September 9, 2021

Muon Collider:

prospects, challenges and the latest progress

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Muon Collider: unique features

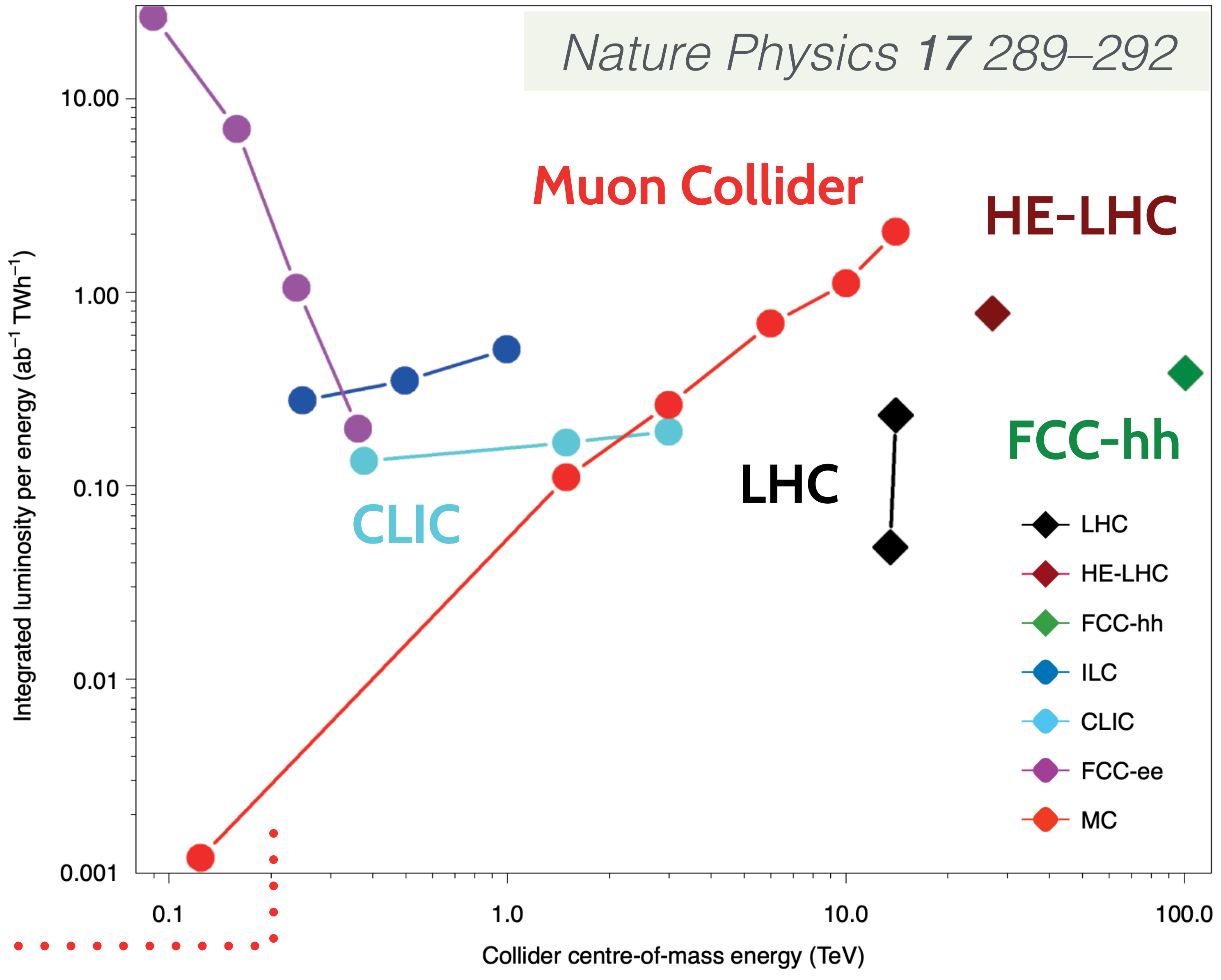
Big question for particle physics today: which facility to build after HL-LHC?

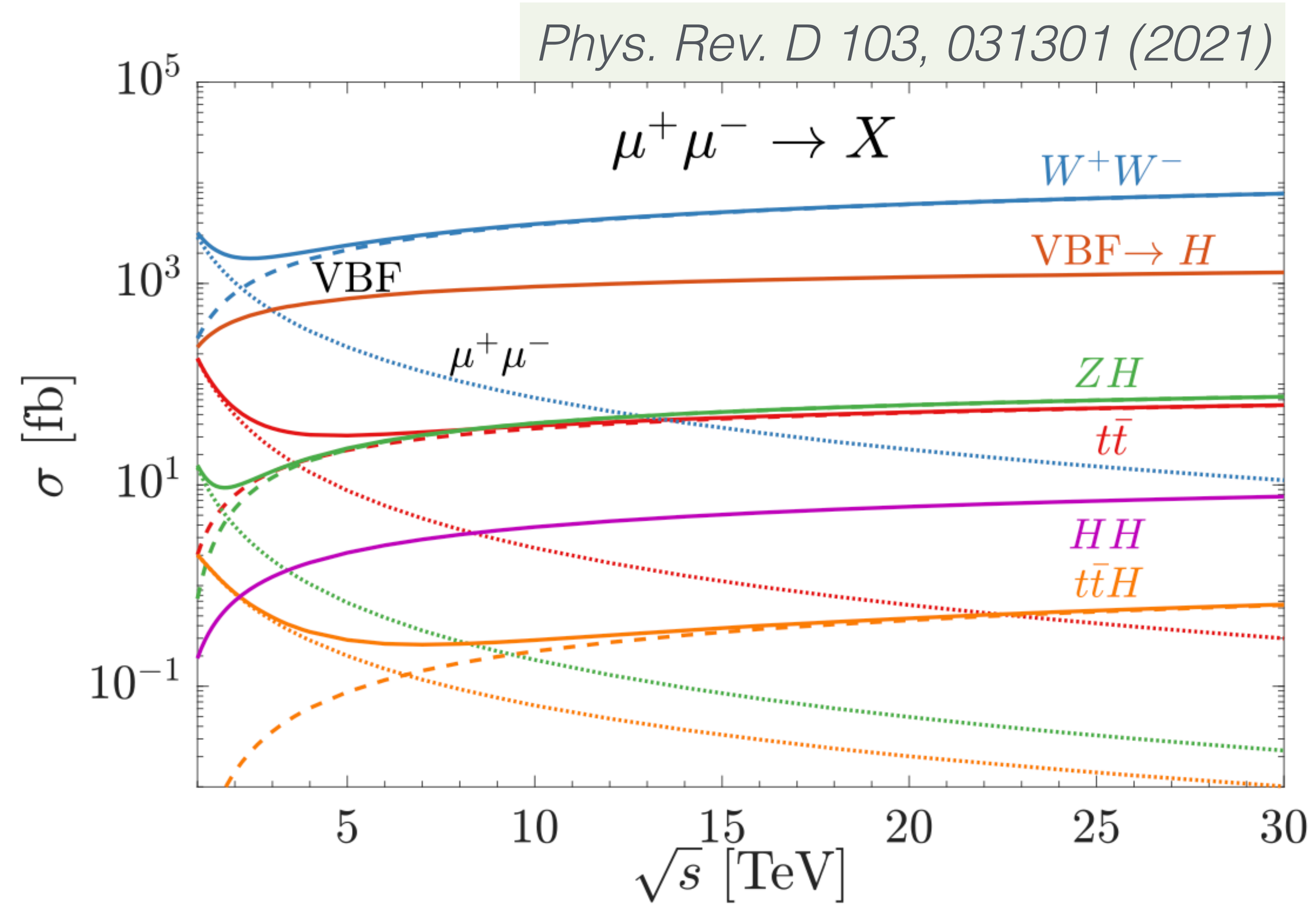
- electron-positron collider (clean collisions vs limited luminosity/energy)
- proton-proton collider (high luminosity/energy vs kinematic precision)

Muon Collider allows to combine in a single facility
high precision of e^+e^- colliders + high energy reach of *pp* colliders

- muons are elementary particles, like e^+/e^-, creating *"clean"* collisions
- ×200 higher mass → ×10^4 less synchrotron radiation losses

At $\sqrt{s} \geq 3$ TeV Muon Collider is the most energy efficient machine





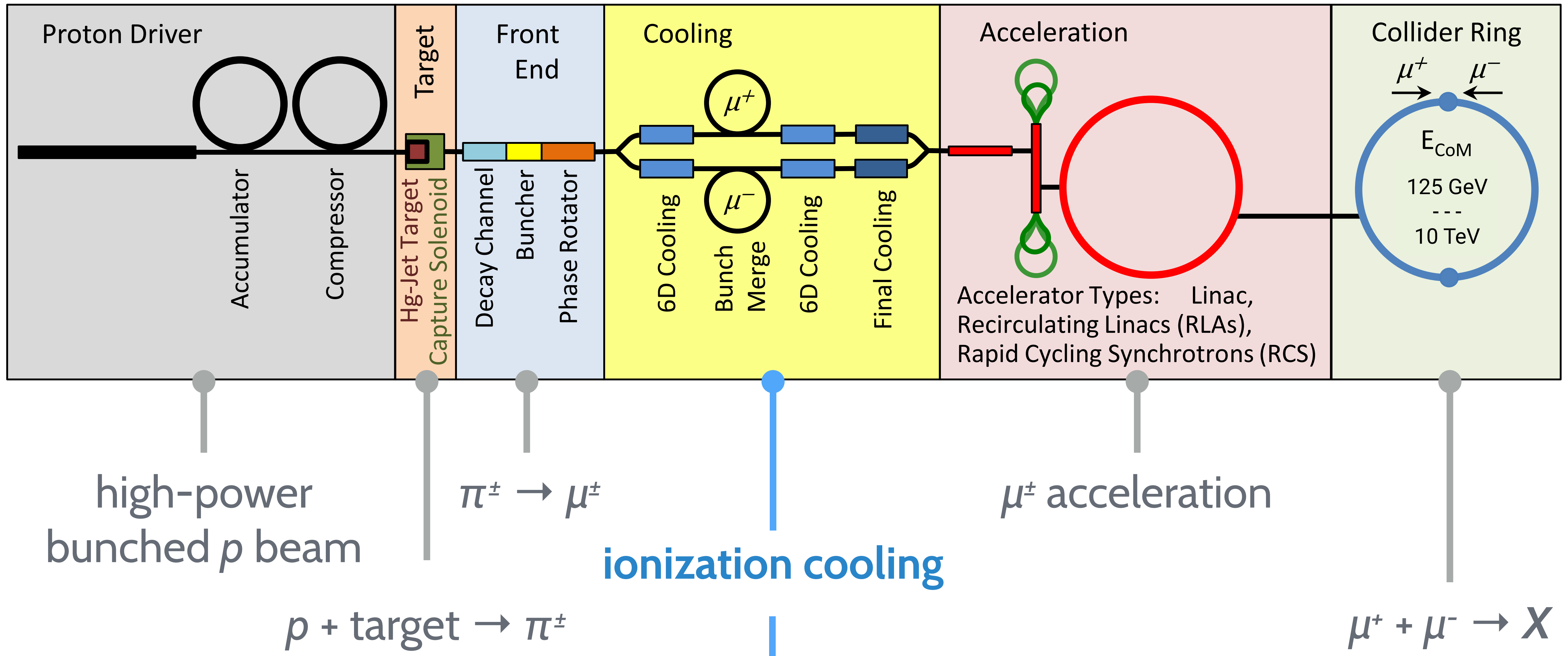
Extremely rich physics program provided by high-energy muon collisions

- $\mu^+\mu^-$ + vector-boson fusion *(increasing at higher energies)*
- unprecedented accuracy of electroweak Higgs couplings
- discovery reach at 14 TeV comparable to FCC-hh at 100 TeV

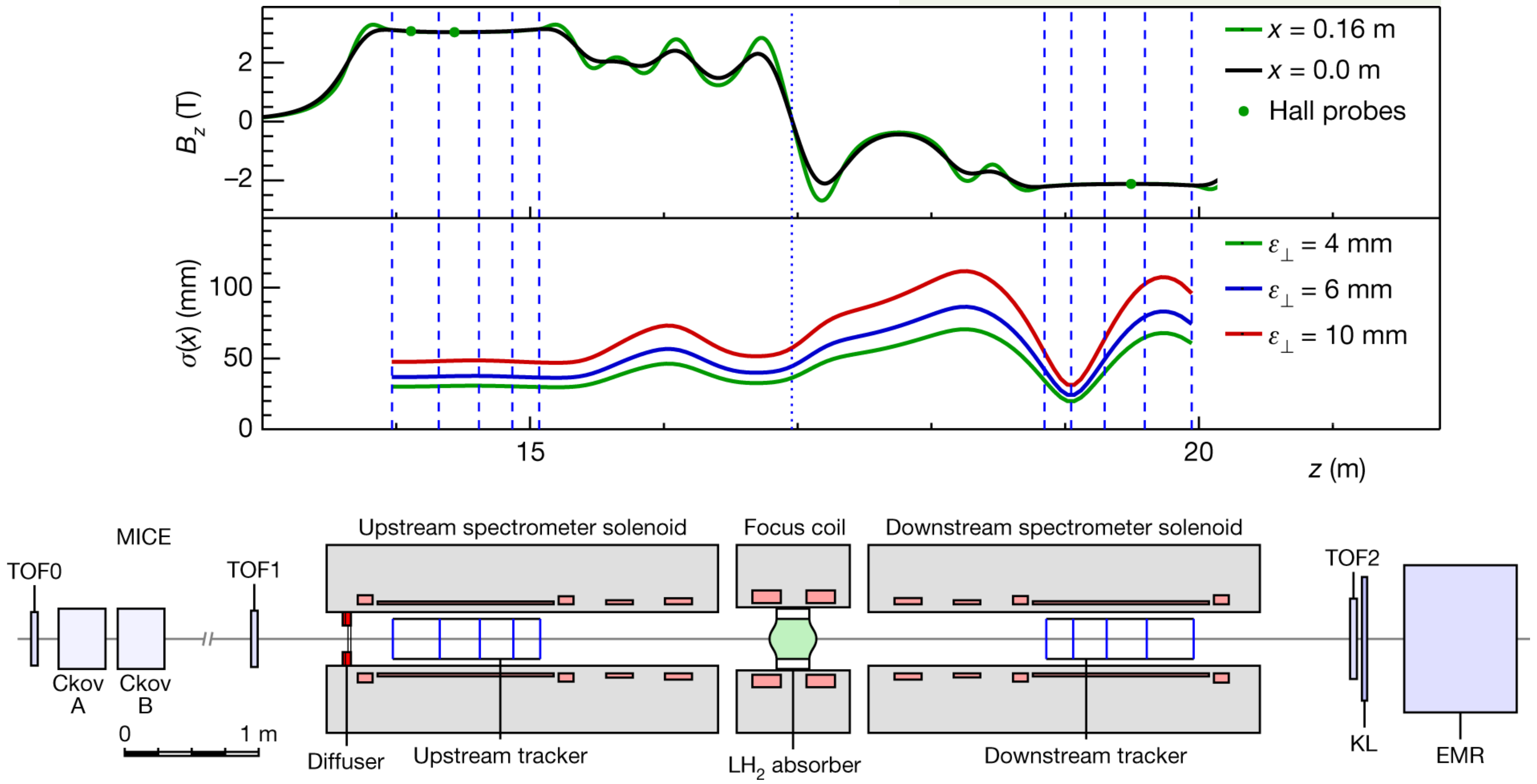
Growing flow of theory papers exploring Muon Collider physics case
considering a wide range of $\sqrt{s}$ = 126 GeV - 100 TeV

- The Muon Smasher's Guide | arXiv:2103.14043 ◀ *one of the most recent*

The baseline muon-production scheme: from a proton beam



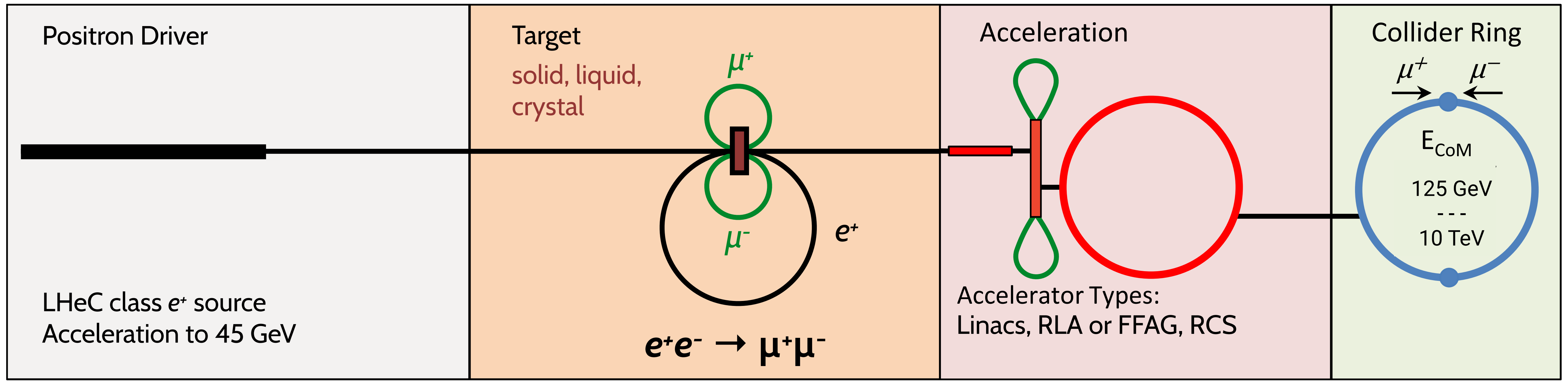
Nature Physics 578 53–59



more in the talk by D. Schulte

Experimentally demonstrated by the MICE collaboration → considered for the Muon Collider test facility

Alternative scheme of a Low Emittance Muon Accelerator in the R&D stage: from a positron beam



No muon cooling needed, but:

- very low $e^+e^- \rightarrow \mu^+\mu^-$ cross section
- extreme positron-beam intensity needed

Challenge 2: muon decays

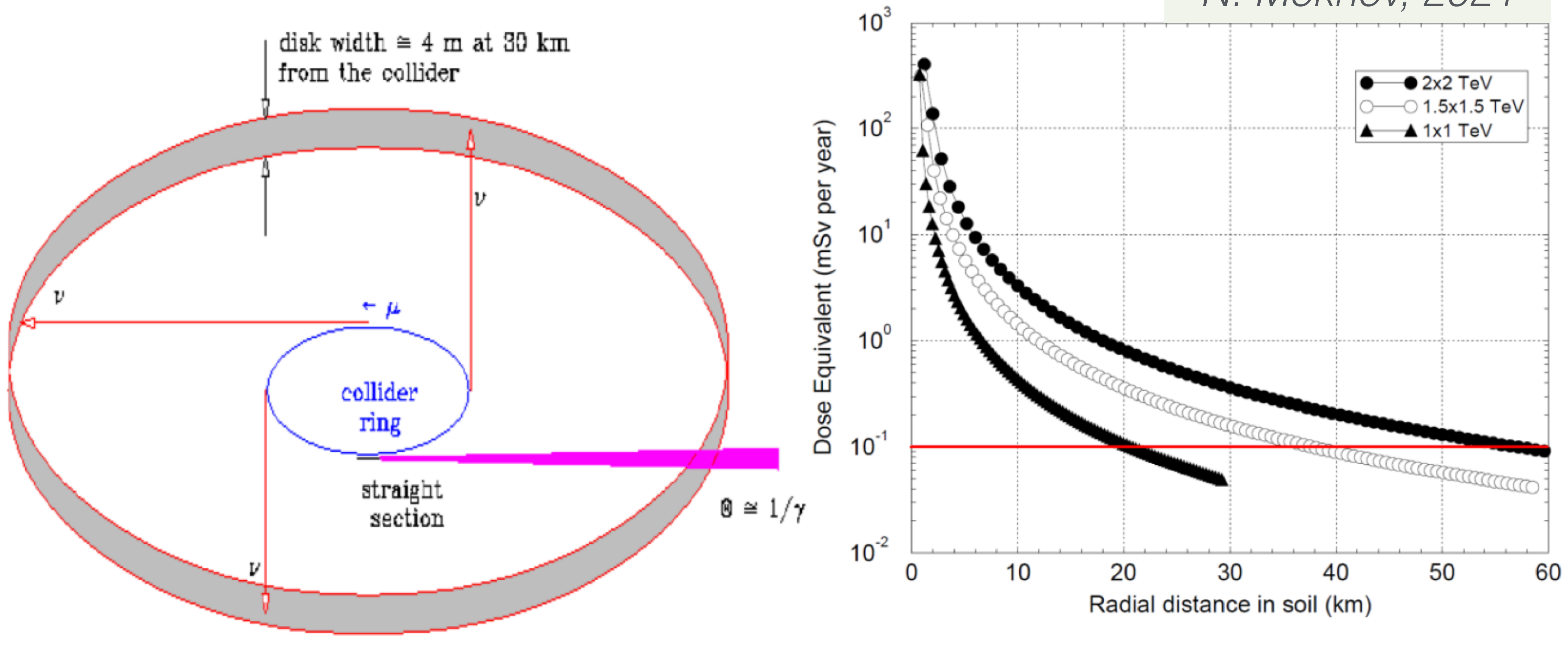
Assuming the beam density of 2×10^{12} muons/bunch → **large number of decays in the collider ring**

e.g. for $\sqrt{s}$ = 1.5 TeV: 4.1 × 10^{5} decays per metre of lattice

Extensive simulation studies performed in the past by the MAP program using MARS15 software

1. Neutrino radiation hazard

N. Mokhov, 2021



Collimated neutrino beams deliver a substantial dose

Careful choice of mitigation strategies needed:

- choice of location *(isolated land, deep underground)*
- lattice design *(avoid straight sections, beam wobbling)*

2. Beam Induced Background (BIB)

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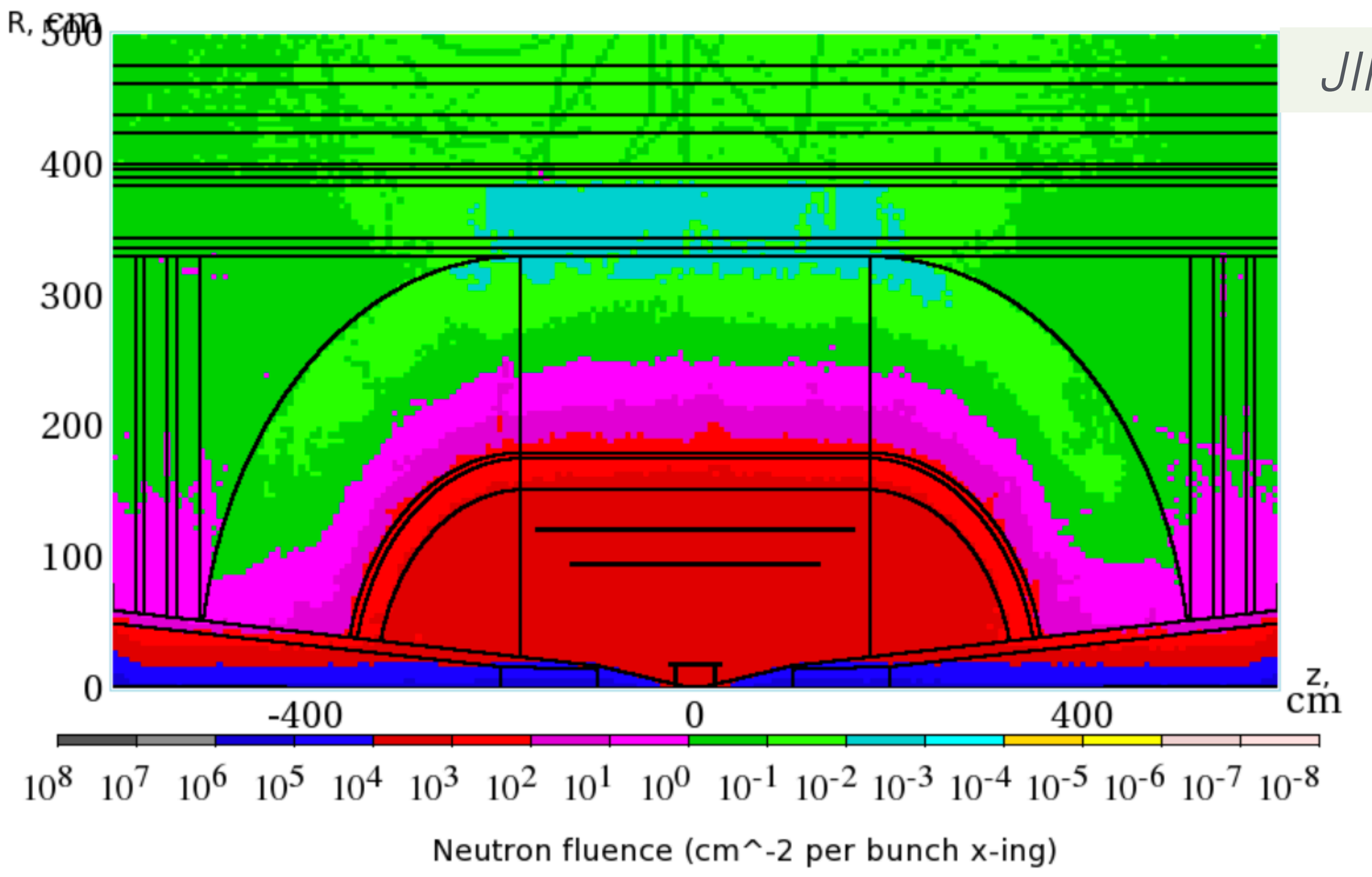


Secondary/tertiary particles reaching the detector

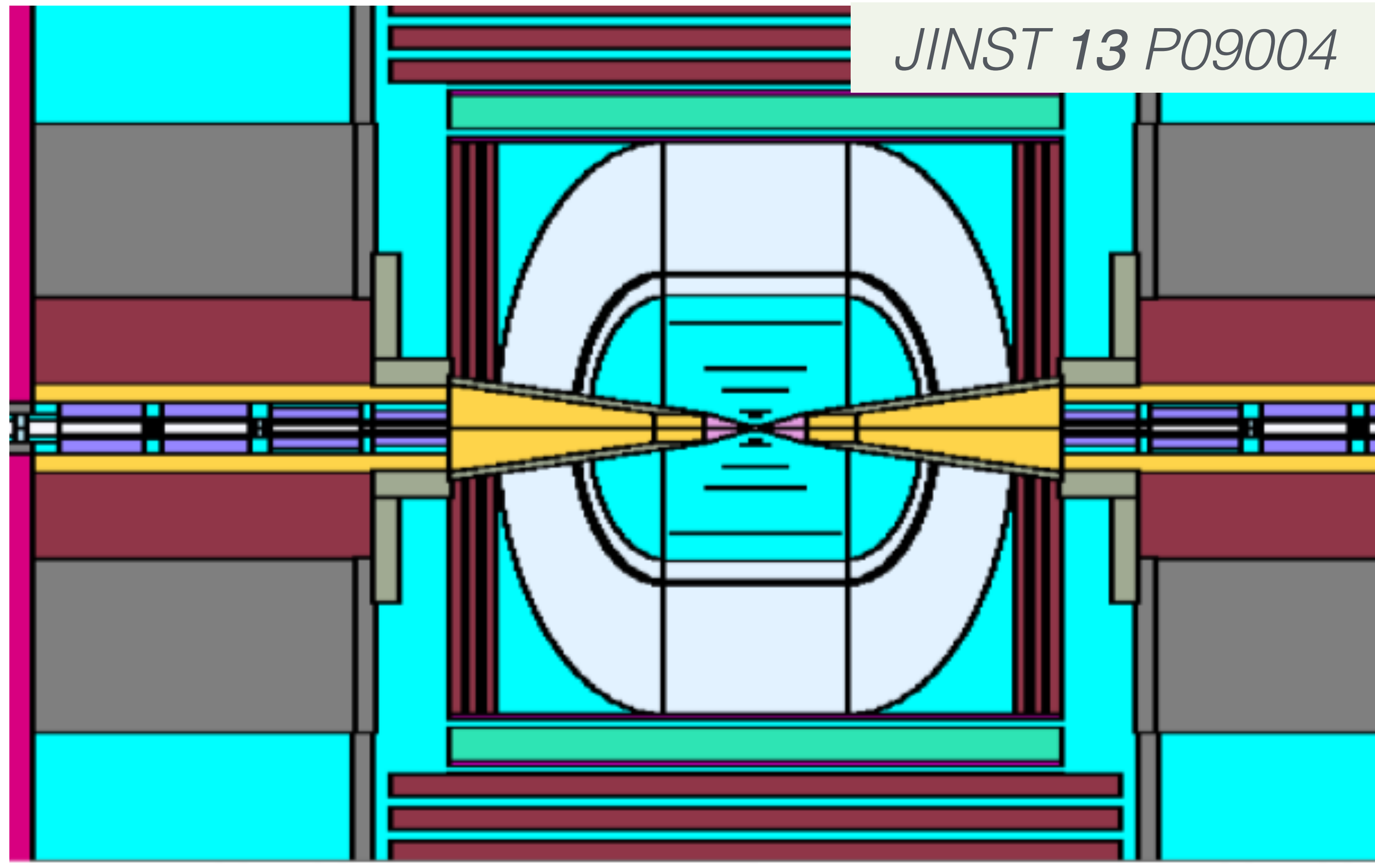
The two main effects:

- radiation damage to the detector
- high occupancy → challenging event reconstruction

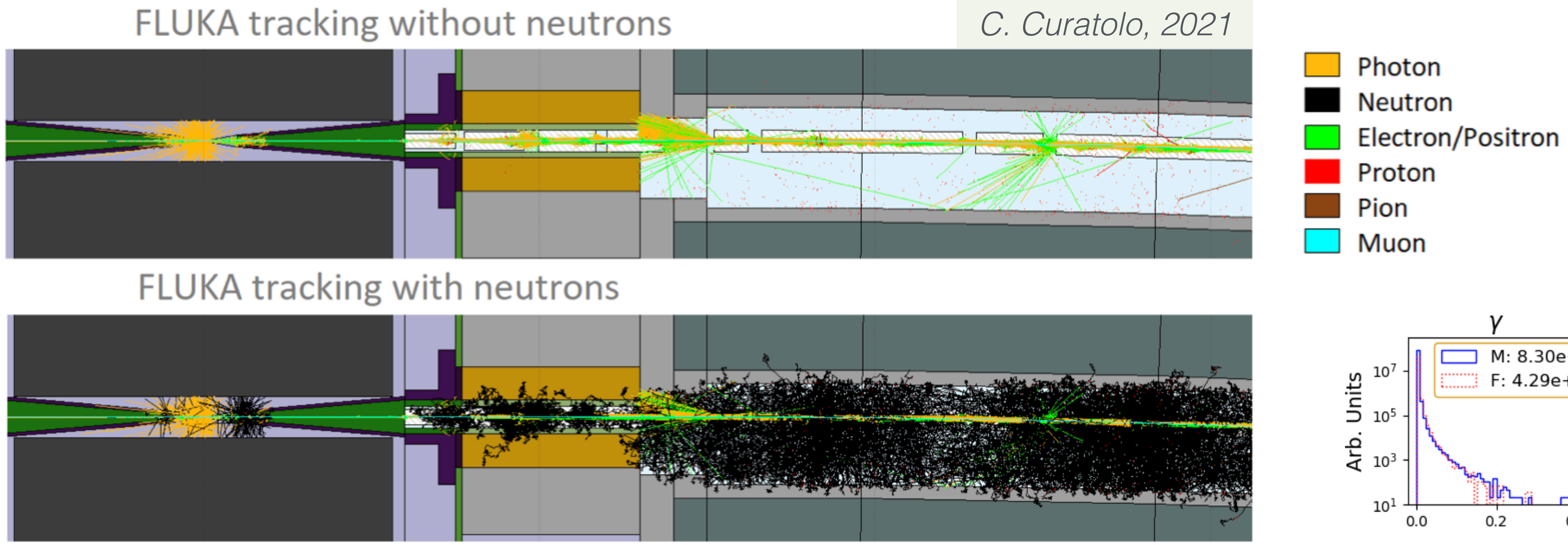
Beam Induced Background: simulation tools

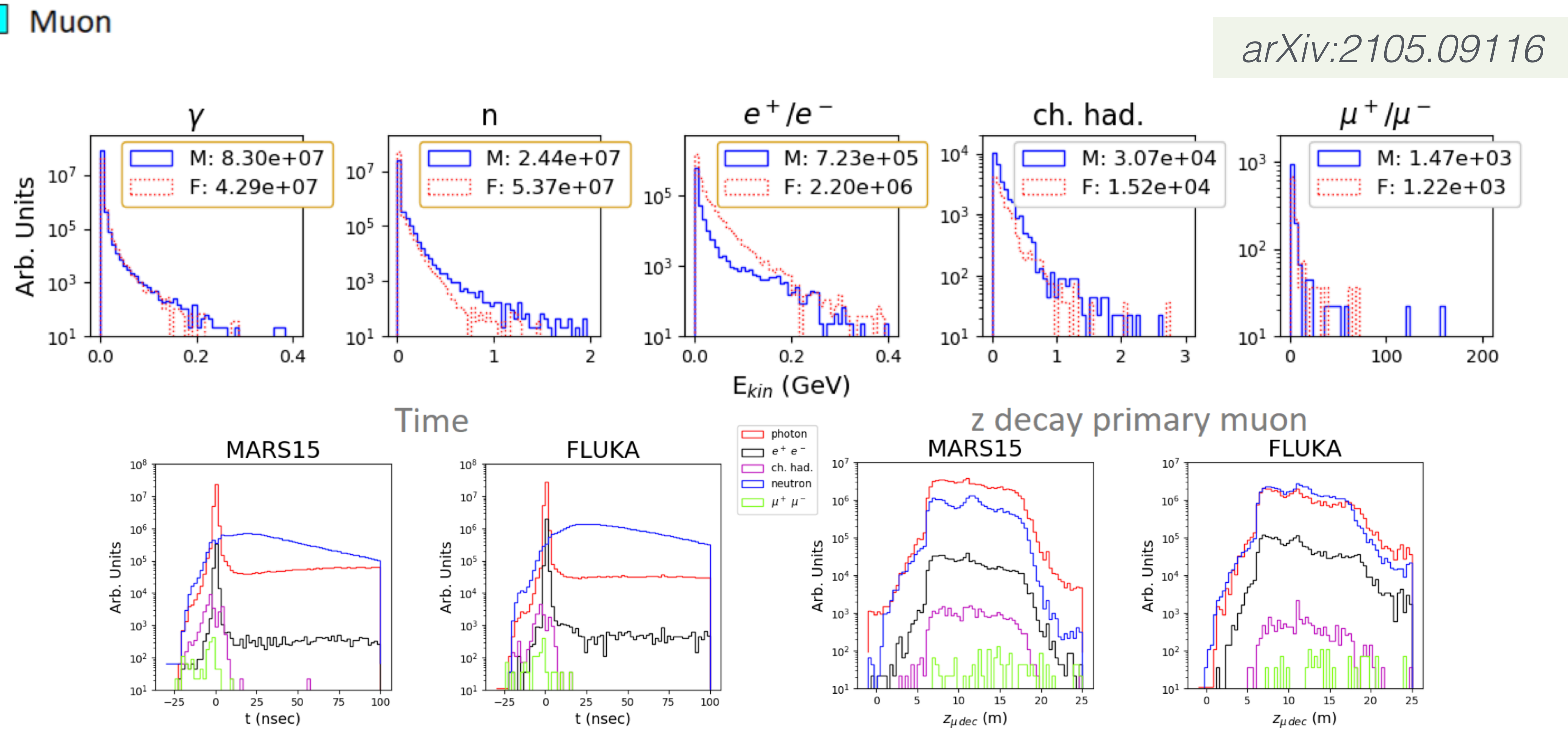
The most detailed design study to date performed by MAP for √s = 1.5 TeV

- accelerator lattice *(±200m from IP relevant for the simulation)*
- Machine Detector Interface (MDI): *tungsten + borated polyethylene* ▶



New BIB simulation workflow in place based on FLUKA software



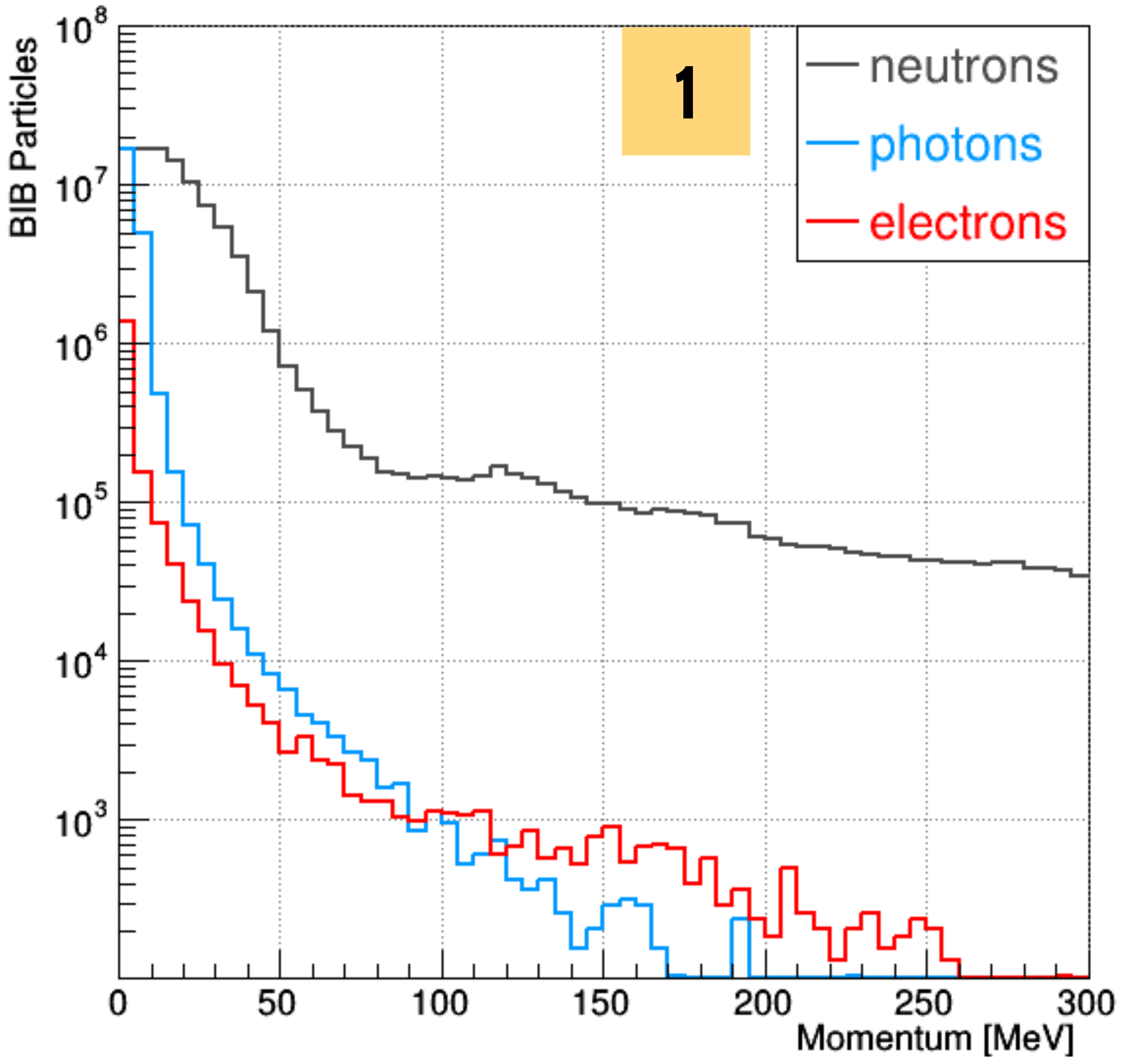


Good agreement with MARS15 simulation for √s = 1.5 TeV ▶

↳ **ready to explore higher energies → √s = 3-10 TeV**

BIB properties: $\sqrt{s}$ = 1.5 TeV

BIB has several **characteristic features** → **crucial for its effective suppression**



1. Predominantly very soft particles (p << 250 MeV) except for neutrons

fairly uniform distribution in the detector → no isolated signal-like deposits

↳ conceptually different from pile-up contributions at the LHC

2. Significant spread in time (few ns + long tails up to a few μs)

$\mu^+\mu^-$ collision time spread: 30ps at $\sqrt{s}$ = 1.5 TeV | ≤20ps at $\sqrt{s}$ = 3 TeV

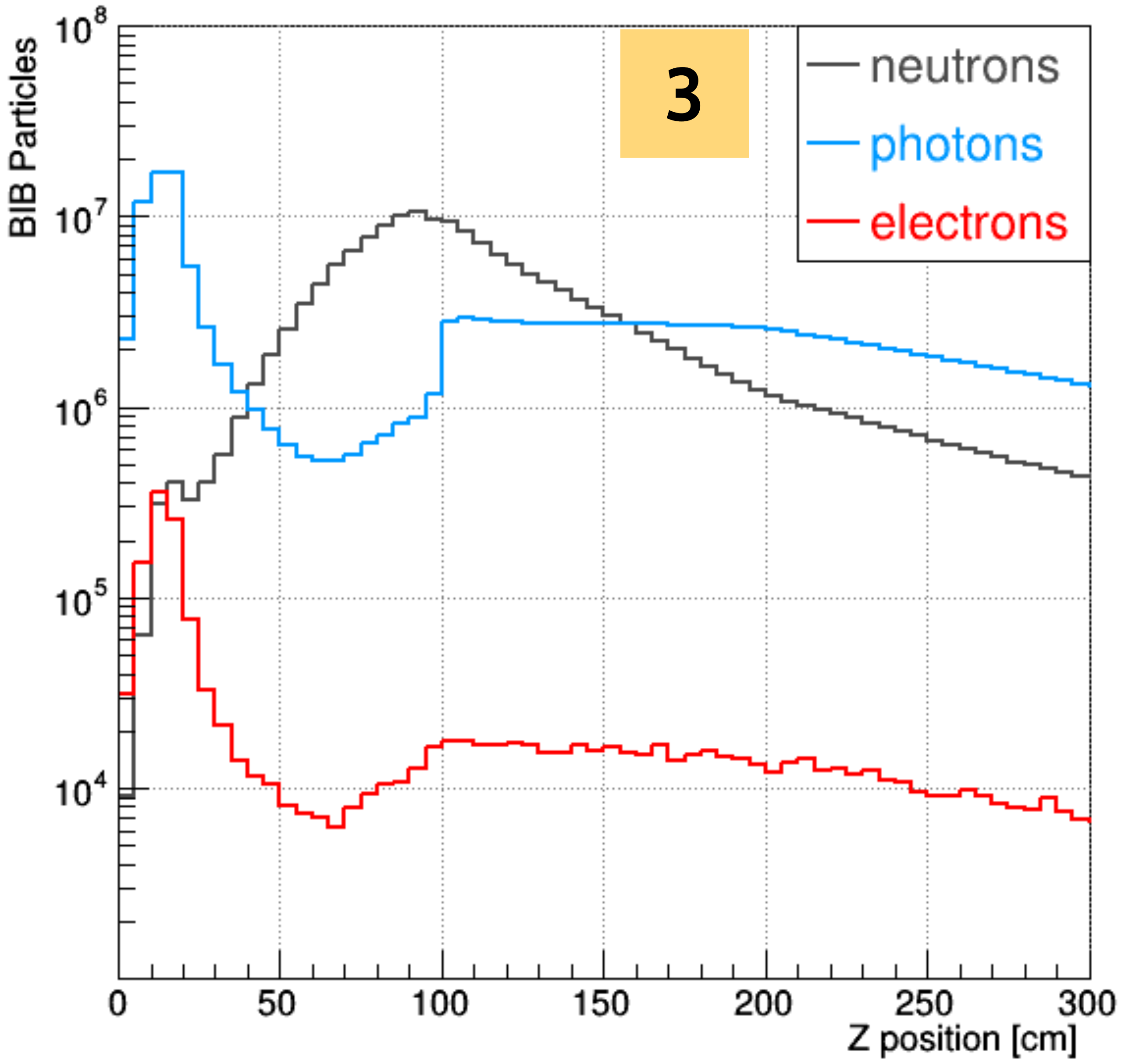
↳ strong handle on the BIB → requires state-of-the-art timing detectors

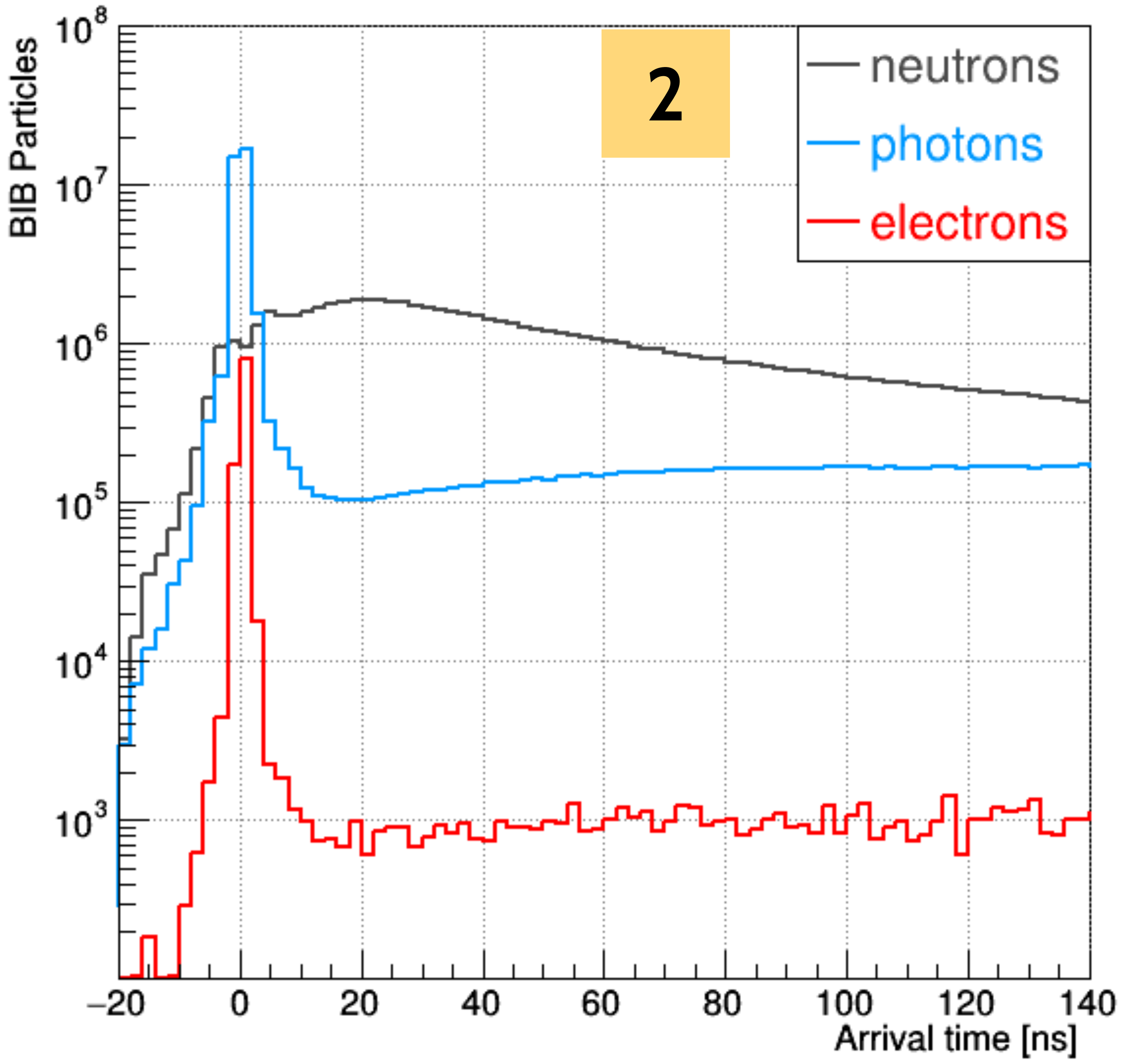
3. Large spread of the origin along the beam

different azimuthal angle wrt the detector surface

+ affecting the time of flight to the detector

↳ relevant for position-sensitive detectors





Sophisticated detector technologies and event-reconstruction strategies required to exploit these features of the BIB

+ detailed full simulation needed to properly evaluate their potential

For 0.75 TeV beams at 2×10^{12} μ/bunch → 2 × 180M particles reaching detector in 1 BX
↳ **interaction with the detector simulated in GEANT4**

Essential component is the MDI: inherited from the MAP study

Detector geometry largely based on the CLIC design *(optimised for e^+e^- collisions)*

+ **Tungsten nozzles:** forward acceptance >10°

All-silicon tracker: B = 3.57 T

- double-layer Vertex Detector
  ↳ doublet selection: matching time + angle

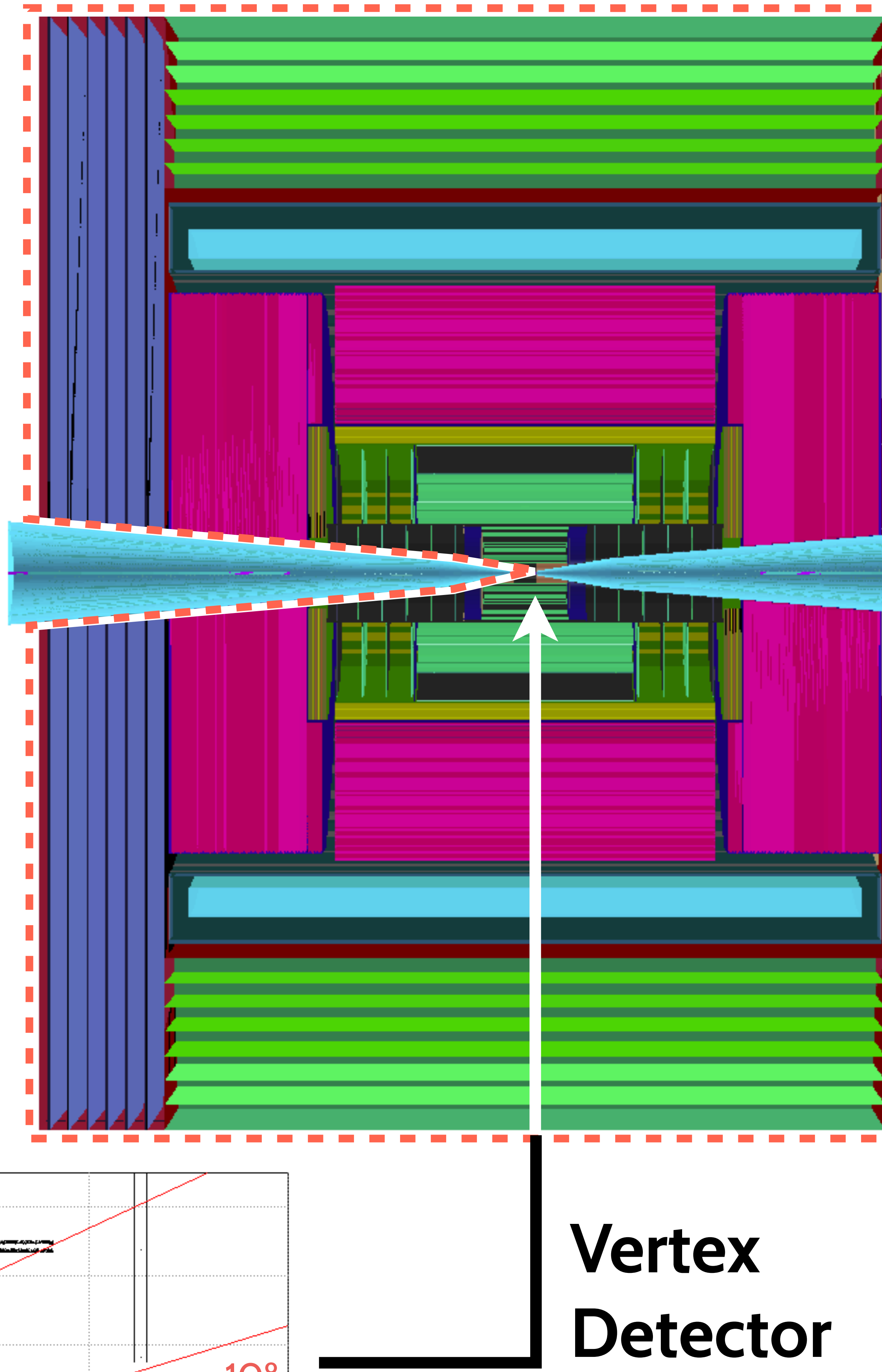
High-granularity sampling calorimeter

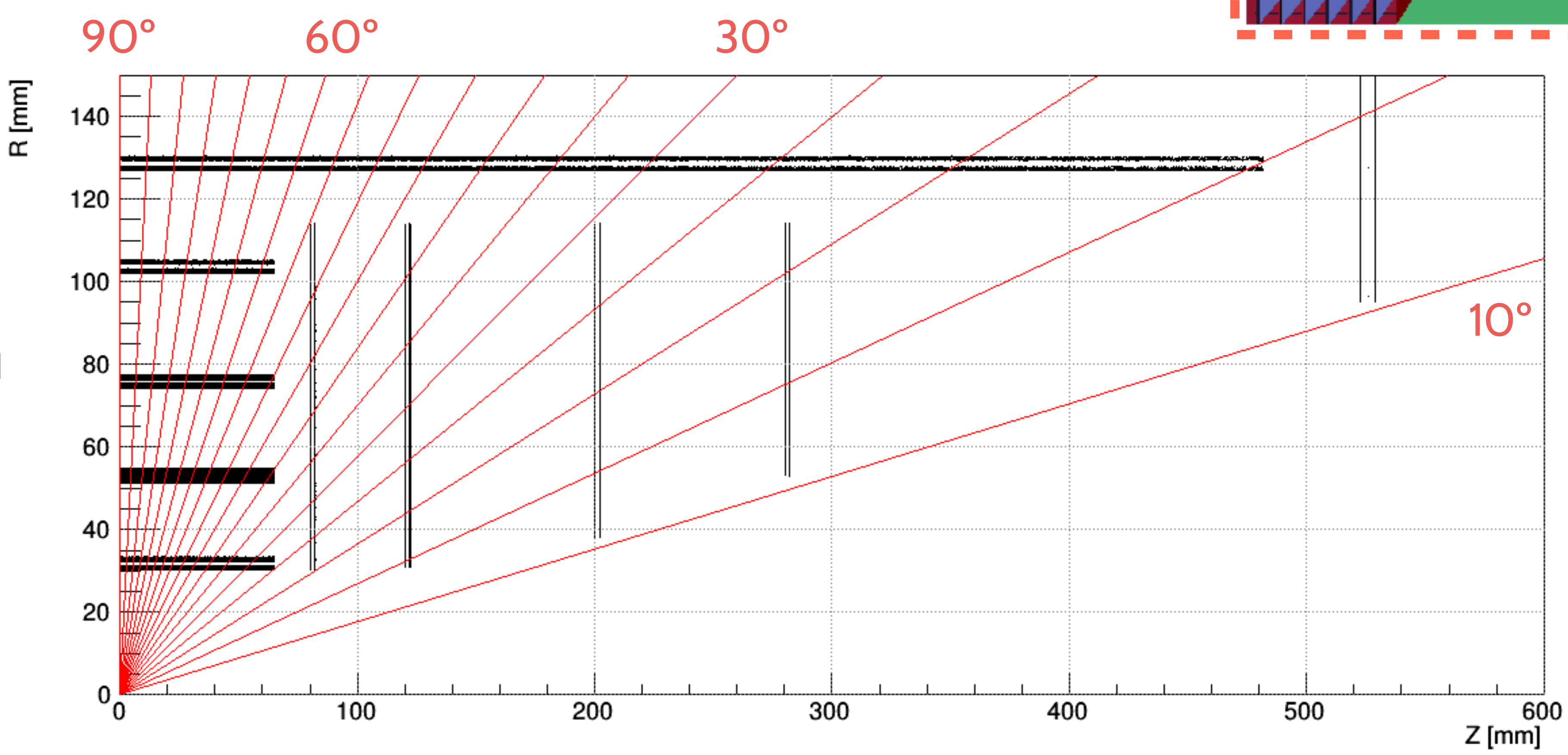
- **ECAL:** 40 layers of **W** + **Si**
- **HCAL:** 60 layers of **Fe** + **scintillator** + **SiPM**

Muon detectors: 7 layers of **Fe** + **RPC**

GEANT4 simulation + digitization + event reconstruction within the ILCSoft framework

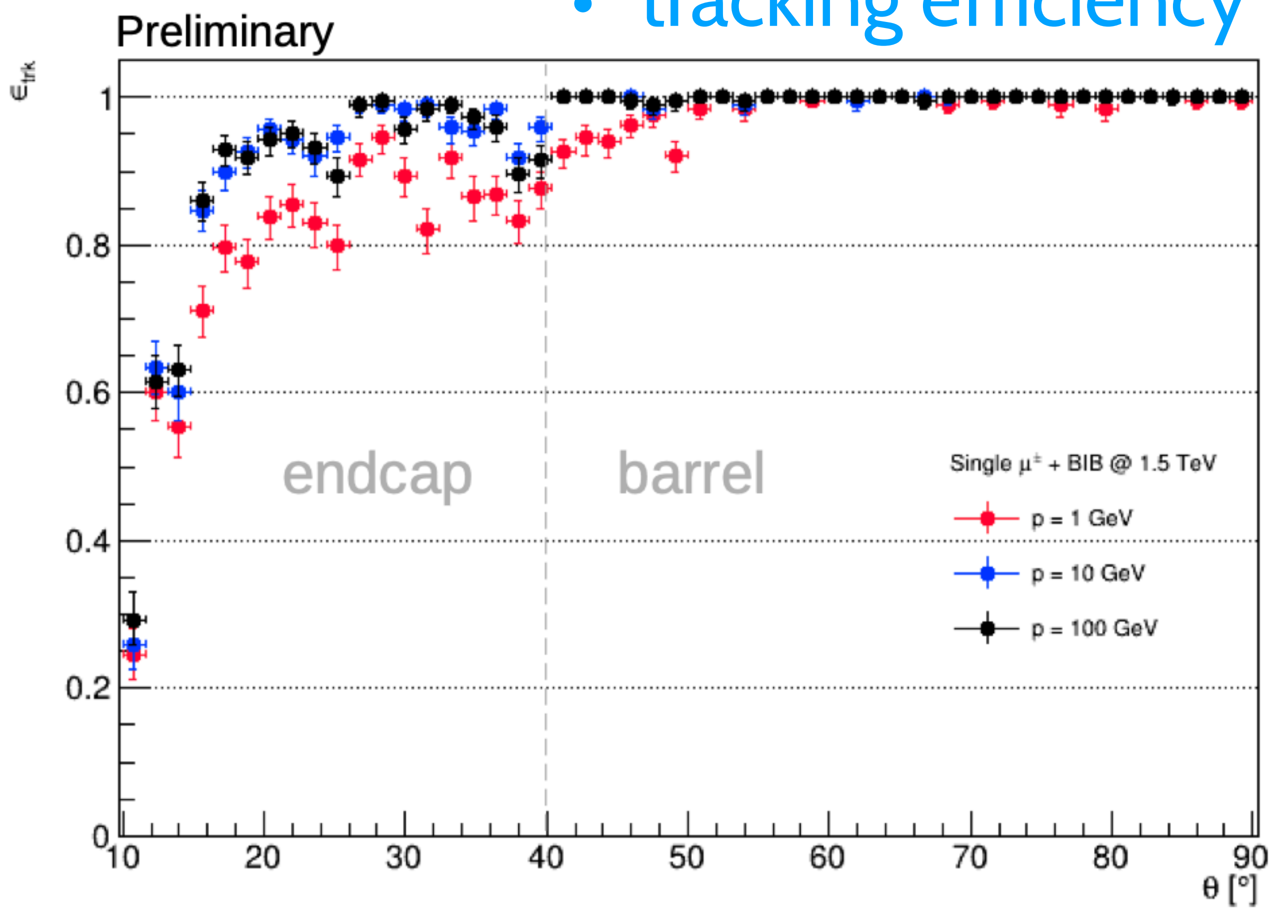
- planning transition to Key4HEP in the future



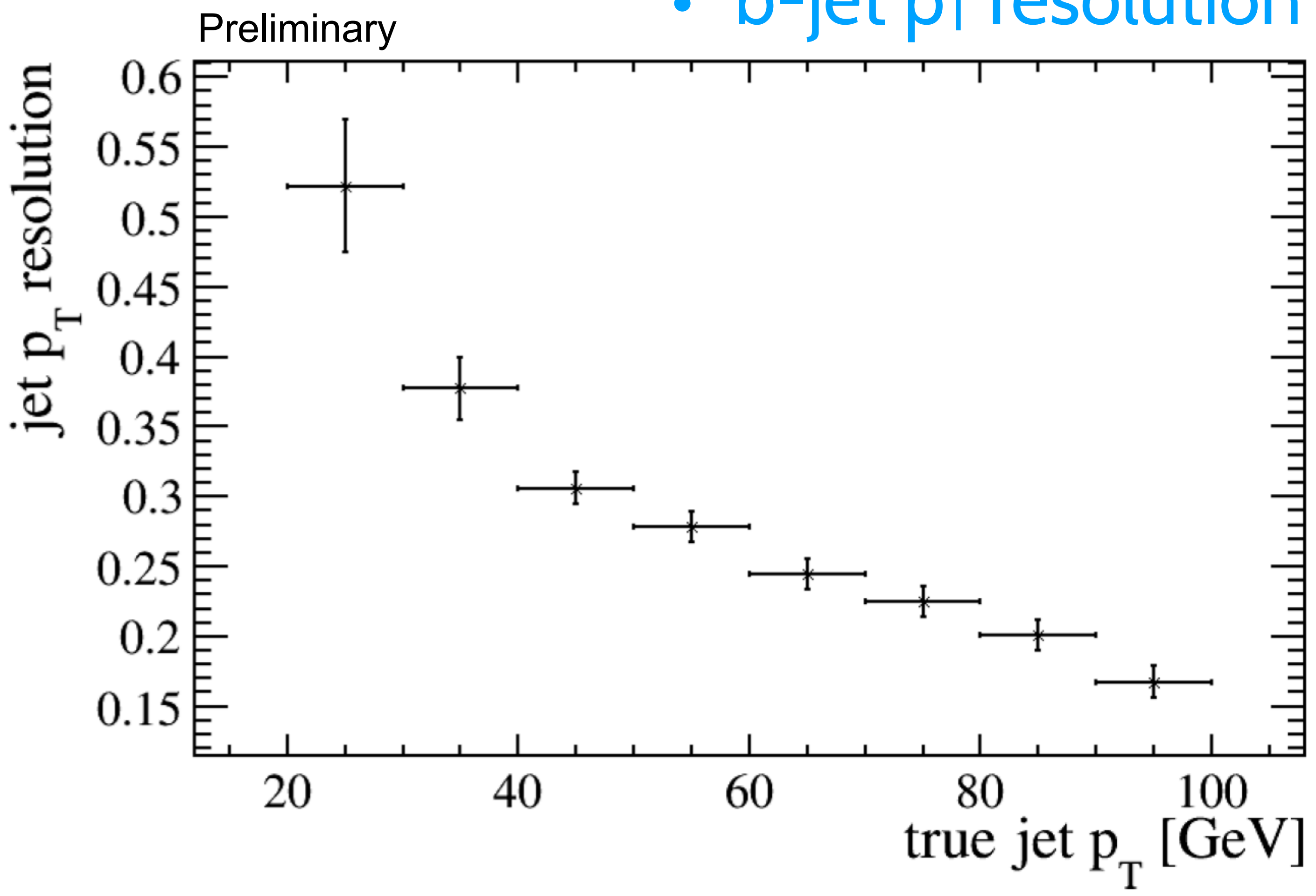


Overall good detector performance achieved at the current stage of the simulation/analysis workflow

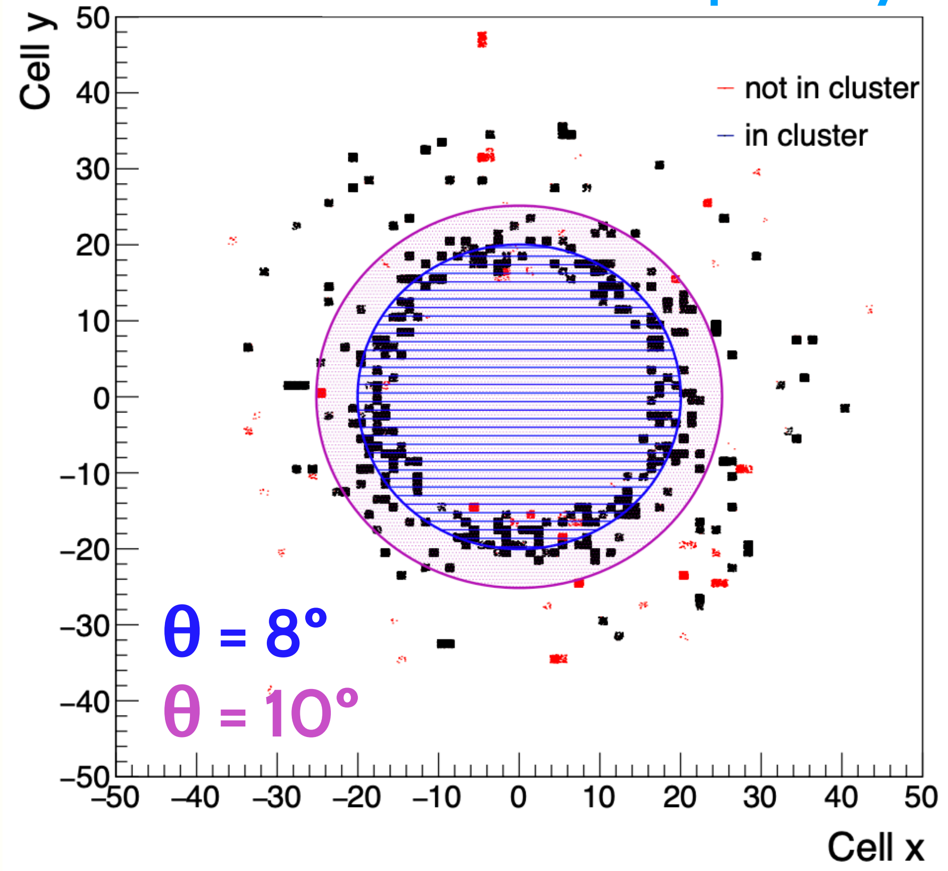
- tracking efficiency



- b-jet p_T resolution



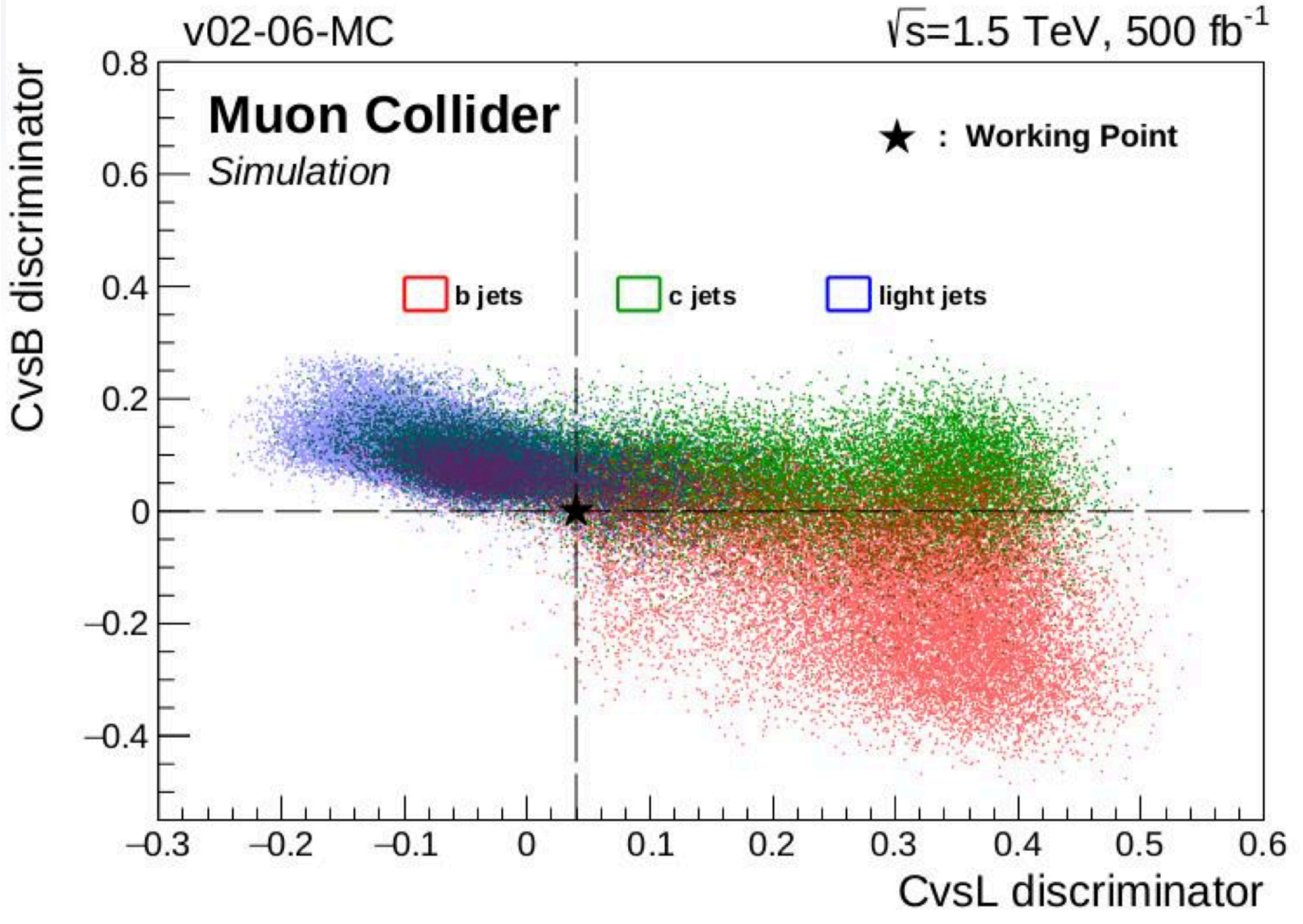
- muon occupancy



several physics analyses already in progress using full detector simulation

Many ongoing efforts within the Snowmass process

- **sensitivity to Higgs coupling to b/c quarks and Z boson**
  at $\sqrt{s}$ = 1.5 and 3 TeV in $\mu^+\mu^- \rightarrow H \rightarrow bb\,\nu\nu \,|\, cc\,\nu\nu \,|\, ZZ^* \rightarrow 4\mu$ →
- **sensitivity to the HH cross section and trilinear coupling**
  at $\sqrt{s}$ = 3 TeV in $\mu^+\mu^- \rightarrow HH\,\nu\nu \rightarrow bb\,bb\,\nu\nu$
- **sensitivity to dark sector through neutralino production**
  at $\sqrt{s}$ = 3 TeV in $\mu^+\mu^- \rightarrow N_1N_1 \rightarrow n_d\,n_d\,\mu^+\mu^-\,\mu^+\mu^-$
- **sensitivity to long-lived particles, luminosity measurements and more**



Summary

Muon Collider is a unique machine for both discoveries and precision measurements
gaining a lot of attention from the theoretical and experimental communities

Feasibility study under way within the International Muon Collider Collaboration
covering the accelerator test facility and detector R&D

Beam Induced Background pushing the detector requirements to the limits
in terms of time resolution, granularity, data rates, ...

Several benchmark physics analyses are ongoing using full detector simulation
with lots of space for improvements and new studies

More on the recent progress of the project:

- 1st Muon Community Meeting
  May 20-21, 2021
- Muon Collider Physics and Detector Workshop
  June 2-4, 2021

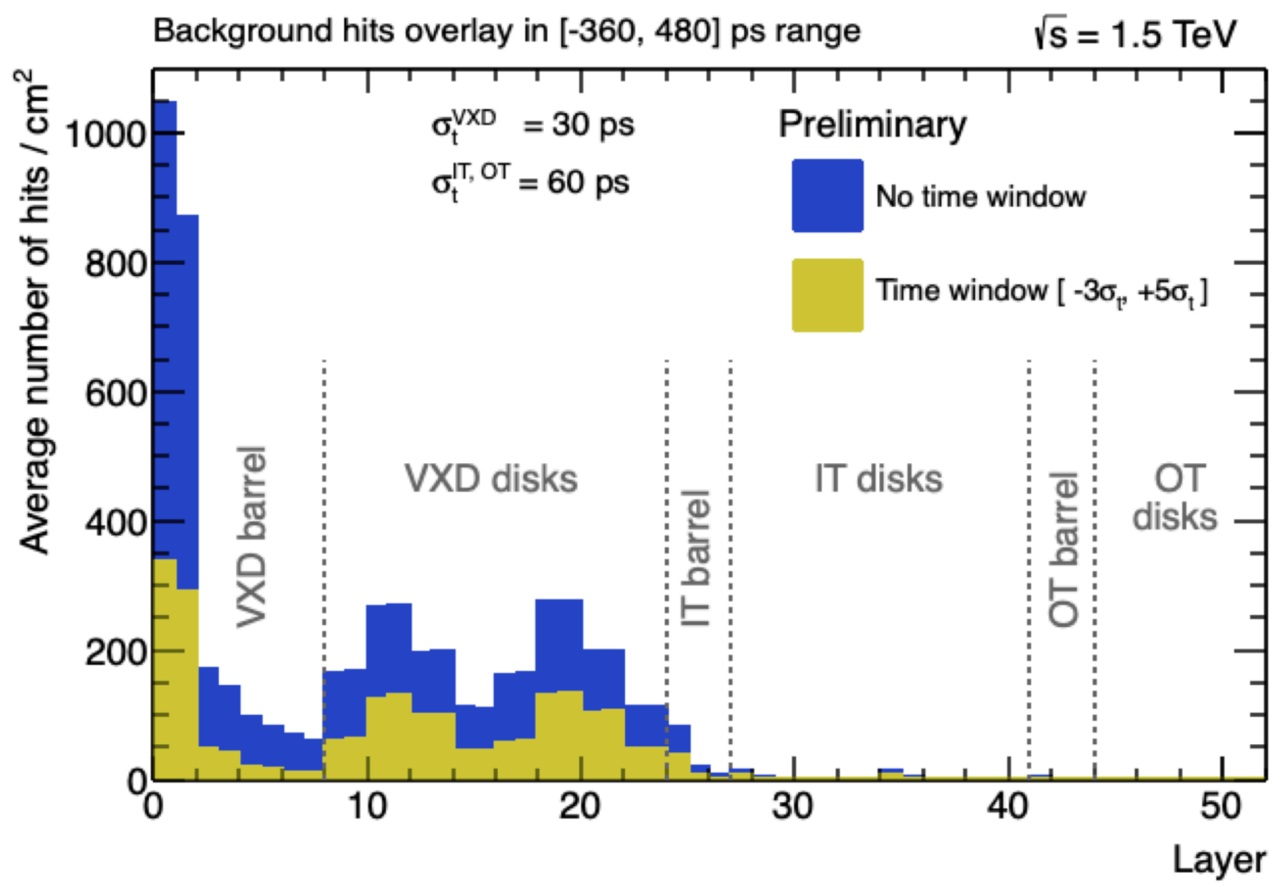
Next Muon Community Meeting:

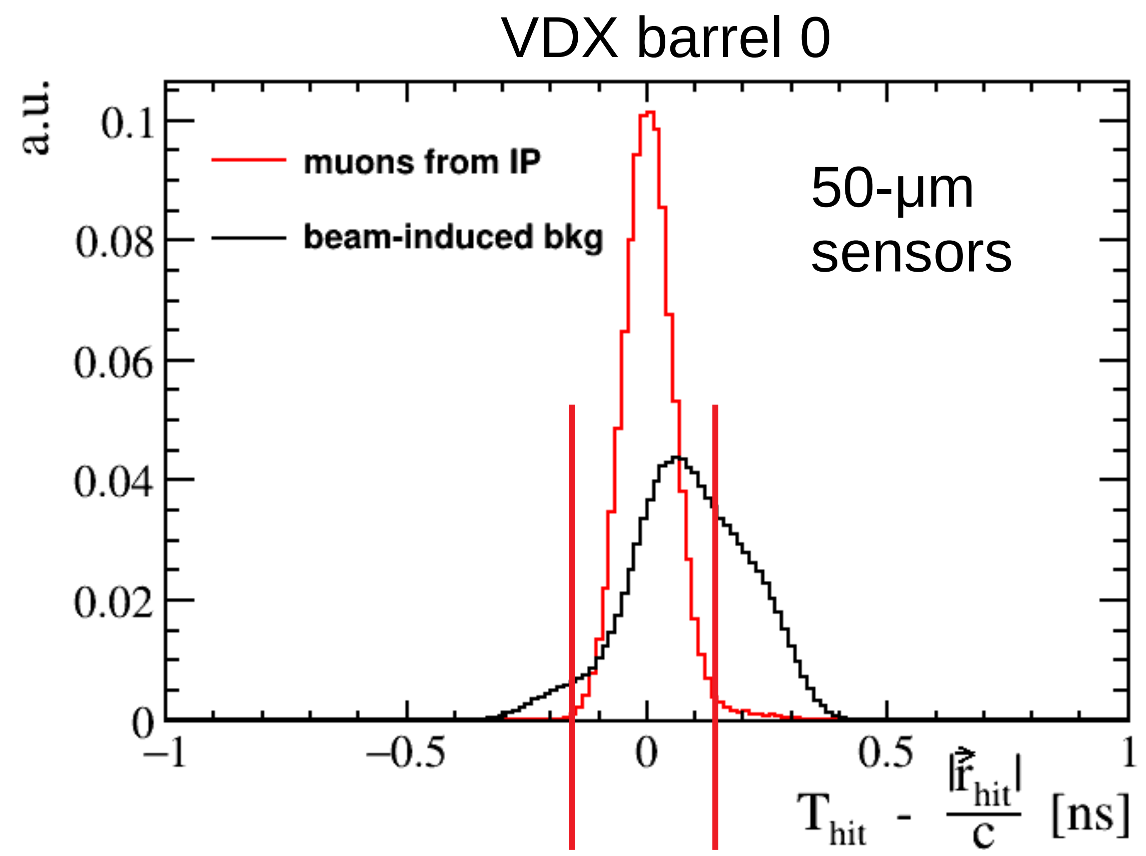
- *October 6-8, 2021*

Backup: Track reconstruction

Very high hit density close to the interaction point: up to 1K hits/cm² in the Vertex Detector

↳ **significant occupancy reduction achieved** with position-dependent timing selection



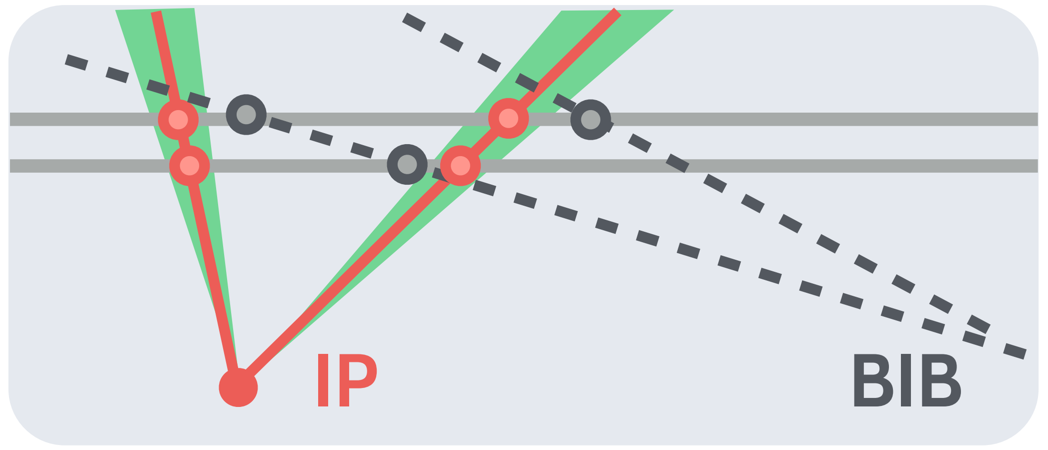


Manageable data rates for triggerless readout at the design collision rate of ≤100 kHz

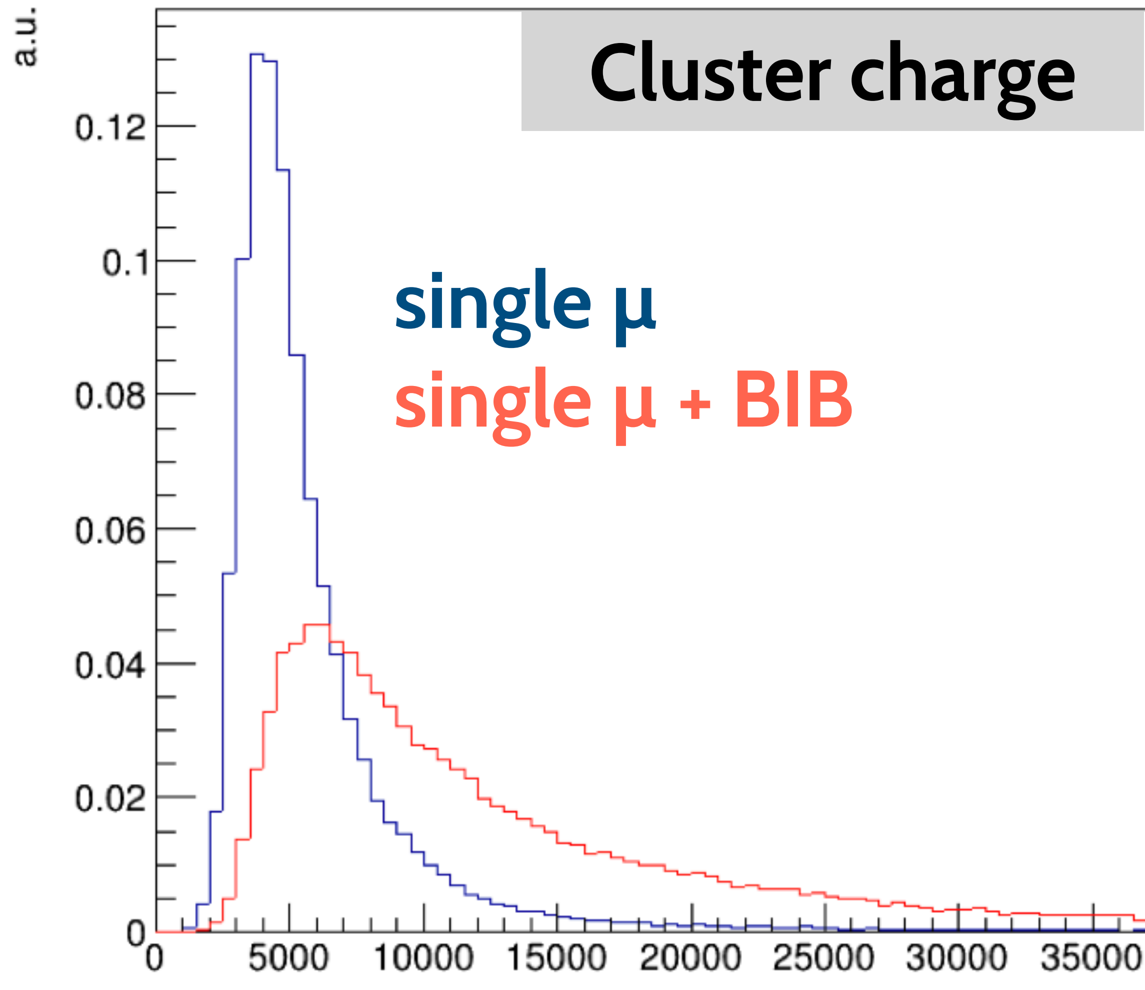
The major bottleneck → track-reconstruction time due to combinatorics in the Vertex seeding region

Promising BIB-suppression strategies are under study: can reduce reconstruction time by factor 10-1000

- **hit doublets aligned with the IP** relies on the knowledge of the IP position



- **cluster shape and charge** sensitive to particle type and crossing angle

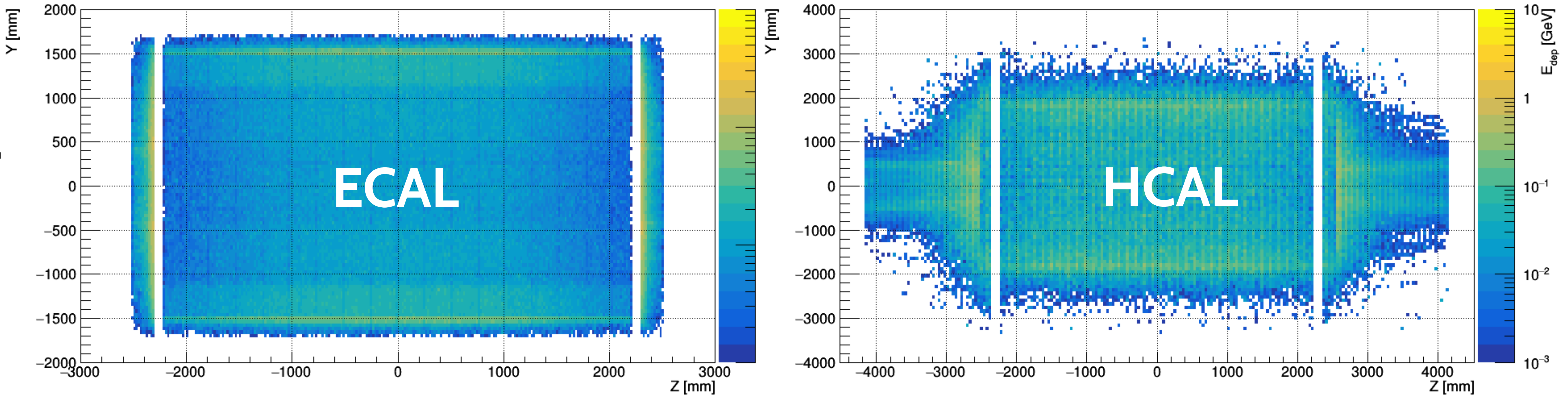


Other generic optimisations are highly relevant: parallelisation, regions of interest, 4D tracking

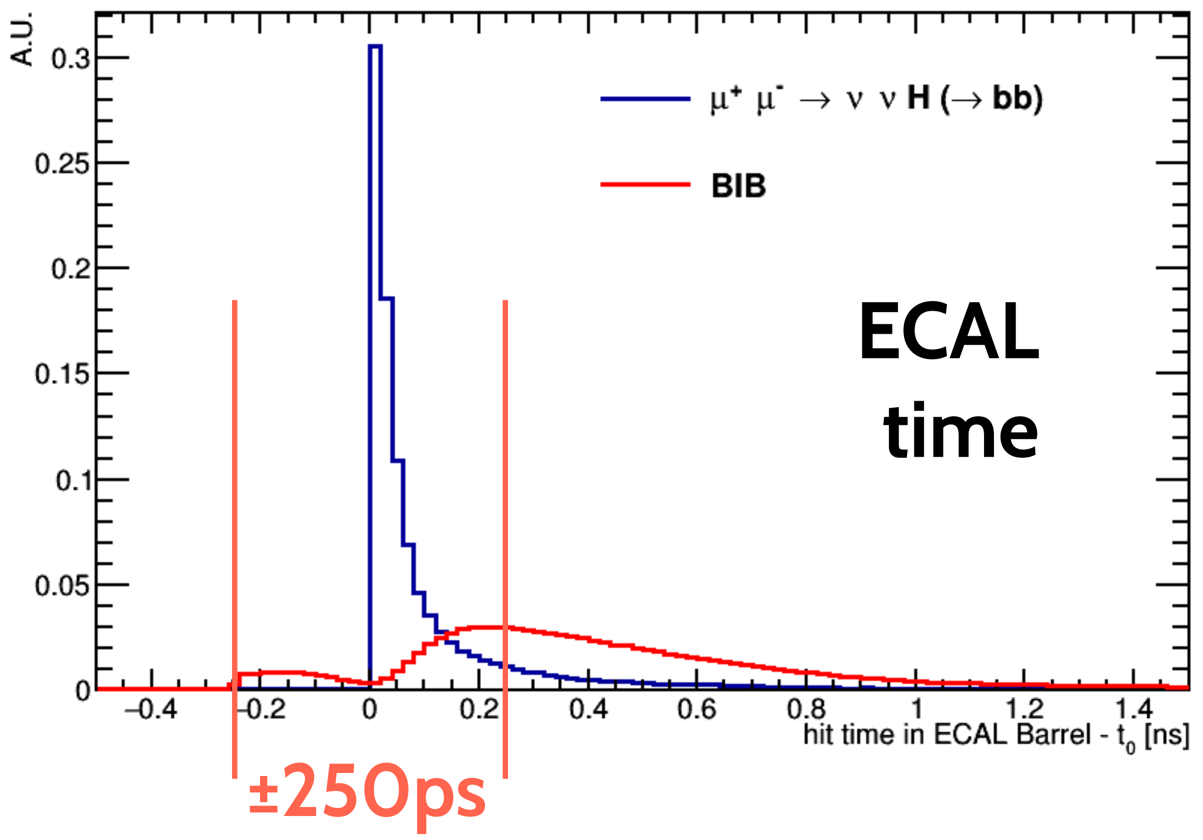
Realistic reconstruction strategy requires flexible optimisation for a specific track topology to keep combinatorics to the minimum during seeding and pattern-recognition stages

Relies on tracks and calorimeter clusters

Energy deposits from BIB diffused across ECAL + HCAL
no signal-like isolated clusters like at the LHC



Timing is again a powerful discriminating factor
+ longitudinal shower profile



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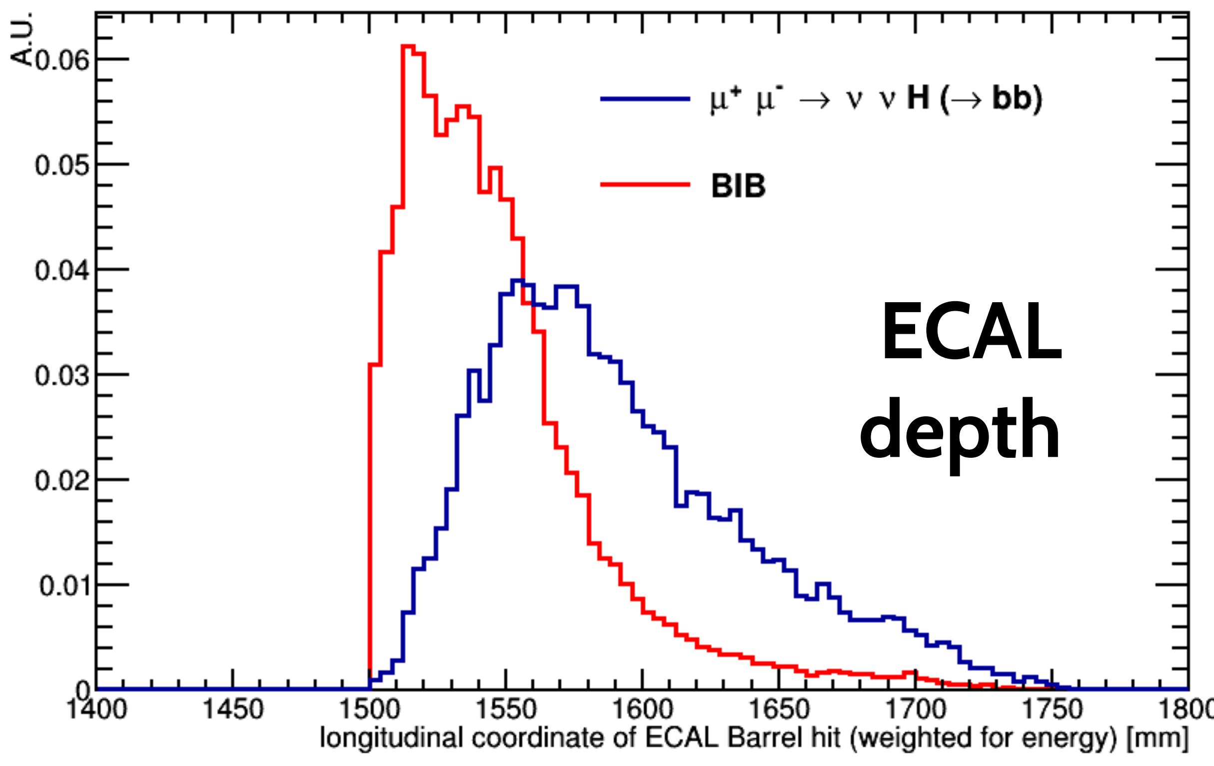

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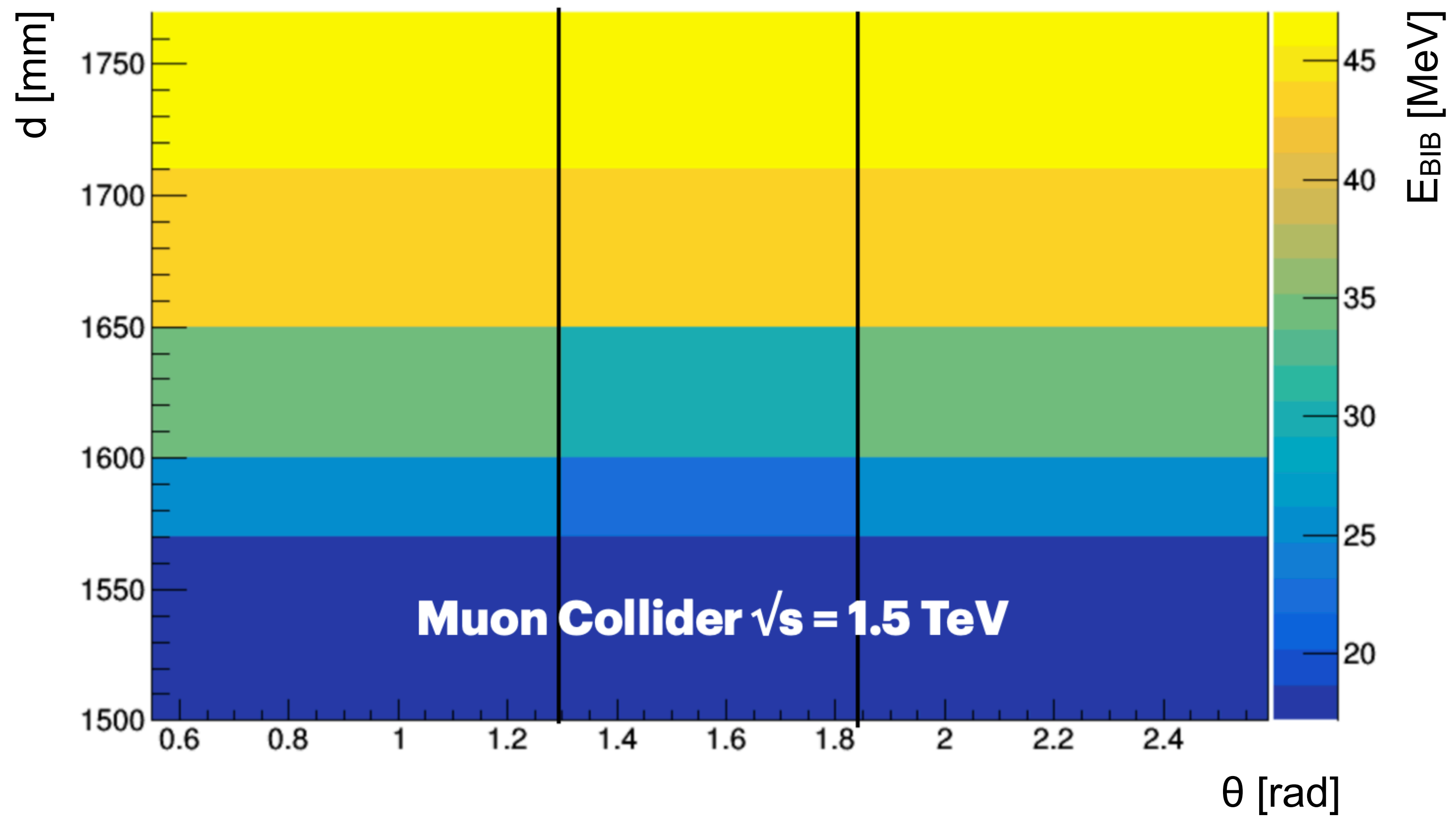
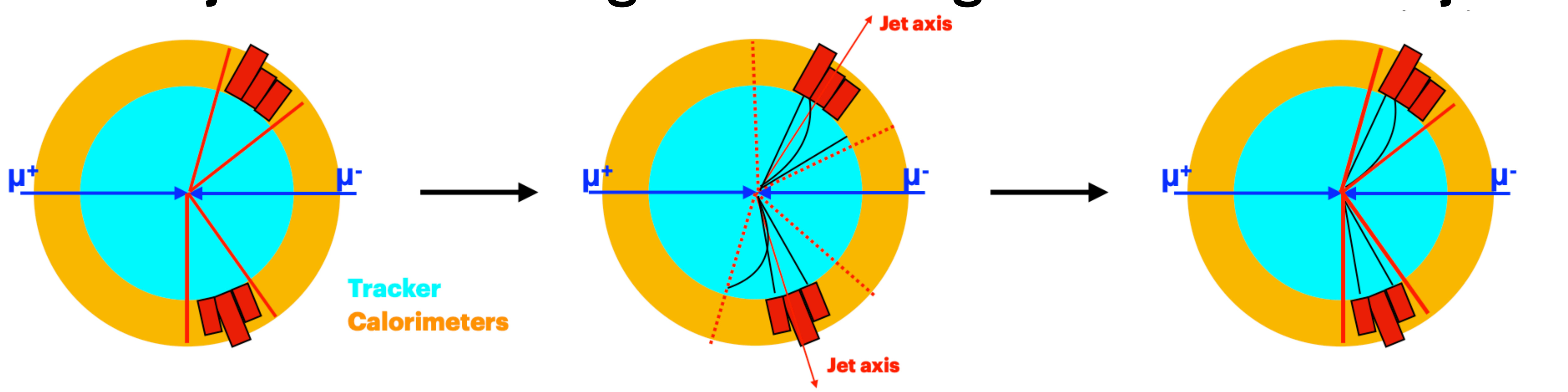


subtracted from reco. hit energy

Current jet reconstruction strategy done in 3 stages:
to cope with combinatorics of track reconstruction



Further improvements under study:

- multivariate BIB subtraction optimisations
- particle-flow algorithm tuning