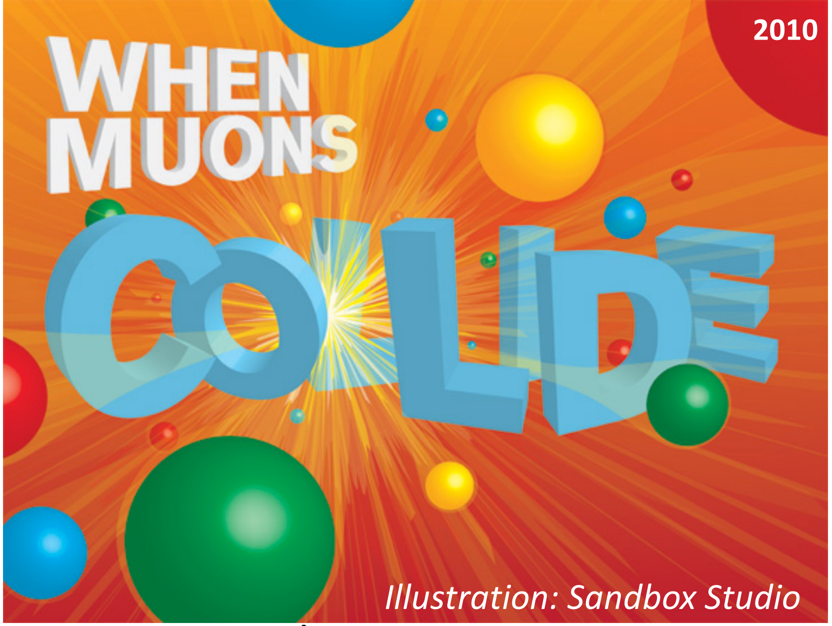


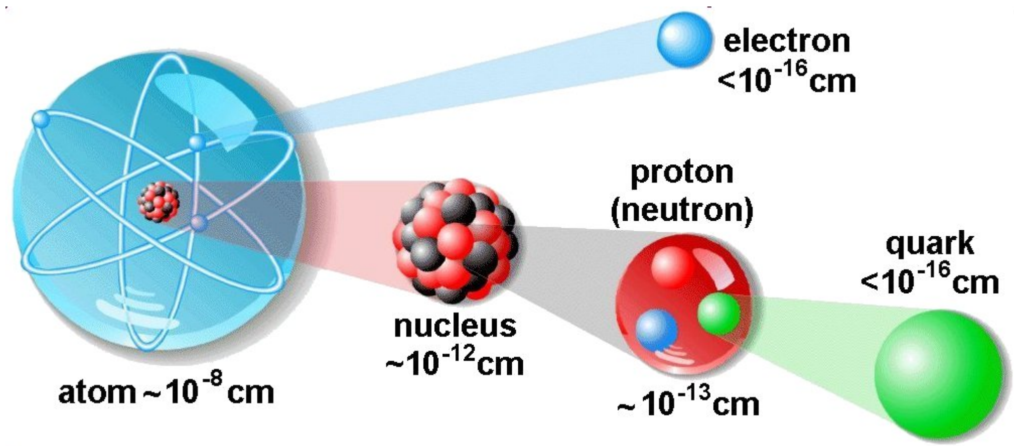
www.symmetrymagazine.org

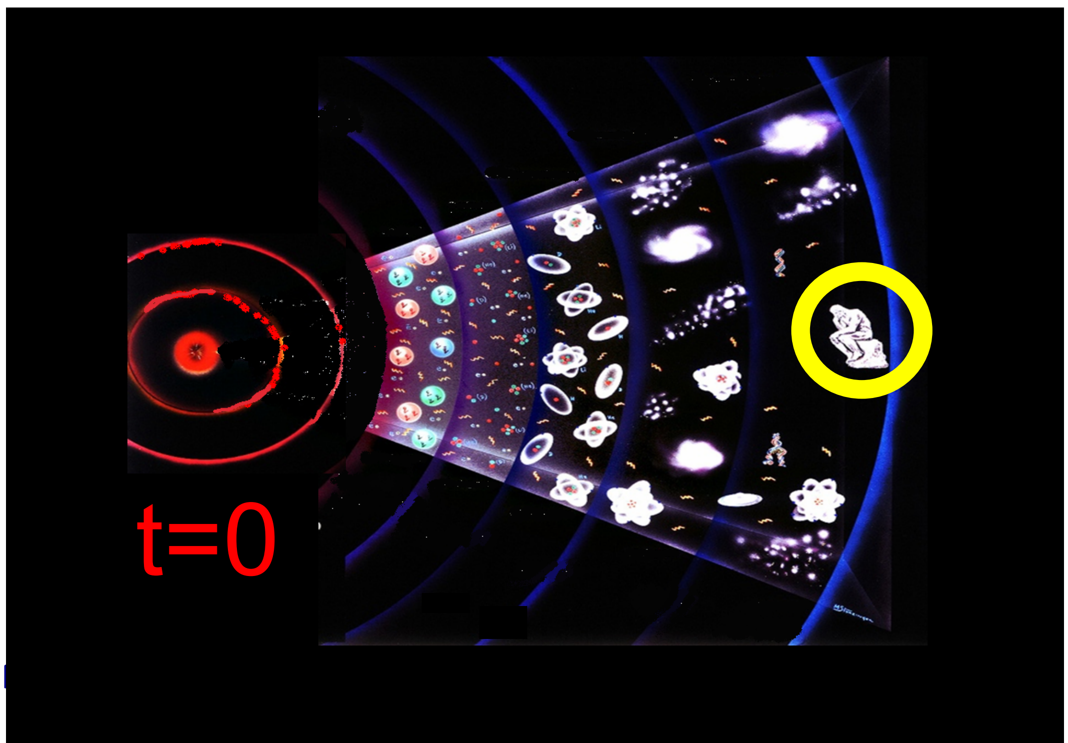
*NIKHEF – September 13th, 2019*

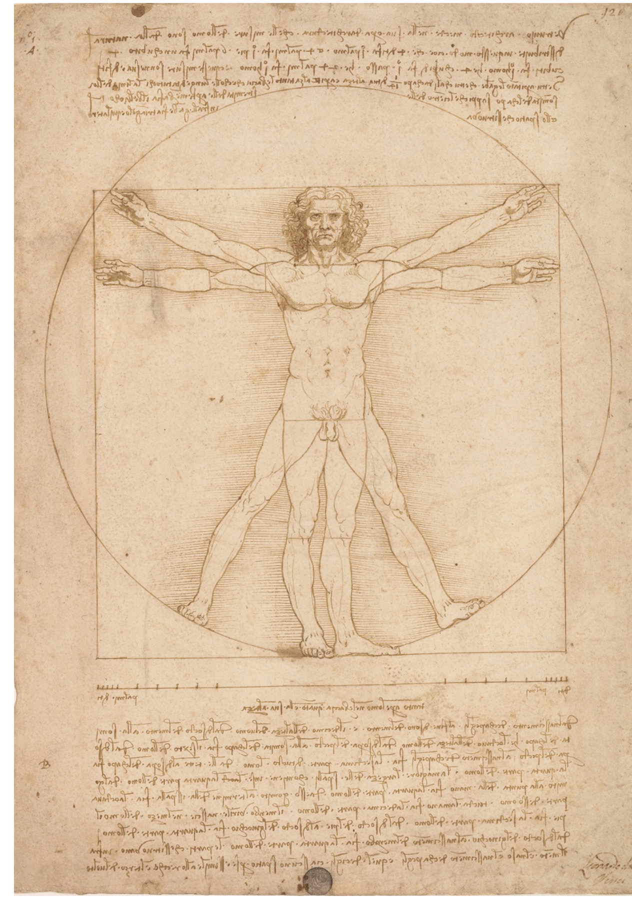
# Muon Colliders: challenges and wonders

**Nadia Pastrone**
INFN TORINO

# Fundamental questions

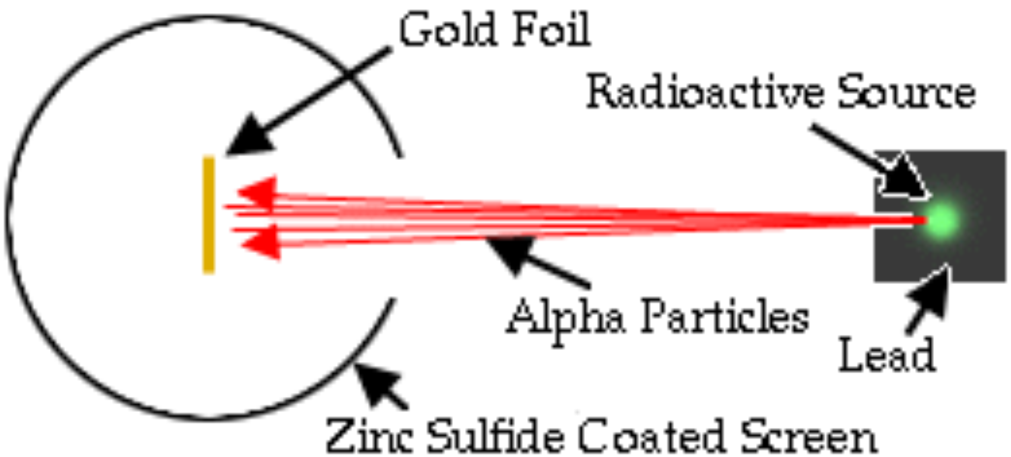


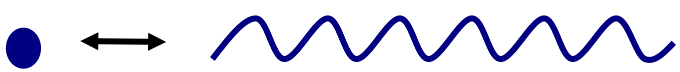



# Modern experimental method

**Rutherford experiment (1911)**

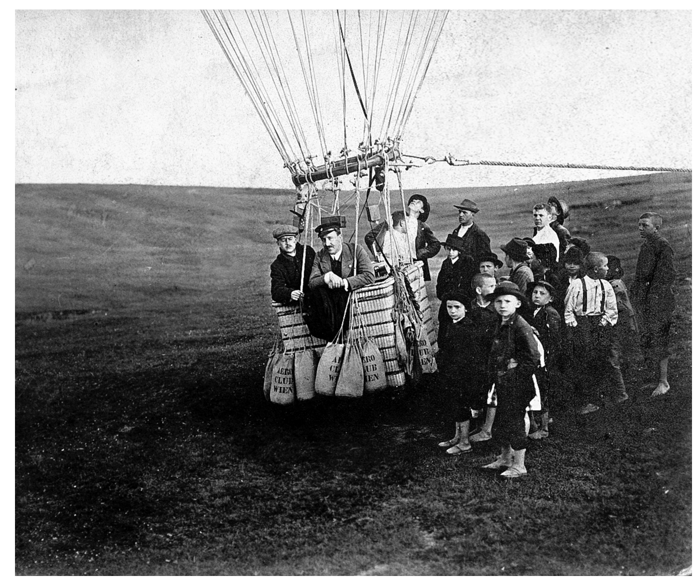


particle

$\lambda = h/p$

**Victor Hess's balloon (1912)**



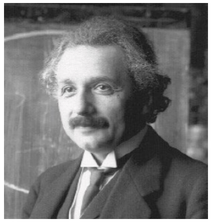
# Accelerators: a fundamental tool

**Reaching the highest energies enables to:**

- explore the smallest dimensions **$E \sim 1/\lambda$**

**Louis de Broglie**

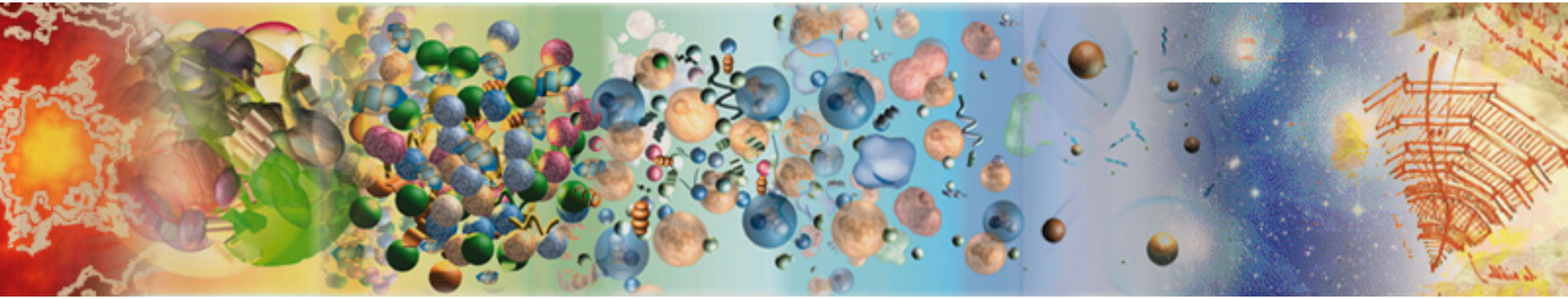
- create particles with higher masses **$E = mc^2$**



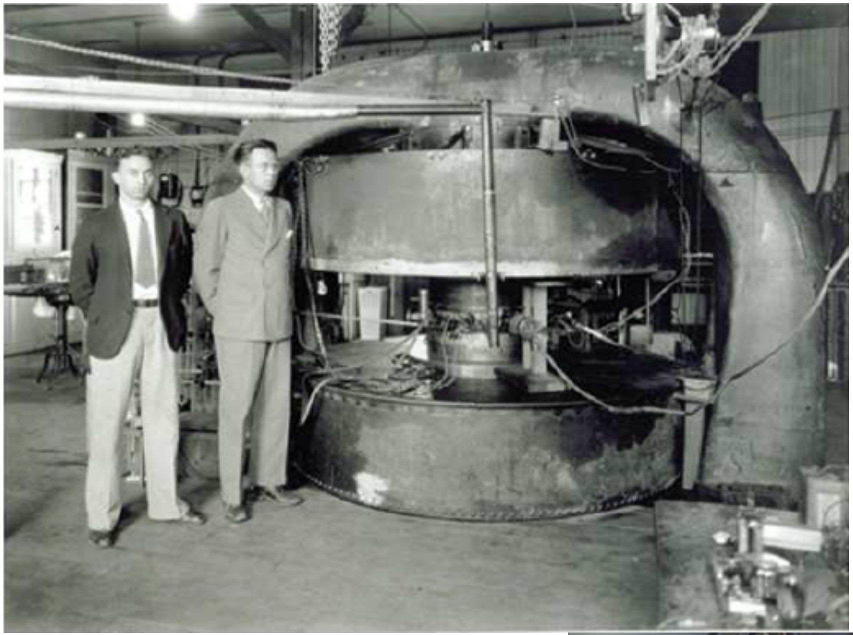
**Albert Einstein**

- explore high temperature regime as in the early Universe **$E = kT$**

**Ludwig Boltzmann**

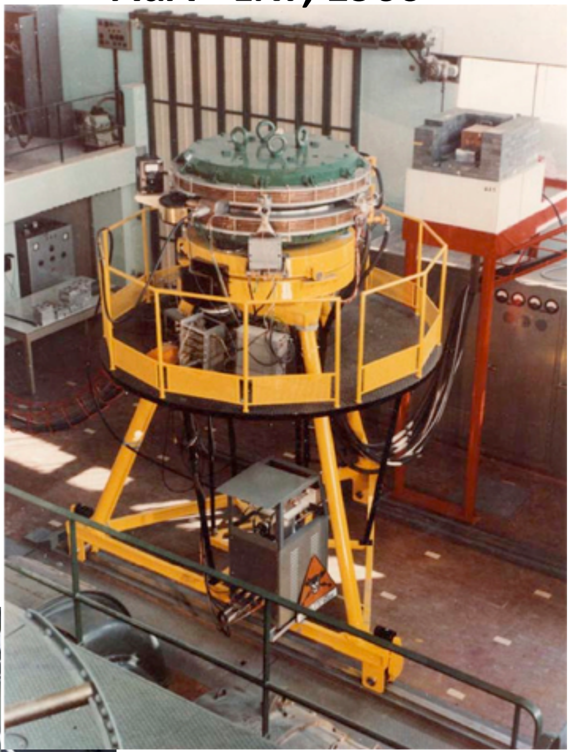


# Ideas & technologies → discoveries

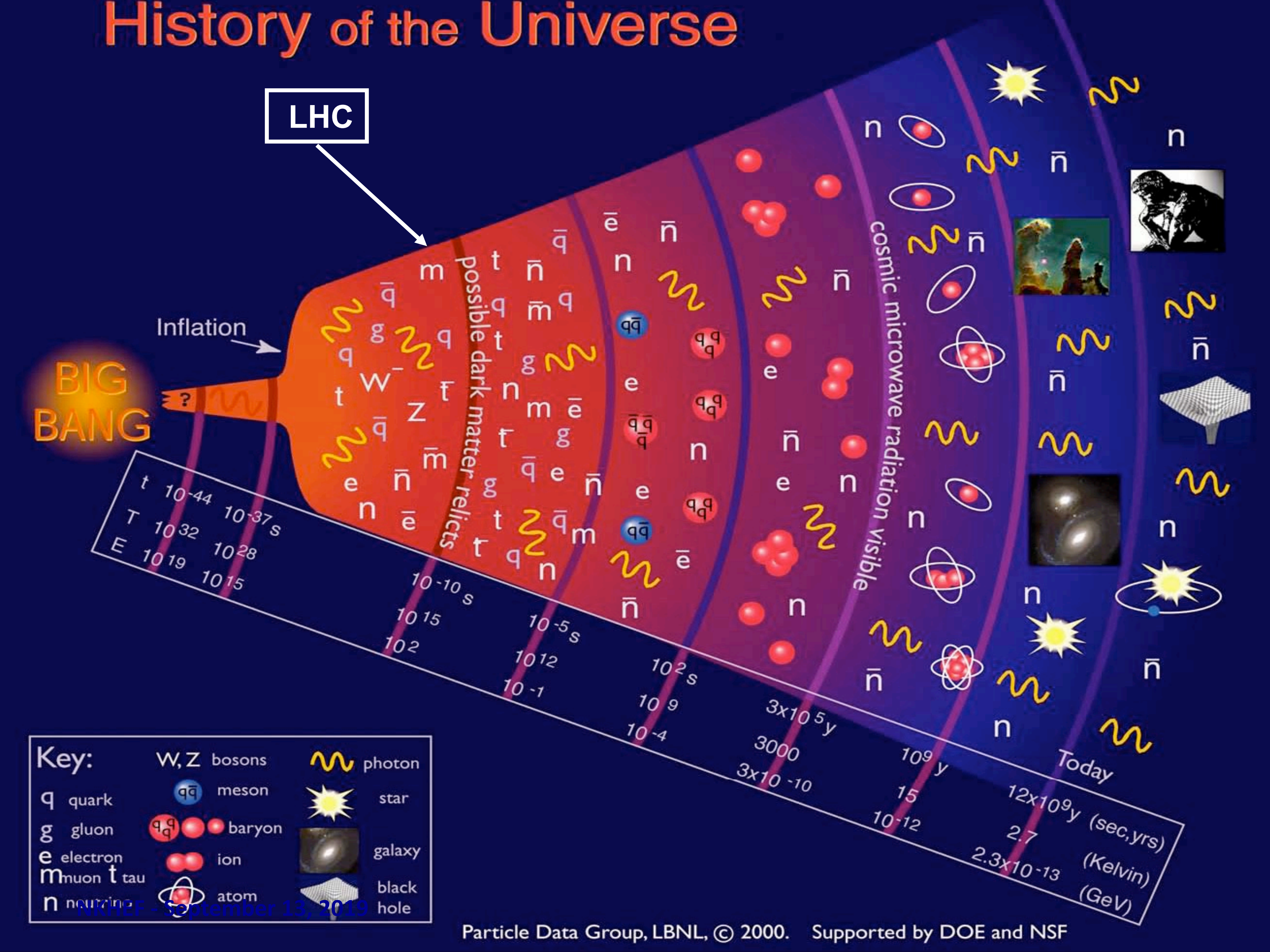


Cyclotron - Berkeley, 1934

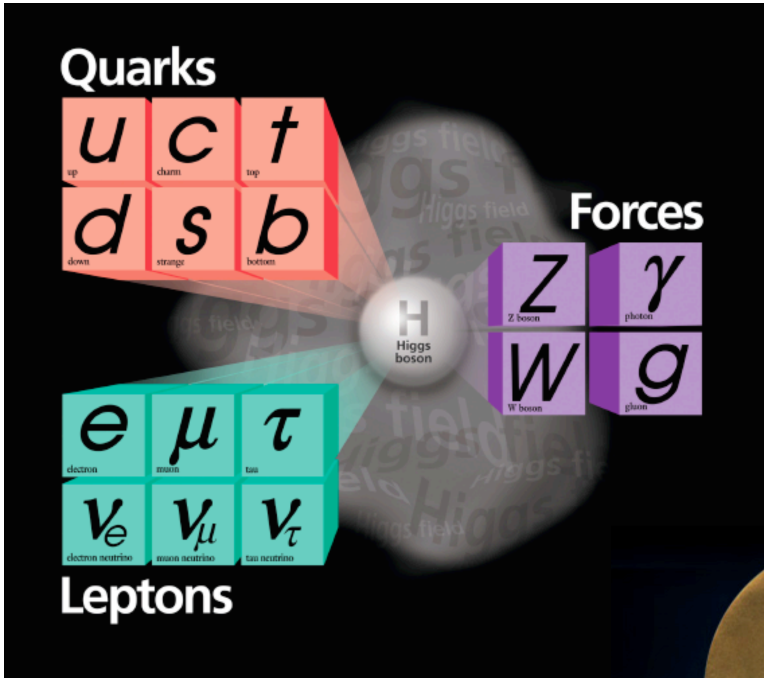
AdA - LNF, 1960



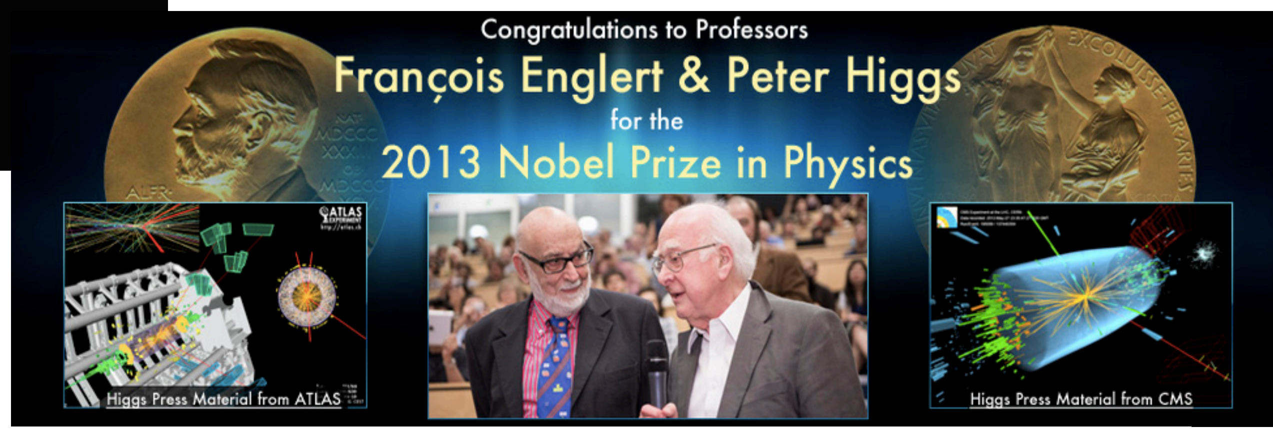
LHC - CERN, 2008


History of the Universe
LHC
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

# Standard Model of Particle Physics




- **Extremely precise measurements and confirmation of Standard Model (SM)**
- **No signal of Beyond Standard Model evidence or SUSY**




*"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

# Open questions

Michelangelo L. Mangano

- **Data driven:**
  - What is DM?
  - What's the origin of neutrino masses?
  - What's the origin of the matter vs antimatter asymmetry?
  - What is Dark energy?

  ...

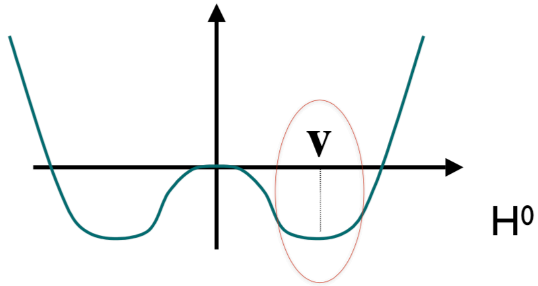
- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Quantum gravity
  - Origin of inflation

  ...

For none of the open questions, the path to an answer is unambiguously defined

***One question, however, has emerged in stronger and stronger terms from the LHC, and appears to single out a unique well defined direction....***

# Question to the future colliders




$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$

**Who ordered that ?**

$$v = (\sqrt{2}G_F)^{-1/2} \sim 246 \text{ GeV}$$

$$\mu = m_H \qquad \lambda = \frac{m_H^2}{2v^2}$$

$g_{3H} \Rightarrow 4\lambda v = \frac{2m_H^2}{v}$

$g_{4H} \Rightarrow \lambda = \frac{m_H^2}{2v^2}$

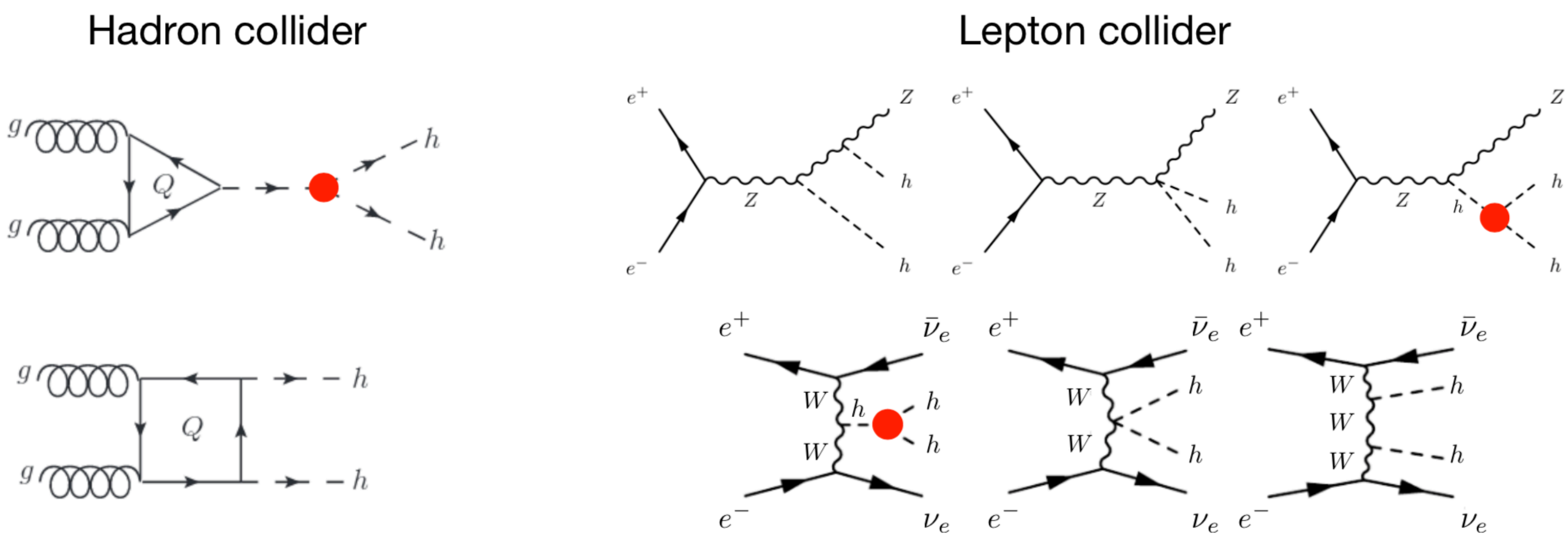
***The relations between Higgs self-couplings, mH and v***
***entirely depend on the functional form of the Higgs potential.***
*Their measurement is an important test of the SM nature of the Higgs mechanism*

# Double Higgs production

arXiv:1905.03764

**The *measurement* of the Higgs potential is a high priority goal on the physics programme of all future colliders**

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




Extracting the value of the Higgs self-coupling, in red, requires a knowledge of the other Higgs couplings that also contribute to the same process

# Update European Strategy of Particle Physics

~ 60 dedicated inputs (+ national inputs) on accelerators and technological developments

- e+e- colliders
- hh colliders
- ep colliders
- FCC
- Gamma factories
- Plasma acceleration
- Muon colliders
- Beyond colliders

## Big Questions

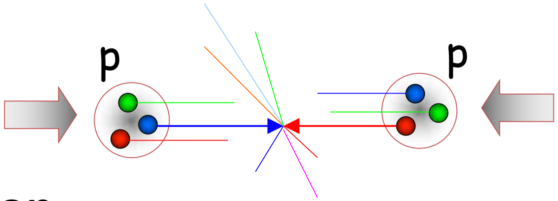
**Caterina Biscari and Lenny Rivkin**

**In particular for the Accelerator Science and Technology**

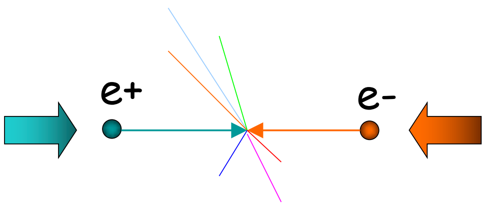
- **What is the best implementation for a Higgs factory?**
  **Choice and challenges for accelerator technology: linear vs. circular?**
- **Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?**
- **How to achieve proper complementarity for the high intensity frontier vs. the high-energy frontier?**
- **Energy management in the age of high-power accelerators?**

# Hadron & Lepton Colliders

- **Hadron colliders as discovery facilities**
  - Broad range scanning
  - Huge QCD background
  - Nucleon energy (partly only) available  in collision



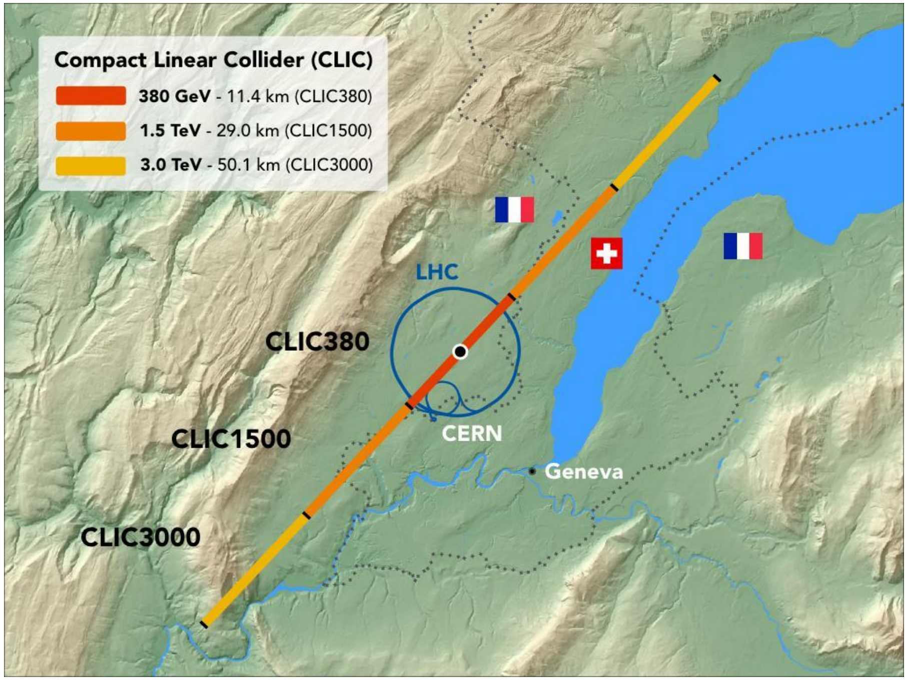

- **Lepton colliders for precision physics**
  - Well defined initial energy for reaction
  - Colliding "point" like particles

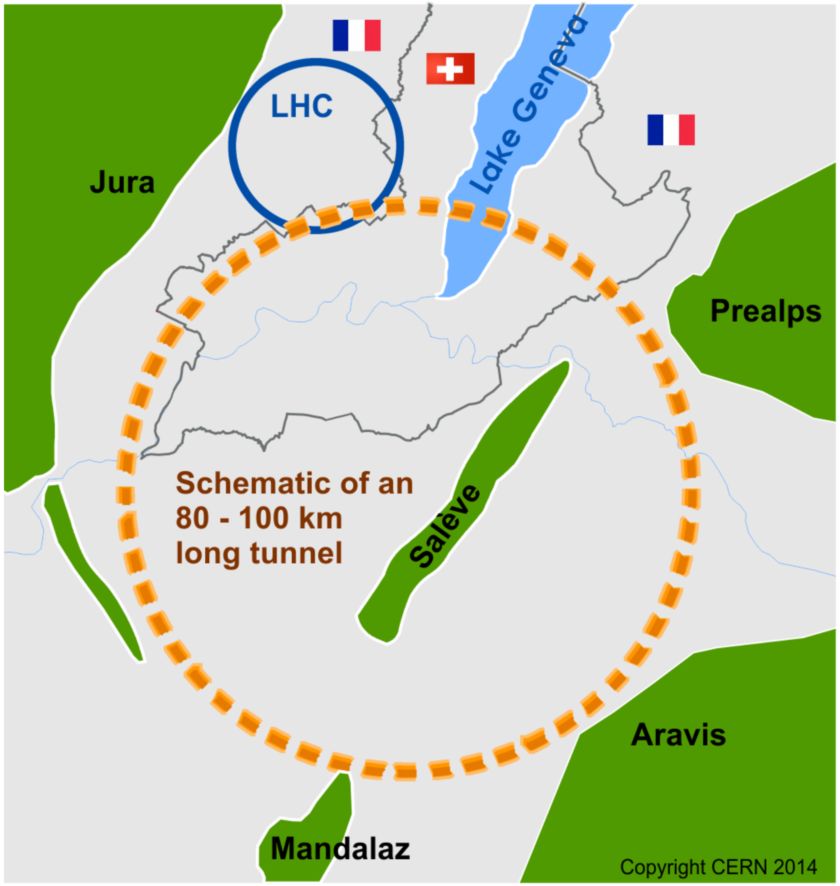



➔ **Lepton Collider as next facility @ High Energy Frontier after LHC ??**
  - Energy determined by LHC discoveries
  - Study in detail the properties of new physics identified by LHC (if any)

**presently HIGGS, possibly BSM in the future**

# Linear vs Circular collider



# Proposed schedule

European Strategy Update

Open Symposium May 13-16 2019

| | $T_0$ … +5 … +10 … +15 … +20 … +26 |
|---|---|
| ILC | 0.5/ab 250 GeV; 1.5/ab 250 GeV; 1.0/ab 500 GeV; 0.2/ab $2m_{top}$; 3/ab 500 GeV |
| CEPC | 5.6/ab 240 GeV; 16/ab $M_Z$; 2.6 /ab $2M_W$; SppC => |
| CLIC | 1.0/ab 380 GeV; 2.5/ab 1.5 TeV; 5.0/ab => until +28 3.0 TeV |
| FCC | 150/ab ee, $M_Z$; 10/ab ee, $2M_W$; 5/ab ee, 240 GeV; 1.7/ab ee, $2m_{top}$; hh,eh => |
| LHeC | 0.06/ab; 0.2/ab; 0.72/ab |
| HE-LHC | 10/ab per experiment in 20y |
| FCC eh/hh | 20/ab per experiment in 25y |

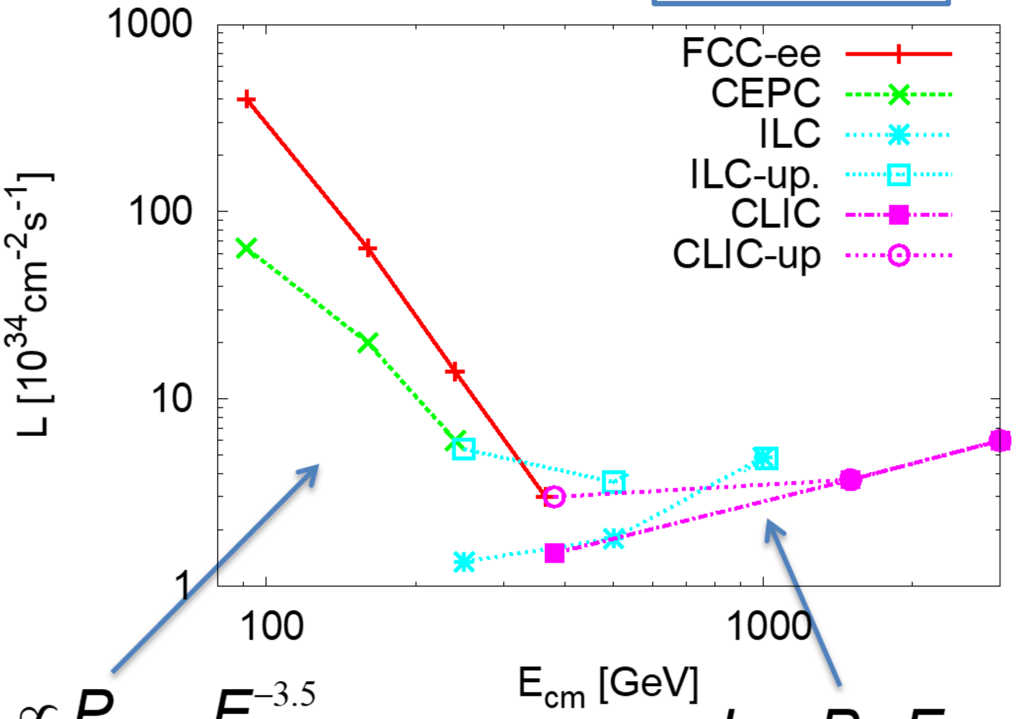
| Project | Start construction | Start Physics (higgs) |
|---|---|---|
| CEPC | 2022 | 2030 |
| ILC | 2024 | 2033 |
| CLIC | 2026 | 2035 |
| FCC-ee | 2029 | 2039 (2044) |
| LHeC | 2023 | 2031 |

**Would expect that technically required time to start construction is O(5-10 years) for prototyping etc.**

# Linear vs Circular lepton collider

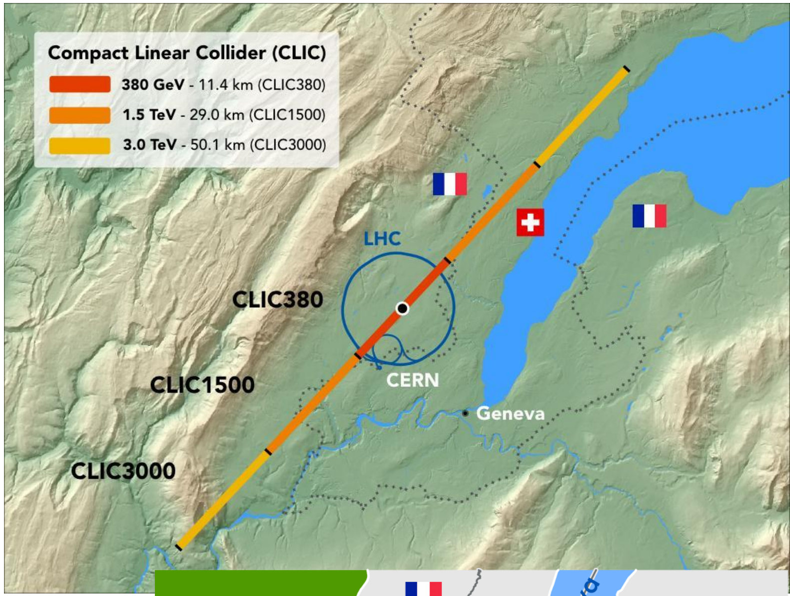
**Luminosity per facility**

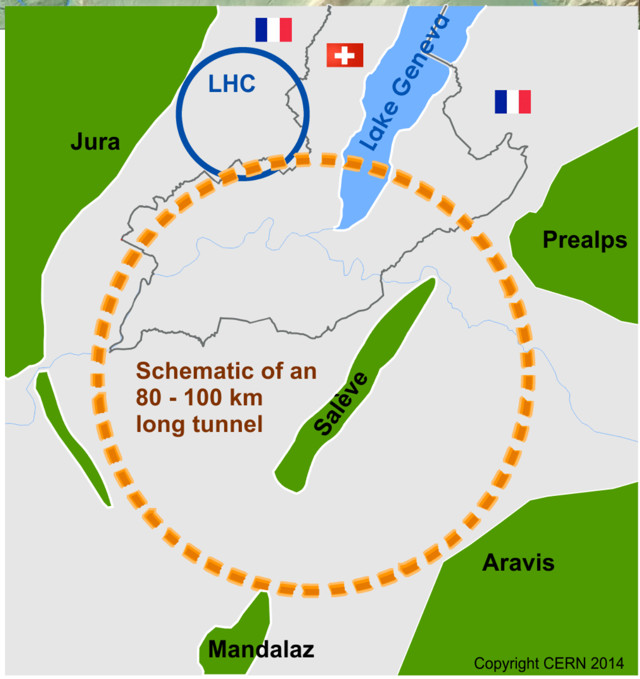
**Daniel Schulte**




$L \propto P_{synrad} E_{cm}^{-3.5}$

$L \propto P_{RF} E_{cm}$



# Why Muons?

Mark Palmer

Physics Frontiers

- **Intense and cold muon beams a unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$$m_\mu = 105.7\, MeV/c^2$$
$$\tau_\mu = 2.2\,\mu s$$

Colliders

- **Opportunities**
  - s-channel production of scalar objects
  - Strong coupling to particles like the Higgs → $\sim \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4 \times 10^4$
  - Reduced synchrotron radiation a multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at IP
- ***BUT* accelerator complex/detector must be able to handle the impacts of μ decay**

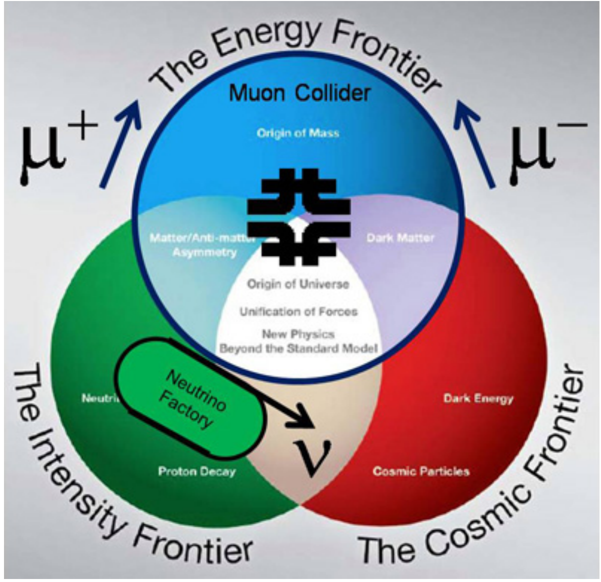
Collider Synergies

- High intensity beams required for a **long-baseline Neutrino Factory** are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

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

# Physics reach

- Muon rare processes
- Neutrino physics
- Higgs factory
- Multi-TeV frontier




http://map.fnal.gov/

# U.S. Muon Accelerator Program (MAP)

- Recommendation from 2008 Particle Physics Project Prioritization Panel (P5)
- Approved by DOE-HEP in 2011
- Ramp down recommended by P5 in 2014

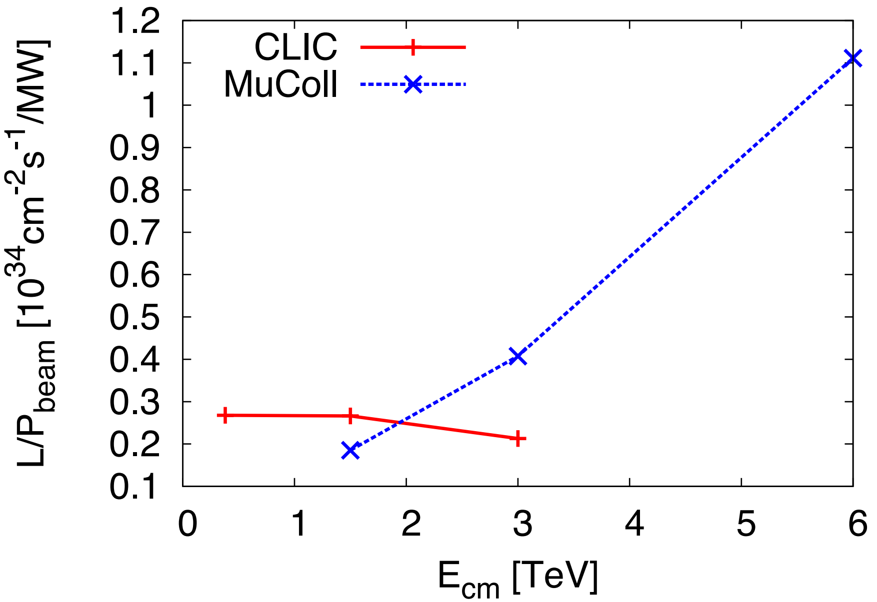
**AIM:** to assess feasibility of technologies to develop muon accelerators for the Intensity and Energy Frontiers:

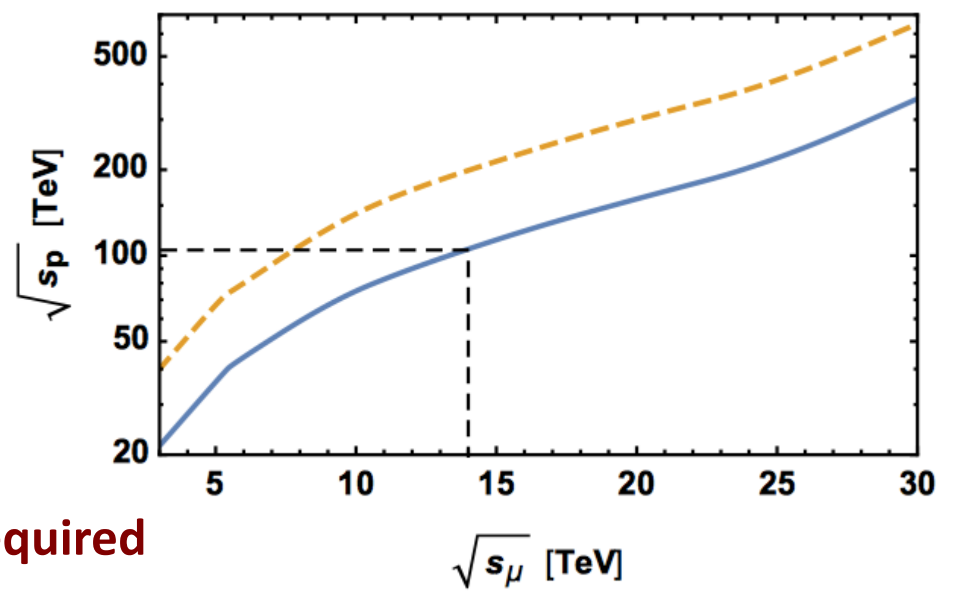
- Short-baseline neutrino facilities (nuSTORM)
- Long-baseline neutrino factory (nuMAX) with energy flexibility
- Higgs factory with good energy resolution to probe resonance structure
- TeV-scale muon collider

# Why a multi-TeV Muon Collider?

**cost-effective and unique opportunity**

**for lepton colliders @ Ecm > 3 TeV**




**sufficient luminosity required**

*Strong interest to reuse existing facilities and infrastructure (i.e. LHC tunnel) in Europe*

# Motivation: Higgs potential

$$V = \frac{1}{2}m_h^2 h^2 + (1 + k_3)\lambda_{hhh}^{SM} v h^3 + (1 + k_4)\lambda_{hhhh}^{SM} h^4$$

**Trilinear coupling, $k_3$**

- $\sqrt{s} = 10\ TeV, \mathcal{L} \sim 10^{35} cm^{-2} s^{-1}$
- 10 $ab^{-1}$

$k_3$ sensitivity ~ 3%

Best sensitivity ~5% FCC combined
(arXiv:1905.03764)

**Quadrilinear coupling, $k_4$**

- $\sqrt{s} = 14\ TeV, \mathcal{L} \sim 10^{35} cm^{-2} s^{-1}$
- 20 $ab^{-1}$

$k_4$ sensitivity $few$ 10%

FCC-hh in a optimistic scenario 30 $ab^{-1}$

$\lambda_4 = \in [\sim -4, \sim +16] @ 68\%\ C.L.$ (arXiv:1905.03764)

**Estimates to be fully studied and demonstrated!**

# Physics at high energy

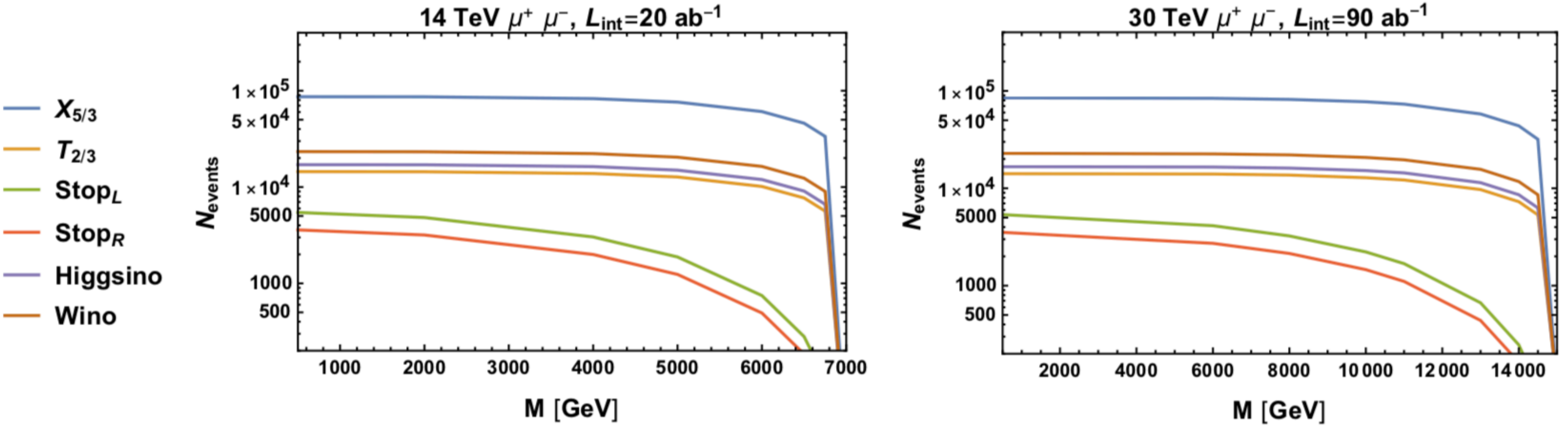
**Multi-TeV energy scale allows to explore physics beyond SM both directly and indirectly**

## Direct Reach

**Andrea Wulzer**

Discover **Generic EW** particles **up to mass threshold**

**exotic** (e.g., displaced) **or difficult** (e.g., compressed) decays to be studied

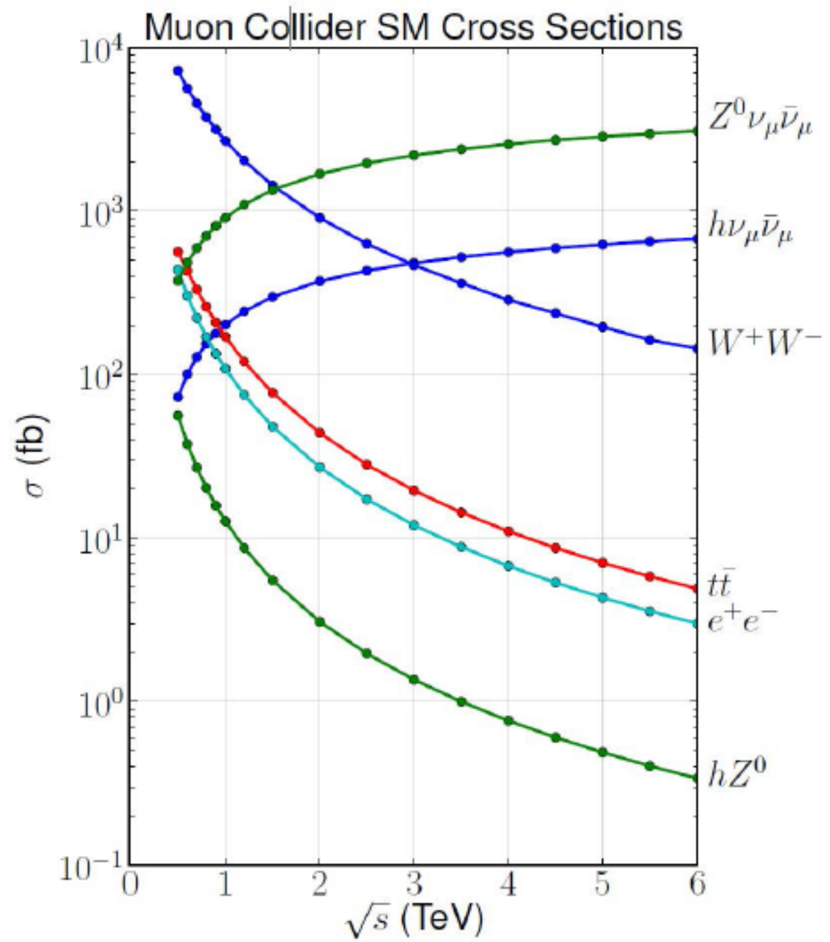


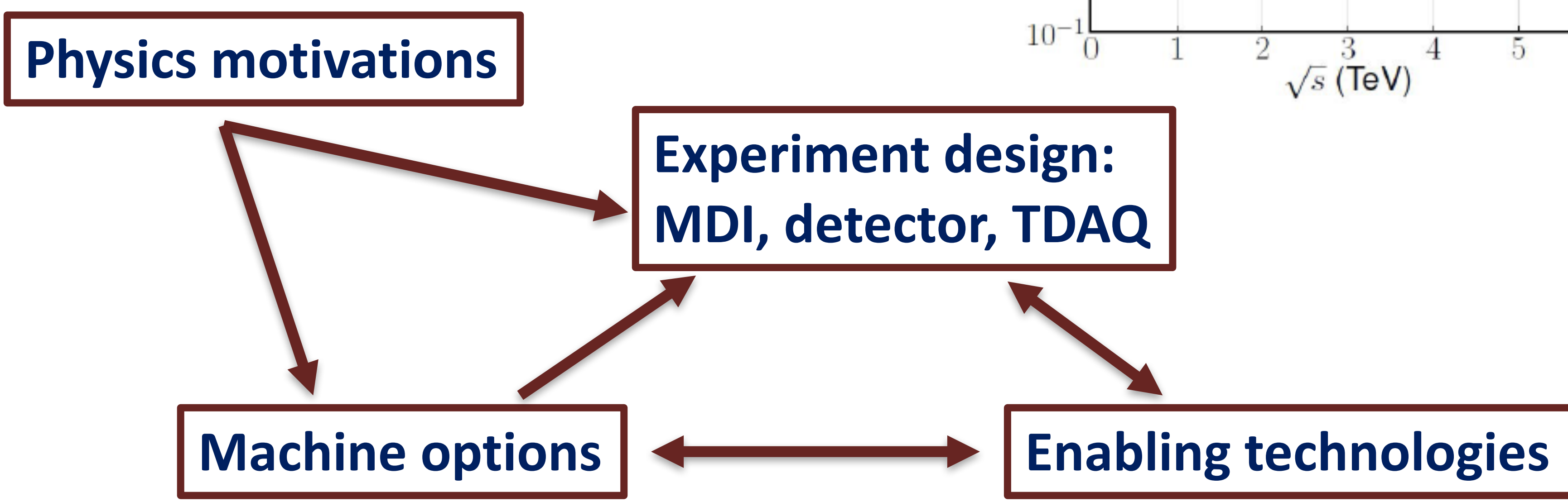
# How do we plan?

- Luminosity requirements

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

- Machine size
- Machine cost
- Efficiency of converting electrical power to luminosity



# Muons: Issues & Challenges

- **Limited lifetime: 2.2 $\mu s$ at rest**
  - Race against death: fast generation, acceleration & collision before decay
  - ☹ Muons decay in accelerator and detector
    - Physics feasibility with large background?
    - Shielding of detector and facility irradiation
  - Decays in neutrinos:
    - Ideal source of well defined electron and muons neutrinos in equal quantities :

☺

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

**The neutrino factory concept**

☹ » Limitation in energy reach by neutrino radiation

- **Generated as tertiary particles in large emittances**
  - ☹ powerful MW(s) driver
  - novel cooling method (6D $10^6$ emittance reduction)

☺ **Development of novel ideas and technologies with key accelerator and detector challenges!**

# Muon beams specific properties

**Muons are leptons with mass (105.7 MeV/c$^2$) 207 times larger than $e^{\pm}$**

➔ **Negligible synchrotron radiation emission (∞ $m^{-4}$)**

- **Multi-pass collisions (1000 turns) in collider ring:**

☺ – **High luminosity with reasonable beam power and wall plug power needs**
  - **relaxed beam emittances & sizes, alignment & stability**

– **Multi-detectors supporting broad physics communities**

– **Large time (15 ms) between bunch crossings**

☺

- **No beam-strahlung at collision:**

– **narrow luminosity spectrum**

☺

- **Multi-pass acceleration in rings or RLA:**

– **Compact acceleration system and collider**

– **Cost effective construction & operation**

☹

- **No cooling by synchrotron radiation in standard damping rings**

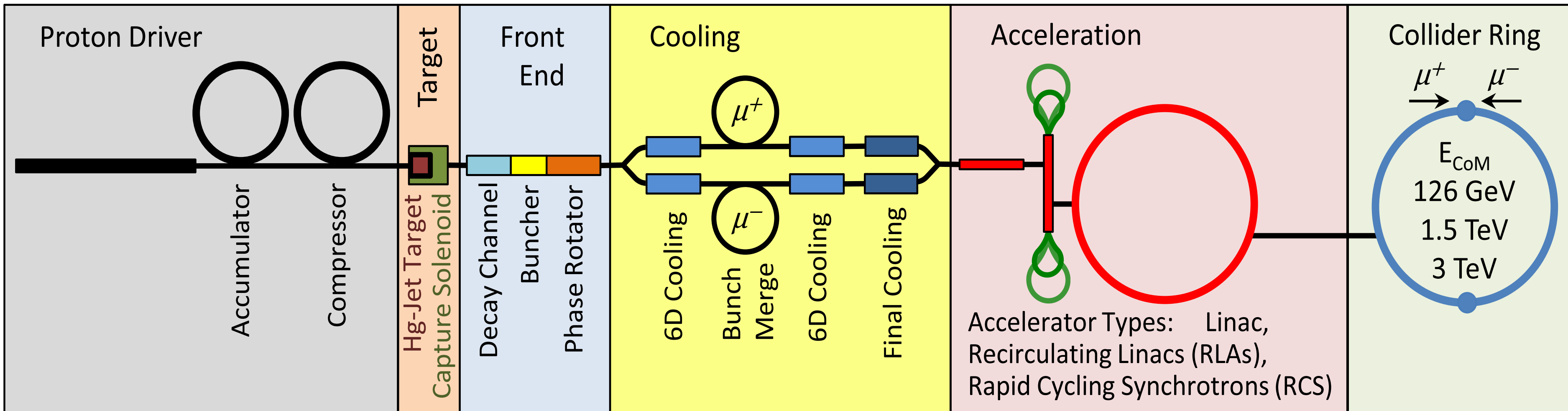
– **Requires development of novel cooling method**

# Key Parameters

From the MAP collaboration: Proton source

| Parameter | Unit | 1.5 TeV | 3 TeV | 6 TeV |
|---|---|---|---|---|
| L | $10^{34}$ $cm^{-2}s^{-1}$ | 1.25 | 4.4 | 12 |
| N | $10^{12}$ | 2 | 2 | 2 |
| $f_r$ | Hz | 15 | 12 | 6 |
| $P_{beam}$ | MW | 6.75 | 10.8 | 10.8 |
| <B> | T | 6.3 | 7 | 10.5 |
| $\varepsilon_L$ | MeV m | 7.4 | 7.4 | 7.4 |
| $\sigma_E$ / E | % | 0.1 | 0.1 | 0.1 |
| $\sigma_z$ | mm | 10 | 5 | 2(.5) |
| β | mm | 10 | 5 | 2.5 |
| ε | μm | 25 | 25 | 25 |
| $\sigma_{x,y}$ | μm | 5.9 | 3.0 | 1.5 |

# Proton driven scheme - MAP




**Key Challenges**

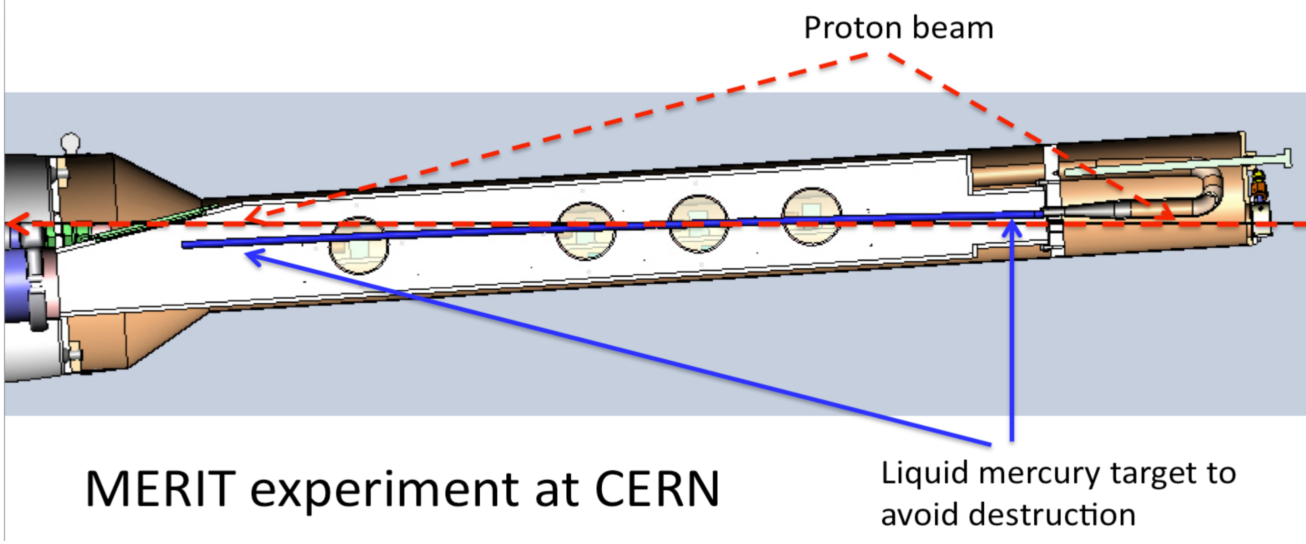
- ~$10^{13}$-$10^{14}$ μ / sec Tertiary particle $p \rightarrow \pi \rightarrow \mu$:
- Fast cooling ($\tau$=2μs) by $10^6$ (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay

**Key R&D**

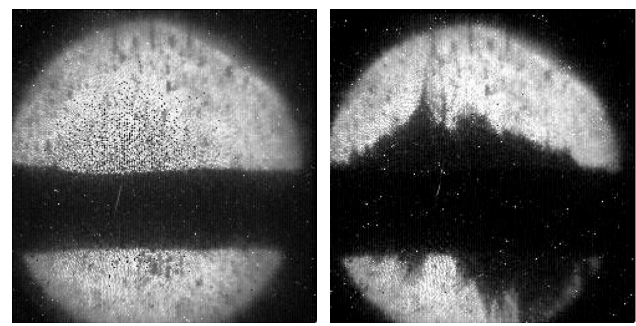
- MW proton driver; MW class target; NCRF in magnetic field
- Ionization cooling; High field solenoids (30T); High Temp Superconductor
- Cost eff. low RF SC; Fast pulsed magnet (1kHz)
- Detector/machine interface

# Source

Protons → Target → Pions → Muons




MERIT experiment at CERN



High power target (8 MW vs. 1.6-4 MW or even less required) has been demonstrated

Maximum pulse tested $30 \times 10^{12}$ protons with 24 GeV

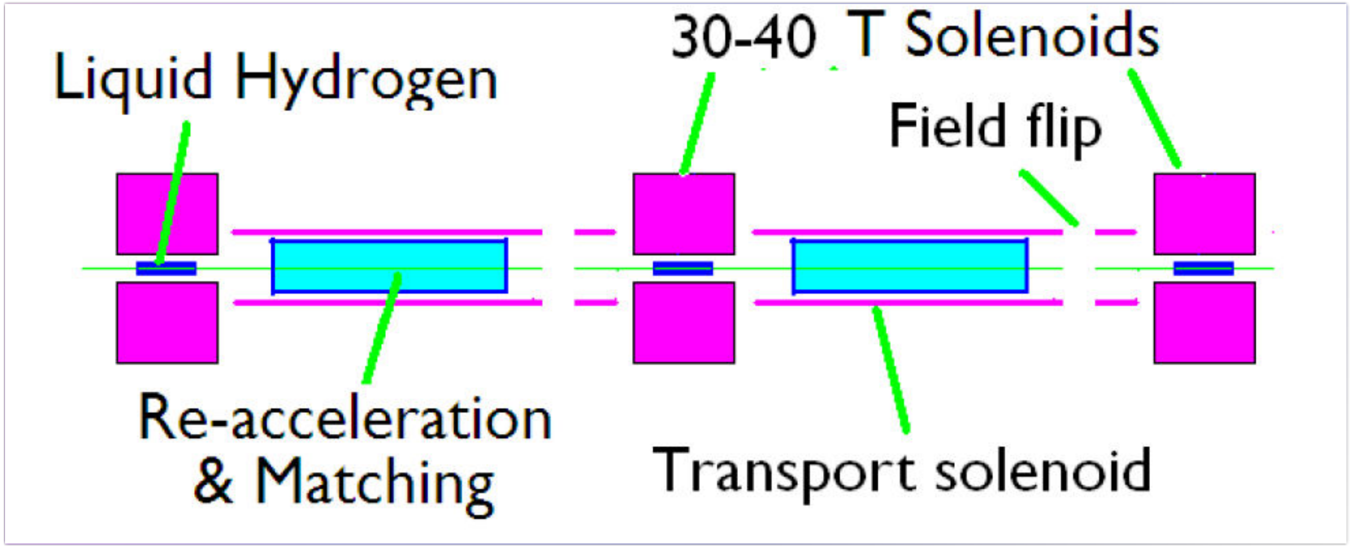
- $9 \times 10^{12}$ muons (loose 90%)

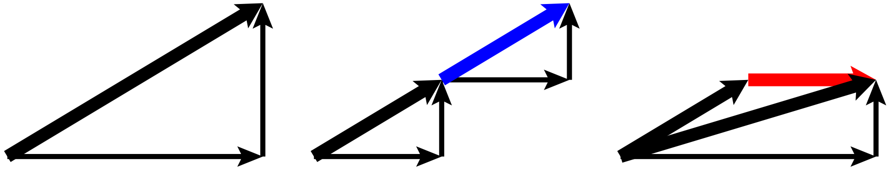
But radiation issues?

Maybe can use solid target

**What could be made available at CERN (or elsewhere) as a proton driver for a potential test facility?**

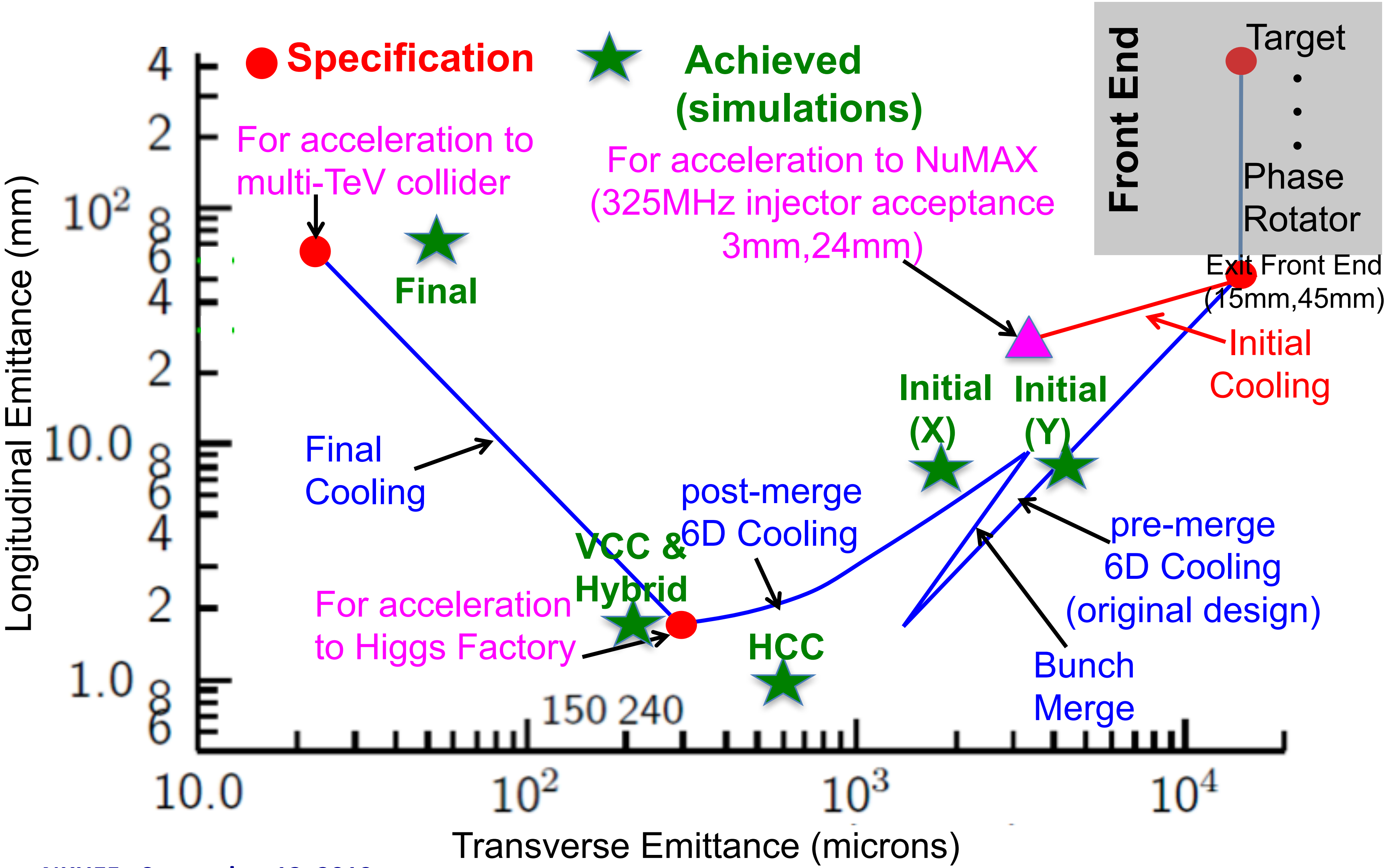
# Transverse Cooling Concept



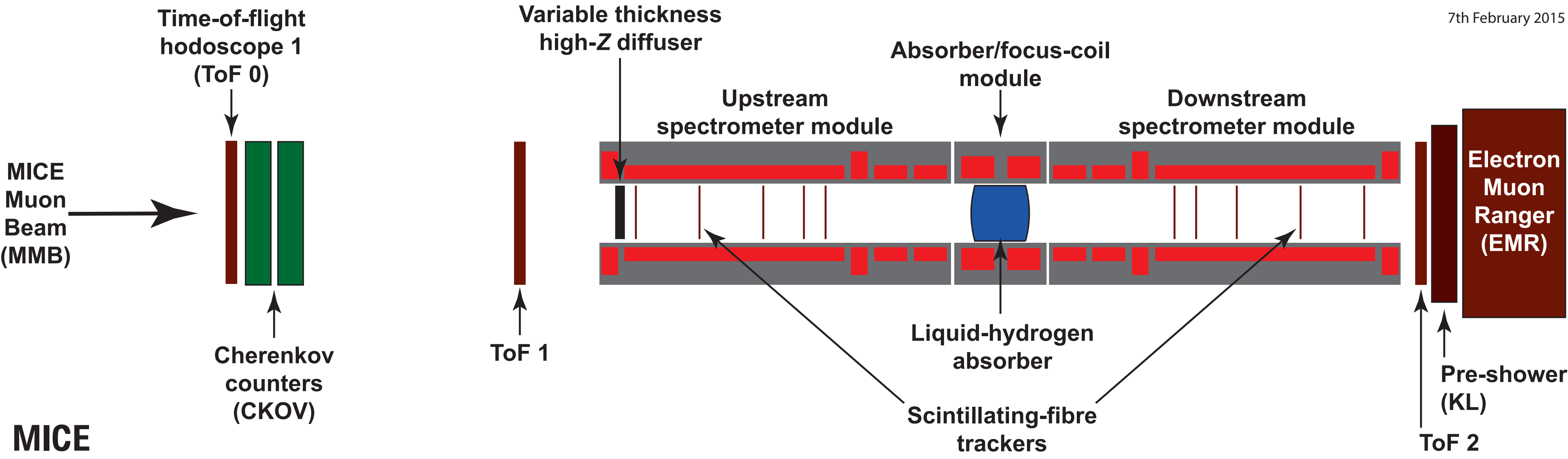




$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

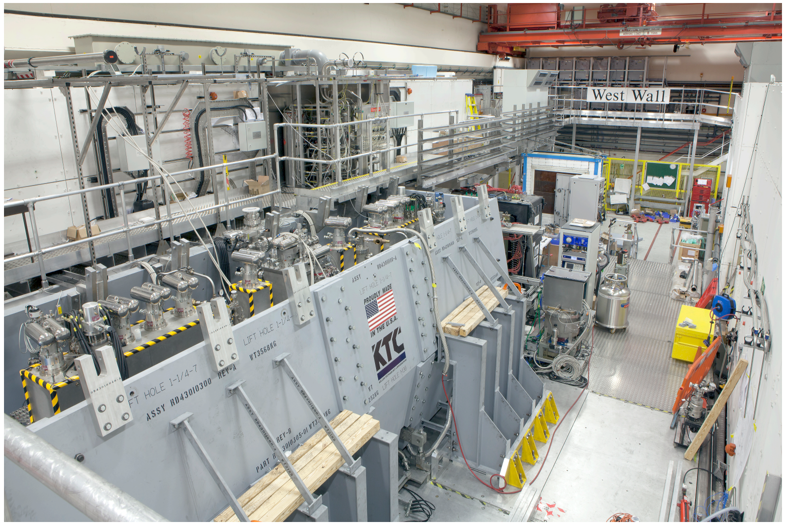
# Cooling: The Emittance Path



# Cooling and MICE




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

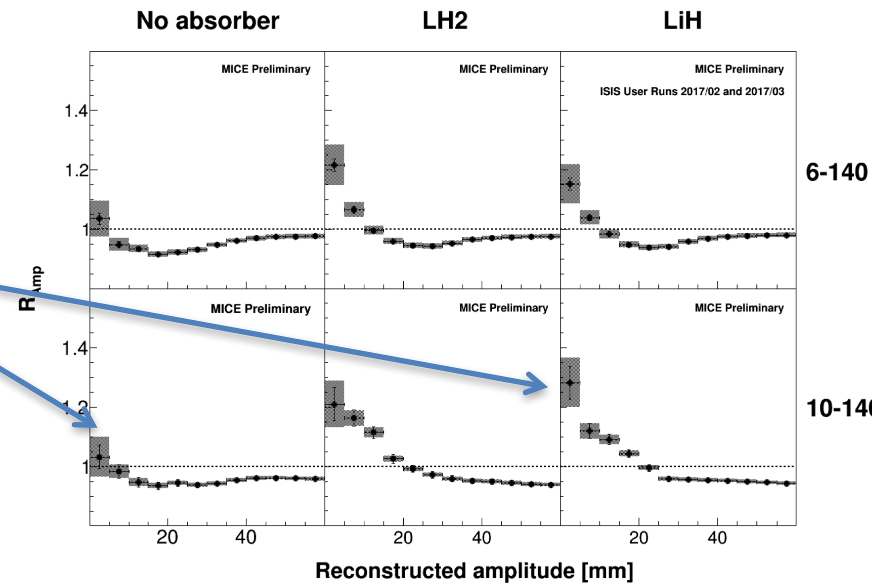



MICE allows to address 4D cooling with low muon flux rate

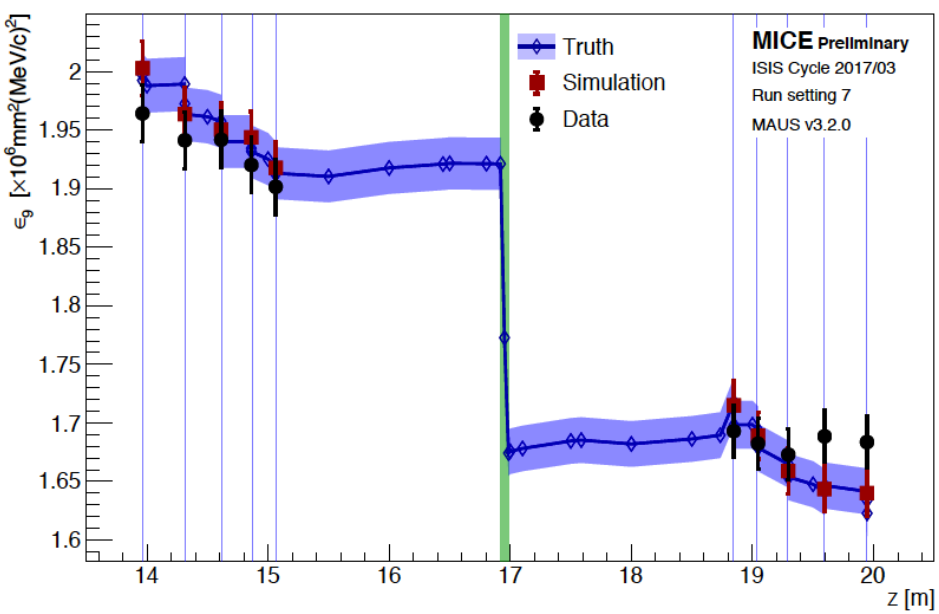
# MICE Results

The absorber reduces the number of particle with large amplitude

They appear with smaller amplitude




Noticeable reduction of 9% emittance



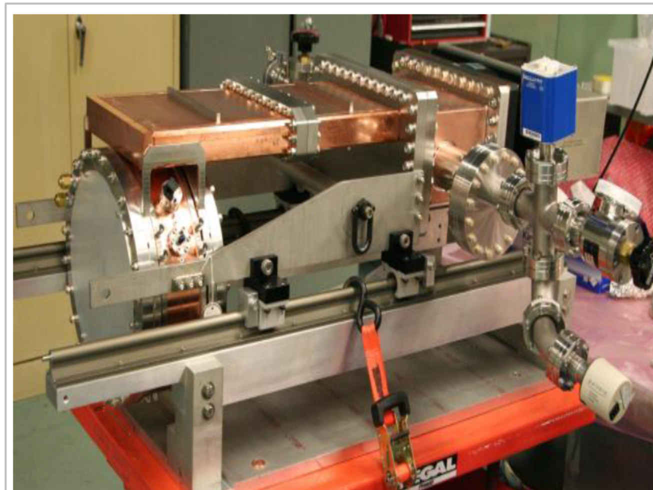

But still some way to go
- 6D cooling
- Stages
- Small emittances

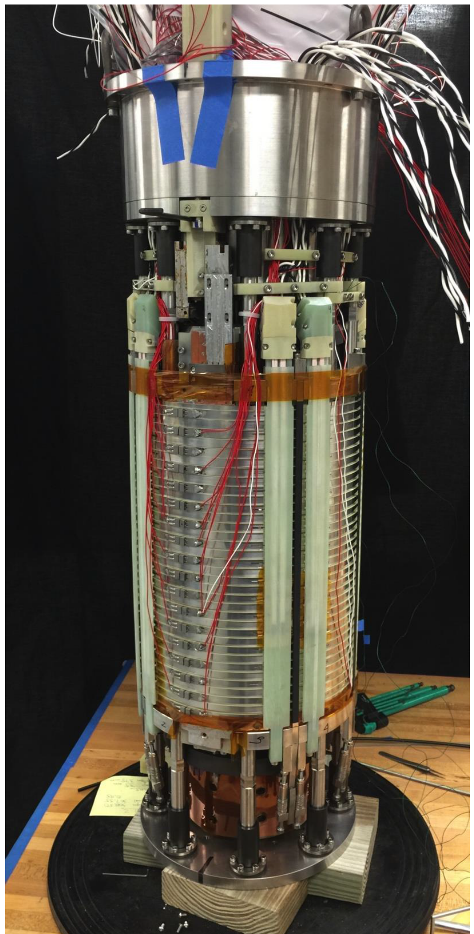
# Other Tests

**FNAL**
Breakthrough in HTS cables

A number of key components has been developed

**MuCool**: >50 MV/m in 5 T field



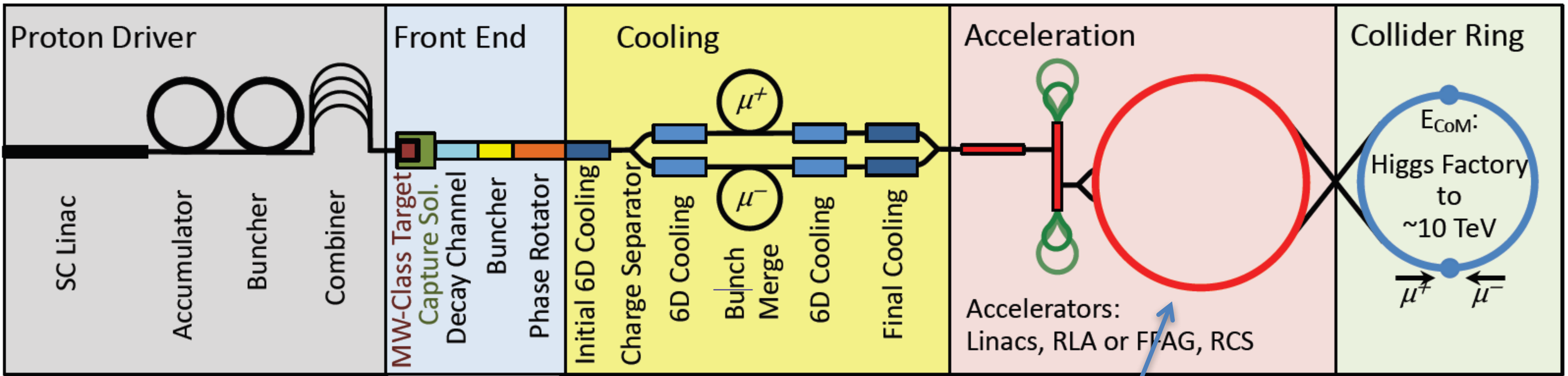


**NHFML**
32 T solenoid with low-temperature HTS

**FNAL**
12 T/s
HTS
0.6 T max

Mark Palmer

# Beam Acceleration




An important cost driver

Important for power consumption

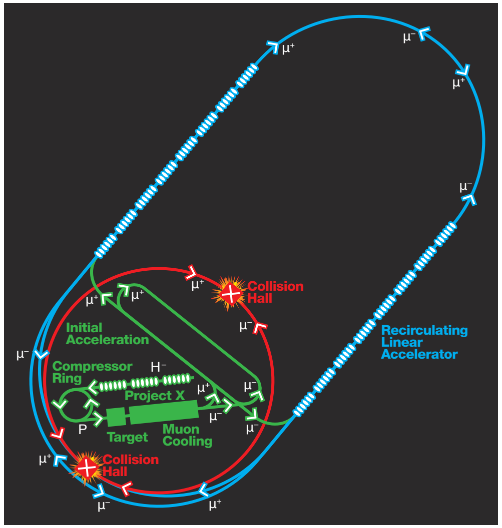
Much larger than collider ring

A trade-off between cost and muon survival

Not detailed design, several approaches considered

- Linacs
- Recirculating linacs
- FFAGs
- Rapid cycling synchrotrons

Challenge is large bunch charge but single bunch



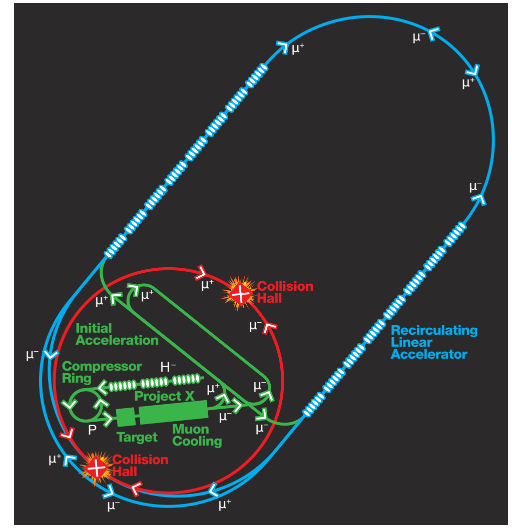
# Potential Approaches

Acceleration is important for cost and power consumption
No conceptual baseline design yet
But different options considered
A whole chain is needed from source to full energy

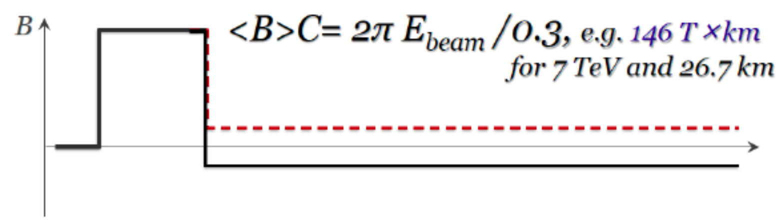
Recirculating linacs
- Fast acceleration but typically only a few passages through RF, hence high RF cost

Rapid cycling synchrotron (RCS)
- Potentially important acceleration range at affordable cost
- Could use combination of static superconducting and ramping normal-conducting magnets
- But have to deal with energy in fast pulsing magnets
- Efficient energy storage is required

FFAGs
- Static high field magnets, can reach factor up to 4 increase in energy, needs design work





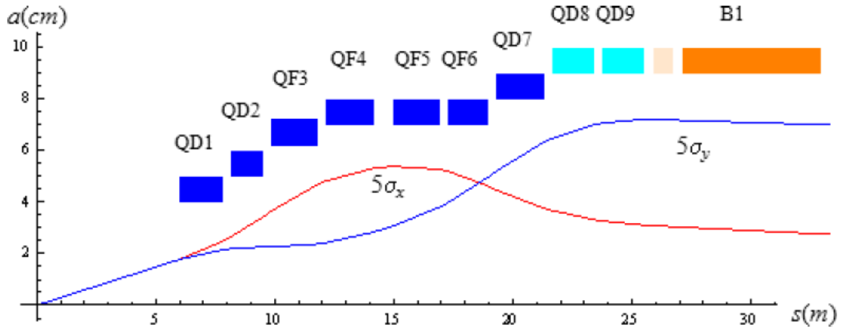



Challenge to achieve a combination of high efficiency, low cost and good beam quality

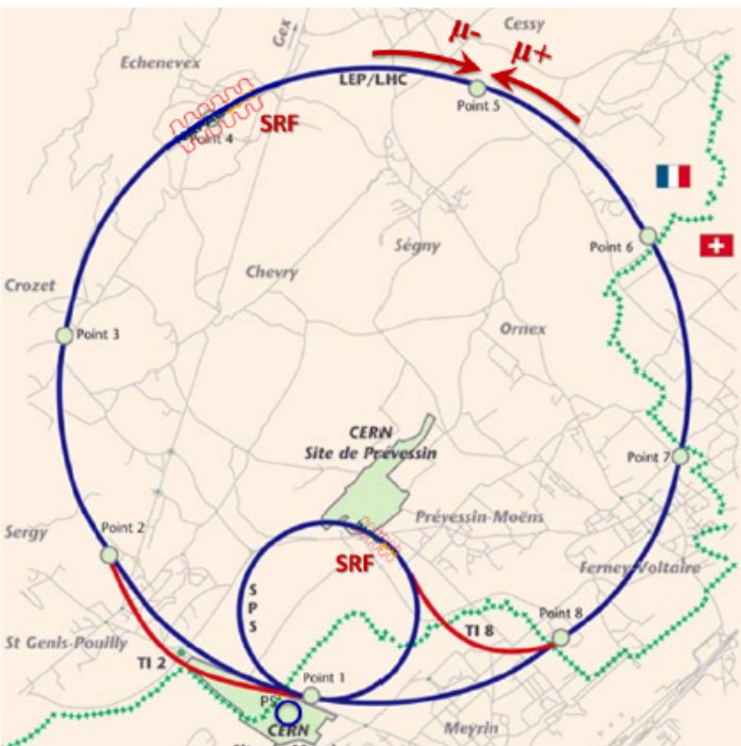
# Collider Ring

Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy

$$\beta \propto \frac{1}{\gamma}$$




High field dipoles to minimise collider ring size and maximise luminosity
Minimise distances with no bending



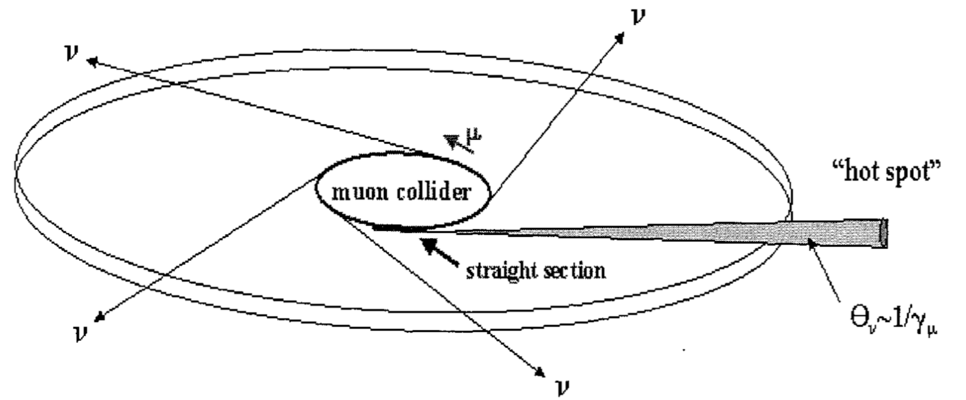

Proposal to combine last accelerator ring and collider ring (Neuffer/Shiltsev) might reduce cost but creates many specific challenges

Decaying muons impact accelerator components, detector and public
The latter becomes much worse with energy

Radiation to public in case LHC tunnel use

Might be best to use LHC tunnel to house muon accelerator and have dedicated new collider tunnel

# Neutrino Radiation Hazard




Neutrinos from decaying muons can produce showers just when they exit the earth

Approximate dose
Particularly high in direction of straights

$$D_{arc} \approx 0.41\,\mathrm{mSv}\frac{N_0 f_r T_{operate}}{10^{20}}\left(\frac{E}{\mathrm{TeV}}\right)^3 \frac{\mathrm{m}}{d}\frac{\langle B\rangle}{B}$$

$$D_{straight} \approx 0.59\,\mathrm{mSv}\frac{N_0 f_r T_{operate}}{10^{20}}\left(\frac{E}{\mathrm{TeV}}\right)^3 \frac{\mathrm{m}}{d}\frac{\langle B\rangle}{\mathrm{T}}\frac{L}{\mathrm{m}}$$

Potential mitigation by

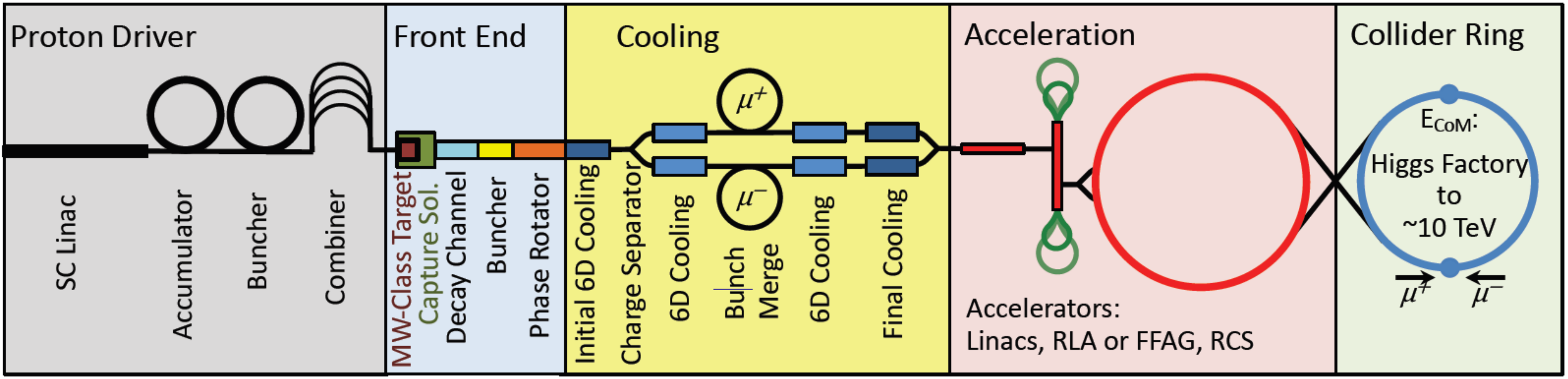
- Owning the land in direction of experimental insertion
- Having a dynamic beam orbit so it points in different directions at each turn in the arcs
- Some gymnastics with beam in straights to make it point in different directions

Need to study for higher energies (scaling $E^3$)

Dose is proportional to integrated luminosity times energy

Straights in LHC might increase problem
⇒ Another reason to consider this as accelerator

# Proton-driven Muon Collider Concept




**Short, intense proton bunches to produce hadronic showers**

**Pions decay into muons that can be captured**

**Muon are captured, bunched and then cooled**

**Acceleration to collision energy**

**Collision**

# Target Parameter Examples

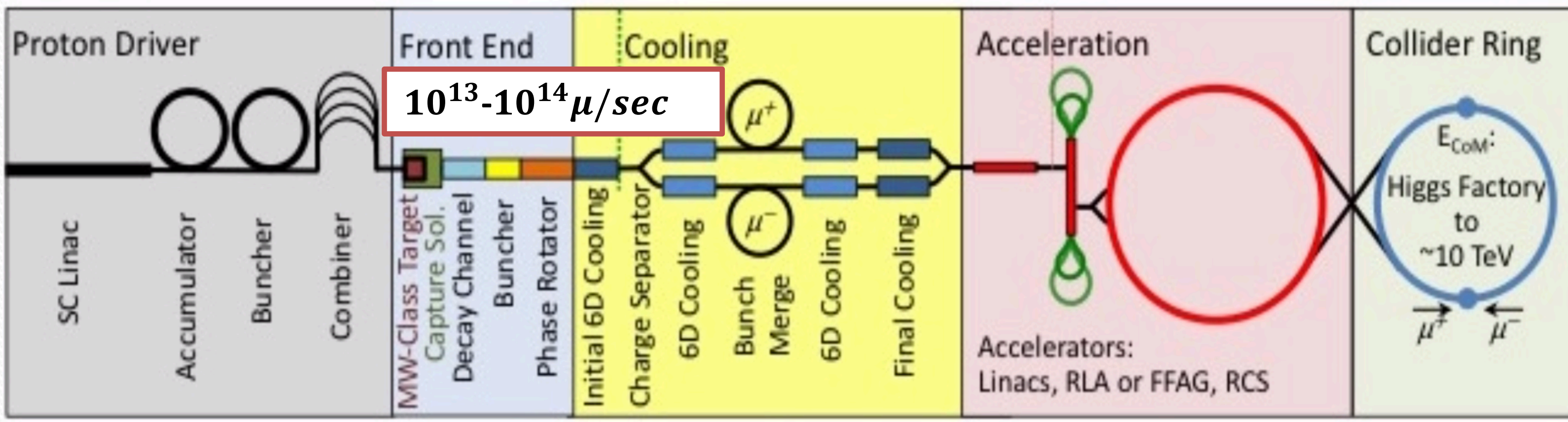
**Muon Collider Parameters**

| | | Higgs | Multi-TeV | | |
|---|---|---|---|---|---|
| ***Parameter*** | ***Units*** | *Production Operation* | | | *Accounts for Site Radiation Mitigation* |
| CoM Energy | TeV | **0.126** | **1.5** | **3.0** | **6.0** |
| Avg. Luminosity | $10^{34}cm^{-2}s^{-1}$ | 0.008 | 1.25 | 4.4 | 12 |
| Beam Energy Spread | % | 0.004 | 0.1 | 0.1 | 0.1 |
| Higgs Production/$10^{7}$sec | | 13,500 | 37,500 | 200,000 | 820,000 |
| Circumference | km | 0.3 | 2.5 | 4.5 | 6 |
| No. of IPs | | 1 | 2 | 2 | 2 |
| Repetition Rate | Hz | 15 | 15 | 12 | 6 |
| $\beta$* | cm | 1.7 | 1 (0.5-2) | 0.5 (0.3-3) | 0.25 |
| No. muons/bunch | $10^{12}$ | 4 | 2 | 2 | 2 |
| Norm. Trans. Emittance, $\varepsilon_{TN}$ | $\pi$ mm-rad | 0.2 | 0.025 | 0.025 | 0.025 |
| Norm. Long. Emittance, $\varepsilon_{LN}$ | $\pi$ mm-rad | 1.5 | 70 | 70 | 70 |
| Bunch Length, $\sigma_s$ | cm | 6.3 | 1 | 0.5 | 0.2 |
| Proton Driver Power | MW | 4 | 4 | 4 | 1.6 |
| Wall Plug Power | MW | 200 | 216 | 230 | 270 |

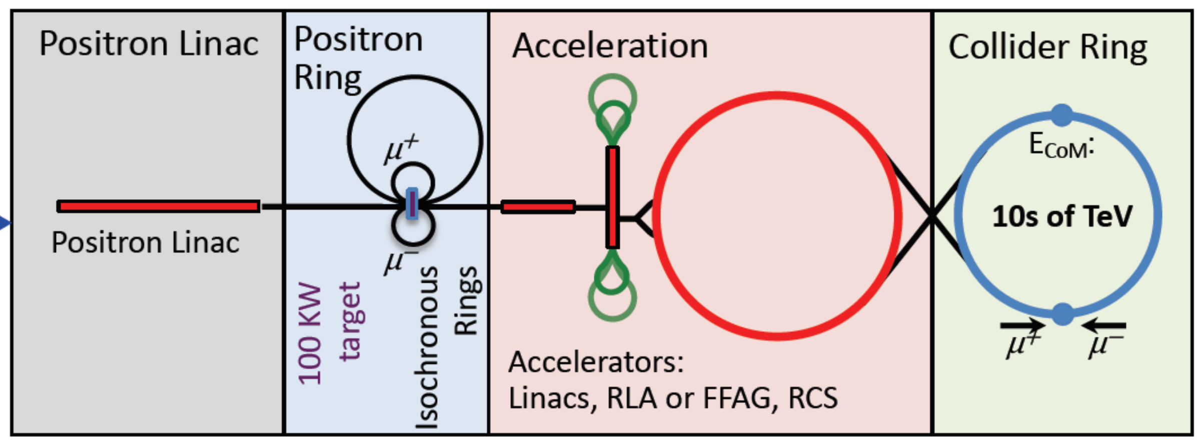
Even at 6 TeV above target luminosity with reasonable power consumption
But have to confirm power consumption estimates

# proton (MAP) vs positron (LEMMA) driven muon source

**MAP**




**Low EMmittance Muon Accelerator (LEMMA):**
$10^{11}$ μ pairs/sec from $e^+e^-$ interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



# LEMMA: main idea

# *Low EMittance Muon Accellerator*

M. Antonelli and P. Raimondi, Snowmass Report (2013) - INFN-13-22/LNF Note

**POSITRON DRIVEN MUON SOURCE : direct $\mu$ pairs production**

Muons produced from $e^+e^- \to \mu^+\mu^-$ at the $\mu^+\mu^-$ threshold @ $\sqrt{s} \approx$ **0.212 GeV**

Asymmetric collisions maximize the $\mu^+\mu^-$ pairs production cross section and minimize the $\mu^+\mu^-$ beam angular divergence and energy spread

➔ **45 GeV positron beam impinging on a target** ($e^-$ at rest)

➔ $\mu^+\mu^-$ produced **@ ~22 GeV** with low transverse emittance with $\gamma(\mu) \approx$ **200** and $\mu$ laboratory **lifetime** of about **500 $\mu$s**

Aimed at obtaining high luminosity with relatively small $\mu^\pm$ fluxes thus reducing background rates and activation problems due to high energy $\mu^\pm$ decays

# Extremely promising

1) muon produced with low emittance ➔ "no/low cooling" needed
2) muon produced already boosted with low energy spread

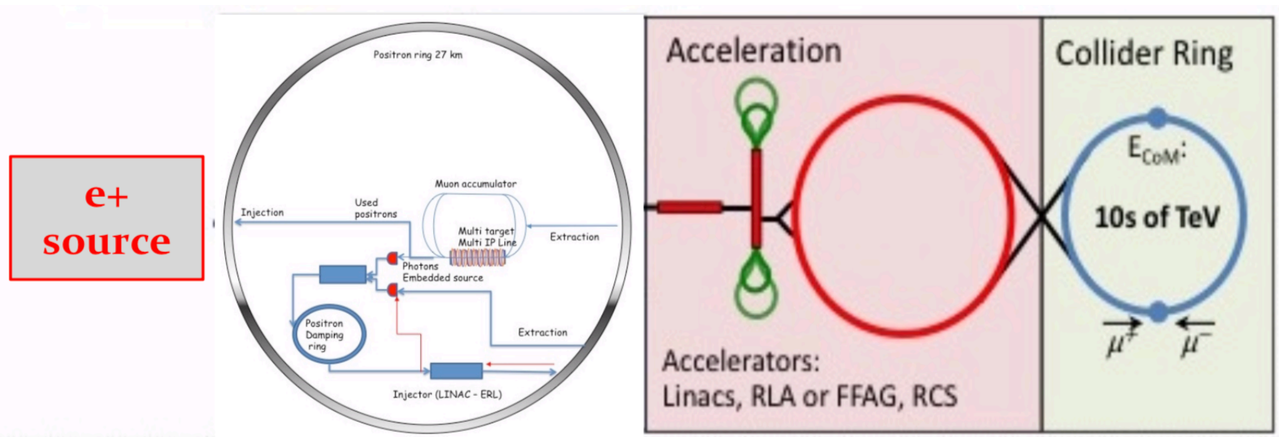
# But difficult

1) **Low** production **cross section**: maximum $\sigma(e^+e^- \to \mu^+\mu^-) \sim 1\ \mu$b
2) **Low** prodution **efficiency** ($\sim 9\times10^{-8}$ μ per $e^+$ using a 3 mm Be target)
3) **Bremsstrahlung** (high Z → $Z^2$) & **multiple scattering** ($\sqrt{X_0}$) in production target
4) **High heat load** and **stress** in μ production target
5) **Synchrotron power** O(100 MW) ⇦ available 45 GeV positron sources

➔ **need for consolidation** to overcome some technical limitations

LEMMA

[arXiv:1905.05747](arXiv:1905.05747)



# LEMMA: main design requirements

- **Positron Source** like CLIC/ILC ➔ ***1 x $10^{14}$ $e^+$/s*** ➔ injection 5 s
- **Damping Ring** has to provide **fast $e^+$ cooling**, limiting total collider cycle

*Lattice may be similar to the main Positron Ring*
*A DR similar to ILC one could provide needed damping time (12 msec) and emittance*
➔ *about 100 wigglers (ILC type) to be installed*
➔ *a shorter ring (i.e. 6.3 km) is preferred to minimize number of damping wigglers*
*First injection - no time constraints, then **1000 bunches** with **5 x $10^{11}$ $e^+$** need to be injected*

- 45 GeV **Positron Ring**: high energy acceptance and low emittance with 27 km ring
➔ *choice of final lattice based on the larger energy acceptance: it is mandatory to successfully re-inject all the "spent" beam from the muon production to be later decelerated and re-injected in the DR for cooling*
***100 km solution will increase the luminosity of at least a factor 3.5***

- **Multi-target system** to alleviate issues due to power deposited and integrated PEDD (*)

**Source needed to replace the positrons lost in the muon production process is a real challenge, since the time available is very short**

(*) Peak Energy Density Deposition

# LEMMA muon source new scheme

arXiv:1905.05747

A viable accelerator complex layout has to overcome known technical limitations:

- too large required # of $e^+$ from source with respect to state-of-the-art (ILC, CLIC)
- too large instantaneous and average energy deposited on production target
- muon bunch charge must be increased

A new scheme envisage a reasonable R&D program to verify the feasibility of the proposed layout, assuming the $e^+$ beam is extracted and imping on external targets

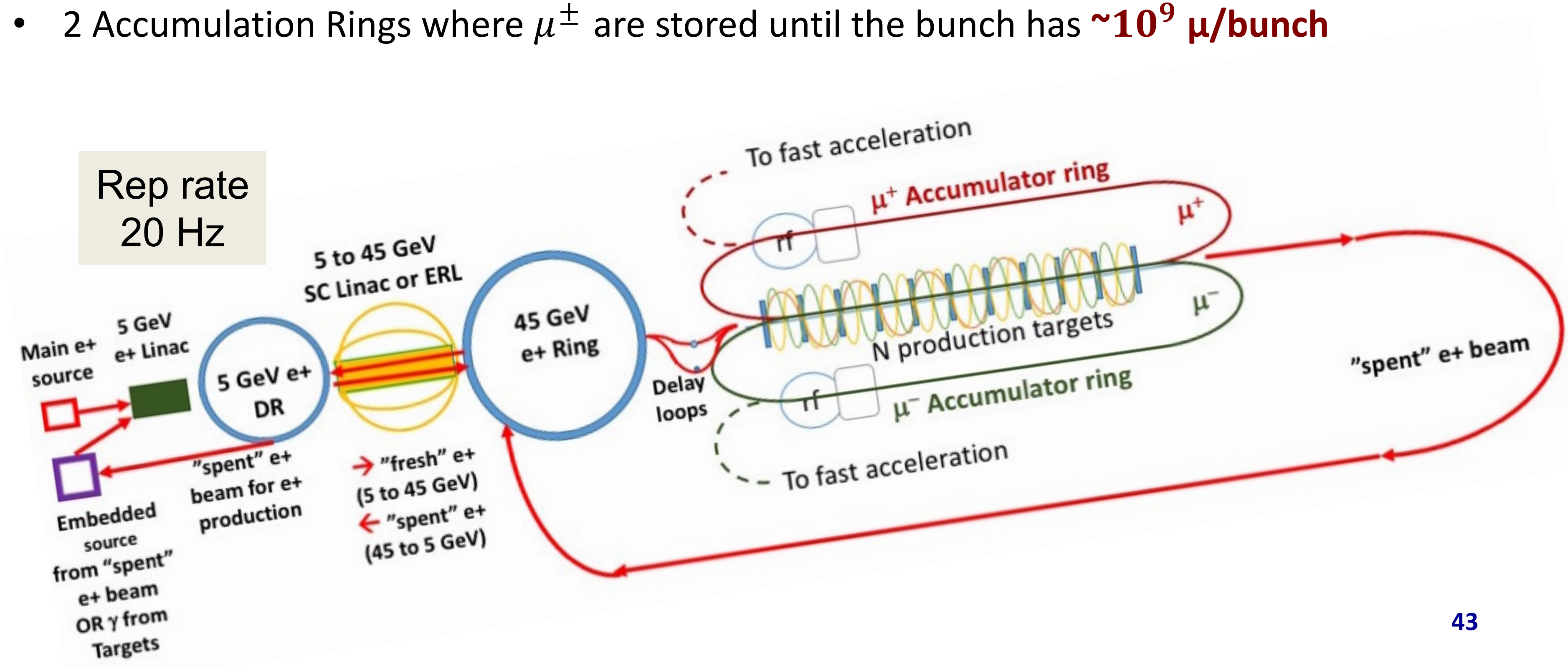
Precise requirements set on the muon source chain:

- complete **μ** production cycle **~410 μs** (lifetime = 467 μs @ 22.5 GeV)
- one complete cycle must last enough time for $e^+$ production and damping
- damping time must be compatible with a reasonable amount of synchrotron power emitted → Damping Ring to cool $e^+$ at lower energy
- possibility to recuperate $e^+$ bunches "*spent*" after the **μ** production, to produce $e^+$ ("*embedded*" $e^+$ source)
- study of **different types of targets** (material, thickness, resistance to heating,…)

# Complex layout

- $e^+$ **source** @300 MeV → 5 GeV Linac
- 5 GeV $e^+$ **Damping Ring** (damping ~10 ms)
- **SC Linac or ERL**:
  from 5 → 45 GeV and 45 → 5 GeV to cool spent $e^+$ beam after $\mu^\pm$ production
- **45 GeV $e^+$ Ring** to accumulate **1000 bunches**: **$5\times10^{11}$ $e^+$/bunch** for $\mu^\pm$ production and e+ spent beam after $\mu^\pm$ production, for slow extraction towards decelerating Linac and the DR
- Delay loops to synchronize $e^+$ and $\mu^\pm$ bunches
- **One (or more) Target Lines** where $e^+$ beam collides with targets for direct $\mu^\pm$ production
- 2 Accumulation Rings where $\mu^\pm$ are stored until the bunch has **~$10^9$ μ/bunch**

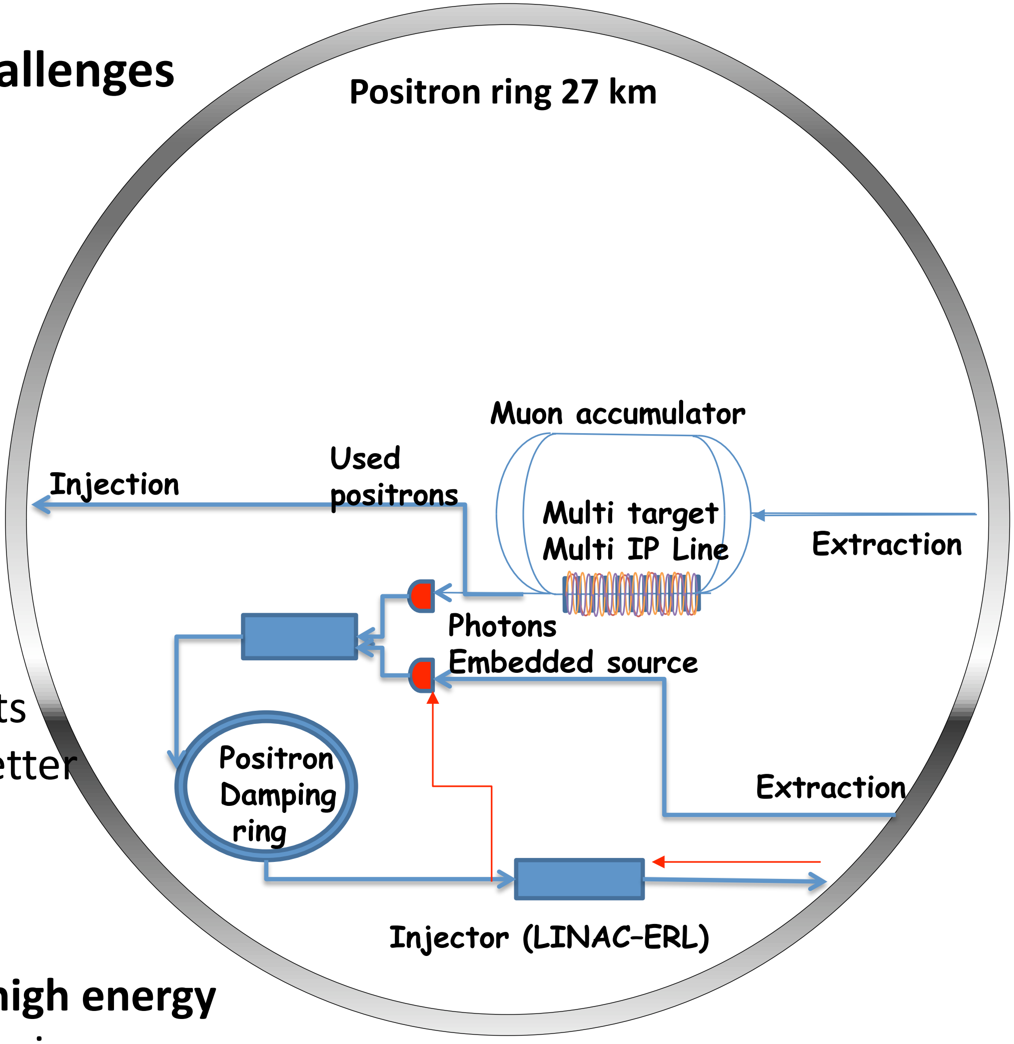
Rep rate
20 Hz



# Ongoing LEMMA Effort

## Ongoing effort to address identified challenges

- **Positron production**
  - Rotating target (like ILC)
  - Use of positron beam for production
- **Positron ring challenge**
  - larger ring, pulsed ring, lower energy accumulator ring
- **Large emittance from target**
  - use sequence of thin targets, $H_2$ targets
  - Increased muon bunch charge, e.g. better capturing, …
  - muon cooling (crystals, stochastic, …)
- **Difficulty of combining muon bunches at high energy**
  - Increasing charge at the source (producing bunches in pulsed fashion)
  - increase muons per positron bunch



# How many $e^+$/s do we need?

- **Repetition frequency 20 Hz, $t_{cycle}$ 50 ms**

  10 ms to produce the $e^+$ and inject into the Damping Ring

  30 ms to damp the beam

  10 ms to extract, accelerate and inject the beam in the main $e^+$ ring at 45 GeV
- **$e^+$ production rate:** $1000 \times \mathbf{5{\times}10^{11}}\ e^+$**/bunch = $\mathbf{5{\times}10^{16}}\ e^+$/s**
- **This is ~500 times the CLIC and ILC rate, too much !?**

- **Repetition frequency 10 Hz, $t_{cycle}$ 100 ms**
  - The luminosity is a factor 2 lower
  - We assume to inject the bunches as soon as they are extracted, using for the injection also the extraction time

    70 ms to produce the $e^+$ and inject into the Damping ring

    30 ms to damp the beam
- $e^+$ production rate: $1000 \times \mathbf{5{\times}10^{11}}/0.07 = \mathbf{7{\times}10^{15}}\ e^+$/s
  - **This is ~70 times the CLIC and ILC rate, still too much…. But closer**

# Positron Source

- $e^+$ source has to provide trains of **1000 bunches with 5 x $10^{11}$ $e^+$/bunch**
- source needed to replace **$e^+$ lost** in the **$\mu$ production** is challenging since the time available to produce, damp and accelerate the $e^+$ is very short (50 ms)
- **~70%** of the **$e^+$ after $\mu$ production** can be recovered, injected in the PR, slowly (~20 ms) extracted, decelerated and injected in a DR for topping up
- Therefore only **~30%** of the required **$e^+$** needs to be produced by the source in a time cycle **$t_{cycle}$ = 50 ms** → **required $e^+$ production rate is 3x$10^{15}$ $e^+$/s**
- Techniques developed for the future linear colliders like **hybrid targets** (crystal + tungsten targets) and **rotating targets** will be explored and R&D on new targets will be developed

# Muon Accumulators

**2 Muon Accumulator Rings**

will store the $\boldsymbol{\mu}^{+}$and $\boldsymbol{\mu}^{-}$produced over several passages of the $\boldsymbol{e}^{+}$ beam

➔ their length must match the timing between $\boldsymbol{e}^{+}$ bunch passages,

i.e. new $\mu^{\pm}$ are created at the moment of passage of the stored $\boldsymbol{\mu}$

to **increase $\mu$ bunch intensity**

➔ they must be short: a large number of turns are complete before $\mu^{\pm}$ decay

A preliminary compact design (123 m circumference) was optimized to get small momentum compaction factor, allowing the recirculation of the $\mu^{\pm}$ beam every **410 ns**, to complete **1000 turns** in one $\mu^{\pm}$ lifetime at **22.5 GeV**

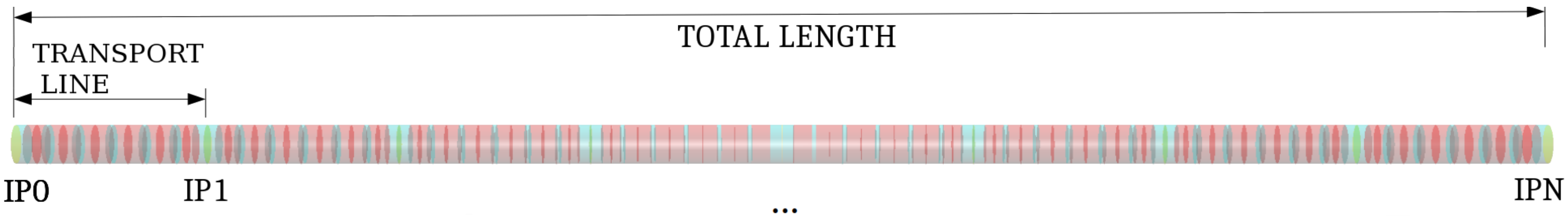
➔ A preliminary "**separation**" region after production, common to $\boldsymbol{e}^{+}$ $\boldsymbol{\mu}^{+}$and $\boldsymbol{\mu}^{-}$ for the 3 beams was designed

# Target Line

- $e^+$ bunches will be extracted from the PR and transported to one (or more) external line where $\boldsymbol{\mu}$ are produced by the $\boldsymbol{\mu}$ impinging on targets
- Delay loops will provide the right timing between the $e^+$ bunches and the $\boldsymbol{\mu}$ bunches already produced
- Two designs studied up to now:
  - **Multiple Interaction Points** (10 IP, 10 targets)
  - **Single Interaction Point** (1 IP, 10 targets)

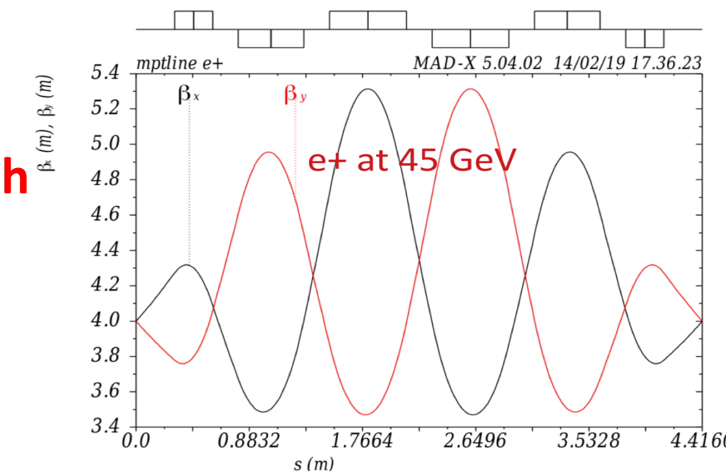
# Multiple IPs Target Line

- Targets are separated by a transport line with magnets common to 3 beams ($\boldsymbol{e^+ \mu^+ \mu^-}$)
- Line must focus (low β) the beams at each IP to achieve the production of new $\boldsymbol{\mu}$ with minimal growth of the final $\boldsymbol{\mu}$ beam emittance
- Length should be as small as possible in order to minimize $\boldsymbol{\mu}$ decay issues
- Chromaticity cannot be corrected with standard method, because this would split the 3 beams → other method used to mitigate the chromatic effect

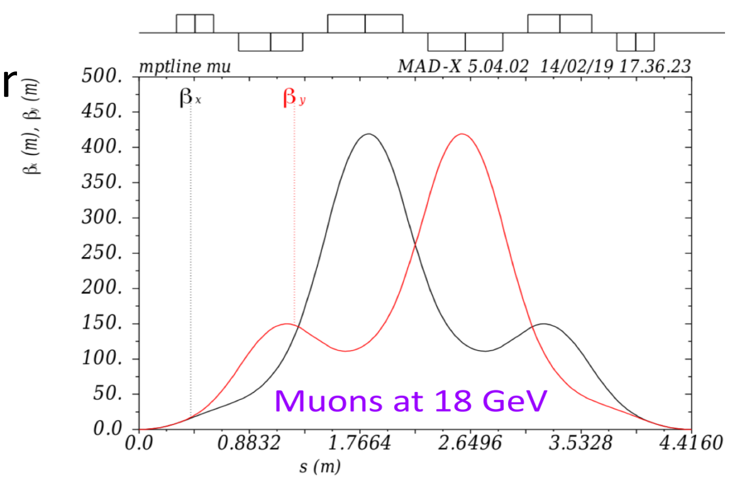


# Multiple IPs transport line optics

- Targets separated by a transport line where magnets are **common to the three beams** (*e*+, μ+ and μ−), focusing the beams at each IP to achieve the production of new muons with **minimal growth to the final beam emittance.**
- **Best lattice design:** Lenght < 5 m
- magnet gradient at 200 T/m; aperture radius 1 cm

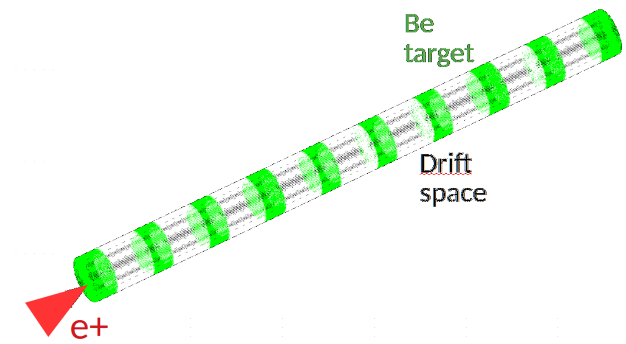


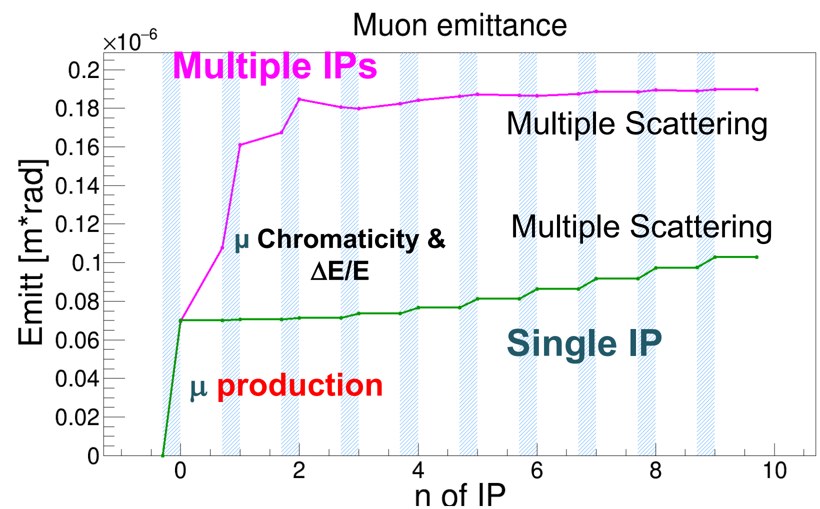

- **Two triplets** are used to focus the beams on both transverse planes, and they are put in asymmetry in order to **partially cancel chromaticity** at 45 GeV as in the apochromatic design
- For an $\mathbf{e^+}$ beam spot at the first target of $\sigma_{e+}$ = 150 μm and 6 nm $\mathbf{e^+}$ beam emittance, the produced $\boldsymbol{\mu}$ emittance is 70 nm (see next slide, magenta line) and grows up to 200 nm, a factor two with respect to the initial $\boldsymbol{\mu}$ emittance



# Single IP Target Line

- One target is cut in 10 thin slices, each one separated by short drifts in order to give space for power dissipation on target
- For an $e^+$ beam spot at the first target of $\sigma_{e+}$ = 150 μm and 6 nm emittance the produced μ emittance is 70 nm (green line) and grows up to 110 nm
- A smaller $e^+$ beam spot $\sigma_{e+}$ (smaller $\beta^*$) at the target gives smaller μ emittance, the limit is the target resistance to temperature and stresses
- Different $\sigma_{e+}$ on target are being studied, as well as different target materials, since this parameter is crucial both for the final μ emittance and for the amount of deposited energy and temperature rise of the target

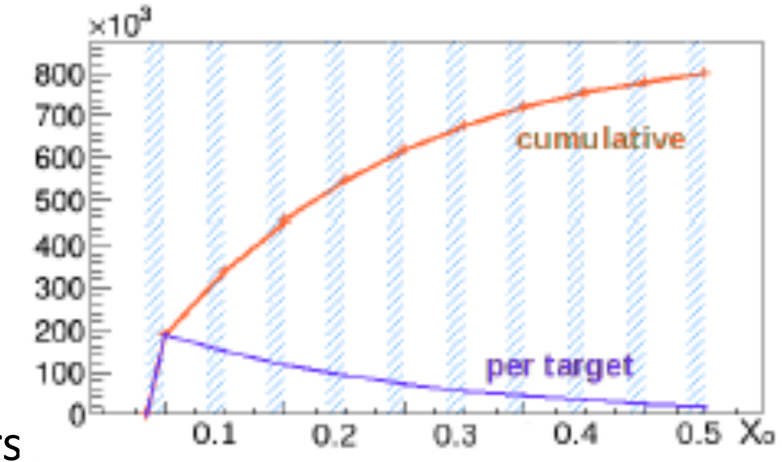



Comparison of μ emittance growth for the Multiple IPs (magenta) and Single IP (green) for same $e^+$ spot on target (150 μm) vs target number

# Muon production efficiency

- The $e^+$ beam loses energy due to the effect of bremsstrahlung in the targets
- While the $e^+$ population is not reduced, the number of produced $\mu$ decreases because less particles remain above the $\mu$ production threshold at 43.7 GeV
- As almost 90% of the $\mu$ are produced in the firs 6 targets, equivalent to 0.3 Xo (10.6 cm Be), this number was used to calculate the target production efficiency, i.e. the ratio of $\mu$ pairs produced by $e^+$ impinging on a target, $\mu/e^+$
- Efficiency evaluated for different target materials




**Number of μ pairs produced by $5 \times 10^{11}\ e^+$ impinging 10 Be targets of 5% radiation length each. The $e^+$ beam population above 43.7 GeV is reduced by bremsstrahlung**

➡

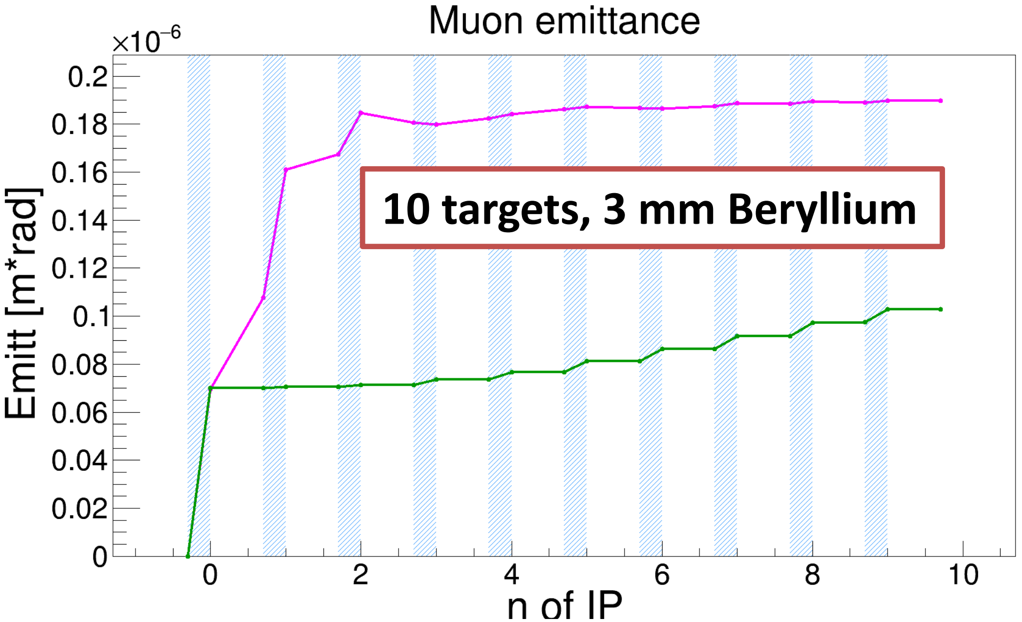
| Material | Density [g/cm$^3$] | Length [m] | Length [$X_0$] | eff [$10^{-6} \mu/e^+$] |
|---|---|---|---|---|
| Be | 1.85 | 0.106 | 0.3 | 1.3 |
| C | 2.27 | 0.057 | 0.3 | 1.0 |
| C A412 | 1.7 | 0.075 | 0.3 | 1.0 |
| $H_2$ | 0.07 | 2.664 | 0.3 | 2.9 |

# Muon production requirements

- Beamline has to maximize muon production ➔ constraint @ target $e^+$ spot size/divergence
- Beamline has to preserve $e^+$ beam (to relax $e^+$ source requirements)

  ➔ constraint to the target but also to the energy acceptance of the beamline
- Beamline as short as possible due to the short lifetime of muons
- Many different **multi-IP beamline optics** (need to split the power on target)
- **Multi-IP beamline optics** made of regular unit cells where targets are placed at the beginning and at the end of each cell.
- Three beams will pass through this beamline: **$e^+$**, $\mu^+\mu^-$

**Comparison of μ emittance growth in the Multiple (magenta) and Single (green) IP schemes.**
**The $e^+$ beam size is 150 μm.**

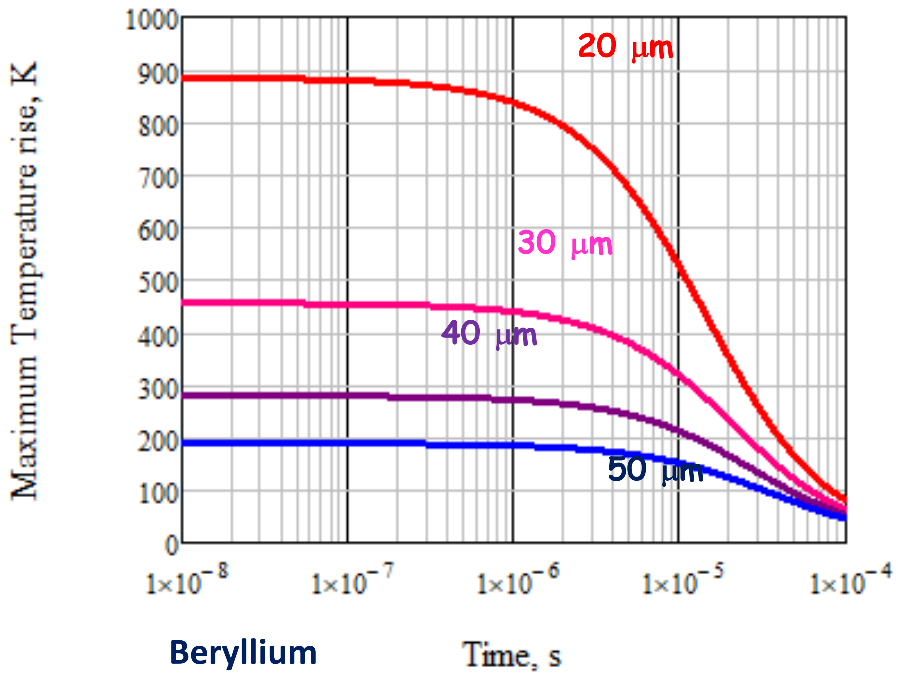


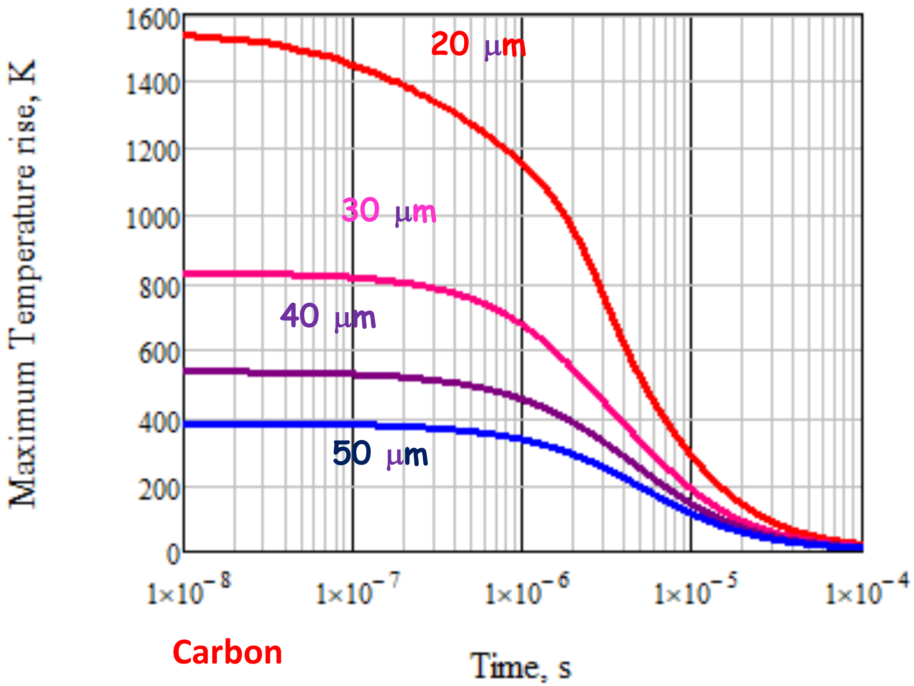
# Target studies

- Both temperature rise and thermal shock related to the $e^+$ beam spot on target
- For a given material the lower limit on the beam size is obtained when there is no pile-up of bunches on the same target position
  → **ideal: both target and $e^+$ beam move**
- **Fast moving targets** can be obtained with rotating disks for solid targets or high velocity jets for liquids
- A power deposition of about **30 kW** is expected for a **0.3 $X_0$** target. The target has to be therefore sliced in many thin targets to easy the power removal
- Recently developed **Carbon based** materials with excellent thermo-mechanical properties are under study for the LHC upgrade collimators
- First study of thermal behavior performed both for **3 mm Be** and **1 mm C** targets
  → an ILC-like rotating system could be used
- Future R&D on **Liquid jet target, $H_2$** pellet/spaghetti (twice more **μ**, less multiple scattering, but difficult to realize) and **crystals**

# Target studies

Different target material:   carbon, hydrogen, liquids, pellet…
Rotation target / multi an single IP test, target rotation and target cooling feasibility
Hydrogen - Spaghetti target instead of pellets
Curved crystals as recombiner, crystal cooling
MW class target for positron source




**Increase in target surface temperature**

(varying the spot size of the Gaussian beam)

# Future R&D

arXiv:1905.05747

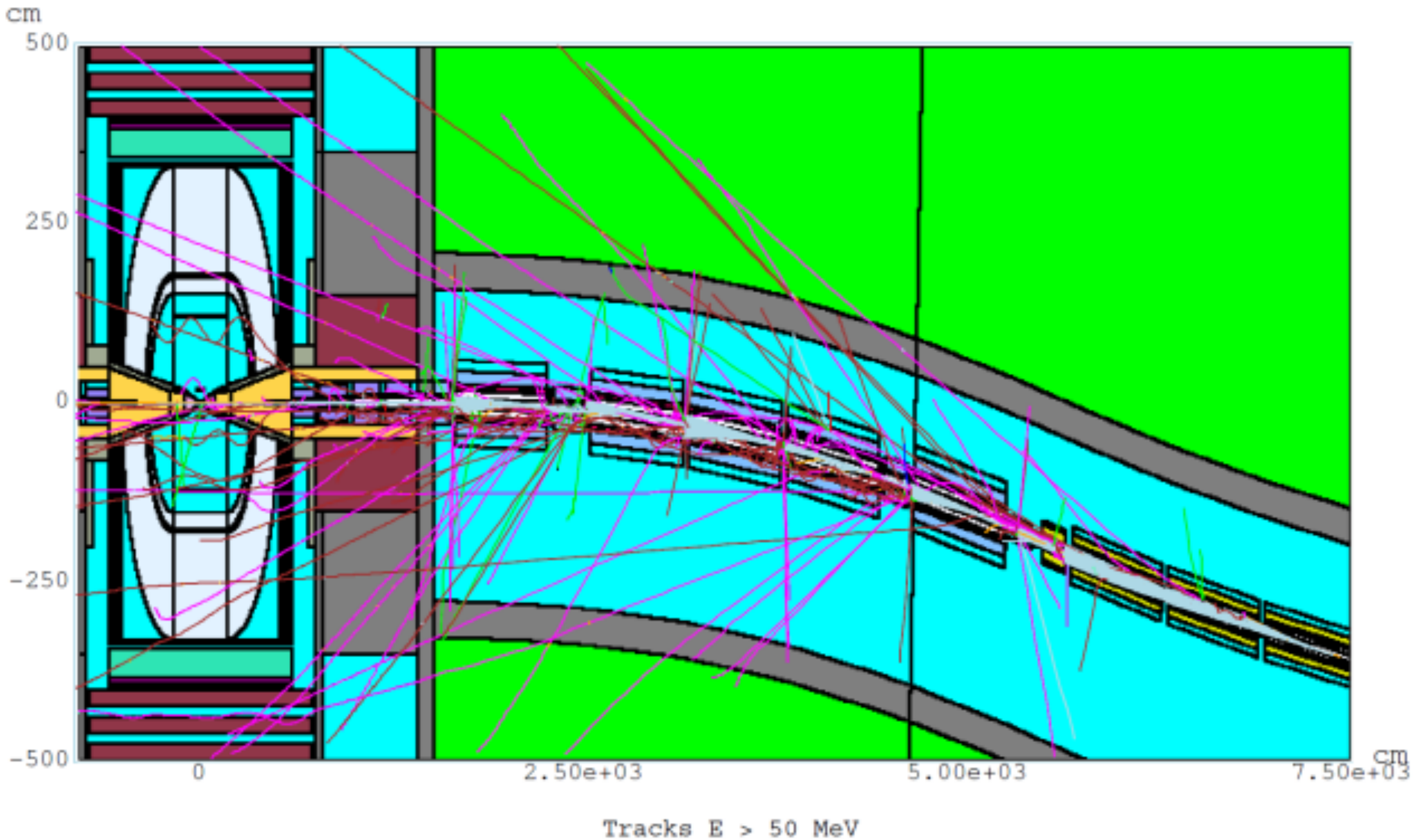
A solid R&D program can increase the **μ** beams quality and the **final luminosity**

- $H_2$ targets could improve the integrated thickness, reducing the number of passages and increasing the rate of "*fresh*" bunches/passage → **with a linear dependence on the μ /bunch number, a quadratic increase of the final luminosity can be expected**, a simple scaling with Z gives a factor 15 increase of the luminosity
- **Rotating target** conceived for ILC and the possibility to develop immersed $e^+$ capture systems with very high peak B field in the AMD (20 T as in MAP), could increase the efficiency of the $e^+$ source and the repetition rate of a factor 5-10, with a linear dependence on the luminosity
- To reduce the **μ** production emittance, a **moderate cooling mechanism**, such as stochastic, optical stochastic, and crystal cooling can be envisaged. A full evaluation of these mechanisms is needed, targeting at a reduction of the μ emittance by 1-2 order of magnitude, with a linear impact on the final luminosity

# Muon related backgrounds

Nikolai Mokhov et al. - MARS15

- A major problem is caused by muon decays, namely electrons from μ decay inside the detector with ≈ $2 \times 10^3$ e/meter/ns, however collimated within an average angle of $10^{-3}$ rad
- A superb collimation is required with the help of absorbers in front of the detector's straight sections.



# Preliminary study of beam-induced background

Donatella Lucchesi et al.

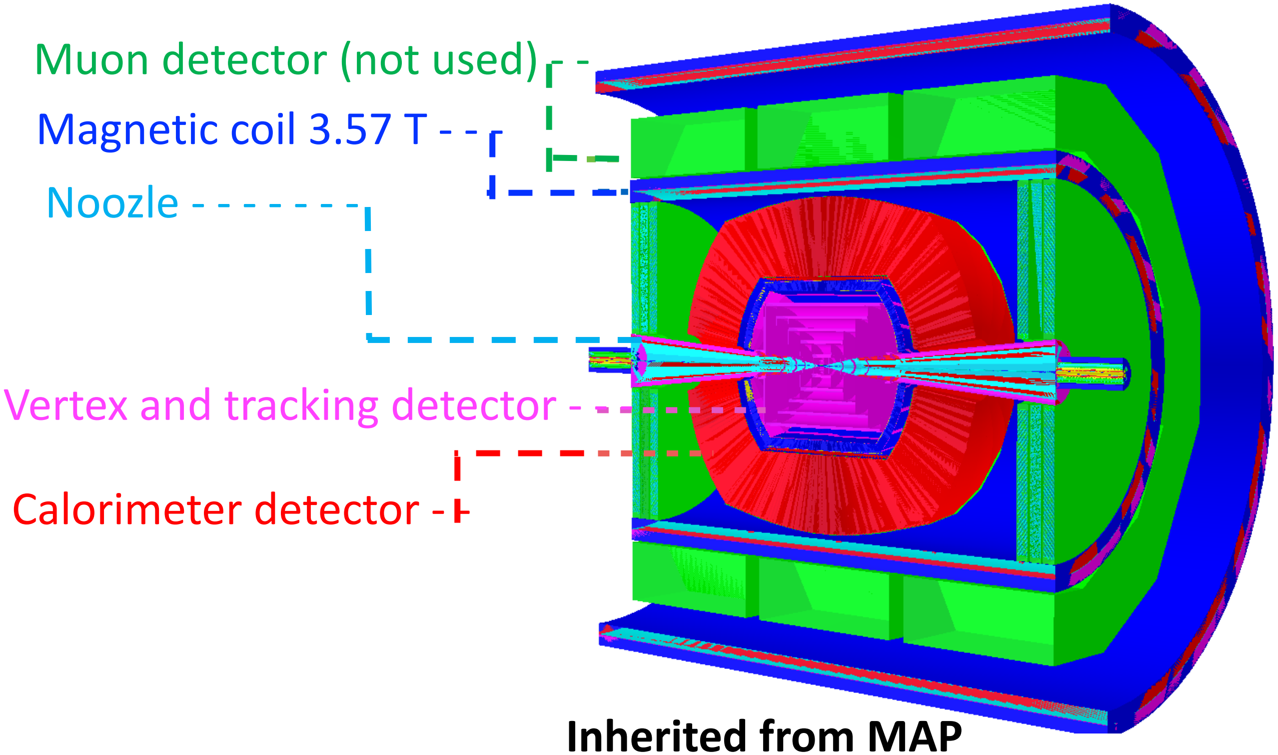
- Muon decay… just a back of the envelope calculation:
  beam 0.75 TeV
  $\lambda = 4.8\times10^{6}$m, with $2\times10^{12}\mu$/bunch $\Rightarrow 4.1\times10^{5}$decay per meter of lattice

- Electromagnetic showers induced by electrons and photons interacting with the machine components generate hadrons, secondary muons and electrons and photons.

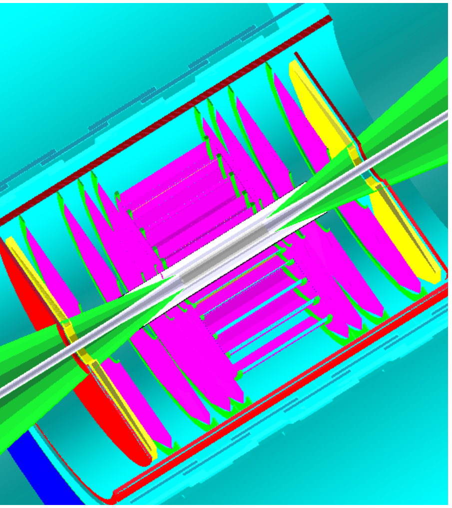
- Muon induced background is critical for:
  - ✓ Magnets, they need to be protected
  - ✓ Detector, the performance depends on the rate of background particles arriving to each subdetector and the number and the distribution of particles at the detector depends on the lattice

# Detector response simulation

- A detailed simulation of the potential detector is necessary to assess the achievable precision of future physics measurements
- Making use of the simulation/reconstruction tools previously developed within the MAP program based on the ILCroot package: supports signal + MARS background merging

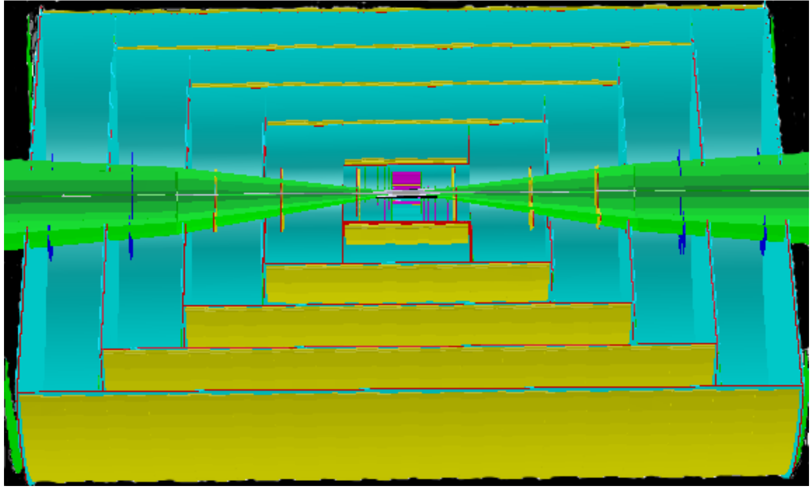



Inherited from MAP



# Tracking

**Beam pipe:**
Beryllium *(Be)*
**thickness:** 400 µm

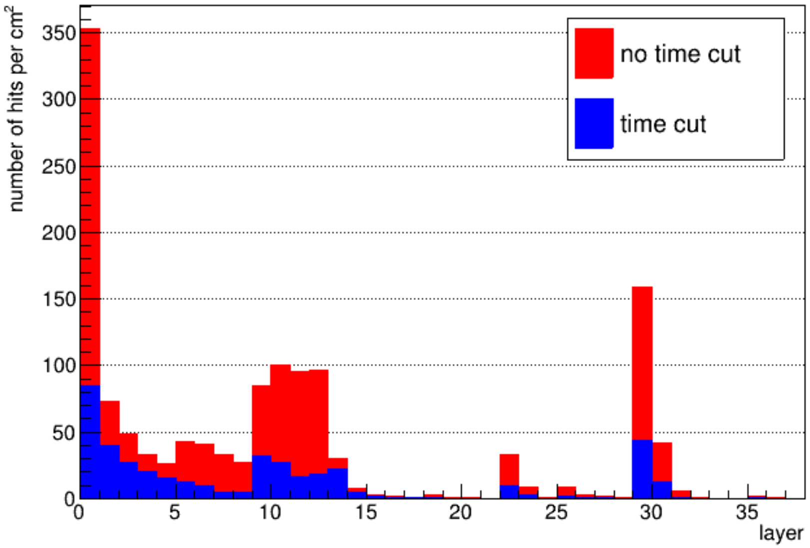


**Silicon Tracker (SiT)** and **Forward Tracking Detector (FTD):**
***Si* pixel sensors:** 50×50 µm pitch, **thickness:** 200 µm
**SiT: Barrel:** 5 layers **Endcap:** 2 × (4 +3) disks
**FTD: Endcap:** 2 × 3 disks

**Vertexing detector (VXD)**
***Si* pixel sensors:** 20×20 µm pitch
**R:** 3-13 cm **L:** 42 cm
**Granularity:**
- **Barrel:** 5 layers *(75 µm thick)*
- **Endcap:** 2 × 4 disks *(100 µm thick)*

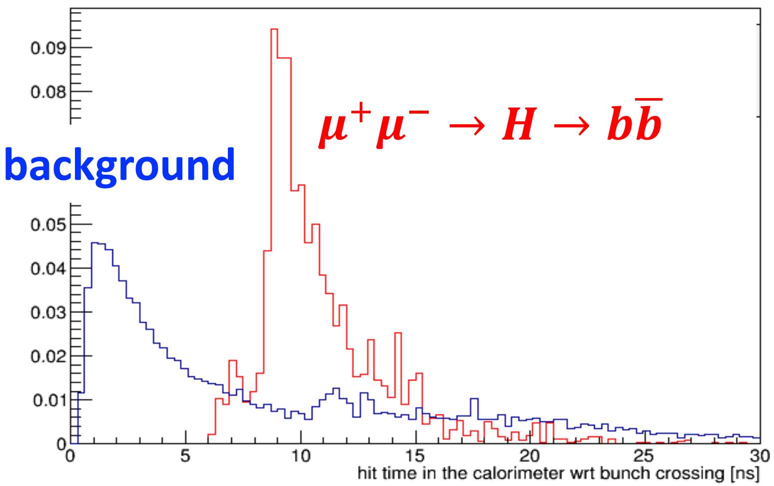
Assuming different time resolution for different Si detectors
Pitch 75 and 100 µm: 50 ps
Pitch 200 µm:100 ps

**A lot of background is removed**



# Calorimeter and jet reconstruction

Beam-induced background influence also the calorimeter performances



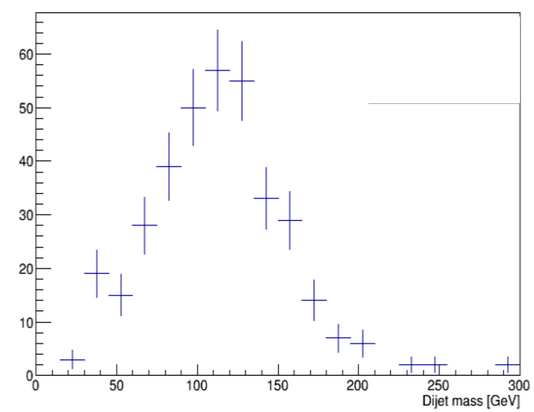

**Time can help to reduce Beam-induced background**

**Sample $\mu^+\mu^- \to H \to b\bar{b}$**
**+ background @ $\sqrt{s} = 1.5\ TeV$**

Use a very simple cone jet algorithm, room for a lot of improvements!

Efficiency
- ~60% per jet
- ~38% per event

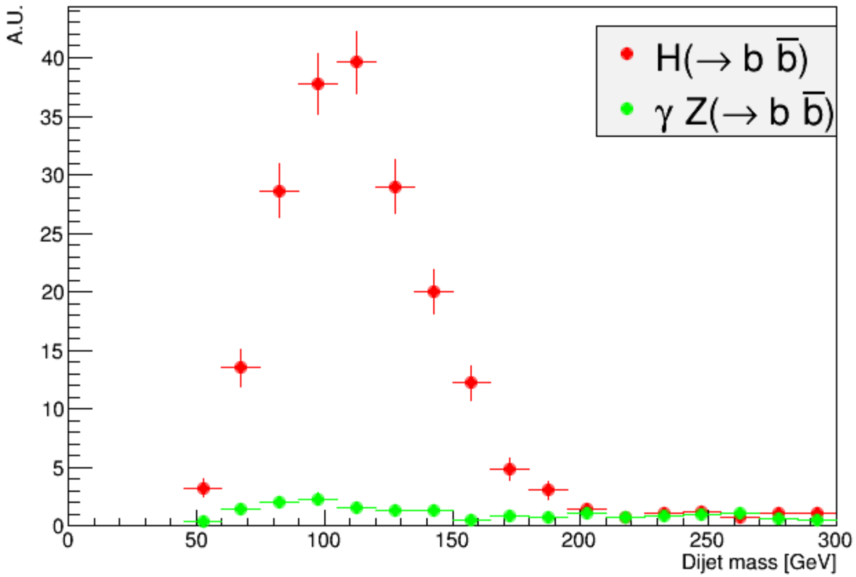
2 b-jets invariant mass (truth match)



# Results and next steps

**$H \to b\bar{b}$ can be reconstructed, no physics background**

arXiv:1905.03725



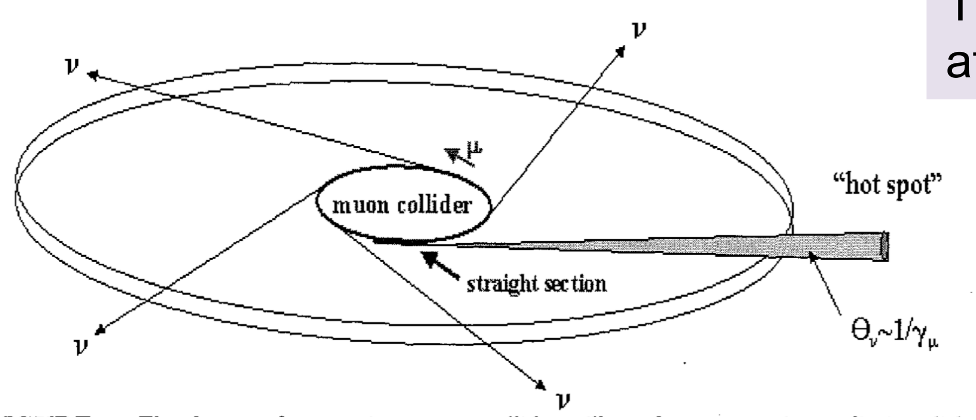

Di-jet mass distributions for Higgs and Z produced in 1.5-TeV muon collisions. The relative normalization of the two distributions is equal to the ratio of the expected number of events, considering the selection efficiencies and the cross sections.

**Plan to move to a new framework** to:

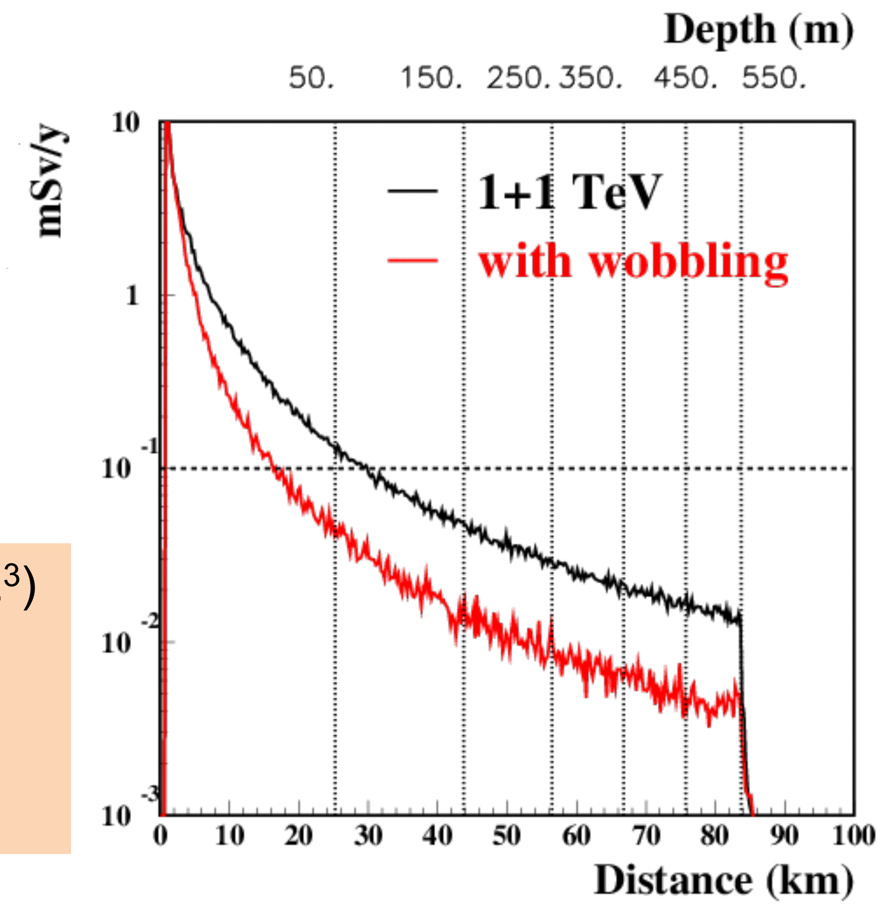
- design new, up-to-date detector where position, energy and time resolution are pushed to the limit.
- study beam-induced background for center-of-mass energies $\sqrt{s} = 3\ TeV$, $\sqrt{s} = 6\ TeV$, $\sqrt{s} = 10\ TeV$, $\sqrt{s} = 14\ TeV$

# Beam induced background studies
## neutrino radiation hazard

The source, ring or section, is placed at the fixed depth of 550 m.




Ambient dose assuming 1.2 × $10^{21}$ decays/year




Need to study for higher energies (scaling $E^3$)

Straights in LHC might increase problem
⇒ Another reason to consider this as accelerator

# Brief history

- The **muon collider idea** was first introduced in **early 1980's**
  *[A. N. Skrinsky and V. V. Parkhomchuk, D. Neuffer ]*
- The idea was further developed by a **series of world-wide collaborations**
- **US Muon Accelerator Program – MAP,** launched in **2011,** was terminated in **2014**
  *MAP developed a **proton driver scheme** and addressed the feasibility of the novel technologies required for Muon Colliders and Neutrino Factories*

  ***"Muon Accelerator for Particle Physics," JINST,***
  *https://iopscience.iop.org/journal/1748-0221/page/extraproc46*

- **MICE (Muon Ionization Cooling Experiment) @ RAL**
- **LEMMA (Low EMittance Muon Accelerator)** concept was proposed in **2013**
  *a new end-to-end design of a **positron driven scheme** is under study by INFN-LNF et al. to overcome technical issues of initial concept* ➔ **arXiv:1905.05747**

# Muon Collider Working Group

*Jean Pierre Delahaye, CERN, Marcella Diemoz, INFN, Italy,*
*Ken Long, Imperial College, UK, Bruno Mansoulie, IRFU, France,*
*Nadia Pastrone, INFN, Italy (chair), Lenny Rivkin, EPFL and PSI, Switzerland,*
*Daniel Schulte, CERN, Alexander Skrinsky, BINP, Russia, Andrea Wulzer, EPFL and CERN*

*appointed by CERN Laboratory Directors Group in September 2017*

**to prepare the Input Document to the European Strategy Update**

"Muon Colliders," **arXiv:1901.06150**

**de facto it is the seed for a renewed international effort**

Past experiences and new ideas discussed at the joint ARIES Workshop

**July 2-3, 2018**

**Università di Padova - Orto Botanico**

https://indico.cern.ch/event/719240/overview

Preparatory meeting to review progress for the ESPPU Simposium

**April 10-11, 2019**

**CERN – Council Room**

https://indico.cern.ch/event/801616

**NEW WORKSHOP @ CERN October 9-11, 2019** https://indico.cern.ch/event/845054/

# Findings

Jean Pierre Delahaye et al.

Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.

The development of the challenging technologies for the frontier muon accelerators has shown enormous progress in addressing the feasibility of major technical issues with R&D performed by international collaborations.

In Europe, the reuse of existing facilities and infrastructure for a muon collider is of interest. In particular the implementation of a muon collider in the LHC tunnel appears promising, but detailed studies are required to establish feasibility, performance and cost of such a project.

A set of recommendations at the end will allow to make the muon collider technology mature enough to be favorably considered as a candidate for ehigh-energy facilities in the future.

# Recommendations

Jean Pierre Delahaye et al.

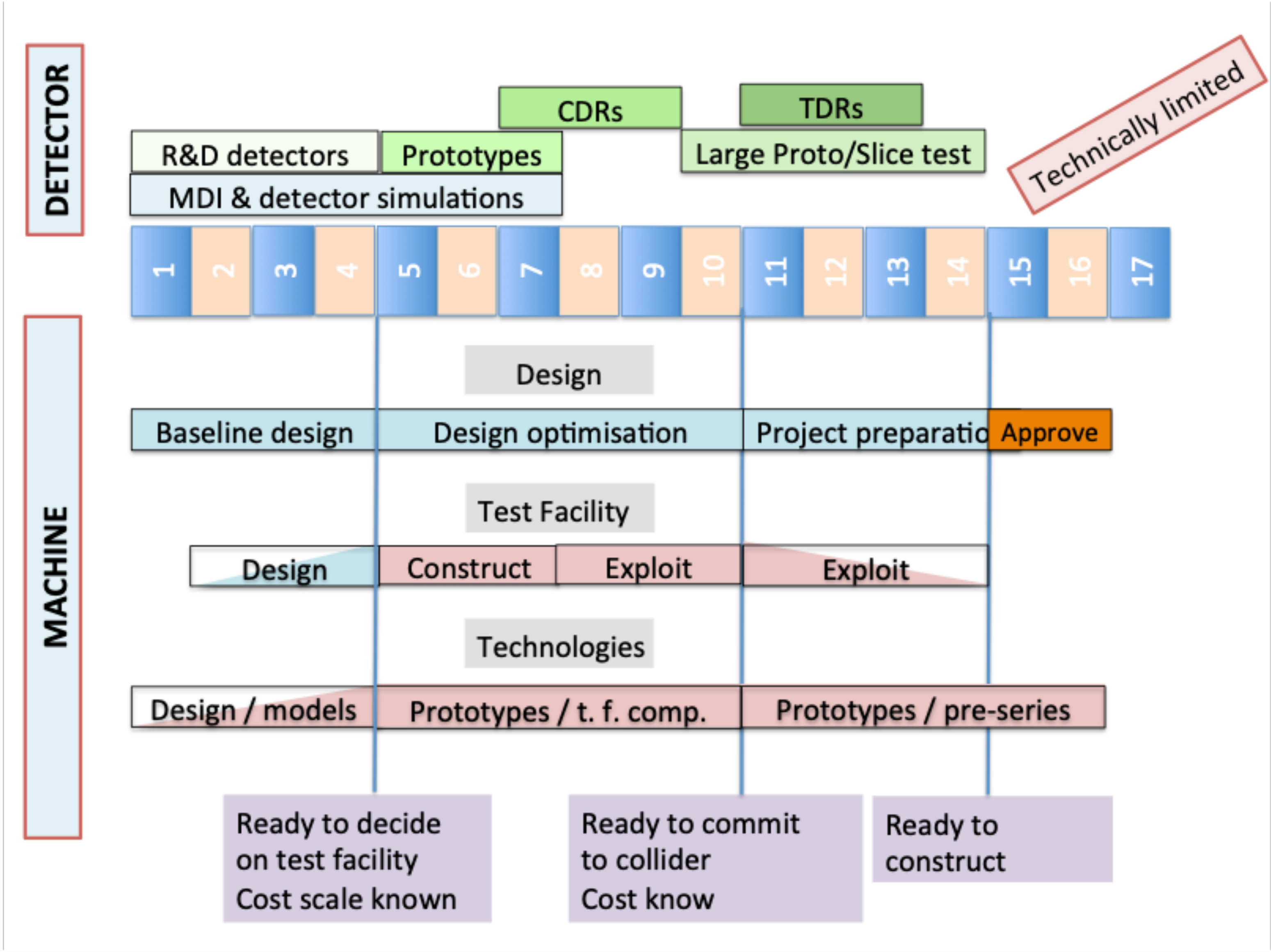
**Set-up an international collaboration to promote muon colliders** and organize the effort on the development of both accelerators and detectors and to define the road-map towards a CDR by the next Strategy update.

**Develop a muon collider concept based on the proton driver and considering the existing infrastructure.**

**Consolidate the positron driver scheme** addressing specifically the target system, bunch combination scheme, beam emittance preservation, acceleration and collider ring issues.

**Carry out the R&D program toward the muon collider**. Based on the progress of the proton-driver and positron-based approaches, develop hardware and research facilities as well as perform beam tests. Preparing and launching a conclusive R&D program towards a multi-TeV muon collider is mandatory to explore this unique opportunity for high energy physics. A well focused international effort is required in order to exploit existing key competences and to draw the roadmap of this challenging project. The development of new technologies should happen in synergy with other accelerator projects. Moreover, it could also enable novel mid-term experiments.

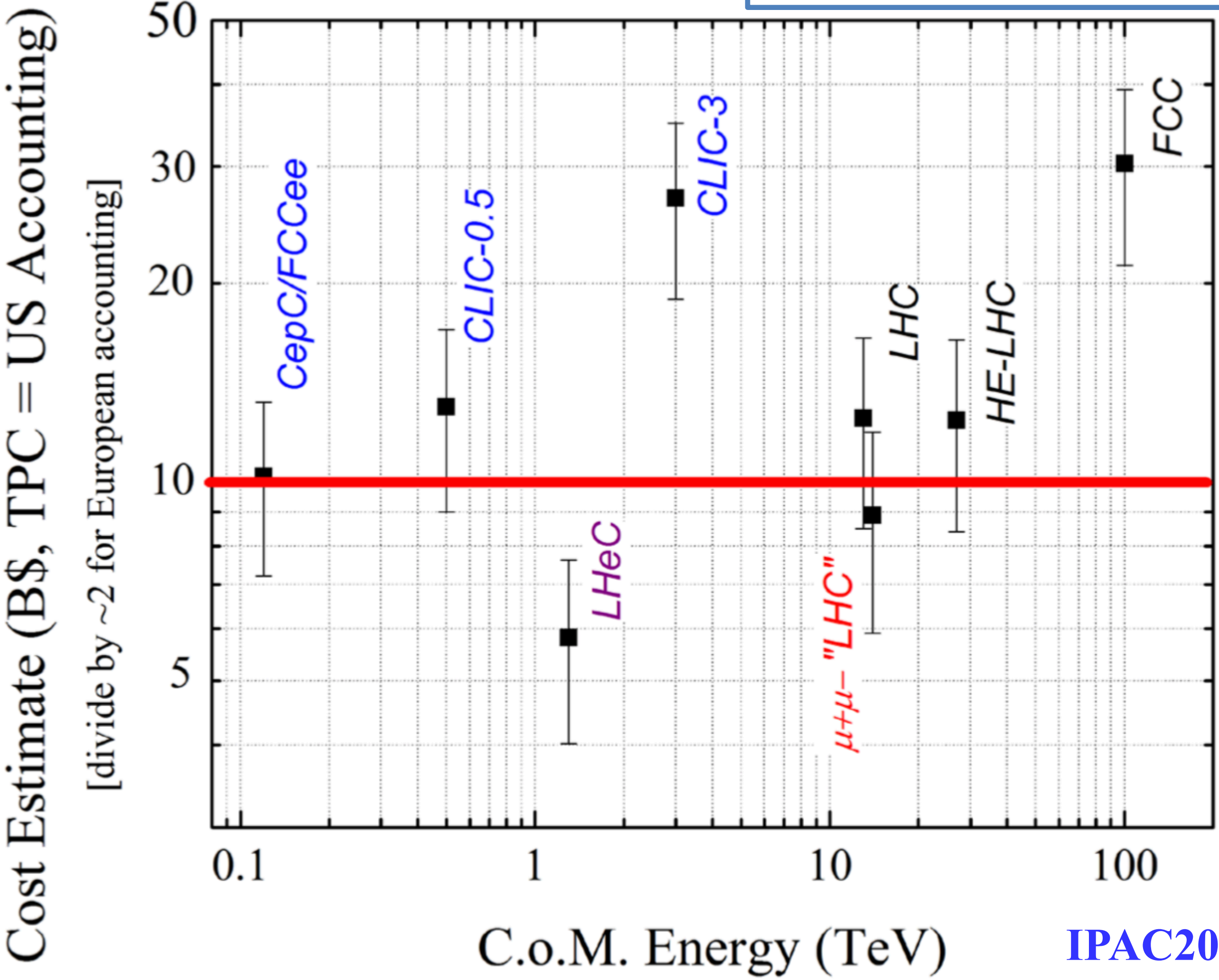
# Proposed Tentative Timeline



# Cost estimate

## NB: all $$ - "US Accounting" (divide by 2-2.4 at CERN)

Vladimir SHILTSEV,David NEUFFER ( Fermilab)




IPAC2018 - MOPMF072

# To face the next challenge

## Expect Shortage of Expert Accelerator Workforce

- ***"Oide Principle"*** :

  1 Accelerator Expert

  can spend intelligently

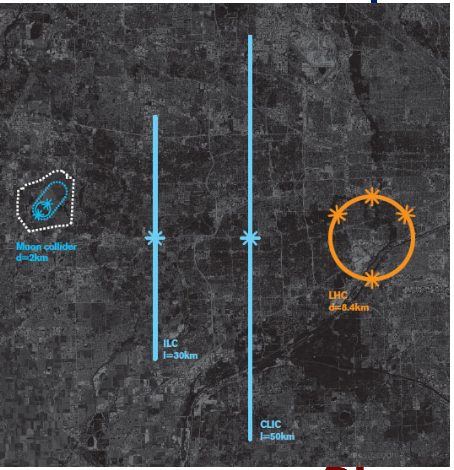
  (only) ~1 M$ a year

- + it takes significant time to get the team together (XFEL, ESS)
- Scale of the team: 10B$/10 years=1 B$/yr → need 1000 experts ← world's total now ~4500

K.Oide (KEK)

# Conclusion

- **Europe (CERN) unique laboratory at the high energy frontier :**
  - **Presently limited expertise**
  - **Opportunity not to be missed to:**
    - **Preserve and develop accumulated expertise in close collaboration with (still available) experts**
    - **Fresh look of muon based technology (including accelerator and detector)**
      - **building up on excellent progress made so far**
      - **possibly integrating novel ideas**




**Ready for launch of**

**International Collaboration on Muon Beams**

**(Accelerator, Detector and Physics)**

**Please register @ CERN Workshop Octoer 9-11, 2019**

# Thanks to many colleagues!

*CERN Muon Collider Working Group*

*MAP, MICE and LEMMA teams and many others*

# Thanks for the attention!

**drawing by Bruno Touschek**