Physics Performance and Detector Requirements at an Asymmetric Higgs Factory

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Parallel Session - WG3

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

HELMHOLTZ

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Future lepton colliders landscape

Circular

(?)

- **Very expensive: O(>10B)**
- **Large environmental impact**
- Power hungry
- High lumi
- Upgradable to hadron collider

Linear

- **Expensive: very roughly O(5B)**
- **Slightly lower environmental impact**
- Less power hungry
- Extendable to higher energy

Cost (€ and environmental) driven by length, not operation

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- => **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)

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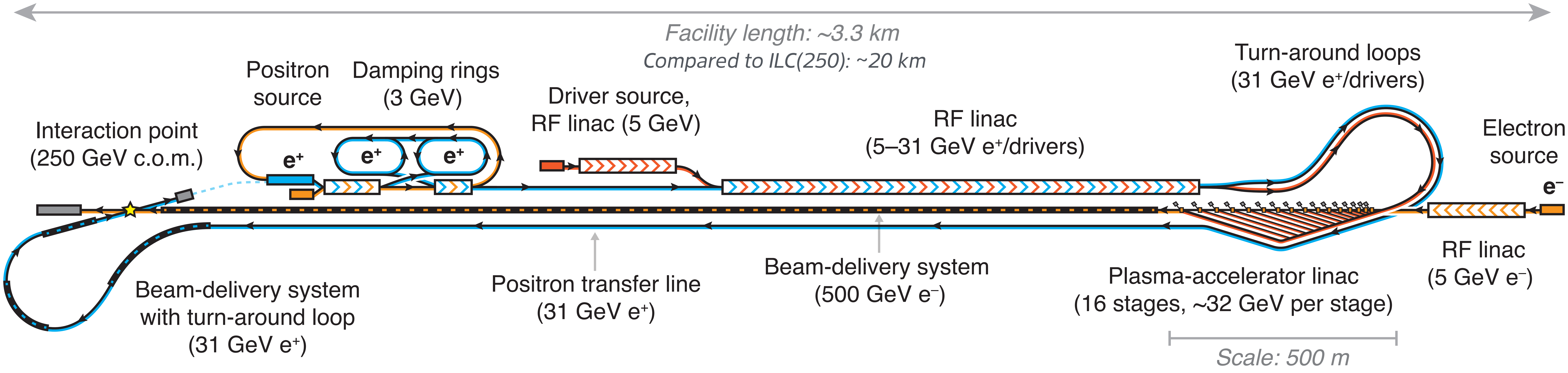
- **Can we do better than 1 km + 10 km?**

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

Now the questions arise

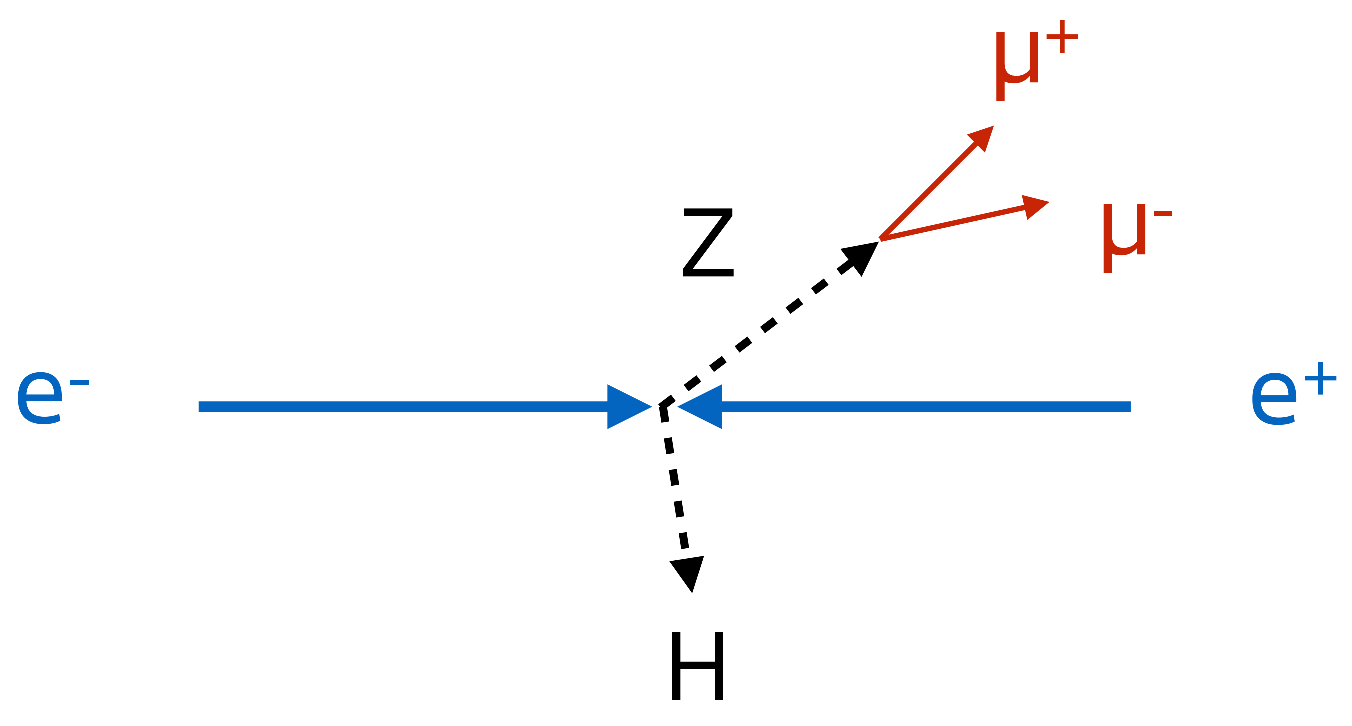
- Asymmetric beam energies => boosted topologies (γ ~ 2.1)
  - **Can we still do physics in such conditions?**
  - Not scary for anyone who worked at HERA (γ = 3)…
  - … Yet, it's not quite the same physics 🙃

- **Study cases**:
  - **Higgs mass** measurement.
  - **Forward/backward asymmetry** measurement.

- Other question: how does it impact the energy efficiency?

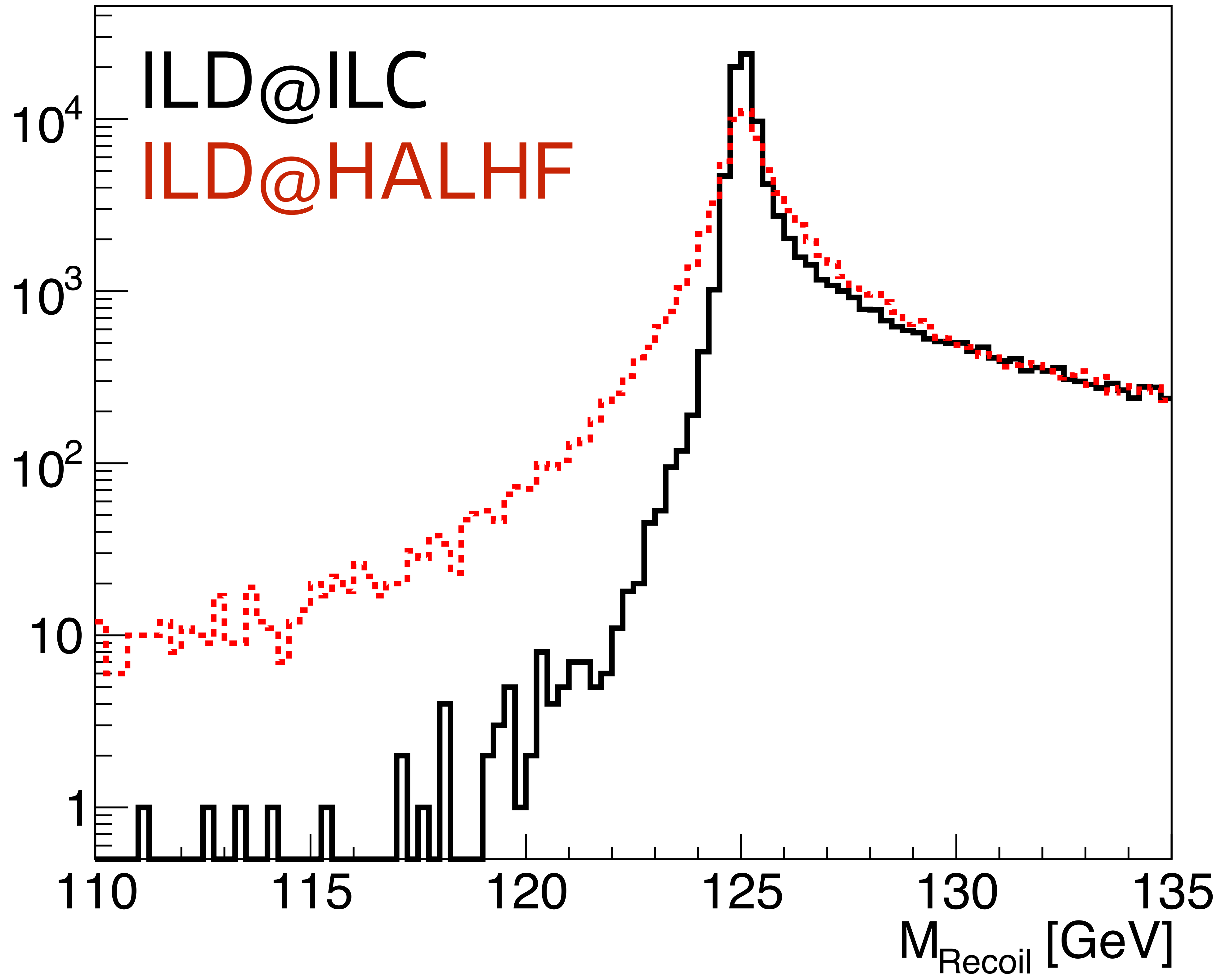
- Not studied here: boost most likely improves jet flavour-tagging.

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.
  - $\sigma_{\text{ILD@HALHF}} = 2.2 \times \sigma_{\text{ILD@ILC}}$



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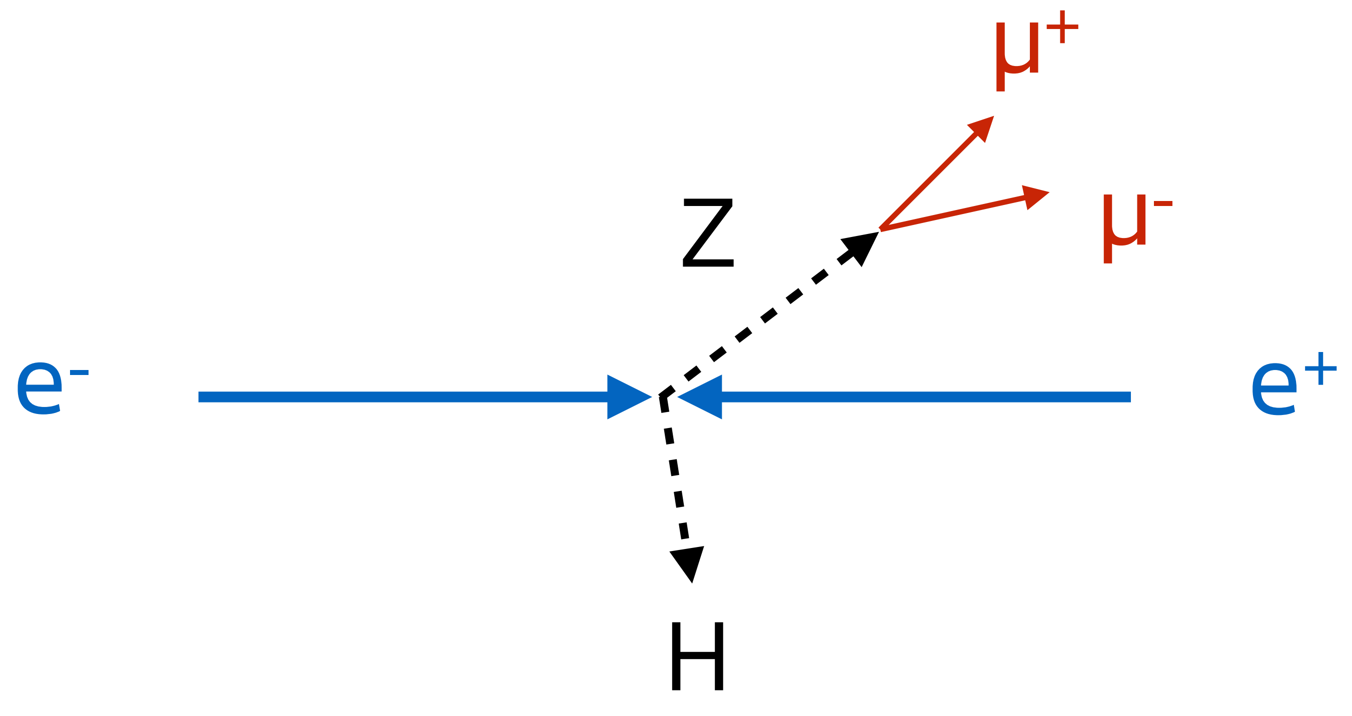

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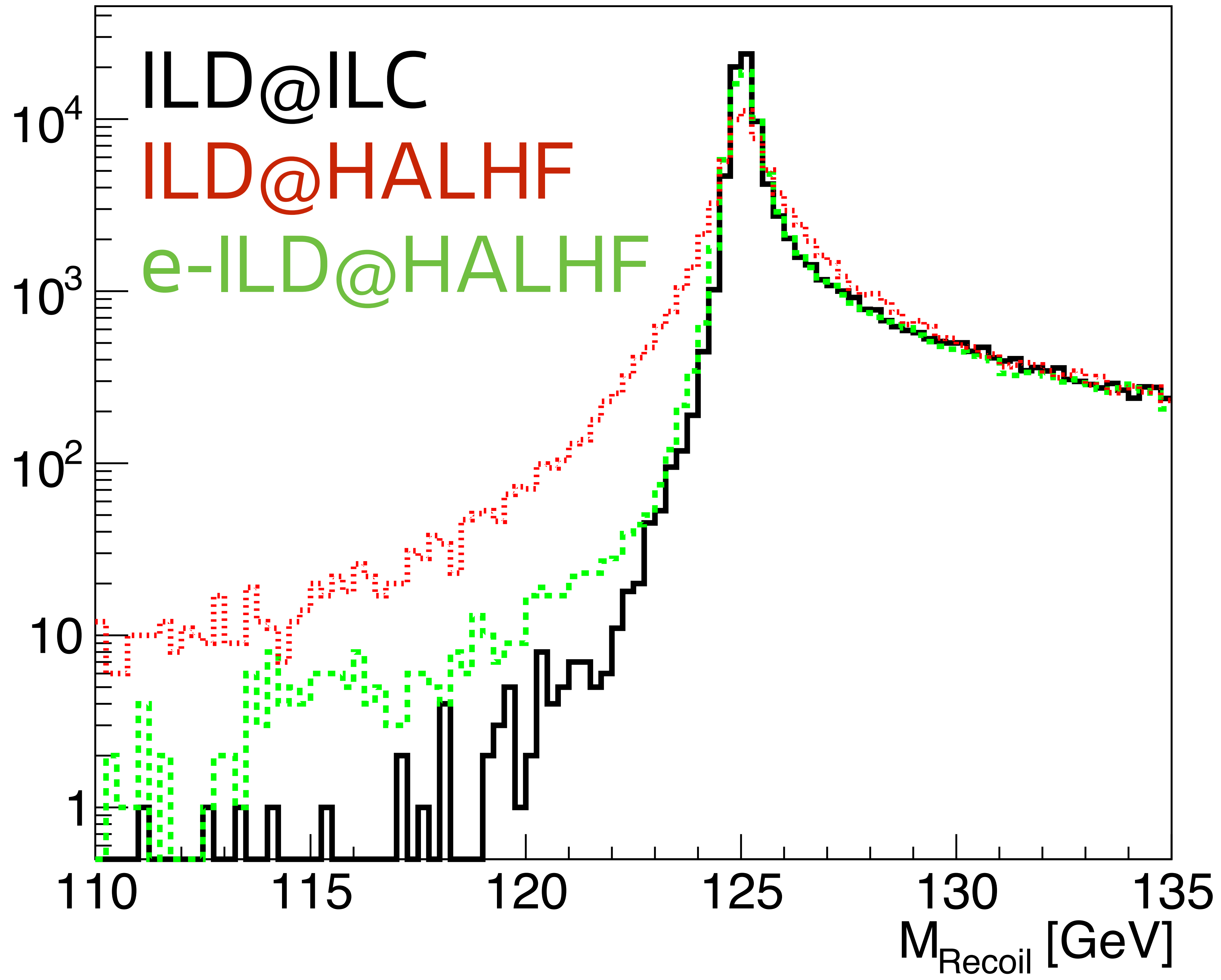
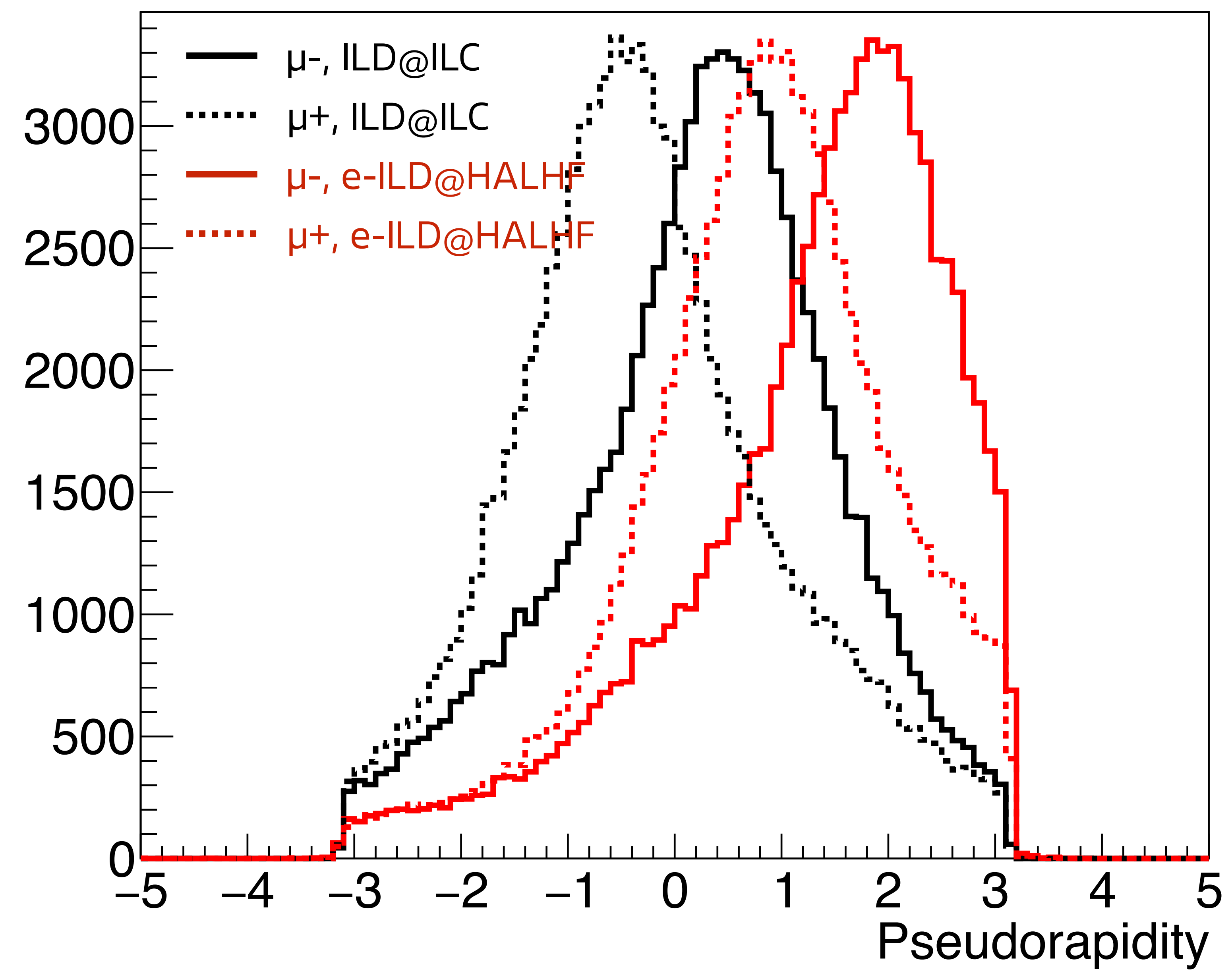
- Mitigation: **extend the barrel in the forward region!**
  - $\sigma_{\text{e-ILD@HALHF}} = 1.2 \times \sigma_{\text{ILD@ILC}}$
  - => loss of only 20% on recoil mass.



Impact on physics: F/B asymmetry

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



Lab frame

Impact on physics: F/B asymmetry

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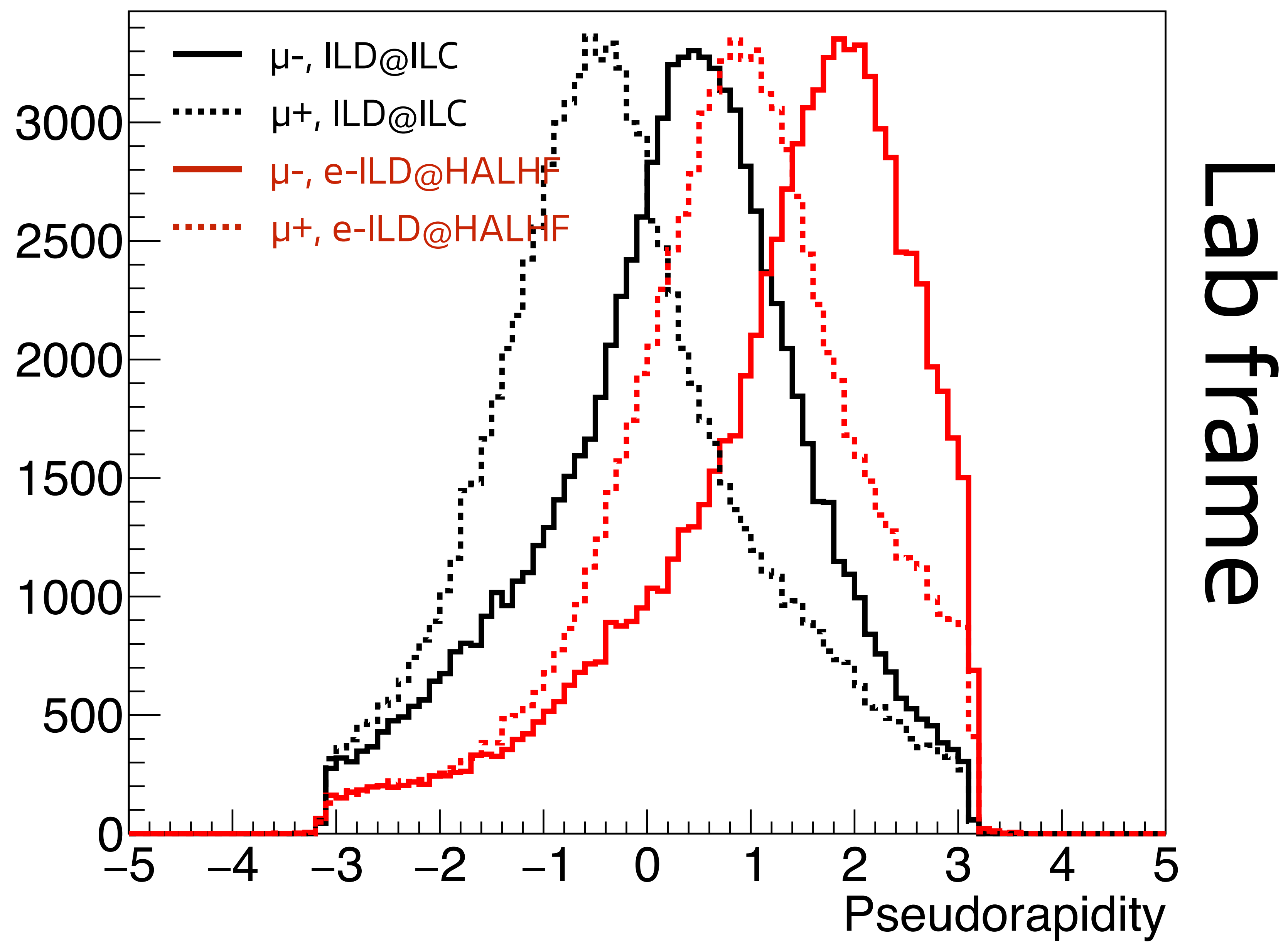
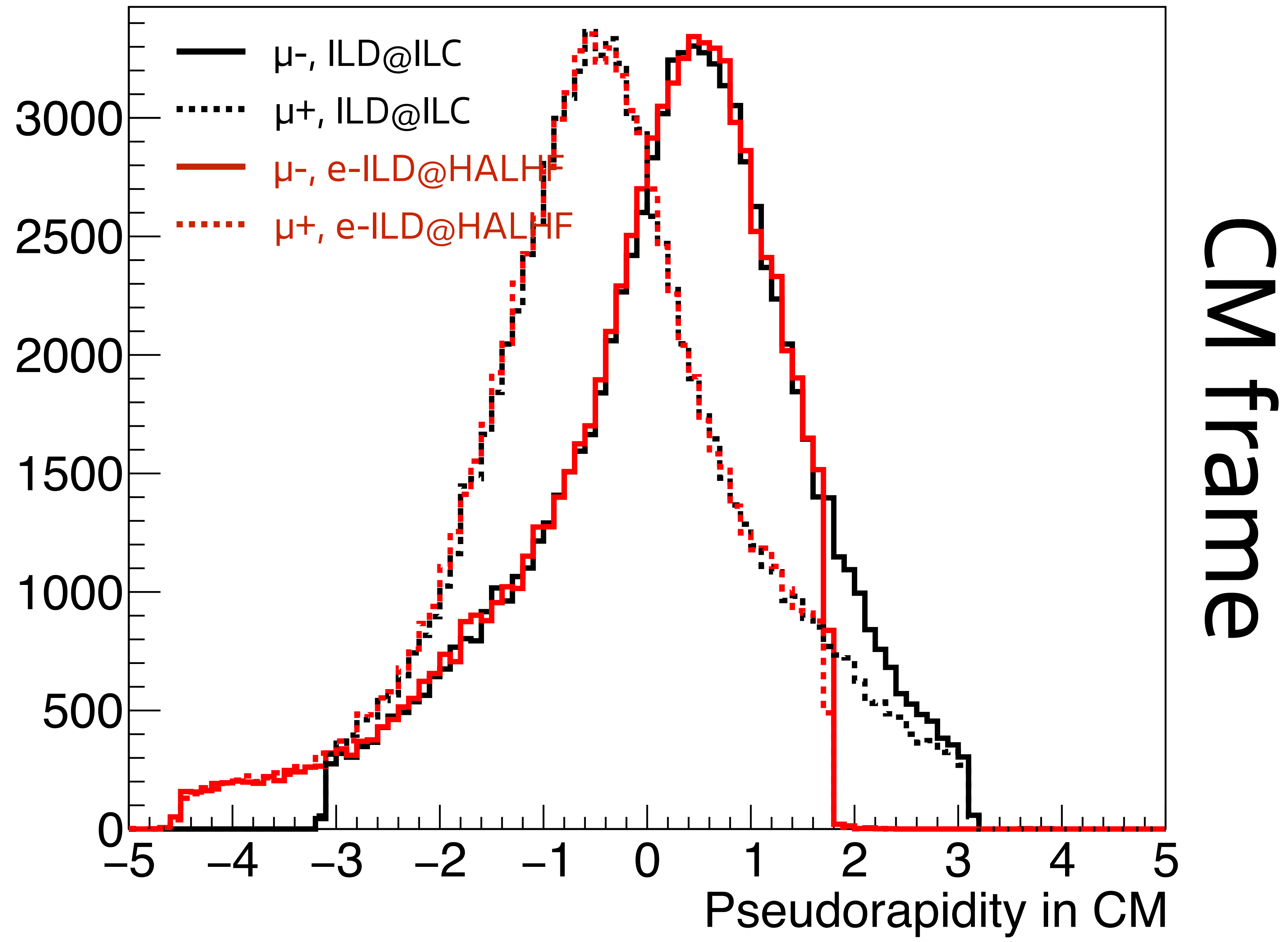


- Move to the CM frame to ease the comparison:
  - Core of distribution is the same (as expected)
  - **Tail extends on one side and is cut on the other**.



- Lose on one side, but gain on the other.
- => **Need more studies, especially for systematic uncertainties** (since setup itself is asymmetric).

Power efficiency

The asymmetry strikes back

- **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)*

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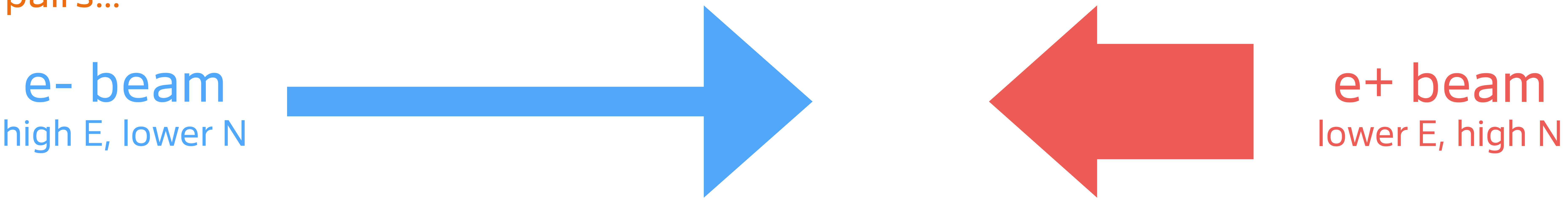
  - Ideally by the opposite factor as energy asymmetry.
  - **Limited by beam-induced background** (see next slides):
    - $N_- : N_+ = 1.33 : 3 \times 10^{10}$ particles / bunch => $P/P_{\mathrm{sym}} = 1.5$

Beam-strahlung

Creation of many e+e- pairs…



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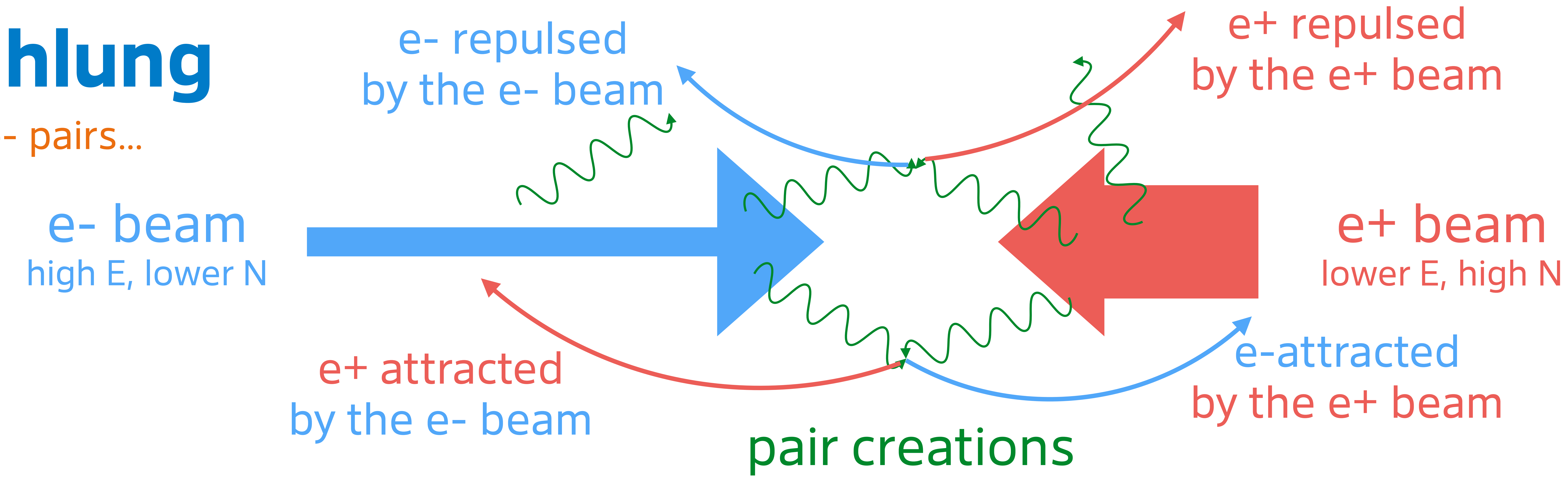

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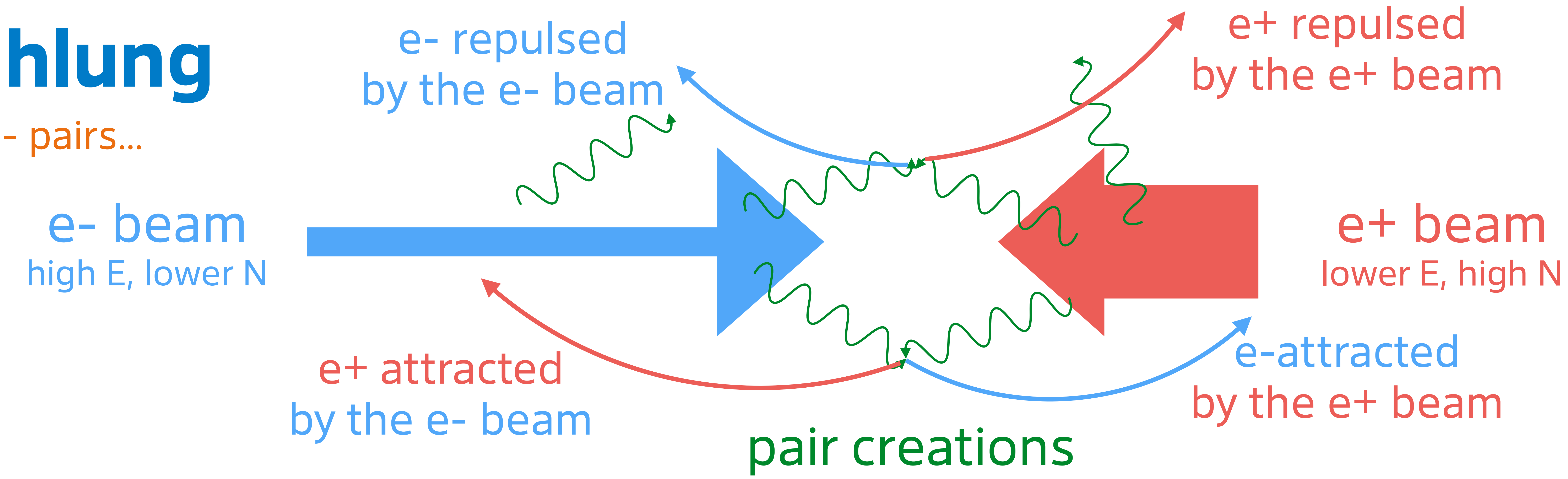
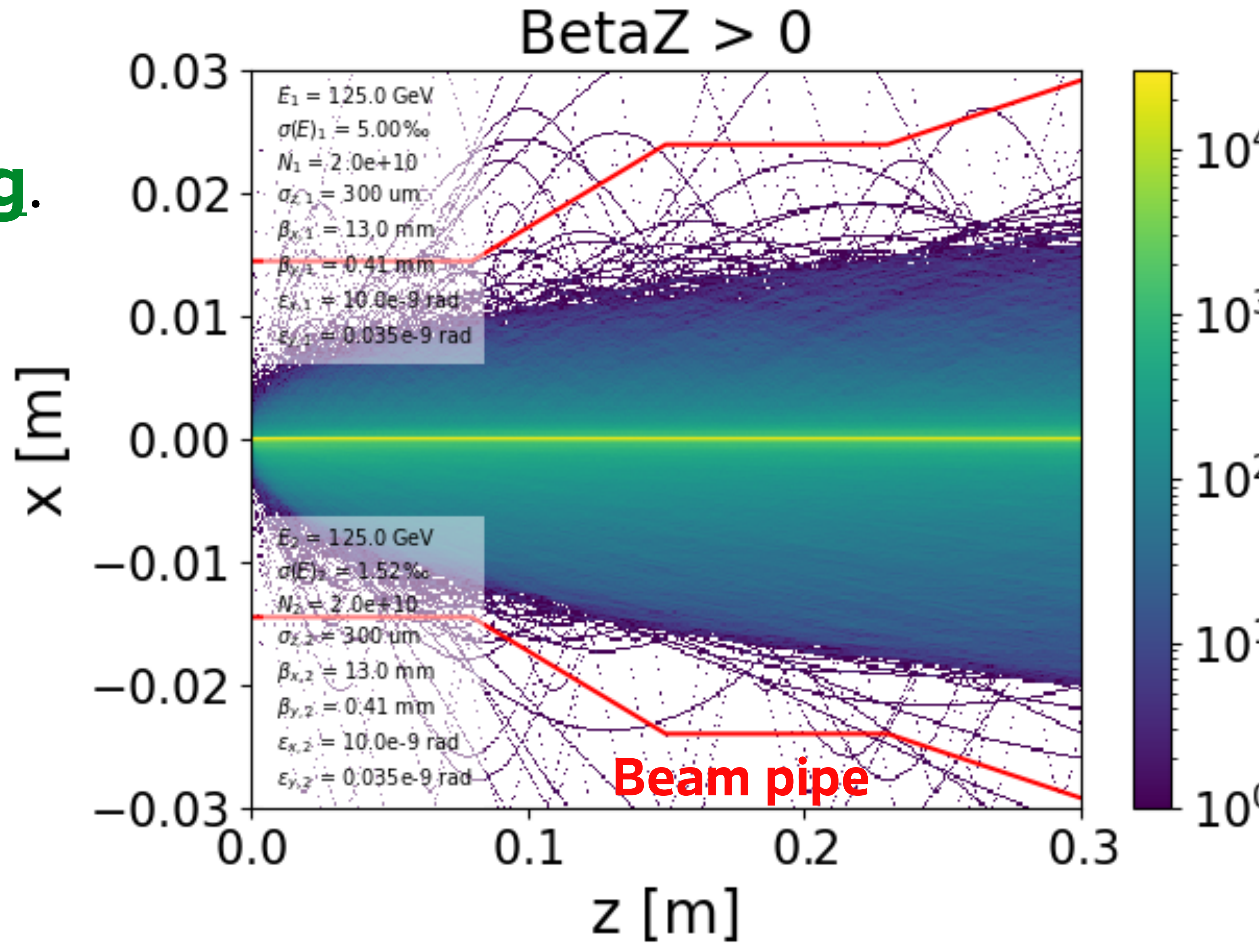


- **Simulate the beam-beam interaction using Guinea-Pig**.
  - Example: plot the trajectories of all pairs created in the forward direction.
  - Here in the ILC configuration (symmetric beams)



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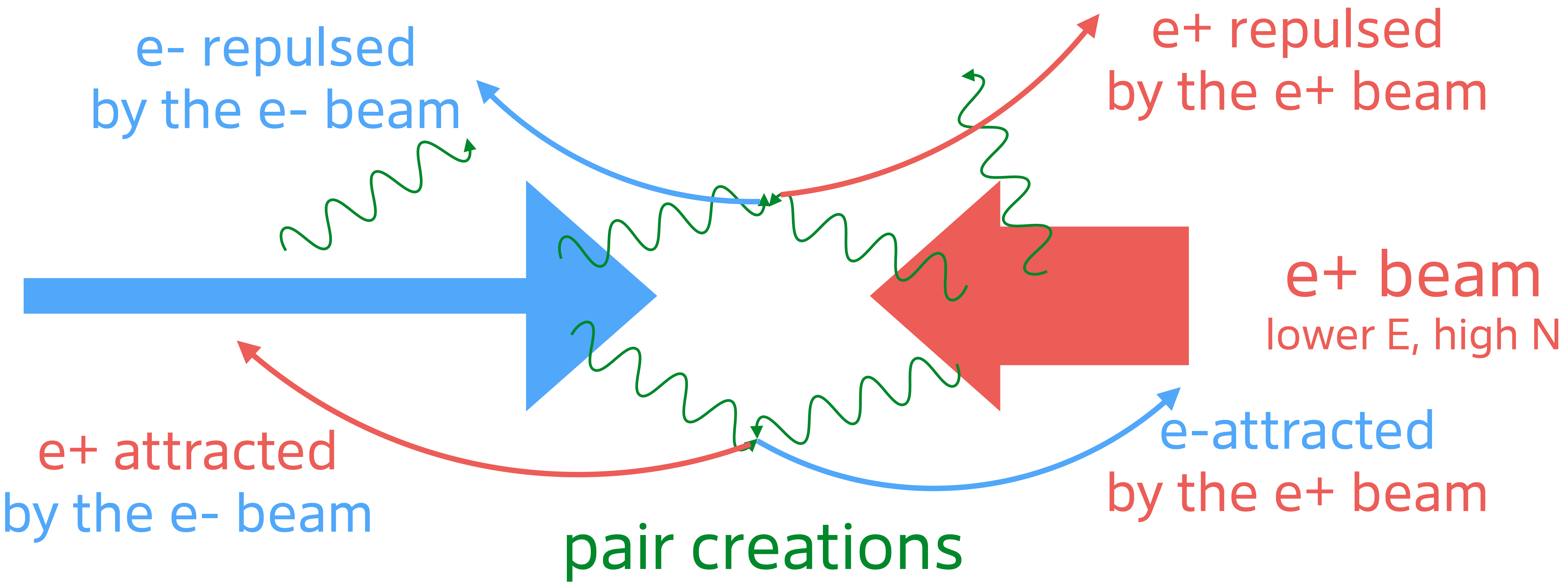

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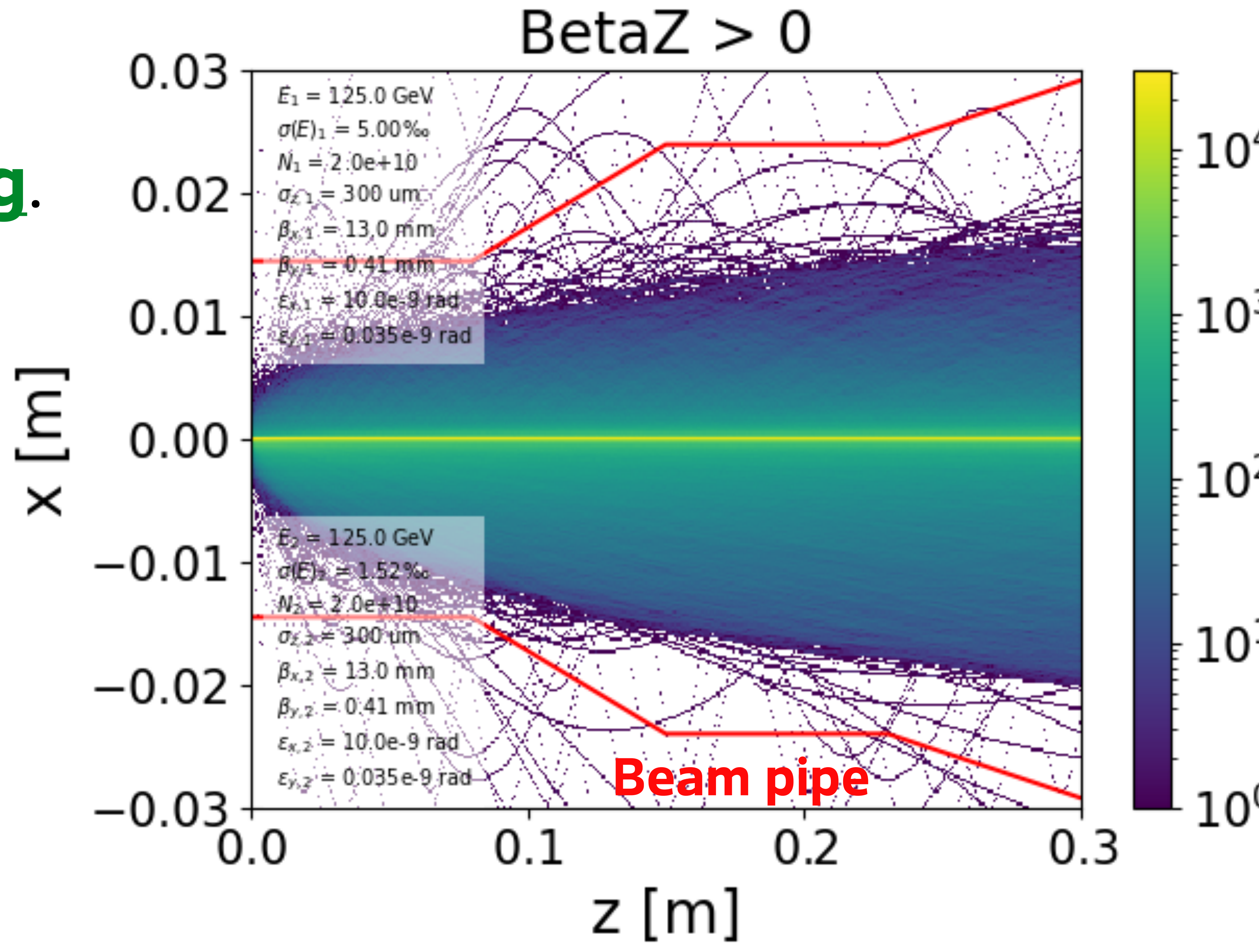

- This is ~ **independent of beam energy**, but rather **depends on the beam charge**.

Beam-strahlung

Drawing the detector like you've never seen it!

- Usual representation of this effect:
  - Let a e-/e+ with given (pT, θ). This fully defines its trajectory (helix), for a given B field.
  - **If/Where does this helix hit the detector?** => "Hit map" in the (pT, θ) space.

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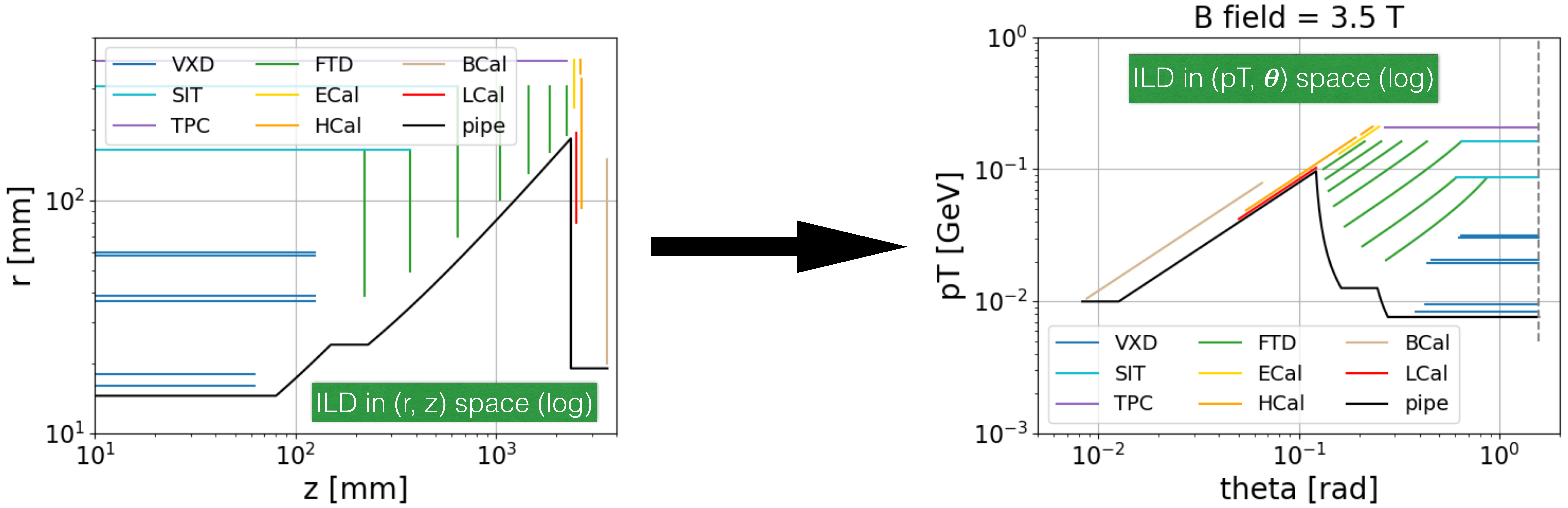
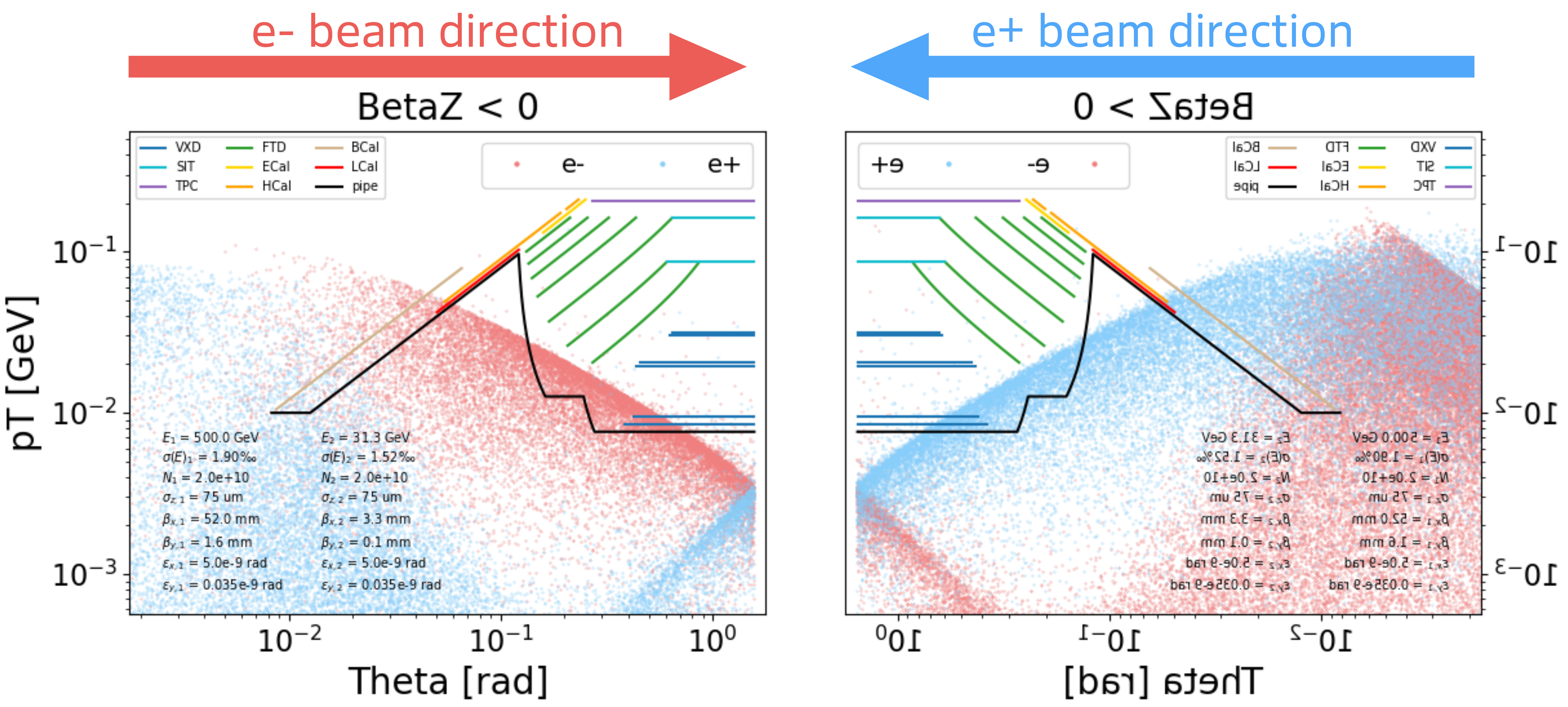
- What does the detector look like in the (pT, θ) space?



Beam-strahlung

- <u>Baseline: symmetric-charge beams</u>
  - Beam energy = 500 : 31.3 GeV
  - Bunch charge = **2 : 2** x 10^{10}
  - Bunch size σ_z = **75 : 75** µm
- **Pairs in the e- beam direction hit the detector.**
  - > O(100 TeV) energy deposited!
  - **Fries the detector!**



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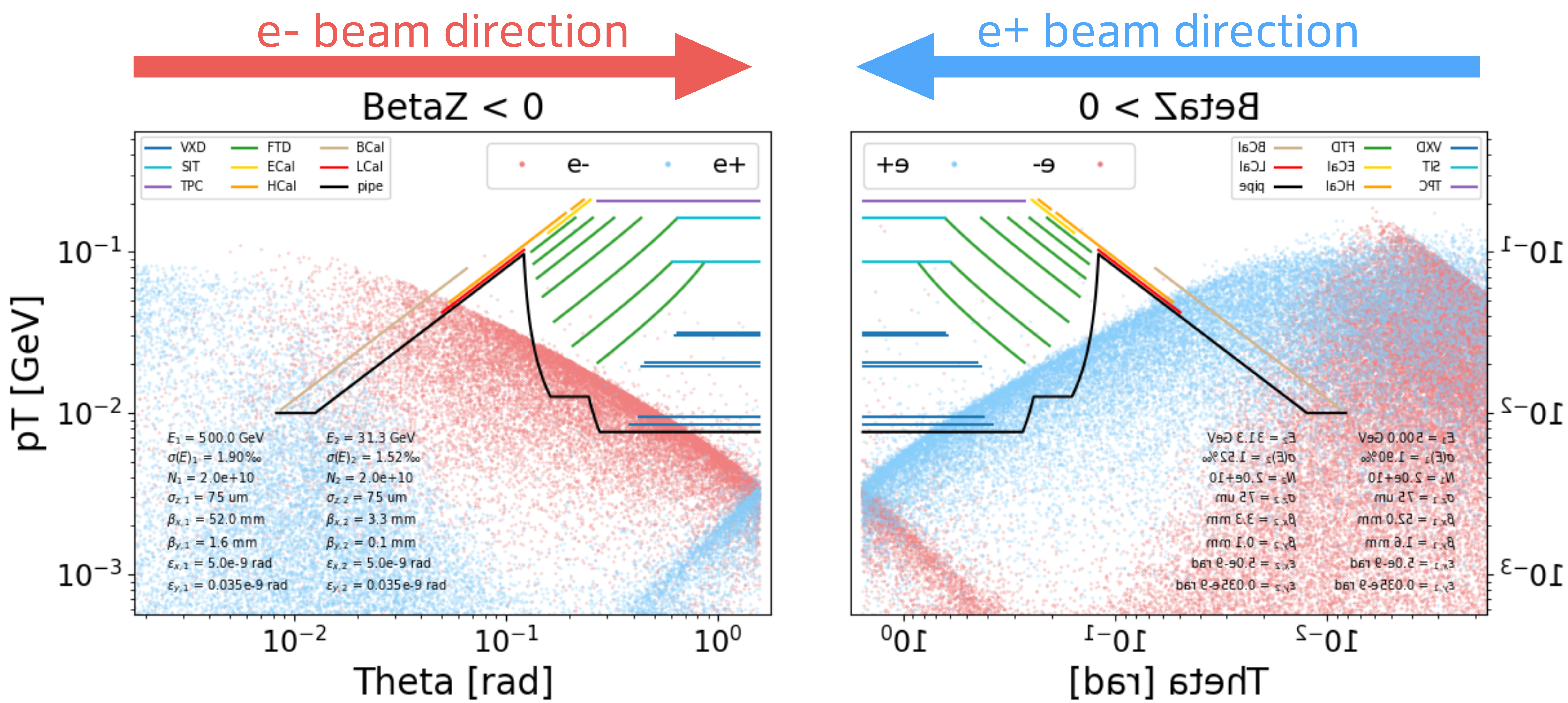
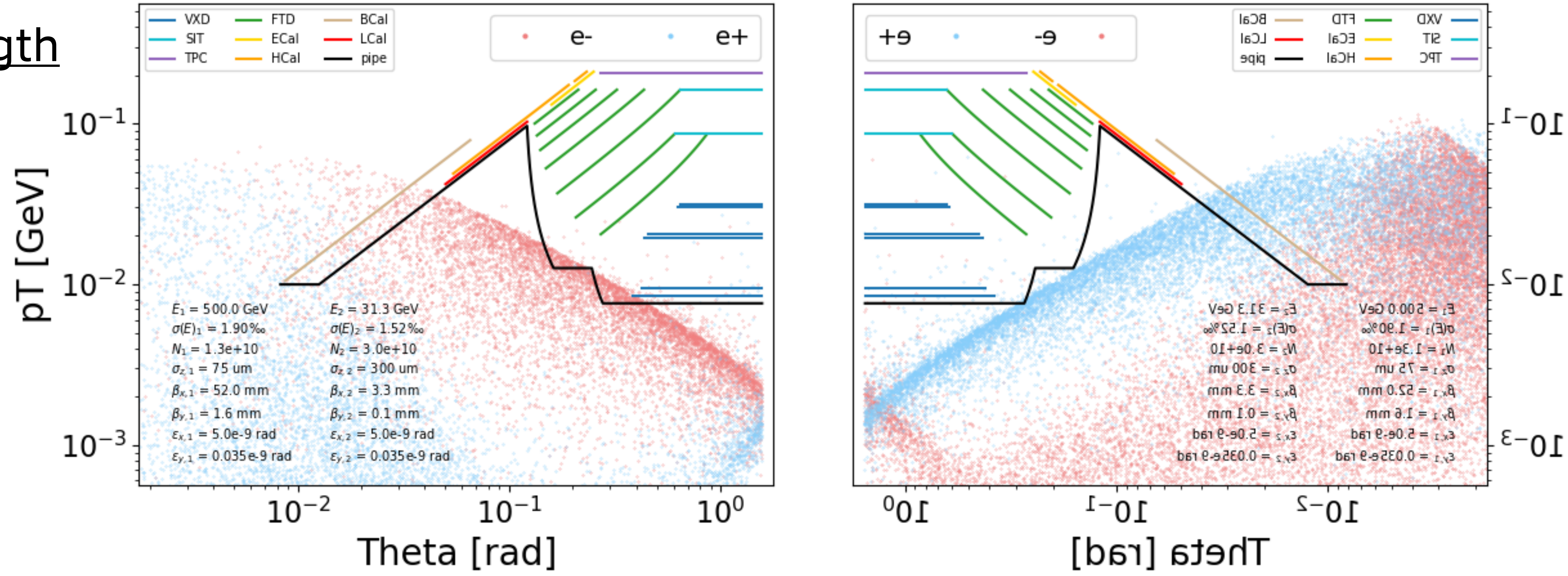


- Improved: asymmetric charge and length
  - Beam energy = 500 : 31.3 GeV
  - Bunch charge = **1.33 : 3** x 10^{10}
  - Bunch size σ_z = **75 : 300** µm (cannot produce long bunches with PWFA)
- **More fine tuning possible**!



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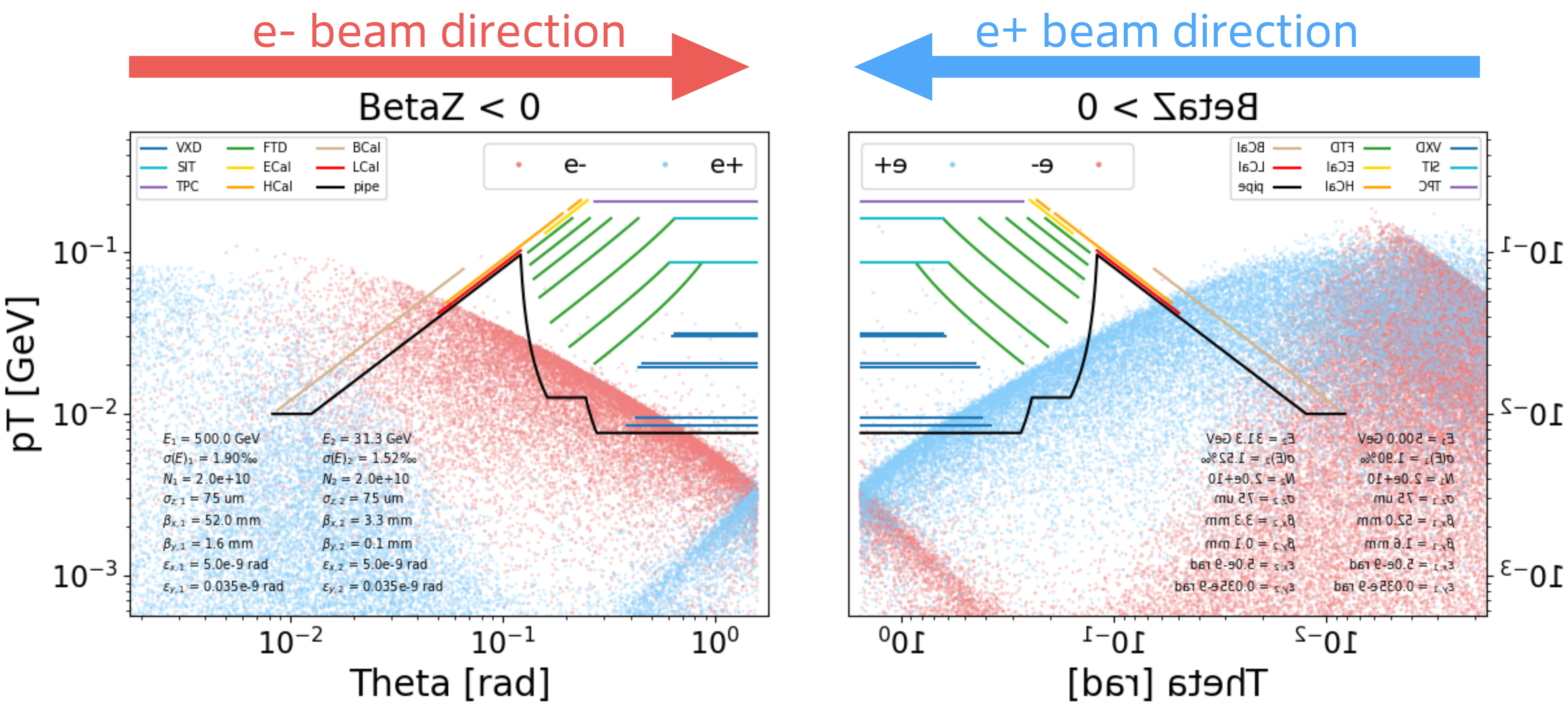

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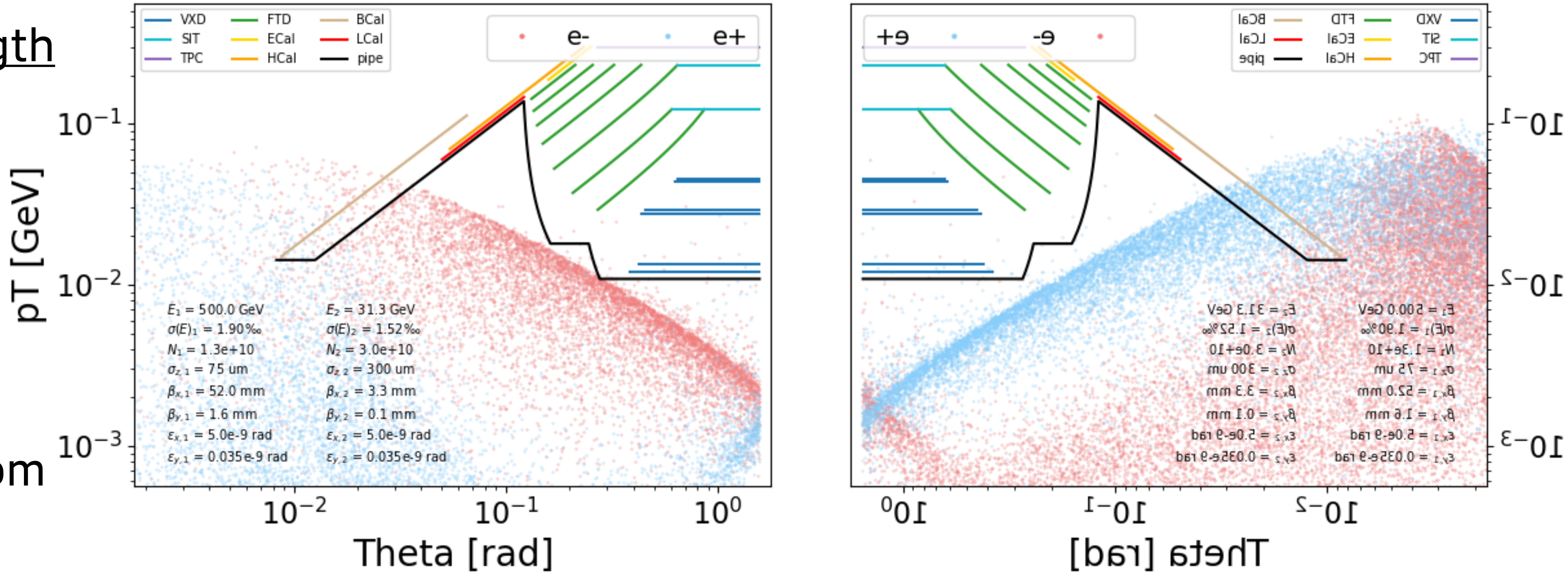
- **More fine tuning possible**!
- And/or **increase the magnetic field** from 3.5 T → 5 T!



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

Conclusions: HALHF the size, twice the fun!

arxiv:2303.10150

Slightly less powerful than ILC, but much more affordable!

- **Brand new project (< 1 year old), small team**.
  - Started to **look into impact on physics from asymmetric beams** (energy, charge, parameters…)
  - Iterate with accelerator colleagues to **find the best beam parameters**:
    - interplay between **lumi / background / power efficiency**.
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- **No show-stoppers so far, but many challenges remain**:
  - **Plasma acceleration**: beam charge, repetition rate, power dissipation, polarisation…
    - Staging PWFA cell concept needs ~10 years development.
  - **Detector design in the forward region.**
    - => next step: modify full-sim ILD into an asymmetric detector and play with B field.
    - => Then re-run physics benchmarks (Higgs recoil, F/B asylum)
  - **Luminosity measurement** (Bhabha counting) to be studied (see discussion this morning).
  - Upgradability to higher CM energy is unclear (until PWFA for e+ becomes available?).

- **Many possibilities for new studies** (physics cases, detector design…)!

Thanks for your attention!

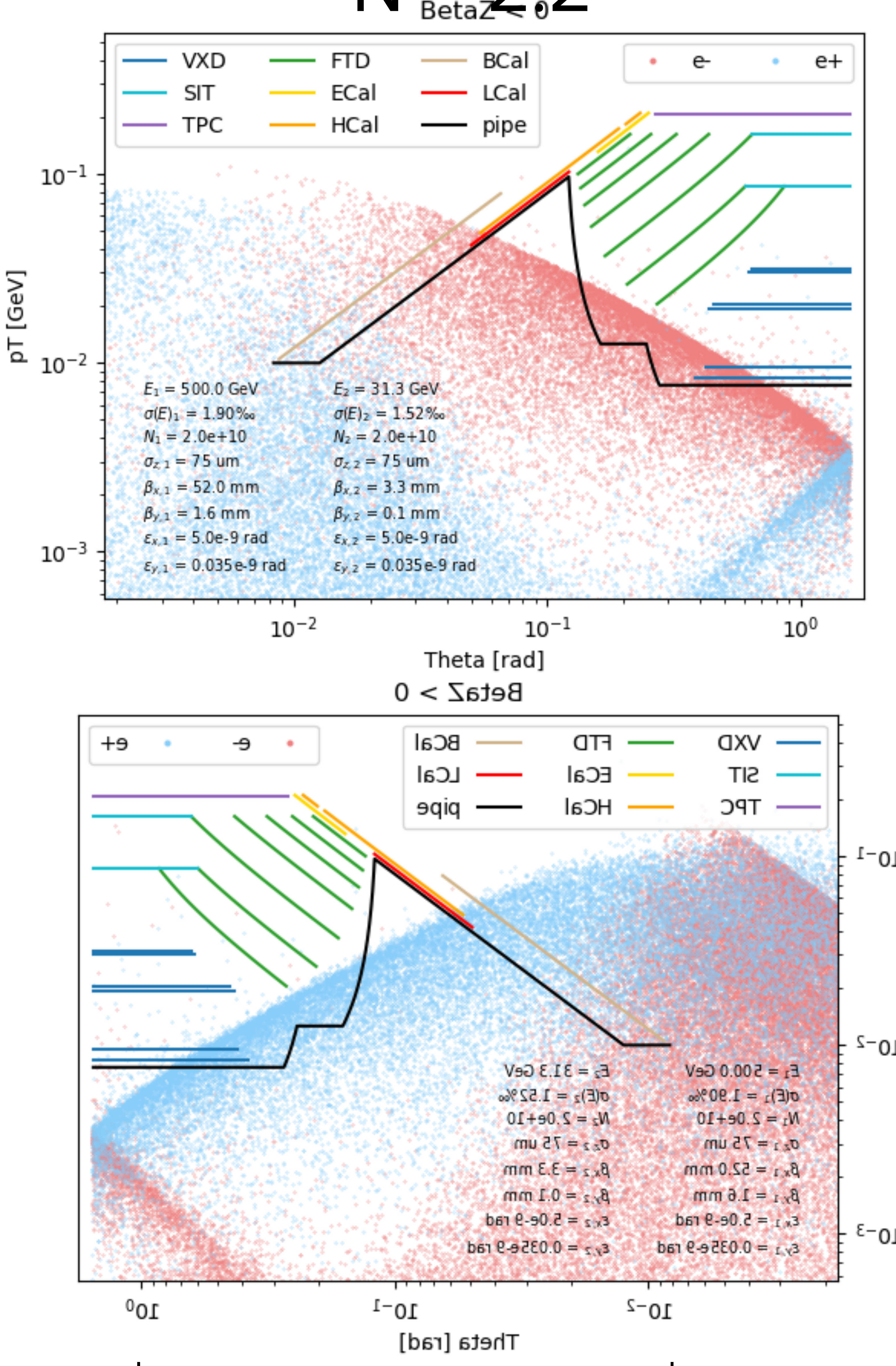
Questions?

- *How much can we let go on the energy efficiency (to gain on luminosity)?*
- *Already-existing asymmetric detector as starting point?*
- *New lumi measurement ideas?*
- *Upgradabililty?*

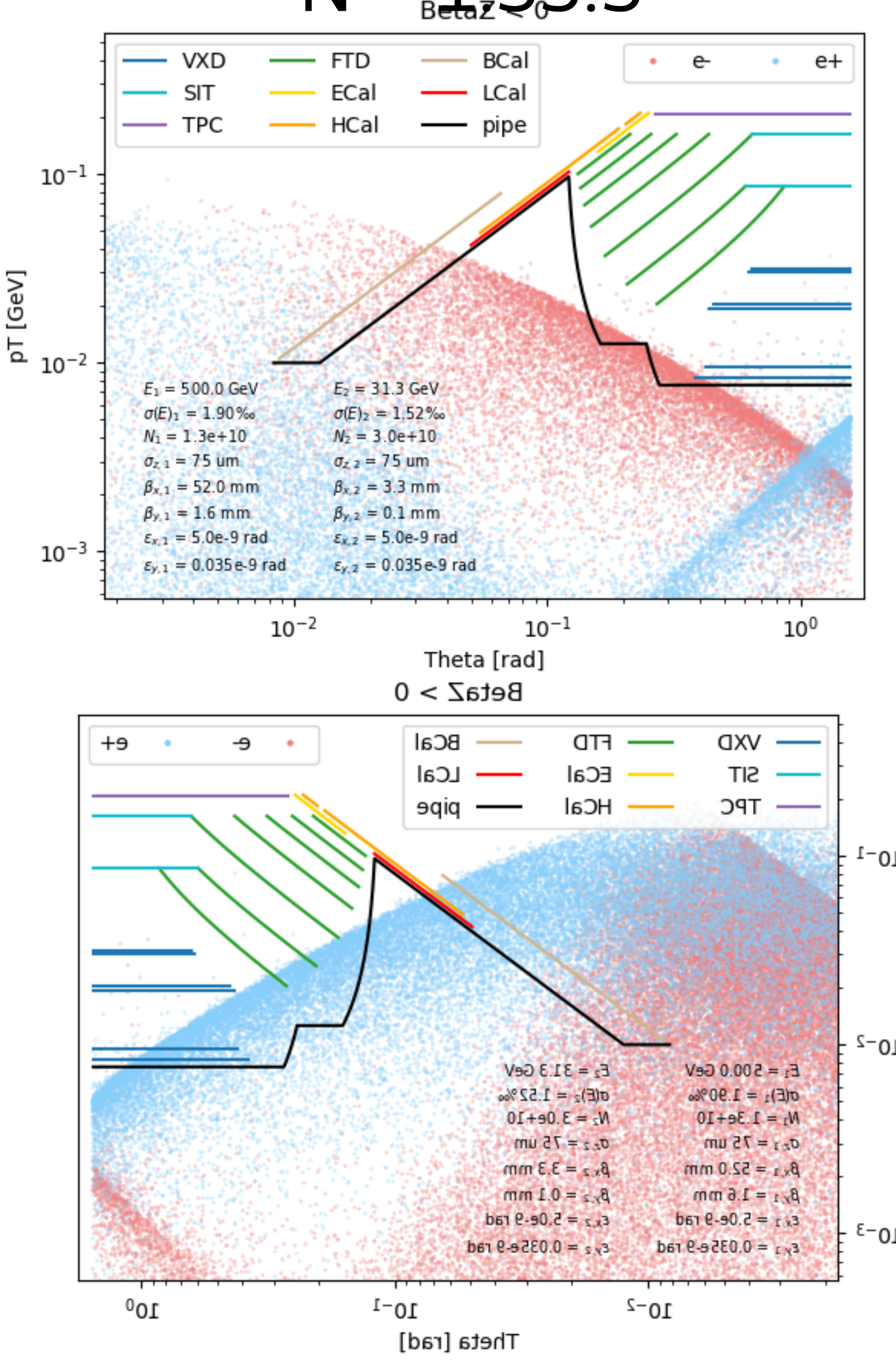
Backup

Beam background hit map, σ_z = 75:75

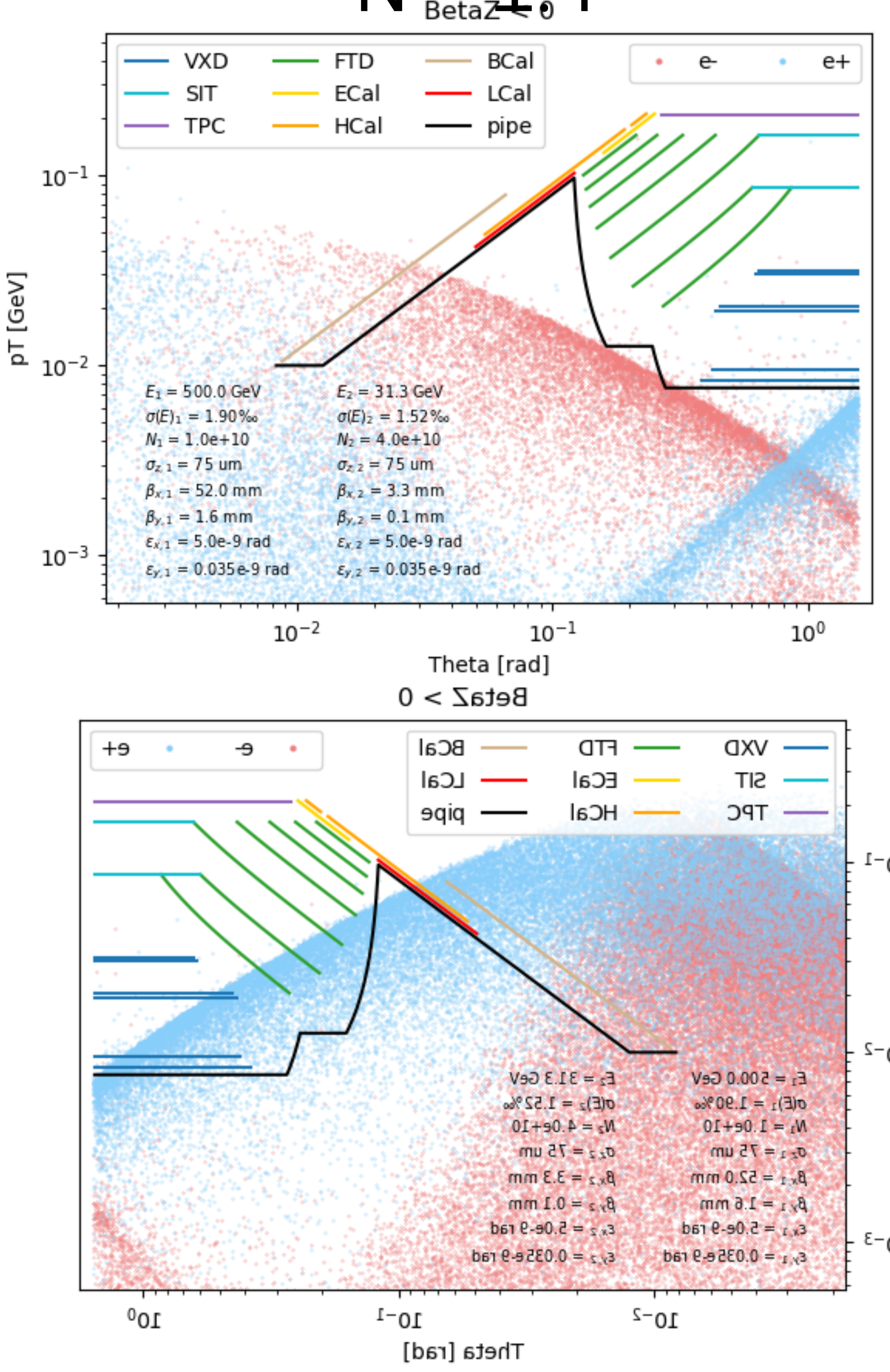
N = 2:2



N = 1.33:3



N = 1:4



Beam background hit map, σ_z = 75:300

N = 2:2 | N = 1.33:3 | N = 1:4

Beam background hit map, σ_z = 300:300

N = 2:2 | N = 1.33:3 | N = 1:4

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").