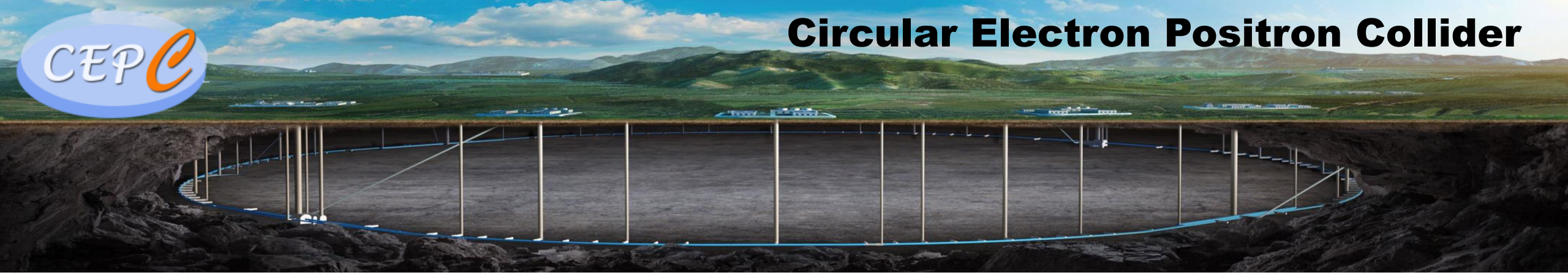


Beam polarization at CEPC

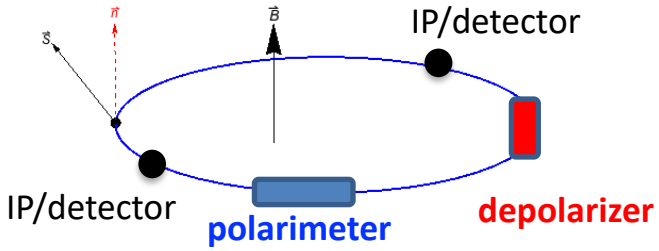
Zhe Duan
On behalf of the CEPC Polarization Working Group

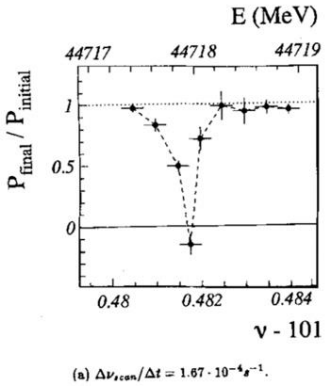
Institute of High Energy Physics, CAS

Motivation of CEPC polarized beam program

Vertical polarization for resonant depolarization

- Essential for precision measurements of Z and W masses
- > 5% ~ 10% polarization

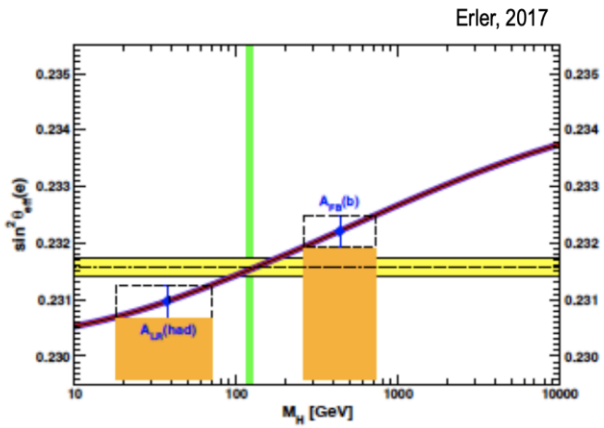




L. Arnaudon, et al., Z. Phys. C 66, 45-62 (1995).

Longitudinal polarization for colliding beams

- Measurements of A_{FB} and A_{LR} @ Z-pole in the same experiment
- Other benefits at W & Higgs energies, e.g. CP studies
- > 50% polarization with a high luminosity



LEP: unpolarized e+/e-
$\sin^2\theta_{eff}(A_{FB}^b)$= 0.23221±0.00029

SLC: polarized e- & unpolarized e+
$\sin^2\theta_{eff}(A_{LR})$= 0.23098±0.00026

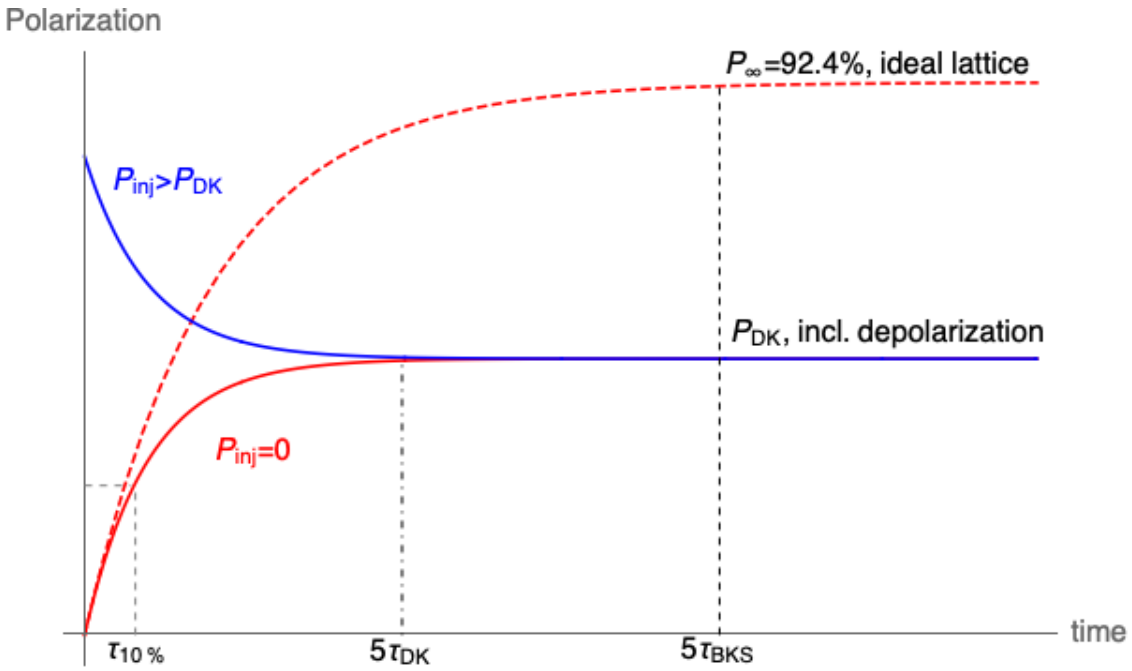
Current central values:
$\sin^2\theta_{eff}$ = 0.23105±0.00087 (LHC)
0.23179±0.00035 (Tevatron)

➡ **Discrepancy between the most precise measurements**
Central value has large impact on physics predictions!

- **Summarized as a chapter in the Appendix of CEPC TDR.**

G. Moortgat-Pick's talk on CEPC Workshop EU @ Marseille, 2024 April

Self-polarization in the CEPC



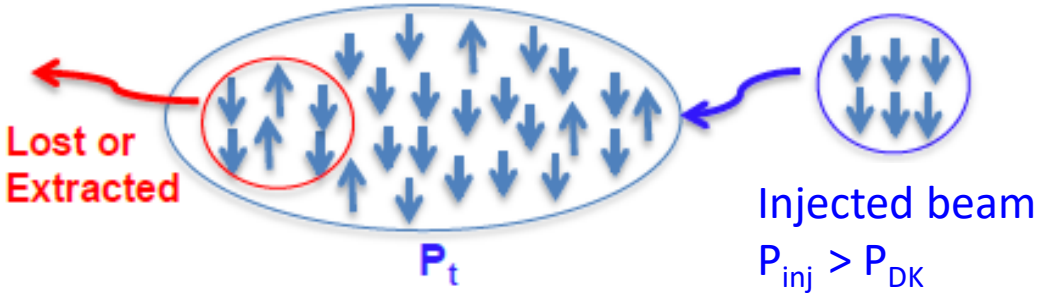
- e+/e- beams become "self-polarized" via the Sokolov-Ternov effect in a storage ring
  - $\tau_{BKS} \propto E^{-5}\rho^2 R$
- Beam polarization build-up rate much slower than the beam decay rate @ Z
  - Boosted with asymmetric wigglers in the Collider (FCC EPOL)
  - Hard to achieve a high-level polarization
  - In conflict with a high luminosity

CEPC CDR parameters	45.6 GeV (Z, 2T)	80 GeV (W)	120 GeV (Higgs)
Polarization build-up time w/o radiative depolarization τ_{BKS} (hour)	256	15.2	2.0
Beam lifetime τ_b (hour)	2.5	1.4	0.43

How to achieve a high-level polarization?

- A high-level polarization (time-averaged) P_{avg} in the Collider is attainable if
  - Top-up injection of highly polarized beam
  - Depolarization rate (τ_{DK}^{-1}) << beam loss rate (τ_b^{-1})

$$P_{\rm avg} = \frac{P_{\rm inj}}{1+\frac{\tau_b}{\tau_{BKS}}\frac{P_\infty}{P_{\rm DK}}} + \frac{P_{\rm DK}}{1+1/\frac{\tau_b}{\tau_{BKS}}\frac{P_\infty}{P_{\rm DK}}}$$

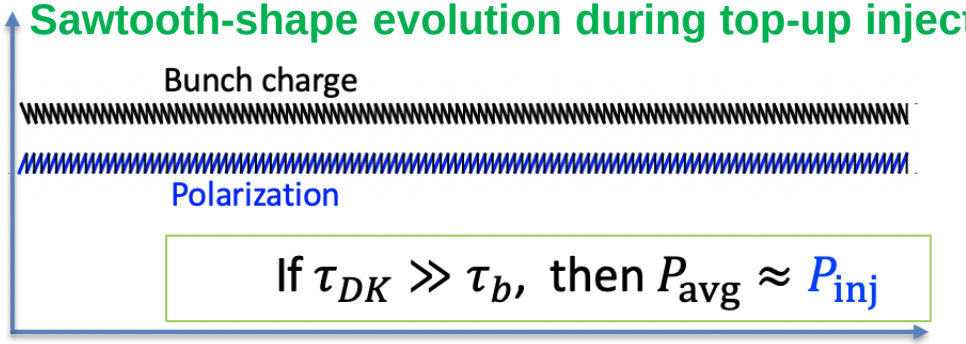


$P_{\rm DK}$ depends on machine imperfections, spin rotators
Assume $P_\infty = 90\%$

$P_{\rm avg} > 50\%$ requires a minimum value of $P_{\rm DK}$

	45.6 GeV (Z)	80 GeV (W)	120 GeV (Higgs)
P_{inj} = 50%	$P_{\rm DK}$>50%	$P_{\rm DK}$>50%	$P_{\rm DK}$>50%
P_{inj} = 60%	$P_{\rm DK}$>4%	$P_{\rm DK}$>23%	$P_{\rm DK}$>33%
P_{inj} = 70%	$P_{\rm DK}$>2%	$P_{\rm DK}$>15%	$P_{\rm DK}$>25%
P_{inj} = 80%	$P_{\rm DK}$>1%	$P_{\rm DK}$>11%	$P_{\rm DK}$>20%

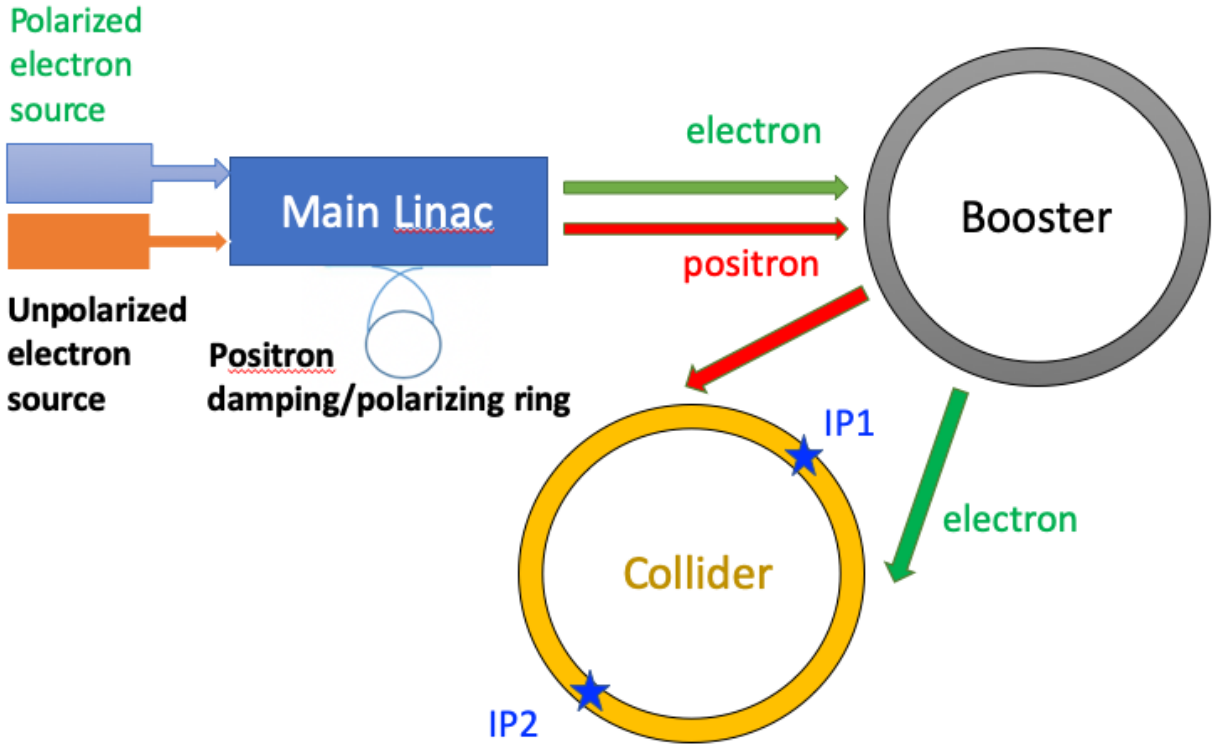
Sawtooth-shape evolution during top-up injection



Amplitude of sawtooth ~ $\frac{|P_{\rm inj}-P_{\rm DK}|}{(\tau_b+\tau_{\rm DK})/dt}$

Polarized injector for CEPC

- Polarized source
  - Polarized electron source
    - parameters less challenging than ILC, EIC
  - Positron damping/polarizing ring



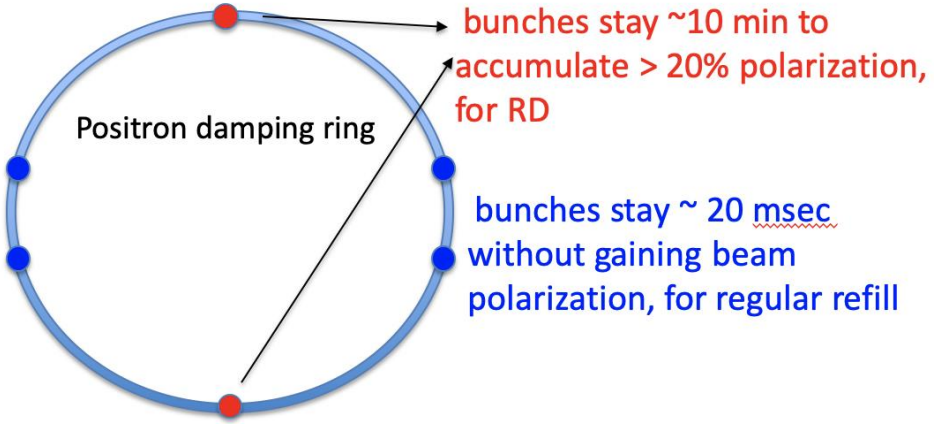
- Linac & Transport lines
  - spin direction matching @injection/extraction
  - helicity adjustment after e+ damping/polarizing ring

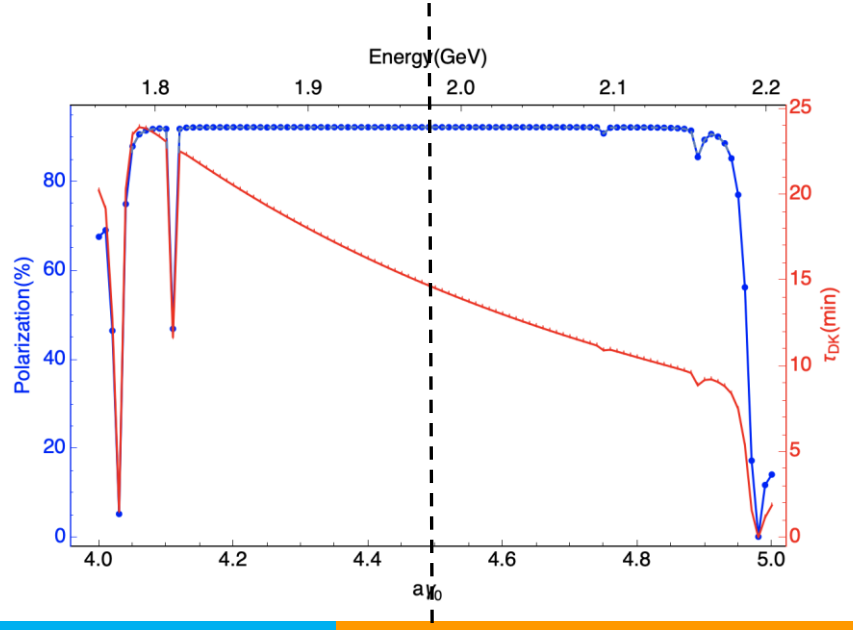
- Booster
  - free from intrinsic spin resonances

T. Chen, Z. Duan, D. H. Ji, D. Wang, Phys. Rev. Accel. Beams, 26, 051003 (2023).

Positron damping/polarizing ring

- Using the self-polarization to generate polarized e+ beams
  - For Resonant depolarization (very promising)
    - polarization build-up time ~ 14.5 min
    - extracted beam polarization @ 10min ~ 44%
  - For polarized colliding beams, more frequent top-up (under study)
    - Higher energy and/or asymmetric wigglers
    - More bunches

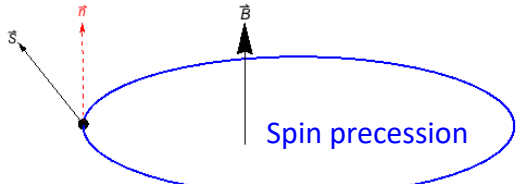




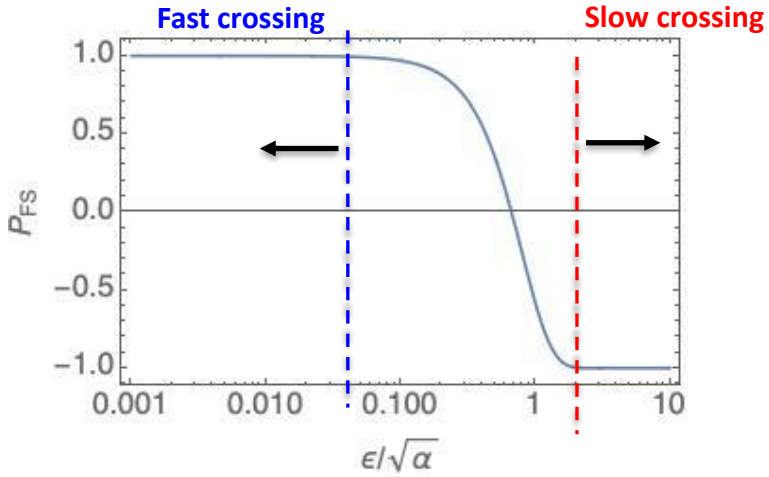
DR V4.0	unpolarized e+	polarized e+
Energy (Gev)	1.983	
Circumference (m)	144.2	
Number of trains	2(4)	
Number of bunches/trian	1(2)	
Total current (mA)	12.4	
Dipole strength B_0 (T)	1.92	
U_0 (kev/turn)	397.9	
Damping time x/y/z (ms)	4.8/4.8/2.4	
Momentum compaction	0.0078	
Storage time	20 ms	10 min
δ_0 (%)	0.0917	
ε_0 (mm.mrad)	132	
injection σ_z (mm)	6	
Extract σ_z (mm)	6.7	6.6
ε_{inj} (mm.mrad)	2500	
$\varepsilon_{ext\ x/y}$ (mm.mrad)	133/13	132/13
$\delta_{inj}/\delta_{ext}$ (%)	0.18 /0.092	
RF acceptance (%)	1.85	
Longitudinal tune	0.025	

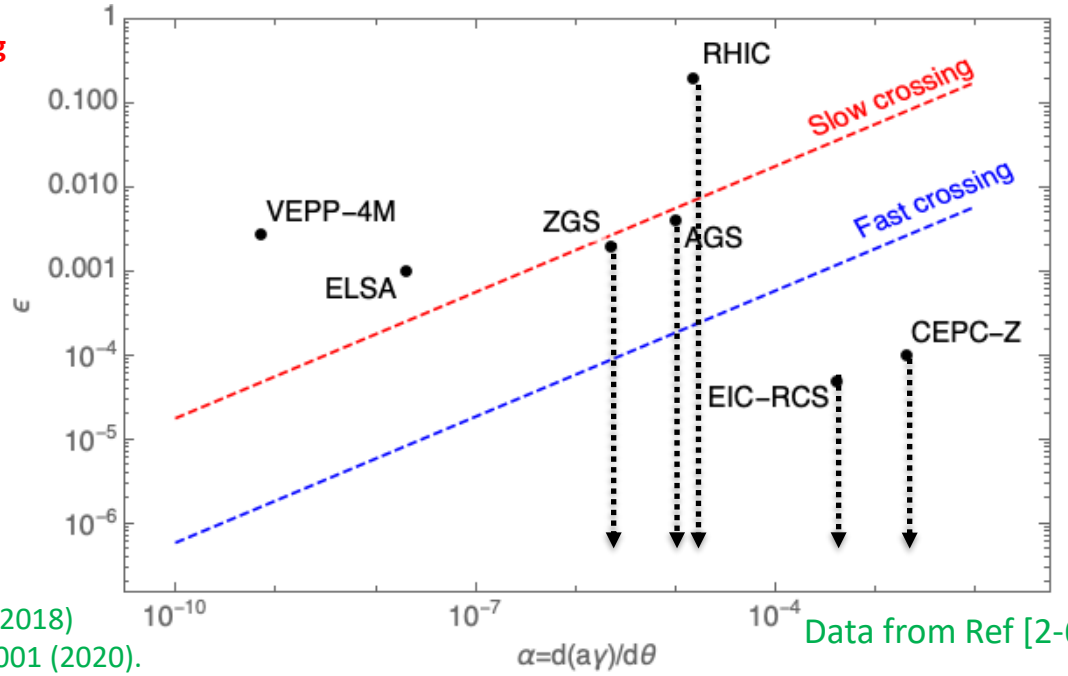
Depolarization in the booster

- The spin tune $\upsilon_s \approx \upsilon_0 \approx a\gamma$ changes and could cross spin resonances $\upsilon_s = k + k_x\upsilon_x + k_y\upsilon_y + k_z\upsilon_z$
  - The spin resonances $\upsilon_0 = k$ are spaced by 440 MeV for e+/e-
- The non-adiabatic crossing could vary $J_s = \vec{S} \cdot \vec{n}$ and lead to depolarization [1]
  - Acceleration rate $\alpha \sim 10^{-6} \frac{dE}{dt}[\mathrm{GeV/s}]C[\mathrm{km}]$
  - Spin resonance strength ε: highly periodic lattice design -> much weaker at lower beam energies
  - Δ|P| < 1% in the regimes of fast crossing & slow crossing
- Previous studies suggested using Siberian snakes to maintain polarization for future 100km-scale boosters[7]



Orbit motion in a helical snake @ RHIC





Data from Ref [2-6]

[1] Froissart and Stora, NIM 7, 297 (1960) [2] A. K. Barladyan, et al., PRAB 22, 112804, (2019)
[3] S. Nakamura, et al., NIM A 411, 93 (1998) [4] T. Khoe et al., Part. Accel. 6, 213 (1975)
[5] Configuration Manual: Polarized Proton Collider at RHIC, 2006 [6] V. Ranjbar, et al., PRAB 21, 111003 (2018)
[7] I. Koop et al., Phys. Part. Nucl. Lett. 13. 7 (2016); S. Nikitin, IJMPA 34, 1940004(2019); IJMPA 35, 2041001 (2020).

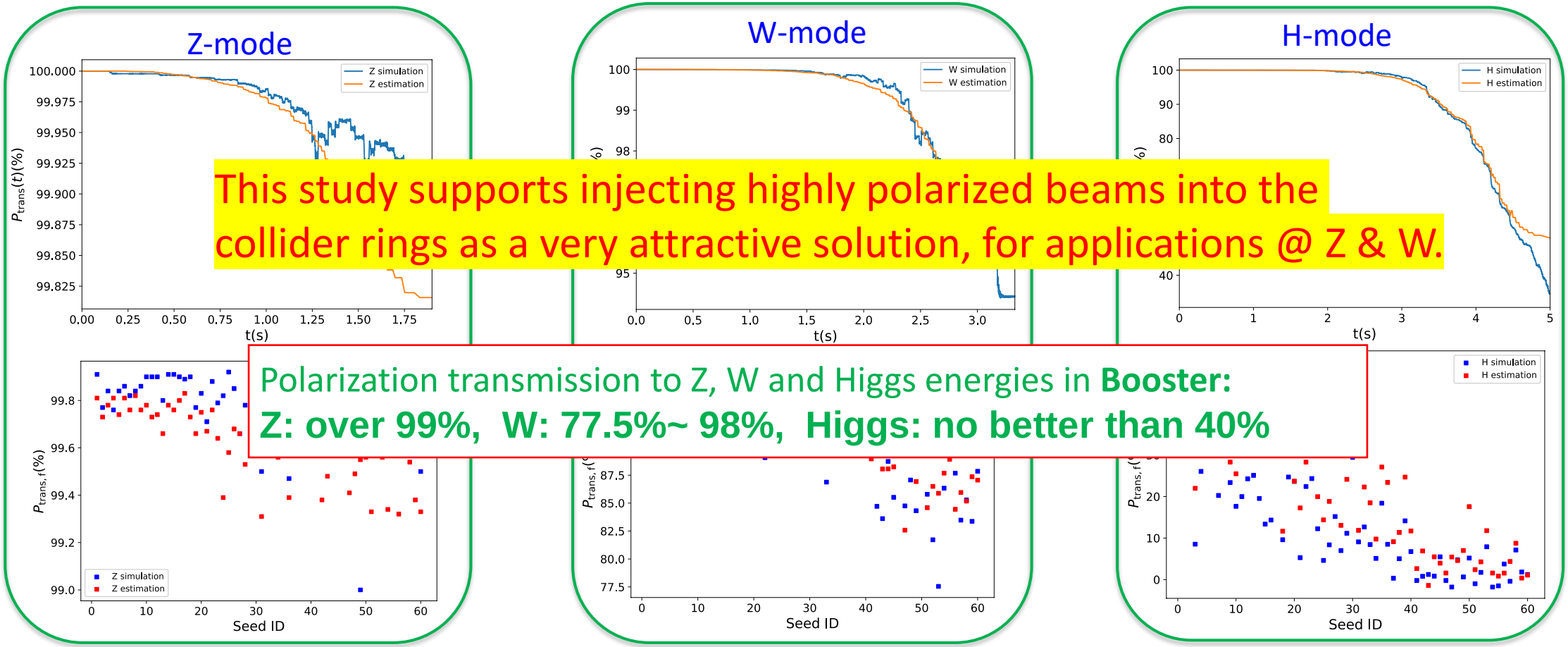
Depolarization effects: simulation vs. estimation

In the acceleration to Z & W

- The spin resonances are generally weak
- Polarization is mostly maintained
- Estimations agree fairly well with simulations

In the acceleration to H

- The spin resonances become stronger at higher energies
- Severe depolarization occurs
- Mitigation methods to be explored



This study supports injecting highly polarized beams into the collider rings as a very attractive solution, for applications @ Z & W.

Polarization transmission to Z, W and Higgs energies in **Booster:**

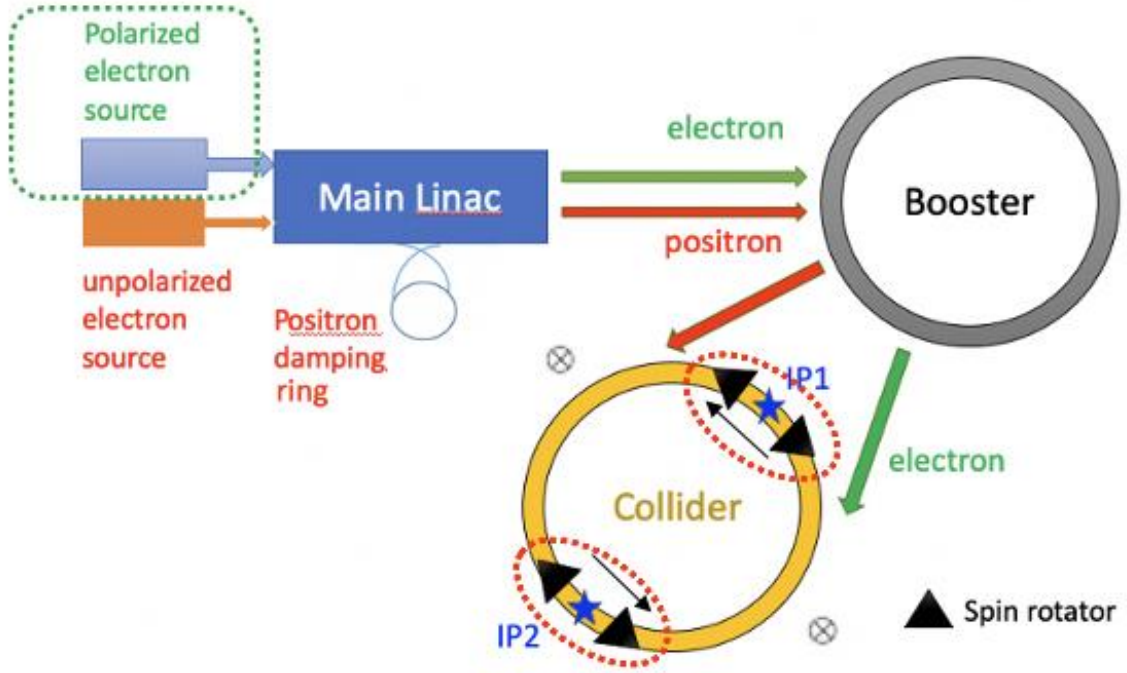
Z: over 99%, W: 77.5%~ 98%, Higgs: no better than 40%

[1] T. Chen, Z. Duan, D. H. Ji, D. Wang, Phys. Rev. Accel. Beams, 26, 051003 (2023).

A high-level longitudinal polarization @ Z-pole

- 50%-70% longitudinal polarization **for e- bunches** is a reasonable goal

- **Over 70% injected e- beam polarization is possible.**
- Polarized e+ source is challenging for CEPC [1],
  - self-polarization at a low energy e+ ring is possible, a tradeoff between the challenges & costs of the ring versus reduction injection rate & luminosity (need more study);
  - polarization transmission efficiency is similar otherwise.



Polarization transmission

Polarized e- source	• Polarization >85% • Ref: ILC, EIC
Linac and transport lines	• Polarization loss < 10% • Ref: SLC, ILC
Booster	• Polarization loss < 5%
Collider	• P_{inj} > 70% after considering these factors

[1] P. Musumeci et al., Positron Sources for Future High Energy Physics Colliders, ArXiv:2204.13245 Phys. (2022).

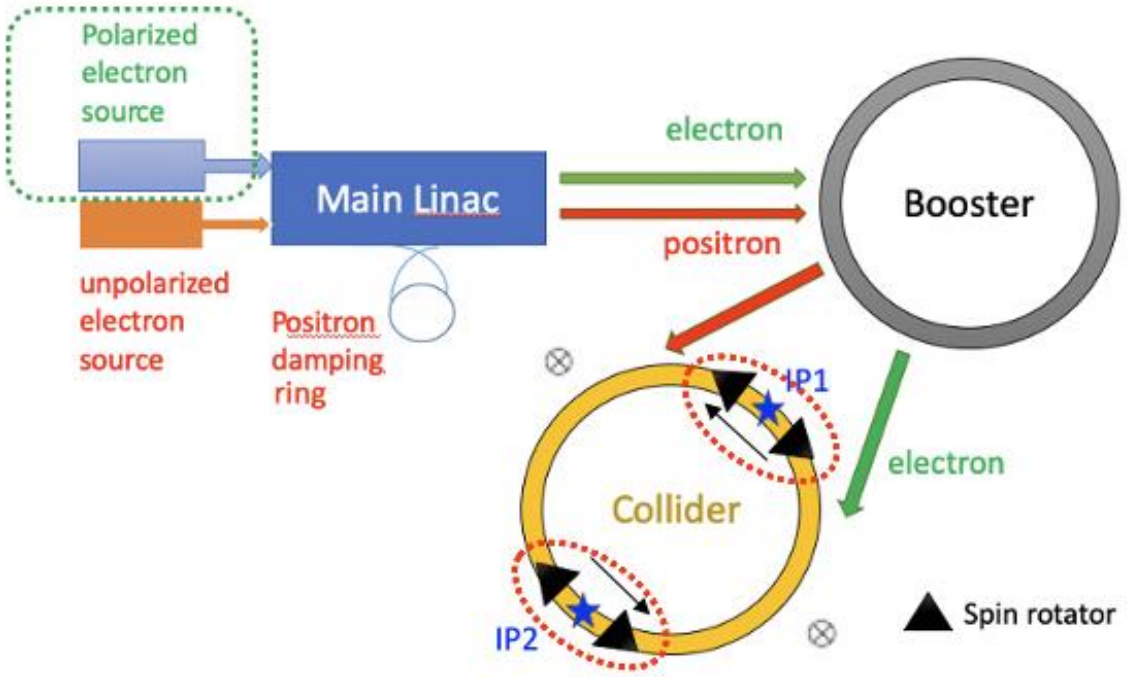
A high-level longitudinal polarization @ Z-pole

- 50%-70% longitudinal polarization for **e- bunches** is a reasonable goal

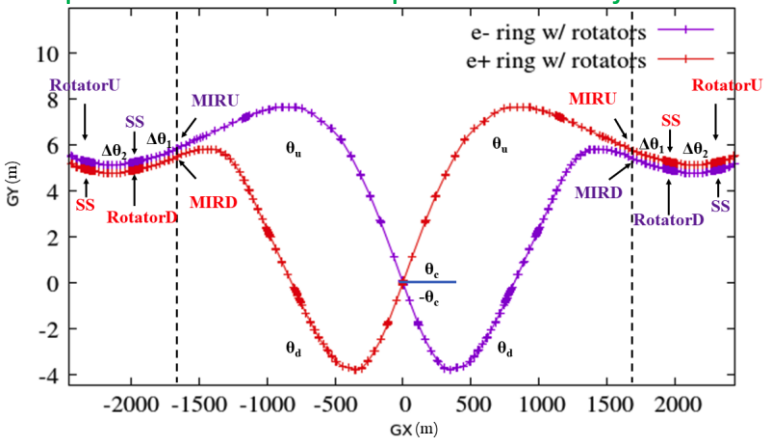
- Over 70% injected e- beam polarization is possible.
- **Simulated equilibrium longitudinal polarization > 70%,**

>> the minimum P_{DK} =2% to attain P_{avg} > 50%

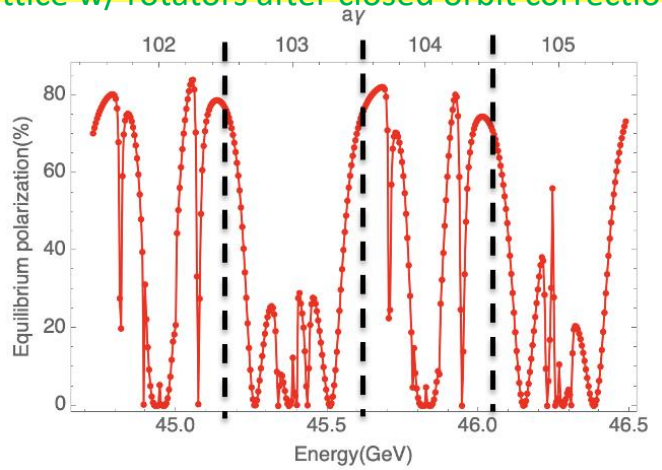
leaving a large margin for effects not yet covered.



Implementation of the spin rotators adjacent to the IR



Simulated equilibrium polarization for an imperfect lattice w/ rotators after closed orbit correction

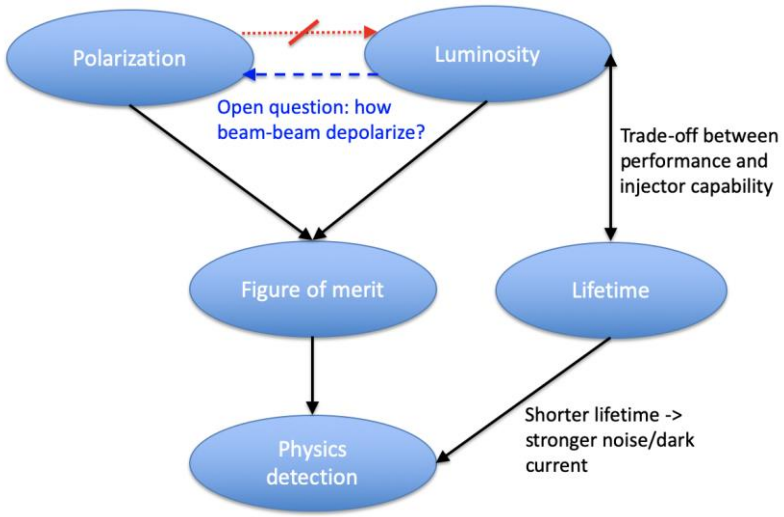


Polarization, luminosity and beam lifetime

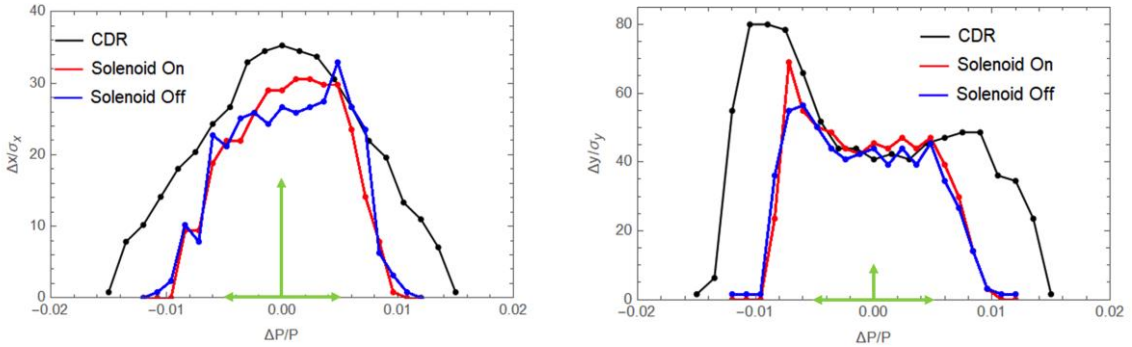
- It is possible to attain 50%-70% e- longitudinal polarization at the **nominal luminosity** and simultaneously with a decent lifetime @ Z-pole

Two pairs of spin rotators

- **240 T·m solenoid each**
- Occupy a space of 2.8 km, can be optimized
- **No interference with the complicated IR design**
- Influence to DA & beam lifetime can be recovered by dedicated sextupole optimization.



Comparison of the dynamic aperture



Contributors to the beam lifetime

Beam lifetime contribution	CDR lattice w/ spin rotators	Comments
Radiative Bhabha	2.9 hour	ref: CEPC TDR
Vacuum lifetime	3 hour	ref: CEPC TDR
Touschek lifetime	4.63 hour	
Lifetime limited by dynamic aperture	**> 9.53 hour**	**no loss in 100 k turns in the tracking simulations**
Total beam lifetime	**> 1 hour**	

W. Xia et al., Investigation of spin rotators in CEPC at the Z-pole, Radiat. Det. Tech. Meth. 6:490 (2022).

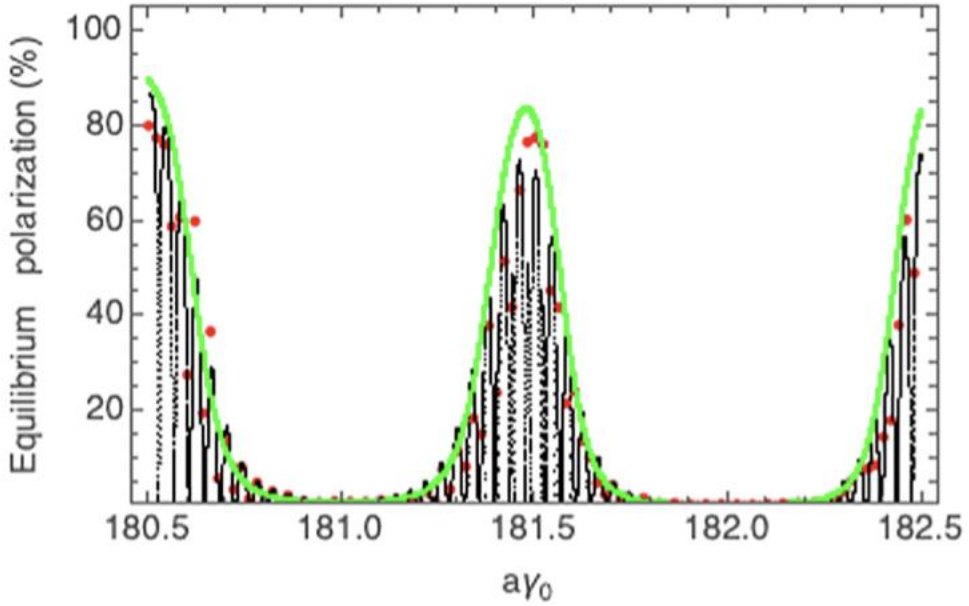
Prospects of Z-pole polarization for CEPC

- Injecting polarized beam(s) to the Collider
- 50%-70% longitudinal polarization for e- versus unpolarized (or lower polarization) e+
  - Polarized e+ source needs more study;
- Spin helicity adjustment
  - e- : changing laser helicity at polarized e- source
  - e+ : a solenoid spin rotator (21 T·m for 2 GeV) in the transport line following the polarizing ring, or a programmed spin flip in the polarizing ring prior to extraction
- RD measurements w/ a few pilot non-colliding bunches, no physics deadtime
- Accurate 3D polarimetry is needed
  - Inside the IR -> deduce longitudinal polarization @ IP
  - Outside the IR -> RD measurements

Longitudinal polarization at W?

- A good chance for >50% e- longitudinal polarization at W
  - Assume injected polarization > 60%, then P_{DK} needs to be above 23%
- Interleaved solenoid + dipole spin rotators to cover a larger energy range (under study)
  - solenoid strength scales ~ linearly with energy

Simulated equilibrium polarization of Collider at W

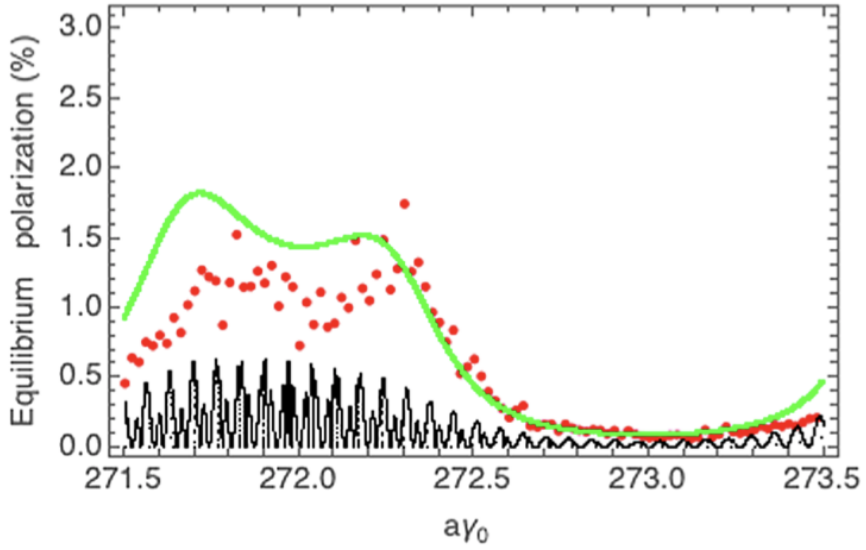


W. H. Xia, et al, Evaluation of radiative depolarization in the future circular electron-positron collider, Phys. Rev. Accel. Beams, 26, 091001, (2023).

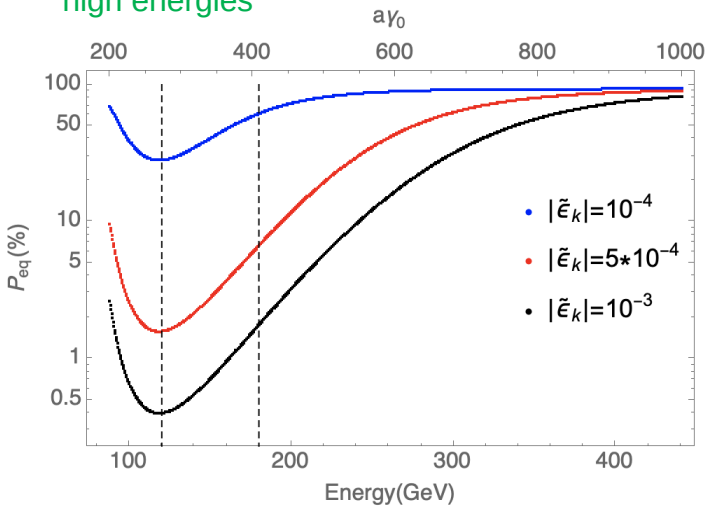
Useful polarization level at Higgs?

- More challenging but possible at Higgs (Under study)
  - Simulated injected polarization < 30% -> improvements in Booster lattice design & mitigation to machine imperfections
  - Simulated equilibrium polarization ~ 1% -> mitigate depolarization by harmonic spin matching, cancellation of Sokolov-Ternov effect
- Interleaved solenoid +dipole spin rotators to cover a larger energy range (under study)

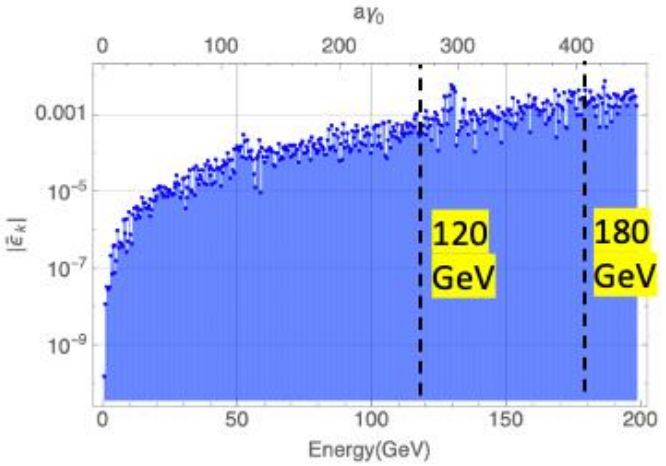
Simulated equilibrium polarization of Collider at Higgs



Prediction of resonant spin diffusion theory at ultra-high energies



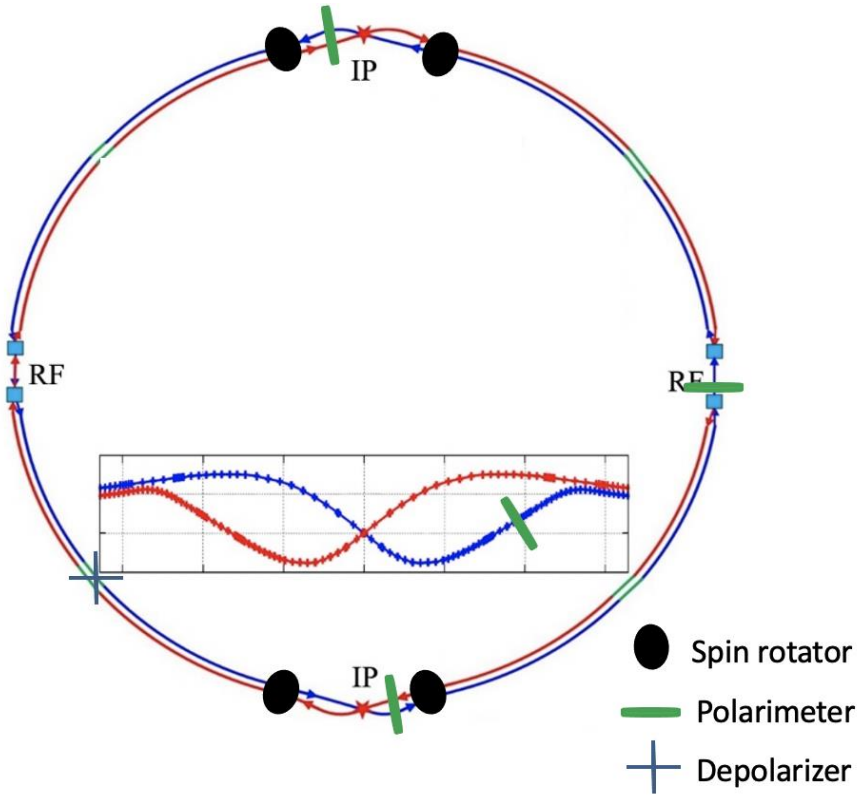
The key is to reduce the spin resonance strength by a factor of 10



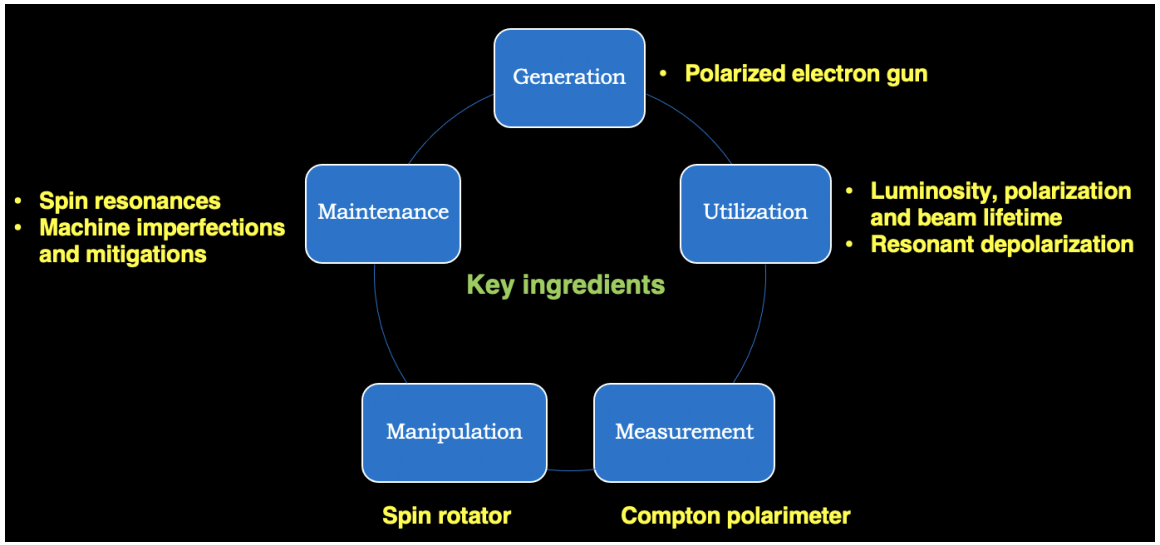
W. H. Xia, et al, Evaluation of radiative depolarization in the future circular electron-positron collider, Phys. Rev. Accel. Beams, 26, 091001, (2023).

Polarization R&D plan in the CEPC EDR Phase

- Implement the spin components in the post-TDR lattice designs
- Study the polarization utilities at Higgs and W energies
- Polarization-related key hardware R&D



Modify the PAPS photocathode DC gun to a Polarized Electron Source



RD @ BEPCII

R&D of high-field SC solenoids

A Compton polarimeter for BEPCII

Summary

- Injecting polarized beams is promising for longitudinal polarization and RD measurements.
- 50%-70% longitudinally polarized e- versus unpolarized (or a lower polarization) e+ at Z with the nominal luminosity is a reasonable goal.
- Further studies of polarized beams towards higher energies as well as related hardware R&D are planned for the CEPC EDR phase.
- Physics motivations for polarized beams are warmly welcome.

Thank you for your attention!

Spin resonance structure of a CEPC Booster lattice

- Strength of intrinsic & imperfection resonances can be approximated by[1]

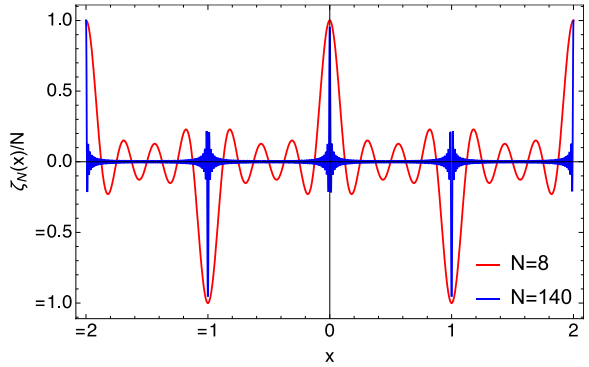
$$|\epsilon| \approx |\epsilon_{FODO}|\, E_P\, E_M$$

due to P superperiods

due to M identical FODOs in each arc

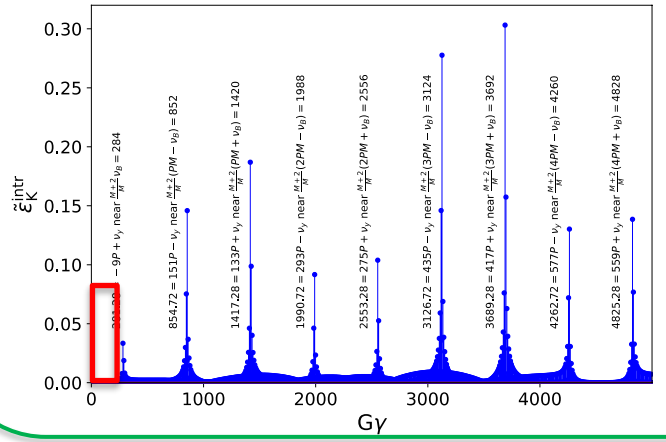
- Enhancement occurs near $\frac{mPM \pm \nu_B}{\eta_{arc}}$, ν_B is the total ν_y in all standard arc cells [2]

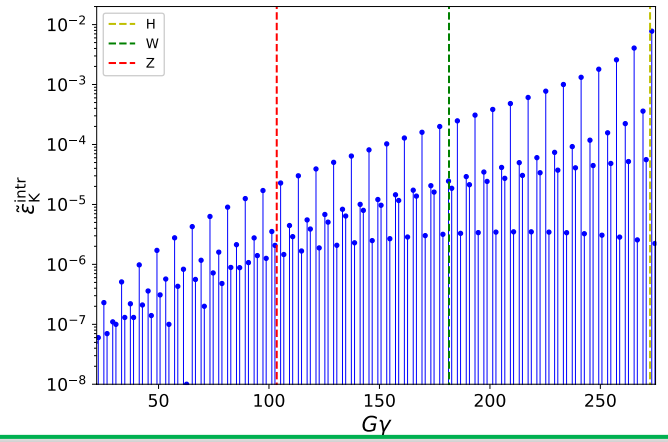
- Resonances at K<< ν_B tend to be weak due to cancellation [2]



Intrinsic resonances: $\upsilon_0 = K = k \pm \upsilon_y$

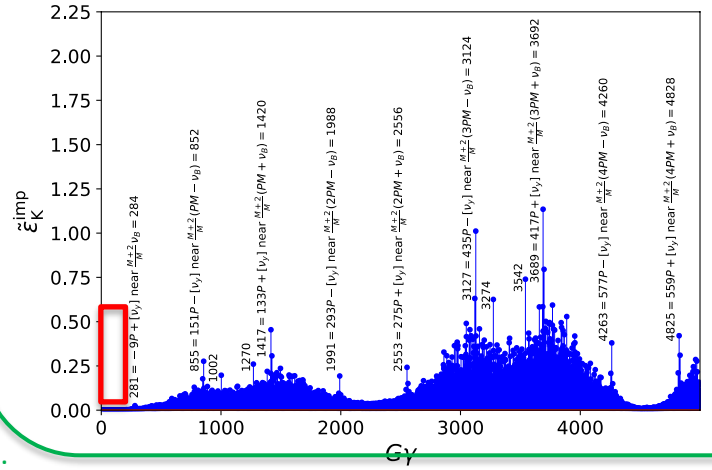
Super strong resonances: $K = nP \pm \nu_y, n \in \mathbb{Z}$ closest to $(mPM \pm \nu_B)/\eta_{\mathrm{arc}}, m \in \mathbb{Z}$

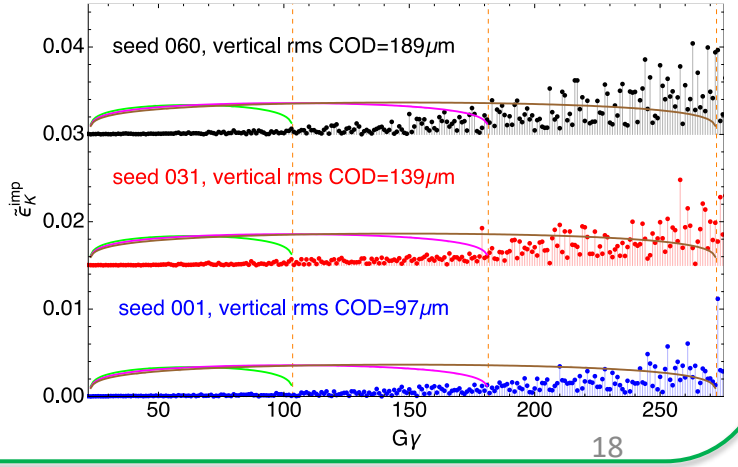




Imperfection resonances: $\upsilon_0 = K$

Super strong resonances: $K = nP \pm [\nu_y], n \in \mathbb{Z}$ and $K = [(mPM \pm [\nu_y]\frac{\nu_B}{\nu_y})/\eta_{\mathrm{arc}}]$



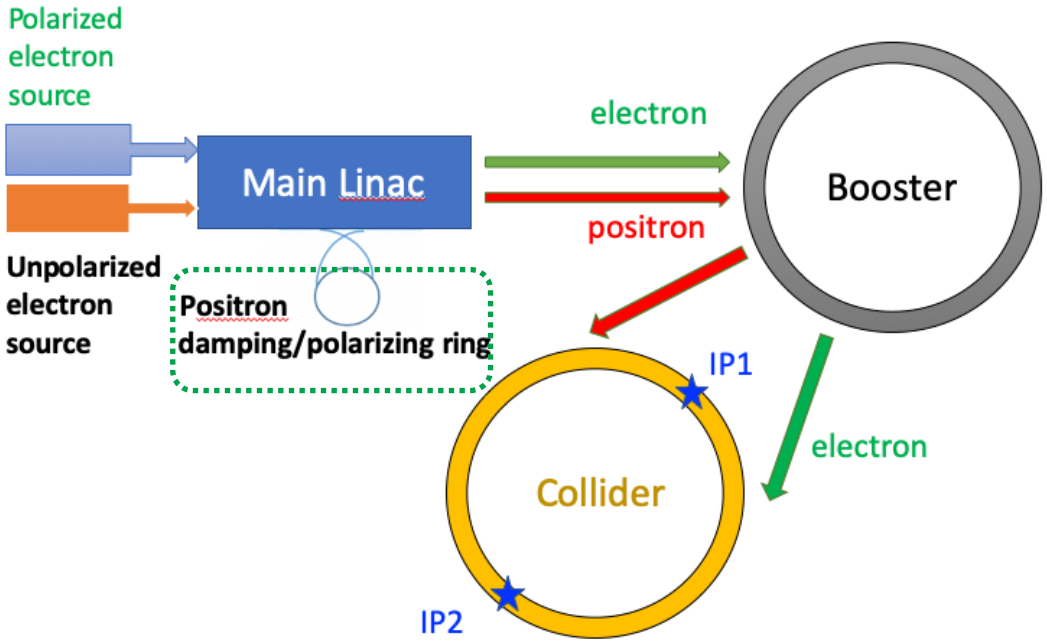


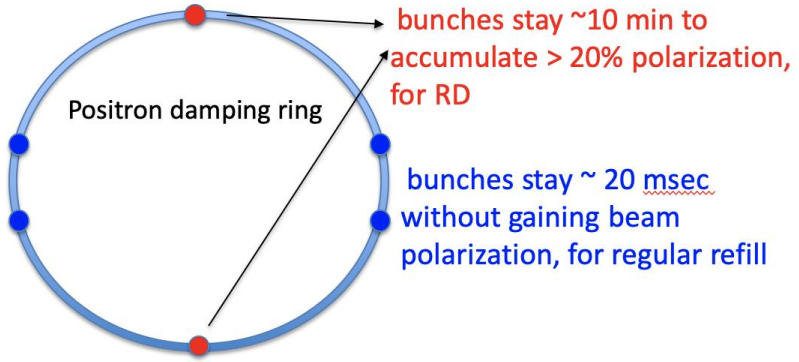
[1] S. Y. Lee, Spin dynamics and snakes in synchrotrons (World Scientific, 1997).
[2] T. Chen, Z. Duan, D. H. Ji, D. Wang, Phys. Rev. Accel. Beams, 26, 051003 (2023).

Resonant Depolarization at Z

- It's possible to inject > 20% polarized beams to enable RD measurements at Z-pole
  - **No dead time for physics, a few pilot bunches**
  - Polarized e+ source ? Dual-purpose damping/polarizing ring (could accommodate both e+/e- beams to gain sufficient polarization)

Approaches		Self-polarization in the collider	Injection of polarized beams
Hardware	Polarized electron gun	None	Yes
	Asymmetric wigglers	In the colliders	In the e+ damping ring or None
Polarization level		5% ~ 10%	> 70% for e-, > 20% e+
Dead time for physics		**Initial 1~2 hours in each fill**	**None**
Frequency of RD measurements		Every ~10 min per beam	More frequent for e- beam
RD on colliding beams		None	Possible at lower bunch charge





One typical design:
beam energy ~ 2 GeV, circumference ~ 150 m
polarization build-up time ~ 14.5 min
Extracted beam polarization @ 10min ~ 44%

RD measurements: endorsed by recent FCC-ee studies

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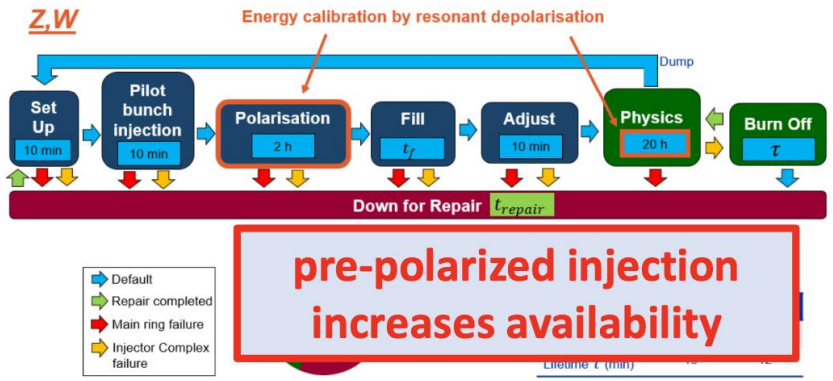
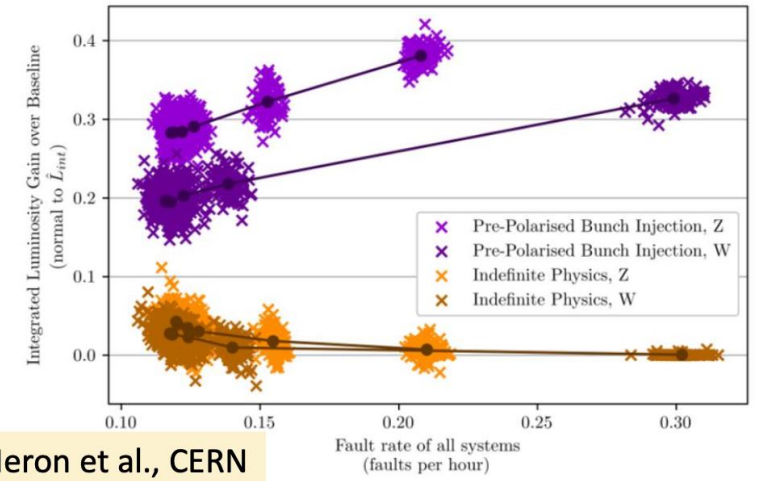
injecting polarized pilot bunches ?

Institute of High Energy Physics, Chinese Academy of Sciences

FCC-ee Operation Cycle



pre-polarized injection increases availability



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booster errors assumed

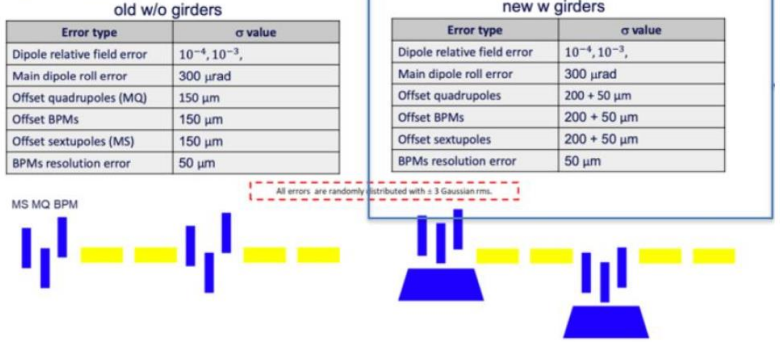
Courtesy: B. Dalena

old w/o girders

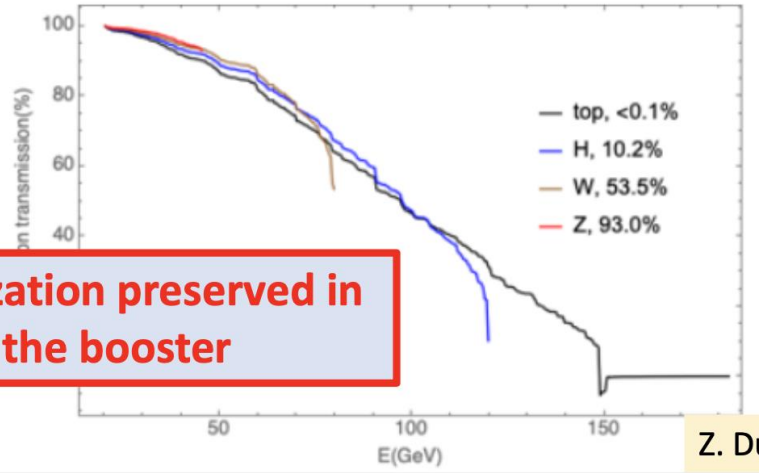
Error type	σ value
Dipole relative field error	$10^{-4}, 10^{-3}$,
Main dipole roll error	300 μrad
Offset quadrupoles (MQ)	150 μm
Offset BPMs	150 μm
Offset sextupoles (MS)	150 μm
BPMs resolution error	50 μm

new w girders

Error type	σ value
Dipole relative field error	$10^{-4}, 10^{-3}$,
Main dipole roll error	300 μrad
Offset quadrupoles	200 + 50 μm
Offset BPMs	200 + 50 μm
Offset sextupoles	200 + 50 μm
BPMs resolution error	50 μm



polarization transmission ~90% (Z), ~60%(W), ~15%(H) and ~0 (top) for different error seeds and lattices



polarization preserved in the booster

Z. Duan, IHEP