CSN1- 10 luglio, 2020

RD_MUCOL

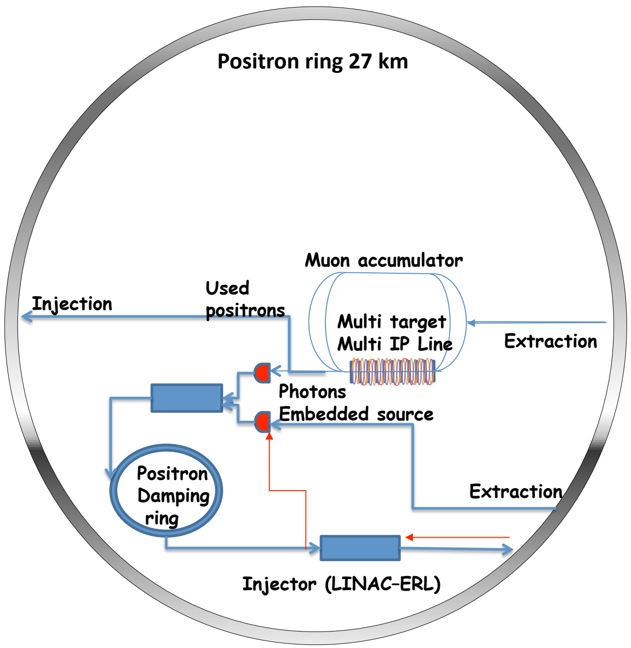
Nadia Pastrone INFN TORINO

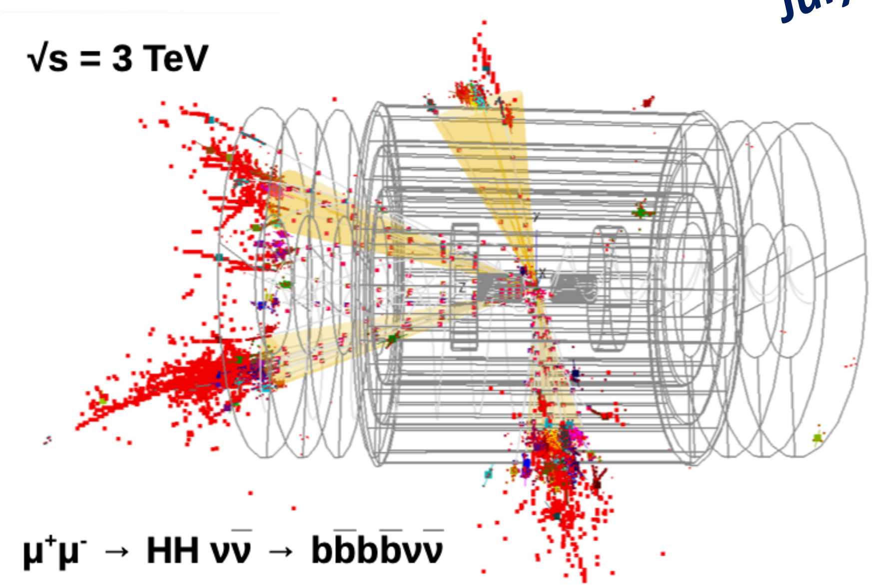
RD_FA WP8 *2016-2020 Mario Antonelli (LNF)*

I.N.F.N. *ongoing activities and interests*

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

July 3rd, 2020





https://indico.cern.ch/event/930508

EU Strategy

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

From the deliberation document of the European Strategy Update – 19 June 2020:

3 | High-priority future initiatives

High-priority future initiatives
[..]In addition to the high field magnets
the **accelerator R&D roadmap** could contain:
[..] an **international design study** for a **muon collider**, as it represents a unique opportunity to achieve a *multi-TeV energy domain beyond the reach of e^+e^- colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, but *novel ideas are being explored*;

International Design Study @ CERN
implemented by LDG chaired by Lenny Rivkin

CERN Laboratory Directors Group (LDG) should establish

Accelerator R&D roadmap to define a route towards implementation of the goals of the 2020 Update of the European Strategy, bringing together the capabilities of CERN and the LNLs to carry out R&D and construction and operation of demonstrators

LDG established in September 2017 the Muon Collider Working Group that states:

The compelling physics reach justifies establishment of an international collaboration to develop fully the muon collider design study and to pursue R&D priorities, according to an agreed upon work plan.

To facilitate implemention of the European Strategy LDG decided (July 2) to:

Agree to start building the collaboration for international muon collider design study

Accept the proposal of organisation

Accept the goals for the first phase

➔ **International Muon Collider Collaboration kick-off virtual meeting**

(>260 participants) https://indico.cern.ch/event/930508/

July 3rd, 2020

LDG Decisions

Lenny Rivkin

Appointment of **Daniel Schulte** as **ad interim project leader**

Will work towards strengthening cooperation and ensuring effective use of complementary capabilities

Core team (Nadia Pastrone, Lenny Rivkin and Daniel Schulte) will start **collecting MoUs**

Proposed Plan

Daniel Schulte

- A start-to-end collider design in particular in the view that 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
- The design of a demonstrator to be built in the second half of the decade

Scope

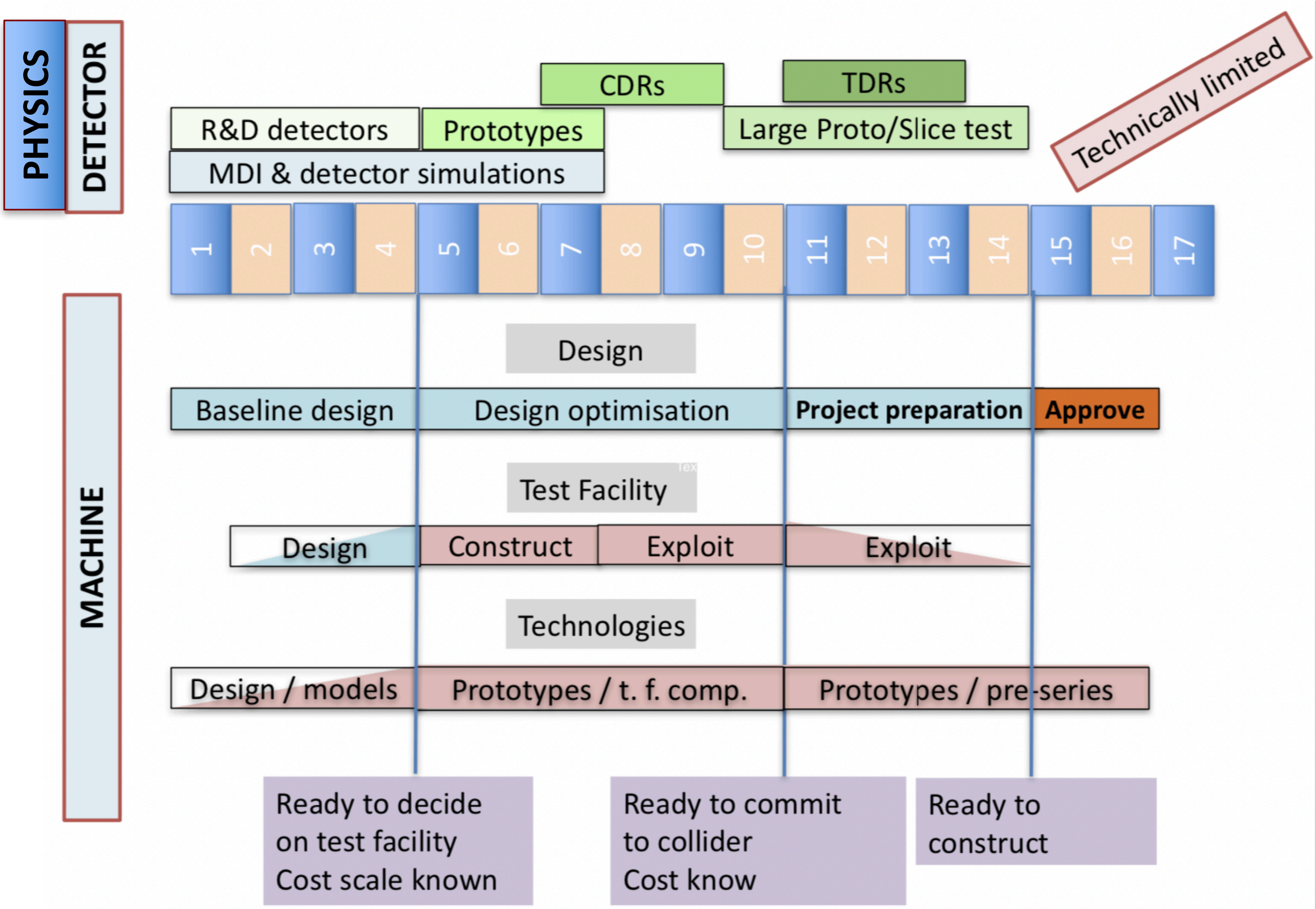
Daniel Schulte

The study aim is to develop a **baseline concept** for a muon collider at two centre-of-mass energy ranges

- The first **around 3 TeV**, well above Higgs factory
- The second **at or above 10 TeV** extends the energy reach well beyond the capabilities of normal conducting linear colliders.
  This would likely require more advanced technologies that might not be ready within the next 10-20 years. Try to find the energy limit.
- The potential to use the technology for other purposes such as a Higgs or neutrino factory will be explored, provided this is found synergetic with the high-energy collider study
- The collaboration will identify an **R&D path** toward a conceptual design
- The collaboration will design a **demonstrator**

Technically Limited Potential Timeline

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



First Period

Daniel Schulte

Objective:

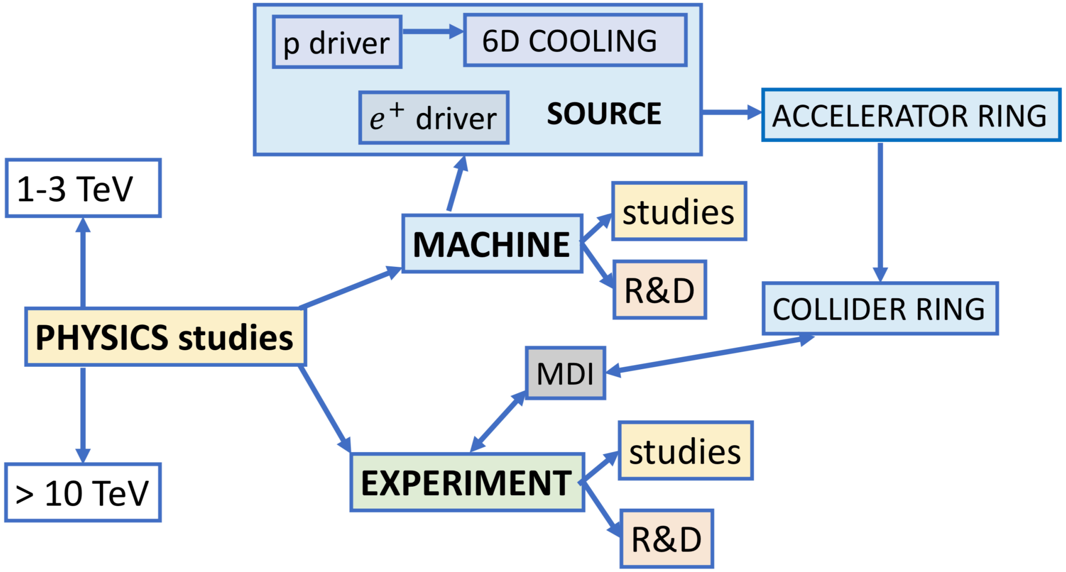
- In time for the next European Strategy for Particle Physics Update, the study aims to establish whether the investment into a full CDR and a demonstrator is justified
- It will provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers.

  It will also identify an R&D path to demonstrate the feasibility of the collider

Deliverables:

- Reports assessing muon collider potential and describing R&D path to CDR including demonstrator

Project



Synergies with other on-going projects are timely and must be further promoted

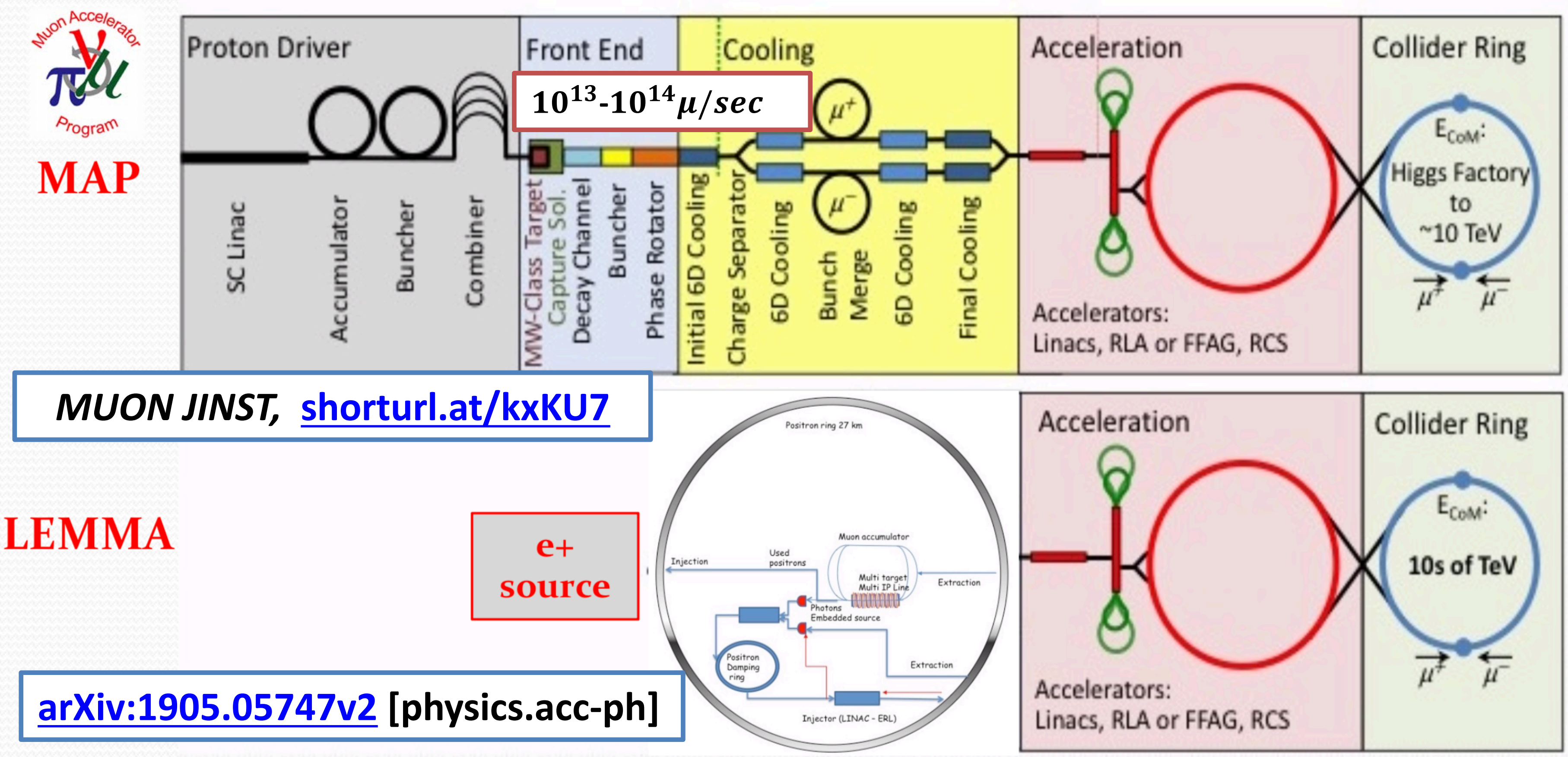
Center-of mass energies **above 10 TeV with $\mathcal{L} > 10^{35} cm^{-2} s^{-1}$** requires:

- detailed physics studies in an uncharted territory
- enabling key technologies to optimize the design of the machine and the experiment and simultaneously studied and developed with focused R&Ds

Center-of-mass energy of **1-3 TeV and luminosity $\mathcal{L} \sim 10^{34} cm^{-2} s^{-1}$ ➔ BASELINE**

- need to be finalized and a CDR prepared according to the proposed timeline
- TDR aimed to be ready in about 20 years with a facility that we consider now feasible

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



MUON JINST, [shorturl.at/kxKU7]

[arXiv:1905.05747v2] [physics.acc-ph]

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

Initial Workplan

Daniel Schulte

Exploratory phase (first two years)

- forming collaboration
- exploration of options → LEMMA
- making choices
- work on already identified key issues → see list
- completion of key issues list
- definition of scope of demonstrator
- definition of prioritised work programme for definition phase

Definition phase

- implementation of work programme
- conceptual design of demonstrator
- conceptual design of key high-energy components, where possible
- hardware tests
- increase in resources required and redirection of work as needed

Note: will exploit synergies, e.g. with magnet development for hadron colliders

Fields of interest

- **Physics Motivation.** Physics potential of the collider, physics benchmark points, requirements for energy and luminosity.
- **Experiment and Physics Simulation.** Performance of collider and detector, event reconstruction, simulation tools, performance benchmark points, detector performance goals.
- **Detector Design and R&D.** Detector development, prototypes, detector performance goals, . . .
- **Machine Detector Interface.** Background, . . .
- **High-energy Collider Design.** Experimental insertion, collider ring, accelerator ring, linacs, . . .
- **Proton-based Muon Source.** Proton complex, muon production, muon cooling, bunch merging
- **Positron-based Muon Source.** Positron production, positron acceleration, muon target, muon accumulation
- **Magnets.** High-field superconducting magnets, final focus quadrupoles, collider ring dipoles/combined function magnets, cooling solenoids, fast ramping magnet systems in accelerator, . . .
- **Radio Frequency Technology.** Superconducting RF for high energy acceleration and and normal-conducting high-gradient RF for the cooling, proton and positron RF, . . .
- **Radiation, Shielding, Losses, Targets, Collimation, Materials.** Detector/magnet shielding, high-power production target, neutrino radiation, beam losses, background, . . .
- **Other Technologies.** Including efficient cooling, good vacuum, robust instrumentation, . . .
- **Civil engineering and Infrastructure.**
- **Synergies.** Includes application of muon collider technology for other purposes, such as a neutrino factory.

attività INFN

- **Simulazioni di fisica**

(collaborazione con CSN4)

➔ **reach di fisica vincolato dal disegno dell'esperimento**

- **Disegno dell'esperimento**

(simulazioni e R&D in sinergia)

- **Machine Detector Interface**
- **Studi di radiazione da neutrino**
- **Sorgente LEMMA - disegno:**

fascio di positroni - bersagli – accumulatore

- **Test Beam @ CERN per 2022**

NEW

- **R&D tecnologia per magneti ++ dedicati al muon collider**

Ongoing activities: Physics-Experiment

International Muon Collider Design Study,
CERN, July 3, 2020

- **Physics Motivation**

Direct/indirect discovery reach – VBF and VBS – precise Higgs measurements

A.Costantini, M.Chiesa, R.Franceschini, F.Maltoni, B.Mele, F.Piccinini, A.Wulzer et al. ++

Quartic Higgs self-coupling: arXiv:2003.13628 [hep-ph]

Vector Boson Fusion: arXiv:2005.10289 [hep-ph]

Benchmarks at different energies steer machine parameters and experiment design

- **Experiment and Physics Validation**

Flexible framework - background simulation, detector simulation and event reconstruction in use to study detector requirements/performances at different center of mass energies

First full-simulation study $\mu\mu \to H\nu\overline{\nu} \to b\overline{b}\nu\overline{\nu}$ @ $\sqrt{s} = 1.5\ TeV$ J. Inst. 15 P05001, 2020

D.Lucchesi et al. + US-MAP + CLICdp *the core team is growing + SnowMass21 interest*

➔ **Machine Detector Interface:** beam induced background shaped by machine optics design at different energies sets constraints on nozzles and experiment design and performances

10+ TeV is a completely new regime to explore!

Ongoing activities: Experiment-Detectors

- **Experiment Design and Detector R&D**

  Flexible framework to study detector requirements/performances at physics benchmarks

  R&D to exploit state of the art "5D" detectors and beyond are mandatory but in synergy with the on-going upgrade of existing experiments and new on-going developments with national and international grants

  INFN experts and infrastructures cover many crucial area of interest to be explored:

  – Sensors and read-out for trackers + timing (DMAPS, LGAD…)
  – Calorimeter developments
  – Exploit new ideas for muon detection
  – Common software tools for simulation and reconstruction also ML techniques

P. Andreetto, N. Bartosik, A. Bertolin, L. Buonincontri, M. Casarsa, F. Collamati, C. Curatolo, A. Gianelle, D. Lucchesi, N. Pastrone, C. Riccardi, P. Sala, L. Sestini, I. Vai

++ al. joining

Strong synergy within the **new submitted EU project AIDAinnova**

Ongoing activities: MDI - Machine

- **Machine Detector Interface**

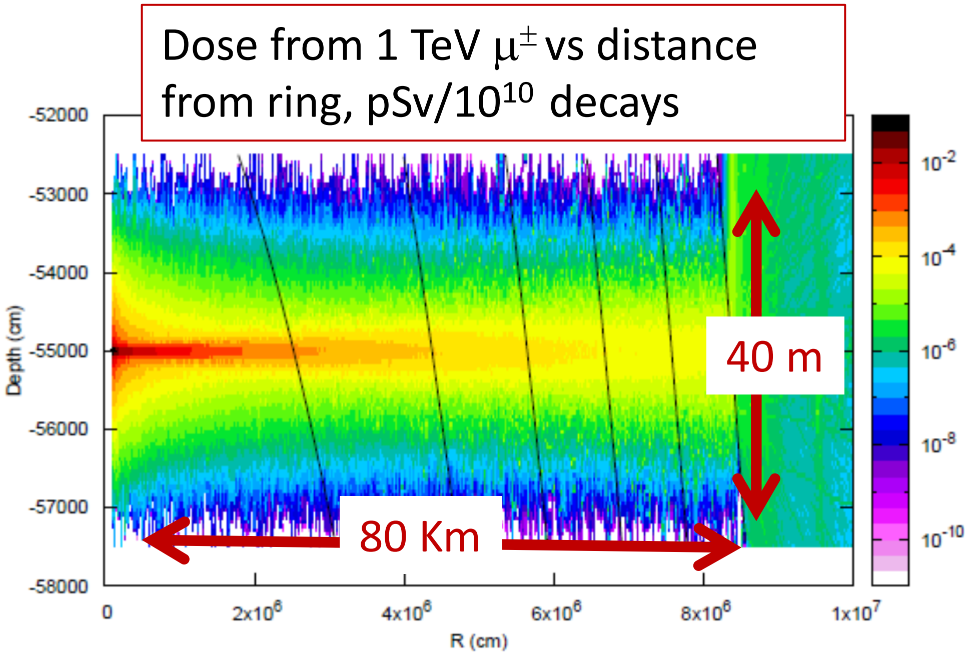
  Optics design required as part of the collider parameters studies. Fix constraints on nozzles design. Simulation tools. Strong collaboration with CERN.

  F.Collamati, et al. + A.Mereghetti CERN

- **Neutrino Radiation Hazard Studies**

  Preliminary full FLUKA simulation: μ decay (ring/straight sections), ν interactions. Checked scaling law. Next: simulations with realistic ring geometries and new orbits design. Strong collaboration with machine design.

  Alfredo Ferrari, Anna Ferrari, P. Sala et al.



Ongoing activities: LEMMA Source

- **Positron-based Muon Source – LEMMA**

Positron production and acceleration, muon targets, muon accumulation

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

arXiv:1905.05747v2 [physics.acc-ph] ➔ paper in preparation

- Positron source studies – collaboration with IJCL *+ A.Bacci, I.Drebot et al.*

  also on crystal applications: *L.Bandiera, A.Mazzolari et al.*

- Material simulations and studies for positron and muon production targets

  M.Antonelli, R.Li Voti, G.M. Cesarini et al. + PoliTO + other interested

  measurements and R&D planned using beam at LNF and CERN

- Muon accumulator optics and multi-target new layout *+ O.Blanco, A. Ciarma*:

  FFAG – with UK multibend-achromat – with ESRF Phys. Rev. Accel. Beams 23, 051001

- CERN test beam to evaluate targets and emittance *J. Inst.* **15** P01036, 20

  ➔ new proposal to run at CERN in 2022 with improved set-up

  + N.Amapane, F. Anulli, A.Bertolin, M.Zanetti et al.

Resource plan towards a pre-CDR submitted by Alessandro Variola (10/19)

need consolidation to prove feasibility

to overcome technical limitations and reach higher muon intensities

Interests: Machine

- **Fast-ramping SC magnet systems for accelerator ring**
  L.Rossi, P.Fabbricatore, S.Farinon, R.Musenich, M.Sorbi, M.Statera et al.
- **Material studies for targets**
- **Crystals manufacturing for targets and collimation**

Strong synergy within the **new submitted EU project I.FAST**

➔ **MUST** – MUon colliders Strategy network

INFN, CERN, CEA, CNRS, KIT, PSI, UKRI

Delivery: International collaboration plans towards a multi-TeV muon collider

- **Synergies on exploiting neutrino beams at facilities**
  M.Bonesini, G.Catanesi, D.Orestano, L.Tortora et al.

LEMMA: *LowEMittanceMuonAccelerator*

M. Antonelli and P. Raimondi, Snowmass Report (2013) - INFN-13-22/LNF Note

- Based on muons production from a 45 GeV positron beam annihilating with the electrons of a target close to threshold for pair creation

  ➔ generating muon beams with low enough transverse emittance for a high energy collider

  ➔ muon pair boost for post-production capture and emittance minimization, drastically reducing the source transverse emittance and, coupled with a collider nano-beam scheme

  ➔ should allow reaching for the luminosity with a lower bunch intensity

- **Scheme under study**:

  ➔ positron bunches extracted to impinge on multiple targets in a dedicated straight section

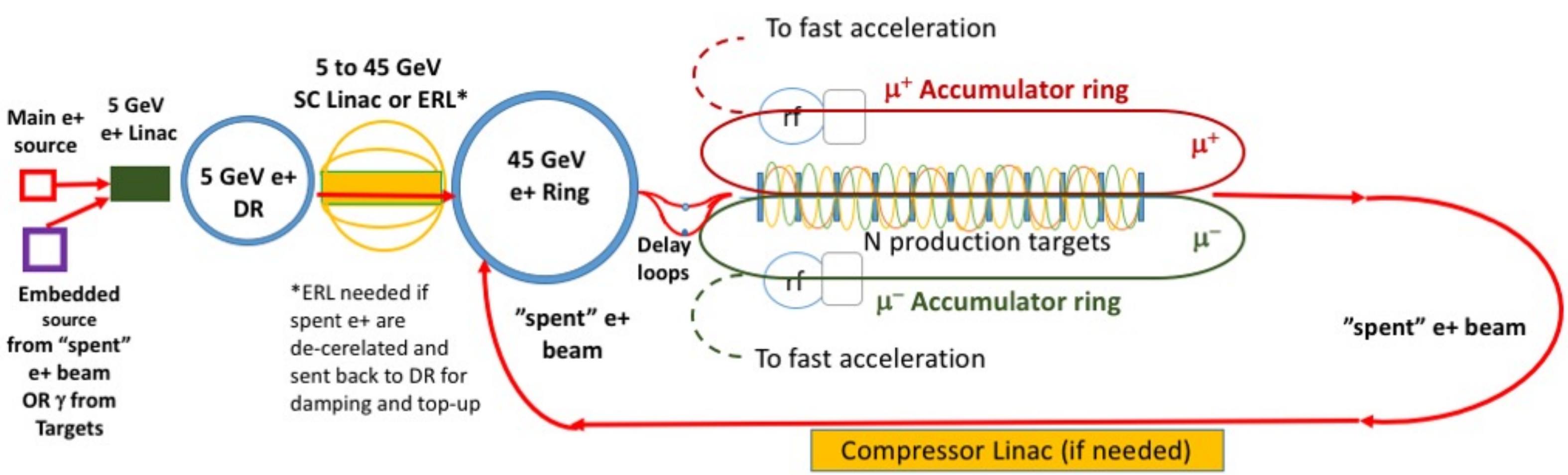
  ➔ muons are then collected in two Accumulation Rings (AR) and stored until the muon bunch has a suitable number of particles.

This scheme aims at releasing the impact of the average power on the targets and also reducing the number of positron needed from the source

LEMMA new scheme in brief

Alessandro Variola, Marica Biagini, Susanna Guiducci et al.

- Positron for first fill produced by Main **e$^+$ source** (MPS) and accelerated to 5 GeV for damping in a 5 GeV **Damping Ring** (DR)
- Acceleration to 45 GeV in SC Linac or ERL and storage of 1000 e$^+$ bunches in **Positron Ring** (PR)
- **Extraction of e$^+$ bunches** to one or more muon production lines, while produced **muons are accumulated in two AR** and a muon bunch is "built" by several passages through the targets, to be then delivered to the **fast acceleration chain**
- Re-injection and damping in the PR @45 GeV of the spent e$^+$ beam to save on the number of needed e$^+$, the MPS and a possible γ-embedded source will provide the refilling of lost e$^+$ Other option: send e$^+$ back to DR (through decelerating ERL) for damping and top-up



LEMMA R&D: TARGETS

Roberto Li Voti, Gianmario Cesarini, Mario Antonelli, M. Bauce, A. Ciarma, F. Collamati et al.

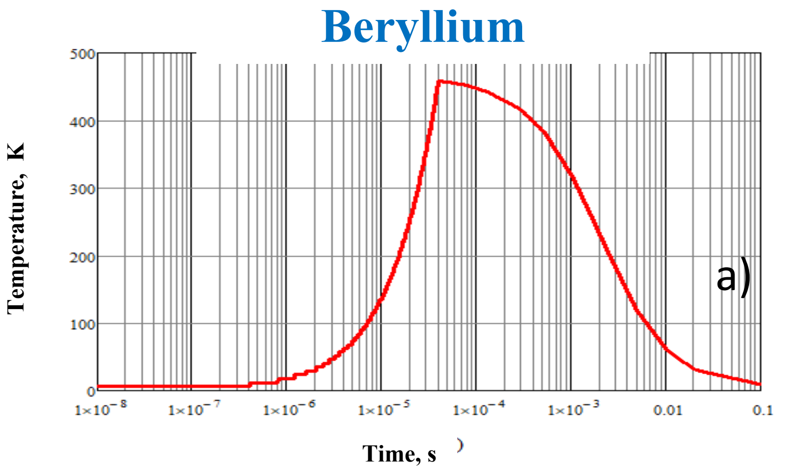
- Targets: common topic for both the positron production and the muon production
- Need to maintain **low PEDD** (Peak Energy Density Deposition), average energy deposition, and temperature, to ensure target durability and efficiency, as well as to maximise the number of produced particles, is a **key R&D topic**
- Determination of damage and fusion thresholds, thermo-mechanical stresses, and evaluation of technical designs for heating evacuation and PEDD remedies

  ➔ need **material studies and experimental test**.

  A prototype of a **rotational target**, both a single thick target or an ensemble of close thin targets, with an amorphous and a granular amorphous material should be built and tested
- **Hydrogen targets (pellet)** would improve the integrated thickness reducing the number of passages and so increasing the ration of “fresh” bunches/passage. However, a different Interaction Region (IR), with the low β-function needed for low emittance muon production, should be designed, since at least 1 meter will be needed to host such a target
- **Crystal targets** to be considered a solution for muons recombination and post-production cooling
- A **test of the DAΦNE** (INFN Frascati National Labs) e^+ beam impinging on a target would allow for benchmarking the simulations of target materials and released power with a real case. Beam lifetime measurements, high currents and beam dynamics studies would help to identify issues and finalise the design. Vacuum tests of different target materials would be also possible

Roberto Li Voti, Gianmario Cesarini
SBAI Roma La Sapienza

Ricerca tecnologica: Simulazioni numeriche atte a valutare il campo ed il gradiente termico, lo stress termomeccanico e la massima densità di energia depositata in bersagli di Berillio e Carbonio (Grafite) partendo dalla distribuzione della densità di energia depositata dal fascio di positroni fornita da Fluka.



Presentazioni orali:
HiRadMat Workshop 10-12 luglio 2019 CERN,
Theoretical modeling for the thermal stability of solid targets in LEMMA muon collider

Muon Collider Meeting 2 aprile 2020,
Theoretical model for the evaluation of the thermal stability and thermal stress of solid targets in a low emittance muon collider

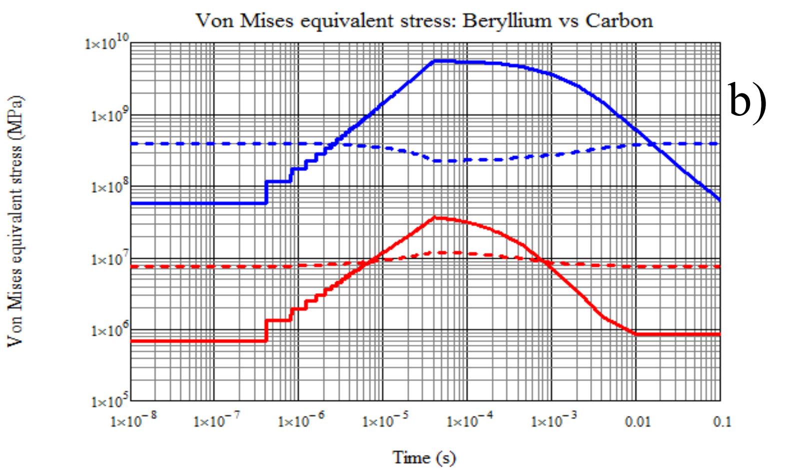


Fig. a : Bersaglio di Berillio, andamento temperatura nel centro dello spot gaussiano in un periodo di 100 ms;
Fig. b : Confronto Berillio-Grafite, andamento dello stress termomeccanico nel bin centrale in funzione del tempo e relative soglie limite.

Programma 2020 – 2021

RM1+SBAI in discussione con LNF, RM3 e PoliTO

Ricerca tecnologica:

Roberto Li Voti, Gianmario Cesarini
SBAI Roma La Sapienza

Training sull'uso di telecamera infrarossa.
Il training verrà effettuato per utilizzare la telecamera infrarossa in regime passivo per misure di emissività e stima della temperatura superficiale, ed in regime attivo con sistema lock in per la determinazione di fratture interne.

Attività sperimentale
1. Misura delle proprietà termoelastiche di targhette di carbonio (grafite).
2. Misura della diffusività termica ed emissività infrarossa con radiometria fototermica e termografia infrarossa.
3. Rivelazione di possibili danneggiamenti e stress termomeccanici quando la targhetta è sottoposta a fasci laser intensi.
4. Test di rilassamento termico su 2 o più targhette in diverse disposizioni geometriche

Attività teorica
1. Simulazione numeriche per la valutazione degli stress termomeccanici su varie architetture di targhette del muon collider
2. Fit teorico-sperimentale per la determinazione dei parametri termici di targhette di carbonio (grafite)

LEMMA R&D: Positron source

A. Variola, S. Guiducci, A. Bacci, F. Collamati in collaborazione con I. Chaikovska (IJCL, France)

- One of the **main limit** in the source repetition frequency is the physical constraint imposed by the positron source given by the **required positron flux, the required cooling and the thermo-mechanical stress on the target**

- In this framework a very interesting development is represented by the use of **rotating target** as already conceived for the ILC.

  Different schemes at a f_{rep} of 50-100 Hz should be implemented in case that high technology targets and high efficiency positron source should deliver a **positron rate higher than 10^{16} e^+/sec**

- This has to take into account also the possibility to develop immersed **large acceptance positron capture systems at 1 GHz**, with very high peak B Field in the AMD (20 T in the MAPS scheme) and in the capture solenoid

LEMMA R&D: Beam dynamics and lattice design

O. Blanco, A. Ciarma, M. Antonelli, M. Boscolo, P. Raimondi, M. Biagini, S. Guiducci, I. Drebot, A. Giribono, S. Liuzzo, C. Vaccarezza, A. Variola

- **e^+ Rings**
  - Large energy acceptance lattice in 45 PR needed to be able to accept the "spent" e+ after muon production
  - Very large energy acceptance of the DR to increase the efficiency of the positron source → increase of the repetition rate of a factor 5-10 will have a linear dependence on the luminosity

- **Muon Accumulator ➔ CRUCIALE per produzione bunch μ intensi**
  - Muon Accumulator Rings (MA) will store the muons produced over several passages of the positron beam: their length must match the timing between positron bunch passages ➔ new muons created at the moment of passage of the stored muons therefore increasing the muon bunch intensity.
  - MA must be short in order to complete a large number of turns before muons decay. A very large energy acceptance is needed in order to avoid muon losses
  - A new lattice with large energy acceptance, similar to the FFA (Fixed Field Accelerator) design, will be studied in collaboration with UK experts

- **Interaction Region for muon production**
  - In the current scheme, muons are not injected but generated directly inside the ring.

    ➔ The Interaction Region is common to a transport line for e+ and two MA rings, one per muon species
  - The design of **multi-targets muon production line**, with low-β functions at the targets to minimise muon emittance will require also an efficient 3-beams separation design, aiming at minimising particle losses

LEMMA R&D: Other topics

- **RF cavities**
  - High gradient SCRF cavities able to cope with a high average train current (order of 100 mA) in Linac or ERL.

  See from EU Strategy: ***"a vigorous R&D on high-intensity, multi-turn energy-recovery linac (ERL) machines, promoting the realisation of demonstrator…"***

- **High field magnets (MI e GE ➔ da definire con una riunione in Settembre-Ottobre)**
  - Need to focus 45 GeV positrons and 22.5 GeV muons together in a short low β-function IR calls for high gradient, large aperture and compact quadrupoles
  - Design of multi-targets muon production line ➔ efficient 3-beams separation design with high field, large aperture dipoles

- **Muon Cooling (A. Variola)**
  - LEMMA source scheme introduces two main advantages:
    - a reduced emittance at the production and a higher production energy resulting in a longer muon lifetime
    - the second allows for enough time to introduce also a moderate cooling mechanism to further reduce the production emittance. Different evaluations for the cooling efficiency given by stochastic cooling, optical stochastic cooling, crystal cooling. A full revaluation of these mechanisms associated to high energy, low emittance and bunch current needs to be done, targeting emittance reduction of 1-2 order of magnitude, linearly impacting final peak luminosity

- **Muon Recombination for higher luminosity (A. Variola)**
- Due to quadratic dependence of the Luminosity on bunch population, testing muon bunches recombination techniques, to increase the number of particle per bunch without drastically affecting emittance increase, could be envisaged. A new hypothesis can be studied: the possible recombination of different muon bunches by injection in a **curved crystal.** Combining the channeling angle with the volume reflection it should be possible to merge two different bunches with a relative emittance increase, mainly in the distribution tail.

  ➔ **The efficiency of this process should be optimized by an extensive R&D program**

SnowMass21

- Marica Biagini contact per LEMMA nel Processo SnowMass21
  ➔ LoI entro 31/8/2020

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/.

Test Beam @ CERN

N. Amapane, M. Antonelli, F. Anulli, M. Zanetti et many al. ➔ growing interest

- Experimentally measure the key parameters of the LEMMA approach
  - **Emittance** of emerging μ beam
  - $\mu^+\mu^-$ production **cross-section at threshold**
  - properties of **spent e^+ beam** (transverse emittance and energy spectrum)
  - Effect of the **target material/thickness**

- Although these are theoretically known and can be obtained from simulations**, precise measurements do not exist at the $\mu^+\mu^-$ production threshold**
  - GEANT does not include e.g. near-threshold Coulomb enhancements, and has not been experimentally tested in this regime

Request for 3-weeks beam time in H4 submitted to SPSC
http://cds.cern.ch/record/2712394

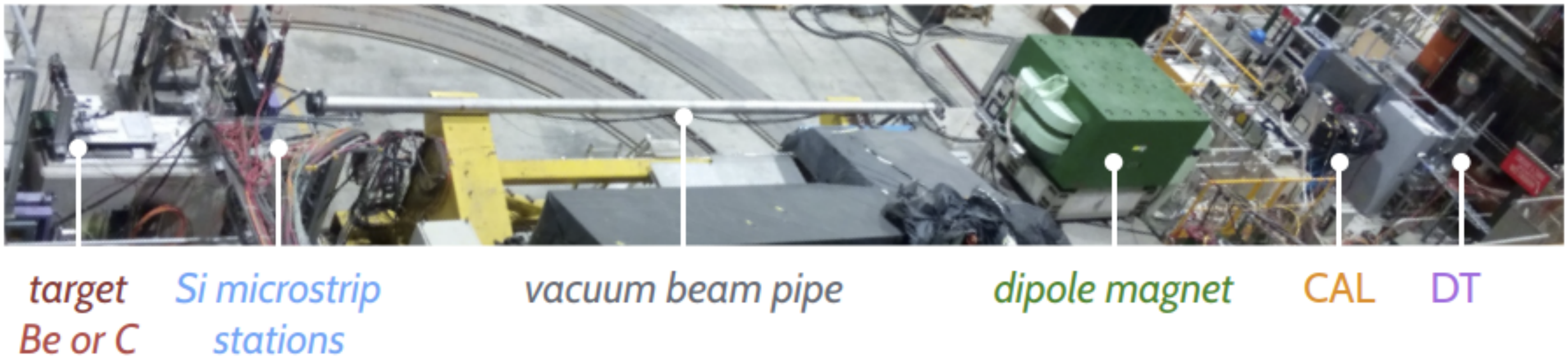
CERN-SPSC-2020-004

LEMMA-TB: an experiment to measure the production of a low emittance muon beam

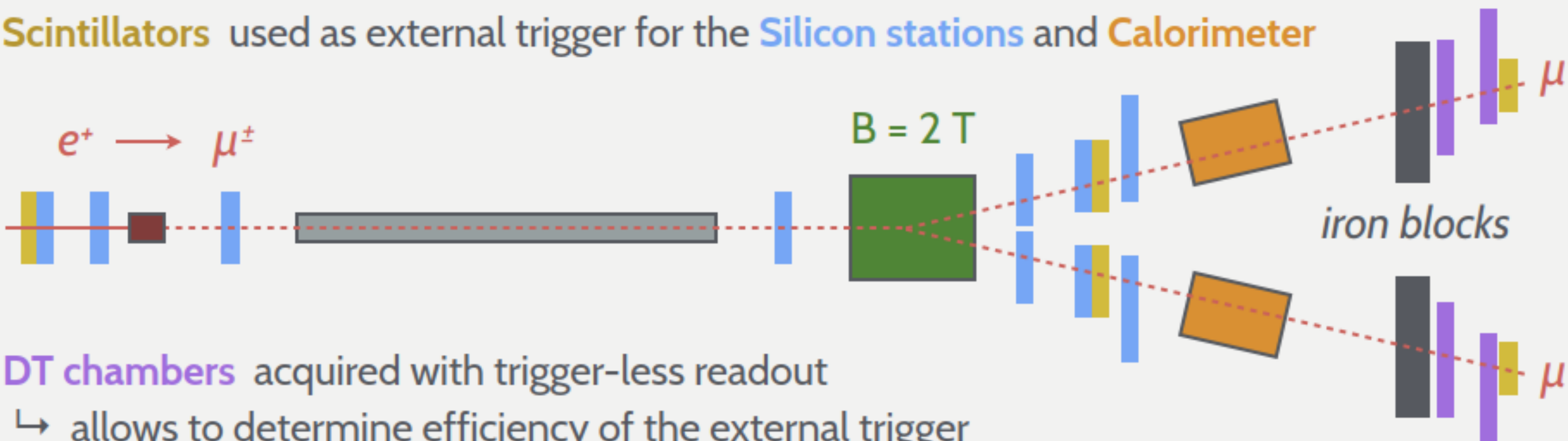
N. Amapane[a,b], M. Antonelli[c], F. Anulli[d], N. Bacchetta[h], N. Bartosik[b], M. Bauce[d], A. Bertolin[h], M. Bianco[m], C. Biino[b], O. R. Blanco-Garcia[c], M. Boscolo[c], A. Braghieri[q], A. Cappati[a,b], F. Casaburo[l,d], M. Casarsa[i], G. Cavoto[l,d], N. Charitonidis[*m], A. Colaleo[p], F. Collamati[d], G. Cotto[a,b], D.Creanza[p], C. Curatolo[h], N. Deelen[t], F. Gonella[h], S. Hoh[n,h], M. Iafrati[c], F. Iacoangeli[d], B. Kiani[b], D. Lucchesi[n,h], V. Mascagna[e,f], S. Mersi[m], A. Paccagnella[n,h], N. Pastrone[b], J. Pazzini[n,h], M. Pelliccioni[b], B. Ponzio[c], M. Prest[e,f], C. Riccardi[q,r], M. Ricci[c], R. Rossin[n,h], M. Rotondo[c], P. Salvini[q], O. Sans Planell[a,b], L. Sestini[h], L. Silvestris[p], A. Triossi[o], I. Vai[q,s], E. Vallazza[f], R.Venditti[p], S. Ventura[h], P. Verwilligen[p], P. Vitulo[q,r], and M. Zanetti.[n,h]

Past Test Beams

Layout of the experimental setup: *August 2018*



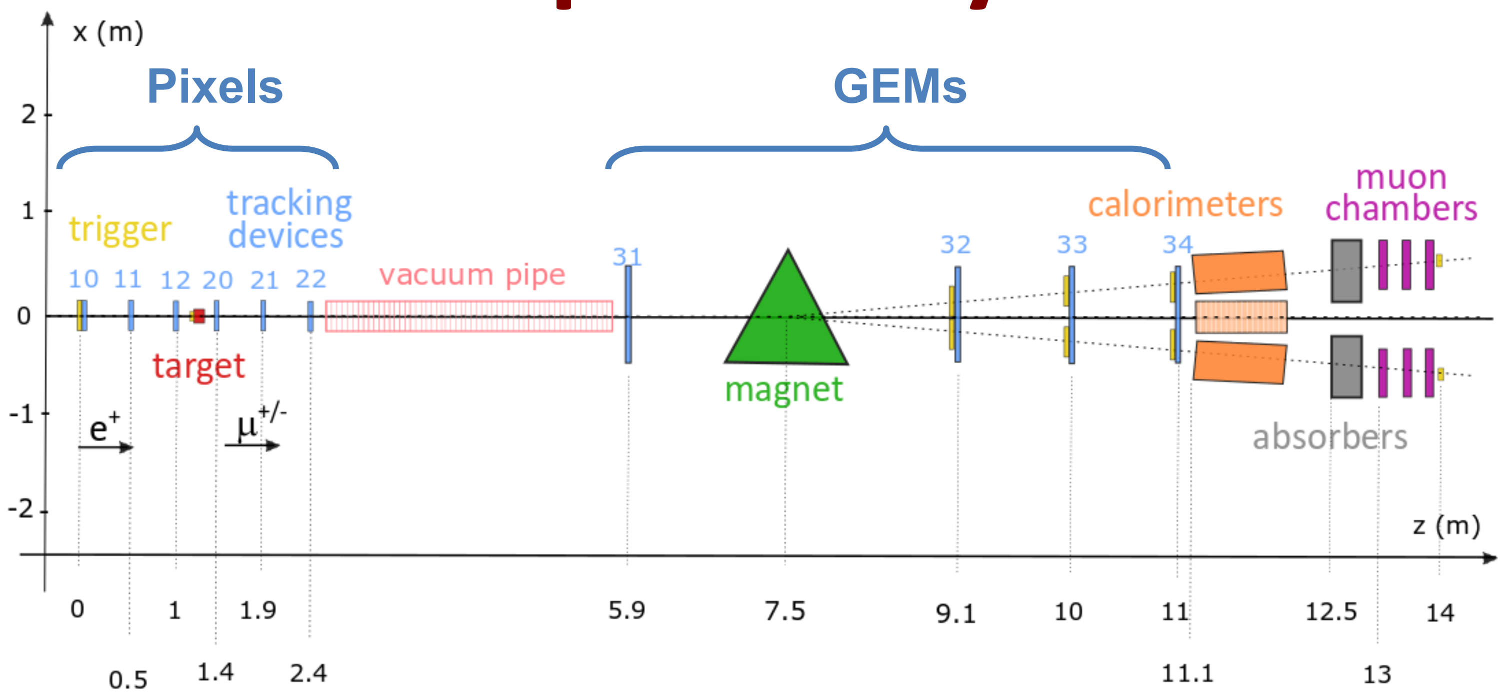
Scintillators used as external trigger for the **Silicon stations** and **Calorimeter**



DT chambers acquired with trigger-less readout

↳ allows to determine efficiency of the external trigger

Proposed layout



- Fast, high-resolution pixel telescopes (CMS modules) before and after the target
- Fast GEM detectors from CMS before and after the magnet
- Combination of several calorimeters
- 4+2 Muon chambers (triggerless readout); ready
- Improved (integrated, low dead time) DAQ system
- Improved trigger system

Richieste 2021 – non finali

- 13 sezioni/laboratori interessati – discussioni in corso per definire impegni
- attività anche in **sinergia** con R&D in corso e futuri progetti in fase di valutazione: **AIDAinnova** e **IFAST**
- **FTE** non finalizzati – previsti **10-20**

TUTTE LE RICHIESTE SARANNO MEGLIO MOTIVATE NEI PREVENTIVI a fine luglio

- **Missioni - collaborazione internaz. + Snowmass21 + riunioni IT e testbeam:**
    - **150 keu**
- **R&D rivelatori – disegno esperimento:**
    - **50 keu tracciatore (sinergia 4D/timing layers)**
    - **30 keu calorimetro (sinergia KLEVER/LHCb)**
- **R&D bersagli/cristalli: 50 keu**
- **R&D magneti fast ramping ➔ DA DEFINIRE entro settembre**
- **TEST BEAM LEMMA @ CERN – completamento: 20 keu**
- **Calcolo (richiesta dedicata)**

INFN groups involved and starting

- Laboratori Nazionali di Frascati
- Milano
- Padova
- Roma1 – collaboration with SBAI
- Roma3
- Torino – collaboration with PoliTO
- Trieste

- Bari
- Bologna
- Cagliari
- Ferrara
- Genova
- Laboratori Nazionali di Legnaro
- Milano Bicocca
- Pavia
- Pisa

Path Forward

International Muon Collider Design Study, CERN, July 3, 2020

Daniel Schulte

Highest priority is to form the collaboration

- All partners taking ownership
  - define the work programme
  - find resources
  - start to work

Next General Meeting	**International Collaboration:**
Physics & Experiment	July 27
Machine	starting September

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

- Will upload information

Mailing lists:

MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch

MUONCOLLIDER_FACILITY@cern.ch

E-group:

MUONCOLLIDER-DETECTOR-PHYSICS

MUONCOLLIDER-FACILITY

e-group
MUONCOLLIDER-INFN

Growing interest in the community

Past experiences and new ideas discussed at the joint ARIES Workshop

July 2-3, 2018 – Università di Padova – Orto Botanico

https://indico.cern.ch/event/719240

Preparatory meeting to review progress for the ESPPU Simposium

April 10-11, 2019 – CERN – Council Room

https://indico.cern.ch/event/801616

Future Plans @ CERN October 9-11, 2019

https://indico.cern.ch/event/845054/

ECFA – Novel Accelerator Technologies @ CERN November 14, 2019

https://indico.cern.ch/event/847002/

Muon Collider General Meeting – remote March 31, April 1-2, 2020

https://indico.cern.ch/event/886491/

Conclusioni

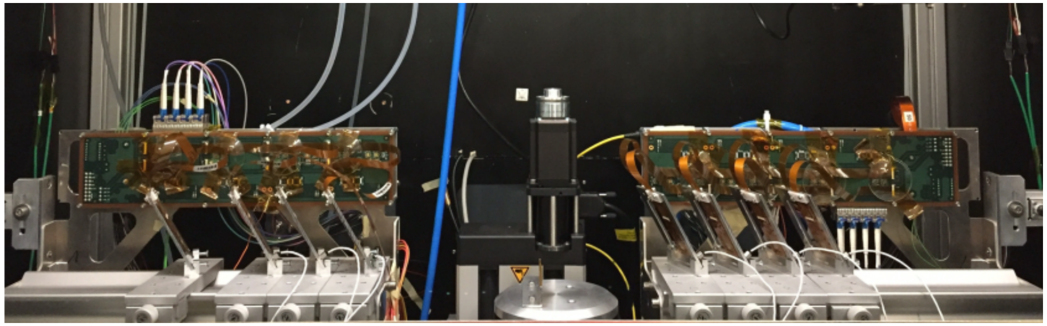
- **Sinergia** con sigle in CSN5 (TimeSPOT, MC-INFN)
  e progetti ERC - timing (UFSD)
  e progetti EU per il futuro:
  - AIDAinnova (rivelatori e software)
  - I.FAST (R&D acceleratori)
- Anagrafica e preventivi in fase di discussione e stesura finale
- Saremo pronti ad incontrare referee a settembre con maggiori dettagli
- **Moltissimo lavoro entusiasmante sia per formare la nuova collaborazione internazionale che nel processo SnowMass21**
  ➔ tantissime possibilità di fare la differenza sul disegno di macchina, MDI ed esperimento e di validazione della fisica

Grazie a tutti quanti hanno contribuito finora

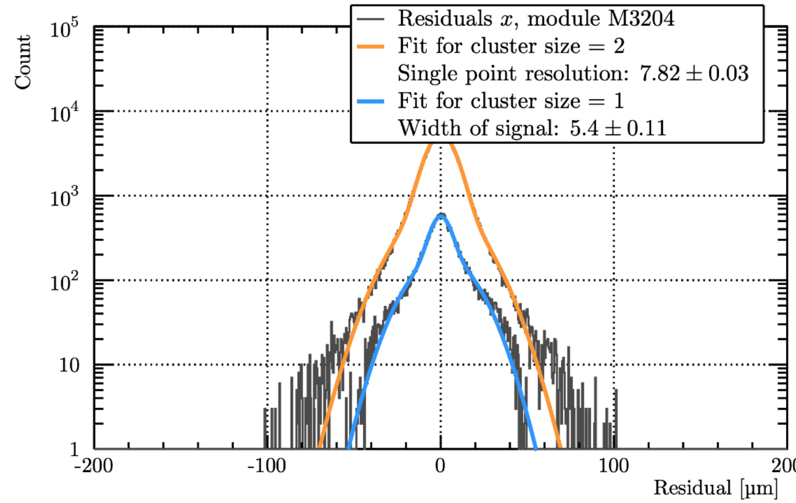
e a quanti stanno cominciando ….o ancora pensando…

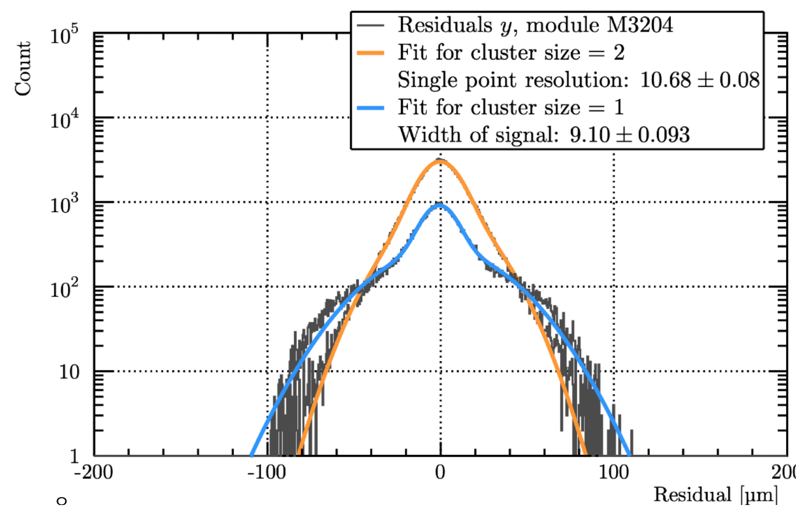
extras

Pixels for TB



- 12 new modules (from CMS upgrades) being produced:
  - 20 kE total, need to grant planned SJ to PD (10 kE)
- PD will take care of mechanical supports
- Expertise and technical support from the CHROMIE community
  - We'll borrow all read-out and powering/control electronics
- Need to develop an appropriate trigger system (TTC based)





N. Deelen, N. Bacchetta

Note: Key Technologies

- Advanced detector concepts and technologies, requiring excellent timing, granularity and resolution, able to reject the background induced by the muon beams.
- Advanced accelerator design and beam dynamics for high luminosity and power efficiency
- Robust targets and shielding for muon production and cooling as well as collider and detector component shielding and possibly beam collimation.
- High field, robust and cost-effective superconducting magnets for the muon production, cooling, acceleration and collision. High-temperature super-conductors would be an ideal option
- High-gradient and robust normal-conducting RF to minimise muon losses during cooling.
- High rate positron production source and high current positron ring.
- Fast ramping normal-conducting, superferric or superconducting magnets that can be used in a rapid cycling synchrotron to accelerate the muons and efficient power converters.

Note: Key Technologies, cont.

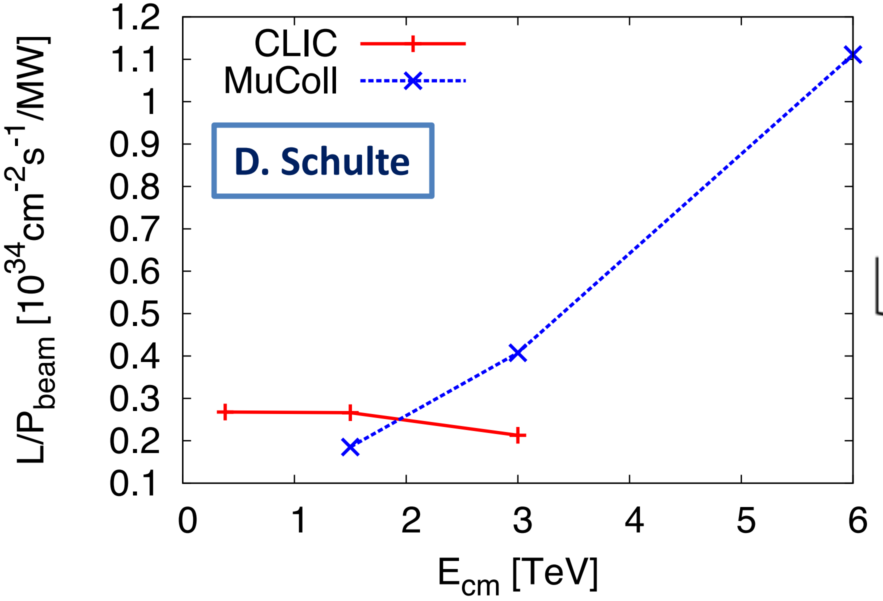
- Efficient, high-gradient superconducting RF to minimise power consumption and muon losses during acceleration.
- Efficient cryogenics systems to minimise the power consumption of the superconducting components and minimise the impact of beam losses.
- Other accelerator technologies including high-performance, compact vacuum systems to minimise magnet aperture and cost as well as fast, robust, high-resolution instrumentation.

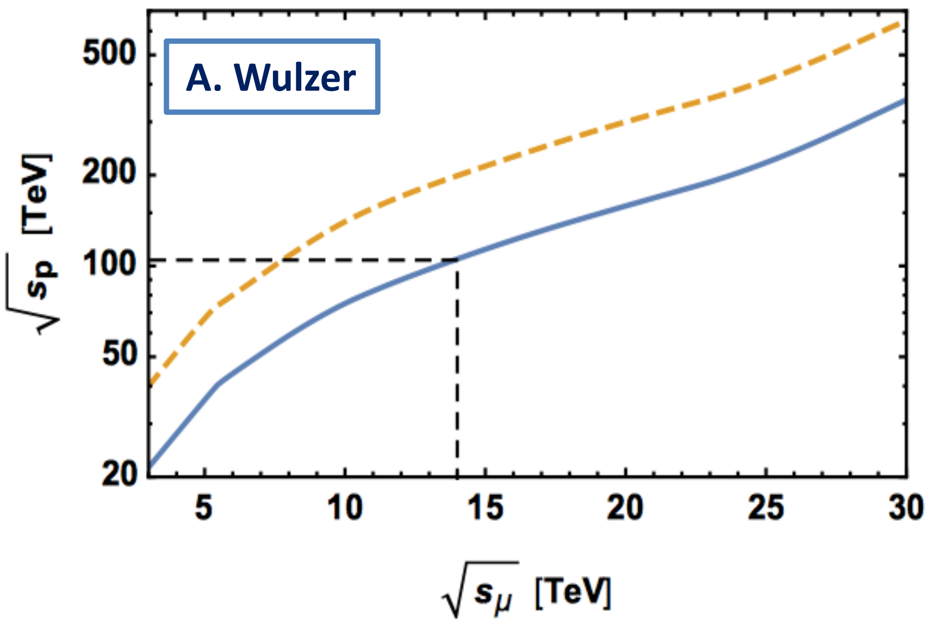
- Some technologies might still need to be identified

- And all the technologies required for the demonstrator

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

Motivation: Higgs potential

M. Chiesa et al. arXiv:2003.13628 [hep-ph]

determine the Higgs potential by measuring trilinear and quadrilinear self coupling

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

Trilinear coupling k_3

$\sqrt{s}$=10 TeV $\mathcal{L} \sim 2 \cdot 10^{35} cm^{-2} s^{-1}$

20 ab^{-1} ➔ $k_3$sensitivity ~ 3%

Best sensitivity ~ 5% FCC combined
arXiv:1905.03764 **[hep-ph]**

Quadrilinear coupling k_4

$\sqrt{s}$=14 TeV $\mathcal{L} \sim 3 \cdot 10^{35} cm^{-2} s^{-1}$

~30 ab^{-1} ➔ $k_4$sensitivity few 10%

significantly better than what is currently expected to be attainable at the FCC-hh with a similar luminosity
arXiv:1905.03764 **[hep-ph]**

This just looking at the Higgs sector!
Top and new physics sectors also to be scrutinized

Physics at high energy

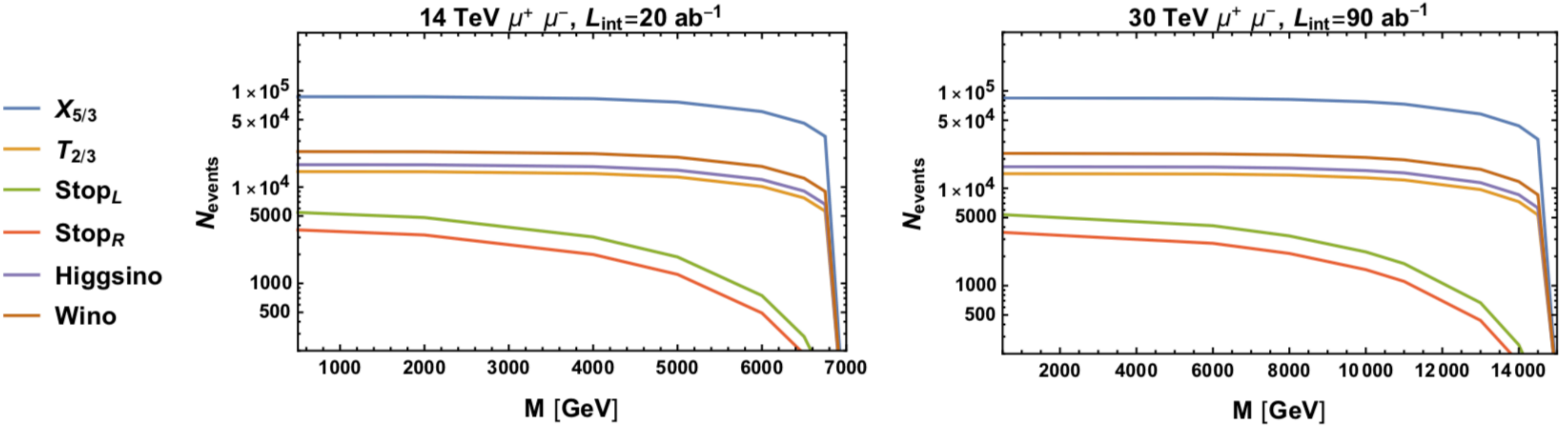
Multi-TeV energy scale allows to explore physics beyond SM both directly and indirectly

Direct Reach

Andrea Wulzer

Discover **Generic EW** particles **up to mass threshold**

exotic (e.g., displaced) **or difficult** (e.g., compressed) decays to be studied



Next steps

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

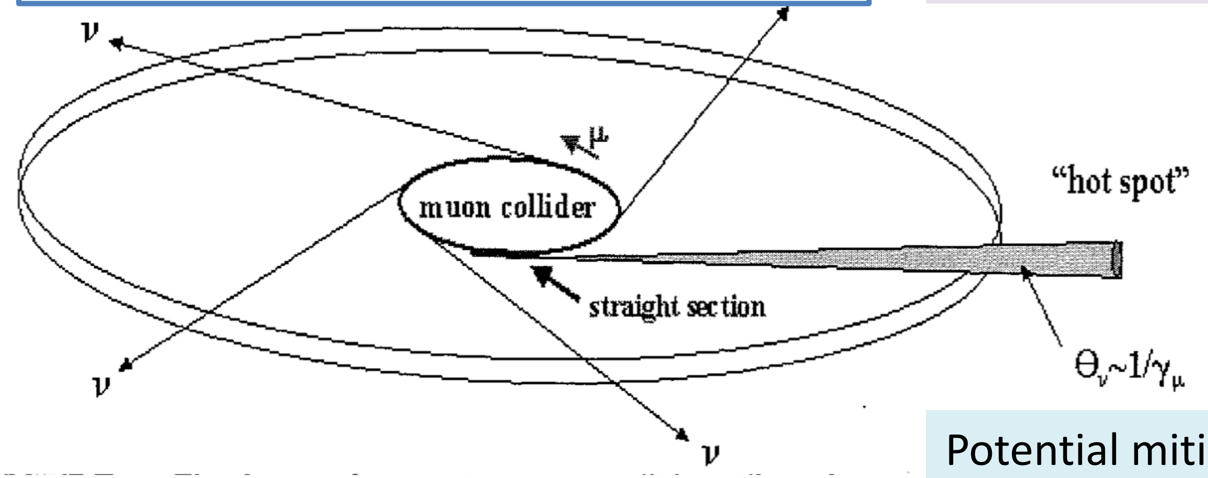
- Several teams from different countries already contributed to present knowledge
- **The on-going work is fostering the preparation of an organized study:**
  - **identification of feasibility issues and potential incremental steps ➔ Documents**
  - **taking advantage of the enormous progress already done ➔ Joint effort on-going**
  - **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)**
  - **new detectors simulations and R&D towards a 5D experiment**

Challenge: Neutrino Radiation Hazard

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

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

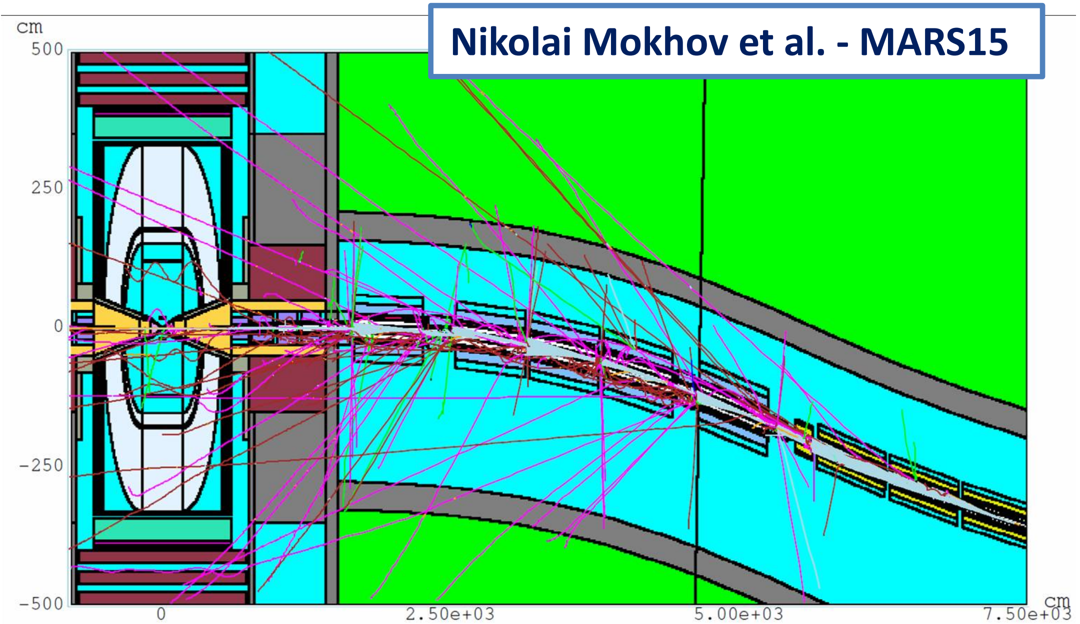
- Site choice
- Owning the land in direction of experimental insertion

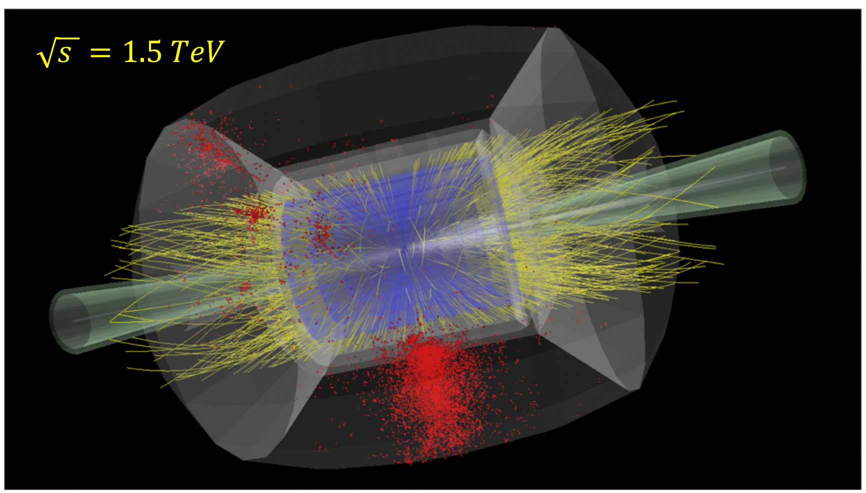
- Having a dynamic beam orbit so it points in different directions at each turn in the arcs
    - Or at least paint the beam in the the straights to dilute radiation

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

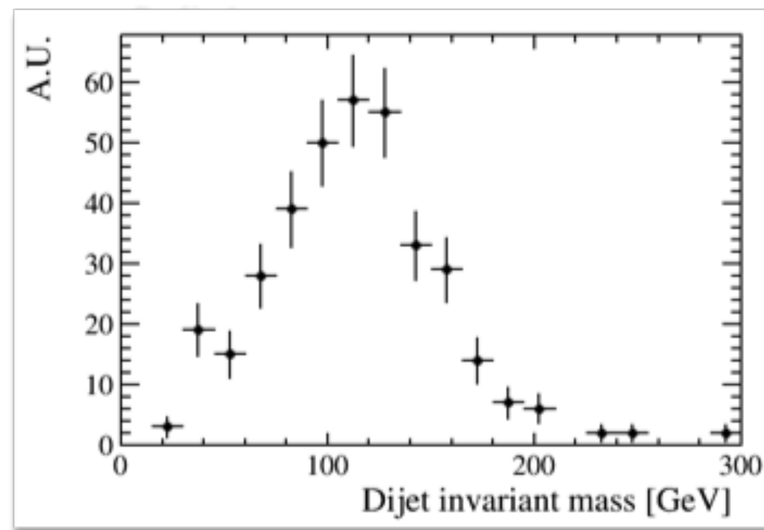
Muon Beams Induced Background

Nikolai Mokhov et al. - MARS15

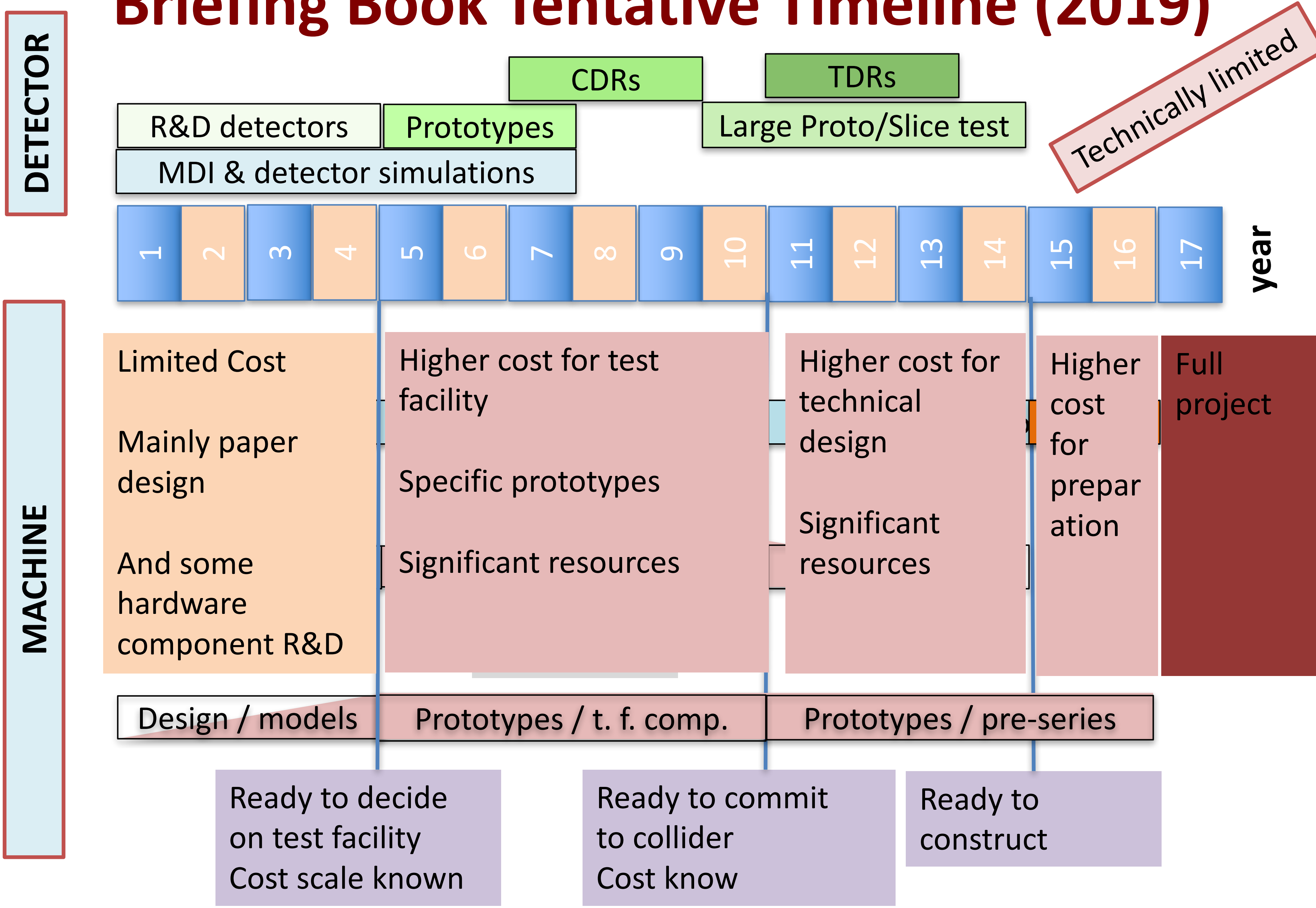




$\mu^+\mu^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated



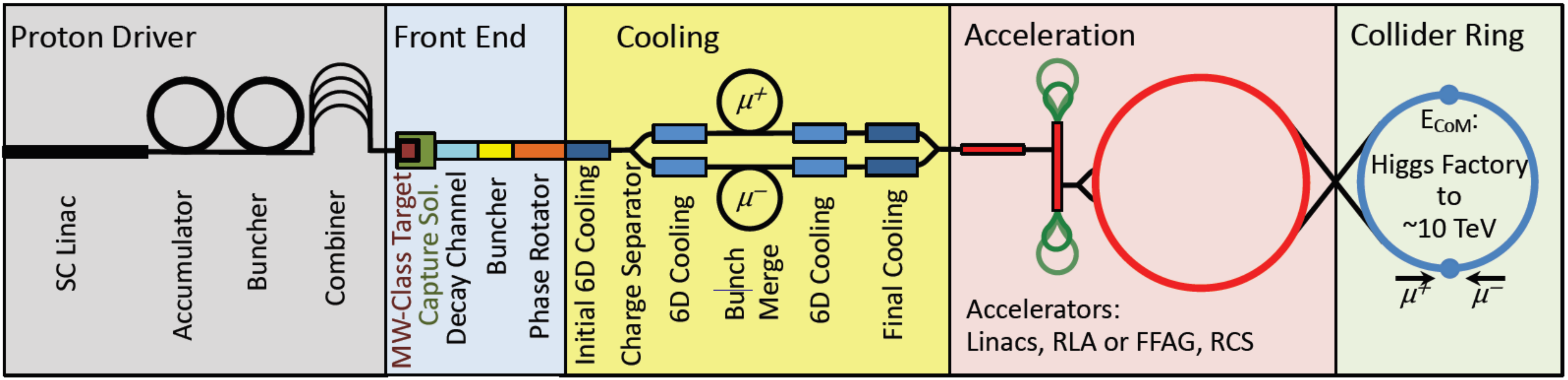
Briefing Book Tentative Timeline (2019)



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

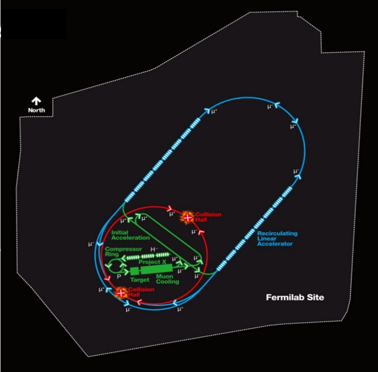
Acceleration to collision energy

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

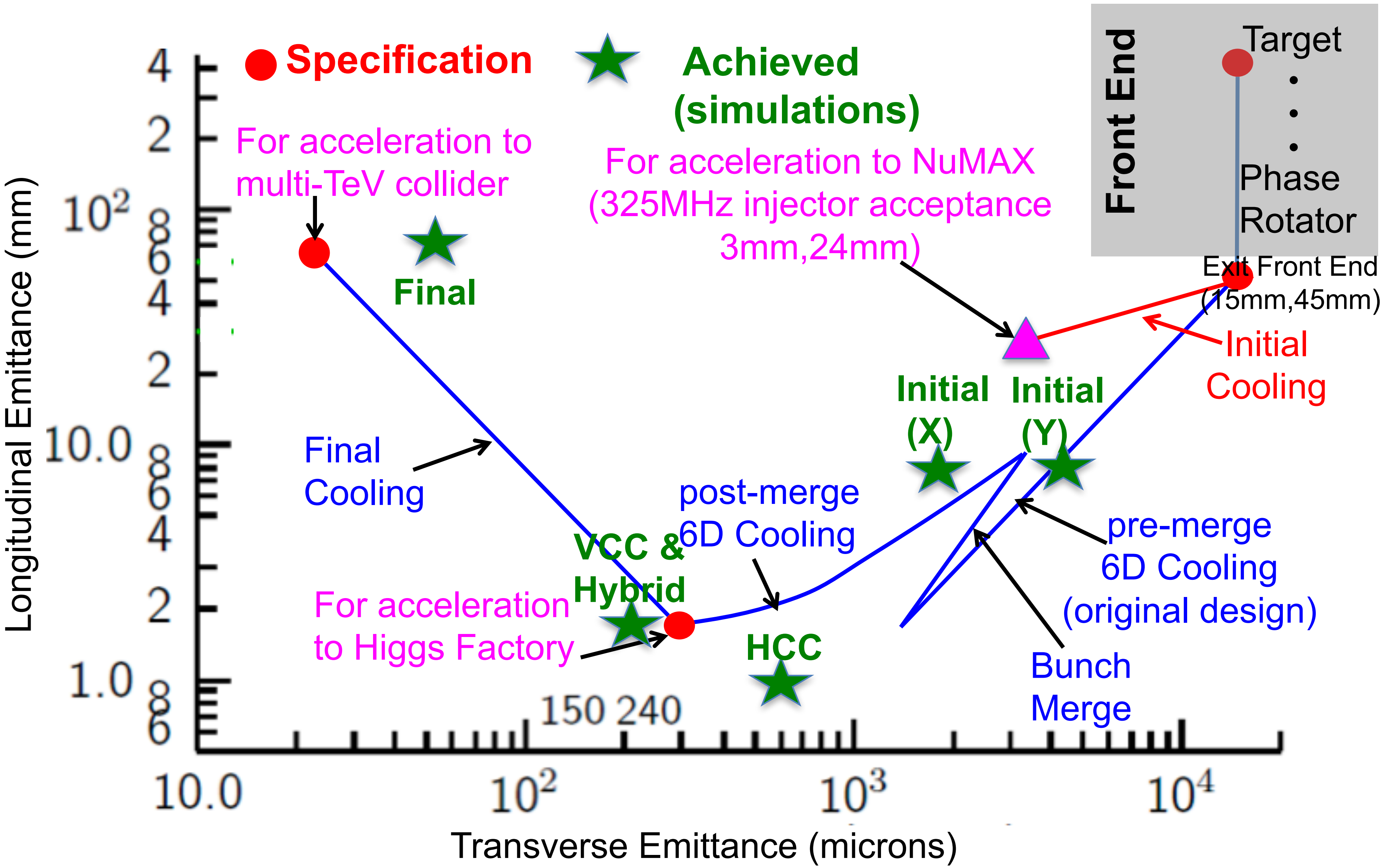
Could begin operation with Project X Stage II beam

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

Cooling: The Emittance Path



Recent LEMMA effort

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

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

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

Extremely promising:

- muons produced with low emittance ➔ "no/low cooling" needed

But difficult:

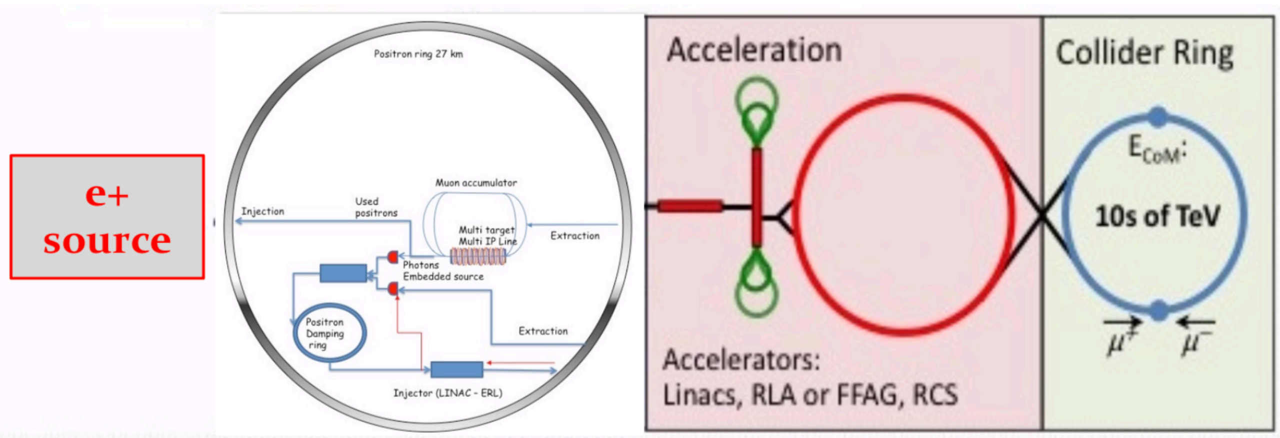
✓ **low** production **cross section**: maximum $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim 1\ \mu b$

✓ **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

Conclusions

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

➔ an immense physics reach

➔ detector studies with beam induced background recently proved physics feasible

➔ a possibly affordable cost and power consumption – exploiting existing tunnels

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

➔ proton driver option can be used NOW as baseline for a CDR @ 3 and 10 TeV

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

- **Opportunity for particle physics with intense stored muon beam**

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

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

Organisation: new international collaboration

The study will be carried out in a collaboration of international partners and address the feasibility of the collider design and the physics experiments. Institutes can join by expressing their intent to collaborate through signing a light Memorandum of Understanding. The study will be initially hosted at CERN, which will provide administrative and organisational support.

Collaboration Board

- Oversees the study and approves important decisions
- One member per institute, elects it's chair
- Elects project leader

Project leader

- Leads study
- Appoints steering committee representing physics, experiment, accelerator and technology, endorsed by Collaboration Board
- Reports regularly to the LDG on the progress

Advisory committee

- review study progress at least once per year
- recommend further actions
- reports to collaboration board

Synergies

- Important synergies exist for the key muon collider technologies
  - Magnet development for hadron colliders
    - e.g. link to high-temperature superconducting magnet development (Daniel Schoerling)
  - Superconducting RF cavities for hadron colliders and ILC
  - Normal-conducting structures for CLIC
  - Cooling for hadron colliders
  - Material, target, shielding, …
  - Instrumentation, vacuum, ...

- Synergies for physics and experiment will also be exploited
  - Physics studies for ALEGRO
  - Simulation tools
  - …

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/.