Polarization Upgrade and Polarimetry at the SuperKEKB Belle II Facility

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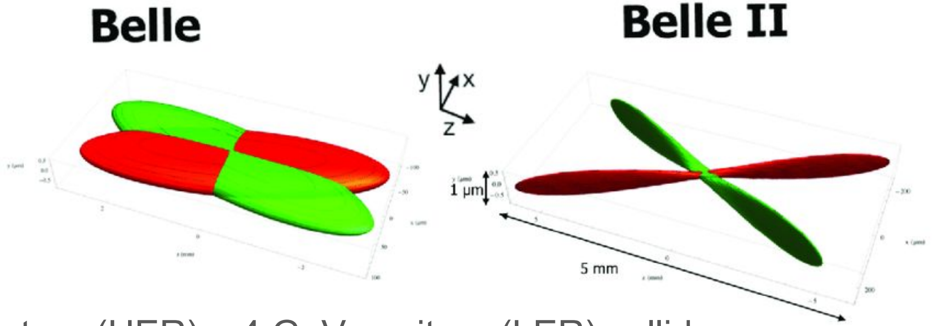
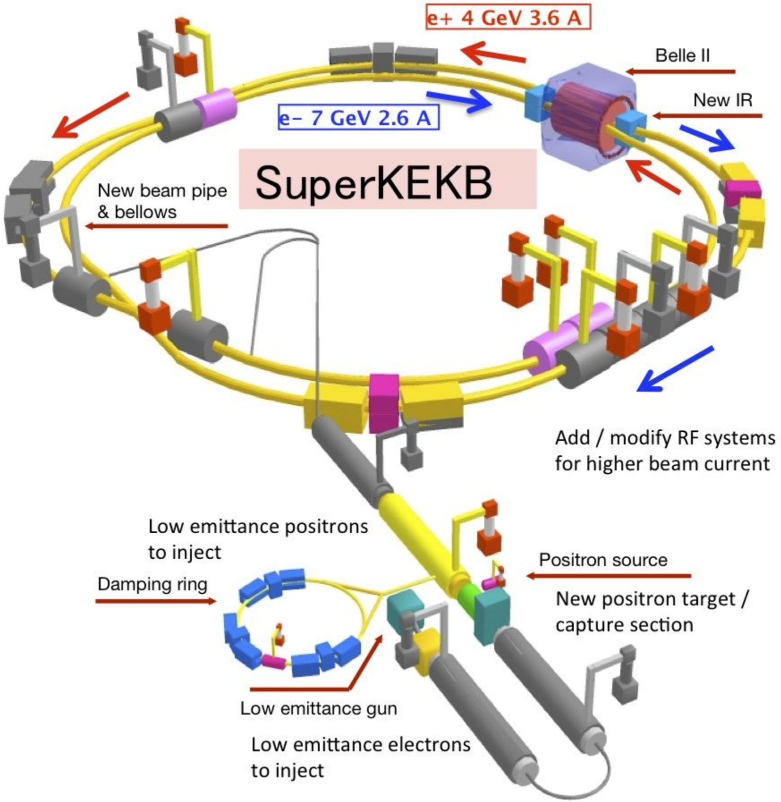
SuperKEKB and Belle II

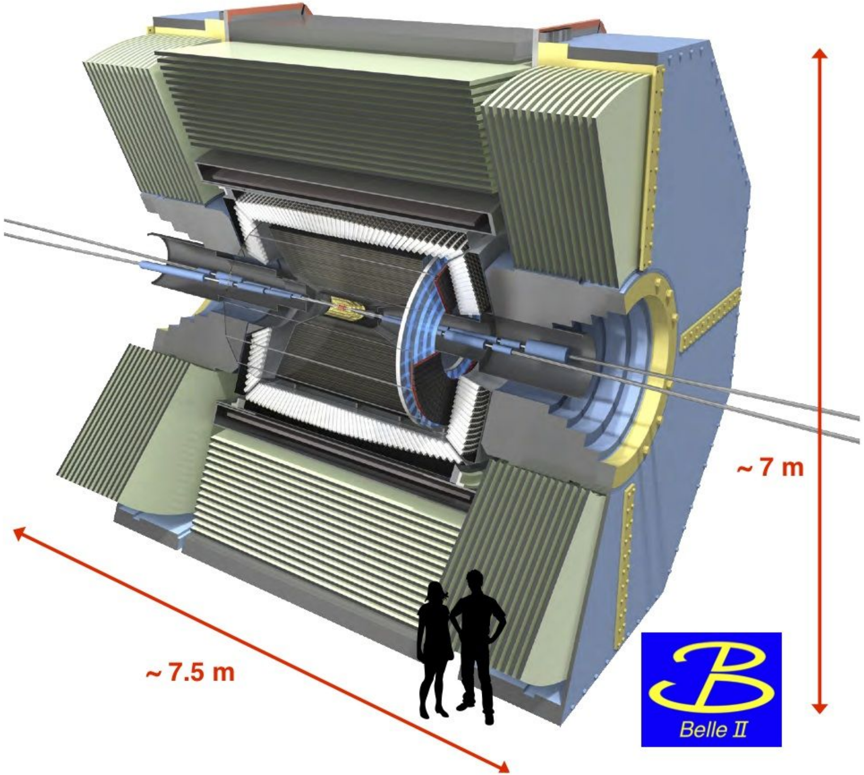


- From KEKB… (1998-2010)
  - 3 km circumference asymmetric 7 GeV electron (HER) – 4 GeV positron (LER) collider
  - World record in instantaneous luminosity of 2.11×10^{34} cm^{-2} s^{-1}, integrated 1 ab^{-1} in 2010
- to **SuperKEKB** (first collisions 2019-04-26)
  - Instantaneous luminosity of 8×10^{35} cm^{-2} s^{-1}, integrated to 50 ab^{-1} by mid-2020s
  - Beam current increased by factor 2
  - Nano-beams: squeezing the beam at the IR to nanometer sizes, at high crossing angle
  - Both beams in SuperKEKB are currently unpolarized

- From Belle…
  - CP-violation in B- and anti-B-meson sector
- to **Belle II**
  - DAQ to optical fibers, upgraded trigger system
  - New pixel detector, silicon vertex tracker, central tracker, TPC, RICH

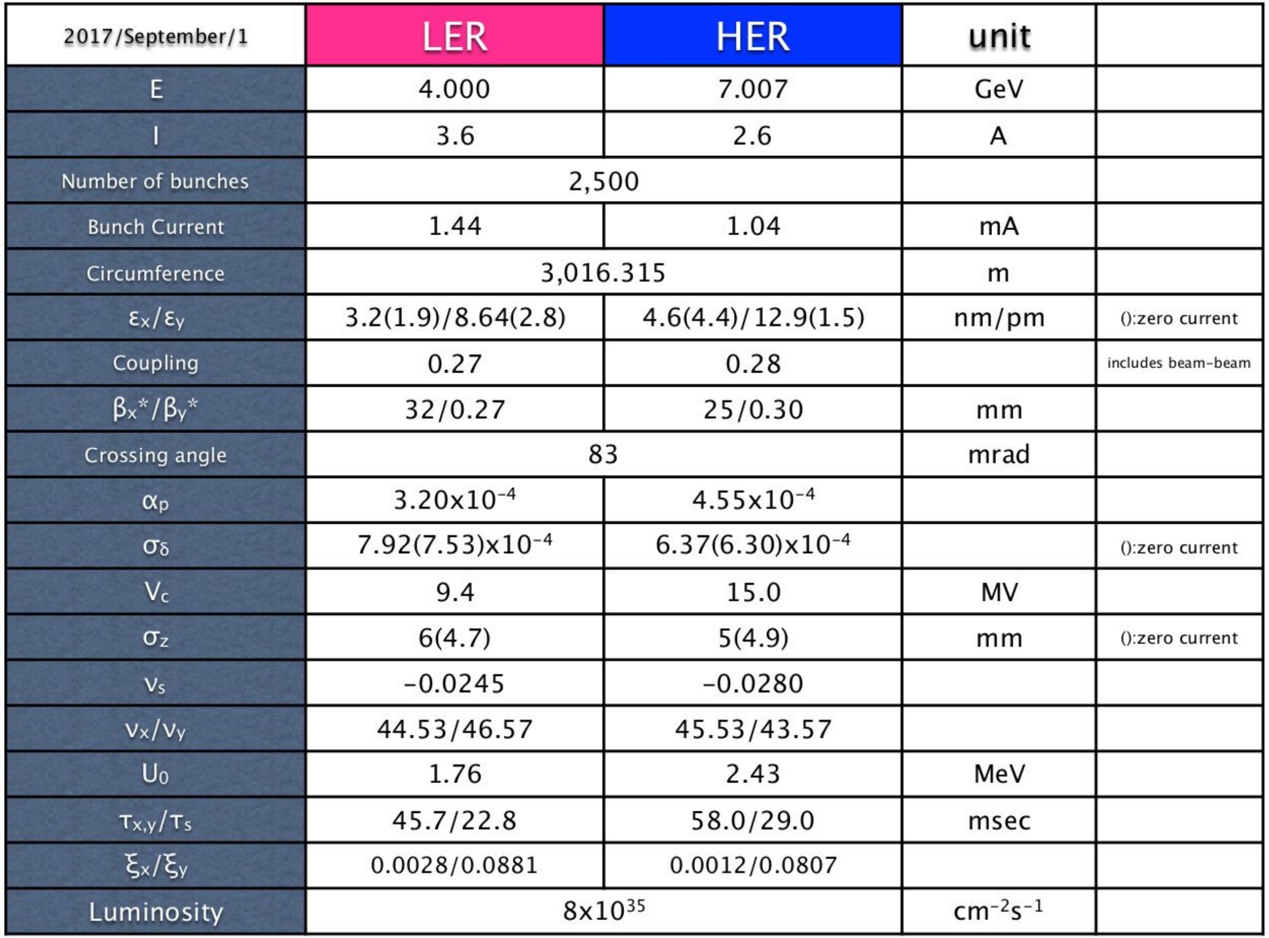
SuperKEKB and Belle II





Machine Parameters

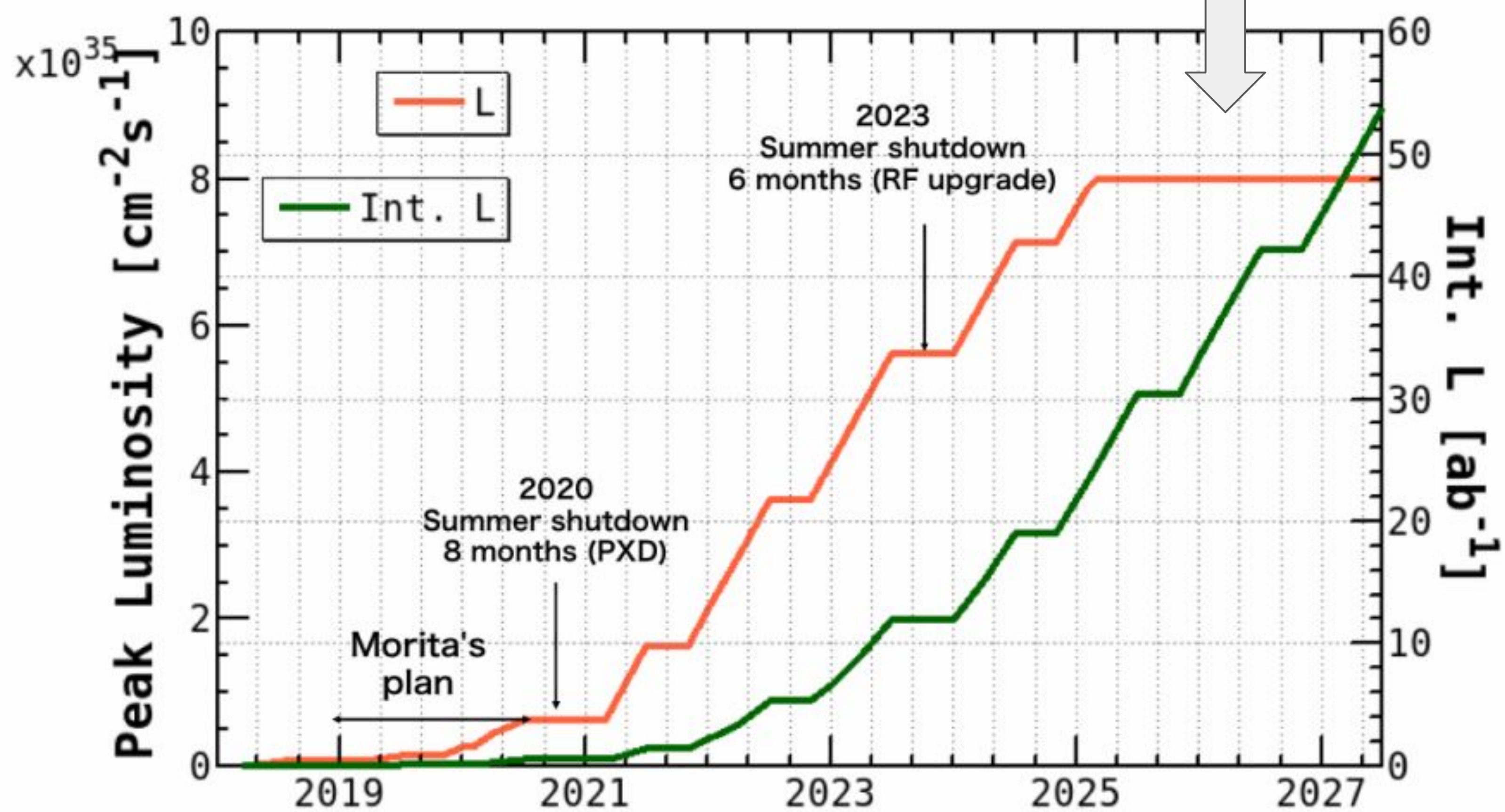
SuperKEKB



2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.20x10^{-4}	4.55x10^{-4}		
σ_δ	7.92(7.53)x10^{-4}	6.37(6.30)x10^{-4}		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8x10^{35}		cm^{-2}s^{-1}	

SuperKEKB and Belle II

Goal for start of polarized SuperKEKB data taking



Electroweak Program with Polarized SuperKEKB

- Access to weak vector couplings in polarized $e^+e^- \to ff$ through left-right asymmetry:

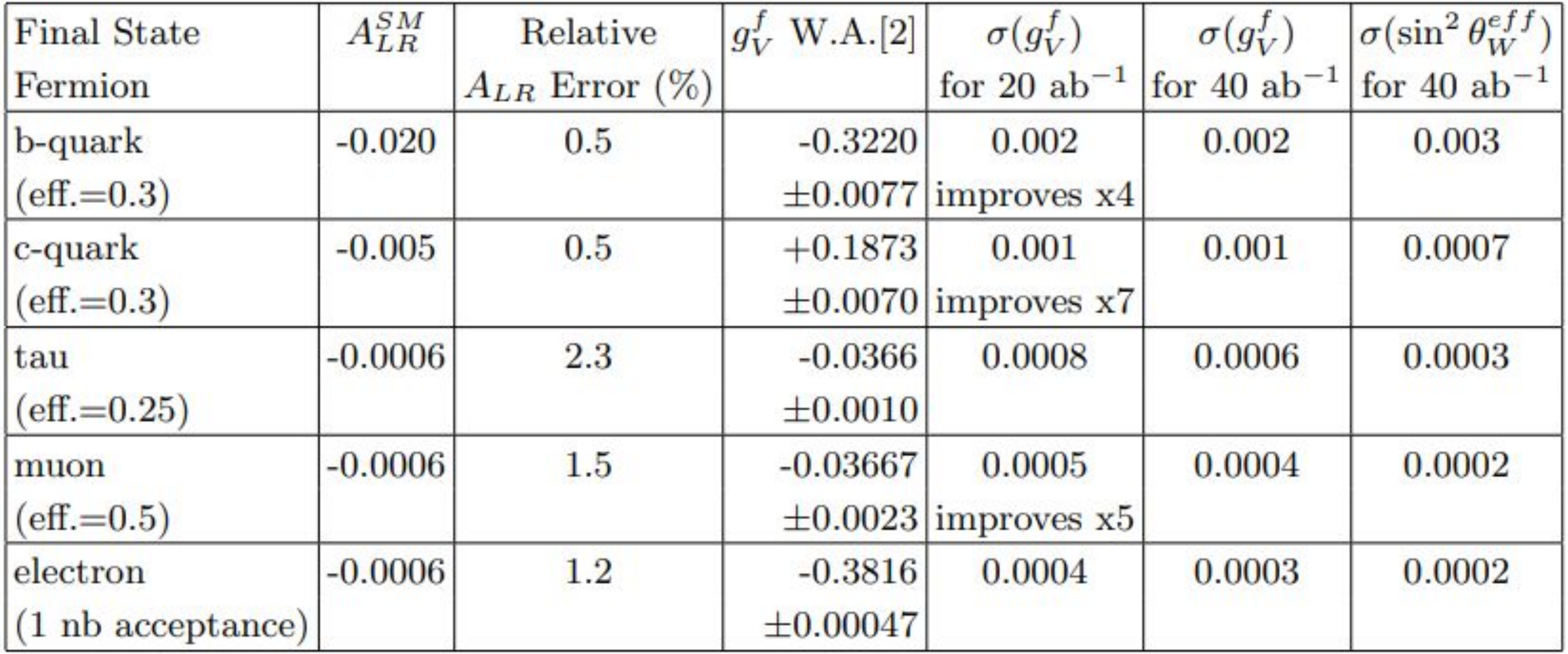
$$A_{LR}^{f} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{sG_F}{\sqrt{2}\pi\alpha Q_f} g_A^e g_V^f \langle Pol \rangle$$

$$\langle Pol \rangle = \frac{1}{2}\left[\left(\frac{N_{eR} - N_{eL}}{N_{eR} + N_{eL}}\right)_{\mathbf{R}} - \left(\frac{N_{eR} - N_{eL}}{N_{eR} + N_{eL}}\right)_{\mathbf{L}}\right]$$

- Of particular interest: $e^+e^- \to \mu^+\mu^-$
  - Enhancement of $A_{LR}(\mu)$ expected in explanations for proton radius in muonic hydrogen, or for $(g\text{-}2)_\mu$ effects

Ref: Electroweak Physics with Polarized Electron Beams in a SuperKEKB Upgrade, M. Roney, https://doi.org/10.22323/1.367.0109, arxiv:1907.03503.

Electroweak Program with Polarized SuperKEKB



Final State Fermion	A_{LR}^{SM}	Relative A_{LR} Error (%)	g_V^f W.A.[2]	$\sigma(g_V^f)$ for 20 ab^{-1}	$\sigma(g_V^f)$ for 40 ab^{-1}	$\sigma(\sin^2\theta_W^{eff})$ for 40 ab^{-1}
b-quark (eff.=0.3)	-0.020	0.5	-0.3220 ±0.0077	0.002 improves x4	0.002	0.003
c-quark (eff.=0.3)	-0.005	0.5	+0.1873 ±0.0070	0.001 improves x7	0.001	0.0007
tau (eff.=0.25)	-0.0006	2.3	-0.0366 ±0.0010	0.0008	0.0006	0.0003
muon (eff.=0.5)	-0.0006	1.5	-0.03667 ±0.0023	0.0005 improves x5	0.0004	0.0002
electron (1 nb acceptance)	-0.0006	1.2	-0.3816 ±0.00047	0.0004	0.0003	0.0002

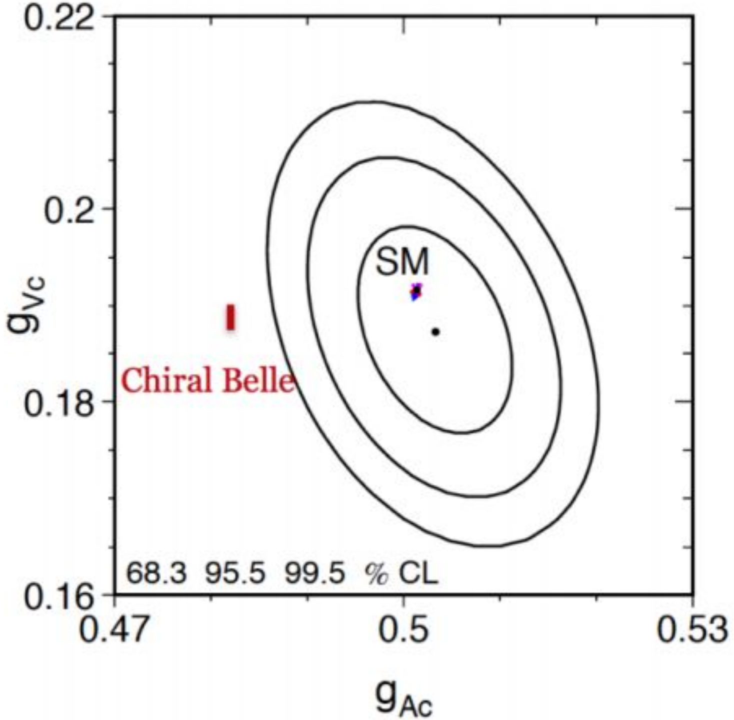
Notes: eff. = final state selection efficiency; Relative A_{LR} Error for 20 ab^{-1}; W.A. = World Average

Electroweak Program with Polarized SuperKEKB

with 20 ab^{-1}

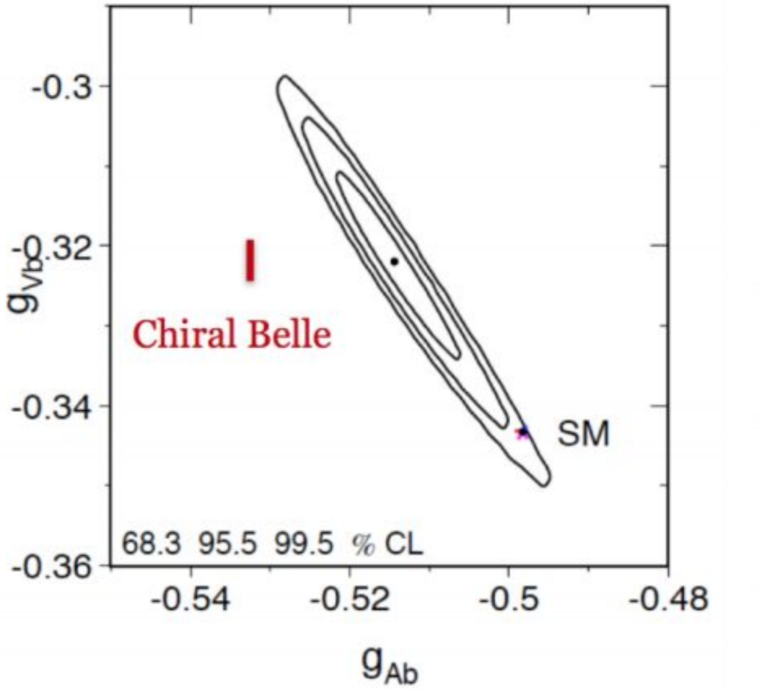
c-quark:

Chiral Belle ~7 times more precise

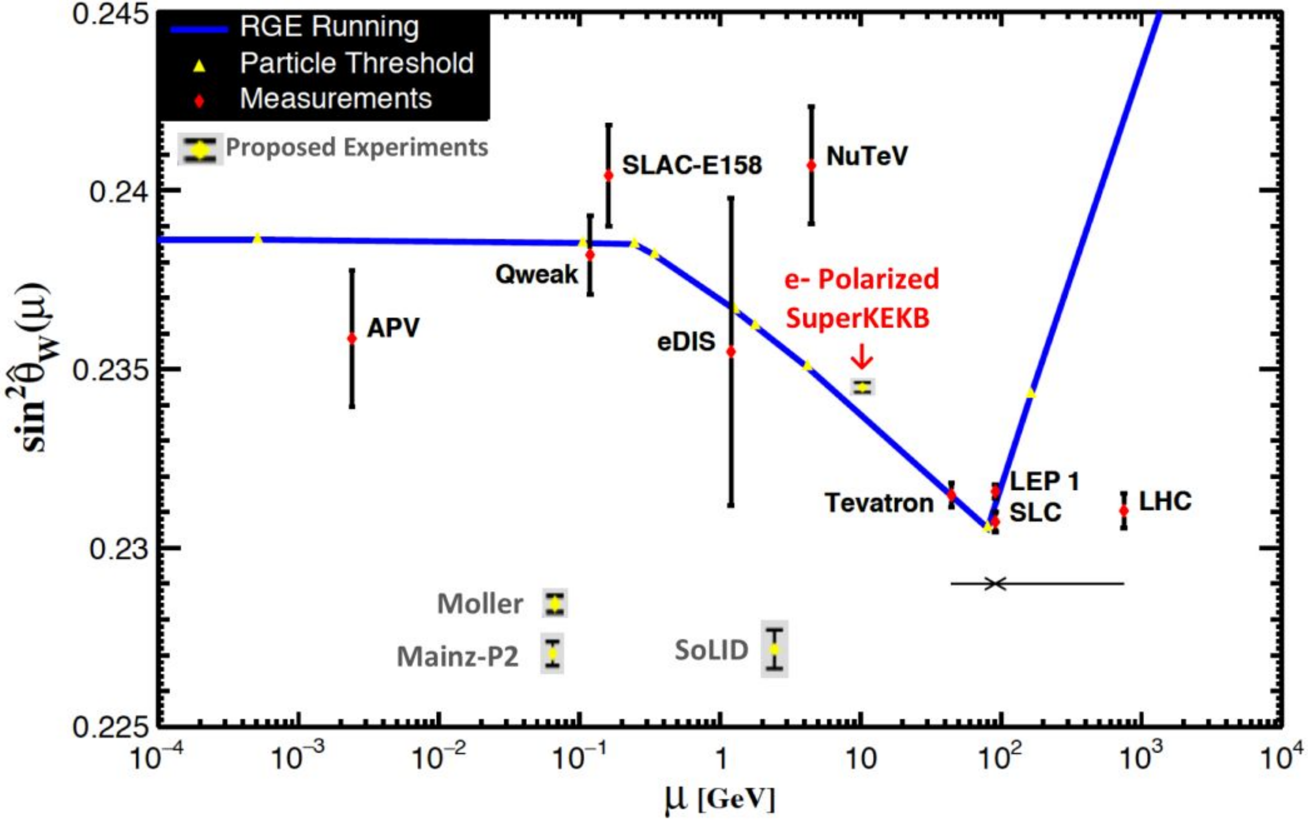


b-quark:

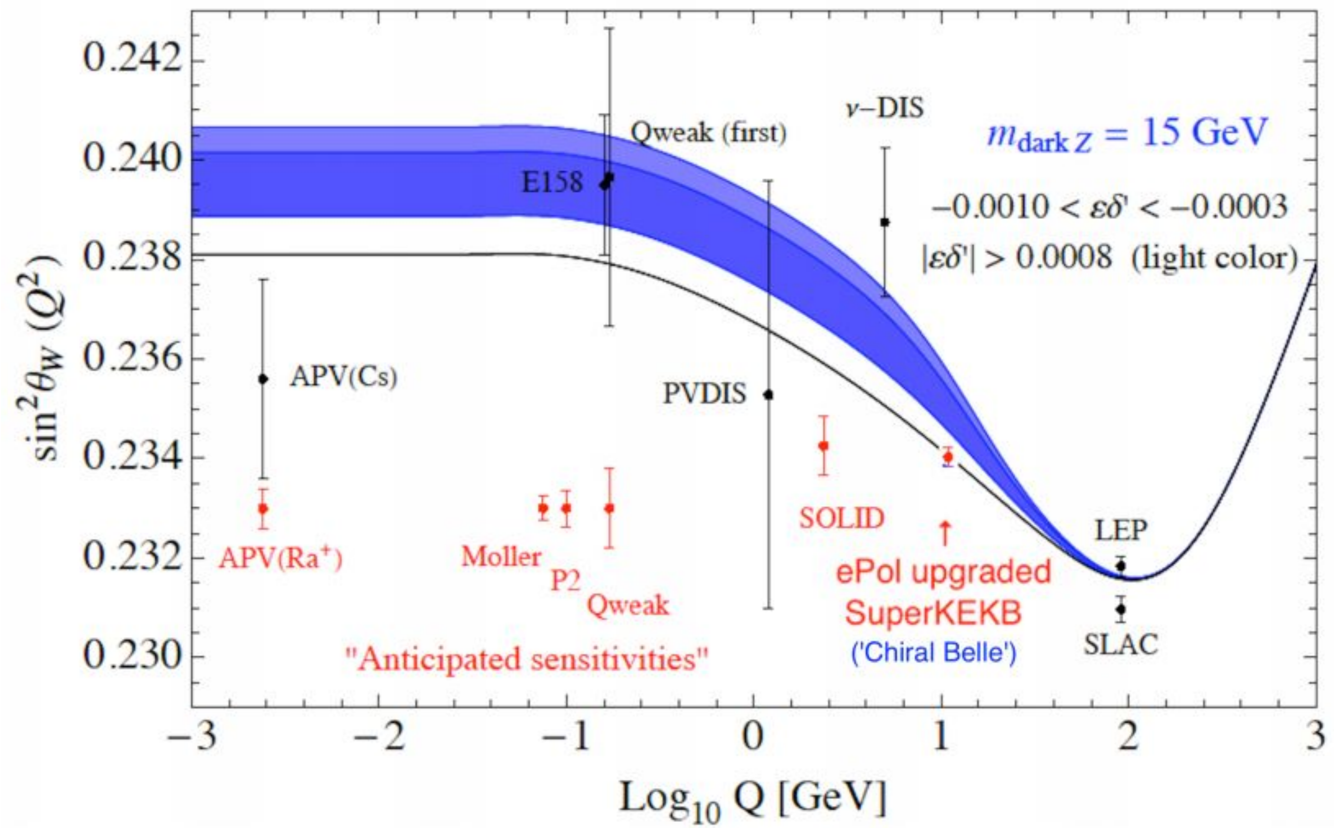
Chiral Belle ~4 times more precise



Electroweak Program with Polarized SuperKEKB



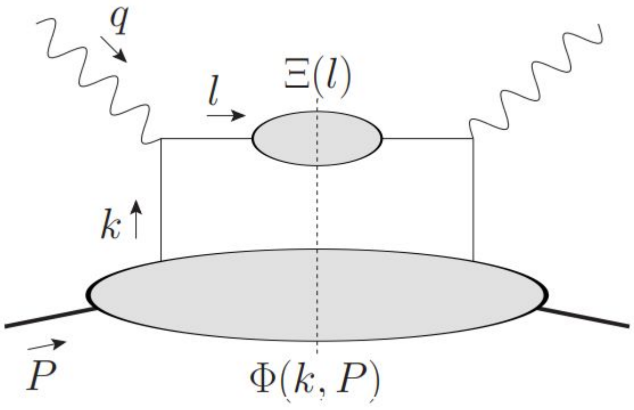
Electroweak Program with Polarized SuperKEKB

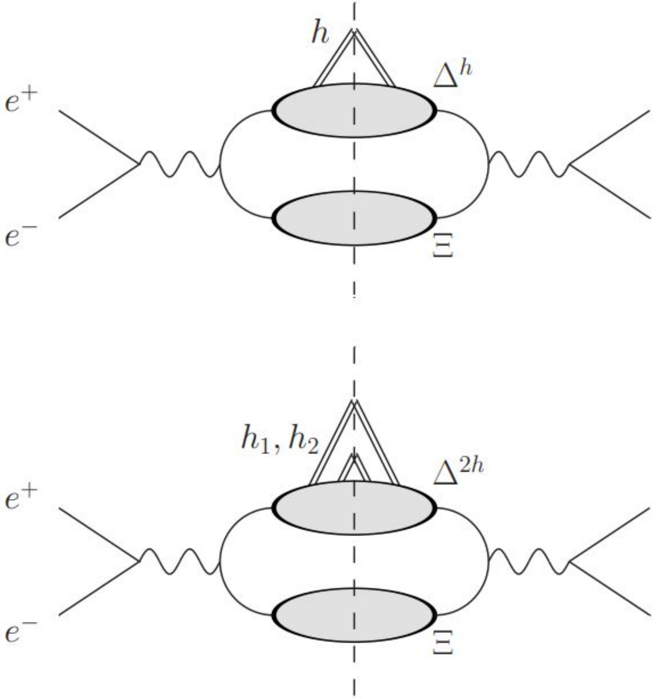


- Unique sensitivity to light neutral dark Z bosons
- In particular when between 10 and 35 GeV
- Or if strongly coupled to 3rd generation

Dynamical Mass Generation in Polarized e^+e^-

- Polarized e^+e^- annihilation into polarized Λ or hadron pair to probe dynamical quark mass generation in QCD





Ref: A. Signore, QCD Evolution 2019

Polarized SuperKEKB Requirements

Overall strategy:

- Low-emittance longitudinally polarized GaAs electron source
  - Spin rotated transverse before entering storage ring
- High energy storage ring spin transport upgrades
  - Transverse polarization in the bending sections of the storage ring
  - Spin rotators around the IR: Transverse → longitudinal at IP → transverse
- Polarimetry
  - Longitudinal Compton polarimeter near IR
  - $\tau \to \pi \nu$ analysis using collision events at IR

Projected systematic uncertainties should be 0.5% or better on $A_{LR}(b)$

- Polarization extrapolation from Compton polarimeter to IR currently largest

Polarized SuperKEKB Requirements: Similar to EIC

- High luminosity prevents use of Sokolov-Ternov self-polarization
- Polarization must be generated at polarized DC gun and injected continuously (as is already done for unpolarized beams at SuperKEKB)
  - Wien filter to rotate spin
- Flexible bunch polarization patterns must be supported
- Bunch-to-bunch polarization measurement
- Within existing accelerator infrastructure

Already existing connections between EIC and this project (e.g. M. Palmer, polarized electron source at BNL)

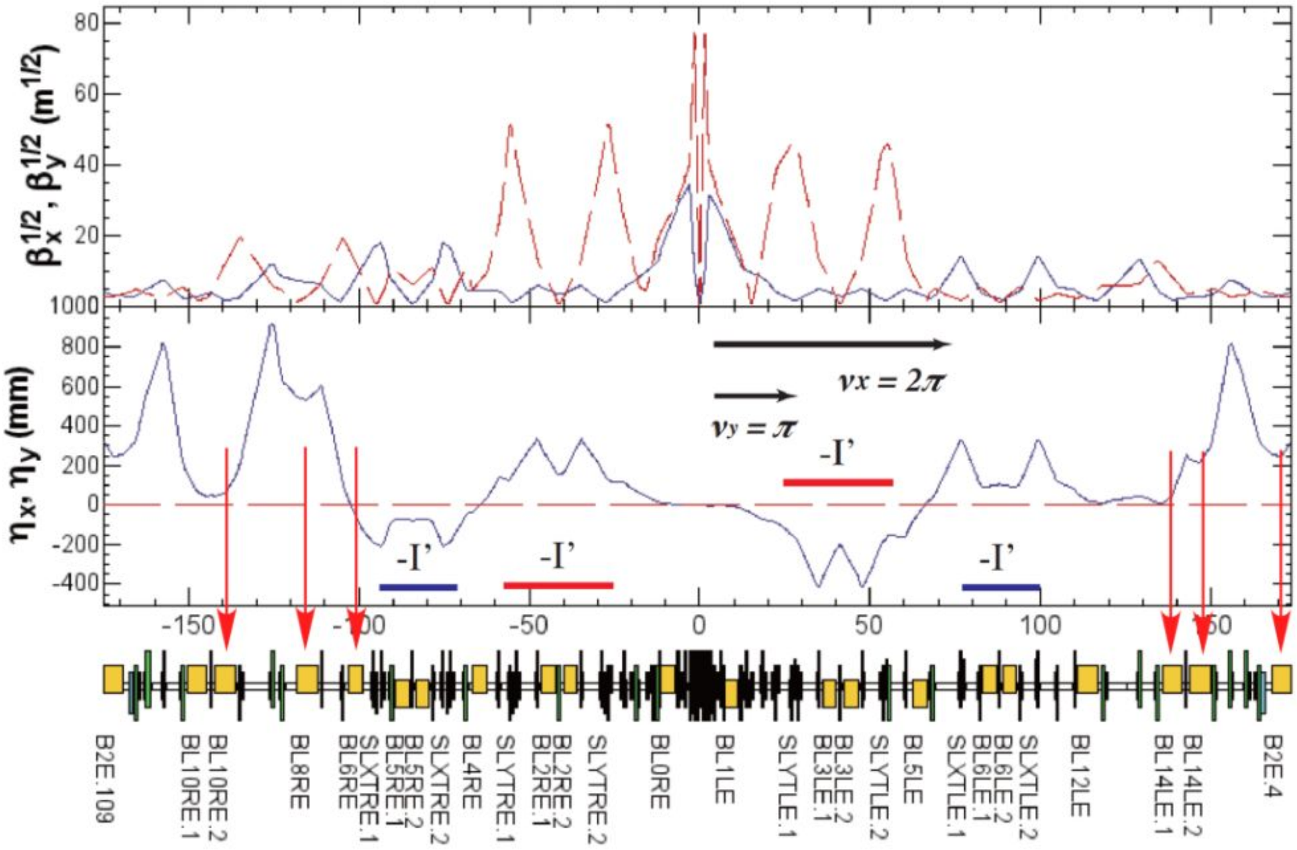
Storage Ring Modifications: Spin Rotators

- Preserve HER/LER ring structure (asymmetric around IR)
- Preserve vertical emittance → only solenoid-dipole spin rotators considered, with the dipole as part of existing ring
- Will have to be symmetric in horizontal bending around IP
  - Prevents strong spin matching, but depolarization time turns out to be long enough to maintain good polarization

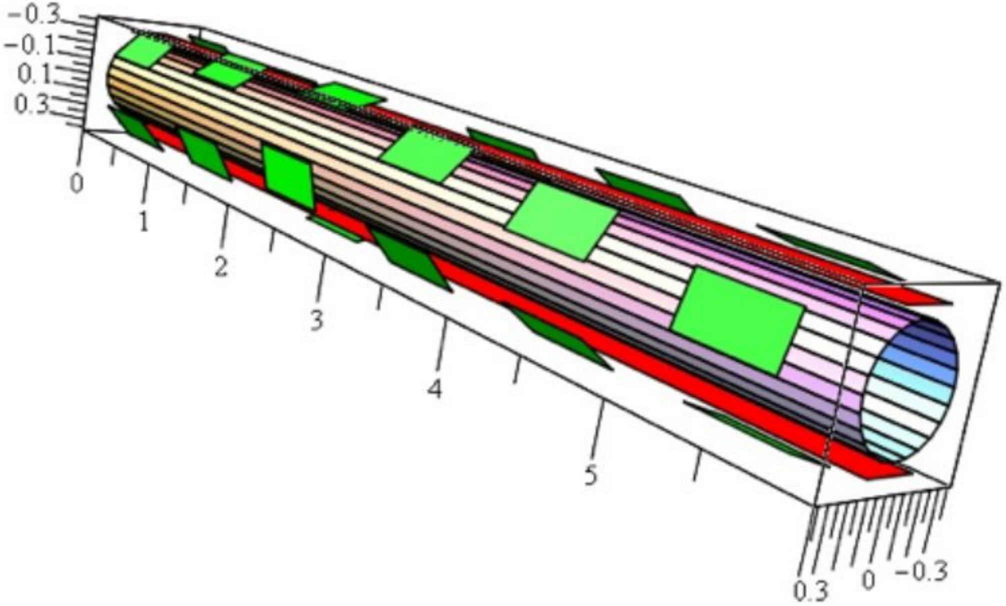
Solution:

- Multifunctional spin rotator magnets that can replace existing dipoles and result in longitudinal polarization at IR

Storage Ring Modifications: Spin Rotators

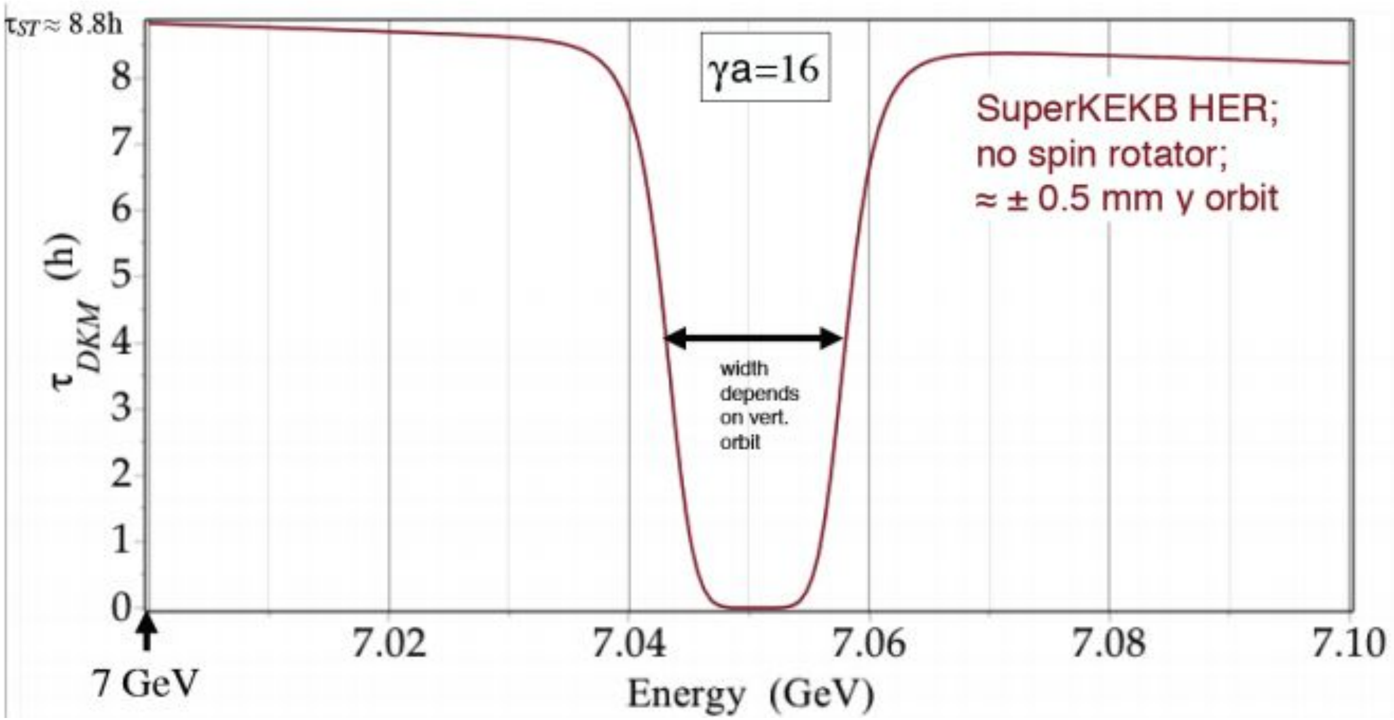


Storage Ring Modifications: Spin Rotators



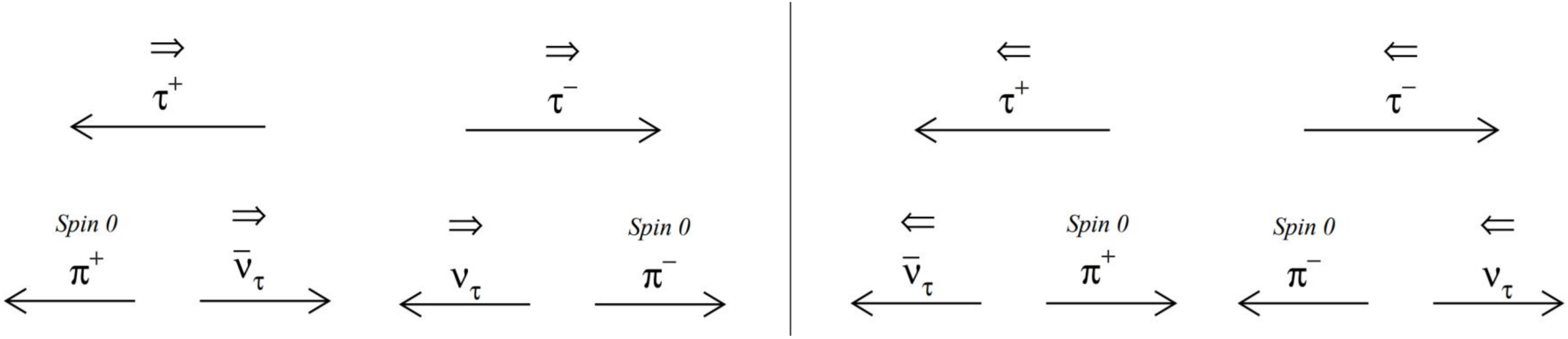
- 3 multifunctional solenoid, dipole, quadrupole magnets on each side of IP
- Could take advantage of BNL direct winding technology
- No vertical shifts needed
- Can back out out by only energizing dipole and quadrupoles

Storage Ring Modifications: Spin Rotators



Ref: Uli Wienands, ANL

Beam Polarization Measurements from $A_{FB}(\tau\rightarrow\pi\nu)$



s-channel production: $e^+e^- \rightarrow \tau^+\tau^-$

Decay channels:

- $\tau^\pm\rightarrow\pi^\pm\nu_\tau$
- $\tau^\pm\rightarrow\pi^\pm\pi_0\nu_\tau$

$A_{FB} \propto \cos\theta_\pi$

Backgrounds:

- $\tau^\pm\rightarrow\mu^\pm\nu_\mu\nu_\tau$
- $e^+e^-\rightarrow\mu^+\mu^-$

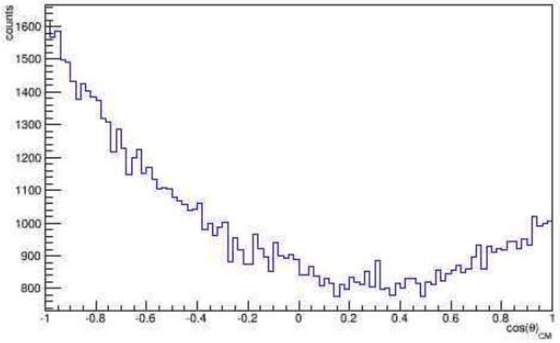
Pure channel: $\tau^+\tau^- \rightarrow \pi^\pm\nu_\tau + \rho^\pm(\pi^\pm\pi^0)\nu_\tau$

(Ref: C. Miller, M. Roney, U. Victoria,

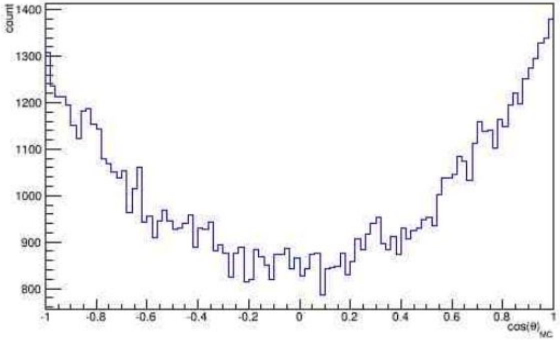
Beam Polarization Measurements from $A_{FB}(\tau\rightarrow\pi\nu)$

- $\cos\theta_\pi$ distributions of π^- depends on polarization
    - No polarization: no preference for forward/backward
    - Positive polarization: π^- preference for forward direction ($\cos\theta_\pi > 0$)
    - Negative polarization: π^- preference for backward direction ($\cos\theta_\pi < 0$)
- Events generated with KK2f + tauola for τ decays
    - full spin correlation density matrix taken into account

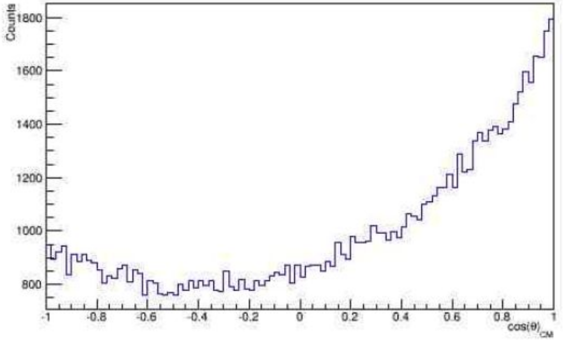
Negative Polarization



No Polarization



Positive Polarization

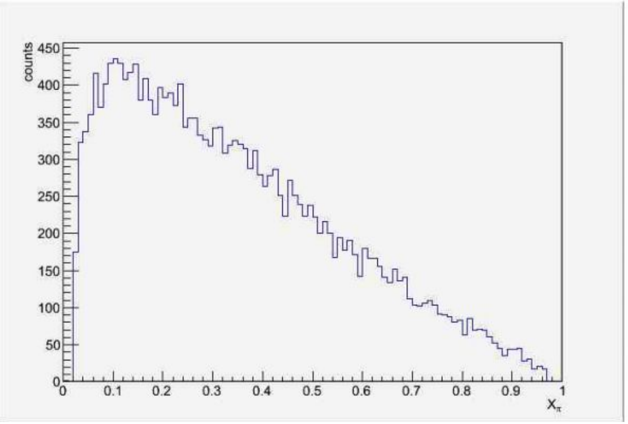


Beam Polarization Measurements from $A_{FB}(\tau\to\pi\nu)$

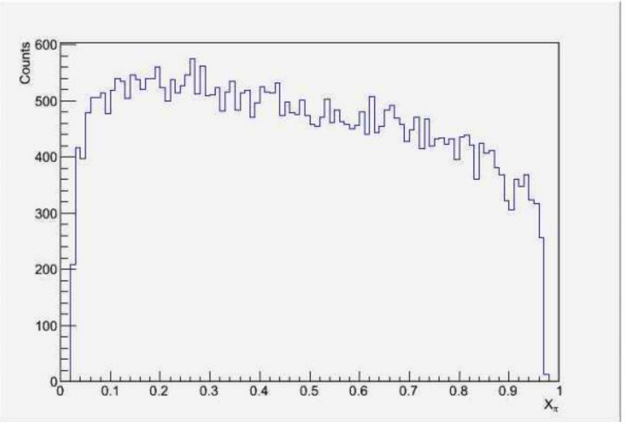
Discriminating power in other kinematic observables (asymmetric boost)

- $X_\pi = P_\pi / E_b$ (pion energy fraction, 0 … 1)

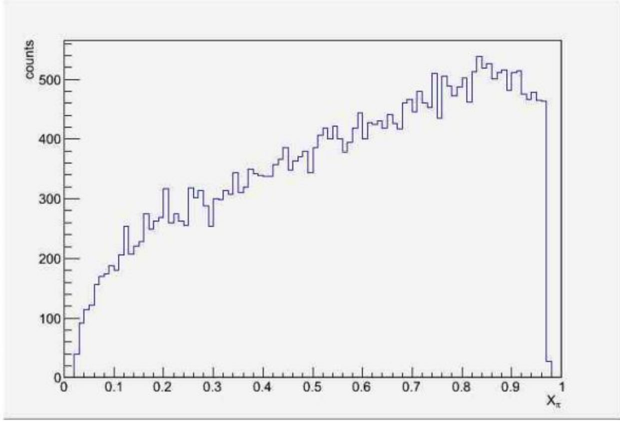
$\cos\theta_\pi < -0.5$



$-0.5 < \cos\theta_\pi < 0.5$



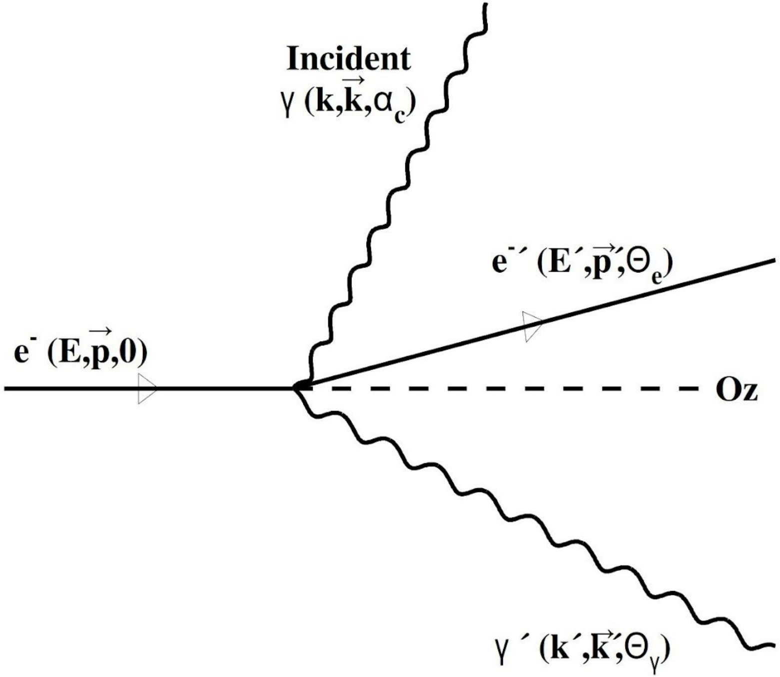
$0.5 < \cos\theta_\pi$



Beam Polarization Measurements from $A_{FB}(\tau\rightarrow\pi\nu)$

- Analysis developed on BaBar Run 3 data by C. Miller (U. Victoria)
- Barlow template fitting method with 2 signal (L and R) and 4 background template distributions in θ_π and X_π
- Unblinding BaBar analysis in July; systematic studies underway; promises better than 0.5% systematic uncertainty
- Statistical uncertainty allows 0.5% per few hundred fb^{-1}

Compton Polarimetry at Polarized SuperKEKB



A. Deshpandea, C. Gala, D. Gaskellb, K. Paschkec. 2020. Letter of Intent for a pulsed laser system for Compton polarimetry at the future EIC facility.
https://wiki.bnl.gov/conferences/index.php/File:EIC_Compton_LOI_Jan-2020.pdf

Incident beams:

Electron (e):

E = initial energy
$\vec{p}$ = initial momentum

Photon (γ):

k = initial energy
$\vec{k}$ = initial momentum

Scattered beams:

Electron (e'):

E' = scattered energy
$\vec{p}'$ = scattered momentum

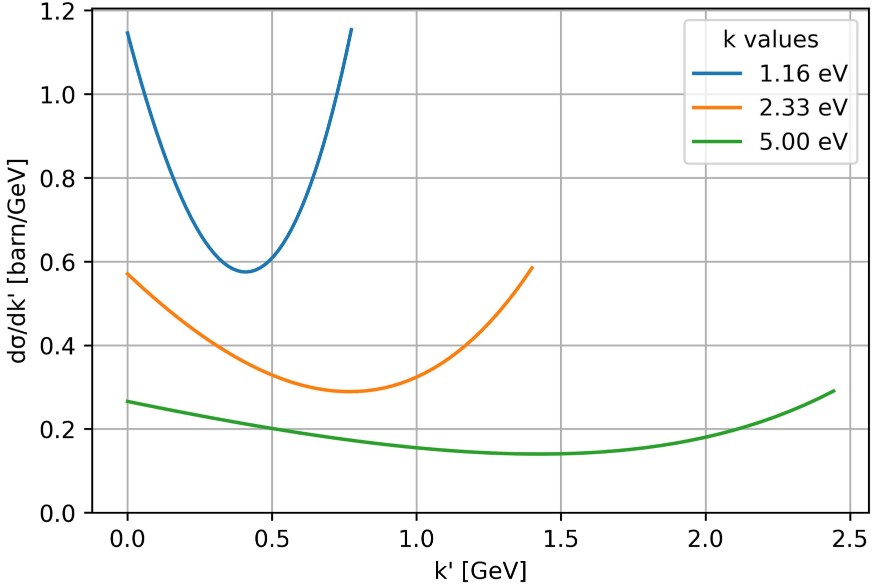
Photon (γ'):

k' = scattered energy
$\vec{k}'$ = scattered momentum

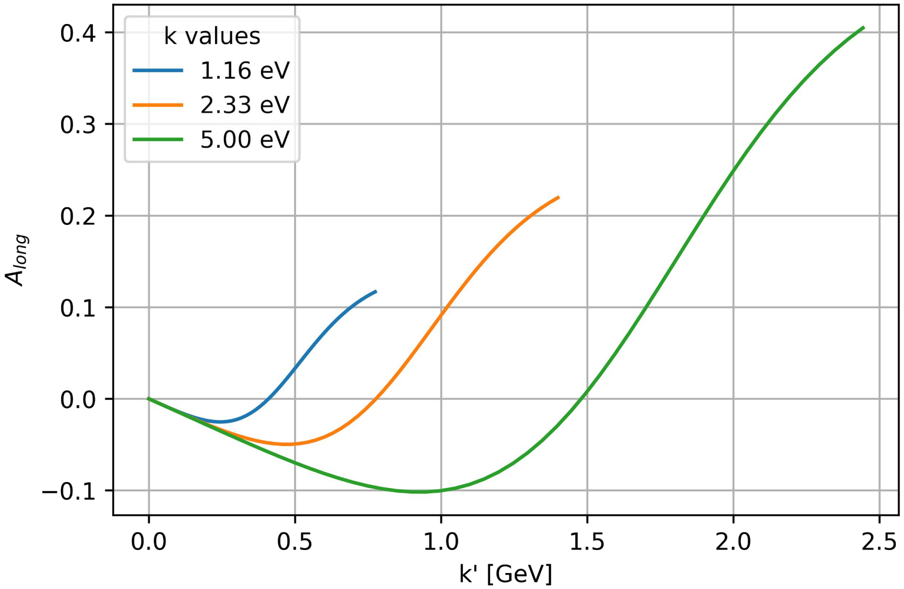
Ref: Omar Hassan,
U. Manitoba

Compton Polarimetry at Polarized SuperKEKB

- HER 7 GeV with various laser wavelength assumptions:
  - 1064 nm, 532 nm, 266 nm



- Longitudinal asymmetry



Compton Polarimetry at Polarized SuperKEKB

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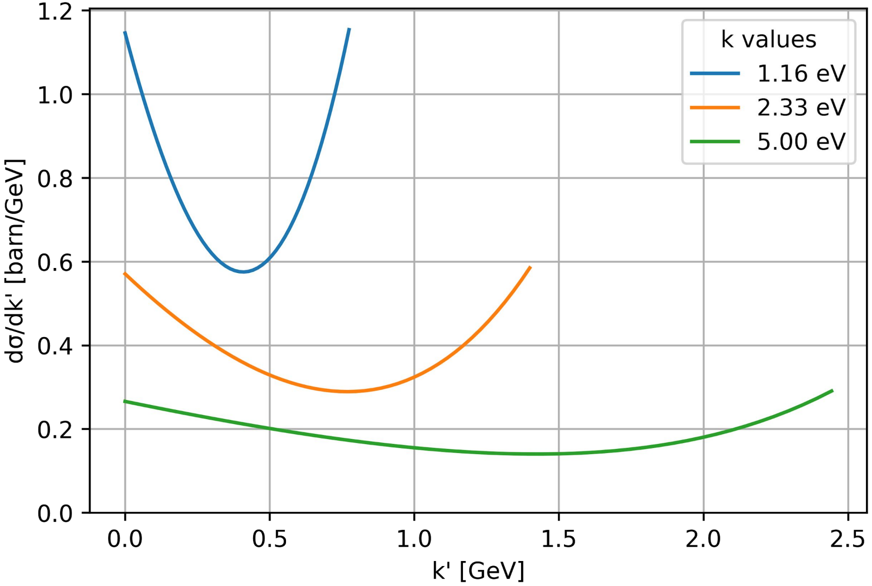
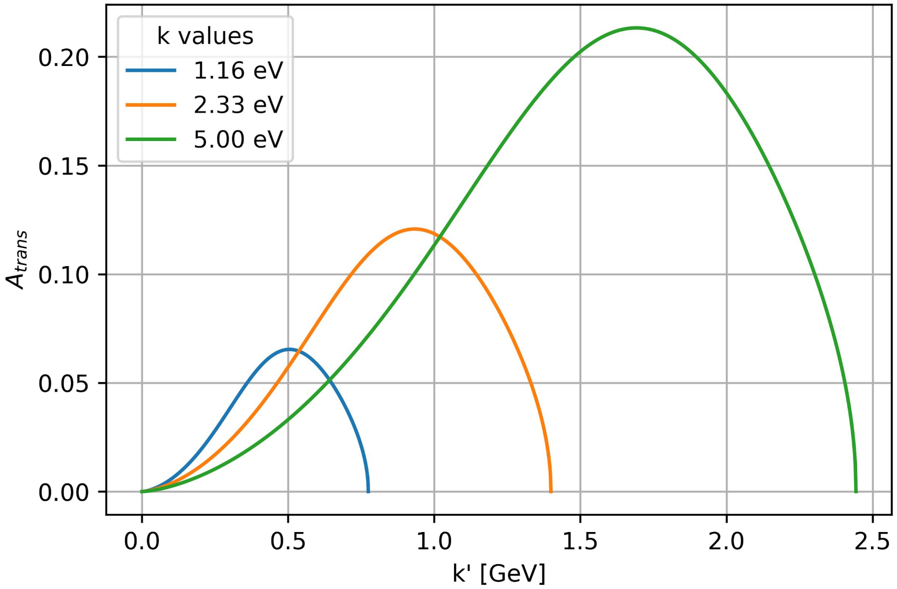


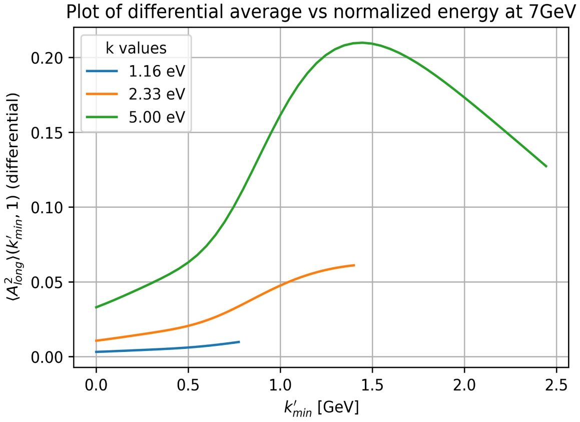
- Transverse asymmetry

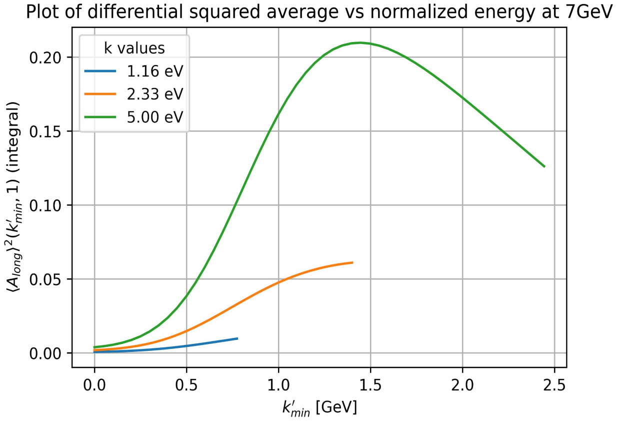


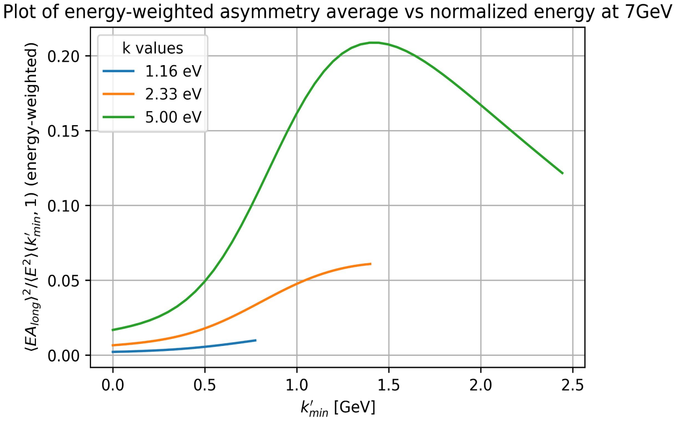
Compton Polarimetry at Polarized SuperKEKB

FOM = time to 1% precision ∝ $1/\langle A^2 \rangle$, integrated from lower threshold k'_{min}

- Differential measurement: $\langle A^2 \rangle$
- Integrating measurement: $\langle A \rangle^2$
- Energy-weighted integrating measurement: $\langle EA \rangle^2 / \langle E^2 \rangle$


Plot of differential average vs normalized energy at 7GeV


Plot of differential squared average vs normalized energy at 7GeV

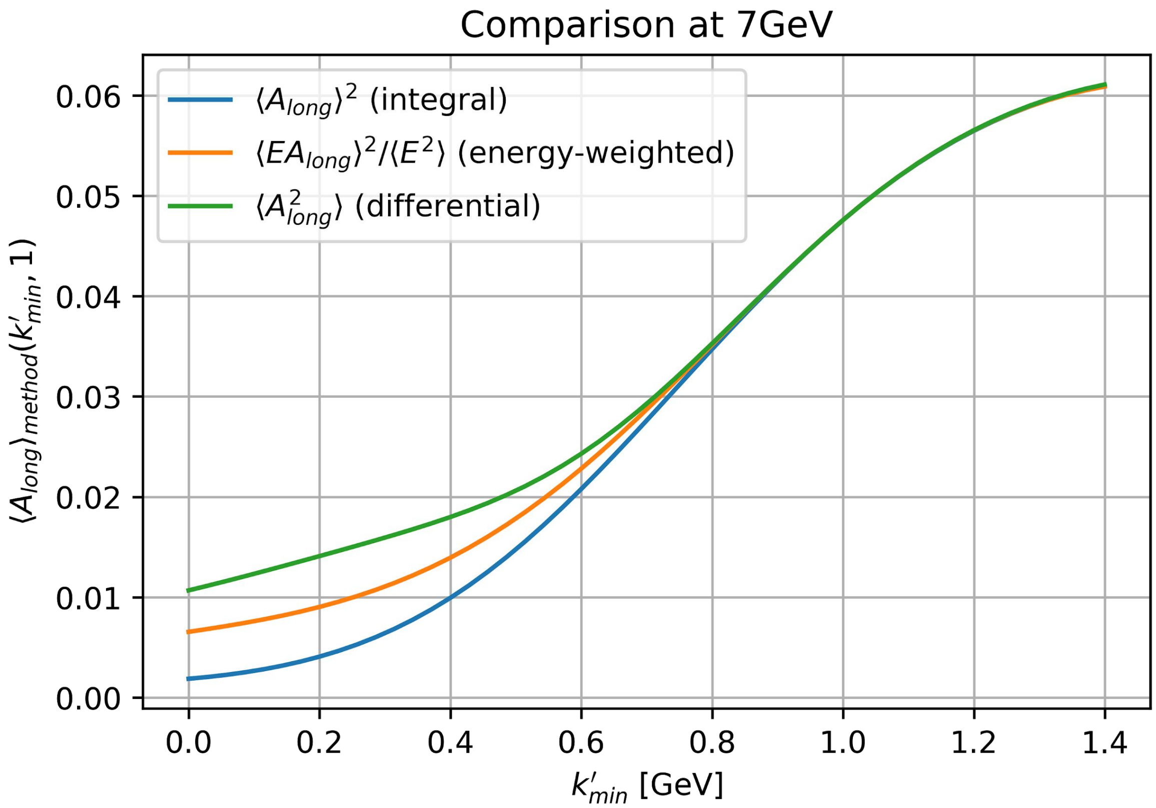

Plot of energy-weighted asymmetry average vs normalized energy at 7GeV

Compton Polarimetry at Polarized SuperKEKB

For thresholdless data acquisition, **differential measurements** have largest analyzing power but sensitive to backgrounds.

Integral measurement using pulsed laser (frequency comb) matched to beam structure less sensitive to backgrounds.

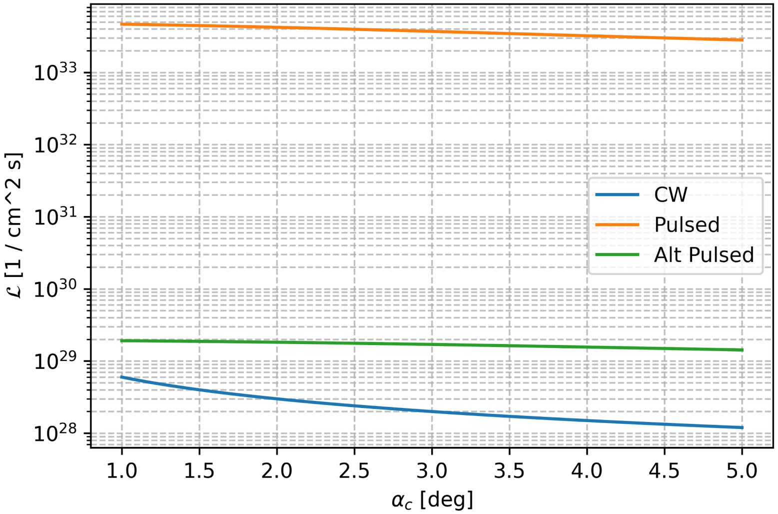
Plot for k = 2.33 eV (532 nm)

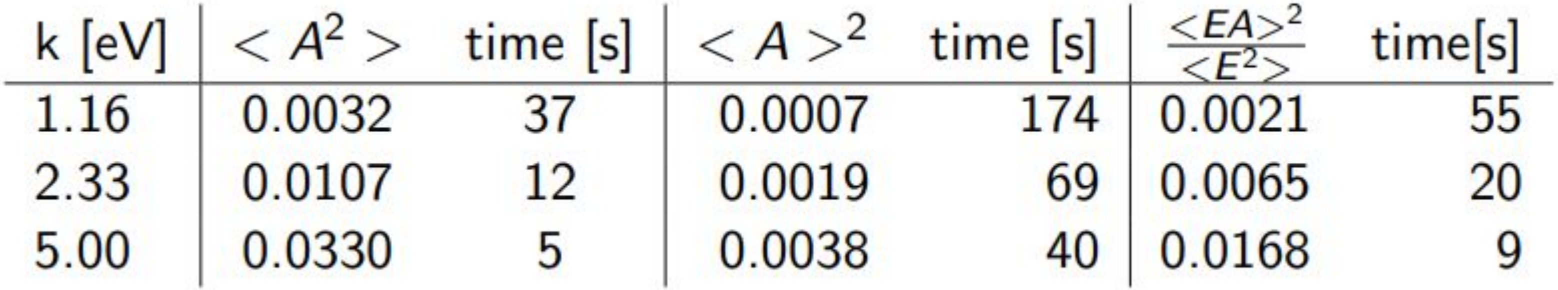


Compton Polarimetry at Polarized SuperKEKB

Luminosity assumptions:

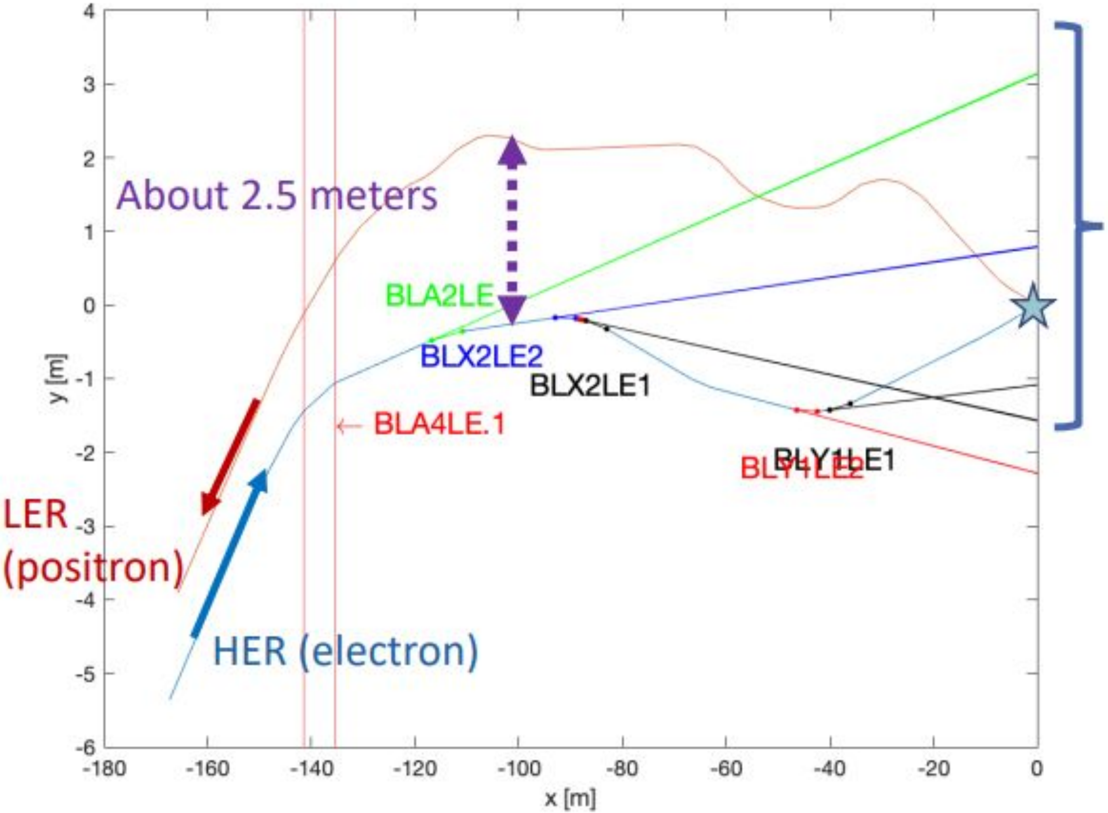
- Continuous laser: 10W cavity
- Pulsed laser: 20W at 250MHz
    - Currently looking at 512 ns, e.g. Menlo Orange high power series
    - 2.2 photons per bunch crossing
- Time to 1% precision:
  (preliminary until we know where in lattice)





k [eV]	$< A^2 >$	time [s]	$< A >^2$	time [s]	$\frac{<EA>^2}{<E^2>}$	time[s]
1.16	0.0032	37	0.0007	174	0.0021	55
2.33	0.0107	12	0.0019	69	0.0065	20
5.00	0.0330	5	0.0038	40	0.0168	9

SuperKEKB Lattice: Location of Polarimetry



About 2.5 meters

LER (positron)

HER (electron)

Line of sight of photons produced at interaction points located right before BLA2LE, BLX2LE(1,2), BLY1LE(1,2)

Ref: A. Martens, Y. Peinaud, F. Zomer, Orsay, IN2P3

Alignment with EIC Electron Polarimetry Efforts

- Similar requirements: high precision, per bunch, faster than cycling time
- Both longitudinal and transverse Compton polarimetry under consideration
- Similar time frame for construction and operation, but with operational e-beam
- SuperKEKB is at lower energies than EIC: 7 GeV

Groups involved in SuperKEKB polarimetry effort:

- Driven by Canadian group in Belle II: U. Victoria
- Synergies with other Canadian groups: U. Manitoba
  - Canadian concentration of EIC efforts is of interest to Canadian SAP groups
- Cavity LPOL group at HERA: Orsay
- Strong support from Belle II and SuperKEKB leadership
- Studies by accelerator groups at SuperKEKB; also BNL, ANL experts

Timeline

- Discussions
- Fall 2019: NSERC Pre-R&D Proposal v1
- Winter 2020-present: Polarized Belle II Working Group meetings
- Winter 2020-present: Periodic updates at Belle II General Meeting
- Summer 2020: Canadian SAP Long Range Planning briefs
- Summer 2020: Polarized Belle II White Paper
- Fall 2020: NSERC Pre-R&D Proposal v2
- …
- Completion of 40 ab^{-1} physics data-taking with polarized SuperKEKB by end of decade

Summary

SuperKEKB is similar in energy range and luminosity as the EIC electron ring, leading to similar operational environment for polarimetry.

Very similar Compton polarimetry efforts are under consideration: high power pulsed laser systems with simultaneous calorimetric photon detection and strip detector (HVMAPS) electron detection.

Backup

Comparison of SuperKEKB and EIC Precision