Physics Opportunities with Polarized Electron Beams in a SuperKEKB Upgrade

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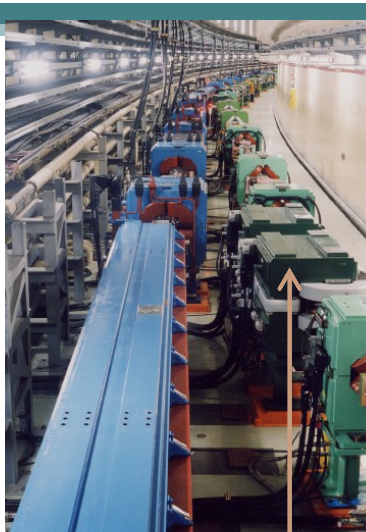
FPCP 2019
Victoria Canada
10 May 2019

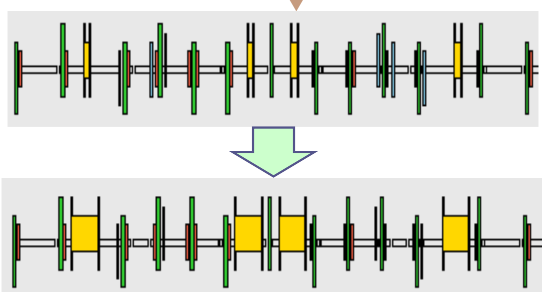
Upgrading SuperKEKB with polarized electrons Opens New Windows for Discovery with Belle II

- Extremely rich and unique high precision electroweak program – focus of this presentation
- Polarized Beam also provides:
  - Improved precision measurements of τ electric dipole moment (EDM) and $(g\text{-}2)_\tau$
  - Reduce backgrounds in $\tau \to \mu\gamma$ and $\tau \to e\gamma$ precision leading to significantly improved sensitivities

SuperKEKB in Japan

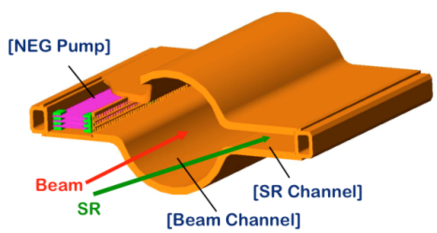


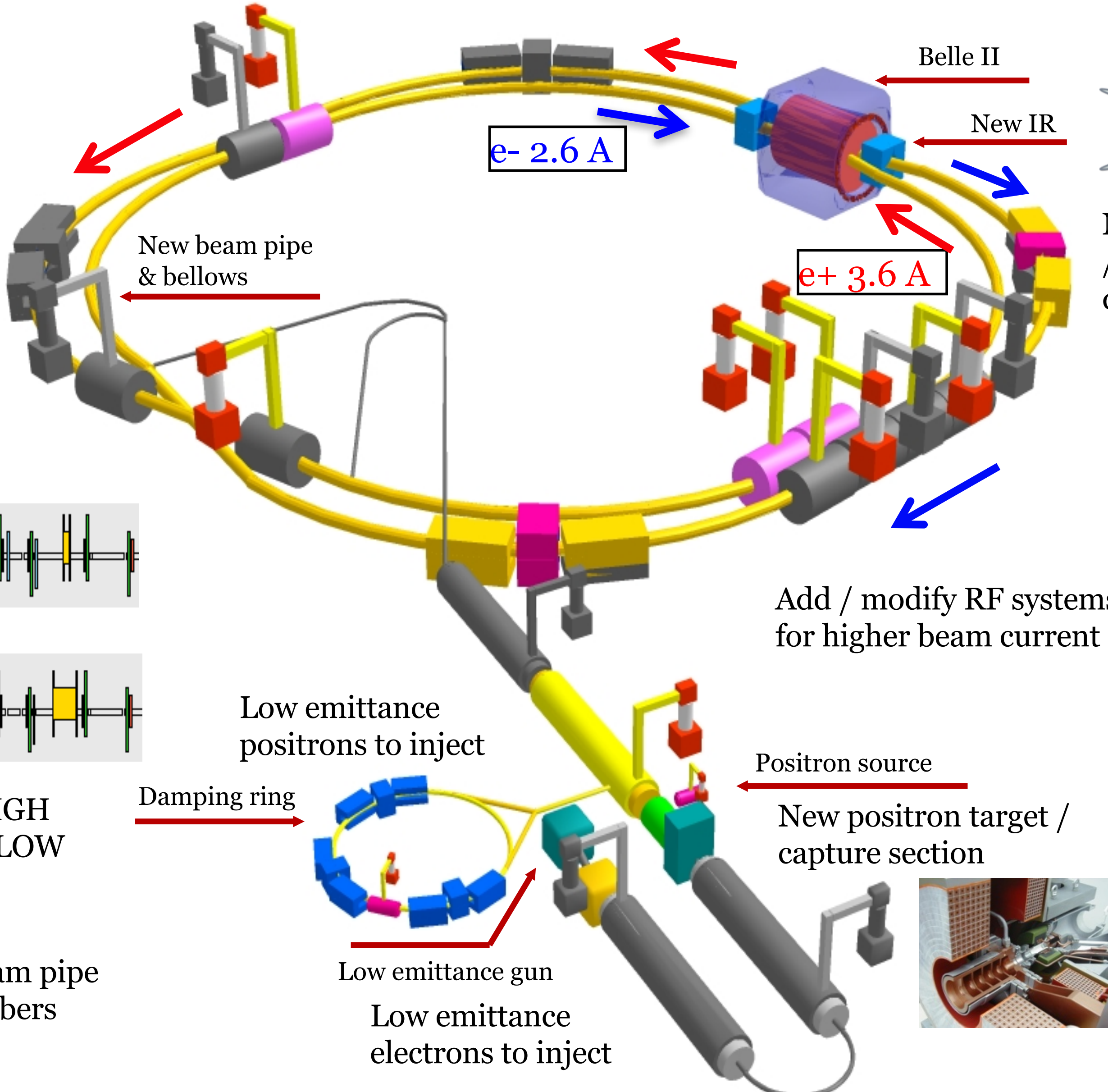
Replace short dipoles with longer ones (LER)



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

TiN-coated beam pipe with antechambers

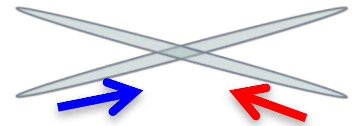




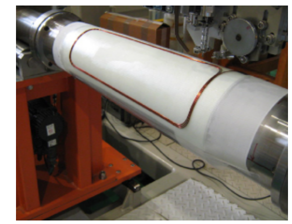
Low emittance positrons to inject

Low emittance electrons to inject

Colliding bunches



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

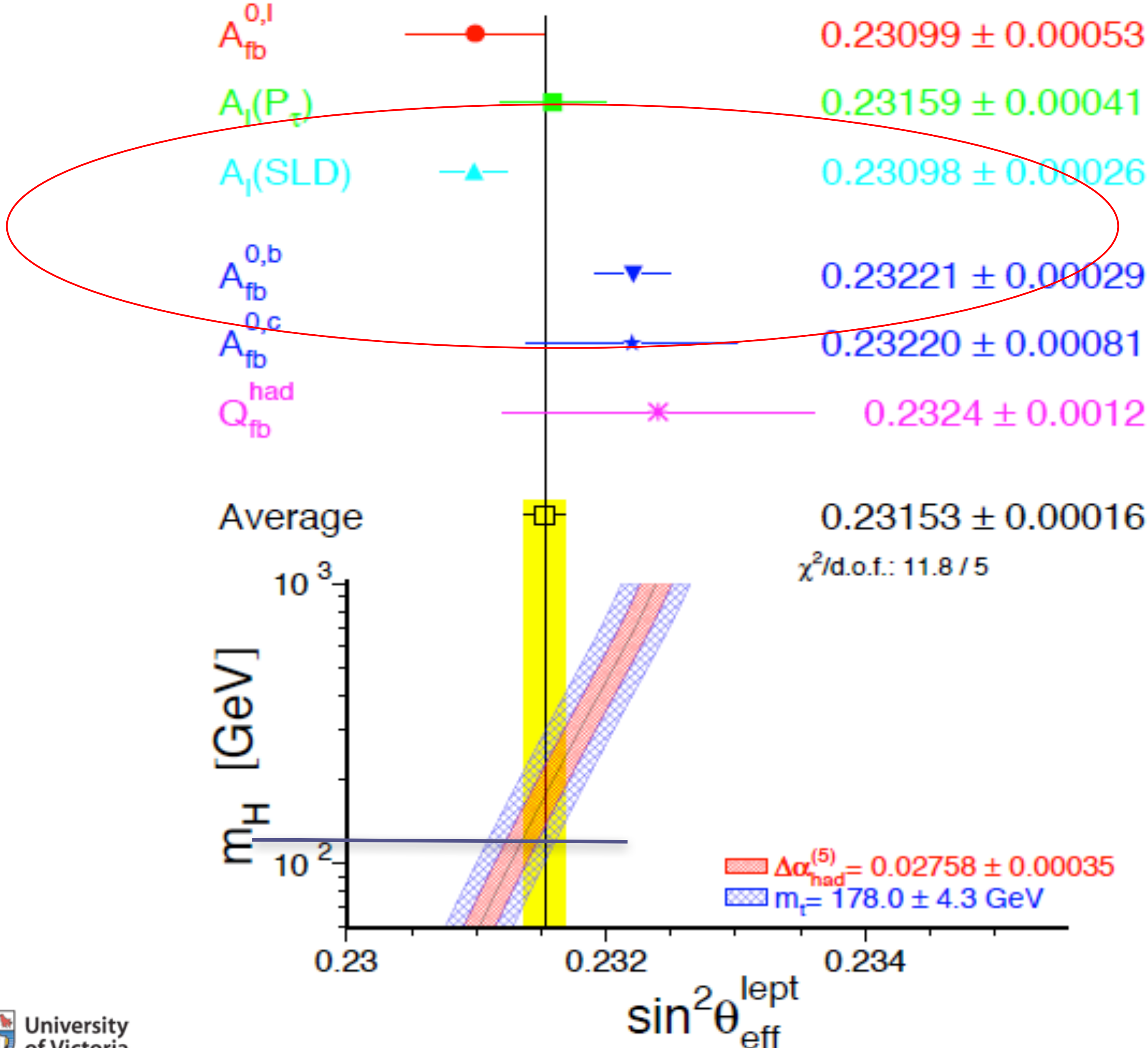
A New Path for Discovery in Precision Neutral Current Electroweak Precision Program

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

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

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

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)

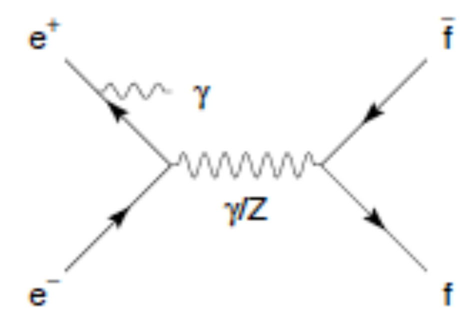
‘Chiral Belle’ -> Left-Right Asymmetries

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

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

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



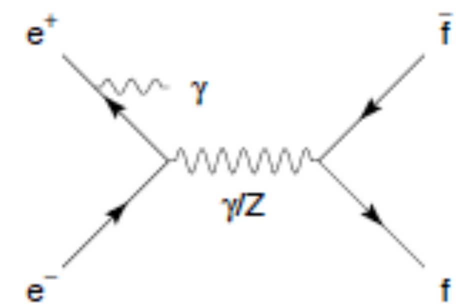
‘Chiral Belle’ Left-Right Asymmetries

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

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

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

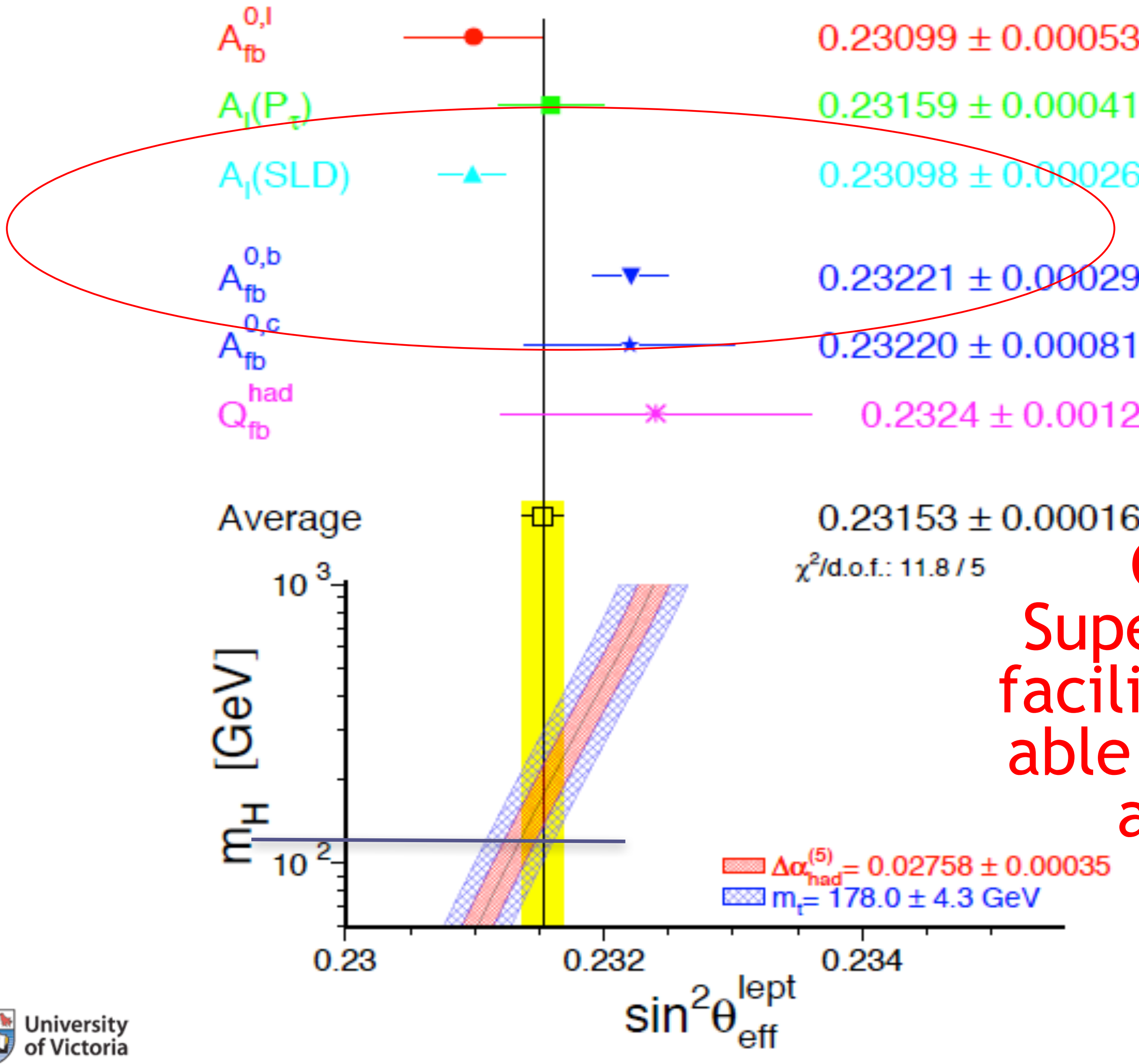
$$\langle Pol \rangle = 0.5\left\{\left(\frac{N_R^{e-} - N_L^{e-}}{N_R^{e-} + N_L^{e-}}\right)_R - \left(\frac{N_R^{e-} - N_L^{e-}}{N_R^{e-} + N_L^{e-}}\right)_L\right\}$$



Source generates mainly right-handed electrons

Source generates mainly left-handed electrons

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 at SuperKEKB is the only facility in next decades able to experimentally address this 3σ deviation

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 20/ab	Relative Error
b-quark (selection eff.=0.3)	-0.0208 ± .0001	0.5%
c-quark (eff. = 0.3)	+0.00572 ±.00003	0.5%
tau (eff. = 0.25)	-0.000684 ±.000015	2.2%
muon (eff. = 0.5)	-0.00068 ±.00001	1.5%
Electron (barrel) (eff. = 0.015)	-0.000684 ±.000008	1.1%

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 (selection 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)	0.0007	0.0004
Muon (eff. = 0.5)	-0.0371 ±.0003	-0.03667 ±0.0023	0.0007 Improve x3	0.0005	0.0003
Electron (eff. = 0.015)	-0.0371 ±.0003	-0.03816 ±0.00047	0.0007	0.0005	0.0003 (*all leptons will give ~current* WA error)

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

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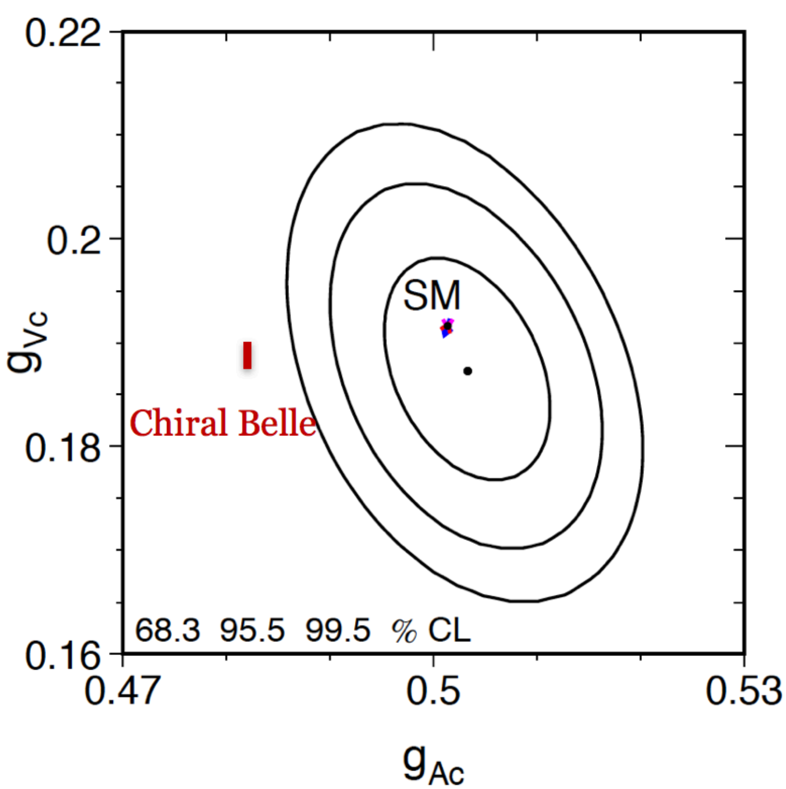
Comparisons with present neutral current vector coupling uncertainties

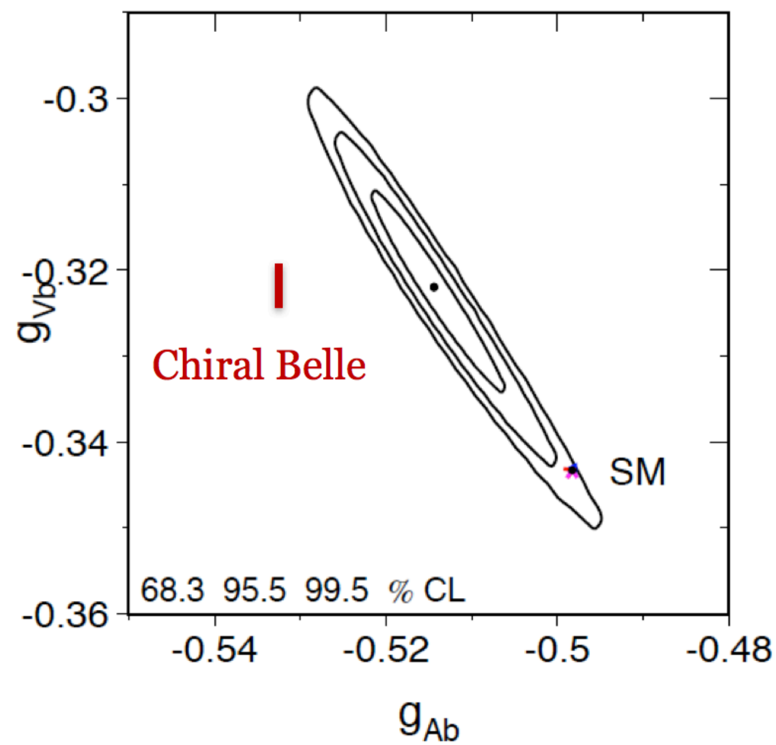
Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

c-quark:
Chiral Belle ~7 times more precise

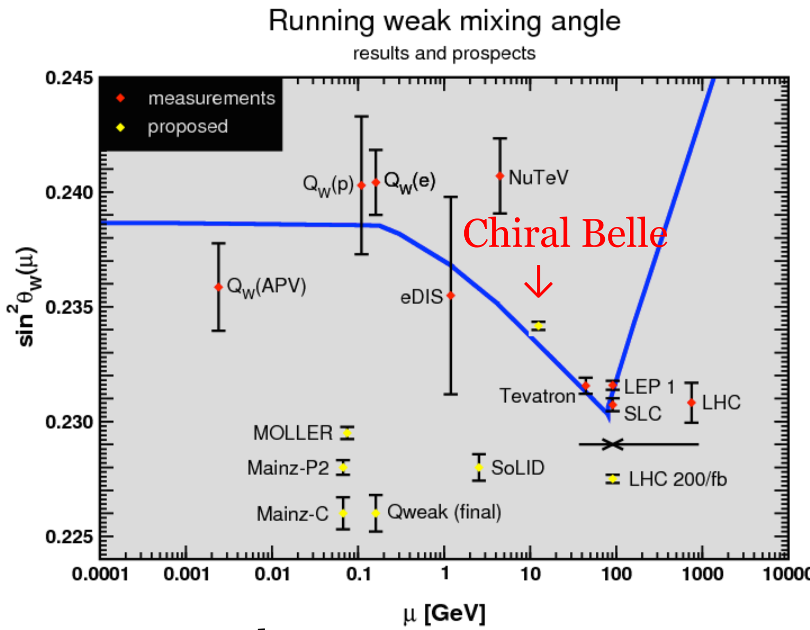
b-quark:
Chiral Belle ~4 times more precise

with 20 ab^{-1}





‘Chiral Belle’ at 10GeV probes both high and low energy scales



Erler, Moriond 2017

arXiv:1704.08330 [hep-ph]

Chiral Belle: σ ~ 0.00018

- 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
- Most precise measurements for charm and beauty
  - probes both heavy quark phenomenology and Up vs Down

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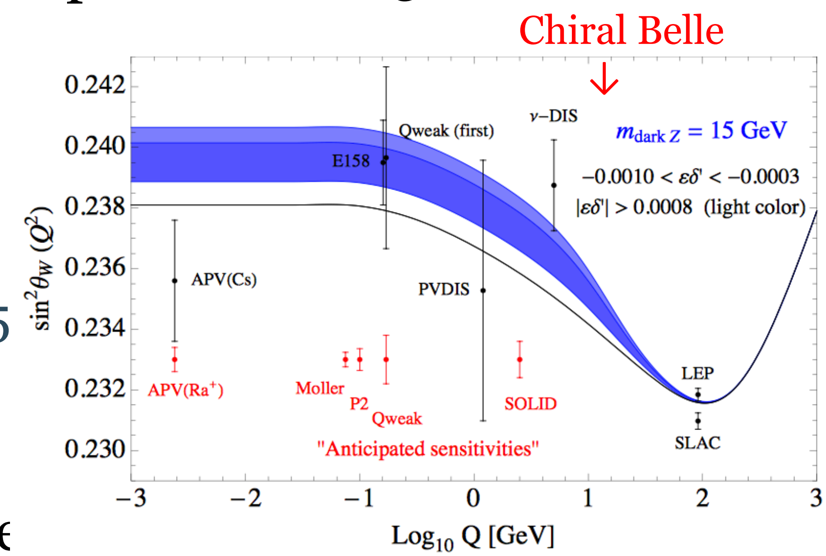
- Unique sensitivity to Dark Sector parity violating light neutral gauge bosons – especially when Z_{dark} is off-shell or couples more to 3rd generation
  - Because couplings are small, this sector would have been hidden
  - See e.g. H. Davoudiasl, H. S. Lee and W. J. Marciano,Phys.Rev. D 92, no. 5,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

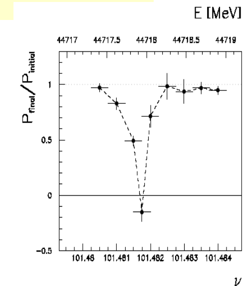


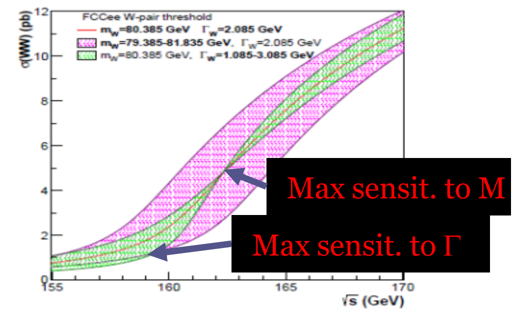
- Using ISR from the un-polarised beam particle parity violating processes in e+e- collisions at lower energies, but with significantly lower precision.
- Global interest in this EW physics:
  - LHC experiments
  - Moller Experiment at Jefferson Lab which will measure $\sin^2\theta_{eff}^{electron}$ below 100MeV with similar precision – Moller is *only* sensitive to electron couplings.
  - Next generation high energy e+e- colliders

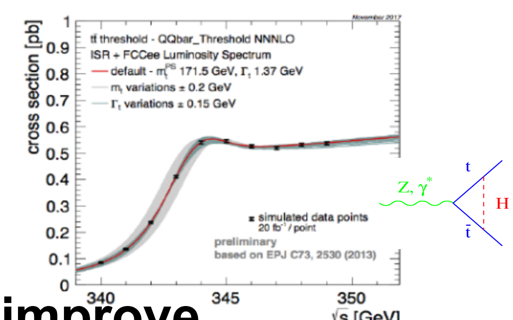
Precision Z EW is important part of FCCee program

observable	Physics	Present precision (PDG)		FCC-ee stat Syst Precision	FCC-ee key	Challenge
M_Z MeV/c2	Input	91187.5 ±2.1	Z Line shape scan	0.004 MeV <±0.1 MeV	E_cal	QED corrections
Γ_Z MeV/c2	$\Delta\rho$ (T) (no $\Delta\alpha$!)	2495.2 ±2.3	Z Line shape scan	0.007 MeV <±0.1 MeV	E_cal	QED corrections
$R_l \equiv \frac{\Gamma_h}{\Gamma_l}$	α_s, δ_b	20.767 (25) (α_s ±0.0011)	Z Peak	0.0001 (2-20) (α_s ±0.00015)	Statistics	QED corrections
N_ν	Unitarity of PMNS, sterile ν's	2.984 ±0.008	Z Peak Z+γ(161 GeV)	0.00008 (40) 0.001	->lumi meast Statistics	QED corrections to Bhabha scat.
R_b	δ_b	0.21629 (66)	Z Peak	0.000003 (20-60)	Statistics, small IP	Hem. correlations
A_{LR}	$\Delta\rho$, ε_3, $\Delta\alpha$ (T, S)	$\sin^2\theta_W^{eff}$ 0.23098(26)	Z peak, Long. polarized	$\sin^2\theta_W^{eff}$ ±0.000006	4 bunch scheme	Design experiment
A_{FB}^{lept}	$\Delta\rho$, ε_3, $\Delta\alpha$ (T, S)	$\sin^2\theta_W^{eff}$ 0.23099(53)		$\sin^2\theta_W^{eff}$ ±0.000006	E_cal & Statistics	
M_W MeV/c2	$\Delta\rho$, ε_3, ε_2, $\Delta\alpha$ (T, S, U)	80379 ± 12	Threshold (161 GeV)	0.5 MeV <0.5 MeV	E_cal & Statistics	QED corrections Theory ~4-5 MeV
m_{top} MeV/c2	Input	173300 ± 400± 500	Threshold scan	m_{top} ~17 MeV Γ_{top} ~45 MeV	E_cal & Statistics	Theory limit at ~40-50 MeV?

Beam E cal. with reson. depolar.





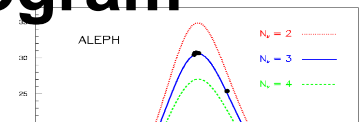


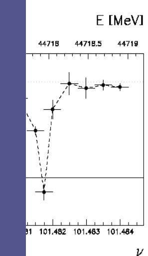
As important is the precision on SM parameters : FCCee will improve precision by > 1 order of magnitude Running at Z pole mandatory, as is progress in theory

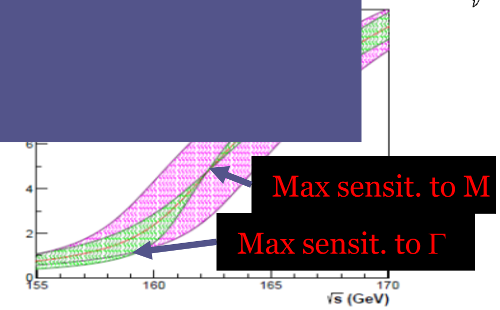
Precision Z EW is important part of FCCee program

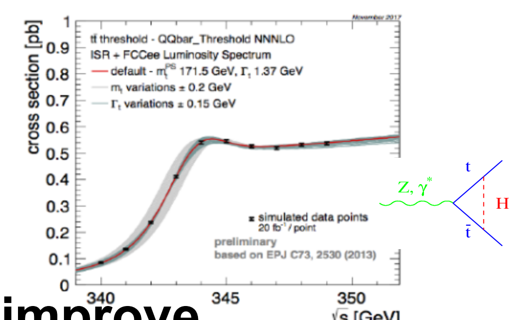
observable	Physics	Present precision		FCC-ee stat Syst Precision	FCC-ee key	Challenge
M_Z MeV/c						
Γ_Z MeV/c						
$R_l \equiv$						
N_ν						
R_b						
A_{LR}	$\Delta\rho, \varepsilon_3, \Delta\alpha$ (T, S)	$\sin^2\theta_w^{eff}$ 0.23098(26)	Z peak, **Long. polarized**	$\sin^2\theta_w^{eff}$ **±0.000006**	4 bunch scheme	Design experiment
A_{FB}^{lept}	$\Delta\rho, \varepsilon_3, \Delta\alpha$ (T, S)	$\sin^2\theta_w^{eff}$ 0.23099(53)		$\sin^2\theta_w^{eff}$ **±0.000006**	**E_cal** & Statistics	
M_W MeV/c2	$\Delta\rho, \varepsilon_3, \varepsilon_2, \Delta\alpha$ (T, S, U)	80379 ± 12	Threshold (161 GeV)	**0.5 MeV** **<0.5 MeV**	**E_cal** & Statistics	QED corrections **Theory ~4-5 MeV**
m_{top} MeV/c2	Input	173300 ± 400± 500	Threshold scan	**m_{top} ~17 MeV** **Γ_{top} ~45 MeV**	**E_cal** & Statistics	Theory limit at **~40-50 MeV**?

SuperKEKB with polarized beams probe Z physics at low energy much earlier









As important is the precision on SM parameters : FCCee will improve precision by > 1 order of magnitude Running at Z pole mandatory, as is progress in theory

Polarized e^- Beam also provides:

- Improved precision measurements of τ electric dipole moment (EDM) and $(g\text{-}2)_\tau$
  - 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.
- SuperB studies showed that e^- beam polarization can be used to reduce backgrounds in $\tau \to \mu\gamma$ and $\tau \to e\gamma$ – leading to improved sensitivities; also electron beam polarization and can be used to distinguish Left and Right handed New Physics currents.
  - See: arXiv:1008.1541v1 [hep-ex]

Polarization in SuperKEKB Hardware needs

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

Polarization in SuperKEKB

- Aim for ~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.
- Inject vertically polarized electrons into the High Energy Ring (HER -> electron ring)
  - use polarized electron source similar to SLC source
  - 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

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

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+ polarization

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

- Now exploring this with BaBar data at UVic

Starting Considerations for a SuperKEKB polarization upgrade

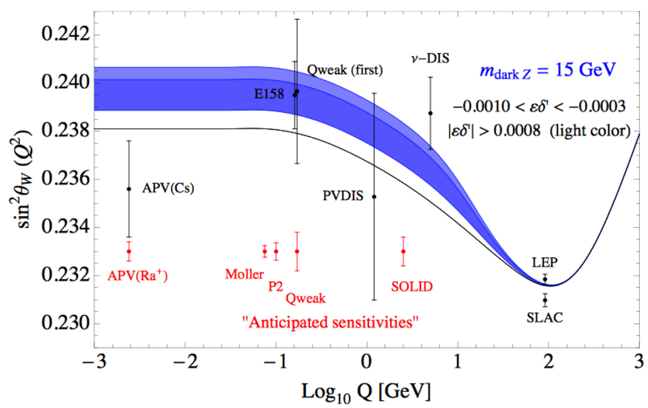
- Building international team
- Bring new resources from international partners to KEK
- Opportunity to build on international partnerships with KEK for a unique discovery machine
- Aim for polarization physics in mid-2020's

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

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 e- polarization project!

Additional Information

Polarization in SuperKEKB Hardware needs

M. Satoh et al, IPAC 2016 Proceedings

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

Current source photo-cathode
With 5 nC/bunch
20 mm-mrad vertical emittance
50 mm-mrad horizontal emittance

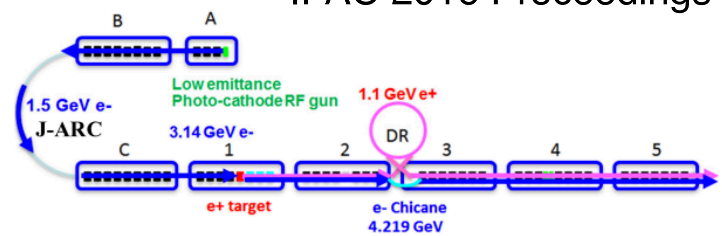


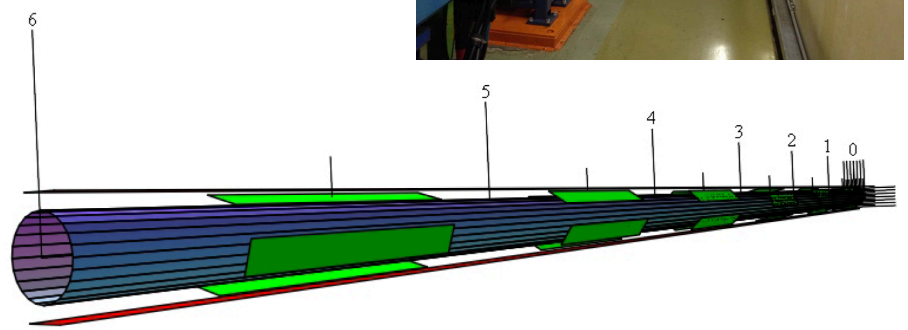
Figure 1: Schematic drawing of the SuperKEKB injector linac.

Table 1: Main Parameters of SuperKEKB Injector Linac

	KEKB		SuperKEKB (Phase III)	
	e-	e+	e-	e+
Beam energy (GeV)	8	3.5	7	4
Bunch charge (nC)	1	1 (10*)	5	4 (10*)
Normalized vertical emittance (mm·mrad)	100	2100	20	20
Normalized horizontal emittance (mm·mrad)	100	2100	50	100
Energy spread (%)	0.05	0.125	0.08	0.07
Bunch length (mm)	1.3	2.6	1.3	0.7
# of bunch	2			
Maximum beam repetition (Hz)	50			

Polarization in SuperKEKB Hardware needs

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



Considering scheme that would combine the solenoid and dipole spin-rotator magnets, plus the quadrupoles needed for decoupling, in three superconducting magnets on either side of the IP which would replace three existing bending magnets. 5.9m long, 150m on either side of interaction point

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 just outside
Cryostats for the final focusing quads

Building International collaboration

- Investigation team building…
  - KEK: D. Zhou, consulting with K. Ohmi, E. Forest,
    keeping overall SuperKEKB team in loop -Y.Ohnishi and T.Miyajima
  - Japan: M. Kuriki (Hiroshima Univ.), …
  - USA: U. Wienands (ANL), expanding to BNL – synergies with eIC
  - Canada: M. Roney, C. Miller (UVic)
    S. Koscielniak, R. Baartman (TRIUMF),
    J. Mammei, M. Gericke(Manitoba)
  - France: F. LeDiberder bringing together a team at LAL
  - Others in Europe being approached…
- Resources
  - Design tools (accelerator physics): SAD, BMAD, PTC, …
  - Electron beam source (find solution for low emittance)
  - Spin rotators (locations and solutions needed for $L=8x10^{35}$)
  - Compton polarimeter (location + solution needed for $L=8x10^{35}$)
- Task definitions, schedule, …