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WIN 2021



Muon Collider: prospects, challenges and the latest progress

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on Weak Interactions and Neutrinos

N. Bartosik ^(a)

L. Buonincontri ^(b), M. Casarsa ^(c), S. Jindariani ^(d), D. Lucchesi ^(b), N. Pastrone ^(a), S. Pagan Griso ^(e), L. Sestini ^(b)

on behalf of the **Muon Collider Physics and Detector group**

^(a) INFN Torino (Italy)

^(b) INFN Padova (Italy)

^(c) INFN Trieste (Italy)

^(d) FNAL (USA)

^(e) LBNL (USA)

Muon Collider: unique features

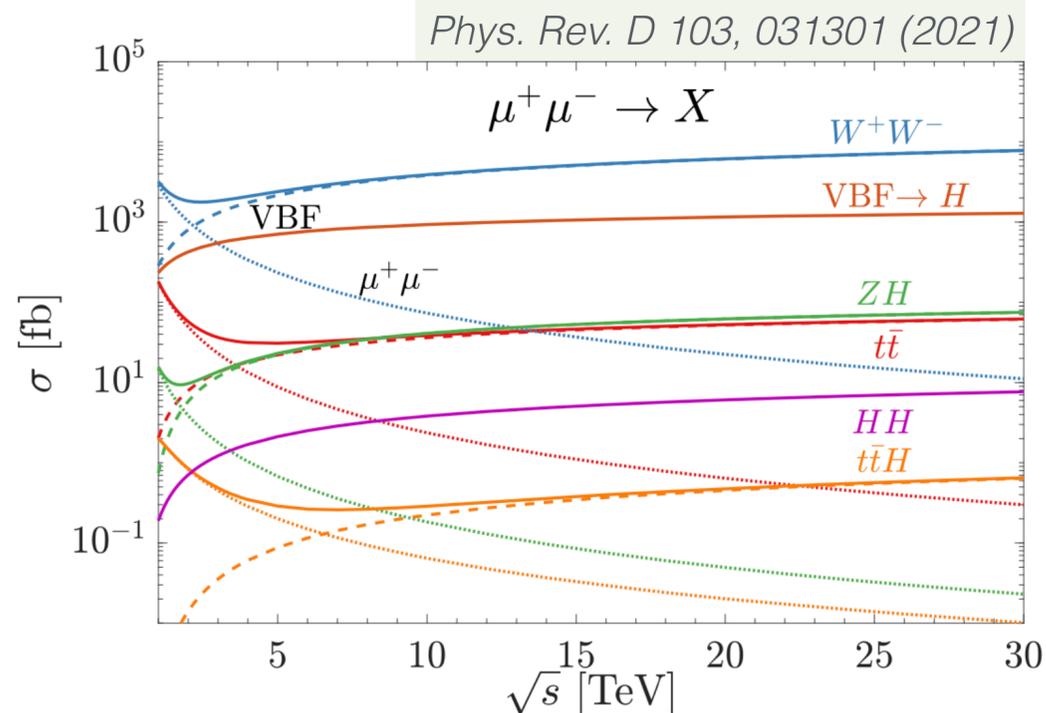
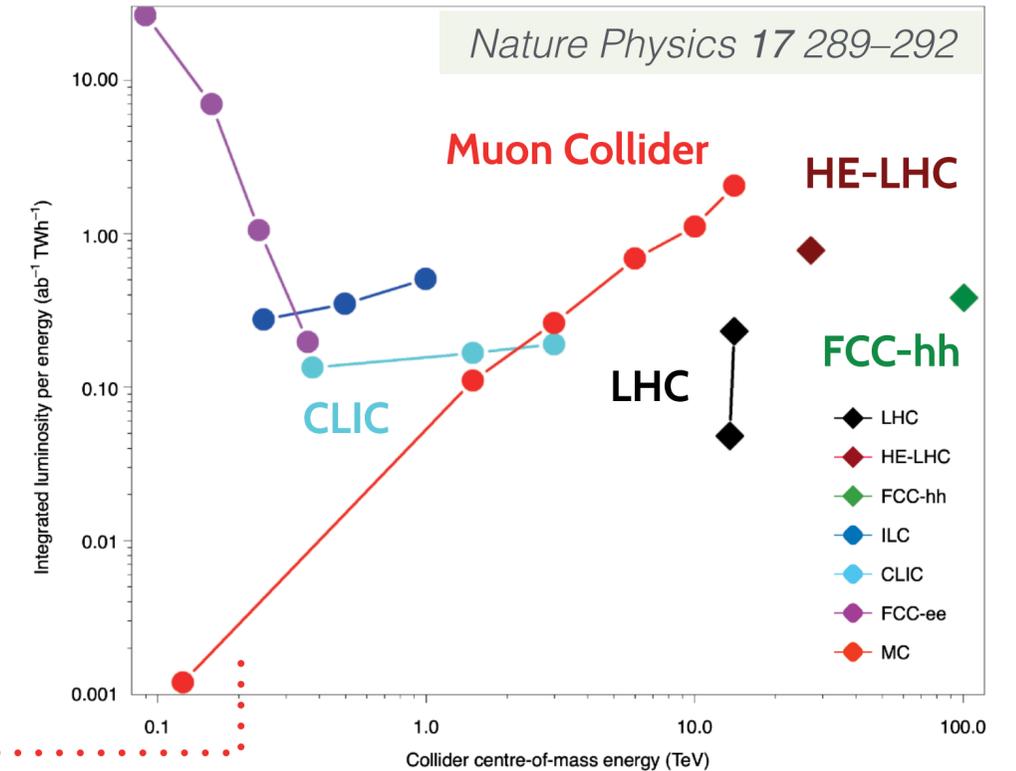
Big question for particle physics today: which facility to build after HL-LHC?

- 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
- $\times 200$ higher mass $\rightarrow \times 10^4$ 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

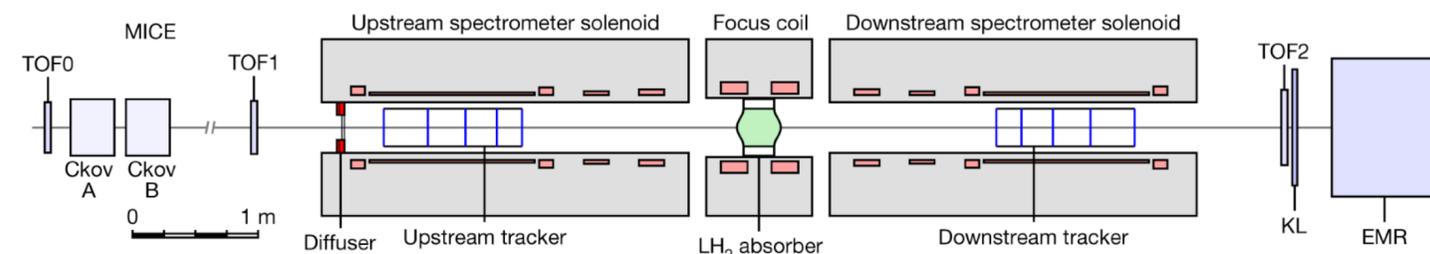
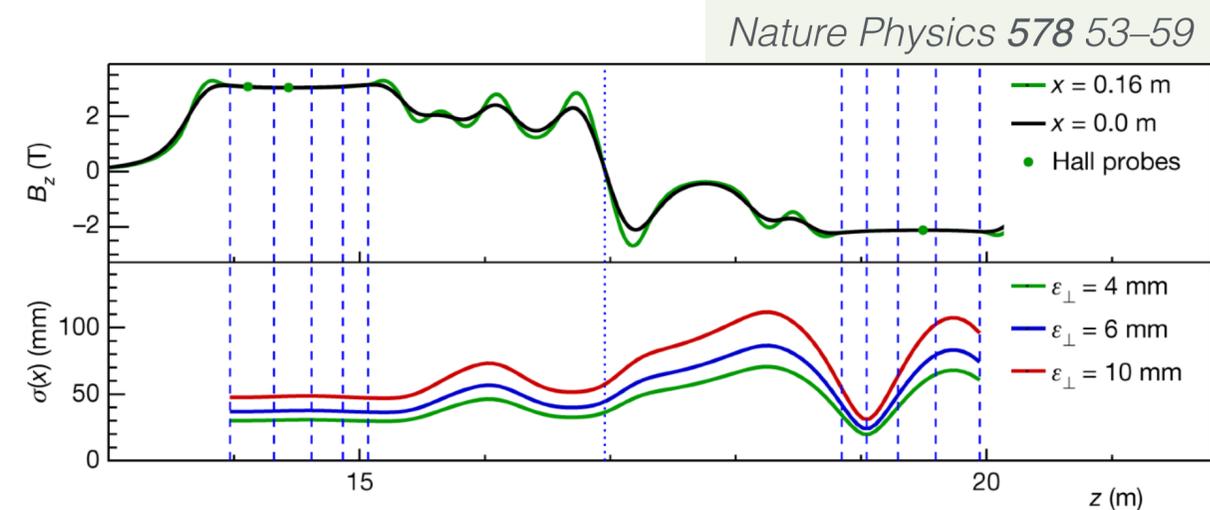
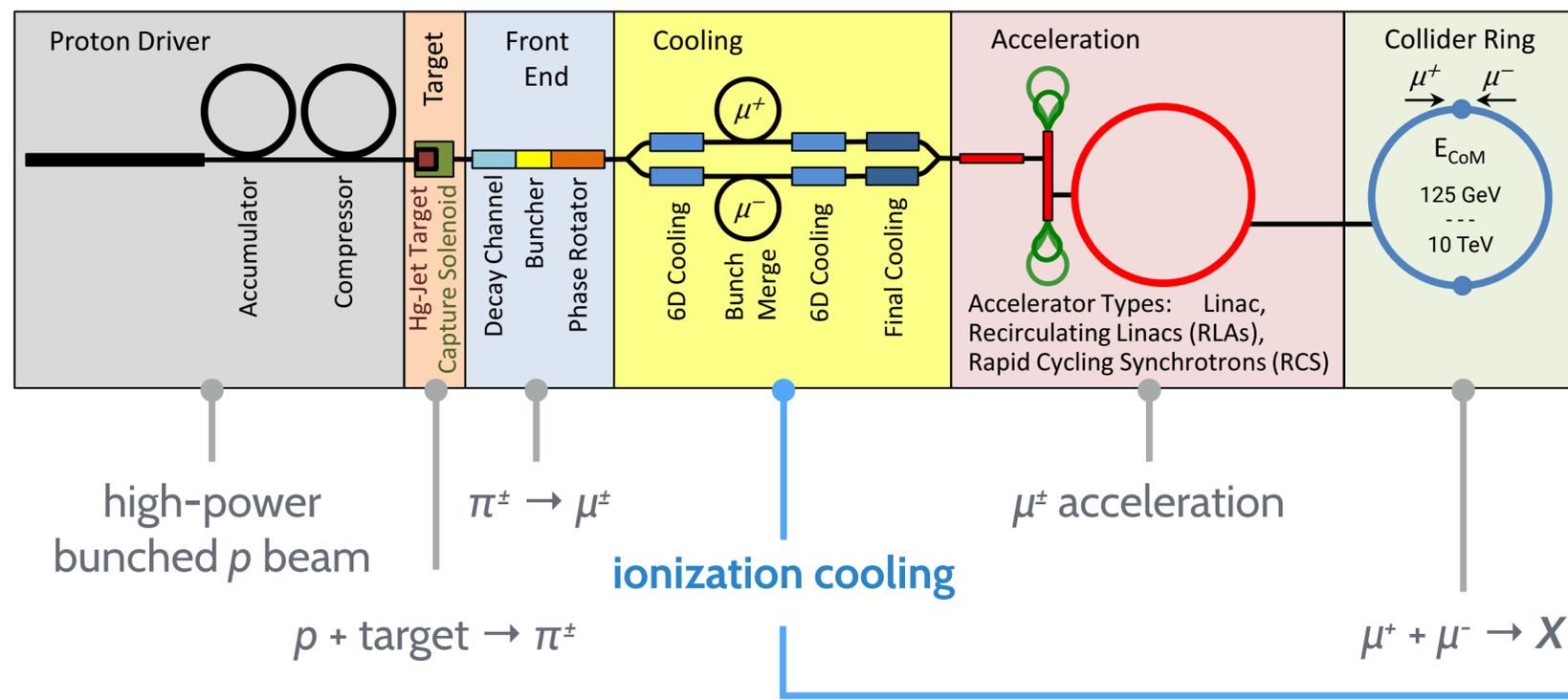
- $\mu^+\mu^-$ + vector-boson fusion (*increasing at higher energies*)
- unprecedented accuracy of electroweak Higgs couplings
- discovery reach at 14 TeV comparable to FCC-hh at 100 TeV

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](https://arxiv.org/abs/2103.14043) ◀ *one of the most recent*

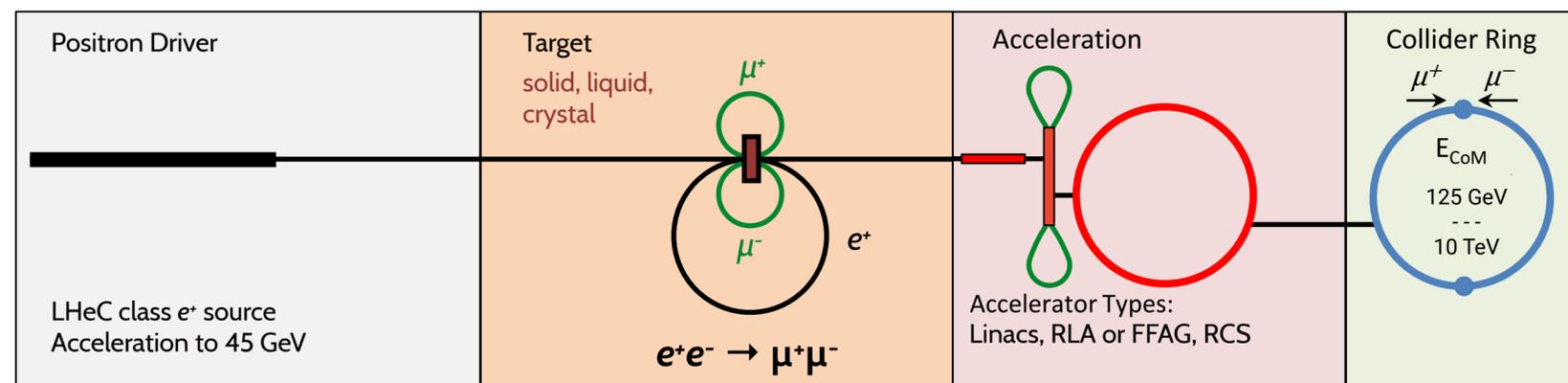
Challenge I: muon acceleration

The baseline muon-production scheme: from a proton beam



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:

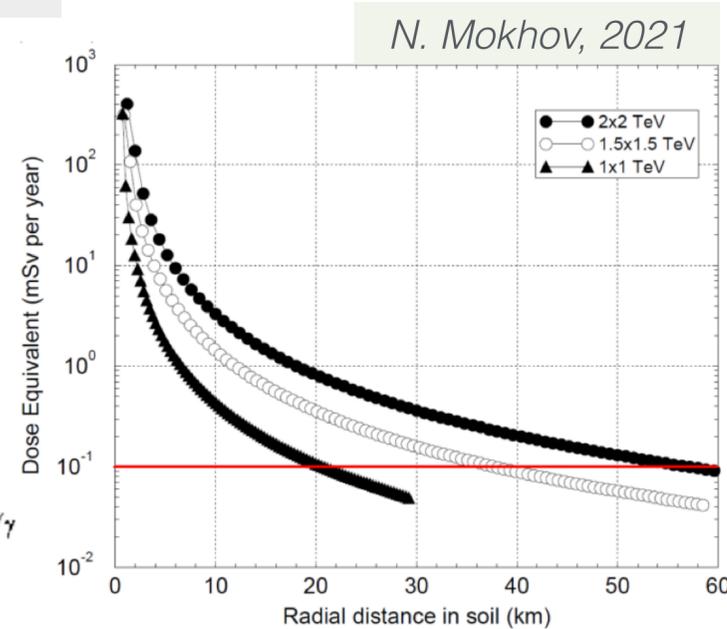
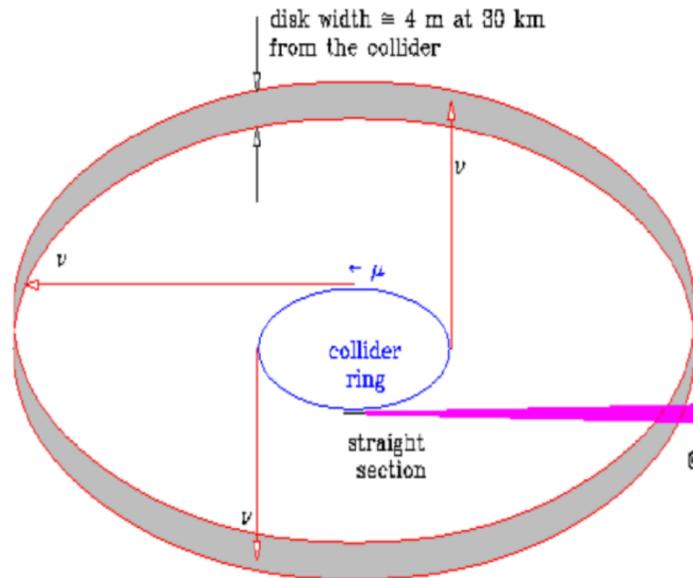
- very low $e^+e^- \rightarrow \mu^+\mu^-$ cross section
- extreme positron-beam intensity needed

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

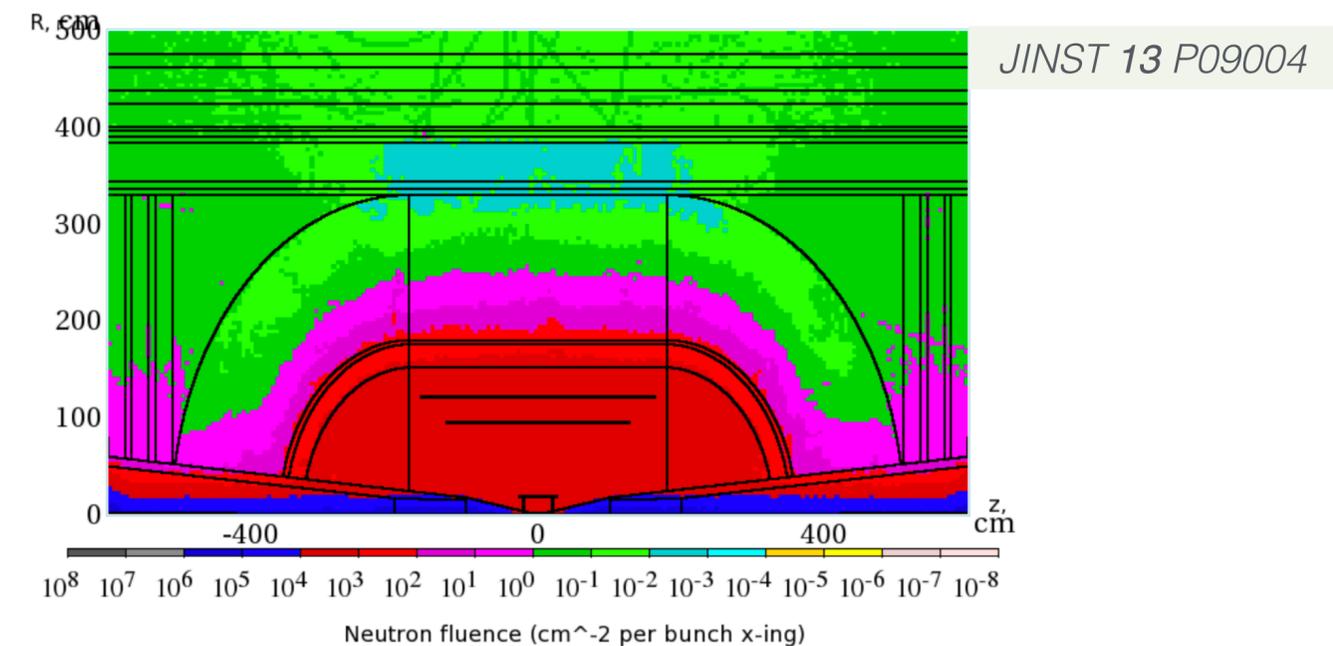


Collimated neutrino beams deliver a substantial dose

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)



Secondary/tertiary particles reaching the detector

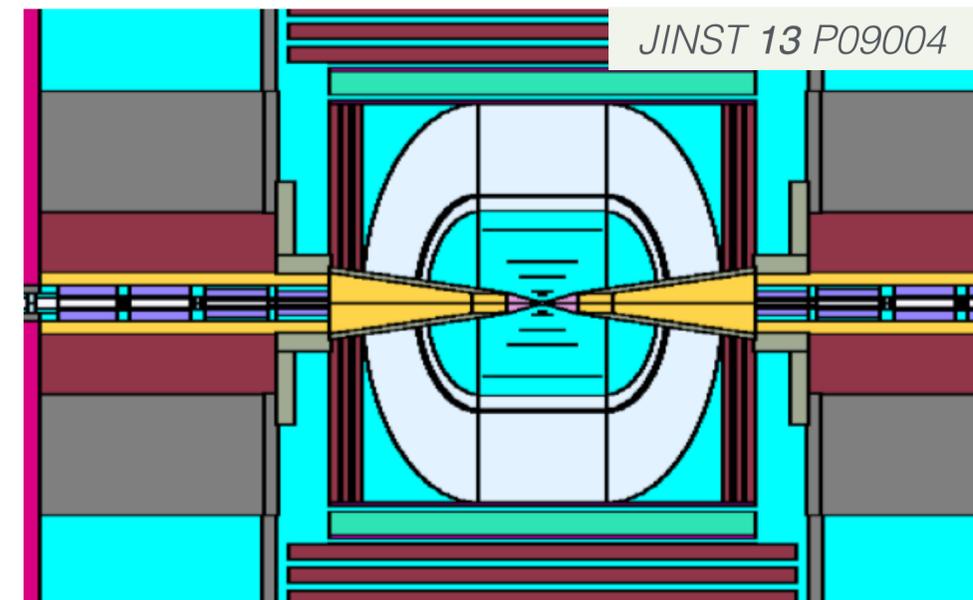
The two main effects:

- 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 $\sqrt{s} = 1.5$ TeV**

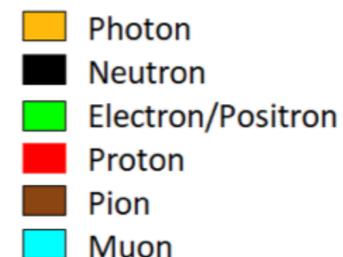
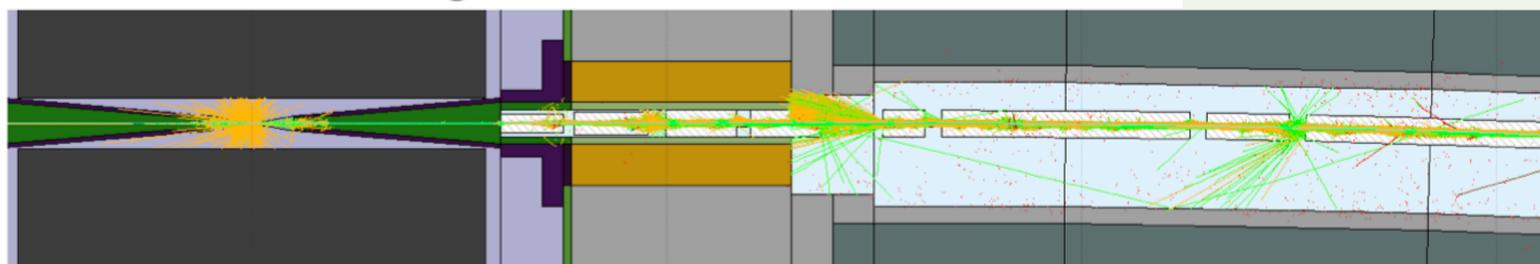
- accelerator lattice ($\pm 200m$ from IP relevant for the simulation)
- Machine Detector Interface (MDI): *tungsten + borated polyethylene* ▶



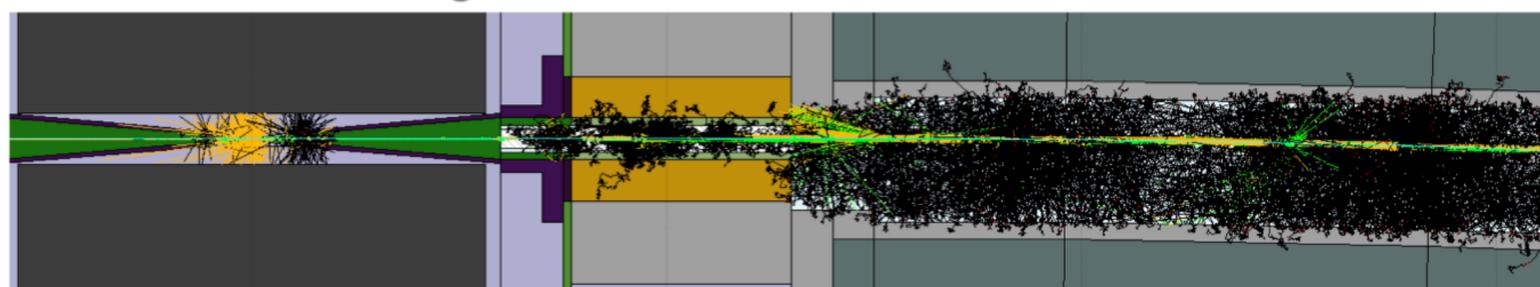
New BIB simulation workflow in place based on **FLUKA software**

FLUKA tracking without neutrons

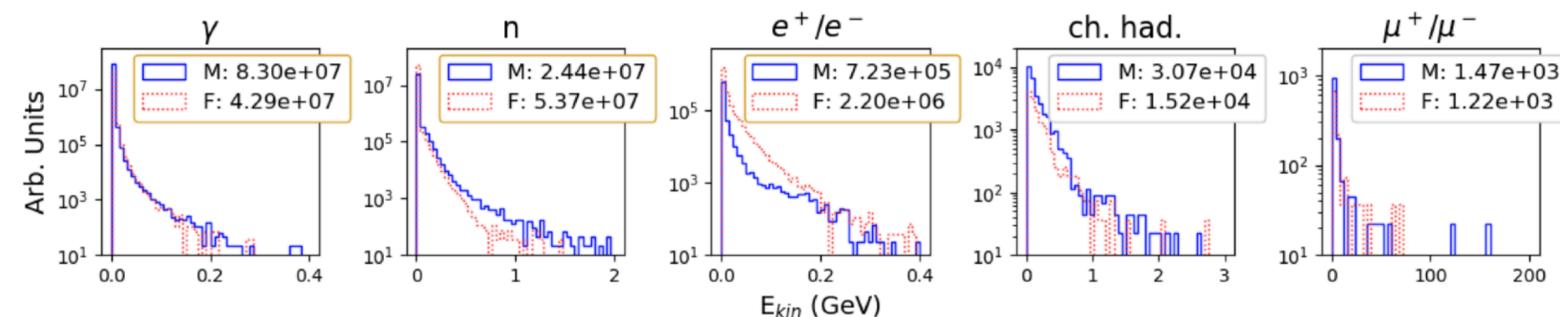
C. Curatolo, 2021



FLUKA tracking with neutrons

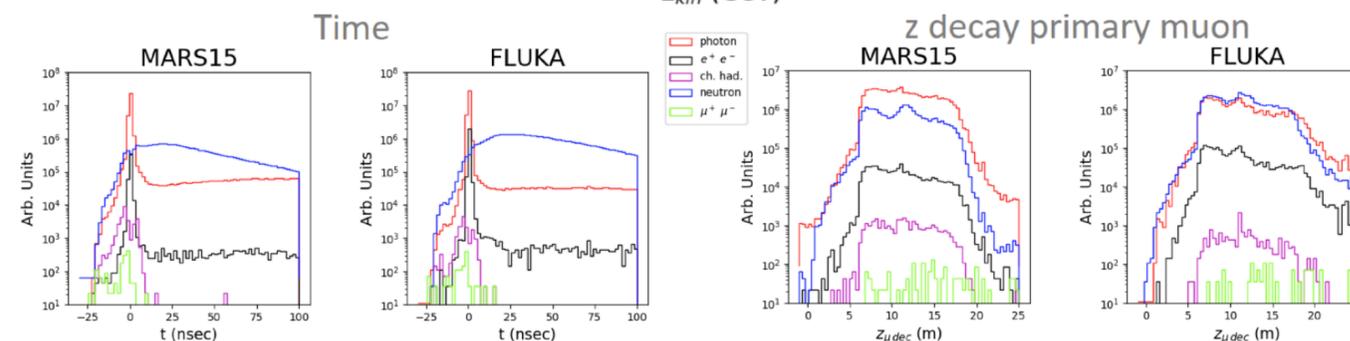


arXiv:2105.09116



Good agreement with MARS15 simulation for $\sqrt{s} = 1.5$ TeV ▶

↳ ready to explore **higher energies** → $\sqrt{s} = 3-10$ TeV



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

1. Predominantly very soft particles ($p \ll 250 \text{ MeV}$) 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 $\sqrt{s} = 1.5 \text{ TeV}$ | $\leq 20\text{ps}$ at $\sqrt{s} = 3 \text{ TeV}$

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

3. Large spread of the origin along the beam

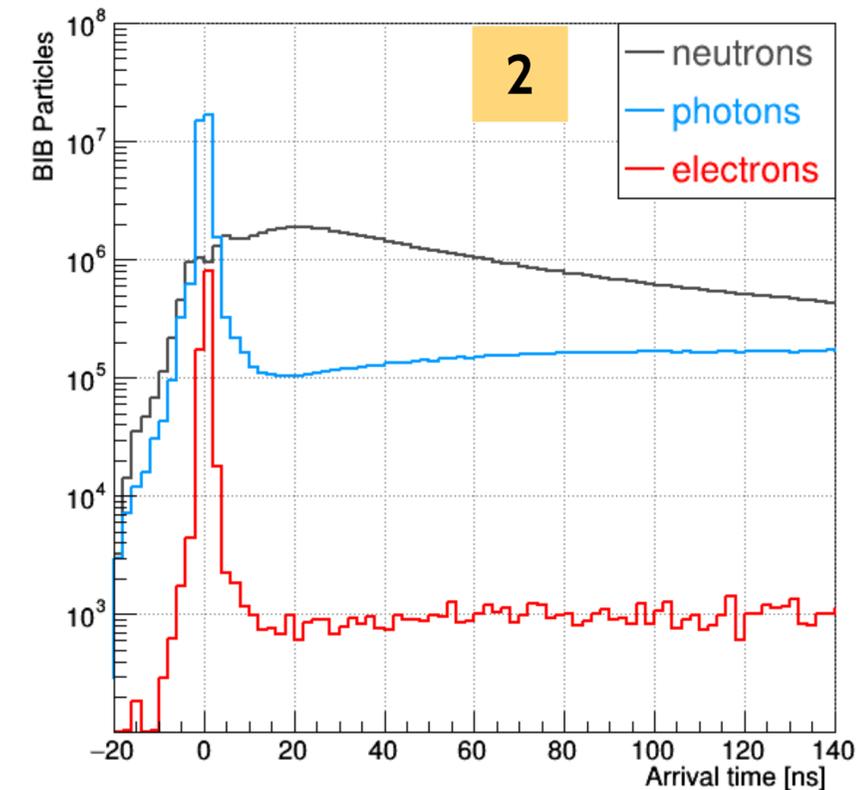
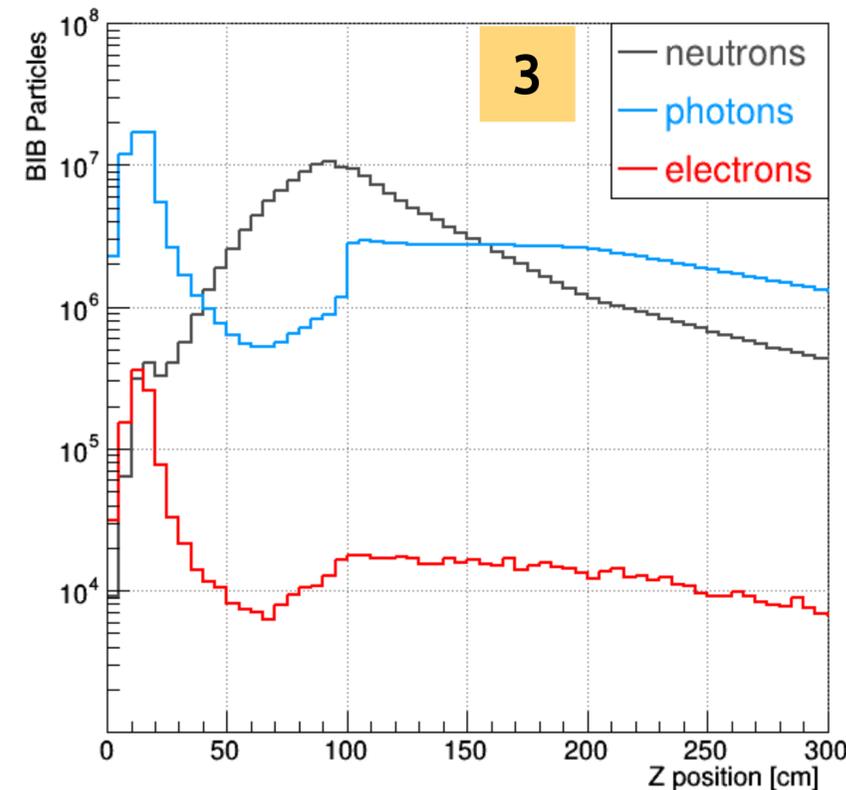
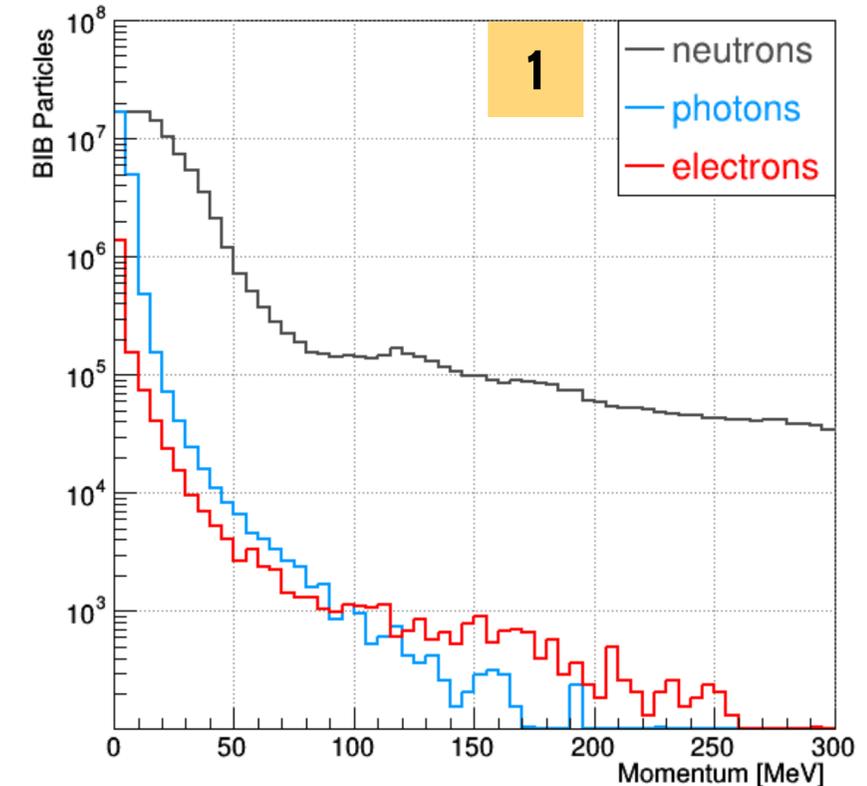
different azimuthal angle wrt the detector surface

+ 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 $2 \times 10^{12} \mu/\text{bunch}$ → $2 \times 180\text{M}$ 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 $>10^\circ$

All-silicon tracker: $B = 3.57\text{ T}$

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

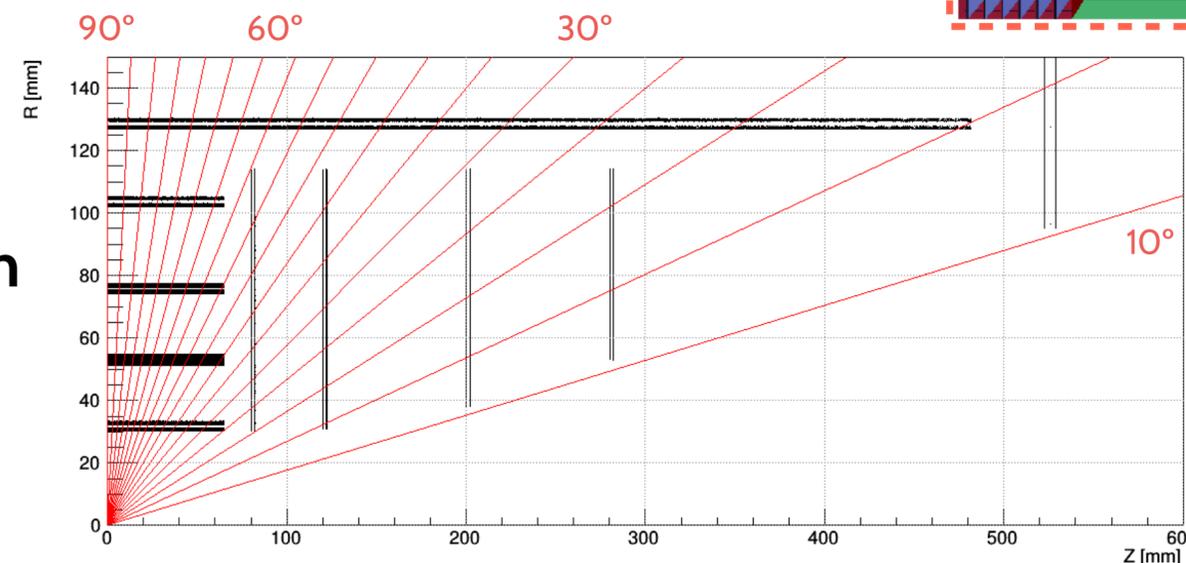
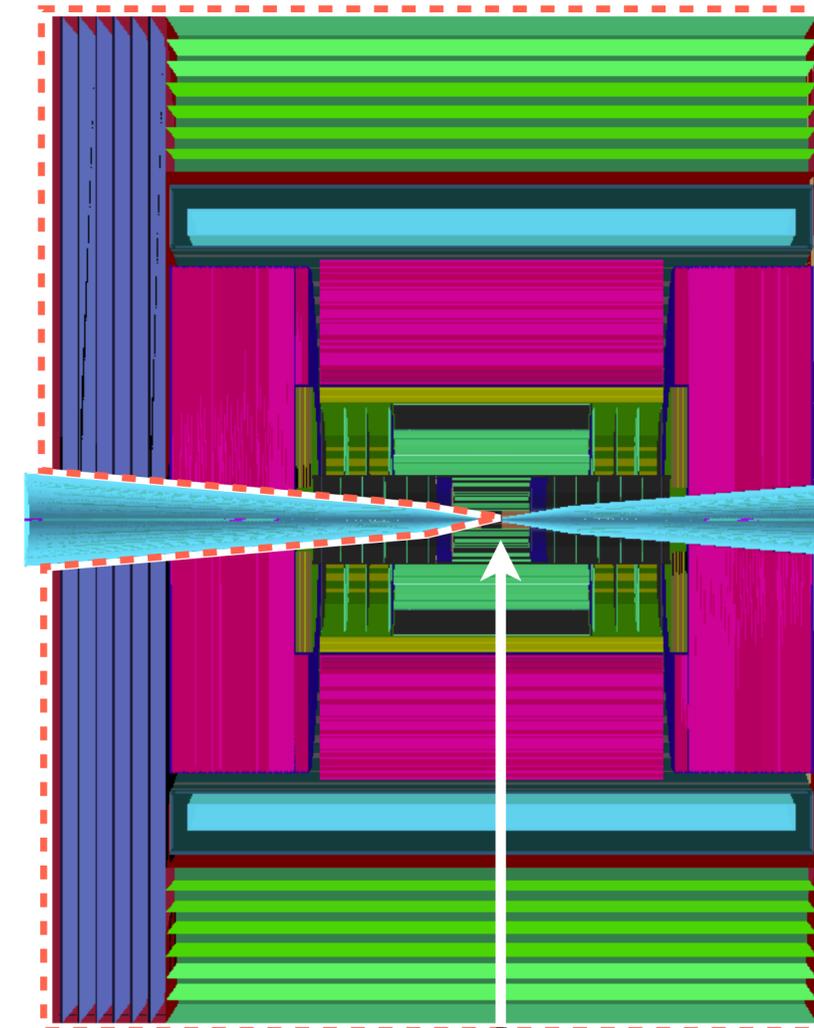
High-granularity sampling calorimeter

- **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



Vertex Detector

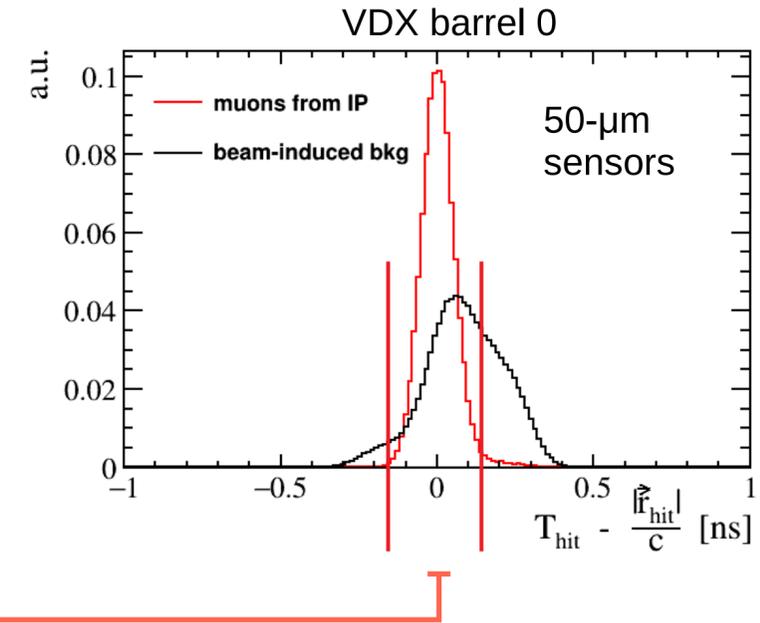
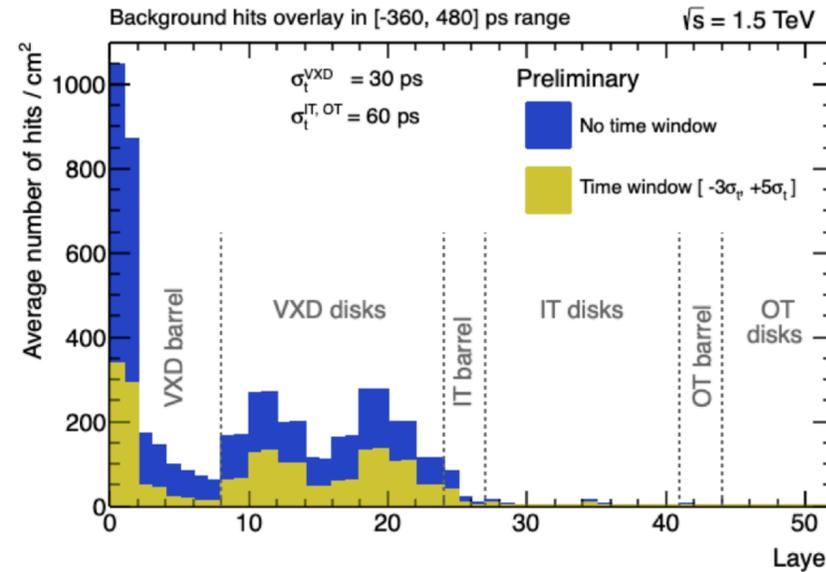
Track reconstruction

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

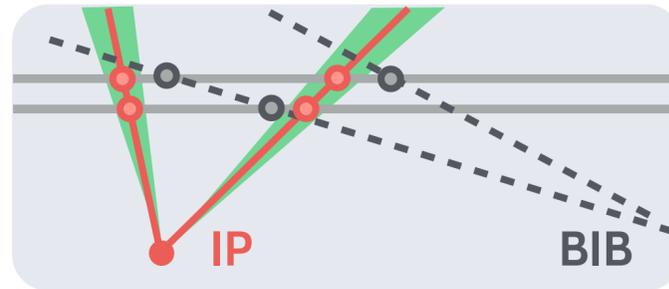
Manageable data rates for **triggerless readout** at the design collision rate of ≤ 100 kHz

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

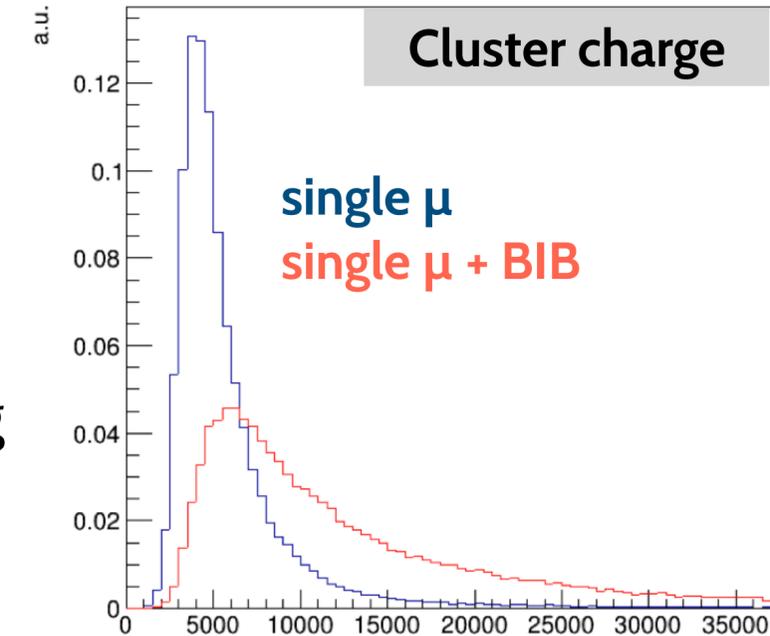


Promising **BIB-suppression strategies** are under study: can reduce reconstruction time by factor 10-1000

- 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

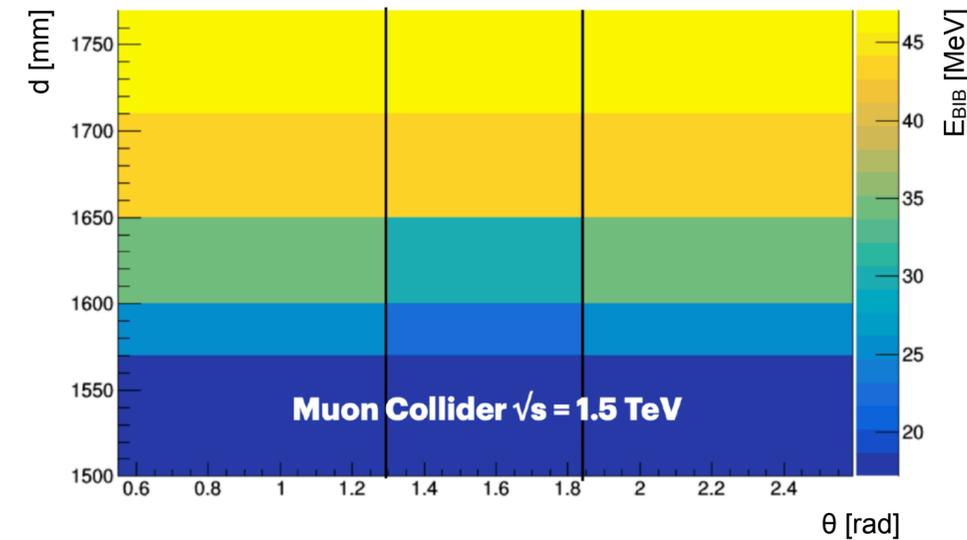
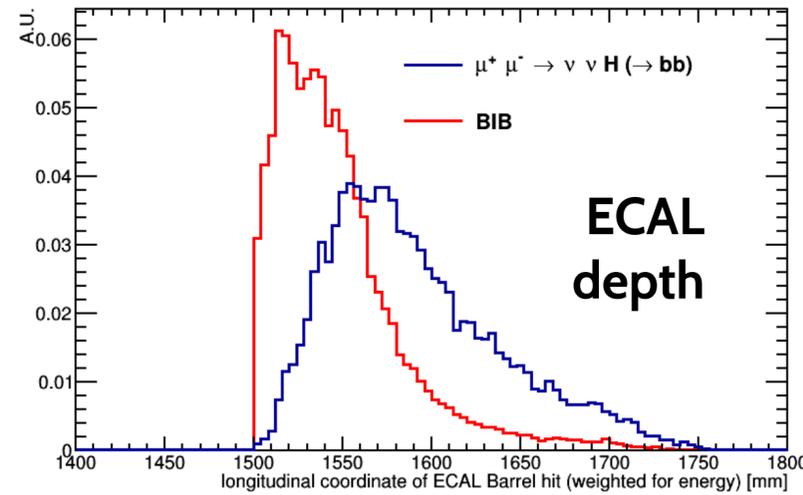
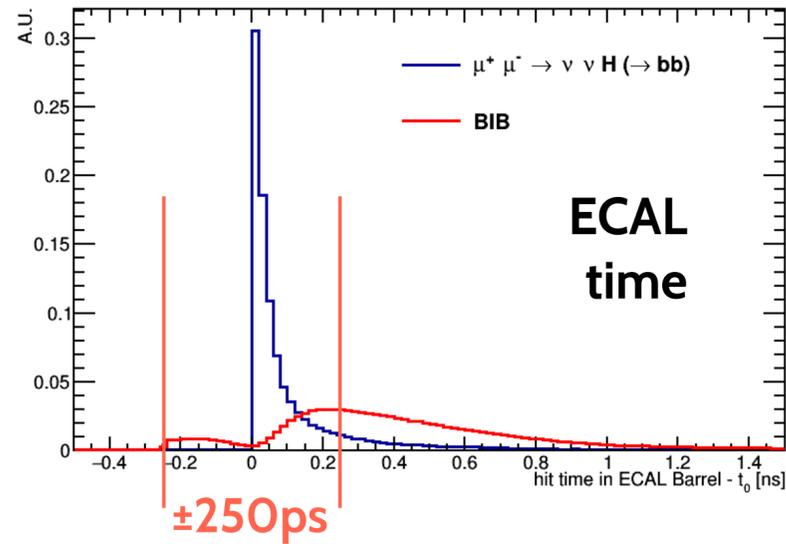
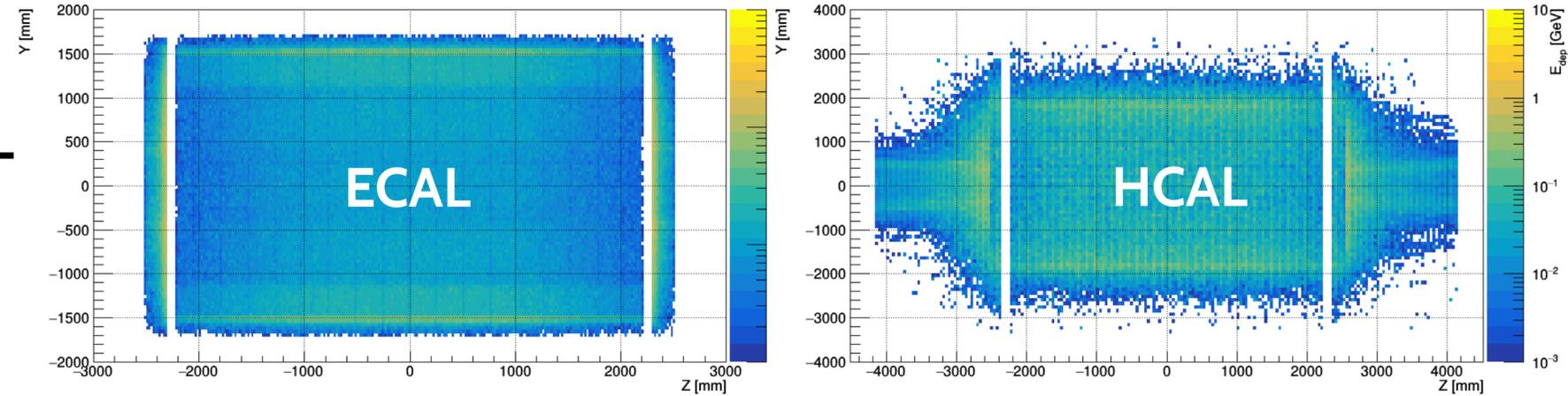
Realistic reconstruction strategy requires flexible **optimisation for a specific track topology** to keep combinatorics to the minimum during seeding and pattern-recognition stages

Jet reconstruction

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

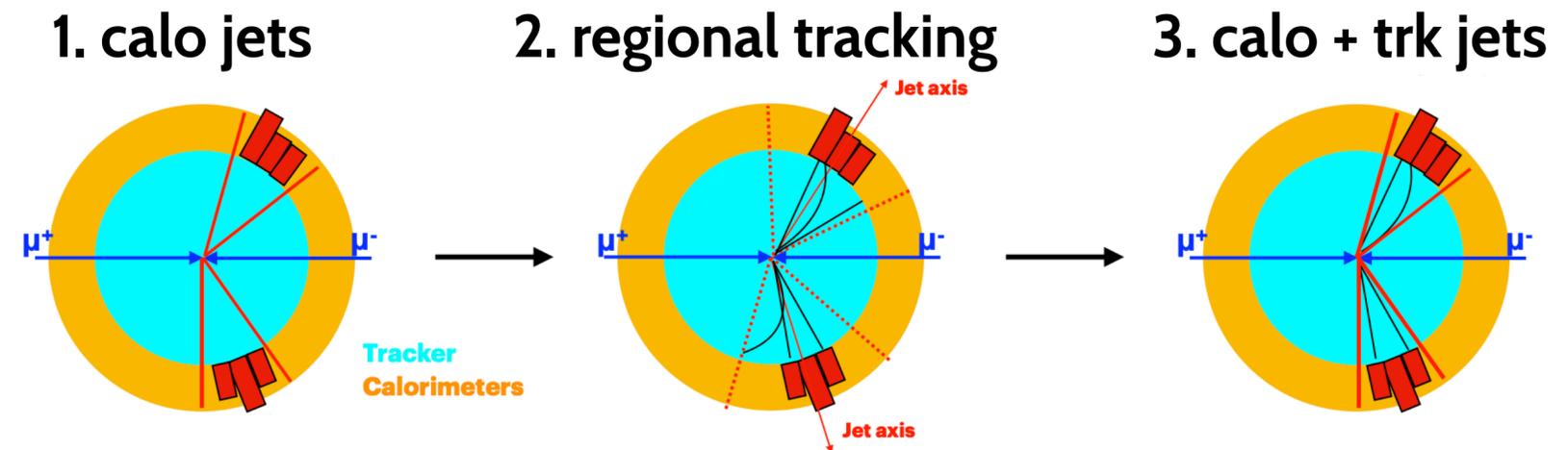


subtracted
from reco.
hit energy

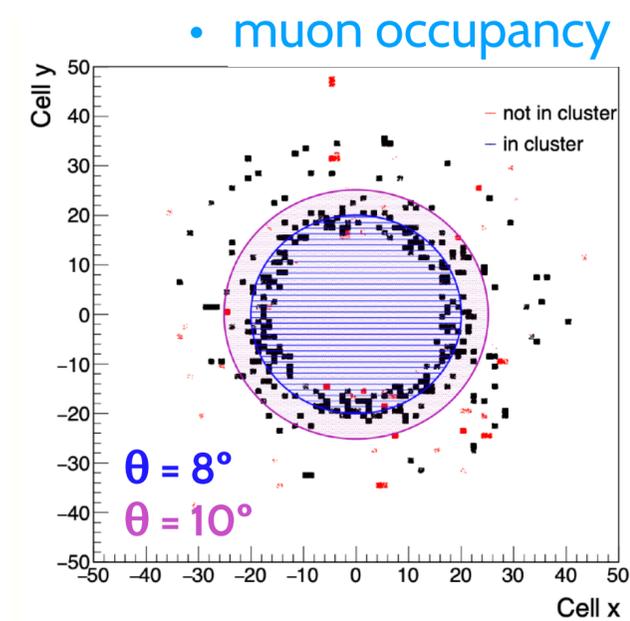
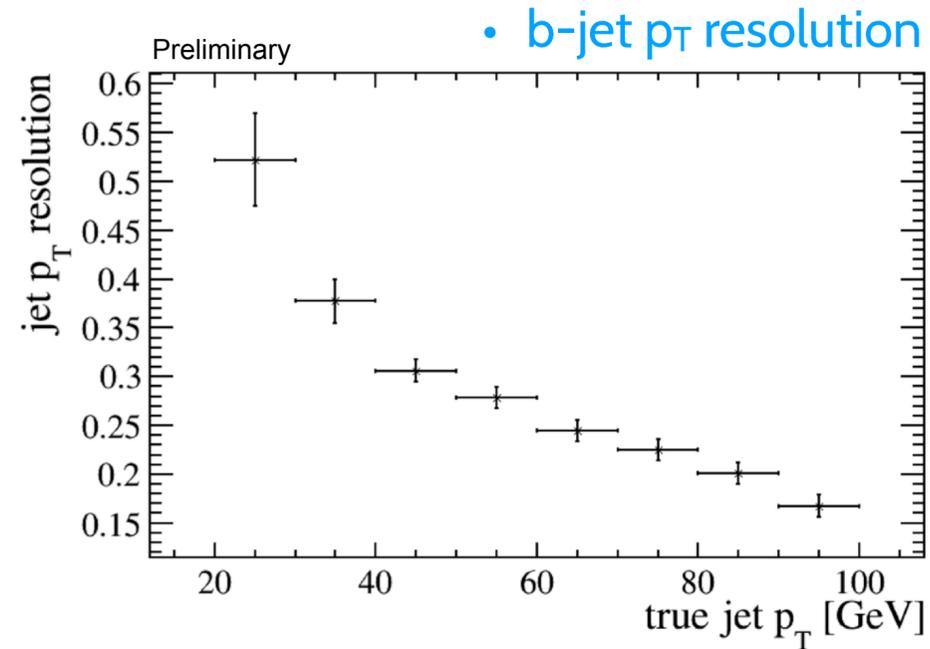
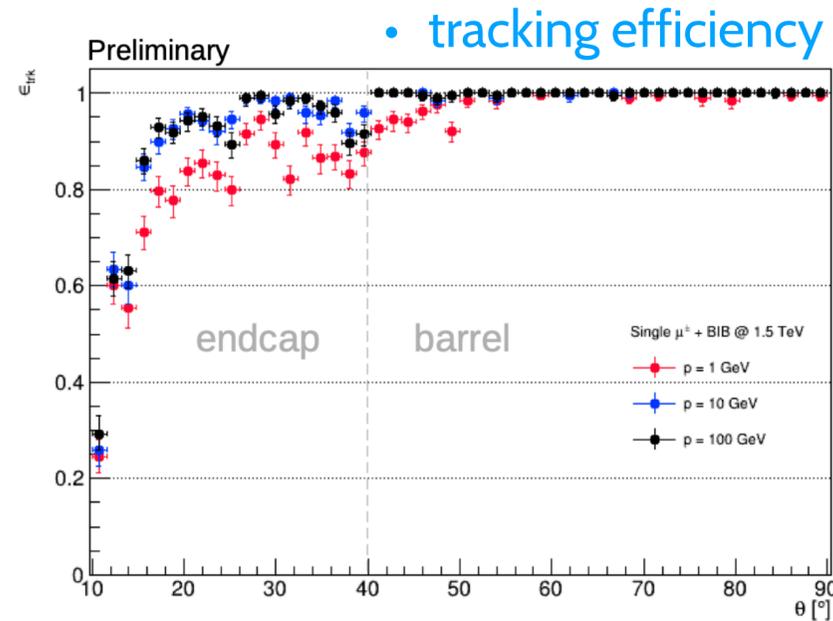
Current jet reconstruction strategy done in 3 stages:
to cope with combinatorics of track reconstruction

Further improvements under study:

- multivariate BIB subtraction optimisations
- particle-flow algorithm tuning



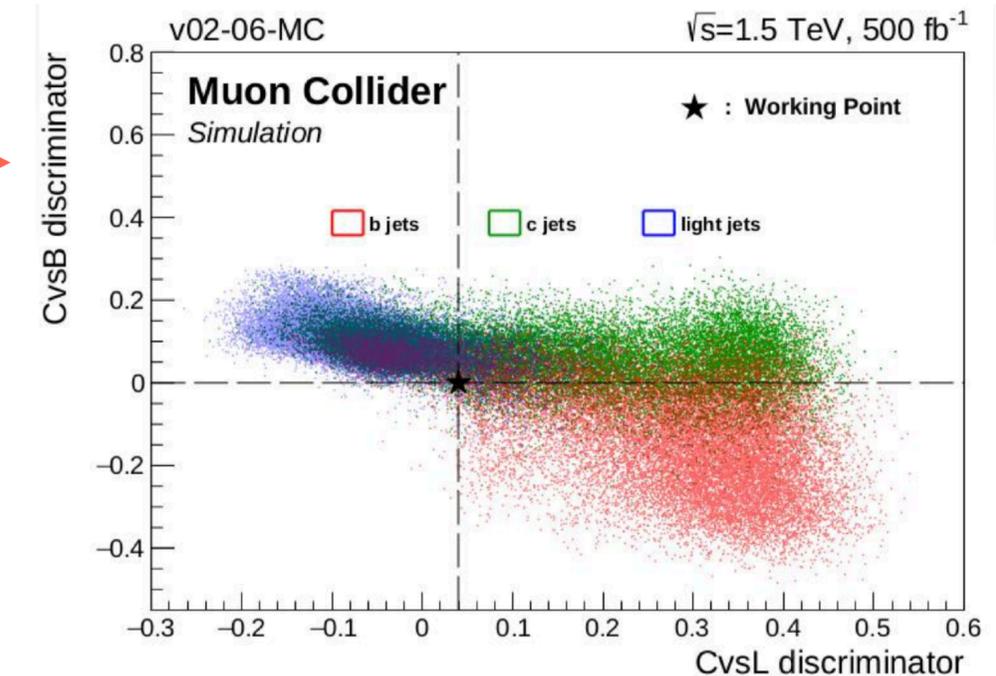
Overall good detector performance achieved at the current stage of the simulation/analysis workflow



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 $\mu^+\mu^- \rightarrow H \rightarrow bb \nu\nu \mid cc \nu\nu \mid ZZ^* \rightarrow 4\mu$ *see talk by R. Venditti*
- 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



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, ...

Innovative and computationally efficient event-reconstruction approaches are needed some of which are being developed already now

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