Unified Theories of the Universe: From Strings to Multiverse Hypotheses

Antoine Niardual (he/him)

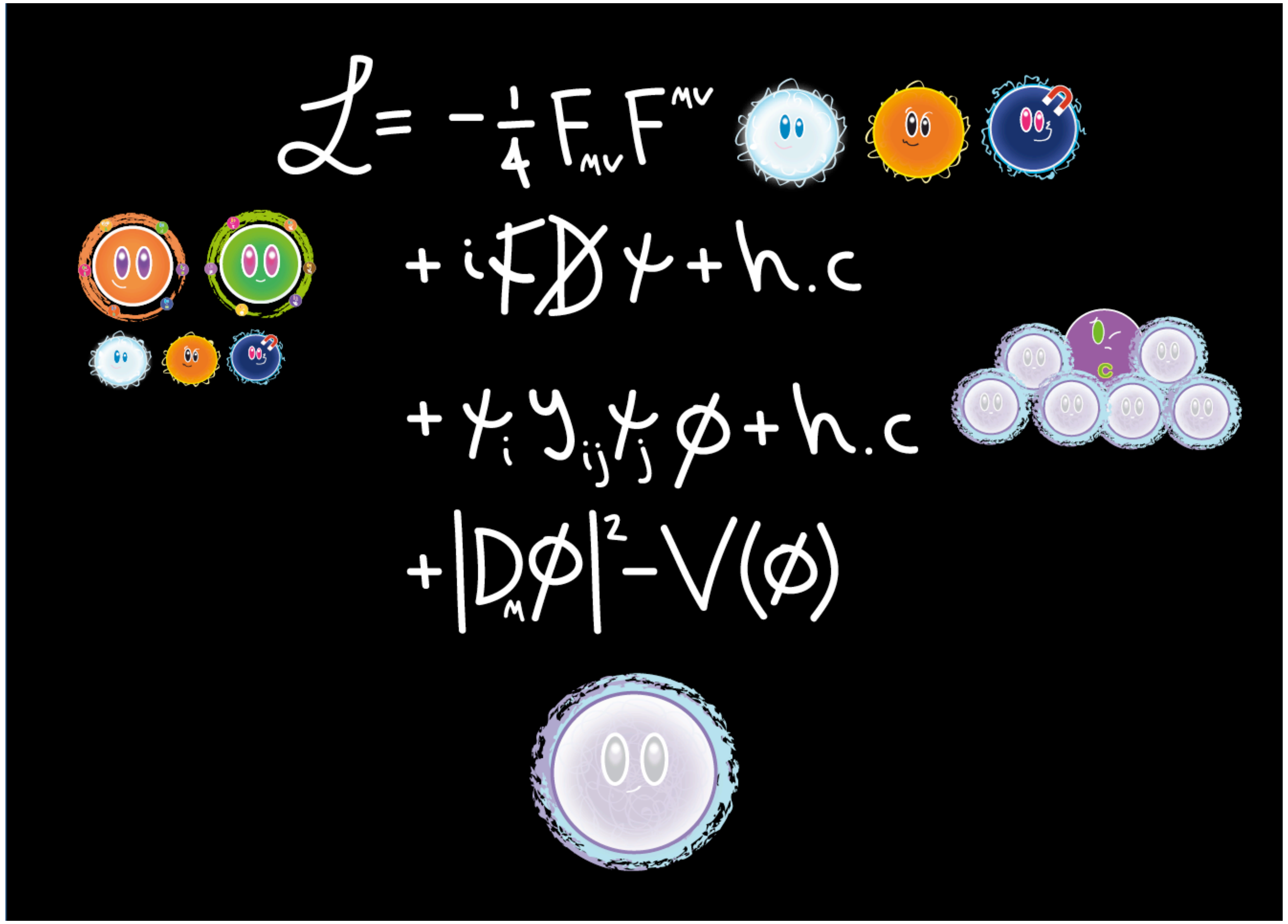
DPG Tagungen — 07.03.21243.2024

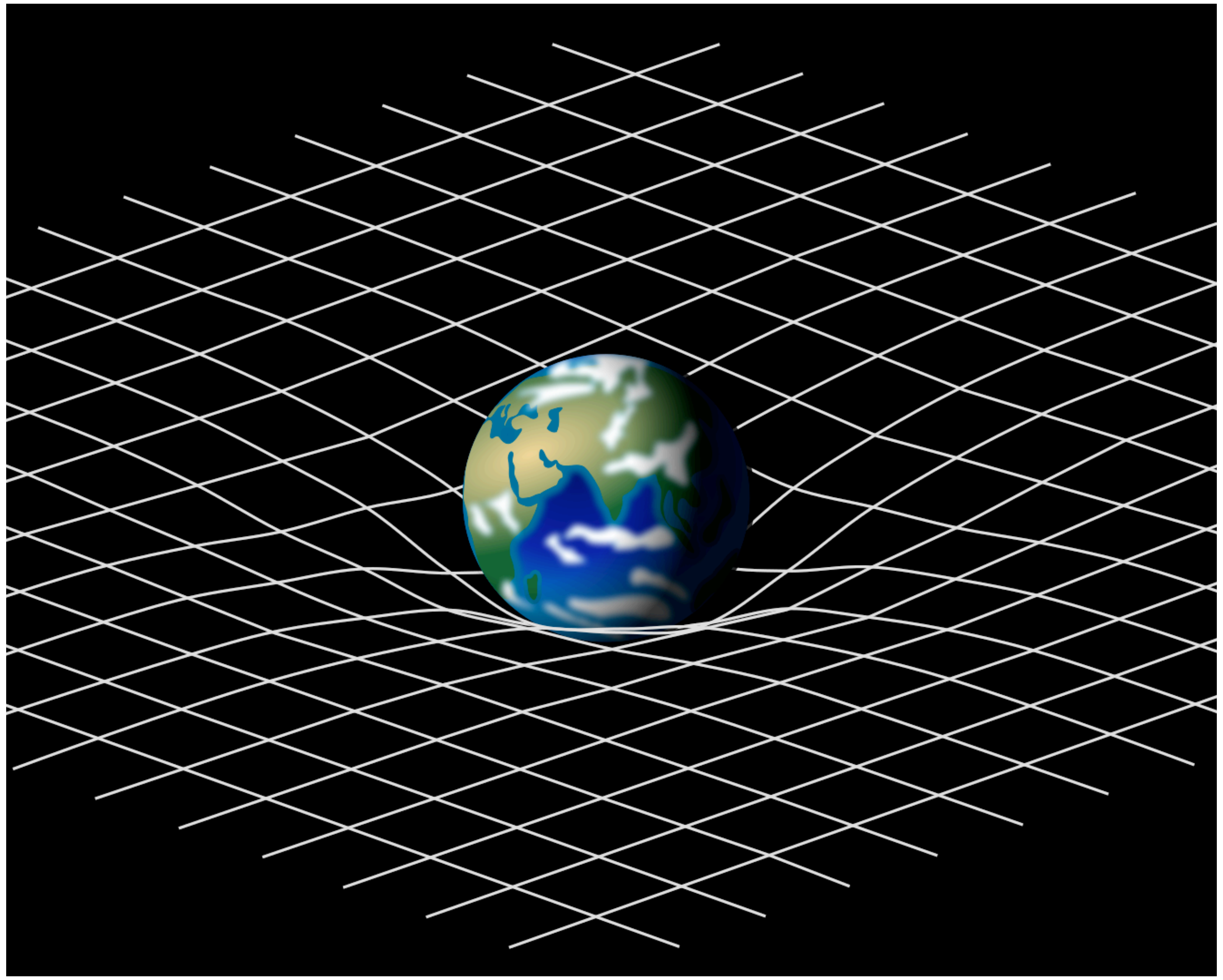
CLUSTER OF EXCELLENCE
QUANTUM Multiverse

HELMHOLTZ

antoine.laudrain@desy.de

String Theory or Loop Quantum Gravity





Experimentation at an Asymmetric Higgs Factory

Antoine Laudrain (he/him)

DPG Frühjahrstagung — 07.03.2024

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QUANTUM UNIVERSE

DESY.

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Future lepton colliders landscape

- LHC will run until 2035 – 2040.
- Next accelerator discussions converge toward a Higgs factory.
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Circular	Linear
FCC, CEPC, International MUON Collider Collaboration (?)	C^3, ilc, clic

- **Expensive: O(5B — 15B)**
- **High environmental impact**
- Power hungry

Circular:

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

Linear:

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

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

How to reduce the cost?

"Simply" decrease the size of the tunnel…

- But shorter tunnel = lower beam energy => 😭

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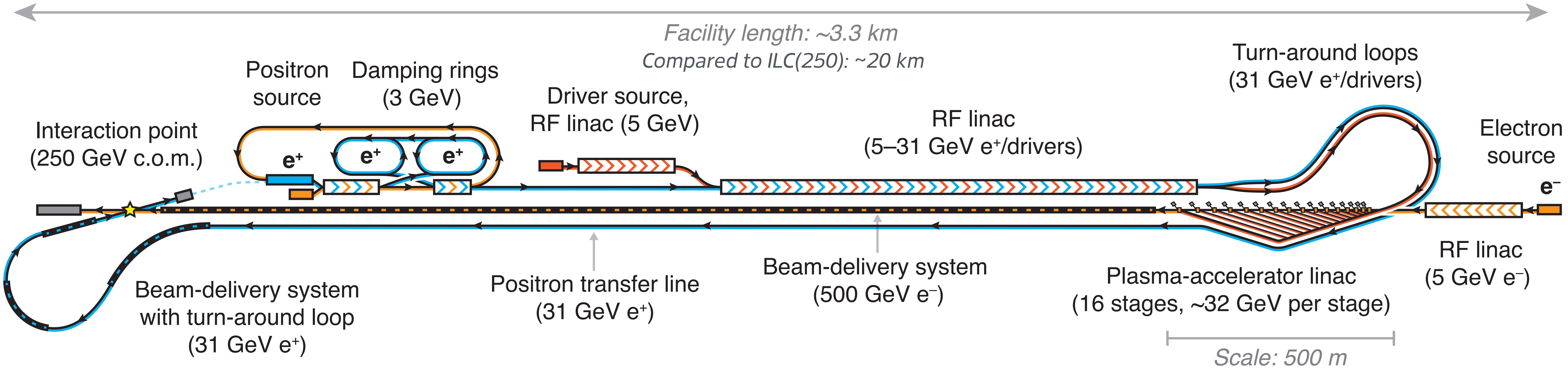
- **Can we do better than 1 km + 10 km?**

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

Asumptions & plan

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- Assumptions for the rest of this talk:
  - Electron-beam driven PWFA is proven **working for electron acceleration** in ~10-15 years.
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  - **Main question: Can we still do physics in such conditions?**
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  - **Higgs mass** measurement (ZH recoil),
  - **Forward/backward asymmetry** measurement.

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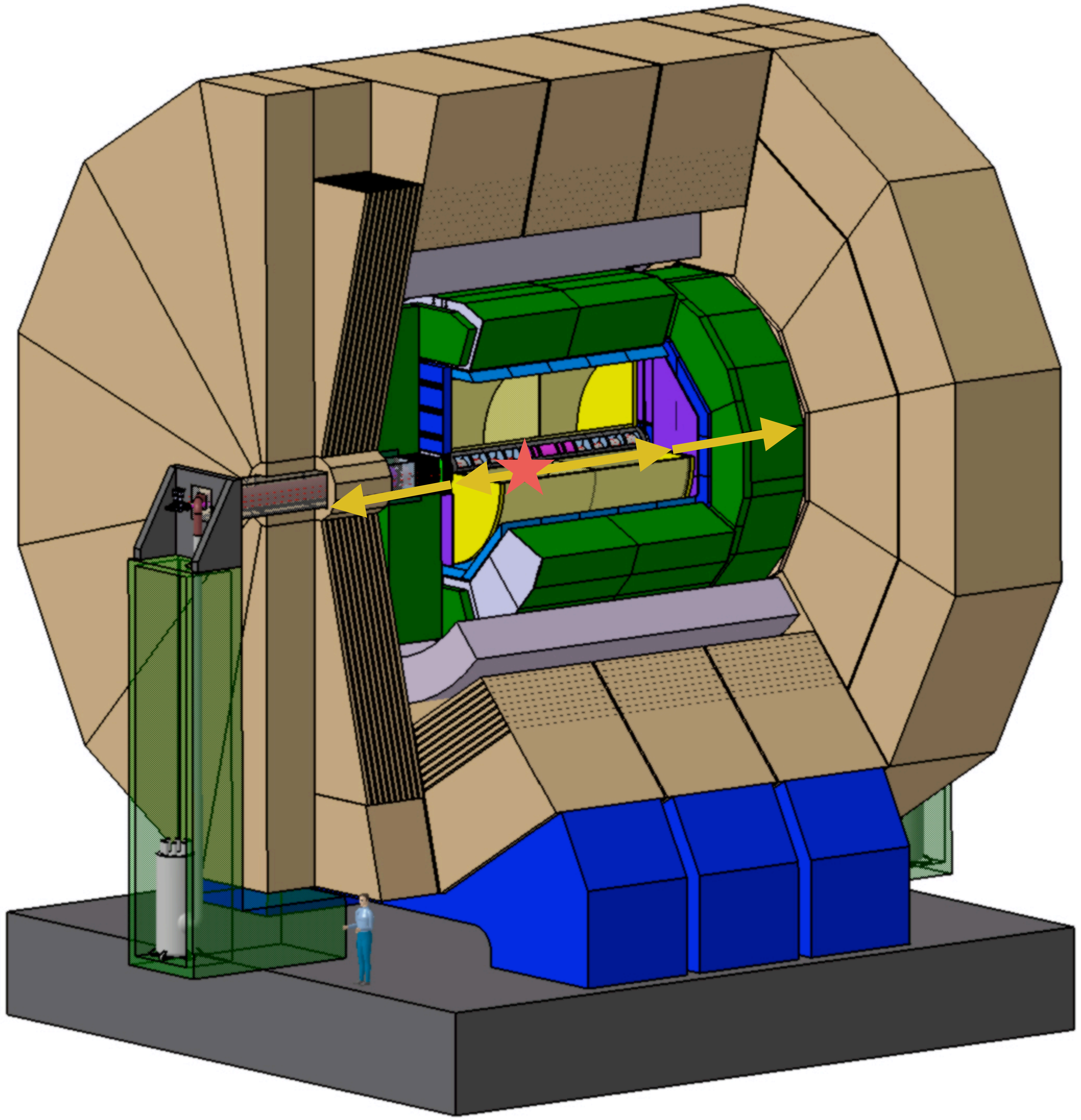
- **Study cases**:
  - **Higgs mass** measurement (ZH recoil),
  - **Forward/backward asymmetry** measurement.

- Not studied here:
  - Boost most likely improves jet flavour-tagging.
  - Luminosity measurement is probably not as straightforward.

Towards an asymmetric detector!

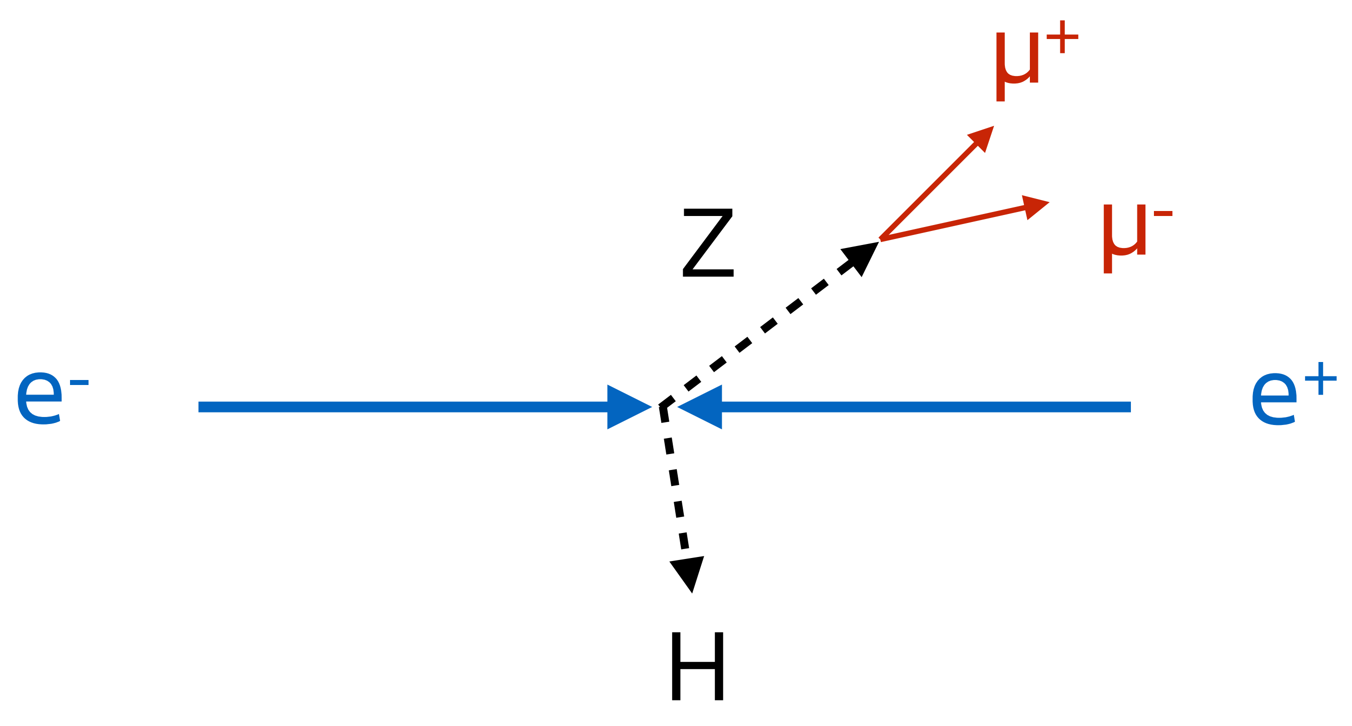
- **Most advanced concept is the ILD at the ILC**.
  - **Fast simulation (SGV) available**.
  - Good comparison point.

- **Step 1: are there major showstoppers**?
  - Modify the fast simulation and run physics analysis benchmarks.
    - **Longer barrel sub-detectors**.
    - **Off-centre interaction point**.
    - **Boosted particles in the simulation**.



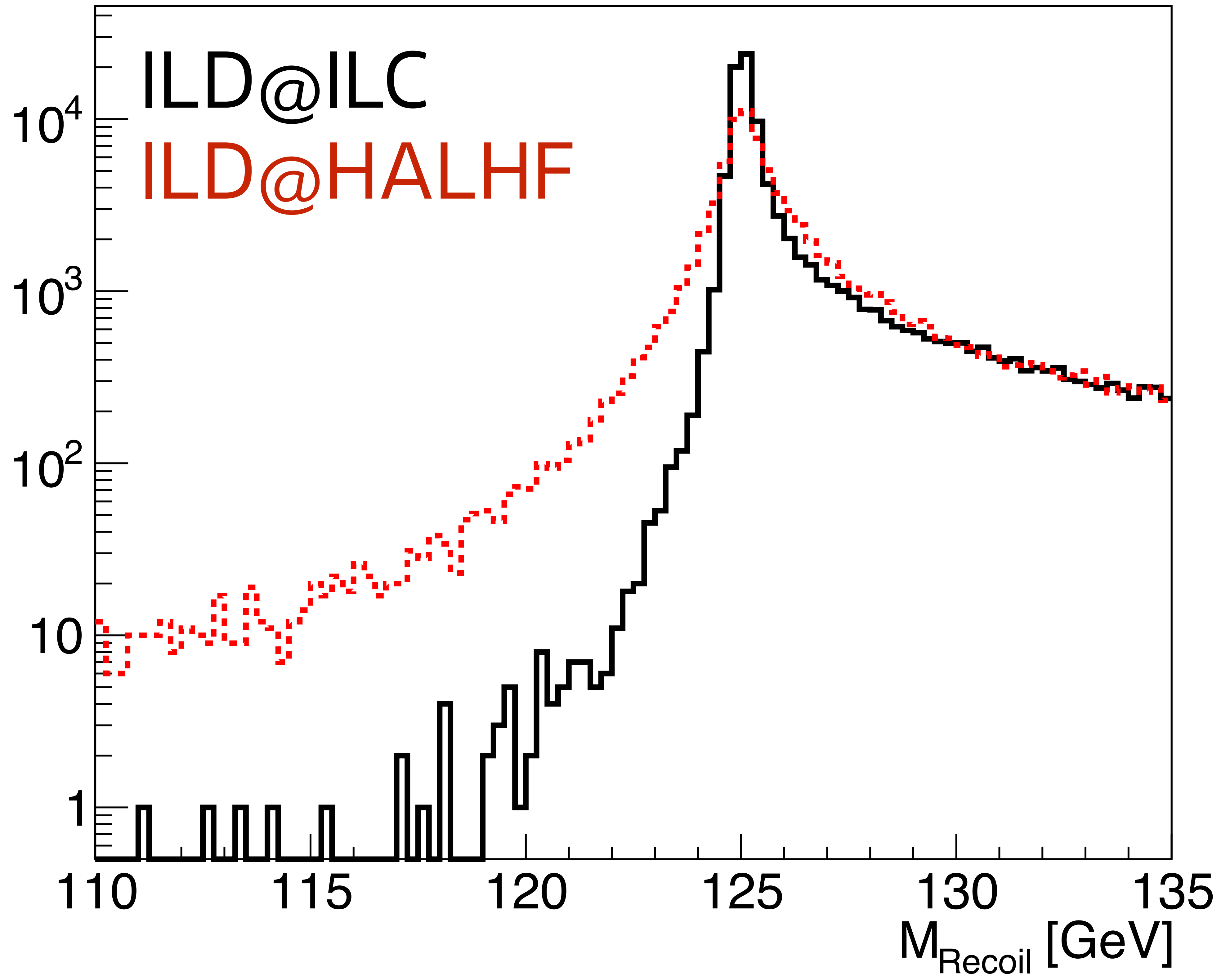
The International Large Detector

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.

- **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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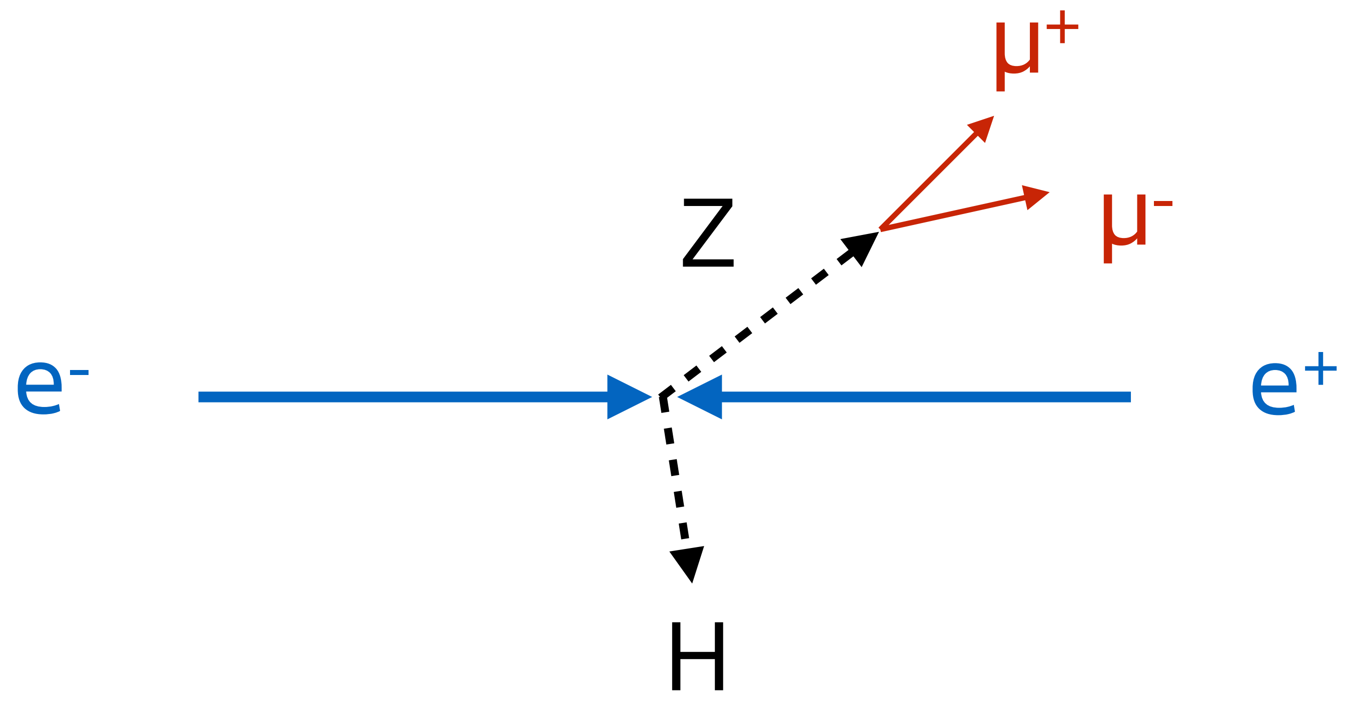

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  - less lever arm => lower muon momentum resolution.
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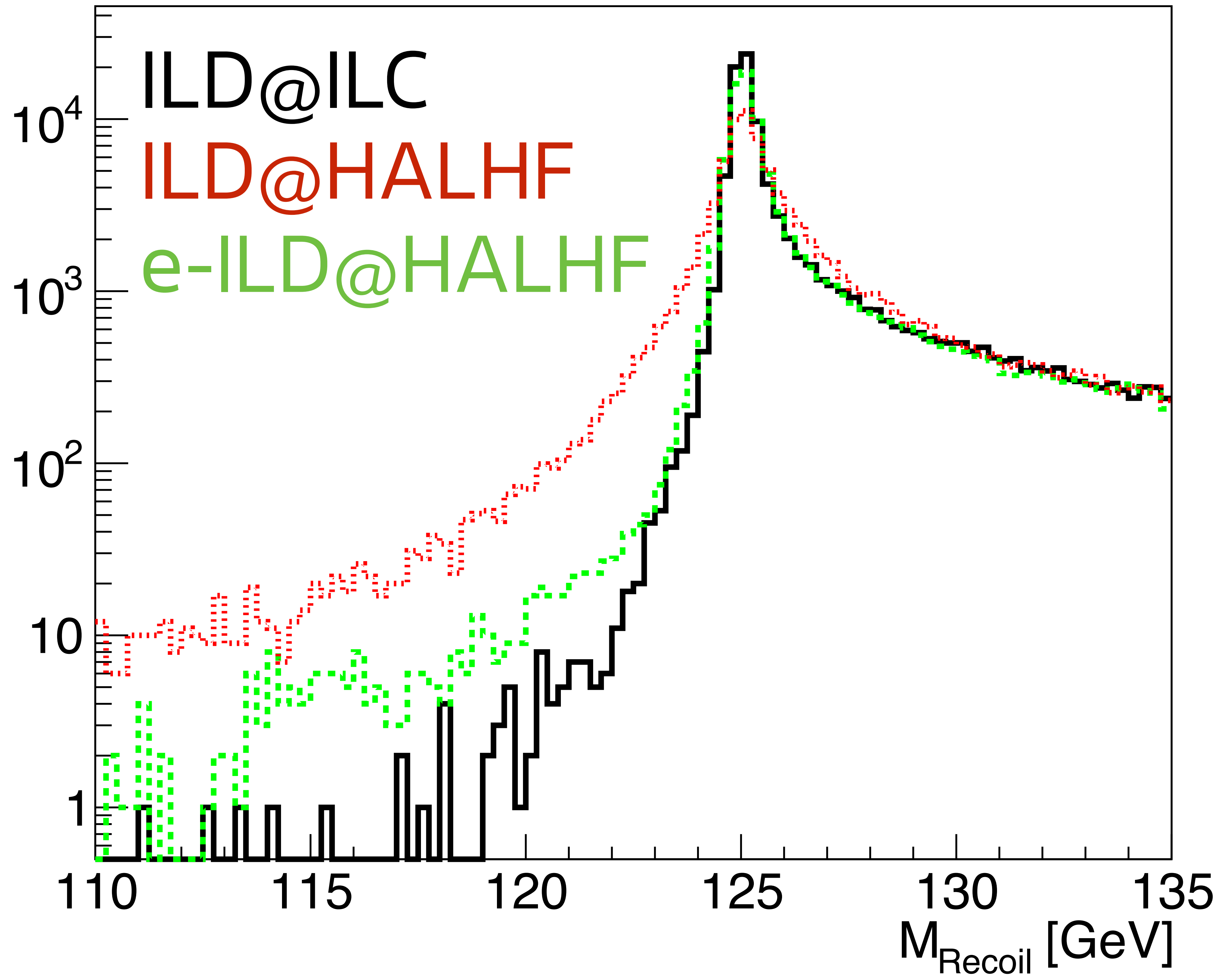
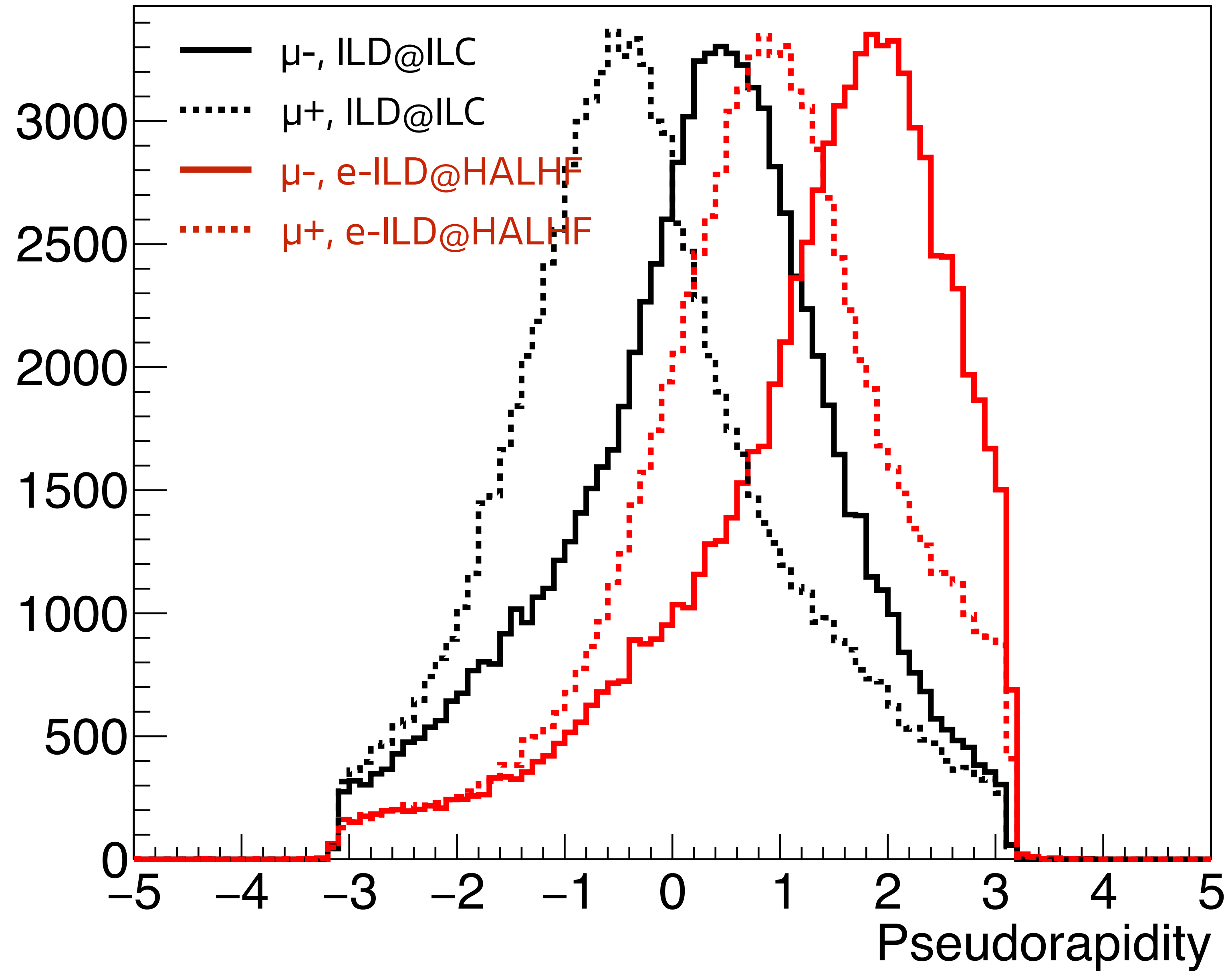
- Mitigation: **extend the barrel in the forward region!**
  - $\sigma_{\text{e-ILD@HALHF}} = 1.2 \times \sigma_{\text{ILD@ILC}}$
  - => loss of only 20% on recoil mass.



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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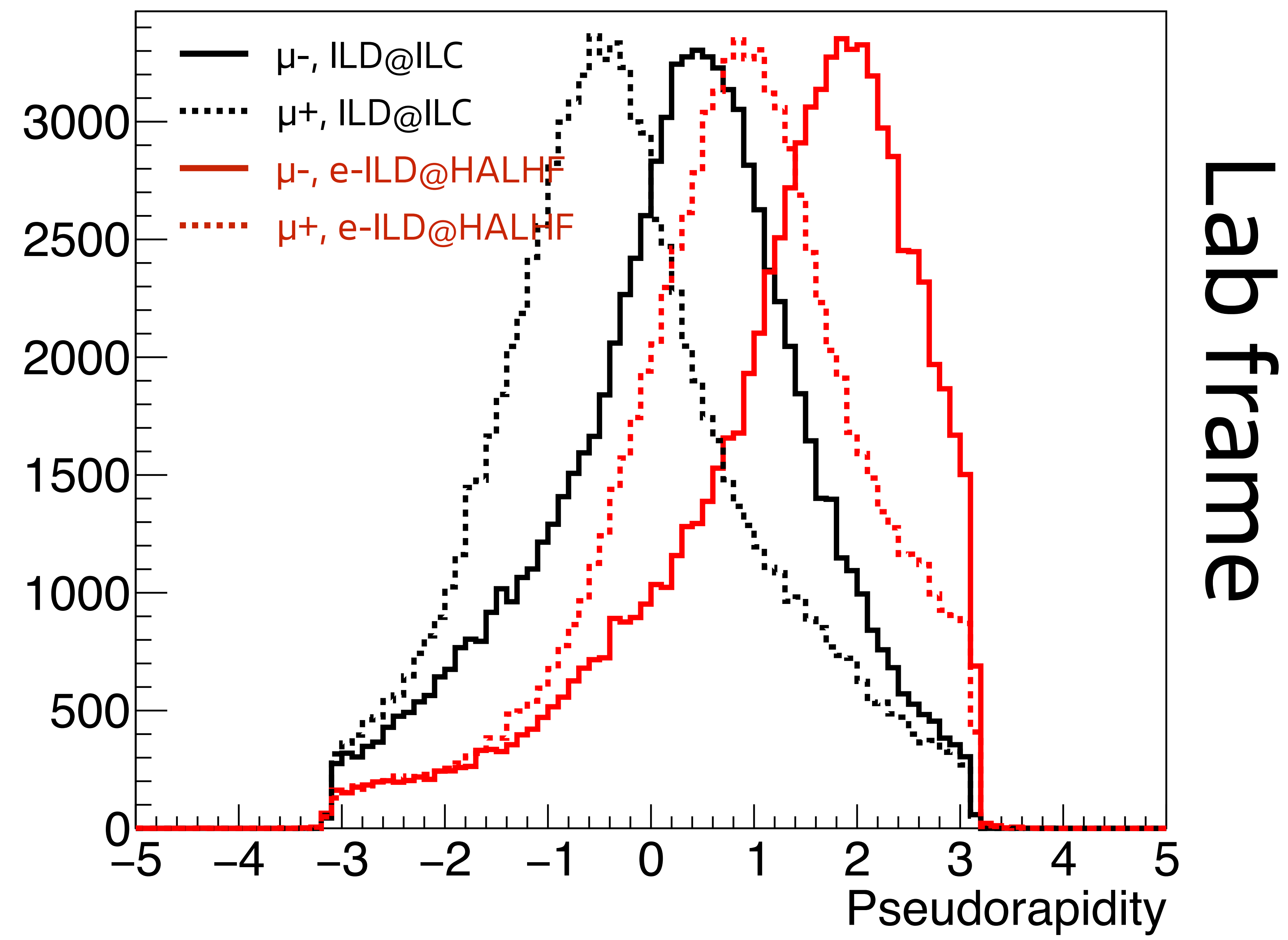
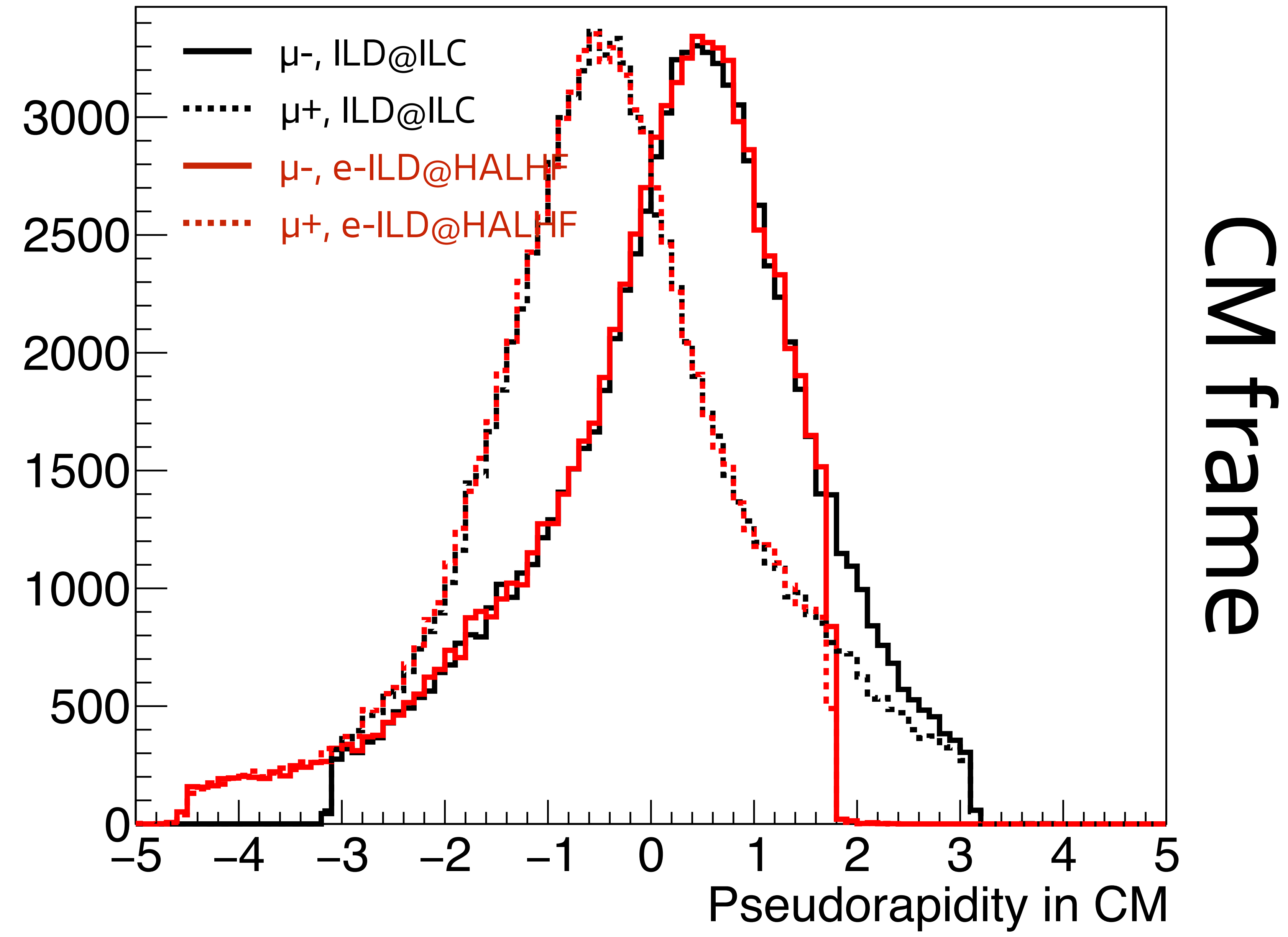


- Move to the CM frame to ease the comparison:
  - Core of distribution is the same (as expected)
    - => in particular: same width
  - **Tail extends on one side and is cut on the other**.



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

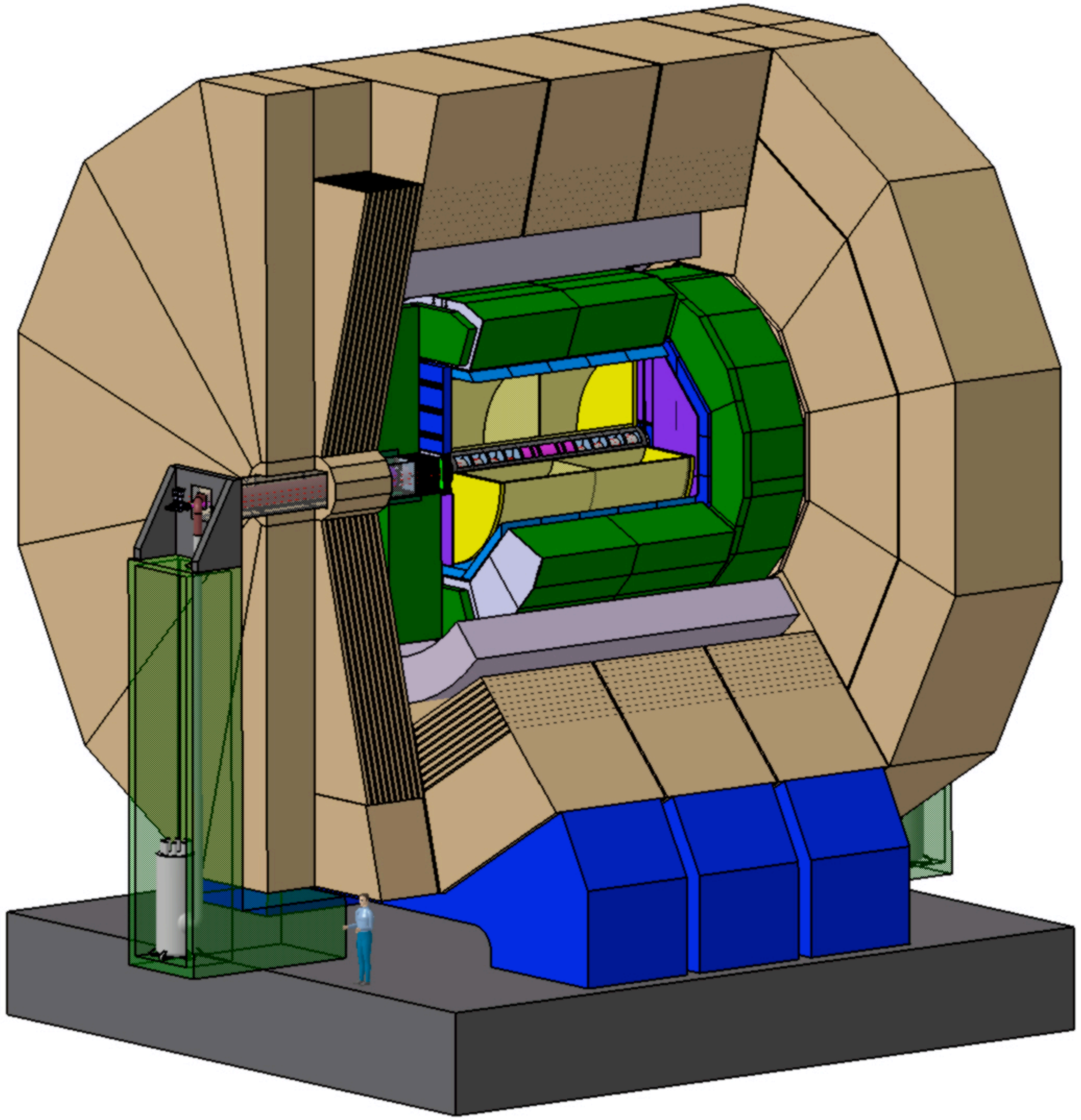
Towards an asymmetric detector!

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

- **Step 1: are there major showstoppers**?
  - Modify the fast simulation and run physics analysis benchmarks.
    - **Longer barrel sub-detectors**.
    - **Off-centre interaction point**.
    - **Boosted particles in the simulation**.

- **<u>Conclusion</u>**:
  - Probably **not straightforward to achieve the same physics performance**…
  - … But **no obvious showstopper**!

- **Step 2**: => **need a more detailed simulation**!



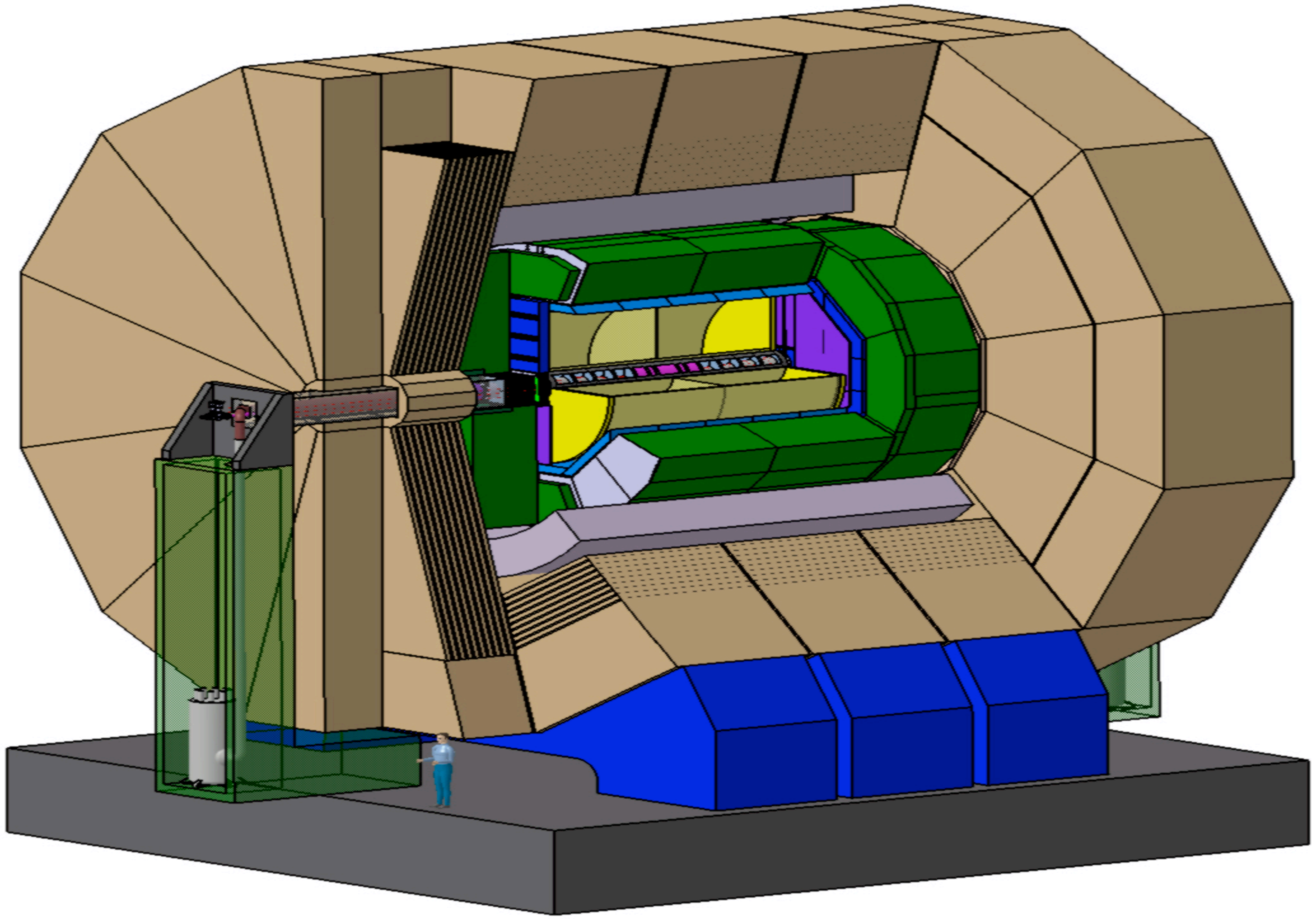
The International Large Detector

Modified full-sim ILD

- Detector:
- Extended barrel.
- Additional dipole magnet in the forward region.

- **Dataset**: large dataset already existing for ILC.
  - Script to boost all particles in forward direction.

- **Now re-run physics benchmarks with this modified full-sim detector**!



Placeholder:
modified ILD display

Probably one or two plots showing particle distributions

lepton distribution

Higgs recoil mass

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**.
  - **Looked at impact of asymmetric beams** (energy, charge, parameters…) **on beam backgrounds**.
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- **No show-stoppers so far, but more detailed studies are needed**:
  - Modified-ILD full-sim is now ready.
    - Extended barrel with off-centre interaction point.
    - Additional forward magnet.
    - Now re-running physics analysis benchmarks.
  - **Luminosity measurement** (Bhabha counting) to be studied.

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

Thanks for your attention!

Questions?

Backup

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,

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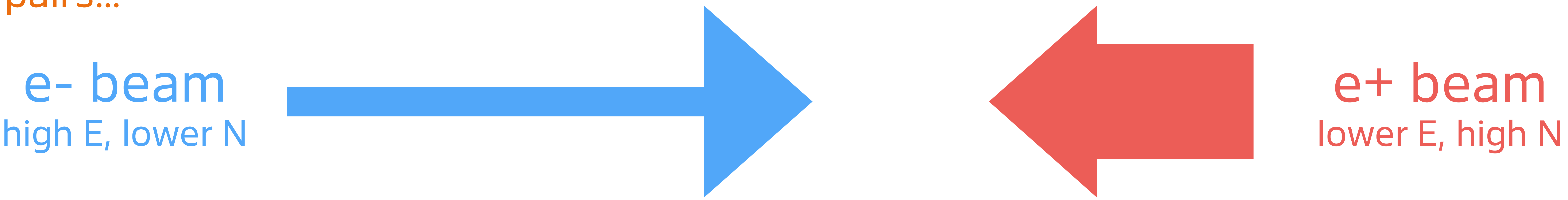
  - Ideally by the opposite factor as energy asymmetry.
  - **Limited by beam-induced background** (see next slides):
    - $N_- : N_+ = 1.33 : 3 \times 10^{10}$ particles / bunch => $P/P_{\mathrm{sym}} = 1.5$

Beam-strahlung

Creation of many e+e- pairs...



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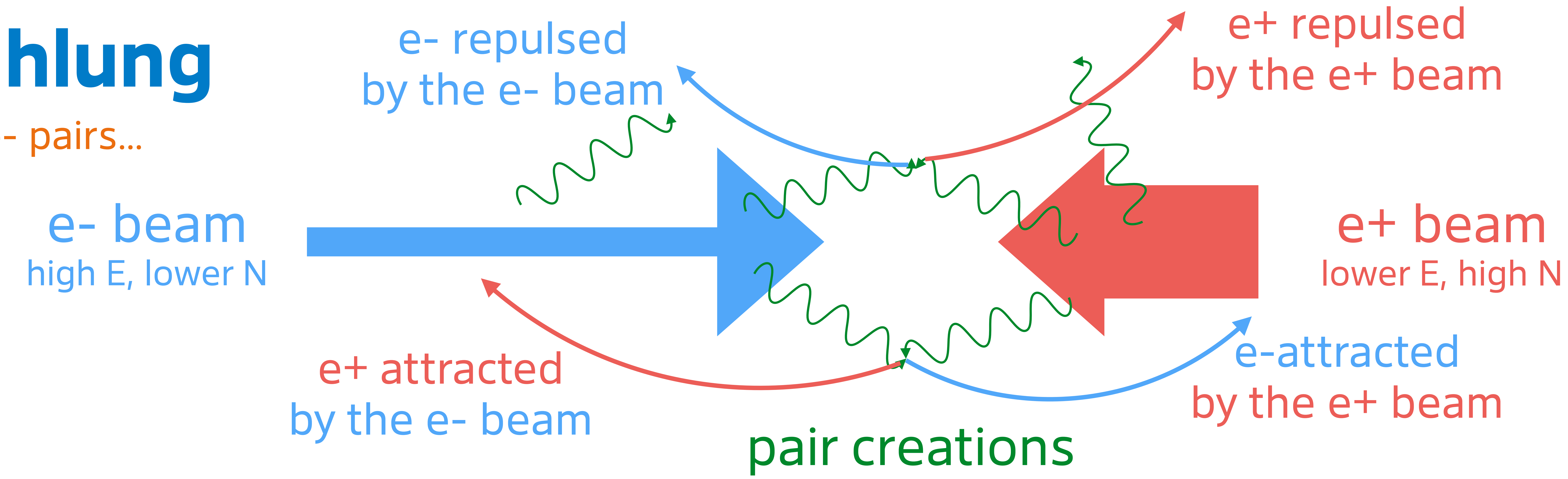

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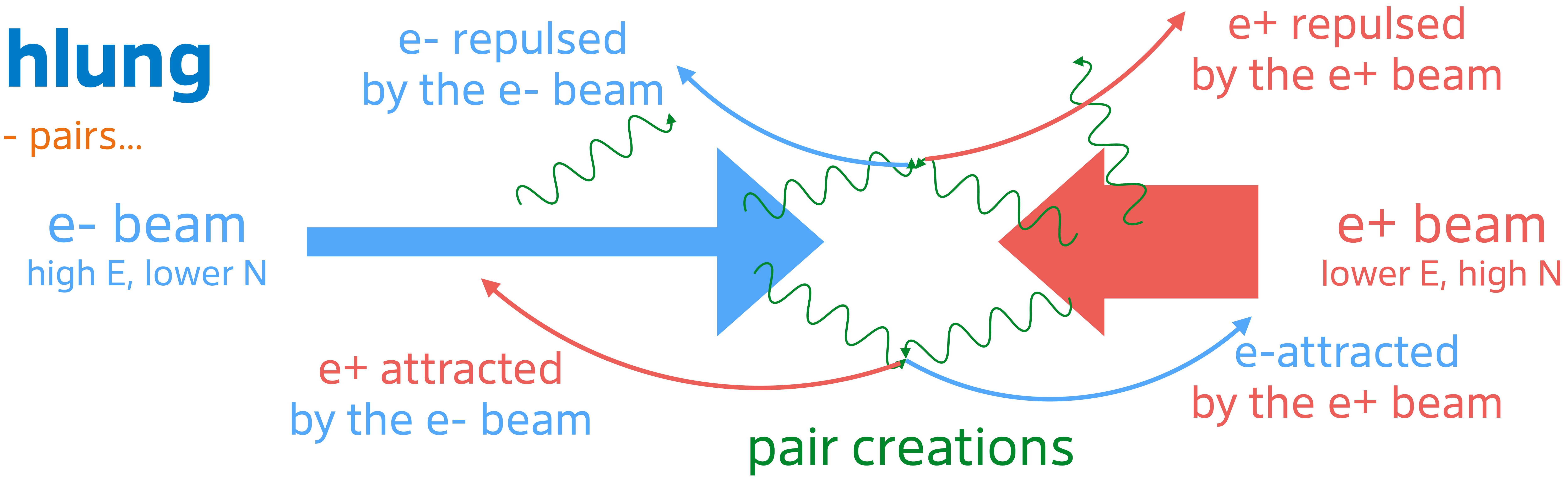
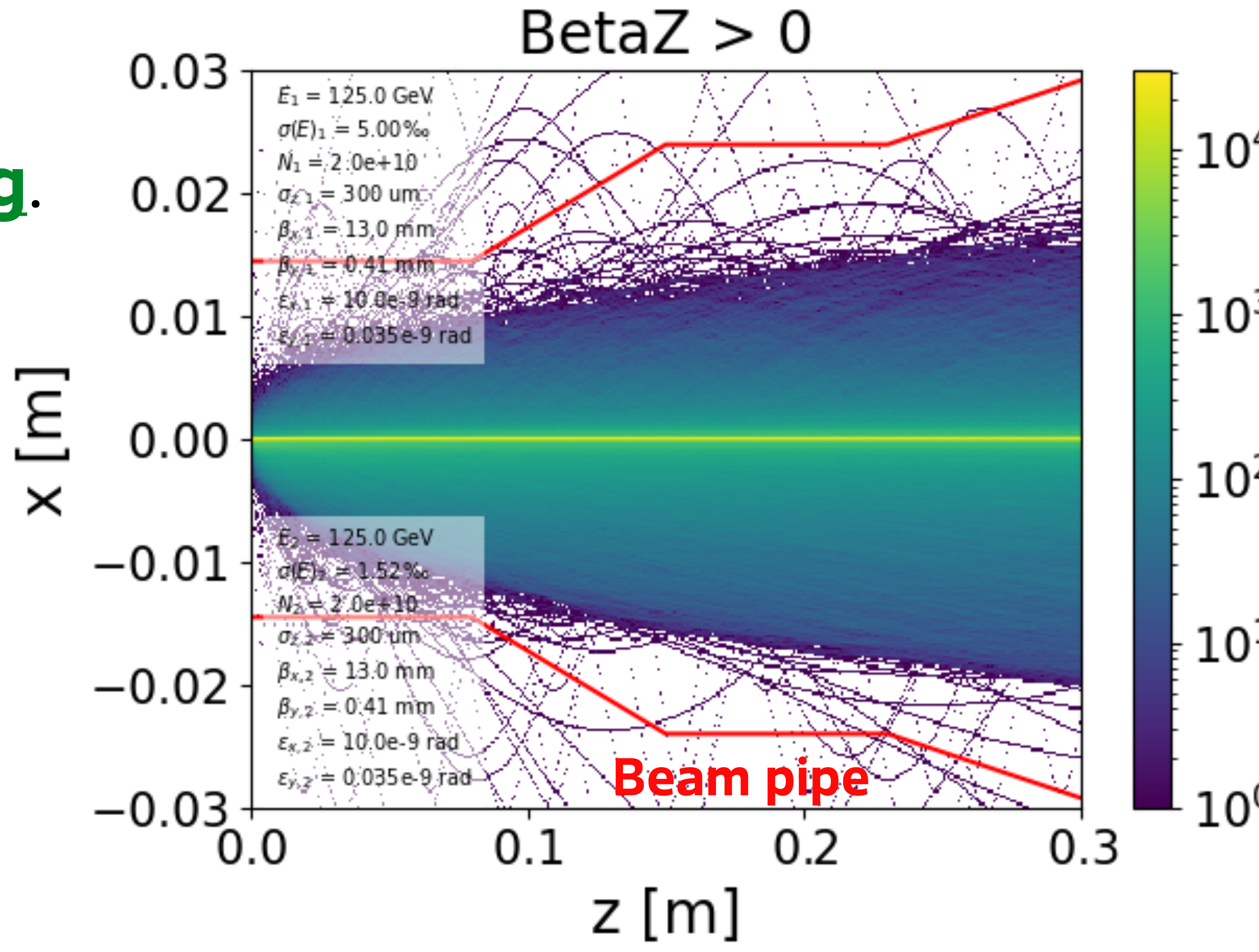


- **Simulate the beam-beam interaction using Guinea-Pig**.
  - Example: plot the trajectories of all pairs created in the forward direction.
  - Here in the ILC configuration (symmetric beams)



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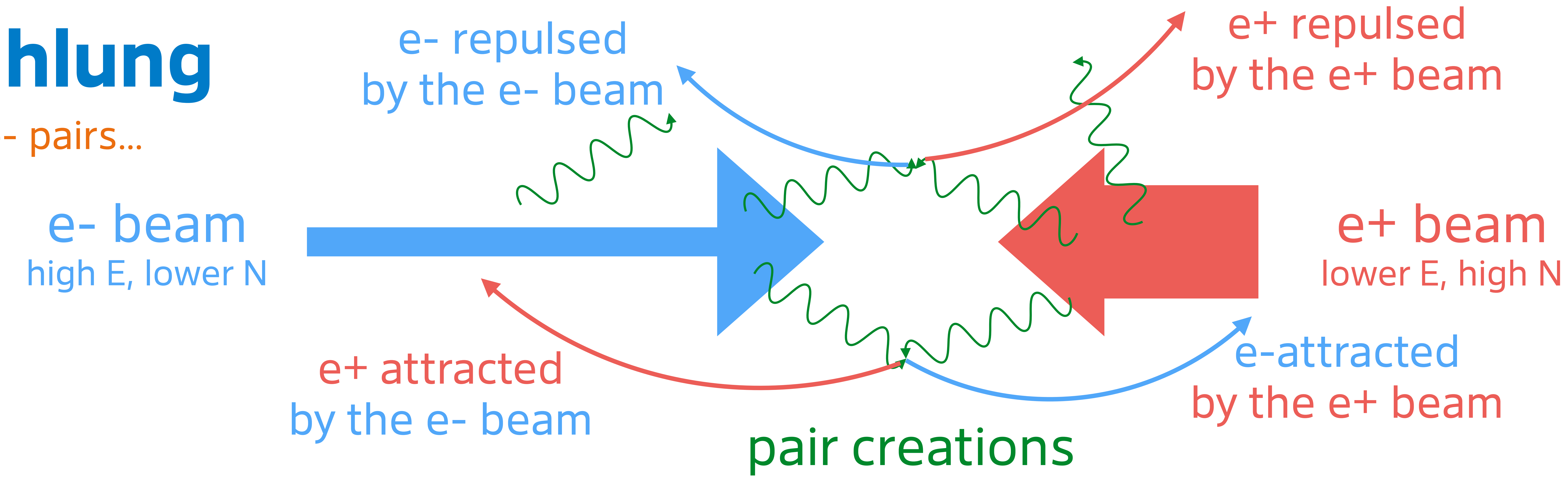

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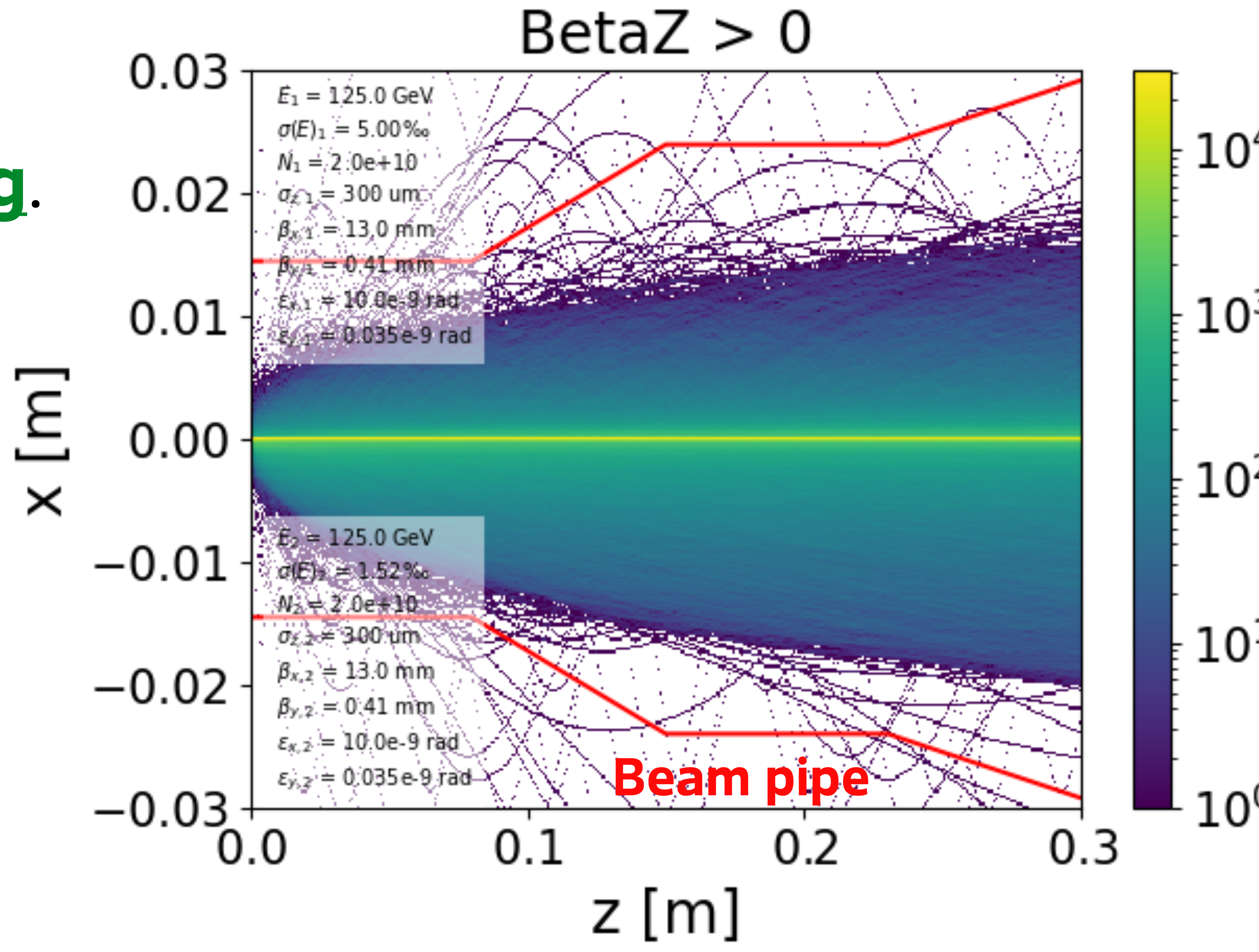
- This is ~ **independent of beam energy**, but rather **depends on the beam charge**.



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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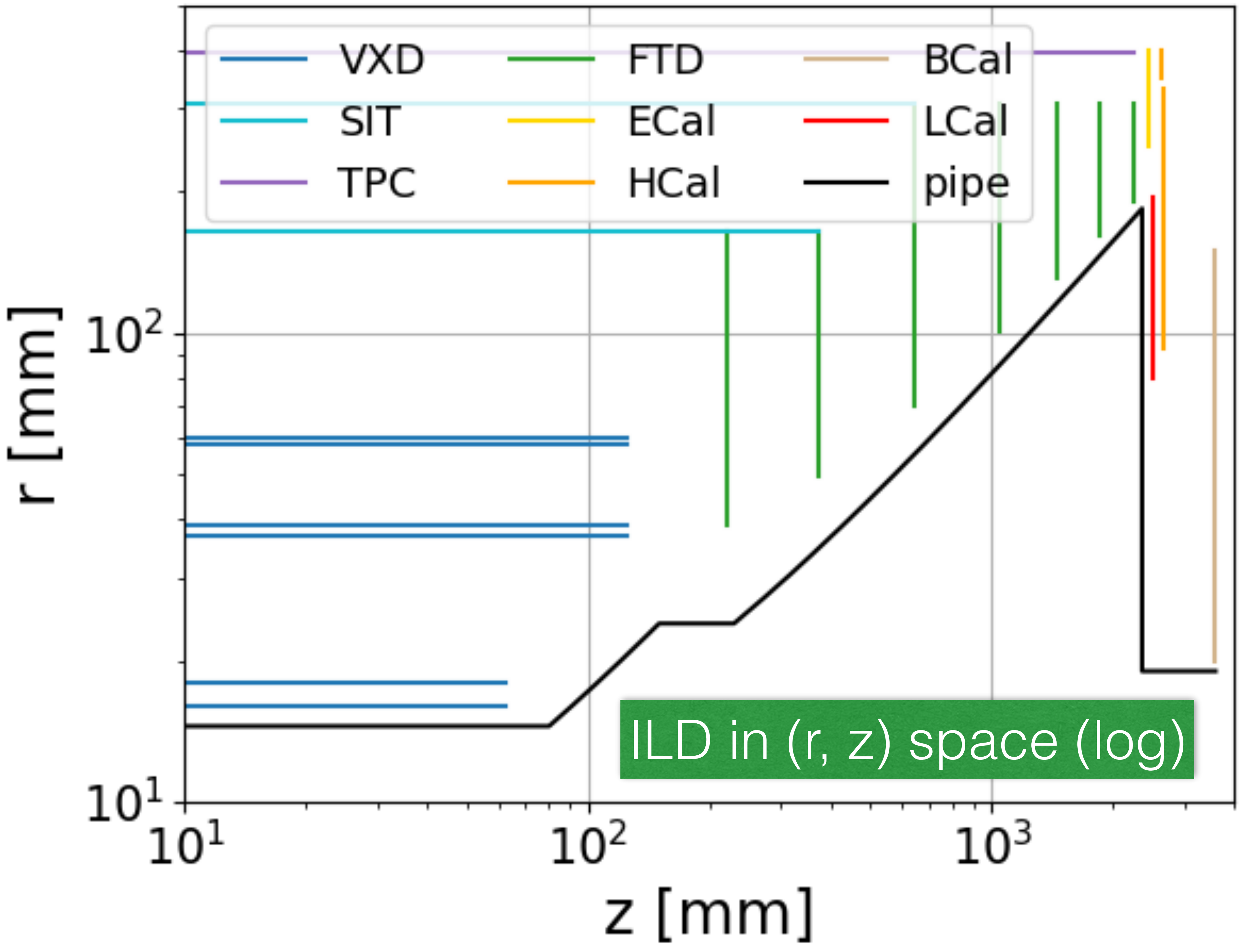
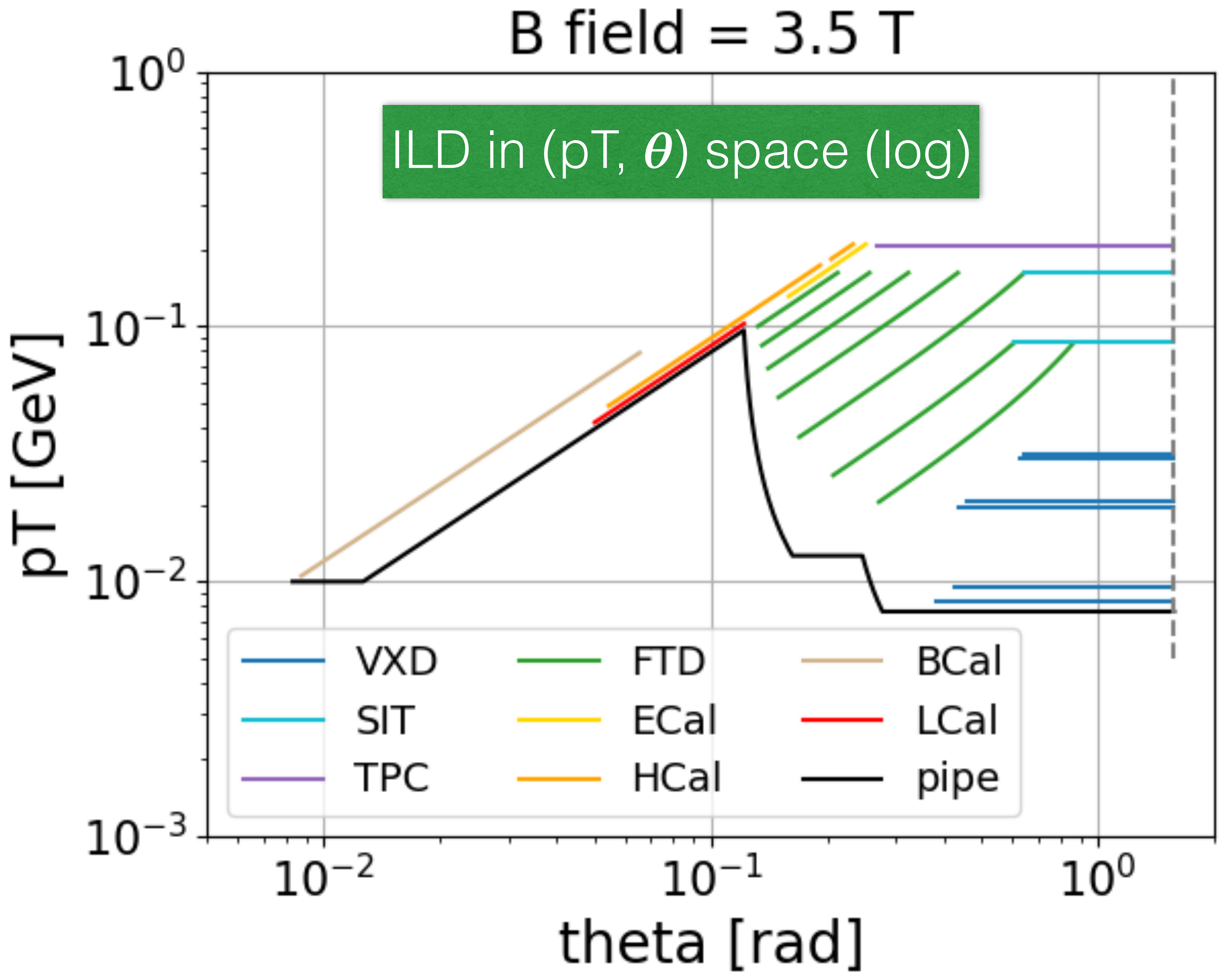
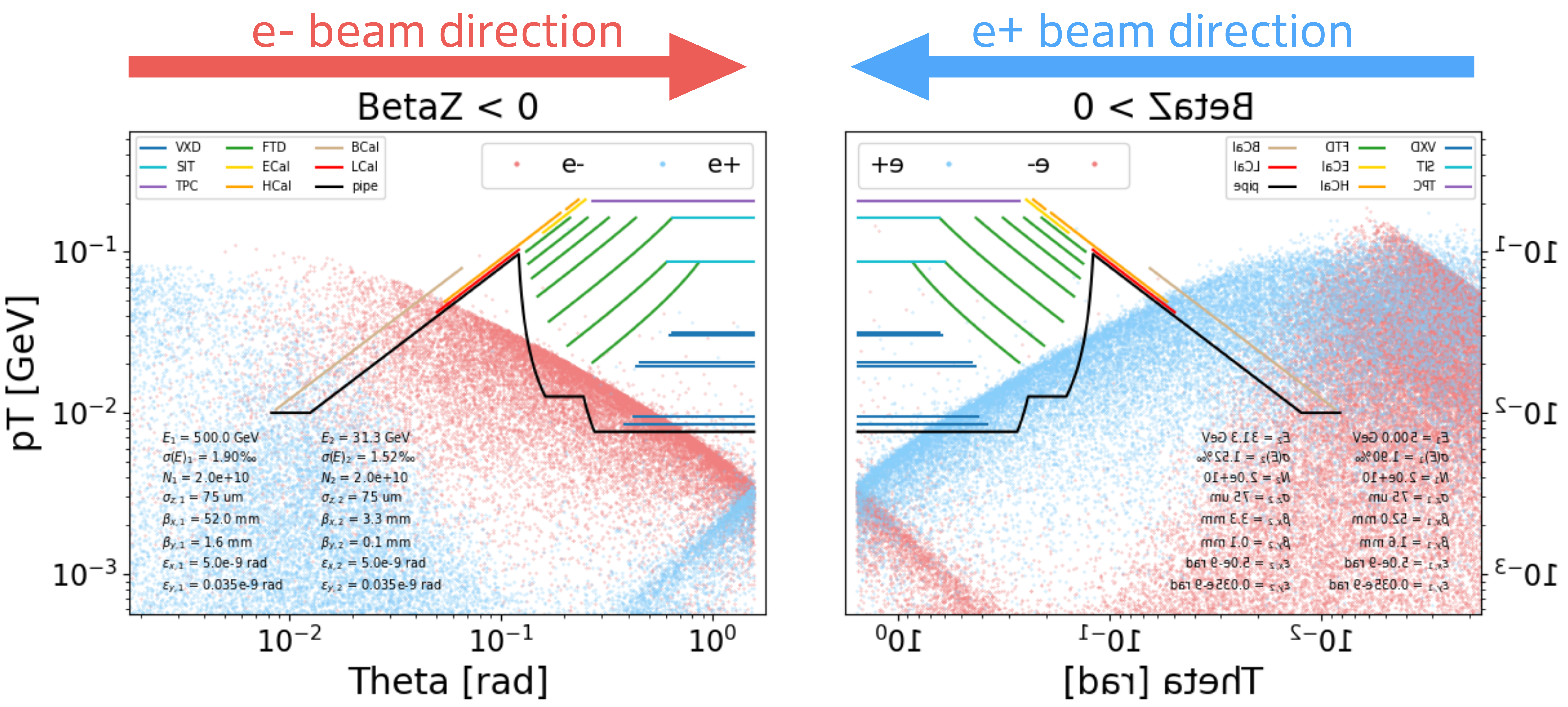
  - **If/Where does this helix hit the detector?** => “Hit map” in the (pT, θ) space.
- What does the detector look like in the (pT, θ) space?





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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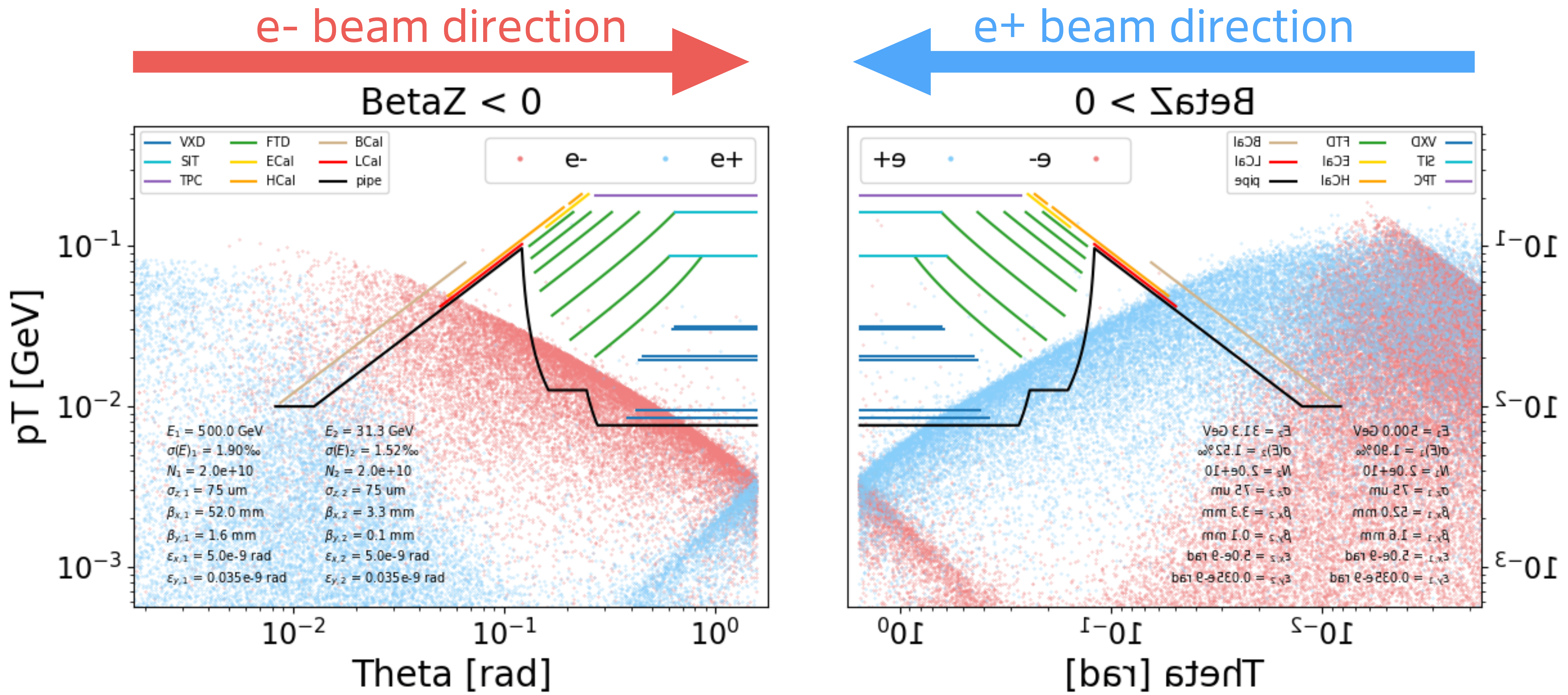

- <u>Improved: asymmetric charge and length</u>
  - Beam energy = 500 : 31.3 GeV
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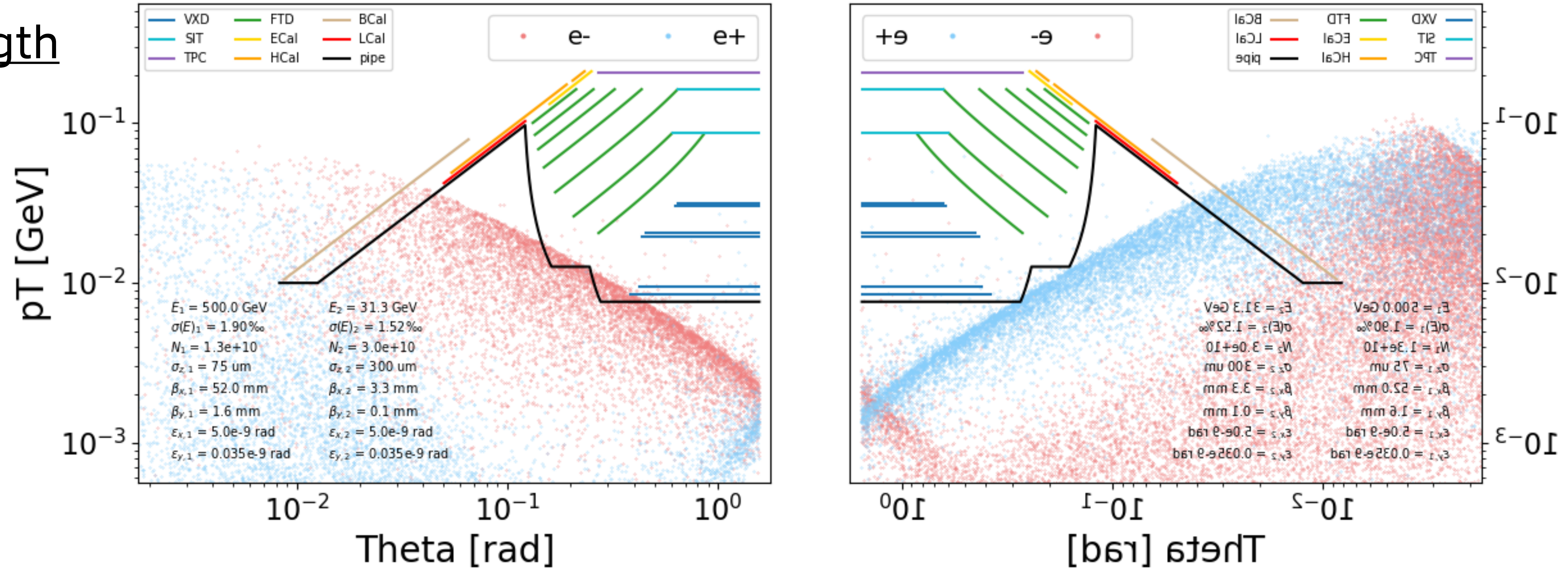
    (cannot produce long bunches with PWFA)



Beam-strahlung

e- beam direction

e+ beam direction

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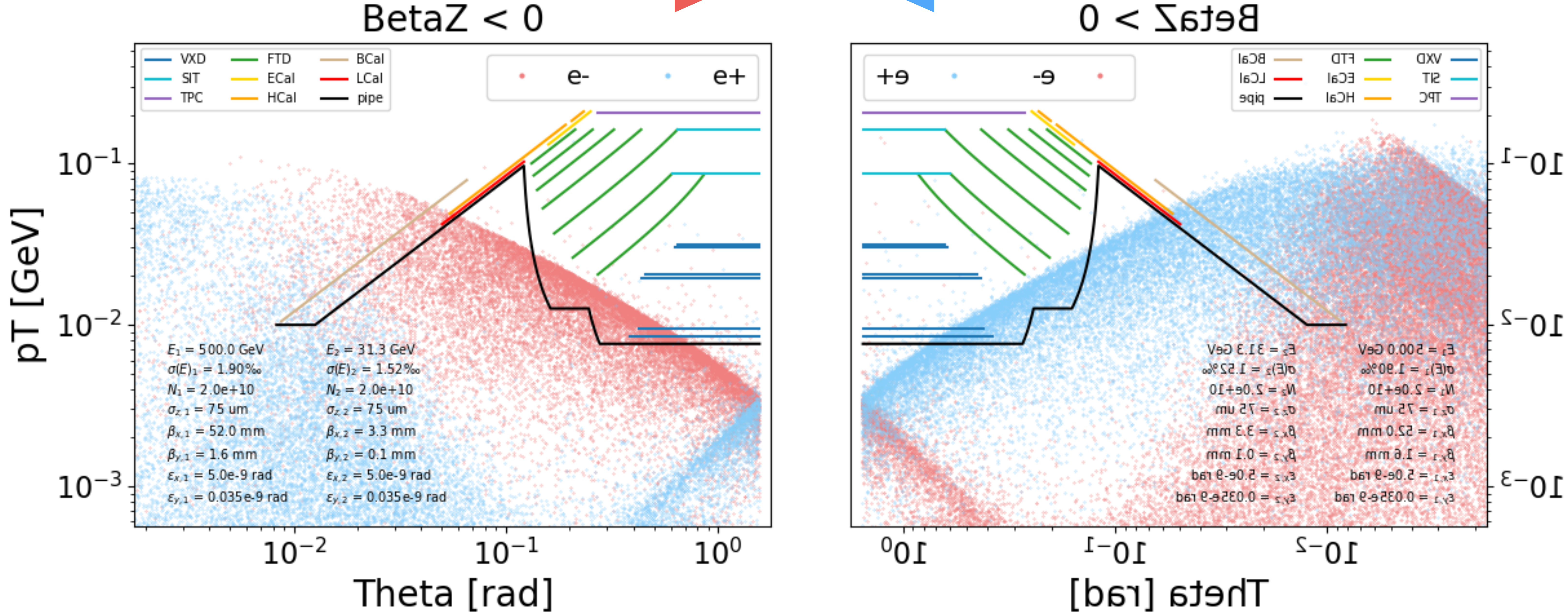

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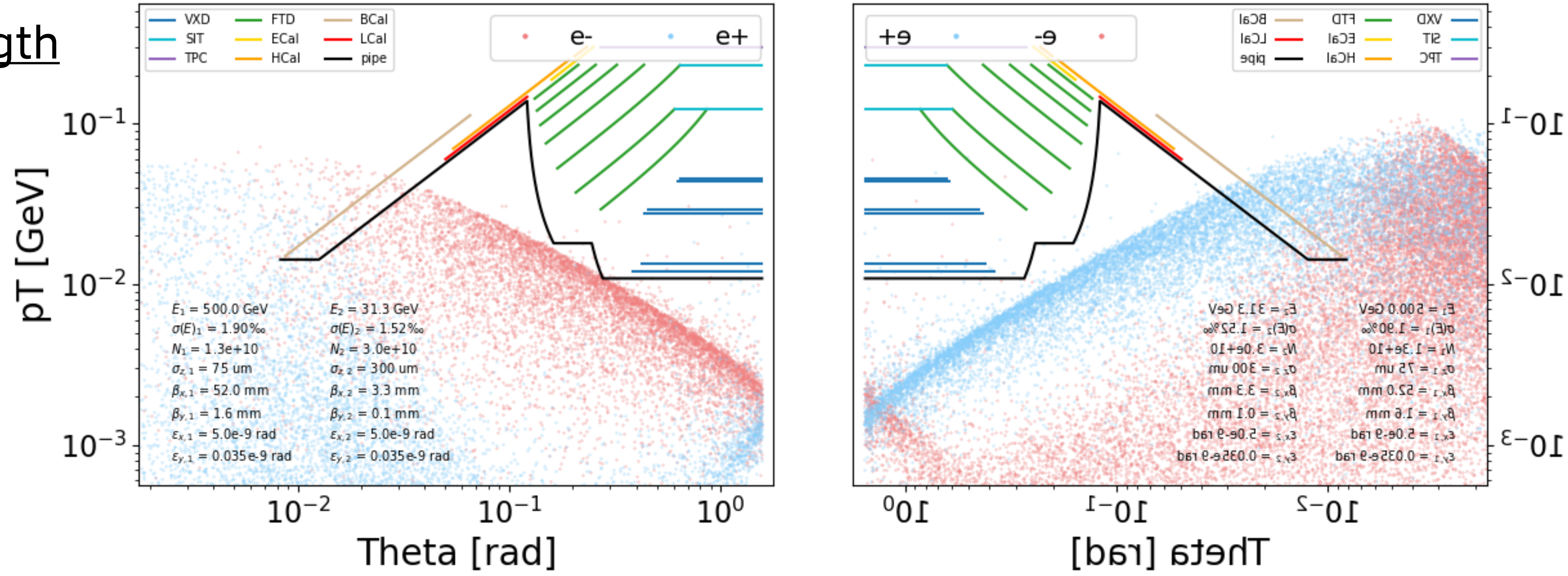

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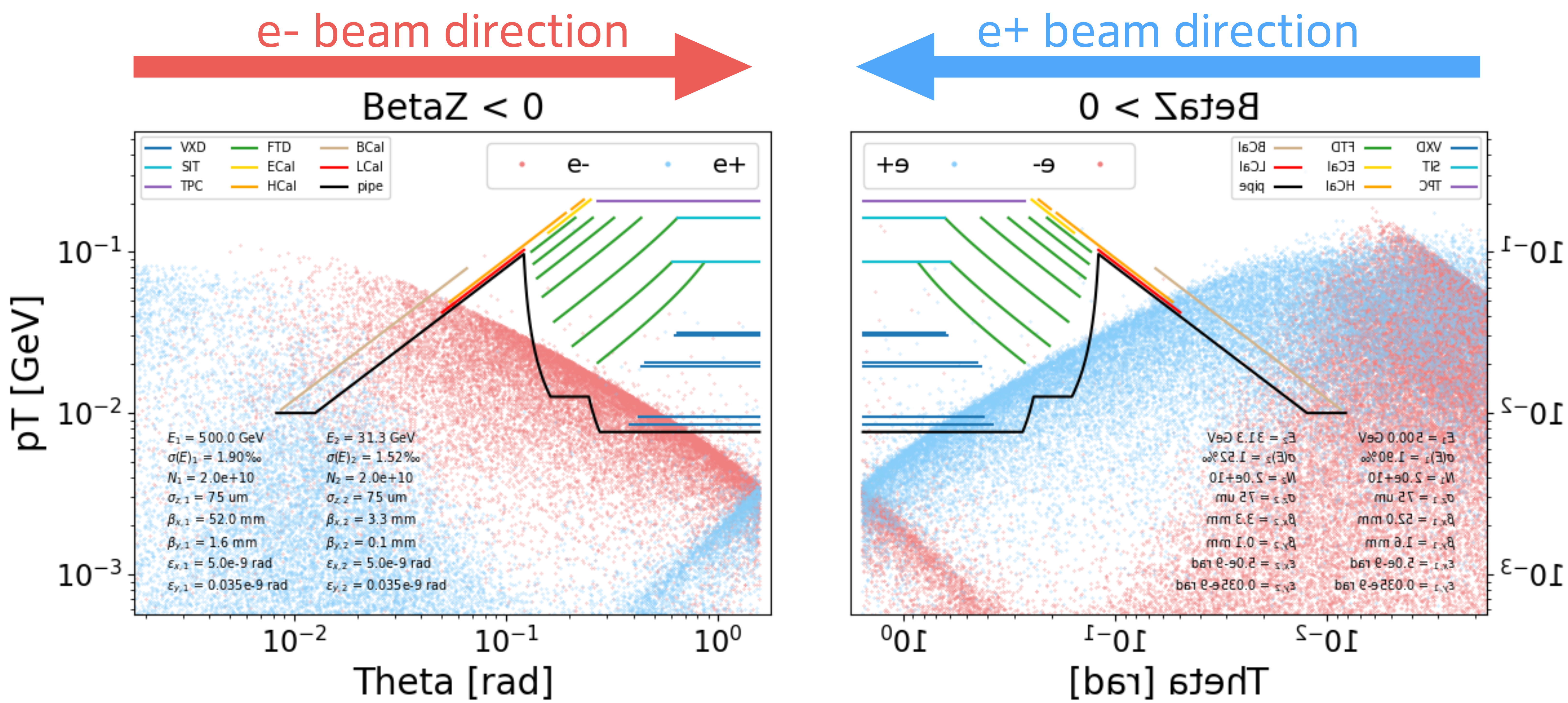

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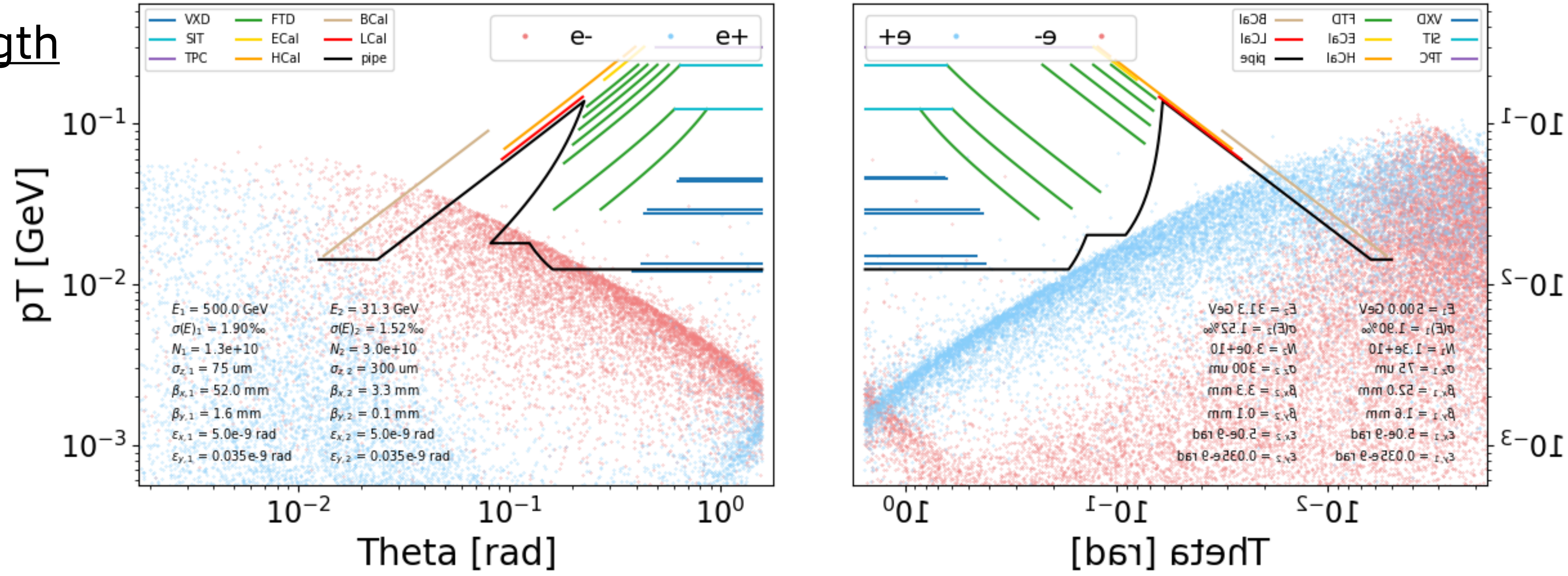
- Make the **detector asymmetric**!
- **More fine tuning possible**!



Beam-strahlung: impact on luminosity

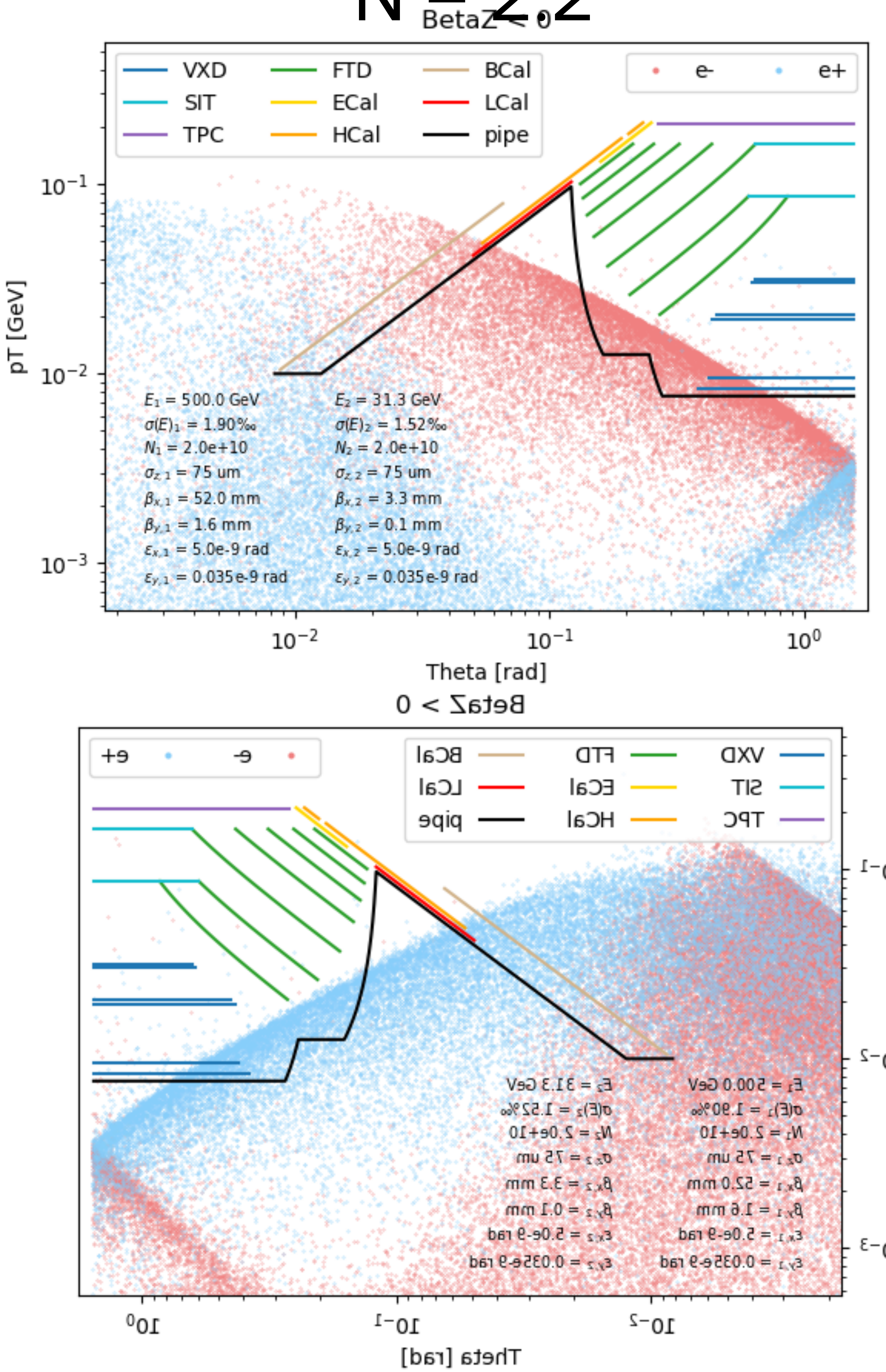
- **Luminosity computed by Guinea-Pig**:
  - Total luminosity
  - Luminosity considering only events within 1% of the nominal CM energy ("peak lumi").

- **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**.

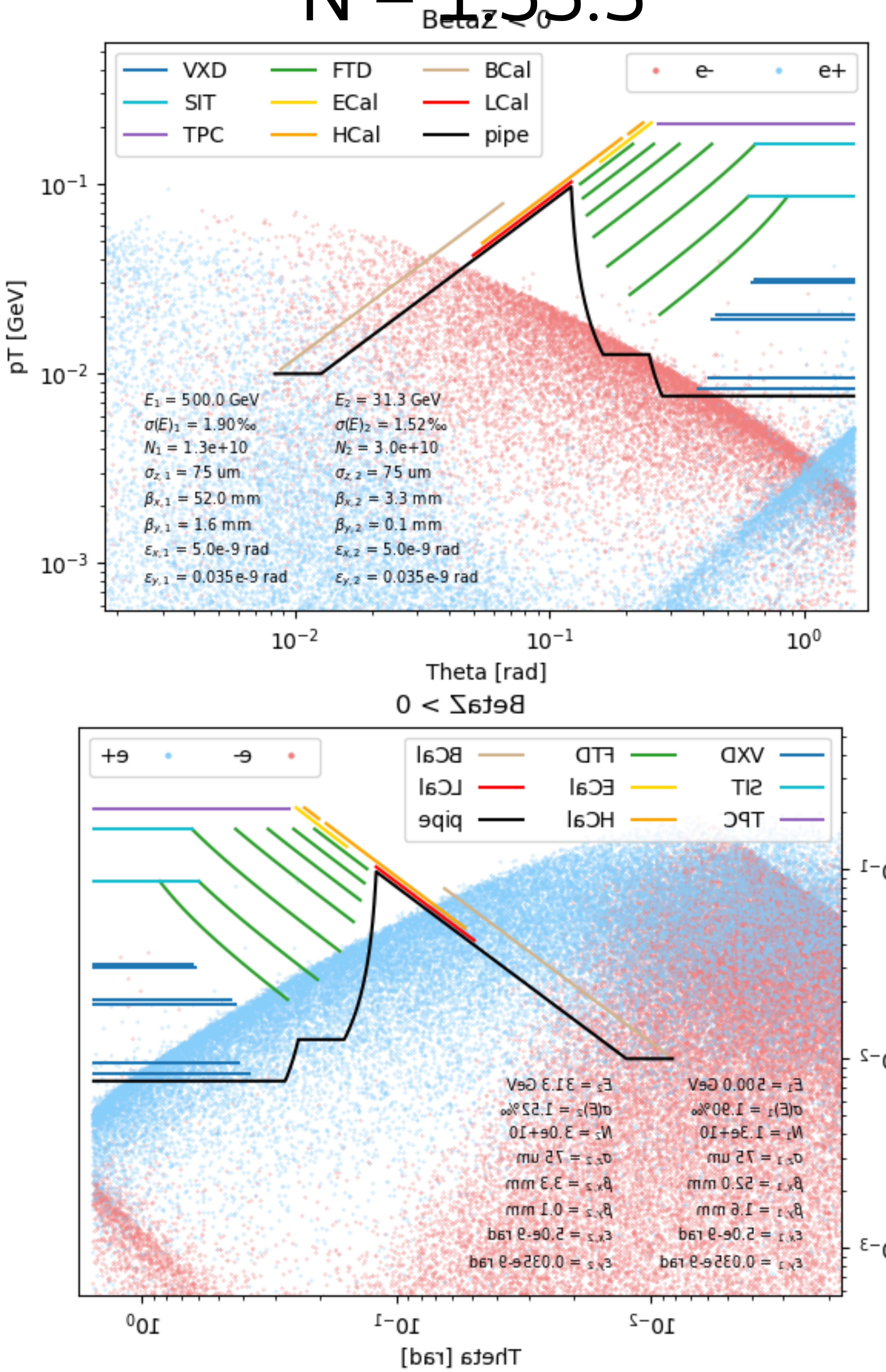
Lumi [μb / bunch]	ILD TDR	HALHF N = 2 : 2 x 10^{10} σ_z = 75 : 75 μm	HALHF N = 1.33 : 3 x 10^{10} σ_z = 75 : 300 μm
Total lumi	1.12	1.35	0.80
Lumi within 1% of nominal CM energy	0.92	0.80	0.56
Beam backgrounds?		large	mitigated

Beam background hit map, σ_z = 75:75

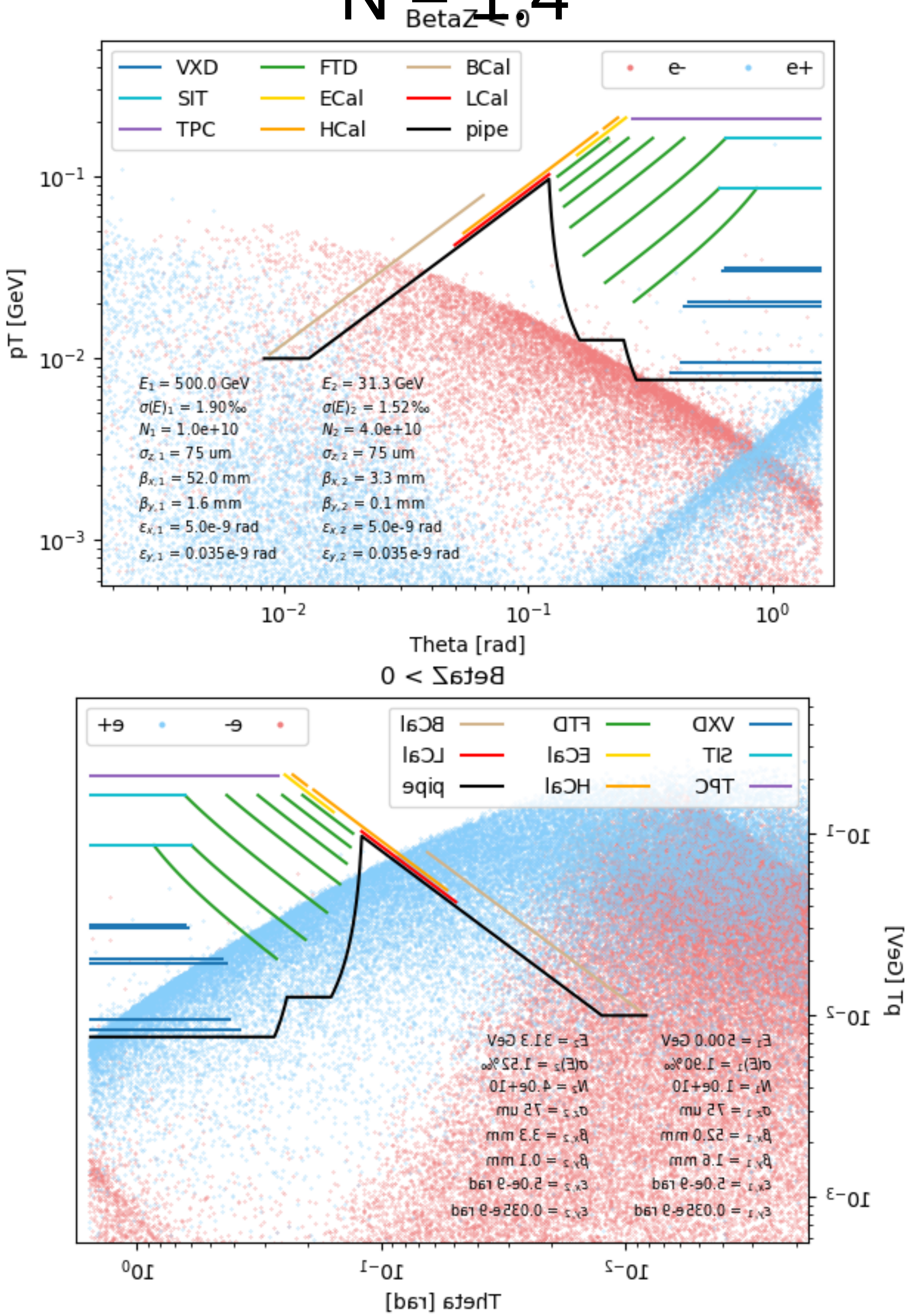
N = 2:2



N = 1.33:3

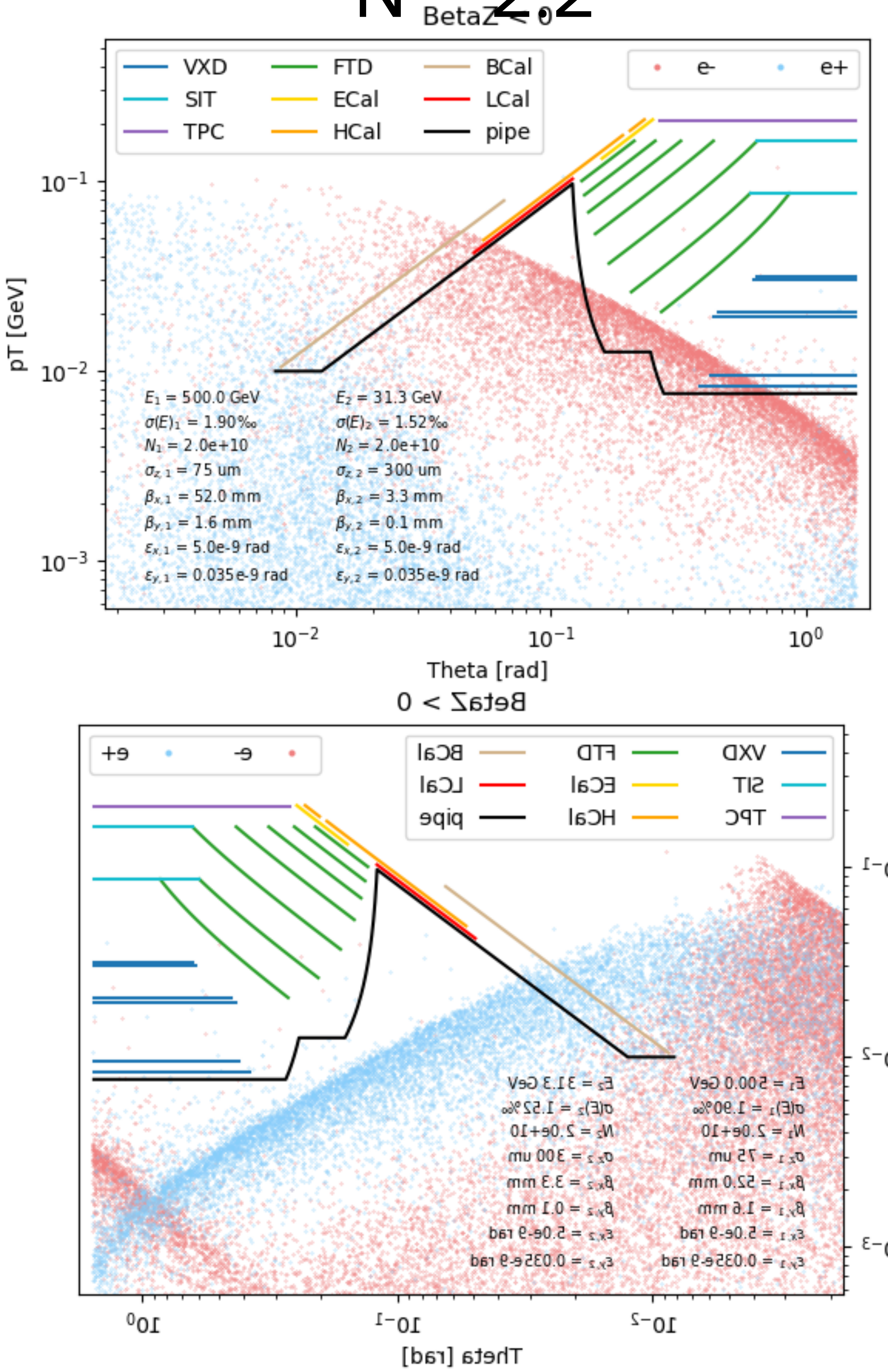


N = 1:4

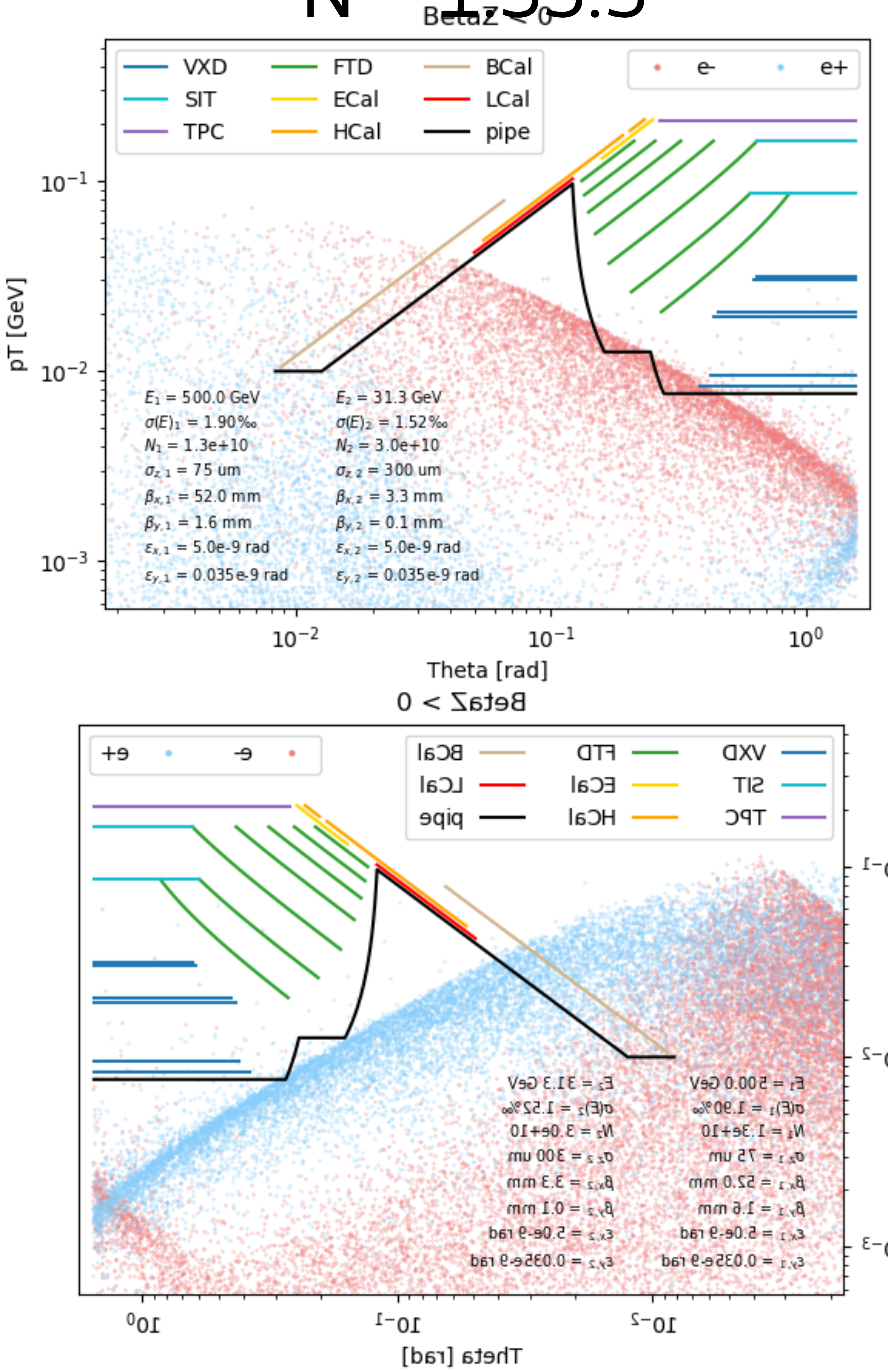


Beam background hit map, σ_z = 75:300

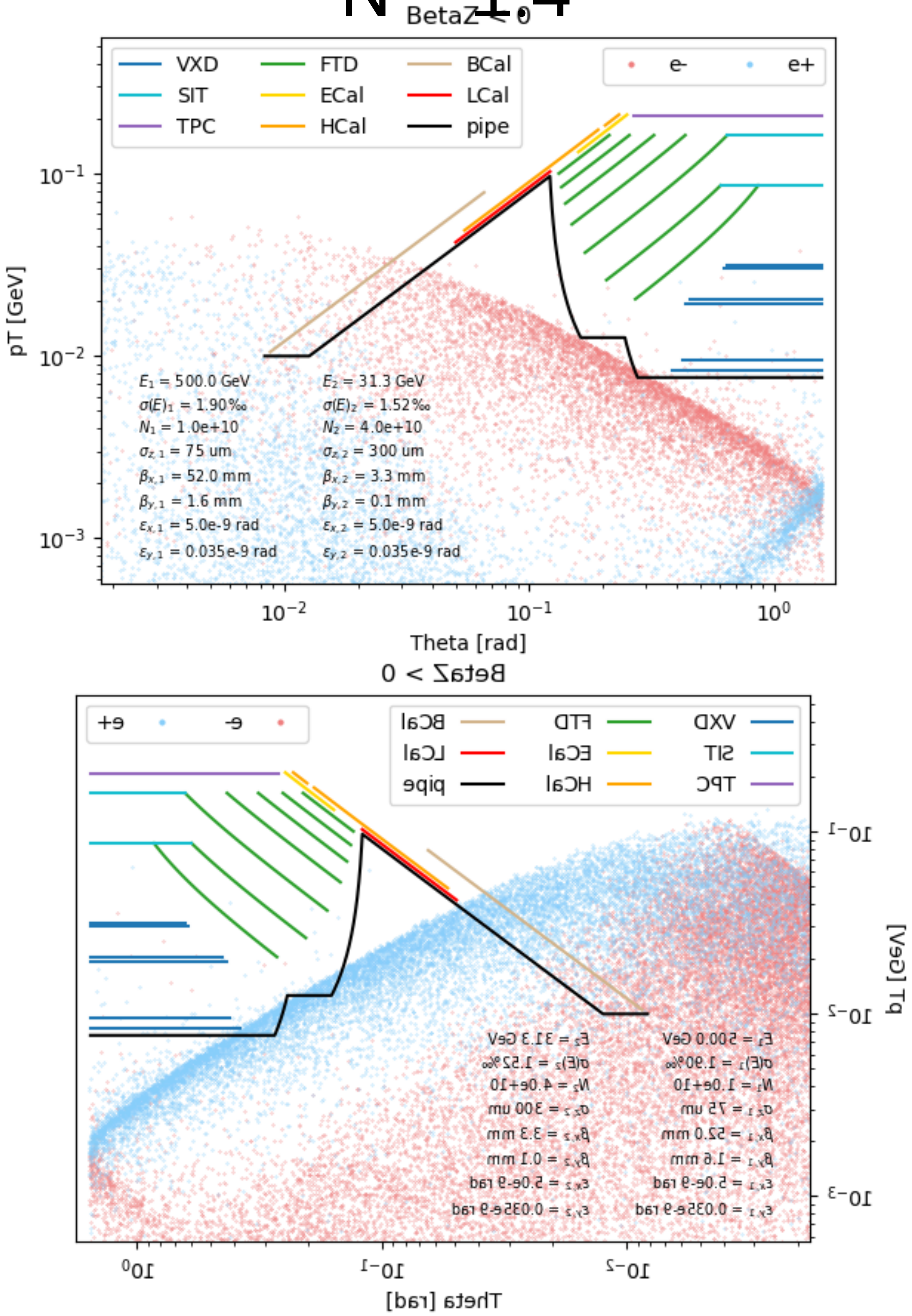
N = 2:2



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").