Muon Collider activities in Padova

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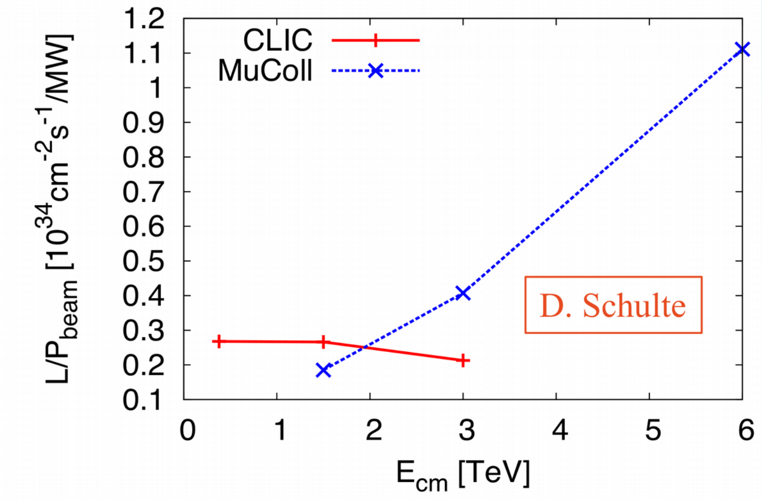
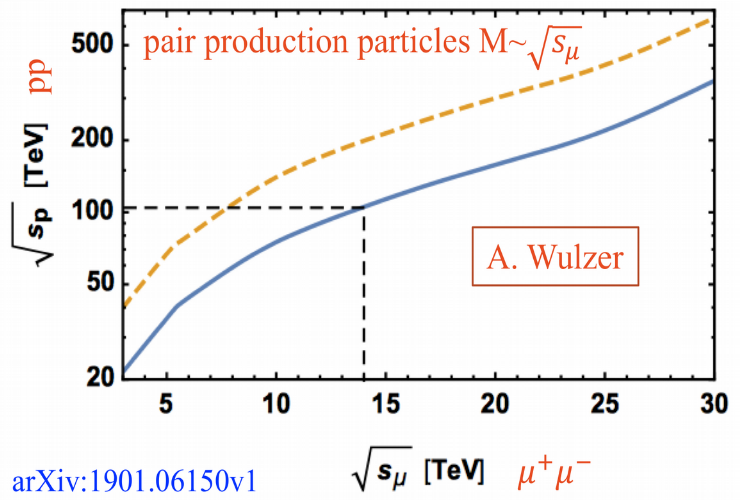
INFN-Padova

Meeting Gruppo 1, Padova, 3/3/2020

Why a Muon Collider?





In linear lepton colliders the luminosity per beam power is independent from collision energy, but **increases linearly in a muon collider.**

In muon colliders the collision energy is entirely available to produce short-distance interactions, while in pp colliders interactions occur between partons which carry a small amount of the total energy.

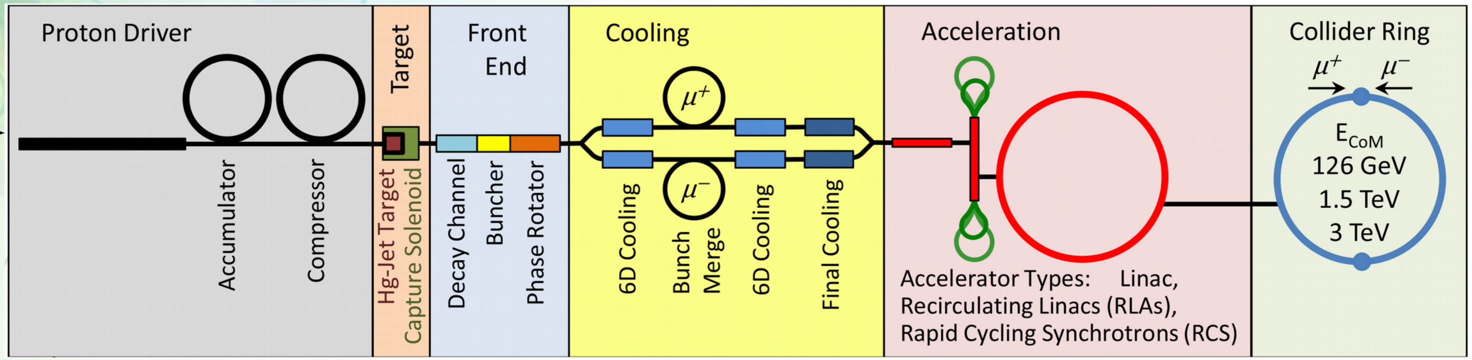
Many challenges:

- **Muon production and cooling** → **LEMMA testbeam @Padova**
- **Beam-induced background** → **Detector and Physics performance @Padova**

Muon Collider schemes

Proton driver + muon cooling

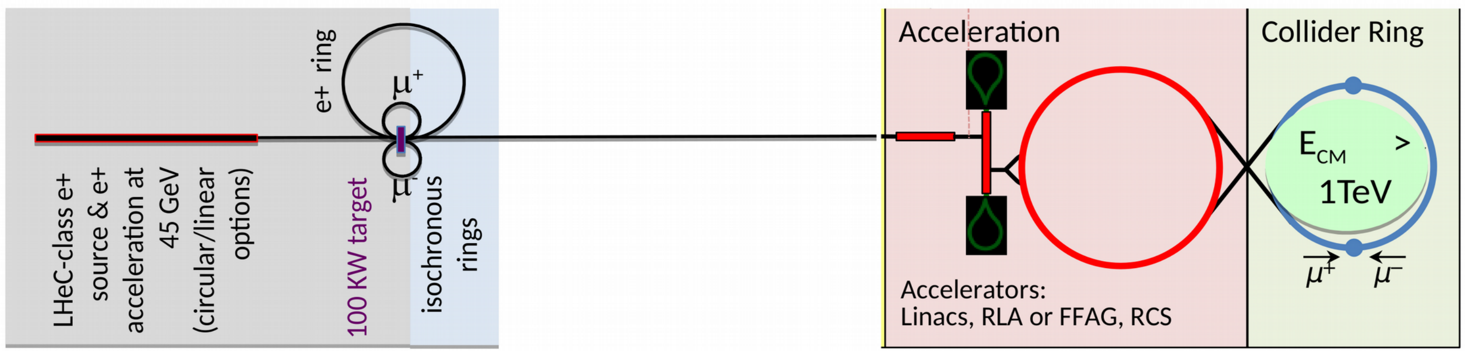
p+h → X $\mu^+\mu^-$



LEMMA

NIM A 807 101-107 (2016)

➔ $e^+e^- \rightarrow \mu^+\mu^-$



LEMMA testbeam

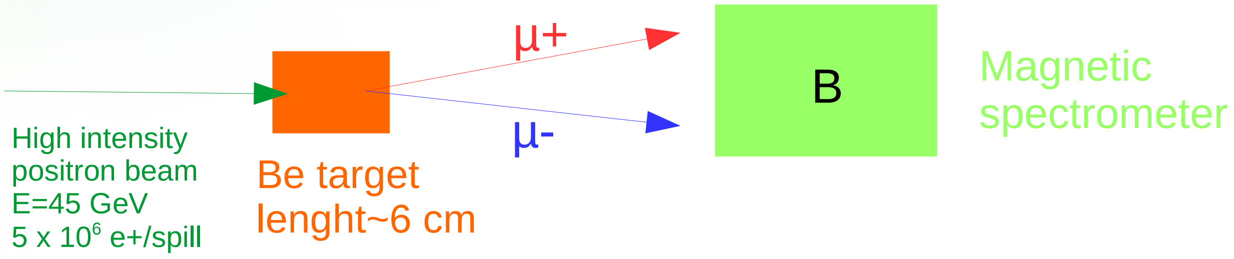
A. Bertolin, C. Curatolo, F. Gonella, S. Hoh, D. Lucchesi,
A. Paccagnella, R. Rossin, L. Sestini, S. Ventura, M. Zanetti, A. Zucchetta

+ INFN Torino, Roma, LNF as main contributors

LEMMA testbeam motivations

Exploit $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold (0.212 GeV) in asymmetric collisions to generate beams of μ^+ and μ^-

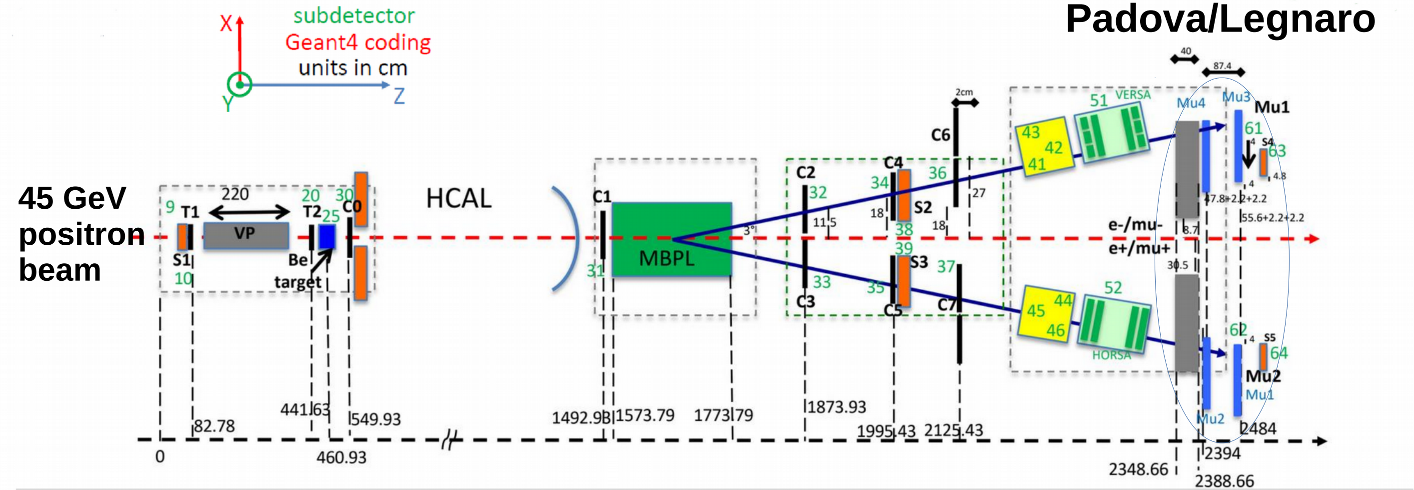
- Low emittance, tunable with $\sqrt{s}$.
- Small muon energy spread at threshold, it gets larger as $\sqrt{s}$ increases.
- Low background: muons can be produced with high boost in asymmetric collisions, reducing losses from decays.
- **But low rate:** $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$~ 1µb at most, to be compared with $\sigma(p+h \rightarrow \mu^+\mu^-)$~mb

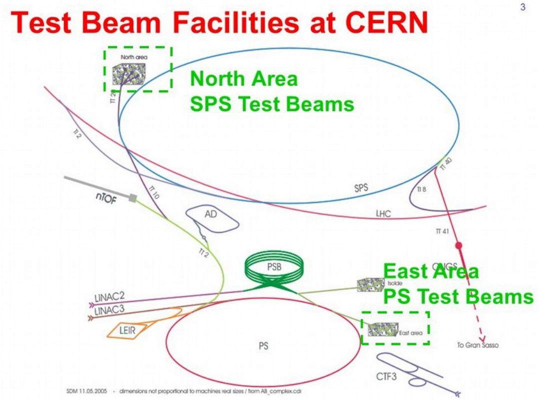


- Measurements:
  - **$\mu^+\mu^-$ production cross section as a function of $\sqrt{s}$** → **Probe Coulomb corrections (~15%)**
  - **μ^+/μ^- emittance: area in the muon phase space** → **Use measured values in MC simulations**

Testbeam layout and operations

Drift tubes built in Padova/Legnaro





- 2 silicon stations upstream of the target: **T1** and **T2** (50 μm)
- 2 silicon stations downstream of the target but upstream of the magnet: **C0** and **C1** (242 μm)
- 3 silicon stations in each harm (downstream of the magnet): **C2 C4** (228 μm) **C6** (465 μm) and **C3 C5** (228 μm) **C7** (465 μm)
- a lead glass, yellow, and a Cerenkov, light green, calorimeters in each harm
- 2 muon stations in each harm: Mu1 Mu2 and Mu3 Mu4
- a set of scintillators to trigger the sub-detectors, orange

Operations (~ 1 week each)

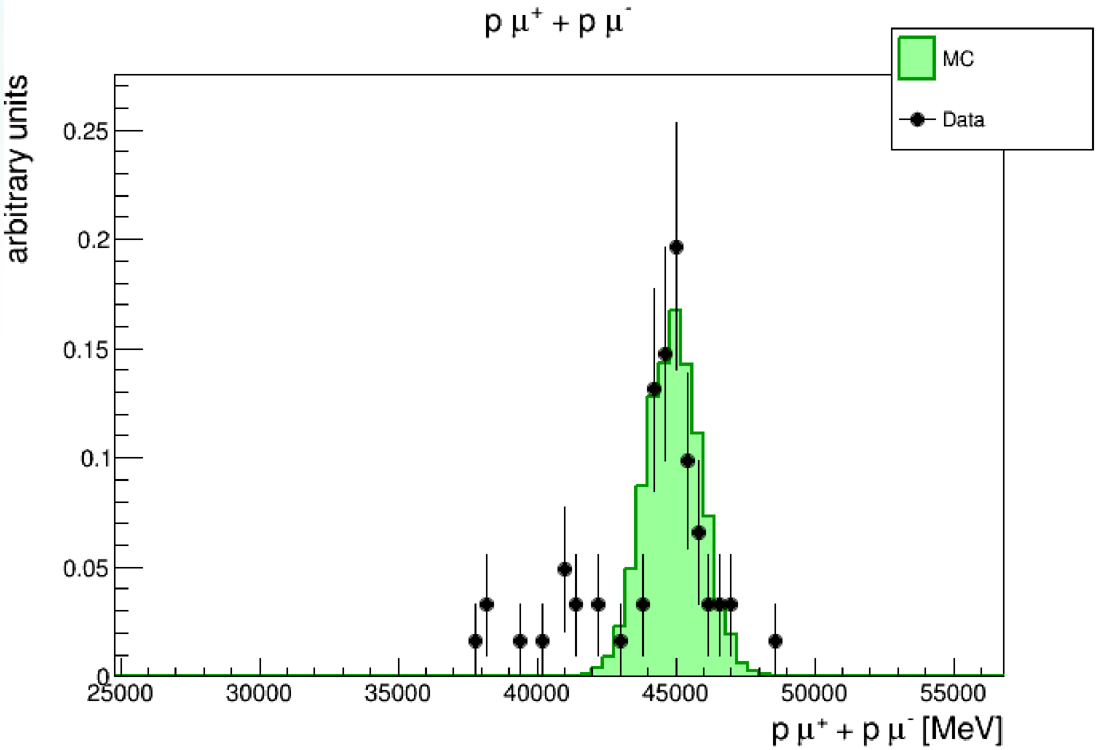
- July-August 2017
- August 2018
- September 2018

Also different beam energies and Carbon target

2018 Testbeam results

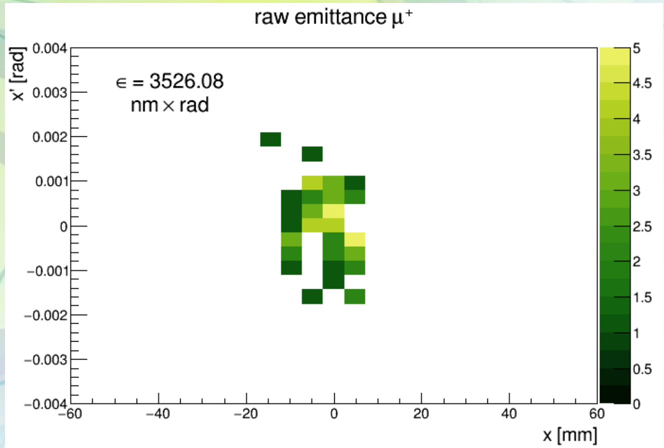
2020 JINST 15 P01036

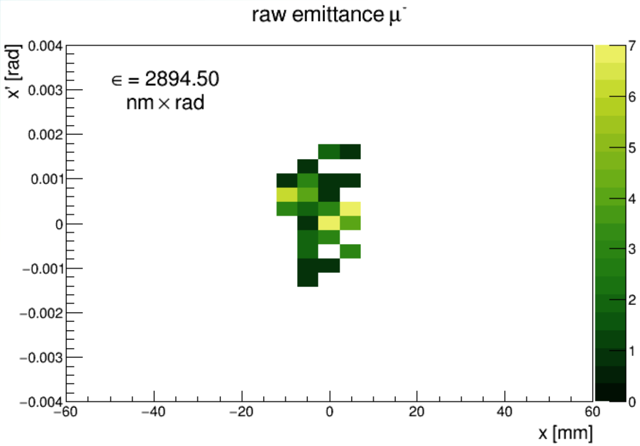
- Signal events identified with two tracks in Drift Tubes
- **Backward tracking algorithm**: from DT to first Silicon sensor after target
- Just 27 signal events in 2017
- **~300 candidates in August 2018**
- Momentum resolution of 3% (from calibration Runs)



2018 Testbeam results

Raw emittance = area in x(μ),x'(μ) space → not deconvolved for positron beam emittance





Expected raw emittance from simulation: 2760 ± 150 nm × rad

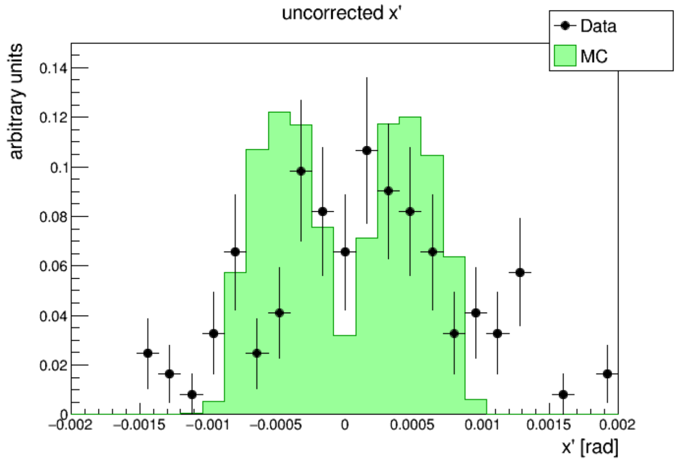
$x = x(\mu) - x(e^+)$

$x' = x'(\mu) - x'(e^-)$

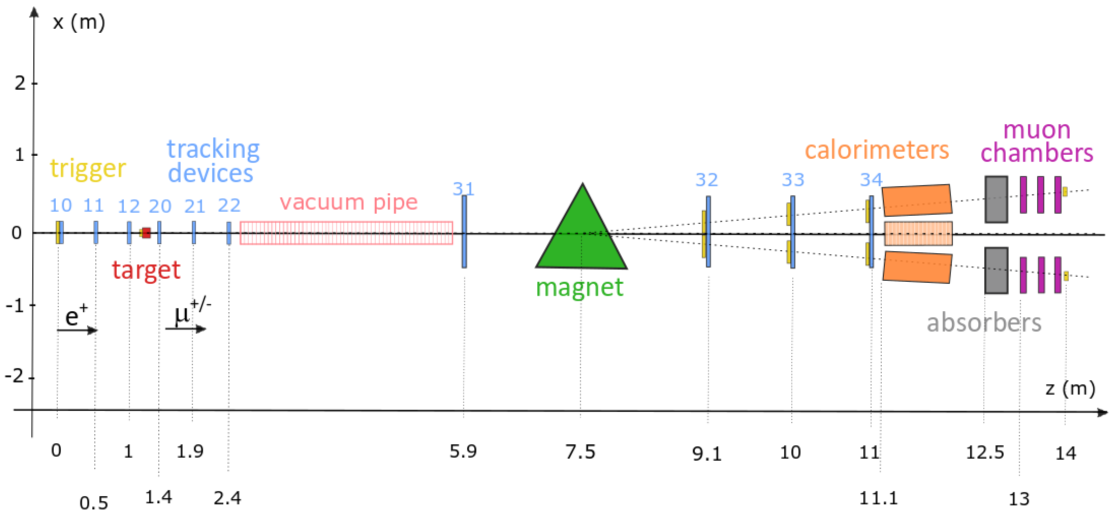
30 μm is the expected width of X distribution: 100 μm precision was achieved by the apparatus.

→ No useful measurement of X can be performed

X' distribution (positron contribution is subtracted) →



Next Testbeams



Simulation studies on next testbeam setup are ongoing:

- More tracking devices in the region after target
- One additional DT layer per arm (measurement of y position) **Support of Mechanics workshop, Electronic design (Bellato), Electronics workshop (Nicoletto) is necessary.**

From next testbeams we expect:

- An improved trigger and readout system
- **More statistics**

Detector and Physics Performance

A. Bertolin, L. Buonincontri, A. Gianelle, D. Lucchesi, L. Sestini
+ INFN Torino, Trieste, Roma, Milano
+ HZDR (Dresden), Fermilab, Brookhaven NL

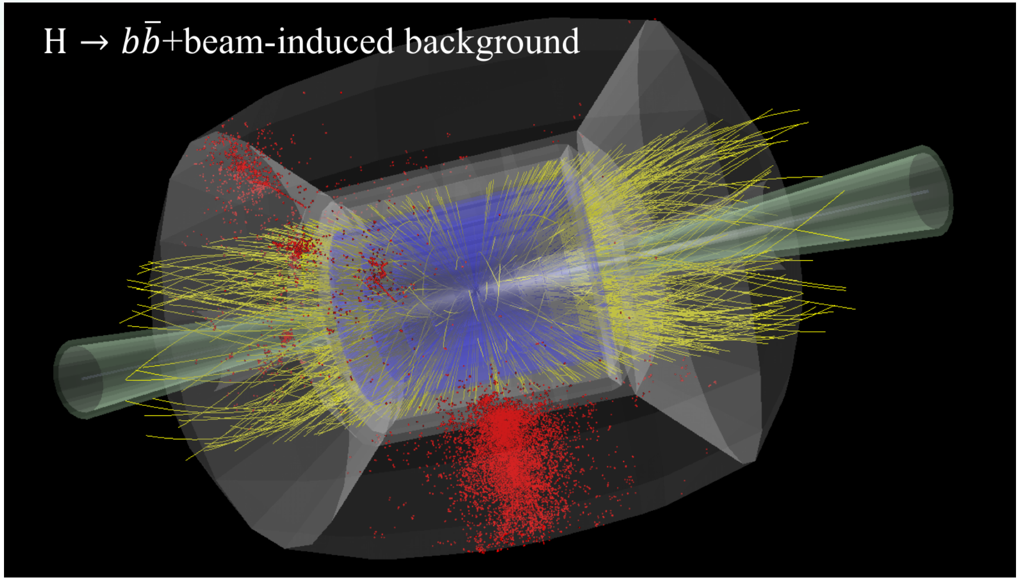
Beam-induced background simulation

- **Beam-induced background (BIB) @ Muon Collider**:
  - Electrons from muons that circulate in the ring radiate synchrotron photons.
  - Electrons and photons interacts with the machine components producing hadrons, secondary muons, electrons and photons.

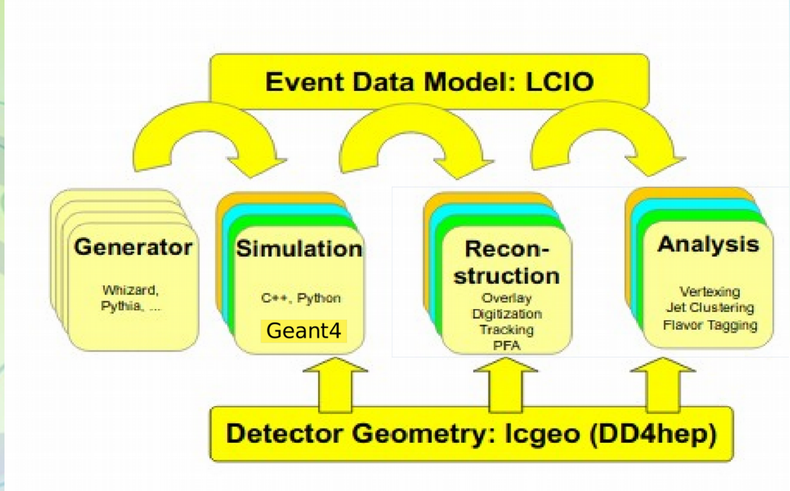
- **Muon Collider physics reach strongly depends on beam-induced background and background suppression.**

Muon Collder simulation activities

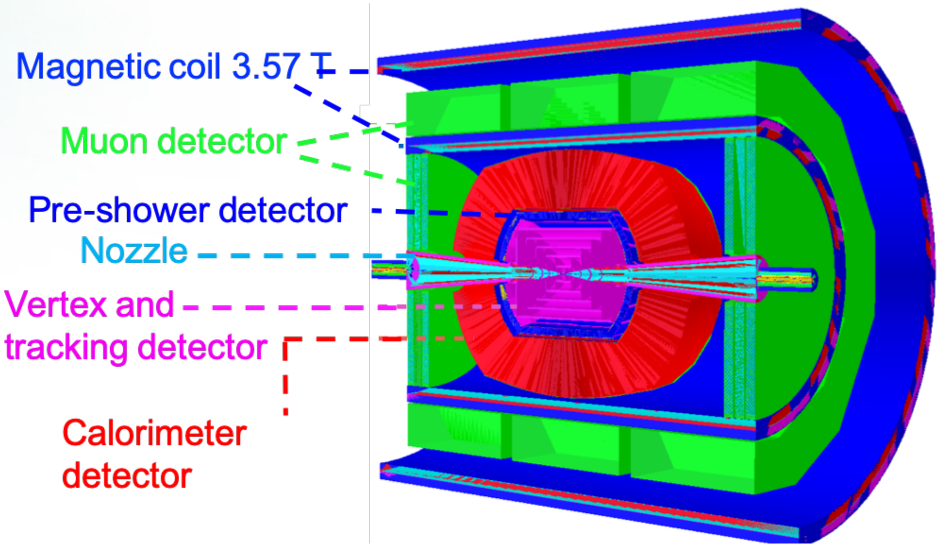
- Simulation framework
- Machine Detector Interface design
- Detectors Design
- Reconstruction algorithms
- Physics reach



Simulation framework

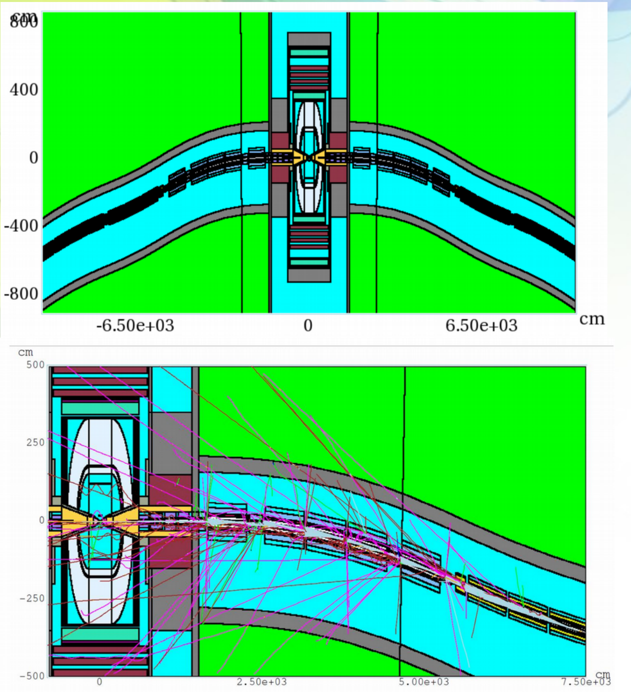


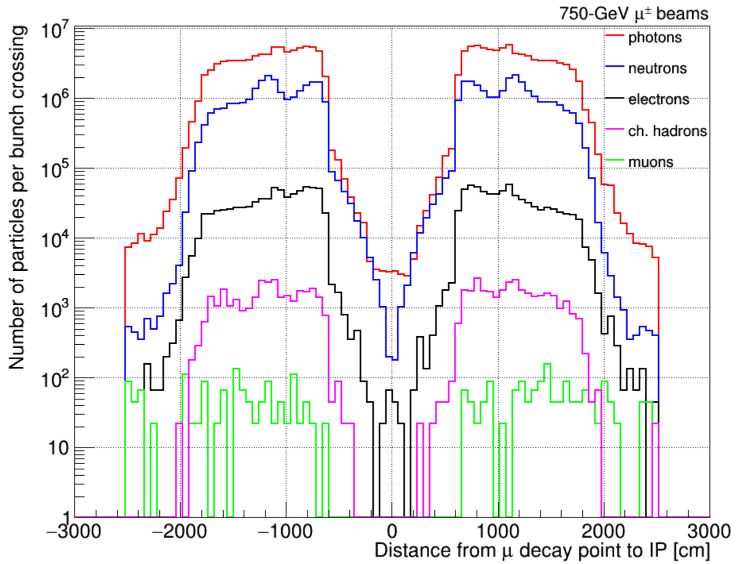
- Simulation framework based on **ILCsoft**
- **Installed and running on Cloud-Veneto farm**
- **Several developments are necessary for Muon Collider:**
  - Management of BIB files with millions of particles.
  - Digitization of Silicon Tracker Hits.
  - Optimization of reconstruction algorithm etc.



Detector description in Geant4.
Initial Detector Design inherited from the MAP collaboration.

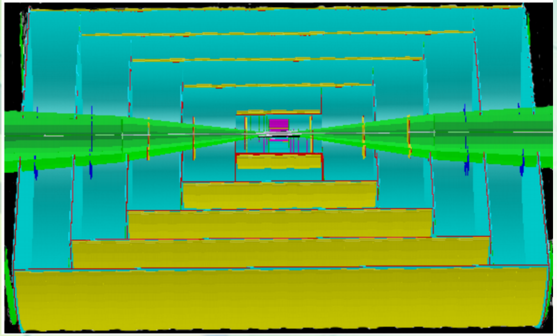
Machine detector interface and BIB generation





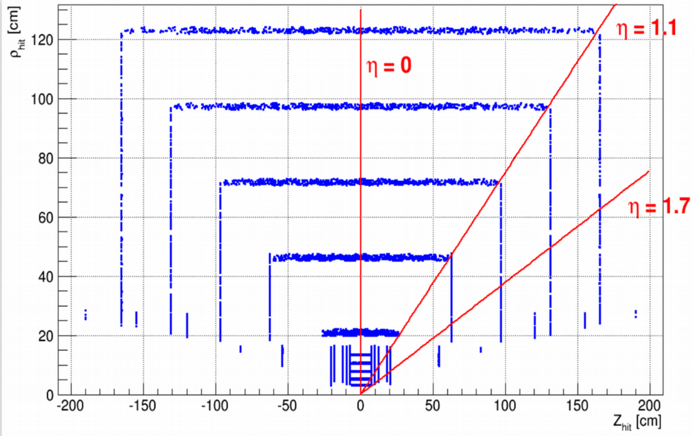
- Initial studies with BIB generated using MARS15 at √s = 125 GeV √s = 1.5 TeV (**prepared by N.V. Mokhov**)
- We are now using FLUKA for MDI description and BIB generation
- Work on-going for MDI optimization (nozzles angle, magnet design etc.)

Detector design: vertex detector and tracker



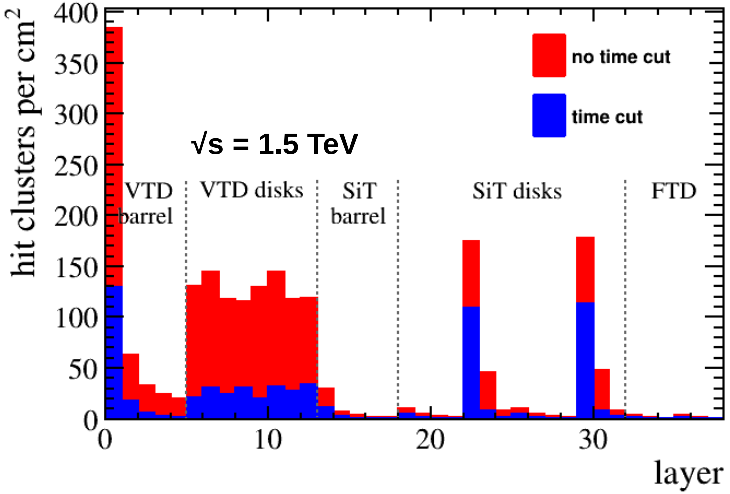
Vertex detector:

- Si Pixels: 20 µm X 20 µm
- Barrel: 5 layers
- Endcap: 2 X 4 disks



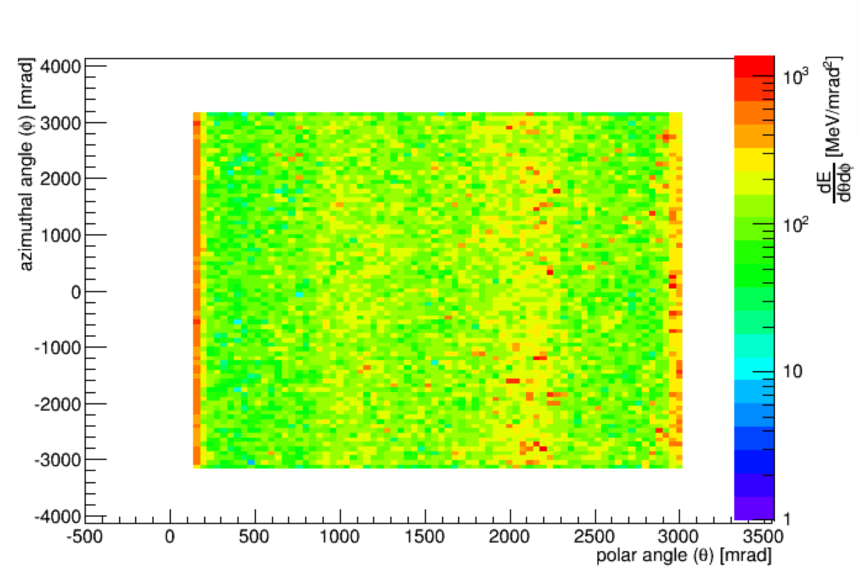
Silicon Tracker:

- Si Pixels: 20 µm X 20 µm
- Barrel: 5 layers
- Endcap: 2 X 3 disks

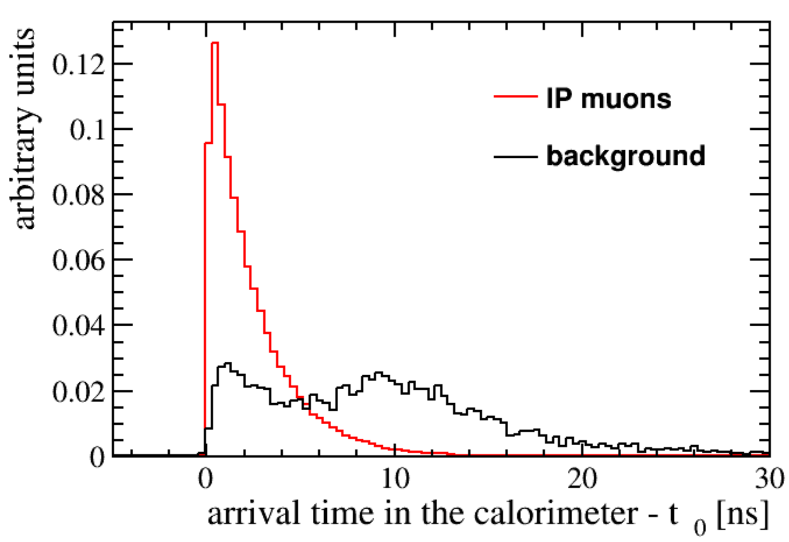


Timing measurement is necessary to reduce beam-induced background hits

Detector design: calorimeter



The background is **diffused**



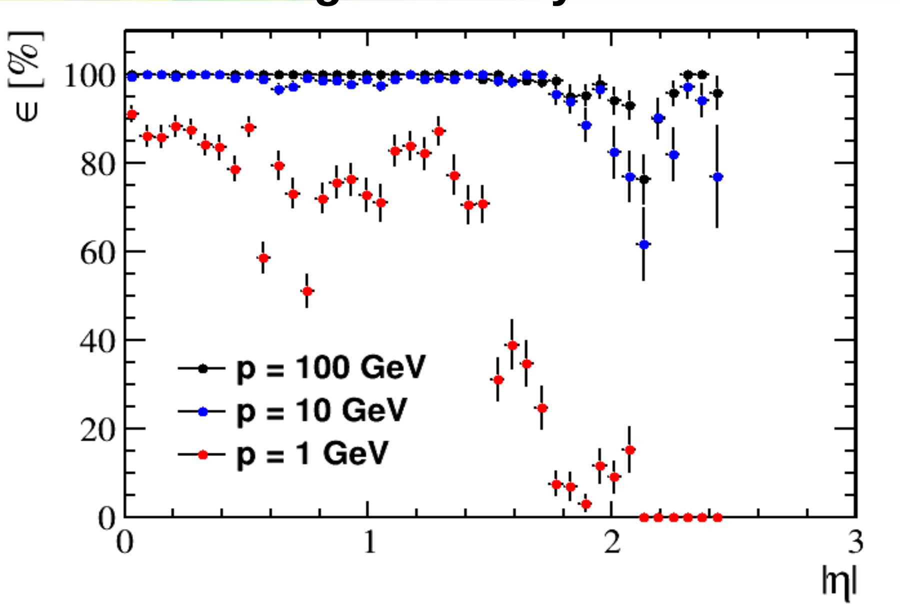
Part of the background is **asynchronous with respect to the signal**

- Initial studies with a Dual Readout calorimeter (Scintillating Crystals + Cherenkov fibers)
- Now moving to ECAL + HCAL system

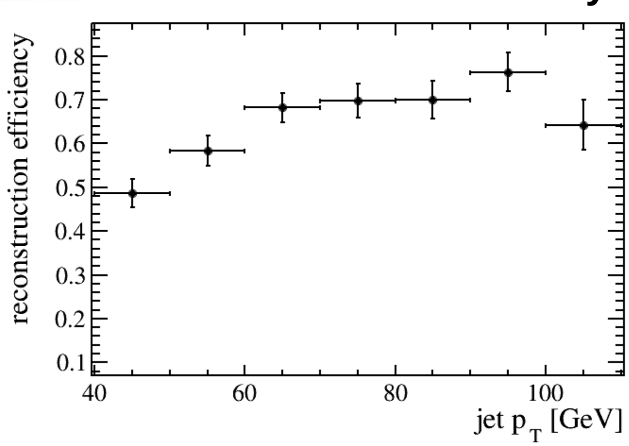
Reconstruction algorithms

Reconstruction algorithms MUST be optimized for MC environment

Tracking efficiency

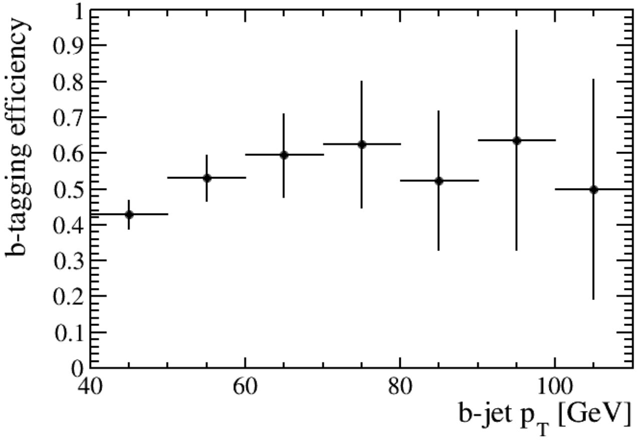


Jet reconstruction efficiency



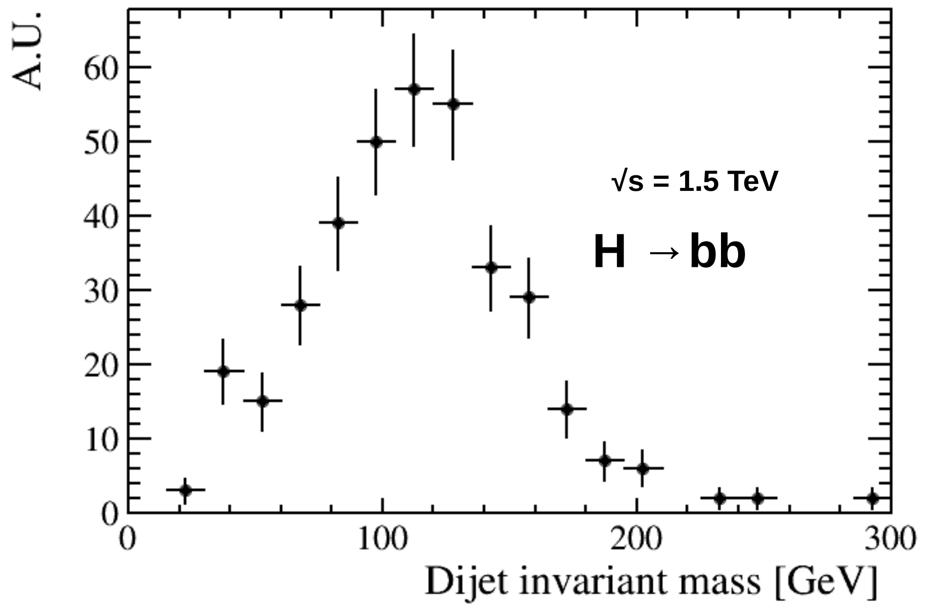
Fake jets ~25% for p_T > 40 GeV

b-tagging efficiency



The mistag is ~1-3%

Muon Collider Physics Reach



~40% mass resolution

- **Higgs coupling with b-quarks as first study** (submitted to JINST)
- More will come: **HH, HHH, ttH** etc.

Expected background events from SM

$\sqrt{s}$ [TeV]	A [%]	ϵ [%]	$\mathcal{L}$ [cm^{-2}s^{-1}]	$\mathcal{L}_{int}$ [ab^{-1}]	σ [fb]	N	B	$\frac{\Delta\sigma}{\sigma}$ [%]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
1.5	35	15	$1.25 \cdot 10^{34}$	0.5	203	5500	6700	2.0	1.9
3.0	37	15	$4.4 \cdot 10^{34}$	1.3	324	33000	7700	0.60	1.0
10	39	16	$2 \cdot 10^{35}$	8.0	549	270000	4400	0.20	0.91

4 years of data-taking assumed for both CLIC and MC

	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [ab^{-1}]	$\frac{\Delta g_{Hbb}}{g_{Hbb}}$ [%]
Muon Collider	1.5	0.5	1.9
	3.0	1.3	1.0
	10	8.0	0.91
CLIC	0.35	0.5	3.0
	1.4	+1.5	1.0
	3.0	+2.0	0.9

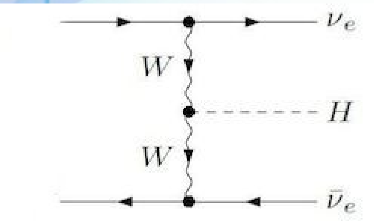
Conclusions and perspective

- **LEMMA testbeam:**
  - **2018 results published in JINST**
  - Simulation studies on next testbeam setup are on-going
  - New detectors: silicon devices and Drift Tubes

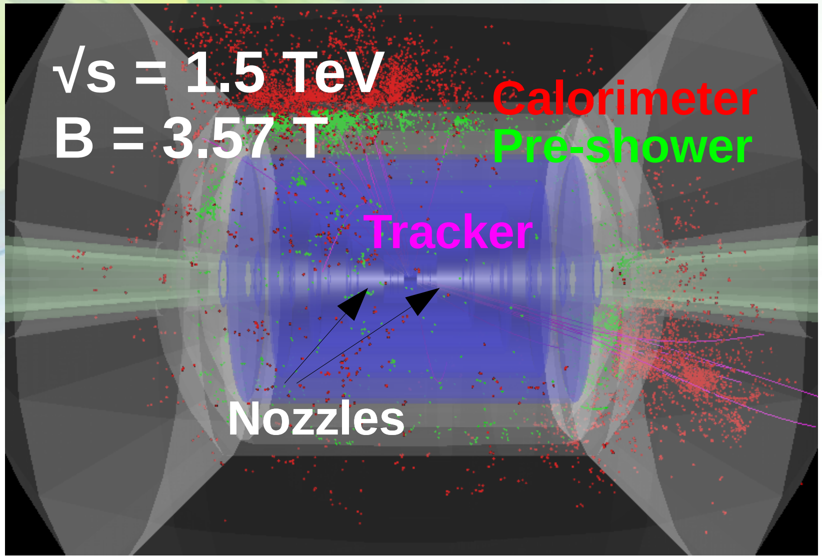
- **Detector and physics performance**
  - **First Detector and Physics Performance paper submitted to JINST**
  - Next steps: design detectors for Muon Collider and Machine-detector interface
  - Double Higgs studies ongoing (trilinear coupling sensitivity)

Backup

$H \rightarrow b\bar{b}$ and background $\sqrt{s}$ = 1.5 TeV

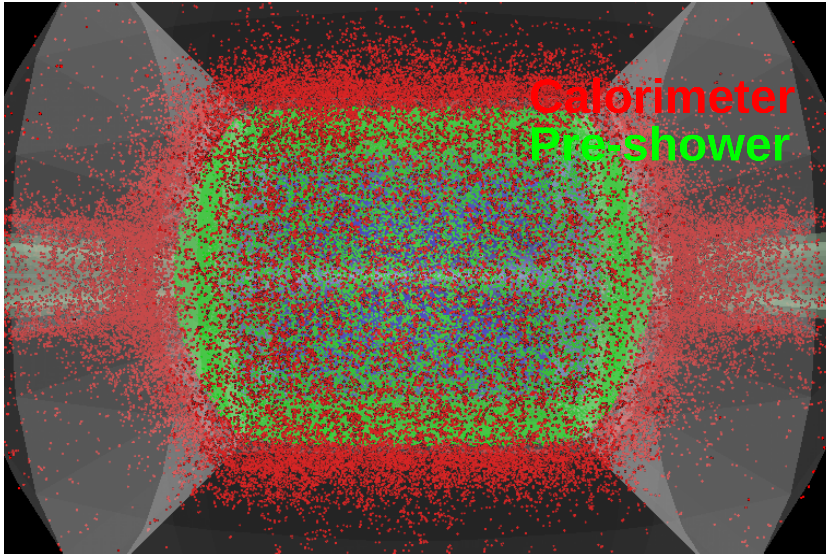


WW fusion



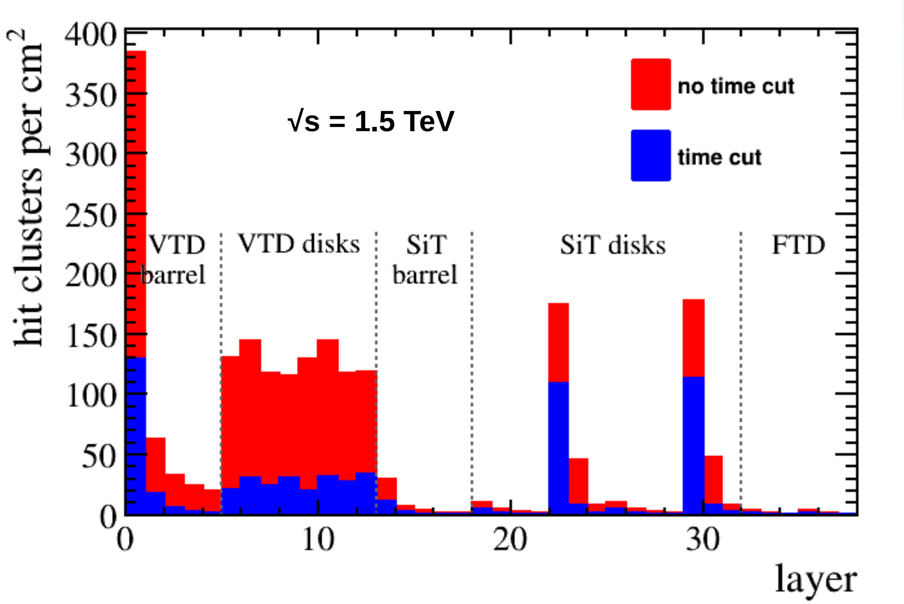
$H \rightarrow b\bar{b}$ signal

+

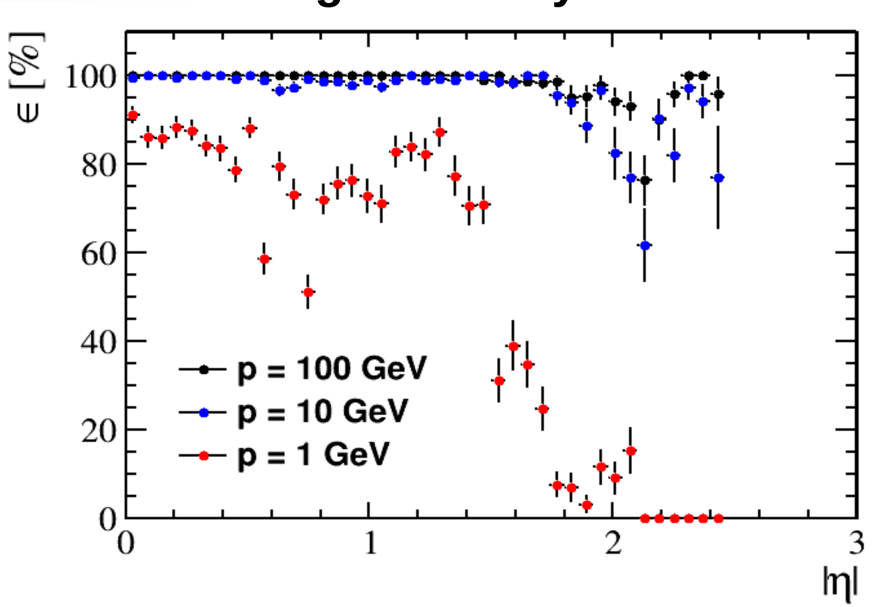


Beam-induced background

Detector design: vertex detector and tracker



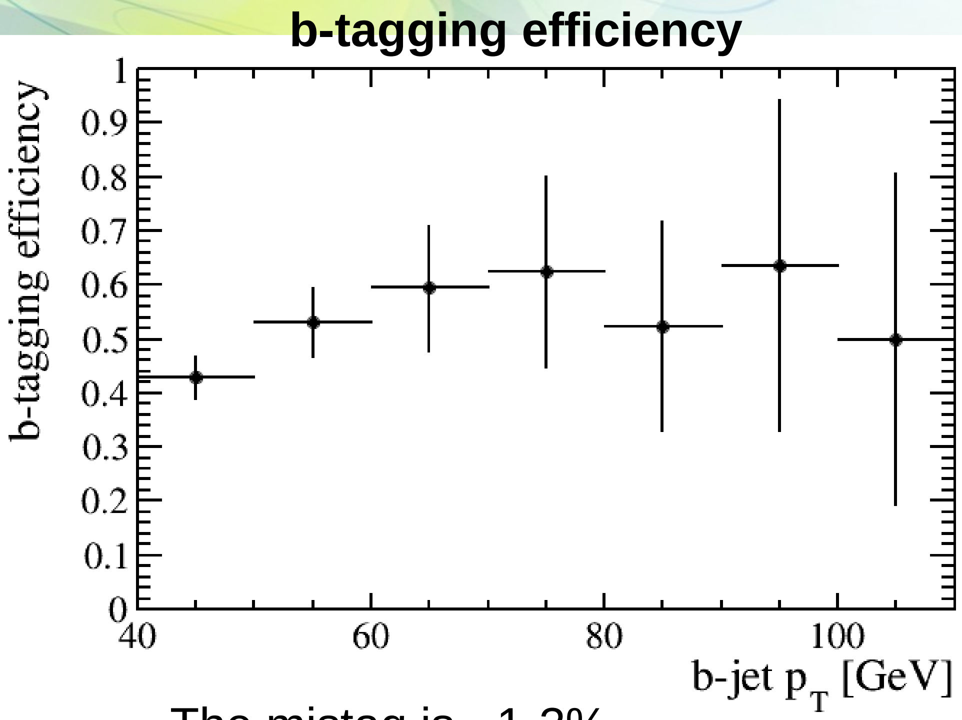
Tracking efficiency



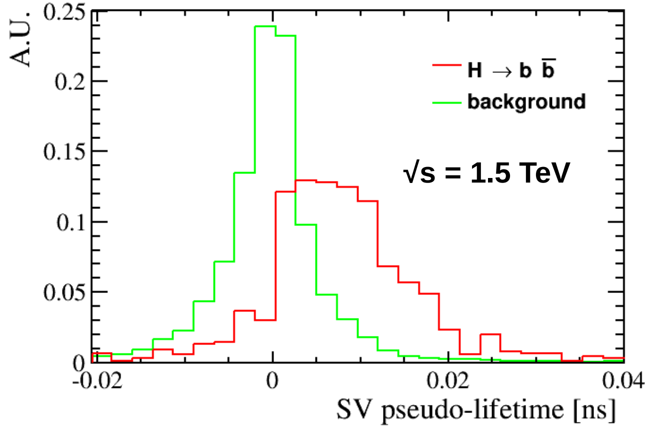
Timing measurement is necessary to reduce beam-induced background hits

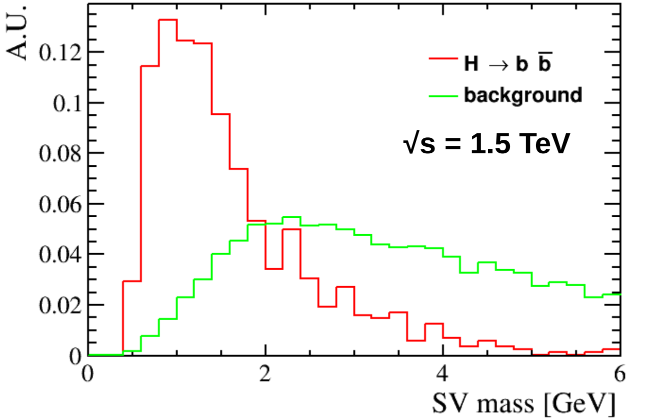
Jet b-tagging

b-tagging: Secondary Vertex reconstruction inspired by LHCb tagging algorithm



The mistag is ~1-3%





Higgs self-coupling: unique to Muon Collider

$$V = \frac{1}{2} m_h^2 h^2 + (1 + k_3)\lambda_{hhh}^{SM} v h^3 + (1 + k_4)\lambda_{hhhh}^{SM} h^4$$

Higgs potential via trilinear and quadrilinear coupling can be determined by measuring the cross-section $\sigma(\mu^+\mu^- \to HH\nu\bar{\nu})$ and $\sigma(\mu^+\mu^- \to HHH\nu\bar{\nu})$.

Trilinear coupling, k_3

- $\sqrt{s} = 10\,TeV, \mathcal{L} \sim 10^{35} cm^{-2} s^{-1}$
- 10 ab^{-1}

k_3 sensitivity ~ 3%

Best sensitivity ~5% FCC combined
(arXiv:1905.03764)

Quadrilinear coupling, k_4

- $\sqrt{s} = 14\,TeV, \mathcal{L} \sim 10^{35} cm^{-2} s^{-1}$
- 20 ab^{-1}

k_4 sensitivity few 10%

FCC-hh in a optimistic scenario 30 ab^{-1}

$\lambda_4 = \in [\sim -4, \sim +16] @ 68\%\ C.L.$ (arXiv:1905.03764)

The importance of the complete reconstruction of the shape of the Higgs potential is being studied by M. Chiesa et al. (to be published soon). If measured with enough precision, it can allow to detect a possible BSM deviation, even in the hypothesis of the trilinear self-coupling being in agreement with the SM.
Full simulation is foreseen to establish the k_4 sensitivity.