Study of the depolarization process at Z and WW

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With many thanks to A. Blondel, D.P. Barber, A. Bondar, A. Martens, N. Muchnoi, A. Otboev, D. Shatilov and Yu. Shatunov

EPOL-2022 workshop, CERN, 29.09.2022

Content

Required accuracies from physics

Baseline RD scheme at Z and W beam energies

Longitudinal Compton polarimeter parameters and possibilities

Coherent spin precession method – complimentary to RD

Discussion on free spin precession method and conclusion

Disentangling of the coherent and SR losses. Ecm reconstruction method.

Requirements from physics (A. Blondel introduction talk)

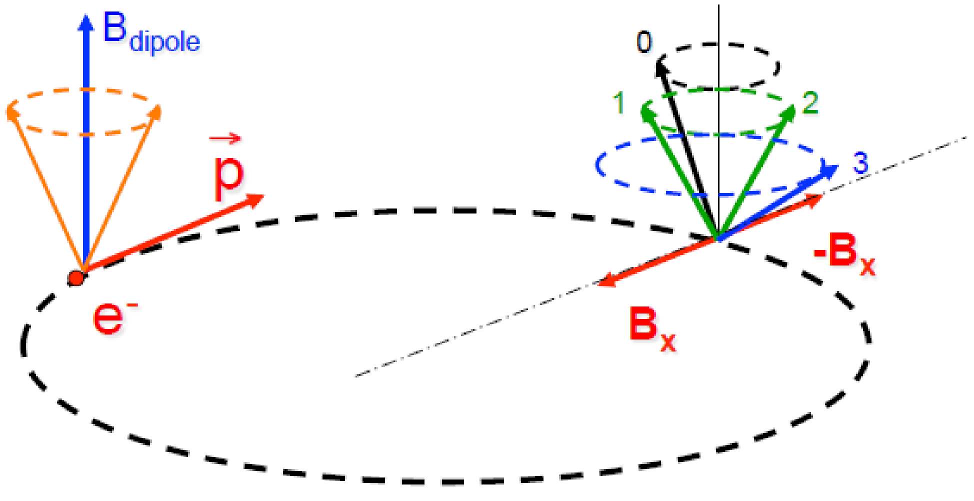
1. Center-of-mass energy determination with precision of ± 4 keV around the Z peak
2. Center-of-mass energy determination with precision of ± 250 keV at W pair threshold
3. For the Z peak-cross-section and width, required energy spread uncertainty $\Delta\sigma_E/\sigma_E = 0.2\%$

$$\nu_s = \frac{g-2}{2}\frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)} \approx N + (0.5 \pm 0.1) \text{ – optimal is near halfinteger}$$

$\mathbf{E_{CM}} = (\nu_{sp} + \nu_{se}) \times 0.4406486$ GeV - plus small corrections due to saw-tooth

Required spin tune precission: $\Delta\nu = \pm 0.00001$ at Z and $\Delta\nu = \pm 0.0005$ at W

Resonant Depolarization by tune scan



spin precession (ν is the *spin tune*)

$$\delta\theta_{spin} = (g-2)/2 \;.\; E/m\ \delta\theta_{trajectory}$$
$$= \nu \;.\; \delta\theta_{trajectory}$$
$$\nu = E_{beam} / 0.4406486$$
$$= 103.5 \text{ at the Z peak}$$

Once the beams are polarized,
an RF kicker at the spin precession frequencv will provoke a spin flip or complete depolarization
Simulation of FCC-ee by I. Koop, see CDR:

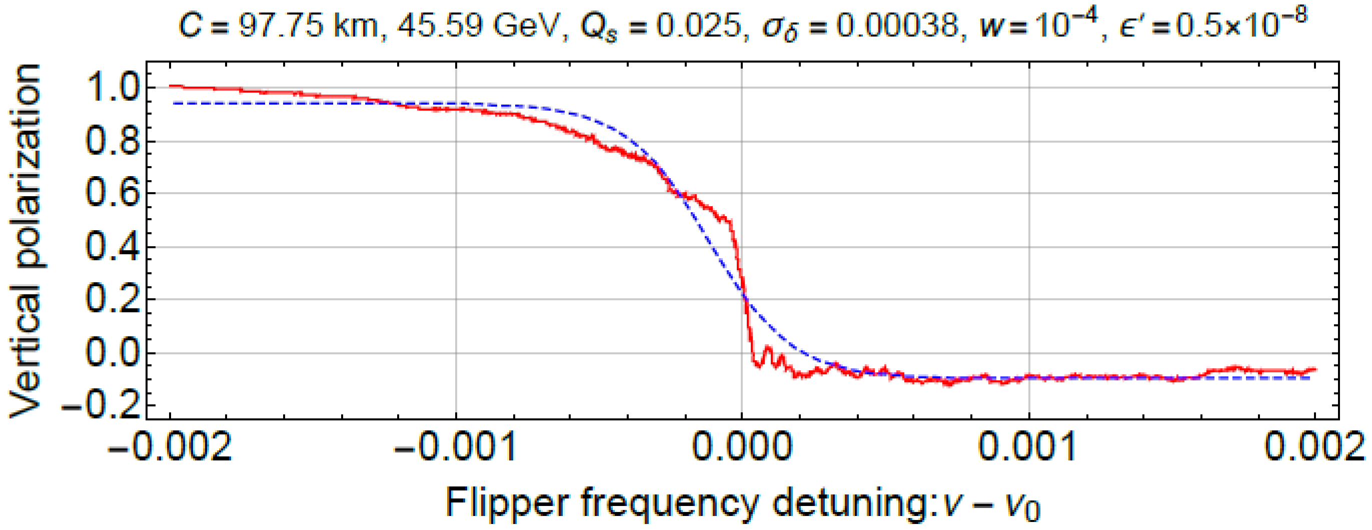
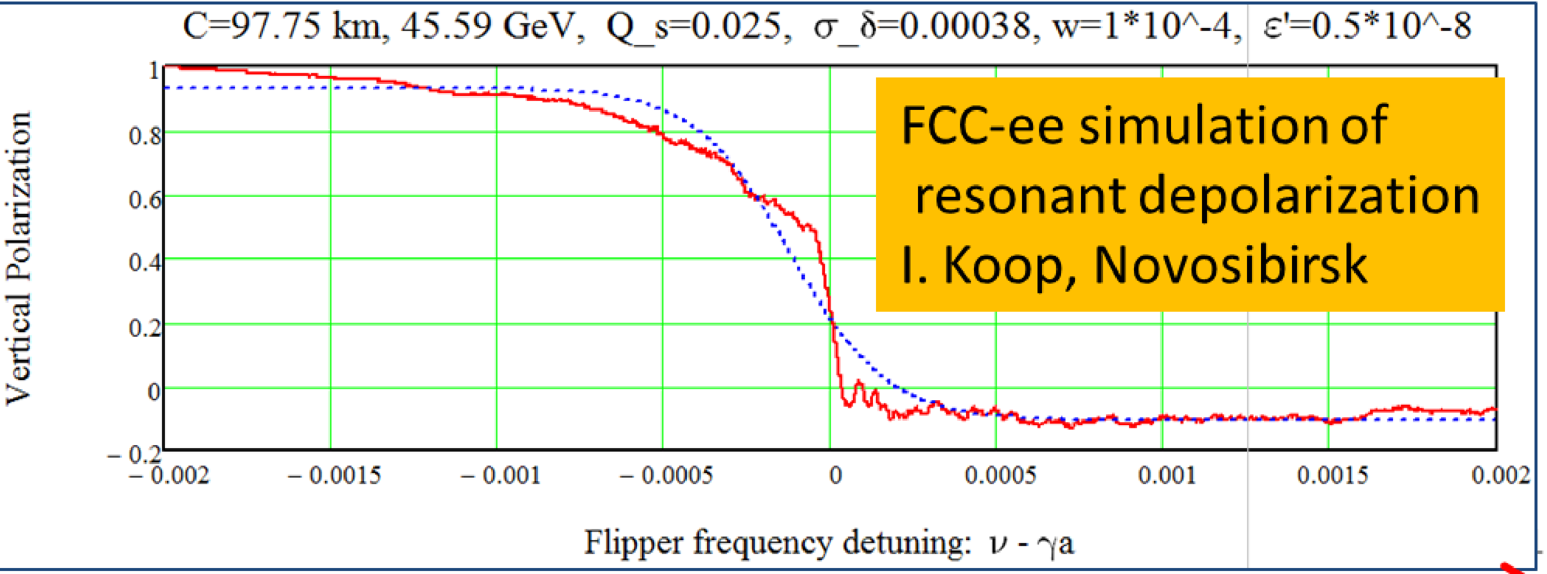
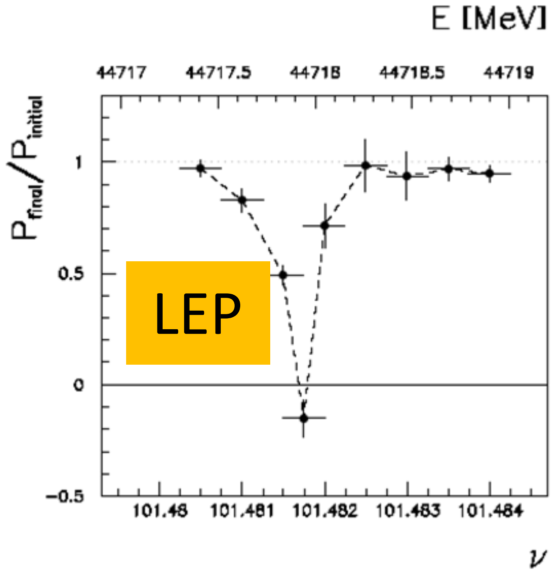


Figure 39. Simulation of a frequency sweep with the depolarizer on the Z pole showing a very sharp depolarization at the exact spin tune value.



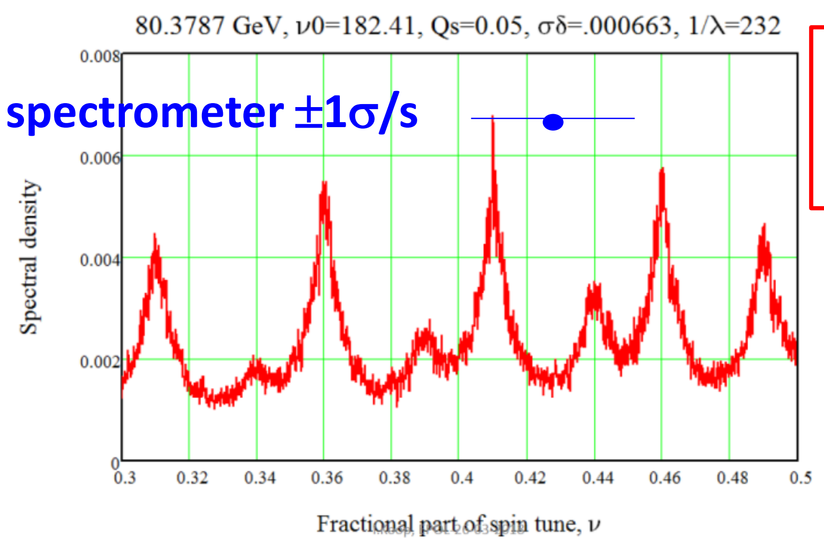
FCC-ee simulation of resonant depolarization
I. Koop, Novosibirsk

260 seconds sweep of depolarizer frequency



LEP

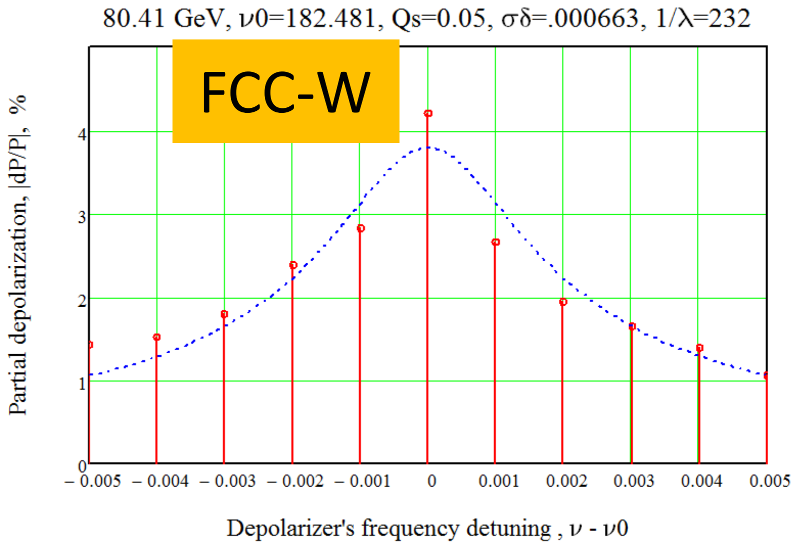
long sweep works well at the Z. Several depolarizations needed: eliminate Qs side band and 0.5 ambiguity
Less well at the W: the Qs side bands are much more excited because of energy spread, need iterations with smaller and smaller sweeps – work in progress. see *I. Koop* presentations at FCC weeks.



spectrometer ±1σ/s

← Fourier analysis shows the side band situation at W.

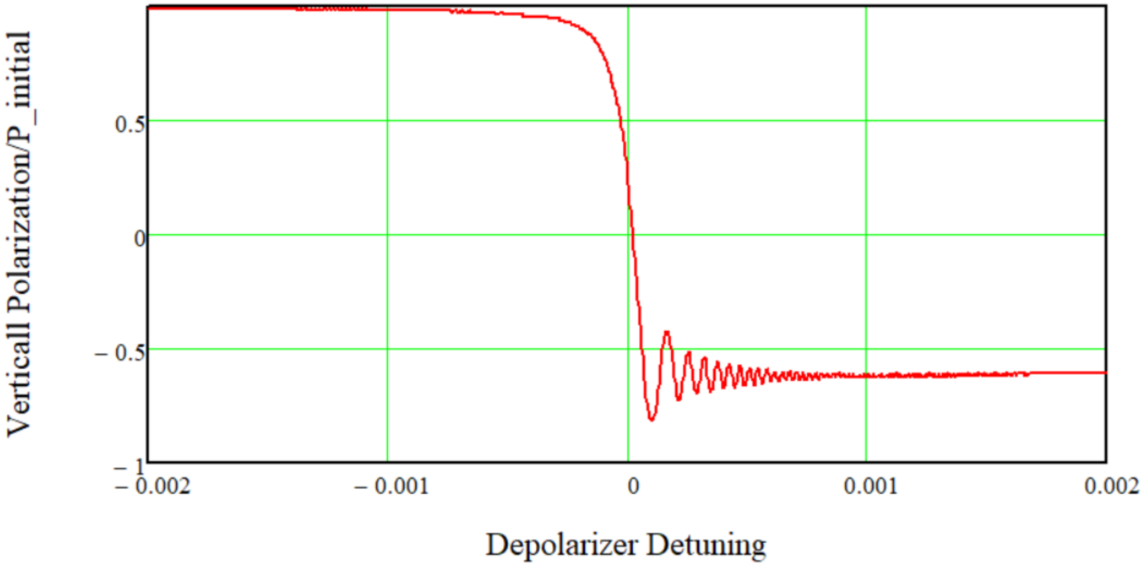
First attempt at 'LEP' multiple sweep technique →



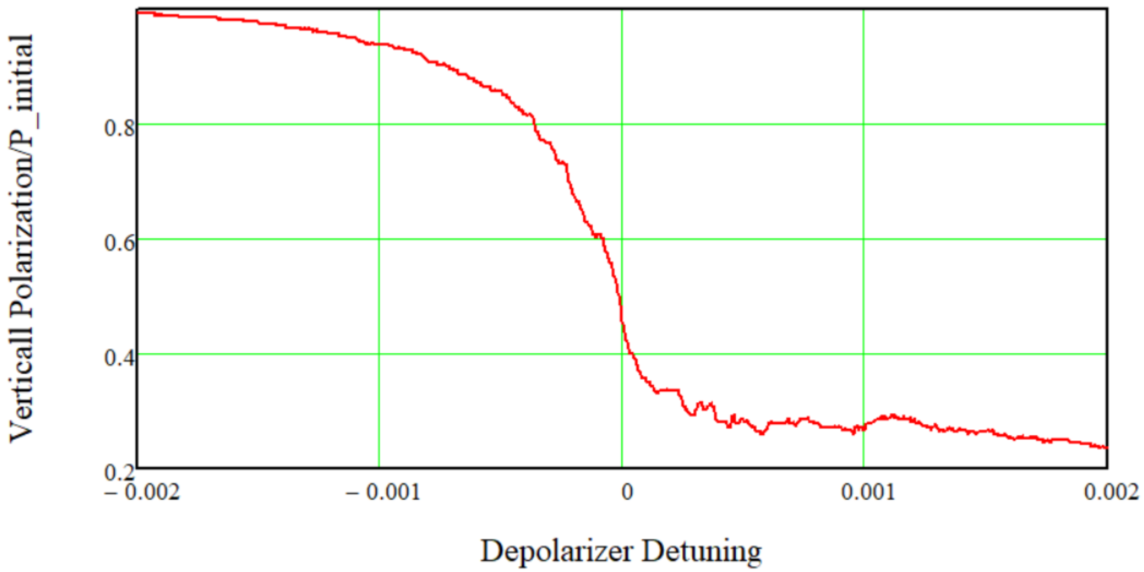
FCC-W

RD frequency sweeps with increased v_s=0.075

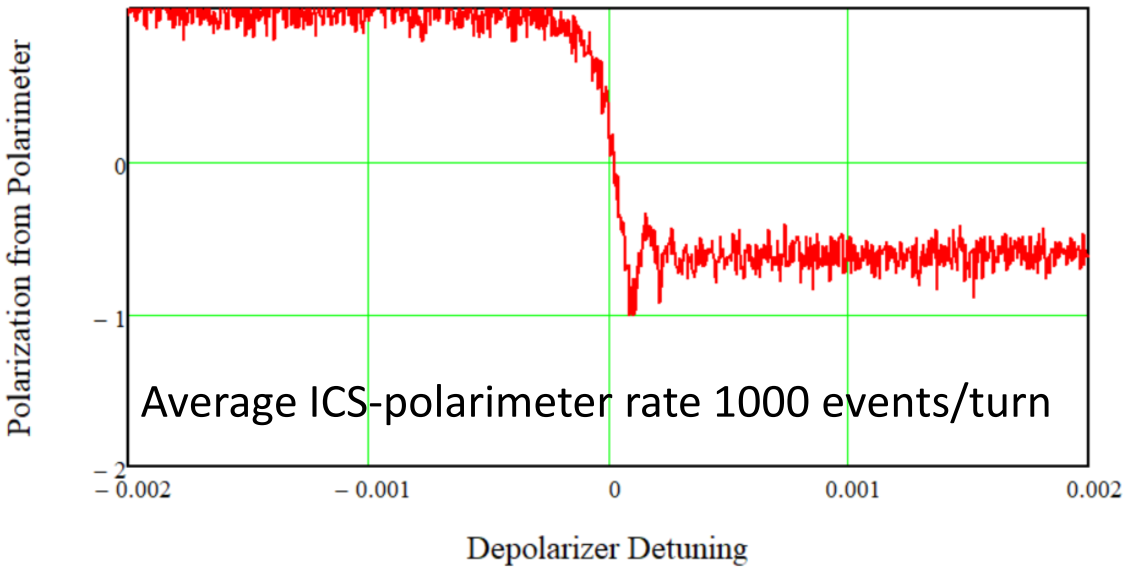
45GeV, ν_s=0.075, σδ=0.00038, w=1.5*10^-4, ε'=2*10^-8



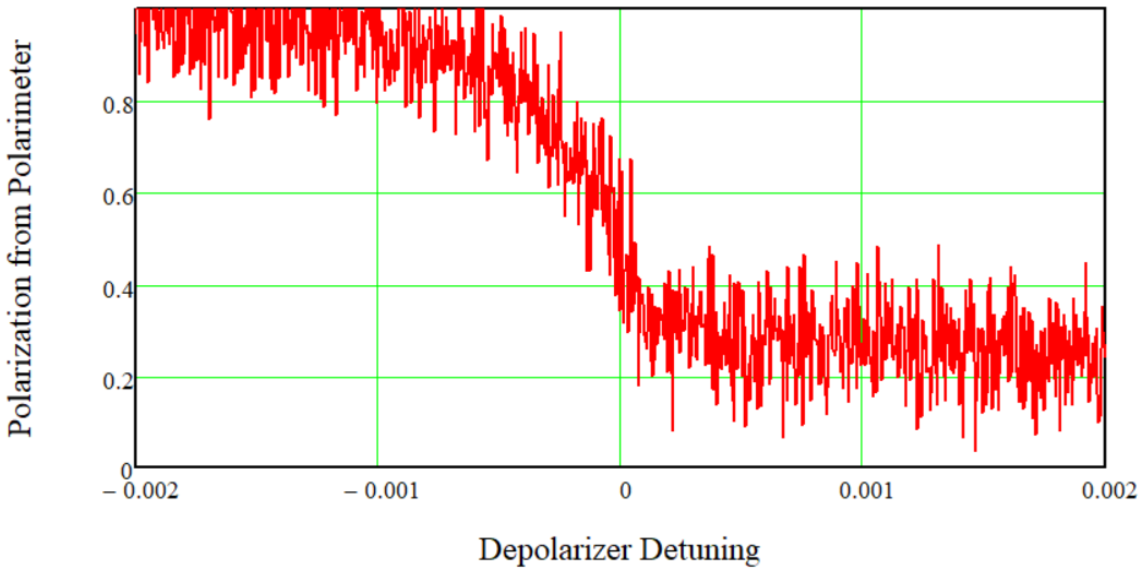
80 GeV, ν_s=0.075, σδ=0.00067, w=1.5*10^-4, ε'=2*10^-8



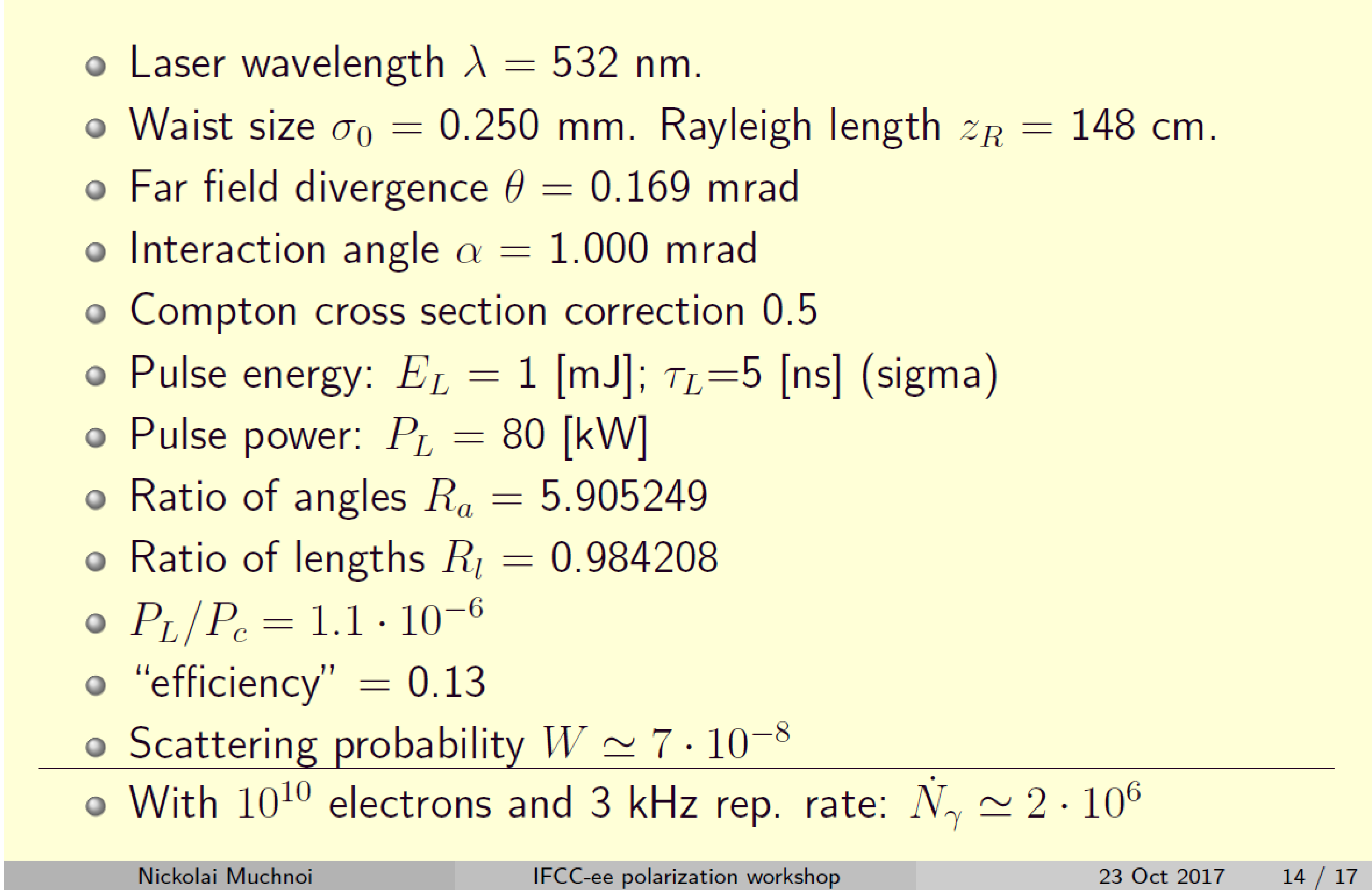
45GeV, ν_s=0.075, σδ=0.00038, w=1.5*10^-4, ε'=2*10^-8


Average ICS-polarimeter rate 1000 events/turn

80 GeV, ν_s=0.075, σδ=0.00067, w=1.5*10^-4, ε'=2*10^-8



Compton Polarimeter: Rates

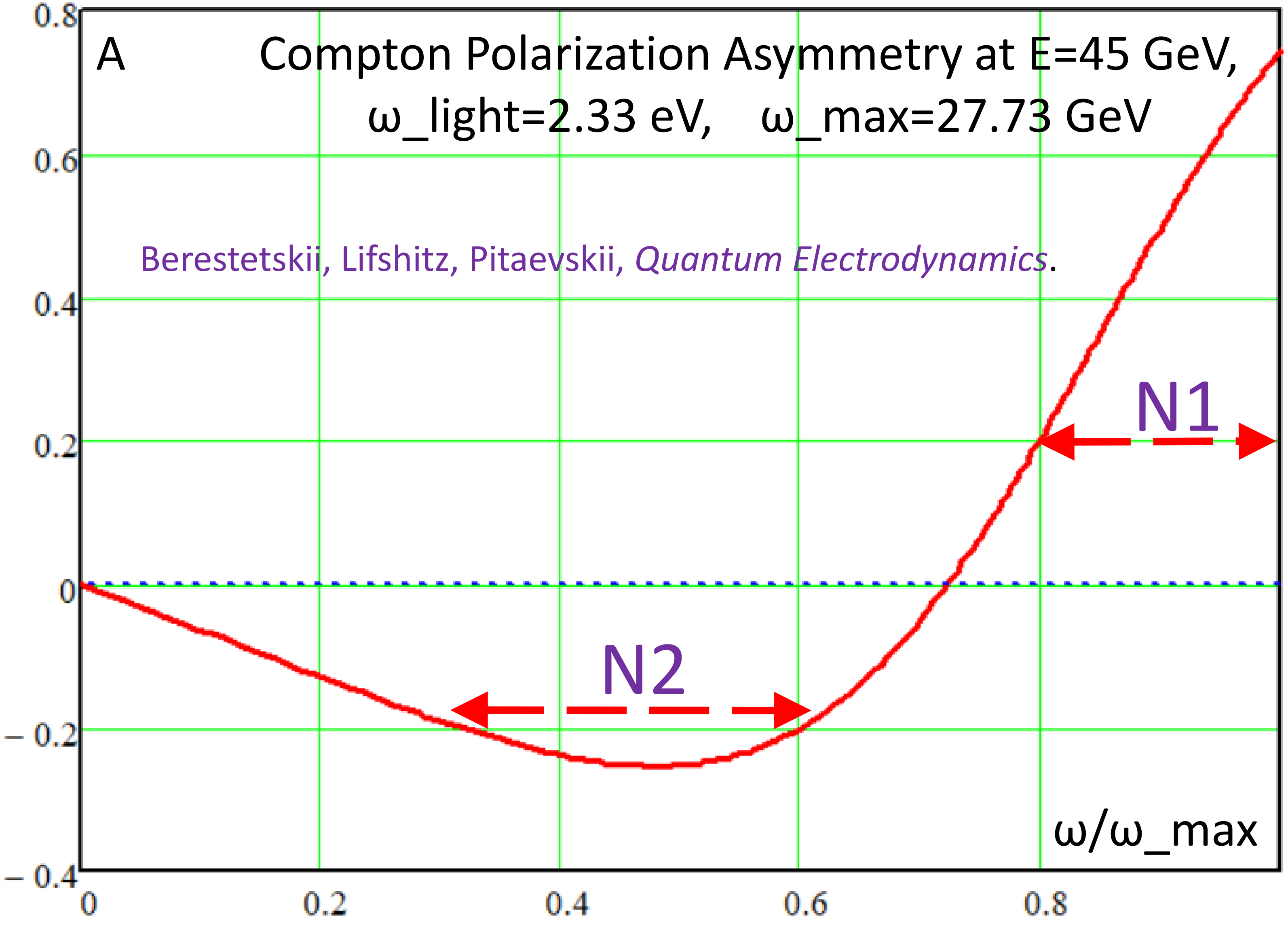


- Laser wavelength $\lambda = 532$ nm.
- Waist size $\sigma_0 = 0.250$ mm. Rayleigh length $z_R = 148$ cm.
- Far field divergence $\theta = 0.169$ mrad
- Interaction angle $\alpha = 1.000$ mrad
- Compton cross section correction 0.5
- Pulse energy: $E_L = 1$ [mJ]; τ_L=5 [ns] (sigma)
- Pulse power: $P_L = 80$ [kW]
- Ratio of angles $R_a = 5.905249$
- Ratio of lengths $R_l = 0.984208$
- $P_L/P_c = 1.1 \cdot 10^{-6}$
- “efficiency” $= 0.13$
- Scattering probability $W \simeq 7 \cdot 10^{-8}$

- With 10^{10} electrons and 3 kHz rep. rate: $\dot{N}_\gamma \simeq 2 \cdot 10^6$

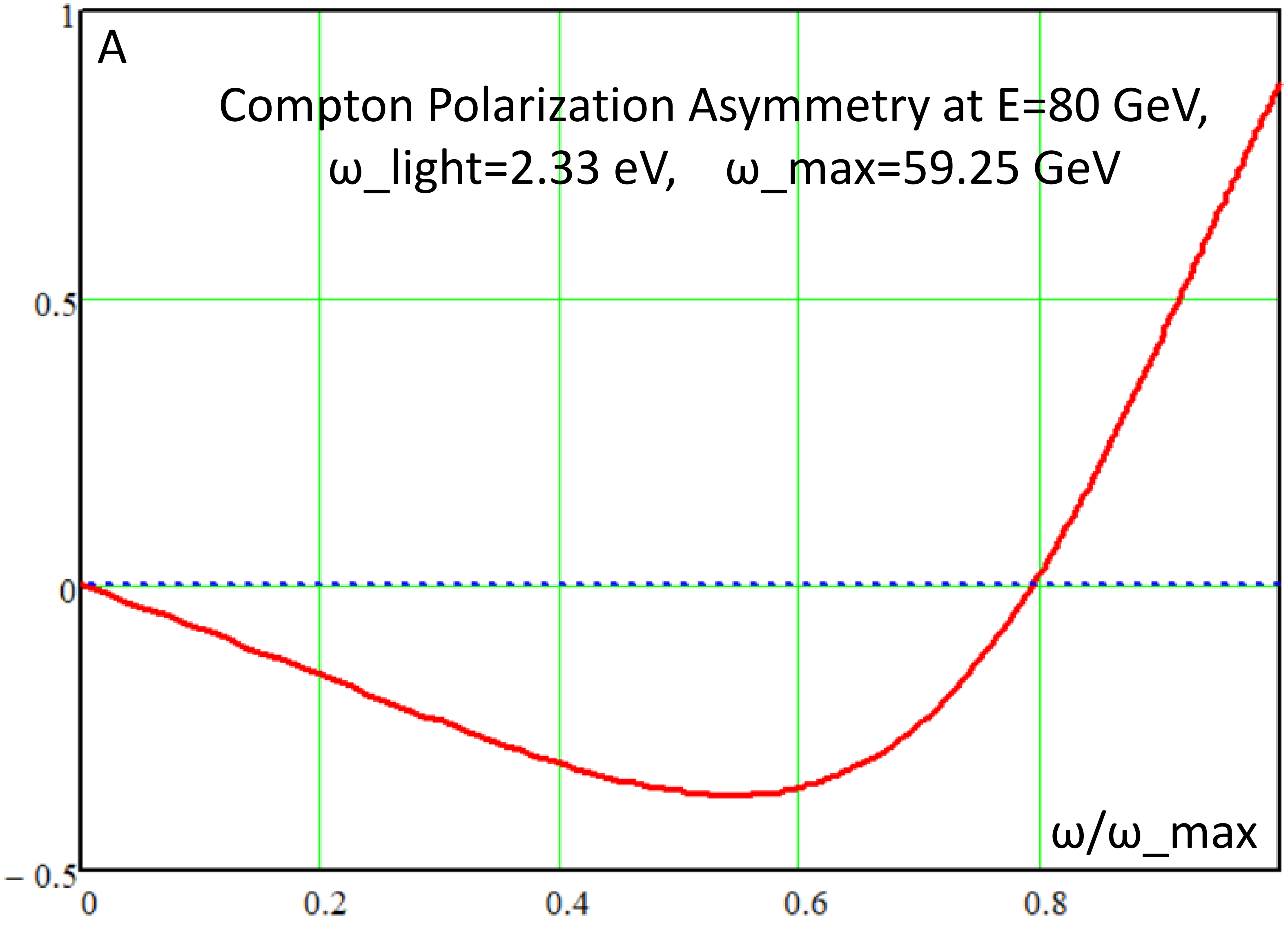
Nickolai Muchnoi | IFCC-ee polarization workshop | 23 Oct 2017 | 14 / 17

Compton polarimeter asymmetry to longitudinal polarization at Z



In case of coherent spin precession we can explore large asymmetry *A* to the longitudinal spin component of the ICS cross-section, selecting events from two regions: ω/ω_max > 0.8 (N1) and 0.3 < ω/ω_max < 0.6 (N2). Then do FFT analysis of a signal: (N1-N2)/(N1+N2), modulated by spin precession.

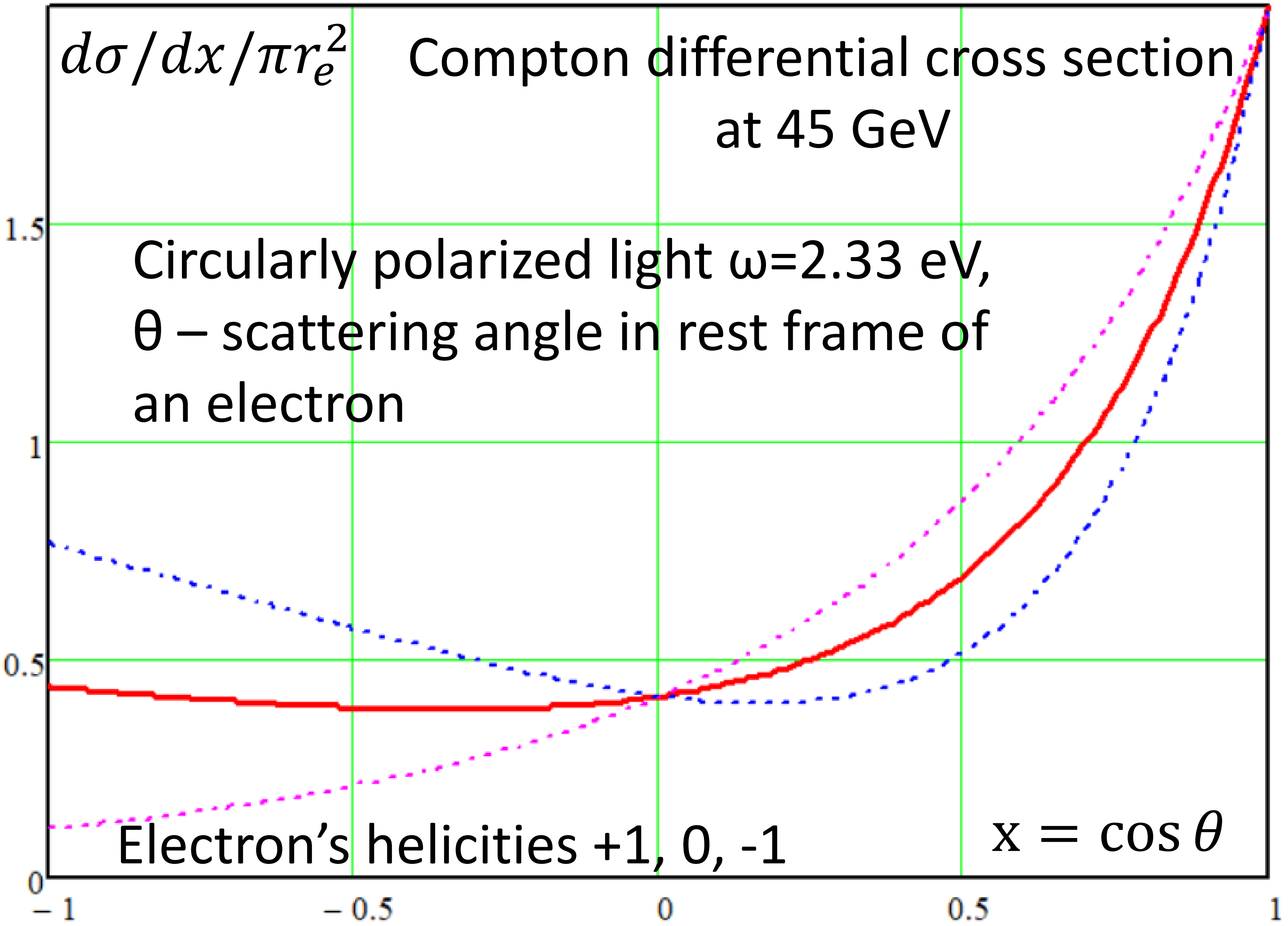
Compton polarimeter asymmetry to longitudinal polarization at W



Expected counting rate is about 1000 events/turn. Photon calorimeter suits well to measure a vertical spin component (up/down asymmetry), while lost energy scattered electrons, intercepted by some granular counter after a bend, could serve as the horizontal spin component polarimeter.

(more details at EPOL, N. Muchnoi)

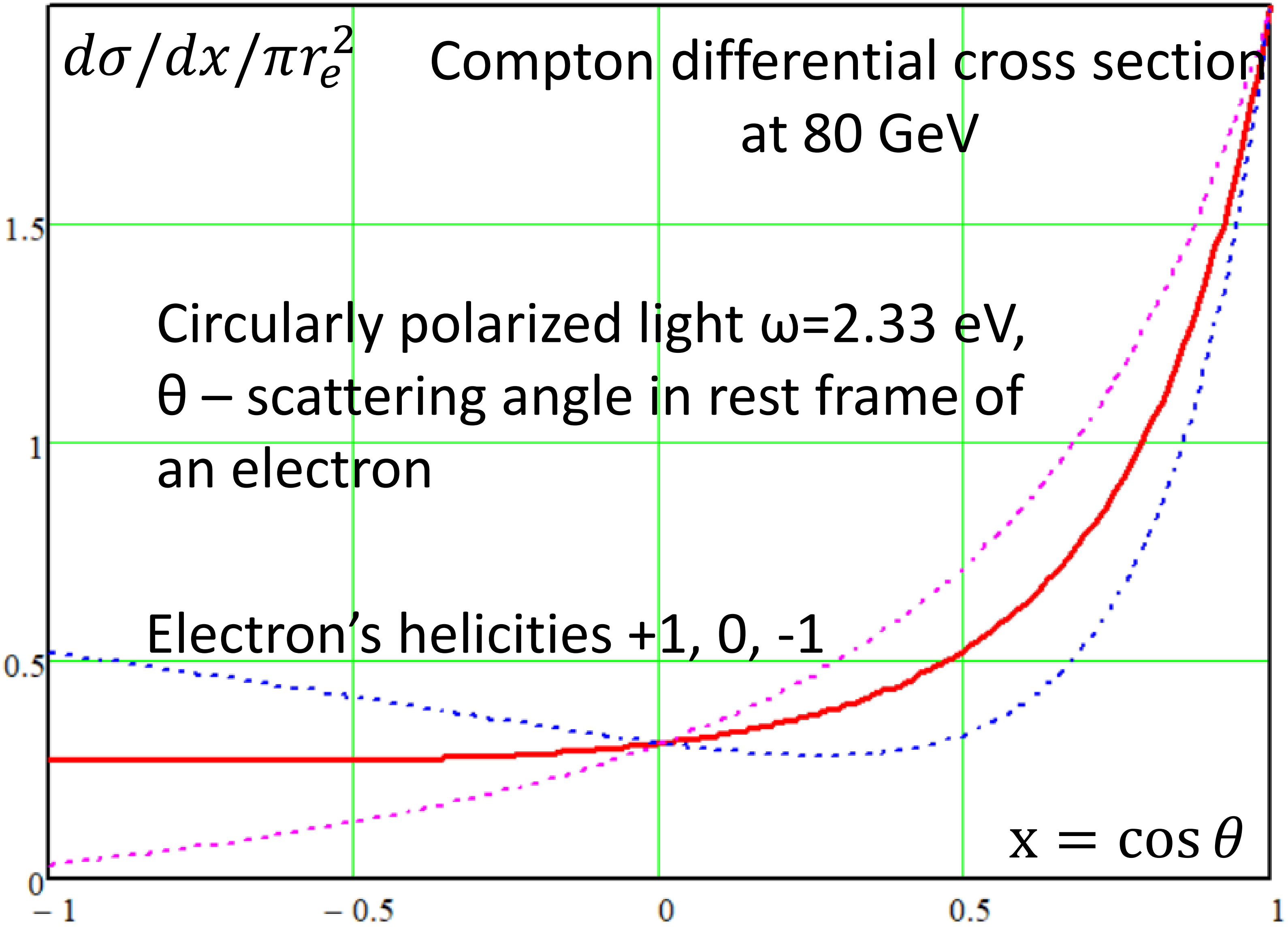
Compton scattering differential cross section at 45 GeV



Back scattering (*cos* θ=-1) of the laser photons shows the largest sensitivity to the longitudinal spin component.

Precess spin may significantly modulate the counting rate of that events.

Compton scattering differetial cross section at 80 GeV



Circularly polarized light ω=2.33 eV, θ – scattering angle in rest frame of an electron

Electron’s helicities +1, 0, -1

Free spin precession: some preceeding works

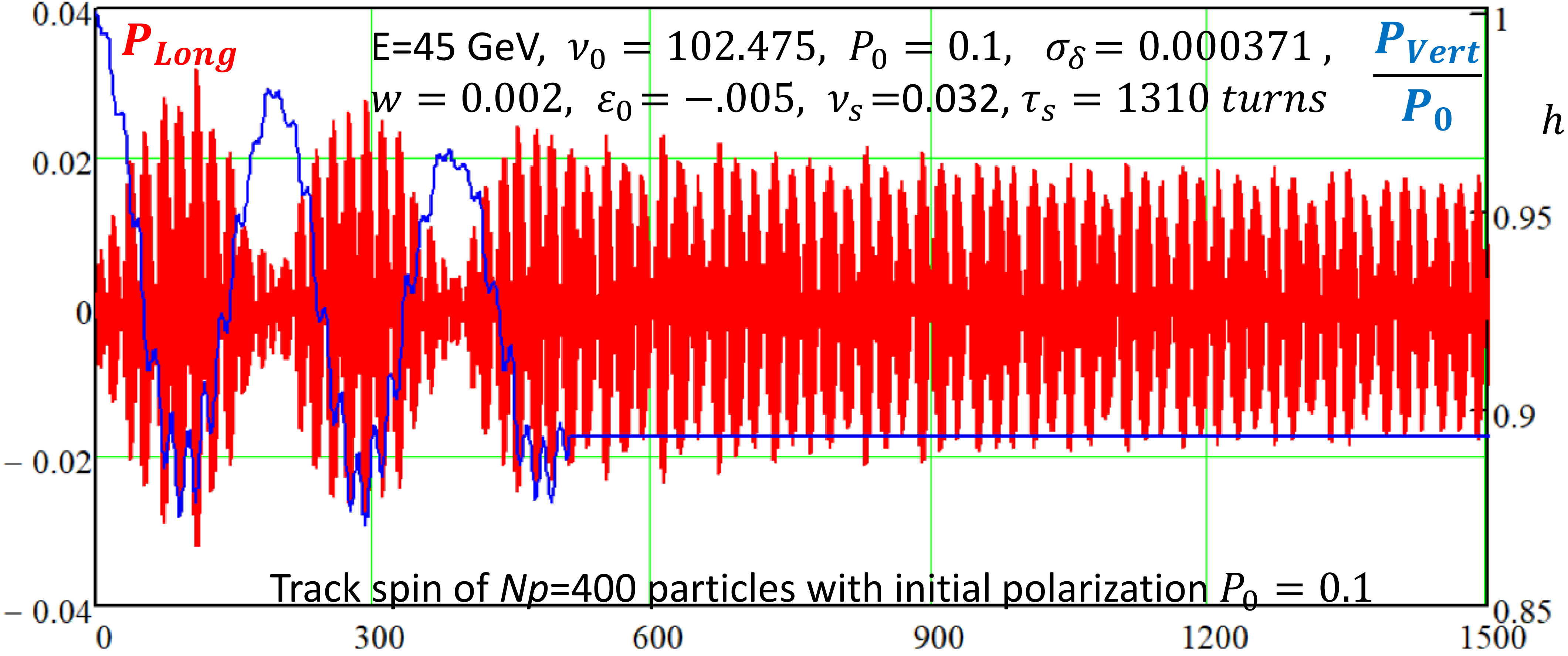
I.B. VASSERMAN et al., “**COMPARISON OF THE ELECTRON AND POSITRON ANOMALOUS MAGNETIC MOMENTS: EXPERIMENT 1987**”, Physics Letters B, Volume 198, number 2, November 1987.

I.A. Koop, Yu.M. Shatunov, “**The spin precession tune spread in the storage ring**”, EPAC1988_0738, 1988.

D.P. Barber, M. Boege, K. Heinemann, H. Mais and G. Ripken, “**Spin Decoherence in Electron Storage Rings**”, Spin94 (Bloomington).

K. Heinemann, “**Some models of spin coherence and decoherence in storage rings**”, Report number DESY-97-166, 1997, https://arxiv.org/abs/physics/9709025 **.**

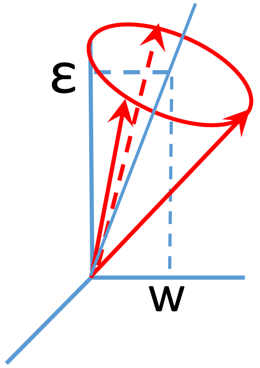
Excitation of the coherent spin precession at Z by Flipper



E=45 GeV, $\nu_0 = 102.475$, $P_0 = 0.1$, $\sigma_\delta = 0.000371$,
$w = 0.002$, $\varepsilon_0 = -.005$, $\nu_s = 0.032$, $\tau_s = 1310$ *turns*

Track spin of *Np*=400 particles with initial polarization $P_0 = 0.1$

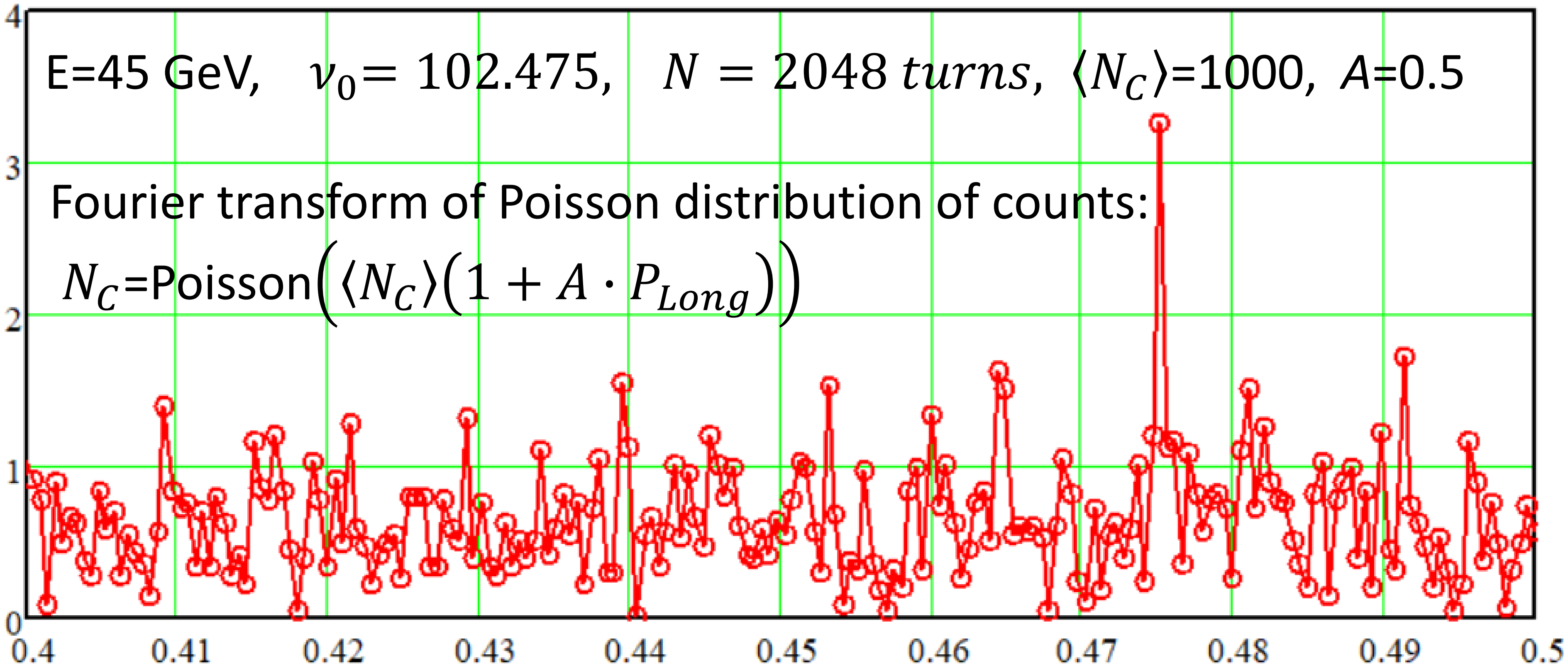
$h = \sqrt{\varepsilon^2 + w^2}$



Spin precession in resonance frame

Coherent rotation of the total spin ensemble is done by powerfull Flipper device: w=0.002. Its frequency is shifted from the resonance by small detuning factor: $\varepsilon_0 = -.005$. Flipper is on 512 turns. After that we observe free spin precession during 2048 turns. Polarization loss is only 10%. In principle, Flipper kicks effectively spin only first 100 turns, or so!

Fourier transform of the counted electrons with high energy loss (at Z)



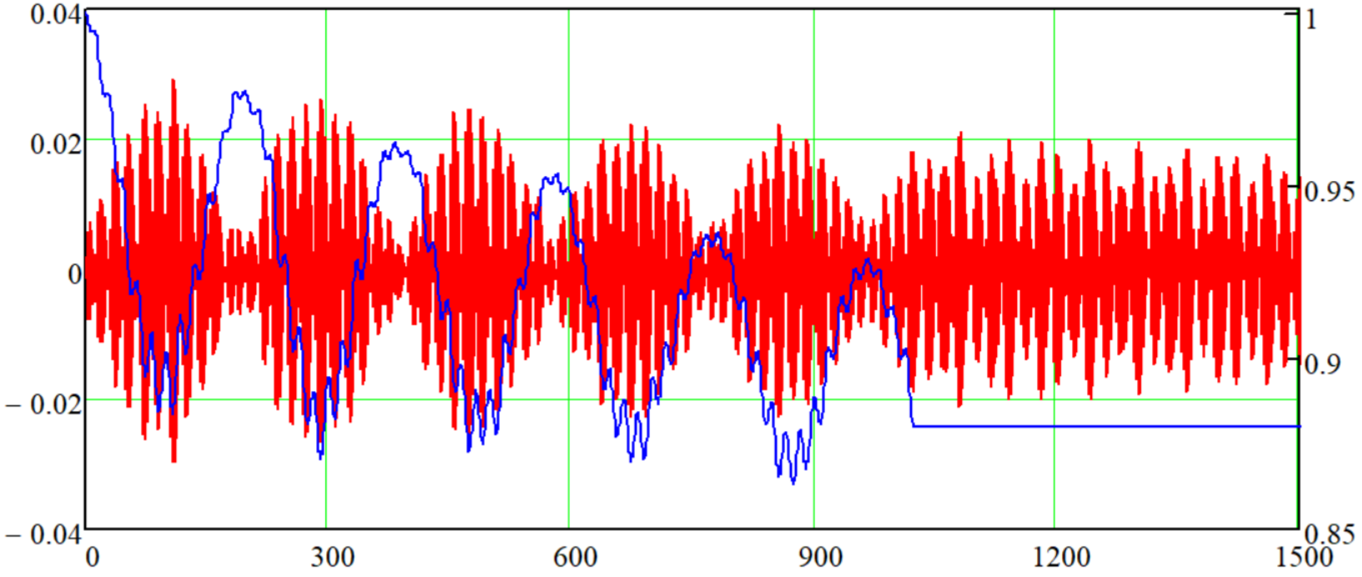
E=45 GeV, $\nu_0 = 102.475$, $N = 2048\ turns$, $\langle N_C \rangle$=1000, A=0.5

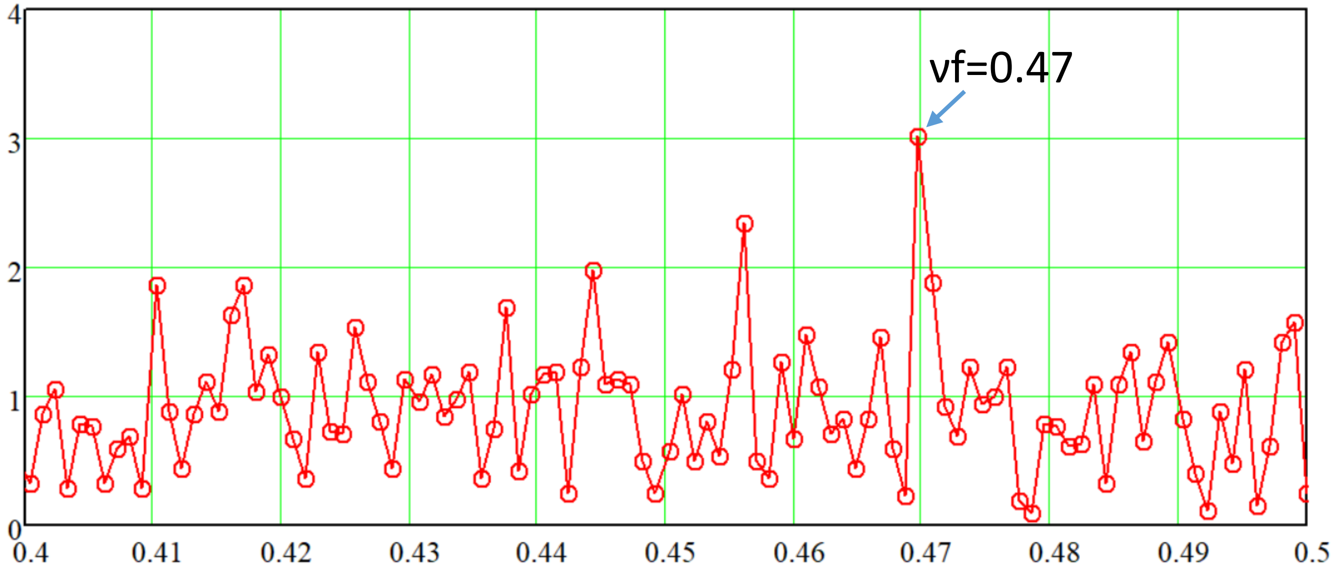
Fourier transform of Poisson distribution of counts:

N_C=Poisson$\left(\langle N_C \rangle \left(1 + A \cdot P_{Long}\right)\right)$

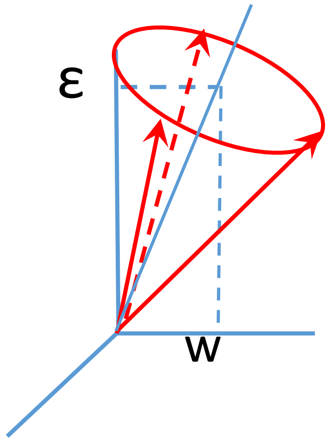
At Z polarization asymmetry of the Compton cross section relative to the longitudinal spin component could easily exceed A>0.5 and the free precession peak at ν=0.475 is well above the statistical noise.

Spectrum of the forced spin precession at Z



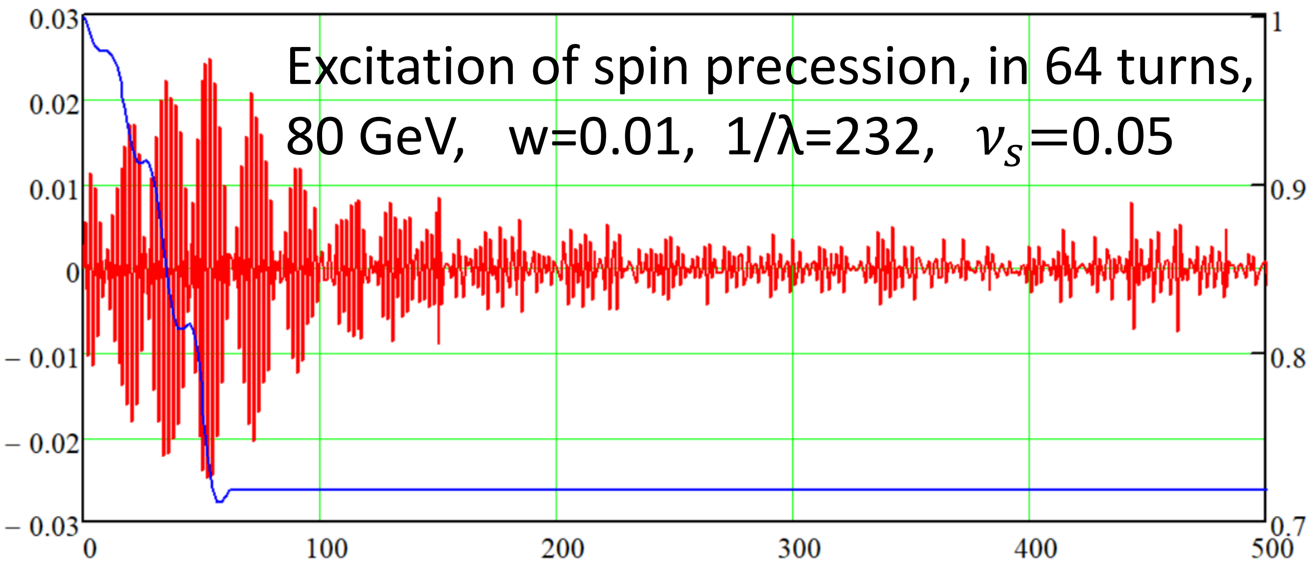


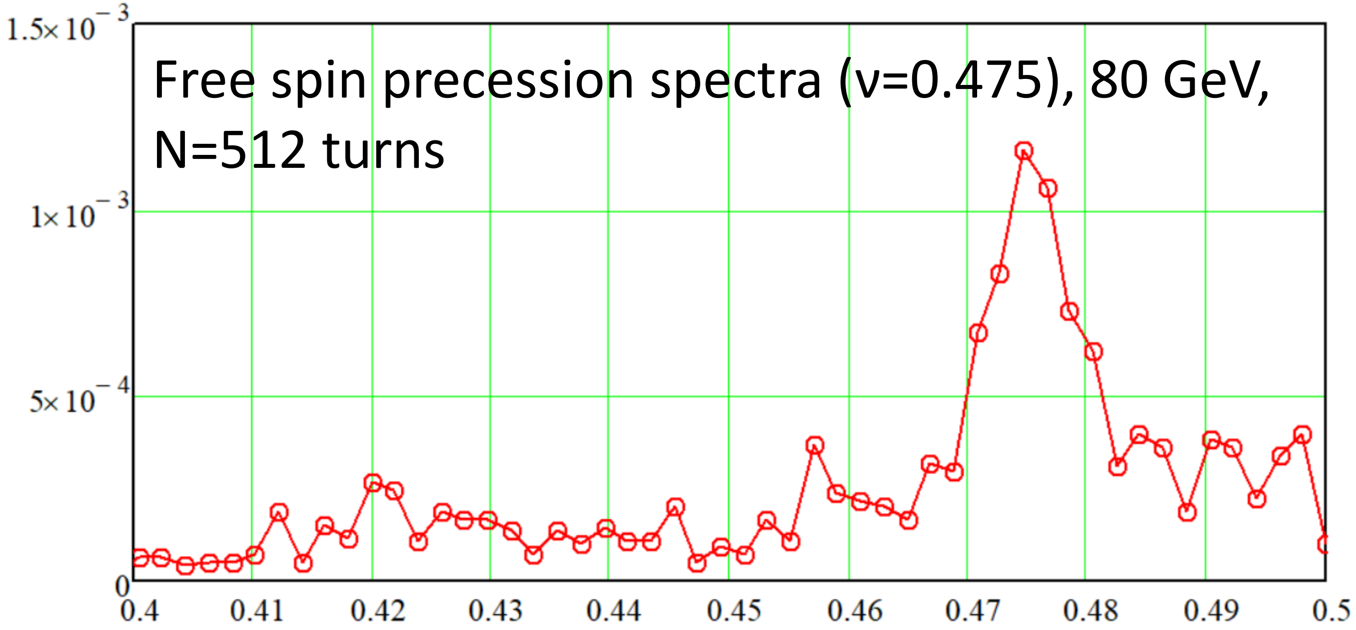
$$h = \sqrt{\varepsilon^2 + w^2}$$



Track spins of *Np*=400 particles with initial vertical polarization $P_0 = 0.1$
Flipper frequency νf=0.47 do not coincide with free precession frequency ν =0.475!
Flipper peak is visible at 1024 turns sample.

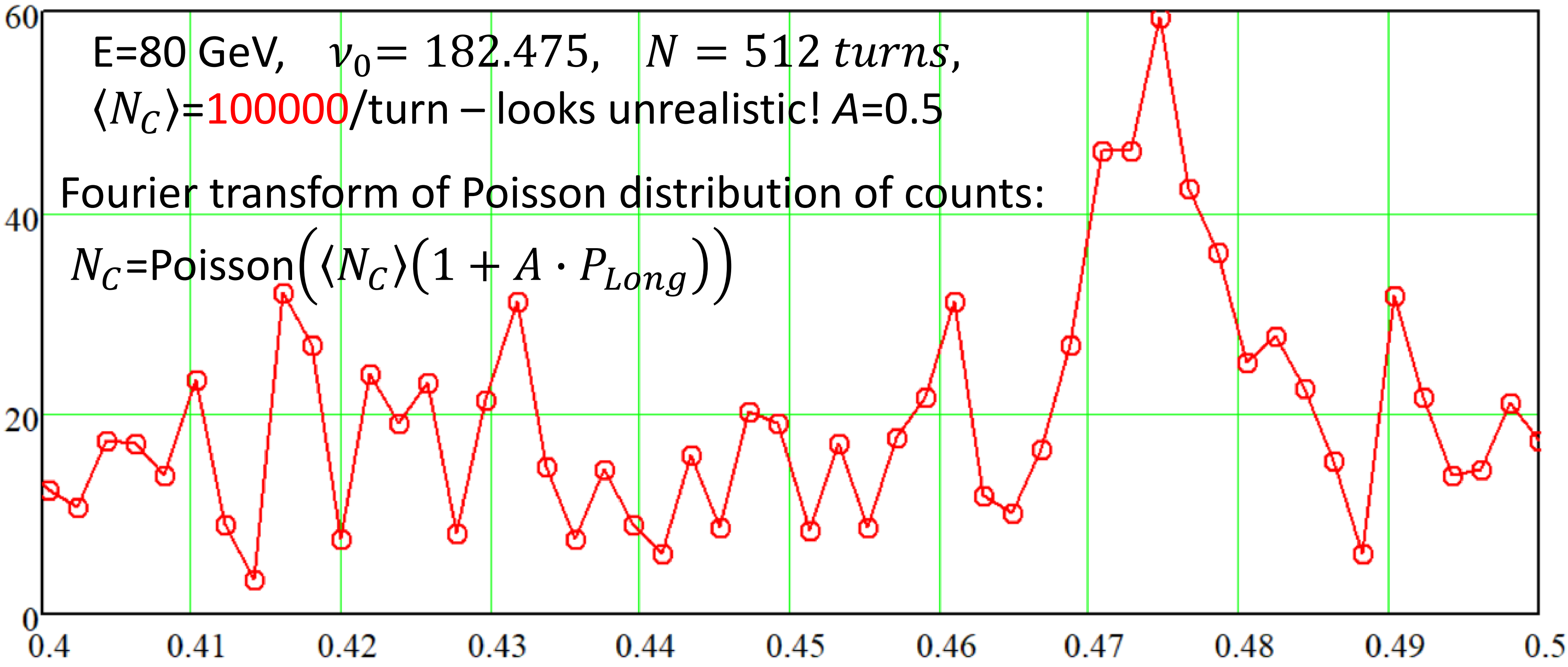
Excitation of the coherent spin precession at W by Flipper





Track spins of *Np*=400 particles with initial polarization $P_0 = 0.1$

Fourier transform of the counted electrons with high energy loss (at W)



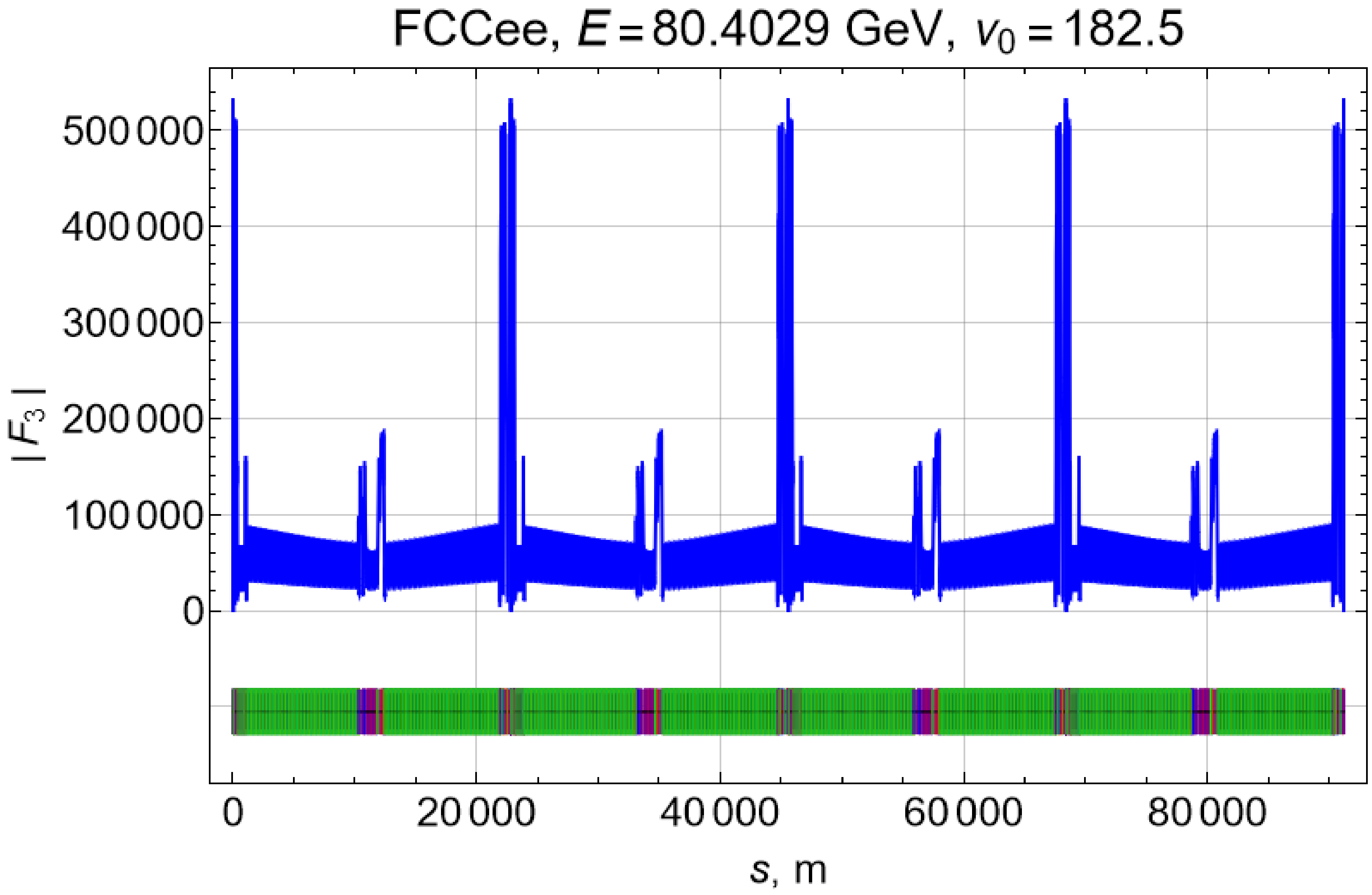
E=80 GeV, $\nu_0 = 182.475$, $N = 512\ turns$,
$\langle N_C \rangle$=100000/turn – looks unrealistic! A=0.5

Fourier transform of Poisson distribution of counts:

N_C=Poisson$\left(\langle N_C \rangle (1 + A \cdot P_{Long})\right)$

At W polarization asymmetry is very high (here we assume only A=0.5). Still free precession peak at ν=0.475 is visible only with very high statistics level: $\langle N_C \rangle$=100000/turn.

Spin response function to the vertical oscillations excitation



A flipper harmonic value $w = \theta \cdot F_3$, where θ is an amplitude of the orbit kick.

$|F_3|$ is very large near the Final Focus lenses.

Optimal location for placing there of a weak depolarizer. The strong one will excite too large vertical oscillations, beyond of the DA.

Discussion on free spin precession method

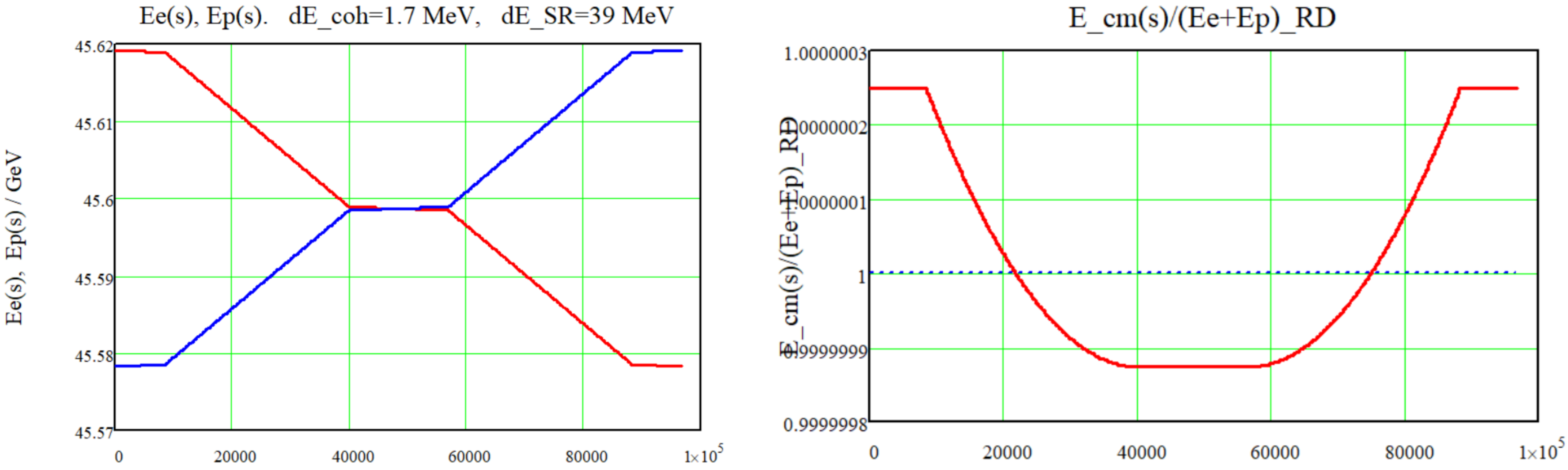
Compton polarimeter statistics (~1000 events/turn) is sufficient to detect the resonance frequency from measurement of the free spin precession, at least for Z beam energy. Short pulse flipper is capable to deflect spins from their natural vertical orientation to a large θ-angle to organize a free spin precession around the vertical axis.

At W the decoherence of spins precession is much faster and makes difficult to play the same game! Could help an increase of the synchrotron tune to a level of 0.075 or so!

Flipper strength is limited by the small DA in the vertical plane, therefore we can not explore large spin response to the vertical orbit excitation by a localized depolarizer! Compensated π or 2π standard FODO cell can be used instead with a pair of pulsed spin kickers at the ends. This idea is now under investigation.

The polarimeter statistics can be used more effectively, if we will count almost all scattered electrons. Longitudinal polarization assymetry is high not only at the edge of the spectrum, but also below the half distance from it, where the asymmetry changes a sign.

Disentangling the coherent and SR losses



Toy-ring with a head-on collision: 2 straights and 2 half-turn arcs. Coherent loss 1.7 MeV/turn, SR 39 MeV/turn.

Equation1: $\Delta E_{boost} = Ee_{RD} + Ue_{coh} \cdot Ie + \Delta Ee_{SR} \cdot (Ee_{RD}/E0)^4 - Ep_{RD} - Up_{coh} \cdot Ip - \Delta Ep_{SR} \cdot (Ep_{RD}/E0)^4$

Equations $2-4$ with different set of measured 5 input parameters: $\Delta E_{boost}, Ee_{RD}, Ep_{RD}, Ie, Ip$

$\textit{Solve Linear System of Equations}, finding\ of\ 4\ unknowns: Ue_{coh}, Up_{coh}, \Delta Ee_{SR}, \Delta Ep_{SR}$

$\textit{Now can find}: E_{cm} = Ee_{RD} + Ue_{coh} \cdot Ie + \Delta Ee_{SR} \cdot (Ee_{RD}/E0)^4 + Ep_{RD} + Up_{coh} \cdot Ip + \Delta Ep_{SR} \cdot (Ep_{RD}/E0)^4$

Important: not expand relative to a reference energy, or a current! Use a model dependence of losses from an energy and a current – then no unknown constant terms appear! A model could be refined for better fit to the measurements.

Accuracy of the reconstruction of Ecm. Conclusion.

With 4 sets of input parameters: Ie=1, 2, 0.5, 1.5; Ip=1, 2.5, 0.5, 1.5;
Ee_RD=45.6·(1, 0.97, 1.02, 0.99); Ep_RD=45.6·(1, 1.015, 1.025, 0.975);
and the calculated corresponding boosts.
I find Ecm with some systematic shift from the known simulated values by
$2.9 \cdot 10^{-7}$.
Needs to be understood.

Conclusion:
Algorithm works in principle! Futher studies will be done in near future.
Other ideas welcome!

Thank you for your attention!