Muon Collider

Daniel Schulte for the Muon Collider Collaboration

Lepton Physics at High Energy

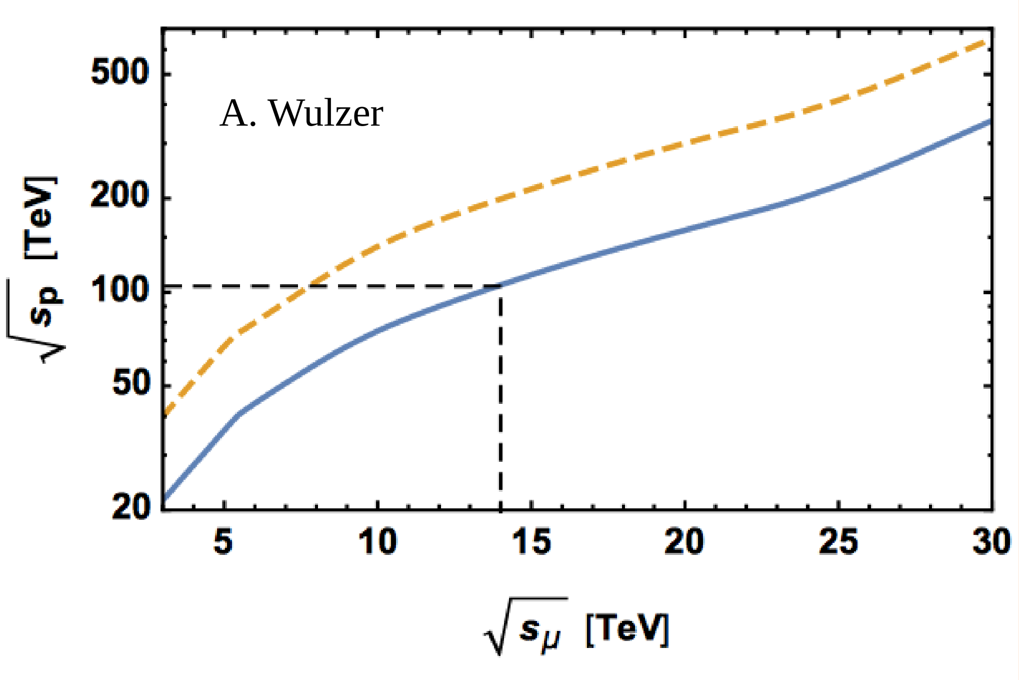
High energy lepton colliders are precision and discovery machines

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

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

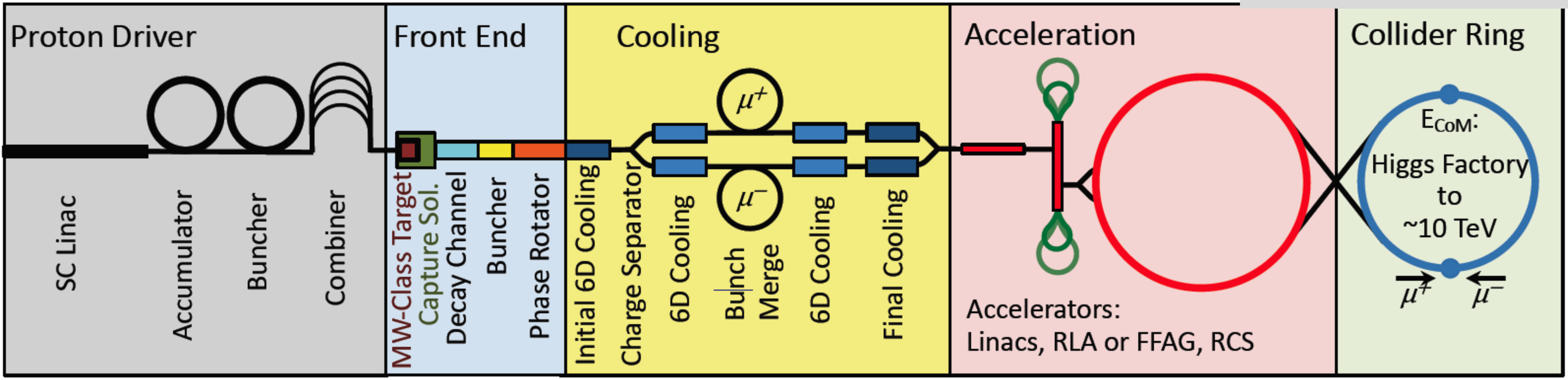
(Factor O(3) less than CLIC at 3 TeV)
4×10^{35} cm^{-2}s^{-1} at 14 TeV

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

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 is unique for very high lepton collision

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

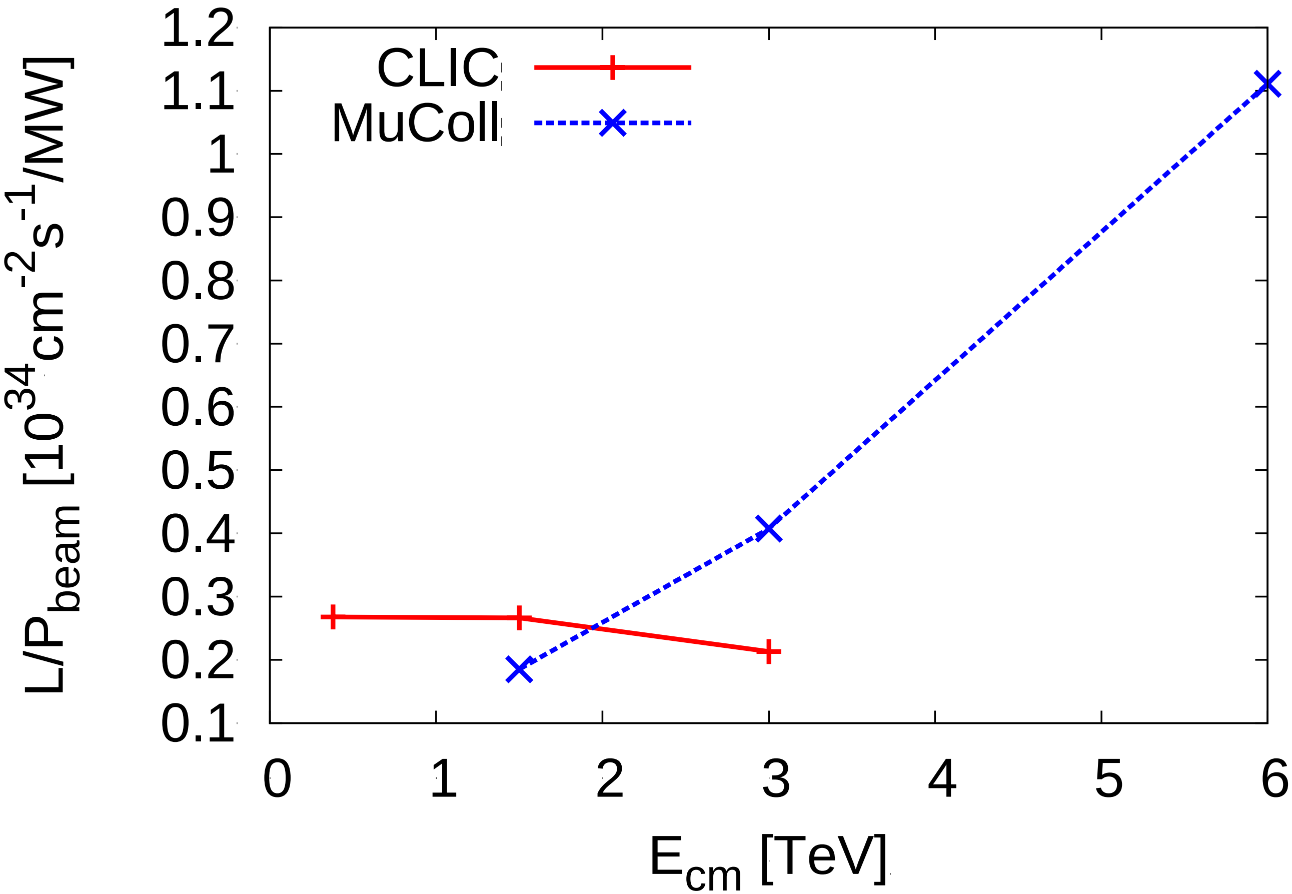
Staging is natural

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

Appears to promise **cost effectiveness**

- but need detailed study

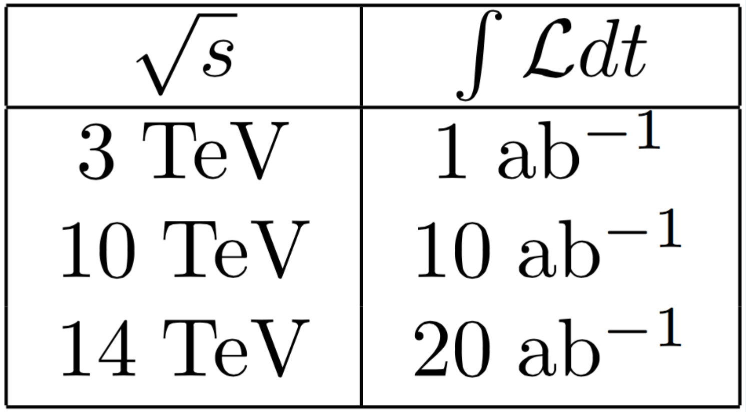
Other **synergies** exist (neutrino/higgs



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

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 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

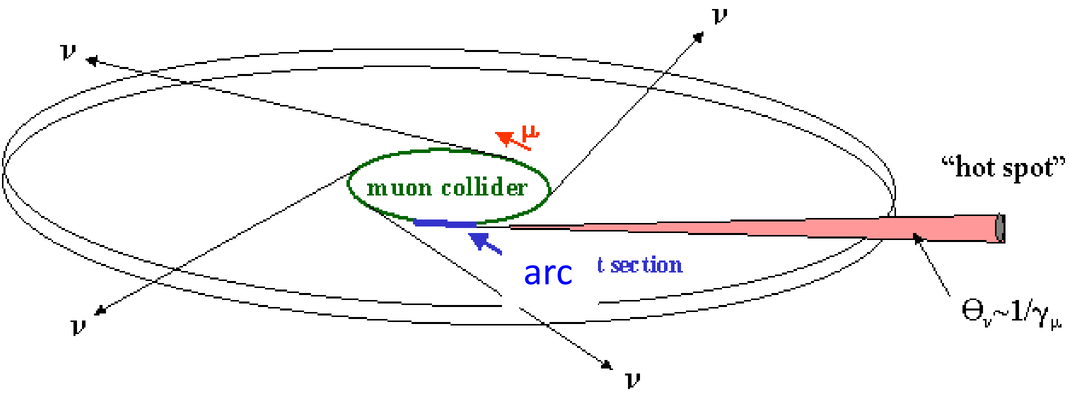
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Key Challenge Areas

10+ TeV is uncharted territory

- **Physics potential** evaluation, including d**etector concept and technologies**
- Impact on the environment
  - The **neutrino flux mitigation** and its impact on the site (first concept exists)
- The impact of **machine induced background** on the detector, as it might limit the physics reach.
- **High-energy systems** after the cooling (acceleration, collision, …)
  - This can limit the energy reach via cost, power, technical risk and beam quality
- **High-quality muon beam production**
  - MAP did study this in detail
  - First experimental verification in MICE
  - Need to optimise and prepare **cooling string demonstration**
- **Integrated Collider Design** with choices, parameters, trade-offs, cost, power, site, …
  - need to cover all accelerator areas

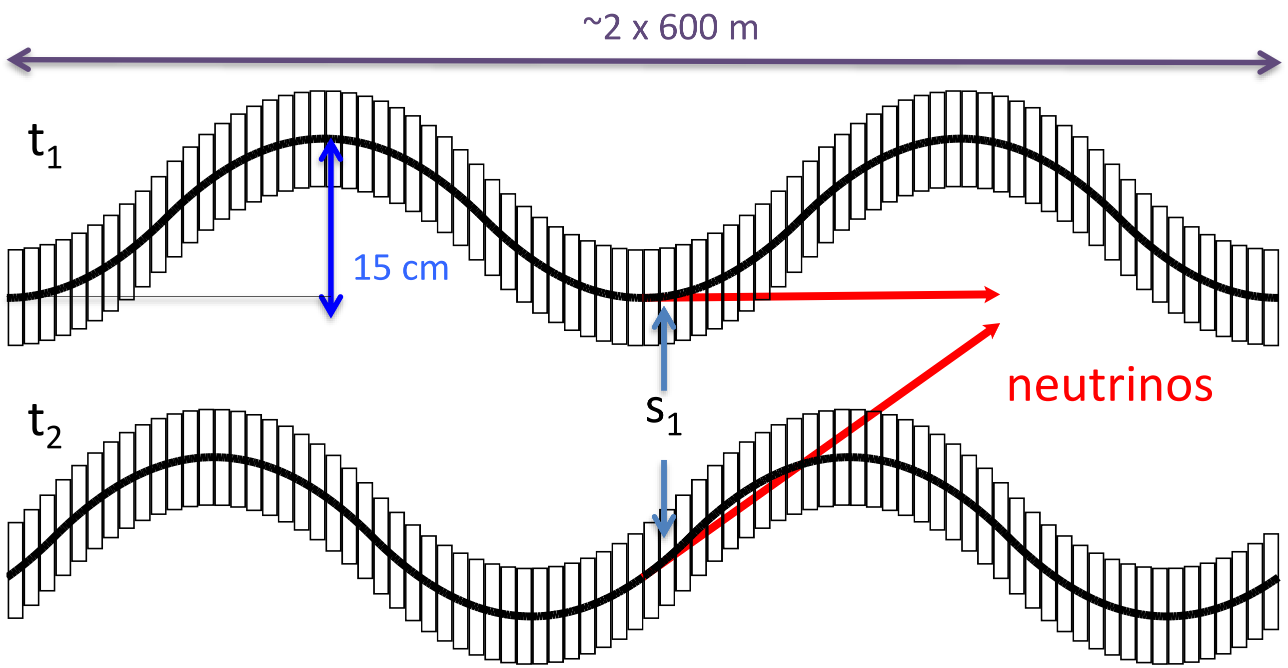
Neutrino Flux Mitigation



Legal limit 1 mSv/year
MAP goal < 0.1 mSv/year
Our goal: arcs below threshold for legal procedure < 10 μSv/year
LHC achieved < 5 μSv/year

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

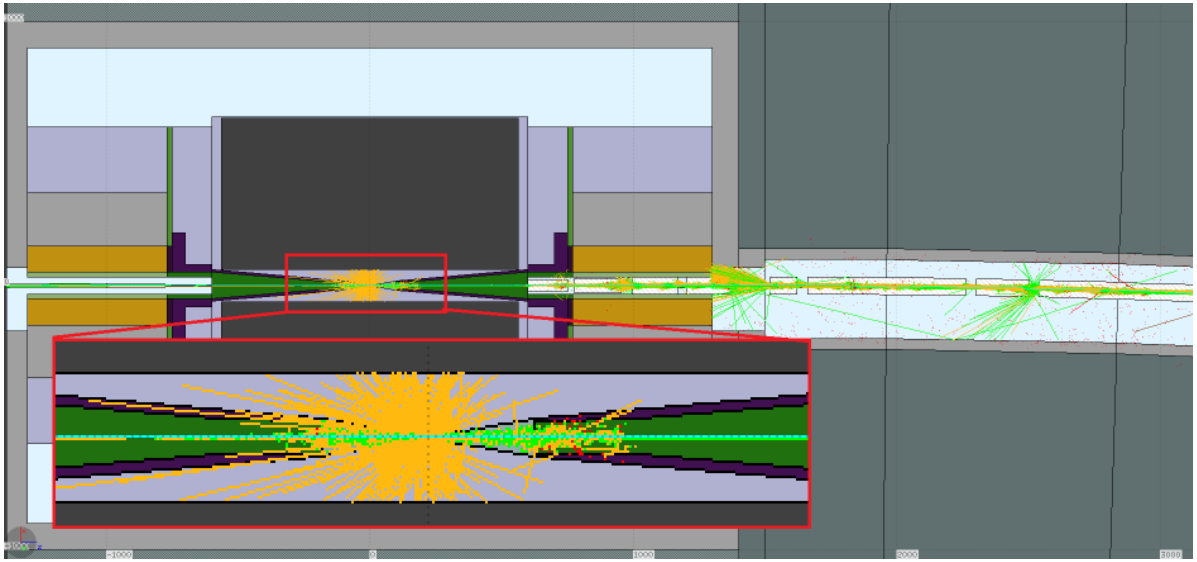
- Theory and phenomenology
- Detector technologies, simulation studies
- Collider and mask design
- Important effort is required

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
- …

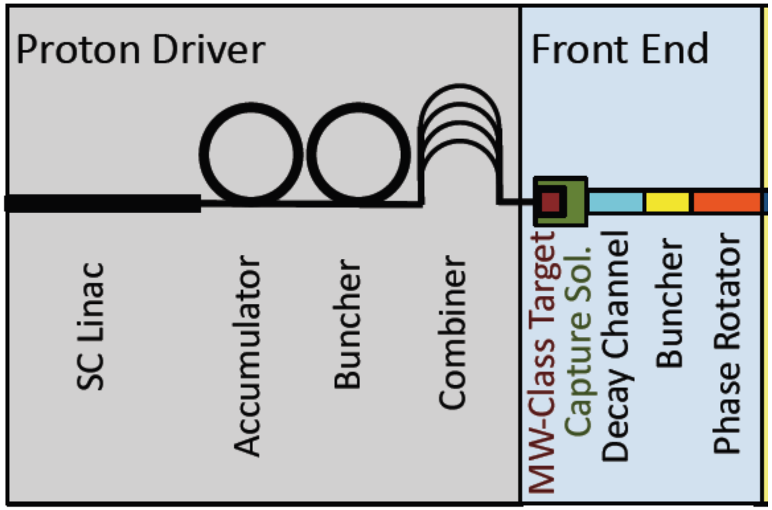


Simulation tools exist

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

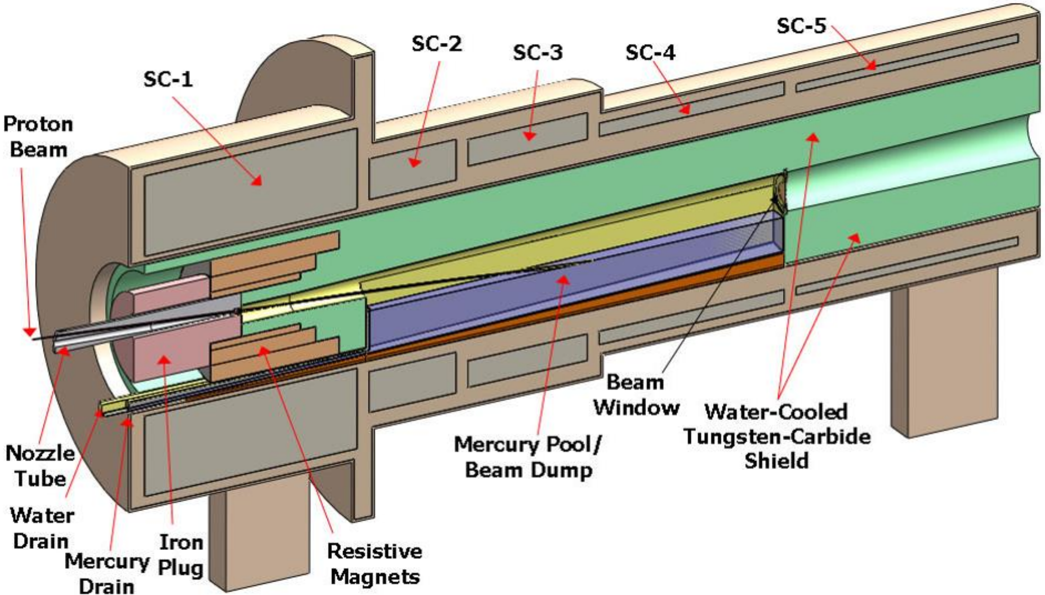
Will develop systems for higher energies

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

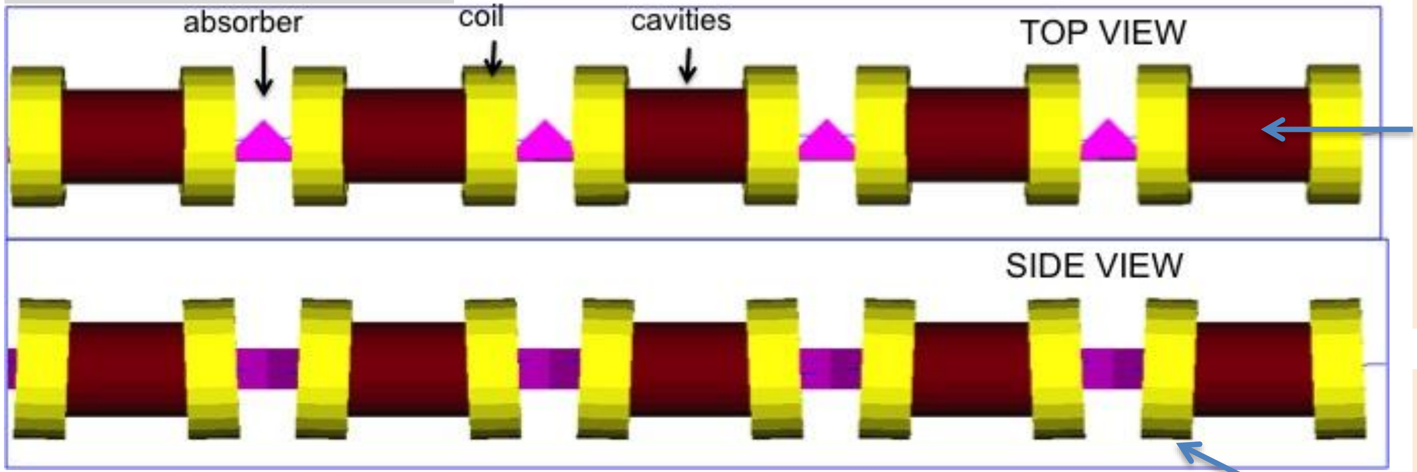


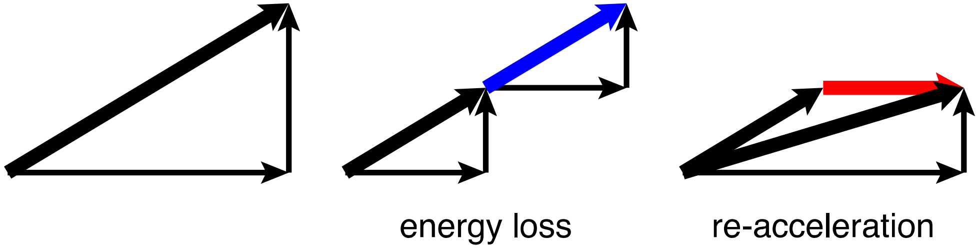
High field to efficiently collect pions/muons: 20 T, then tapering
Using copper solenoid in superconducting solenoid

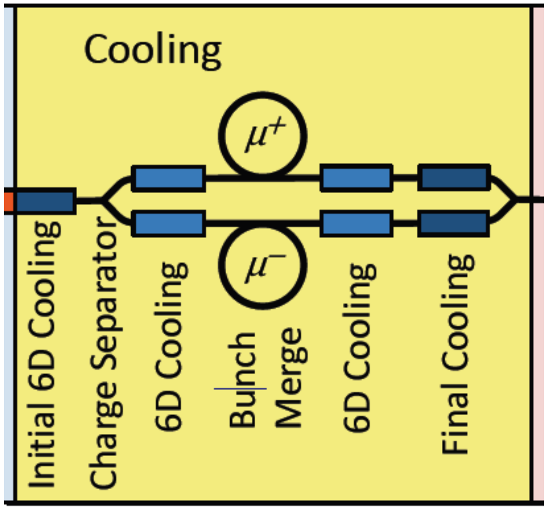
Large aperture O(1.2m)
to allow shielding

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

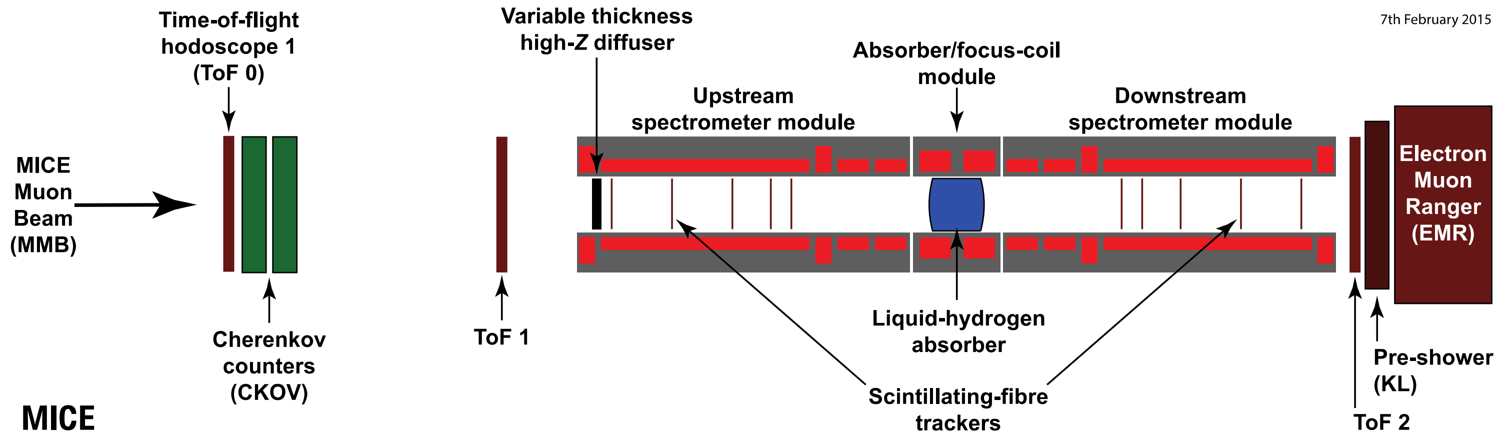
Compact integration to minimise muon loss

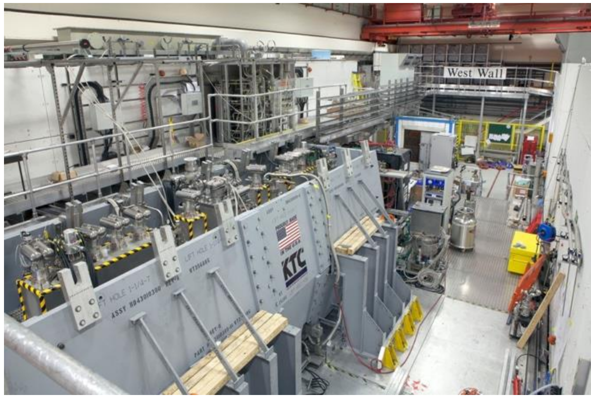
Minimise betafunction with **strongest solenoids (40+ T)**
32 T achieved, 40+ T planned

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

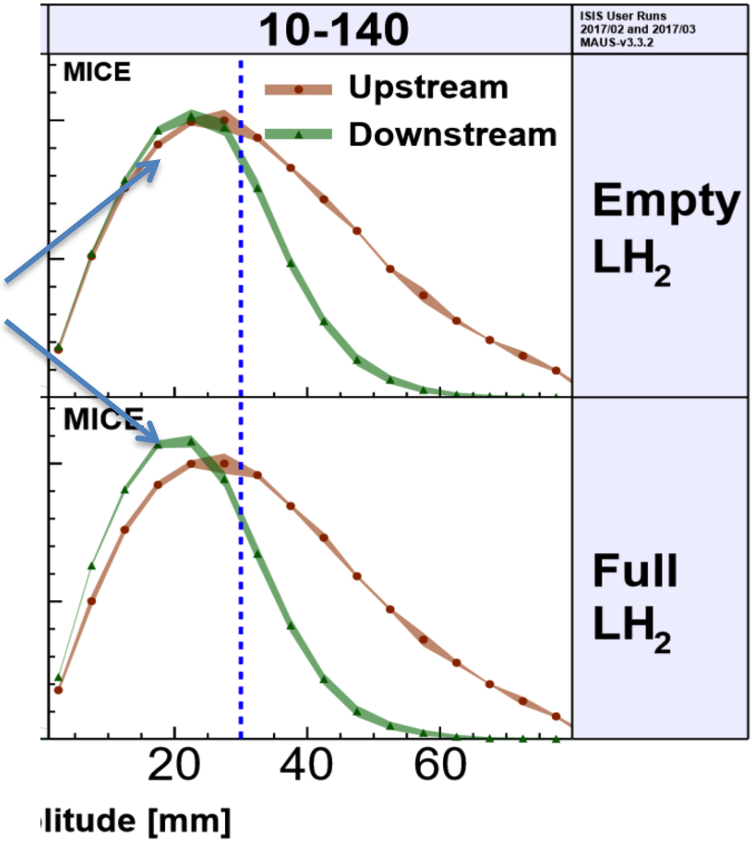
This is the **unique** and **novel** system of the muon collider
Will need a **test facility**
The principle has been demonstrated in MICE

MICE (in the UK)





More particles at smaller amplitude after absorber is put in place



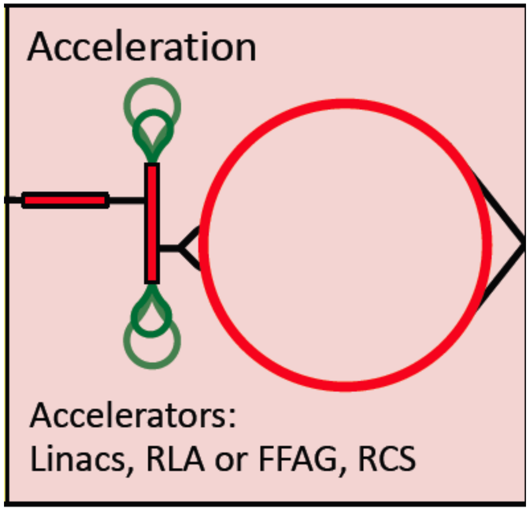
Nature volume 578, pages 53-59 (2020)

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

High-energy Acceleration

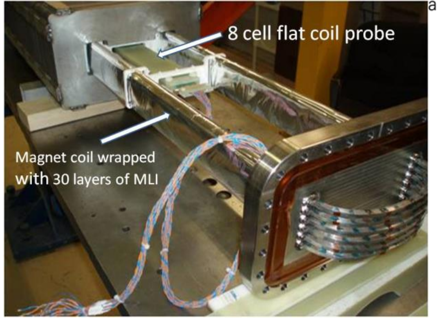


Acceleration

Accelerators:
Linacs, RLA or FFAG, RCS

FNAL
12 T/s HTS
now 290 T/s

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



System of linacs followed by sequence of RCS and/or FFA

RF system

- **Important single-bunch beam loading**

FFA

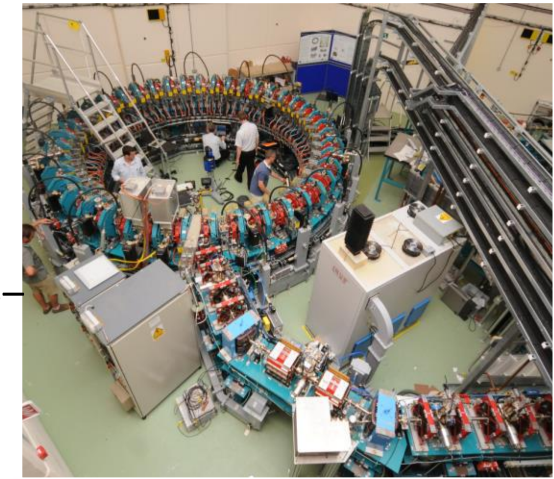
- Fixed (high-field) magnets but large energy acceptance
- Challenging **lattice design** for large bandwidth and limited cost
- **Complex high-field magnets**
- Challenging beam dynamics

Rapid cycling synchrotron (RCS)

- Combine static and ramping magnets
- **Ramp magnets** to follow beam energy
  - normal conducting
  - or novel HTS
- **Power consumption** of fast-ramping systems is important

EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)



Final Focus

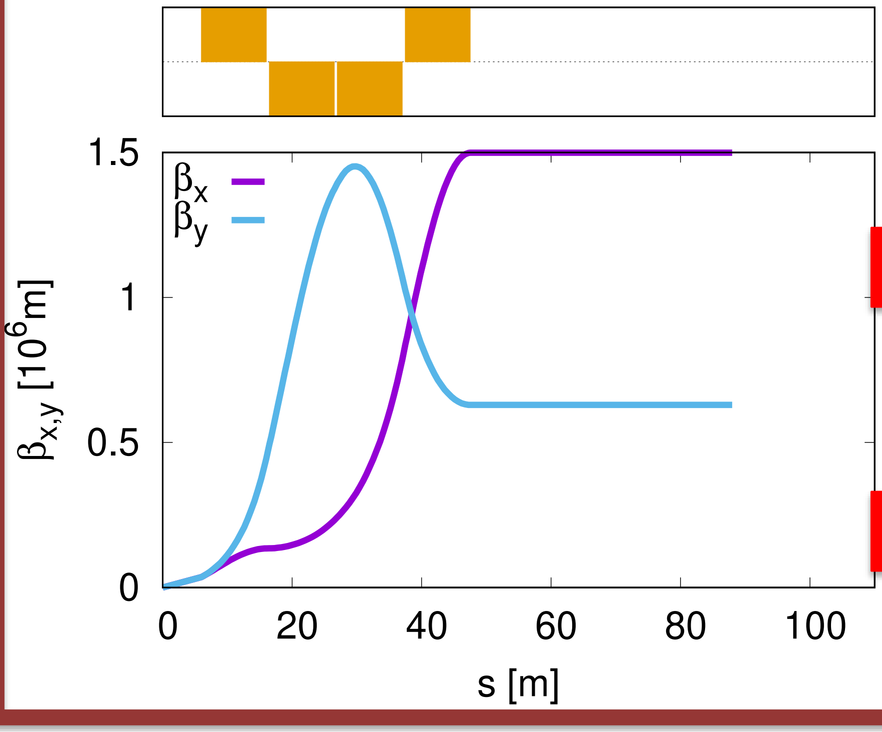
Strong focusing at IP to minimise betafunction and maximise luminosity

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

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

At 10+ TeV: Higher field is likely required

First considerations on 14 TeV Design (R: Tomas)



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

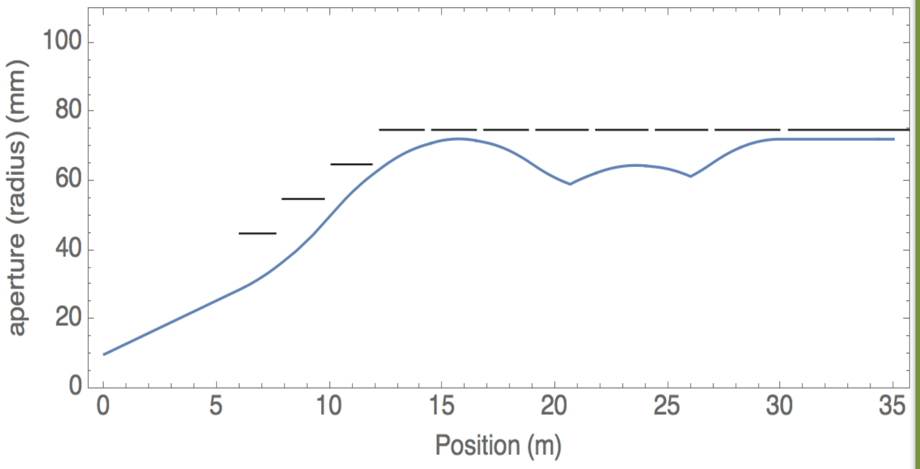
B_{peak} = 18 T

$N_\sigma = 6\ \sigma$

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

At 3 TeV:

Close to state of the art

At 10+ TeV:

Higher field Nb_3Sn or better HTS is potentially required

Collider Ring Arcs

High field dipoles to minimise collider ring size and maximise luminosity

Beam loss protection O(500 W/m)

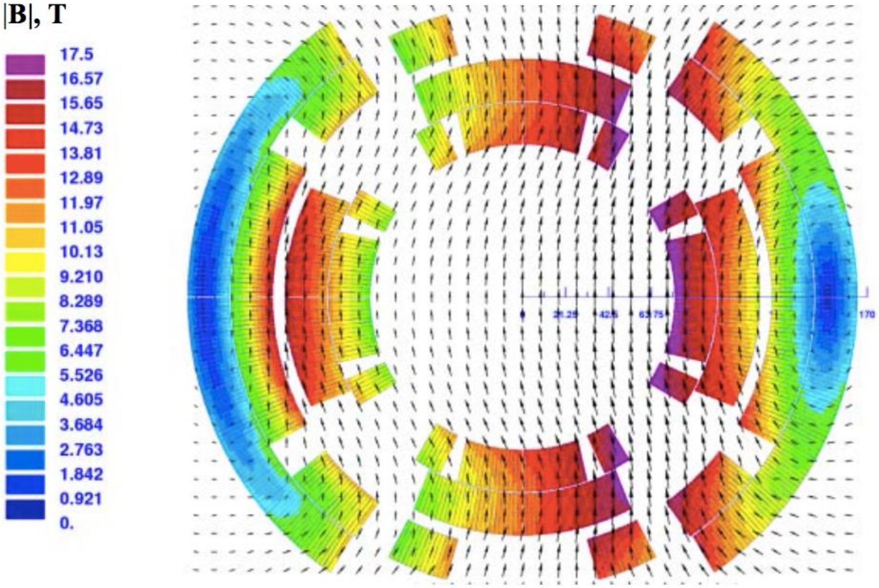
MAP 3 TeV example:

- **10.4 T** in dipoles, 150 mm aperture
- 5 m-long combined function magnets with **8 T and 85 T/m** and **9 T and -35 T/m**

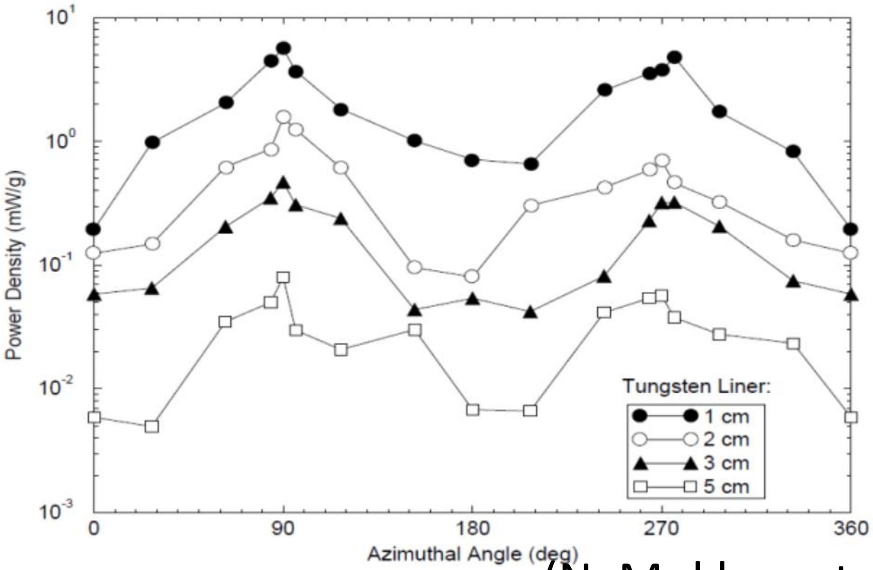
- **50/30 mm shielding**
- Acceptable losses in cold mass: 1%, maximum of 1.5 mW/g

At 10 TeV

- Currently no real design
- Ring length assume shorter ring per TeV at 10+ TeV, 16 T might be sufficient
- But will adjust to magnet performance
- Expect shielding/aperture not to increase dramatically with beam energy



(V.V. Kashikhin et al.)



(N. Mokhov et al.)

Facility Design

Design of the key accelerator systems

- e.g. muon cooling, collider ring, …
- Lattice design with functional specifications
- Beam dynamics
- Neutrino flux mitigation (impact on beam, components and site)
  - Promising concept needs to be further developed
- Beam loss mitigation
  - Shielding and collimation, optics, component robustness
- Some basis from MAP studies but
  - Some challenges in proton complex
  - Need improvement for muon production and cooling complex
  - Novel design for 10 TeV and improvement of 3 TeV

Develop R&D programme to demonstrate functional specifications where they exceed state of the art and to develop maturity

- For implementation after next ESPPU
- Design of important systems
- Some experimental efforts already before next ESPPU

Considerations on cost, power and site

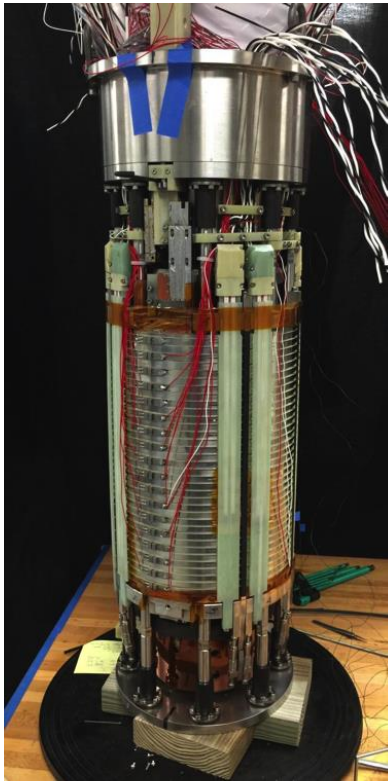
- Identification of cost, power and site drivers (tentative list exists)
- Determination of cost scale
- and integration into overall optimisation

Magnet Development

- Will depend on high-field programme (Roadmap), in particular for HTS
- **Fast-ramping magnets** and **powering** is muon collider specific
  - needs to be further developed, longest part of the accelerator

- For 3 TeV
  - **Final cooling solenoid**: small aperture, highest field
    - HTS solenoids are quite advanced but will know more in 5 years
    - goal 45 T (beam studies may relax), 32 T demonstrated, 40 T planned
    - risk is factor two in luminosity
  - **Target solenoid** is engineering challenge
    - Ni_3Sn with resistive insert or HTS
    - engineering challenge, mitigation options can be explored
  - Other cooling solenoids within reach
  - Interaction region and collider arc magnets are very close

- In addition, at 10 TeV
  - Timescale depends on the HTS progress, will know more in 5 years
  - Have been warned to remain open for important progress



NHFML
32 T solenoid with
HTS

Planned efforts to
push even further

Other Technology Development

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
- **Superconducting RF** needs to be further developed

Target:

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

Neutrino radiation mitigation:

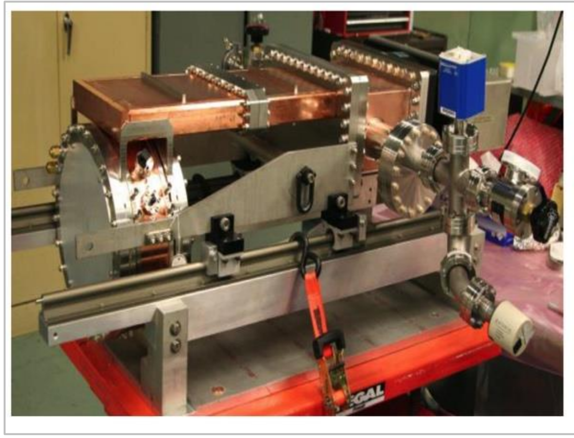
- Design the system
    - Impact on **magnet, cryogenics** etc.
    - Impact on **operation**

Cooling cell design:

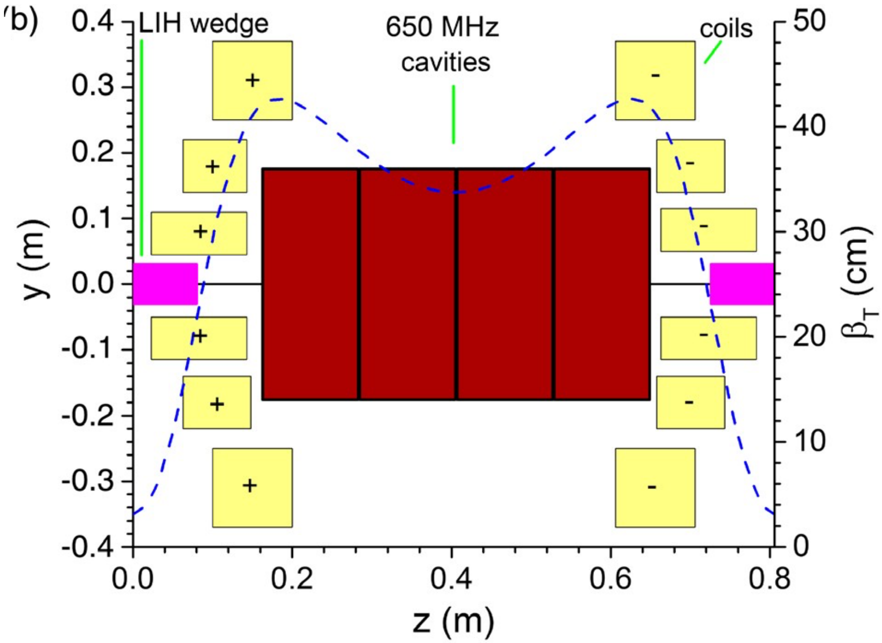
- Very involved engineering design required

Sofar, no showstopper identified
no inconsistency with 10-20 years timescale identified

Will know at next ESPPU



MuCool: >50 MV/m in 5 T



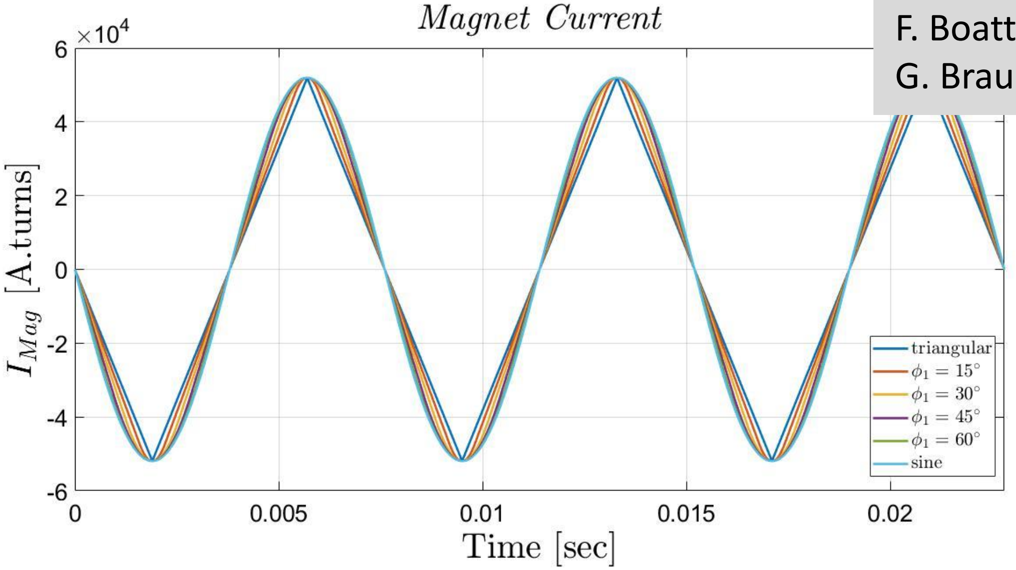
Selected Recent Progress

Ramping **magnet challenge**

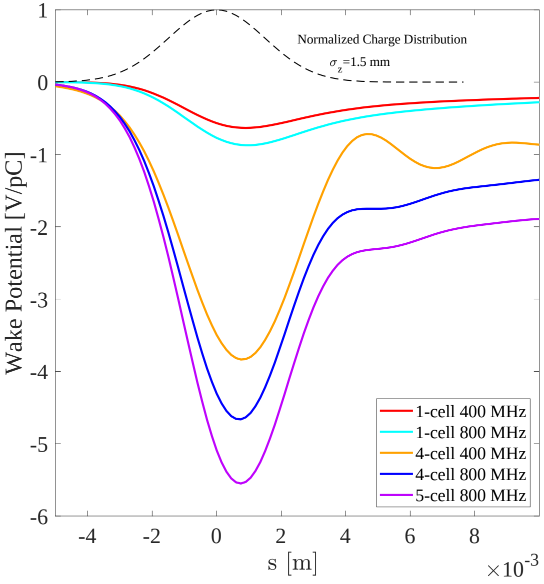
At 14 TeV, energy in field is O(200 MJ)

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

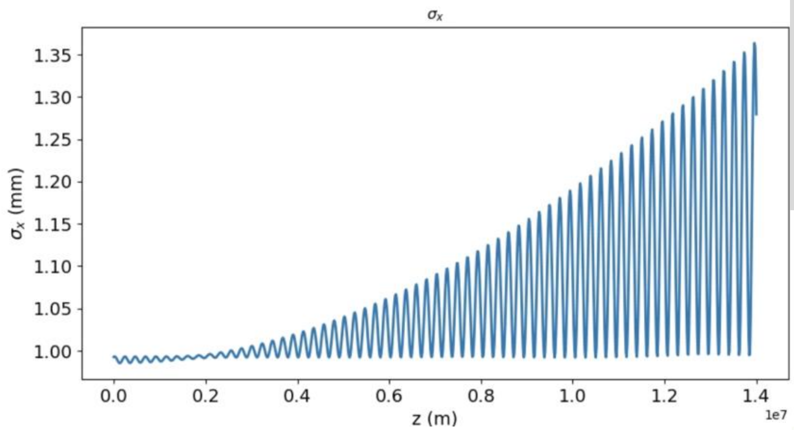
RF challenge (also for FFA):

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.

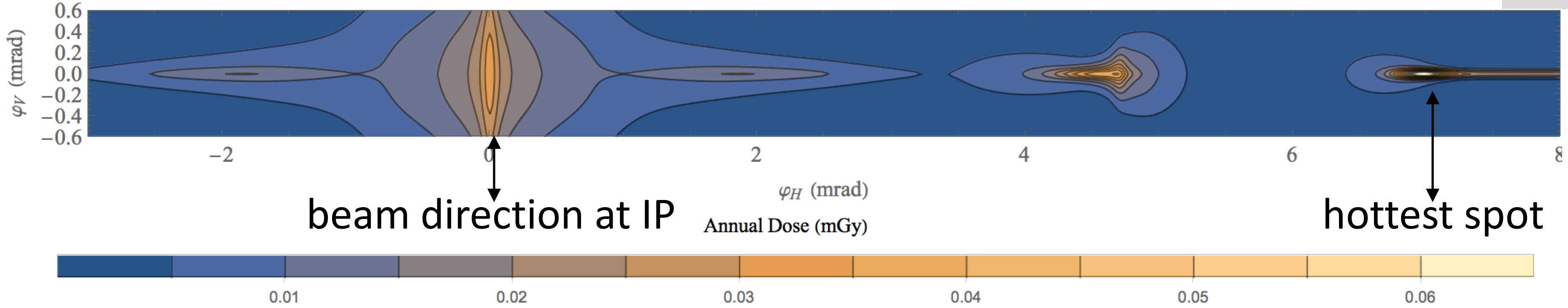
Collective effects might be a bottleneck

Revisiting for higher energies

Need to develop tools for collective effects in matter

Selected Recent Progress, cont.

C. Carli

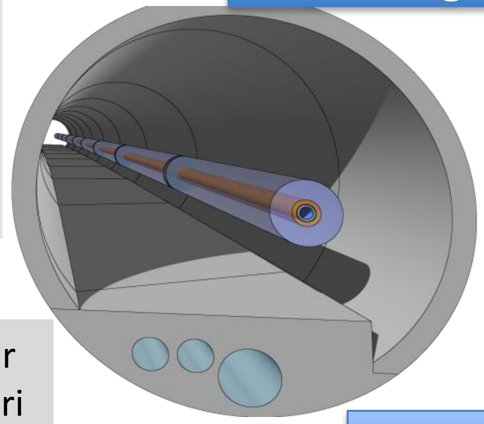


beam direction at IP

hottest spot

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

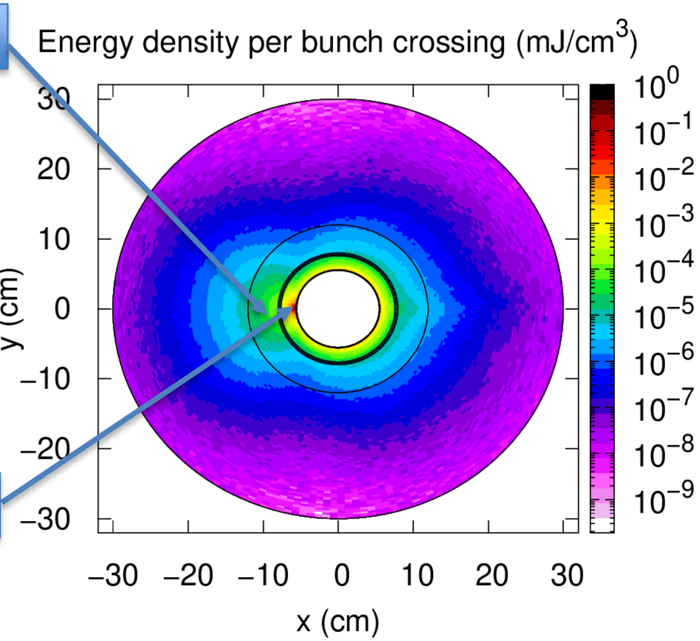
Loss challenge in collider ring:
Loss per unit length is constant
fewer, but higher energy particles
Simulations of shielding started



A. Lechner
D. Calzolari

Shielding

Coils



Demonstrator Considerations

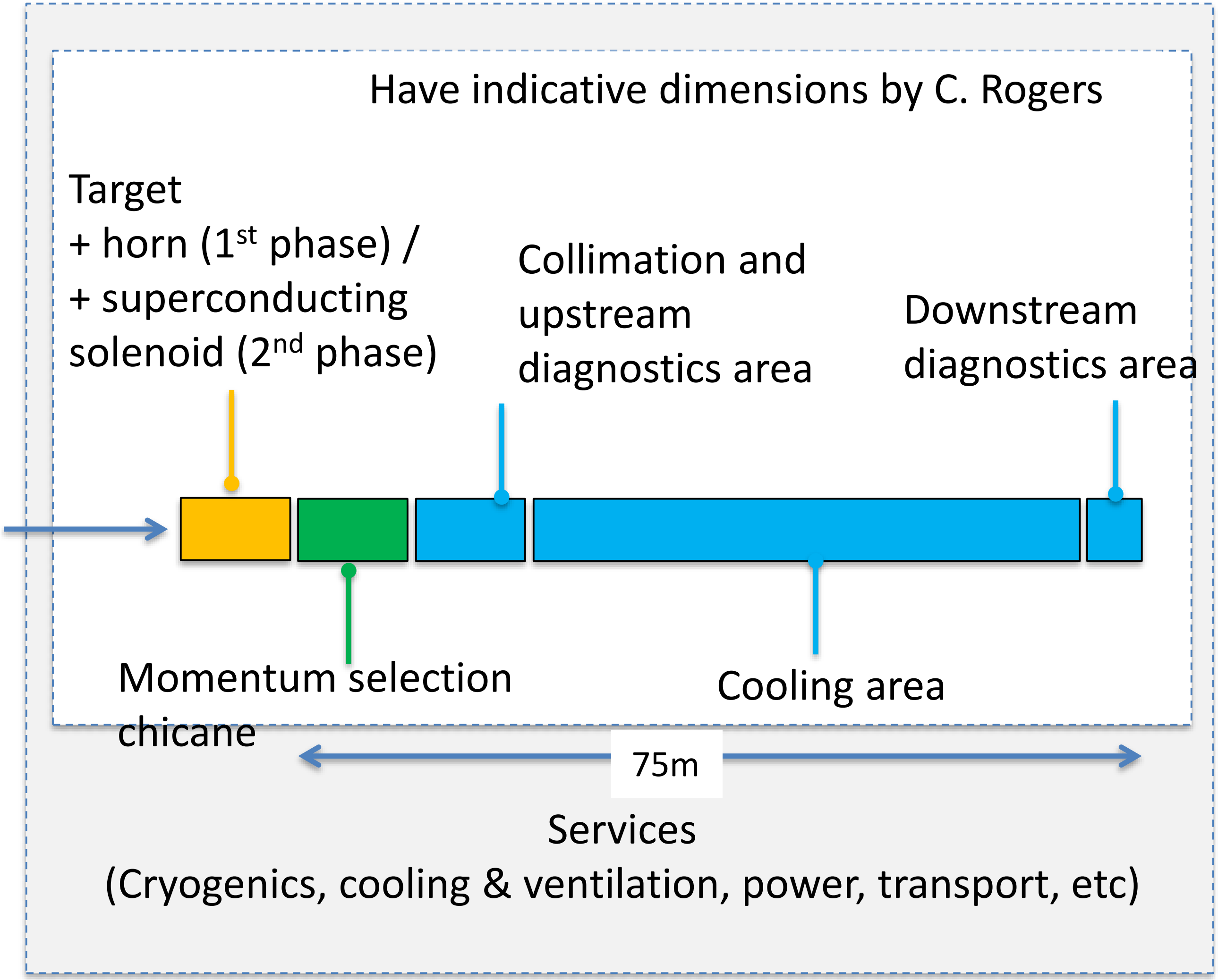
Muon cooling is the key novel and unique component of muon collider
⇒ need a test in a demonstrator
Other technology challenges exist but can be addressed with prototypes (e.g. collider dipoles), also in other locations

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

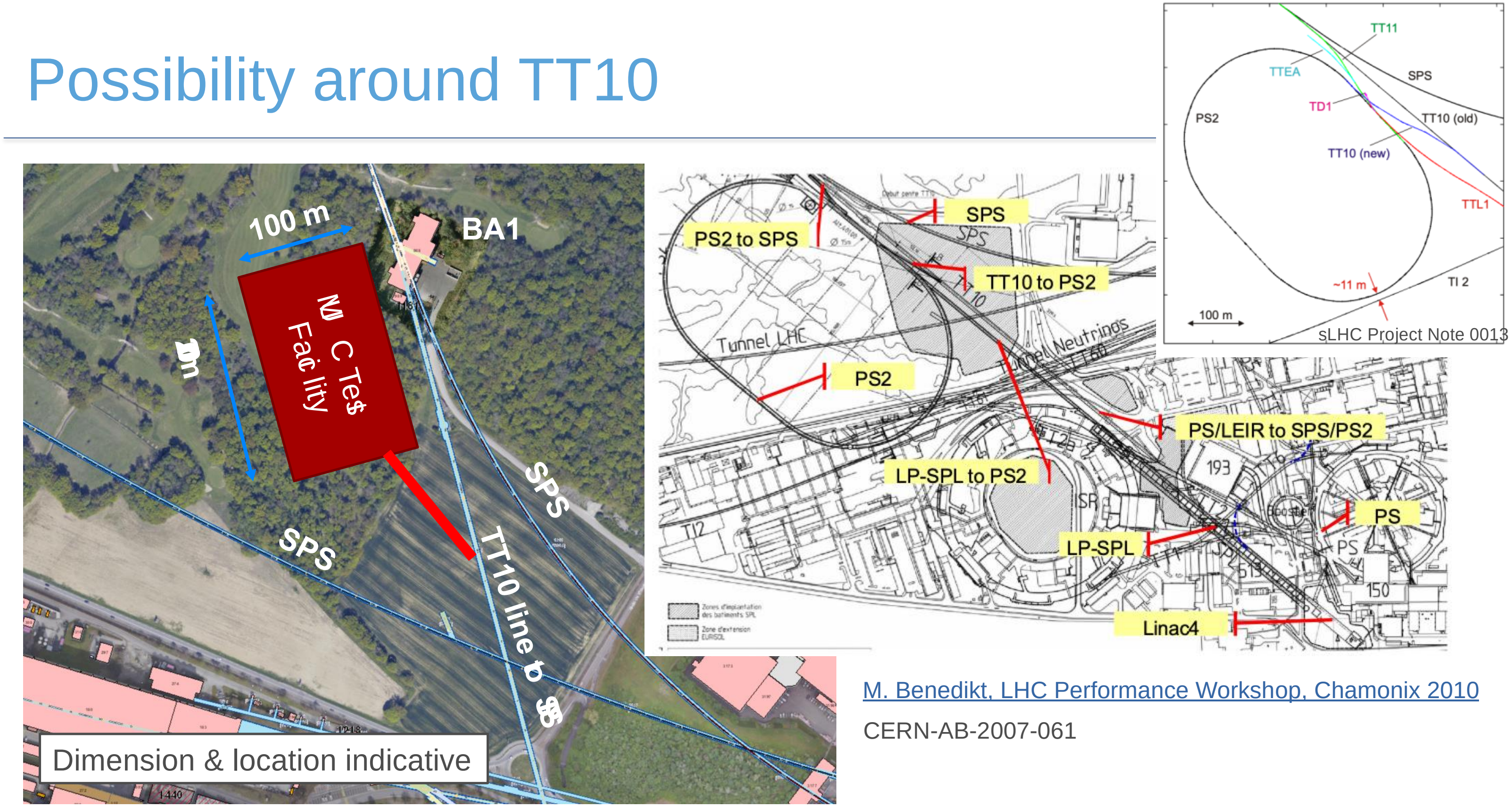


CERN Site Example

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

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

Possibility around TT10



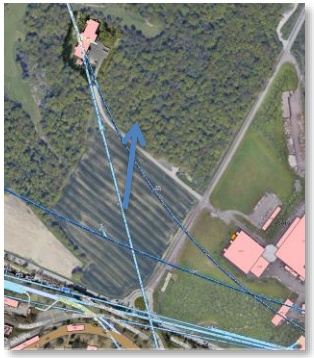
Dimension & location indicative

sLHC Project Note 0013

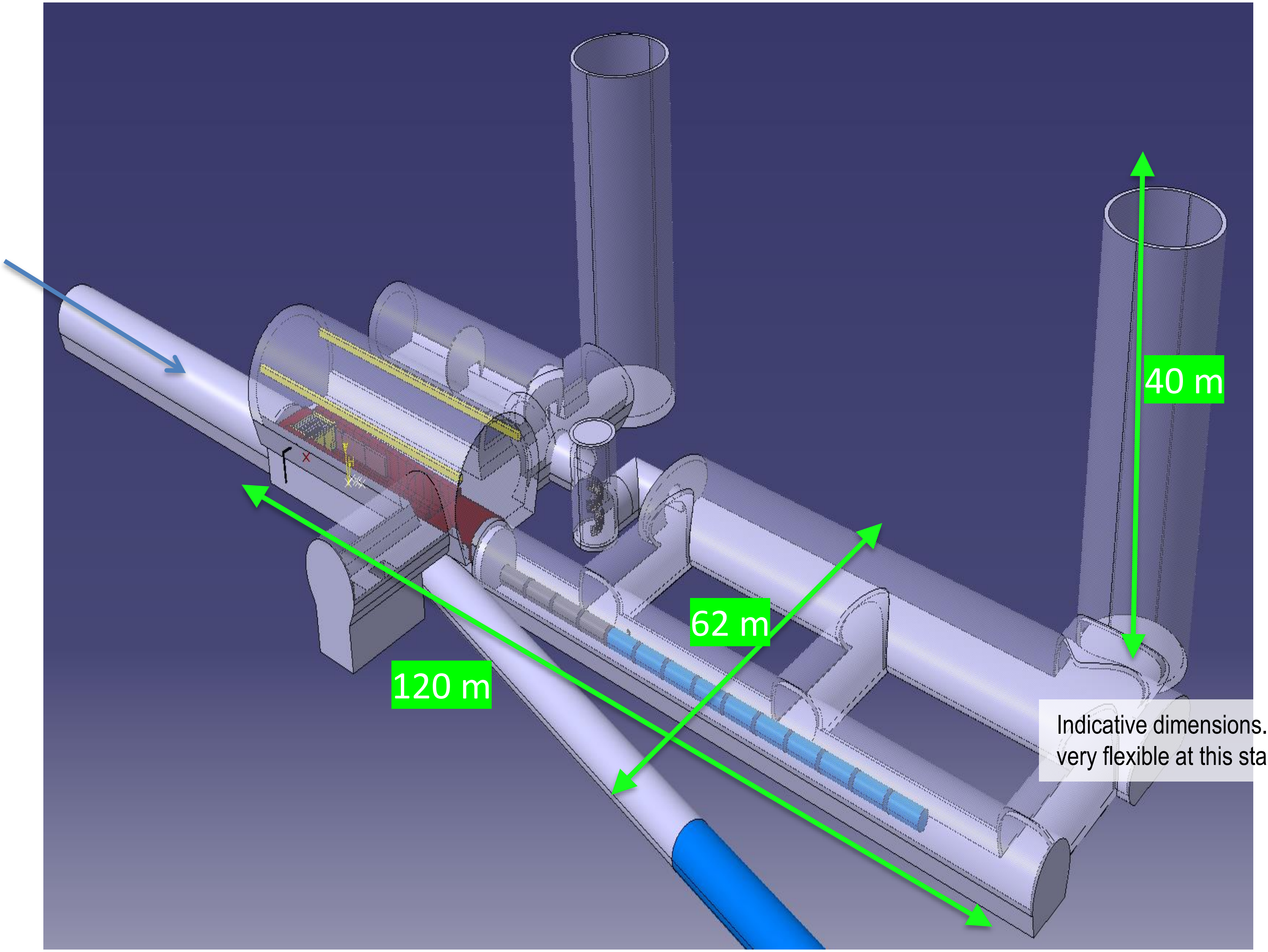
M. Benedikt, LHC Performance Workshop, Chamonix 2010

CERN-AB-2007-061

Tentative Layout



CERN TT10
branch

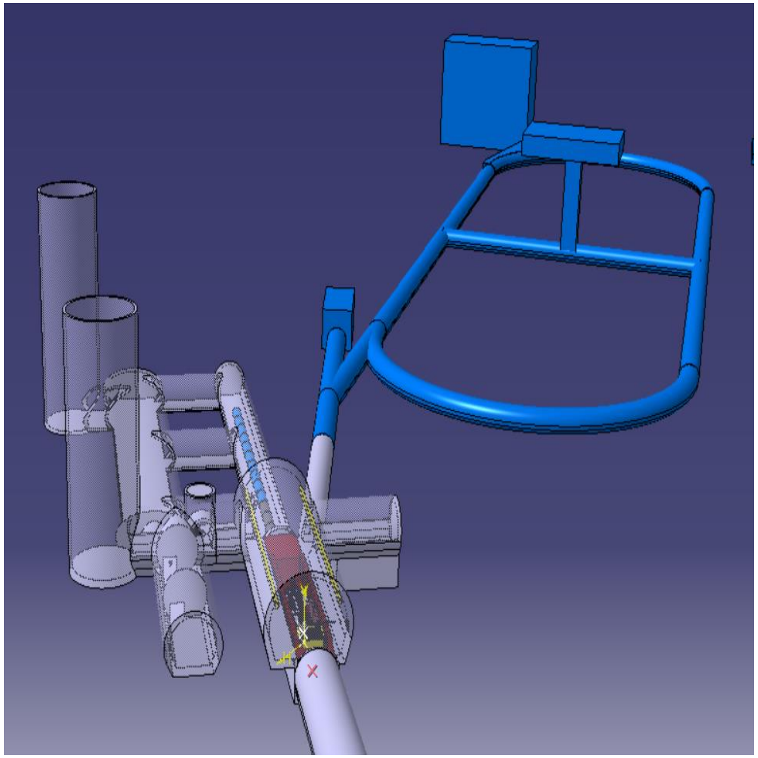


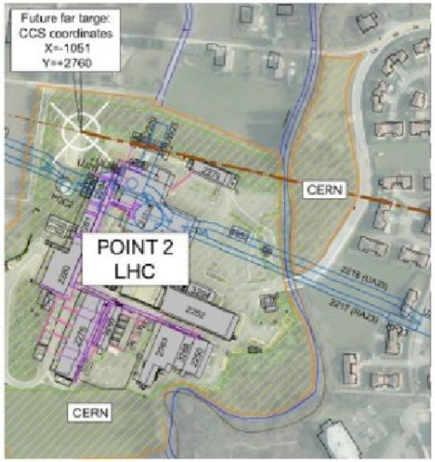
Indicative dimensions. Model is very flexible at this stage

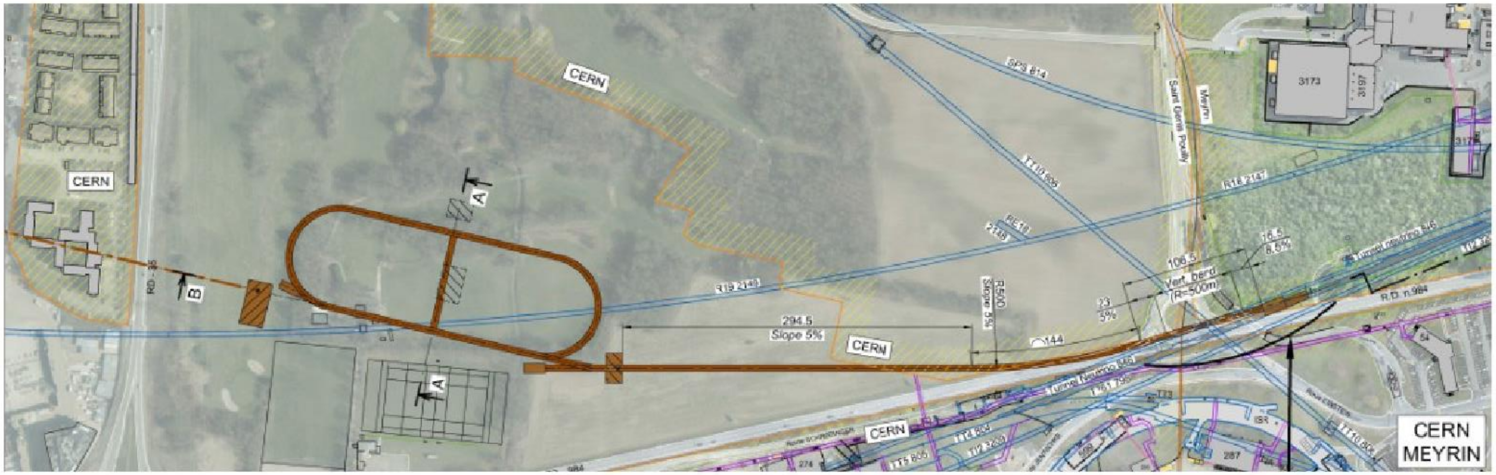
Synergy

The Facility could accommodate other experiments.

- **nuSTORM** and potentially **ENUBET** could be branched from the target of the Demonstrator
- roughly half the nuSTORM cost would be shared
- 26 GeV/c beam from the PS is appropriate for nuSTORM
- Would be on CERN land (other location using SPS as injector is not but has higher proton energy)







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.

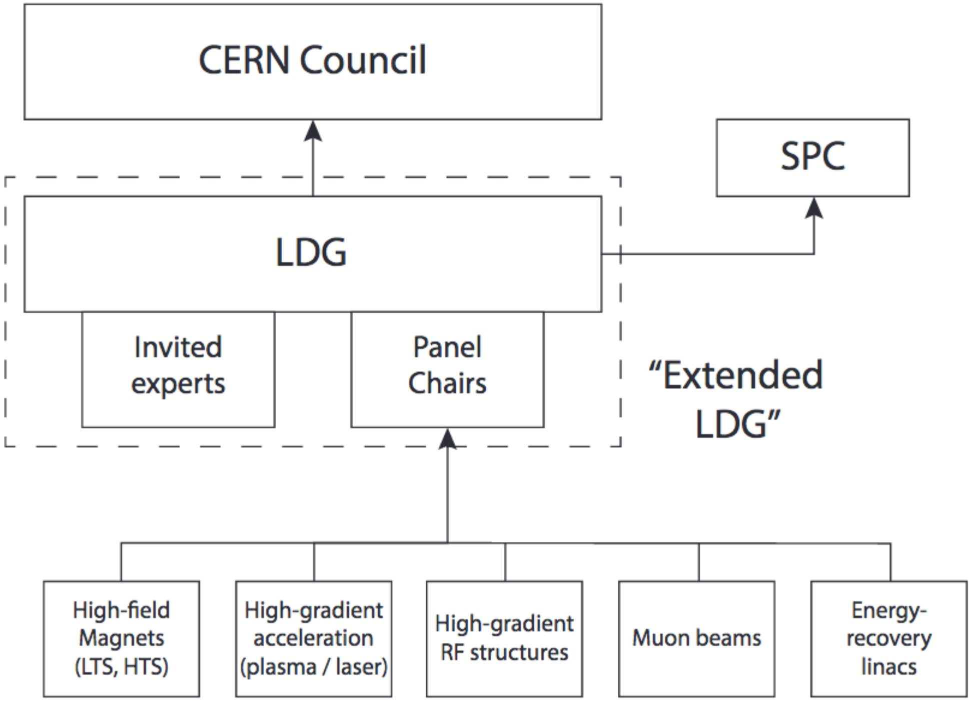
and potential ramp-up

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

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

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 (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).

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.

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 (2026)

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

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 mid2040s) in case Europe does not build higgs factory

Tentative Target for Aggressive Timeline

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

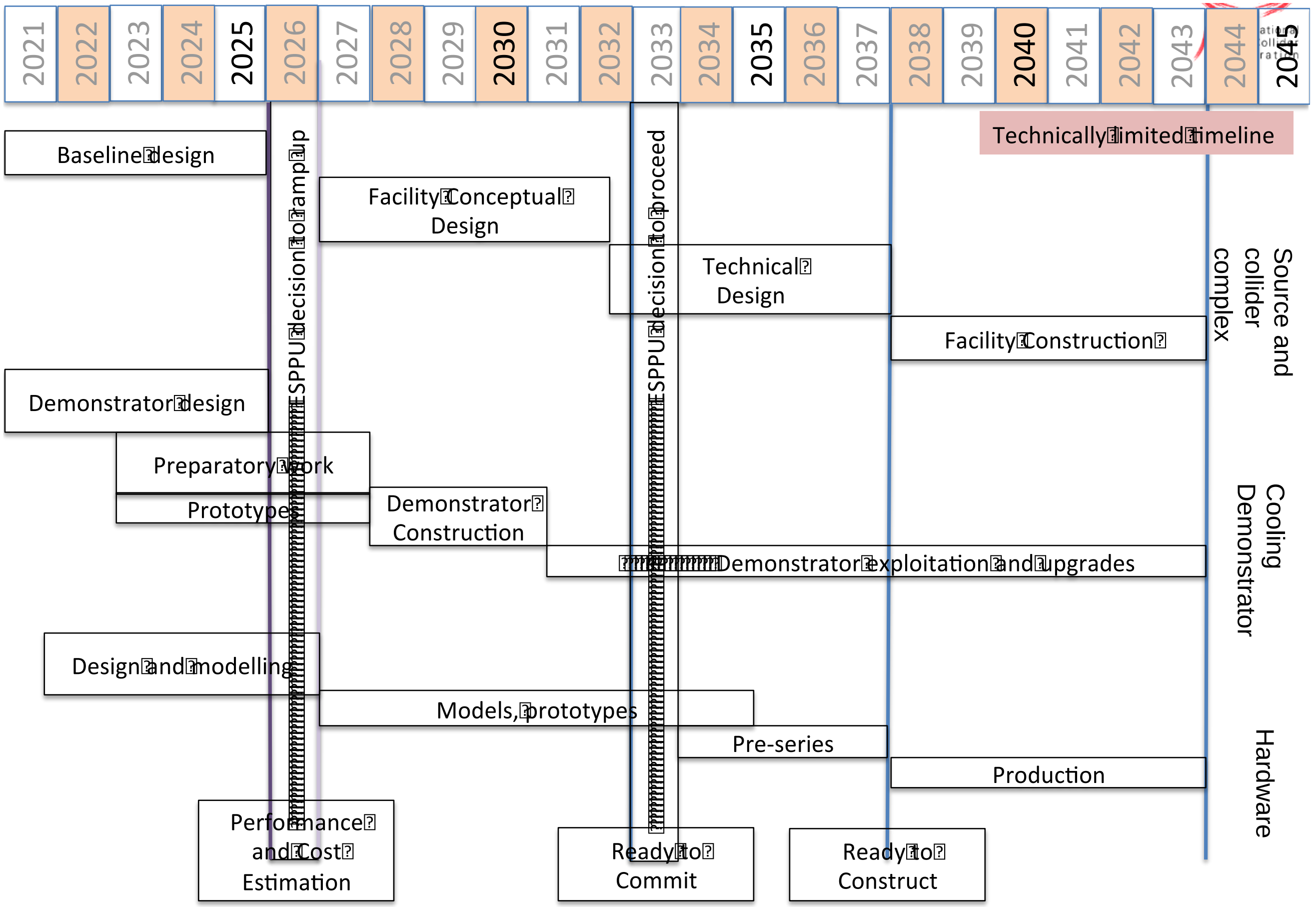
Exploring shortest possible aggressive timeline with initial 3 TeV stage on the way to 10+ TeV

- 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.



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

Technically limited timeline

Baseline design

ESPPU decision to ramp up

Facility Conceptual Design

ESPPU decision to proceed

Technical Design

Facility Construction

Source and collider complex

Demonstrator design

Preparatory work

Prototypes

Demonstrator Construction

Demonstrator exploitation and upgrades

Cooling Demonstrator

Design and modelling

Models, prototypes

Pre-series

Production

Hardware

Performance and Cost Estimation

Ready to Commit

Ready to Construct

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

Reserve

Memorandum of Cooperation

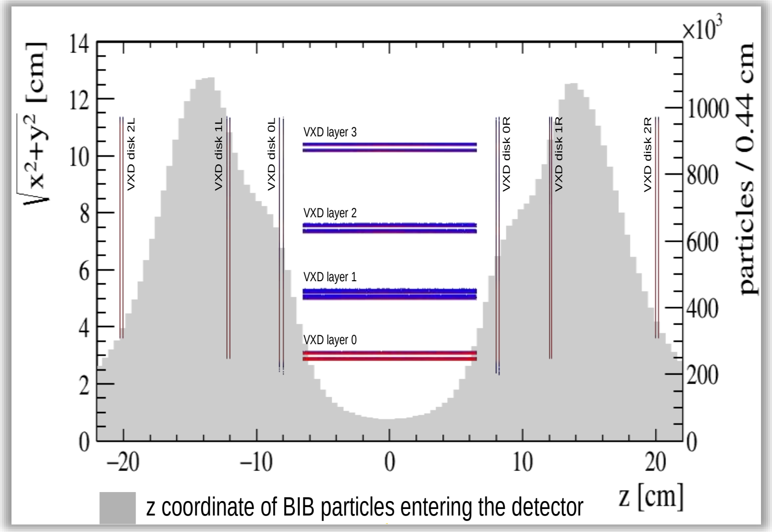
CERN is initially hosting the study

- 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

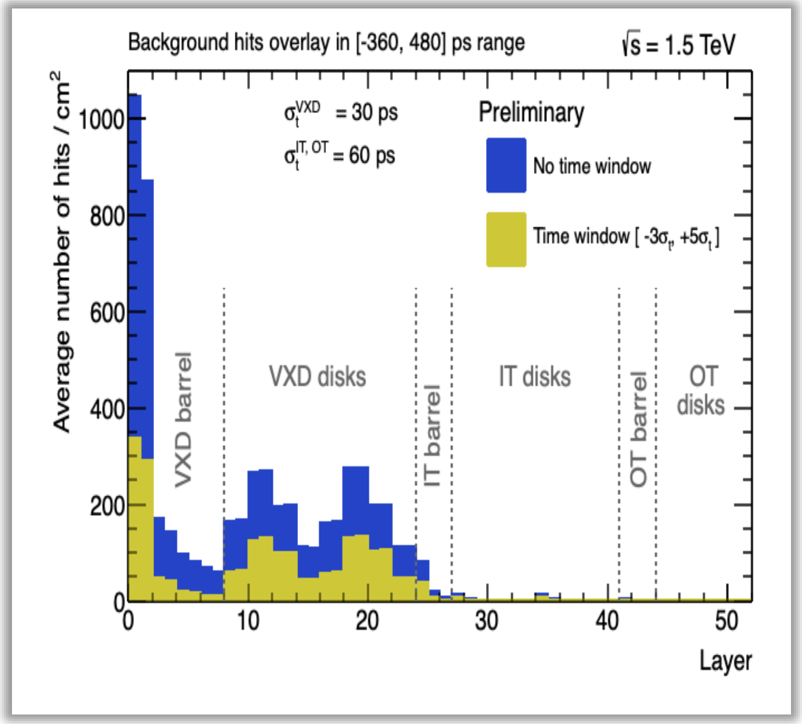
MDI and Detector Design

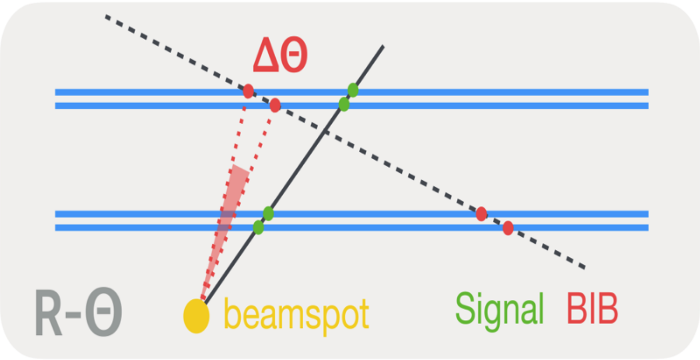
Preliminary



Vertex detector properly designed to not overlap with the BIB hottest spots around the interaction region.

Preliminary





BIB particles not coming from primary vertex, double layer structure can be exploited correlate hit pairs on adjacent sensors to estimate incoming particle direction.

Tracking performance have been studied applying timing on clusters reconstruction compatible with IP time spread.

Collaboration Timeline Goals

3 TeV collider option

- Goal: option ready to take data before 2045
- Important step up in energy after a higgs factory
- Maximum energy of CLIC
  - CLIC integrated cost is 18 GCHF and it uses 590 MW power)
  - aim for significantly lower cost and power consumption
- One option with technologies expected to be available in 15-20 years
  - will adjust design accordingly

10+ TeV collider option

- Goal: Highest lepton energies, well above the reach even of CLIC
- To explore energy reach for a realistic collider and understand if muon collider is right direction for long-term future
  - aim for competitive cost and power
- Employing advanced technologies, not yet concerned about schedule
- Could be upgrade of a 3 TeV collider
  - splitting the cost into two stages, only 3 TeV collider ring cost is lost

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

Production and 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 have a test facility that produces and cools muons

Cooling Challenges and Status

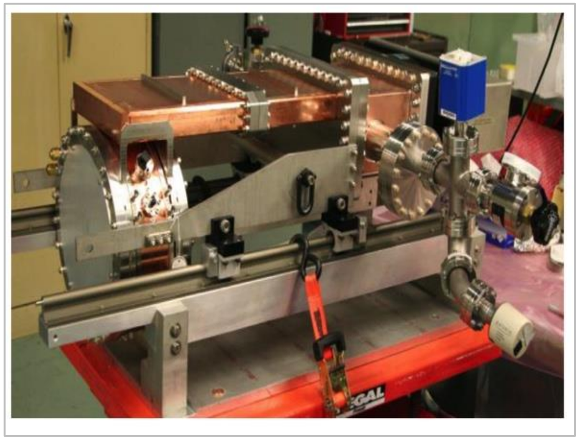
FNAL
12 T/s
HTS
0.6 T max

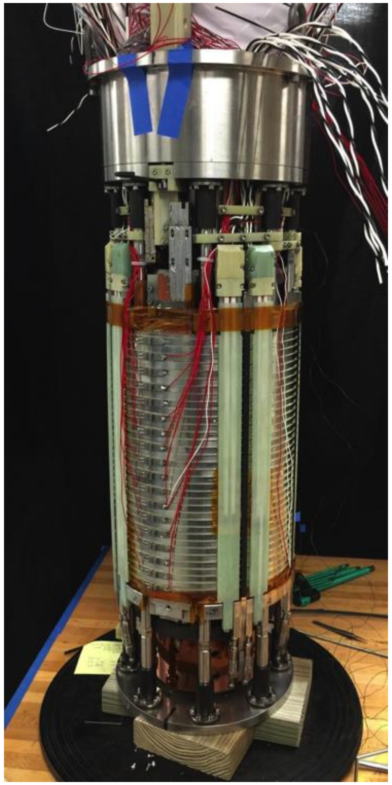
Need to push in field and speed

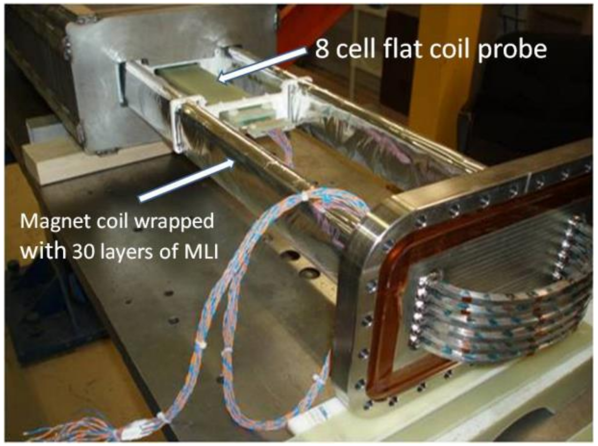
Test of **fast-ramping normal-conducting magnet** design

MuCool: >50 MV/m in 5 T field

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



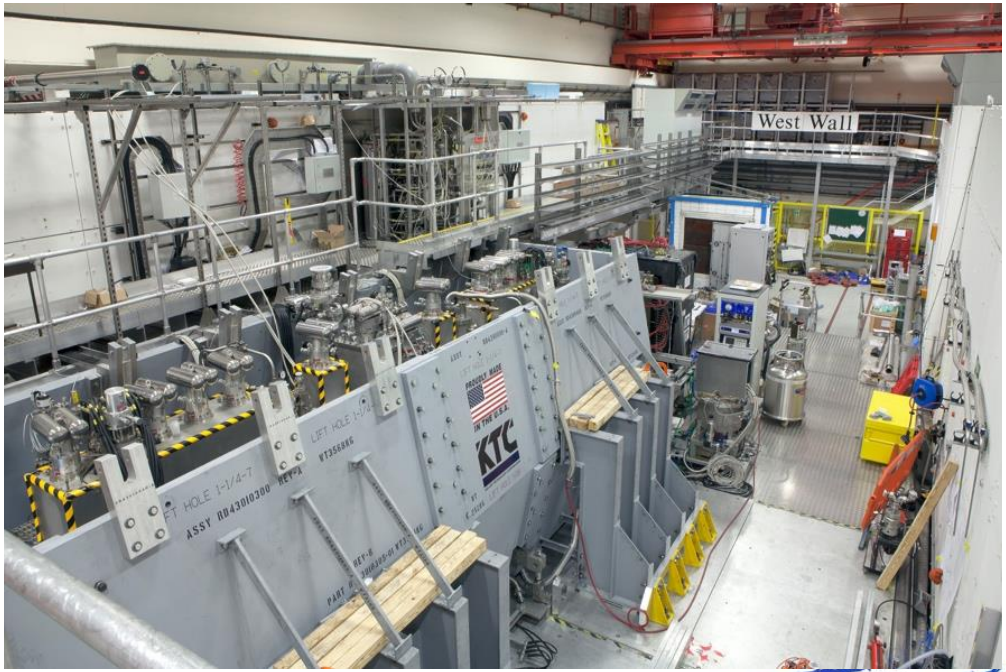




NHFML
32 T solenoid with HTS

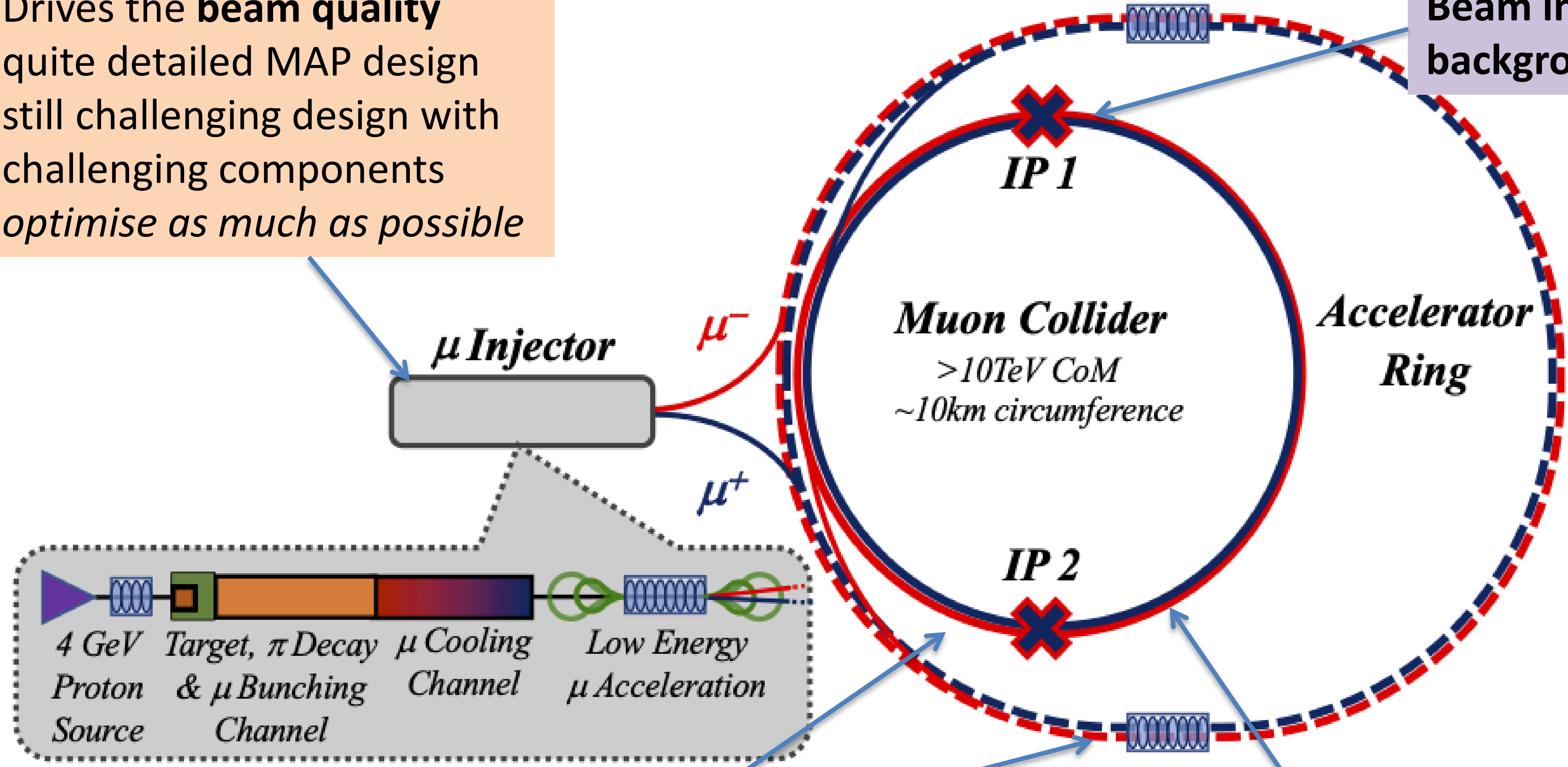
Planned efforts to push even further

MICE (UK) Muon cooling principle



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

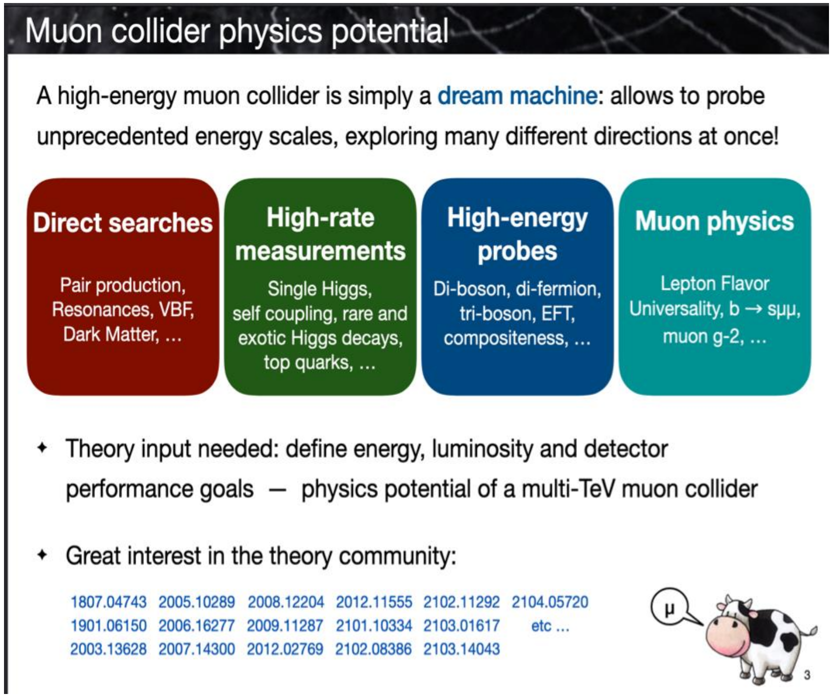
Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts **beam quality**

Physics at Muon Collider

Muon Collider can be the game changer

[The Muon Smasher's Guide](#)

D. Buttazzo



Muon collider physics potential

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 → sμμ, 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

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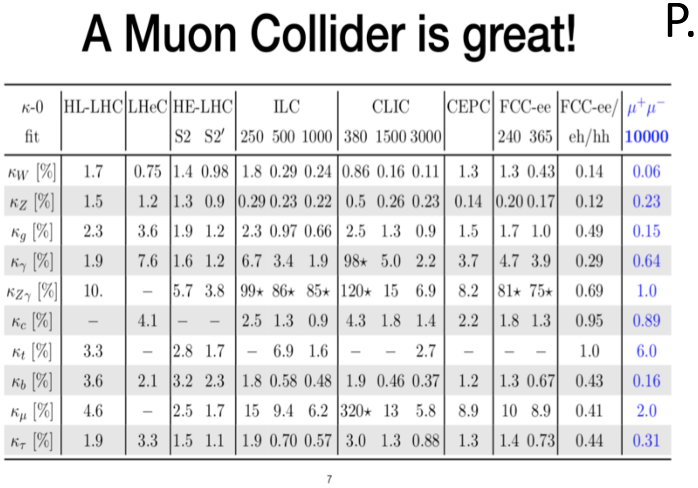
P. Maede



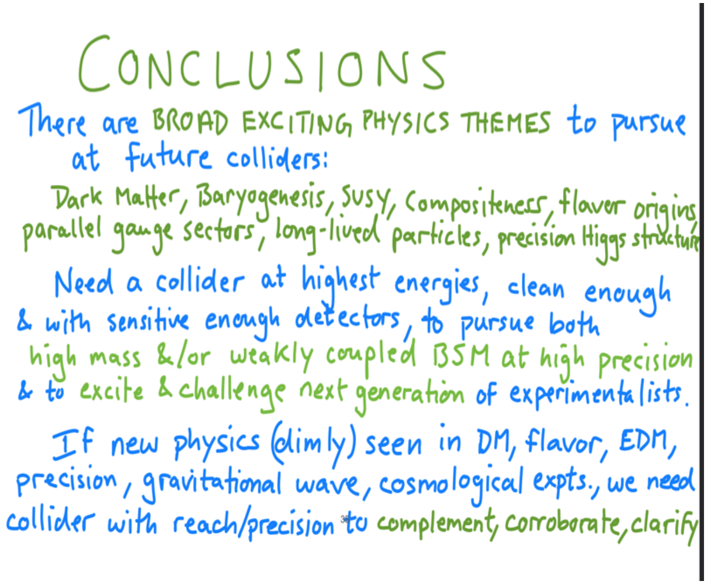
A Muon Collider is great!

κ-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
κ_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
κ_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
κ_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
κ_γ [%]	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
κ_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
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	6.0
κ_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
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.0
κ_τ [%]	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

R. Sundrum



CONCLUSIONS

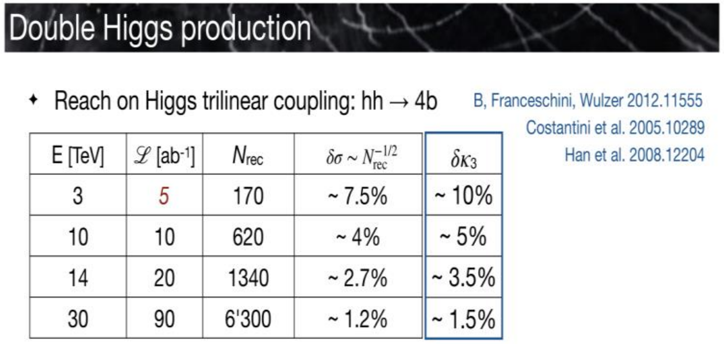
There are BROAD EXCITING PHYSICS THEMES to pursue at future colliders:

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

Di-Higgs too!



Double Higgs production

- Reach on Higgs trilinear coupling: hh → 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

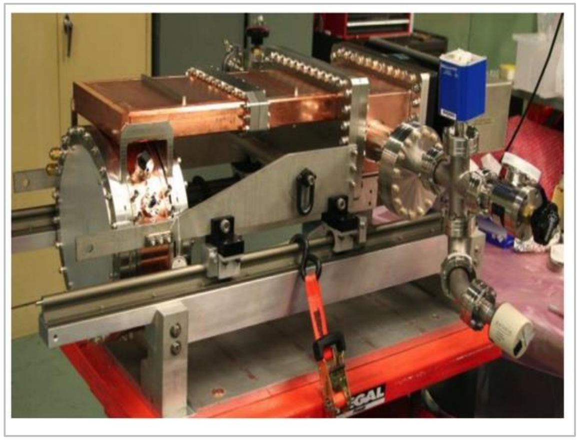
FNAL
12 T/s HTS
0.6 T max

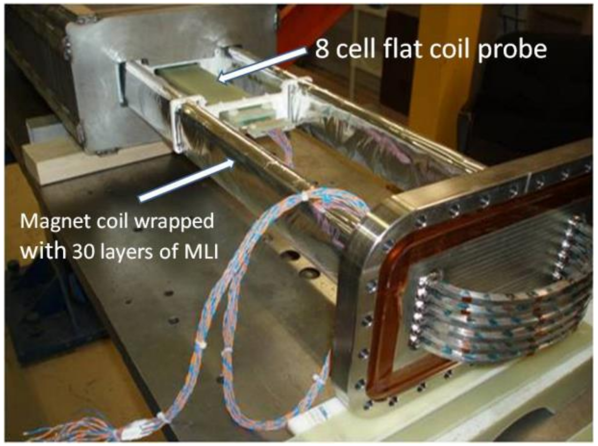
now 290 T/s

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

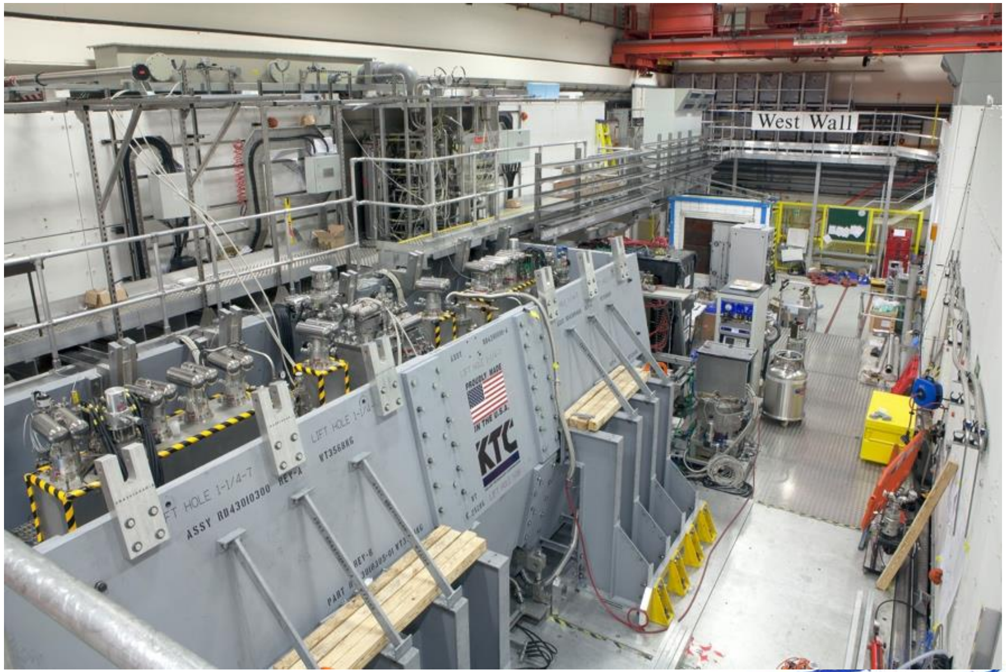
MuCool: >50 MV/m in 5 T field

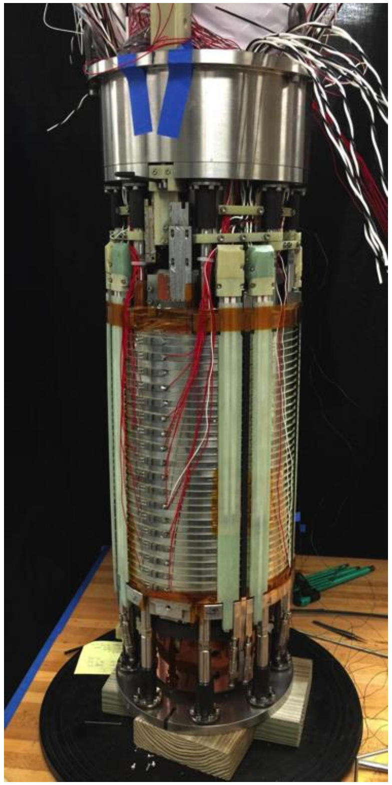
Two solutions
- Copper cavities filled with hydrogen
- Be end caps





MICE (UK) Muon cooling principle



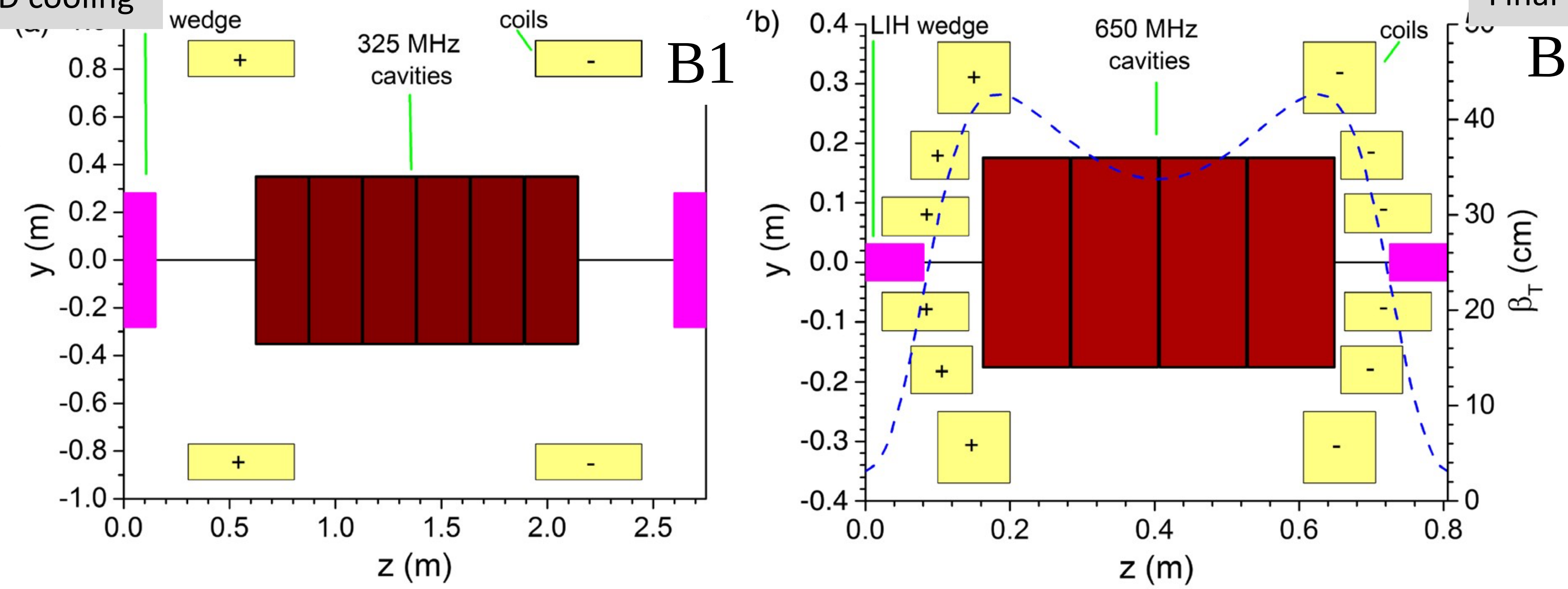


NHFML
32 T solenoid
with HTS

Planned efforts
to push even
further

Example Cell Designs

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



Initial 6D cooling

B1

2.2 T

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, …