105th Plenary ECFA meeting - CERN

14-15 November 2019

Europe/Zurich timezone

Challenges and perspectives for a muon collider

Donatella Lucchesi INFN & University of Padova

for

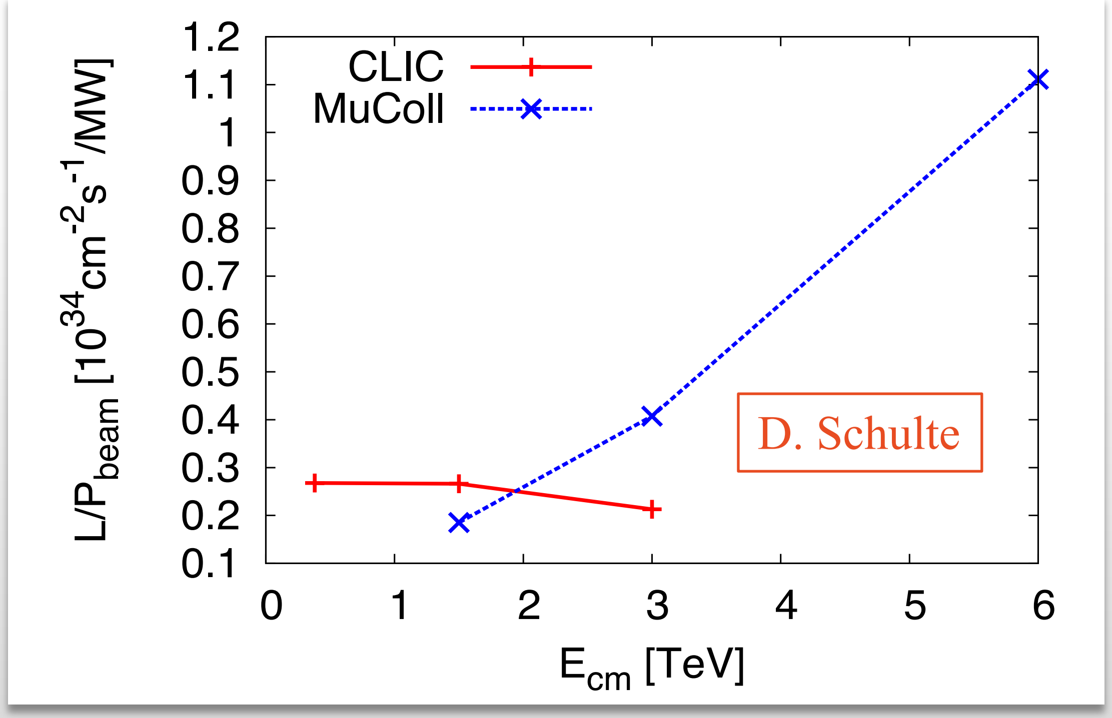
N. Bartosik, A. Bertolin, L. Buonincontri, M. Casarsa, F. Collamati, Al. Ferrari, An. Ferrari, A. Gianelle, N. Mokhov, N. Pastrone, P. Sala, L. Sestini, S. Striganov

UNIVERSITÀ DEGLI STUDI DI PADOVA

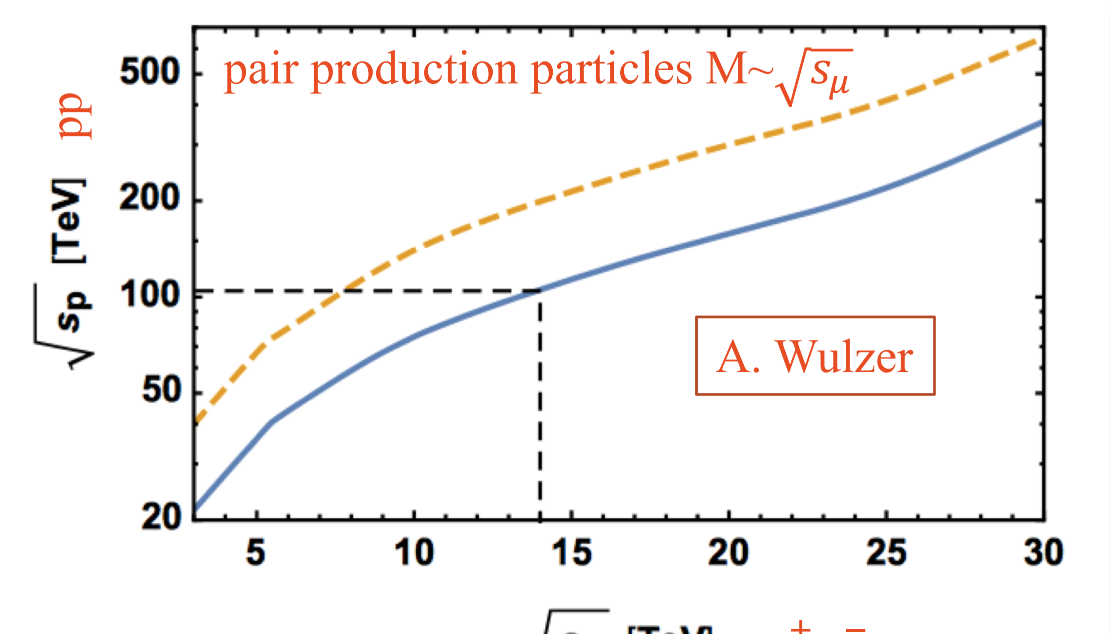
INFN Istituto Nazionale di Fisica Nucleare

Why a muon collider

The luminosity per beam power is independent of collision energy in linear lepton colliders, but increases linearly for muon colliders



The advantage in colliding muons rather than protons is that $\sqrt{s_\mu}$ is entirely available to produce short-distance reactions. At a proton collider the relevant interactions occur between the proton constituents, which carry a small fraction of $\sqrt{s_p}$



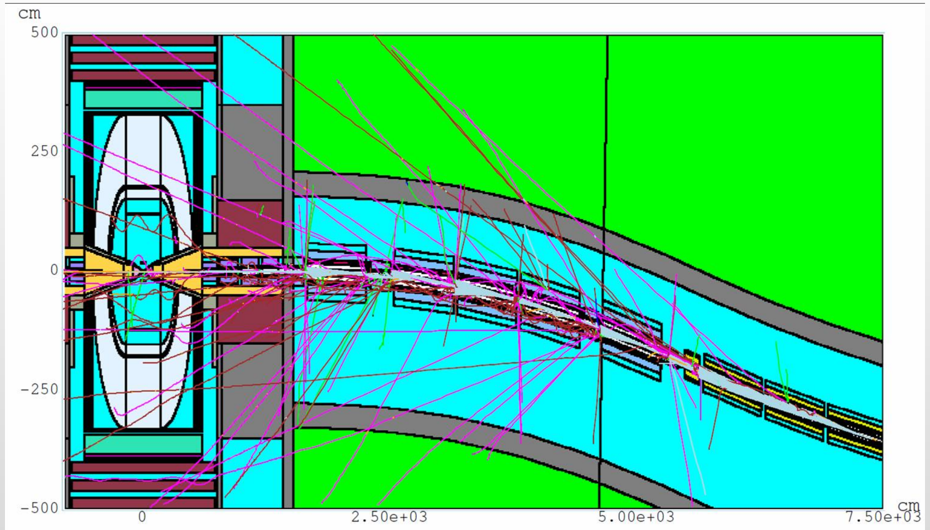
arXiv:1901.06150v1

The Challenge: beam-induce background

- Muon decay… just a back of the envelope calculation:
  beam 0.75 TeV $\lambda = 4.8{\times}10^6$m, with $2{\times}10^{12}\mu$/bunch $\Rightarrow 4.1{\times}10^5$decay per meter of lattice

It gets better when the energy increases

- Muon induced background is critical for
  - ❑ Magnets, they need to be protected
  - ❑ Detector, the performance depends on the rate of background particles arriving to each subdetector and the number and the distribution of particles at the detector depends on the lattice



Electromagnetic showers induced by electrons and photons interacting with the machine components generate hadrons, secondary muons and electrons and photons.

Muon Accelerator Program, MAP (https://map.fnal.gov)

Beam-induced background simulation at $\sqrt{s}$ =1.5 TeV

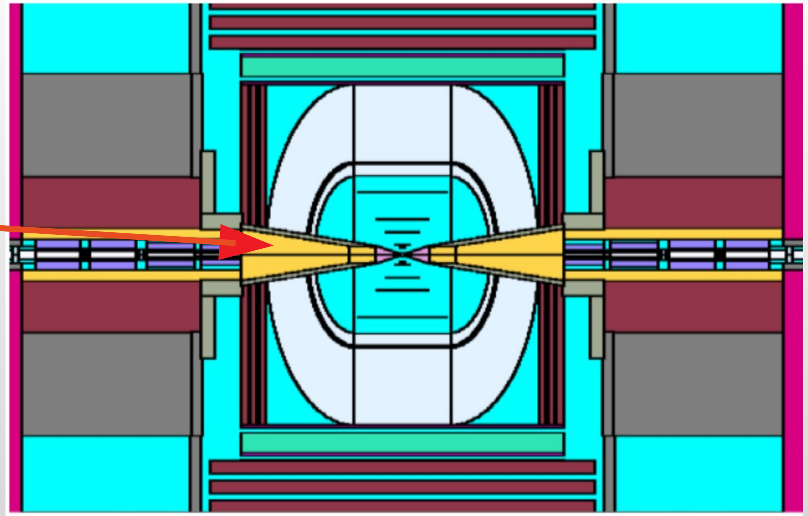
MAP developed a realistic simulation of beam-induced backgrounds in the detector:

- implements a model of the tunnel ±200 m from the interaction point, with realistic geometry, materials distribution, machine lattice elements and magnetic fields, the experimental hall and the machine-detector interface (MDI);
- Secondary and tertiary particles from muon decays are simulated with MARS15 then transported to the detector.

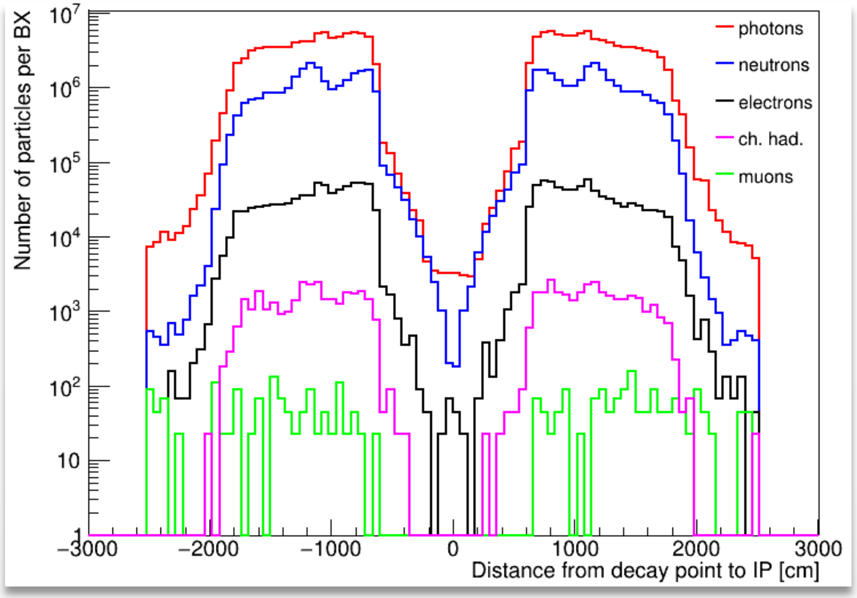
For each collider energy the machine elements, the MDI and IP have to be properly designed and optimized.

In particular, the two tungsten nozzles, cladded with a 5-cm layer of borated polyethylene, play a crucial role in background mitigation inside the detector.

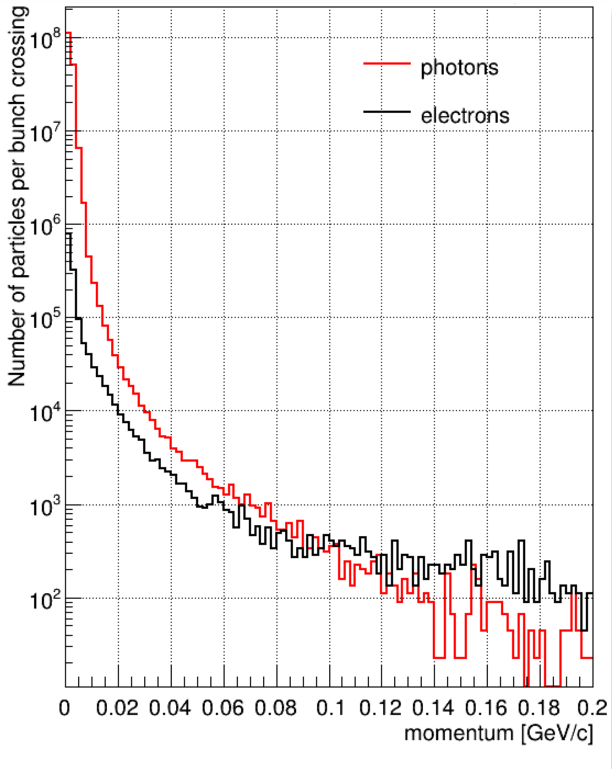
N.V. Mokhov and S.I. Stiganov, arXiv:1204.6721v1 (2012)

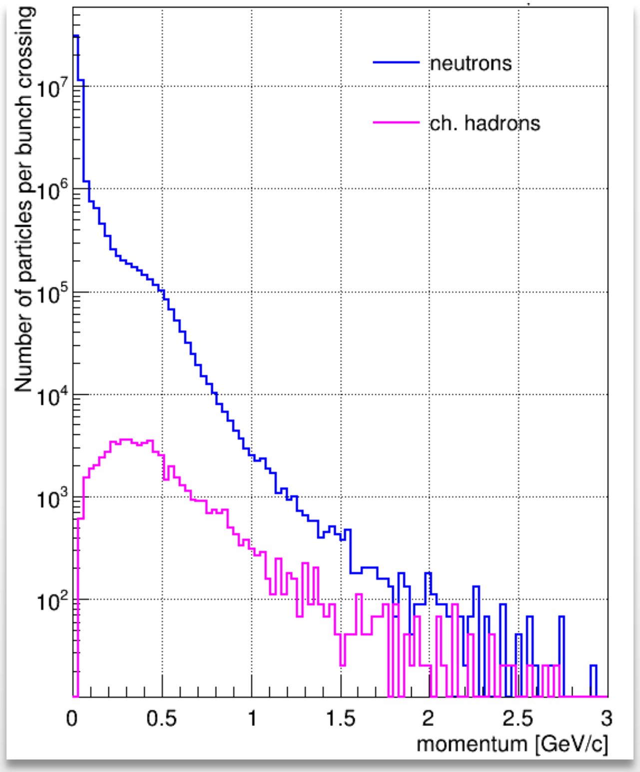


Beam-induced background properties $\sqrt{s}$ =1.5 TeV



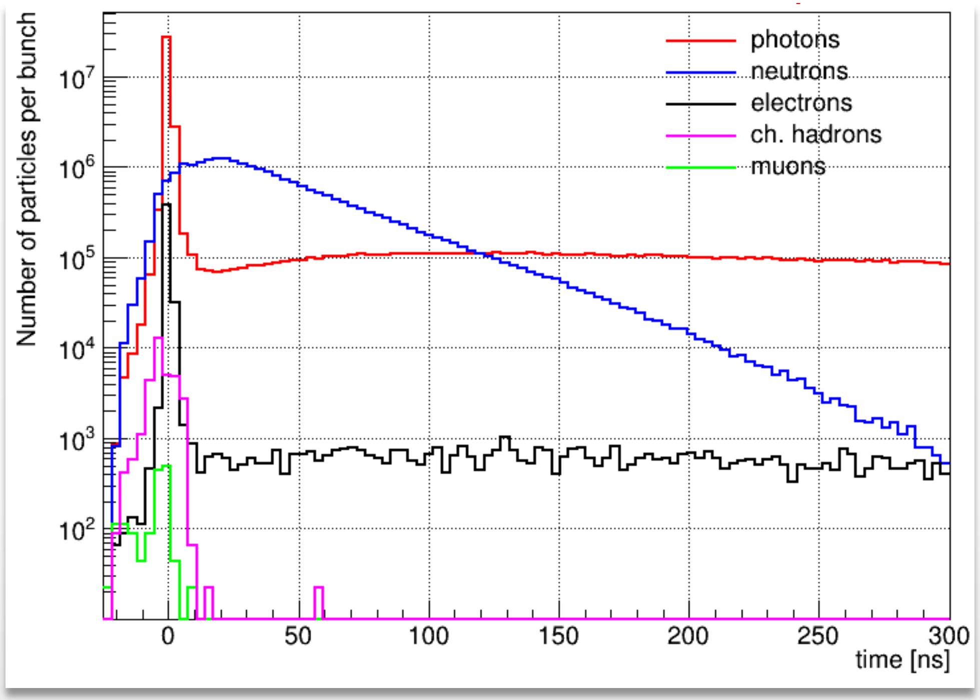
Contributions form μ decays |z| > 25 m become negligible for all background species but Bethe-Heitler muons

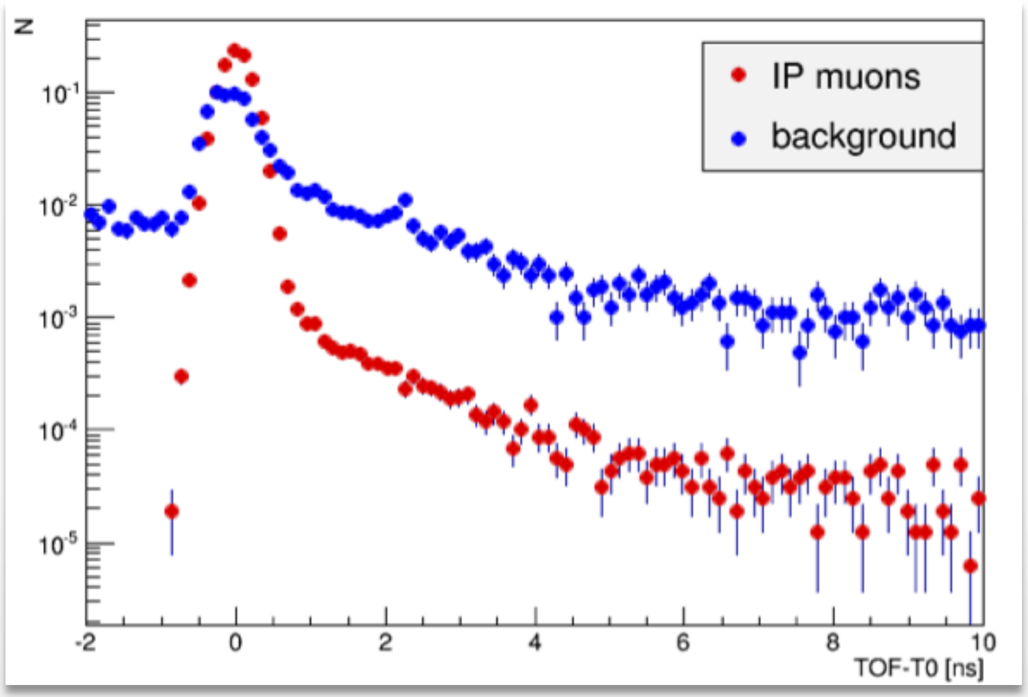




Secondary and tertiary particles have low momentum

Beam-induced background properties $\sqrt{s}$ =1.5 TeV



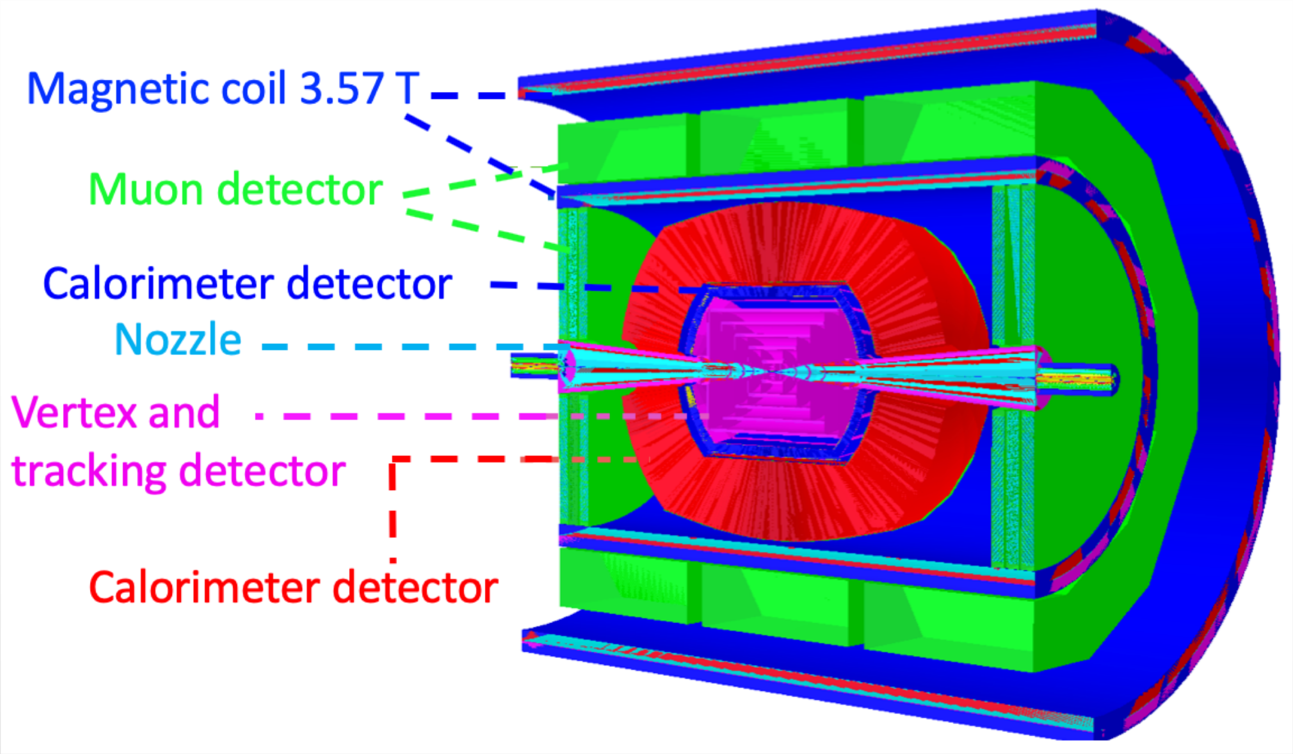


Time information are crucial to reduce the beam-induced background

New detectors generations help to mitigate the effects

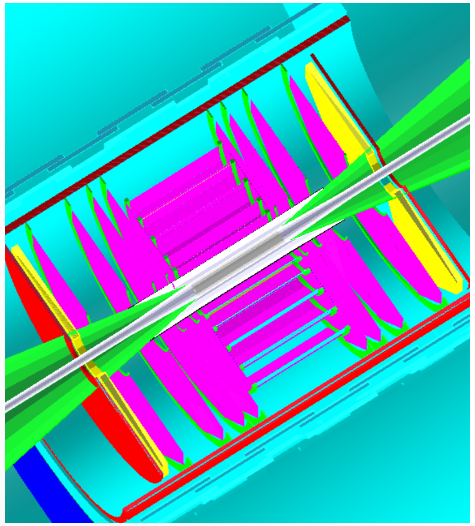
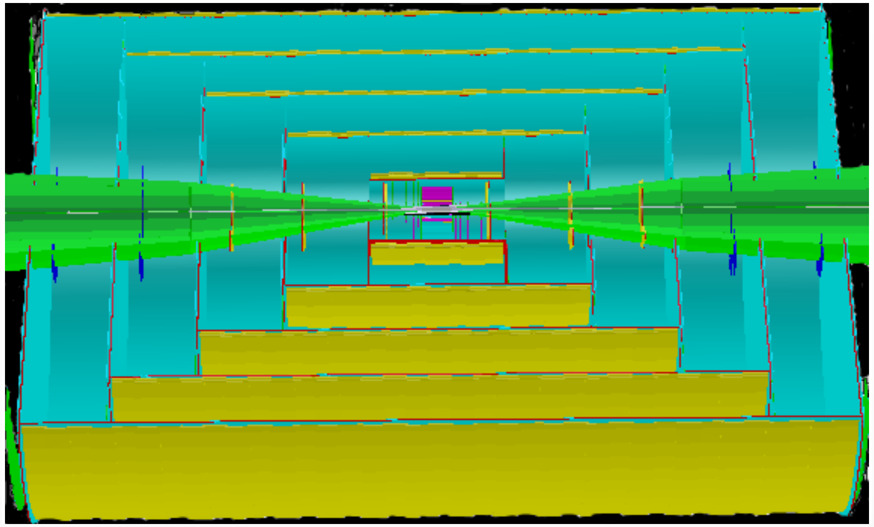
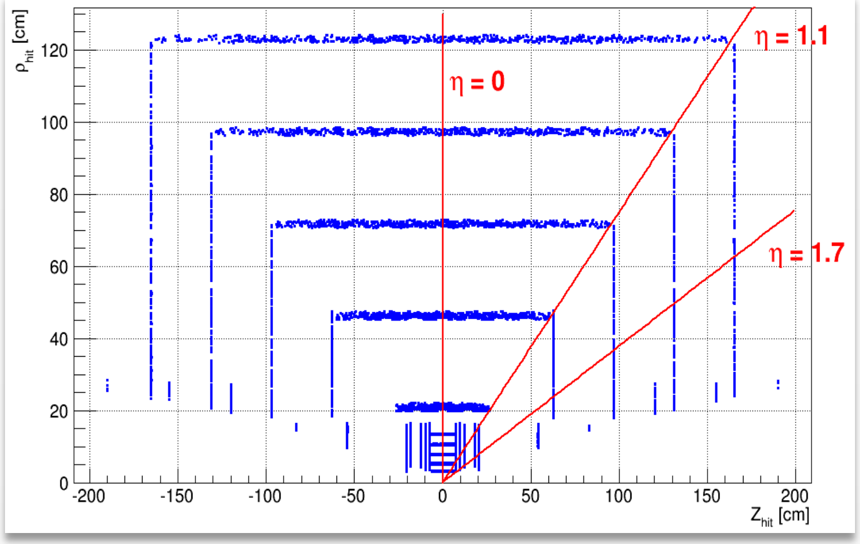
Current Detector Response Simulation at $\sqrt{s}$ =1.5 TeV

- A detailed simulation of the potential detector is necessary to assess the achievable precision of future physics measurements
- Making use of the simulation/reconstruction tools previously developed within the MAP program based on the ILCroot package: supports signal + MARS15 background merging



Inherited from MAP

Tracking detectors for $\sqrt{s}$ =1.5 TeV

Beam pipe: Beryllium *(Be)* **thickness:** 400 μm

Vertexing detector (VTX) precise tracking
***Si* pixel sensors:** 20×20 μm pitch
R: 3-13 cm **L:** 42 cm
Granularity:
- **Barrel:** 5 layers *(75 μm thick)*
- **Endcap:** 2 × 4 disks *(100 μm thick)*

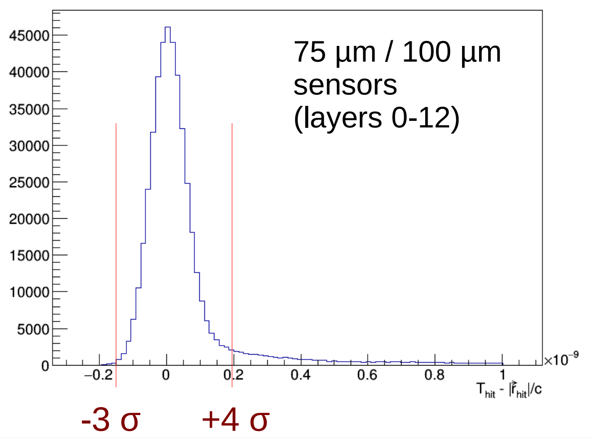
Silicon Tracker (SiT) and
Forward Tracking Detector (FTD):
***Si* pixel sensors:** 50×50 μm pitch, **thickness:** 200 μm
SiT: Barrel: 5 layers **Endcap:** 2 × (4 +3) disks
FTD: Endcap: 2 × 3 disks

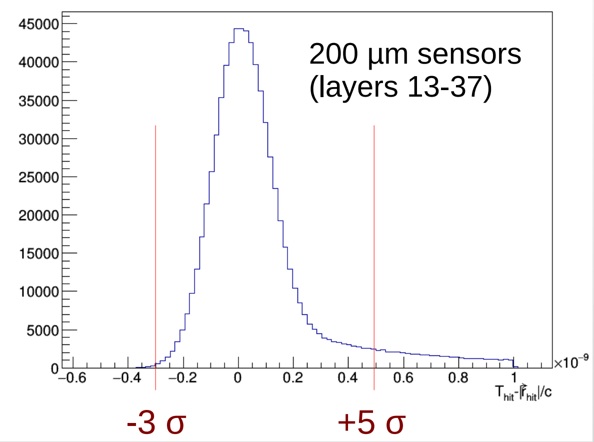
Tracking Detector Occupancy at $\sqrt{s}$ =1.5 TeV

Assuming different time resolution for different Si detectors

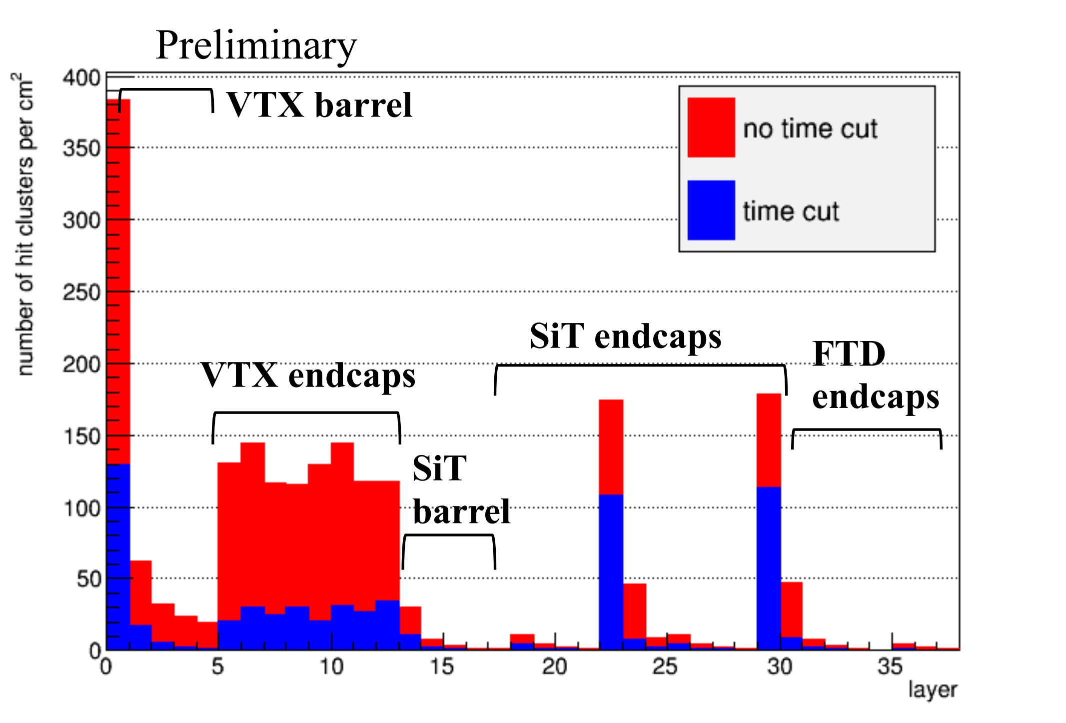
Pitch 75 and 100 µm: 50 ps

Pitch 200 µm:100 ps





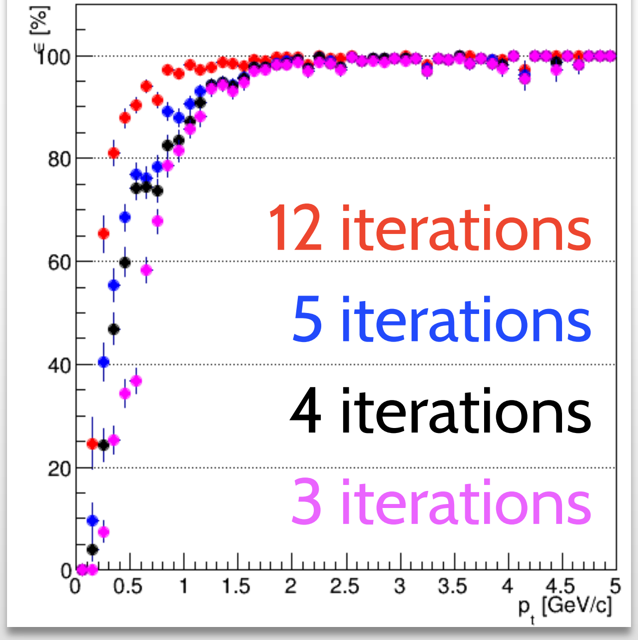
A lot of background can be removed with "4D" Si detectors!



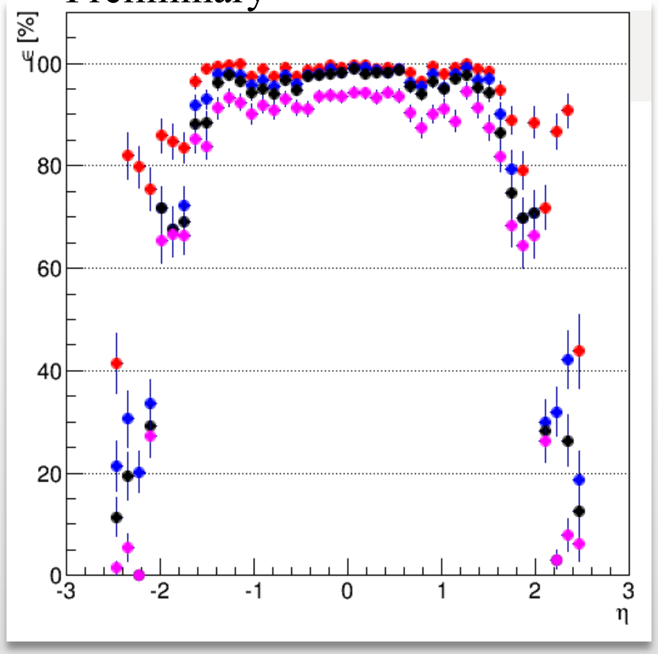
Tracking Algorithm at $\sqrt{s}$ =1.5 TeV

Hit assignment and track refitting performed iteratively: more iterations → better tracking efficiency in particular at low momentum since more iterations are needed. But the current version of the code is very slow. Working to move to a better, optimized software.

Preliminary



Preliminary

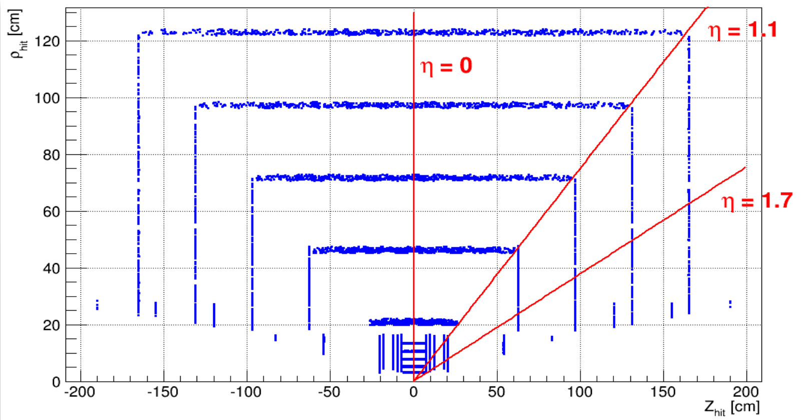


Five iterations affect the reconstruction of low momentum and forward tracks

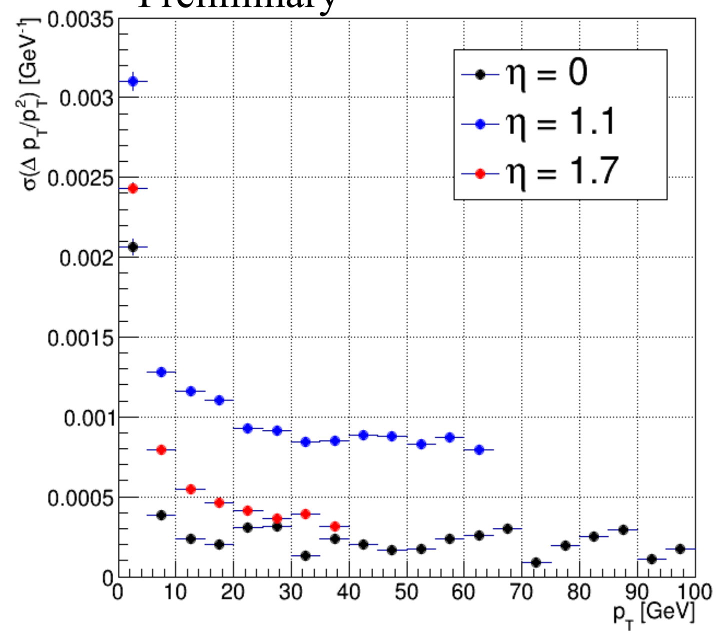
Tracking Performance at $\sqrt{s}$ =1.5 TeV

Evaluate track p_T resolution and efficiency by using 1M of single muons.

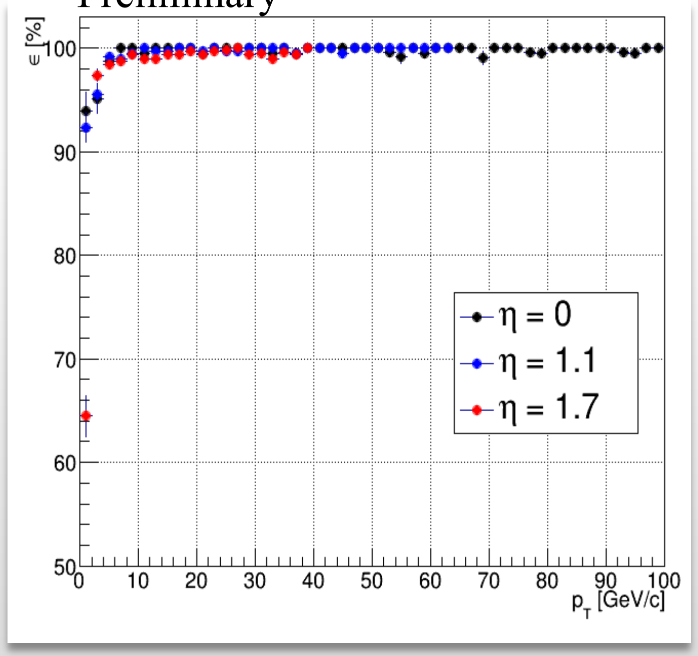
Three pseudo-rapidity values



Preliminary



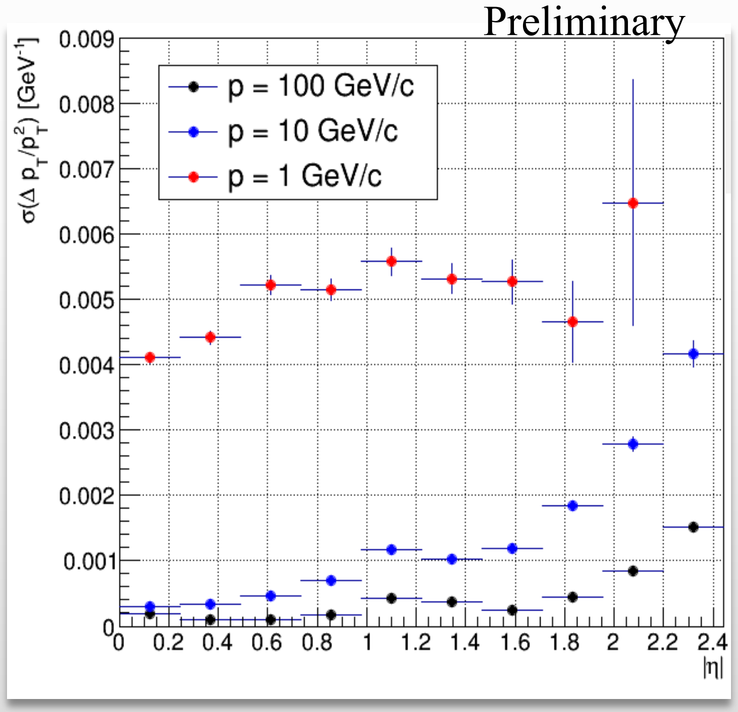
Preliminary

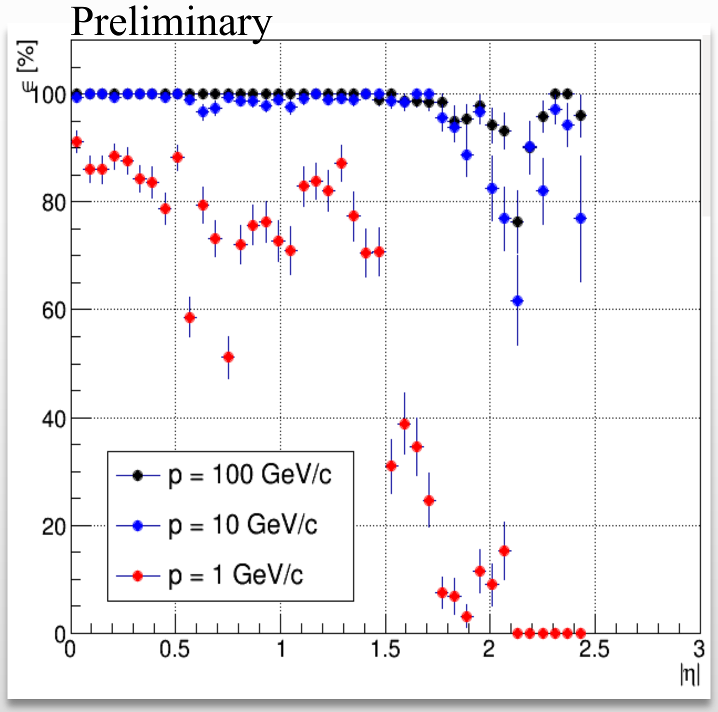


Tracking Performance at $\sqrt{s}$ =1.5 TeV cont'd

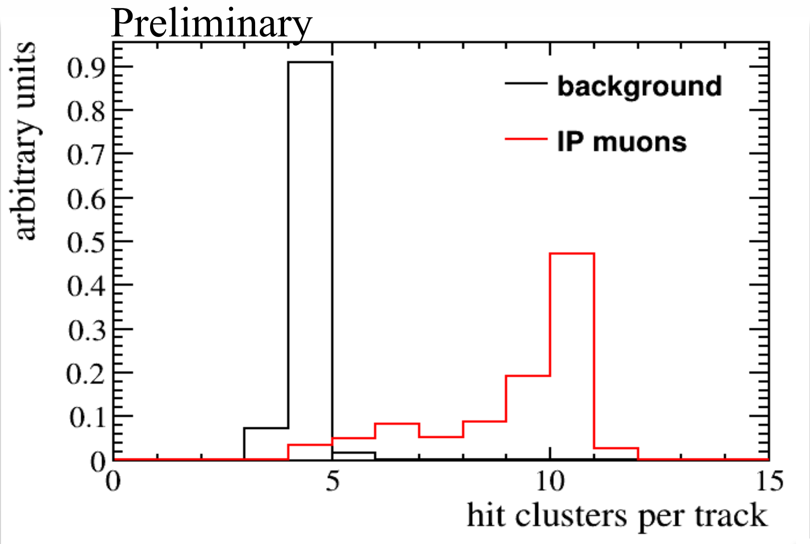
Evaluate track p_T resolution and efficiency by using 1M of single muons

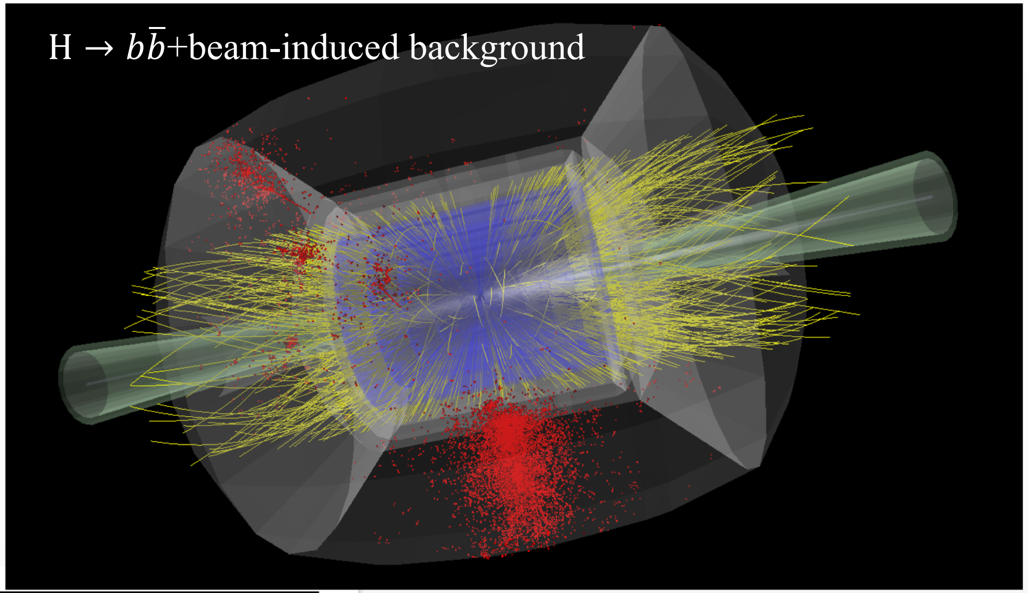
Three momentum values

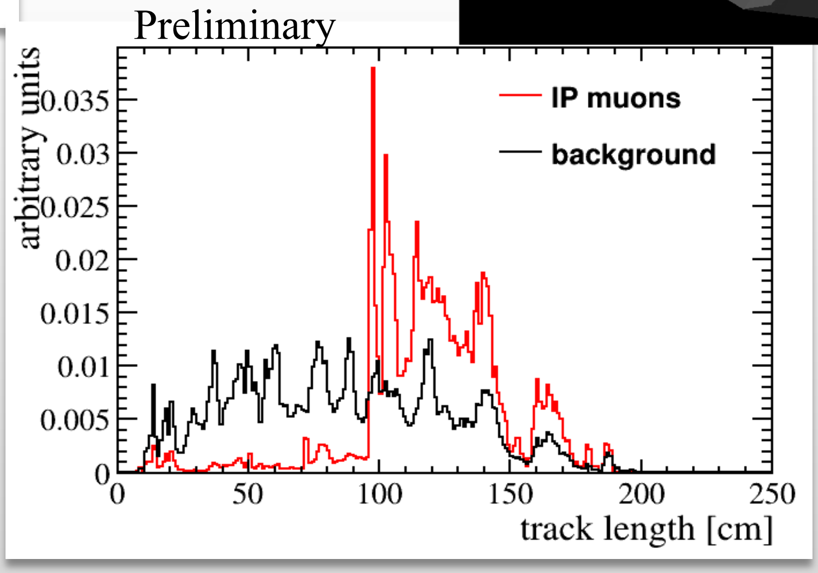




Tracking Performance at $\sqrt{s}$ =1.5 TeV cont'd







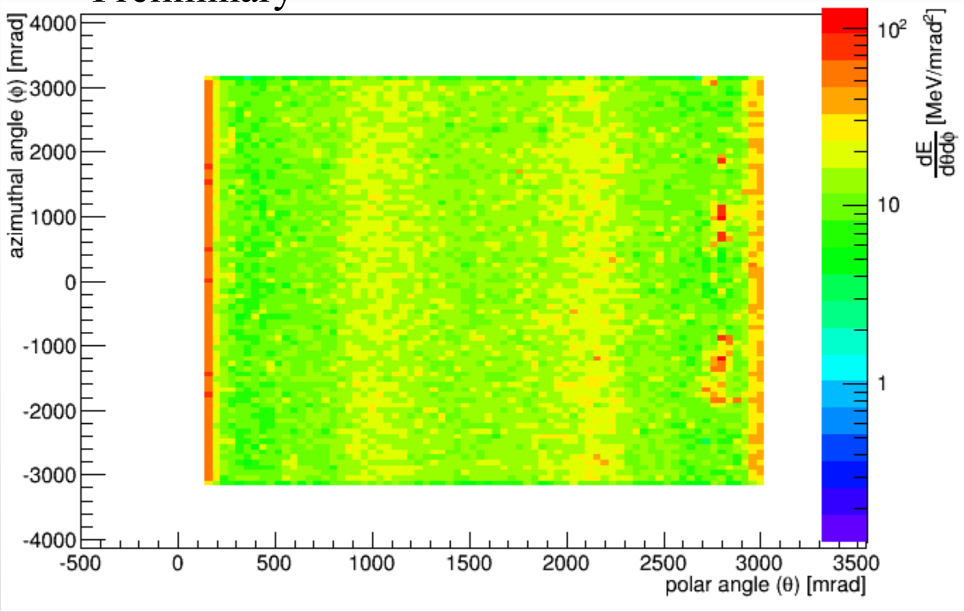
Compare single muons tracks properties with the beam-induced background

Calorimeter detector at $\sqrt{s}$ =1.5 TeV

Dual read-out technology for the moment, best suited calorimeter has to be studied

Beam-induced background generates diffuse occupancy in the calorimeter

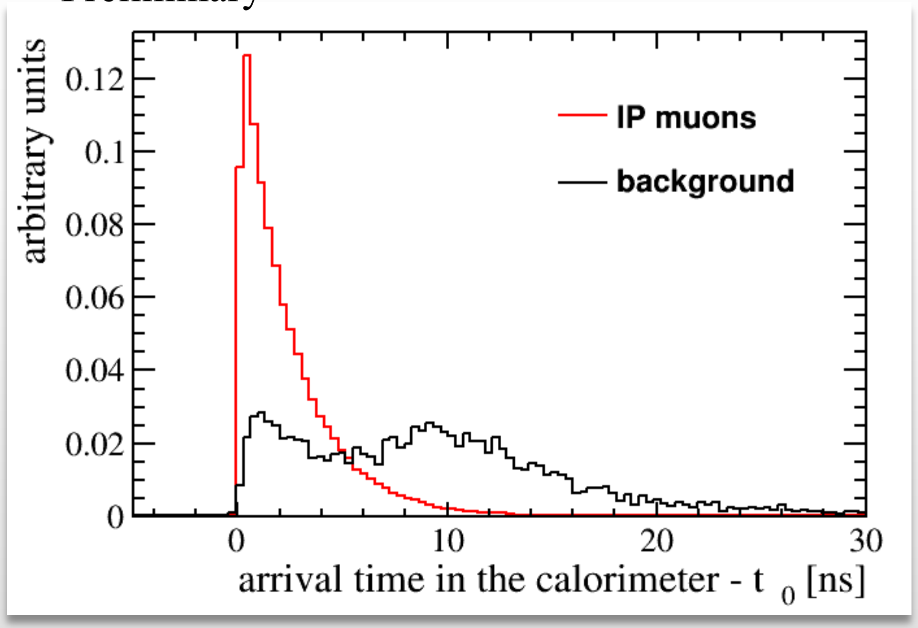
Preliminary



Time requirements will help to reduce beam-induced background on each cell

"5D" detectors has to be developed!

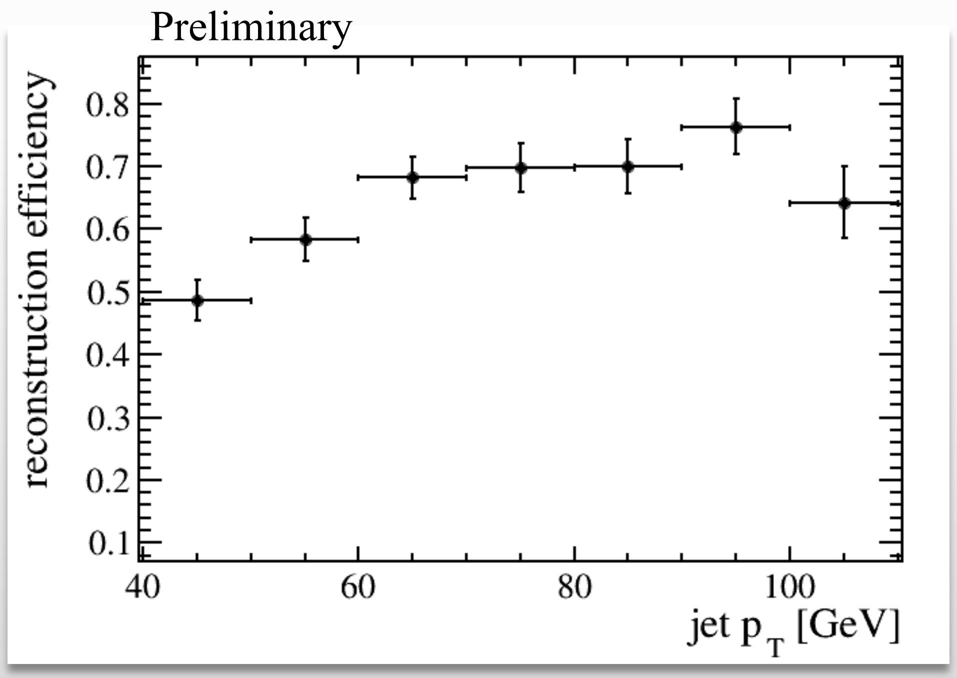
Preliminary



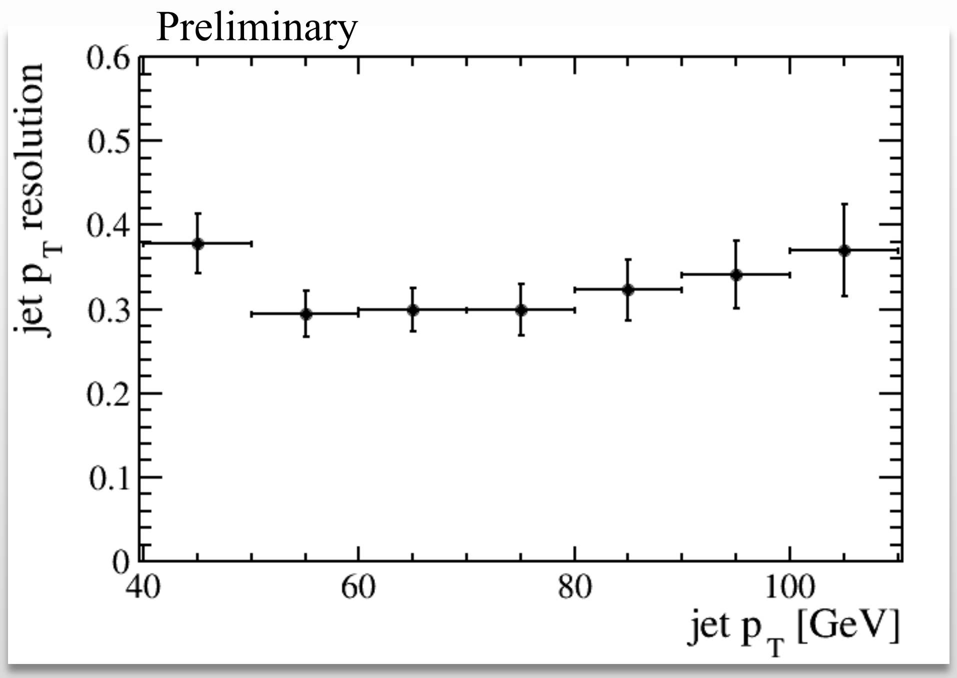
Jet Reconstruction Performance at $\sqrt{s}$ =1.5 TeV

Use a very simple cone jet algorithm, room for a lot of improvements!

- Removal of the "average" energy as if it is underlying event:
  - mean deposited energy $\bar{E}$ and σ_E are calculated for each "wedge"
- If the cluster energy $E_{cl} - \bar{E} > 2\times\sigma_E \Longrightarrow$ the cluster is used in the algorithm with $E_{cl}^N = E_{cl} - \bar{E}$
- Use the cone algorithm with $R = 0.5$



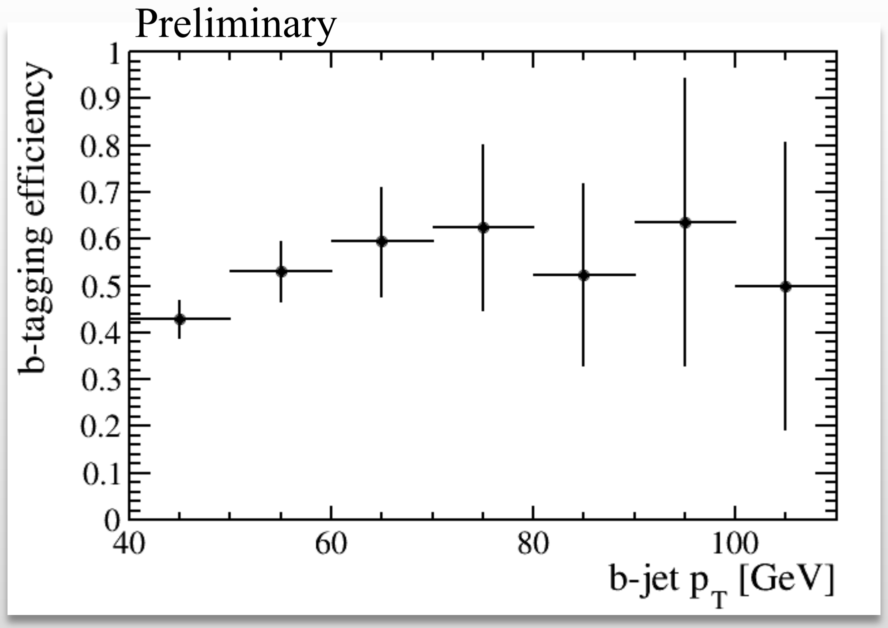
Fake jets
~25%



b-Jet Tagging Performance at $\sqrt{s}$ =1.5 TeV

Very simple tagging algorithm, inspired by LHCb:

- Select tracks with $p_T > 500$ MeV and impact parameter $d > 400$ μm w.r.t. interaction point;
- Form two-tracks vertices by requiring the distance of closest approach $d_{ca} < 200$ μm and $p_T^{2tracks} > 2$ GeV;
- Three-tracks vertices are formed starting from the two-tracks couples.



Background tagging:

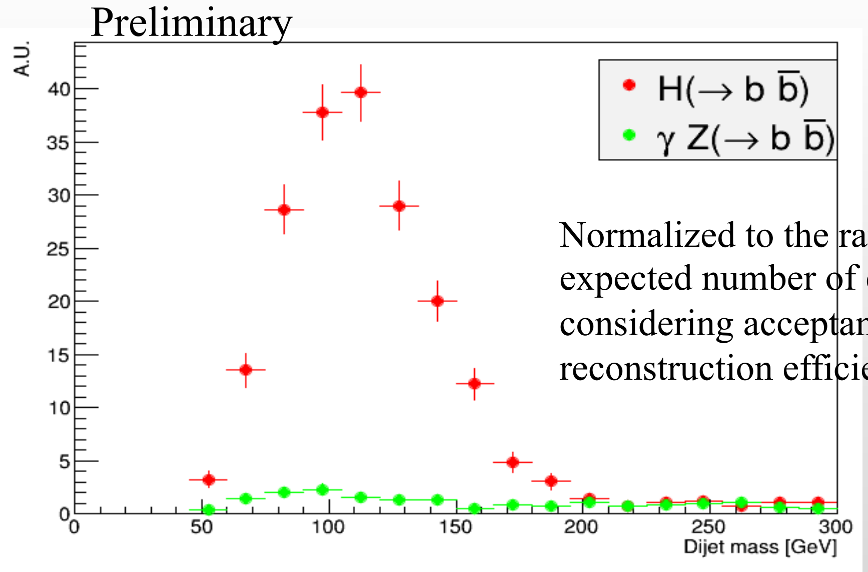
- Low statistics when all clean-up cuts are applied
- fake rate: 1 ÷ 3 %

It needs to be studied with more statistics.
Tests done so far show fake rate is manageable.

$b\bar{b}$ Studies at $\sqrt{s}$ =1.5 TeV

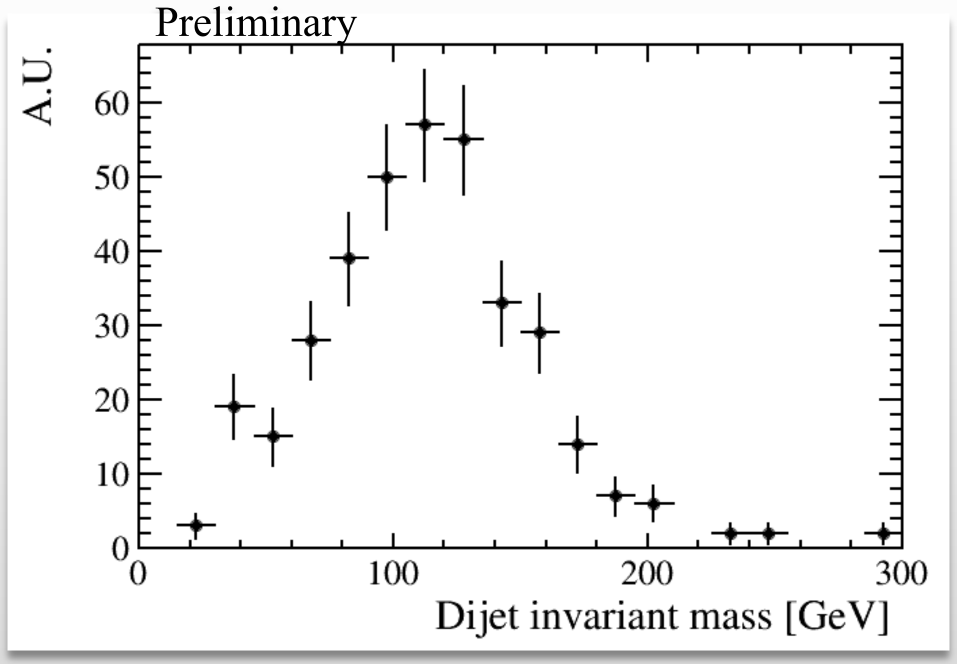
Events $\mu^+\mu^- \rightarrow b\bar{b}X$ @$\sqrt{s}$ = 1.5 TeV are generated with PYTHIA 8

Process	cross section [pb]
$\mu^+\mu^- \rightarrow \gamma^*/Z \rightarrow b\bar{b}$	0.046
$\mu^+\mu^- \rightarrow \gamma^*/Z\gamma^*/Z \rightarrow b\bar{b}$ +X	0.029
$\mu^+\mu^- \rightarrow \gamma^*/Z\gamma \rightarrow bb\gamma$	0.12
$\mu^+\mu^- \rightarrow HZ \rightarrow b\bar{b}$ +X	0.004
$\mu^+\mu^- \rightarrow \mu^+\mu^- H\ H \rightarrow b\bar{b}$ (ZZ fusion)	0.018
$\mu^+\mu^- \rightarrow \nu_\mu\nu_\mu H\ H \rightarrow bb$ (WW fusion)	0.18



Normalized to the ratio of the expected number of events considering acceptance and reconstruction efficiencies

$\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated



Physics measurements are possible at muon collider ⇒ physics possibilities are investigated.

Higgs $b\bar{b}$ Couplings: Assumptions

$$\sigma(\mu^+\mu^- \to H\nu\bar{\nu}) \cdot BR(H \to b\bar{b}) \propto \frac{g^2_{HWW} g^2_{Hbb}}{\Gamma_H}$$

$$\sigma(\mu^+\mu^- \to H\nu\bar{\nu}) \cdot BR\big(H \to b\bar{b}\big) = \frac{N_s}{A\varepsilon\mathcal{L}T}$$

$$\frac{\Delta\sigma}{\sigma} \simeq \frac{\sqrt{N_s + N_B}}{N_s}$$

$$4\left(\frac{\Delta g_{Hbb}}{g_{Hbb}}\right)^2 = \left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta(g^2{}_{HWW}/\Gamma_H)}{g^2{}_{HWW}/\Gamma_H}\right)^2$$

Taken from e^+e^- with several approximations
arXiv:1608.07538v2

N_s : number of signal events.
N_B: number of background events, $\mu^+\mu^- \to q\bar{q}$ from Pythia + beam-induced background
σ: cross section times BR
A: acceptance; removed nozzle region for $\sqrt{s}$ =1.5 TeV, 2 jets $|\eta| < 2.5$, and $p_T > 40$ GeV
for $\sqrt{s} = 3, 10$ TeV same nozzle angle is conservatively assumed
ε: measured with the full simulation at $\sqrt{s}$ =1.5 TeV, used the same at $\sqrt{s} = 3, 10$ TeV (conservative)
$\mathcal{L}$: $2 \cdot 10^{35}$cm^{-2}s^{-1}
One detector

Higgs $b\bar{b}$ Couplings: Preliminary Results

$\mu^+\mu^-$ $\mathcal{L}: 2 \cdot 10^{35}$cm^{-2}s^{-1}, one detector

$\sqrt{s}$[TeV]	$A\varepsilon[\%]$	$L_{int}[fb^{-1}]$	N_S	N_B	$\frac{\Delta\sigma}{\sigma}[\%]$	$\frac{\Delta g_{Hbb}}{g_{Hbb}}[\%]$
1.5	5.3	2000	22000	27000	1.0	1.1
3	5.6	2000	37000	8700	0.58	0.95
10	6.2	2000	67000	1100	0.39	0.92

$\frac{\Delta(g^2{}_{HWW}/\Gamma_H)}{(g^2{}_{HWW}/\Gamma_H)}$: 2% (1.4 TeV)

1.8% (3 TeV)

Taken from e^+e^- with several approximations

arXiv:1608.07538v2

e^+e^-

$\sqrt{s}$[TeV]	$A\varepsilon[\%]$	$L_{int}[fb^{-1}]$	N_S	N_B	$\frac{\Delta\sigma}{\sigma}[\%]$	$\frac{\Delta g_{Hbb}}{g_{Hbb}}[\%]$
1.4	27	1500	65000	270000	0.4	1.0
3	14	2000	120000	840000	0.3	0.9

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.

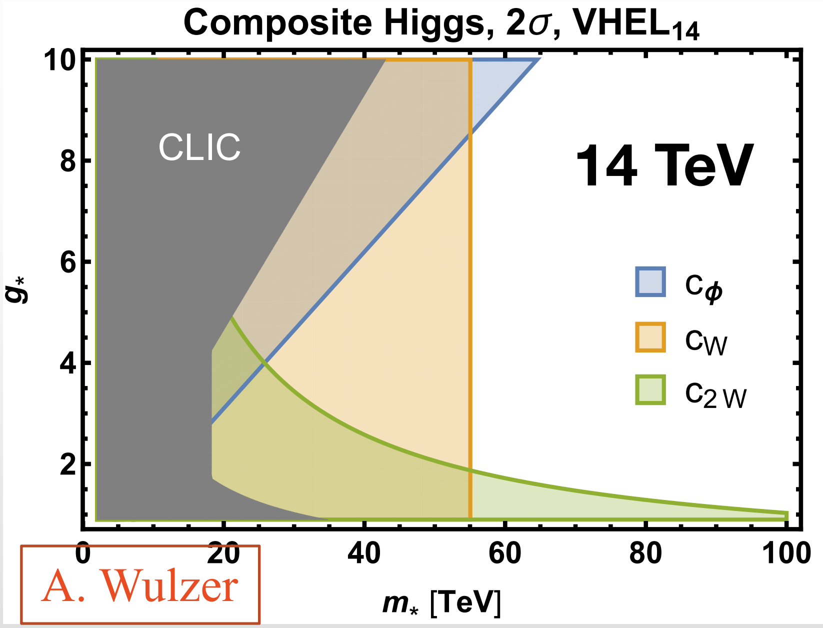
Full simulation is foreseen to establish the k_4 sensitivity.

New Physics

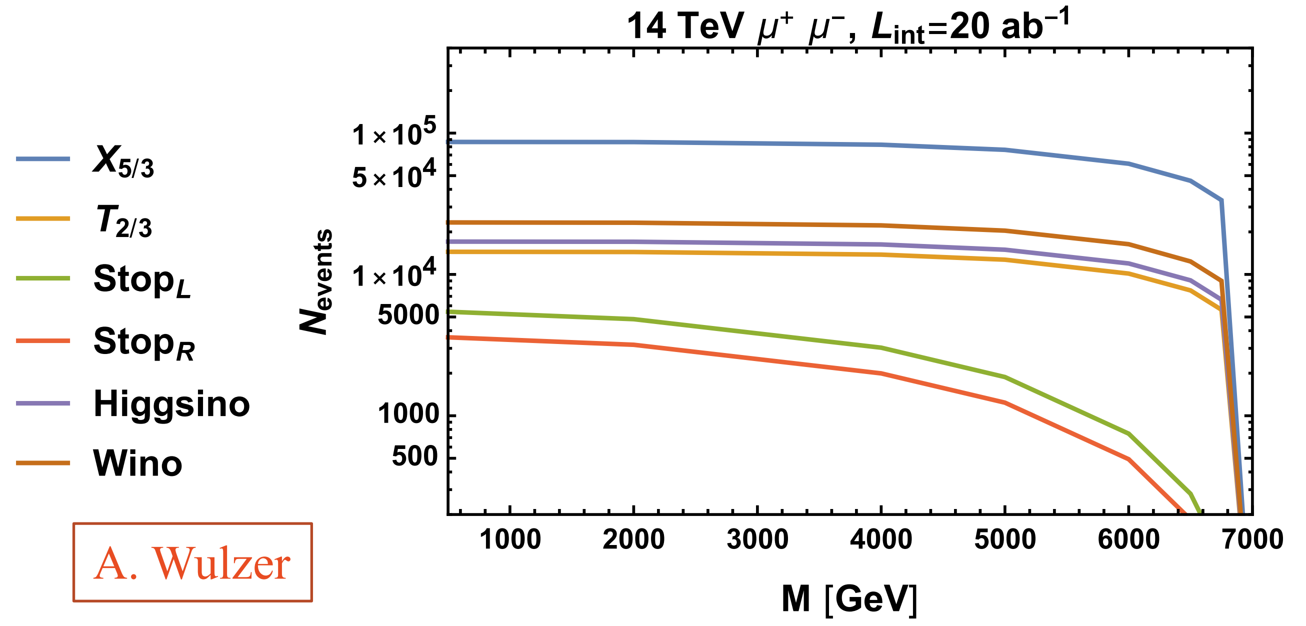
Muon Collider at high energy has great possibilities:

- Higgs compositeness, at $\sqrt{s} = 14$ TeV can reach 60 TeV
- in searching for *new particles*

Wulzer@LHCP-2019



A. Wulzer



A. Wulzer

Summary

- Muon collider allows to access collisions at the highest energy for a given beam energy, and this opens a new research field that has been not only unexplored but even not considered till now

- By using the MAP framework and simulated beam-induced background, first detector performance is assessed demonstrating that precision measurement are possible @$\sqrt{s} = 1.5\ TeV$.
Preliminary results are arXiv:1905.03725. A paper in progress: to be submitted to JINST

Next Challenging Steps

- Moving to the Future Collider Software to make comparison with other colliders easier.

- Advanced reconstruction methods and analysis techniques have to be developed and applied.

Then a change in the paradigm is needed: MDI and detector have to be studied and designed together!

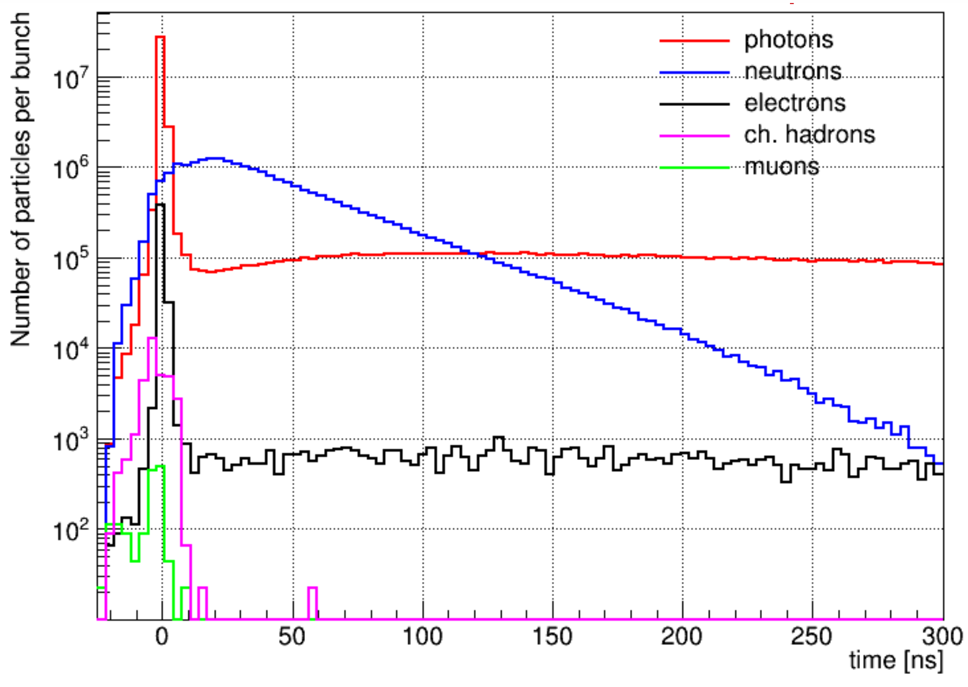
- MDI is available for $\sqrt{s} = 3\ TeV$, $\sqrt{s} = 6\ TeV$, from MAP, $\Rightarrow$ beam-induced background has to be studied and then design a possible detector.

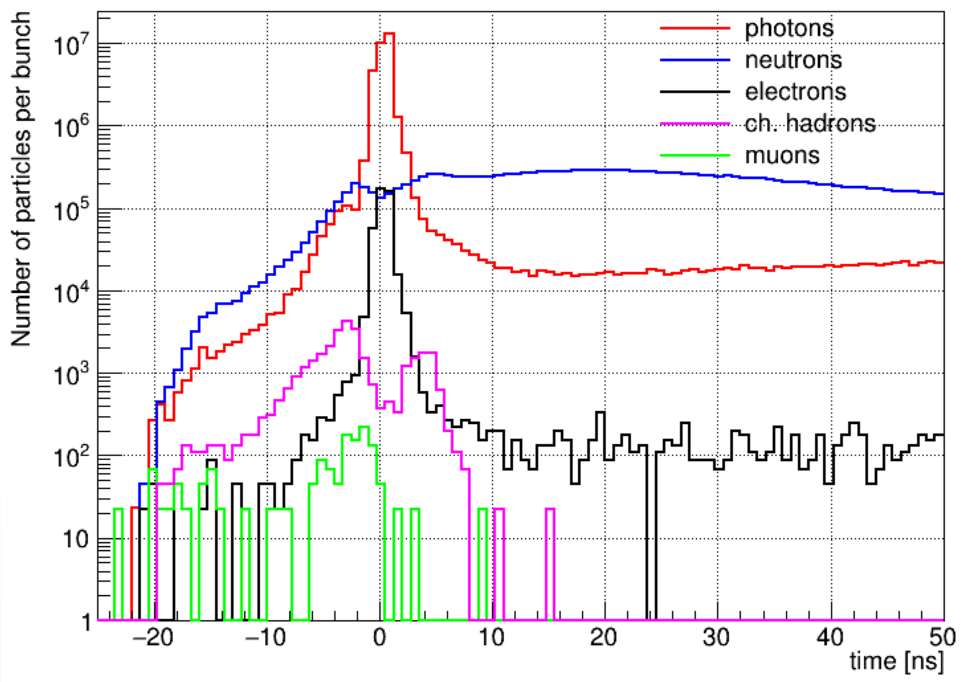
- Interaction Region is needed for $\sqrt{s} = 10\ TeV, \ldots$ MDI and detector have to be designed and optimized. The option of $\sqrt{s} = 340\ GeV$ can be studied as well.

- New detectors have to be designed where position, energy and time resolution are pushed to the limit.

BACKUP

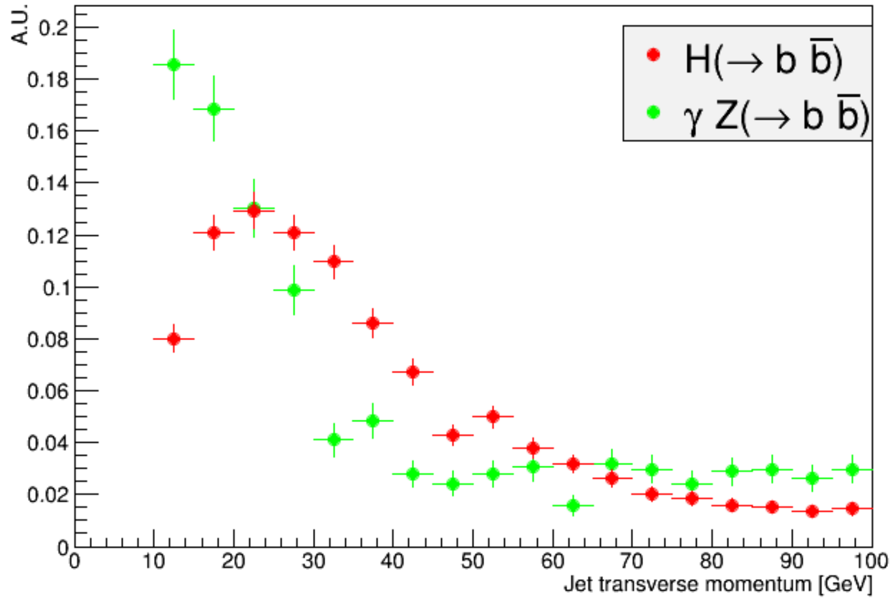
Beam-induced background properties for 750 GeV μ^- beam

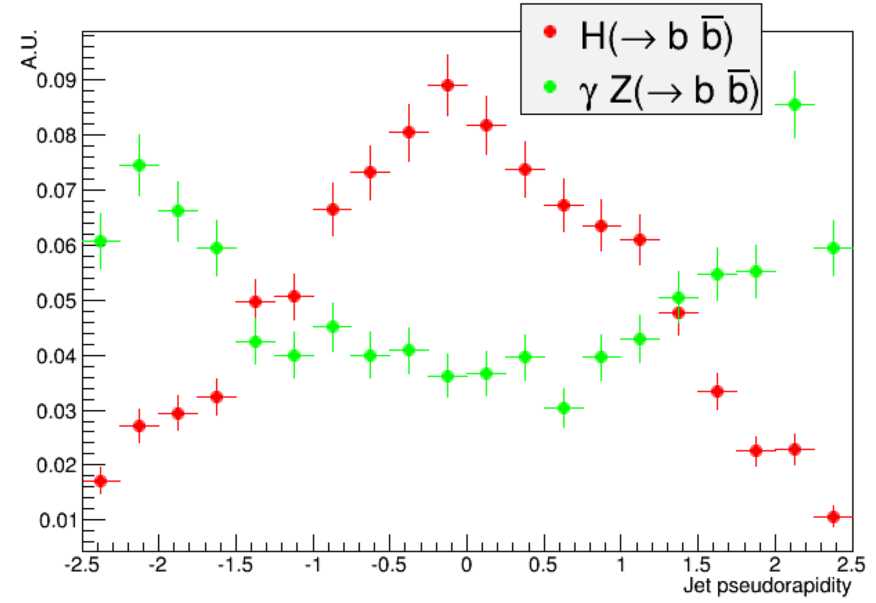




Time information are crucial to reduce the background

Higgs Studies at $\sqrt{s}$ =1.5 TeV



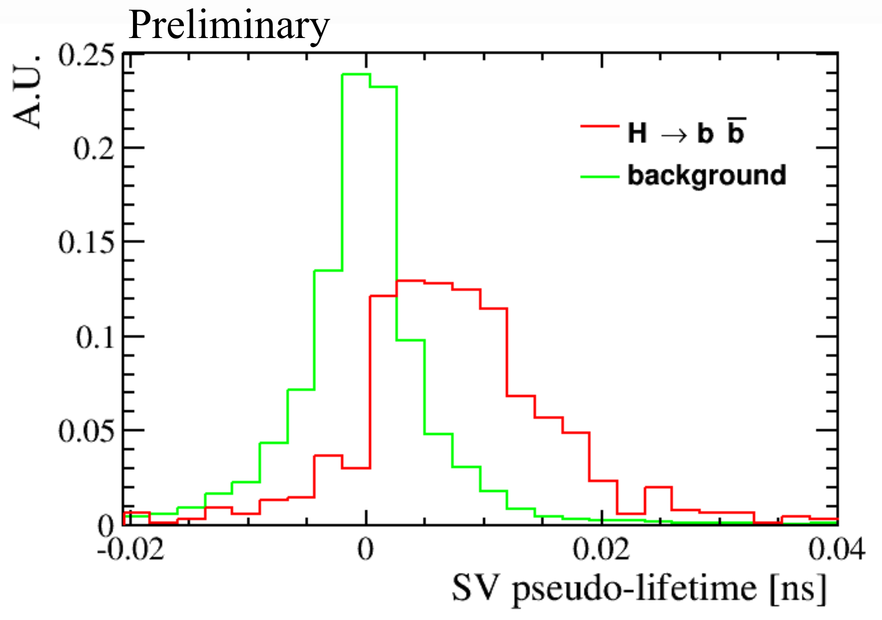


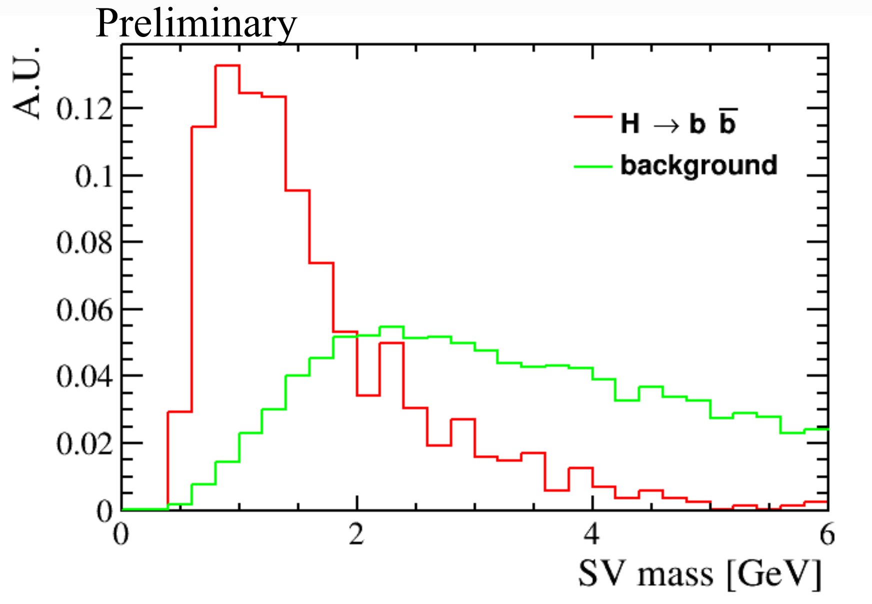
Di-jet mass distributions for Higgs and Z produced in 1.5-TeV muon collisions. The relative normalization of the two distributions is equal to the ratio of the expected number of events, considering the selection efficiencies and the cross sections.

arXiv:1905.03725

b-Jet Tagging Studies at $\sqrt{s}$ =1.5 TeV

Characteristics associated to the tagged vertex are not fully exploited, machine learning algorithms will improve a lot performance





Pseudo-lifetime $t = \frac{m(B)\lambda}{p}$

$t > 0$

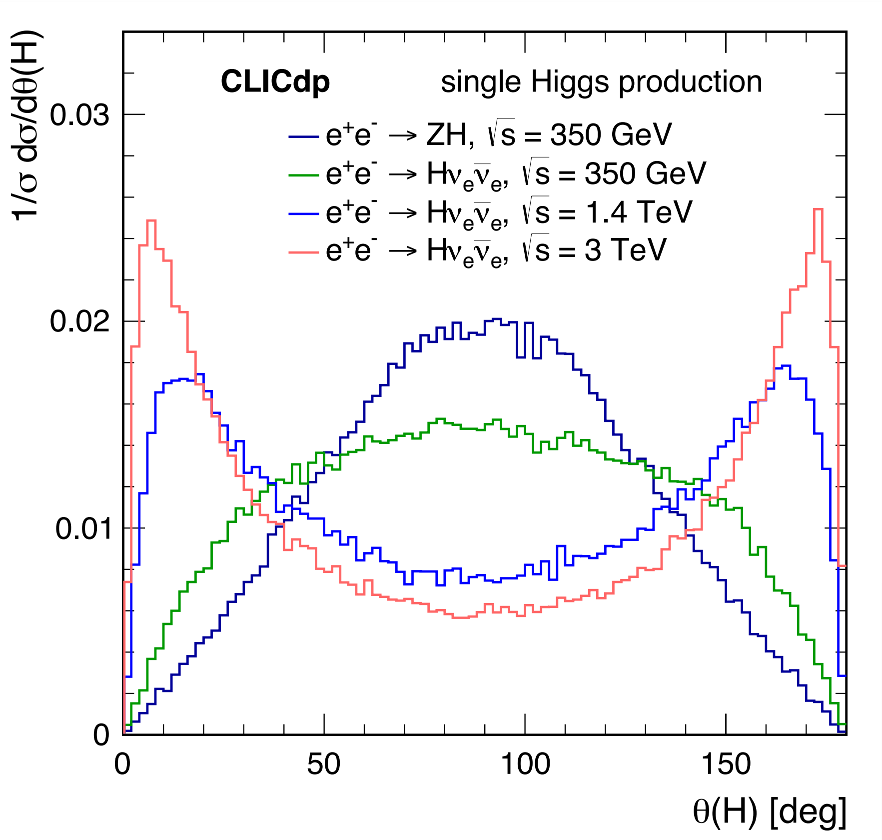
No requirements on the vertex associated mass

Higgs $b\bar{b}$ Couplings: Preliminary Results

$\mu^+\mu^-$ $\mathcal{L}: 2 \cdot 10^{35}\text{cm}^{-2}\text{s}^{-1}$ $T: 10^7\text{s}$

$\sqrt{s}$[TeV]	$A[\%]$	$\varepsilon[\%]$	$A\varepsilon[\%]$	$L_{int}[fb^{-1}]$	N_S	N_B	$\frac{\Delta\sigma}{\sigma}[\%]$	$\frac{\Delta g_{Hbb}}{g_{Hbb}}[\%]$
1.5	35	15	5.3	2000	22000	27000	1.0	1.1
3	37	15	5.6	2000	37000	8700	0.58	0.95
10	39	16	6.2	2000	67000	1100	0.39	0.92

Higgs production



Polar angle distributions for single Higgs events at $\sqrt{s} = 350$GeV, 1.4TeV and 3TeV, including the effects of the CLIC beamstrahlung spectrum and ISR.
The distributions are normalised to unity.