FCC-ee Energy Calibration and Polarization

D. Barber, M. Benedikt, A. Blondel*, A. Bogomyagkov, F. Carlier, E. Gianfelice-Wendt, A. Faus-Golfe, M. Hofer, J. Keintzel, I. Koop, M. Koratzinos, P. Janot, H. Jiang, A. Martens, N. Muchnoi, S. Nikitin, K. Oide, T. Persson, T. Pieloni, R. Tomàs, D. Sagan, D. Shatilov, J. Wenninger*, Y. Wu, and F. Zimmermann

Int. Conf. on High Energy Physics (ICHEP) 2022

Accelerators: Physics, Performance and R&D for Future Facilities

6th - 13th July 2022

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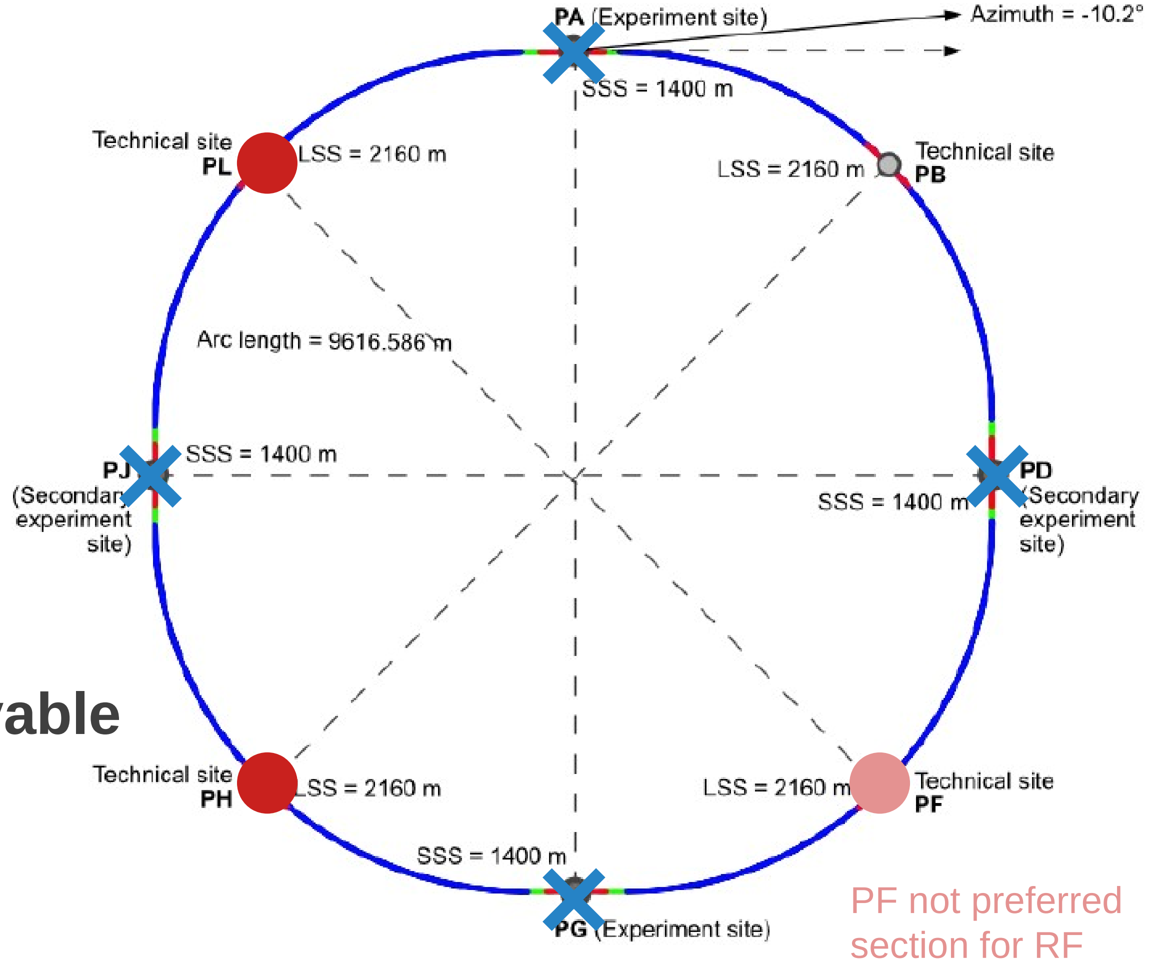
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

K. Oide

Overview FCC-ee

- Higgs and electro-weak factory
- 4 different beam energies
- New “lowest risk” 4 IPs scenario (✕)
  - Perfect symmetry
  - Perfect 4-fold superperiodicity
- 1 or 2 RF-sections (●)
- High precision physics experiments
- → **Up to few keV statistical precision achievable**



PF not preferred section for RF

K. Oide: indico.cern.ch/event/1085318

Energy calibration and polarization working group

indico.cern.ch/category/8678

A. Blondel, E. Gianfelice-Wendt

Z-Line Shape Precision Measurement

Observable	statistics	$\Delta\sqrt{s}_{abs}$ 100 keV	$\Delta\sqrt{s}_{syst-ptp}$ **40 keV**	calib. stats. 200 keV$/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ 85 $\pm$ **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_W^{eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)} \times 10^5$	3	0.1	**0.9**	–	**0.1**

- Uncertainties strongly affected by ECM uncertainties
- A new high precision EW/Higgs factory for improving measurement precision → FCC-ee

For example: Gain factor 5 for precision of Z-width

Demands knowledge of ECM and boosts as precise as possible

- Using resonant depolarization of transversely polarized pilot bunches for average energy measurement

- From average beam energy to ECM and boosts not trivial

Talk: M. Hofer, "FCC-ee Collider Design Overview", Friday 8th July 2022, 09:40

A. Blondel et al., arXiv:2019.12245, 2019.

F. Carlier, E. Gianfelice-Wendt, T. Pieloni, Y. Wu

Polarization and Spin Tune

- Lepton beams polarize naturally transversely over time → Sokolov-Ternov-Effect
- Depolarization naturally from synchrotron radiation, resonances, etc.
- Maximum polarization at about 92.4 % in lepton storage rings

$$\tau^{-1} = \tau_{bks}^{-1} + \tau_{dep}^{-1}$$

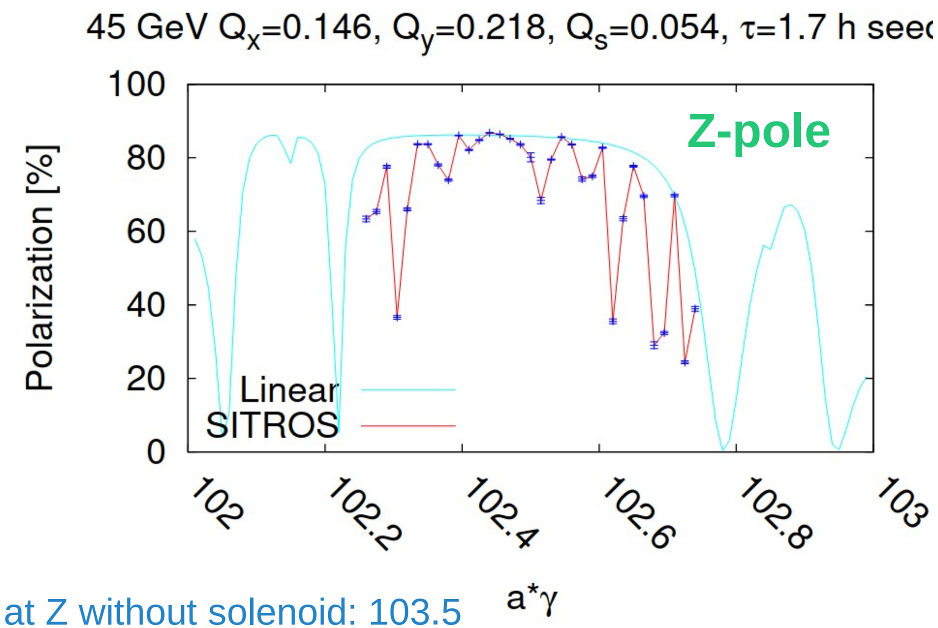
Effective polarization rate — Depolarization rate

Baier-Katkov-Strakhovenko polarization rate

$$\tau_{bks}^{-1} = \frac{5\sqrt{3}}{8}\frac{\hbar r_e \gamma^5}{m_e C}\oint ds \frac{1 - \frac{2}{9}(\hat{n}_0(s)\cdot\hat{s})^2}{|\rho(s)|^3}$$

Polarization direction in ŷ for planar ring

Strong unexpected resonance found for SITROS simulations



aγ at Z without solenoid: 103.5

E. Gianfelice-Wendt, indico.cern.ch/event/727555/contributions/3468285, 2019.

- Resonances with transverse and longitudinal axis

Q_x … horizontal tune
Q_y … vertical tune
Q_s … synchrotron tune
m_i, k … integer
a … gyromagnetic moment
γ … relativistic gamma

$$a\gamma + m_x Q_x + m_y Q_y + m_s Q_s = k$$

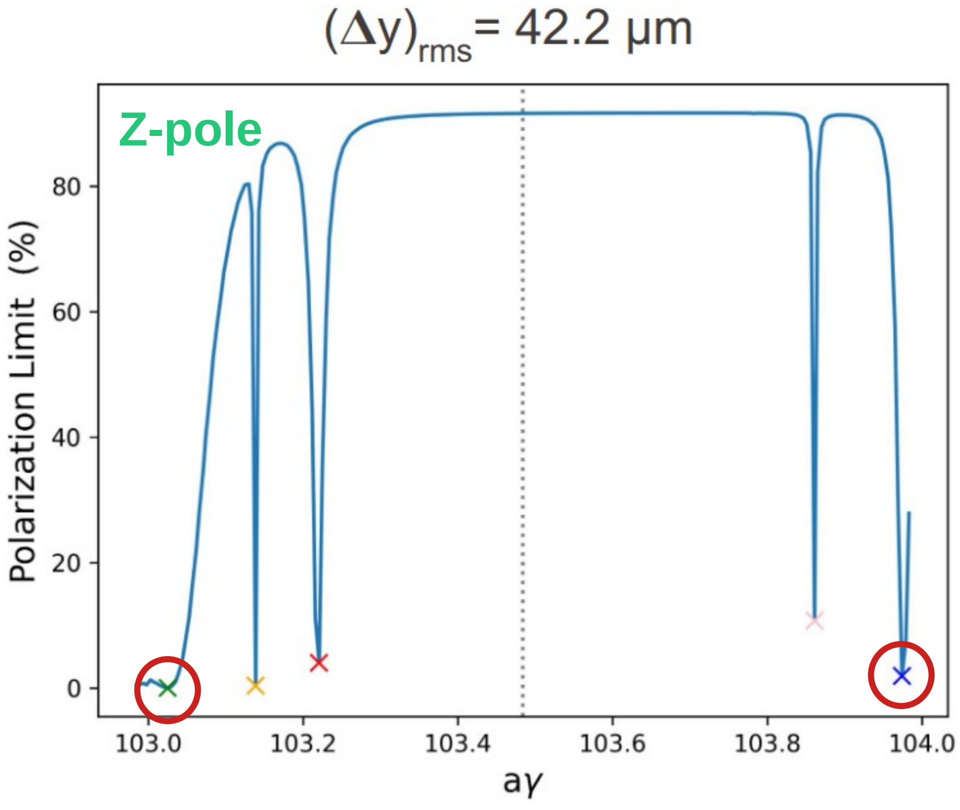
$a\gamma$: Spin tune for ideal machine; $m_x Q_x + m_y Q_y$: Transverse planes; $m_s Q_s$: Longitudinal plane

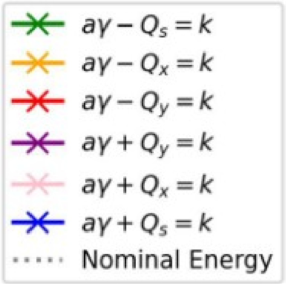
Y. Wu: indico.cern.ch/event/1119730/

F. Carlier, T. Pieloni, Y. Wu

Error Sensitivity

- Resonances enhanced with increasing closed orbit
- More misalignments can reduce maximum polarization → orbit corrections essential



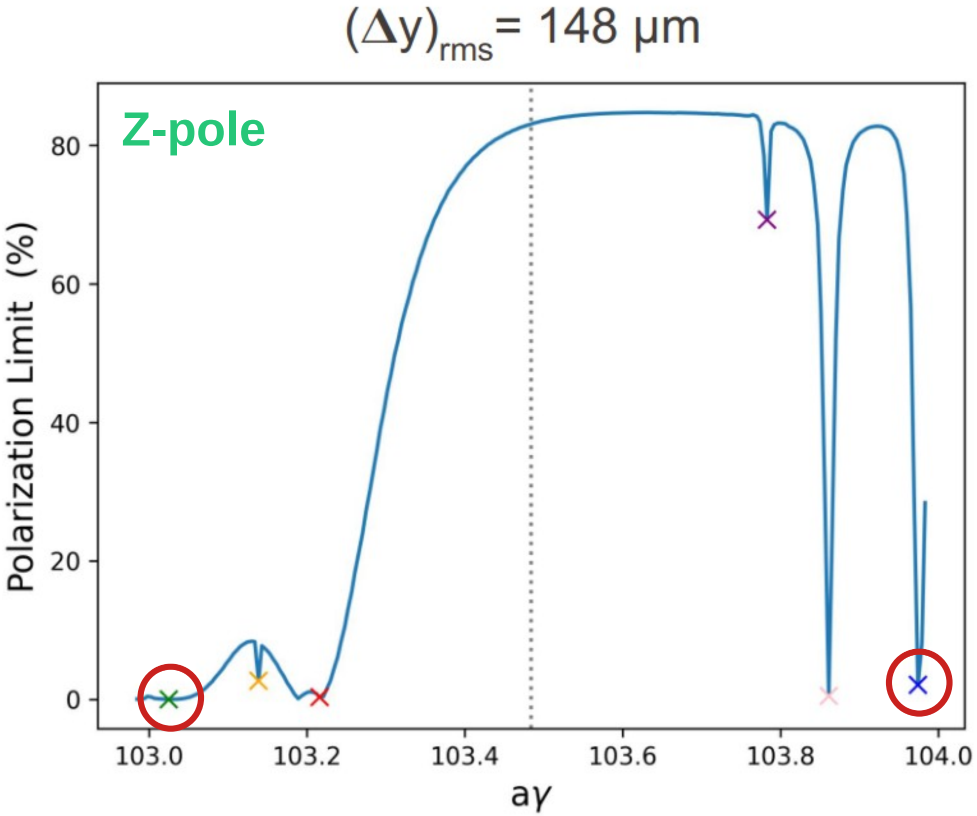


Misalignment errors in Dipoles, quadrupoles Sextupoles

Q_x = .139 Q_y = .219

Q_s = 0.025

Small emittances and large Q_s –> Resonances with the longitudinal plane dominating and symmetric ± Q_s



Y. Wu: indico.cern.ch/event/1119730/

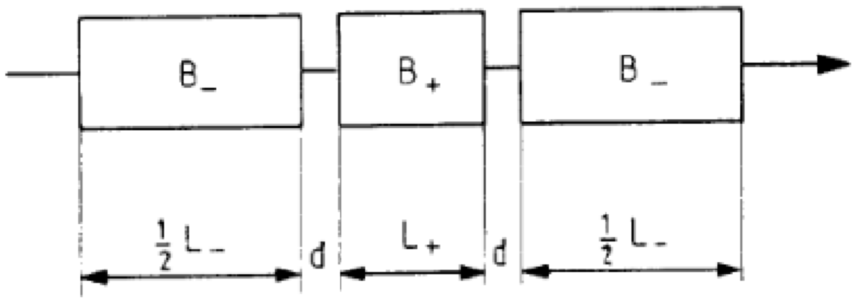
M. Hofer, K. Oide

Wigglers I

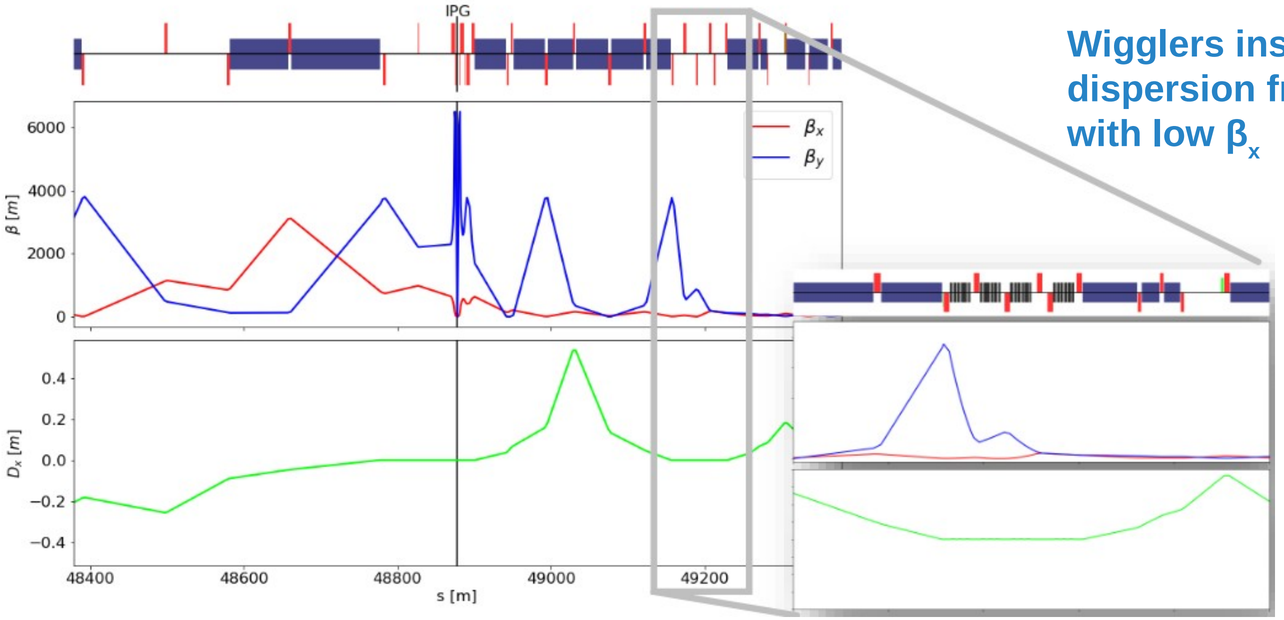
- Very long natural polarization time in FCC-ee
- Wigglers improve polarization time significantly

$$\left(\frac{\sigma_E}{E}\right)^2 \propto \frac{E^4}{\gamma^3 \tau_p \Delta E_{loss}} \qquad r = \frac{B_+}{B_-} = \frac{L_-}{L_+}$$

Follow 3 three-block design from LEP



Parameter	FCC-ee	LEP
Number of units per beam	24	8
B_+ [T]	0.7	1.0
L_+ [mm]	430	760
r	6	2.5
d [mm]	250	200
Crit. Energy of SR photons [keV]	968	1350



Wigglers installed in dispersion free section with low β_x

Polarization time decreases from 248 h to 12 h

Energy spread increases from 17 MeV to 64 MeV

M. Hofer: indico.cern.ch/event/1080577/

M. Hofer, K. Oide

Wigglers II

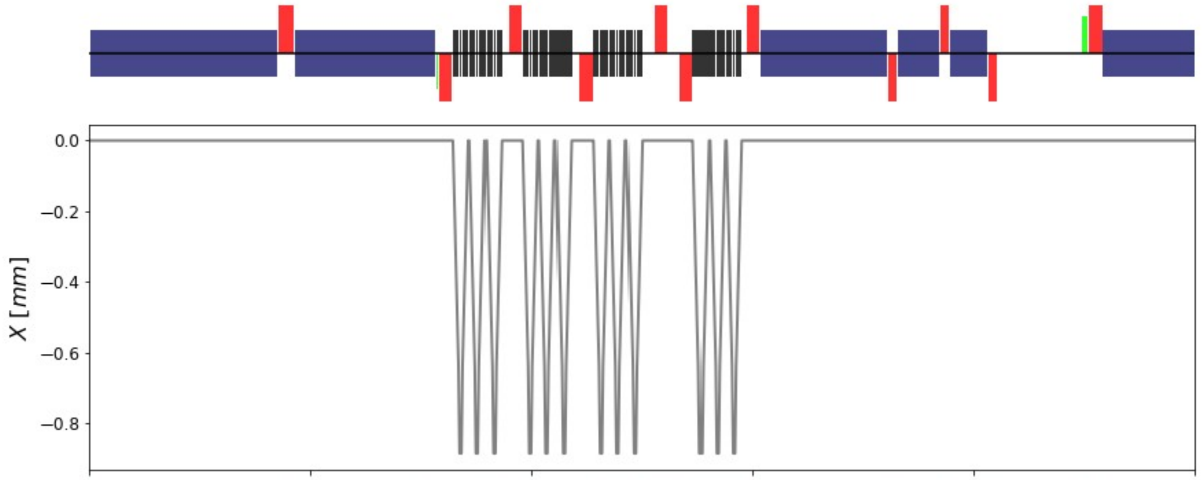
- Operational scenario:
  - Inject few pilot bunches
  - Use wigglers to reach ~5 % polarization
  - Switch wigglers off
  - Inject all bunches
  - Measure polarization to retrieve energy

Resonant depolarization together with polarimeter

Determining average energy

Measurement of photons from e+e- –> μ+μ-(γ)

Determining boosts



- Caveat of wigglers:
- Orbit generates synchrotron radiation
- Photons with critial energy O(MeV)
- → Can generate neutrons
- Radiation protection challenges

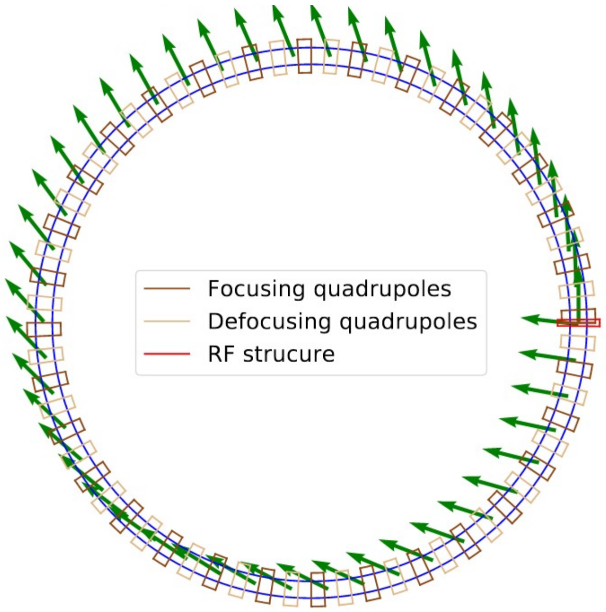
M. Hofer: indico.cern.ch/event/1080577/

A. Bogomyagkov, V. Caudan, E. Gianfelice-Wendt

Energy from Spin Tune

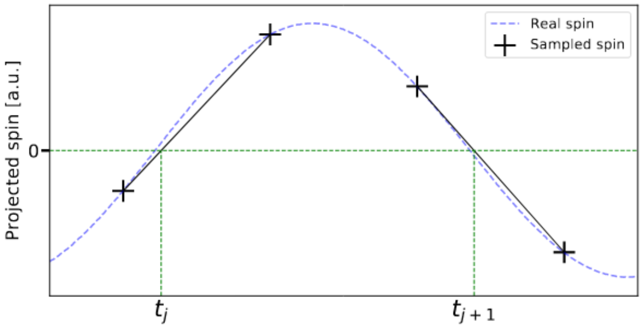
- Using resonant depolarization and polarimeter to determine average beam energy
- Promising simulations performed for simple FODO cell lattice with 100 m circumference

Precession of spin over one revolution in ideal machine with spin tune of about 0.25



E … energy
m … mass
c … speed of light
ν … spin tune
a … anomalous magnetic dipole moment

$$E = mc^2 \left(\frac{\nu}{a} - 1 \right)$$



$$\nu_j \approx \frac{1}{2(t_{j+1} - t_j)} \frac{1}{f_{\text{rev}}}$$

Spin tune measurement might not be exact beam energy measurement

Various contributions on the average beam energy estimated

synchrotron oscillations	ΔE/E	-2 10^{-14}
Energy dependent momentum compaction	ΔE/E	10^{-7}
Solenoid compensation		2 10^{-11}
Horizontal betatron oscillations	ΔE/E	2.5 10^{-7}
Horizontal correctors*)	ΔE/E	2.5 10^{-7}
Vertical betatron oscillations **)	ΔE/E	2.5 10^{-7}
Uncertainty in chromaticity correction O(10^{-6}) ΔE/E		5 10^{-8}
invariant mass shift due to beam potential		4 10^{-10}

E. Gianfelice, I. Kopp, N. Muchnoi, S. Nikitin, J. Wenninger

Resonant Depolarization

- Spin precession frequency Ω given by energy

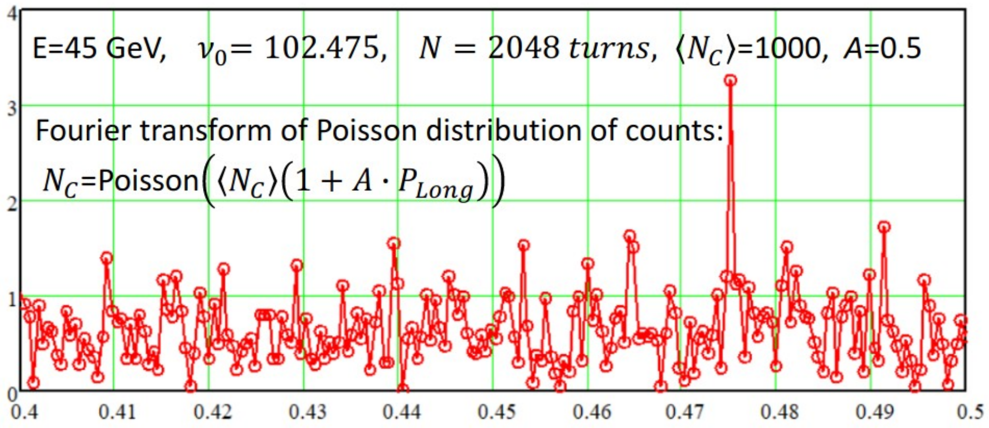
ω_0 … revolution frequency
aγ … ~ spin tune

$$\Omega = \omega_0 \left(1 + a\gamma\right)$$

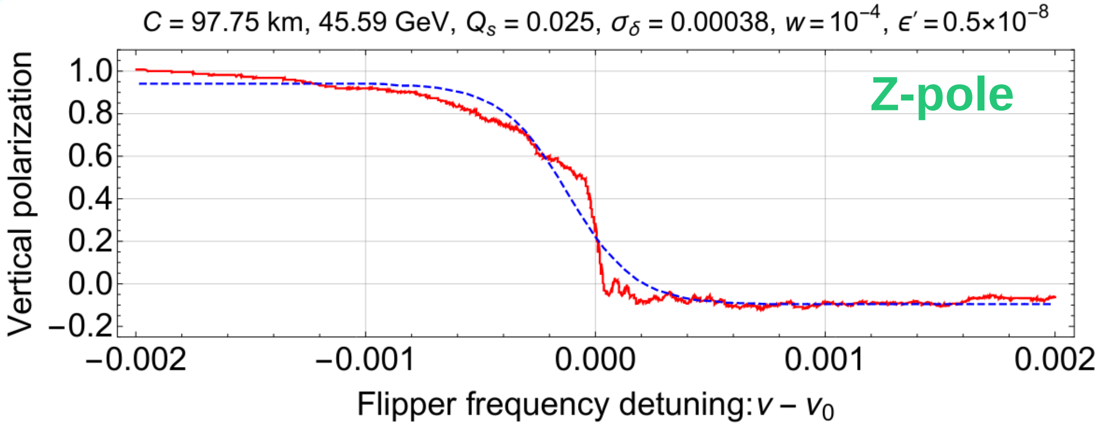
- Measuring depolarizing frequency Ω
- Resonant depolarization by RF kicker with ω_d
- Resonant condition given by $\Omega = n\omega_0 \pm \omega_d$
- Technique used in various machines
- Measured precision of a few keV

Simulations for FCC-ee
Sweep through driving frequencies (260 s duration)

Fourier transformation of counted electrons with high energy loss



Specify depolarizer for FCC-ee ongoing

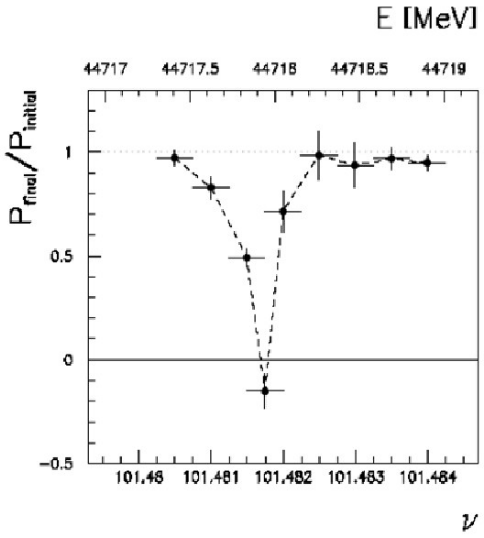


E. Gianfelice, The polarization code challenge, FCC November Week 2020.
N. Muchnoi, FCC-ee polarimeter, arXiv:1803.09595, 2021.
S. Nikitin, Possible beam studies at VEPP-4M, FCC November Week 2020.
FCC-ee polarization workshop, 18-27 October 2017.
I. Koop, indico.cern.ch/event/1147611/ , 2022.

E. Gianfelice-Wendt, I. Kopp

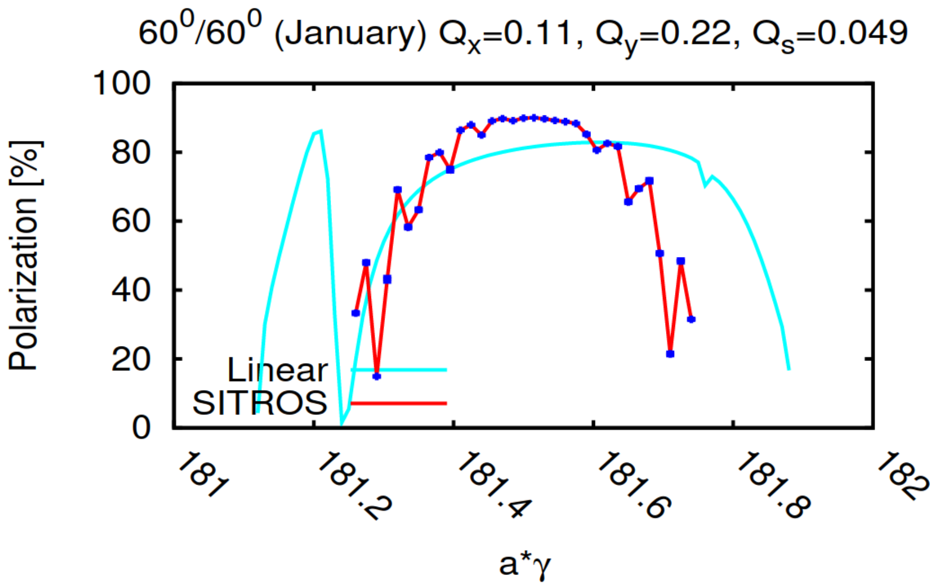
Polarization at W-pole

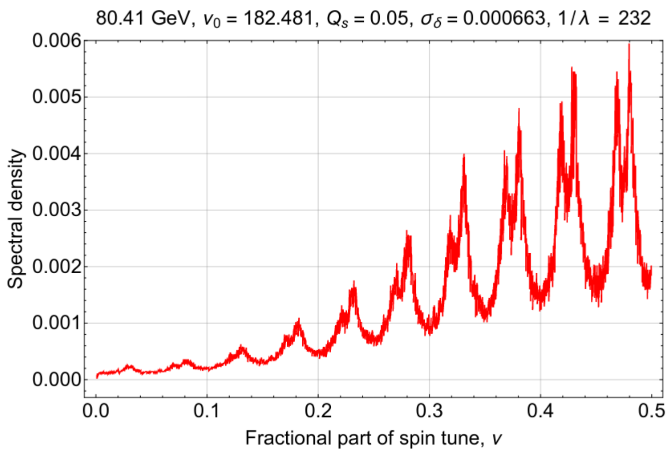
- Same errors as for Z-pole gives sufficient polarization for W
- Sweeping as at Z does not work as Qs sidebands too strong

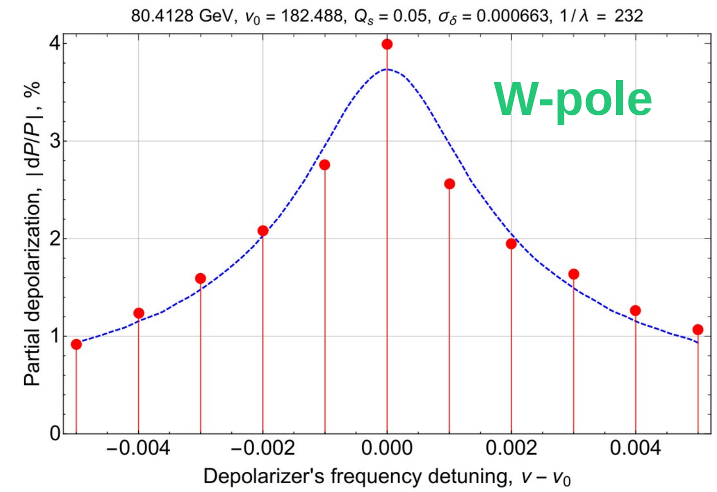


Measurements at LEP Shorter depolarization steps to improve precision

Large synchrotron sidebands after Fourier transform caused by large energy spread







ay at W without solenoid: 181.55

Polarization after applying misalignment errors and correction of vertical dispersion

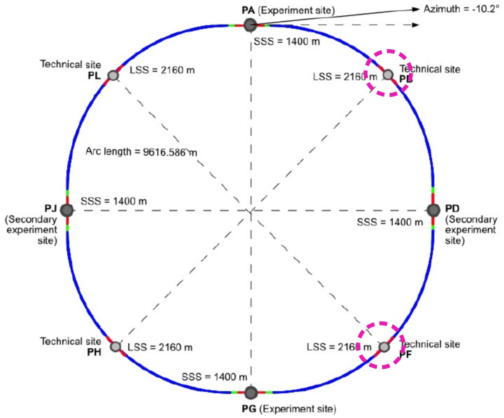
Several short depolarization steps required instead of one long sweep, similar to LEP

A. Blondel et al., arXiv:2019.12245, 2019.

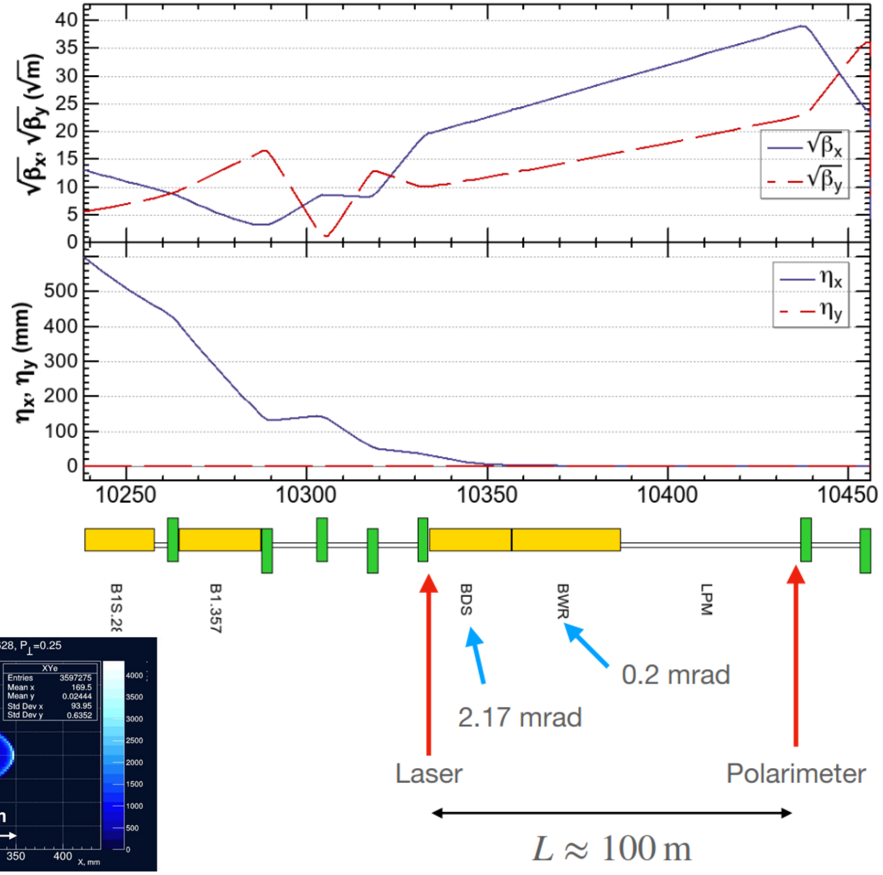
M. Hofer, A. Martens, N. Muchnoi, K. Oide, J. Wenninger

Polarimeter

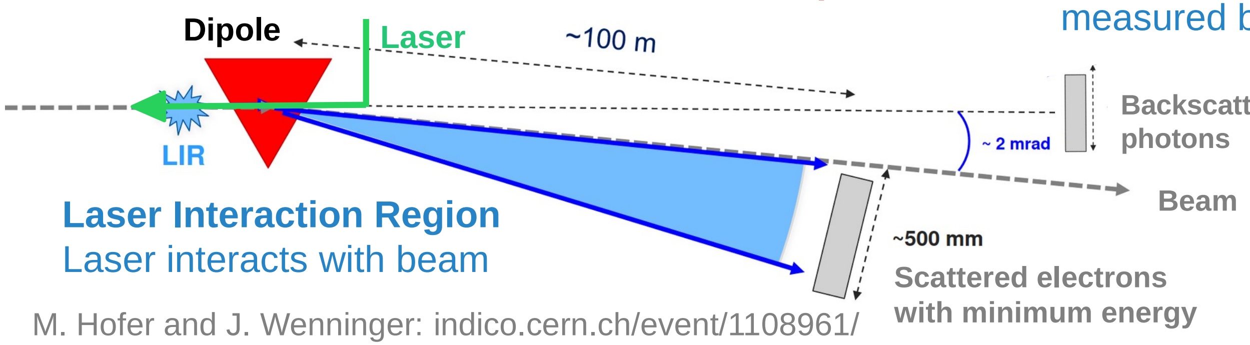
- One polarimeter per beam
- First definition of specifications
  - 2 mrad angle
  - 100 m drift space
  - 2 m space for LIR (monitoring of location to be designed)



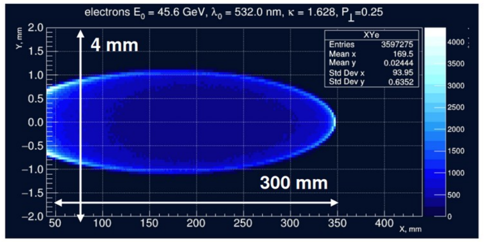
Polarimeter implemented in straight section without IP or RF



Allows measurement of three coordinates of beam polarization



Scattered electrons to be measured by Si pixel detector



Laser Interaction Region
Laser interacts with beam

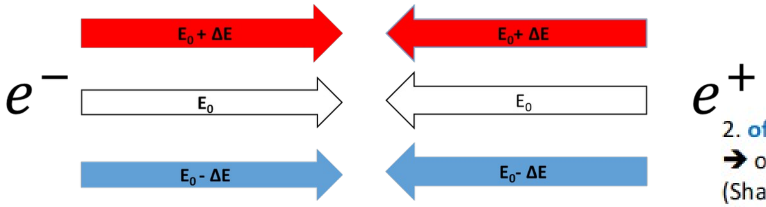
M. Hofer and J. Wenninger: indico.cern.ch/event/1108961/
N. Muchnoi: indico.cern.ch/event/1119730/
K. Oide: indico.cern.ch/event/1162192

A. Blondel, J. Keintzel, T. Persson, D. Shatilov

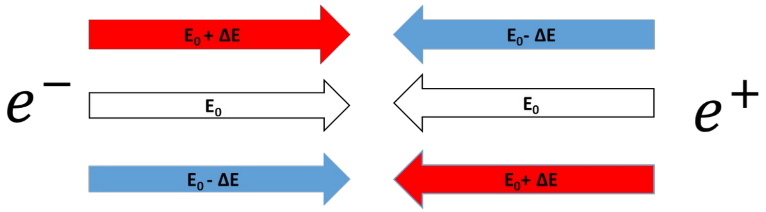
From Average Energy to ECM

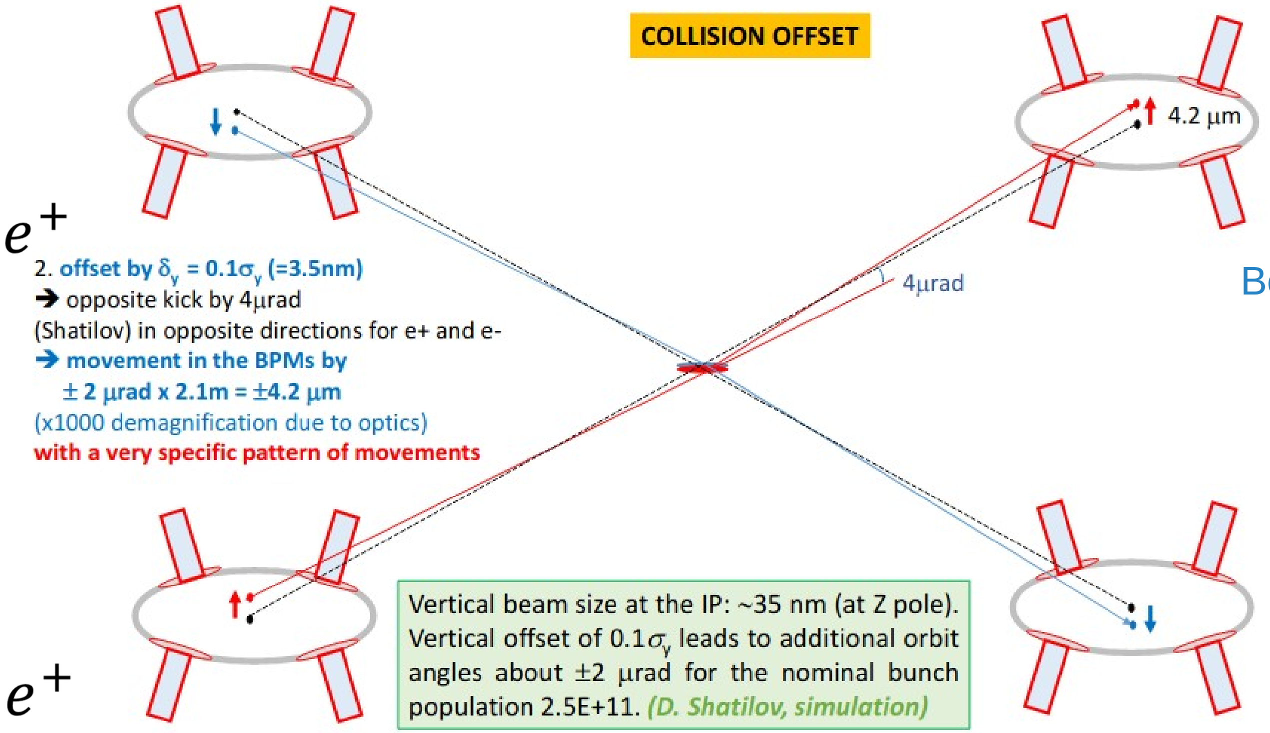
- ECM depends on many factors (collision offsets, dispersion, beamstrahlung, radiation losses, ...)

Same sign dispersion at the IP leads to change of ECM



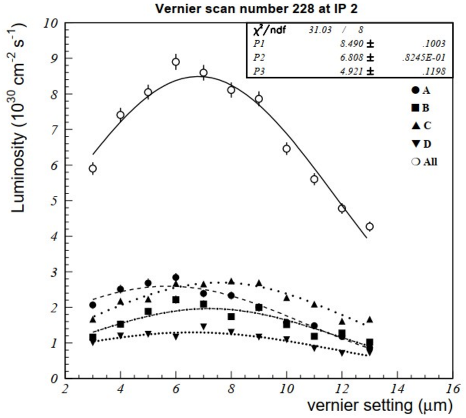
Opposite sign dispersion helps reducing ECM spread
→ **Monochromatization**



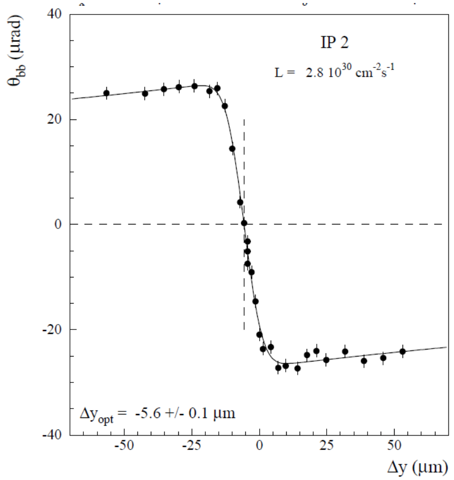


A. Blondel: https://indico.cern.ch/event/1064327/

Vernier-scans performed at LEP



Beam-beam deflection at LEP

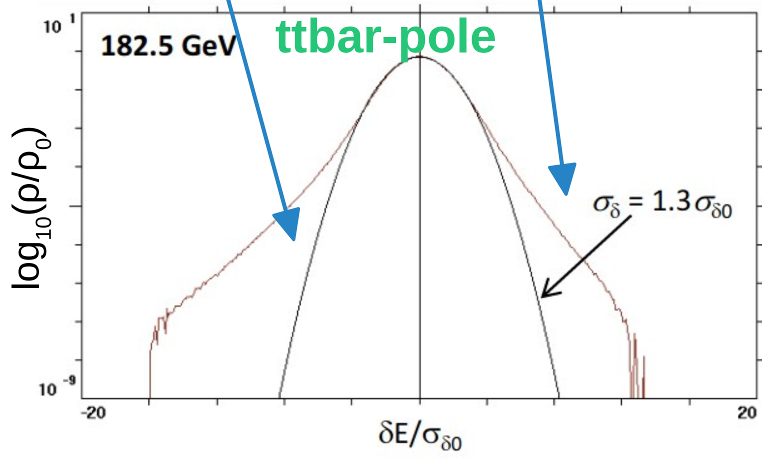


A. Blondel, P. Janot, D. Shatilov

Beamstrahlung and Boosts

- Beamstrahlung (BS): crossing bunches interact with force field created by the other bunch
- Dominant effect: increased energy spread
- **Does not shift peak energy**

Beam energy spectrum with and without beamstrahlung

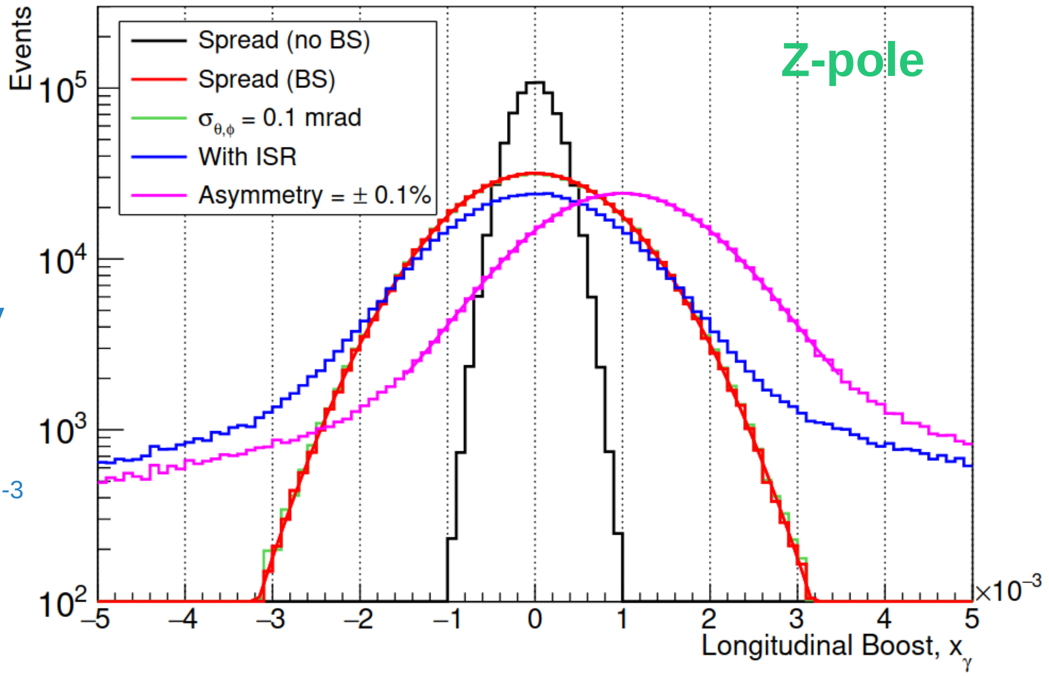


Black: no beamstrahlung
Red: + beamstrahlung
Green: + angular resolution
Blue: + photon emission
Pink: + asymmetry between electron and positron energy

Only asymmetric energies shift the center of the energy spectrum for dimuon events

Measuring 10^6 dimuon events yields precision of 10^{-3}
5 min measurements at FCC Z-mode gives boost precision of 50 keV and one 8 h shift will give 5 keV

Statistics of 1 million dimuon events at Z-pole
e+e- –> μ+μ- (γ)
(γ)… Initial-State-Photon (ISR)



A. Blondel et al., arXiv:2019.12245, 2019.

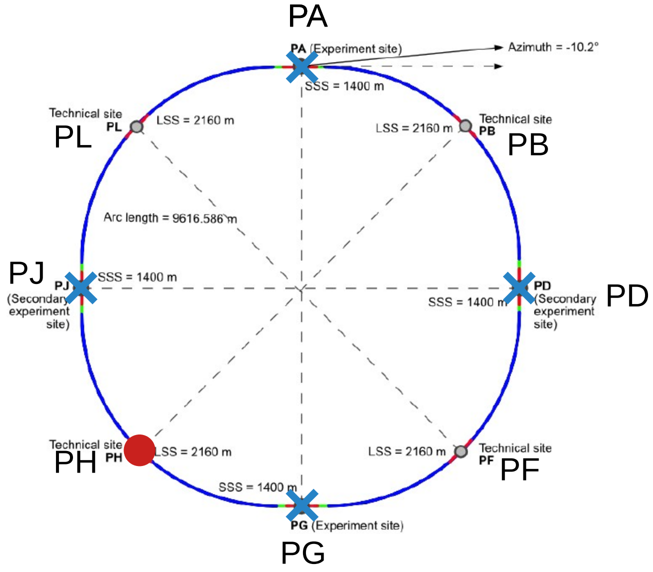
A. Blondel, J. Keintzel, T. Persson, D. Shatilov

ECM and Boosts for Z-Mode

- **PH: 0.1 GV, 400 MHz** cavity
- ≲ 0.62 MeV beamstrahlung losses per beam and IP (simulations)
- 40 MeV radiation losses per revolution

One 8 h shift will give 5 keV precision

Sum of losses close to sum of absolute boosts



Simulations performed in MAD-X
Benchmarking with analytical equations ongoing
→ Exact numbers not final

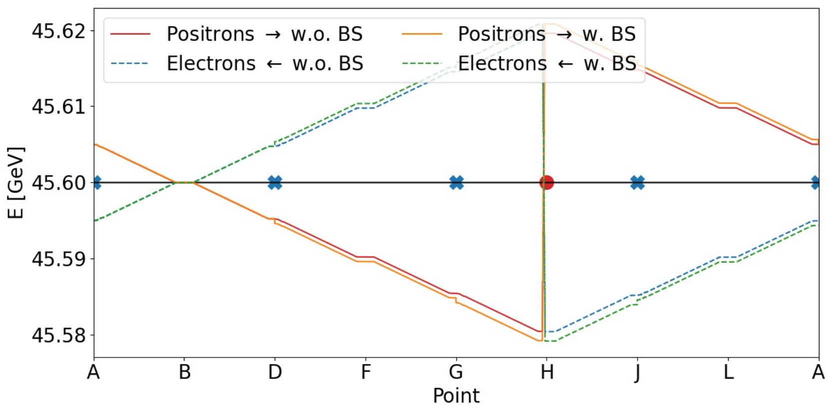
1 RF → almost constant ECM

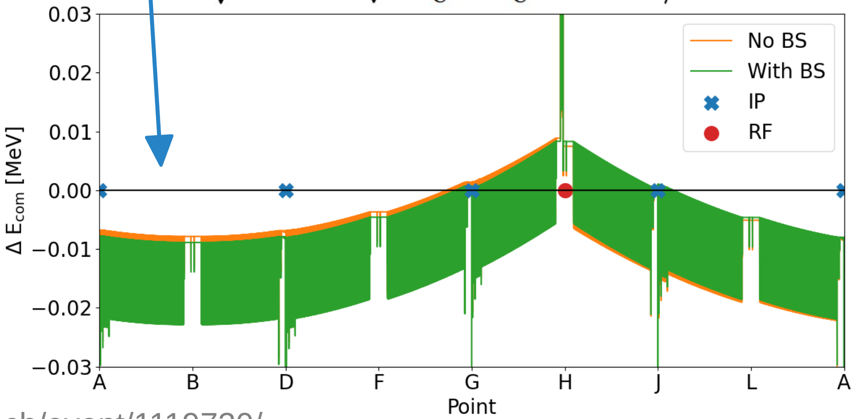
IP	ΔECM [keV]	Boost [MeV]
PA	- 7.851	10.665
PD	- 7.931	- 10.108
PG	0.570	- 30.883
PJ	0.844	31.439

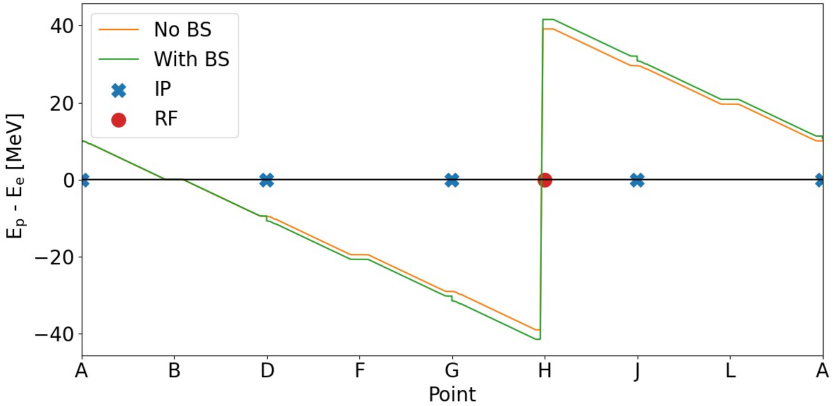
$$\Delta E \propto \gamma_{\mathrm{rel}}^4$$

$$\sqrt{s} = 2\sqrt{E_{e+}E_{e-}}\cos\alpha/2$$

Boost: + for e+; - for e-







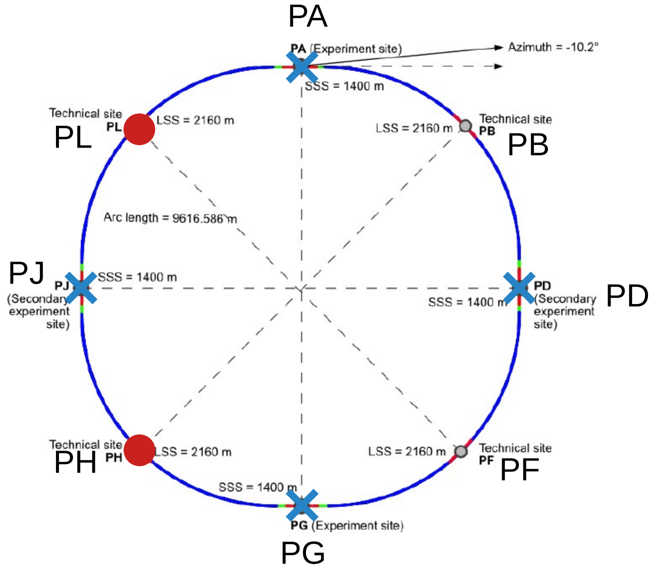
J. Keintzel: indico.cern.ch/event/1119730/

A. Blondel, J. Keintzel, T. Persson, D. Shatilov

ECM and Boosts for ttbar-Mode

- **PH: 5 GV, 400 MHz** cavity and **PL: 6.7 GV, 800 MHz** cavity
- ≲ 14 MeV beamstrahlung losses per beam and IP (simulations)
- 10 GeV radiation losses per revolution

IP	ΔECM [MeV]	Boost [GeV]
PA	42.813	5.187
PD	- 30.176	0.157
PG	34.236	- 4.873
PJ	-152.467	- 0.233



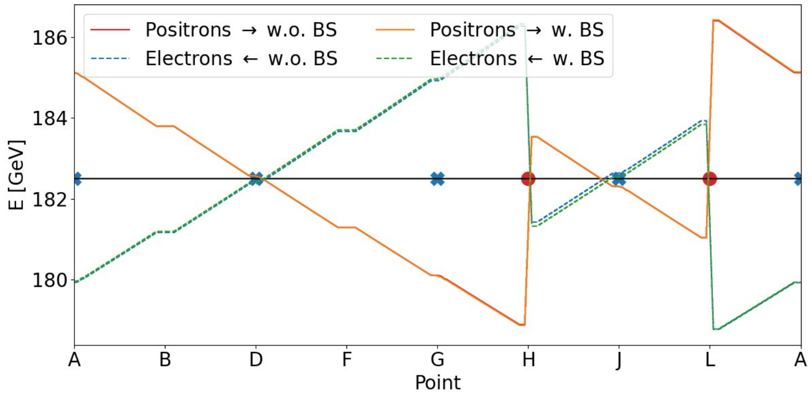
Different ECM and boosts at the IPs result from asymmetric RF placement, radiation losses and BS

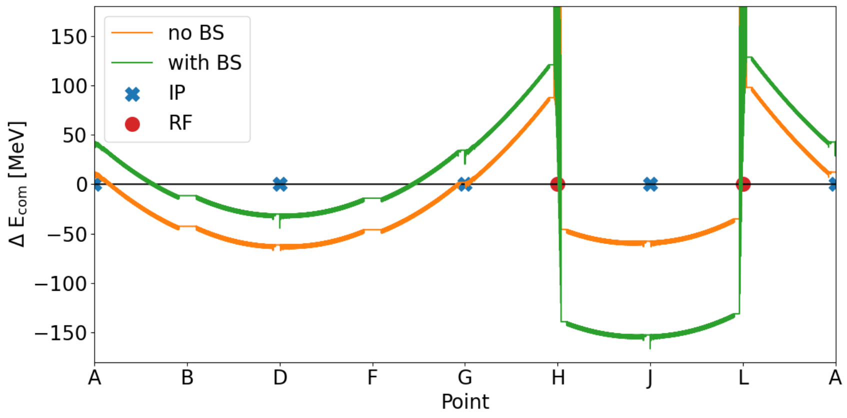
BS small impact on boosts

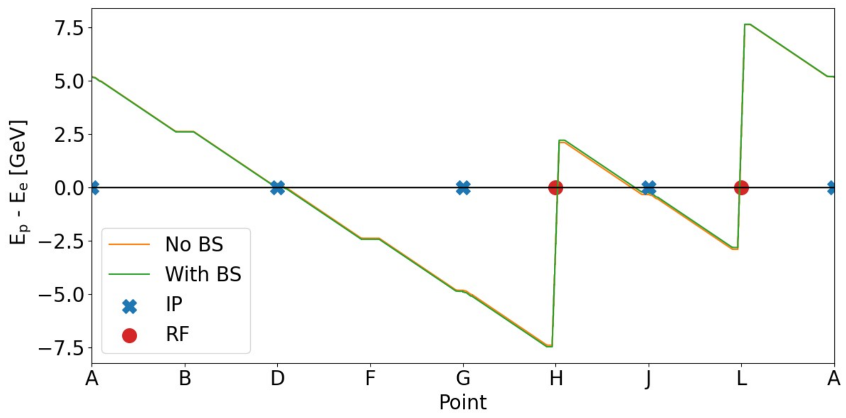
$$\Delta E \propto \gamma_{\mathrm{rel}}^4$$

$$\sqrt{s} = 2\sqrt{E_{\mathrm{e+}} E_{\mathrm{e-}}} \cos \alpha/2$$

Boost: + for e+; - for e-







Goals and Summary

- Simulation and optimization of beam polarization (at least 10 % required)
  - Improving polarization time with wigglers and studying lifetime
  - Studying depolarization sensitivity of various machine errors
  - Simulate resonant depolarization process including sensitivity on beam parameters
- Define parameters for crucial beam diagnostics
  - Polarimeter placement and design
  - Collision monitoring (beamstrahlung monitor, etc.)
- Prediction of beam energies, ECM and boosts at all IPs for all energy stages
  - Including studying the sensitivity of the RF-placement
- Exploration and validation of monochromatization techniques

A lot of work still remains, but already numerous promising results of recent progress presented here

A lot of fun ahead of us!

Energy calibration and polarization
indico.cern.ch/category/8678

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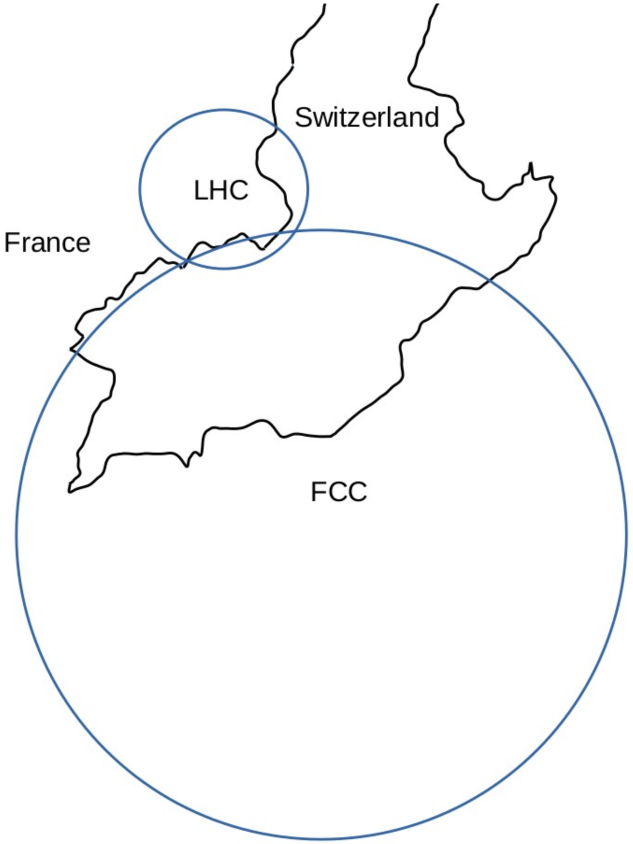
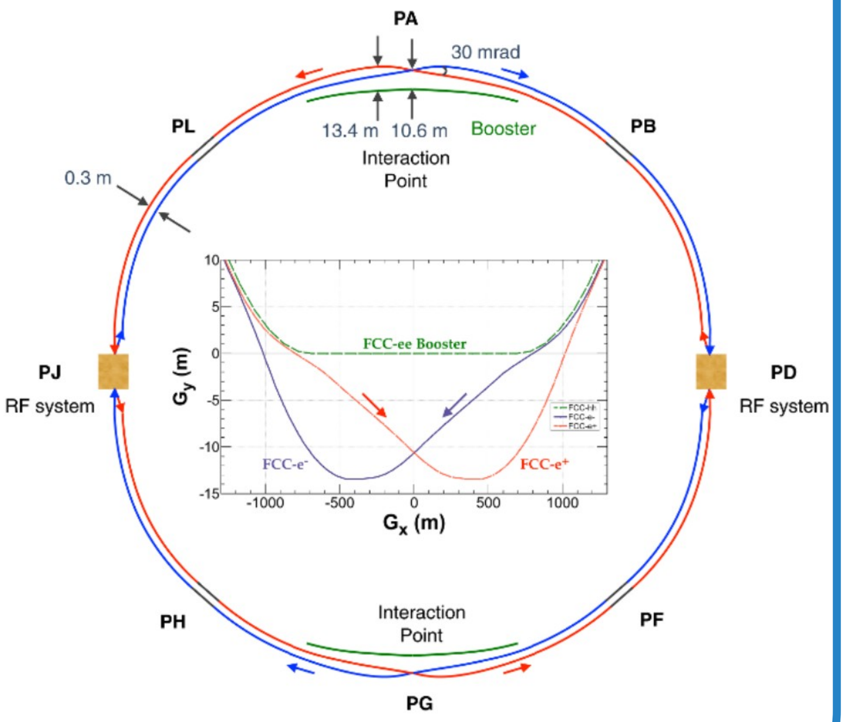
Future Circular Colliders

Inspired by LEP-LHC programm

Re-using CERN infrastructure

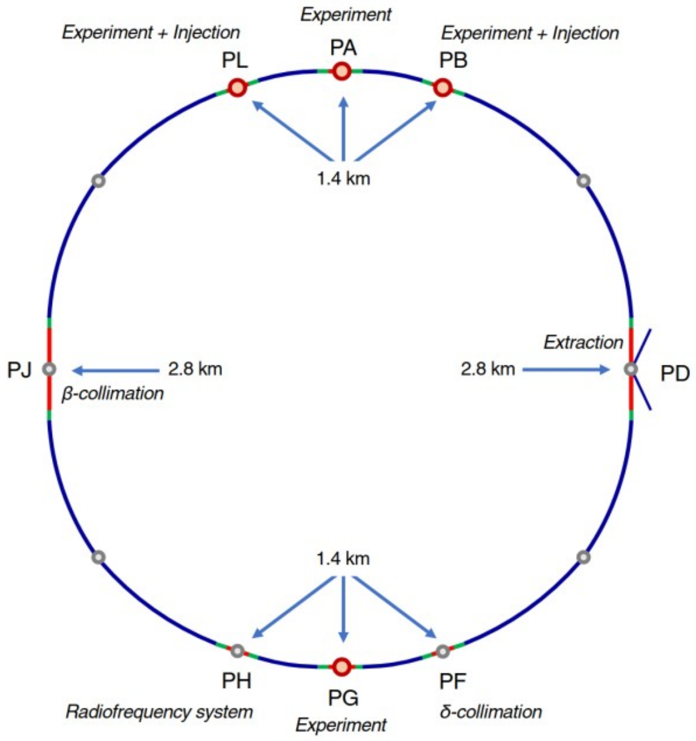


FCC-ee
Electron-positron collider



M. Benedikt et al. (ed), FCC CDR, Eur. Phys. J. Spec. Top. 228, p. 261-623, 2019.

FCC-hh
Proton-proton collider

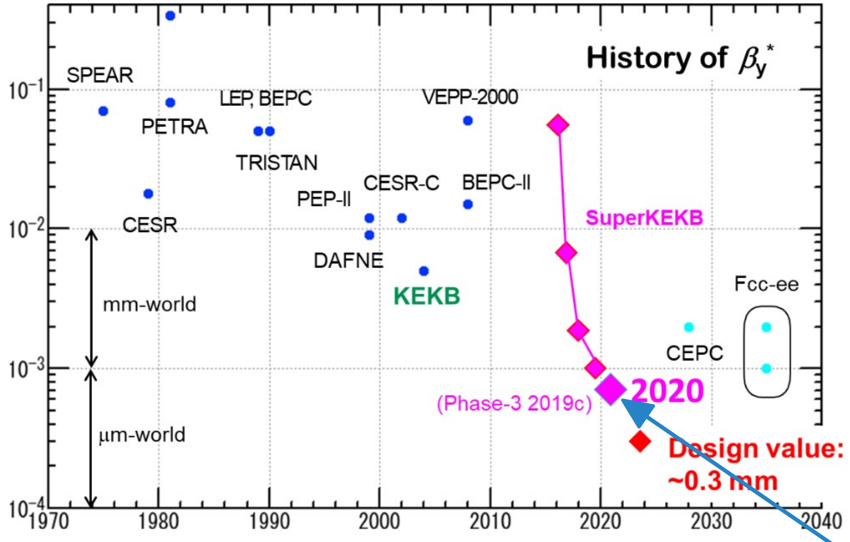


M. Benedikt et al. (ed), FCC CDR, Eur. Phys. J. Spec. Top. 228, p. 755-1107, 2019.

K. Oide

Overview FCC-ee

- Higgs and electro-weak factory
- 4 different beam energies



Parameter	Z	WW	ZH	ttbar
Beam energy [GeV]	45	80	120	182.5
Beam current [mA]	1390	147	29	5.4
Bunches per Beam	16640	2000	393	48
Bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss per turn [GeV]	0.036	0.34	1.72	9.21
Long. damping times [turns]	1281	235	70	20
Polarization time [min]	15000	900	120	15
β_x^*/β_y^* [cm]	15/0.08	20/0.1	30/0.1	100/0.16
ε_y^* [pm]	1.0	1.7	1.3	2.9
Bunch length with SR/BS [mm]	3.5/12.1	3.0/6.0	3.3/5.3	2.0/2.5
Luminostiy per IP [10^{34} cm^{-2}s^{-1}]	230	28	8.5	1.55

β_y^* of 0.8 mm already demonstrated at SuperKEKB

A. Blondel, J. Keintzel, T. Persson, D. Shatilov

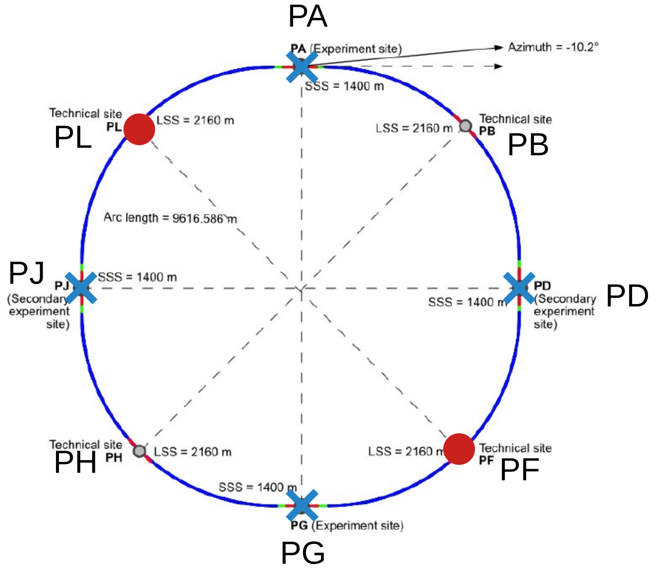
ECM and Boosts for ttbar-Mode

- PH: 5 GV, 400 MHz cavity and PL: 6.7 GV 800 MHz cavity
- 14 MeV beamstrahlung losses per beam and IP (simulations)
- 10 GeV radiation losses per revolution

Different ECM and boosts at the IPs result from, radiation losses and BS

BS small impact on boosts

IP	ΔECM [MeV]	Boost [GeV]
PA	12.663	2.574
PD	11.043	- 2.455
PG	- 46.531	2.573
PJ	- 48.155	- 2.454



$$\Delta E \propto \gamma_{\mathrm{rel}}^4$$

$$\sqrt{s} = 2\sqrt{E_{e+}E_{e-}}\cos \alpha/2$$

Boost: + for e+; - for e-