# Detector status, challenges and requirements

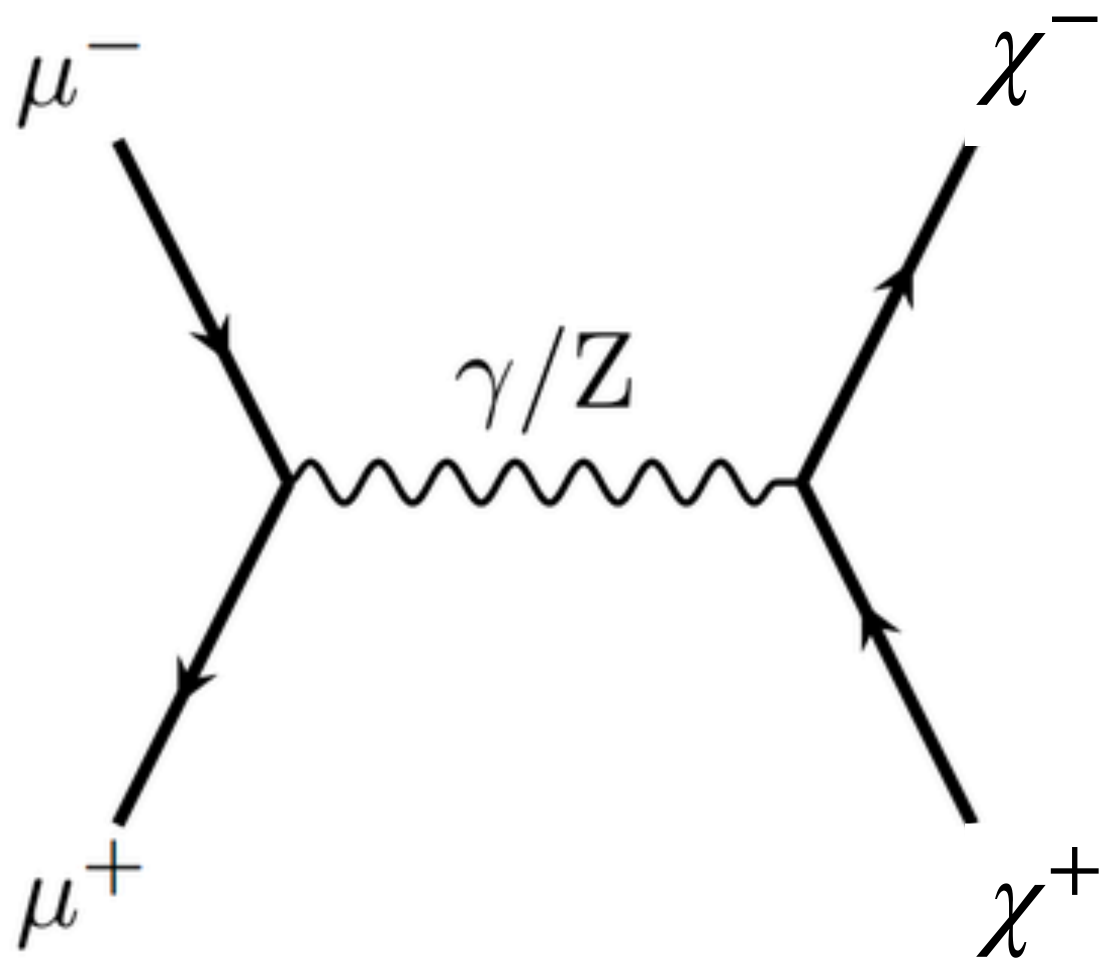
Karri Folan DiPetrillo
University of Chicago
US Muon Collider Workshop
24 February 2024

# Intro, Challenges, Requirements

# What we want

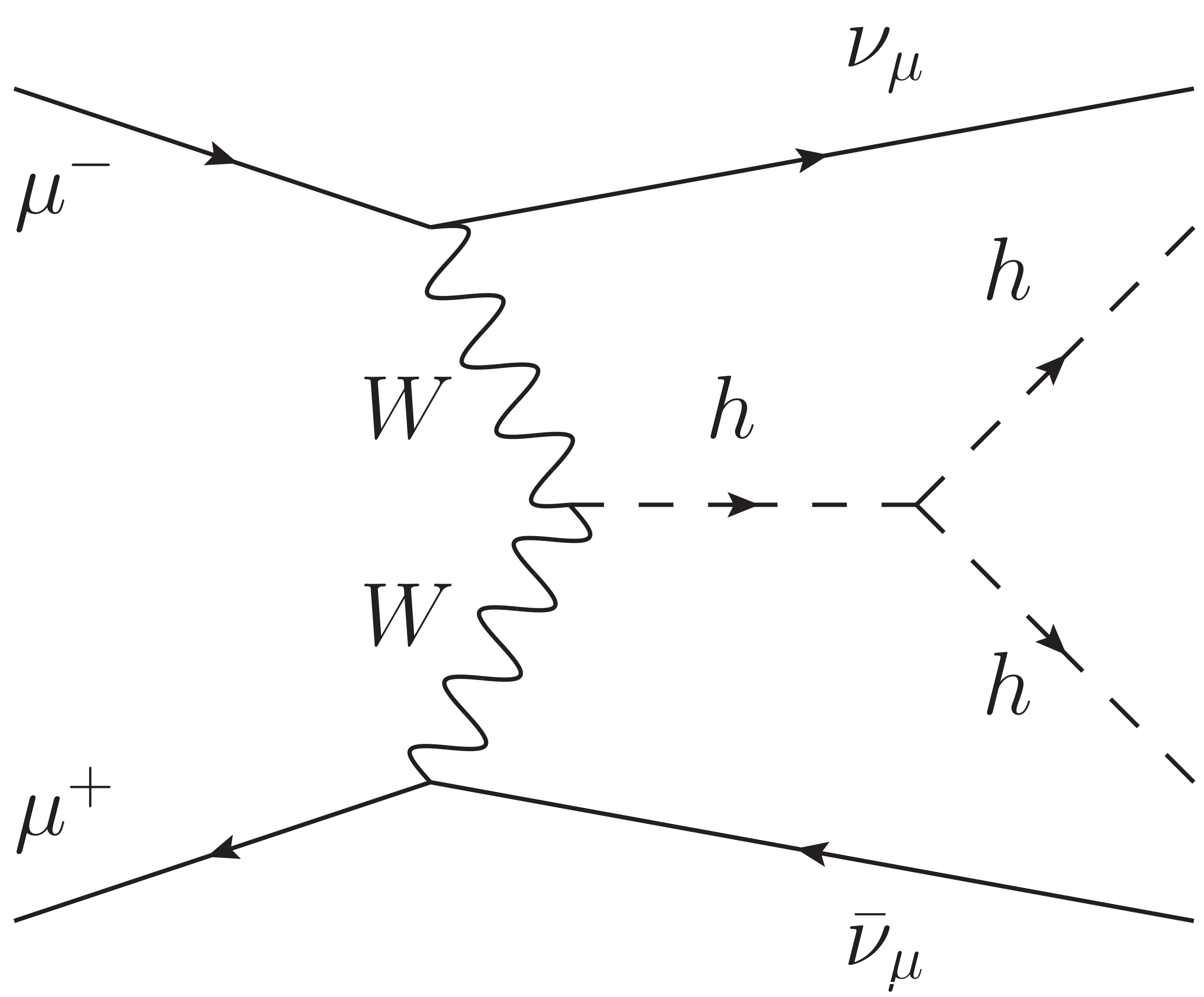
Access to energy and precision in one machine

Multi-TeV scale BSM physics




Good mass resolution for central high $p_T$ objects, retain sensitivity to unconventional signatures

GeV scale SM physics




Forward jets/leptons, flavor tagging, Z/h separation, forward muons, luminosity, etc

# Beam induced background

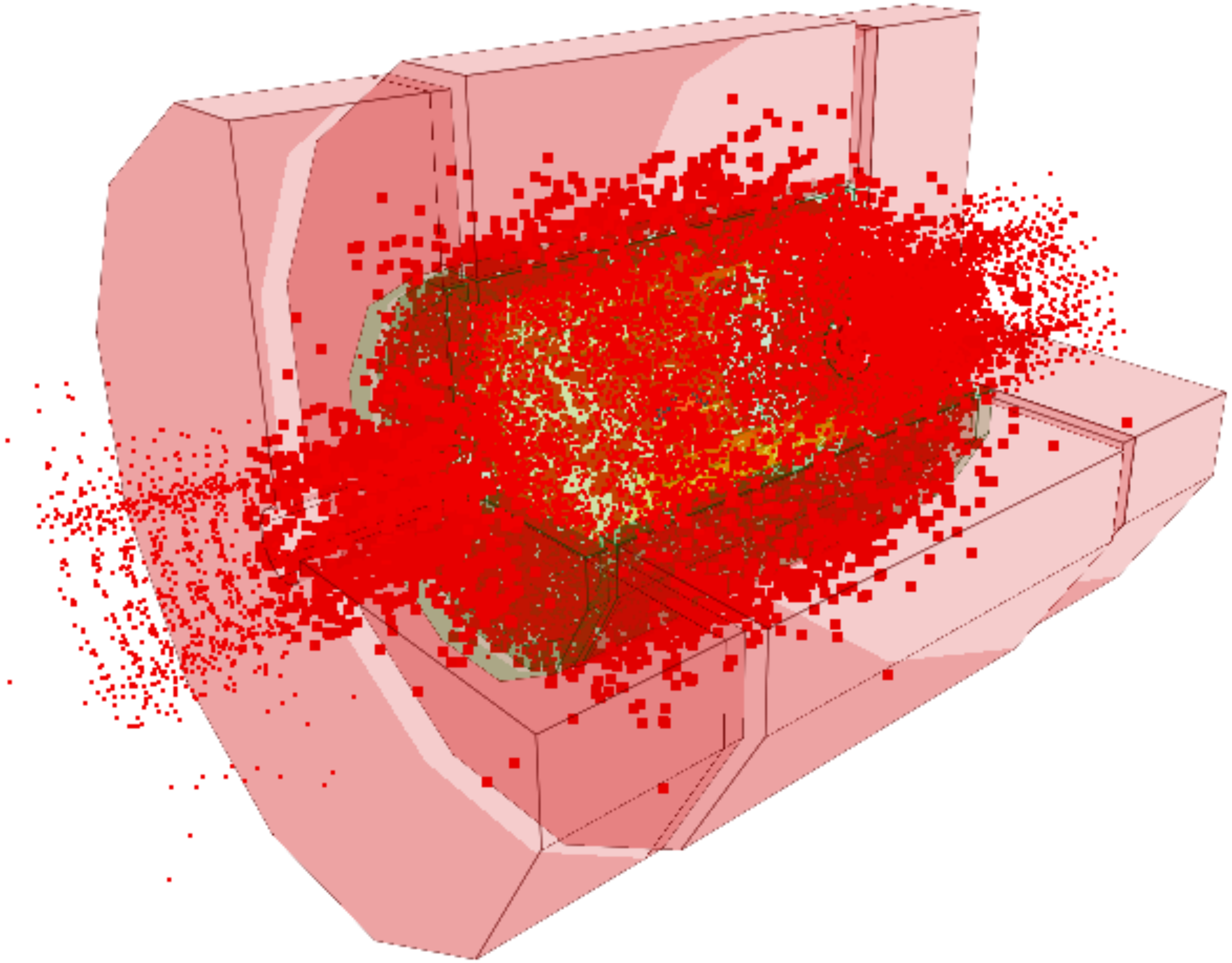
**Primary challenge for μC detector**

Decays w/in 20 m of interaction point: ~$10^7$

Total energy of decay products: ~ 50 EeV

Full simulation with BIB = CPU intensive
Requires input from FLUKA/MARS

More from Simone



# Luminosity target & collider environment

## Depends on energy, physics goals, and cross-sections

Goal: measure di-higgs cross-section (few fb) with few % uncertainty

Need ~10 $ab^{-1}$ at 10 TeV

Assuming 5 years of runtime

~30% efficiency

Translates to

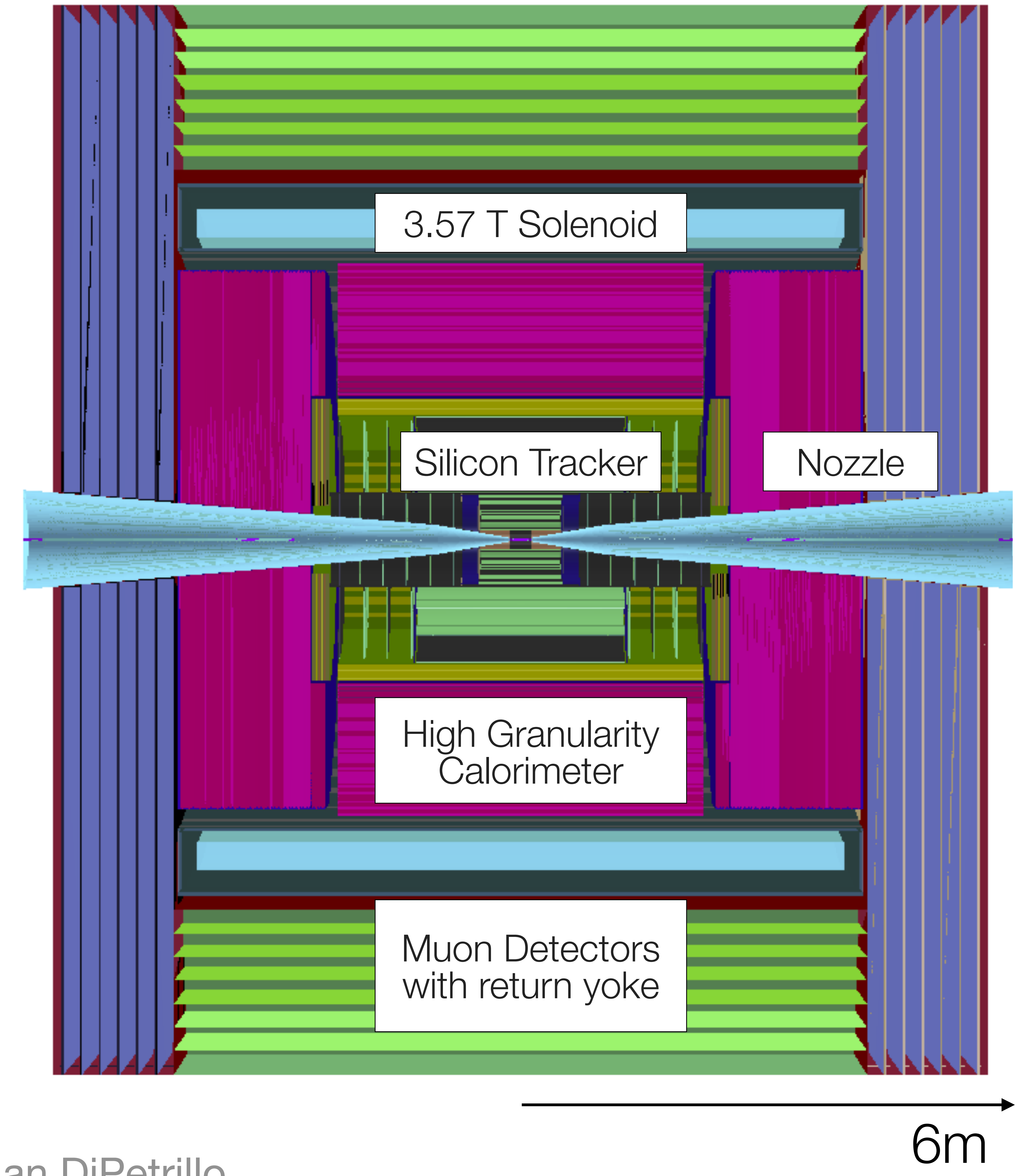
$$\langle \mathscr{L}_{inst} \rangle = \frac{N_1 N_2 n_b f}{4\pi \sigma_x \sigma_y} = 10^{35} cm^{-2} s^{-1}$$

### Circulate two beams & re-fill when depleted

| | |
|---|---|
| Set $n_b$ = 1 and maximize $N_\mu$ per bunch | ~$2 \cdot 10^{12}$ $N_\mu$ |
| Minimize $\sigma_x \sigma_y$ beam size, aim for | ~O(10) μm |
| Minimize circumference, maximize f | 1/30 μs |
| Re-inject every 1/βγτ | 1/100 ms |

# Baseline Detector

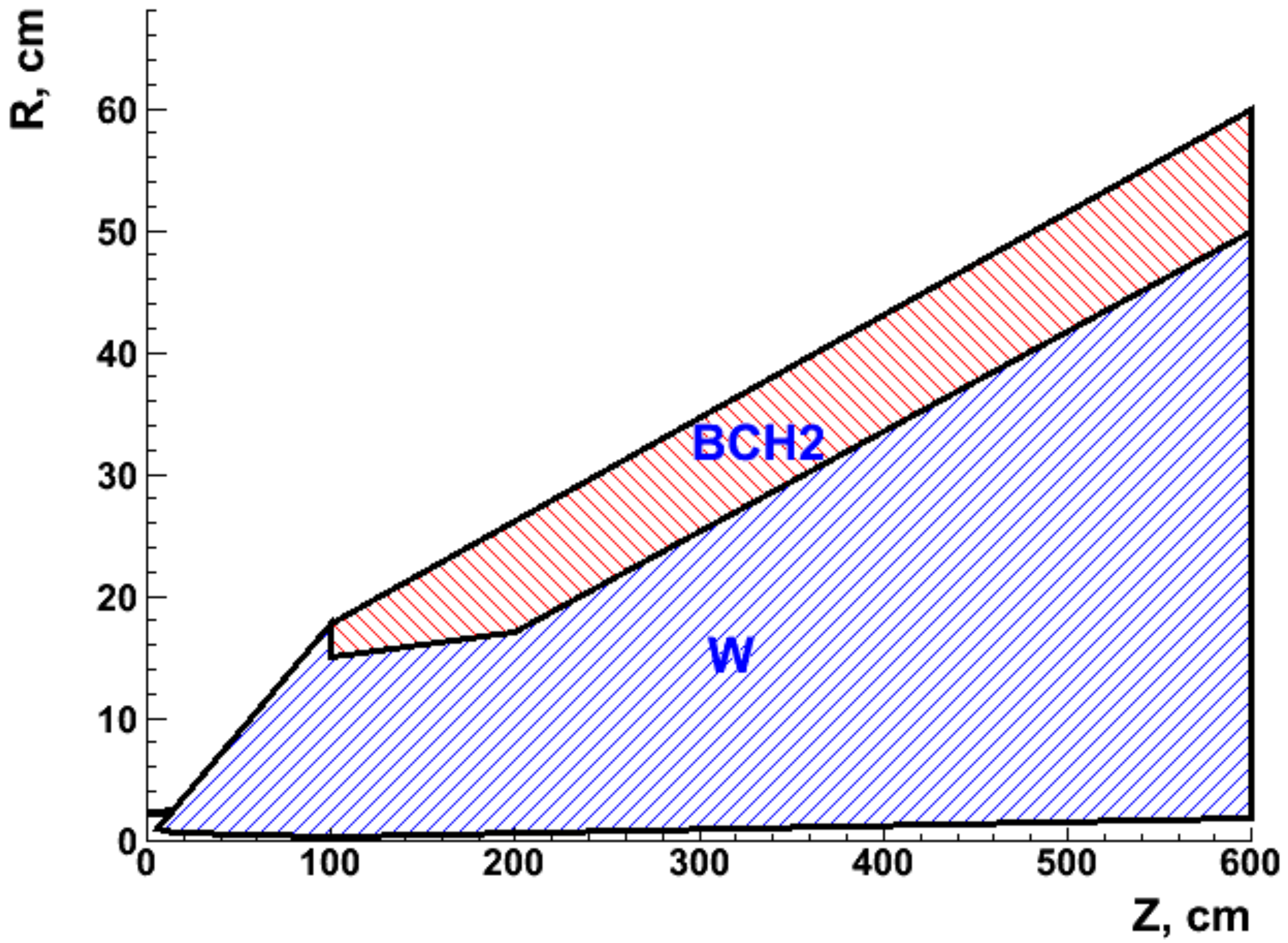





3 TeV design adapted from CLIC to Muon Collider environment

Major outcome from Snowmass & IMCC

Unique: Tungsten Nozzles



# Nozzle impact on background

Suppress high energy component

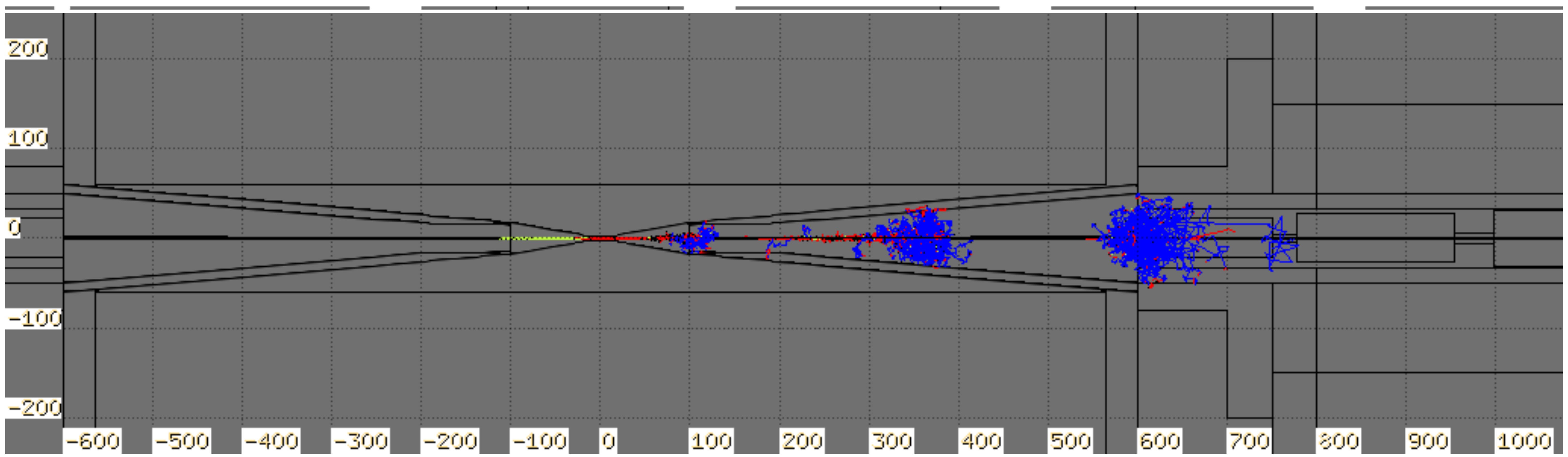
Tradeoff: increase in low energy neutrons

Open question: optimal nozzle shape/material to reduce BIB & maximize signal acceptance

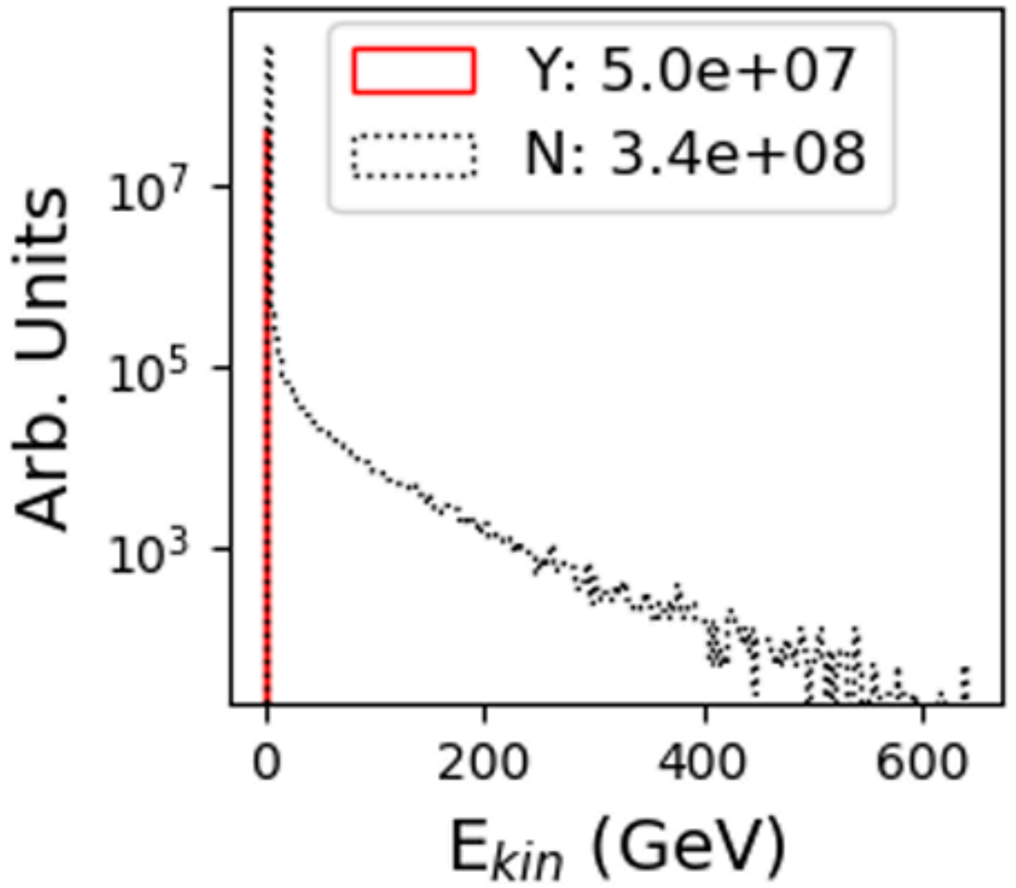
EPS 2023 Proceedings

Single μ decay

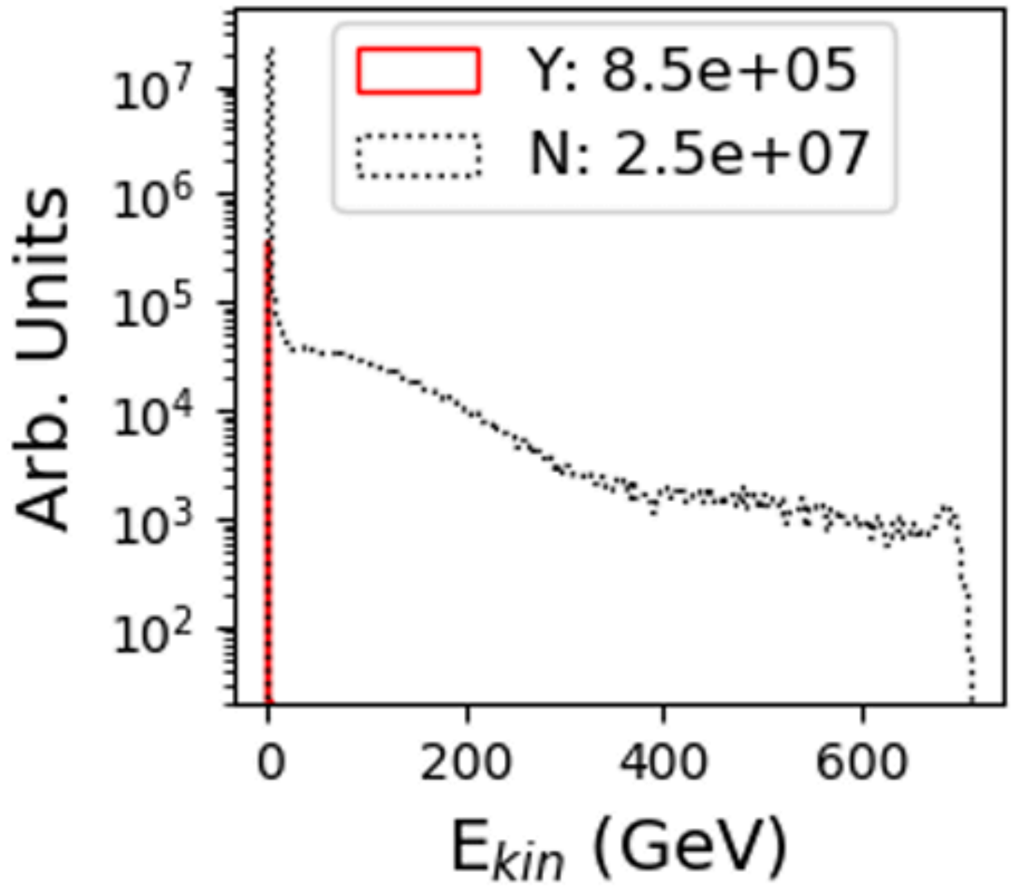
$e^+$ $e^-$ γ n



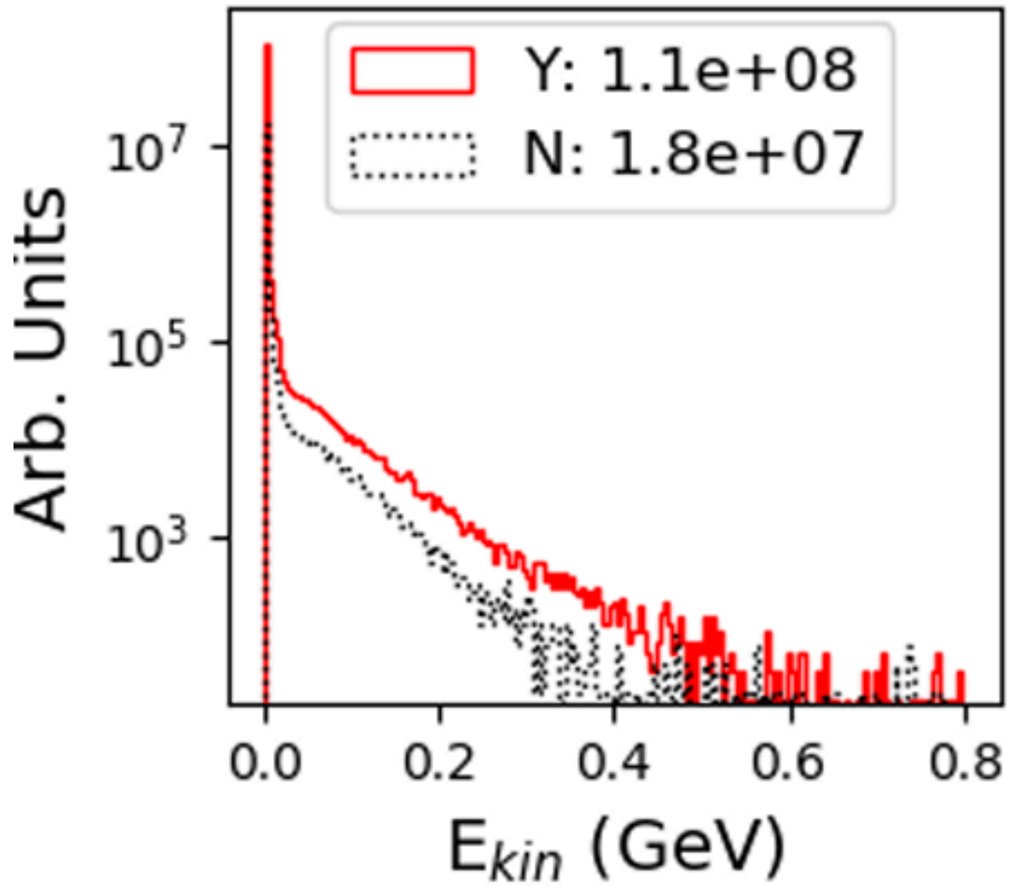

Photons




Electrons




Neutrons



# Overall environment

## Compared to HL-LHC

Up to ~10 x hit density

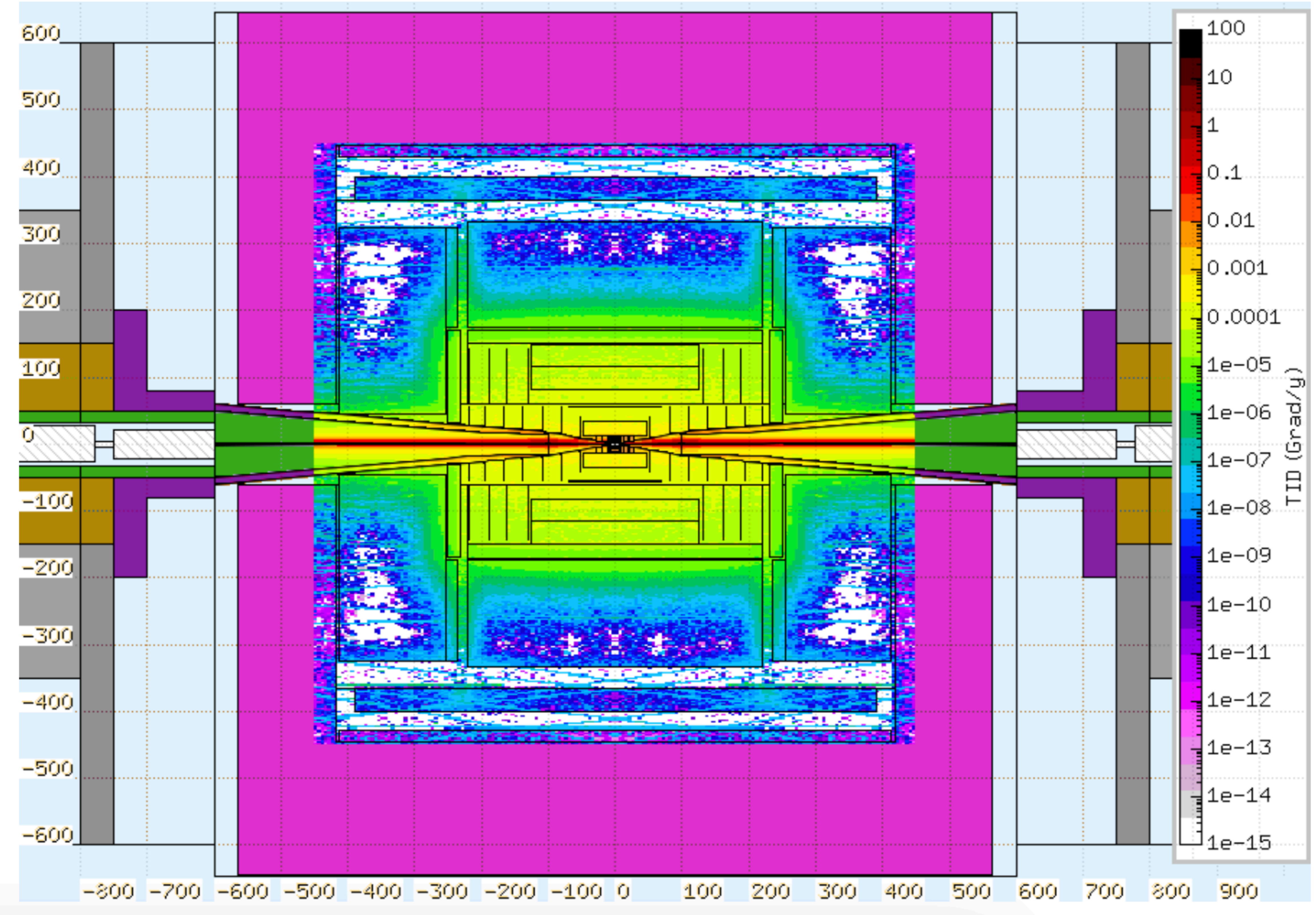
~1/1000 event rate

Similar dose & fluence

100 TeV pp ~3 orders of magnitude worse

~$10^{18}$ MeV-neq /cm$^2$

For one year of operation



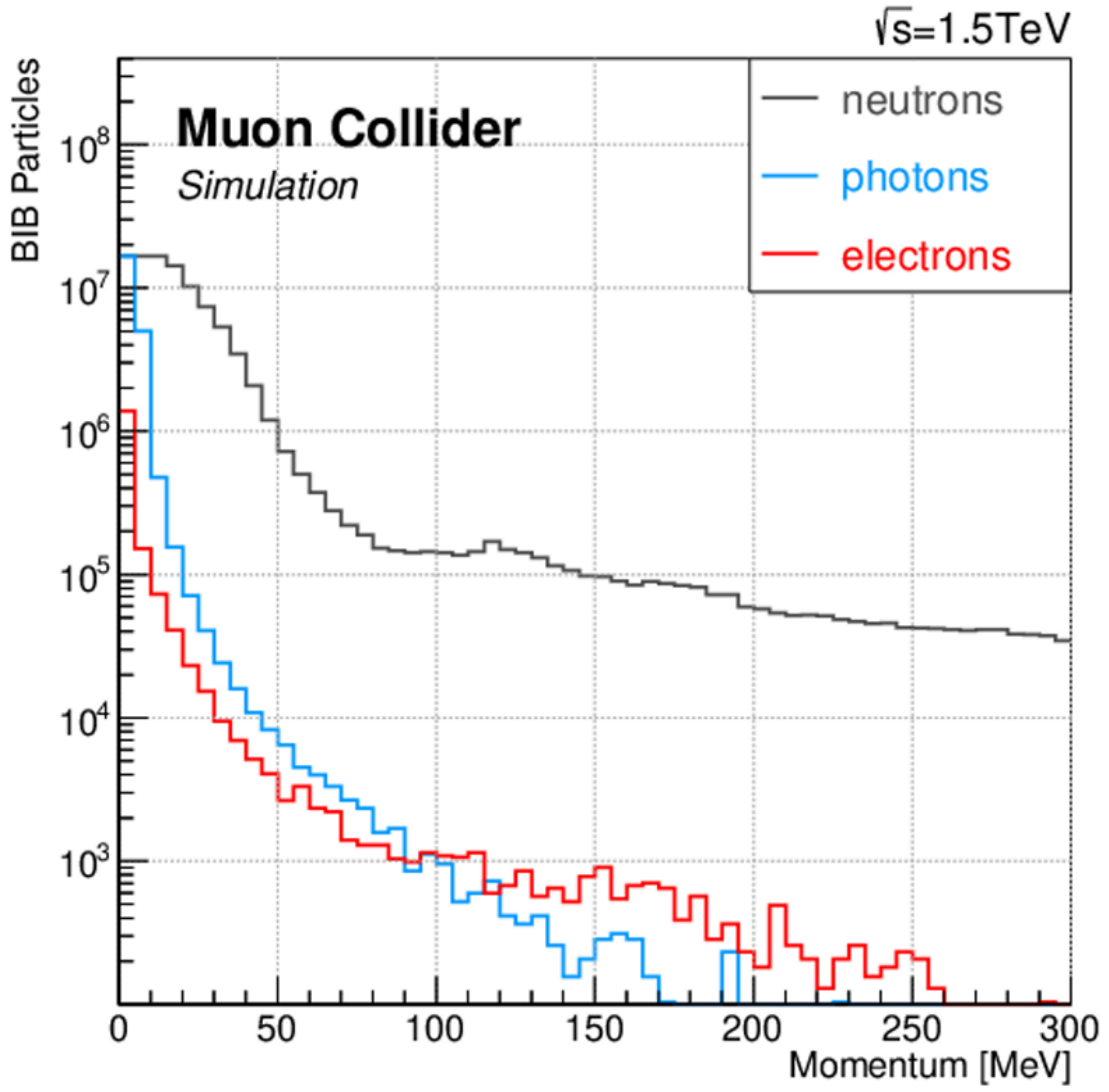

| | Maximum Dose (Mrad) | | Maximum Fluence (1 MeV-neq/cm$^2$) | |
|---|---|---|---|---|
| | R= 22 mm | R= 1500 mm | R= 22 mm | R= 1500 mm |
| Muon Collider | 10 | 0.1 | $10^{15}$ | $10^{14}$ |
| HL-LHC | 100 | 0.1 | $10^{15}$ | $10^{13}$ |

# Background properties

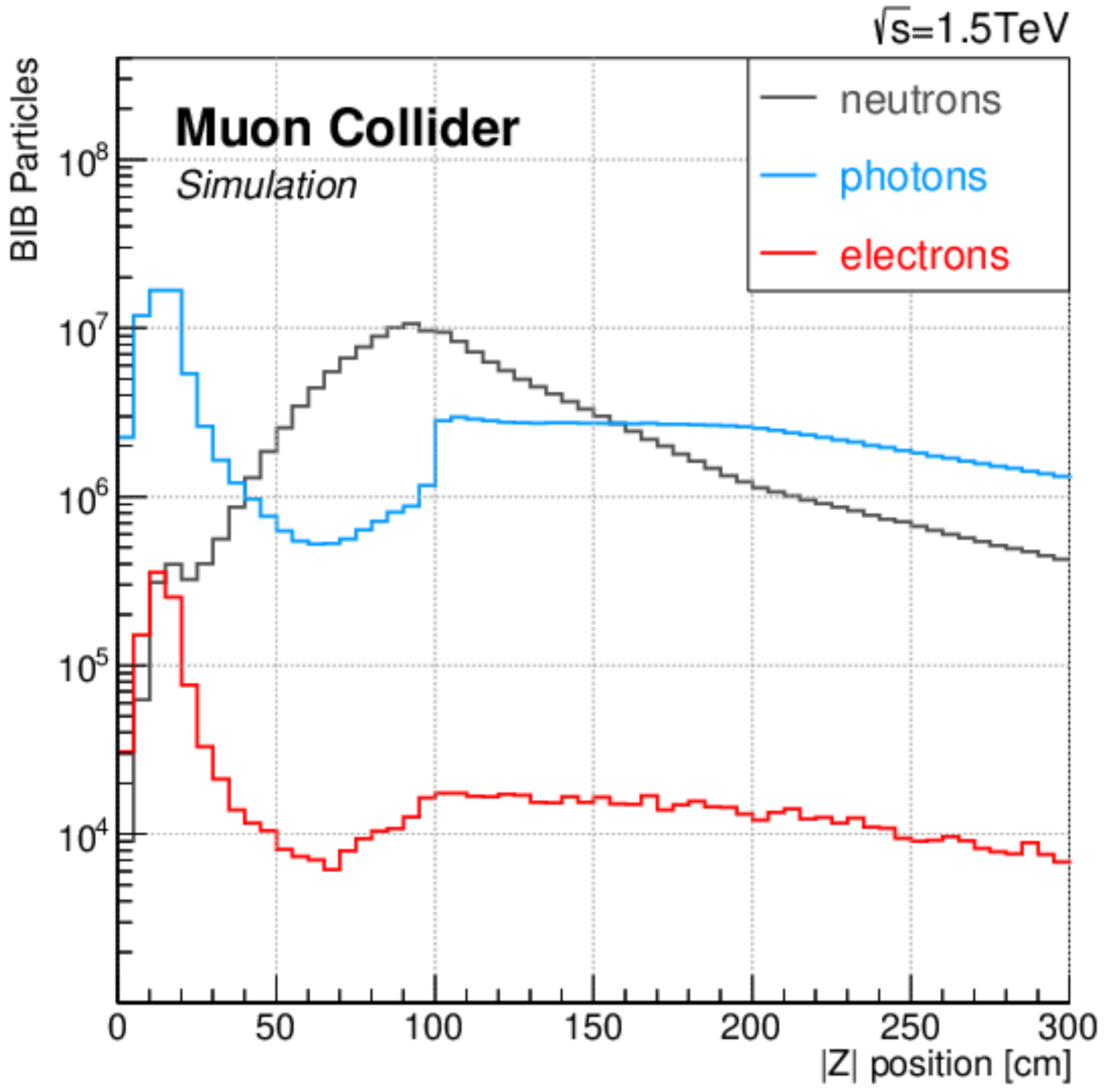
**With standard nozzle ~$10^8$ low momentum particles per event**

But this background looks very different from signal!

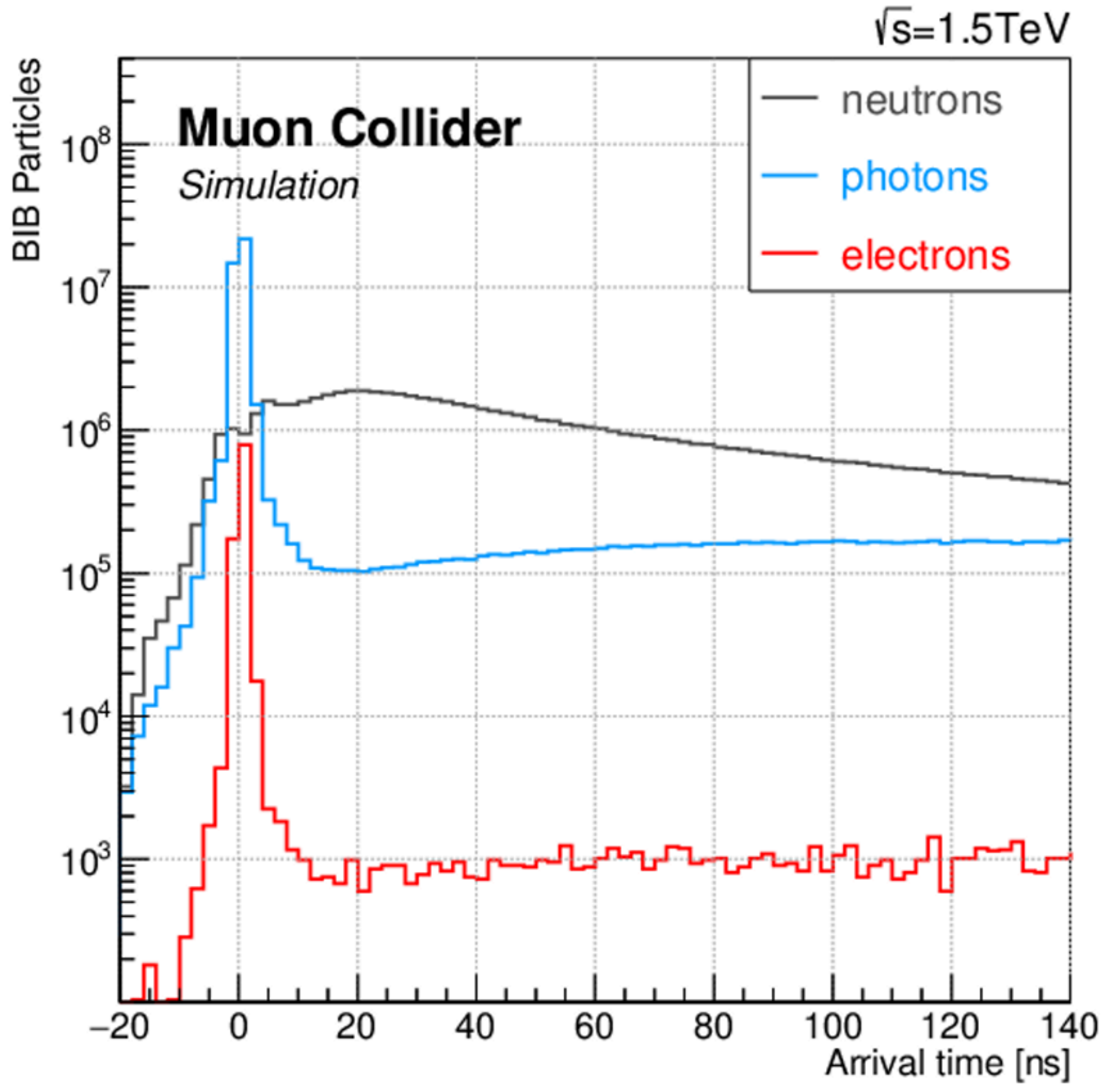
Majority < 200 MeV




Unusual position & direction




Partially out of time



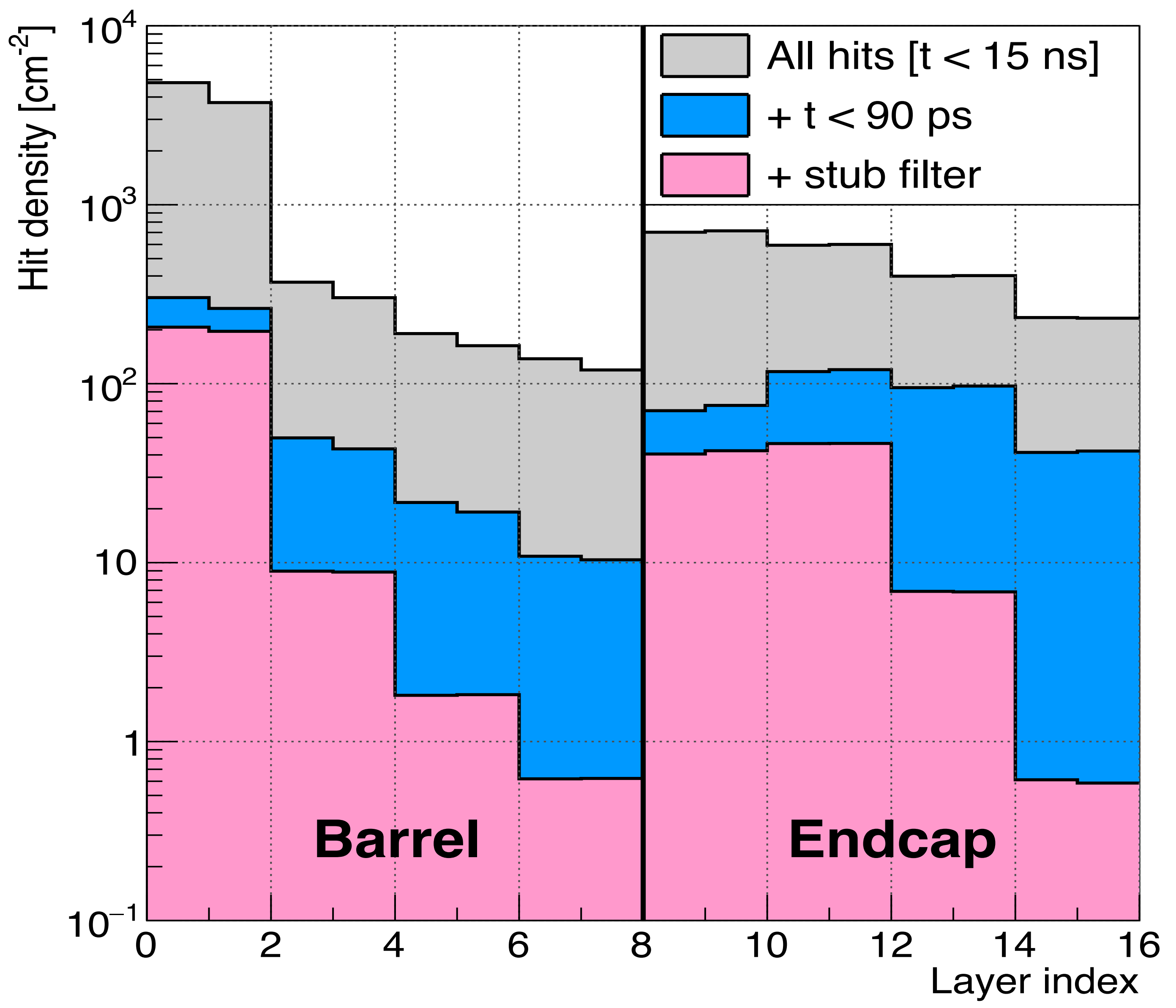

Details depend on beam energy, collider lattice, <u>nozzle</u>, and solenoid

# Hit rates, pointing, and timing

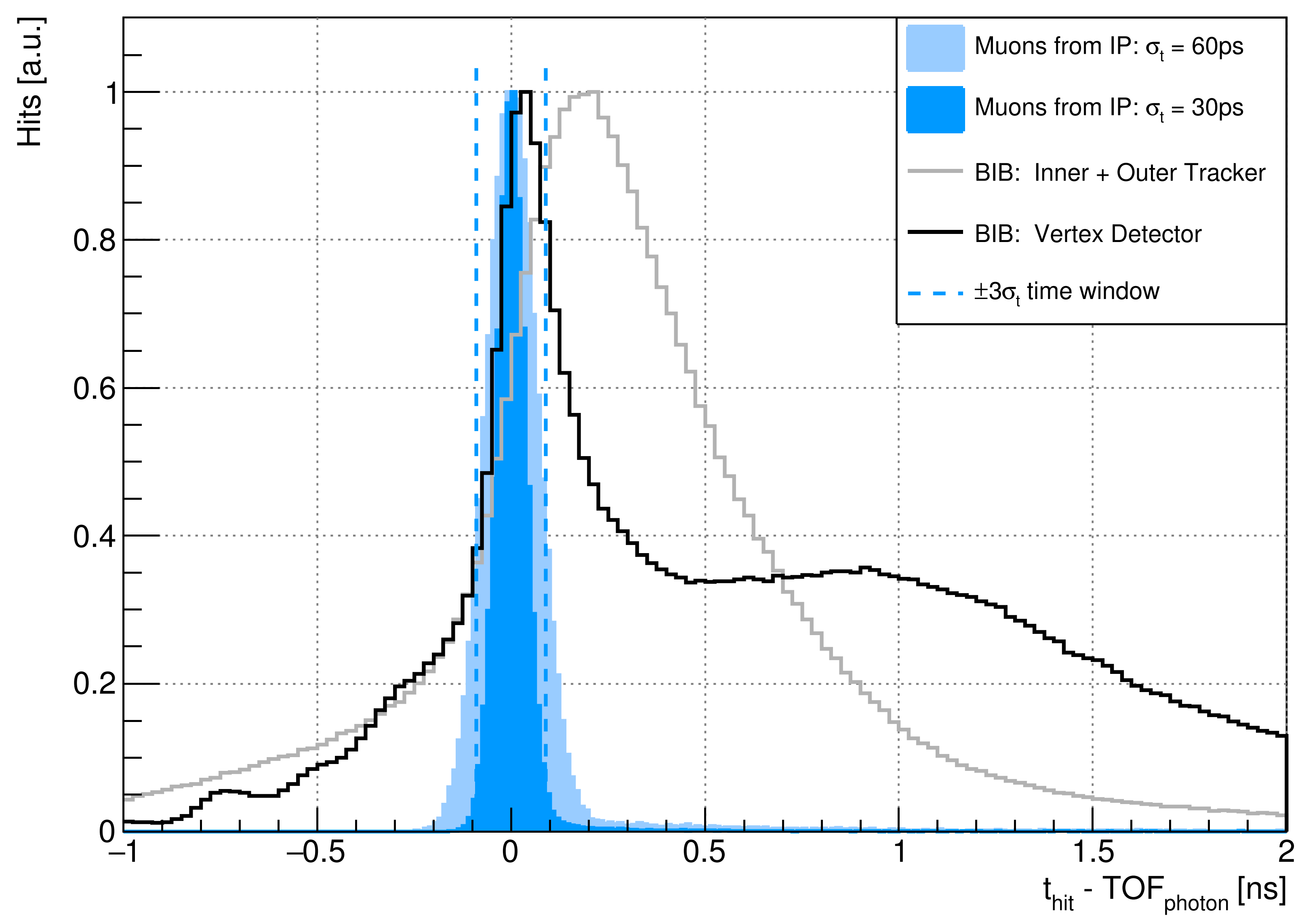
**Occupancy most challenging for the innermost layers of the tracker**

Optimize for <1% & leverage techniques from HL-LHC upgrades

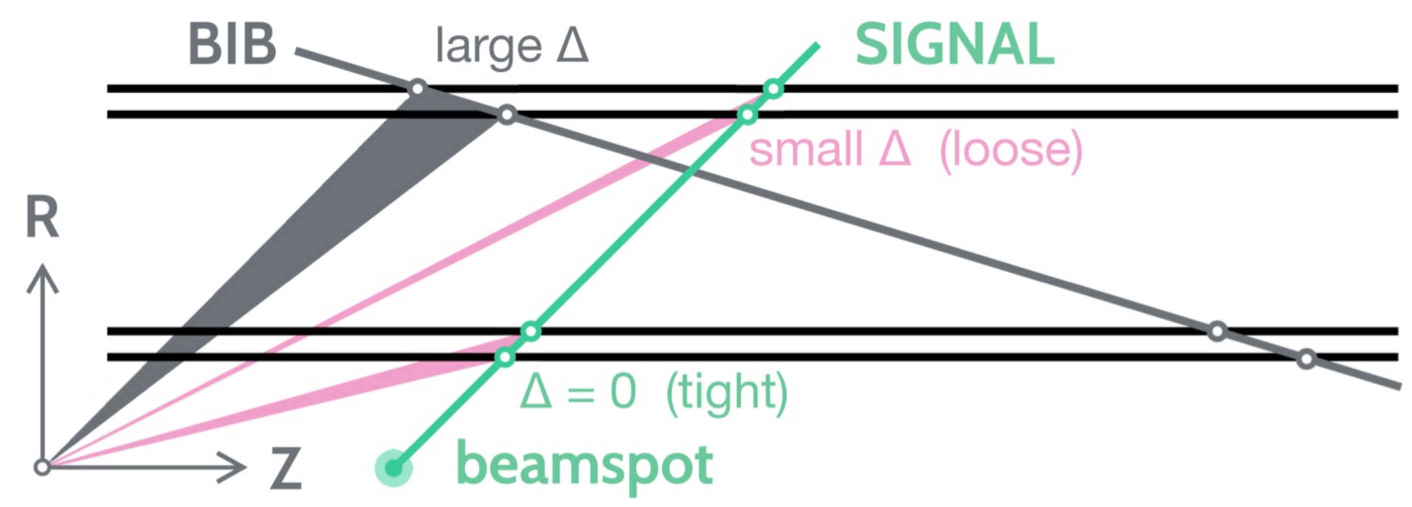
Pixel starts with >1000 hits/cm²




Only select hits in ±3σ time window



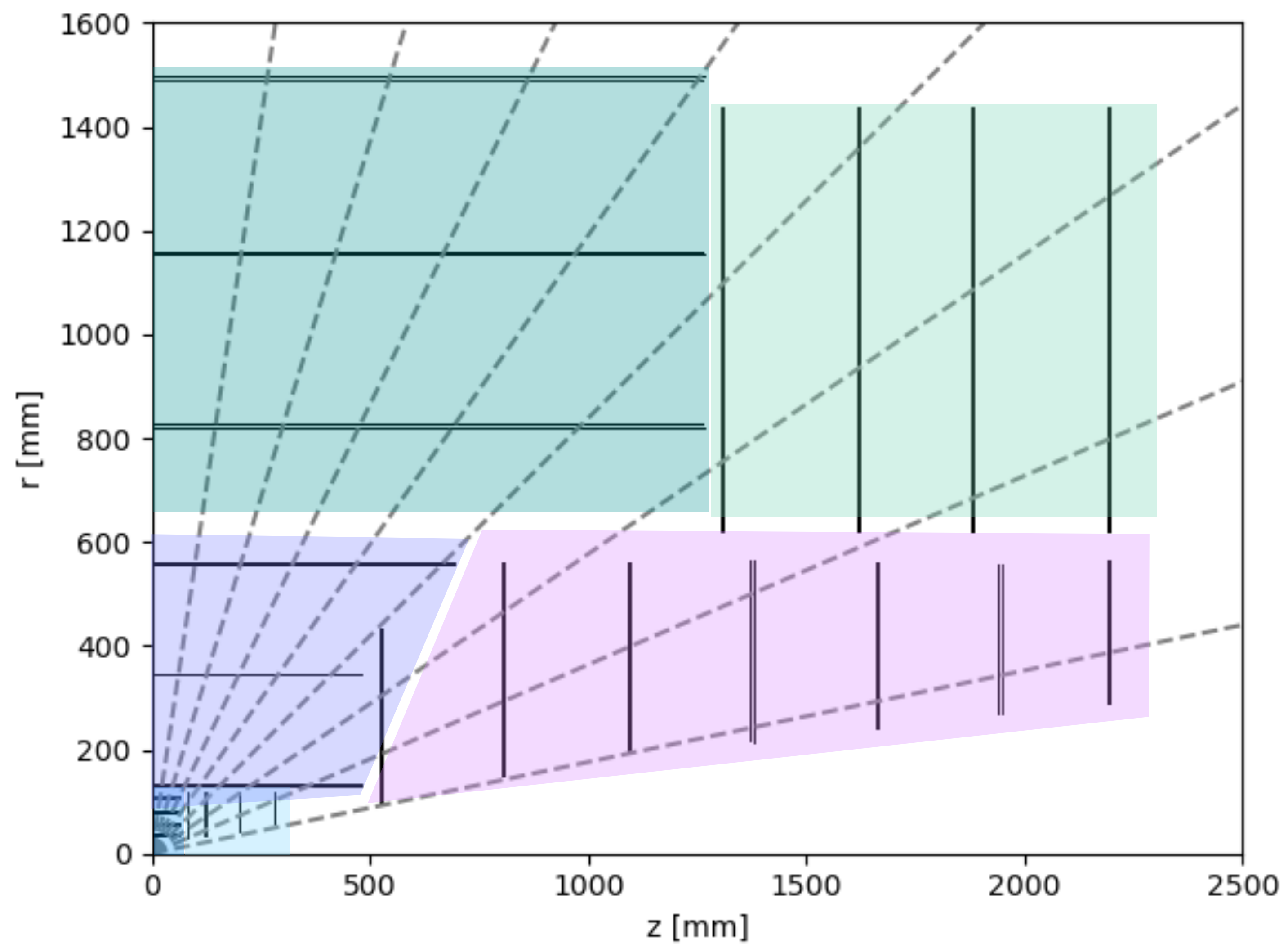

Use doublet layers



# Tracker Requirements

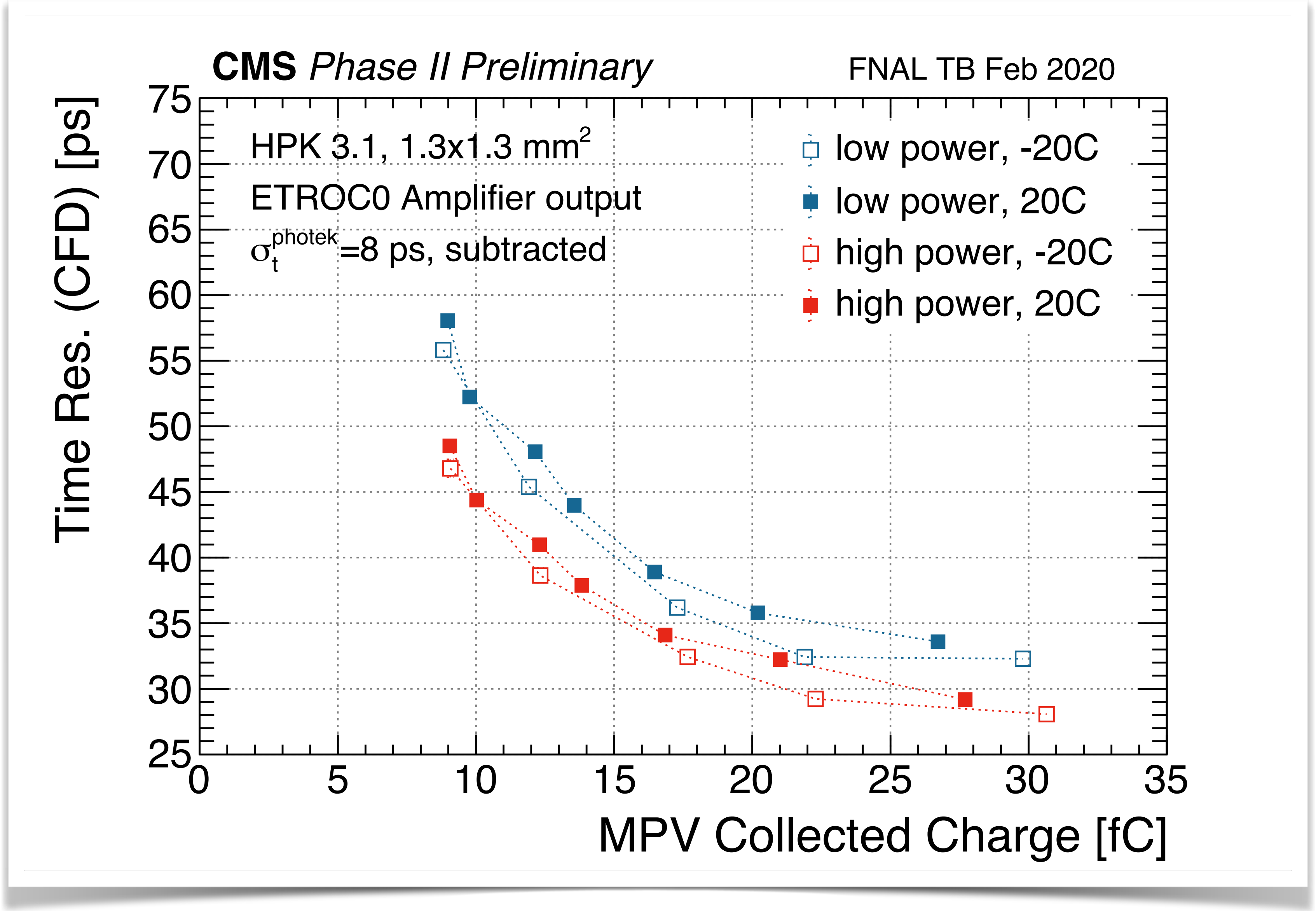
2203.07224

- Large area & highly granular
  - ~100 $m^2$ of silicon sensors
  - ~ 2B channels
- Promising R&D directions
  - Monolithic sensors
  - Devices with intrinsic gain
  - Intelligent sensors
- Challenges:
  - Power consumption
  - DAQ/trigger: O(100) TB/s
  - "Streaming" readout looks feasible




| Sub detector | Size | Timing |
|---|---|---|
| Vertex Detector | 25 x 25 $\mu m^2$ | 30 ps |
| Inner Tracker | 50 µm x 1 mm | 60 ps |
| Outer Tracker | 50 µm x 10 mm | 60 ps |

ATLAS & CMS building timing layers with ~30 ps timing resolution for HL-LHC



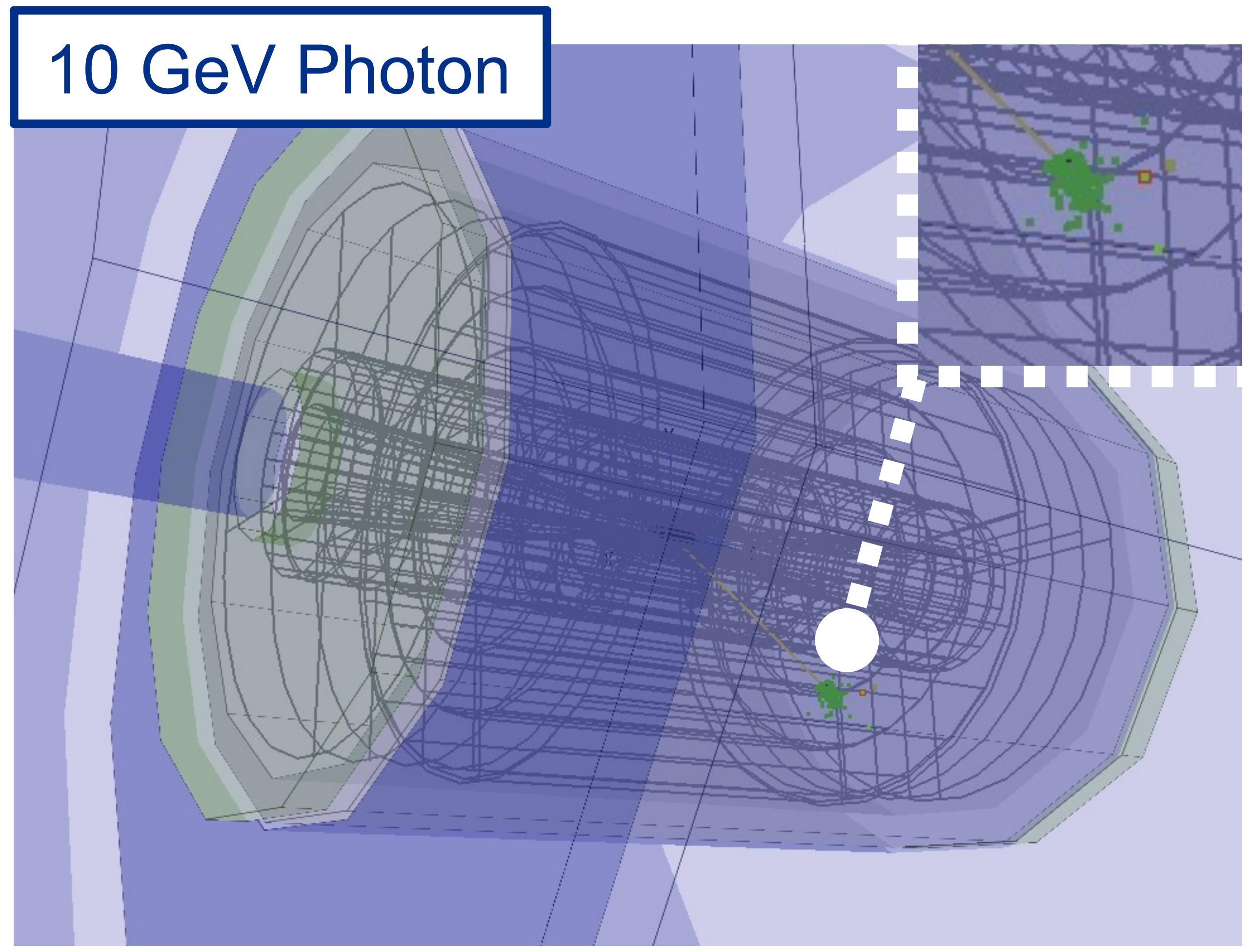

More from Timon

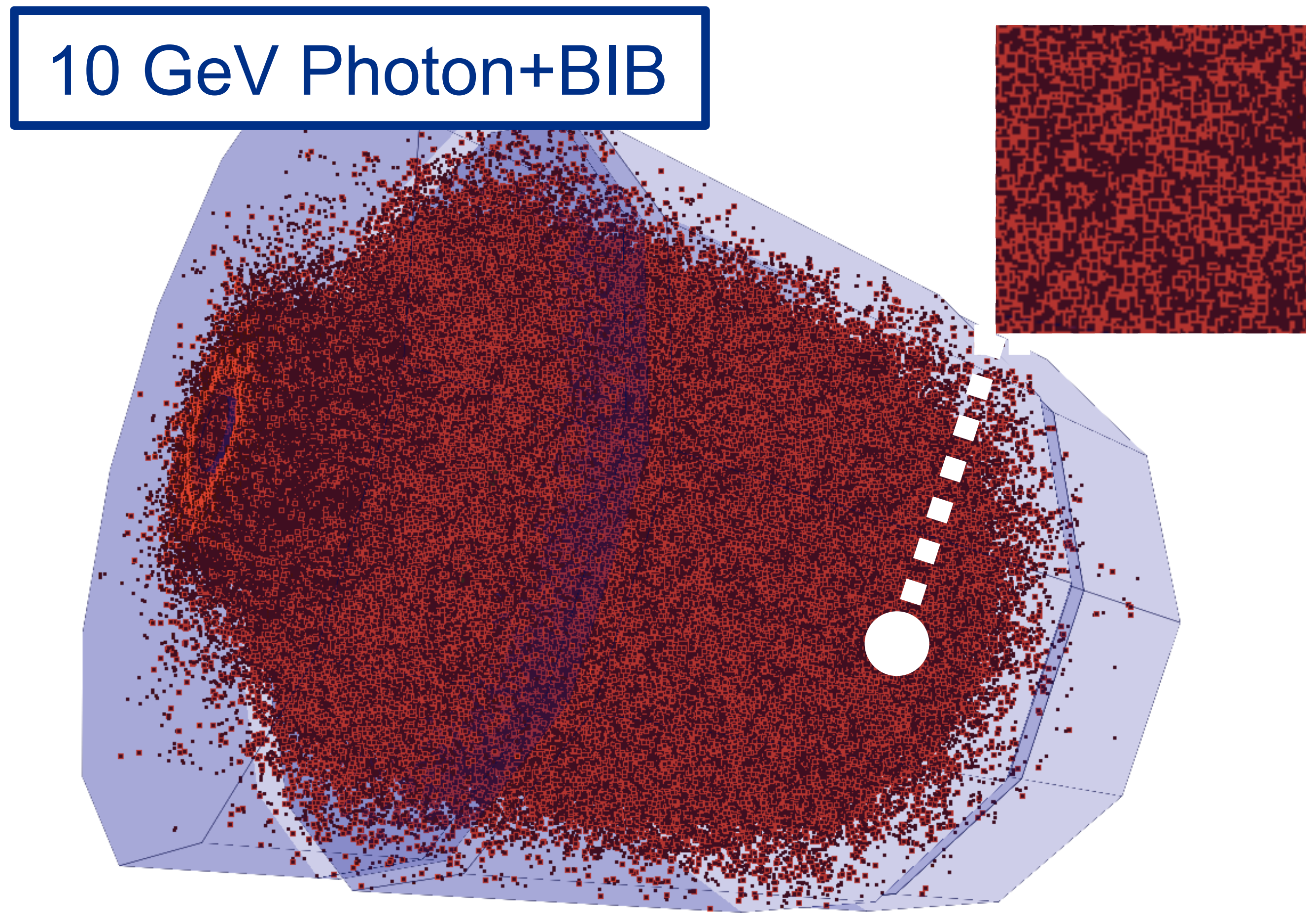
# High Granularity Calorimeter

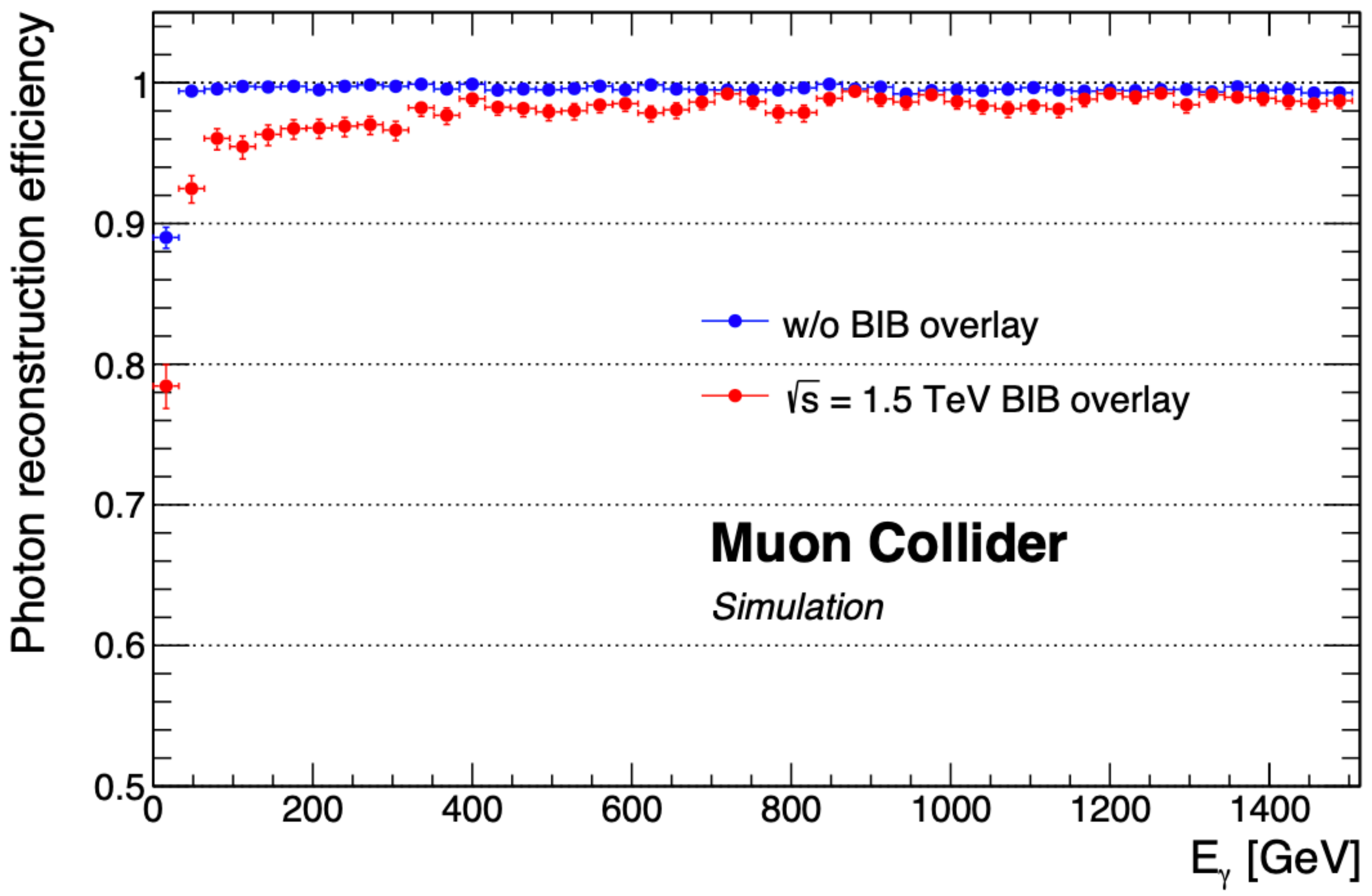
**Background = large, out of time low energy cloud of neutrals**
~2 MeV γ (96%)
~500 MeV n (4%)

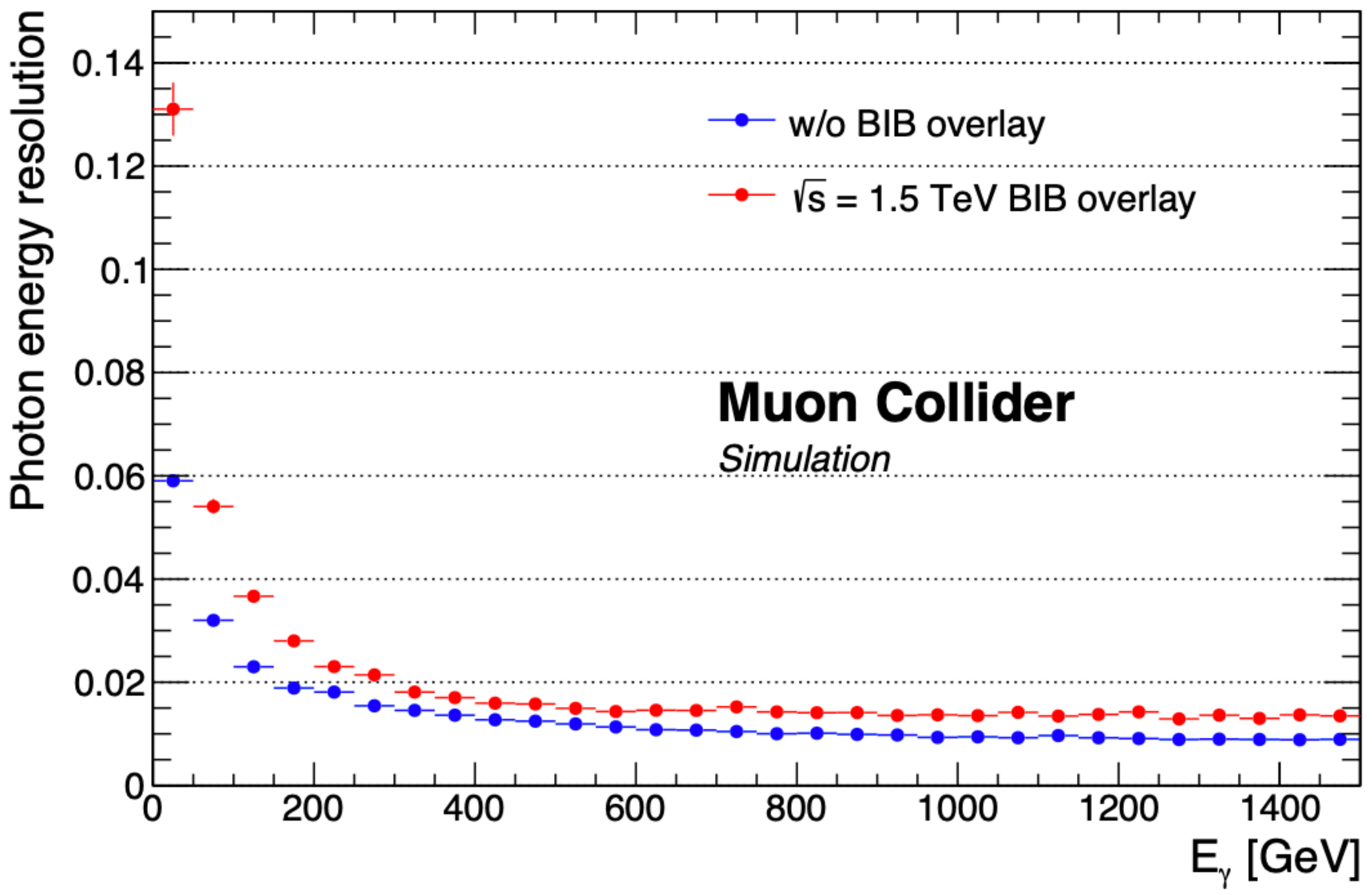
**Current design assumes**
ECAL: Silicon+Tungsten 5x5 $mm^2$ cells
HCAL: Steel+Scintillator 30x30 $mm^2$ cells
Timing resolution (~100 ps)
+ Longitudinal segmentation

**Room for new ideas**
(e.g. Crilin, Calvision?)




More from Chris

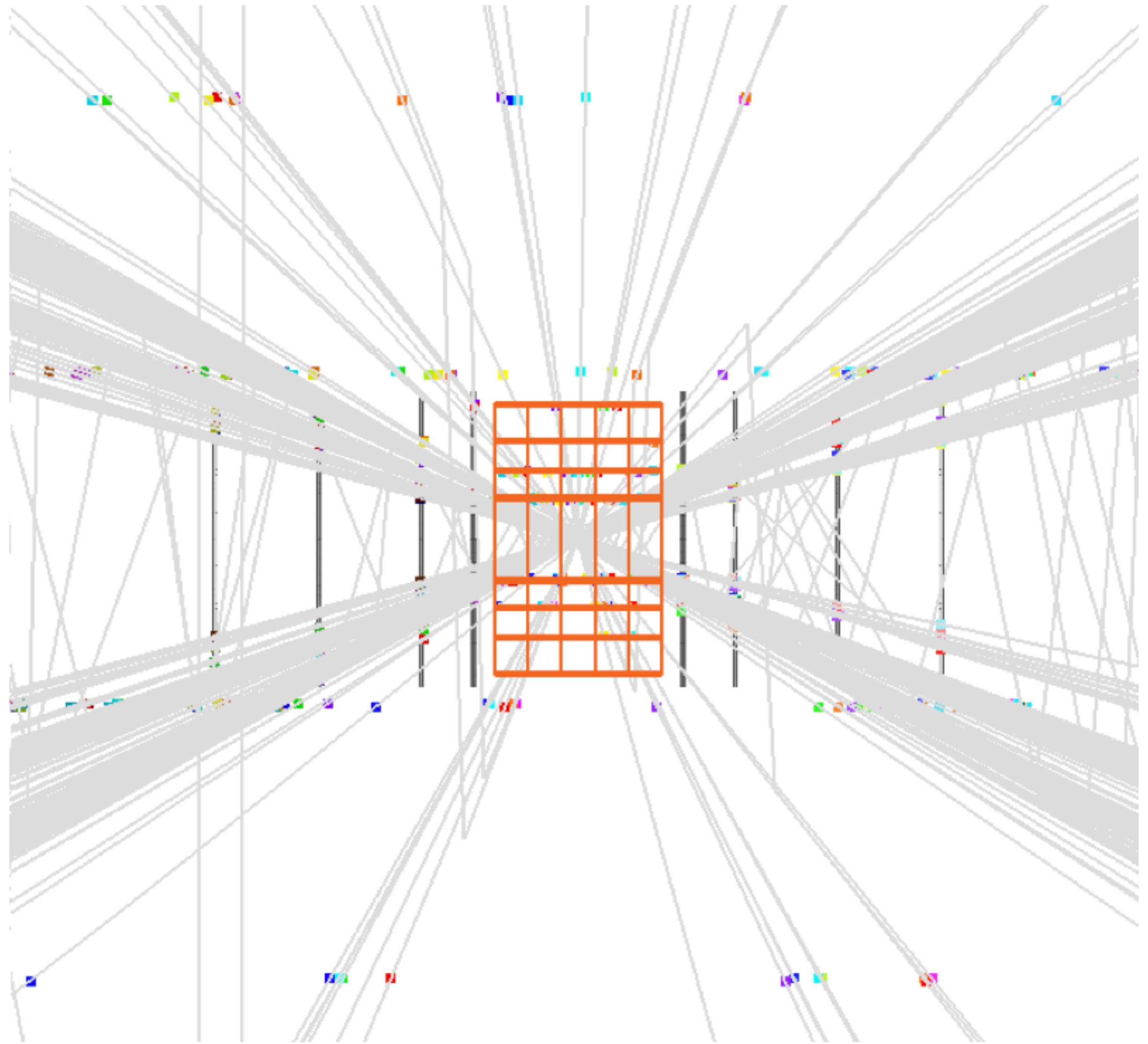
# Reconstruction

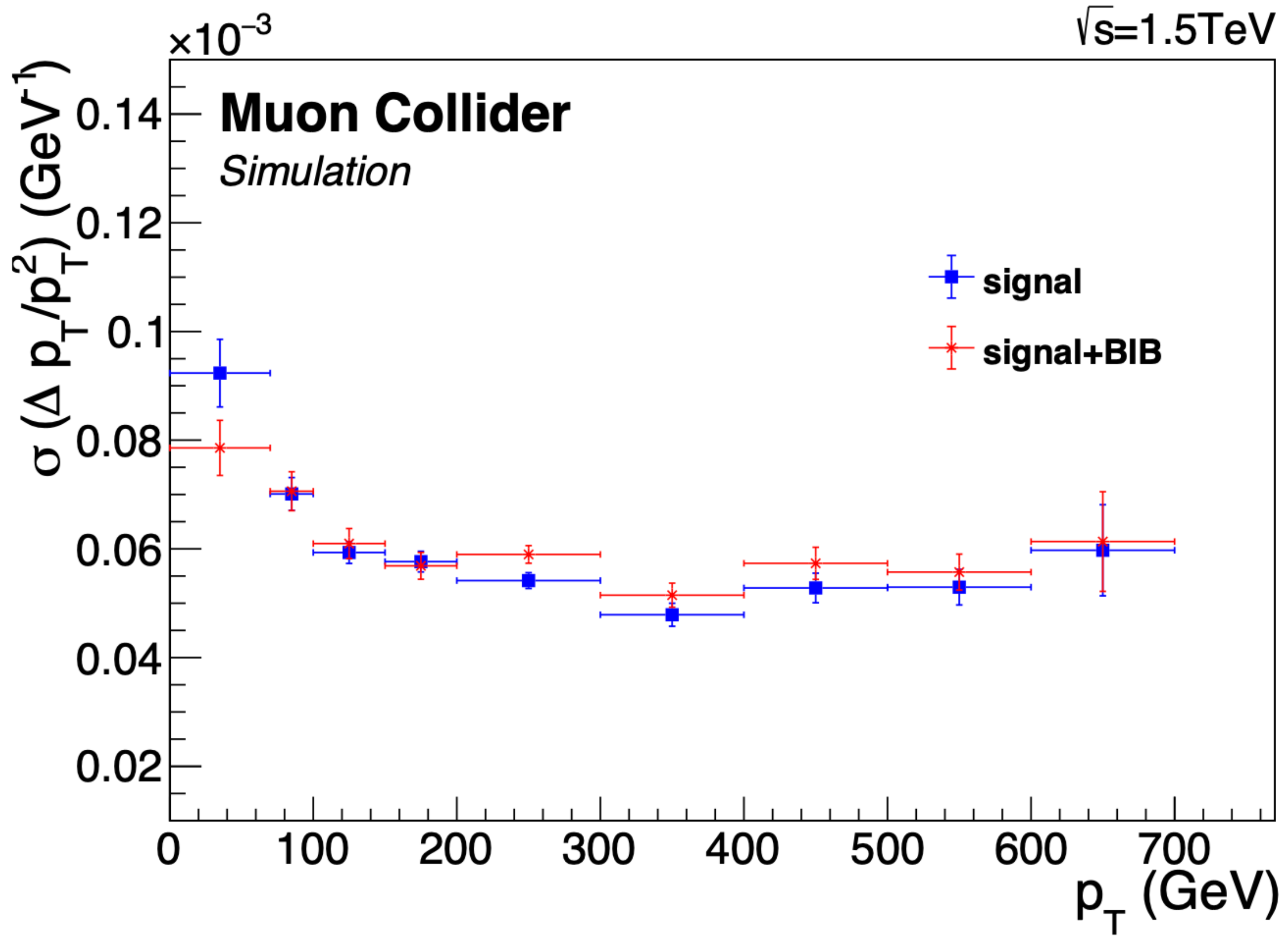
Works well! But is an active area of development

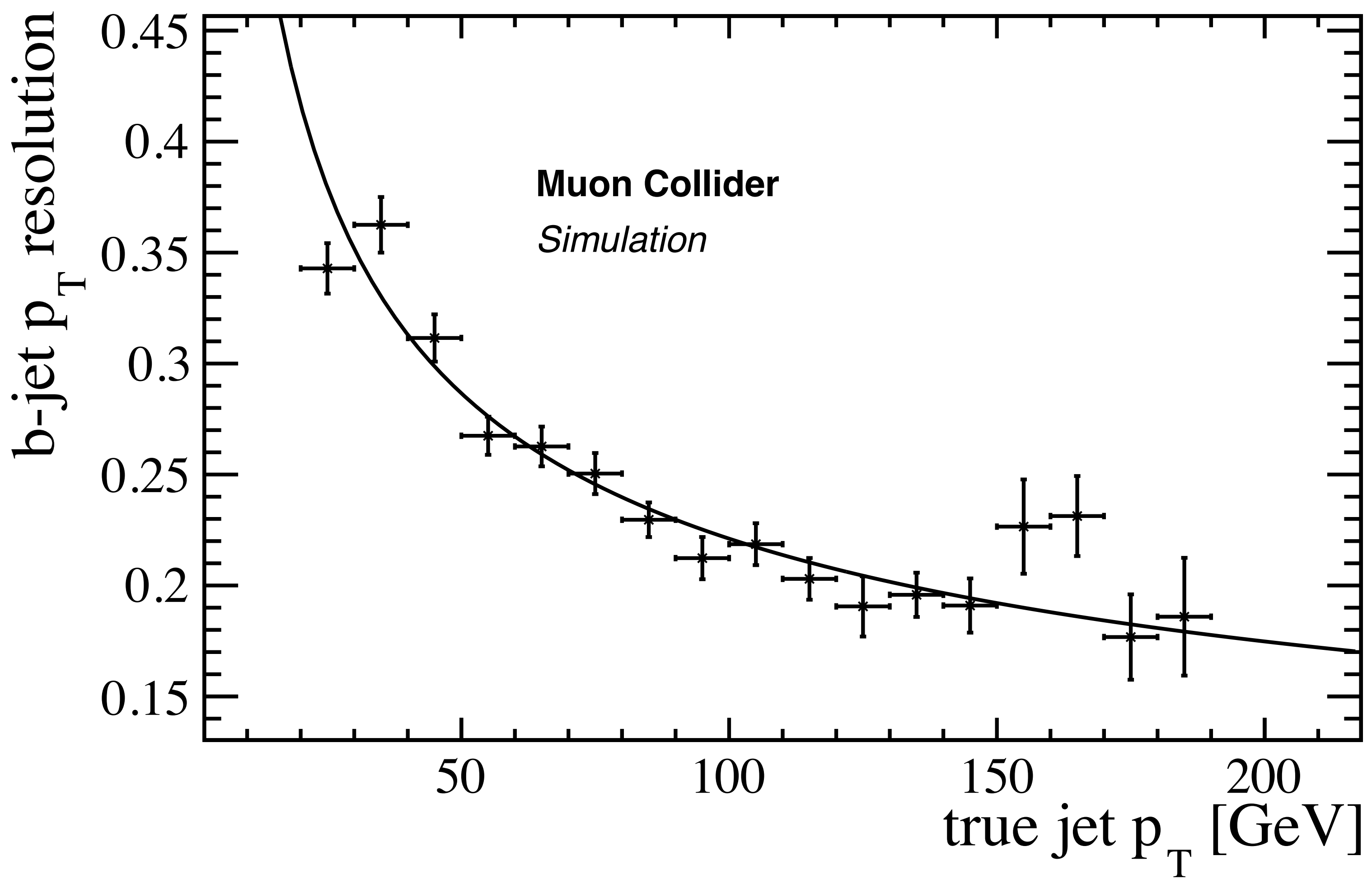
O(100) tracks per event after $p_T$, $n_{hits}$, quality of fit requirements

Photon and particle flow jet performance similar to hadron collider

Combinatoric tracks





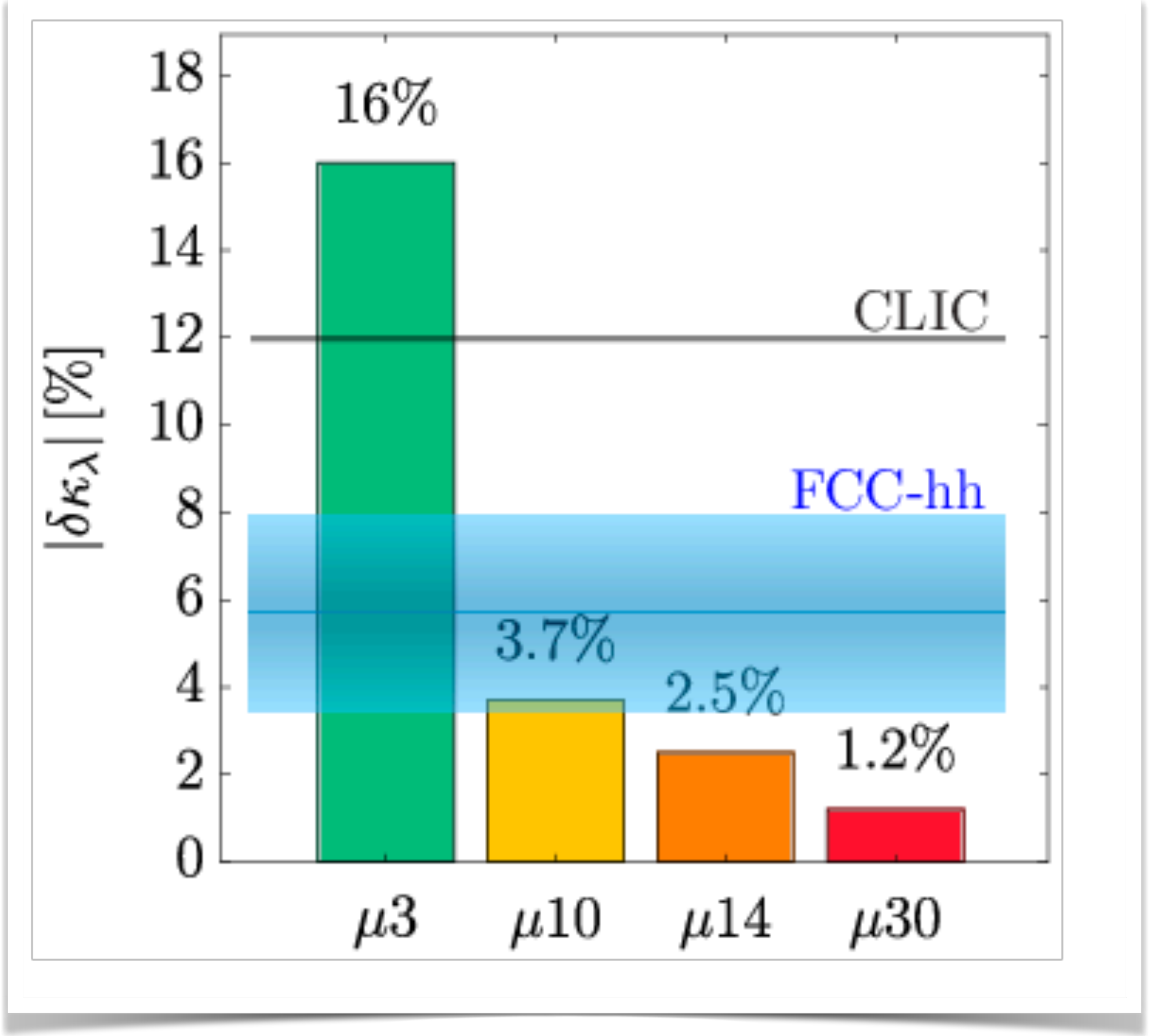



# Extracting Physics

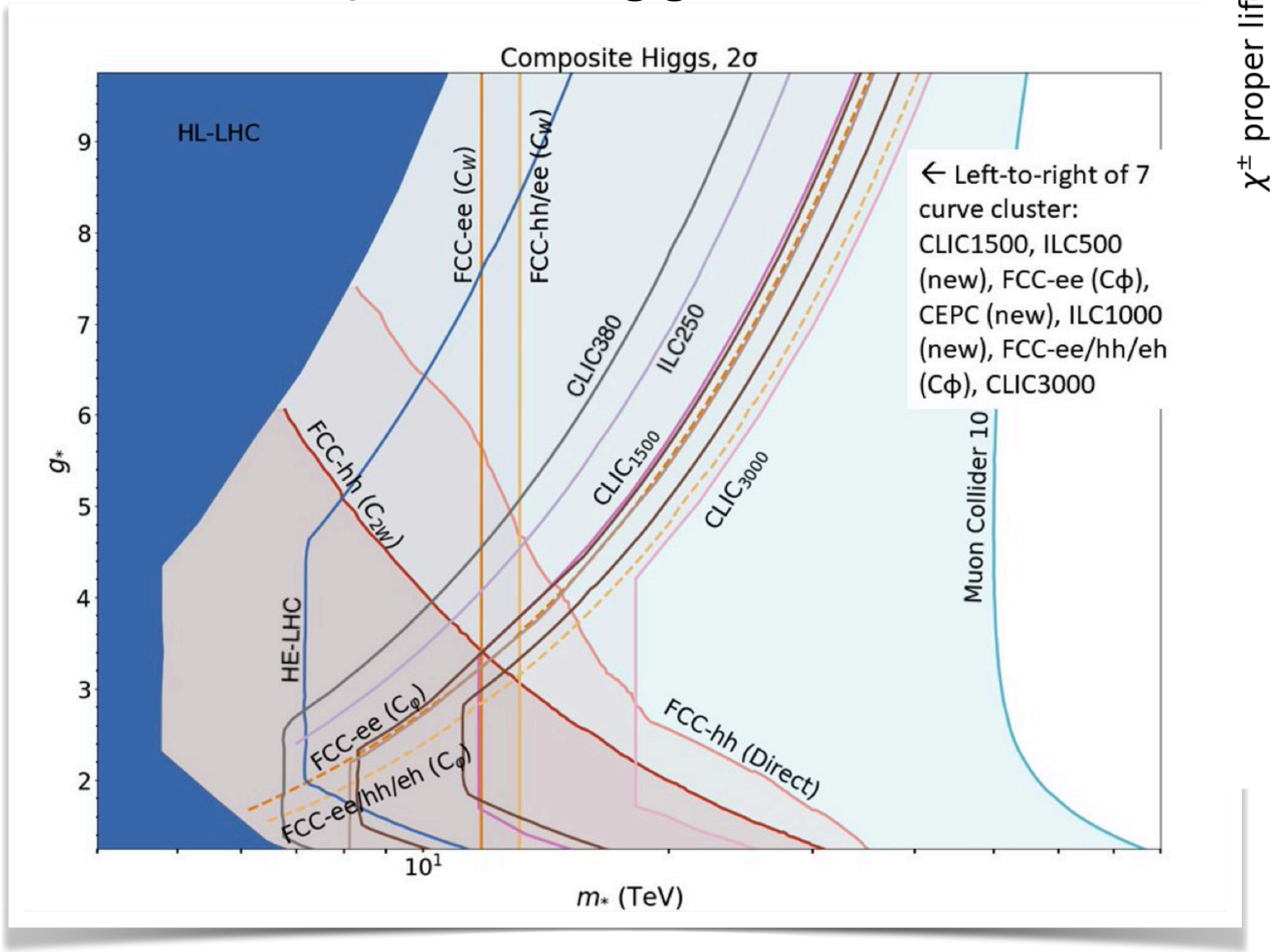
2209.01318

High quality physics demonstrated in full simulation - in good agreement with fast sim!

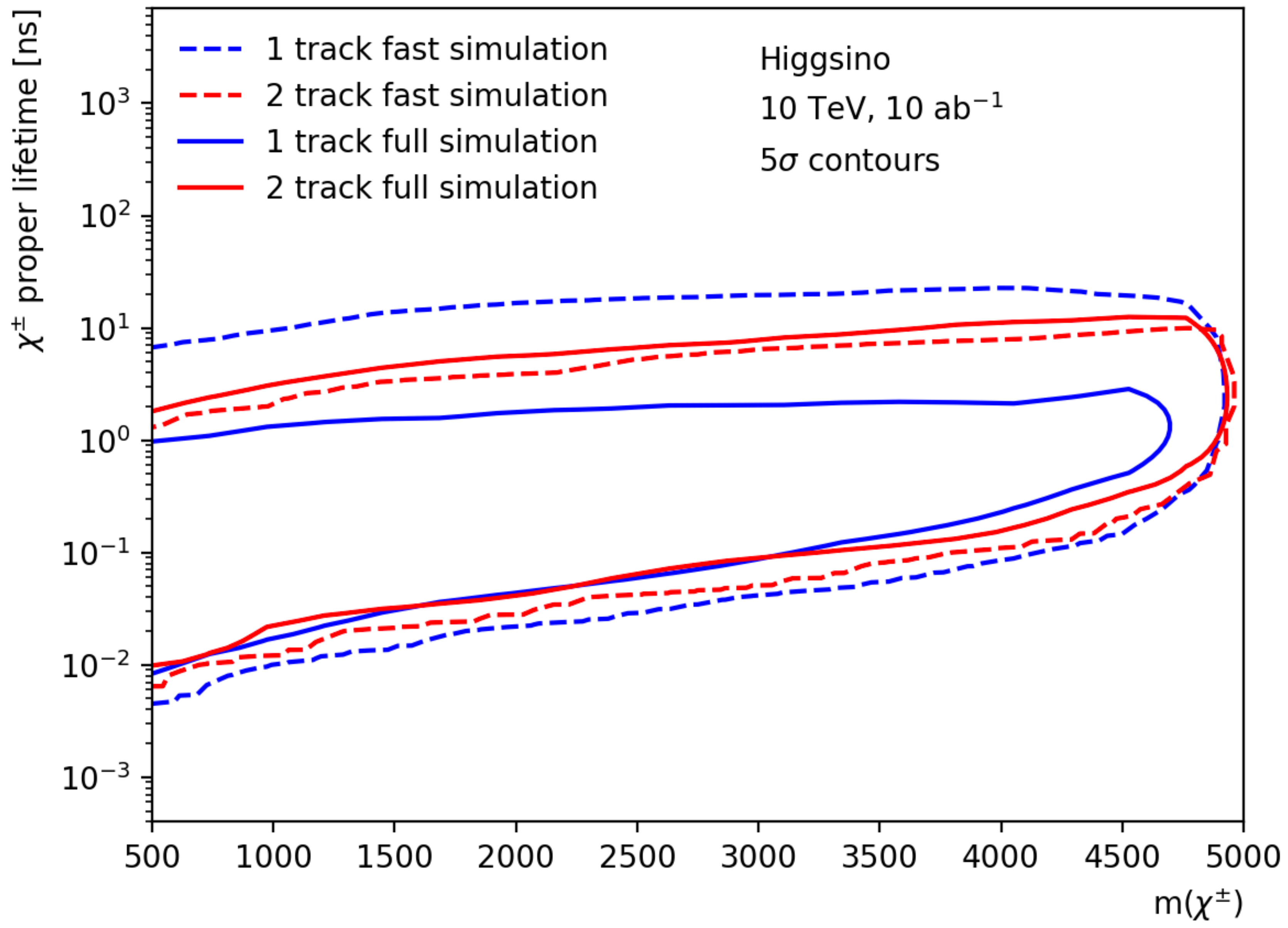
Higgs self-coupling




Composite Higgs Scenarios




Disappearing track



# Status, Open Questions

# Since Snowmass: 10 TeV efforts

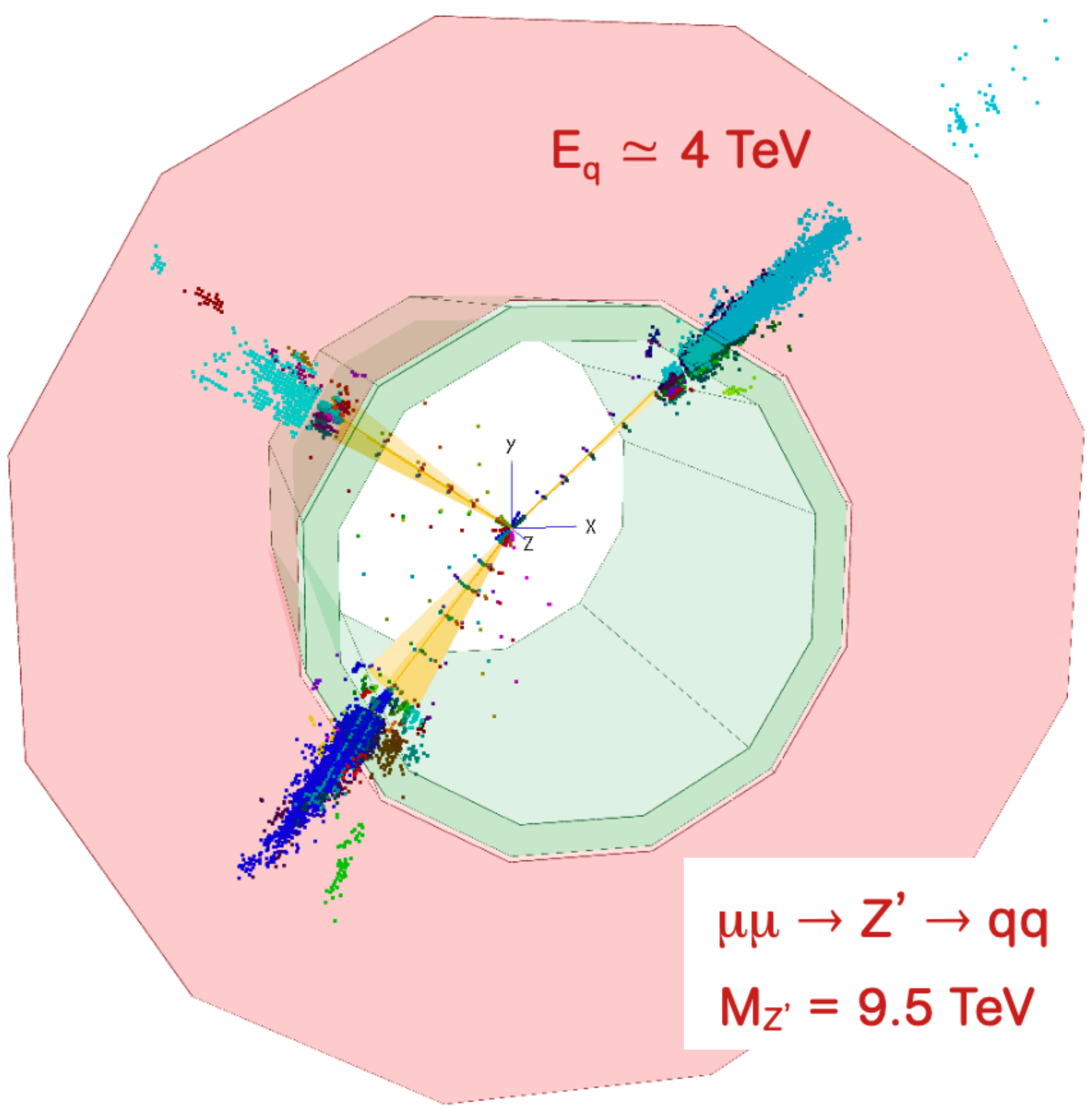
Challenge: detector size needs to grow with energy

Eg. Solenoid field (5T)
& tracker size R=1.5 m

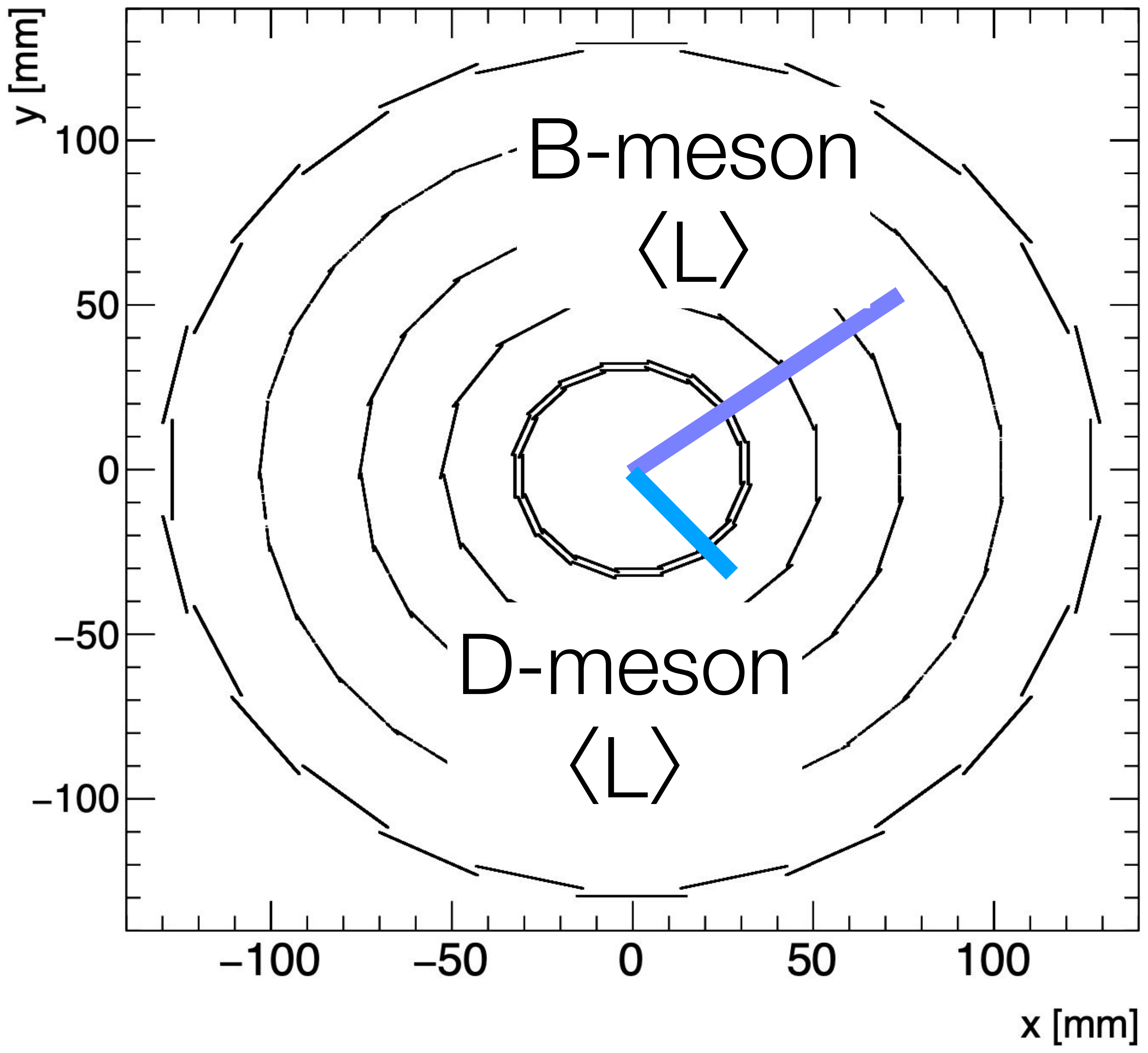
$$\left(\frac{\sigma_{p_T}}{p_T}\right) \sim \frac{p_T}{BL^2}\frac{\sigma_{\text{point}}}{\sqrt{N}}$$

Two 10 TeV detector efforts
ATLAS/CMS style

Shower containment



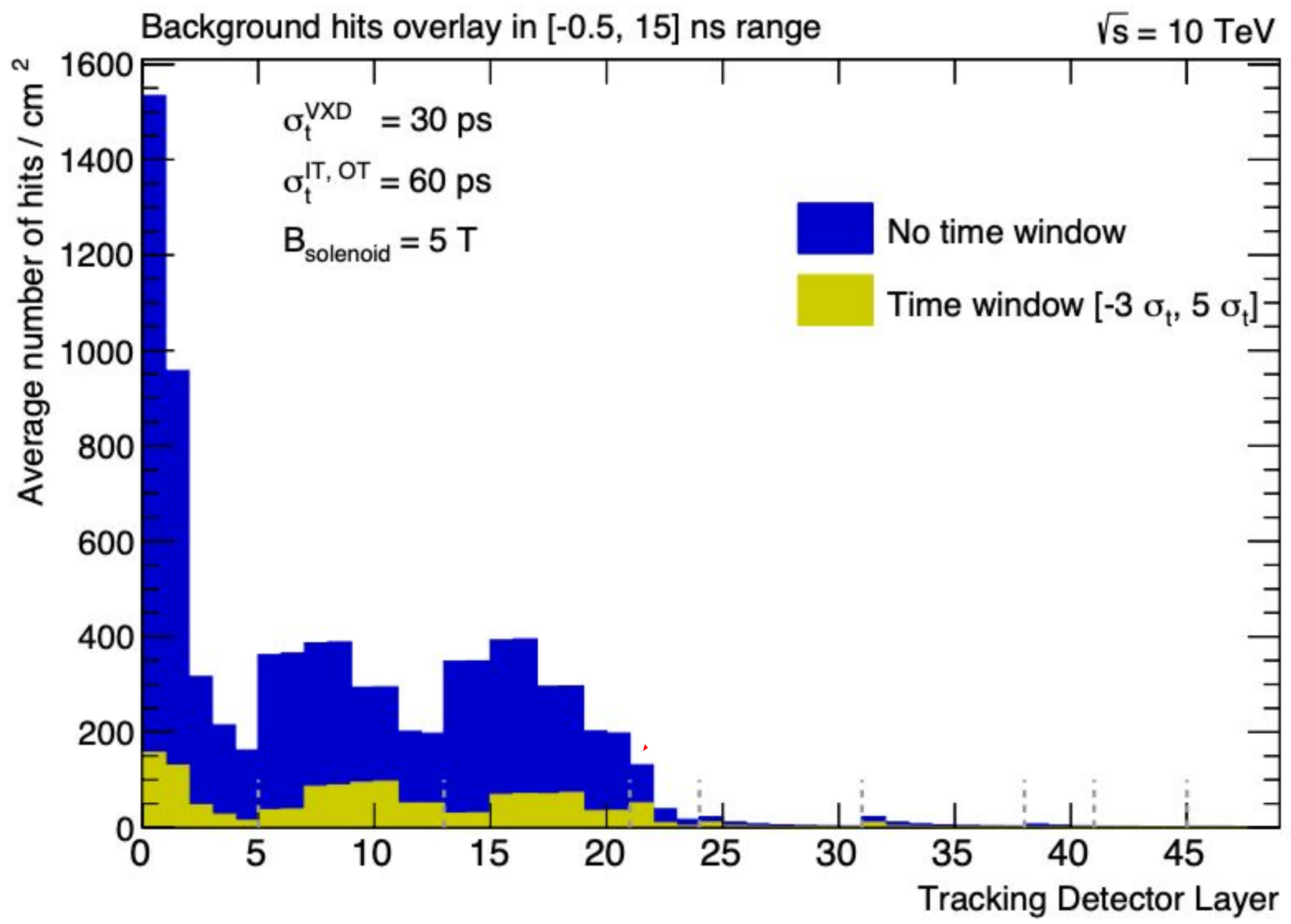

SM particle mean decay lengths



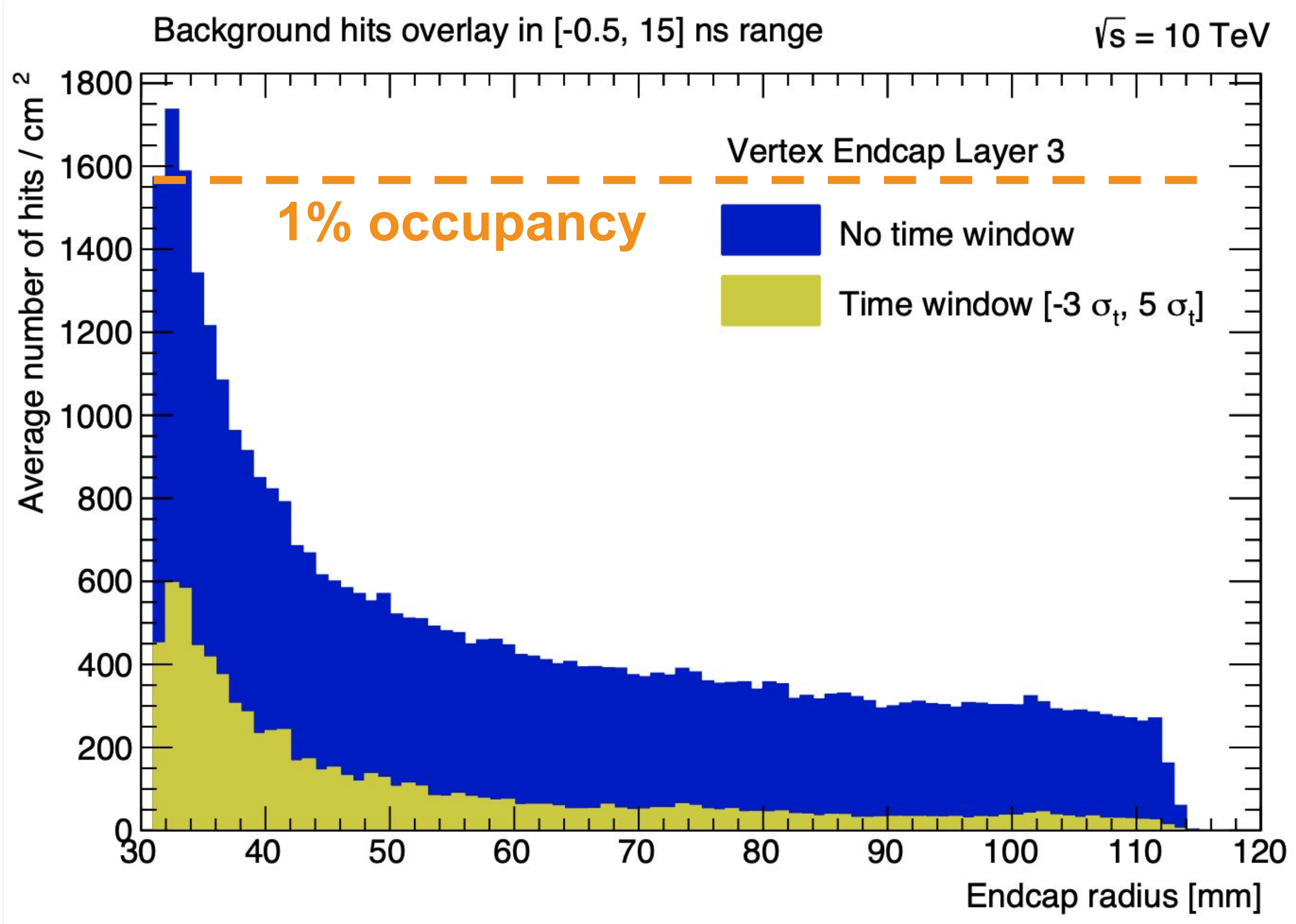
# BIB at 10 TeV

F. Meloni, D. Calzorani

IMCC has made massive progress on 10 TeV BIB with Fluka
Occupancies similar to 3 TeV or slightly lower




Innermost pixel layers reduced by ~50%

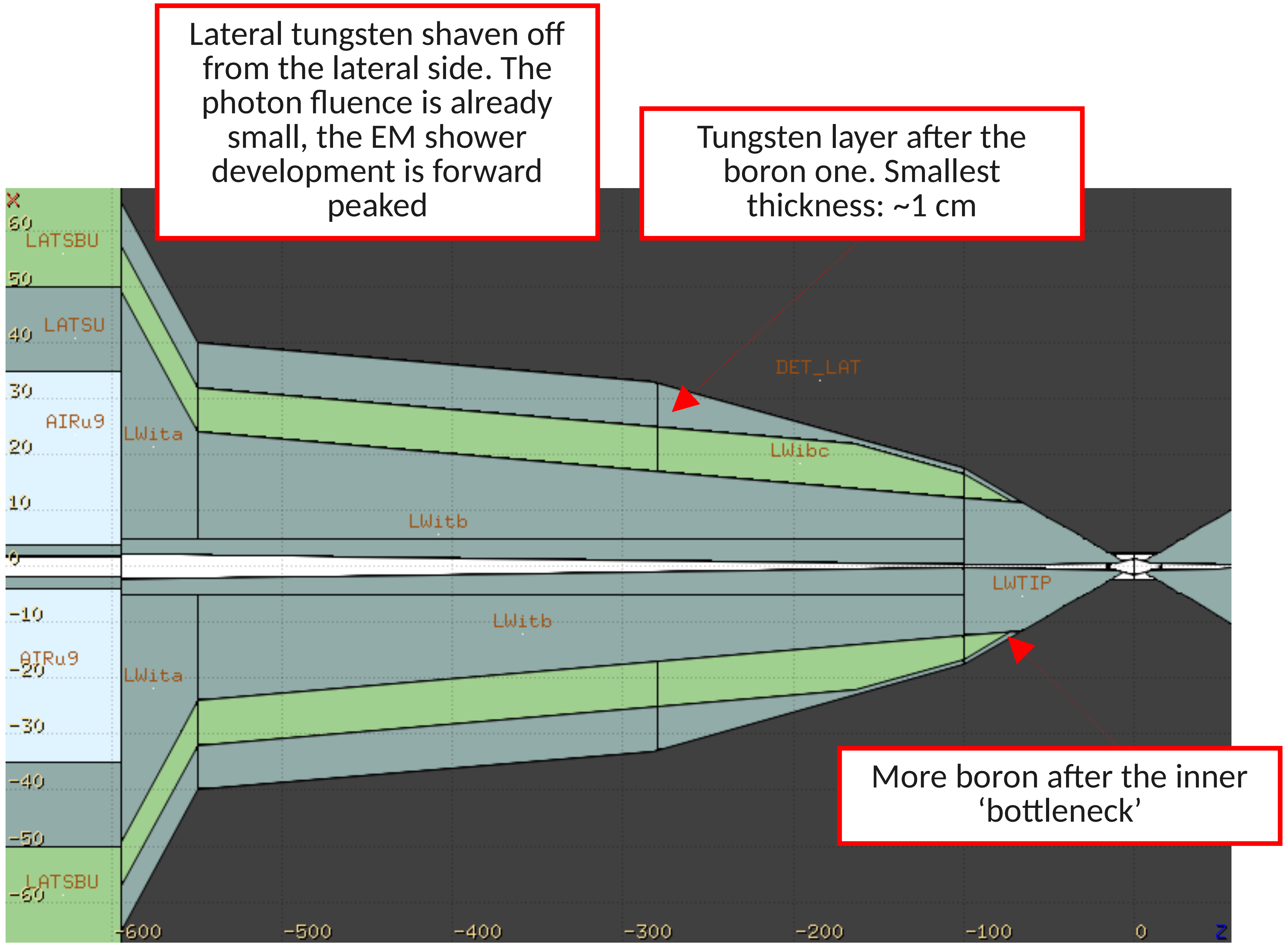


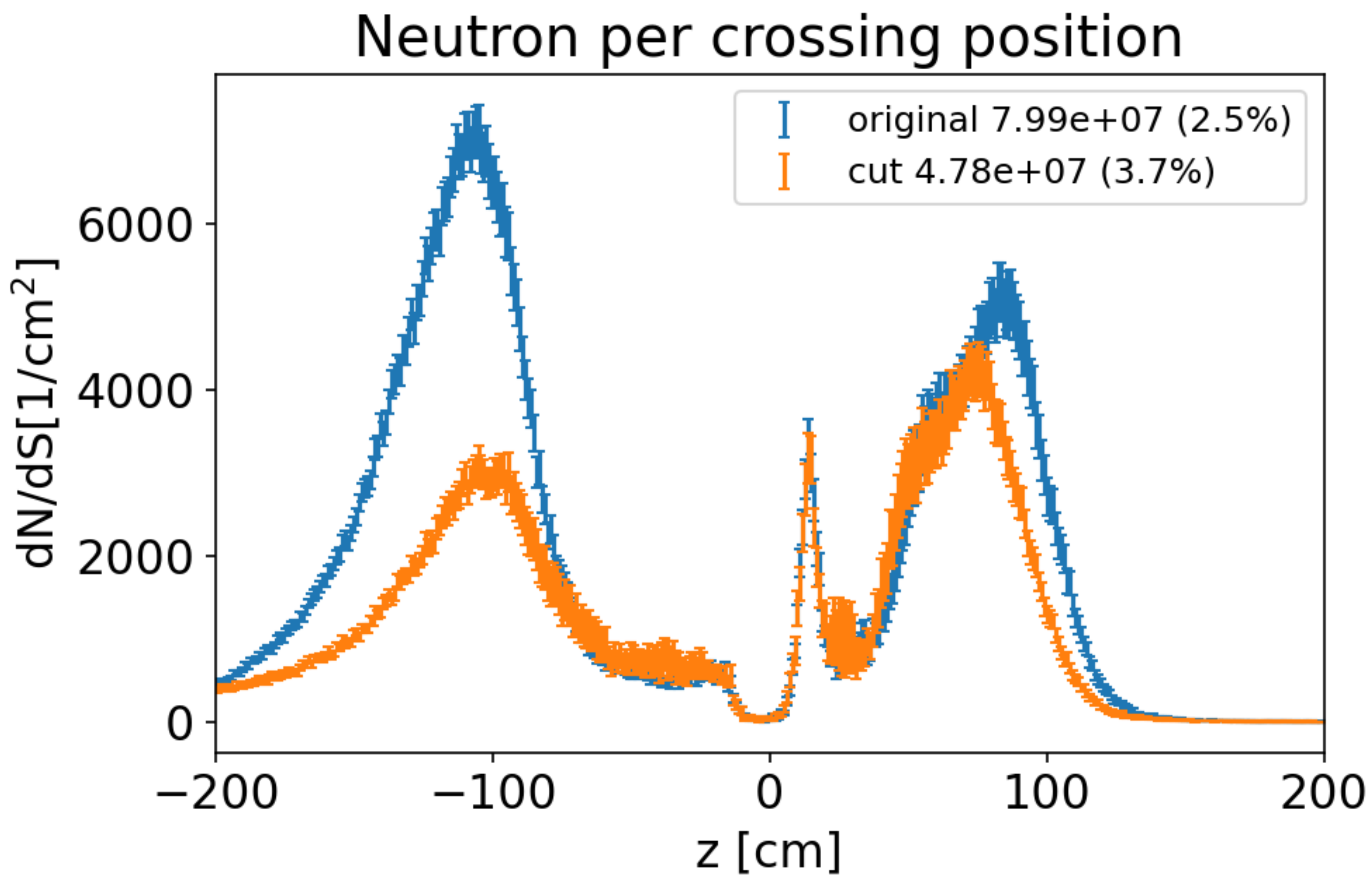

Endcaps close to occupancy limits near nozzles

# Work in progress: MDI

D. Calzolari @ICHEP

Initial look at varying interaction region lattice & nozzle configuration
Changing nozzle seems more promising than changing lattice




Can we also improve forward acceptance?

# Work in progress: forward muon tagging

## Important for Higgs Width and Couplings

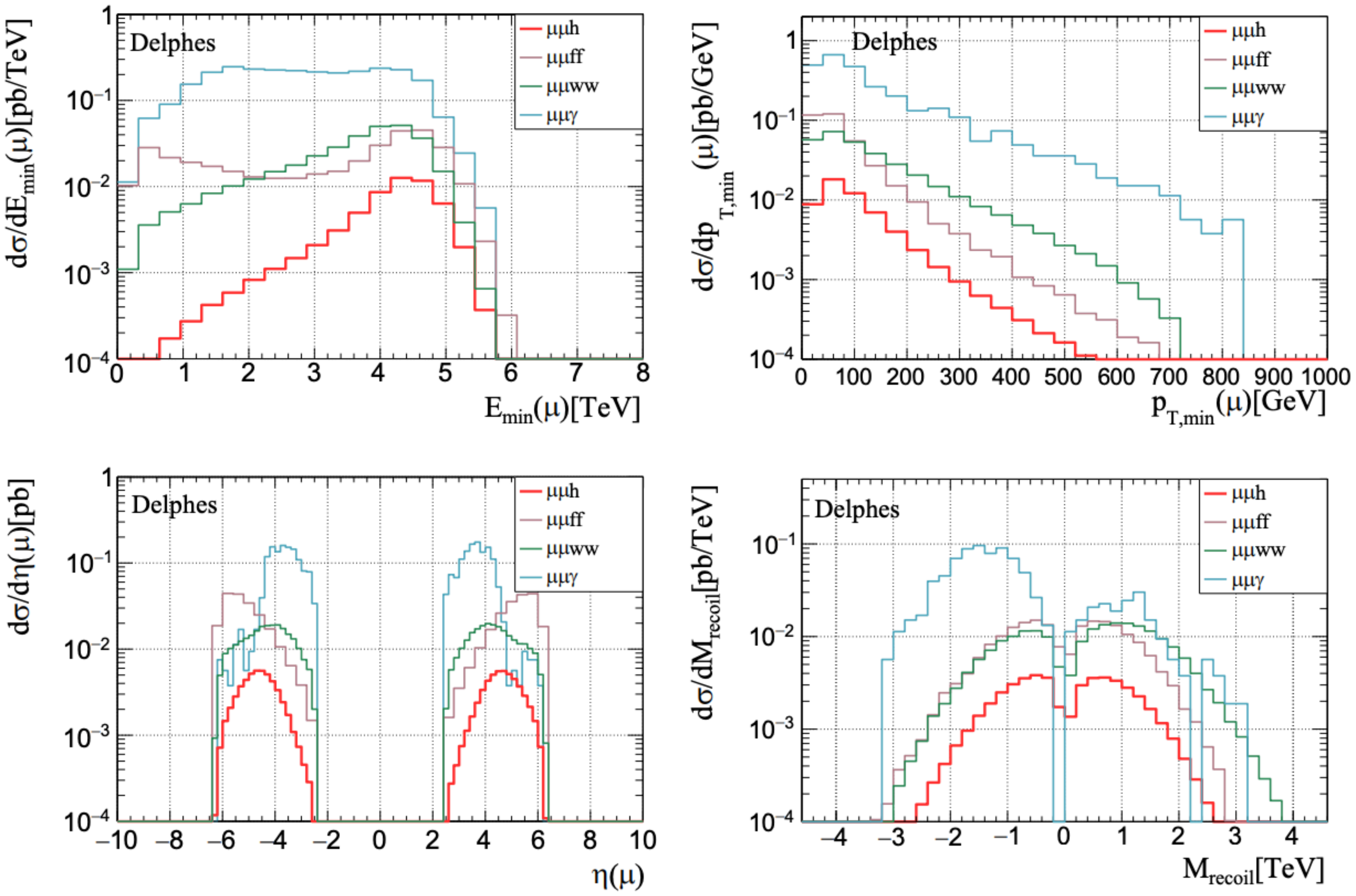
2401.08756

Initial Conclusions from theorists:

Need to tag high-energy muons up to $|\eta|=6$

Don't necessarily need to measure their momentum

Difficult question to address in simulation
Configuration? Rates? Detector requirements?

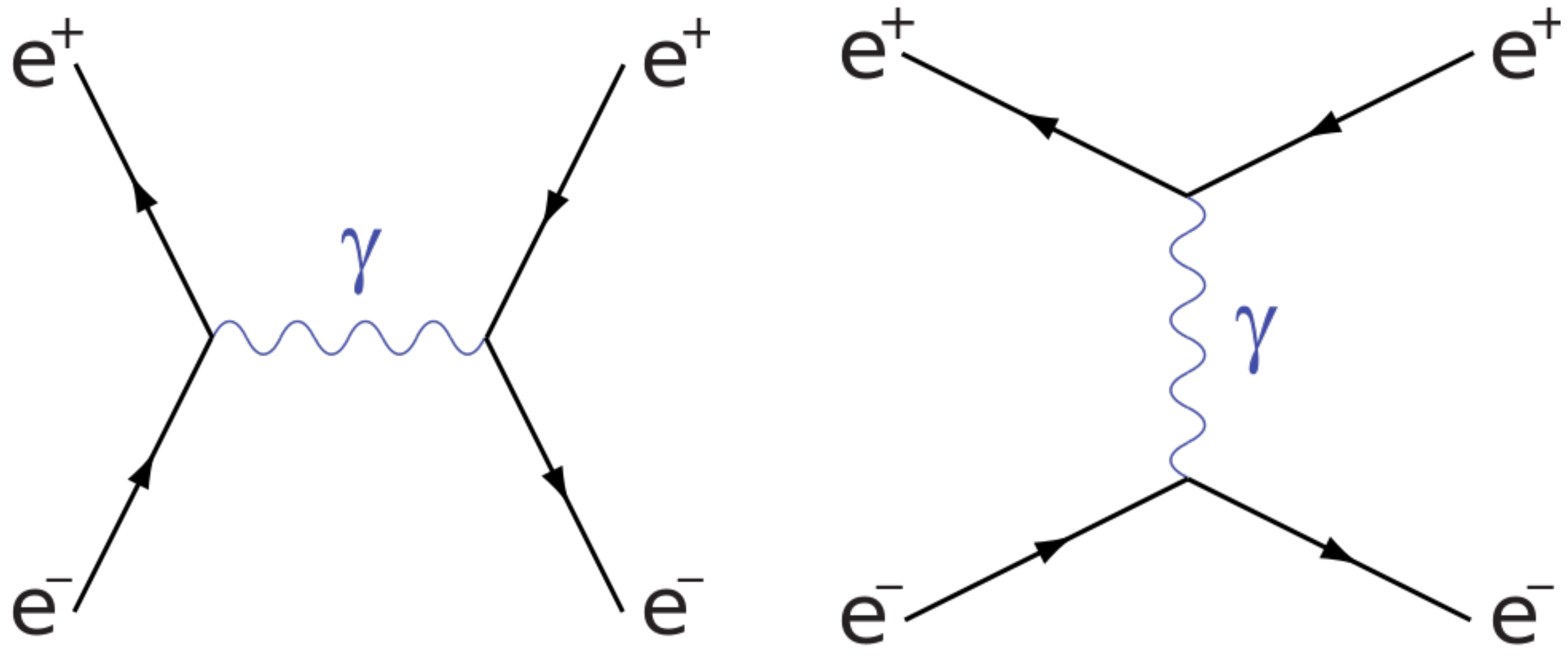


# Open Question: Luminosity



Previous lepton colliders:
Forward electrons from Bhabha scattering

$$\mathscr{L} = \frac{N}{\epsilon \sigma_{th}}$$




Proposal to use central muons for µC
Questions: Stats? Theory precision?

$\sqrt{s}$=1.5 TeV, lumi = 1e34
Remaining events

Assuming a Snowmass year = $10^7$seconds
$\mathcal{L}=1.25 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
Total events: 213 K

$$\frac{\Delta\mathcal{L}}{\mathcal{L}} \sim \frac{1}{\sqrt{N}} = 0.002$$

# Work in progress: detectors requirements for R&D

Need to think about μC detectors as complete systems

Urgent: define unique μC technology needs & map to US strengths

Subtle: feed this back into physics sensitivity

Eg. For the pixel detector

| | $e^+e^-$ | $\mu^+\mu^-$ | hh |
|---|---|---|---|
| Granularity | 25 x 25 μm | 25 x 25 μm | 25 x 25 μm |
| Timing | Time of flight for PID | ~30 ps/hit for BIB | ~5ps/track for pileup |
| Event Rates | up to 10 μs | 30 μs | 25 ns |
| Max Hit Rates | 40 hits/cm$^2$ | ~10$^3$ hits/cm$^2$ | ? |
| Cooling | air | -30C | ? |
| Radiation | - | ~10$^{15}$ | ~10$^{18}$ |

**Eg. Trench/AC-LGADs:**

+ meet granularity & timing needs

- electronics consume 100x too much power

**Eg. Data reduction on chip:**

+ seems possible w/ cluster shapes

- need to incorporate μC assumptions

- need to balance bandwidth/latency constraints w/ physics needs

# Missing: novel ideas

10 TeV μC designs = iteration on 3 TeV μC =  iteration on CLIC = iteration on X

No one has looked at multi-TeV muon collider and tried a fundamentally new approach
- we need to enable people to do this

Main bottle neck full sim
Need to simulate BIB for any nozzle/detector changes

Computationally expensive
We (US) don't have the capability to do this
Only ~a few people in Europe do

More from Simone

# Person power questions

So far US design efforts have been a few PIs with ~10% of time + undergrads
Small progress relative to IMCC, which has a few full time people

How can we onboard most efficiently?

Is it realistic to have students/postdocs work on muC with a larger fraction of time?

**How can we gain & maintain critical expertise (MDI/simulation) ASAP?**

# Strategy questions

Goal should be to

1. Demonstrate feasibility to deliver physics case
2. Ensure necessary technology R&D begins now

Suggestion: Make a list of focused questions we want to answer.
Each question = 1 paper, prioritize a few at a time

Suggestion: pair physics/design questions to hardware R&D
Potentially useful in terms of student education & obtaining funding

# Backup

Karri Folan DiPetrillo
University of Chicago
US Muon Collider Workshop
24 February 2024

# Detector Opportunities

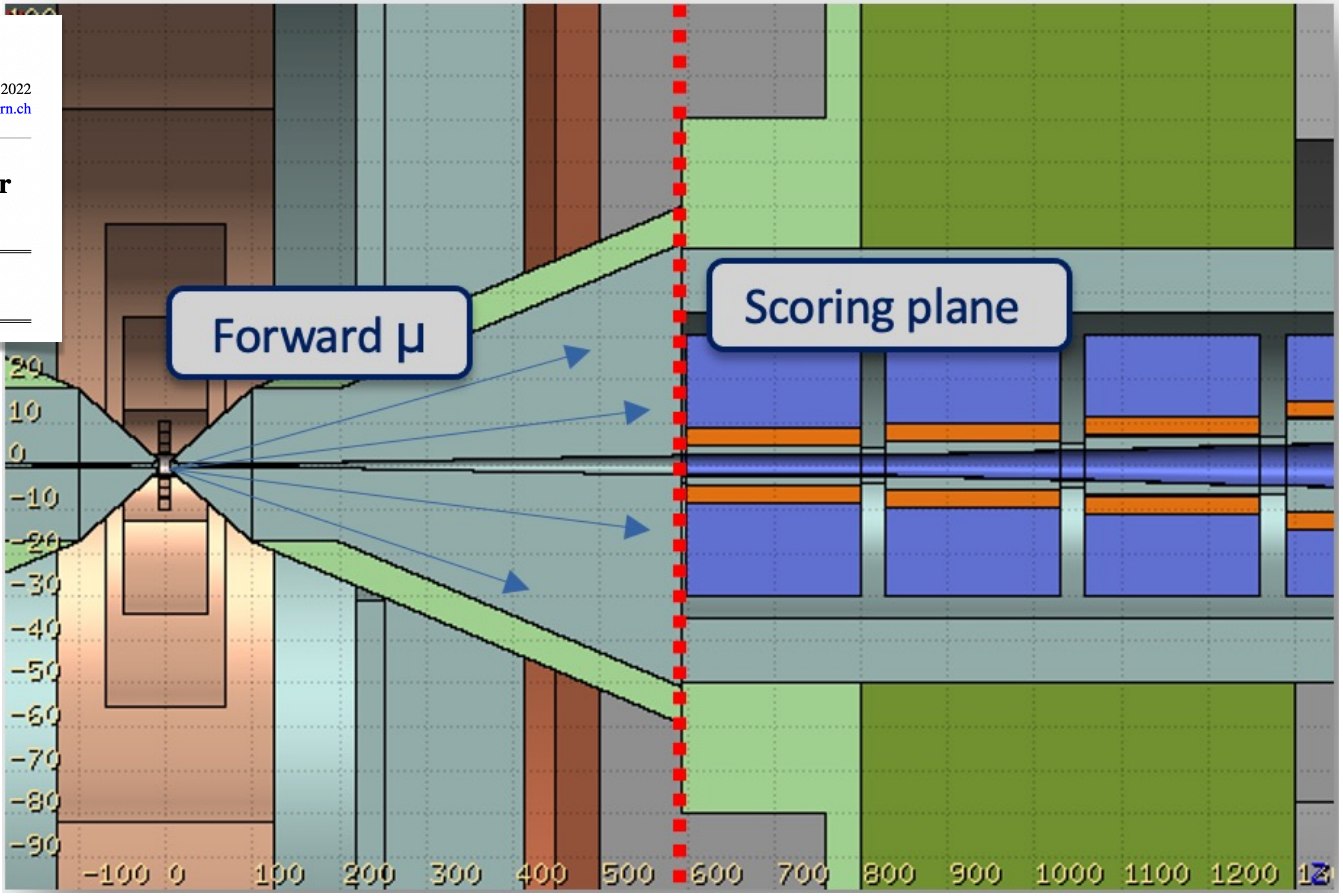
[Promising Detector Technologies](#)

International MUON Collider Collaboration

March 15, 2022
https://muoncollider.web.cern.ch

**Promising Technologies and R&D Directions for the Future Muon Collider Detectors**

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)



# Data Acquisition and trigger

It's a lepton collider, goal is to save every event

## Trigger constraints

with respect to HL LHC

~10 x hit density

~1/1000 event rate

O(100) Tb/s

~Similar to LHCb in Run 3

Streaming within reach

Store reconstructed/filtered events

## On-detector constraints

rate per pixel module

rate = $N_{hits}$ · hit-size · event rate · safety factor

$N_{hits}$/module = 1000/mm² · 20 cm² ~20k hits

Hit size = 32 bits to encode x/y/amp/time

rate = 30k · 32-bit · 30 kHz · 2

**rate = 50 Gb/s → Per front-end ~ 20 Gb/s**

~Double compared to HL-LHC

Needs R&D but within reach!

Benefits from on-detector data reduction

# Incoherent e+e- background

9601273

e +e– pairs production via collision of two virtual photons due to beamstrahlung

Typical low energy, move along the beam, depends on solenoid B-field
Studied at √s=2 TeV, need to understand at higher energies

| | Larmor Radius | Detector | XS | N/bunch |
|---|---|---|---|---|
| < 100 MeV | < 1 mm | Invisible | 10 mb | 10^5 |
| 100 MeV - 1 GeV | 1 mm - 1 cm | Vertex | 1 mb | 10k |
| 1 GeV - 10 GeV | 1 cm - 10 cm | Main detector | 0.4 mb | 4k |

total energy flux about 10 TeV per bunch crossing.

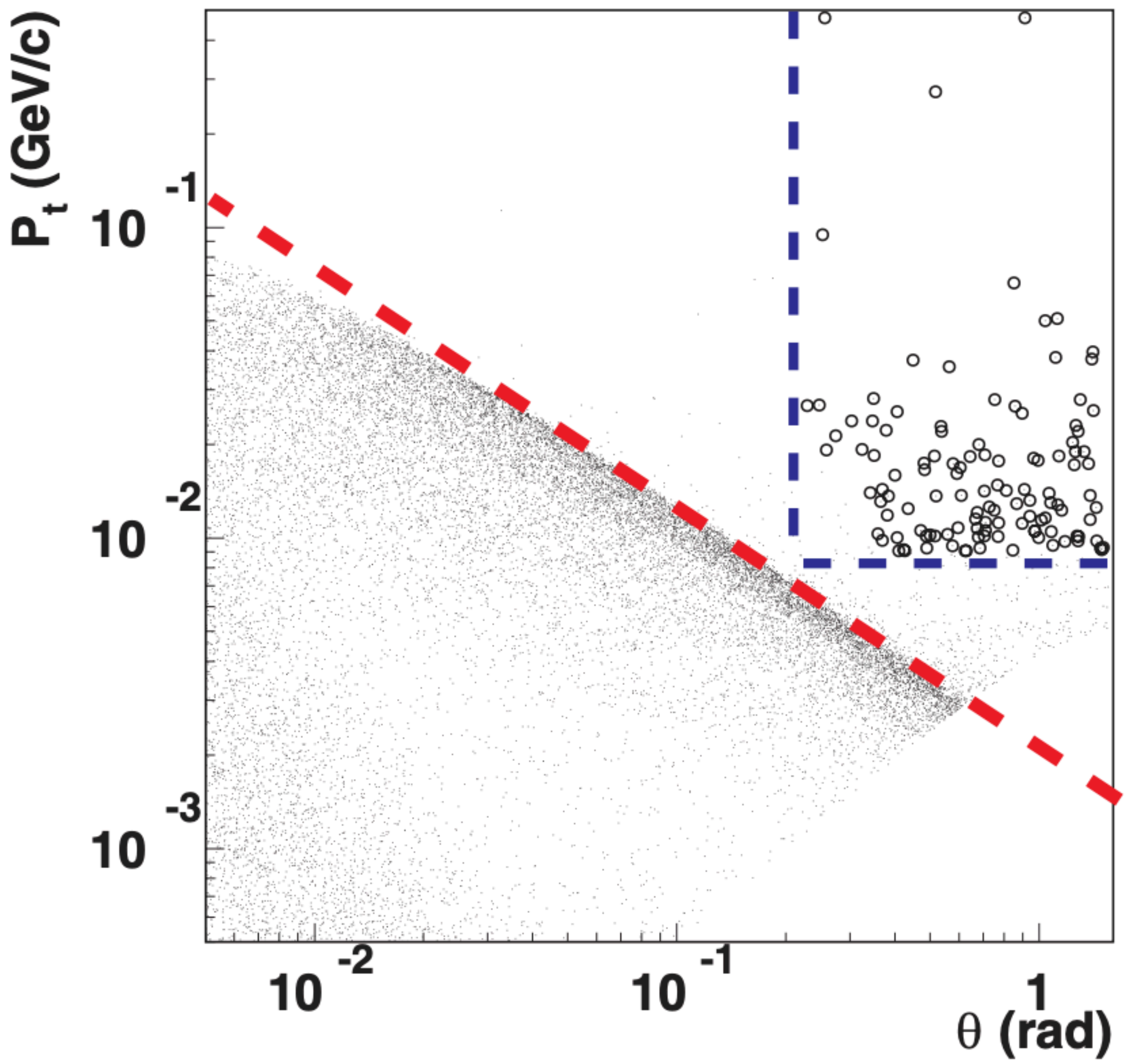



FIG. 7. (Color) Distribution of $P_t$ versus $\theta$ for electrons from IPC processes. The region corresponding to particles reaching the VD (circles) is indicated with the two dashed lines for the detector configuration described in the text. A thick dotted line highlights the edge of the beam-beam deflection induced accumulation zone.