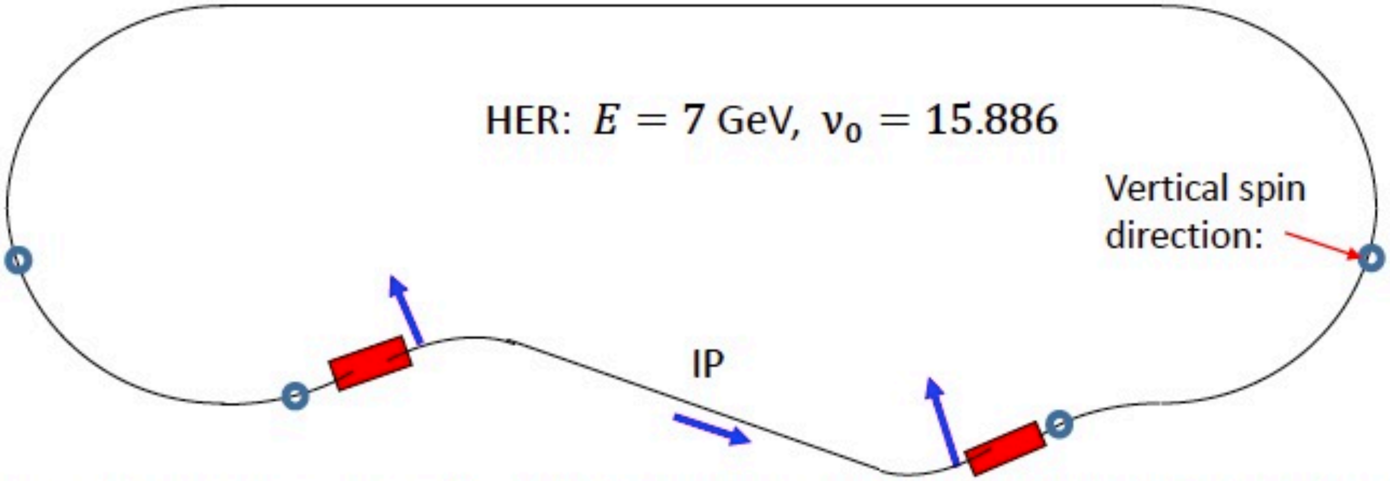


"B2E"	"BLA6RE"	"BLA4RE"	"BLA2RE"	"BLX1RE"	"BLB2RE"	"BLY2RE"	"BLC2RE"
0.0557427	0.0501498	0.0271539	0.0557427	−0.0221788	0.0234696	0.027	0.00591985
"BLC1LE"	"BLY1LE"	"BLB1LE"	"BLX2LE"	"BLA2LE"	"BLA4LE"		
−0.00591047	−0.0270414	−0.0387835	0.0532119	−0.0181419	0.0663659		

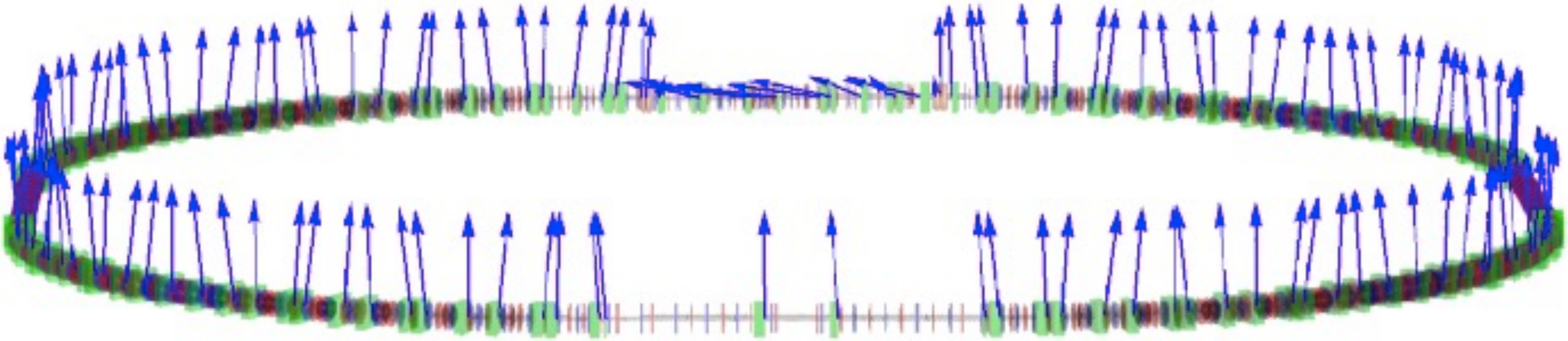
From I. Koop, A.Otboev and Yu.Shatunov, BINP, Novosibirsk preliminary considerations on the longitudinal polarization at SuperKEKB

Preliminary studies by BINP group

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

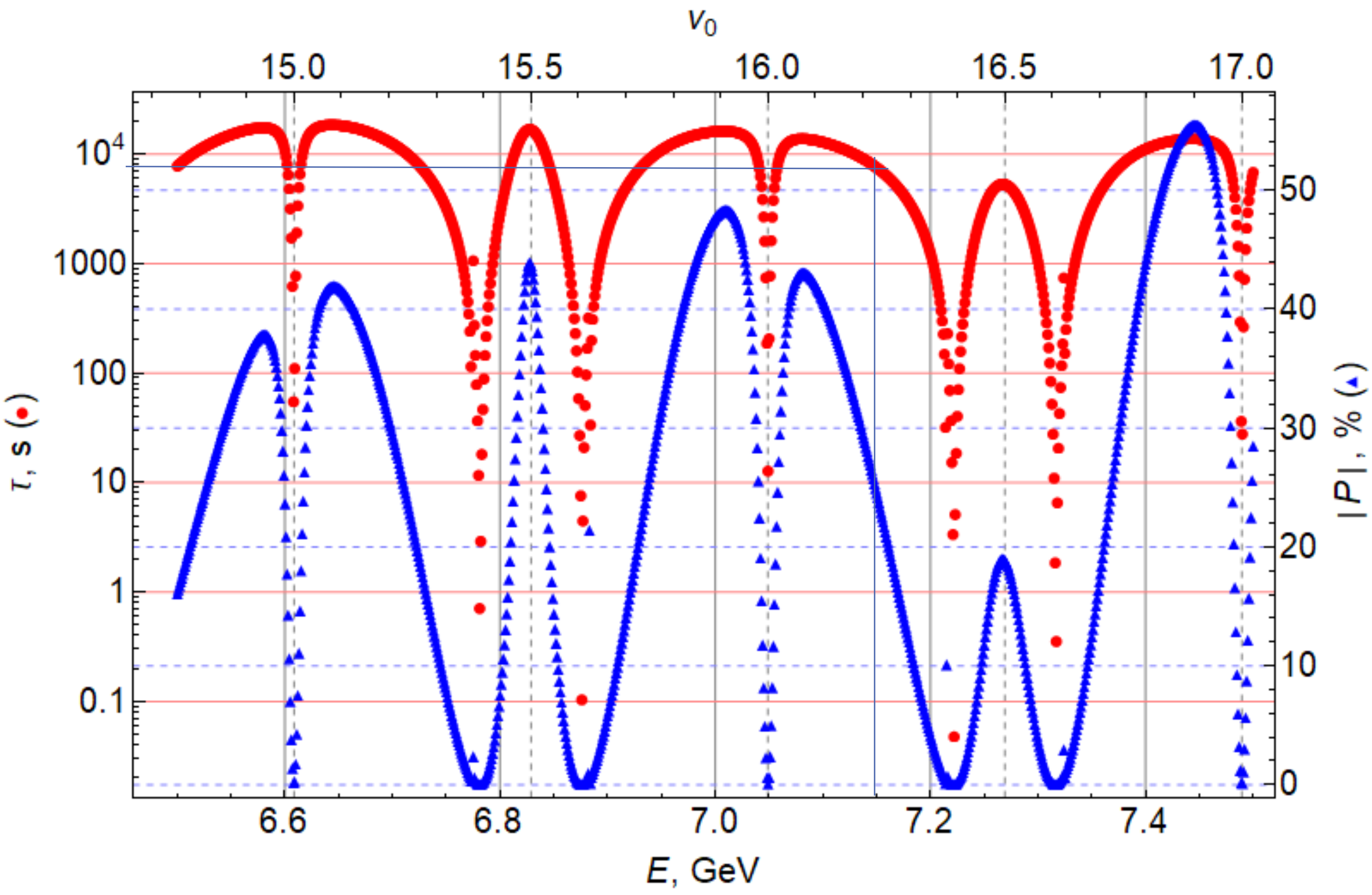


Spin direction is vertical in the main part of HER. Then it is rotated to the horizontal plane by the set of two solenoids, which are comprising the 90^0 spin rotator.



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

Preliminary studies by BINP group

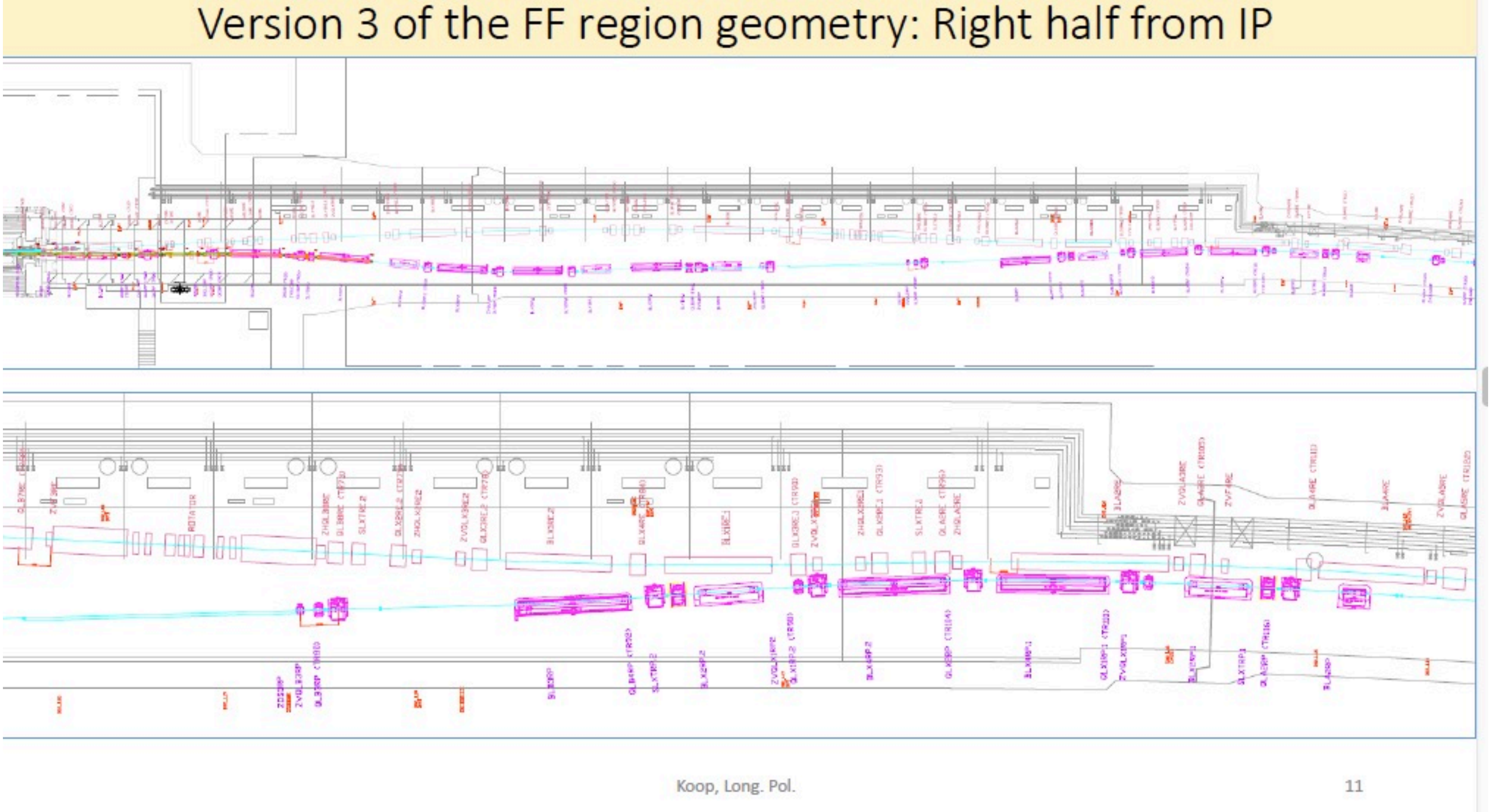


Depolarization lifetime at E=7.15GeV is 7500s (~2 hrs)

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

Preliminary studies by BINP group



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

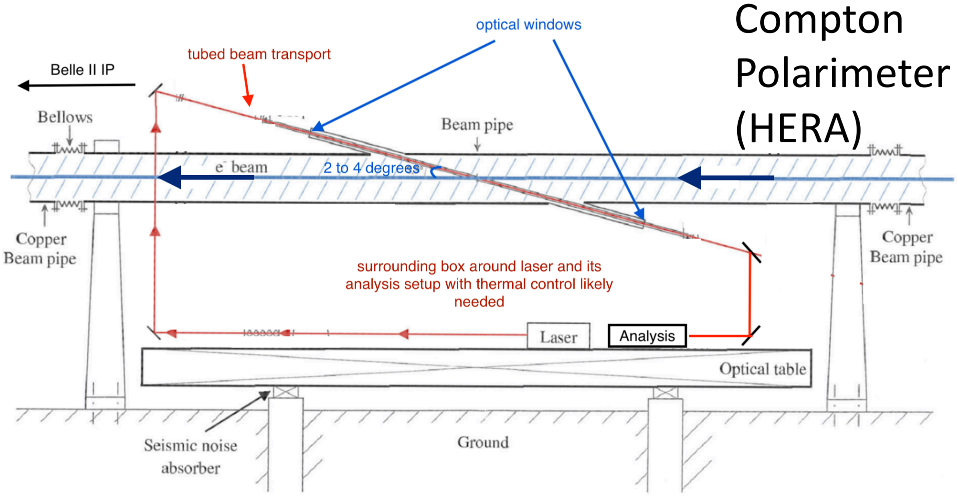
Koop, Long. Pol.

11

Polarization in SuperKEKB

Hardware needs

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



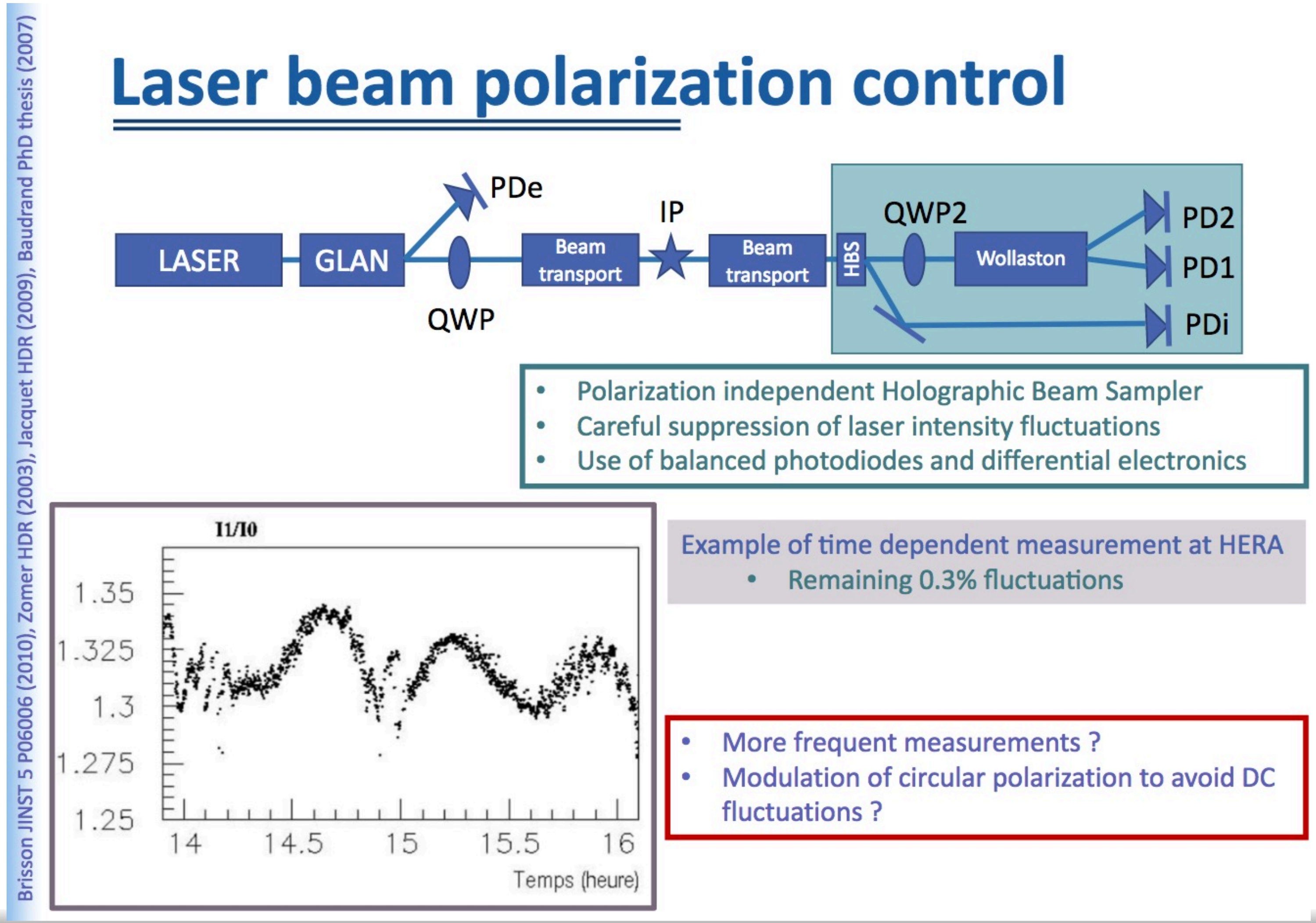
Compton Polarimeter (HERA)

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 –

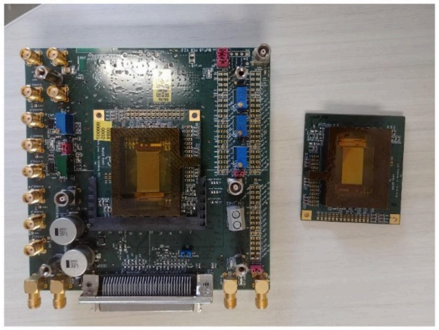
Using HPVMAPs as Compton e- Detector at MOLLER

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).

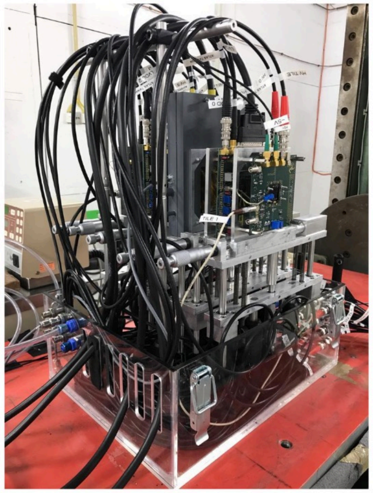
If it performs well, version 11 (2020 submission) will be the production chip we use for MOLLER.



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:

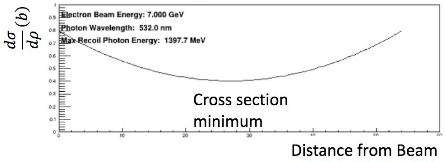
- ATLAS
- Mu3e
- PANDA
- P2
- MOLLER



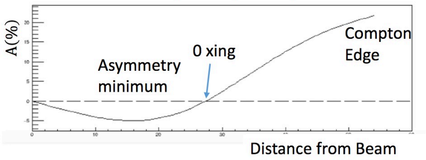
The implementation as a Compton detector is done by the Manitoba group.

Calculations/Simulations

Compton Cross section

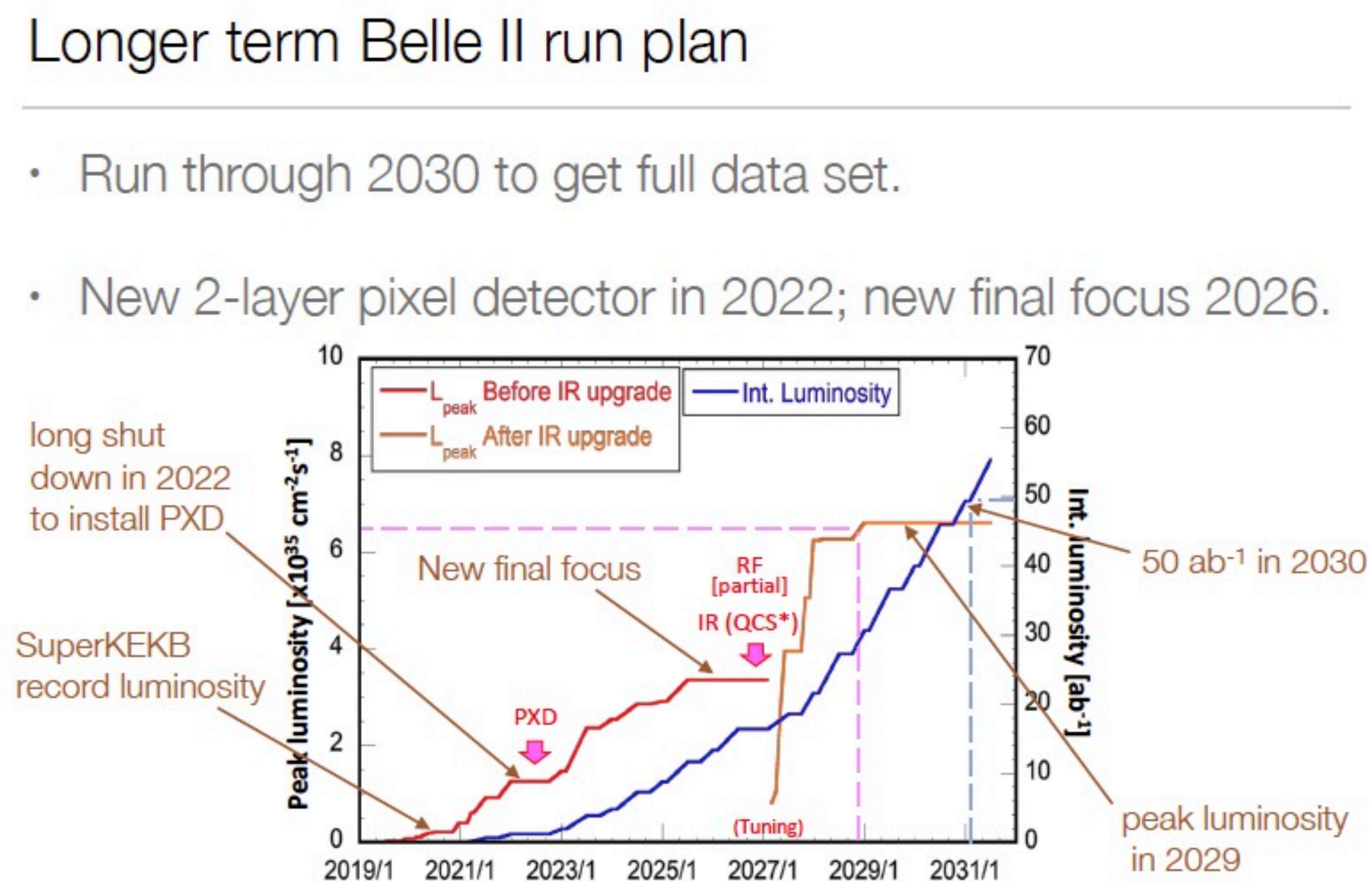


Compton Asymmetry



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.

long shut down in 2022 to install PXD

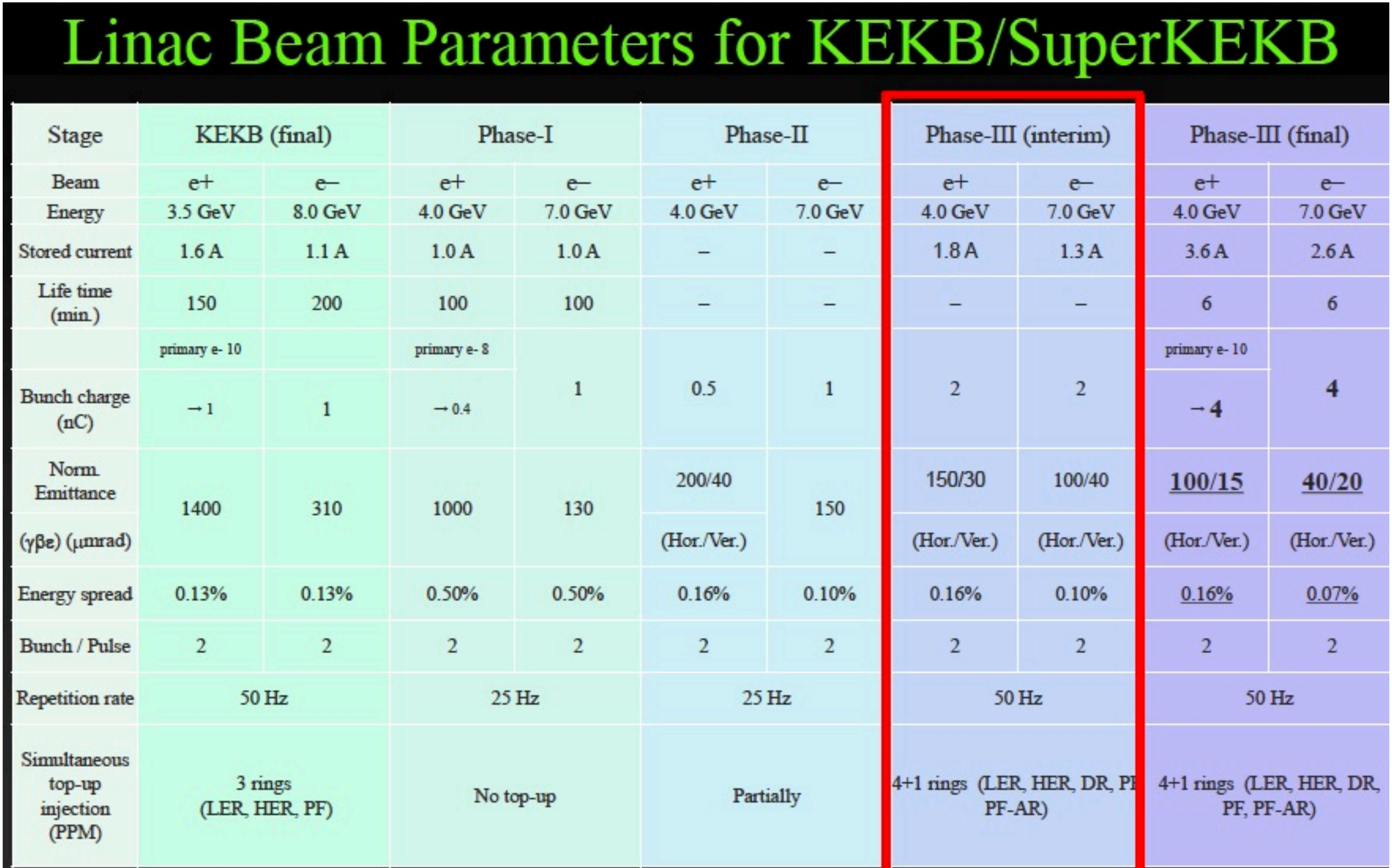
SuperKEKB record luminosity

New final focus

50 ab^{-1} in 2030

peak luminosity in 2029

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)	

Work packages…

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
- 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

Global interest in this Neutral Current 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.)
- Next generation high energy e^+e^- colliders: ILC & FCC-ee
- EIC at Brookhaven will probe weak mixing angle in this energy regime with light quarks but with lower precision