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

Upgrading SuperKEKB with polarized e- beams

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University of Victoria
6 October 2020

SNOWMASS Community Planning Meeting:
AF5 Organization with Contributors

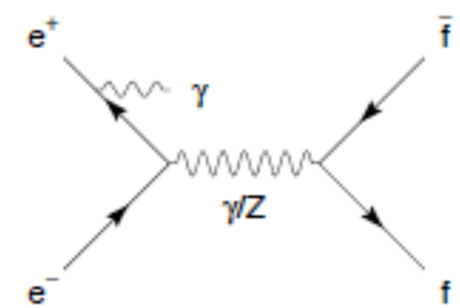
On behalf of Belle II & SuperKEKB e- Polarization Upgrade Working Group

'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 **$\sigma(\sin^2\theta_W)$ ~ 0.00016 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

Will probe both high and low energy scales

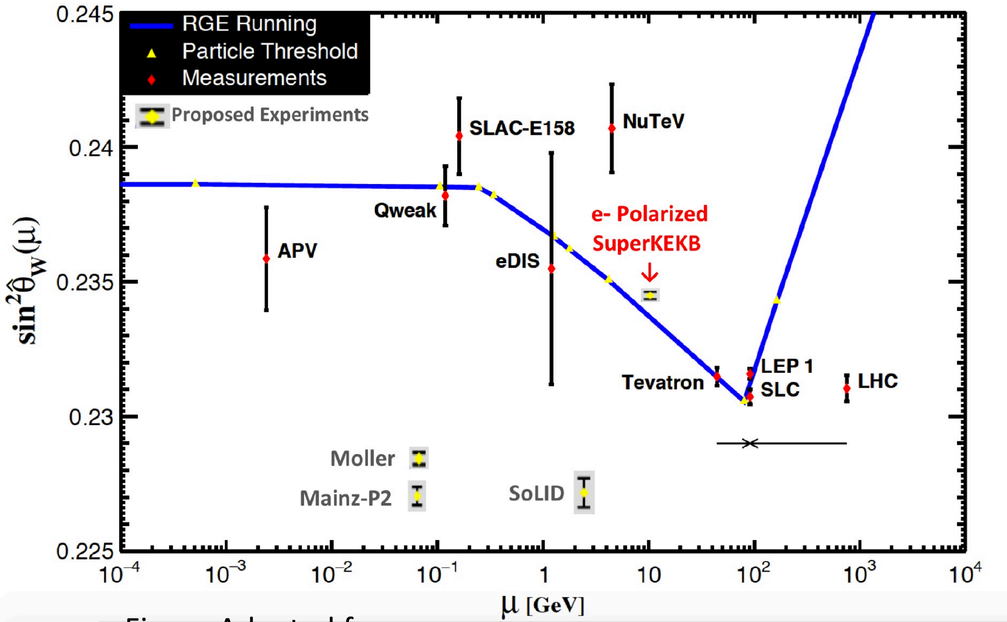


Figure Adapted from
J. Erler and A. Freitas, (PDG) Phys. Rev. D98 , 030001 (2018)

Chiral Belle: σ ~ 0.00016 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**

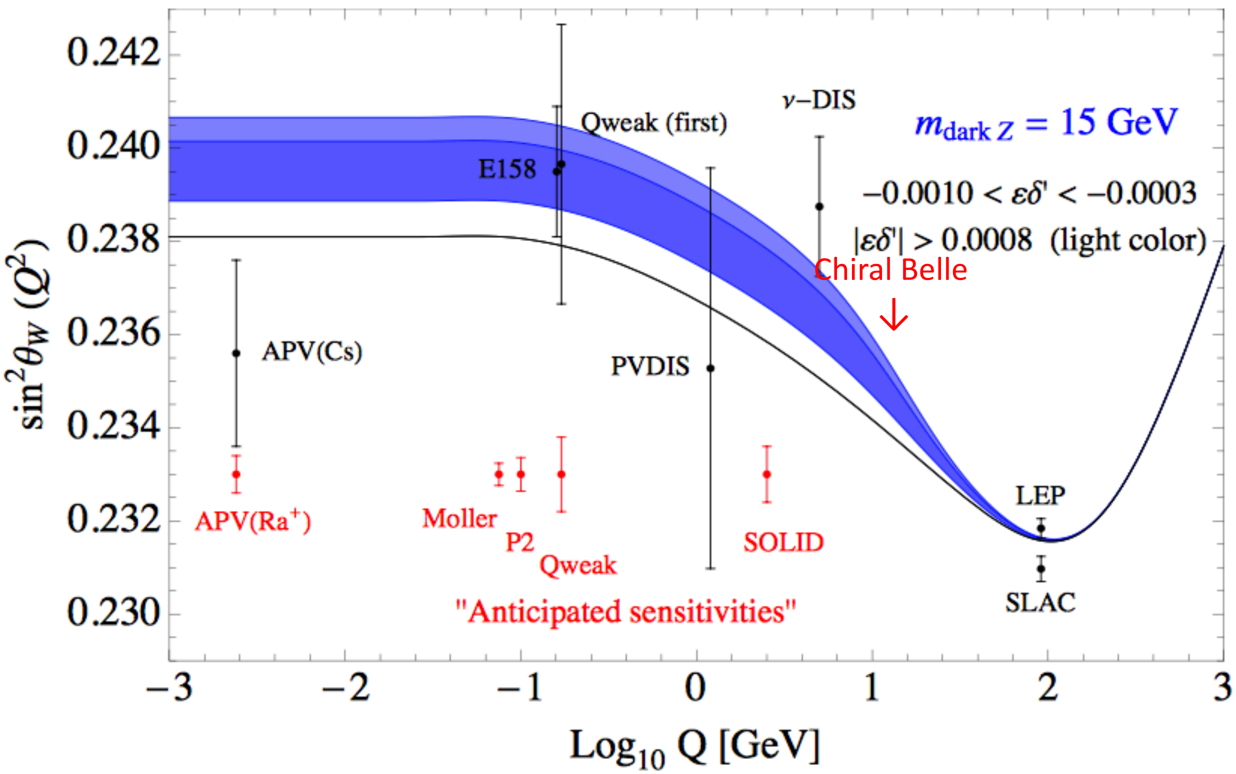
More information at arxiv.org/abs/1907.03503

- **Highest precision test or neutral current vector coupling universality as beam polarization error cancels: e.g. < 0.05% relative error for ratio: g^V_b/g^V_c, *cf* 4% now**
- **Most precise measurements for charm and beauty (and muons) 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

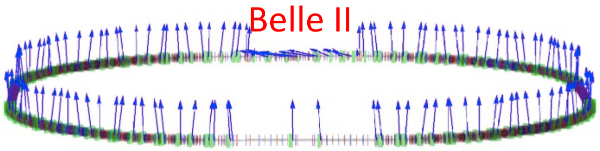
- Improved precision measurements of τ electric dipole moment (EDM) and $(g\text{-}2)_\tau$
  - See J. Bernabéu, G. A. Gonzalez-Sprinberg, and J. Vidal, "CP violation and electric dipole moment at low energy tau production with polarized electrons", Nucl. Phys. B763:283–292, 2007, hep-ph/0610135.

- e^- beam polarization can be used to reduce backgrounds in $\tau \rightarrow \mu\gamma$ 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

Upgrading SuperKEKB with Polarized e- Beam

NEW HARDWARE FOR POLARIZATION UPGRADE:

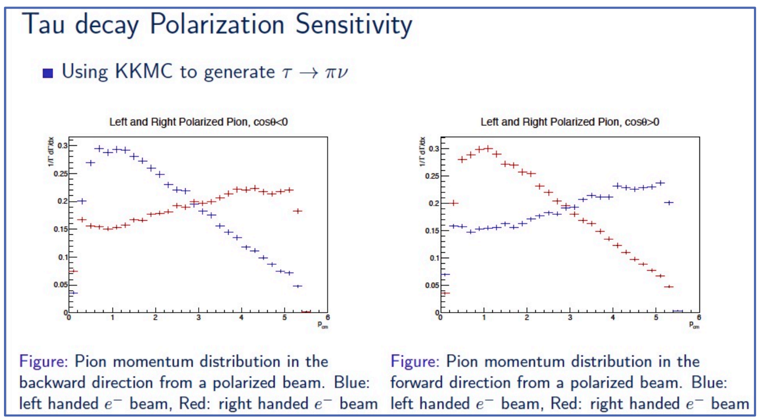
- **Low emittance polarized Source:** electron helicity can be flipped bunch-to-bunch by controlling circular polarization of source laser illuminating a GaAs photocathode (à la SLC). Inject vertically polarized electrons into the 7GeV e- Ring. Needs low enough emittance source to be able to inject. 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)



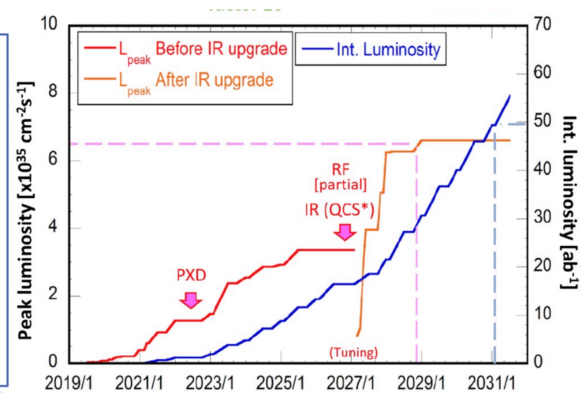
e- spin vector around ring

- **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



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



Thankyou for your attention…

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

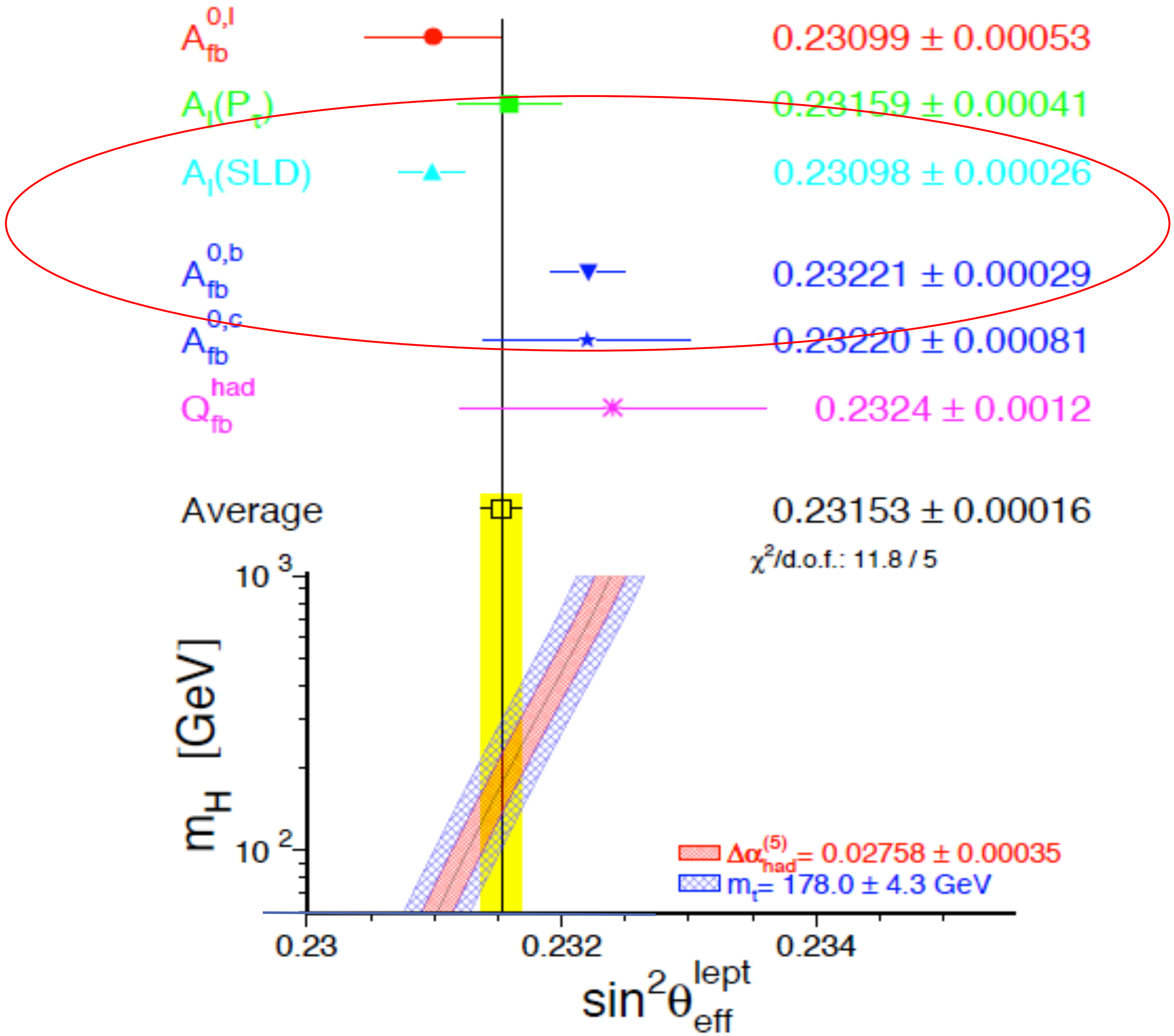
- Beam dynamics and spin tracking
- Spin rotator design
- Compton polarimetry – detector expertise
- Polarized low emittance source
- Tau decay polarimetry – use as many decay channels as possible
- Detailed physics MC studies with final-state fermion selection optimizing signal to background: b, c, tau, mu and e, as well as light quarks
- Precision EW theoretical calculations
- Bhabha MC generator with polarized beams

Additional Material

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

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

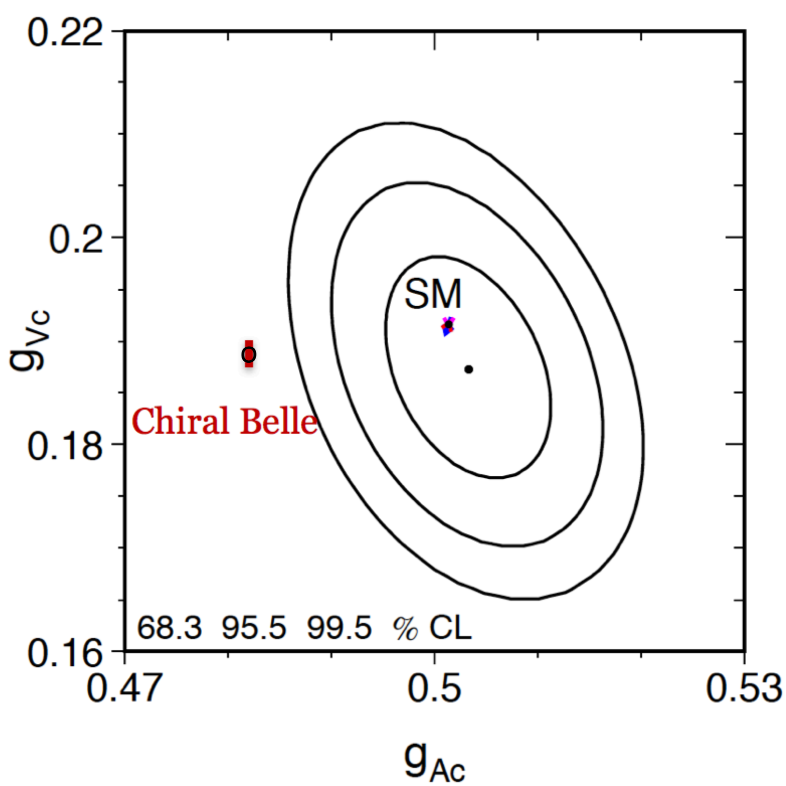
$\sin^2\Theta_W$ - all LEP+SLD measurements combined WA = 0.23153 ± 0.00016

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

Charm and Beauty Couplings Substantially more Precise

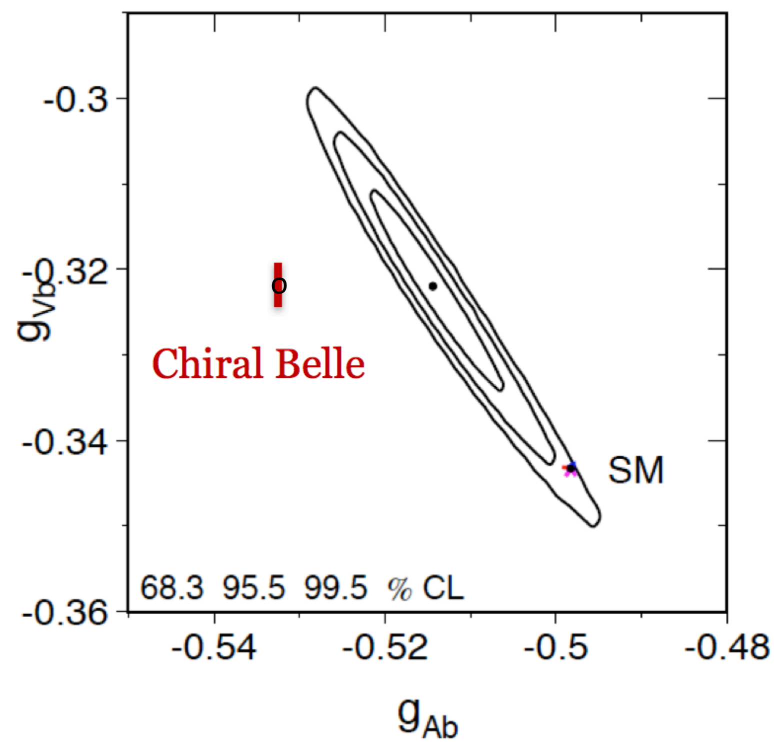
Physics Report Vol 427, Nos 5-6 (2006), ALEPH, OPAL, L3, DELPHI, SLD

c-quark:
Chiral Belle ~7 times more precise



b-quark:
Chiral Belle ~4 times more precise

with 20 ab^{-1}

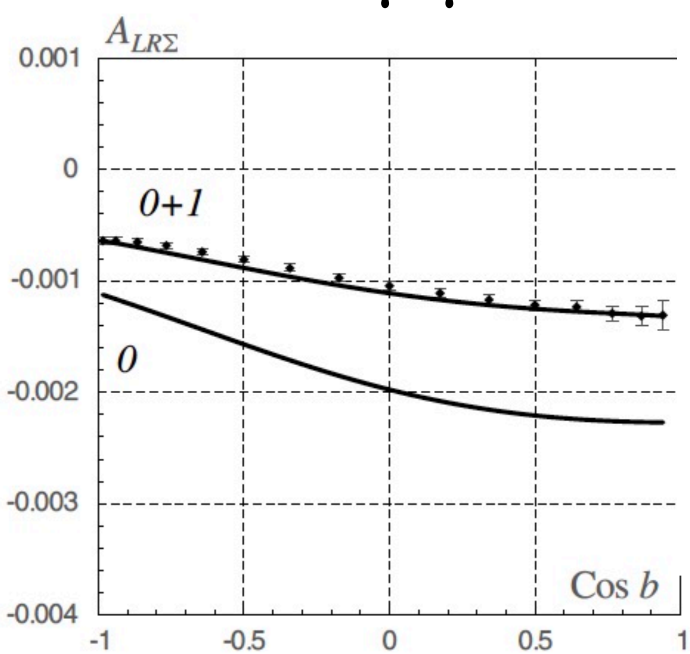


International collaboration of Accelerator and Particle Physicists

➤ **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)**

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

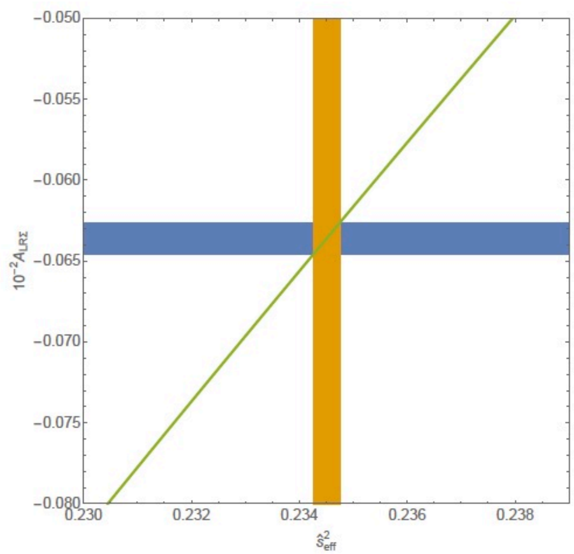


$$\Sigma_L^C = \int_{\cos b}^{\cos a} \sigma_L^C \cdot d(\cos\theta), \quad \Sigma_R^C = \int_{\cos b}^{\cos a} \sigma_R^C \cdot d(\cos\theta)$$

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

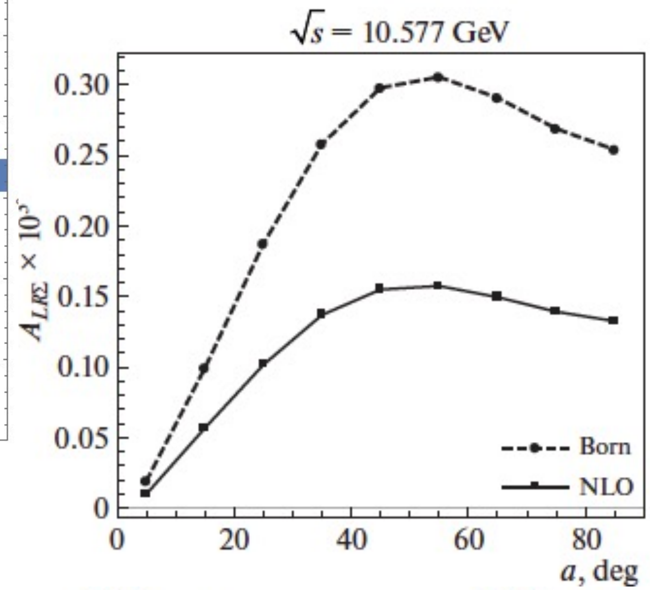
Phys.Rev. D101 (2020) no.5, 053003

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



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

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



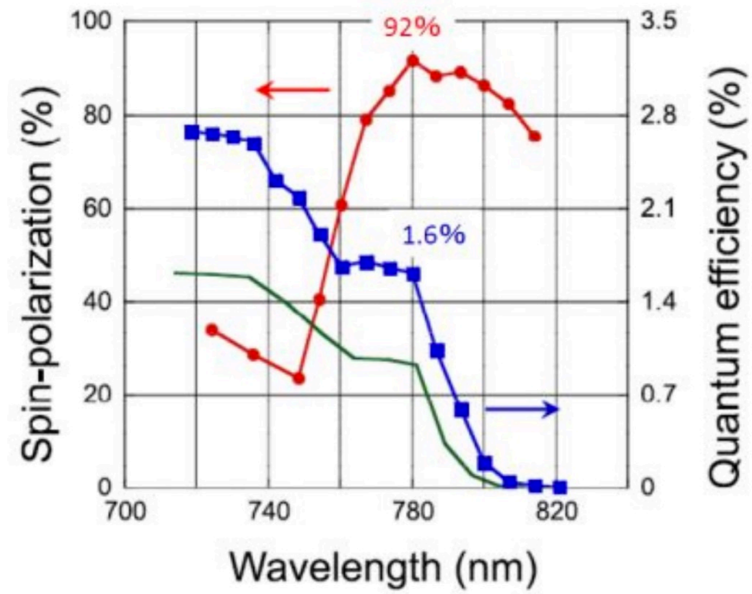
$$\Sigma_L^C = \int_{-\cos a}^{\cos a} \frac{d\sigma_{L0}^C}{dc} \cdot dc, \quad \Sigma_R^C = \int_{-\cos a}^{\cos a} \frac{d\sigma_{R0}^C}{dc} \cdot dc.$$

PHYSICS OF ATOMIC NUCLEI Vol. 83 No. 3 2020

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

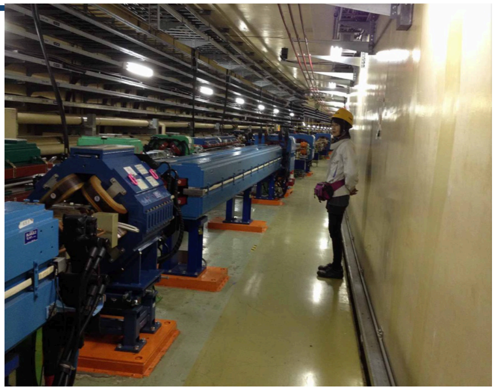
20 mm-mrad vertical emittance

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

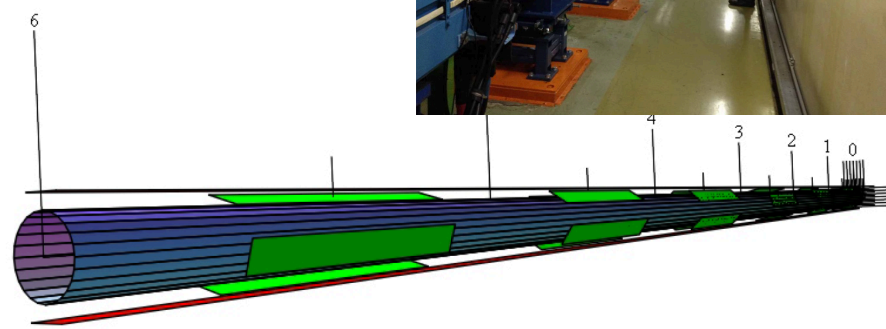
Use of solenoids and dipoles, plus the quadrupoles (needed for decoupling) on either side of interaction point

BINP, ANL, BNL, TRIUMF-Victoria Groups

Polarization in SuperKEKB

Hardware needs

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



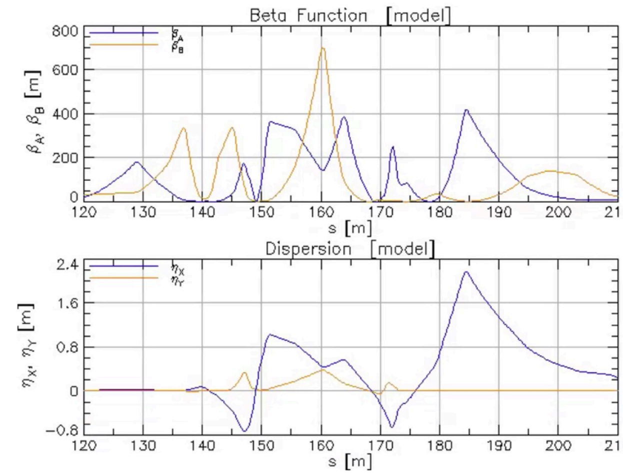
In preliminary studies, one concept (U. Wienands, ANL) is to used combined-function magnets which would replace three existing bending magnets. 5.9m long, 150m on either side of interaction point.

BINP, ANL, BNL, TRIUMF-Victoria Groups

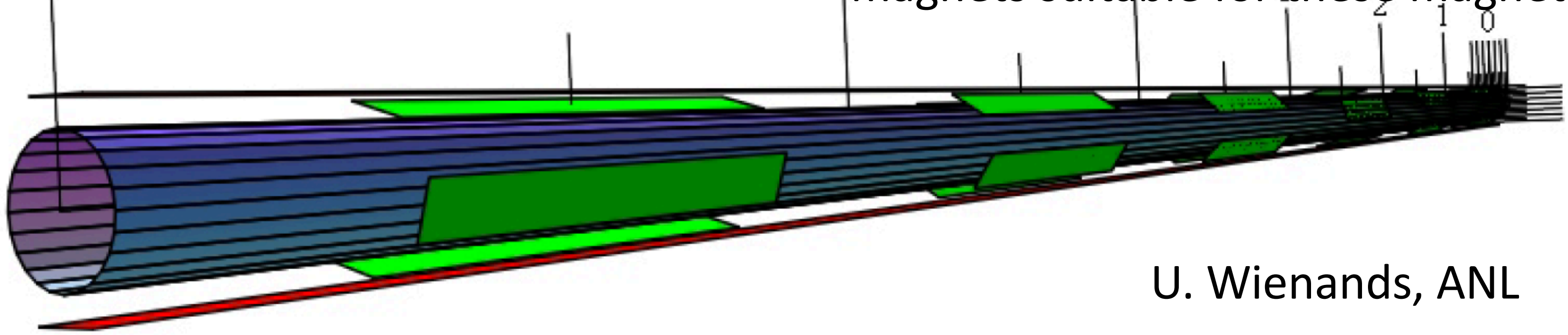
Compact Spin Rotator

- 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



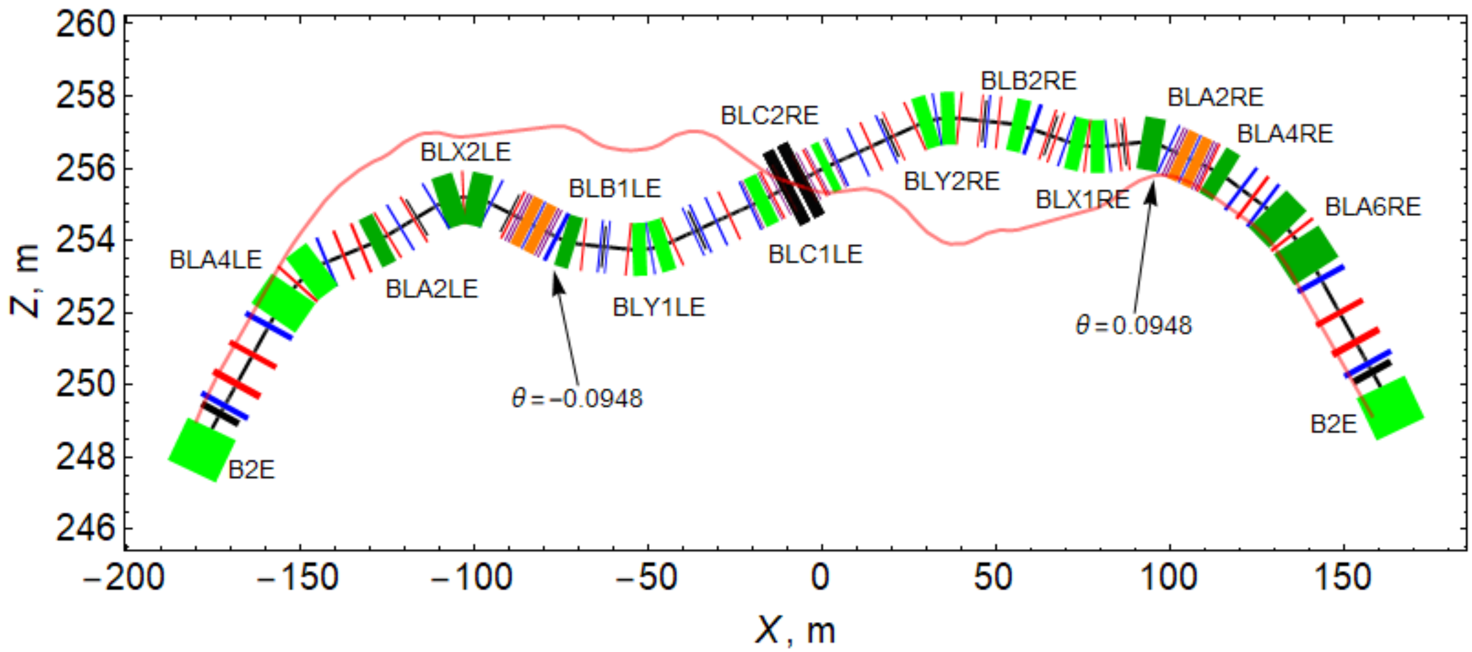
(BNL expertise in construction of direct wind magnets suitable for these magnets)



U. Wienands, ANL

Recent preliminary studies by BINP group

Another Concept: install spin-rotator magnets in drift regions



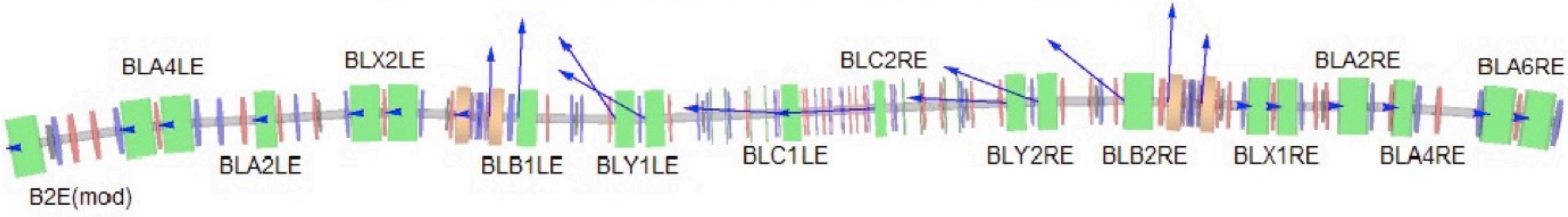
"B2E"	"BLA6RE"	"BLA4RE"	"BLA2RE"	"BLX1RE"	"BLB2RE"	"BLY2RE"	"BLC2RE"
0.0557427	0.0501498	0.0271539	0.0557427	−0.0221788	0.0234696	0.027	0.00591985

"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

$\mathbf{n}_0$ along machine, $E = 7.15\,\text{GeV}$, HER, IP region

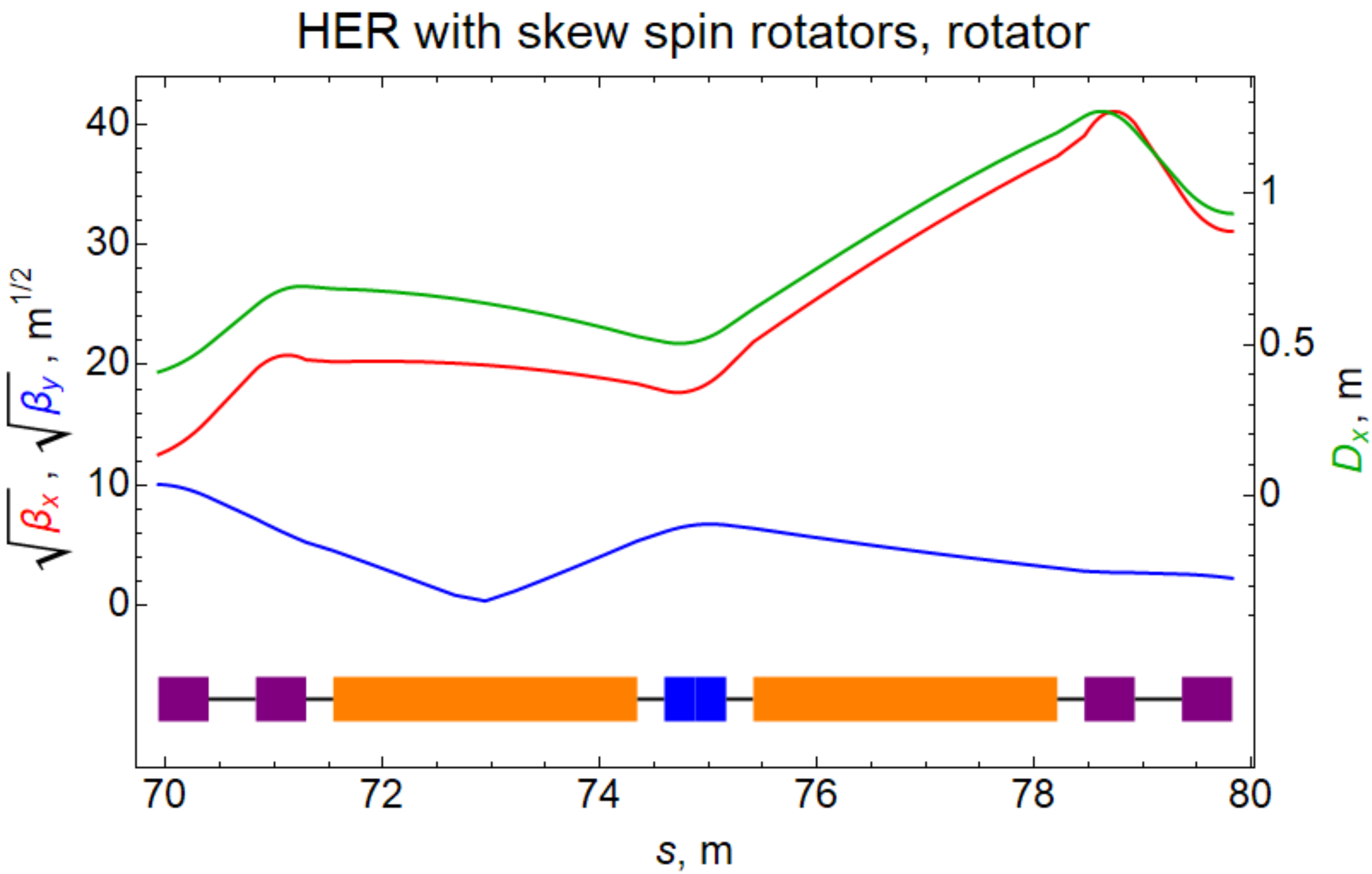


"B2E(mod)"	"BLA2LE"	"BLA2RE"	"BLA4LE"	"BLA4RE"	"BLA6RE"	"BLB1LE"
0.0745895	−0.0181419	0.0591537	0.0520765	0.0280687	0.0501498	−0.0368136
"BLB2RE"	"BLC1LE"	"BLC2RE"	"BLX1RE"	"BLX2LE"	"BLY1LE"	"BLY2RE"
0.0548871	−0.00591049	0.0059199	−0.0310501	0.0570931	−0.0270415	0.018

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

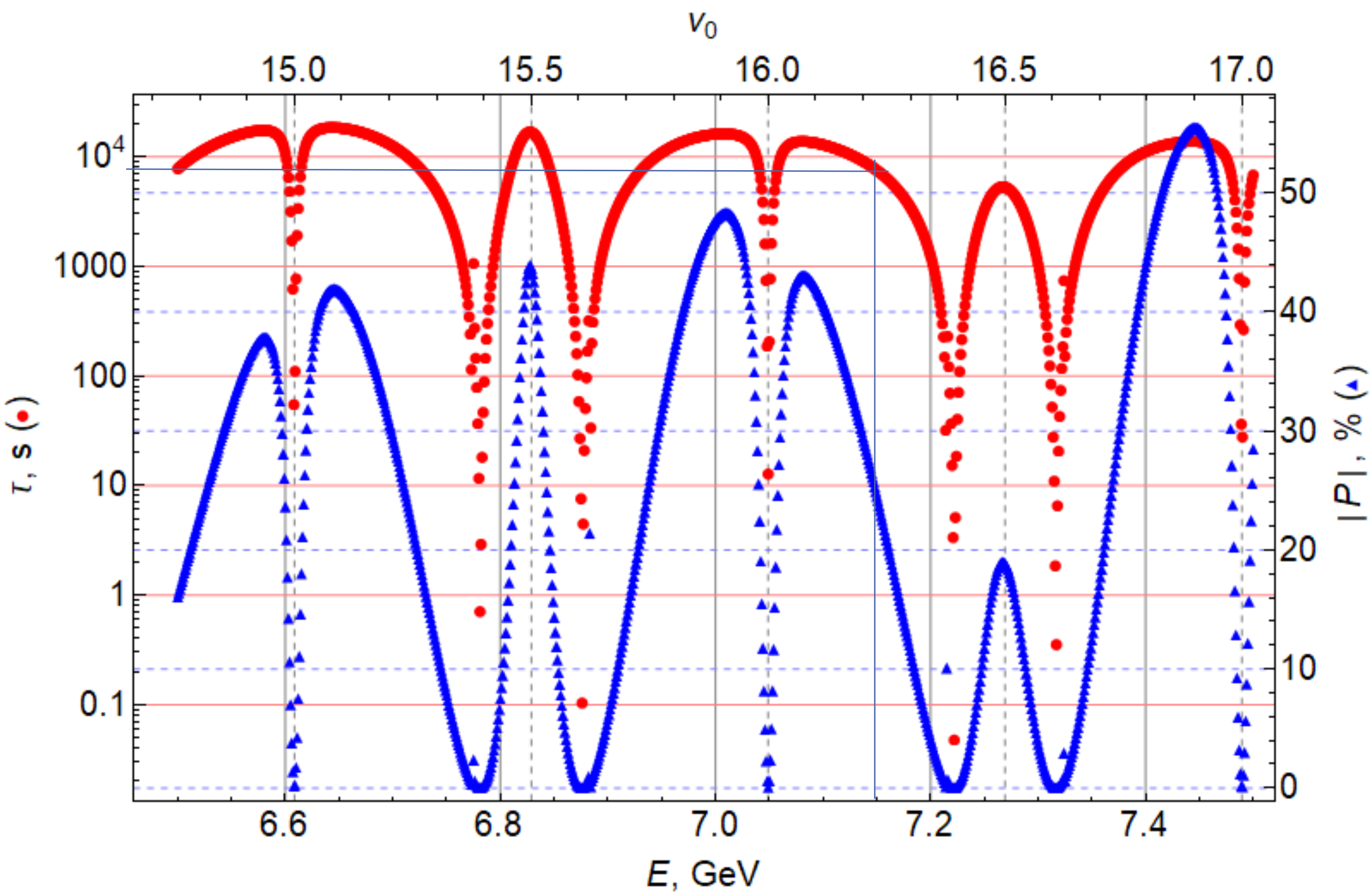
Recent preliminary studies by BINP group



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

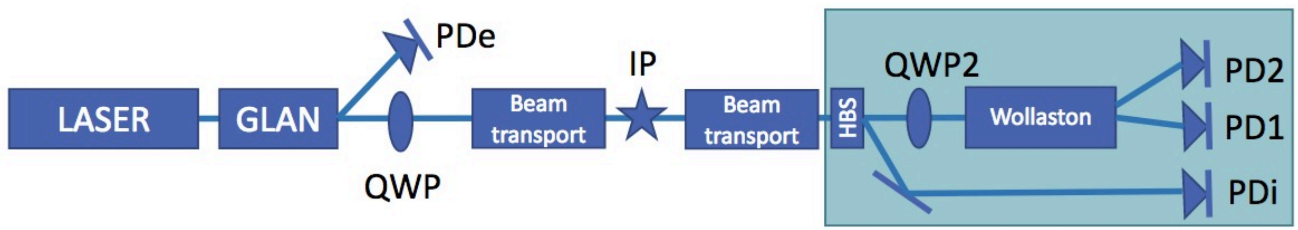
LAL Orsay and U. Manitoba groups

Polarization in SuperKEKB

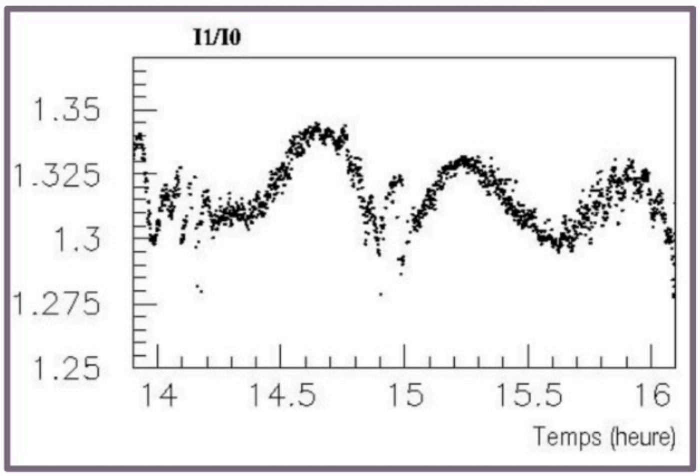
LAL Orsay team (A. Martens, Y. Peinaud,F. Zomer, P. Bambade,F. Le Diberder, K. Trabselsi) **HERA Compton Polarimeter experience**

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 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

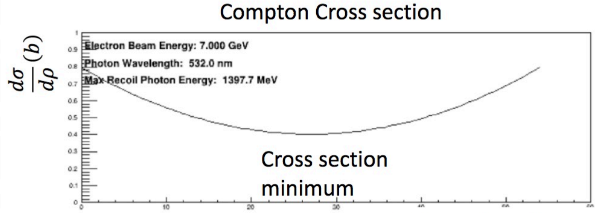
The chip is primarily developed by groups at the U. of Heidelberg and the Karlsruhe Institute of Technology, and intended for various experiments:

- ATLAS
- Mu3e
- PANDA
- P2
- MOLLER

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

Calculations/Simulations

Compton Cross section



Compton Asymmetry