12th Beam Telescopes and Test Beams Workshop

Physics Opportunities and Challenges at Future Multi-TeV Muon Collider

April 18, 2024 Edinburgh

Donatella Lucchesi University and INFN of Padova

for the

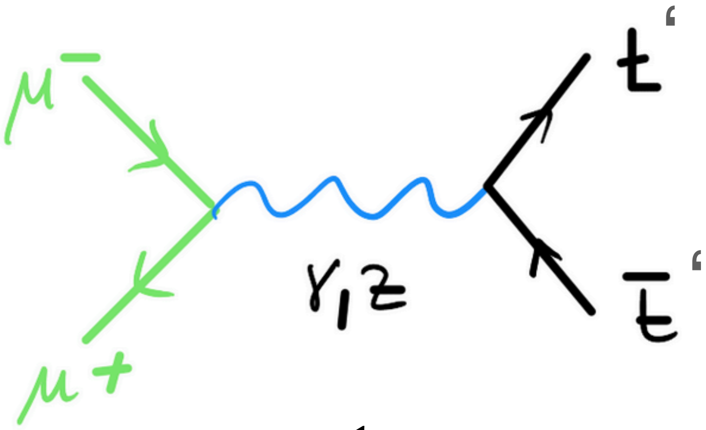
International Muon Collider Collaboration

This project has received funding from the European Union's Research and Innovation programme under GAs No 101094300 and No 101004730.

Physic processes: two colliders in one

F. Maltoni
"Physics Overview" Annual Meeting IMCC

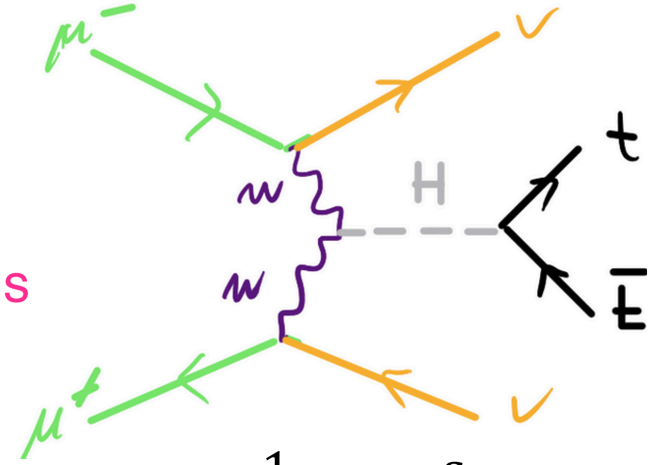
Multi-TeV muon collider opens a completely new regime :



$$\sigma \sim \frac{1}{s}$$

Energetic final states
(heavy particle or very boosted)

Different physics can be probed in the two channels



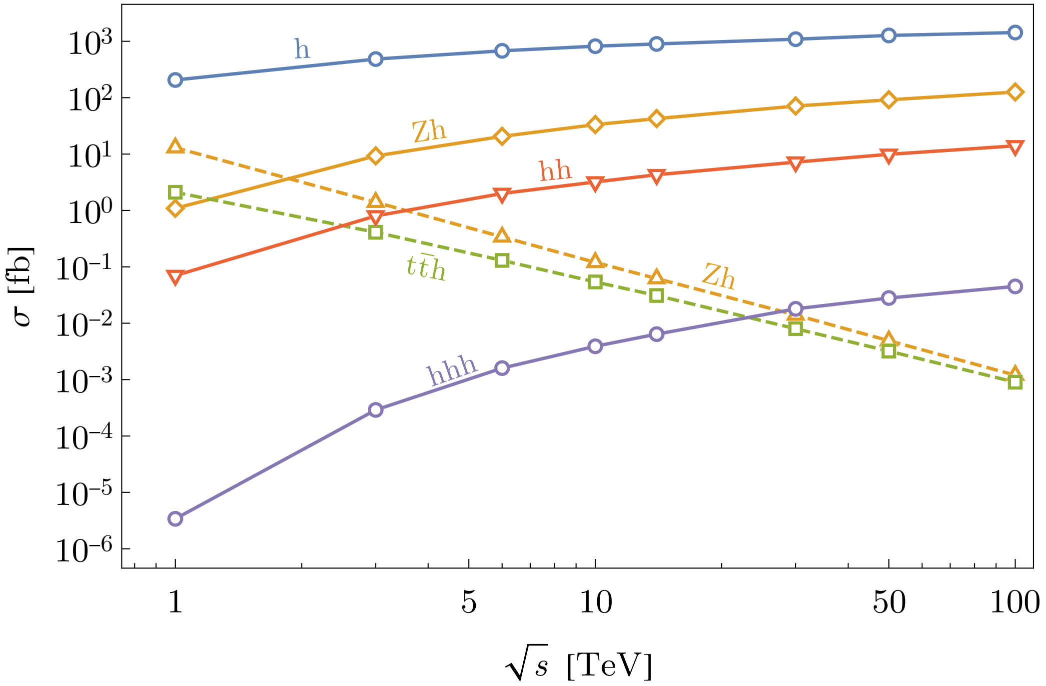
$$\sigma \sim \frac{1}{M^2} log^n \frac{s}{M}$$

Standard Model coupling measurements
Discovery light and weakly interacting particles

Muon Colliders, 1901.06150
The muon Smasher's guide, *Rept.Prog.Phys.* 85 (2022) 8, 084201 2103.14043
Muon Collider Forum Report, 2209.01318
Towards a Muon Collider, *Eur.Phys.J.C* 83 (2023) 9, 864, 2303.08533

Higgs Physics at Muon Collider

Ali HA et al.



- - - - - annihilation
—— VBF

⇒

M. Casarsa et al. EPS-HEP2023 408

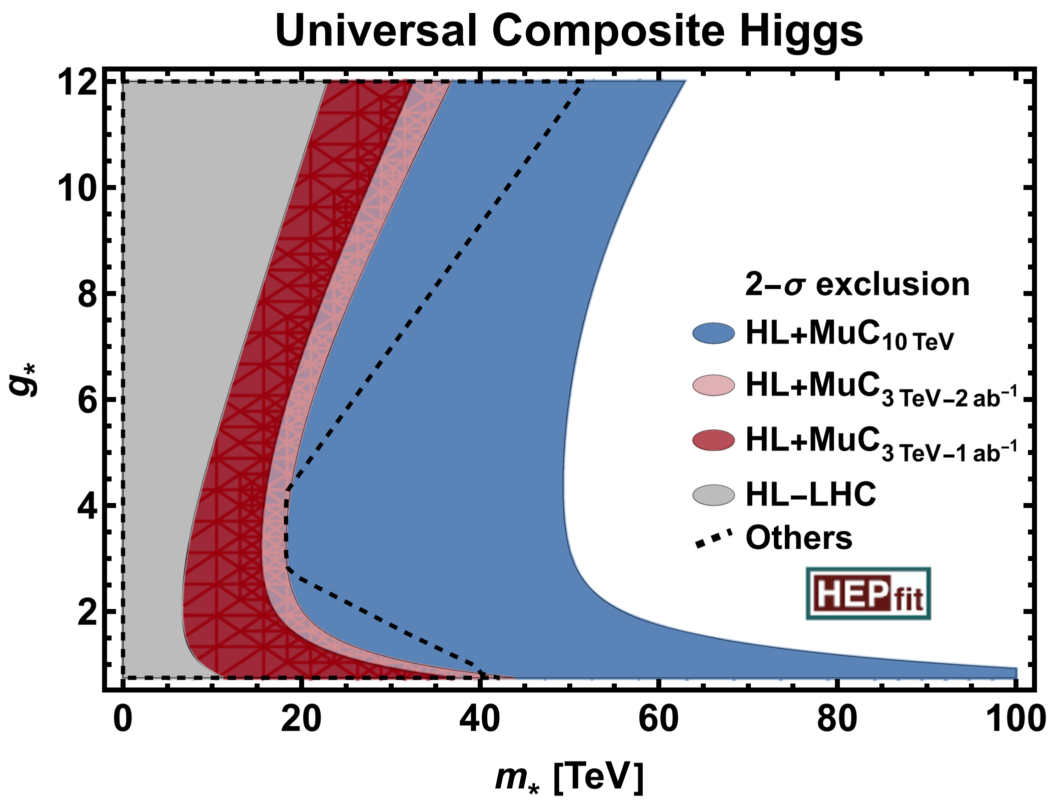
	cross section [fb]		expected events	
	3 TeV	10 TeV	1 ab^{-1} at 3 TeV	10 ab^{-1} at 10 TeV
H	550	930	5.5×10^{5}	9.3×10^{6}
ZH	11	35	1.1×10^{4}	3.5×10^{5}
$t\bar{t}H$	0.42	0.14	420	1.4×10^{3}
HH	0.95	3.8	950	3.8×10^{4}
HHH	3.0×10^{-4}	4.2×10^{-3}	0.30	42

$\sqrt{s}$ = 3 TeV 1 ab^{-1} 5 years one experiment

$\sqrt{s}$ = 10 TeV 10 ab^{-1} 5 years one experiment

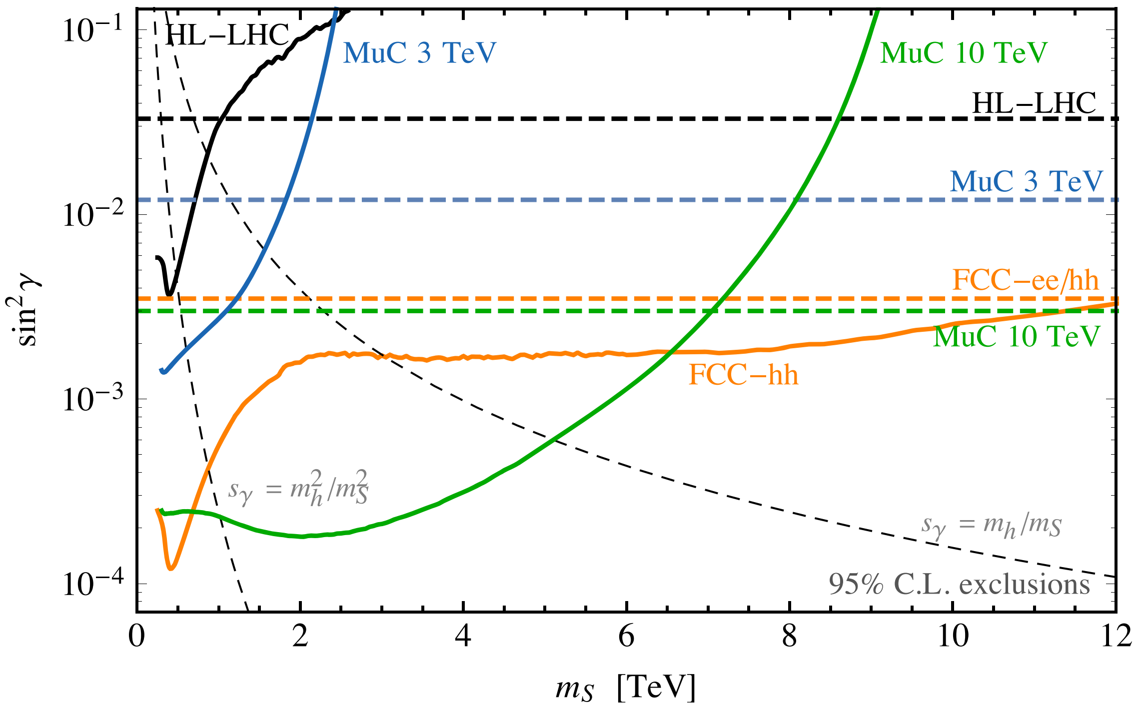
The power of $\sqrt{s} = 10$ TeV muon collisions for BSM searches

SM EFT including HL-LHC + MuC Higgs @10 TeV



Composite Higgs: dynamics parameterised in terms of single coupling, g_* , and mass, m_*

Higgs portal: new scalar field with no color



Scalar field singlets, mass: m_s mixing parameter: $\sin\gamma$

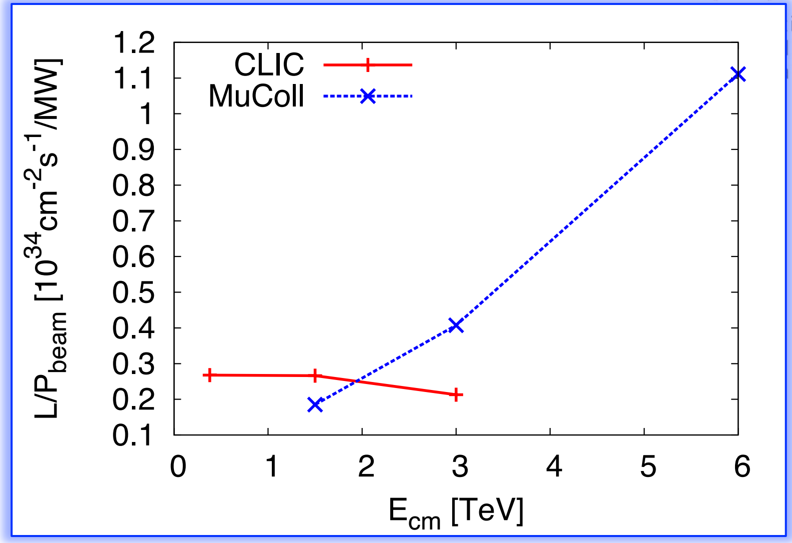
—— direct sensitivity - - - - indirect sensitivity

C. Accettura et al. "Towards a muon collider”

Muon Collider: a new concept facility

Muons do not suffer from synchrotron radiation in this energy range

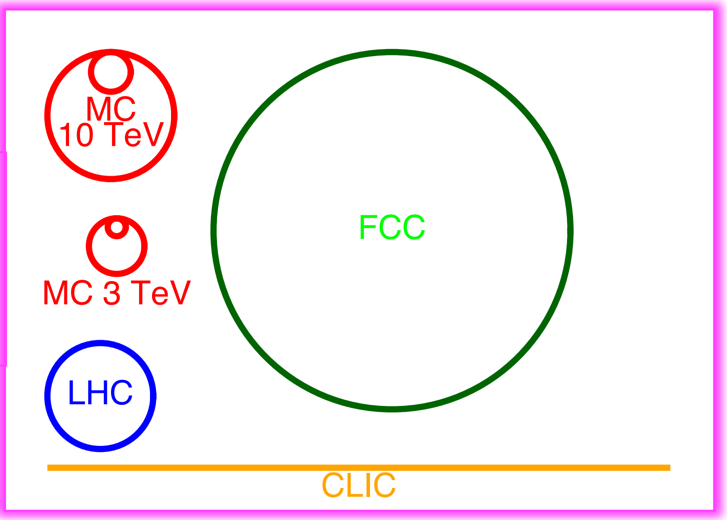
High center of mass energy & high luminosity & power efficient: luminosity increase per beam power



C. Accettura et al. "Towards a muon collider"

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	2	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	$N_{\pm}$	1×10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Total beam power	$P_{-}+P_{+}$	MW	5.3	14	20
Longitudinal emittance	ε_{l}	MeV m	7.5	7.5	7.5
Transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.1
IP beta-function	$\beta^*_{\perp}$	mm	5	1.5	1.1
IP beam size	$\sigma_{\perp}$	µm	3	0.9	0.6

Compact: cost effective & sustainable



Integrated luminosity:

$\sqrt{s} = 3$ TeV 1 ab^{-1} 5 years one experiment

$\sqrt{s} = 10$ TeV 10 ab^{-1} 5 years one experiment

The Facility

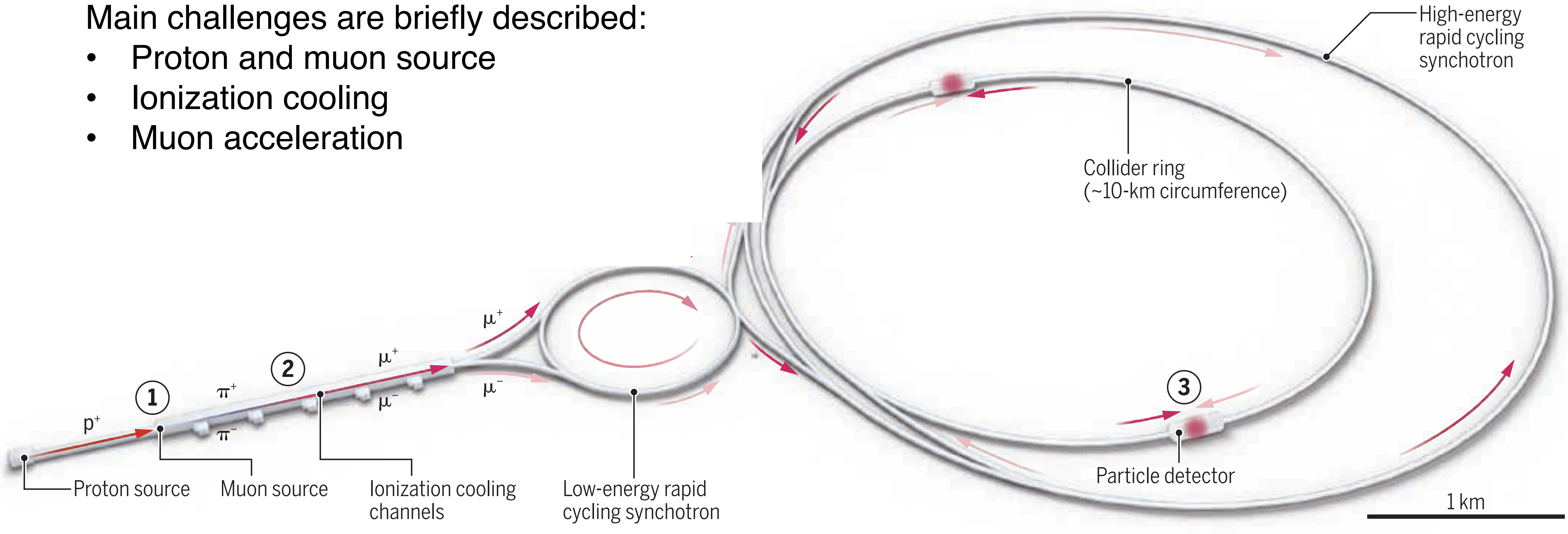
- Next generation of accelerator complex
- Neutrino physics experiments, not discussed here
- Experiments at a $\sqrt{s}$ ranging from few TeV to 10-ish TeV

Accelerator complex

Facility complex

Main challenges are briefly described:

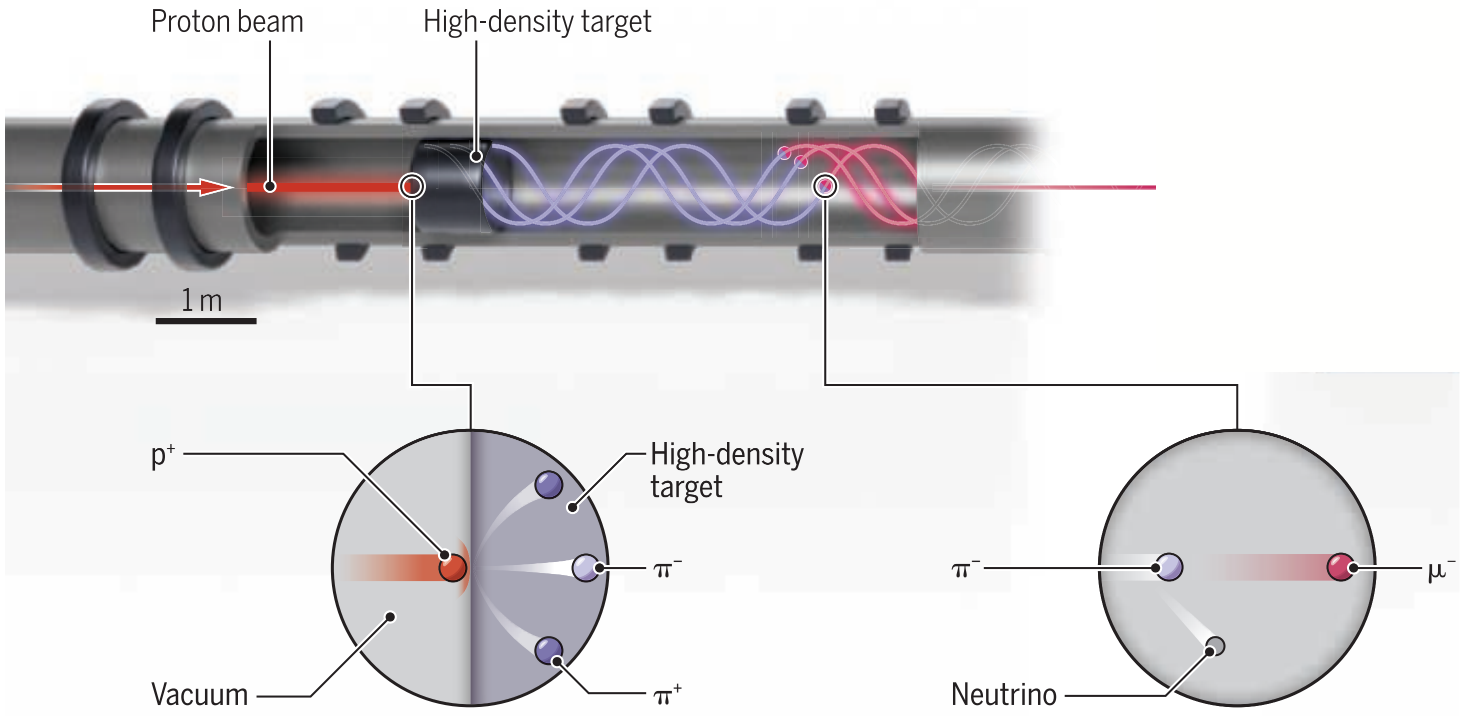
- Proton and muon source
- Ionization cooling
- Muon acceleration



Graphic by: A. Fisher/*Science*. From A. Cho 'The Dream Machine' *SCIENCE* 28 March 2024, doi: 10.1126/science.zt5zf4g. Reproduced with permission from AAAS.

1) Proton and muon source

- High intense proton driver with short (1-3 ns), high-charge bunches to produce short pions bunches to finally have high efficiency in muons capture . Short proton bunch allows small beam spot which help to have small emittance.
- Multi-MW target immersed in 15-20 T magnetic field to contain pion beam.



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Facility complex

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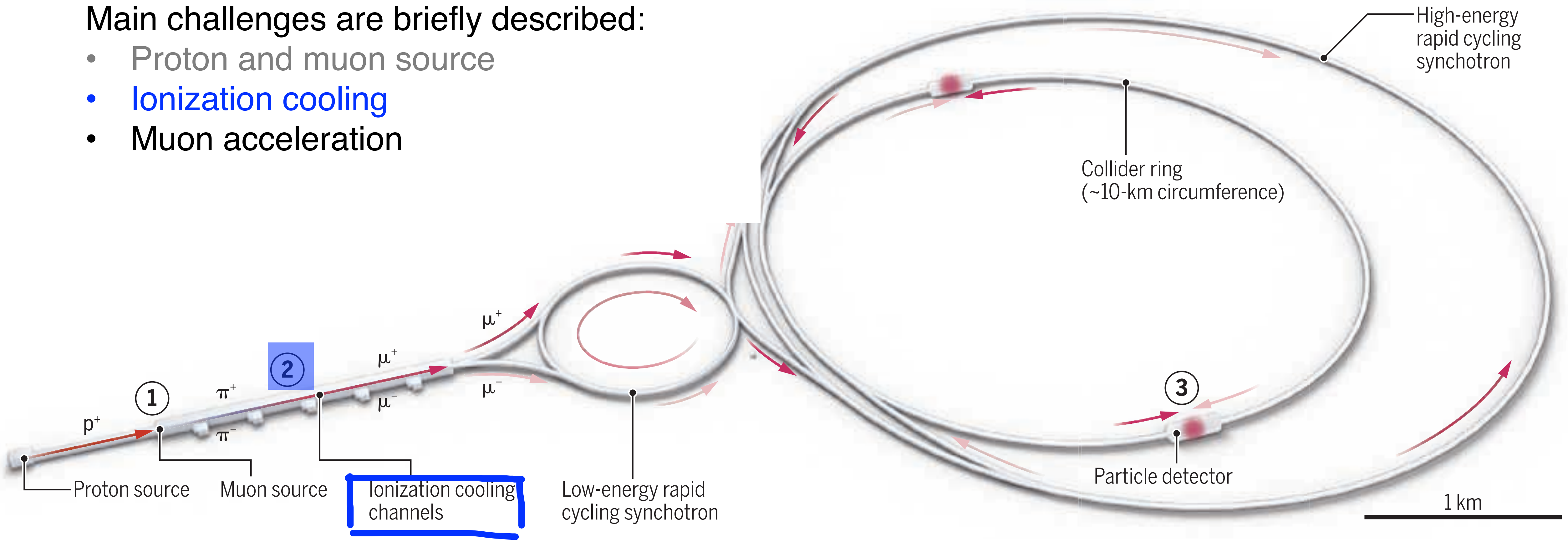

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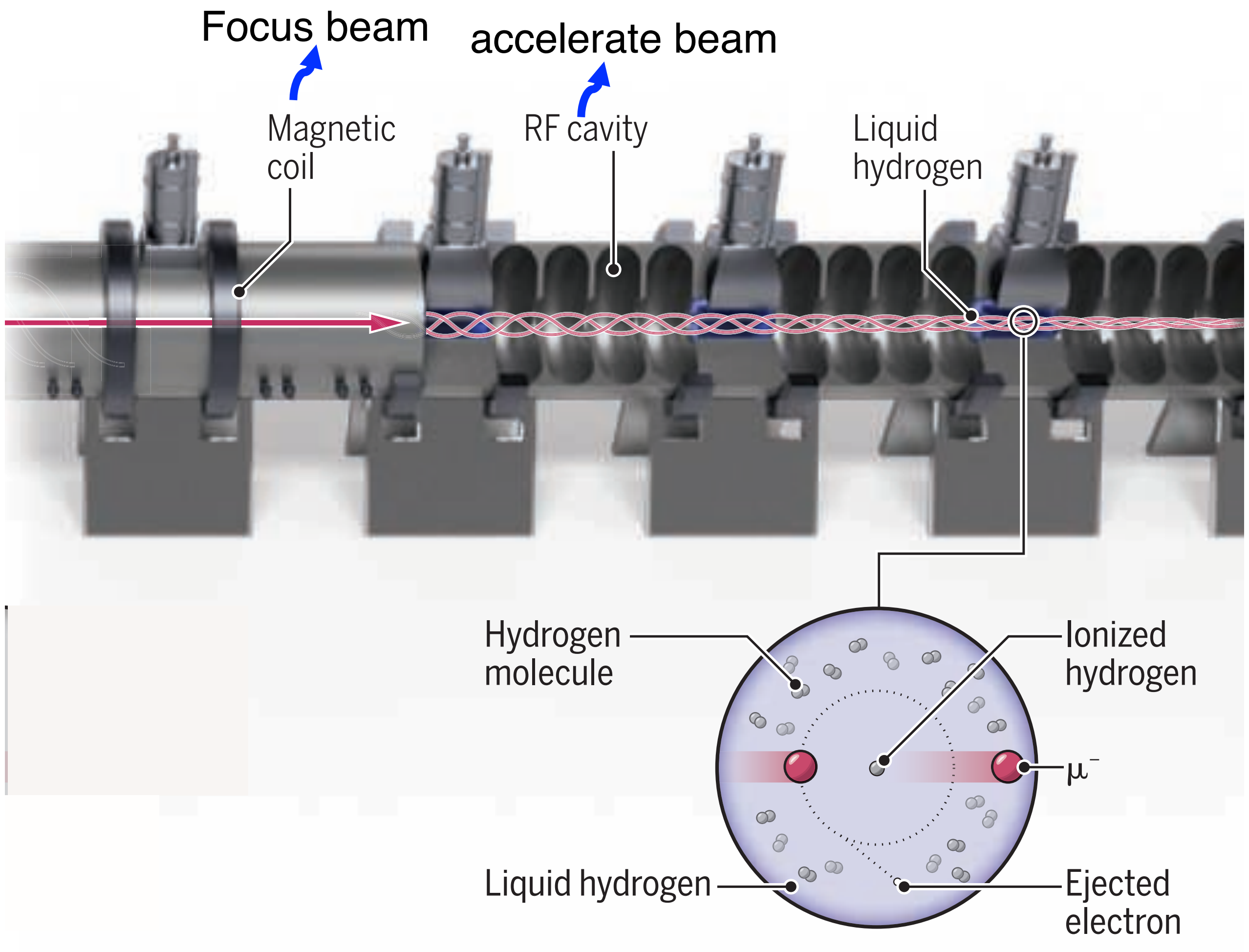
2) The muon ionization cooling principle



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- Transverse and longitudinal momentum reduced by passing through absorbers, then re-accelerated.
- Absorbers low Z material (Lithium hydride for first phase*, liquid H for final cooling) in high magnetic field to minimize the effect of multiple scattering
- RF cavities in magnetic field: accelerate the muon beam

Proposed two cooling stages:

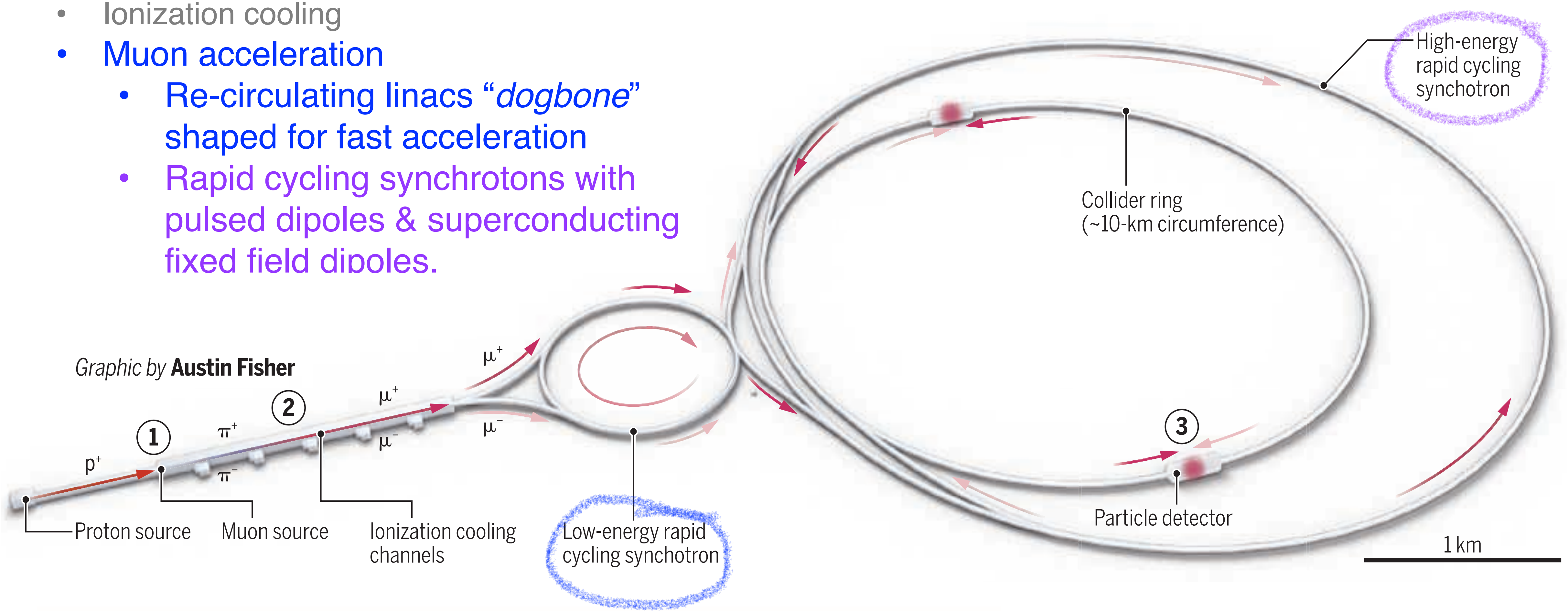
1) muons cooled both transversely and longitudinally, rectilinear cooling.
2) muons cooled transversely, final cooling.

*Demonstrated by Muon Ionization Cooling Experiment

The muon acceleration

Main challenges are briefly described:

- Proton and muon source
- Ionization cooling
- Muon acceleration
  - Re-circulating linacs “*dogbone*” shaped for fast acceleration
  - Rapid cycling synchrotons with pulsed dipoles & superconducting fixed field dipoles.



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Dense neutrino flux

Muons per bunch: 1.8×10^{12} → Nº decay per meter of lattice:

2×10^{5} at $\sqrt{S}=3$ TeV

6×10^{4} at $\sqrt{S}=10$ TeV

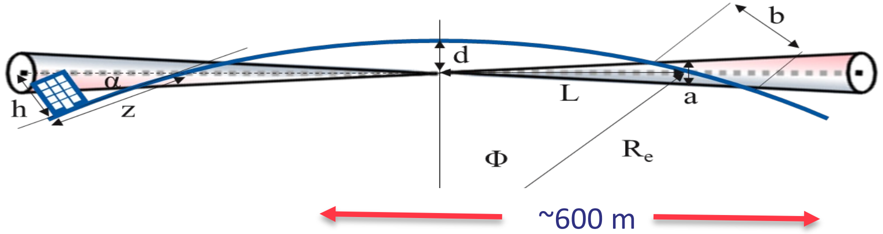
Hadronic/electromagnetic showers produced by high-energy neutrinos interacting with the underground environment can induce radiation when exiting.

Collider arcs:

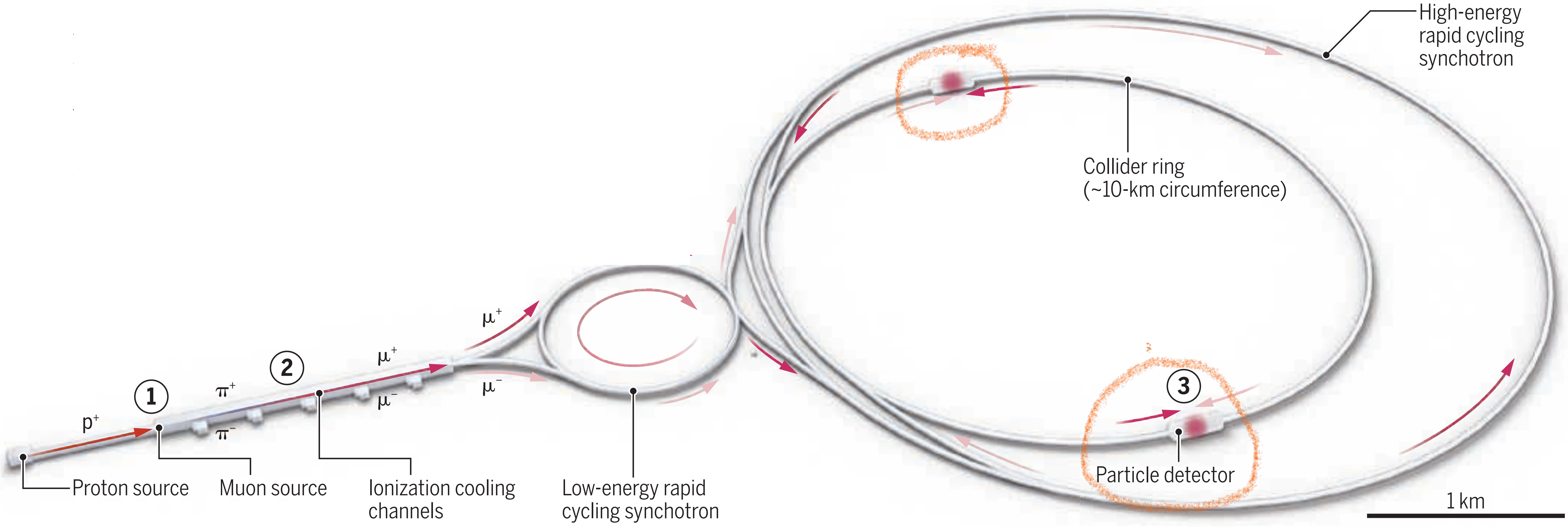
- Keep induced radiation at the level of LHC
  - Not an issue at $\sqrt{s}=3$ TeV if at 200 m.
  - At $\sqrt{s}=10$ TeV, beam movement inside magnet aperture should be enough.

Straight sessions, interaction points:

At higher energy, $\sqrt{s}\sim10$ TeV, beam parameters and surface map need to be used (GeoProfiler) to determine the effects of fluxes.



Facility complex



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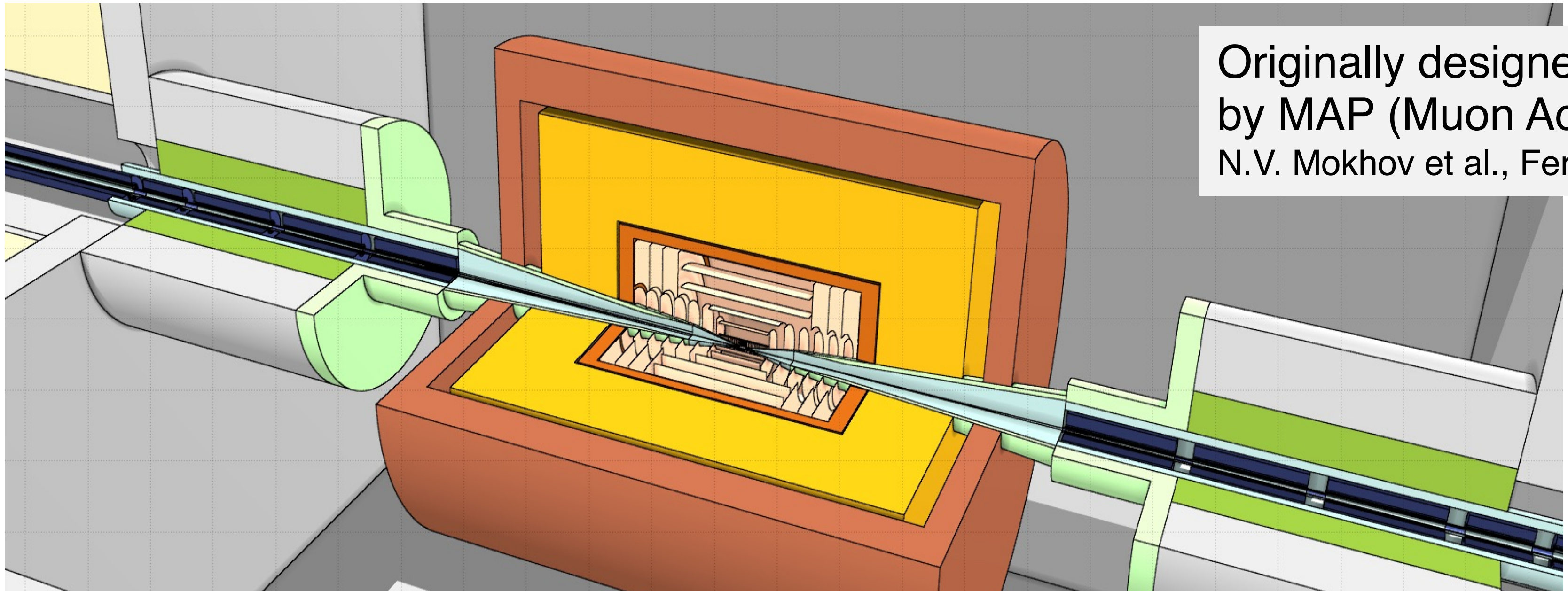
Beam background sources in the detector region

- ✗ Muon decay along the ring, $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$: dominant process at all center-of-mass energies
  - ❊ photons from synchrotron radiation of energetic electrons in collider magnetic field
  - ❊ electromagnetic showers from electrons and photons
  - ❊ hadronic component from photonuclear interaction with materials
  - ❊ Bethe-Heitler muon, $\gamma + A \rightarrow A' + \mu^+\mu^-$
- ✗ Incoherent e^-e^+ production, $\mu^+\mu^- \rightarrow \mu^+\mu^-e^+e^-$: important at high $\sqrt{s}$
  - ❊ small transverse momentum $e^-e^+ \Longrightarrow$ trapped by detector magnetic field
- ✗ Beam halo: level of acceptable losses to be defined, not an issue now

F. Collamati et al. 2021 JINST 16 P11009

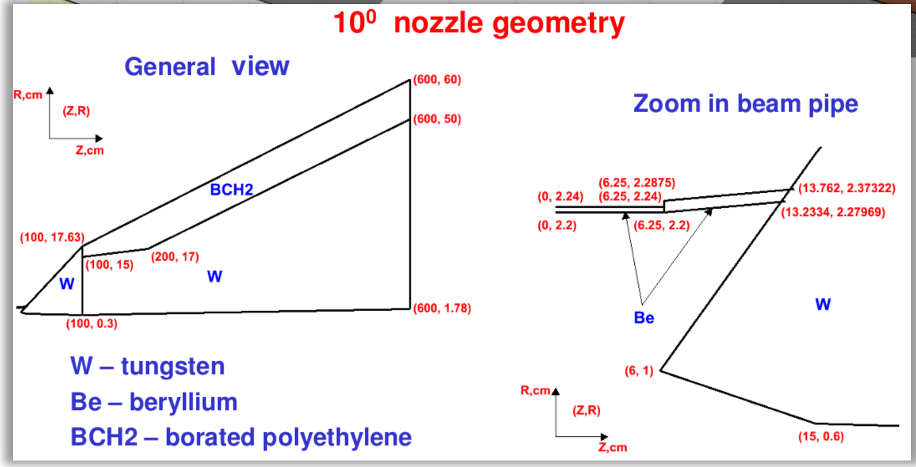
Shielding structure: the nozzles

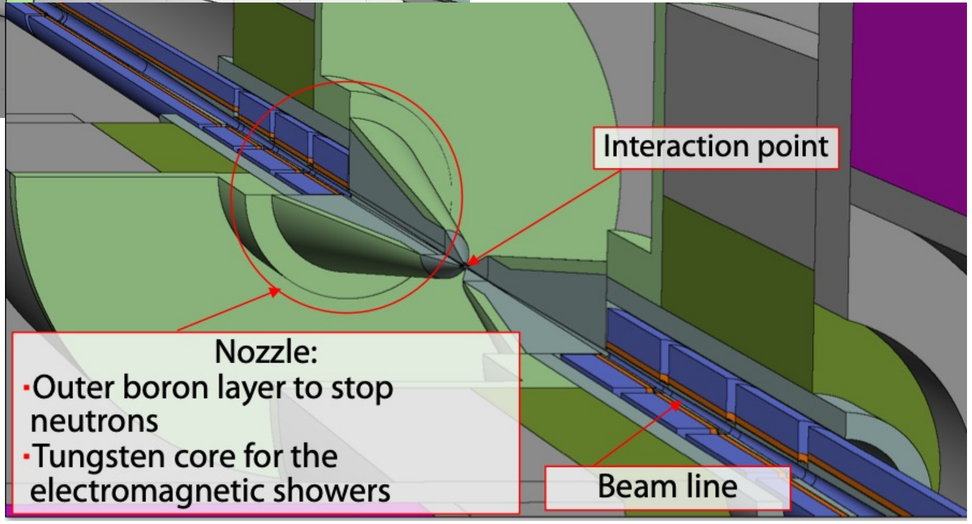


Originally designed for $\sqrt{s} = 1.5$ TeV
by MAP (Muon Accelerator Program)
N.V. Mokhov et al., Fermilab-Conf-11-094-APC-TD

Nozzles reduce background particle flux by 2-3 orders of magnitude

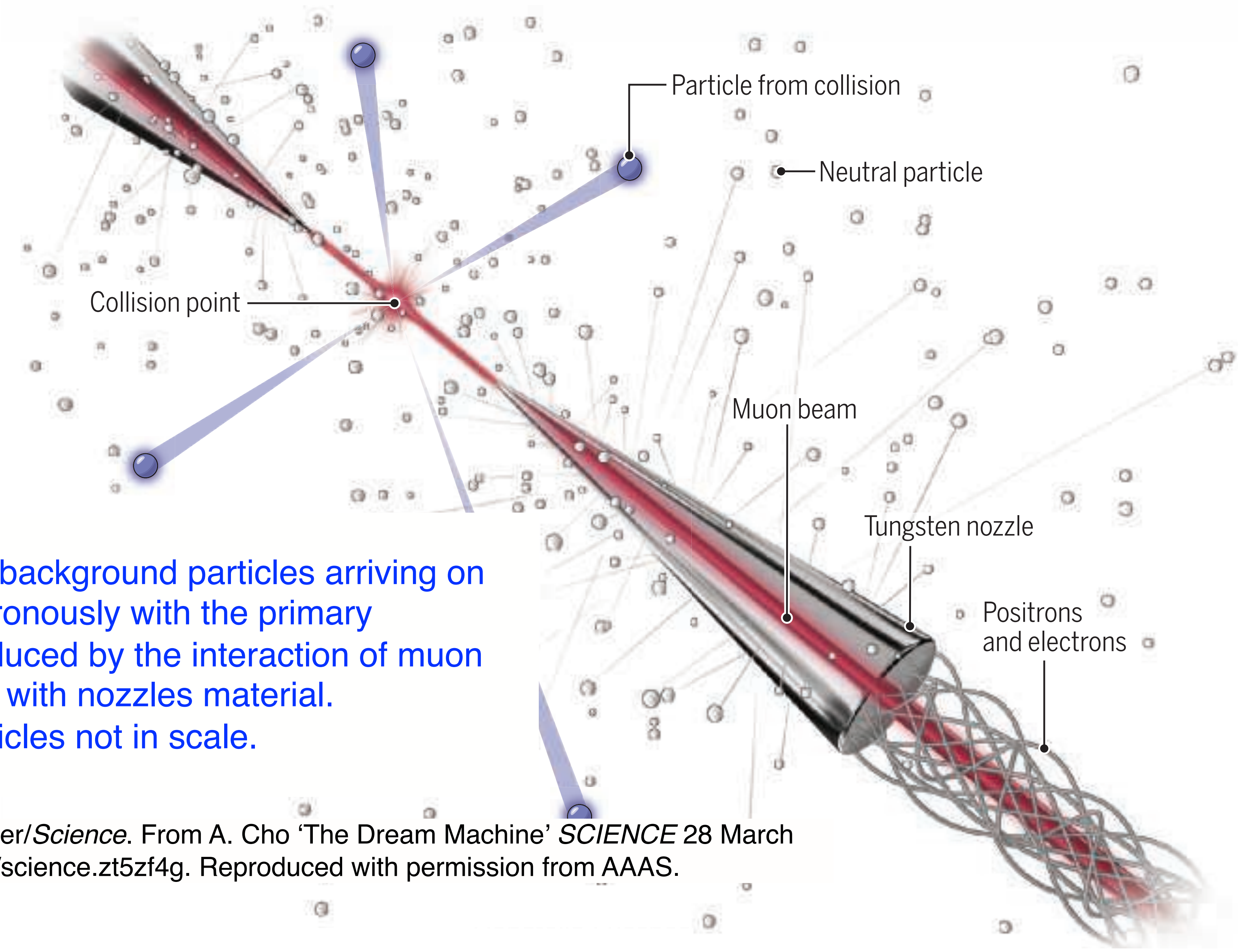
10^0 nozzle geometry





Nozzle:
- Outer boron layer to stop neutrons
- Tungsten core for the electromagnetic showers

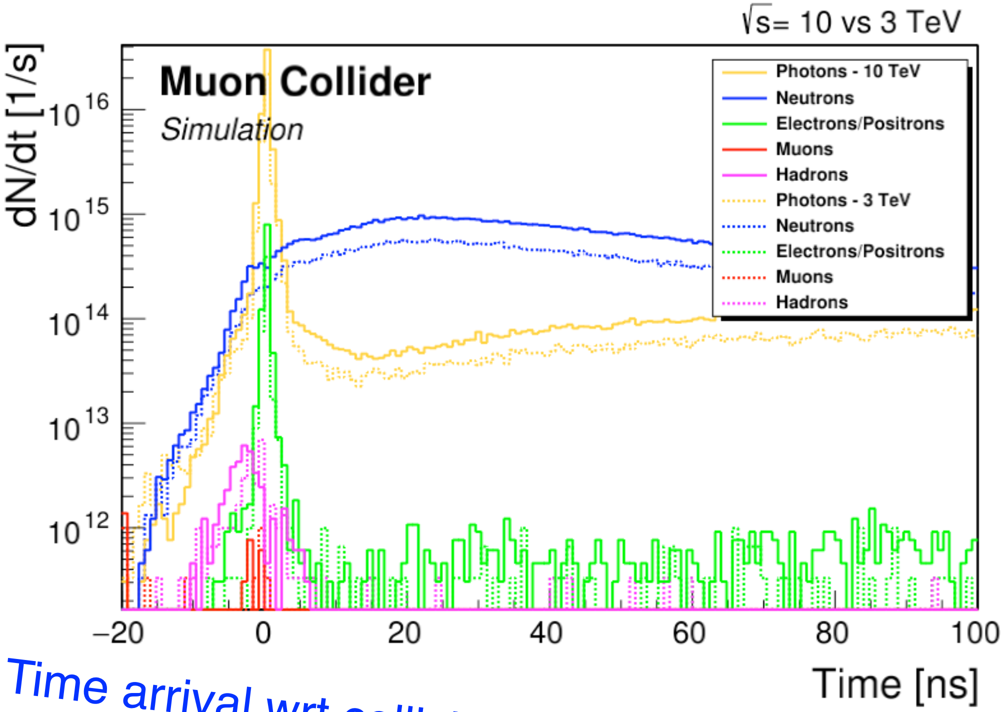
D. Calzolari
[IMCC Ann. meeting Orsay 2023]



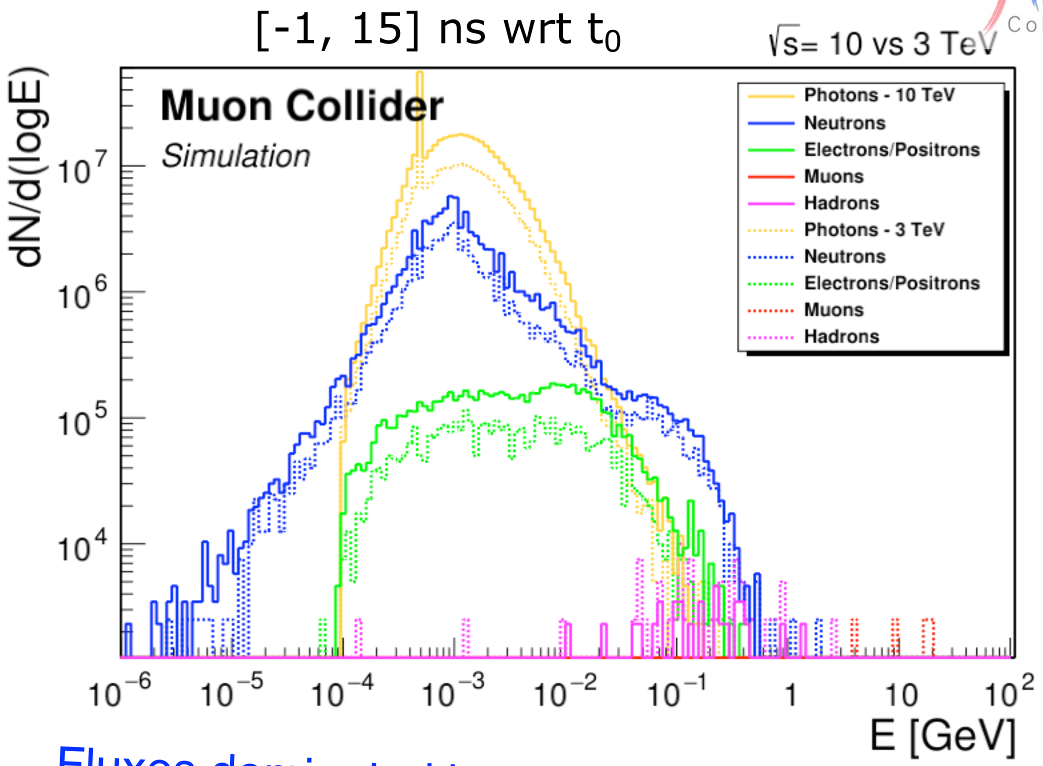
Beam-induced background particles arriving on detector synchronously with the primary interaction produced by the interaction of muon decay particles with nozzles material.
Number of particles not in scale.

Graphic by: A. Fisher/*Science*. From A. Cho 'The Dream Machine' *SCIENCE* 28 March 2024, doi: 10.1126/science.zt5zf4g. Reproduced with permission from AAAS.

Survived beam-Induced background (BIB) properties



Time arrival wrt collision time



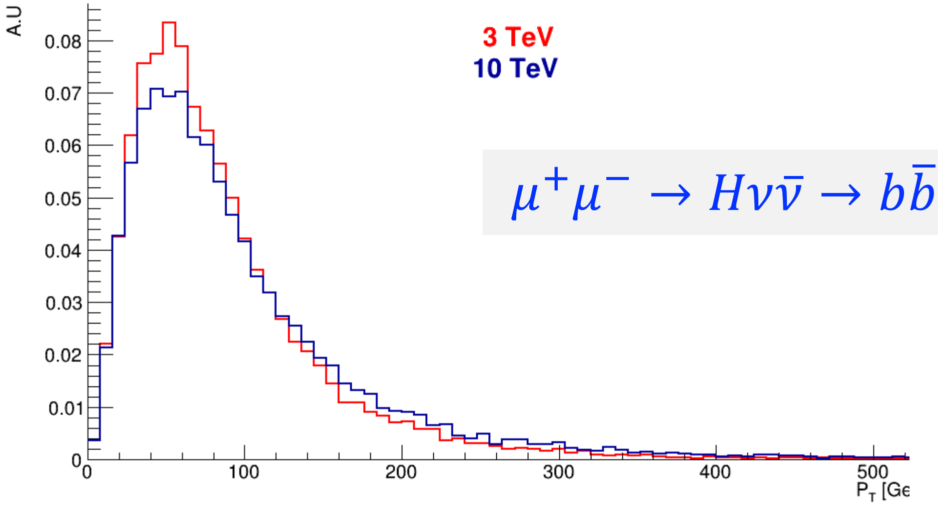
Fluxes dominated by low momentum particles

- Use the same nozzle structure of $\sqrt{s} = 1.5$ TeV $\Longrightarrow$ optimization for $\sqrt{s} = 3$ TeV and $\sqrt{s} = 10$ TeV in progress
- Fluxes at $\sqrt{s} = 3$ and $\sqrt{s} = 10$ TeV quite similar $\Longrightarrow$ beam-induced background characteristics determined by the nozzles

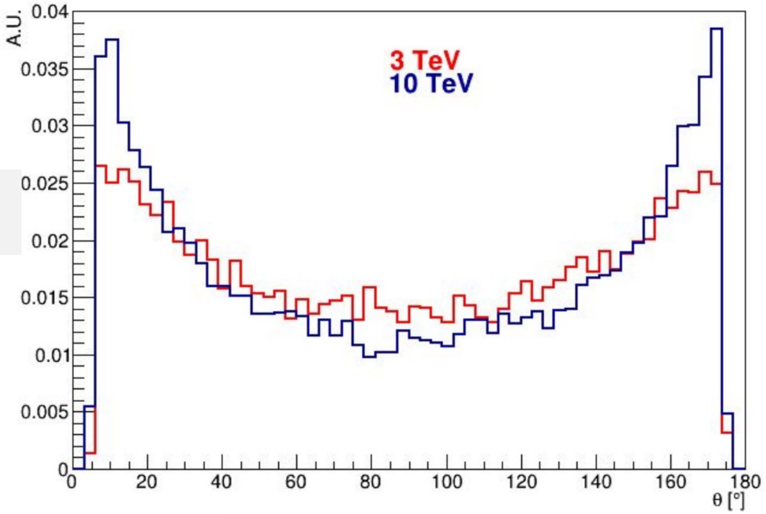
Detector and physics performance

High and low energy physics kinematic properties

Low momentum,
forward-boosted
phenomena,
ex. Higgs boson.

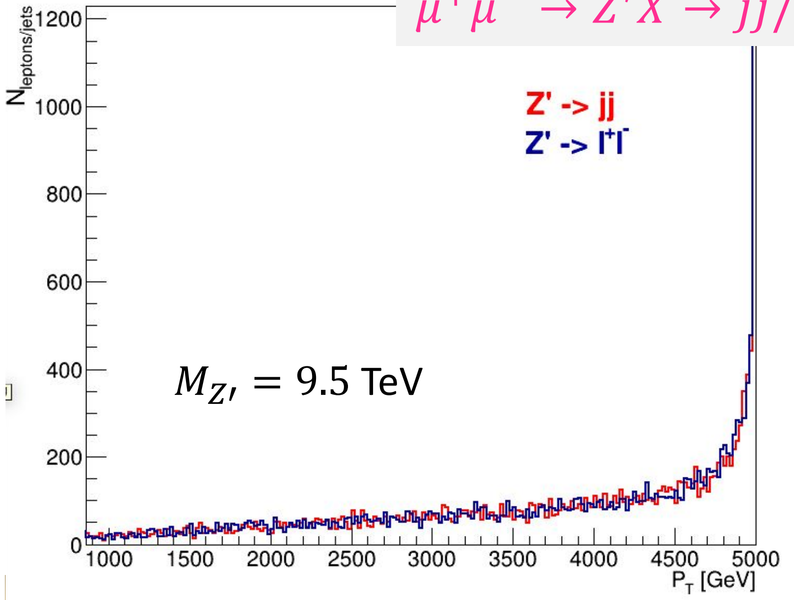


$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$

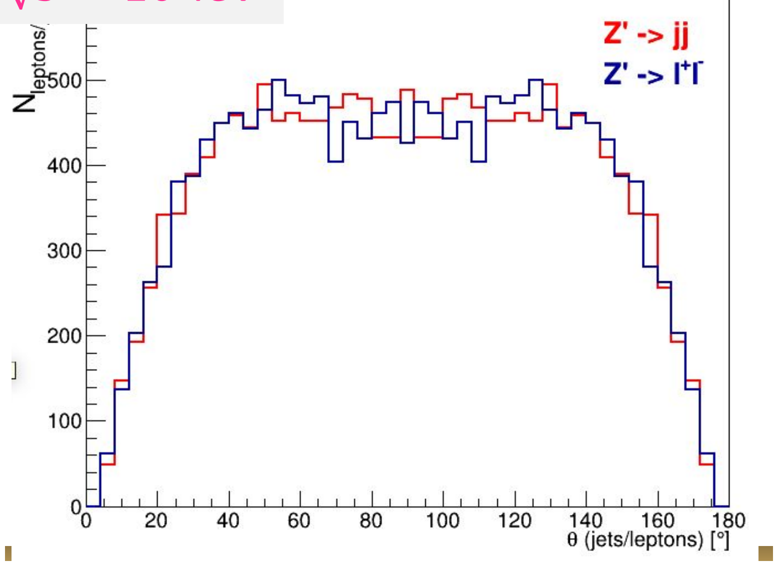


High momentum
central phenomena,
ex. Z'

$\mu^+\mu^- \to Z'X \to jj/\ell\ell X \; \sqrt{s} = 10$ TeV



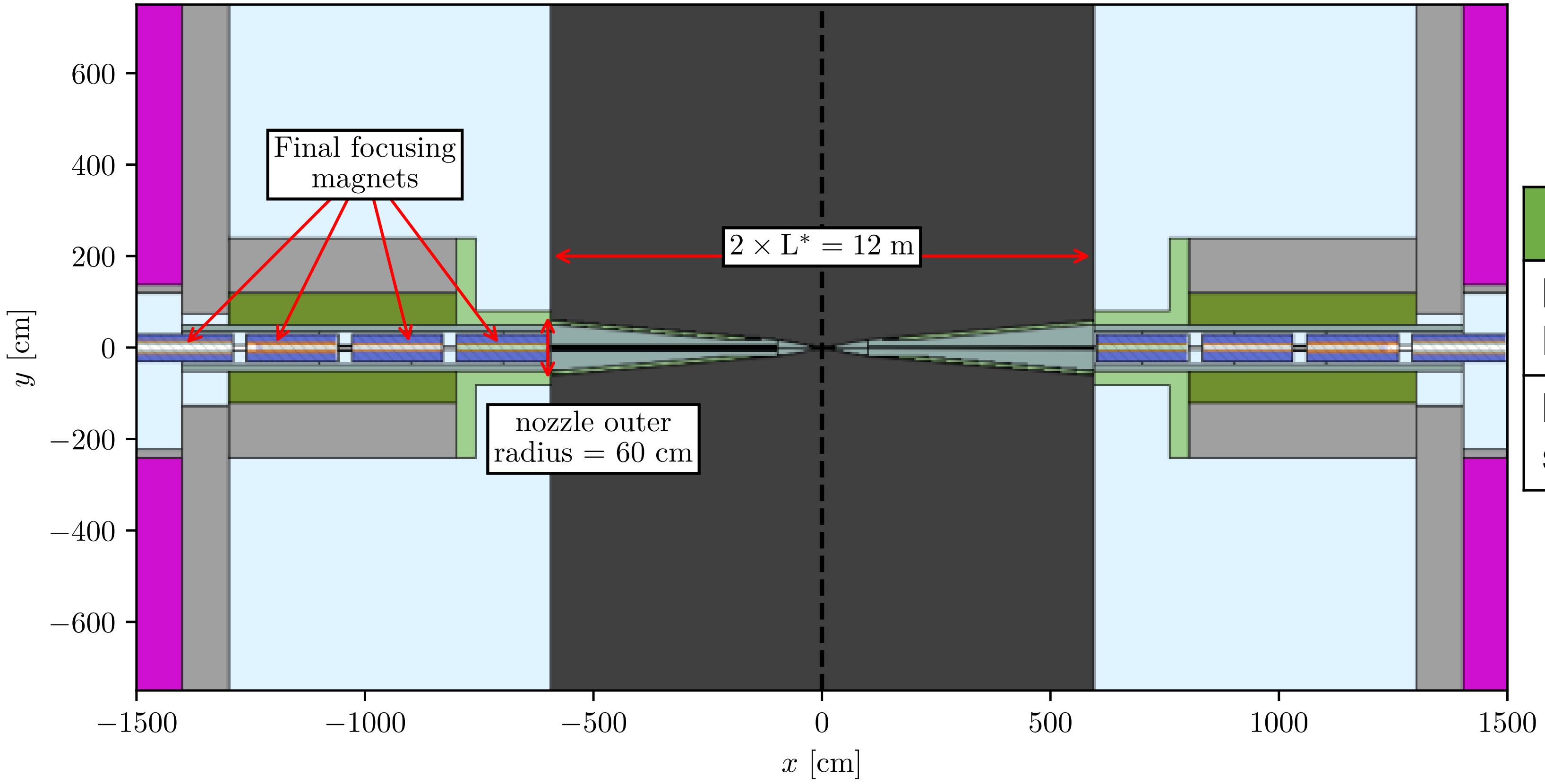
$M_{Z'} = 9.5$ TeV



Collider interaction region requirements

Longitudinal size of the detector determined by position of final focusing magnets.
At $\sqrt{s} = 10$ TeV it would be very difficult from the the lattice point of view to have more than ± 6 m

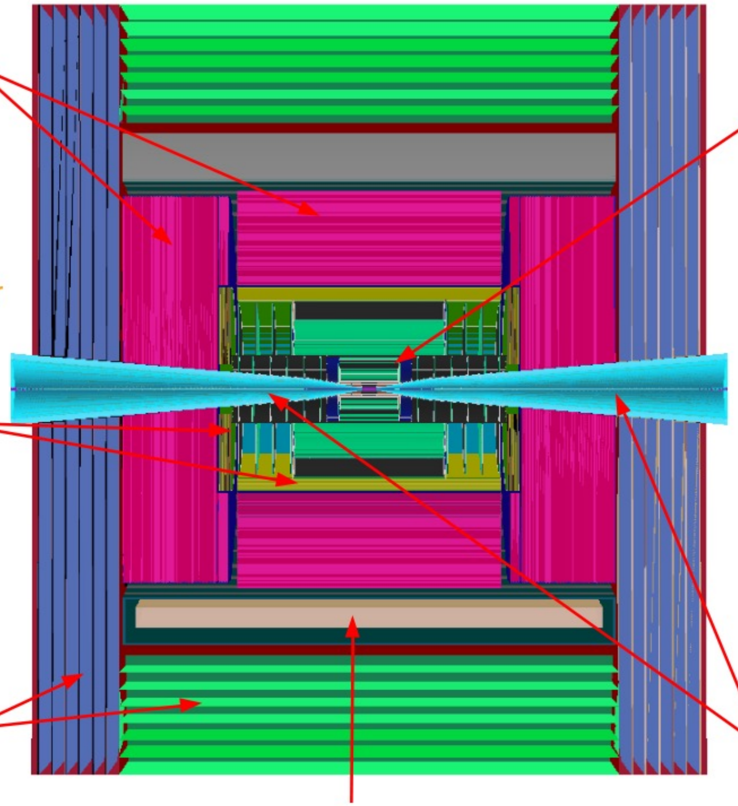
C. Carli, A. Lechner, **D. Calzolari**, K. Skoufaris



	LHC	MC
bunch length σ_z	7.7 cm	1.5 mm
bunch size $\sigma_\perp$	16.7 μm	0.9 μm

Detector concept at $\sqrt{S} = 3$ TeV based on CLIC's detector design CLICdp-Note-2017-001

- Removed forward luminosity detectors
- Inserted nozzles
- Adapted tracker detector
- Magnetic field modified to cope with available beam-induced background



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.

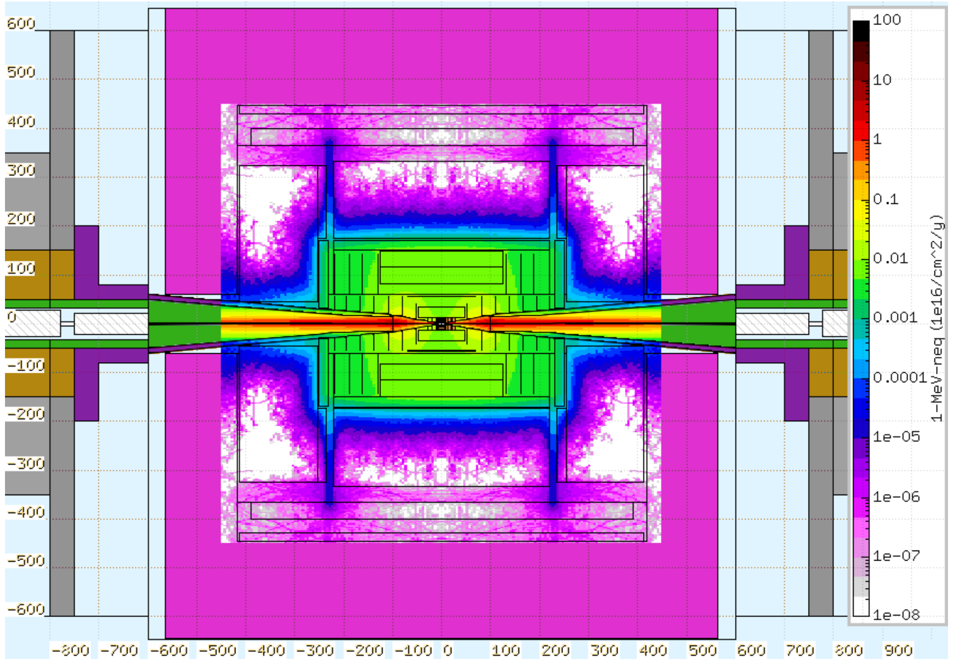
shielding nozzles

- Tungsten cones + borated polyethylene cladding.

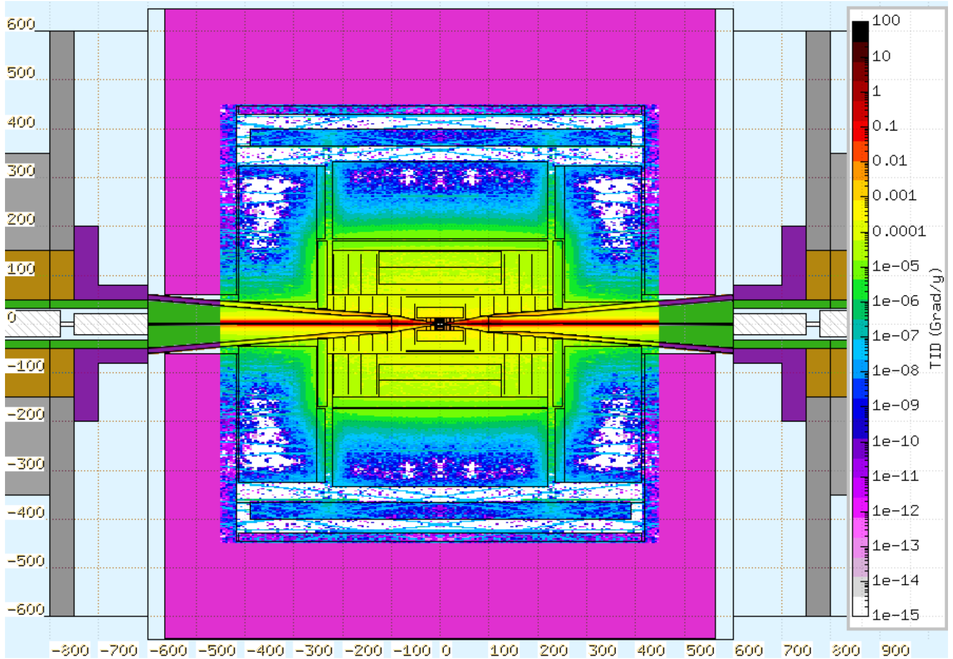
ILCSoft is the simulation and reconstruction framework, forked from CLIC's software.
Transition to key4hep in progress, timeline depending on person power.
Tutorial available if interested to play with.

Radiation environment

1-MeV neutron equivalent fluence per year



Total ionizing dose per year



Assumptions:

- Collision energy 1.5 TeV
- Collider circumference 2.5 km
- Beam injection frequency 5Hz
- Days of operation/year 200

Radiation hardness requirements like HL-LHC (expected)

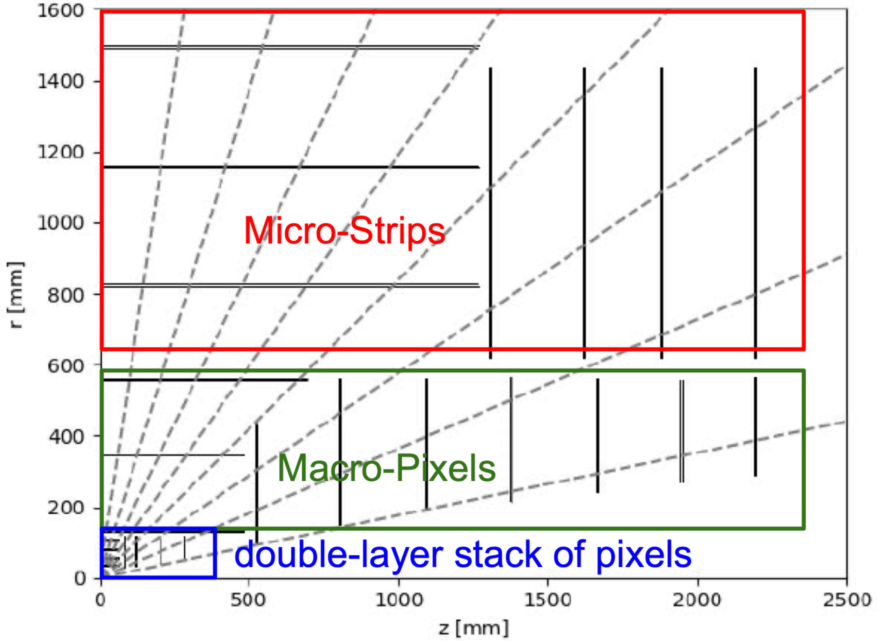
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

K. Black, Muon Collider Forum Report

$\sqrt{S} = 3$ TeV similar, $\sqrt{S} = 10$ TeV under study, expected similar

Tracker system: full detector & BIB simulations

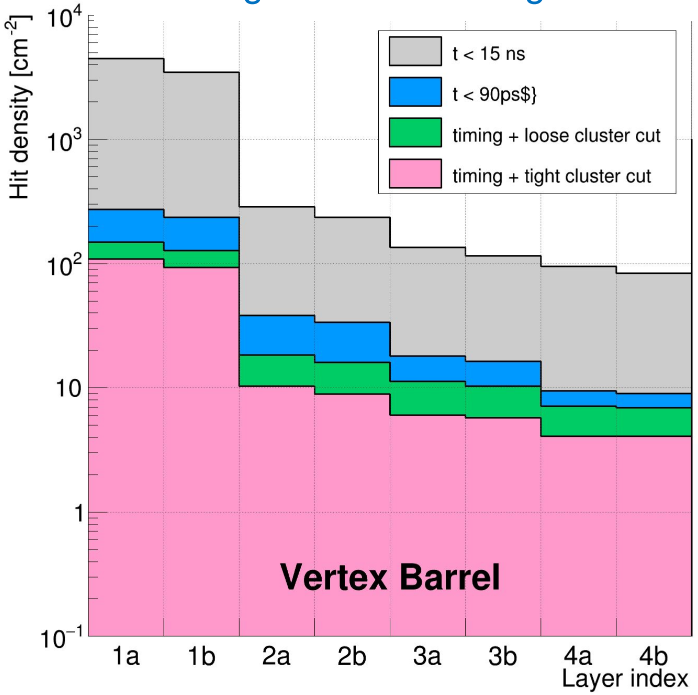
First layers of barrel vertex detector & forward disks highly impacted BIB



Tracker requirements

- Timing: high resolution to suppress out of time BIB.
- Energy deposition: exploit different cluster shapes.
- Double layers: apply directional filtering.

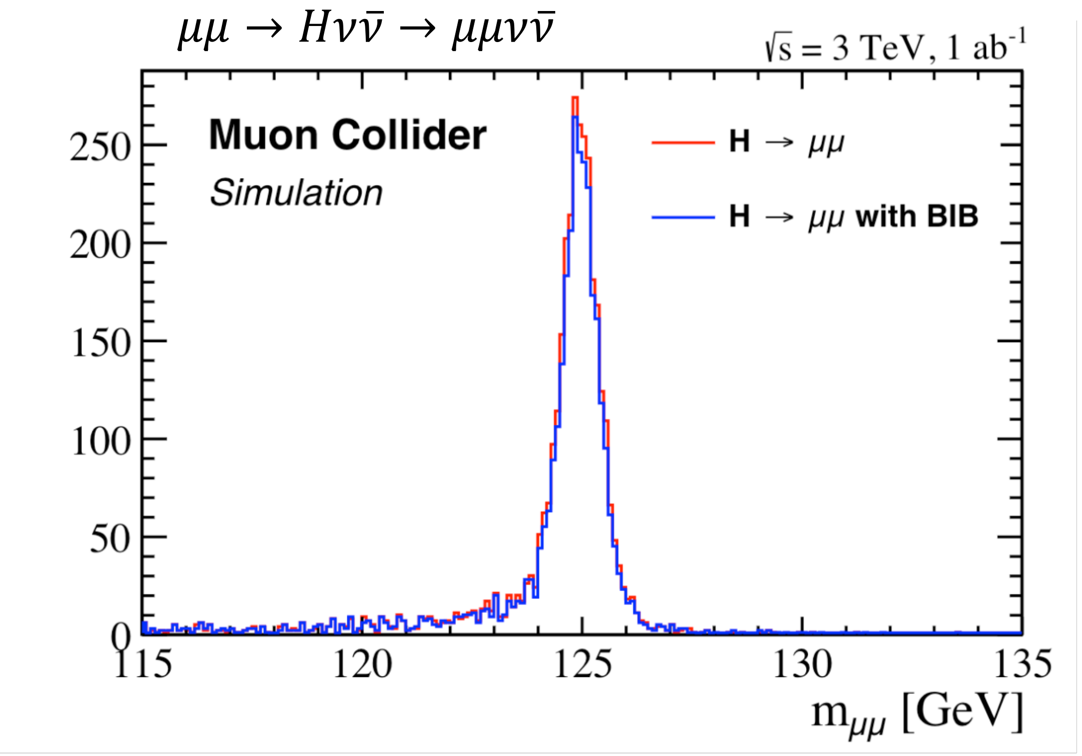
S. Pagan Griso C. Sellgren

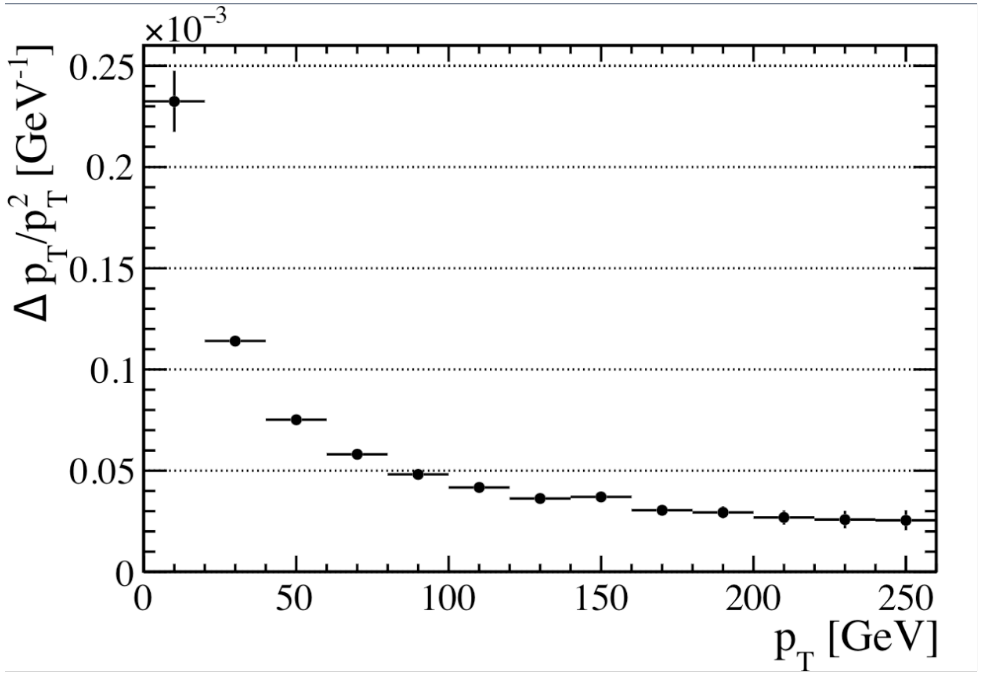


Higher occupancies respect to LHC detectors crossing rate 100 kHz vs 40 MHz

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

Central muons, that do not suffer from BIB, are used to study momentum resolution





$\frac{\Delta\sigma_{H\to\mu\mu}}{\sigma_{H\to\mu\mu}} \sim 38\%$ 1 experiment 1 ab^{-1}

CLIC at 3 TeV 2 ab^{-1}: 25%

R&D status for trackers

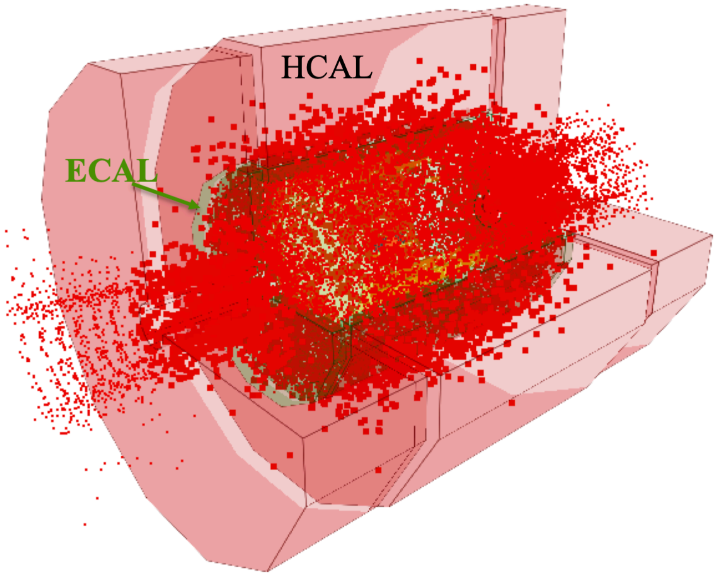
General assumption :

- Use silicon pixel & silicon macro-pixels for vertex detector & tracker detector

IMCC fully engaged in ECFA DRD and CPADS silicon tracker, there is no dedicated efforts so far.

Muon collider detector will have first layers of barrel vertex detector & forward disks highly impacted BIB, synergies with FCC-hh/ SppC detectors

Calorimeter system: full detector & BIB simulations



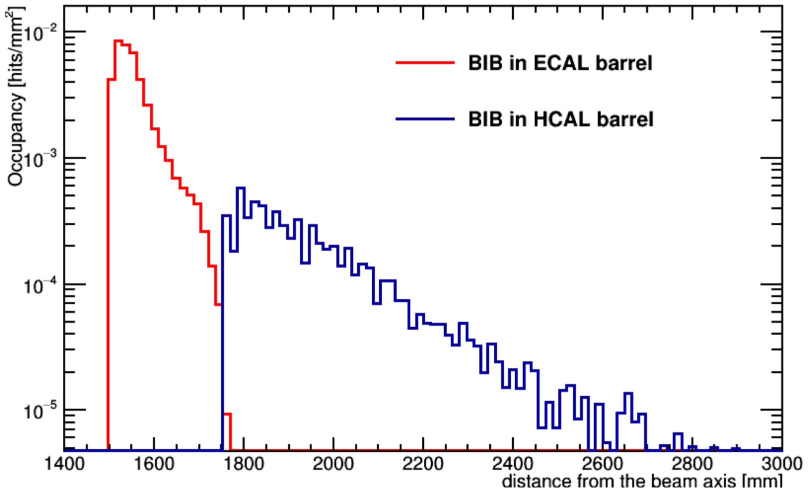
ECAL surface flux: 300 particle/cm^2

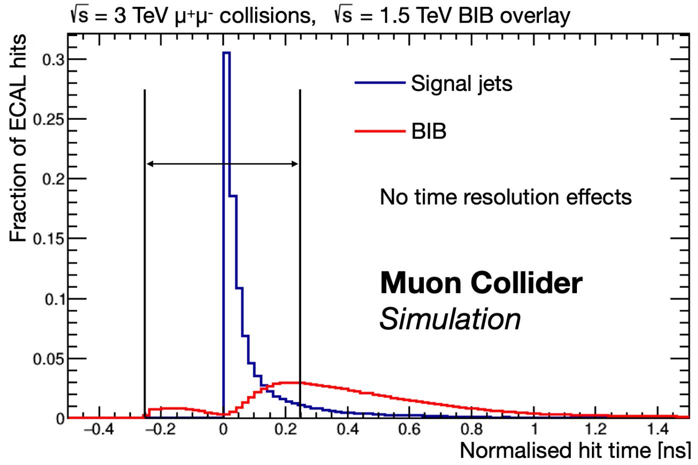
- 96% photons, 4% neutrons
- $E_{\gamma}^{Ave.}$~1.7 MeV

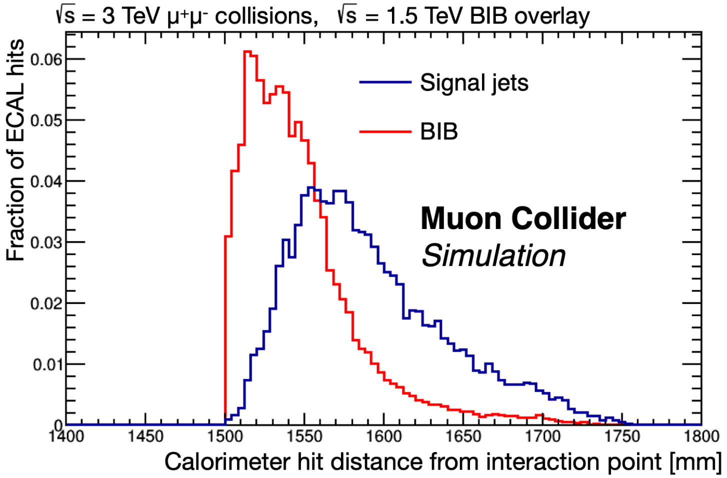
Calorimeter requirements

- time-of-arrival: resolution ~100 ps to reject out-of-time particles.
- Longitudinal segmentation: different profile signal vs. BIB.
- High granularity: to separate BI particles from signal avoiding overlaps in the same cell.

Occupancy: ECAL > 10 times HCAL







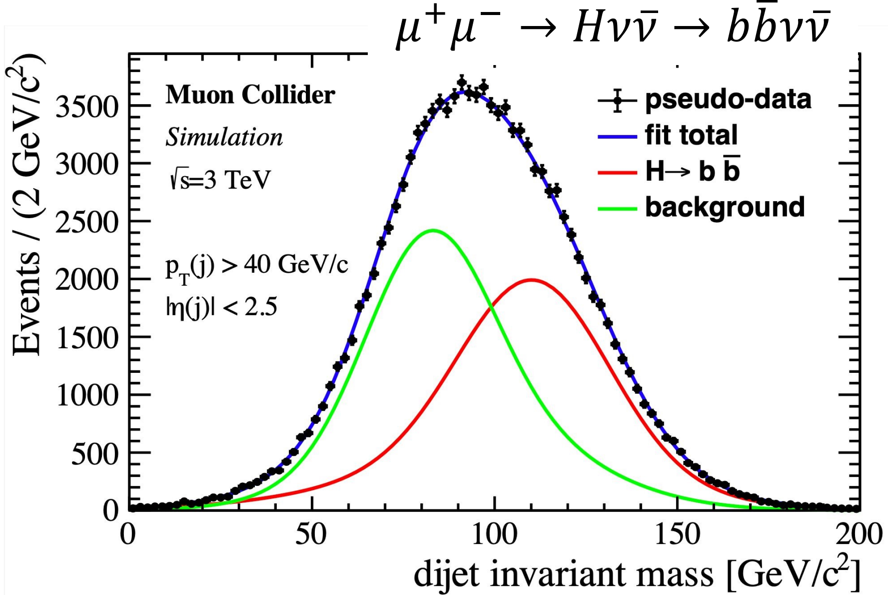
Jet reconstruction performance

- $E_{th} \geq 2$ MeV EM calorimeter cells to mitigate BIB effect
- efficiency: $80 \div 90\%$
- Negligible fake rate

b-jet identification:

- Simple algorithm, secondary vertex
- Efficiency:45% (20 GeV) 70% (120 GeV)
- c-jet mis-identification ~20%
- light jets mis-identification few %

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



Invariant mass resolution: 18%

No major issues with photon reconstruction

The $\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow \gamma\gamma\nu\bar{\nu}$ reconstructed obtaining

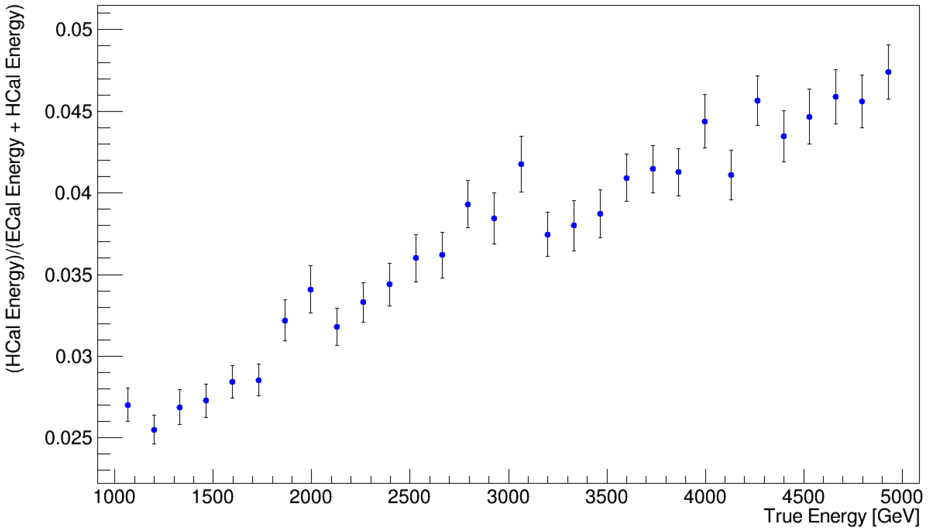
$\frac{\sigma_m}{m} \approx 2.5\%$ $\frac{\Delta\sigma_{H\rightarrow\gamma\gamma}}{\sigma_{H\rightarrow\gamma\gamma}} = 7.6\%$ 1 experiment 1 ab^{-1}

CLIC at 3 TeV 2 ab^{-1}: 10%

$\frac{\Delta\sigma_{H\rightarrow b\bar{b}}}{\sigma_{H\rightarrow b\bar{b}}} \sim 0.75\%$ 1 experiment 1 ab^{-1}

CLIC at 3 TeV 2 ab^{-1}: 0.3%

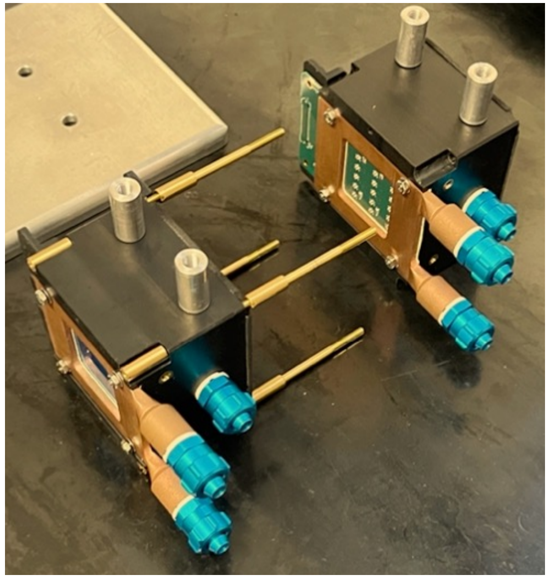
R&D status for calorimeters



Deeper (~$25x_0$ ~$8.5\lambda_i$) calorimeter to contain high energy particle with characteristics

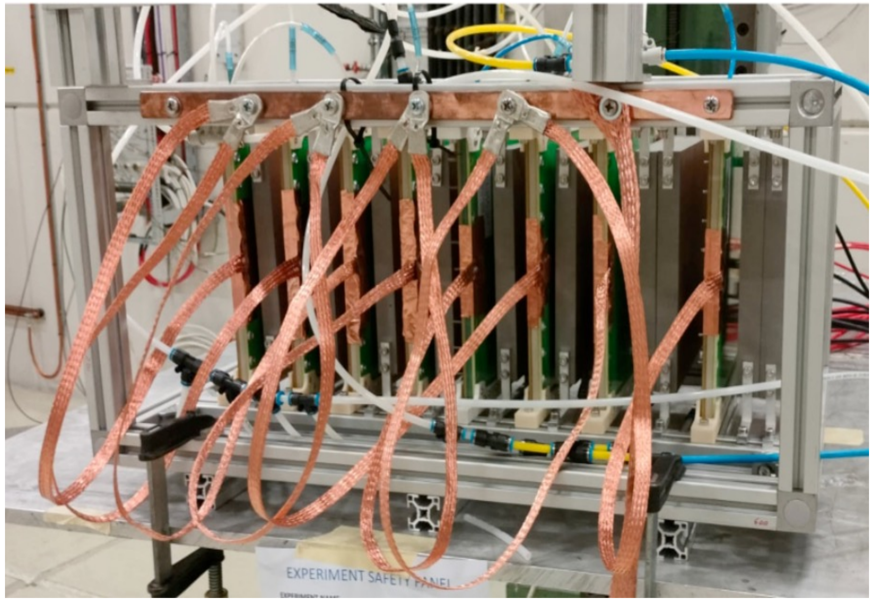
- time-of-arrival resolution ~100 ps
- Longitudinal segmentation
- High granularity

IMCC fully engaged in ECFA DRD and CPAD calorimeters



CRILIN: semi-homogeneous, PbF2 crystals. Each module has 5 layers of 10x10x40 mm^3 crystals. Cerenkov light detected by SiPMs

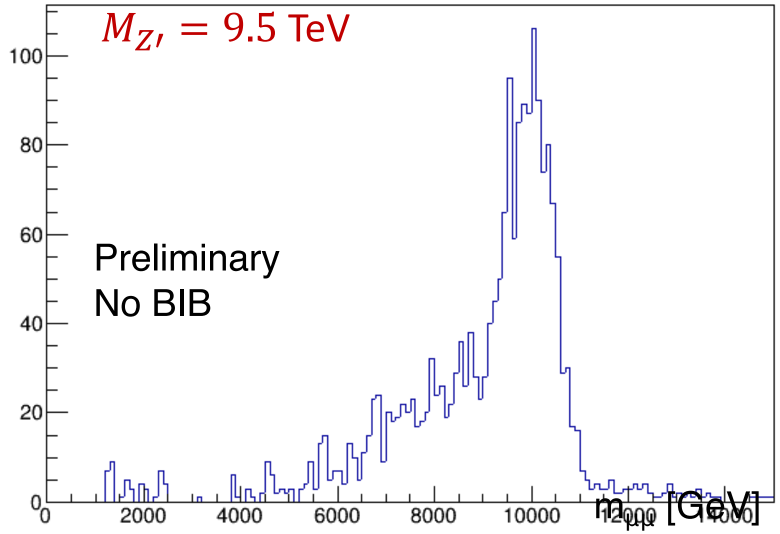
Micro-Pattern Gas Detectors, µRWell, RPWell, MicroMega, as active layer



Muon reconstruction and R&D

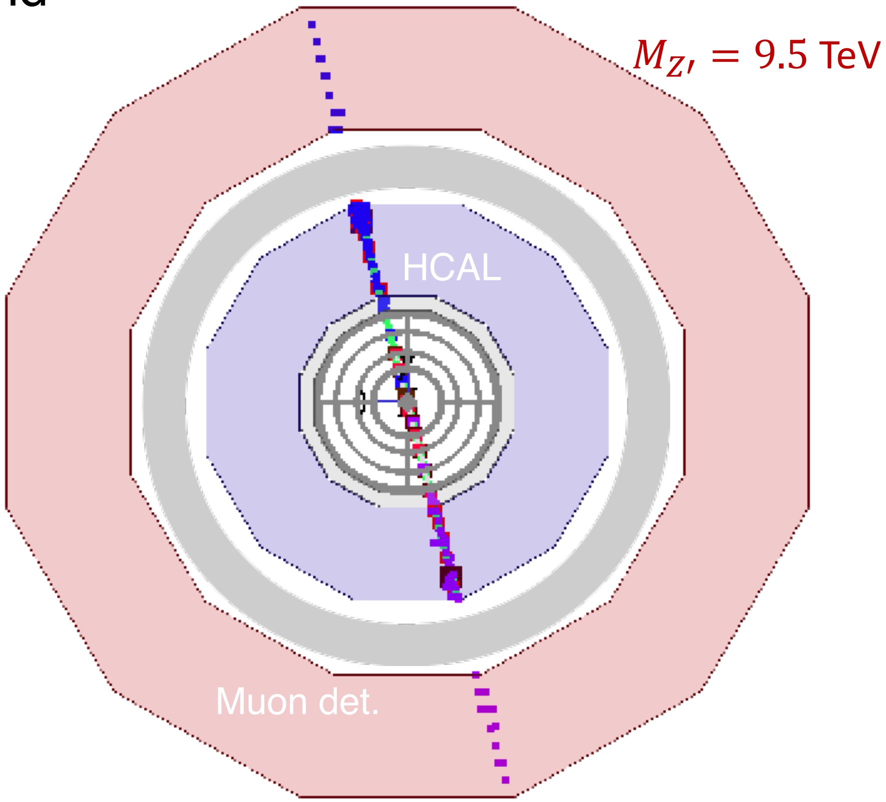
- Need to cover a momentum range from few GeV up to TeV
- New approach needed:
  - usual methods for low momentum;
  - combine information from muons detector, tracker and calorimeter information, jet-like structure;
  - Picosec technology is investigated to replace RPC.
    See Matteo Brunoldi presentation Friday 19th

$\mu^+\mu^- \rightarrow Z'X \rightarrow \mu\mu X \ \sqrt{s} = 10$ TeV



B = 5 T

$\mu^+\mu^- \rightarrow Z'X \rightarrow \mu\mu X \ \sqrt{s} = 10$ TeV



Expectation in Higgs physics

Expectations in Higgs physics: determination of couplings

David A, et al., arXiv:1209.0040

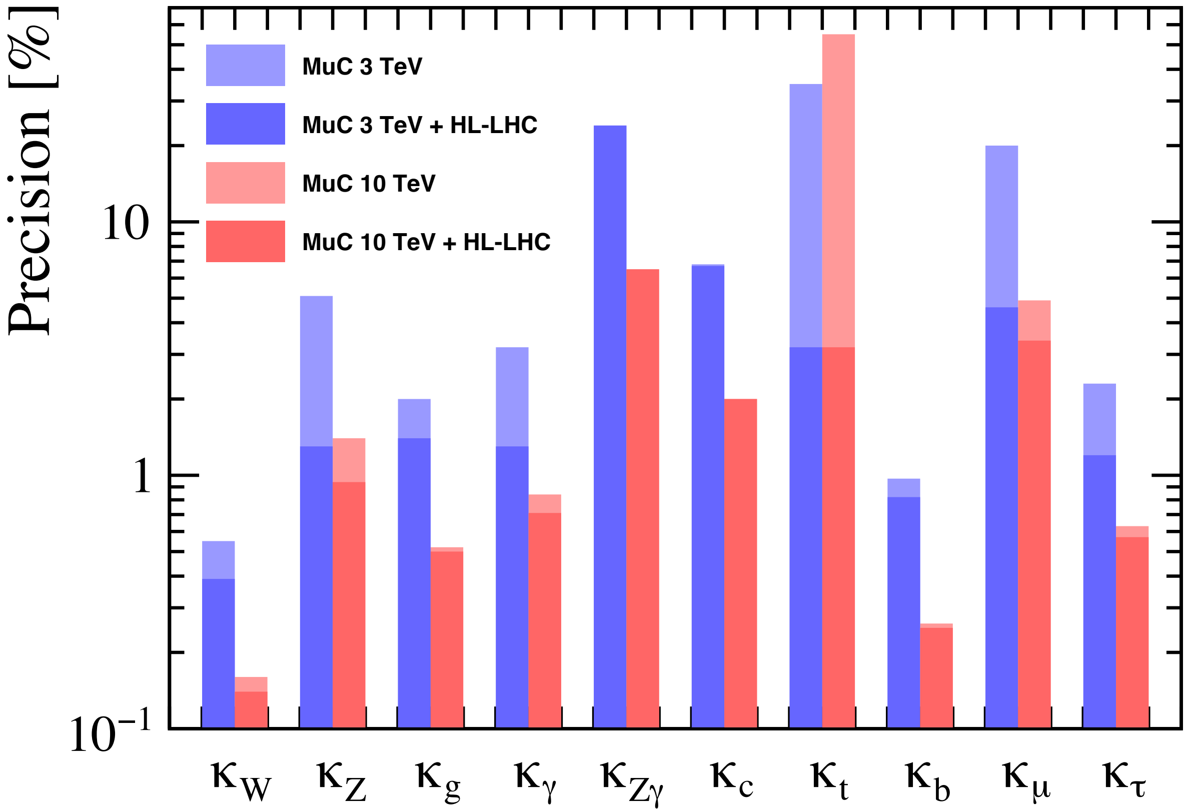
Measurement of $\sigma_H \times BR(H \to f)$ allows determination of H to f coupling in the k-framework
k_i coupling modifiers: ratio between the measured and the standard model values.

Studied performed so far do not cover all the relevant H decay modes

Exercises benchmark parametric studies at $\sqrt{s} = 3$ TeV and $\sqrt{s} = 10$ TeV

Forslund M, Meade P. J. High Energ. Phys. 2022:185 (2022)

M. Casarsa et al.



Expectations in Higgs physics: sensitivity on Higgs potential parameters

$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

Good performance on Higgs trilinear self coupling determination, even if not optimal

Process: $\mu^+\mu^- \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$ only

M. Casarsa et al.

Han T, Liu D, Low I, Wang X.
Phys. Rev. D 103:013002 (2021)

$\sqrt{s} = 3$ TeV full detector and BIB simulation,1 experiment 1 ab^{-1}

$$\frac{\Delta\sigma_{HH\to b\bar{b}b\bar{b}}}{\sigma_{HH\to b\bar{b}b\bar{b}}} \sim 33\%$$

$$\frac{\Delta\lambda_3}{\lambda_3} \sim 20 - 30\%\ (25\%)$$

parametric study

CLIC at 3 TeV 2 ab^{-1}+ final states: 22%

$\sqrt{s} = 10$ TeV parametric studies

$$\frac{\Delta\lambda_3}{\lambda_3} = 5.6\%$$

1 experiment 10 ab^{-1} 5 years

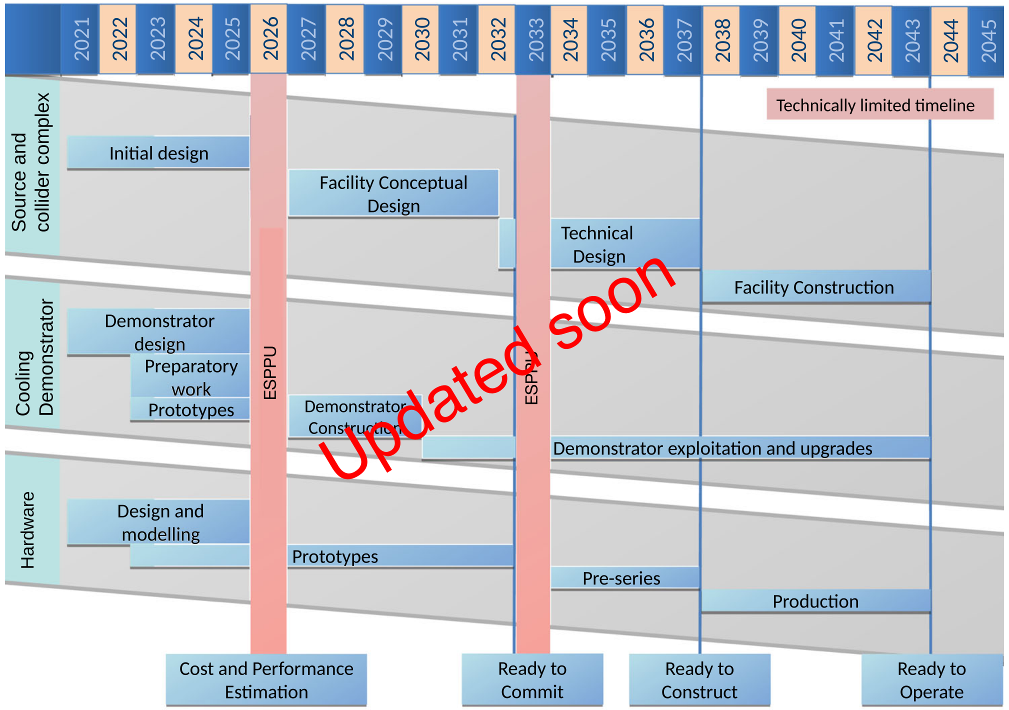
Chiesa M, et al. J. High Energ.
Phys. 2020:98 (2020)

Parametric study on quartic self coupling

- Only $\mu^+\mu^- \to HHH\nu\bar{\nu} \to b\bar{b}b\bar{b}b\bar{b}\nu\bar{\nu}$
- No background considered
- No BR applied
- No selections optimization

Accuracy of $\sim 50\%$ with 20 ab^{-1}

You may think that the muon collider is far in time… … true, but the activities on the facility can start with the demonstrator on a very short time scale!



A technically limited timeline for the muon collider R&D program.

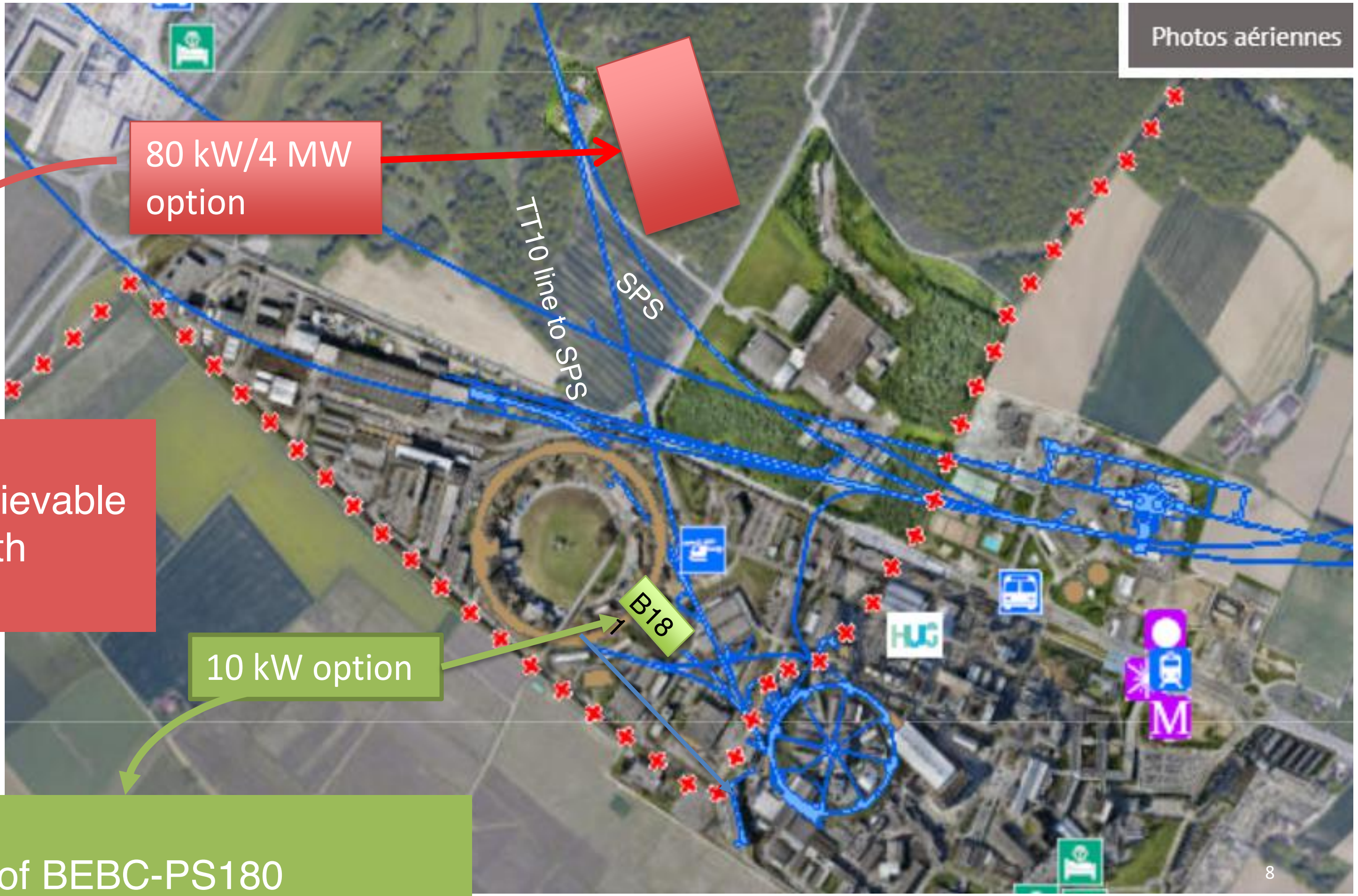
Demonstrator facility will allow:

- Test muon cooling cell and, later, muon cooling functionalities for 6D cooling principle at low emittance including re-acceleration.
- Study high gradients and relatively high-field solenoid magnets for the machine.
- Develop and test high-power production target.
- Identify and construct detectors to measure beam emittances.
- Physics?

CERN option, other solutions could be possible. Fermilab and JPARC expressed interested

Both use maximum intensity per pulse ~10^{13} ppp (or more) in pulses of few ns at 20+ GeV.
Different repetition rate:

- 1 pulse/few second
- 1÷2 pulse/per minute



80 kW/4 MW option

High power
O(80kW) on target easily achievable
No showstopper for 4 MW with beam at a depth of 40 m

10 kW option

Low power:
Reuse line of BEBC-PS180 Collaboration, decommissioned, extending it towards B181 (now magnet factory)

R. Losito IMCC-2023

Summary

The detector concept for a $\sqrt{s} = 3$ TeV Muon Collider, even if not optimized, exhibits physics objects reconstruction performance sufficiently robust for high-precision measurements and searches for new physics.

A $\sqrt{s} = 10$ TeV detector is being designed, dedicated sub-detectors are proposed to cope to muon collider environment. New reconstruction algorithms need to be thought.

Demonstrator facility, besides enabling numerous measurements, will actively engage the community in experimental activities, preventing the loss of valuable expertise and knowledge.

If you would like to join the effort or are interested in following

International
MUON Collider
Collaboration

Contact me and/or subscribe CERN e-group:
MUONCOLLIDER-DETECTOR-PHYSICS@cern.ch

A coordinated effort is starting in UK:

- July 3rd a kick-off meeting in Birmingham (to be confirmed)
- Contact Karol Krizka (karol.krizka.at.cern.ch) or subscribe the mailing list:
  https://www.jiscmail.ac.uk/cgi-bin/webadmin?A0=UK-MUON-DETECTOR

Thank you !

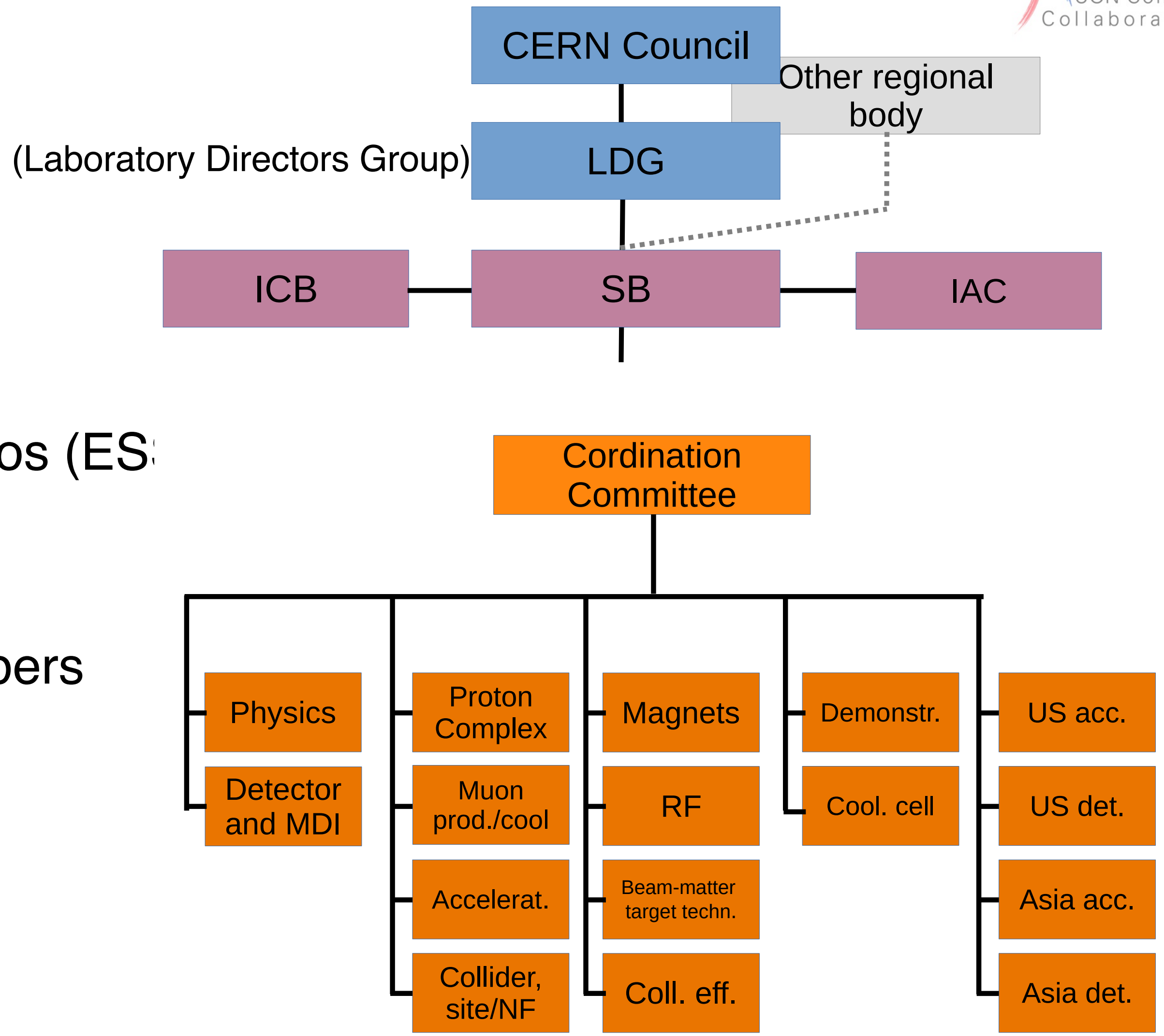
Additional material

International Muon Collider Collaboration

- **Collaboration Board (ICB)**
  - Elected chair: Nadia Pastrone

- **Steering Board (SB)**
- Chair Steinar Stapnes
- CERN members: M. Lamont, G. Arduini
- ICB members: D. Newbold (STFC), M. Lindroos (ES
  P. Vedrine (CEA), N. Pastrone (INFN)
- Study members: SL and deputies
- Will add US but wait for US decision on members

- **Advisory Committee:** To be defined
- **Coordination committee (CC)**
- Study Leader: Daniel Schulte
- Deputies: A. Wulzer, D. Lucchesi, C. Rogers



CERN Council

Other regional body

(Laboratory Directors Group) LDG

ICB

SB

IAC

Cordination Committee

Physics

Detector and MDI

Proton Complex

Muon prod./cool

Accelerat.

Collider, site/NF

Magnets

RF

Beam-matter target techn.

Coll. eff.

Demonstr.

Cool. cell

US acc.

US det.

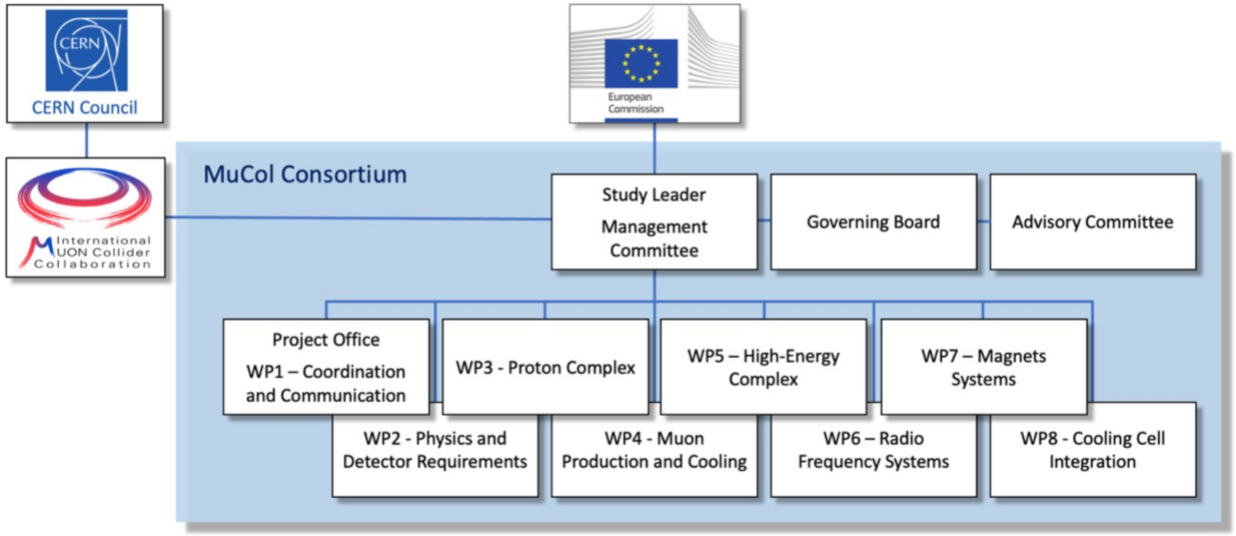
Asia acc.

Asia det.

European design study and funds

MuCol:

- European project started in March 2023
- It provides 3 MEUR from the European Commission.
- Additional funds from UK and Switzerland.
- Additional dedicated funds from Italy, INFN.



CERN Council

European Commission

International MUON Collider Collaboration

MuCol Consortium

Study Leader
Management Committee

Governing Board

Advisory Committee

Project Office
WP1 – Coordination and Communication

WP2 - Physics and Detector Requirements

WP3 - Proton Complex

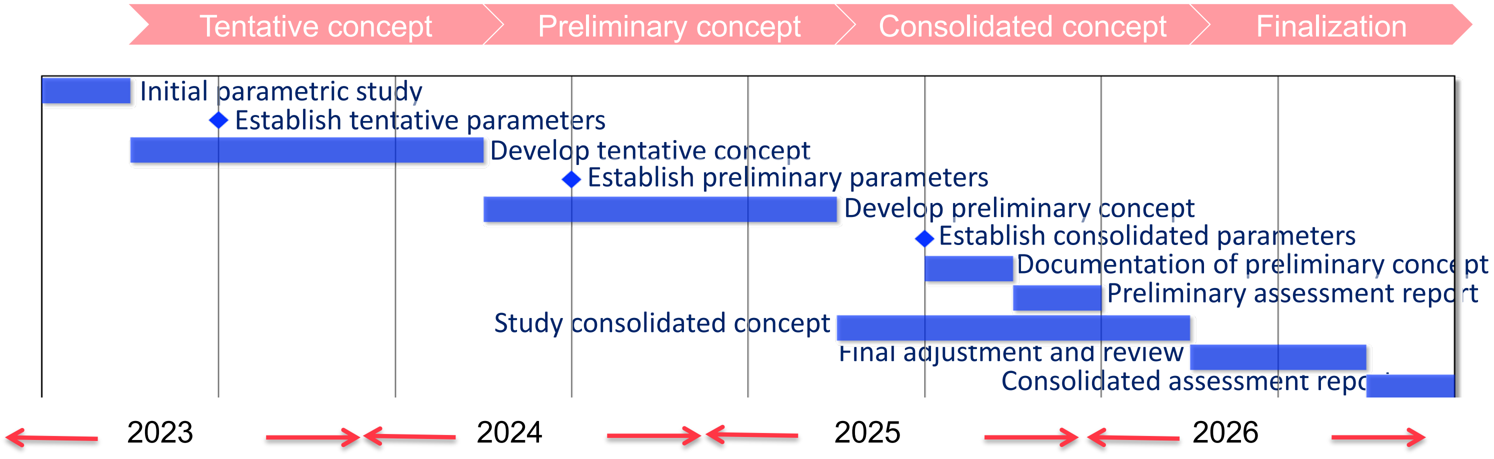
WP4 - Muon Production and Cooling

WP5 – High-Energy Complex

WP6 – Radio Frequency Systems

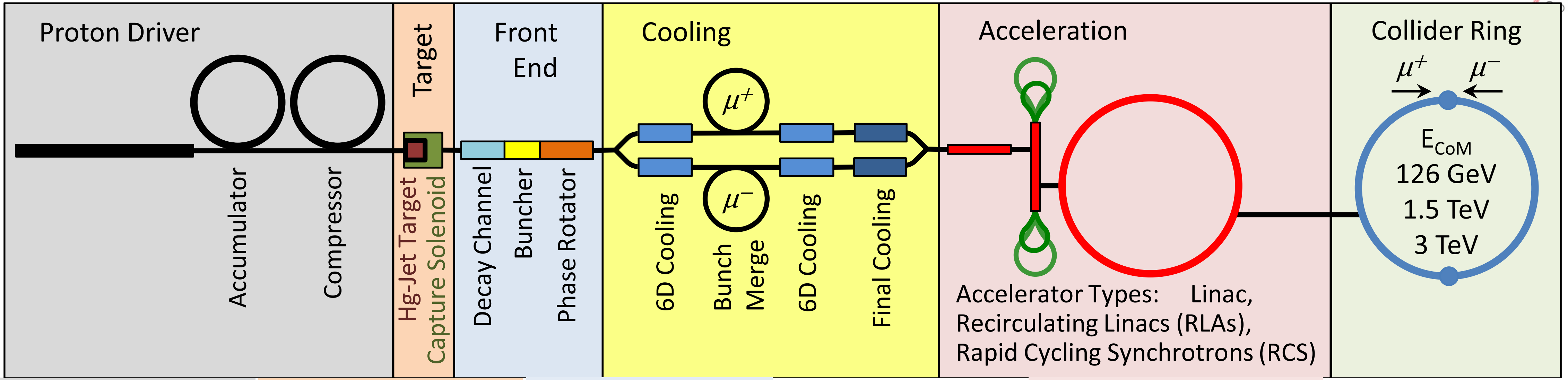
WP7 – Magnets Systems

WP8 - Cooling Cell Integration



Proton-driven Muon Collider Concept

Muon Accelerator Program (MAP)



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

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

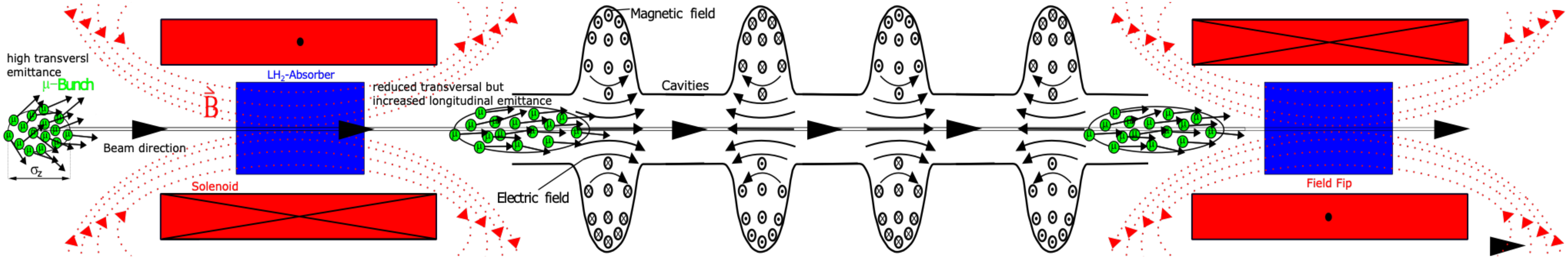
- RF cavities bunch & phase rotate $\mu^\pm$ into bunch train

- Ionization cooling 6D
- MICE

- Fast acceleration
- Use RF and SC

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

Muon ionization cooling principle



- Absorber: low Z material (Lithium hydride for first phase, liquid H for final cooling) in high magnetic filed to minimize the effect of multiple scattering
- RF cavities in magnetic field: accelerate the beam

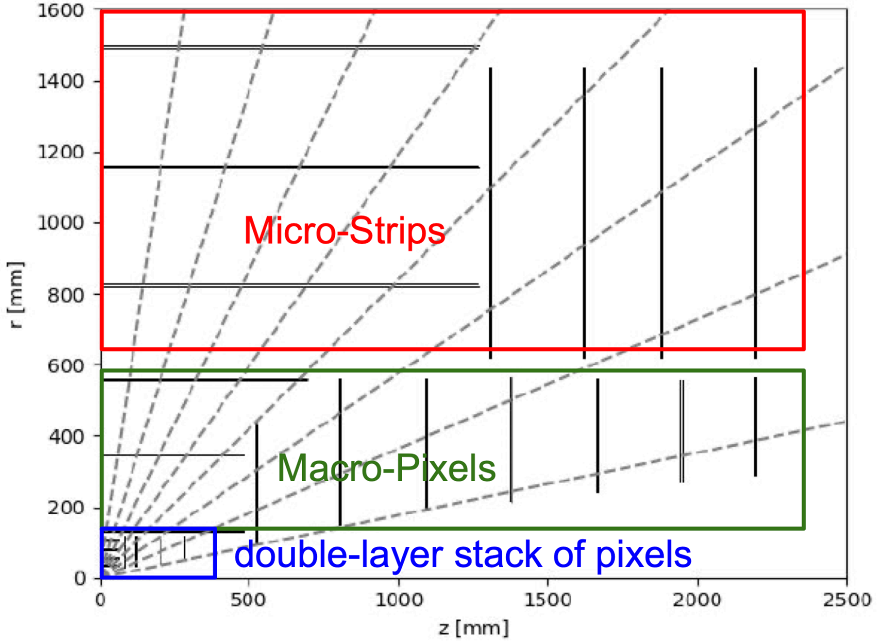
Mice Coll. Demonstration of cooling by the Muon Ionization Cooling Experiment

Two cooling stages:

1) muons cooled both transversely and longitudinally, rectilinear cooling.
2) muons cooled transversely, final cooling.

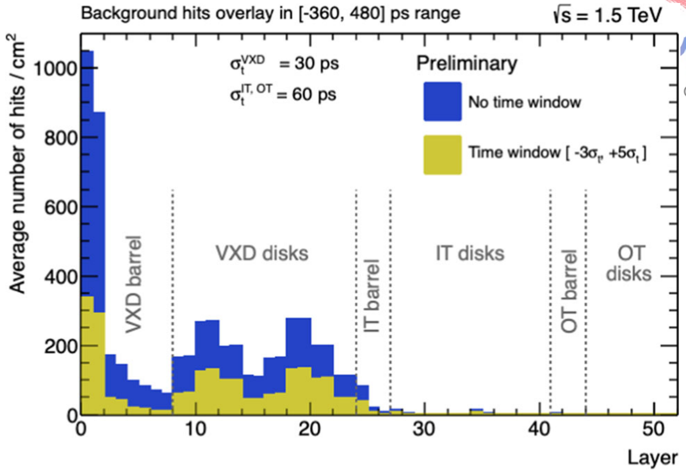
Tracker system: full detector & BIB simulation

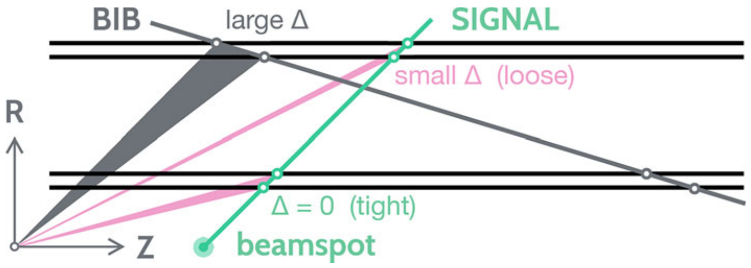
First layers of barrel vertex detector & forward disks highly impacted by BIB



Tracker requirements

- Timing: high resolution to suppress out of time BIB.
- Double layers: apply directional filtering.
- Energy deposition: exploit different cluster shapes.



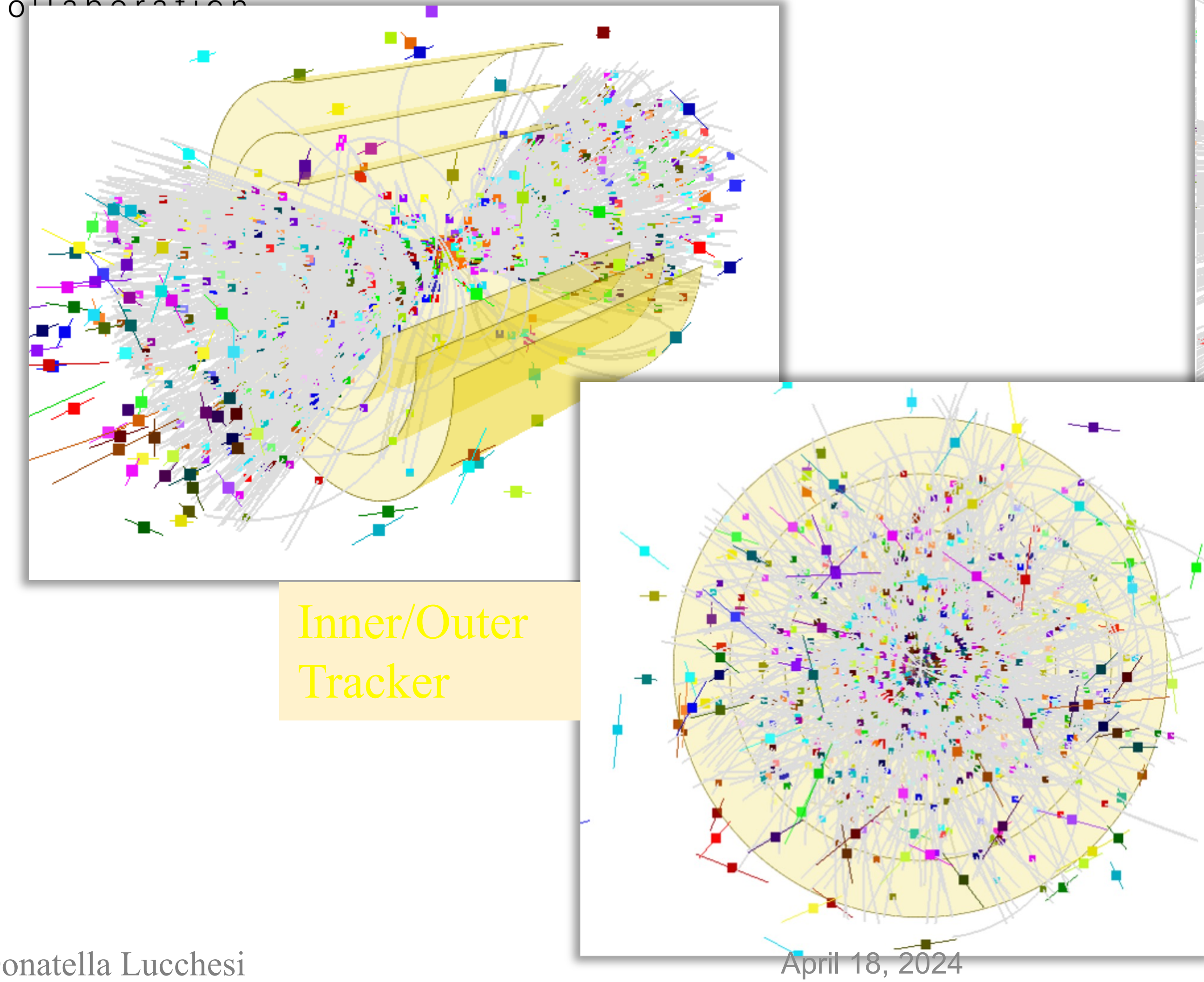


Higher occupancies respect to LHC detectors crossing rate 100 kHz vs 40 MHz

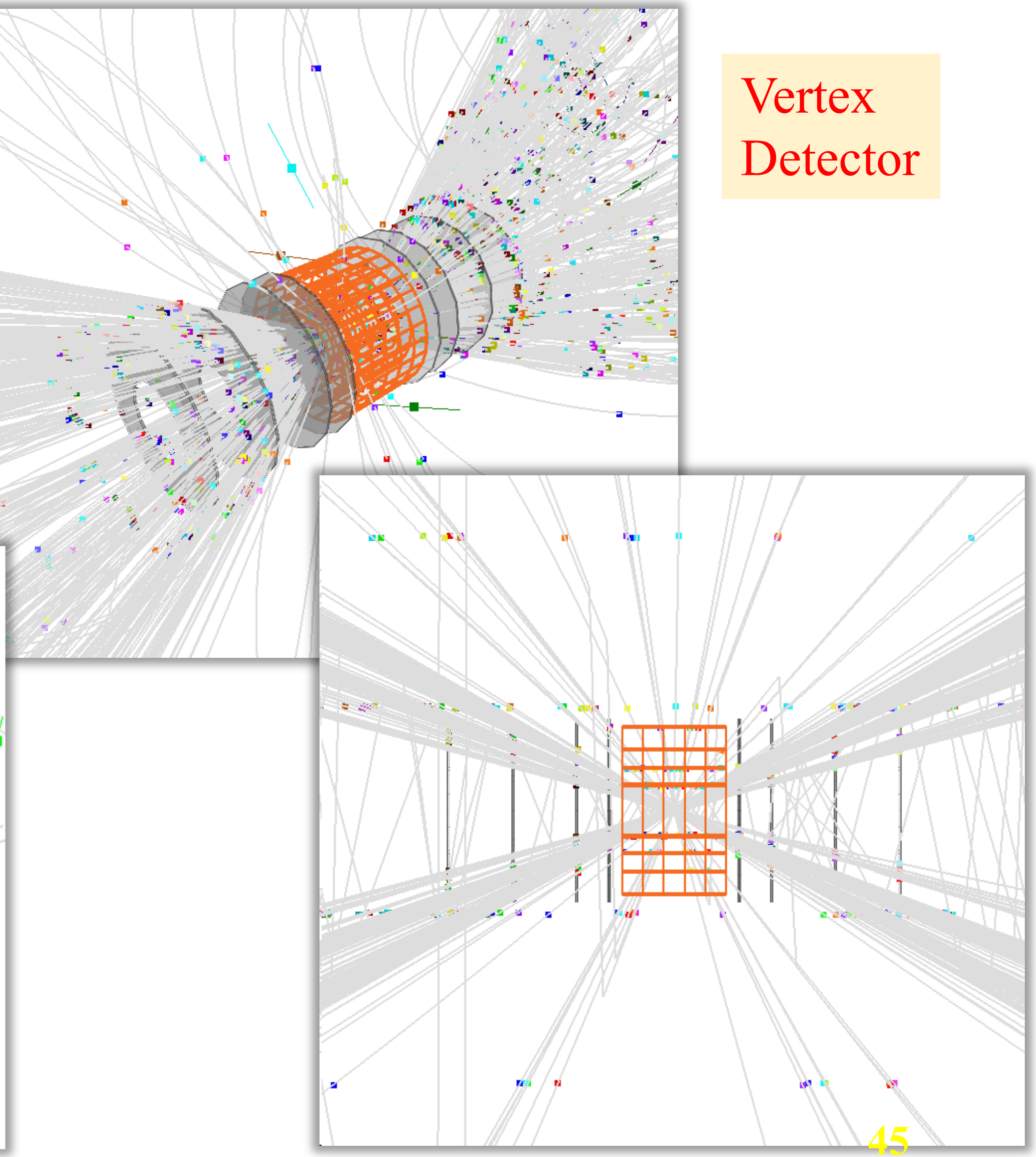
Engaged in ECFA DRD3: silicon vertex and tracker

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

Beam-Induced Background in the tracker

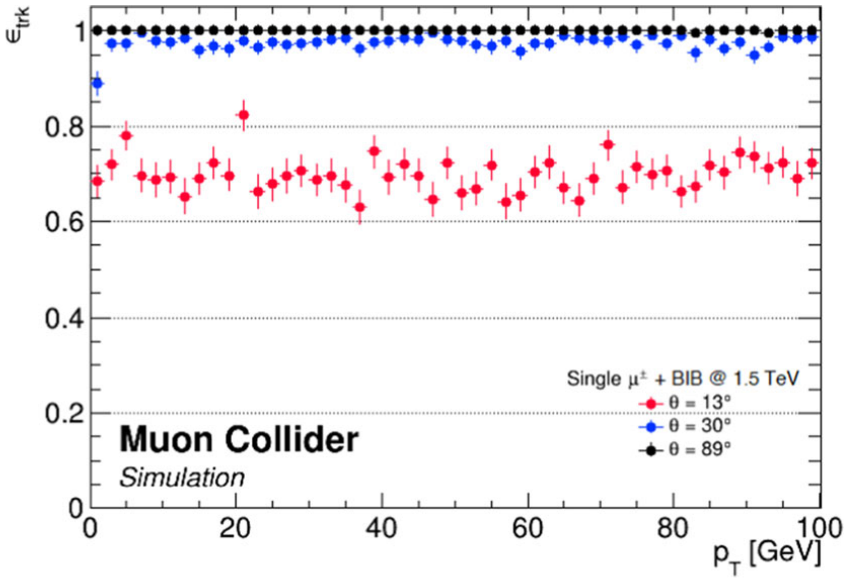


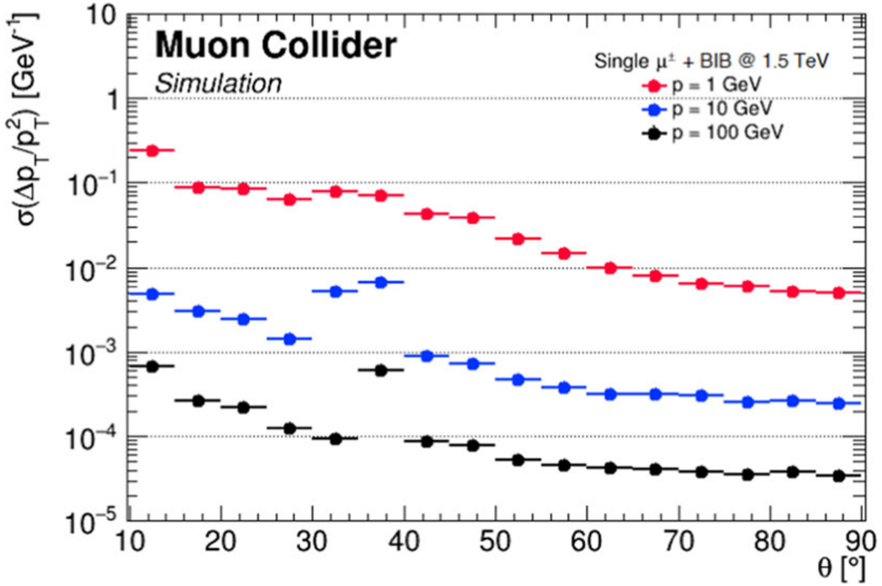
Inner/Outer Tracker

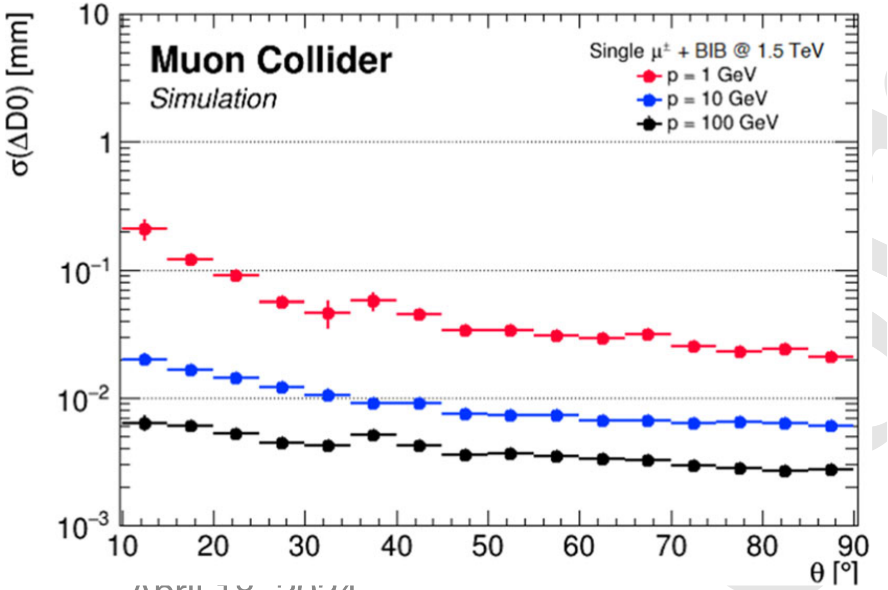


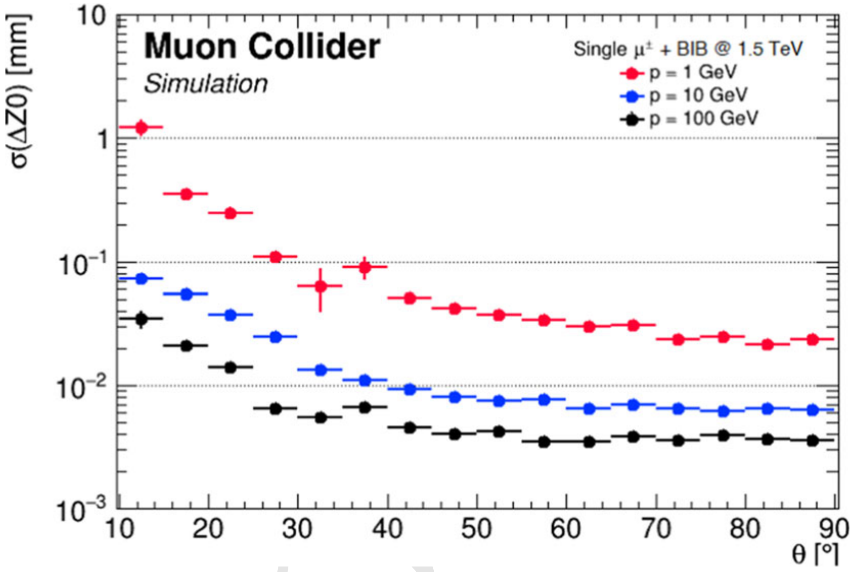
Vertex Detector

Track reconstruction performance







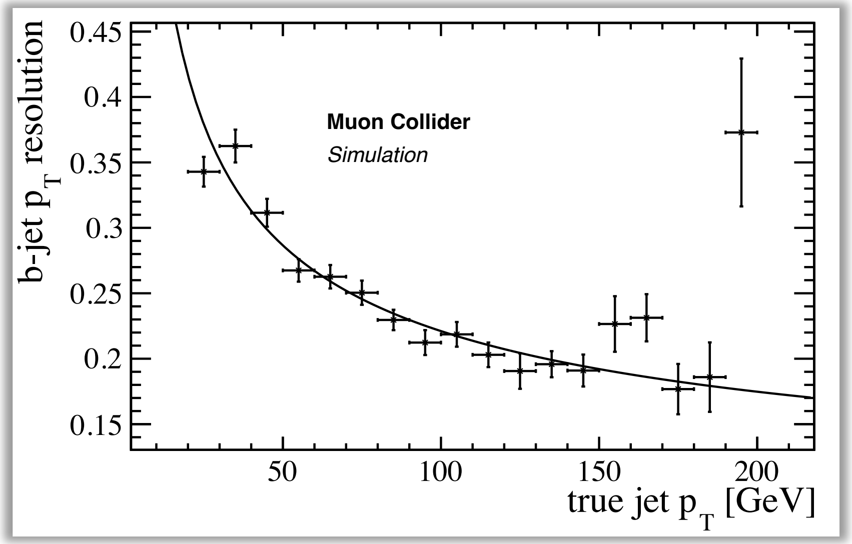


Jets reconstruction performance

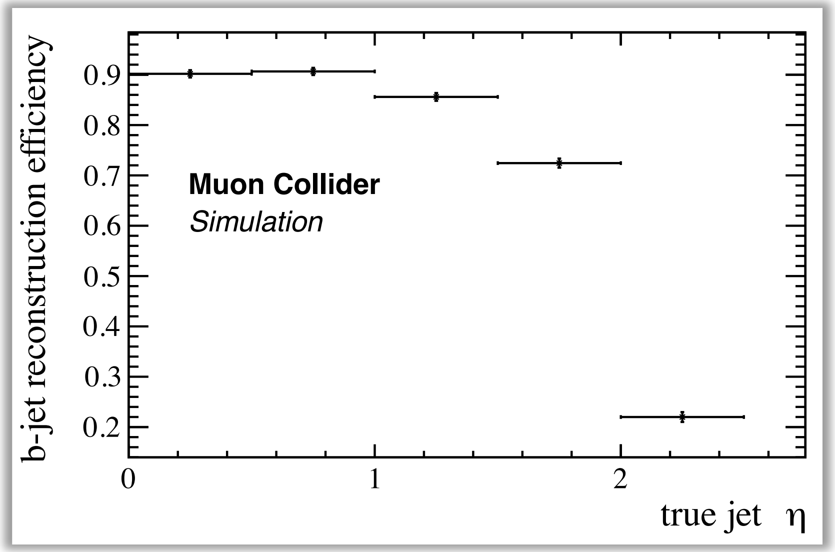
Jets reconstruction proceeds:

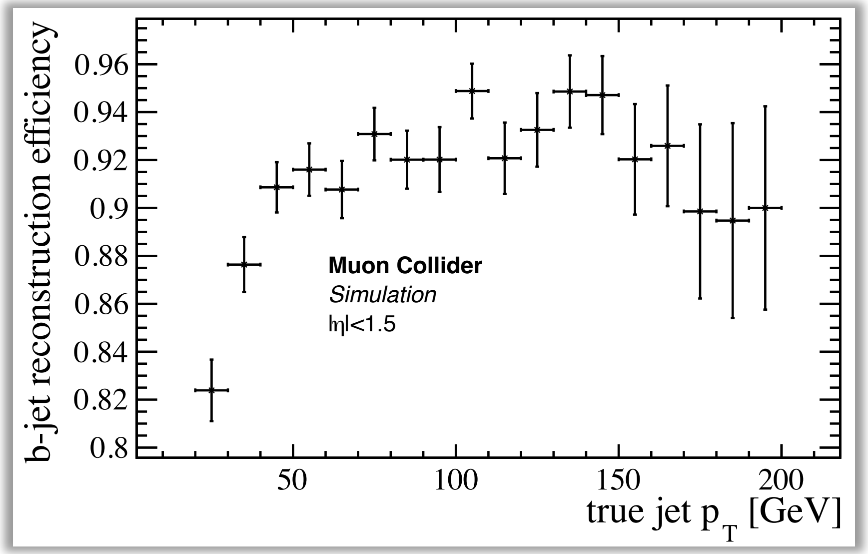
- Filter ”on time” calorimeter hits
- Combine track and calorimeter information to reconstruct particles
- Use k_T algorithm to cluster particles in jets
- Apply requirements to remove fake jets (max 0.7%)
- Correct energy

Resolution



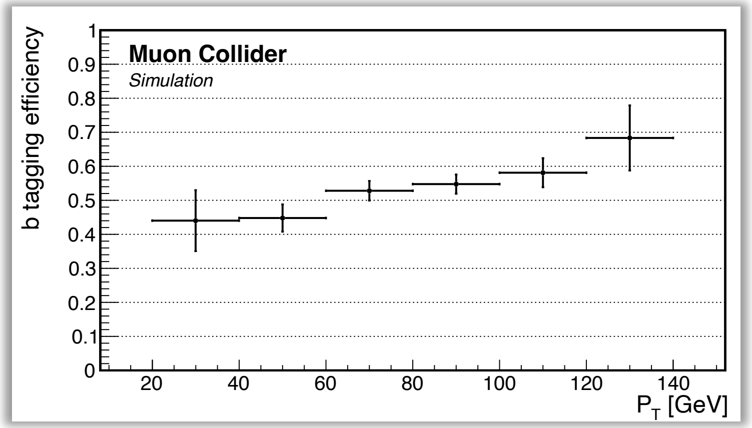
Efficiency

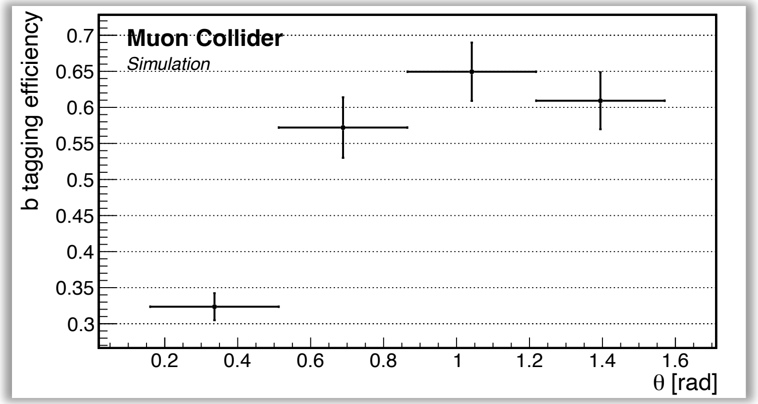




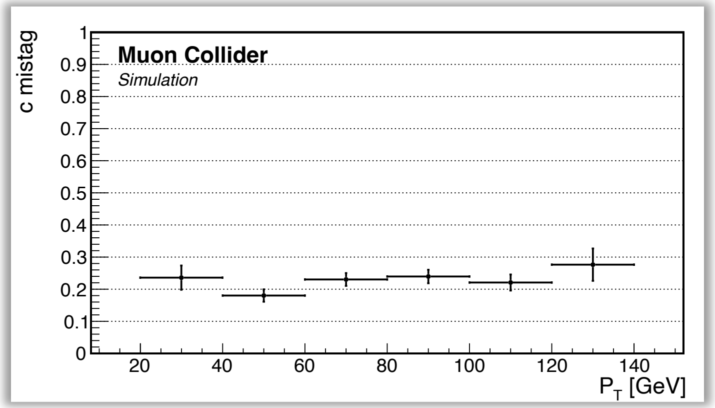
Heavy Flavor Jets Identification Performance

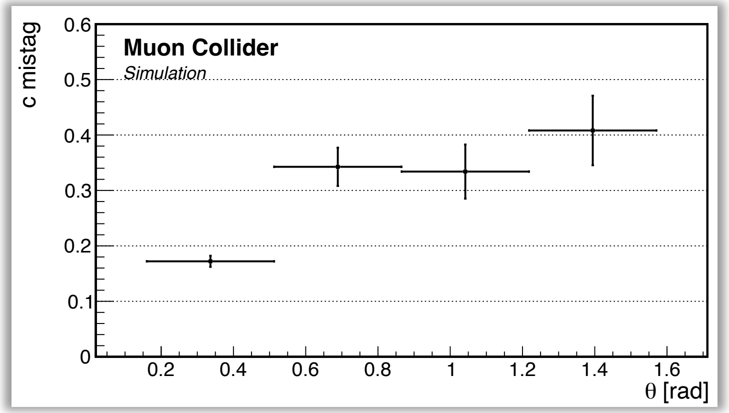
b-quark



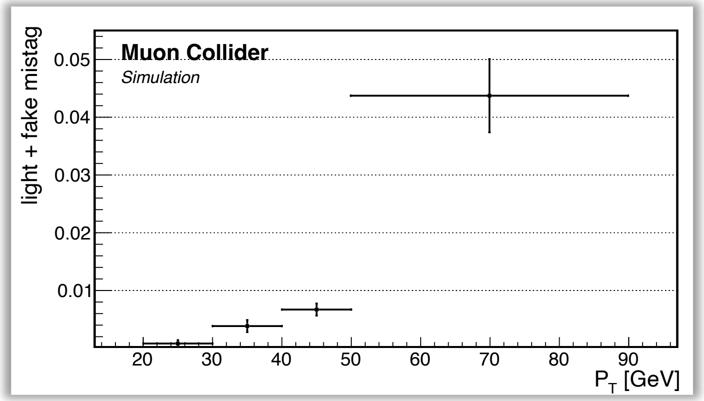


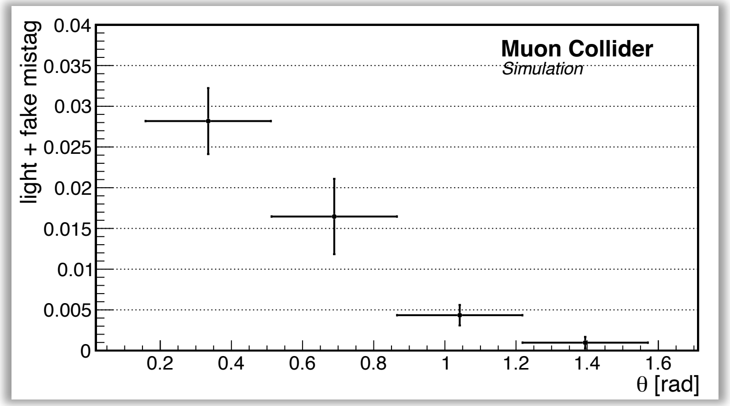
c-quark





light-quark/fake jets





Which magnetic field for the detector?

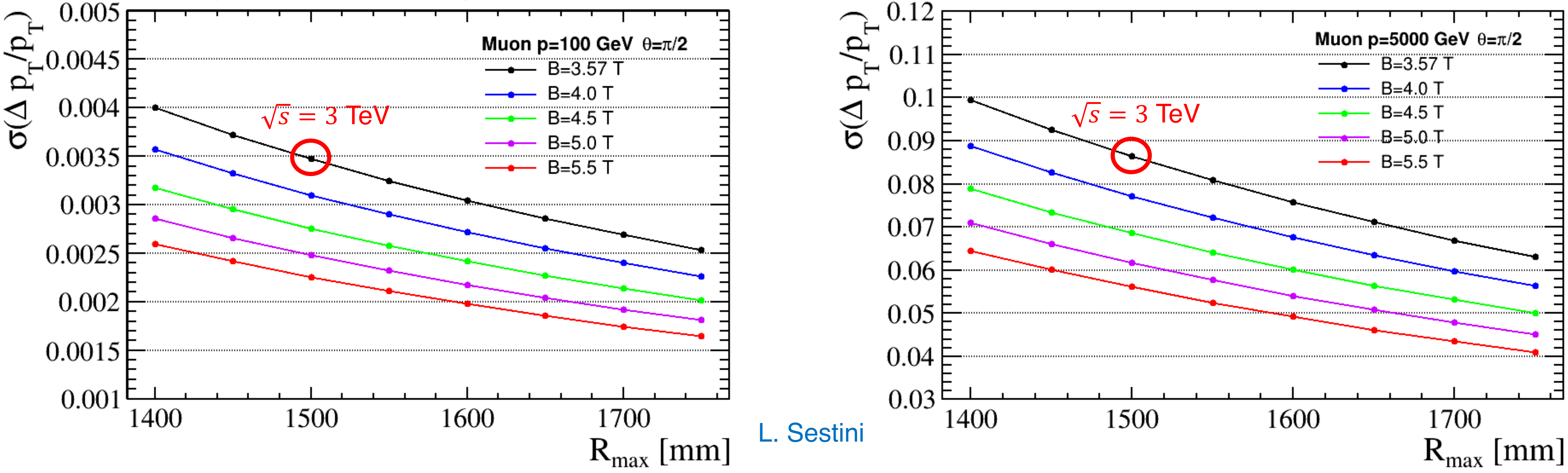
Analytic formula to relate magnetic field and track momentum resolution

$$\frac{\sigma_{p_T}}{p_T} \cong \frac{12\sigma_{r\varphi} p_T}{0.3BL^2}\sqrt{\frac{5}{N+5}}$$

Z. Drasal and W. Riegler,
NIM A 910 (2018) 127

p_μ = 100 GeV at θ_μ = 90°

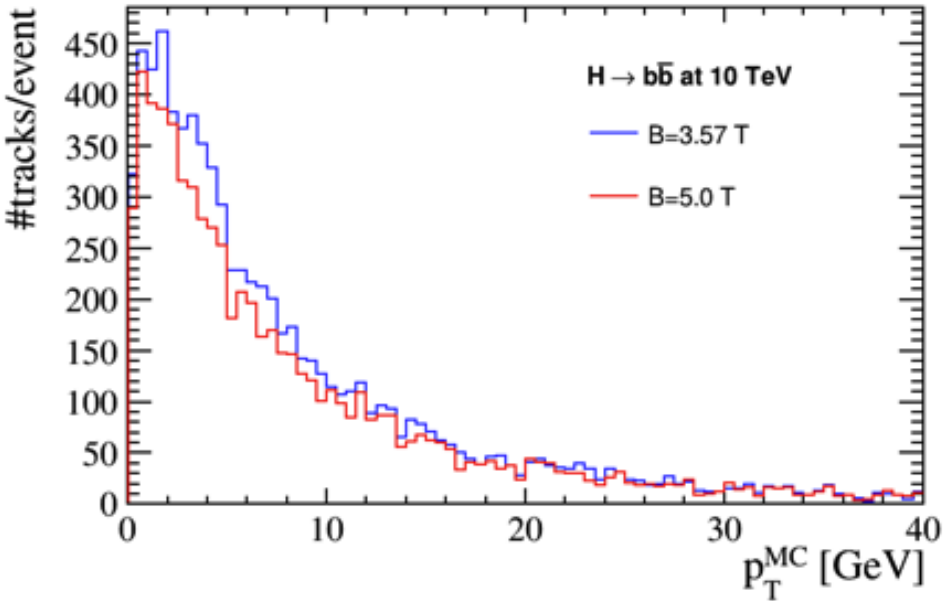
p_μ = 5000 GeV at θ_μ = 90°



L. Sestini

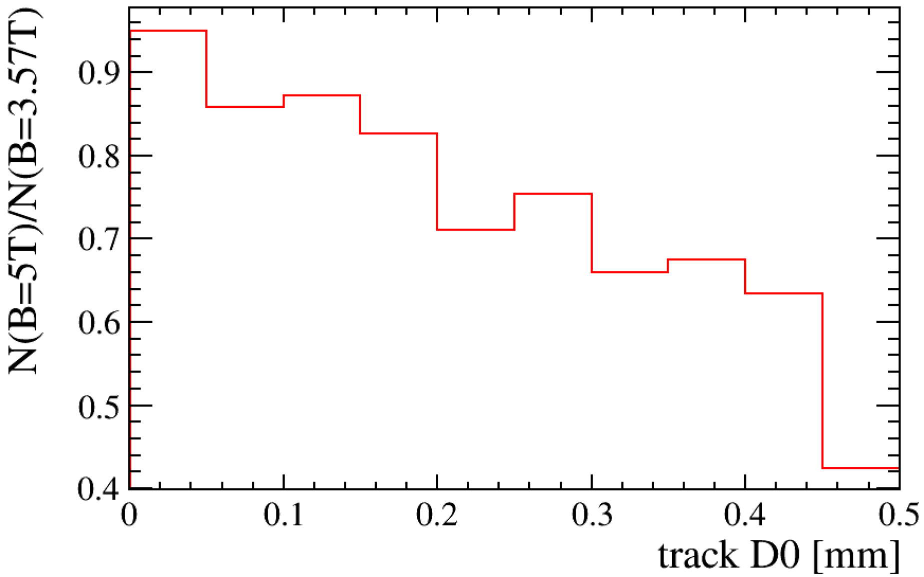
Tracking and magnetic field

generator-level p_T of reconstructed tracks



L. Sestini

N_{tracks}(B=5 T)/N_{tracks}(B=3.57 T) vs track impact parameter



Study of track efficiency with B= 5 T vs. B = 3.57 T by using $H \rightarrow b\bar{b}$ generated at $\sqrt{s} = 10$ TeV:

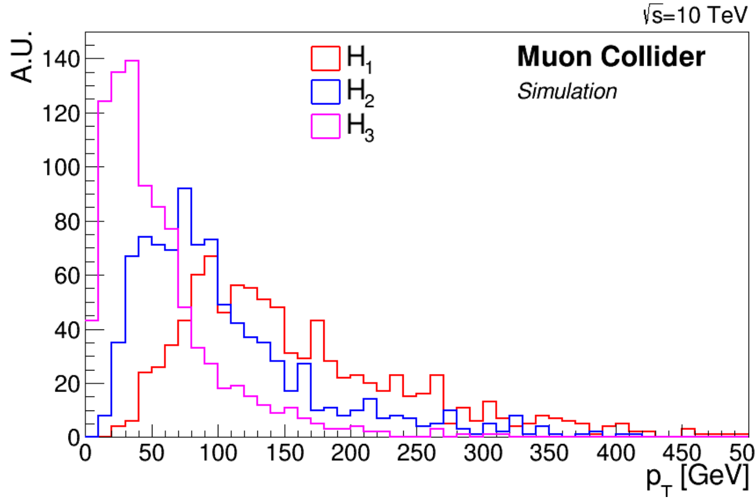
- inefficiency ~ 15%
- mainly due to displaced tracks

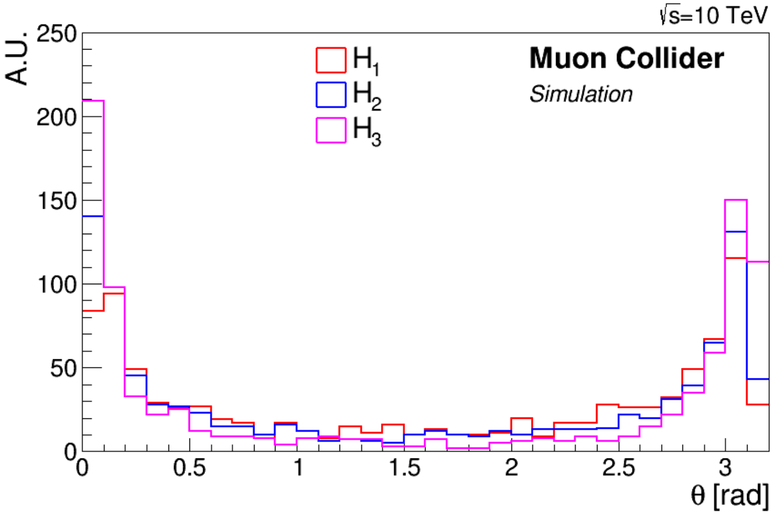
A magnetic field of about 4 T or 5 T is needed
Magnet should not be a problem, but…

Triple Higgs

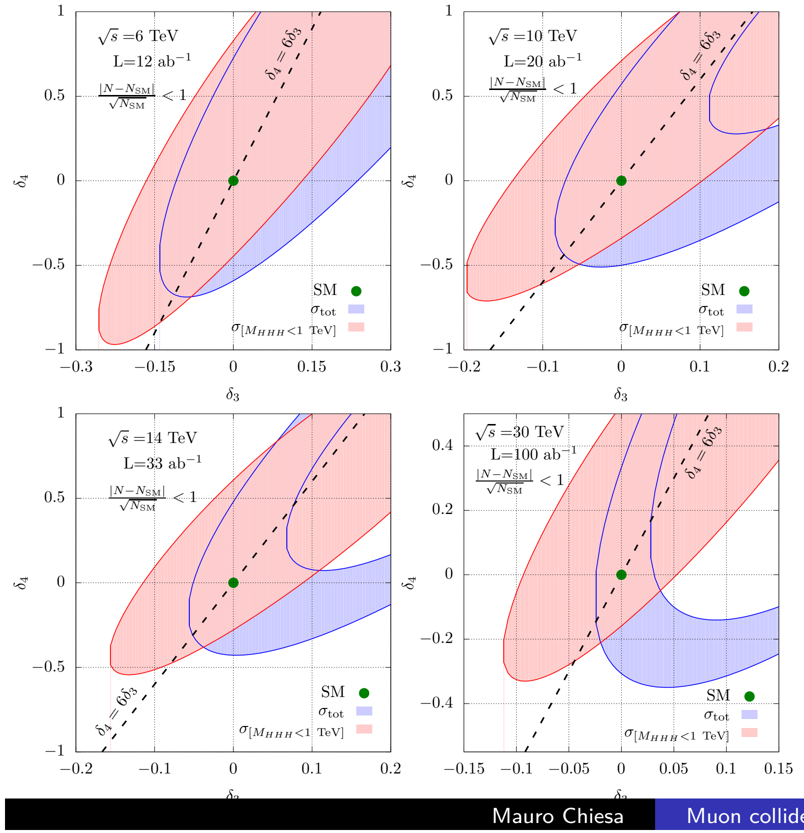
[M. Chiesa et al. JHEP 98, 2020]

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





One sigma exclusion plots



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

$\delta_3 = 0$

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

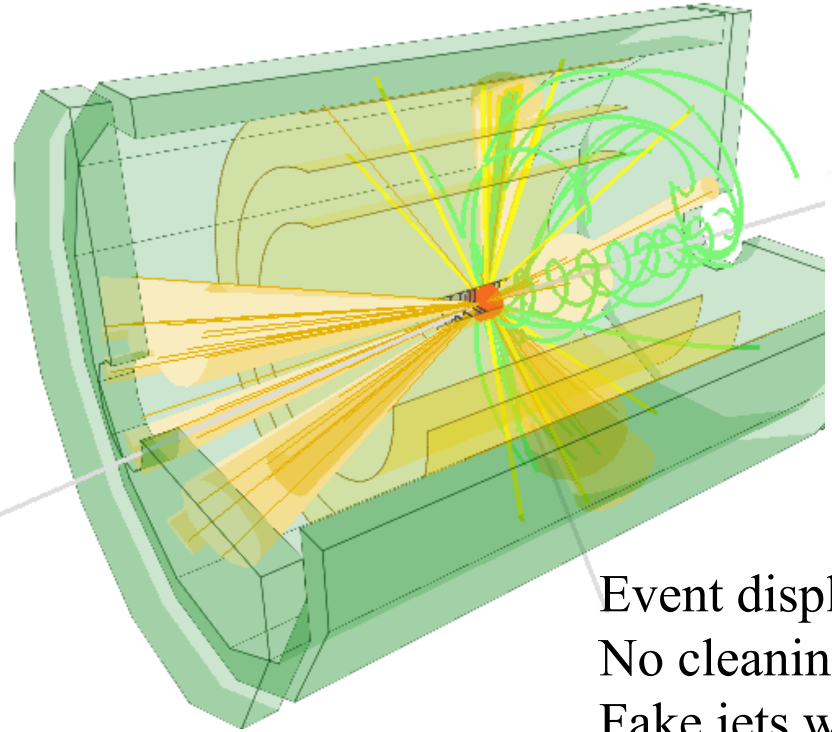
Sensitivity evaluated in term of standard deviation from standard model

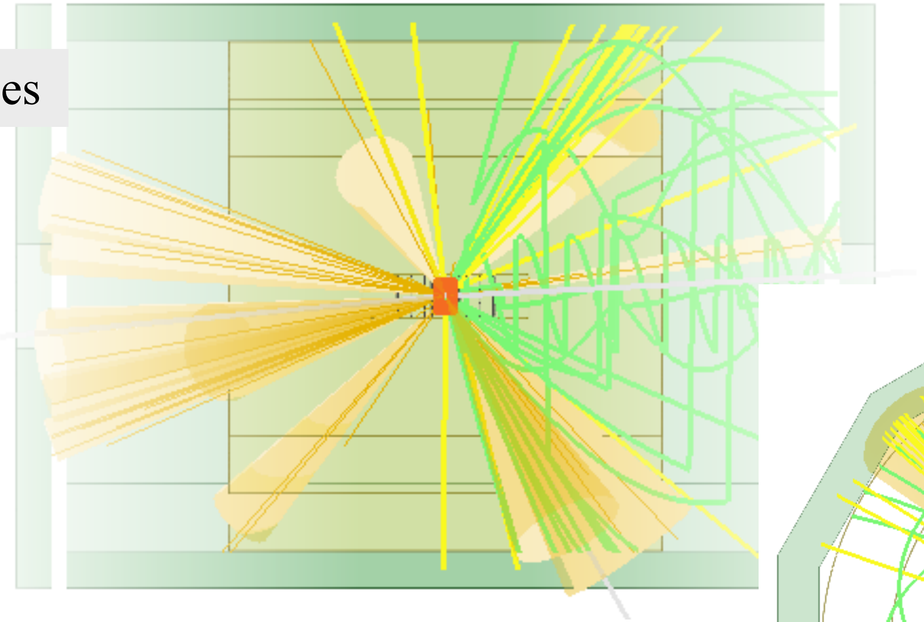
$$\frac{|N - N_{SM}|}{\sqrt{N_{SM}}}$$

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

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

Yellow/green tracks: Montecarlo particles

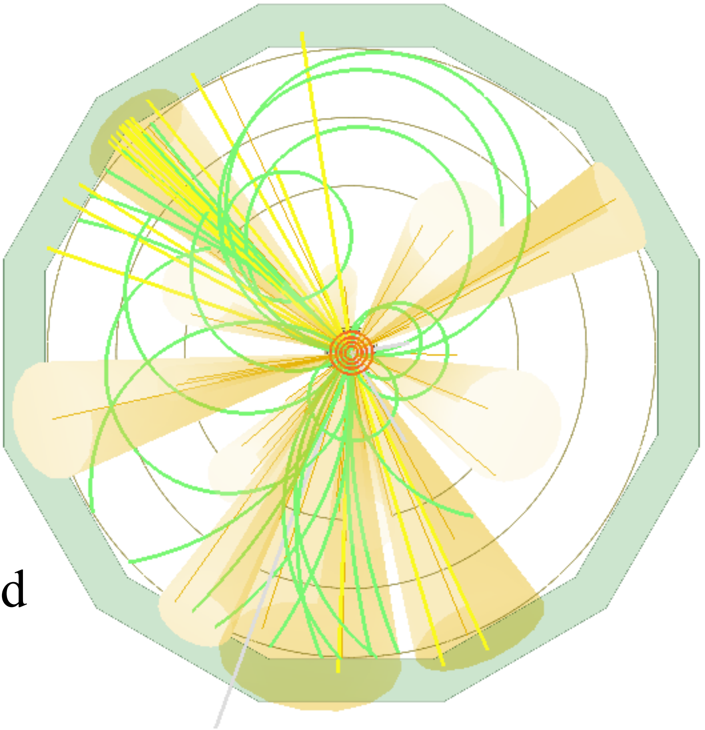




ECAL

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

ILCSoft software stack:		**Key4hep software stack:**
1. LCIO	**TO BE DONE** → long term	EDM4hep
2. DD4hep		DD4hep
3. Marlin		Gaudi
4. ILCSoft		Spack

used only by us → no other maintainers

NO multithreading support

used and maintained by other experiments

built with multithreading in mind

All EDM4hep data classes defined in a single YAML file: edm4hep.yaml → generates actual C++ code

Switching from LCIO → EDM4hep will change input for all our simulation code

↳ each processor has to be adapted to the new data format → **substantial amount of work**