International
MUON Collider
Collaboration

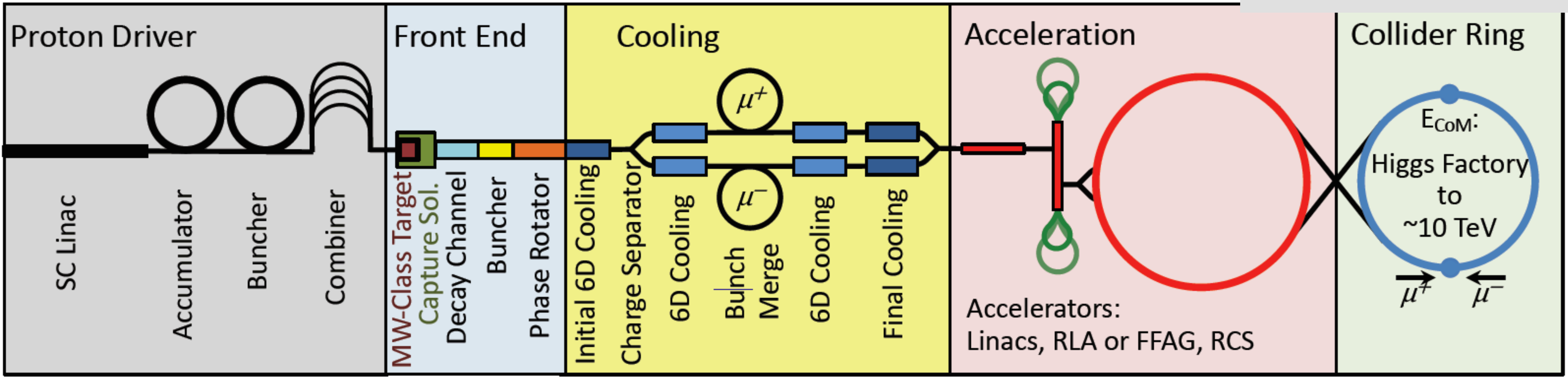
Muon Collider

Daniel Schulte for the Muon Collider Collaboration

Proton-driven Muon Collider Concept

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

MAP collaboration



Short, intense proton bunches to produce hadronic showers

Protons produce pions
Pions decay to muons

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

Acceleration to collision energy

Collision

Muon collider is unique for very high lepton collision

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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**

Ongoing Timeline Discussions

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

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

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

- Important ramp-up 2026

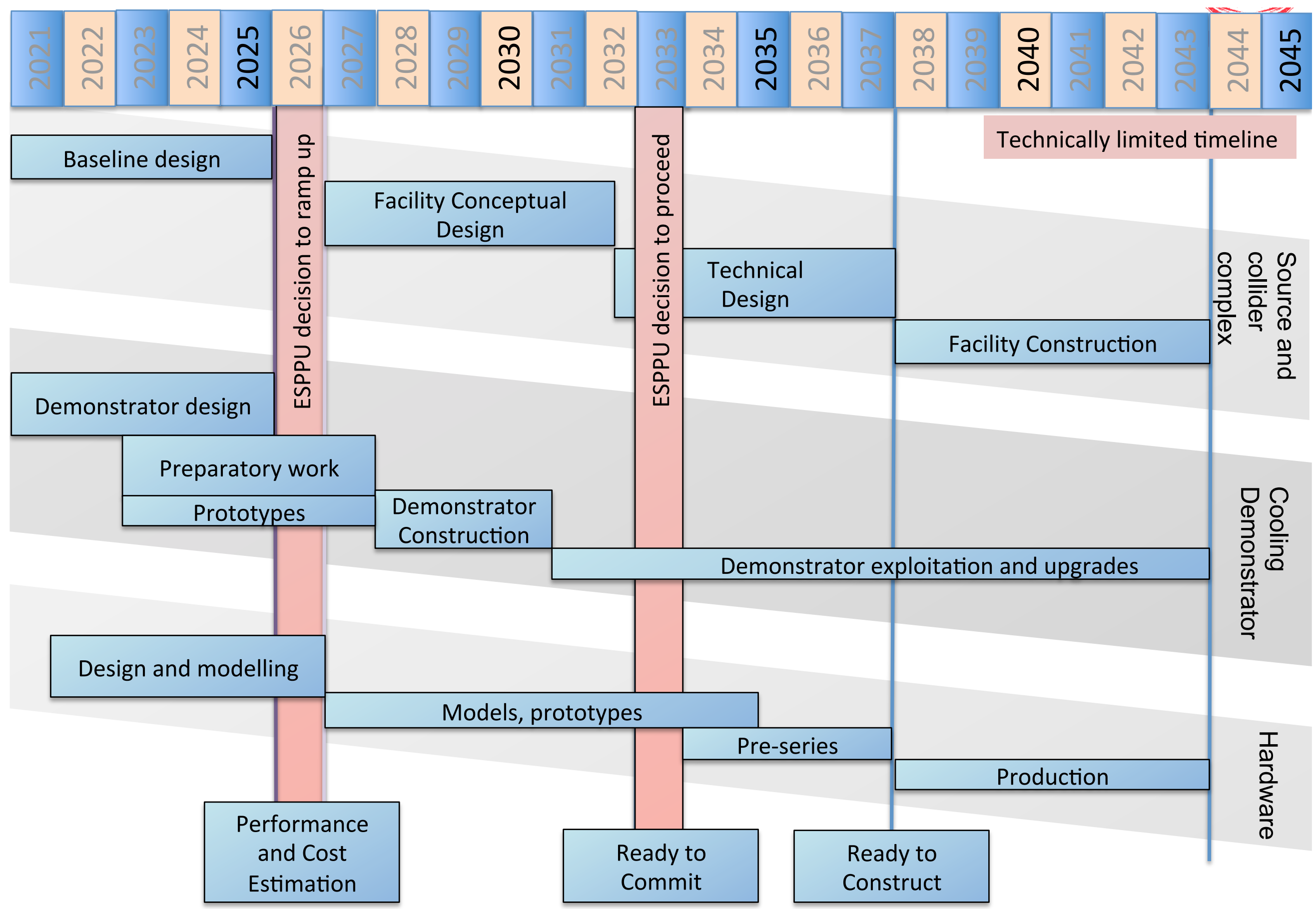
High-field magnet and RF programmes will allow to judge maturity what can be reached in a collider with this timeline

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

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

Tentative Target for Aggressive Timeline

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

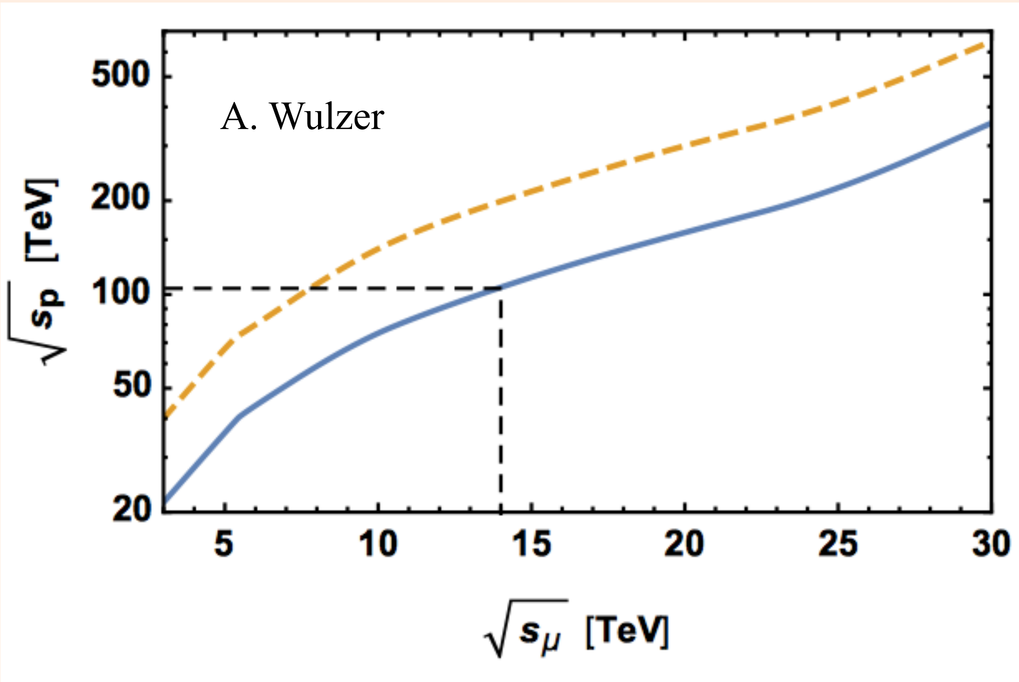


Lepton Physics at High Energy

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

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}}\right)^2 2\cdot10^{35}\text{cm}^{-2}\text{s}^{-1}$$

Muon Collider Promises

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

- No obvious way to strongly improve luminosity

Luminosity per beam power increases with energy in muon collider

- **power efficient**

Site is **compact**

- 10 TeV comparable to 3 TeV CLIC

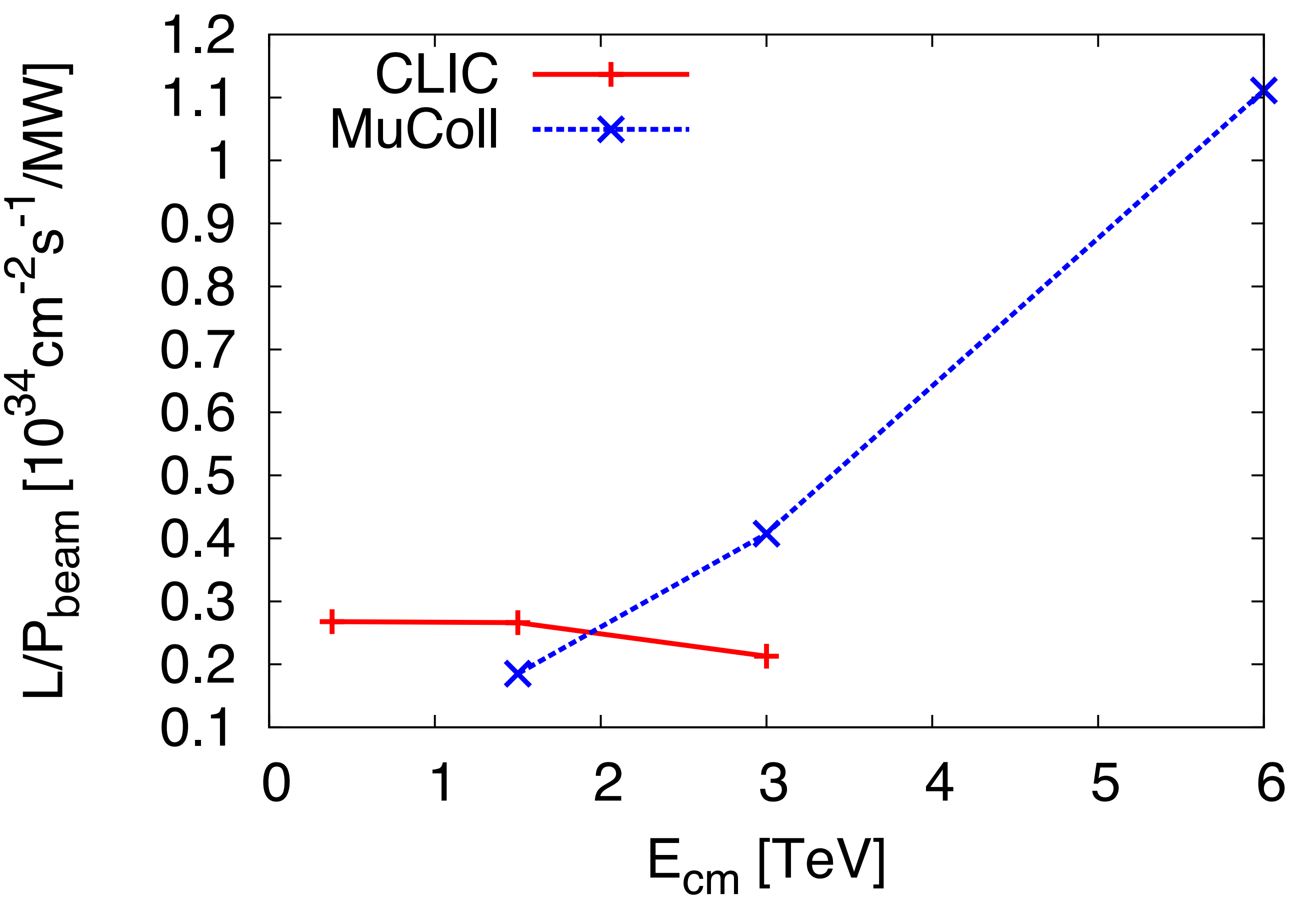
Staging is natural

- Each ring accelerates by a factor of a few

Promises **cost effectiveness**

- but need detailed study

Other **synergies** (neutrino/higgs)



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

Luminosity Goals

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Target integrated luminosities

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

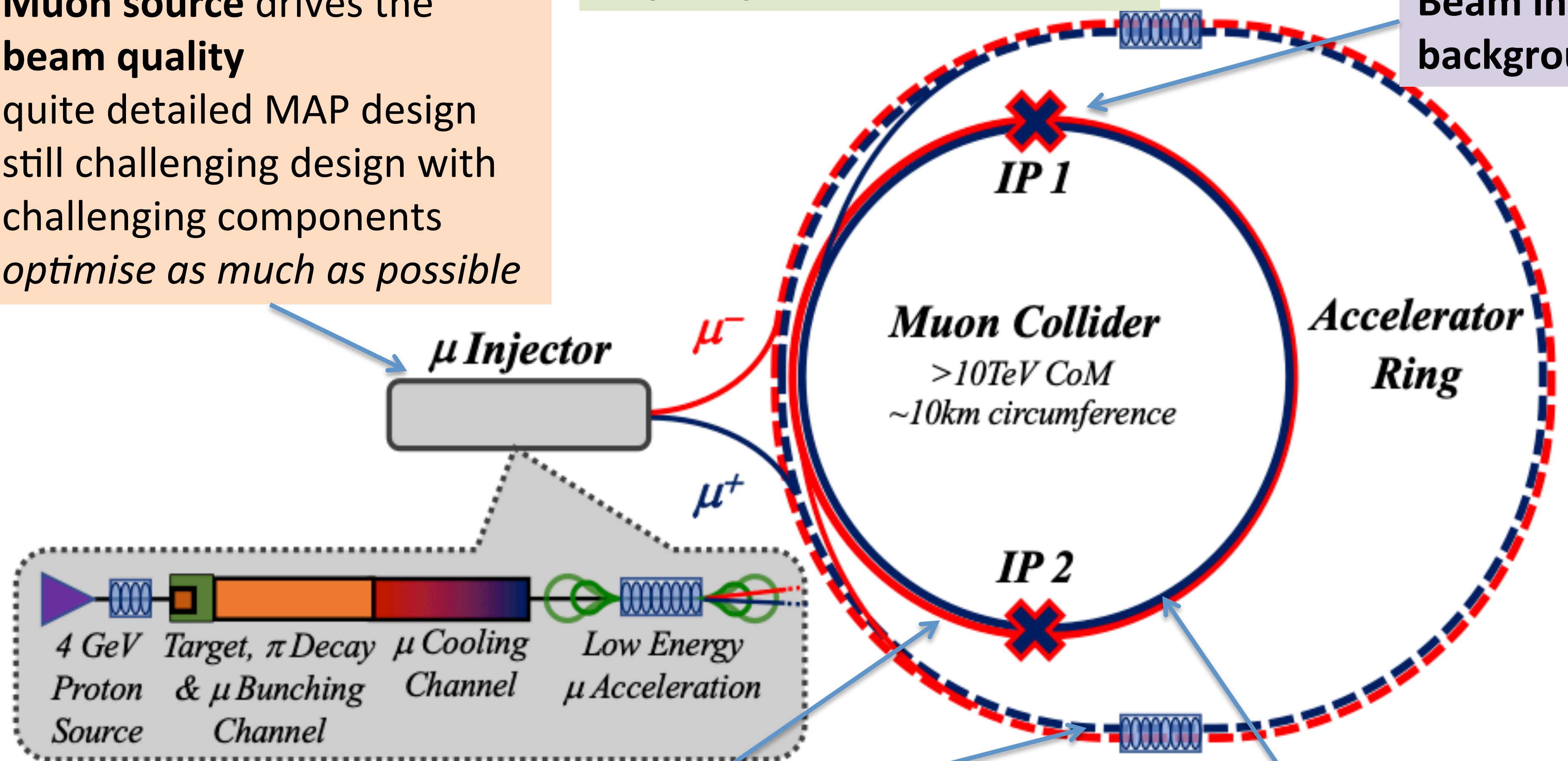
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Key Challenges

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

Physics potential assessment

Beam induced background



Dense neutrino flux
mitigated by mover system and site selection

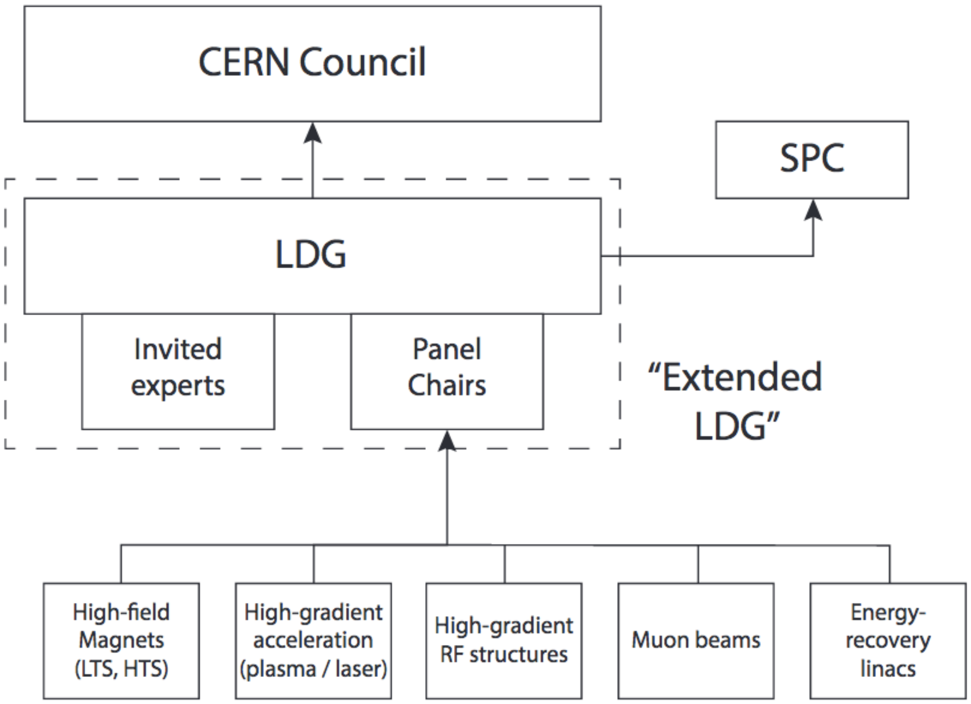
High energy complex
Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts **beam quality**

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

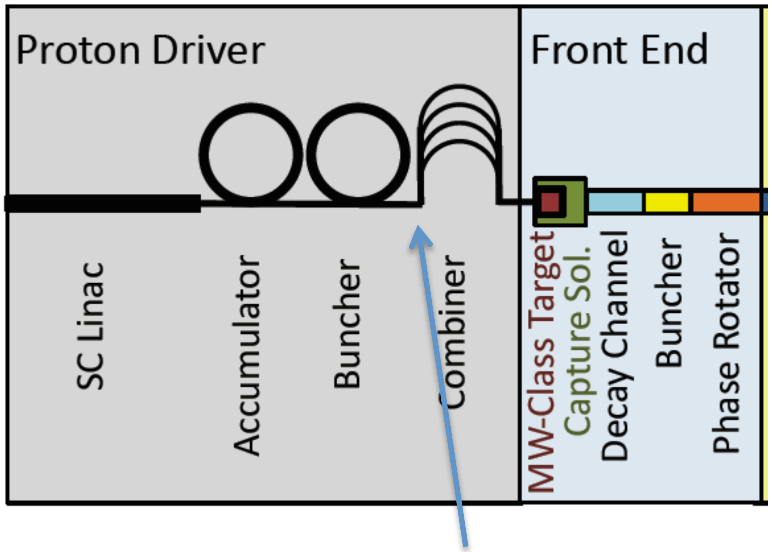


Muon Beam Panel members: Daniel Schulte (CERN, chair), Mark Palmer (BNL, co-chair), Tabea Arndt (KIT), Antoine Chance (CEA/IRFU) Jean-Pierre Delahaye (retired), Angeles Faus-Golfe (IN2P3/IJClab), Simone Gilardoni (CERN), Philippe Lebrun (European Scientific Institute), Ken Long (Imperial College London), 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)

Panel discussions:

- Muon collider has high potential
  - expect attractive cost and power consumption
  - reach beyond linear colliders
- Challenges but no showstoppers
  - not as mature as CLIC
- Way forward proposed
  - workplan, but require funding
- ramp-up required for fast implementation

Proton Complex and Lattice Design

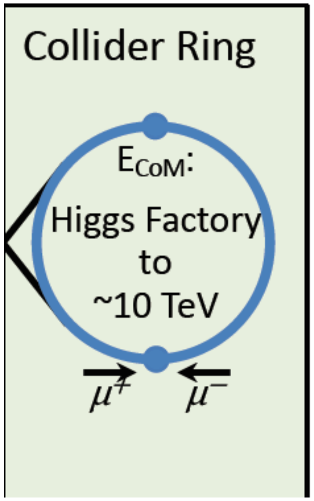


Proton beam power is no issue, some look required at **H- source** and **accumulator and combiner complex**
$\Rightarrow$ **Combining protons into one bunch**

CLIC synergy
RF deflectors and fast kickers

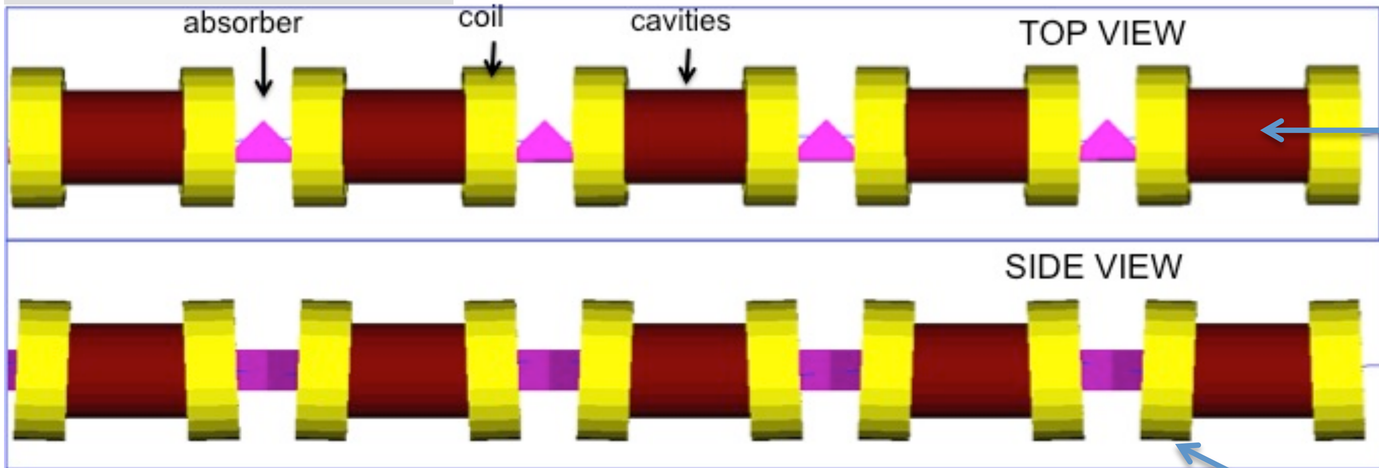
CLIC synergy
Ambitious final focus optics
- triplet, quadruplet, …
- can profit from CLIC optimisation tools

Achromatic arcs needed



Cooling Concept

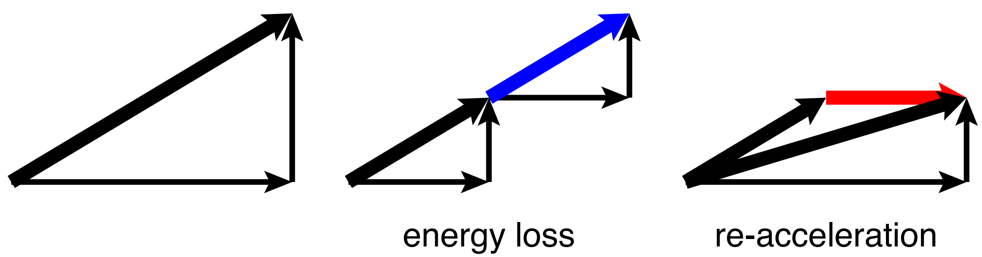
MAP collaboration

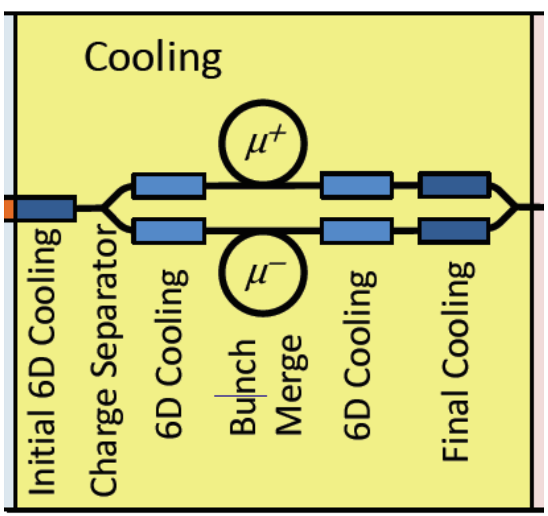


Limit muon decay, cavities with **high gradient in a magnetic field**
tests much better than design values but need to develop

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

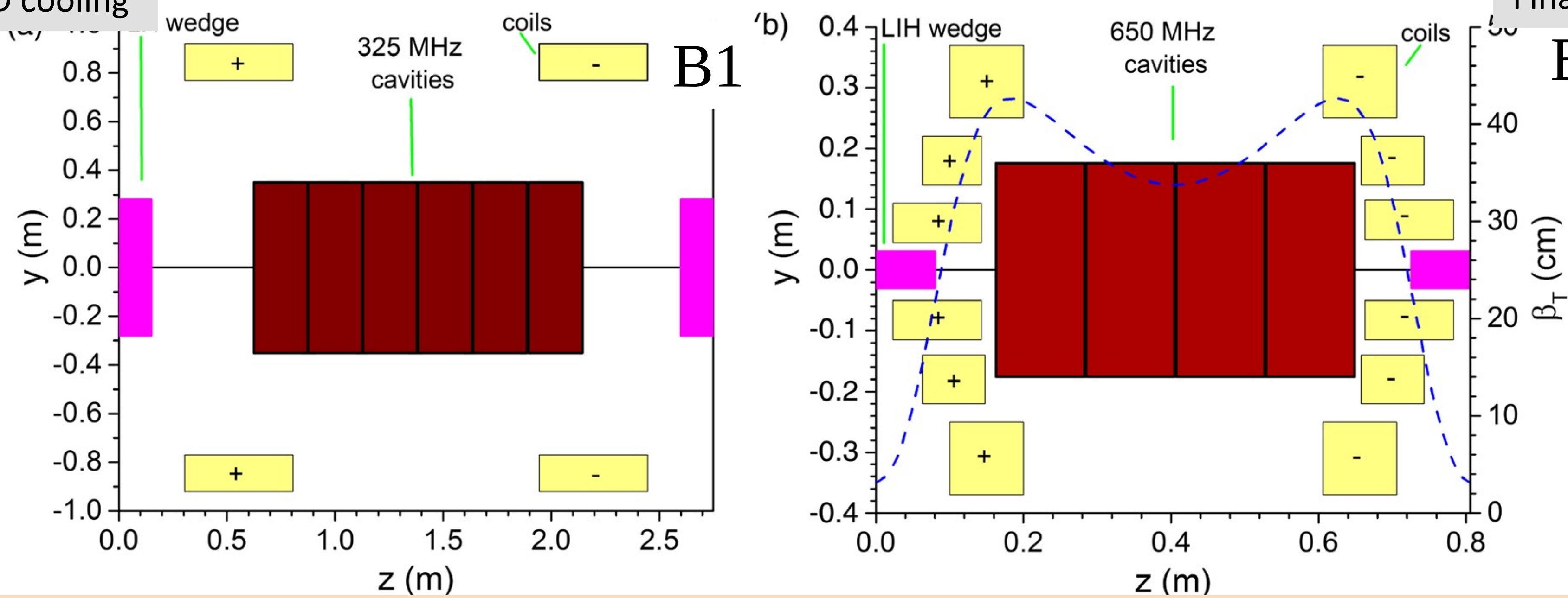
This is the **unique** and **novel** system of the muon collider
Will need a **test facility**
The principle has been demonstrated in MICE

Engineering Design of Cooling Cell

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

Initial 6D cooling

2.2 T



Final 6D cooling

13.6 T

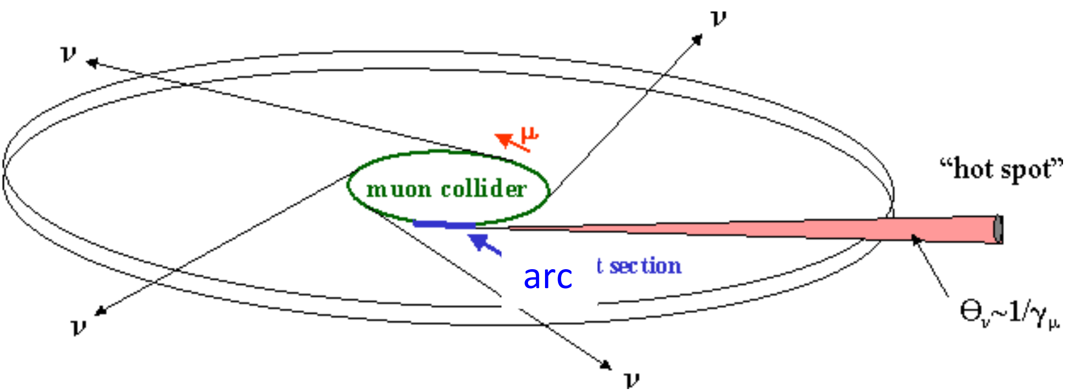
CLIC synergy:
Normal-conducting cavities (O(350 MHz) and O(700 MHz))

- high pressure gas or Be
- should also consider cool copper, HTS coating, …
- can strongly profit from CLIC experience and future efforts

Need high power O(0.1 ms) RF pulse

- scaling from CLIC drive beam klystron reduces klystron number by order of magnitude
  $\Rightarrow$ several thousand becomes several hundred
- Also profit from high efficiency

Neutrino Flux Mitigation

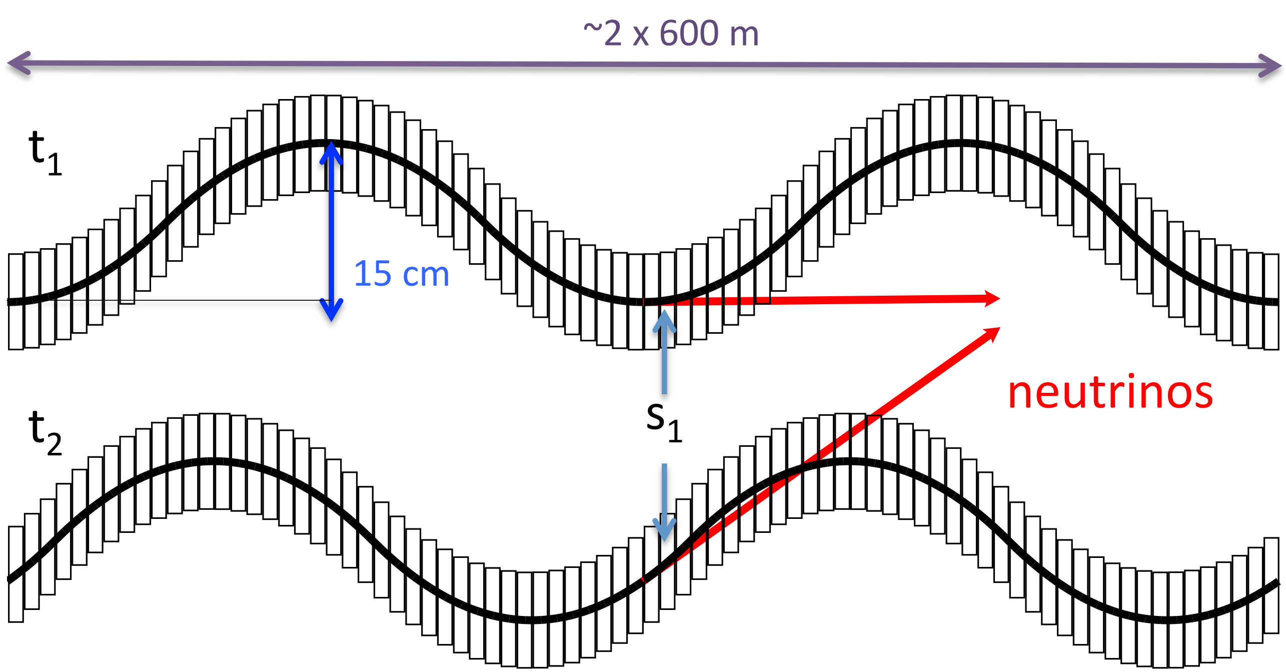


Concentrate neutrino cone from arcs can approach legal limits for 14 TeV

Goal is to reduce to level similar to LHC

3 TeV, 200 m deep tunnel is about OK

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



Opening angle ± 1 mradian

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

CLIC synergy:

- Large stoke, high precision mover system, mechanical support system with magnets, connections
- Reliable alignment reference system

Physics Potential, Detector and MDI

Physics potential studies including detector and background

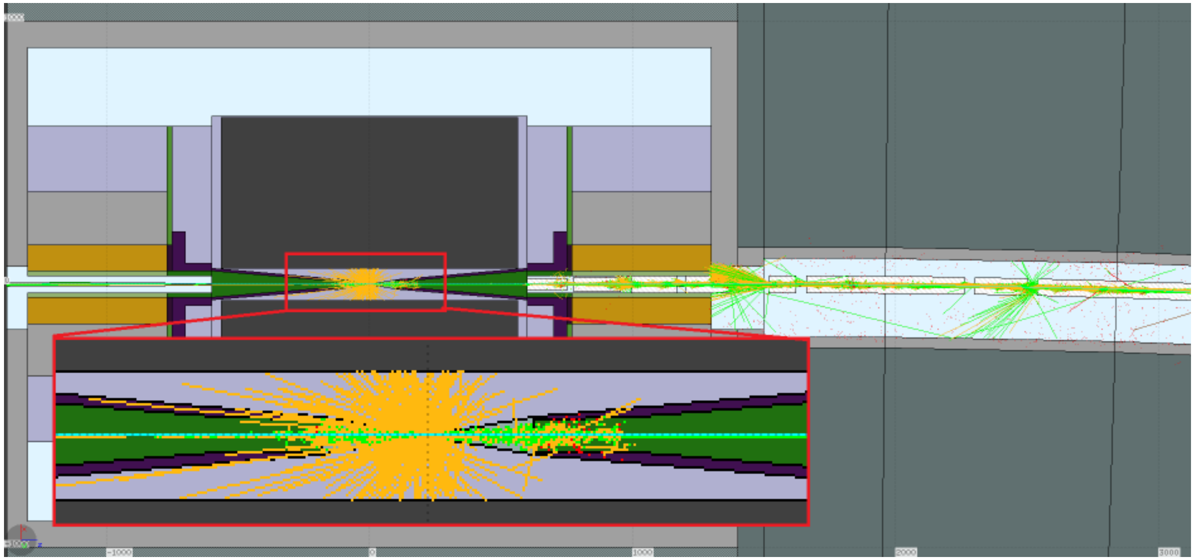
- Theory and phenomenology
- Detector technologies, simulation studies
- Collider and mask design
- Important effort is required

Main background sources

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

CLIC synergy:

- Detector design based on CLIC
- Strong software support
- Strong synergy on physics studies at 3 TeV
- Beam-beam simulations (special GUINEA-PIG version)



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

Conclusion

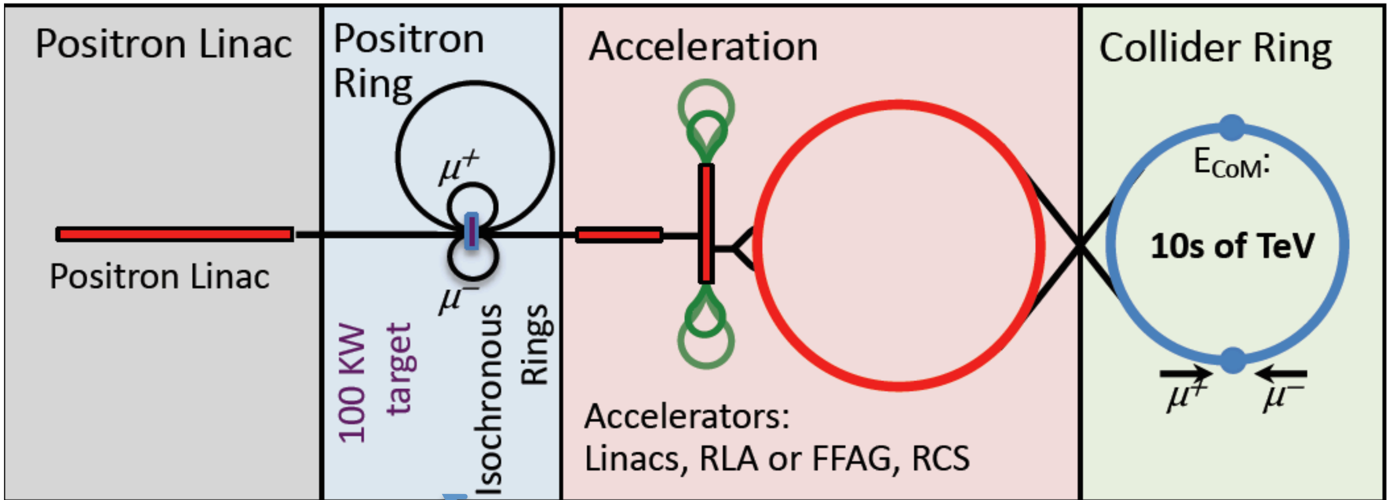
- Muon colliders are a unique opportunity for a high-energy, high-luminosity lepton collider
  - expect high luminosity to beam power ratio
  - cost and power efficiency to be assessed
- Two different options considered
  - 3 TeV collider that can start construction in less than 20 years
  - 10 TeV collider that uses advanced technologies
- Not as mature as ILC or CLIC
  - have to address **important R&D** items
  - but **no showstopper** identified
- Important synergy with CLIC and ILC, but also hadron colliders
- Aim to develop concept to a **maturity level** that allows to make **informed choices by the next ESPPU** and other strategy processes
- 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

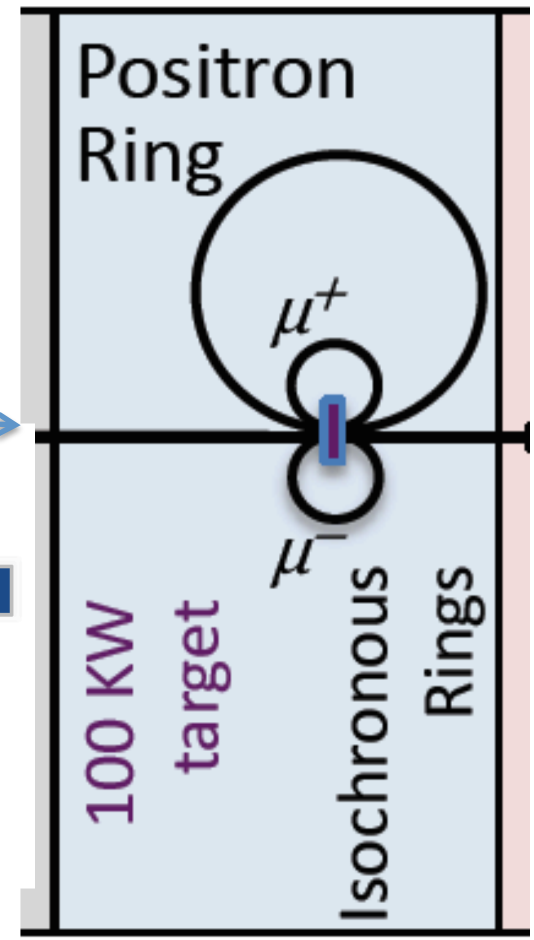
Alternatives: The LEMMA Scheme

LEMMA scheme (INFN)
P. Raimondi et al.



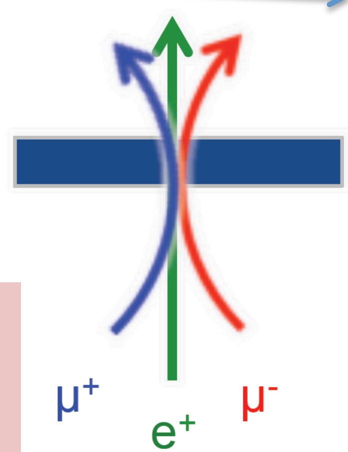
Note: New proposal by C. Curatolo and L. Serafini needs to be looked at

- Uses Bethe-Heitler production with electrons



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

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



Excellent idea, but nature is cruel

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

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

Muon Collider Luminosity Scaling

Fundamental limitation

Assumes no emittance growth after source and no technical limitation

Applies to MAP and LEMMA scheme

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

High energy

High field in collider ring
= small ring
= many collisions

Large energy acceptance
= short bunch
= small betafunction

Dense beam

High beam power

Note: emittances are normalised

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

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

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

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

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

Example to reach luminosity is

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

Note: Additional beam combination schemes can reduce positron bunch charge but increase energy in pulse

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

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

Assume 3 mm thick Be target, 0.86 mm beta

⇒ 0.6 nm emittance growth per muon beam passage through target (optimum case)

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

⇒ Positron beam energy 2 GJ/burst, 5 burst per second

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

⇒ Extremely challenging, not sure even a fluid target can do this

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

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

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

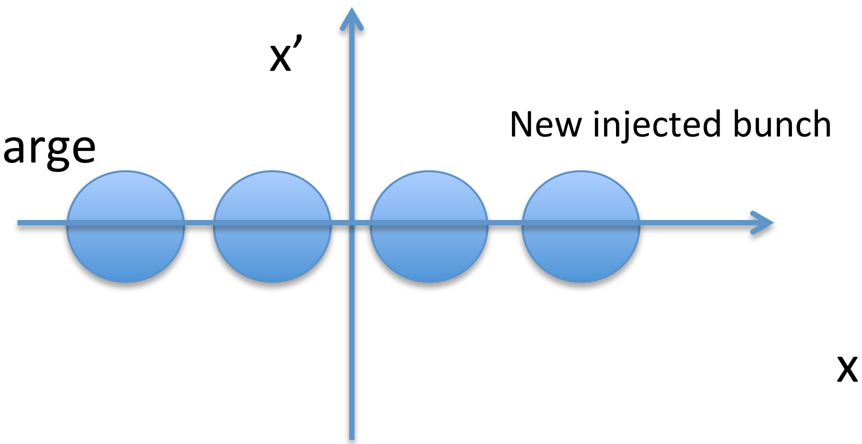
⇒ Need 70 times denser beam for same luminosity

⇒ Lose 1.4 10^{16} positrons per second

Note: Stacking

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

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



Stacking in transverse plane can help because

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

stacking m^2 bunches leads to

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

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

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

and the luminosity scales as

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

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

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Some Comments

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

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

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

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

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

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

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

the LEMMA scheme

at 14 TeV:
9 GW beam power

even 30 times more beam particles

Physics at Muon Collider

International MUON Collider Collaboration

Muon Collider can be the game changer

[The Muon Smasher's Guide]

Muon collider physics potential

D. Buttazzo

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

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

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

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

3

A Muon Collider is great!

P. Maede

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

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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

P. Maede

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

Challenges and Status

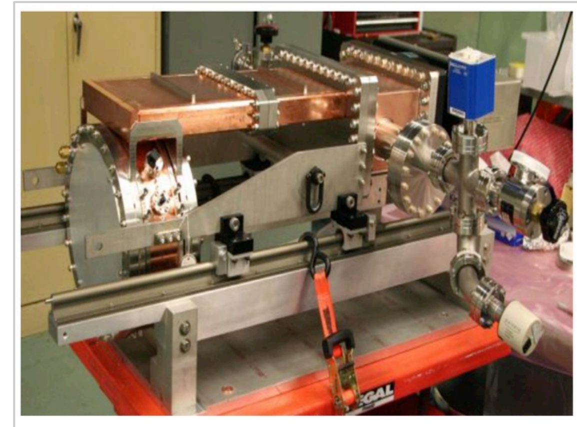
FNAL
12 T/s HTS
0.6 T max

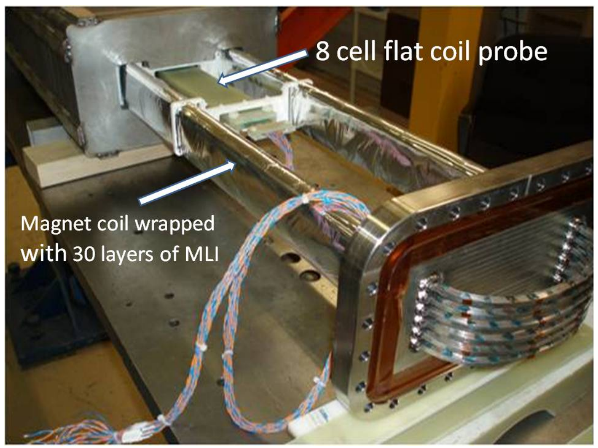
now 290 T/s

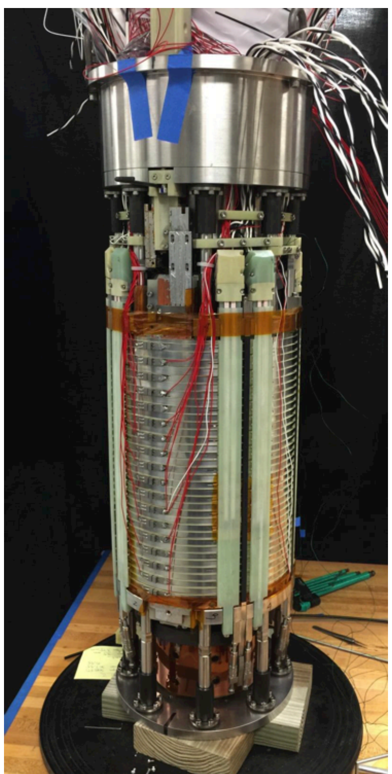
Test of **fast-ramping normal-conducting magnet** design

MuCool: >50 MV/m in 5 T field

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







NHFML
32 T solenoid with HTS

Planned efforts to push even further

MICE (UK) Muon cooling principle