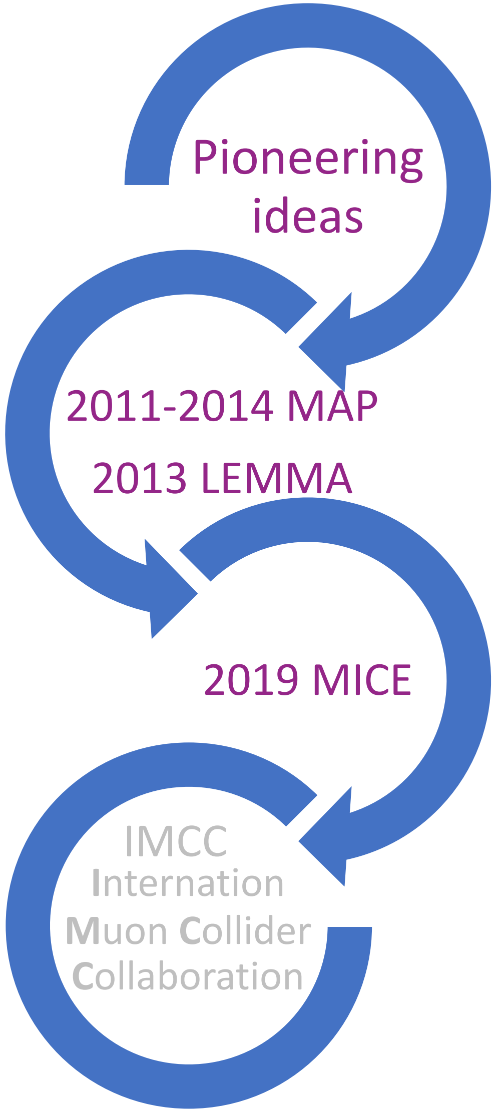
The Muon Collider: a challenge for the future

C. Riccardi

on behalf of the International Muon Collider Collaboration

Toward the Muon Collider



1968 F. Tikhonin *“On the effects at colliding μ meson beams”*
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1981 Skrinsky, Parkhomchuk *“Methods of cooling beams of charged particles”*

Muon **A**ccelerator **P**rogram
Low **EM**ittance **M**uon **A**ccelerator

Muon **I**onization **C**ooling **E**xperiment,
M.Bogomilov et al.,“ *Demonstration of cooling by the Muon Ionization Cooling Experiment* ”

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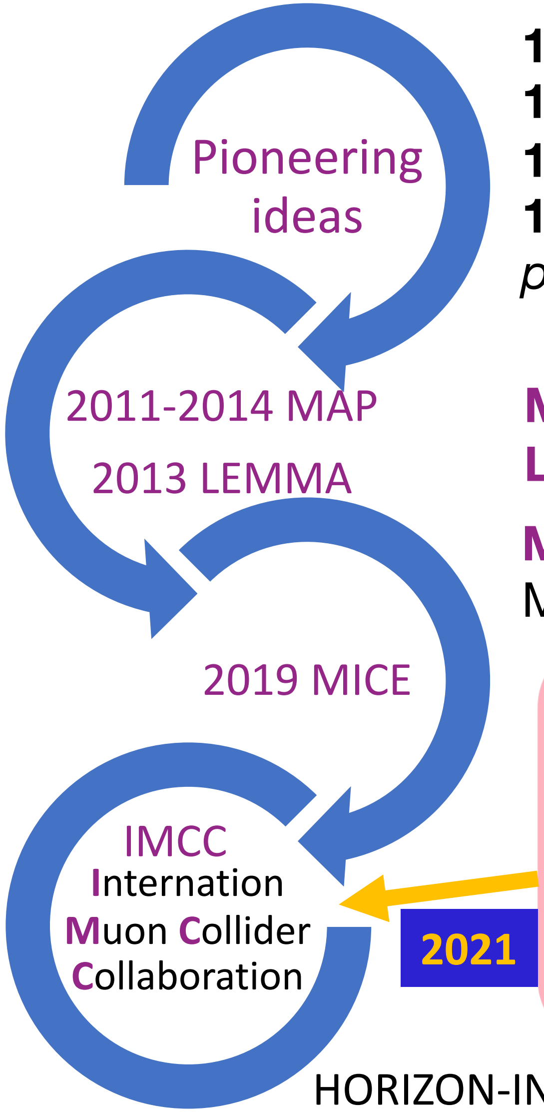

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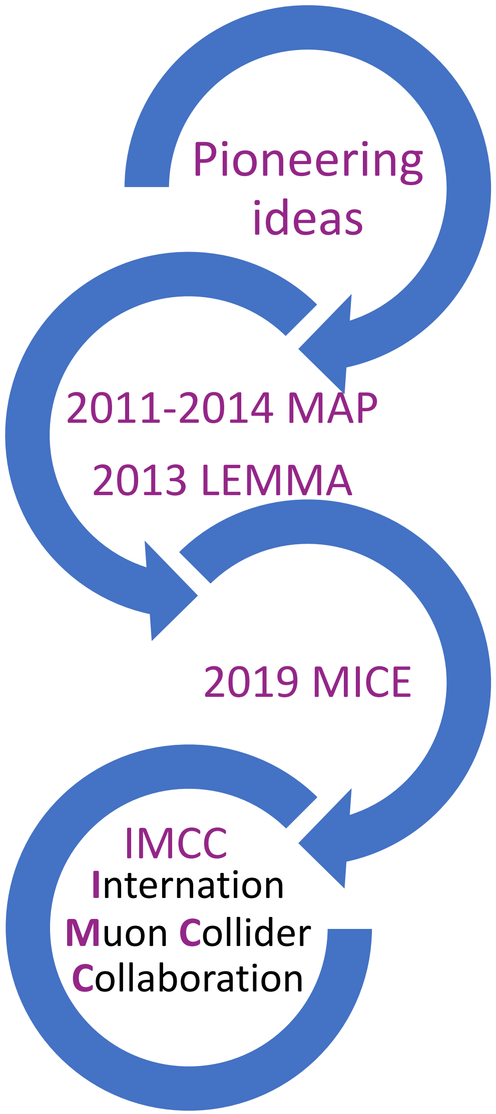
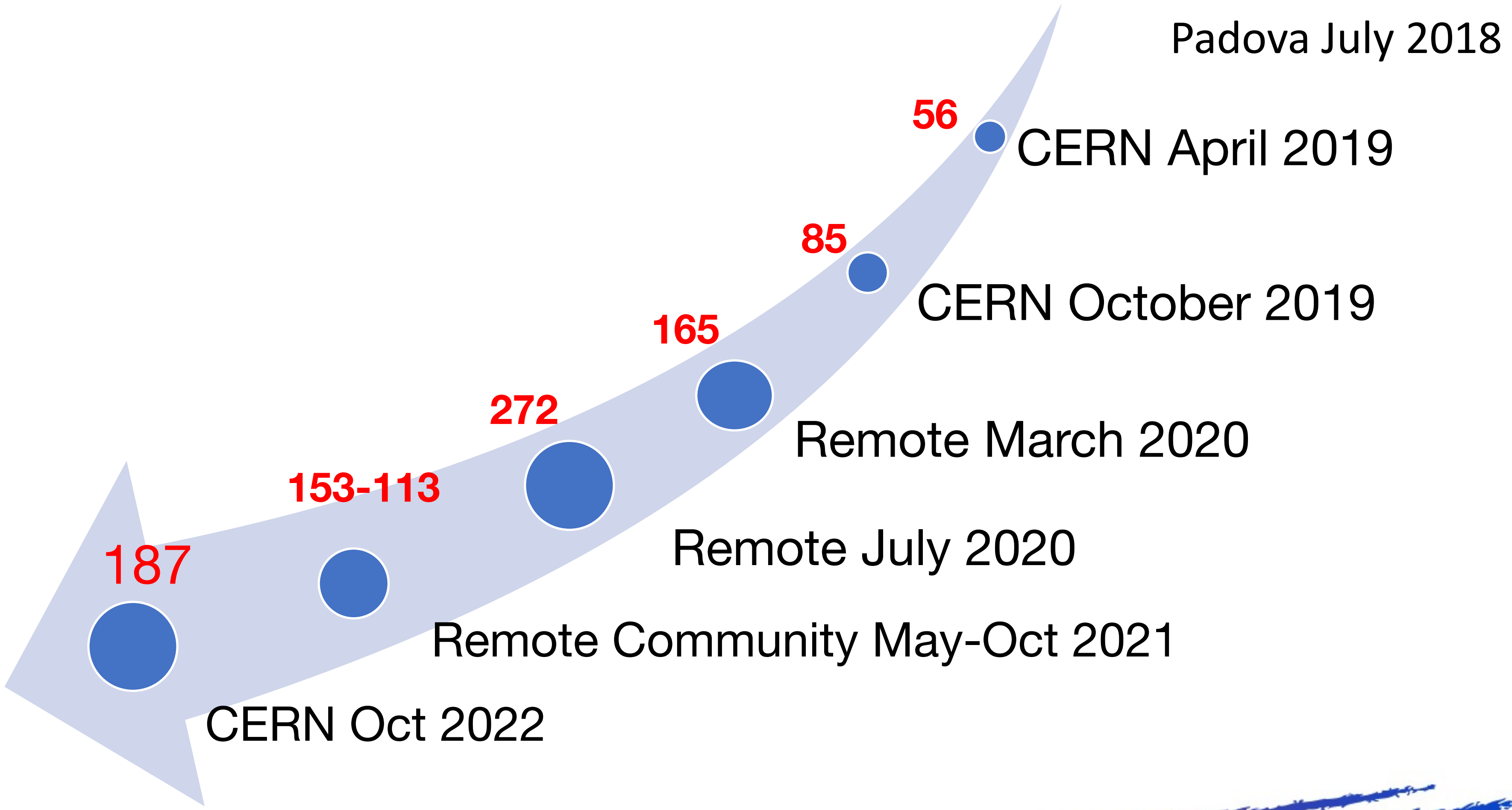
***European* Strategy Update – June 19, 2020**:
[] an **international design study** for a **muon collider**, as it represents a **unique opportunity** to achieve **a multi-TeV energy domain** beyond the reach of e + e – colliders, and potentially within a more compact circular tunnel than for a hadron collider. The **biggest challenge** remains to produce an intense beam of cooled muons, but *novel ideas are being explored*

HORIZON-INFRA-2022-DEV-01-01 **EU MUCOL project approved for 2023-2026**

Toward the Muon Collider

Partecipants number to Muon Collider meetings shows great and growing interest

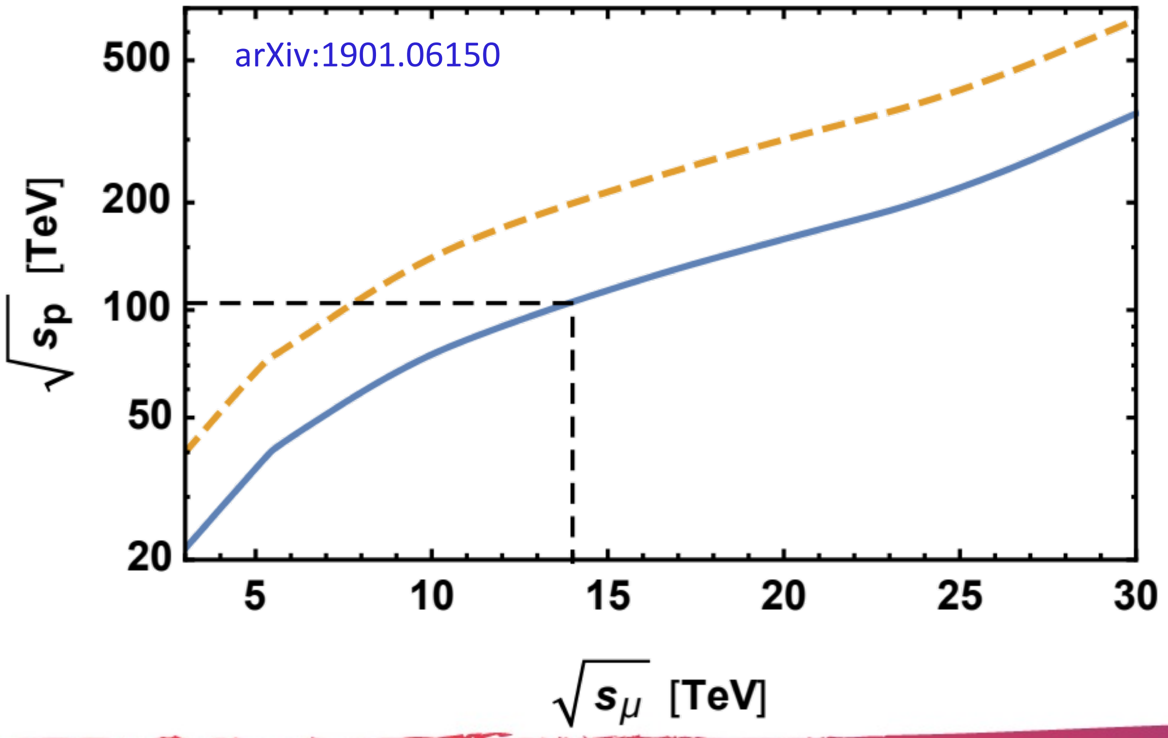




Why the Muon Collider

A Muon Collider is a unique possibility of combining high energy with very precise measurements

- pp machines ⟶ no limitations from synchrotron radiation
- e^+e^- machines ⟶ nominal E_{cm} entirely available



Discovery reach

14 TeV lepton collisions are comparable to 100-200 TeV proton collisions for production of heavy particle pairs

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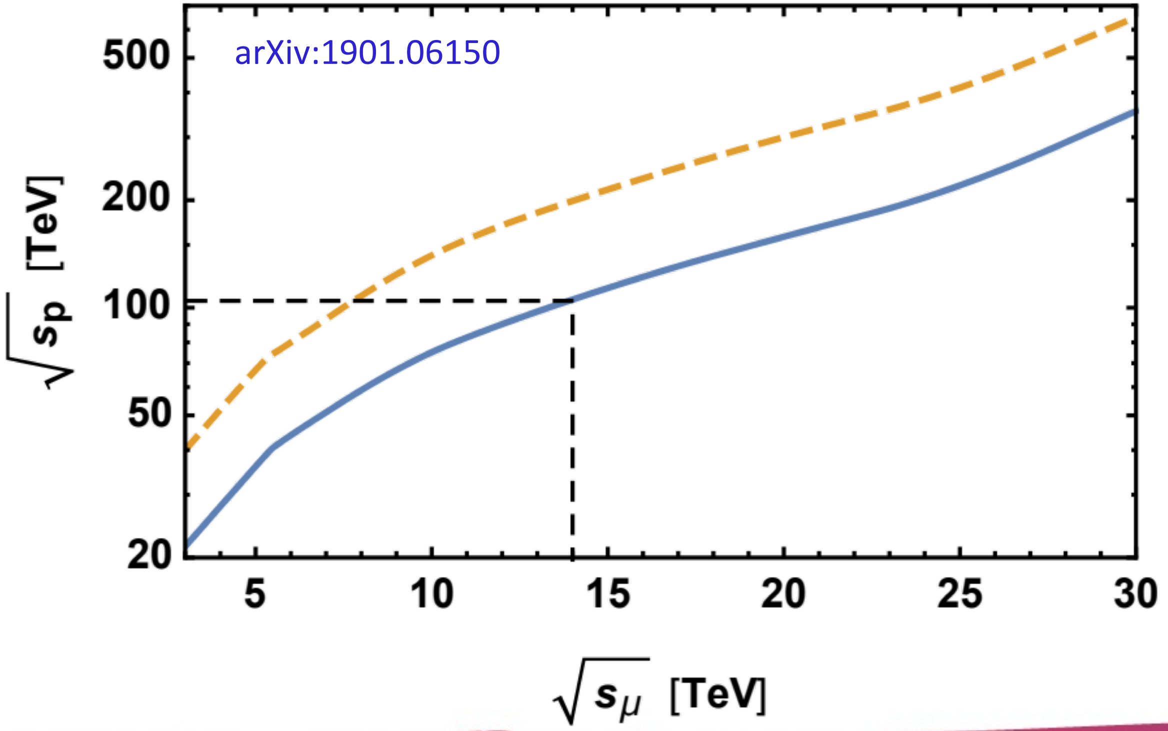

Parameter	Target value		
E_{cm}	3 TeV	10 TeV	14 TeV
$\mathcal{L}$	1.8 10^{34} cm^{-2} s^{-1}	20 10^{34} cm^{-2} s^{-1}	40 10^{34} cm^{-2} s^{-1}
N	2.2 10^{12}	1.8 10^{12}	1.8 10^{12}

arXiv: 2203.08033

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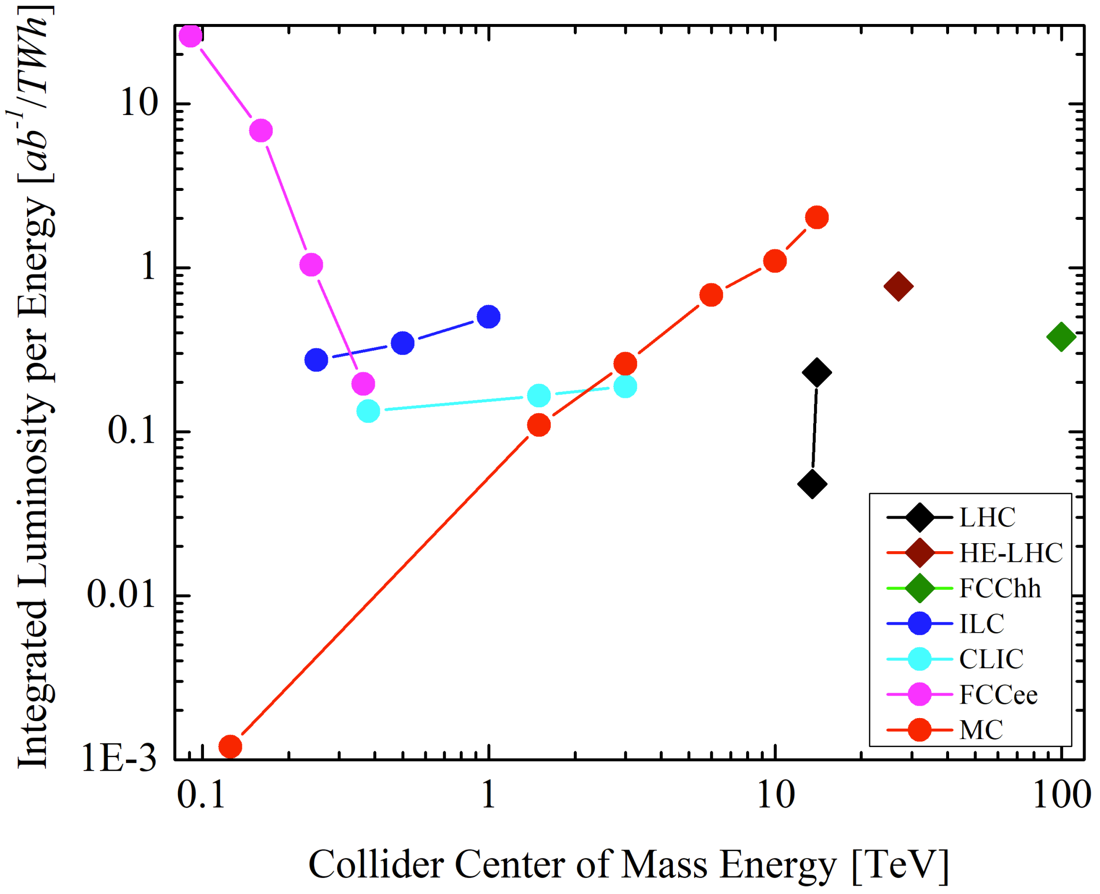


Already at 2TeV a muon collider is the most efficient option. Moreover, the luminosity increases linearly with the center-of-mass energy and this drives a broad physics case.

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}}\right)^2 2 \cdot 10^{35}\text{cm}^{-2}\text{s}^{-1}$$

$\mathcal{L} = (E_{CM}/10\text{TeV})^2 \times 10\ \text{ab}^{-1}$

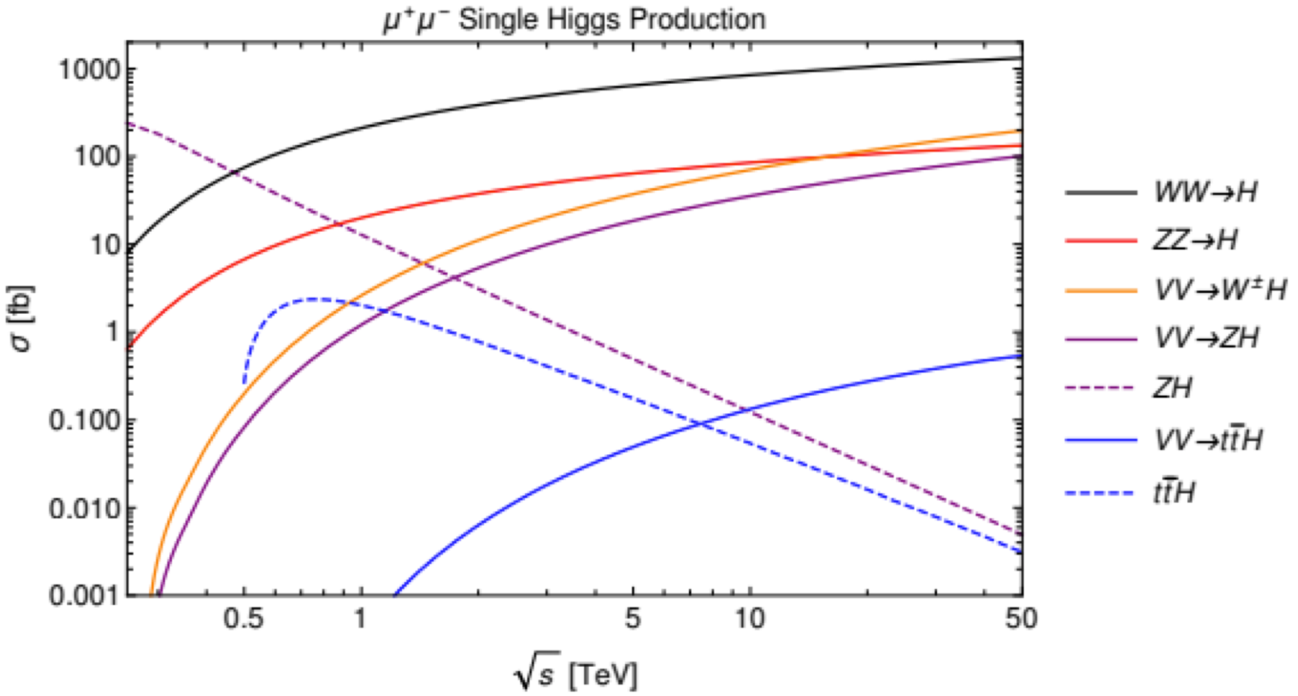
@ 3 TeV ~ 1 ab^{-1} 5 years

@ 10 TeV ~ 10 ab^{-1} 5 years

Physics potential

A Muon Collider offers a novel unprecedented physics program

- Higgs physics
- Beyond Standard Model
- Muon specific opportunities



At 3 TeV and L = 1 ab^{-1} high production cross sect (500k single Higgs)
High rates are accessible for multi-Higgs processes (expected 30k HH at 10 TeV and 10 ab^{-1})

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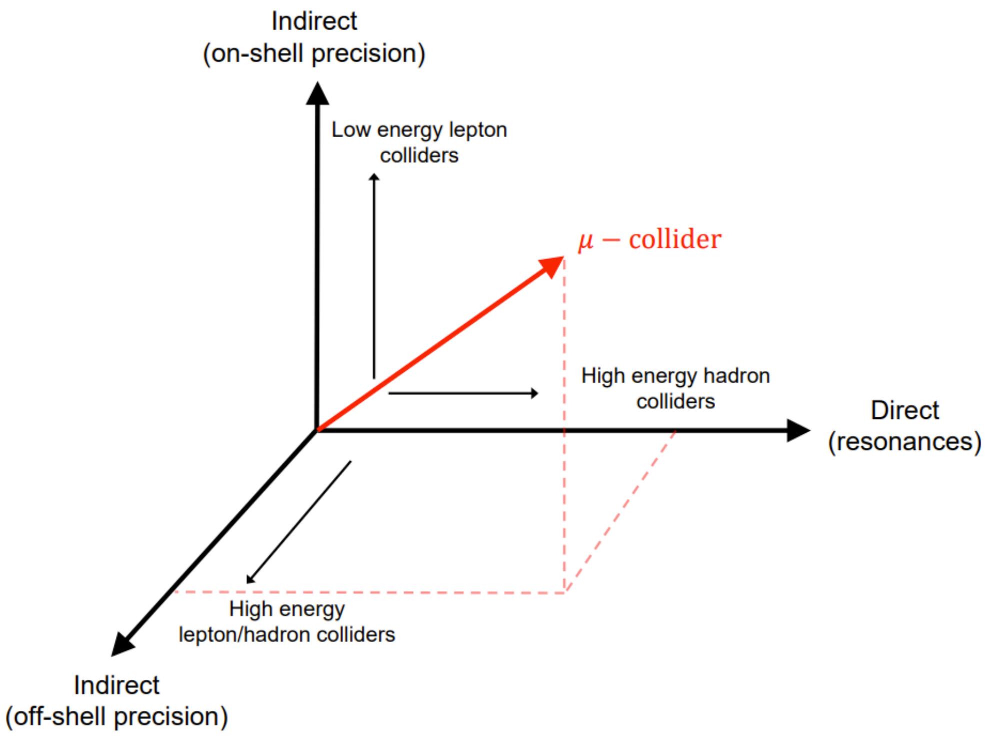
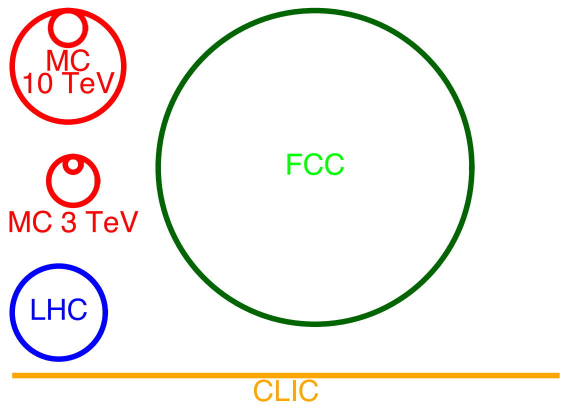
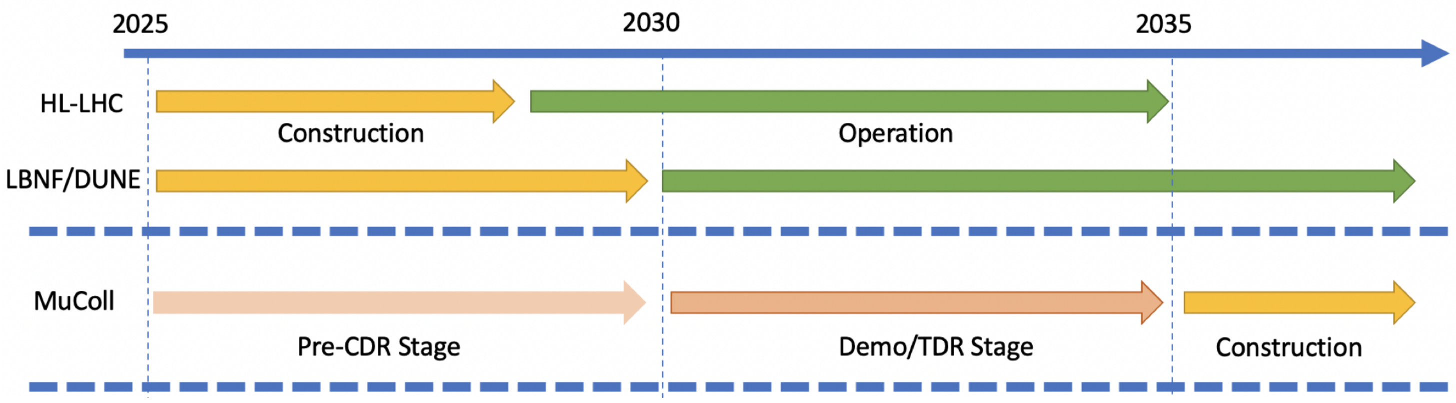


☛ R. Torre, *BSM perspective on a Future Muon Collider*

International Design Study facility

A Muon Collider has a technically limited timeline

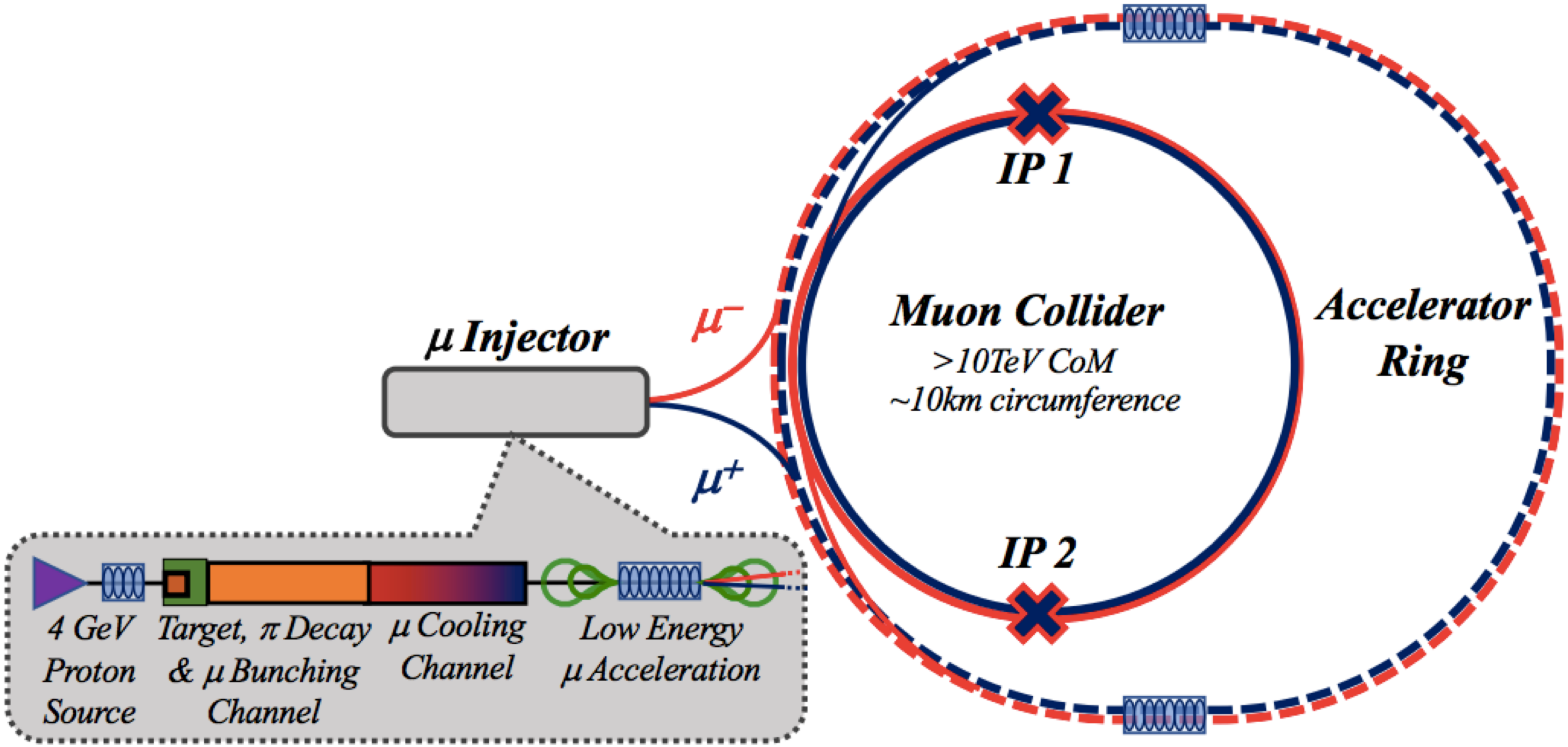




A development path that can address the major challenges foresees the delivery of a 3 TeV muon collider by 2045; more advanced technology needed for 10+ TeV

International Design Study facility

Proton drive production as baseline

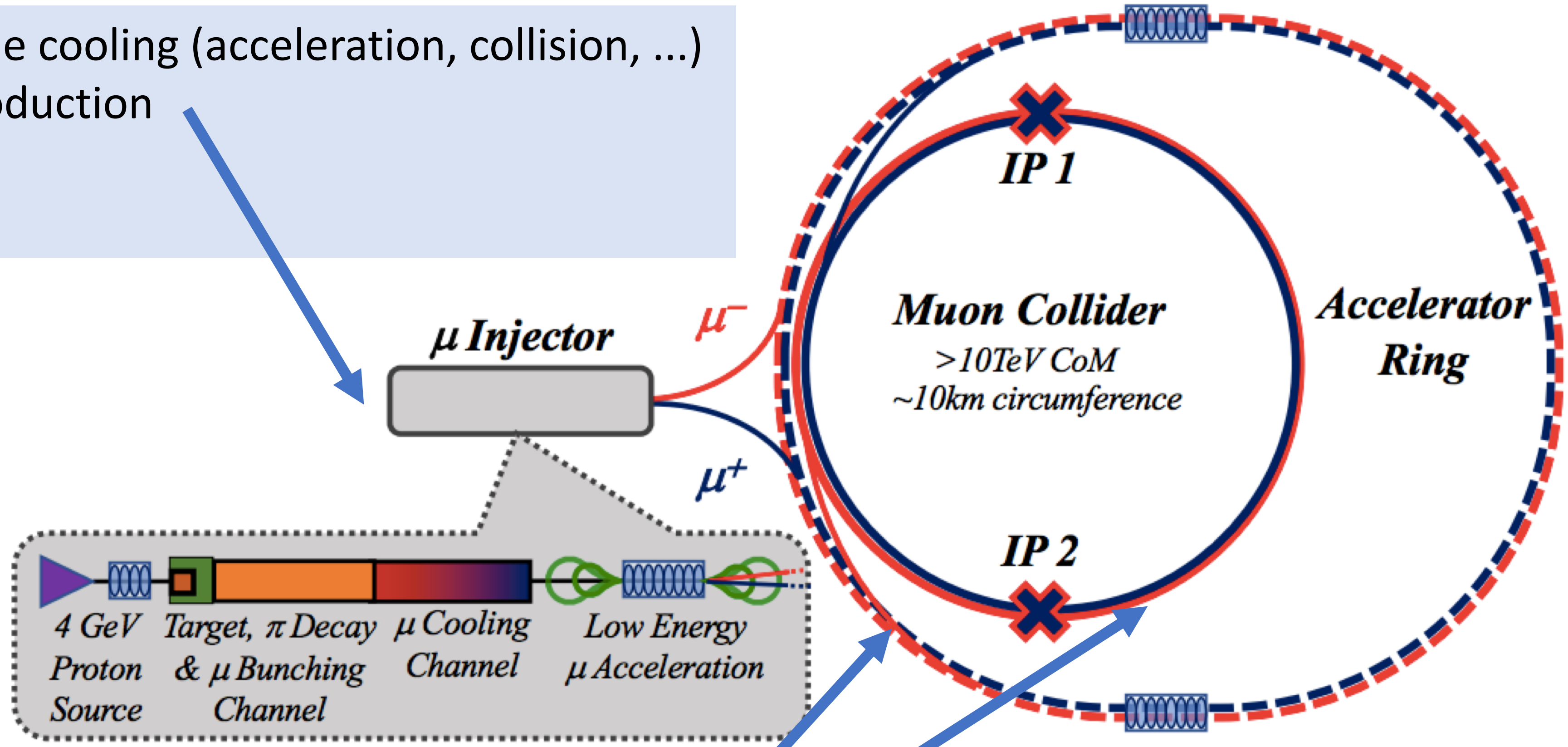


International Design Study facility

Key challenge areas - beam quality

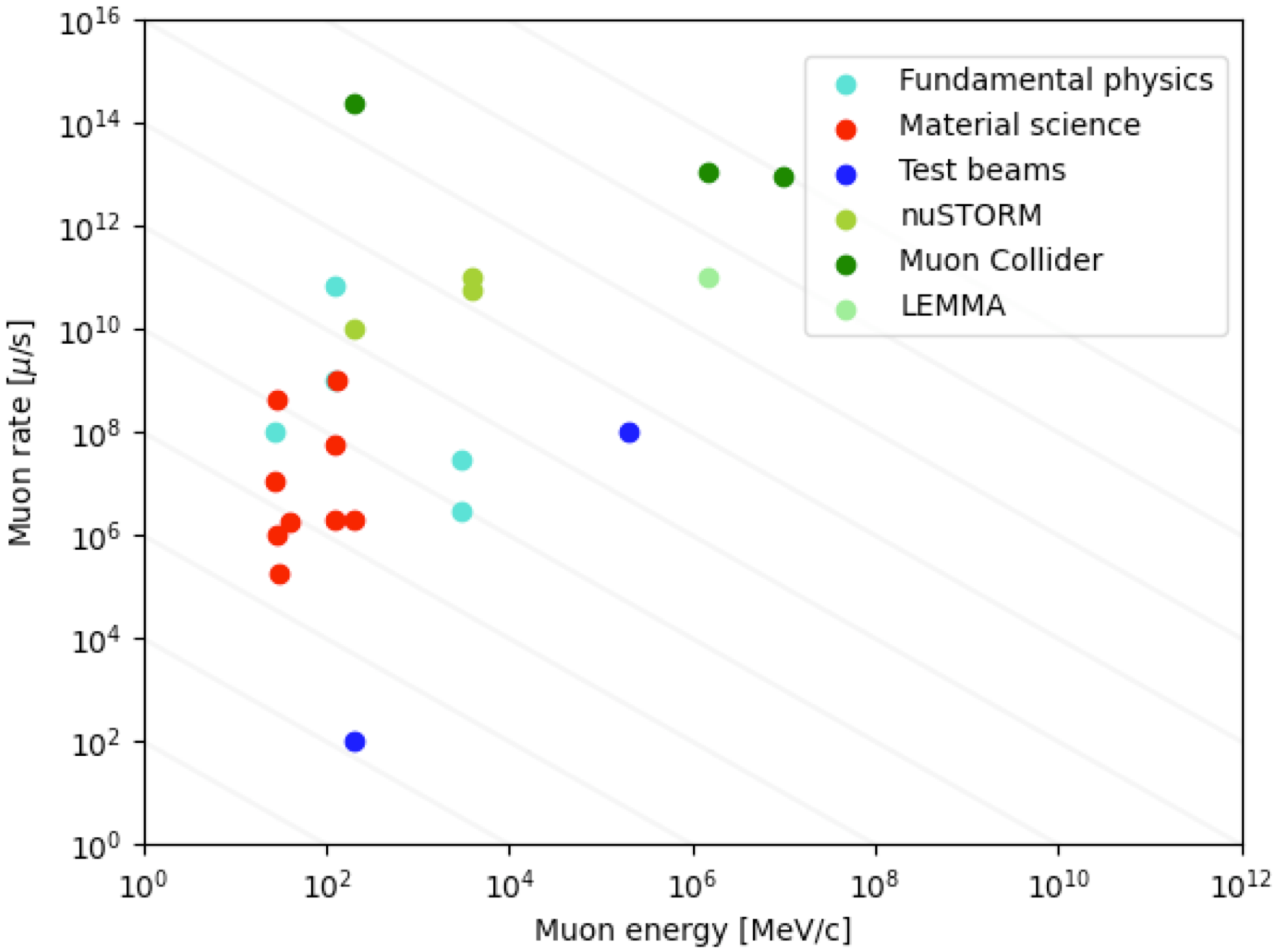
- High-energy systems after the cooling (acceleration, collision, ...)
- High-quality muon beam production

- Full accelerator chain



Cost and power consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring

Synergies with other concepts or existing facilities

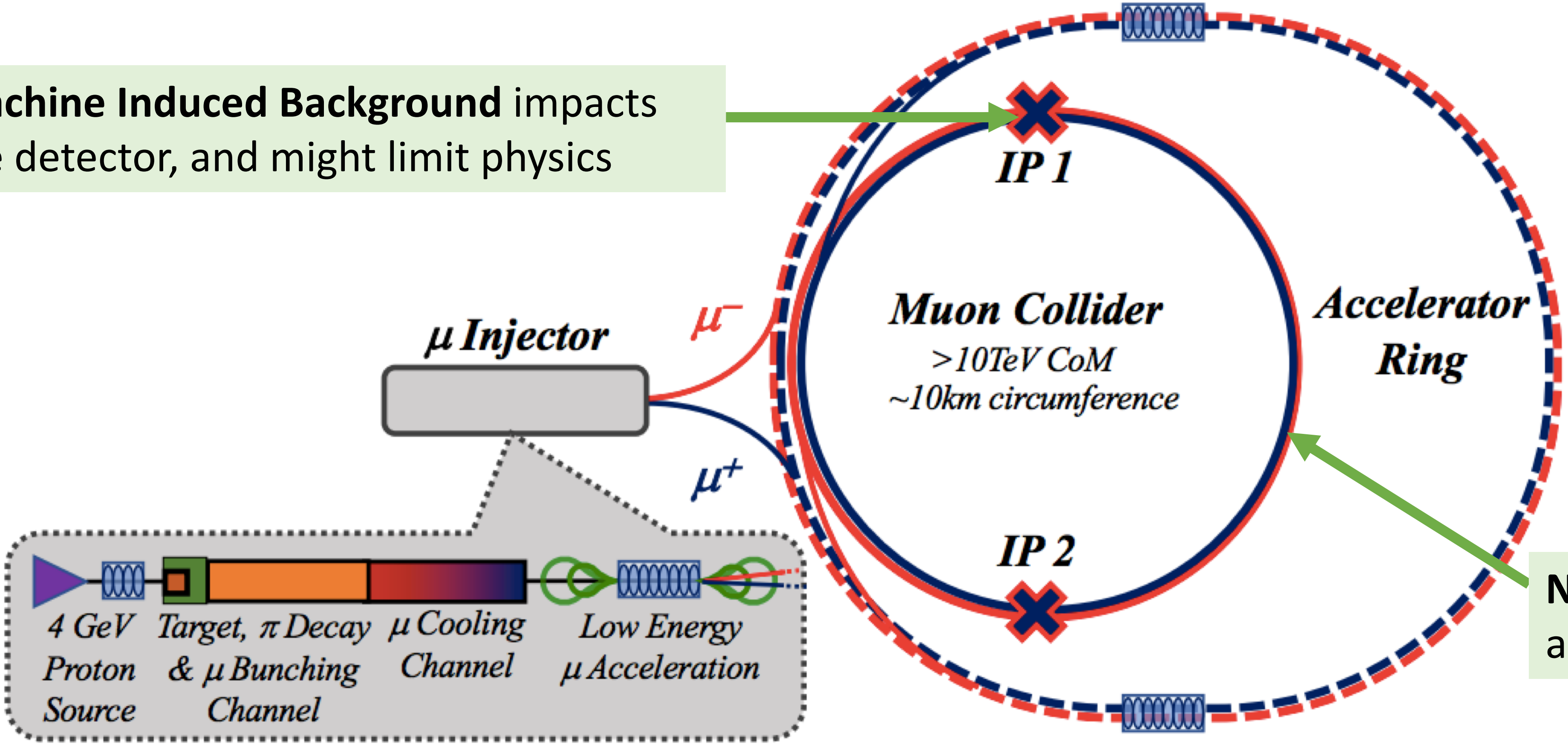


The progress in other accelerator facilities will also benefit the design and construction of the muon collider in the future.

International Design Study facility

key challenge areas - Impact on the environment

Machine Induced Background impacts the detector, and might limit physics

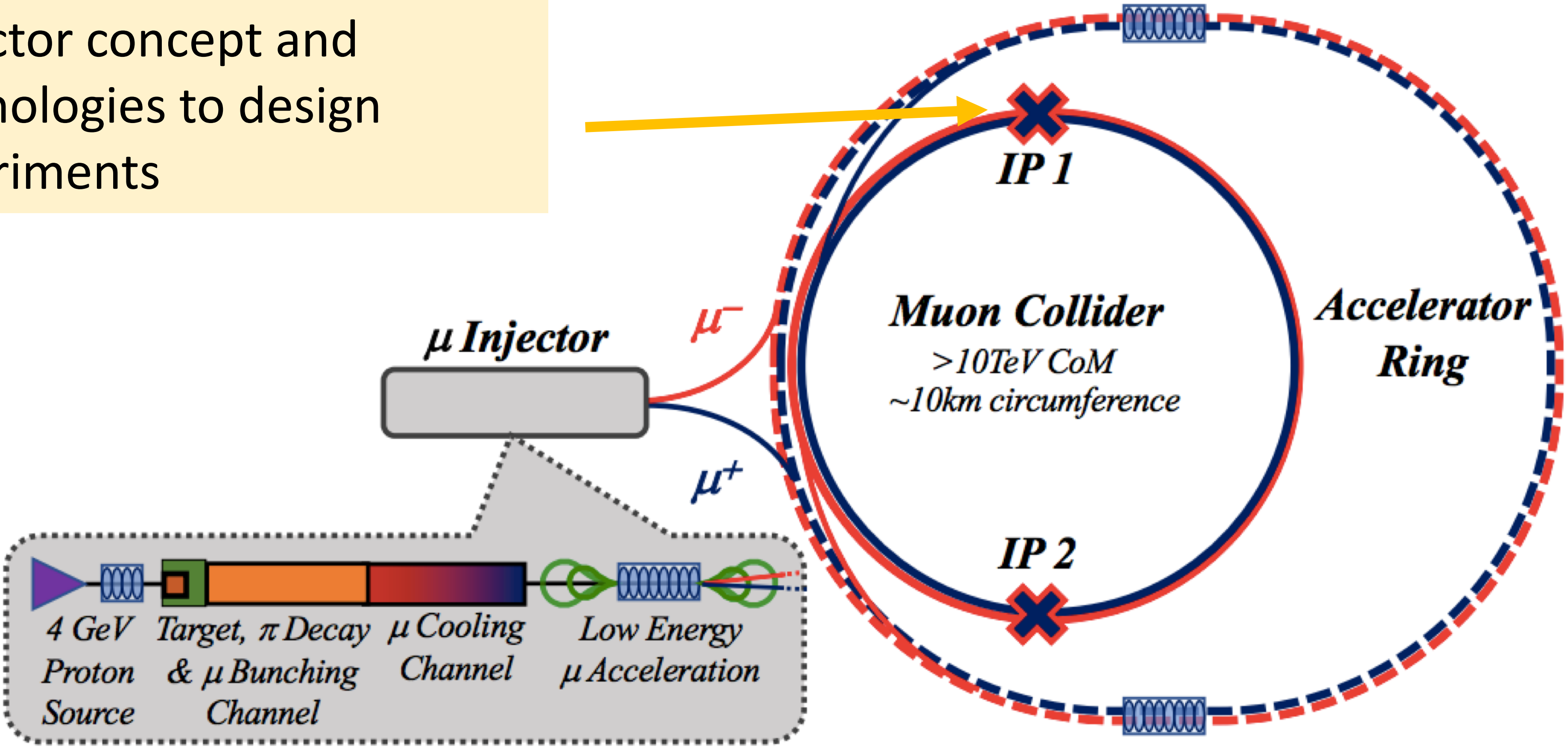


Neutrino flux mitigation and its impact on the site

International Design Study facility

key challenge areas - Physics potential evaluation

detector concept and technologies to design experiments



Beam-induced Background

The main challenge to operating a detector is the fact that muons decay

$$\mu^- \longrightarrow e^- \; \overline{\nu}_e \; \nu_\mu$$

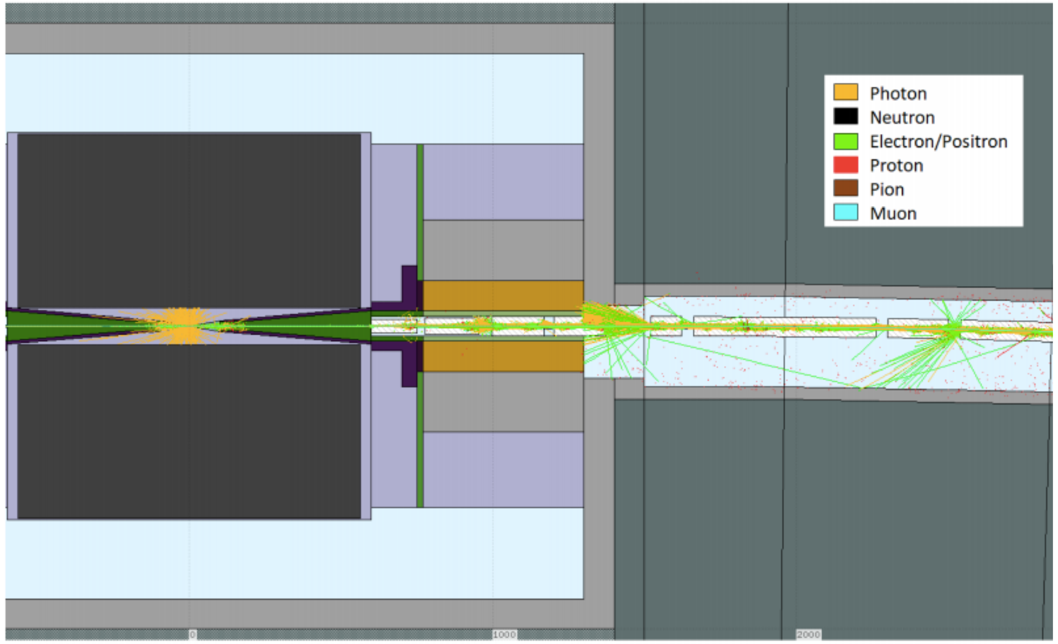
interaction with machine components

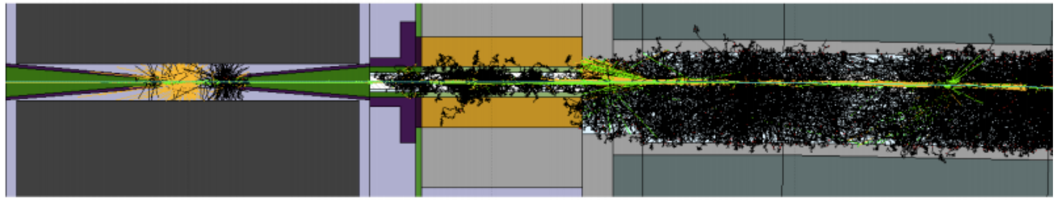
secondary particles:

- charged hadrons
- neutral hadrons
- Bethe-Heitler muons
- electrons
- photons

BIB may degrade detector performance:

- shielding nozzles
- proper detector design

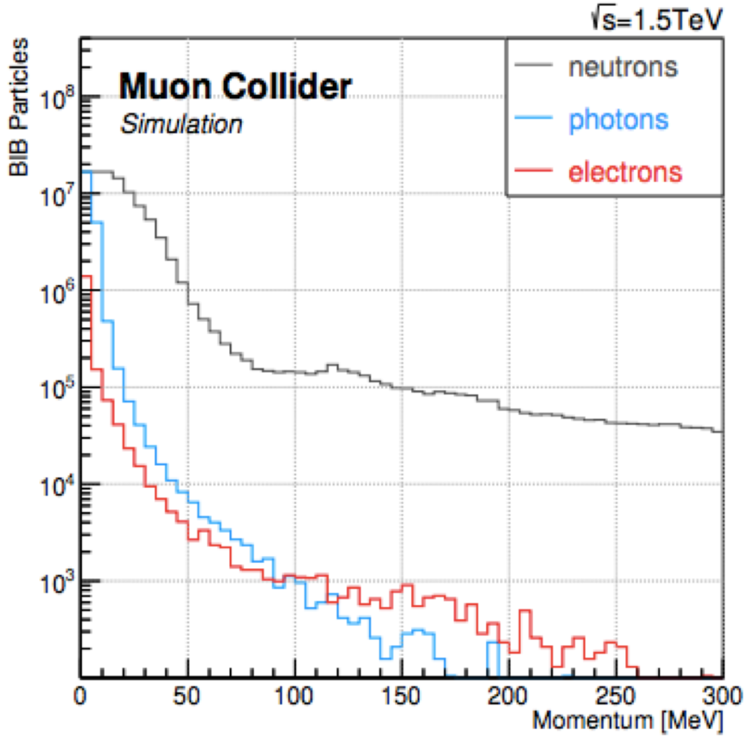


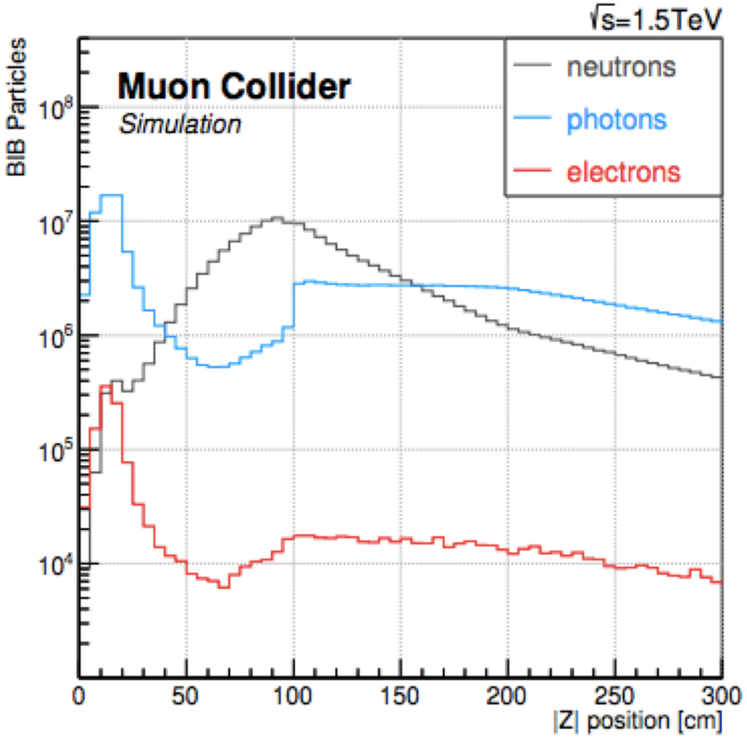


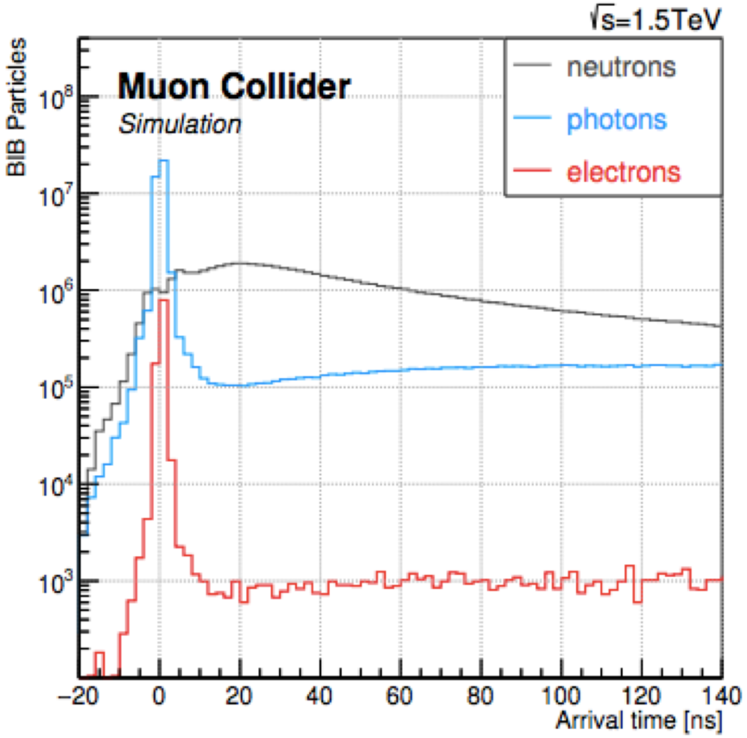
2021 JINST 15 P11009

BIB properties at $\sqrt{s} = 1.5$ TeV

BIB particles are characterized by extremely large number and low momentum



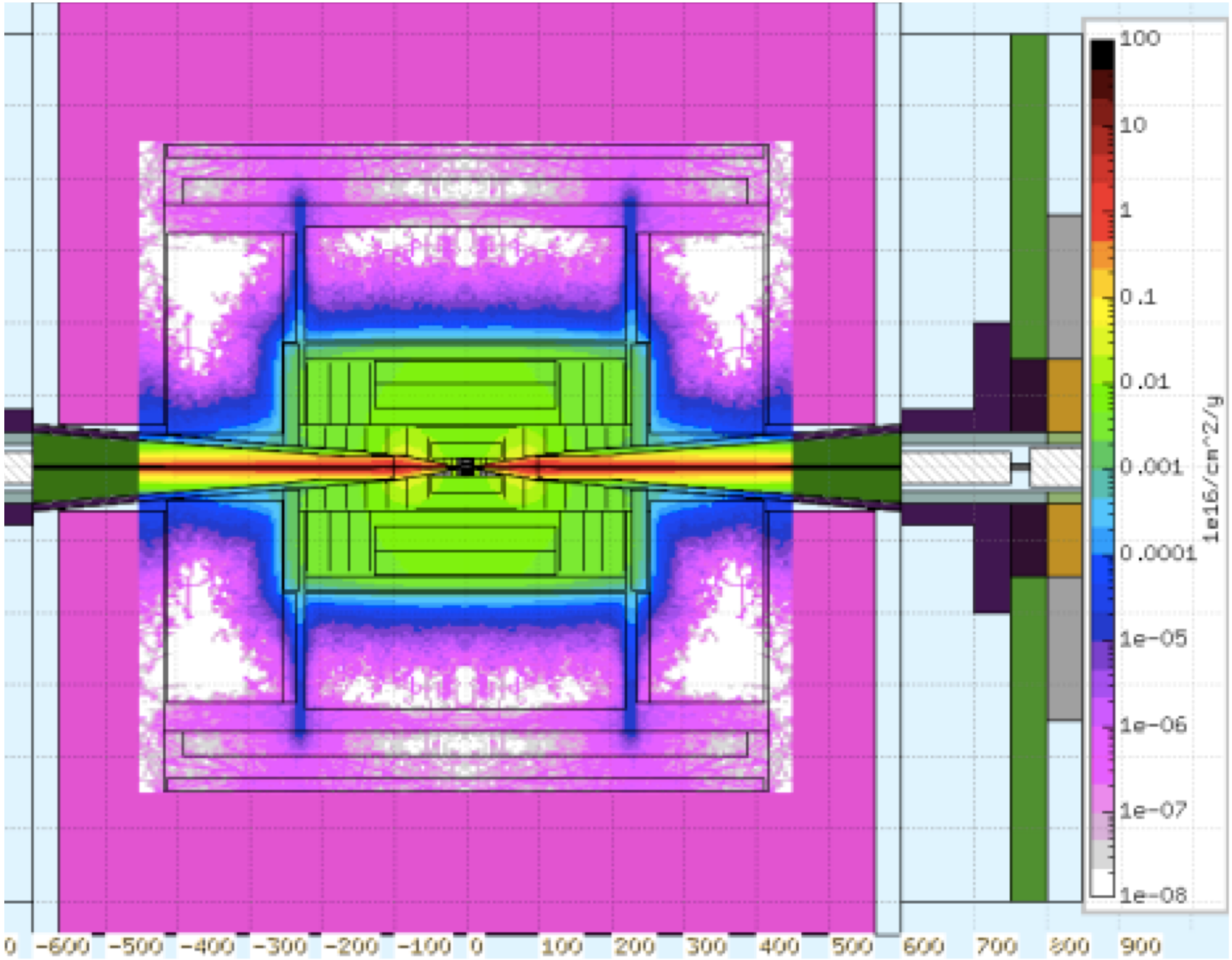




1204.6721 1905.03725 2105.09116

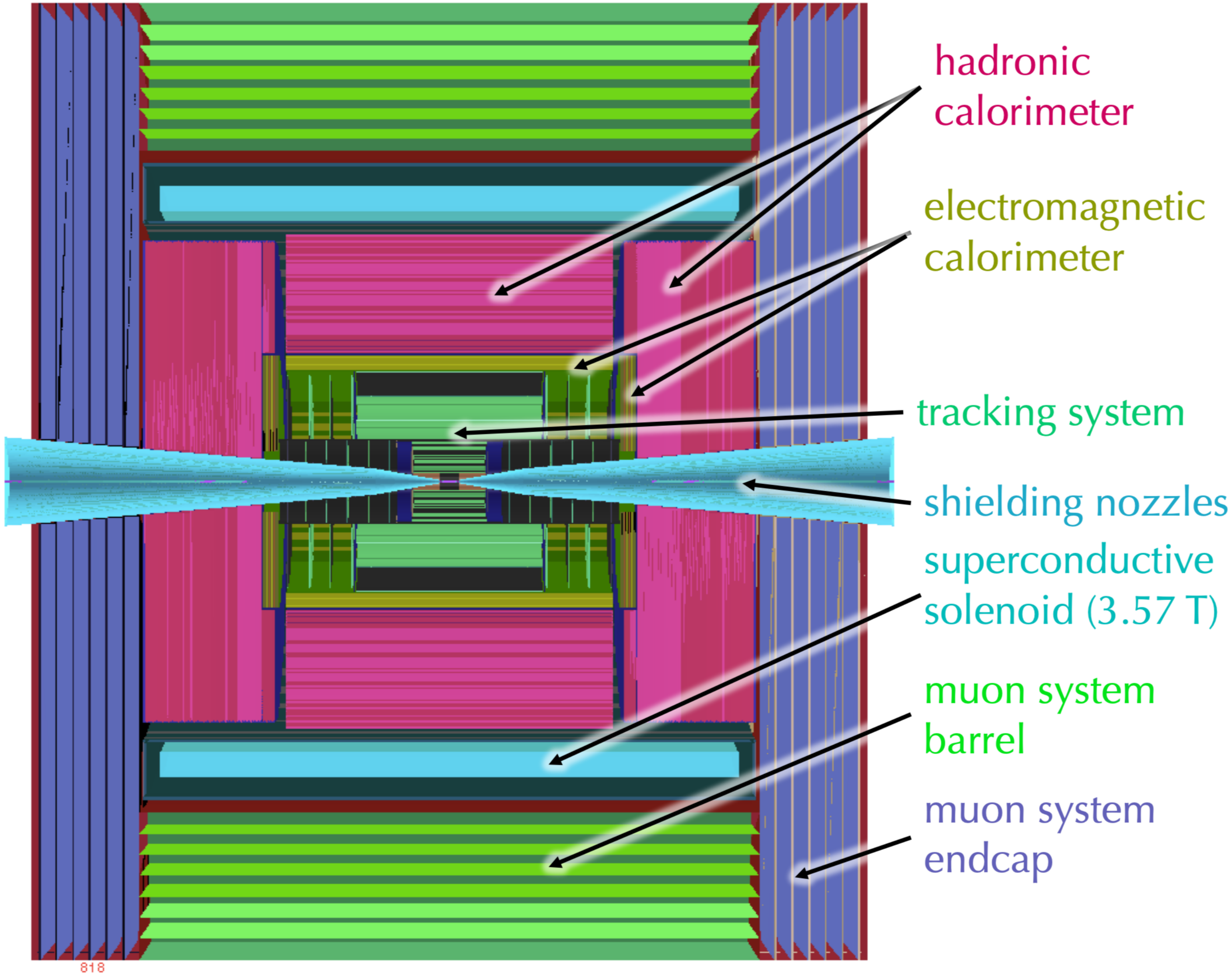
arXiv: 2203.07964

Beam-induced Background



1 MeV neutron equivalent fluence

Detector



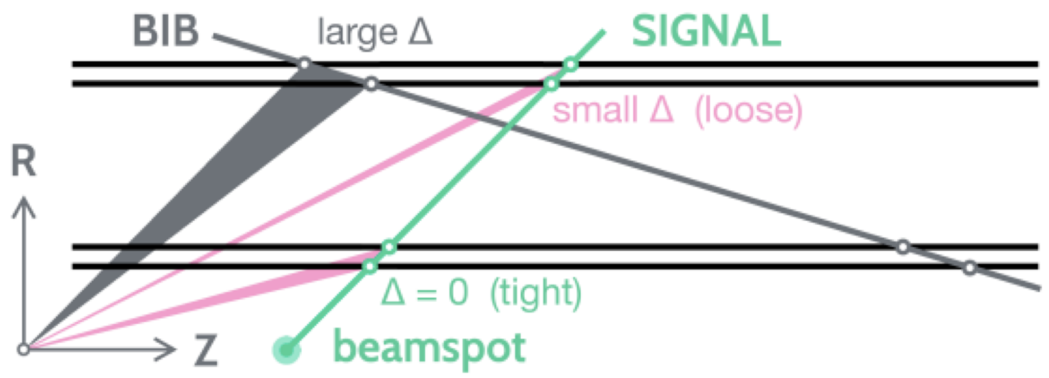
Geometry based on CLIC detector + tracker

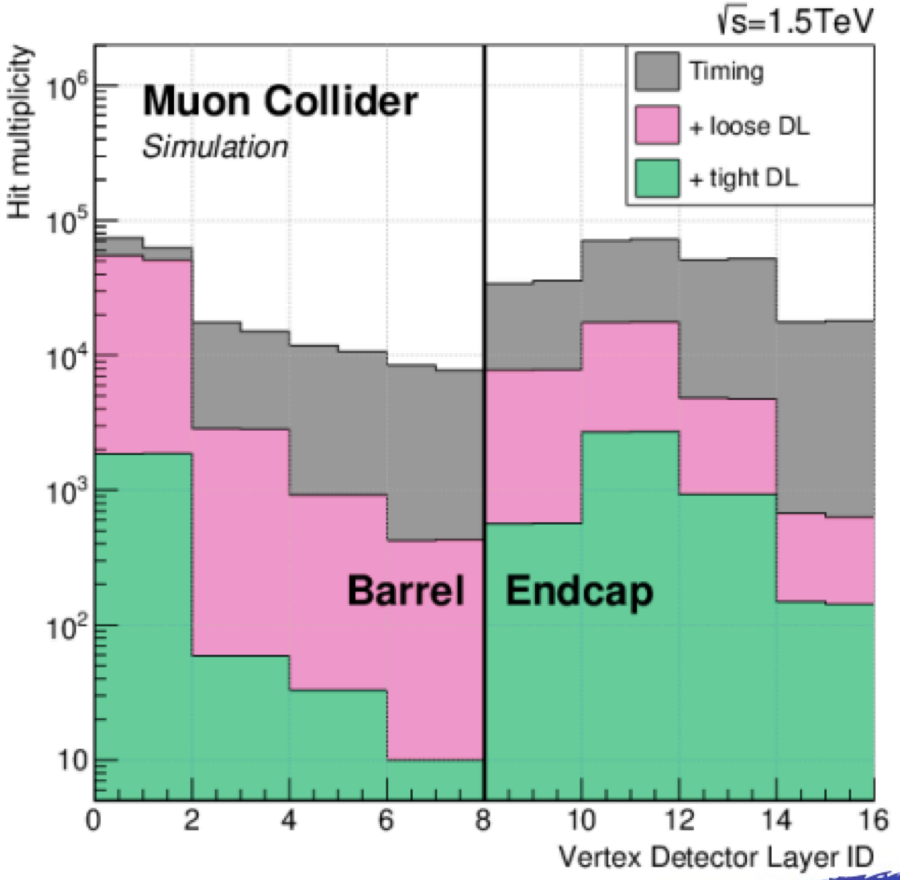
arXiv:1202.5940 [physics.ins-det]

Tracks reconstruction

Tracker is the closest detector to the IP and the most affected by BIB

Double Layer filter





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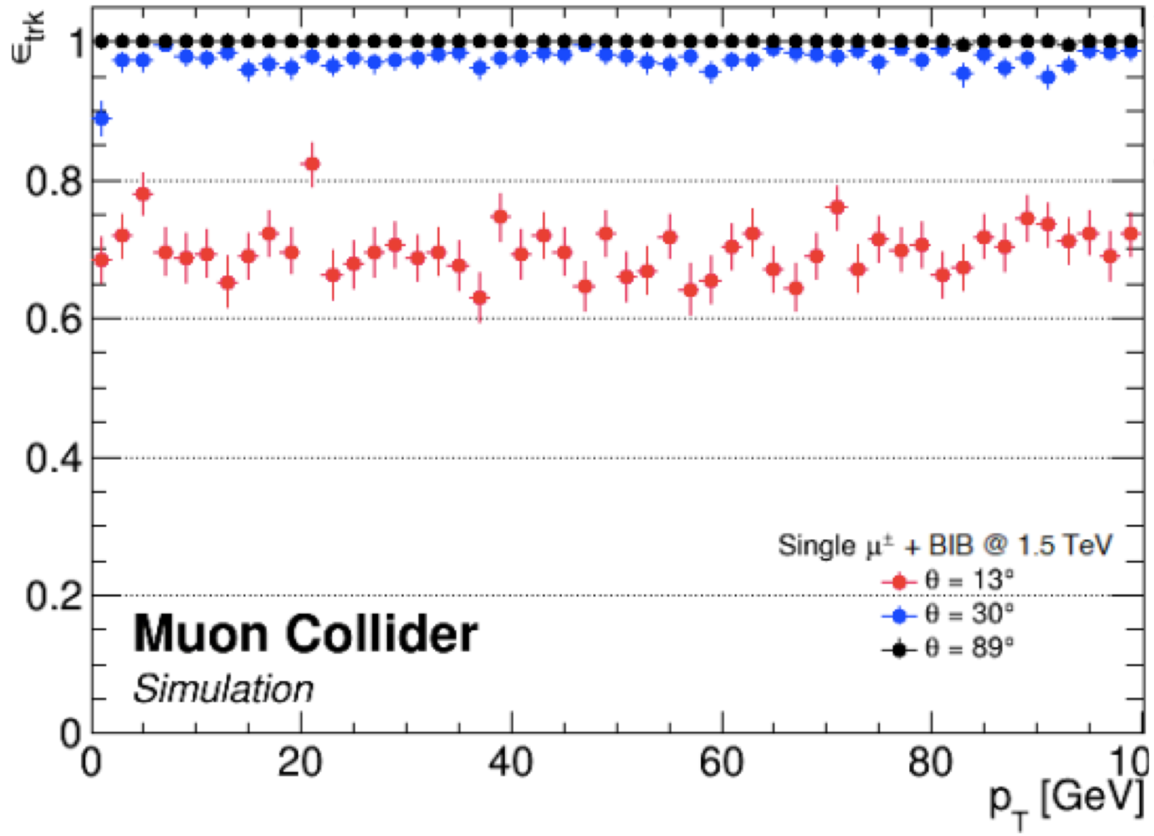
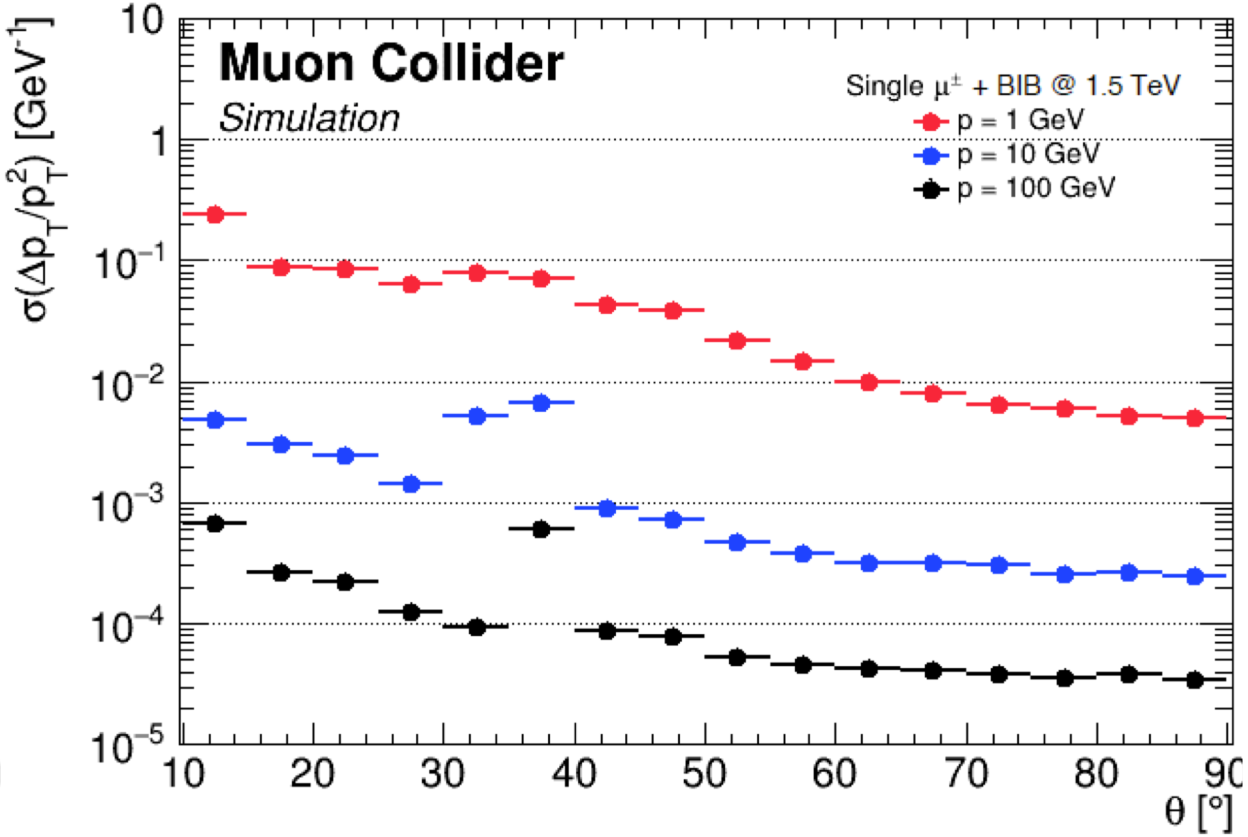
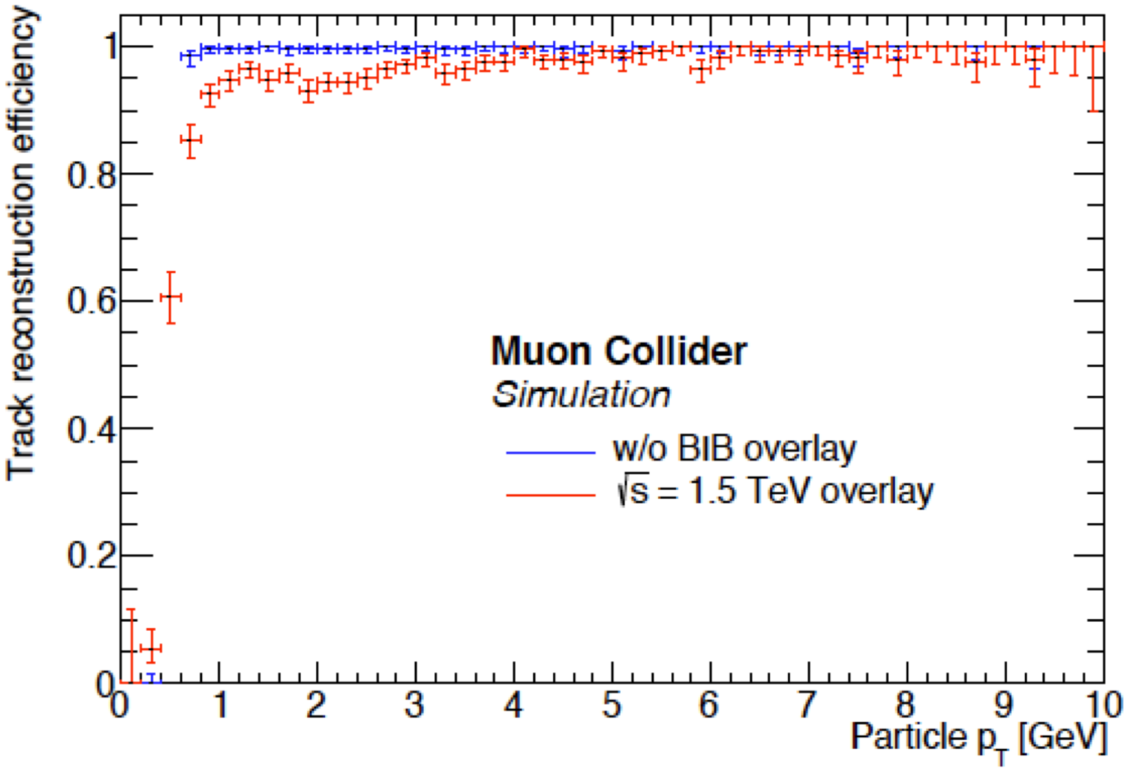
Conformal Tracking

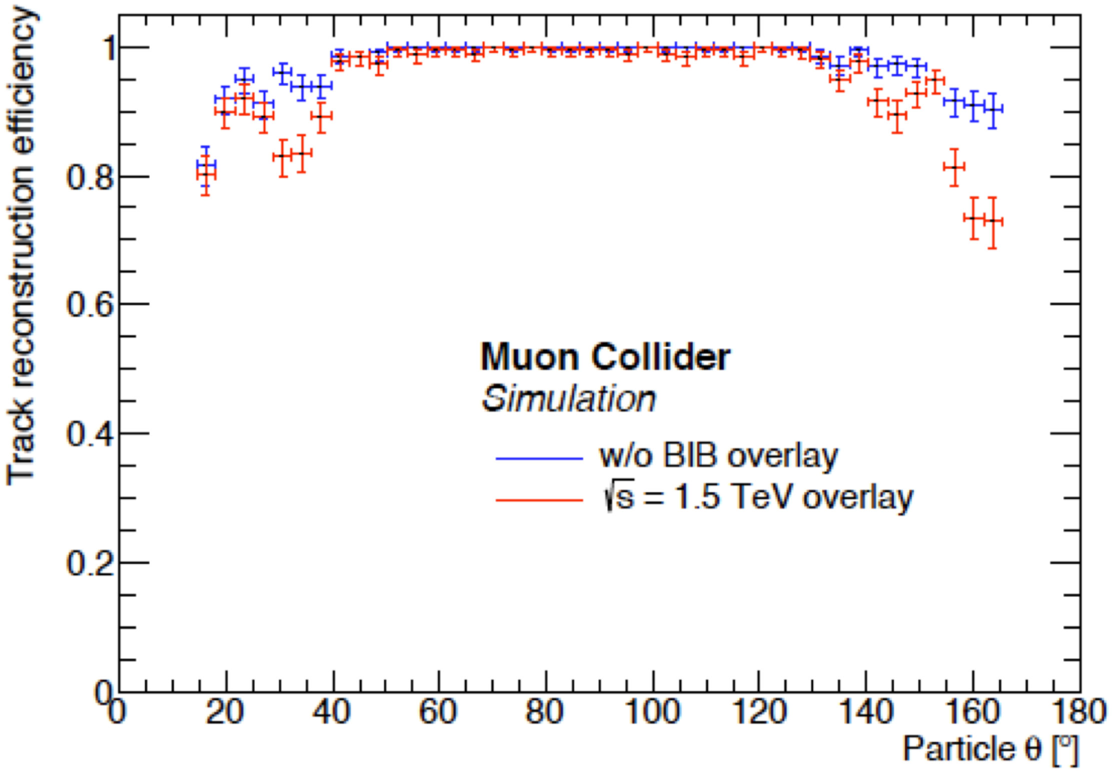




Track reconstruction

Combinatorial Kalman Filter algorithm seeded using hit triplets

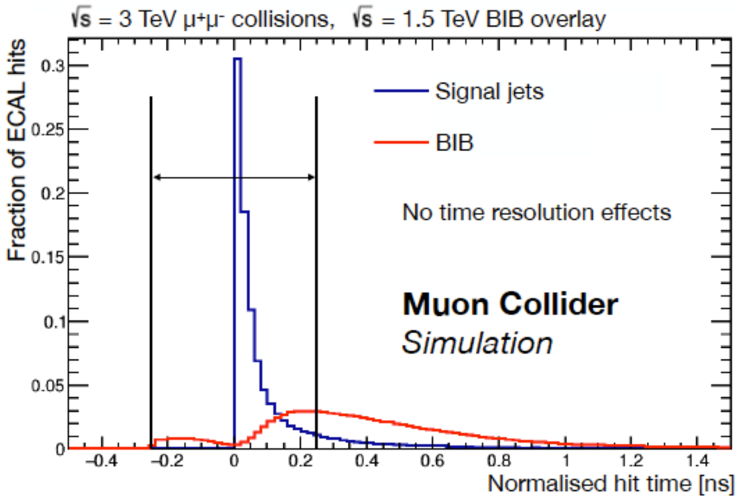


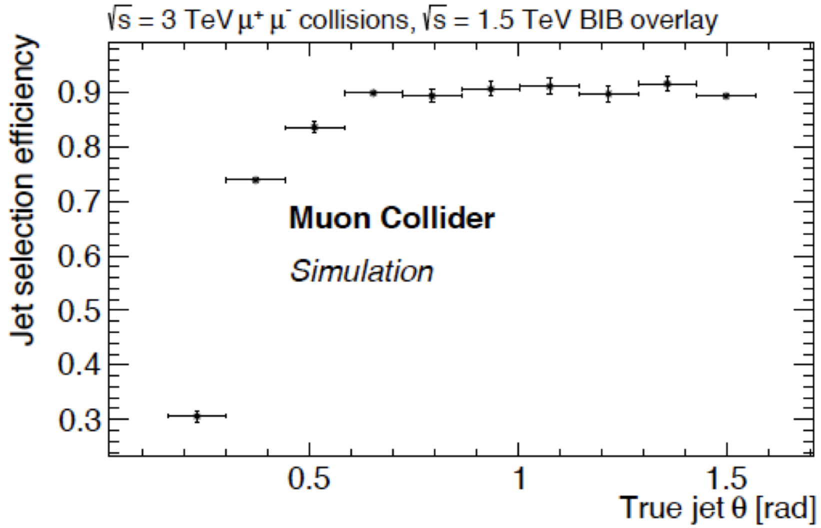


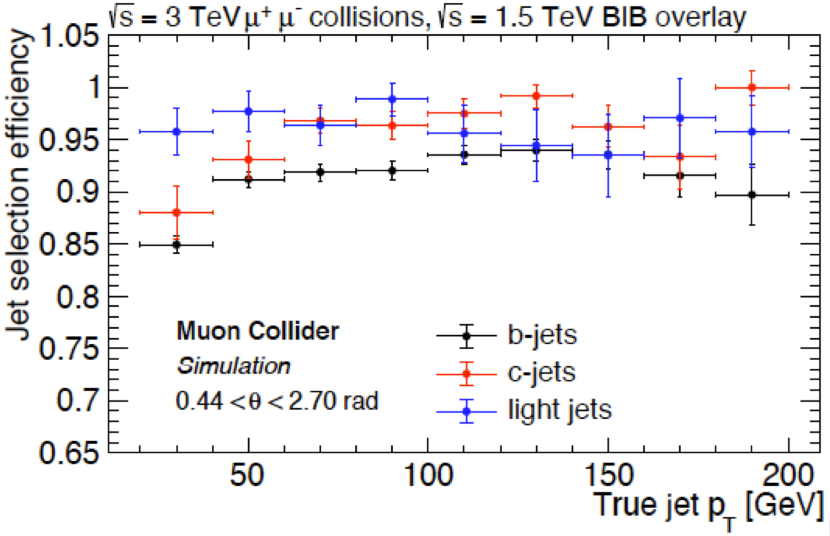
Jets reconstruction

Jet reconstruction is one of the most difficult reconstruction tasks

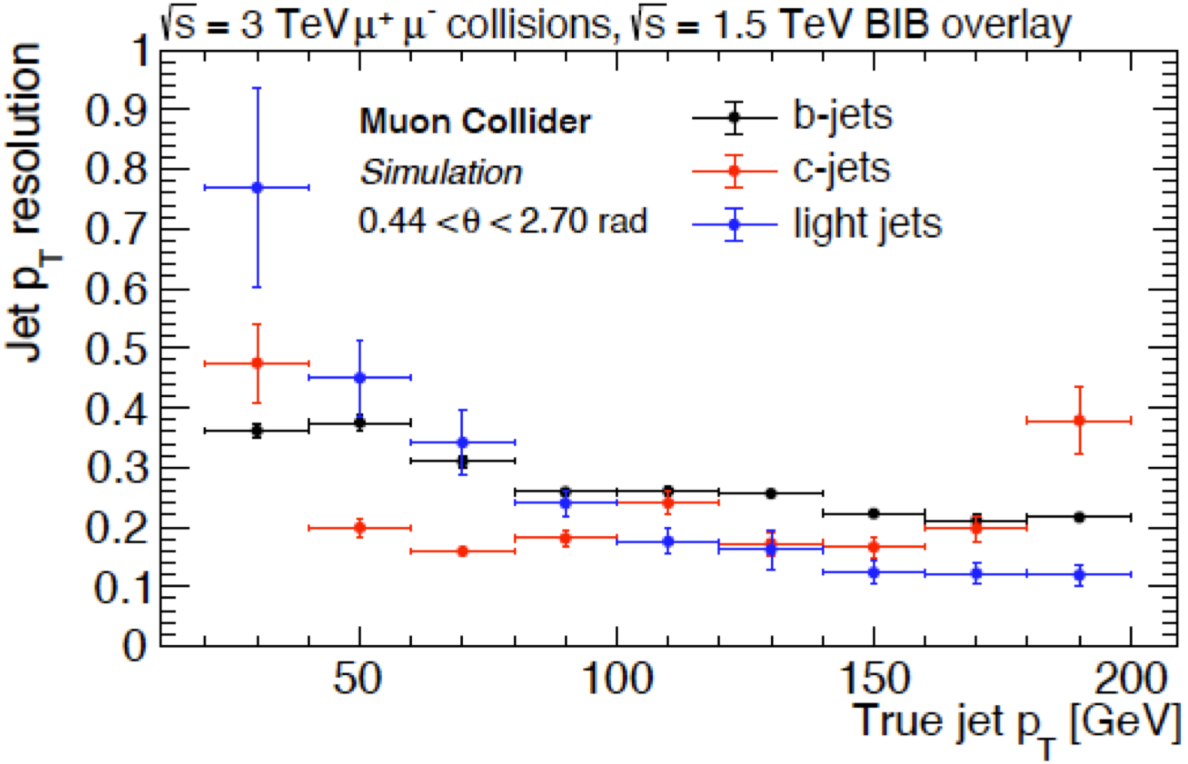
1. tracks reconstructed with CKF and filtered
2. calorimeter hits selected with hit time and energy
3. particles reconstructed with PandoraPFA algorithm
4. Pandora clustered into jets with k_t algorithm
5. fake jets removed
6. energy correction applied

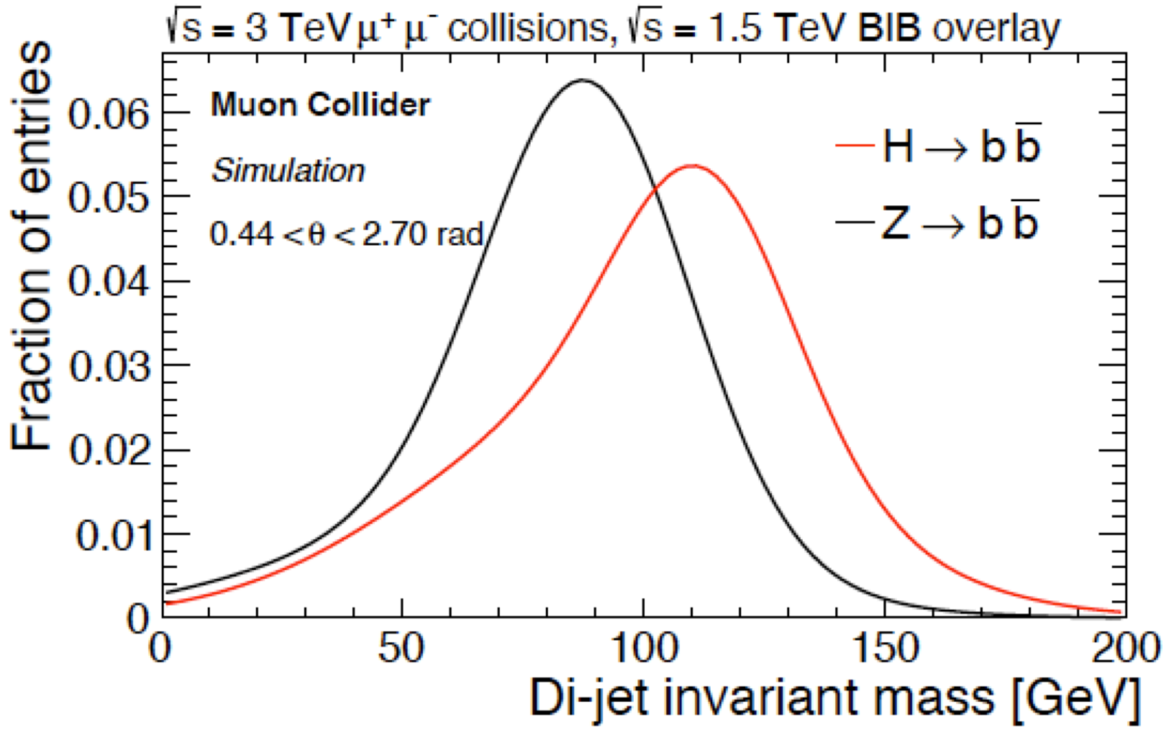






Jets reconstruction performance

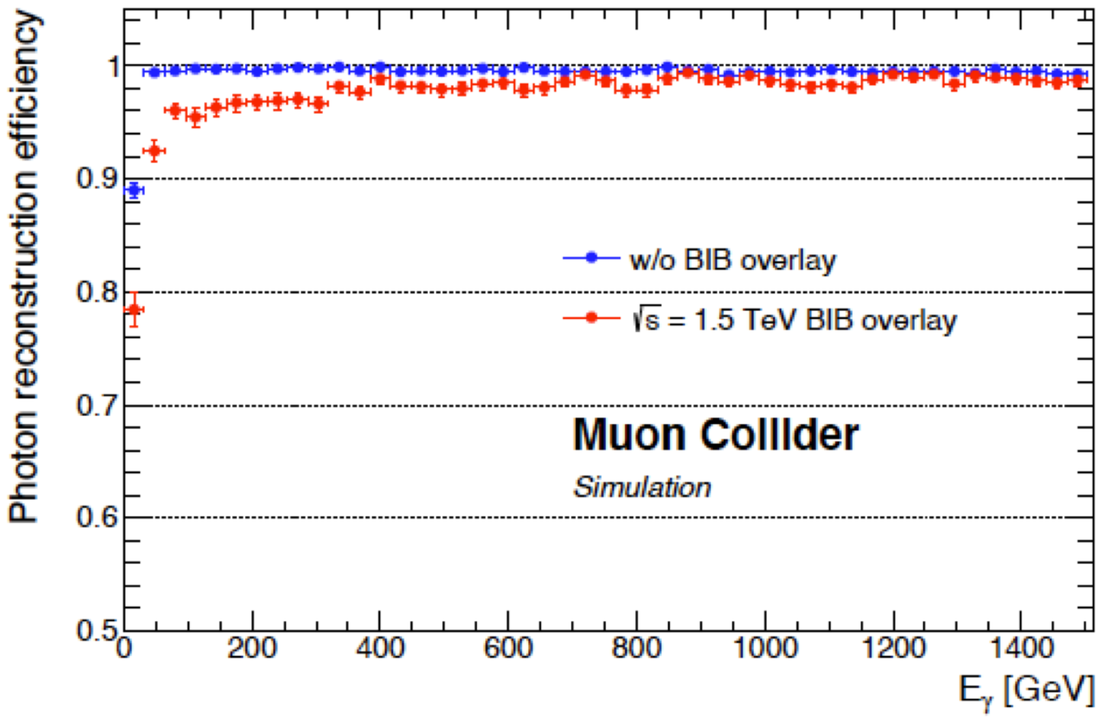


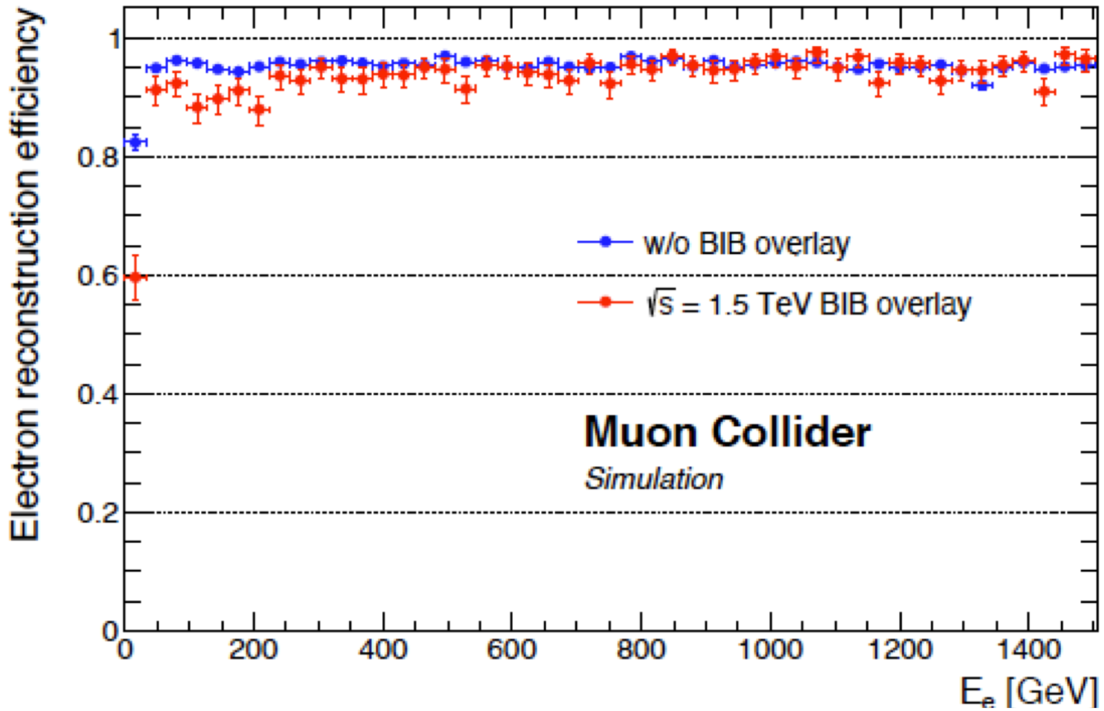


Relative width

- H-->bb: 27%
- Z-->bb: 29%

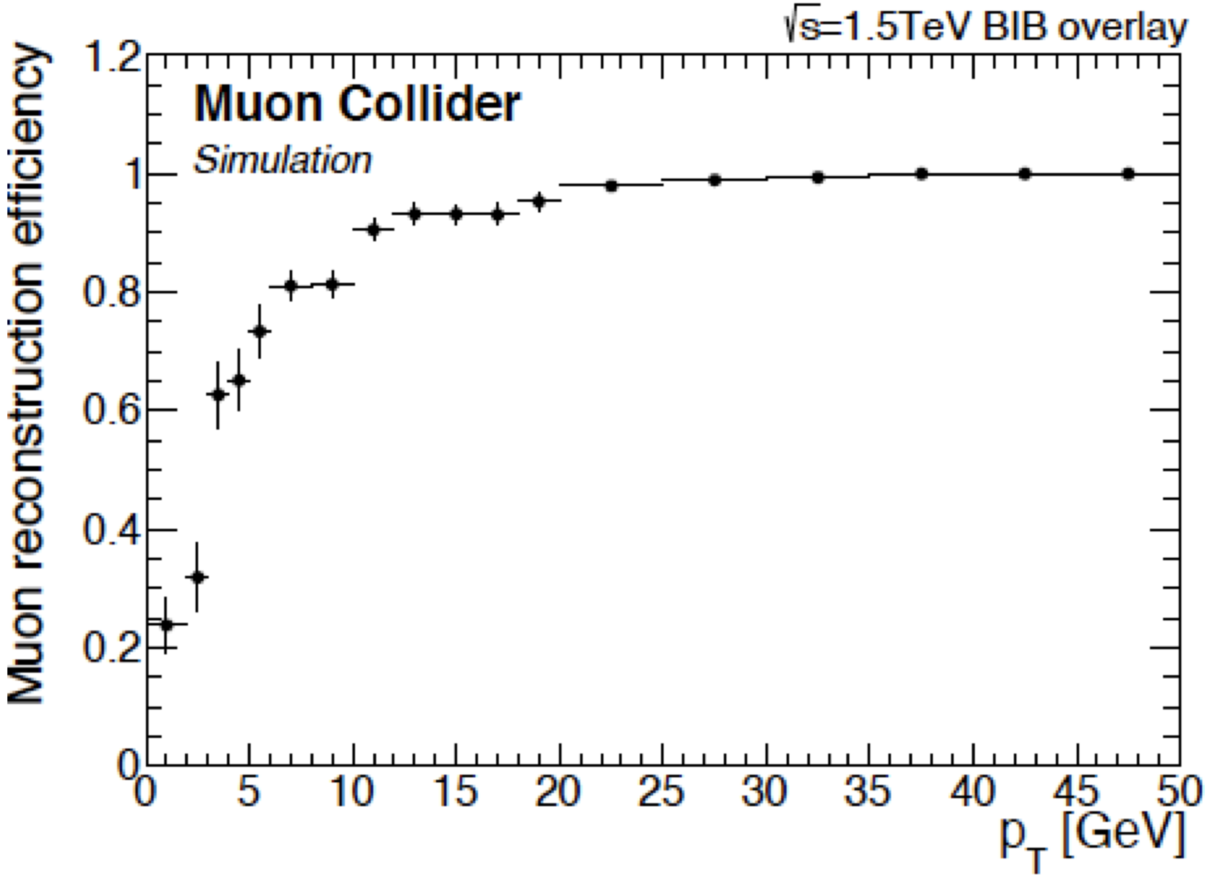
Photons and electrons reconstruction

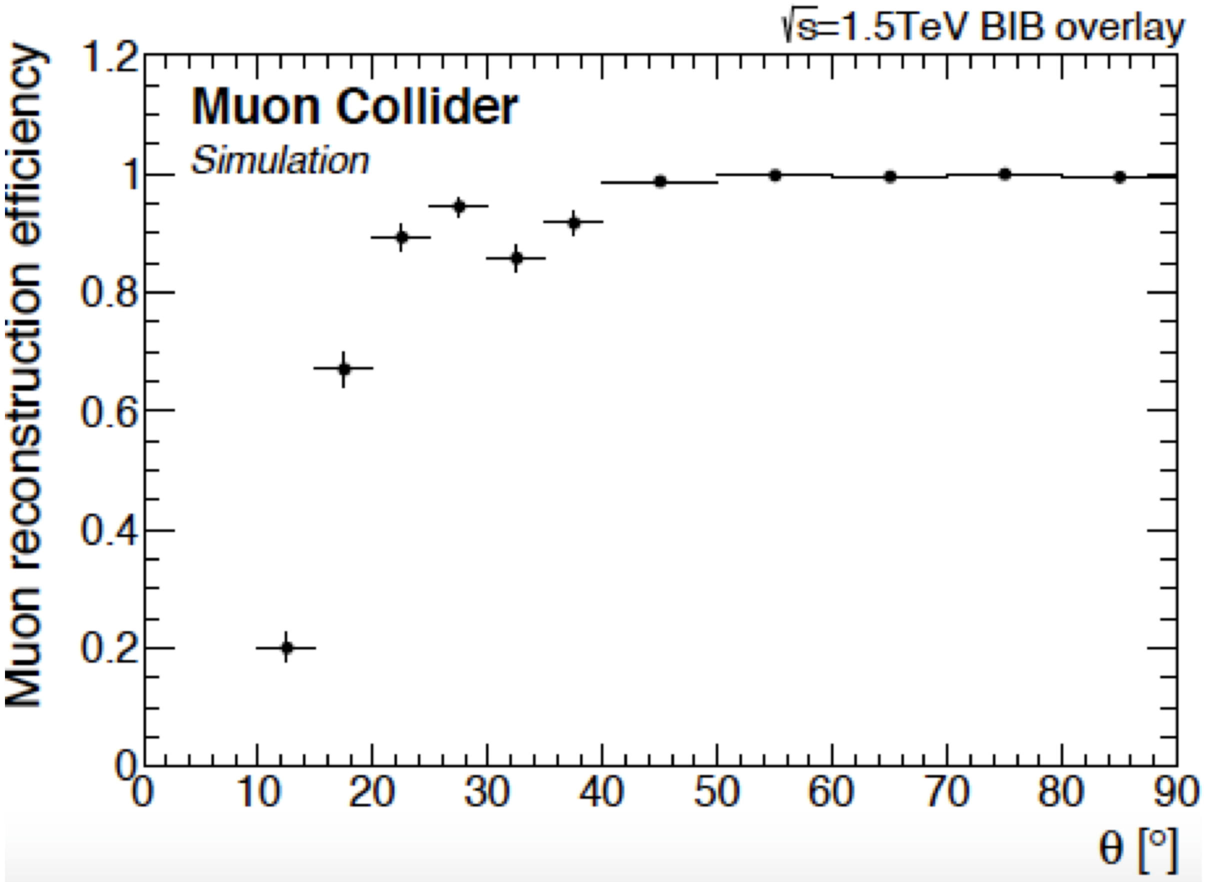




Muons reconstruction

BIB occupancy in the muon system is very low





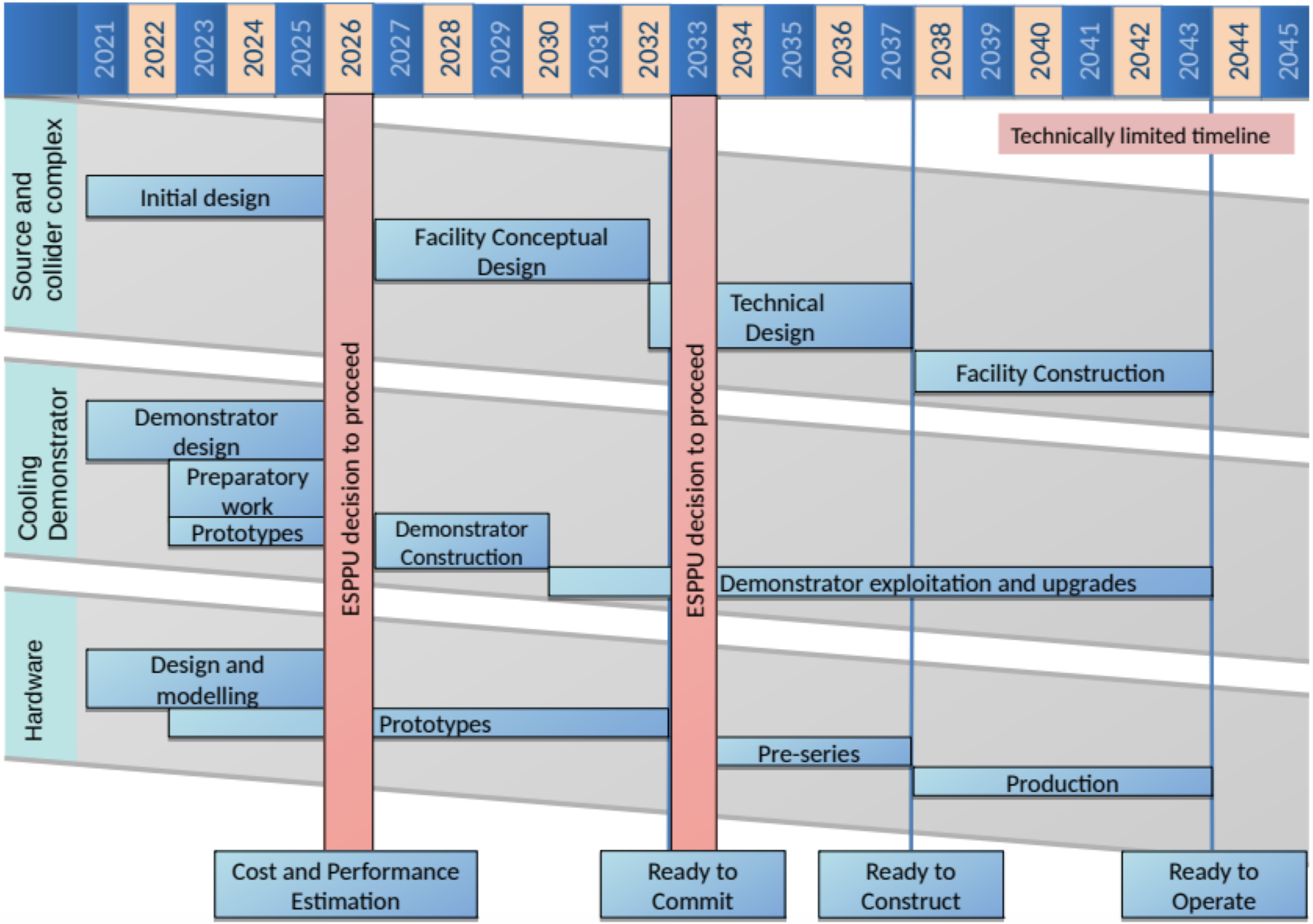
Conclusions

A **Muon Collider** is a unique possibility for the future of high energy physics

- The Muon Collider offers a novel unprecedented physics program
- The biggest challenges are related to the beam quality and the impact on the environment
- Beam-induced Background represents the main challenge in designing the detector
- Detector requirements, performance and the physics reach of a 3 TeV and a 10 TeV muon collider are under study

Thanks for your attention

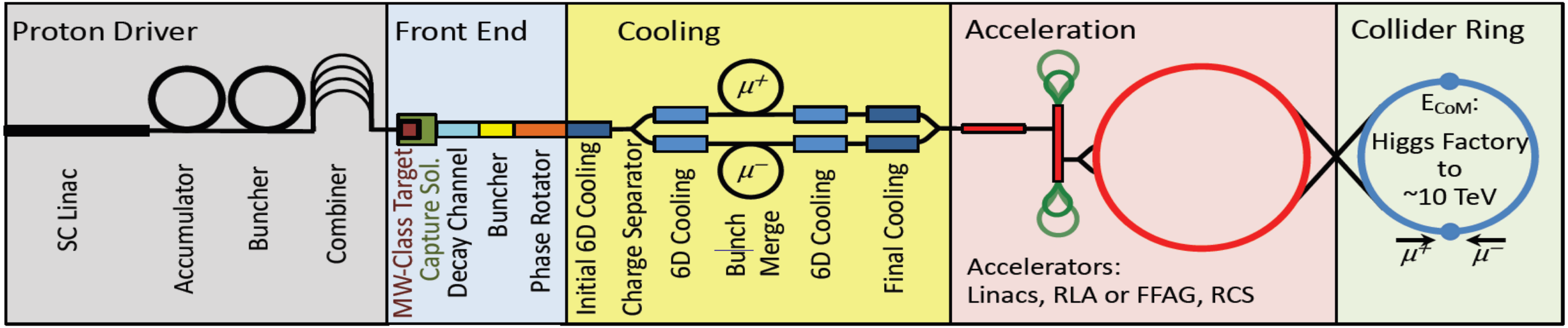
A timeline for the muon collider R&D programme.



Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_{L}	MeV m	7.5	7.5	7.5
Transverse emittance	ϵ	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP beta-function	β	mm	5	1.5	1.07
IP beam size	σ	µm	3	0.9	0.63

Proton-driven Muon Collider concept

Fully driven by muon lifetime, otherwise would be easy



Short, intense proton bunch

Protons produce pions which decay into muons muons are captured

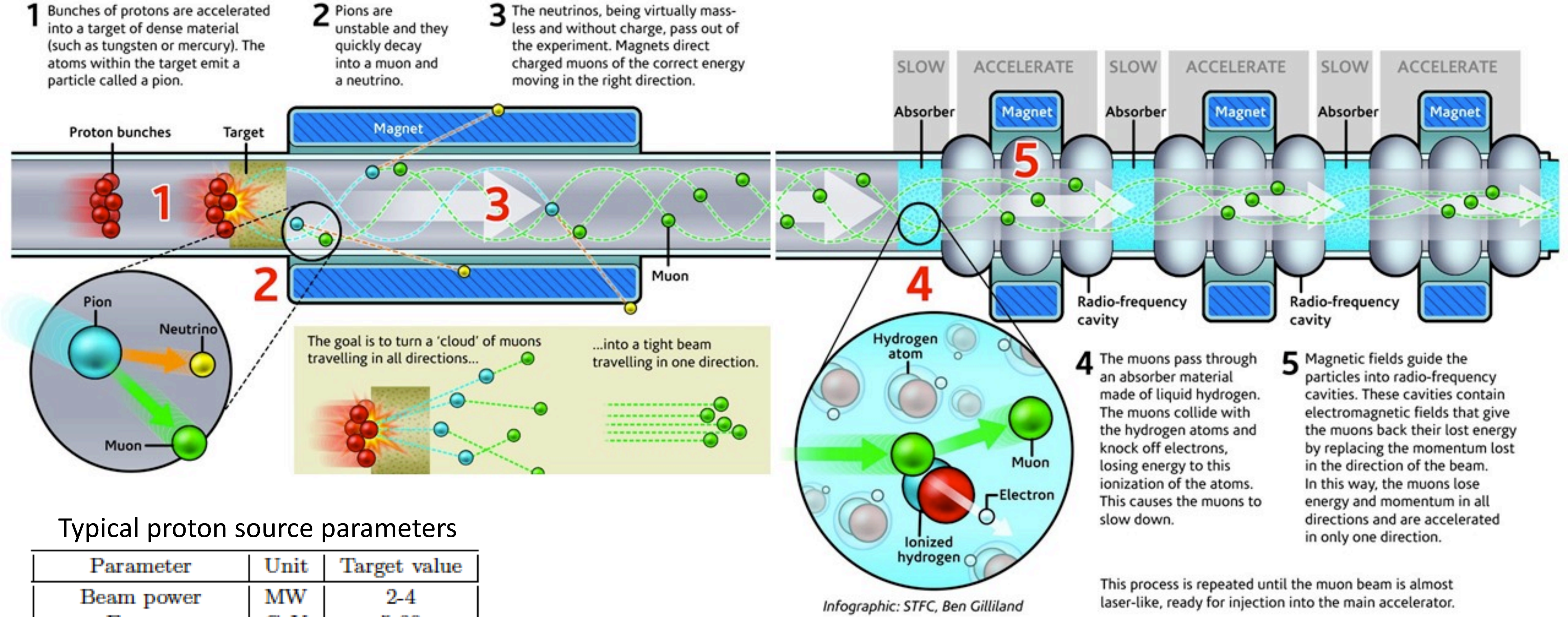
Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

1-4 MW proton beam @ **5-20 GeV**, compressed to **1-3 ns** bunches at a **5-10 Hz** frequency

Ionization cooling-channel scheme

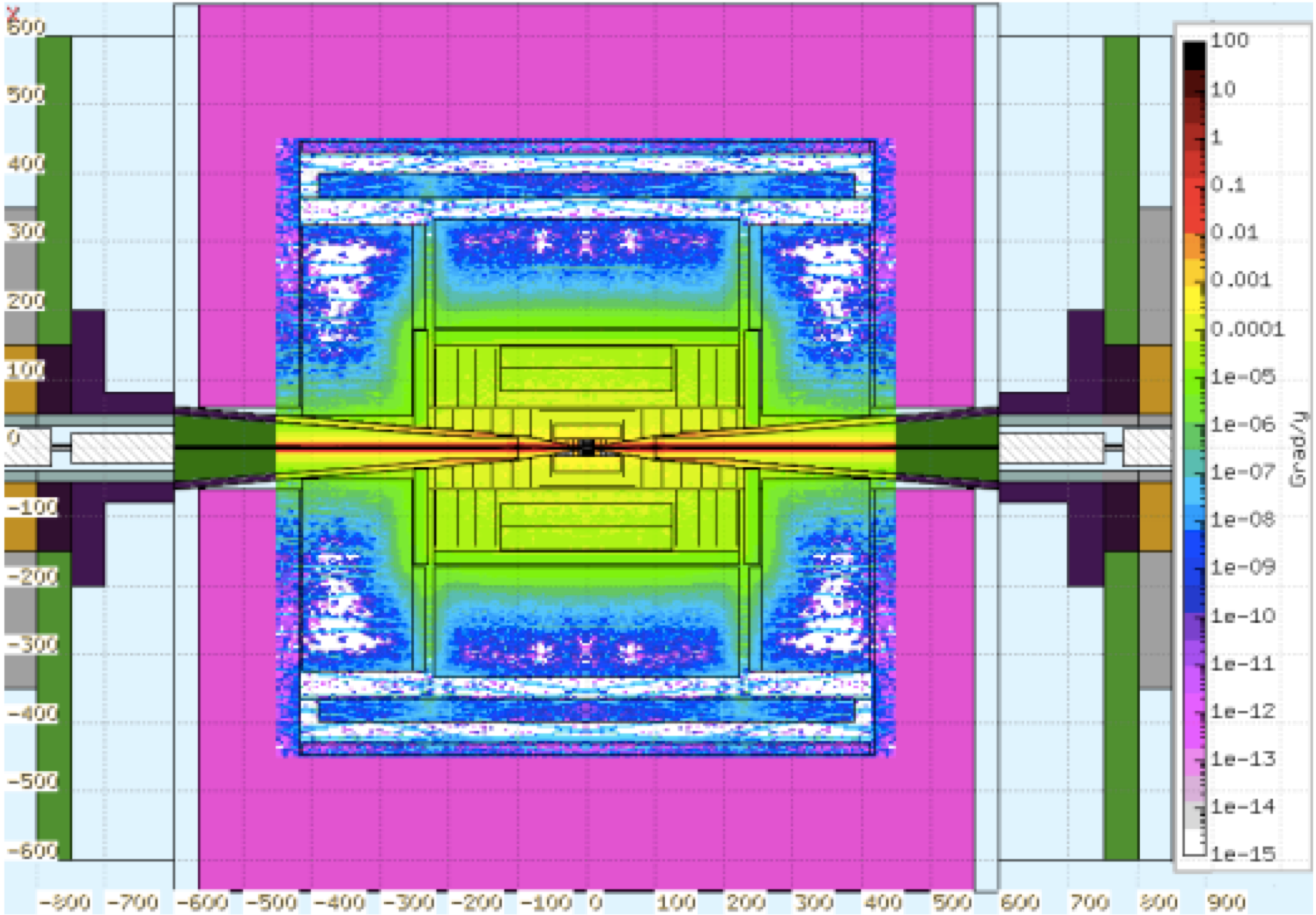


Typical proton source parameters

Parameter	Unit	Target value
Beam power	MW	2-4
Energy	GeV	5-30
Repetition Rate	Hz	5-10
RMS bunch length	ns	1-3

MICE: Nature vol. 578, p. 53-59 (2020)

Total ionising dose



Subsystem	Region	R dimensions [cm]	|Z| dimensions [cm]	Material
Vertex Detector	Barrel	3.0 – 10.4	65.0	Si
	Endcap	2.5 – 11.2	8.0 – 28.2	Si
Inner Tracker	Barrel	12.7 – 55.4	48.2 – 69.2	Si
	Endcap	40.5 – 55.5	52.4 – 219.0	Si
Outer Tracker	Barrel	81.9 – 148.6	124.9	Si
	Endcap	61.8 – 143.0	131.0 – 219.0	Si
ECAL	Barrel	150.0 – 170.2	221.0	W + Si
	Endcap	31.0 – 170.0	230.7 – 250.9	W + Si
HCAL	Barrel	174.0 – 333.0	221.0	Fe + PS
	Endcap	307.0 – 324.6	235.4 – 412.9	Fe + PS
Solenoid	Barrel	348.3 – 429.0	412.9	Al
Muon Detector	Barrel	446.1 – 645.0	417.9	Fe + RPC
	Endcap	57.5 – 645.0	417.9 – 563.8	Fe + RPC

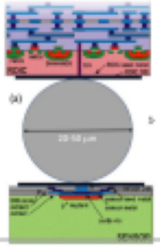
Tracking detectors: technology

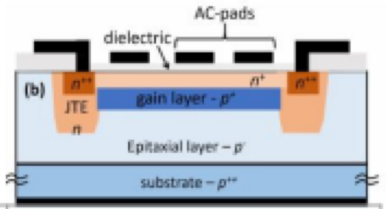
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\mu m \times 25\mu m$	$50\mu m \times 1mm$	$50\mu m \times 10mm$
Sensor Thickness	$50\mu m$	$100\mu m$	$100\mu m$
Time Resolution	30ps	60ps	60ps
Spatial Resolution	$5\mu m \times 5\mu m$	$7\mu m \times 90\mu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

Multiple technological choices being investigated for accurate timing-aware tracking

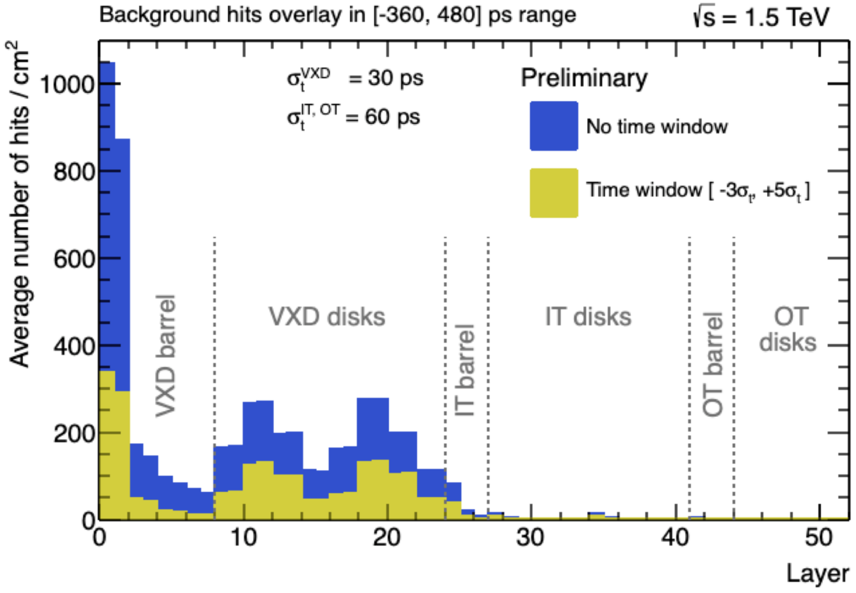
- Hybrid pixels, CMOS-based, LGAD-based, …
- Thin sensor (layer)
- Need for powerful yet power-efficient ASICs (smaller feature size)

Synergy with HL-LHC and other projects





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



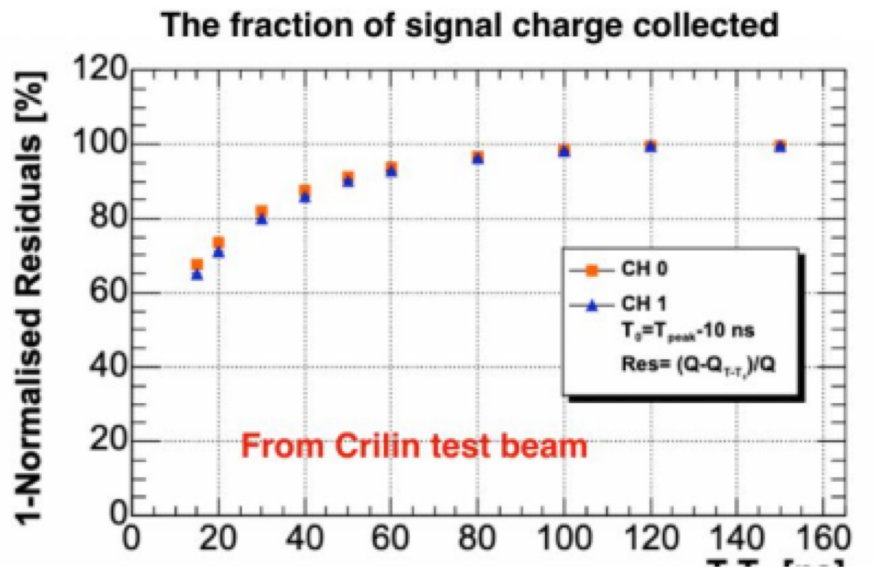
Calorimeters: performance and technology

Key detector characteristics:

- short integration time
- good time-of-arrival resolution
- longitudinal segmentation
- good radiation hardness
- good energy resolution for physics.

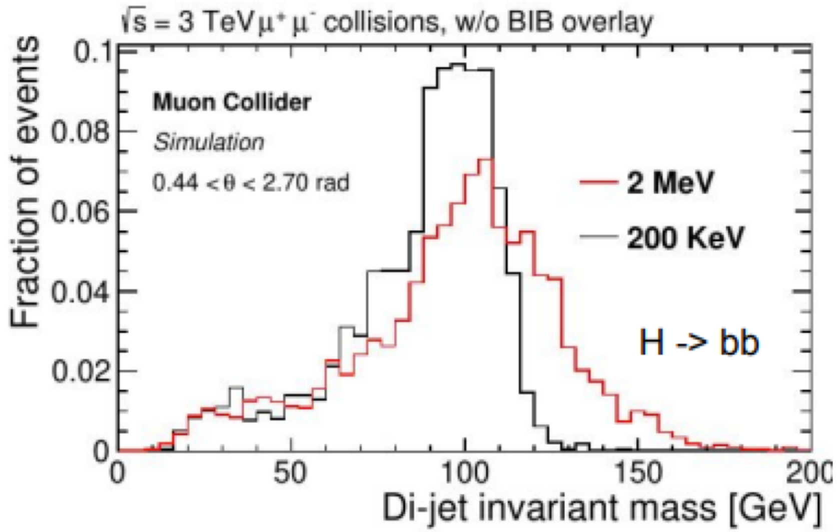
Exploring new technology

- e.g. semi-homogeneous Crilin calorimeter R&D already ongoing



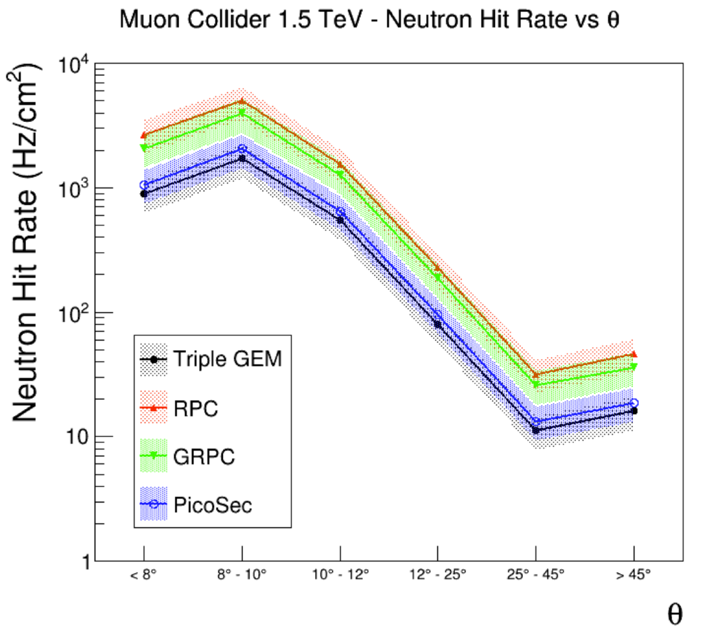
Event reconstruction, key points:

- calorimeter cell energy selection
- particle-flow approach, integrating charged particle information with appropriate selections
- energy calibration
- residual "fake" energy clusters (jets) removal

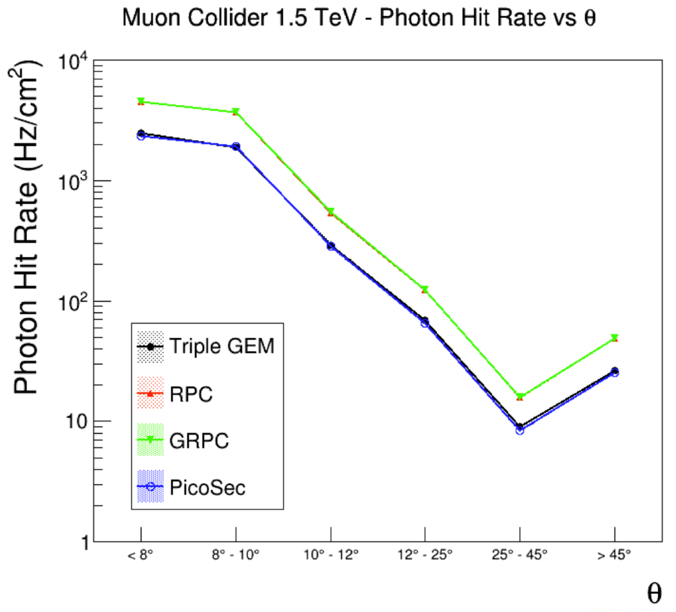


Muon System

Detector	σ_t	σ_x	Rate capability
RPC (HPL o Glass)	1 ns	~mm	~ 1 kHz/cm^2
Standard MPGD (GEM, Micromegas)	5-10 ns	~100 μm	> 100 kHz/cm^2



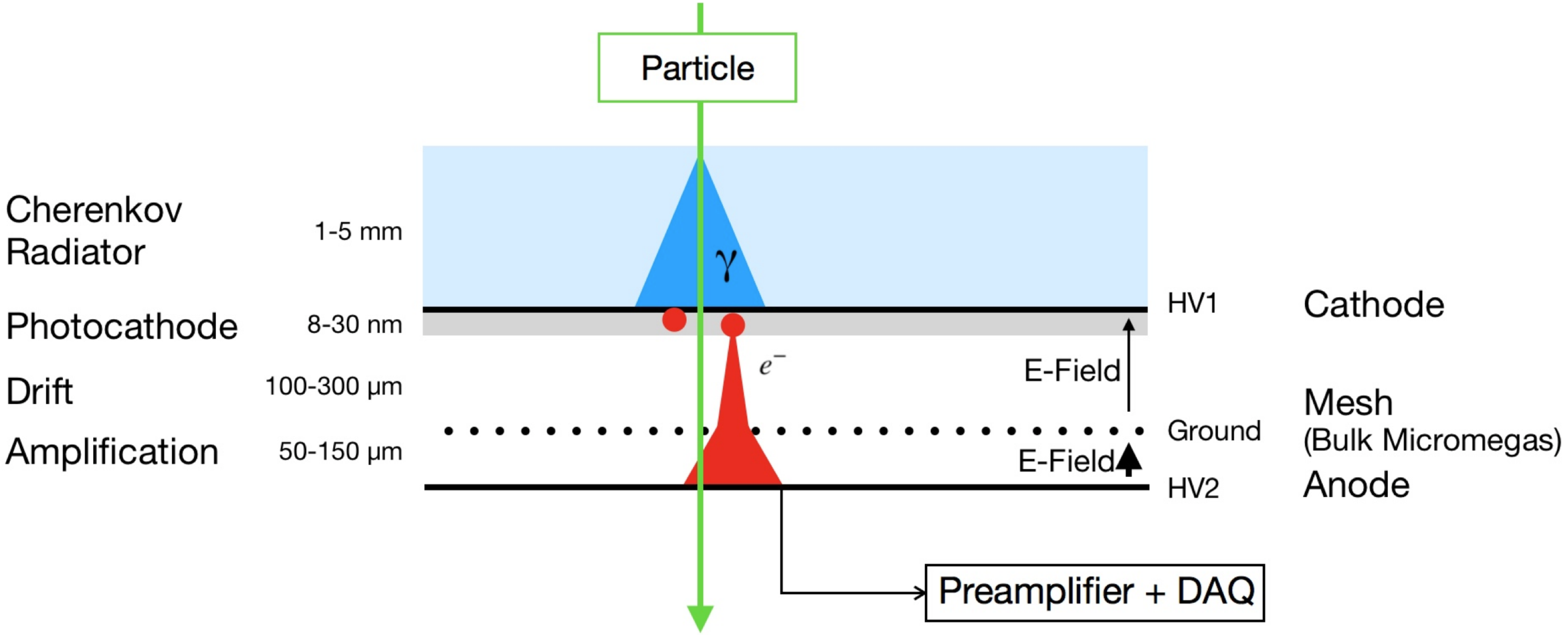
R&D Goal: develop a detector able to reach good performance on all the three items



Requirements on spatial (~100μm) and time (<1ns) resolutions

Muon System

On going R&D on sub-ns timing with MicroMegas and eco-friendly gas mixtures



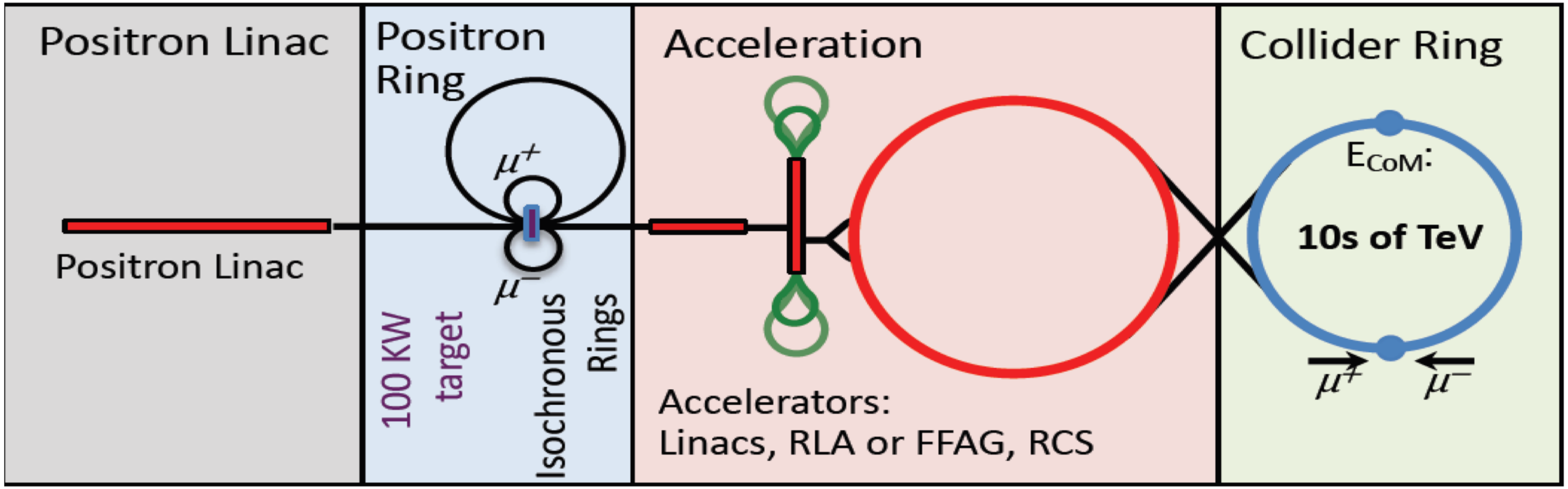
1. Look at **Cherenkov light**, not the ionisation

   Photo-electrons created promptly with the MIP passage

2. Remove the drift gap and start the avalanche as soon as possible

Alternatives: The LEMMA Scheme

LEMMA scheme (INFN) P. Raimondi et al.



45 GeV positrons to produce muon pairs; accumulate muons from several steps

$$e^+e^- \to \mu^+\mu^-$$

Excellent idea, but nature is cruel

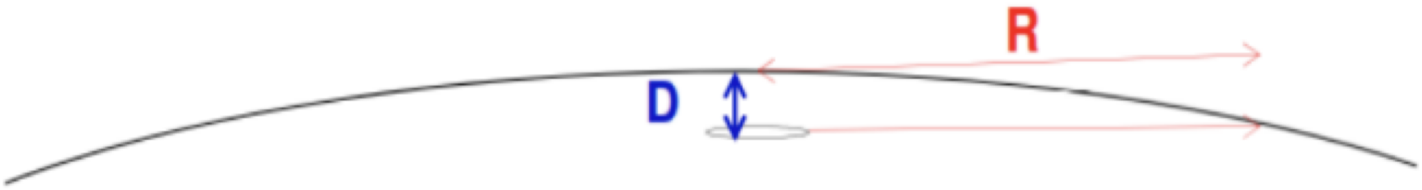
Detailed estimates of fundamental limits show that we require a very large positron bunch charge to reach the same luminosity as the proton-based scheme

$\Rightarrow$ Need same game changing invention

Neutrino Flux

Goal is to reduce to negligible level, similar to LHC

- **3 TeV, 200 m deep tunnel is about OK**



$$R = \sqrt{2R_{earth}D}$$

	$\sqrt{s}$ (TeV)	0.5	1	2	3	4
	$N \times 10^{21}$	0.2	0.2	1.2	1.2	1.2
1 mSv	R (km)	0.4	1.1	6.5	12	18
	D (m)	≤ 1	≤ 1	3.3	11	25
0.1 mSv	R (km)	1.2	3.2	21	37	57
	D (m)	≤ 1	≤ 1	34	107	254

0.01 mSv/yr -> D=300 m for 3TeV case