Muon colliders R&D

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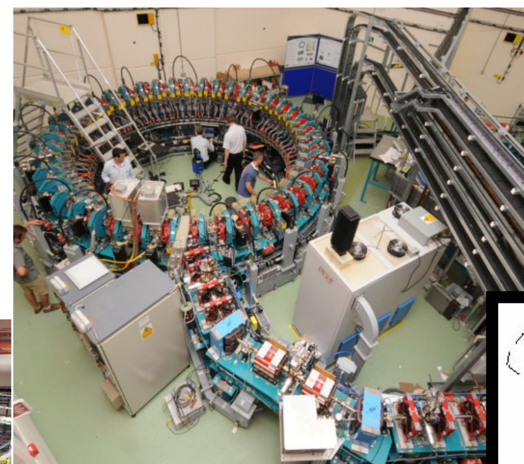
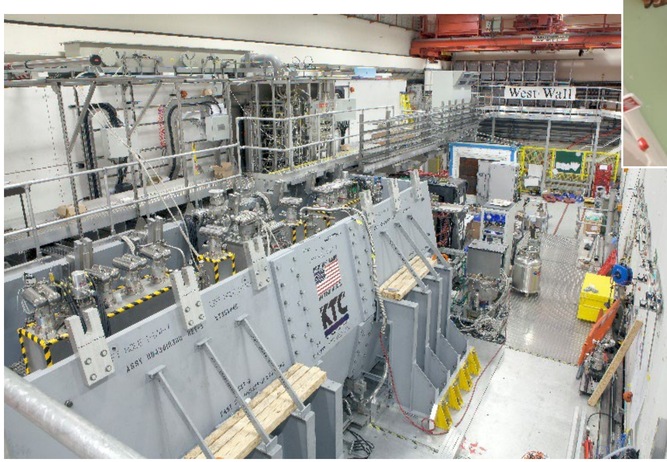
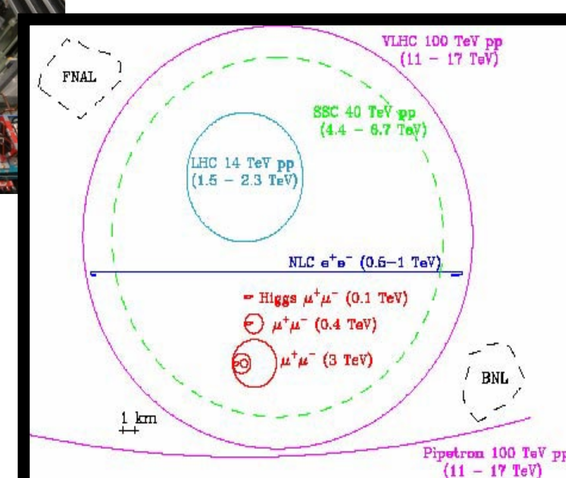




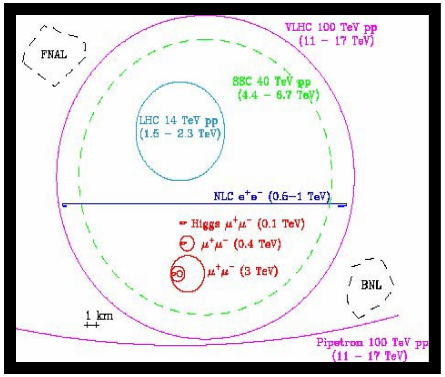


Why muon beams

- **Muon beams have potential to :**
  - Serve neutrino physics with intense beams ($\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu}$) that have equal fractions of electron and muon neutrinos at high intensity with a precisely known energy spectrum - the Neutrino Factory (NF) concept
  - Muon collisions offer a large coupling to the "Higgs mechanism" (Higgs factory)

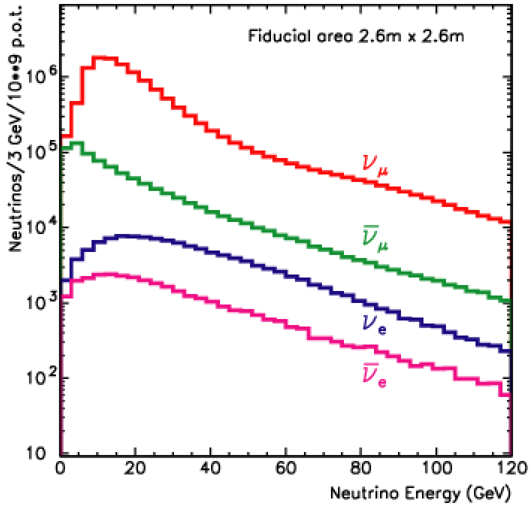
$$\sim \left(\frac{m_\mu^2}{m_e^2} \right) \cong 4 \times 10^4$$

  - As with an e^+e^- collider, a $\mu^+\mu^-$ collider would offer a precision probe of fundamental interactions
    - **With extremely small energy spread;**
    - **Most effective way to achieve E_{cm} > 1 TeV**
    - **Small footprint to fit inside existing HEP labs**
- **Potential applications outside HEP**
  - Muon radiography
  - Muon capture studies of archelogical materials (CHNET)
  - Study of fundamental physics (proton radius puzzle, QED … FAMU at RIKEN-RAL)



ν beams: conventional and NF beams

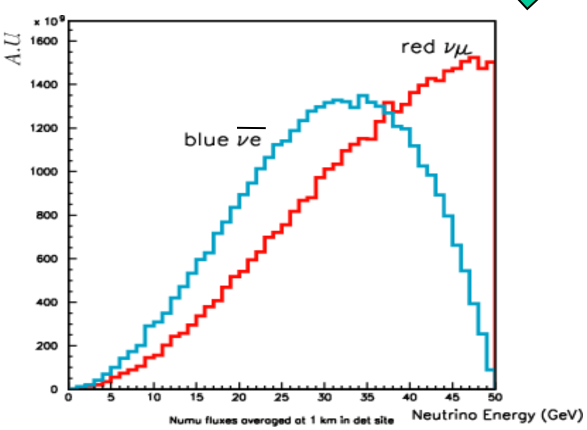
WANF (conventional ν beam at SPS)



- **Problem in conventional ν beams: a lot of minority components (beam understanding)**
- **Following muon collider studies, accelerated muons are ALSO an intense source of “high energy” ν**

$$\mu^- \to e^- \nu_\mu \bar{\nu}_e \qquad \mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$

NUFACT beam

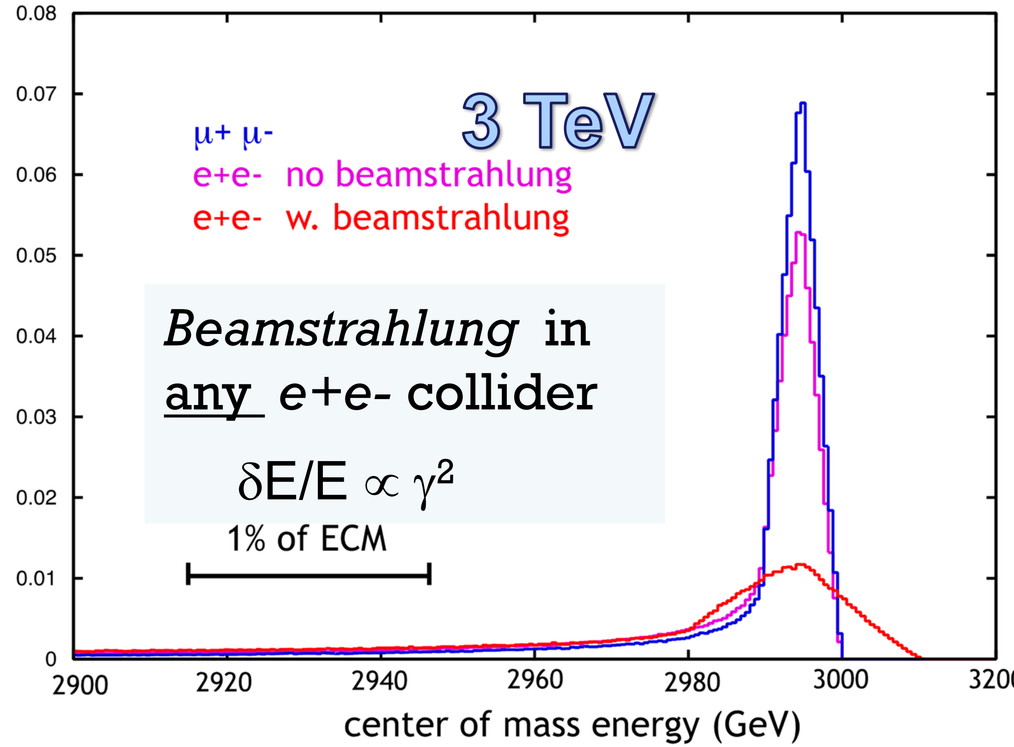


- **Crucial features:**
  - high intensity (x 100 conventional beams)
  - known beam composition (50% ν_μ 50% ν_e)
  - Possibility to have an intense ν_e beam
- **Essential detector capabilities:**

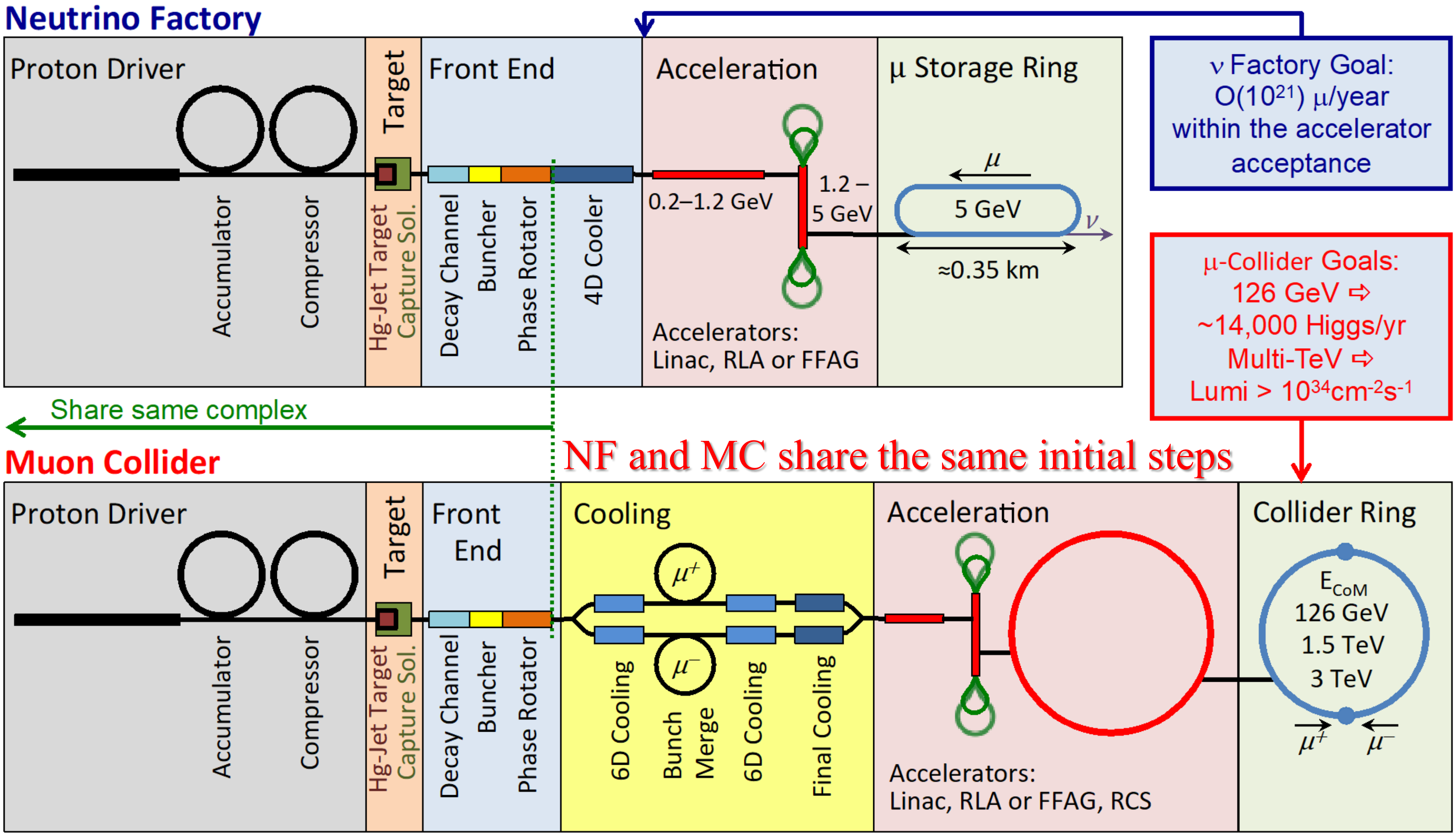
detect μ and determine their sign

Key points

- μ – an elementary charged lepton:
  - 200 times heavier than the electron
  - 2.2 μs lifetime at rest
- The large muon mass strongly suppresses synchrotron radiation
  - ⇨ Muons can be accelerated and stored using rings at much higher energy than electrons
  - ⇨ Colliding beams can be of higher quality with reduced beamstrahlung



The Muon Accelerator Program (MAP)



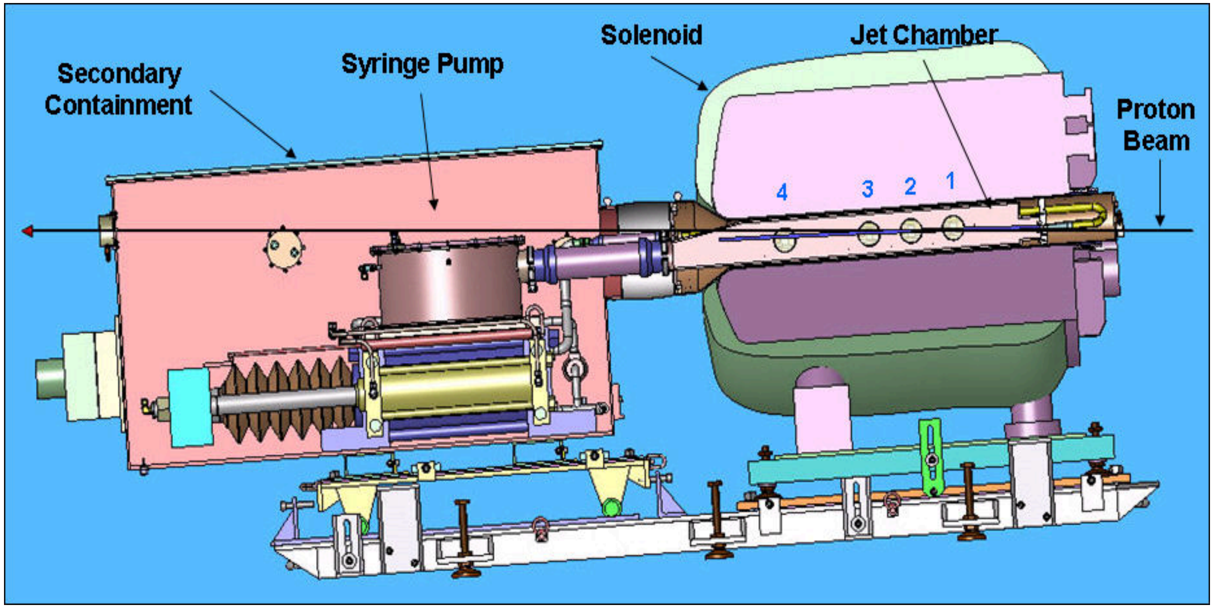
Technical challenges for MC and NF: a long list

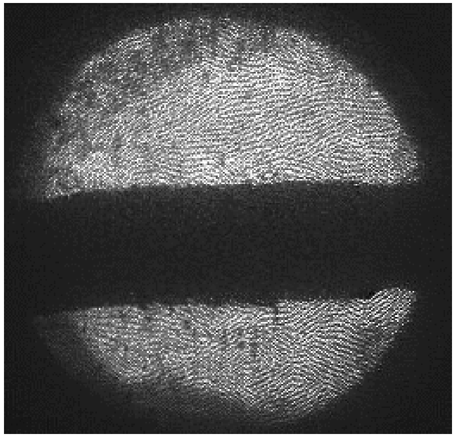
1. High-power (multi-MW) p beam (e'g. SNS, ESS, … proton driver)
2. Suitable targetry (MERIT @CERN, 2007 demonstrated that a > 4 MW Hg jet target is feasible)
3. Muon cooling (small 4D cooling (transverse) sufficient for NF , final 6D cooling essential for MC)
   - μ unstable -> must cool quickly [MICE]
   - Requires high-gradient RF cavities in B > 1 T fields [FNAL MTA]
4. Rapid acceleration
   - Linac-RLAs-(FFAGs)-RCS [EMMA@DL, 2011 proved principle of non-scaling FFAG technique]
5. High storage-ring bending field (to maximize # of cycles before decay and small β _|_ for high $\mathcal{L}$

   [solution devised @ FNAL B~10 T, β ~1 cm]

Key Technologies – Target

- The MERIT Experiment at the CERN
  - Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid and hit with a 115 KJ/pulse beam!
  - ⇨ Jets could operate with beam powers up to **8 MW** with a repetition rate of 70 Hz

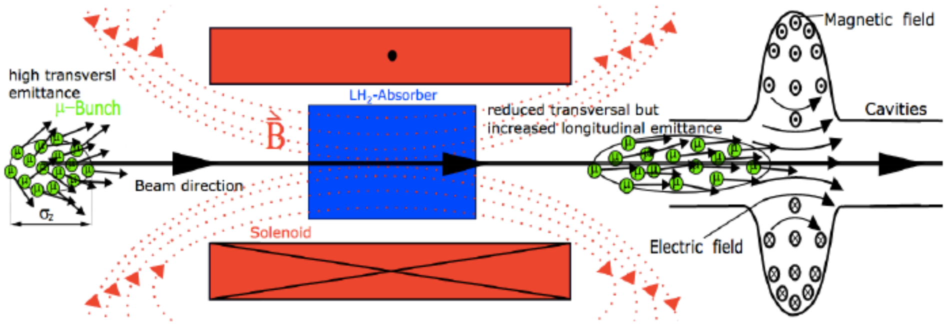


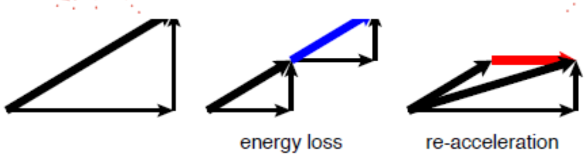


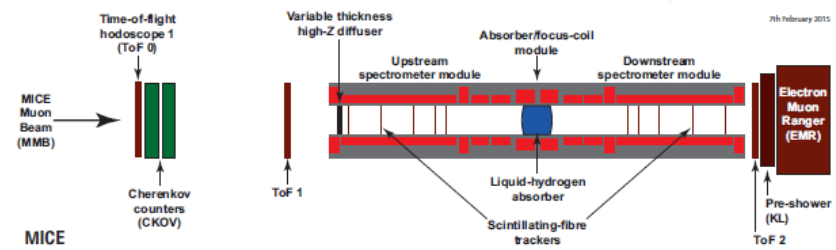
Hg jet in a 15 T solenoid with measured disruption length ~ 28 cm

Ionization cooling

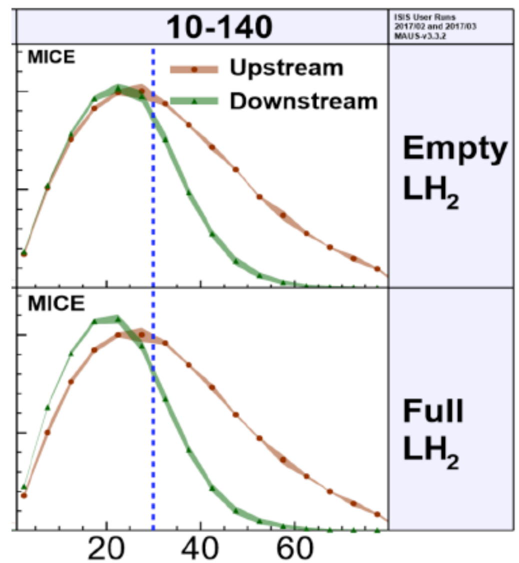
Cooling Principle and Demonstration

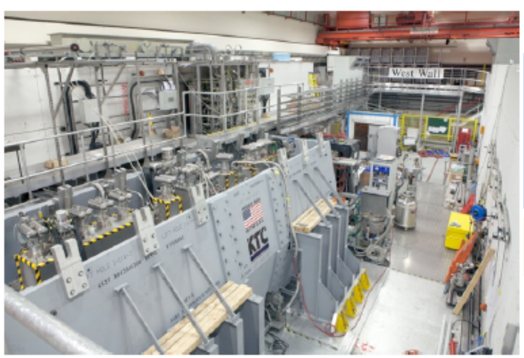






More particles at smaller amplitude after absorber is put in place





Principle of ionisation cooling has been demonstrated in **MICE at RAL**
Use of data for benchmarking is still ongoing

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

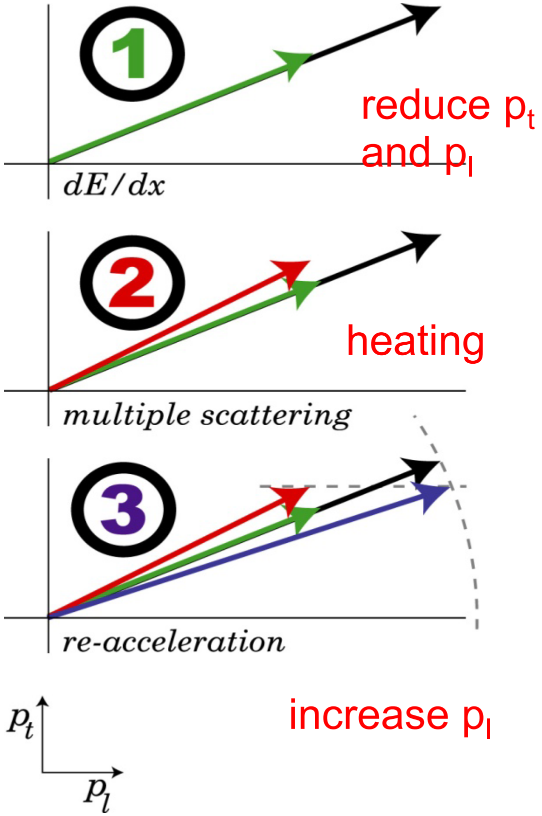
WEPOPT053

Muon ionization cooling

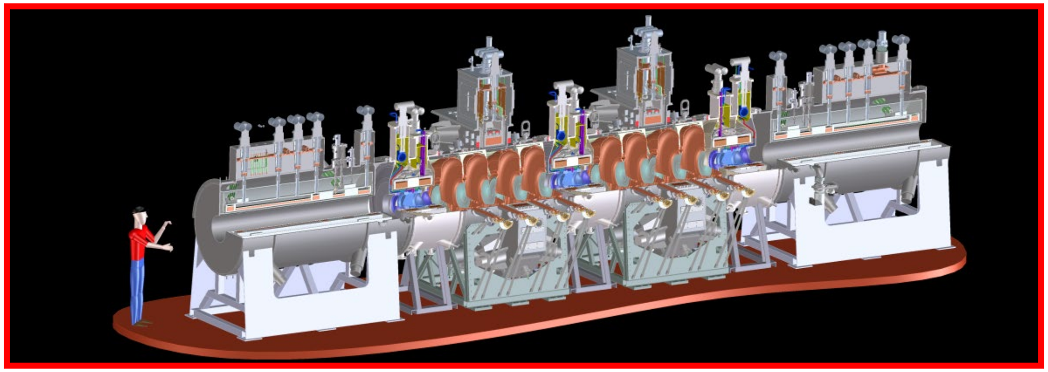
Stochastic cooling is too slow.

A novel method for μ+ <u>and</u> μ- is needed: **ionization cooling**

principle



reality including beam diagnostics(MICE)



- Build a section of cooling channel long enough to provide measurable cooling (10%) and short enough to be affordable and flexible
- Wish to measure this change to 1%
- Requires measurement of emittance of beams into and out of cooling channel to 0.1% !
- Cannot be done with conventional beam monitoring device
- Instead perform a single particle experiment:
  - High precision measurement of each track (x,y,z,px,py,pz,t,E)
  - Build up a virtual bunch offline
  - Analyse effect of cooling channel with bunches of different emittances
  - Study cooling channels parameters over a range of initial beam momenta and emittances

A test facility at CERN ?

From 1st Community meeting of the International Muon Colliders Design Study - 21 May 2021:

``a beam test facility, presumably at CERN, should demonstrate **items of critical importance for the MC luminosity**, namely, the ***6D cooling*** and ***integrated engineering of the cooling cells*** (also, some collider targetry and RF elements can be tested, too)''

MICE follow up ?

Scenario #1 – inside of ISR

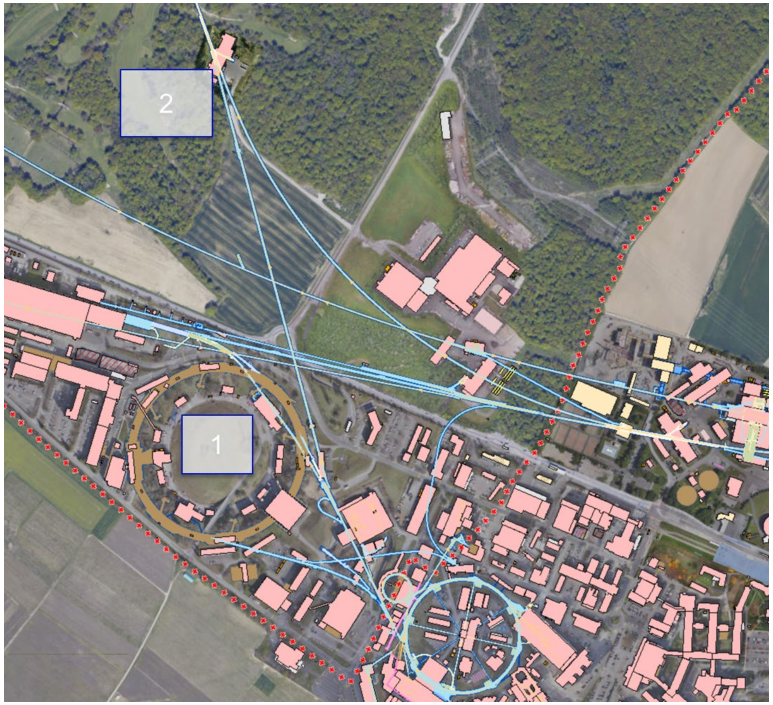
– No upgrade possible to future muon complex (<10 kW or RP issue)

Scenario #2 – on TT10, transfer line to SPS

– Compatibility with future upgrades towards a collider and HP-SPL to be studied.

– O(80kW) should be easily feasible by going sufficiently underground.

– 4 MW to be studied, but not impossible a priori.



Possible thesis arguments

- ❑ Inside the International Muon Collider collaboration (CERN based)
  - Application of the cooling techniques (follow up of MICE, with STFC,…)
  - Contribution to the design of a demonstrator

For more details:

- https://muoncollider.web.cern.ch/welcome-page-muon-collider-website
- https://indico.cern.ch/event/1030726/
- http://mice.iit.edu/

For infos:

- Maurizio.bonesini@mib.infn.it

The MUonE Project

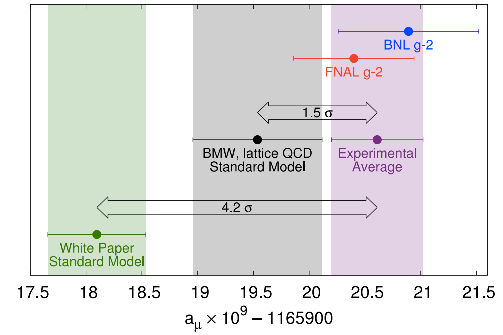
Per informazioni rivolgersi a C. Matteuzzi

The MUonE project: motivations

Dirac equation : $g_l = 2$

Quantum corrections → the anomaly

$$a_l \equiv \frac{g_l - 2}{2}$$



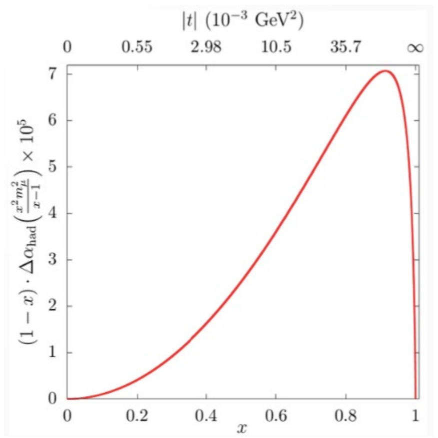
Determine $\Delta\alpha_{had}(t)$, the hadronic contribution to the running of the electromagnetic coupling costant, measuring the differential cross section $d\sigma/dt$ as a function of the momentum transfer t of the elastic process $\mu e \rightarrow \mu e$

$$\frac{d\sigma_{data}/dt}{d\sigma_{MC}^{\text{no VP}}/dt} = \frac{1}{|1 - \Delta\alpha_{lep}(t) - \Delta\alpha_{had}(t)|^2}$$

From theoretical calculation

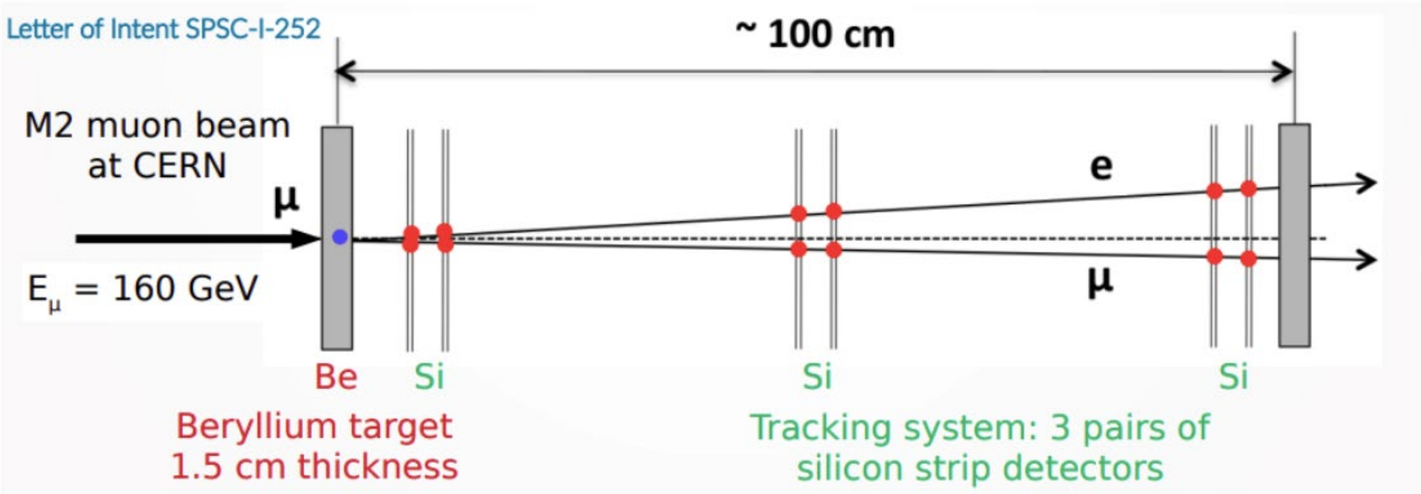
To be measured

$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$



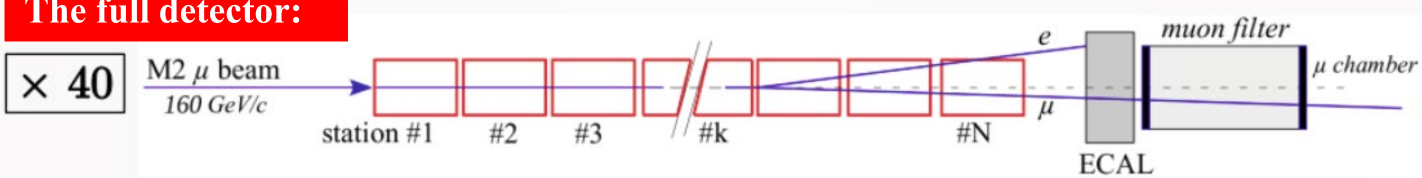
The MUonE project: detector and collaboration

The detector (1 station):



$$\mu\ e \rightarrow \mu\ e$$

The full detector:



The collaboration:

July 2022

Elements of the detector

- **Si tracker :** *use 2S sensors from **CMS***

  The Phase-2 Upgrade of the CMS Tracker",CERN-LHCC-2017-009;CMS-TDR-014

- **Calorimeter**

  Crystals PbWO4

  (*For the moment 25 crystals PbWO4 for ~14x14 cm2 lended by CMS)*

- **Muon filter**

  iron blocks interspersed with tracking planes *(2S modules or others)*

- **Software**

  1) **FairRoot** framework (with benchmark testbeam 2018 final analysis and simulation of the Test Run 2023 setup detailed description)
  2) use of GEANT4 simulation, digitization, reconstruction, analysis and NLO MC generator.

Argomenti di tesi

- Title: **A testbeam for the feasibility of the MUonE experiment**
  Participazione e Analisi del test run di MUonE .
  Presa dati prevista dal 15 ottobre 2022 per 1 settimana
  e in giugno 2023 per 3 settimane

- Title: **Use of the calorimeter in the MUonE detector**
  Uno studio della simulazione del rivelatore MUonE per
  determinare le performance di un calorimetro necessarie
  a identificare eventi elastici mu-e → mu-e

Per piu' informazione:

1) Eur. Phys. J. C77 (2017) 139 [hep-ex/169.8987]
2) Letter of Intent: the MUonE Project CERN SPSC02019-026/SPSC-I-252 June2019
3) JINST 15(2020) P01017
4) JINST 16(2021) P06005

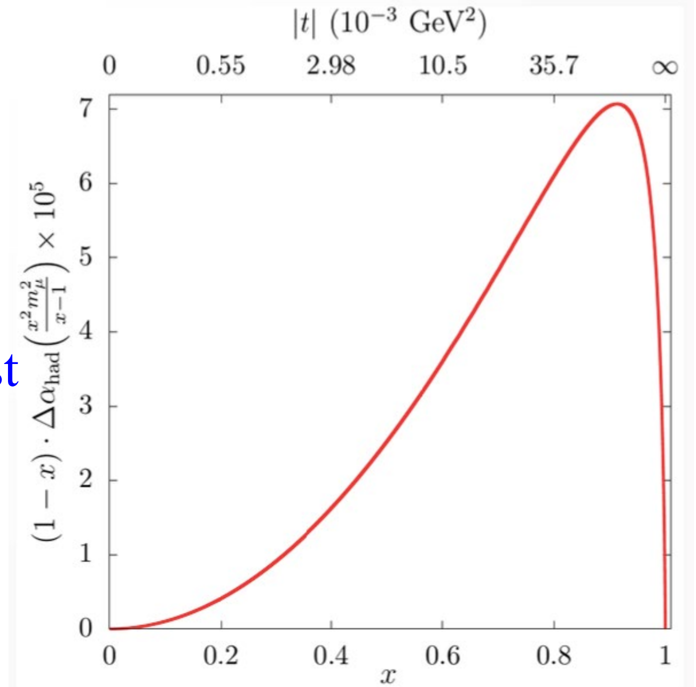
More info slides ….

La misura della sezione d'urto differenziale $d\sigma/dt$ in funzione del momento trasferito t del processo elastico

$$\mu\ e \rightarrow \mu\ e$$

da' l'integrale della funzione nella figura di destra. Questa e' l'osservabile che i calcoli su lattice predicono.

La misura di MUonE quindi puo' fornire l'unico test sperimentale del calcolo teorico su lattice.



$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

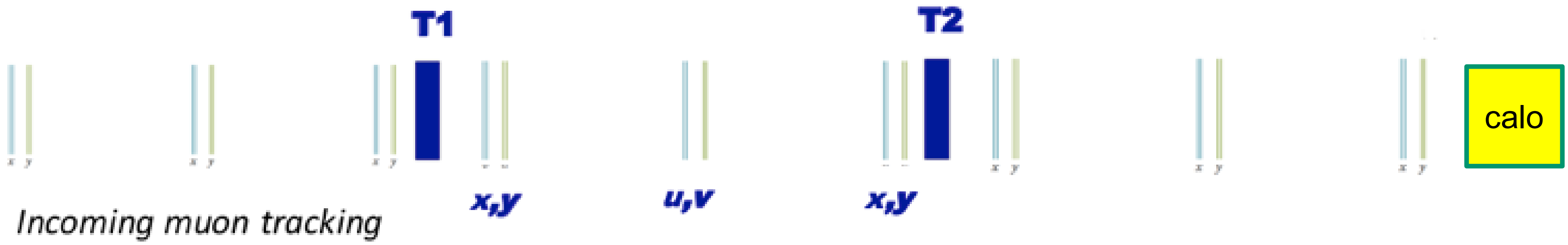
The MUonE Test Run (3 weeks allocated in 2023)

- **Location:**

  upstream COMPASS after the *Beam Momentum Station* (BMS)

- **3 weeks at mid-year of 2023** *(due to the Si planes availability)*

  ➡ to run with the configuration with 2 targets :



➡ the apparatus will be in a thermalized volume

⬇

The pilot run should provide ~ 10^8 elastic events