Physics performance and detector requirements at an Asymmetric Higgs Factory

Antoine Laudrain (he/him)

& Ties Behnke, Mikael Berggren, Karsten Büsser, Frank Gaede, Christophe Grojean, Benno List, Jenny List, Jürgen Reuter, Christian Schwanenberger

ICHEP 2024, Prague

Session: Detectors for Future Facilities, R&D, Novel Techniques — 20.07.2024

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

HELMHOLTZ

antoine.laudrain@desy.de

Future lepton colliders landscape

Circular

- High lumi at "low" energy (Z/H)
- Upgradable to hadron collider

Linear

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

Future lepton colliders landscape

Circular

- High lumi at "low" energy (Z/H)
- Upgradable to hadron collider

Linear

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

All big and expensive machines.
Large CO2 footprint.

How to reduce the cost?

"Simply" decrease the size of the tunnel…

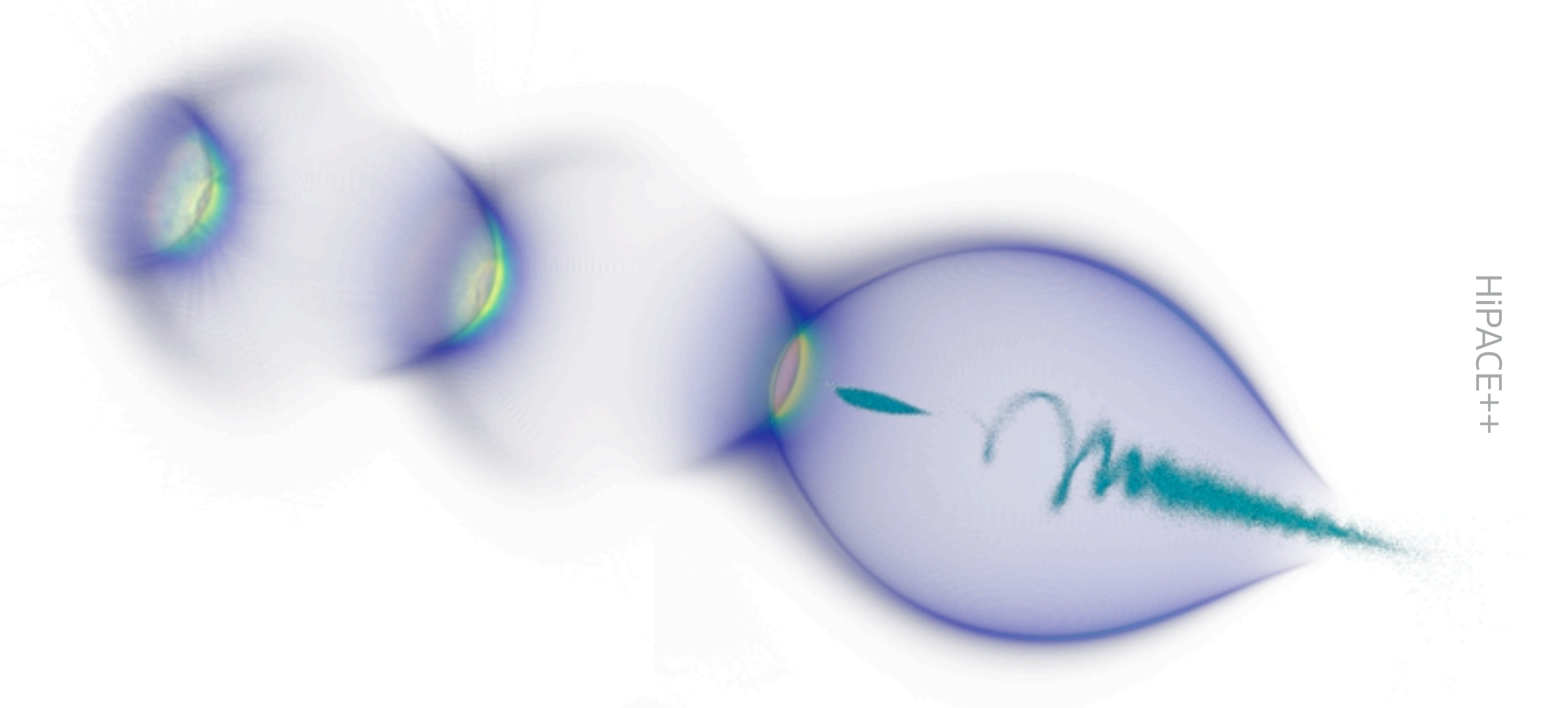
- But shorter tunnel = lower beam energy => 😭

HiPACE++

How to reduce the cost?

"Simply" decrease the size of the tunnel...

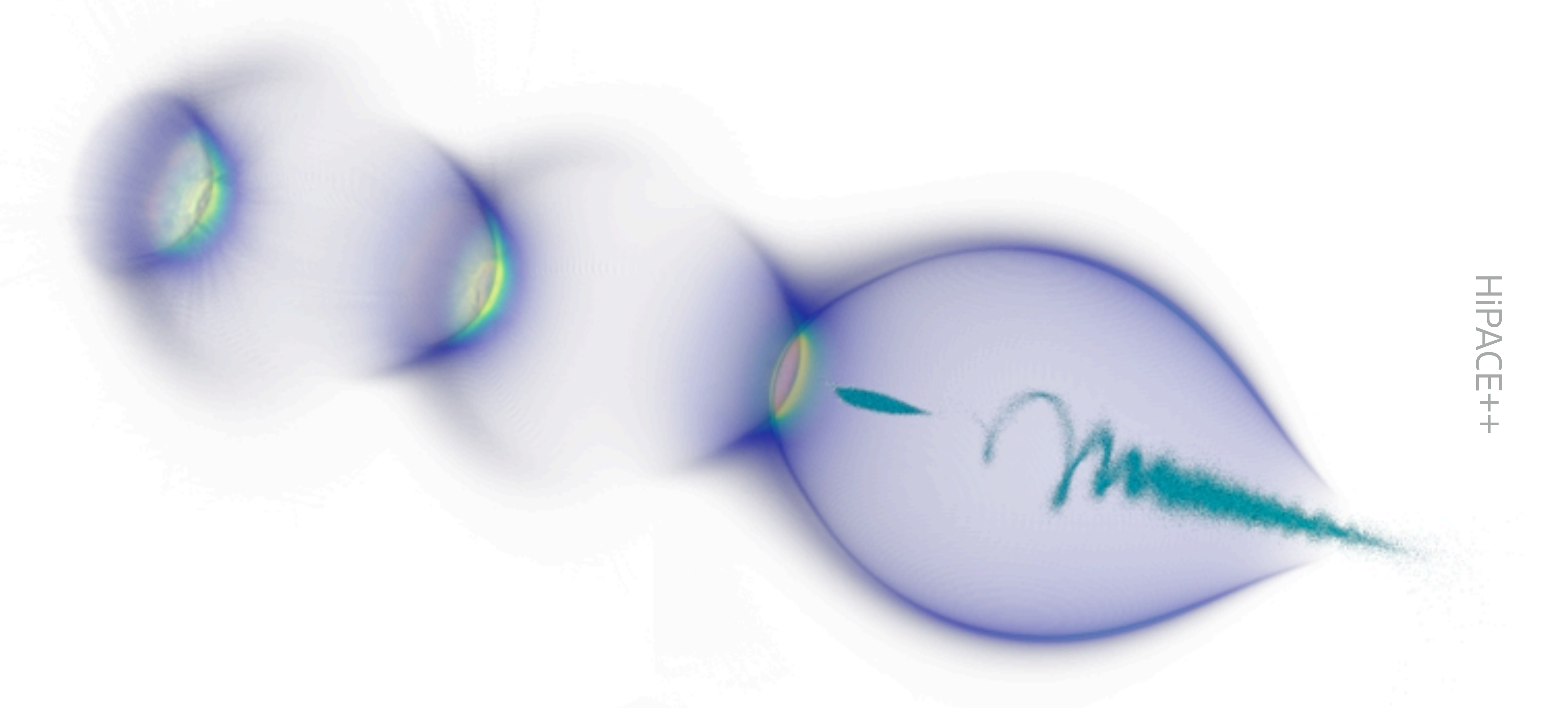
- But shorter tunnel = lower beam energy => 😭
- Except if you can get higher gradients!
  - RF: ~30 MV/m (ILC)
  - **Plasma wake field acceleration** (PWFA) cavities: ~ expected O(1000 MV/m) — ie x30!



How to reduce the cost?

"Simply" decrease the size of the tunnel…

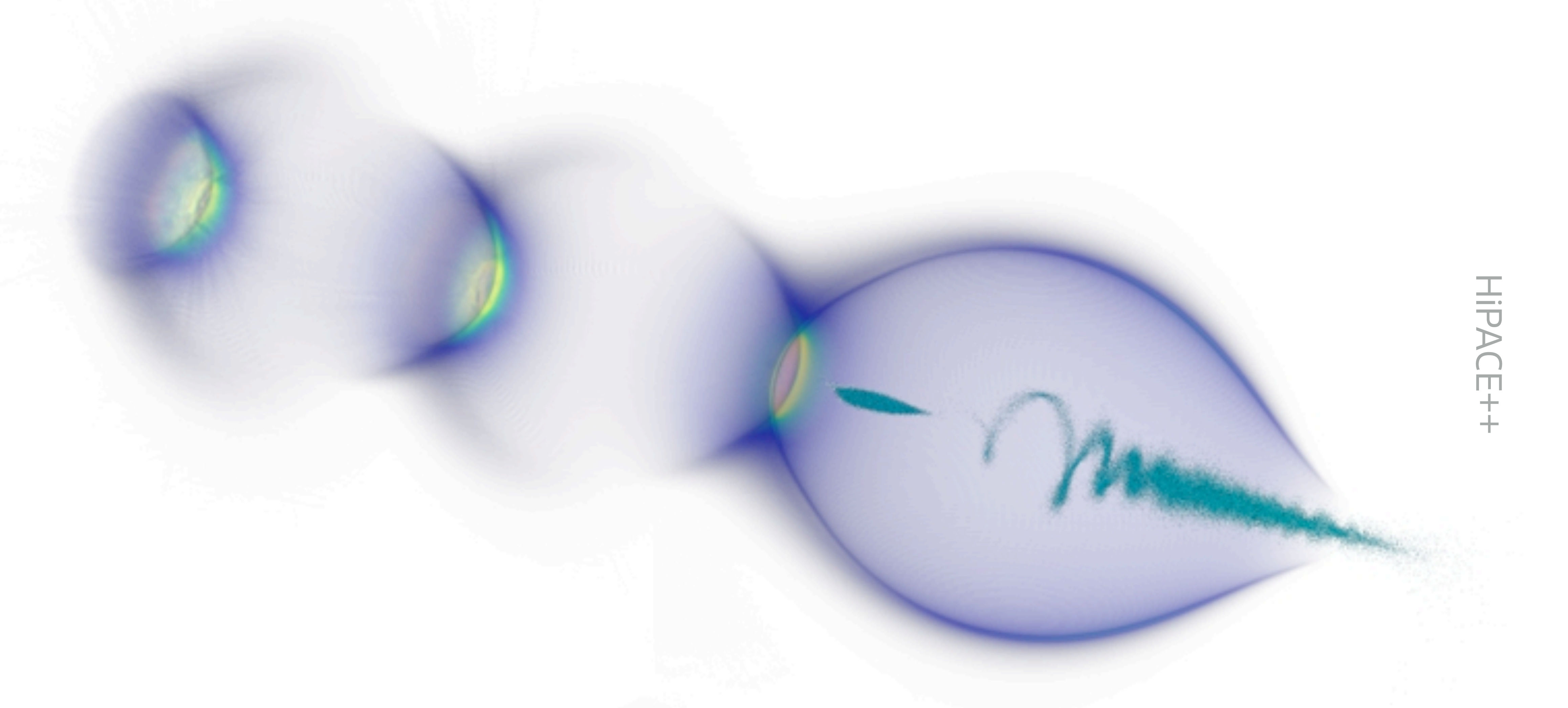
- But shorter tunnel = lower beam energy => 😭
- Except if you can get higher gradients!
  - RF: ~30 MV/m (ILC)
  - **Plasma wake field acceleration** (PWFA) cavities: ~ expected O(1000 MV/m) — ie x30!



- PWFA not yet available:
  - **Requires ~10 years of development**.
  - **Only for electron acceleration**.

How to reduce the cost?

"Simply" decrease the size of the tunnel…



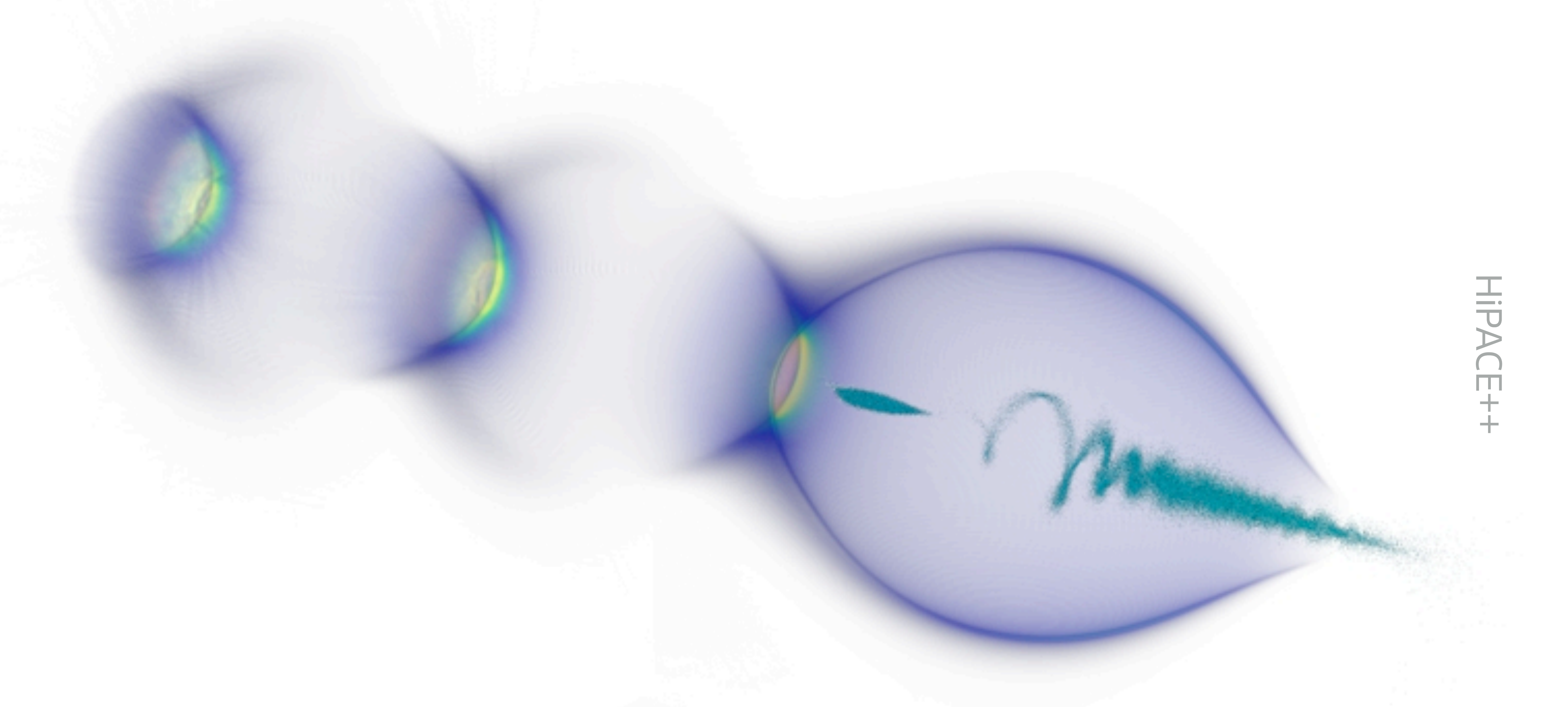
- But shorter tunnel = lower beam energy => 😭
- Except if you can get higher gradients!
  - RF: ~30 MV/m (ILC)
  - **Plasma wake field acceleration** (PWFA) cavities: ~ expected O(1000 MV/m) — ie x30!

- PWFA not yet available:
  - **Requires ~10 years of development**.
  - **Only for electron acceleration**.

- => Size of the facility could be reduced by a factor ~2 (on the electron side):
  - ILC(250 GeV): 10 km (e-, SRF) + 10 km (e+, SRF)
  - Hybrid: <1 km (e-, PWFA) + 10 km (e+, SRF)

How to reduce the cost?

"Simply" decrease the size of the tunnel…



- But shorter tunnel = lower beam energy => 😭
- Except if you can get higher gradients!
  - RF: ~30 MV/m (ILC)
  - **Plasma wake field acceleration** (PWFA) cavities: ~ expected O(1000 MV/m) — ie x30!

- PWFA not yet available:
  - **Requires ~10 years of development**.
  - **Only for electron acceleration**.

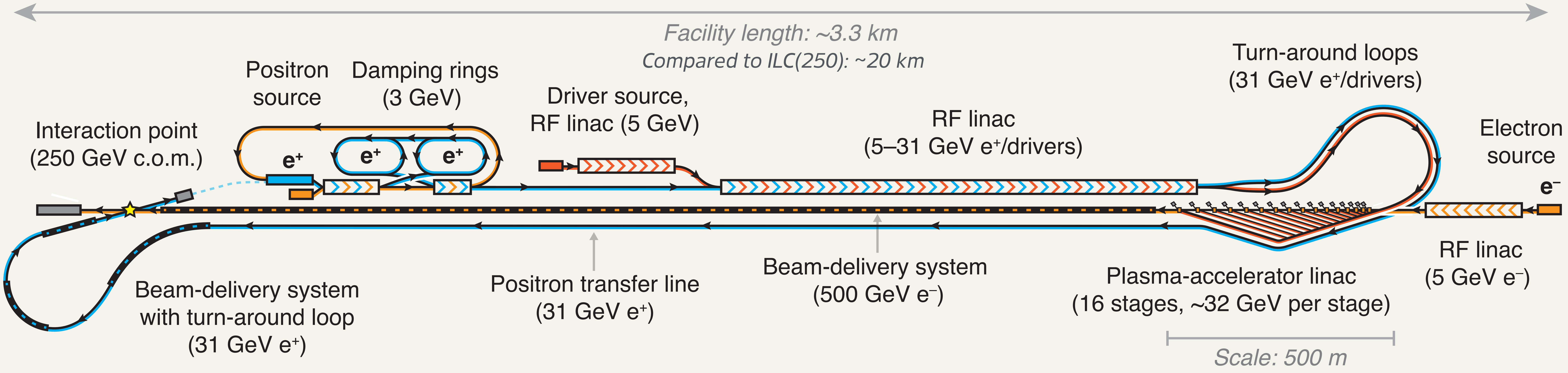
- => Size of the facility could be reduced by a factor ~2 (on the electron side):
  - ILC(250 GeV): 10 km (e-, SRF) + 10 km (e+, SRF)
  - Hybrid: <1 km (e-, PWFA) + 10 km (e+, SRF)

- **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 $\sqrt{s}$ = 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 a specialist of PWFA.
- Assumptions for the rest of this talk:
  - Electron-beam driven PWFA is proven **working for electron acceleration** in ~10-15 years.
  - We can build a collision-quality beam in ~5 more years.
  - PWFA for **positron is still not available**.
- These might be strong assumptions, but we need a **starting point** to think about a detector!
  - => In the following I focus 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!

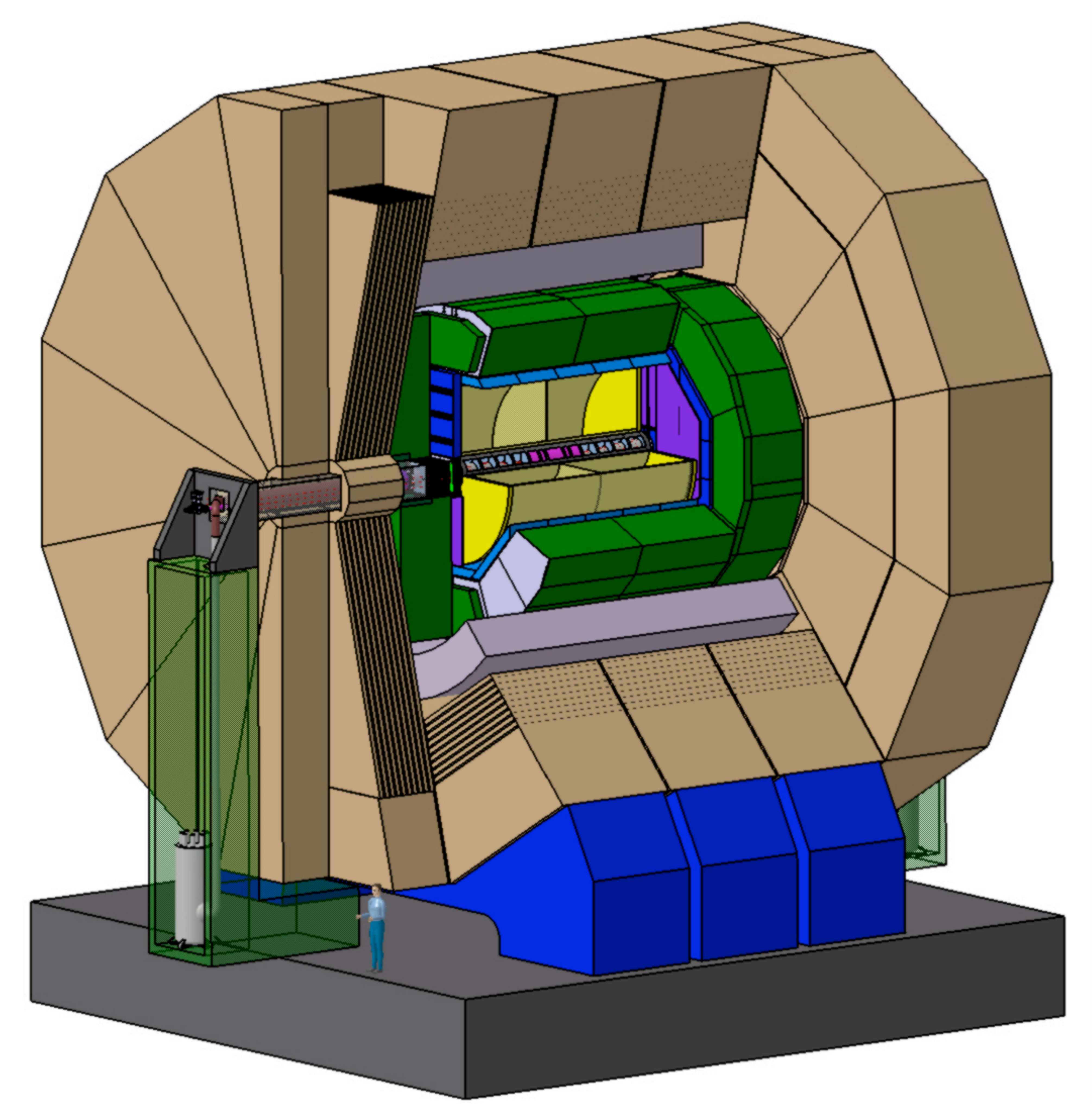
Towards an asymmetric detector

- 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!

- **Study cases**: **Higgs mass** measurement (ZH recoil).

Towards an asymmetric detector

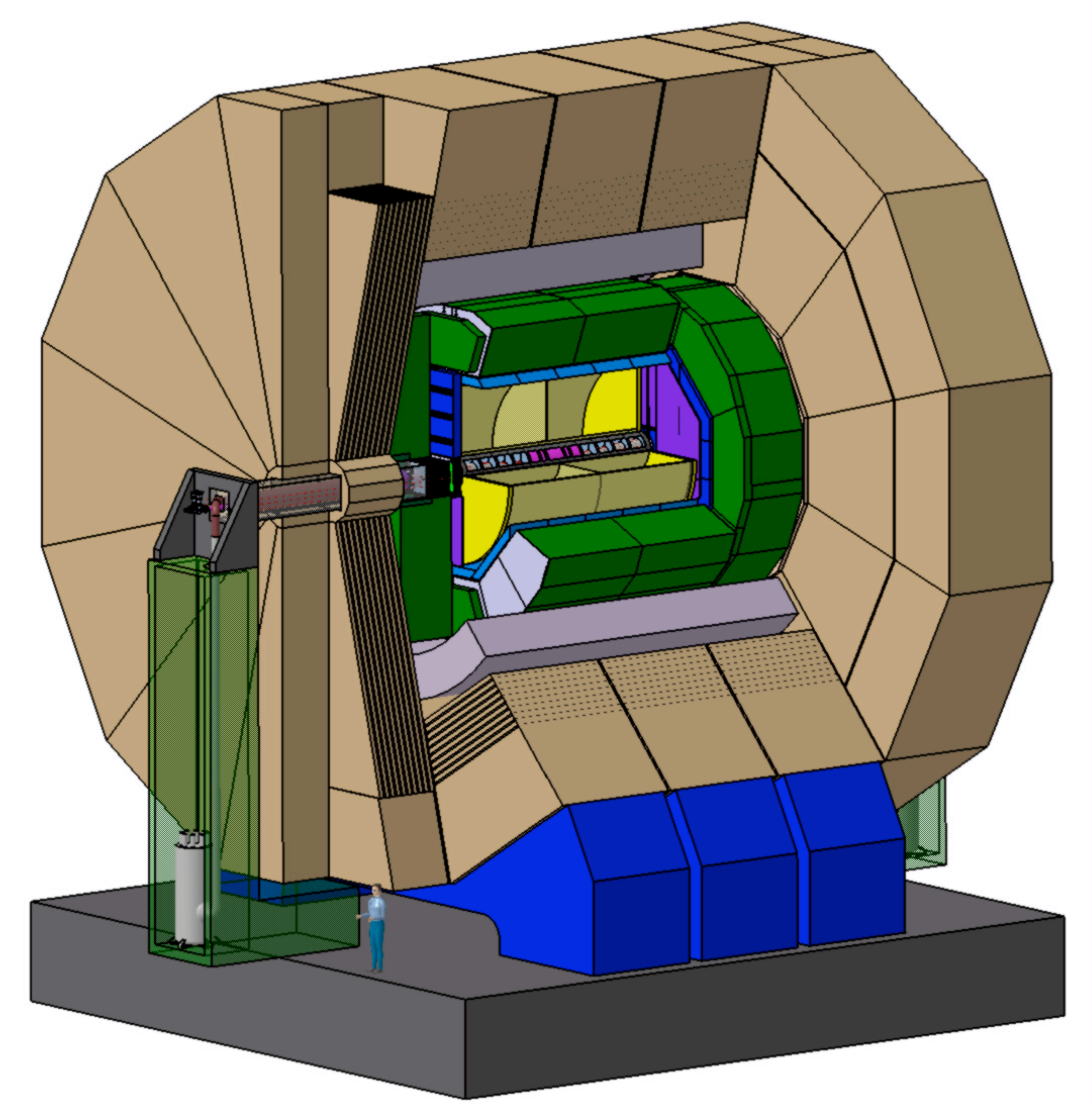
- Baseline: 500 GeV e^- and 31 GeV e^+ => $\gamma \sim 2.1$.
  - **Can we still do Higgs physics in such conditions?**
  - Experience: HERA had $\gamma = 3$…
  - … Yet, it's not quite the same physics!
- **Study cases**: **Higgs mass** measurement (ZH recoil).
- **Most advanced concept is the ILD at the ILC**.
  - Fast simulation available.
  - Good comparison point.



The International Large Detector

Towards an asymmetric detector

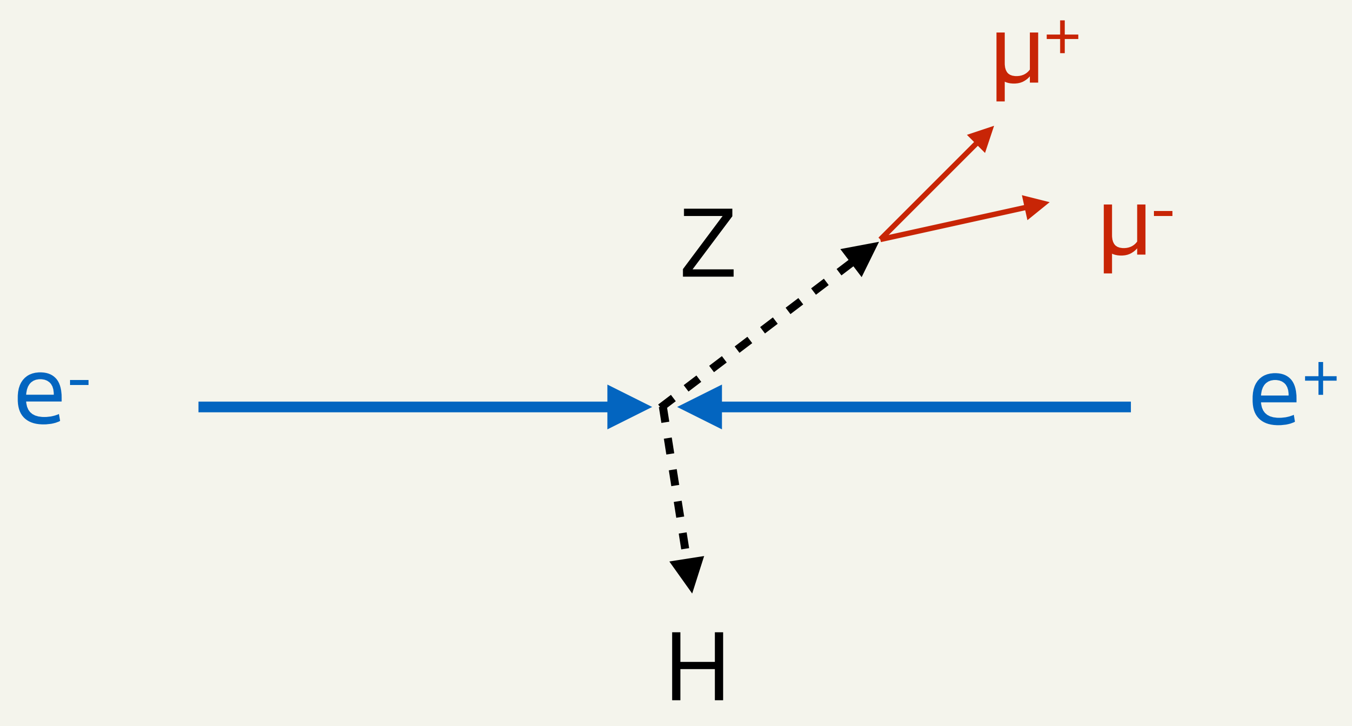
- Baseline: 500 GeV e^- and 31 GeV e^+ => $\gamma \sim 2.1$.
  - **Can we still do Higgs physics in such conditions?**
  - Experience: HERA had $\gamma = 3$…
  - … Yet, it's not quite the same physics!
- **Study cases**: **Higgs mass** measurement (ZH recoil).
- **Most advanced concept is the ILD at the ILC**.
  - Fast simulation available.
  - Good comparison point.
- Modify the fast simulation and run physics analysis benchmarks.

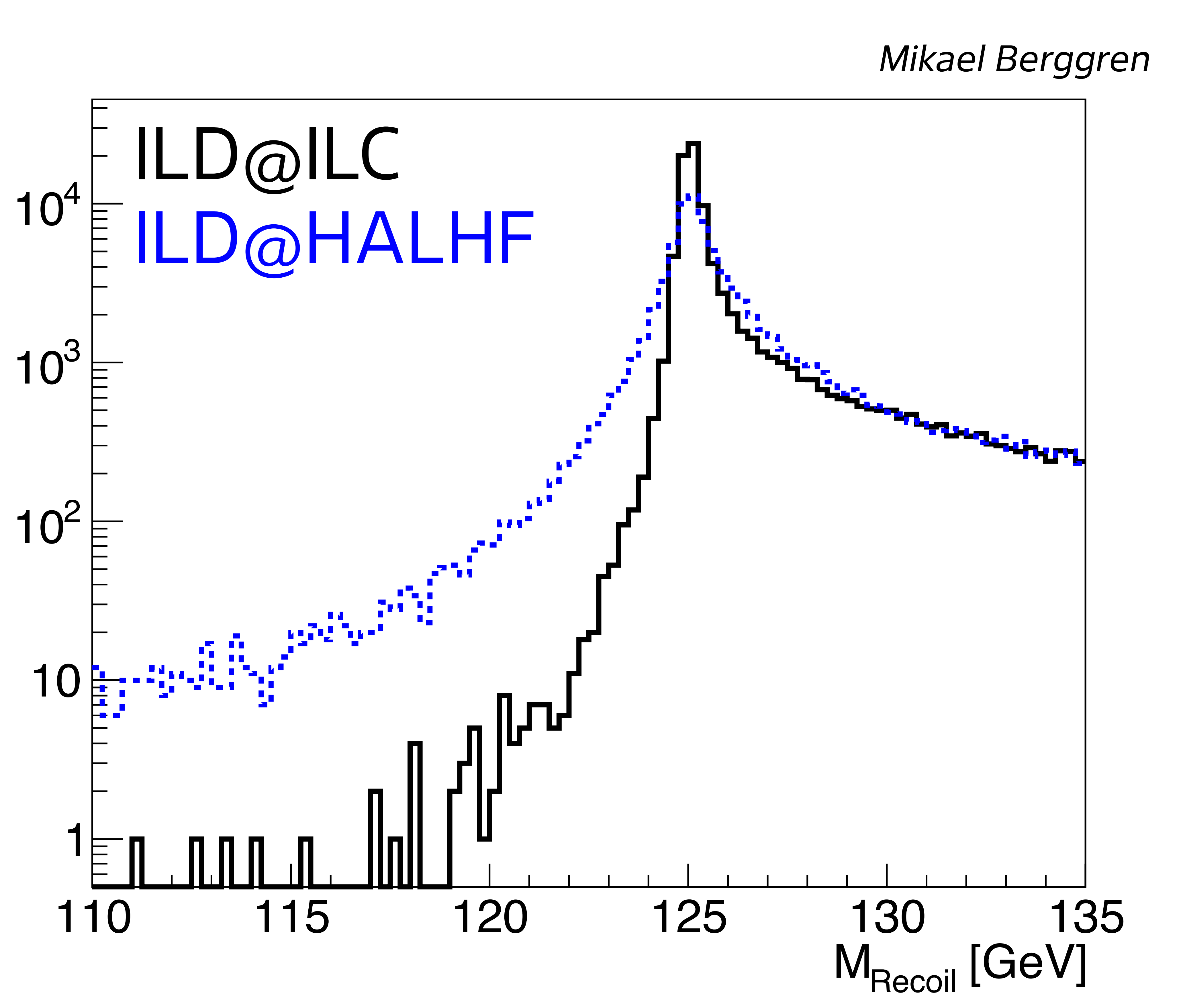


The International Large Detector

Impact on physics: Higgs

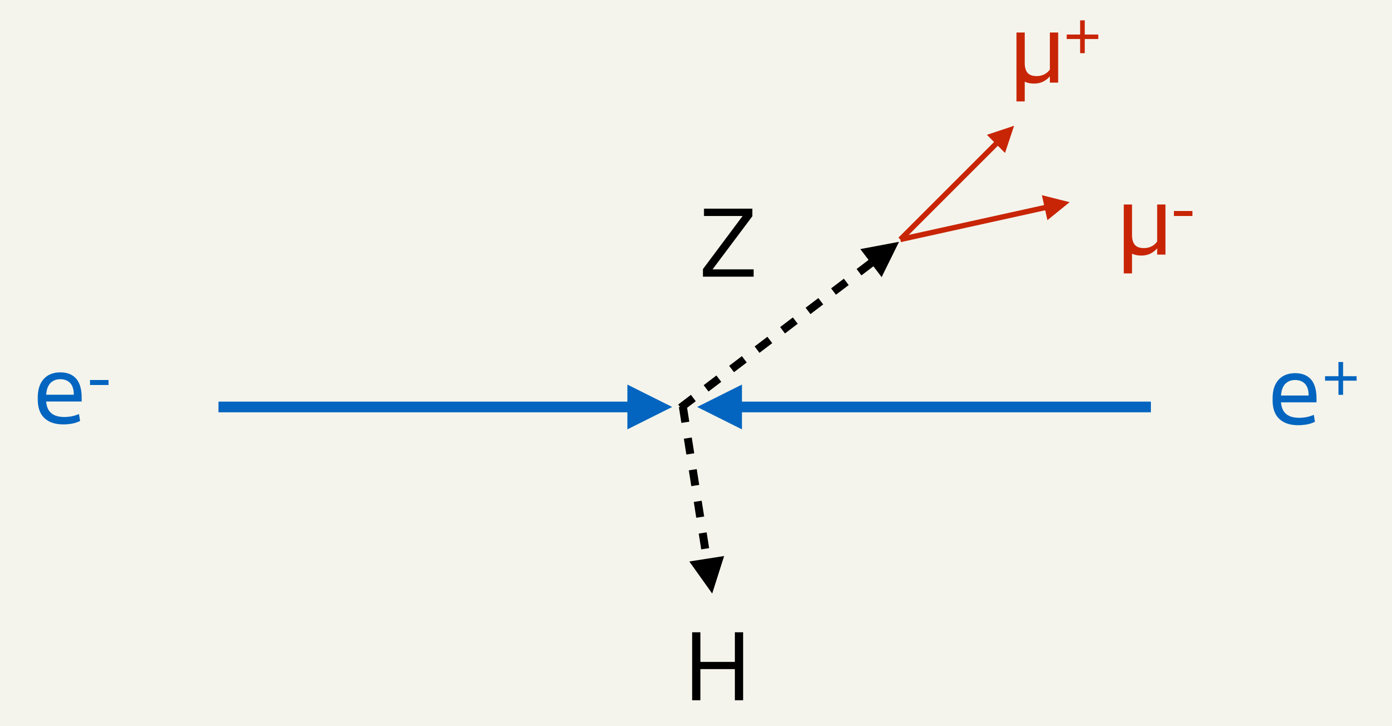
- Process: $e^+e^- \rightarrow Z(\mu^+\mu^-)H$
- Measure Higgs mass via recoil mass.
- Detector: ILD with fast simulation (SGV), including correct tracking.





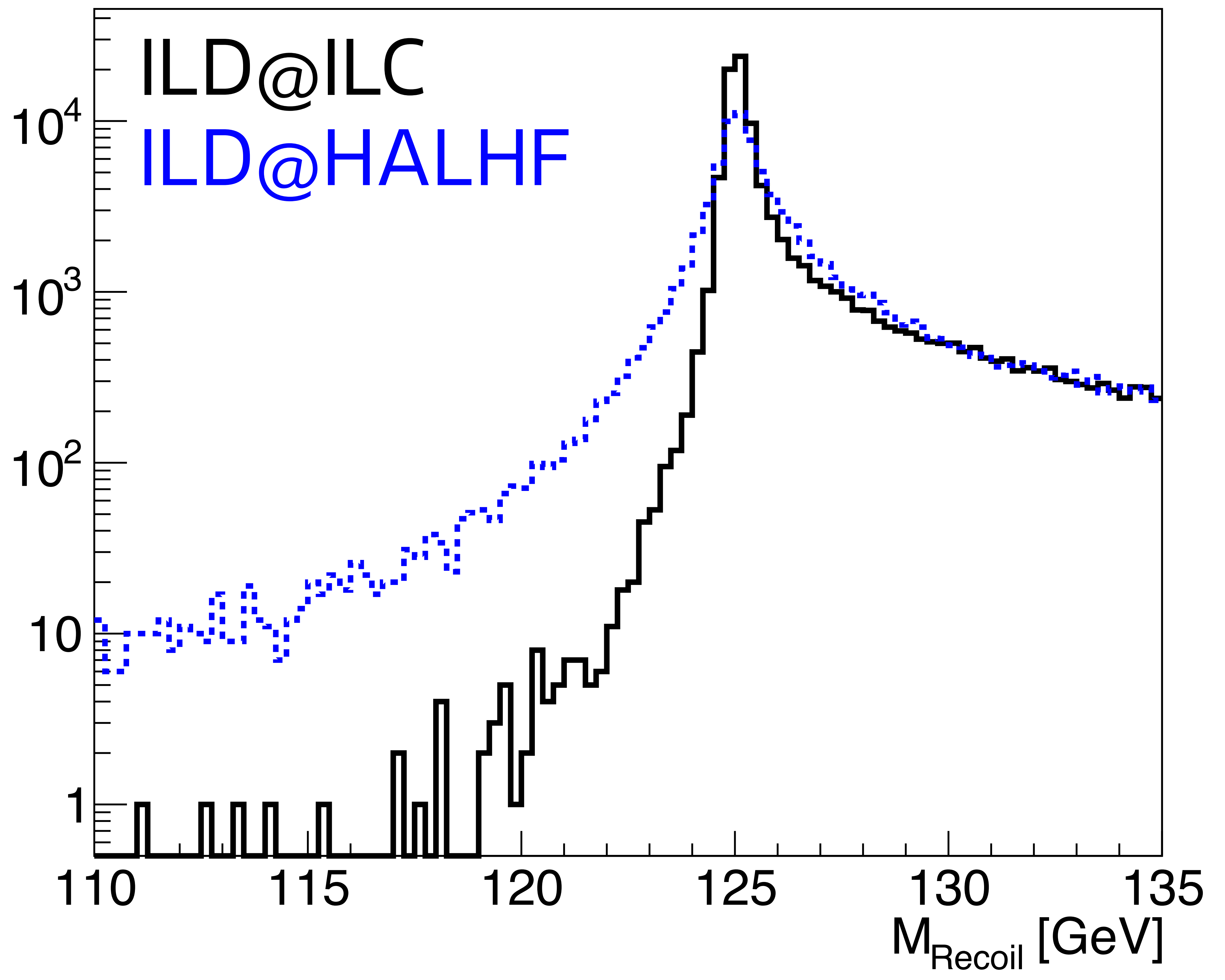
Impact on physics: Higgs

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



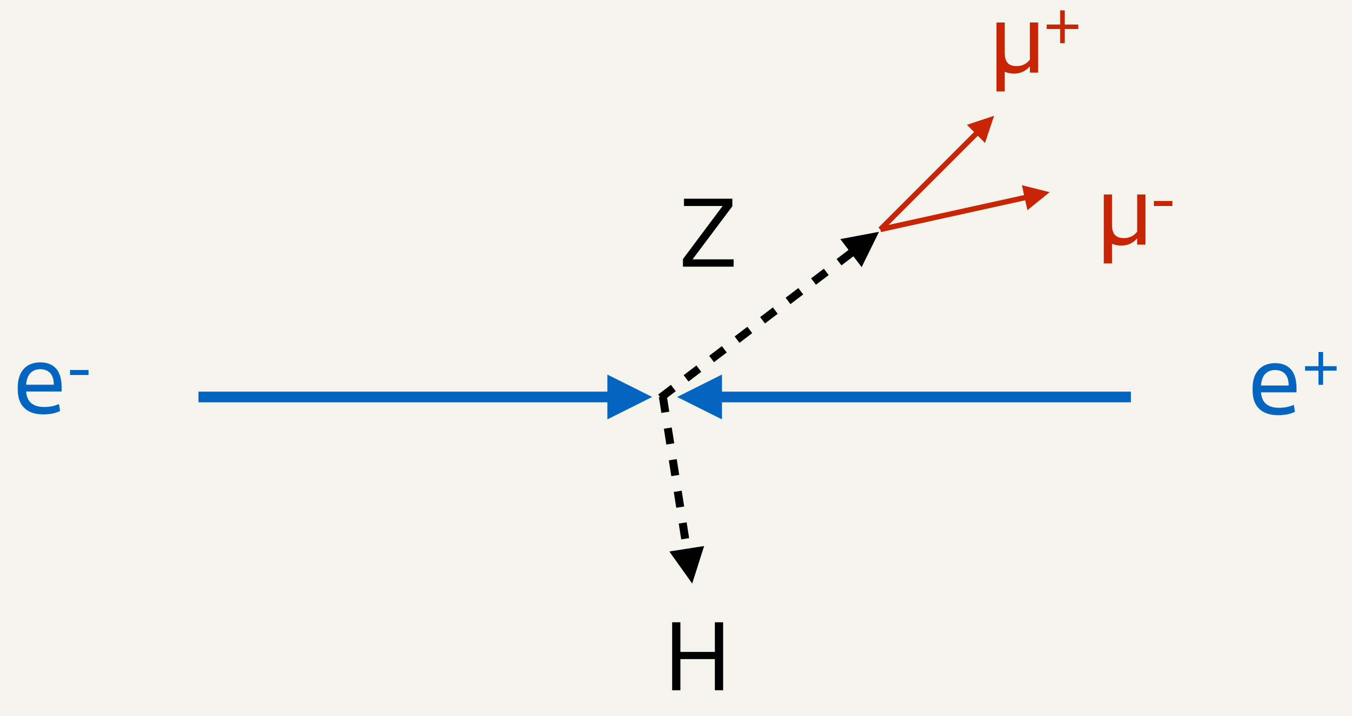
- **Resolution loss due muons being boosted forward**:
  - less lever arm => lower muon momentum resolution.
  - $\sigma_{\mathrm{ILD@HALHF}} = 2.2 \times \sigma_{\mathrm{ILD@ILC}}$

Mikael Berggren



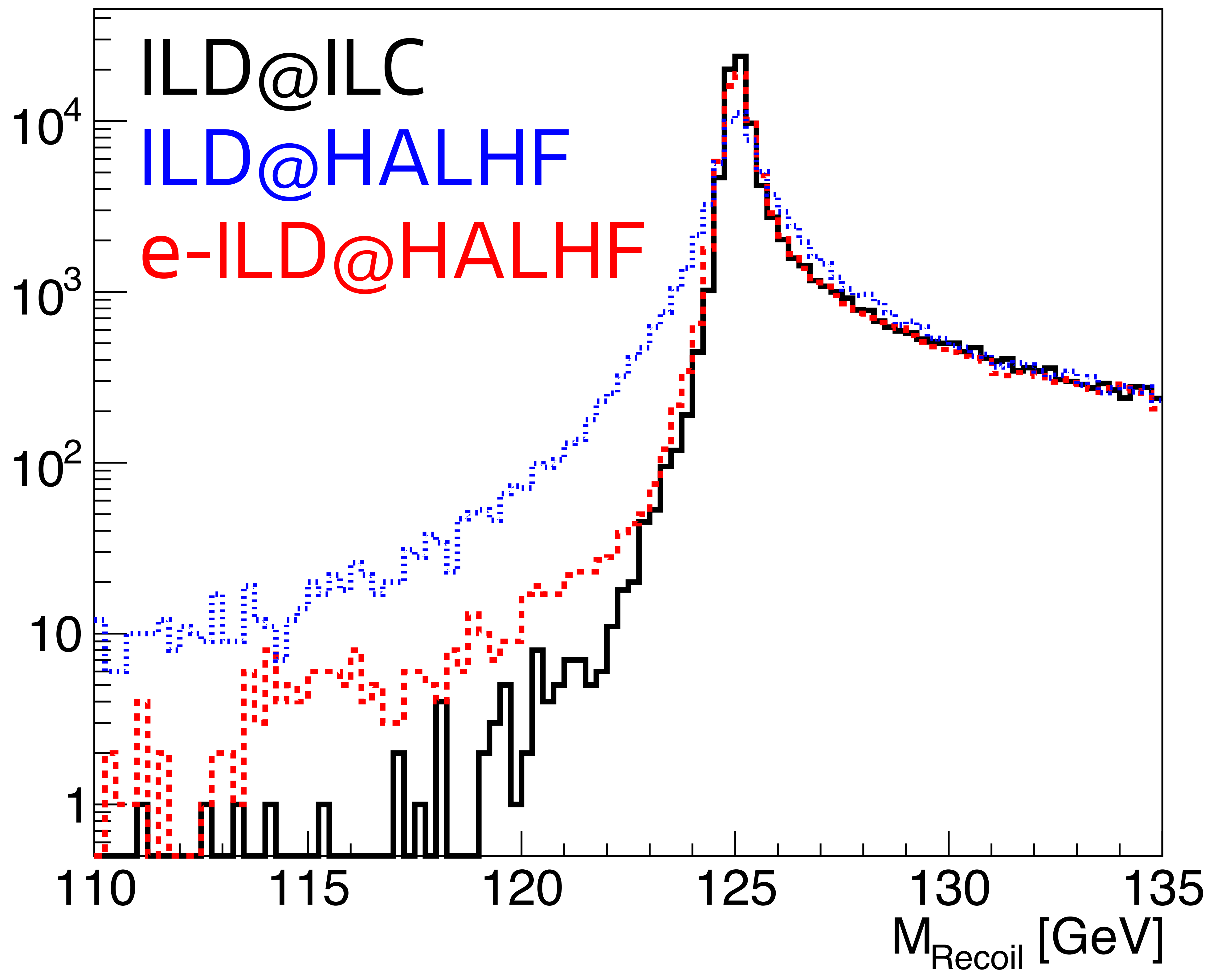
Impact on physics: Higgs

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



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



Beam parameters

- **Asymmetric energy => loss of "energy efficiency"** compared to symmetric case (some energy goes in the boost)
  - $$\frac{P}{P_{\text{sym}}} = \frac{E_- N_- + E_+ N_+}{\sqrt{N_- N_+}\sqrt{s}}$$
  - With:
    - $E_- = 500$ GeV and $E_+ = 31$ GeV,
    - $N_- : N_+ = 2 : 2 \times 10^{10}$ particles / bunch,

  } $P/P_{\text{sym}} = 2.13$ *(= boost factor)*

Beam parameters

- **Asymmetric energy => loss of "energy efficiency"** compared to symmetric case (some energy goes in the boost)
  - $$\frac{P}{P_{\text{sym}}} = \frac{E_- N_- + E_+ N_+}{\sqrt{N_- N_+}\sqrt{s}}$$
  - With:
    - $E_- = 500$ GeV and $E_+ = 31$ GeV,
    - $N_- : N_+ = 2 : 2 \times 10^{10}$ particles / bunch,

  $\Big\}\; P/P_{\text{sym}} = 2.13$ *(= boost factor)*

- But what matters is **luminosity $\mathscr{L} \propto N_- \times N_+$ => same $\mathscr{L}$ while being more energy-efficient** by:
  - decreasing the bunch charge of the high-energy beam (e-)
  - <u>and</u> increasing the bunch charge of the low-energy beam (e+).

Beam parameters

- **Asymmetric energy => loss of "energy efficiency"** compared to symmetric case (some energy goes in the boost)
  - $$\frac{P}{P_{\text{sym}}} = \frac{E_- N_- + E_+ N_+}{\sqrt{N_- N_+}\sqrt{s}}$$
  - With:
    - $E_- = 500$ GeV and $E_+ = 31$ GeV,
    - $N_- : N_+ = 2 : 2 \times 10^{10}$ particles / bunch,

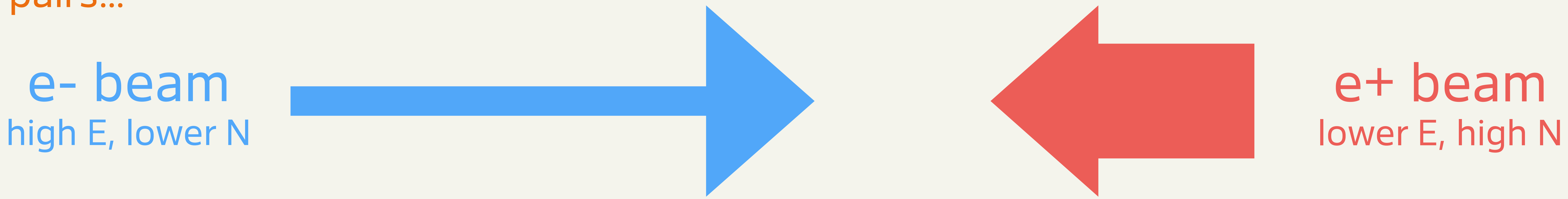
    $\Big\}$ $P/P_{\text{sym}} = 2.13$ *(= boost factor)*

- But what matters is **luminosity $\mathscr{L} \propto N_- \times N_+$ => same $\mathscr{L}$ while being more energy-efficient** by:
  - decreasing the bunch charge of the high-energy beam (e-)
  - and increasing the bunch charge of the low-energy beam (e+).

  - Ideally by the opposite factor as energy asymmetry.
  - **Limited by beam-induced background** (see next slides):
    - $N_- : N_+ = 1.33 : 3 \times 10^{10}$ particles / bunch => $P/P_{\text{sym}} = 1.5$

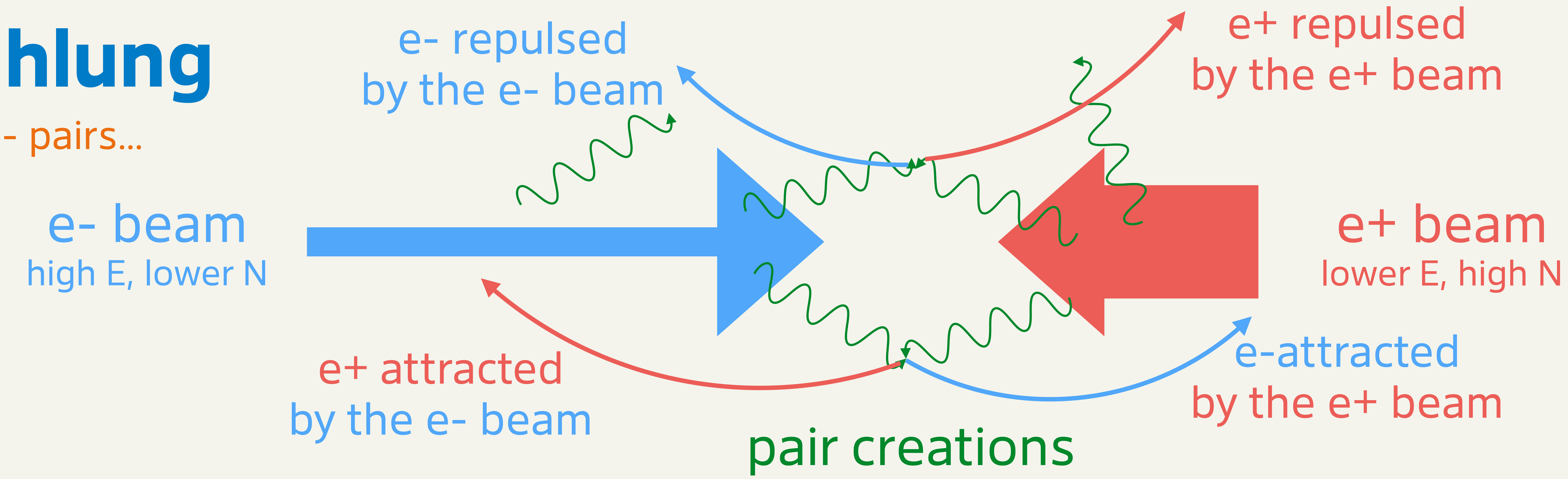
Beam-strahlung

Creation of many e+e- pairs…



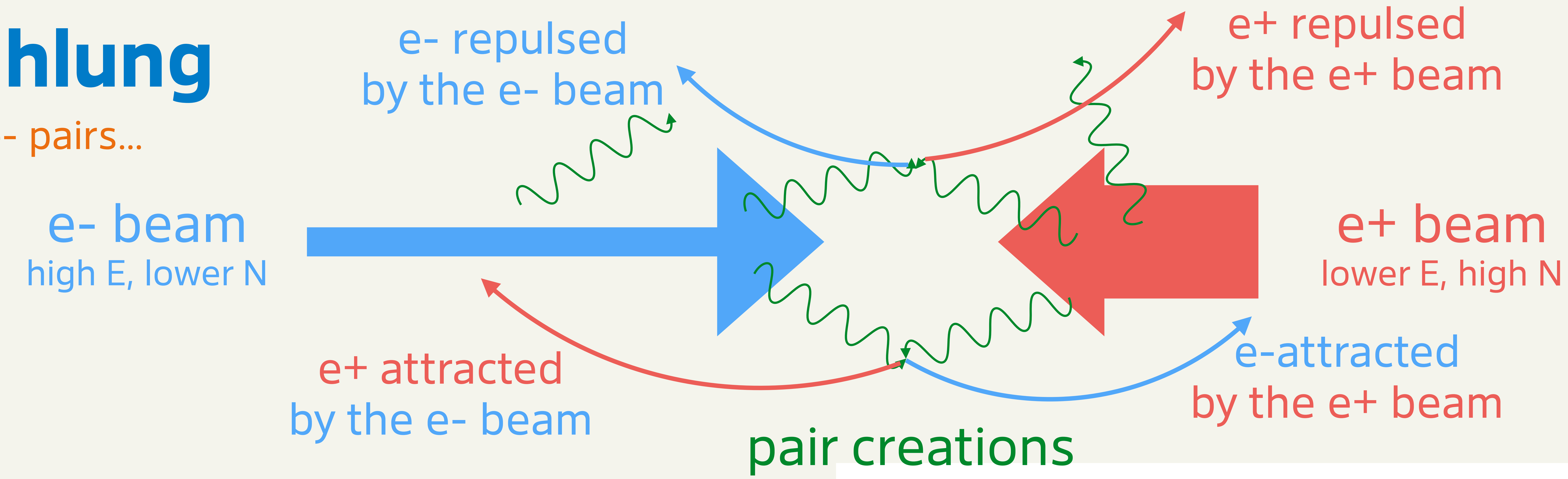
Beam-strahlung

Creation of many e+e- pairs...

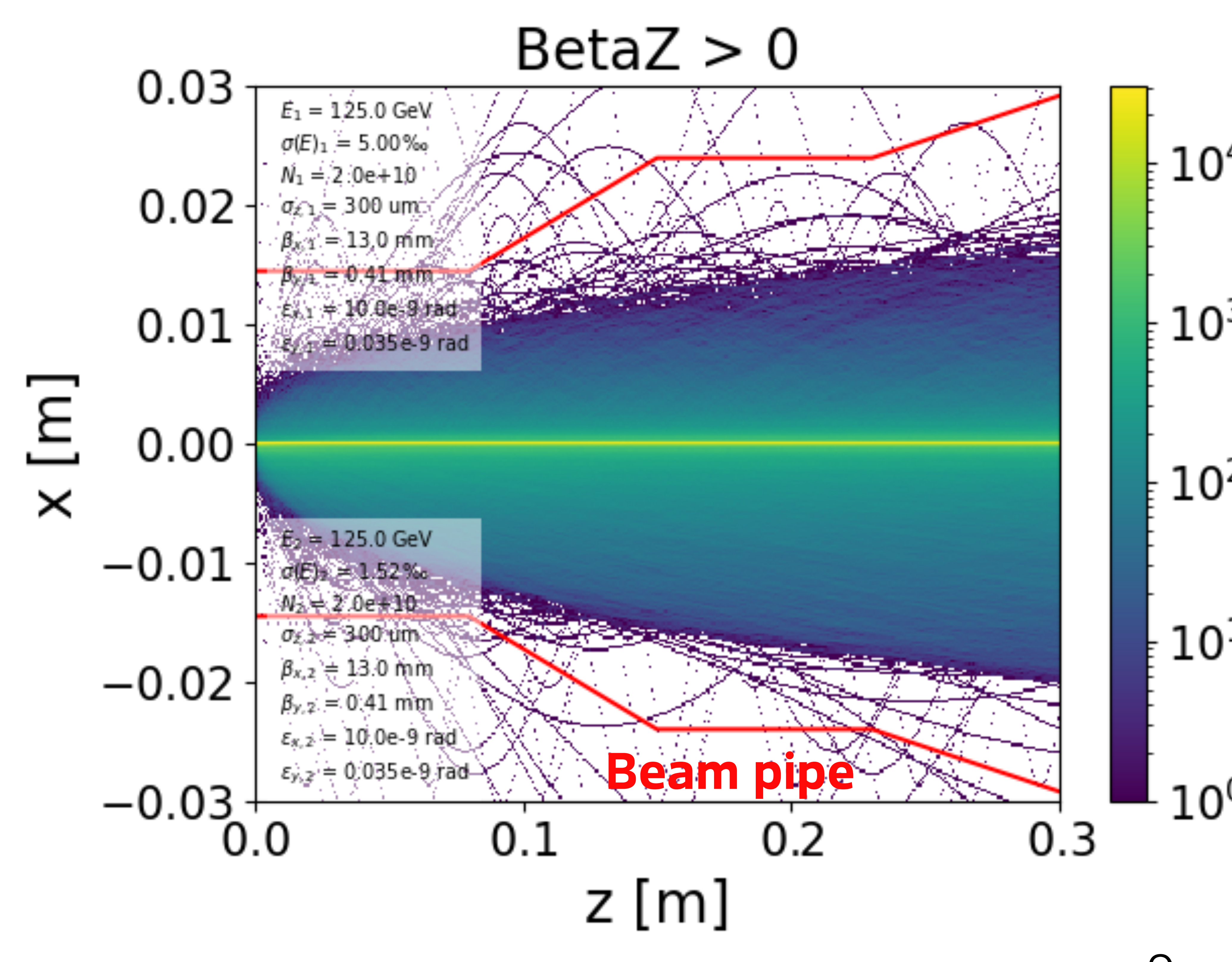


Beam-strahlung

Creation of many e+e- pairs…

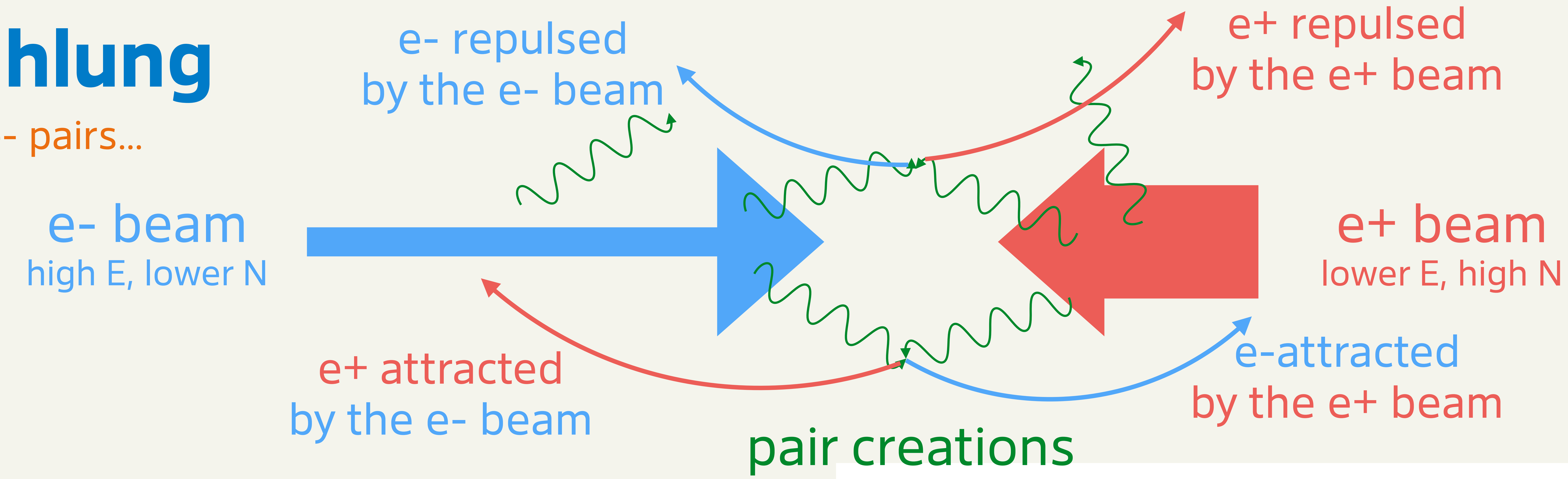


- **Simulate the beam-beam interaction using Guinea-Pig**.
  - Example: plot the trajectories of all pairs created in the forward direction.
  - Here in the ILC configuration (symmetric beams) →

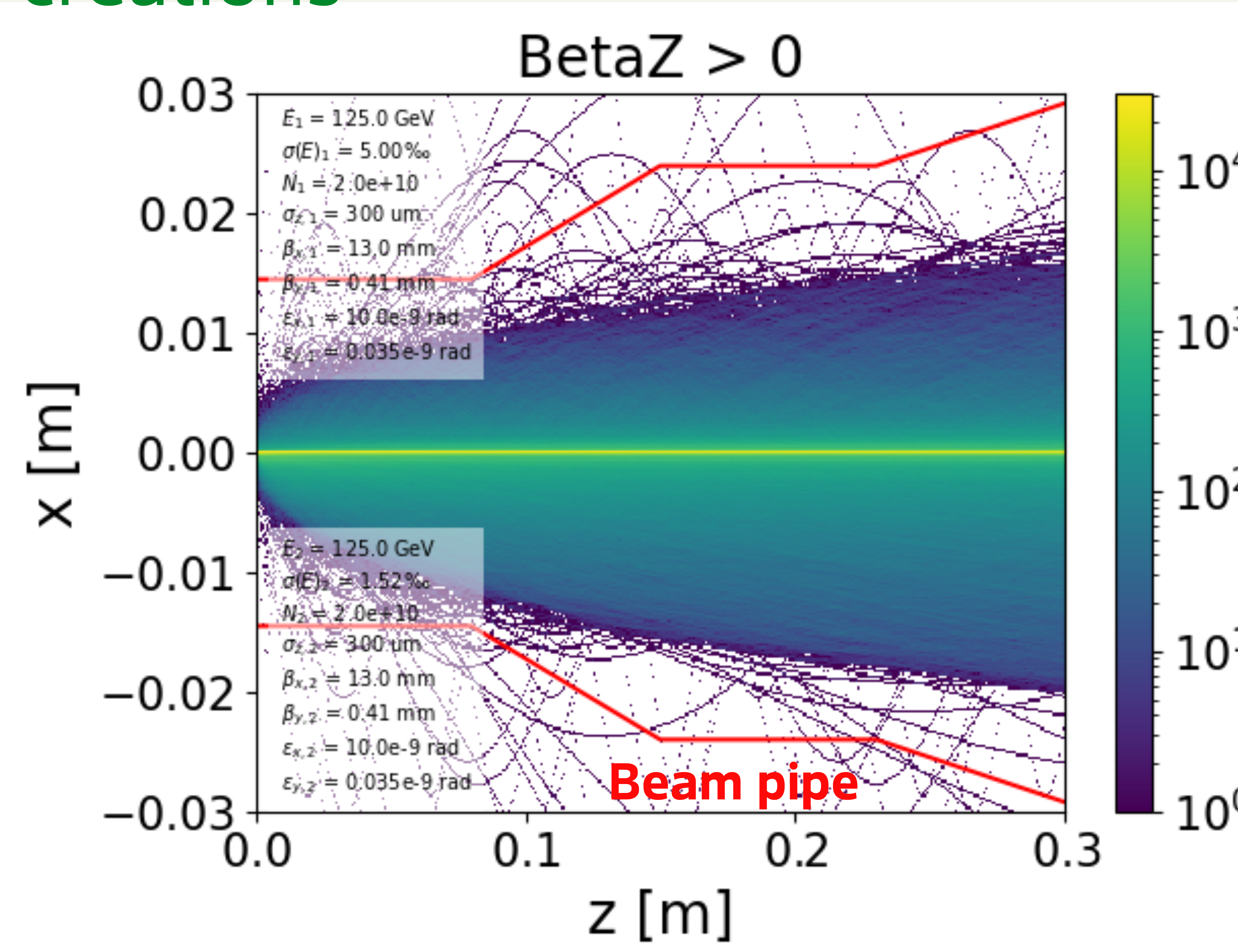


Beam-strahlung

Creation of many e+e- pairs...



- **Simulate the beam-beam interaction using Guinea-Pig**.
  - Example: plot the trajectories of all pairs created in the forward direction.
  - Here in the ILC configuration (symmetric beams) →

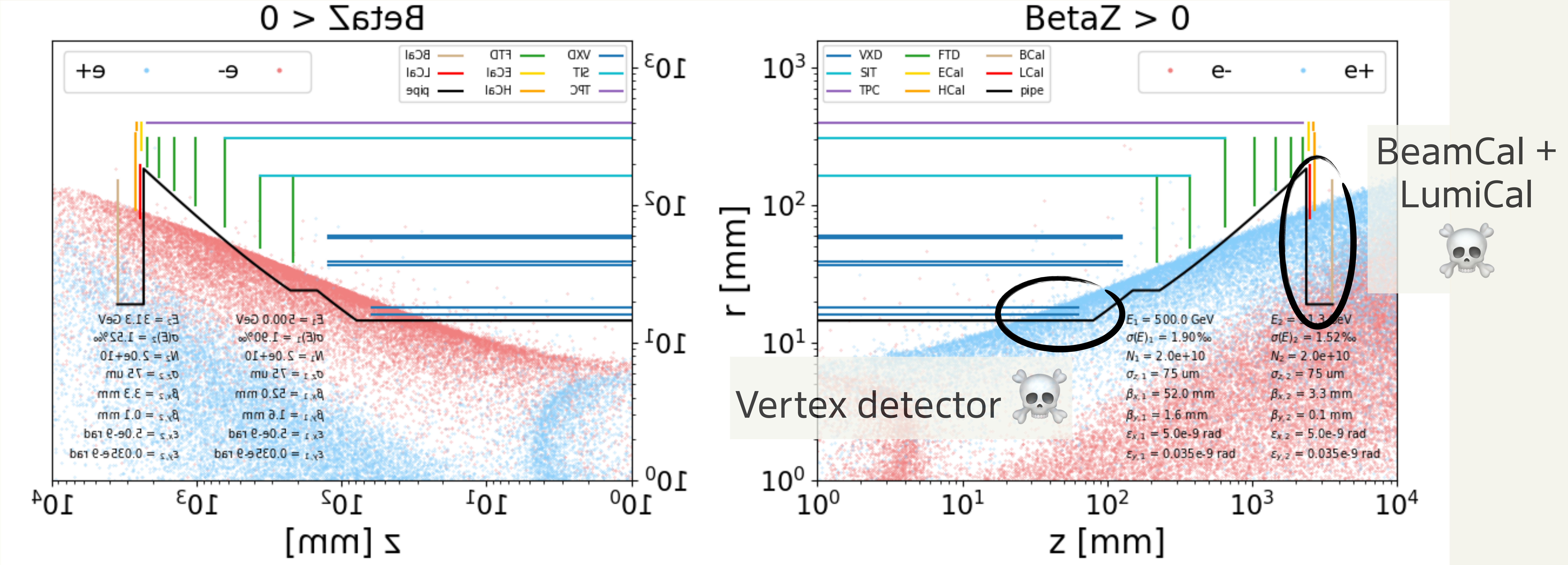


- Next plots: instead of showing the whole trajectory, show the spatial distribution of the apex of the trajectory.

Beam-strahlung: impact of beam charge

- Energy = 500 : 31.3 GeV
- charge = **2 : 2** x 10^{10} particles
- σ_z = 75 : 75 µm HALHF:

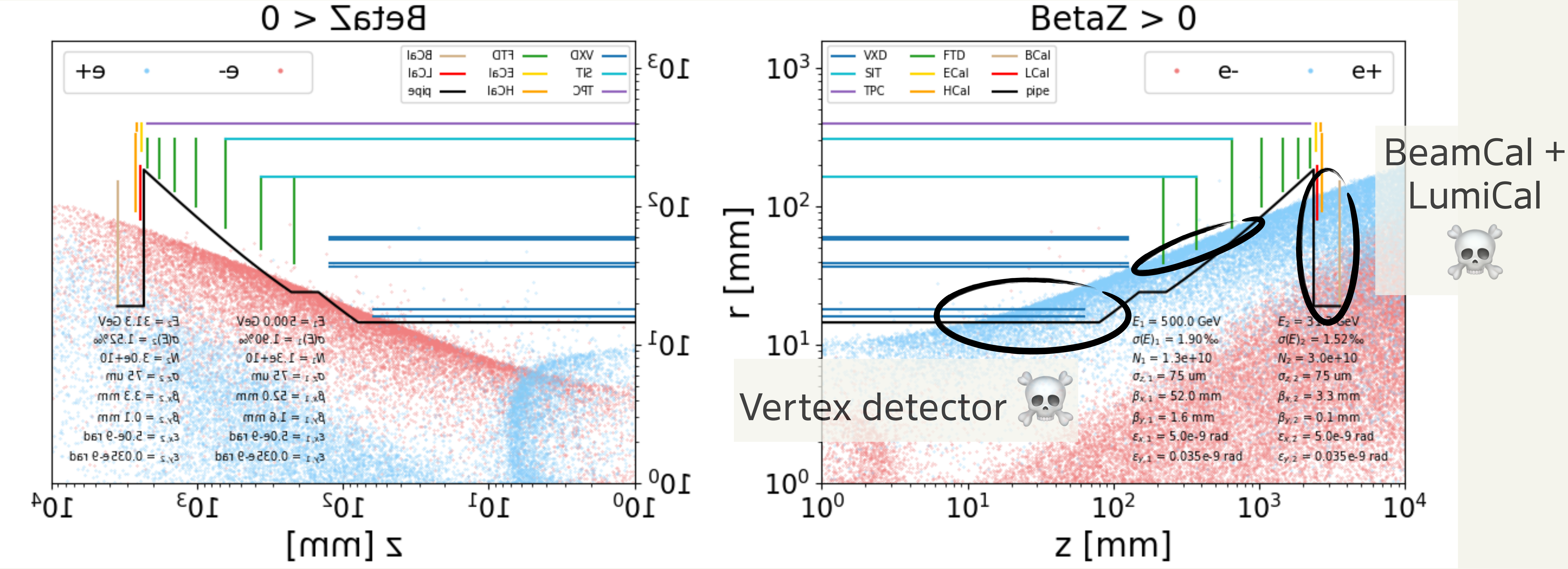
Same charge: symmetric pairs distribution.



Detector model: ILC

Beam-strahlung: finding a suitable config…

- Energy = 500 : 31.3 GeV
- charge = **1.33 : 3** x 10^{10} particles **=> imbalance left/right: is it really helpful?**
- σ_z = 75 : 75 µm HALHF:

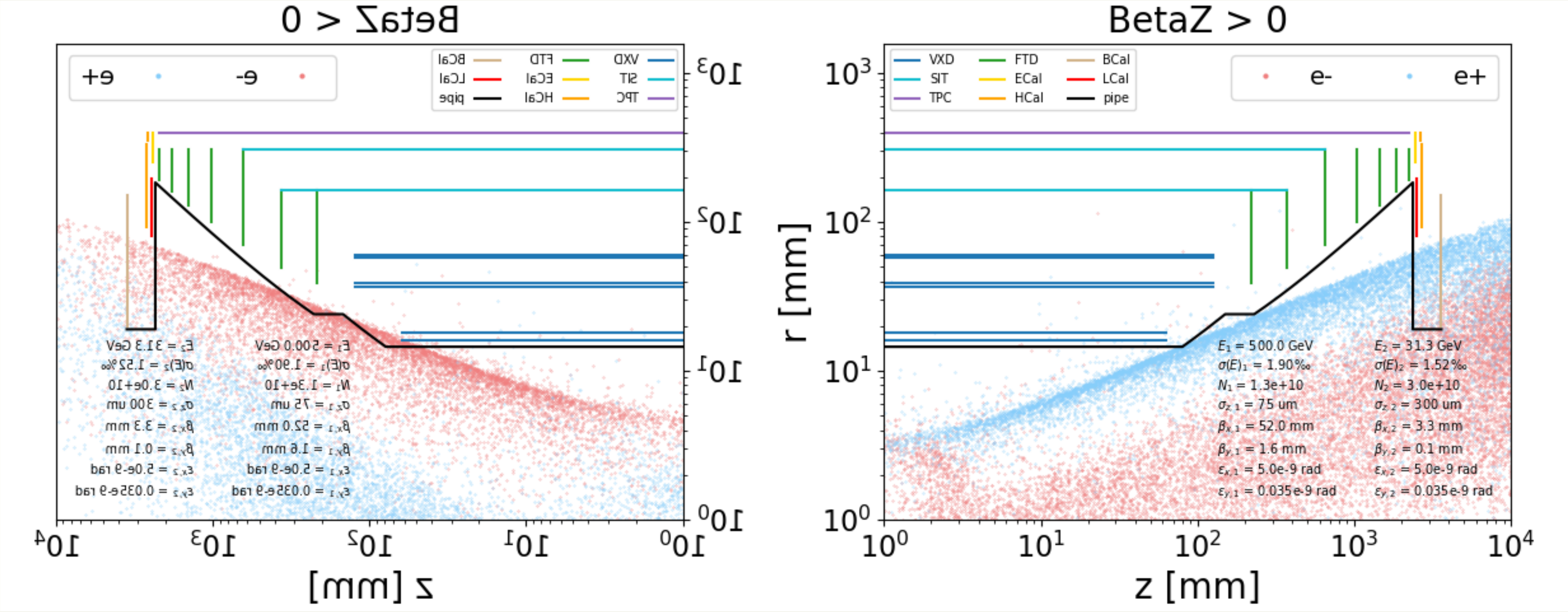


Detector model: ILC

Beam-strahlung: finding a suitable config…

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

If combined with bunch length extension, yes!
But still not enough… Other ideas?



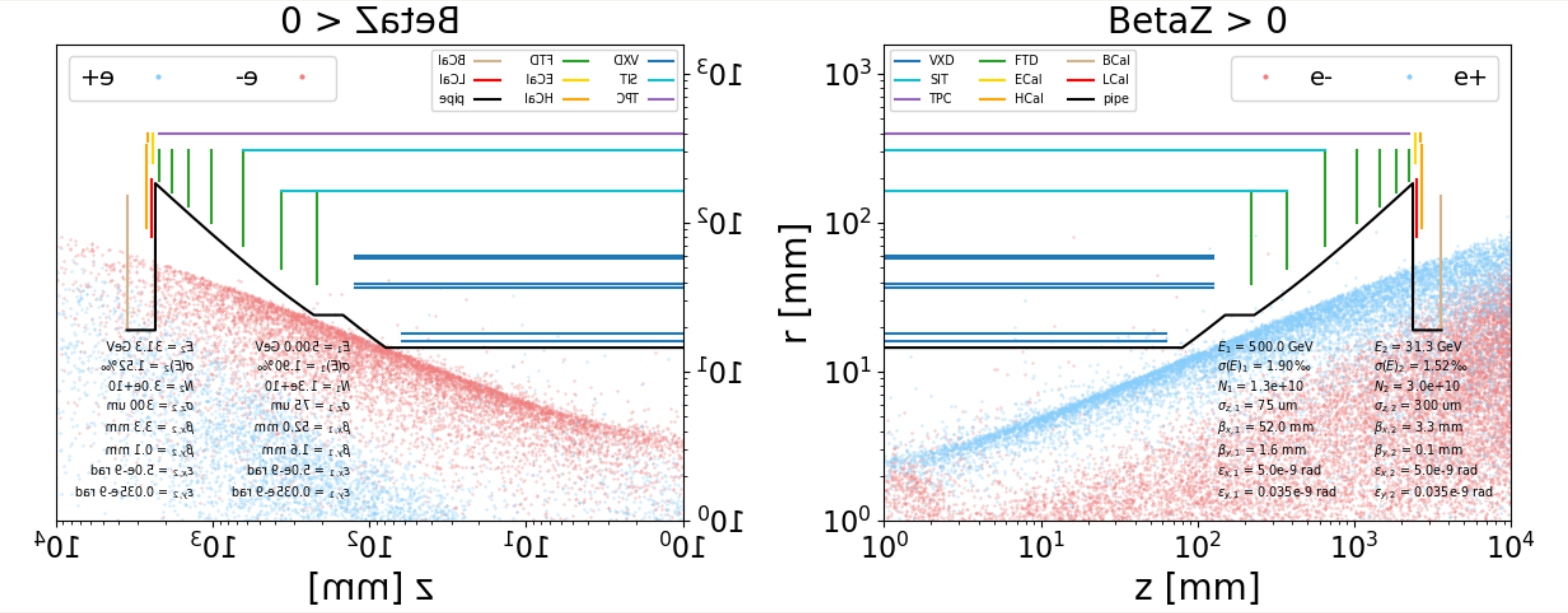
Detector model: ILC

Beam-strahlung: finding a suitable config…

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

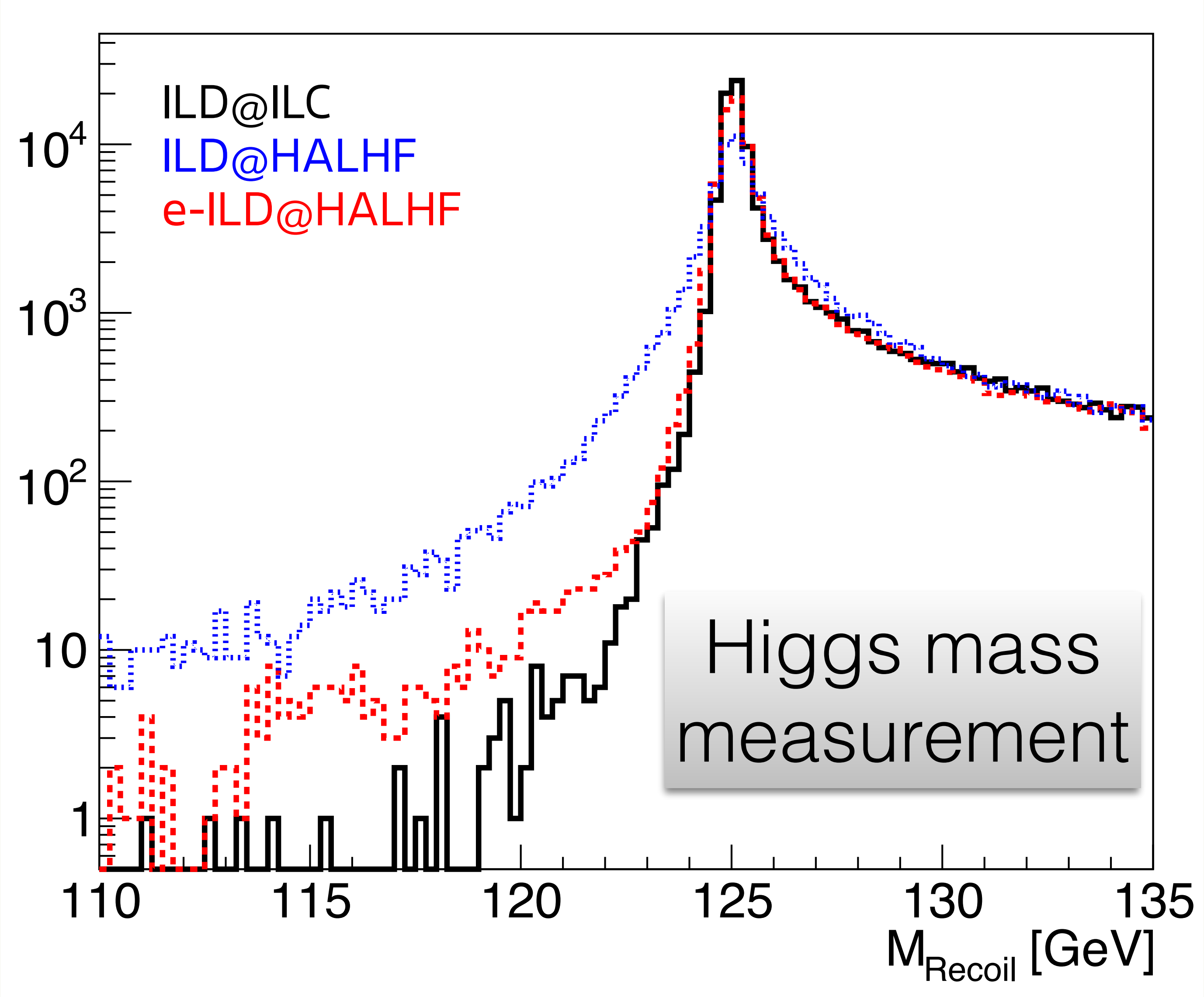
Detector model: ILC…
with **5 T magnetic field**

=> **looks OK** !

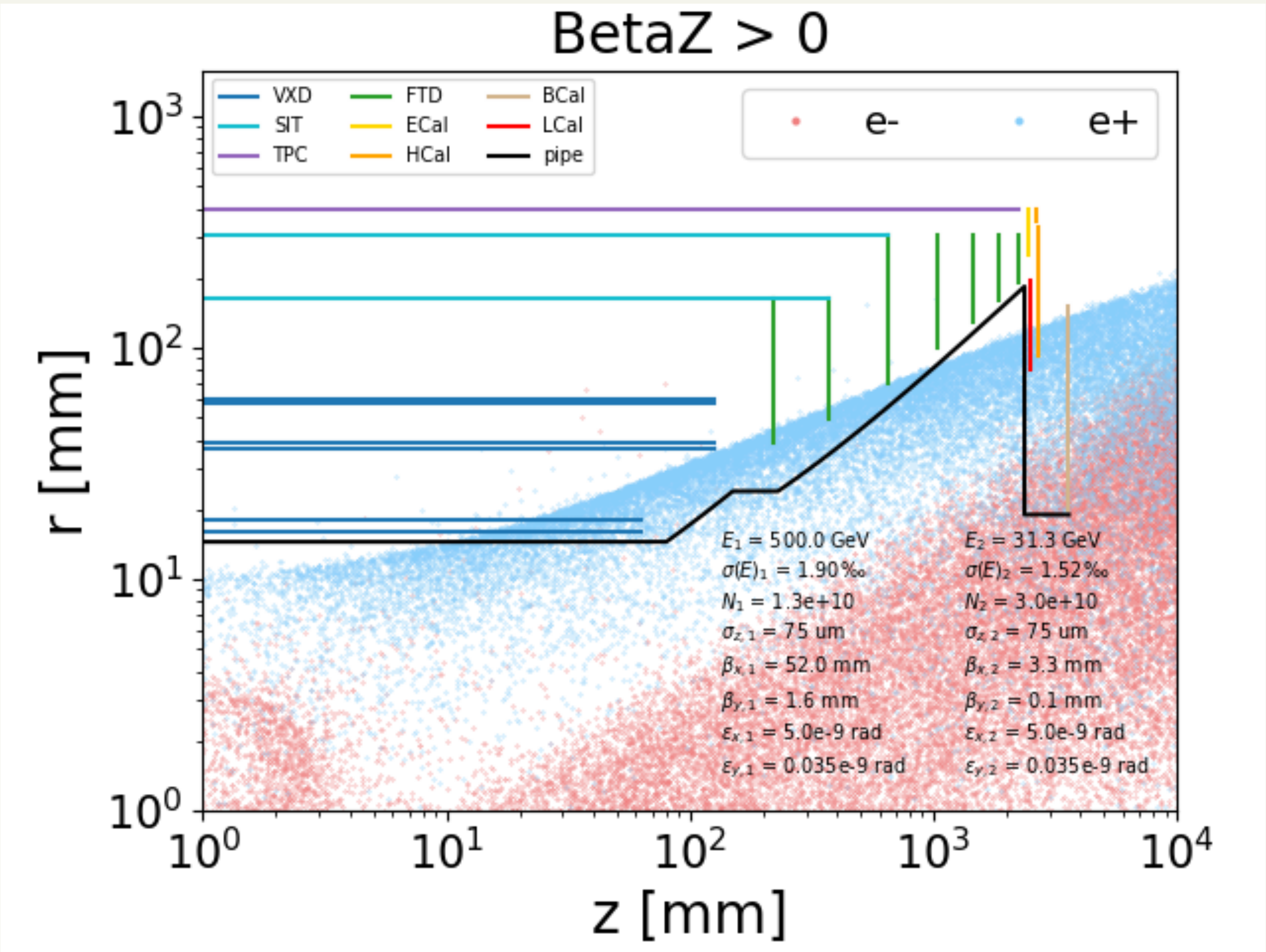


Constraints from the detector

- **Physicists wishes**:
  - Instrument as low forward angles as possible.
    - Backward direction has less importance…
  - Higher magnetic field to improve muon resolution.



- **Constraints**:
  - **Beam backgrounds**: define the available phase space for the detector.
  - **High-field magnets** inside experiments are a challenge.



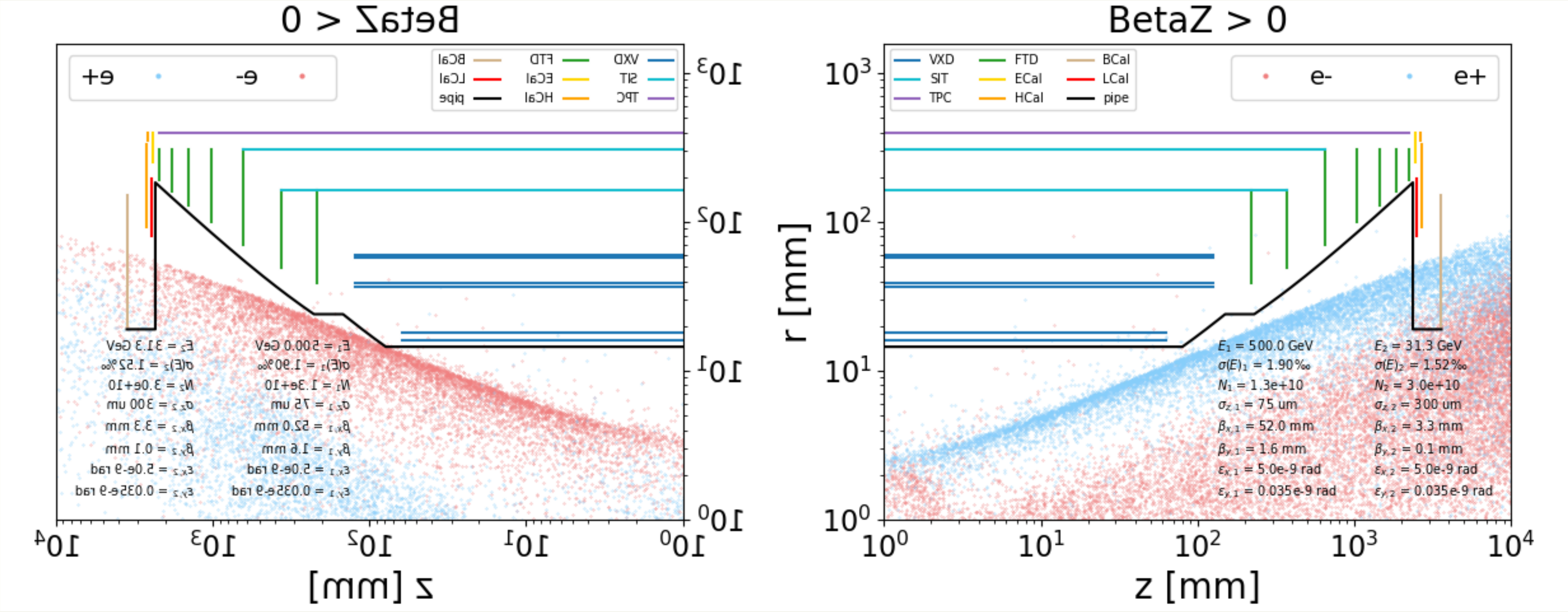
Beam-strahlung: finding a suitable config...

repeat from the previous slide

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

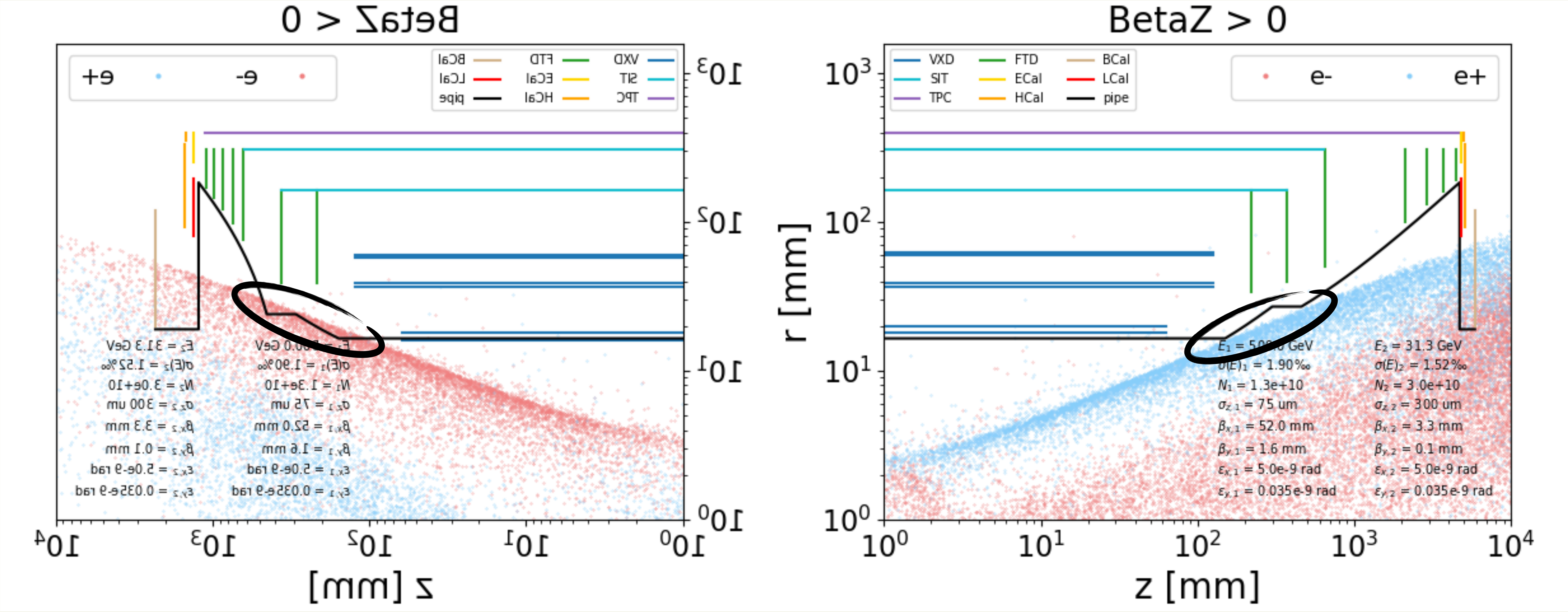
Detector model: ILC...
with **5 T magnetic field**

=> **looks OK** !



Towards an asymmetric detector

- First design of "**extended-ILD**" (5T magnet) made before these background studies.
  - Beam pipe position tuning is needed to avoid hitting the pairs.
  - May extend to even lower angle in the forward end-caps.



Conclusions

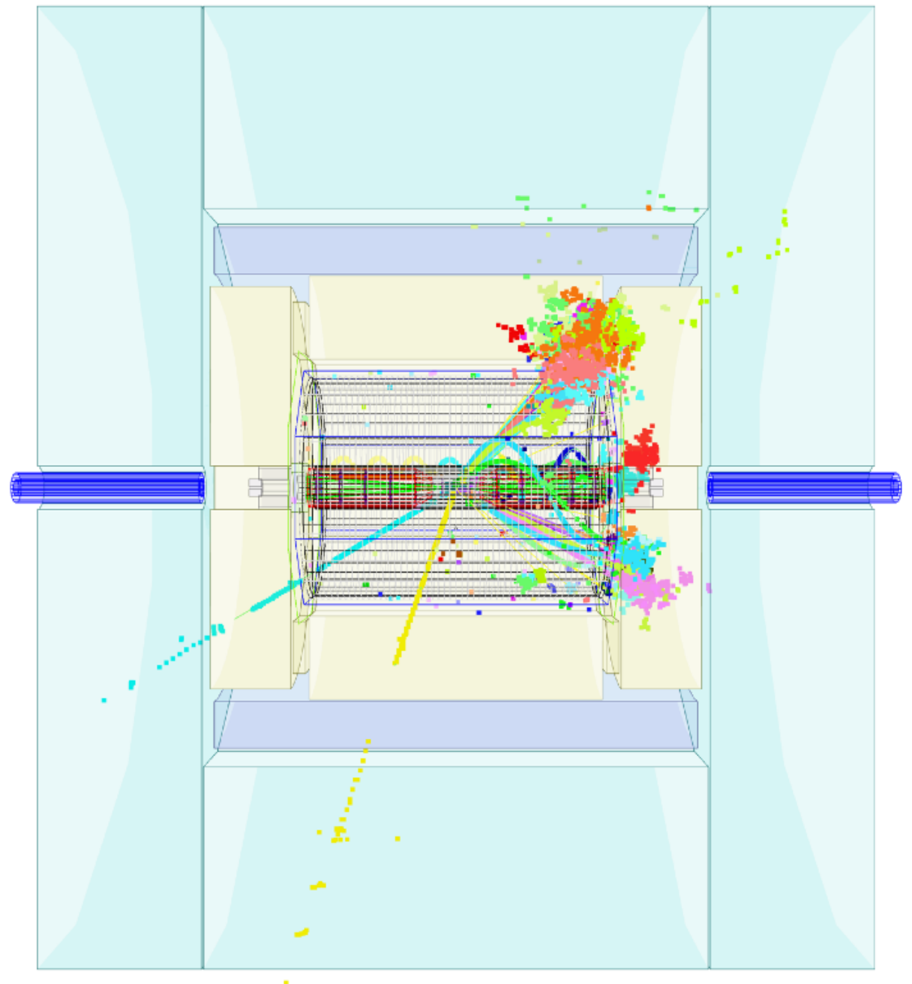
- **Beam backgrounds constrain the available space for the detector** (and the beam pipe shape and location too).
- **Beam parameters** choice is a **balance** between:
  - energy efficiency,
  - luminosity,
  - control of beam backgrounds.

- Experiment's magnet may help with containing the beam backgrounds… … but not a miracle solution (cost + technical challenge).

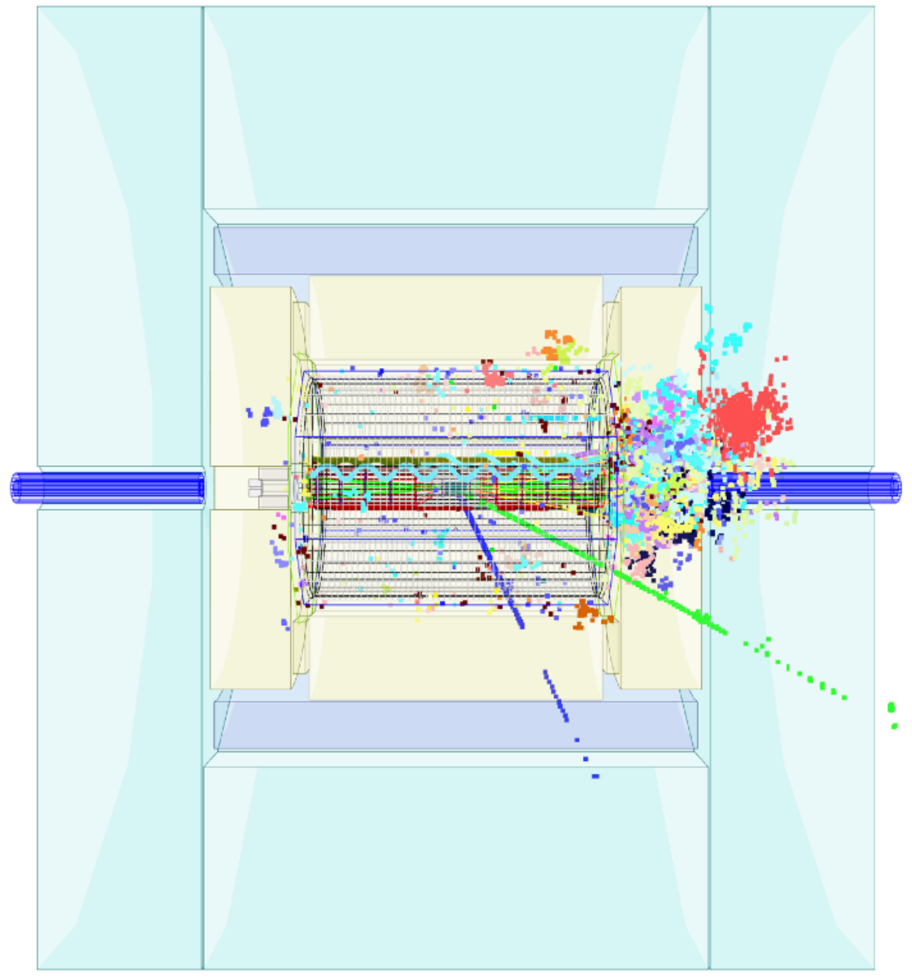
- **Asymmetric collisions require an asymmetric detector**.
  - => Allows for asymmetric background constraints (backward direction less sensitive than forward direction)

- Current physics studies done with SGV ("fast-sim" ILD)
- Work ongoing to implement an asymmetric detector (ILD-based) in Geant4 for more precise results.

$e^+e^- \rightarrow Z(\mu\mu)H$



↑ At the ILC
↓ At HALHF (same event)



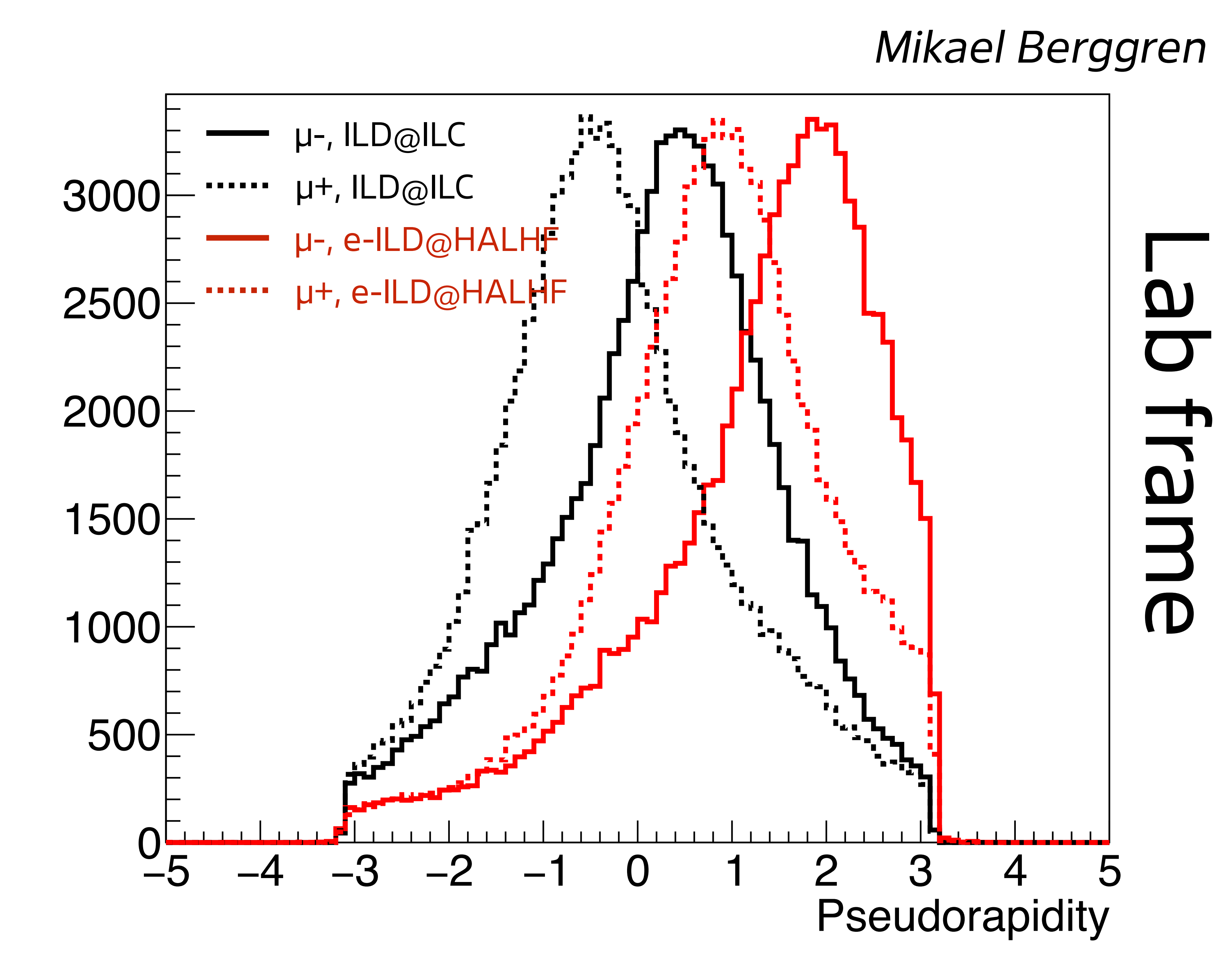
(ILD detector)

Thanks for your attention!

Questions?

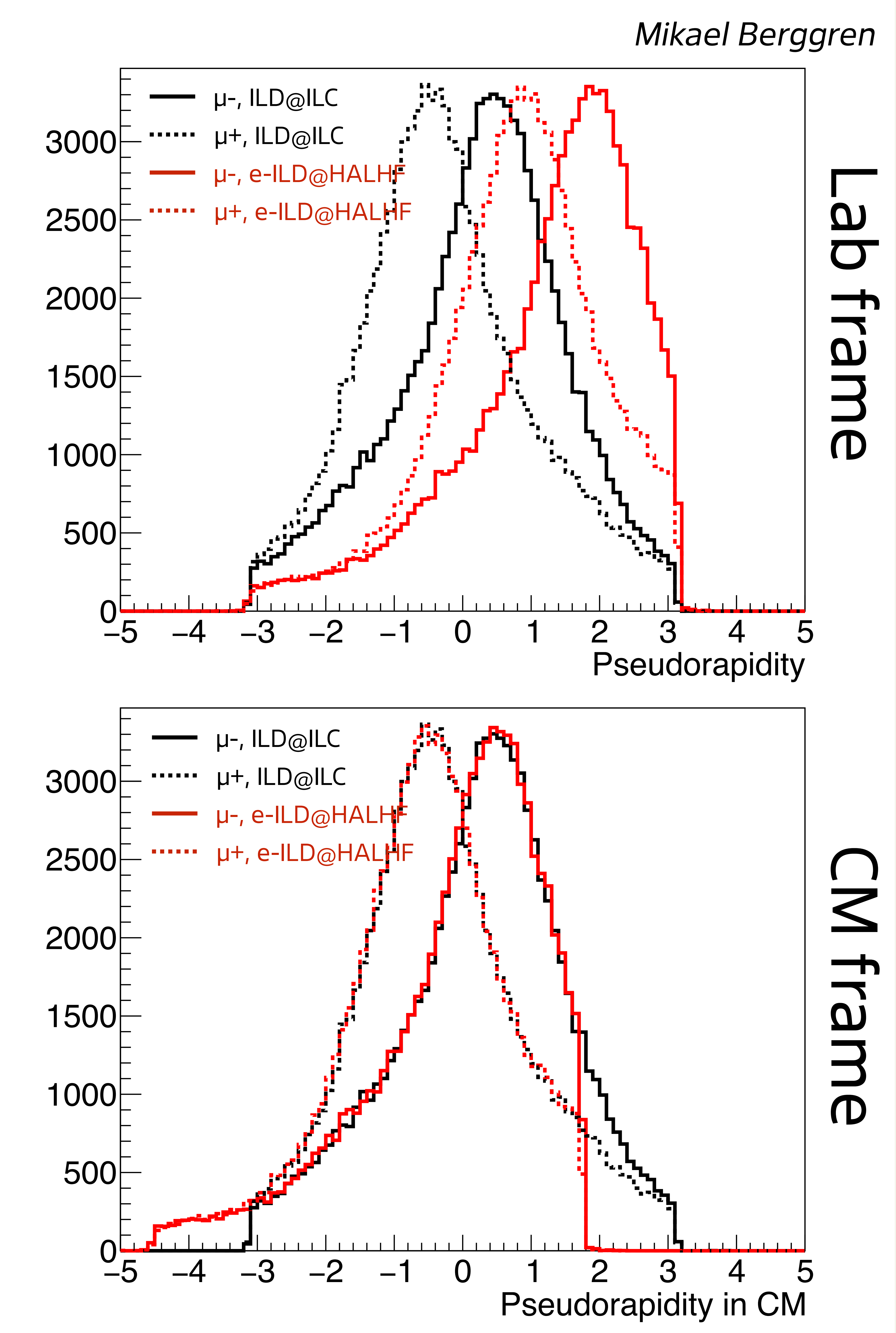
Impact on physics: F/B asymmetry

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



Impact on physics: F/B asymmetry

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

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