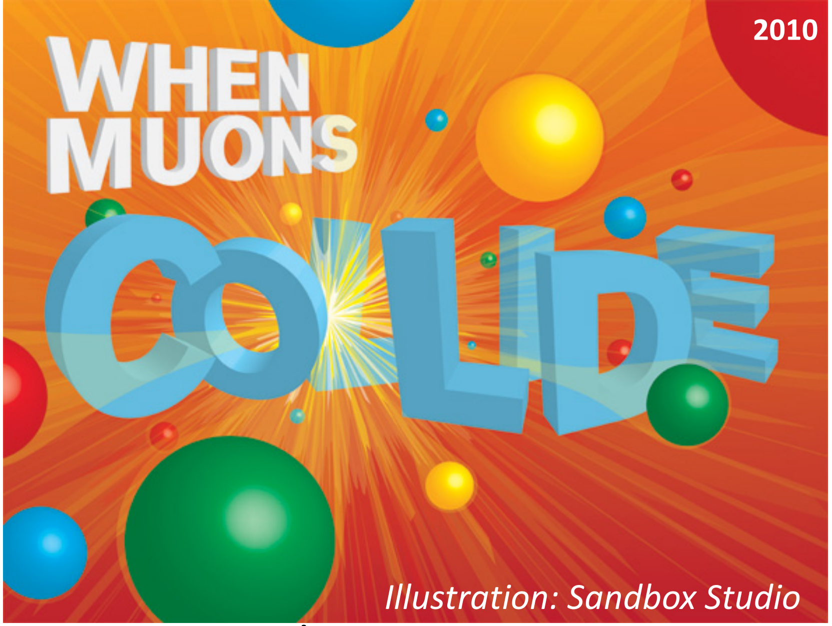


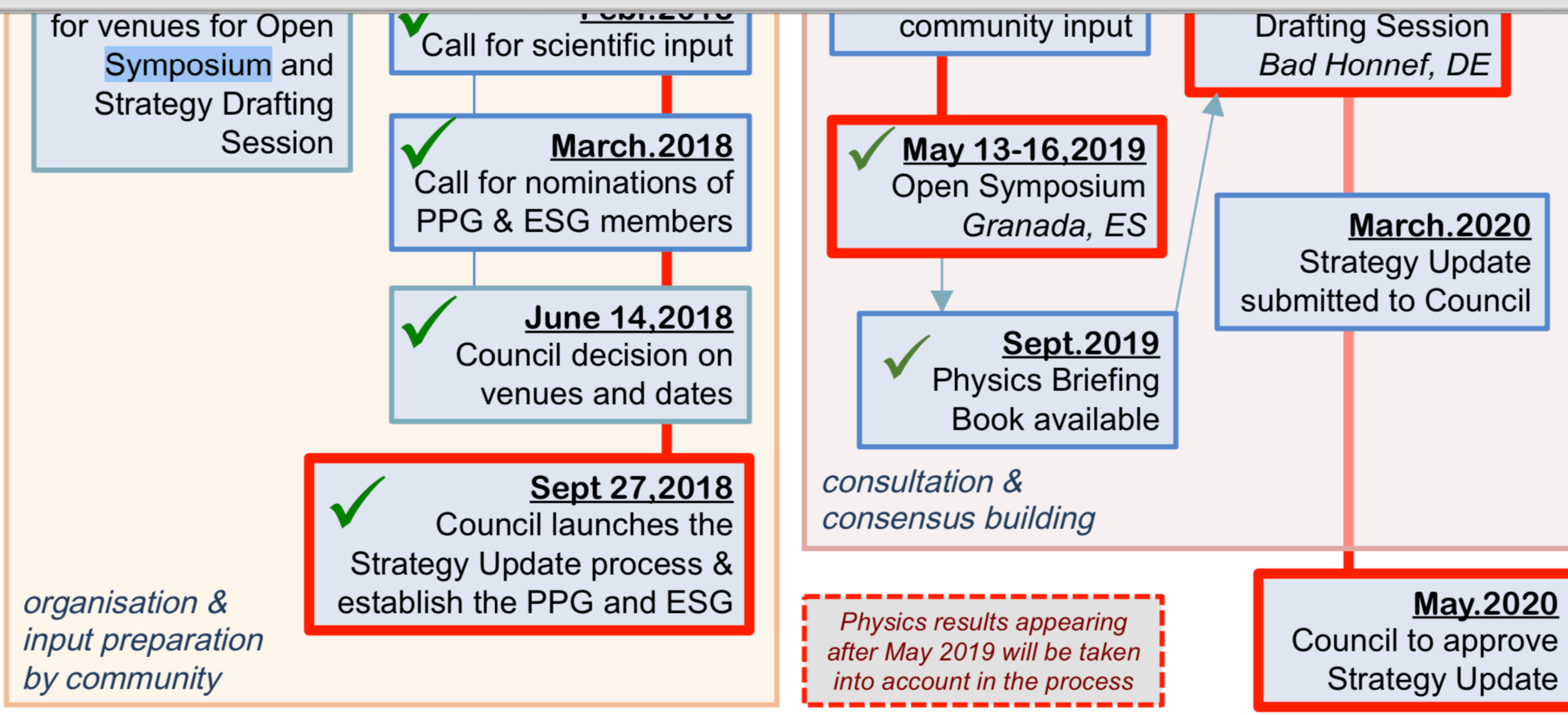
www.symmetrymagazine.org

DESY – Zeuthen
December 18th, 2019

Muon Colliders: challenges and wonders

Present status & Future plans

Nadia Pastrone INFN TORINO


for venues for Open Symposium and Strategy Drafting Session
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
Drafting Session
Bad Honnef, DE
March.2020
Strategy Update submitted to Council
consultation & consensus building
Physics results appearing after May 2019 will be taken into account in the process
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

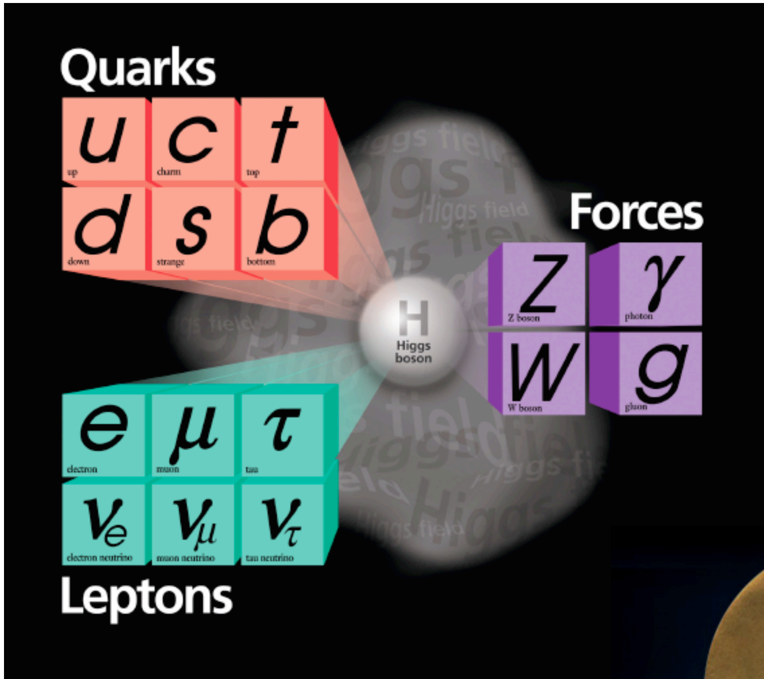
J.P. Delahaye et al.

- **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

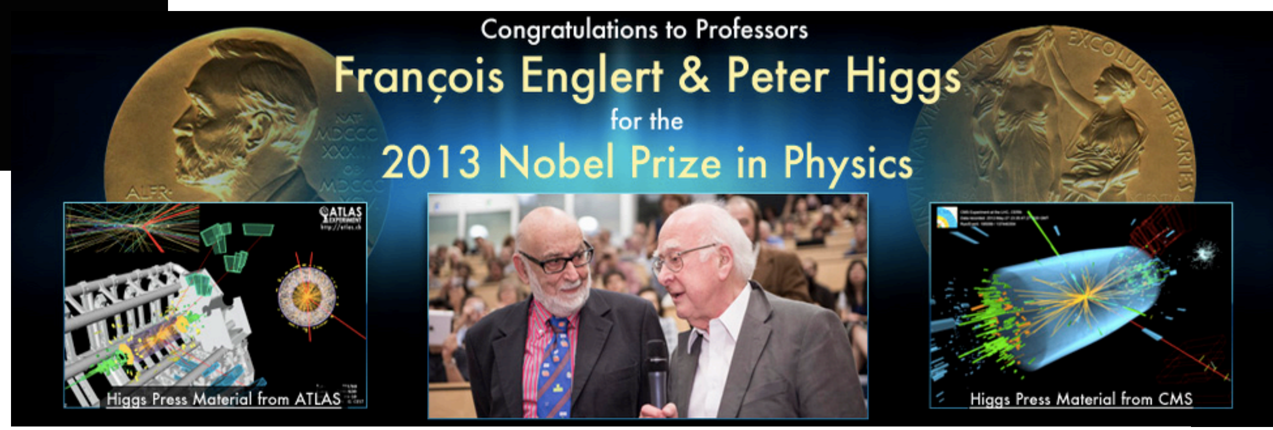
  ……
- **Carry out the R&D program toward the muon collider**

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**



"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

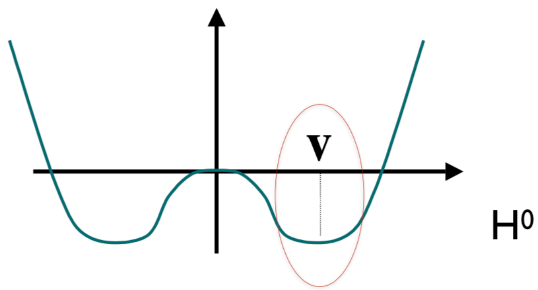
- **Data driven:**
  - What is DM?
  - What's the origin of neutrino masses?
  - What's the origin of the matter vs antimatter asymmetry?
  - What is Dark energy?
  - ...

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

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

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 ?

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

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

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

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

The relations between Higgs self-couplings, 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

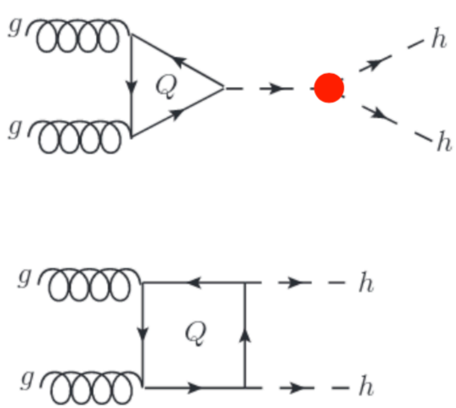
Double Higgs production

arXiv:1905.03764

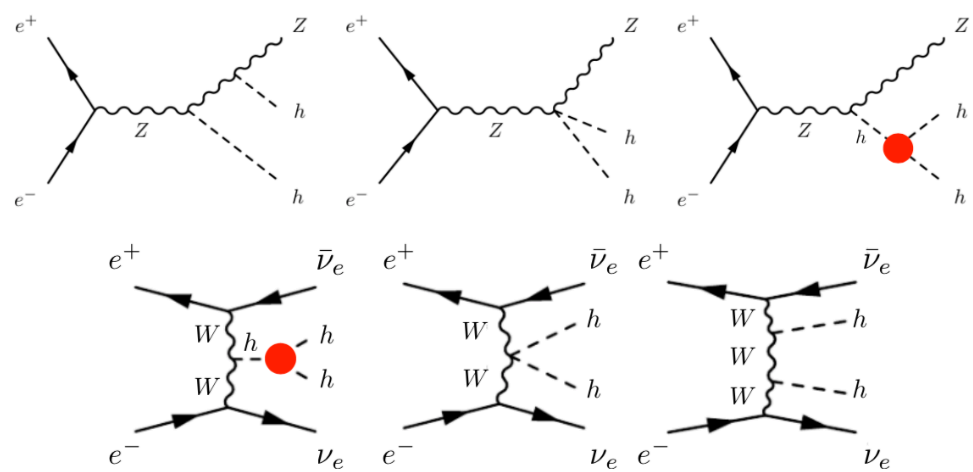
The *measurement* of the Higgs potential is a high priority goal on the physics programme of all future colliders

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

Hadron collider



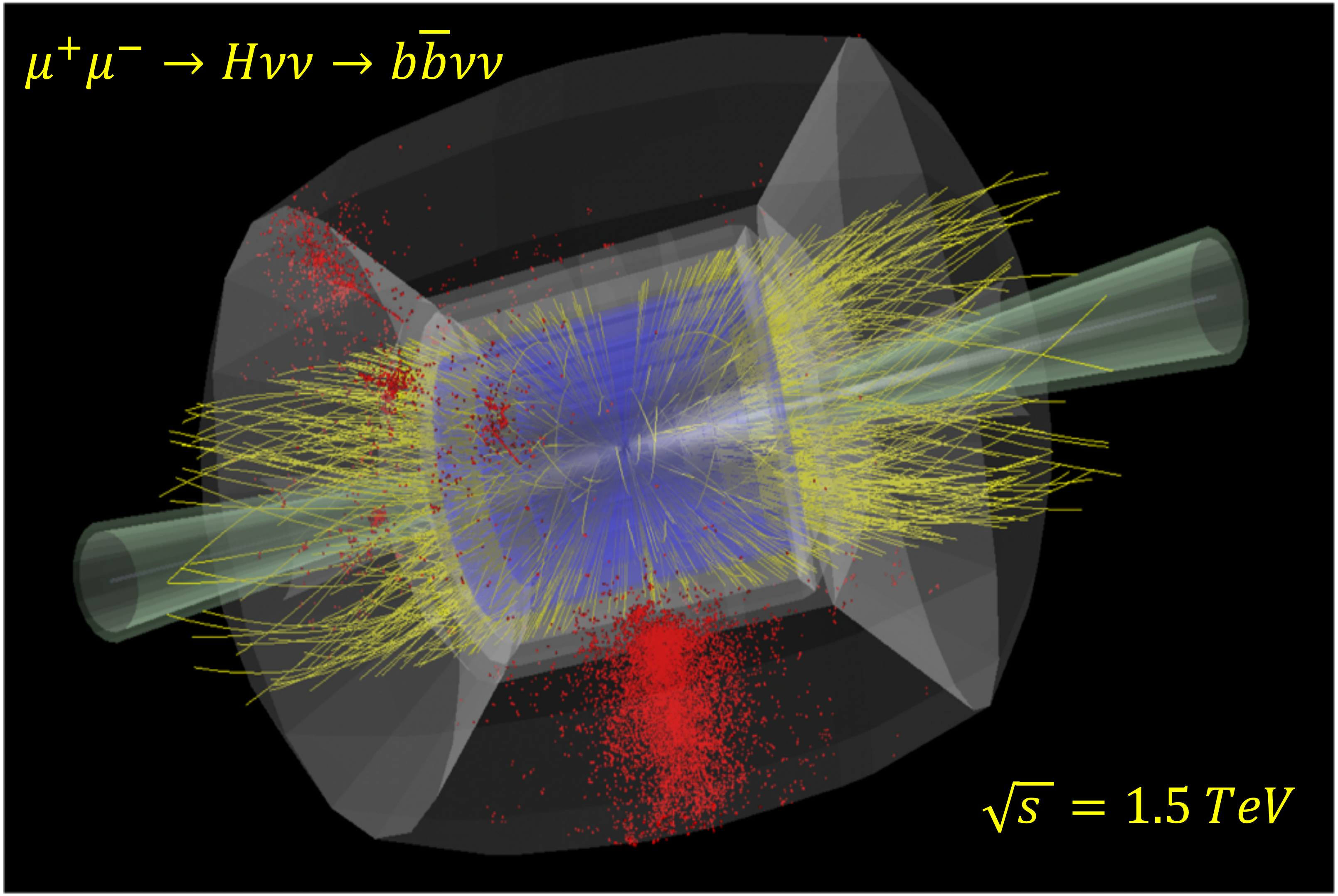
Lepton collider



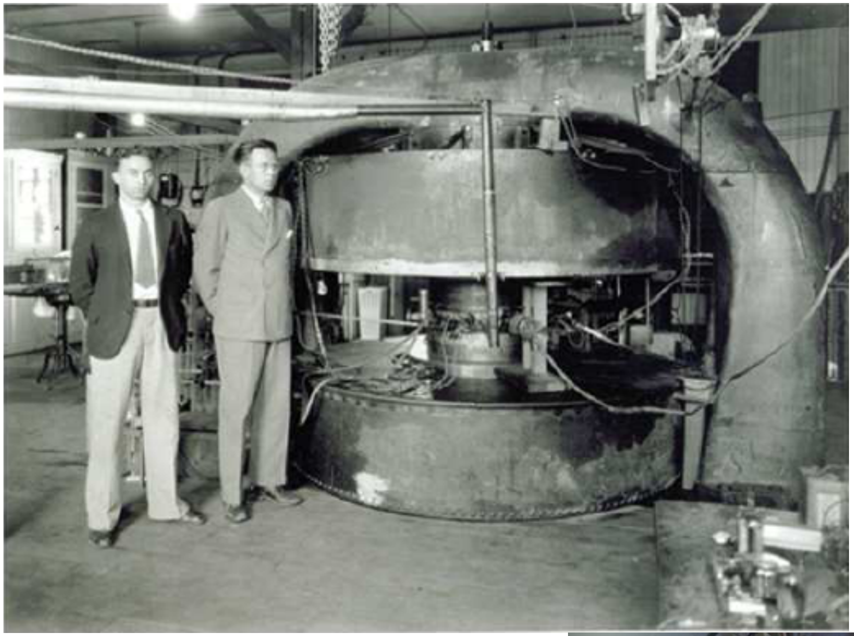
Extracting the value of the Higgs self-coupling, in red, requires a knowledge of the other Higgs couplings that also contribute to the same process

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

Donatella Lucchesi et al.

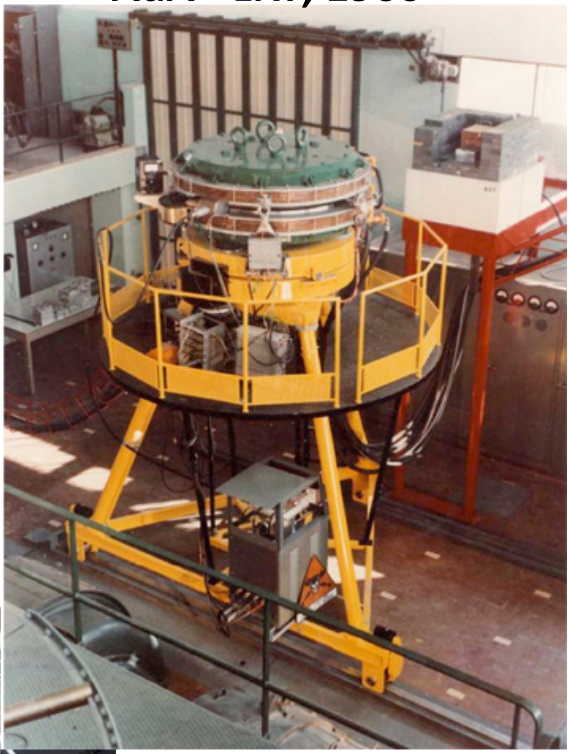


Ideas & technologies → discoveries



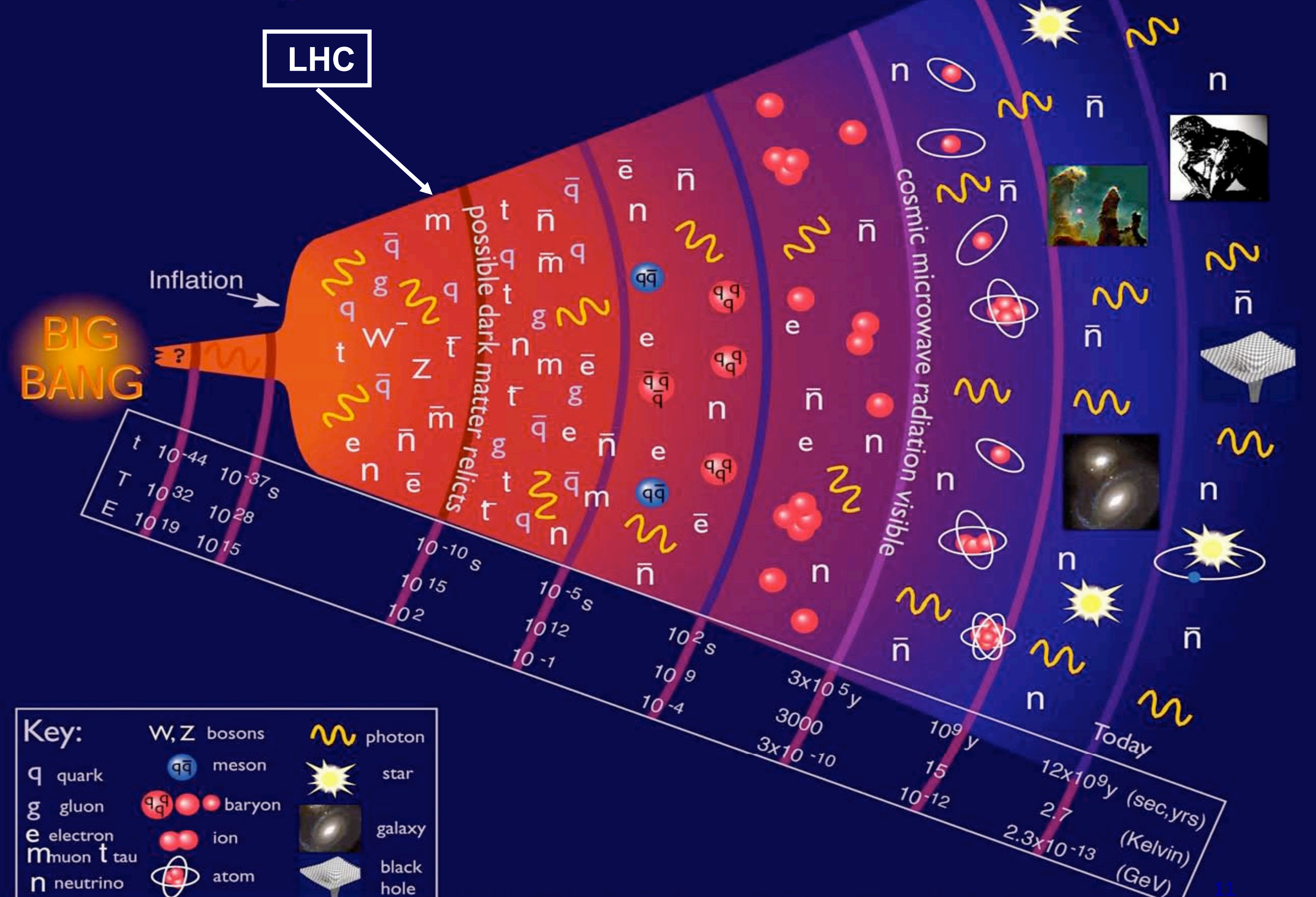
Cyclotron - Berkeley, 1934

AdA - LNF, 1960



LHC - CERN, 2008

History of the Universe



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

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

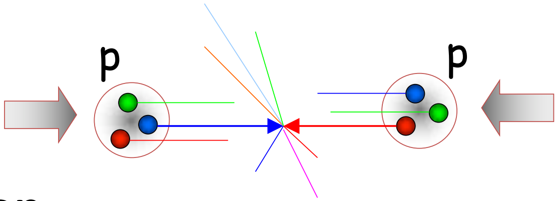
Caterina Biscari and Lenny Rivkin

In particular for the Accelerator Science and Technology

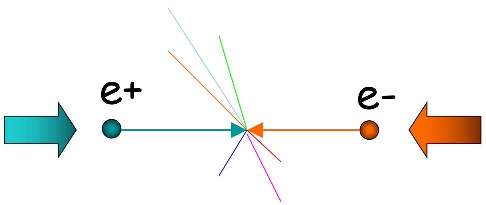
- **What is the best implementation for a Higgs factory?**
  Choice and challenges for accelerator technology: linear vs. circular?
- **Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?**
- **How to achieve proper complementarity for the 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

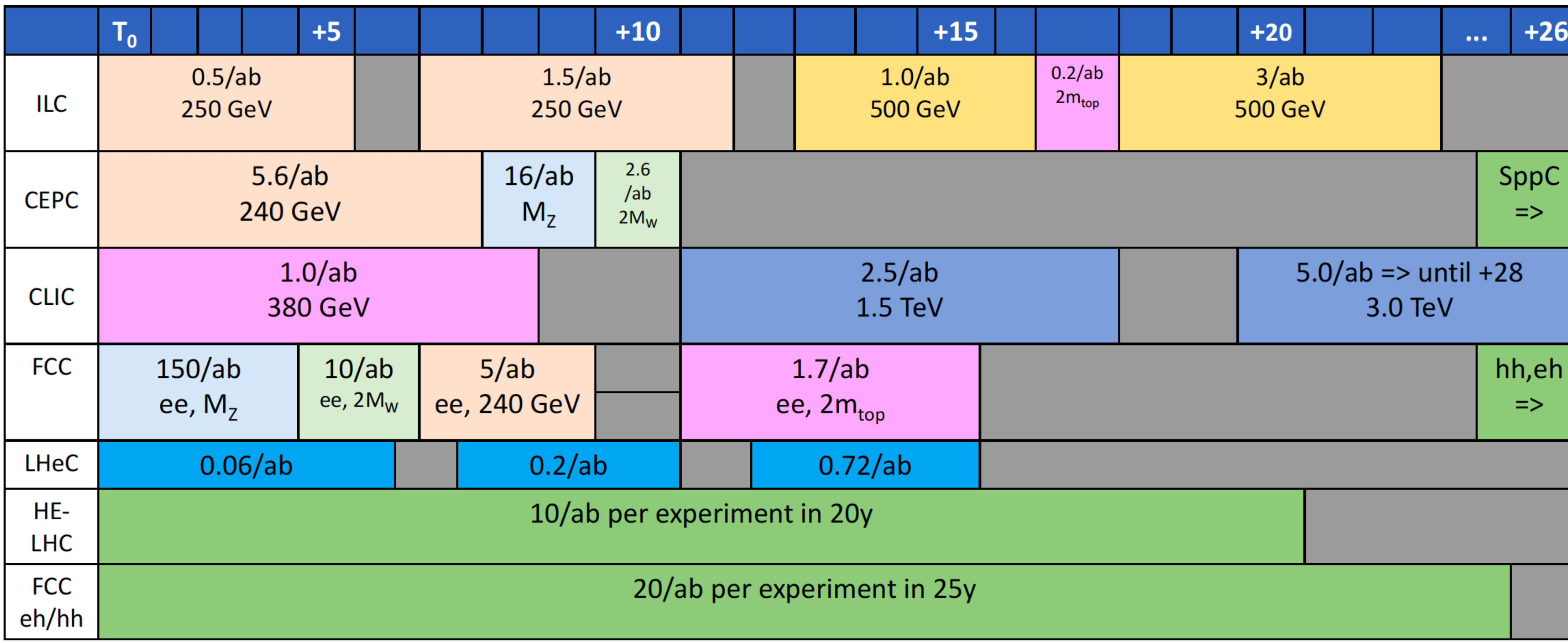


➔ **Lepton Collider as next facility @ High Energy Frontier after LHC ??**
  - Energy determined by LHC discoveries
  - Study in detail the properties of new physics identified by LHC (if any)

presently HIGGS, possibly BSM in the future

Proposed schedule

Open Symposium May 13-16 2019



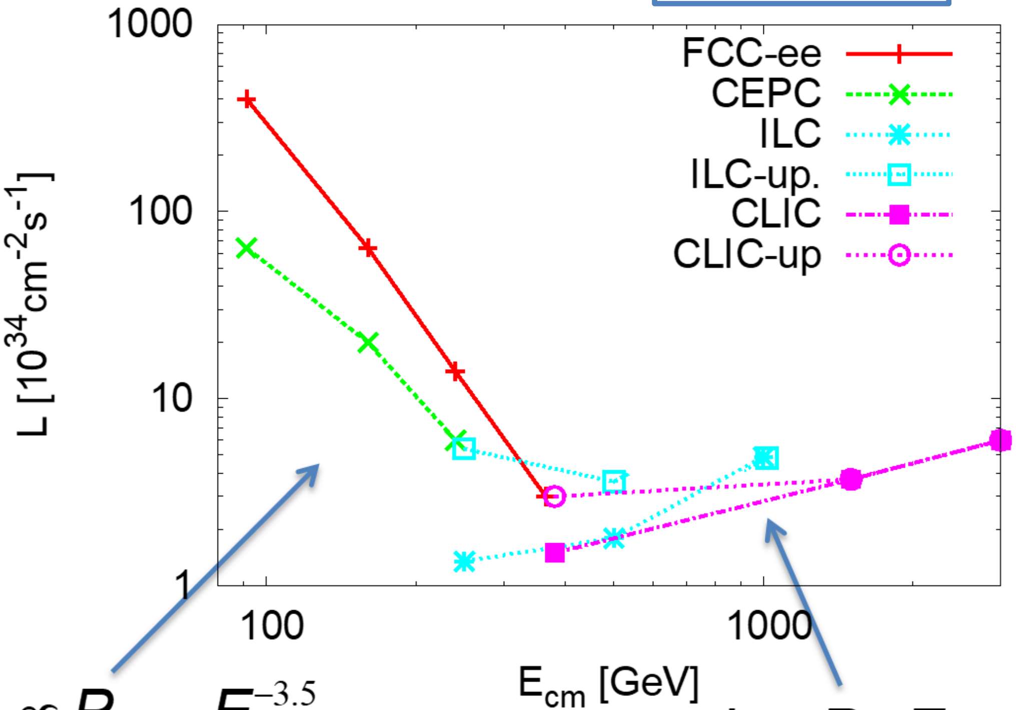
Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

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

Linear vs Circular lepton collider

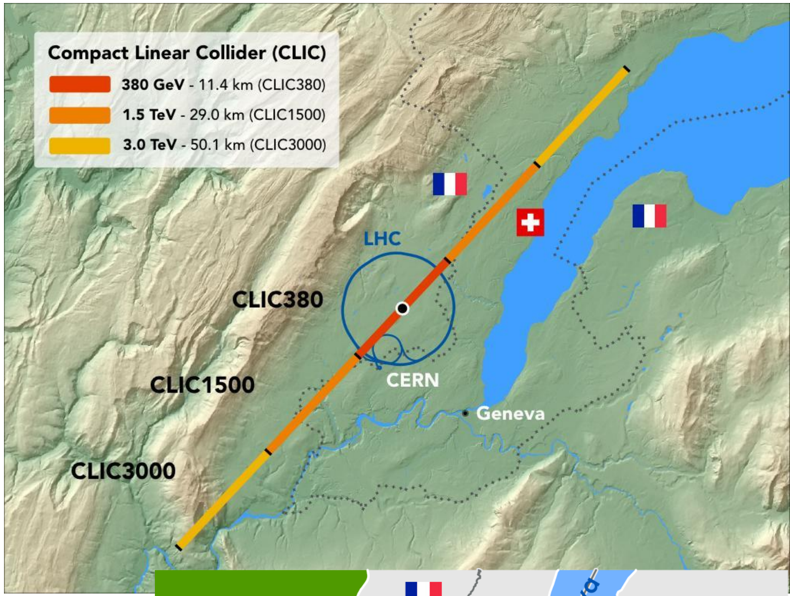
Luminosity per facility

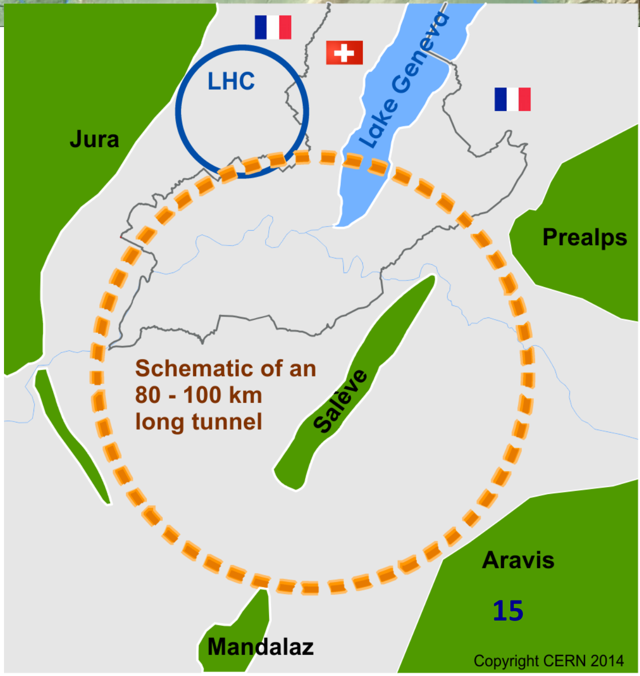
Daniel Schulte



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

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





Why Muons?

Mark Palmer

Muon Accelerator Program

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 → $\sim\left(\frac{m_\mu^2}{m_e^2}\right) \cong 4\times10^4$
  - 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

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

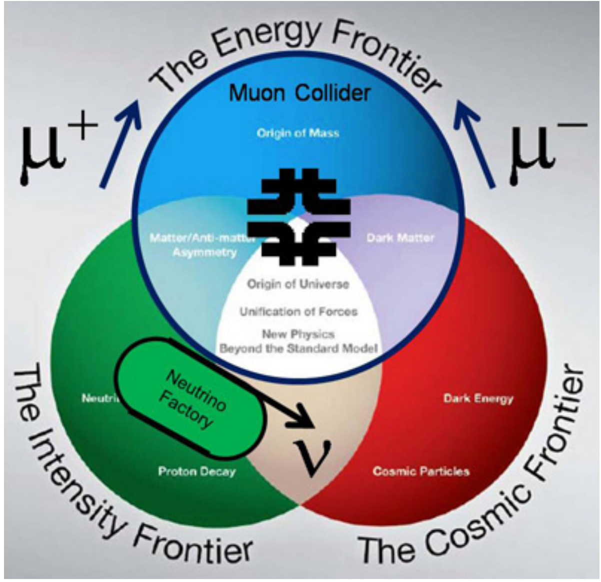
Brief history

- 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)

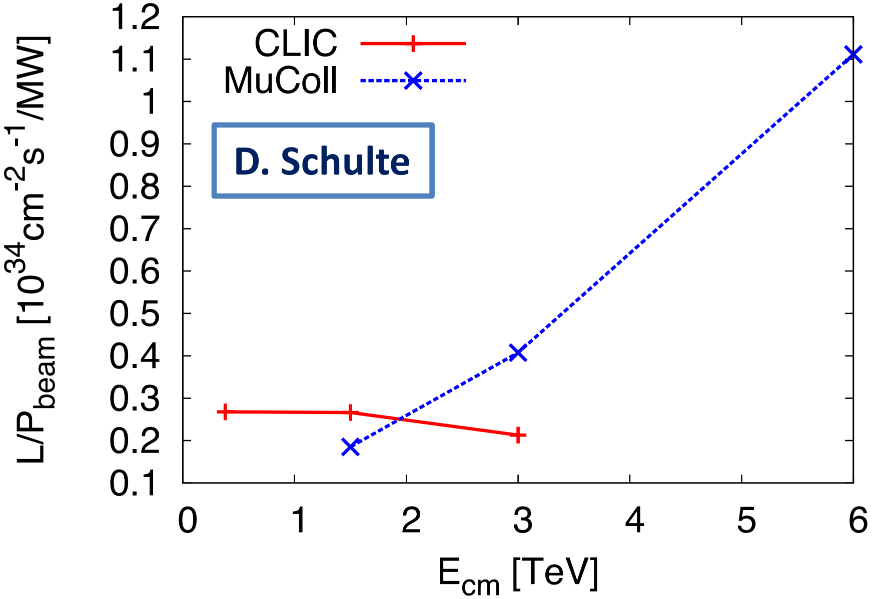
- Recommendation from 2008 Particle Physics Project Prioritization Panel (P5)
- Approved by DOE-HEP in 2011
- Ramp down recommended by P5 in 2014

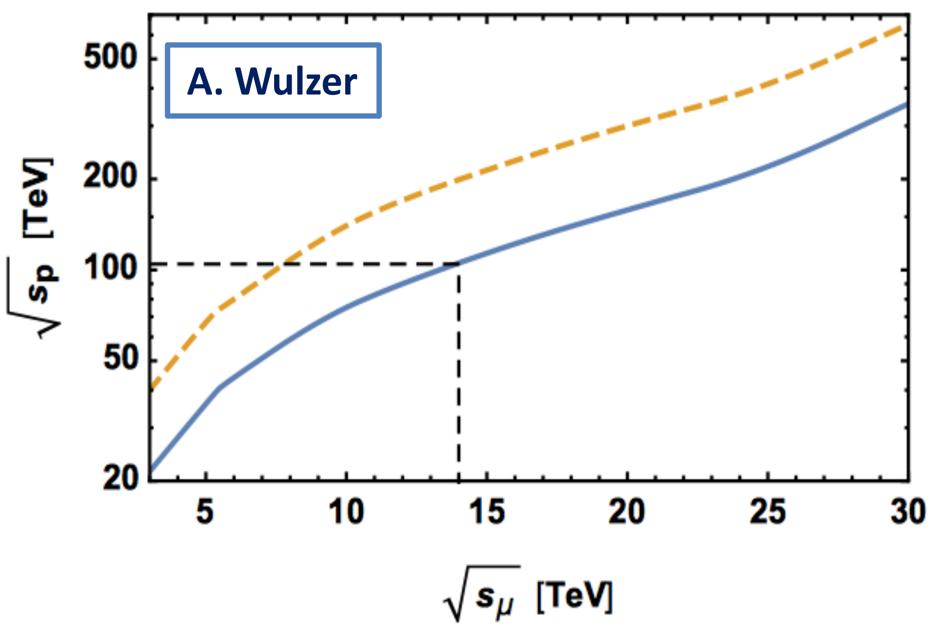
AIM: to assess feasibility of technologies to develop muon accelerators for the Intensity and Energy Frontiers:

- 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 ~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

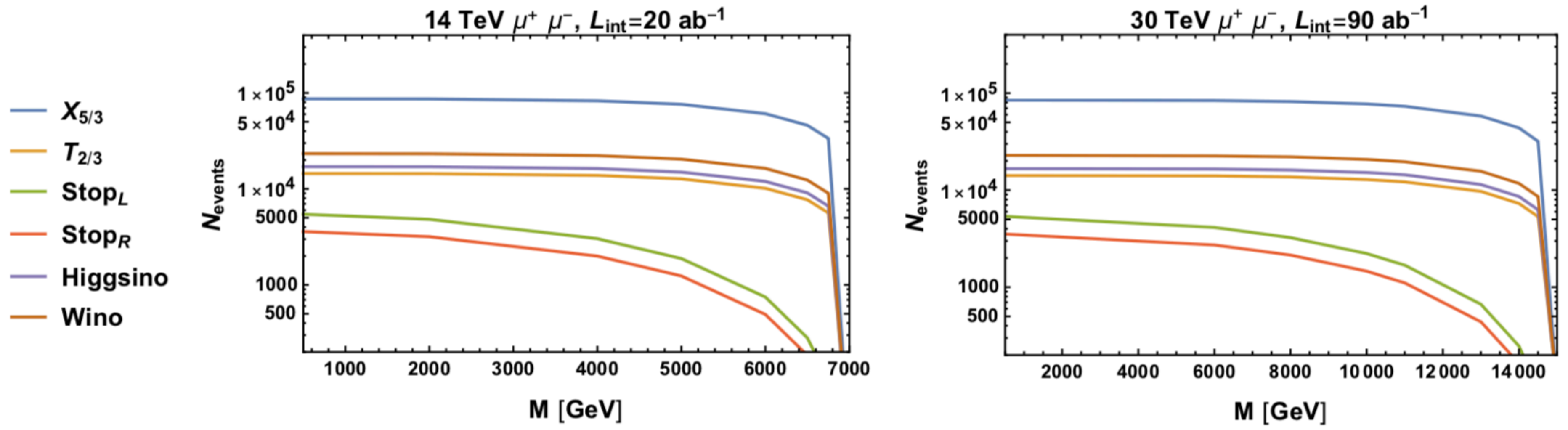
Multi-TeV energy scale allows to explore physics beyond SM both directly and indirectly

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

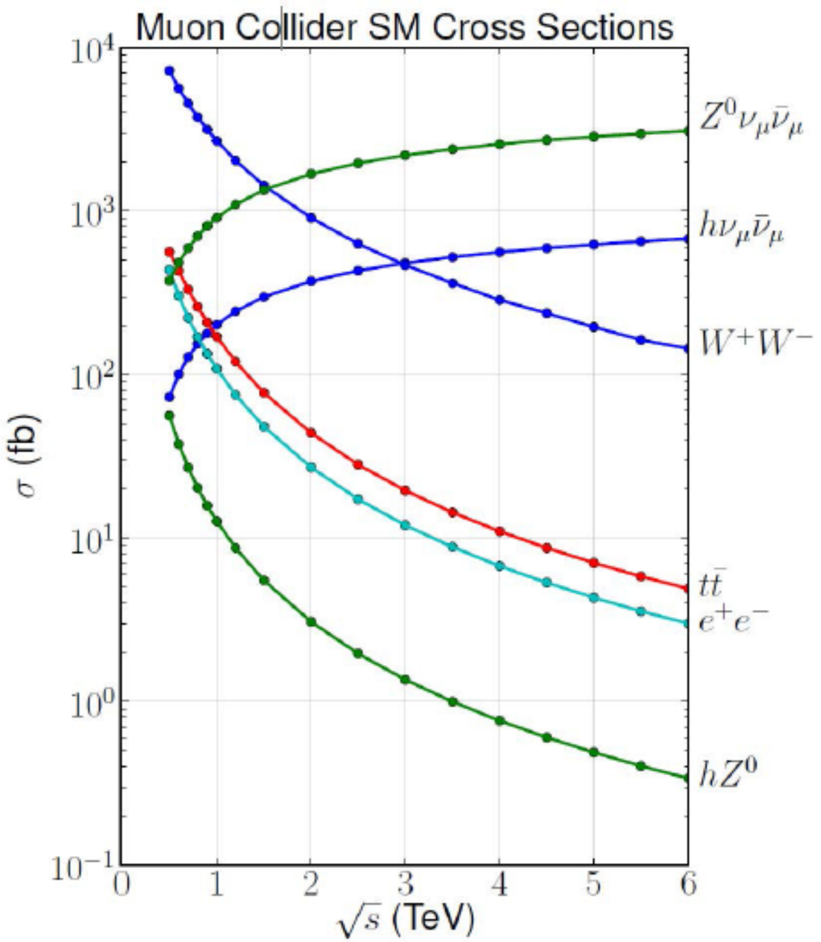


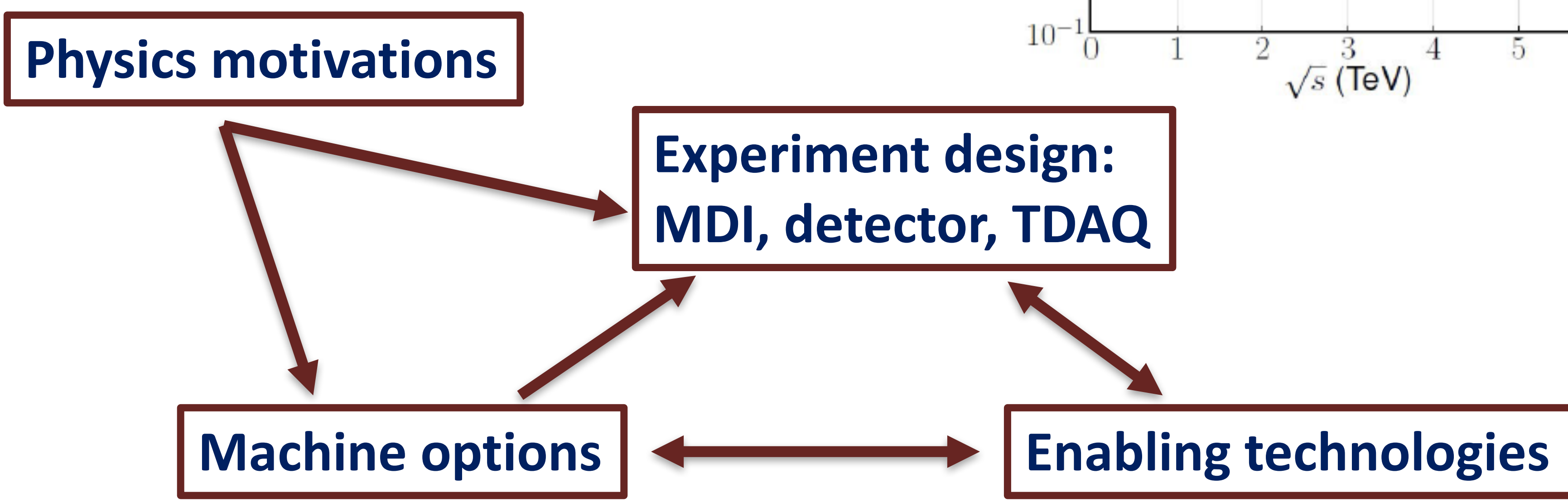
How do we plan?

- 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





Muons: Issues & Challenges

- **Limited lifetime: 2.2 μs 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 :

☺

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

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/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

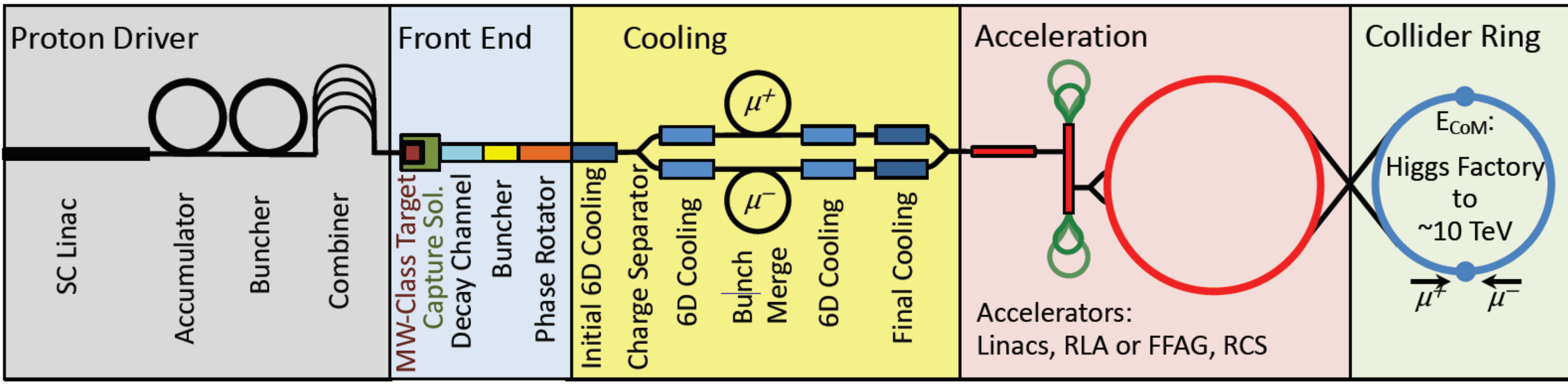
☺
- **Multi-pass acceleration in rings or RLA:**
  - Compact acceleration system and collider
  - Cost effective construction & operation

☹
- **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

Target Parameter Examples

M. Palmer: https://map.fnal.gov/

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/10^7sec		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
β^*	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, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_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

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

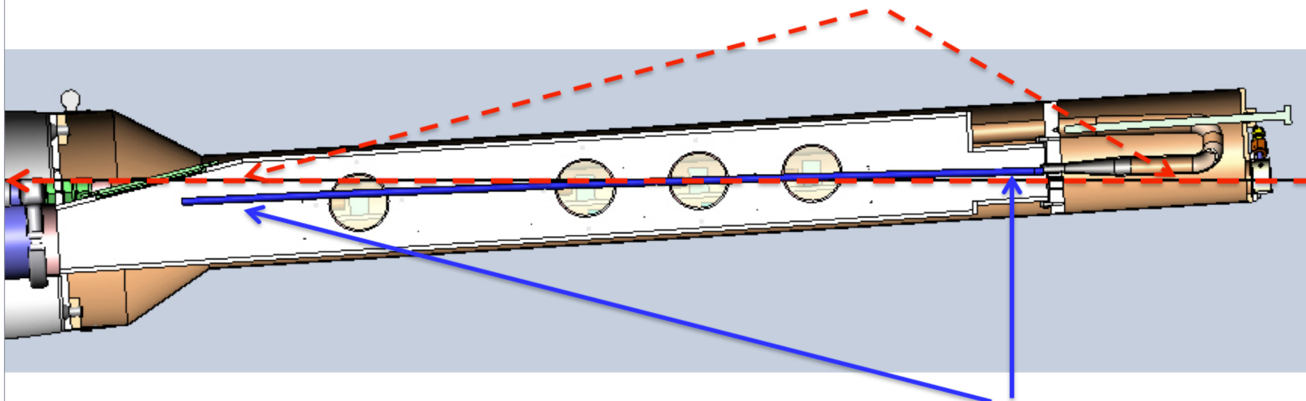
Provided all technical limits can be solved

Constant current for required luminosity increase

Better scaling than linear colliders

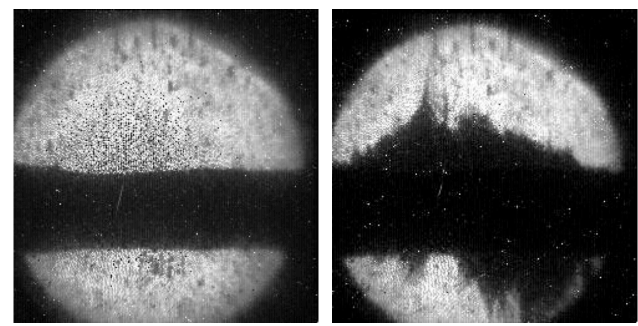
Source

Protons → Target → Pions → Muons



MERIT experiment at CERN

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



Maximum pulse tested 30x10^{12} protons with 24 GeV

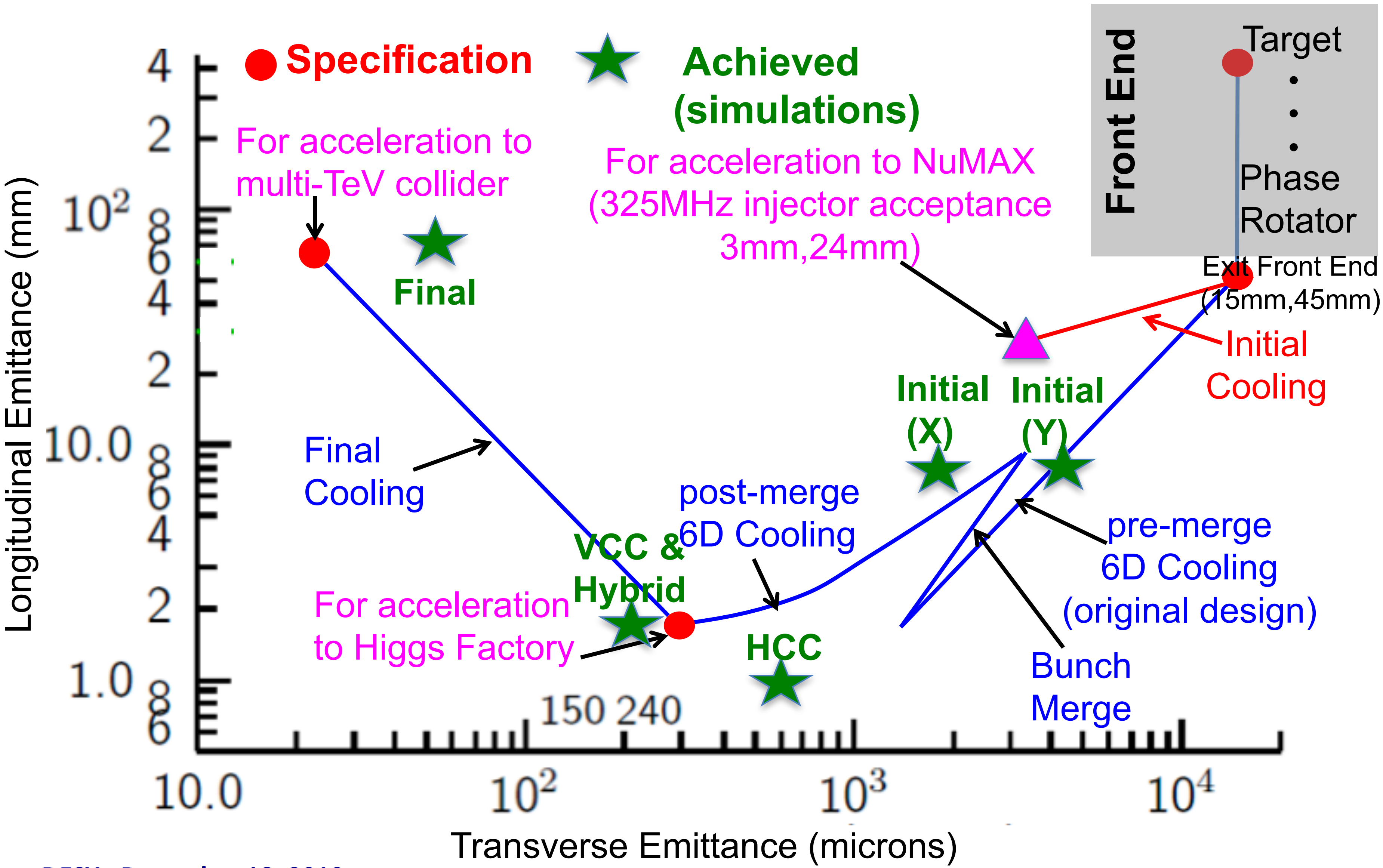
- 9x10^{12} muons (loose 90%)

But radiation issues?

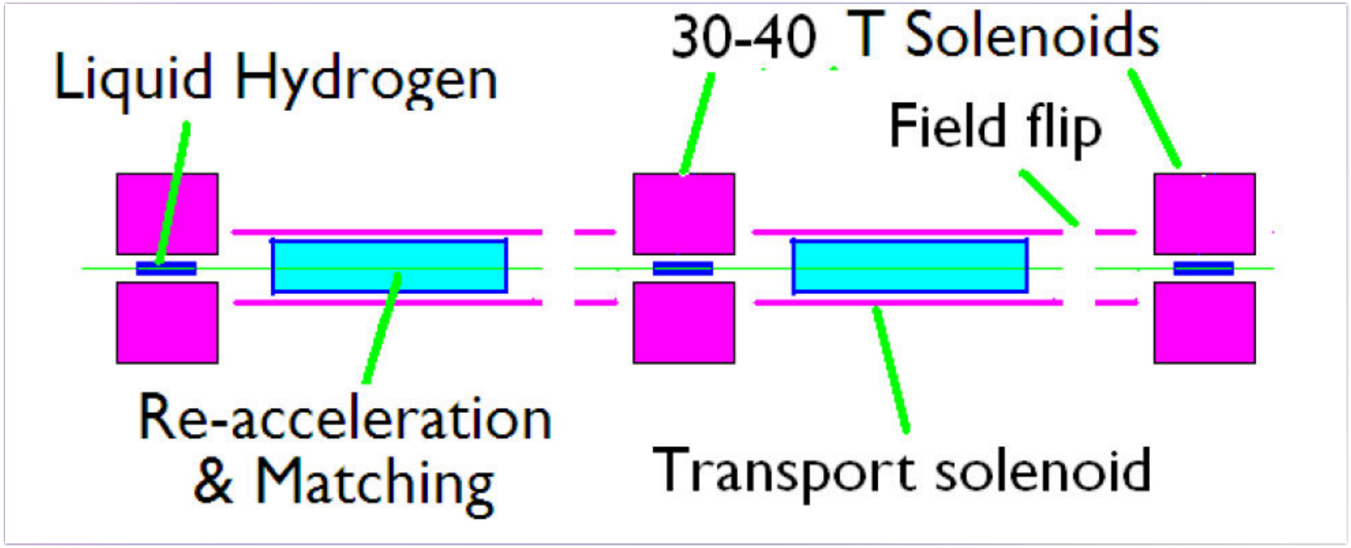
Maybe can use solid target

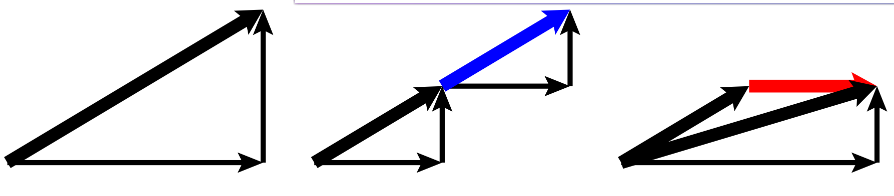
What could be made available at CERN (or elsewhere) as a proton driver for a potential test facility?

Cooling: The Emittance Path



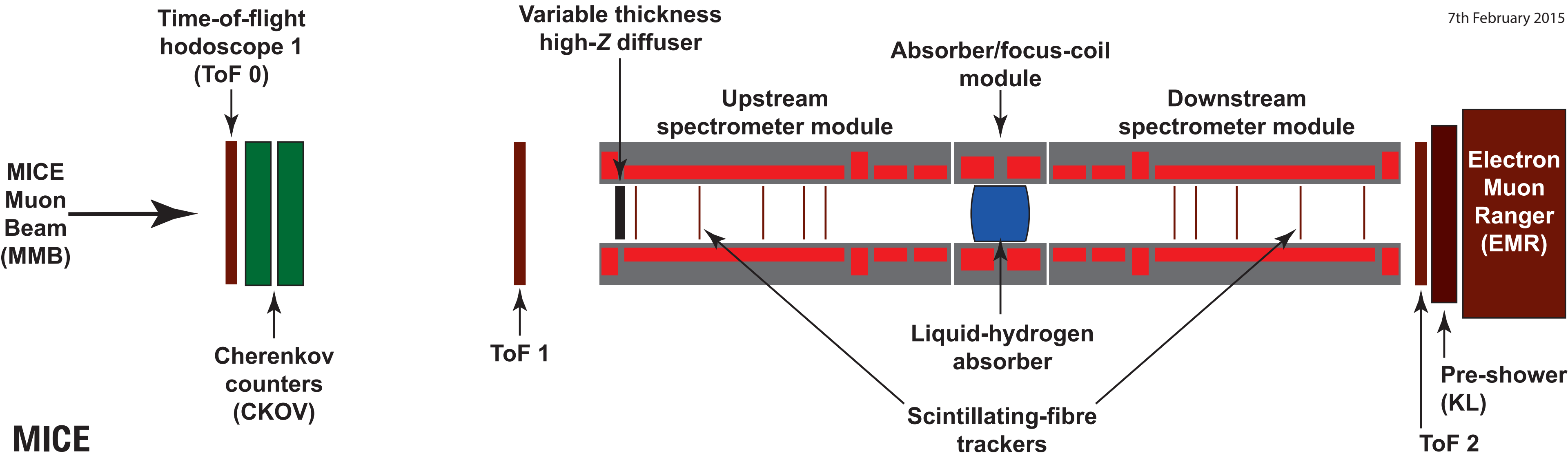
Transverse Cooling Concept



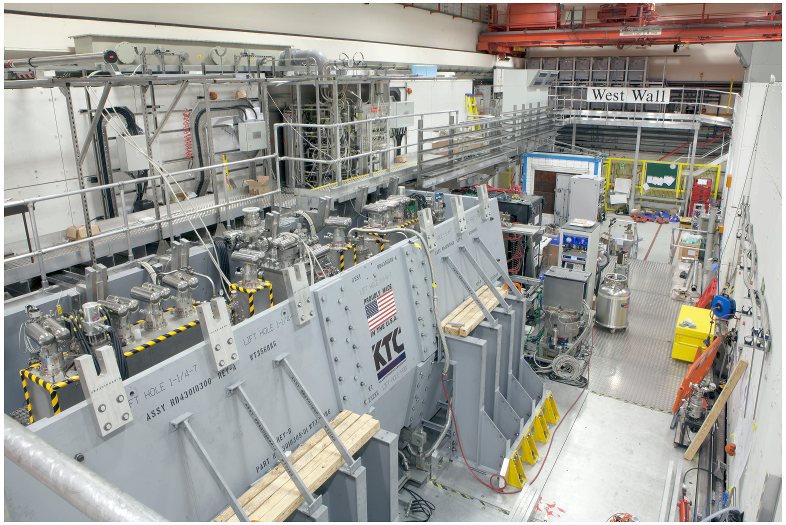


$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

Cooling and MICE



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

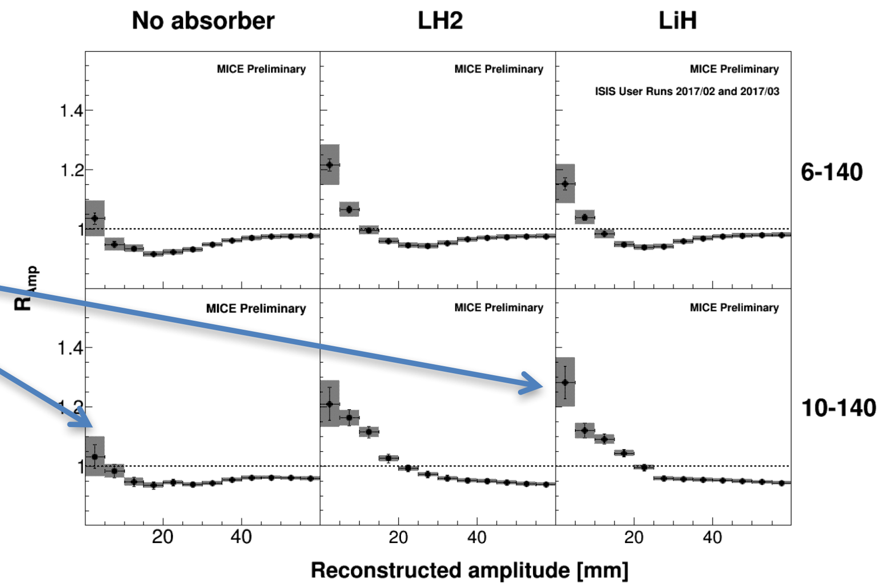


MICE allows to address 4D cooling
with low muon flux rate

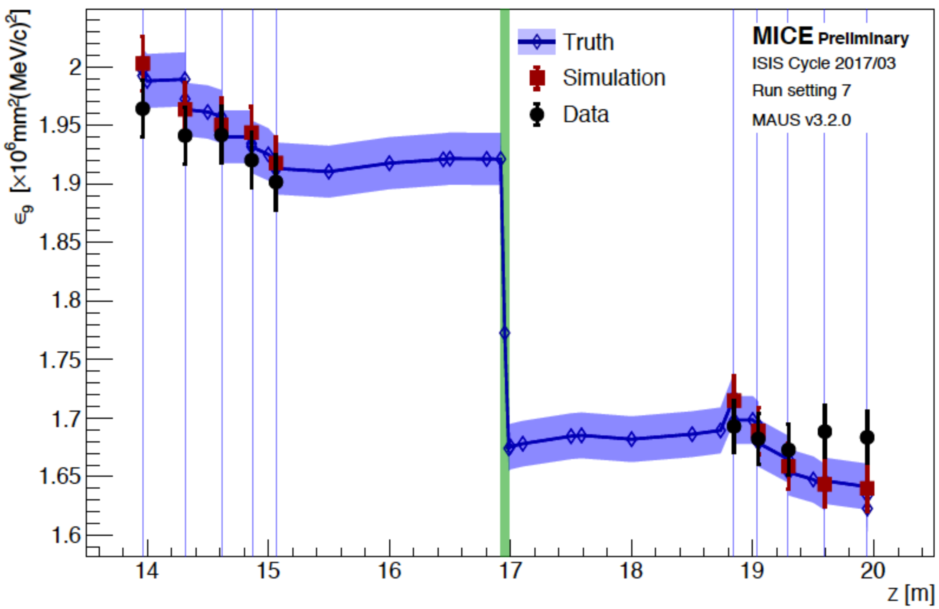
MICE Results

The absorber reduces the number of particle with large amplitude

They appear with smaller amplitude



Noticeable reduction of 9% emittance

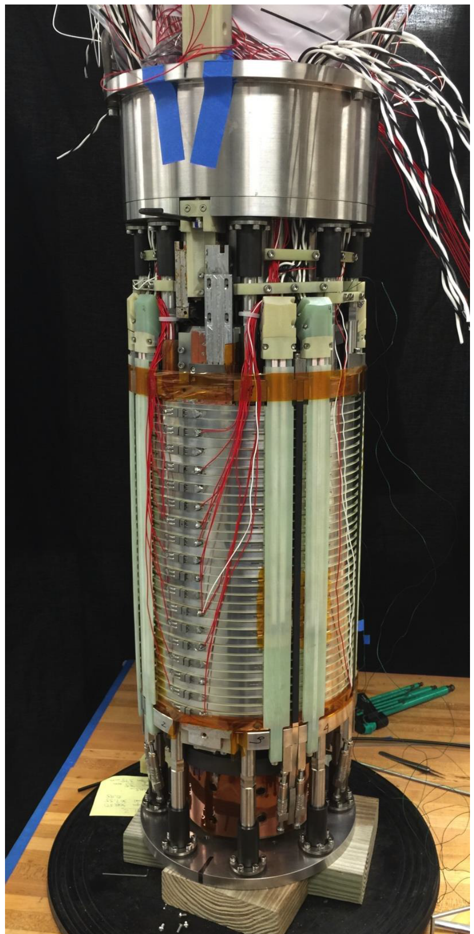


But still some way to go
- 6D cooling
- Stages
- Small emittances

Other Tests

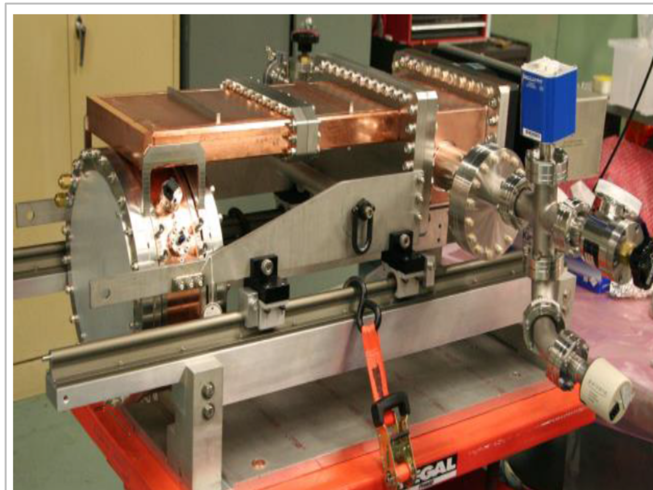
FNAL
Breakthrough in HTS cables

A number of key components has been developed



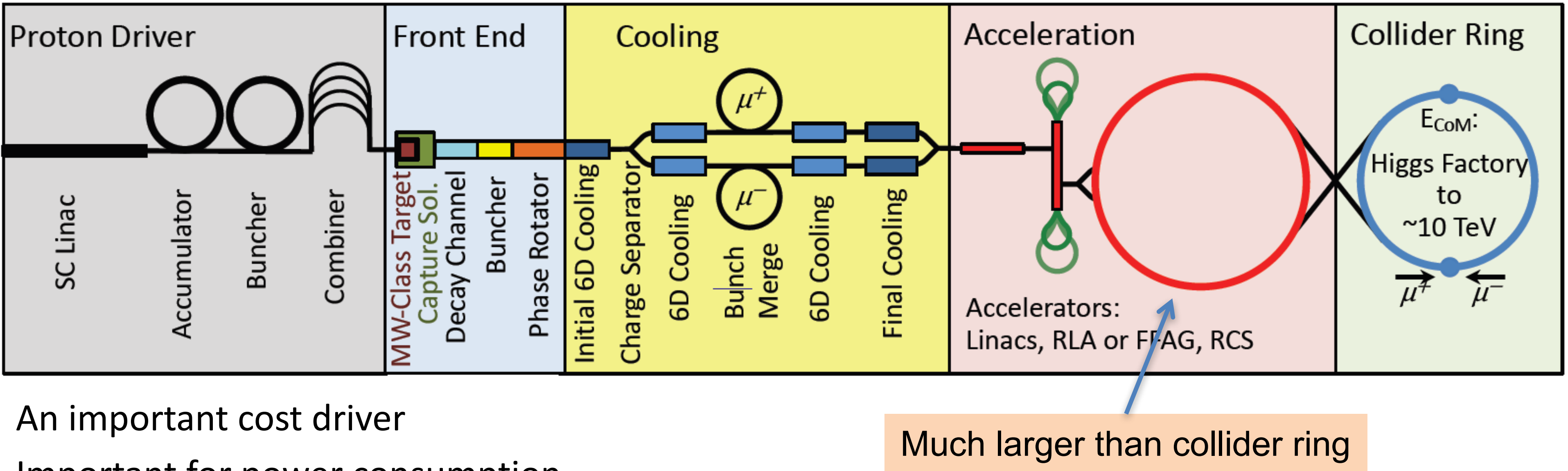
NHFML
32 T solenoid with low-temperature HTS

MuCool: >50 MV/m in 5 T field



FNAL
12 T/s
HTS
0.6 T max

Beam Acceleration



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

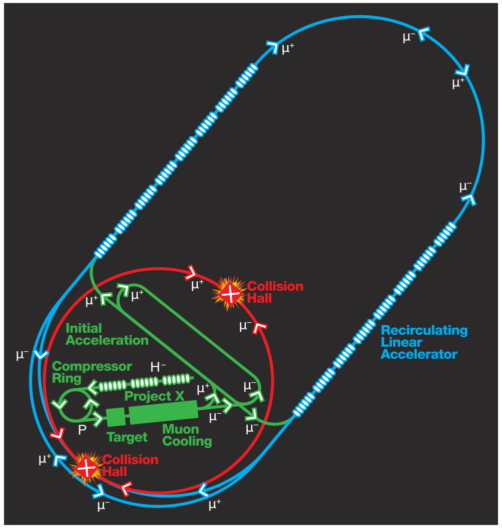
Potential Approaches

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

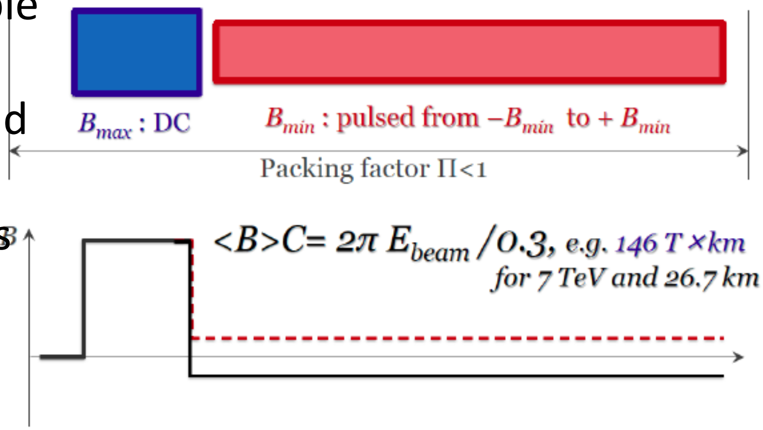


Recirculating linacs

- 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

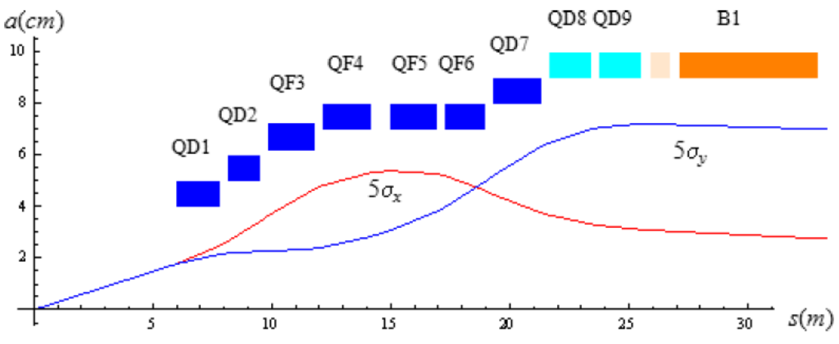
- Static high field magnets, can reach factor up to 4 increase in energy, needs design work

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

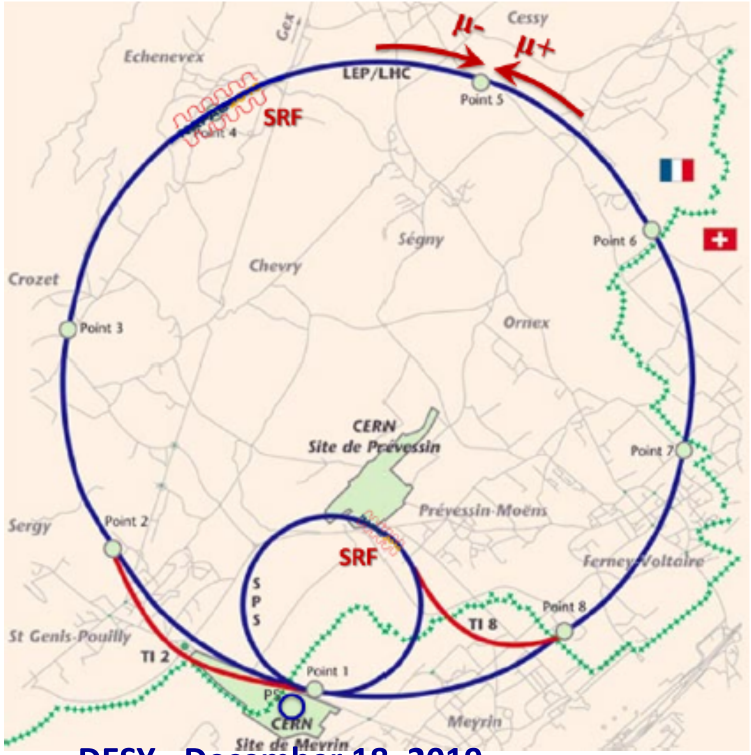
Collider Ring

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

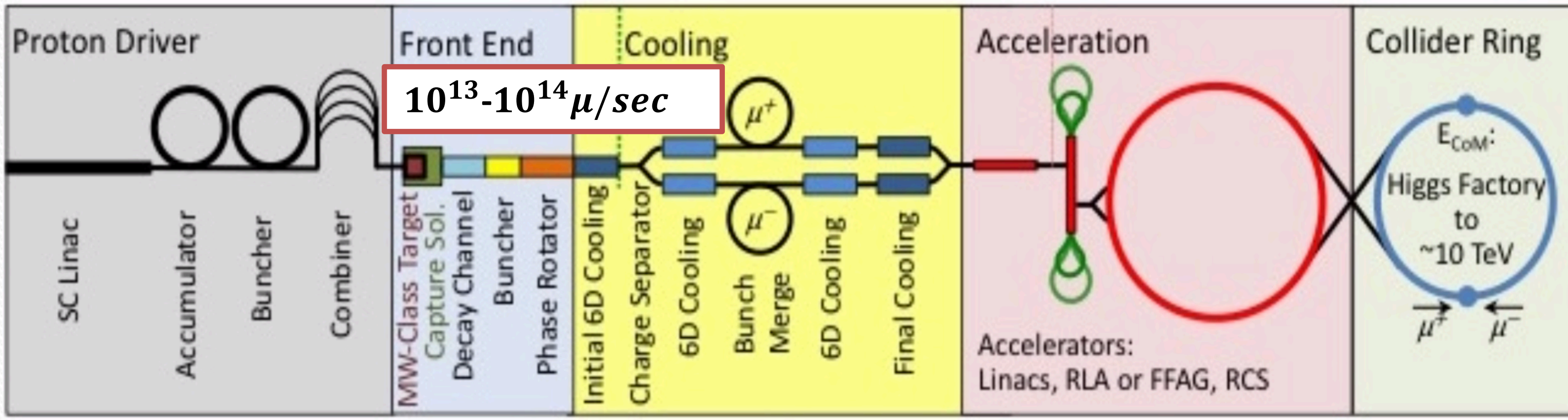
Decaying muons impact accelerator components, detector and public
The latter becomes much worse with energy

Radiation to public in case LHC tunnel use

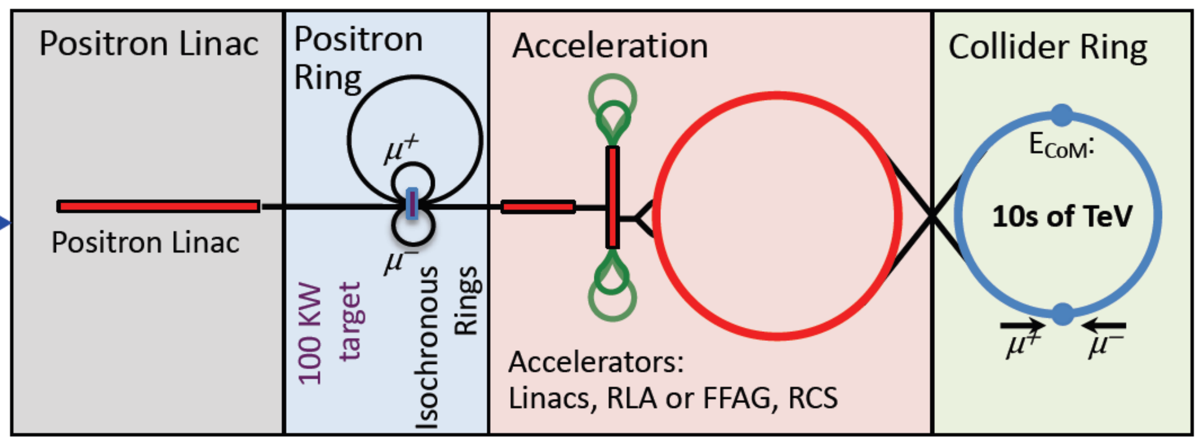
Might be best to use LHC tunnel to house muon accelerator and have dedicated new collider tunnel

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.



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 μ 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 $\gamma(\mu)$ ≈**200** and μ laboratory **lifetime** of about **500 μs**

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

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

Extremely promising:

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

But difficult:

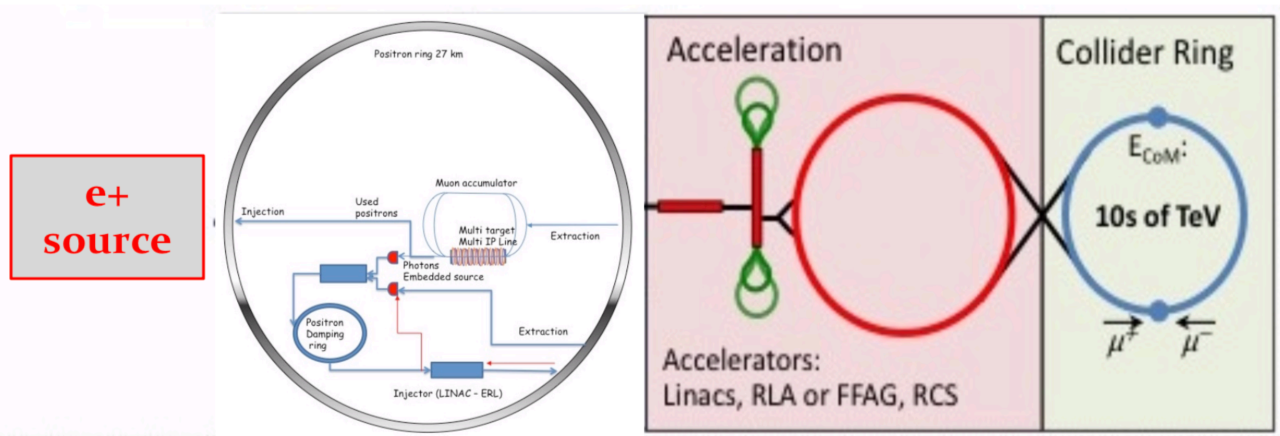
✓ **low** production **cross section**: maximum $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim 1\ \mu b$

✓ **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 18, 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

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:

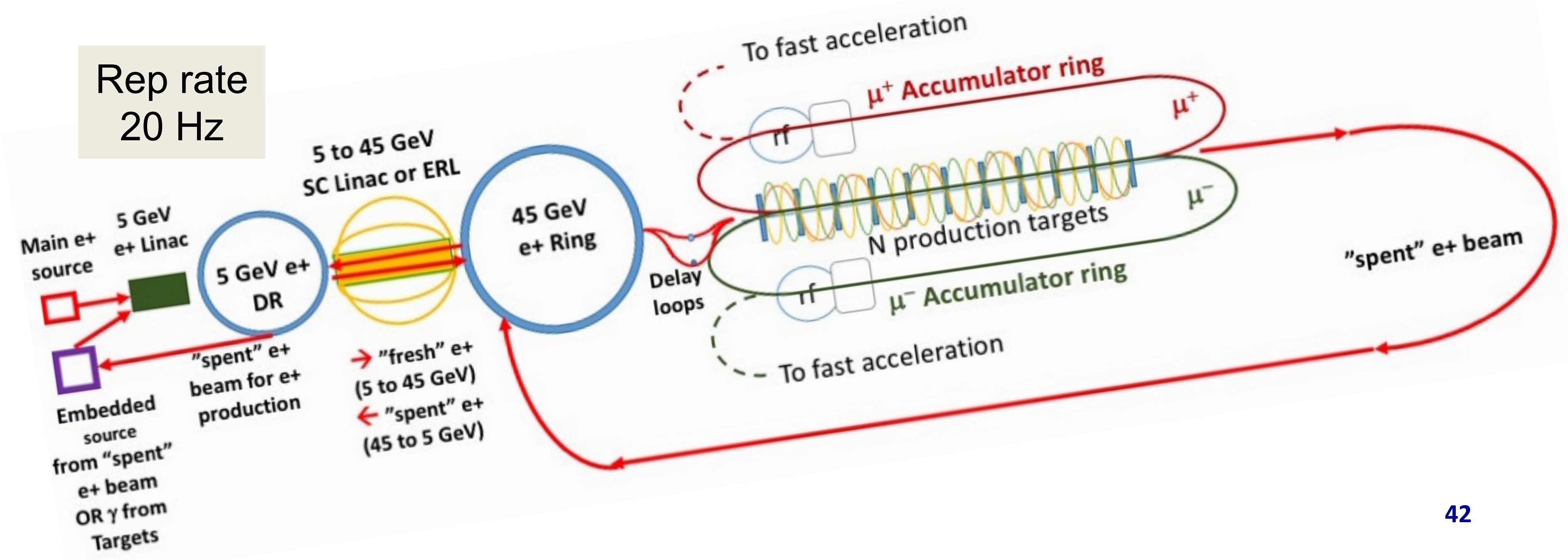
- complete **μ** production cycle **~410 μs** (lifetime = 467 μs @ 22.5 GeV)
- one complete cycle must last enough time for e^+ production and damping
- damping time must be compatible with a reasonable amount of synchrotron power emitted → Damping Ring to cool e^+ at lower energy
- possibility to recuperate 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**:

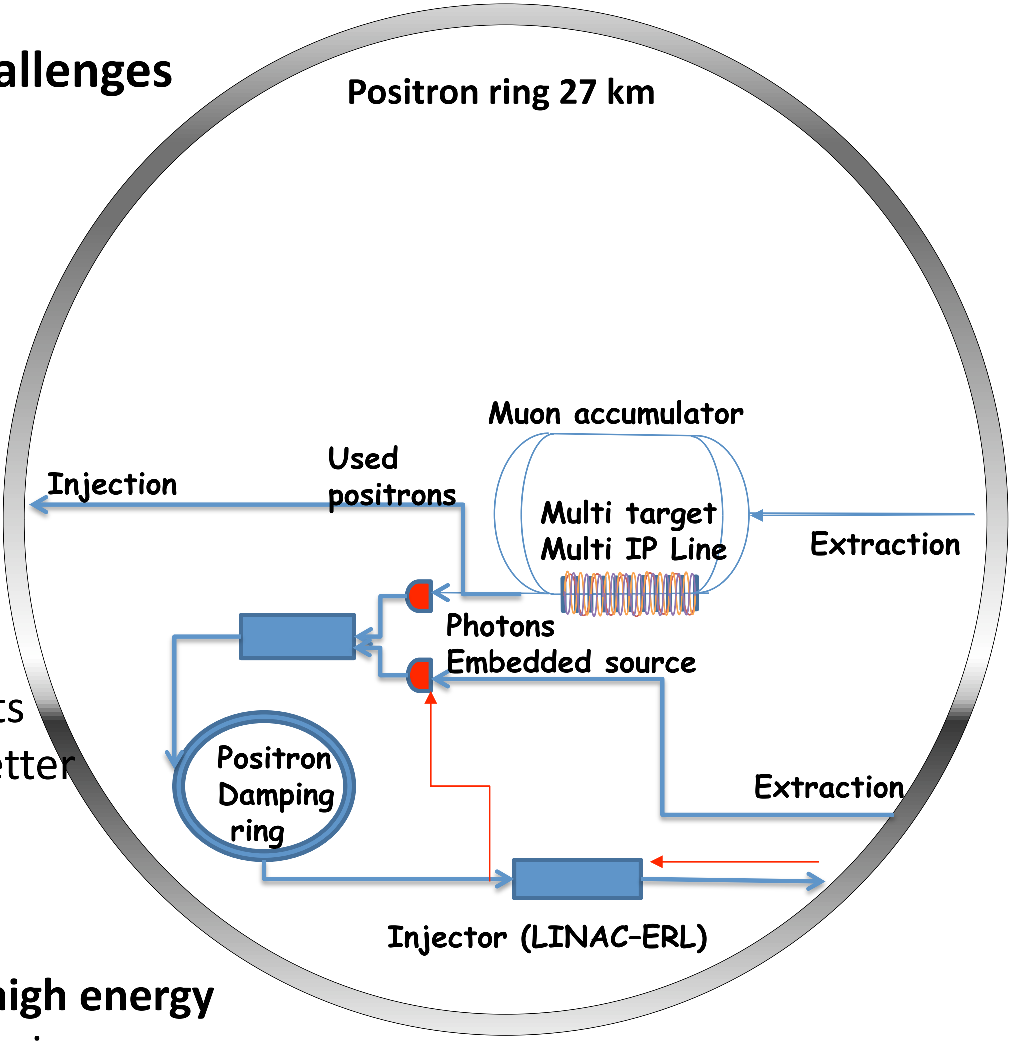
  from 5 ➔ 45 GeV and 45 ➔ 5 GeV to cool spent e^+ beam after $\mu^\pm$ production
- **45 GeV e^+ Ring** to accumulate **1000 bunches**: **5×10^{11} e^+/bunch** for $\mu^\pm$ production and e+ spent beam after $\mu^\pm$ production, for slow extraction towards decelerating Linac and the DR
- Delay loops 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

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 ……

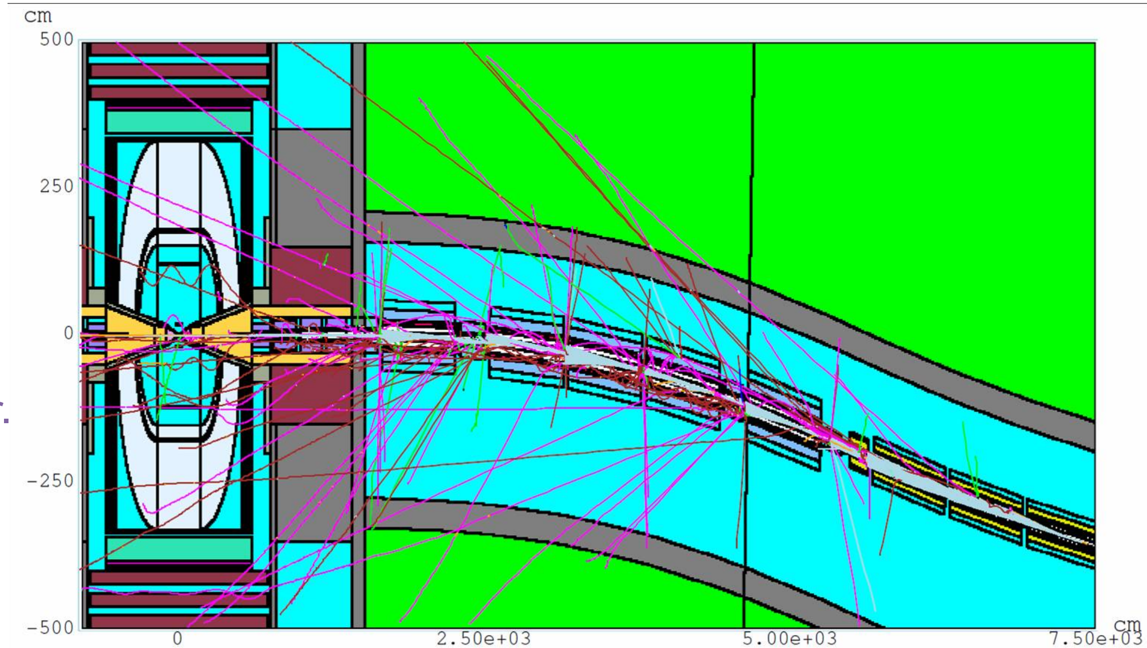
Full simulation: beam induced background

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.



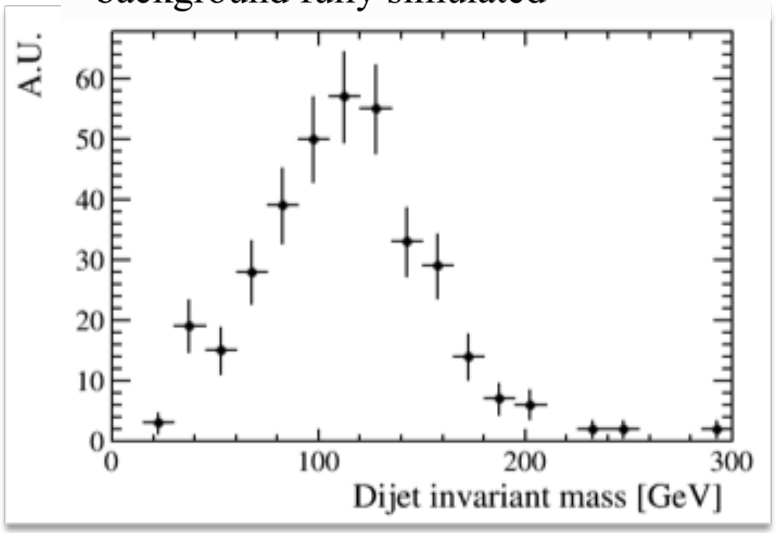
For each collider energy the machine elements, the MDI and interaction region have to be properly designed and optimized

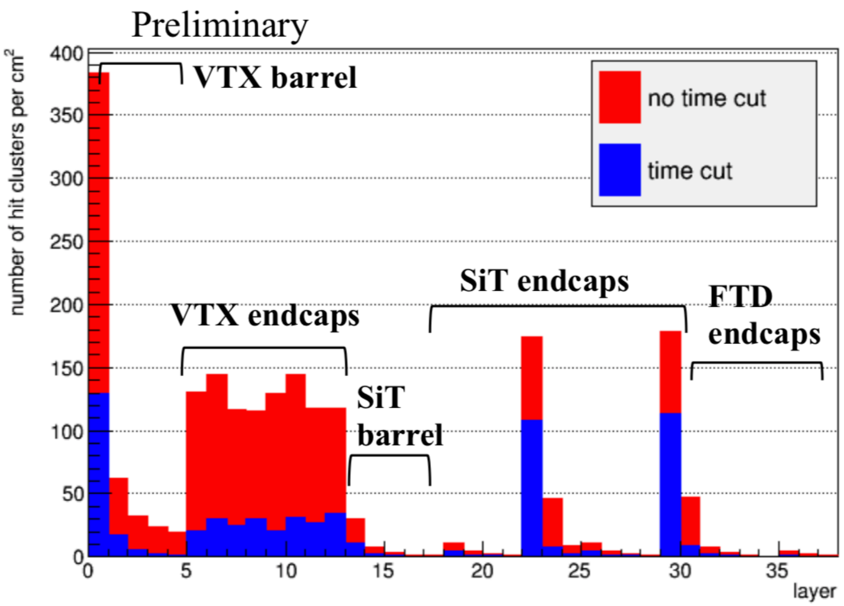
Is physics possible?

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**

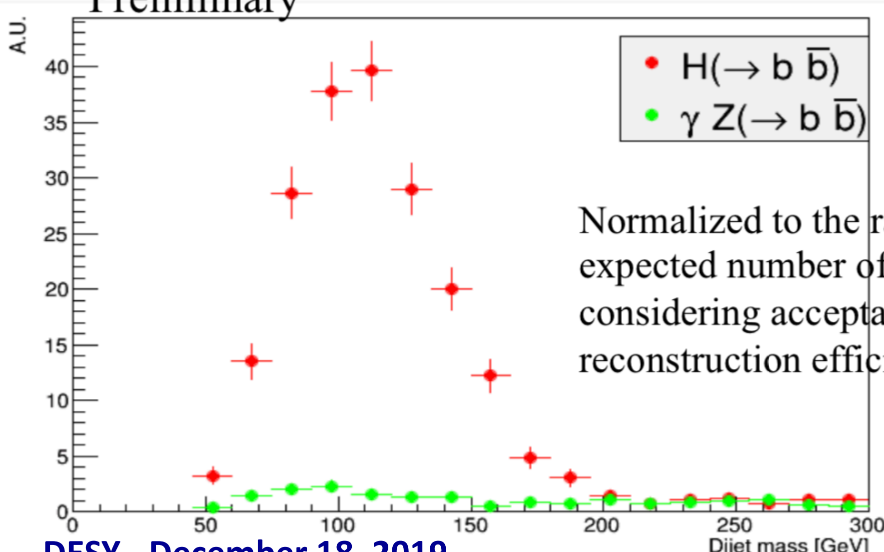
$b\bar{b}$ Studies at $\sqrt{s}$ =1.5 TeV

D. Lucchesi et al.

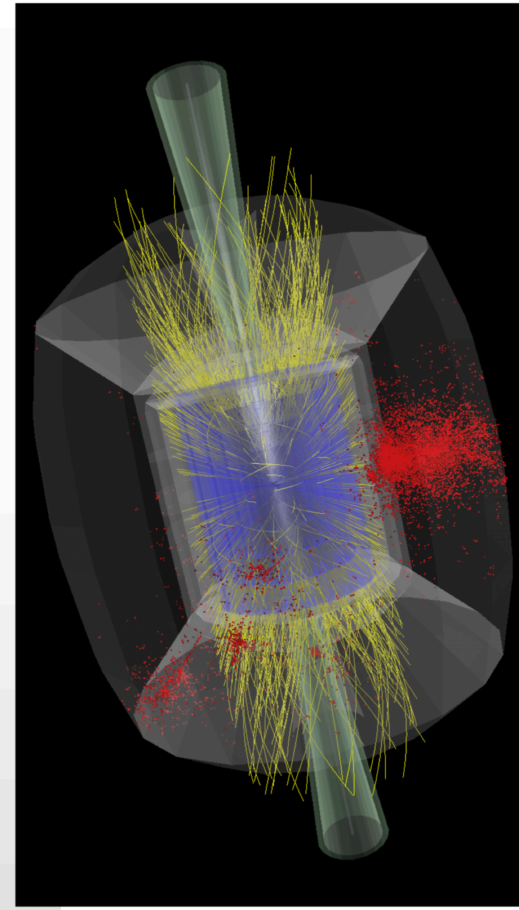
Events $\mu^+\mu^- \to b\bar{b}X$ @$\sqrt{s} = 1.5\ TeV$ are generated with PYTHIA 8

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
$\mu^+\mu^- \to \gamma^*/Z\gamma \to b\bar{b}\gamma$	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

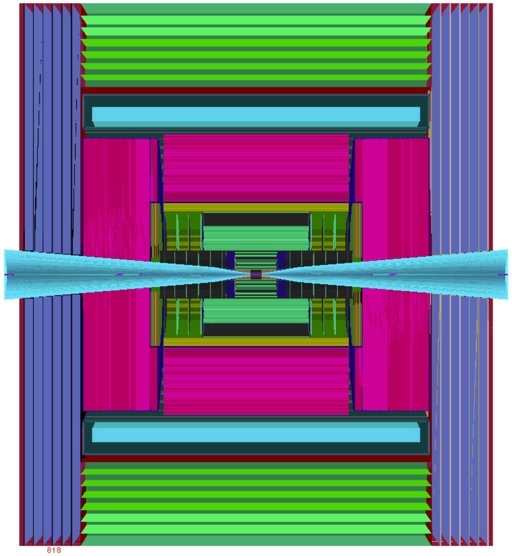


Normalized to the ratio of the expected number of events considering acceptance and reconstruction efficiencies



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

Next steps

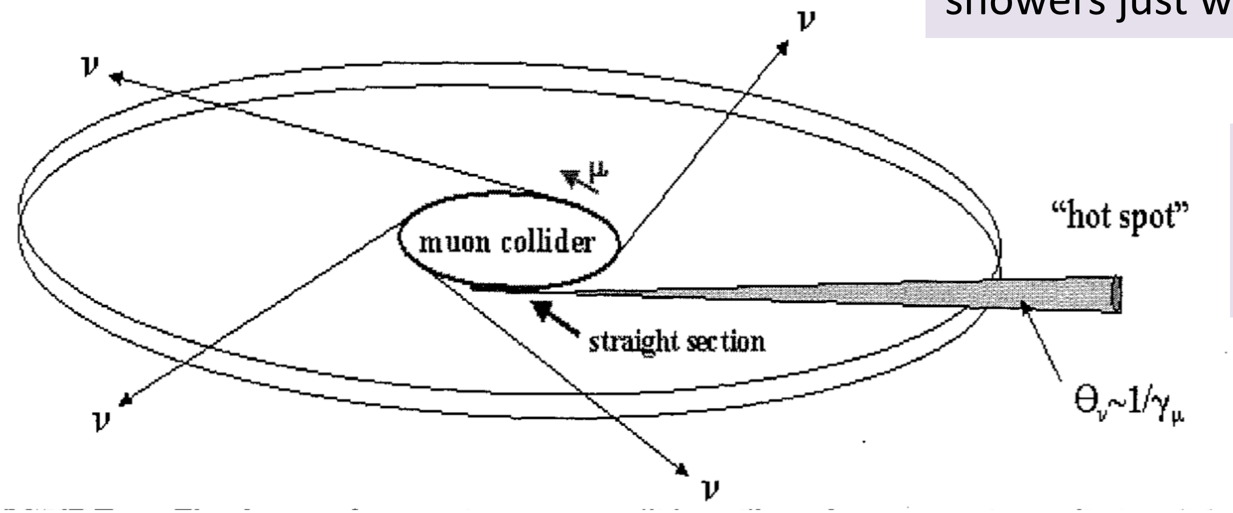


- **Move to use the Future Collider Framework**
  - Description of the detector already done including the nozzle
  - A new, up to the state of the art detector is needed
- **Simulate the beam-induced background with FLUKA**
  - MDI and IR descriptions provided by MAP collaboration for 1.5 and 3 TeV $\sqrt{s}$
  - 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
ε_L	MeV m	7.5	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1	0.1
σ_z	mm	10	5	2(.5)	1.07
β	mm	10	5	2.5	1.07
ε	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)**

- **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**

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

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(3×10^4 mSv/year)

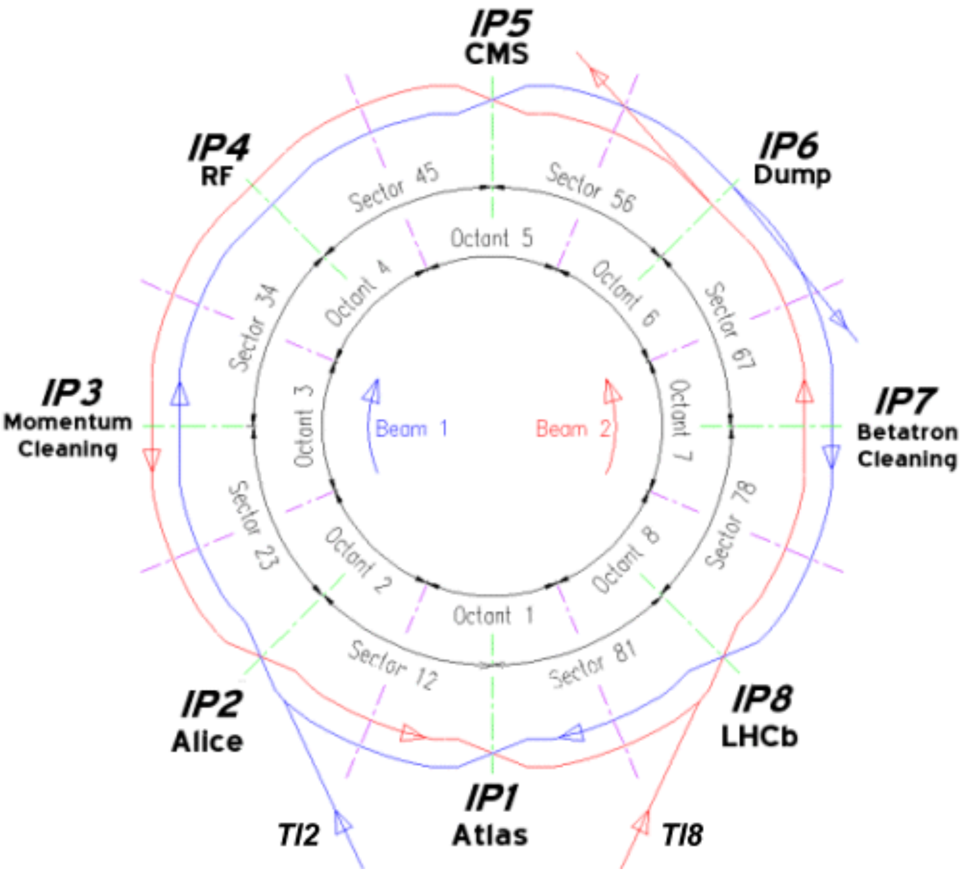
Important mitigation is required

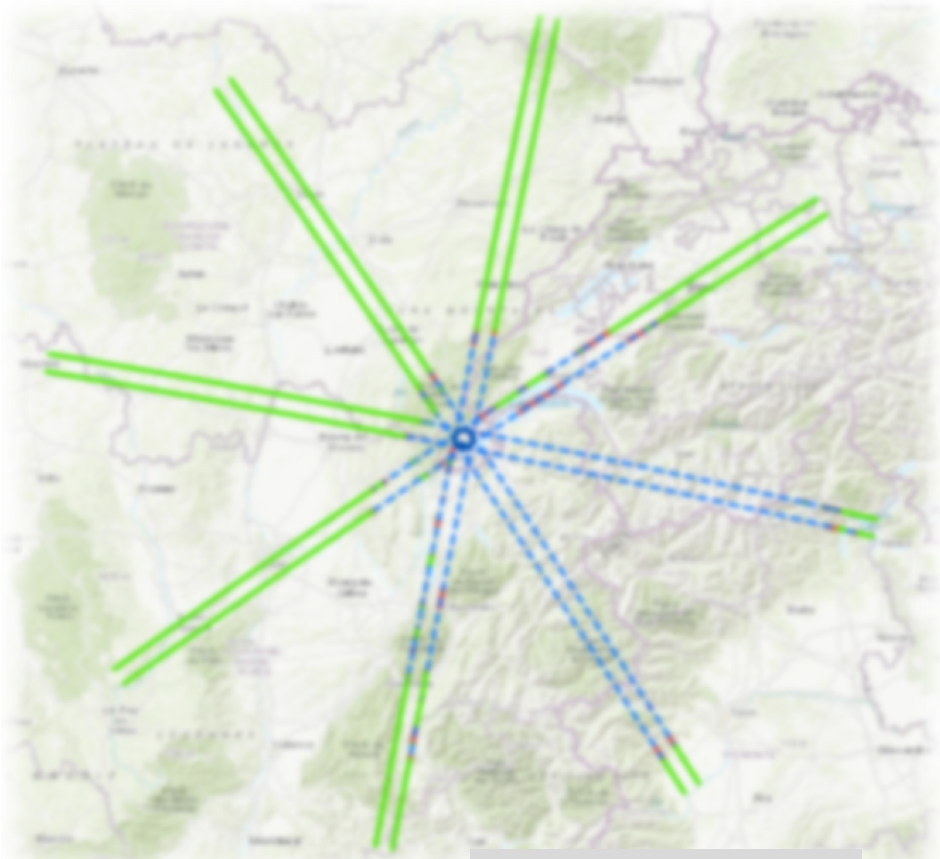
- Arcs would be OK for 2 TeV
- Can we wiggle the beam?
- Can we paint it around in the straights?
- **Seems an important issue**

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 , …

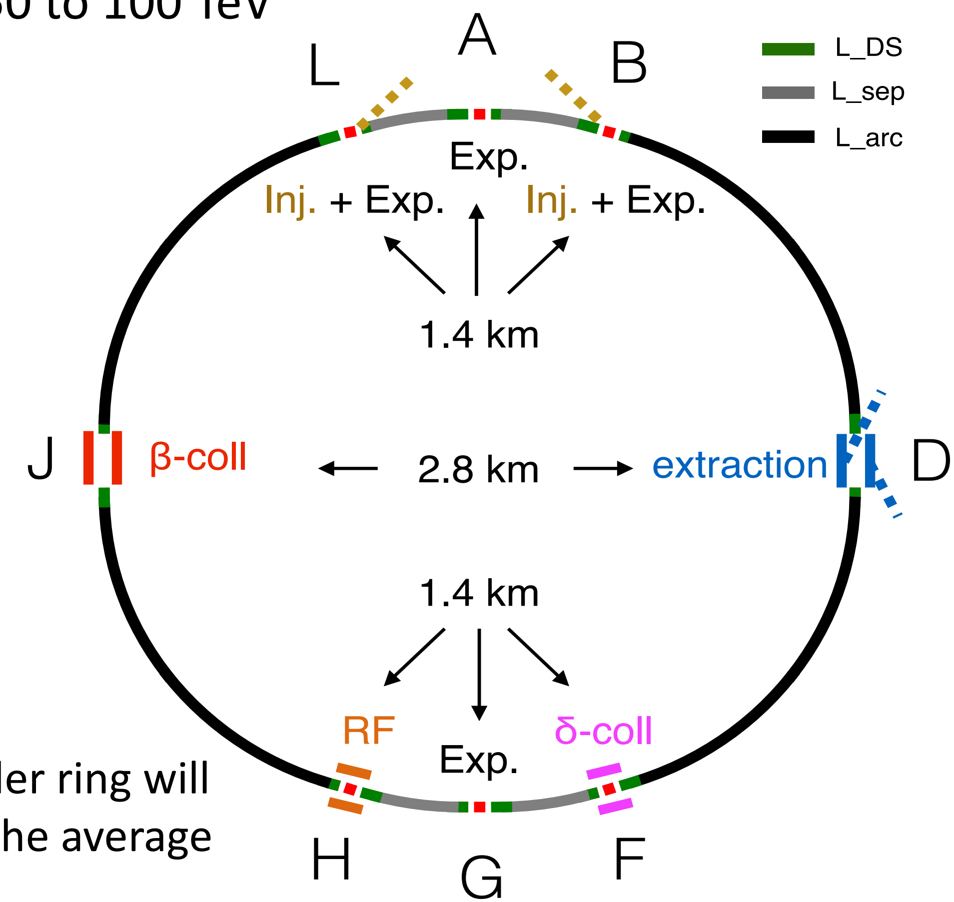
Minimum distance is 17 km, corresponds to effective depth of d = 23 m
Second shortest is 25 km (d = 50 m), longest is 263 km (d = 5430 m)

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

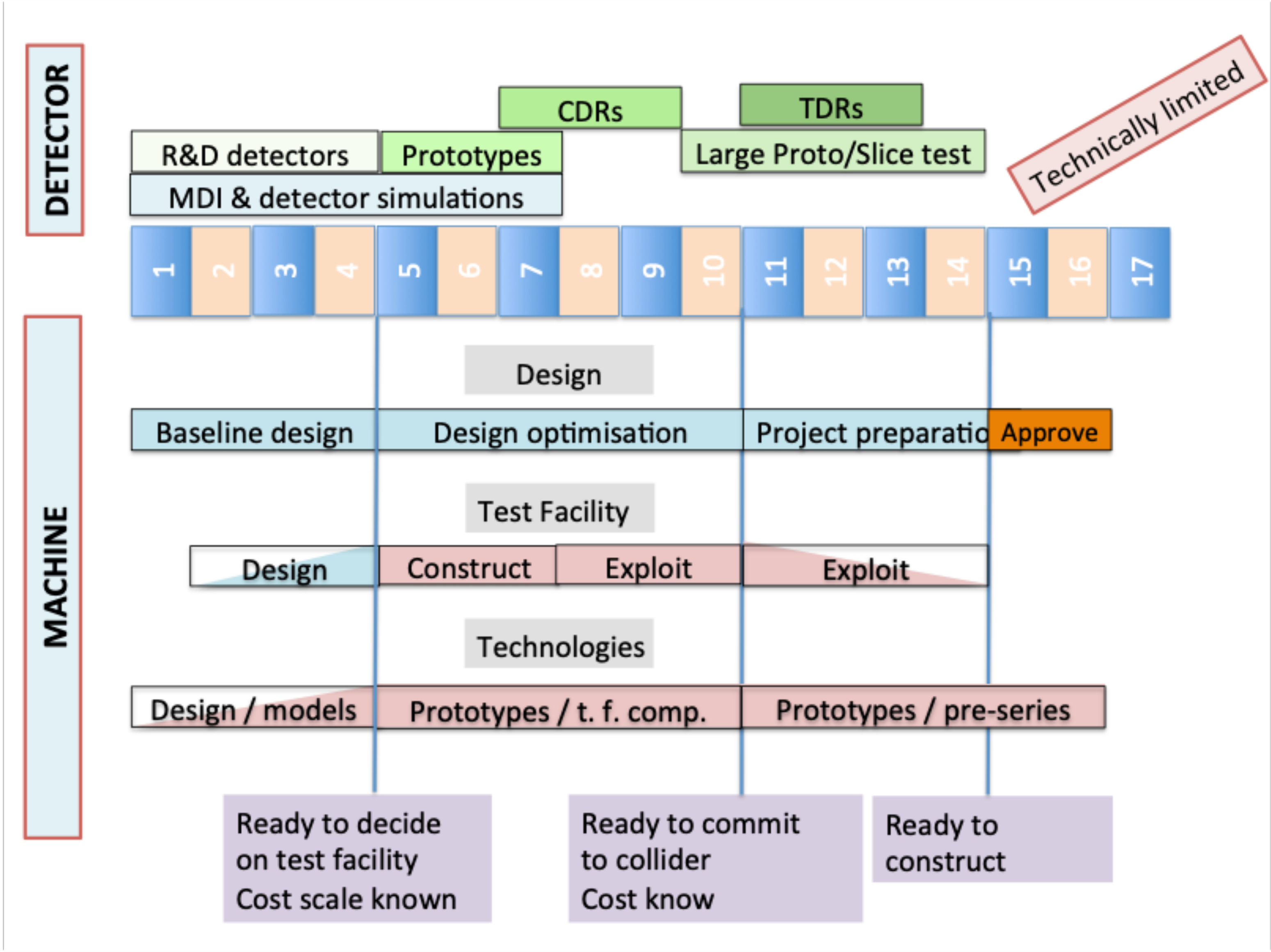
- **For 1.5 TeV beam in LHC** (e.g. fast-ramping 1.4-1.8 T magnets, 45 GV RF)
  - Gaps of O(30 m) are still OK
  - Straights would be O(20) too high, requires improvement (helical trajectory?)

- **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

R&D detectors | Prototypes | CDRs | TDRs | Large Proto/Slice test

MDI & detector simulations

Technically limited

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

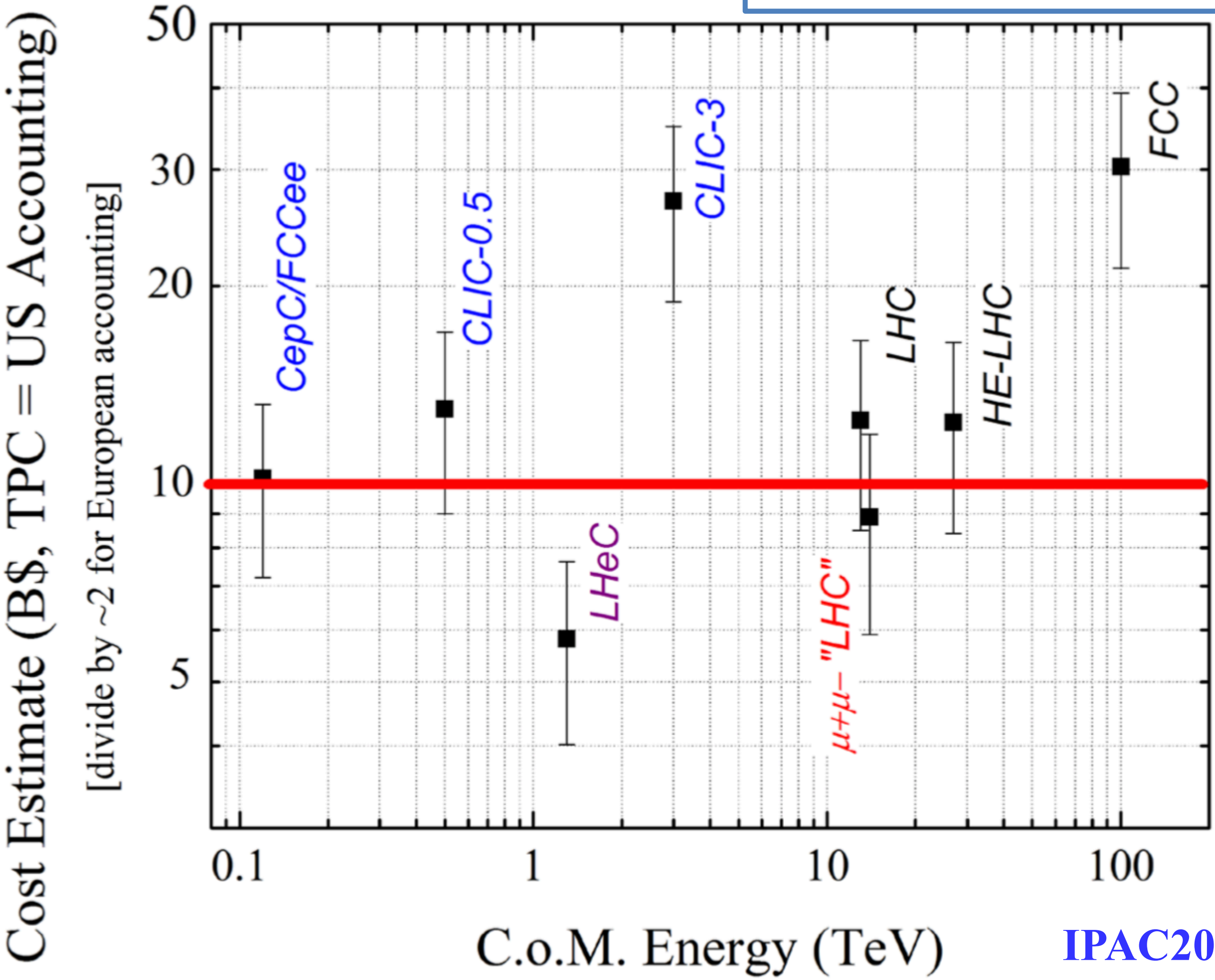
Ready to commit to collider
Cost know

Ready to construct

Cost estimate

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)

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

e-group: *MUONCOLLIDER-FACILITY*

MUST-mac@cern.ch

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

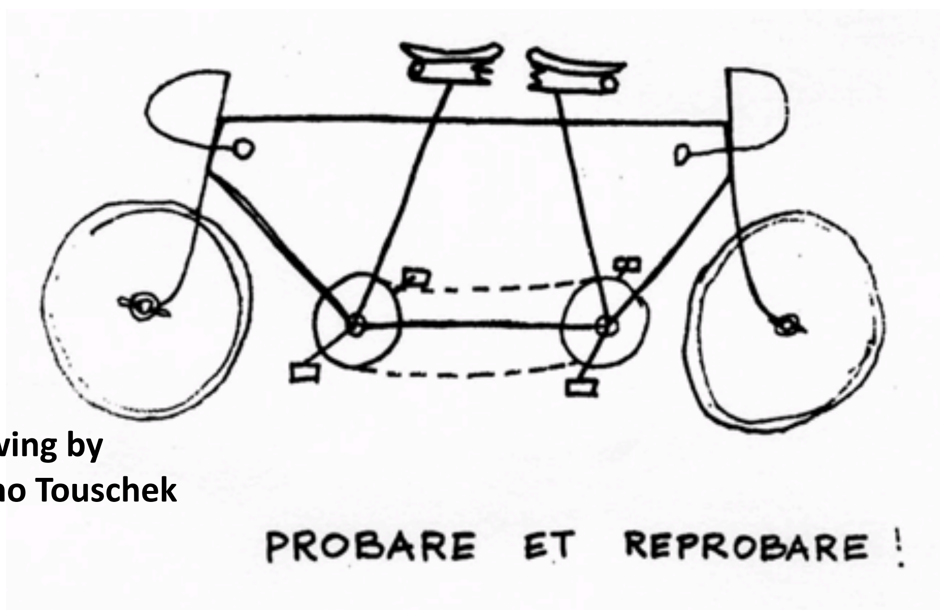
Thanks to many colleagues!

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