Future plans towards a muon collider

International environment and INFN activities

Nadia Pastrone INFN TORINO

Input Document to EU Strategy Update - Dec 2018:
"Muon Colliders," **[arXiv:1901.06150]**
by *CERN-WG on Muon Colliders*

J.P. Delahaye et al.

FINDINGS and RECCOMENDATIONS:

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

……

Carry out the R&D program toward the muon collider

Facts

- June Council could possibly release the update of the EU Strategy
- U.S. Snowmass21 process was lauched at: https://snowmass21.org/start
- Muon Collider community is ready to establish the **international collaboration** as announced at the General Meeting: https://indico.cern.ch/event/886491/

⇩

A Muon Collider has the potential to largely extend the energy frontier:

- an immense physics reach ➔ to be further explored
- a start-to-end collider design faces challenges & requires key enabling technologies
- detector studies with beam induced background proved physics feasible @ 1-3 TeV

  ➔ new experiment design and studies at the energy frontier are needed
- possible re-use of existing infrastructures must be analyzed considering rad-hazard

multi-TeV circular muon colliders

have the unique potential to reach centre-of-mass energies of tens of TeV:

- direct searches for new particles over a wide range of unexplored masses
- accurate tests of the Standard Model
- Vector Boson Fusion and Vector Boson Scattering processes

unique and overwhelming physics reach

but

requirements for high instantaneous luminosity faces technical challenges due to:

  - the short muon-lifetime
  - the difficulty of producing large numbers of muons in bunches with small emittance

- Muon production beam source defines viable machine parameters
- Accelerator and collider rings require developments of key technologies
- Radiation hazard by neutrino's fluxes must be carefully evaluated
- Machine detector interface constraints experiment design
- Beam-induced background requires detectors technology beyond status of the art

international collaboration

to develop an integrated muon collider design concept that encompasses the physics, the detectors, and accelerator

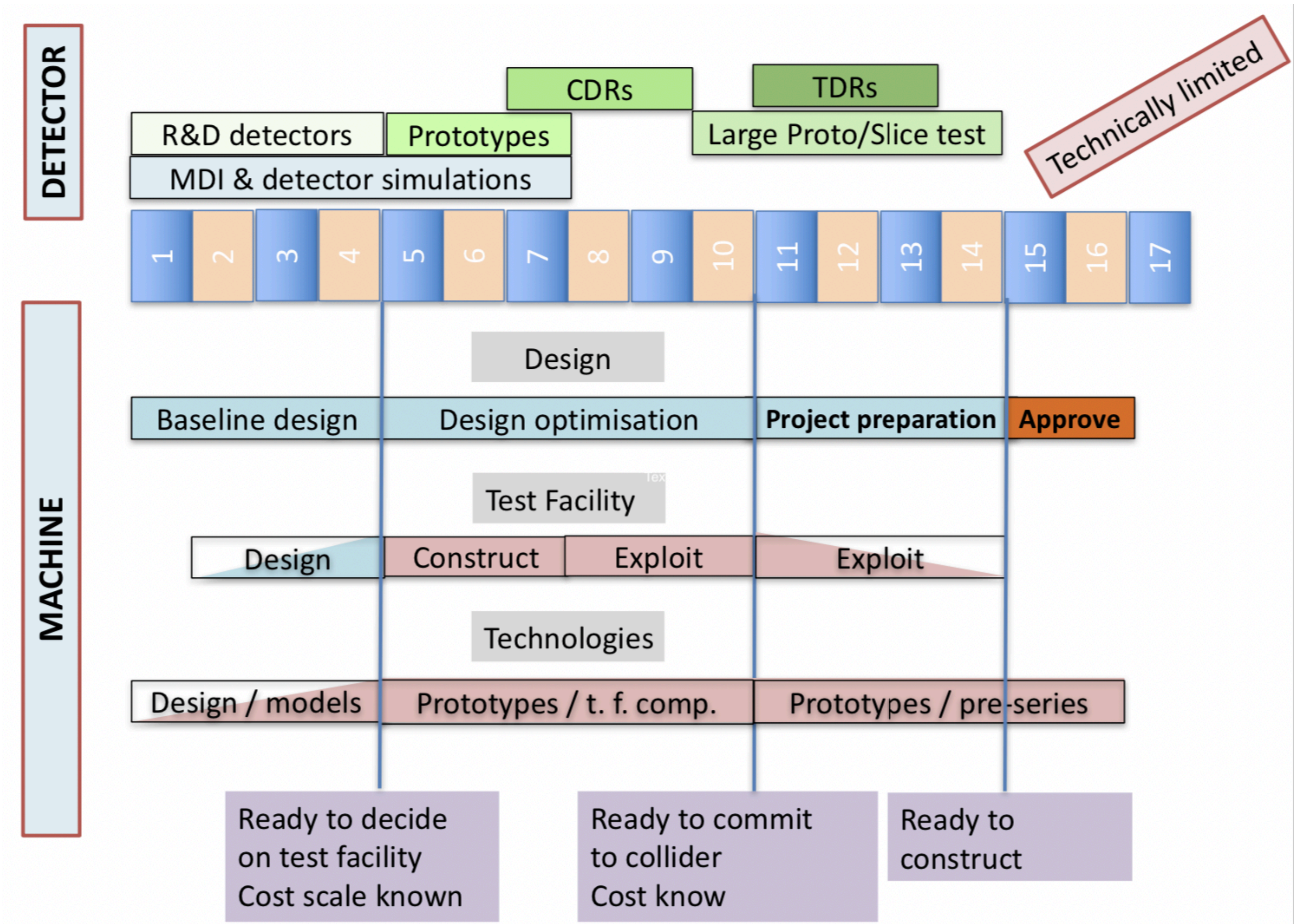
- to develop fully the muon collider design study
  ➔ exploring the various options
- to pursue R&D priorities, according to an agreed upon work plan

Master plan:

- A start-to-end collider design ➔ this would be the first facility of its kind
- A machine detector interface that protects the detector from collider background while allowing good machine performance
- A physics and detector study to assess the physics reach of the collider

Technically Limited Potential Timeline

Physics Briefing Book arXiv:1910.11775v2 [hep-ex]



Briefing Book Tentative Timeline (2019)

DETECTOR

R&D detectors | Prototypes | CDRs | TDRs | Large Proto/Slice test

MDI & detector simulations

Technically limited

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 year

MACHINE

Limited Cost

Mainly paper design

And some hardware component R&D

Higher cost for test facility

Specific prototypes

Significant resources

Higher cost for technical design

Significant resources

Higher cost for preparation

Full project

Design / models | Prototypes / t. f. comp. | Prototypes / pre-series

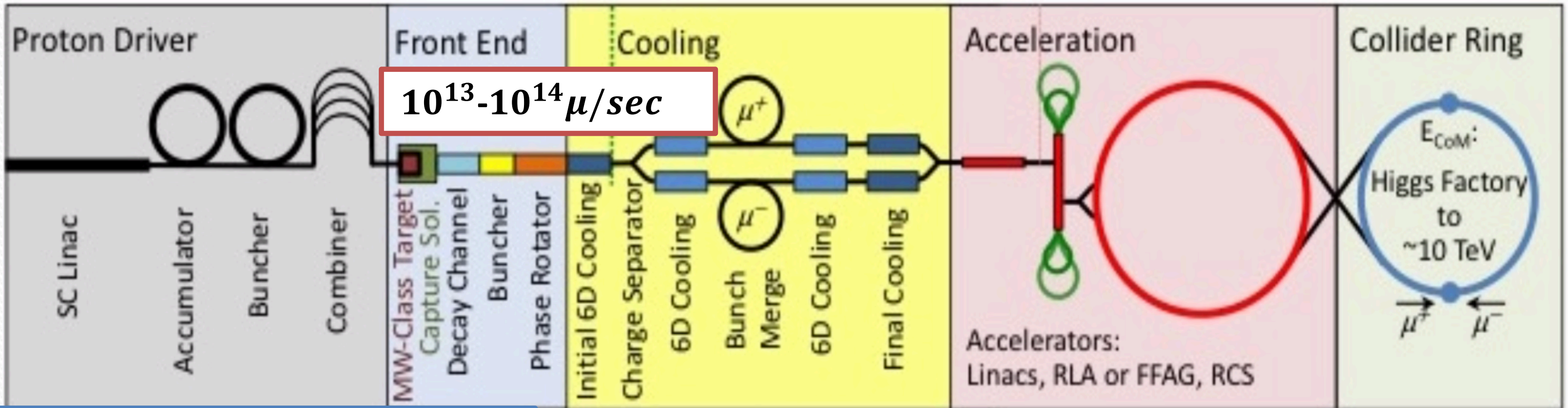
Ready to decide on test facility
Cost scale known

Ready to commit to collider
Cost know

Ready to construct

proton (MAP) vs positron (LEMMA) driven muon source

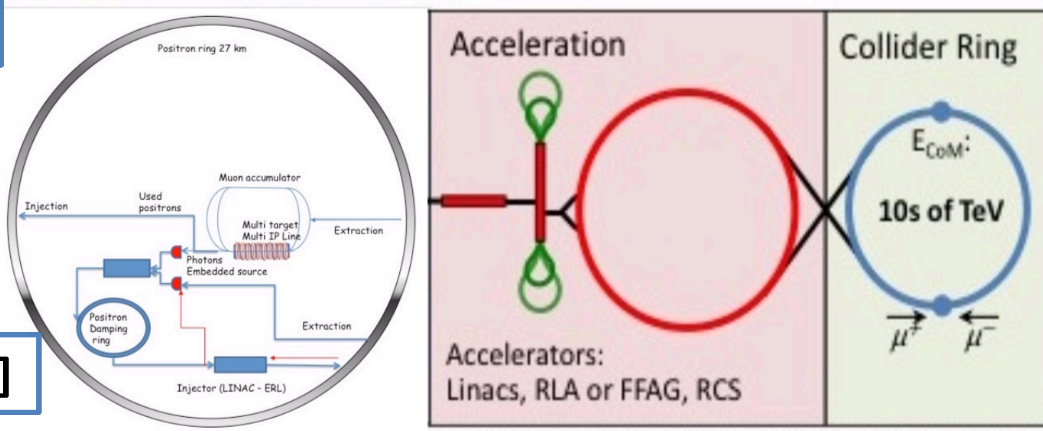
MAP



MUON JINST, shorturl.at/kxKU7

LEMMA

e+ source

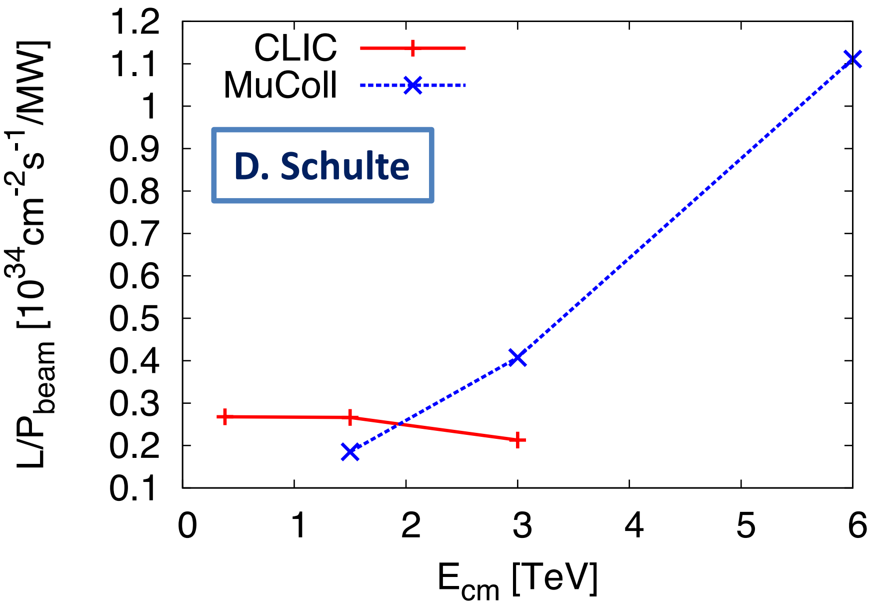


arXiv:1905.05747v2 [physics.acc-ph]

➔ **need consolidation** to overcome technical limitations to reach higher muon intensities

muons produced with low emittance ➔ "no/low cooling" needed
low production **cross section**: maximum $\sigma(e^+e^- \to \mu^+\mu^-) \sim 1\ \mu b$
high heat load and **stress** in μ production target
synchrotron power O(100 MW) ⬅ available 45 GeV positron sources

Factor of merit



MAP studies addressed design issues from muon production to final acceleration:

➔ **proton driver option: advanced studies for a 3-6 TeV machine**

➔ **however a 6D cooling TEST FACILITY is MANDATORY to demonstrate feasibility**

A new idea not requiring 6D cooling – **LEMMA** – represent an appealing scheme:

➔ **further studies and solid R&D program needed for such positron driven option**

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

- **Key R&D list with priorities**
  - Identify key / feasibility issues
    - i.e. largest technical risks
    - Key cost driver, if critical
    - Key power consumption, if critical
  - Entry point for collaborators

Proposed MUST
(MUon collider STudy network)
submitted I.FAST EU project

Next steps

Muon Colliders is a unique opportunity at the high-energy frontier

- Several teams from different countries already contributed to present knowledge
- **The on-going work is fostering the preparation of an organized study:**
  - **identification of feasibility issues and potential incremental steps**
  - **resurrect studies of Muon Colliders taking advantage of the enormous progress already done**
  - **identify resources required to address most critical issues**
  - **launch international collaboration on Muon Colliders covering Physics, Detector and Accelerator**
- Synergies with other future accelerators can be easily identified for example on:
  - **high field magnets and fast ramping magnets with efficient energy recovery**
  - **efficient RF power production and high field cavities**
  - **robust targets**
  - **techniques for the large acceptance, rapid acceleration (RLA, LEMMA and other applications)**

Conclusions

14:00 → 14:20 **Contesto internazionale - prossimi passi**
Speaker: Nadia Pastrone (TO)

14:20 → 14:50 **Progetto LEMMA**
Speaker: Alessandro Variola (LNF)

14:50 → 15:00 **Discusione**

15:00 → 15:15 **Test beam @ CERN**
Speaker: Nicola Carlo Amapane (TO)

15:15 → 15:30 **SImulazioni radiazione da neutrini**
Speaker: Paola Sala (MI)

15:30 → 15:45 **MDI:stato simulazioni**
Speaker: FRANCESCO COLLAMATI (ROMA1)

15:45 → 16:05 **Simulazioni: fisica ed framework**
Speaker: Donatella Lucchesi (PD)

16:05 → 16:30 **Simulazioni: detector e ricostruzione**
Speaker: Massimo Casarsa (TS)

16:30 → 16:40 **Discusssione**

16:40 → 17:00 **Fisica: benchmarks e piani di studio**
Speaker: Barbara Mele (ROMA1)

17:00 → 17:10 **Discussione**

17:10 → 17:30 **Possibili altri contributi**

17:30 → 18:00 **Discussione**

- INFN plays a crucial role on many activities
- This meeting was planned to briefly review:
  - work done
  - work in progress
  - plans
- A general international meeting will be help June 29-30 (2-6 pm) to agree on the new work plan and future steps of the international collaboration
- To be noted a renew interest on Muon Colliders in the SnowMass21 on-going US process

e-groups
towards an international collaboration

E-group: ***MUONCOLLIDER-DETECTOR-PHYSICS***

MUST-phydet@cern.ch

E-group: ***MUONCOLLIDER-FACILITY***

MUST-mac@cern.ch

Thanks to the 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 Directorate in September 2017

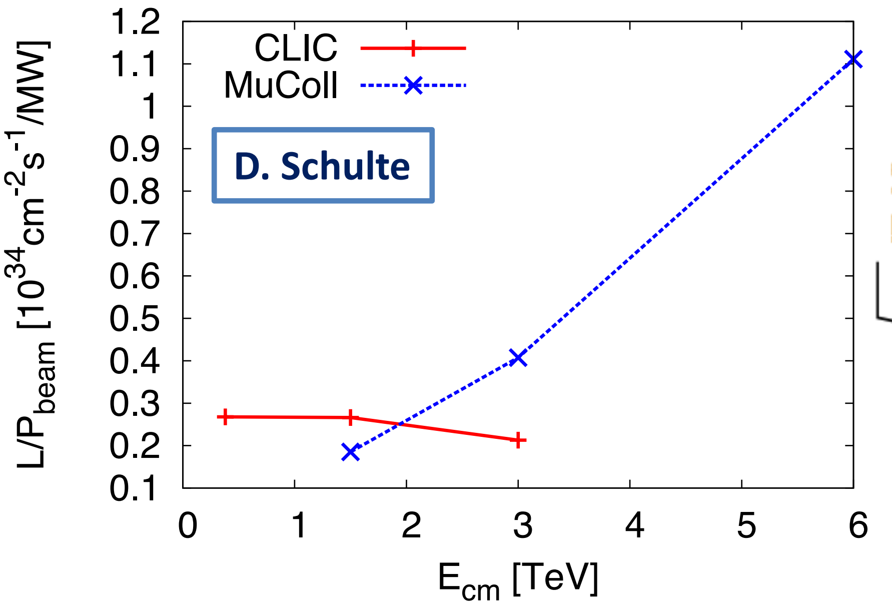
to prepare an Input Document to the European Strategy Update

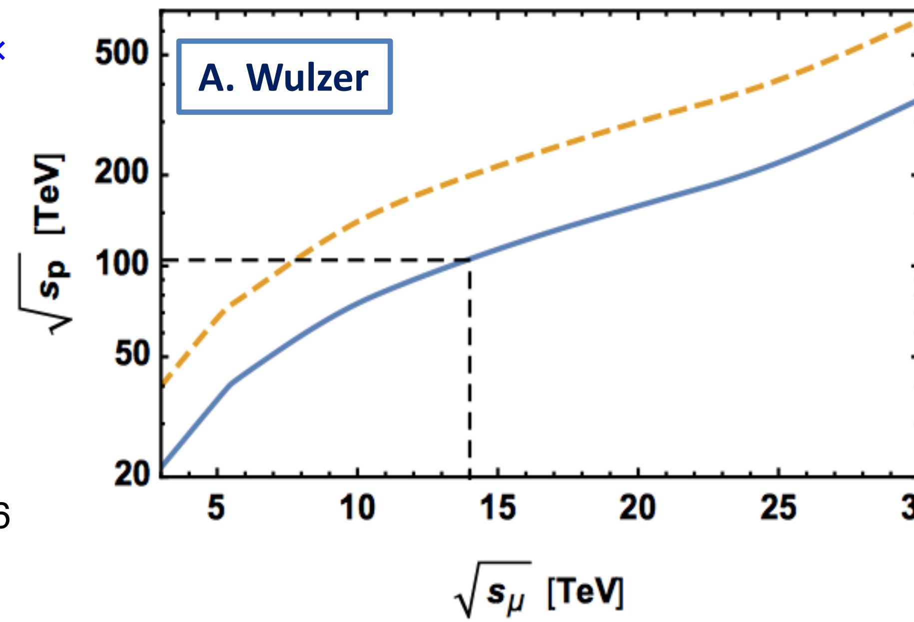
de facto the seed of a renewed on-going international effort

extras

Why a multi-TeV Muon Collider?

cost-effective and unique opportunity for lepton colliders @$\sqrt{s}$ >3 TeV





The luminosity per beam power is independent of collision energy in linear colliders, but increases linearly for muon colliders

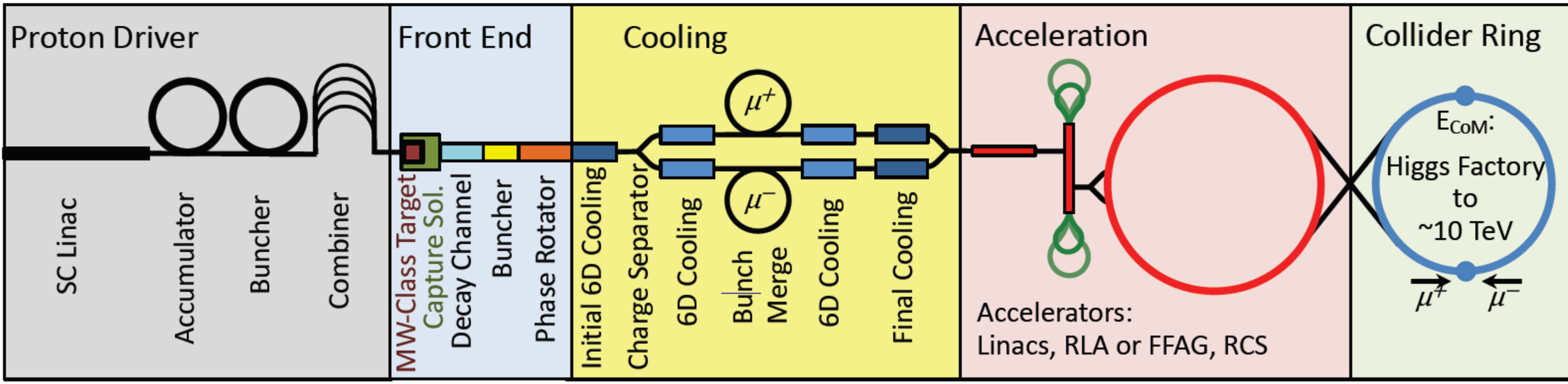
Full collision energy available for particle production: 14 TeV lepton collisions are comparable to 100 TeV proton collisions for selected new physics process, **if sufficient luminosity is provided ~ $10^{35}cm^{-2}s^{-1}$**

Strong interest to reuse existing facilities and infrastructure (i.e. LHC tunnel) in Europe

Proton-driven Muon Collider Concept

US Muon Accelerator Program – MAP, launched in **2011,** wound down in **2014**

MAP developed a ***proton driver scheme*** *and addressed the feasibility of the novel technologies required for Muon Colliders and Neutrino Factories*



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled

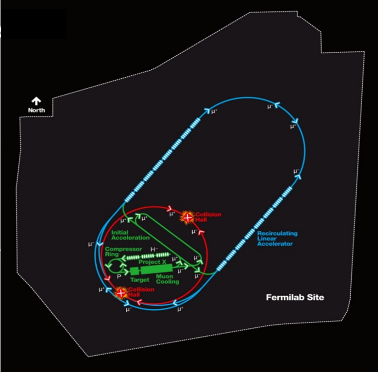
Acceleration to collision energy

Collision

Design is not complete but did not find anything that does not work

No CDR exists No coherent baseline No reliable cost estimate

"Muon Accelerator for Particle Physics," JINST,
https://iopscience.iop.org/journal/1748-0221/page/extraproc46



Muon Collider Parameters

M. Palmer: https://map.fnal.gov/

Muon Collider Parameters

Parameter	*Units*	Higgs Factory: *Startup Operation*	Higgs Factory: *Production Operation*	Top Threshold Options: *High Resolution*	Top Threshold Options: *High Luminosity*	Multi-TeV Baselines	Multi-TeV Baselines	*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top^{+} Production/10^7sec		3,500*	13,500*	7,000^{+}	60,000^{+}	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	$4^{\#}$	4	4	4	4	4	1.6

Could begin operation with Project X Stage II beam

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts ⇨ several × 10^{32}

Site Radiation mitigation with depth and lattice design: ≤ 10 TeV

Recent Tentative Target Parameters

D. Schulte – CERN Muon Collider Meeting https://indico.cern.ch/event/886491/

Parameter	Unit	3 TeV	3 TeV*	10 TeV	10 TeV*	14 TeV	14 TeV*
L	10^{34} cm^{-2}s^{-1}	1.8	1.8	20	20	40	40
N	10^{12}	~~2~~ 2.2	~~2~~ 2.2	1.8	1.8	1.8	1.8
f_r	Hz	~~6~~ 5	~~35~~ 29	~~4~~ 5	~~10~~ 12	~~4~~ 5	~~7~~ 9
P_{beam}	MW	~~5.8~~ 5.3	~~34~~ 32	~~12.8~~ 14.4	~~32~~ 35	~~18~~ 20	~~32~~ 37
C	km	4.5	26.7	10	26.7	14	26.7
<B>	T	7	1.2	10.5	3.9	10.5	5.5
ε_L	MeV m	7.5	7.5	7.5	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1	0.1	0.1	0.1
σ_z	mm	5	5	1.5	1.5	1.07	1.07
β	mm	5	5	1.5	1.5	1.07	1.07
ε	µm	25	25	25	25	25	25
$\sigma_{x,y}$	µm	3.0	3.0	0.9	0.9	0.63	0.63

Adjust for staging, G = 1 MV from 1.5 to 5 TeV, or 1.3 MV from 1.5 TeV to 7 TeV

***Use of LHC tunnel for collider**

Recent LEMMA effort

M.Antonelli, M.E.Biagini, M.Boscolo, S.Guiducci, P.Raimondi, A.Variola et al.

Asymmetric collisions $e^+e^- \rightarrow \mu^+\mu^-$ at the $\mu^+\mu^-$ threshold ($\sqrt{s} \approx$ **0.212 GeV**)

- maximize $\mu^+\mu^-$ pairs production cross section
- minimize the $\mu^+\mu^-$ beam angular divergence and energy spread

Extremely promising:

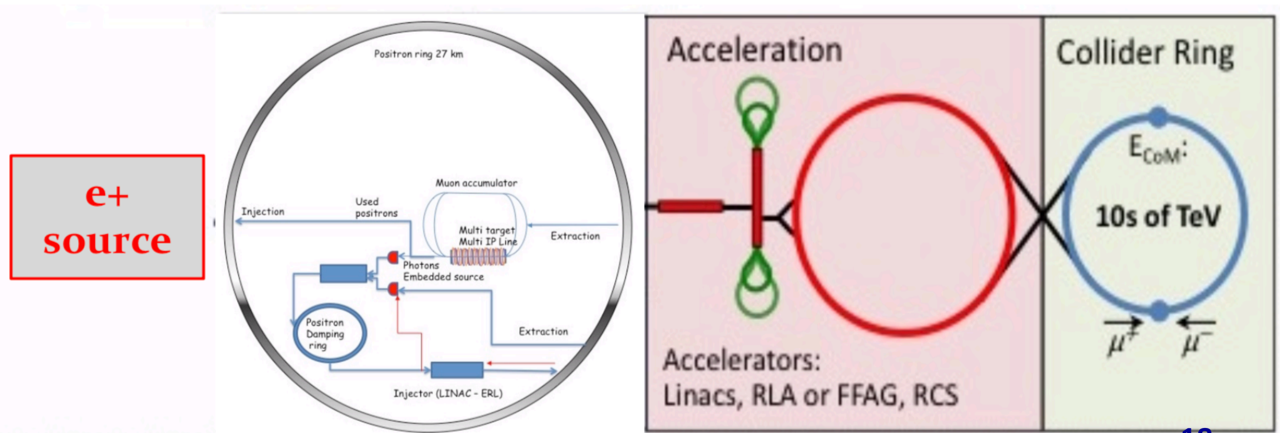
- muons produced with low emittance ➔ “no/low cooling” needed

But difficult:

- ✓ **low** production **cross section**: maximum $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim 1\ \mu b$
- ✓ **high heat load** and **stress** in μ production target
- ✓ **synchrotron power** O(100 MW) 🡰 available 45 GeV positron sources

➔ **need consolidation** to overcome technical limitations to reach higher muon intensities

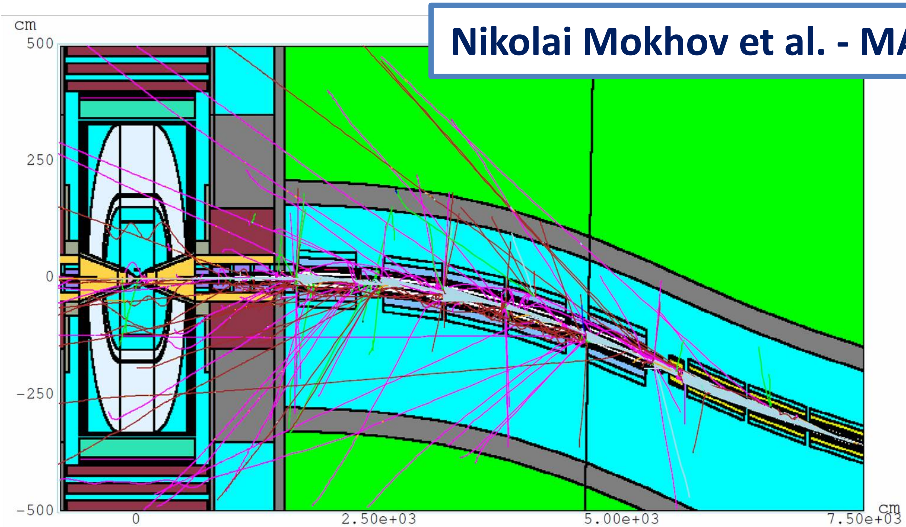
LEMMA

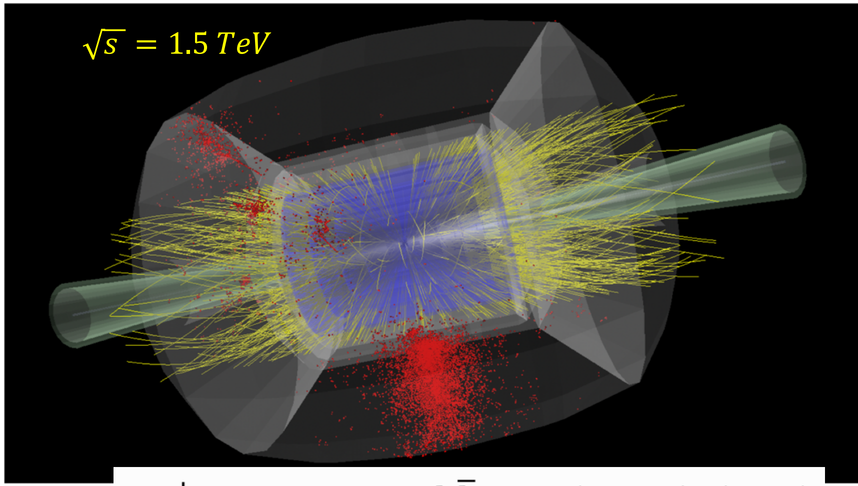


arXiv:1905.05747

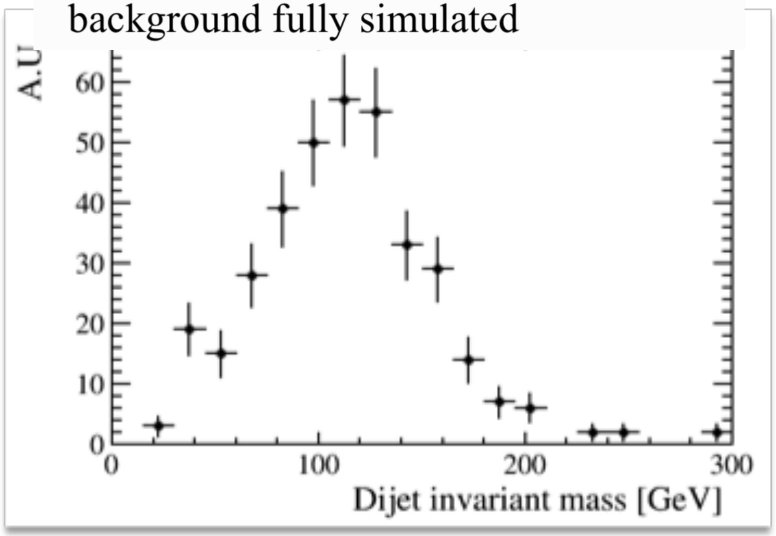
Muon Beams Induced Background

Nikolai Mokhov et al. - MARS15



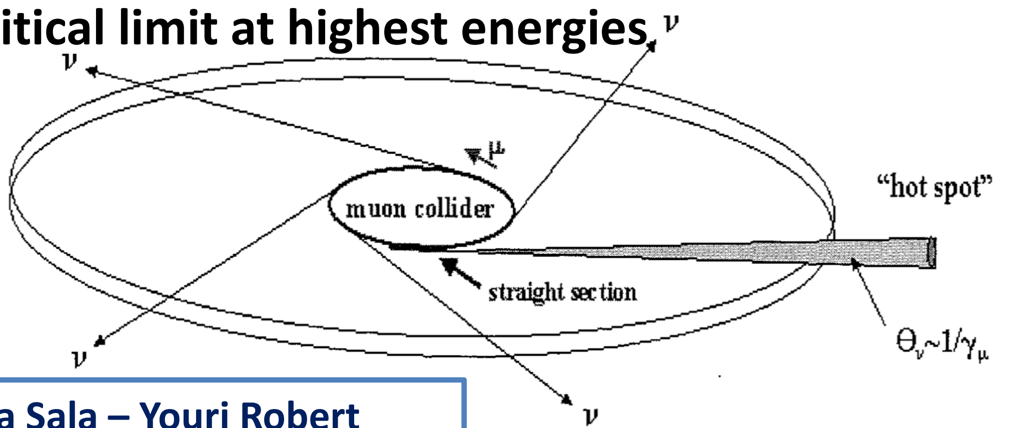


$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated



Neutrino radiation

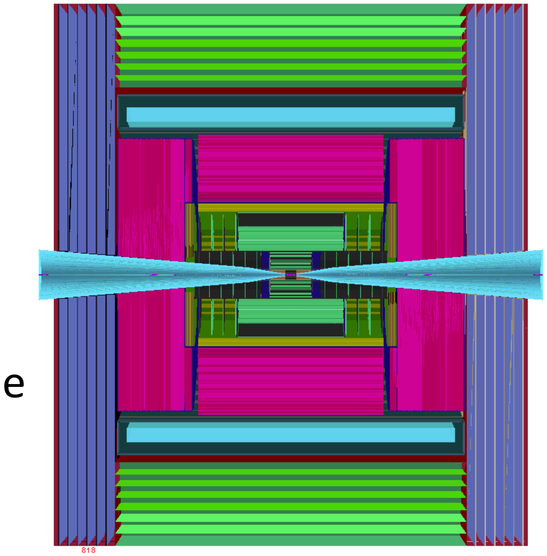
critical limit at highest energies



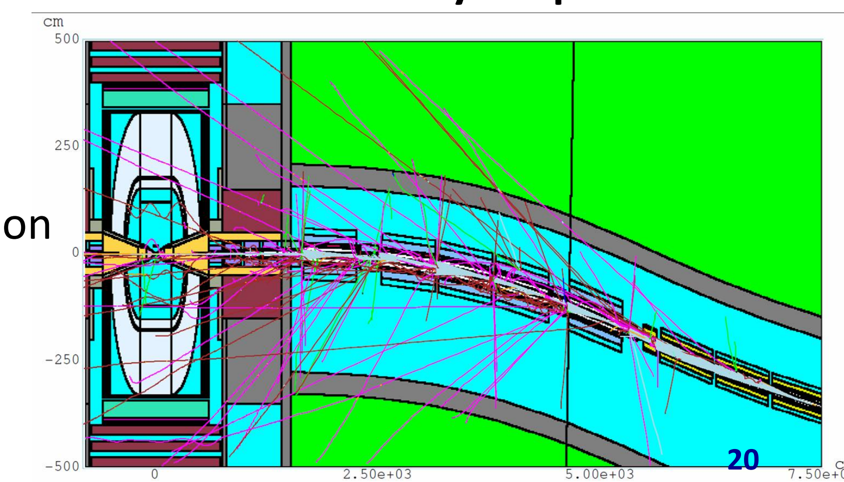
Paola Sala – Youri Robert
CERN Muon Collider Meeting
https://indico.cern.ch/event/886491/

On-going simulations and studies for mitigation even with existing/future tunnels

Next steps



- **Move to use the Future Collider Framework**
  - Description of the detector already done including the nozzle
  - A new, up to the state of the art detector is needed
- **Simulate the beam-induced background with FLUKA**
  - MDI and IR descriptions provided by MAP collaboration for 1.5 and 3 TeV $\sqrt{s}$
  - Importing the description in FLUKA and generate new beam-induced background
- **Re-evaluate Physics performance** @ $\sqrt{s}$=1.5 TeV as double check then study Physics performance @ $\sqrt{s}$=3 TeV with full simulation
- **Collaborate with MAP to have MDI and IR @ $\sqrt{s}$=10 TeV to evaluate Physics performance**
- Determine physics objects efficiency and resolution for each configuration and parametrize them to estimate broad physics reaches smearing Monte Carlo generated process



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, …

Other Options

Variations of the muon sources were suggested

e.g. W. Krasny, X. Buffat, …

- 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

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

e.g. V. Shiltsev, D. Neuffer

- Could maybe save some cost
- But likely will compromise performance
- And generate its own challenges
- So trade-off has to be understood

Also some other ideas

- But too early ……

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

Some synergies → Key Accelerator Technologies

- **High-field, robust collider magnets with minimum gap**
  - Dipoles, solenoids, … for collider ring
- **Efficient fast ramping magnets with efficient energy recovery – magnet powering**
  - 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** (instrumentation)
- **Beam-dynamics and accelerator design**
  - Start-to-end design and simulations, source design, …

Snowmass 2021

Snowmass Planning Meeting Fermilab November 4 - 6, 2020

Snowmass Summer Study Univ. of Washington, Seattle July 11 - 20, 2021

Letters of Interest (submission period: April 1, 2020 – August 31, 2020)

Letters of interest allow Snowmass conveners to see what proposals to expect and to encourage the community to begin studying them. They will help conveners to prepare the Snowmass Planning Meeting that will take place on November 4 - 6, 2020 at Fermilab. Letters should give brief descriptions of the proposal and cite the relevant papers to study. Instructions for submitting letters are available at https://snowmass21.org/loi.

Authors of the letters are encouraged to submit a full writeup for their work as a contributed paper.

Contributed Papers (submission period: April 1, 2020 – July 31, 2021)

Contributed papers will be part of the Snowmass proceedings. They may include white papers on specific scientific areas, technical articles presenting new results on relevant physics topics, and reasoned expressions of physics priorities, including those related to community involvement. These papers and discussions throughout the Snowmass process will help shape the long-term strategy of particle physics in the U.S. Contributed papers will remain part of the permanent record of Snowmass 2021. Instructions for submitting contributed papers are available at https://snowmass21.org/submissions/.