FUTURE CIRCULAR COLLIDER

CERN

FCC-ee Energy Calibration, Polarization and Monochromatization

R. Aßmann, D. Barber, J. Bauche, M. Benedikt, A. Blondel, E. Blomley, A. Bogomyagkov, M. Boscolo, F. Carlier, A. Ciarma, A. Faus-Golfe, D. Gaskell, E. Gianfelice-Wendt, B. Härer, M. Hofer, P. Janot, H. Jiang, J. Keintzel*, I. Koop, M. Koratzinos, T. Lefevre, E. Levitchev, A. Martens, N. Muchnoi, S. Nikitin, I. Nikolaev, K. Oide, T. Persson, T. Pieloni, P. Raimondi, T. Raubenheimer, R. Rossmanith, D. Sagan, D. Shatilov, R. Tomàs, J. Wenninger, G. Wilkinson*, Y. Wu, Z. Zhang, and F. Zimmermann

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US-FCC Workshop

Brookhaven National Laboratory

24th - 26th April 2023

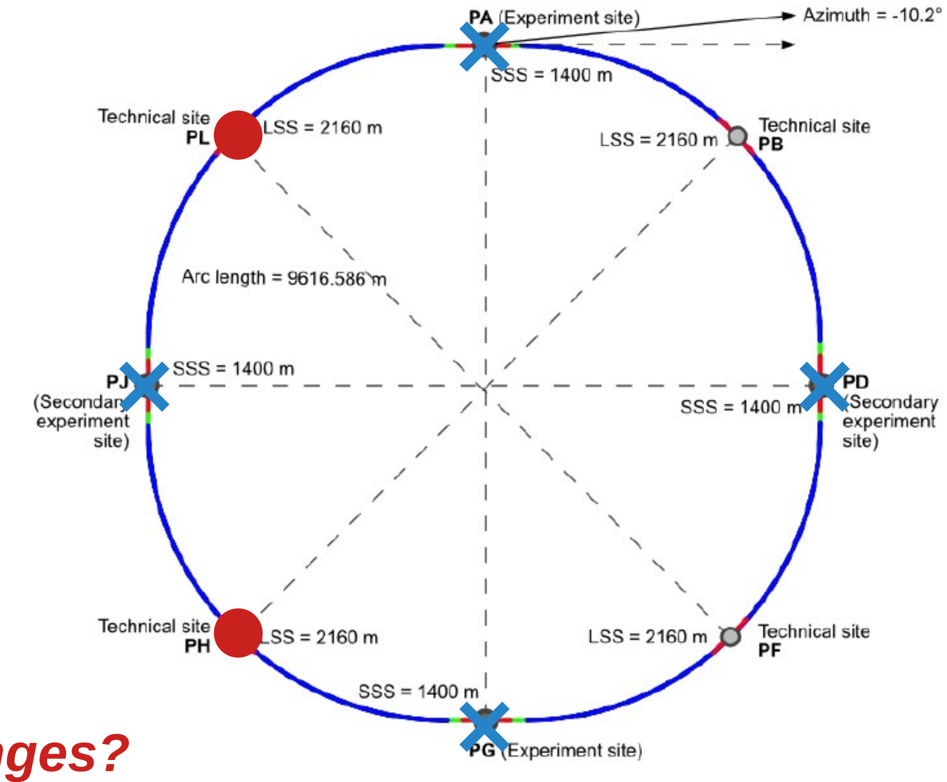
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

Overview FCC-ee

- Higgs and electro-weak factory
- 4 different beam energies
- "Lowest risk" 4 (or 2) IPs scenario (✕)
  - Perfect symmetry
  - Perfect 4-fold superperiodicity
- 1 RF-section for main rings and 1 for booster (●)
- High precision physics experiments
- → **Up to few keV statistical precision achievable**

First set of results obtained in the FCC Design Study:

Polarization and Centre-of-mass Energy Calibration at FCC-ee, **arXiv:1909.12245**



Energy calibration and polarization working group
With regular meetings since October 2021:
indico.cern.ch/category/8678
What have we achieved and what are the present challenges?

Precision Measurements

Quantity	statistics	ΔE_{CMabs} 100 keV	$\Delta E_{CMSyst-ptp}$ **40 keV**	calib. stats. 200 keV/$\sqrt{(N^i)}$	σE_{CM} (84) $\pm$ **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	–
$\frac{\Delta\alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)} \times 10^5$	**3**	0.1	**0.9**	–	**0.05**
*)			**300 keV**	**150 keV**	
m_W(MeV)	**0.200**	**(?)**		**75 keV?**	
Γ_W(MeV)			(75?)	small	OK

Z

WW

Statistical precisions

4 keV at Z

100 keV per W

Aim for same order of magnitude for systematic precision

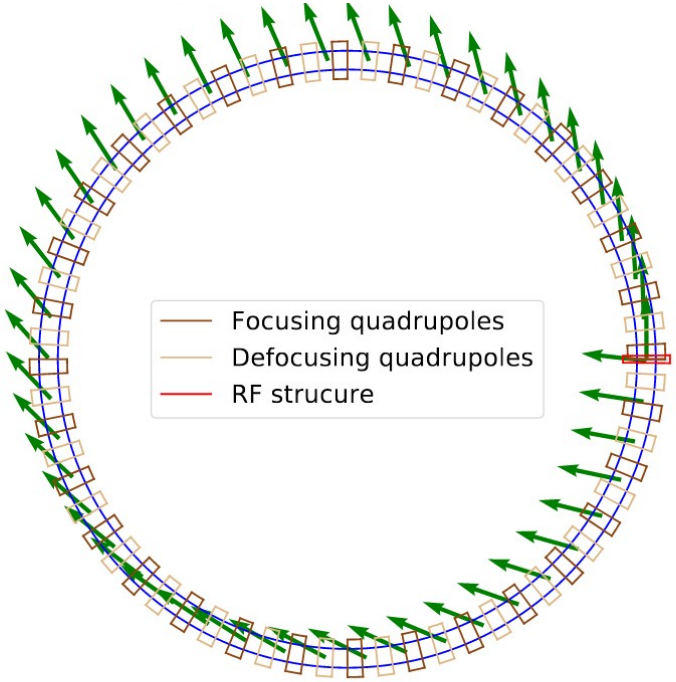
*) further clarification/documentation needed for W uncertainties in WW studies (threshold meast, direct reconstruction)

EPOL working group aims at reducing the systematic error on the E_{CM} measurement

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

Beam Energy and Spin Tune

- Beam energy is closely related to the spin tune ν



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

Measurement of spin tune will yield the beam energy
→ To be performed for the electron and the positron beam

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

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

Spin tune measurement might not be exact beam energy measurement, e.g. **shift due to vertical or longitudinal magnetic fields → to be studied in detail**

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		$4\ 10^{-10}$

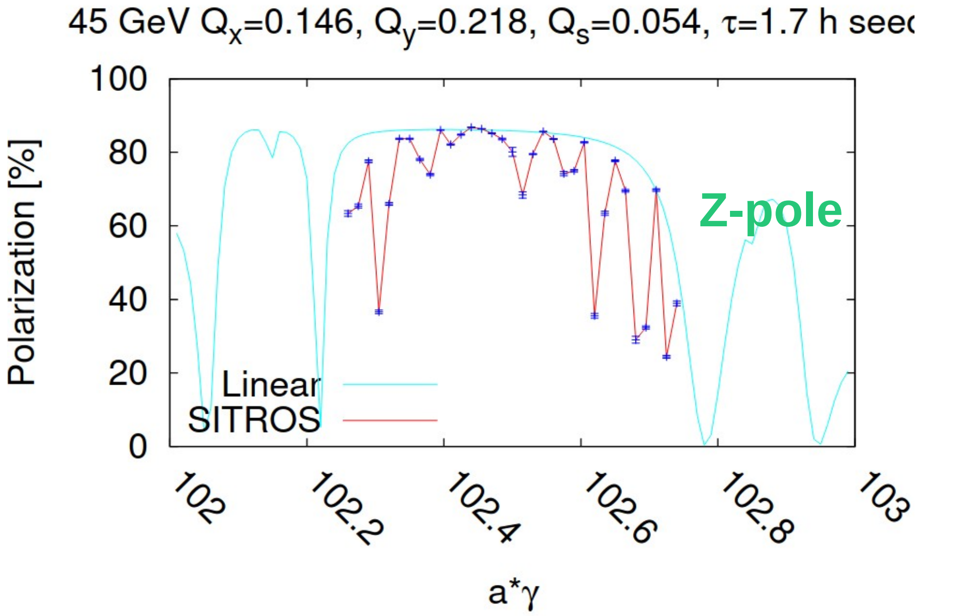
F. Carlier, E. Gianfelice-Wendt, T. Pieloni, Y. Wu

Polarization and Spin Tune

- Lepton beams polarize naturally transversely over time → Sokolov-Ternov-Effect
- Depolarization naturally from radiation, resonances, etc.
- Maximum polarization of ~ 92.4 %
- Resonances lead to depolarization

$$\underbrace{a\gamma}_{\text{Spin tune for ideal machine}} + \underbrace{m_x Q_x + m_y Q_y}_{\text{Transverse planes}} + \underbrace{m_s Q_s}_{\text{Longitudinal plane}} = k$$

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



ay at Z without solenoid: 103.5

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

Open question:

- Can we inject already polarized electron beams? At which cost?

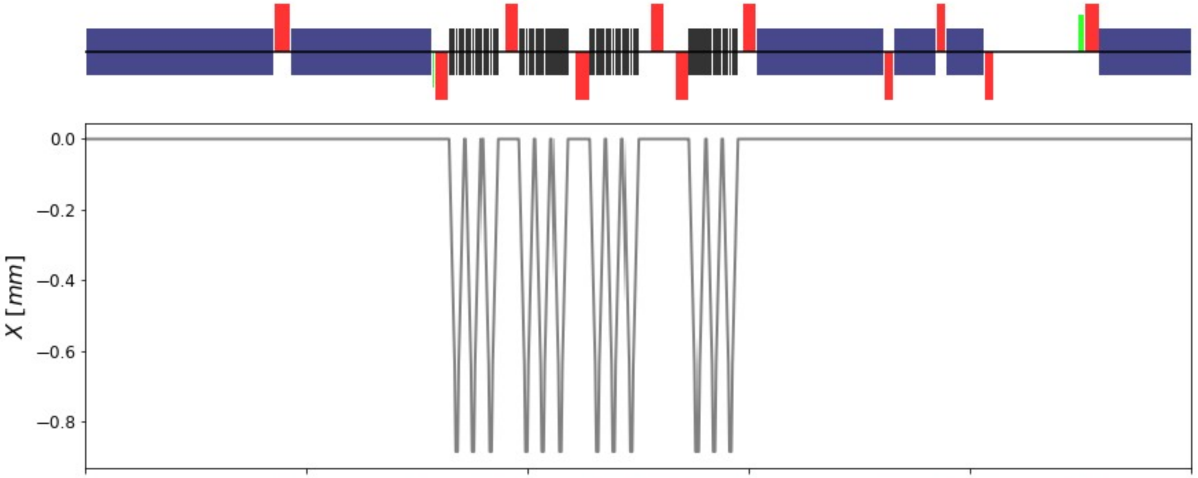
- Do we need special optics and/or tunes?

Talk: "Polarization studies in EIC and FCC" – Eliana Gianfelice

M. Hofer, K. Oide

Wigglers

- Operational scenario
  - Inject few (~200) pilot bunches
  - Use wigglers to reach ~5-10 % polarization
  - Switch wigglers off and inject all bunches
  - Measure polarization to retrieve energy
- Photons generated with critical energy O(MeV)



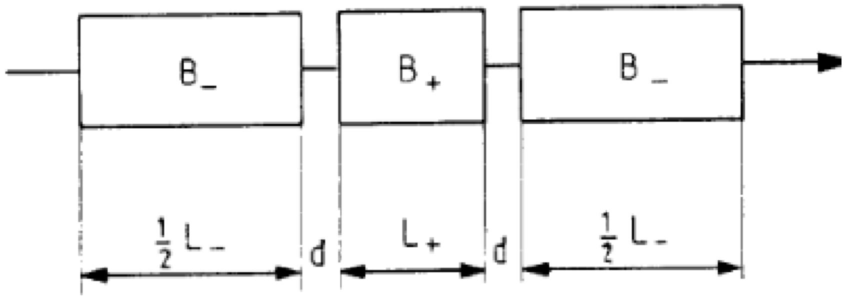
Polarization time decreases from 248 h to 12 h

Energy spread increases from 17 MeV to 64 MeV

Open Questions:

- Are 5-10% adequat for polarization measurements?

- What is the expected lifetime of pilot bunches?



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

Follow 3 three-block design from LEP

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

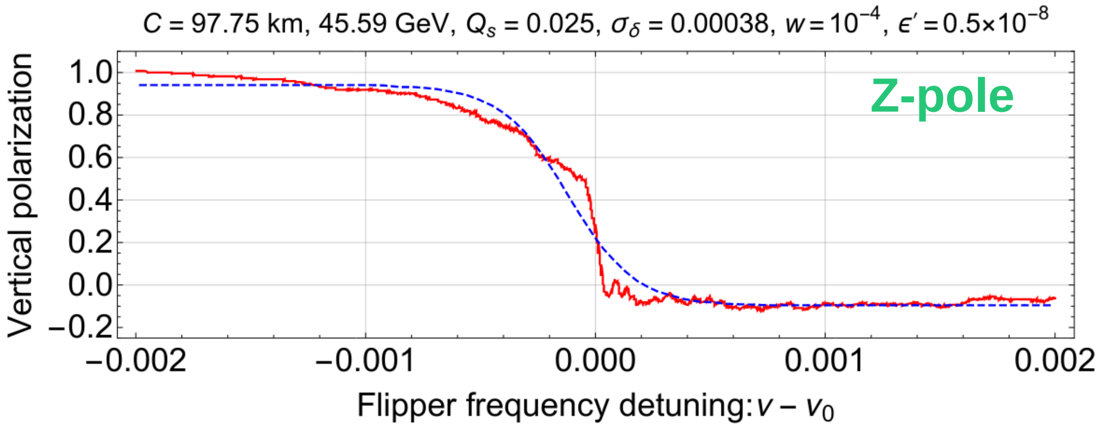
I. Koop, S. Nikitin, I. Nikolaev

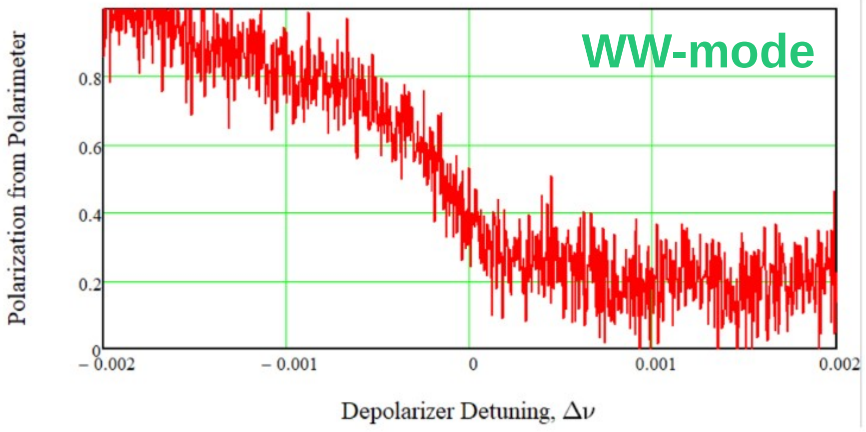
Resonant Depolarization

- Continous resonant depolarization (RDP) proceedure foreseen at the Z- and the WW- mode
- Depolarizer sweeps through frequencies ω_d
- Resonant condition $\Omega = n\omega_0 \pm \omega_d$
- Depolarization for dertimination of spin tune

ω_0 … revolution frequency
$a\gamma$ … ~ spin tune

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





Natural width of spine line due to radiative diffusion much larger than desired level of precision (Z: 200 keV and W: 1.4 MeV)

Proposal: Scan in both direction → accuracy better than 10 keV

Open Questions:

- What is the best location for the depolarizer in the lattice?

- Can we use the same pilot bunches more than once?

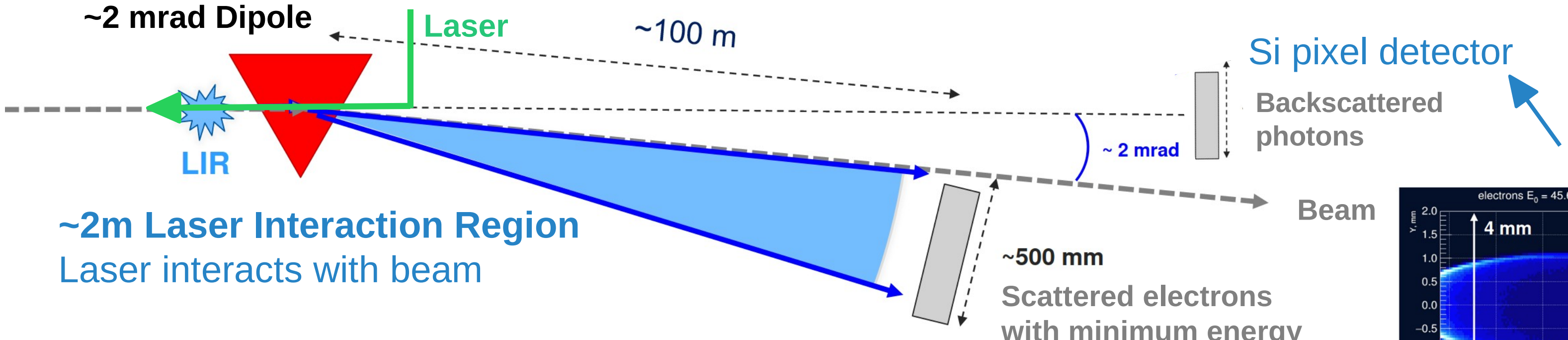
D. Gaskell, M. Hofer, A. Martens, N. Muchnoi, K. Oide, T. Lefevre, J. Wenninger

Polarimeter

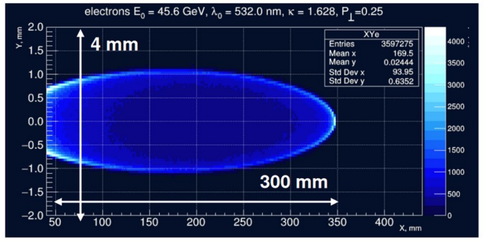
- For now, most requirements driven by Z-pole requirements and presently studied in detail
- At least one polarimeter per beam required

parameter	pilots	colliding bunches
$f_{\mathrm{rep.}}$	3 kHz	30 kHz
U	1 mJ	10x0.5 mJ
σ_t	5 ps	5 ps
$\sigma_{x,y}$ [ps]	300 μm	300 μm
P	3 W	150 W

Allows measurement of three coordinates of beam polarization



M. Hofer and J. Wenninger



N. Muchnoi

Laser requirements
Ytterbium mode-lock laser technology frequency doubled to provide green light at about 515 nm

Open Questions:

- What is the advantage and price of one polarimeter per IP and beam instead of one per beam?

- What are the required parameters to measure polarization of pilot bunches and colliding bunches?

- How can EIC and FCC studies best benefit from each other?

Talk: “Polarimeters at FCC” – Dave Gaskell

A. Blondel, T. Persson, D. Shatilov

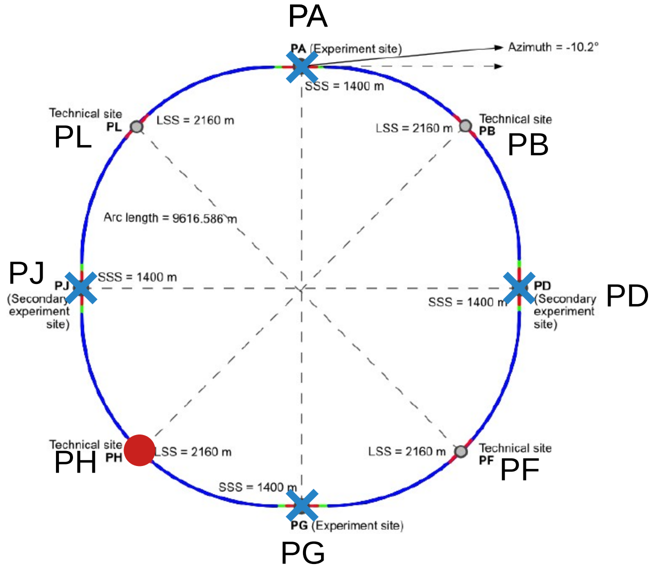
ECM and Boosts for Z-Mode

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

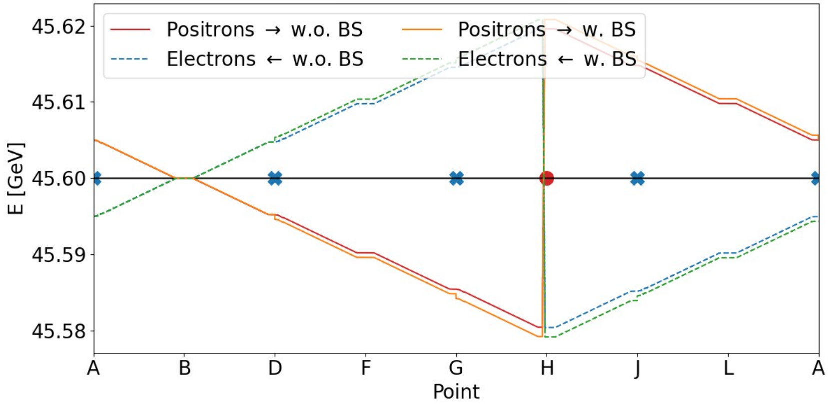
One 8 h shift will give 5 keV precision

Sum of losses close to sum of absolute boosts

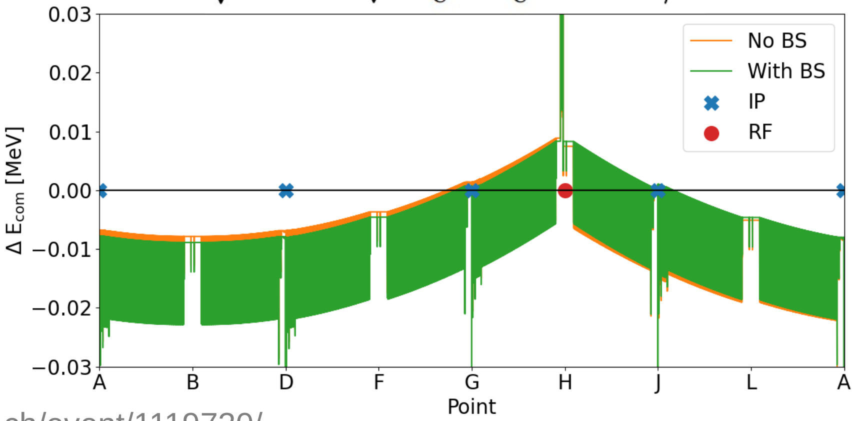
IP	ΔECM [keV]	Boost [MeV]
PA	- 7.851	10.665
PD	- 7.931	- 10.108
PG	0.570	- 30.883
PJ	0.844	31.439



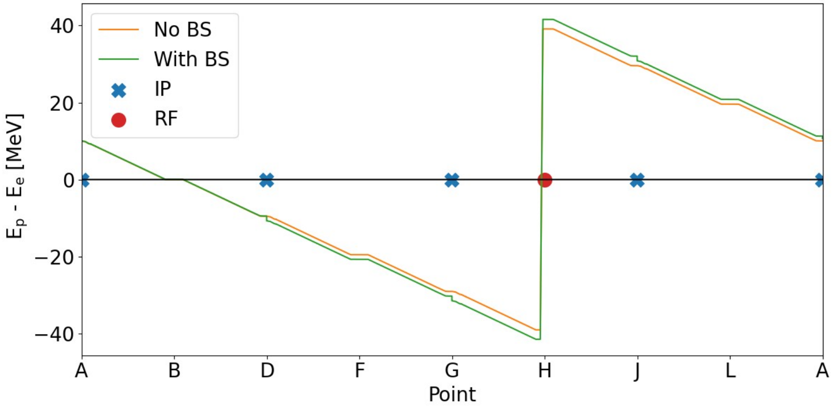
$$\Delta E \propto \gamma_{\rm rel}^4$$



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



Boost: + for e+; - for e-



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

A. Blondel, J. Wenninger

Dispersion and Collision Offsets

- ECM shifts due to opposite sign dispersion → obtained with BPMs around IP

→ Requires about **1 μm precision for BPMs close to IP**

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

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

For **$\Delta D^* = 10$ μm**, 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.**

- Even closer to 0.01 nm for σ ~ 20 nm → at the level of a % of the beam size.

- Luminosity or beam-beam (BB) deflection scan to determine collision offsets

Open Questions:

- What can we learn from non-colliding bunches with different intensities?

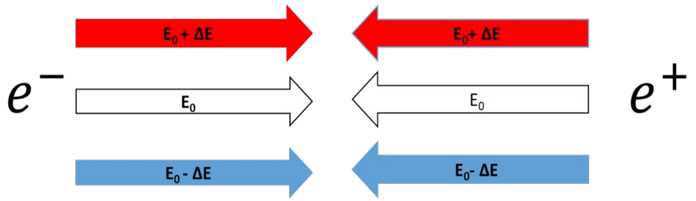
- How well can we control dispersion and collision offsets?

A. Faus-Golfe, H. Jiang, P. Raimondi, F. Zimmermann

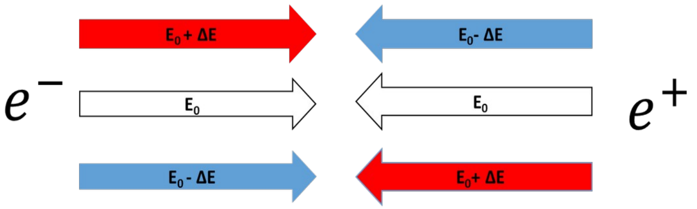
Monochromatization

- ECM depends on many factors (collision offsets, dispersion, beamstrahlung, radiation, …)
- Monochromatization required to minimize energy spread for certain operation modes

Same sign dispersion at the IP leads to change of ECM



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

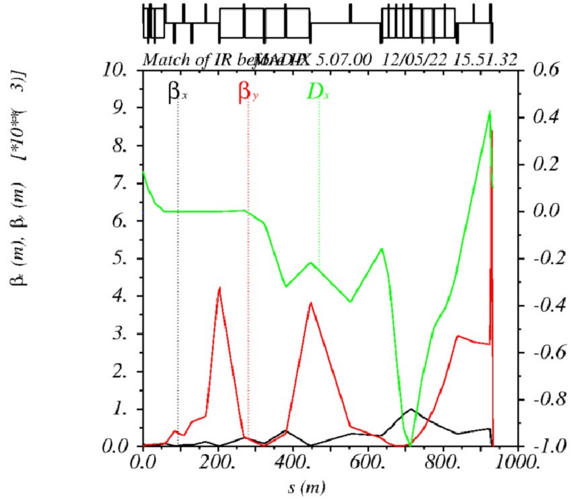


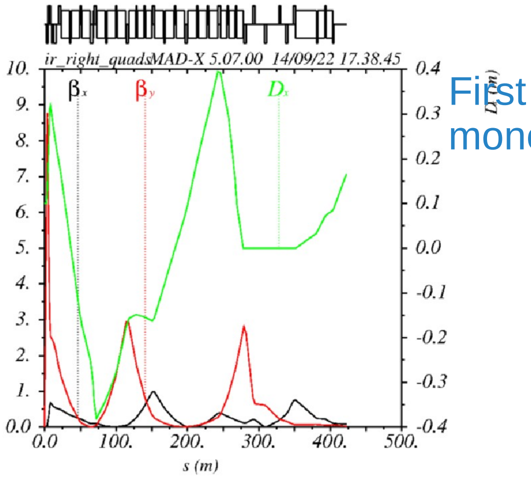
Open Questions:

- Can we have sufficient monochromatization at the Higgs-mode?

- What is the impact on luminosity?

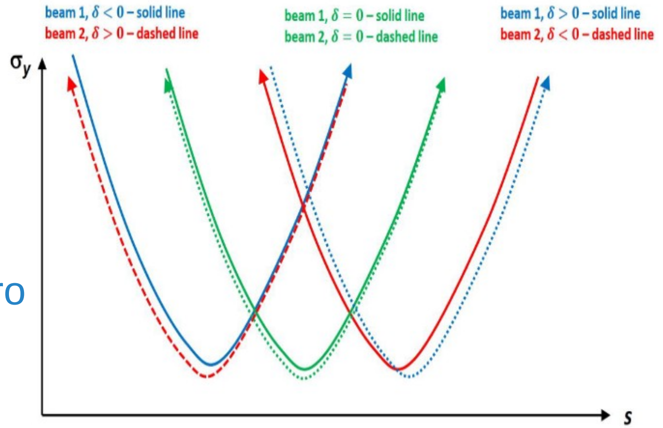
- Can we test it somewhere, e.g. at DAFNE?





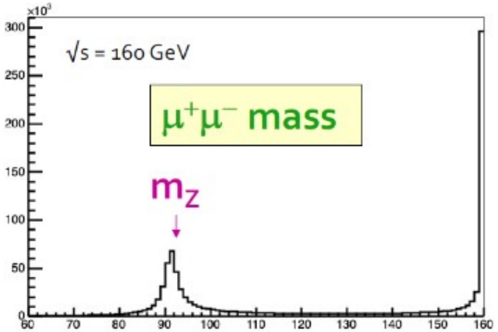
First design of monochromatization optics

Introducing residual non-zero local vertical chromaticity → Monochromatization



Experiments

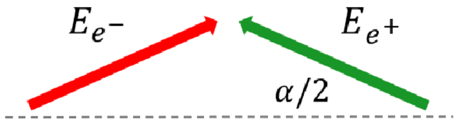
- ***G. Wilkinson:* Di-muon events: “The gift that keeps on giving”**
- Requires reliable and frequent logging of parameters



Radiative returns to the Z can be used to measure E_{CM} at higher energies, with excellent statistical precision
Already exploited during LEP 2

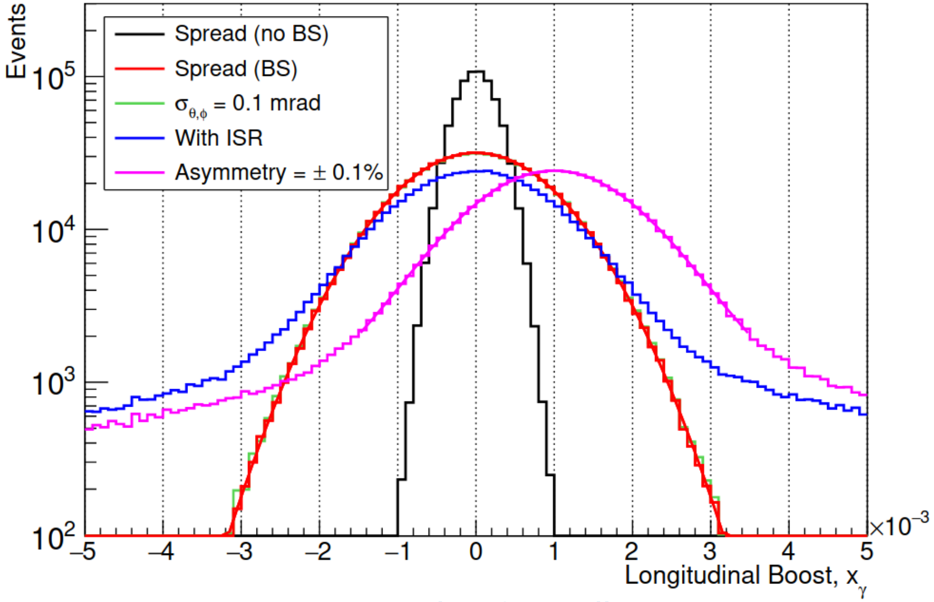
What is the real systematic uncertainty ?

Crossing angle determination from di-muon events



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

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



Boost reconstruction from di-muon events

Important message / **Open questions**

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 !

Synergies with Other Machines

- LEP: polarimeter, operation, depolarization, wigglers, di-fermion events, ...
- LHC: operation, orbit measurements

First joint FCC-EIC workshop on EPOL

Second joint FCC-EIC workshop on MDI

- EIC: polarimeter, spin simulations, depolarization, energy measurements, operations, …
- SuperKEKB: operations, option of polarized beams presently studied
- VEPP-4M: resonant depolarization
- ANKA-KARA: possible experiments
- DAFNE: monochromatization tests
- ...

Test FCC-ee polarization concepts at existing synchrotrons with high polarization

Documentation

- Overleaf document presently being prepared and updated
- Milestones: mid-term report by mid 2023 and final version end of 2025

Many thanks to all contributing colleauges!

Preliminary draft 15:26 24 April 2023

24 April 2023

Accelerator and physics requirements for the calibration of the collision energy

R. Aßmann, J. Bauche, D. Barber, M. Benedikt, A. Blondel[1], E. Blomley, M. Boscolo, A. Bogomyagkov, A. Ciarma, F. Carlier, F. Ewald, A. Faus-Golfe, D. Gaskell, E. Gianfelice-Wendt, B. Härer, M. Hofer, P. Janot, H. Jiang, J. Keintzel[2], I. Koop, M. Koratzinos, T. Lefevre, E. Levitchev, A. Martens, N. Muchnoi, S. Nikitin, I. Nikolaev, K. Oide, T. Persson, T. Pieloni, P. Raimondi, T. Raubenheimer, R. Rossmanith, D. Sagan, D. Shatilov, R. Tomás, J. Wenninger[3], G. Wilkinson[4], Y. Wu, Z. Zhang, F. Zimmermann,
On behalf of the energy calibration, polarization and monochromatization working group
CERN, 1211 Geneva 23, Switzerland

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

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

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

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Thank you!

FCC-ee energy calibration, polarization and monochromatization

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Parameters

		Z	WW	ZH	$t\bar{t}$
Circumference	[km]	91.174			
Bending radius	[km]	9.937			
SR power per beam	[MW]	50			
Half crossing angle	[mrad]	15			
Beam Energy	[GeV]	45.6	80	120	182.5
Beam Current	[mA]	1280	135	26.7	5.0
Bunches/beam	[-]	10000	880	248	40
Bunch population	[10^{11}]	2.43	2.91	2.04	2.37
Horizontal emittance	[nm]	0.71	2.16	0.64	1.49
Vertical emittance	[pm]	1.42	4.32	1.29	2.98
Arc cell phase advance	[°]	90/90			
Arc cell length	[m]	100		50	
Momentum compaction factor	[10^{-6}]	28.5		7.33	
Arc sextupole families	[-]	75		146	
Betatron tunes	[-]	214.260 / 214.380		402.224 / 394.360	
Synchrotron tune	[-]	0.0370	0.0801	0.0328	0.0826
β_x^* / β_y^*	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Energy spread with SR/BS	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.221
Bunch length with SR/BS	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	1.95 / 2.75
RF-frequency	[MHz]	400	400	400	400 + 800
Total RF voltage	[GV]	0.120	1.0	2.08	11.25
Long. damping time	[turns]	1168	217	64.5	18.5
Energy acceptance	[%]	±1.3	±1.3	±1.7	−2.8 +2.5
Luminostiy / IP	[10^{34} cm^{-2}s^{-1}]	182	19.4	7.26	1.25
Polarization time	[s]	15000	900	120	4.6
SR losses/turn	[GeV]	0.039	0.370	1.869	10.0

A. Blondel, G. Wilkinson

Where to Start?

Entry points for EPOL-related tasks (non-exhaustive list)

Experimental inputs to calibration of energy-related quantities

Di-fermion events can be used to calculate boost, energy spread, crossing angle and energy.

Almost all studies to date performed with muons, and under idealised conditions.
Should be repeated in more realistic detector and physics framework, investigating in particular the impact of QED corrections and misalignments. True systematics of radiative return events for determination of beam energy should be investigated. Need to be extended beyond dimuons.

Input on polarimeter design

FCC-ee polarimeters will be highly precise calorimeters, with a demanding high-power laser system.
Great opportunity for institute involvement !

Accelerator physicist and particle physicist input to core calibration issues

- Depolarisation and free-spin precision strategies
- Development of time-dependent energy model – impact on key observables
- Strategy for interaction-point specific corrections (in particular opposite sign dispersion studies)
- Monochromatization-related issues…
- ……

EPOL Working Shop

- A dedicated workshop on "FCC-ee energy calibration, polarization and monochromatization (EPOL)" took place from September 19 to 30 2022 at CERN
- At this occasion there was an **EIC-FCC Collaboration Working Meeting** on Polarization from September 19 to 23 2022.

113 registered participants

127 contributions

Indico Event:
https://indico.cern.ch/e/EPOL2022

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.

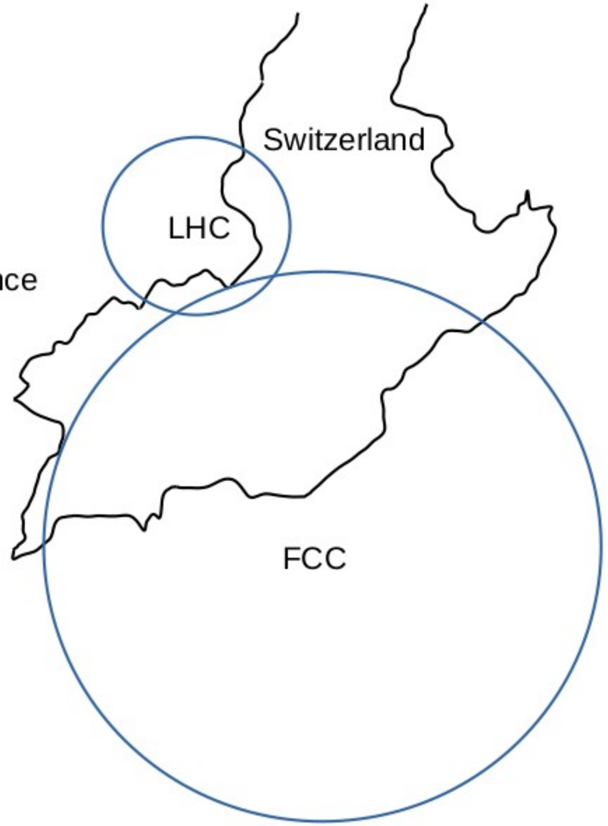
Lepton Future Circular Collider, FCC-ee
Hadron Future Circular Collider, FCC-hh

$\Big\}$ **FCC Integrated Project**

Future Circular Colliders

Inspired by LEP-LHC programm

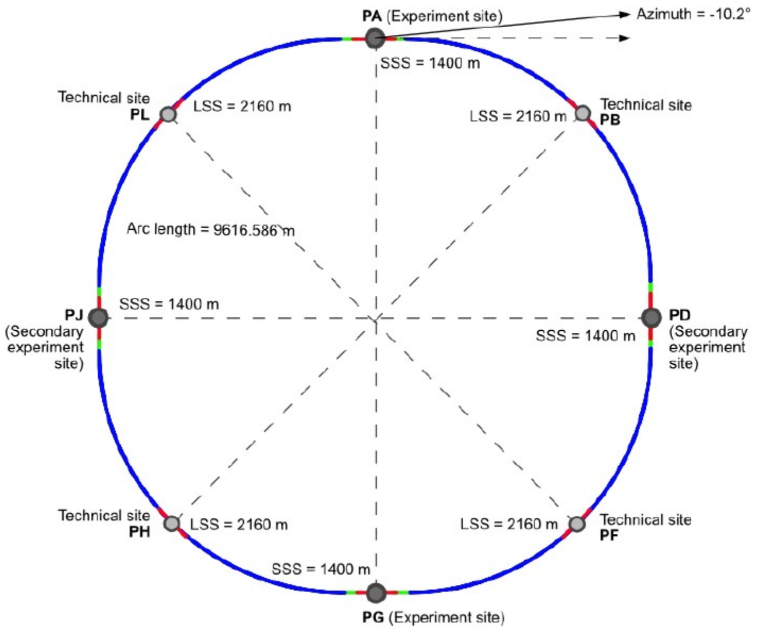
Re-using CERN infrastructure



Compatible lattice designs

FCC-ee

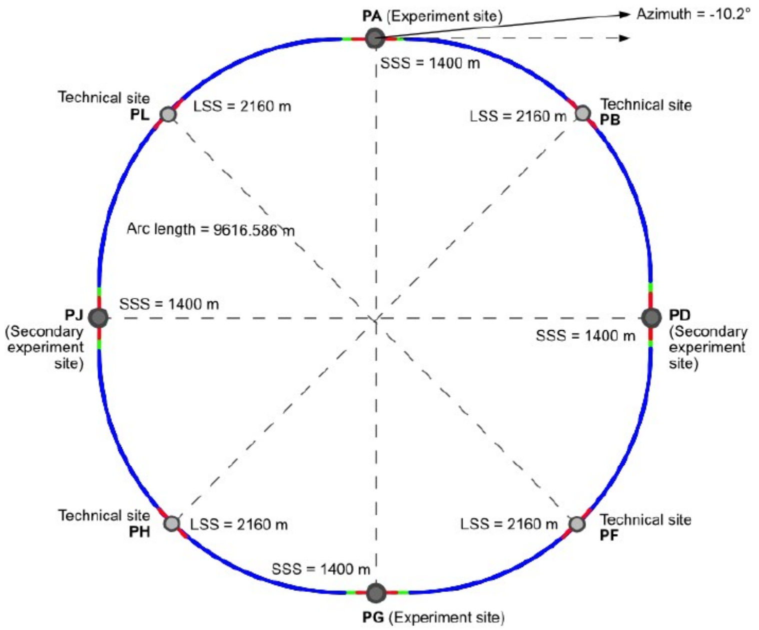
Electron-positron collider



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.

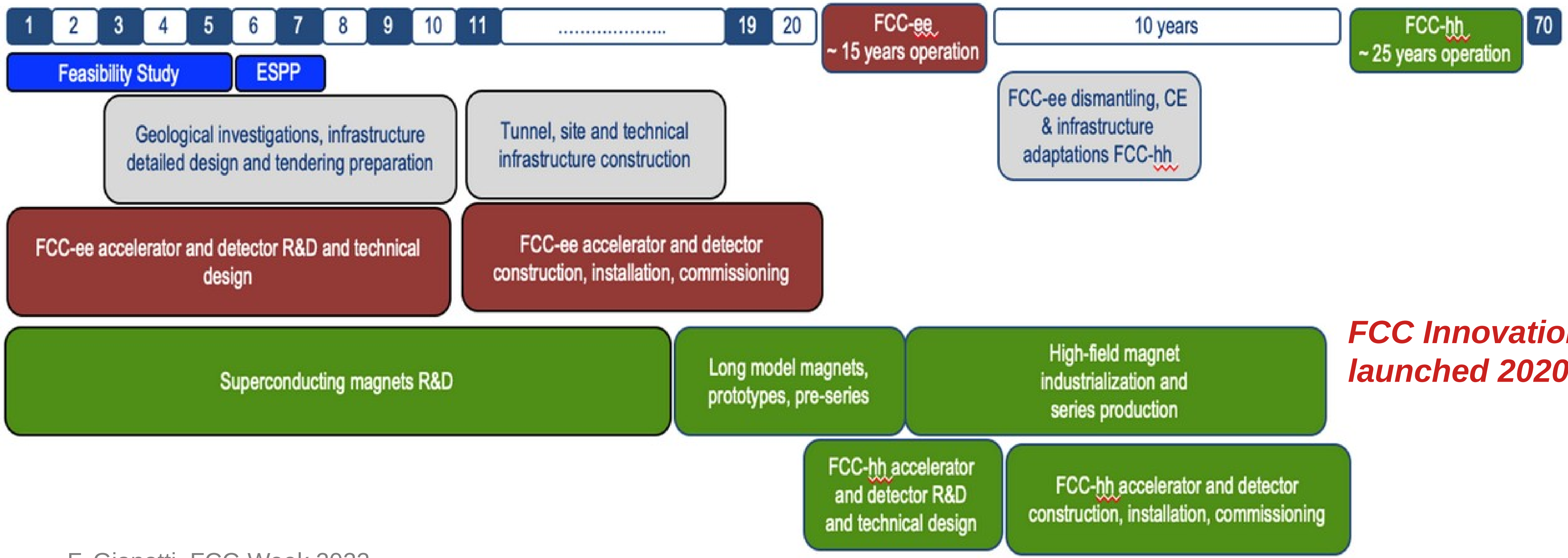
FCC Integrated Project

Lepton collider (FCC-ee) followed by hadron collider (FCC-hh)

FCC-ee commissioning second half of the 2040s

FCC-hh commissioning around 2070

Starts at 2021



FCC Innovation Study launched 2020

F. Gianotti, FCC-Week 2022.

J. Gutleber, V. Mertens

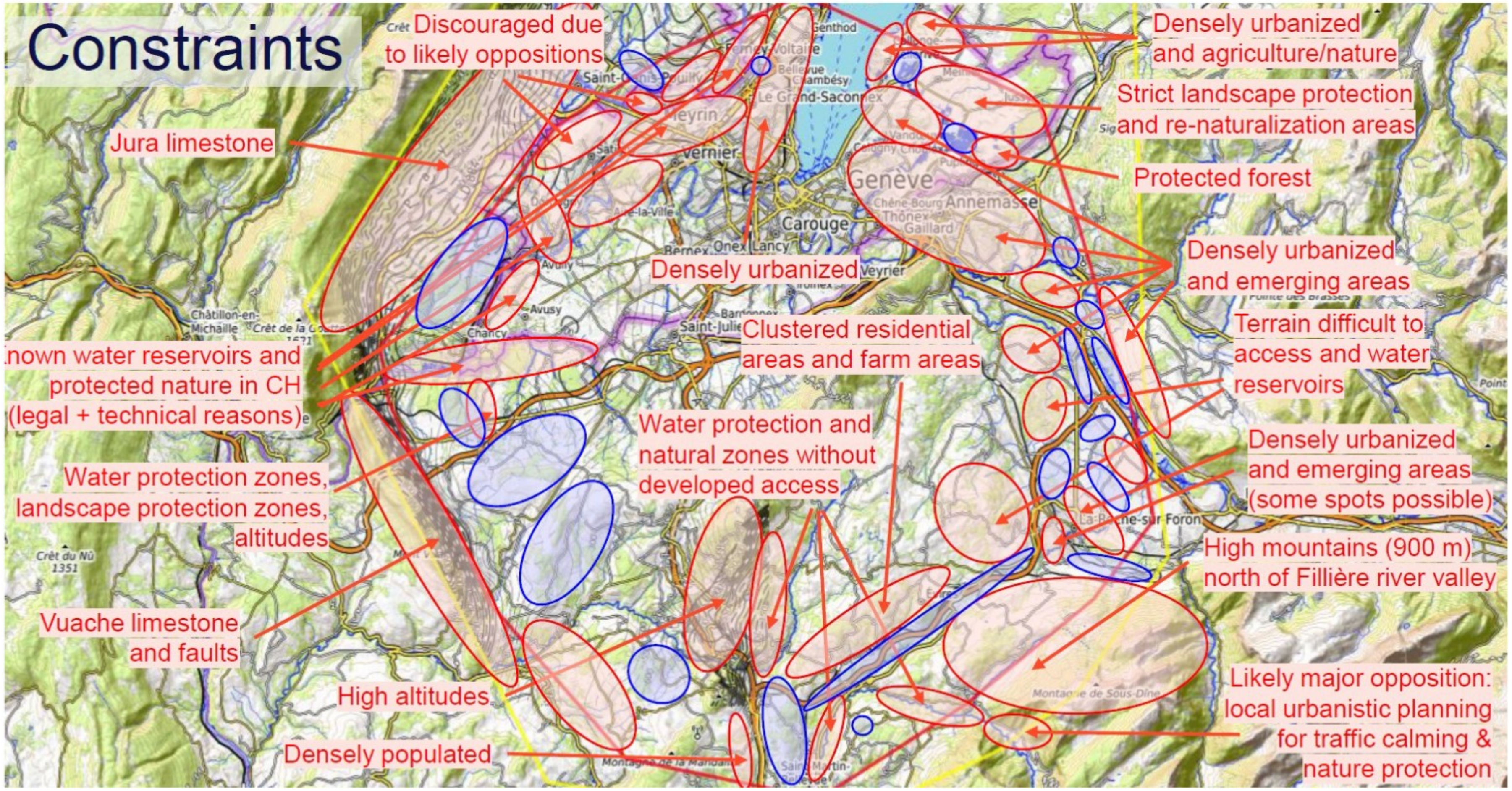
Placement Studies

Constraints:

- 8 or 12 surface sites
- Topography
- Geology
- Infrastructure
- …

Result:

89 km to 91 km best geolical and territorial fits



P. Boillon: indico.cern.ch/event/995850

A. Blondel

Precision Measurements

Table 15: Calculated uncertainties on the quantities most affected by the center-of-mass energy uncertainties, under the final systematic assumptions.

	Quantity	statistics	$\Delta E_{CM\,abs}$ 100 keV	$\Delta E_{CMSyst-ptp}$ **40 keV**	calib. stats. 200 keV/$\sqrt{(N^i)}$	σE_{CM} (84) $\pm$ **0.05** MeV
Z	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	–
	$\frac{\Delta\alpha_{QED}(M_Z)}{\alpha_{QED}(M_Z)} \times 10^5$	**3**	0.1	**0.9**	–	**0.05**
WW	*)			**300 keV**	**150 keV**	
	m_W(MeV)	**0.200**	**(?)**	**75 keV?**		
	Γ_W (MeV)			(75?)	small	OK

abs: absolute scale error

ptp: point-to-point errors

*) further clarification/documentation needed for W uncertainties in WW studies (threshold meast, direct reconstruction)

A. Blondel

E_{CM} Uncertainties

$$\frac{\Delta m_Z}{m_Z} = \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\mathrm{abs}} \oplus \left\{\frac{\Delta(\sqrt{s_+}+\sqrt{s_-})}{\sqrt{s_+}+\sqrt{s_-}}\right\}_{\mathrm{ptp-syst}} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\mathrm{sampling}},$$

$$\frac{\Delta\Gamma_Z}{\Gamma_Z} = \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\mathrm{abs}} \oplus \left\{\frac{\Delta(\sqrt{s_+}-\sqrt{s_-})}{\sqrt{s_+}-\sqrt{s_-}}\right\}_{\mathrm{ptp-syst}} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\mathrm{sampling}},$$

$$\Delta A^{\mu\mu}_{\mathrm{FB}}(\mathrm{pole}) = \frac{\partial A^{\mu\mu}_{\mathrm{FB}}}{\partial\sqrt{s}}\left\{\Delta(\sqrt{s_0}-0.5(\sqrt{s_+}+\sqrt{s_-}))\right\}_{\mathrm{ptp-syst}} \oplus_i \frac{\partial A^{\mu\mu}_{\mathrm{FB}}}{\partial\sqrt{s}}\left\{\frac{\Delta\sqrt{s^i_{0,\pm}}}{\sqrt{N^i_{0,\pm}}}\right\}_{\mathrm{sampling}},$$

$$\frac{\Delta\alpha_{\mathrm{QED}}(m_Z^2)}{\alpha_{\mathrm{QED}}(m_Z^2)} = \left\{\frac{\Delta\sqrt{s}}{\sqrt{s}}\right\}_{\mathrm{abs}} \oplus \left\{\frac{\Delta(\sqrt{s_+}-\sqrt{s_-})}{\sqrt{s_+}-\sqrt{s_-}}\right\}_{\mathrm{ptp-syst}} \oplus_i \left\{\frac{\Delta\sqrt{s^i_\pm}}{\sqrt{s^i_\pm N^i_\pm}}\right\}_{\mathrm{sampling}},$$

$$\text{with } \frac{\partial A^{\mu\mu}_{\mathrm{FB}}}{\partial\sqrt{s}} \simeq 0.09/\mathrm{GeV}$$

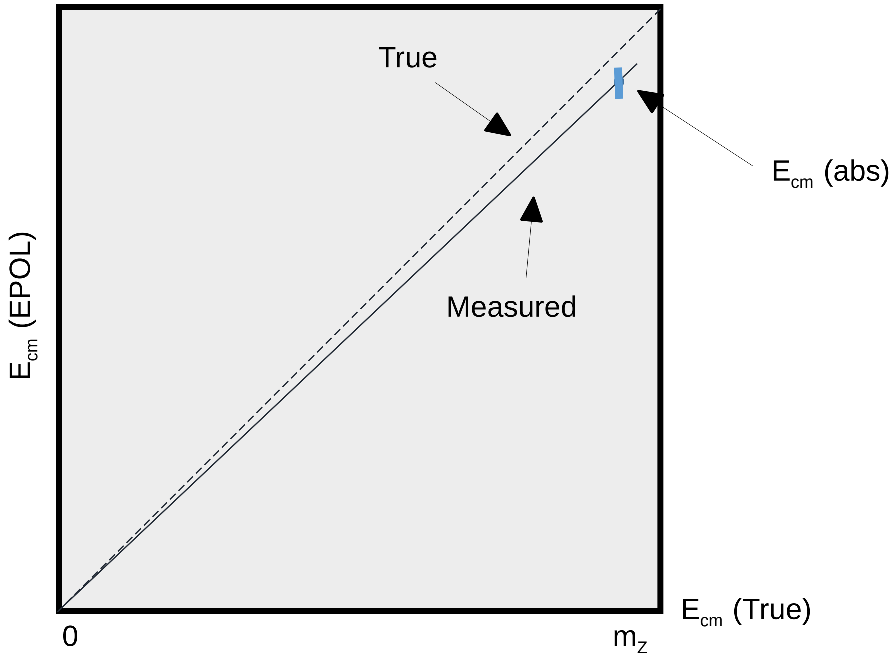
A_{FB} **Forward-Backward Assymmetry**

Error categories:
- abs: dominant for Z and W mass
- ptp: dominant for ΓZ, ΓW and AFB (peak and off-peak)
- sampling: negligible for 1 measurement / 15 mins=1000s → 10^4 measurements
- **syst: systematic uncertainty aimed to be reduced to ~4 keV and ~100 keV for Z and W mass**

A. Blondel

Uncertainties

Absolut scale error (abs)

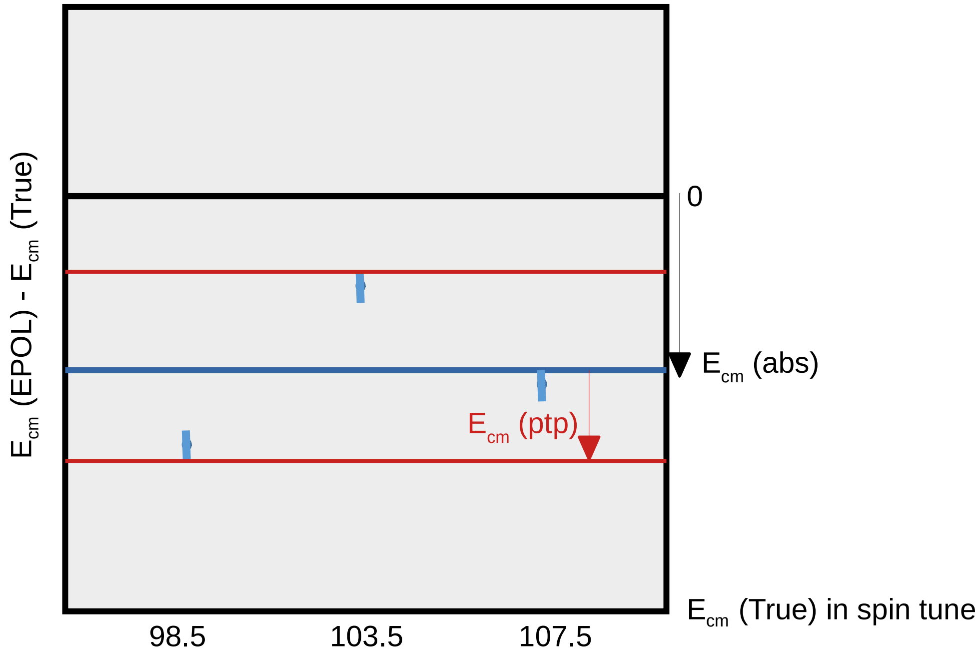


Absolute scale of correspondance between true E_{cm} and the EPOL group estimate

➔ large effect on Z,W mass, small on Z,W width

From: electron mass error, systematic error in RF frequency, or systematic IP dispersion/offset, systematic shift of depolarization wrt resonance, unforeseen energy losses etc.

Point-to-point errors (ptp)



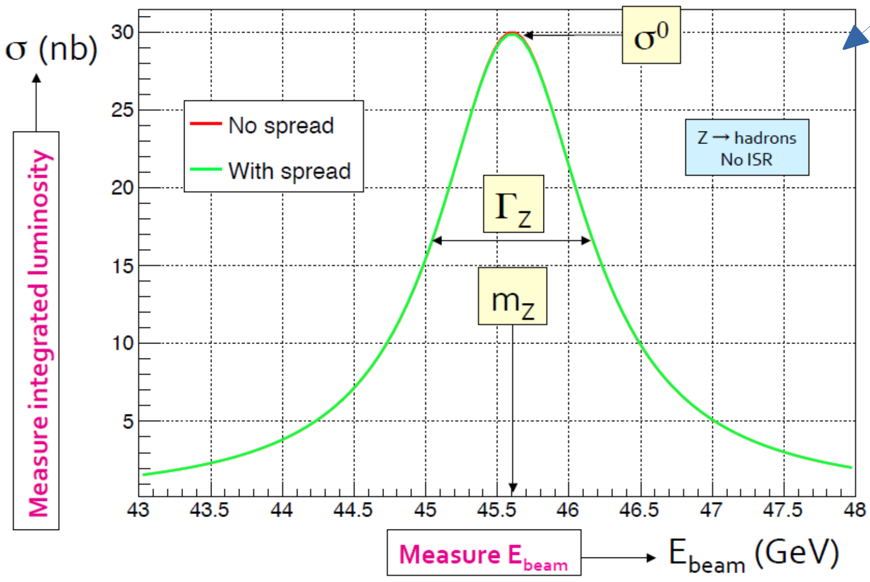
Point-to-point differences in EPOL calibration

➔ dominant effect on Z and W width, m_W/m_Z, A_{FB}

From: spin tune dependence of RDP vs E(true) due to interferences with underlying resonances, variability of running conditions wrt IP effects or ground motion, non-linearity of energy losses, etc.

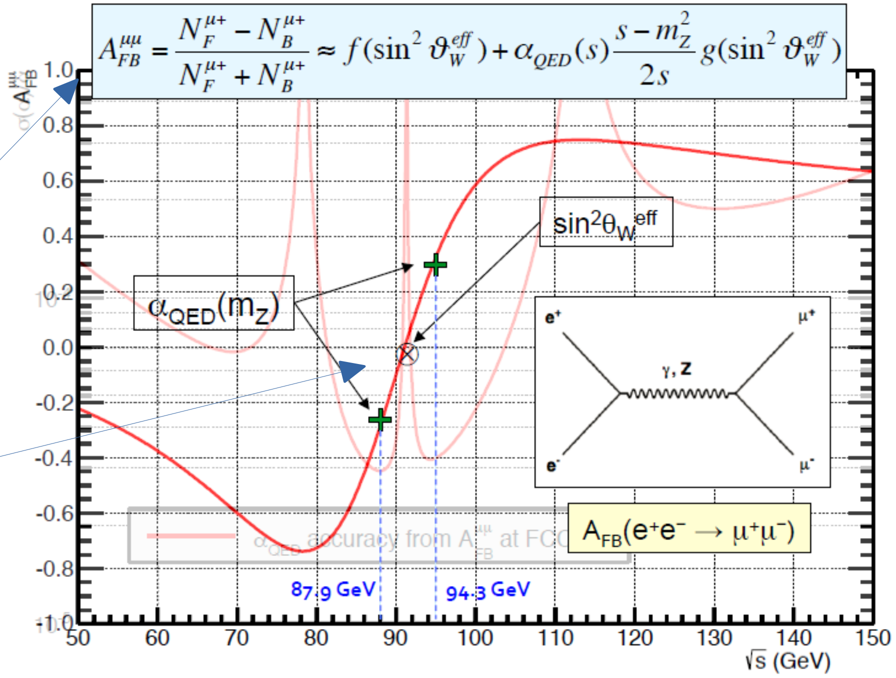
A. Blondel

Scan Points



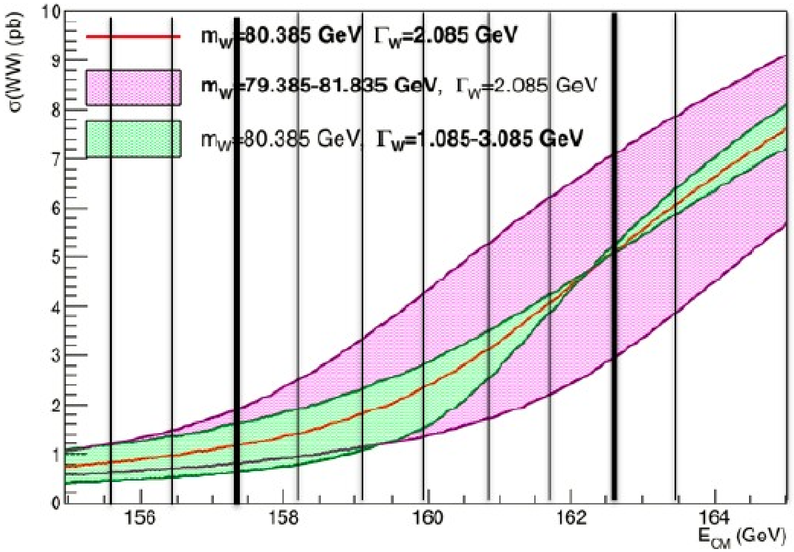
Z mass and width

Forward-Backward Assymmetry links the weak coupling with the EM-coupling



To measure the slope around the Z resonance at E_{CM} = 91 GeV, a scan at different energies is proposed

Scan point	$\sqrt{s}$ (GeV)	E_b (GeV)	Spin tune
$\sqrt{s_-}$ A	87.69	43.85	99.5
$\sqrt{s_-}$ Request	87.9	43.95	99.7
$\sqrt{s_-}$ B	88.57	44.28	100.5
$\sqrt{s_0}$	91.21	45.61	103.5
$\sqrt{s_+}$ A	93.86	46.93	106.5
$\sqrt{s_+}$ Request	94.3	47.15	107.0
$\sqrt{s_+}$ B	94.74	47.37	107.5



W mass and width have presenlty rather large uncertainties → aim to be reduced

Structure of the EPOL Team

A- Simulations of polarization and spin-tune to beam energy relationship

-- simulations of spin polarization in realistic machine (also able to calculate emittances, luminosity)

-- res. depolarization at Z and WW threshold

-- design and integration of wigglers, RF kickers, in FCC-ee

B. Simulation of the relationship between beam energies and centre-of-mass energy

-- studies of operation scenarios

-- control of offsets and vertical dispersion

-- Impact and control of energy losses: Synchrotron rad., Beamstrahlung, impedance, etc.

C. Polarimeter design and performance

-- now working to build a global collaboration

-- Aim to provide integration of polarimeters,

-- conceptual design and cost estimate of polarimeter for FCC FS

D. Measurements in Particle Physics Experiments

-- use of dimuons and other processes to determine centre-of-mass energy spread, boost, at and within IP

E. Monochromatization

-- new ideas for monochromatization in other dimensions than horizontal (x) axis. (time, z)

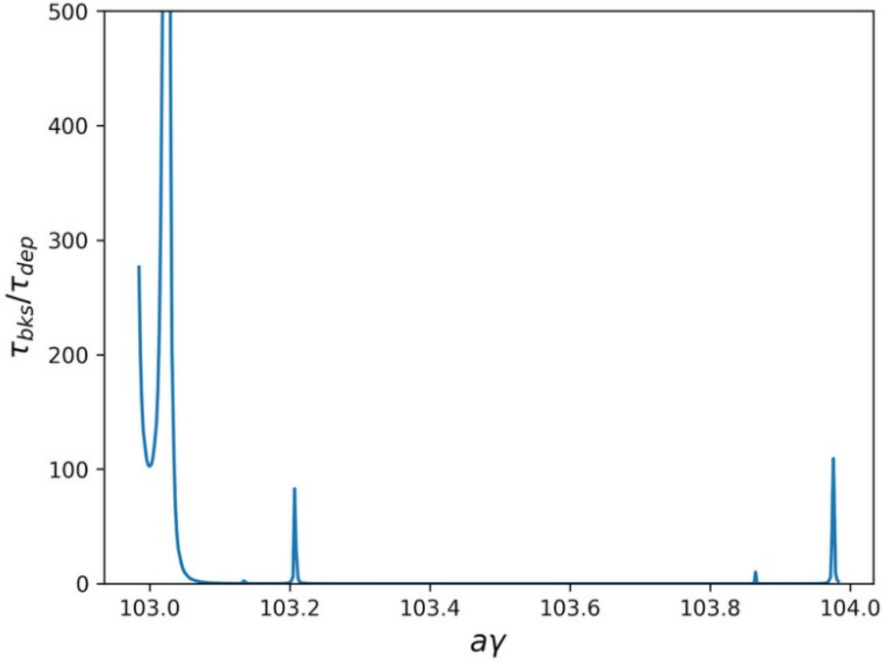
-- what its the limit?

F. Carlier, T. Pieloni, Y. Wu

Error Sensitivity

- Depolarization strength at spin-orbit resonance is sensitive to the orbit
- After closed orbit correction, harmonic spin matching is needed to increase polarization
- Minimum 8 bumps arcs, each with 3 vertical correctors (strength and location under study)

$(\Delta y)_{rms} = 43.7\ \mu m$



Excellent optics tuning, measurement and correction techniques will ensure sufficient polarization

Open question:

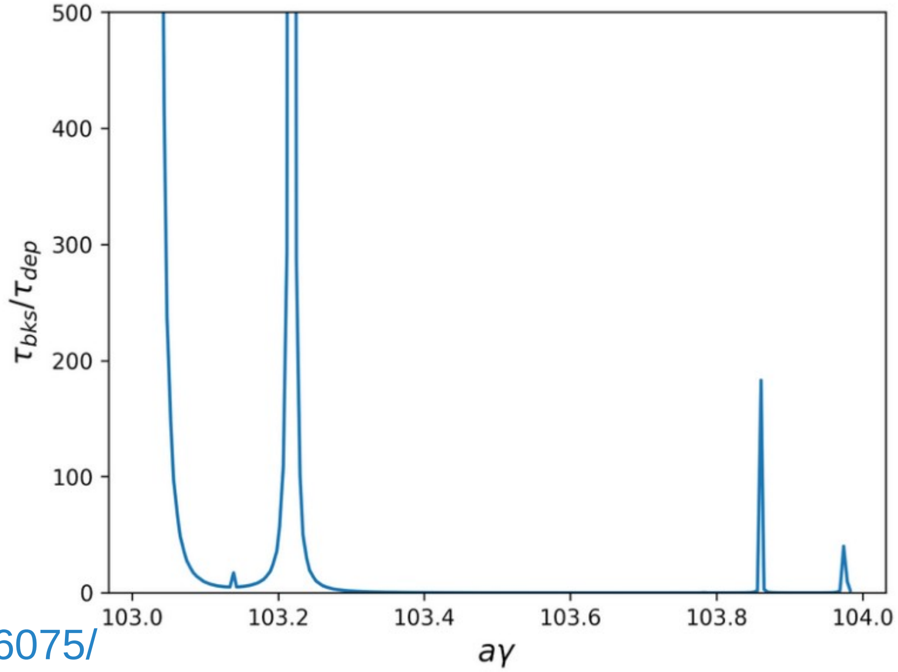
- How well do we need to correct orbit?

- What are the tolerances on Alignment and BPMs?

$Q_x = .139$ $Q_y = .219$ $Q_s = 0.025$

Regular optics tuning meetings: https://indico.cern.ch/event/1226075/

$(\Delta y)_{rms} = 148\ \mu m$



F. Carlier, T. Pieloni, Y. Wu

Error Sensitivity

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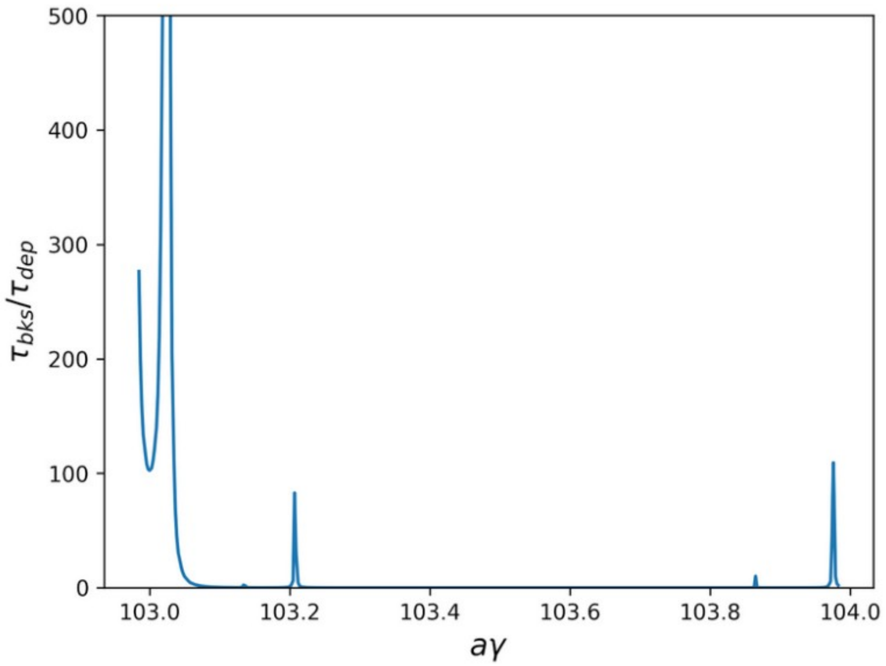
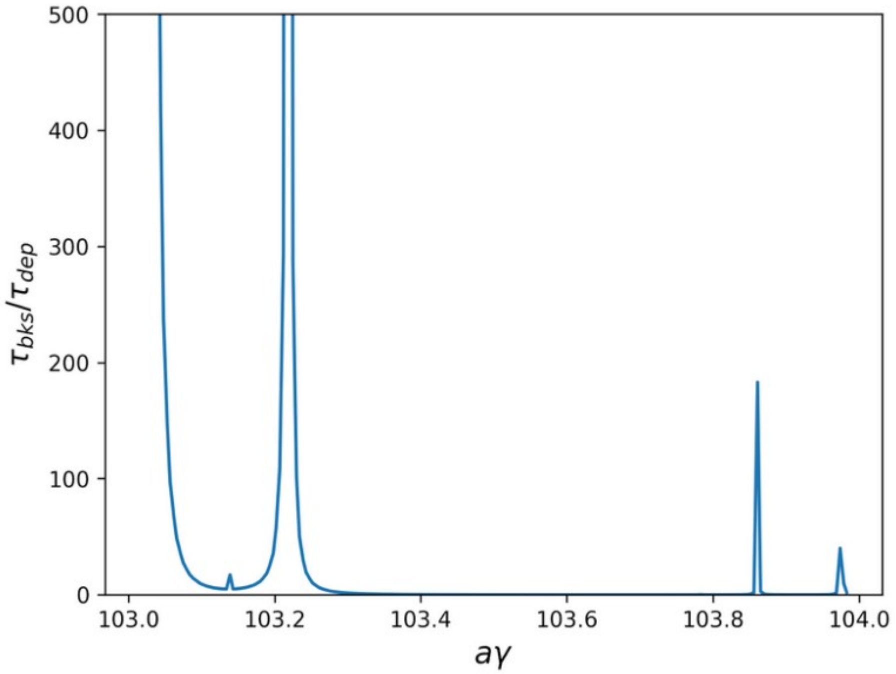


Misalignment errors in Dipoles, quadrupoles Sextupoles to generate effective lattice

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

$(\Delta y)_{rms} = 148\ \mu m$

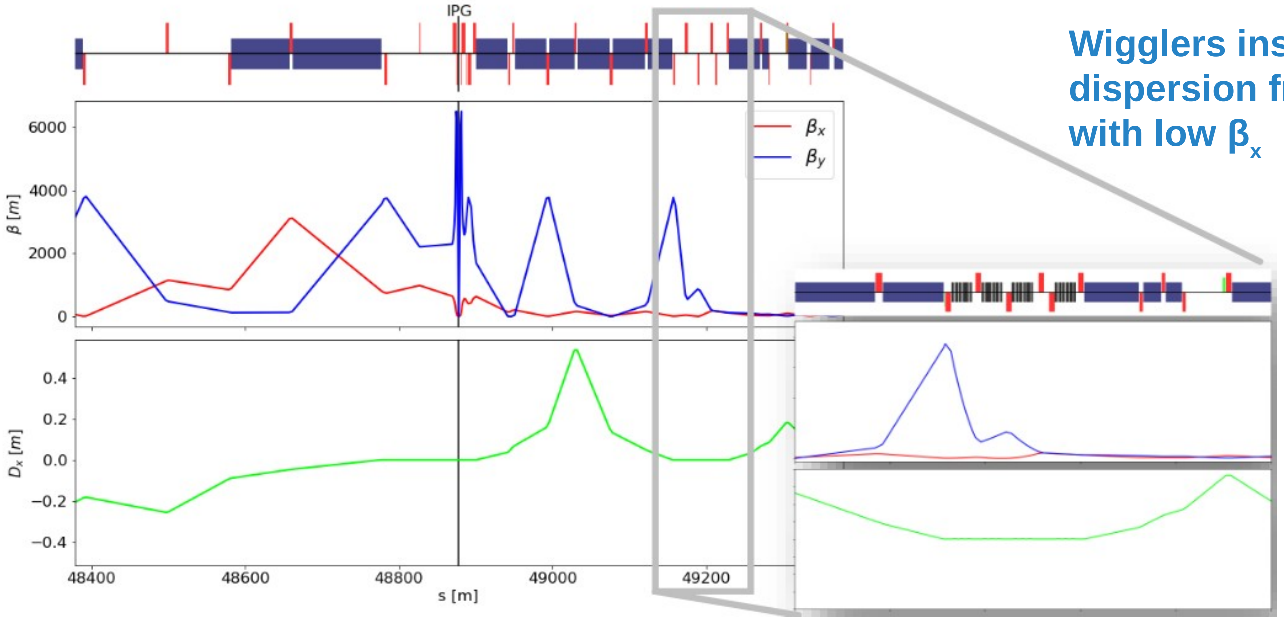


M. Hofer, K. Oide

Wigglers I

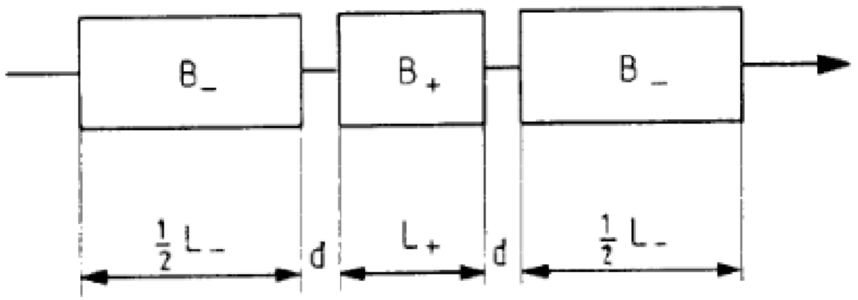
- Very long natural polarization time in FCC-ee
- Wigglers improve polarization time significantly

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



Wigglers installed in dispersion free section with low β_x

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

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, G. Wilkinson

Wigglers III

- Transverse polarization
  - For polarization measurements
- Longitudinal polarization
  - Residual polarization could spoil physics experiments
  - → Goal: to be controlled

    to 10^{-5}

LEP: RDP measurements were performed outside physics collisions; while at FCC-ee, measurements will be performed throughout

• However, dead-time at start of fill at Z energies, as we must wait for polarisation level to accumulated in pilot bunches, when wigglers are in operation

• No physics bunches circulating when wigglers are on (synchrotron radiation)

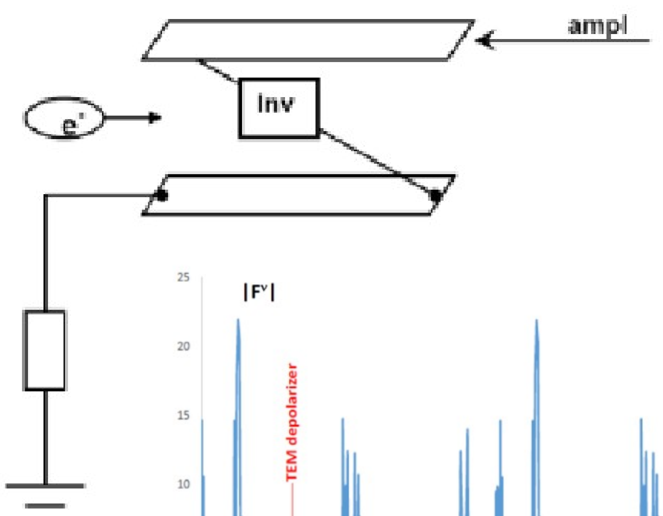
• Estimated time to reach ~10% polarization is ~100 minutes. Significant dead time, the overall impact of which will depend on length of fills.

• **Question: are lower levels of polarisation adequate for RDP when current is higher? If so, maybe possible to reduce time of wiggler operation.**

I. Koop, S. Nikitin, I. Nikolaev, J. Wenninger

Depolarizer

- Transverse depolarization for two pilot bunches simultaneously for polarization measurements
- Longitudinal depolarization for colliding bunches

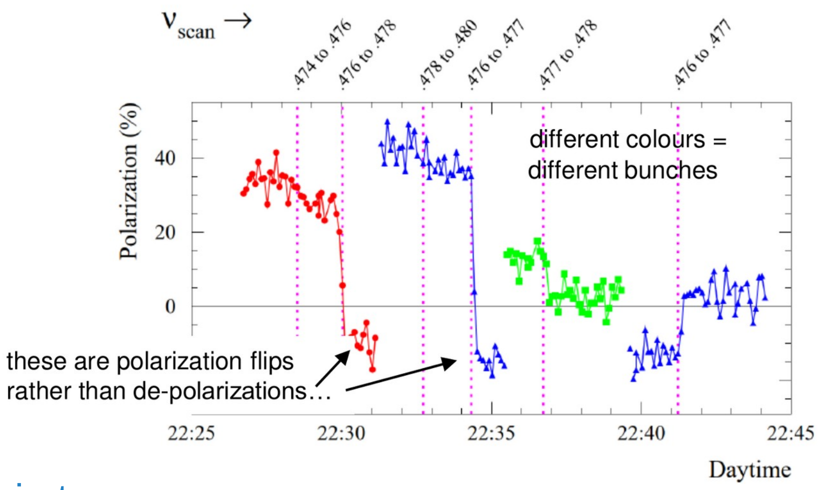


TEM wave propagating towards beam
Harmonic amplitude created

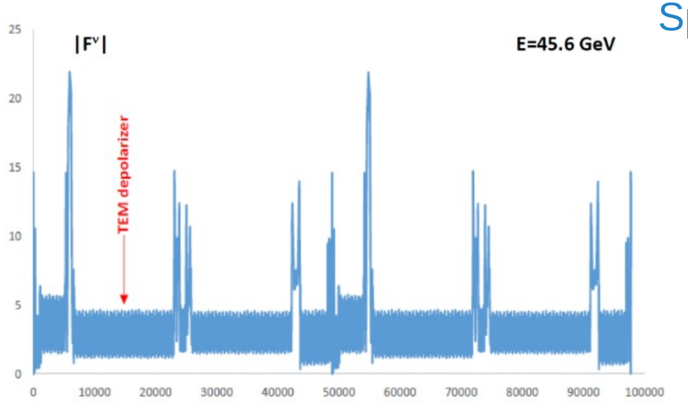
$$|w_k| = \frac{\nu B l}{2\pi B\rho}|F^{\nu}| = |F^{\nu}|\frac{\nu\phi}{2\pi}$$

Spin response function

ν … spin tune
B … amplitude of TEM wave
l … strip-line length
νφ … spin rotation angle



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



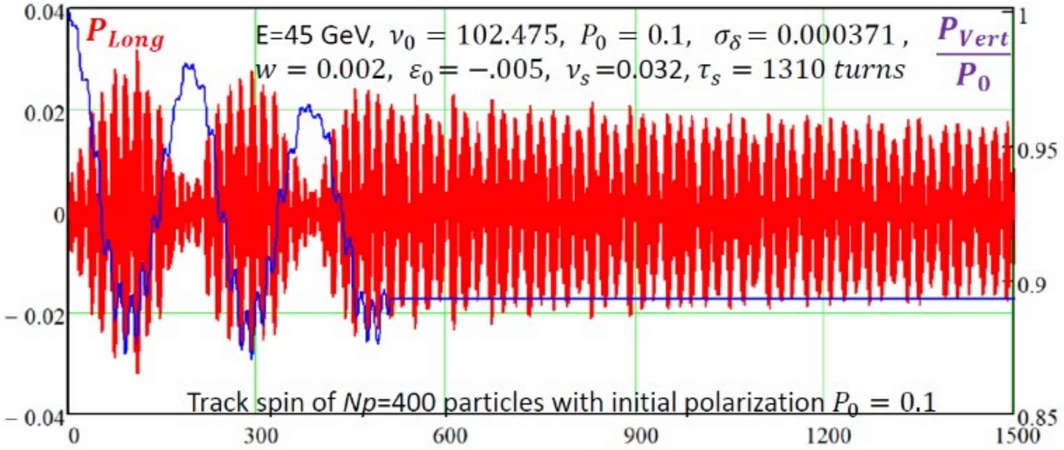
S. Nikitin

Open Questions:
- What is the best location for the depolarizer in the lattice?
- Can we use the same pilot bunches more than once?
- Can we observe free spin precession in a realistic lattice for Z- and W- energy?

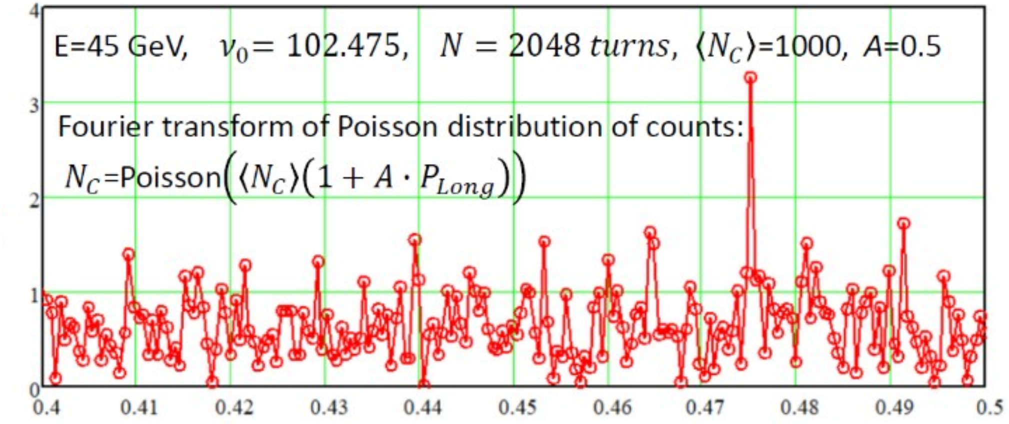
I. Koop, S. Nikitin, I. Nikolaev, G. Wilkinson

Free Spin Precession (FSP) I

- Spin rotation with very strong depolarizer $\mathbf{w_k \sim 10^{-3}}$
- Measure oscillation of spin between planes
- Obtain spin tune with Fourier Transformation
- Possibly faster than resonant depolarization



FSP at Z



Open Questions:
Does this require more / less / same level of polarisation as RDP ?

How well must polarisation be measured by polarimeter ?

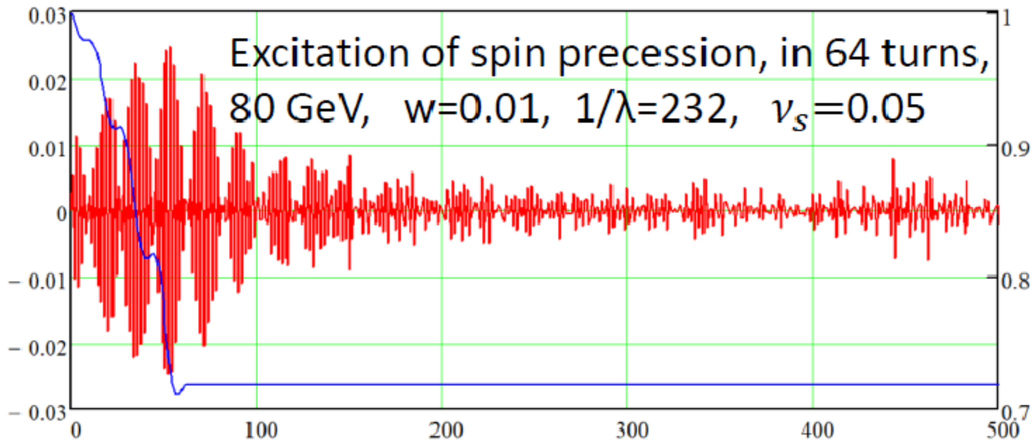
What are the systematics and intrinsic precision ?

How often should measurement be made, e.g. one to accompany every RDP measurement, or less frequently ?

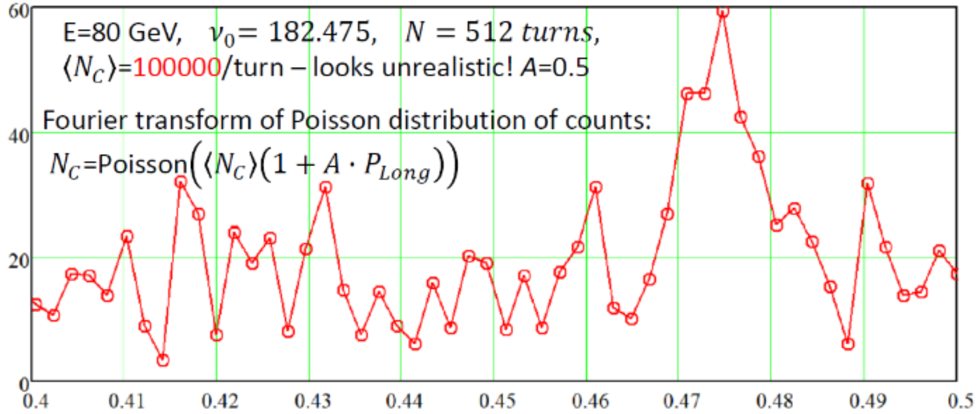
I. Koop, S. Nikitin, I. Nikolaev, G. Wilkinson

Free Spin Precession (FSP) II

- Spin rotation with very strong depolarizer **$w_k \sim 10^{-3}$**
- Measure oscillation of spin between planes
- Obtain spin tune with Fourier Transformation
- Possibly faster than resonant depolarization



FSP at W



Open question:
Is measurement feasible in W+W- regime, and if so what are requirements and what is precision ?