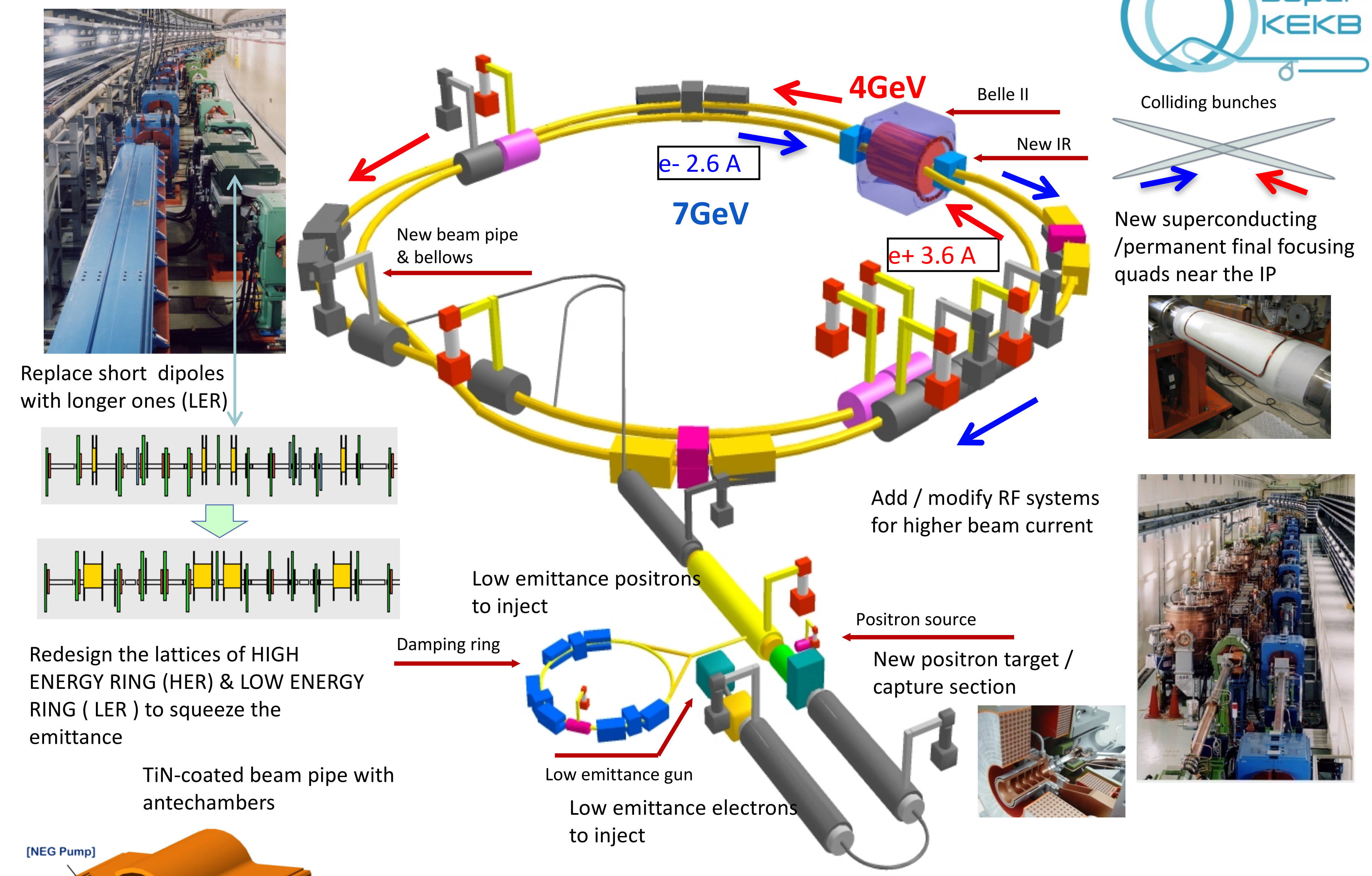
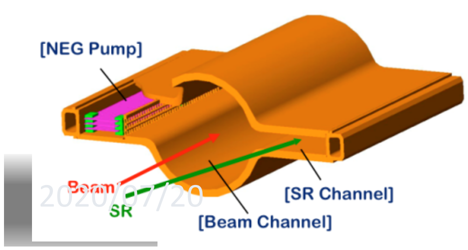
Upgrading SuperKEKB with polarized e- Beams

J. Michael Roney
University of Victoria
29 July 2020

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

SuperKEKB in Japan





To obtain x40 higher luminosity

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)	

Chiral Belle→Left-Right Asymmetries in e^+e^- @10.58GeV

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

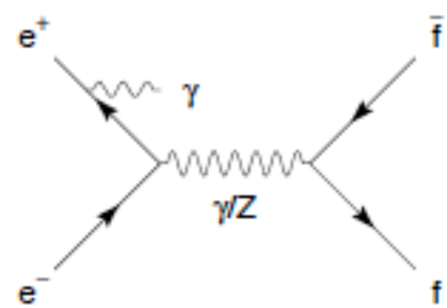
•Same technique as SLD A_{LR} measurement at the Z-pole giving single most precise measurement of :

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

•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:

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

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



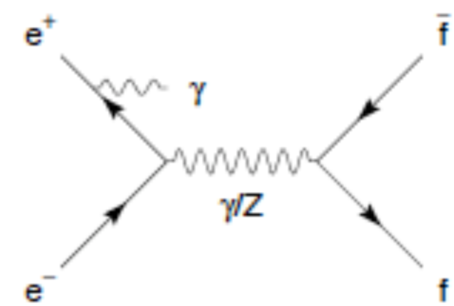
Chiral Belle→ Left-Right Asymmetries in e^+e^- @10.58GeV

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

New and Unique Windows for Discovery

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

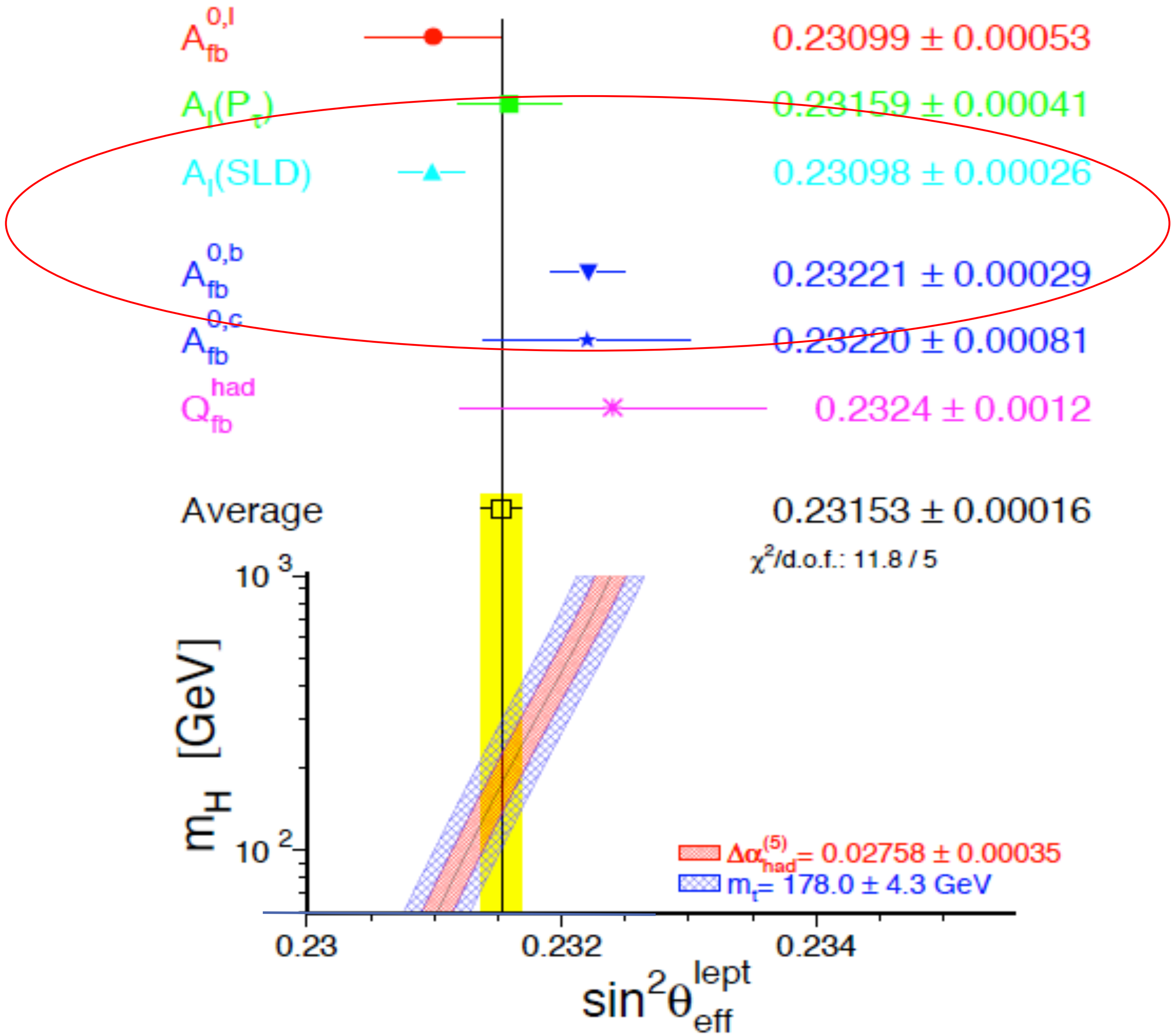
- Left-Right Asymmetries (A_{LR}) yield measurements of unprecedented precision of the neutral current vector couplings (g_V) to each of five fermion flavours, *f* :
  - beauty (D-type)
  - charm (U-type)
  - tau
  - muon
  - electron

  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

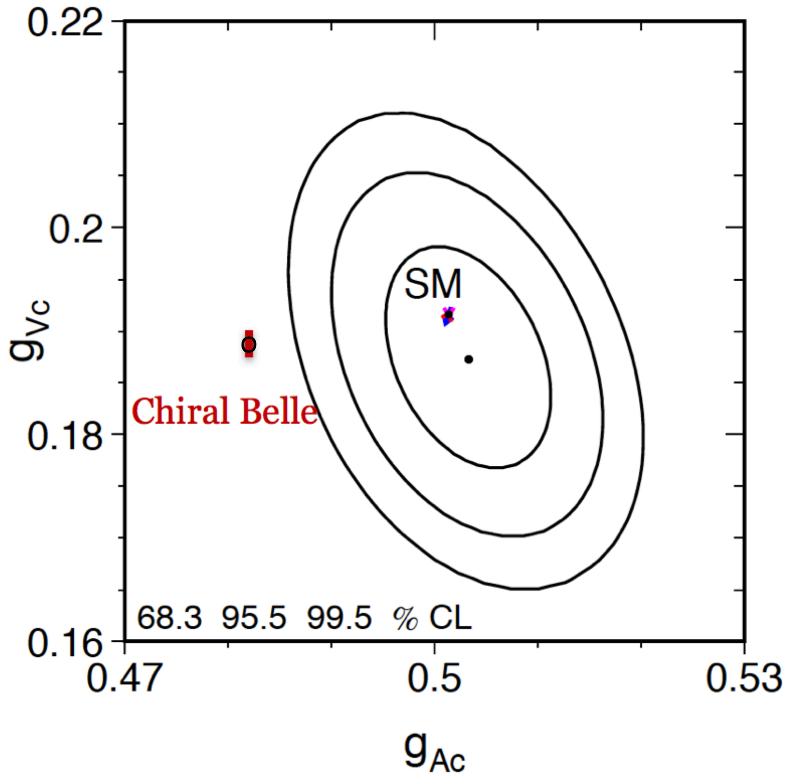
$\sin^2\Theta_W$ - all LEP+SLD measurements combined WA = 0.23153 ± 0.00016

$\sin^2\Theta_W$ - Chiral Belle combined leptons with 20 ab^{-1} have error ~ 0.00016

Chiral Belle probes both high and low energy scales

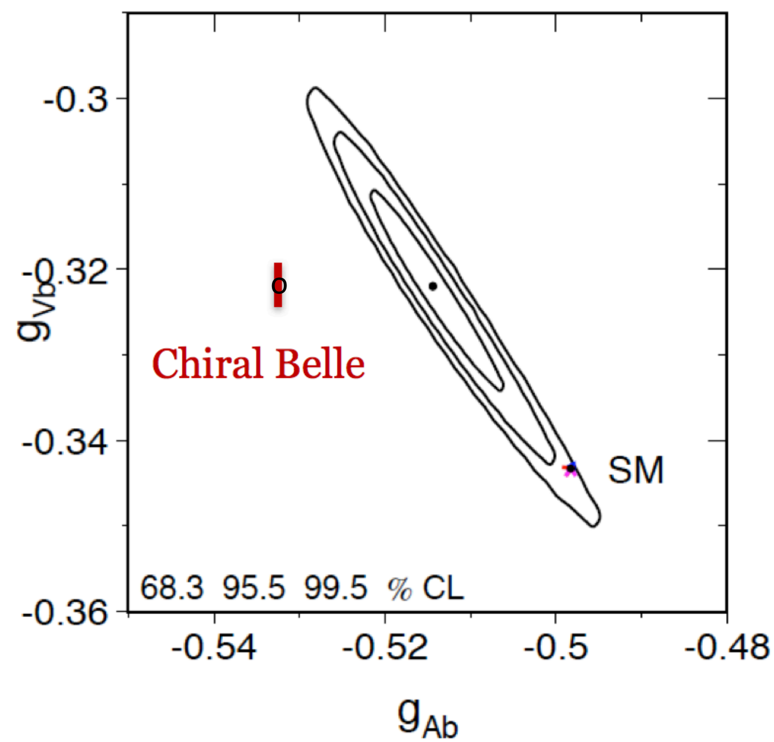
Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

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

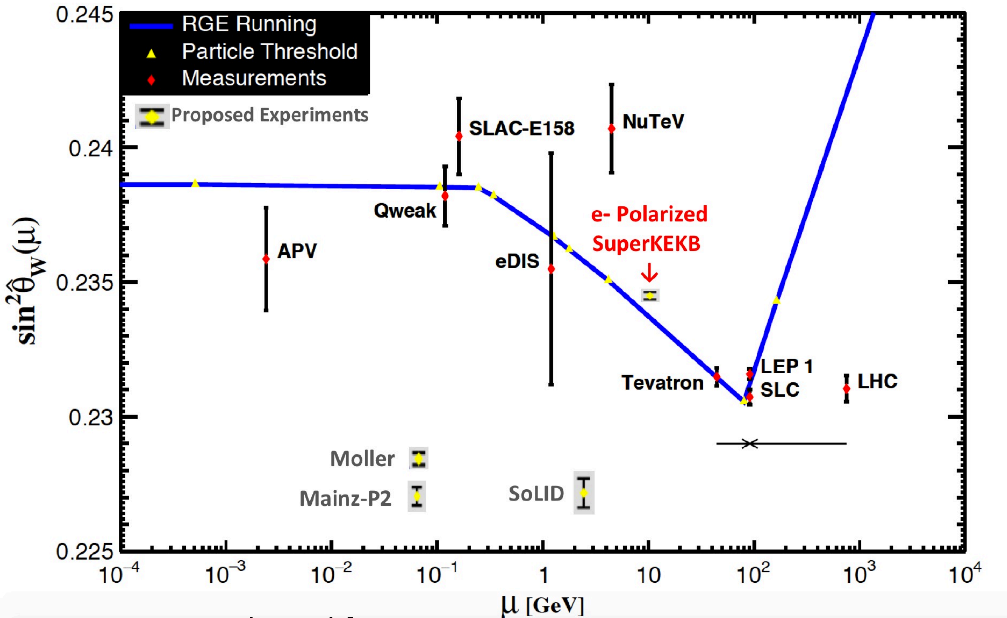


Figure Adapted from
J. Erler and A. Freitas, (PDG) Phys. Rev. D98 , 030001 (2018)

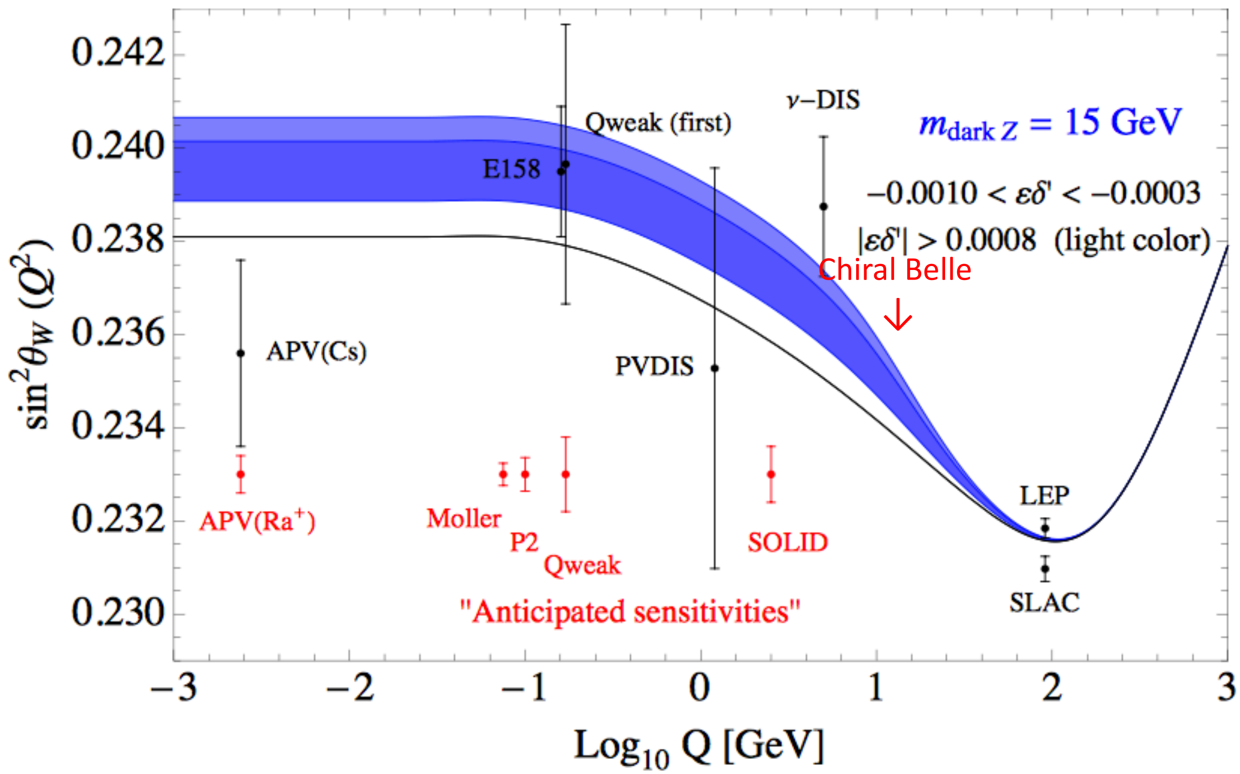
Chiral Belle: $\sigma \sim 0.00016$ with 20 ab^{-1}
Using only clean leptonic states

- **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 (< 0.05% 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:

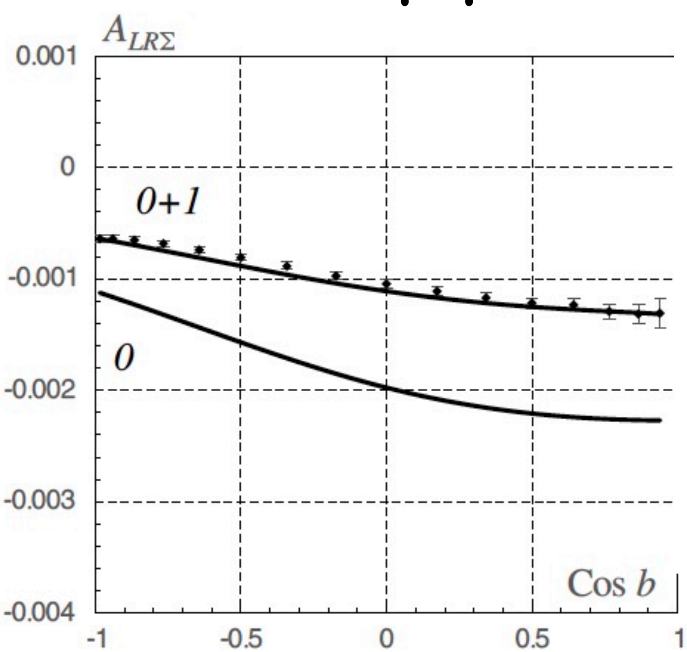
- LHC experiments
- APV measurements at lower energy scales
- Moller Experiment at Jefferson Lab which will measure $\sin^2\theta_{eff}^{electron}$ below 100MeV with similar precision (note: Moller is only sensitive to electron couplings.)
- Next generation high energy e+e- colliders: ILC & FCC-ee (where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

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)**

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

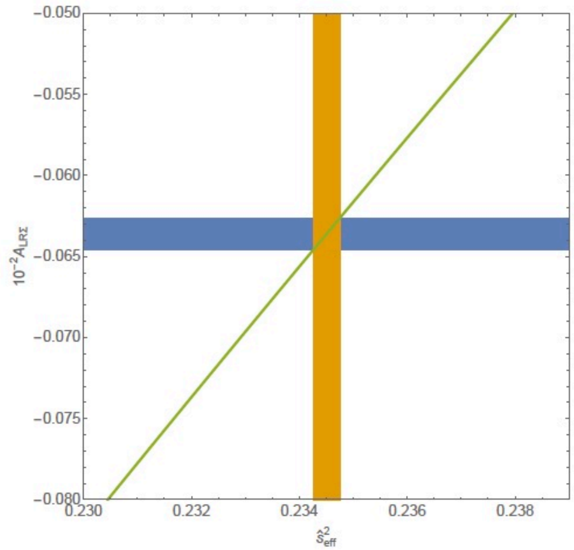


$$\Sigma_L^C = \int_{\cos b}^{\cos a} \sigma_L^C \cdot d(\cos\theta), \quad \Sigma_R^C = \int_{\cos b}^{\cos a} \sigma_R^C \cdot d(\cos\theta)$$

a=10^o & energy of photons < 2GeV

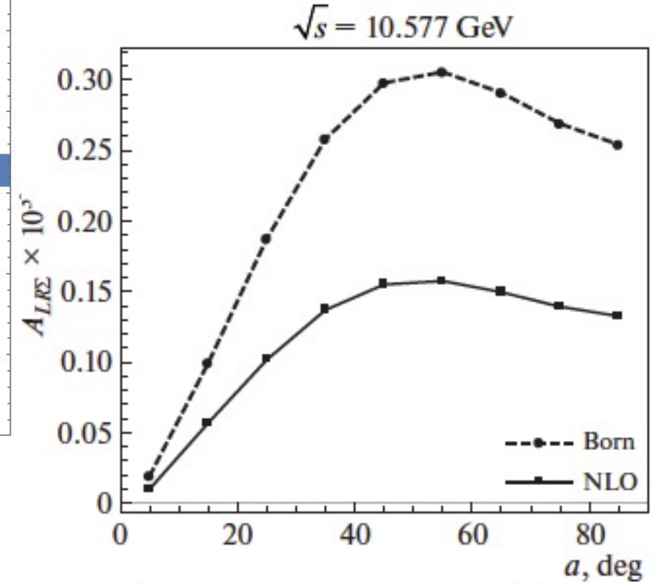
Phys.Rev. D101 (2020) no.5, 053003

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



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

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



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

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Chiral Belle 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.

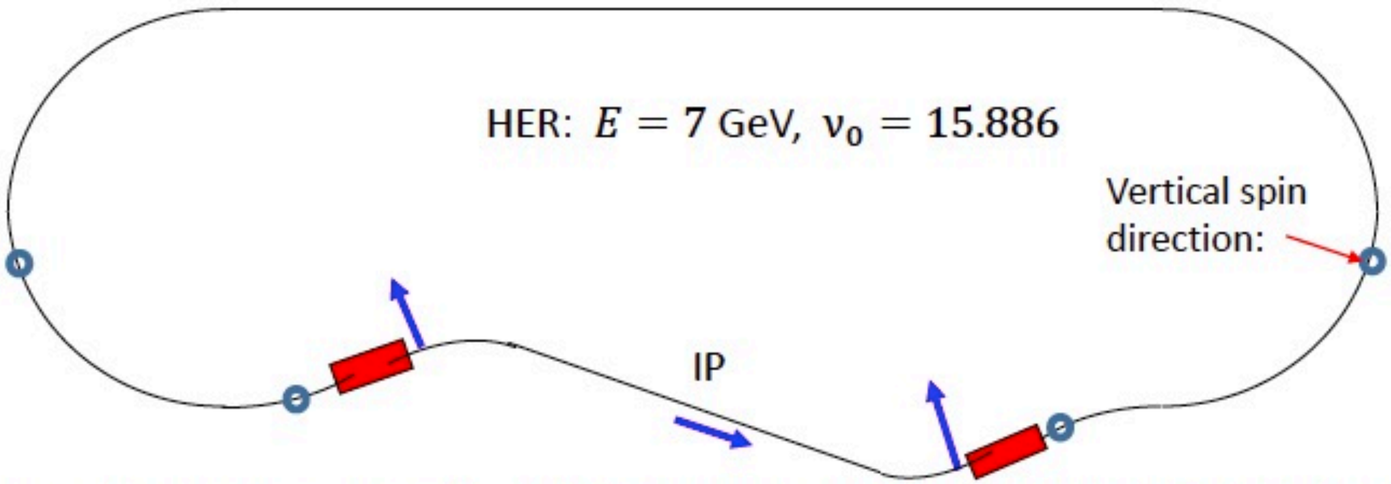
- e^- beam polarization can be used to reduce backgrounds in $\tau \to \mu\gamma$ and $\tau \to e\gamma$ – leading to improved sensitivities; also electron beam polarization and can be used to distinguish Left and Right handed New Physics currents.
  - See: arXiv:1008.1541v1 [hep-ex]
- Polarized e+e-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

Polarization in SuperKEKB

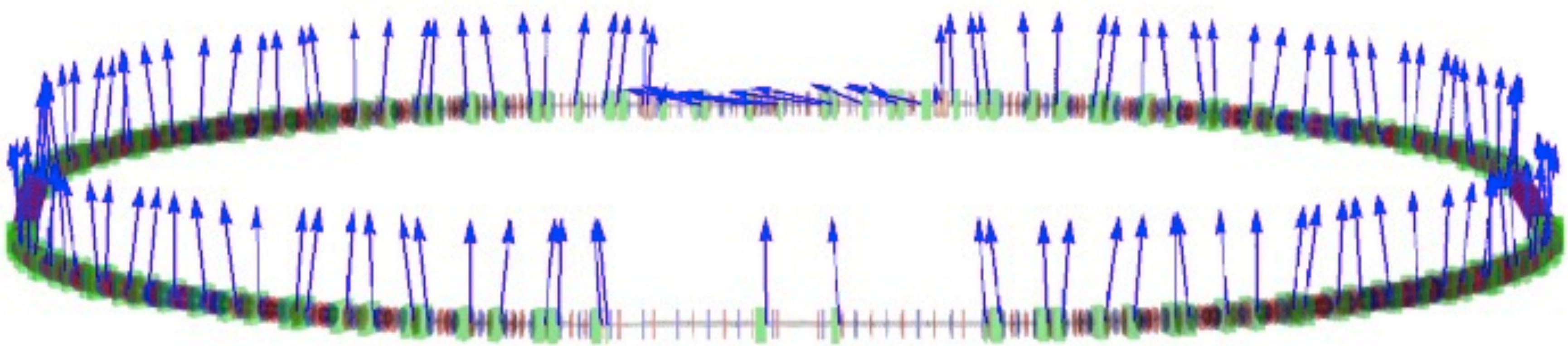
- Goal is ~70% polarization with 80% polarized source (SLC had 75% polarization at the experiment)
- Electron helicity would be chosen randomly pulse-to-pulse by controlling the circular polarization of the source laser illuminating a GaAs photocathode (similar to SLC source)
- Inject vertically polarized 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

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.

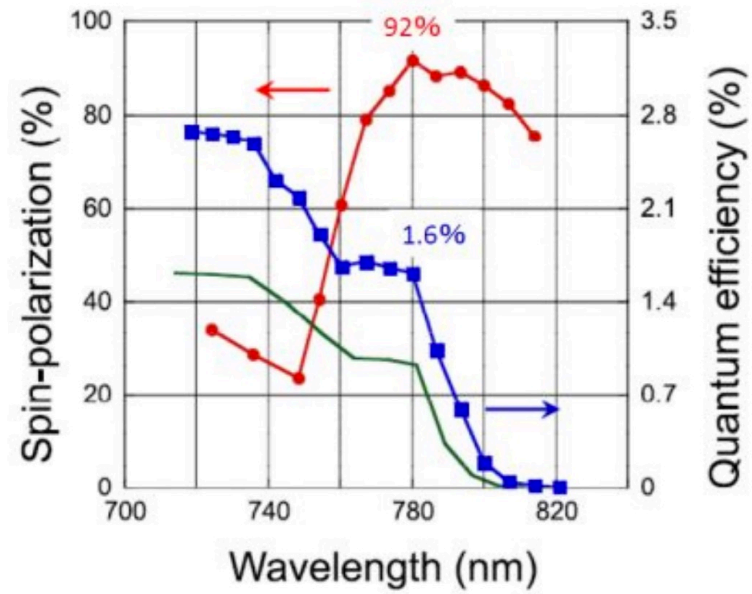


From I. Koop, A.Otboev and Yu.Shatunov, BINP, Novosibirsk preliminary considerations on the longitudinal polarization at SuperKEKB

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

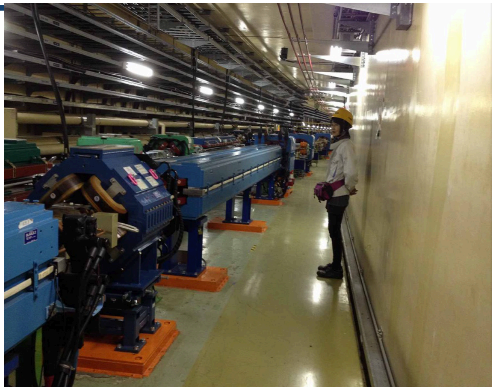
20 mm-mrad vertical emittance

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

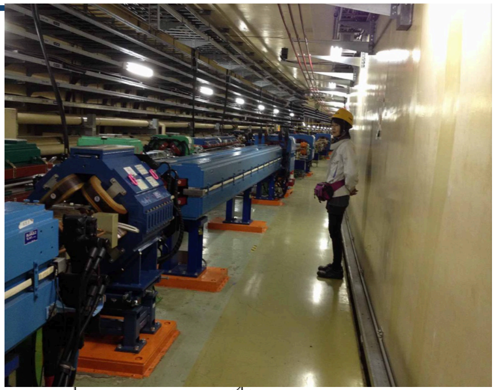
Use of solenoids and dipoles, plus the quadrupoles (needed for decoupling) on either side of interaction point

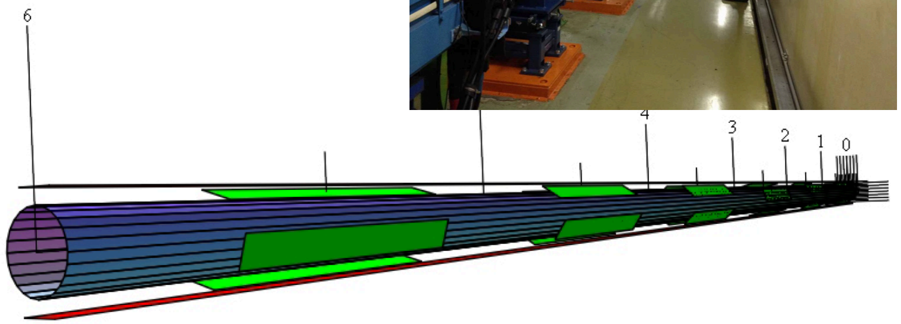
BINP, ANL, BNL, TRIUMF-Victoria Groups

Polarization in SuperKEKB

Hardware needs

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





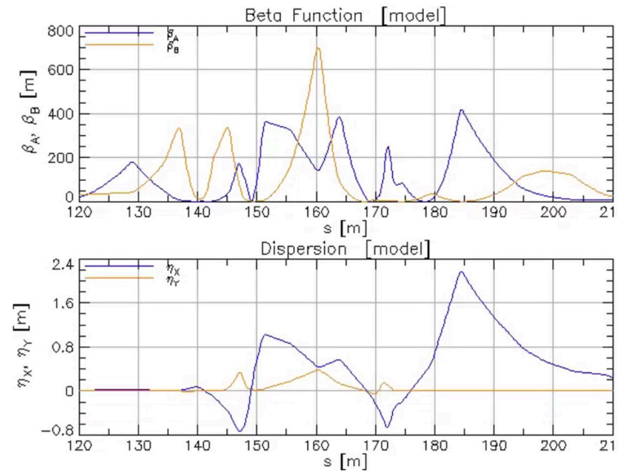
In preliminary studies, one concept (U. Wienands, ANL) is to used combined-function magnets which would replace three existing bending magnets. 5.9m long, 150m on either side of interaction point.

BINP, ANL, BNL, TRIUMF, Victoria Groups

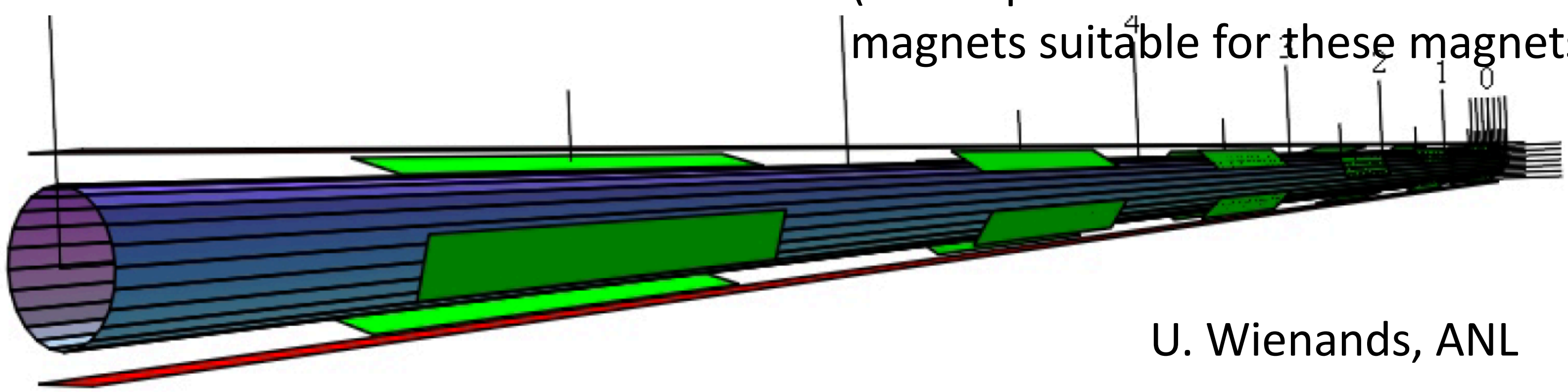
Compact Spin Rotator

- 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



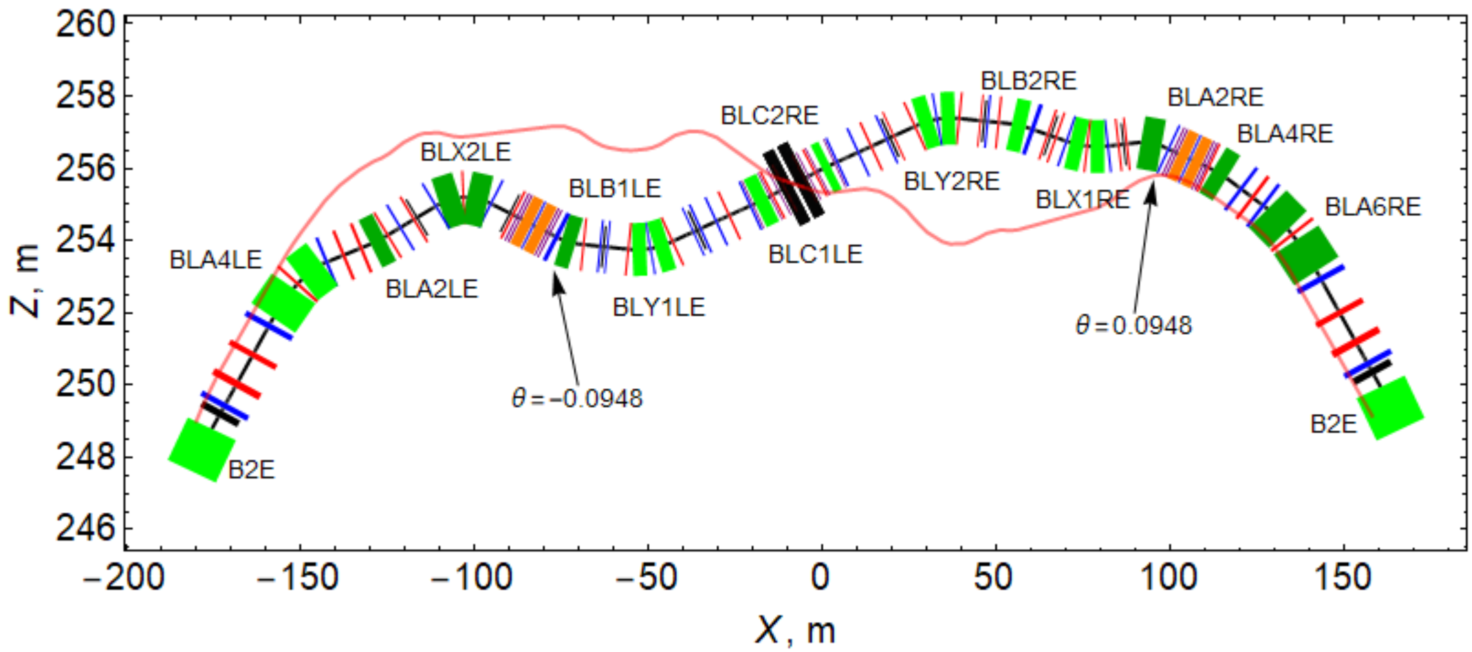
(BNL expertise in construction of direct wind magnets suitable for these magnets)



U. Wienands, ANL

Recent preliminary studies by BINP group

Another Concept: install spin-rotator magnets in drift regions

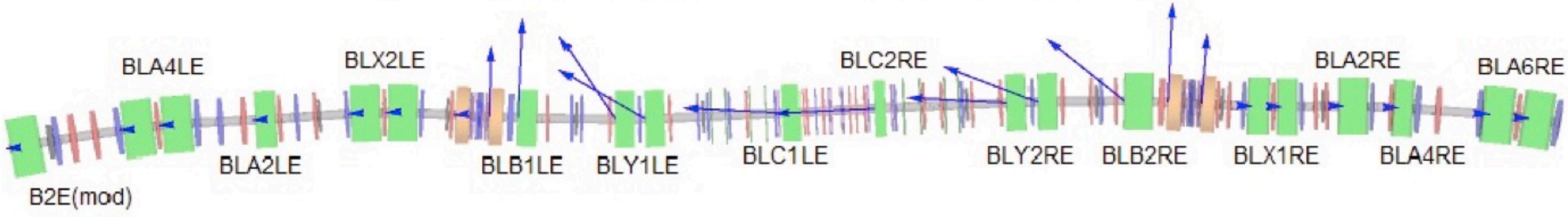


"B2E"	"BLA6RE"	"BLA4RE"	"BLA2RE"	"BLX1RE"	"BLB2RE"	"BLY2RE"	"BLC2RE"
0.0557427	0.0501498	0.0271539	0.0557427	−0.0221788	0.0234696	0.027	0.00591985

"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

Recent preliminary studies by BINP group

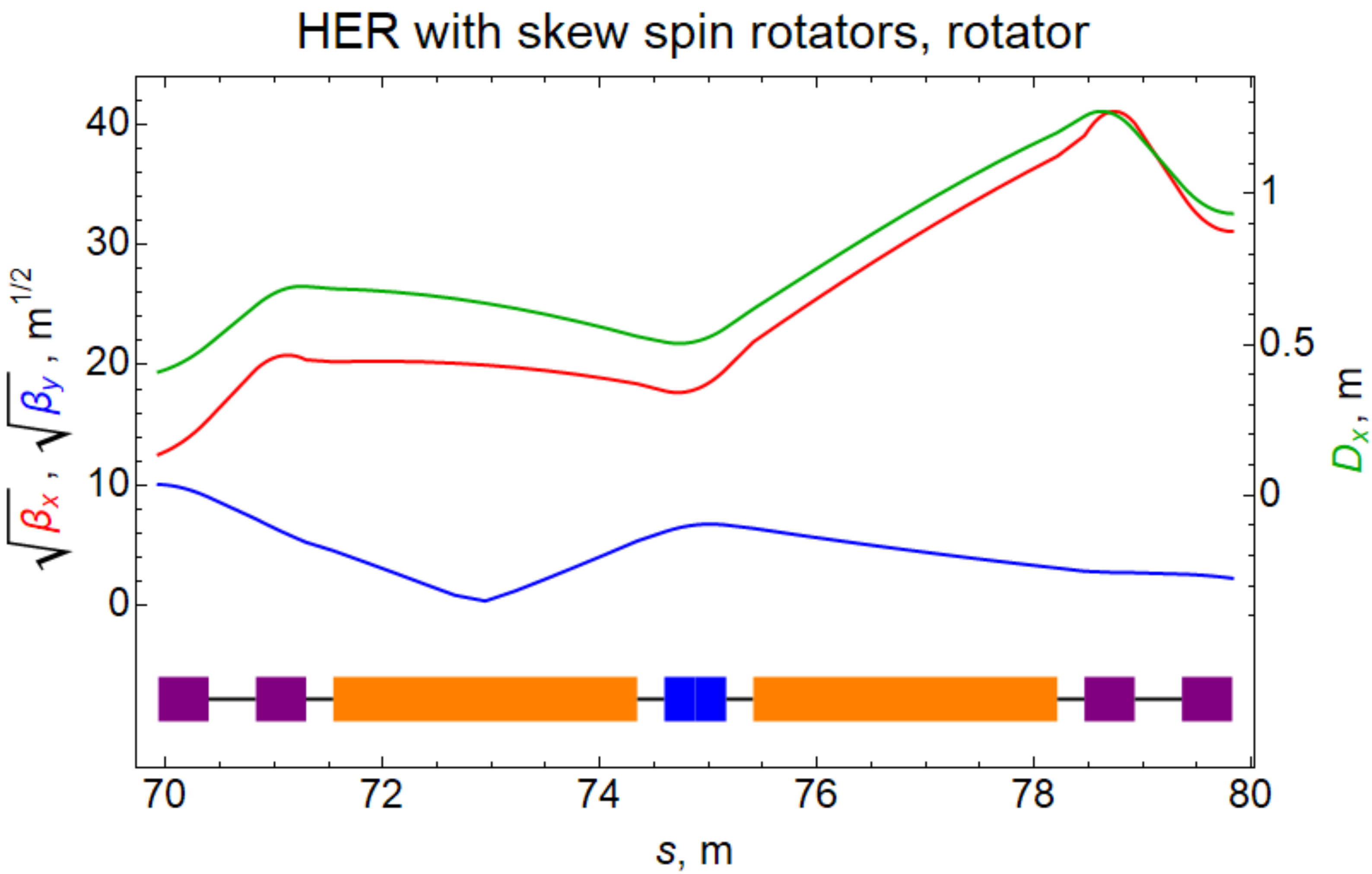


"B2E(mod)"	"BLA2LE"	"BLA2RE"	"BLA4LE"	"BLA4RE"	"BLA6RE"	"BLB1LE"
0.0745895	−0.0181419	0.0591537	0.0520765	0.0280687	0.0501498	−0.0368136
"BLB2RE"	"BLC1LE"	"BLC2RE"	"BLX1RE"	"BLX2LE"	"BLY1LE"	"BLY2RE"
0.0548871	−0.00591049	0.0059199	−0.0310501	0.0570931	−0.0270415	0.018

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

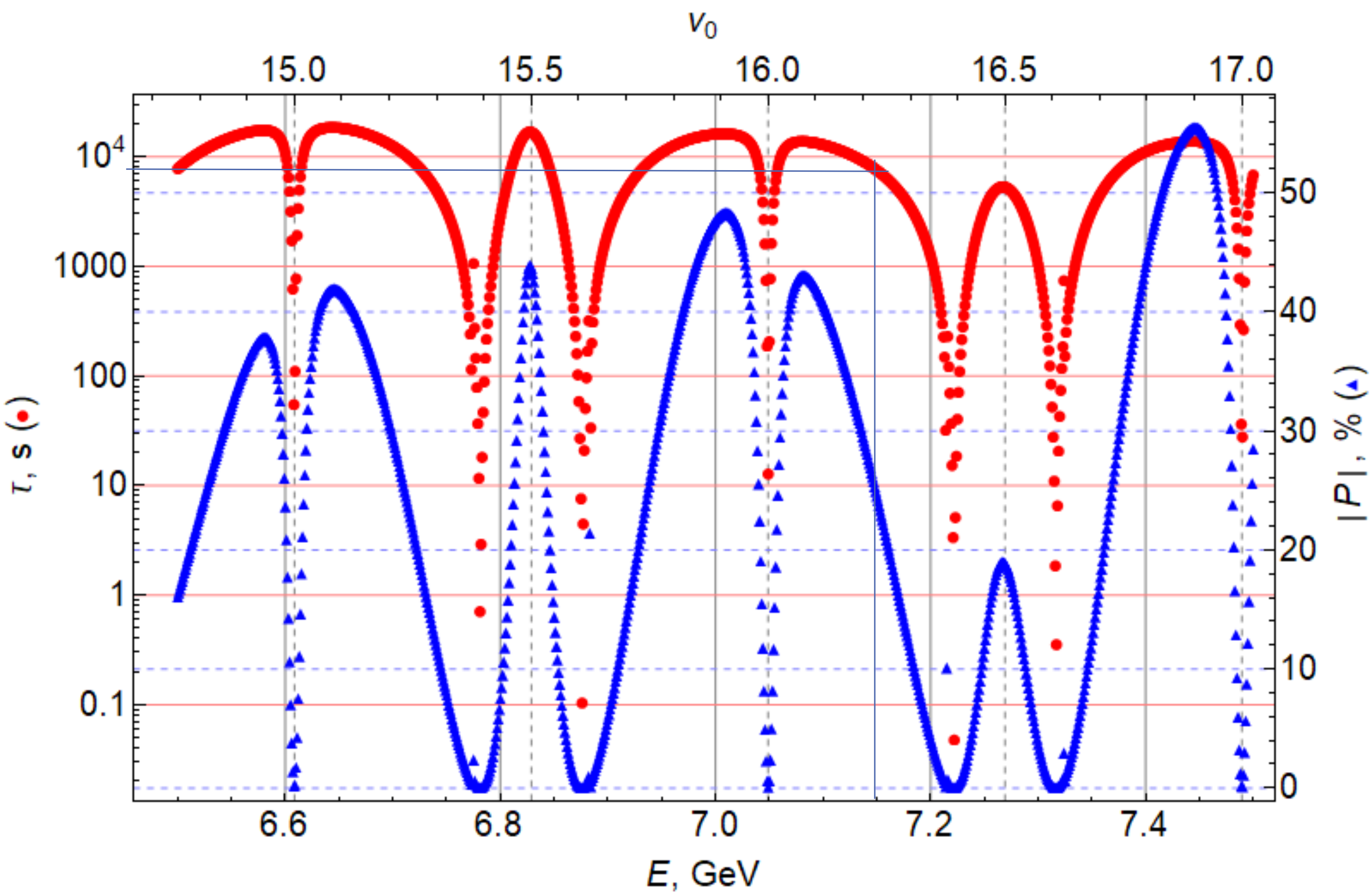
Recent preliminary studies by BINP group



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

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

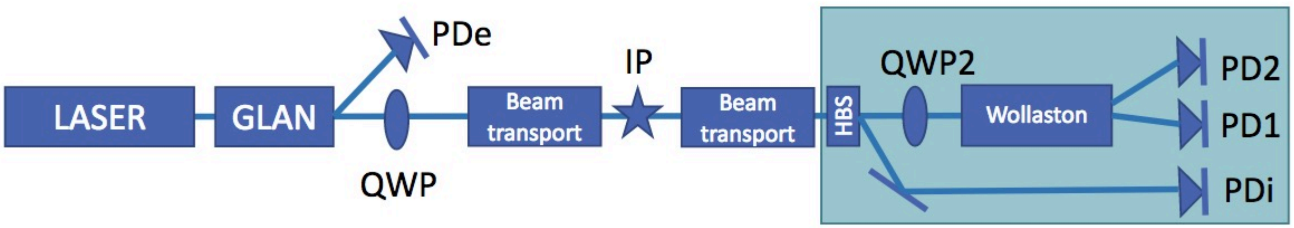
LAL Orsay and U. Manitoba groups

Polarization in SuperKEKB

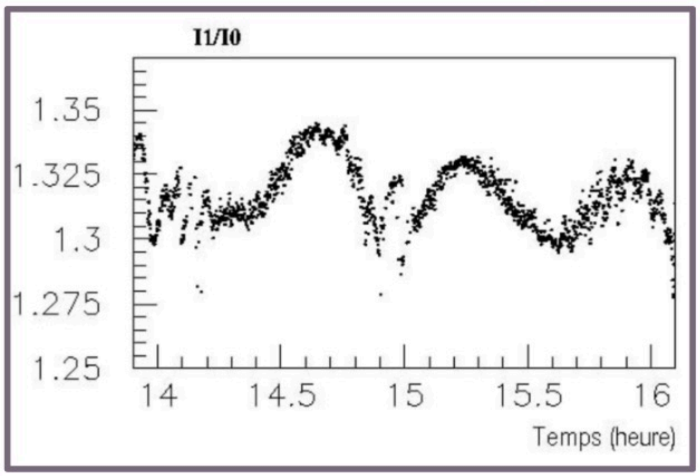
LAL Orsay team (A. Martens, Y. Peinaud,F. Zomer, P. Bambade,F. Le Diberder, K. Trabselsi)   **HERA Compton Polarimeter experience**

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 8^{th} (2x1 cm^2) and 9^{th} 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

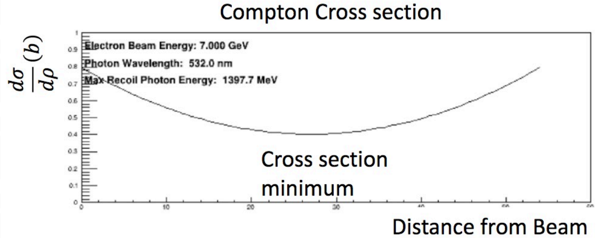
The chip is primarily developed by groups at the U. of Heidelberg and the Karlsruhe Institute of Technology, and intended for various experiments:

- ATLAS
- Mu3e
- PANDA
- P2
- MOLLER

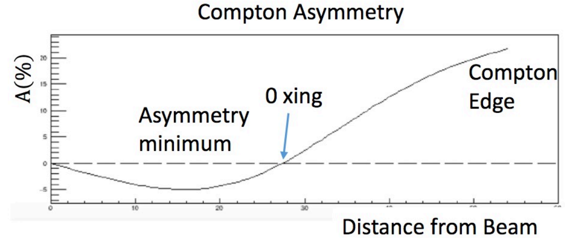
The implementation as a Compton detector is done by the Manitoba group.

Calculations/Simulations

Compton Cross section



Compton Asymmetry



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
- C. Miller is exploring 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

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

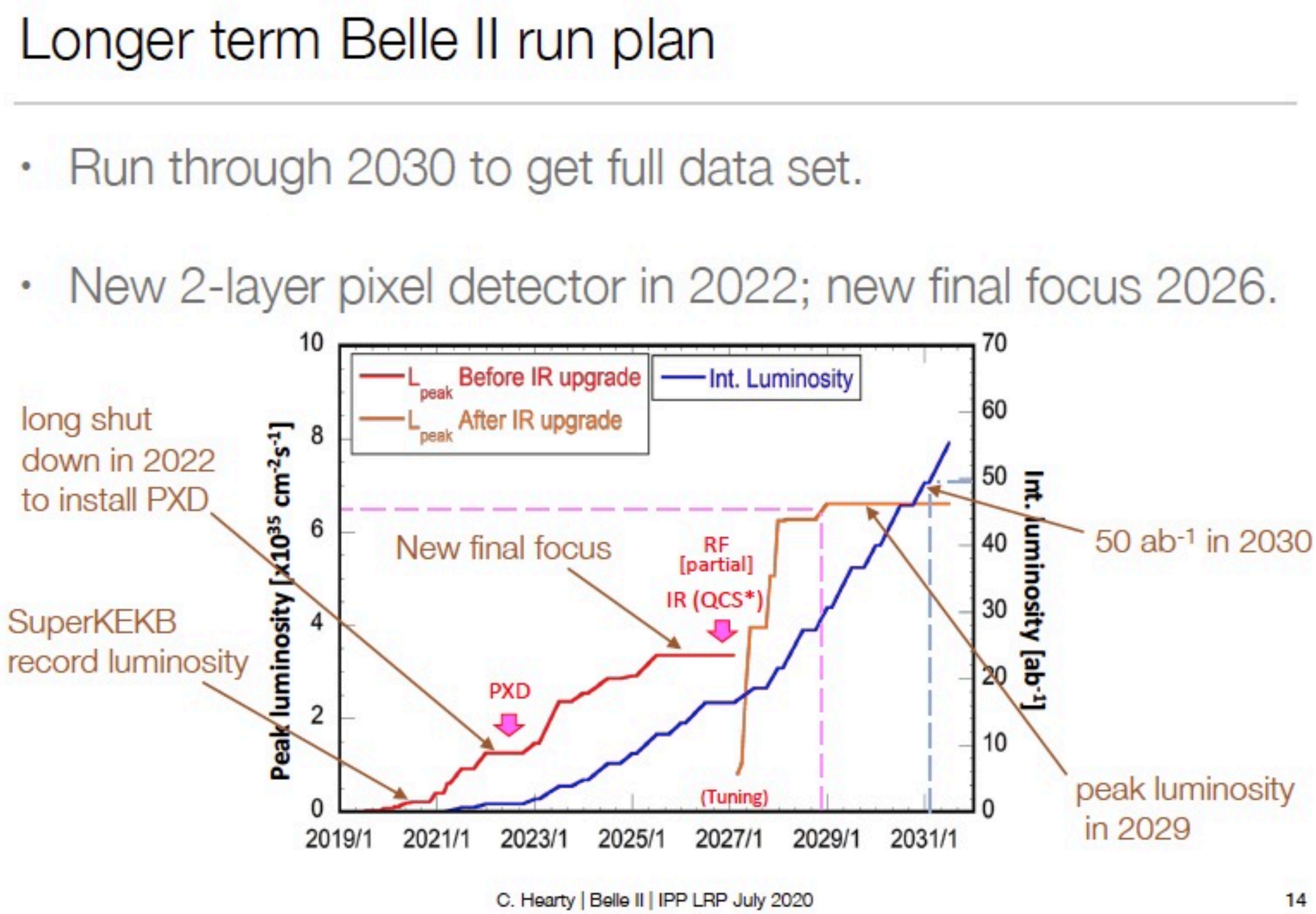
Theorists in Canada, Italy, Russia & U.S. published recently on physics enabled by this project

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 in 2026 – preparing for MEXT KEK Roadmap 2021-26



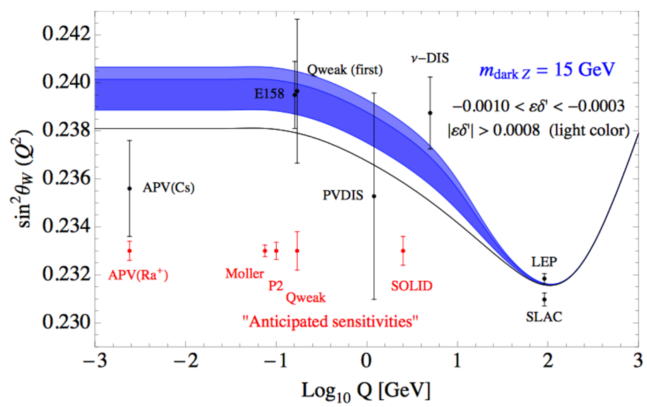
Summary

- 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, g-2 and EDM

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
- 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

Additional Information

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

Recent studies by BINP group

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

Koop, Long. Pol. 11

Tau decay Polarization Sensitivity

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

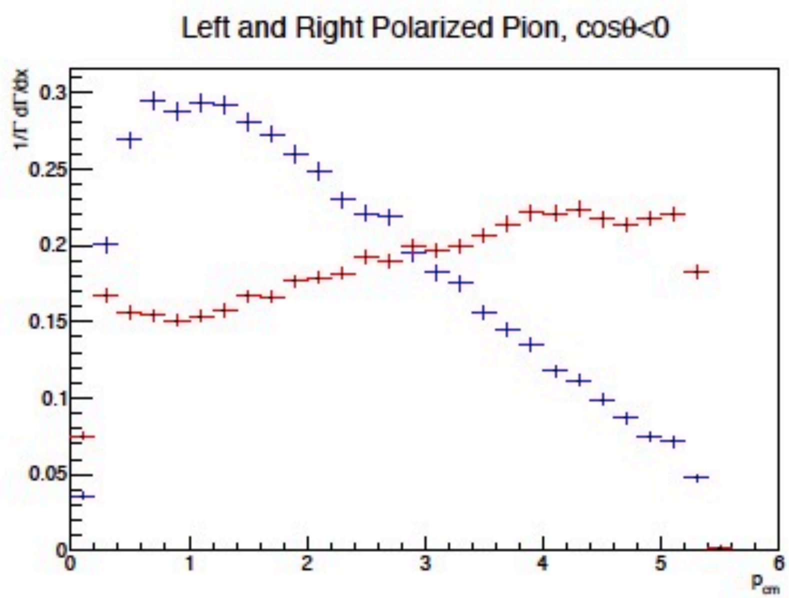


Figure: Pion momentum distribution in the backward direction from a polarized beam. Blue: left handed e^- beam, Red: right handed e^- beam

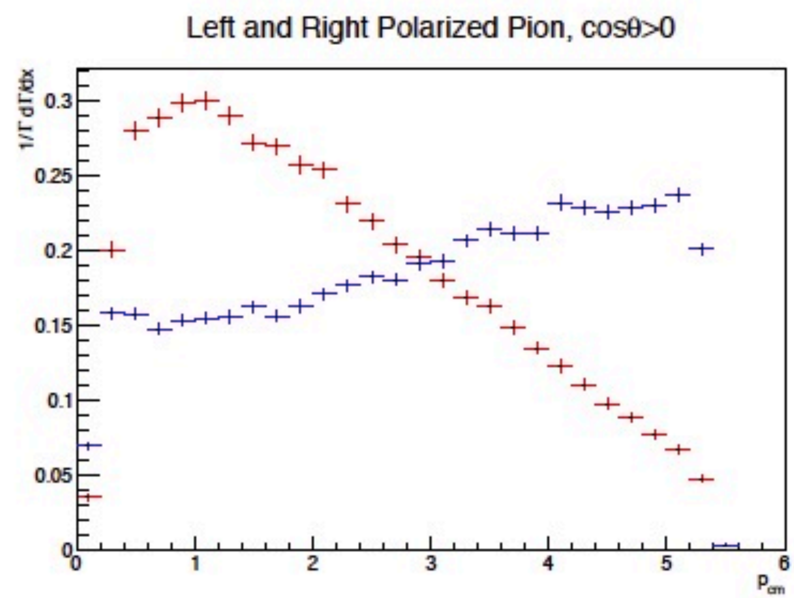
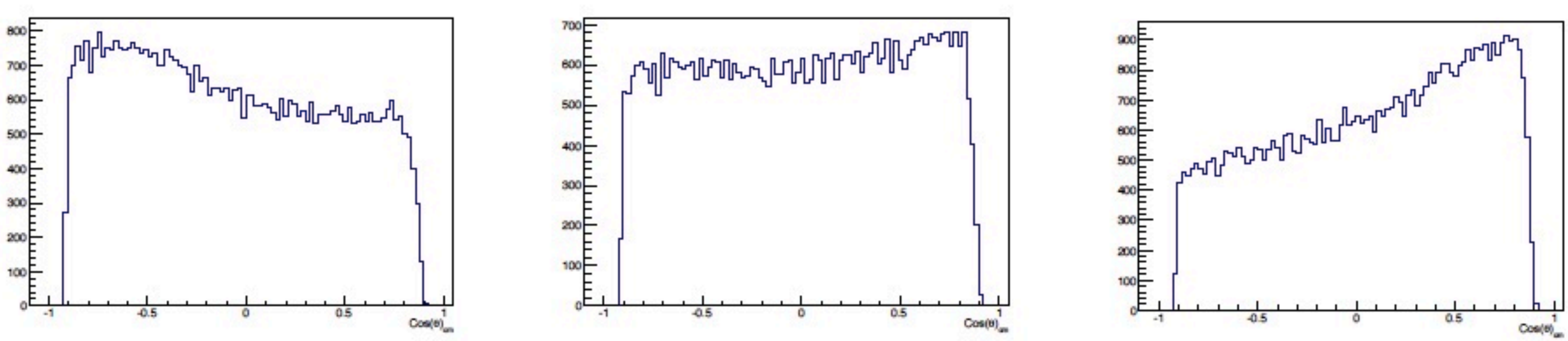


Figure: Pion momentum distribution in the forward direction from a polarized beam. Blue: left handed e^- beam, Red: right handed e^- beam

Pion Angular Distributions with Polarization

$\pi^- \cos\theta$ distributions

Left Polarization | No Polarization | Right Polarization



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