2019 DPF Northeastern

Muon Accelerator Program

Progress on
Muon Ionization Cooling with MICE

DPF2019 – July 31, 2019

Mark Palmer


Photo by Matthew Modoono/Northeastern University

APS DIVISION OF PARTICLES & FIELDS

Northeastern College of Science

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

The MICE collaboration

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University of Mississippi, Oxford, MS, USA
University of California, Riverside, CA, USA

Progress on Muon Ionization Cooling with MICE

MOTIVATION

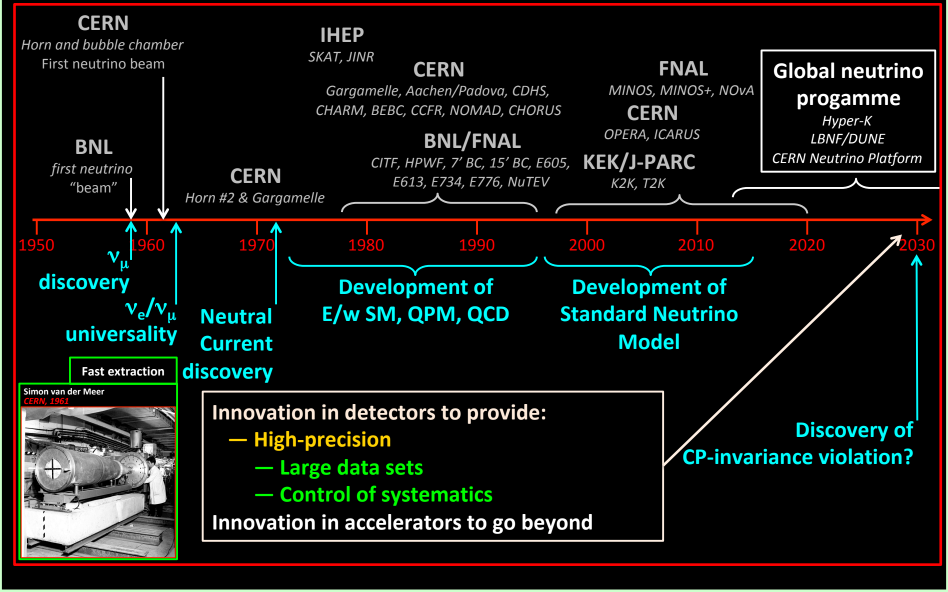
Unique advantages of muon accelerators

Energy frontier lepton-antilepton:

- No brem-/beamstrahlung
  - Rate ∝ m^{-4}
    [5 × 10^{-10} cf e]
- Efficient acceleration
  - Favorable rigidity
- Enhanced Higgs coupling
  - Production rate ∝ m^{2}
    [5 × 10^{4} cf $e^{+}e^{-}$]

Neutrino beams

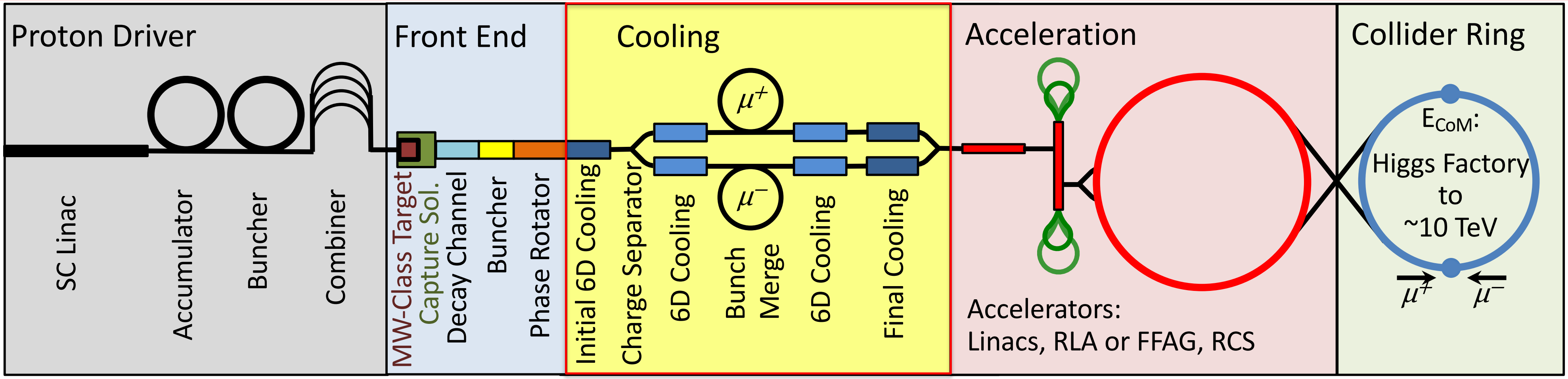
- ν_e, ν_μ
- Precisely known energy spectrum



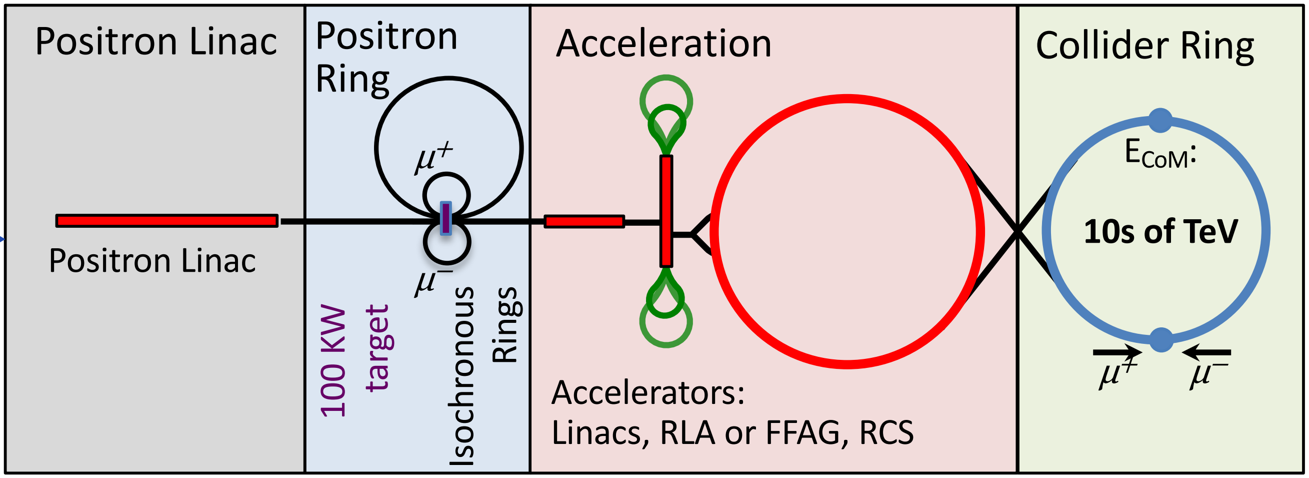
Innovation in detectors to provide:
- High-precision
  - Large data sets
  - Control of systematics

Innovation in accelerators to go beyond

Resurgence of interest: Pastrone Panel



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.

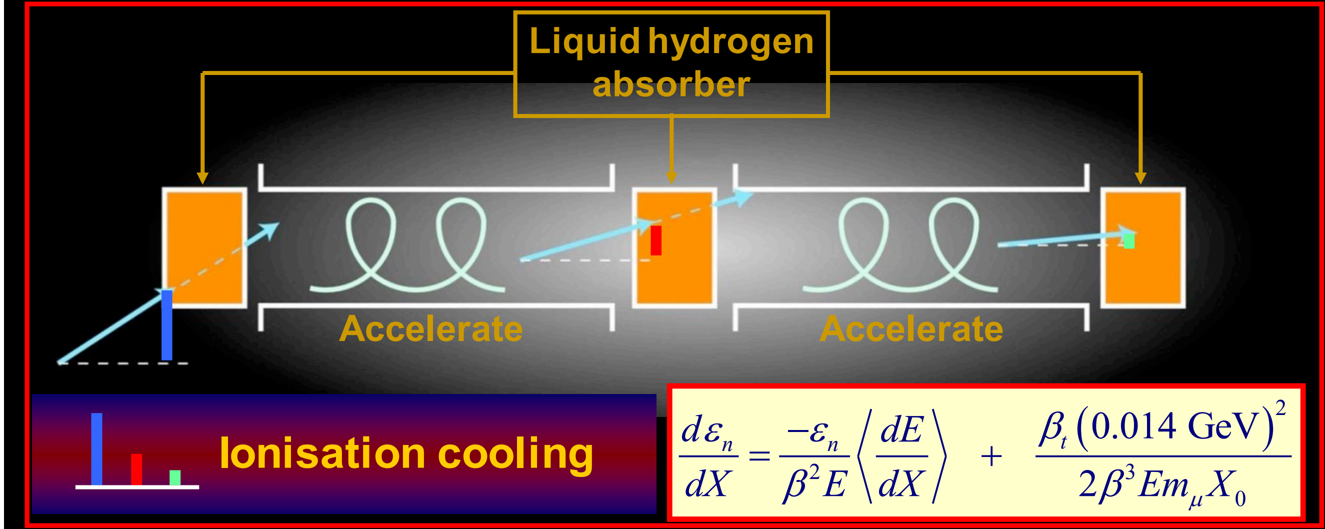


Pastrone et al.

Progress on Muon Ionization Cooling with MICE

IONIZATION COOLING AND MICE

The principle of ionization cooling

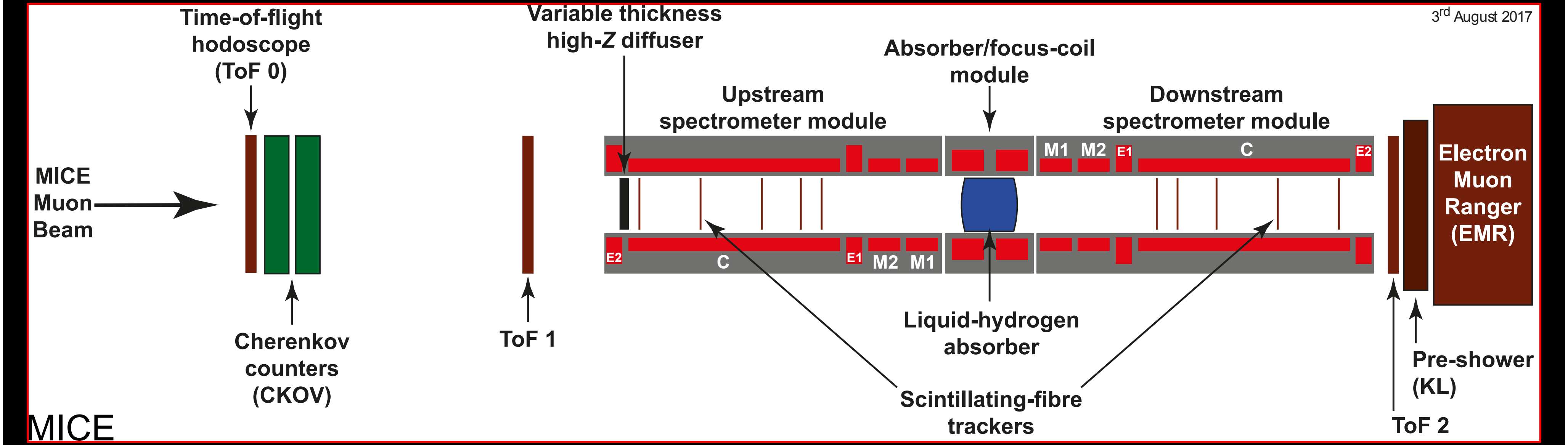


$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (0.014\ \mathrm{GeV})^2}{2\beta^3 E m_\mu X_0}$$

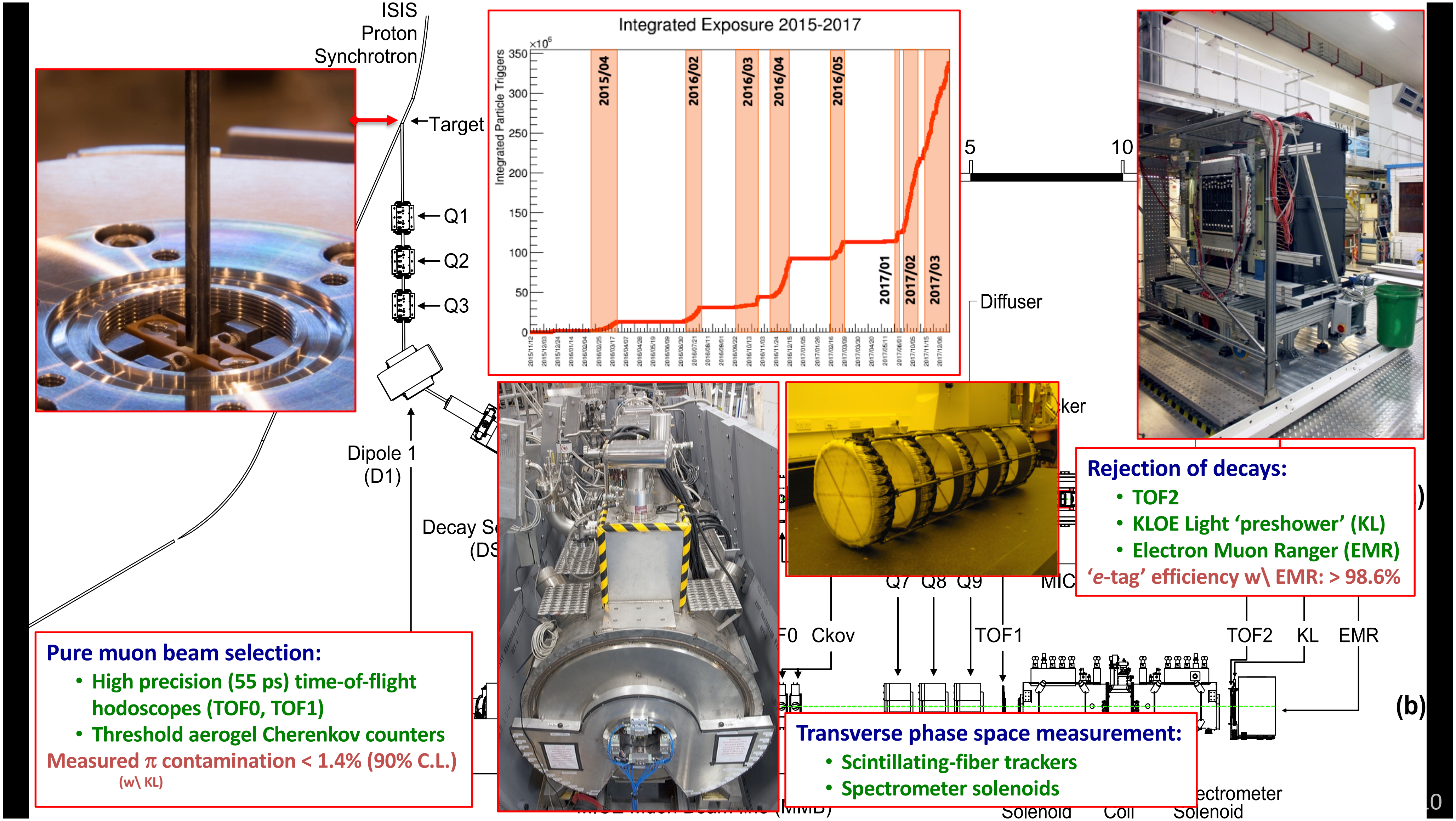
	Z	FoM	Rel. 4D cooling
H	1	252.6	1.000
He	2	182.9	0.524
Li	3	130.8	0.268
C	6	76.0	0.091
Al	13	38.8	0.024

- Competition between:
  - dE/dx [cooling]
  - MCS [heating]
- Optimum:
  - Low *Z*, large X_0
  - Tight focus
  - H_2 gives best performance

Schematic of the experiment



HIGHLIGHTS OF THE DATA TAKING



Pure muon beam selection:

- High precision (55 ps) time-of-flight hodoscopes (TOF0, TOF1)
- Threshold aerogel Cherenkov counters

Measured π contamination < 1.4% (90% C.L.)
(w\ KL)

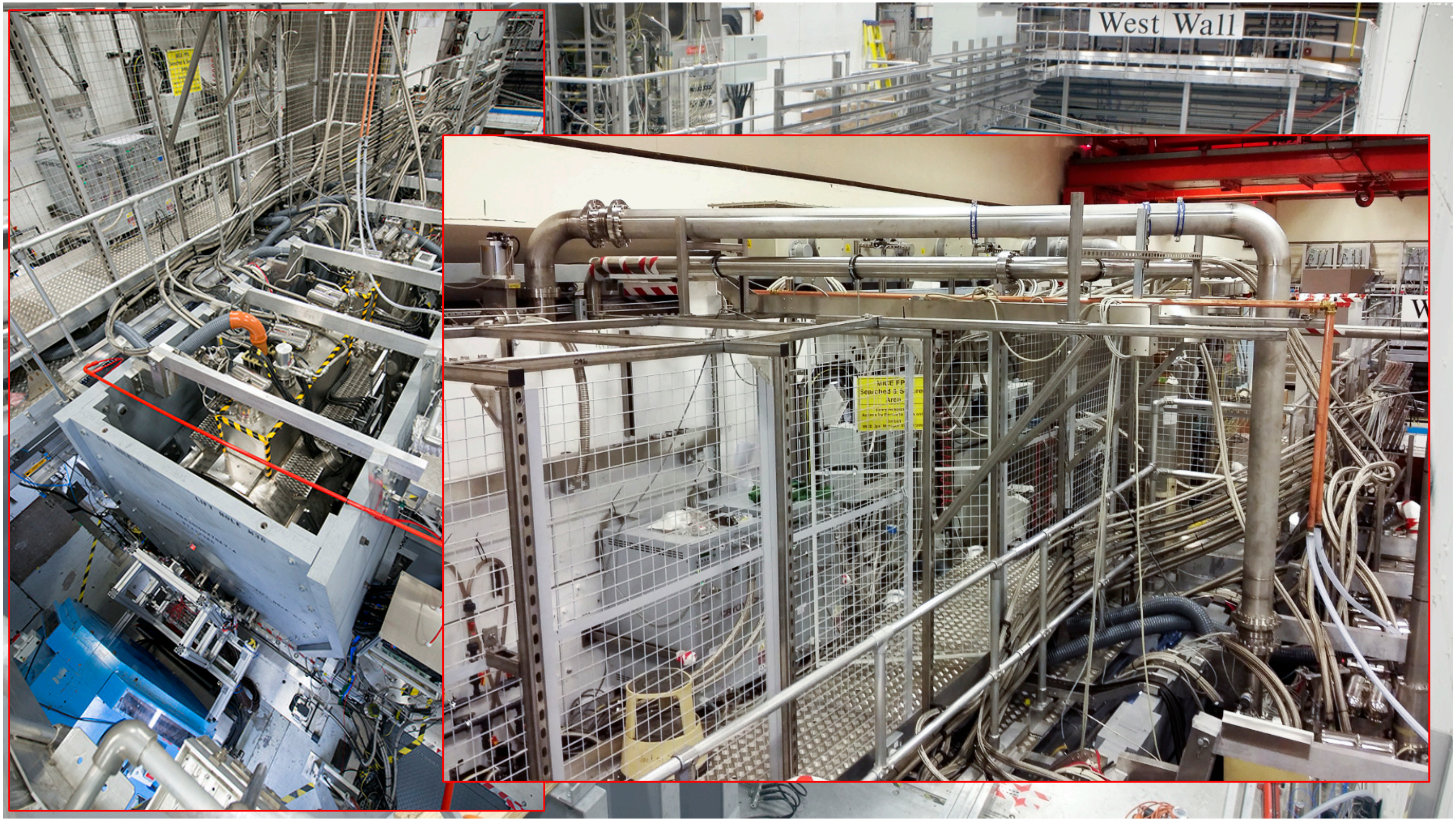
Rejection of decays:

- TOF2
- KLOE Light 'preshower' (KL)
- Electron Muon Ranger (EMR)

'*e*-tag' efficiency w\ EMR: > 98.6%

Transverse phase space measurement:

- Scintillating-fiber trackers
- Spectrometer solenoids

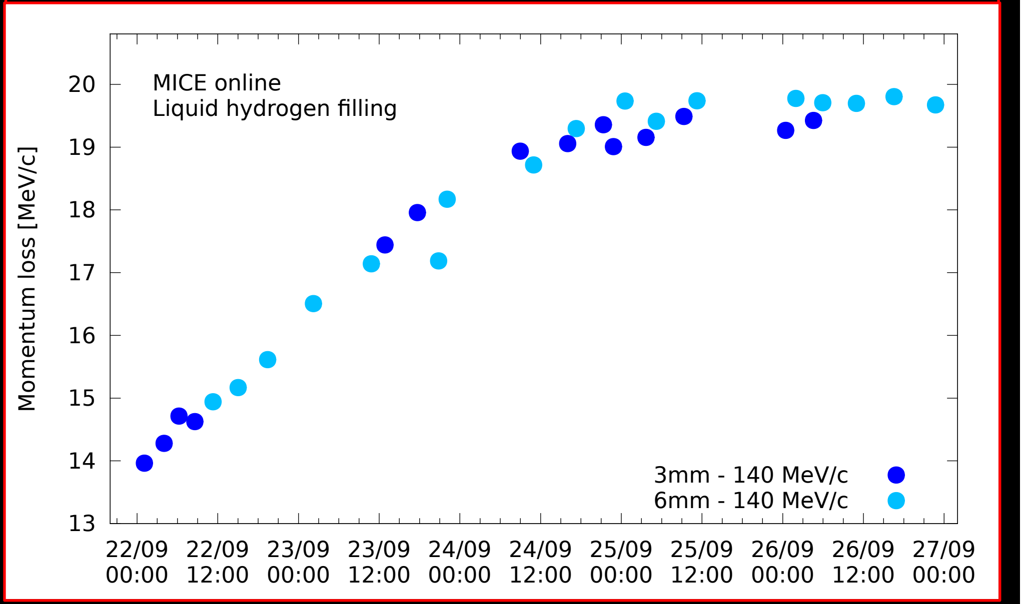

West Wall
MICE FP

Liquid-hydrogen absorber

Online reconstruction:

Mean momentum lost by muons as they pass through the liquid-hydrogen absorber.

The data were recorded while the absorber was filling.



Characterisation of the cooling equation

- Evolution of normalized transverse emittance:

$$\frac{d\varepsilon_T}{ds} \approx -\frac{\varepsilon_T}{\beta_R^2 E}\left\langle\frac{dE}{ds}\right\rangle + \frac{\beta_T\,(13.6\mathrm{MeV})^2}{2\beta_R^3 E m_\mu X_0}$$

Analagous to SR cooling

  - Measured dependence on:
    - Input emittance:
      - Vary beam optics/diffuser;
    - Material:
      - Absorber LH2; LiH ←
    - *p*, *E* and β:
      - Vary beam momentum, optics

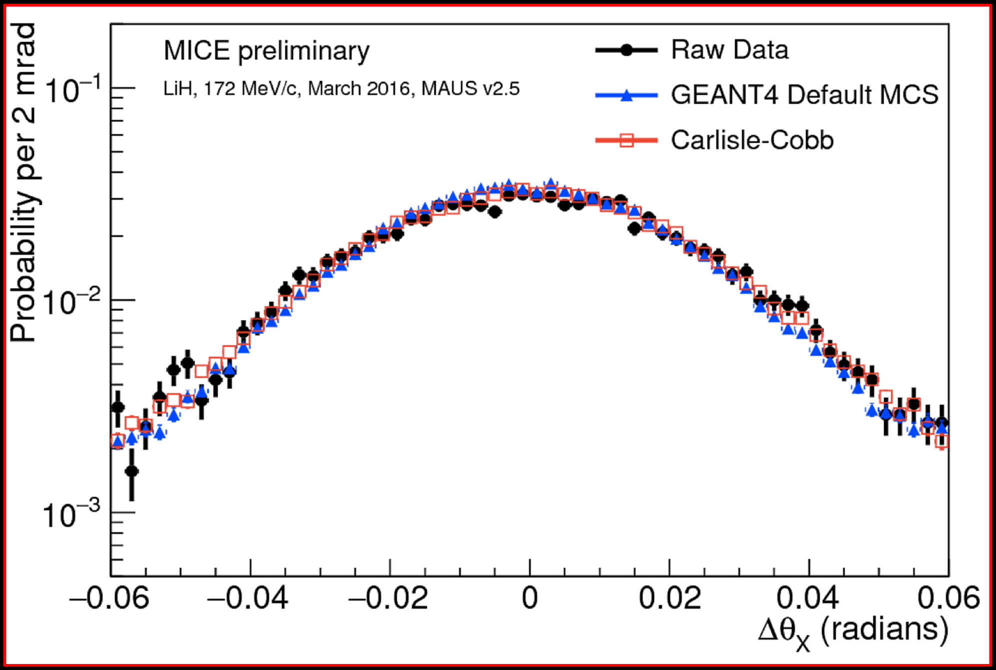
Absorbers:

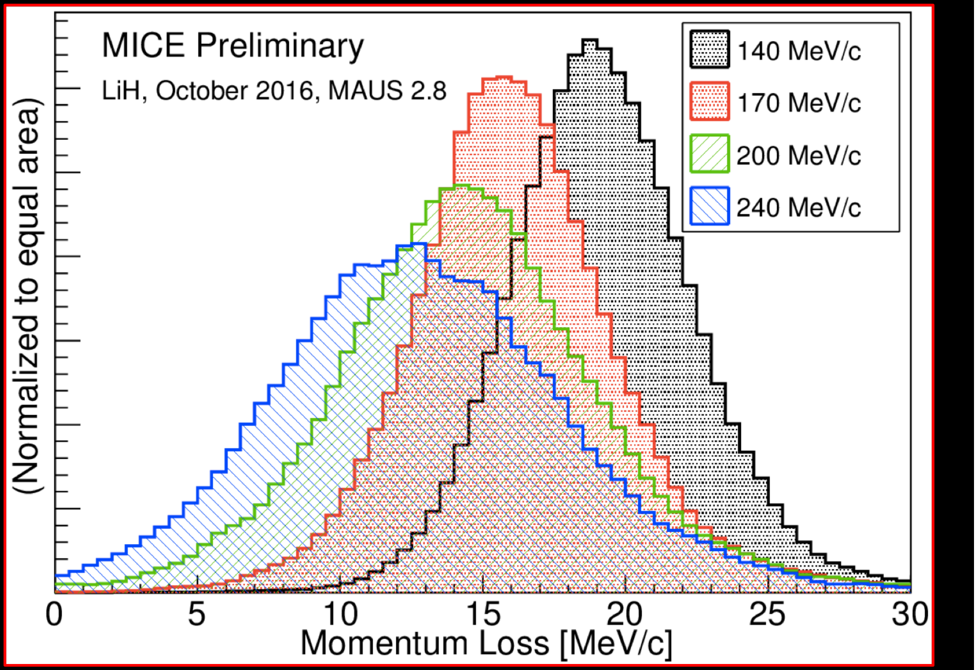
65 mm thick lithium hydride disk

350 mm thick liquid hydrogen vessel

45° polythene wedge absorber

Measurement of muon-LiH scattering

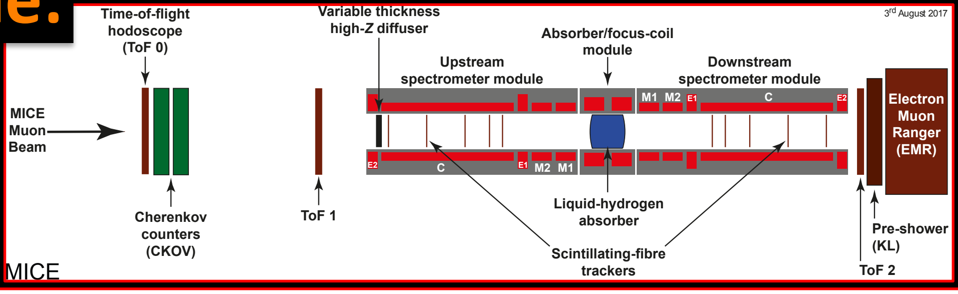


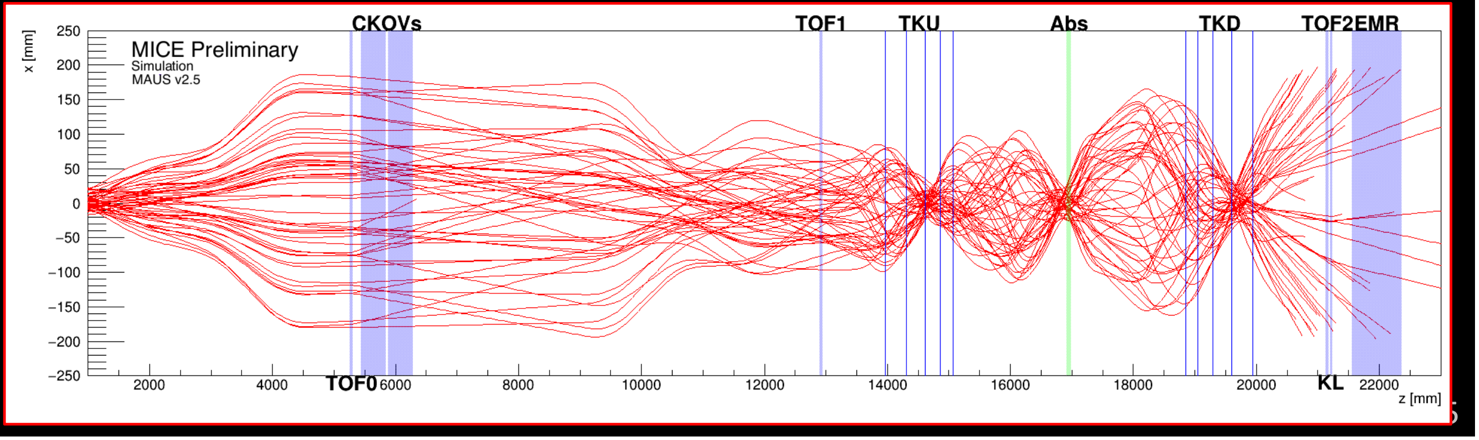


- Precision measurement of MCS
- Validate consistency of energy-loss model

Single-particle technique

- Powerful! Fully measure one muon at a time:
  - – Fast instrumentation, matched to beam intensity:
    - Measure all 6D phase-space coordinates of each muon
  - – Build muon ensemble offline:
    - Calculate ensemble properties
      - – E.g. ε_T

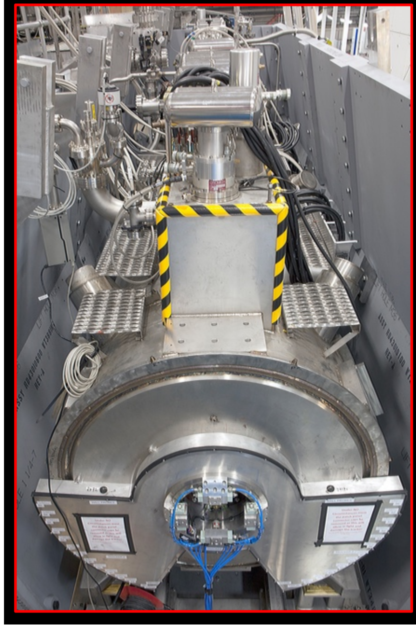


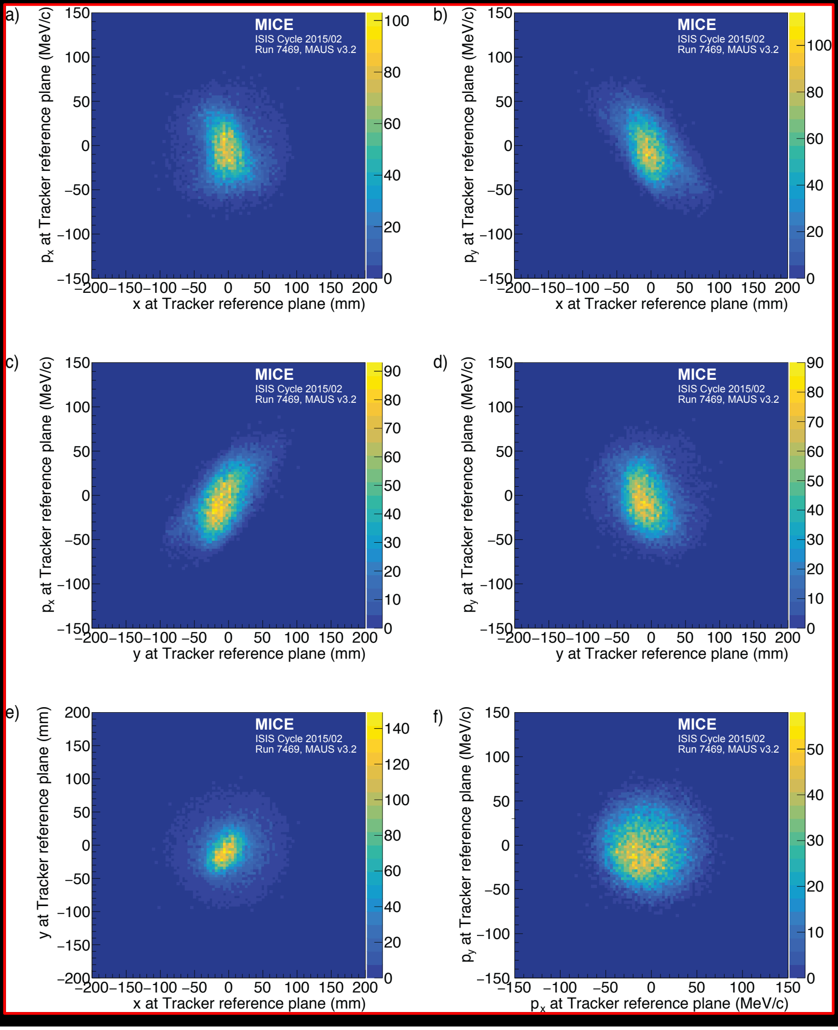


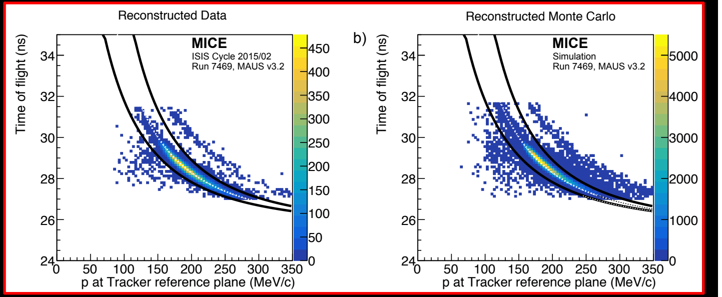
Emittance determination

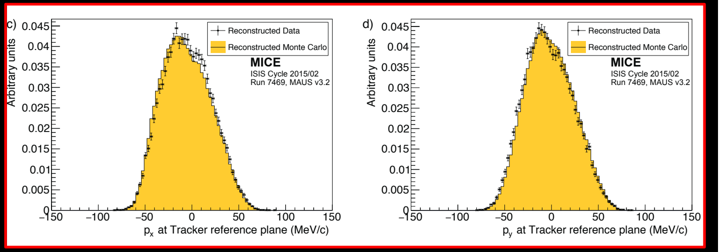
Phase space: $\mathcal{P} = (x, p_x, y, p_y)^{\mathrm{T}}$
Covariance: $\mathcal{C} = \langle \Delta\mathcal{P}\Delta\mathcal{P}^{\mathrm{T}} \rangle$

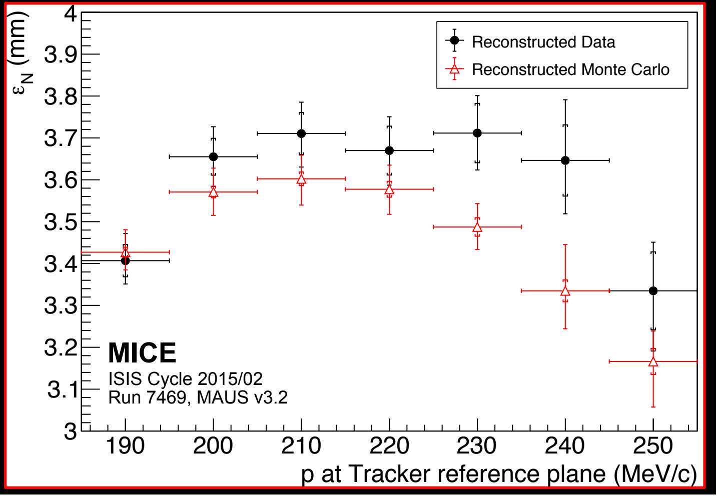
Emittance: $\varepsilon_T = \frac{|\mathcal{C}|^{\frac{1}{4}}}{m_\mu}$



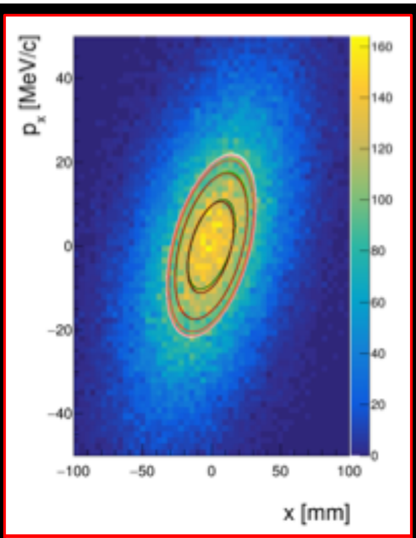


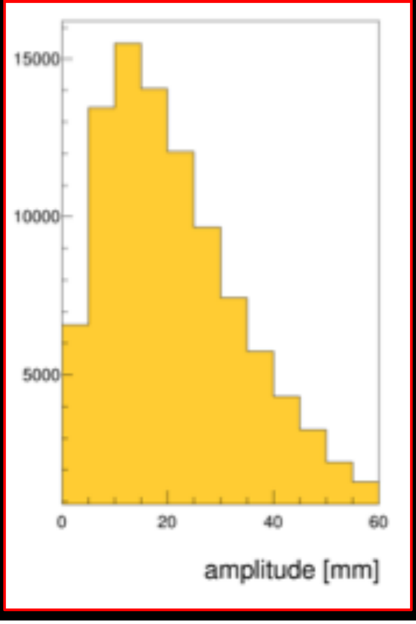






Emittance and amplitude





Phase space, covariance, emittance and amplitude

Phase space: $\mathcal{P} = (x, p_x, y, p_y)^{\mathrm{T}}$

Covariance: $\mathcal{C} = \left\langle \Delta\mathcal{P}\Delta\mathcal{P}^{\mathrm{T}} \right\rangle$

Normalised transverse emittance: $\varepsilon_T = \frac{|\mathcal{C}|^{\frac{1}{4}}}{m_\mu}$

Transverse amplitude: $A_T = \varepsilon_T \mathcal{P}^{\mathrm{T}}\mathcal{C}^{-1}\mathcal{P}$

- **Emittance:**
  - Evaluated from RMS beam ellipse
- **Amplitude:**
  - Distance from core of beam
- **Mean amplitude ~ RMS emittance**

Effect of the absorber

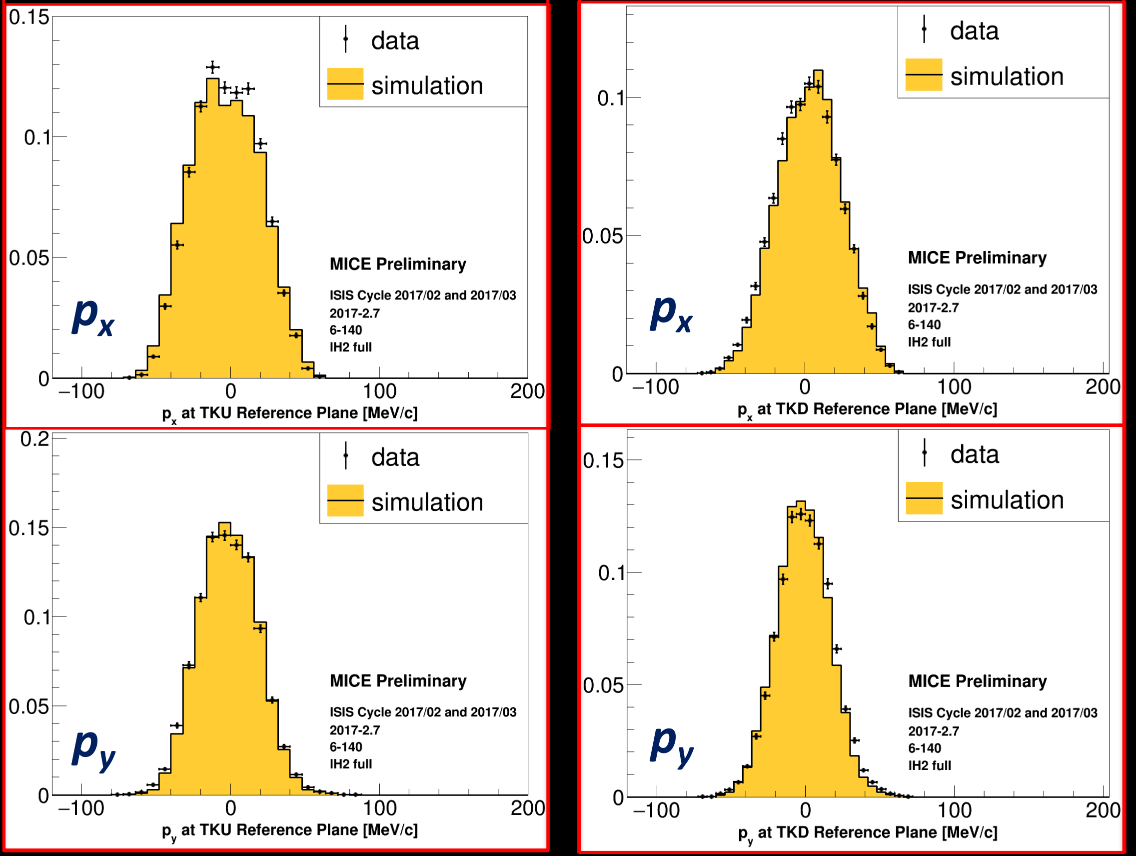
Simulation in good agreement with data

- Example:
  - ε_T = 6 mm
  - P = 140 MeV/c

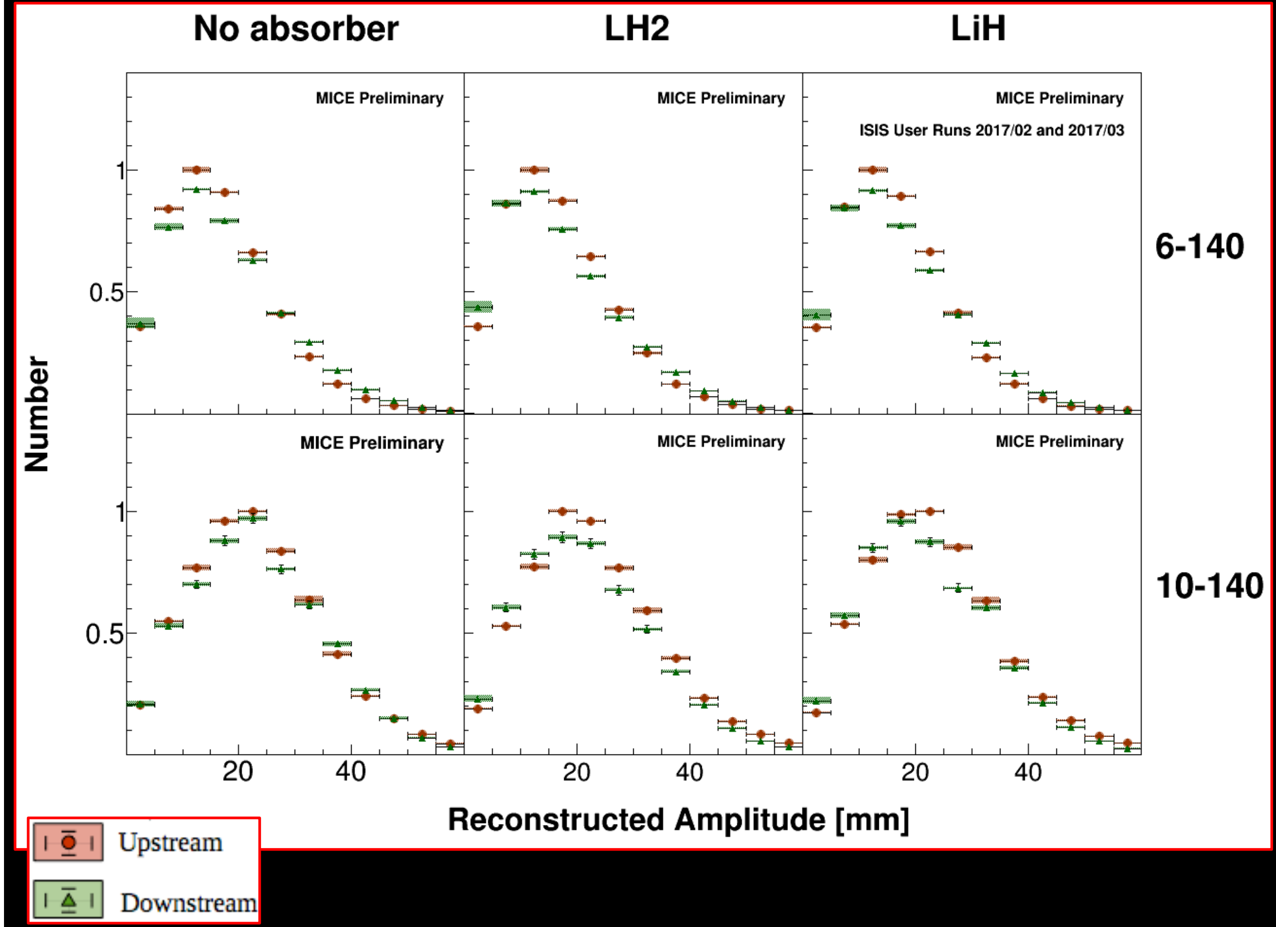
Notation: P-ε_T = 6-140

Upstream

Downstream



Change in amplitude across absorber

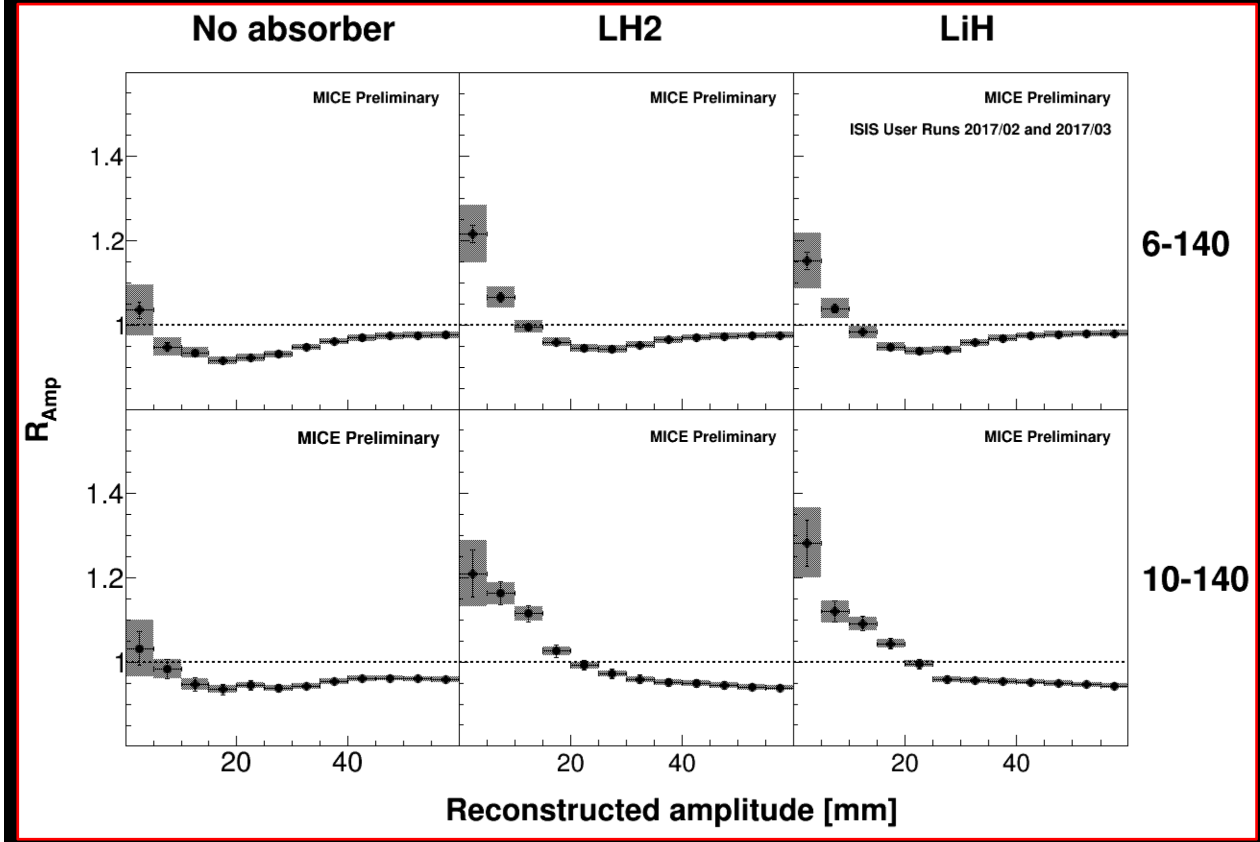


Muons in beam core:

- ***Decrease** with no absorber*
- ***Increase*** **with LiH and LH2 absorbers**

Ionization-cooling signal

Core-density change across absorber



R_{amp} = ratio of cumulative density downstream to upstream

Core-density:

- *Increases* with LiH and LH2 absorbers
- *Consistent with 'no change'* for no absorber

Ionization-cooling signal

Paper in preparation

Progress on Muon Ionization Cooling with MICE

NEXT STEPS

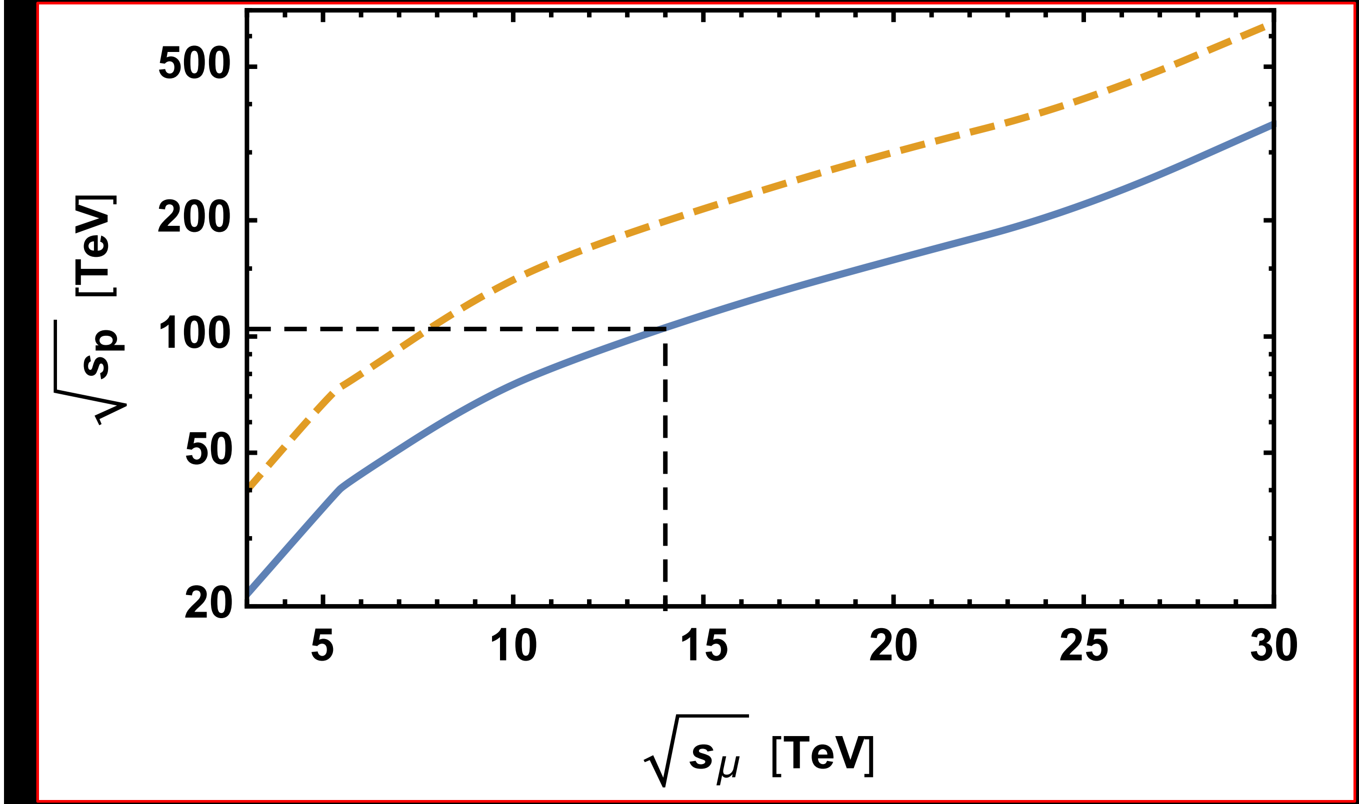
Next steps in study of ionization cooling

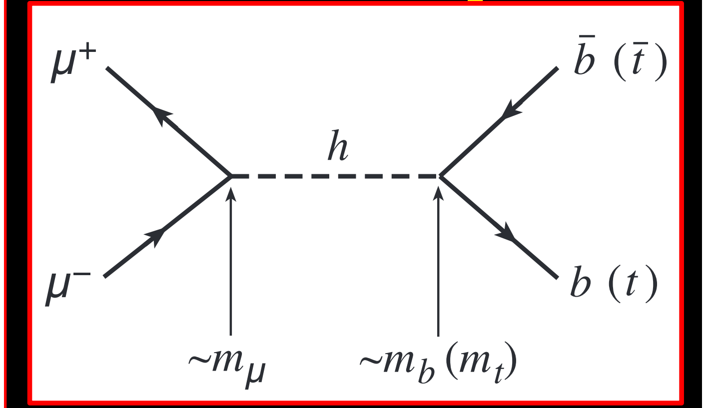
- MICE has:
  - Demonstrated principle of 4D ionization cooling
- Analysis of MICE data will:
  - Measure the factors that determine the ionization-cooling effect
  - Study ionization cooling as a function of:
    - Input beam emittance and momentum;
    - Lattice optics and absorber material (LiH and LH2);
  - Study emittance exchange with wedge absorber

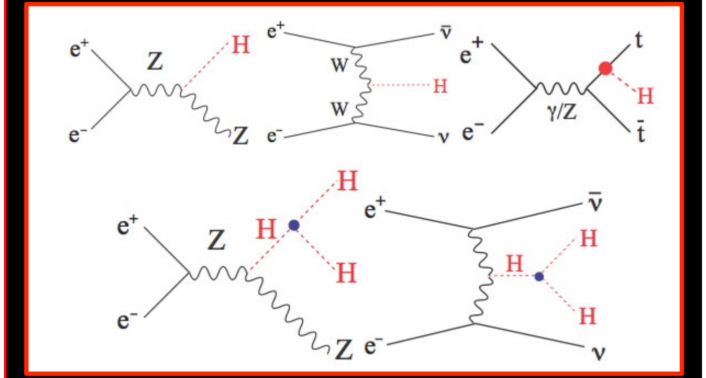
- Ambitious next step:
  - Design and implement a 6D cooling experiment
    - Essential R&D for development of multi-TeV muon collider
  - Such a demonstration could be performed at nuSTORM

Thank you

The Standard Model and beyond

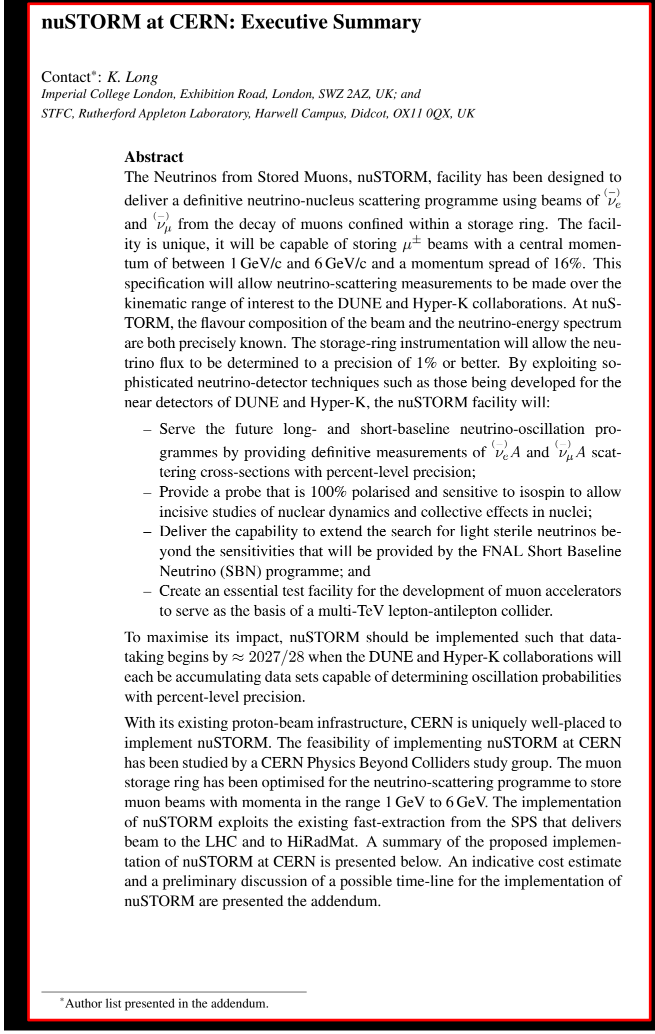






- Energy frontier: big advantage over pp because fundamental fermion
- Future study of the Higgs:
  - Line width; establish single resonance (?) in s-channel with $\mu^+\mu^-$
  - Couplings; requires > 1 TeV for complete, precise study

European Strategy for Particle Physics Update



nuSTORM at CERN: Executive Summary

Contact*: *K. Long*
Imperial College London, Exhibition Road, London, SW2 2AZ, UK; and
STFC, Rutherford Appleton Laboratory, Harwell Campus, Didcot, OX11 0QX, UK

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.

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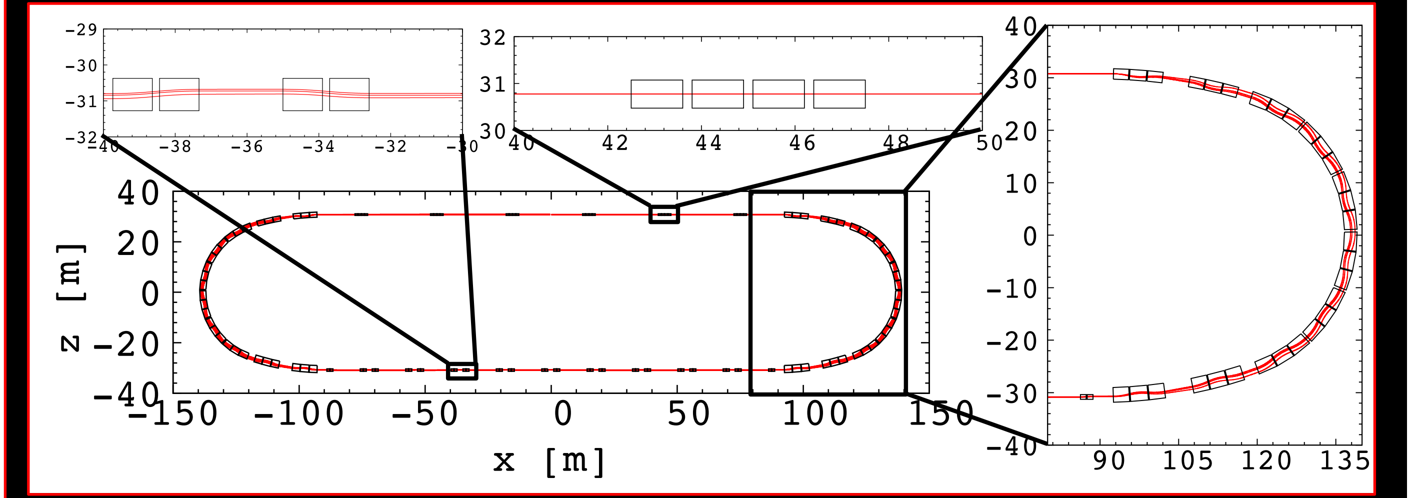
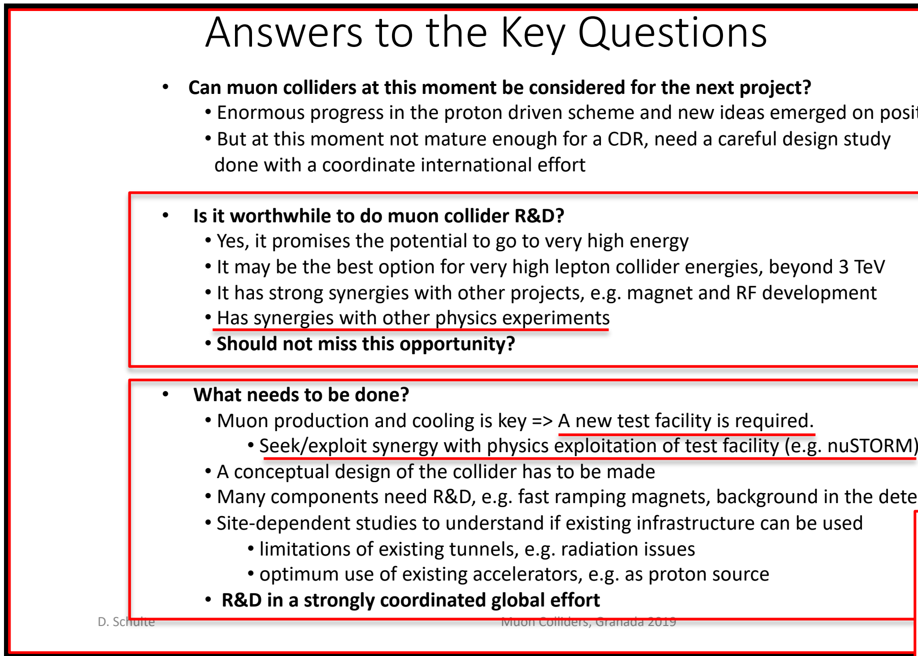
[*] Author list presented in the addendum.



Americas:	29
Asia:	7
Europe:	81
Total:	***117***

Muon collider

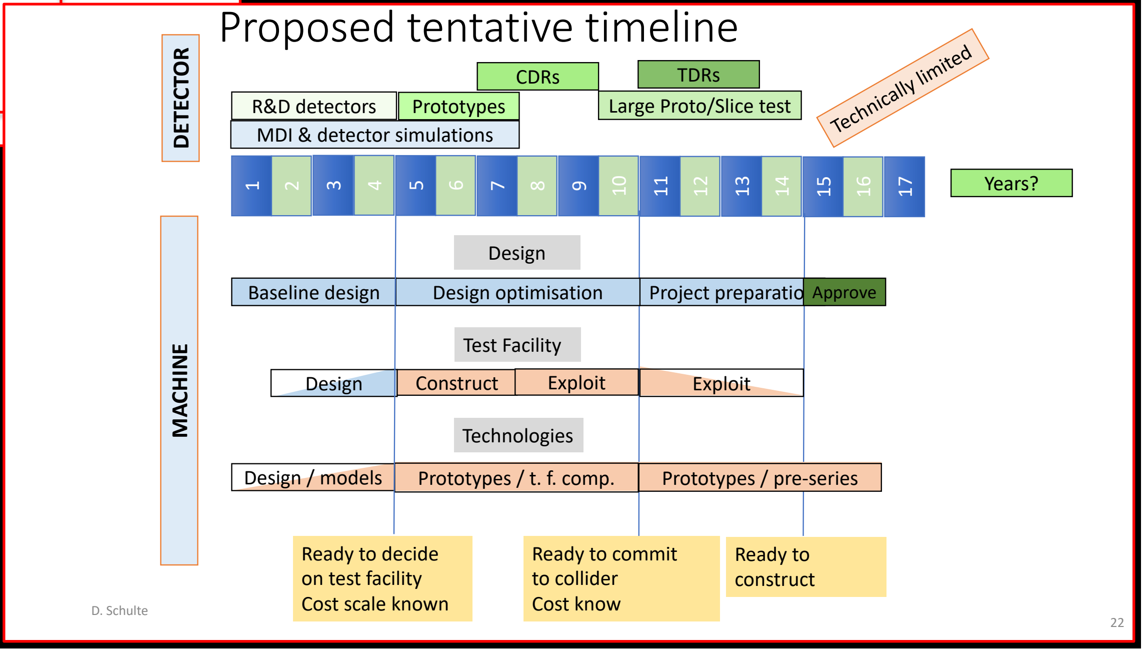


Answers to the Key Questions

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged on positron one
  - But at this moment not mature enough for a CDR, need a careful design study done with a coordinate international effort

- **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.
    - Seek/exploit synergy with physics exploitation of test facility (e.g. nuSTORM)
  - 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
  - **R&D in a strongly coordinated global effort**



Proposed tentative timeline

Ready to decide on test facility Cost scale known

Ready to commit to collider Cost know

Ready to construct

European Strategy Update

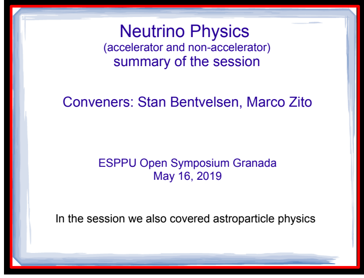
Accelerators summary

Caterina Biscari and Lenny Rivkin, Phil Burrows, Frank Zimmermann

Open Symposium towards updating the European Strategy for Particle Physics

May 13-16, 2019, Granada, Spain

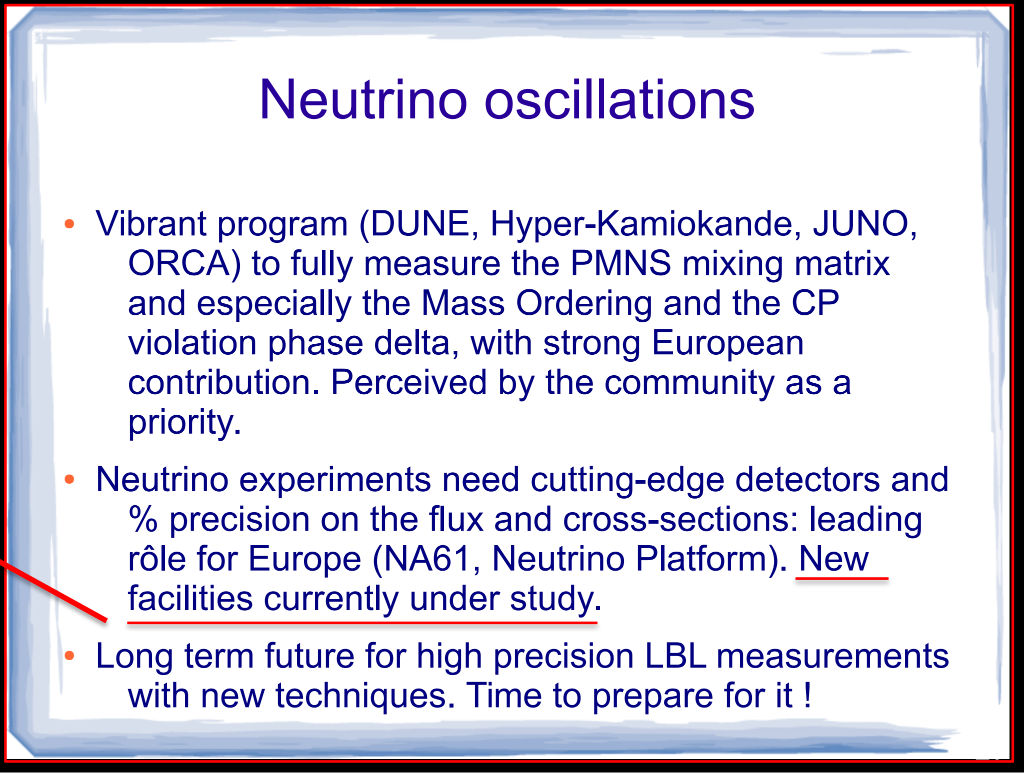
Neutrinos


Neutrino Physics
(accelerator and non-accelerator)
summary of the session

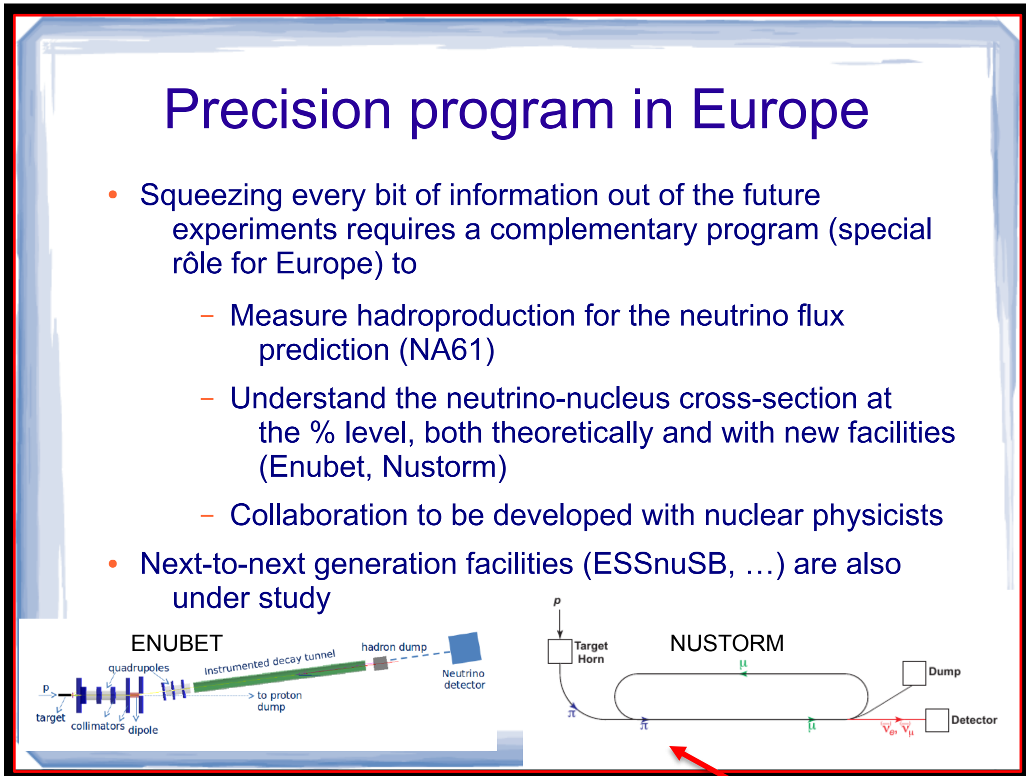
Conveners: Stan Bentvelsen, Marco Zito

ESPPU Open Symposium Granada
May 16, 2019

In the session we also covered astroparticle physics

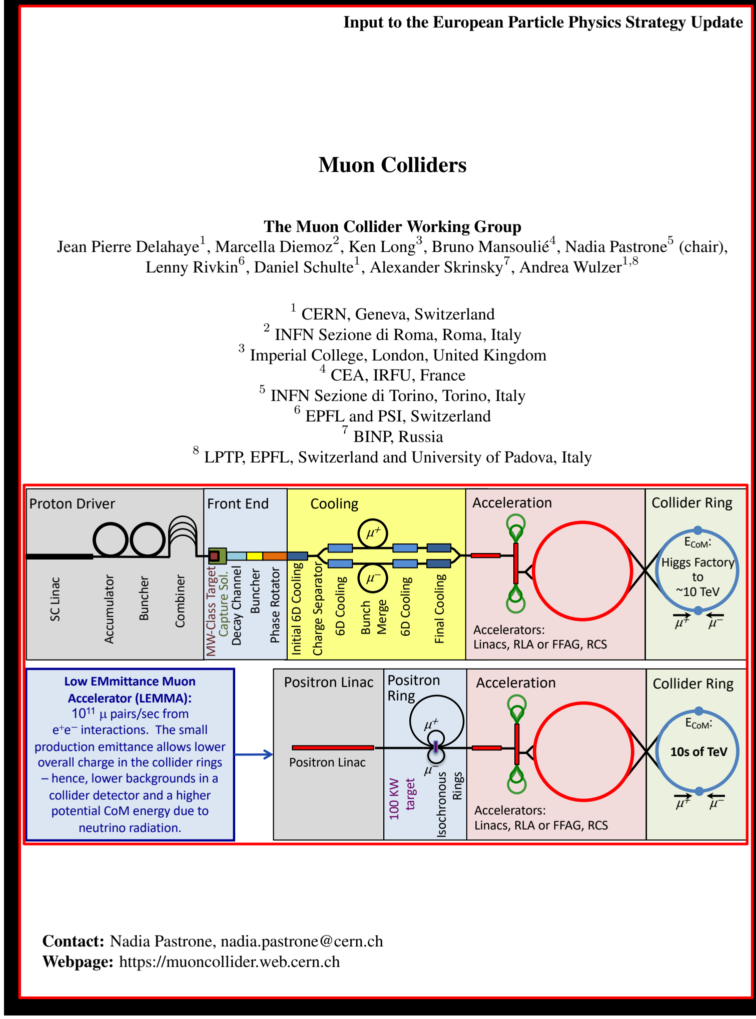

Neutrino oscillations

- Vibrant program (DUNE, Hyper-Kamiokande, JUNO, ORCA) to fully measure the PMNS mixing matrix and especially the Mass Ordering and the CP violation phase delta, with strong European contribution. Perceived by the community as a priority.
- Neutrino experiments need cutting-edge detectors and % precision on the flux and cross-sections: leading rôle for Europe (NA61, Neutrino Platform). New facilities currently under study.
- Long term future for high precision LBL measurements with new techniques. Time to prepare for it !


Precision program in Europe

- Squeezing every bit of information out of the future experiments requires a complementary program (special rôle for Europe) to
  - Measure hadroproduction for the neutrino flux prediction (NA61)
  - Understand the neutrino-nucleus cross-section at the % level, both theoretically and with new facilities (Enubet, Nustorm)
  - Collaboration to be developed with nuclear physicists
- Next-to-next generation facilities (ESSnuSB, …) are also under study

European Strategy for Particle Physics Update



Input to the European Particle Physics Strategy Update

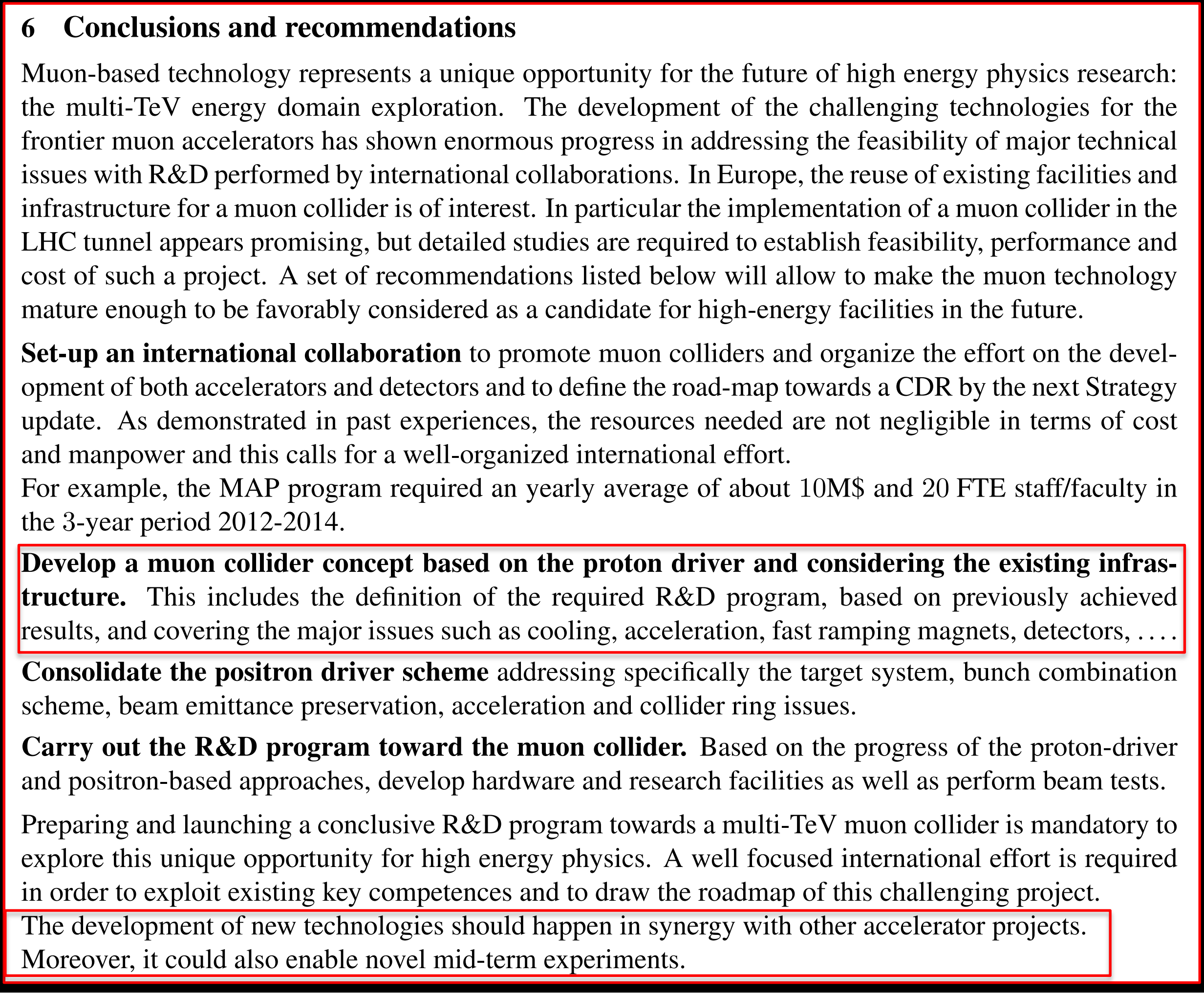
Muon Colliders

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]

[1] CERN, Geneva, Switzerland
[2] INFN Sezione di Roma, Roma, Italy
[3] Imperial College, London, United Kingdom
[4] CEA, IRFU, France
[5] INFN Sezione di Torino, Torino, Italy
[6] EPFL and PSI, Switzerland
[7] BINP, Russia
[8] LPTP, EPFL, Switzerland and University of Padova, Italy

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.

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.

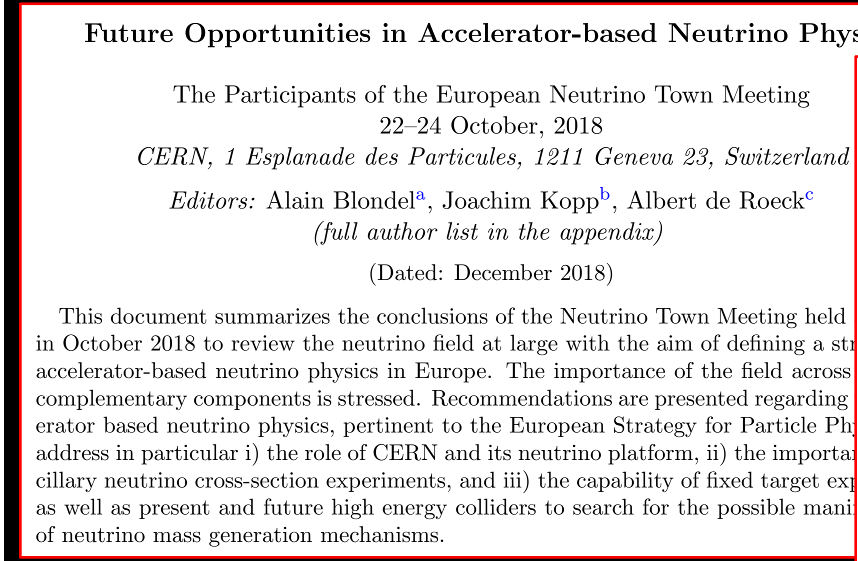
Develop a muon collider concept based on the proton driver and considering the existing infrastructure. This includes the definition of the required R&D program, based on previously achieved results, and covering the major issues such as cooling, acceleration, fast ramping magnets, detectors, ...

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

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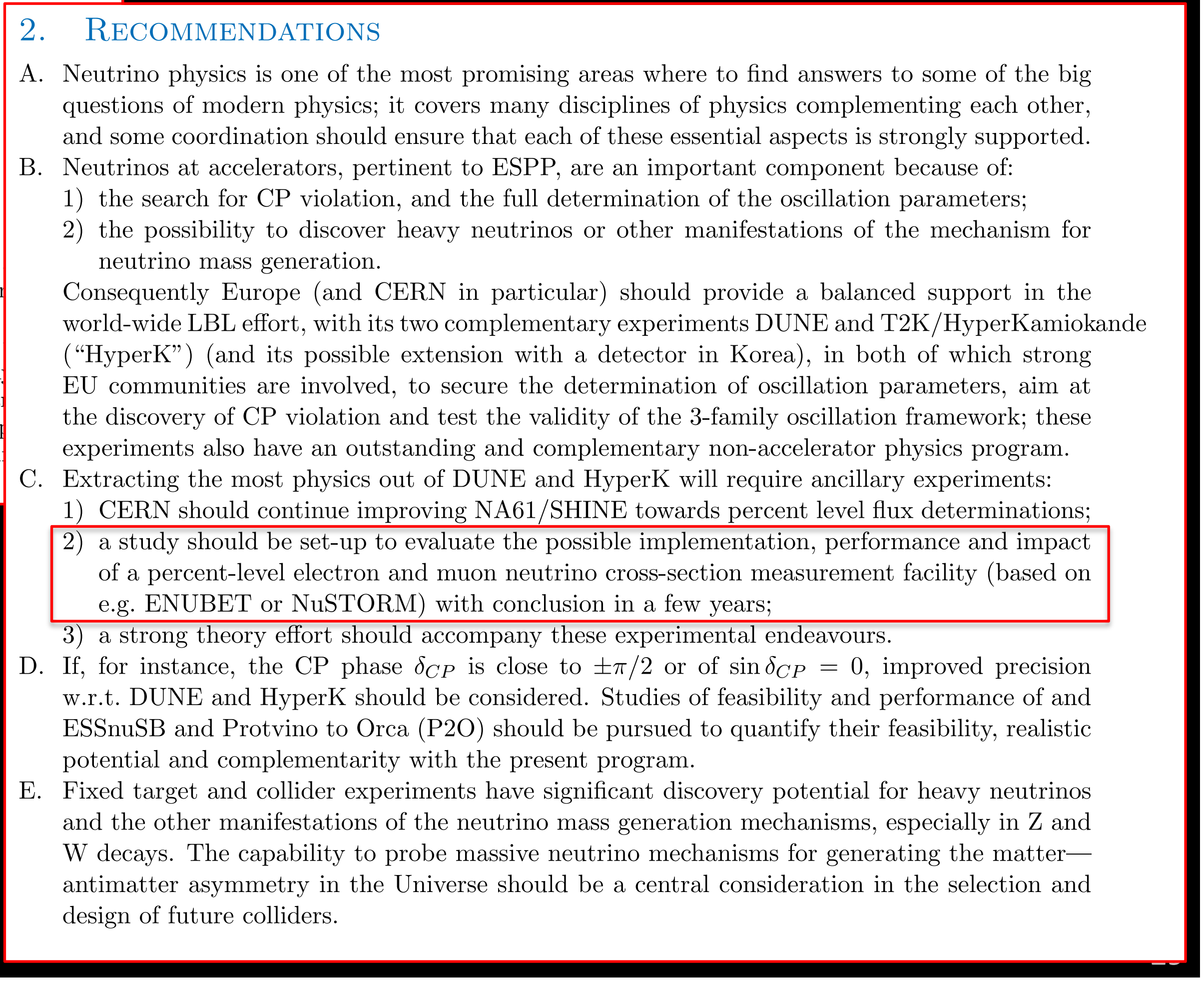
(full author list in the appendix)

(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.