Potentiality of a muon beam: Higgs factory and neutrino factory

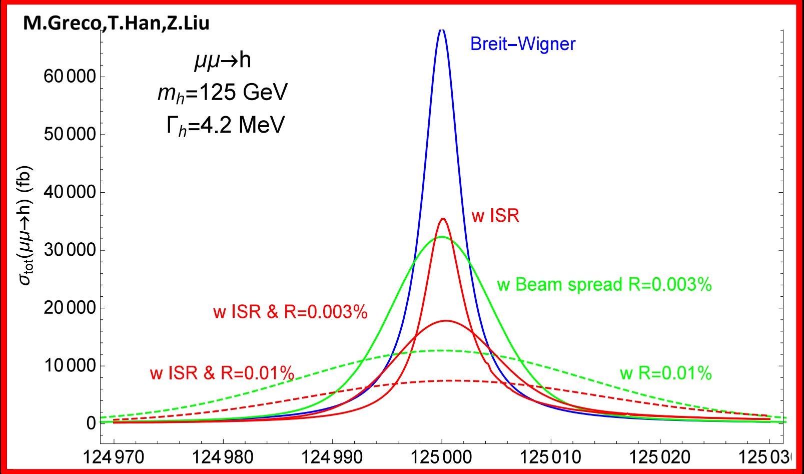
K. Long, 11 April, 2019

Basis of potential

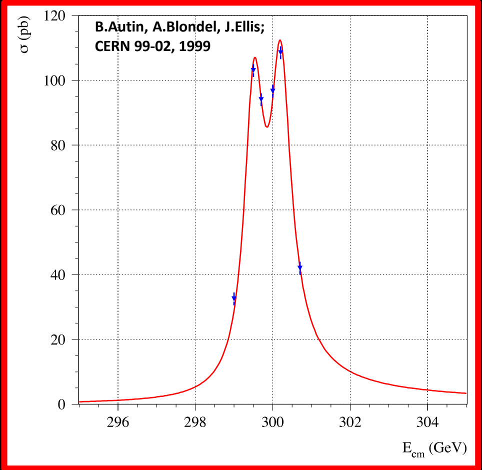
- **Muon mass:**
  - $200\,m_e \sim m_\mu \sim 0.1\,m_p$
- **Energy frontier:**
  - No brem-/beam-strahlung
    - Rate $\propto m^{-4}$
      [5×10^{-10} cf e]
  - Enhanced coupling to Higgs
    - Production rate $\propto m^2$
      [5×10^4 cf e^+e^-]
  - Efficient acceleration
    - Favourable rigidity
- **Muon decay:**
  - ν_e, ν_μ
  - Precisely known energy spectrum
- **Physics of flavour:**
  - Precision neutrino physics
  - Sensitive cLFV searches

Line shape

- **Standard Model Higgs:**
  - *M* = 125 GeV; Γ=4.5 MeV
    - Exquisite resolution
      - R < 0.003%



- **"Two-state" Higgs:**
  - Deviation from SM line shape
  - Resolve states
    - Exquisite resolution!



Couplings/branching ratios

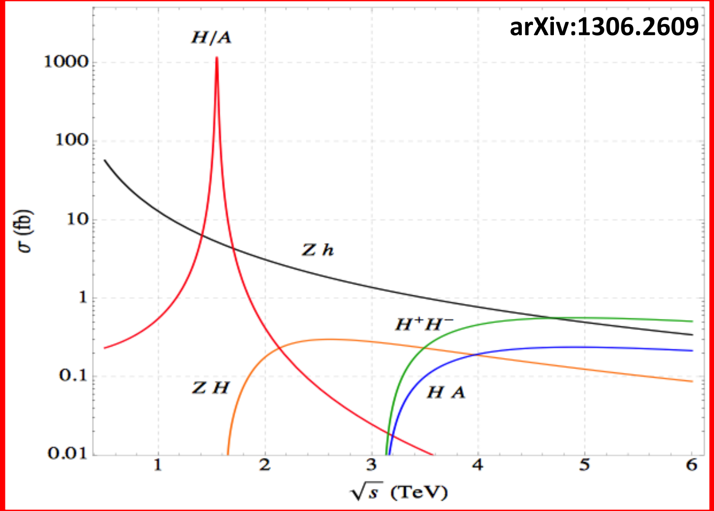
- Standard Model Higgs
  - Accurate threshold measurement
  - Exploiting accurate knowledge of (narrow) energy spectrum

R (%)	$\mu^+\mu^- \to h$	$h \to b\bar{b}$		$h \to WW^*$	
	$\sigma_{\rm eff}$ (pb)	σ_{Sig}	σ_{Bkg}	σ_{Sig}	σ_{Bkg}
0.01	7.3	3.4	20	1.7	0.051
0.003	17	8.0		2.5	

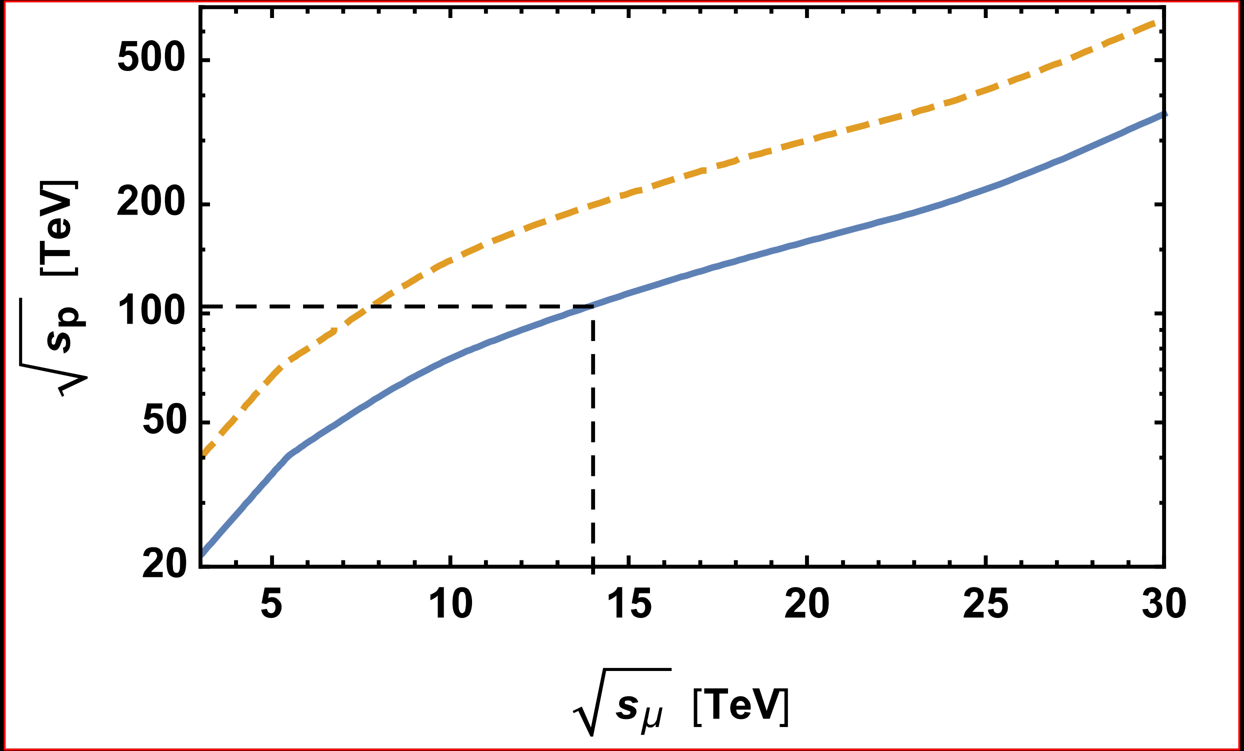
M.Greco,T.Han,Z.Liu

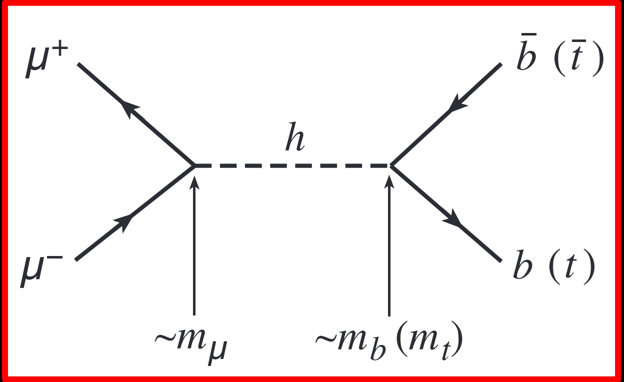
m_{bb} > 100 GeV

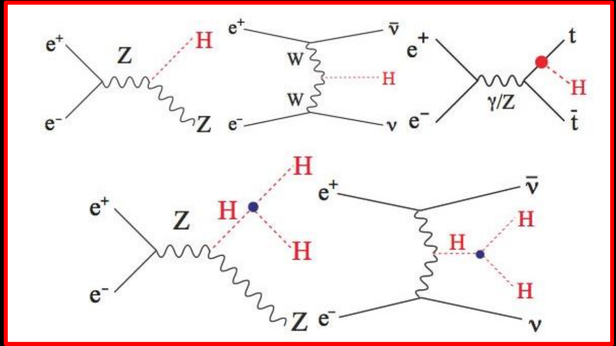
- Beyond SM Higgs
  - Exploit narrow energy spectrum to search for :
    - Narrow resonances
    - Unexpected thresholds



The Standard Model and beyond

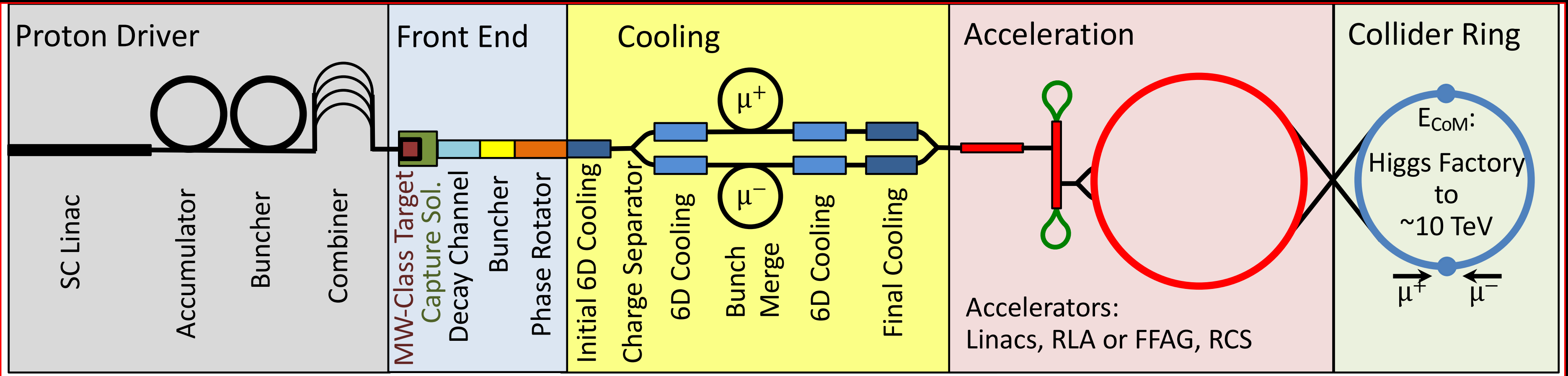




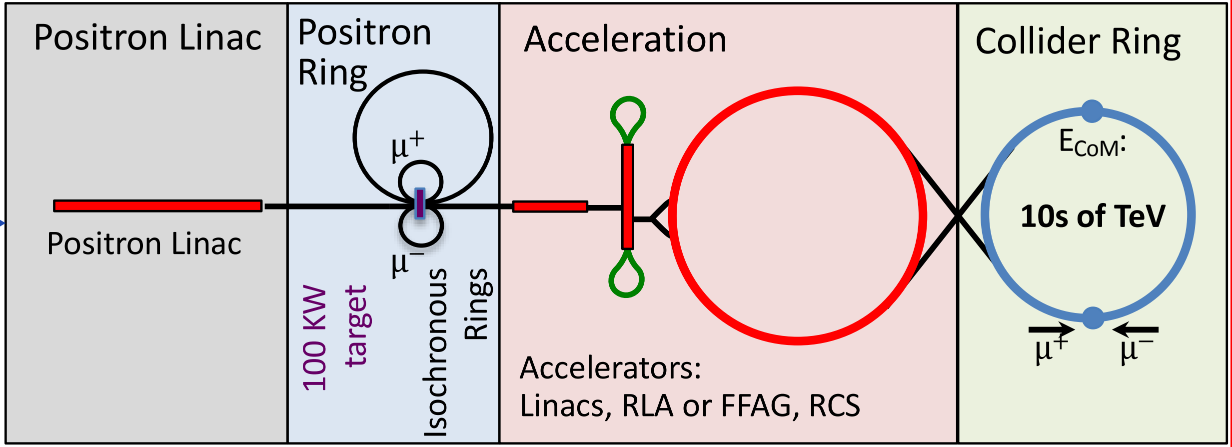


- Energy frontier: big advantage over pp because fundamental fermion
- Future study of the Higgs:
  - Line width; establish single resonance (?) in s-channel with $\mu^+\mu^-$
  - Couplings; requires > 1 TeV for complete, precise study

Resurgence of interest: Pastrone Panel



Low EMmittance Muon Accelerator (LEMMA):
10^{11} ∝ 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.



Future Lepton Colliders: Higgs boson

Janot EP Faculty Meeting Jun '18

- In numbers

(+) With -80%/+30% polarization
(*) Infrastructure exists already

Collider (#IPs)	Lumi (10^{34} cm^{-2}s^{-1}) at …		Time (yrs) for …	Length (km)	Energy frontier (TeV)
	240-250 GeV	350-380 GeV	10^6 HZ events		
ILC (1)	1.5	–	20$^{(+)}$	23	0.35 – 0.5 (ILC?)
CLIC (1)	–	1.5	30$^{(+)}$	11	3 (CLIC)
LEP3 (4)	4.4	–	10	27$^{(*)}$	27 (HE-LHC)
CEPC (2)	6.0	–	7	100	70 (SppC)
FCC-ee (2)	17.	3.4	2.5	100	100 (FCC-hh)
μColl (1-2)	0.15	0.20	200	0.6	20 (FCC-μμ?)

13k/yr in '*s*-channel'

Muon collider as Higgs factory

- **Opportunity:**
  - **Detailed study of Higgs line shape:**
    - **Motivation from LHC or future collider results?**

CERN
Horn and bubble chamber
First neutrino beam

IHEP
SKAT, INR

CERN
Gargamelle, Aachen/Padova, CDHS, CHARM, BEBC, CCFR, NOMAD, CHORUS

FNAL
MINOS, MINOS+, NOvA

CERN
OPERA, ICARUS

BNL
first neutrino
“beam”

CERN
Horn #2 & Gargamelle

BNL/FNAL
CITF, HPWF, 7’ BC, 15’ BC, E605, E613, E734, E776, NuTEV

KEK/J-PARC
K2K, T2K

Global neutrino progamme
Hyper-K
LBNF/DUNE
CERN Neutrino Platform

1950 1960 1970 1980 1990 2000 2010 2020 2030

n_m discovery

n_e/n_m universality

Neutral Current discovery

Development of E/w SM, QPM, QCD

Development of Standard Neutrino Model

Discovery of CP-invariance violation?

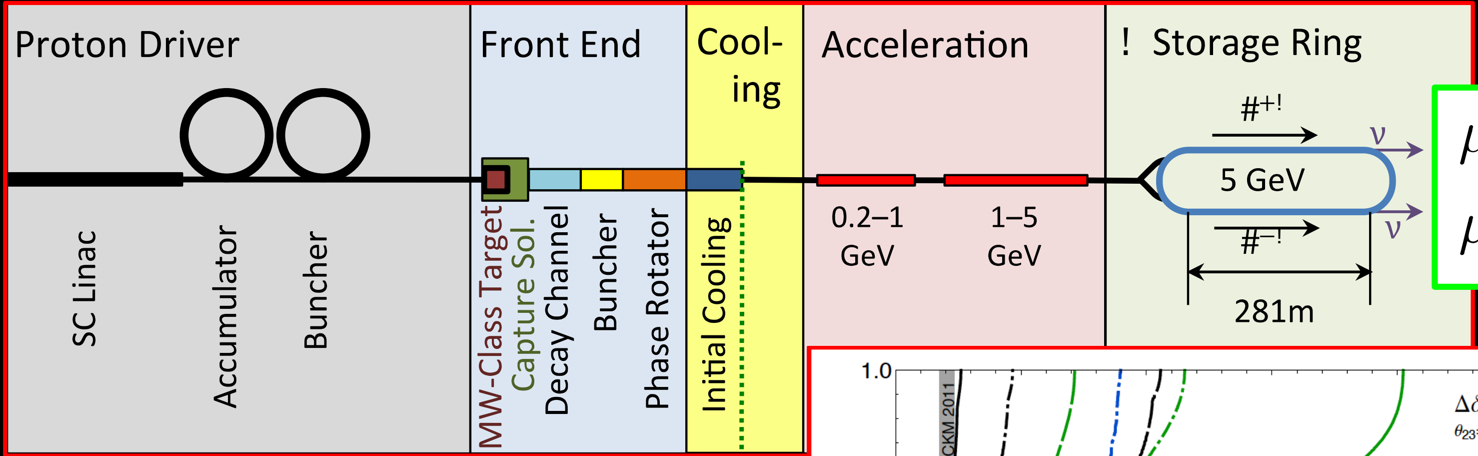
Fast extraction

Simon van der Meer
CERN, 1961

Innovation in detectors to provide:
- **High-precision**
- **Large data sets**
- **Control of systematics**

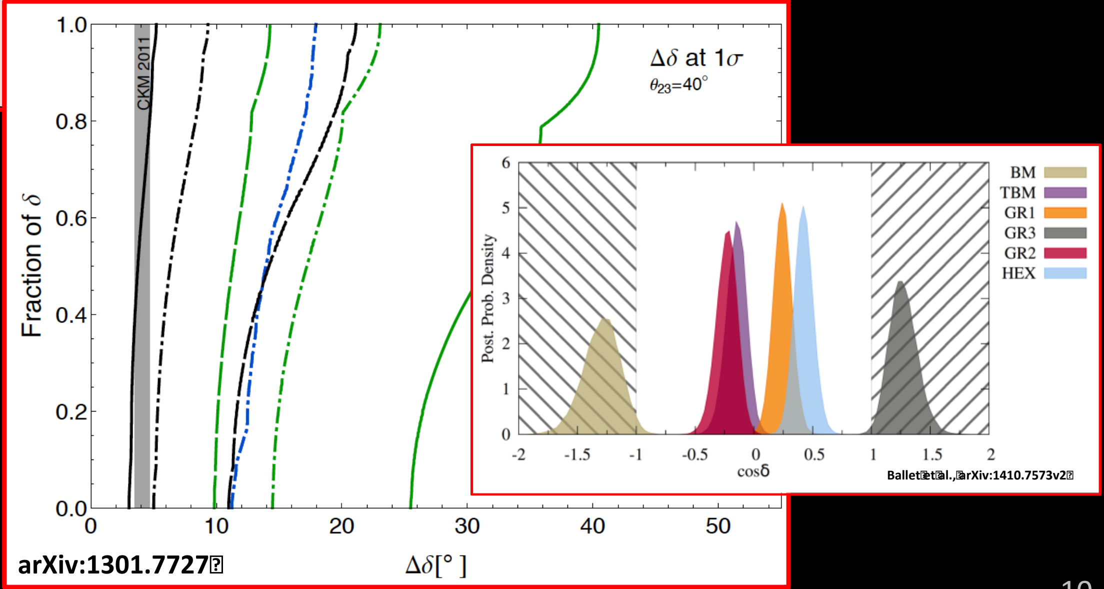
Innovation in accelerators to go beyond

Neutrino Factory: sensitivity & precision

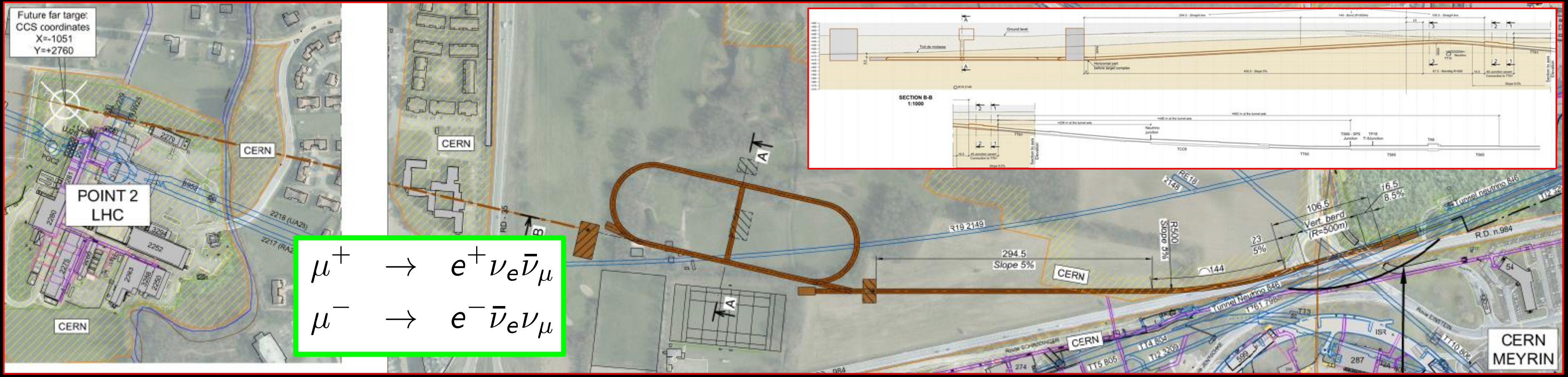


$$\mu^{+} \rightarrow e^{+}\nu_{e}\bar{\nu}_{\mu}$$
$$\mu^{-} \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu}$$

- **Unique:**
  - Large, high-energy ν_e ($\bar{\nu}_e$) flux
    - *Muon-beam cooling*
  - Favourable rigidity:
    - Optimise *E* for given *L*



Neutrinos from stored muons



$$\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$$
$$\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$$

- **Scientific objectives:**
  1. %-level ($\nu_e N$)cross sections
     - Double differential
  2. Sterile neutrino search
     - Beyond Fermilab SBN

- **Precise neutrino flux:**
  - Normalisation: < 1%
  - Energy (and flavour) precise
- **π ®μ injection pass:**
  - "Flash" of muon neutrinos

Personal remarks

- Muon collider:
  - Well motivated as energy-frontier l^+l^- machine
  - R&D programme:
    - Valuable in itself; and
    - Essential part of ‘energy-frontier’ risk-mitigation
- Strategic development of muon collider:
  - Must include (near)medium-term particle physics
    - Not necessarily nuSTORM
      - But nuSTORM is a candidate
  - Must include balanced ‘RD’ programme
    - With decision points

Neutrino programme using stored muons

- Articulated in IDS-NF and MASS:
  - nuSTORM:
    - As first step, serves as accelerator test facility
  - Neutrino factory:
    - Dictated by requirements of physics beyond DUNE & Hyper-K
- Develop/prove techniques for muon collider
- Build user community
- Does not ‘pre-commit’ to proton-driven approach

Thank you

European Strategy for Particle Physics Update

nuSTORM at CERN: Executive Summary

Contact*: *K. Long*
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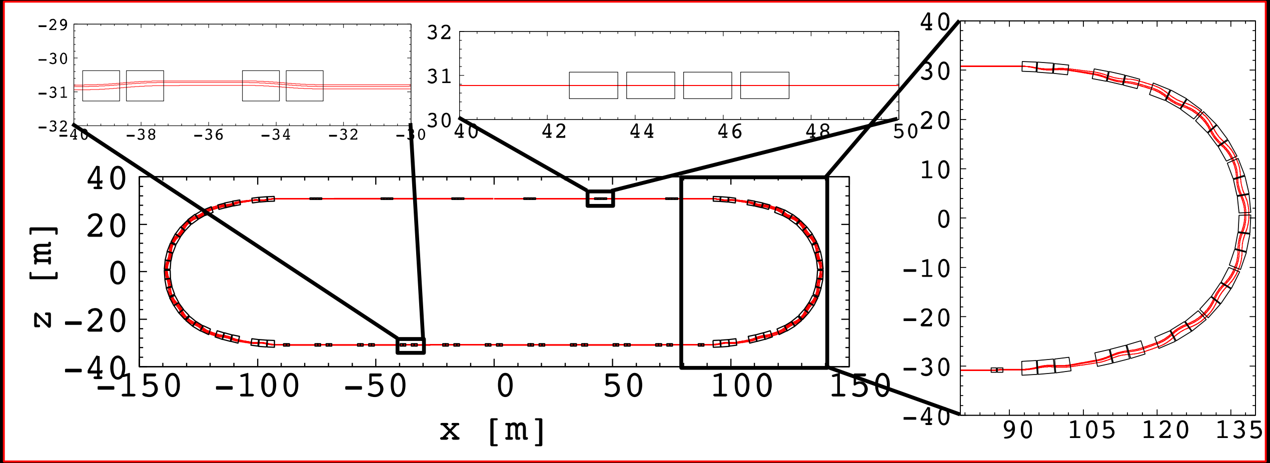
Abstract
The Neutrinos from Stored Muons, nuSTORM, facility has been designed to deliver a definitive neutrino-nucleus scattering programme using beams of $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ from the decay of muons confined within a storage ring. The facility is unique, it will be capable of storing $\mu^\pm$ beams with a central momentum of between 1 GeV/c and 6 GeV/c and a momentum spread of 16%. This specification will allow neutrino-scattering measurements to be made over the kinematic range of interest to the DUNE and Hyper-K collaborations. At nuSTORM, the flavour composition of the beam and the neutrino-energy spectrum are both precisely known. The storage-ring instrumentation will allow the neutrino flux to be determined to a precision of 1% or better. By exploiting sophisticated neutrino-detector techniques such as those being developed for the near detectors of DUNE and Hyper-K, the nuSTORM facility will:

- Serve the future long- and short-baseline neutrino-oscillation programmes by providing definitive measurements of $\overset{(-)}{\nu}_e A$ and $\overset{(-)}{\nu}_\mu A$ scattering cross-sections with percent-level precision;
- Provide a probe that is 100% polarised and sensitive to isospin to allow incisive studies of nuclear dynamics and collective effects in nuclei;
- Deliver the capability to extend the search for light sterile neutrinos beyond the sensitivities that will be provided by the FNAL Short Baseline Neutrino (SBN) programme; and
- Create an essential test facility for the development of muon accelerators to serve as the basis of a multi-TeV lepton-antilepton collider.

To maximise its impact, nuSTORM should be implemented such that data-taking begins by $\approx 2027/28$ when the DUNE and Hyper-K collaborations will each be accumulating data sets capable of determining oscillation probabilities with percent-level precision.

With its existing proton-beam infrastructure, CERN is uniquely well-placed to implement nuSTORM. The feasibility of implementing nuSTORM at CERN has been studied by a CERN Physics Beyond Colliders study group. The muon storage ring has been optimised for the neutrino-scattering programme to store muon beams with momenta in the range 1 GeV to 6 GeV. The implementation of nuSTORM exploits the existing fast-extraction from the SPS that delivers beam to the LHC and to HiRadMat. A summary of the proposed implementation of nuSTORM at CERN is presented below. An indicative cost estimate and a preliminary discussion of a possible time-line for the implementation of nuSTORM are presented the addendum.

*Author list presented in the addendum.



113 authors; 45 from the UK
47 groups; 13 from the UK

European Strategy for Particle Physics Update

Input to the European Particle Physics Strategy Update

Muon Colliders

The Muon Collider Working Group

Jean Pierre Delahaye[1], Marcella Diemoz[2], Ken Long[3], Bruno Mansoulié[4], Nadia Pastrone[5] (chair), Lenny Rivkin[6], Daniel Schulte[1], Alexander Skrinsky[7], Andrea Wulzer[1,8]

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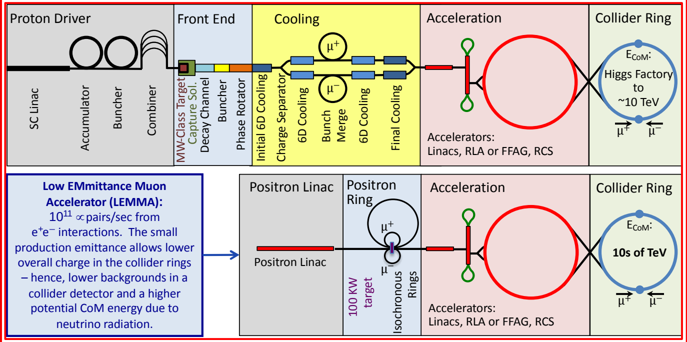

Contact: Nadia Pastrone, nadia.pastrone@cern.ch
Webpage: https://muoncollider.web.cern.ch

6 Conclusions and recommendations

Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration. The development of the challenging technologies for the frontier muon accelerators has shown enormous progress in 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. In particular the implementation of a muon collider in the LHC tunnel appears promising, but detailed studies are required to establish feasibility, performance and cost of such a project. A set of recommendations listed below will allow to make the muon technology mature enough to be favorably considered as a candidate for high-energy facilities in the future.

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. As demonstrated in past experiences, the resources needed are not negligible in terms of cost and manpower and this calls for a well-organized international effort.
For example, the MAP program required an yearly average of about 10M$ and 20 FTE staff/faculty in the 3-year period 2012-2014.

Develop a muon collider concept based on the proton driver and considering the existing infrastructure. This includes the definition of the required R&D program, based on previously achieved results, and covering the major issues such as cooling, acceleration, fast ramping magnets, detectors, ...

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.

European Strategy for Particle Physics Update

Future Opportunities in Accelerator-based Neutrino Physics

The Participants of the European Neutrino Town Meeting
22–24 October, 2018
CERN, 1 Esplanade des Particules, 1211 Geneva 23, Switzerland

Editors: Alain Blondel[a], Joachim Kopp[b], Albert de Roeck[c]
(full author list in the appendix)

(Dated: December 2018)

This document summarizes the conclusions of the Neutrino Town Meeting held in October 2018 to review the neutrino field at large with the aim of defining a str accelerator-based neutrino physics in Europe. The importance of the field across complementary components is stressed. Recommendations are presented regarding erator based neutrino physics, pertinent to the European Strategy for Particle Ph address in particular i) the role of CERN and its neutrino platform, ii) the importa cillary neutrino cross-section experiments, and iii) the capability of fixed target exp as well as present and future high energy colliders to search for the possible mani of neutrino mass generation mechanisms.

2. Recommendations

A. Neutrino physics is one of the most promising areas where to find answers to some of the big questions of modern physics; it covers many disciplines of physics complementing each other, and some coordination should ensure that each of these essential aspects is strongly supported.

B. Neutrinos at accelerators, pertinent to ESPP, are an important component because of:
   1) the search for CP violation, and the full determination of the oscillation parameters;
   2) the possibility to discover heavy neutrinos or other manifestations of the mechanism for neutrino mass generation.

   Consequently Europe (and CERN in particular) should provide a balanced support in the world-wide LBL effort, with its two complementary experiments DUNE and T2K/HyperKamiokande ("HyperK") (and its possible extension with a detector in Korea), in both of which strong EU communities are involved, to secure the determination of oscillation parameters, aim at the discovery of CP violation and test the validity of the 3-family oscillation framework; these experiments also have an outstanding and complementary non-accelerator physics program.

C. Extracting the most physics out of DUNE and HyperK will require ancillary experiments:
   1) CERN should continue improving NA61/SHINE towards percent level flux determinations;
   2) a study should be set-up to evaluate the possible implementation, performance and impact of a percent-level electron and muon neutrino cross-section measurement facility (based on e.g. ENUBET or NuSTORM) with conclusion in a few years;
   3) a strong theory effort should accompany these experimental endeavours.

D. If, for instance, the CP phase δ_{CP} is close to $\pm\pi/2$ or of $\sin\delta_{CP} = 0$, improved precision w.r.t. DUNE and HyperK should be considered. Studies of feasibility and performance of and ESSnuSB and Protvino to Orca (P2O) should be pursued to quantify their feasibility, realistic potential and complementarity with the present program.

E. Fixed target and collider experiments have significant discovery potential for heavy neutrinos and the other manifestations of the neutrino mass generation mechanisms, especially in Z and W decays. The capability to probe massive neutrino mechanisms for generating the matter—antimatter asymmetry in the Universe should be a central consideration in the selection and design of future colliders.