Tau Physics and Precision Electroweak Physics with Polarized Beams at SuperKEKB/Belle II:

Upgrading SuperKEKB with polarized e- beams

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SNOWMASS EF04 Topical Group Community Meeting

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

Prospects of τ physics at Belle II

	Luminosity (L)	$N_\tau = 2L\sigma$
BaBar	500 fb^{-1}	$1x10^9$
Belle	1 ab^{-1}	$2x10^9$
Belle II	50 ab^{-1}	$1x10^{11}$

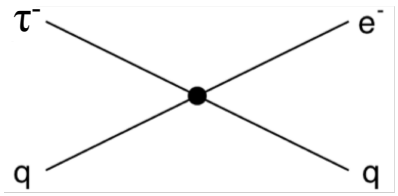
← x 40 increase In World Sample of tau's

- Stringent tests of charged current lepton universality – CC LVU
- Tests of CKM unitarity via $|V_{us}|$ measurements
- Search for electric dipole moment of the tau lepton - EDM
- Search for anomalous magnetic moment of the tau lepton – g-2
- Search for charge parity violation in lepton sector - CPV
- Stringent tests of CPT violations ($m_{\tau+}$ vs $m_{\tau-}$, $\tau_{\tau+}$ vs $\tau_{\tau-}$)
- Search for isospin violation in second class currents

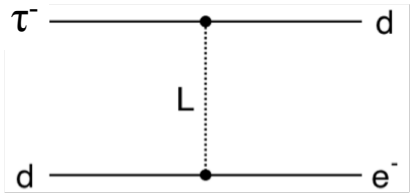
"Tau Physics and Precision Electroweak Physics with Polarized Beams at SuperKEKB/Belle II" (RF/SNOWMASS21-RF0_RF0-EF4_EF0-AF5_AF0_Banerjee_Roney-046.pdf)

Prospects of τ physics at Belle II

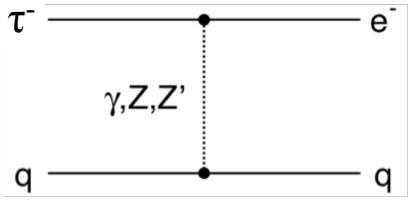
- Searches for lepton flavor/number & baryon number violation



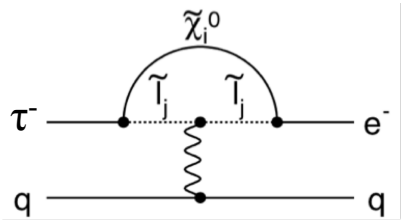
Compositeness



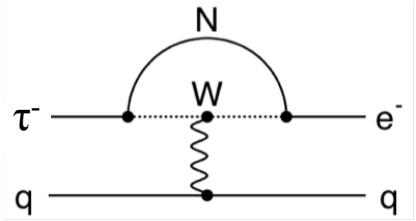
Leptoquarks



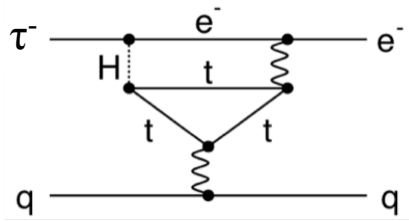
New Heavy Bosons / Anomalous Couplings



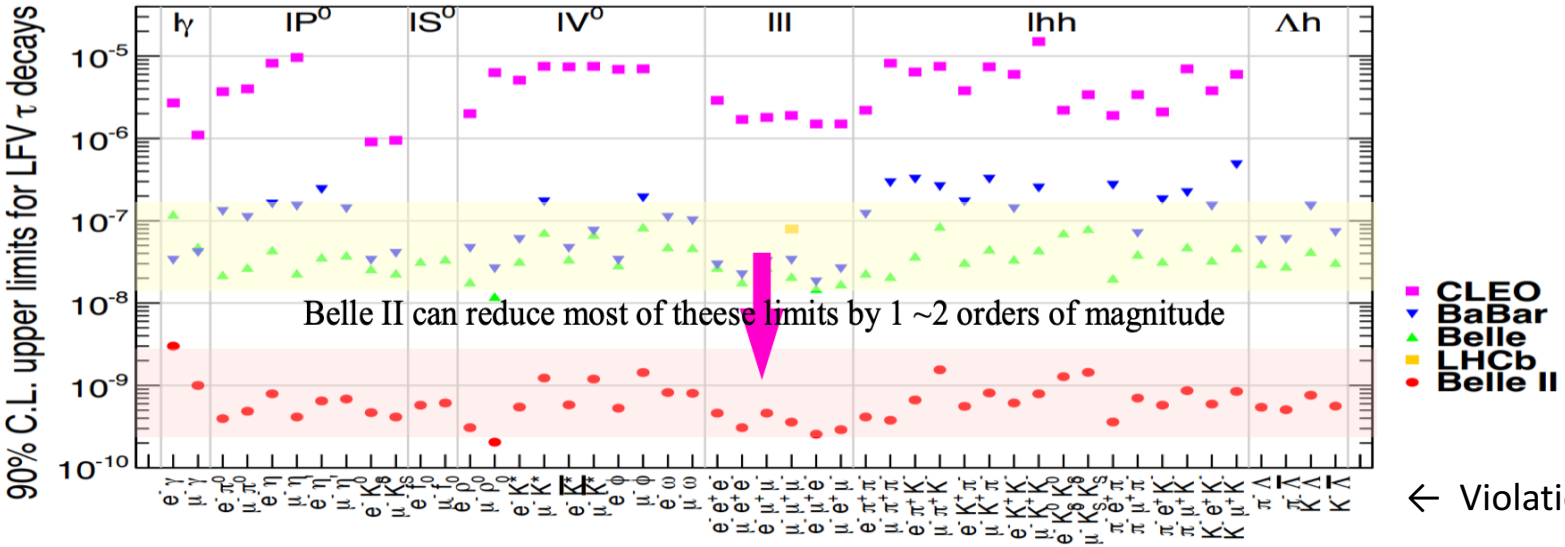
Supersymmetry



Heavy Neutrinos



Extended higgs models



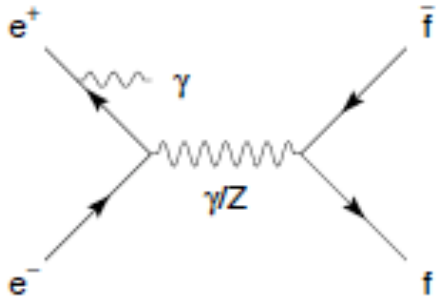
← Violation channel

'Chiral Belle': A_{LR} Left-Right Asymmetries in e^+e^- @10.58GeV

- 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 that gave single most precise value: $\sin^2\theta_{eff}^{lepton} = 0.23098(26)$
- 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 - will have error of **$\sigma(\sin^2\theta_W) \sim 0.0002$ with 20 ab^{-1} and 70% polarization at IP**

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

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



New and Unique Windows for Discovery

A UNIQUE New Path in World-wide Precision Neutral Current Electroweak Precision Program

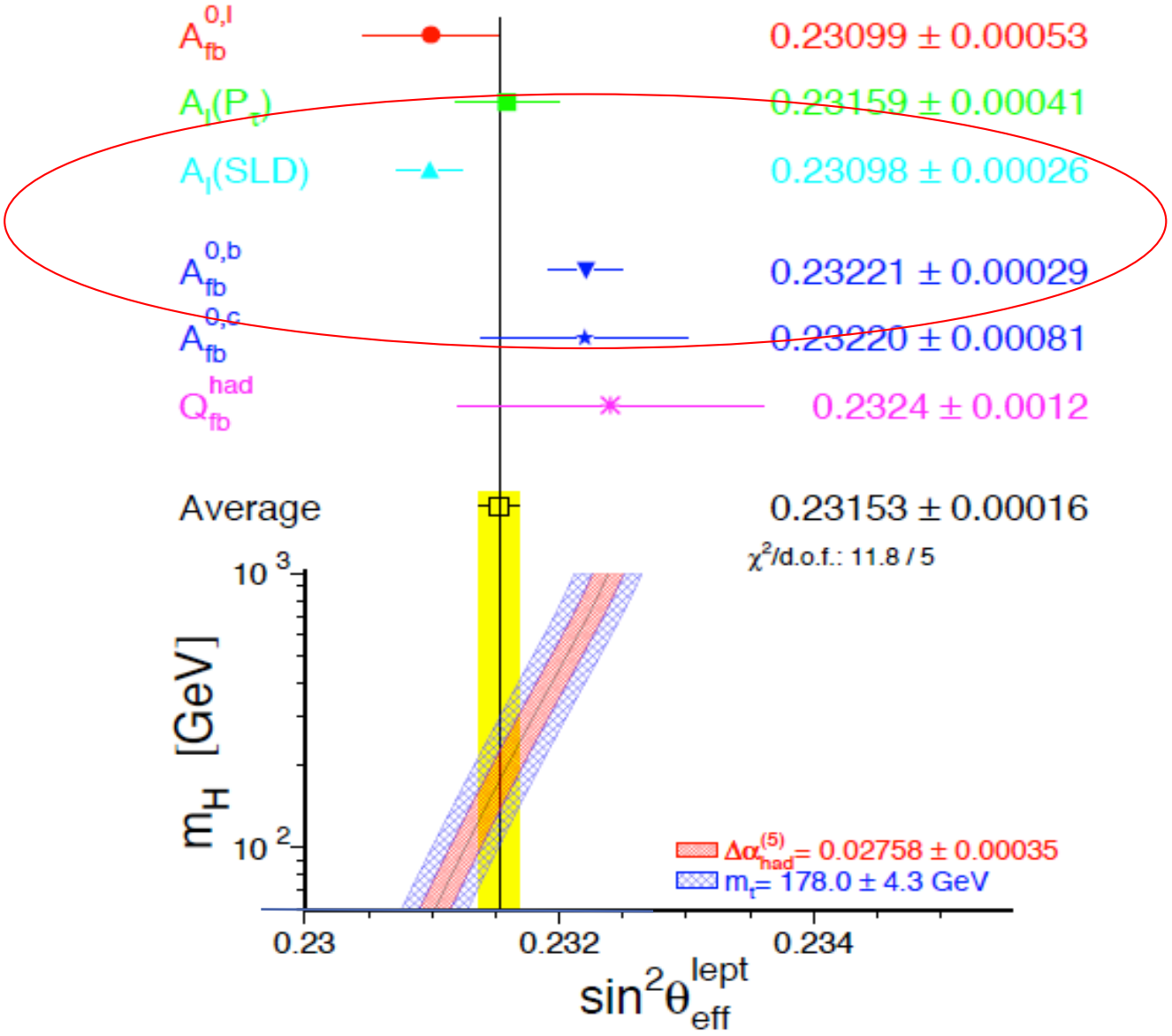
- Left-Right Asymmetries (A_{LR}) yield measurements of unprecedented precision of the neutral current vector couplings (g_V) to each of five fermion flavours, f :
  - beauty (D-type)
  - charm (U-type)
  - tau
  - muon
  - electron

  as well as light quarks

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

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)

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	0.0007
Tau (eff. = 0.25)	-0.0371 ±.0003	-0.0366 ± 0.0010	0.0008	0.0006	0.0003
Muon (eff. = 0.5)	-0.0371 ±.0003	-0.03667±0.0023	0.0005 Improve x 5	0.0004	0.0002
Electron (1nb acceptance)	-0.0371 ±.0003	-0.03816 ±0.00047	0.0004	0.0003	0.0002

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 40ab^{-1} will have ~ 0.00016 error

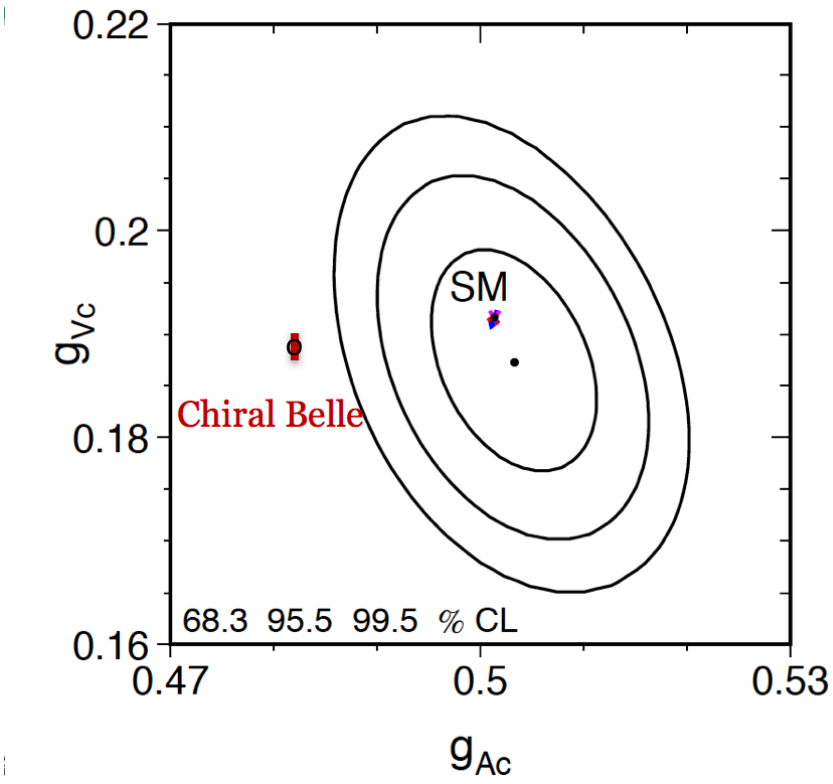
Charm and Beauty Couplings Substantially more Precise

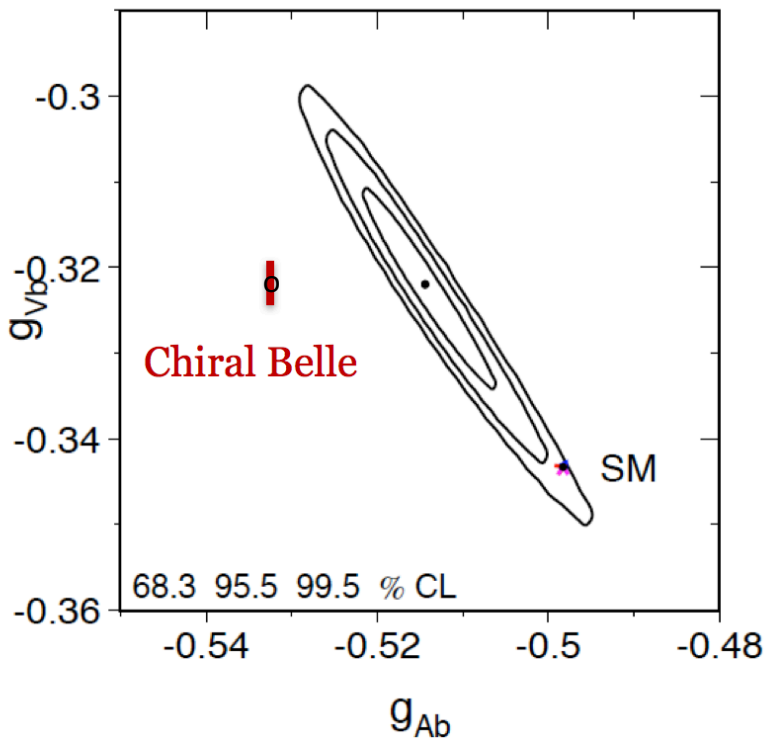
Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

c-quark:
Chiral Belle ~7 times more precise

b-quark:
Chiral Belle ~4 times more precise

with 20 ab^{-1}



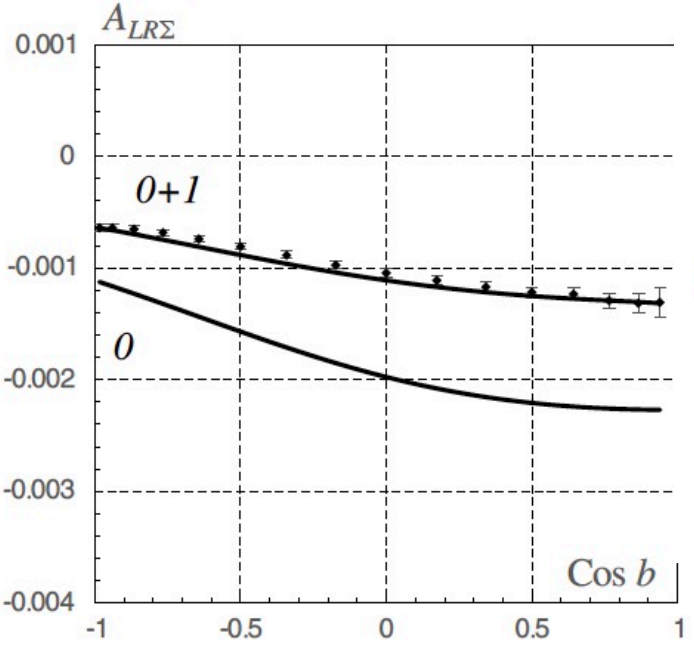


International collaboration of Accelerator and Particle Physicists

➢ **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)**

$e^+e^- \to \mu^+\mu^-$

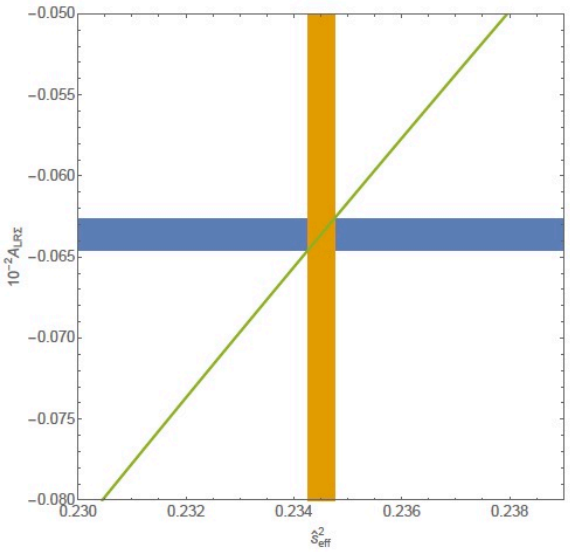


$$\Sigma_L^C = \int_{\cos b}^{\cos a} \sigma_L^C \cdot d(\cos\theta), \quad \Sigma_R^C = \int_{\cos b}^{\cos a} \sigma_R^C \cdot d(\cos\theta)$$

a=10° & energy of photons < 2GeV

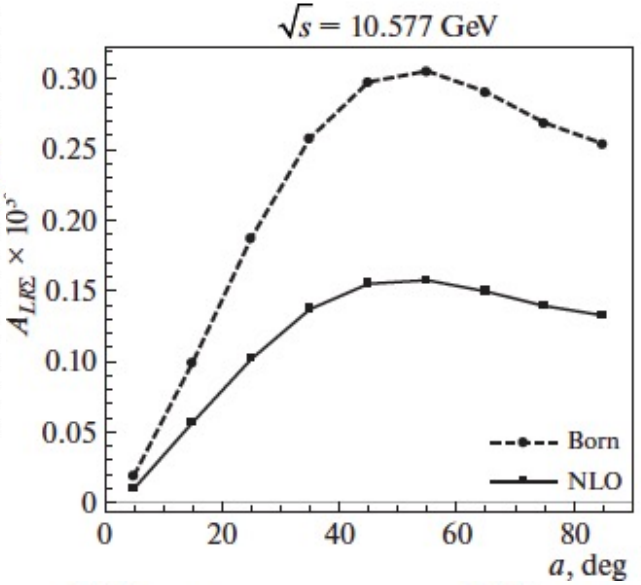
Phys.Rev. D101 (2020) no.5, 053003

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



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

$e^+e^- \to e^+e^-$



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

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Will probe both high and low energy scales

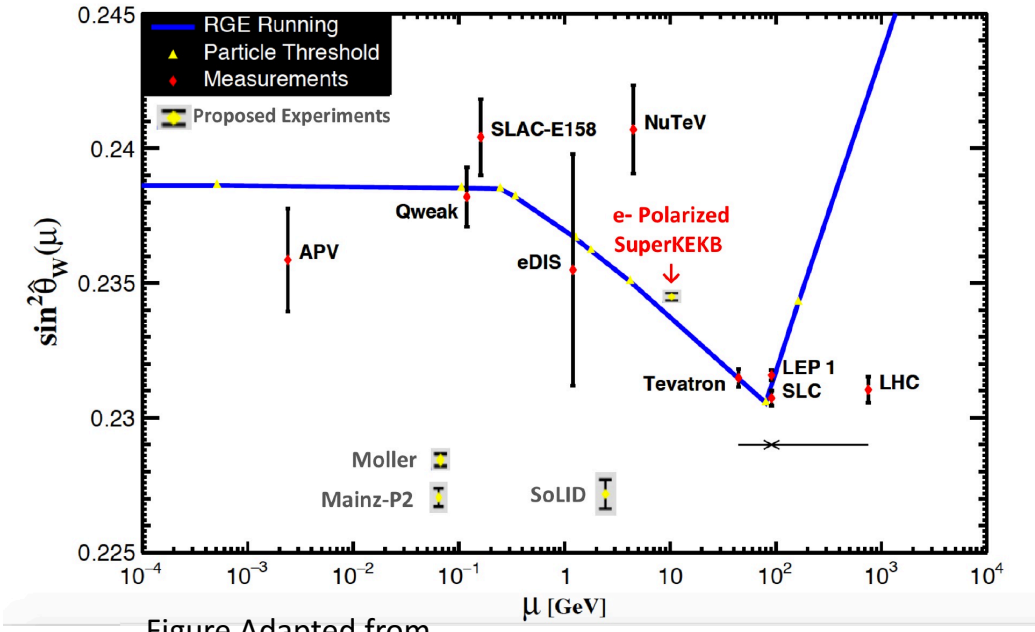


Figure Adapted from
J. Erler and A. Freitas, (PDG) Phys. Rev. D98 , 030001 (2018)

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**

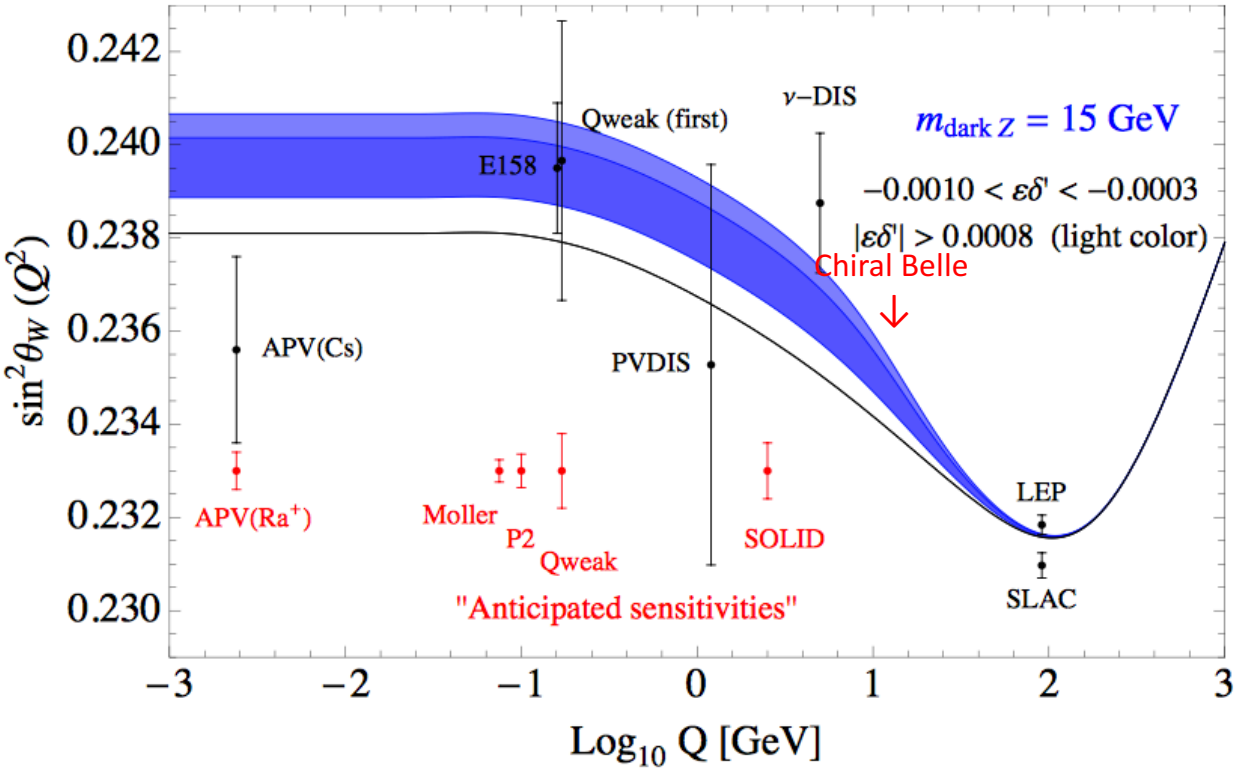
More information at arxiv.org/abs/1907.03503

- **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)



Beyond Precision Electroweak Physics

- Improved precision measurements of τ electric dipole moment (EDM) and $(g-2)_\tau$
  - 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.

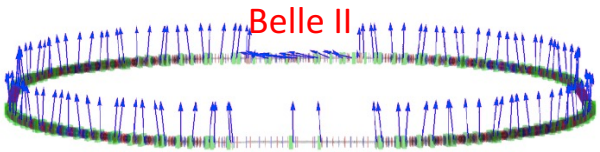
- e^- beam polarization can be used to reduce backgrounds in $\tau \to \mu\gamma$ and $\tau \to e\gamma$ – leading to improved sensitivities; also electron beam polarization and can be used to distinguish Left and Right handed New Physics currents.
  - See: arXiv:1008.1541v1 [hep-ex]
- Polarized e+e- annihilation into a polarized Λ or a hadron pair experimentally probes dynamical mass generation in QCD

Additional Material

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

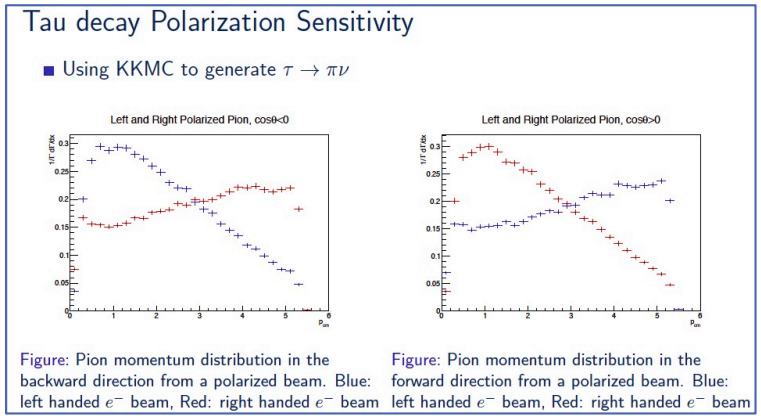
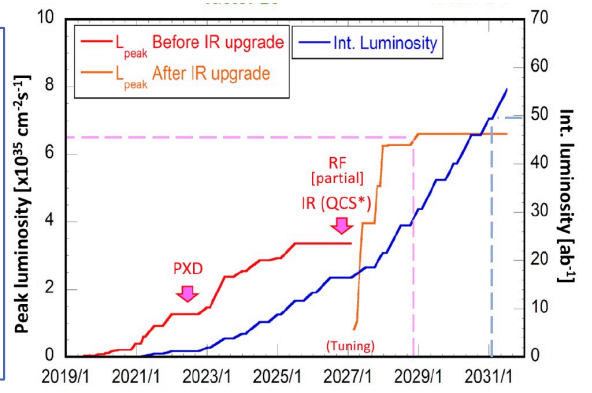


Figure: Pion momentum distribution in the backward direction from a polarized beam. Blue: left handed e^- beam, Red: right handed e^- beam

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 ~2026 in mid-decade upgrade window for new final focus;
This upgrade proposal to be included in KEK Roadmap for MEXT to be submitted 2021



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