International
MUON Collider
Collaboration

MuCol: a new Muon Collider initiative for Europe

Lund Science Coffee seminar

PRESENTED BY NATALIA MILAS

2022-09-05

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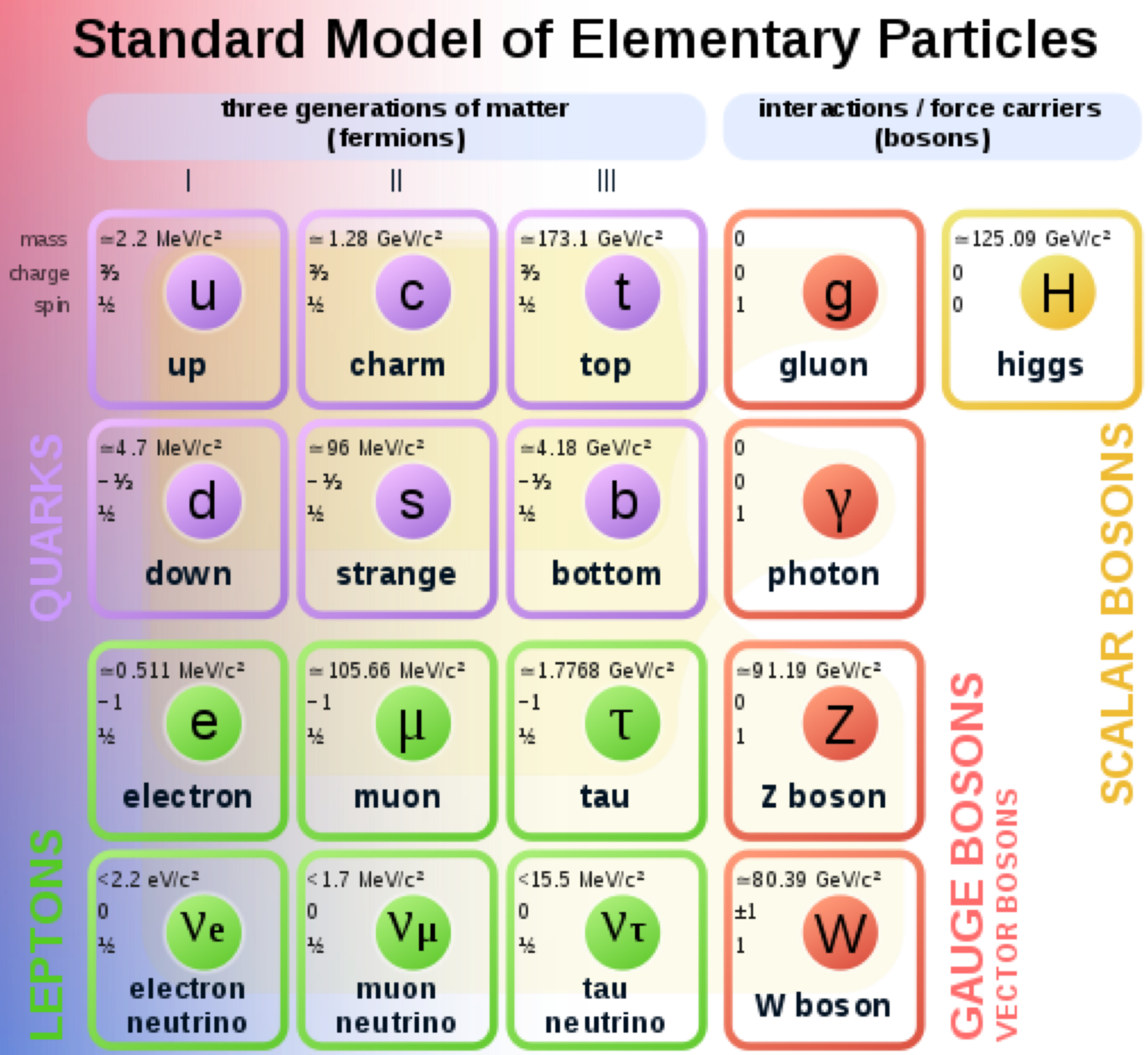
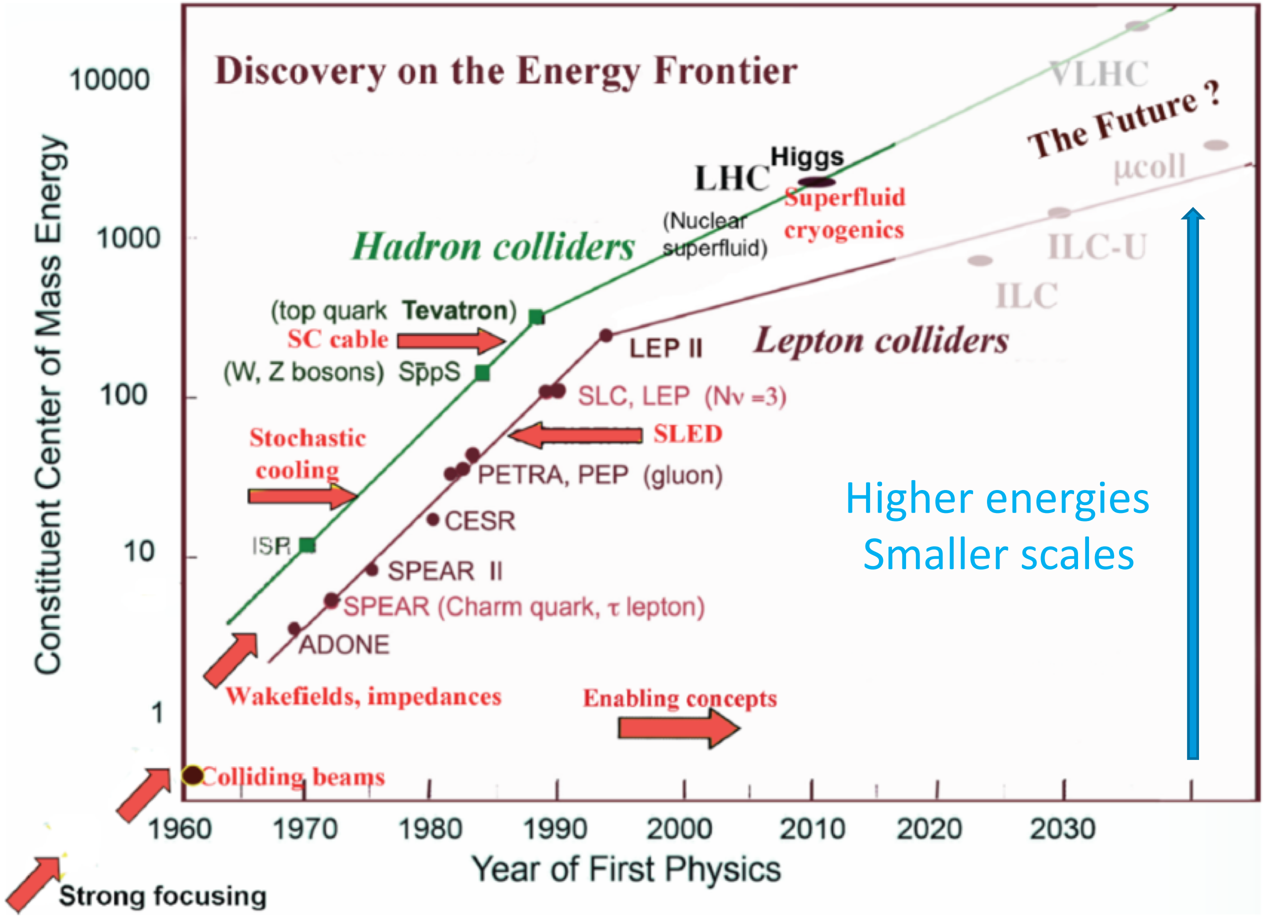
Why Muons?

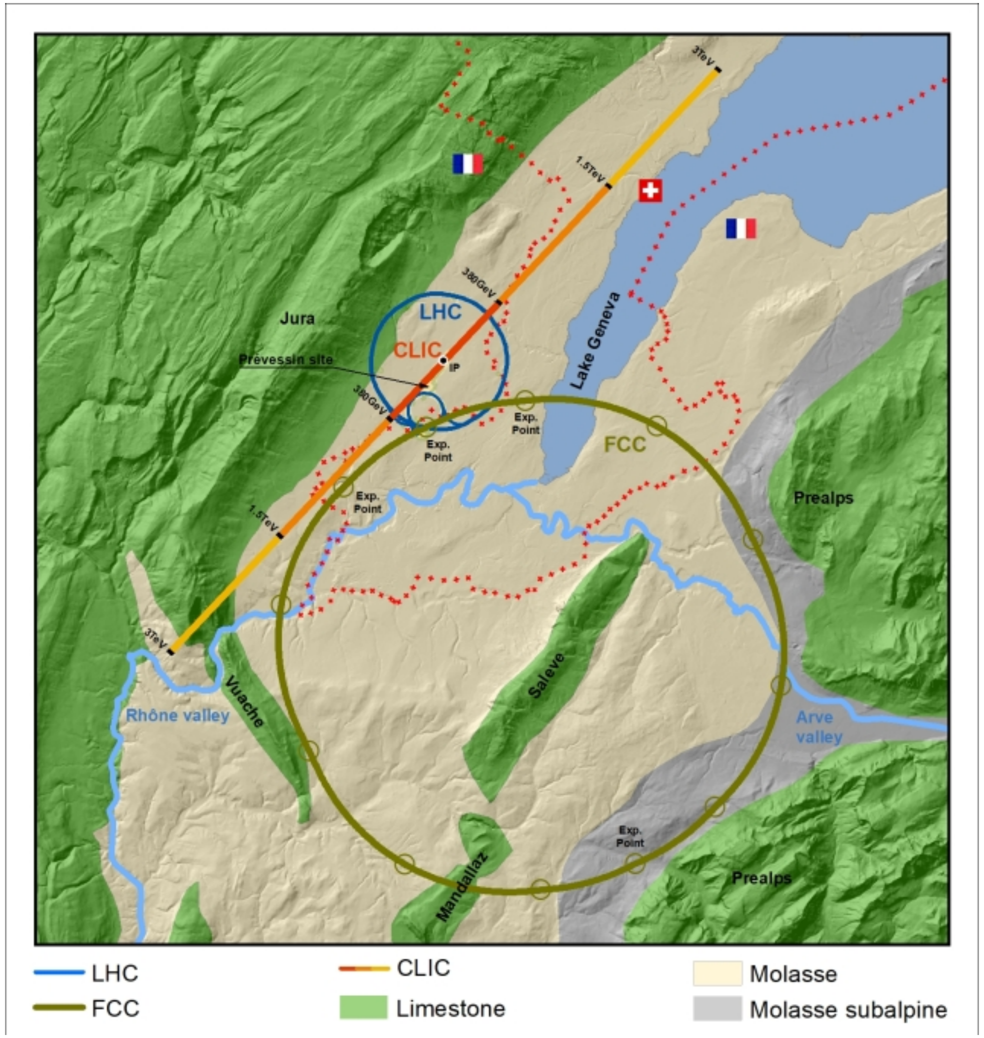

Standard Model of Elementary Particles
three generations of matter (fermions)
interactions / force carriers (bosons)
I
II
III
mass
charge
spin
≈2.2 MeV/c²
⅔
½
u
up
≈1.28 GeV/c²
⅔
½
c
charm
≈173.1 GeV/c²
⅔
½
t
top
0
0
1
g
gluon
≈125.09 GeV/c²
0
0
H
higgs
≈4.7 MeV/c²
−⅓
½
d
down
≈96 MeV/c²
−⅓
½
s
strange
≈4.18 GeV/c²
−⅓
½
b
bottom
0
0
1
γ
photon
≈0.511 MeV/c²
−1
½
e
electron
≈105.66 MeV/c²
−1
½
μ
muon
≈1.7768 GeV/c²
−1
½
τ
tau
≈91.19 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
½
νe
electron neutrino
<1.7 MeV/c²
0
½
νμ
muon neutrino
<15.5 MeV/c²
0
½
ντ
tau neutrino
≈80.39 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS

What limits a collider energy?



- Hadron (proton) colliders are limited by bending magnetic field
  - This limits the bending radius -> tunnel length
- Electron rings are limited by Synchrotron radiation
  - Synchrotron radiation is much stronger for low mass particles
- Electron linacs are limited by available acceleration
  - Cannot accelerate electrons without extremelly long tunnels

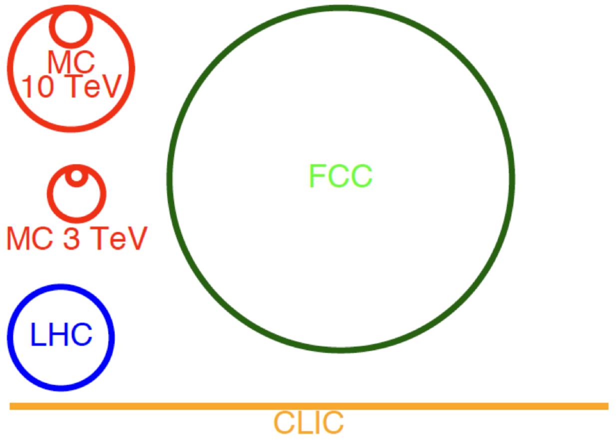
Example of Colliders



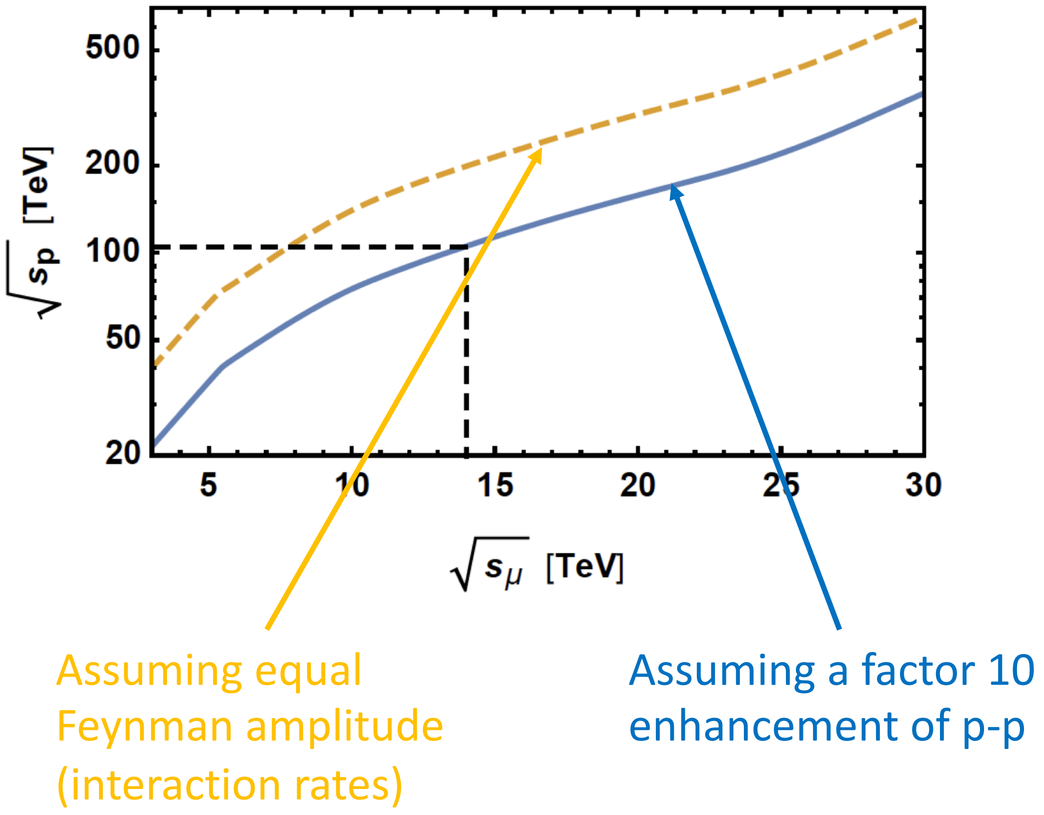
- LEP/LHC:
  - 14 TeV proton-proton (LHC)
  - 209 GeV for electron-position (LEP)
  - 27 km circumference
- FCC (proposed):
  - 90-350 GeV for electron-position
  - 100 TeV for proton-proton
  - 100 km circumference
- CLIC (proposed)
  - 500 GeV (3 TeV) for electron-position
  - 11 (50.1) km

Advantages of using Muons

- Proton collisions have a lot of "wasted energy"
  - More energy available for the collision since muons are elementary particles
- $m_\mu = 200\ m_e$ this mitigates the radiation issues since power dissipated in synchrotron radiation $\propto 1/m^4$



Energy at which the cross-section is equal



https://muoncollider.web.cern.ch/introduction

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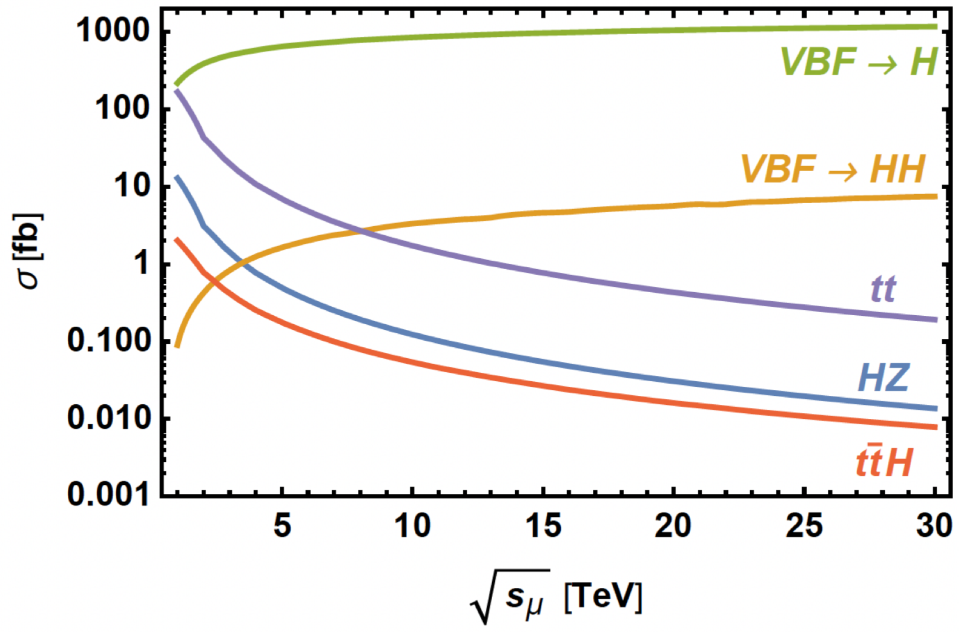
Physics Case Behind the Muon Collider

What can be done with the Muons ?

An accelerator physicist view

- Because of lack of breamstrahlung a muon collider can have a small energy spread thus allowing precision measurements of mass width.
- **Direct exploration** on several beyond-the-SM questions:
  - search extensively for new particles coupled with the Higgs boson,
  - Dark matter
- As well as probe **New Physics** indirectly:
  - some of the key processes for Higgs physics, have very large cross-sections and a muon collider might allow a satisfactory program of Higgs couplings determination.



- The decay of the stored muons lead to a neutrino flux about 1000 times the ones presently available.
  - Neutrino oscillations and other interesting neutrino physics.

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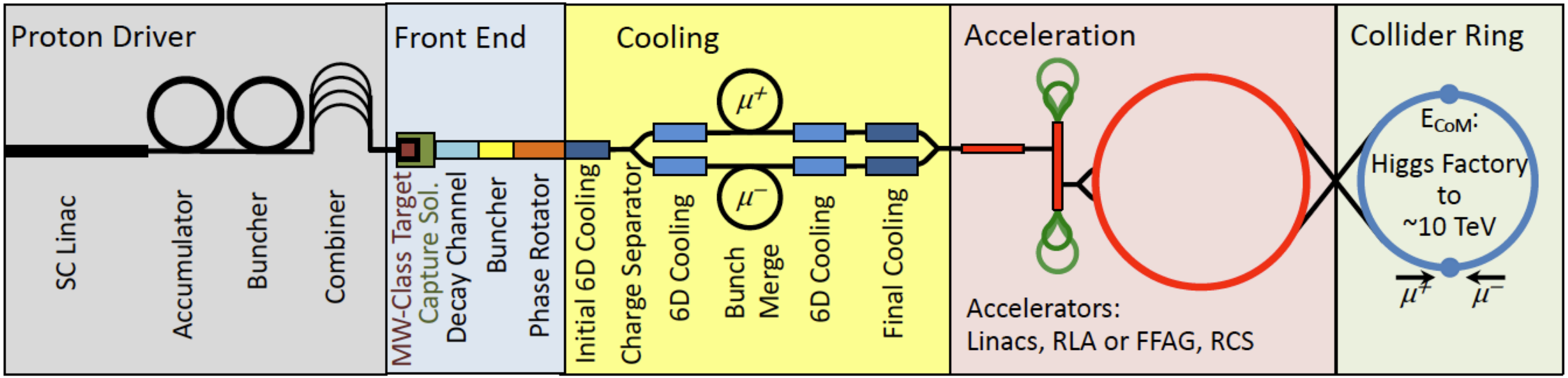
Main components of a Muon Collider

“Maybe we need different types of clubs for different types of situations.”

A Muon Collider in a nutshell

Building Blocks

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2\ \mu s$



Short and intense proton bunch

Protons produce pions which decay into muons
muons are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

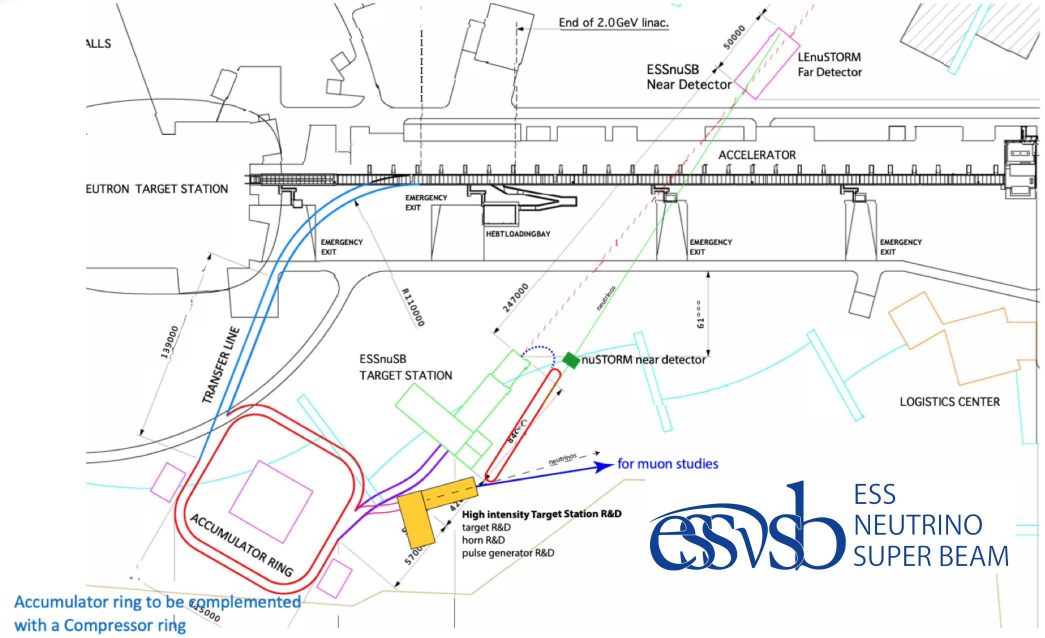
Collision!

Creation of short and intense proton bunch

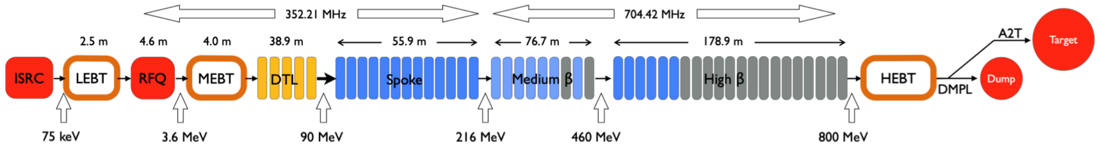
- Parameters are driven by the main collider.
- Latest parameters (MuCol): 2MW, 5Hz with a possible upgrade to 5 MW.
- 10^{14} -10^{15} protons per bunch
- 1 ns bunch length at the Target

} O(kA) peak current

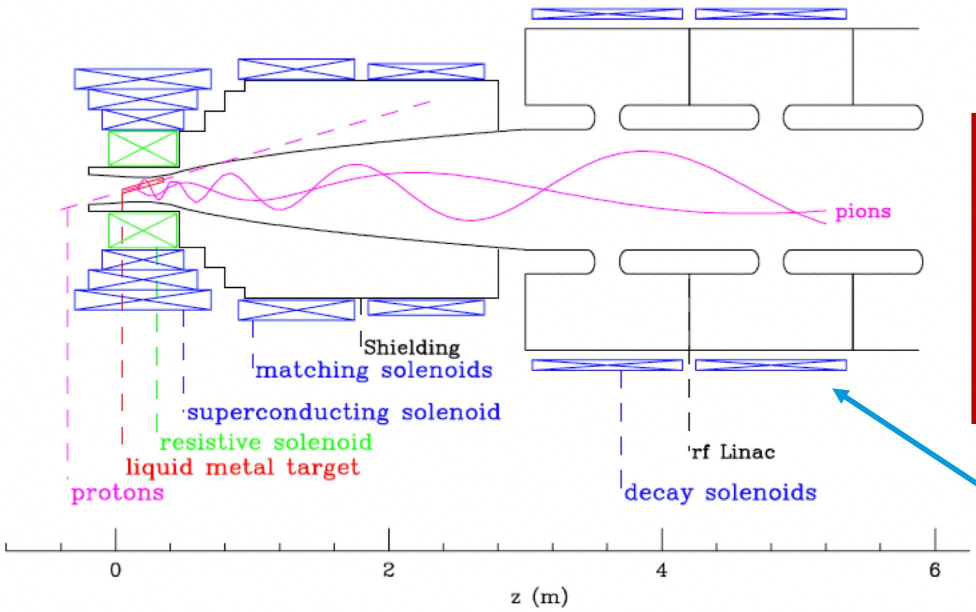
In order to meet the Muon requirements:
- Increase the current **and/or**
- Increase the Pulse length **and/or**
- Increase the energy



Protons to the target:
- 5 MW
- 1 us pulse
- About 10^{13} protons per pulse
- 14 Hz rep rate
- 2.5 GeV

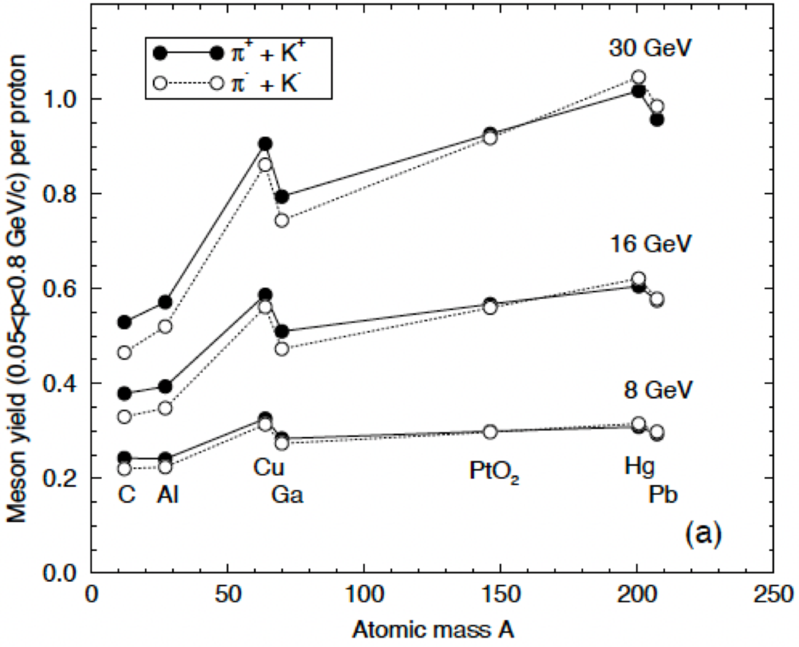


Pion production and capture



Solenoids:
- 15 T fields
- large aperture

Sinergies with **ITER**



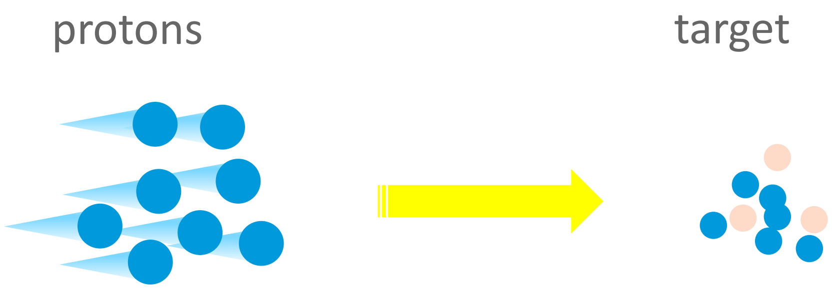
- The high muon beam intensity for the collisions requires a very high efficiency pion/muon capture
- We aim at colliding ¾ of the muons that are cooled.
- However estimates show that only ¼ of the muons survive the capture and cooling.

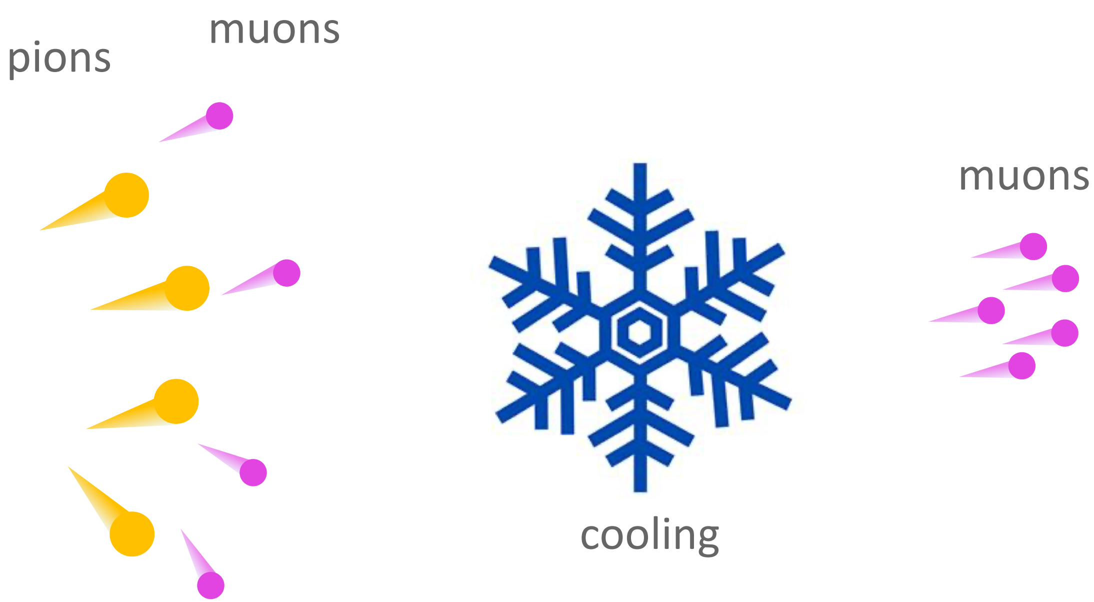
Phase rotation linac

The pions (and muons) created in the collision of protons with the target have an rms energy spread of 100% and mean energy of 100 MeV.

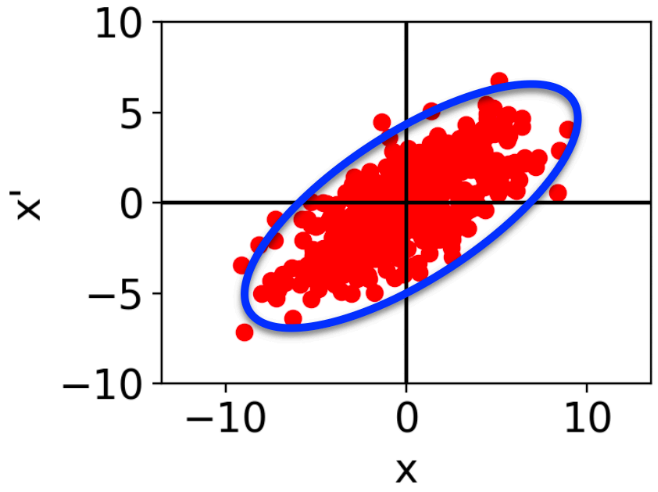
Phys.Rev STAB, vol 2, 081001 (1999)

Why cooling is needed?





- An orderly beam of protons
- Pions leave the target in many directions
- Pions decay also in many different directions



- Low Brightness beam
- High Emittance beam

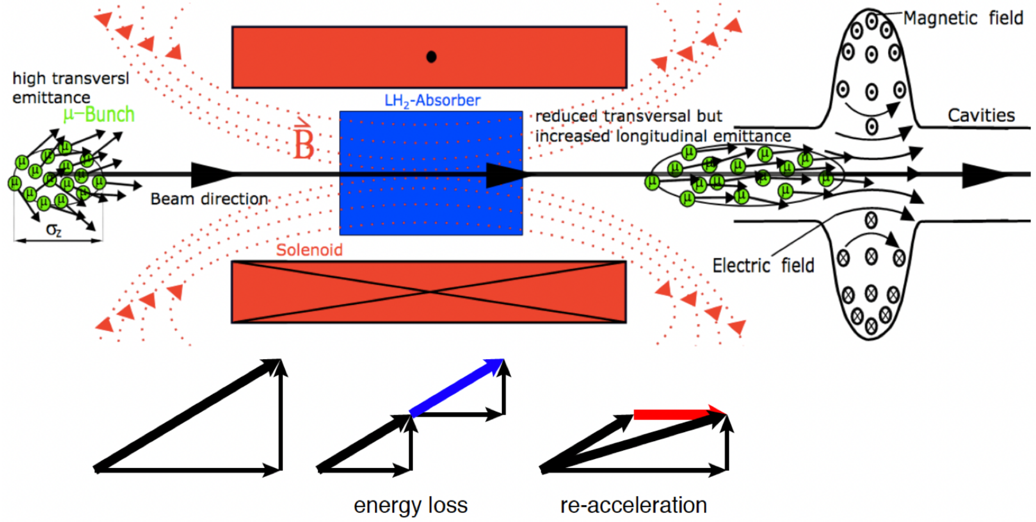
Muon cooling

Cooling must happen in a time scale compatible with the muon lifetime.

- Electron cooling : overlap the beam with another with matching emittance and transfer the “heat” from one to another
- Stochastics cooling: Measured the beam profiles and have a set of correctors to shrink it

Too slow for Muons

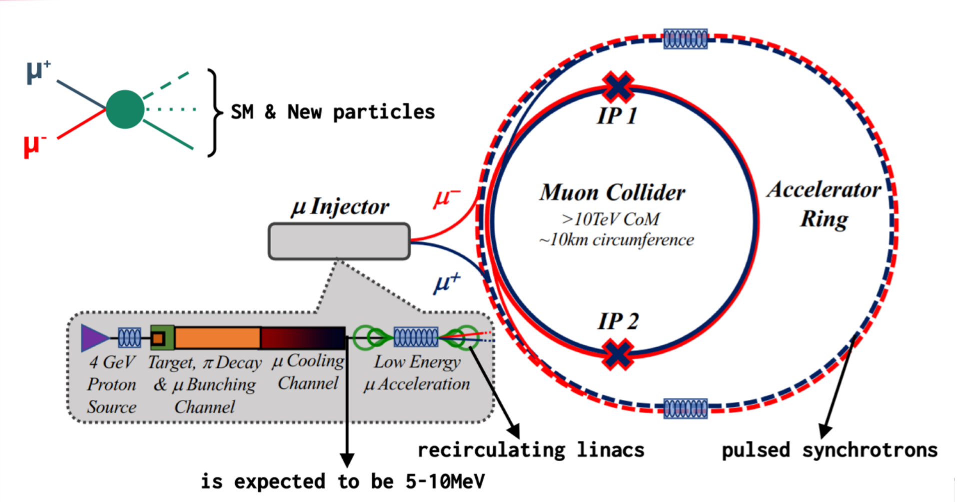
- Ionisation cooling: Uses the fact that muon weak interaction with matter. Pass the beam through a material which causes energy losses through ionization (transverse and longitudinal). Replenishes the longitudinal part using RF -> Effective reduction of transverse momenta.
- For the longitudinal plane cooling -> have a trajectory that is energy dependent and shape the ionisation material as wedges -> higher energy particles loose more energy



$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu L_R}$$

cooling scattering

Acceleration and collision



Muons will decays into electrons and neutrinos inside the collider. Where all those particles end and what is the effect over machine components and beyond?

- **Acceleration:**
  - Crucial to be as fast as possible up to ~100 GeV because of the muon decay time
  - Muon energy of cooling channels is ~ 10 MeV -> linacs are more efficient (recirculating linacs are options)
  - Latter FFAs or RCS are more efficient.
  - Likely the most expensive part of the complex.
- **Collider**:
  - Receives 2 bunches of particles, a μ^+ and a μ^- one.
  - Mainy constraints to be able to deliver the required luminosity.
    - IR with extremelly low β^* of a few cm (for the 3 TeV case)
    - Acceptable dynamic aperture
    - Strong instability effects (high charge and small bunch length). But in this case the Muon decay my be a blessing…

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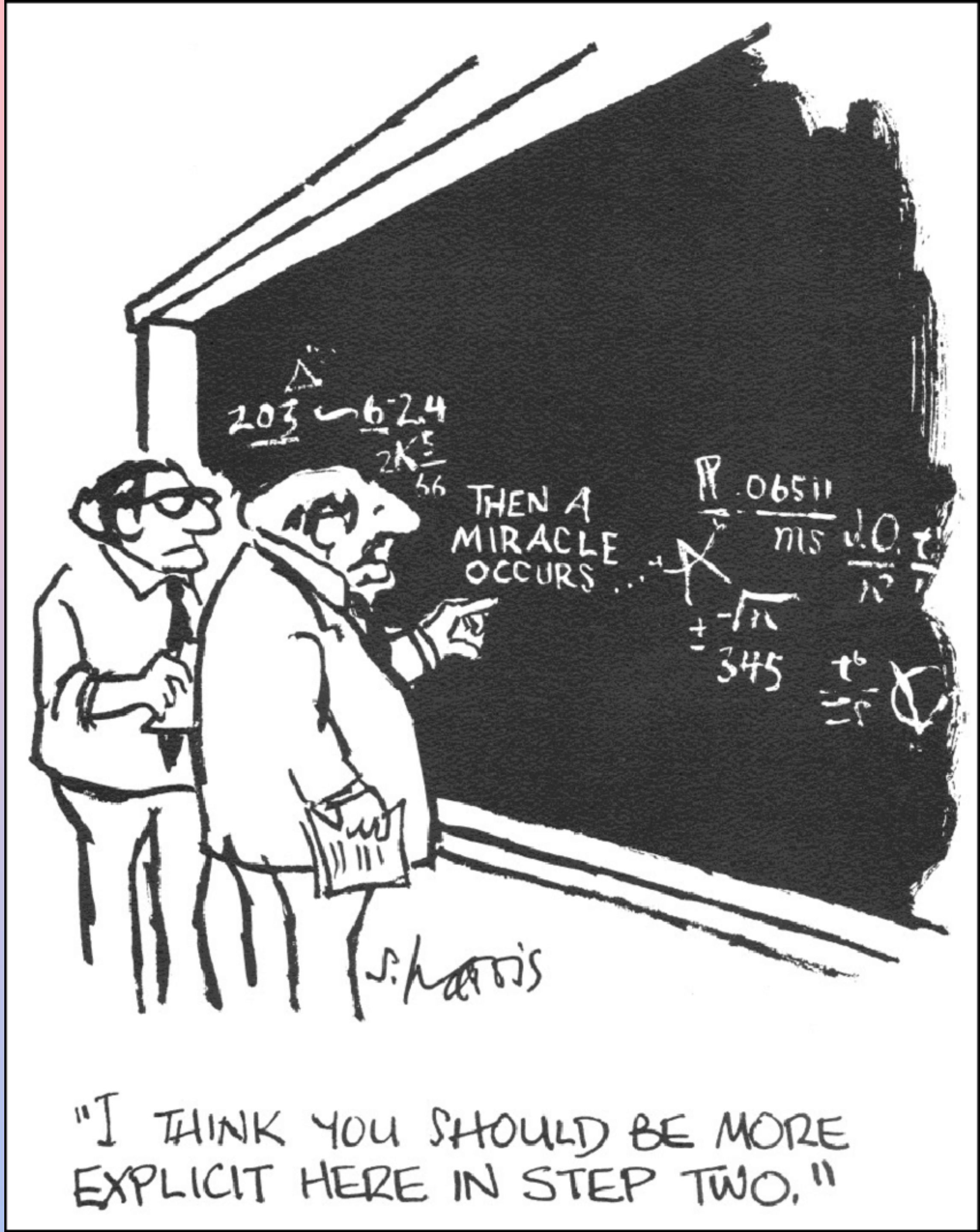
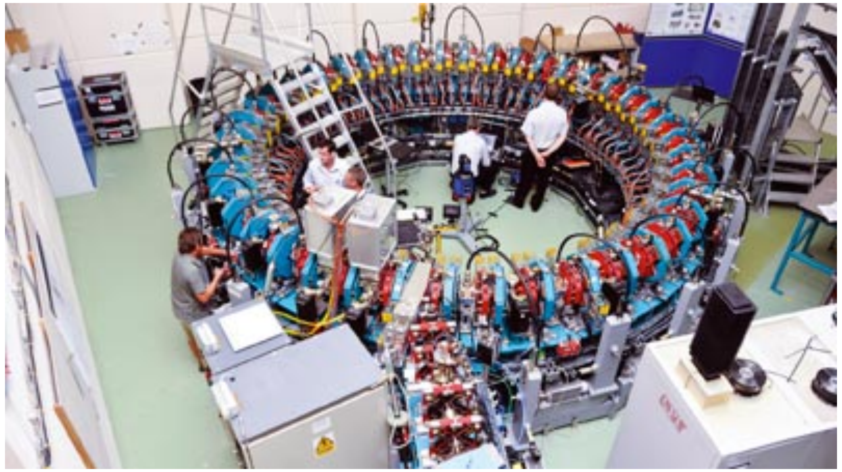
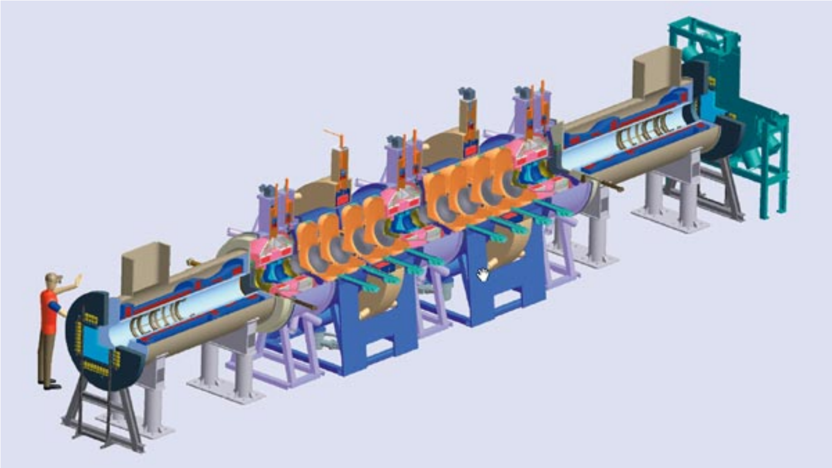
What are the challenges?



Muon R&D in the last decade

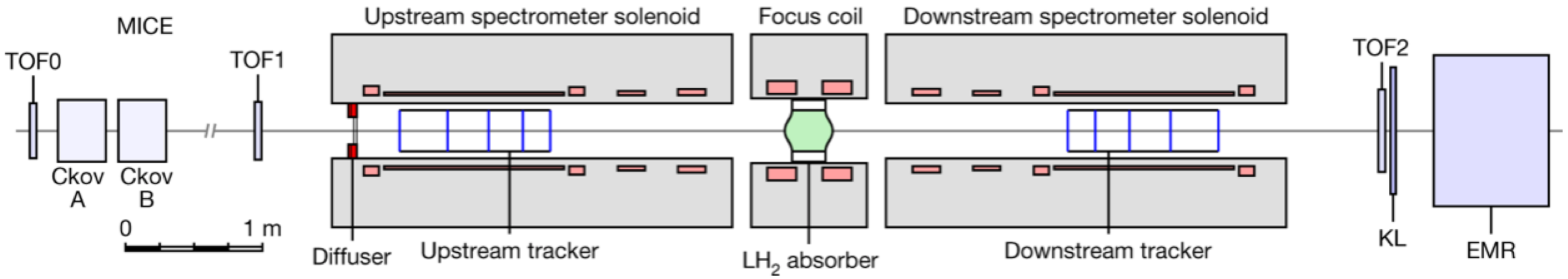
- MERIT:
  - Demonstrated principles of pion production in solenoid fields
- EMMA:
  - Demonstrated acceleration in FFAs
- MUCOOL:
  - Radio-frequency accelerating cavities R&D
  - Demonstrated operation of cavities at high gradient inside strong magnetic fields
    - Breakdown suppression using high pressure gas
    - Careful RF coupler design and cleaning
- Muon Ionization Cooling Experiment (MICE)
  - Need to increase the beam brightness
  - Proof-of-principle of Ionization cooling



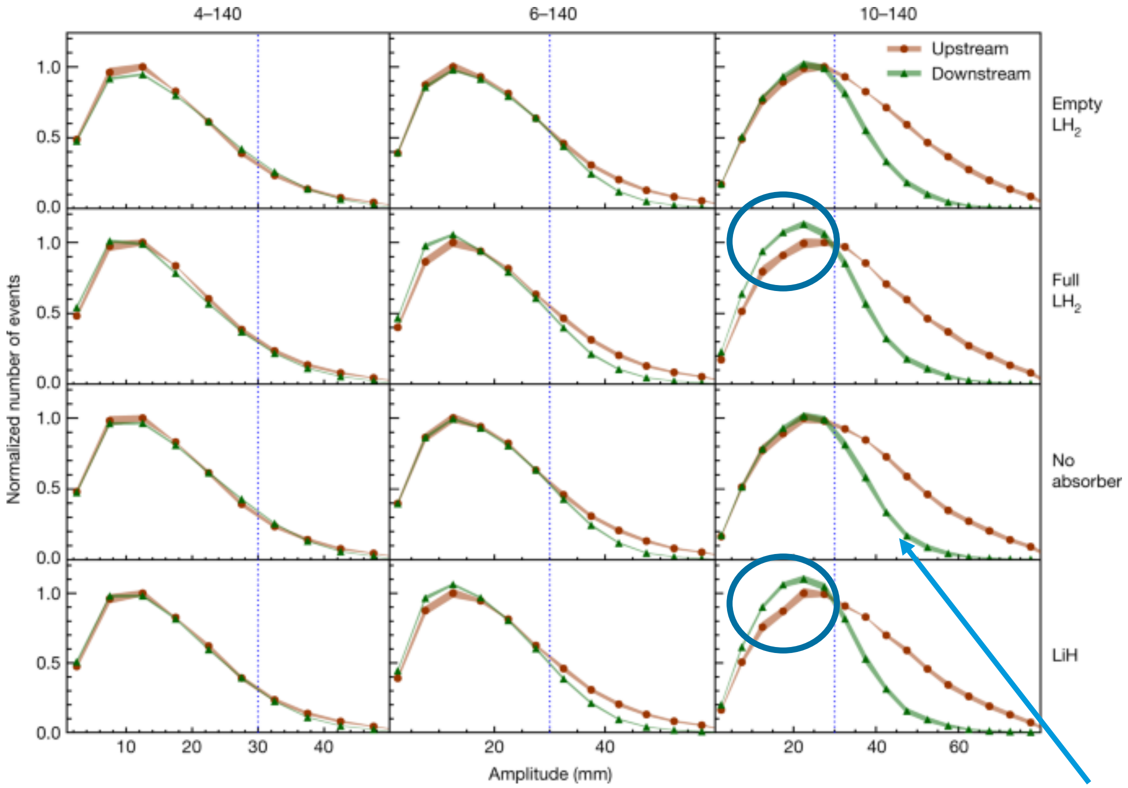


The MICE experiment

MICE Collaboration 2020 *Nature* **578** 53



Beam emittance → larger



Particles loss (only)

- Curves are build ups of single muons measurements
- The increase on muons in the core indicate that there is cooling
- Simulations and measurements agree very well which is important for the next stages modeling
- MICE only explored a fraction of the cooling needed for a Muon Collider
  - Recycles cooling -> RINGS

The Neutrino problem

arXiv:hep-ex/0005006v1 3 May 2000

Neutrino radiation and detector background

The radiation hazard arises from the showers of penetrating charged particles produced through neutrino interactions with any material bathed by the neutrino radiation disk.

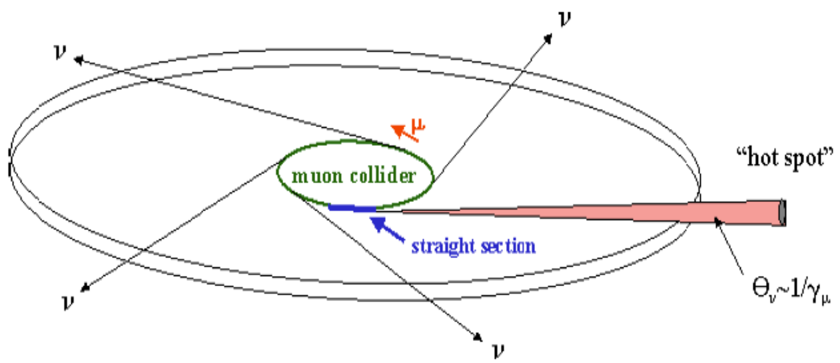


FIGURE 1. The decays of muons in a muon collider will produce a neutrino radiation disk emanating out tangentially from the collider ring. Radiation hot spots in the disk will occur directly downstream from straight sections in the collider ring.

Table 1: Radial distance, R, from the ring center with center-of-mass energy, $\sqrt{s}$, and depth, d, needed to reduce neutrino-induced dose at surface to DOE (100 mrem) and Fermilab (10 mrem) annual off-site limits at N_D decays/yr.

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

center of mass energy, E_{CoM}	0.1	4 TeV	10 TeV	100 TeV
additional description	H^0 factory	"lite"	2^{nd} gen.	3^{rd} gen.
collider luminosity, $\mathcal{L}$ [$cm^{-2}.s^{-1}$]	1×10^{31}	6×10^{33}	1×10^{36}	1×10^{36}
collider int. lum., $\int \mathcal{L}$ [fb^{-1}/yr]	0.1	60	10 000	10 000
muon beam energy, E_μ [TeV]	0.05	2	5	50
muon decays/yr, N_μ^+ [10^{20}]	6	0.08	8	0.4
collider reference depth, d [m]	10	300	100	100
ν beam distance to surface, L [km]	11	62	36	36
ν beam radius at surface [m]	24	3.3	0.8	0.08
ave. rad. dose in plane [mSv/yr]	2×10^{-5}	5×10^{-4}	2.3	10
str. sec. len. for 10x ave. rad. [m]	1.9	1.1	1.0	4.2

Depth of LCH tunnel: between 45 and 170 m
ESS public average dose: 10 mrem/year

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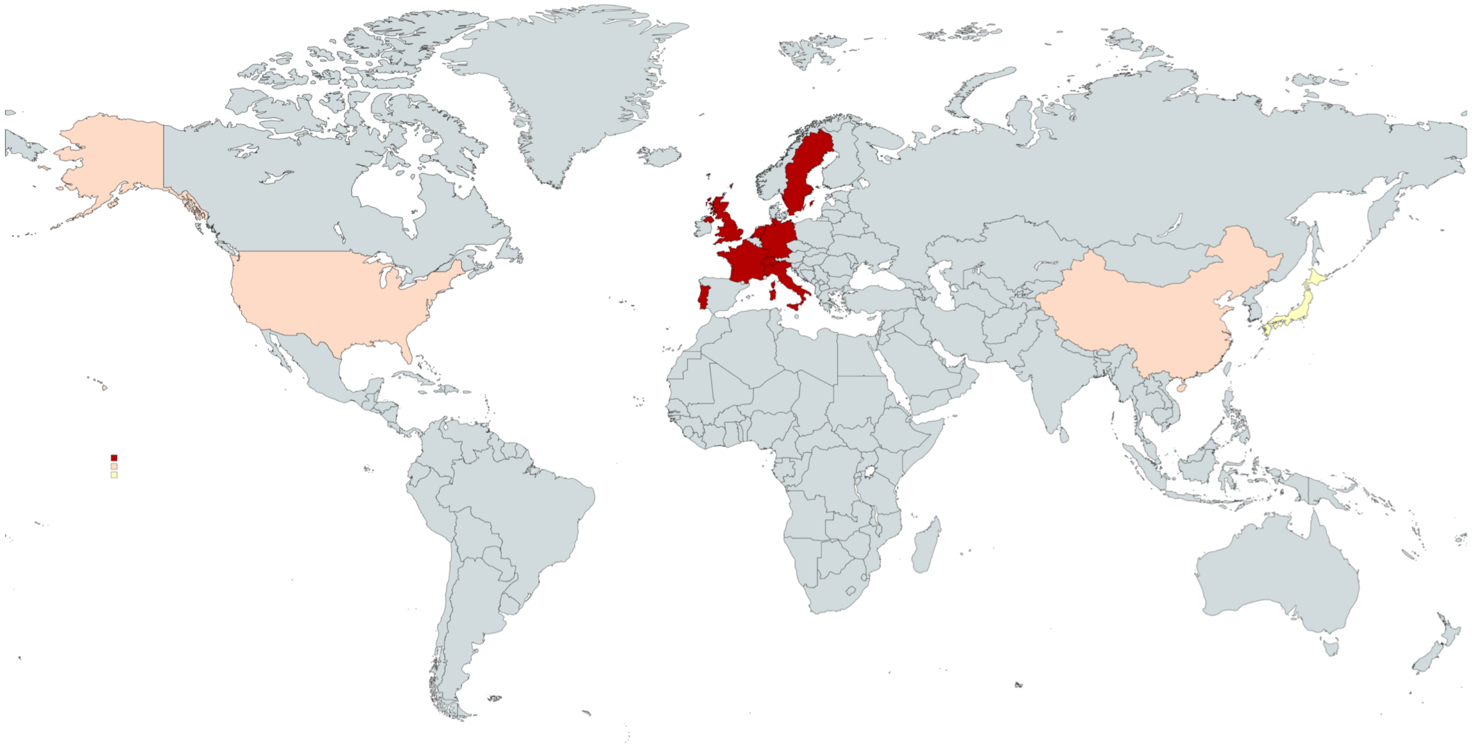
MuCol initiative

International MUON Collider Collaboration

Collaboration in EU and beyond

- Collaboration meetings started in the beginning of 2021.
- Presentation of an new Muon Collider Study to the CERN Council

Preparation and Submission of a EU grant **HORIZON-INFRA-2022-DEV-01** -> Approved in August 2022 and starting January 2023 (running for 4 years)



Partners

Associates

Observing/Consulting

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Next Steps

"PUTTING A BOX AROUND IT, I'M AFRAID, DOES NOT MAKE IT A UNIFIED THEORY."

Studies in the pipeline

- Review proton complex
  - Average power of 2 MW is no problem
  - Merging into 5 pulses of 400 kJ per second needs to be verified
  - Target design to sustain a 5Mw beam
- **A lot more simulation and R&D work on the cooling part (crucial for the project)**
- Collective effects across the whole complex to identify botlenecks
  - Review apertures, feedback and other specifications
  - First results for aperture requirements
  - Potential instability of interaction of muon beam with mater
- Preliminary deisgn of the acceleration complex chain
- Power and cost optimisation
- Vacuum and absorber, instrumentalon, cryogenics, magnets, RF…
- Reuse of existing infrastructure, e.g. LHC tunnel to house the accelerator

ESS, CERN and Uppsala

TECH proposal: Cooling Demonstrator Test Facility

- Cooling was demonstrated only for a region of parameters needed.
- In the final Muon collider a cooling facto of 10^6 is needed

Planning **demonstrator**
production target and c

Suitable **site exists** on C
proton beam
- could combine with

Other sites should be e:

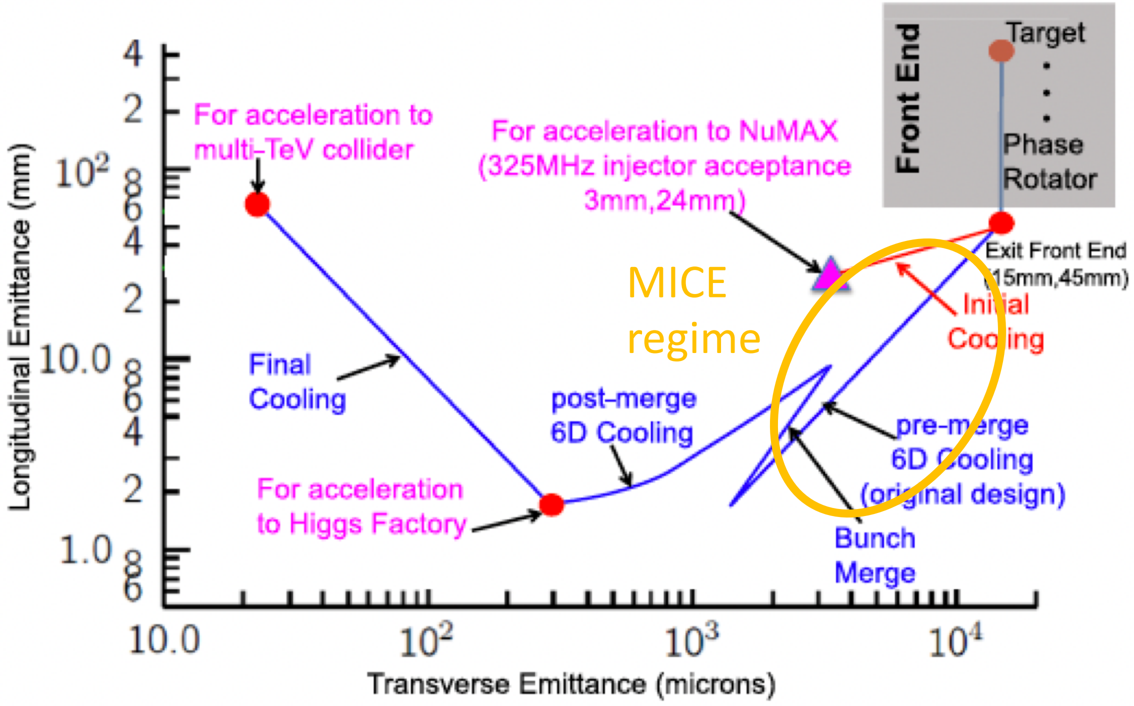
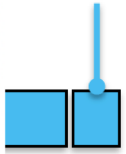


Fig. 3. Ionization cooling path in the 6D phase space.

ıstream
ostics area



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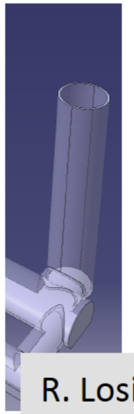

R. Losito et al.

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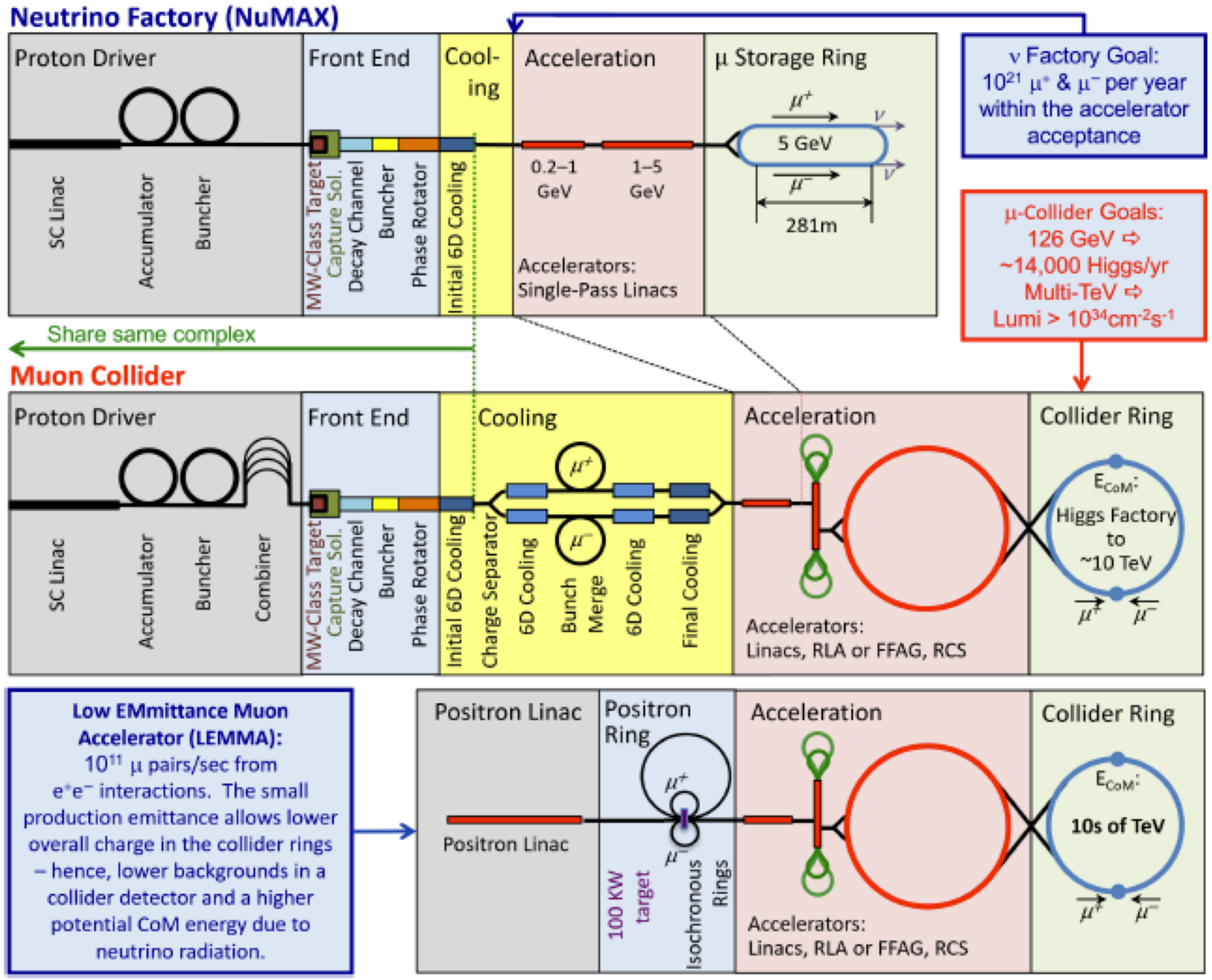
Thank you!
Questions?

2022-09-05

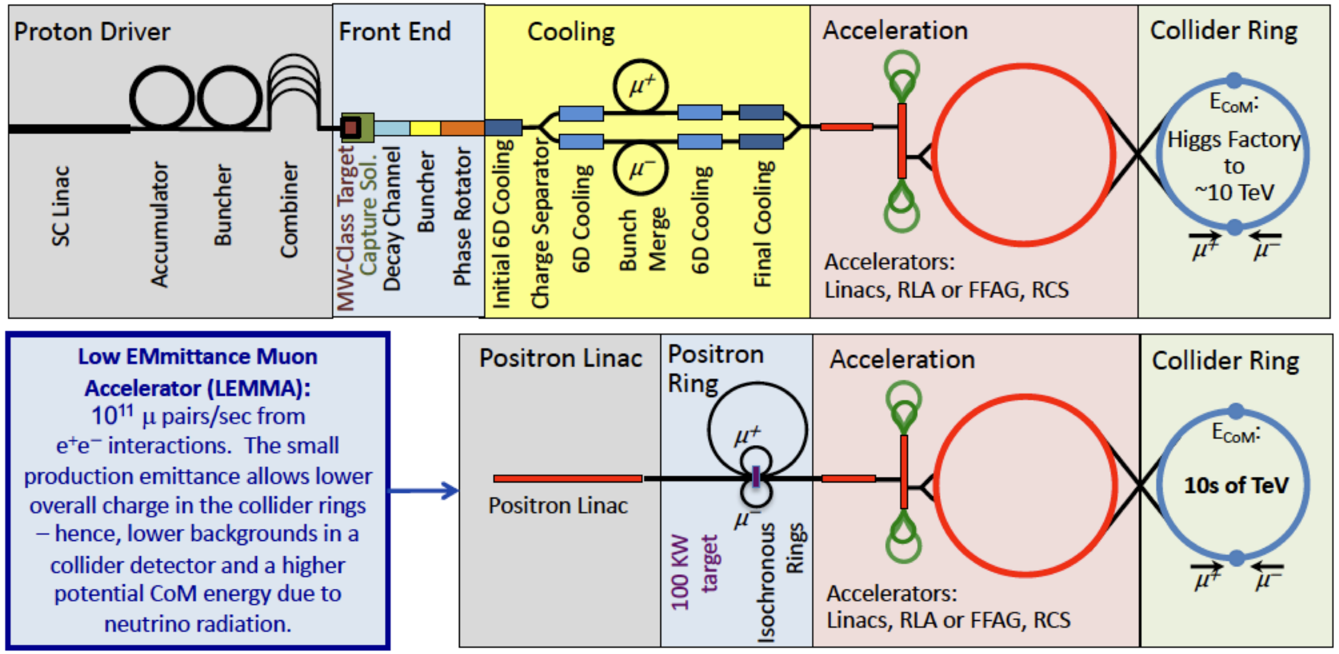
Muon Collider Staging



An alternative to the proton driver

An alternative driver

A novel approach of the Low Emittance Muon Accelerator (LEMMA) based on muon pair production with a positron beam impinging on electrons at rest in a target, was recently proposed and is now under conceptual study.



- **Pros:**
  - Muon beam with smaller emittance – no cooling needed
  - Muon produced already at 22 GeV (500 µs lifetime)
- **R&D**:
  - Intensity requirement of the positron source (order of magnitude higher than ILC levels)
  - Problem with beam density on the target