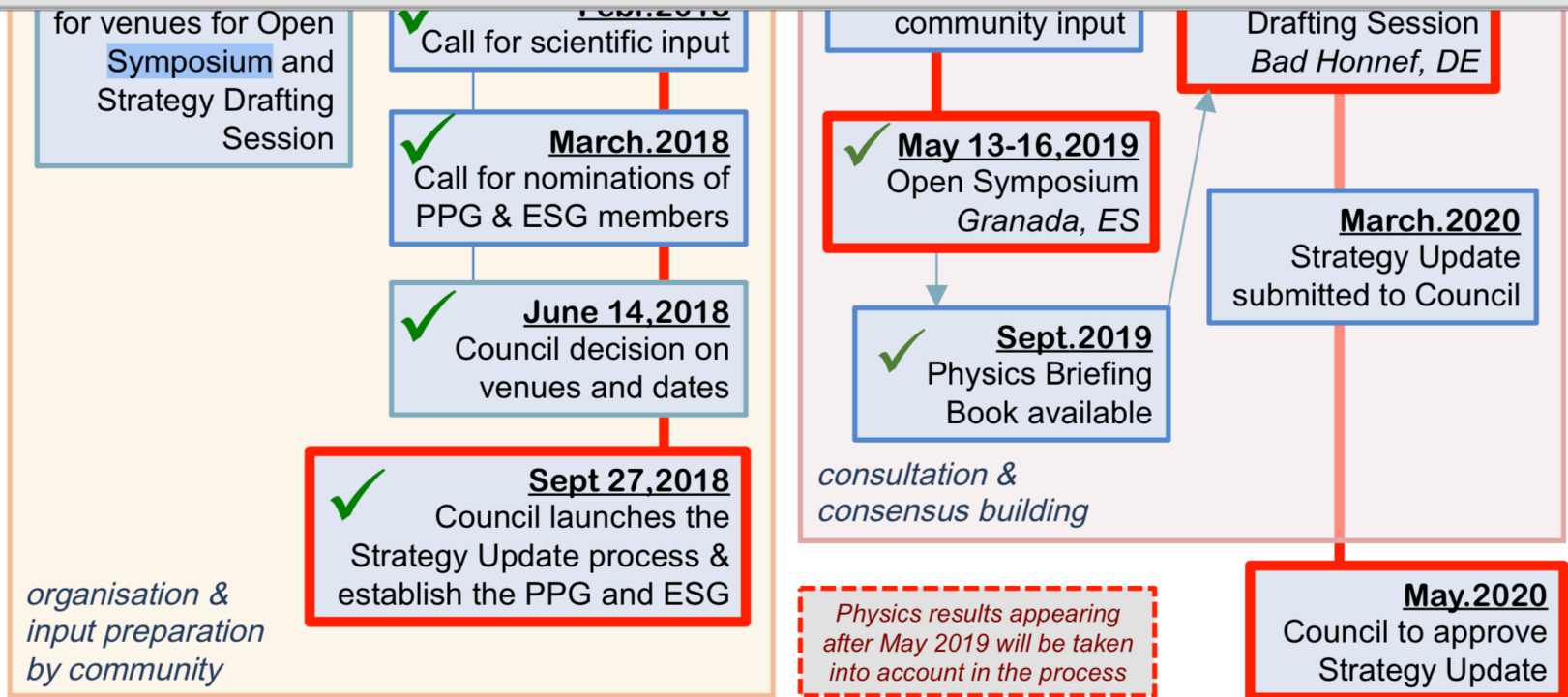*DESY – Hamburg*
*December 17th, 2019*

# Muon Colliders: challenges and wonders

## *Present status & Future plans*

## Nadia Pastrone  INFN TORINO

for venues for Open Symposium and Strategy Drafting Session

✓ ~~Febr.2018~~
Call for scientific input

✓ **March.2018**
Call for nominations of PPG & ESG members

✓ **June 14,2018**
Council decision on venues and dates

✓ **Sept 27,2018**
Council launches the Strategy Update process & establish the PPG and ESG

*organisation & input preparation by community*

community input

✓ **May 13-16,2019**
Open Symposium
*Granada, ES*

✓ **Sept.2019**
Physics Briefing Book available

*consultation & consensus building*

*Physics results appearing after May 2019 will be taken into account in the process*

Drafting Session
*Bad Honnef, DE*

**March.2020**
Strategy Update submitted to Council

**May.2020**
Council to approve Strategy Update

# 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 Directorate 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

Preparatory meeting to review progress for the ESPPU Simposium
**April 10-11, 2019 – CERN – Council Room**
https://indico.cern.ch/event/801616

**Future Plans @ CERN October 9-11, 2019**    https://indico.cern.ch/event/845054/
**ECFA – Novel Accelerator Technologies @ CERN  November 14, 2019**
https://indico.cern.ch/event/847002/

# Findings & Reccomendations

J.P. 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

  ......

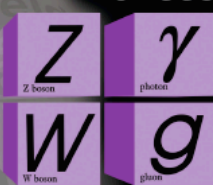- **Carry out the R&D program toward the muon collider**

**Input Document to EU Strategy Update -  Dec 2018:**
"Muon Colliders," arXiv:1901.06150
by *CERN-WG on Muon Colliders*

# Standard Model of Particle Physics



- **Extremely precise measurements and confirmation of Standard Model (SM)**

- **No signal of Beyond Standard Model evidence or SUSY**



Congratulations to Professors
**François Englert & Peter Higgs**
for the
**2013 Nobel Prize in Physics**

Higgs Press Material from ATLAS

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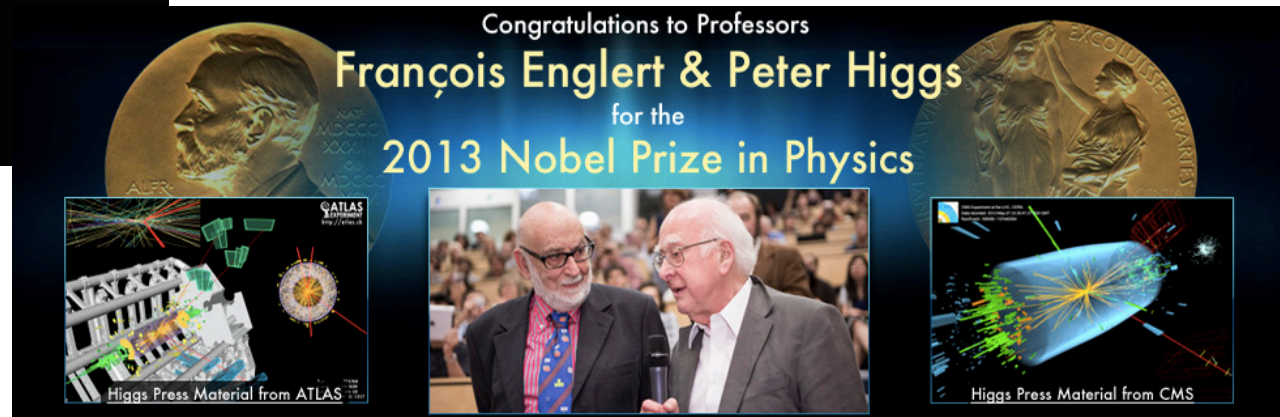
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

# 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

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

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

**v**

$H^0$
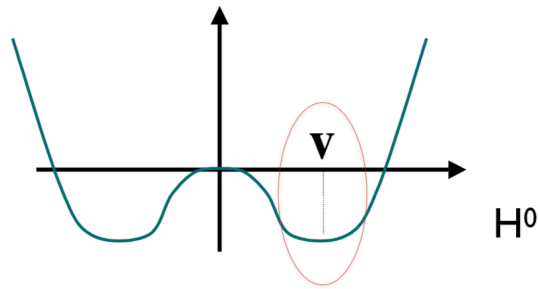
$V(H) = - \mu^2 |H|^2 + \lambda |H|^4$

**Who ordered that ?**

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

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

*The relations between Higgs self-couplings, $m_H$ 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*
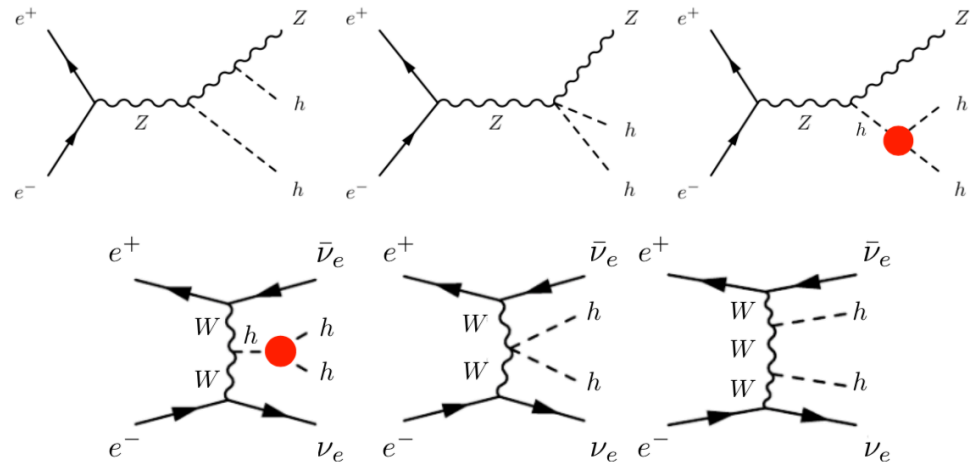
# Double Higgs production

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

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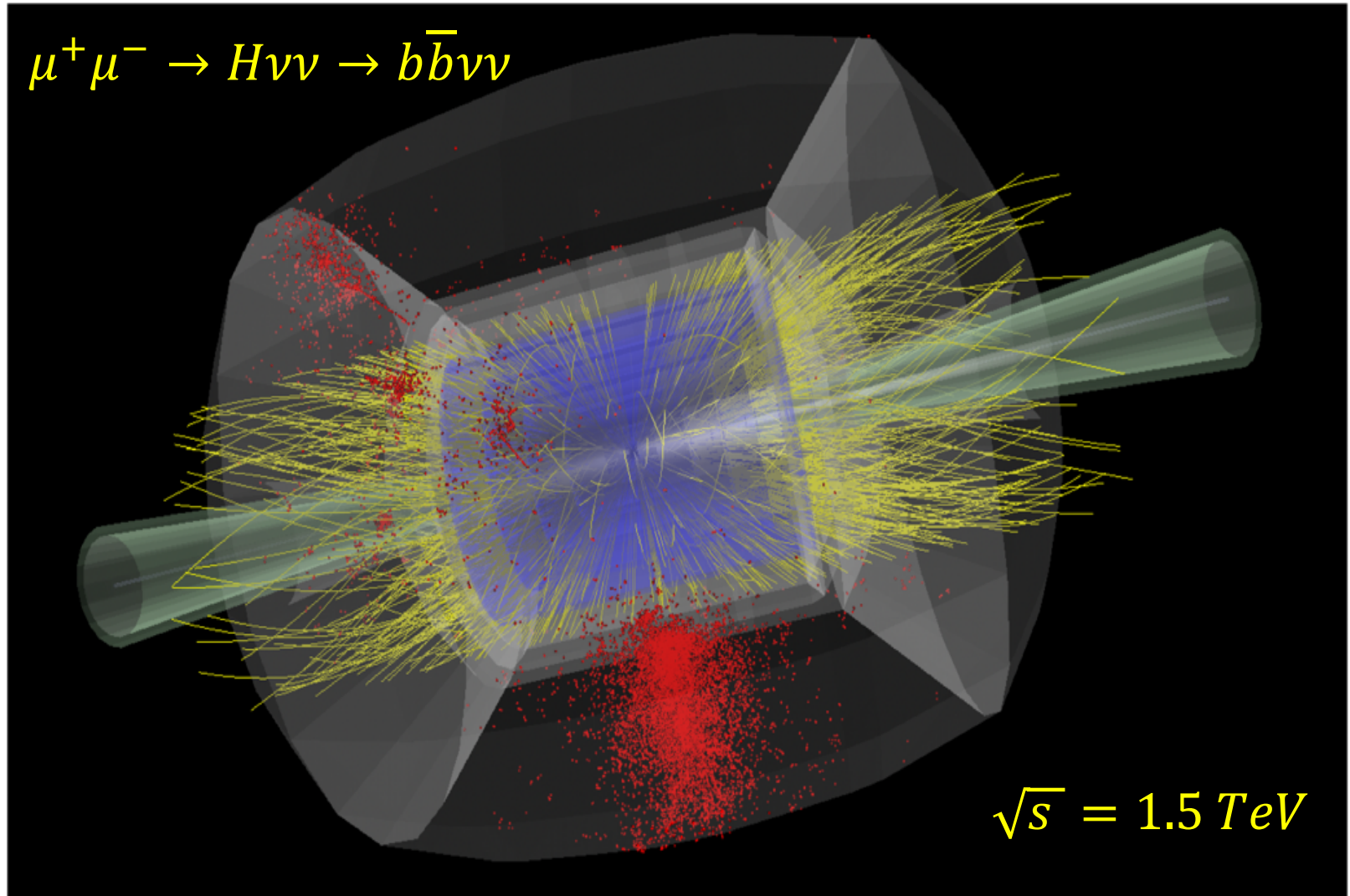
Hadron collider
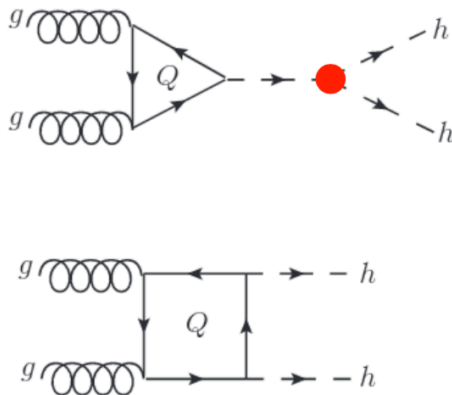
Lepton collider



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

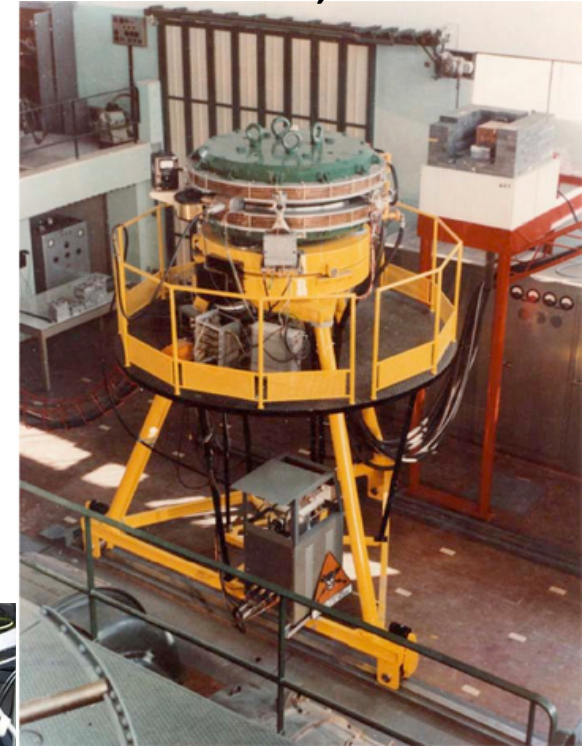# $H \rightarrow b\bar{b}$ + muon beams induced backgound

Donatella Lucchesi et al.



$\mu^+ \mu^- \rightarrow H\nu\nu \rightarrow b\bar{b}\nu\nu$

$\sqrt{s} = 1.5 \, TeV$

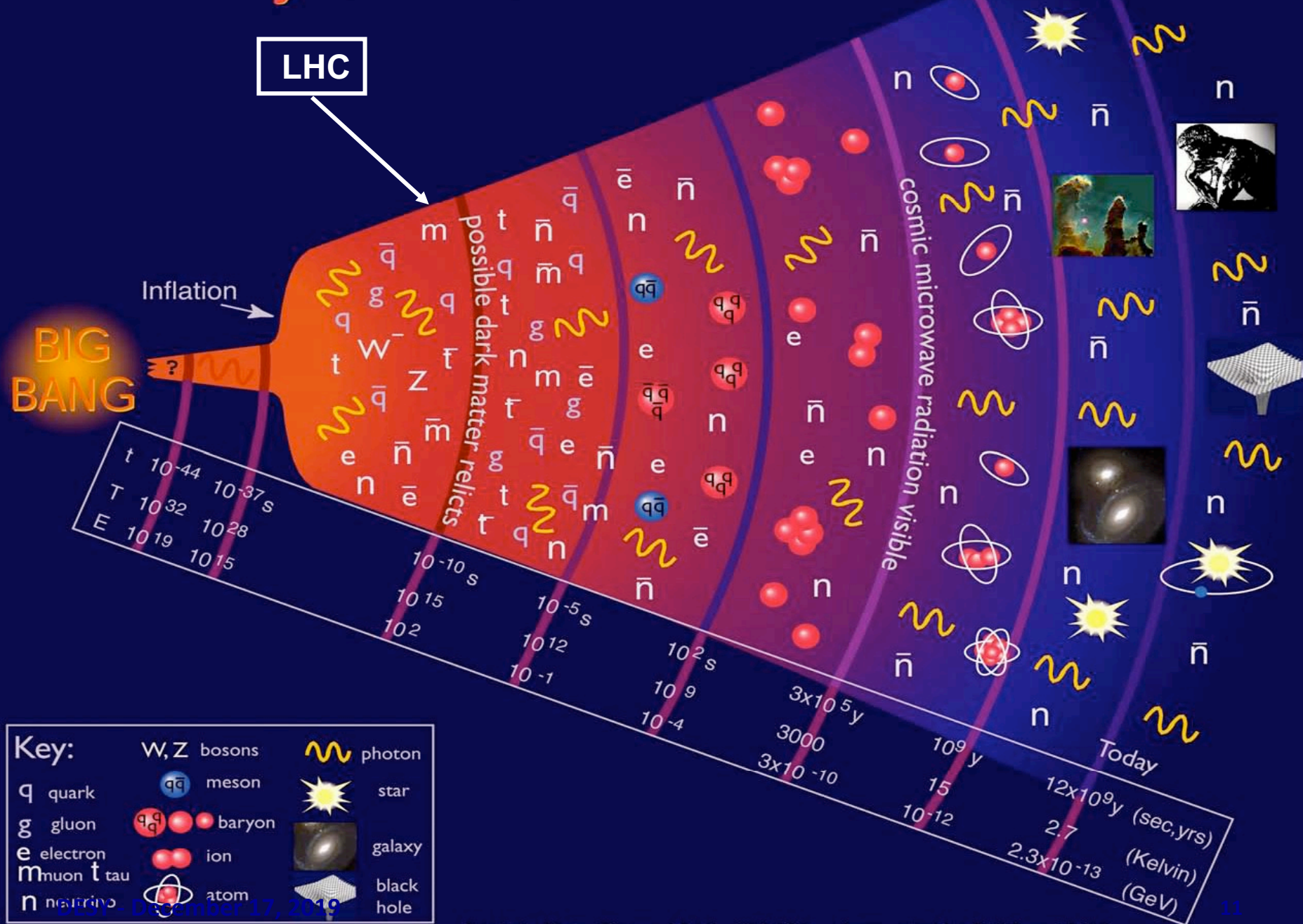# Ideas & technologies → discoveries

**AdA - LNF, 1960**

**LHC - CERN, 2008**

**Cyclotron - Berkeley, 1934**

# History of the Universe

# 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?
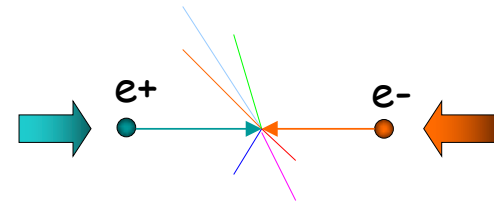
# Hadron & Lepton Colliders

- **Hadron colliders as discovery facilities**
  - **Broad range scanning**
  - **Huge QCD background**
  - **Nucleon energy (partly only) available in collision**
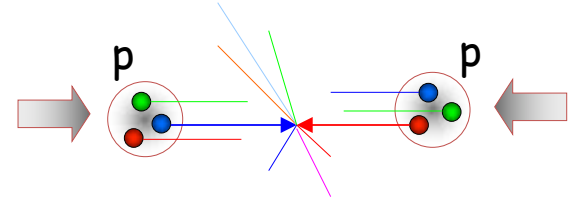
- **Lepton colliders for precision physics**
  - **Well defined initial energy for reaction**
  - **Colliding "point" like particles**

➡ **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**

# Proposed schedule

| 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



Legend:
- FCC-ee
- CEPC
- ILC
- ILC-up.
- CLIC
- CLIC-up

Axes: $L\ [10^{34} cm^{-2} s^{-1}]$ versus $E_{cm}\ [GeV]$

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

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



**Compact Linear Collider (CLIC)**
- 380 GeV - 11.4 km (CLIC380)
- 1.5 TeV - 29.0 km (CLIC1500)
- 3.0 TeV - 50.1 km (CLIC3000)

LHC
CLIC380
CLIC1500
CERN
Geneva
CLIC3000



LHC
Jura
Lake Geneva
Prealps
Salève
**Schematic of an 80 - 100 km long tunnel**
Aravis
Mandalaz
Copyright CERN 2014
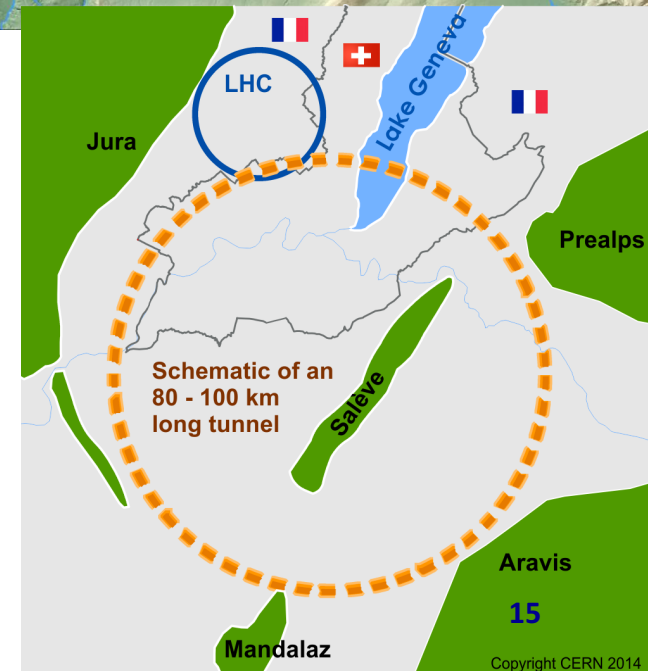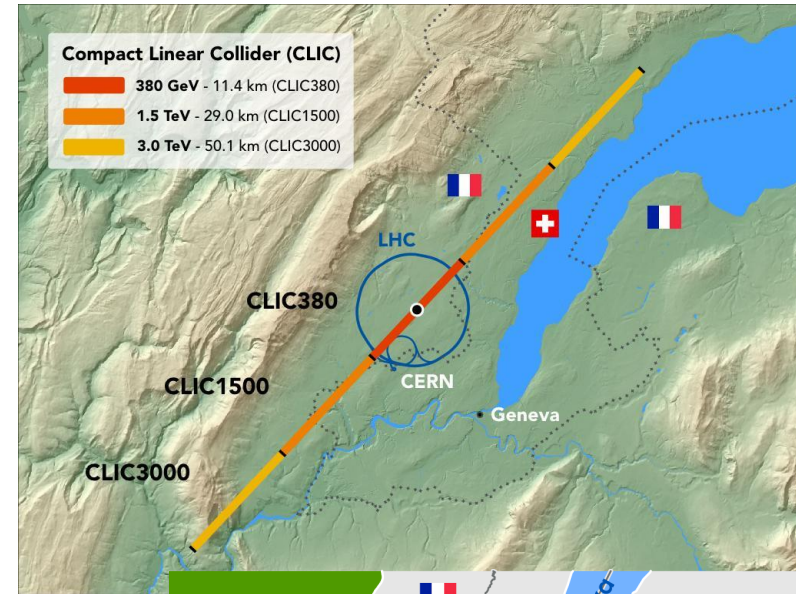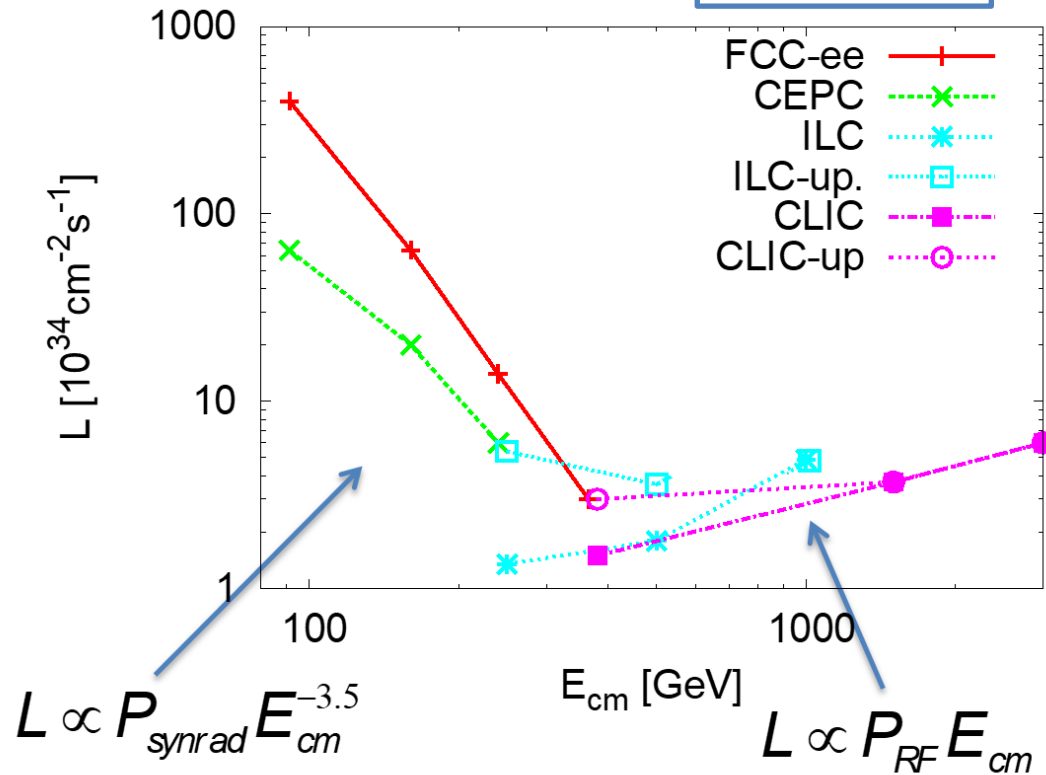
# Why Muons?

**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 $\longrightarrow$
  - 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

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

**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

$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$$

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

# 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**

# Physics reach



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

http://map.fnal.gov/
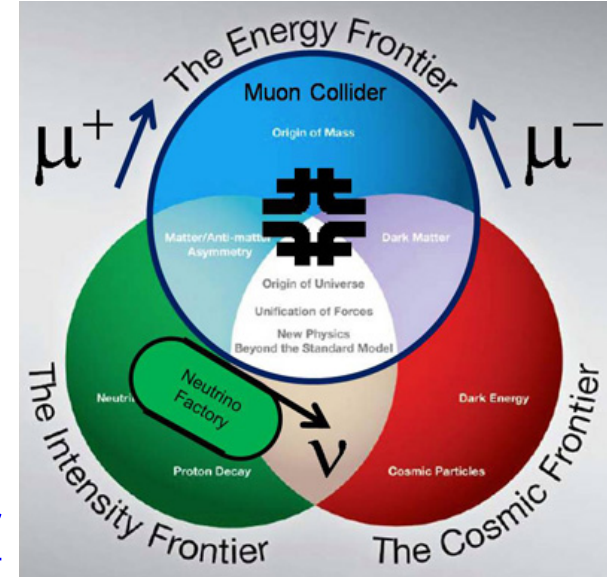
# U.S. Muon Accelerator Program (MAP)

- 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 @$\sqrt{s}$ >3 TeV**
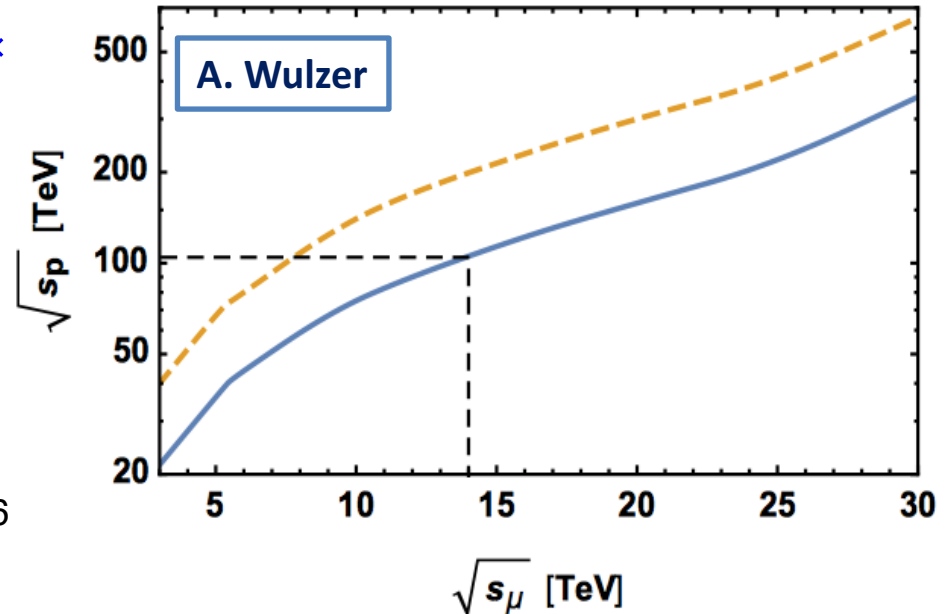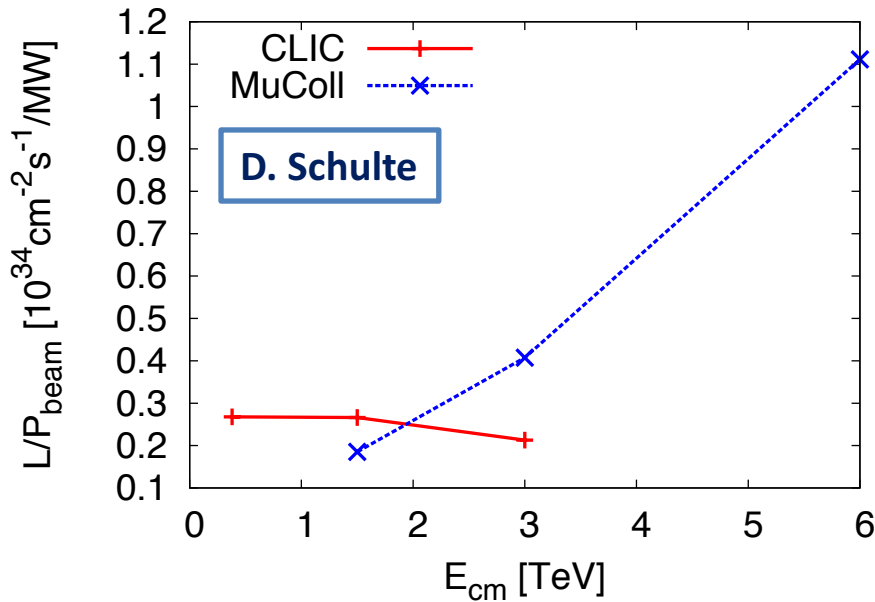


The luminosity per beam power is independent of collision energy in linear colliders, but increases linearly for muon colliders

Full collision energy available for particle production: 14 TeV lepton collisions are comparable to 100 TeV proton collisions for selected new physics process, if sufficient luminosity is provided

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

# Motivation: Higgs potential

B. Mele et al.

Demonstrate that at muon collider it is possible to determine the Higgs potential by measuring trilinear and quadrilinear self coupling

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

Trilinear coupling, $k_3$
- $\sqrt{s} = 10\, TeV, \mathcal{L} \sim 10^{35} cm^{-2} s^{-1}$
- 10 ab$^{-1}$

$k_3$ sensitivity $\sim 3\%$

Best sensitivity $\sim$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)

**This just looking at the Higgs sector!**
**Top and new physics sectors also to be scrutinized**

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

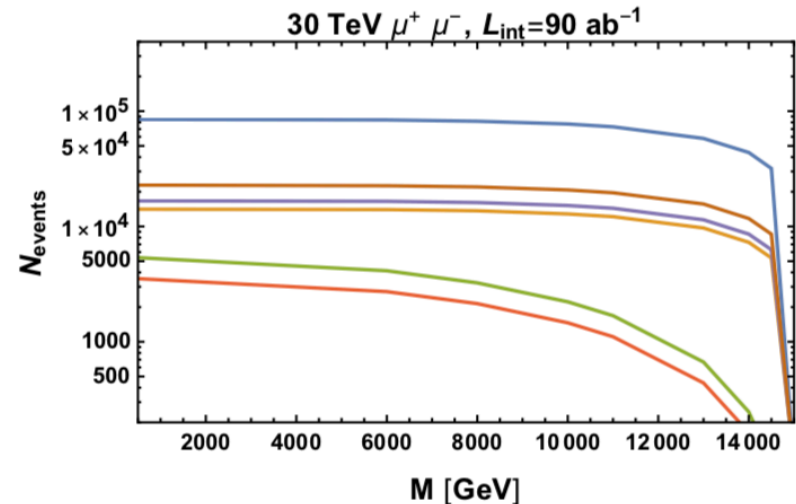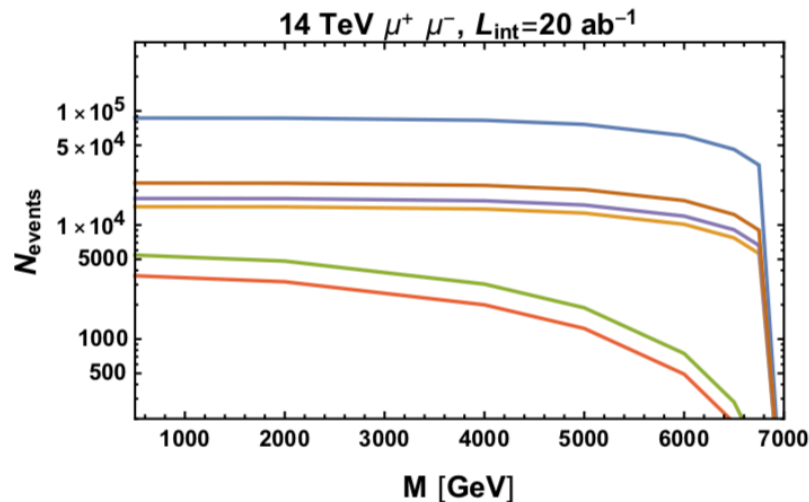see also: Preparatory meeting April 2019 @ CERN https://indico.cern.ch/event/801616

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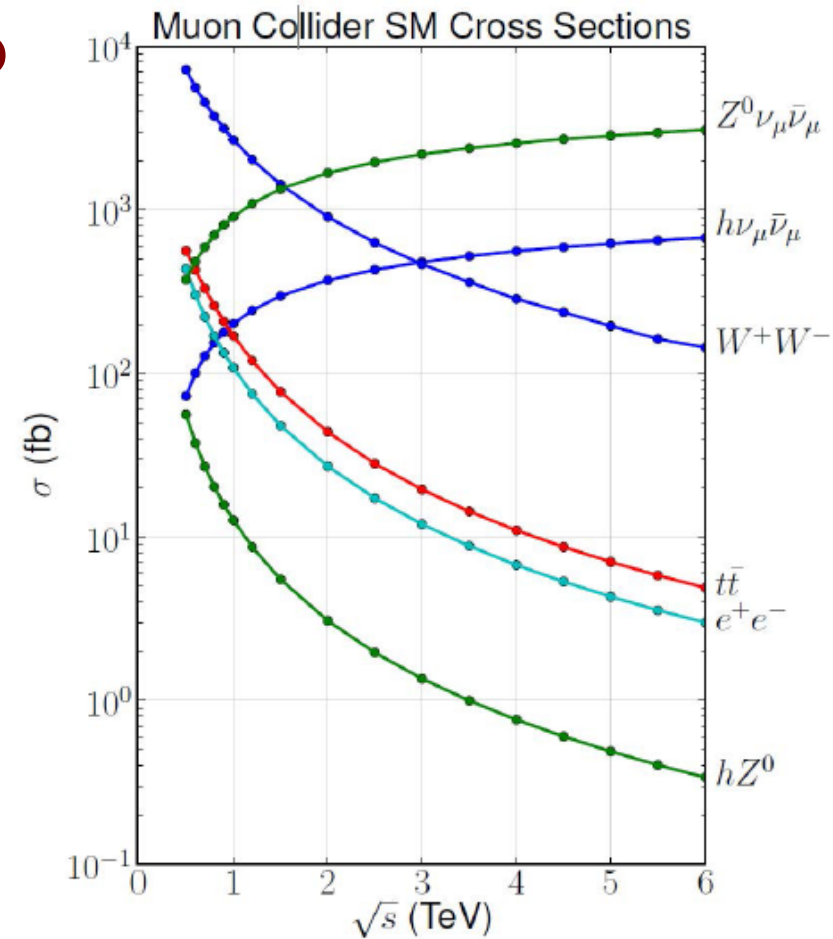**exotic** (e.g., displaced) **or difficult** (e.g., compressed) decays to be studied

# 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



Muon Collider SM Cross Sections

**Physics motivations**

**Experiment design: MDI, detector, TDAQ**

**Machine options**

**Enabling technologies**

# Muons: Issues & Challenges

– **Limited lifetime: 2.2 $\mu s$ at rest**

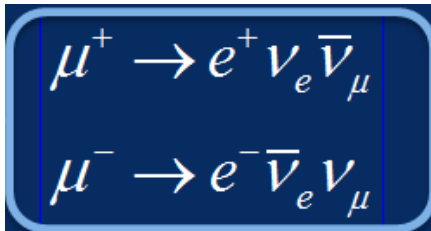    • **Race against death: fast generation, acceleration & collision before decay**

☹     • **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 :**

☺
$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$$
$$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$$
    **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/c²) 207 times larger than $e^{\pm}$**

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

- **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

# Proton-driven Muon Collider Concept

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*
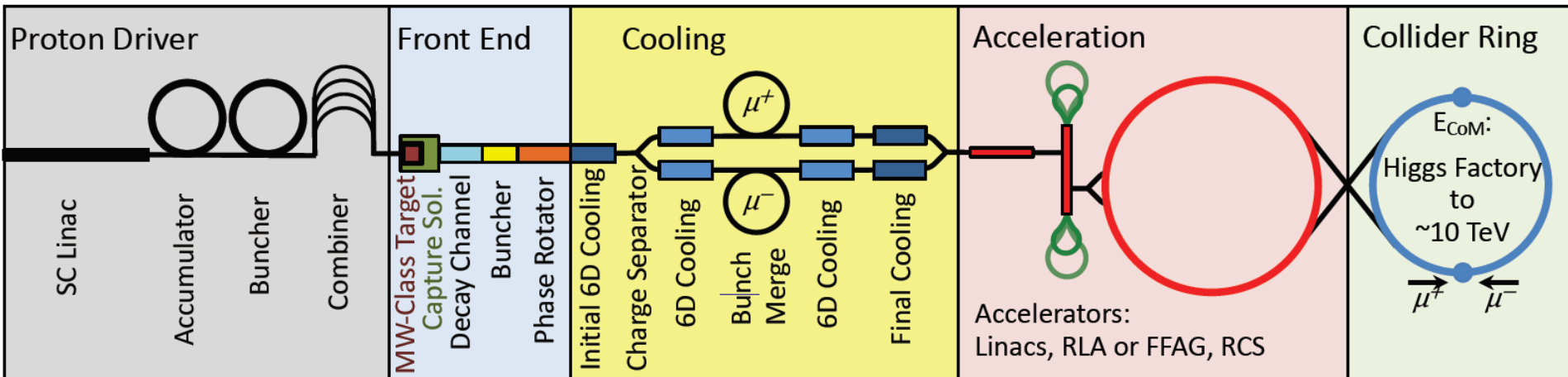


**Short, intense proton bunches to produce hadronic showers**

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

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

**Acceleration to collision energy**

**Collision**

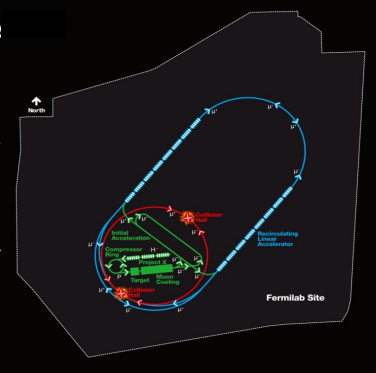**Design is not complete but did not find anything that does not work**

**No CDR exists No coherent baseline No reliable cost estimate**

*"Muon Accelerator for Particle Physics," JINST,*
https://iopscience.iop.org/journal/1748-0221/page/extraproc46    **25**

# Muon Collider Parameters

| Parameter | Units | Higgs Factory | | Top Threshold Options | | Multi-TeV Baselines | | Accounts for Site Radiation Mitigation |
|---|---|---|---|---|---|---|---|---|
| | | Startup Operation | Production Operation | High Resolution | High Luminosity | | | |
| CoM Energy | TeV | 0.126 | 0.126 | 0.35 | 0.35 | 1.5 | 3.0 | 6.0 |
| Avg. Luminosity | $10^{34} cm^{-2}s^{-1}$ | 0.0017 | 0.008 | 0.07 | 0.6 | 1.25 | 4.4 | 12 |
| Beam Energy Spread | % | 0.003 | 0.004 | 0.01 | 0.1 | 0.1 | 0.1 | 0.1 |
| Higgs* or Top+ Production/$10^7$sec | | 3,500* | 13,500+ | 7,000+ | 60,000+ | 37,500* | 200,000* | 820,000* |
| Circumference | km | 0.3 | 0.3 | 0.7 | 0.7 | 2.5 | 4.5 | 6 |
| No. of IPs | | 1 | 1 | 1 | 1 | 2 | 2 | 2 |
| Repetition Rate | Hz | 30 | 15 | 15 | 15 | 15 | 12 | 6 |
| $\beta^*$ | cm | 3.3 | 1.7 | 1.5 | 0.5 | 1 (0.5-2) | 0.5 (0.3-3) | 0.25 |
| No. muons/bunch | $10^{12}$ | 2 | 4 | 4 | 3 | 2 | 2 | 2 |
| No. bunches/beam | | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Norm. Trans. Emittance, $\varepsilon_{TN}$ | $\pi$ mm-rad | 0.4 | 0.2 | 0.2 | 0.05 | 0.025 | 0.025 | 0.025 |
| Norm. Long. Emittance, $\varepsilon_{LN}$ | $\pi$ mm-rad | 1 | 1.5 | 1.5 | 10 | 70 | 70 | 70 |
| Bunch Length, $\sigma_s$ | cm | 5.6 | 6.3 | 0.9 | 0.5 | 1 | 0.5 | 0.2 |
| Proton Driver Power | MW | 4# | 4 | 4 | 4 | 4 | 4 | 1.6 |

# Could begin operation with Project X Stage II beam

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts ⇨ several × $10^{32}$

Site Radiation mitigation with depth and lattice design: ≤ 10 TeV

# Muon Collider Luminosity Scaling

Fundamental limitation
Requires emittance preservation and advanced lattice design
Applies to MAP scheme

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

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

Luminosity per power naturally increases with energy
Provided all technical limits can be solved
Constant current for required luminosity increase
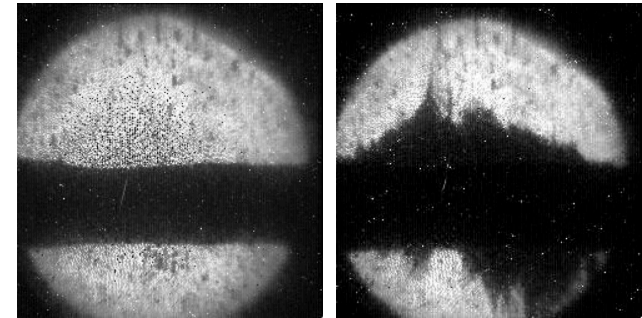Better scaling than linear colliders

# Source

Protons → Target → Pions → Muons

Proton beam



MERIT experiment at CERN

Liquid mercury target to avoid destruction
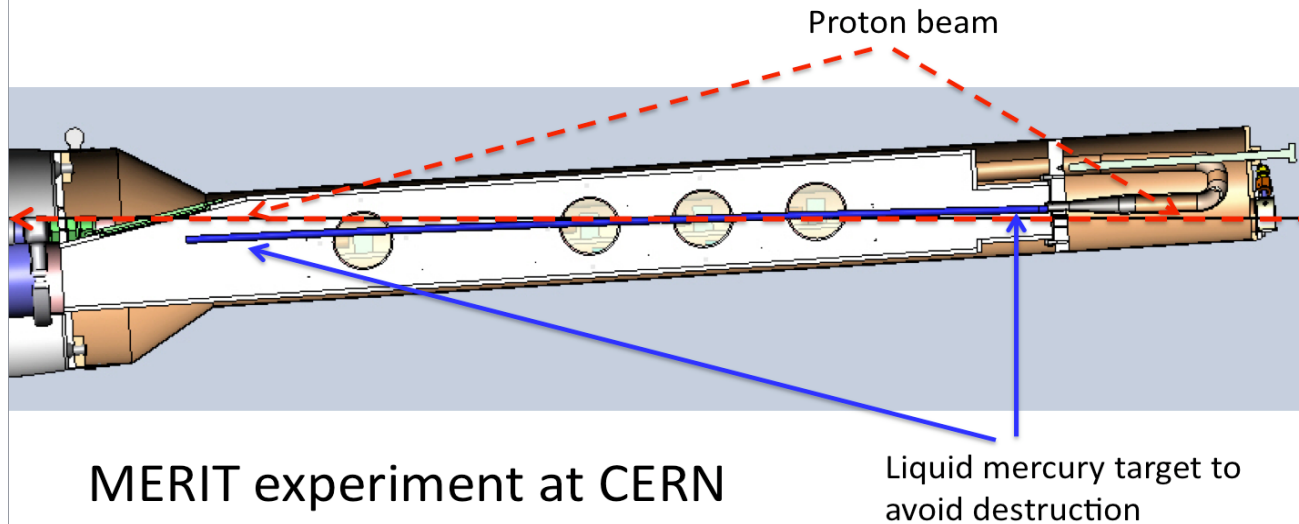


High power target (8 MW vs. 1.6-4 MW or even less required) has been demonstrated

Maximum pulse tested $30 \times 10^{12}$ protons with 24 GeV
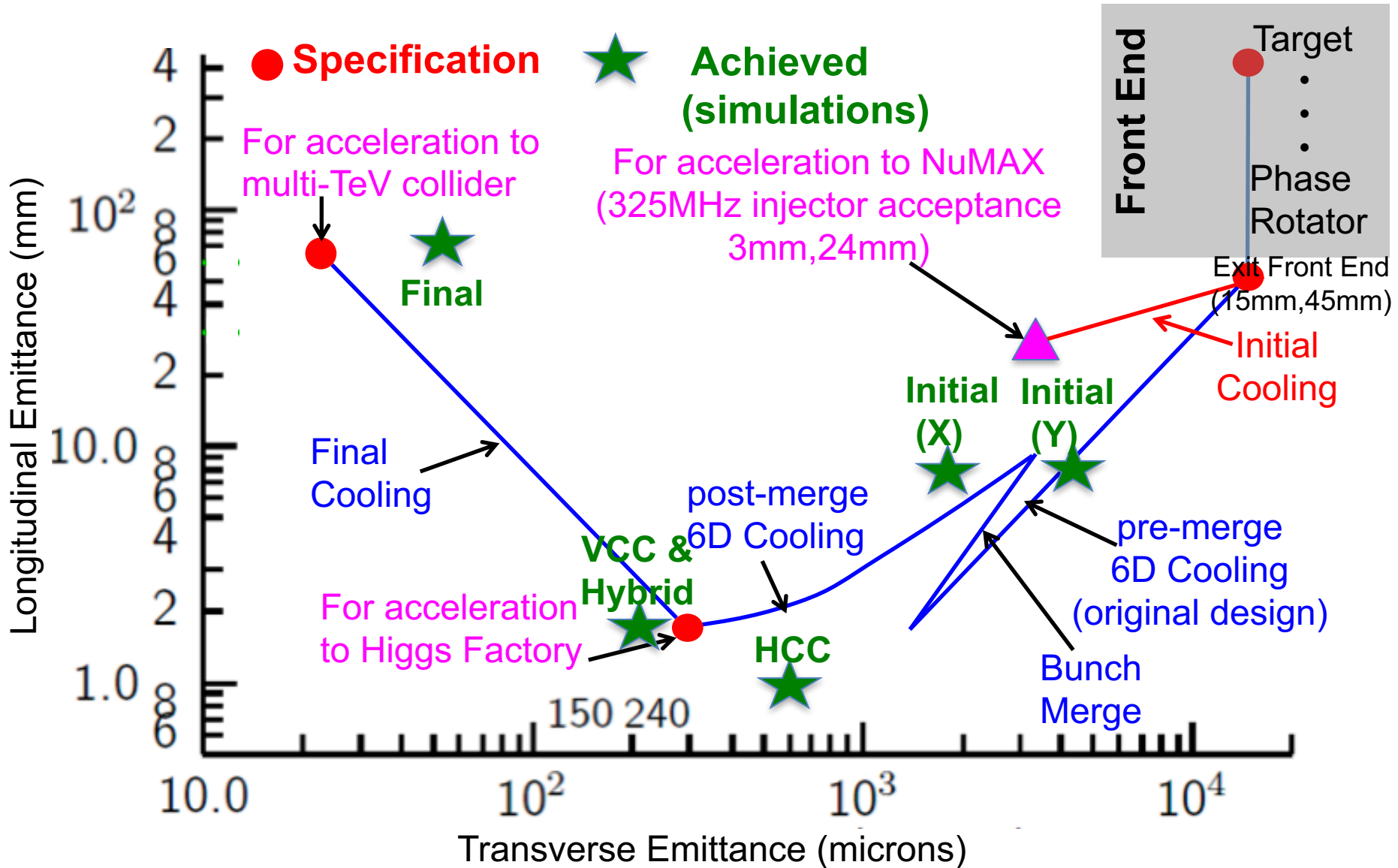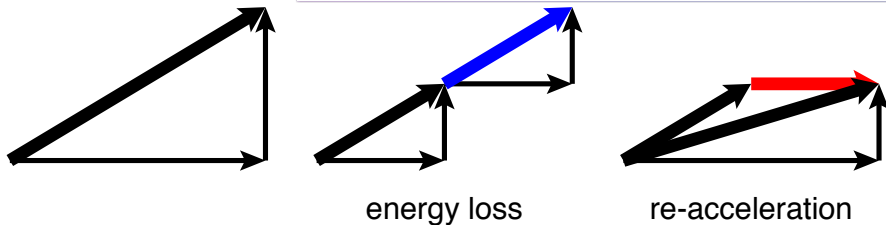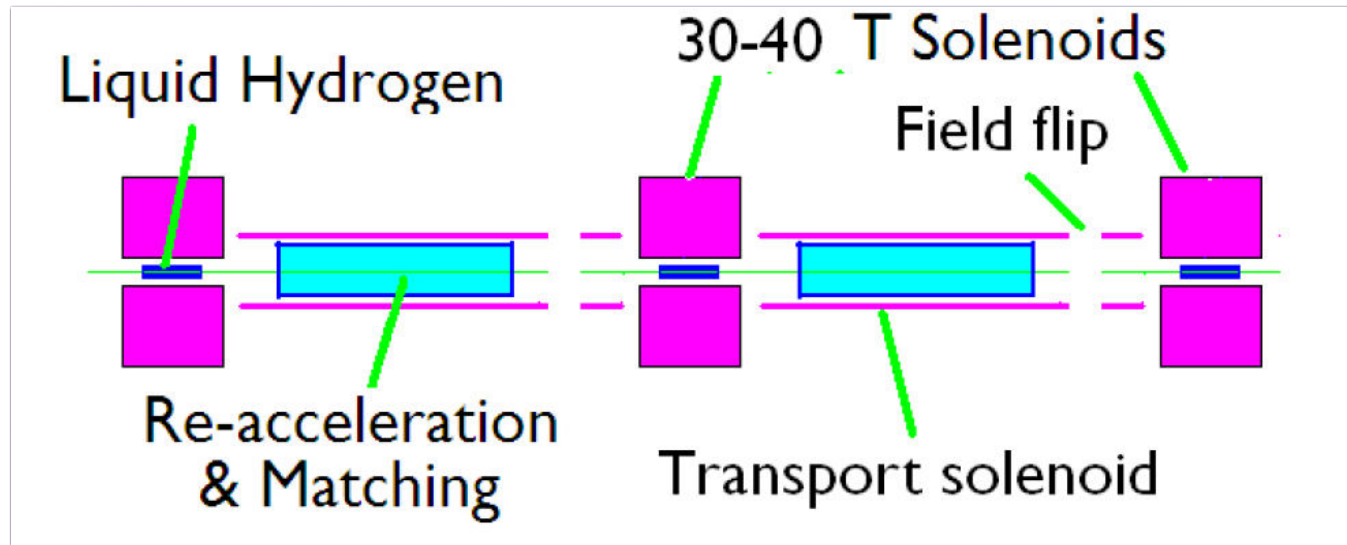- $9 \times 10^{12}$ muons (loose 90%)

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?**

# Cooling: The Emittance Path



DESY - December 17, 2019

# 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 and MICE

**Time-of-flight hodoscope 1 (ToF 0)**

**Variable thickness high-Z diffuser**

**Absorber/focus-coil module**

**Upstream spectrometer module**

**Downstream spectrometer module**

**MICE Muon Beam (MMB)**

**Electron Muon Ranger (EMR)**

**Cherenkov counters (CKOV)**

**ToF 1**

**Liquid-hydrogen absorber**

**Scintillating-fibre trackers**

**Pre-shower (KL)**

**ToF 2**

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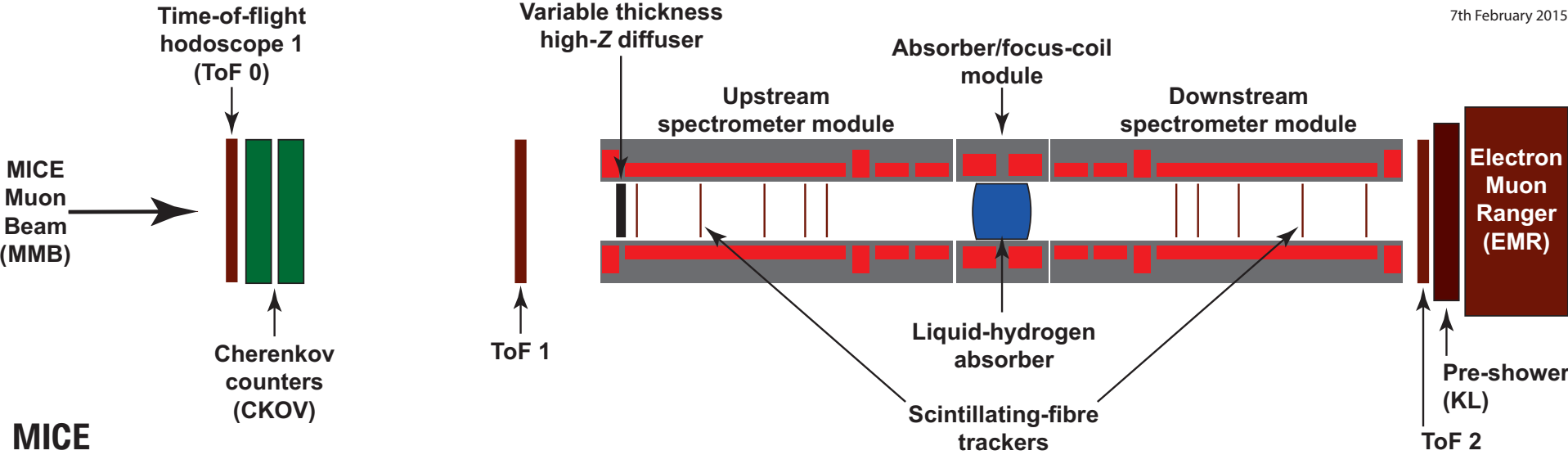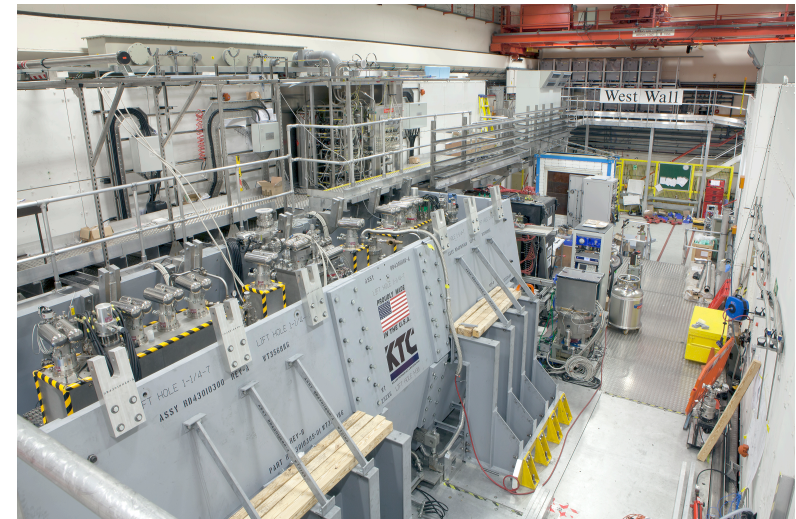
$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

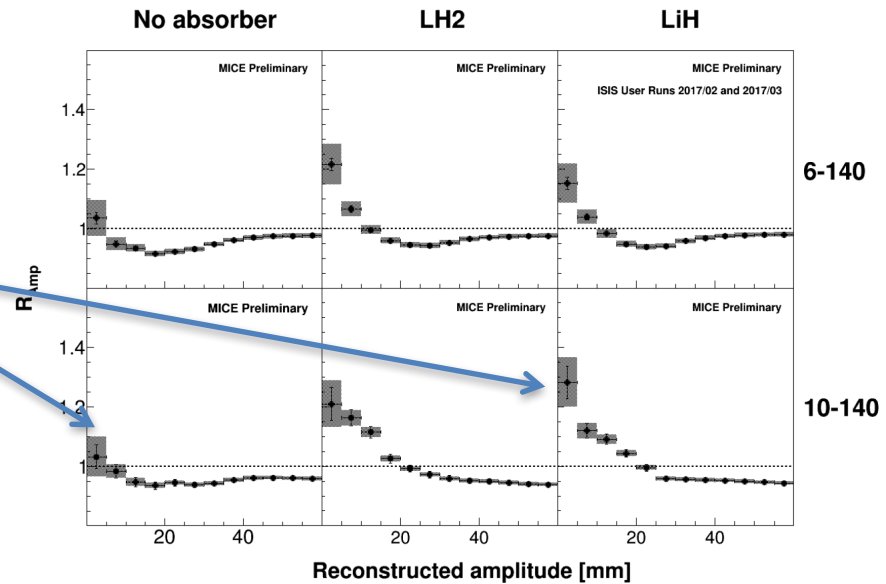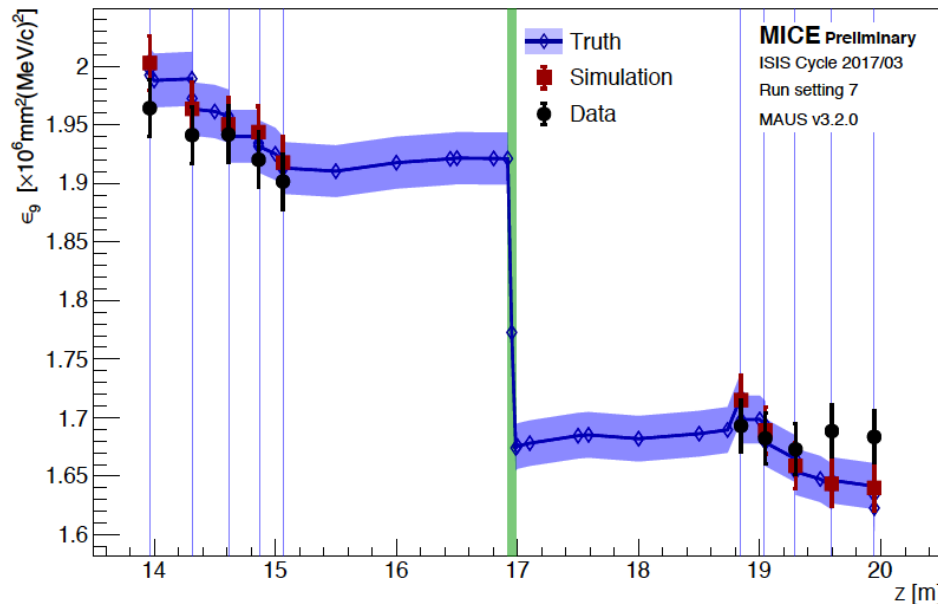MICE allows to address 4D cooling with low muon flux rate

# 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
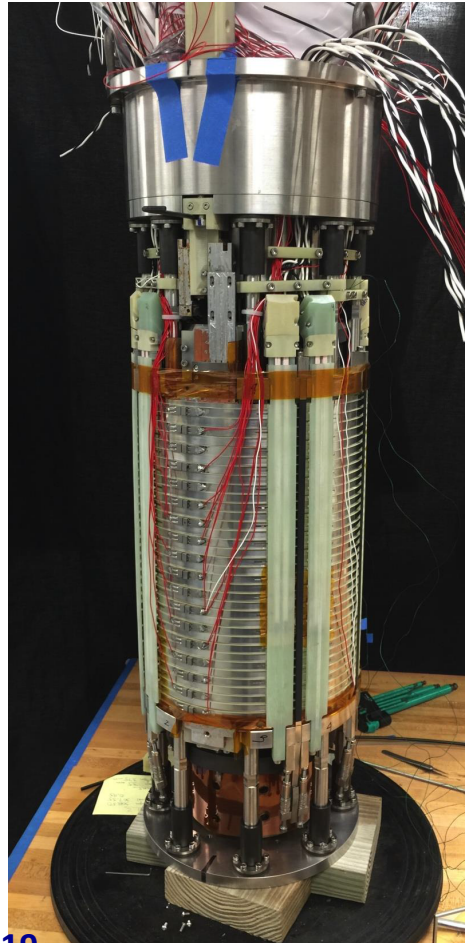• Small emittances

# Other Tests
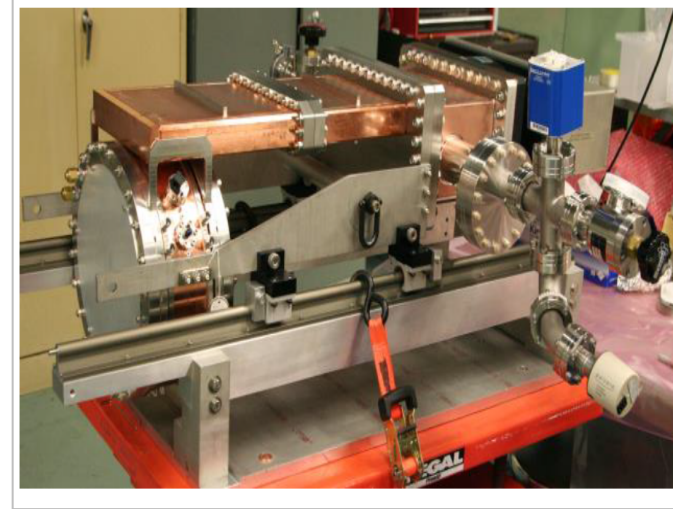


**FNAL**
Breakthrough in HTS cables

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

A number of key components has been developed

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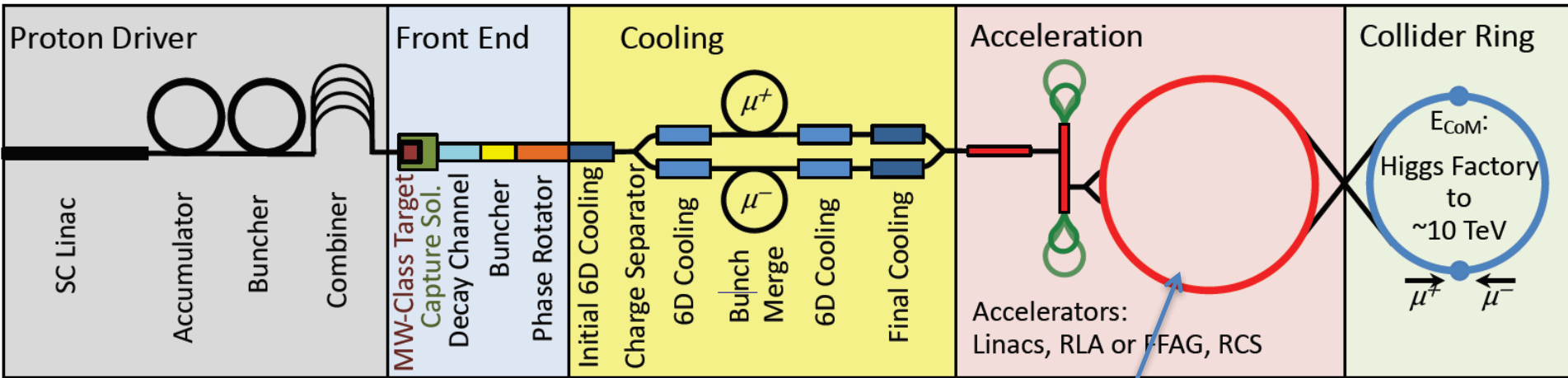


**FNAL**
12 T/s
HTS
0.6 T max

Mark Palmer

# Beam Acceleration



**Proton Driver** — SC Linac, Accumulator, Buncher, Combiner

**Front End** — MW-Class Target, Capture Sol., Decay Channel, Buncher, Phase Rotator

**Cooling** — Initial 6D Cooling, Charge Separator, 6D Cooling, Bunch Merge, 6D Cooling, Final Cooling, $\mu^+$, $\mu^-$

**Acceleration** — Accelerators: Linacs, RLA or FFAG, RCS

**Collider Ring** — $E_{CoM}$: Higgs Factory to ~10 TeV, $\mu^+$ $\mu^-$

Much larger than collider ring

An important cost driver

Important for power consumption

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

- We mainly also consider **experimental conditions** and **neutrino radiation** as critical

Level of many issues has not been clear because **no baseline existed**

- We anticipate critical issues there, e.g. design and cost of accelerator complex

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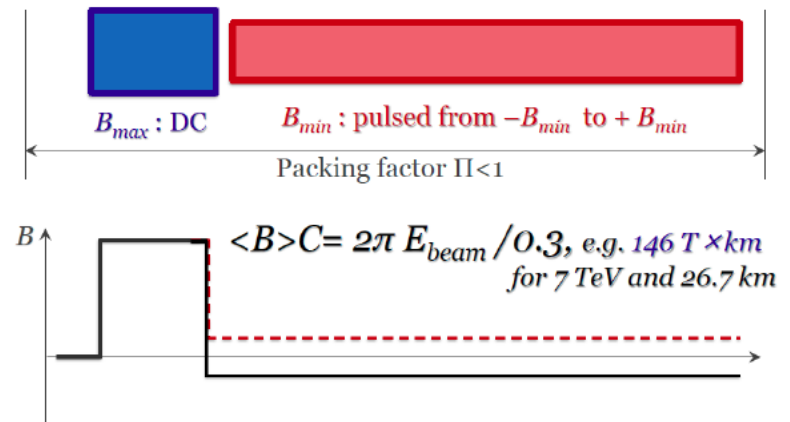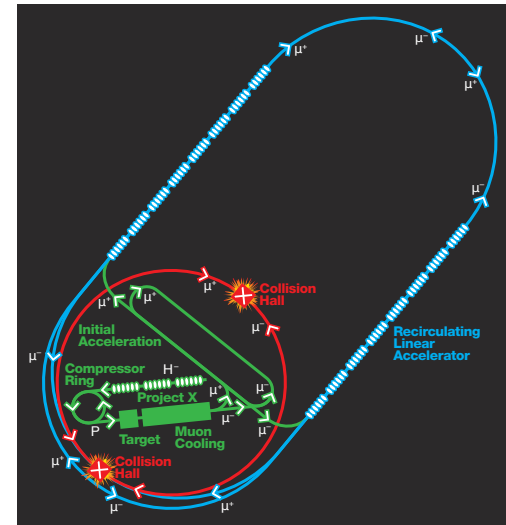- Fast acceleration but typically only a few passages through RF, hence high RF cost

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

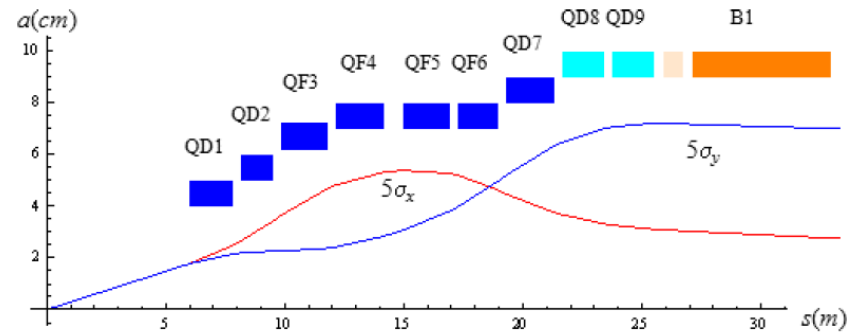Challenge to achieve a combination of  high efficiency, low cost and good beam quality



$B_{max}$ : DC        $B_{min}$ : pulsed from $-B_{min}$ to $+B_{min}$

Packing factor $\Pi < 1$

$<B>C = 2\pi\, E_{beam}\,/0.3$, e.g. $146\,T \times km$ for 7 TeV and 26.7 km

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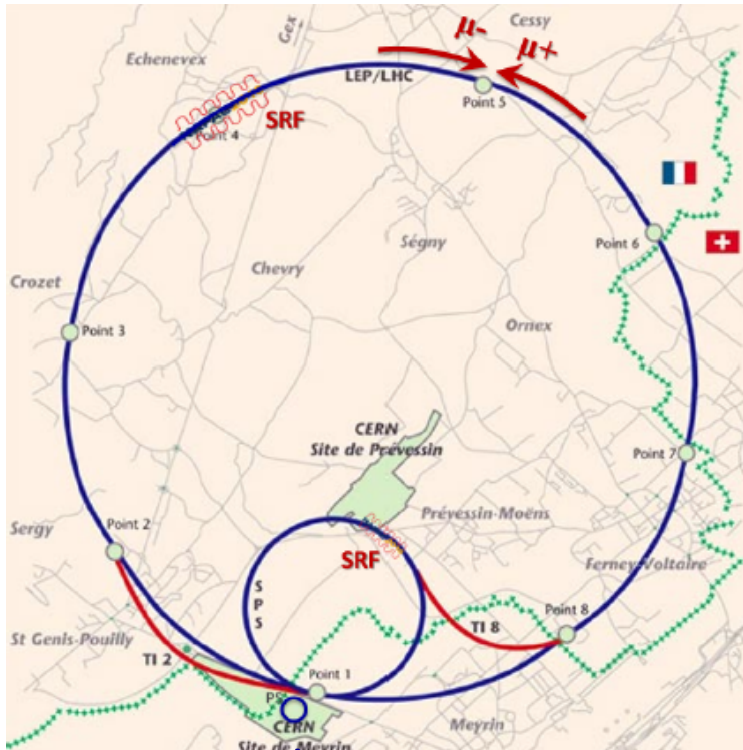
# proton (MAP) vs positron (LEMMA) driven muon source

**MAP**
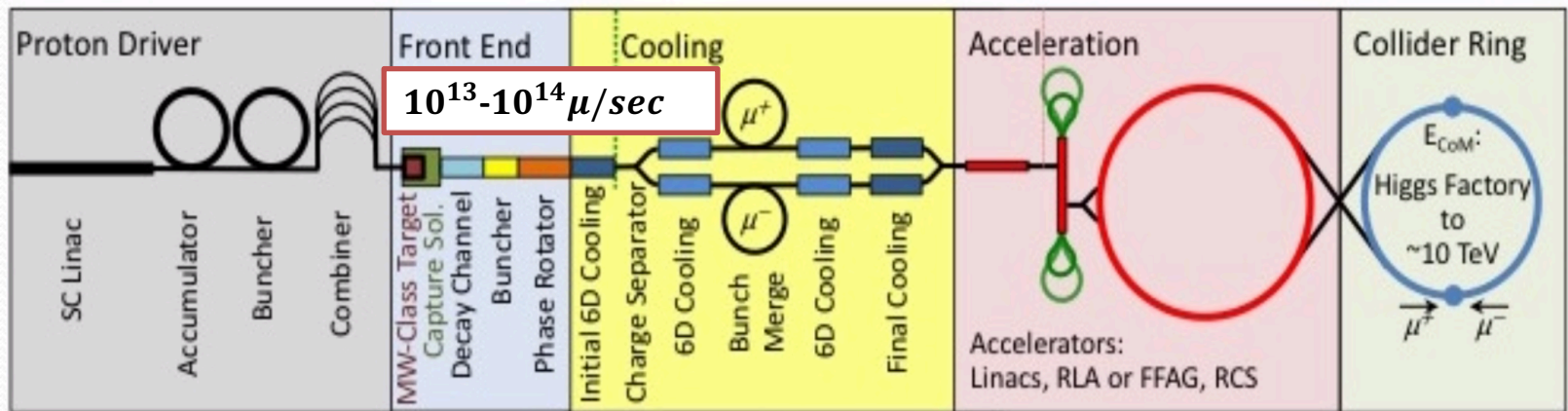


**Low EMmittance Muon Accelerator (LEMMA):** $10^{11}$ μ pairs/sec from $e^+e^-$ interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

$10^{13}$-$10^{14}$ $\mu/sec$

# LEMMA: main idea
## *Low EMittance Muon Accellerator*

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

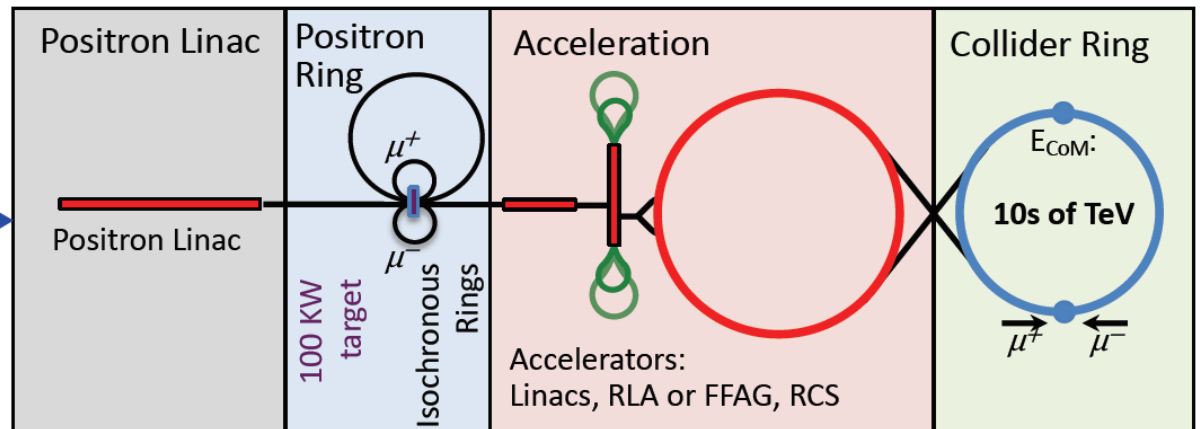**POSITRON DRIVEN MUON SOURCE : direct $\mu$ pairs production**

Muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ 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

# Recent LEMMA effort

M.Antonelli, M.E.Biagini, M.Boscolo, S.Guiducci, P.Raimondi, A.Variola et al.

Asymmetric collisions $e^+e^- \rightarrow \mu^+\mu^-$ at the $\mu^+\mu^-$ threshold ($\sqrt{s} \approx$ **0.212 GeV**)

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

## Extremely promising:

- muons produced with low emittance ➔ "no/low cooling" needed

## But difficult:

- ✓ **low** production **cross section**: maximum $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim 1\ \mu b$
- ✓ **high heat load** and **stress** in μ production target
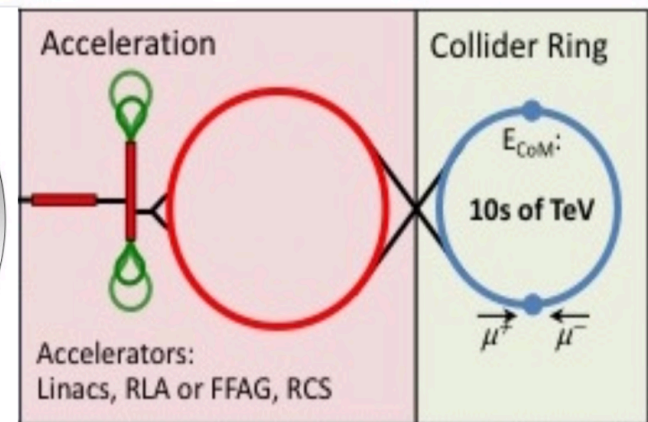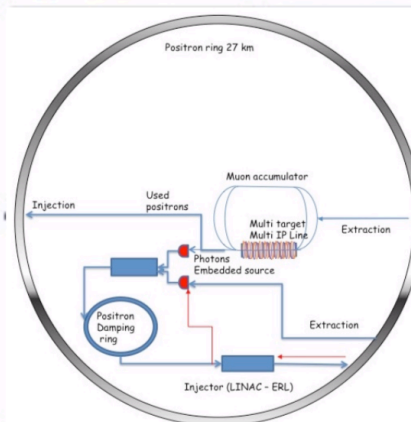- ✓ **synchrotron power** O(100 MW) ⬅ available 45 GeV positron sources

➔ **need consolidation** to overcome technical limitations to reach higher muon intensities

**LEMMA**



**arXiv:1905.05747**

**DESY - December 17, 2019**

# 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

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**
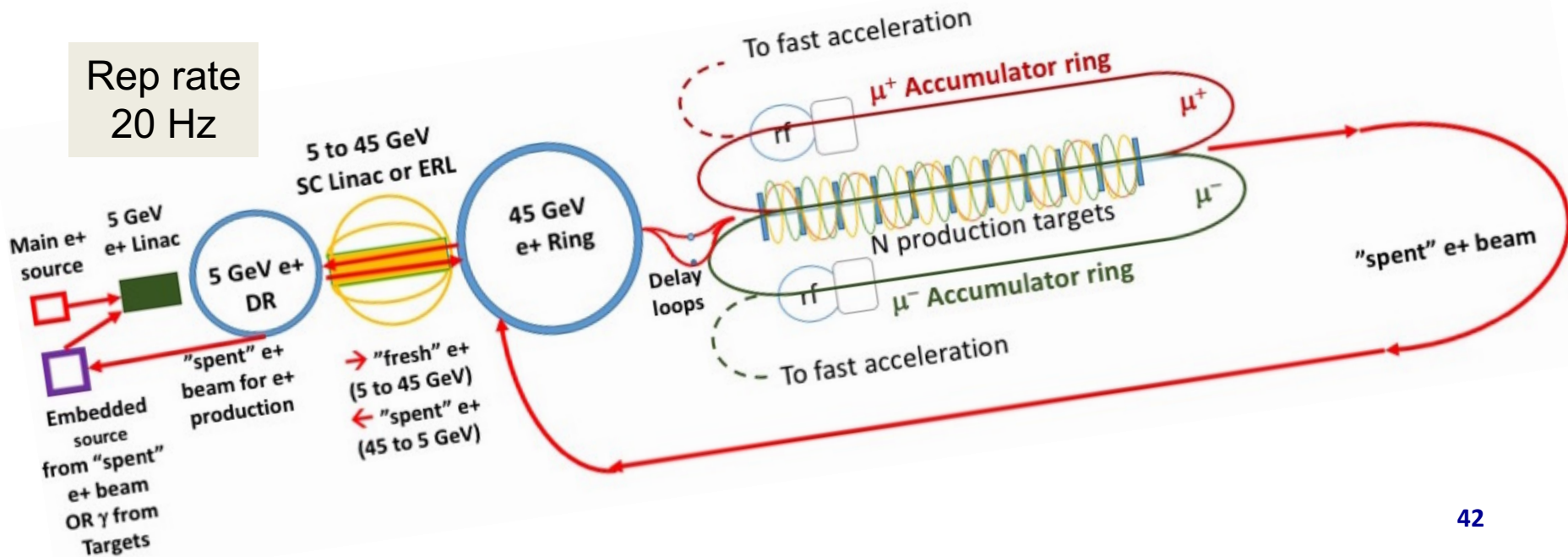
# Ongoing LEMMA Effort

**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
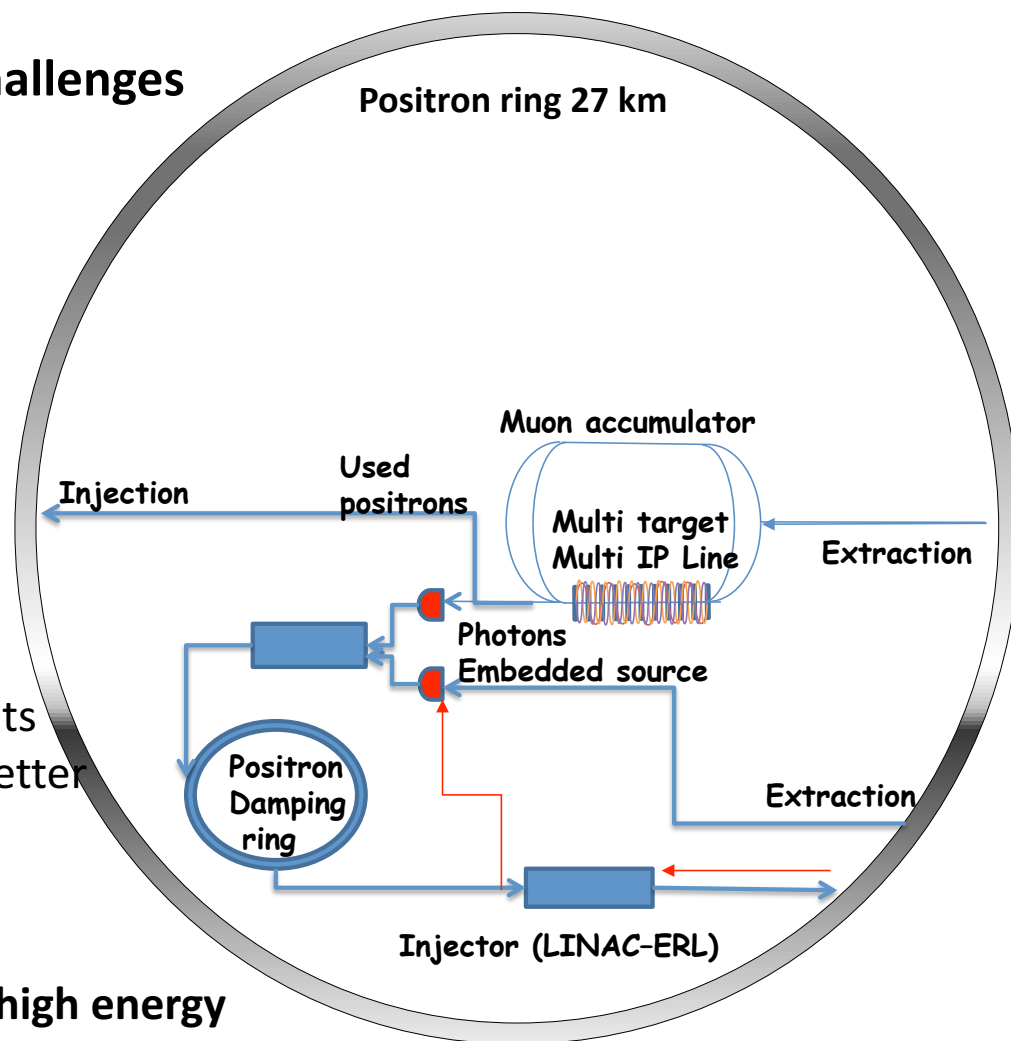
# Other Options

**Variations of the muon sources were suggested**

- E.g. use of channeling in crystals
- Use of gamma factory to produce muons
- Use of gamma factory to produce positrons for LEMMA

But all at a very tentative level for now

e.g. W. Krasny, X. Buffat, …

Also suggested were use of LHC and FCC tunnel for the collider ring

- Obviously something that needs to be explored
- Come back to this later

e.g. V. Shiltsev, D. Neuffer, F. Zimmermann, …

**Combination of final accelerator stage and collider ring**

- Could maybe save some cost
- But likely will compromise performance
- And generate its own challenges
- So trade-off has to be understood

e.g. V. Shiltsev, D. Neuffer

Also some other ideas

- But too early ……

# Full simulation: beam induced background

Nikolai Mokhov et al. - MARS15

**MAP developed realistic simulation of beam-induced backgrounds in the detector**:

- implemented a model of the tunnel ±200 m from the interaction point, with realistic geometry, materials distribution, machine lattice elements and magnetic fields, the experimental hall and the machine-detector interface (MDI)
- secondary and tertiary particles from muon decay are simulated with MARS15 then transported to the detector borders

In particular, the two tungsten nozzles, cladded with a 5-cm layer of borated polyethylene, play a crucial role in background mitigation inside the detector.
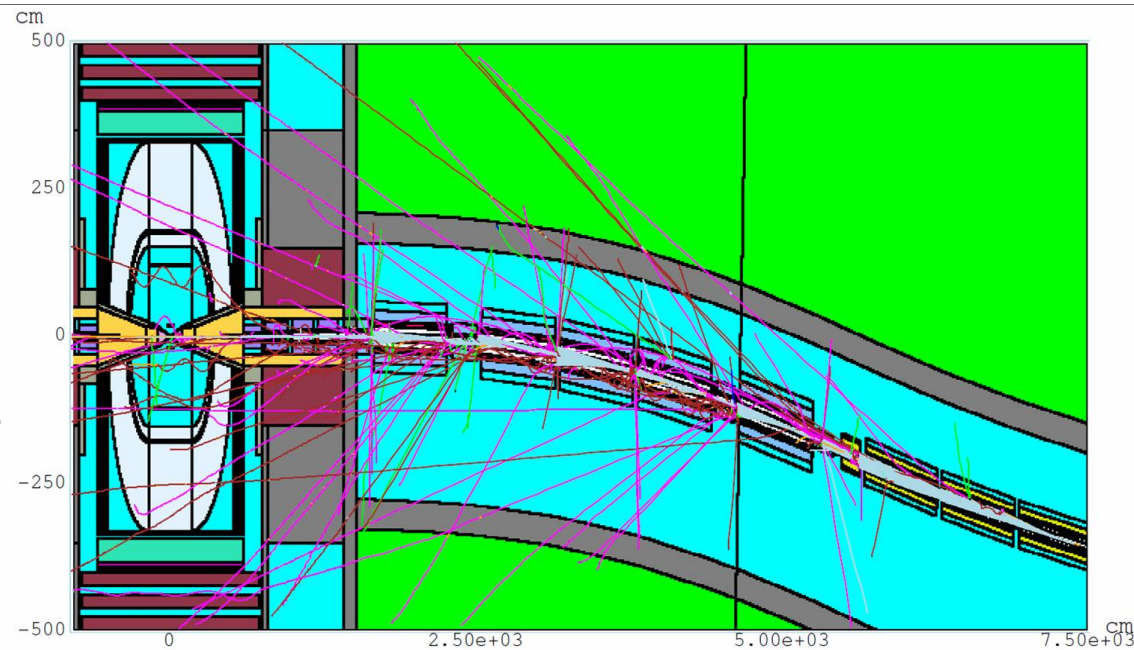
**For each collider energy the machine elements, the MDI and interaction region have to be properly designed and optimized**

# Is physics possible?

D. Lucchesi et al.

- Detector for muon collider is different from any current or conceived detector up to now, because muon decays
- Effect of beam induced background can be reduced with appropriate detectors to exploit time information to cut beam-induced background
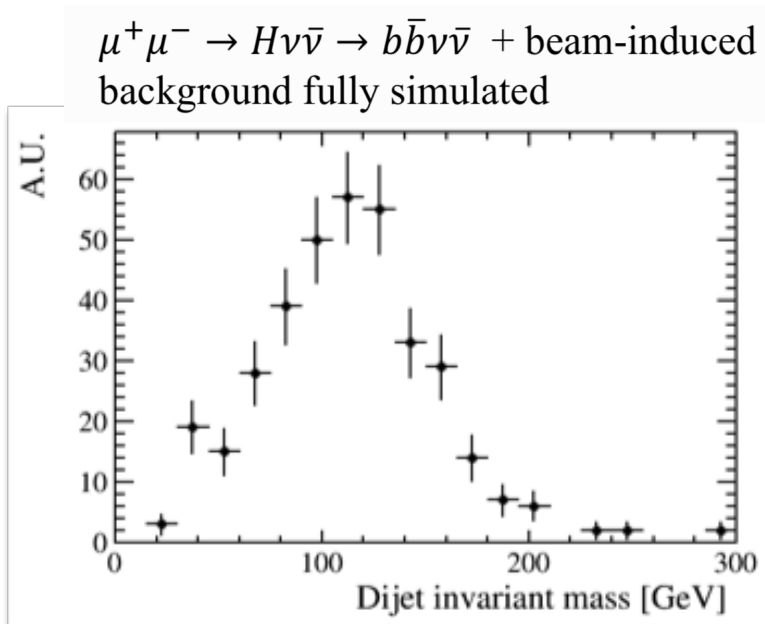- MAP developed a realistic simulation of beam-induced backgrounds in the detector for few muon beams → **studied in details 750 GeV case**
- It has been demonstrated with a full simulation that physics measurements can be done using one of the most difficult physics process: $\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$

$\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated
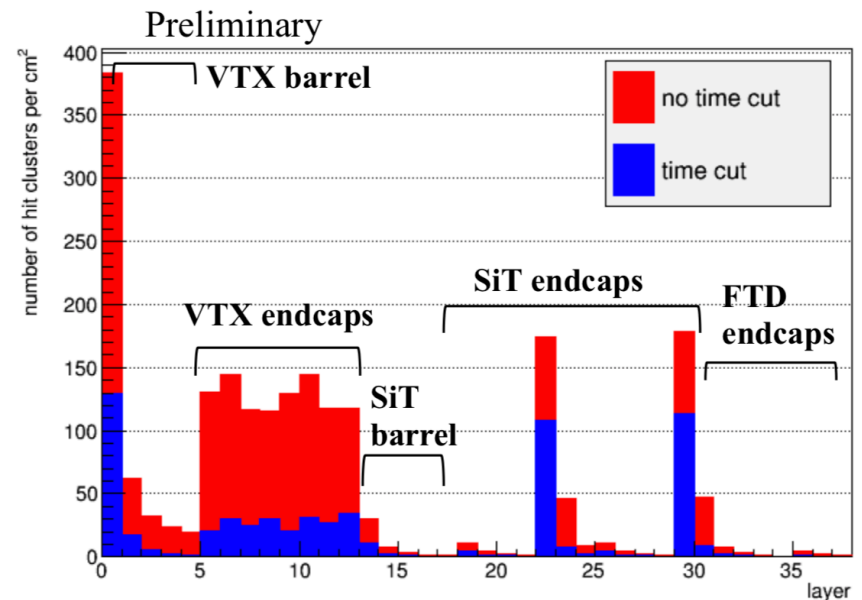
**arXiv:1905.03725** to be published soon

# $b\bar{b}$ Studies at $\sqrt{s} = 1.5$ TeV

D. Lucchesi et al.

Events $\mu^+\mu^- \to b\bar{b}X$ @$\sqrt{s} = 1.5\ TeV$ are generated with PYTHIA 8

| Process | cross section [pb] |
|---|---|
| $\mu^+\mu^- \to \gamma^*/Z \to b\bar{b}$ | 0.046 |
| $\mu^+\mu^- \to \gamma^*/Z\gamma^*/Z \to b\bar{b}$ +X | 0.029 |
| $\mu^+\mu^- \to \gamma^*/Z\gamma \to bb\gamma$ | 0.12 |
| $\mu^+\mu^- \to HZ \to b\bar{b}$ +X | 0.004 |
| $\mu^+\mu^- \to \mu^+\mu^- H\ H \to b\bar{b}$ (ZZ fusion) | 0.018 |
| $\mu^+\mu^- \to \nu_\mu\nu_\mu H\ H \to b\bar{b}$ (WW fusion) | 0.18 |



Preliminary

- H($\to b\ \bar{b}$)
- $\gamma$ Z($\to b\ \bar{b}$)

Normalized to the ratio of the expected number of events considering acceptance and reconstruction efficiencies

https://indico.cern.ch/event/847002/

47
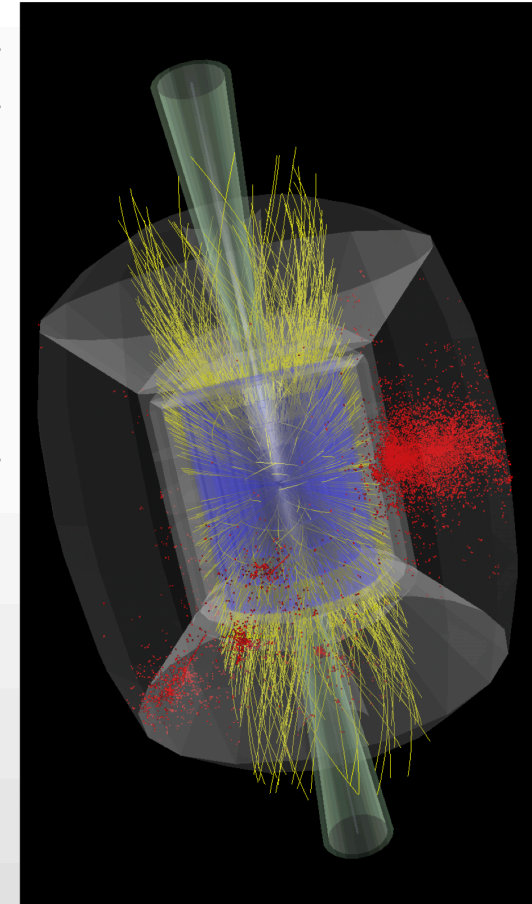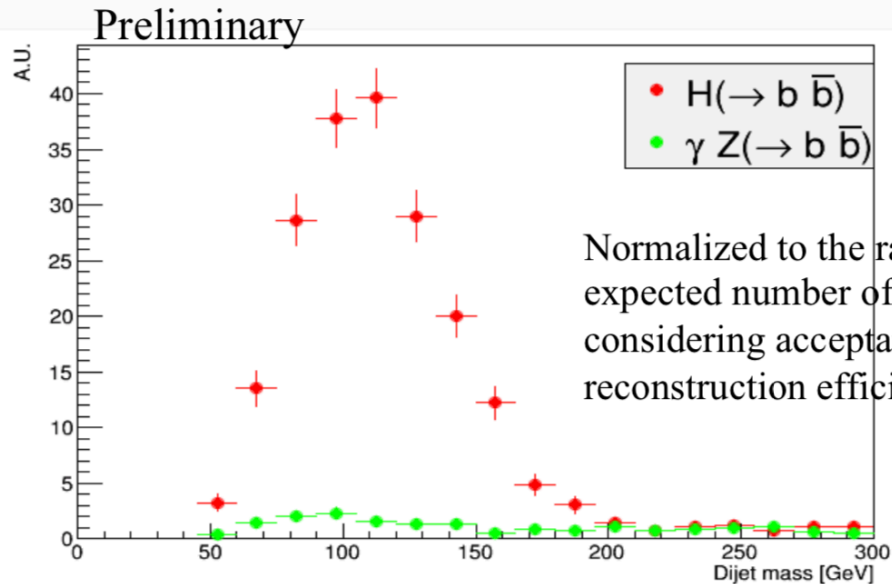
# Next steps
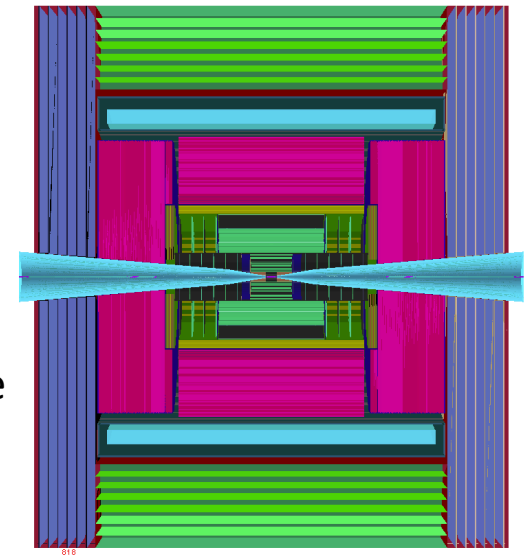
❑ **Move to use the Future Collider Framework**
- ▪ Description of the detector already done including the nozzle
- ▪ A new, up to the state of the art detector is needed

❑ **Simulate the beam-induced background with FLUKA**
- ▪ MDI and IR descriptions provided by MAP collaboration for 1.5 and 3 TeV $\sqrt{s}$
- ▪ Importing the description in FLUKA and generate new beam-induced background

❑ **Re-evaluate Physics performance @ $\sqrt{s}$=1.5 TeV as double check then study Physics** performance @ $\sqrt{s}$=3 TeV with full simulation

❑ **Collaborate with MAP to have MDI and IR @ $\sqrt{s}$=10 TeV to evaluate Physics performance**

❑ Determine physics objects efficiency and resolution for each configuration and parametrize them to estimate broad physics reaches smearing Monte Carlo generated process

# Neutrino Radiation Hazard

Neutrinos from decaying muons can produce showers just when they exit the earth
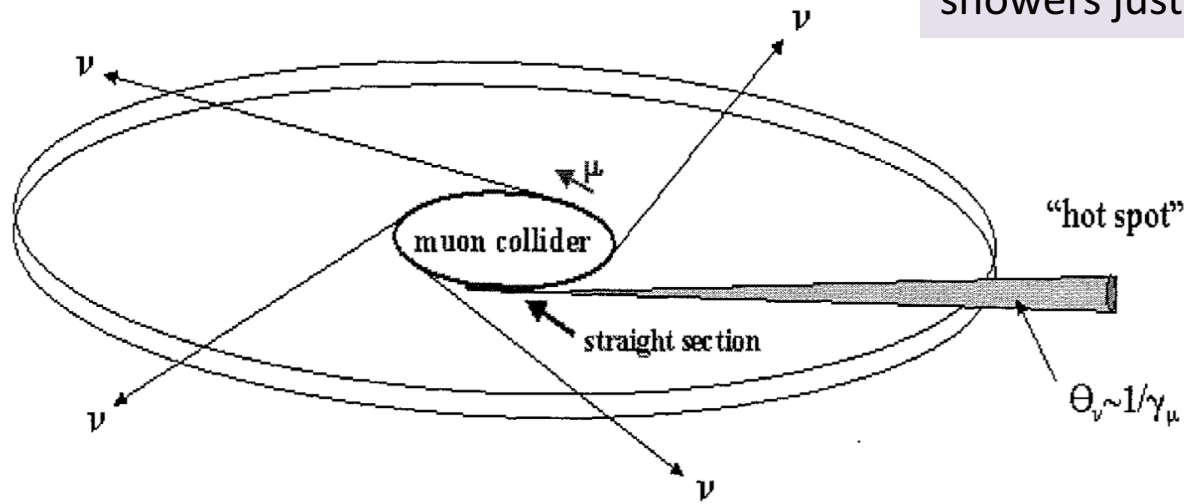
Particularly bad in direction of straights
But also an issue in the arcs



Becomes more important at higher energies (scaling $E^3$)

US study concluded that 6 TeV parameters are OK

Reasonable goal is 0.1 mSv/ year, but to be verified

Potential mitigation by
- Site choice
- 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
  - Or at least paint the beam in the the straights to dilute radiation

# How could 14 TeV look like?

Very tentative target parameters based on scaling from MAP, to be studied

| Parameter | Unit | 1.5 TeV | 3 TeV | 6 TeV | 14 TeV |
|---|---|---|---|---|---|
| L | $10^{34}$ cm$^{-2}$s$^{-1}$ | 1.25 | 4.4 | 12 | 40 |
| N | $10^{12}$ | 2 | 2 | 2 | 2 |
| $f_r$ | Hz | 15 | 12 | 6 | 3.7 |
| $P_{beam}$ | MW | 6.75 | 11.5 | 11.5 | 16.6 |
| <B> | T | 6.3 | 7 | 10.5 | 10.5 |
| $\varepsilon_L$ | MeV m | 7.5 | 7.5 | 7.5 | 7.5 |
| $\sigma_E / E$ | % | 0.1 | 0.1 | 0.1 | 0.1 |
| $\sigma_z$ | mm | 10 | 5 | 2(.5) | 1.07 |
| $\beta$ | mm | 10 | 5 | 2.5 | 1.07 |
| $\varepsilon$ | μm | 25 | 25 | 25 | 25 |
| $\sigma_{x,y}$ | μm | 5.9 | 3.0 | 1.5 | 0.63 |

Note: CLIC beam power at 3 TeV is 28 MW

Challenging optics
Maybe hard to make short bunches

# Tentative Considerations on Baseline

- **Focus on first stage with energy of O(1.5 + 1.5 = 3 TeV)**
  - To come after higgs factory and matching highest CLIC energy
  - Using the high-energy strength of muon colliders
  - Realistic design for implementation at CERN, with cost power and risk scale
  - If successful, feasibility demonstration for CDR

- **Explore 14 TeV as further step**
  - To match FCC-hh discovery potential
  - Mainly exploration of parameters to guide choices
  - Provide evidence for feasibility, maybe cost frame

- **Some exploration of lower energies / Higgs factory**
  - Scaling from higher energies
  - Not a main focus, except if other projects do not cover lower energies

- Open for input

# Effort for Baseline Design

- **Put together coherent design requires (mainly human) resources**
  - This goes beyond US effort
  - Consistent parameters and layouts
  - Integration of collider systems, trade-offs, choices, …
  - May highlight additional important issues
  - Requires (mainly human) resources
  - Currently MAP is main option, LEMMA is alternative

- **Current first step: define key R&D list**
  - **Tentative list started, goal to finish by end of the year**
  - Identify key / feasibility issues
    - i.e. largest technical risks
    - Key cost driver, if critical
    - Key power consumption, if critical
  - Entry point for collaborators

**Will speed up things if European Strategy recommends R&D**

**Proposed MUST
(MUon collider STudy network)
In ARIES2 to have EU label
You are welcome to join**

# Tentative Key R&D Items

- **Integrated design (to make sure that things fit)**
  - Definition of parameters for key systems
  - Choices between different options
  - Many systems could be difficult, depending on choices, see US study
  - E.g. lose 90% of muons before collision, can this be reduced?
  - Important cross effects, e.g. beam emittance
  - Collective effects
  - …

- **Neutrino radiation (critical limit at highest energies)**
  - See in later slides

- **Experimental conditions**

# Potential Key R&D Items, cont.

- **Beam production and cooling**
  - **Critical parameter driver**
  - **Emittance drives design, lower emittance: less radiation to public, detector, …; less power; less risk**
  - Proton beam production / compression
  - Paper design of cooling does not reach full performance
  - **Many key components: robust targets, RF with gas, high-field solenoids**
  - Take full advantage of MICE (data, installation)
  - **Will need new facility to improve test compared to MICE**
  - **Anticipated to be core of new testing programme**
    - **6-D cooling, stages to reach significant emittance reduction, radiation effect on equipment, …**
    - **Parametric cooling to be tested**
    - **Likely the core of the experimental programme**

# Potential Key R&D Items, cont.

- Collider ring design (important parameter and cost driver)
  - Is it affordable (cost)?
  - **High field superconducting magnets, minimal gap, radiation hard**
  - **Improved lattice design beyond 3 TeV**
  - Injection, safety concept

- Reuse of existing infrastructure (potential cost saving)
  - Proton facilities
  - Tunnels (maybe more for acceleration than for collision)

- **LEMMA concept and new ideas (could be breakthrough for parameters)**
  - **Consolidation**
  - **Alternative low-emittance sources (gamma factory, crystals, …)**
  - **Could define the source test facility**
  - **Long-term alternative development**

# Some synergies ➜ Key Accelerator Technologies

- **High-field, robust collider magnets with minimum gap**
  - Dipoles, solenoids, … for collider ring
- **Efficient fast ramping magnets with efficient energy recovery – magnet powering**
  - For the beam acceleration
- **Efficient cryogenics, vacuum and shielding systems**
  - Significant beam loss
- **Robust targets and beam cleaning**
- **High field cavities**
  - In a solenoid for the cooling system
- **Efficient RF power production**
- **Civil engineering**
- **Other systems** (instrumentation)
- **Beam-dynamics and accelerator design**
  - Start-to-end design and simulations, source design, …

Similar to what is needed for proton colliders

Expertise in Europe and at CERN

# Use of Existing Infrastructure

**Might be able to reuse much of the proton and general infrastructure**
- Needs detailed study
- Much of the expertise is available

**Use of the largest tunnels, i.e. LHC or potentially FCC**
- Can house positron ring in the LEMMA case
    - In FCC, even lepton equipment might exist from FCC-ee
    - Large rings means less synchrotron radiation and power consumption
- Consider to use ring as a collider
    - But means to have larger ring for acceleration
    - Or to use combined final accelerator / collider
        - This compromises luminosity and generates technical challenges but may save cost
- **Use tunnel for final accelerator**
    - Have a small optimised collider ring
    - Seems natural solution

Some proposals made, e.g. LEMMA team, V. Shiltsev, D. Neuffer, F. Zimmermann, …

# Use of LHC Tunnel for Collisions

**Useful collider energy range 14-25 TeV**

Daniel Schulte

- For 3 TeV collider 6 km tunnel would be sufficient and yields 5 times more luminosity
  Use **MAP-type beam** with 4 Hz repetition rate and $10^7$ s operation per year
  ➔ **Achieves luminosity target**

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

Radiation to public can be limiting
- Maximum radiation from arcs (14 TeV, 4 ab$^{-1}$ per year, B = 8 T, L = 0.2 m):
  **O(18.8 mSv/year)**
- The straights increase neutrino radiation (14 TeV, 4 ab$^{-1}$ per year, B = 8 T, L = 500 m)
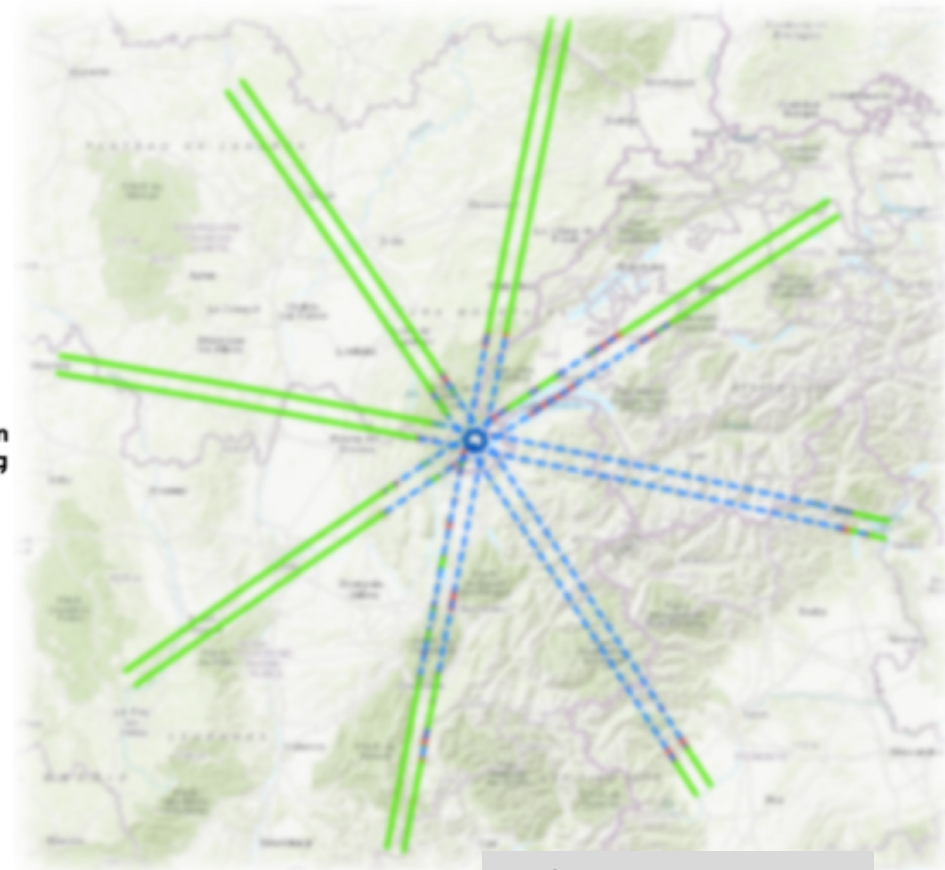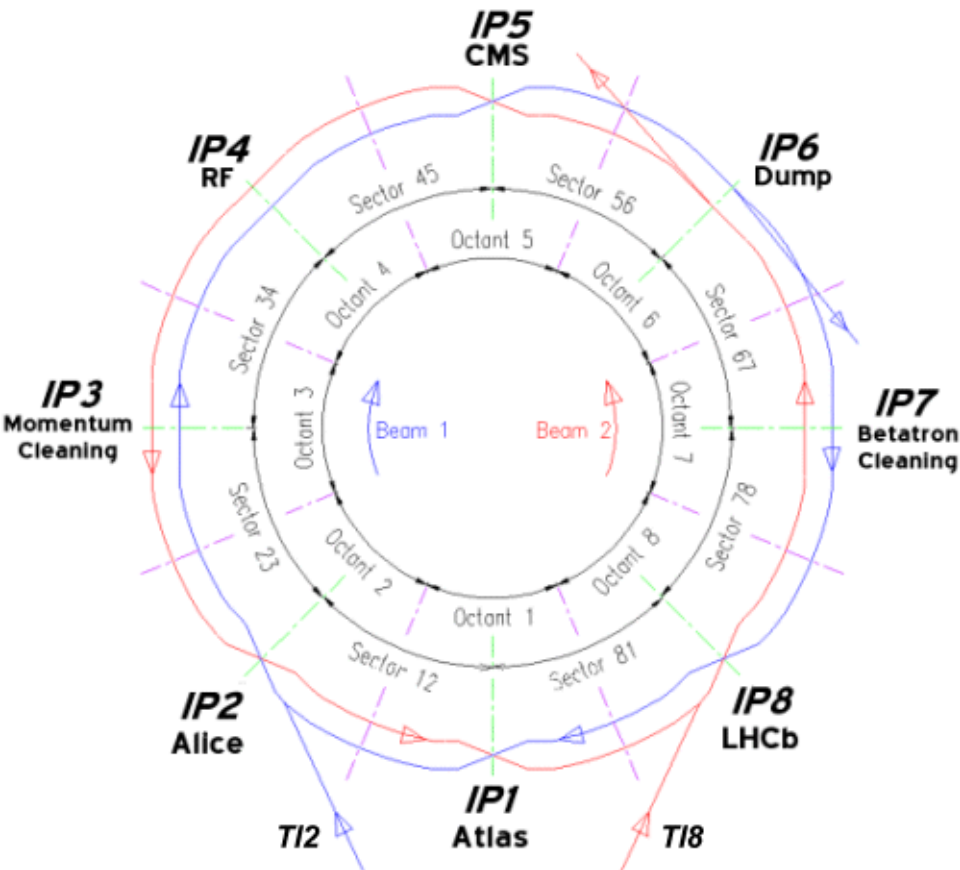  **O(3x10$^4$ mSv/year)**

## Important mitigation is required

- Arcs would be OK for 2 TeV
- Can we wiggle the beam?
- Can we paint it around in the straights?
- **Seems an important issue**

A much reduced current would help
- A reason to continue to work on other sources (LEMMA etc.)
- Note: LEMMA-type beam $10^{11}$ muons/s would give factor 80, still problem in straights

# Effective Depth of LHC



J. Osborn, Y. Robert
, …

Minimum distance is 17 km, corresponds to effective depth of d = 23 m
Second shortest is 25 km (d = 50 m), longest is 263 km (d = 5430 m)

# Collision in FCC Tunnel

**Daniel Schulte**

Would be at even higher energies ➔ 50 to 100 TeV

- Radiation is much worse
- But can still define layout
  - In particular arrange straights
  - e.g. racetrack design?
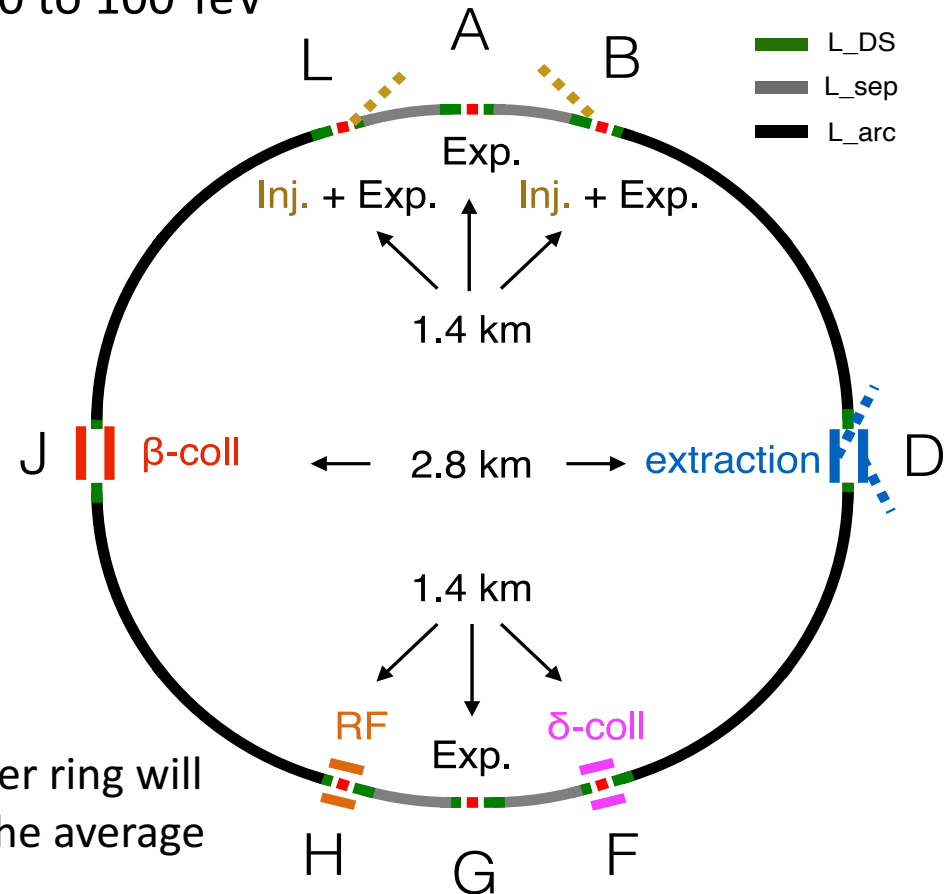


Solutions with combined accelerator/collider ring will have even more radiation from arcs since the average field is lower

**Low emittance beam would help:**
- Need factor 200 less current

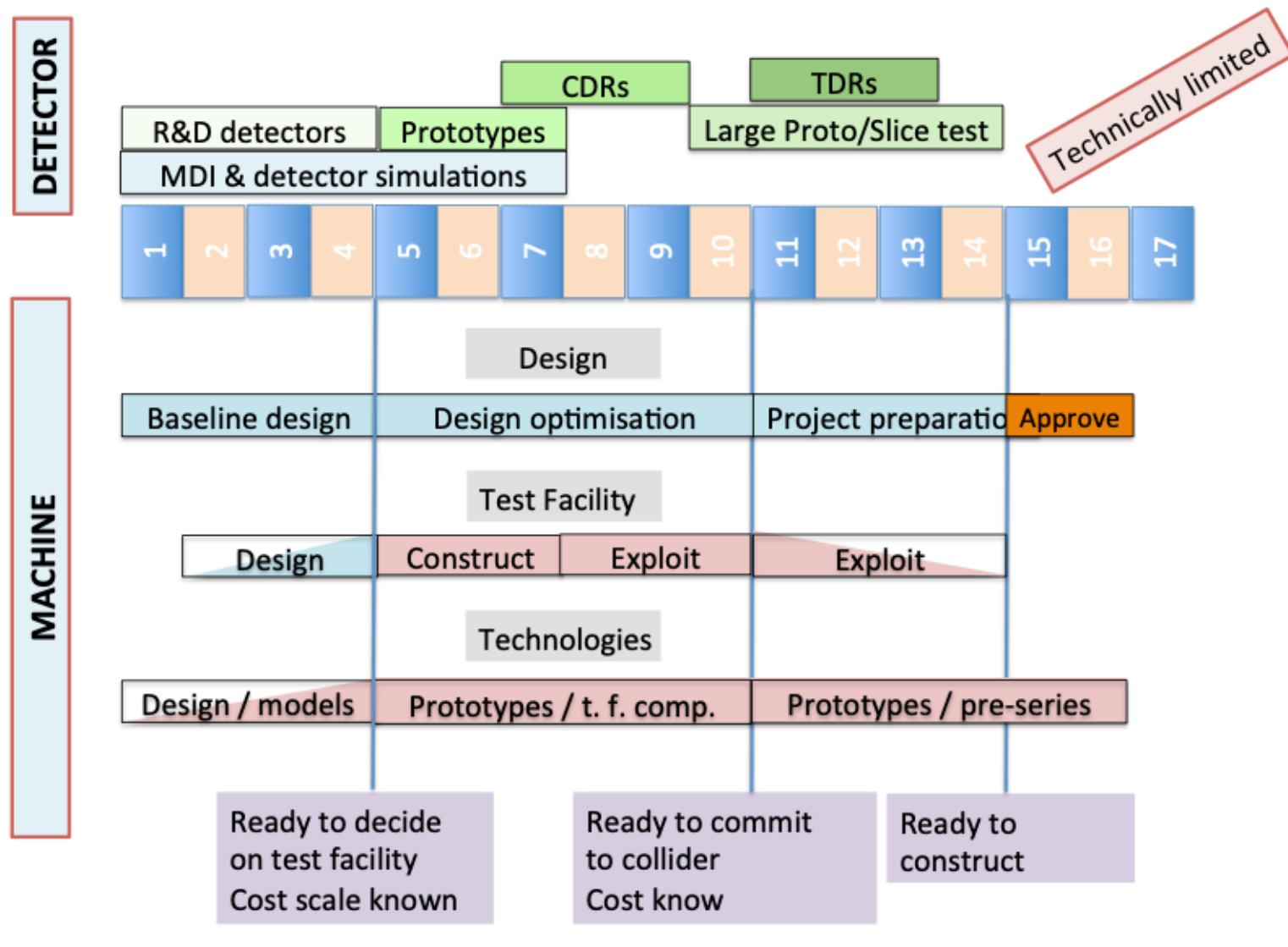# Acceleration in LHC/FCC Tunnel

Daniel Schulte

- Lower radiation than collider ring (fewer turns and mostly lower energy)
  - Typically factor O(10) to O(100), use 30 as example below
  - Maybe can use energy change to distribute distribute radiation more

- **For 1.5 TeV beam in LHC** (e.g. fast-ramping 1.4-1.8 T magnets, 45 GV RF)
  - Gaps of O(30 m) are still OK
  - Straights would be O(20) too high, requires improvement (helical trajectory?)

- **For 3 TeV beam in LHC**
  - e.g. could be mixture of superconducting and fast-ramping normal magnets
  - Gaps of 3 m would be OK
  - O(200) too high in straights

- **For 7 TeV beam in FCC** (e.g. fast-ramping 1.8 T magnets)
  - radiation from arcs sufficient at 300 m depth
  - need to anticipate arrangement of straights

Need to study mitigation of radiation from straights
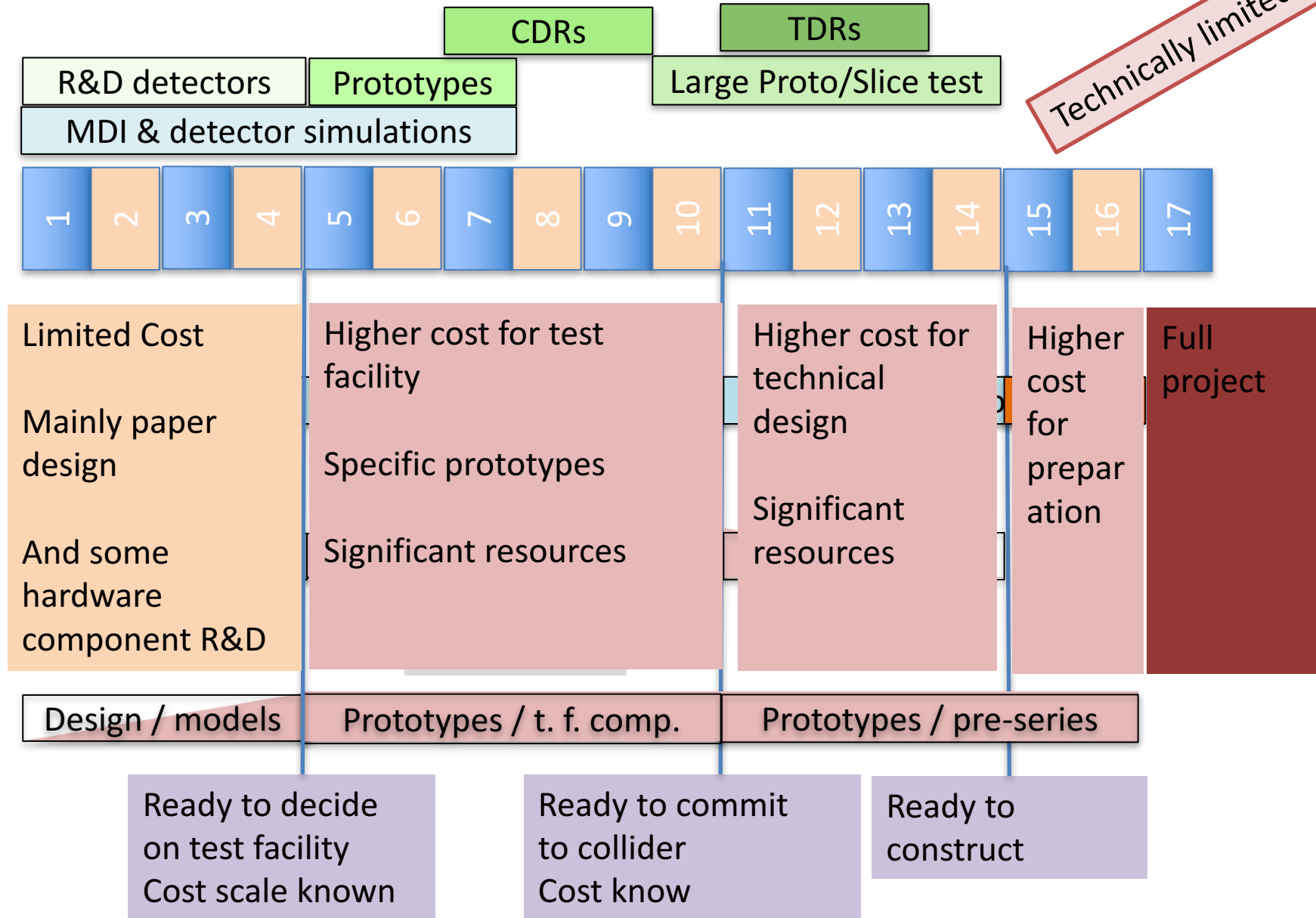
# Proposed Tentative Timeline

# Proposed Tentative Timeline (2019)

**DETECTOR**

| CDRs | TDRs |
|------|------|

**Technically limited**

| R&D detectors | Prototypes |
| MDI & detector simulations |

| Large Proto/Slice test |

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|

**MACHINE**

Limited Cost

Mainly paper design

And some hardware component R&D

Higher cost for test facility

Specific prototypes

Significant resources

Higher cost for technical design

Significant resources

Higher cost for preparation

Full project

| Design / models | Prototypes / t. f. comp. | Prototypes / pre-series |

Ready to decide on test facility
Cost scale known

Ready to commit to collider
Cost know

Ready to construct

# Cost estimate

**Vladimir SHILTSEV, David NEUFFER ( Fermilab)**
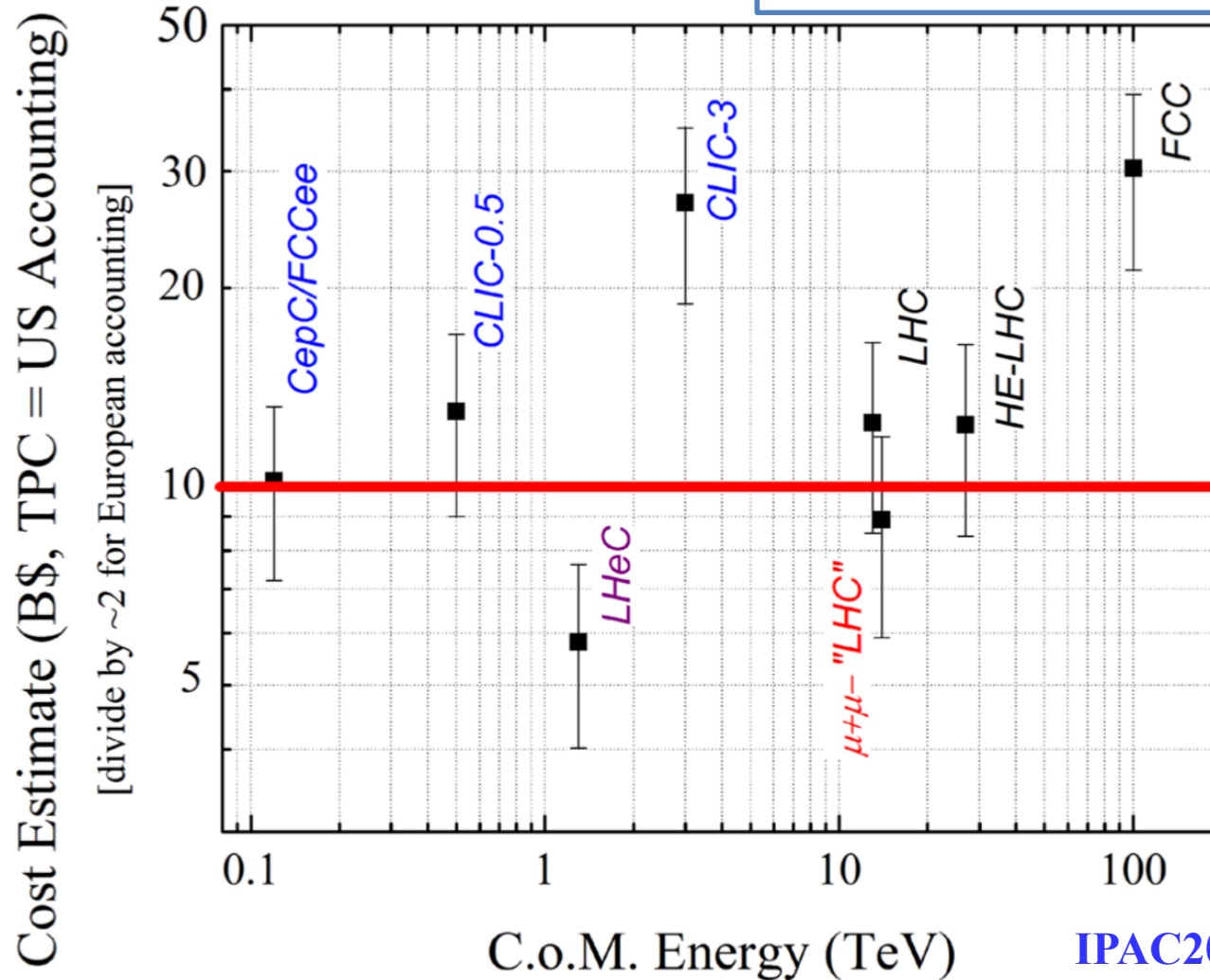


IPAC2018 - MOPMF072

# To face the next challenge
## Expect Shortage of Expert Accelerator Workforce

- *"Oide Principle"* :

  1 Accelerator Expert

  can spend <u>intelligently</u>

  (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)

# At present we can state

A Muon Collider has the potential to largely extend the energy frontier:

➔ an immense physics reach

➔ detector studies with beam induced background recently proved physics feasible

➔ a possibly affordable cost: [5-10] GCHF - also exploiting existing tunnels

**MAP** studies addressed design issues from muon production to final acceleration:

➔ **proton driver option can be used NOW as baseline for a CDR of a 3-6 TeV machine**

➔ **however a 6D cooling TEST FACILITY is MANDATORY to demonstrate feasibility**

A new idea not requiring 6D cooling – **LEMMA** – could represent an appealing scheme:

➔ **further studies and solid R&D program needed for such positron driven option**

# Conclusion

- **A plan for the future is under construction with an international effort**
  - Need people and money ➜ maintain know-how!
  - Try to obtain network-like activity (via ARIES2)

- **Need to develop baseline**
  - Energy and luminosity choice: both for MAP and LEMMA approach (gaps exist)
  - Need to bring knowledge to life again
  - And address holes
  - For LEMMA consolidation is attempted

- **Need to address neutrino radiation**
  - Confirm results from US study
  - Lower radiation at 14 TeV
  - Potentially strong point of the LEMMA scheme

- **Need to develop experimental R&D plan ➜ to be discussed early next year!**
  - Key is likely test facility for muon generation
  - Will depend on progress of baseline design

**A strong recommendation for a vigorous R&D programme on**

**Muon Colliders will be key**

**to support the international collaboration**

**to develop this unique opportunity for High Energy Physics**

# Ready to launch an
# International Collaboration on Muon Beams
# (Accelerator, Detector and Physics)

*Please register at the following:*

**e-group: *MUONCOLLIDER-DETECTOR-PHYSICS***

[MUST-phydet@cern.ch](mailto:MUST-phydet@cern.ch)

**e-group: *MUONCOLLIDER-FACILITY***

[MUST-mac@cern.ch](mailto:MUST-mac@cern.ch)

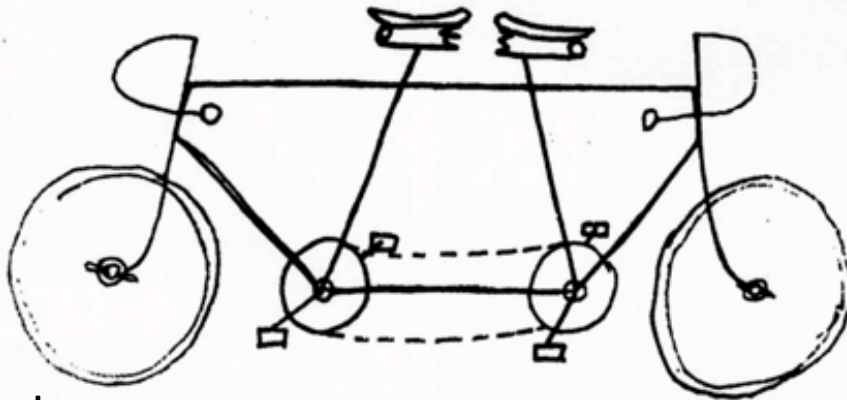**Meetings next year and a CERN Workshop end of March 2020**
**will be announced soon**

# Thanks to many colleagues!

*CERN Muon Collider Working Group*
*MAP, MICE and LEMMA teams,*
*and among many others: Donatella Lucchesi, Mark Palmer,*
*Marica Biagini, Susanna Guiducci, Vladimir Shiltsev……*

# Thanks you for the attention!

**drawing by**
**Bruno Touschek**

PROBARE ET REPROBARE !