# Perspectives for a Muon Collider as the next generation precision and discovery machine

**Francesco Paciolla**

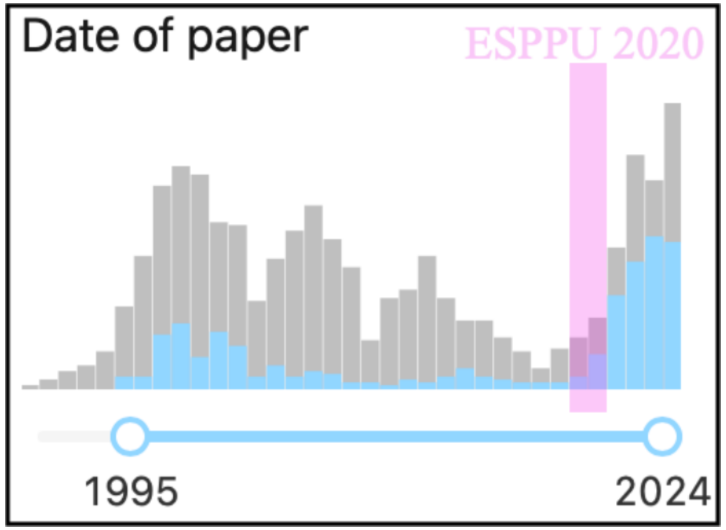
UNIVERSITÀ DI SIENA 1240

High Energy Physics – 23 October 2025
PhD Fisica 39° ciclo

# Overview

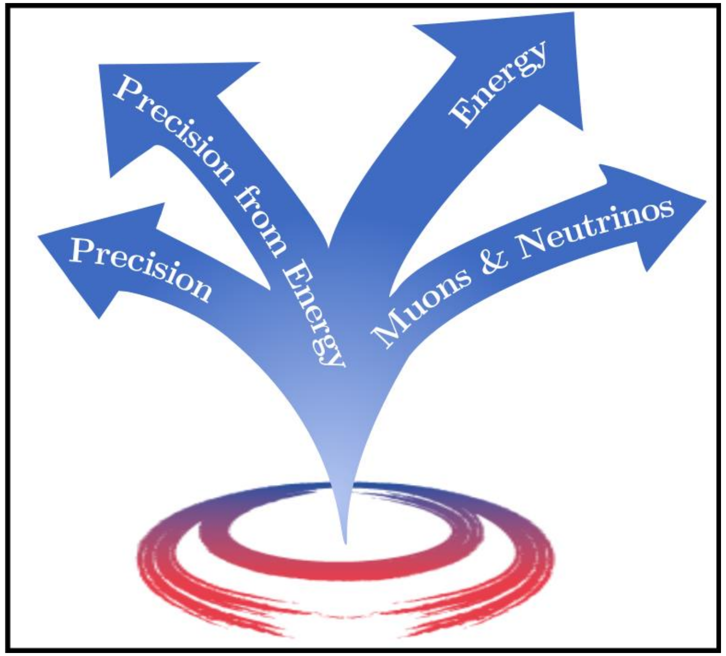
## Topics:

- Open physics questions
- Next Generation Collider options
- The Muon Collider
- $ee$ or $hh$ vs $\mu\mu$
- Precision and discovery
- Muon collider design
    - Proton beam, Target, Cooling, Accelerator ring, Collider ring
- Neutrinos




## History:

- 1960s: First mention of Muon Colliders in the literature
- 1990s-2010: Design studies through US institutional collaborations
- 2011-2016: Muon Accelerator Program was approved by DOE
- 2021: International Muon Collider Collaboration (IMCC) formed
- 2023: Formation of the US Muon Collider R&D coordination group



# Where to go next?

## Open questions:

- **Precision tests** of the Standard Model (SM)
  - Higgs properties
  - Flavour physics
- Study of the **flavour sector**
  - Quarks
  - Leptons
- Direct searches of **New Physics** (NP)
  - Dark Matter

## Common problem

**No specific energy range** to explore
- Contrast that with $H$ discovery at LHC
- Model dependent energy limits exists

## Next Generation Colliders

FUTURE CIRCULAR COLLIDER

CLIC

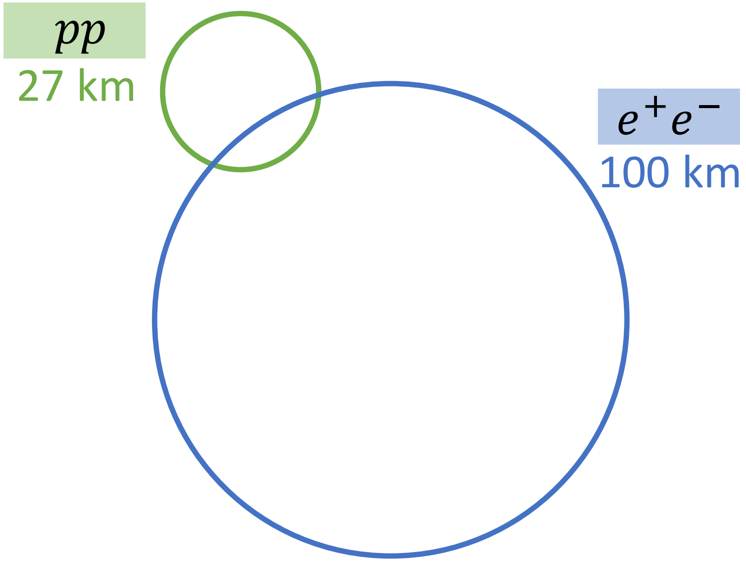
CEPC

MuCol

# Let's explore the options

## Circular $e^+e^-$

- Huge energy loss due to **bremsstrahlung**
- **Multiple collisions** from a single beam
- Elementary particles $\Longrightarrow$ **precision** measurement




FUTURE CIRCULAR COLLIDER

CLIC

CEPC

MuCol

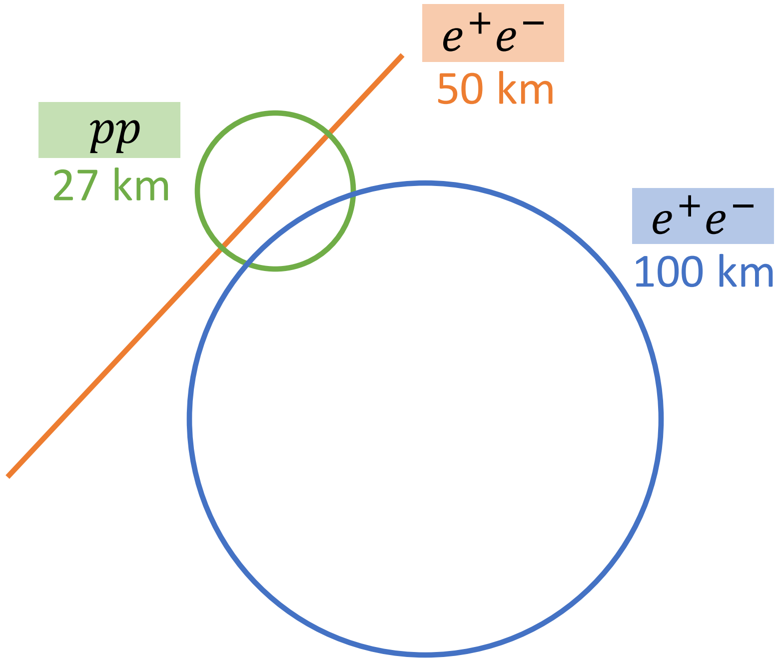
# Let's explore the options

## Circular $e^+e^-$

- Huge energy loss due to **bremsstrahlung**
- **Multiple collisions** from a single beam
- Elementary particles $\Longrightarrow$ **precision** measurement

## Linear $e^+e^-$

- Negligible bremsstrahlung
- **Single pass**, high luminosity requires high power
- Elementary particles $\Longrightarrow$ **precision** measurement



# Let’s explore the options

## Circular $e^+e^-$

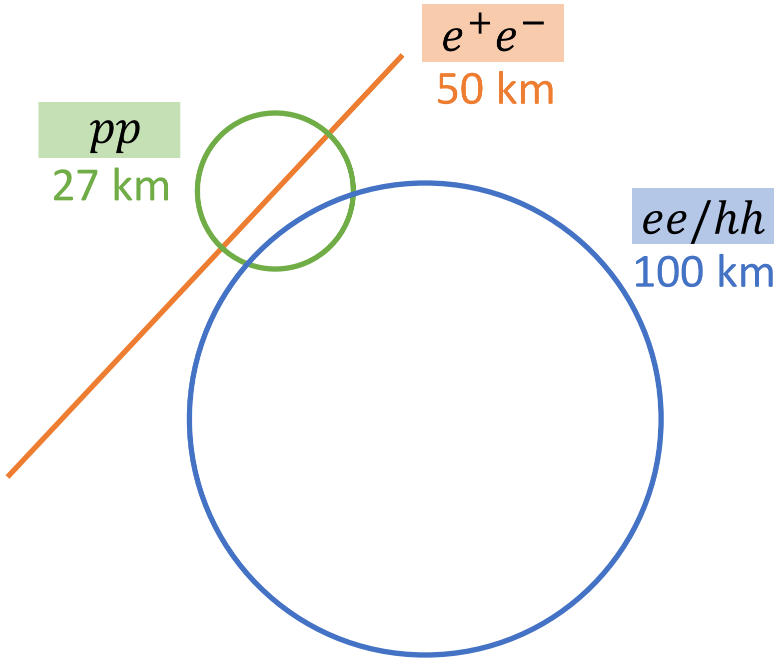
- Huge energy loss due to **bremsstrahlung**
- **Multiple collisions** from a single beam
- Elementary particles $\Longrightarrow$ **precision** measurement

## Linear $e^+e^-$

- Negligible bremsstrahlung
- **Single pass**, high luminosity requires high power
- Elementary particles $\Longrightarrow$ **precision** measurement

## Circular $pp$

- No bremsstrahlung but energy reach $\ll$ beam energy
- Same beam can produce multiple collision
- Composite particles $\Longrightarrow$ **discovery** measurement




FUTURE CIRCULAR COLLIDER

MuCol

# Let’s explore the options: the Muon Collider

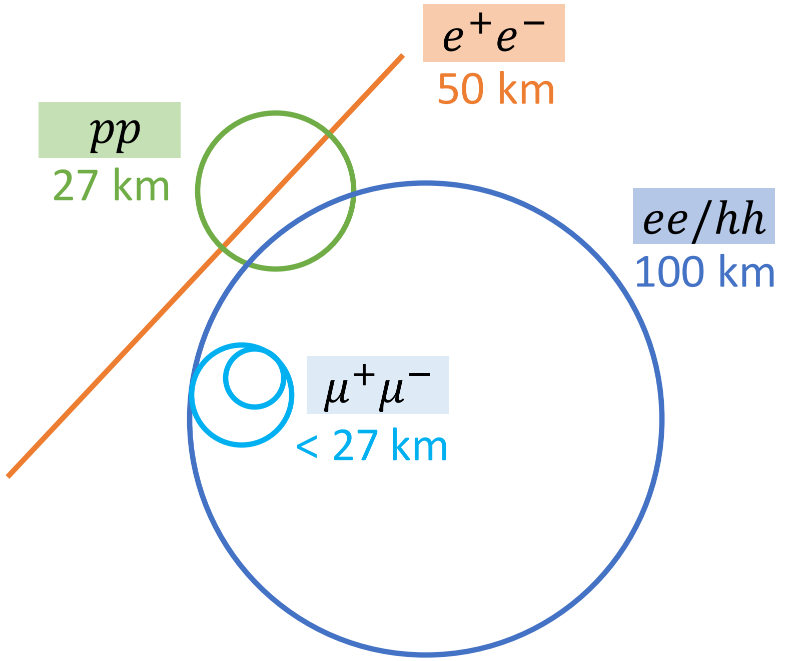
## $\mu$ collider

- **Less bremsstrahlung** *wrt* $e^+e^-$
- **Multiple collisions** from a single beam
- Massive elementary particles: **precision & discovery**

## New features

- $\mu$ beam is not stable
  - Need $\boldsymbol{p}$ **beam** to produce $\mu$
  - $\boldsymbol{\mu}$ **decay** in flight
- Collider features depends on $E_\mu$
  - **Luminosity increase** with $E_\mu$
  - **Decays decrease** with $E_\mu$
- **Staging** possibility
  - **3 TeV** followed by a **10 TeV** machine

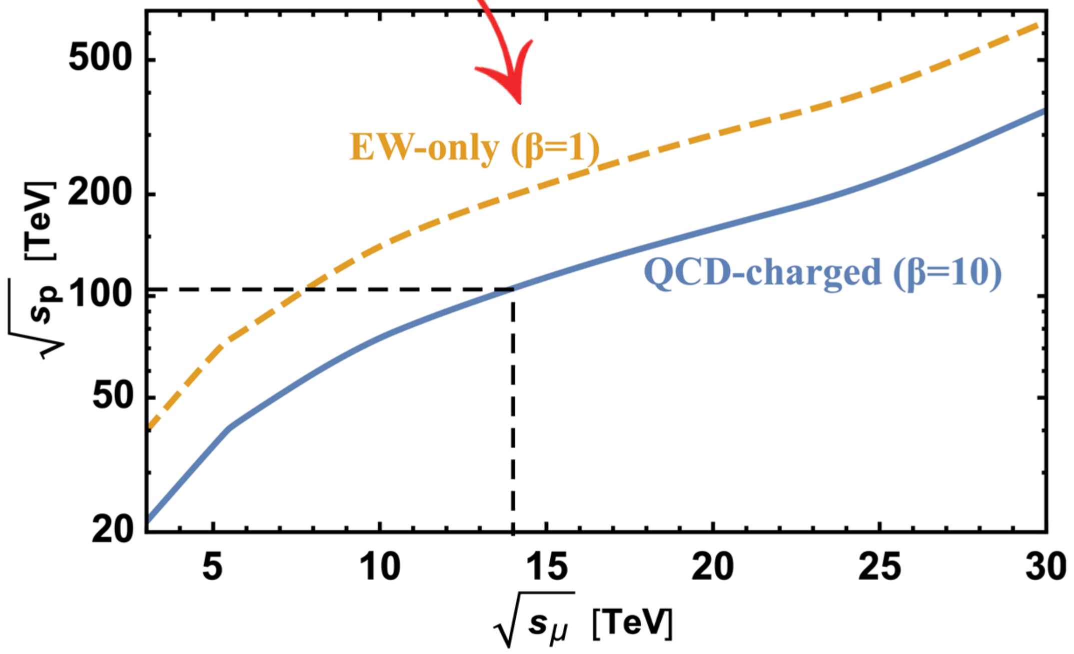
$$\tau_\mu = 21\ \mathrm{ms}\left(\frac{E_\mu}{1\ \mathrm{TeV}}\right)$$

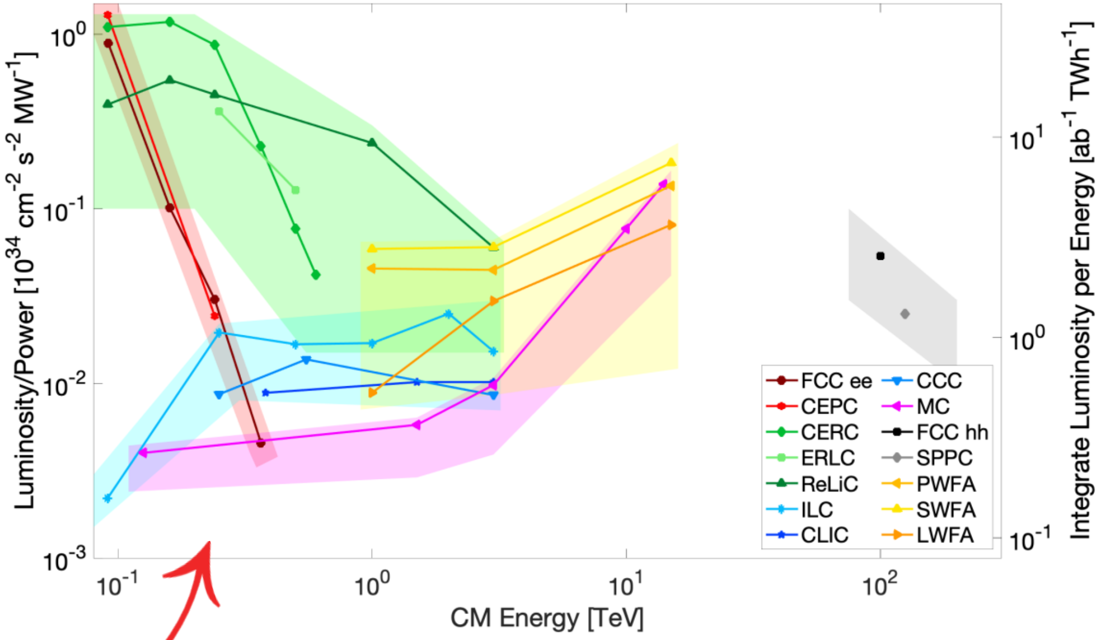


# $ee$ or $hh$ vs $\mu\mu$

## $\sqrt{s_\mu}$

- $m_\mu \gg m_e \implies$ **smaller rings** at same $E_{CM}$
- $\mu$ is elementary particle $\implies$ $\sqrt{s_\mu}$ **entirely available**
- $p$ is composite $\implies \sqrt{s_p} \neq$ beam energy
- $\sqrt{s_p}/\sqrt{s_\mu} \propto \beta$ (parton to muon relative coupling of NP)




## $\mathcal{L}$

$$\mathcal{L} = \frac{5\text{ years}}{\text{time}}\left(\frac{E_{CM}}{10\text{ TeV}}\right)^2 2\cdot 10^{35}\,\text{cm}^{-2}\text{s}^{-1}$$

- $\boldsymbol{\mathcal{L} \propto E_{CM}^2}$ because bremsstrahlung is negligible on beam focusing at interaction point
- $\boldsymbol{\mathcal{L} \propto}$ **dipole fields** $\implies$ collider ring $<$ acceleration ring
- $\boldsymbol{\mathcal{L} \propto 1/\varepsilon_\perp \varepsilon_\parallel}$ ($\varepsilon$ is the emittance)

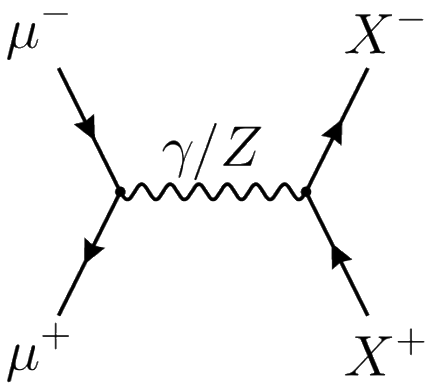
International Muon Collider Collaboration, C. Accettura et al., "*Towards a muon collider*", [2303.08533]
S. Gourlay, T. Raubenheimer, V. Shiltsev et al., "*Snowmass'21 Accelerator Frontier Report*", [2209.14136]

# $\mu\mu$: precision & discovery

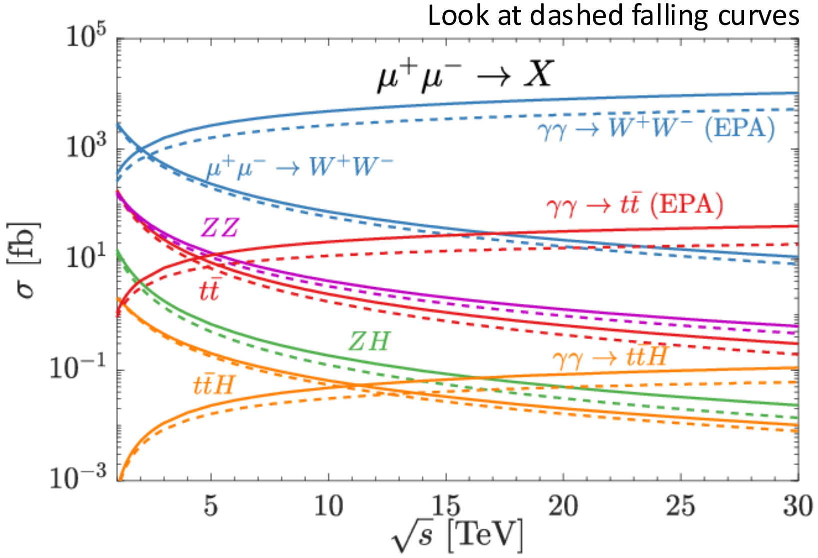
## Annihilation

- **Full beam energy** available for production
- Precision study of resonances

$$\sigma \sim \frac{1}{\boldsymbol{E}^2}$$



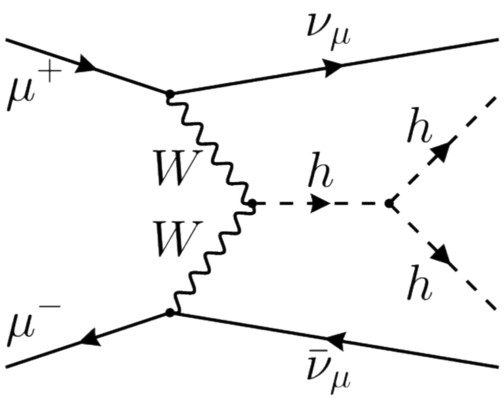

Look at dashed falling curves



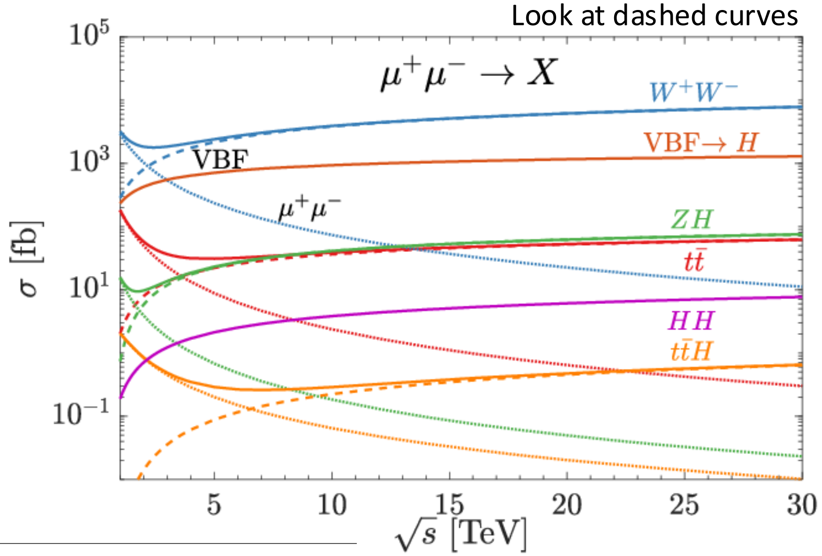

## Vector Boson Fusion

- **% of beam energy** available for production
- Main way to produce $H, Z, W,$ etc.

$$\sigma \sim \frac{1}{M^2} \log^2 \frac{\boldsymbol{E}^2}{M}$$




Look at dashed curves




T. Han, Y. Ma, K. Xie, *"High energy leptonic collisions and electroweak parton distribution functions"*, [PRD.103.L031301]

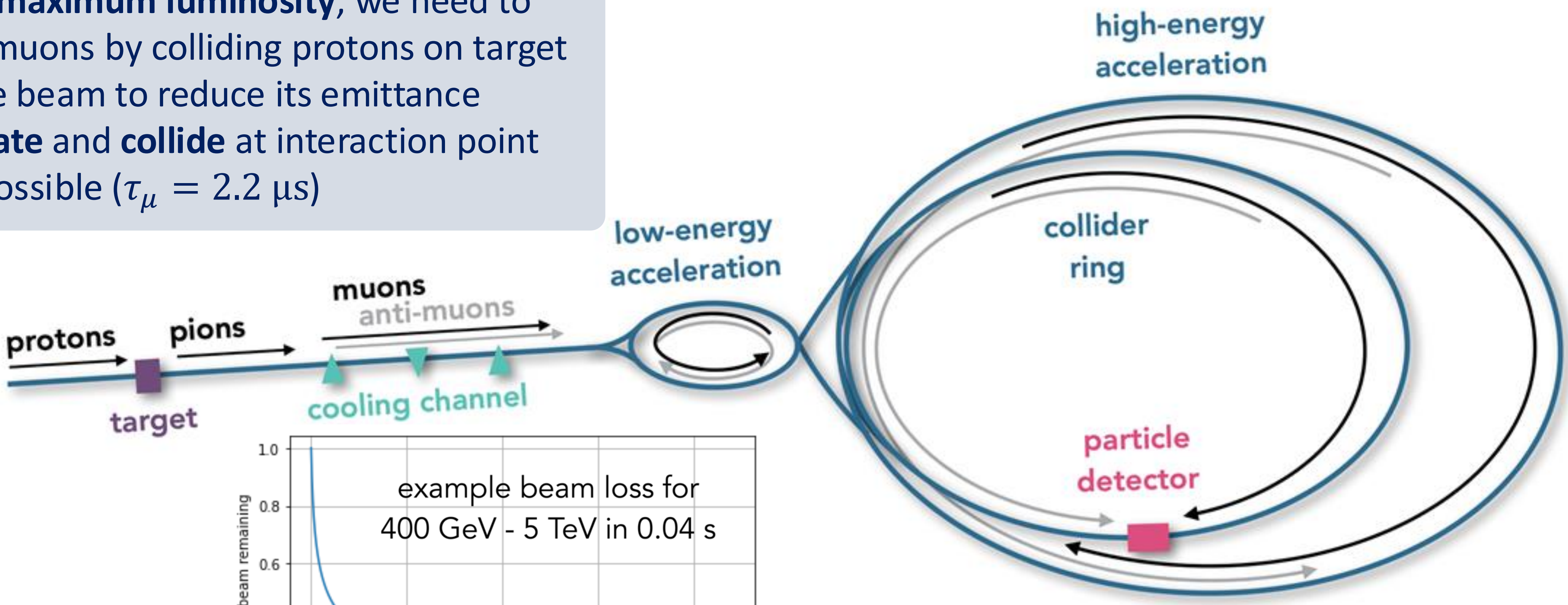
# Muon Collider design outline

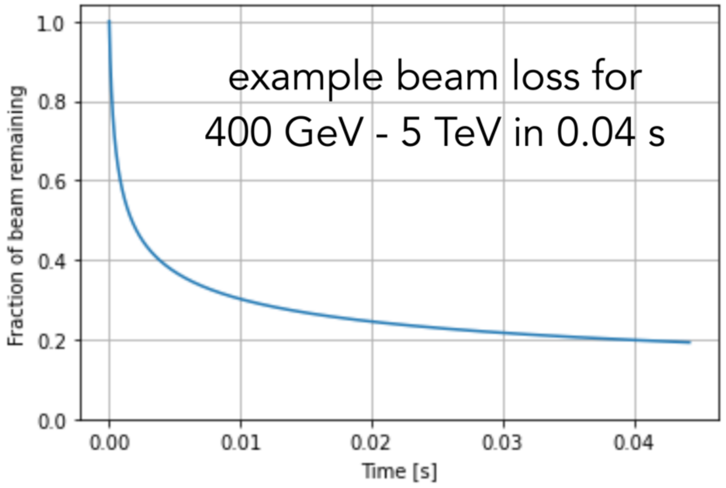
## Key steps

To achieve **maximum luminosity**, we need to

- **Create** muons by colliding protons on target
- **Cool** the beam to reduce its emittance
- **Accelerate** and **collide** at interaction point

as fast as possible ($\tau_\mu = 2.2\ \mu\text{s}$)



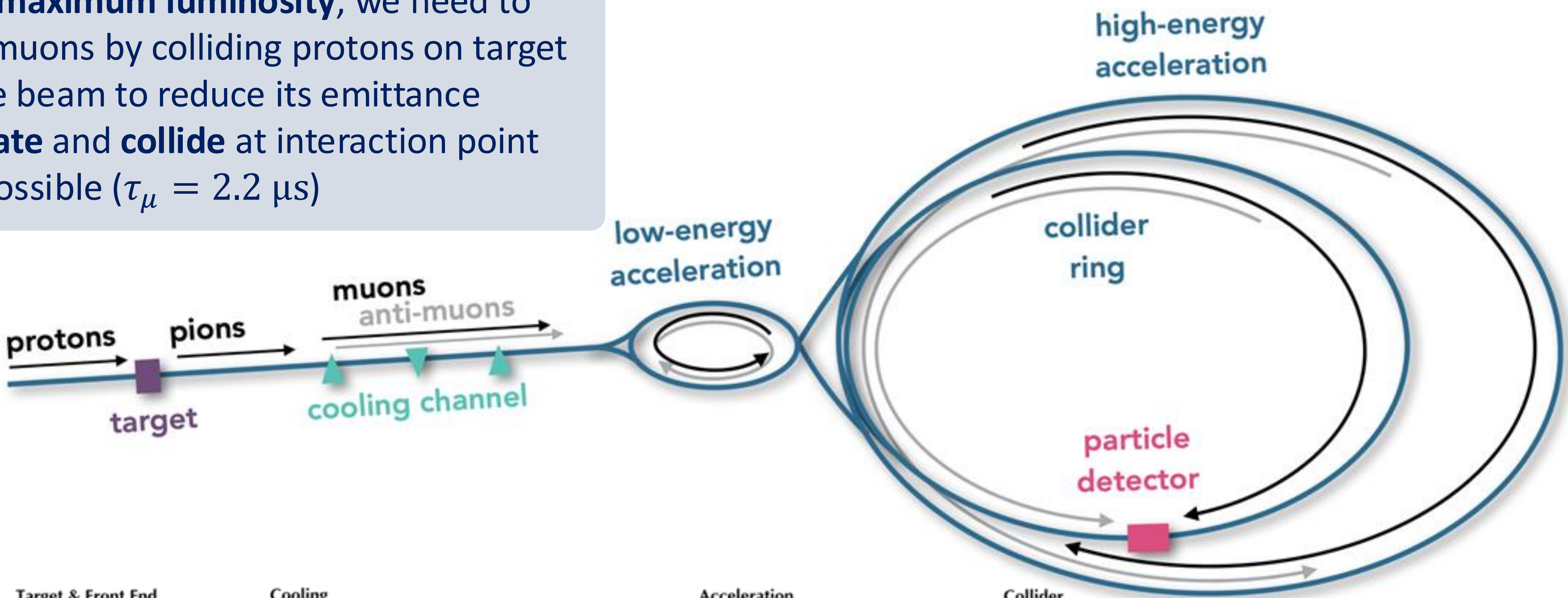



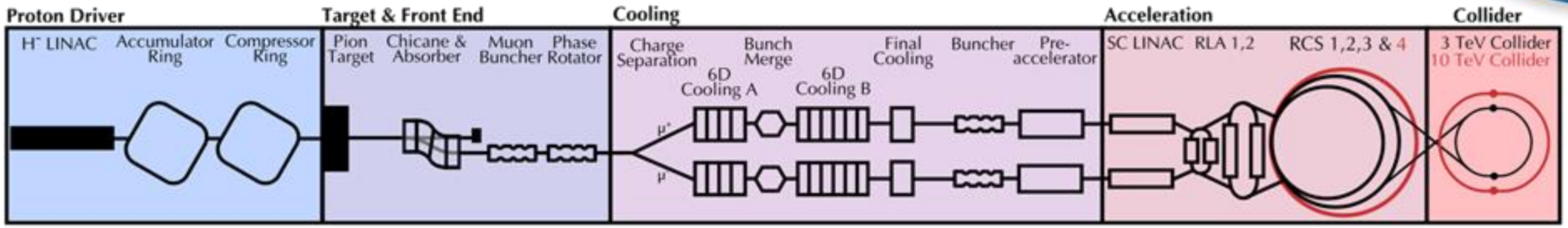
# Muon Collider design outline

## Key steps

To achieve **maximum luminosity**, we need to
- **Create** muons by colliding protons on target
- **Cool** the beam to reduce its emittance
- **Accelerate** and **collide** at interaction point

as fast as possible ($\tau_\mu = 2.2\ \mu s$)



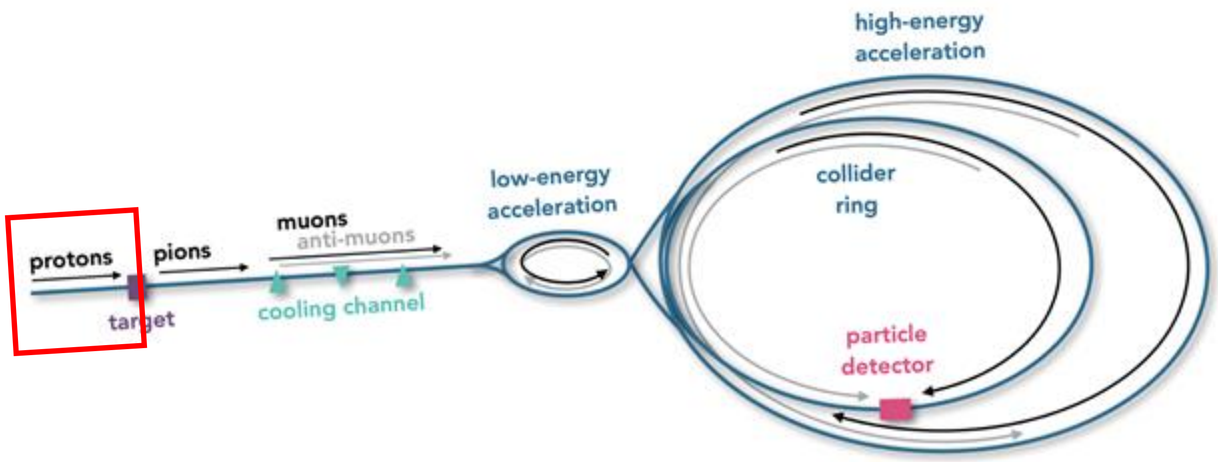



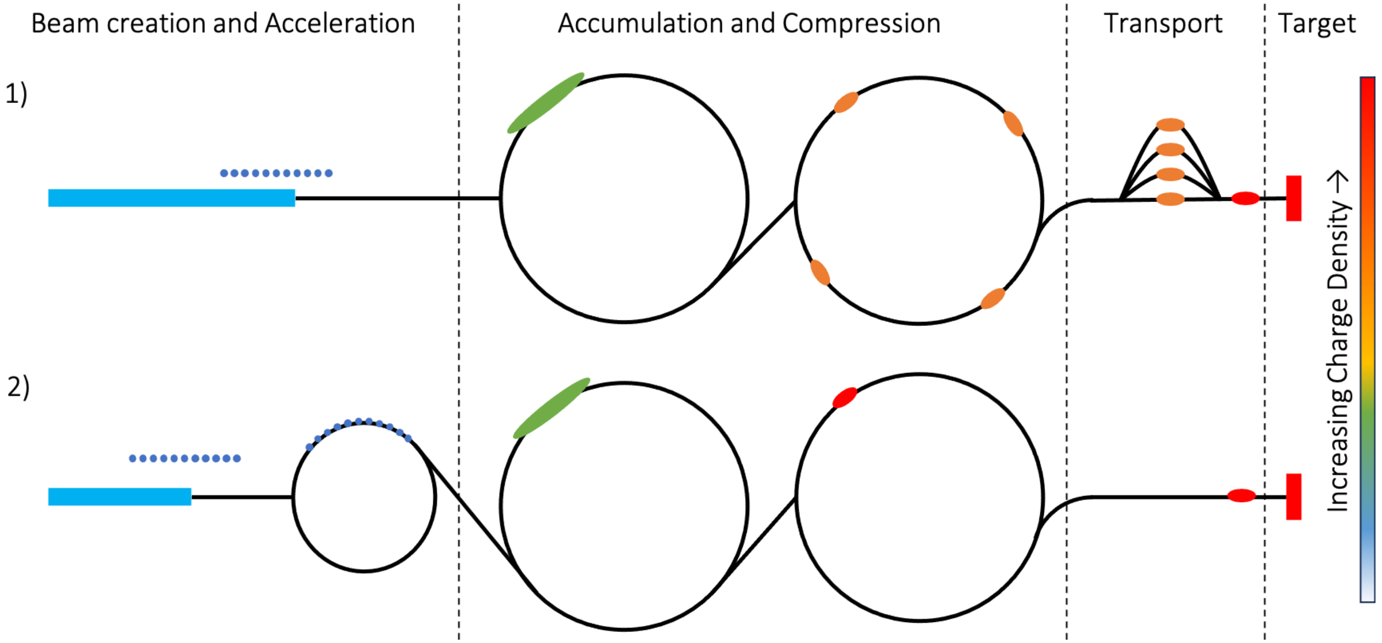
# Proton beam

## Goals

Proton beam characteristics constrains final yield

- Deliver **high number** of useful **protons**
- **Efficient** proton-to-muon **conversion**
- **Small** muon beam initial **emittance**



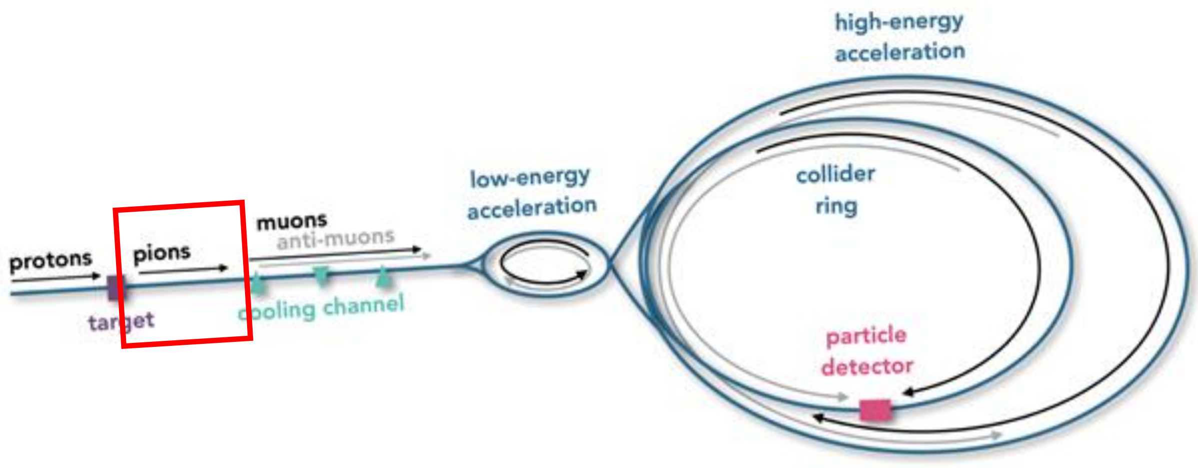

## Characteristics

- Power: $2 - 4$ MW
- $E_p = 5 - 15$ GeV
- Bunch length: $2 - 4$ ns

# Target

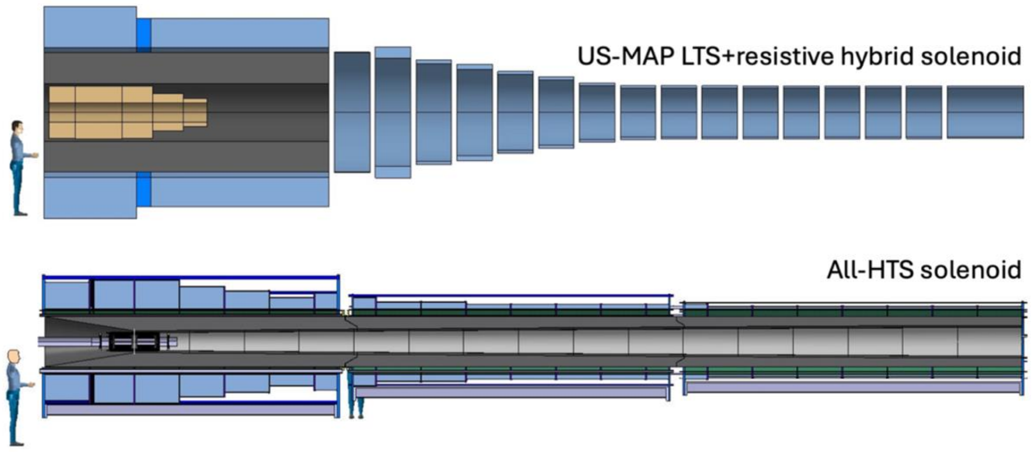
## Goals

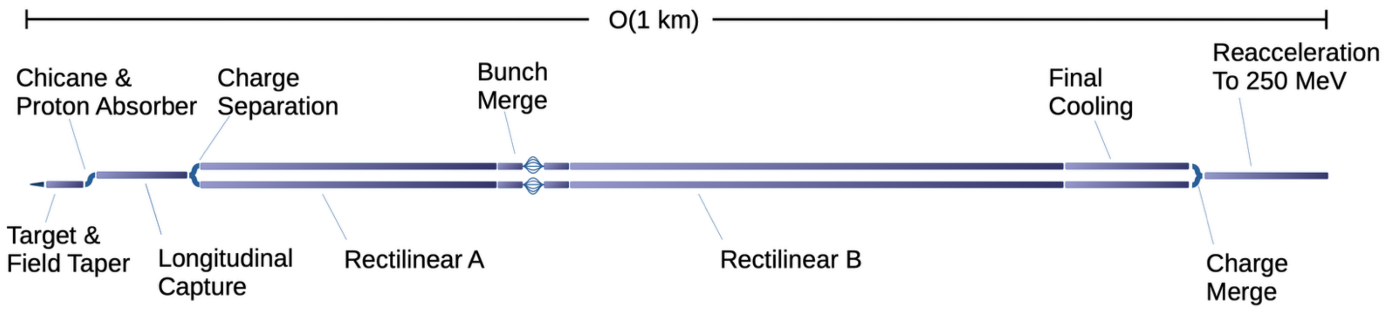
Provide a reliable way to produce pions
- **High density** target
- **Collect** as **many pions** as possible
- **Resist** high power **radiation damage**




## Characteristics

- Target material: Graphite
- Solenoid field: 20 T
- Solenoid radius: 0.7 m

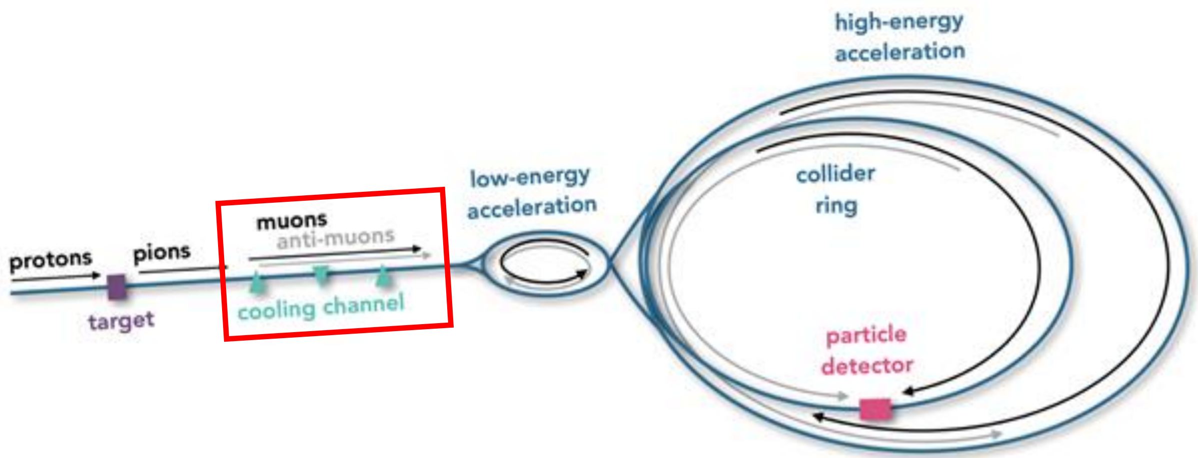


## Goals

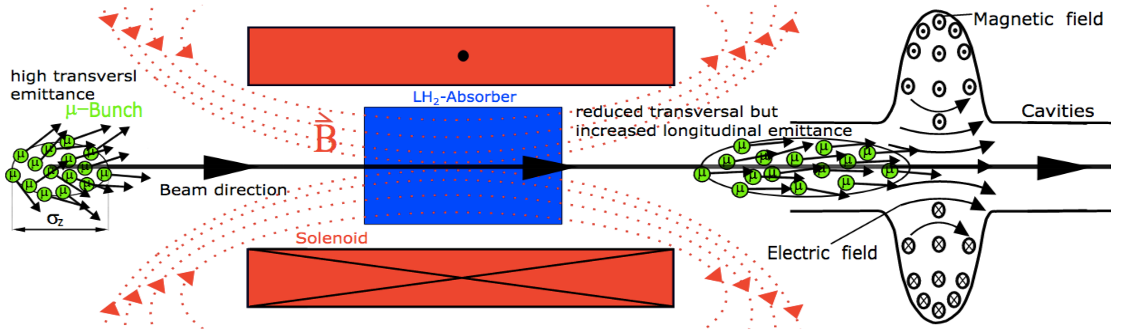
Luminosity depends on beam emittance

- **Reduce** muons phase space **emittance**
- Avoid loss of muon due to decays
- **Strong focusing** before acceleration phase



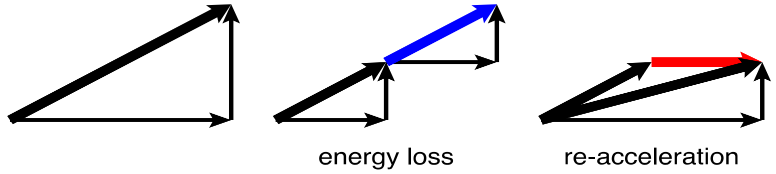

## Characteristics

- Absorber: $LH_2$
- Multiple [absorber + cavity] sections
- Solenoid field up to 40 T




Energy loss = cooling Multiple Scattering = Heating

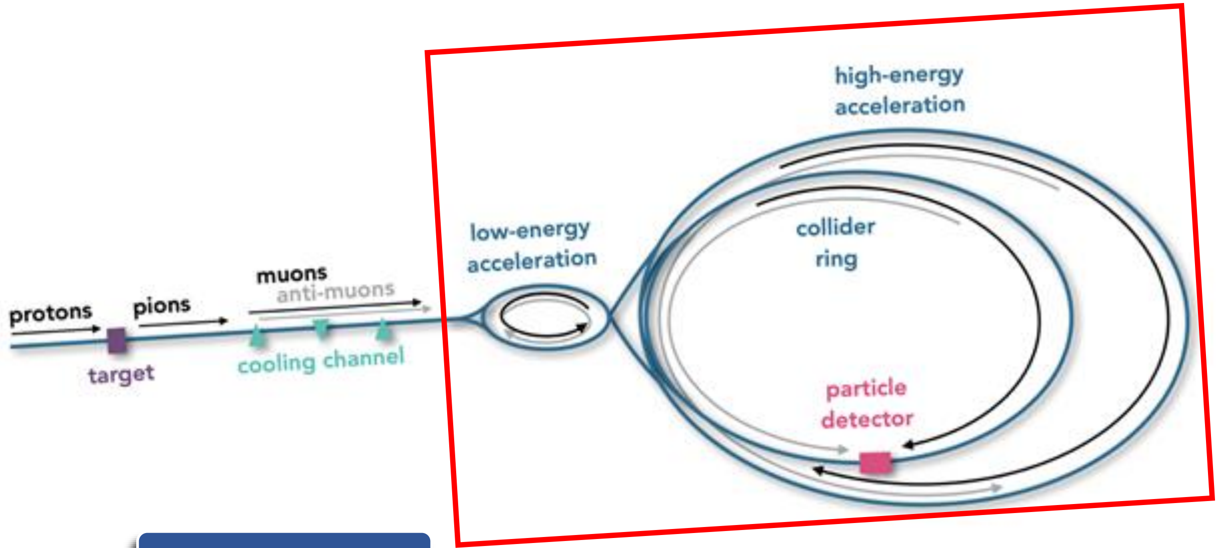
$$\frac{d\varepsilon_\perp}{ds} = \boxed{-\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\varepsilon_\perp}{E}} \boxed{+\frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\ \mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}}$$

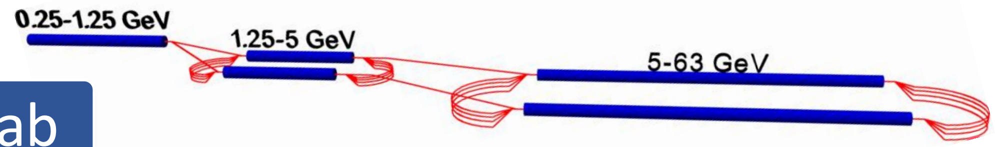


# Acceleration

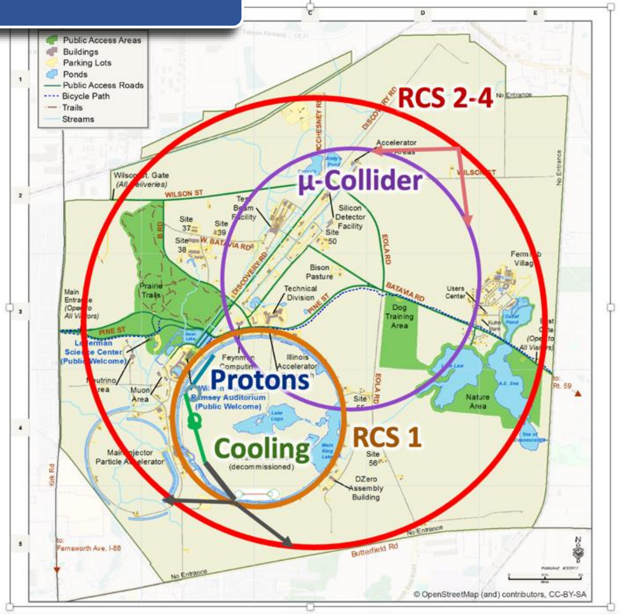
## Goals

Muons **decays decrease with energy**
- Increase **acceleration gradient**
- Low energy section: recirculating **linacs**
- High energy section: **rapid cycling synchrotrons**



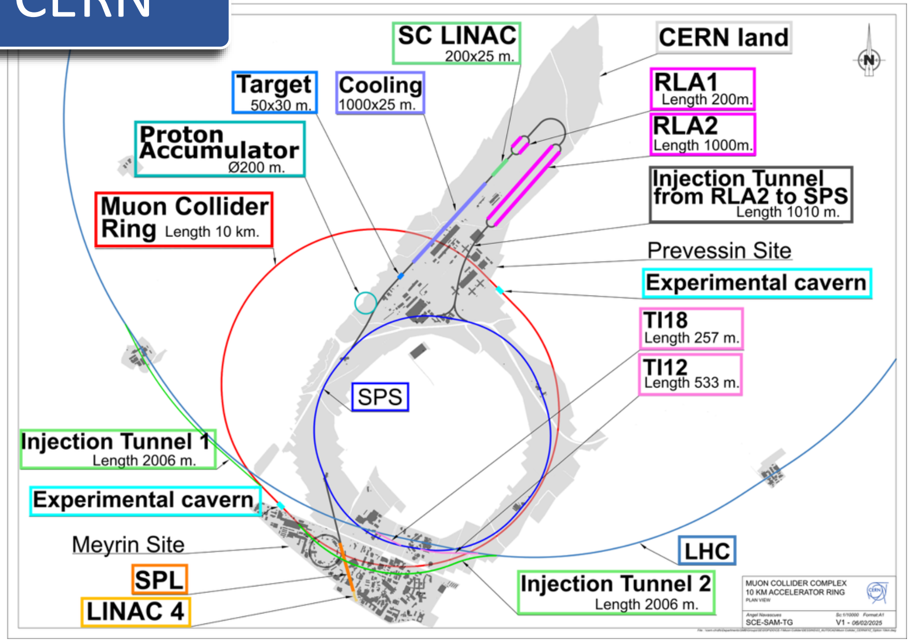

## Fermilab




## Characteristics

- Avg. Gradient: 2.4 MV/m
- Ramp rate: order of kT/s

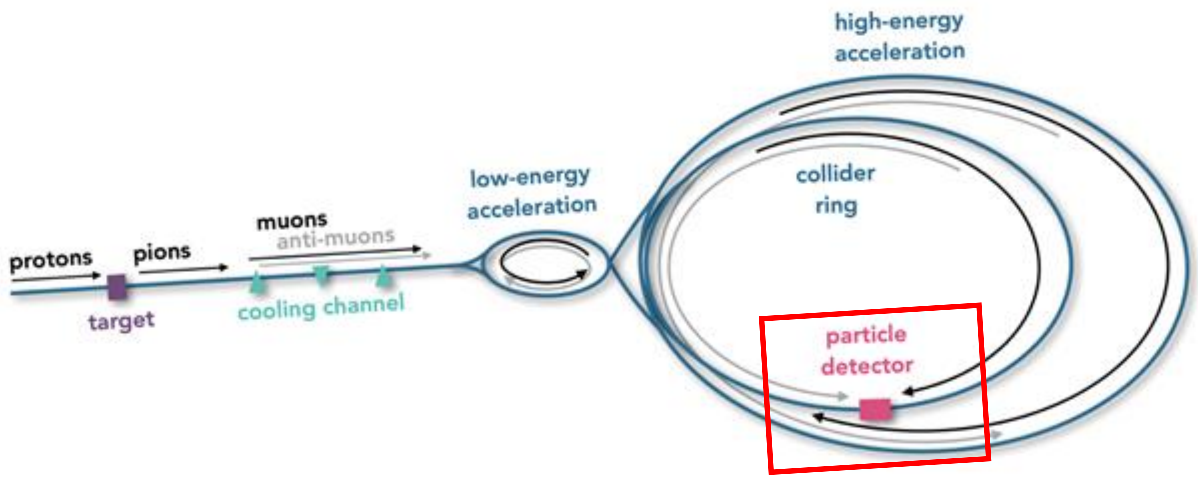
## CERN

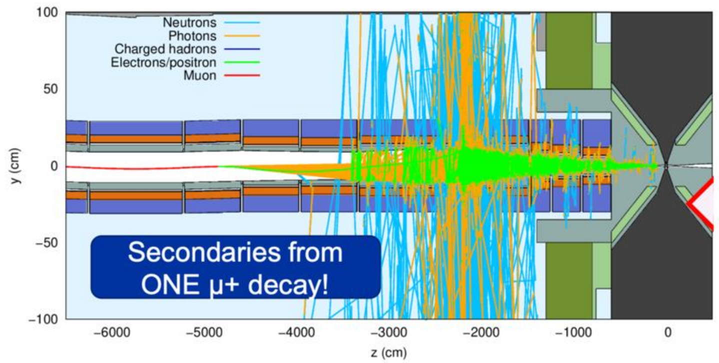


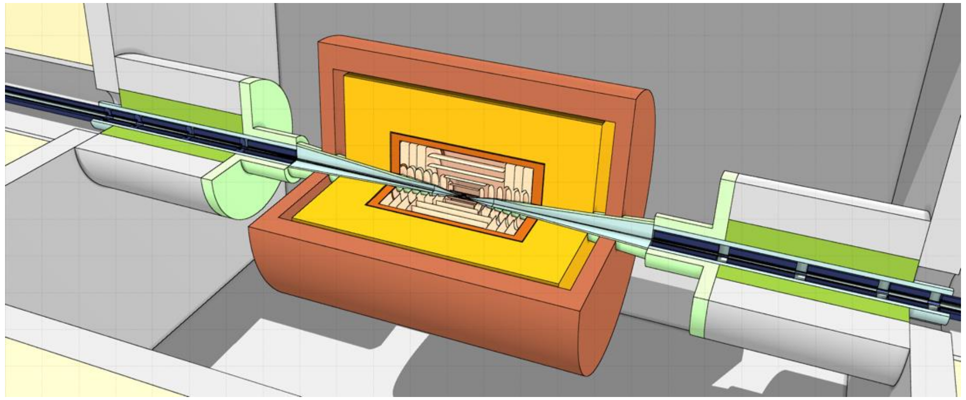
# Collision point

## Goals

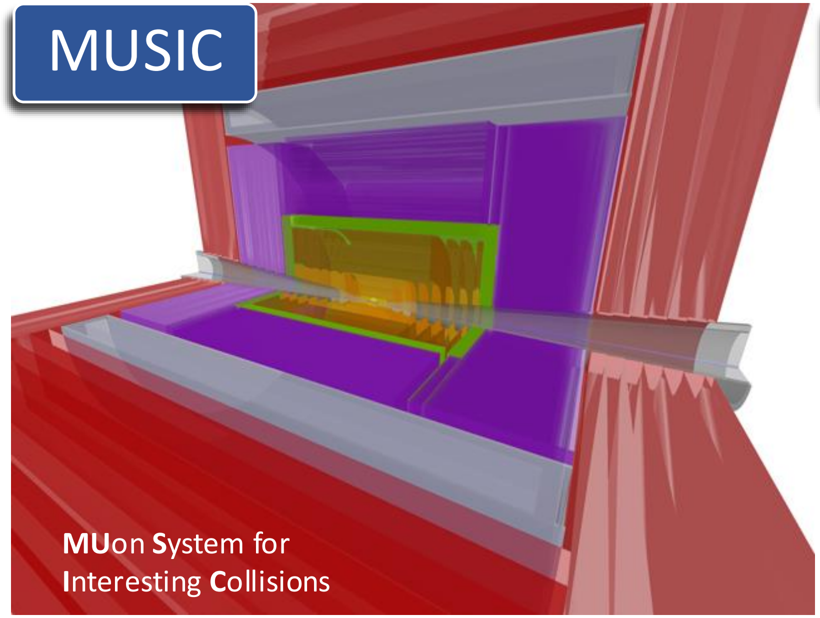
Minimize Beam Induced Background (BIB) effects
- High detector **granularity** to reduce occupancy
- High **timing precision** for B/S discrimination
- High tolerance for **radiation damage**



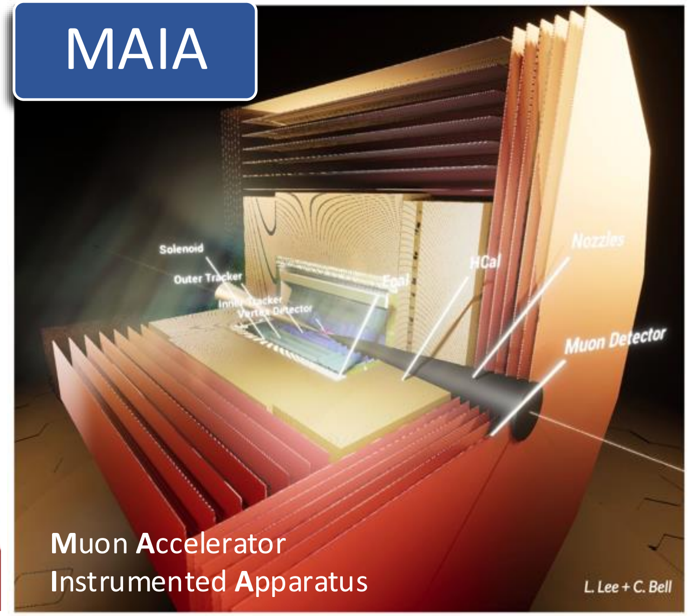



## MUSIC



**MU**on **S**ystem for **I**nteresting **C**ollisions

## MAIA

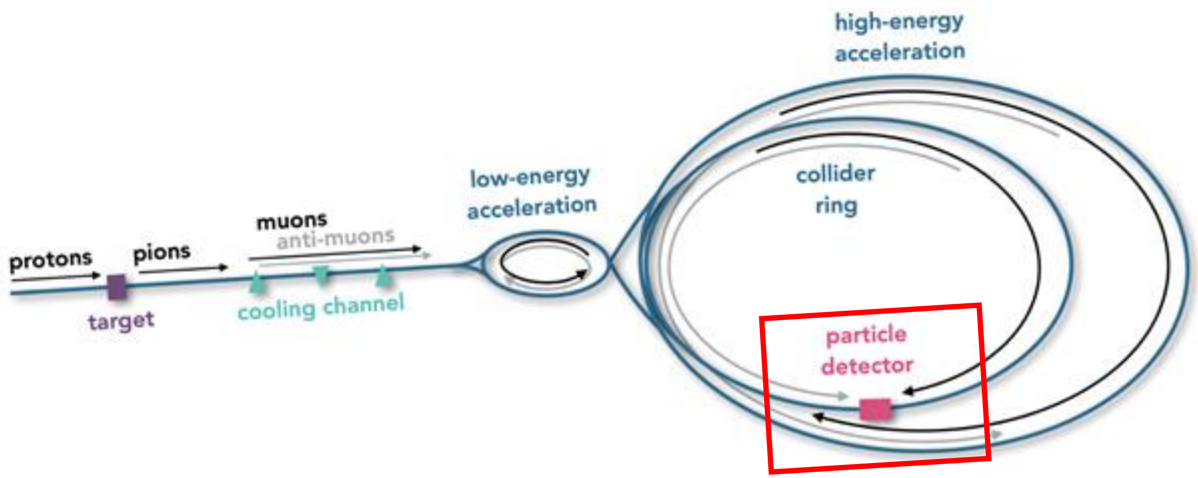


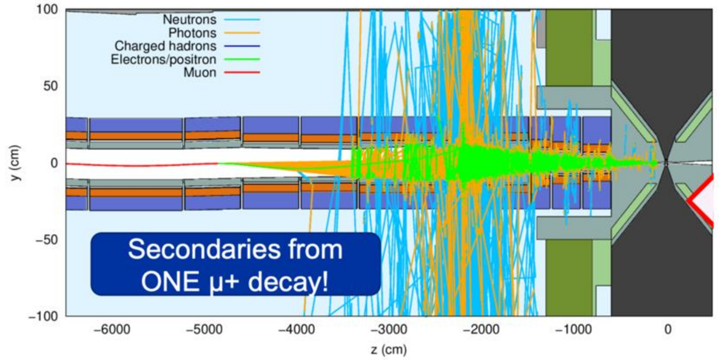

**M**uon **A**ccelerator **I**nstrumented **A**pparatus

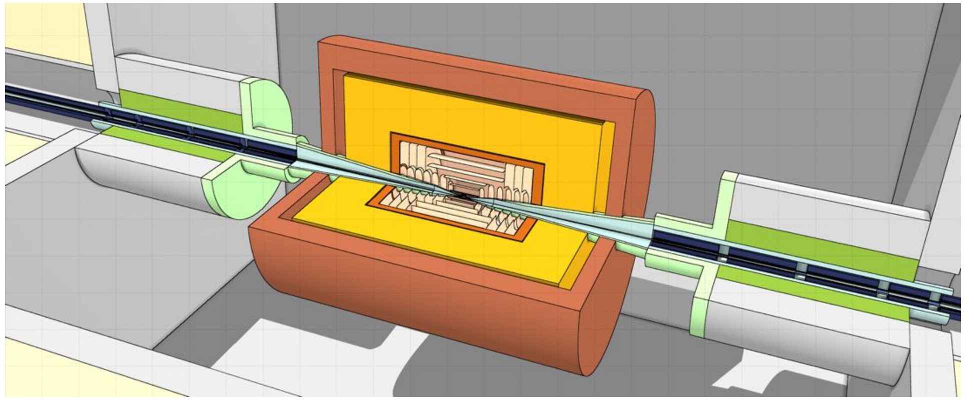
# Collision point

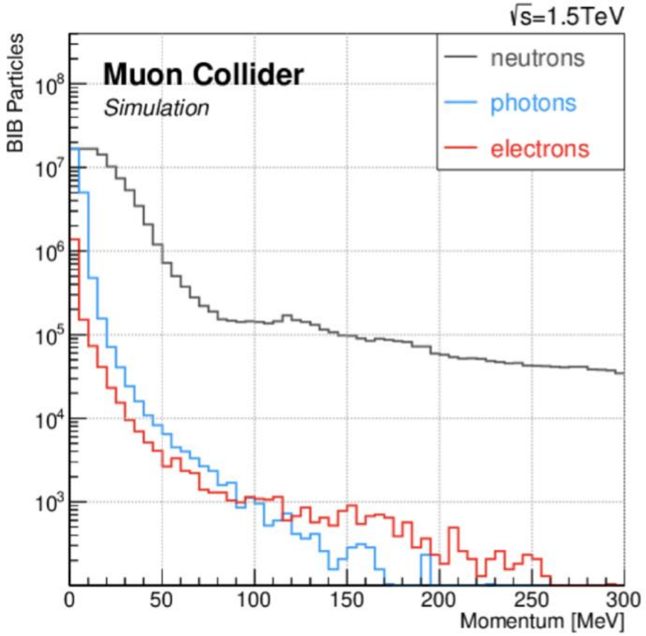
## Goals

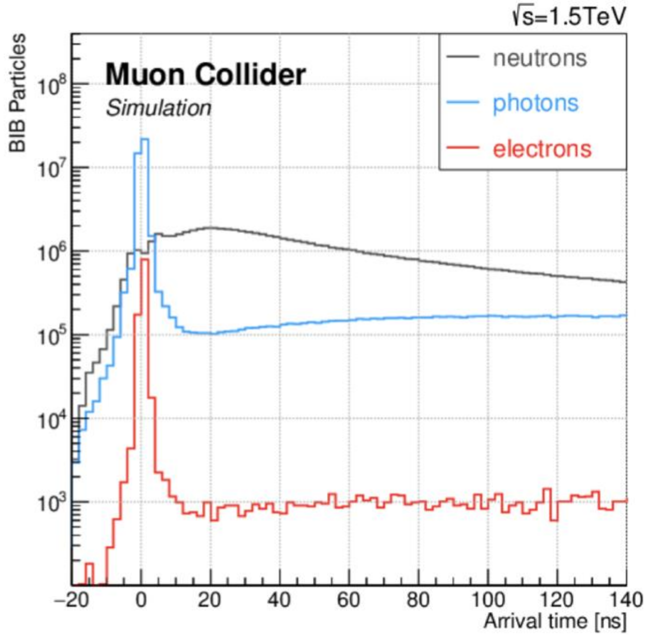
Minimize Beam Induced Background (BIB) effects
- High detector **granularity** to reduce occupancy
- High **timing precision** for B/S discrimination
- High tolerance for **radiation damage**





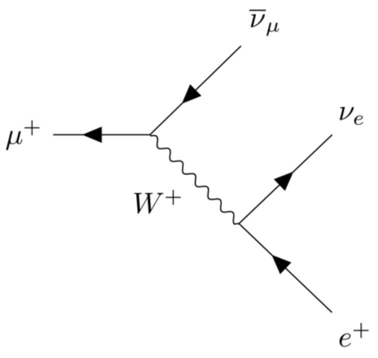



# Neutrinos

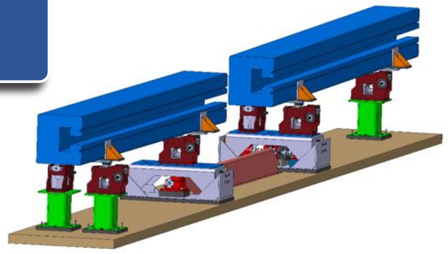
## Not just $\mu$

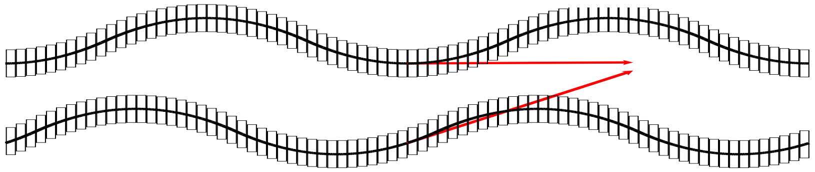
Muons decays produce a **high flux of neutrinos**

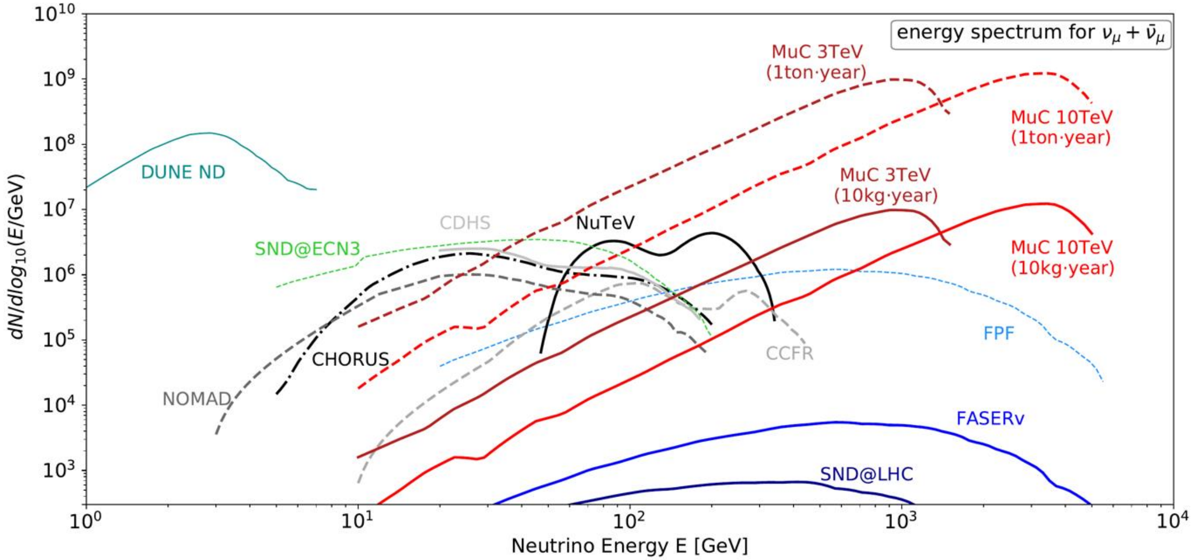
- Unprecedented **density** and **energy**
- Might create **environmental problems**
- Might lead to **new experiments** or spinoffs



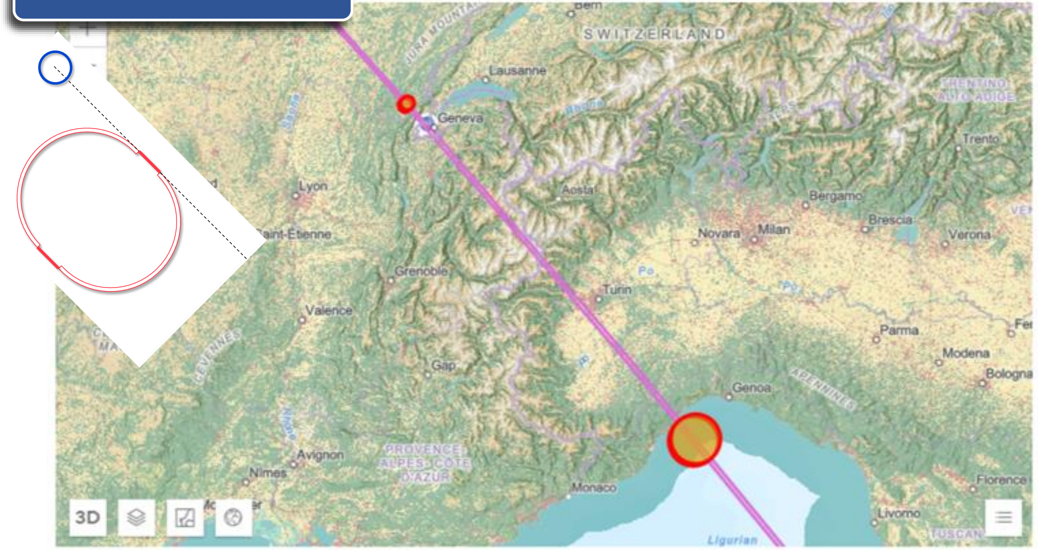

## Mover








## Placement



# Breaking News

21.10.2025

**Preliminary report of the ESG WG2a on Project Assessment**
**(17/10/25)**

G. Arduini (co-convener), F. Bordry (co-opted accelerator expert), R. Brinkmann (co-opted accelerator expert), P. Burrows (co-convener), K. Desch, S. Farrington, F. Gianotti, K. Hanagaki, N. Holtkamp (co-opted accelerator expert), J. Keintzel (scientific secretary), B. Kilminster, T. Lesiak, L. Rivkin (co-opted accelerator expert), F. Sabatié, M. Tuts, A. Zoccoli.

The overall assessment of the Large-Scale Projects is based on the information made available by the proponents either in their formal submissions to the 2026 update of the European Strategy for Particle Physics (ESPP) or in their replies to our questions and, in some cases, during dedicated discussions with them. It refers therefore to the present status of the respective projects. Below we summarize briefly the preliminary key findings for the projects in alphabetical order.

**MC**

Among the large-scale collider proposals submitted to the ESPP2026, the Muon Collider (MC), together with the FCC-hh, promises a potentially energy-efficient path toward high-luminosity collisions at a parton centre-of-momentum energy of 10 TeV. However, the MC has not yet reached the level of maturity of the other proposals.

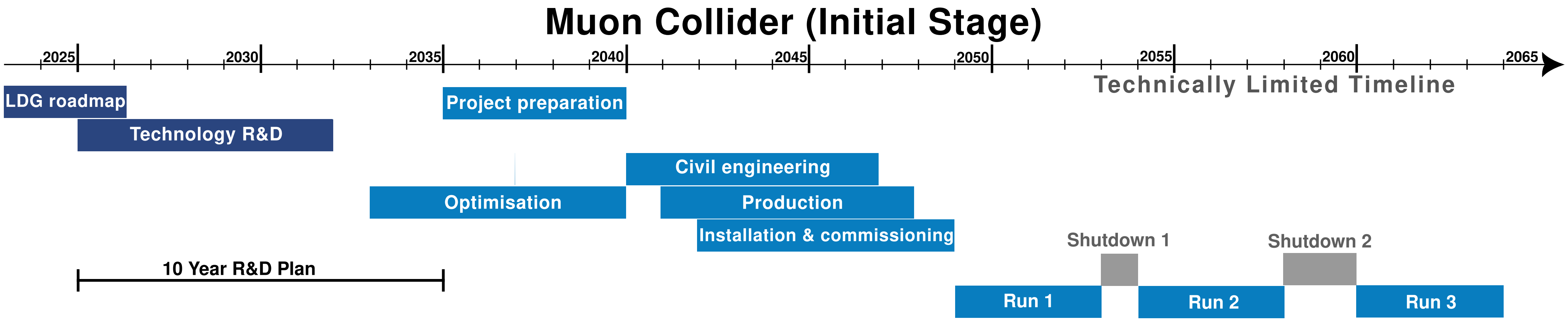
[…]

The technologies underpinning the MC design are in the early phases of exploration. A comprehensive R&D roadmap has been developed with the 6D-cooling demonstration facility as its cornerstone. 300 MCHF and 1800 FTEy over ten years (320 MCHF and 2700 FTEy including the experiments) represent the absolute minimum investment necessary to achieve the R&D programme.

[…]

Among the risks identified, the ionizing radiation generated at distance by the large neutrino flux resulting from muon decays is an issue and potential showstopper that needs to be addressed for any selected location and in particular for those close to populated areas as the CERN site.

# Conclusions




## Key takeaways:

- **Muon colliders** represent a **promising next-generation technology**
- They combine the **advantages of both $e^+e^-$ and $pp$** colliders, enabling:
  - **High-precision measurements** of fundamental parameters
  - **Discovery potential** at the energy frontier
- Offer excellent **power efficiency** and intrinsically **high luminosity**
- Present **strong synergies** with other fields, such as **neutrino physics** and accelerator R&D
- The **short muon lifetime** remains the main technical challenge, **requiring advanced innovation**
- These challenges are **achievable**, with potential valuable **technological spin-offs**

# References


1. T. Han, Y. Ma, K. Xie, *"High energy leptonic collisions and electroweak parton distribution functions"*, [PRD.103.L031301]
2. International Muon Collider Collaboration, C. Accettura et al., "*Towards a muon collider*", [2303.08533]
3. International Muon Collider Collaboration, C. Accettura et al., "*The Muon Collider*", [2504.21417]
4. S. Gourlay, T. Raubenheimer, V. Shiltsev et al., "*Snowmass'21 Accelerator Frontier Report*", [2209.14136]
5. International Muon Collider Collaboration, C. Accettura et al., "*Interim report for the International Muon Collider Collaboration (IMCC)*", [2407.12450]
6. D. Schulte, Open Symposium on the European Strategy for Particle Physics, "Muon Collider", [INDICO]
7. I. Ojalvo, INFIERI 2005 International Summer School, "*A high energy, 3-10 TeV, muon collider*", [INDICO]

# Thank you for your attention