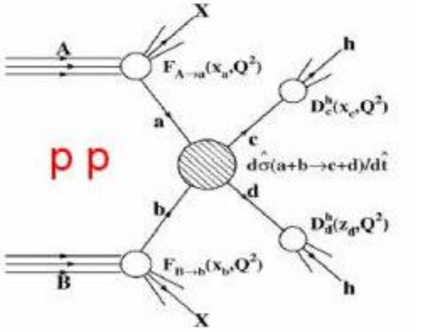
International
MUON Collider
Collaboration

The Muon Collider

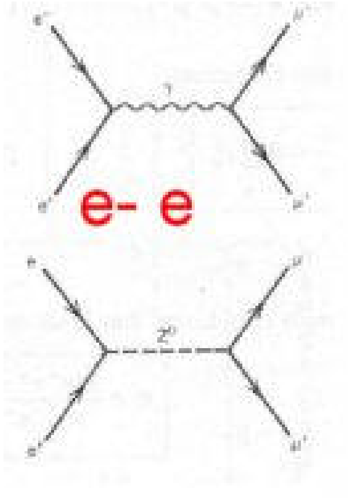
Daniel Schulte

Collider Choices

- Hadron collisions: compound particles
  - Protons or ions
  - Mix of quarks, anti-quarks and gluons: variety of processes
  - Parton energy spread
  - QCD processes large background sources
  - Hadron collisions ⇒ can typically achieve higher collision energies



- Lepton collisions: elementary particles
  - Electrons, positrons and probably muons
  - Collision process known
  - Well defined energy
  - Less background
  - Lepton collisions ⇒ precision measurements



- Photons also possible

Lepton Physics at High Energy

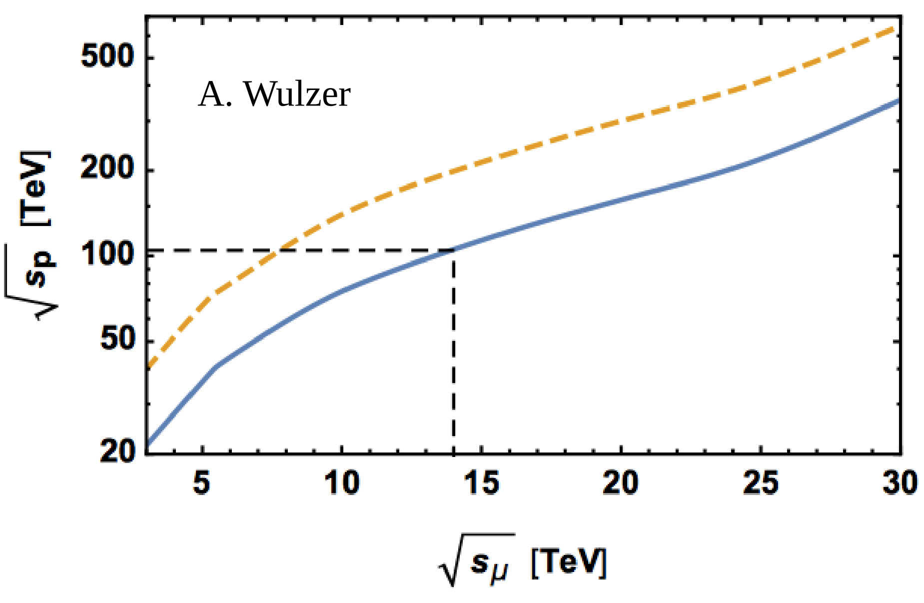
High energy lepton colliders are precision and discovery machines

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

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)
4×10^{35} $cm^{-2}s^{-1}$ at 14 TeV

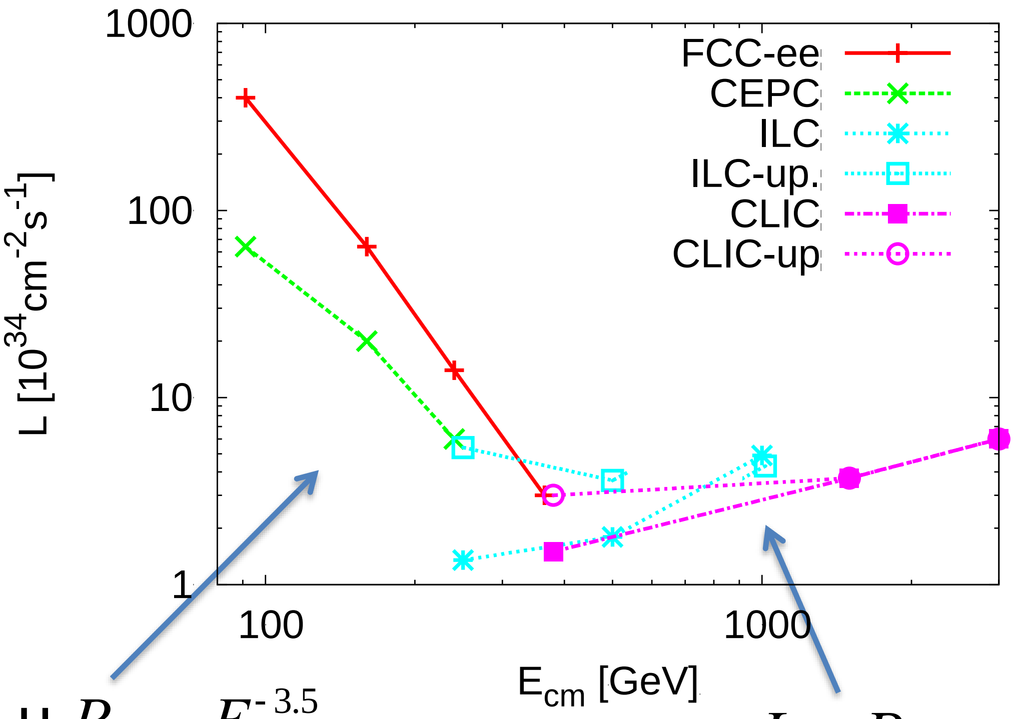
$$L \gtrsim \frac{5\,\text{years}}{\text{time}}\left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}}\right)^2 2 \cdot 10^{35}\text{cm}^{-2}\text{s}^{-1}$$

Comparisons of Projects with CDR

Project	Type	Energy [TeV]	Int. Lumi. $[a^{-1}]$	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Proposed Lepton Colliders (ESU)

Luminosity per facility



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

$L \mu P_{RF}$

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

Maximum proposed energy CLIC 3 TeV

- Cost estimate total of 18 GCHF
  - In three stages
  - Largely main linac, i.e. energy
- Power 590 MW
  - Part in luminosity, a part in energy
- Similar to FCC-hh (24 GCHF, 580 MW)

Technically possible to go higher in energy

But is it affordable?

Cost roughly is linear with energy

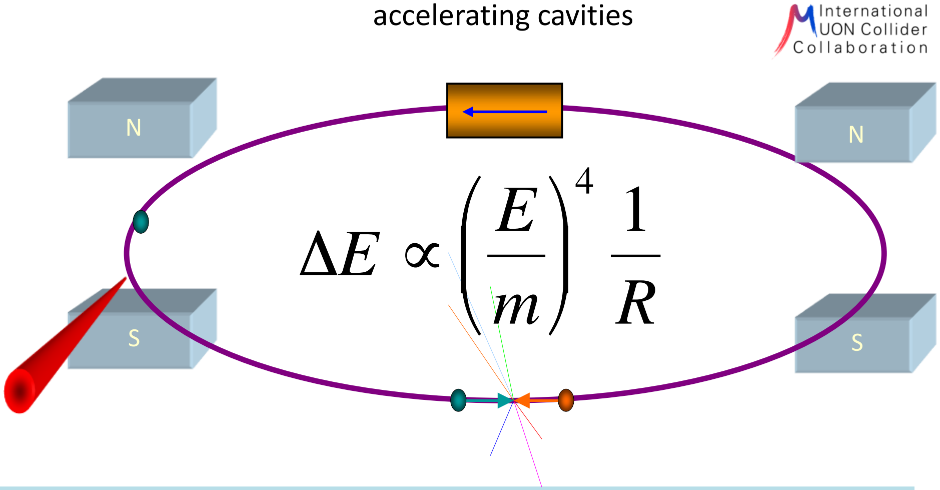
Power consumption roughly goes with the square of energy

Energy Limit

Electron-positron rings are **multi-pass** colliders limited by synchrotron radiation

Strong dependence on particle mass

Hence **proton rings** are energy frontier

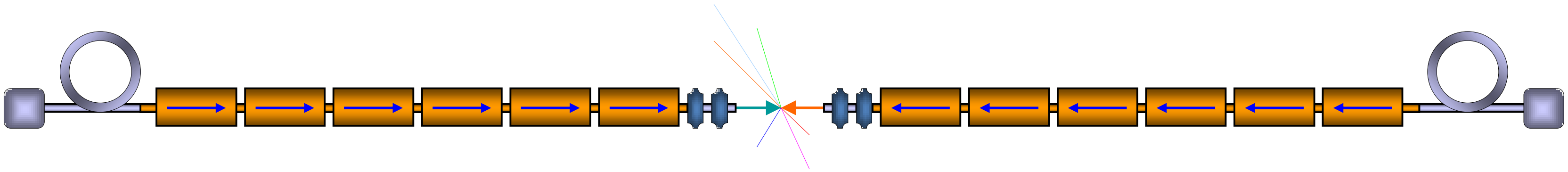


$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Electron-positron linear colliders avoid synchrotron radiation, but **single pass**

Energy challenge
Need full voltage in main linac which is costly

Luminosity challenge
Need very small beam size at collision is required, leads to strong beam-beam effects, requires extremely tight tolerances



Comparing Luminosity in MAP vs. CLIC

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

- No obvious way to improve

Luminosity per beam power increases with energy in muon collider

- **power efficient**

Site is **compact**

- 10 TeV comparable to 3 TeV CLIC

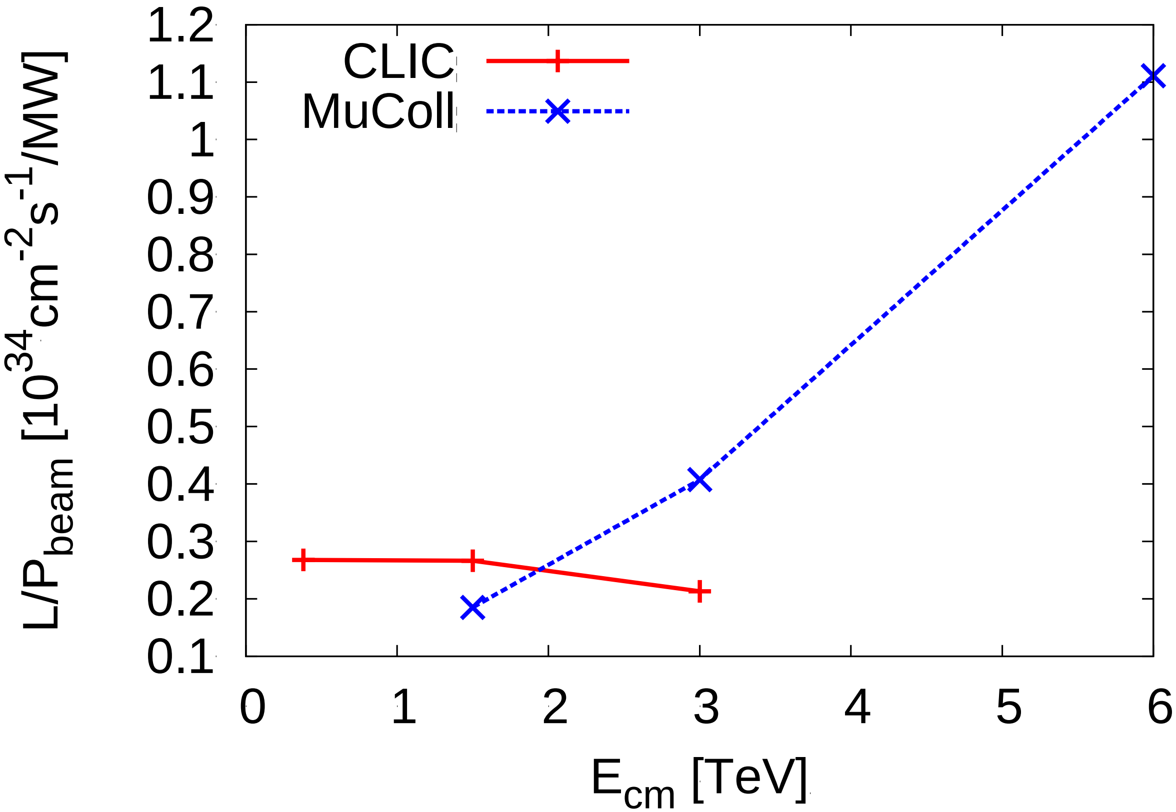
Staging is natural

- acceleration by a factor of a few is done in rings

Appears to promise **cost effectiveness**

- but need detailed study

Other **synergies** exist (neutrino/higgs



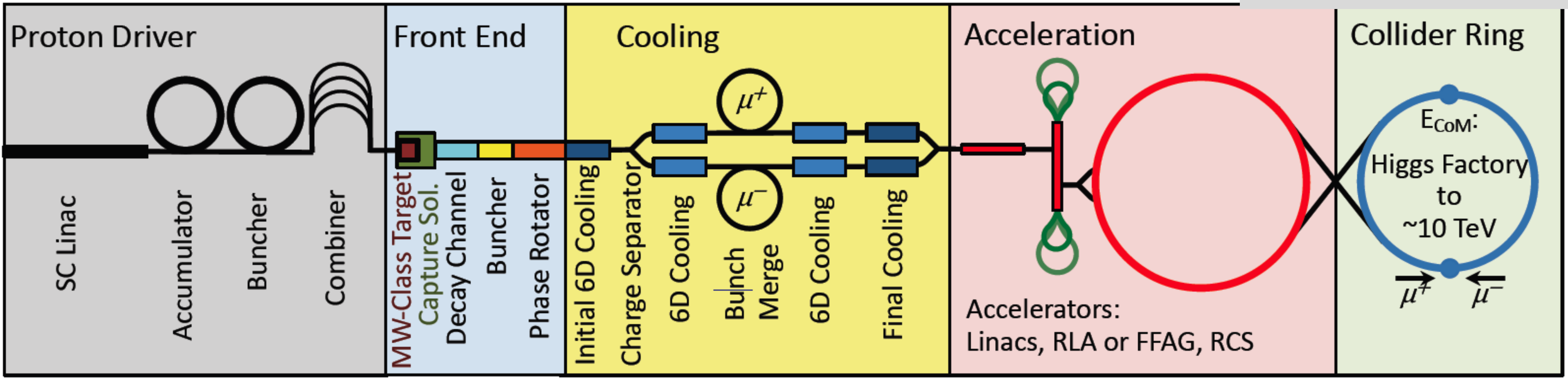
Muon collider promises unique opportunity for a **high-energy, high-luminosity lepton collider**

Main challenge **muons are not stable** (2.2 μs at rest)

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, some effort on alternative mainly at INFN

MAP collaboration



Short, intense proton bunches to produce hadronic showers

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

Collision

Protons produce pions
Pions decay to muons

Acceleration to collision energy

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

Main challenge: **muons are not stable** (2.2 μs at rest)

Luminosity Goals

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 no staging
Would only do 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	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	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
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	μm	25	25	25
$\sigma_{x,y}$	μm	3.0	0.9	0.63

Physics Potential

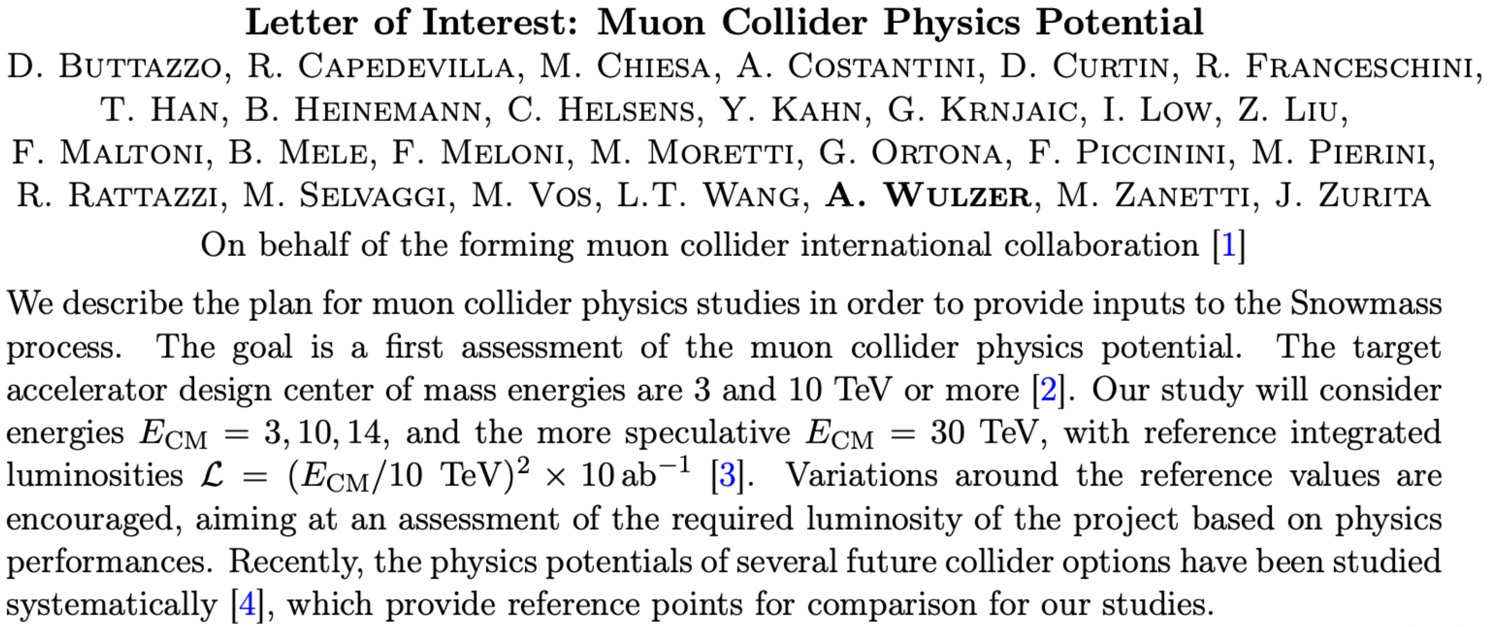
A. Wulzer et al.

The muon collider physics potential emerges from **a variety** of measurements and searches that offer **opportunities** for new physics **discoveries** that are **comparable** or **superior** to “standard” future colliders.

Our studies must be illustrative of the MC potential for new physics exploration in **multiple directions**.

Our plans for Snowmass21:

https://indico.cern.ch/event/944012/contributions/3989516/attachments/2091456/3518021/Physics_SnowMass_LoI.pdf



Letter of Interest: Muon Collider Physics Potential

D. Buttazzo, R. Capedevilla, M. Chiesa, A. Costantini, D. Curtin, R. Franceschini, T. Han, B. Heinemann, C. Helsens, Y. Kahn, G. Krnjaic, I. Low, Z. Liu, F. Maltoni, B. Mele, F. Meloni, M. Moretti, G. Ortona, F. Piccinini, M. Pierini, R. Rattazzi, M. Selvaggi, M. Vos, L.T. Wang, **A. Wulzer**, M. Zanetti, J. Zurita

On behalf of the forming muon collider international collaboration [1]

We describe the plan for muon collider physics studies in order to provide inputs to the Snowmass process. The goal is a first assessment of the muon collider physics potential. The target accelerator design center of mass energies are 3 and 10 TeV or more [2]. Our study will consider energies $E_{\mathrm{CM}} = 3, 10, 14$, and the more speculative $E_{\mathrm{CM}} = 30$ TeV, with reference integrated luminosities $\mathcal{L} = (E_{\mathrm{CM}}/10\ \mathrm{TeV})^2 \times 10\,\mathrm{ab}^{-1}$ [3]. Variations around the reference values are encouraged, aiming at an assessment of the required luminosity of the project based on physics performances. Recently, the physics potentials of several future collider options have been studied systematically [4], which provide reference points for comparison for our studies.

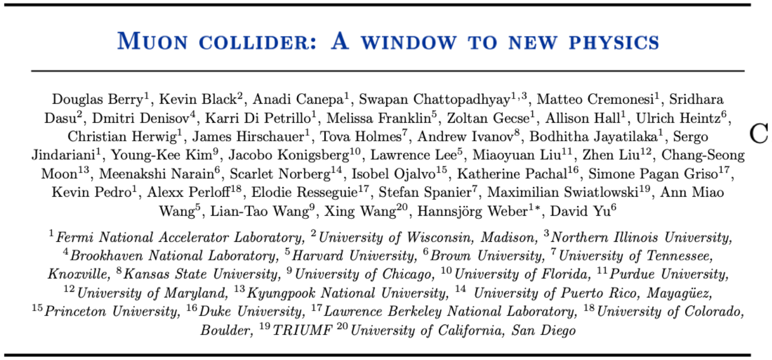
Physics Potential

A. Wulzer et al.

The muon collider physics potential emerges from **a variety** of measurements and searches that offer **opportunities** for new physics **discoveries** that are **comparable** or **superior** to “standard” future colliders.

Our studies must be illustrative of the MC potential for new physics exploration in **multiple directions**.

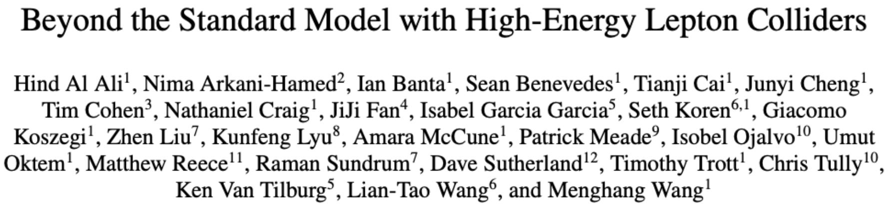
And we are not alone



MUON COLLIDER: A WINDOW TO NEW PHYSICS

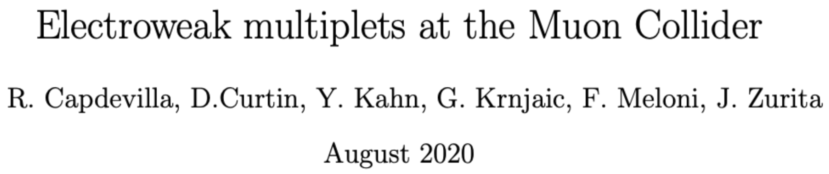
Douglas Berry[1], Kevin Black[2], Anadi Canepa[1], Swapan Chattopadhyay[1,3], Matteo Cremonesi[1], Sridhara Dasu[2], Dmitri Denisov[4], Karri Di Petrillo[1], Melissa Franklin[5], Zoltan Gecse[1], Allison Hall[1], Ulrich Heintz[6], Christian Herwig[1], James Hirschauer[1], Tova Holmes[7], Andrew Ivanov[8], Bodhitha Jayatilaka[1], Sergo Jindariani[1], Young-Kee Kim[9], Jacobo Konigsberg[10], Lawrence Lee[5], Miaoyuan Liu[11], Zhen Liu[12], Chang-Seong Moon[13], Meenakshi Narain[6], Scarlet Norberg[14], Isobel Ojalvo[15], Katherine Pachal[16], Simone Pagan Griso[17], Kevin Pedro[1], Alexx Perloff[18], Elodie Resseguie[17], Stefan Spanier[7], Maximilian Swiatlowski[19], Ann Miao Wang[5], Lian-Tao Wang[9], Xing Wang[20], Hannsjörg Weber[1*], David Yu[6]

[1] *Fermi National Accelerator Laboratory,* [2] *University of Wisconsin, Madison,* [3] *Northern Illinois University,* [4] *Brookhaven National Laboratory,* [5] *Harvard University,* [6] *Brown University,* [7] *University of Tennessee, Knoxville,* [8] *Kansas State University,* [9] *University of Chicago,* [10] *University of Florida,* [11] *Purdue University,* [12] *University of Maryland,* [13] *Kyungpook National University,* [14] *University of Puerto Rico, Mayagüez,* [15] *Princeton University,* [16] *Duke University,* [17] *Lawrence Berkeley National Laboratory,* [18] *University of Colorado, Boulder,* [19] *TRIUMF* [20] *University of California, San Diego*



Beyond the Standard Model with High-Energy Lepton Colliders

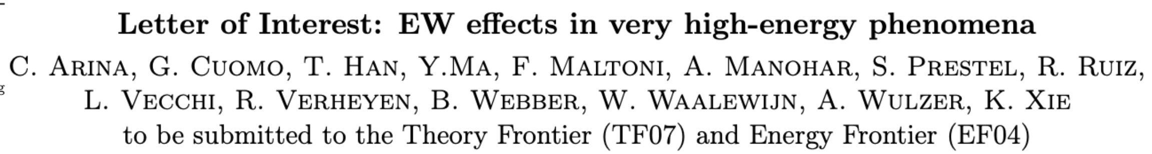
Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Tianji Cai[1], Junyi Cheng[1], Tim Cohen[3], Nathaniel Craig[1], JiJi Fan[4], Isabel Garcia Garcia[5], Seth Koren[6,1], Giacomo Koszegi[1], Zhen Liu[7], Kunfeng Lyu[8], Amara McCune[1], Patrick Meade[9], Isobel Ojalvo[10], Umut Oktem[1], Matthew Reece[11], Raman Sundrum[7], Dave Sutherland[12], Timothy Trott[1], Chris Tully[10], Ken Van Tilburg[5], Lian-Tao Wang[6], and Menghang Wang[1]



Electroweak multiplets at the Muon Collider

R. Capdevilla, D.Curtin, Y. Kahn, G. Krnjaic, F. Meloni, J. Zurita

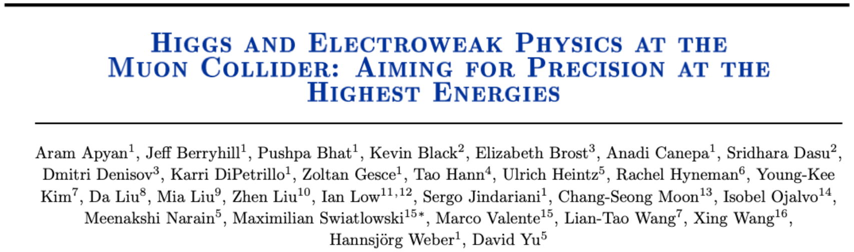
August 2020



Letter of Interest: EW effects in very high-energy phenomena

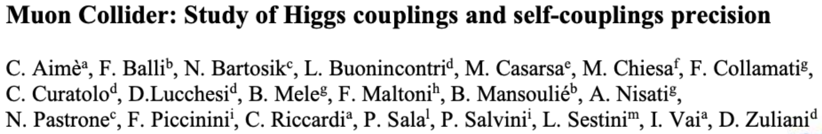
C. ARINA, G. CUOMO, T. HAN, Y.MA, F. MALTONI, A. MANOHAR, S. PRESTEL, R. RUIZ, L. VECCHI, R. VERHEYEN, B. WEBBER, W. WAALEWIJN, A. WULZER, K. XIE

to be submitted to the Theory Frontier (TF07) and Energy Frontier (EF04)



HIGGS AND ELECTROWEAK PHYSICS AT THE MUON COLLIDER: AIMING FOR PRECISION AT THE HIGHEST ENERGIES

Aram Apyan[1], Jeff Berryhill[1], Pushpa Bhat[1], Kevin Black[2], Elizabeth Brost[3], Anadi Canepa[1], Sridhara Dasu[2], Dmitri Denisov[3], Karri DiPetrillo[1], Zoltan Gesce[1], Tao Hann[4], Ulrich Heintz[5], Rachel Hyneman[6], Young-Kee Kim[7], Da Liu[8], Mia Liu[9], Zhen Liu[10], Ian Low[11,12], Sergo Jindariani[1], Chang-Seong Moon[13], Isobel Ojalvo[14], Meenakshi Narain[5], Maximilian Swiatlowski[15*], Marco Valente[15], Lian-Tao Wang[7], Xing Wang[16], Hannsjörg Weber[1], David Yu[5]



Muon Collider: Study of Higgs couplings and self-couplings precision

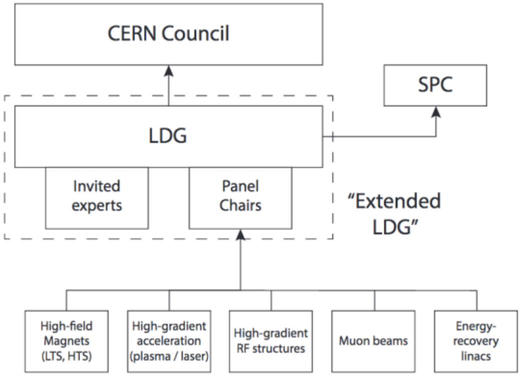
C. Aimè[a], F. Balli[b], N. Bartosik[c], L. Buonincontri[d], M. Casarsa[e], M. Chiesa[f], F. Collamati[g], C. Curatolo[d], D.Lucchesi[d], B. Mele[g], F. Maltoni[h], B. Mansoulié[b], A. Nisati[g], N. Pastrone[c], F. Piccinini[i], C. Riccardi[a], P. Sala[l], P. Salvini[i], L. Sestini[m], I. Vai[a], D. Zuliani[d]

Muon Collider Collaboration and Panel

Following the European Strategy, Laboratory Directors Group (LDG) initiated an **International Muon Collider Collaboration**
A **Memorandum of Cooperation** can be signed to join

Council charged LDG to deliver a **European Accelerator R&D Roadmap**

The extended LDG will deliver to **council** a report with a **prioritised workplan**



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

Muon 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), Magnet Panel link, Tor Raubenheimer (SLAC), Chris Rogers (STFC-RAL), Mike Seidel (EPFL and PSI),Diktys Stratakis (FNAL), Akira Yamamoto (KEK and CERN)
Contributors: Alexej Grudiev (CERN), RF panel link, Roberto Losito (CERN), Test Facility link, Donatella Lucchesi (INFN) MDI link

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 15-20 years**
  - **10+ TeV**, with more advanced technology, **the reason to do muon colliders**
- Explore synergy with other options (neutrino facility/higgs factory at resonance)
- Define **R&D path**

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If no higgs factory not in Europe, might be candidate for next large project after LHC, i.e. operation mid 2040s would need massive ramp-up after next ESPPU

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  - **10+ TeV**, with more advanced technology, **the reason to do muon colliders**
- Explore synergy with other options (neutrino facility/higgs factory at resonance)
- Define **R&D path**

If interest after other higgs factory or if no other higgs factory

Community Meeting Convener

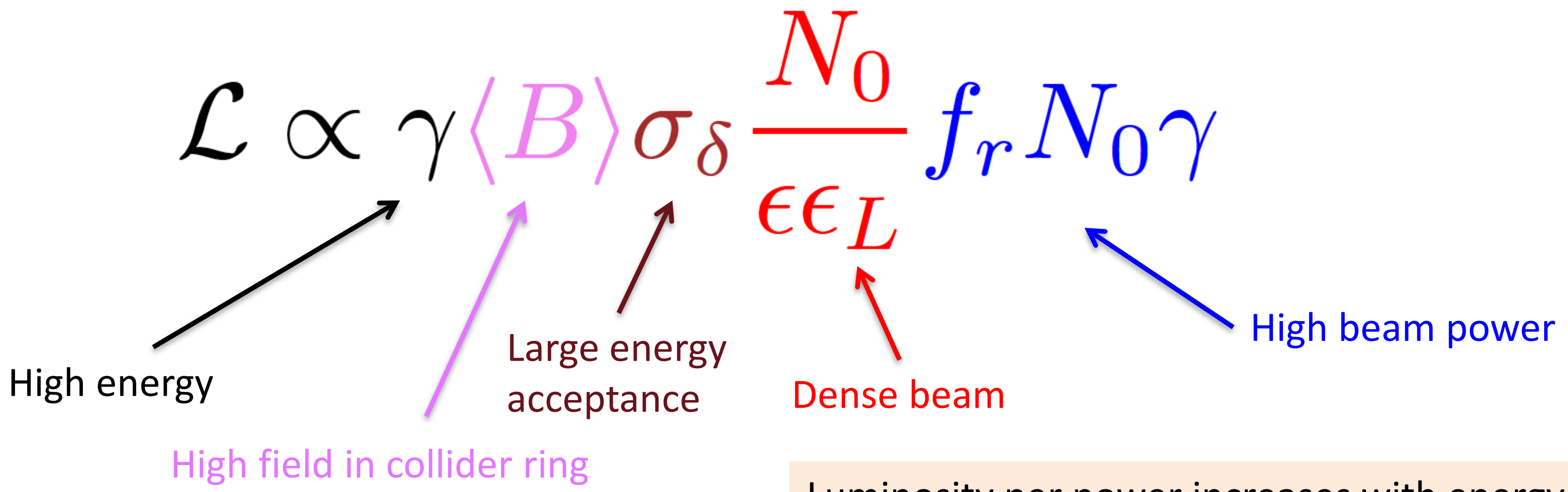
Conveners list (to be updated)

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).

Muon Collider Luminosity Drivers

Fundamental limitation

Requires emittance preservation and advanced lattice design



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

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

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

Luminosity per power increases with energy

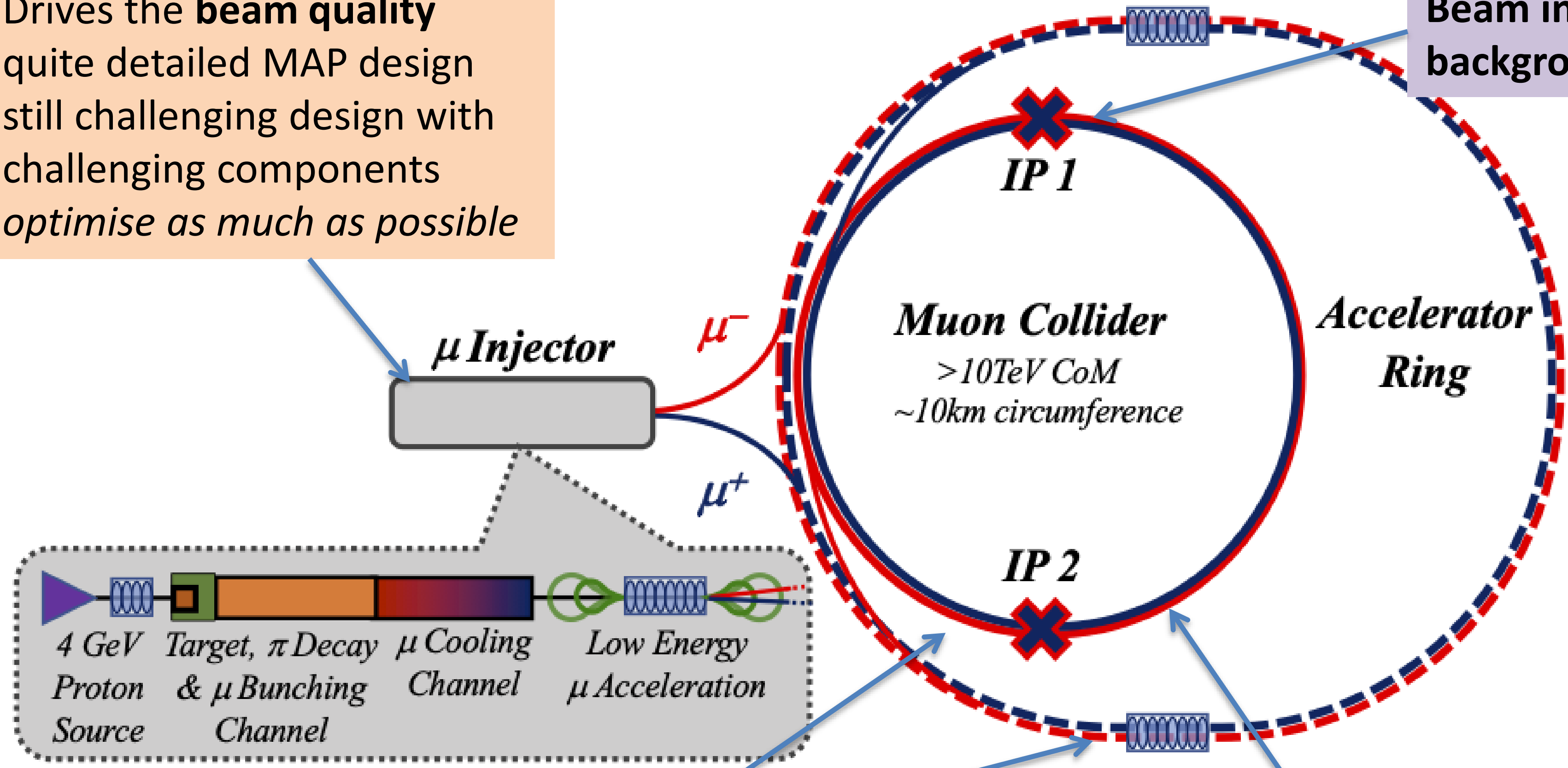
Provided all technical limits can be solved

Constant current for required luminosity

Better scaling than linear colliders

Key Challenges

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

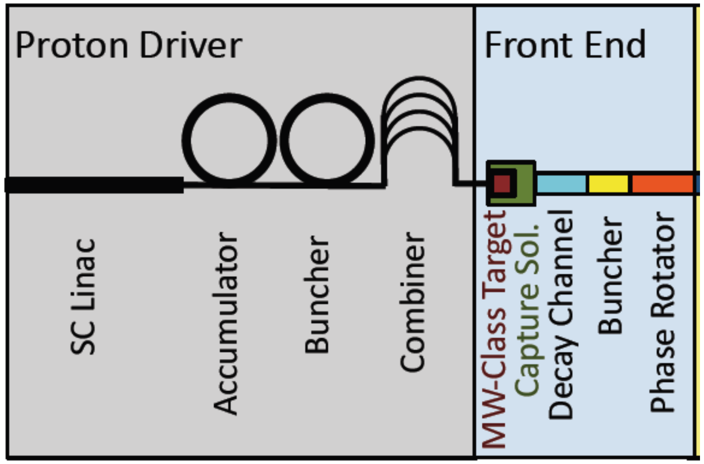


Beam induced background

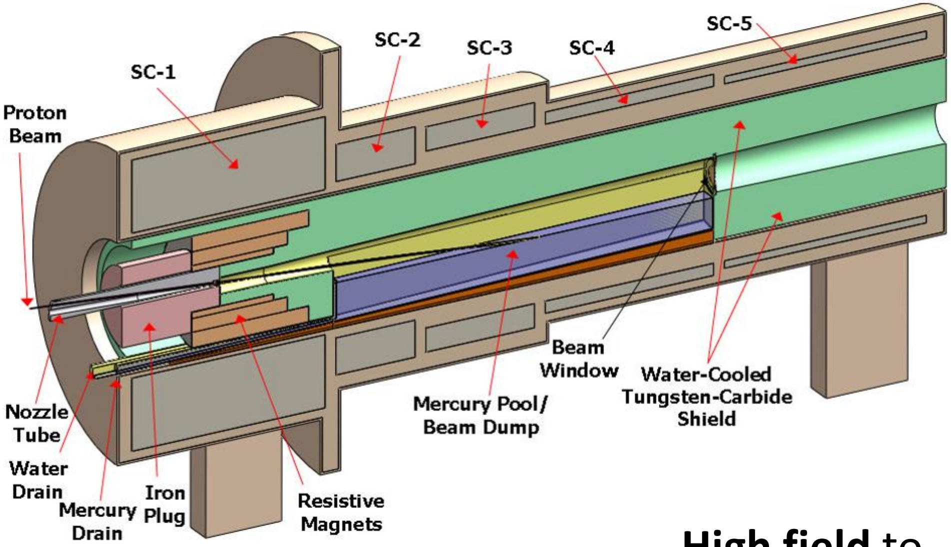
Dense neutrino flux
mitigated by mover system
and site selection

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 complex**



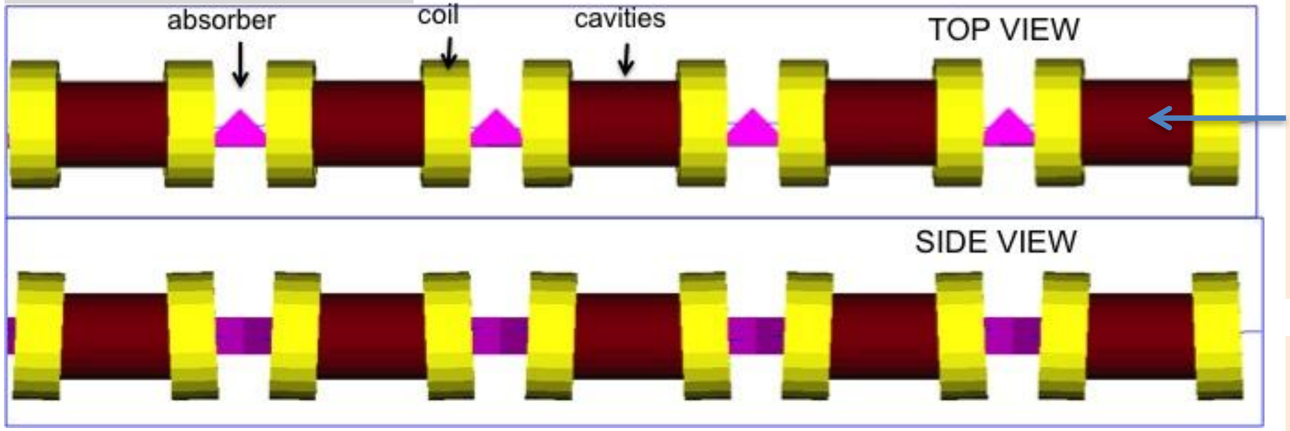
2 MW proton beam requires radiation protection mainly of the solenoid

Large aperture O(1m) to allow shielding

High field to efficiently collect pions/muons: 20 T then tapering

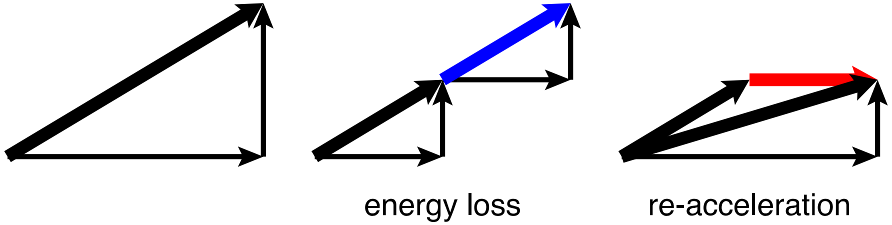
Cooling Concept

MAP collaboration



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

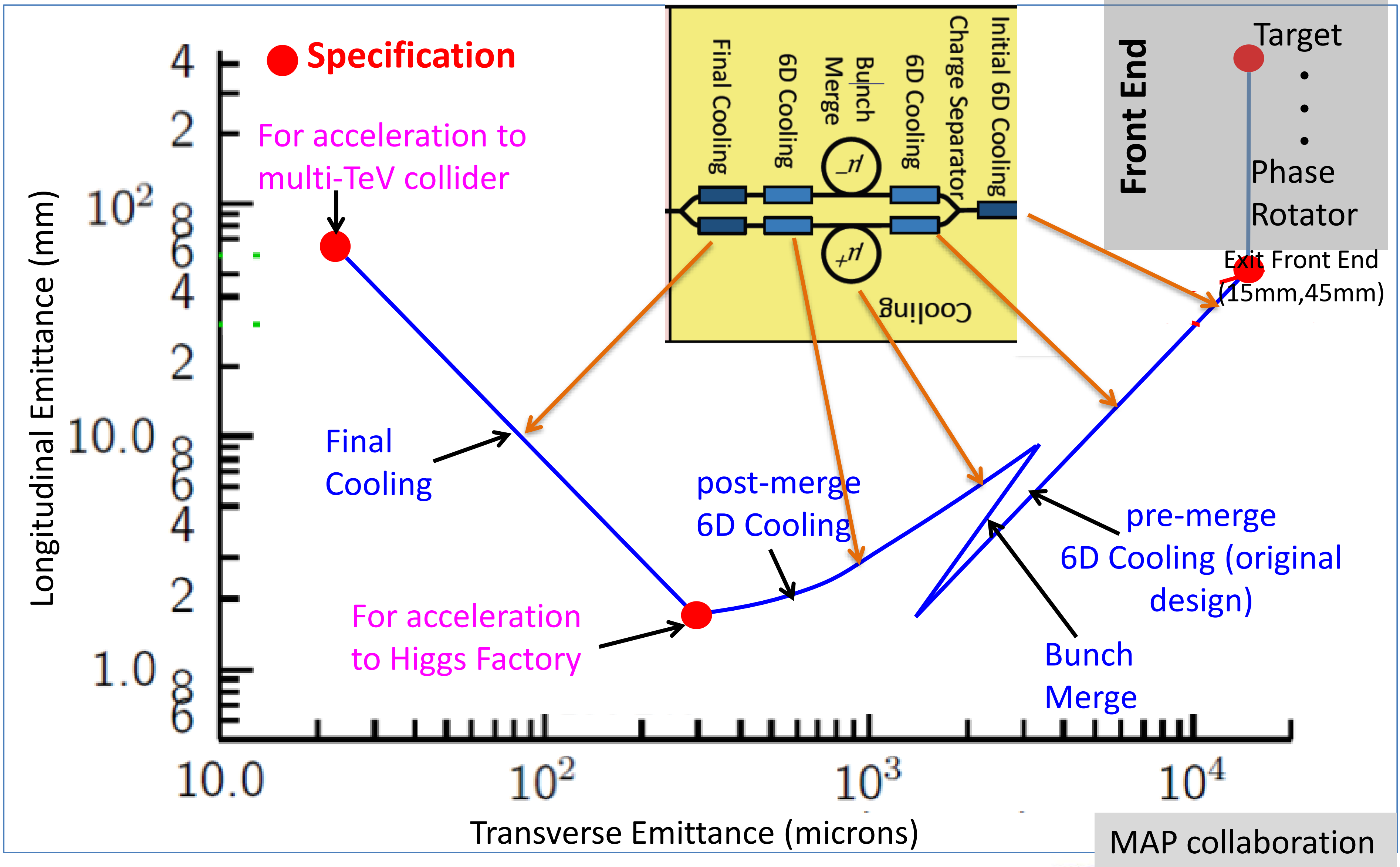
Compact integration to minimise muon loss



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

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

Cooling: The Emittance Path



● **Specification**

For acceleration to multi-TeV collider

Final Cooling

post-merge 6D Cooling

pre-merge 6D Cooling (original design)

Bunch Merge

For acceleration to Higgs Factory

Exit Front End (15mm,45mm)

MAP collaboration

Cooling Challenges and Status

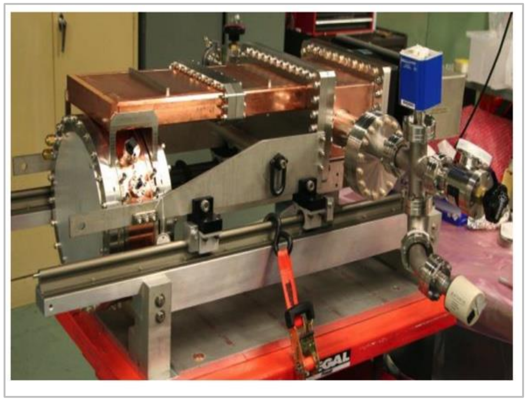
Cavities with very **high accelerating gradient in strong magnetic** field

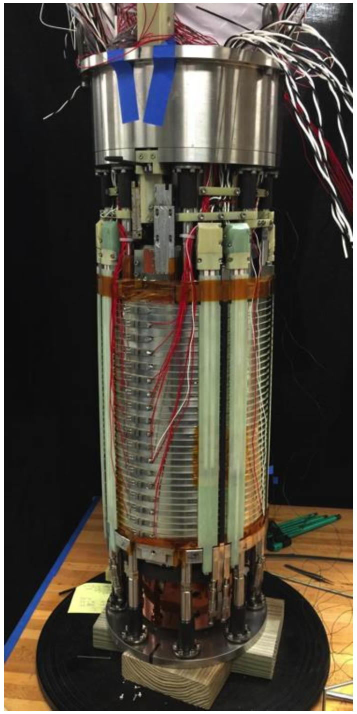
Very strong solenoids (> 30 T) for the final cooling
- simplified: Luminosity is proportional to the field

Integrated system test

MuCool: >50 MV/m in 5 T field

Two solutions
- Copper cavities filled with hydrogen
- Be end caps



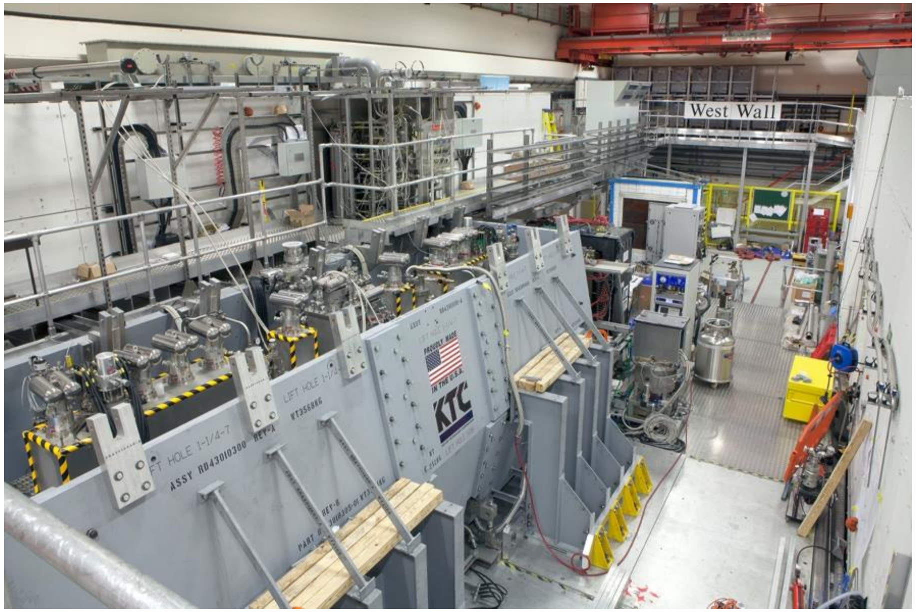


NHFML
32 T solenoid with low-temperature HTS

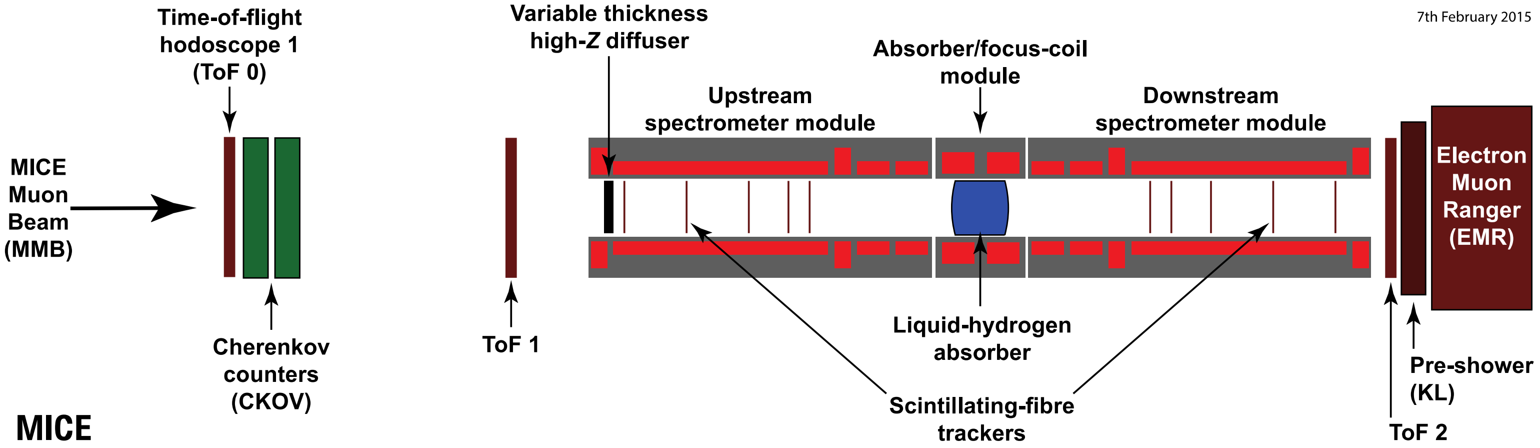
We would like to push even further

Plans for 40+ T exist

MICE (UK)

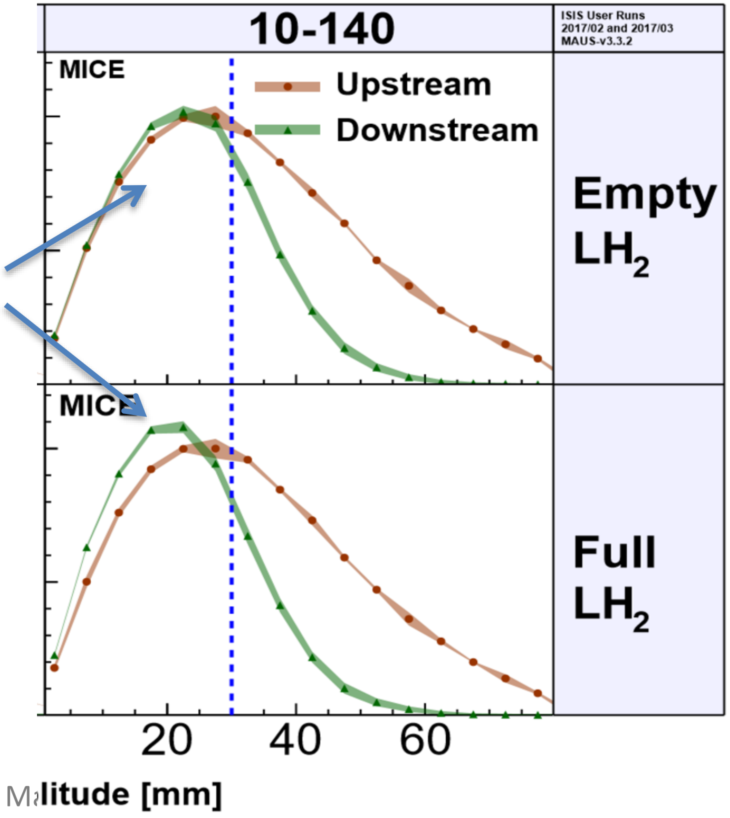


MICE (in the UK)



7th February 2015

More particles at smaller amplitude after absorber is put in place



Nature volume 578, pages 53-59 (2020)

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

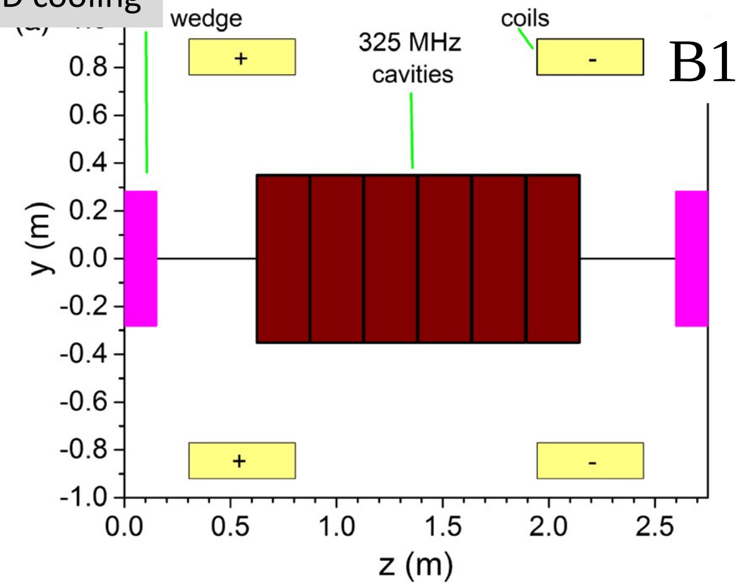
Example Cell Designs

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

Initial 6D cooling

2.2 T

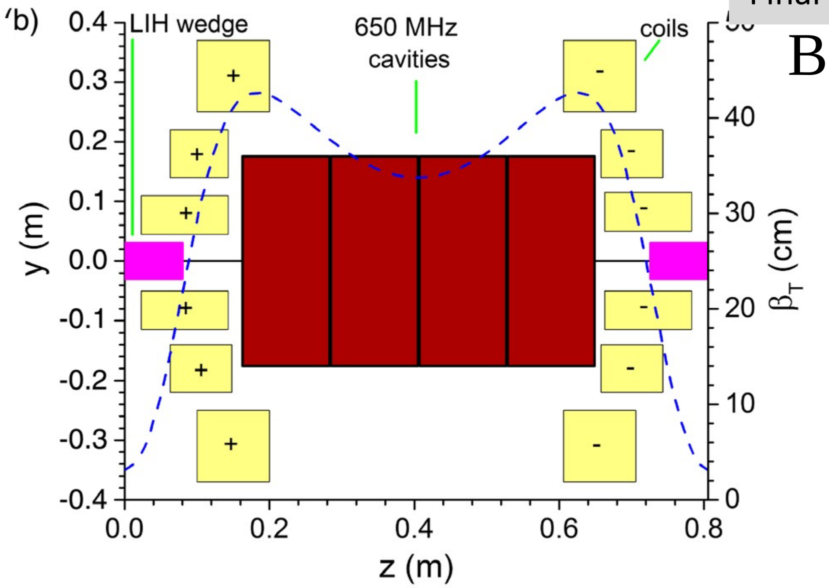
B1



Final 6D cooling

B8

13.6 T



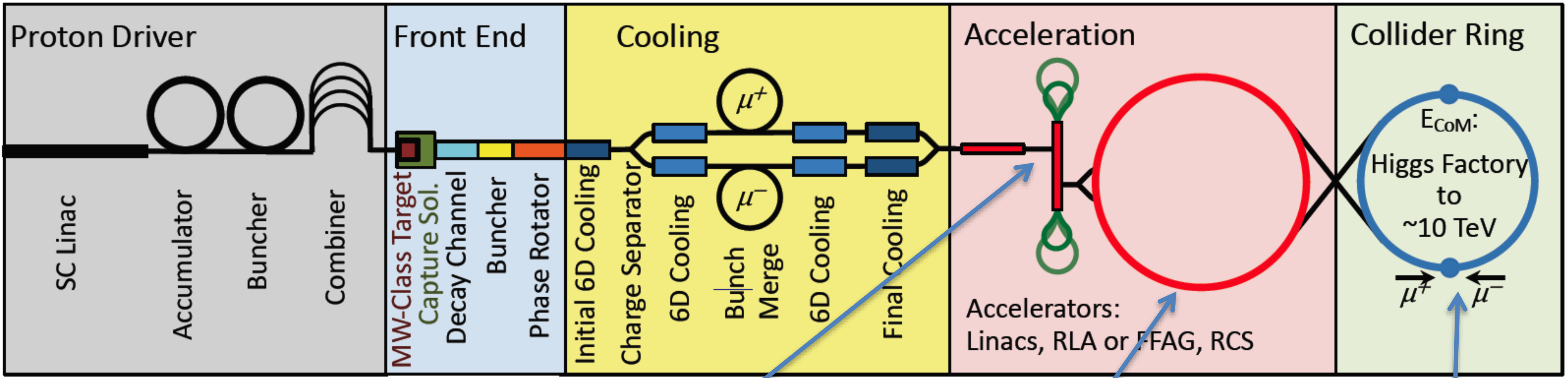
Are already aware of slightly violated space constraints

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

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

Beam operation is important, e.g. beam position on absorber wedge, diagnostics integration, …

High-energy Complex



Initial acceleration

Linacs/recirculating linacs

Detailed designs from MAP

Alex Bogacz

Final acceleration

- FFAG (static superconducting magnets)
- or RCS (rapid cycling synchrotron)

High-energy designs required

Start-to-end simulations

To be started

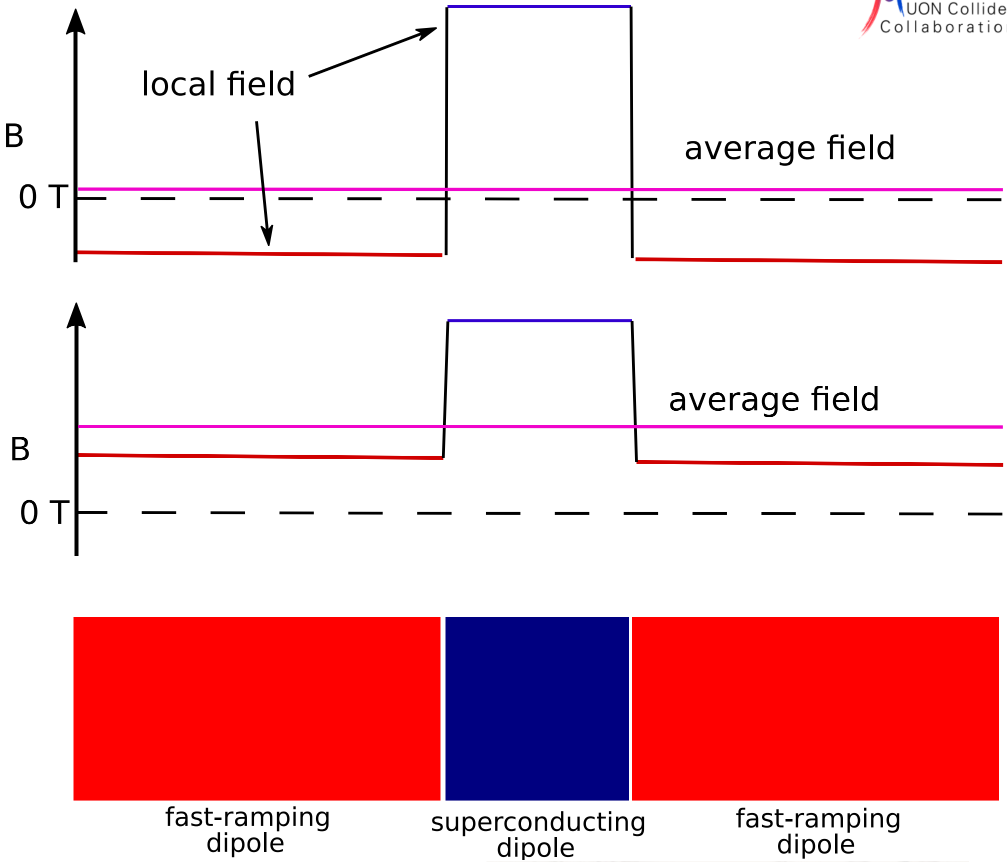
Collider ring

High-energy designs required

High-energy Acceleration

Rapid cycling synchrotron (RCS)

- Ramp magnets to follow beam energy
- Combine static and ramping magnets
- Possible circumference
  - 14-26.7 km at 3 TeV
  - O(30 km) for 10 and 14 TeV
- Power consumption of fast-ramping systems is important

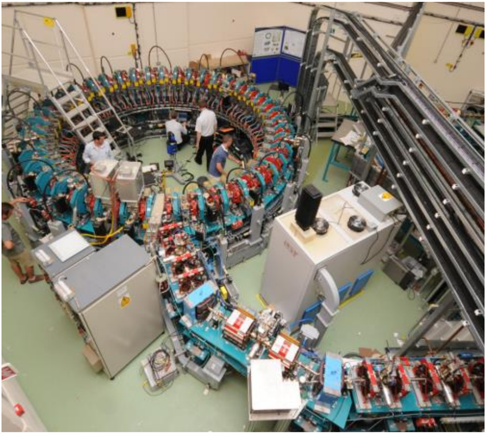


FFAG

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

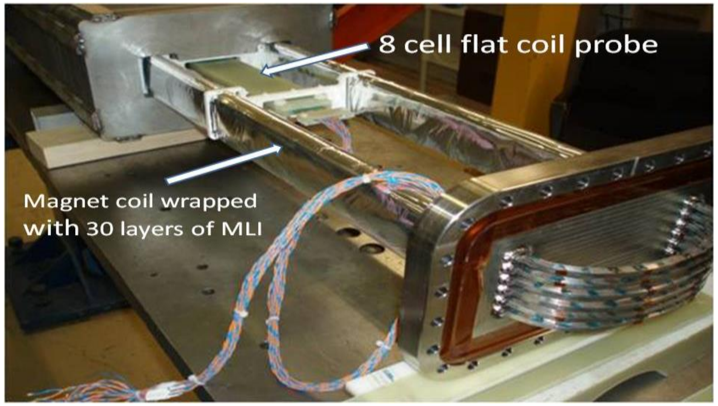
EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)



Key RCS Components

Fast-ramping, normal-conducting magnets
(5 km of 2 T of per TeV beam energy in hybrid design)
Design optimisation needed



⇒ S. Prestemon, D.14.00003

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

Fast, high-field HTS ramping magnets could benefit 10+ TeV design
Need O(100) improvement in speed and O(few) in amplitude

Acceleration 0.3 to 1.5 TeV				
Length	km	13.8	26.7	26.7
8 T dipole	km	2.36	2.36	-
L_{ramp}	km	6.3	15.8	18.2
B_{ramp}	T	-2 / 2	-1 / 1	0.34 / 1.7

FNAL
12 T/s HTS
0.6 T max

Need to push in field and speed

Power converters (recovery of energy in ramping magnets, O(200 MJ) at 14 TeV) *Design started*

RF (also for FFA):
Single-bunch beam, high charge (10 x HL-LHC), maintain small longitudinal emittance, high efficiency
Design started

Final Focus

Pushing beta-functions down at higher energy is key to luminosity

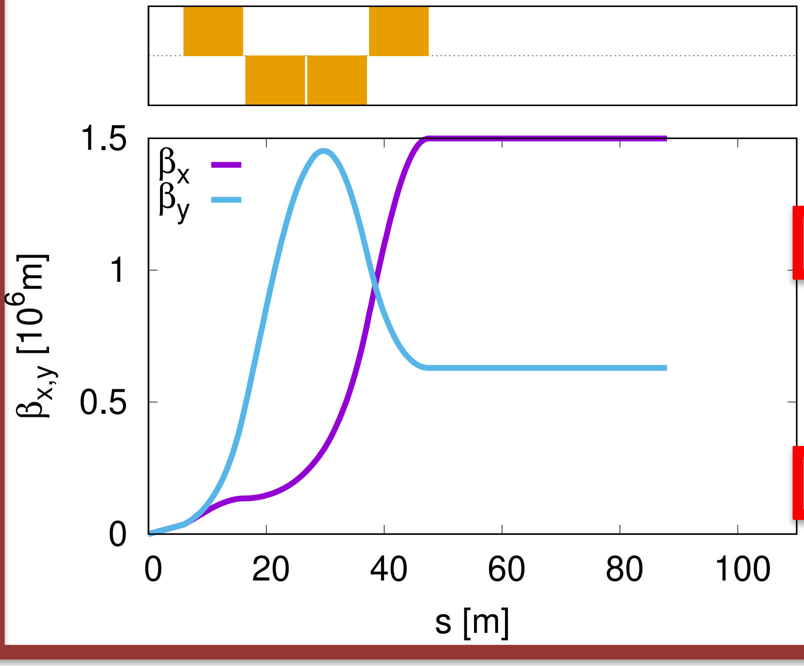
$$b^{*} \mu \frac{1}{E}$$

Focusing of higher energy beam is more difficult

Want to keep triplet short

- rule of thumb: shorter triplet is better for the beam

First considerations on 14 TeV Design (R: Tomas)



$\beta^*_{x,y}$ = 1 mm

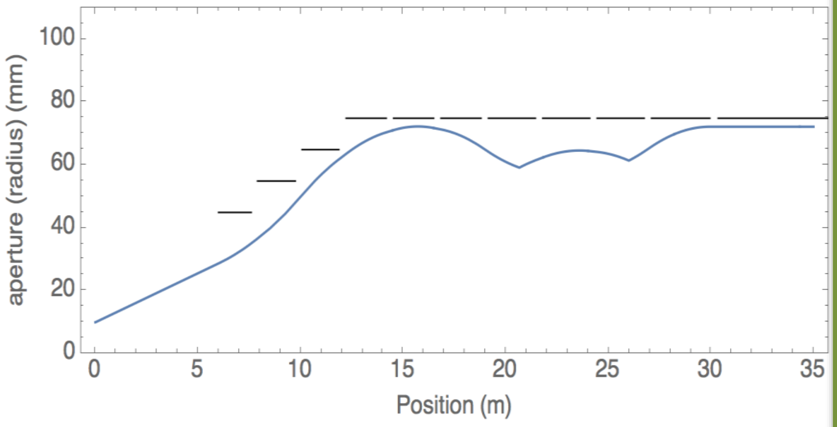
B_{peak} = 18 T

N_σ = 6 σ

E = 7 TeV

Aper. = 0.3 m

3 TeV 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

High gradient important at high energy

- HL-LHC level at 3 TeV
- HTS at 14 TeV

What can we hope for from Nb_3Sn and HTS in 30 years?

Collider Ring Arcs

MAP 3 TeV example:

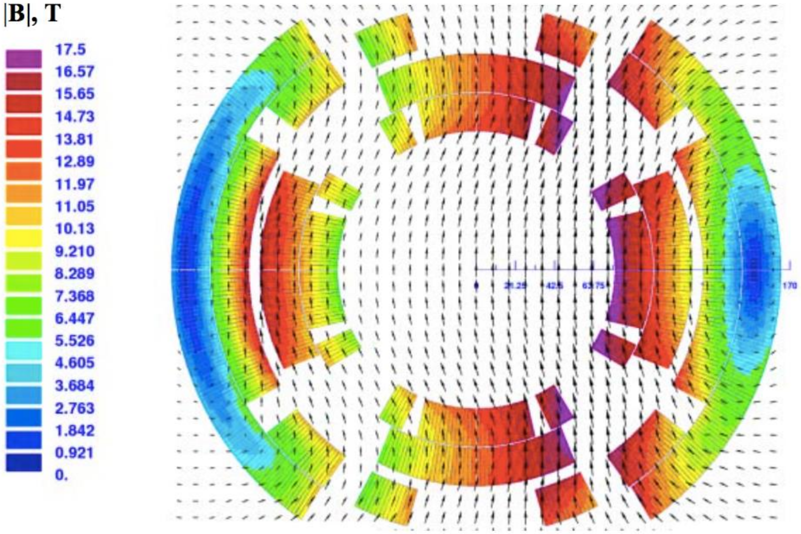
- **10.4 T** 6 m-long dipoles, 150 mm aperture
- and combined function magnets
- 500 W/m losses
- **50/30 mm shielding**
- In cold mass 1.5 mW/g but 10 W/m

10 TeV:

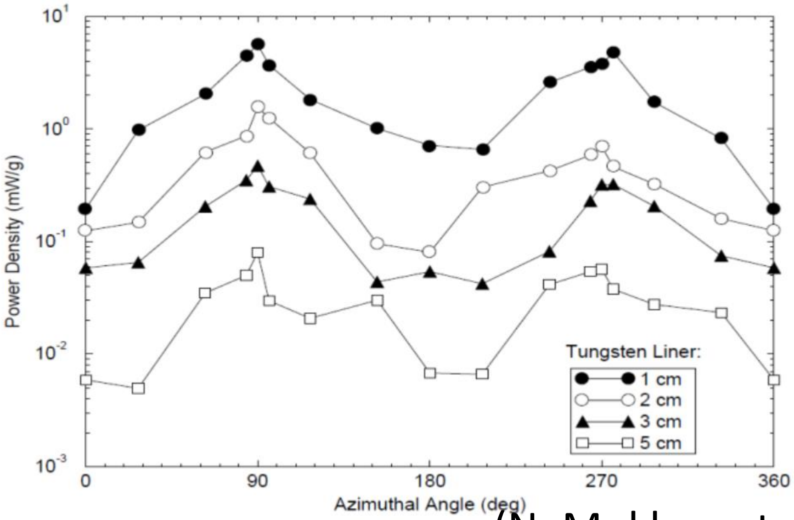
- Expect modest increase of shielding/aperture with beam energy
- Currently no 10 TeV design is developed
- Would go for highest reasonable field (16 T?)

At 3 TeV: Is NbTi worth considering for cost effectiveness?

What can we expect for each technology?



(V.V. Kashikhin et al.)



(N. Mokhov et al.)

Technology Progress

Important progress on high-field magnets for many projects, HL-LHC, FCC, …

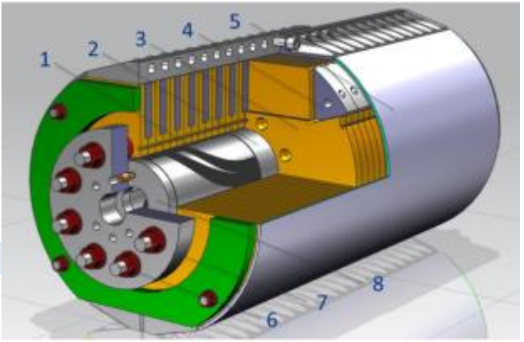
General development of magnets (Nb_3Sn and HTS) in all regions

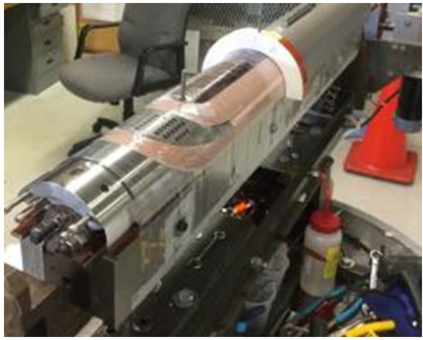
Consider more conventional for first stage, more advanced technology for second stage

U.S. MAGNET DEVELOPMENT PROGRAM

Fermilab
50 Years of Discovery

15 T dipole demonstrator, 60-mm aperture, 4-layer graded coil





Development of conductors (FCC)

Switzerland
CERN

Japan
KEK
FURUKAWA ELECTRIC
JASTEC SUPERCONDUCTOR

Russia
BOCHVAR INSTITUTE OF INORGANIC MATERIALS JSC VNIINM
FUEL COMPANY OF ROSATOM TVEL

Korea
Kiswire

China
Western Superconducting Technologies Co., Ltd.

Austria
TU WIEN

Germany
TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG
Die Ressourcenuniversität. Seit 1765.

Italy
Columbus Superconductors

Finland/USA
LUVATA SPECIAL PRODUCTS

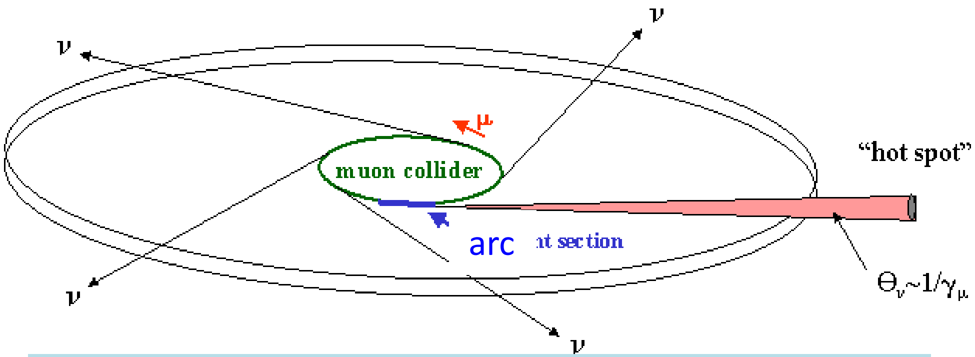
Italy
SPIN

Switzerland
UNIVERSITÉ DE GENÈVE

7 companies, two universities and two national research institutes

Magnet progress is important
Need to share magnet work for muon collider

Neutrino Radiation



Important luminosity limitation

Particularly high in direction of the straights

⇒ buy land in direction of straights

Have to still cover arcs

Typical legal limit 1 mSv/year

MAP goal < 0.1 mSv/year

No legal procedure < 10 µSv/year

LHC achieved < 5 µSv/year

No mitigation, 500 m deep tunnel:

3 TeV: close to LHC

14 TeV: around legal limit

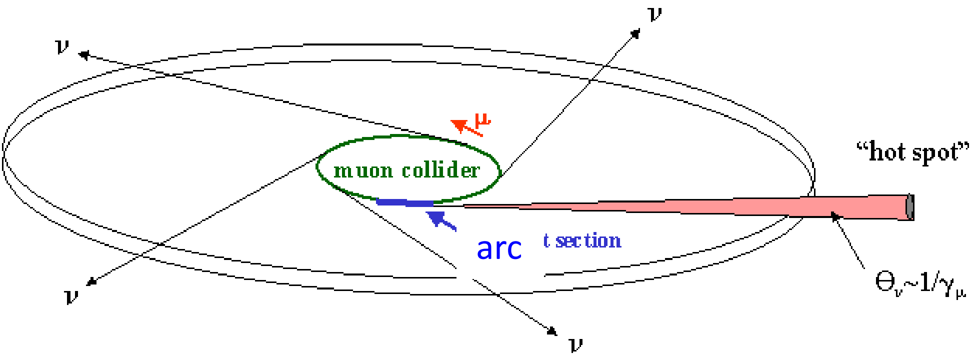
Needed to find a solution

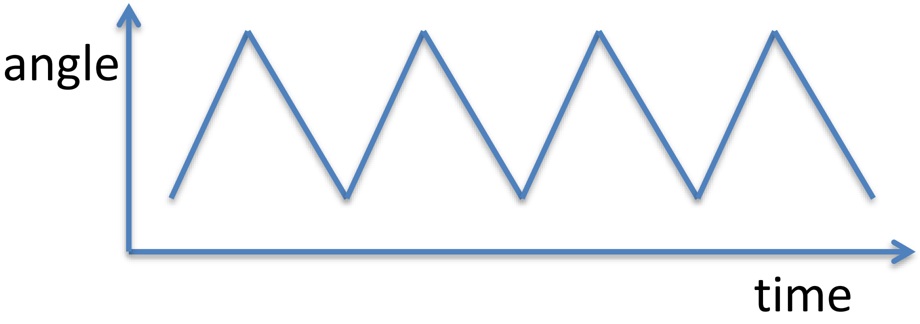
Work with **Radiation Protection, Civil Engineering, Geometers** and **Lattice Design** started to find solutions

Mitigate radiation to a level as low as reasonably achievable

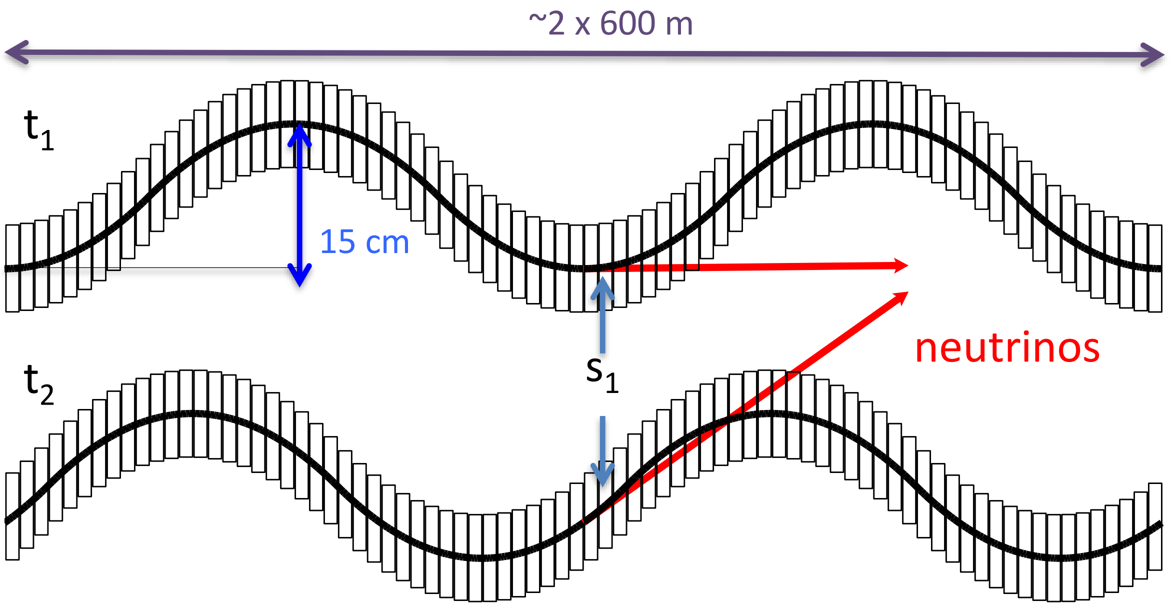
Similar to LHC

Neutrino Radiation Mitigation Proposal





Mokhov, Ginneken: move beam in collider aperture
Investigating: move collider ring components, e.g. vertical bending with 1% of main field



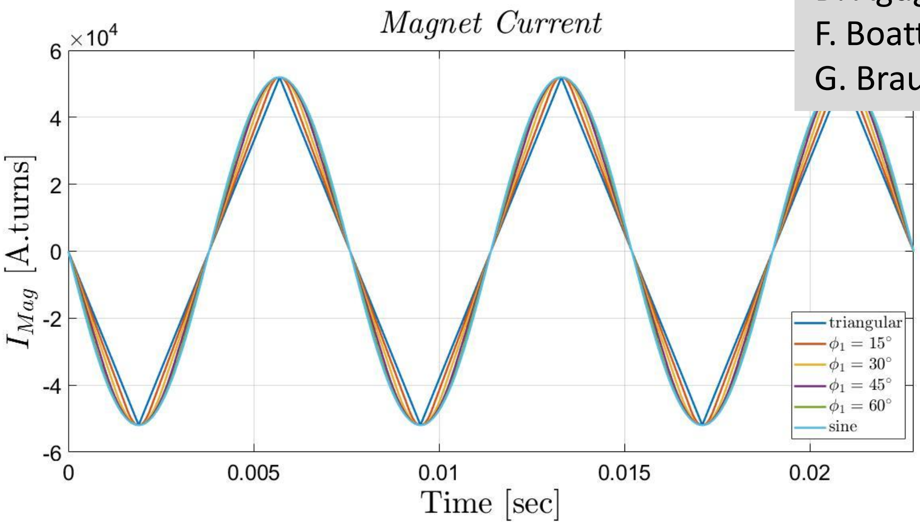
Opening angle ± 1 mradian

Even at 14 TeV
200 m deep tunnel would be comparable to LHC case

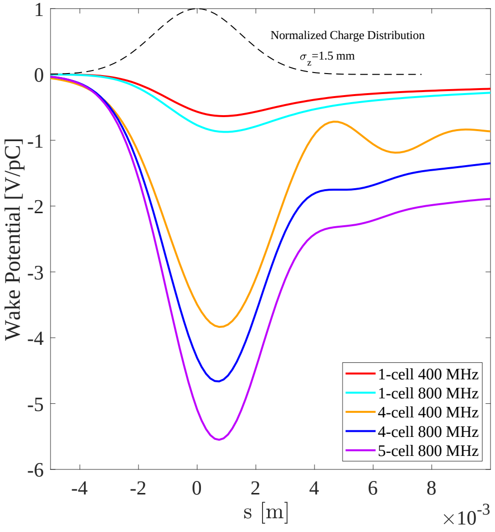
Need to study impact on beam operation, e.g. dispersion control, and components

Selected Recent Progress

Ramping **magnet challenge**
At 14 TeV, energy in field is O(200 MJ)
Need to recover it pulse to pulse
Started to develop **powering scheme** with energy recovery

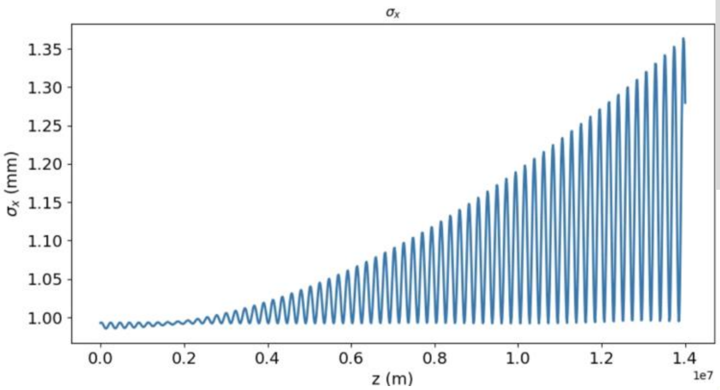


D. Aguglia
F. Boattini
G. Brauchli



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

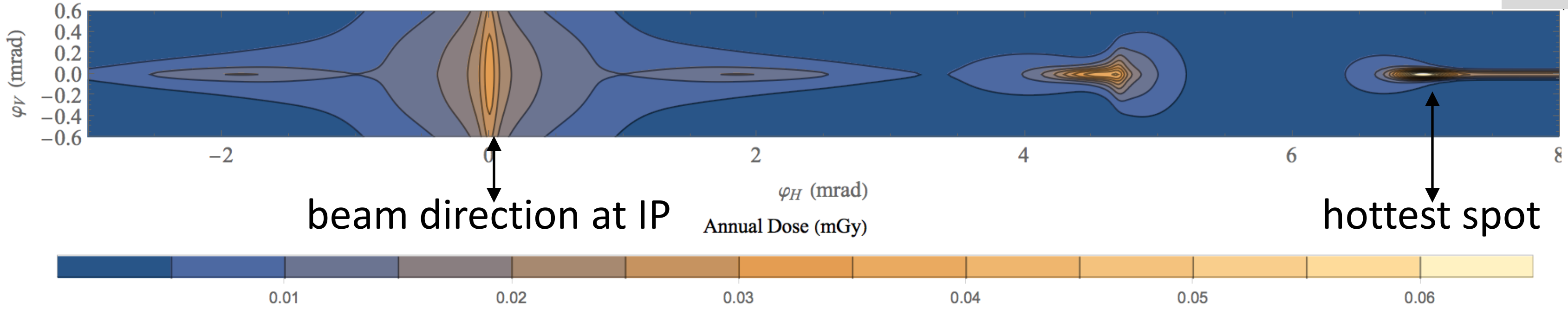


M. Magliorati
E. Metral,
T. Raubenheimer
D.S.

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

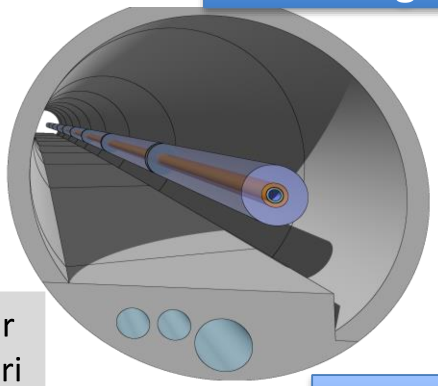
Selected Recent Progress, cont.

C. Carli

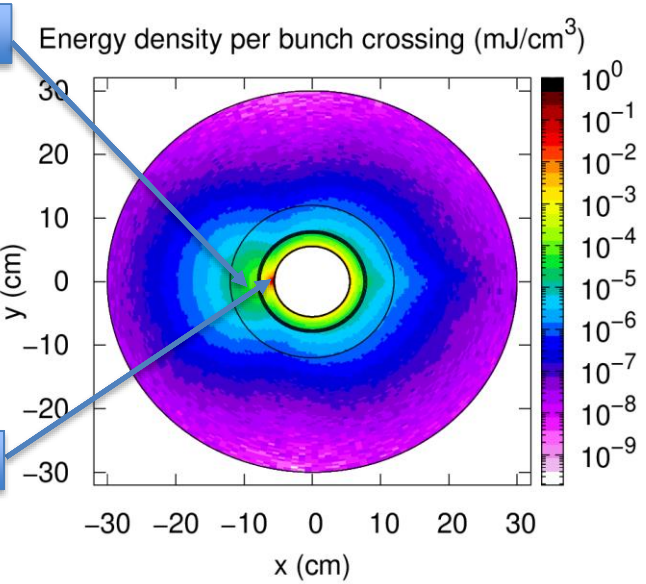


Collider Ring Lattice Design:
Based on MAP design, lattice design for high energy is starting
Started production of **radiation maps** and identified hot spots around IP and in arcs
Need to include radiation considerations in lattice design

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



A. Lechner
D. Calzolari



Tentative Detector Performance Specification

10+ TeV collider enters uncharted territory

Need to establish physics case and detector feasibility

Established tentative detector performance specifications in form of DELPHES card (thanks to M. Selvaggi, Werner Riegler, Ulrike Schnoor, A. Sailer, D. Lucchesi, N. Pastrone M. Pierini, F. Maltoni, A. Wulzer et al.), based on FCC-hh and CLIC performances, including masks against beam induced background (BIB)

- For use by physics potential studies
  - Are the performances sufficient or too good?
- For detector studies to work towards
  - make sure technologies are reasonable
  - ensure background is OK
- Please find the card here: https://muoncollider.web.cern.ch/node/14

Detector simulation studies/design will now have to verify/ensure that this is realistic considering background and technologies

Physics Potential, Detector and MDI

Main background sources

- Muon decay products (40,000 muons/m/crossing at 14 TeV)
  - tertiary muons produced far from collision point
  - showers products produced in final triplets
- Beam-beam background

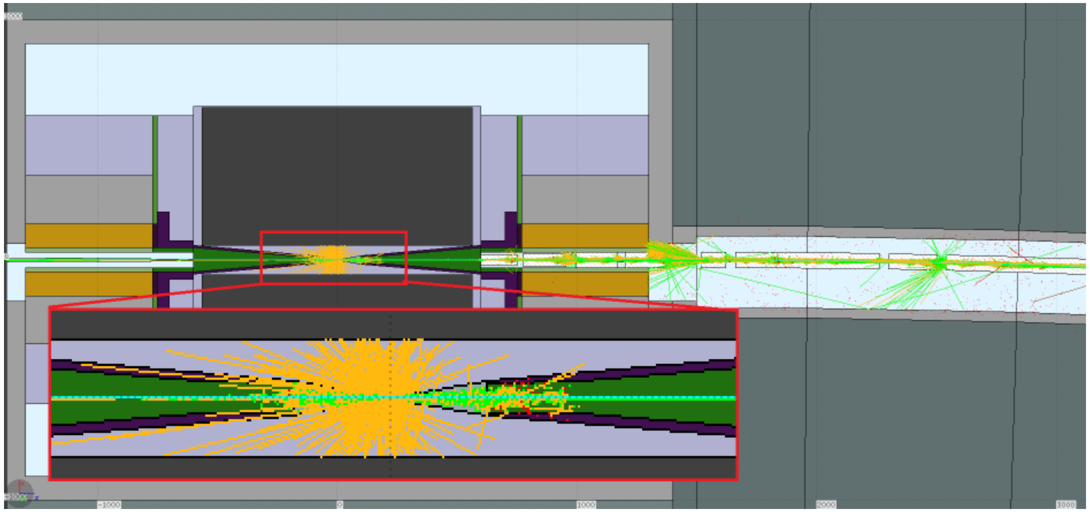
Background reduces while beam decays

- part luminosity delivered with lower background
- consider worst condition

Mitigation methods

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

Need to ensure they do not compromise physics



Simulation tools exist

First studies at lower energies (125 GeVand 1.5 TeV are encouraging

Will develop systems for higher energies

Test Programme

High-energy complex mostly consists of known components with pushed performances

- Can be tested as individual prototypes
- Synergies with other developments exist
- Some beam experiments might be useful but could be considered at other accelerators, e.g. control of longitudinal phase space

Muon cooling complex is novel and unique to the muon collider

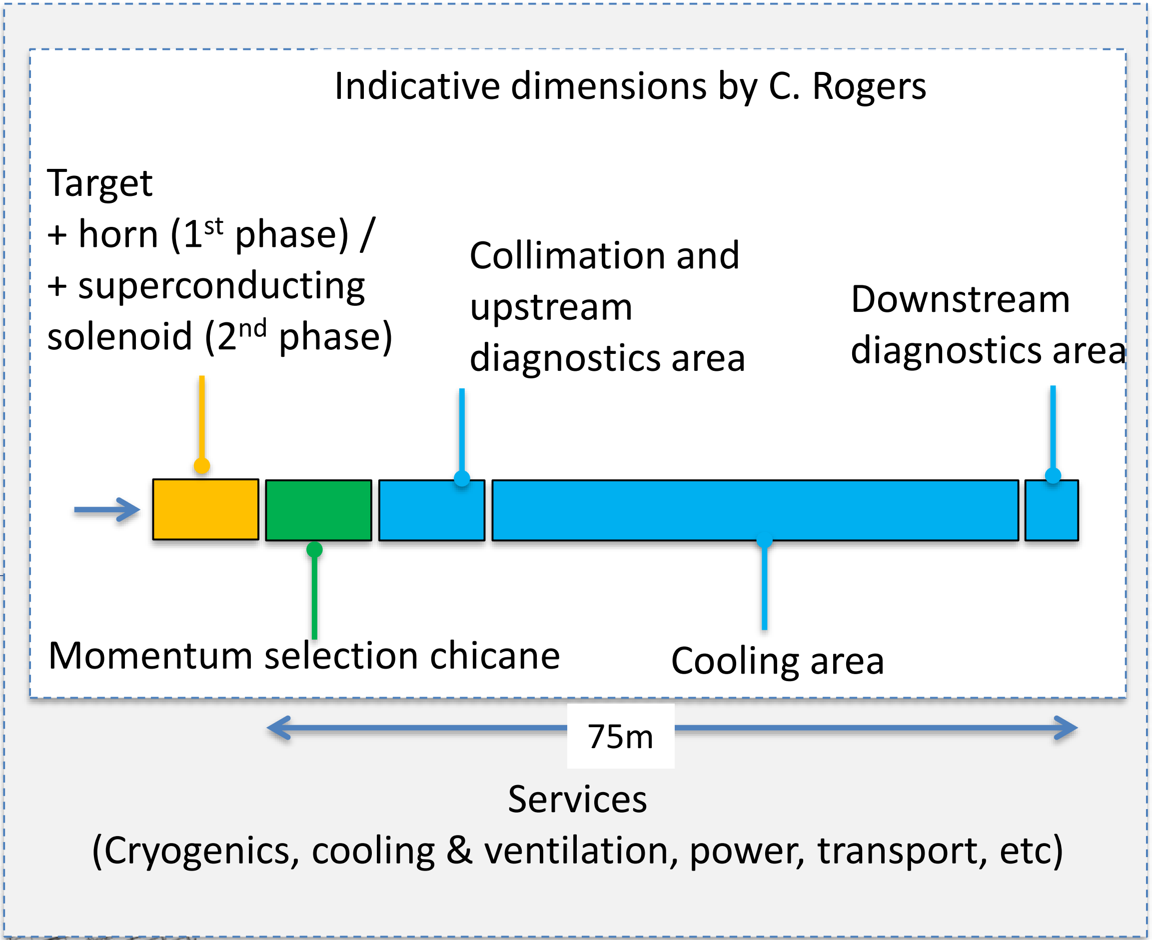
- Many components are unconventional
  - e.g. high-gradient cavities in magnetic field with Be windows or filled with gas
  - massive use of absorbers in the beam path
- Novel technologies beyond MAP design can be considered
  - e.g. very short RF pulse to reduce breakdown probability
  - e.g. use of cooled copper
- Also compact integration is required to maximise muon survival
  - strong superconducting solenoids next to RF at room temperature
  - complex lattice design optimisation
- Almost no experience with beam in these components
  - MICE has been a limited model (no RF, single muons, …)

⇒ Need to test a string of cooling cells, ultimately with beam

Test Facility Considerations

Test **cooling cell string**, ultimately with beam

Option:
CERN land, extract PS beam from TT10 (10^{13} 26 GeV protons in 5 ns, O(10%) of collider, with O(Hz))
In molasse (no ground water)



Indicative dimensions by C. Rogers

Target
+ horn (1^{st} phase) /
+ superconducting solenoid (2^{nd} phase)

Collimation and upstream diagnostics area

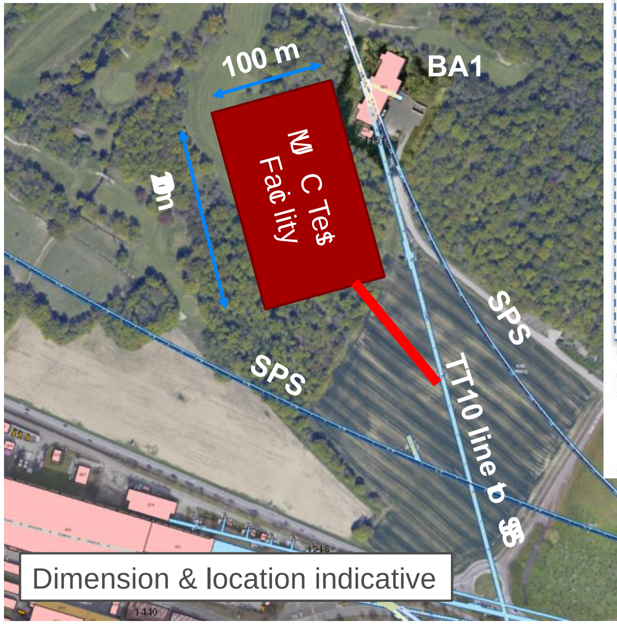
Downstream diagnostics area

Momentum selection chicane

Cooling area

75m

Services
(Cryogenics, cooling & ventilation, power, transport, etc)



Dimension & location indicative

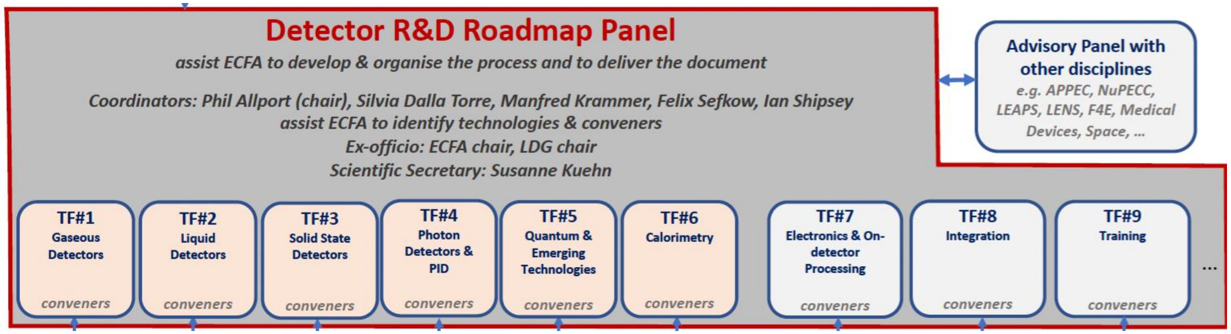
Other options to be explored

Accumulator test at ESS?

Detector Technologies

Will rely largely on European Detector R&D Roadmap (ECFA)

- Will provide link persons to relevant working groups



Detector R&D Roadmap Panel

assist ECFA to develop & organise the process and to deliver the document

Coordinators: Phil Allport (chair), Silvia Dalla Torre, Manfred Krammer, Felix Sefkow, Ian Shipsey
assist ECFA to identify technologies & conveners
Ex-officio: ECFA chair, LDG chair
Scientific Secretary: Susanne Kuehn

Advisory Panel with other disciplines
e.g. APPEC, NuPECC, LEAPS, LENS, F4E, Medical Devices, Space, …

TF#1	TF#2	TF#3	TF#4	TF#5	TF#6	TF#7	TF#8	TF#9
Gaseous Detectors	Liquid Detectors	Solid State Detectors	Photon Detectors & PID	Quantum & Emerging Technologies	Calorimetry	Electronics & On-detector Processing	Integration	Training
conveners	conveners	conveners	conveners	conveners	conveners	conveners	conveners	conveners

…

Currently consider the following most important (N. Pastrone)

- solid state tracking
- calorimetry
- emerging technologies
- electronics and in detector processing

Will also include other regions

Physics potential studies and machine background studies will verify if performances similar to CLIC and FCC-hh are sufficient

US Snowmass/P5

Submitted a number of proposals for white papers

- physics potential
- detector
- accelerator

Growing interest in the community

Aiming to coordinate the regional efforts

International Muon Collider Collaboration (corresponding author: D. Schulte)
Muon Collider Facility (c.a.: D. Schulte)
Muon Collider Physics Potential (c.a.: A. Wulzer)
Machine Detector Interface Studies at a Muon Collider (c.a.: D. Lucchesi)
Muon Collider experiment: requirements for new detector R&D and reconstruction tools (c.a.: N. Pastrone)
A Proton-Based Muon Source for a Collider at CERN (c.a.: Chr. Rogers)
Issues and Mitigations for Advanced Muon Ionization Cooling (c.a.: Chr. Rogers)
LEMMA: a positron driven muon source for a muon collider (c.a.: M.E. Biagini)
Applications of Vertical Excursion FFAs(vFFA)and Novel Optics (c.a.: Sh. Machida)

Timeline

Initial Design Phase
2021-2025

Establish whether investment into full CDR and demonstrator is scientifically justified.

Provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers.

Identify an R&D path toward the collider, considering High-field Magnet and RF Roadmap results.

Conceptual Design Phase
2026-

Develop concept and technology to be ready to commit

Verify performance of all key components. In particular, build cooling cell string and test with beam. Build and test magnet models and RF components. Start building industrial base for production. Develop site and infrastructure. Determine cost, power, construction schedule. Optimise design.

Technical Design Phase

Prepare approval and project implementation

Prepare industrial production of components, e.g. build magnet prototypes and preseries with industry. Prepare site for construction. Refine cost, power and construction schedule.

Strategy decision

Define performance goals and timeline for muon collider

Potentially ramp up of muon collider effort

Decision to move to technical design

Pre-commitment to project

Project Approval

Timeline Discussion

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

But should also prudently have **back-up scenario** in case Europe does not build higgs factory

- next large project after HL-LHC

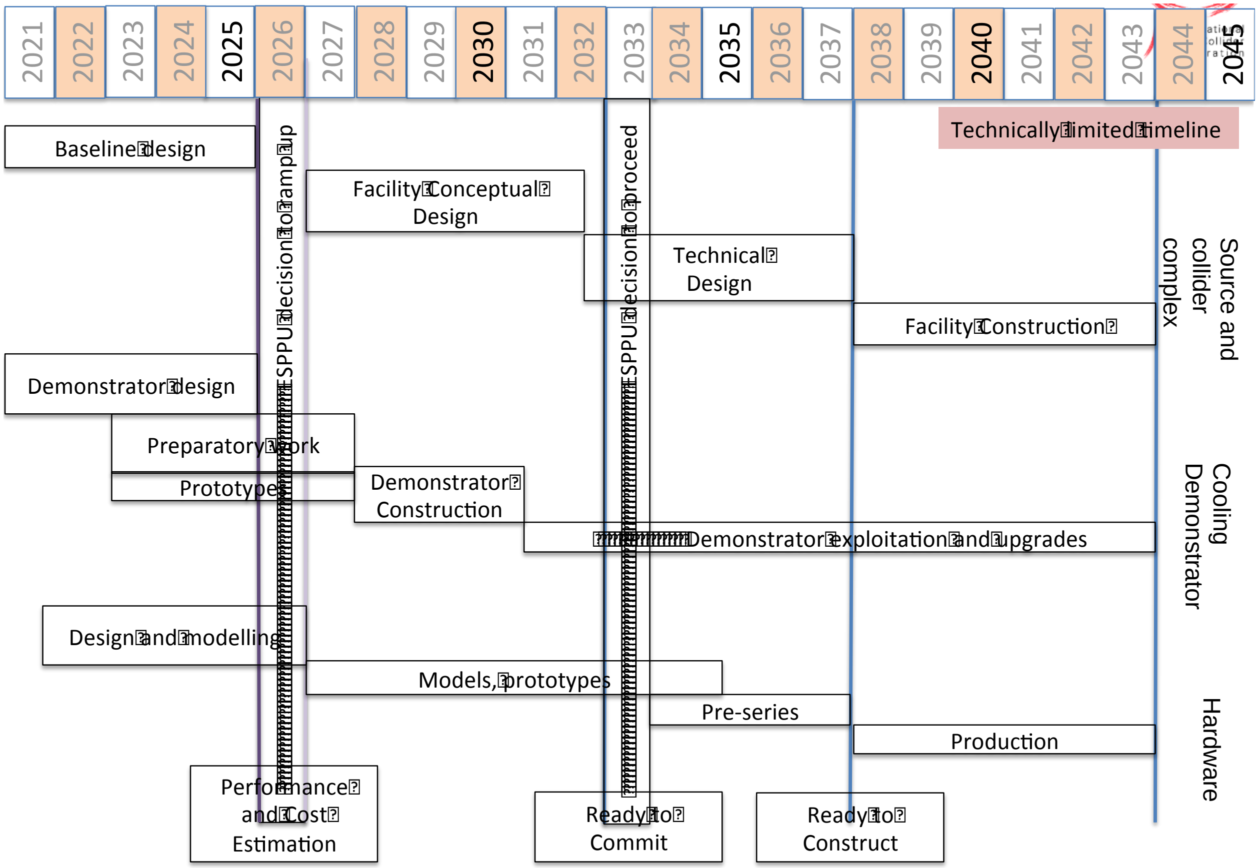
Exploring shortest possible aggressive timeline

- Initial 3 TeV stage on the way to 10+ TeV

Will have more solid evaluation for next ESPPU

Tentative Target for Aggressive Timeline

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



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

ESPPU decision to ramp up

ESPPU decision to proceed

Technically limited timeline

Source and collider complex

Baseline design

Facility Conceptual Design

Technical Design

Facility Construction

Cooling Demonstrator

Demonstrator design

Preparatory work

Prototypes

Demonstrator Construction

Demonstrator exploitation and upgrades

Hardware

Design and modelling

Models, prototypes

Pre-series

Production

Performance and Cost Estimation

Ready to Commit

Ready to Construct

My Impression of Panel 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.

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

- Need 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

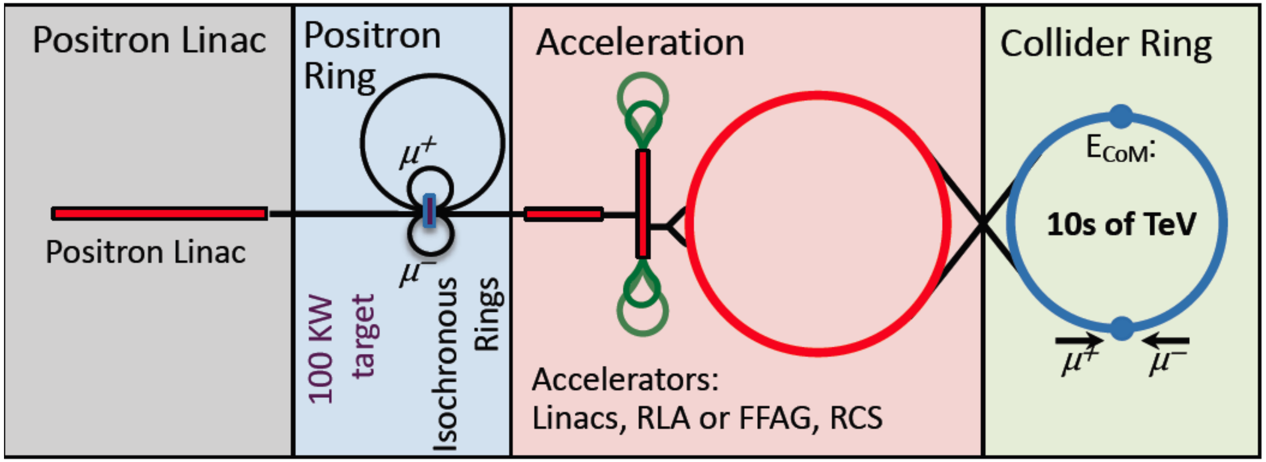
- An important opportunity that we should not miss

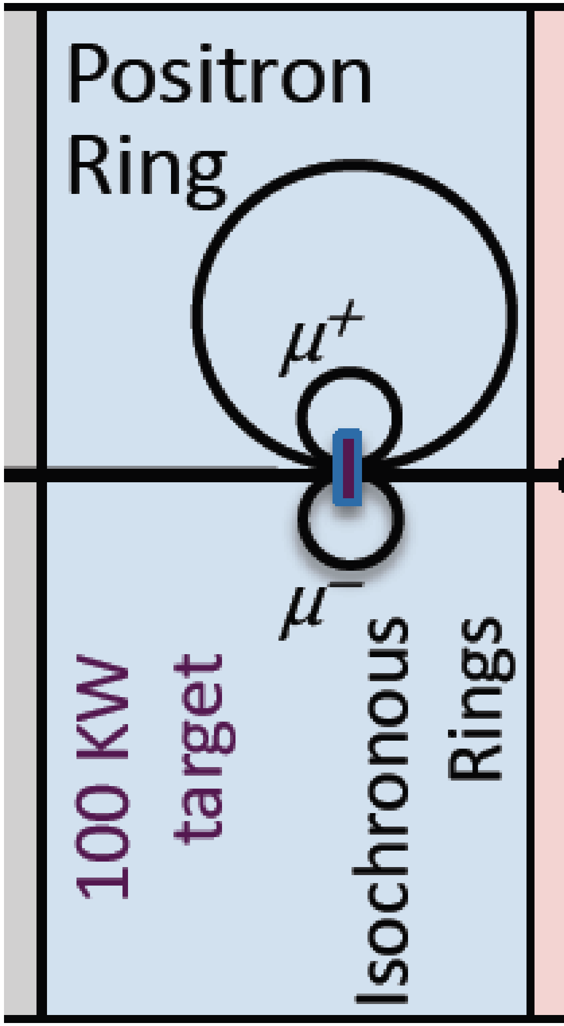
- Web page: http://muoncollider.web.cern.ch

Many thanks to the Muon Beam Panel, the collaboration, the MAP study, the MICE collaboration, Mark Palmer, Chris Rogers and many others

Reserve

Alternative: The LEMMA Scheme





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

Low-emittance muon beam can reduce radiation

Less mature than proton-driven scheme
Large positron current required
Target is challenging
Large positron production rate [O(10^{17}/s)]
Currently do not reach luminosity goal

Target Parameter Scaling

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} 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
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	μm	25	25	25
$\sigma_{x,y}$	μm	3.0	0.9	0.63

Scaled from MAP parameters

Emittance is constant

$$\sigma_E \sigma_z = \text{const}$$

Collider ring acceptance is constant

$$\frac{\sigma_E}{E} = \text{const}$$

Bunch length decreases

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

Betafunction decreases

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