Muon Collider Experiment

Fermilab Accelerator Complex Evolution (ACE) Workshop, 14-15 June 2023

Marco Valente

on behalf of the International Muon Collider Collaboration (IMCC)

Particle Physics department
TRIUMF, Canada's particle accelerator centre
marco.valente@cern.ch

Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Introduction

- A Muon Collider could **open an entire new avenue** in particle physics (both precision and high-energy!)
  - It also opens **new challenges** for accelerators and detectors (muons are unstable!).
- Talk purpose: **overview of current detector concept**, recent **simulated performance** and **new ideas**.
  - More details on physics and acceleration in other talks.
- Caveats:
  - Current **detector design far from being optimal** (still room for improvement!). But it **gives us a lower bound** on the achievable performance of a Muon Collider detector.
  - **Just a selection of results** here! For more details you can refer to arXiv:2303.08533, arXiv:2201.07895 and arXiv:2203.07964

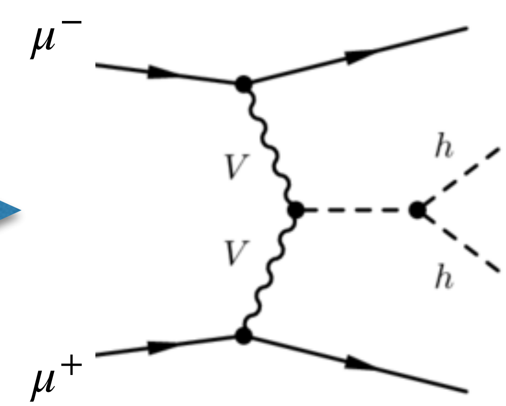
Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Muon collisions

From collision environment to detector concept

- **To define a suitable detector** and evaluate its performance, first we **need to understand**:
  1. What is the physics target and the collision $\sqrt{s}$?

$\sqrt{s} = 10$ TeV good benchmark for physics (including first stage @ 3 TeV)



VBF production becomes important (e.g. Higgs production). Need a 4π detector!

μ^- beam

μ^+ beam

Muon collisions

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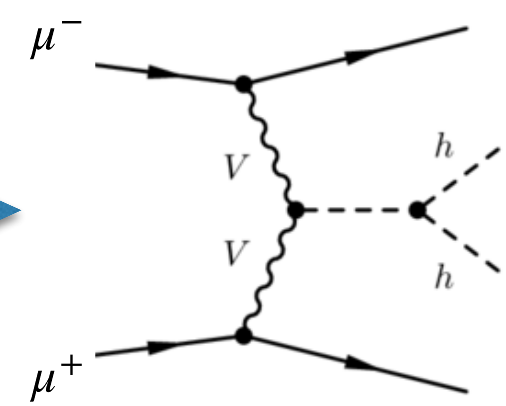

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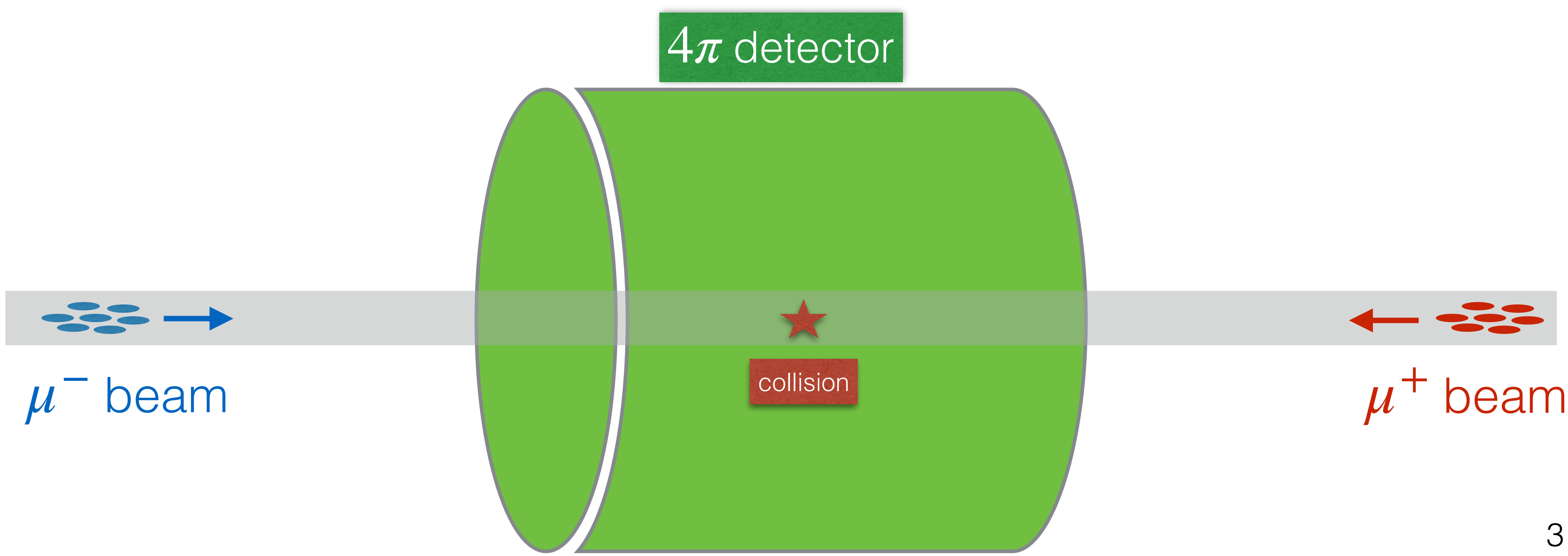

Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

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TRIUMF, Canada's particle accelerator Centre

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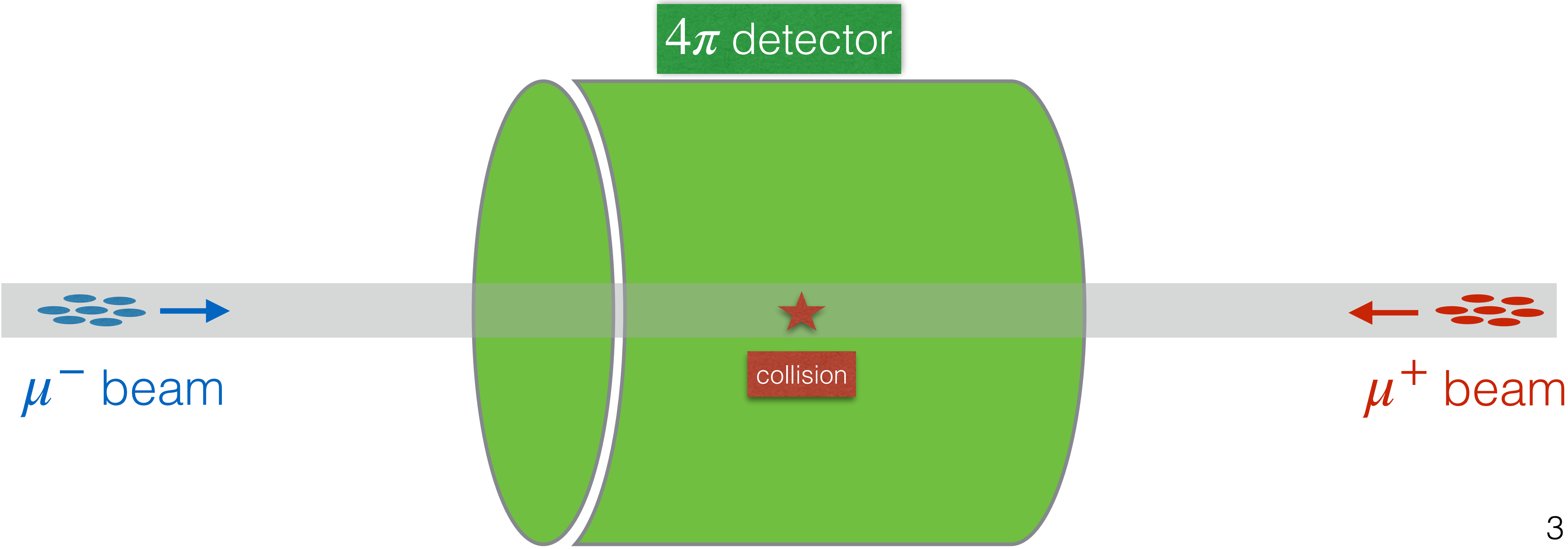


Muon collisions

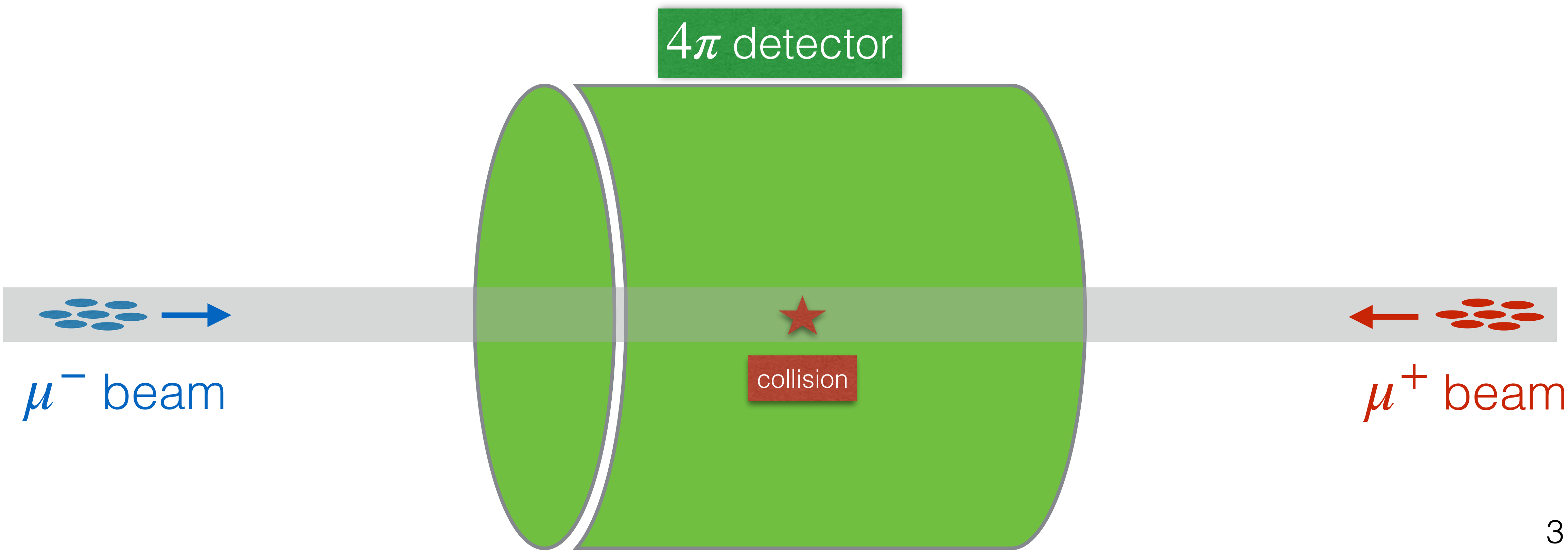
From collision environment to detector concept

- **To define a suitable detector** and evaluate its performance, first we **need to understand**:
    1. What is the physics target and the collision $\sqrt{s}$?
    2. Collision rate f?

$$f = c/L = 30 \text{ kHz} \times \left(\frac{10 \text{ km}}{L}\right)$$

$$\xrightarrow{L = 3\,km} \quad f \leq 100 \text{ kHz}$$

LHC much larger than this! Might need a software-based trigger, but we can do it!



Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Muon collisions

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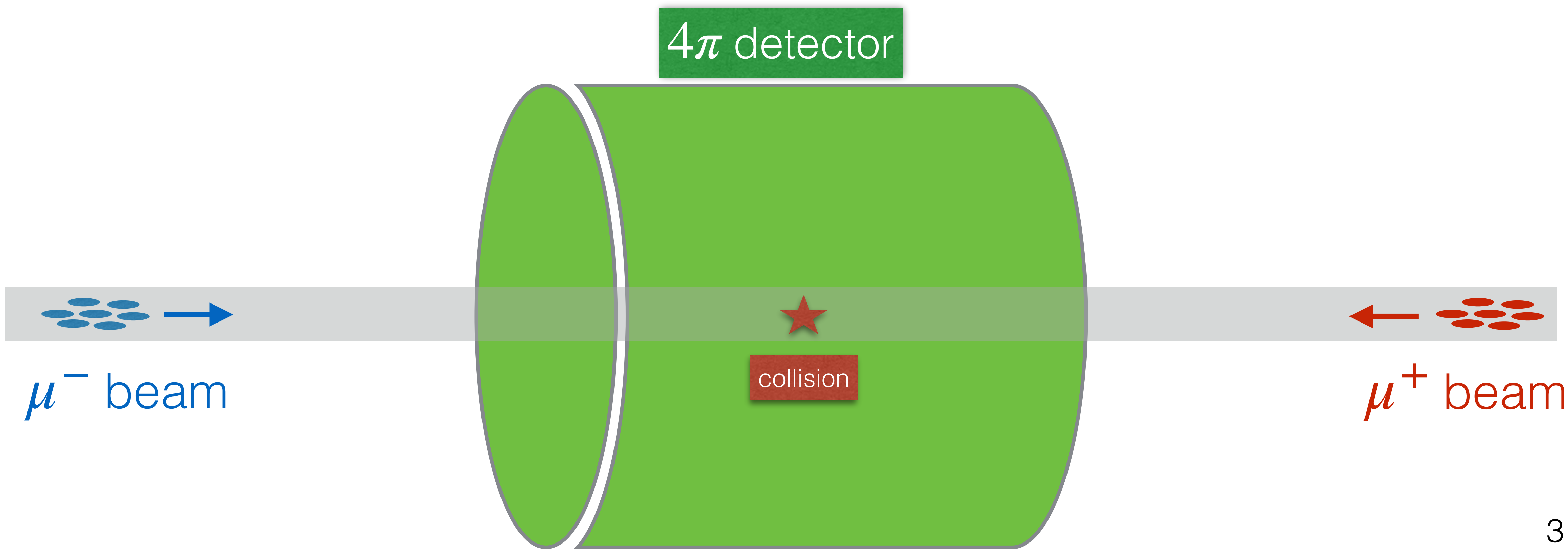
  3. How do these collisions look like? Are they clean like e^+e^-?



Muon collisions

From collision environment to detector concept

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$$f = c/L = 30\text{ kHz} \times \left(\frac{10\text{ km}}{L}\right) \xrightarrow{L=3\,km} \Rightarrow f \leq 100\text{ kHz}$$

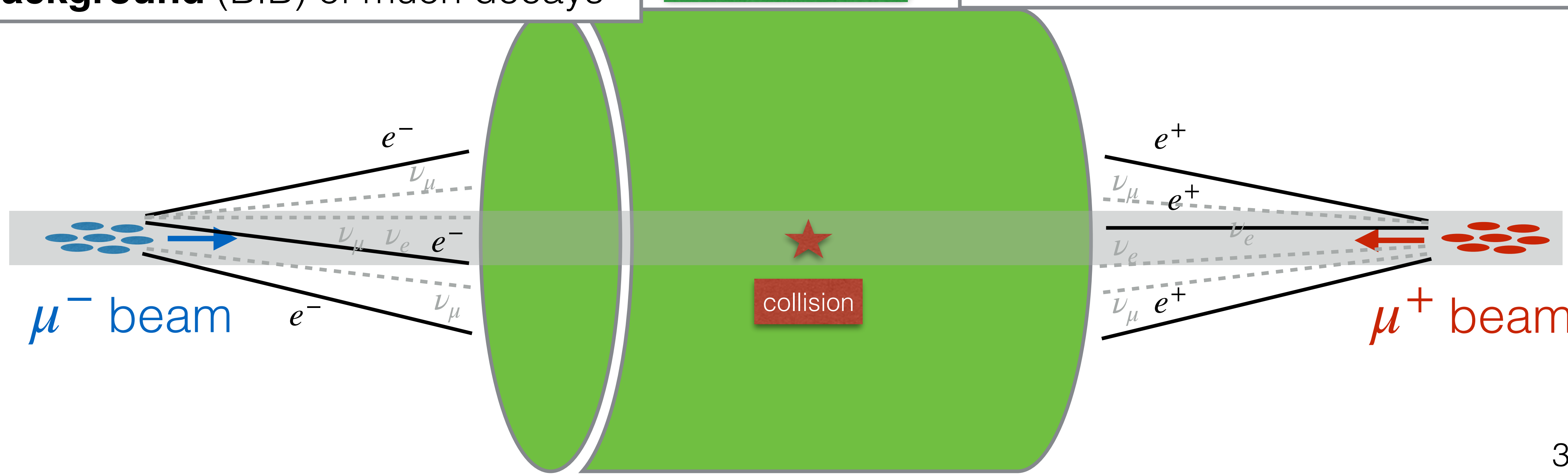
LHC much larger than this! Might need a software-based trigger, but we can do it!

  3. How do these collisions look like? Are they clean like e^+e^-?

No! Large noise from **Beam Induced Background** (BIB) of muon decays

4π detector

$O(10^5)$ muon decays/bunch/meter (decreases with energy!)



Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

A shield for our detector

The nozzles

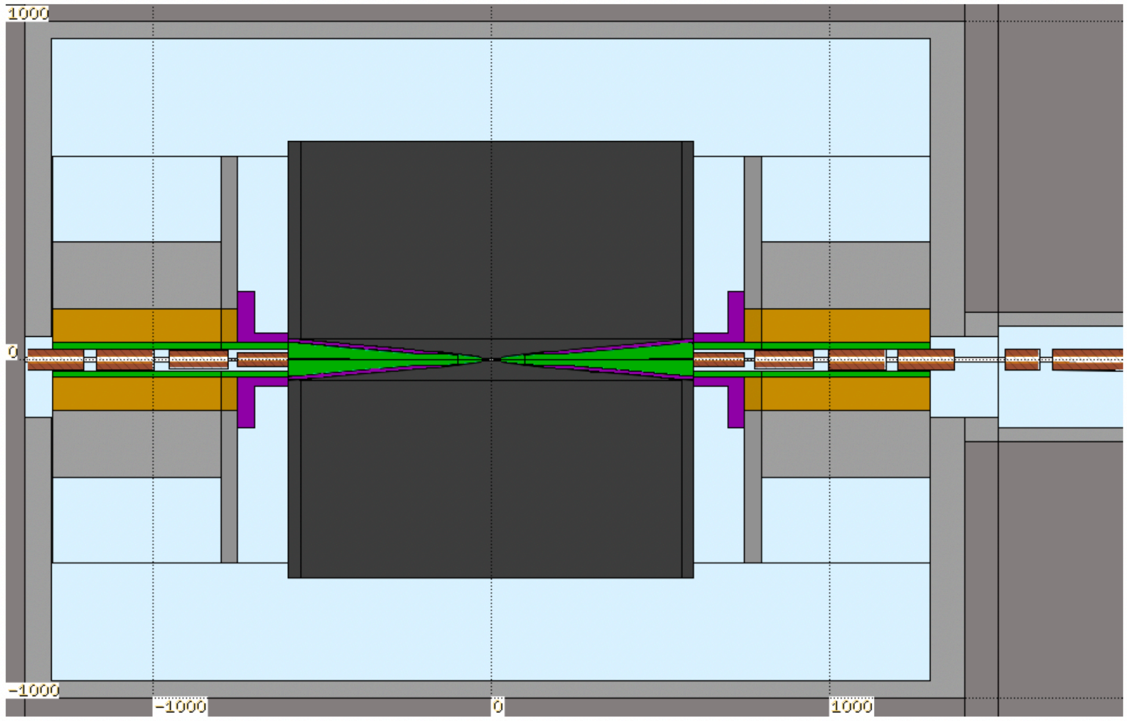
- We need a **standard** 4π **detector** (silicon tracker, calorimeters, muon chambers) with **additional shielding** for BIB.
  - Adaptation of CLIC detector with **tungsten-based nozzles for shielding.**

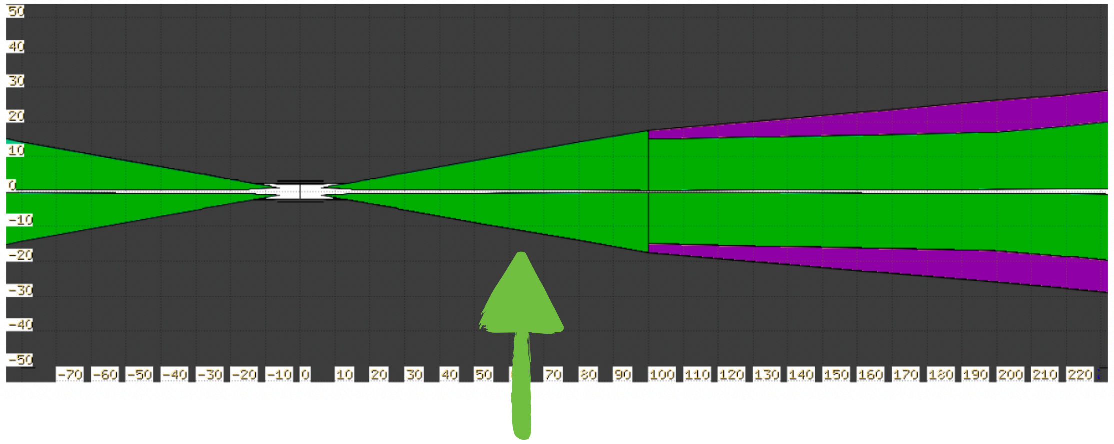
Very effective at mitigating high-energy BIB (> 1 GeV): **3 orders of magnitude reduction**

- Current nozzles design optimised for $\sqrt{s} = 1.5$ TeV

Still room to improve BIB reduction with nozzles optimised for $\sqrt{s} = 3, 10$ TeV

arXiv:1204.6721





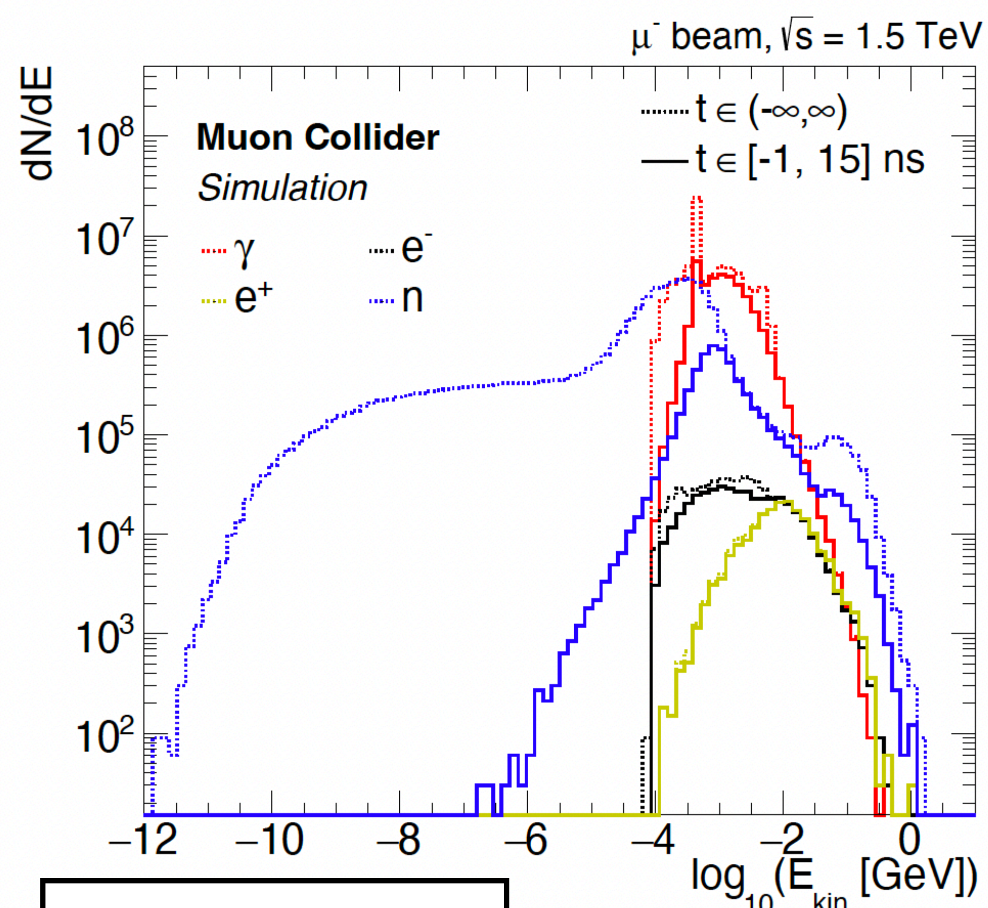
Located at 6-600 cm from the Interaction Point (IP)

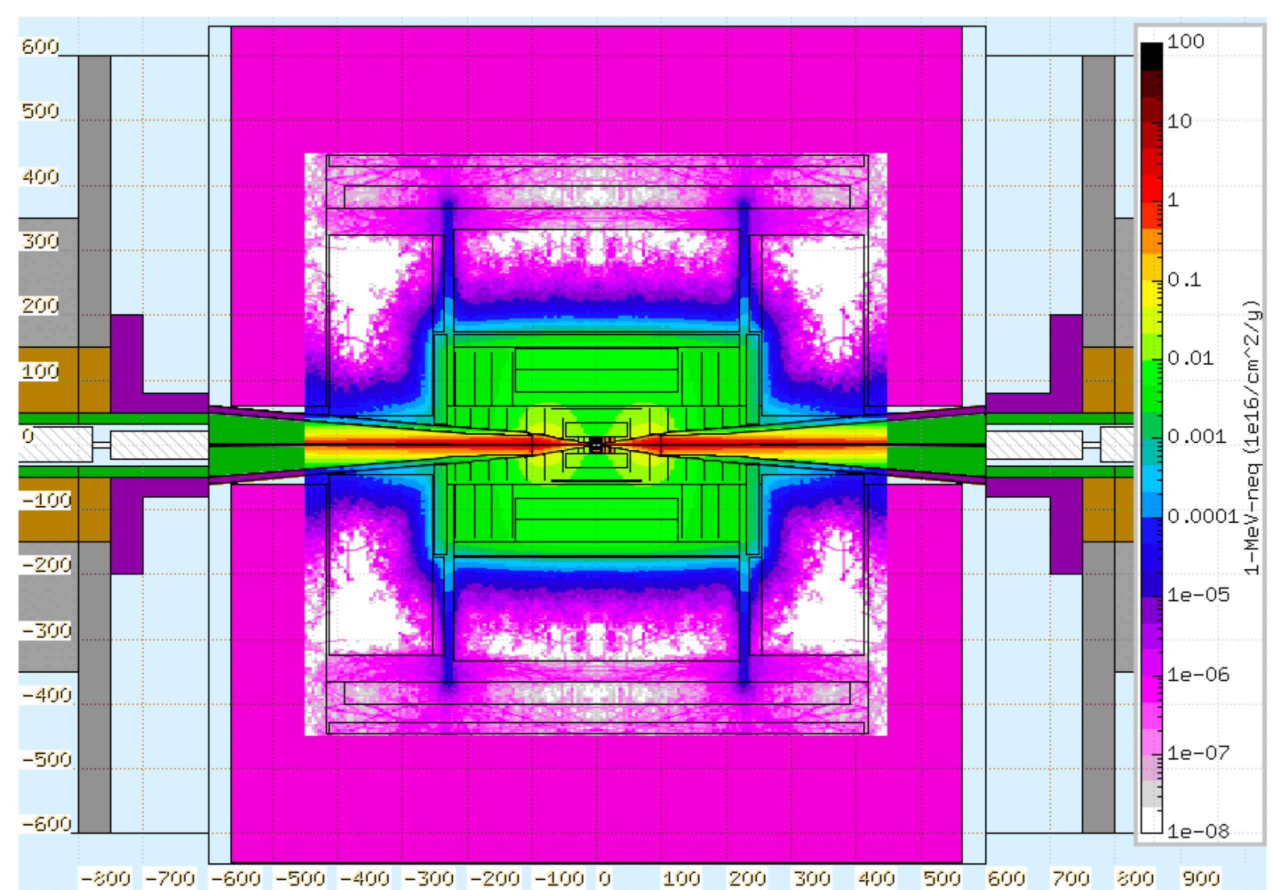
Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Are the nozzles sufficient?

BIB after shielding

- Even with nozzles, **large number of low-energy particles** will enter the detector:
  - Contamination **dominated by low-energy photons** with $\langle E_\gamma \rangle \sim 1$ MeV.
    - Especially challenging for innermost components of the detector (i.e. tracker and calorimeters).
  - Our detector needs to be able to **reject these low-energy particles**.
- Radiation doses: in the tracker 1-MeV-neq fluence is 10^{14-15}cm^{-2}y^{-1} (same ballpark as HL-LHC)





arXiv:2303.08533

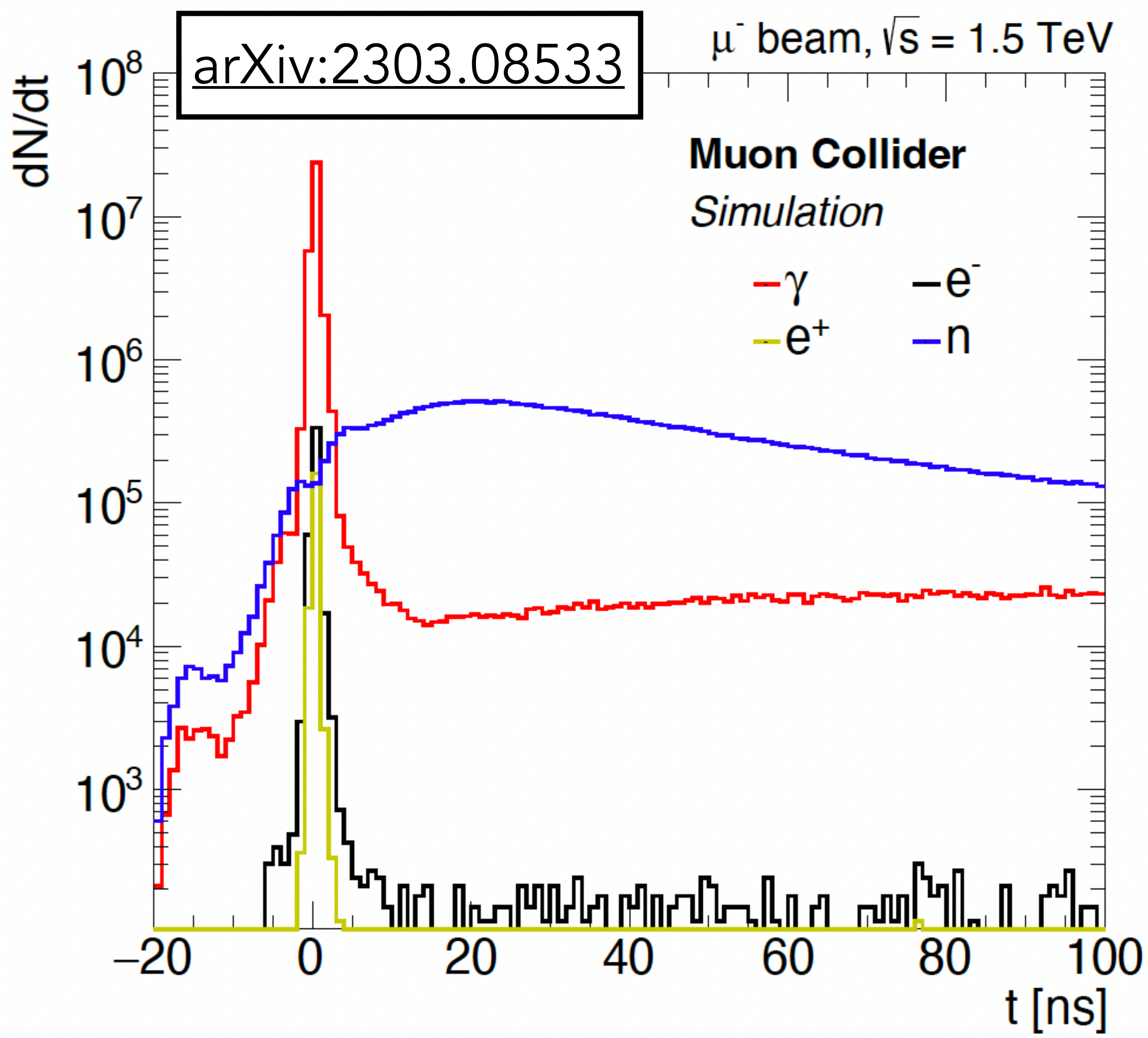
Residual BIB features

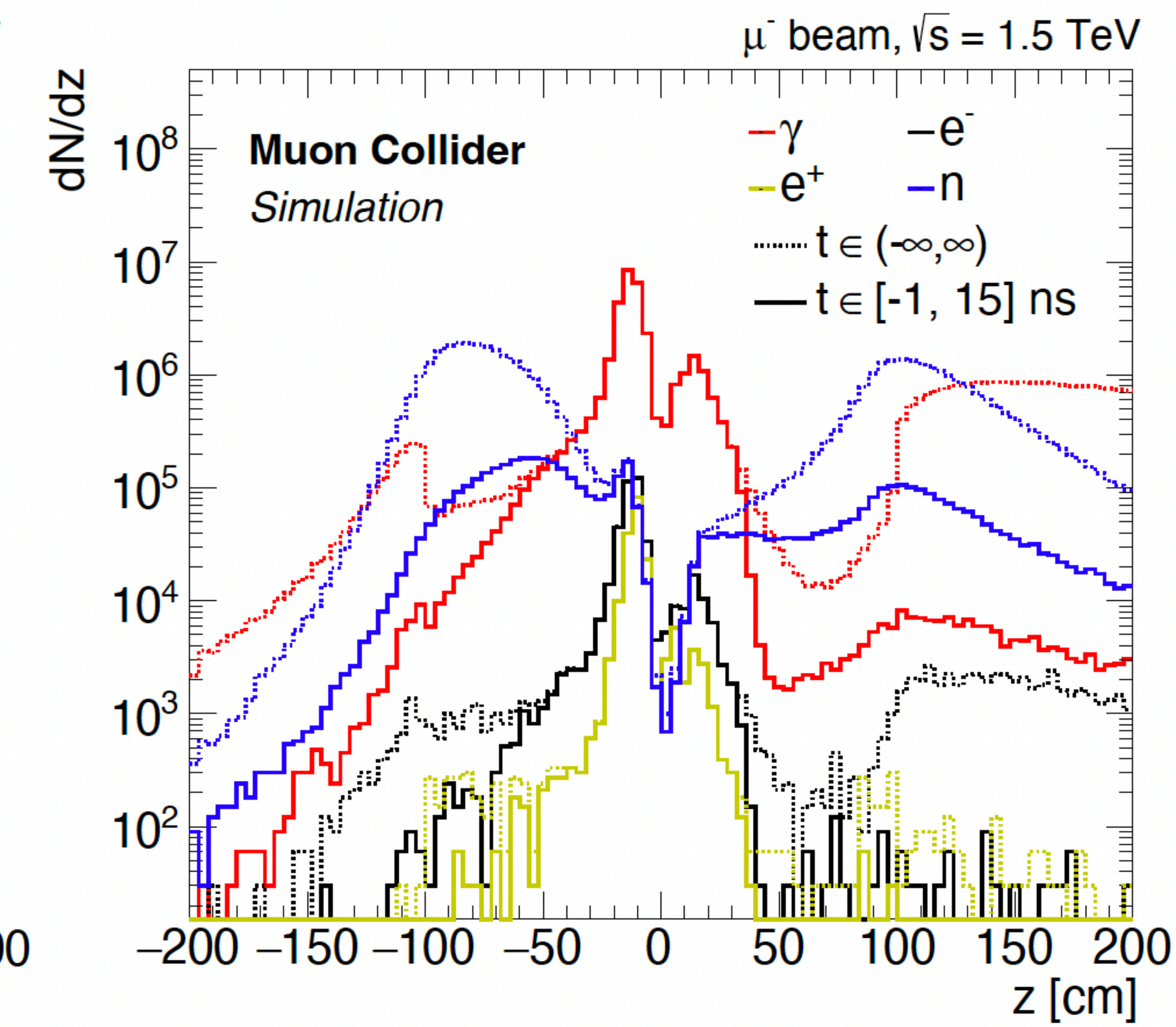
5D detectors!

- To obtain optimal physics performance we will need to to reject these soft particles.
  - Not only low energy! Residual **BIB very out of time and far away from interaction point**!

A good detector for the Muon Collider would need excellent energy, time and space resolutions (**5D detectors**!)

arXiv:2303.08533





Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Can we build a detector that can deal with this environment?

How good would the final reconstruction performance be?

Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

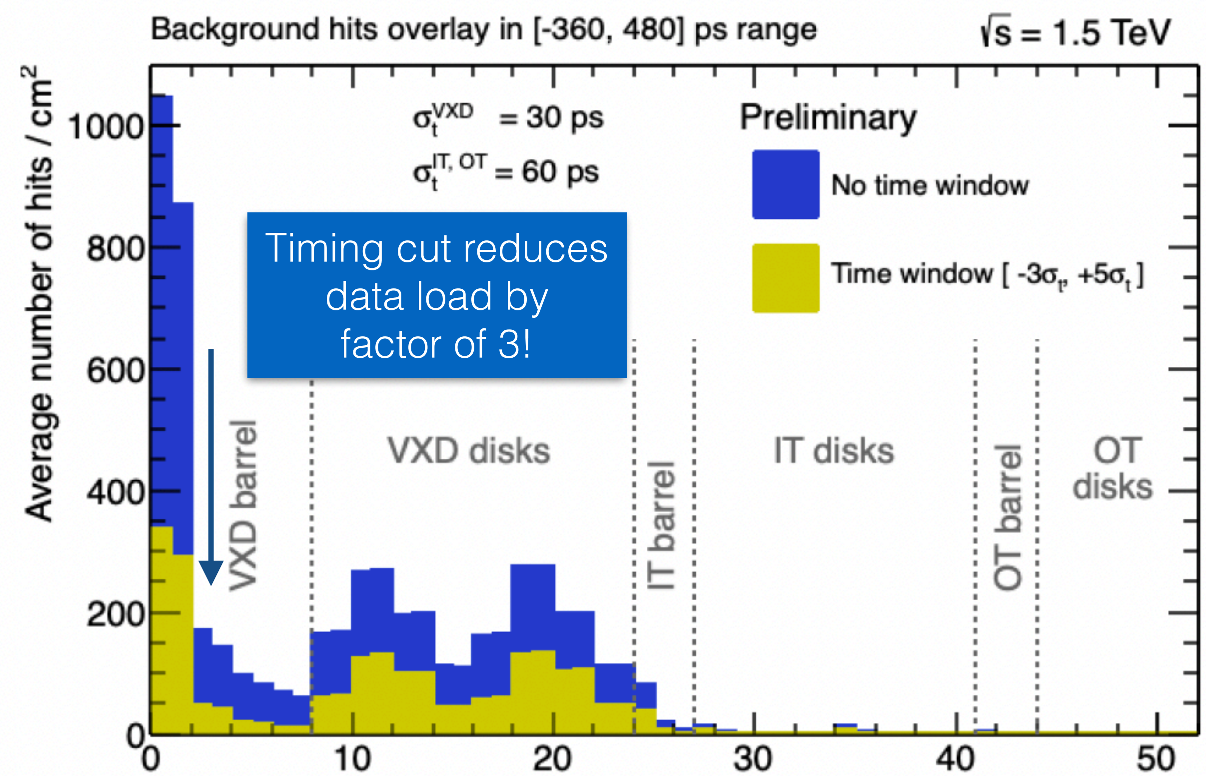
Tracking

From hits to particles

arXiv:2303.08533

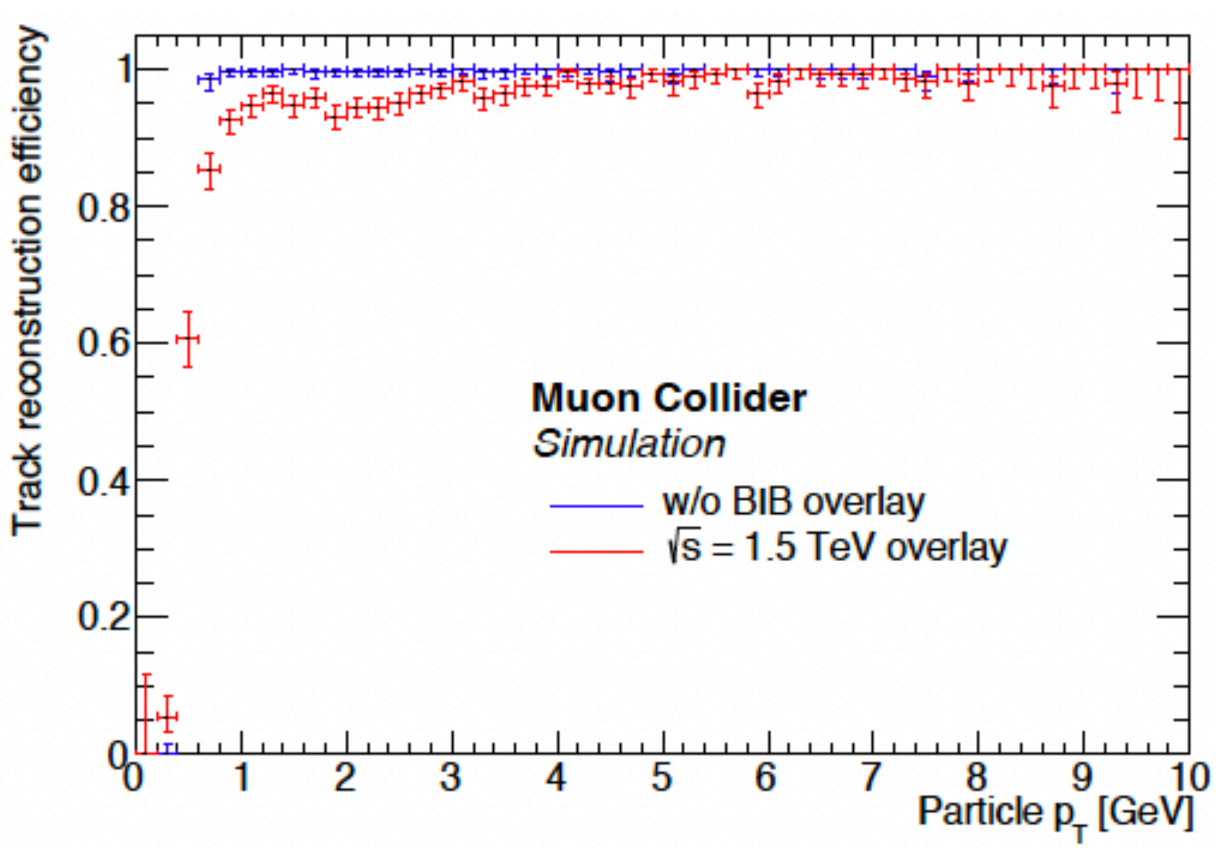
- Tracking certainly the **biggest challenge:**
  - **Large hit occupancy** (1000 hits/cm2) implies high data volumes, large combinatorics.
- For 1% hit occupancy goal will need **high granularity silicon detector with timing capabilities**:
  - Optimal configuration found for pixels of size 25x25 μm^2 (σ_t = 30ps), 50x100 μm^2 (σ_t =60ps) and strips of 50μm x 10mm (σ_t = 60ps).
  - **Promising R&D technologies**: hybrids, monolitic CMOS, LGADs, and more…

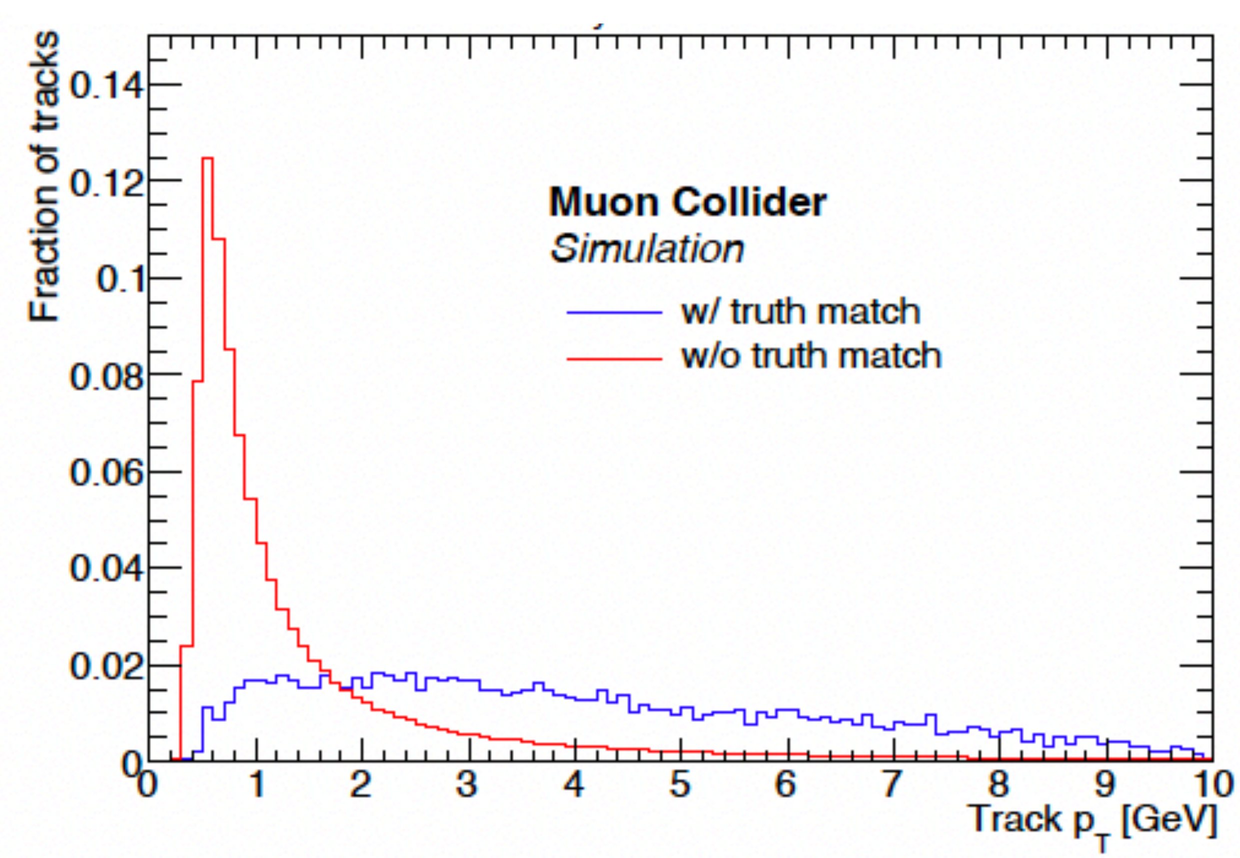
10x more hits than HL-LHC!



Tracking reconstruction

- Recently also benefits from **common tracking libraries** (**ACTS**, arXiv2106.13593) designed for LHC experiments and heavily optimised for efficient computing.
  - Track reconstruction time reduced from several days/event to **4 min/event with Combinatorial Kalman Filter**!
  - **>95% efficiency achieved for $p_T > 1$ GeV** in BIB environment. **100k fakes** at low p_T can be largely reduced **through quality handles** (e.g. track number of hits)
- And this using ACTS **without optimization for Muon Collider detector**! More to gain!





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Marco Valente
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TRIUMF, Canada's particle accelerator Centre

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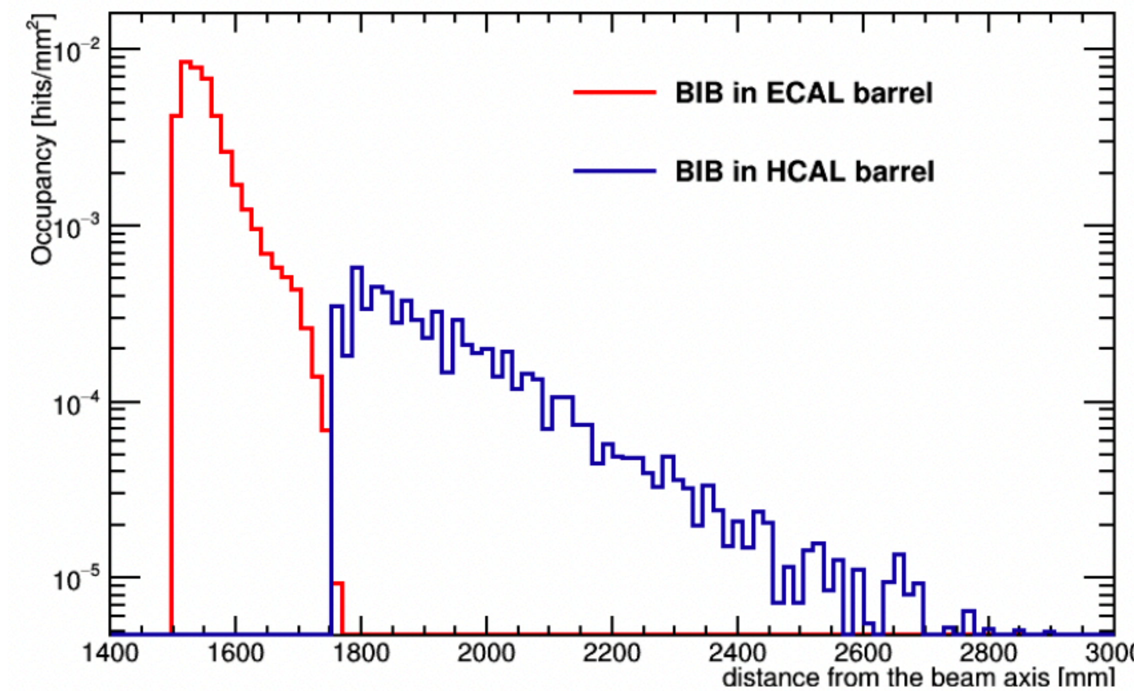
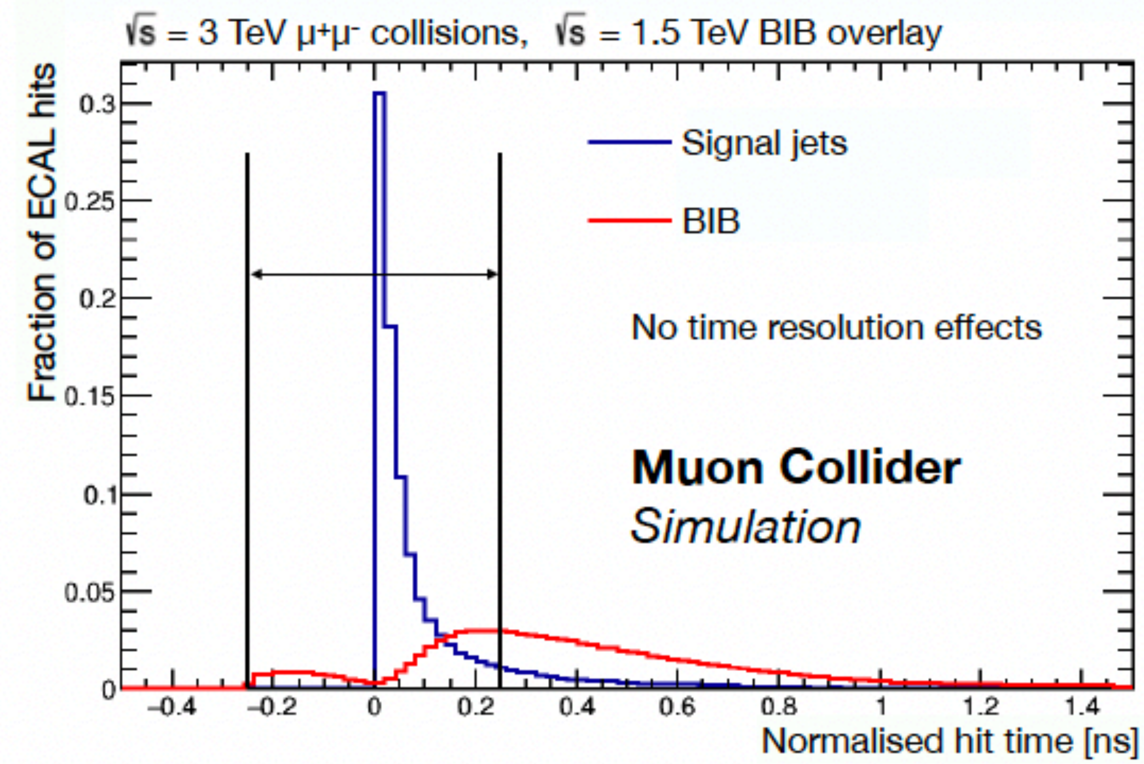
Calorimeters

- **BIB particularly affects first layers** of calorimeters
- Need calorimeter with:
    - **High granularity** (less overlapping particles in the innermost layers).
    - Good **timing resolution** (100 ps).

± 250 ns window allowed to reject BIB calo hits

- Current design (CLIC):
    - ECAL: 5x5 mm^2 silicon sensor pads alternated with tungsten plates ($\sigma(E) = 10\,\% / \sqrt{E}$)
    - HCAL: 30x30 mm^2 scintillating tiles alternated with steel absorbers ($\sigma(E) = 35\,\% / \sqrt{E}$)
- **Promising R&D technologies**: multi-readout, Particle Flow (CALICE) and semi-homogeneous with SiPMs readout (CRILIN)





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Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Jet reconstruction

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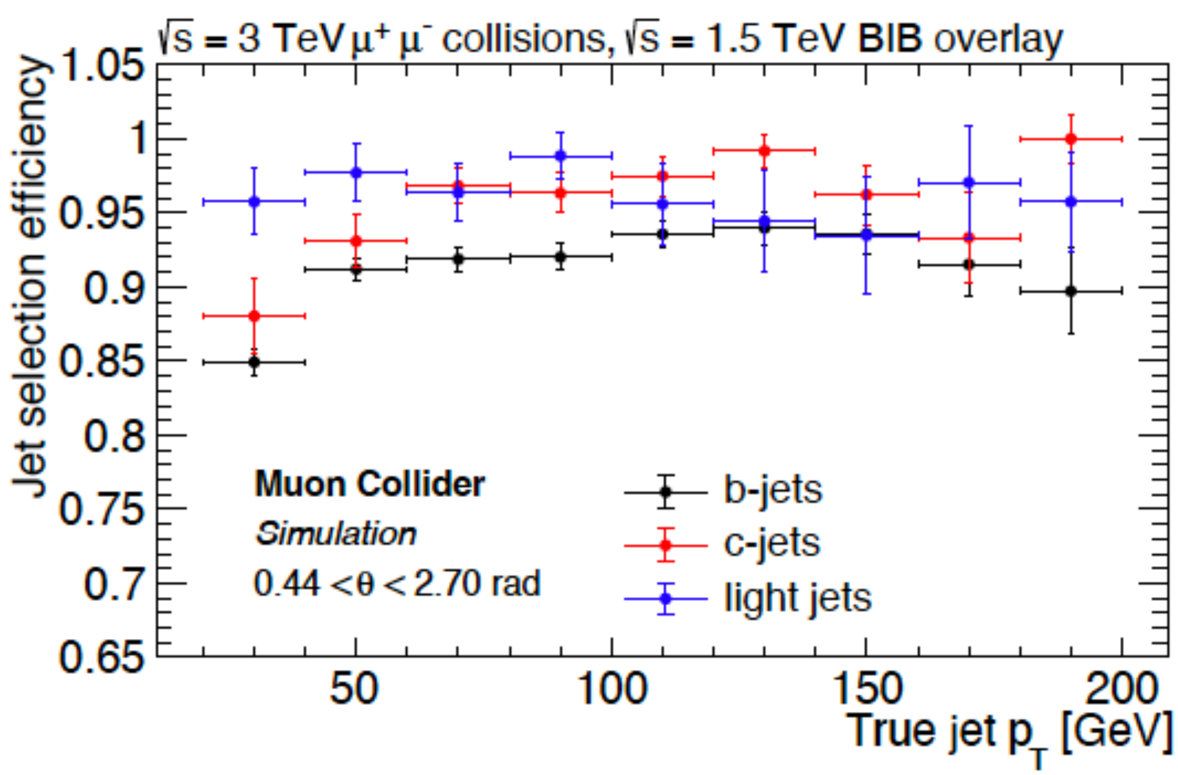
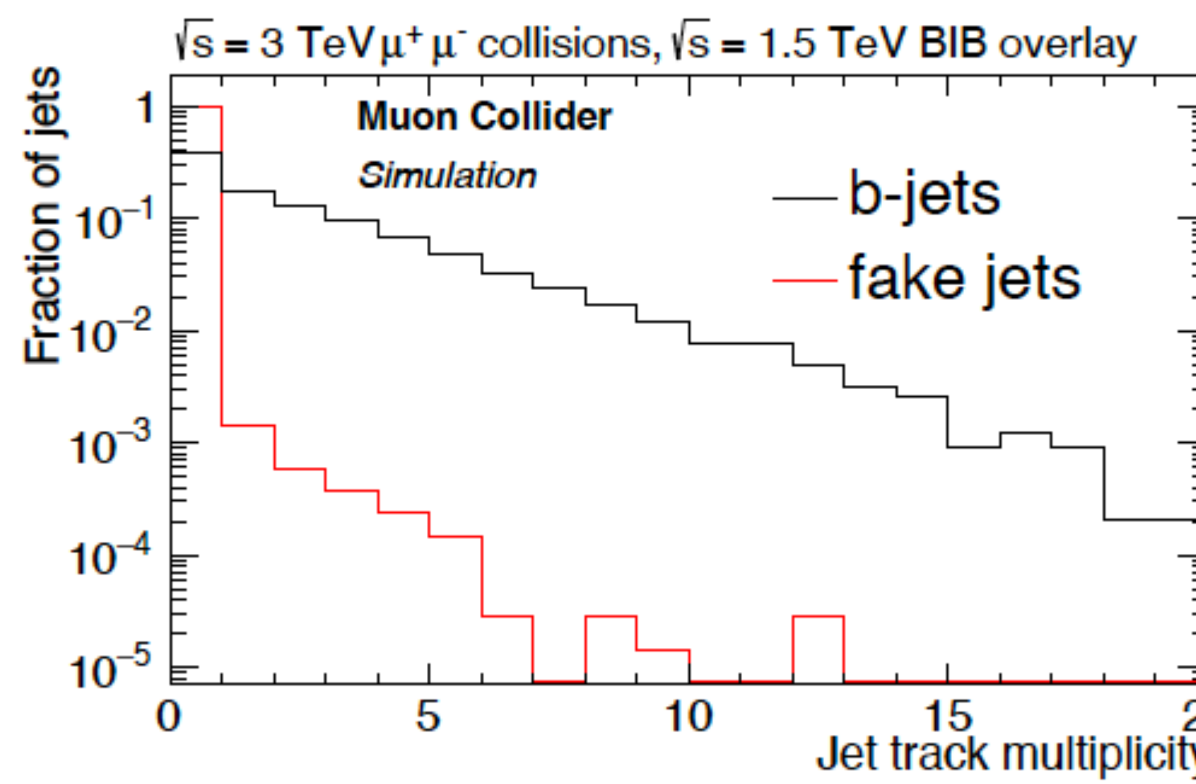
- **PandoraPFA used to combine calorimeter and tracker information** before jet building:
  - PFA outputs passed to **kT algorithm with R=0.5** to build jets.
  - After calibrations and quality selections, jet **efficiency found to be above 85%**.
  - On average **13 fake jets per event** from BIB are found!

By requiring at least 1 track per jet, **fake rate is reduced by two orders of magnitude**.



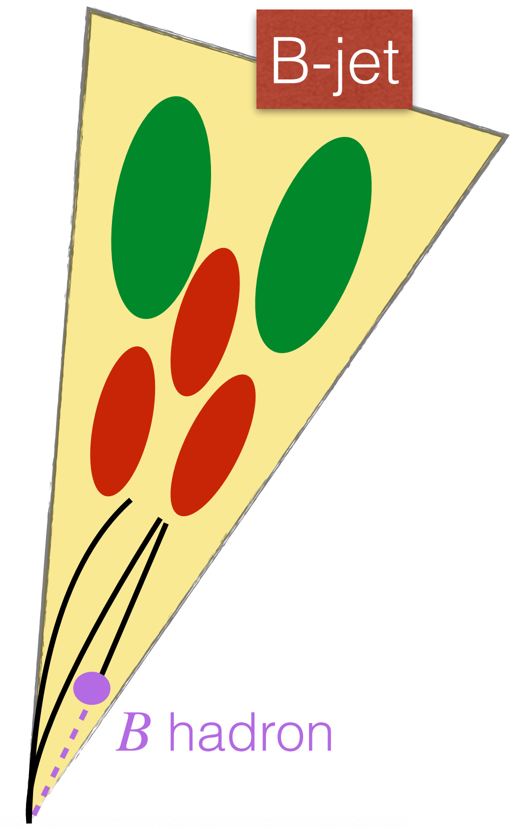


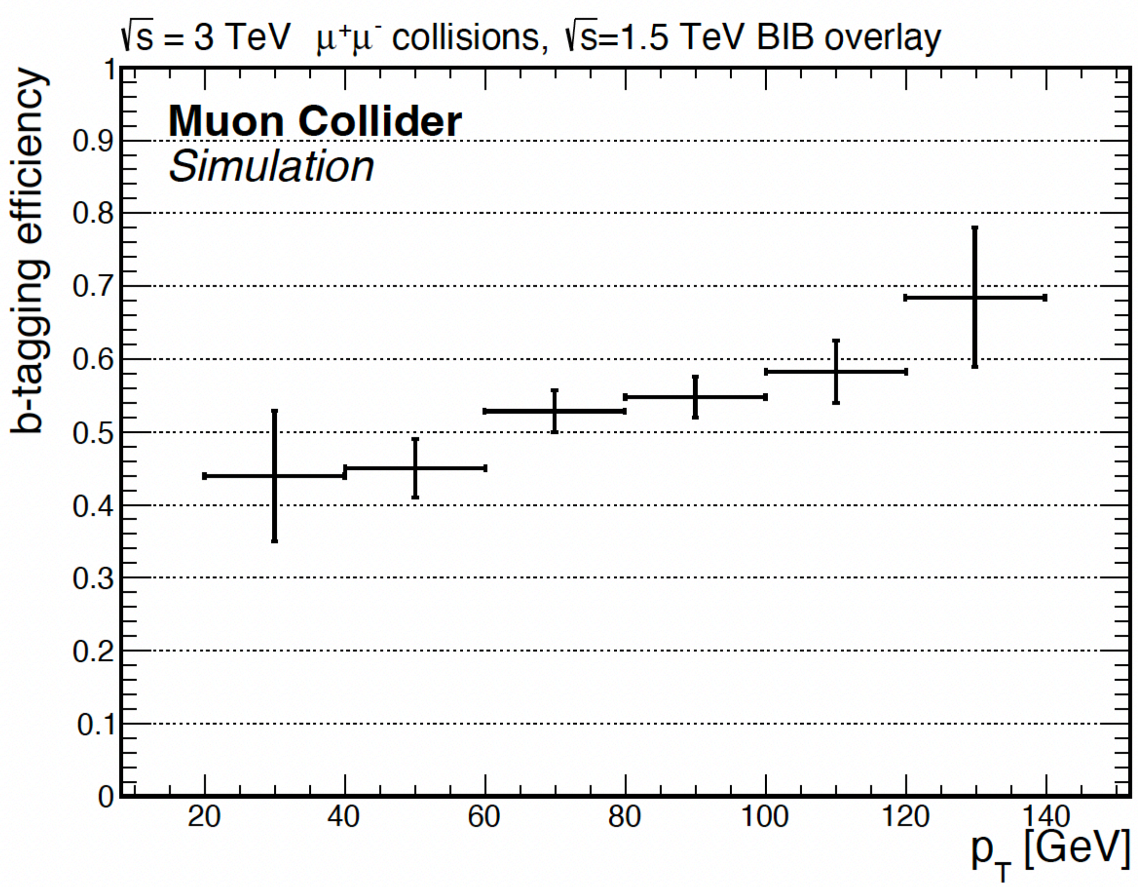
Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

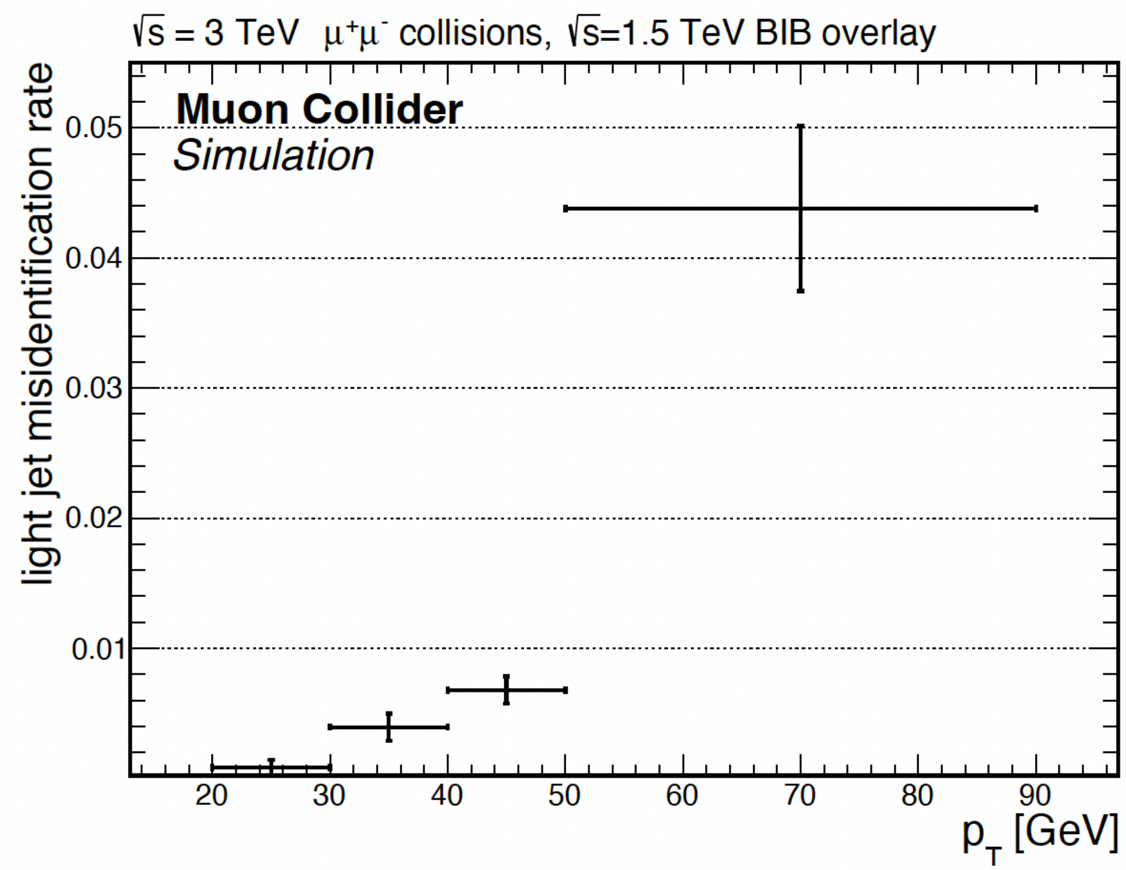
Flavour tagging

arXiv:2303.08533

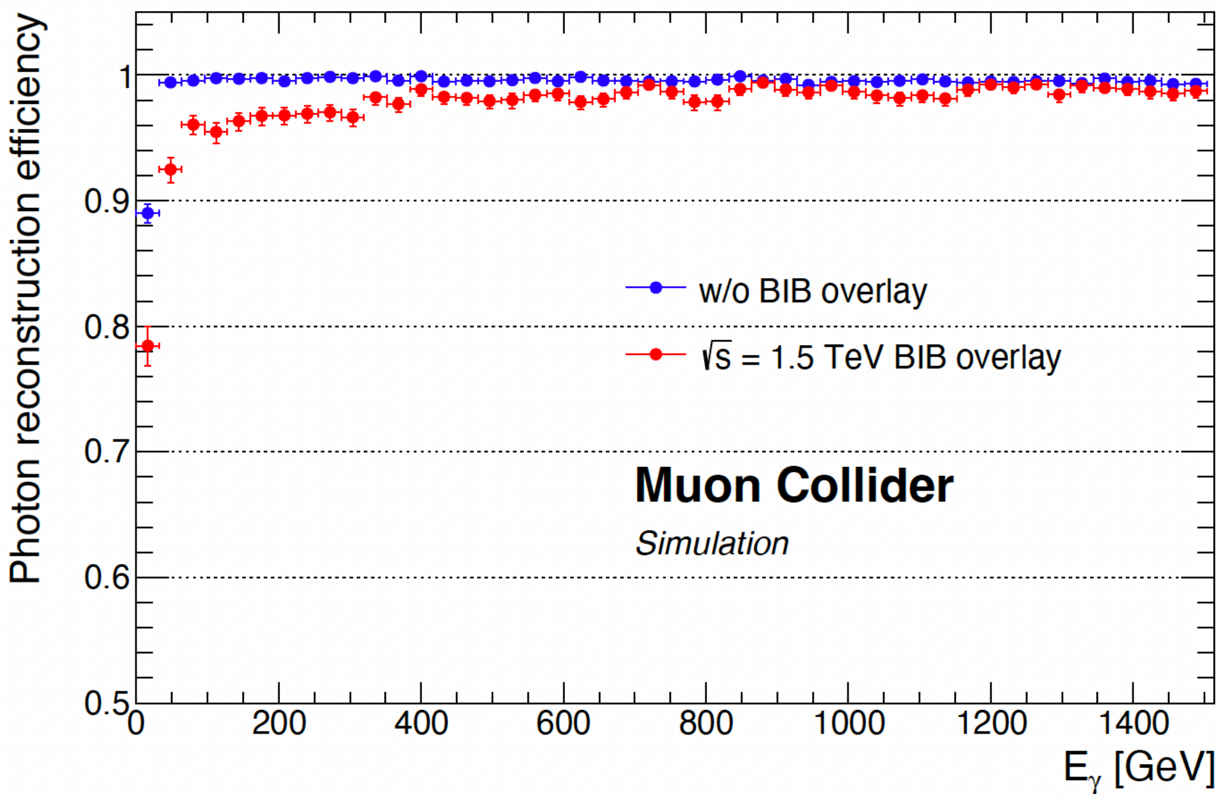
- B-jet identification very important for physics case (in particular for Higgs physics).
  - B-tagging relies on secondary vertices reconstructed through tracks not associated to the Primary vertex.
- **B-tagging efficiency found to be within 50-70%** for light-jet mis-tagging rate between 0.1% and 5%

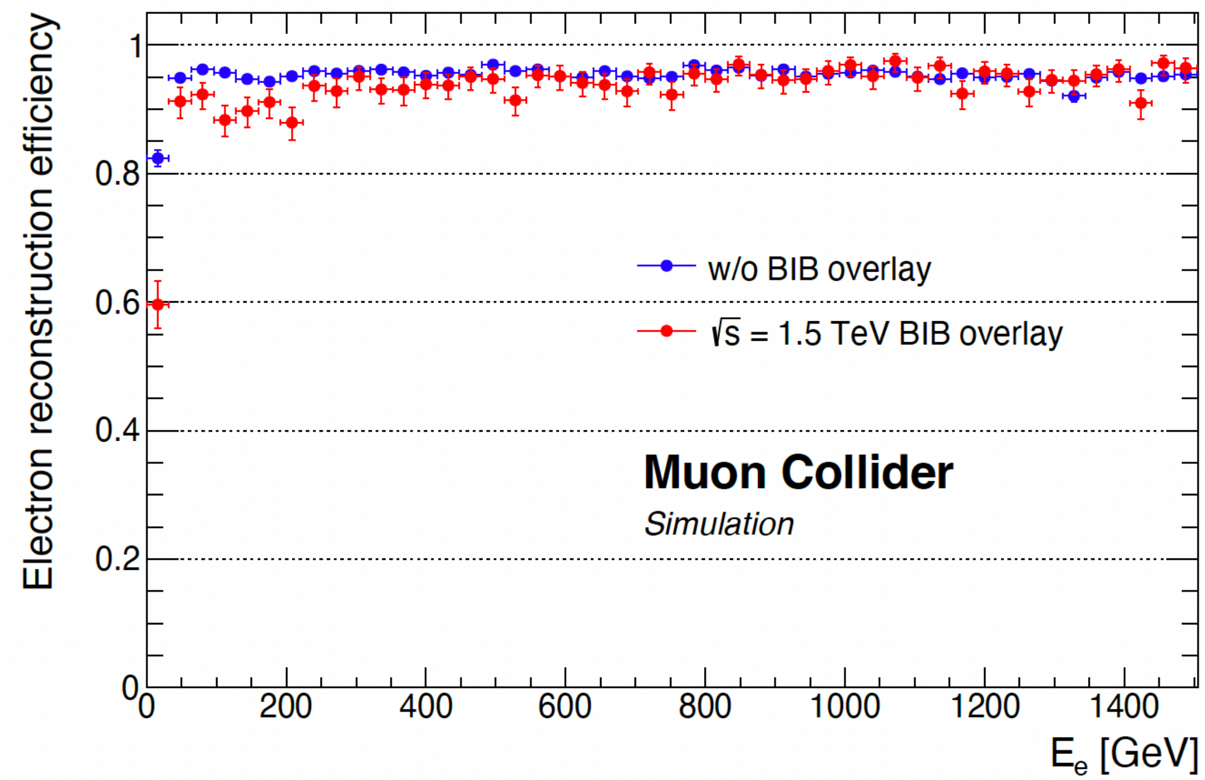




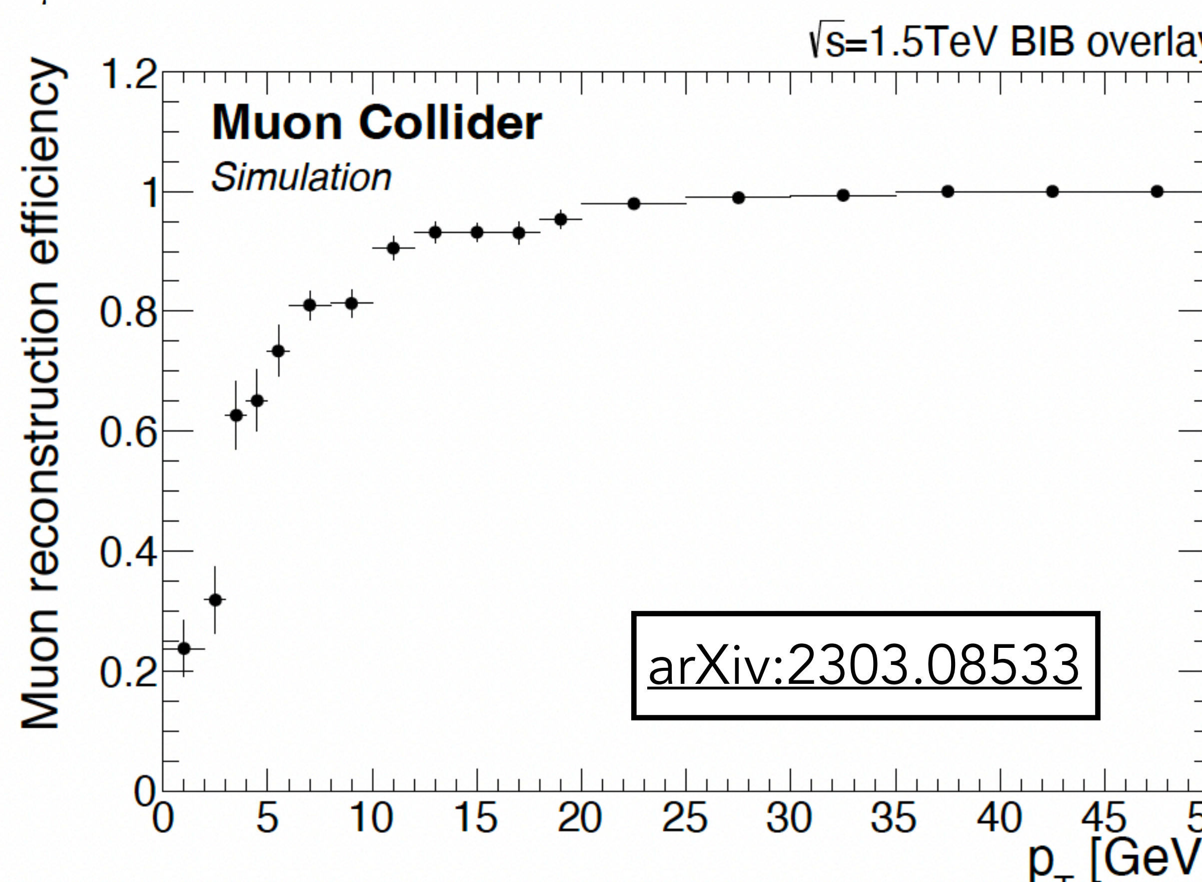


Photons, electrons and muons





Detector well capable of dealing with BIB contaminations and overall good performance observed also for electrons, photons and muons



Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Summary and outlook

- Muon colliders are one of the **most promising paths to the 10 TeV physics scale.**
  - Targeting TDR and readiness to construct in **early 2040s**.
- BIB is a big (and exciting) challenge!
  - Current detector studies based on CLIC design have shown that **it is well possible to mitigate BIB** contamination**.**
    - This will need to rely on **clever detector design** (nozzles, etc.), **cutting edge detector technologies** (5D detectors) and **modern reconstruction softwares** (ACTS, Pandora PFA, etc.).
    - **Radiation doses** in the **same order as HL-LHC**!
- **Significant detector R&D will be necessary** to achieve physics goals, but **promising technologies already exist** (LGADs, CRILIN, etc.) and synergies with other areas of HEP are well possible!
- **A lot already explored**, but a lot more **to do to reach a fully optimized detector** and reconstruction performance (more gains possible!)

Interested to join the detector studies?
Check https://muoncollider.web.cern.ch and get in touch!

Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Backup

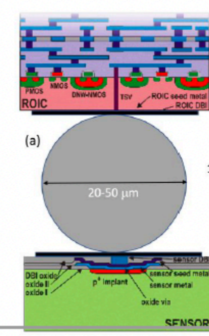
Inner tracker

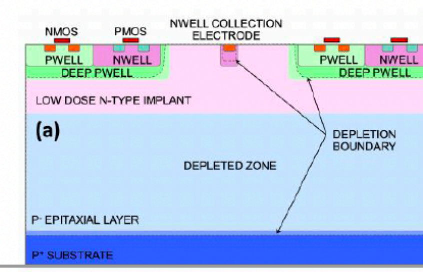
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\mu m \times 25\mu m$	$50\mu m \times 1mm$	$50\mu m \times 10mm$
Sensor Thickness	$50\mu m$	$100\mu m$	$100\mu m$
Time Resolution	30ps	60ps	60ps
Spatial Resolution	$5\mu m \times 5\mu m$	$7\mu m \times 90\mu m$	$7\mu m \times 90\mu m$

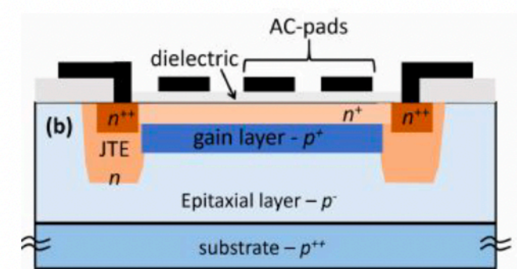
Multiple technological choices being investigated for accurate timing-aware tracking

- Hybrid pixels, CMOS-based, LGAD-based, …
- Thin sensor (layer)
- Need for powerful yet power-efficient ASICs (smaller feature size)

Synergy with HL-LHC and other projects







	Hybrid	CMOS-like	LGAD-like
Timing	–	+	+
Spatial Resolution	+	+	–/+
Radiation Hardness	+	–	–

Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

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Particle Physics department
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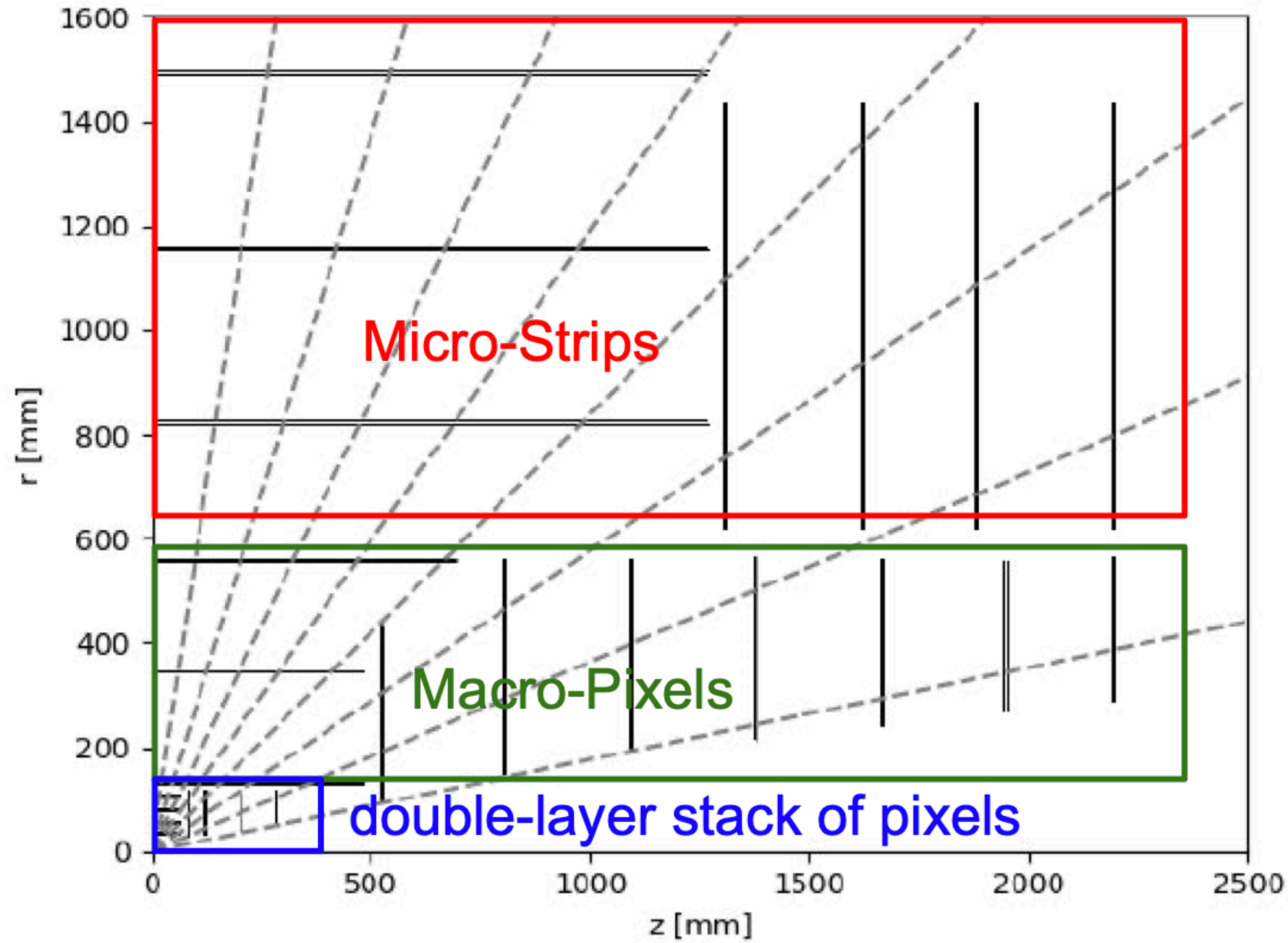
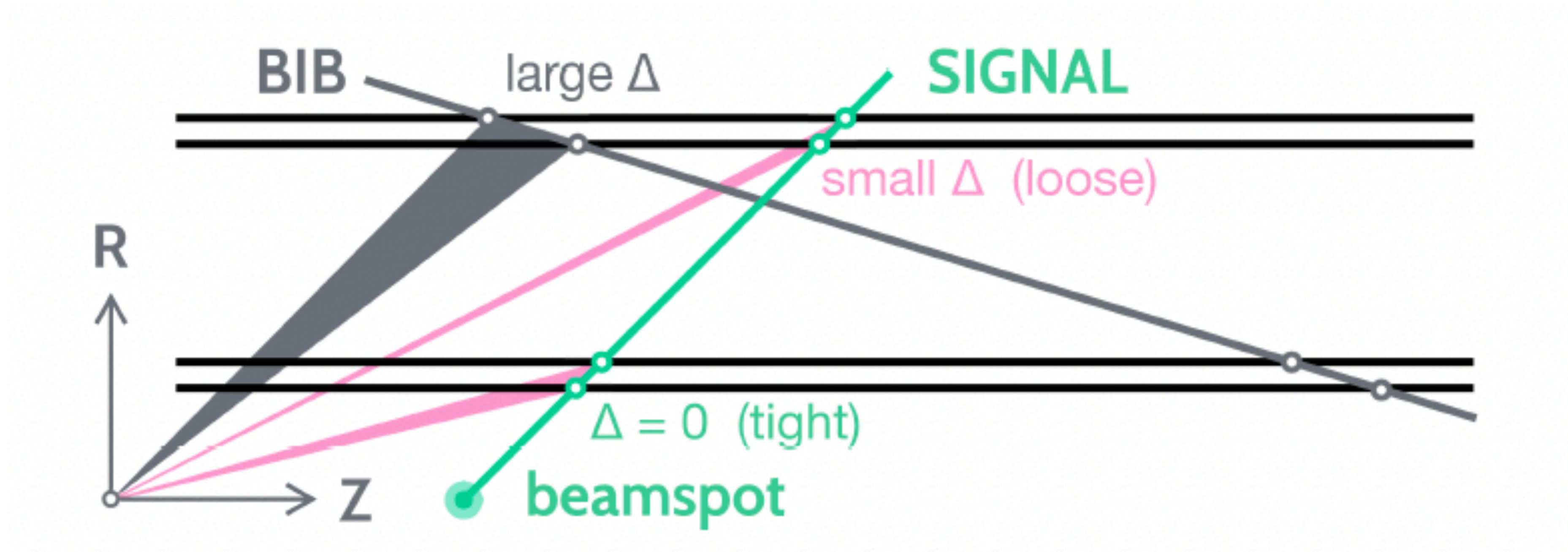
Tracker layout



Double layers tracking

arXiv:2303.08533

Double layers concept



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Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Beam Induced Background (BIB)

Table 3: Multiplicities of different types of particles after the shielding structure, therefore arriving on the detector surface. A single bunch crossing with $2 \cdot 10^{12}$ muons is considered. In all cases, the MAP 1.5 TeV collider design and optimised MDI is assumed.

Monte Carlo simulator	MARS15	MARS15	FLUKA	FLUKA	FLUKA
Beam energy [GeV]	62.5	750	750	1500	5000
μ decay length [m]	$3.9 \cdot 10^5$	$46.7 \cdot 10^5$	$46.7 \cdot 10^5$	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$51.3 \cdot 10^5$	$4.3 \cdot 10^5$	$4.3 \cdot 10^5$	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
Photons ($E_\gamma > 0.1$ MeV)	$170 \cdot 10^6$	$86 \cdot 10^6$	$51 \cdot 10^6$	$70 \cdot 10^6$	$107 \cdot 10^6$
Neutrons ($E_n > 1$ MeV)	$65 \cdot 10^6$	$76 \cdot 10^6$	$110 \cdot 10^6$	$91 \cdot 10^6$	$101 \cdot 10^6$
Electrons & positrons ($E_{e^\pm} > 0.1$ MeV)	$1.3 \cdot 10^6$	$0.75 \cdot 10^6$	$0.86 \cdot 10^6$	$1.1 \cdot 10^6$	$0.92 \cdot 10^6$
Charged hadrons ($E_{h^\pm} > 0.1$ MeV)	$0.011 \cdot 10^6$	$0.032 \cdot 10^6$	$0.017 \cdot 10^6$	$0.020 \cdot 10^6$	$0.044 \cdot 10^6$
Muons ($E_{\mu^\pm} > 0.1$ MeV)	$0.0012 \cdot 10^6$	$0.0015 \cdot 10^6$	$0.0031 \cdot 10^6$	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Radiation and fluency

- For 200 days of operation in 1 year, 1-MeV-neq fluence is expected to be 10^{14-15}cm^{-2}y^{-1} n the region of the tracking detector and of 10^{14}cm^{-2}y^{-1} in the ECAL.

- Total ionising dose in the tracker 10^{-3}Grad$/y$ and 10^{-4}Grad$/y$ in the ECAL.

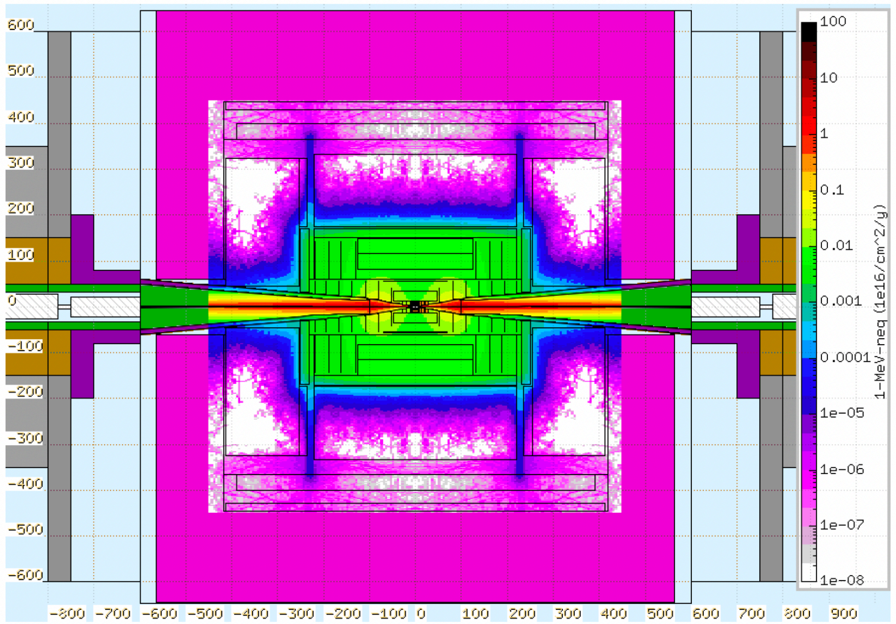

Fig. 20 Map of the 1-MeV-neq fluence in the detector region, shown as a function of the position along the beam axis and the radius. The map is normalised to one year of operation (200 days/year) and a collision rate of 100 kHz.

Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Calorimeters

- Two approaches: Particle flow and multi-readout (for reduction of statistical fluctuation component) for independent measurement of electromagnetic and hadronic component.

Charged particle reconstruction

Table 4: Comparison of the hit density in the tracking detector between a MuC with full BIB overlay, the ATLAS ITk and ALICE ITS3 upgrades for HL-LHC. The hit densities for the first and second layers of the vertex detectors are shown. The MCD hit densities are reported after timing cuts.

Detector Reference	**Hit Density** $[mm^{-2}]$ **MCD**	**ATLAS ITk**	**ALICE ITS3**
Pixel Layer 0	3.68	0.643	0.85
Pixel Layer 1	0.51	0.022	0.51

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Particle Physics department
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Charged particle reconstruction

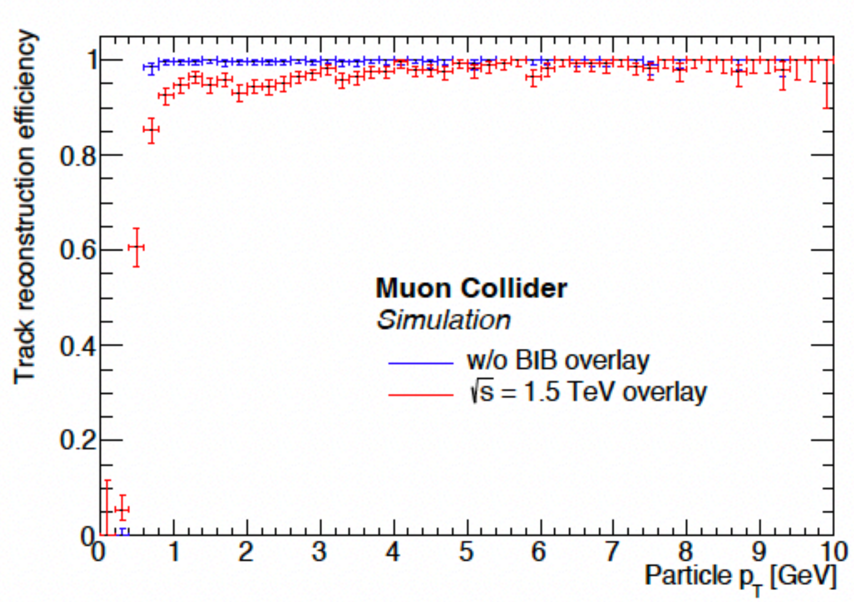


Fig. 46 Track reconstruction efficiency for events containing a single muon with (red) and without (blue) BIB overlay as a function of the true muon p_T.

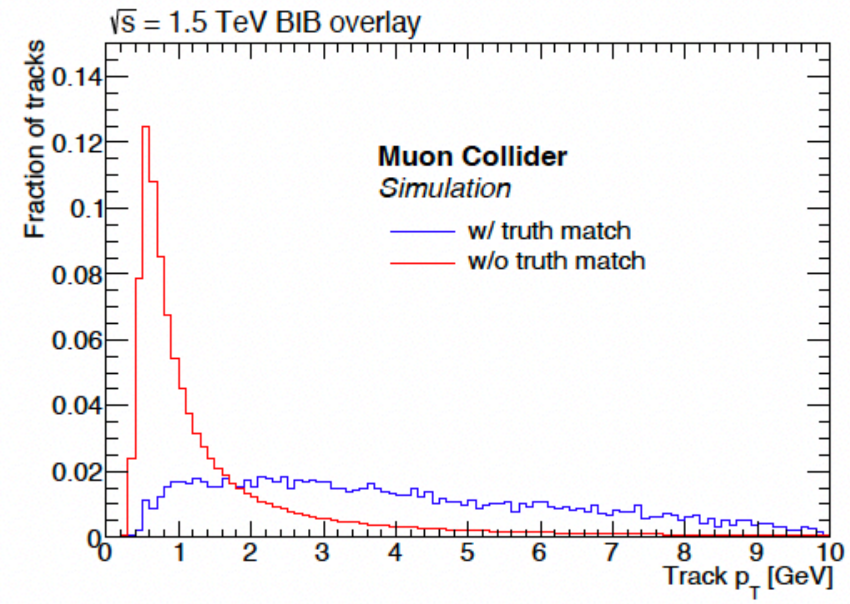


Fig. 48 Track p_T distributions for tracks with (blue) and without (red) a match to the true simulated tracks, for single muon events with BIB overlay.

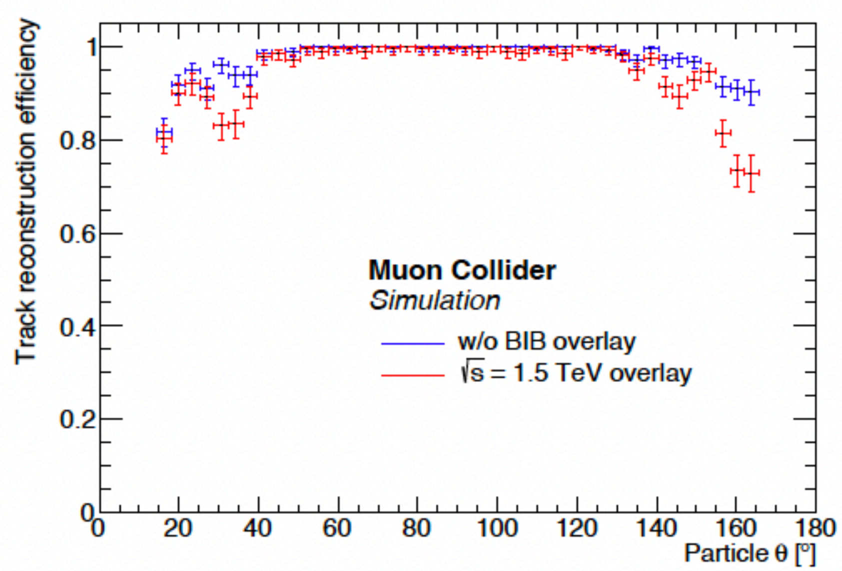


Fig. 47 Track reconstruction efficiency for events containing a single muon with (red) and without (blue) BIB overlay as a function of the true muon θ.

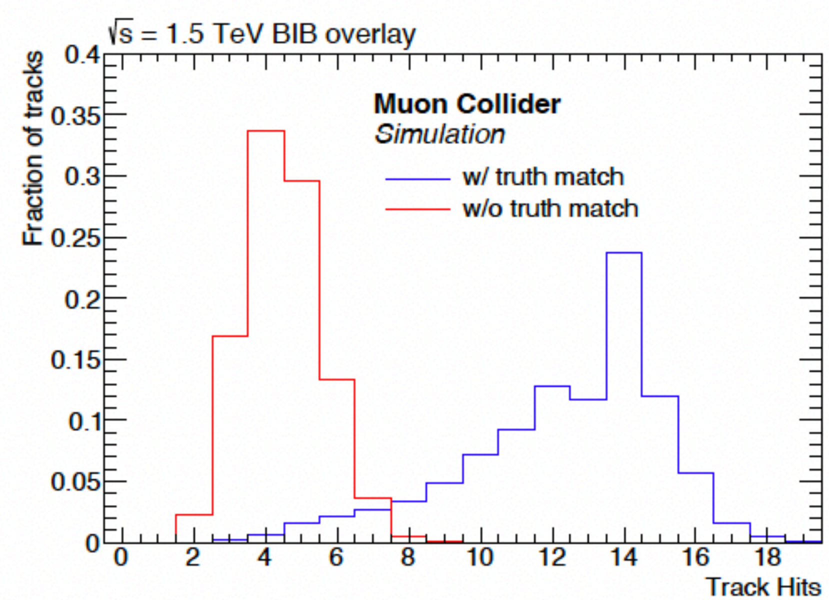
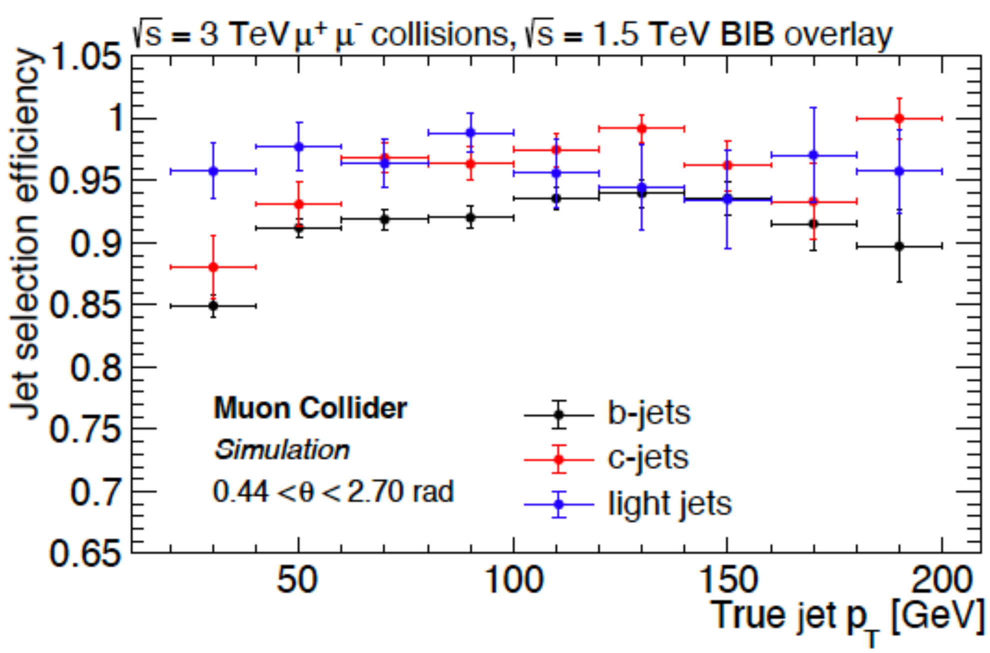


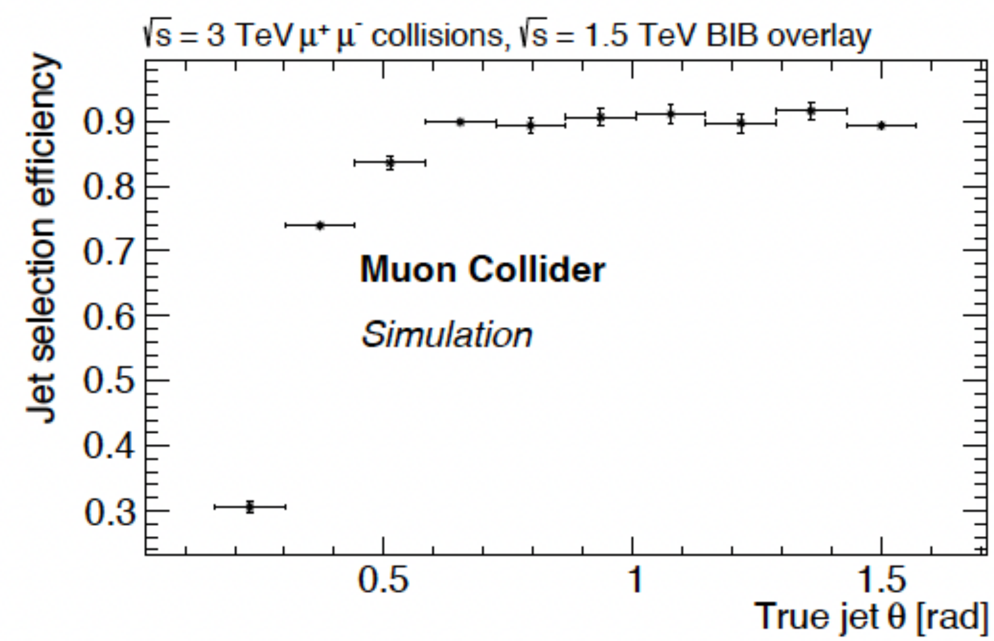
Fig. 49 Hit multiplicity $N_{\rm hit}$ distribution for tracks with (blue) and without (red) a match to the true simulated tracks, for single muon events with BIB overlay.

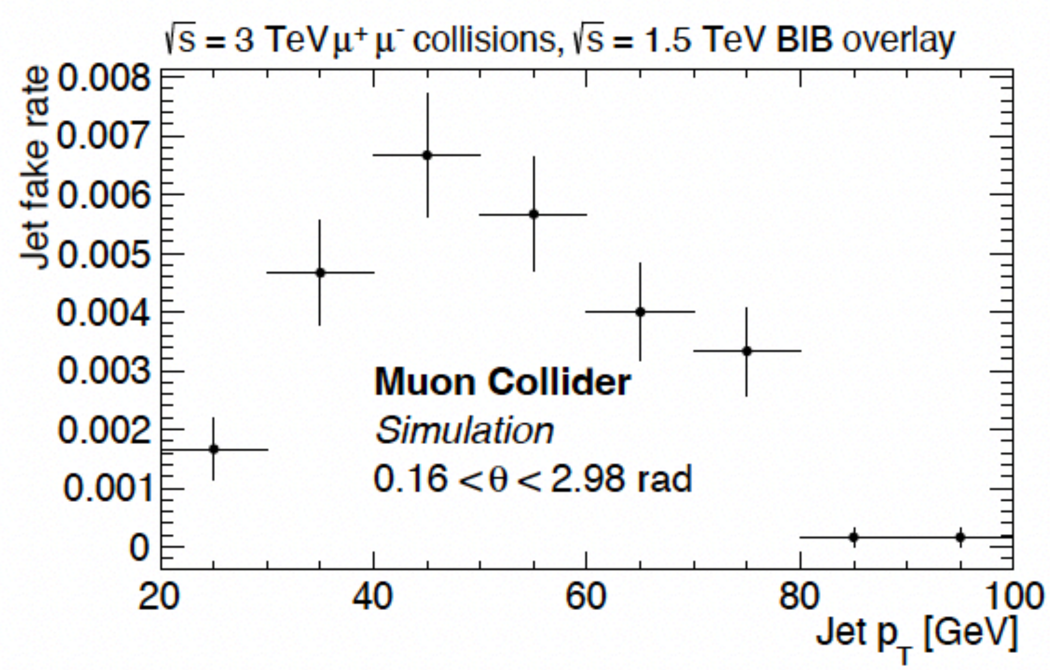
Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Jet reconstruction

- Efficiency pretty much flat in pT
- Drop in the forward region (theta < 0.5) due to requirement of at least 1 track (no tracker in forward region)



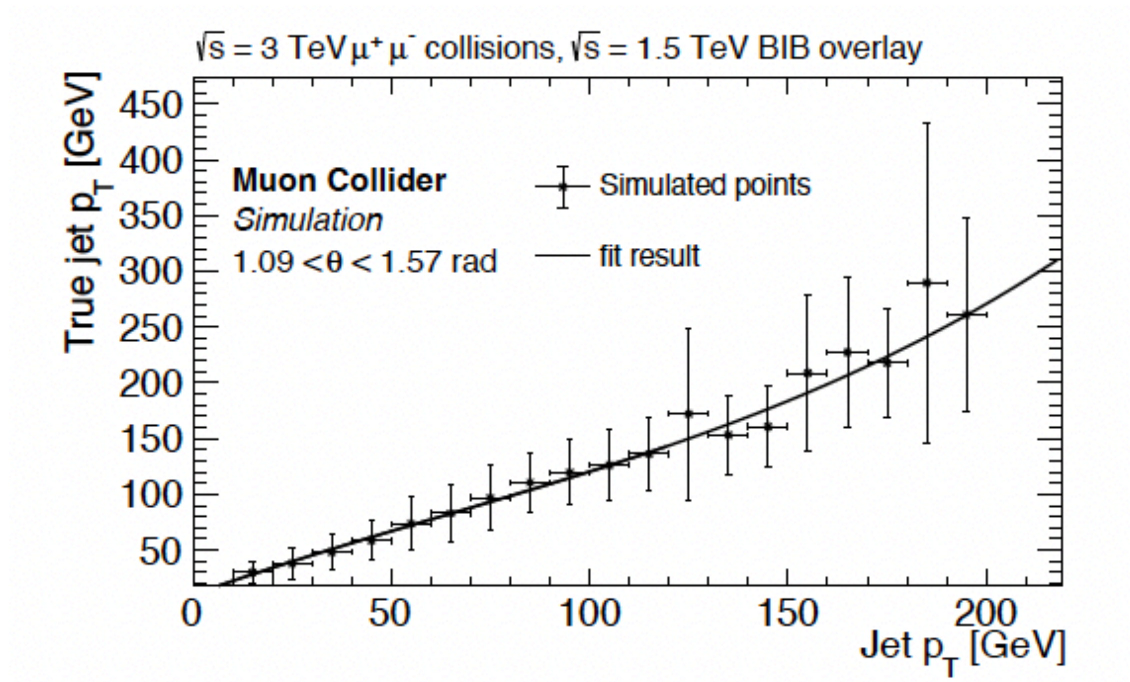


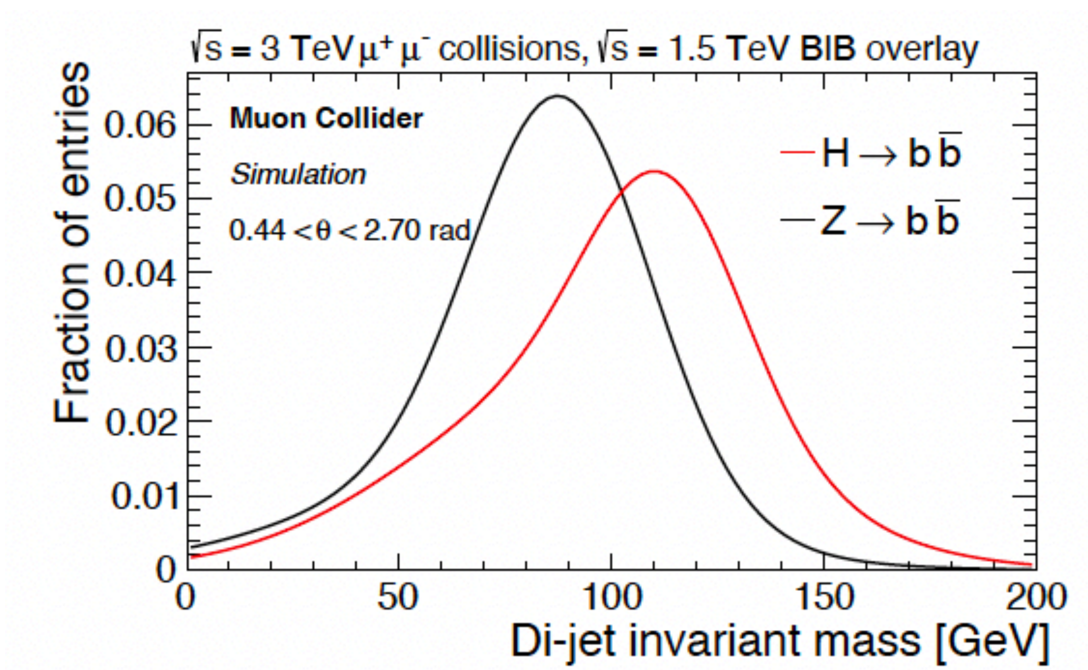


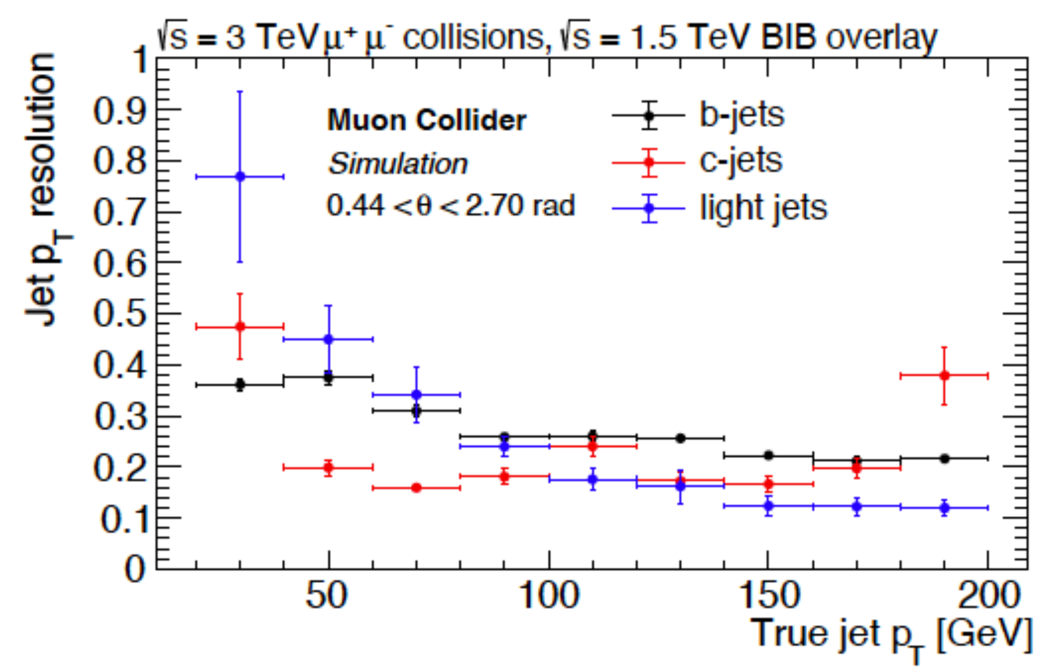
Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre

Jet calibration

- Calibration applied by fitting true jet pT vs reco jet pT in different theta bins







Marco Valente
Particle Physics department
TRIUMF, Canada's particle accelerator Centre