Beam Polarization For Future e+e- Colliders

Jacqueline Keintzel

On behalf of

The FCC-ee EPOL working group

Special thanks to: Alain Blondel, Rogelio Tomas, Guy Wilkinson and Frank Zimmermann

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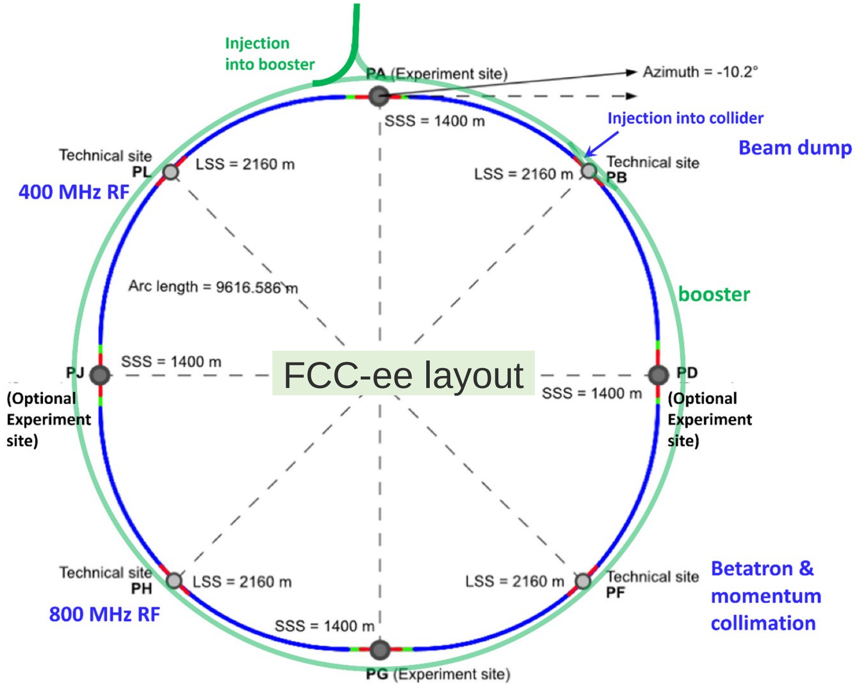
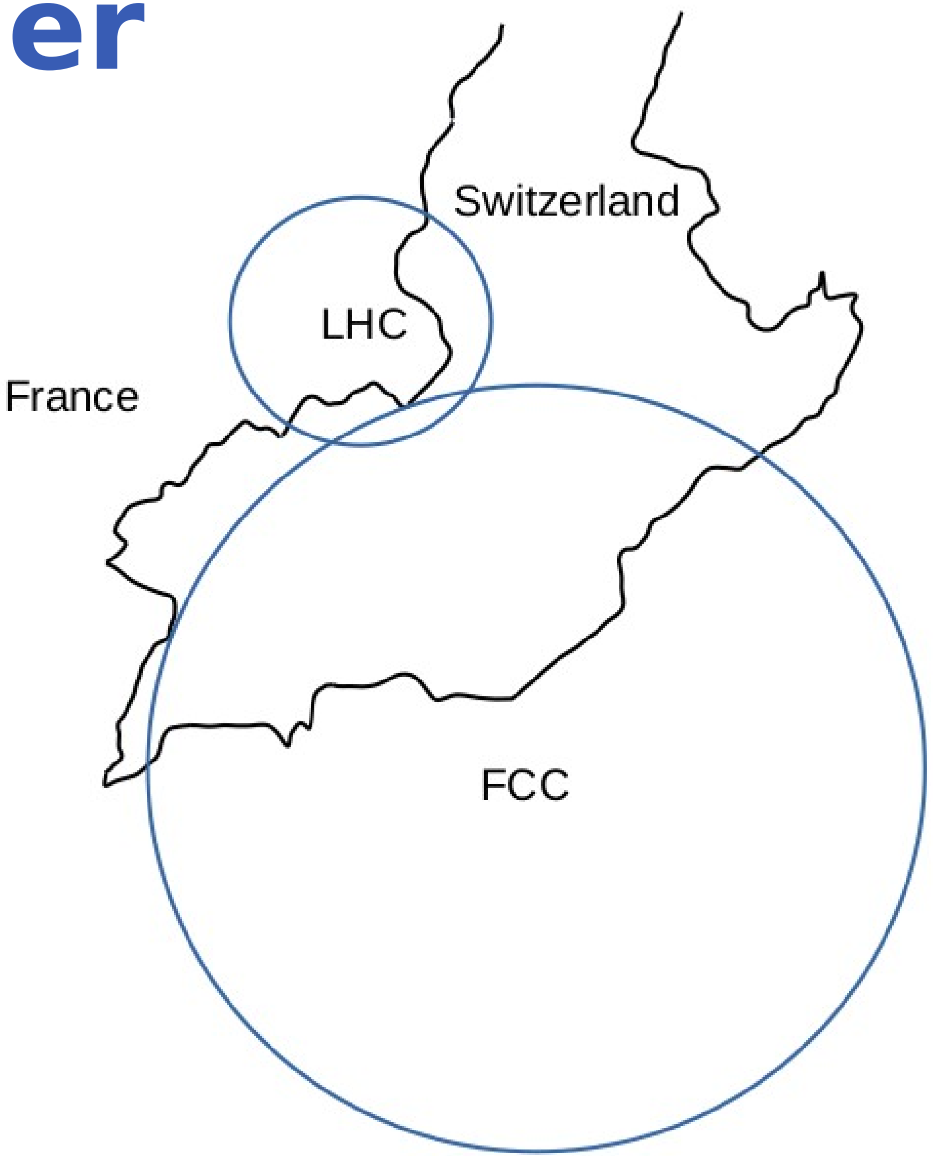
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union’s H2020 Framework Programme under grant agreement no. 951754.

Future Circular Collider

- Integrated FCC project inspired by LEP – LHC programm
- Seamless continuation after HL-LHC
- ~91 km cicumference





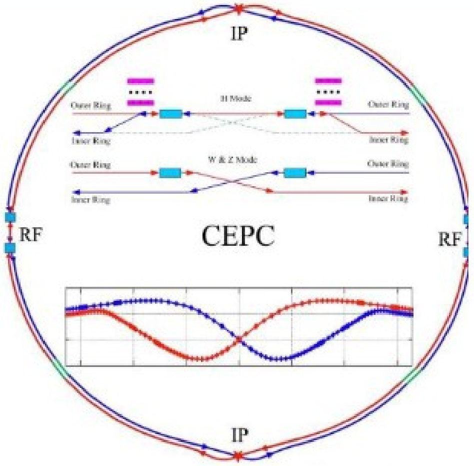
Focus on FCC-ee in this talk

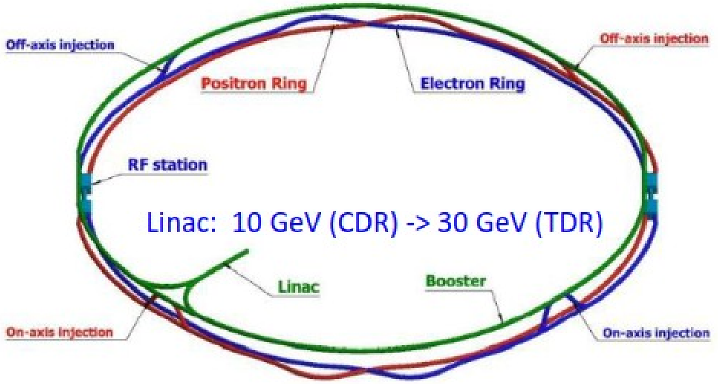
Circular Electron Positron Collider

Courtesy: Z. Duan

- Basic design
  - As a Higgs(120 GeV), Z (45.6GeV) & W(80GeV) Factory
  - Upgradable to High Lumi Z & ttbar(175 GeV)
  - Compatible with SppC
- Progress
  - CDR released in 2018
  - TDR to be delivered in 2023
  - Beam polarization as a chapter in Appendix
    - Transverse polarization for resonant depolarization at Z & W
    - Longitudinally polarized colliding beams at Z-pole (and beyond)

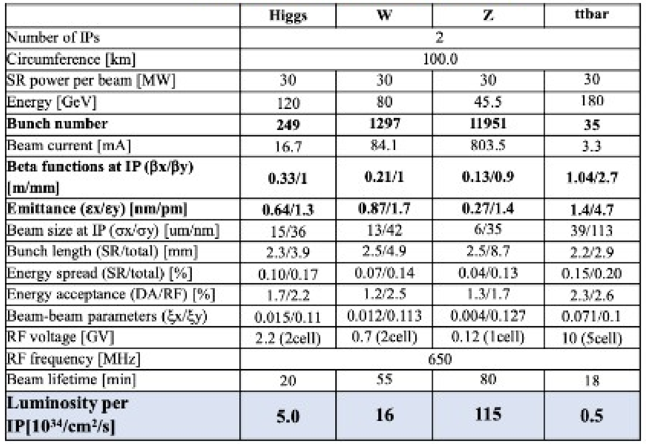
[1] Slides of Beam Polarization Studies presented on CEPC Accelerator TDR Review Meeting 14/06/2023, Hong Kong https://indico.ihep.ac.cn/event/19262/contributions/135019/attachments/69261/83123/CEPC_polarization_study_v5_uploaded.pptx



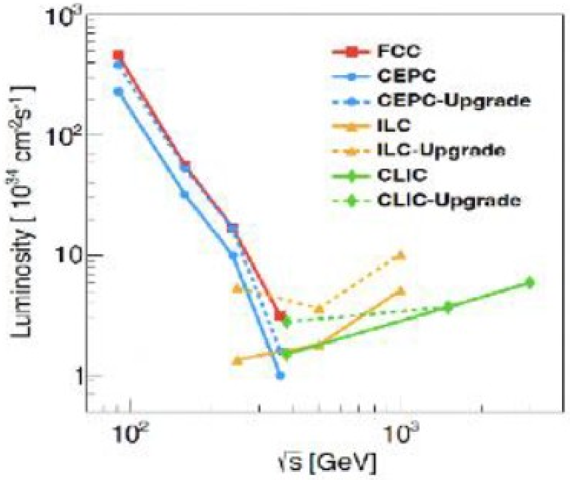


Linac: 10 GeV (CDR) -> 30 GeV (TDR)

TDR, High luminosity (30MW)



	Higgs	W	Z	ttbar
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	30	30	30	30
Energy [GeV]	120	80	45.5	180
Bunch number	**249**	**1297**	**11951**	**35**
Beam current [mA]	16.7	84.1	803.5	3.3
Beta functions at IP (βx/βy) [m/mm]	**0.33/1**	**0.21/1**	**0.13/0.9**	**1.04/2.7**
Emittance (εx/εy) [nm/pm]	**0.64/1.3**	**0.87/1.7**	**0.27/1.4**	**1.4/4.7**
Beam size at IP (σx/σy) [um/nm]	15/36	13/42	6/35	39/113
Bunch length (SR/total) [mm]	2.3/3.9	2.5/4.9	2.5/8.7	2.2/2.9
Energy spread (SR/total) [%]	0.10/0.17	0.07/0.14	0.04/0.13	0.15/0.20
Energy acceptance (DA/RF) [%]	1.7/2.2	1.2/2.5	1.3/1.7	2.3/2.6
Beam-beam parameters (ξx/ξy)	0.015/0.11	0.012/0.113	0.004/0.127	0.071/0.1
RF voltage [GV]	2.2 (2cell)	0.7 (2cell)	0.12 (1cell)	10 (5cell)
RF frequency [MHz]	650			
Beam lifetime [min]	20	55	80	18
Luminosity per IP[10^{34}/cm^2/s]	**5.0**	**16**	**115**	**0.5**

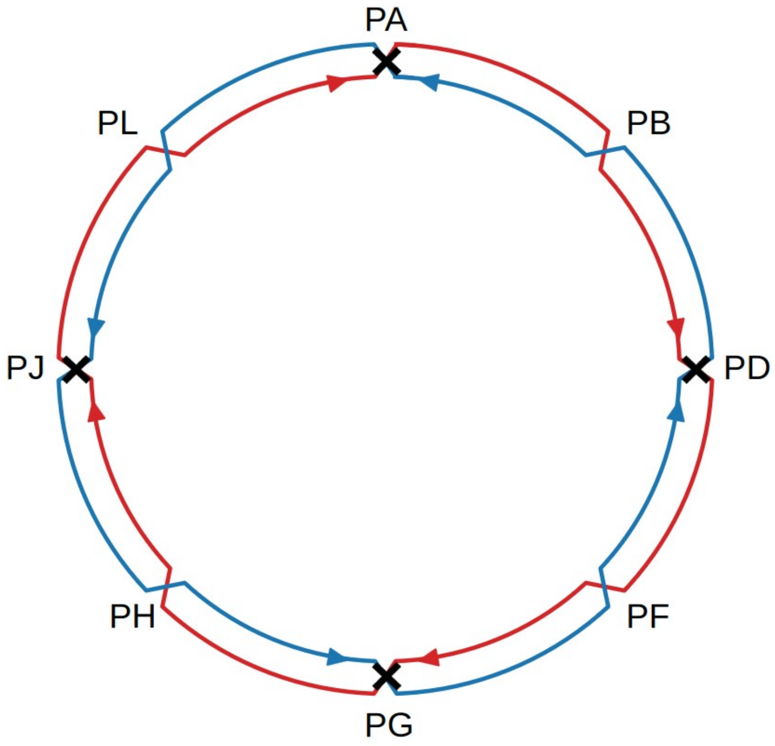


Talk: Z. Duan –> Tuesday 16:10

FCC-ee Overview

Particle Physics:

- Higgs and electro-weak factory
- 4 baseline beam energies and diverse particle physics program
  - 45.6 GeV: Z-pole
  - 80 GeV: W-pair-threshold
  - 120 GeV: ZH-production
  - 182.5 GeV: top-pair-threshold
- High number of statistics



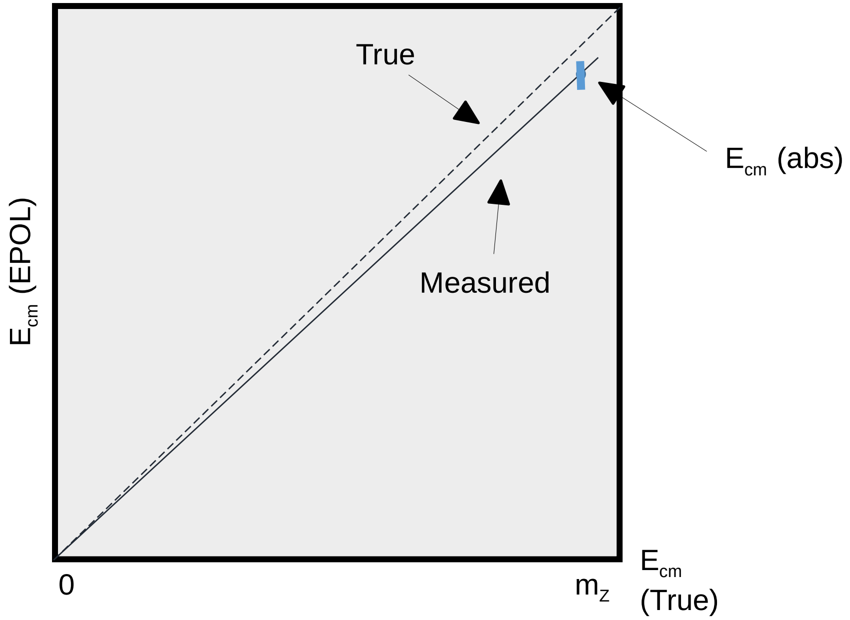
Accelerator Physics:

- 4-fold super-symmetric layout
  - Up to 4 Interaction Points (IPs)
  - 2 points with RF-cavities
  - 1 collimation section
  - 1 section for injection and dump
- Nanometer beam size at IPs
- Strong synchrotron radiation

Precision particle physics experiments ⟺ Center-of-mass energy determination

Center-of-mass Energy Uncertainty

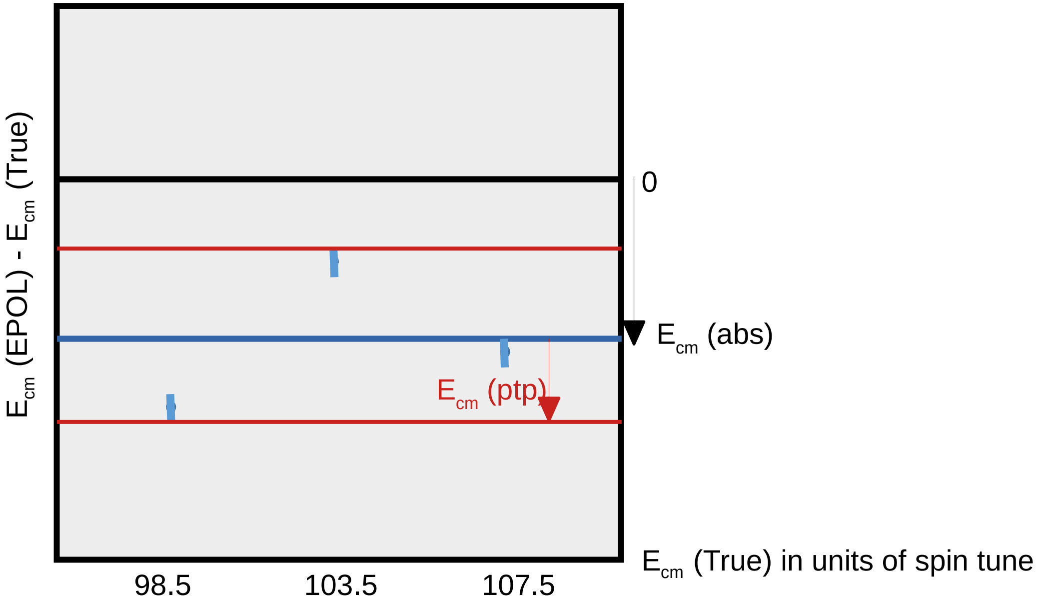
Absolut scale error (abs)



Error between measured and true E_{cm}

- Large effect on mass measurement
- Stems from systematic errors

Point-to-point errors (ptp)

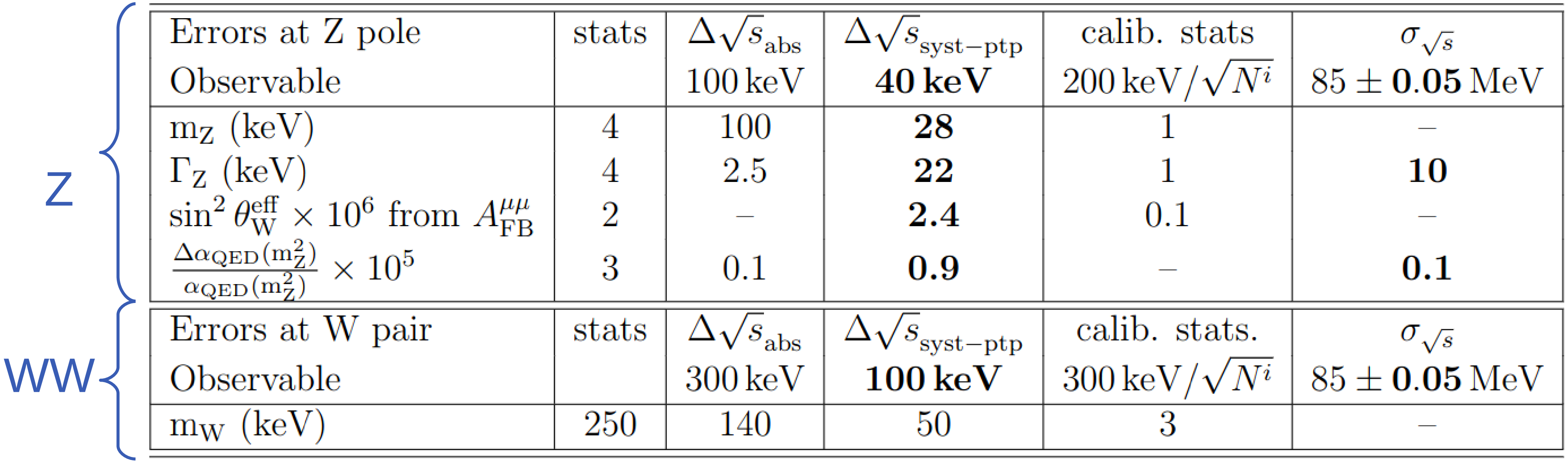


Fluctuation between measurements

- Large effect on width and assymmetry measurements
- Stems from variability of measurement conditions

Courtesy: A. Blondel

Expected Precision



Errors at Z pole Observable	stats	$\Delta\sqrt{s}_{\mathrm{abs}}$ 100 keV	$\Delta\sqrt{s}_{\mathrm{syst-ptp}}$ **40 keV**	calib. stats $200\,\mathrm{keV}/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ $85 \pm \mathbf{0.05}\,\mathrm{MeV}$
$\mathrm{m_Z}$ (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_\mathrm{W}^\mathrm{eff} \times 10^6$ from $A_\mathrm{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_\mathrm{QED}(\mathrm{m_Z^2})}{\alpha_\mathrm{QED}(\mathrm{m_Z^2})} \times 10^5$	3	0.1	**0.9**	–	**0.1**
Errors at W pair Observable	stats	$\Delta\sqrt{s}_{\mathrm{abs}}$ 300 keV	$\Delta\sqrt{s}_{\mathrm{syst-ptp}}$ **100 keV**	calib. stats. $300\,\mathrm{keV}/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ $85 \pm \mathbf{0.05}\,\mathrm{MeV}$
$\mathrm{m_W}$ (keV)	250	140	50	3	–

Large expected luminosity → huge statistics → small statistical error: **4 / 100 keV per Z / W - boson**

Aim to achieve same order of magnitude for systematic errors → Scope of the **EPOL working group**

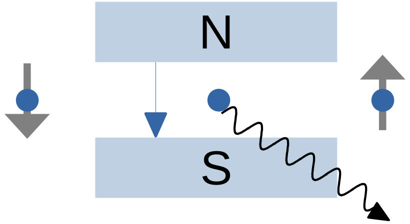
EPOL: Energy calibration, polarization and monochromatization

arXiv:1909.12245

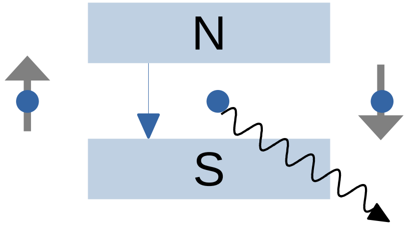
Courtesy: E. Gianfelice, G. Hoffstaetter

Polarization Build-Up

More likely
(by factor ~25)



Less likely



- Statistically every $10^{10\text{th}}$ emitted synchrotron photon flips the spin
- Probability depends on the initial spin orientation

- Leads to a natural **polarization build-up** over time
- Orientation is **anti-parallel** to the guiding magnetic field
- In a flat synchrotron only vertical bending → vertical spin orientation
- Known as Solokov-Ternov-Effekt

- Maximum theoretical polarization of **92.4 %**
- In real accelerator max. polarization depends on various factors

Polarization time:

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e\hbar\,\gamma^5}{m_0 C}\oint\frac{ds}{|\rho|^3}$$

Spin Tune

- Spin precesses through the lattice
- Spin tune ν: Number of spin precessions per turn

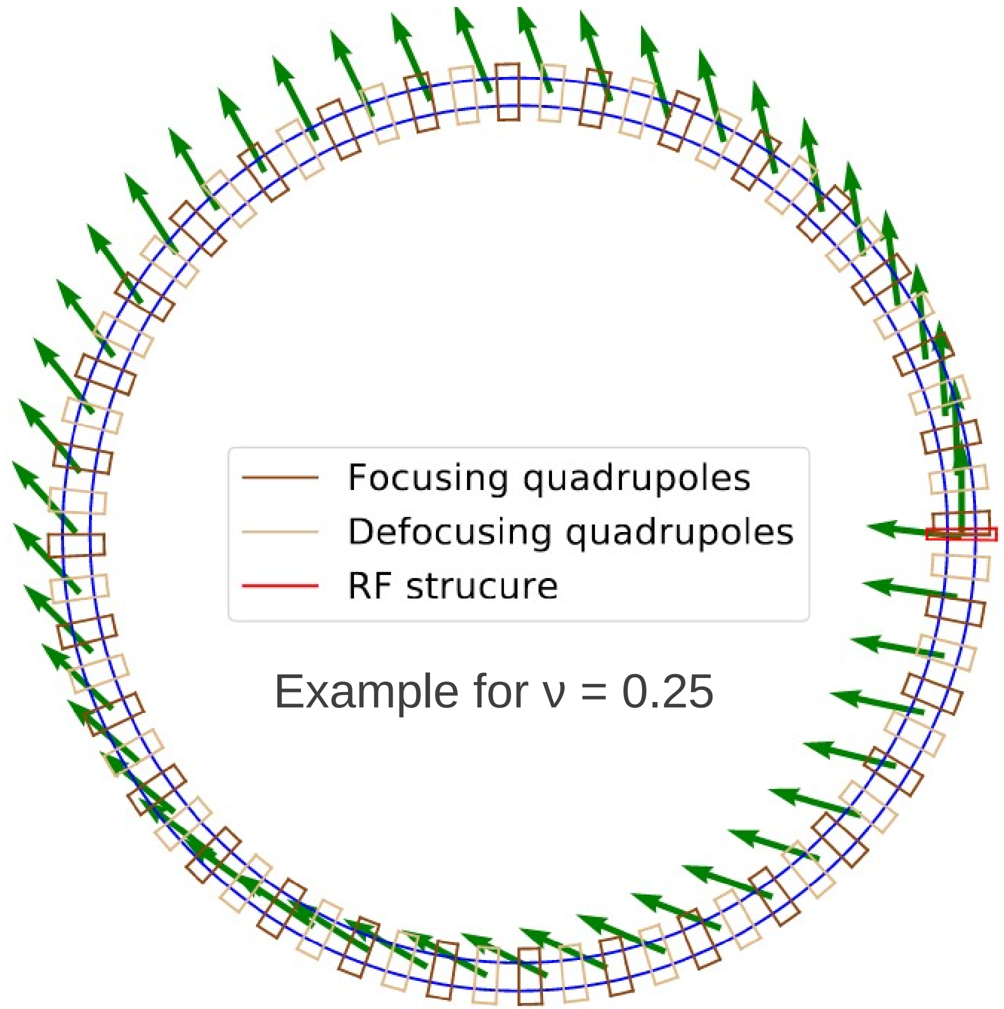
- In an error-free flat machine without solenoids:
- 45.6 GeV e^+/e^- –> 103.5 spin tune
- Purely vertical spin orientation

a … gyro-magnetic anomaly
γ_{Rel} … Lorentz-factor

$$\boxed{\nu = a * \gamma_{Rel}}$$

Principle:

Spin tune measurement ⟺ **Beam energy determination**



Example for ν = 0.25

Courtesy: V. Caudan

Contributions to the Beam Energy

~4 keV at 45.6 GeV beam energy measurement –> ambitious goal of ~ **10^{-7}** statistical and systematic **errors**

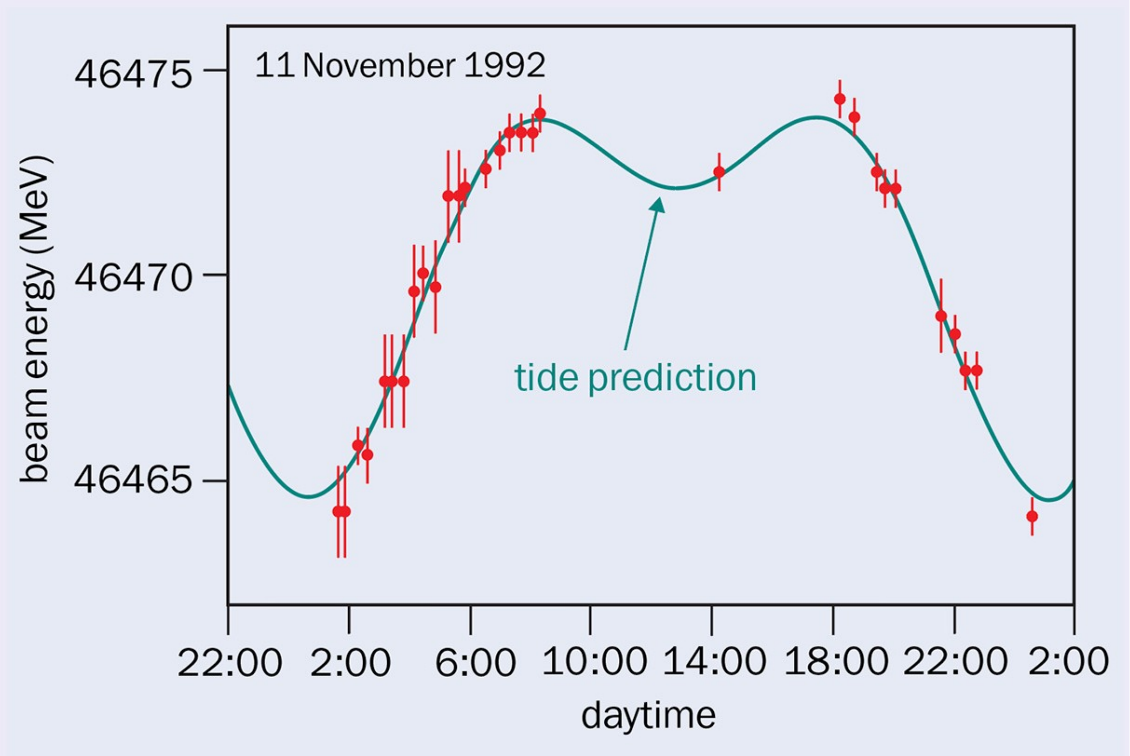
Selected impacts on the beam energy

- Synchrotron radiation losses
- Earth Tides, energy followed by RF-cavities
- Chromaticity uncertainty ~ 10^{-6}: $\Delta E/E \sim 10^{-8}$
- Energy dependent path length: $\Delta E/E \sim 10^{-7}$
- Betatron oscillations: $\Delta E/E \sim 10^{-7}$
- Orbit corrections: $\Delta E/E \sim 10^{-7}$
- …

What other large sources must be considered?

Courtesy: A. Bogomyagkov

Beam energy change due to Earth tides at LEP



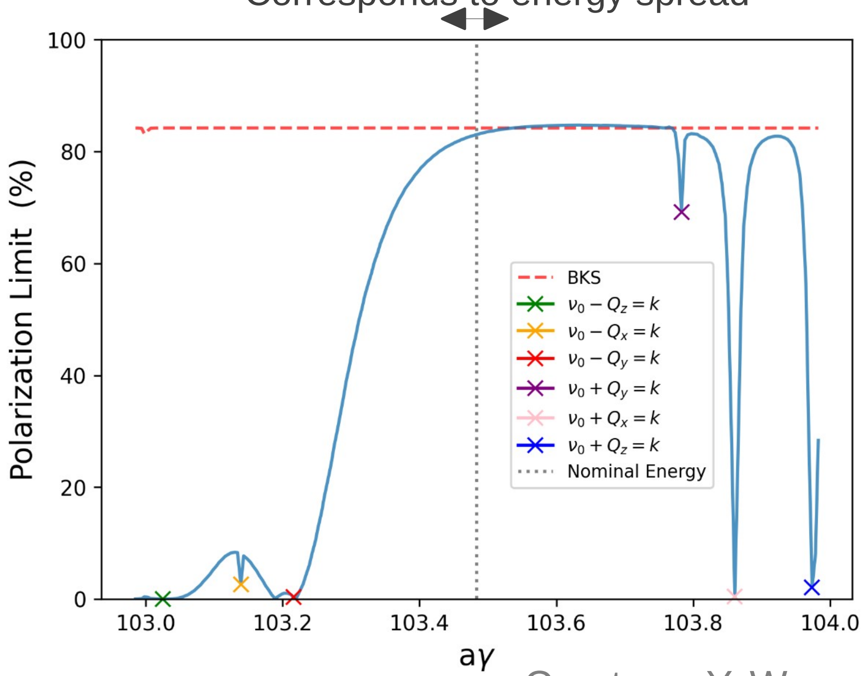
Courtesy: J. Wenninger

Resonances

Spin tune for ideal machine

$$\left\{ a\gamma + \underbrace{m_xQ_x + m_yQ_y}_{\text{Transverse planes}} + \underbrace{m_sQ_s}_{\text{Longitudinal plane}} = k \right.$$

m_x, m_y, m_s, $k \in \mathbb{Z}$



Corresponds to energy spread

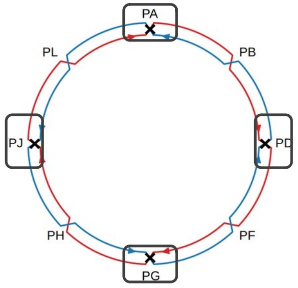
Courtesy: Y. Wu

- Resonances
  - Lead to particle loss
  - Lead to polarization loss
- Origins
  - Misalignment and multipole errors
  - Enhance with larger closed orbit and errors

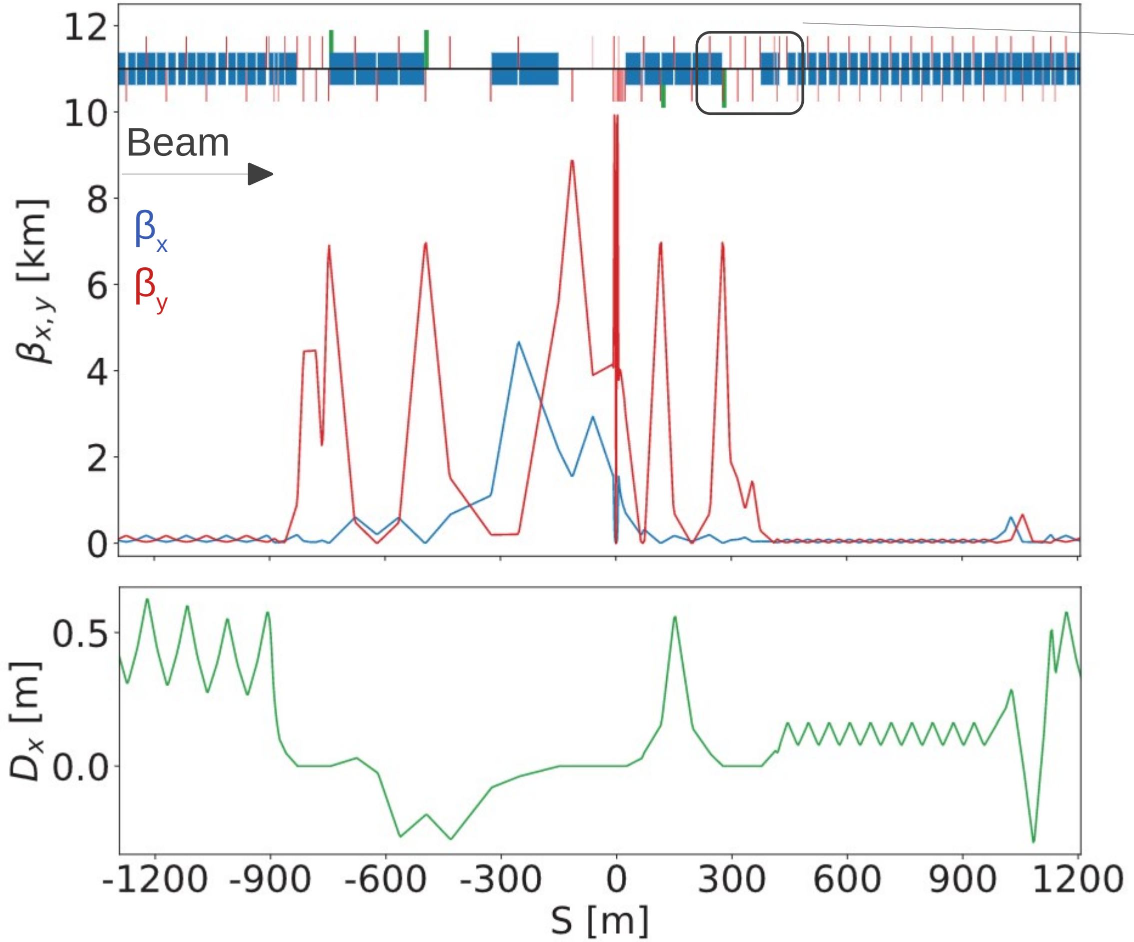
Requires excellent beam optics tuning, measurements and corrections

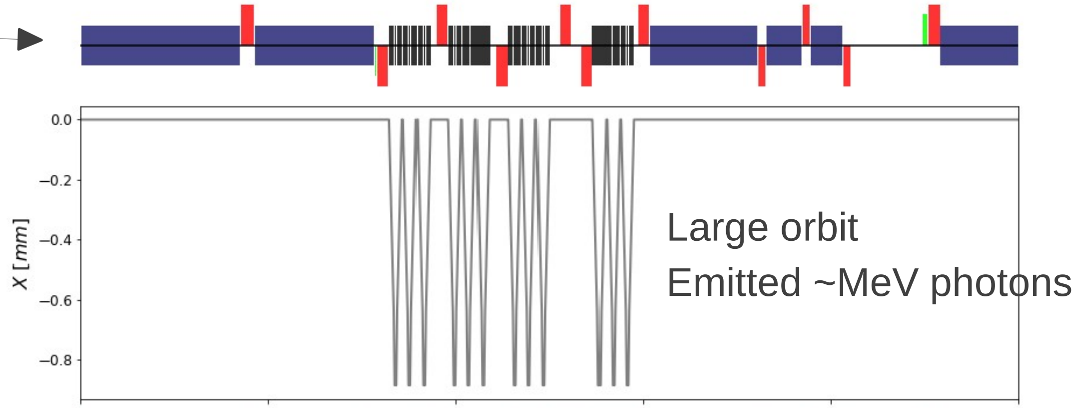
How well must the orbit and misalignments be controlled?

Wigglers



Blue: Dipoles; Red: Quadrupoles





Large orbit

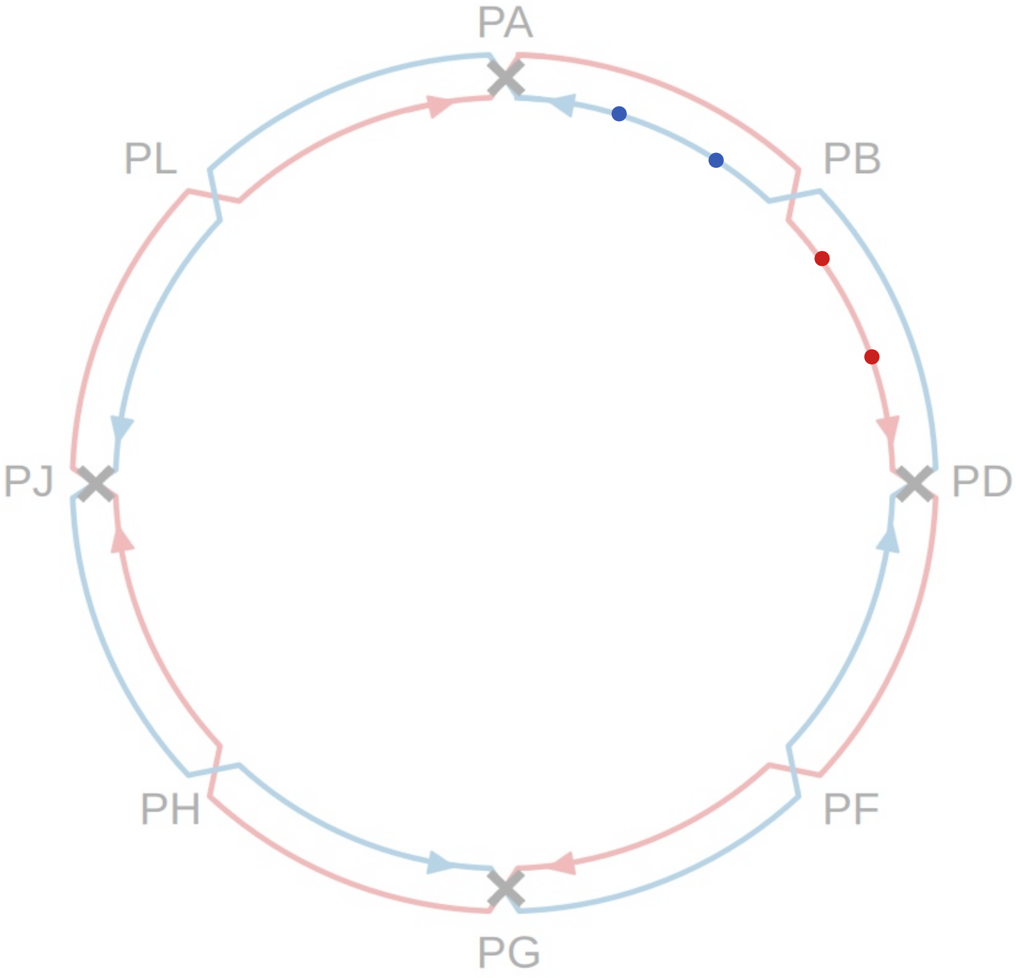
Emitted ~MeV photons

Courtesy: M. Hofer

- At 45.6 GeV energy: Polarization time of 248 h
- Solution: wiggler magnets
  - Reduce polarization time to 12 h
  - Increase energy spread by factor ~ 3.5

Operational Scenario

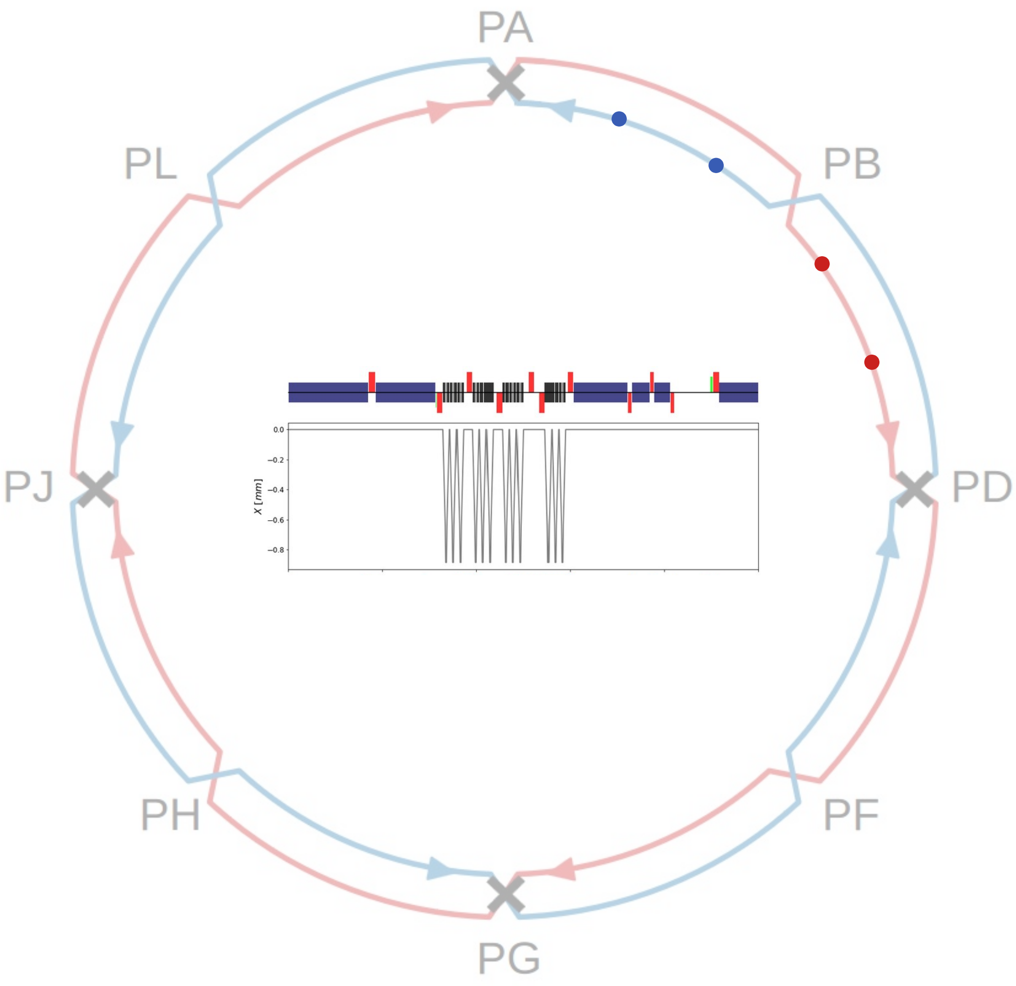
- Inject a few (100-200) non-colliding pilot bunches (~10^{10} ppb)



Operational Scenario

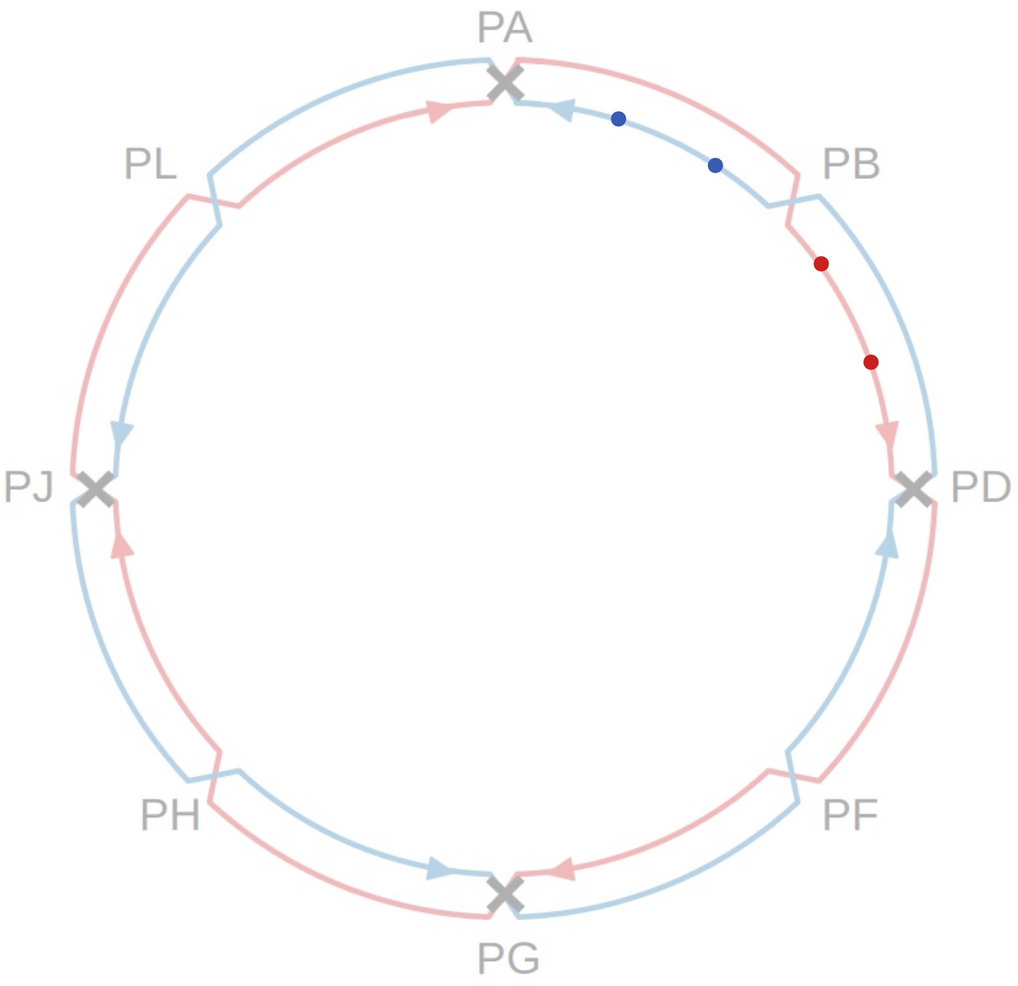
- Inject a few (100-200) non-colliding pilot bunches (~10^{10} ppb)

- Use wigglers until ~5-10 % **vertical polarization** reached



Operational Scenario

- Inject a few (100-200) non-colliding pilot bunches (~10^{10} ppb)
- Use wigglers until ~5-10 % **vertical polarization** reached
- Switch wigglers off



Operational Scenario

- Inject a few (100-200) non-colliding pilot bunches (~10^{10} ppb)
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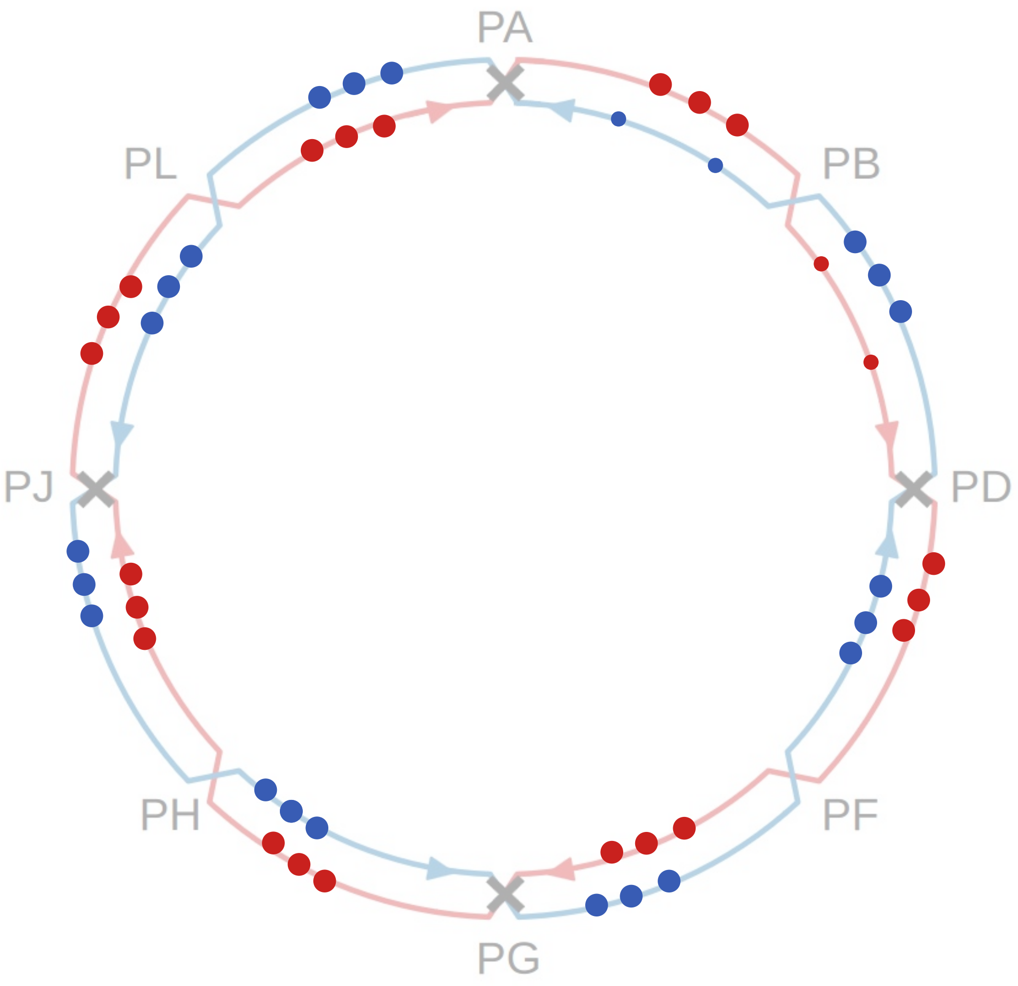
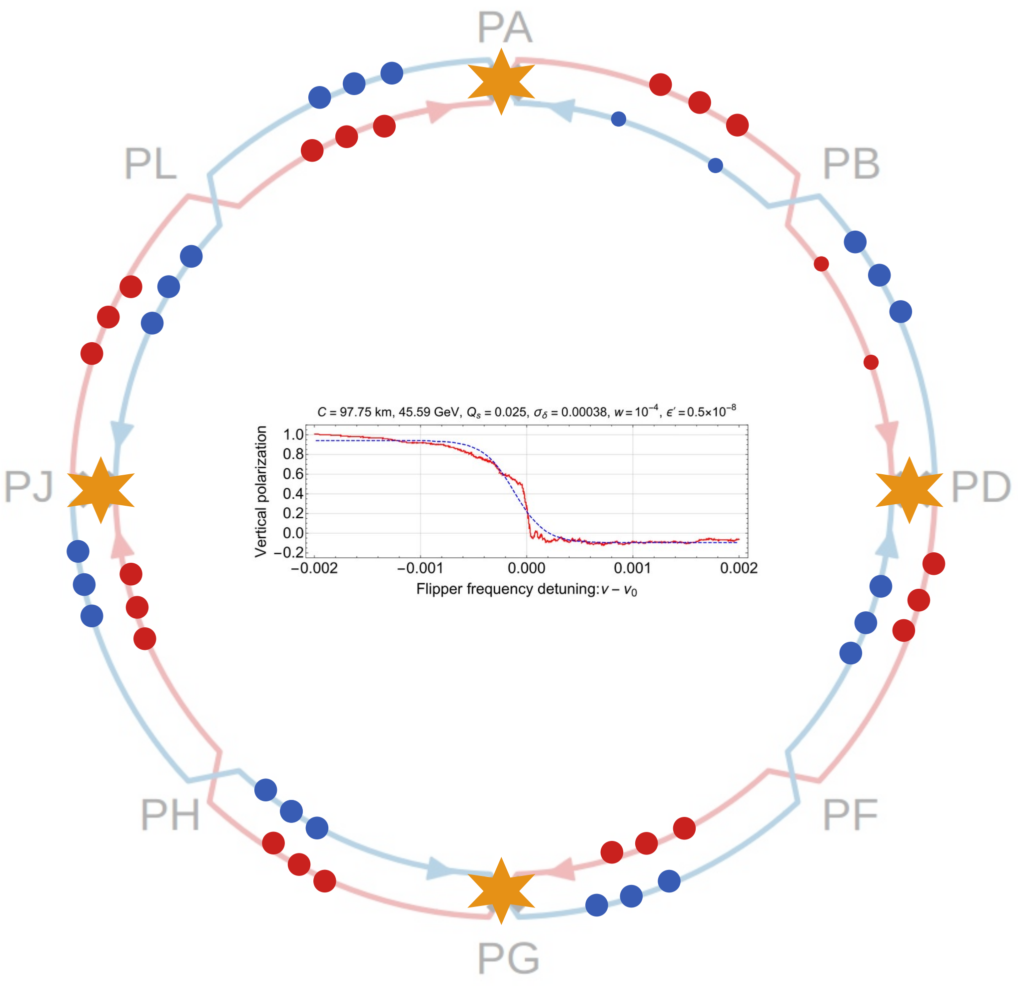
- Switch wigglers off
- Inject ~10000 colliding bunches (~2 x 10^{11} ppb)



Operational Scenario

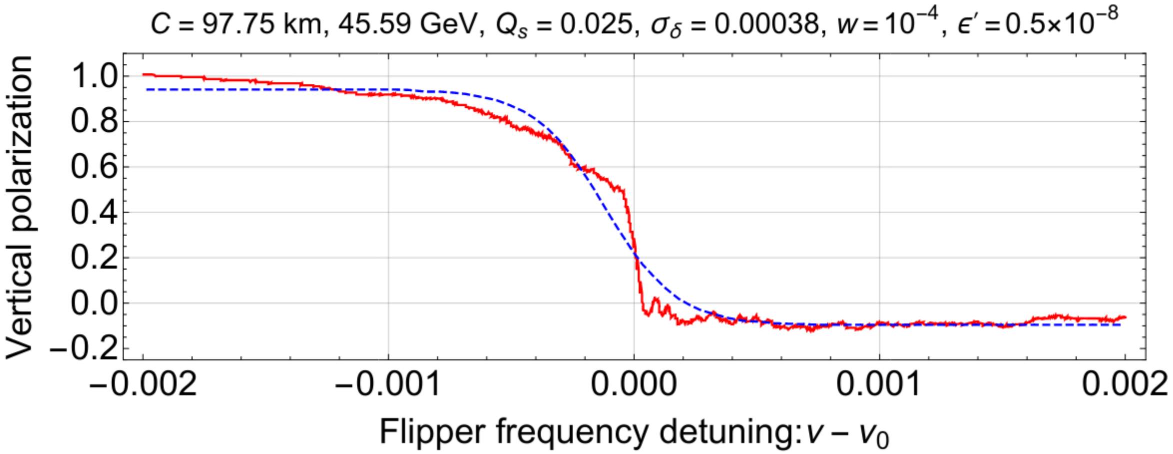
- Inject a few (100-200) non-colliding pilot bunches (~10^{10} ppb)
- Use wigglers until ~5-10 % **vertical polarization** reached
- Switch wigglers off
- Inject ~10000 colliding bunches (~2 x 10^{11} ppb)
- Measure beam energy with pilots while collisions take place



What is the minimum required polarization?

Resonant Depolarization

Simulations for Z-pole



Courtesy: I. Koop

Natural width ~ 200 keV at Z

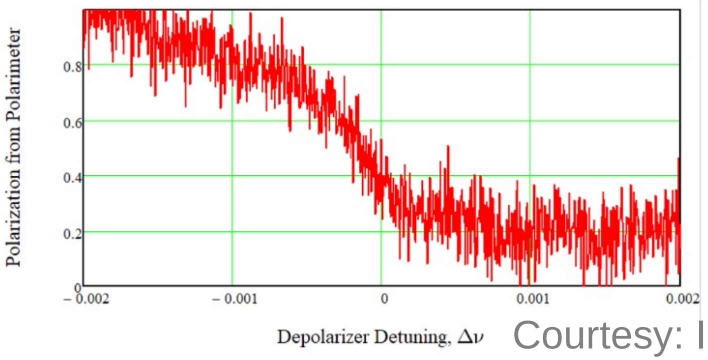
Suggestion: Alternating scanning directions

Simulations achieved better than 10 keV

- Independent depolarizers per beam
- TEM wave propagating towards a pilot bunch
- Varying exciting frequency

Excitation frequency = spin tune = depolarization

Simulations for W-pair-threshold



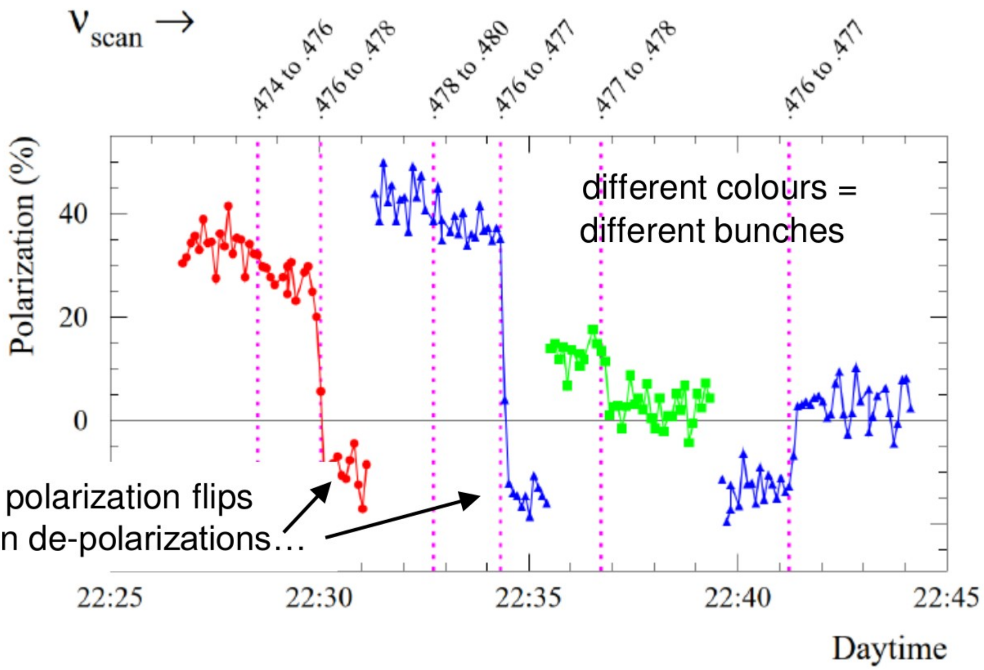
Courtesy: I. Koop

Natural width ~ 1.4 MeV at W

Experience from LEP

- Resonant depolarization also used at LEP

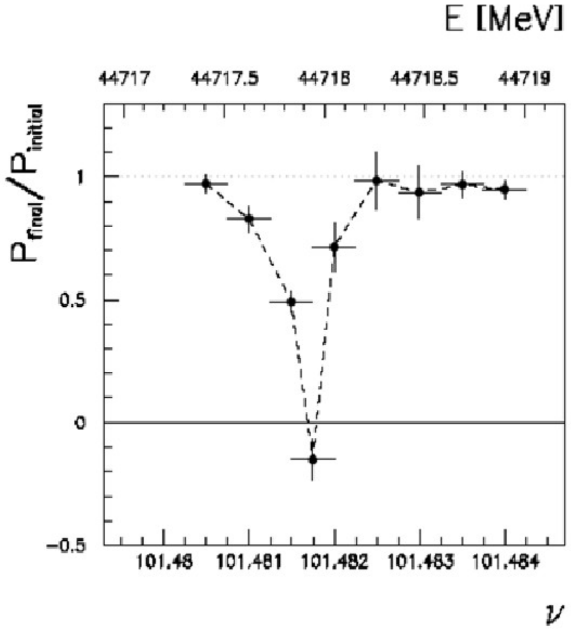
- Strong depolarizers have lead to polarization flips
- Possibly re-use of the same pilot bunches



different colours = different bunches

these are polarization flips rather than de-polarizations…

[L. Arnaudon *et al.*, Z. Phys. C66 (1995) 45]



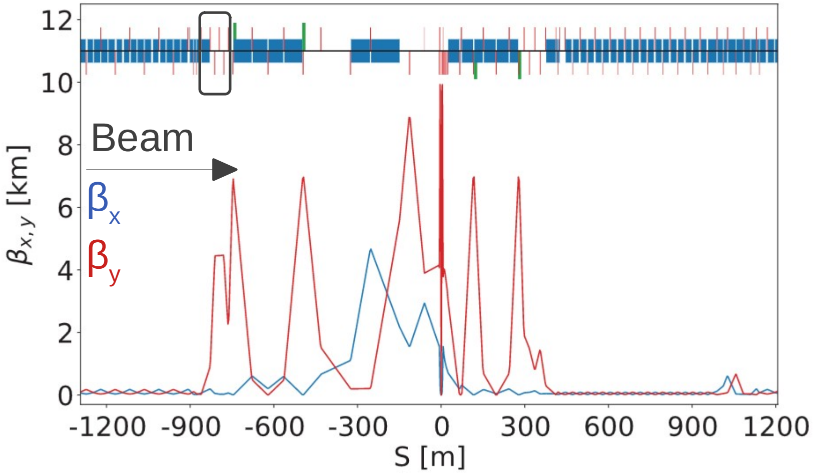
- At LEP resonant depolarization not feasible for W
- Several shorter depolarization steps at discrete frequencies

How often could the polarization be flipped?

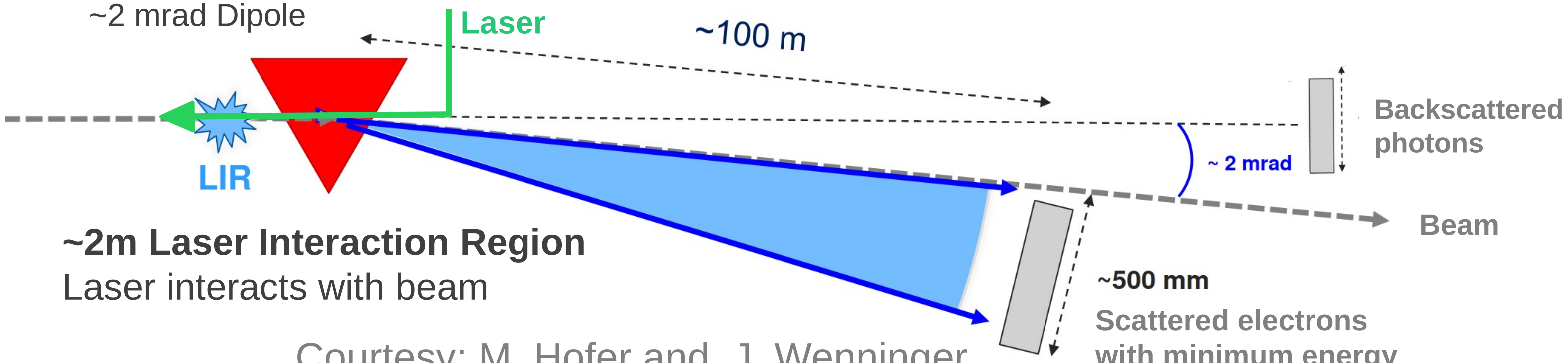
Polarimeter

- ~ 520 nm circular **polarized laser** interacts with beam
- **Back-scattered photons** sufficient for resonance measurement
- Additional measurement of **scattered electrons** for 3D spin vector
- At least 1 polarimeter per beam

Blue: Dipoles; Red: Quadrupoles



Spin tune ⟺ **Beam energy measurement**

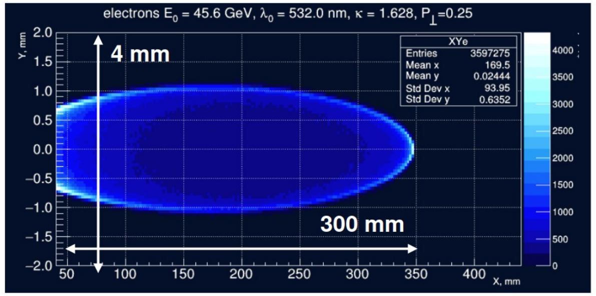


~2m Laser Interaction Region

Laser interacts with beam

Courtesy: M. Hofer and J. Wenninger

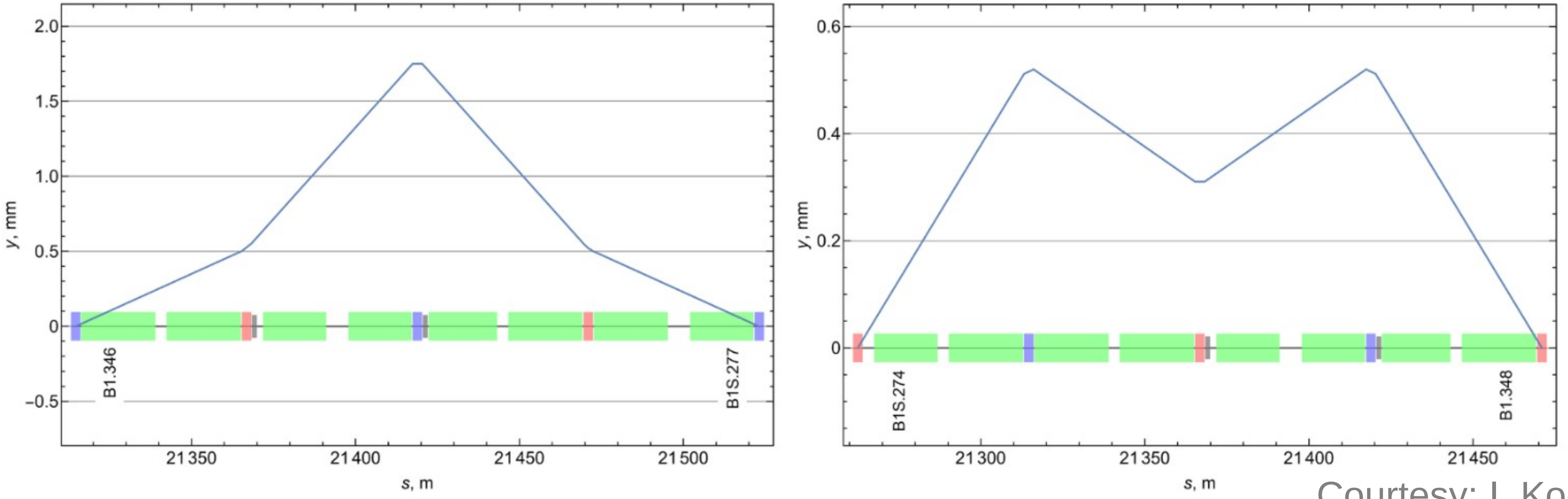
Scattered electrons to be measured by Si pixel detector



Courtesy: N. Muchnoi

What can be gained from more polarimeters?

Colliding Bunches Polarization



Courtesy: I. Koop

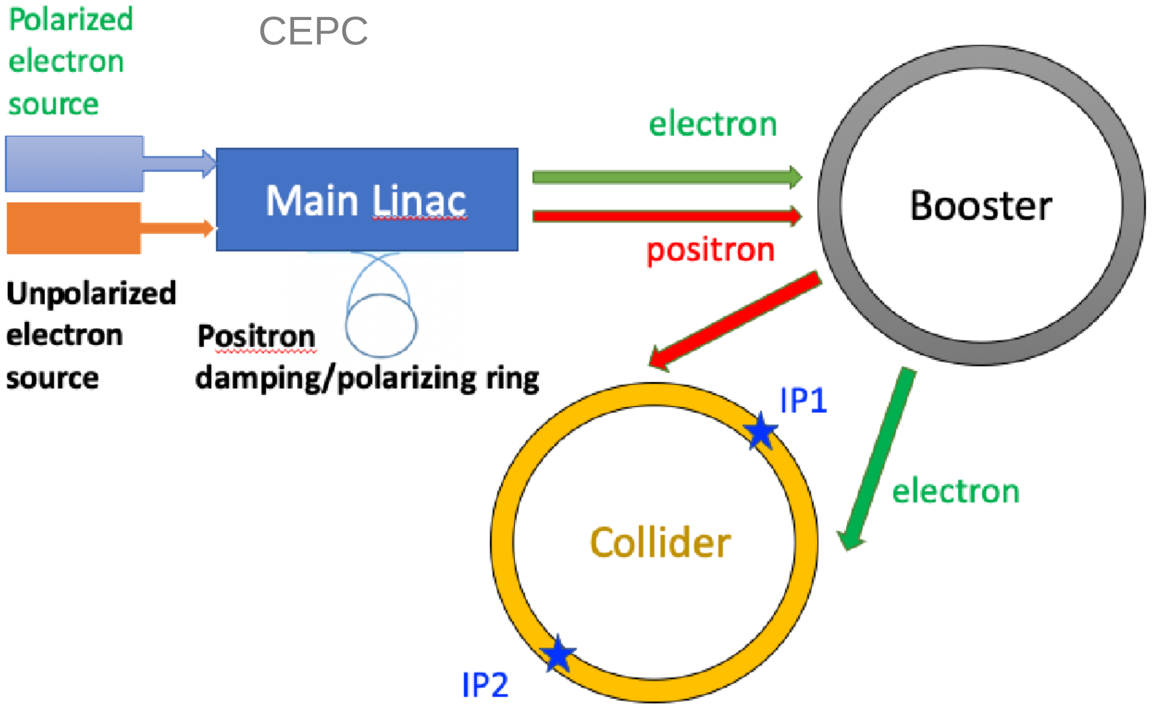
Take away message:

- **Residual longitudinal** polarization could spoil measurements and must be **$< 10^{-5}$**
- Depolarizers must also act on colliding bunches → Consider closed-orbit bumps to avoid impact at IP
- To be measured also with polarimeters

What are the best designs for depolarizer and polarimeter systems for pilot and colliding bunches?

Longitudinal Polarization

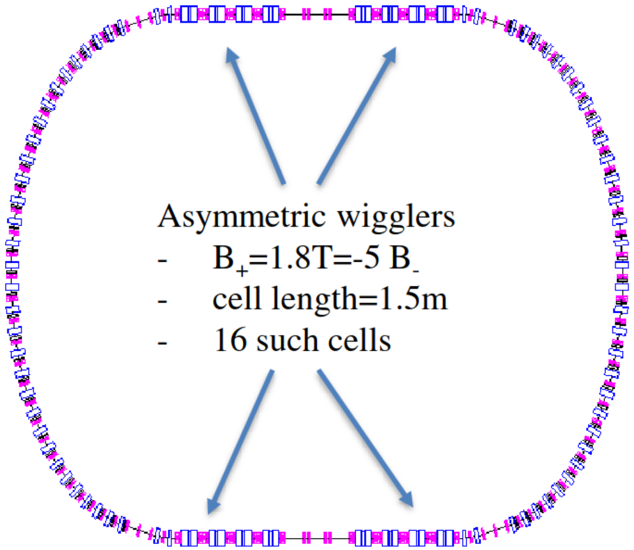
- Collisions with highly polarized beams for physics
- Injection of highly polarized beams required
- Spin rotators to transform to longitudinal plane



Courtesy: Z. Duan

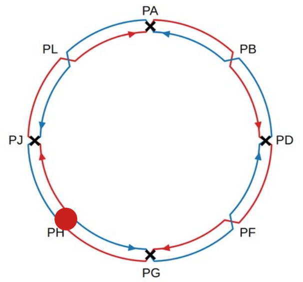
- Polarization ring could be combined with damping ring
- Present damping ring design in CEPC:

Positron damping ring
1.542 GeV



Self-polarization of >20% achievable in 10 min [1]
Consistent with the requirements of RD measurements, but not sufficient for top-up injection of colliding bunches

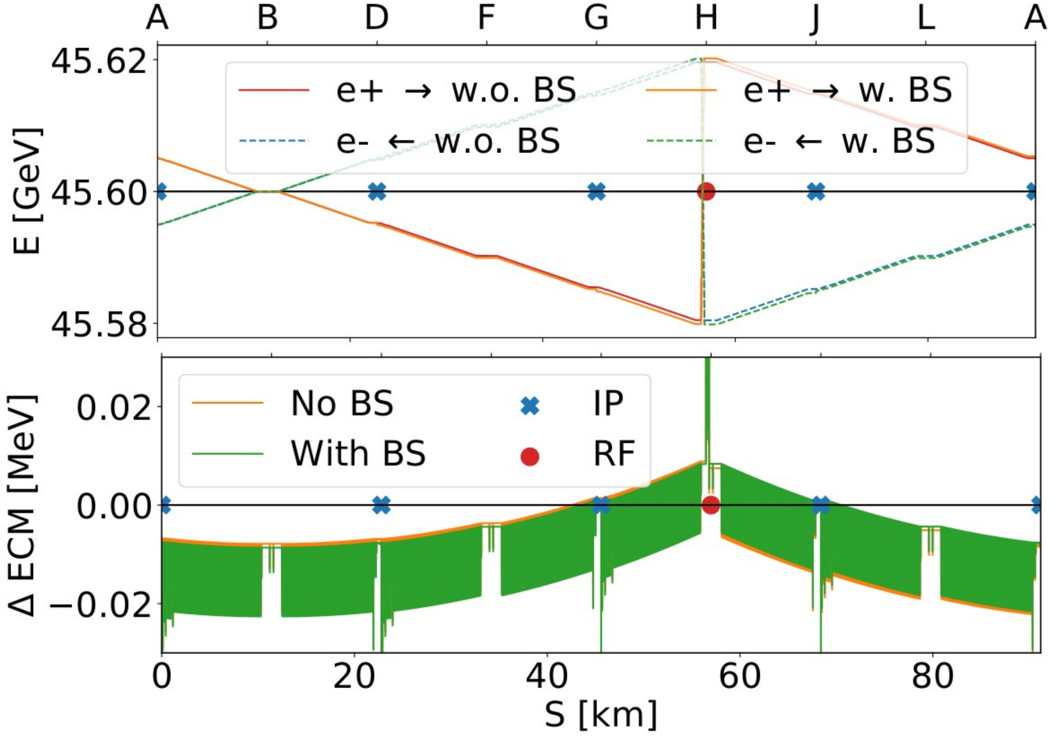
From Beam Energy to E_{CM}



- 40 MeV synchrotron radiation losses per turn
- Additional beamstrahlung (BS) (synchrotron radiation due to field of colliding bunch) $\lesssim$ 0.62 MeV/beam/IP

- 1 RF section assumed in PH to compensate losses
- ΔE_{cm} ~ -8 keV (PA, PD) and ~0.7 keV (PG, PJ)
- Boosts ~ +/- 10 MeV (PA, PD) and ~ +/- 30 MeV (PG, PJ)

- Pilot and colliding bunches have different local energy
- **Accurate models essential**



What are the systematics between pilot and colliding bunch energies?

Dispersion and Collision Offset

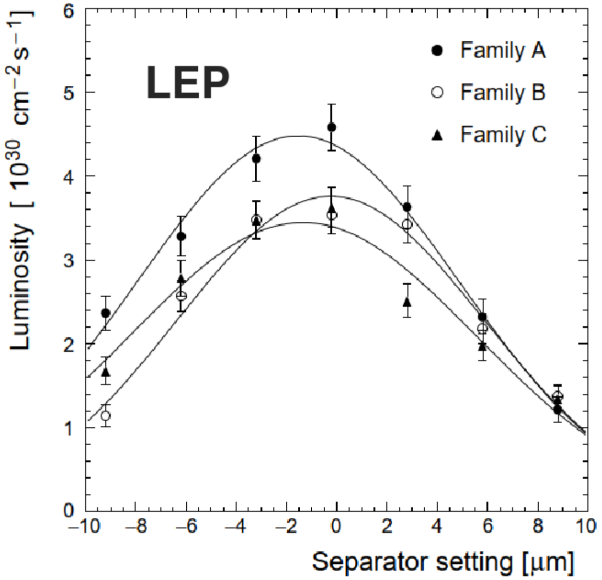
$$\Delta\sqrt{s} = -u_0 \frac{\sigma_E^2 \Delta D^*}{E_0 \sigma_u^2} \quad \Rightarrow \quad |\Delta\sqrt{s}| = 96\ |u_0|\ [\mathrm{keV/nm}]$$

D… Dispersion
σ_u … transverse beam size
u_0 … collision offset

for $\Delta D^* = 1\ \mu$m, $\sigma_E/E = 0.13\%$

For **$\Delta D^* = 10\ \mu$m**, the CM error is **~1 MeV/nm**, i.e., the uncertainty on / average separation must be below **$u_0 < 0.1$ nm to limit the systematic errors < 100 keV.**

- Only relevant for colliding bunches
- Measurement and control of dispersion at collision point essential
  - **ΔD < 1 µm** relaxes requirements on collision offsets
- Collision offsets determined with e.g. luminosity scans
  - Presently collision offsets must be demonstrated to be controlled to **~0.1σ_y**



J. Wenninger: Beam-beam and OSVD

Summary

- Electro-weak and Higgs-factory highest priority for future collider –> FCC-ee (CERN), CEPC (China)
- High precision particle physics experiments require **excellent determination of E_{cm} and collision boosts**
- Presently aimed to achieve **4 / 100 keV** systematic uncertainty for the **Z- / W- mass** for FCC-ee

Regular FCC-ee EPOL meetings:
indico.cern.ch/category/8678/
Typically every second Thursday 16:30-18:30

Any help is welcome!

Mailing list:
fcc-ee-PolarizationAndEnergyCalibration@cern.ch

Self-subscription from:
https://e-groups.cern.ch/e-groups/EgroupsSearch.do

Thank you!

Jacqueline Keintzel

On behalf of

The FCC-ee EPOL working group

Special thanks to: Alain Blondel, Rogelio Tomas, Guy Wilkinson and Frank Zimmermann

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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.

ESPP Update 2020

In 2020 the European strategy upgrade of particle physics (ESPP) expressed the long-term plan for particle colliders:

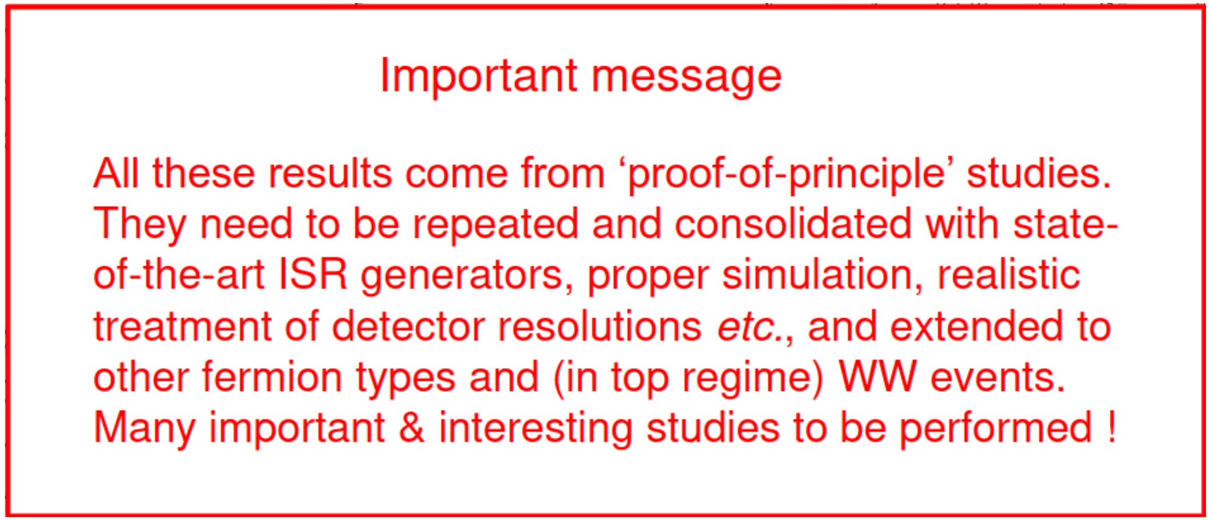
Europe, together with its international partners, should investigate the technical and financial feasibility of a **future hadron collider** at CERN with a center-of-mass energy of at least **100 TeV** and with an **electron-positron** Higgs and electroweak factory as a possible **first stage**.

Lepton Future Circular Collider, FCC-ee
Hadron Future Circular Collider, FCC-hh

} Integrated FCC Project

Experiments

- G. Wilkinson: *Di-muon events - “The gift that keeps on giving”*
- Reliable and frequent logging of parameters essential
- Possibility to measure Z-bosons from higher E_{cm} events



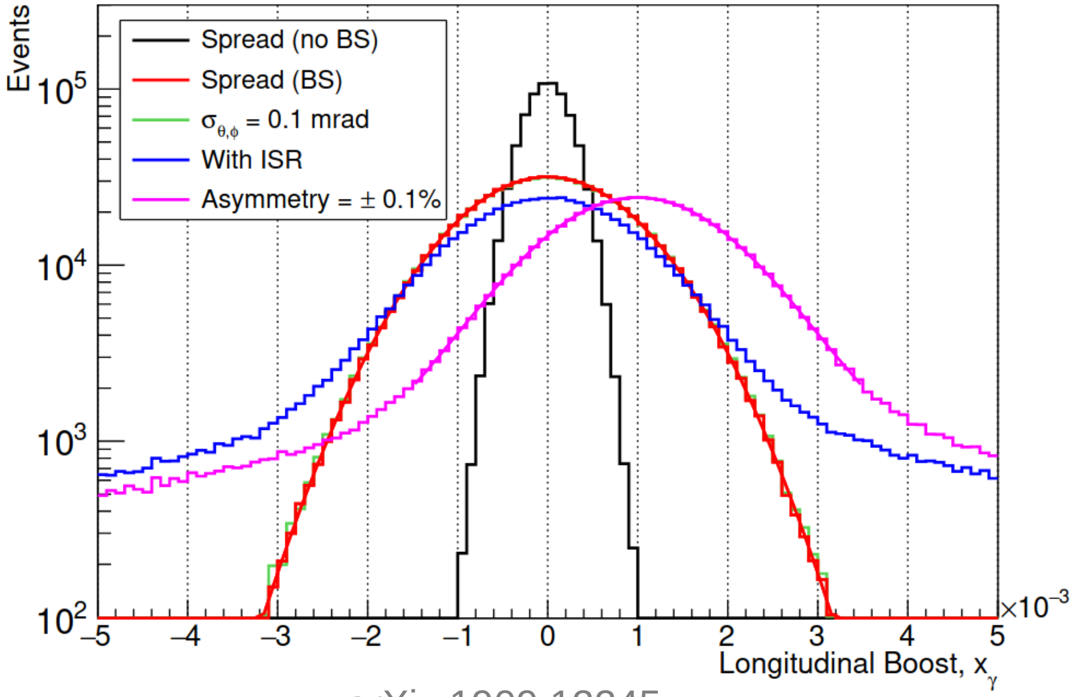
Important message

All these results come from ‘proof-of-principle’ studies. They need to be repeated and consolidated with state-of-the-art ISR generators, proper simulation, realistic treatment of detector resolutions *etc.*, and extended to other fermion types and (in top regime) WW events. Many important & interesting studies to be performed !

One million di-muon events per 8h shift
~ 5 keV statistical precession achievable

10^6 dimuon events at Z-pole: e+e- –> μ+μ- (γ)
(γ)… Initial-State-Photon (ISR)

Boost reconstruction from di-muon events



arXiv:1909.12245

Colliding Bunches Polarization

Consider forward-backward asymmetry of $b\bar{b}$ at Z pole: $A^b_{\mathrm{FB}} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b$

where in the SM $\mathcal{A}_e \approx 0.15, \quad \mathcal{A}_b \approx 0.95 \Longrightarrow A^b_{\mathrm{FB}} \approx 0.11$

Now, if there is longitudinal polarisation, asymmetry becomes: $\left(A^b_{\mathrm{FB}}\right)' = \frac{3}{4}\mathcal{A}'_e\mathcal{A}_b$

where $\mathcal{A}'_e = -\left(\frac{\mathcal{A}_e - P}{1 - \mathcal{A}_e P}\right)$ with $P = \frac{(P_z)_{e^-} - (P_z)_{e^+}}{1 - (P_z)_{e^-}(P_z)_{e^+}}$

and $(P_z)_{e^\pm}$ the longitudinal polarisation of the $e^\pm$.

So, if $(P_z)_{e^-} = (P_z)_{e^+}$ (no reason to be so) = 10^{-5} (ballpark guess)

$$P = 2 \times 10^{-5} \quad \Longrightarrow \quad \frac{\left(A^b_{FB}\right)' - A^b_{FB}}{A^b_{FB}} = 1.3 \times 10^{-4}$$

G. Wilkinson: Requirements for polarization measurements

Take away message:

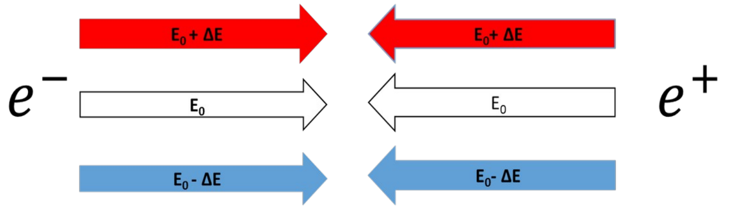
- **Redidual longitudinal** polarization could spoil measurements and must be **< 10-5**
- To be measured also with polarimeters
- Depolarizers must also act on colliding bunches

What are the best designs for depolarizer and polarimeter systems for pilot and colliding bunches?

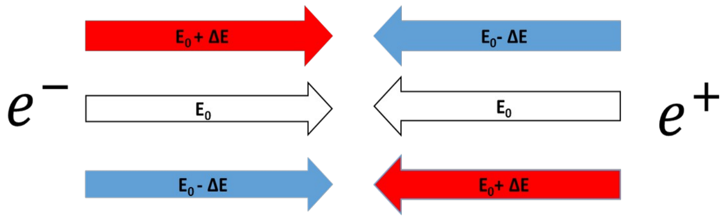
Monochromatization

- 62.5 GeV beam energy corresponds to the peak of Higgs-production with narrow width of 4.2 MeV
- For minimization of collision energy spread –> monochromatization techniques required

Introducing dispersion



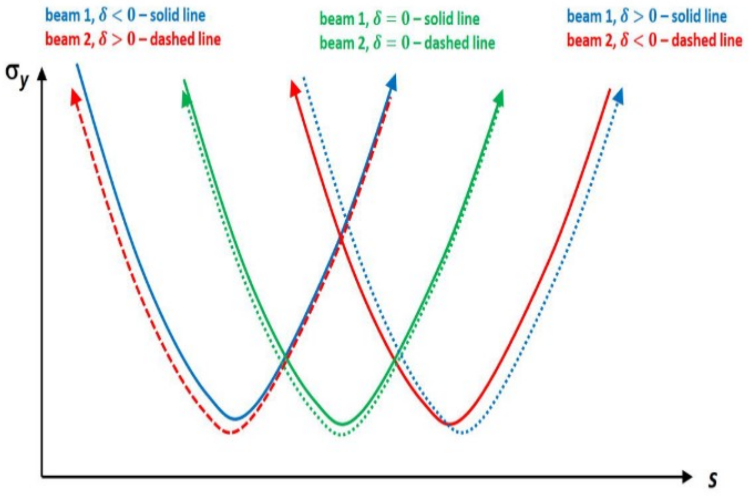
Same sign dispersion at the interaction point leads to change of E_{CM}



Opposite sign (horizontal) dispersion helps reducing E_{CM} spread

Courtesy: A. Faus-Golfe, H. Jiang and P. Raimondi

Introducing chromaticity



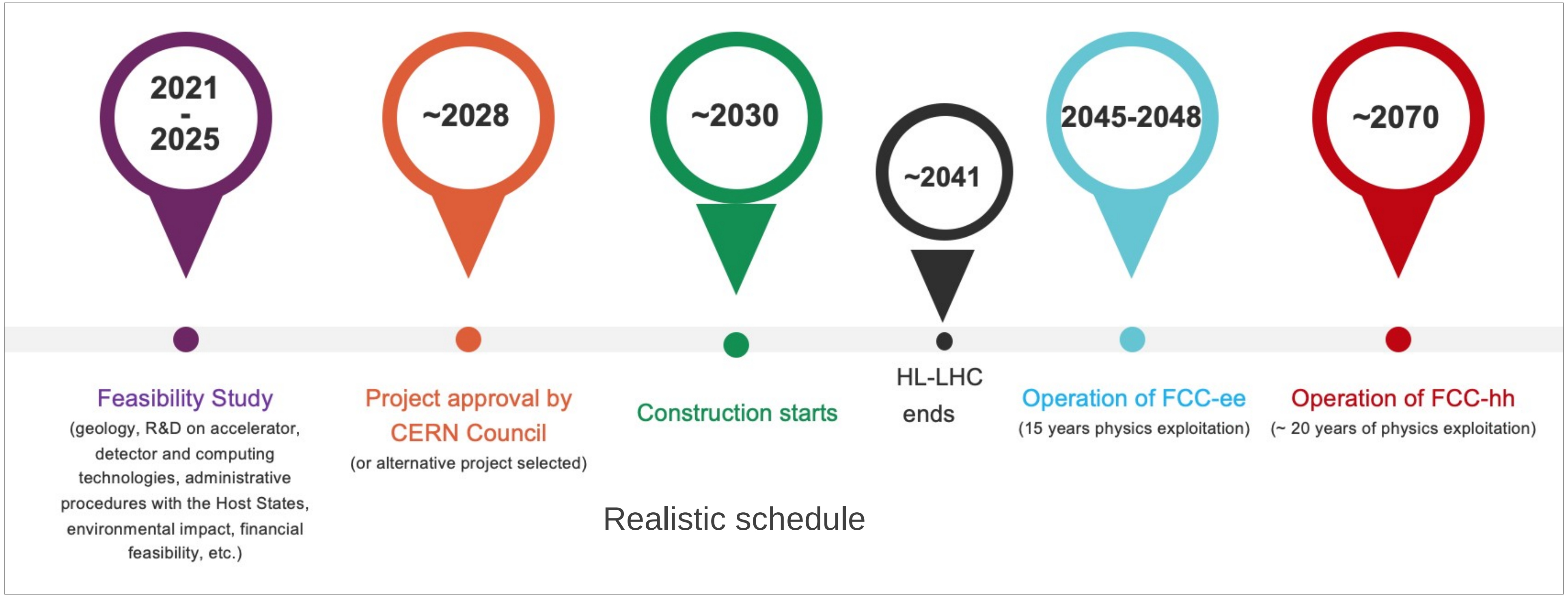
Non-zero local vertical chromaticity to reduce collision energy spread presently explored

What is the most suitable monochromatization technique?

Feasibility Study and Schedule

- From 2021-2025 with mid-term review end of 2023 and final Feasibility Study Report end of 2025

Goal: Demonstration of the geological, technical, environmental, financial and administrative feasibility of the FCC-ee, including its optimisation



2021 - 2025

Feasibility Study
(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

~2028

Project approval by CERN Council
(or alternative project selected)

~2030

Construction starts

~2041

HL-LHC ends

2045-2048

Operation of FCC-ee
(15 years physics exploitation)

~2070

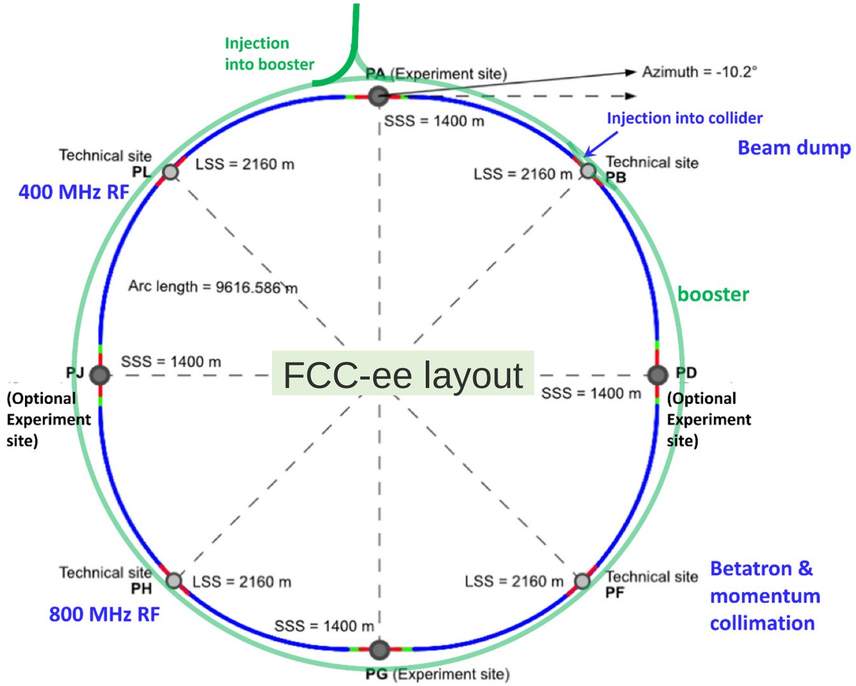
Operation of FCC-hh
(~ 20 years of physics exploitation)

Realistic schedule

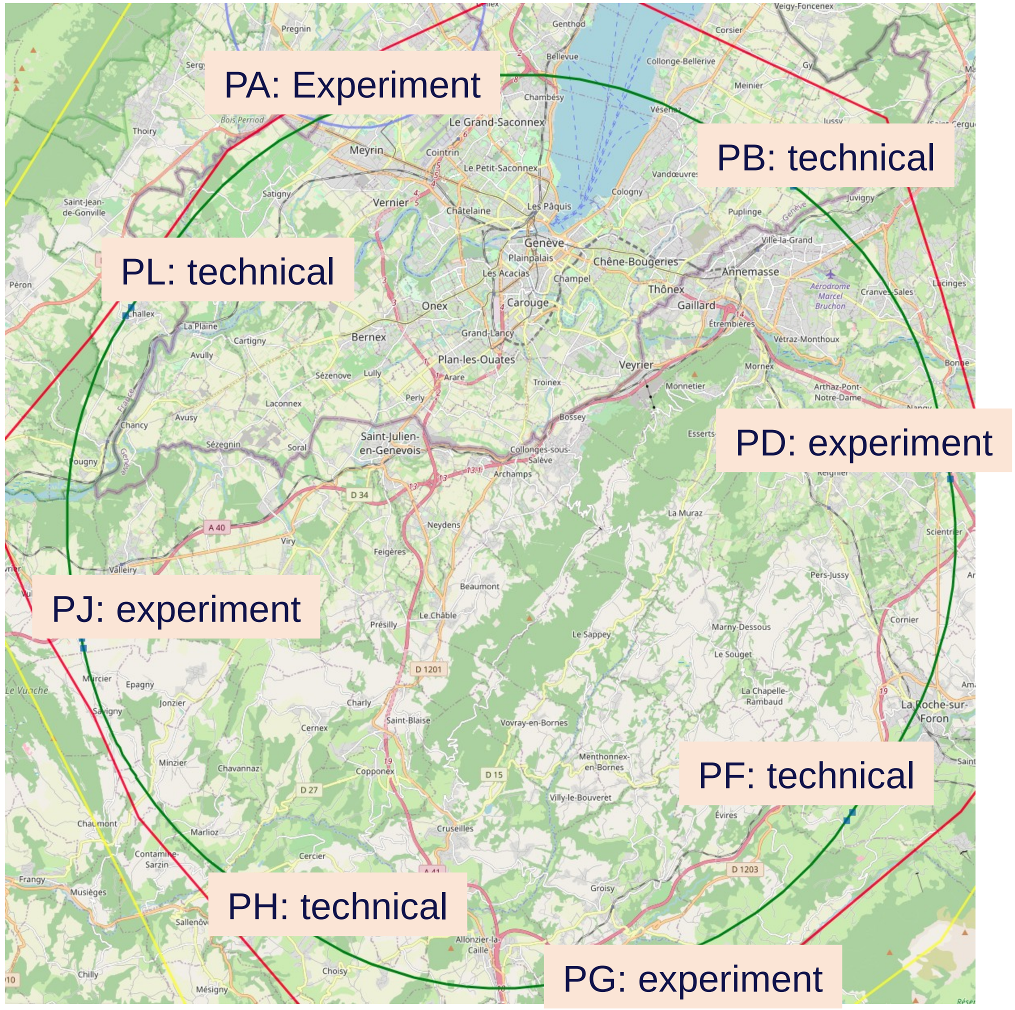
Courtesy: F. Gianotti

Optimized Placement

- Optimized considering constraints on geology and surface
- 90.7 km circumference with 8 surface points
- Compatible layout between FCC-ee and FCC-hh



FCC-ee layout



Courtesy: J. Gutleber