International MUON Collider Collaboration

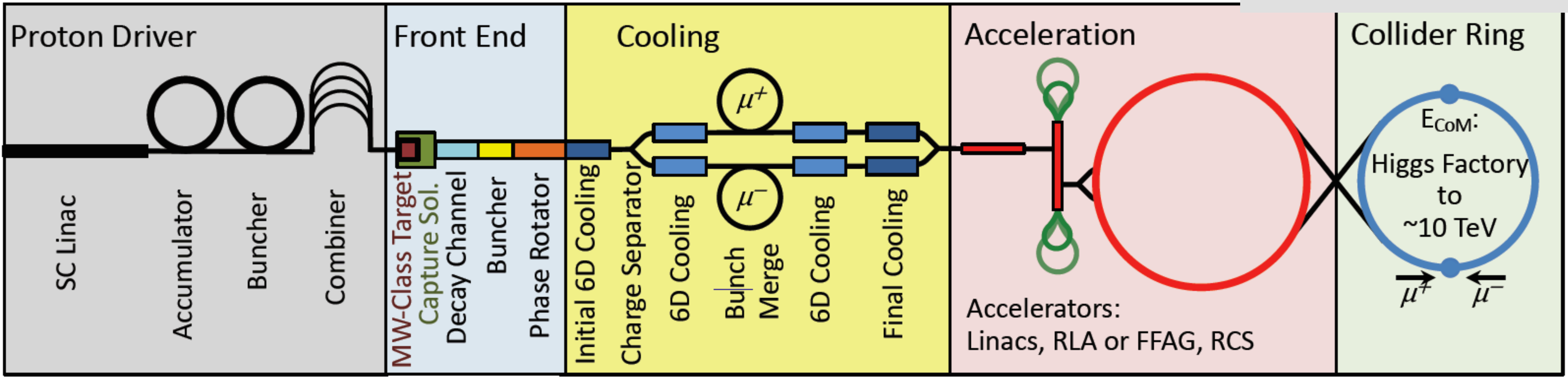
# Muon Collider

Daniel Schulte for the Muon Collider Collaboration

# Proton-driven Muon Collider Concept

The muon collider has been developed by the MAP collaboration mainly in the US
Muon cooling demonstration by MICE in the UK
Note: LEMMA alternative mainly at INFN revived the interest

MAP collaboration




Short, intense proton bunches to produce hadronic showers

Protons produce pions
Pions decay to muons

Muon are captured, bunched and then cooled by ionisation cooling in matter

Acceleration to collision energy

Collision

Muon collider is unique for very high lepton collision

# International Muon Collider Collaboration

Objective:

In time for the next European Strategy for Particle Physics Update, the study aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.

It will provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers. It will also identify an R&D path to demonstrate the feasibility of the collider.

Scope:

- Focus on two energy ranges:
  - **3 TeV**, if possible with technology ready for construction in 10-20 years
  - **10+ TeV**, with more advanced technology, **the reason to chose muon colliders**
- Explore synergy with other options (neutrino/higgs factory)
- Define **R&D path**

# Community Meeting Convener

Conveners list

***Radio-Frequency (RF):*** Alexej Grudiev (CERN), Jean-Pierre Delahaye (CERN retiree), Derun Li (LBNL), Akira Yamamoto (KEK).

***Magnets:*** Lionel Quettier (CEA), Toru Ogitsu (KEK), Soren Prestemon (LBNL), Sasha Zlobin (FNAL), Emanuela Barzi (FNAL).

***High-Energy Complex (HEC):*** Antoine Chance (CEA), J. Scott Berg (BNL), Alex Bogacz (JLAB), Christian Carli (CERN), Angeles Faus-Golfe (IJCLab), Eliana Gianfelice-Wendt (FNAL), Shinji Machida (RAL).

***Muon Production and Cooling (MPC):*** Chris Rogers (RAL), Marco Calviani (CERN), Chris Densham (RAL), Diktys Stratakis (FNAL), Akira Sato (Osaka University), Katsuya Yonehara (FNAL).

***Proton Complex (PC):*** Simone Gilardoni (CERN), Hannes Bartosik (CERN), Frank Gerigk (CERN), Natalia Milas (ESS).

***Beam Dynamics (BD):*** Elias Metral (CERN), Tor Raubenheimer (SLAC and Stanford University), Rob Ryne (LBNL).

***Radiation Protection (RP):*** Claudia Ahdida (CERN).

***Parameters, Power and Cost (PPC):*** Daniel Schulte (CERN), Mark Palmer (BNL), Jean-Pierre Delahaye (CERN retiree), Philippe Lebrun (CERN retiree and ESI), Mike Seidel (PSI), Vladimir Shiltsev (FNAL), Jingyu Tang (IHEP), Akira Yamamoto (KEK).

***Machine Detector Interface (MDI):*** Donatella Lucchesi (University of Padova), Christian Carli (CERN), Anton Lechner (CERN), Nicolai Mokhov (FNAL), Nadia Pastrone (INFN), Sergo R Jindariani (FNAL).

***Synergy:*** Kenneth Long (Imperial College), Roger Ruber (Uppsala University), Koichiro Shimomura (KEK).

***Test Facility (TF):*** Roberto Losito (CERN), Alan Bross (FNAL), Tord Ekelof (ESS,Uppsala University).

# Lepton Physics at High Energy

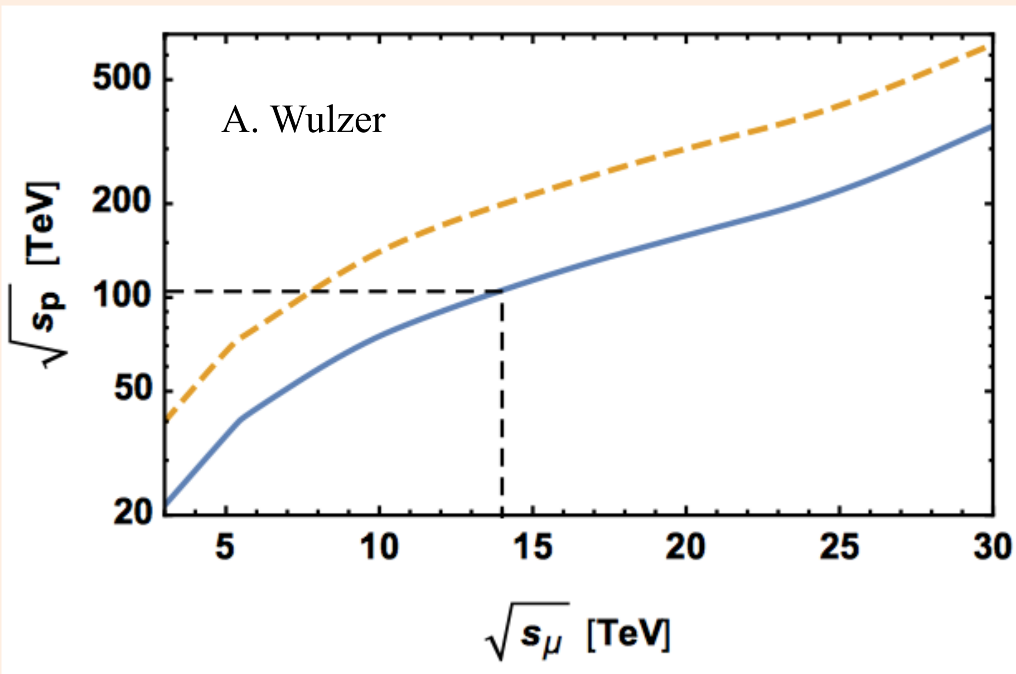
High energy lepton colliders are precision and discovery machines

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

Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao
Muon Collider - Preparatory Meeting

## Precision potential

Measure $k_4$ to some 10%
With 14 TeV, 20 $ab^{-1}$




## Discovery reach

14 TeV lepton collisions are comparable to 100 TeV proton collisions for production of heavy particle pairs

## Luminosity goal

(Factor O(3) less than CLIC at 3 TeV)
$4 \times 10^{35}$ $cm^{-2}s^{-1}$ at 14 TeV

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

# Muon Collider Promises

CLIC is at the limit of what one can do (decades of R&D)

- No obvious way to improve luminosity

Luminosity per beam power increases with energy in muon collider

- **power efficient**

Site is **compact**

- 10 TeV comparable to 3 TeV CLIC

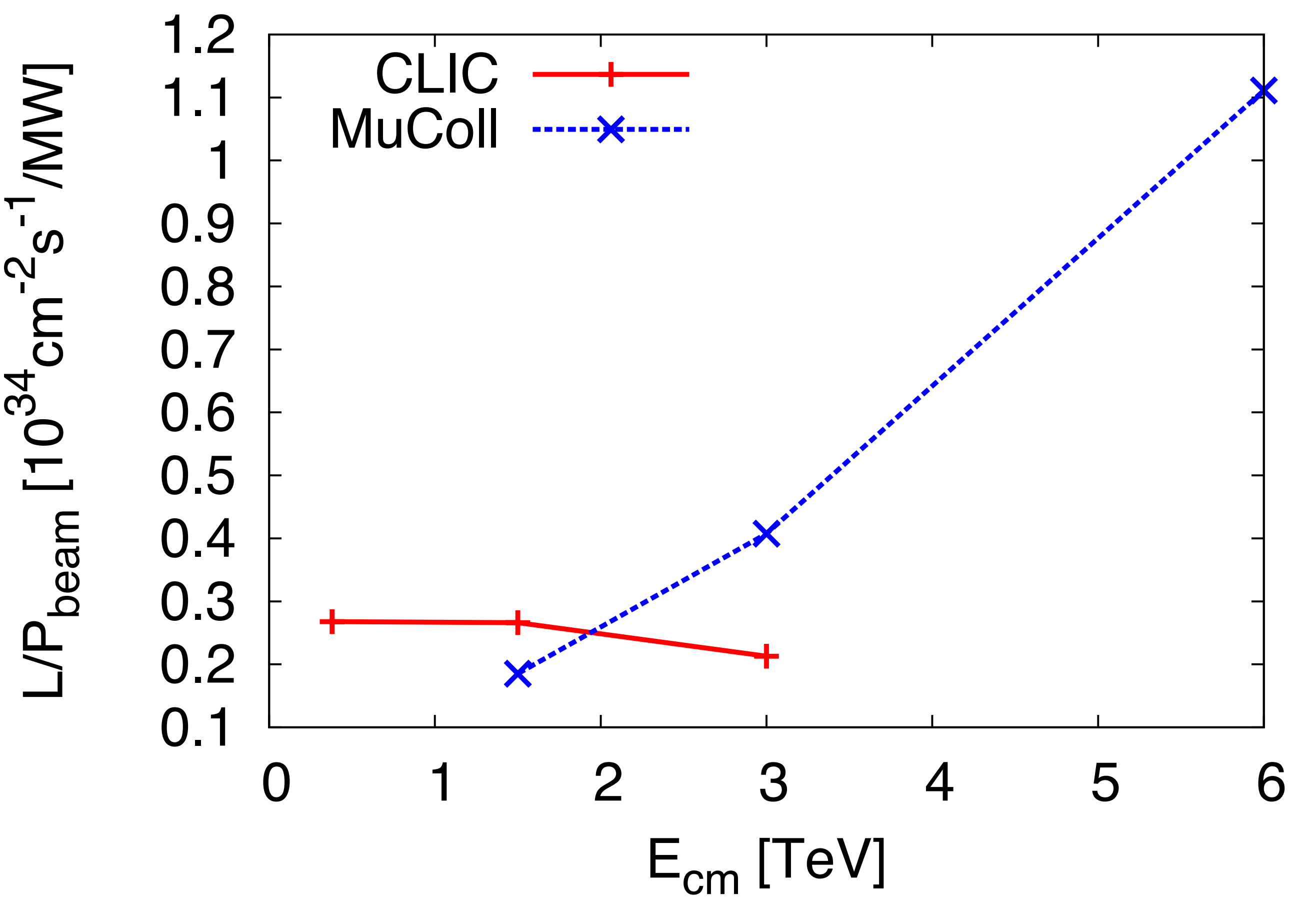
**Staging** is natural

- Each ring accelerates by a factor of a few

Promises **cost effectiveness**

- but need detailed study

Other **synergies** (neutrino/higgs)




Muon collider promises unique opportunity for a **high-energy, high-luminosity lepton collider**

# Luminosity Goals

International MUON Collider Collaboration

Target integrated luminosities

| $\sqrt{s}$ | $\int \mathcal{L}dt$ |
|---|---|
| 3 TeV | $1\ \mathrm{ab}^{-1}$ |
| 10 TeV | $10\ \mathrm{ab}^{-1}$ |
| 14 TeV | $20\ \mathrm{ab}^{-1}$ |

**Note: currently consider 3 TeV and either 10 or 14 TeV**

- Tentative parameters achieve goal in 5 years
- FCC-hh to operate for 25 years
- Might integrate some margins
- Aim to have two detectors

**Now study if these parameters lead to realistic design with acceptable cost and power**

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

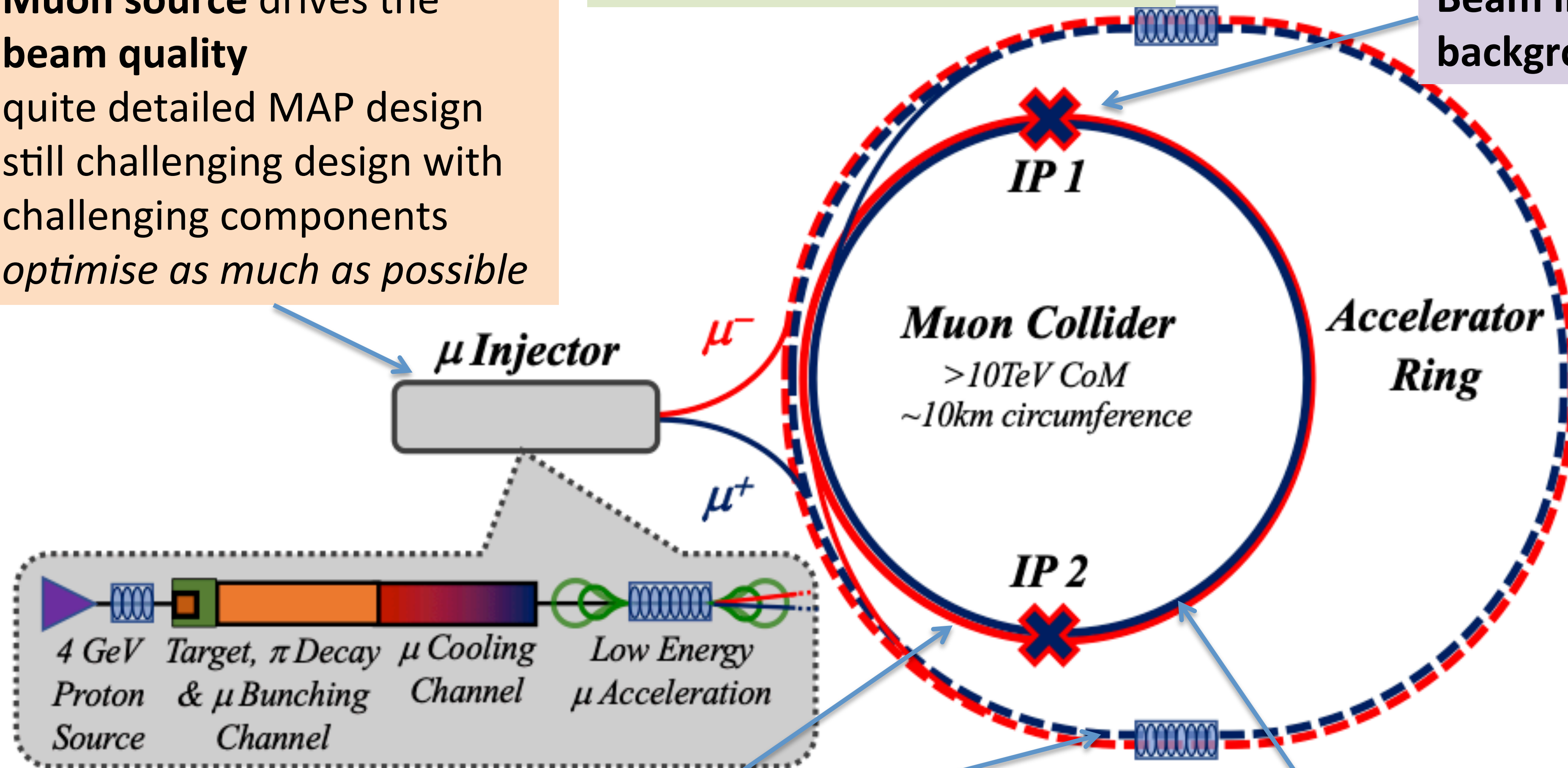
| Parameter | Unit | 3 TeV | 10 TeV | 14 TeV |
|---|---|---|---|---|
| L | $10^{34}\ \mathrm{cm^{-2}s^{-1}}$ | 1.8 | 20 | 40 |
| N | $10^{12}$ | 2.2 | 1.8 | 1.8 |
| $f_r$ | Hz | 5 | 5 | 5 |
| $P_{beam}$ | MW | 5.3 | 14.4 | 20 |
| C | km | 4.5 | 10 | 14 |
| <B> | T | 7 | 10.5 | 10.5 |
| $\varepsilon_L$ | MeV m | 7.5 | 7.5 | 7.5 |
| $\sigma_E$ / E | % | 0.1 | 0.1 | 0.1 |
| $\sigma_z$ | mm | 5 | 1.5 | 1.07 |
| $\beta$ | mm | 5 | 1.5 | 1.07 |
| $\varepsilon$ | µm | 25 | 25 | 25 |
| $\sigma_{x,y}$ | µm | 3.0 | 0.9 | 0.63 |

# Key Challenges

**Physics potential assessment**

**Muon source** drives the **beam quality**
quite detailed MAP design
still challenging design with challenging components
*optimise as much as possible*

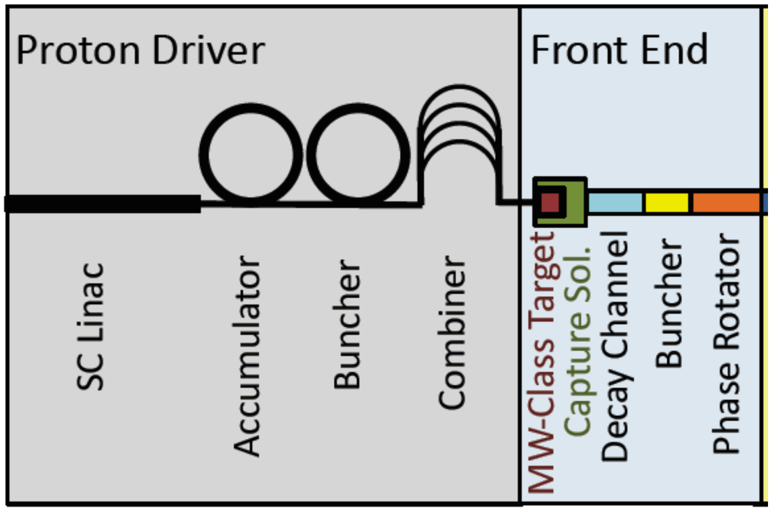
**Beam induced background**




**Dense neutrino flux**
mitigated by mover system and site selection

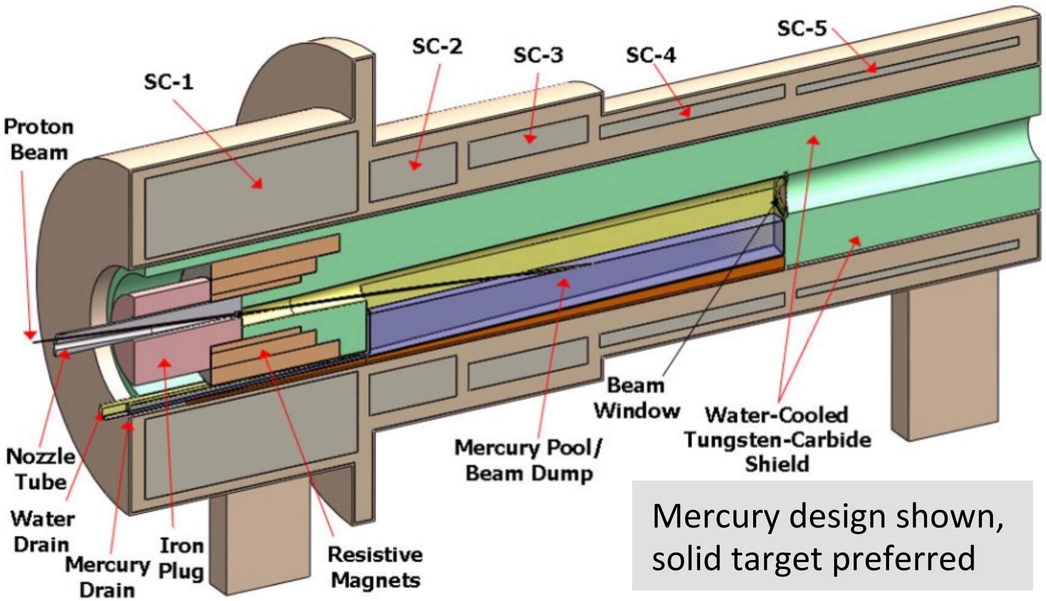
**High energy complex**
**Cost** and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts **beam quality**

# Proton Complex and Target Area




Proton beam power is no issue, some look required at **H- source** and **accumulator and combiner complex**

**2 MW proton beam**
requires radiation protection



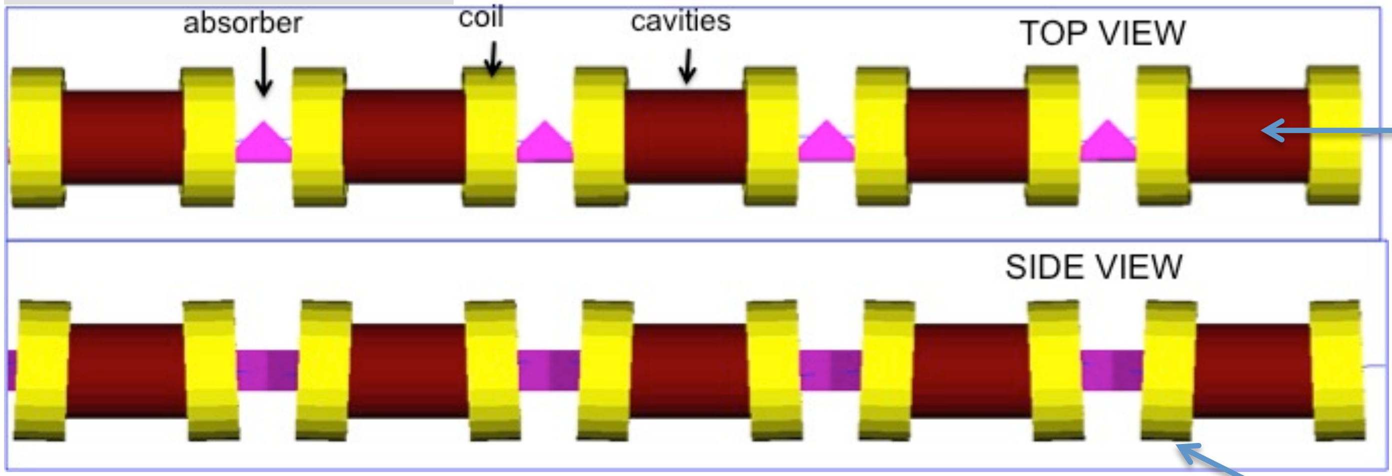

Mercury design shown, solid target preferred

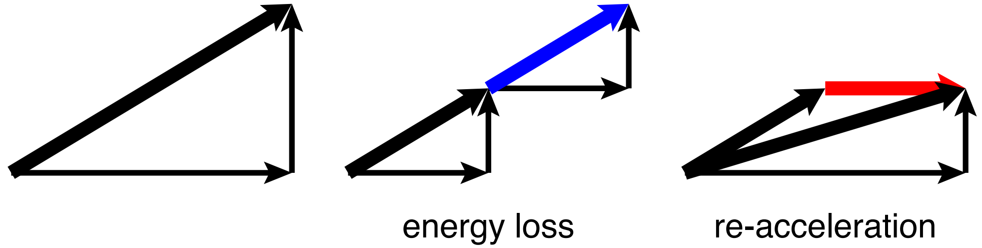
**High field** to efficiently collect pions/ muons: 20 T, then tapering
Using copper solenoid in superconducting solenoid

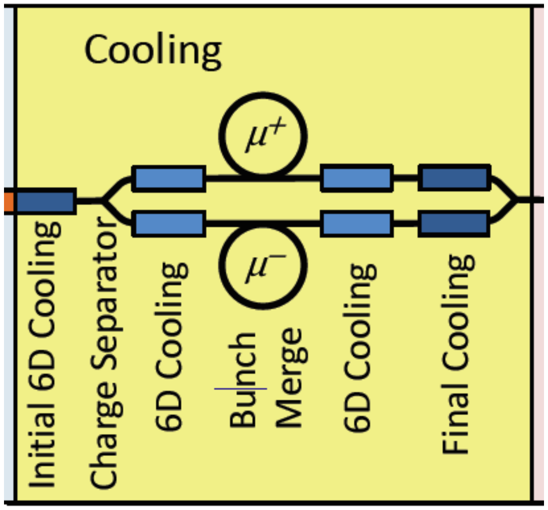
**Large aperture** O(1.2m) to allow shielding

# Cooling Concept

MAP collaboration




Limit muon decay, cavities with **high gradient in a magnetic field**
tests much better than design values but need to develop

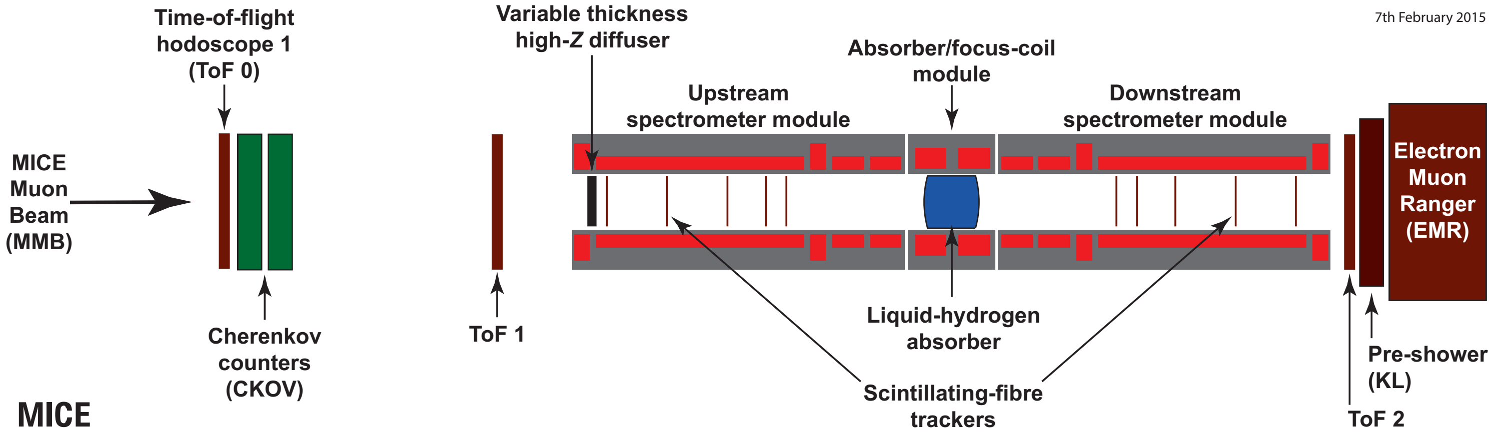
**Compact integration** to minimise muon loss

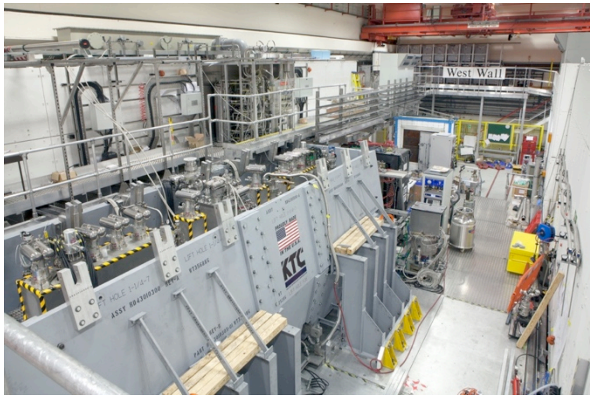
Minimise betafunction with **strongest solenoids (40+ T)**
32 T achieved, 40+ T planned

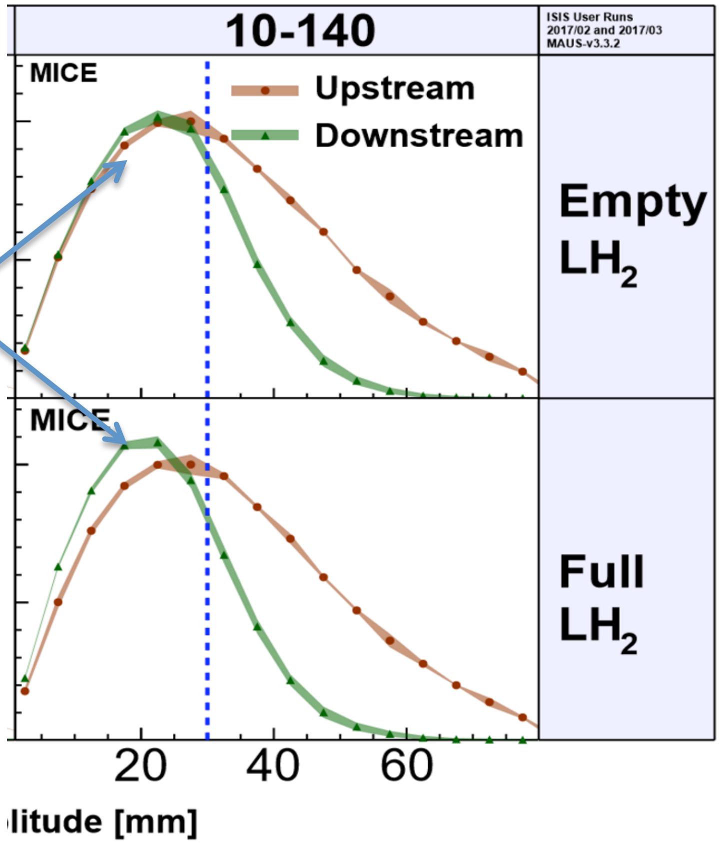
Need to **optimise lattice design** to gain factor 2 in emittance, integrating demonstrated better hardware performances

This is the **unique** and **novel** system of the muon collider
Will need a **test facility**
The principle has been demonstrated in MICE

# MICE (in the UK)




**Nature volume 578, pages 53-59 (2020)**

More particles at smaller amplitude after absorber is put in place

Principle of ionisation cooling has been demonstrated

More complete experiment with higher statistics, more than one stage required

Integration of magnets, RF, absorbers, vacuum is engineering challenge

# High-energy Acceleration

*Rapid cycling synchrotrons (RCS)*
- Combine static and ramping magnets

- **Fast-ramping magnets** to follow beam energy
  - normal conducting or novel HTS
  - O(kT/s) required

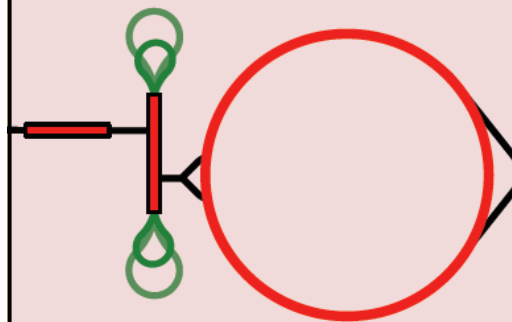
- **Efficient magnets and power converters** with energy recovery
  - O(95%) efficiency

*RF system*
- **Important single-bunch beam loading**
- 2 x 10 $^{12}$ particles in O(mm)-long bunch at 5 TeV

*FFA*
- Fixed (high-field) magnets but large energy acceptance
- Challenging **lattice design** for large bandwidth and limited cost
- **Complex high-field magnets**
- Challenging beam dynamics

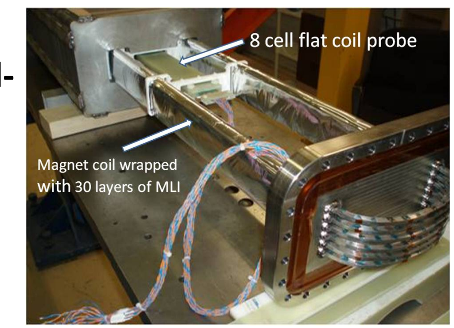
**FNAL** 290 T/s HTS magnet

Acceleration



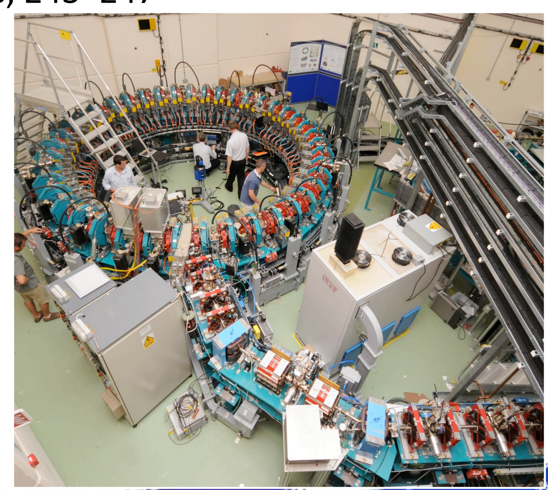
Accelerators:
Linacs, RLA or FFAG, RCS

Test of **fast-ramping normal-conducting magnet** design




**EMMA** proof of FFA principle

Nature Physics 8, 243–247 (2012)



# Collider Ring

**High field dipoles** to minimise collider ring size and maximise luminosity

- At **3 TeV**: 3 km of O(11 T) dipoles (HL-LHC level)
- At **10 TeV**: prefer 7 km of 15 T dipoles (FCC-hh level)

**Beam loss protection** O(500 W/m)

- Large 150 mm aperture to fit shielding
- **3 TeV**: 50/30 mm tungsten shielding leads to 1%, maximum of 1.5 mW/g
- **10 TeV**: expect not to be much worse

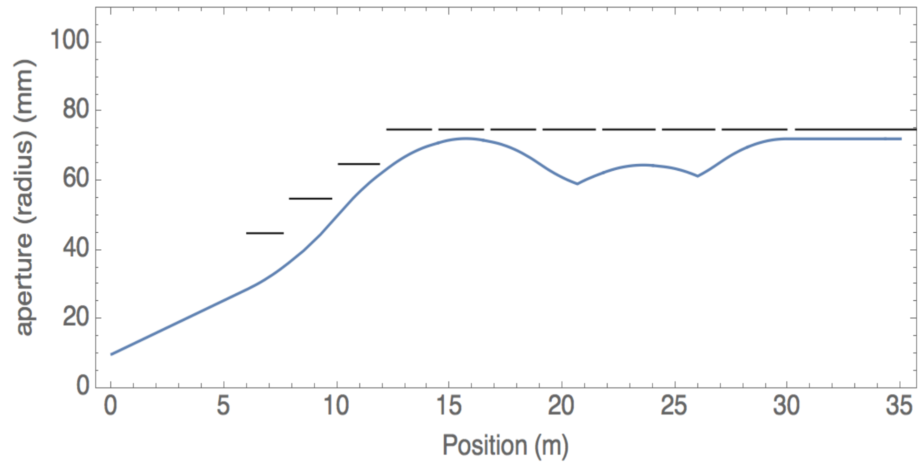
**Strong focusing** at IP to minimise beta-function and maximise luminosity

$$\beta^* \propto \frac{1}{E}$$

**At 3 TeV**: Field level close to HL-LHC (12 vs 11 T), similar aperture

**At 10+ TeV**: Higher field and aperture are likely required, consider even HTS, will depend on European Roadmap for Accelerator R&D

3 TeV FFS Design (MAP)

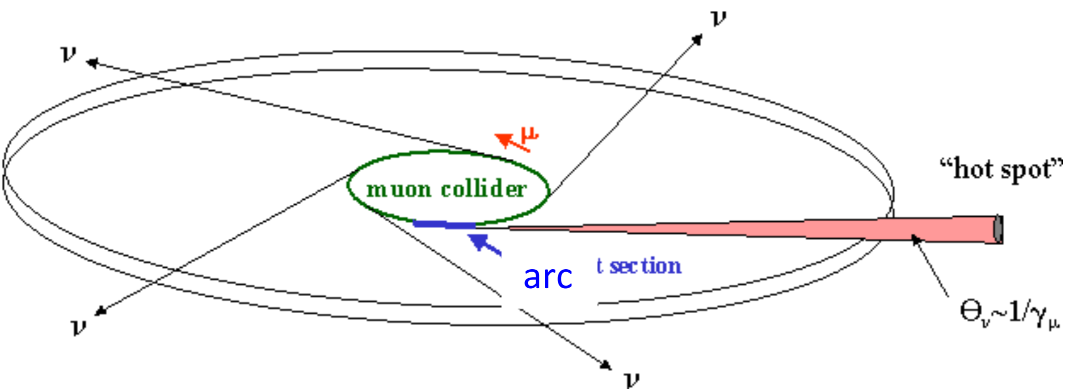



| Parameter | Q1 | Q1 | Q3 | Q4 |
|---|---|---|---|---|
| Aperture (mm) | 90 | 110 | 130 | 150 |
| Gradients (T/m) | 267 | 218 | -154 | -133.5 |
| Peak field (T) | 12 | 12 | 10+ | 10+ |
| Dipole field (T) | 0 | 0 | 2.00 | 2.00 |

At 3 TeV:
Close to state of the art

At 10+ TeV:
Higher field $Nb_3Sn$ or even HTS is potentially required

# Neutrino Flux Mitigation

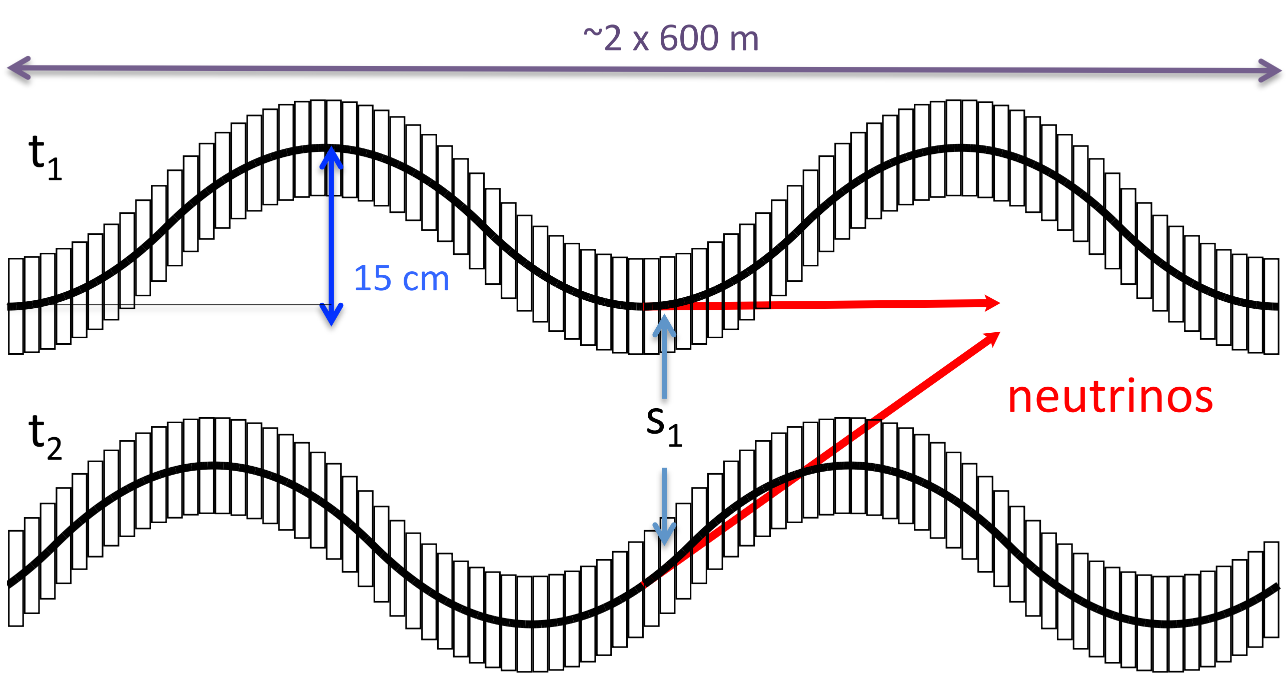



Concentrate neutrino cone from arcs can approach legal limits for 14 TeV

**Goal is to reduce to level similar to LHC**

**3 TeV, 200 m deep tunnel is about OK**

**Need mitigation of arcs at 10+ TeV**: idea of Mokhov, Ginneken to move beam in aperture
Our approach: move collider ring components, e.g. vertical bending with 1% of main field




Opening angle ± 1 mradian

**14 TeV, in 200 m deep tunnel comparable to LHC case**

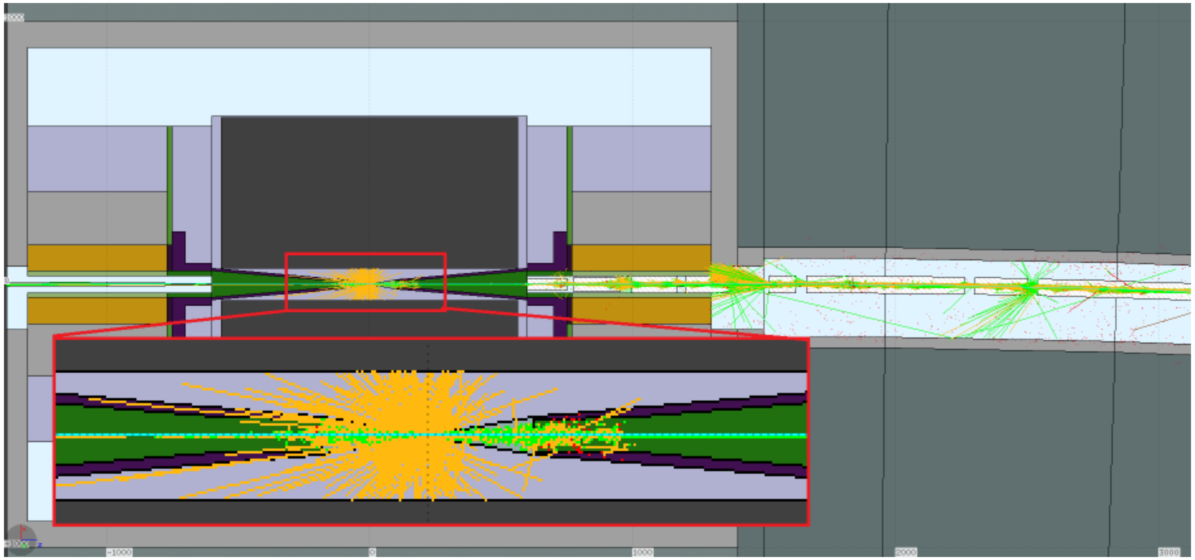
**Need to study mover system, magnet, connections and impact on beam**

**Working on different approaches for experimental insertion**

# Physics Potential, Detector and MDI

**Physics potential** studies including detector and background
- Theory and phenomenology
- Detector technologies, simulation studies
- Collider and mask design
- Important effort is required

Main background sources
- Muon decay products (40,000 muons/m/crossing at 14 TeV)
- Beam-beam background
- Note: background reduces while beam burns off



Mitigation methods
- masks
- detector granularity
- detector timing
- solenoid field
- event reconstruction strategies
- …

Simulation tools exist

First studies at lower energies (125 GeV and 1.5 TeV are encouraging (D. Lucchesi et al.)

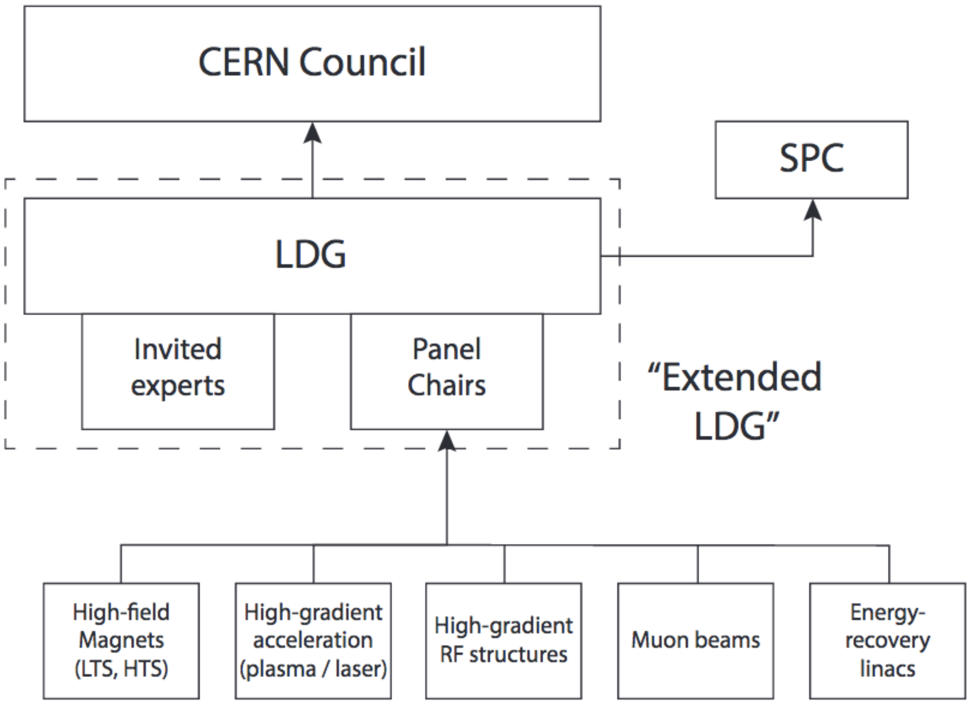
Will develop systems for higher energies

# European Accelerator R&D Roadmap

**Council** charged Laboratory Directors Group (LDG) to deliver European **Accelerator R&D Roadmap** by the end of the year

Panels

- Magnets: P. Vedrine
- Plasma: R. Assmann
- RF: S. Bousson
- Muons: D. Schulte
- ERL: M. Klein




Muon Beam Panel members: Daniel Schulte (CERN, chair), Mark Palmer (BNL, co-chair), Tabea Arndt (KIT), Antoine Chance (CEA/IRFU) Jean-Pierre Delahaye (retired), Angeles Faus-Golfe (IN2P3/IJClab), Simone Gilardoni (CERN), Philippe Lebrun (European Scientific Institute), Ken Long (Imperial College London), Elias Metral (CERN), Nadia Pastrone (INFN-Torino), Lionel Quettier (CEA/IRFU), Tor Raubenheimer (SLAC), Chris Rogers (STFC-RAL), Mike Seidel (EPFL and PSI), Diktys Stratakis (FNAL), Akira Yamamoto (KEK and CERN)
Contributors: Alexej Grudiev (CERN), Donatella Lucchesi (INFN-Padua), Roberto Losito (CERN), Andrea Wulzer (EPFL, CERN, Padua)

Roles of panel members and European (other regions to be added) contact persons at https://muoncollider.web.cern.ch/organisation

# My Impression of Discussions

**Muon collider has a high potential**

- The muon collider presents enormous potential for fundamental physics research at the energy frontier.
- Not as mature as some other lepton collider options such as ILC and CLIC; but promises attractive cost, power consumption and time scale for the energy frontier, reaching beyond linear colliders.

**Challenges but no showstoppers**

- The panel identified the key R&D challenges.
- At this stage the panel did not identify any showstopper in the concept.
- Strong support of feasibility from previous studies.
- The panel considers baseline parameter set viable starting point.

**Panel sees way forward**

- The panel will propose the R&D effort that it considers essential to address these challenges during the next five years to a level that allows estimation of the performance and cost with greater certainty.
- Ongoing developments in underlying technologies will be exploited as they arise in order to ensure the best possible performance.
- This R&D effort will allow the next ESPPU to make fully informed decisions. It will also benefit equivalent strategy processes in other regions.

**and potential ramp-up**

- Based on these decisions a significant ramp-up of resources could be envisaged, in particular if a fast implementation is deemed essential.

# Ongoing Timeline Discussions

Muon collider is a long-term direction toward high-energy, high-luminosity lepton collider

Collaboration prudently also explores if muon collider can be option as next project (i.e. operation mid-2040s) in case Europe does not build higgs factory

Exploring shortest possible aggressive timeline with initial 3 TeV stage on the way to 10+ TeV

- Important ramp-up 2026

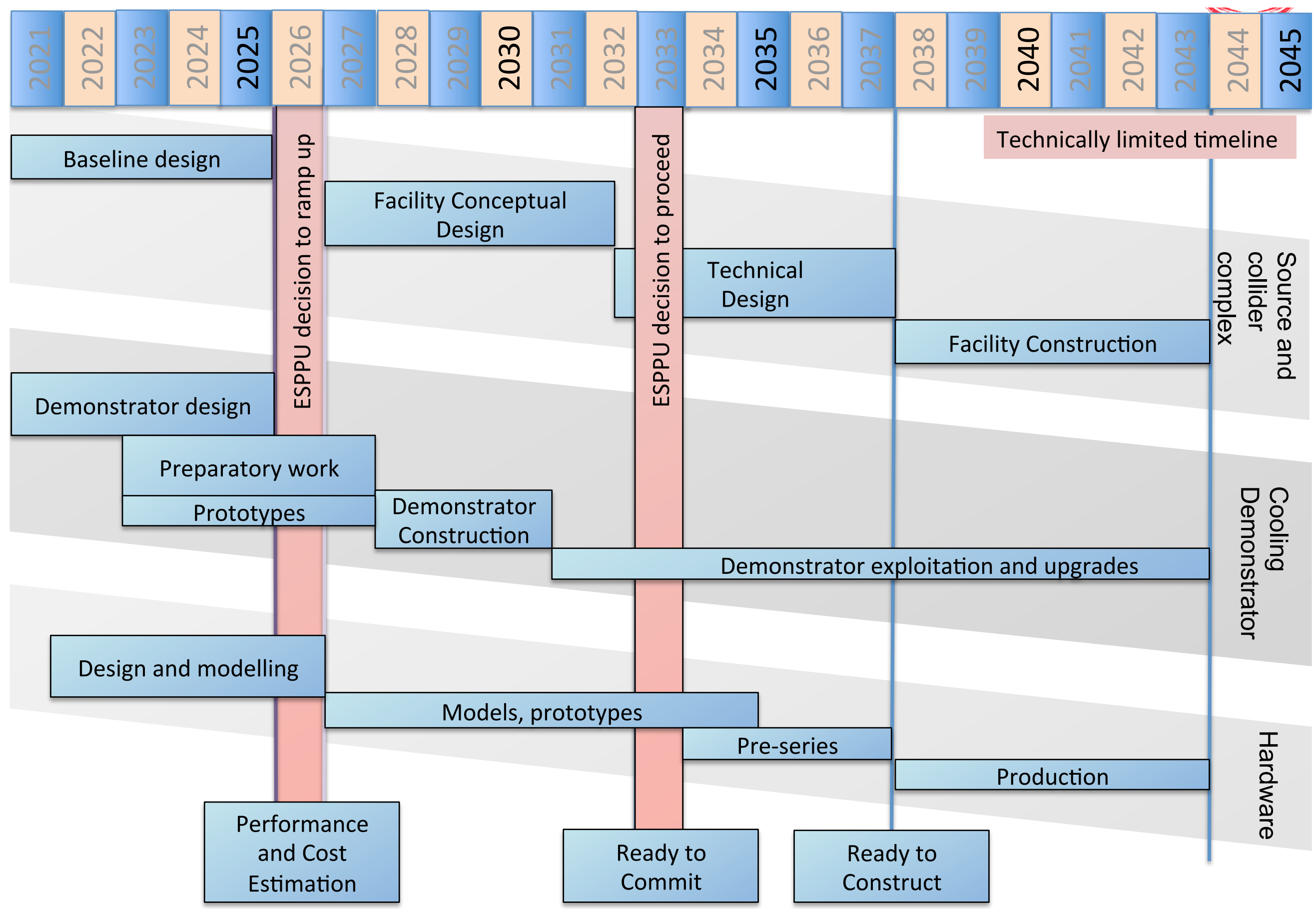
**High-field magnet and RF programmes** will allow to judge maturity what can be reached in a collider with this timeline

**Preparation of R&D programme** needs to be advanced enough for implementation after next ESPPU

Based on strategy decisions a significant ramp-up of resources could be made to accomplish construction by 2045 and exploit the enormous potential of the muon collider.

## Tentative Target for Aggressive Timeline

to assess when 3 TeV could be realised, assuming massive ramp-up in 2026



# Way Forward

**Develop the physics case**

- including background and detector technologies

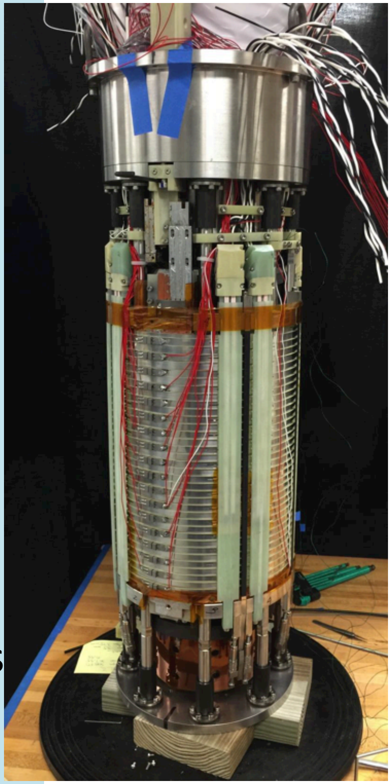
**Proposed ambitious programme in Roadmap:**

- **Design the key accelerator systems**
- **Transfer technology developments and address specific technologies**
  - Magnet roadmap programme
  - RF roadmap programme
  - MDI
  - Fast-ramping magnets and RF system for acceleration
  - Neutrino flux mitigation
  - Muon cooling module
  - RF for muon cooling module
  - Solenoids
  - Targets
  - Absorbers
  - …

Incomplete list of interest: INFN, BNL, CEA, IJCLab-In2p3, JLAB, UKRI-STFC, ESSnuSB Collaboration, ESS Laboratory, CERN, PSI, IHEP, KTI, Rostock, Darmstadt, Strathclyde, Lancaster, LBNL, EPFL

# Magnet Development

- Will exploit high-field programme (Roadmap), in particular for HTS
- Dipoles and quadrupoles
  - For 3 TeV dipoles and quadrupoles are similar to HL-LHC
    - studies to understand larger aperture in arc, but single aperture
  - For 10 TeV would like to push similar to FCC-hh
    - But smaller total cost for the project
  - Will know better in 2025
- Solenoids are demanding
  - **Final cooling solenoids**: small aperture, highest field, small number
    - 32 T demonstrated, US programme to demonstrate 40 T HTS solenoids
  - **Target solenoid** is engineering challenge
  - 6D cooling solenoids within reach, but consider HTS to improve
- **Fast-ramping magnets** and **powering** is muon collider specific
  - needs to be further developed, longest part of the accelerator
  - O(10 GW peak power) to magnets
  - O(1 GW) average power flow
  - Develop cost-effective, highly-efficient system



**NHFML**
32 T solenoid with HTS

Planned efforts to push even further

# Other Technology Development

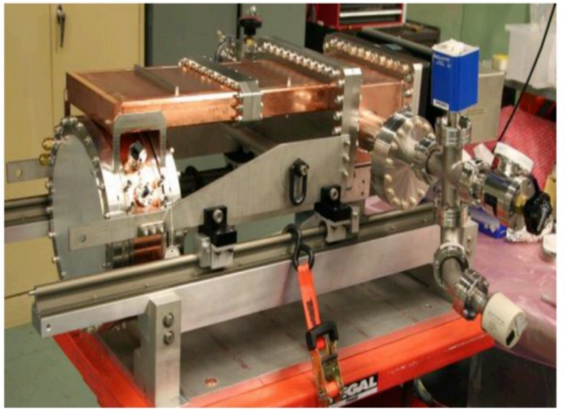
- **Neutrino radiation mitigation**:
  - Impact on **magnet, cryogenics** etc.
  - Required accurate **alignment**, mover system
  - Impact on beam **operation**

- **Muon cooling RF**:
  - Proof of principle **of cooling RF** in **high magnetic field** exists for two options and reach more than the target gradient
  - Move from single demonstrations into practical cavities
  - **Need an RF test stand**

- **Superconducting RF** needs to be further developed
  - In particular high-beam loading with short bunches

- **Target**:
  - Studies of the shock by **beam impact** and of **radiation**
  - Some material test to improve shock resistance

- **Shielding** in collider ring: Experiment and machine



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

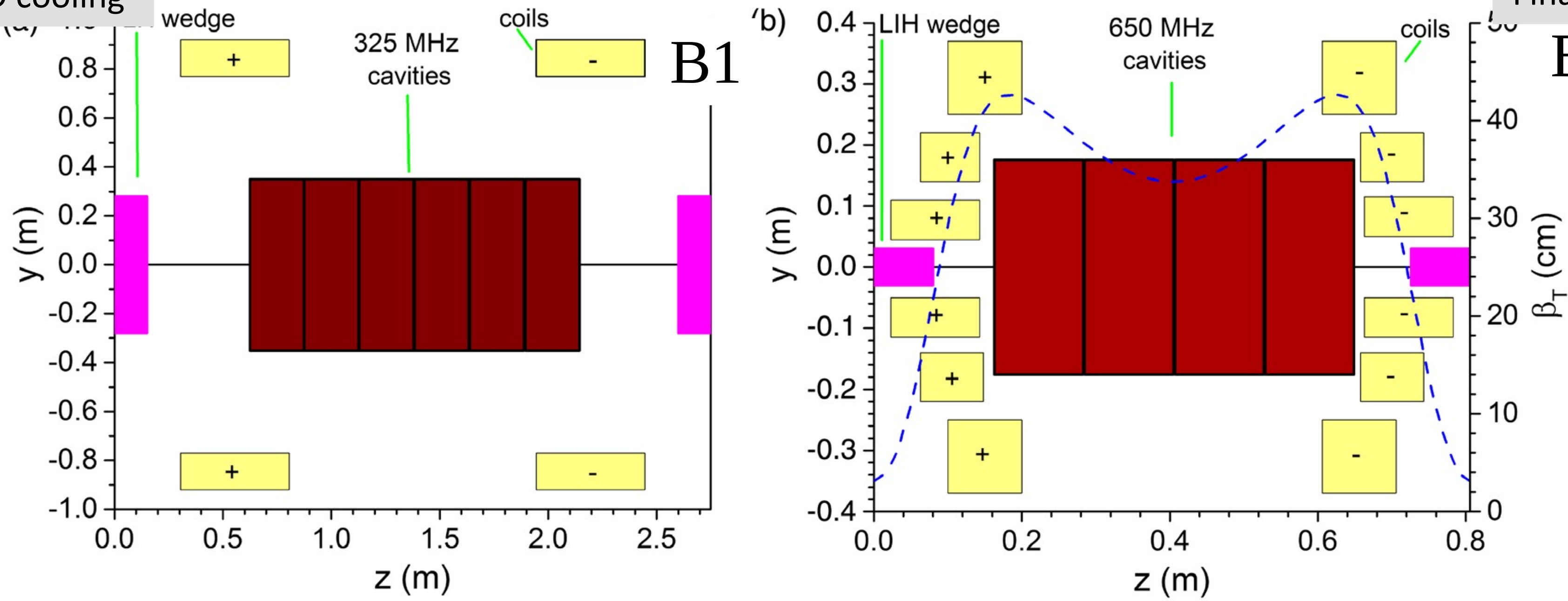
# Engineering Design of Cooling Cell

Main 6D-cooling has many magnets and needs **tight integration** with RF and absorbers

Initial 6D cooling

Final 6D cooling

2.2 T




13.6 T

Are already aware of slightly violated space constraints

- maybe cool copper can help both gradient, space and peak power

Alignment has to be integrated (e.g. additional bellows)

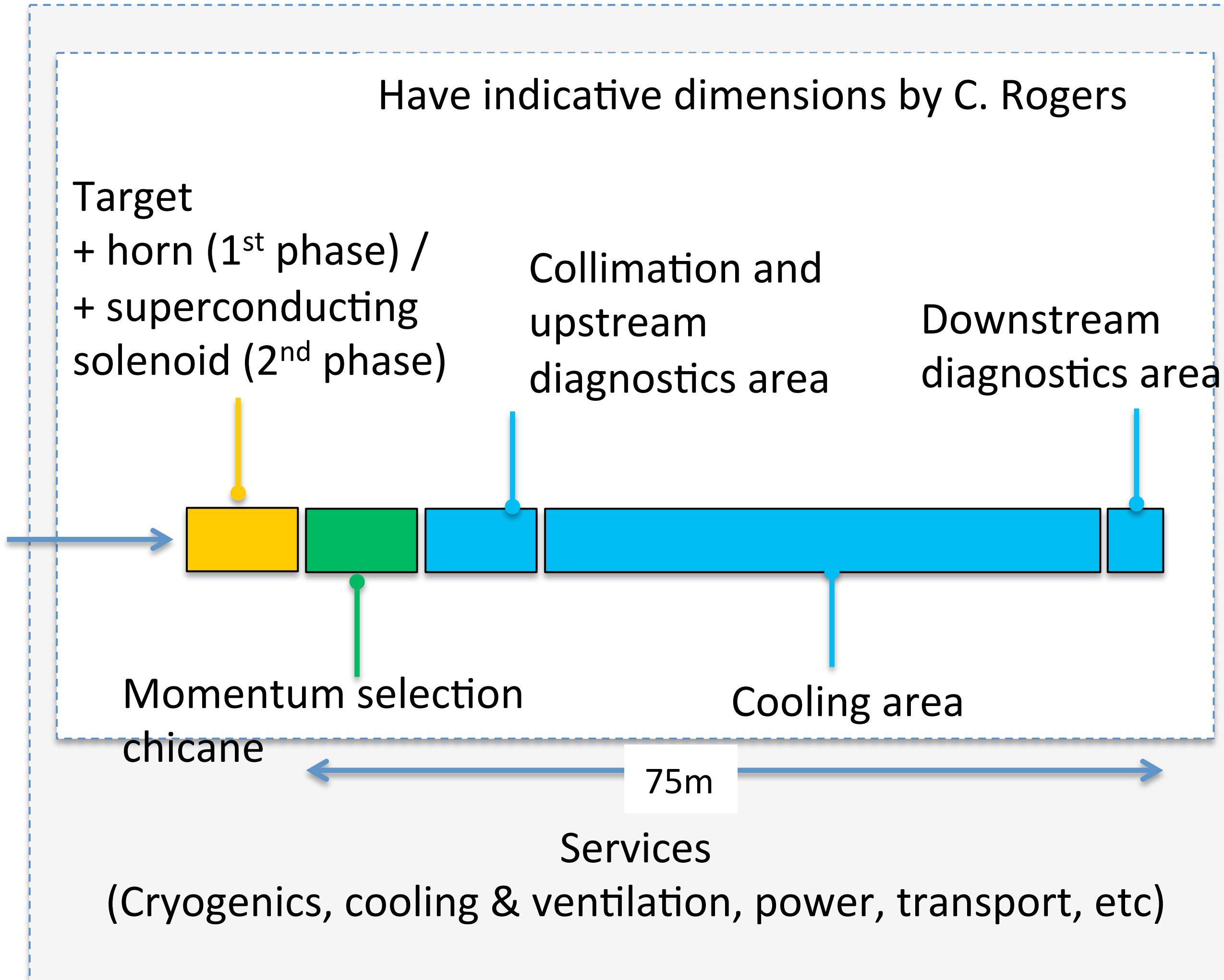
**RF cavites should be developed early**

# Demonstrator Considerations

Muon cooling is the key novel and unique component of muon collider
$\Rightarrow$ need a test in a demonstrator
Other technology challenges exist but can be addressed with prototypes (e.g. collider dipoles), also in other locations

Modular approach to demonstrator: start with minimum complex and upgrade as demonstration progresses

Identified components of test facility with approximate dimensions



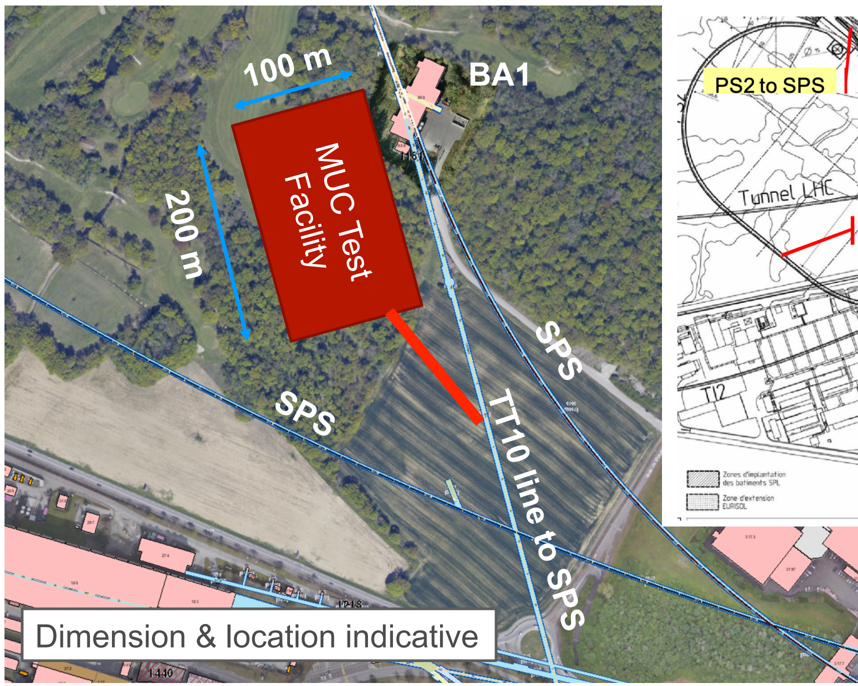

Will also explore alternative options, if resources permit

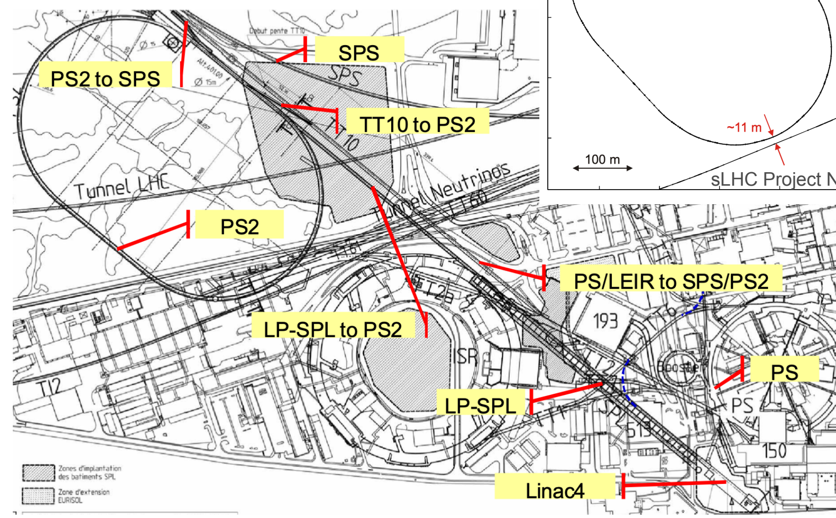
- e.g. PIC, parametric ionization cooling

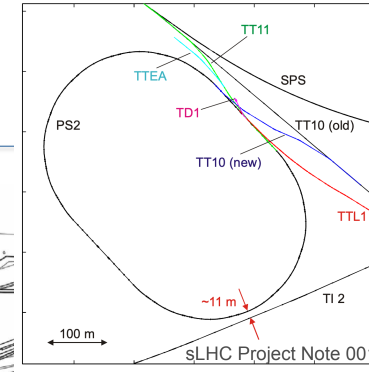
# CERN Site Example

Will consider site proposed by partners and at CERN, but need at least one

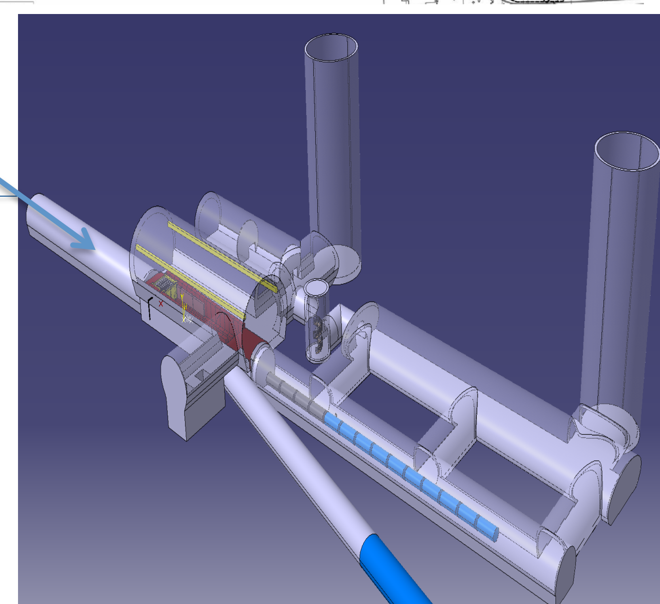
## Possibility around TT10



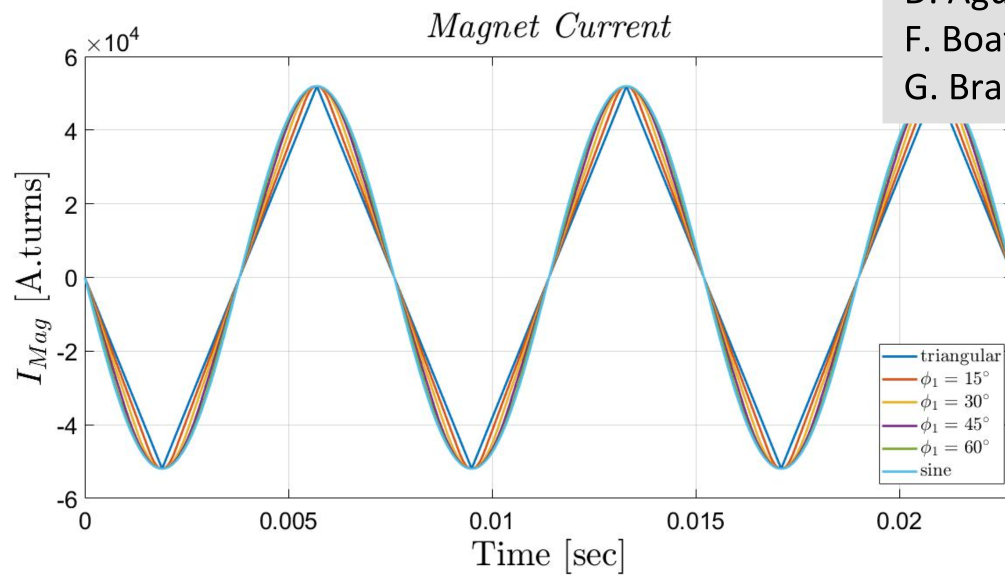

First option considered:
Could use CERN land close to TT10 and inject beam from PS



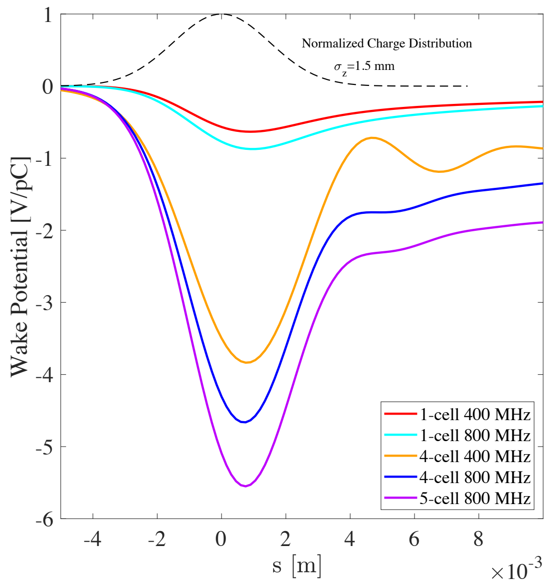
- $10^{13}$ 26 GeV protons in 7ns, produces a few $10^{12}$ muons per pulse
- Would be in molasse (no radiation to ground water), could accommodate 4 MW
- Could later upgrade with SPL and accumulator ring to have full power option

# Selected Recent Progress

Ramping **magnet challenge**
At 14 TeV, energy in field is O(200 MJ)
ramped 5 x 2 times per second
Need to recover energy pulse to pulse
Started to develop **powering scheme** with energy recovery

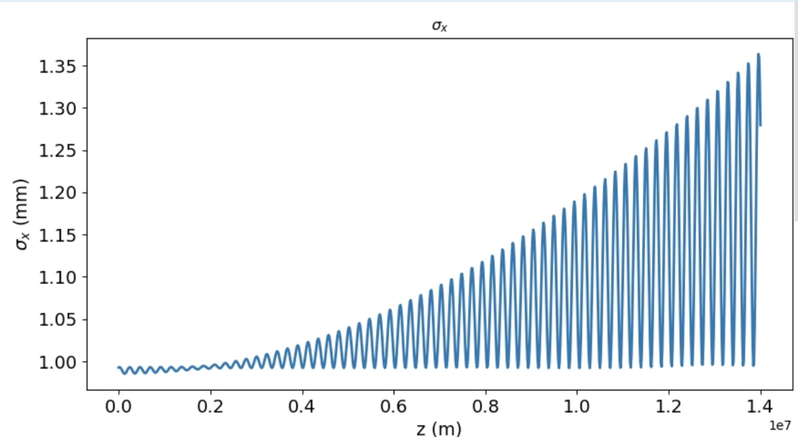



D. Aguglia
F. Boattini
G. Brauchli




University of Rostock
S. Zadeh
U. van Rienen

**RF challenge** (also for FFA):
High efficiency for power consumption
High-charge (10 x HL-LHC), short, single-bunch beam
Maintain small longitudinal emittance
Studies on cavity wakefields and longitudinal dynamics started

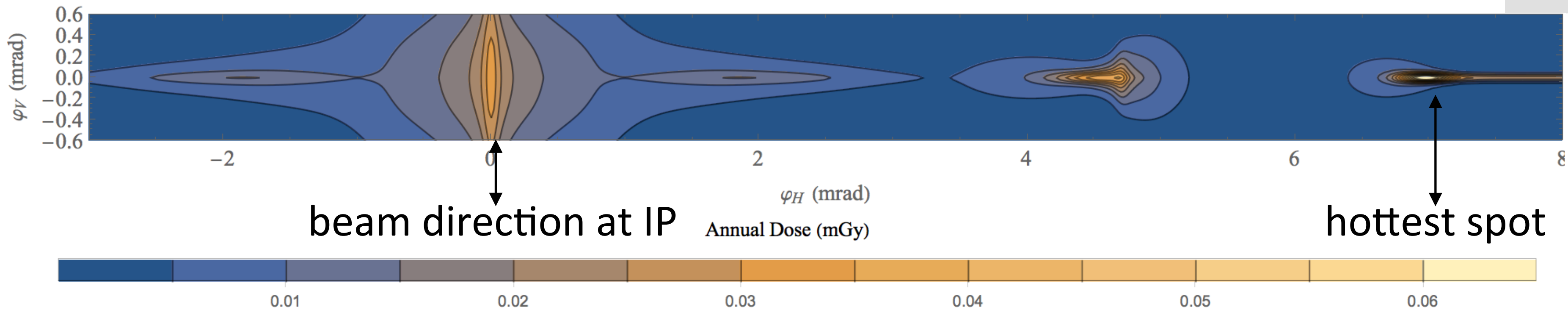



M. Magliorati
E. Metral,
T. Raubenheimer
D.S.

**Collective effects** might be a bottleneck
Revisiting for higher energies
Need to develop tools for collective effects in matter

# Selected Recent Progress, cont.

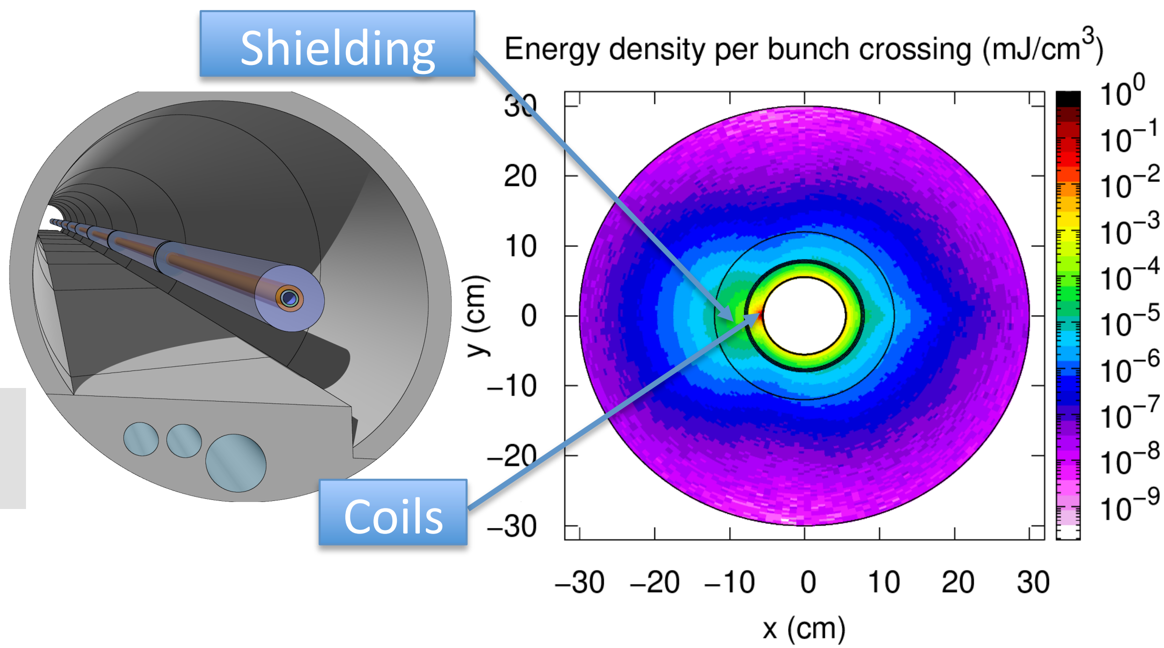
C. Carli




**Collider Ring Lattice Design:**
Based on MAP design, lattice design for high energy is starting
Started production of **radiation maps** and identified hot spots around IP and in arcs
Need to include radiation considerations in lattice design

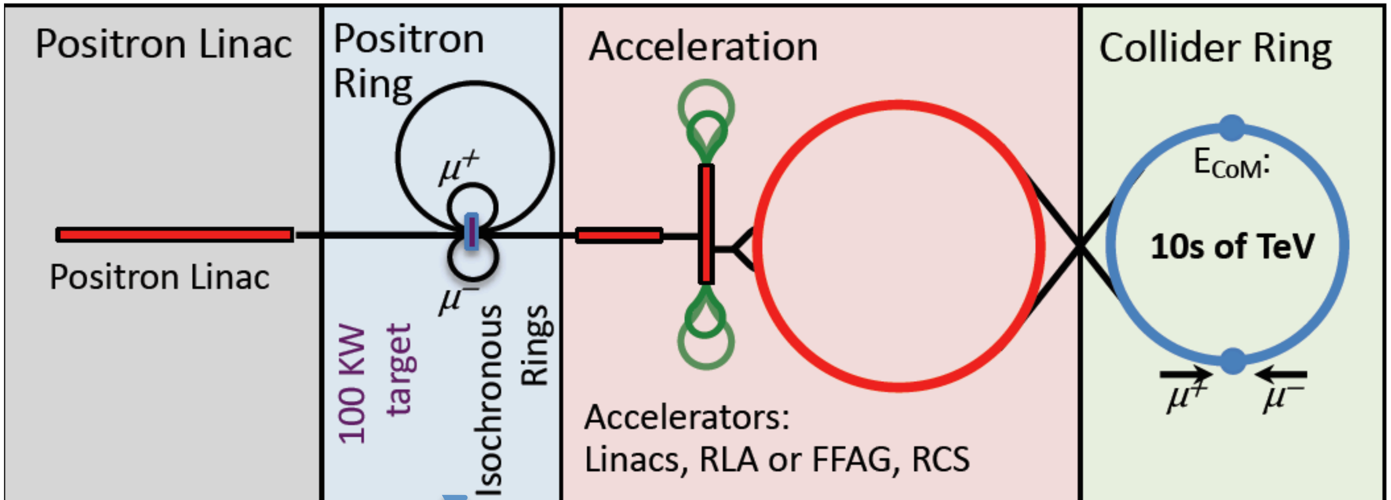
**Loss challenge** in collider ring:
Loss per unit length is constant
fewer, but higher energy particles
Simulations of shielding started

A. Lechner
D. Calzolari



# Alternatives: The LEMMA Scheme

LEMMA scheme (INFN)
P. Raimondi et al.

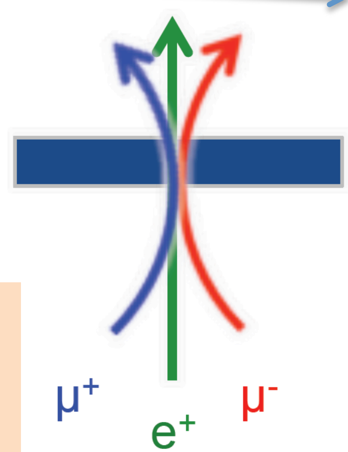


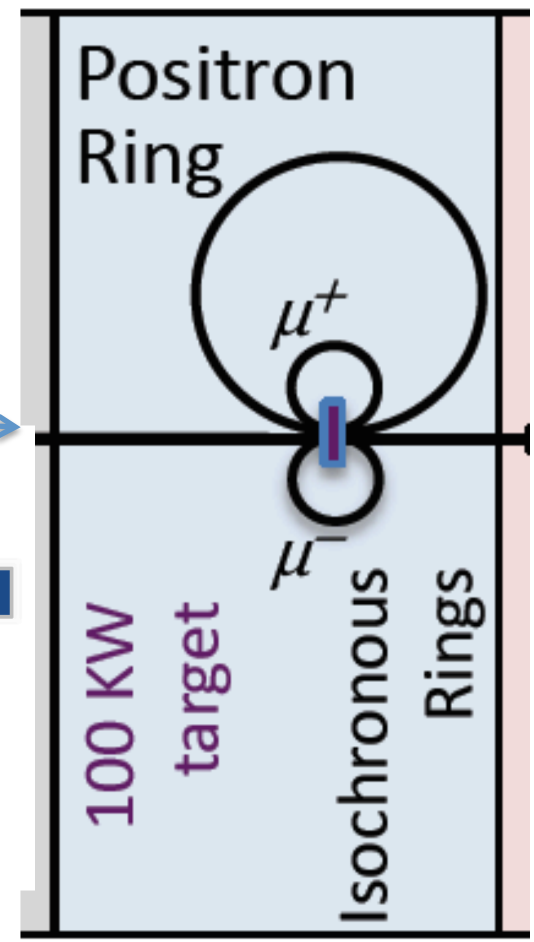

Note: New proposal by C. Curatolo and L. Serafini needs to be looked at

- Uses Bethe-Heitler production with electrons

45 GeV positrons to produce muon pairs
Accumulate muons from several passages

$$e^+e^- \rightarrow \mu^+\mu^-$$




**Excellent idea, but nature is cruel**

Detailed estimates of fundamental limits show that we require a very large positron bunch charge to reach the same luminosity as the proton-based scheme

$\Rightarrow$ **Need same game changing invention**

# Conclusion

- Muon colliders are a unique opportunity for a high-energy, high-luminosity lepton collider
  - high luminosity to beam power ratio
  - cost efficiency to be assessed

- Two different options considered
  - 3 TeV collider that can start construction in less than 20 years
  - 10 TeV collider that uses advanced technologies

- Not as mature as ILC or CLIC
  - have to address **important R&D** items
  - but **no showstopper** identified

- Aim to develop concept to a **maturity level** that allows to make **informed choices by the next ESPPU** and other strategy processes
  - Baseline design
  - R&D and demonstration programme

- An important opportunity that we should not miss
- http://muoncollider.web.cern.ch

Many thanks to the Muon Beam Panel, the collaboration, the MAP study, the MICE collaboration, and many others

# Memorandum of Cooperation

INFN already signed

CERN is initially hosting the study

- International collaboration board (ICB) representing all partners
  - elect chair and study leader
  - can invite other partners to discuss but not vote (to include institutes that cannot sign yet)
- Study leader
- Advisory committee reporting to ICB

Addenda to describe actual contribution of partners

# Reserve

# Muon Collider Luminosity Scaling

Fundamental limitation
Assumes no emittance growth after source and no technical limitation
Applies to MAP and LEMMA 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
= small ring
= many collisions

Large energy acceptance
= short bunch
= small betafunction

Dense beam

High beam power

Note: emittances are normalised

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Same for MAP and LEMMA

O(1%) of proton scheme
= 100 MW of positrons lost

$$e^+e^- \to \mu^+\mu^-$$
$$e^+e^- \to e^+e^-\gamma$$

Bremsstrahlung $O(10^5)$ times more likely than pair production
O(150mb), $E_\gamma \geq 0.01\ E_p$
O(60mb), $E_\gamma \geq 0.1\ E_p$

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Each passage in target increases emittance (multiple scattering)
⇒ Need to produce enough muons per passage for high N/ε

Example to reach luminosity is

- 3 mm BE target, 0.86 mm betafunction (optimum)
- $3 \times 10^{15}$ positrons per bunch (22 MJ)
  - 60 kJ lost in target, temperature jump of MK
- at least 100 bunches per pulse (2 GJ)
  - (only 1% is lost)

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International MUON Collider Collaboration

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**Unfortunately, seems too hard from fundamental physics**
**Need a new game-changing invention**

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

Assume 3 mm thick Be target, 0.86 mm beta

$\Rightarrow$ 0.6 nm emittance growth per muon beam passage through target (optimum case)

$\Rightarrow$ Need bunches with 3 x $10^{15}$ positrons (=22 MJ) to obtain required

$\Rightarrow$ Positron beam energy 2 GJ/burst, 5 burst per second

$\Rightarrow$ Energy deposition in target 60 kJ per pulse (minimum ionisation) 4.5 MK temperature rise per bunch (linear approximation)

$\Rightarrow$ Extremely challenging, not sure even a fluid target can do this

LEMMA scheme needs O(0.7 mJ) positrons lost per produced muon pair

$\Rightarrow$ 100 MW loss yield 1.4 x $10^{11}$ $s^{-1}$ muon pairs

- (proton case: 1 x $10^{13}$ $s^{-1}$)

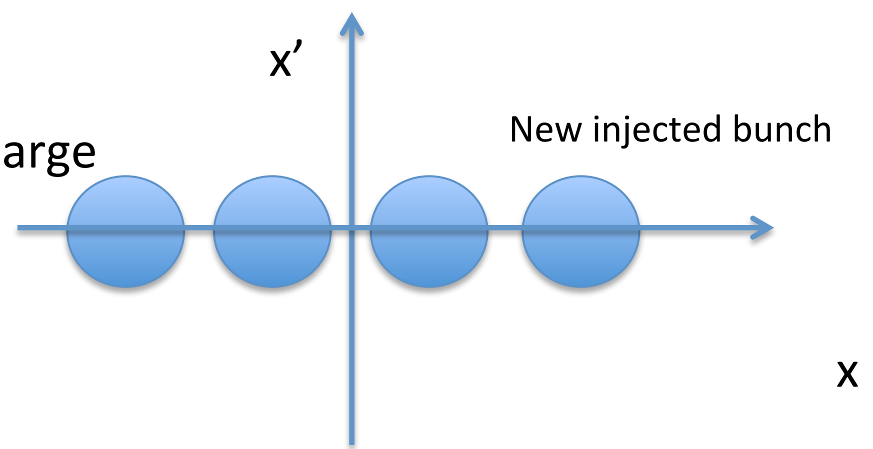
$\Rightarrow$ Need 70 times denser beam for same luminosity

$\Rightarrow$ Lose 1.4 $10^{16}$ positrons per second

# Note: Stacking

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

stacking in longitudinal plane does not increase luminosity
bunch length and beta-function increase with the charge




Stacking in transverse plane can help because

$$\epsilon = \sqrt{\epsilon_x \epsilon_y}$$

stacking $m^2$ bunches leads to

$$N = m^2 N_1 \qquad \epsilon = m \epsilon_1$$

and the luminosity scales as

$$\frac{N}{\epsilon} = m \frac{N_1}{\epsilon_1}$$

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

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta m \frac{N_0}{\epsilon_0 \epsilon_{L,0}} f_{r,0} N_0 \gamma$$

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \sqrt{f_{r,0} \tau \gamma} \frac{N_0}{\epsilon_0 \epsilon_{L,0}} f_{r,0} N_0 \gamma$$

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International MUON Collider Collaboration

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# Some Comments

F. Zimmermann 2018 J. Phys.: Conf. Ser.1067 022017 claims

$$L \approx f_{\rm rev} \dot{N}_\mu \frac{\dot{N}_\mu}{\varepsilon_N} \frac{1}{3^6} \gamma \tau^2 \frac{1}{4\pi\beta^*}$$

$$= \frac{1}{3^6} \left\{ \left( \frac{eF_{\rm dip}}{2\pi m_\mu} \right)^3 \frac{\tau_0^2}{4\pi c^2} \right\} \left[ B^3 C^2 \right] \left[ \dot{N}_\mu \frac{\dot{N}_\mu}{\varepsilon_N} \right] \frac{1}{\beta^*}$$

$$\mathcal{L} \propto \frac{(f_r N)^2}{\epsilon}$$

The paper assumes that muons can be stacked but ignores the associated emittance growth
This is wrong, with these assumption LEMMA would be viable

the LEMMA scheme

New proposal by C. Curatolo and L. Serafini needs to be looked at
Uses Bethe-Heitler production with electrons

| scheme | $p$-$\gamma$ | G.-F. $\mu$ | $e^+$ | G.-F. $e^+$ |
|---|---|---|---|---|
| base | LHC/FCC-hh | | FCC-ee | FCC |
| rate $\dot{N}_\mu$ [GHz] | 1 | 400 | 0.003 | 100 |
| $\mu$/pulse [$10^4$] | 0.01 | 4 | 0.2 | 6,000 |
| p. spacing [ns] | 100 | 100 | 15 | 15 |
| energy [GeV] | 2.5 | 0.1 | 22 | 22 |
| rms en. spread | 3% | 10% | 10% | 10% |
| n. emit. [$\mu$m] | 7 | 2000 | 0.04 | 0.04 |
| $\dot{N}_\mu/\varepsilon_N$ [$10^{15}$ m$^{-1}$s$^{-1}$] | 0.1 | 0.2 | 0.1 | 3,000 |

at 14 TeV:
9 GW beam power

even 30 times more beam particles

# Physics at Muon Collider

International MUON Collider Collaboration

## Muon Collider can be the game changer

[The Muon Smasher's Guide]

### Muon collider physics potential

D. Buttazzo

A high-energy muon collider is simply a **dream machine**: allows to probe unprecedented energy scales, exploring many different directions at once!

| **Direct searches** | **High-rate measurements** | **High-energy probes** | **Muon physics** |
|---|---|---|---|
| Pair production, Resonances, VBF, Dark Matter, ... | Single Higgs, self coupling, rare and exotic Higgs decays, top quarks, ... | Di-boson, di-fermion, tri-boson, EFT, compositeness, ... | Lepton Flavor Universality, $b \to s\mu\mu$, muon g-2, ... |

- Theory input needed: define energy, luminosity and detector performance goals — physics potential of a multi-TeV muon collider
- Great interest in the theory community:

1807.04743 2005.10289 2008.12204 2012.11555 2102.11292 2104.05720
1901.06150 2006.16277 2009.11287 2101.10334 2103.01617 etc ...
2003.13628 2007.14300 2012.02769 2102.08386 2103.14043


3

R. Sundrum

## CONCLUSIONS

There are BROAD EXCITING PHYSICS THEMES to pursue at future colliders:
Dark Matter, Baryogenesis, SUSY, Compositeness, flavor origins, parallel gauge sectors, long-lived particles, precision Higgs structure

Need a collider at highest energies, clean enough & with sensitive enough detectors, to pursue both high mass &/or weakly coupled BSM at high precision & to excite & challenge next generation of experimentalists.

If new physics (dimly) seen in DM, flavor, EDM, precision, gravitational wave, cosmological expts., we need collider with reach/precision to complement, corroborate, clarify

## A Muon Collider is great!

P. Maede

| $\kappa$-0 fit | HL-LHC | LHeC | HE-LHC S2 | HE-LHC S2′ | ILC 250 | ILC 500 | ILC 1000 | CLIC 380 | CLIC 1500 | CLIC 3000 | CEPC | FCC-ee 240 | FCC-ee 365 | FCC-ee/eh/hh | $\mu^+\mu^-$ **10000** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\kappa_W$ [%] | 1.7 | 0.75 | 1.4 | 0.98 | 1.8 | 0.29 | 0.24 | 0.86 | 0.16 | 0.11 | 1.3 | 1.3 | 0.43 | 0.14 | 0.06 |
| $\kappa_Z$ [%] | 1.5 | 1.2 | 1.3 | 0.9 | 0.29 | 0.23 | 0.22 | 0.5 | 0.26 | 0.23 | 0.14 | 0.20 | 0.17 | 0.12 | 0.23 |
| $\kappa_g$ [%] | 2.3 | 3.6 | 1.9 | 1.2 | 2.3 | 0.97 | 0.66 | 2.5 | 1.3 | 0.9 | 1.5 | 1.7 | 1.0 | 0.49 | 0.15 |
| $\kappa_\gamma$ [%] | 1.9 | 7.6 | 1.6 | 1.2 | 6.7 | 3.4 | 1.9 | 98⋆ | 5.0 | 2.2 | 3.7 | 4.7 | 3.9 | 0.29 | 0.64 |
| $\kappa_{Z\gamma}$ [%] | 10. | – | 5.7 | 3.8 | 99⋆ | 86⋆ | 85⋆ | 120⋆ | 15 | 6.9 | 8.2 | 81⋆ | 75⋆ | 0.69 | 1.0 |
| $\kappa_c$ [%] | – | 4.1 | – | – | 2.5 | 1.3 | 0.9 | 4.3 | 1.8 | 1.4 | 2.2 | 1.8 | 1.3 | 0.95 | 0.89 |
| $\kappa_t$ [%] | 3.3 | – | 2.8 | 1.7 | – | 6.9 | 1.6 | – | – | 2.7 | – | – | – | 1.0 | 6.0 |
| $\kappa_b$ [%] | 3.6 | 2.1 | 3.2 | 2.3 | 1.8 | 0.58 | 0.48 | 1.9 | 0.46 | 0.37 | 1.2 | 1.3 | 0.67 | 0.43 | 0.16 |
| $\kappa_\mu$ [%] | 4.6 | – | 2.5 | 1.7 | 15 | 9.4 | 6.2 | 320⋆ | 13 | 5.8 | 8.9 | 10 | 8.9 | 0.41 | 2.0 |
| $\kappa_\tau$ [%] | 1.9 | 3.3 | 1.5 | 1.1 | 1.9 | 0.70 | 0.57 | 3.0 | 1.3 | 0.88 | 1.3 | 1.4 | 0.73 | 0.44 | 0.31 |

7

P. Maede

## Di-Higgs too!

### Double Higgs production

- Reach on Higgs trilinear coupling: $hh \to 4b$

B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289
Han et al. 2008.12204

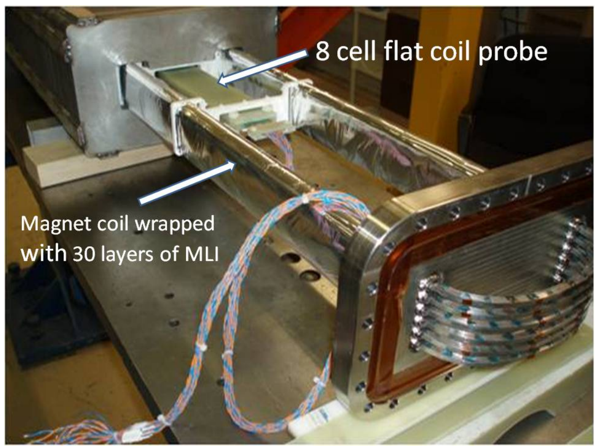
| E [TeV] | $\mathscr{L}$ [ab$^{-1}$] | $N_{rec}$ | $\delta\sigma \sim N_{rec}^{-1/2}$ | $\delta\kappa_3$ |
|---|---|---|---|---|
| 3 | 5 | 170 | ~ 7.5% | ~ 10% |
| 10 | 10 | 620 | ~ 4% | ~ 5% |
| 14 | 20 | 1340 | ~ 2.7% | ~ 3.5% |
| 30 | 90 | 6'300 | ~ 1.2% | ~ 1.5% |

# Challenges and Status

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

now 290 T/s

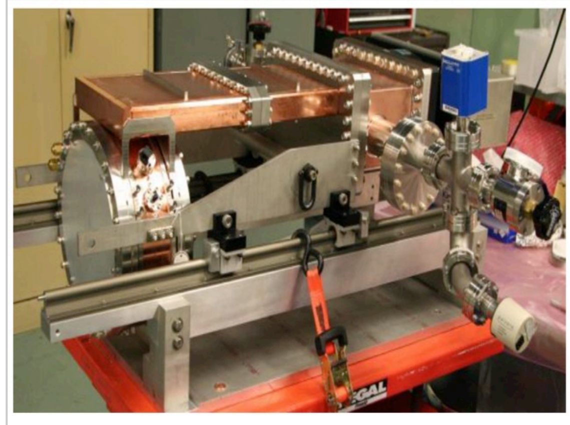
Test of **fast-ramping normal-conducting magnet** design

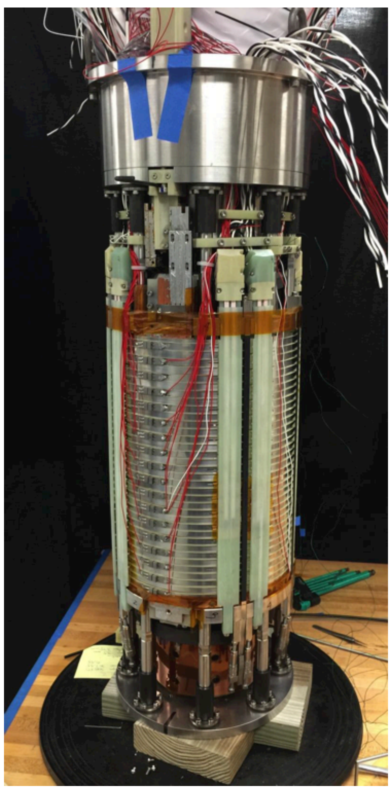



**MuCool**: >50 MV/m in 5 T field

Two solutions

- Copper cavities filled with hydrogen
- Be end caps





**NHFML**
32 T solenoid
with HTS

Planned efforts to push even further

**MICE (UK)** Muon cooling principle