International
MUON Collider
Collaboration

Higgs Pairs Workshop 2022

Double Higgs Prospects at Muon Collider

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Yet another collider

Muons are fundamental point-like particles:

- ✯ well defined initial state and cleaner final states;
- ✯ collision energy fully available in the hard-scattering process.

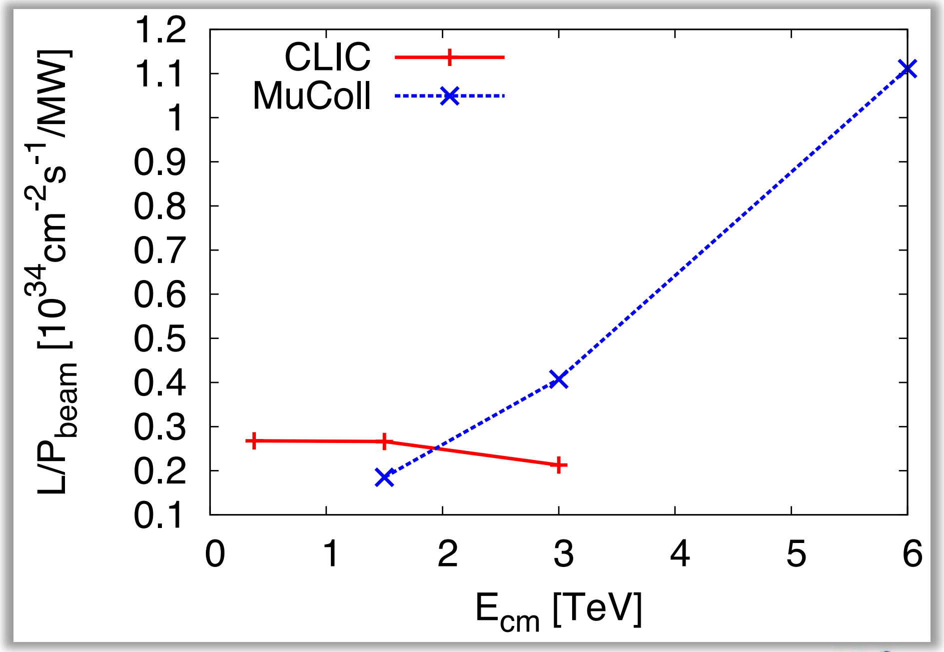
Muons can be accelerated to a multi-TeV energy:

- low synchrotron radiation losses ($m_\mu/m_e \sim 200$)

  ⇓

  compact circular machine with a relatively small footprint
- no significant beam-strahlung.

Therefore, muon collider is most power-efficient machine at high energies



International Muon Collider Collaboration

International MUON Collider Collaboration

- IMCC started officially on July 3rd 2020: Web site
- Several institutions are collaborating, US via the Snowmass process
- Muon collider is part of European Accelerator R&D Roadmap Yellow Report
- A lot of contributions submitted to the Snowmass process

International MUON Collider Collaboration
March 15, 2022
https://muoncollider.web.cern.ch
https://arxiv.org/abs/2203.07256

Muon Collider Physics Summary

Submitted to the Proceedings of the US Community Study

International MUON Collider Collaboration
https://arxiv.org/abs/2203.07964
March 16, 2022
https://muoncollider.web.cern.ch

Simulated Detector Performance at the Muon Collider

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

International MUON Collider Collaboration
https://arxiv.org/abs/2203.07224
March 15, 2022
https://muoncollider.web.cern.ch

Promising Technologies and R&D Directions for the Future Muon Collider Detectors

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

International MUON Collider Collaboration
April 1, 2022
https://muoncollider.web.cern.ch
https://arxiv.org/abs/2203.08033

A Muon Collider Facility for Physics Discovery

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

International MUON Collider Collaboration
https://arxiv.org/abs/2203.07261
March 15, 2022
https://muoncollider.web.cern.ch

The physics case of a 3 TeV muon collider stage

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Patrick Meade talk

Timeline

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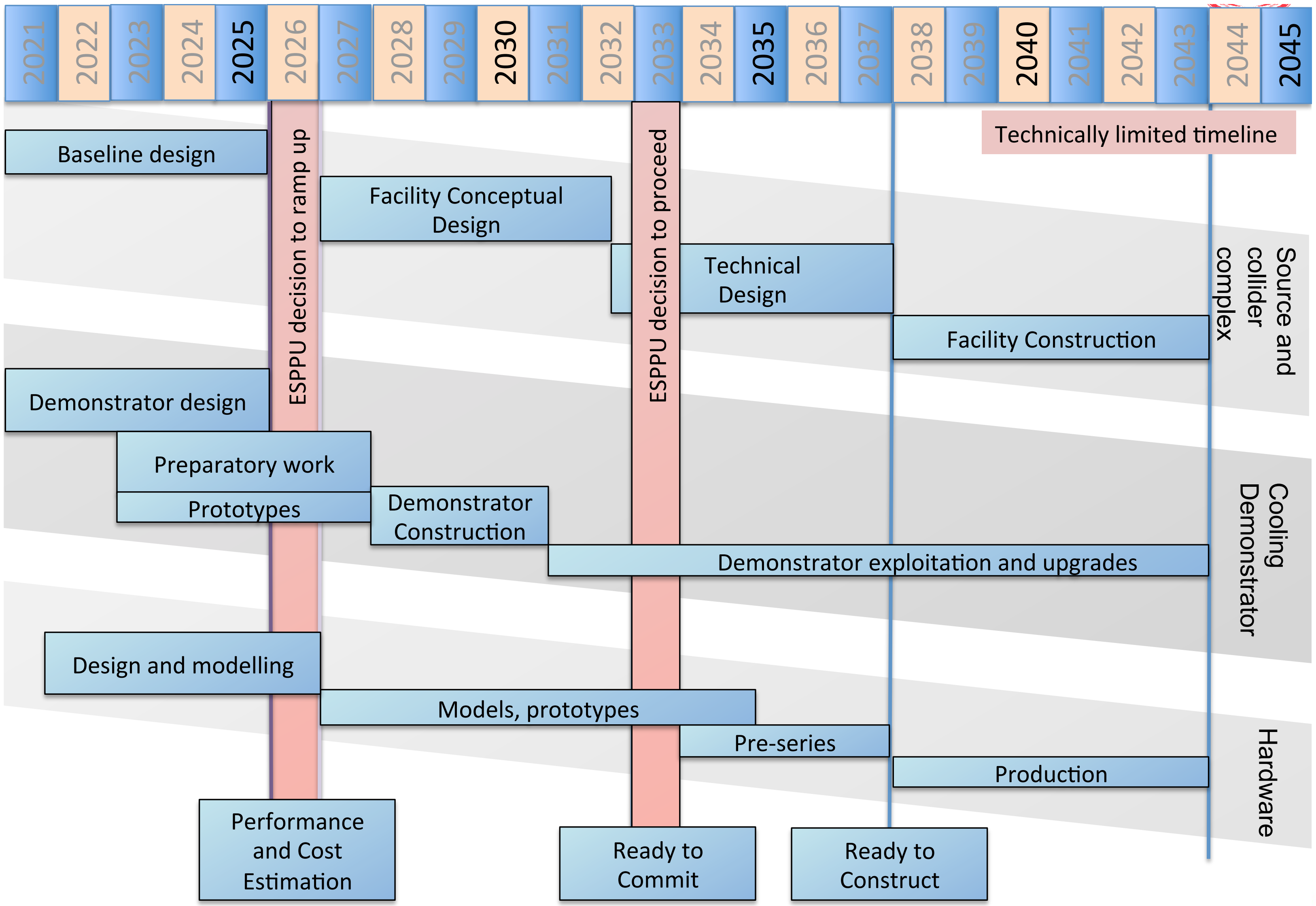
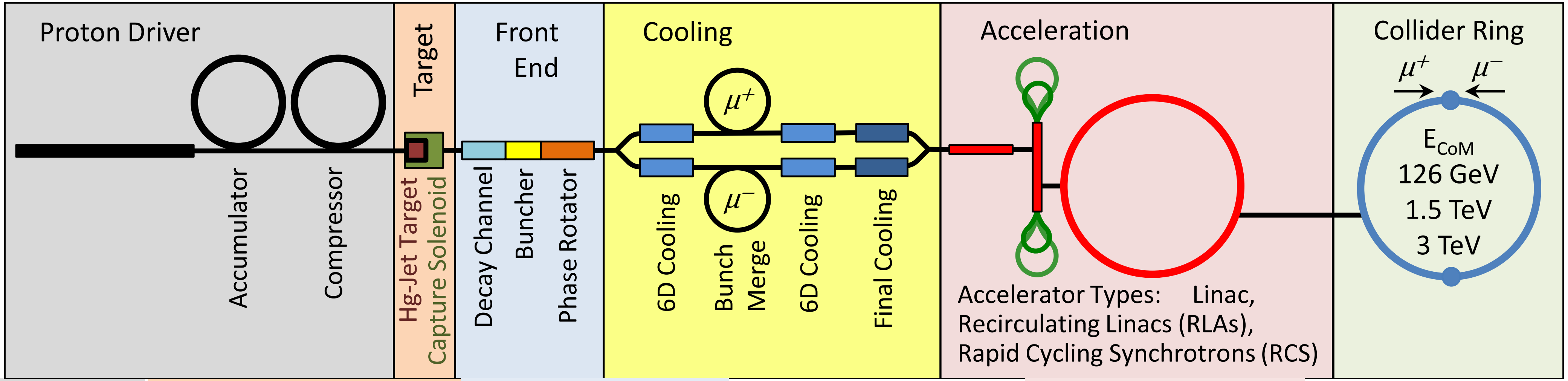
- ✓ Presented to CERN Council in December
- ✓ Published in the Yellow report

A 3 TeV muon collider could be ready by 2045, as reviewed by the Roadmap



Proton-driven Muon Collider Concept

Muon Accelerator Program



- Based on 6-8 GeV Linac Source
- H- stripping requirements similar to neutrino ones

- high power target
- π production in high-field solenoid

- RF cavities bunch & phase rotate $\mu^{\pm}$ into bunch train

- Ionization cooling 6D
- MICE

- Fast acceleration
- Use RF and SC

- $\mu^{\pm}$ decay background
- Critical Machine Detector Interface

Baseline Facility

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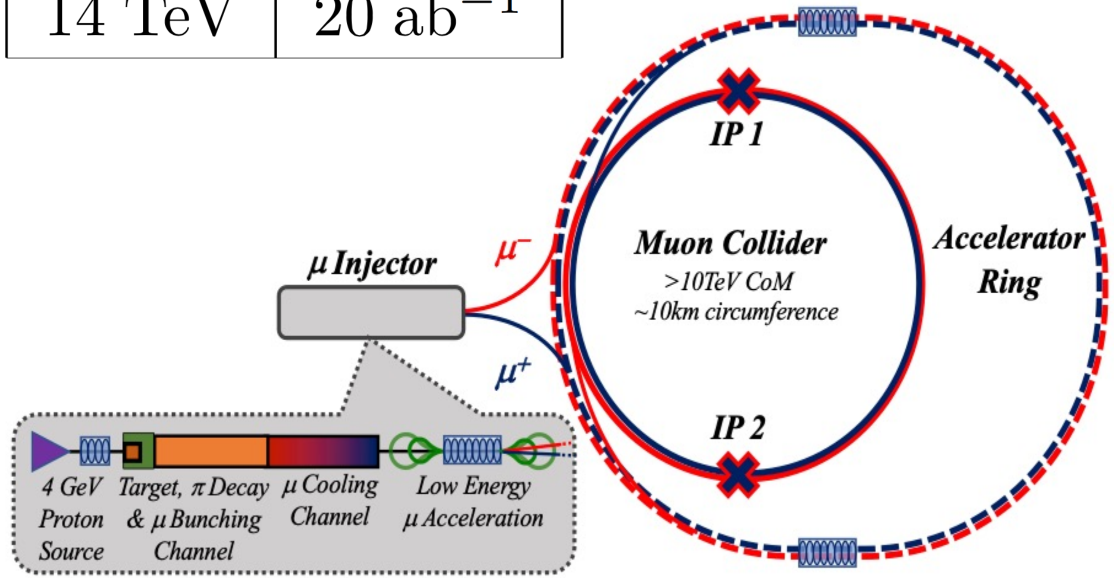
Target Integrated Luminosity in 5 years one experiment

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	$1\ \text{ab}^{-1}$
10 TeV	$10\ \text{ab}^{-1}$
14 TeV	$20\ \text{ab}^{-1}$



Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\ \text{cm}^{-2}\text{s}^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Every rose has its thorn

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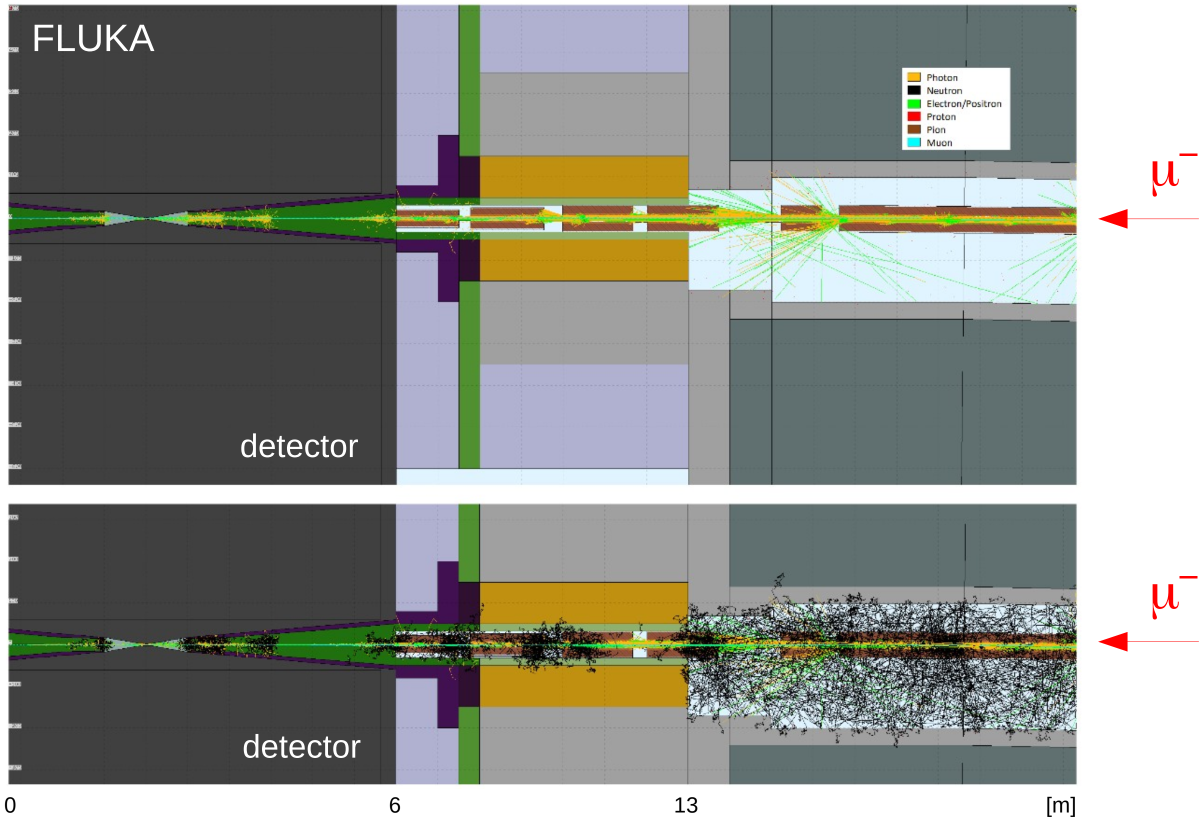
Muons decays with $N_\mu \sim 2 \cdot 10^{12}$ per bunch with E_{beam}= 0.750 TeV produce $4{\times}10^5$decays/meter of lattice

Mainly: electrons/positrons, photons, neutrons, charged hadrons and muons

Current solution to mitigate particle fluxes effects on detector is the nozzles, two conical tungsten shieldings (*nozzles*) cladded with borated polyethylene:

- reduce the background particle flux into the detector by 2-3 orders of magnitude;
- filter out the high-energy tails of the electromagnetic BIB component;
- but reduce detector acceptance.

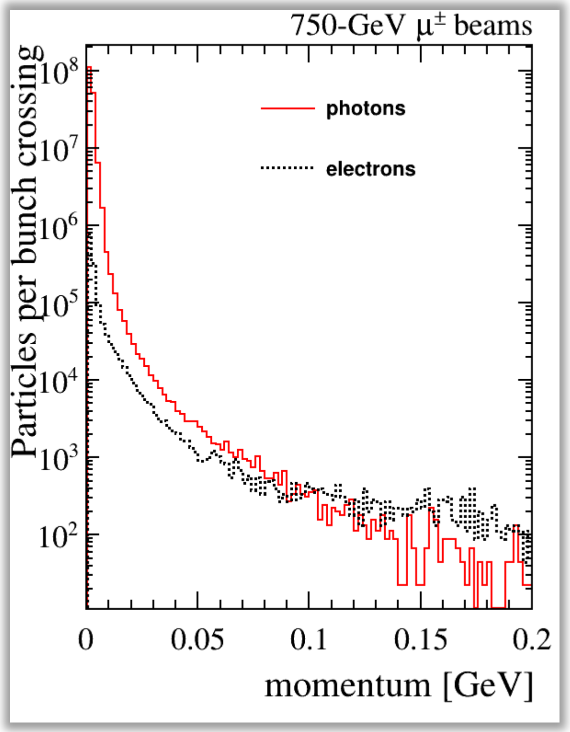
F. Collamati *et al.*, 2021 JINST 15 P11009

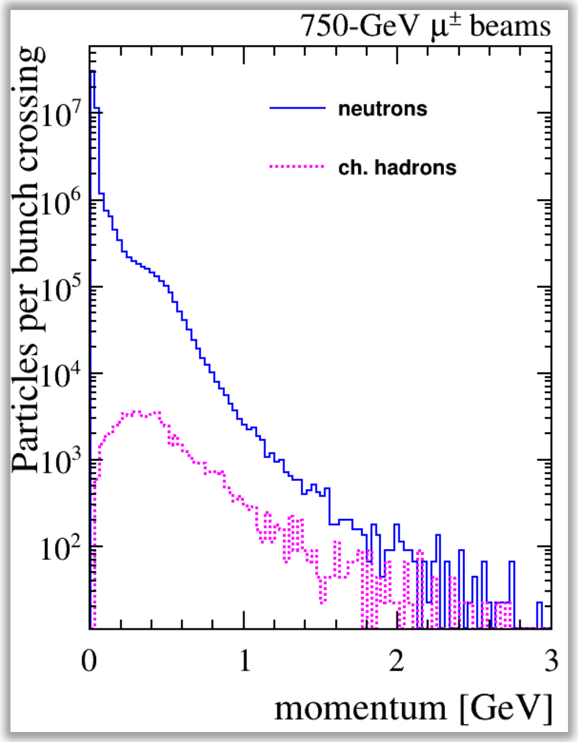


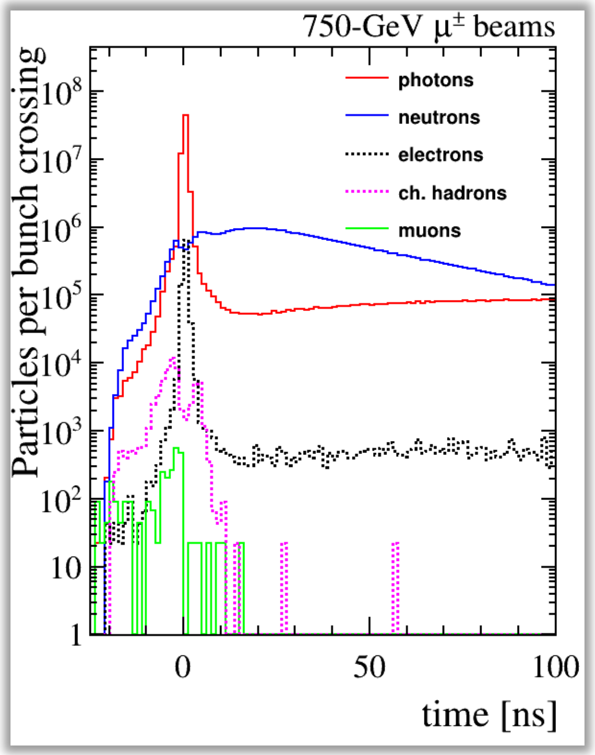
Beam-Induced Background and Detector

Beam-Induced Background Main Properties

N. Bartosik *et al* 2020 *JINST* **15** P05001







- Low momentum particles
- Partially out of time with respect to beam crossing t_0

hadronic calorimeter

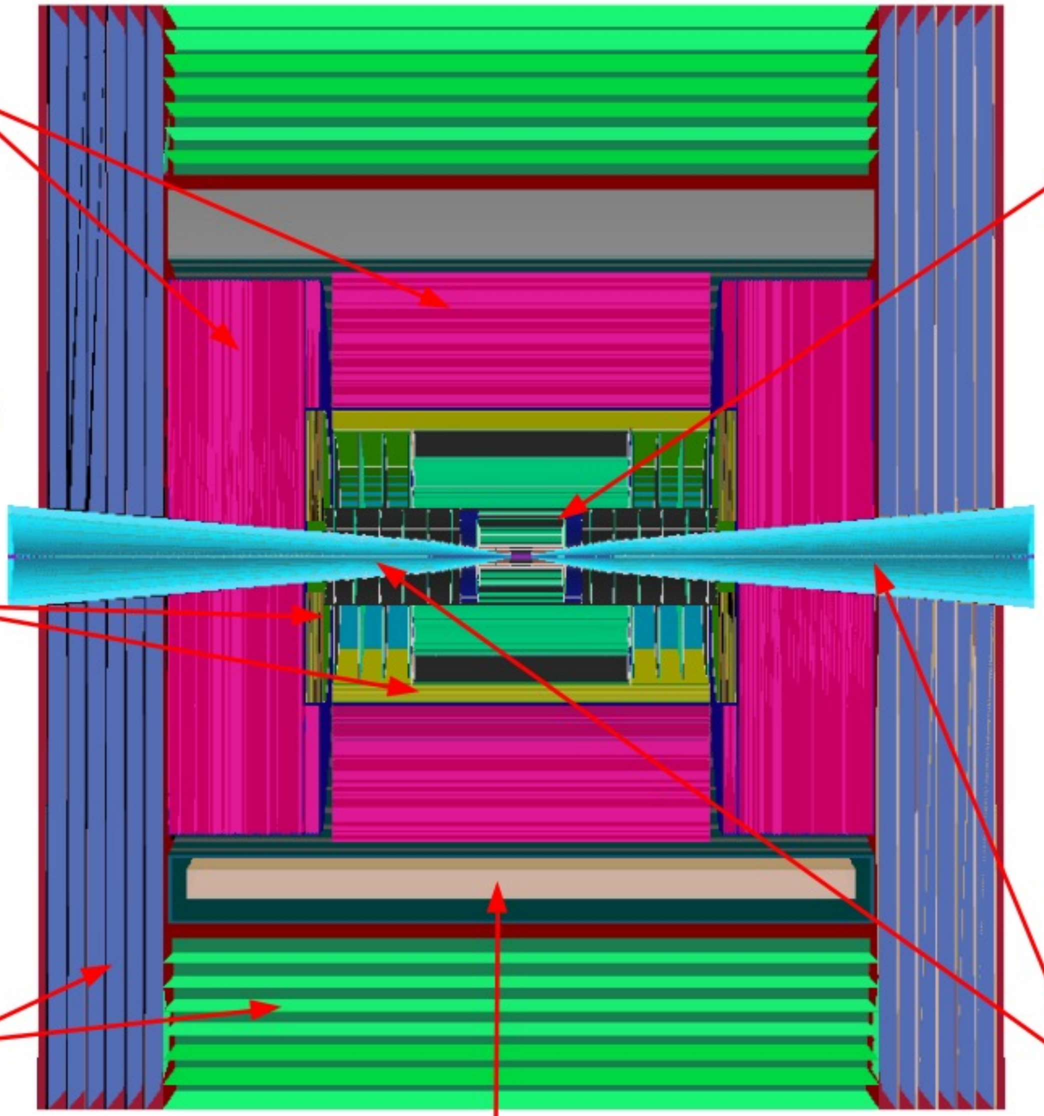
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

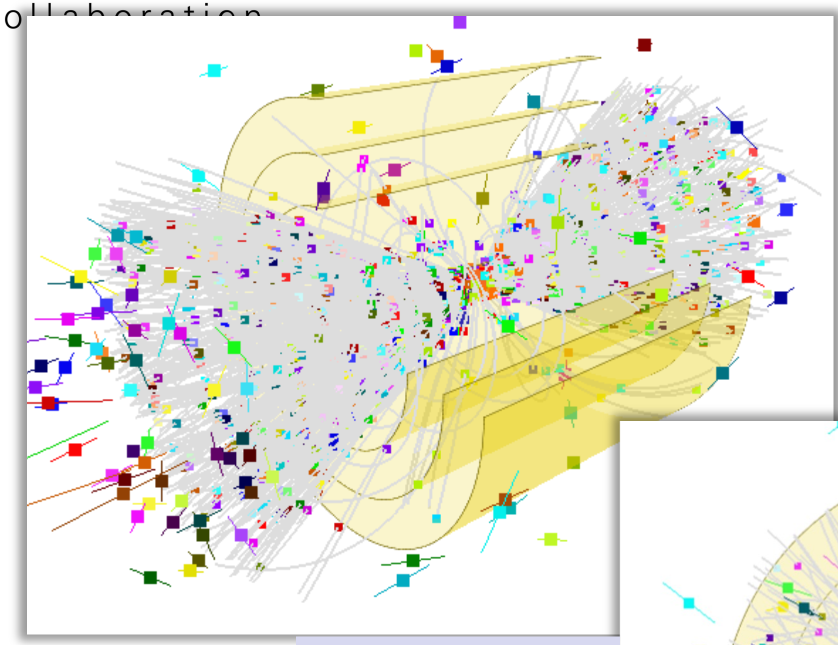
tracking system

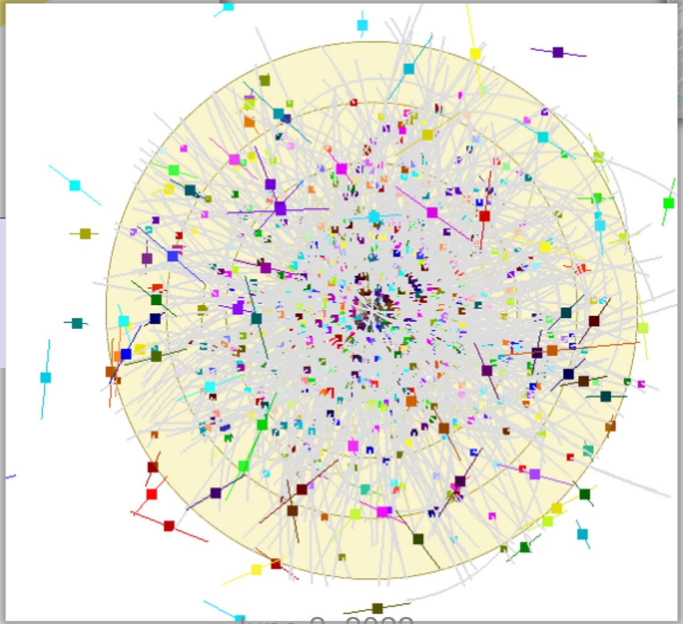
- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 µm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 µm x 10 mm micro-strip Si sensors.

shielding nozzles

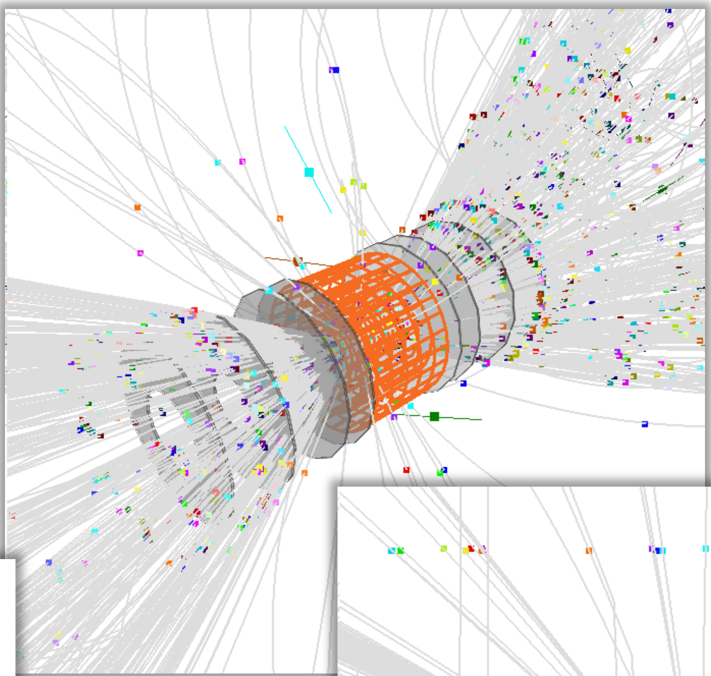
- Tungsten cones + borated polyethylene cladding.

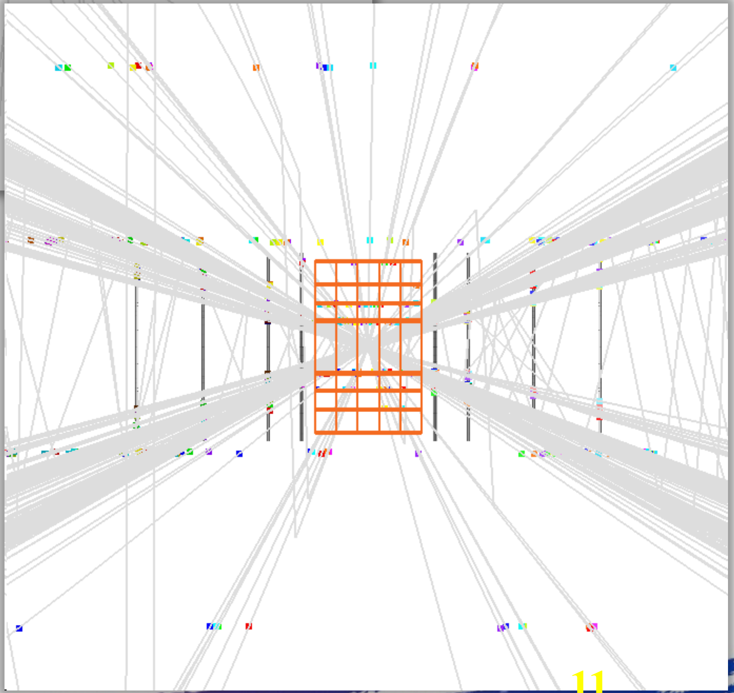
Beam-Induced Background in the tracker





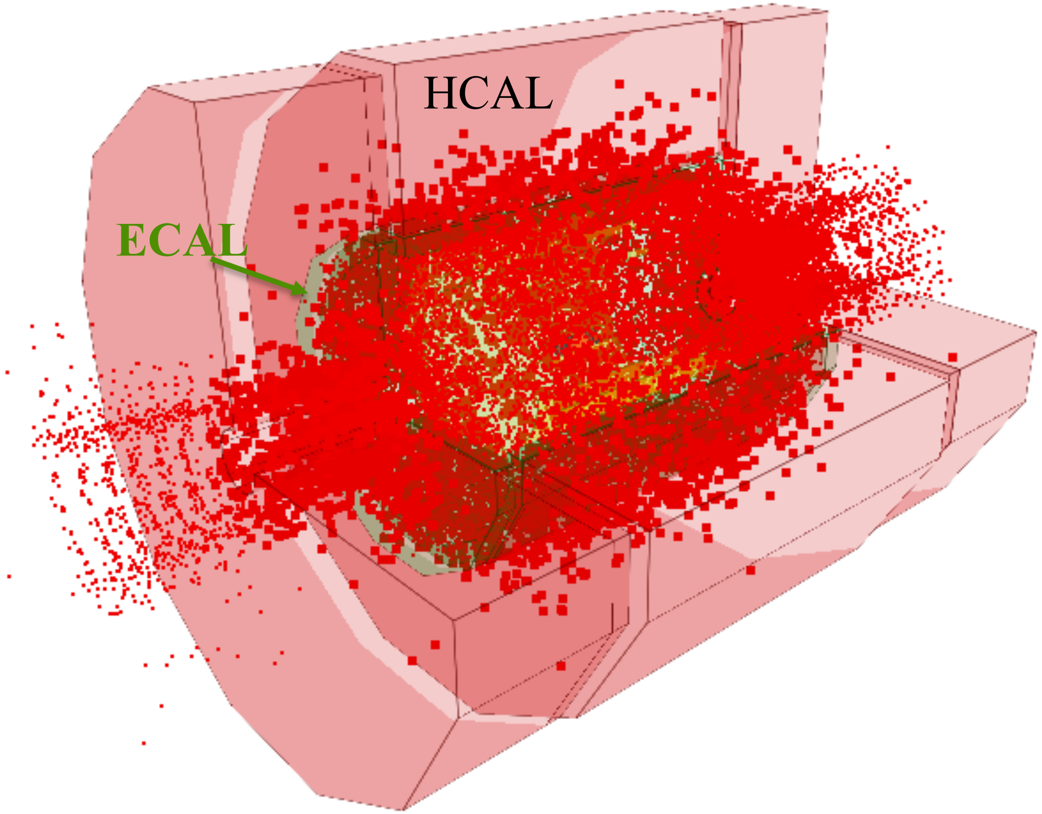
Inner/Outer Tracker

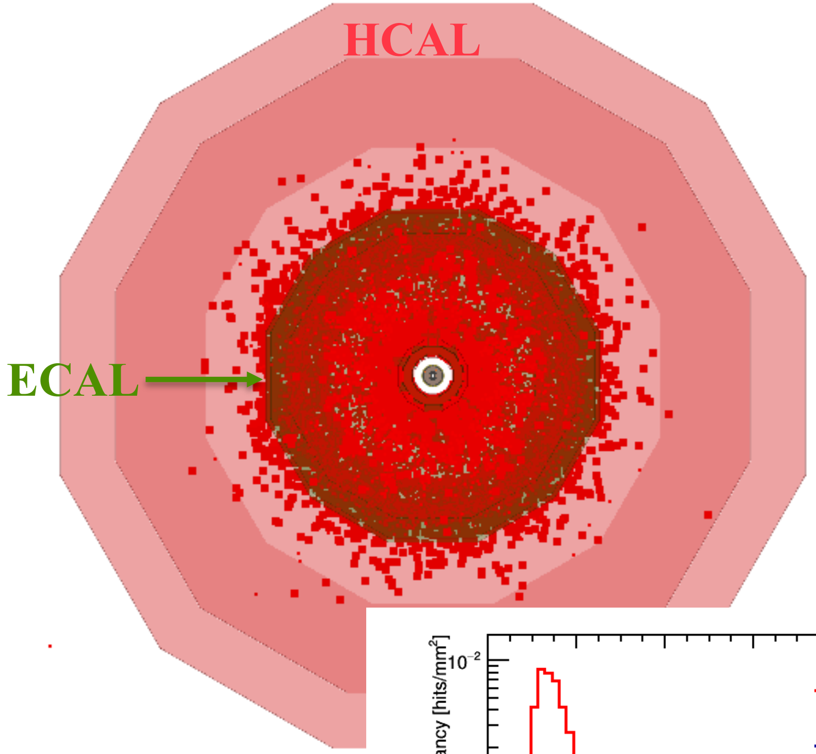


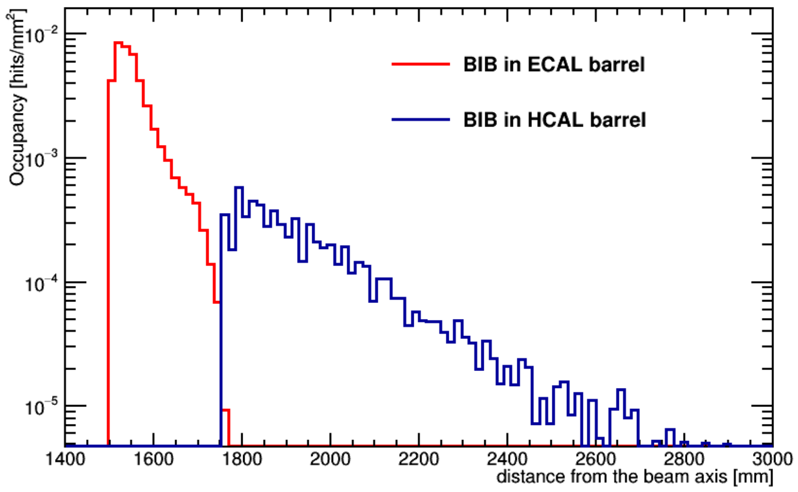


Vertex Detector

Beam-Induced Background in the Calorimeter







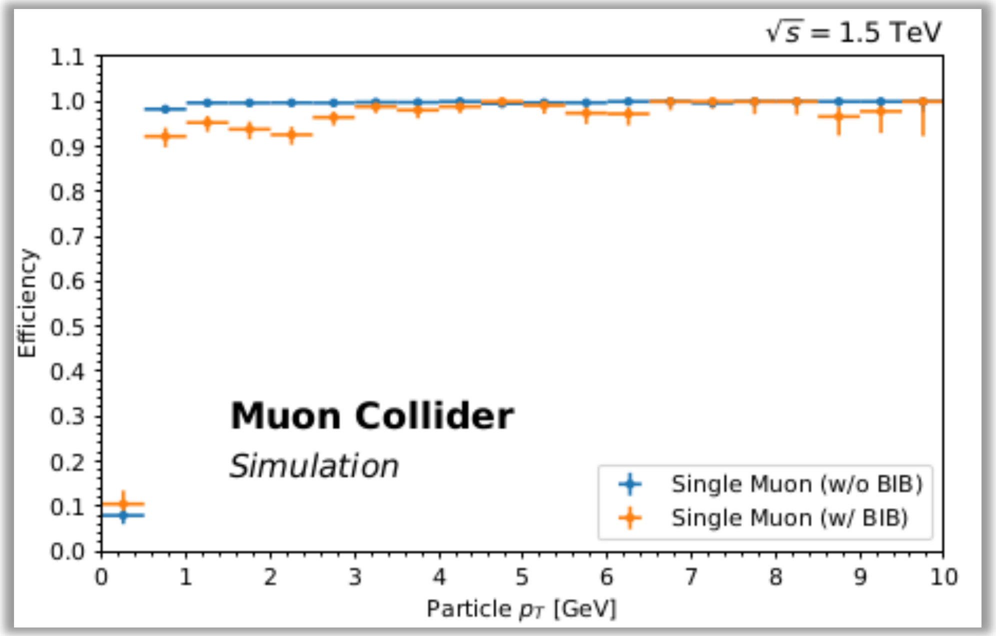
Beam background is not an issue for HCAL

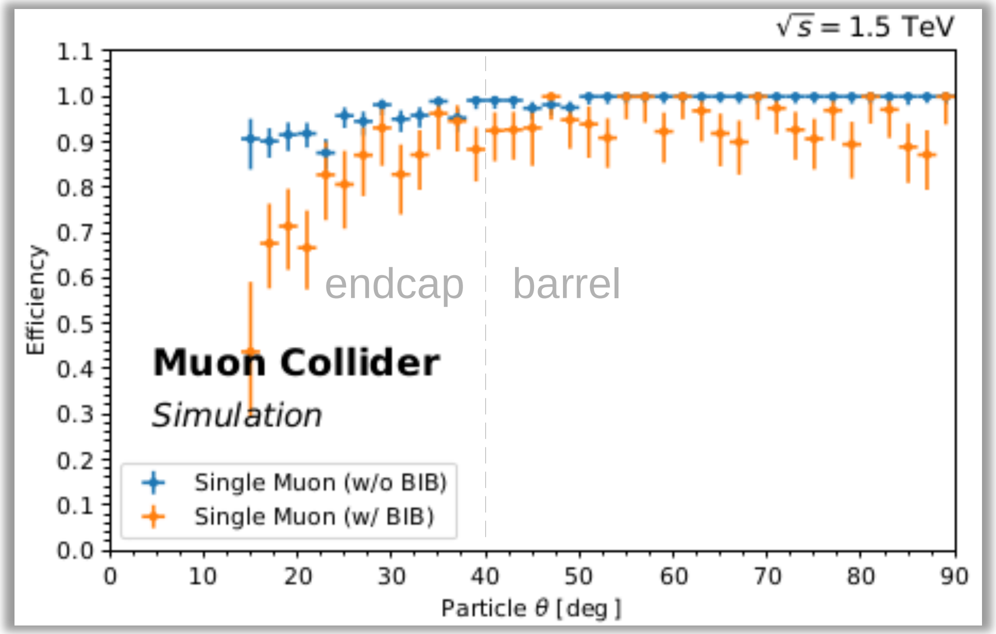
Detector Performance

Tracks reconstruction performance

Despite:
- Use shieldings to mitigate beam-induced background
- Track reconstruction algorithms not optimize yet

Track reconstruction performance already satisfactory



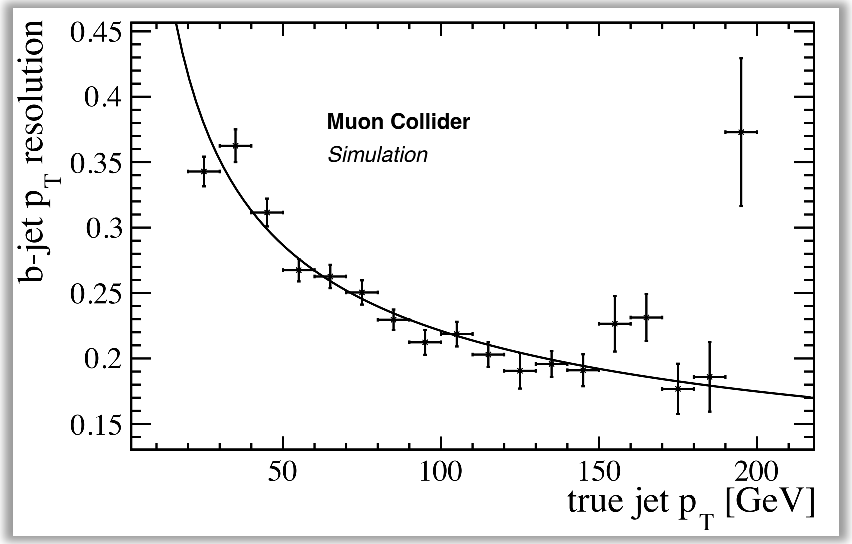


Jets reconstruction performance

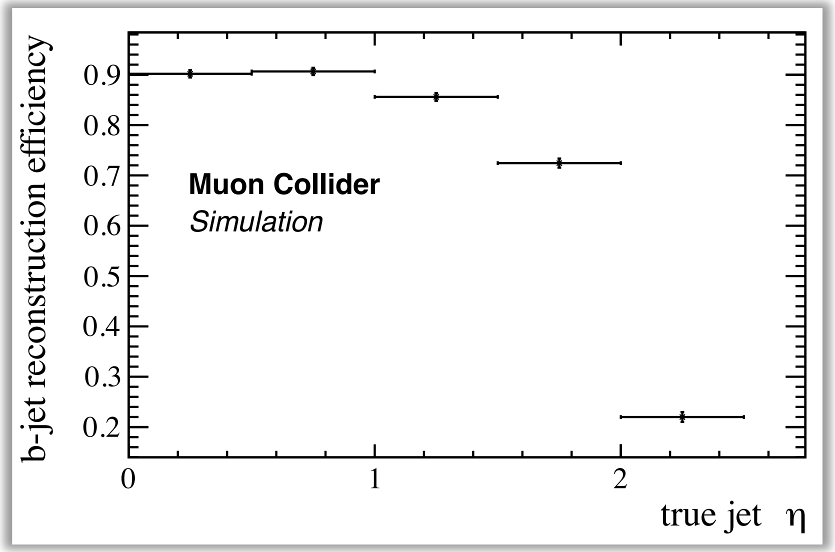
Jets reconstruction proceeds:

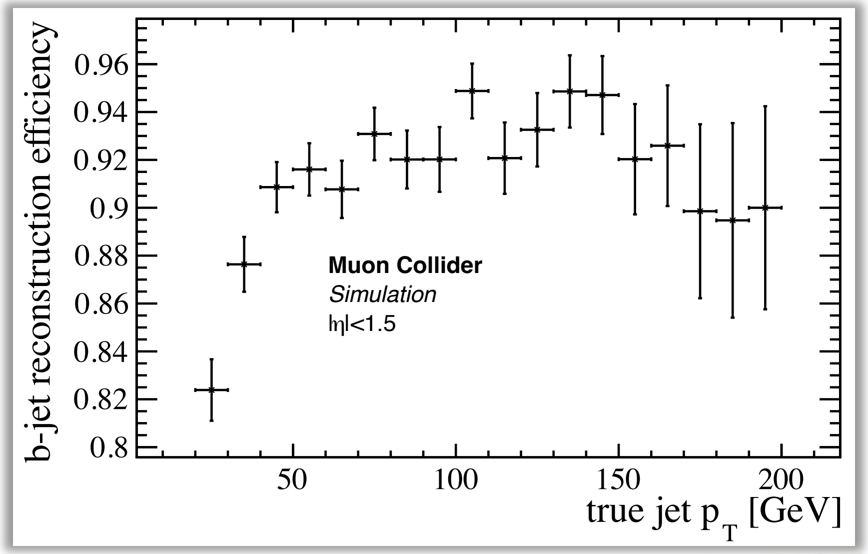
- Filter "on time" calorimeter hits
- Combine track and calorimeter information to reconstruct particles
- Use k_T algorithm to cluster particles in jets
- Apply requirements to remove fake jets (max 0.7%)
- Correct energy

Resolution



Efficiency



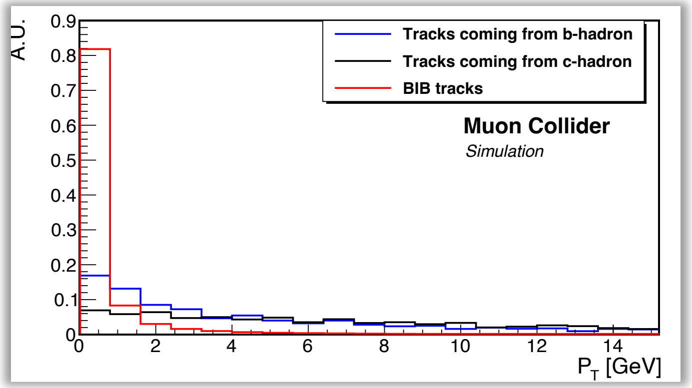


Heavy Flavor Jets Identification

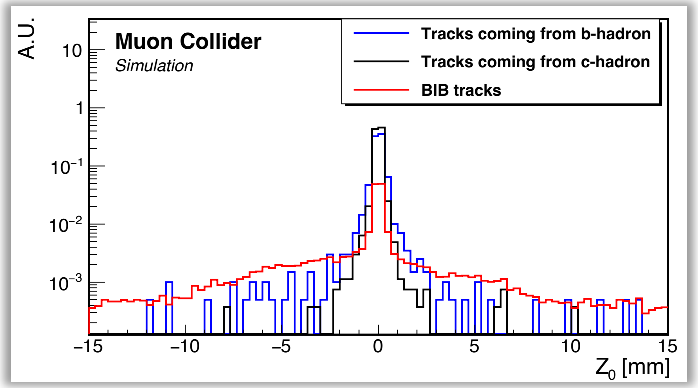
Heavy flavor jets identification :

- Primary vertex (PV) reconstruction
- Secondary vertex (SV) identification: use tracks not compatible with PV rejecting as much as possible fake tracks
- Apply requirements to further reject fake SV

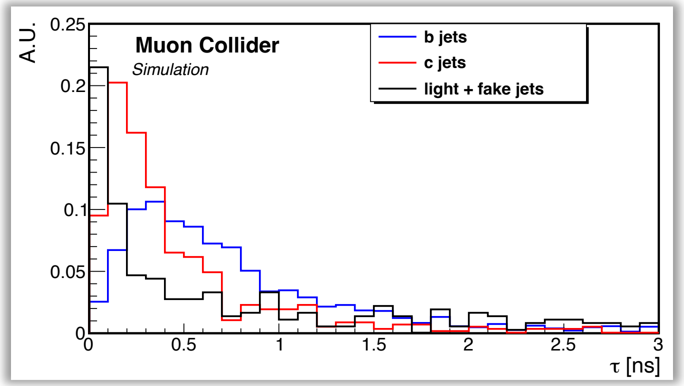
Transverse momentum



Z_0, position along beam



Lifetime



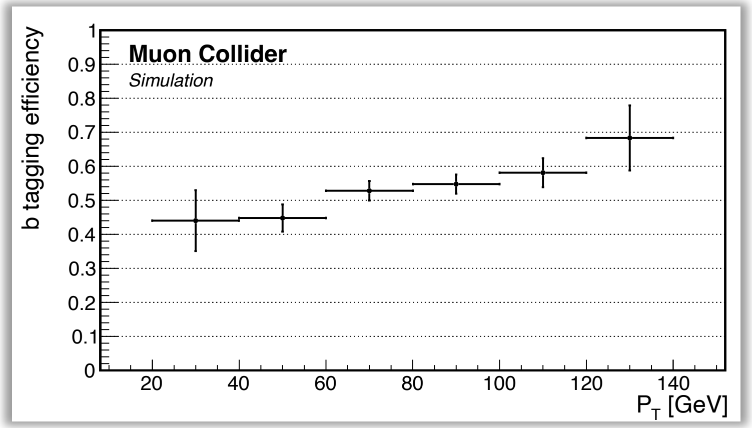
Definitions

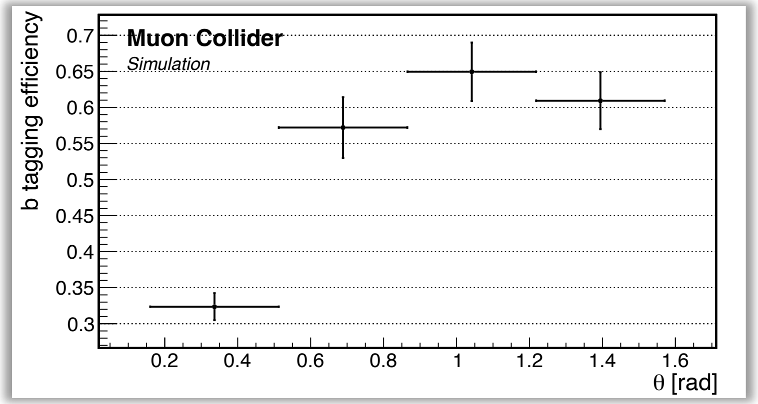
Efficiency $\epsilon_b = \frac{N_{b,SV}}{N_b}$

Mistag $_{\text{c,(light)}}$ $M_{c,(light/fake)} = \frac{N_{c,(light/fake),SV}}{N_{c\,(light/fake)}}$

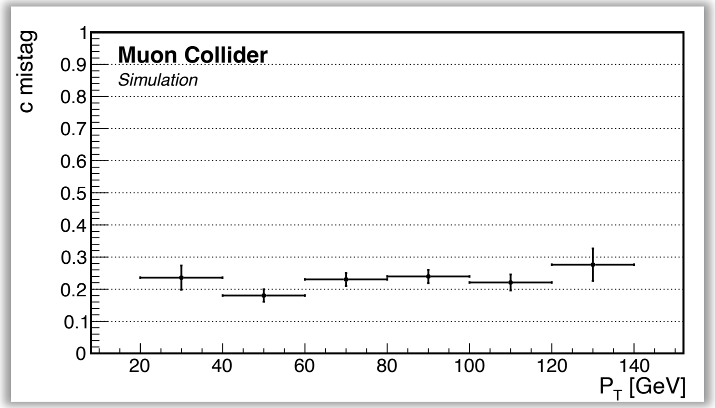
Heavy Flavor Jets Identification Performance

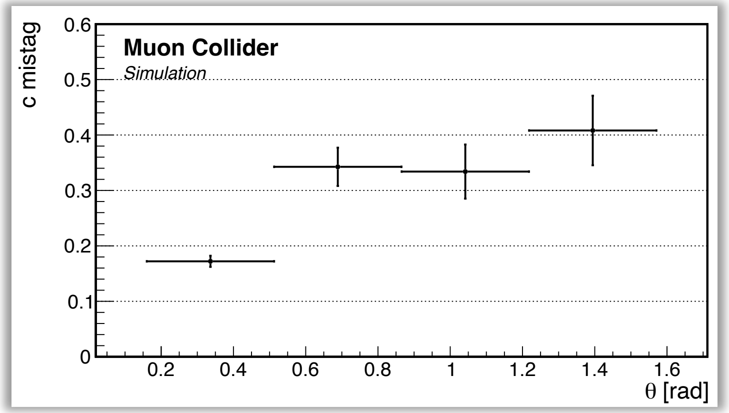
b-quark



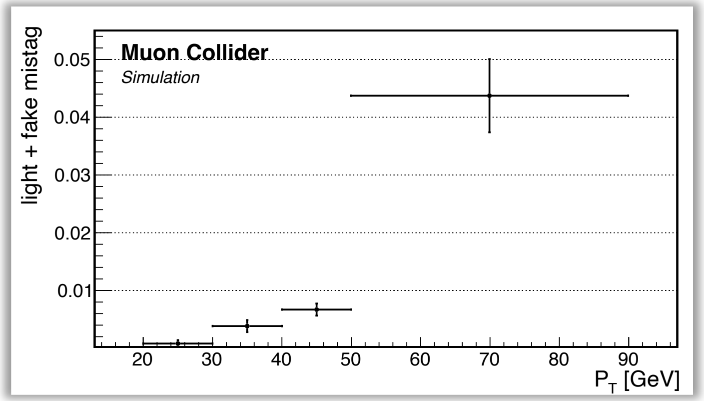


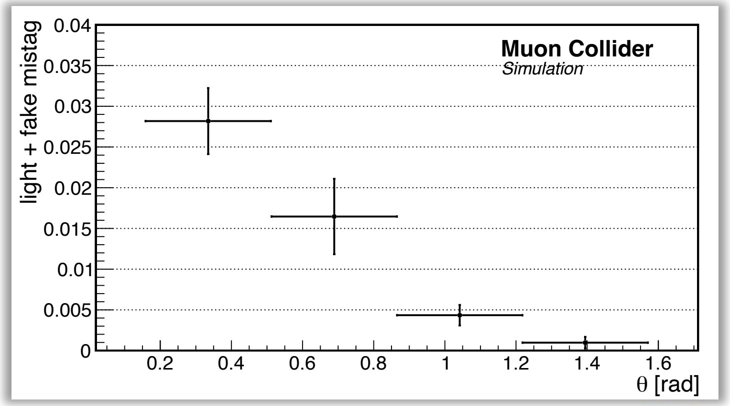
c-quark





light-quark/fake jets





$H \rightarrow b\bar{b}$ decay channel reconstruction

For theory see Zhen Liu talk

For $\sqrt{S} > 1.5$ TeV Higgs production dominated by WW fusion

Whizard used to generate at $\sqrt{S} = 3$ TeV:

- $\mu^+ \mu^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$
- $\mu^+ \mu^- \rightarrow Z\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$
- $\mu^+ \mu^- \rightarrow b\bar{b}\nu\bar{\nu}$, $\mu^+\mu^- \rightarrow c\bar{c}\nu\bar{\nu}$ removing the above processes

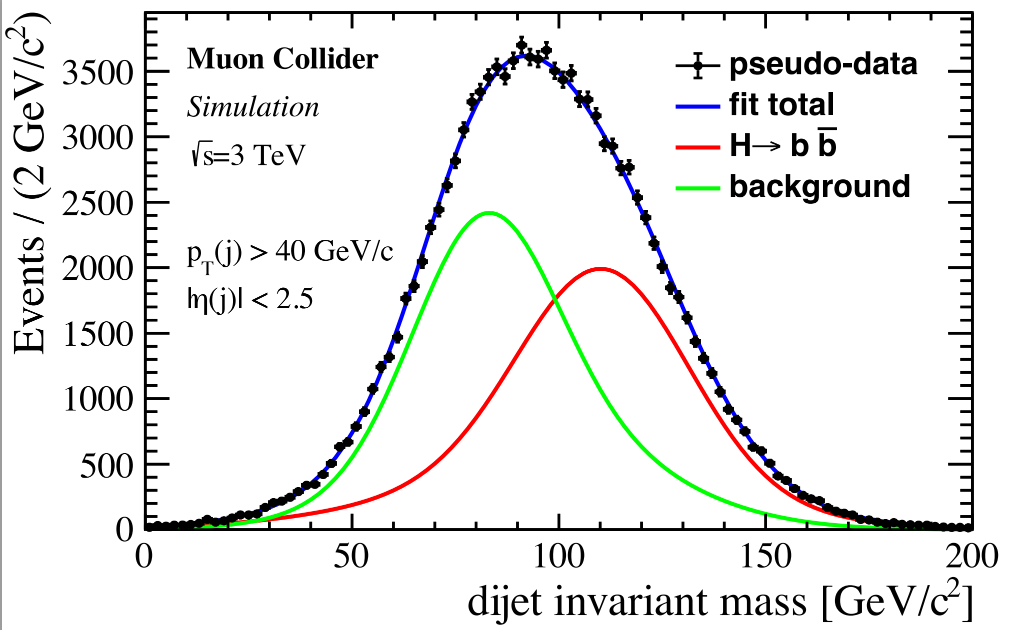
Samples reconstructed taking into account the beam-induced background

In 1 ab^{-1} (5 years) expected:

- 59.5k signal events
- 65.4k background events

Pseudo-data, generated by using signal & background invariant mass models, fitted by using unbinned maximum likelihood fit

uncertainty on the signal yield: 0.75%



$\mu^+\mu^- \to Hx \to b\bar{b}x$ with Beam-Induced Background at 3 TeV

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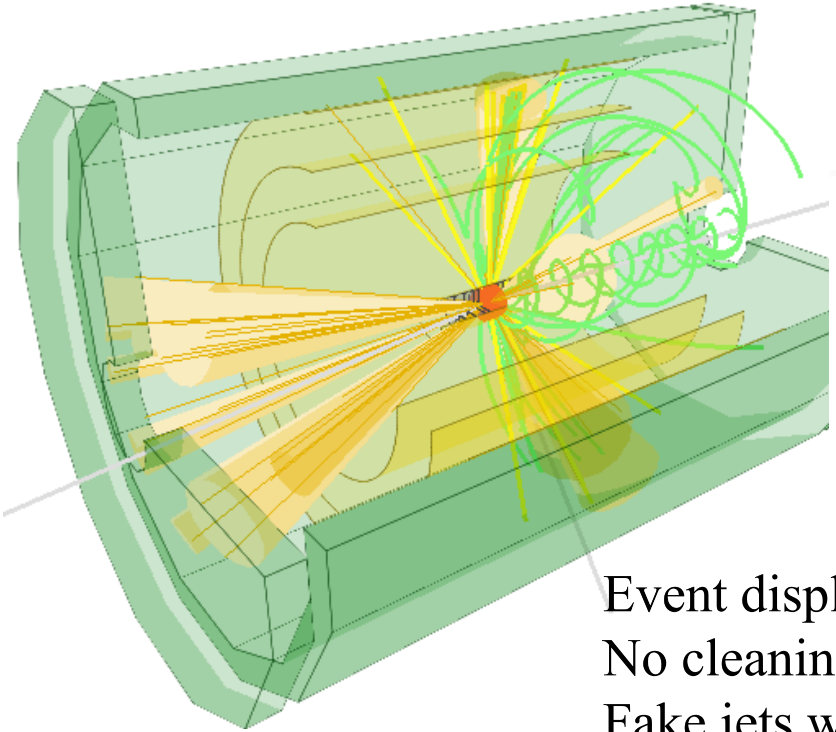
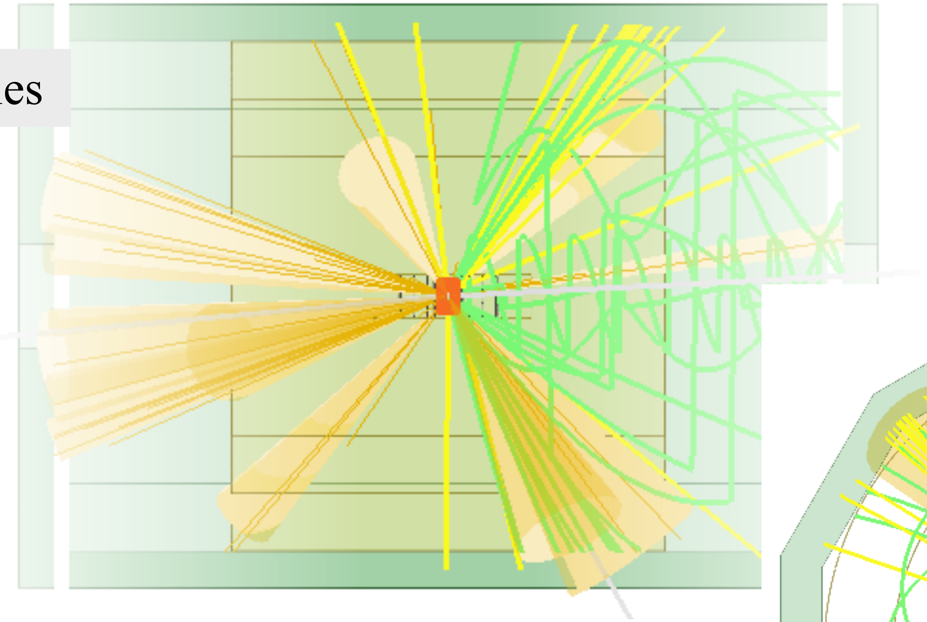
Yellow/green tracks: Montecarlo particles

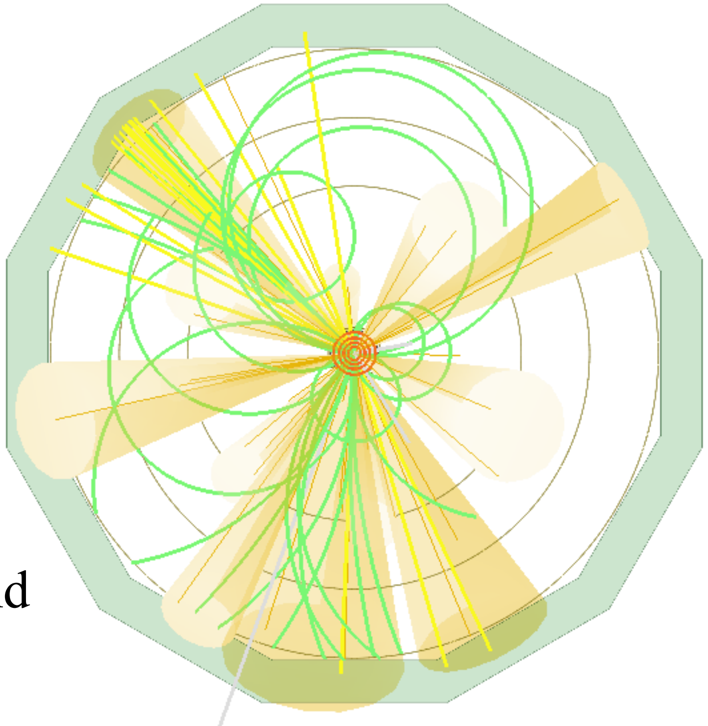




ECAL

Inner/Outer Tracker

Vertex Detector



Event 1300, Run 13

Event display after the reconstruction
No cleaning cuts, no analysis requirements
Fake jets with contributions of beam background removed during the analysis

Double and Triple Higgs

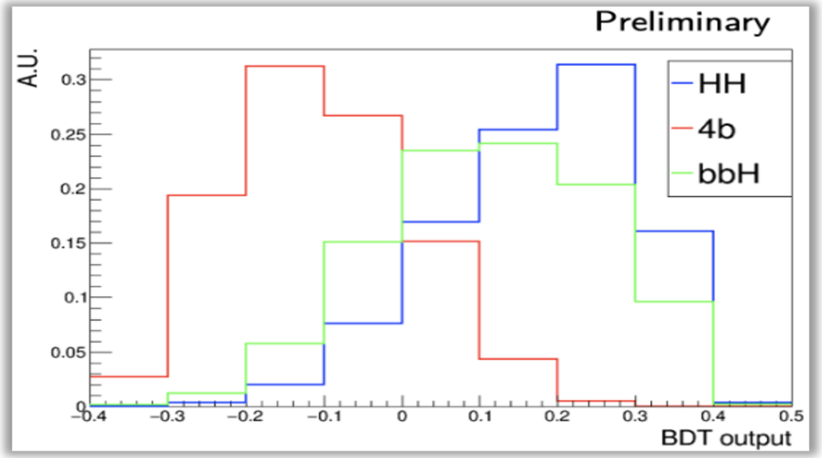
HH Cross Section at $\sqrt{S} = 3$ TeV

Whizard used to generate at $\sqrt{S} = 3$ TeV:

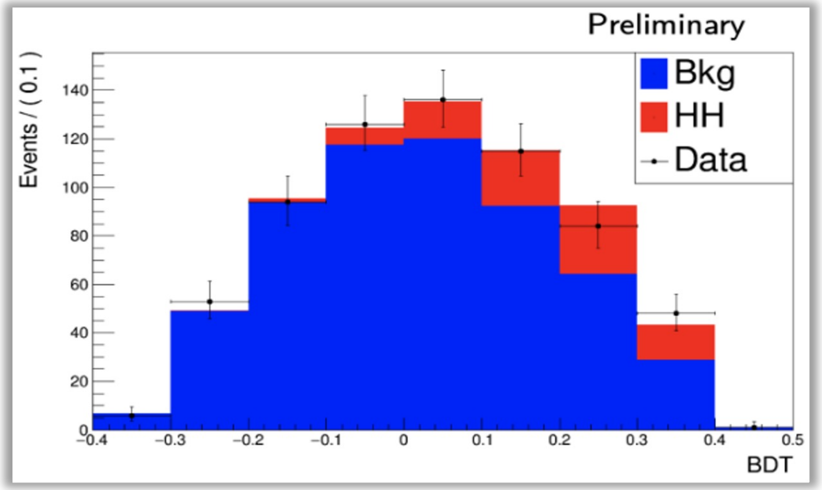
Signal $\mu^+\mu^- \rightarrow HH\nu\bar{\nu} \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$

Background $\mu^+\mu^- \rightarrow Hb\bar{b}\nu\bar{\nu} \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$

Background $\mu^+\mu^- \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$



- Signal and background reconstructed in the detector:
  - $p_T^{jet} > 20$ GeV, at least two SV-tagged jets
- Boosted Decision Tree trained to separate signal from background exploiting kinematical information.
- Minimize the figure of merit $F = \sqrt{(m_{12} - m_H)^2 + (m_{34} - m_H)^2}$
- Expected: 50 events signal, 430 events background
- Fit pseudo-data to extract precision on cross-section



Preliminary result:

Uncertainty of **30%** on cross section x BR with 1 ab^{-1}

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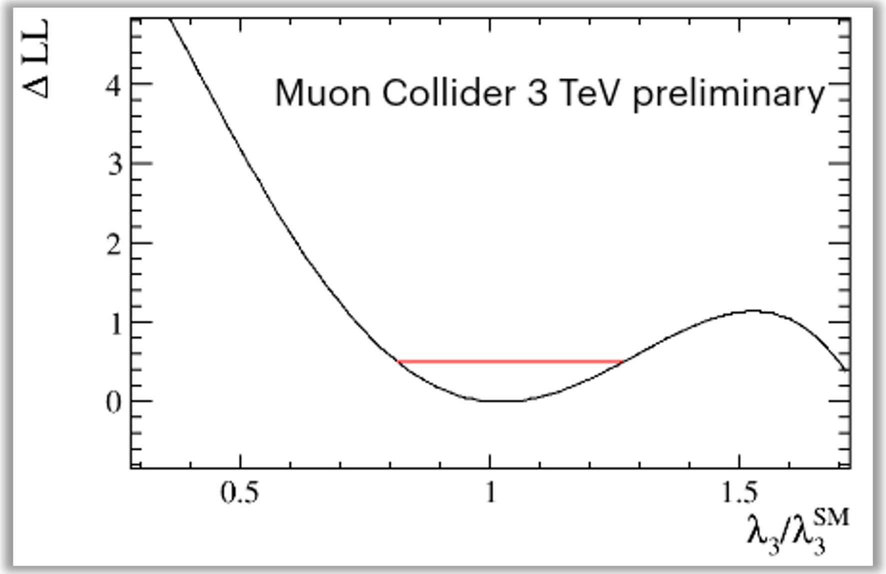
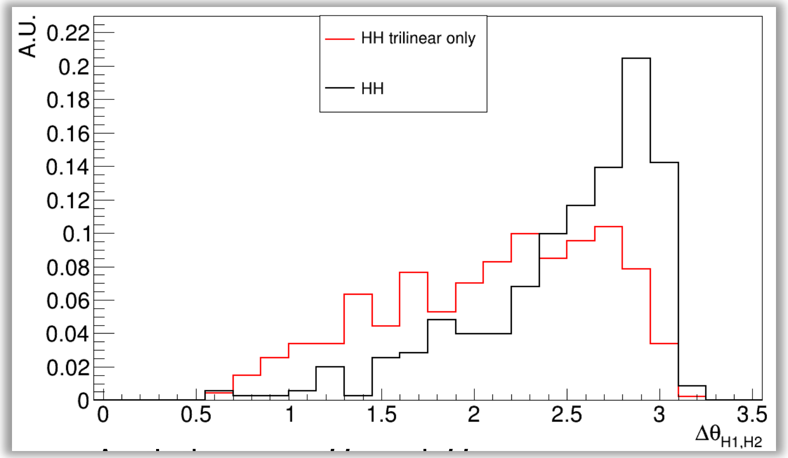
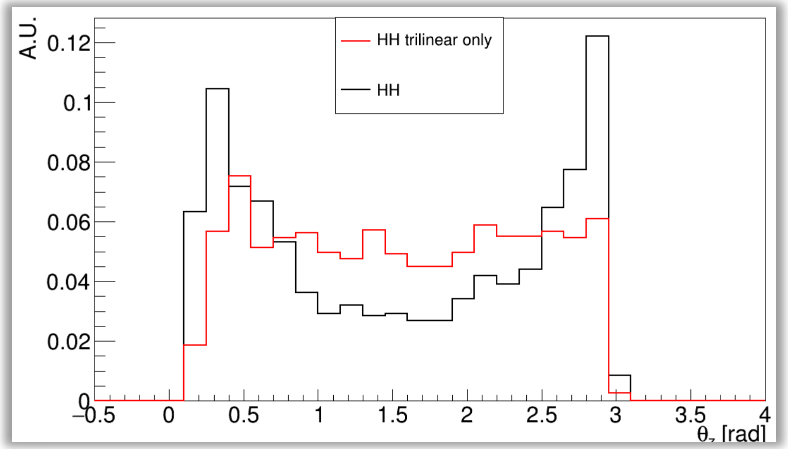
Trilinear coupling evaluation at $\sqrt{s} = 3$ TeV

Two Multi-Layer Perceptrons to:

- distinguish HH signal from background
- select events with trilinear coupling among all HH events







Produced and analyzed sample with Whizard with λ_3 varied respect to Standard Model: statistical uncertainty **~20% at 68% CL** with 1 ab^{-1}

Trilinear coupling evaluation at High Energies

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Machine interaction region, machine detector interface, detector design and events reconstruction algorithms at $\sqrt{S} = 10$ TeV in progress.

Detector acceptance: $\frac{HH_{10}}{HH_3} = 81\%$ (using the same shielding structure, it is expected to be improved)

Phenomenological evaluation

$$V = \frac{1}{2} m_h^2 h^2 + \lambda_{SM}(1 + \delta\kappa_3) v h^3 + \frac{\lambda_{SM}}{4}(1 + \delta\kappa_4) h^4$$

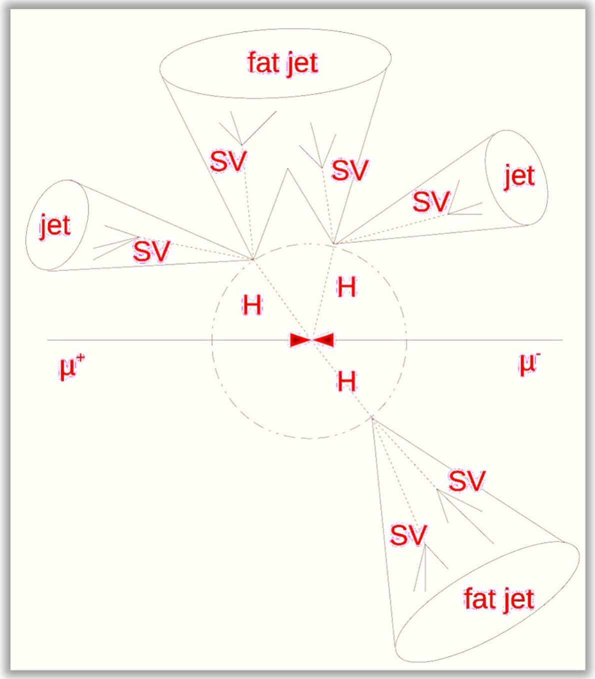
B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289
Han et al. 2008.12204

Results based on “old” detector performance, improved during last year!

E [TeV]	$\mathscr{L}$ [ab^{-1}]	N_{rec}	$\delta\sigma \sim N_{rec}^{-1/2}$	$\delta\kappa_3$
3	5	170	~ 7.5%	~ 10%
10	10	620	~ 4%	~ 5%
14	20	1340	~ 2.7%	~ 3.5%
30	90	6'300	~ 1.2%	~ 1.5%

Triple Higgs Production Cross Section and Quadrilinear Coupling evaluation

- Produced a signal sample $\mu^+\mu^- \rightarrow HHH\nu\bar{\nu} \rightarrow b\bar{b}b\bar{b}b\bar{b}\nu\bar{\nu}$ with Whizard at $\sqrt{S} = 10$ TeV to investigate the topology;
- Machine interaction region, machine detector interface, detector design and events reconstruction algorithms at $\sqrt{S} = 10$ TeV that are in progress;
- Dedicate events/jets reconstruction/identification algorithm is needed.



- ✗ Generation of the irreducible background $\mu^+\mu^- \rightarrow b\bar{b}b\bar{b}b\bar{b}\nu\bar{\nu}$ not an easy task… Whizard never ends…
- ✗ Ideas of using Whizard and/or AlpGen…

Quadrilinear Coupling evaluation

M. Chiesa et al. JHEP 98, 2020

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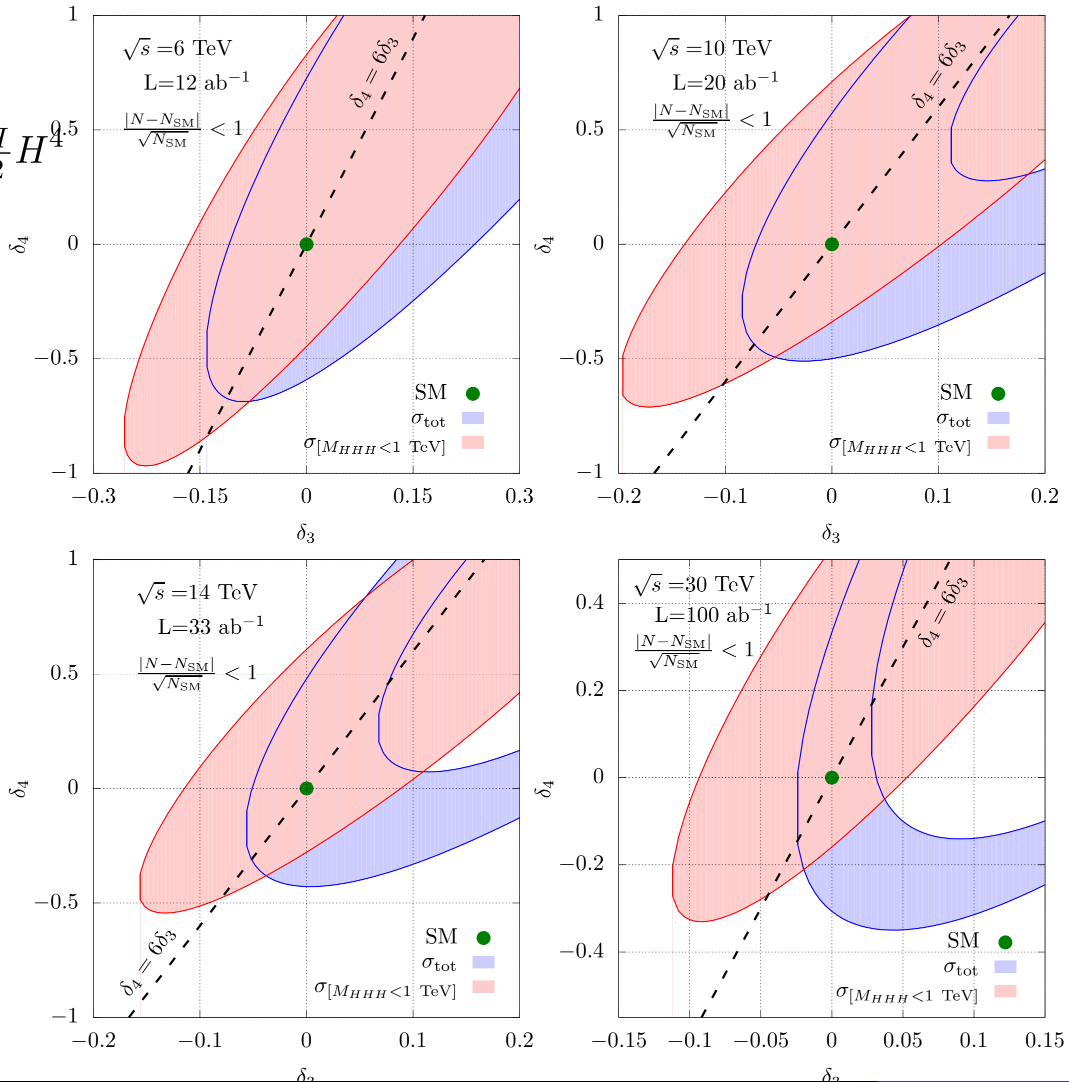
$$\mathcal{L} = -\frac{1}{2}M_H^2 H^2 - \left(1+\delta_3\right)\frac{M_H^2}{2v}H^3 - \left(1+\delta_4\right)\frac{M_H^2}{8v^2}H^4$$

One sigma exclusion plots



- no cuts
- $M_{HHH} < 1$ TeV

☆ No background considered
☆ No BR applied
☆ No selections optimization

Sensitivity evaluated in term of standard deviation from standard model

$$\frac{|N - N_{SM}|}{\sqrt{N_{SM}}}$$

$\delta_3 = 0$

6 TeV $\delta_4 \sim [-0.45, 0.8]$

10 TeV $\delta_4 \sim [-0.4, 0.7]$

14 TeV $\delta_4 \sim [-0.35, 0.6]$

30 TeV $\delta_4 \sim [-0.2, 0.5]$

Summary

✓ Two different muon collider energies options considered so far:

- First stage at $\sqrt{S} = 3$ TeV and then go to $\sqrt{S} = 10 +$ TeV

✓ Deep screen during the European Accelerator R&D Roadmap, not showstopper identified

✓ Feasibility has been addressed

✓ Muon collider offers unique possibility for high energy leptons interactions, for a complete review The MuonsSmasher 's Guide

✓ Currently efforts are focused to Seattle Community Summer Study Workshop

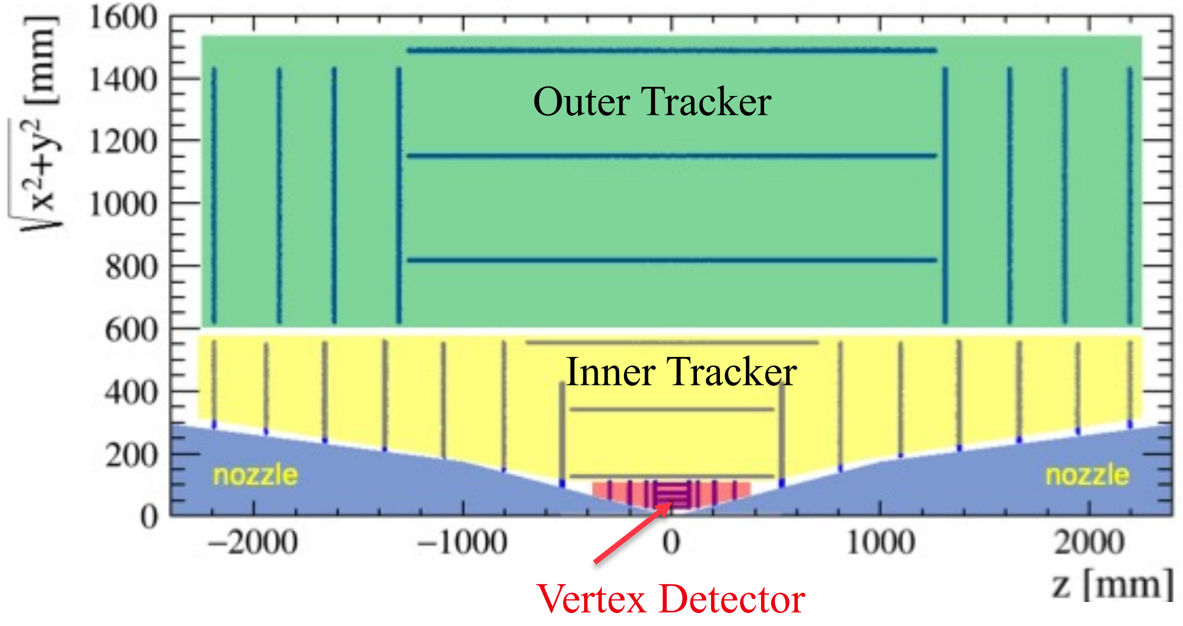
Muon Collider is an opportunity not to be missed and

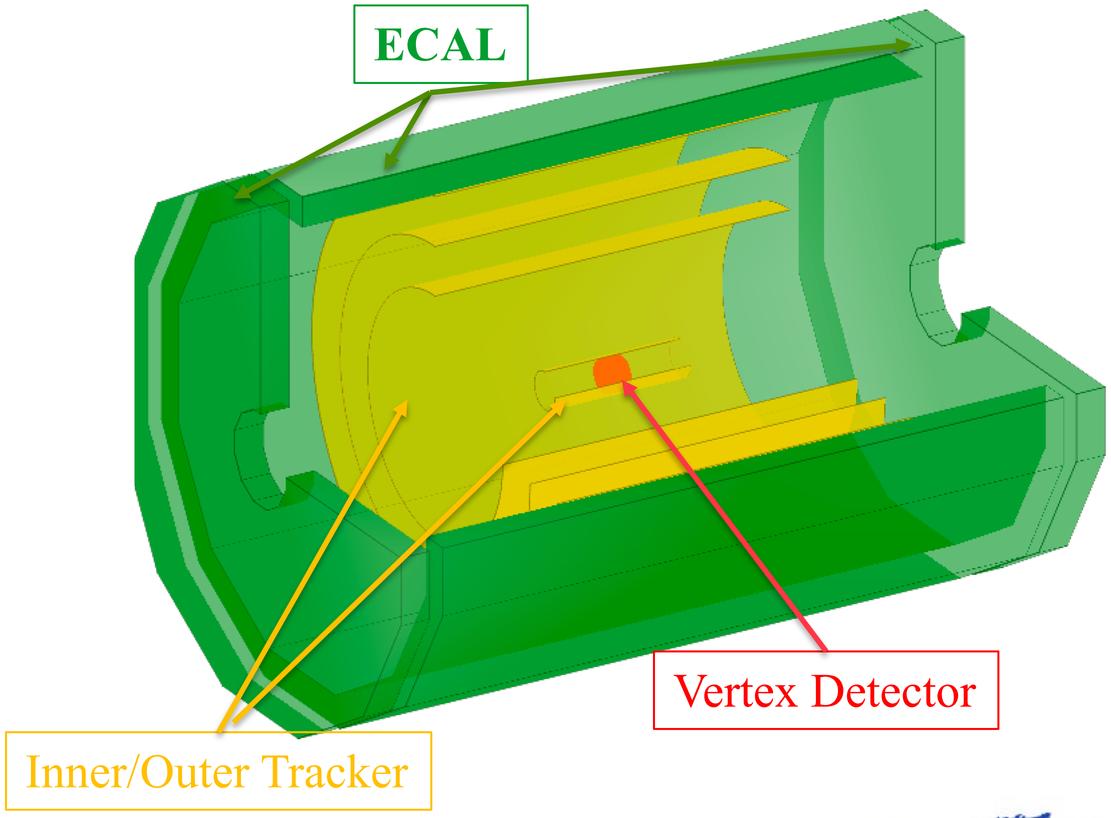
"Nothing is more expensive than a missed opportunity"

Jackson Brown Jr.

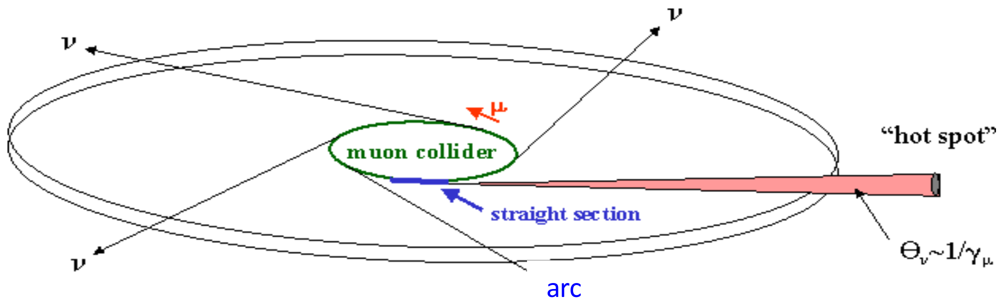
BACKUP

Beam-Induced Background affects mainly tracker and electromagnetic calorimeter





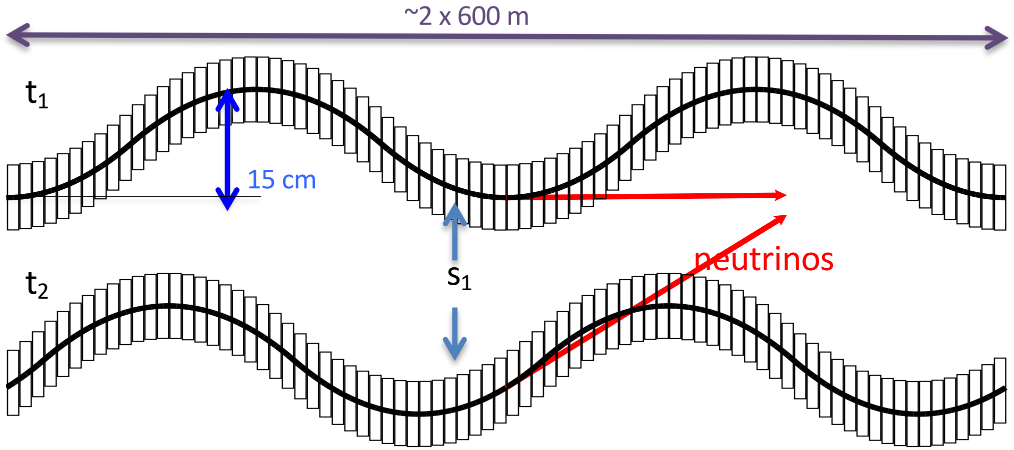
Neutrino Flux Mitigation



Legal limit 1 mSv/year
MAP goal < 0.1 mSv/year
Our goal: arcs below threshold for legal procedure < 10 μSv/year
LHC achieved < 5 μSv/year

3 TeV, 200 m deep tunnel is about OK

Need mitigation of arcs at 10+ TeV:
idea of Mokhov, Ginneken to move beam in aperture
our approach: move collider ring components, e.g. vertical bending with 1% of main field



Opening angle ± 1 mradiant

14 TeV, in 200 m deep tunnel comparable to LHC case

Need to study mover system, magnet, connections and impact on beam

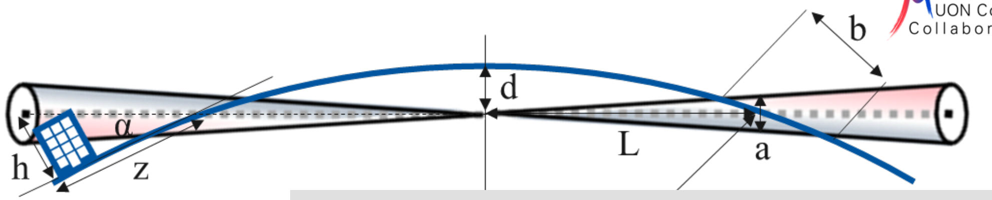
Working on different approaches for experimental insertion

Neutrino Flux

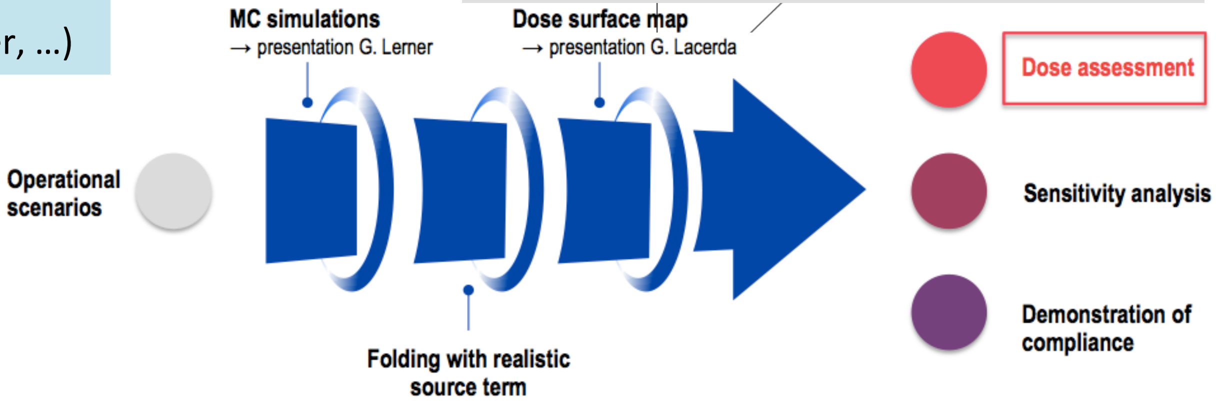
Team of RP experts, civil engineers, beam physicist and FLUKA experts

Goal to be **similar to LHC**: i.e**. negligible**, “fully optimised” (10 x better than MAP goal, 100 x better than legal requirements)

- With indirect effects (air, ground water, …)



C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke



Addressed by:

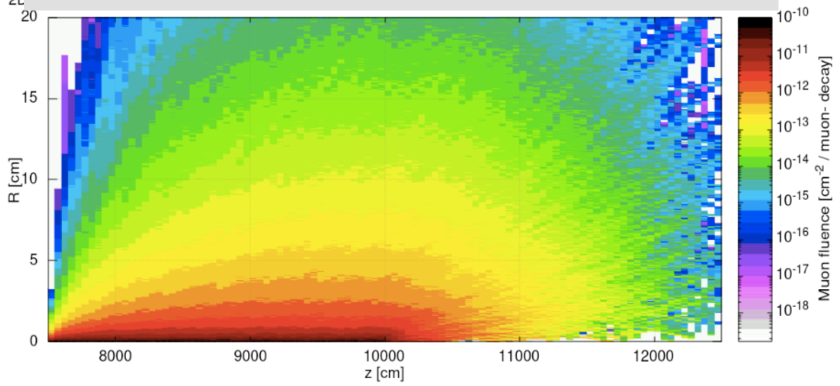
Site choice in direction of experiments

- tools in preparation

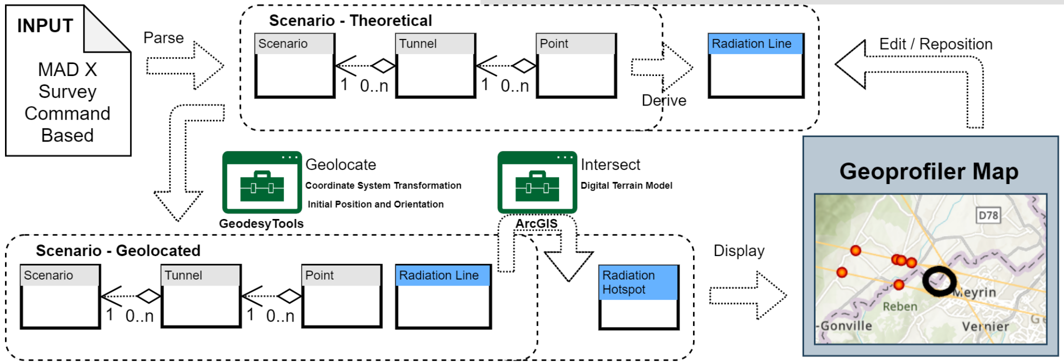
Mechanical mover system in arcs

- allows 14 TeV in 200 m deep tunnel

G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

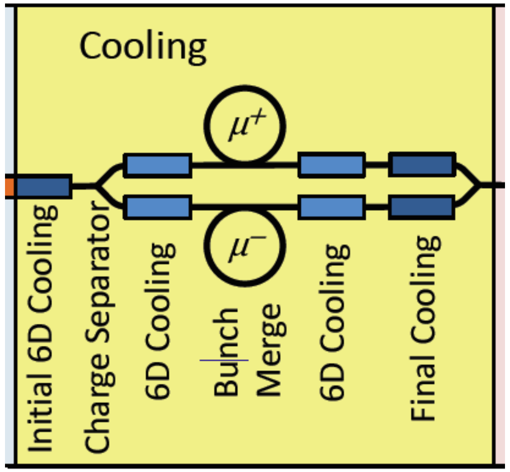


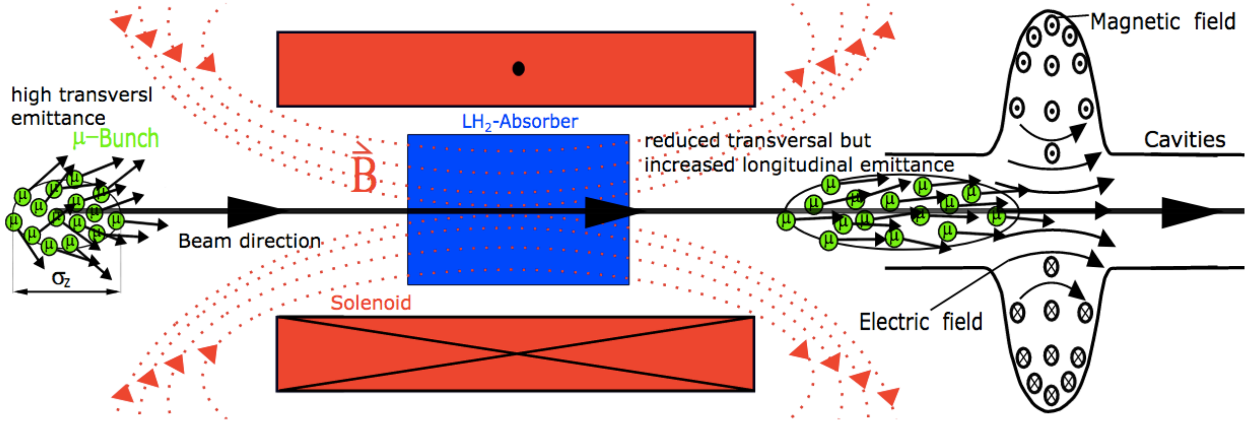
G. Lacerda, Y. Robert, N. Guilhaudin

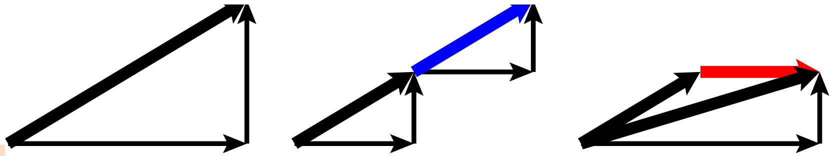


Mover system and impact on beam will be addressed in the coming years before end if 2025

Cooling Concept

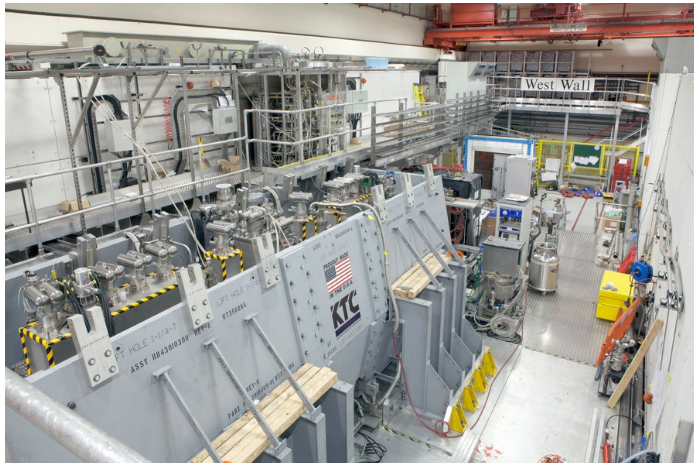






Principle has been demonstrated

MICE (UK) Muon cooling principle



For final cooling **highest-field solenoids** minimise beta-function and impact of multiple scattering

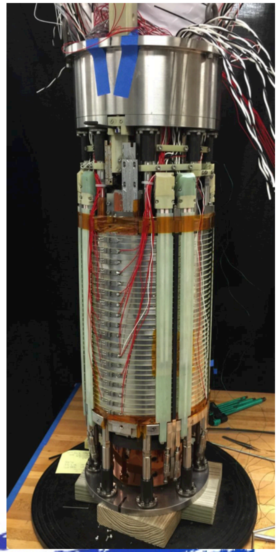
32 T reached with sufficient aperture,

40+ T magnet is being designed

even 50+ T appears possible

NHFML

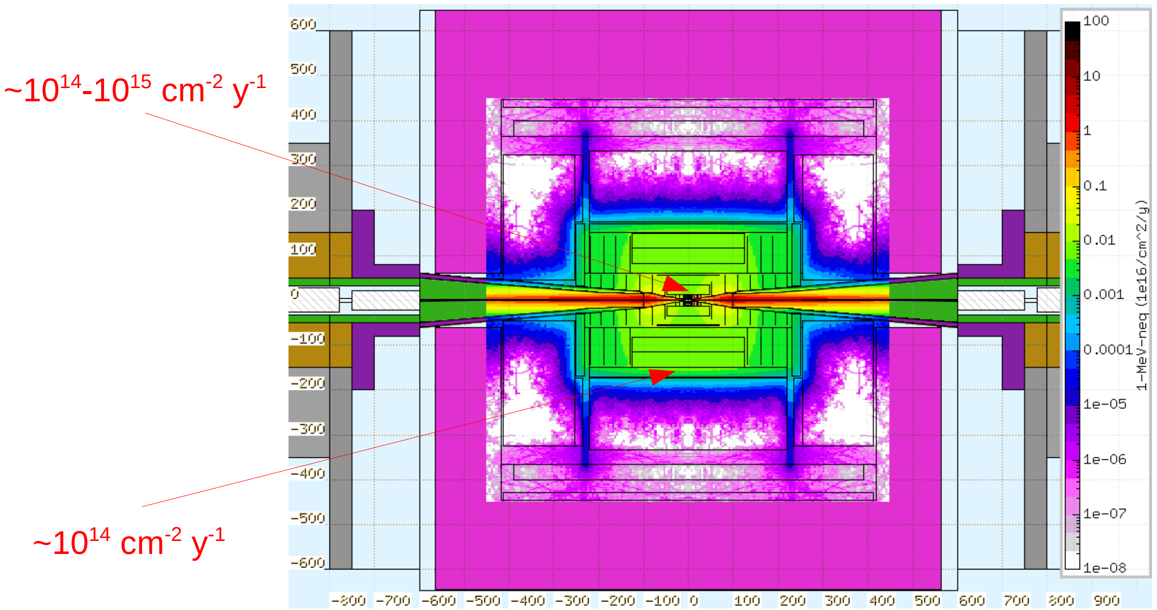
32 T solenoid with HTS



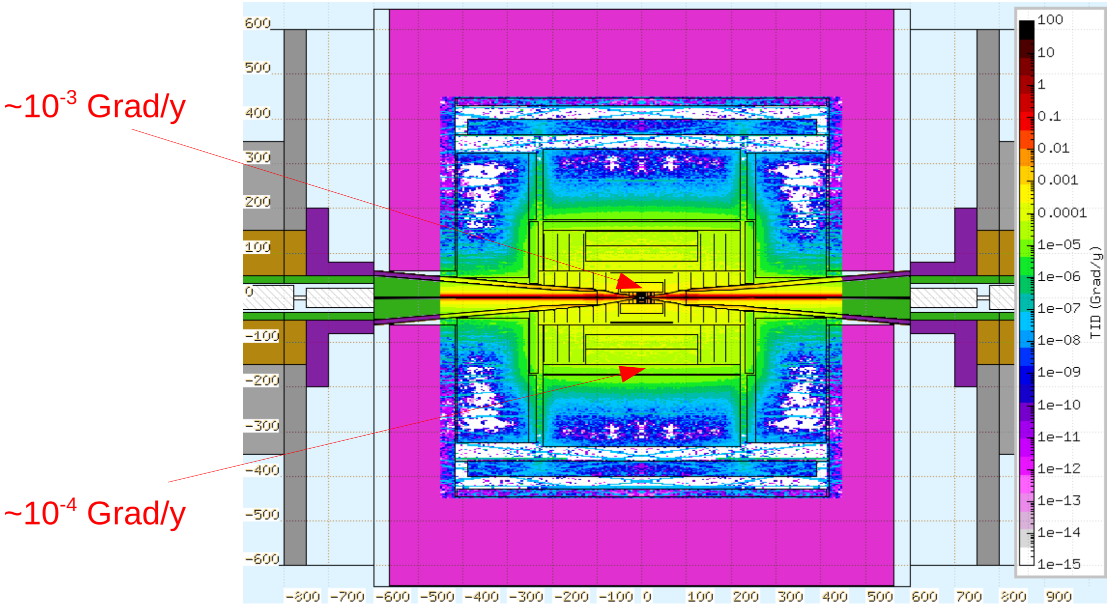
- A muon collider detector must be radiation-hard.
- Radiation levels in the detector will strongly depend on the collider operation mode.

Assumptions:
- collision energy: 1.5 TeV;
- collider circumference: 2.5 km;
- average beam intensity: 1.1×10^{12} μ/bunch;
- average bunch crossing frequency: 15 kHz;
- days of operation per year: 200.

1-MeV neutron equivalent fluence per year



total ionizing dose per year



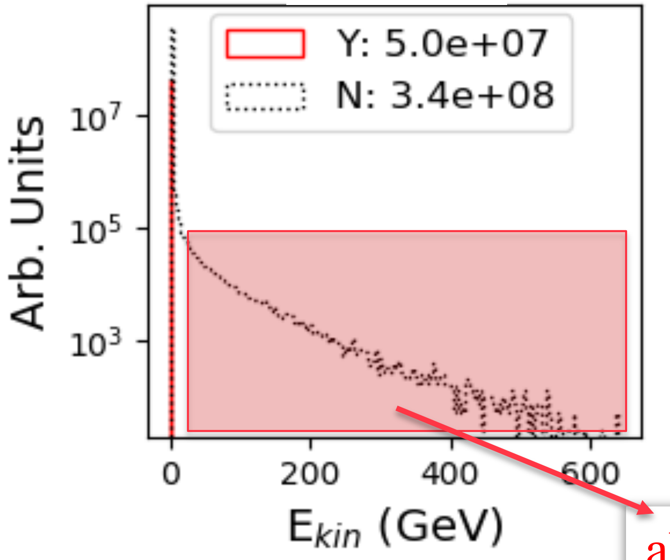
S. Jindariani *et al.*, arXiv:2203.07224

What the nozzles do?

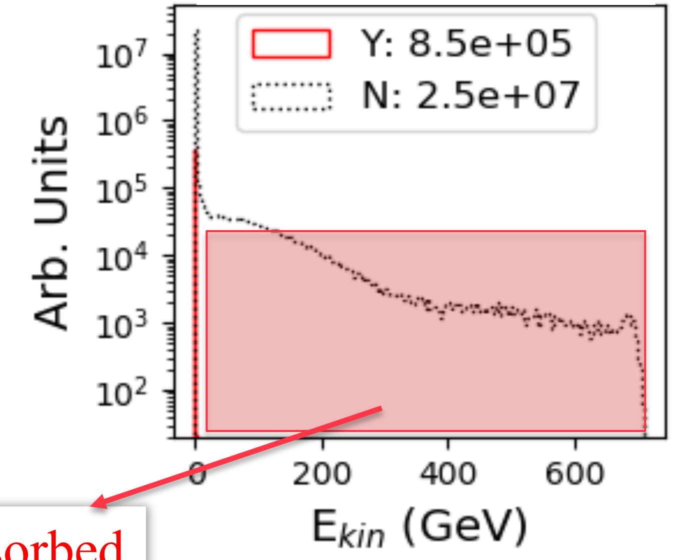
F. Collamati et al. 2021 JINST 16 P11009

Muon beam 0.75 TeV

Photons



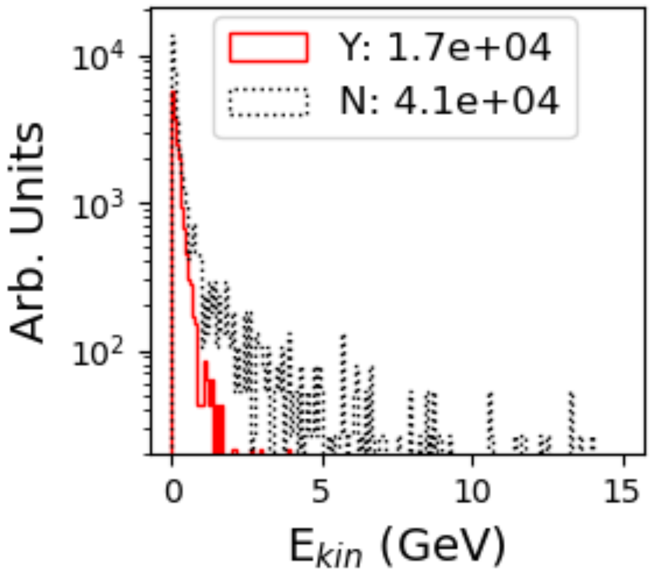
electrons/positrons



absorbed

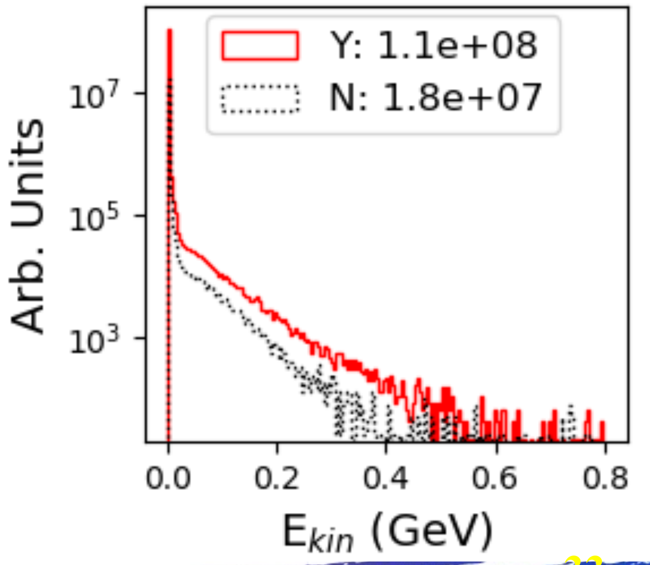
Charged hadrons absorbed

charged hadrons



Neutrons increased

neutrons



Change cladding materials?
Lythium Polyethylene instead of BCH2?