Muon Collider Conceptual Design and Future Plans

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Many thanks to Mark Palmer, Vladimir Shiltsev and the MAP and LEMMA teams

Findings of 2018 Review

A first, high-level review of the two schemes with proton-based (MAP) and positron-based (LEMMA):

Muon-based technology represents a unique opportunity for the future of **high energy** physics research: the multi-TeV energy domain exploration.

First focus has been on promising positron-based scheme (**LEMMA**), but identified **need for consolidation**

No showstopper found for proton scheme (**MAP**), many systems have been studied but much more detailed understanding is required to judge performance, cost and power. **No CDR exists**.

Important progress of the technologies, addressing the feasibility of major technical issues with R&D performed by international collaborations.

In Europe, the **reuse of existing facilities and infrastructure** for a muon collider is of interest (e.g. LHC).

Documents: see first slide of the reserve

Findings of 2018 Review

A first, high-level review of the two schemes with proton-based (MAP) and positron-based (LEMMA):

Muon-based technology represents a unique opportunity for the future of **high energy** physic

First fo … ed **need for consol**

No sho … died but much r … power. **No CDR ex**

Since then had two workshops

To prepare Granada:
https://indico.cern.ch/event/801616/

To continue the work and provide input for European Strategy Update
https://indico.cern.ch/event/845054/

Important progress of the technologies, addressing the feasibility of major technical issues with R&D performed by international collaborations.

In Europe, the **reuse of existing facilities and infrastructure** for a muon collider is of interest (e.g. LHC).

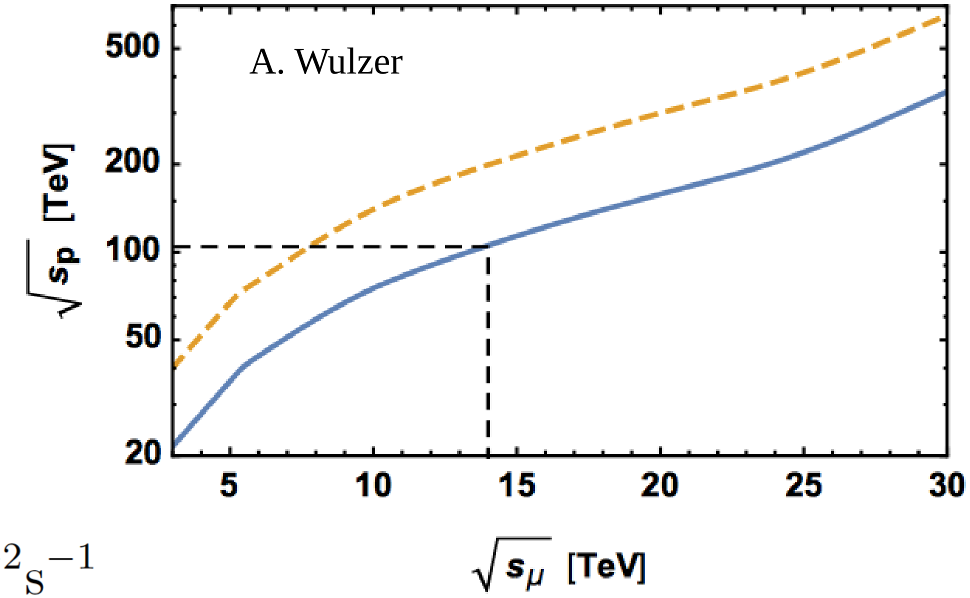
Documents: see first slide of the reserve

Motivation for High Energy, Physics

High energy lepton colliders are precision and discovery machines

Discovery reach

14 TeV lepton collisions are comparable to 100 TeV proton collisions



Luminosity goal (for s-channel)

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

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

4×10^{35} $cm^{-2}s^{-1}$ at 14 TeV

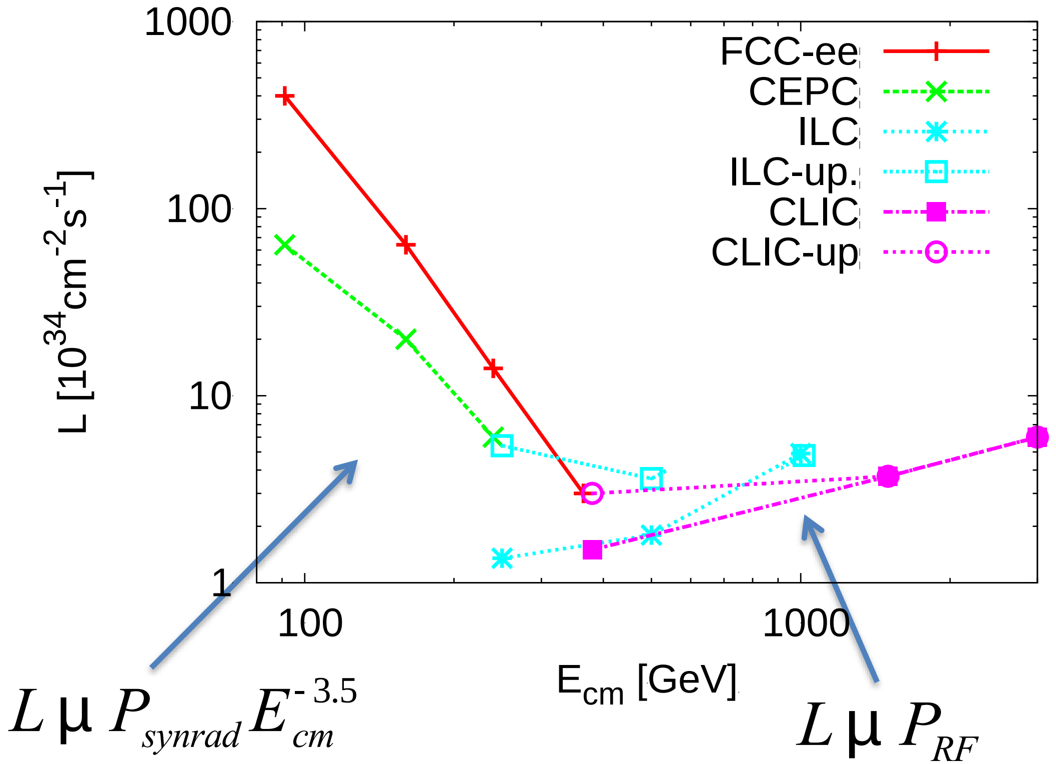
200×10^{35} $cm^{-2}s^{-1}$ at 100 TeV

Current working assumption

Any input is welcome

Proposed Lepton Colliders (Granada)

Luminosity per facility



CLIC can reach 3 TeV

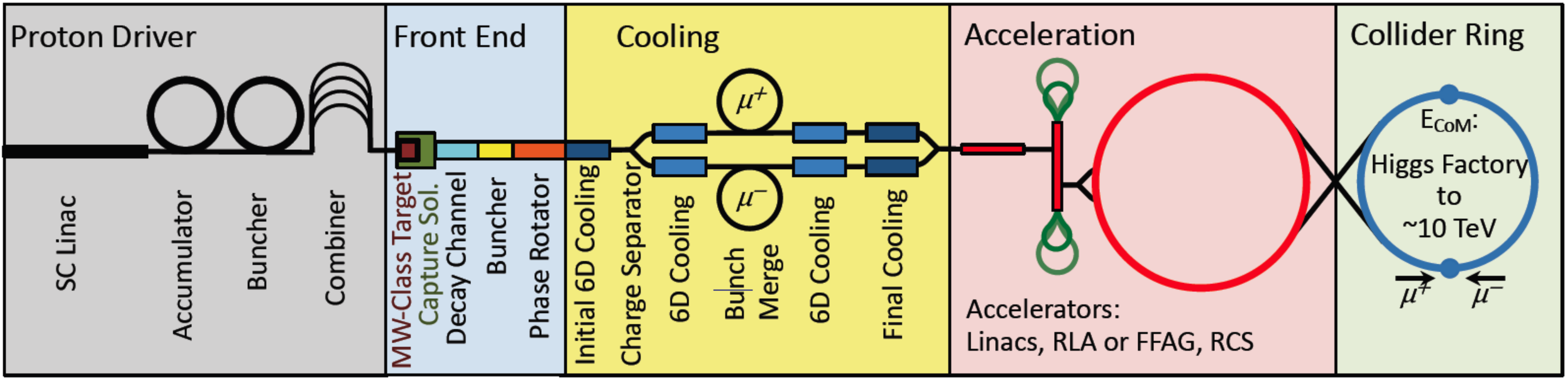
- Cost estimate total of 18 GCHF
  - In three stages
  - Largely main linac, i.e. energy
- Power 590 MW
  - Part in luminosity, a part in energy
- Similar to FCC-hh (24 GCHF, 580 MW)

Technically possible to go higher in energy

But is it affordable?

R&D required towards higher energies (or improvement of 3 TeV)
- Reduction of cost per GeV (improved NC acceleration, novel acceleration technologies
- Improved power consumption (higher RF to beam efficiency, higher beam quality)

Proton-driven Muon Collider Concept (MAP)



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled

Acceleration to collision energy

Collision

Did find that design is not complete but did not find that does not work

No CDR exists, no coherent baseline of machine
No reliable cost estimate

Target Parameter Examples

From the MAP collaboration:
Proton source (M. Palmer et al.)

Muon Collider Parameters

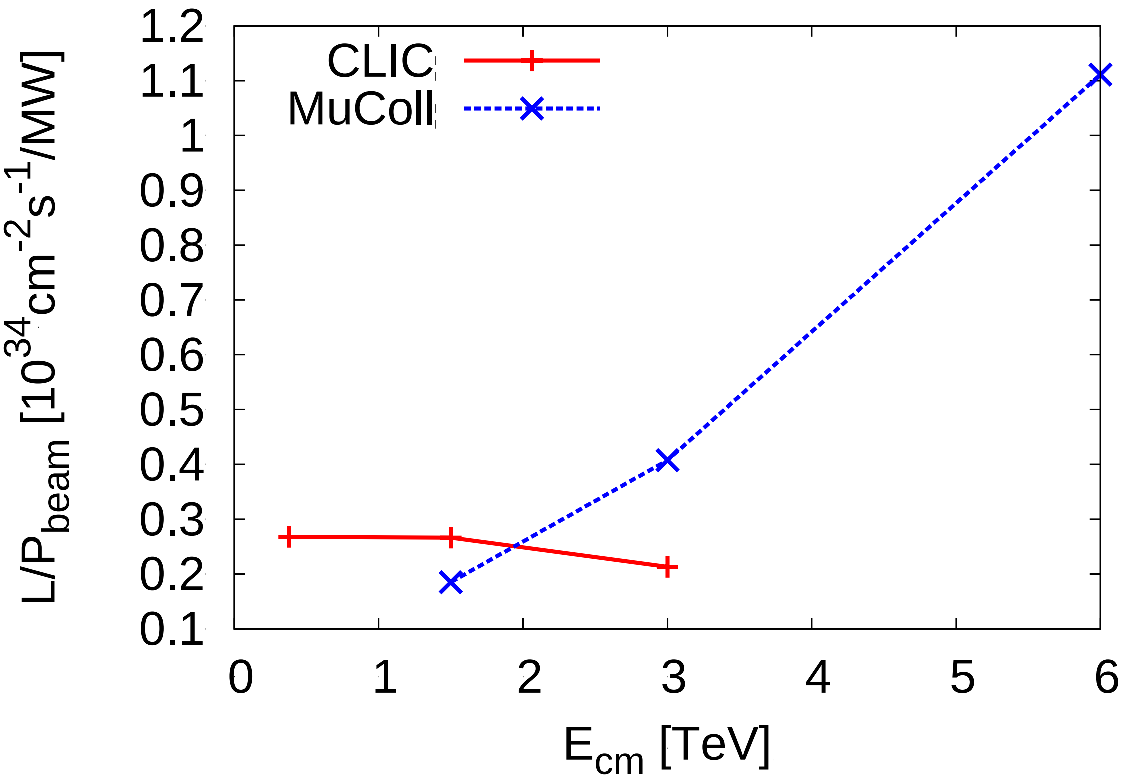
		Higgs			
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
b*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, e_{TN}	p mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1.5	70	70	70
Bunch Length, s_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Even at 6 TeV above target luminosity with reasonable power consumption
But have to confirm power consumption estimates

Luminosity Comparison

The luminosity per beam power is about constant in linear colliders

It can increase in proton-based muon colliders



Strategy CLIC:
Keep all parameters at IP constant
(charge, norm. emittances, betafunctions, bunch length)
⇒ Linear increase of luminosity with energy (beam size reduction)

Strategy muon collider:
Keep all parameters at IP constant
With exception of bunch length and betafunction
⇒ Quadratic increase of luminosity with energy (beam size reduction)

⇒ Proton-based muon collider promising at high energies

Key Parameters

From the MAP collaboration:
Proton source

Parameter	Unit	1.5 TeV	3 TeV	6 TeV
L	10^{34} cm^{-2}s^{-1}	1.25	4.4	12
N	10^{12}	2	2	2
f_r	Hz	15	12	6
P_{beam}	MW	6.75	11.5	11.5
<B>	T	6.3	7	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	10	5	2(.5)
β	mm	10	5	2.5
ε	μm	25	25	25
$\sigma_{x,y}$	μm	5.9	3.0	1.5

Muon Collider Luminosity Scaling

Fundamental limitation

Requires emittance preservation and advanced lattice design

Applies to MAP 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

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 naturally increases with energy

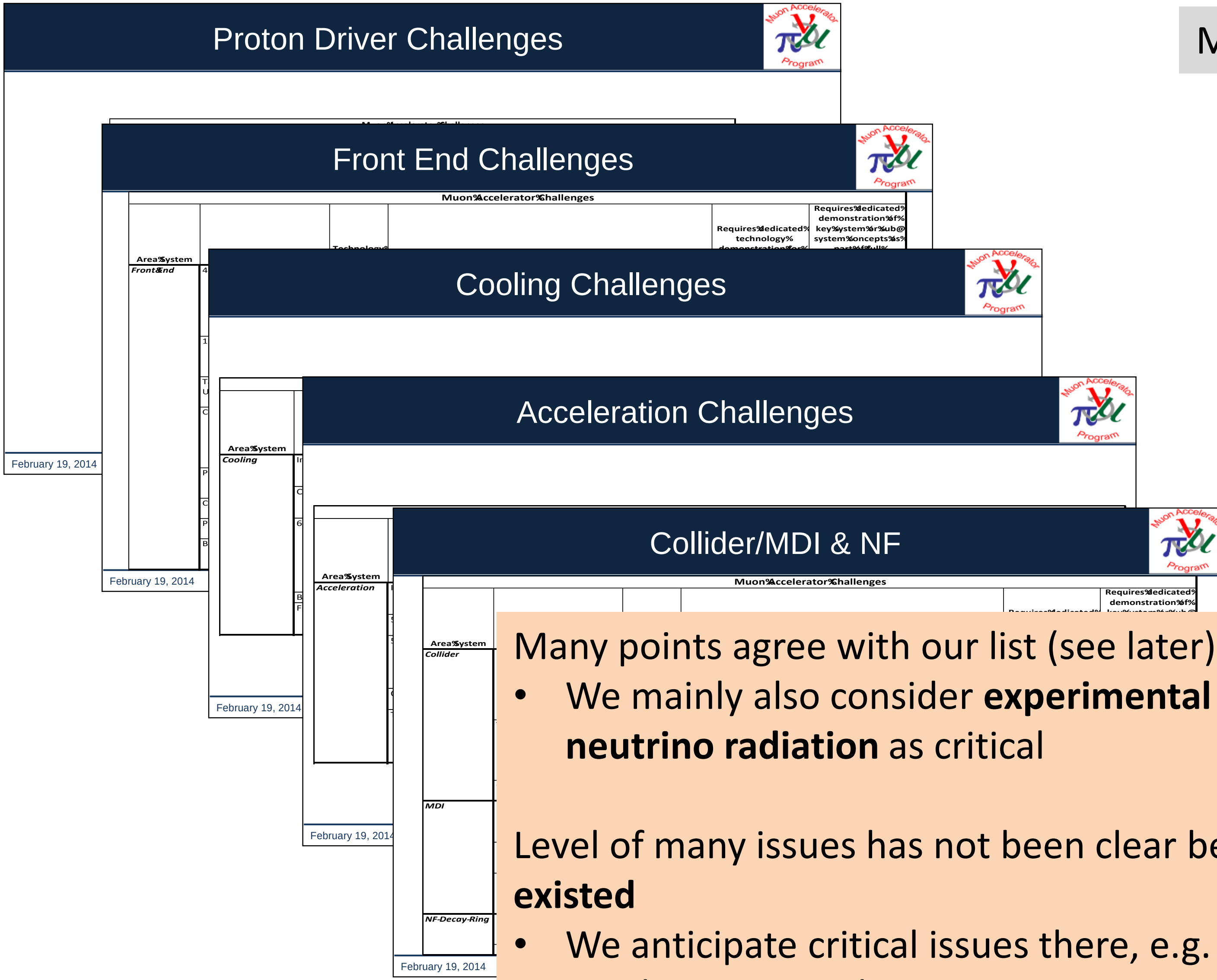
Provided all technical limits can be solved

Constant current for required luminosity increase

Better scaling than linear colliders

US View on Key Issues

M. Palmer et al.



Many points agree with our list (see later)

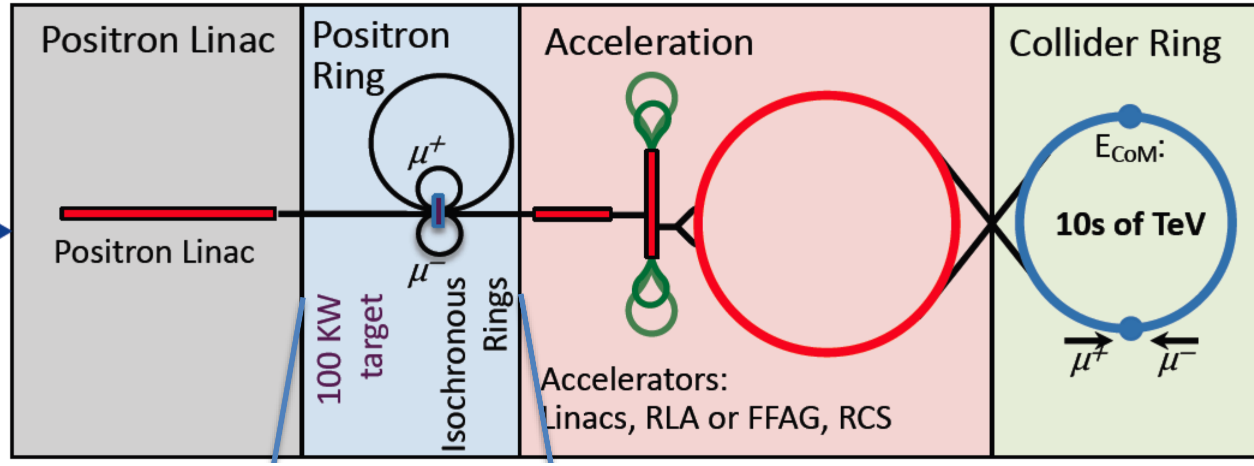
- We mainly also consider **experimental conditions** and **neutrino radiation** as critical

Level of many issues has not been clear because **no baseline existed**

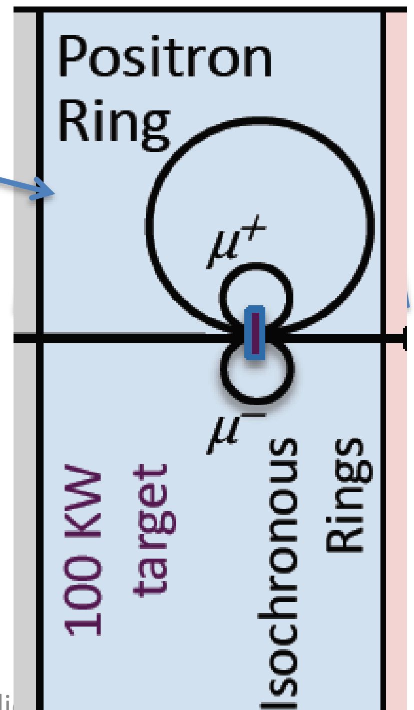
- We anticipate critical issues there, e.g. design and cost of accelerator complex

The LEMMA Scheme (2018)

Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Key concept:
Produce muon beam with low emittance using a positron beam
No cooling required



Muon current 10^{11} s^{-1} is 80-300 times lower compared to 3 x 10^{13} s^{-1} for proton driver

Emittance O(10^{-3}) smaller than in proton scheme, 40 ns vs. 25 μm

In design of 2018 two important issues were found
- Muon multiple scattering
- Issue with phase space

Attempt to consolidate is ongoing
⇒ Premature to judge

Other Options

Variations of the muon sources were suggested
- E.g. use of channeling in crystals
- Use of gamma factory to produce muons
- Use of gamma factory to produce positrons for LEMMA

But all at a very tentative level for now

e.g. W. Krasny, X. Buffat, …

Also suggested were use of LHC and FCC tunnel for the collider ring
- Obviously something that needs to be explored
- Come back to this later

e.g. V. Shiltsev, D. Neuffer, F. Zimmermann, …

Combination of final accelerator stage and collider ring
- Could maybe save some cost
- But likely will compromise performance
- And generate its own challenges
- So trade-off has to be understood

e.g. V. Shiltsev, D. Neuffer

Also some other ideas
- But too early to

Recommendations (2018)

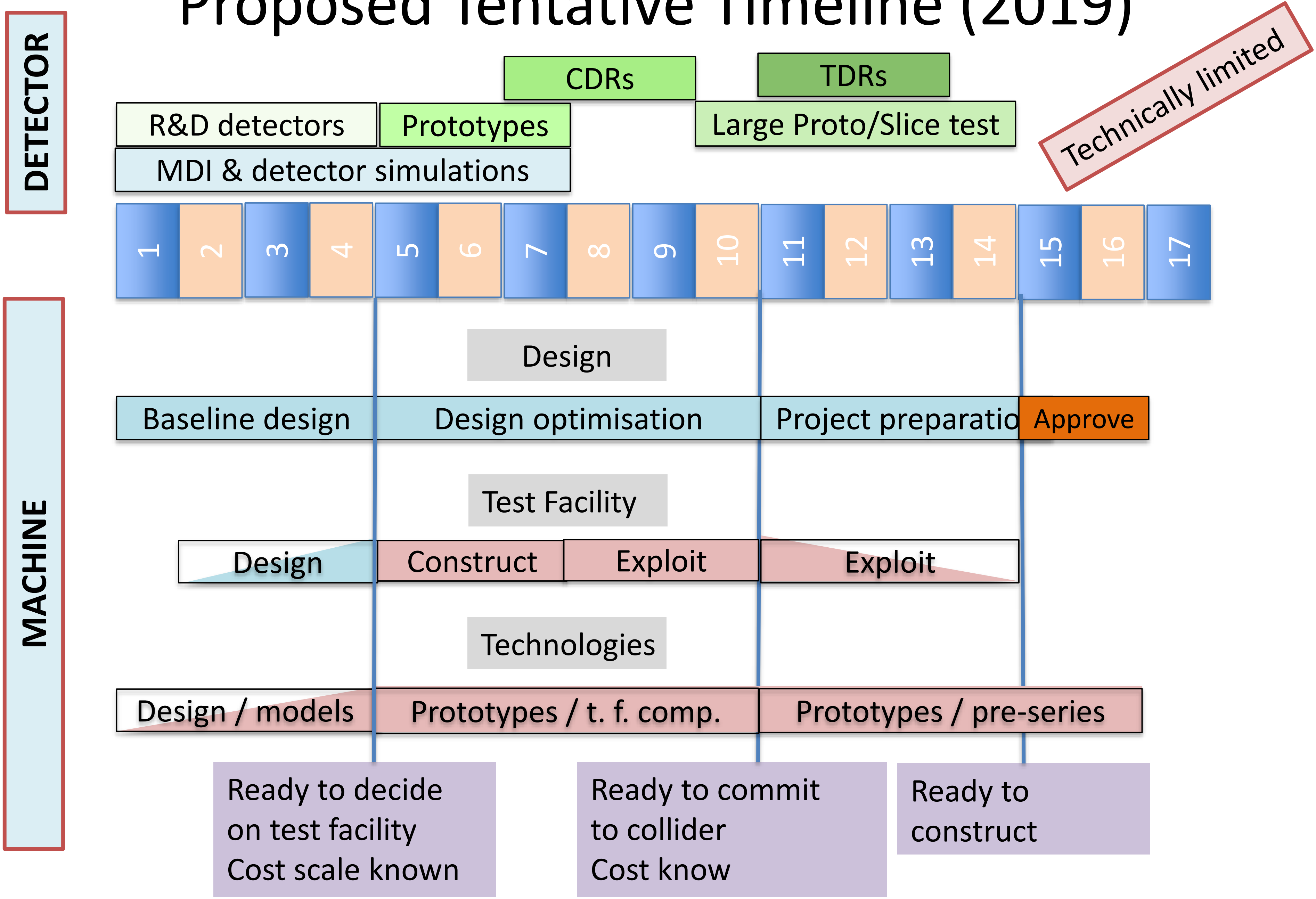
Set-up an international collaboration to promote muon colliders and organize the effort on the development of both accelerators and detectors and to define the road-map towards a CDR by the next Strategy update.

Develop a muon collider concept based on the proton driver and considering the existing infrastructure. No integrated design exists. But many components have been designed.

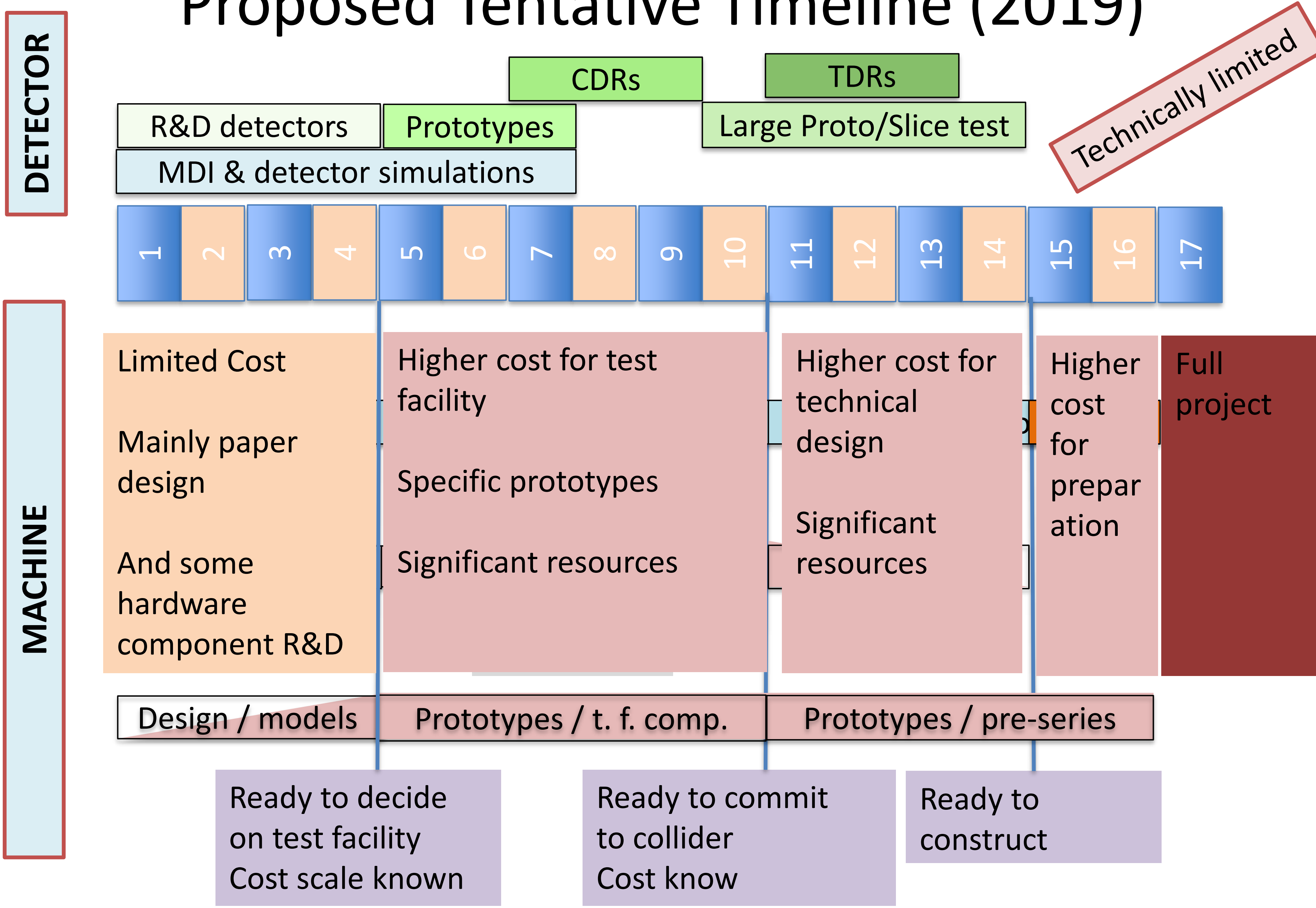
Consolidate the positron driver scheme addressing specifically the target system, bunch combination scheme, beam emittance preservation, acceleration and collider ring issues.

Carry out the R&D program toward the muon collider. Based on the progress of the proton-driver and positron-based approaches, develop hardware and research facilities as well as perform beam tests. Preparing and launching a conclusive R&D program towards a multi-TeV muon collider is mandatory to explore this unique opportunity for high energy physics. A well focused international effort is required in order to exploit existing key competences and to draw the roadmap of this challenging project. The development of new technologies should happen in synergy with other accelerator projects. Moreover, it could also enable novel mid-term experiments.

Proposed Tentative Timeline (2019)



Proposed Tentative Timeline (2019)



Tentative Considerations on Baseline

- Focus on first stage with energy of O(1.5 + 1.5 = 3 TeV)
  - To come after higgs factory and matching highest CLIC energy
  - Using the high-energy strength of muon colliders
  - Realistic design for implementation at CERN, with cost power and risk scale
  - If successful, feasibility demonstration for CDR

- Explore 14 TeV as further step
  - To match FCC-hh discovery potential
  - Mainly exploration of parameters to guide choices
  - Provide evidence for feasibility, maybe cost frame

- Some exploration of lower energies / Higgs factory
  - Scaling from higher energies
  - Not a main focus, except if other projects do not cover lower energies

- Open for input

Effort for Baseline Design

- Put together coherent design requires (mainly human) resources
  - This goes beyond US effort
  - Consistent parameters and layouts
  - Integration of collider systems, trade-offs, choices, …
  - May highlight additional important issues
  - Requires (mainly human) resources
  - Currently MAP is main option, LEMMA is alternative

- Current first step: define key R&D list
  - Tentative list started, goal to finish by end of the year
  - Identify key / feasibility issues
    - i.e. largest technical risks
    - Key cost driver, if critical
    - Key power consumption, if critical
  - Entry point for collaborators

Will speed up things if European Strategy recommends R&D

Proposed MUST
(MUon collider STudy network)
In ARIES2 to have EU label
You are welcome to join

Tentative Key R&D Items

- Integrated design (to make sure that things fit)
  - Definition of parameters for key systems
  - Choices between different options
  - Many systems could be difficult, depending on choices, see US study
  - E.g. lose 90% of muons before collision, can this be reduced?
  - Important cross effects, e.g. beam emittance
  - Collective effects
  - …
- **Neutrino radiation (critical limit at highest energies)**
  - See in later slides
- **Experimental conditions**
  - See Donatalla’s talk

Potential Key R&D Items, cont.

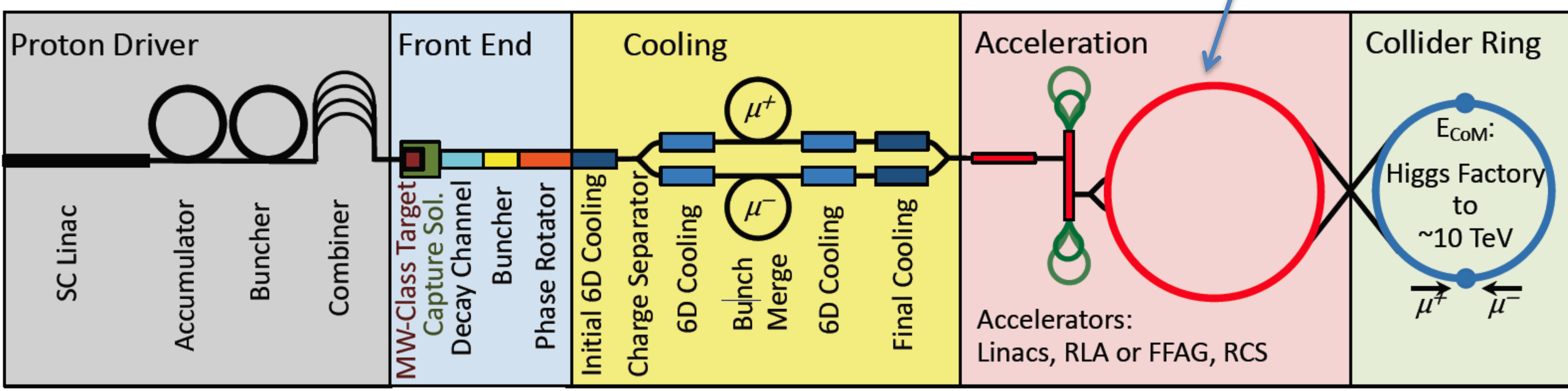
- **Beam production and cooling**
  - **Critical parameter driver**
  - **Emittance drives design, lower emittance: less radiation to public, detector, …; less power; less risk**
  - Proton beam production / compression
  - Paper design of cooling does not reach full performance
  - **Many key components: robust targets, RF with gas, high-field solenoids**
  - Take full advantage of MICE (data, installation)
  - **Will need new facility to improve test compared to MICE**
  - **Anticipated to be core of new testing programme**
    - **6-D cooling, stages to reach significant emittance reduction, radiation effect on equipment, …**
    - **Parametric cooling to be tested**
    - **Likely the core of the experimental programme**

Potential Key R&D Items, cont.

- Acceleration complex design (important cost driver)
  - Is it affordable (cost and power)?
  - **Fast ramping magnets (for RCS), magnet powering scheme**
  - High-field superconducting magnets
  - Beamline design
  - Collimation
  - …

E.g. different options to accelerate muons
- Fast-cycling synchrotron (RCS)
- FFA
- Recirculating linac

This is larger than collider ring



Potential Key R&D Items, cont.

- Collider ring design (important parameter and cost driver)
  - Is it affordable (cost)?
  - **High field superconducting magnets, minimal gap, radiation hard**
  - **Improved lattice design beyond 3 TeV**
  - Injection, safety concept

- Reuse of existing infrastructure (potential cost saving)
  - Proton facilities
  - Tunnels (maybe more for acceleration than for collision)

- **LEMMA concept and new ideas (could be breakthrough for parameters)**
  - **Consolidation**
  - **Alternative low-emittance sources (gamma factory, crystals, …)**
  - **Could define the source test facility**
  - **Long-term alternative development**

Note: Key Accelerator Technologies

- High-field, robust collider magnets with minimum gap
  - Dipoles, solenoids, …
- Efficient fast ramping magnets with efficient energy recovery
  - For the beam acceleration
- Efficient cryogenics, vacuum and shielding systems
  - Significant beam loss
- Robust targets and beam cleaning
- High field cavities
  - In a solenoid for the cooling system
- Efficient RF power production
- Civil engineering
- Other systems
  - E.g. instrumentation
  - …
- Beamdynamics and accelerator design
  - Start-to-end design and simulations, source design, …

Similar to what is needed for proton colliders

Expertise in Europe and at CERN

How Could 14 TeV Look Like?

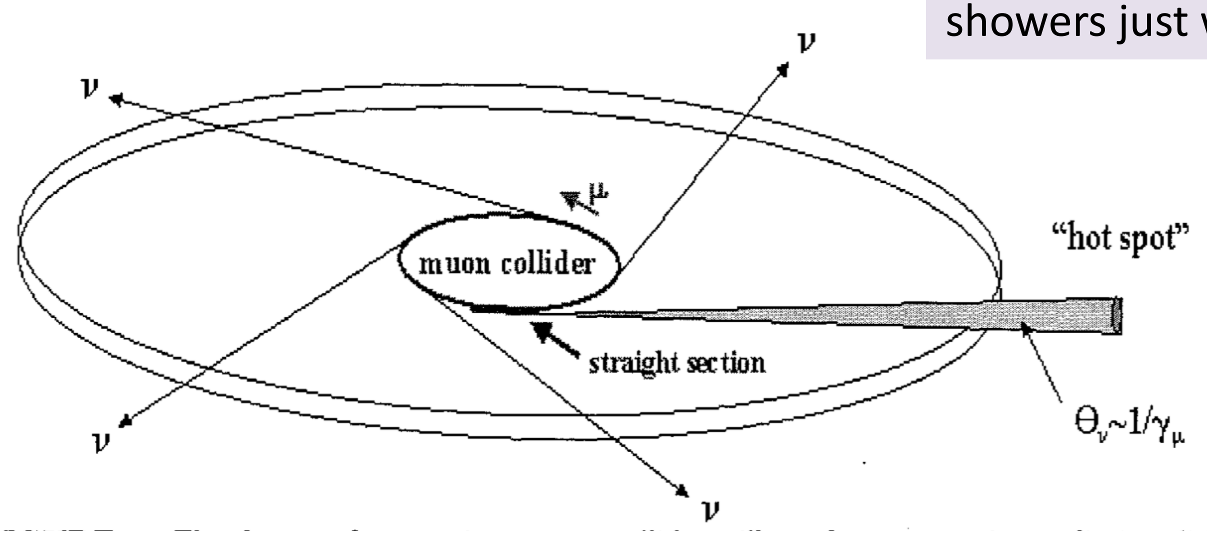
Very tentative target parameters based on scaling from MAP, to be studied

Parameter	Unit	1.5 TeV	3 TeV	6 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.25	4.4	12	40
N	10^{12}	2	2	2	2
f_r	Hz	15	12	6	3.7
P_{beam}	MW	6.75	11.5	11.5	16.6
<B>	T	6.3	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1	0.1
σ_z	mm	10	5	2(.5)	1.07
β	mm	10	5	2.5	1.07
ε	μm	25	25	25	25
$\sigma_{x,y}$	μm	5.9	3.0	1.5	0.63

Note: CLIC beam power at 3 TeV is 28 MW

Challenging optics
Maybe hard to make short bunches

Neutrino Radiation Hazard



Neutrinos from decaying muons can produce showers just when they exit the earth

Particularly bad in direction of straights
But also an issue in the arcs

Becomes more important at higher energies (scaling E^3)

US study concluded that 6 TeV parameters are OK

Reasonable goal is 0.1 mSv/ year, but to be verified

Potential mitigation by

- Site choice
- Owning the land in direction of experimental insertion

- Having a dynamic beam orbit so it points in different directions at each turn in the arcs
  - Or at least paint the beam in the the straights to dilute radiation

Radiation to Luminosity Scaling

Reasonable goal could be 0.1 mSv/year

Simple to derive scaling of radiation per integrated luminosity with parameters
Note: target integrated luminosity increases with energy

$$\frac{D}{\int \mathcal{L}} \propto aE \left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}} \right) \frac{1}{d} \frac{\epsilon_T \epsilon_L}{N_0} \frac{1}{\sigma_\delta}$$

D: radiation dose
E: beam energy
B: Magnetic field
d: depth underground

Using Bruce Kings parametrisations of radiation with beam current one finds

$$a \approx 4 \times 10^{-4} \frac{mSv}{ab^{-1}} \frac{1}{eV^{-2} m}$$

Note: find 0.1 mSv/Year for MAP at 6 TeV,
i.e. consistent with this set being limited by radiation

Needs to be verified for each case but gives reasonable indication

Radiation in Purpose-built Tunnel

Assume MAP-type beam
B = 10.5 T, L = 0.2 m
Deep tunnel d = 500 m

$$\frac{D}{\int \mathcal{L}} \propto aE \left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}} \right) \frac{1}{d} \frac{\epsilon_T \epsilon_L}{N_0} \frac{1}{\sigma_\delta}$$

At 7+7 TeV at target of 4 ab^{-1} radiation would be 0.8 mSv/year

I.e. 8 times too large
⇒ Need to improve

$$\frac{D}{\int \mathcal{L}} = \frac{0.8mSv}{4ab^{-1}}$$

At 3.5+3.5 TeV radiation would be 0.1 mSv/year
(1 ab^{-1} per year)
1.5+1.5 TeV would allow d = 40 m

But need to deal with straights and study exact site

Mitigation Approaches

Tricks
e.g. beam wiggling, dumping the beam, …

$$\frac{D}{\int \mathcal{L}} \propto aE \left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}} \right) \frac{1}{d} \frac{\epsilon_T \epsilon_L}{N_0} \frac{1}{\sigma_\delta}$$

Higher field in collider ring
And shorter gaps

Magnet design

Deeper tunnel

Civil engineering

Denser beam

Source design

Larger energy
spread acceptance

Lattice design work

More efficient physics
More years of running

How to gain a factor 8 in radiation?
Seems hard but not impossible

Some Tools to Reduce Radiation

- Shorter gaps between magnets
  - e.g. 7 cm halves radiation
- More brilliant beams
  - Halving emittance halves radiation
- Wiggling the beam
  - O(8 sigma) starts to help (for 100 m beta-function)
- Dumping the beam before fully decayed
  - Fractional saving
- Cutting large amplitude muons
  - Does not help
- Spread out programme over more years
- Add the two detectors
- …

Use of Existing Infrastructure

Might be able to reuse much of the proton and general infrastructure

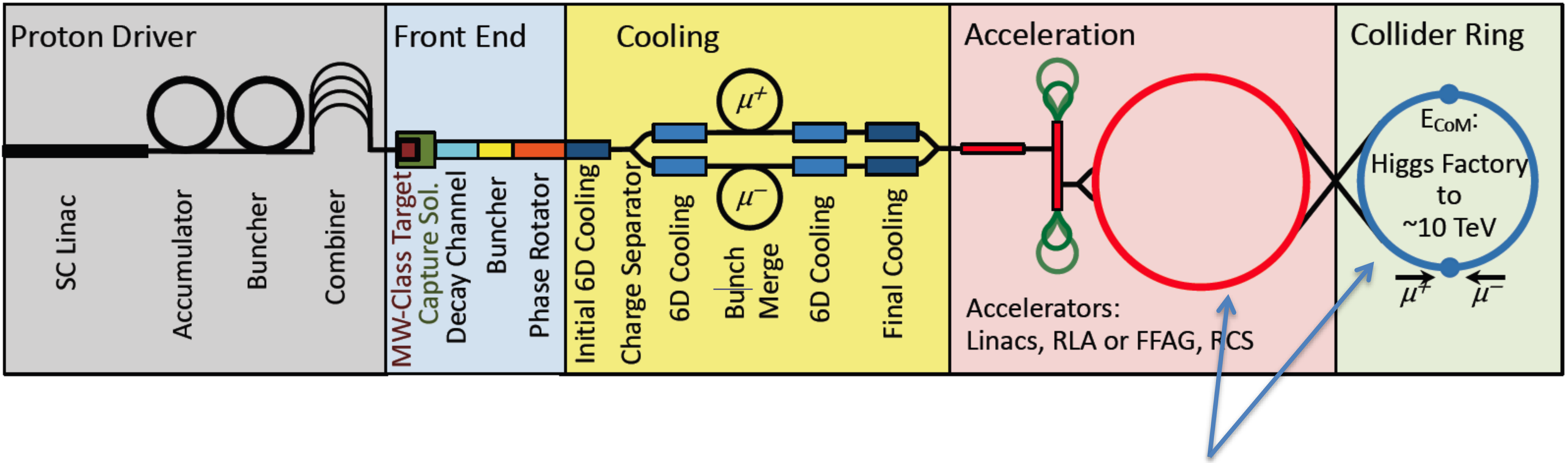
- Needs detailed study
- Much of the expertise is available

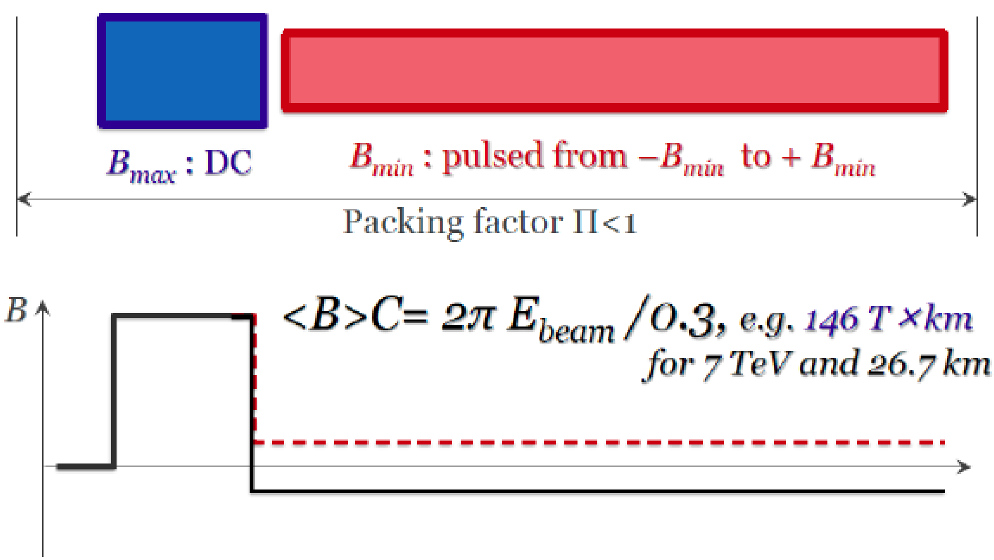
Use of the largest tunnels, i.e. LHC or potentially FCC

- Can house positron ring in the LEMMA case
  - In FCC, even lepton equipment might exist from FCC-ee
  - Large rings means less synchrotron radiation and power consumption
- Consider to use ring as a collider
  - But means to have larger ring for acceleration
  - Or to use combined final accelerator / collider
    - This compromises luminosity and generates technical challenges but may save cost
- Use tunnel for final accelerator
  - Have a small optimised collider ring
  - Seems natural solution

Some proposals made, e.g. LEMMA team, V. Shiltsev, D. Neuffer, F. Zimmermann, …

Comment: Collider Ring

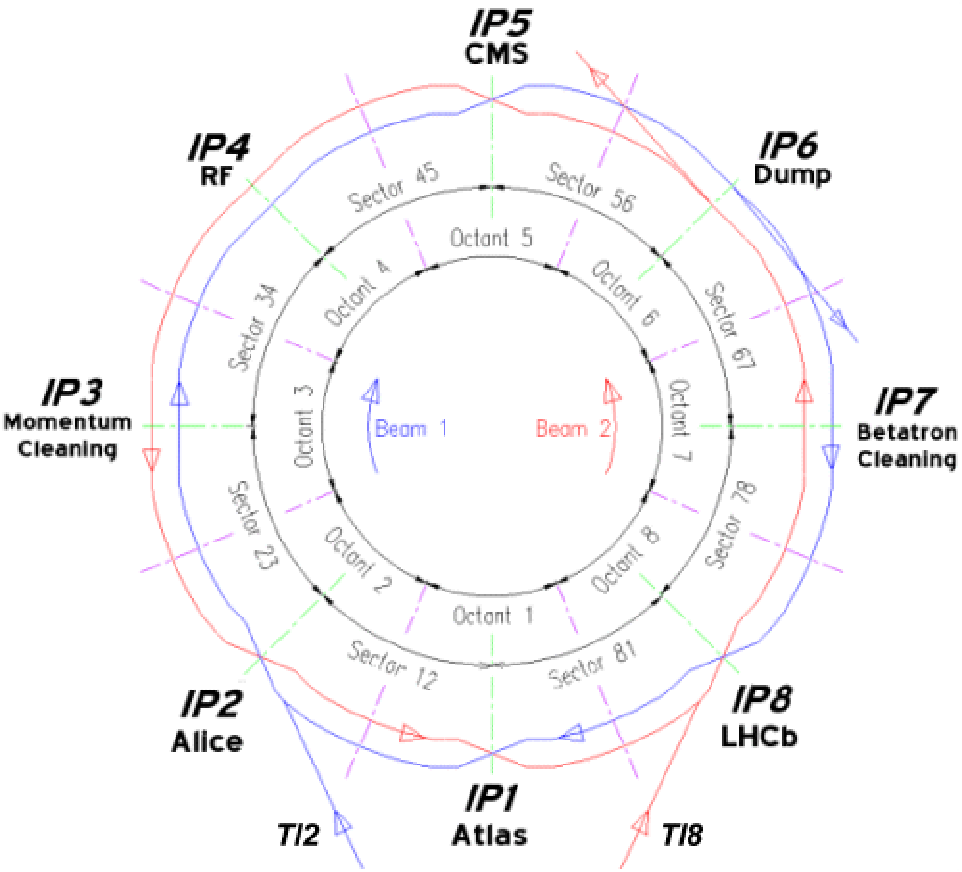


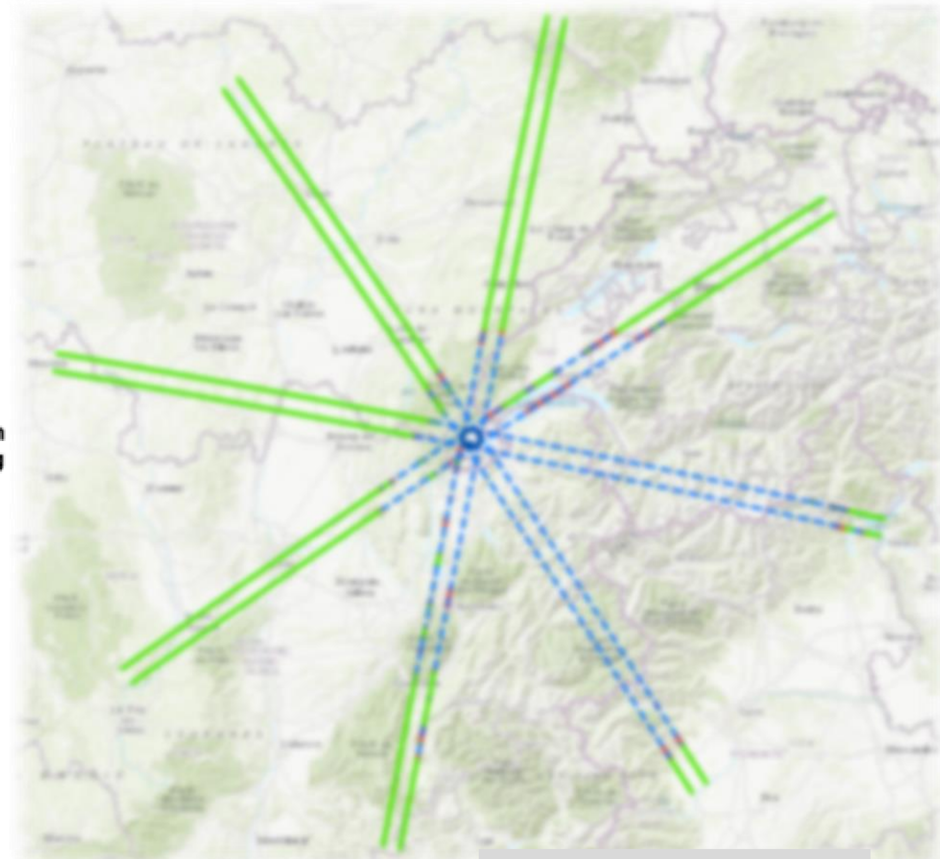


Proposal to combine last accelerator ring and collider ring (Neuffer/Shiltsev) might reduce cost but creates many specific challenges

This would be largest tunnel

Effective Depth of LHC





J. Osborn, Y. Robert , …

Minimum distance is 17 km, corresponds to effective depth of d = 23 m
Second shortest is 25 km (d = 50 m), longest is 263 km (d = 5430 m)

Use of LHC Tunnel for Collisions

Useful collider **energy range 14-25 TeV**

- For 3 TeV collider 6 km tunnel would be sufficient and yields 5 times more luminosity

Use **MAP-type beam** with 4 Hz repetition rate and 10^7s operation per year

- Achieves luminosity target

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

Radiation to public can be limiting

- Maximum radiation from arcs (14 TeV, 4 ab^{-1} per year, B = 8 T, L = 0.2 m):
  - **O(18.8 mSv/year)**
- The straights increase neutrino radiation (14 TeV, 4 ab^{-1} per year, B = 8 T, L = 500 m)
  - **O(3x10^4 mSv/year)**

Important mitigation is required

- Arcs would be OK for 2 TeV
- Can we wiggle the beam?
- Can we paint it around in the straights?
- Seems an important issue

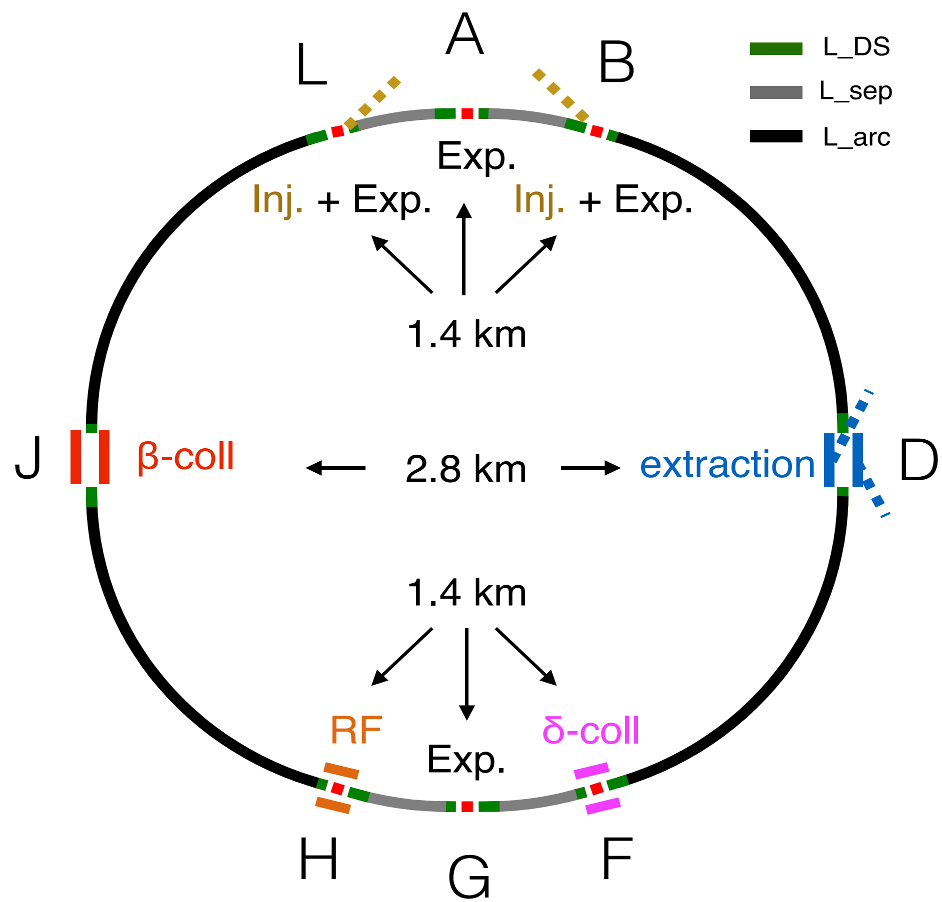
A much reduced current would help

- A reason to continue to work on alternative sources (LEMMA etc.)
- Note: LEMMA-type beam 10^{11} muons/s would give factor 80, still problem in straights

Collision in FCC Tunnel

Would be at even higher energies (50 to 100 TeV cm)

- Radiation is much worse
- But can still define layout
  - In particular arrange straights
  - e.g. racetrack design?



Solutions with combined accelerator/collider ring will have even more radiation from arcs since the average field is lower

Low emittance beam would help

- Need factor 200 less current

Acceleration in LHC/FCC Tunnel

- Lower radiation than collider ring (fewer turns and mostly lower energy)
  - Typically factor O(10) to O(100), use 30 as example below
  - Maybe can use energy change to distribute distribute radiation more

- For 1.5 TeV beam in LHC (e.g. fast-ramping 1.4-1.8 T magnets, 45 GV RF)
  - Gaps of O(30 m) are still OK
  - Straights would be O(20) too high, requires improvement (helical trajectory?)

- For 3 TeV beam in LHC
  - e.g. could be mixture of superconducting and fast-ramping normal magnets
  - Gaps of 3 m would be OK
  - O(200) too high in straights

- For 7 TeV beam in FCC (e.g. fast-ramping 1.8 T magnets)
  - radiation from arcs sufficient at 300 m depth
  - need to anticipate arrangement of straights

Need to study mitigation of radiation from straights

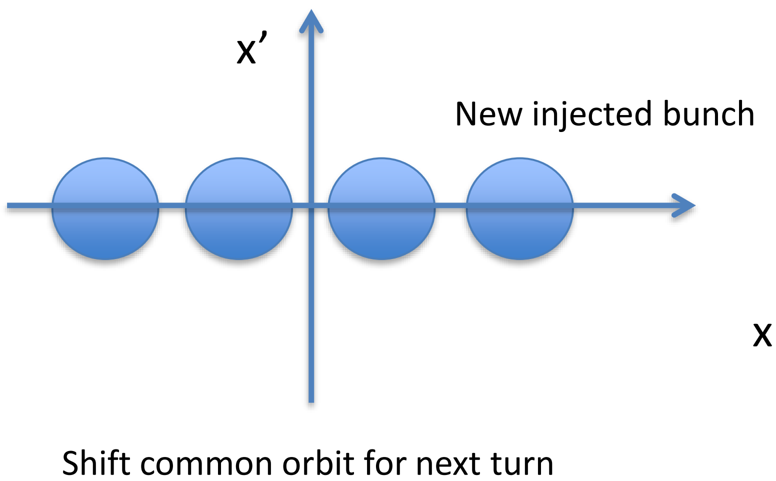
Note: Stacking

Can increase relevant beam density by stacking n bunches

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma \qquad \epsilon = \sqrt{\epsilon_x \epsilon_y}$$

Could combine bunches in transverse phase space
Theoretically, $\varepsilon_x \varepsilon_y$ scales with number of bunches
Charge also scales with number of bunches
Hence

$$\frac{N}{\epsilon} \approx \sqrt{n} \frac{N_0}{\epsilon_0}$$



But difficult to do…

Particularly interesting for LEMMA with high rate of bunches
But only with square root of combination factor

Conclusion

- Have a tentative plan for the future
  - In case muon collider R&D is proposed by the European Strategy
  - But need people and money
  - Try to obtain network-like activity (via ARIES2)

- Need to develop baseline
  - Energy and luminosity choice
  - For MAP and LEMMA approach important gaps exist
  - Need to bring knowledge to life again
  - And address holes
  - For LEMMA consolidation is attempted

- Need to address neutrino radiation
  - Confirm results from US study
  - Lower radiation at 14 TeV
  - Potentially strong point of the LEMMA scheme

- Need to develop experimental R&D plan
  - Key is likely test facility for muon generation
  - Will depend on progress of baseline design

E-groups:
MUONCOLLIDER-DETECTOR-PHYSICS
MUST-phydet@cern.ch

MUONCOLLIDER-FACILITY
MUST-mac@cern.ch

Reserve

Muon Collider Working Group

Jean Pierre Delahaye, CERN, Marcella Diemoz, INFN, Italy,
Ken Long, Imperial College, UK, Bruno Mansoulie, IRFU, France,
Nadia Pastrone, INFN, Italy (chair), Lenny Rivkin, EPFL and PSI, Switzerland,
Daniel Schulte, CERN, Alexander Skrinsky, BINP, Russia, Andrea Wulzer, EPFL and CERN

appointed by CERN Laboratory Directors Group in September 2017

to prepare the Input Document to the European Strategy Update

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de facto it is the seed for a renewed international effort

Past experiences and new ideas discussed at the joint ARIES Workshop

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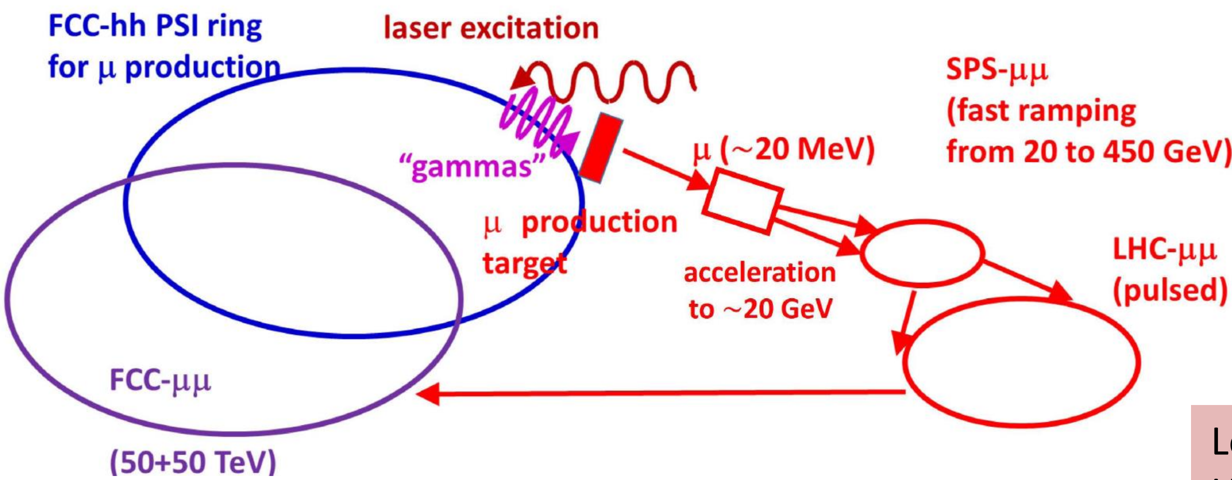
Note: FCC as Collider

100 TeV μ collider FCC-μμ with FCC-hh PSI μ± production

F. Zimmermann



Low luminosity
Uses flawed LEMMA bunch stacking

Needs additional accelerator
Or B > 16 T
Or fast-ramping 16 T magnets

Radiation from arcs still 10-60 times too high

	LHC based, using γ factory e⁺ & LEMMA	FCC based, using γ factory muons	FCC based. using γ factory e⁺ & LEMMA
$\mu^+\mu^-$ c.m. energy [TeV]	27	100	100
#bunches / beam	1	1	1
average #μ / bunch [10^9]	4	16	4
β* [mm]	1	1	1
norm. emittance γε [μm]	0.04 (0.2?)	2000	0.04 (0.2?)
av. luminosity [10^{34} cm^{-2}s^{-1}]	0.05 (0.01)	0.003	10 (2)
comment	LEMMA emittance ?		LEMMA emittance ?

Linear Collider Scaling with Energy

Normalised emittances always used

$$\mathcal{L} \propto H_D \frac{n_\gamma^{\frac{3}{2}}}{\sqrt{\sigma_z}} \frac{1}{\sqrt{\epsilon_y \beta_y}} \frac{R+1}{R} \frac{\eta P_{wall}}{mc^2}$$

Beamstrahlung limited by physics requirements
Bunch length limited by acceleration and detector background

Beam quality and focusing design

RF-to-beam efficiency
Power consumption

At high energy

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

For unchanged technologies:
Luminosity per power remains constant with energy
Provided we can focus the beam accordingly

$R=\sigma_x/\sigma_y$

Findings of Muon Collider Working Group

A first, high-level review of the two schemes with proton-based (MAP) and positron-based (LEMMA):

Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.

First focus promising positron-based scheme, but identified need for consolidation

No showstopper found for proton scheme, but much more detailed understanding is required to judge performance, cost and power. No CDR exists.

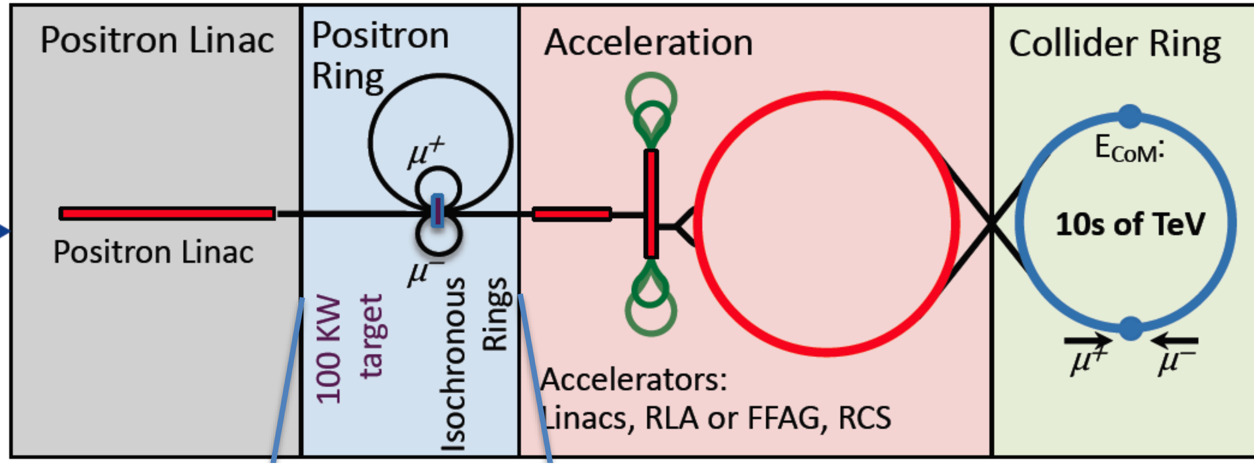
Important progress of the technologies, addressing the feasibility of major technical issues with R&D performed by international collaborations.

In Europe, the reuse of existing facilities and infrastructure for a muon collider is of interest (e.g. LHC).

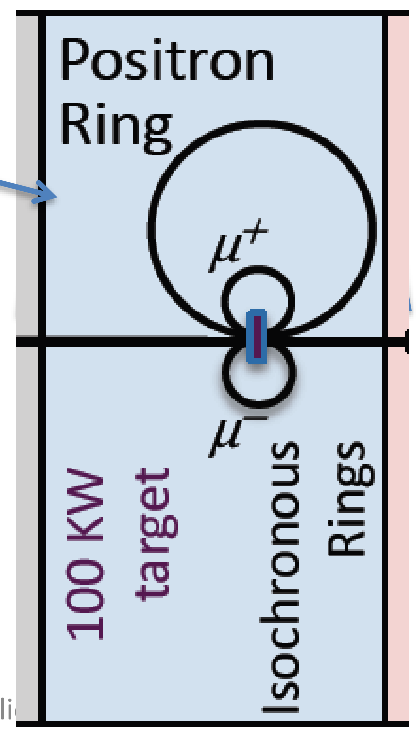
Documents: see first slide of the reserve

The LEMMA Scheme

Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Key concept:
Produce muon beam with low emittance using a positron beam
No cooling required



Muon current 10^{11} s^{-1} is 300 times lower compared to 3 x 10^{13} s^{-1} for proton driver

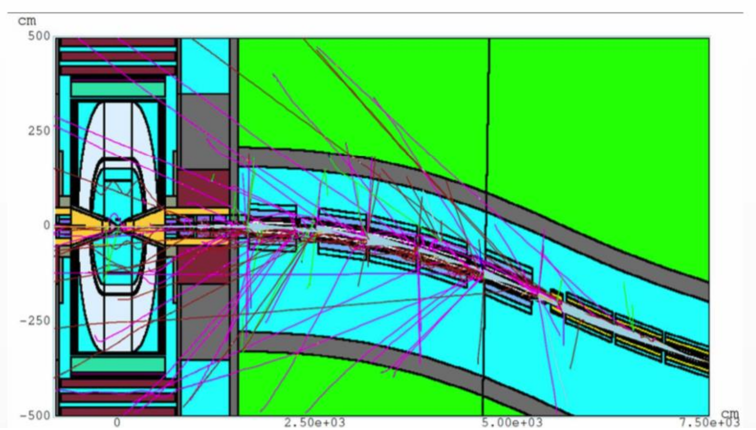
Emittance $O(10^{-3})$ smaller than in proton scheme, 40 ns vs. 25 μm

In design of 2018 two important issues were found
- Muon multiple scattering
- Issue with phase space

Attempt to consolidate is ongoing
⇒ Nadia's talk

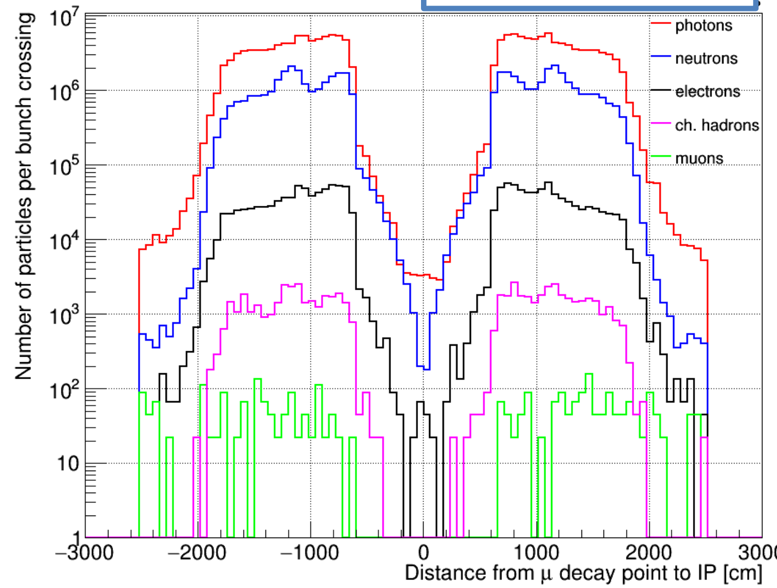
Beam induced background studies on detector at $\sqrt{s}$ =1.5 TeV

arXiv:1905.03725

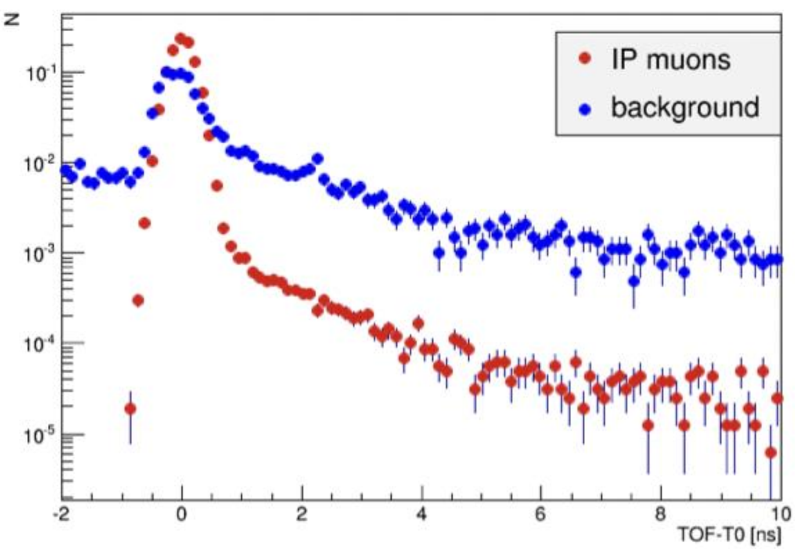


MARS15 simulation in a range of ±100 m around the interaction point

750 GeV beam



Particle composition of the beam-induced background as a function of the muon decay distance from the interaction point



Simulated time of arrival (TOF) of the beam background particles to the tracker modules with respect to the expected time (T0) of a photon emitted from IP

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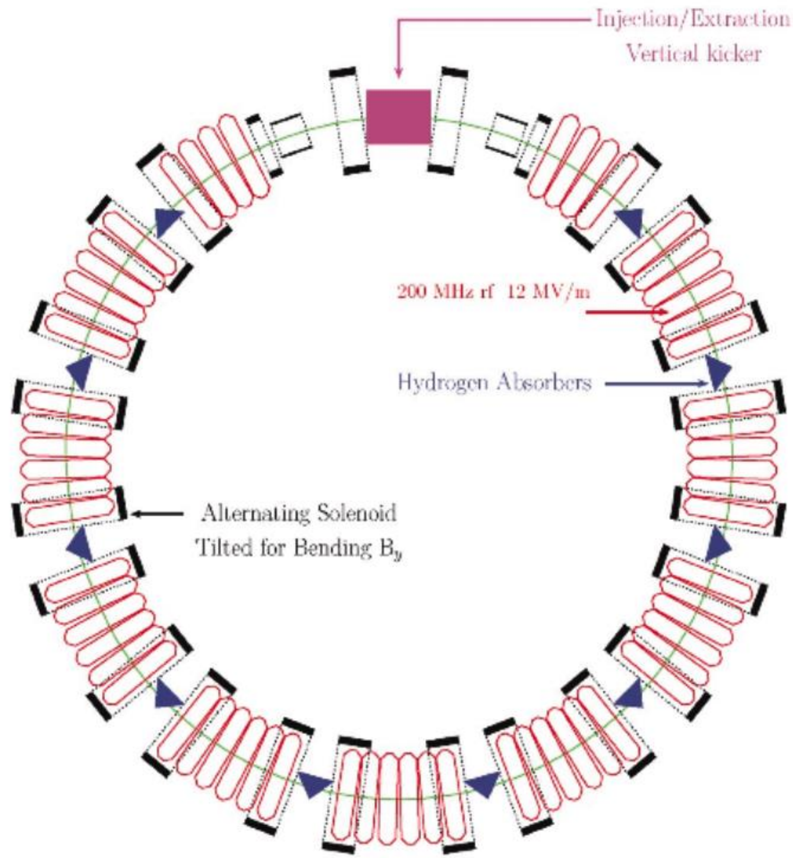
Test Facility Example

Carlo Rubbia: The experimental realization of the presently described μ+μ- Ring Collider may represent the most attractive addition of the future programs on the Standard Model to further elucidate the physics of the Ho, requiring however a substantial amount of prior R&D developments, which must be experimentally confirmed by the help of the Initial Muon Cooling Experiment(al) program.

Initial Cooling Experiment
Use 100 ns ESS pre-pulse with 3×10^{11} protons
Yields 3×10^{7} μ^- and 6×10^{7} μ^+ around 250 MeV

Test of parametric cooling would be useful
A fancy way of making beta small

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



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Luminosity per power remains constant with energy
Provided we can focus the beam accordingly

$R=\sigma_x/\sigma_y$

Note: Total Power Consumption

Power consumption estimates are based on a table calculated by R. Palmer

- Leaves out a number of components, e.g. magnets
- Quote: “These numbers are preliminary, with large uncertainties”

J.-P. Delahaye added a constant value

Table 2. Estimated collider wall power requirements for 1.5 TeV center of mass; this does not include detectors, buildings, air conditioning, etc. ‘PS’ refers to Power Supplies, ‘4 K’ and ‘20 K’ refer to cryogenic power to cool elements to these temperatures.

	Length	Static	Dynamic	—	—	—	Total
		4° K	rf	PS	4° K	20° K	
	m	MW	MW	MW	MW	MW	MW
Proton driver (SC linac)							(20)
Target and taper	16			15.0	0.4		15.4
Decay and phase rot	95	0.1	0.8		4.5		5.4
Charge separation	14						
6D cooling before merging	222	0.6	7.2		6.8	6.1	20.7
Merging	115	0.2	1.4				1.6
6D cooling after merging	428	0.7	2.8			2.6	6.1
Final 4D cooling	78	0.1	1.5			0.1	1.7
NC rf acceleration	104	0.1	4.1				4.2
SC rf linac	140	0.1	3.4				3.5
SC rf RLAs	10,400	9.1	19.5				28.6
SC rf RCSs	12,566	11.3	11.8				23.1
Collider ring	2600	2.3		3.0	10		15.3
Total	26	24.6	52.5	18.0	21.7	8.8	145.6

Need to have conceptual start-to-end design to estimate power correctly
Efficiency of wall plug to beam is not very different from CLIC

LHC Tunnel

For the arcs (presumably worst point, based on straights)

$$\frac{D}{\int \mathcal{L}} \propto aE\left(\frac{\mathrm{T}}{B}+\frac{L}{0.7\,\mathrm{m}}\right)\frac{1}{d}\frac{\epsilon_T\epsilon_L}{N_0}\frac{1}{\sigma_\delta}$$

$$= \frac{0.1 mSv}{0.059 ab^{-1}}$$

$$a \approx 4 \times 10^{-4} \frac{mSv}{ab^{-1}} \frac{1}{eV^{-2} m}$$

E = 0.85 TeV

MAP-type beam

B = 1 T

L = 0.2 m

d_{equiv} = 23 m

LHC Tunnel

For the straights (worst point)

$$\frac{D}{\int \mathcal{L}} \propto aE\left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}}\right)\frac{1}{d}\frac{\epsilon_T \epsilon_L}{N_0}\frac{1}{\sigma_\delta}$$

$$= \frac{0.1 mSv}{0.059 ab^{-1}}$$

$$a \approx 4 \times 10^{-4} \frac{mSv}{ab^{-1}} \frac{1}{eV^{-2} m}$$

E = 0.1 TeV

MAP-type beam

B = 1 T

L = 500 m

d_{equiv} = 23 m - 5430 m

Muon Collider Luminosity Scaling

$$\frac{D}{\int \mathcal{L}} \propto aE\left(\frac{\mathrm{T}}{B}+\frac{L}{0.7\,\mathrm{m}}\right)\frac{1}{d}\frac{\epsilon_T\epsilon_L}{N_0}\frac{1}{\sigma_\delta}$$

How to gain a factor 8 in radiation?
Seems hard but not impossible

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$$\frac{D}{\int \mathcal{L}} \propto aE \left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}} \right) \frac{1}{d} \frac{\epsilon_T \epsilon_L}{N_0} \frac{1}{\sigma_\delta}$$

Higher field in collider ring
And shorter gaps

Deeper tunnel

Denser beam

Larger energy
spread acceptance

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$$\frac{D}{\int \mathcal{L}} \propto aE \left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}} \right) \frac{1}{d} \frac{\epsilon_T \epsilon_L}{N_0} \frac{1}{\sigma_\delta}$$

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Magnet design

Deeper tunnel

Civil engineering

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Source design

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Lattice design work

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Lattice design work

More efficient physics
More years of running

How to gain a factor 8 in radiation?
Seems hard but not impossible

Collision in LHC / FCC Tunnel

Collision in LHC tunnel:
- The straights increase neutrino radiation (L = 500 m)
- Equivalent depth of LHC is only 23 m (using shortest distance from straight to surface)
  - At 14 TeV cm and for 4 ab^{-1} per year 33×10^{3} mSv/year (B = 8 T, L = 500 m)
  - Can we use special optics or wiggle the beam enough?
  - Typically need to wiggles beam by 10 sigma to obtain some spreading of radiation
- Even arcs are limiting
  - For 14 TeV and 4 ab^{-1} per year 18.8 mSv/year (B = 8 T, L = 0.2 m)

Collision in FCC tunnel:
- Would be at even higher energies, so radiation is much worse
- But can still change layout
  - In particular arrange straights

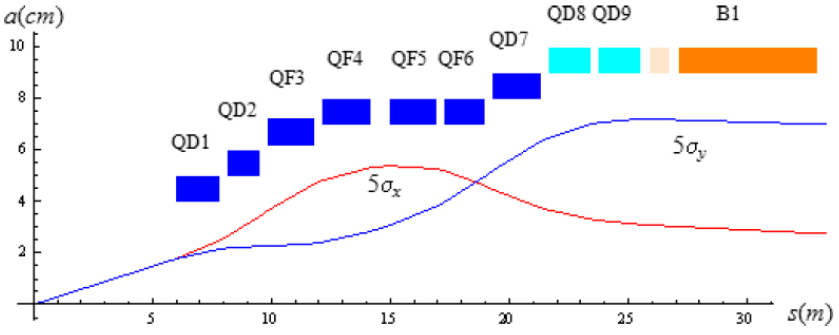
Solutions with acceleration and collision in LHC or FCC tunnel will have even more radiation from arcs since the average field is lower

Low emittance beam would help
- Need factor 200 less current

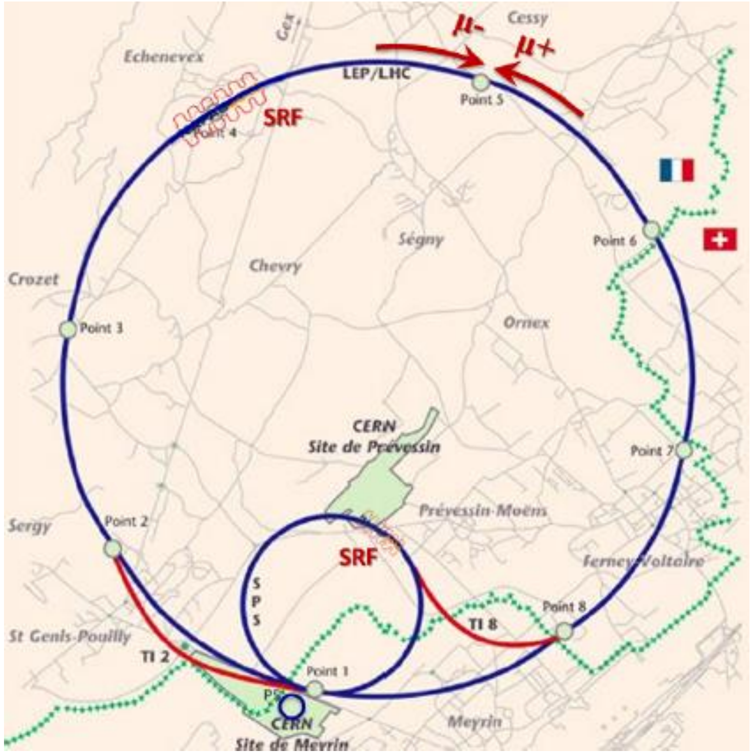
Collider Ring

Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy

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



High field dipoles to minimise collider ring size and maximise luminosity
Minimise distances with no bending



Proposal to combine last accelerator ring and collider ring (Neuffer/Shiltsev) might reduce cost but creates many specific challenges

Decaying muons impact accelerator components, detector and public
The latter becomes much worse with energy

Radiation to public in case LHC tunnel use

Might be best to use LHC tunnel to house muon accelerator and have dedicated new collider tunnel

Potential Approaches

Acceleration is important for cost and power consumption
No conceptual baseline design yet
But different options considered
A whole chain is needed from source to full energy

Recirculating linacs

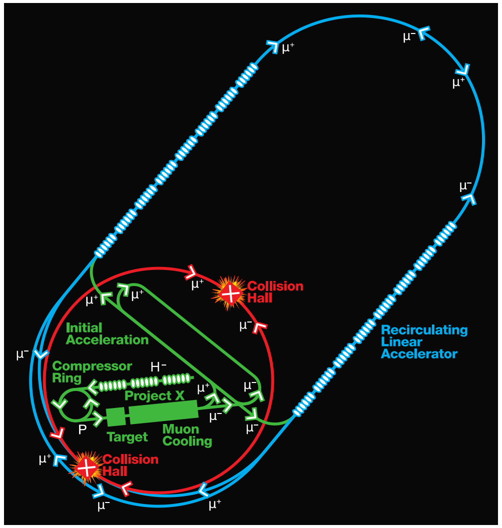
- Fast acceleration but typically only a few passages through RF, hence high RF cost

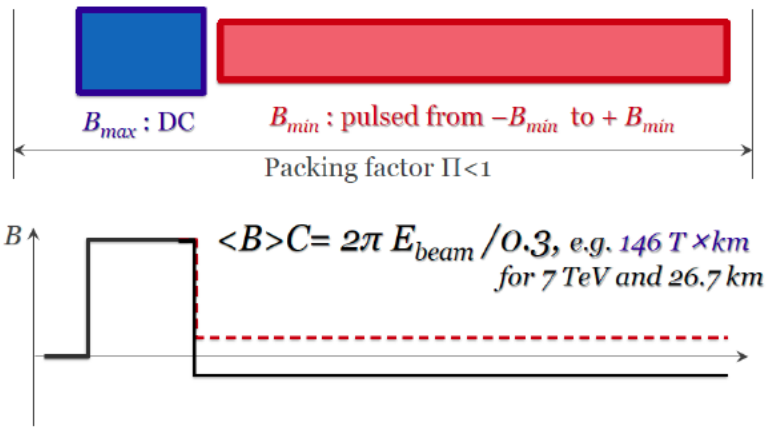
Rapid cycling synchrotron (RCS)

- Potentially important acceleration range at affordable cost
- Could use combination of static superconducting and ramping normal-conducting magnets
- But have to deal with energy in fast pulsing magnets
- Efficient energy storage is required

FFAGs

- Static high field magnets, can reach factor up to 4 increase in energy, needs design work





Challenge to achieve a combination of high efficiency, low cost and good beam quality

Review Conclusion

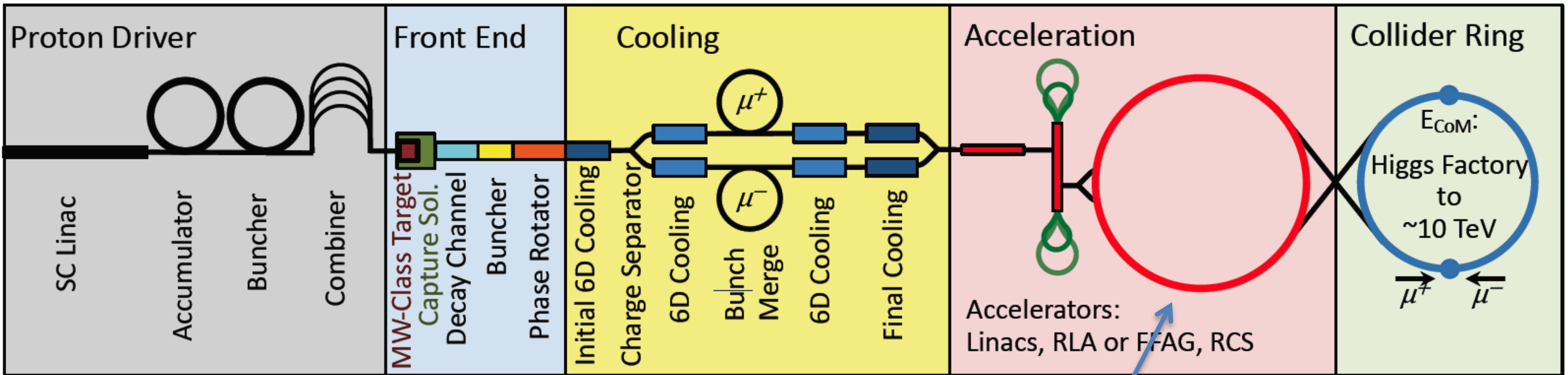
We think we can answer the following questions

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged
  - But at this moment not mature enough for a proposal

- **Is it worthwhile to do muon collider R&D?**
  - Yes, it promises the potential to go to very high energy
  - It may be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other physics experiments
  - Should not miss this opportunity

- **What needs to be done?**
  - Muon production and cooling is key => A new test facility is required.
  - A conceptual design of the collider has to be made
  - Many components need R&D, e.g. fast ramping magnets, background in the detector
  - Site-dependent studies to understand if existing infrastructure can be used
    - limitations of existing tunnels, e.g. radiation issues
    - optimum use of existing accelerators, e.g. as proton source

Beam Acceleration



An important cost driver

Important for power consumption

Much larger than collider ring

A trade-off between cost and muon survival

Not detailed design, several approaches considered

- Linacs
- Recirculating linacs
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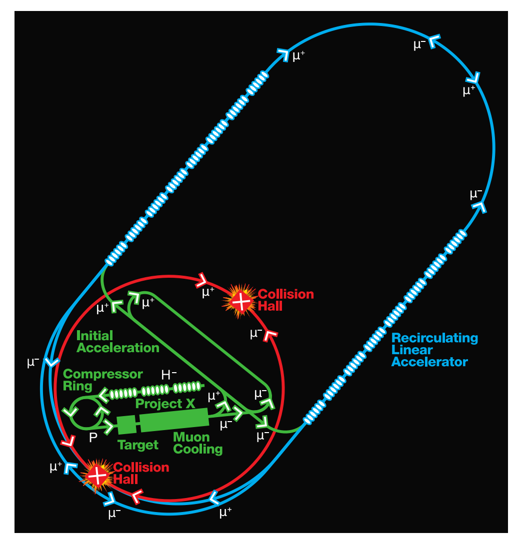
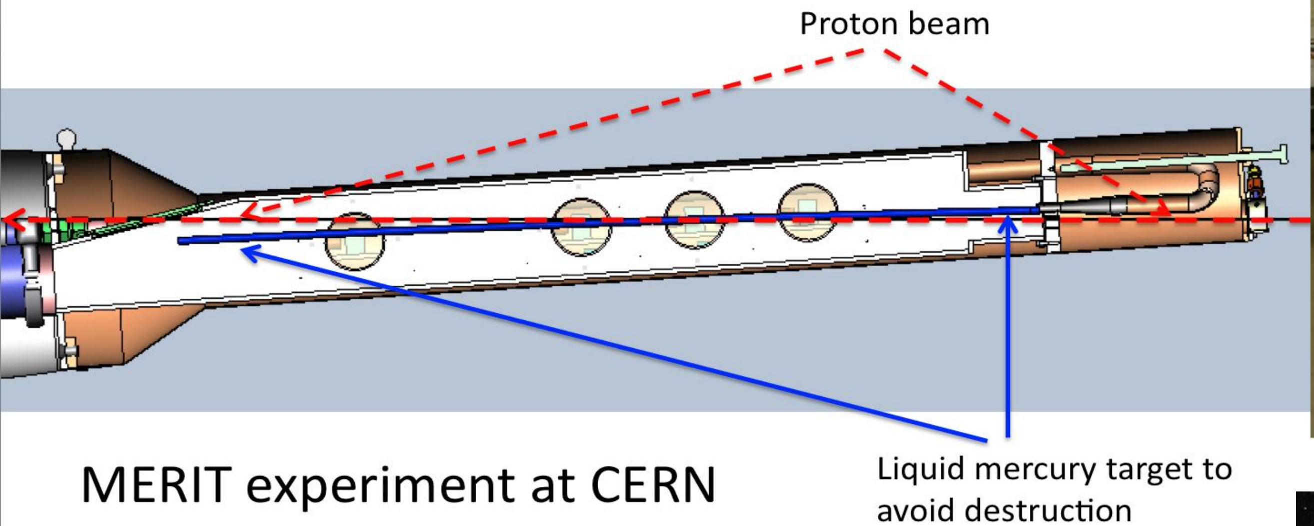
- Rapid cycling synchrotrons



Challenge is large bunch charge but single bunch

Reminder: Source

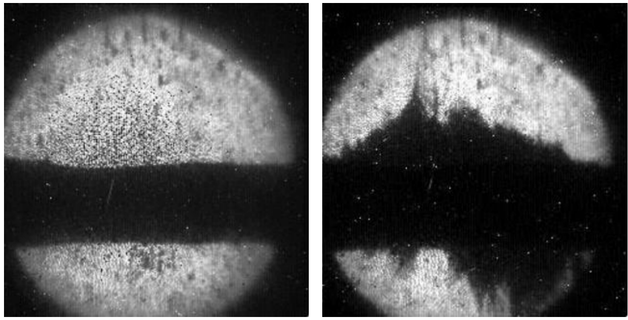
Protons → Target → Pions → Muons



MERIT experiment at CERN

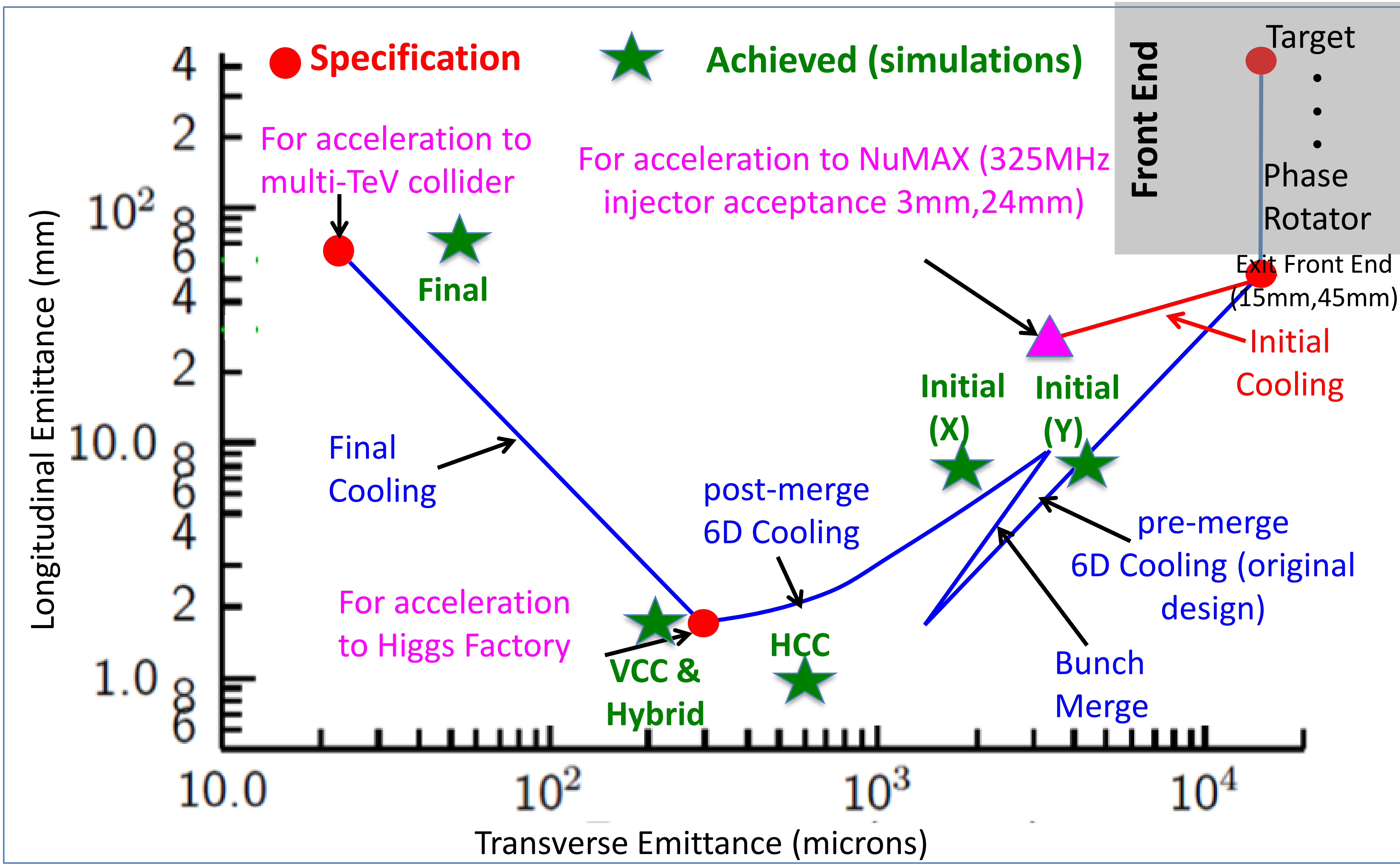
High power target (8 MW vs. 1.6-4 MW or even less required) has been demonstrated

- 30×10^{12} protons with 24 GeV yield 9×10^{12} muons
- Almost enough (loose 90%)
- But cannot generate short muon bunch because proton pulse is too long
- Better to use solid target
- Looks good but more work required

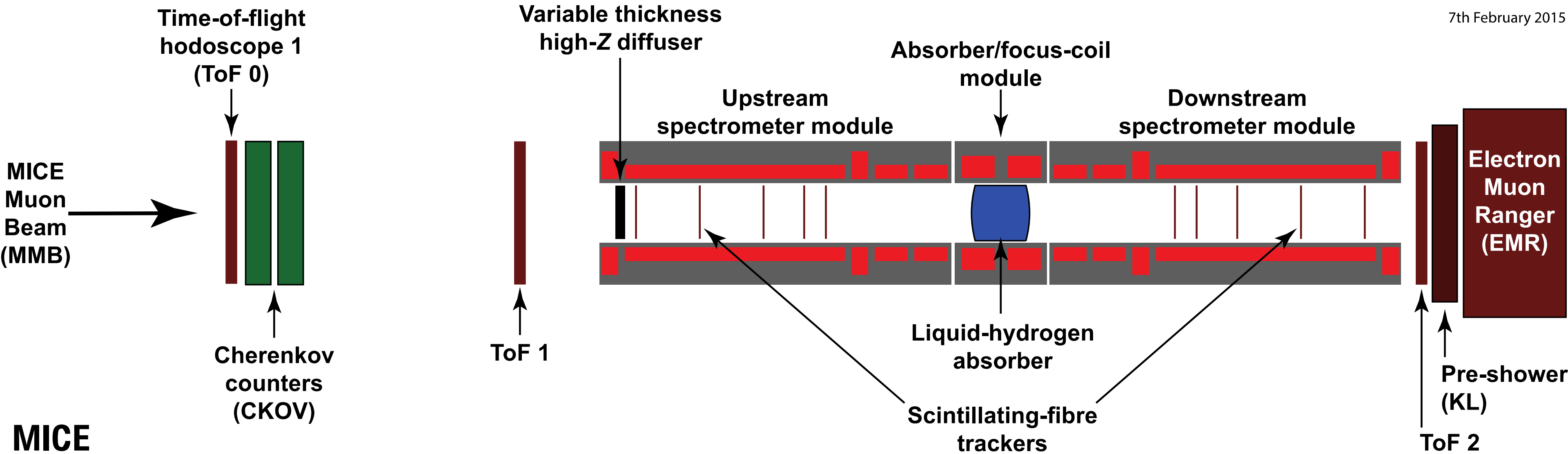


What could be made available at CERN (or elsewhere) as a proton driver for a potential test facility?

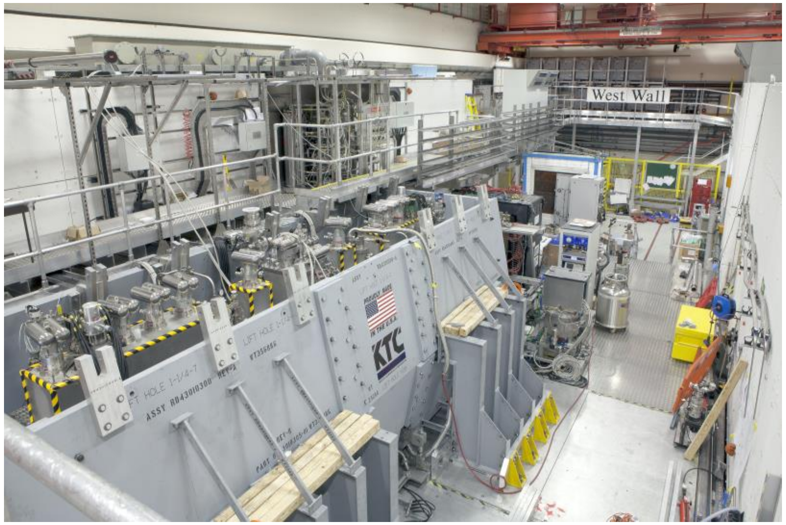
Reminder: The Emittance Path



Reminder: Cooling and MICE



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

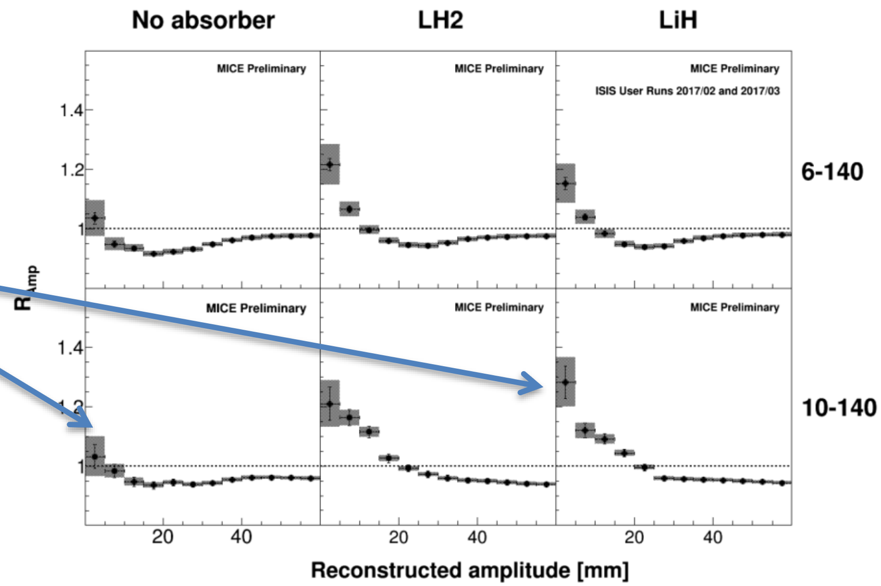


MICE allows to address 4D cooling with low muon flux rate

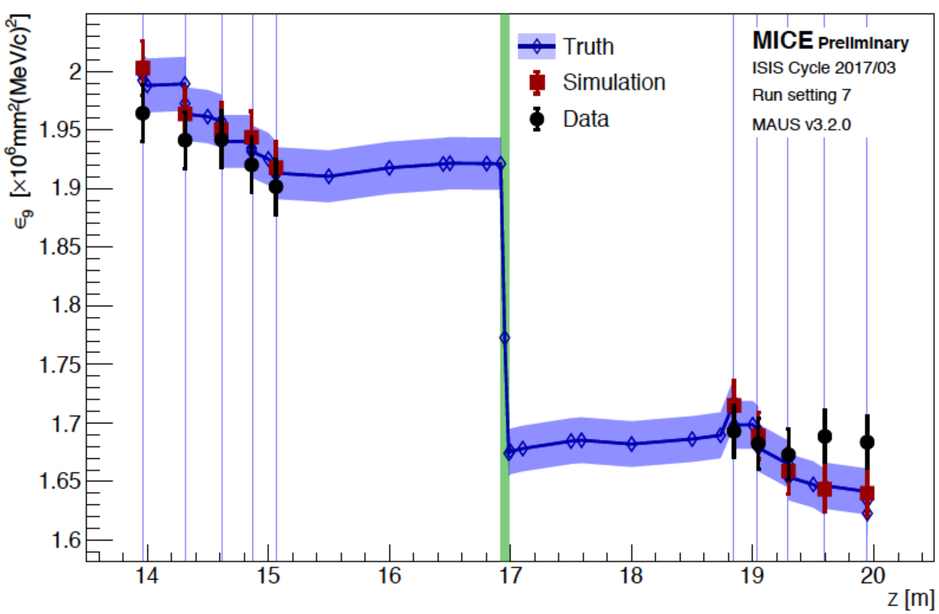
Reminder: MICE Results

The absorber reduces the number of particle with large amplitude

They appear with smaller amplitude



Noticeable reduction of 9% emittance



But still some way to go

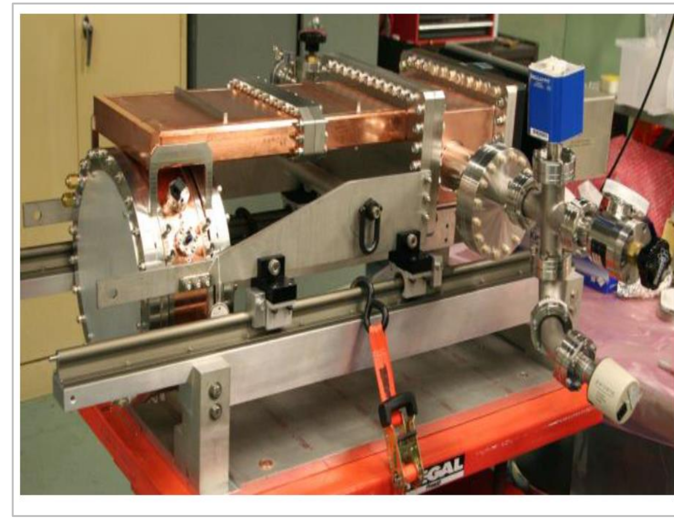
- 6D cooling
- Stages
- Small emittances

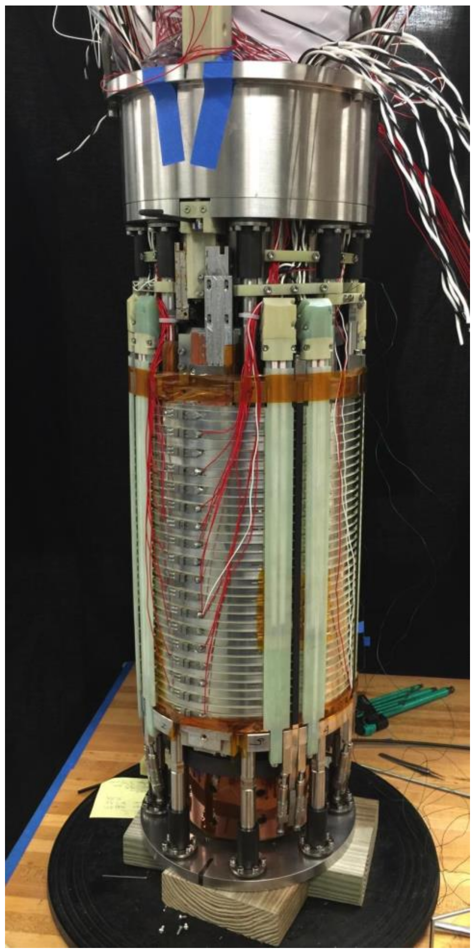
Reminder: Other Tests

FNAL
Breakthrough in
HTS cables

A number of key components has been developed

MuCool: >50 MV/m in 5 T field



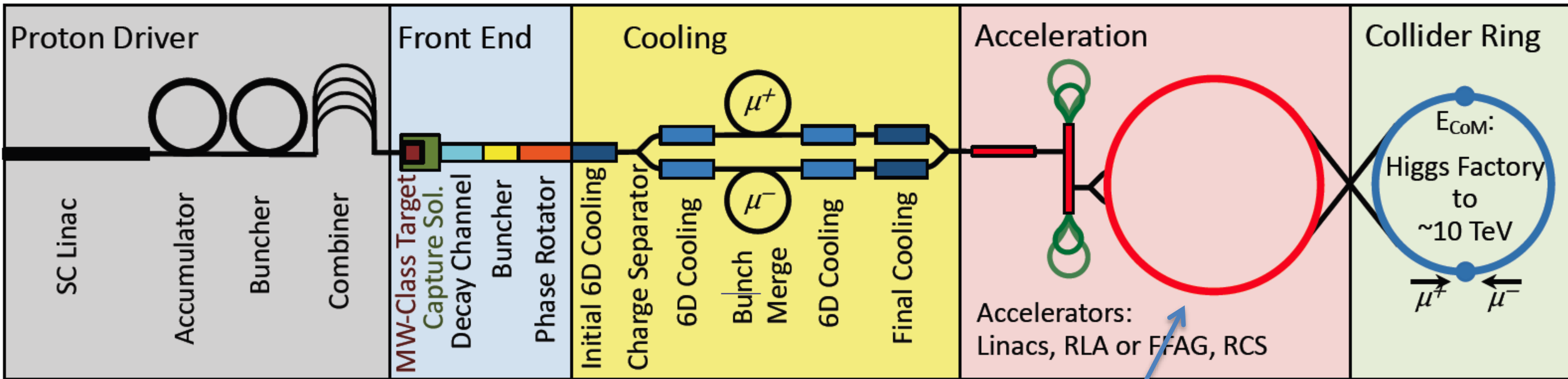


NHFML
32 T solenoid with
low-temperature
HTS

FNAL
12 T/s HTS
0.6 T max

Mark Palmer

Reminder: Beam Acceleration



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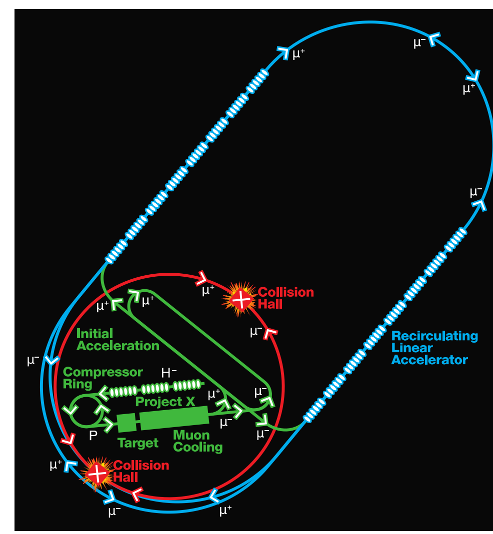

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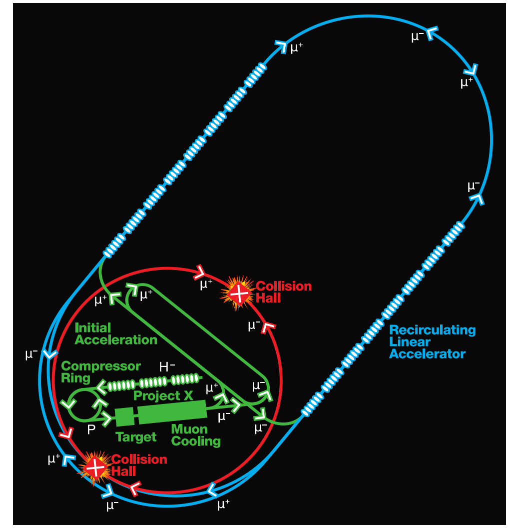

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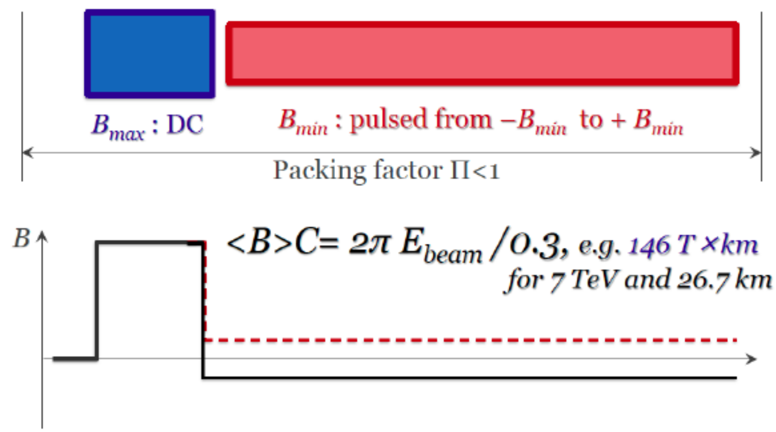

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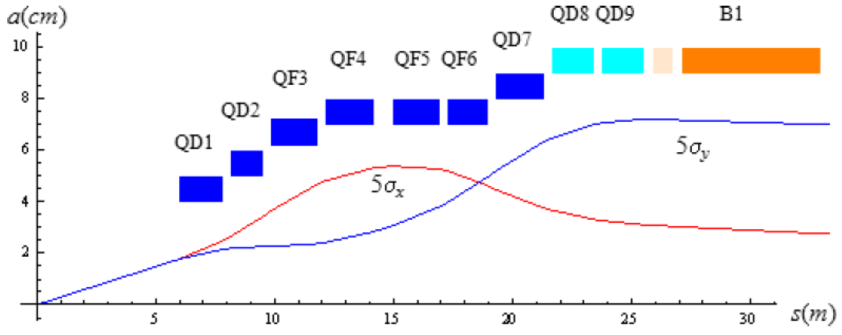
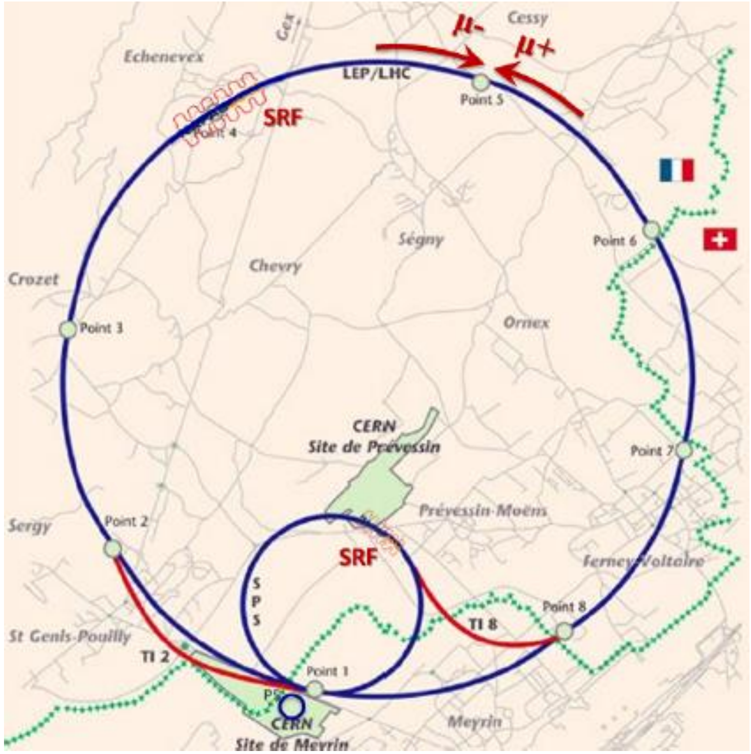
Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy

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



High field dipoles to minimise collider ring size and maximise luminosity
Minimise distances with no bending



Proposal to combine last accelerator ring and collider ring (Neuffer/Shiltsev) might reduce cost but creates many specific challenges

Decaying muons impact accelerator components, detector and public
The latter becomes much worse with energy

Radiation to public in case LHC tunnel use

Might be best to use LHC tunnel to house muon accelerator and have dedicated new collider tunnel