Towards an asymmetric detector for HALHF

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& Mikael Berggren, Jenny List, Martina Mezzolla

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Parallel session WG3 — 10.10.2024

HELMHOLTZ

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CLUSTER OF EXCELLENCE
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DESY.

Future lepton colliders landscape

Circular

- High lumi at “low” energy (Z/H)
- Upgradable to hadron (muon?) collider

Linear

- Higher lumi at higher energies (> ttbar)
- Extendable to higher energy

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All big and expensive machines.
Large CO2 footprint.

How to reduce the cost?

"Simply" decrease the size of the tunnel…

- But shorter tunnel = lower beam energy => 😭

HiPACE++

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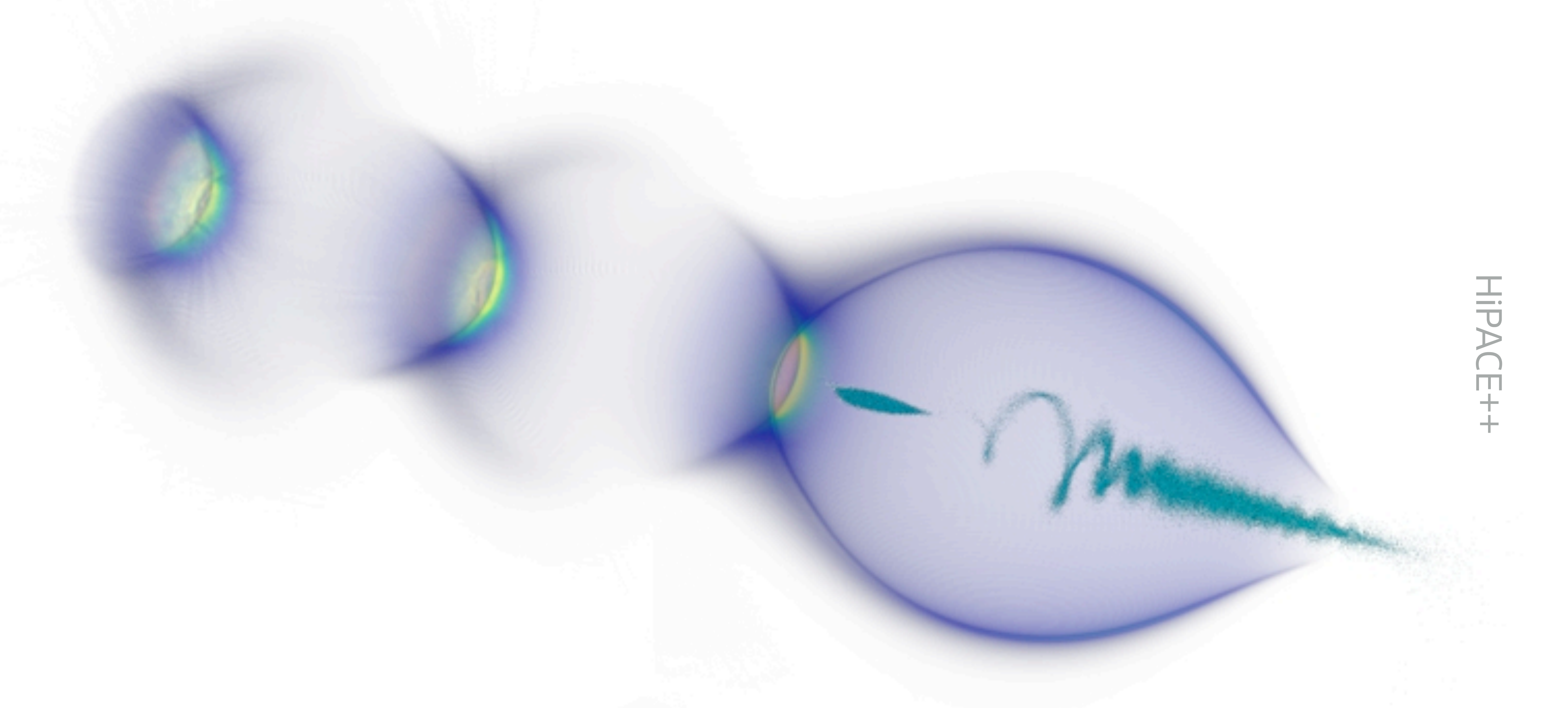
  - RF: ~30 MV/m (ILC)
  - **Plasma wake field acceleration** (PWFA) cavities: ~ expected O(1000 MV/m) — ie x30!



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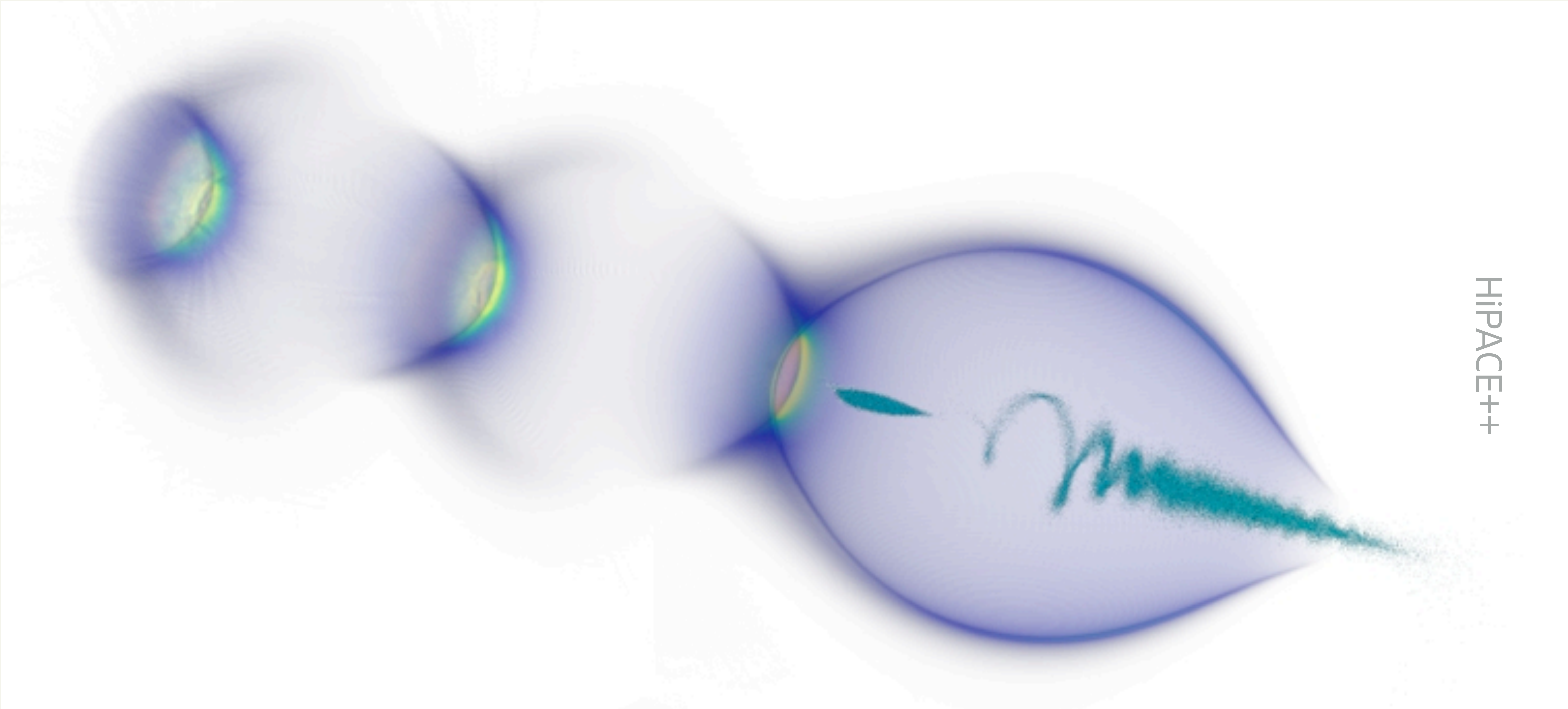

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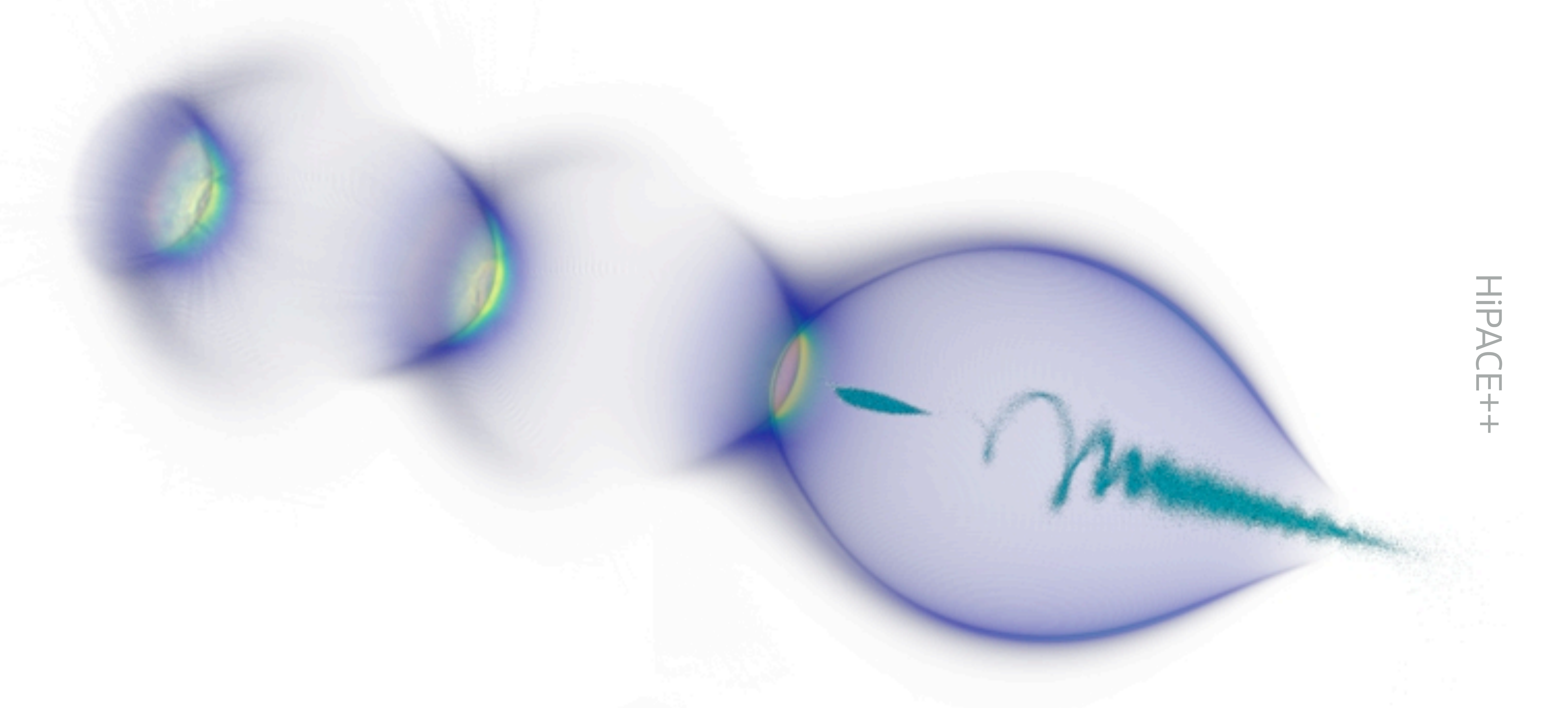

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  - ILC(250 GeV): 10 km (e-, SRF) + 10 km (e+, SRF)
  - Hybrid: <1 km (e-, PWFA) + 10 km (e+, SRF)

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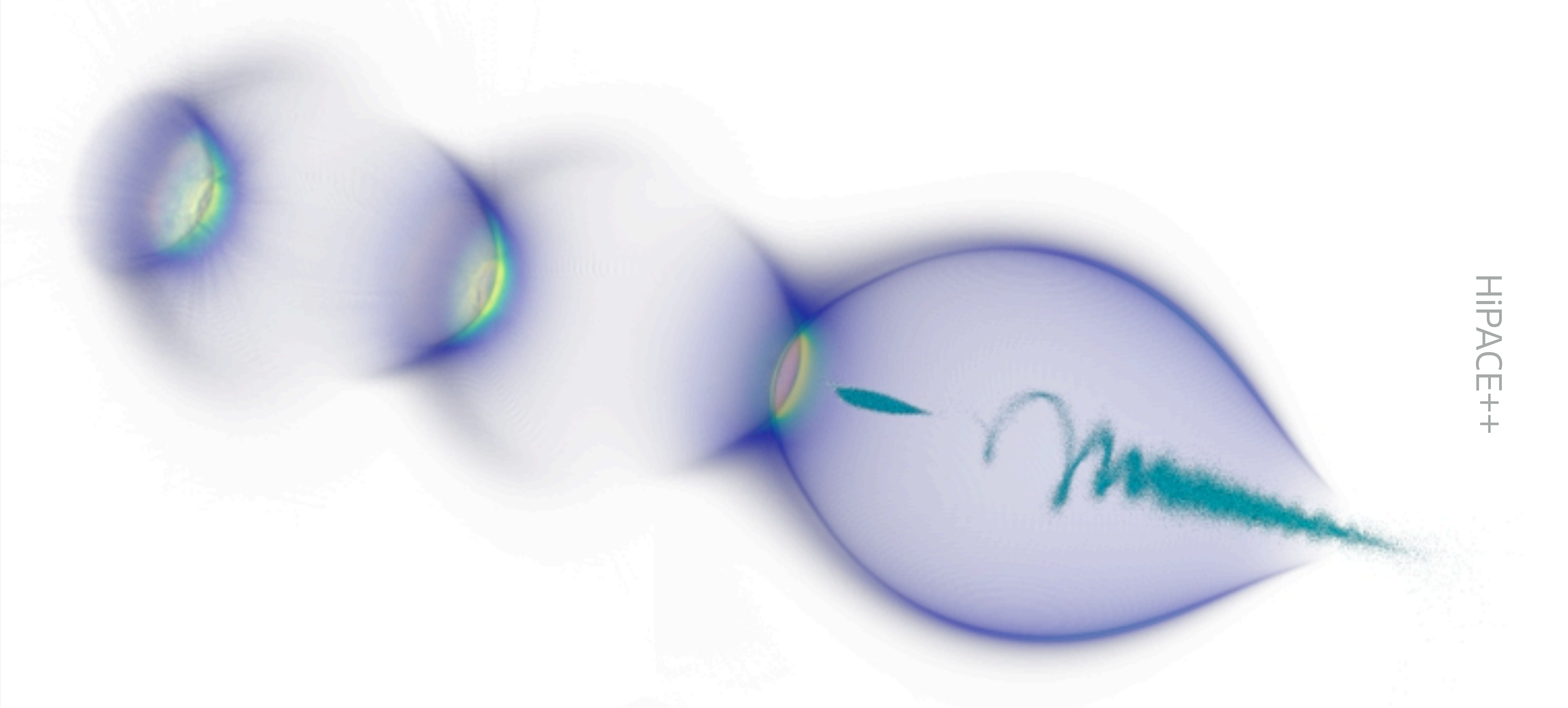

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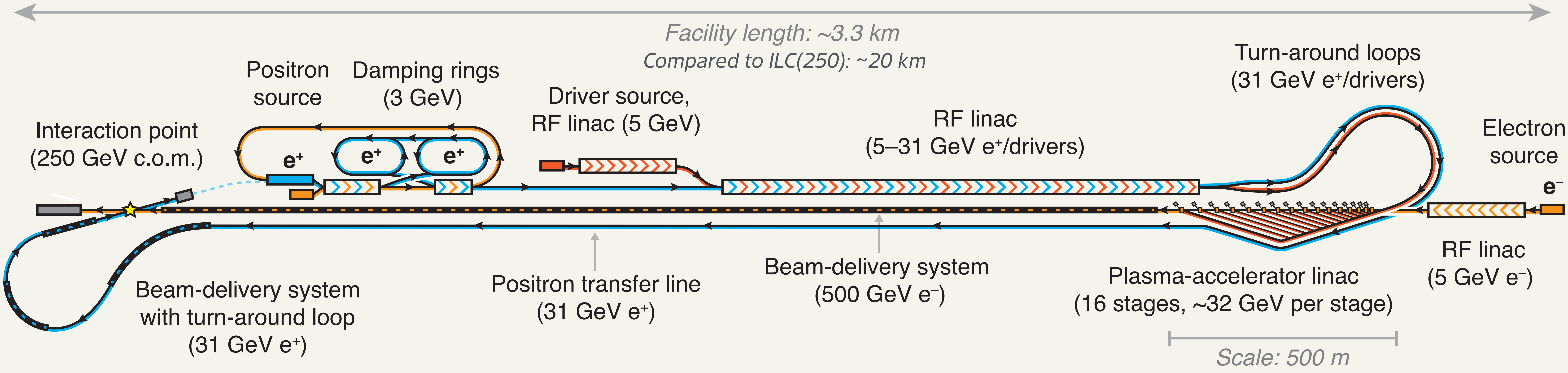
- **Can we do better than 1 km + 10 km?**

The HALHF concept

arxiv:2303.10150

Hybrid : mix of plasma (e^-) and SRF (e+) acceleration
Asymmetric : **500 GeV e^- & 31.3 GeV e^+** (also gives √s = 250 GeV)
Linear : (not circular)
Higgs : (but could go up to ttbar threshold)
Factory



Length = ~3.3 km: similar to XFEL@DESY
Cost = ~2.1 B€ +/- 25% = ~ ILC/4 = ~ EIC

Length dominated by e- BDS
Cost still dominated by tunnel and RF linac

Disclaimer

- I am **not** an accelerator physicist, not an expert of PWFA.
- **Assumptions for the rest of this talk**:
  - Electron-beam driven PWFA is proven **working for electron acceleration** in ~10-15 years.
  - PWFA for **positron is still not available**.
- These might be strong assumptions, but we need a **starting point** to think about a detector!
  - => This talk **focuses on the physics and detector side**, not accelerator side.

Towards an asymmetric detector

- Baseline: 500 GeV e^- and 31 GeV e^+ => $\gamma \sim 2.1$.
  - **Can we still do Higgs physics in such conditions?**
  - Experience: HERA had $\gamma = 3$…
  - … Yet, it's not quite the same physics!

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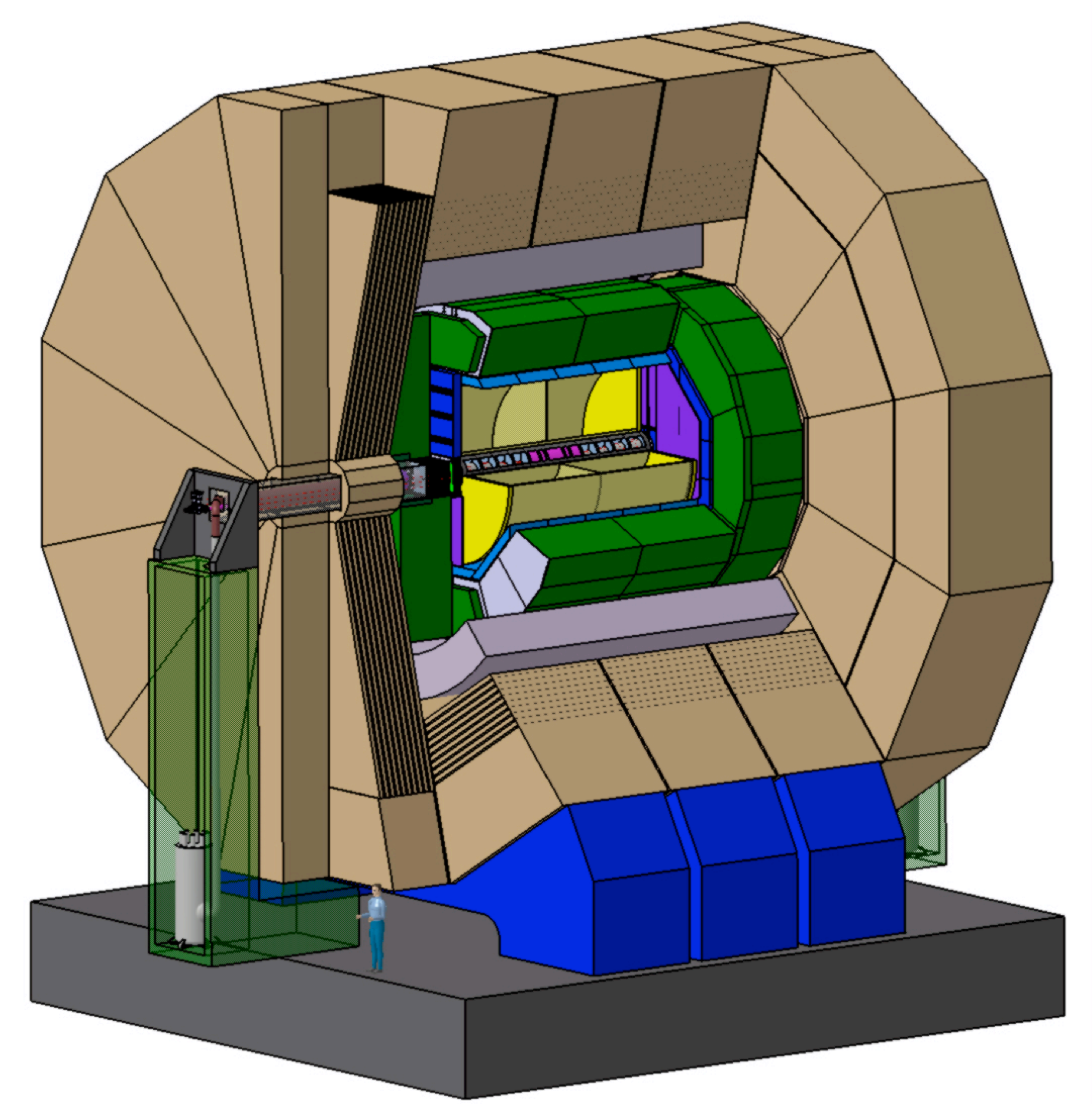
- **Most advanced concept is the ILD at the ILC**.
  - Fast simulation available.
  - Good comparison point.



The International Large Detector

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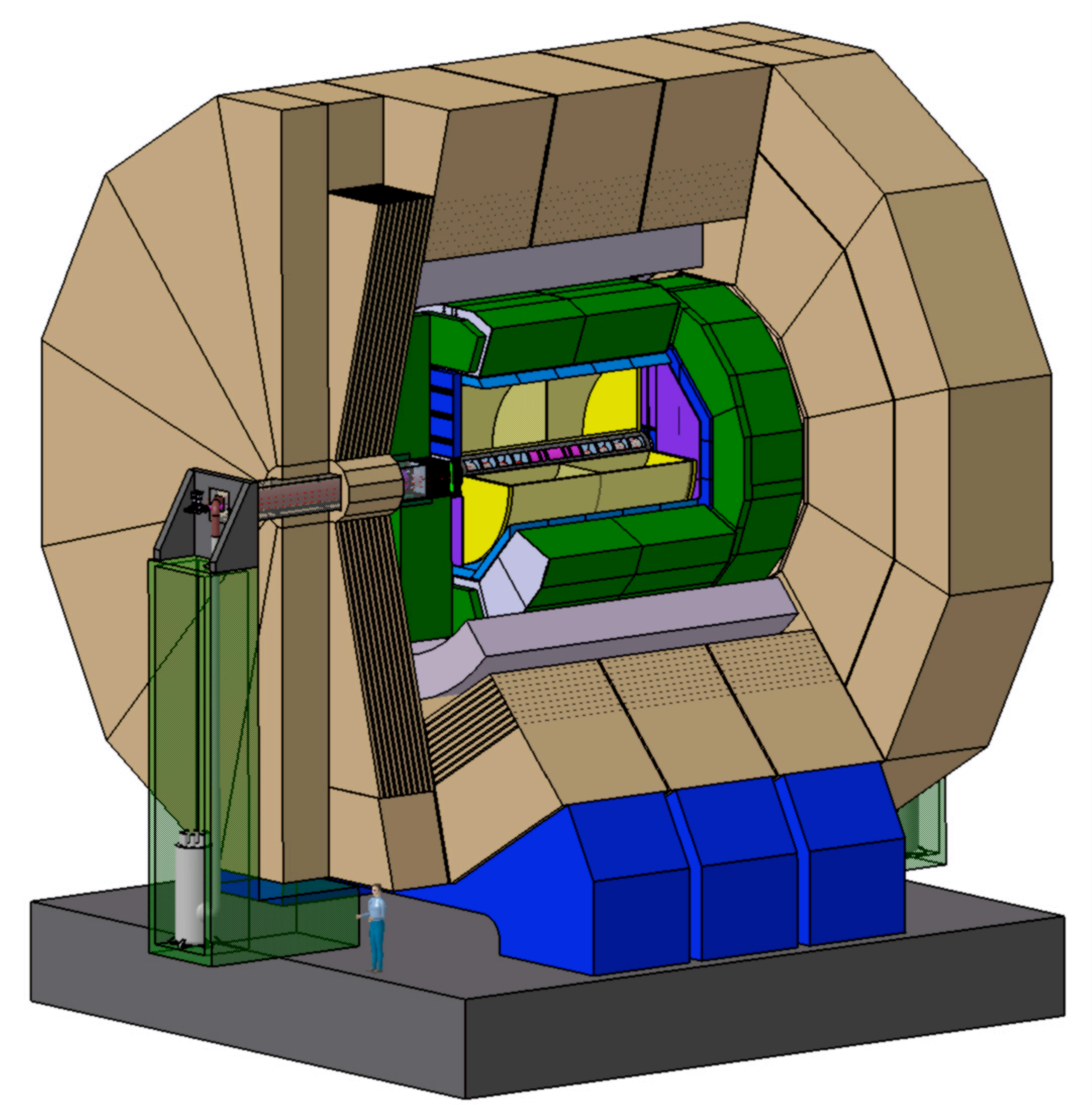
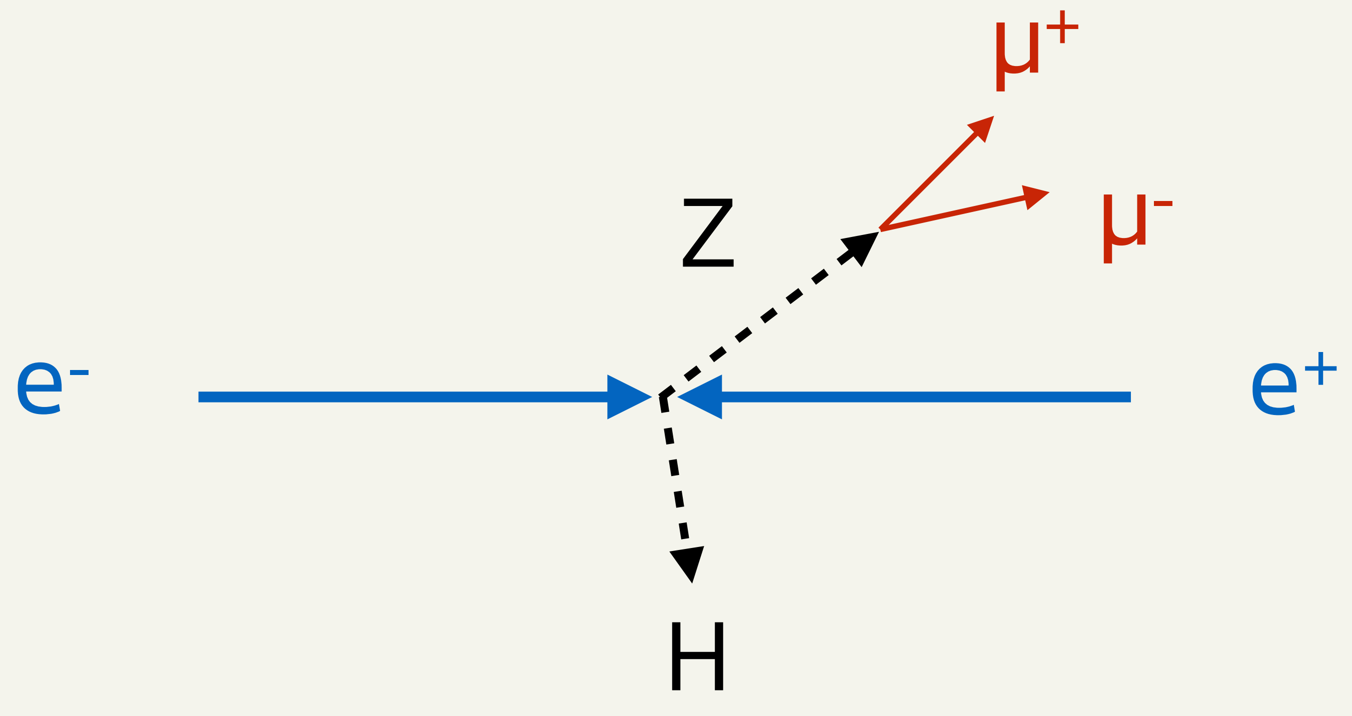
  - Fast simulation available.
  - Good comparison point.
- Modify the fast simulation and run physics analysis benchmarks.

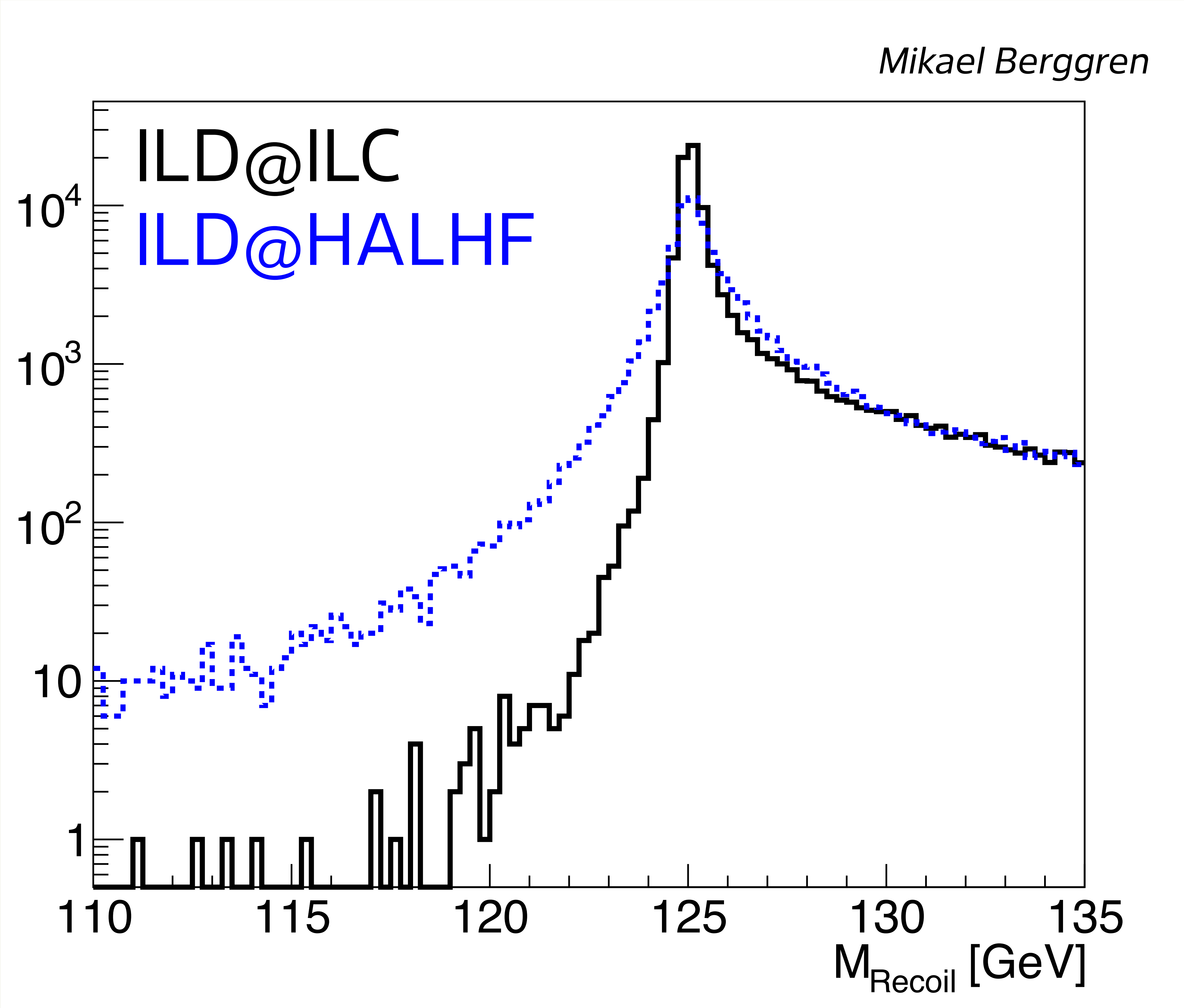


The International Large Detector

Impact on physics: Higgs

- Process: $e^+e^- \to Z(\mu^+\mu^-)H$
- Measure Higgs mass via recoil mass.
- Detector: ILD with fast simulation (SGV), including correct tracking.





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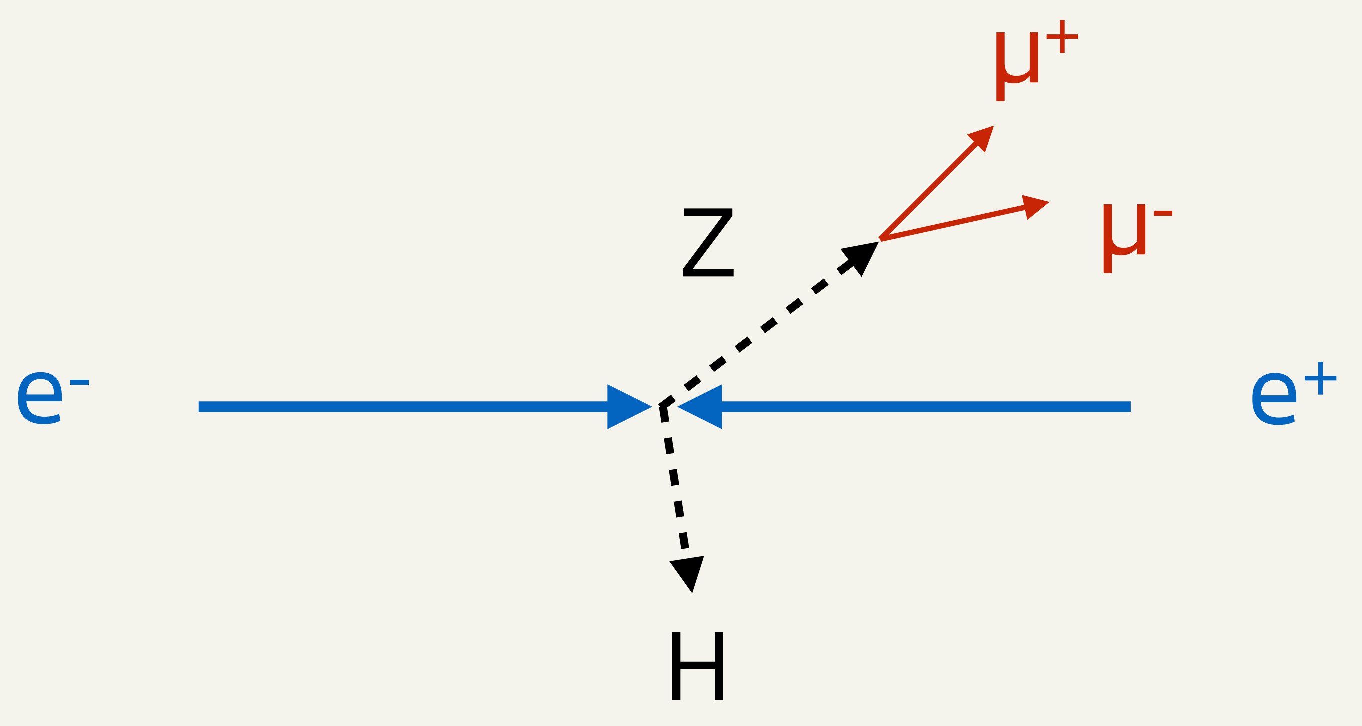
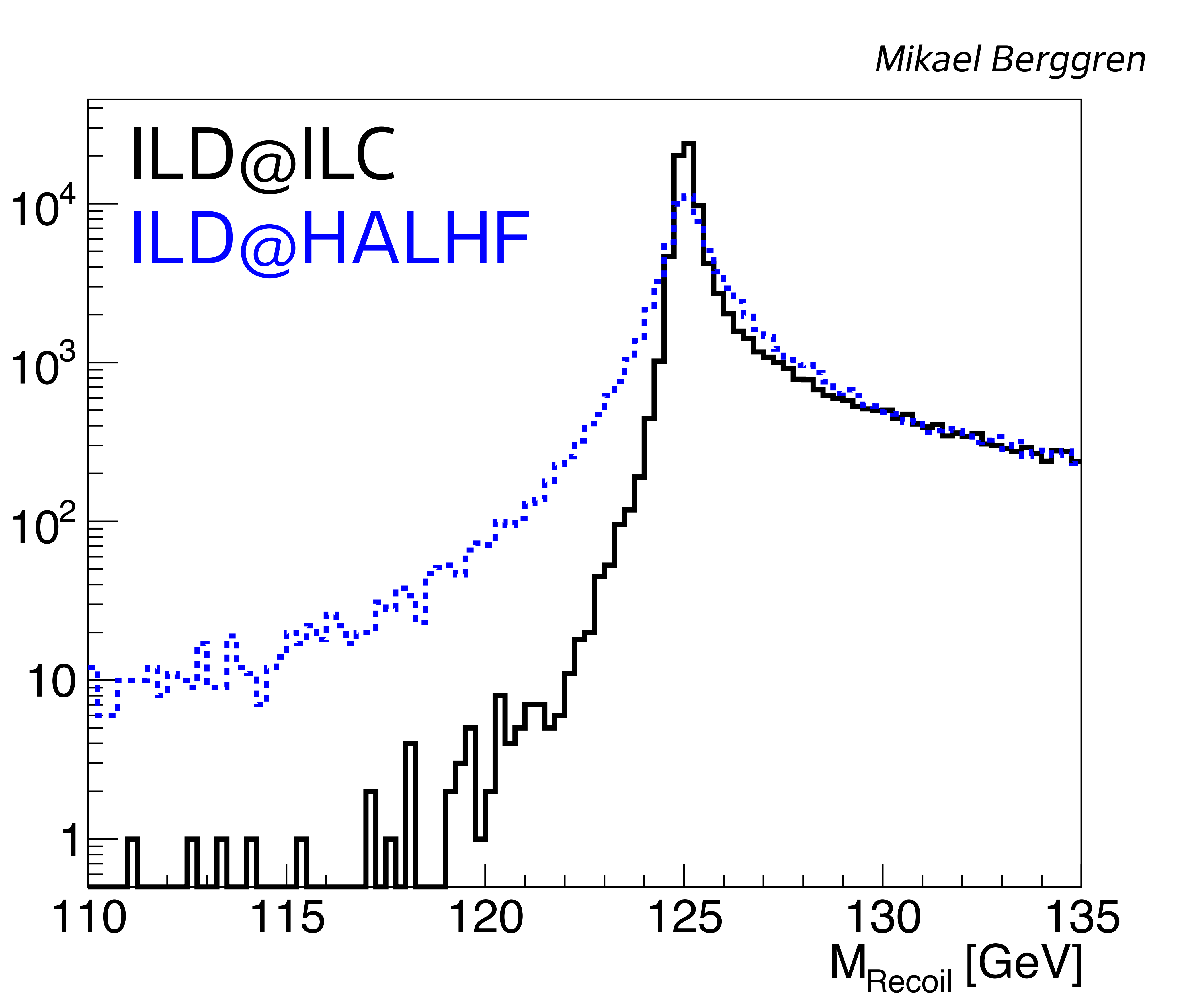


- **Resolution loss due muons being boosted forward**:
  - less lever arm => lower muon momentum resolution.
  - $\sigma_{\text{ILD@HALHF}} = 2.2 \times \sigma_{\text{ILD@ILC}}$



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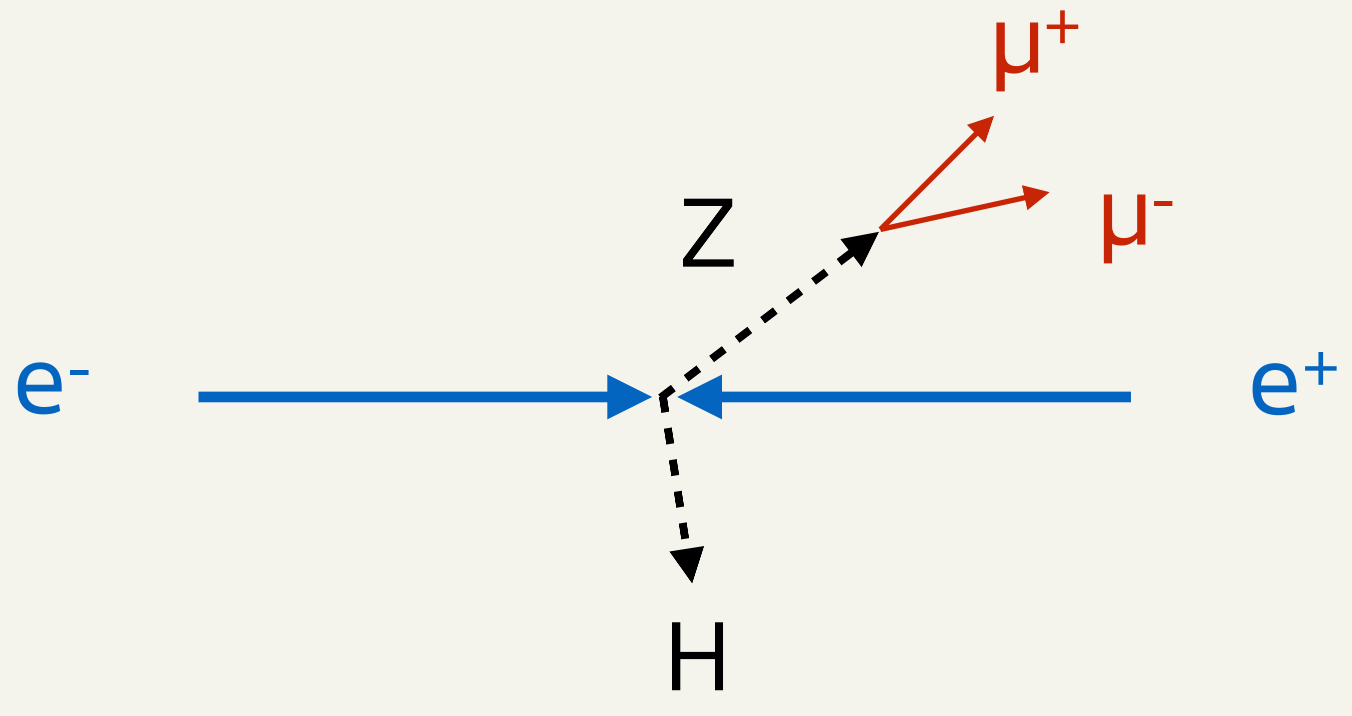

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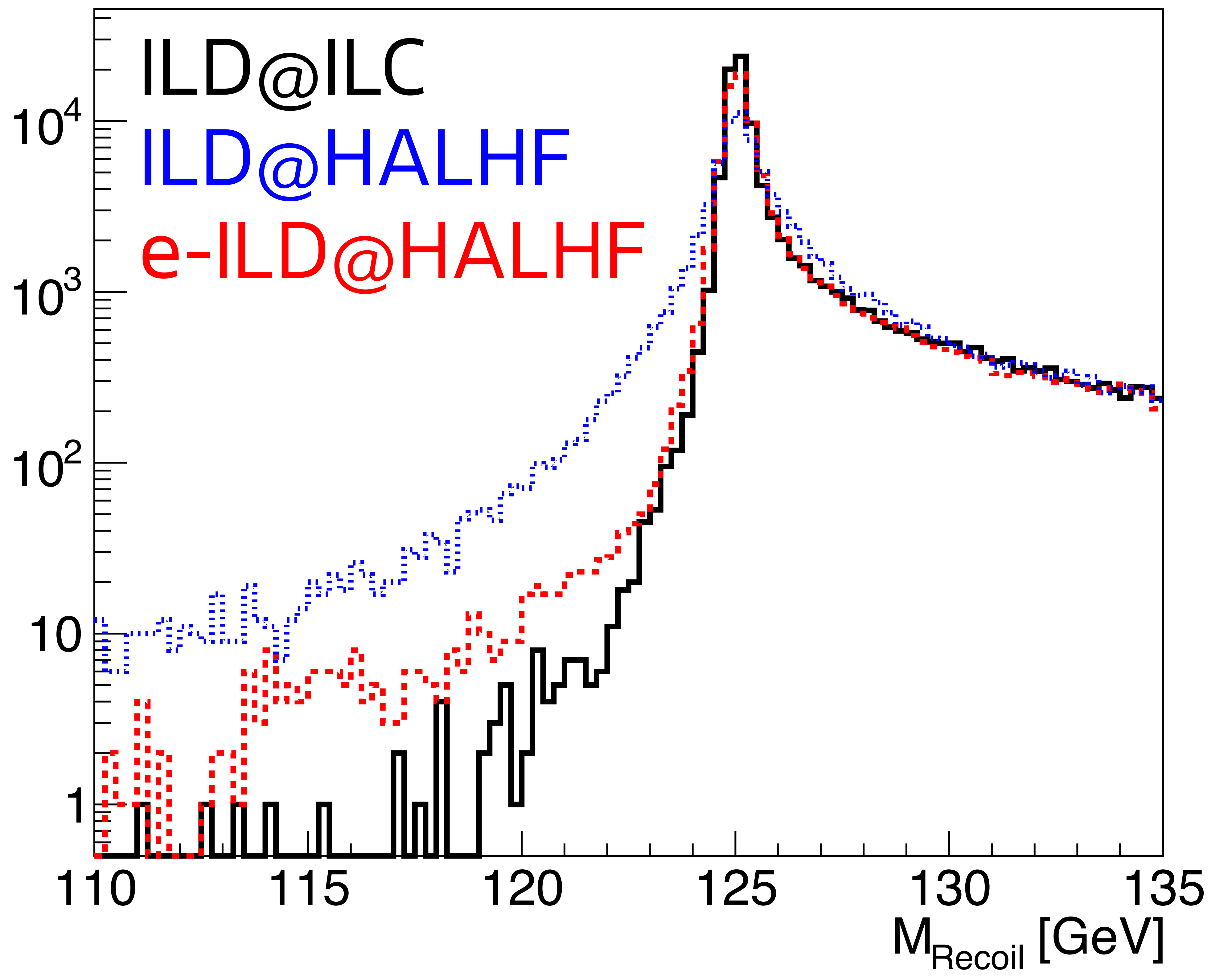
- Mitigation: **extend the barrel in the forward region!**
  - $\sigma_{\text{e-ILD@HALHF}} = 1.2 \times \sigma_{\text{ILD@ILC}}$
  - => loss of only 20% on recoil mass.

Mikael Berggren



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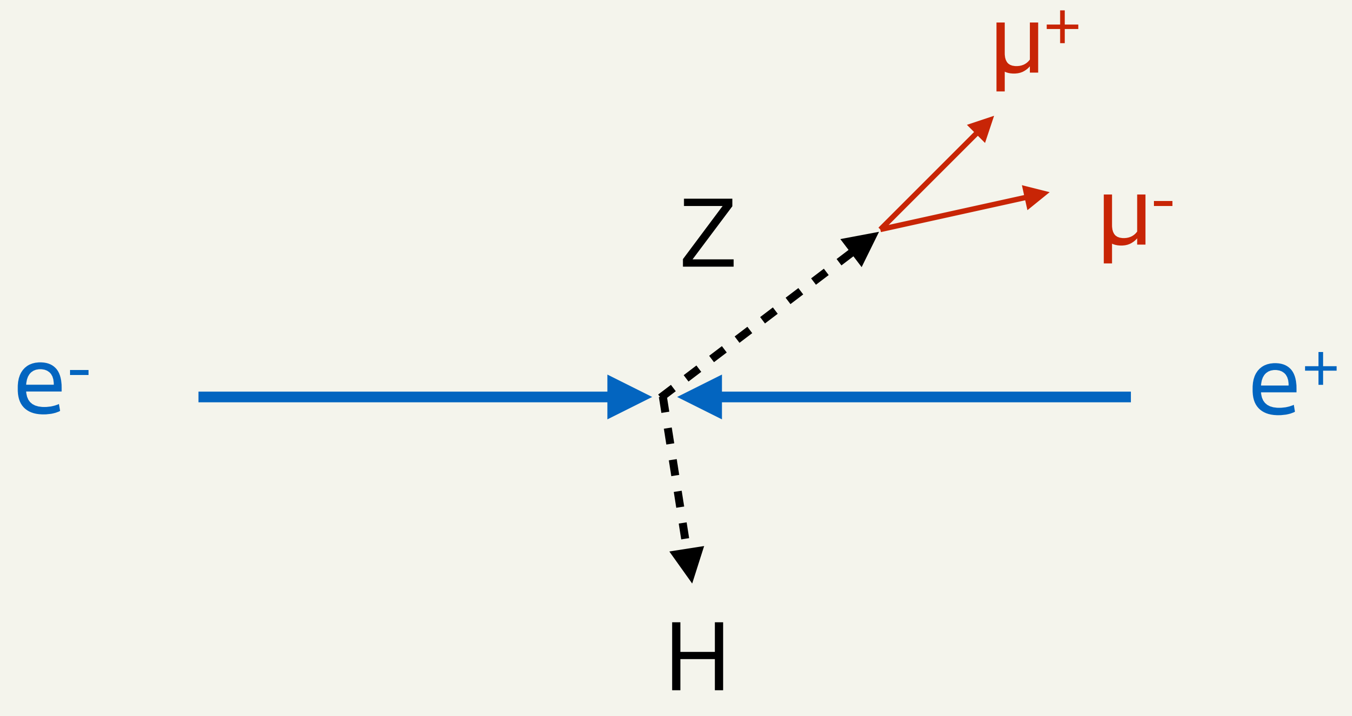

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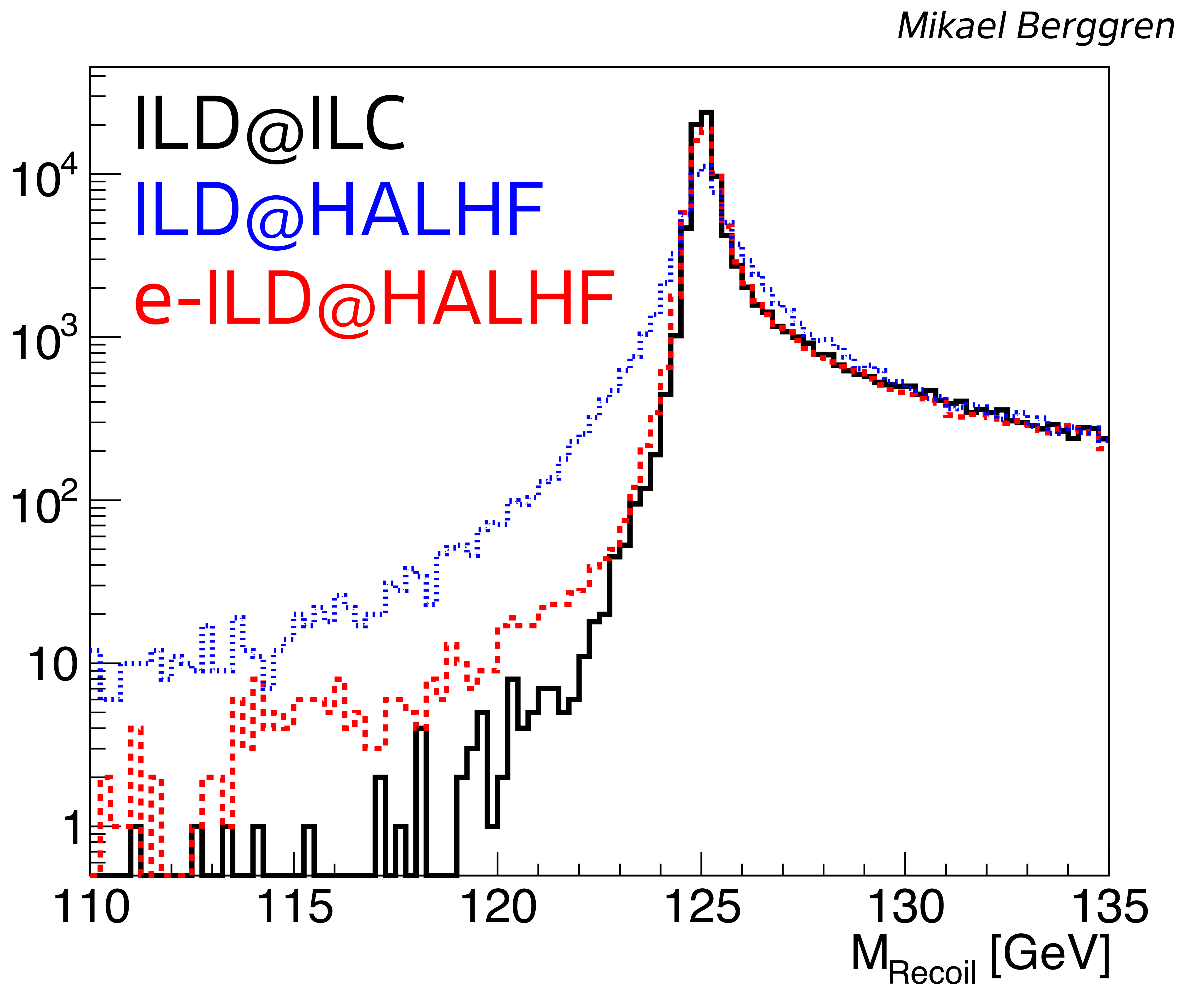

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=> What constrains these modifications?

Beam-strahlung

Creation of many e+e- pairs…

e- beam
high E, lower N

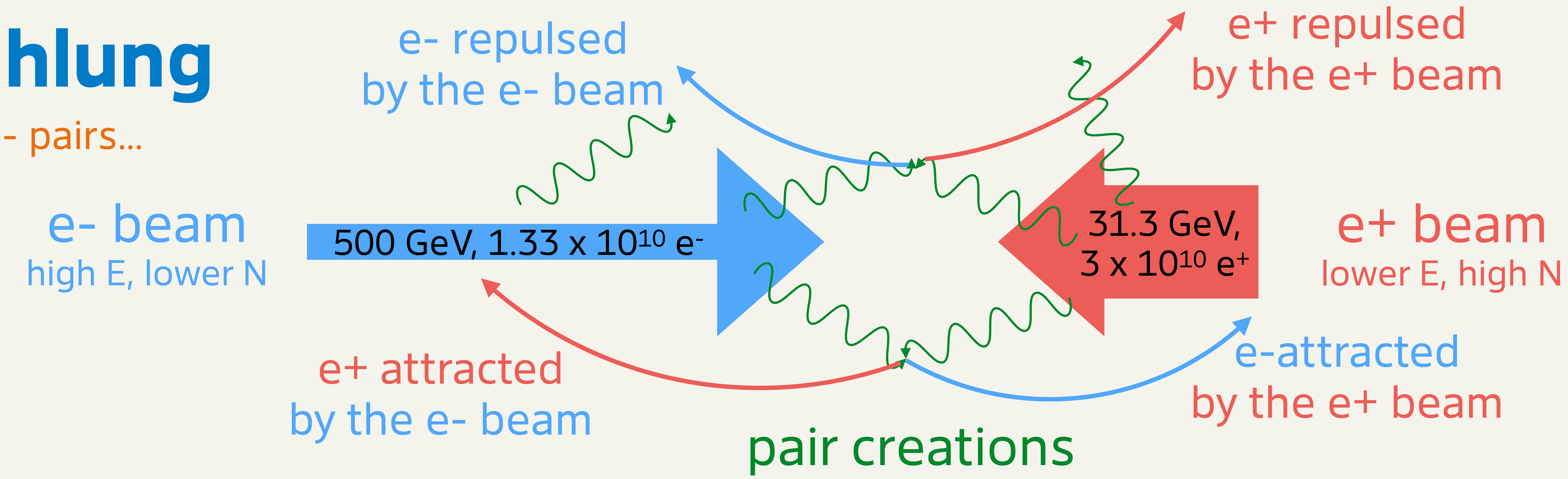
500 GeV, 1.33×10^{10} e^-

31.3 GeV,
3×10^{10} e^+

e+ beam
lower E, high N

Beam-strahlung

Creation of many e+e- pairs...



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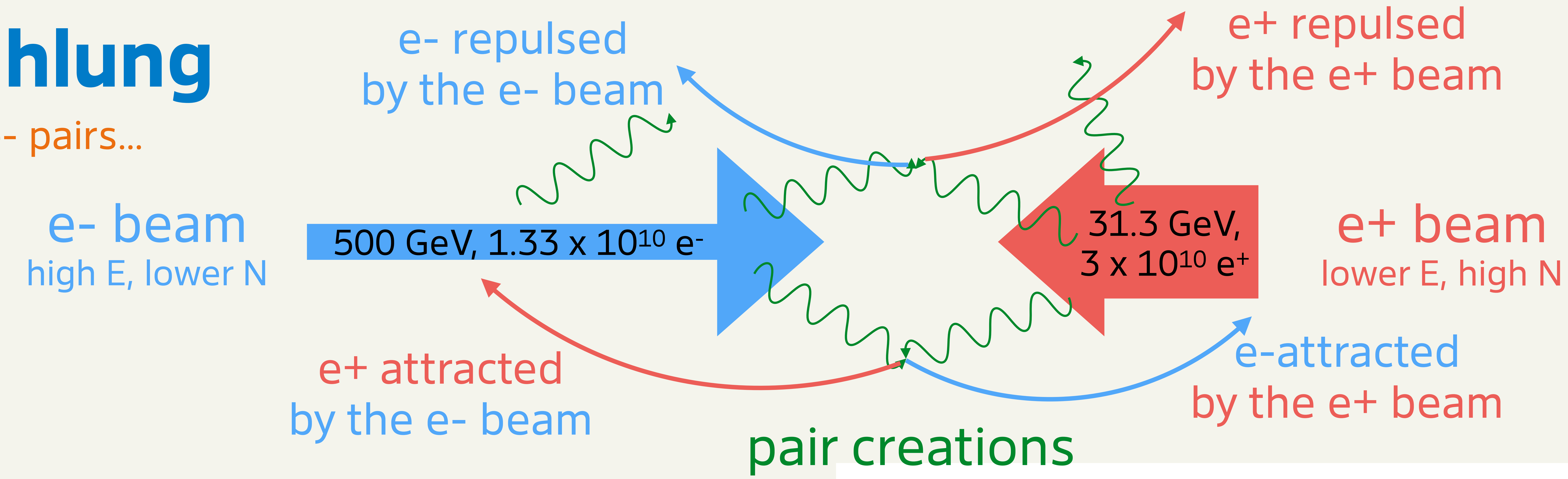

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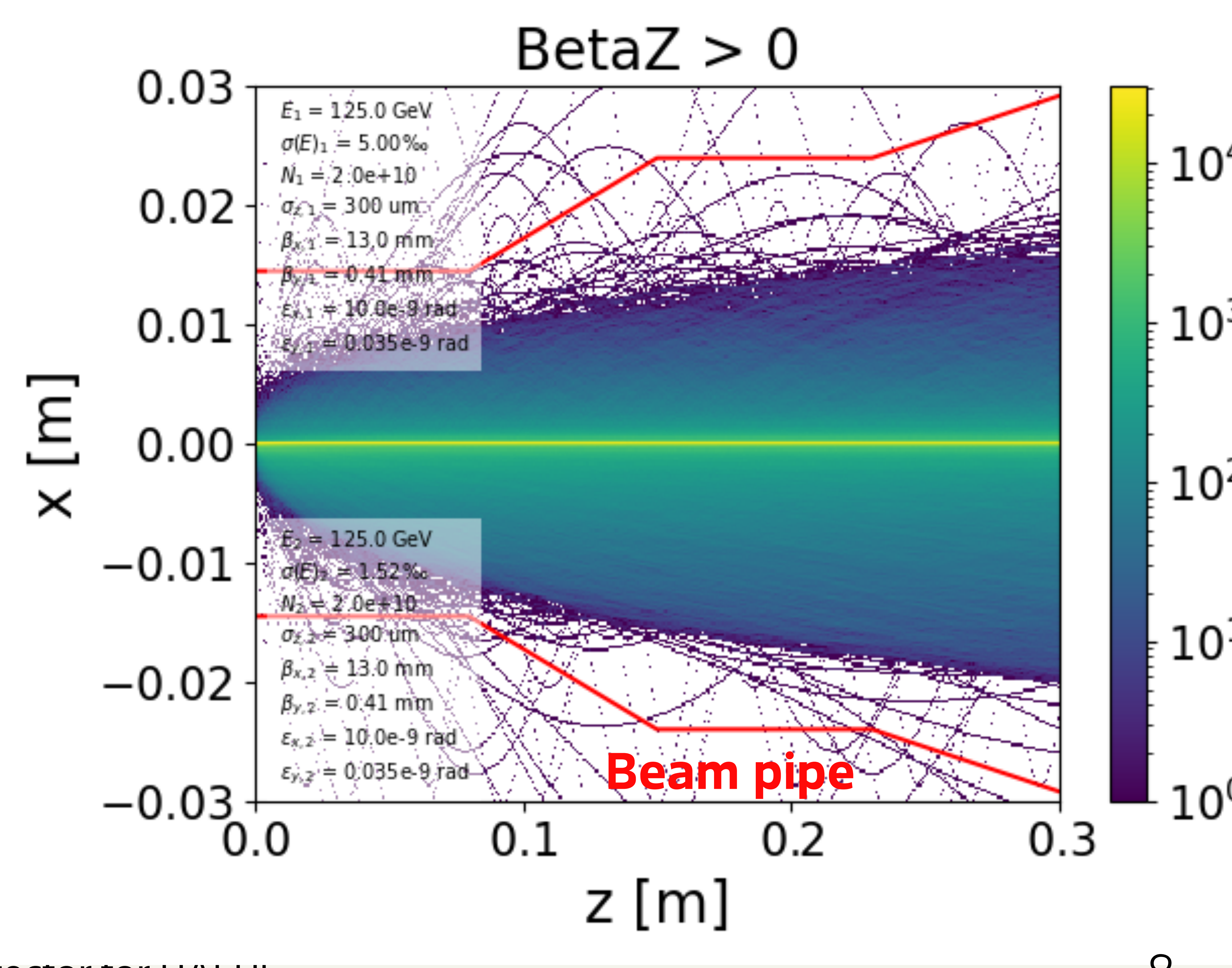
  - Example: plot the trajectories of all pairs created in the forward direction.
  - Here in the ILC configuration (symmetric beams) →



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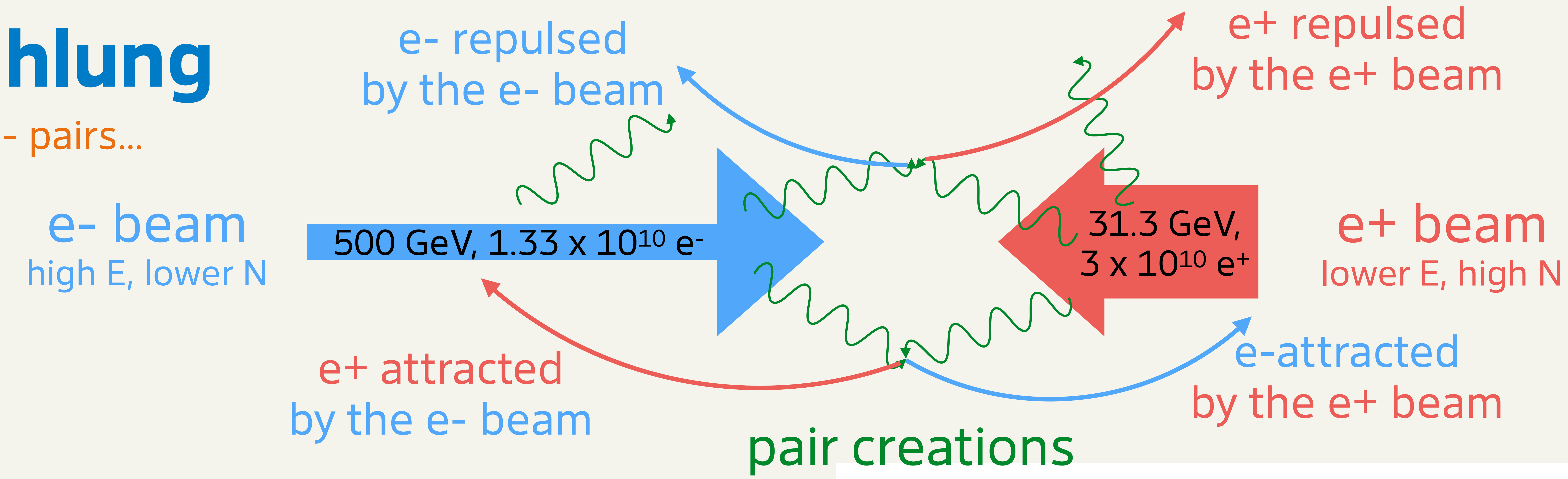

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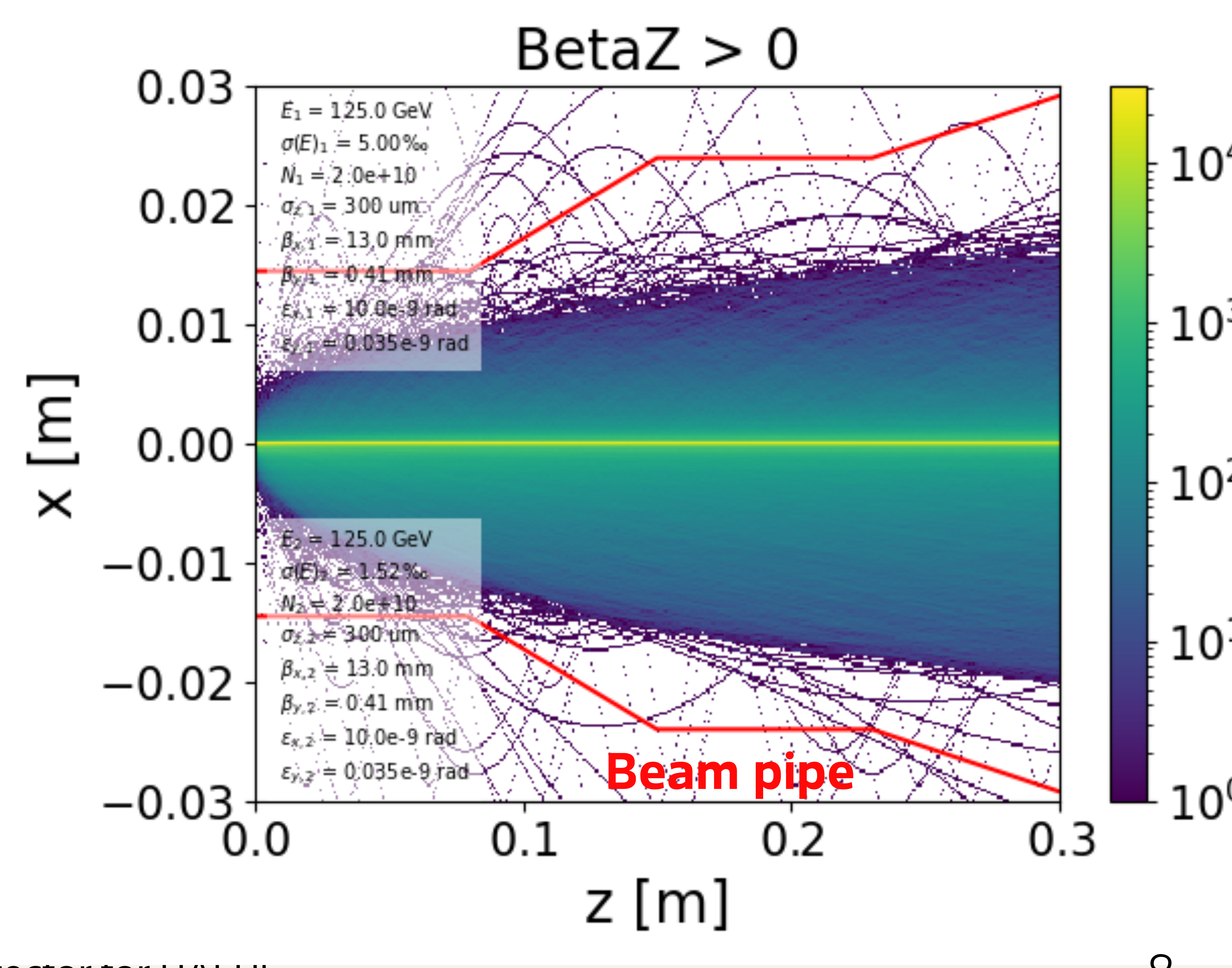

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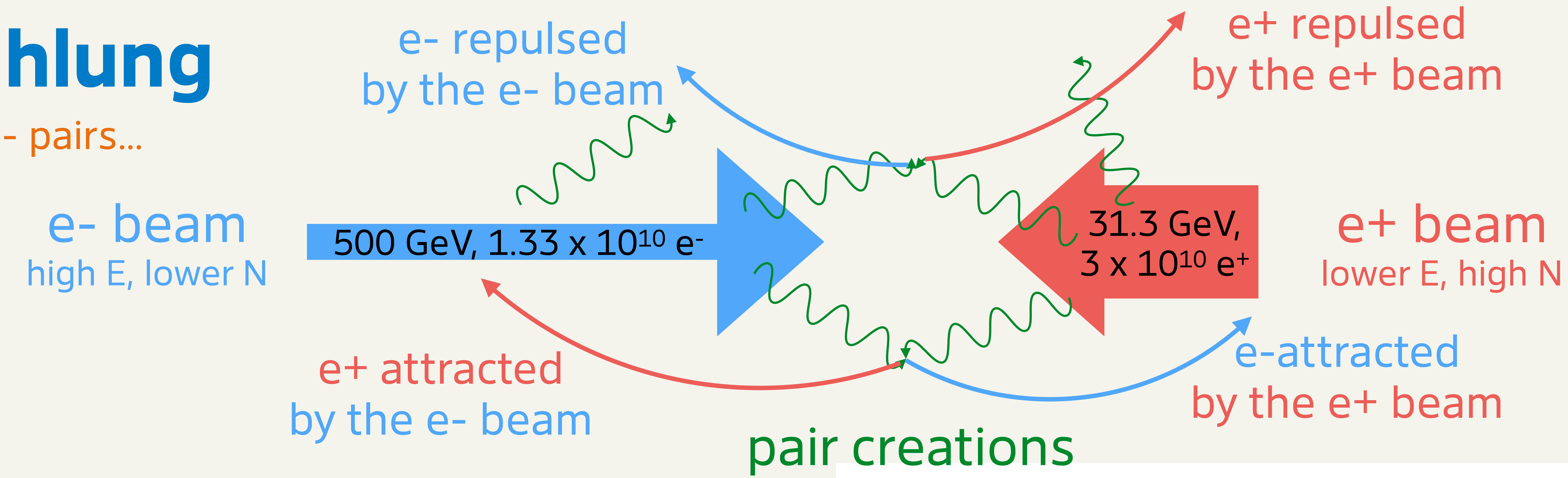

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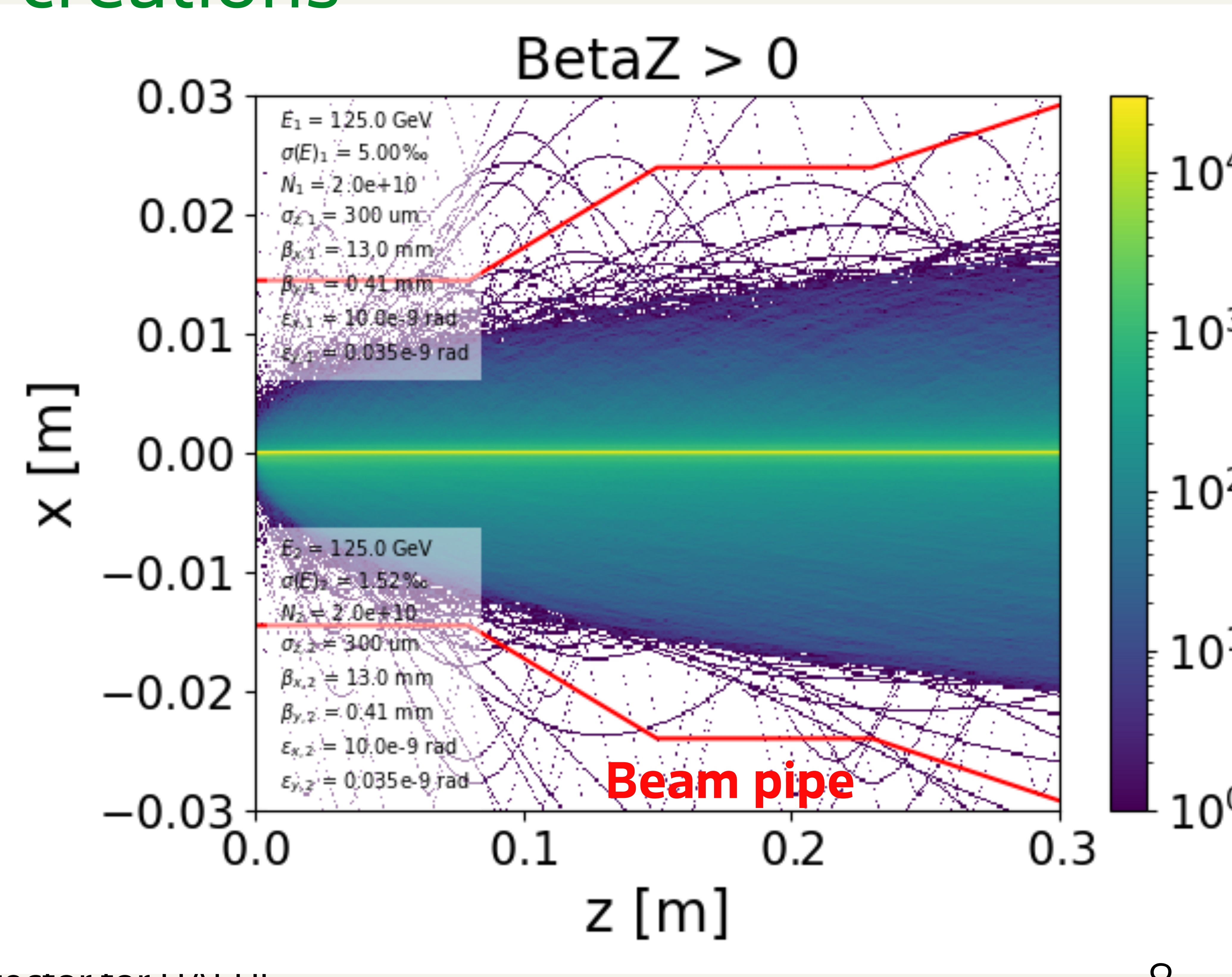
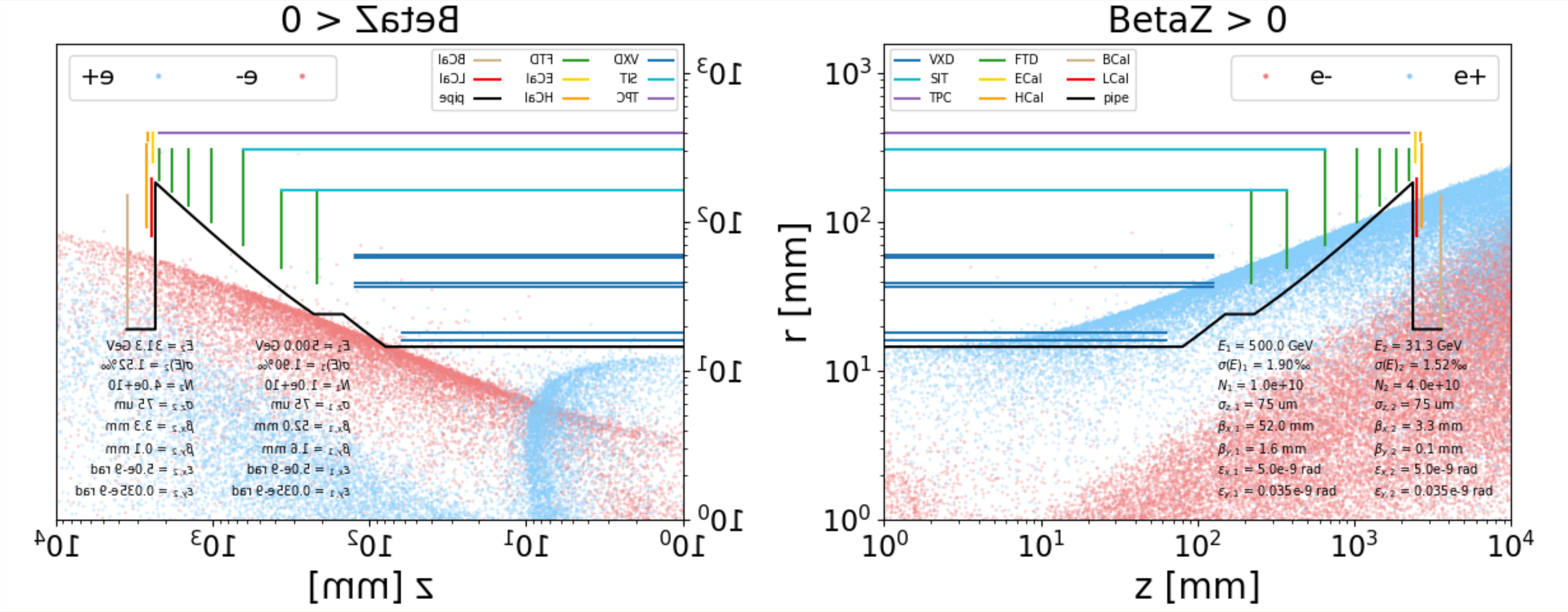
- Next plots: instead of showing the whole trajectory, show the spatial distribution of the apex of the trajectory.



Beam-strahlung: impact of beam charge

- Energy = 500 : 31.3 GeV
- charge = 1 : 4 x 10^{10} particles*
- σ_z = 75 : 75 μm

Baseline HALHF, ILD detector model



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Detector model: ILC

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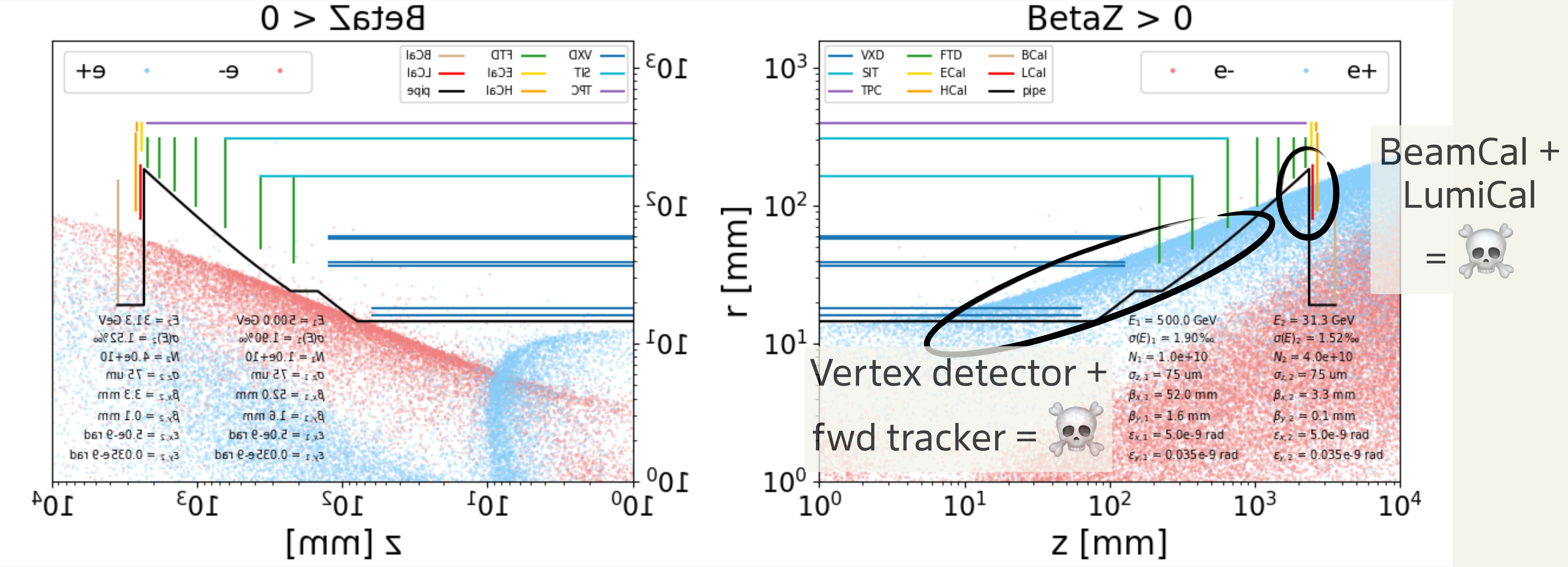

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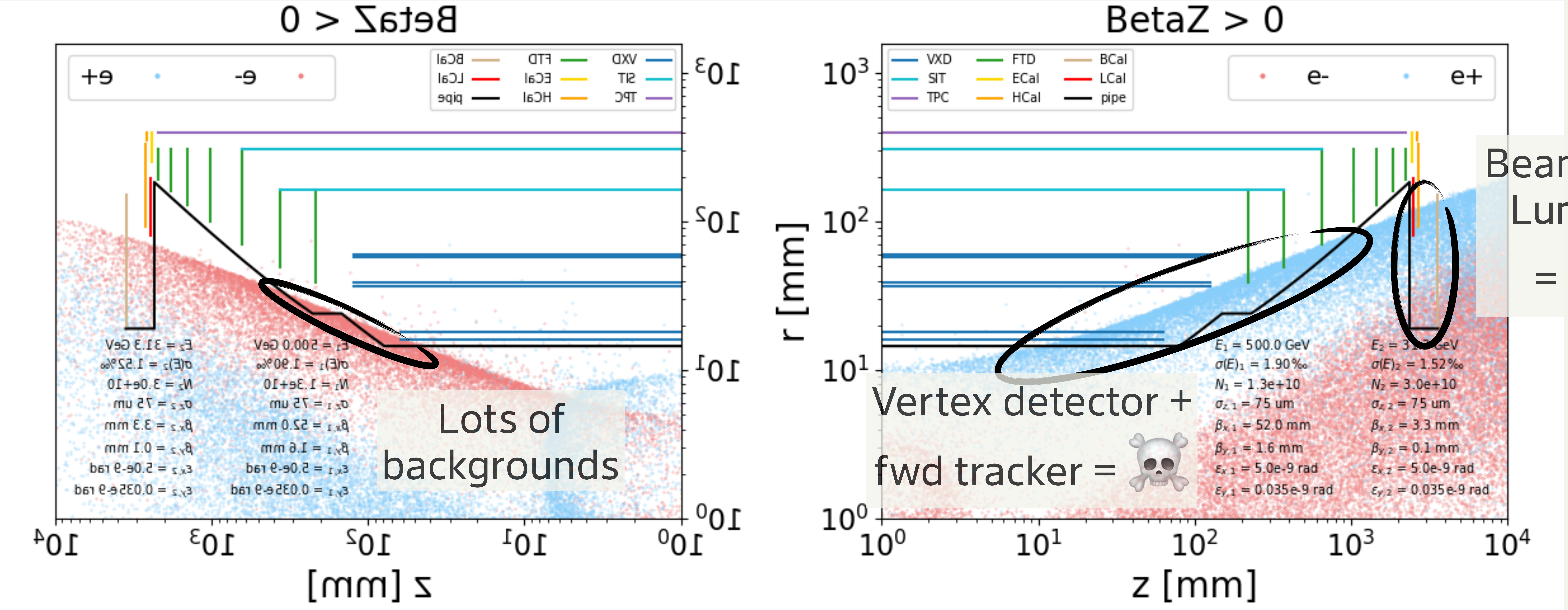
Detector model: ILC

Beam-strahlung: finding a suitable config…

- Energy = 500 : 31.3 GeV
- charge = **1.33 : 3** x 10^{10} particles
- σ_z = 75 : 75 µm HALHF:

=> Reduce the charge asymmetry:
a bit better forward, a bit worse backward.

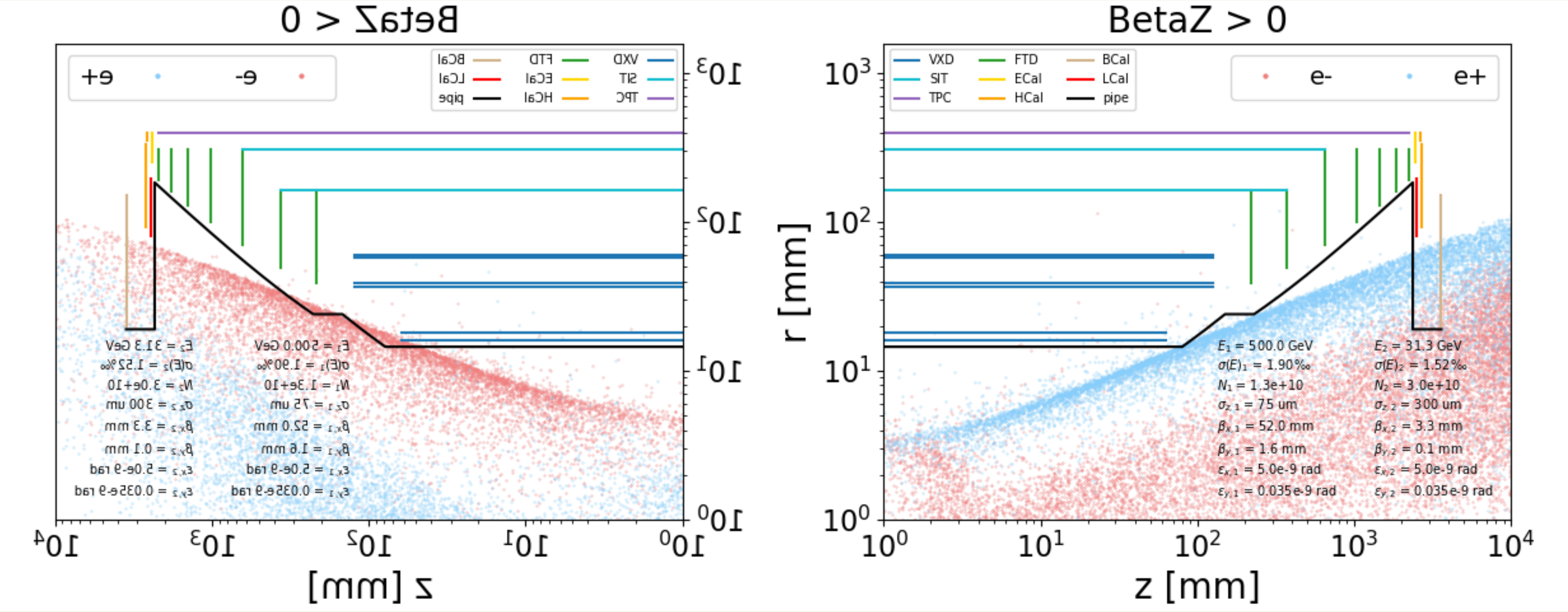


Detector model: ILC

Beam-strahlung: finding a suitable config…

- Energy = 500 : 31.3 GeV
- charge = 1.33 : 3 x 10^{10} particles
- σ_z = **75 : 300 µm**

Increase bunch length, almost there.
Other ideas?



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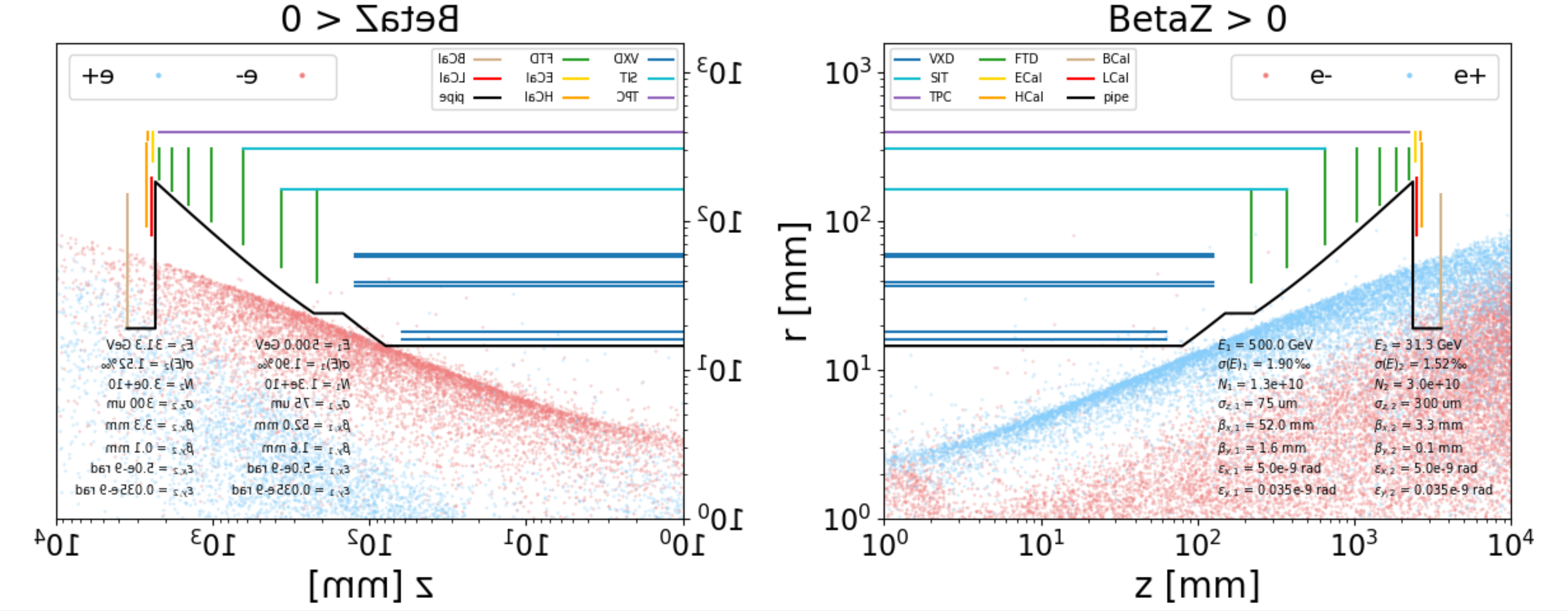
Detector model: ILC…
with **5 T magnetic field**

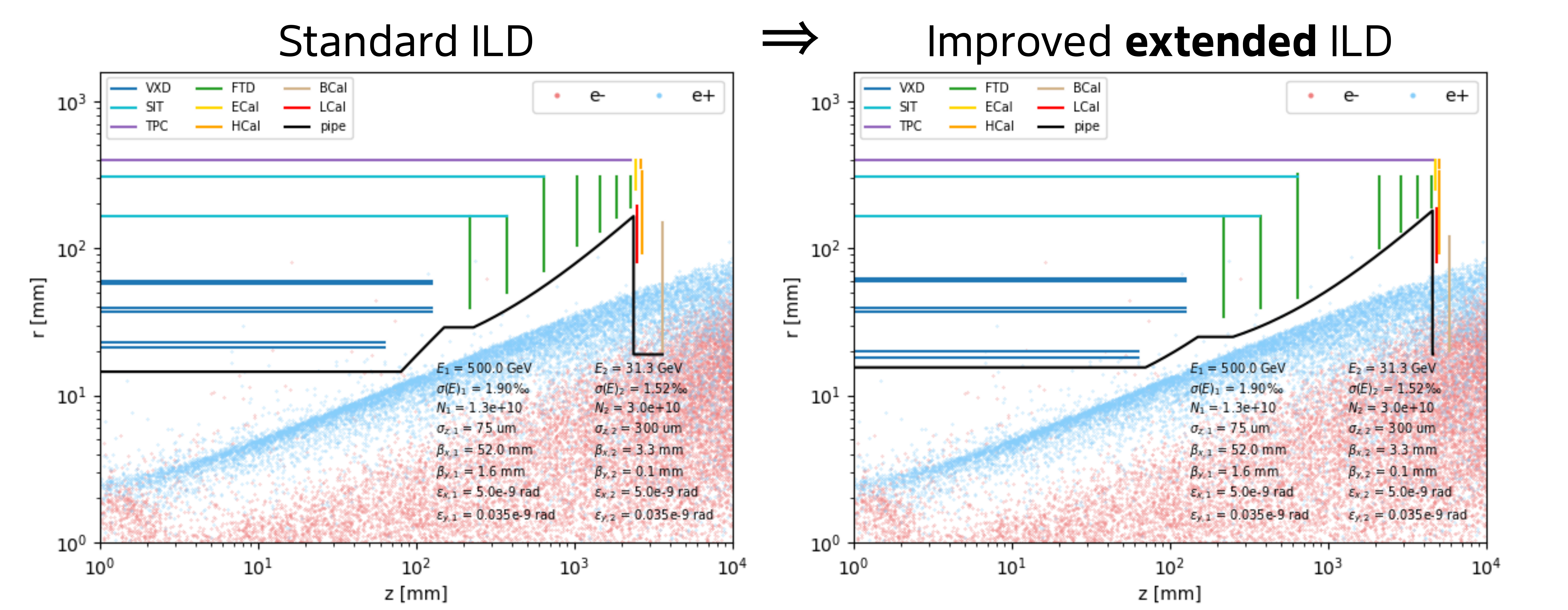
=> **looks OK** !



Detector model: ILC

Beam-strahlung: optimising the detector config

- Minimum clearance between beam pipe and backgrounds = 5 mm.
- TPC length doubled: 2350 mm → 4700 mm.
- FTD positions rescaled accordingly.
- VXD extended as much as possible without hitting the beam pipe.



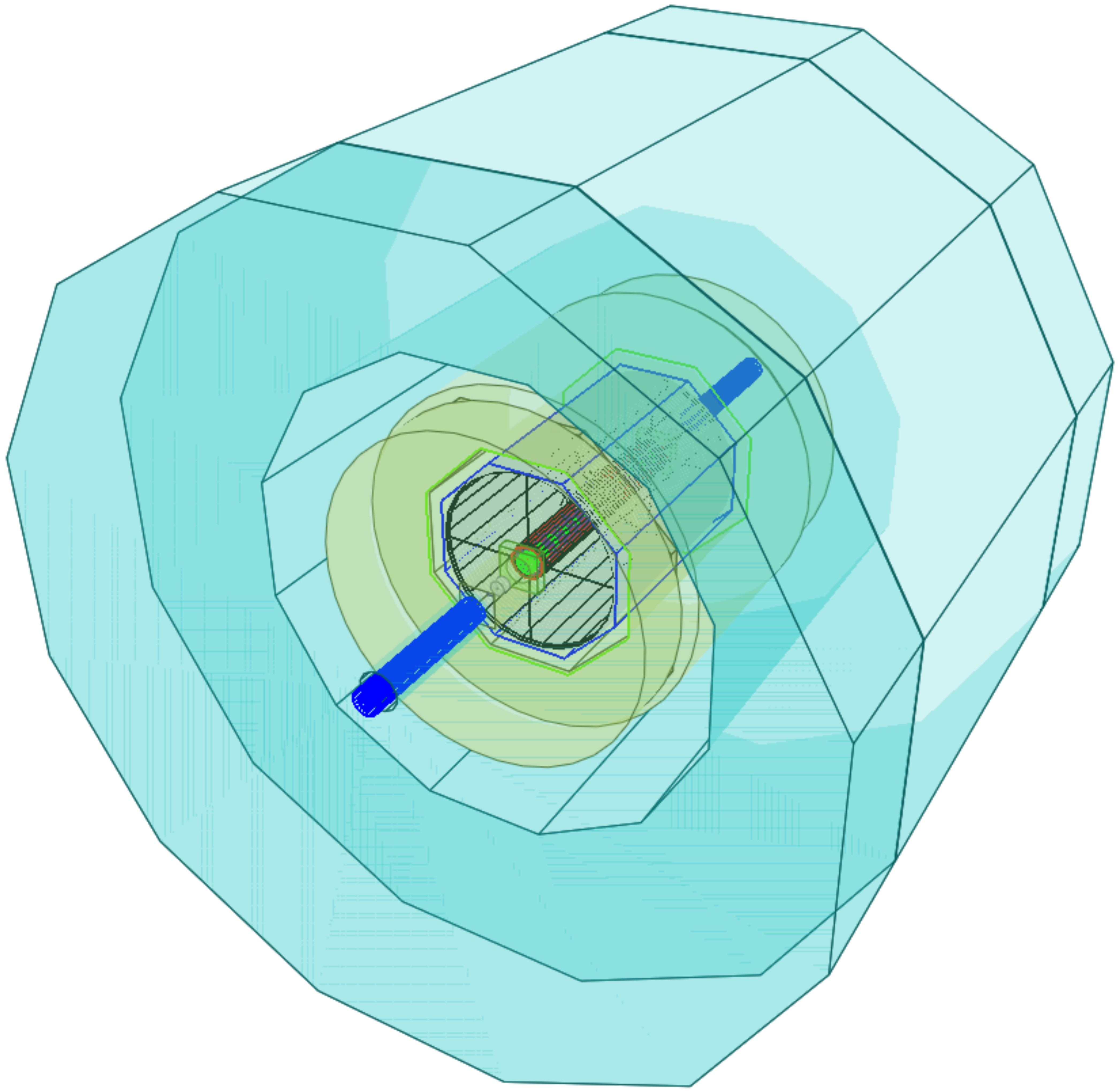
Towards a Geant4 implementation

- **Why is it needed**?
  - **Additional magnetic field** in the forward direction (for example additional dipole) **could help muon momentum resolution**.
  - SGV only allows for simple solenoidal magnetic field…

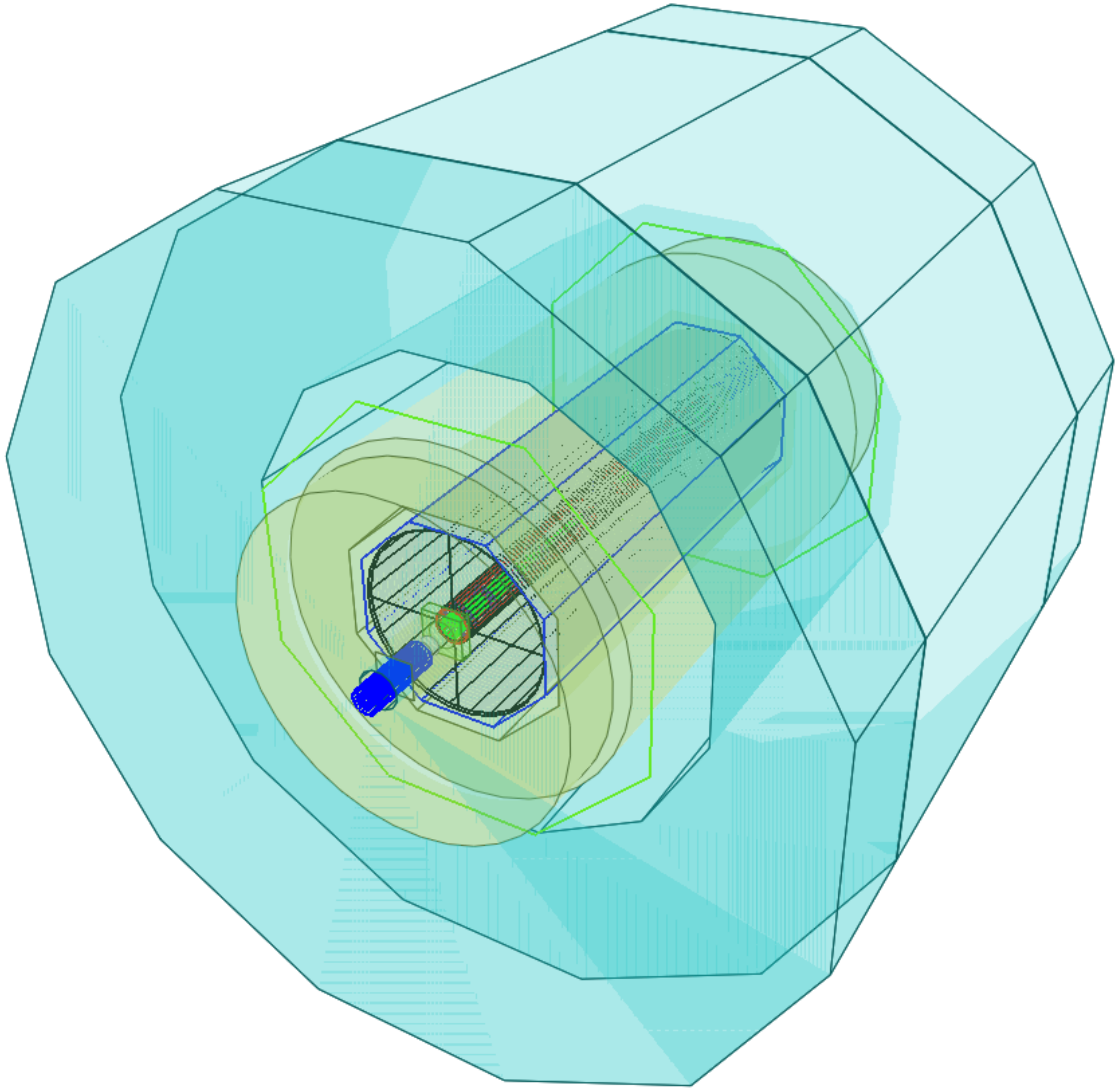
- => Modify G4 ILD detector model with the previous modifications.
  - ILD geometry implementation does not easily allow for asymmetric detectors.
  - => use the symmetric extended detector and focus on the forward region.

Towards a Geant4 implementation

Standard ILD



Improved e-ILD



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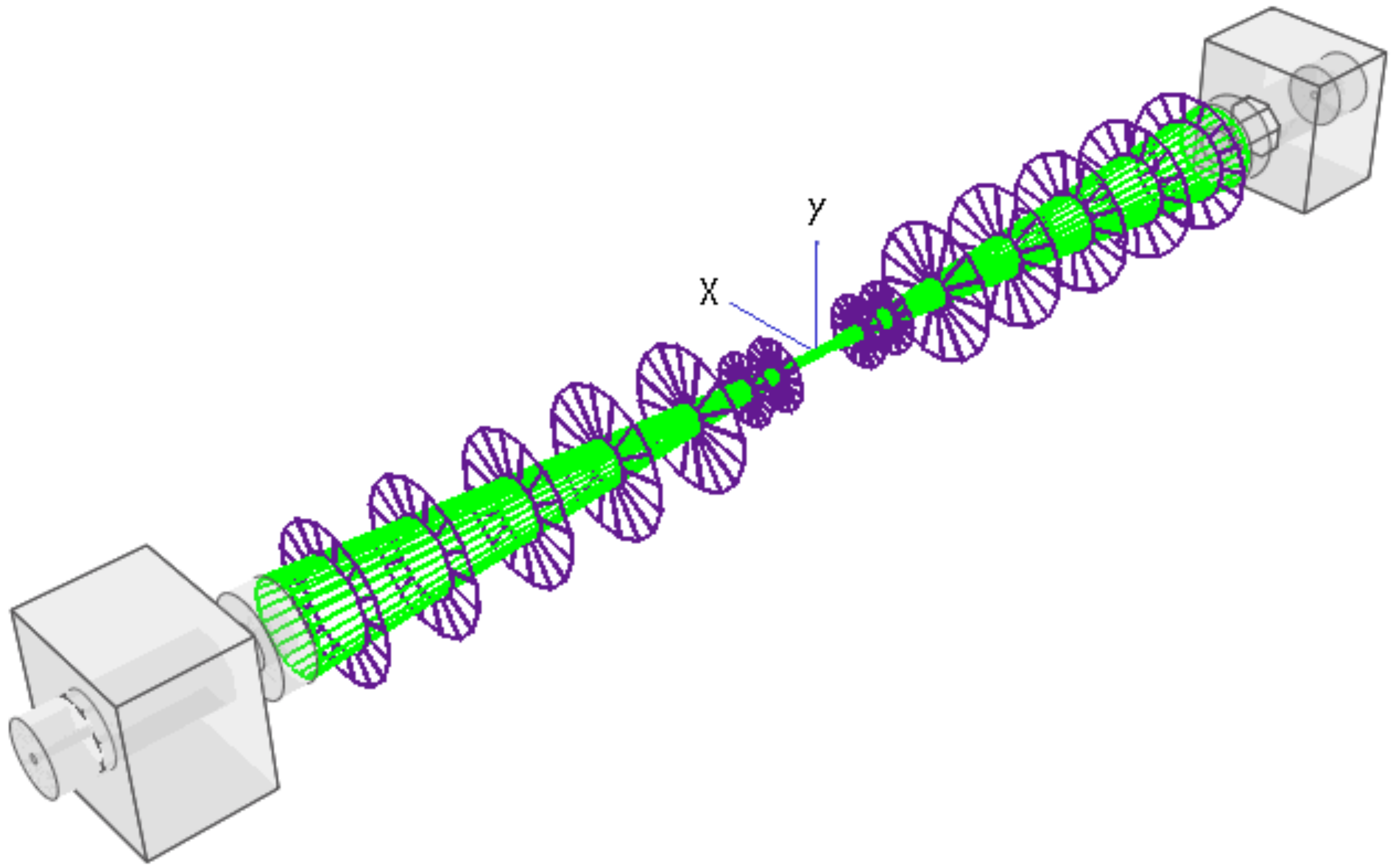

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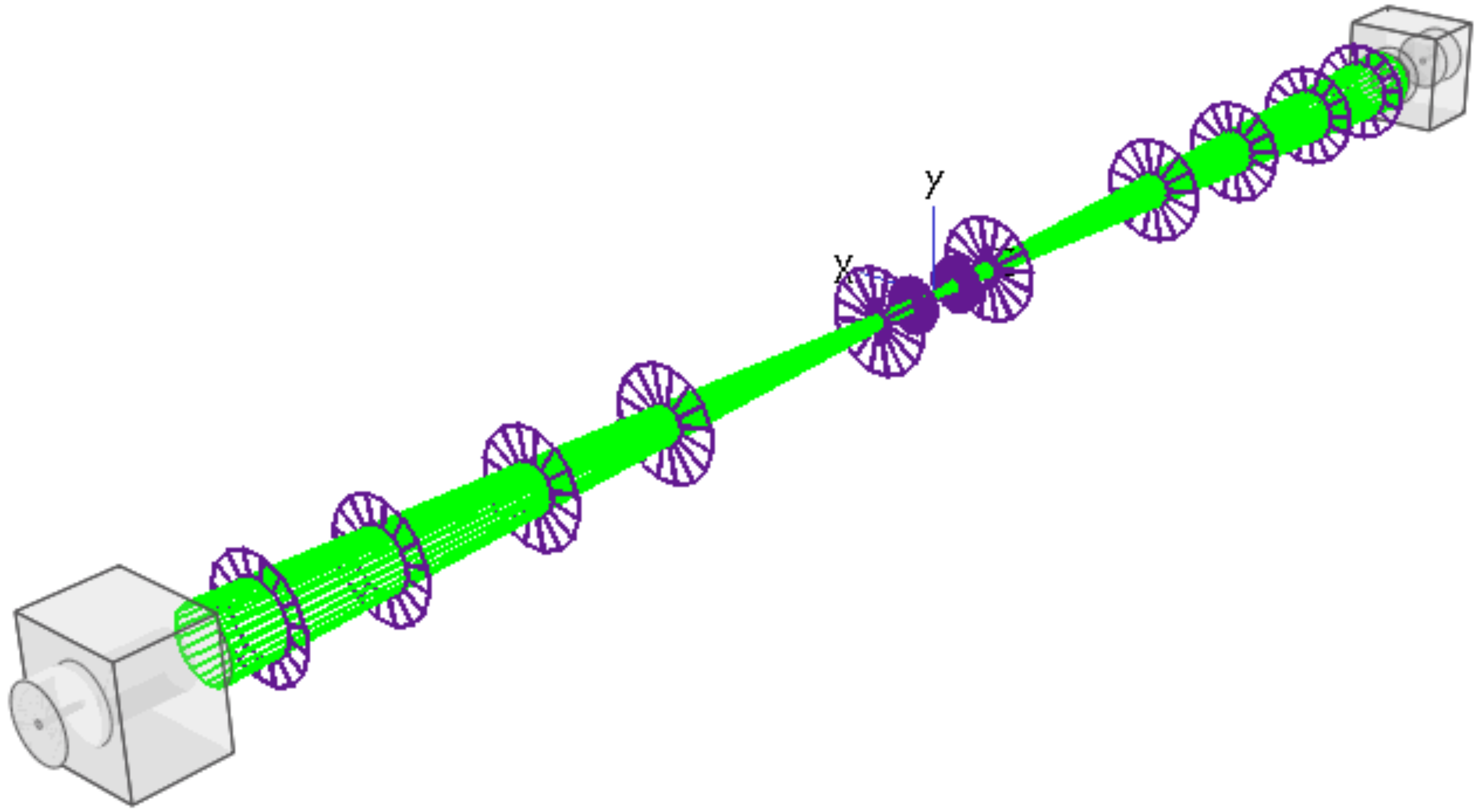
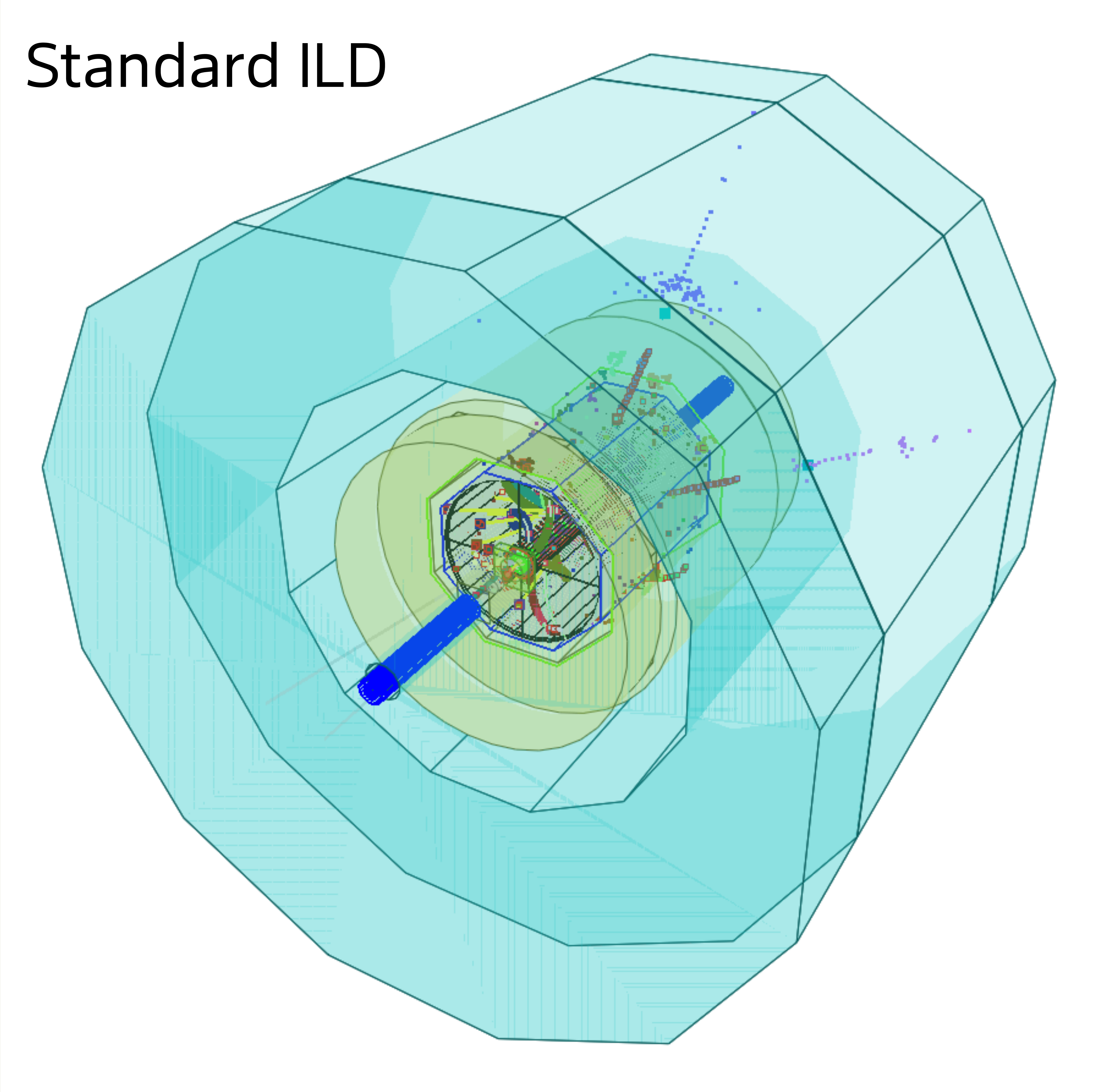
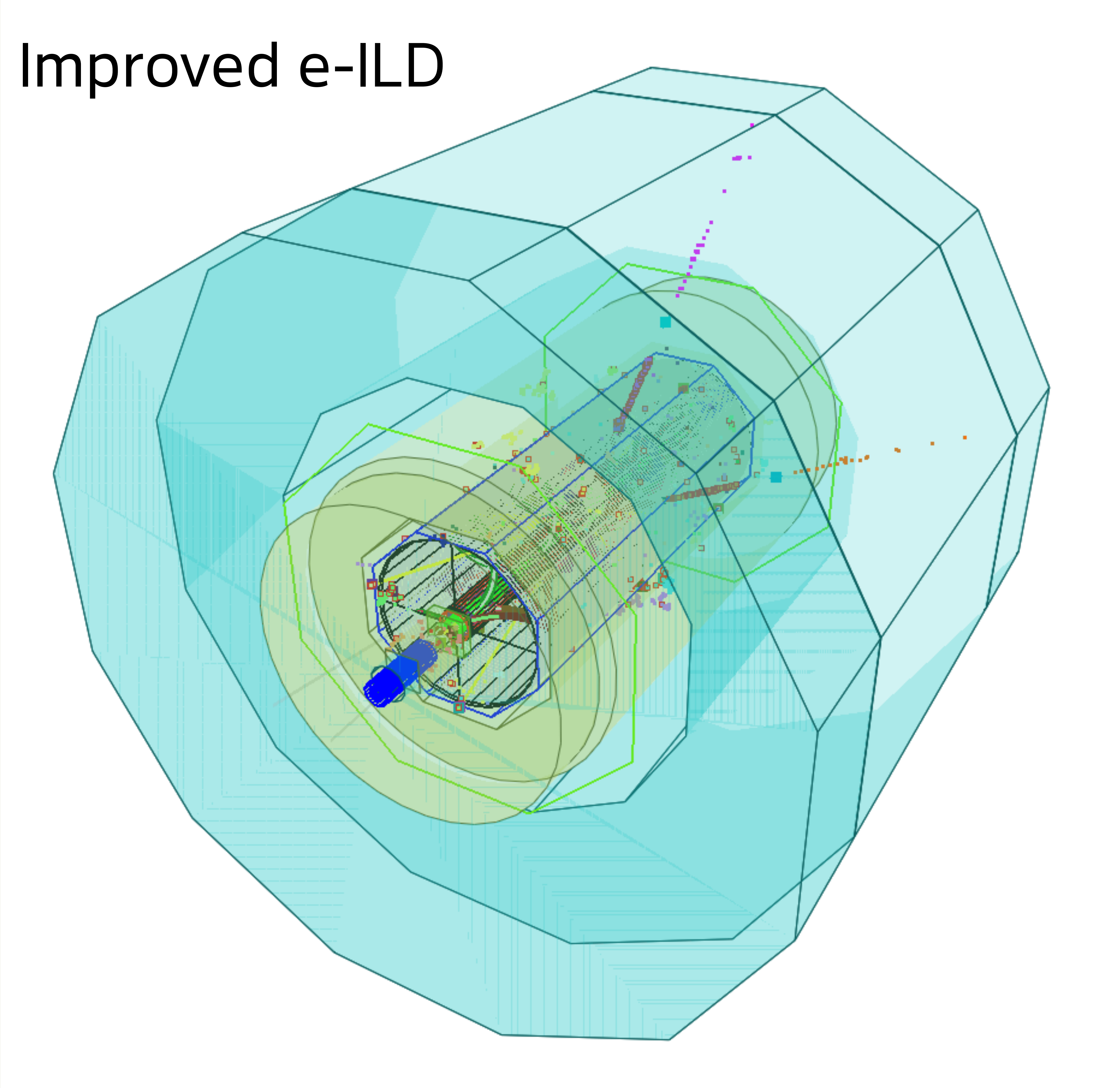


Towards a Geant4 implementation

Single (non-boosted) Z(μμ)H event





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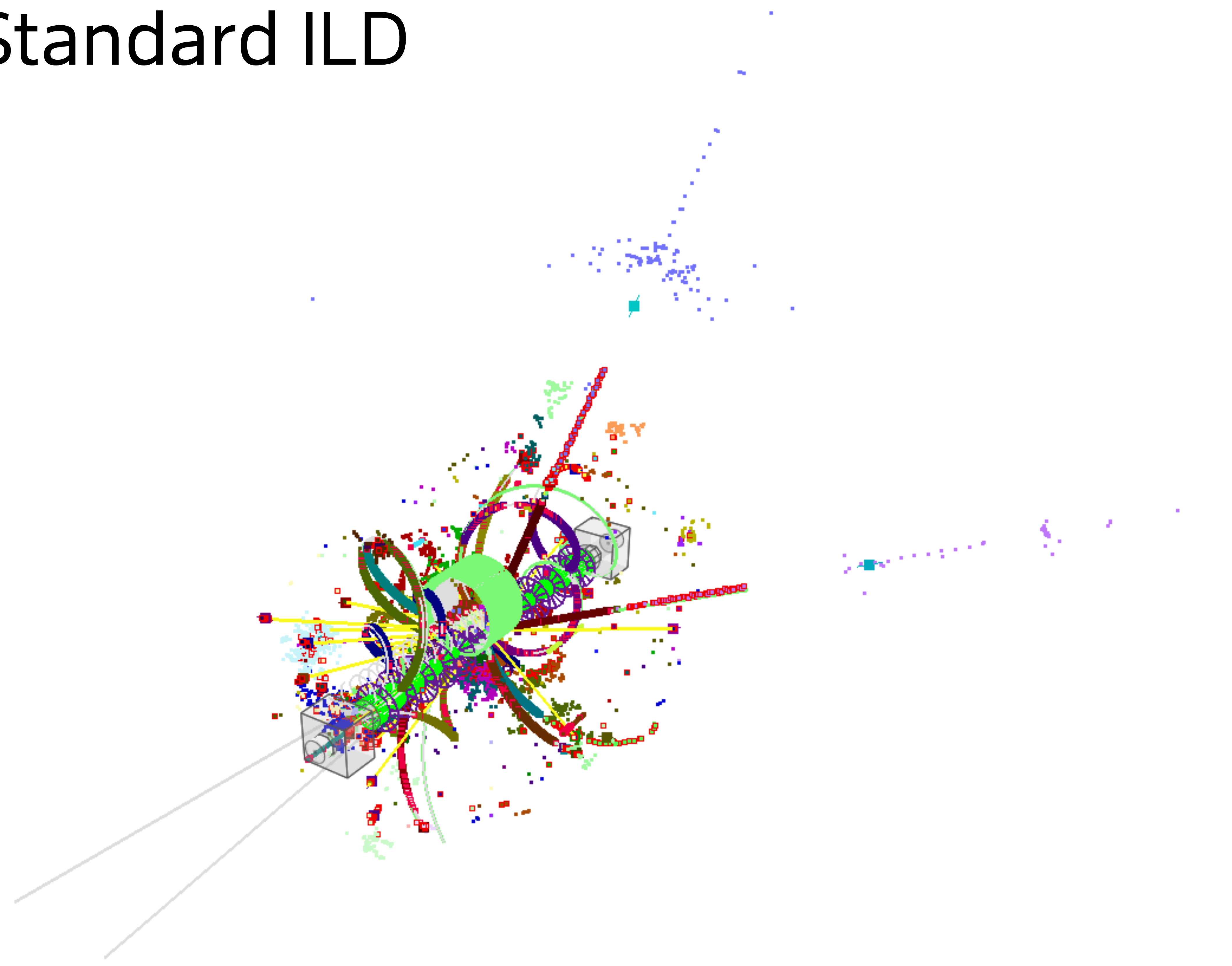

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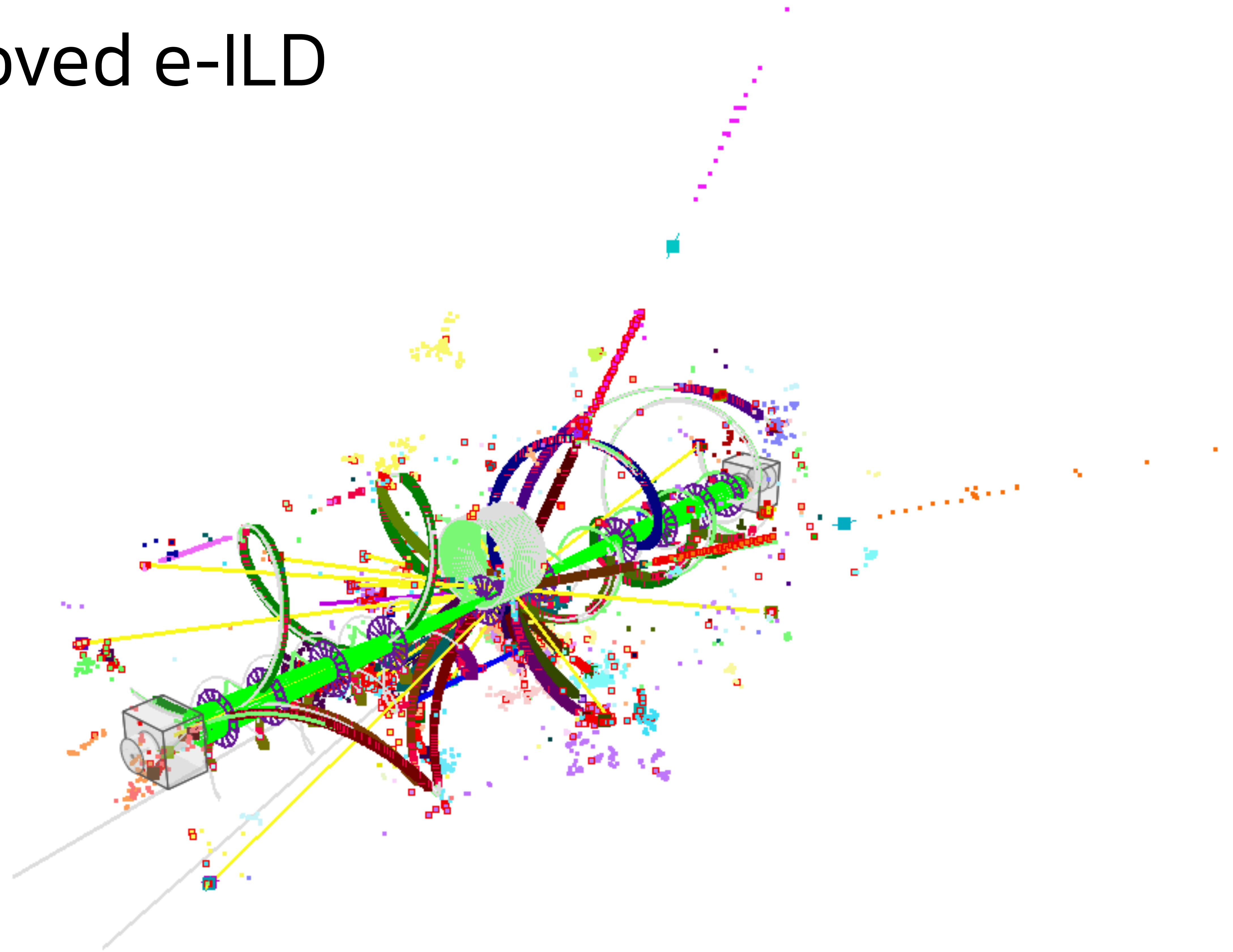


Conclusion: HALHF the size, twice the fun!

- **Beam backgrounds constrain the available space for the detector**.
  - Fixed a set of beam parameters (1.3:3 x 10^{10} e/bunch, 75:300 μm bunch length).
  - Enables more detailed detector design (esp. forward region, B field to come)

- **Large MC samples from ILC available** for SGV and G4.
- **SGV** ("fast-sim" ILD) can now **include asymmetric detectors**.
  - Impact of boost on luminosity measurement (Bhabha's / ee → γγ)
  - Impact of boost on flavour tagging.
- **Improved geometry implemented in Geant4** (as modification of ILD).
  - Will allow playing with magnetic field configuration.

Very limited person-power, contributors welcome!

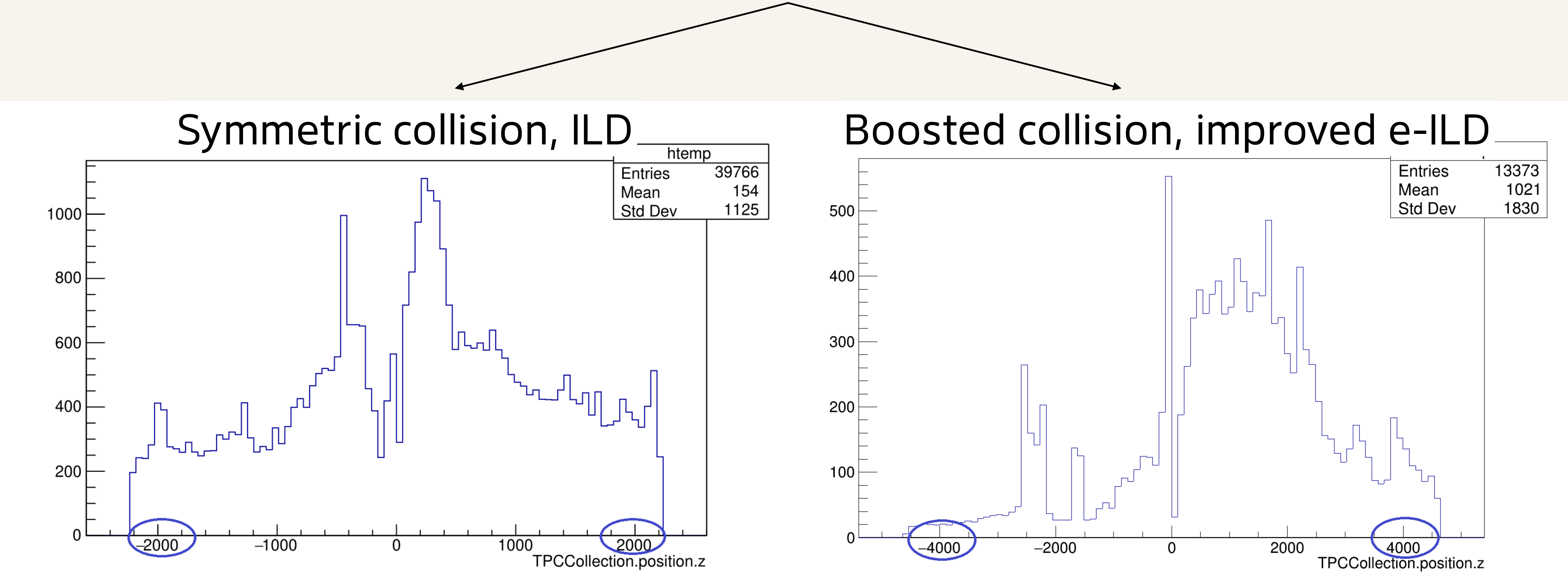
- There will be a HALHF contribution to the EPPSU (will be finalised at next HALHF workshop, end Feb. 2025)!

Thanks for your attention!

Questions?

Improved detector with boosted collisions

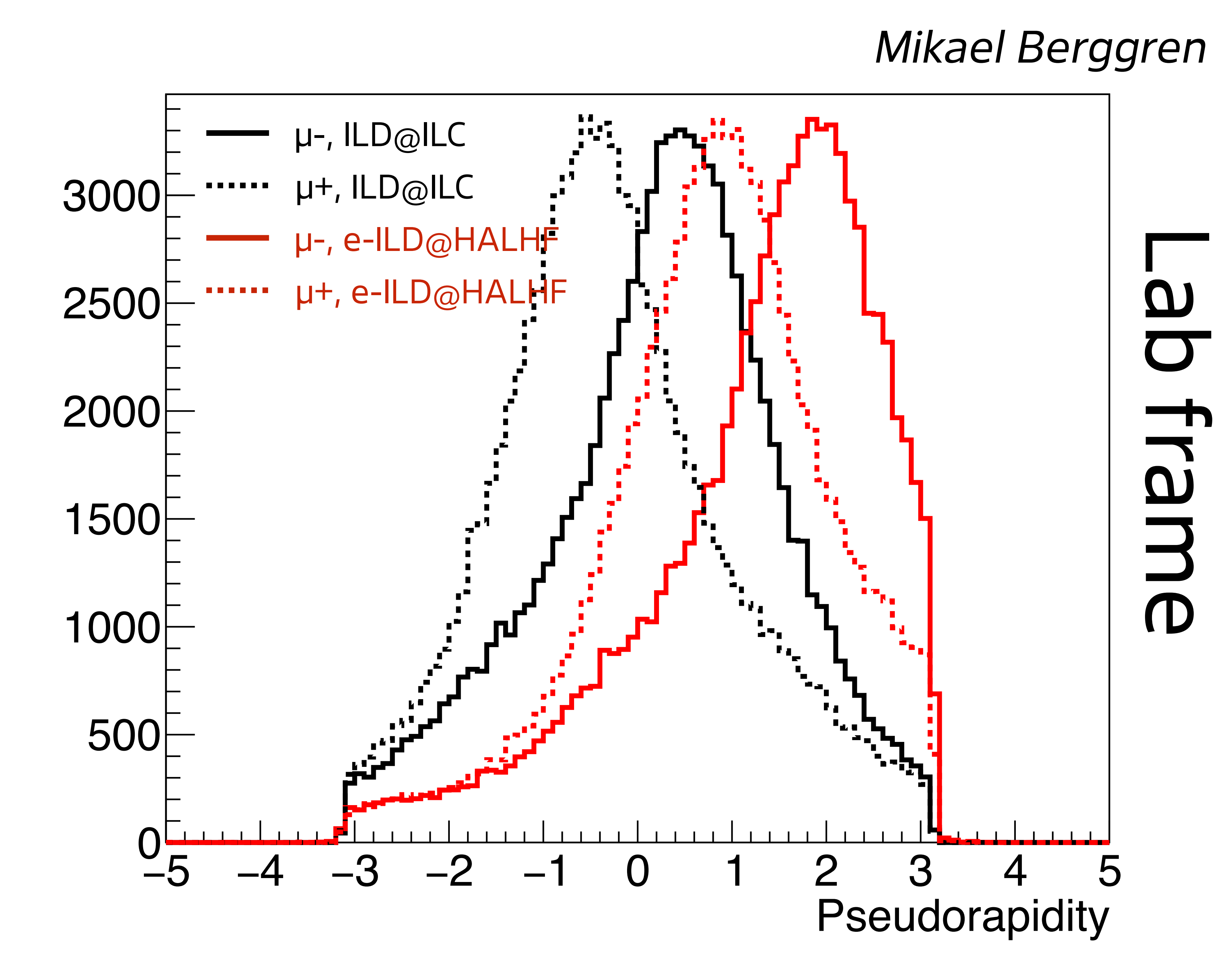
TPC hits distribution (z axis)



- Some events crash the reconstruction, technical issue to be solved.

Impact on physics: F/B asymmetry

- Process: $e^+e^- \to \mu^+\mu^-$
  - **[black] ILD@ILC**
  - **[red] extended ILD @ HALHF**



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- Process: $e^+e^- \rightarrow \mu^+\mu^-$
  - **[black] ILD@ILC**
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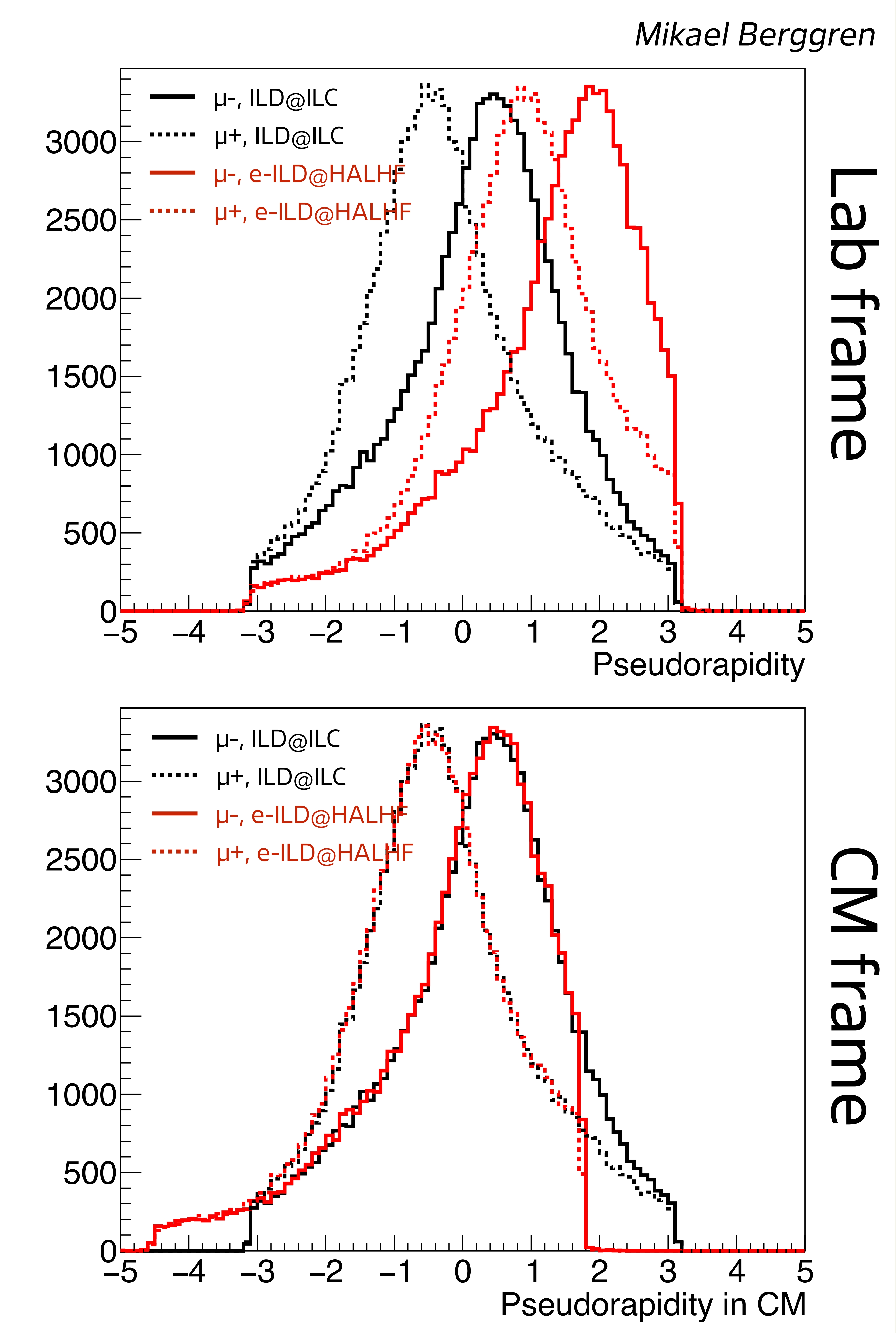
- Move to the CM frame to ease the comparison:
  - Core of distribution is the same (as expected)
    - => in particular: same width
  - **Tail extends on one side and is cut on the other**.
- Lose on one side, but gain on the other.
- => **Need more studies, especially for systematic uncertainties** (since setup itself is asymmetric).



Beam-strahlung: impact on luminosity

- **Luminosity computed by Guinea-Pig**:
  - Total luminosity
  - Luminosity considering only events within 1% of the nominal CM energy ("peak lumi").

- **Using bunch charge N = 1.33:3 x 10^{10} with σ_z = 75:300 µm**:
  - **reduces beam backgrounds to acceptable levels**…
  - … while **only reducing peak lumi by 35% compared to ILC design**.

Lumi [μb / bunch]	ILD TDR	HALHF N = 2 : 2 x 10^{10} σ_z = 75 : 75 μm	HALHF N = 1.33 : 3 x 10^{10} σ_z = 75 : 300 μm
Total lumi	1.12	1.35	0.80
Lumi within 1% of nominal CM energy	0.92	0.80	0.56
Beam backgrounds?		large	mitigated

Impact of beam parameters on luminosity

The price of solving beam backgrounds…

- All points: $E_- = 500$ GeV, $E_+ = 31.3$ GeV.
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  - Total luminosity
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