Muon Collider for HEP

Daniel Schulte for the forming international muon collider collaboration

Introduction

Muon collider had been studied mainly in the US (MAP), effort reduced after P5

Other activities mainly in UK (demonstration of ionisation cooling) and at INFN (alternative muon production scheme)

The Laboratory Directors Group (LDG) appointed a working group (chair N. Pastrone) to review the muon collider for the European Strategy Update

- The report was favorable

The updated strategy recommends R&D on muon beams

Council charged LDG to develop European Accelerator R&D Roadmap in 2021

CERN will host the study, we are finalising a Memorandum of Cooperation

- current CERN budget 2 MCHF/year for the next 5 years

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.

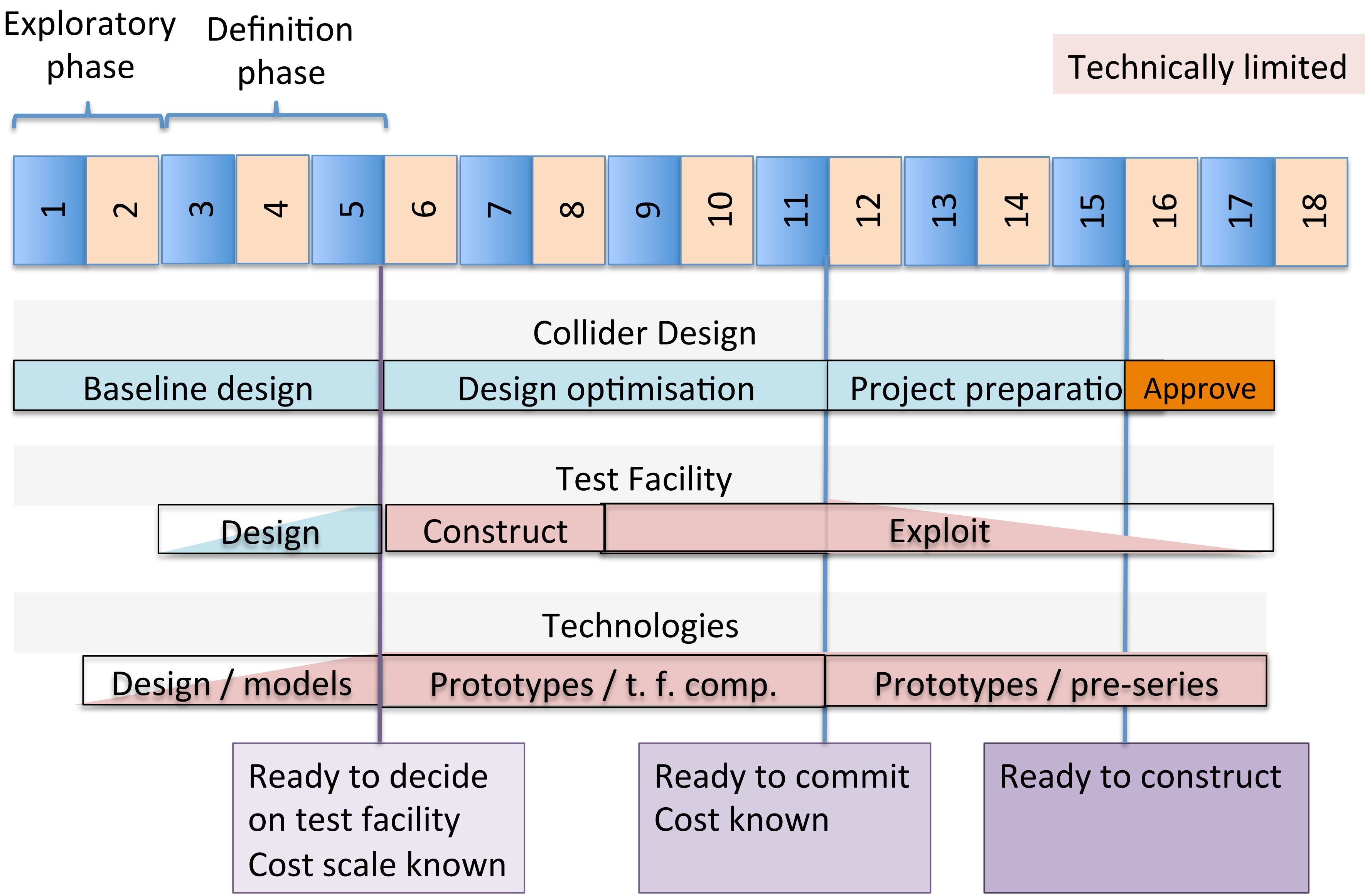
Deliverable:

Report assessing muon collider potential and describing R&D path to CDR

Scope:

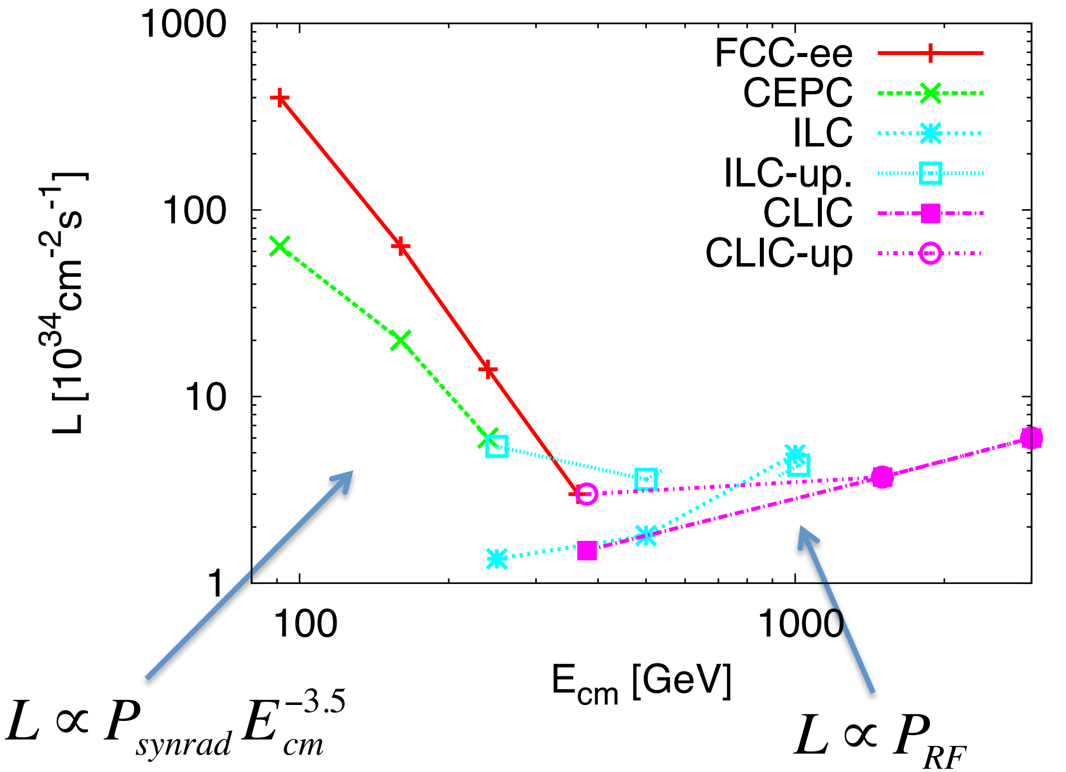
- Focus on two energy ranges:
  - **3 TeV**, if possible with technology ready for construction in 10-20 years
  - **10+ TeV**, with more advanced technology
- Explore synergy with other options (neutrino/higgs factory)
- Define **R&D path**

Potential Long-Term Timeline



Proposed Lepton Colliders (ESU)

Luminosity per facility



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?

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

Luminosity goal increases with centre-of-mass energy squared

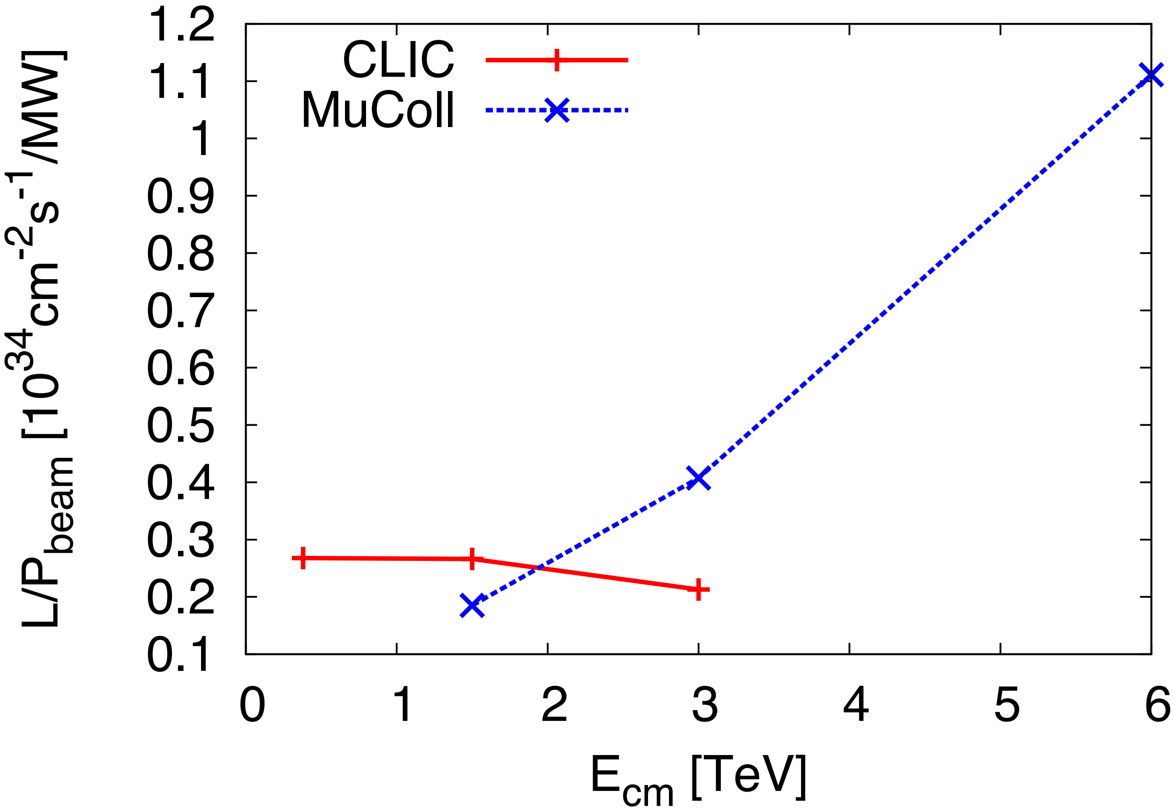
Comparing Luminosity in MAP vs. CLIC

In linear colliders luminosity per beam power is independent of collision energy for same technology

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

No obvious way to improve

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$



Luminosity per beam power increases with energy in muon collider

Muon colliders have the potential for high energies

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

Linear Collider Scaling

Cost

CLIC upgrade 3 TeV to 14 TeV is O(40-50 GCHF)

- (14 TeV - 3 TeV) / 1.5 TeV * 8 GCHF = **59 GCHF**
- some cost reduction due to large-scale production

Maybe other non-mature technologies can be cheaper

Power

For CLIC about **190 MW beam power** to reach 40 x $10^{34}cm^{-2}s^{\wedge-1}$ at 14 TeV

- If we consider only luminosity above 99% of nominal centre-of-mass energy, we need about **570 MW beam power**

Efficiency from wall plug power into RF systems to beam power is O(10%)

- so **O(2-6 GW)** of **total power** consumption

Need to add the other systems (which also will increase compared to 300 MW)

Hard to see other linear colliders do any better

Preservation of beam quality is more challenging in plasma-based accelerators than in CLIC

Luminosity Goals

Target integrated luminosities

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

Reasonably conservative

- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- But might need some operational margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

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

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
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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

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

Key Topics

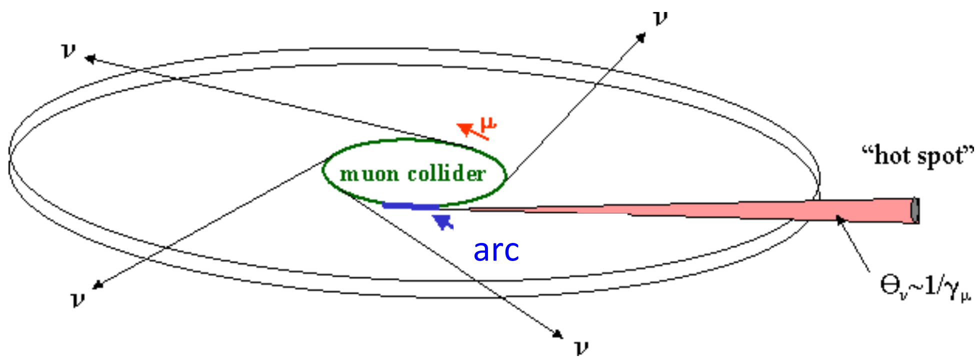
10+ TeV is uncharted territory

- **Physics potential** evaluation

see Tao Han's presentation

- Impact on the environment
  - The **neutrino radiation** and its impact on the site
- 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 and beam quality
- **High-quality beam production** of cooled muon beam
  - MAP did study this in detail
  - Need to optimise and prepare test facility

Neutrino Radiation



Neutrinos from muon decays can produce showers when exiting the earth

Due to narrow neutrino beam, radiation can become relevant
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

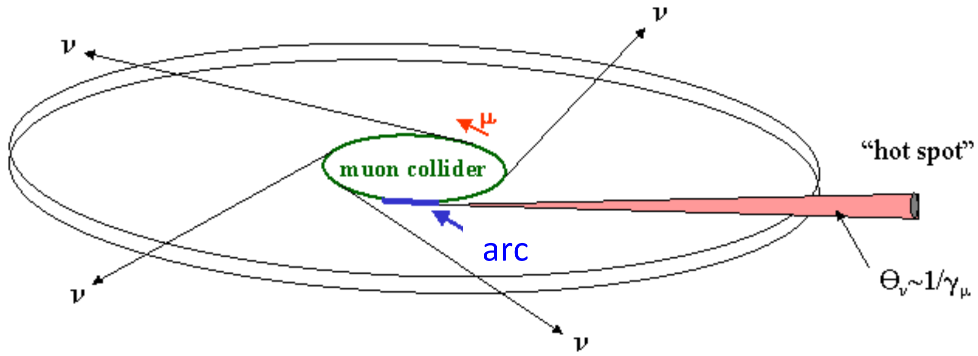
LHC achieved < 5 μSv/year

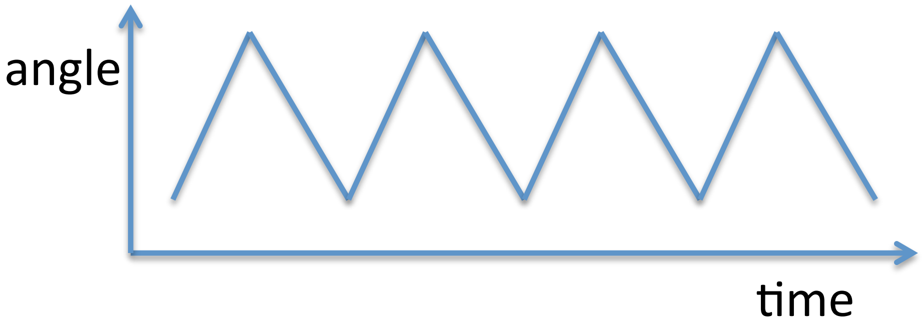
Work with **Radiation Protection, Civil Engineering** and **Lattice Design** started to find solutions

Mitigate radiation to a level as low as reasonably possible

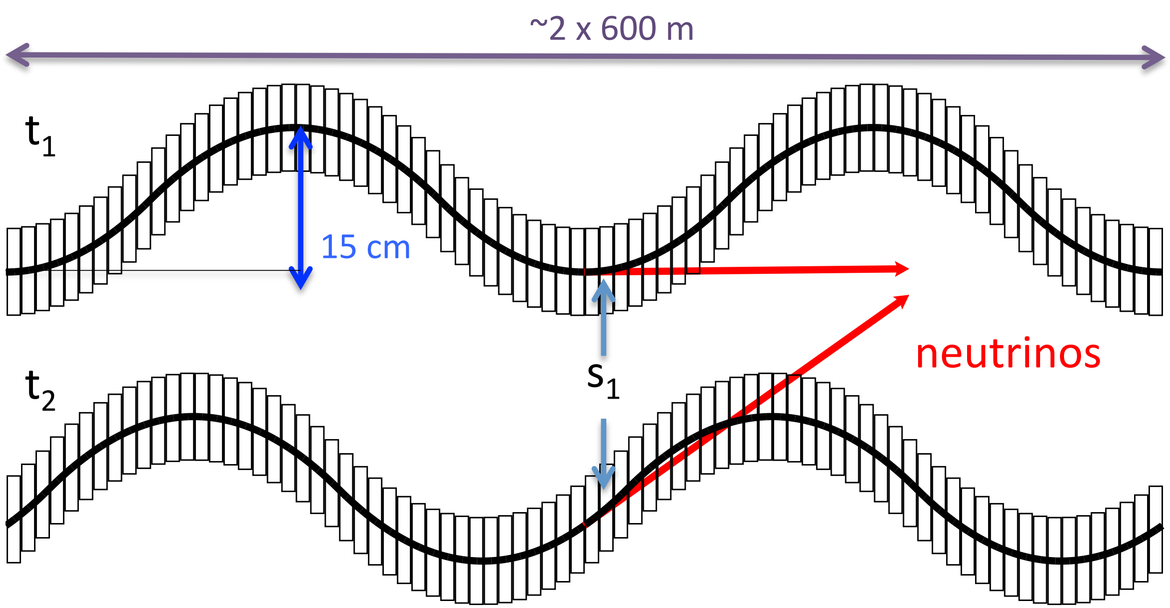
Similar to LHC

Neutrino Radiation Mitigation





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 and operation, e.g. dispersion control

Tentative Detector Performance Specification

Established tentative detector performance specifications

- in form of DELPHES card
- for feedback from physics and detector studies
- based on FCC-hh and CLIC performances
- including masks against beam induced background (BIB)
- Please find the card here: https://muoncollider.web.cern.ch/node/14

(thanks to M. Selvaggi, Werner Riegler, Ulrike Schnoor, A. Sailer, D. Lucchesi, N. Pastrone M. Pierini, F. Maltoni, A. Wulzer et al.)

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

Detector Background Studies

Detector is based on CLIC detector

Nozzles added to protect from beam-induced background (BIB)

Each beam contains one bunch crossing every 15 μs (3 TeV) or 47 μs (14 TeV)

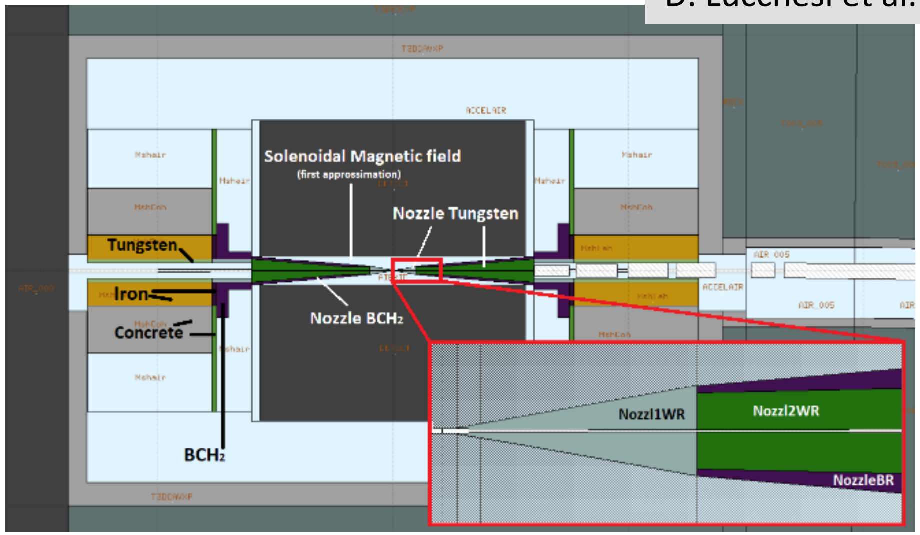
Muon decay rate

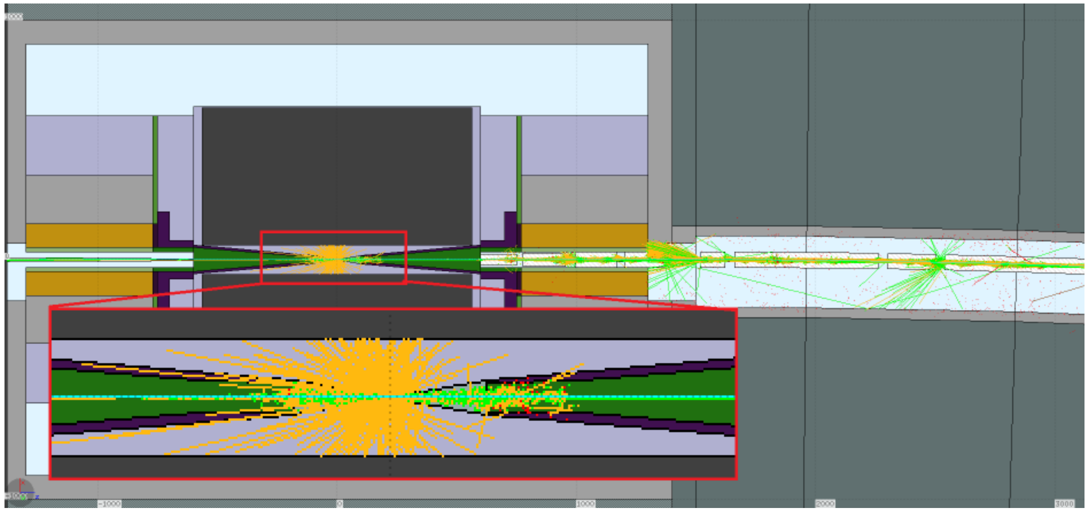
- at 3 TeV: 200,000 $bx^{-1}\ m^{-1}$
- at 14 TeV: 40,000 $bx^{-1}\ m^{-1}$

Simulations for 1.5 TeV with FLUKA comparing to previous MAP results (MARS)

Will study higher energies as machine designs become available

D. Lucchesi et al.

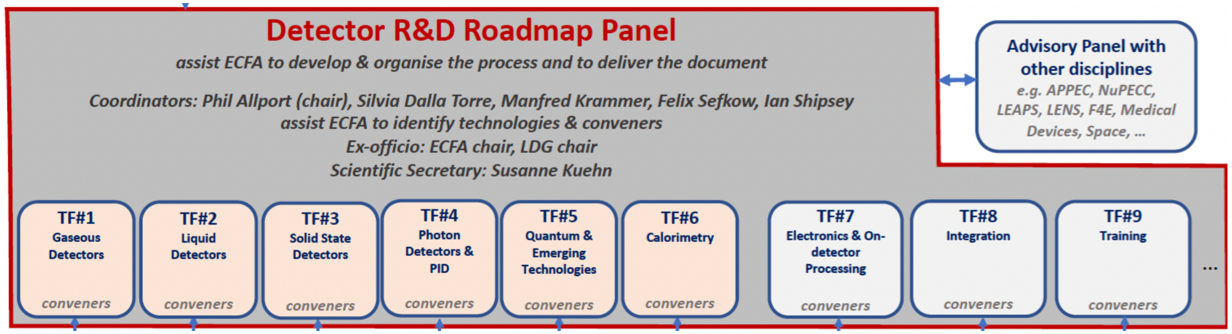




Detector Technologies

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

- Will provide link persons to relevant working groups



Currently consider the following most important (N. Pastrone)

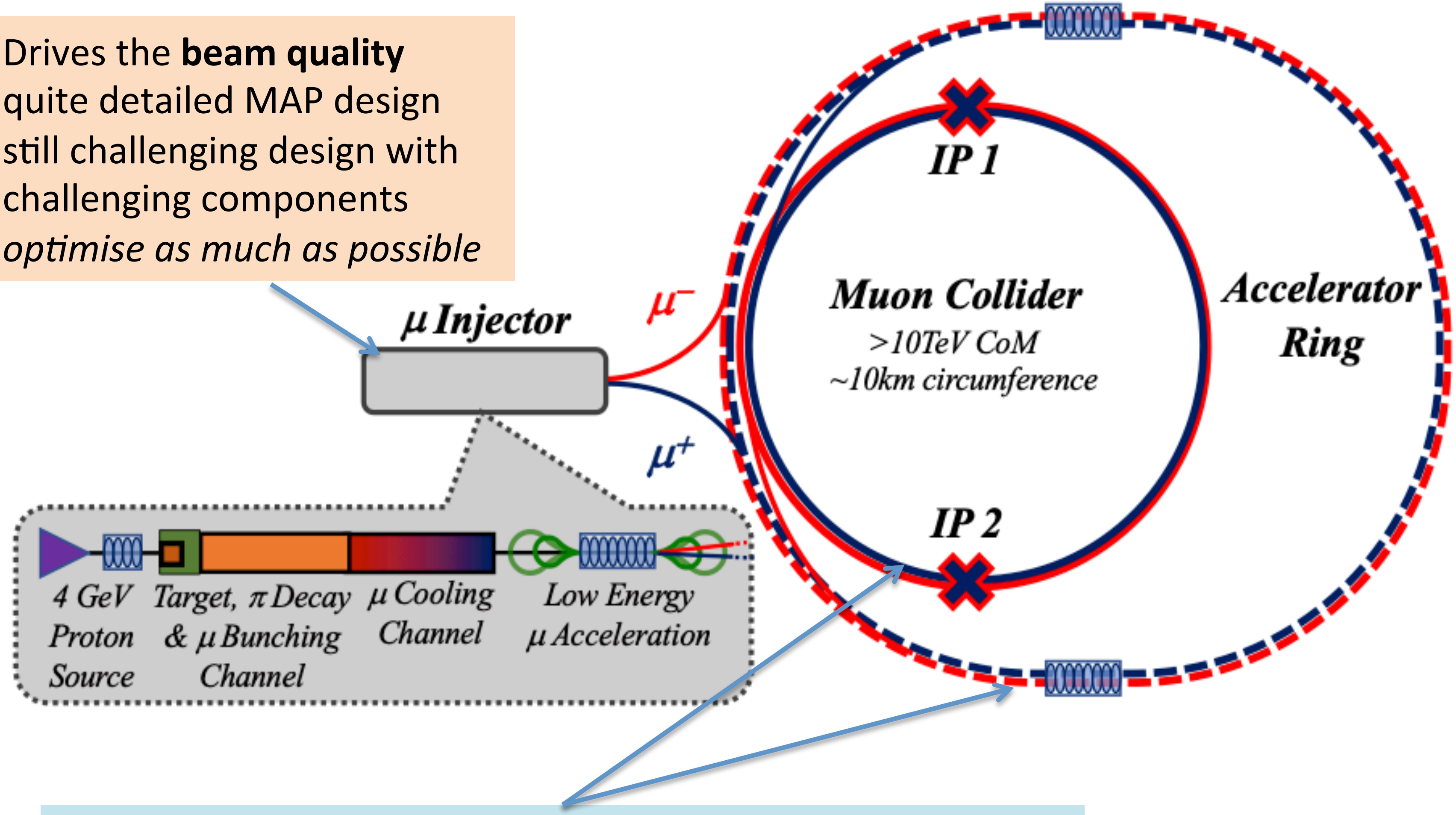
- solid state tracking
- calorimetry
- emerging technologies
- electronics and in detector processing

Will also include other regions

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

Overall Considerations

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



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**
Drives **neutrino radiation** and **beam induced background**

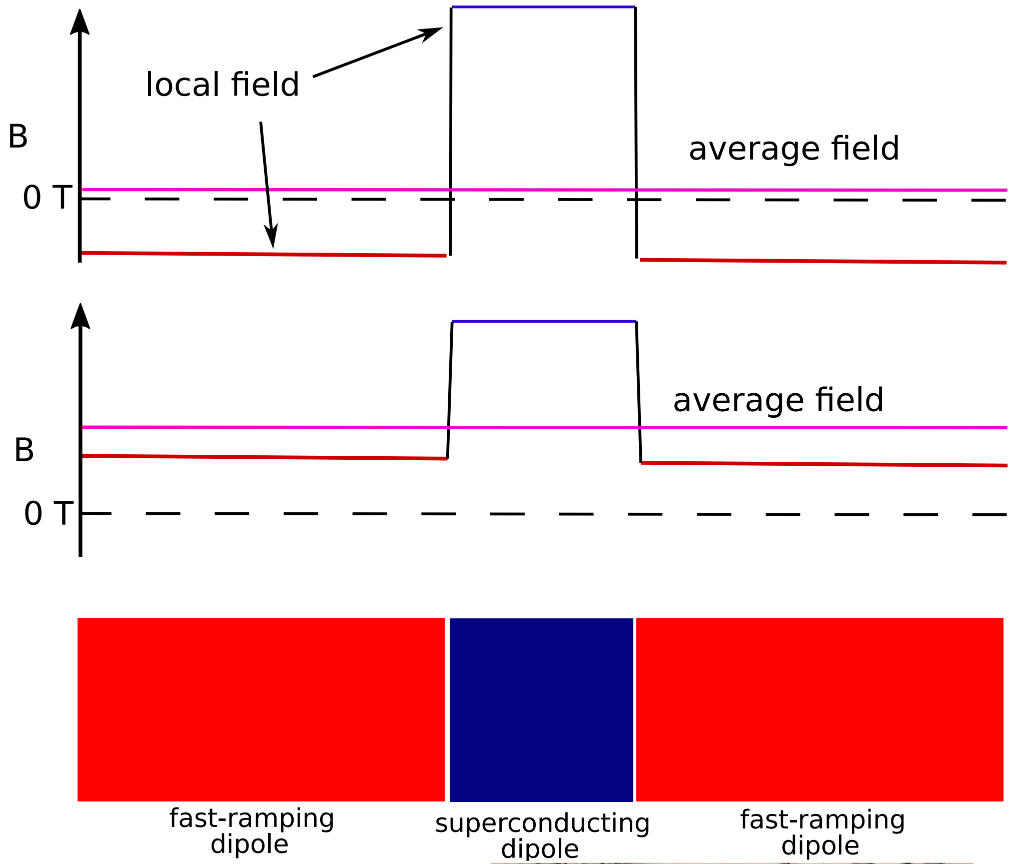
High-energy Acceleration

Rapid cycling synchrotron (RCS)

- Ramp magnets to follow beam energy
- Combination of static and ramping magnets
- Possible circumference
  - 14-26.7 km at 3 TeV
  - O(30 km) for 10 and 14 TeV

Fast-pulsing magnets (O(ms) ramps))

Magnetic field **energy recovery**



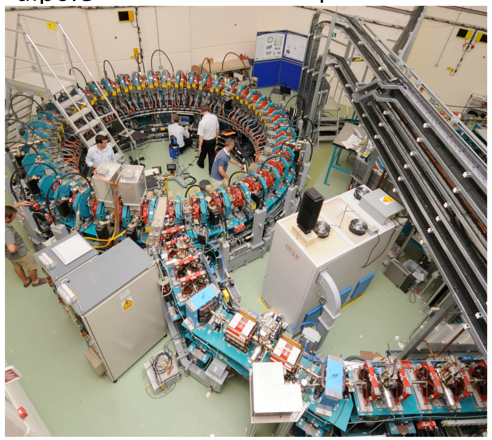
FFAG

Lattice with high-field magnets that are static and accommodates different energies at different location in the magnets

- 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)

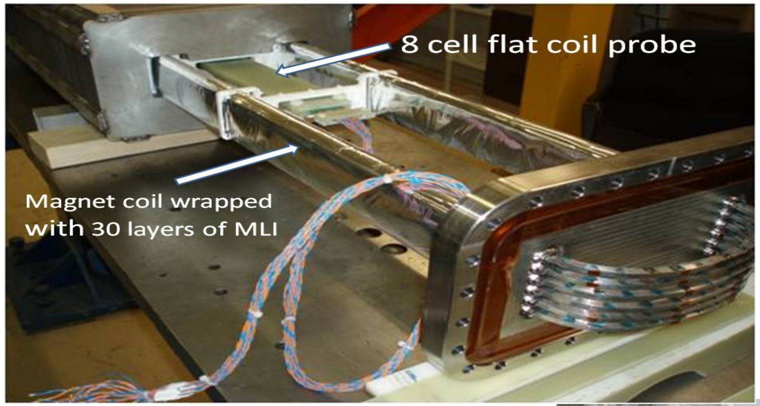


RCS

In hybrid design, need 5 km of 2 T of **fast-ramping, normal-conducting magnets** per TeV beam energy

O(30 km) for 1.5-5/7 TeV
- for 7 TeV two rings in same tunnel
- or **higher field HTS ramping magnets**

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



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

Started to work on **power converters** (efficient recovery of energy in ramping magnets, O(200 MJ) at 14 TeV

FNAL
12 T/s HTS
0.6 T max

Need to push in field and speed

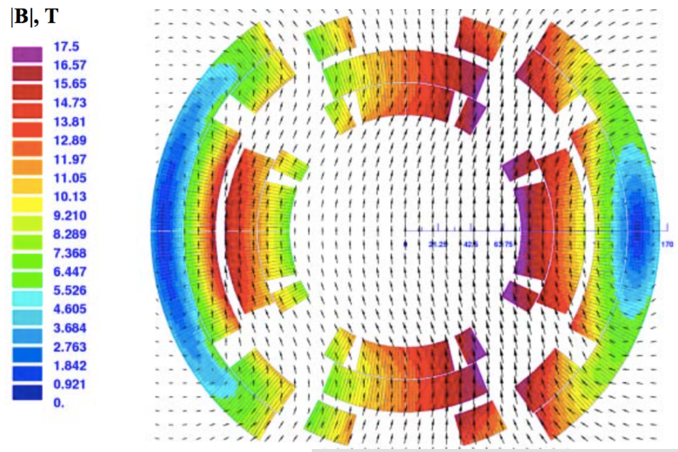
RF challenge (also for FFA):
High efficiency for power consumption
High-charge, single-bunch beam (10 x HL-LHC)
Maintain small longitudinal emittance

Collider Ring

High field dipoles to minimise collider ring size and maximise luminosity
4.5 km/10 T at 3 TeV, 10/14 km/15 T at 10/14 TeV

Need to **protect** from O(500 W/m) **beam loss**
- independent of energy, magnetic dipole field etc.
- depends on emittance, betafunction etc.
- large aperture and shielding
  - 150 mm in MAP at 3 TeV, 30-50 mm shielding
- open mid-plane magnets
- efficient cooling

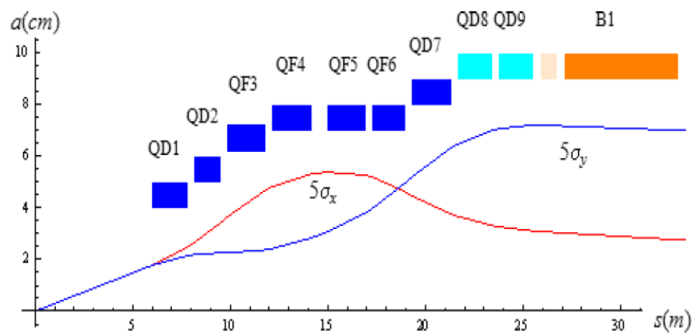
Combined function magnet design



V.V. Kashikhin et al.

Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy
Divergence independent of energy
Challenging triplet design

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



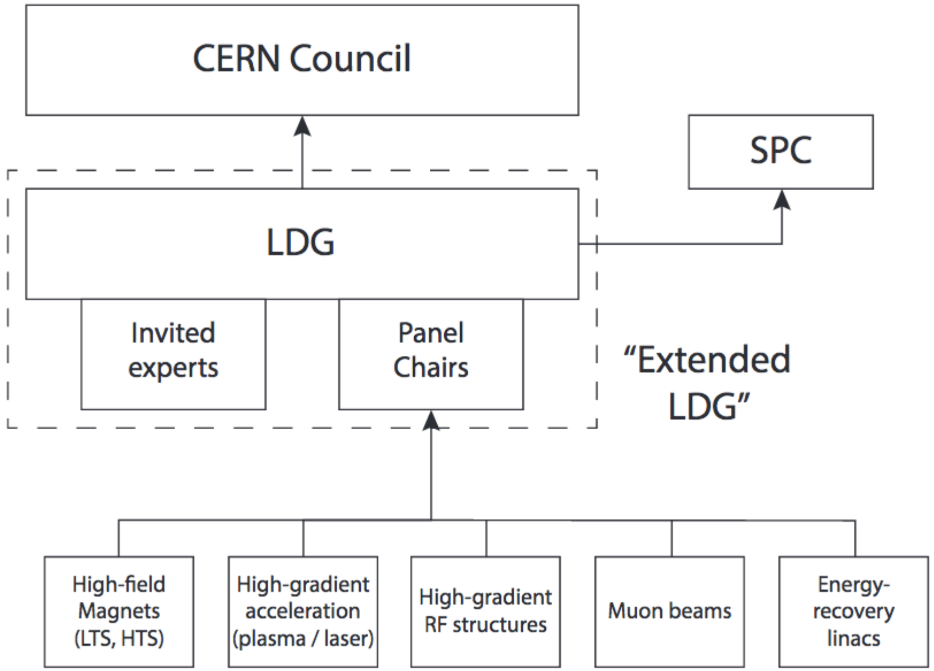
Maintaining **very short bunch** (1 mm) in large ring
- Careful control of longitudinal motion
- Beam dynamics of frozen beam

European Accelerator R&D Roadmap

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

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

Report to **council** will include
- Potential deliverables and **demonstrators** for the next decade
- A **prioritised work plan**, taking into account the capabilities and interests of stakeholders
- A **range of scenarios** for engagement, ranging from '**minimal investment**' to '**maximum possible rate of progress**', with a first estimate of resources and timeline.



- June Council: present background to process (no recommendations)
- July EPS-HEP: public presentation of progress for feedback
- September SPC / Council: present of interim findings (facts, not priorities)
- December Council: gain approval of the final report

Muon Beam Panel

Members: Daniel Schulte (CERN), Mark Palmer (BNL), 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)

Foresee three community meetings

- First in May, date to be defined
- Please contribute

Will profit from workshop on the muon collider testing opportunities (with physics potential of test facility):

https://indico.cern.ch/event/1009746/ .

Report ready in September, given to Council in December

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

We do see this as a global effort

- profit from US expertise
- and new enthusiasm in Europe
- prepare to include the US in the collaboration after P5
  - and before, where possible

Conclusion

The muon is a unique promising option at highest lepton energies

We need to fully explore the physics case, which goes well beyond 3 TeV (studied for CLIC)

Have to address the feasibility

A great challenge but also a great opportunity

Many thanks to all that contributed
MAP collaboration
MICE collaboration
Muon collider collaboration
LEMMA team
Muon collider working group
European Strategy Update
LDG
…

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

Mailing lists:
MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch,
MUONCOLLIDER_FACILITY@cern.ch
go to https://e-groups.cern.ch and search for groups with "muoncollider" to subscribe

Reserve

Memorandum of Cooperation

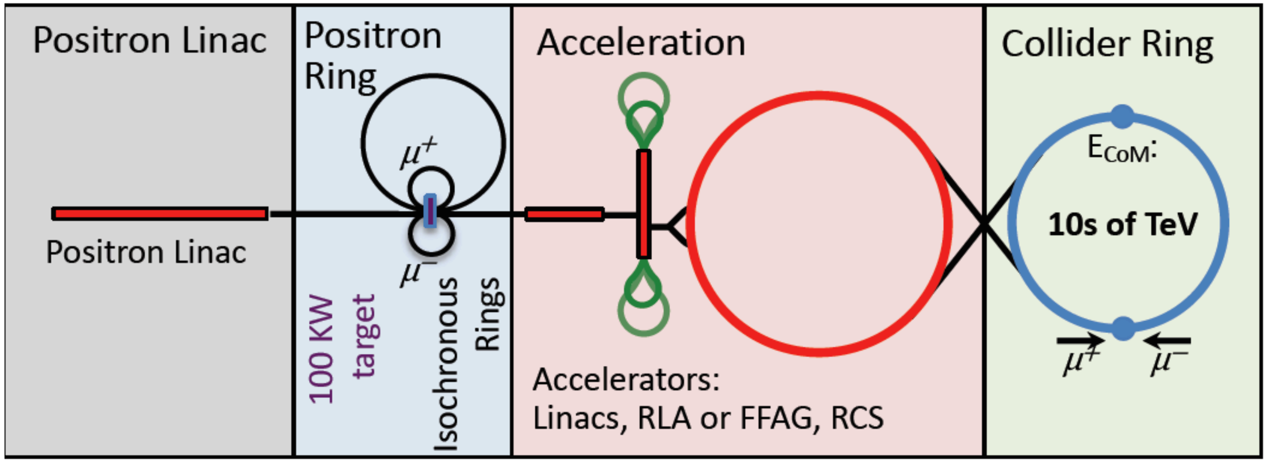
Basically ready, waiting for final polishing

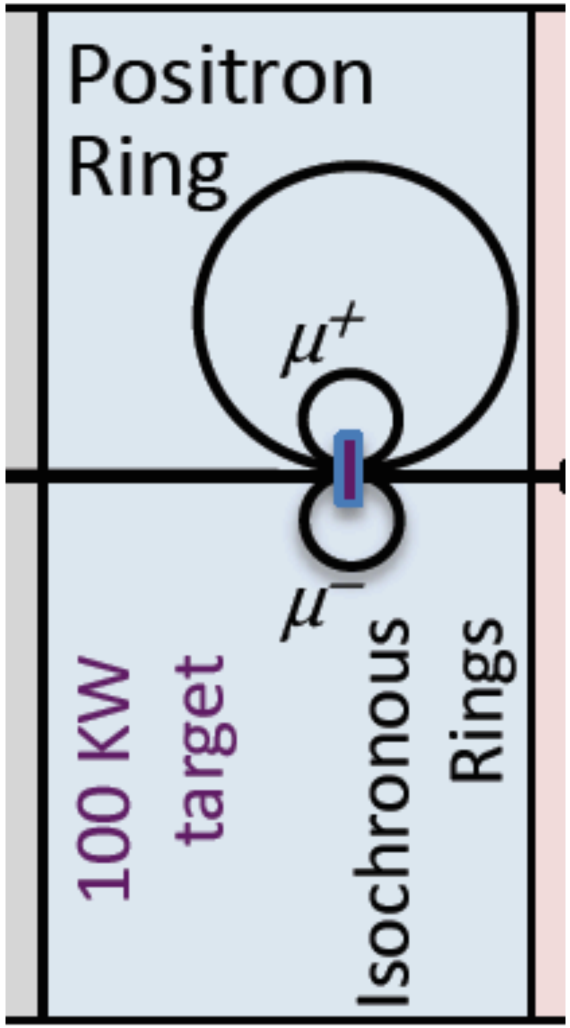
CERN is initially hosting the study

- 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

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

Proposed Projects (ESU)

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

Linear Collider Cost

CLIC cost at 3 TeV is about 18 GCHF

CLIC additional cost at 14 TeV: around 40-50 GHCF

- upgrade 1.5 to 3 TeV about 8 GCHF
- (14 TeV - 3 TeV) / 1.5 TeV * 8 GCHF = **59 GCHF**
- some cost reduction due to large-scale production
- upgrade could be performed in affordable steps but might have limited interest in each step

Plasma technology might potentially lead to a cheaper accelerator once it is mature

- much higher gradients
- but many issues to be solved

Linear Collider Luminosity

CLIC requires about 300 MW of wall plug power for the RF to produce 28 MW of beam power and 300 about MW for other systems (e.g. magnets)

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

For CLIC about **190 MW beam power** to reach 40 x 10^{34}cm^{-2}s$^{\wedge-1}$ at 14 TeV

If we consider only luminosity above 99% of nominal centre-of-mass energy, we need about **570 MW beam power**

Efficiency from wall plug power into RF systems to beam power is O(10%)

- so **O(2-6 GW)** of **total power** consumption

Need to add the other systems (which also will increase compared to 300 MW)

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

Beam-beam Effect

Bunches are squeezed strongly to maximise luminosity

↓

Electron magnetic fields are very strong

↓

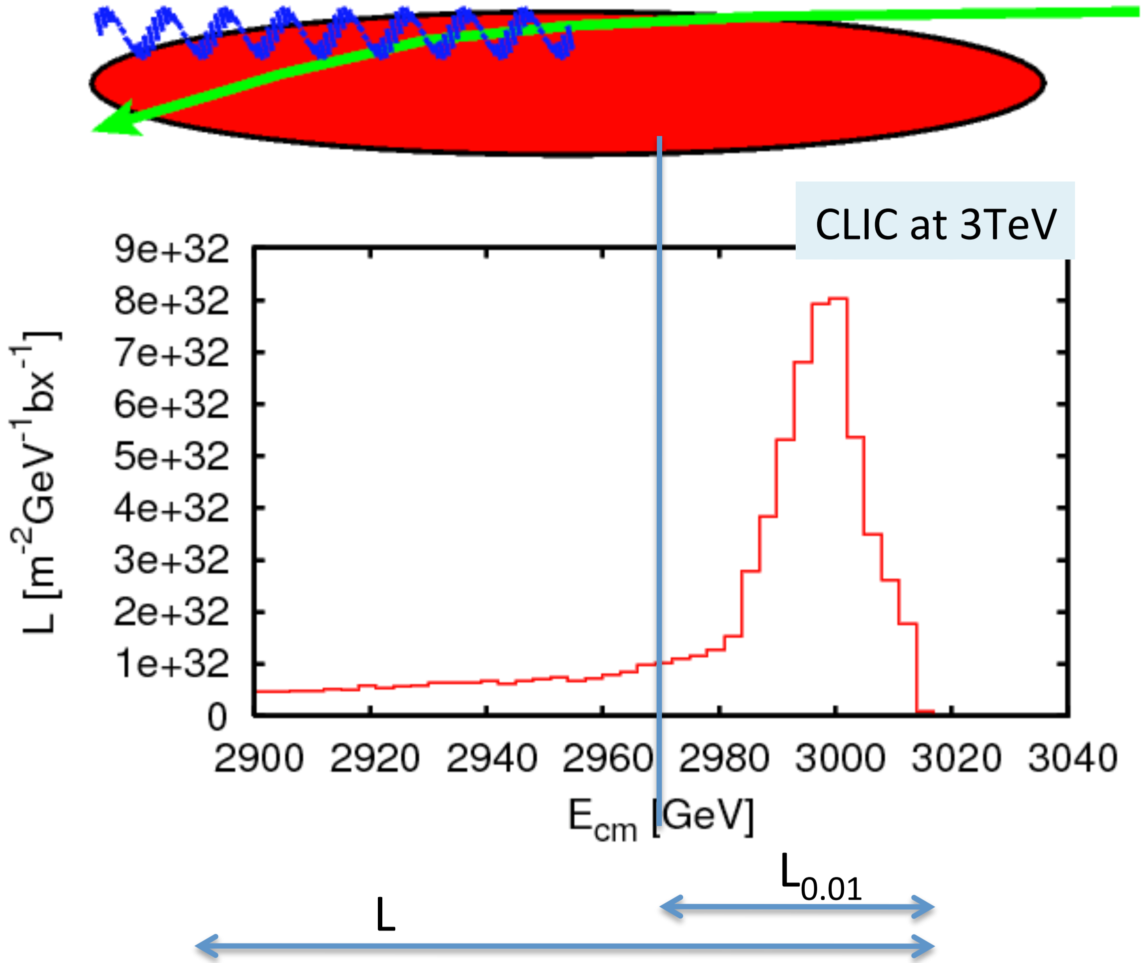
Beam particles travel on curved trajectories

↓

They emit photons (O(1)) (beamstrahlung)

↓

They collide with less than nominal energy



$L_{0.01}$ is luminosity with $E_{cm} > 0.99\ E_{cm,0}$

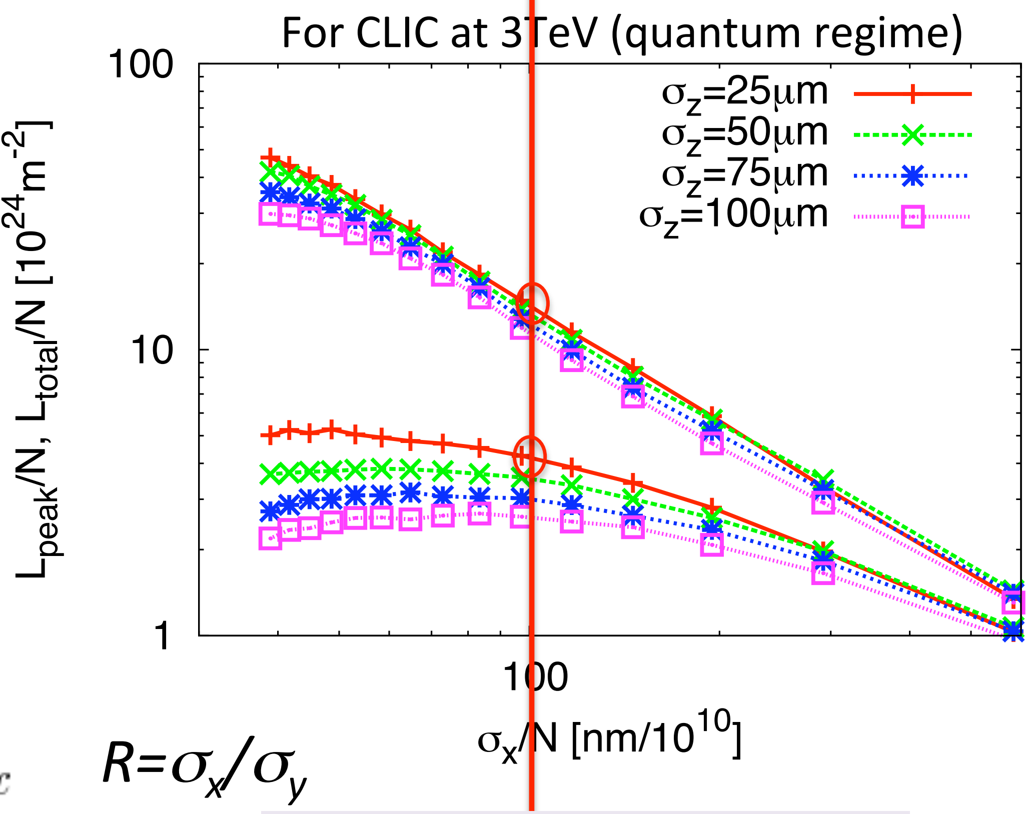
Request from physics
$L_{0.01}/L > 0.6$ below 500GeV
$L_{0.01}/L > 0.3$ at 3TeV

Beamstrahlung Optimisation

$$n_\gamma \propto \left(\frac{\sigma_z}{\gamma}\right)^{\frac{1}{3}} \left(\frac{N}{\sigma_x + \sigma_y}\right)^{\frac{2}{3}}$$

$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y} I_{beam}$$

$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x \qquad R=\sigma_x/\sigma_y$$



CLIC parameter choice $n_\gamma \approx 2$

$$\sqrt{\beta_x \epsilon_x} \propto N$$

$$\sqrt{\beta_x \epsilon_x} \propto N \sqrt{\sigma_z}$$

Optimum horizontal beam size scales with charge
Must not be smaller
First formula for classical regime
Second formula is for quantum regime

Parameter Examples

Parameter	Unit	"CLIC"	"CLIC"
E_{cm}	TeV	14	14
L	10^{35} $cm^{-2}s^{-1}$	13	0.65
$L_{0.01}$	10^{35} $cm^{-2}s^{-1}$	4	0.2
Coh.		0.5	0.5
Trid.		0.014	0.014
N	10^9	3.73	3.73
f_r	kHz	220	11
P_{beam}	MW	562	28
σ_z	µm	44	44
β_x / β_y	mm	16 / 0.04	16 / 0.04
ε_x / ε_y	nm	660 / 30	
σ_x / σ_y	nm	28 / 0.3	28 / 0.3

Inofficial parameter list

Full luminosity and constant beam power option

f_r values are not ideal

L/P_{beam} is indeed constant but only with a small trick

Had to decrease horizontal betafunction because of beamstrahlung

Assume aggressive vertical betafunction, **requires important improvement in focusing,** may not be realistic

Do not forget: harder at higher energy

How to Obtain More Luminosity?

Push beam power

Assume the same bunch charge (it is likely similar)

Hard to beat CLIC efficiency (optimistic PWFA from past Snowmass promised factor 2, but seems rather less), hard to increase total power consumption

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

$$\sqrt{\beta_x \epsilon_x} \propto N \sqrt{\sigma_z}$$

Beamstrahlung limit is improved by shorter bunch in plasma, but need novel ideas to reduce betafunction or emittance

CLIC pushed for many years

Need novel ideas to reduce betafunction or emittance

Linear colliders tried for years

A most critical field that requires inventions