ECFA

European Committee for Future Accelerators

Muon Colliders

towards the highest possible energy

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INFN TORINO

103rd Plenary ECFA @ CERN – November 16th, 2018

Higgs physics potential

Report of the ECFA Chairperson

Towards new discoveries via the Higgs sector

- No clear indication where new physics is hiding, hence experimental observations will have to guide us in our exploration.
- One of the avenues is to explore as fast as possible, and as wide as possible, the Higgs sector.
  - Yukawa couplings
  - Self-couplings (HHH and HHHH)
  - Couplings to Z/W/γ/g
  - Rare SM and BSM decays (H→Meson+γ, Zγ, FCNC, μe/$\tau\mu$/τe, …)
  - CP violation in Higgs decays
  - Invisible decay
  - Mass and width
  - …
- Important progress will be made on Higgs physics with the LHC and the HL-LHC.
- To discover new physics inaccessible to the (HL-)LHC, future colliders will be complementary.

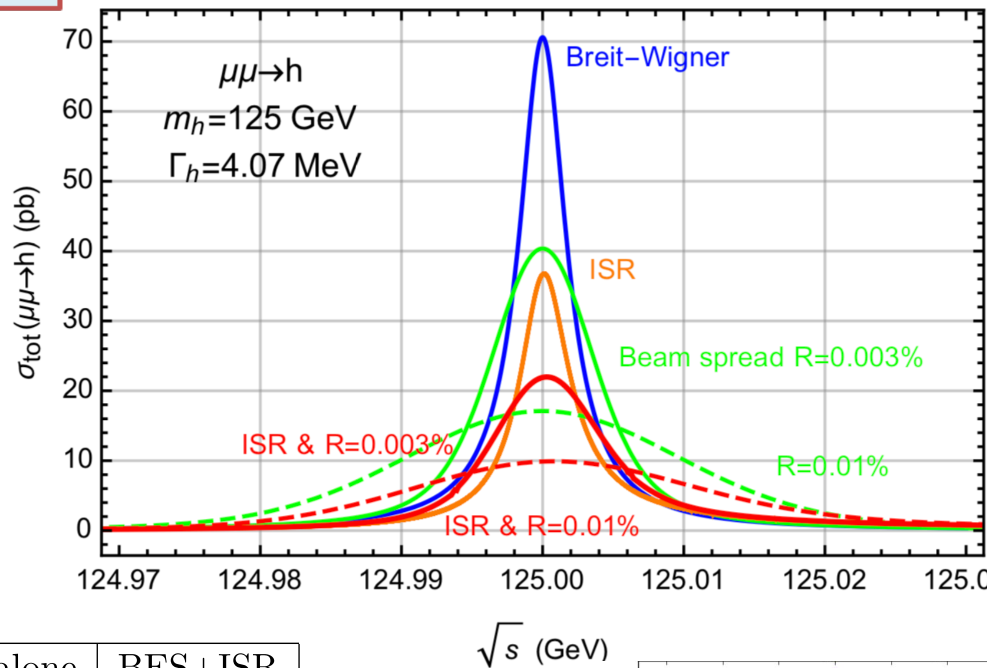
Lepton Colliders: μ vs e @ √s=125 GeV

Back on the envelope calculation:

$$\sigma(\mu^+\mu^- \to H) = \left(\frac{m_\mu}{m_e}\right)^2 \times\sigma(e^+e^- \to H) = \left(\frac{105.7MeV}{0.511\,MeV}\right)^2 \times\sigma(e^+e^- \to H)$$

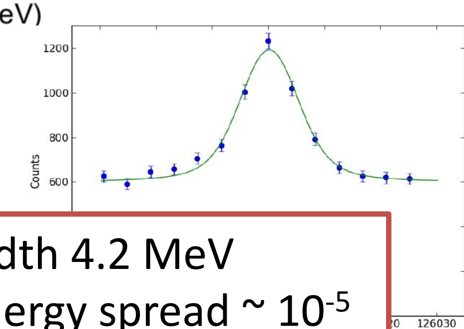
$$\sigma(\mu^+\mu^- \to H) = 4.3\times10^4\times\sigma(e^+e^- \to H)$$

More precise determination
by M. Greco et al. arXiv:1607.03210v2



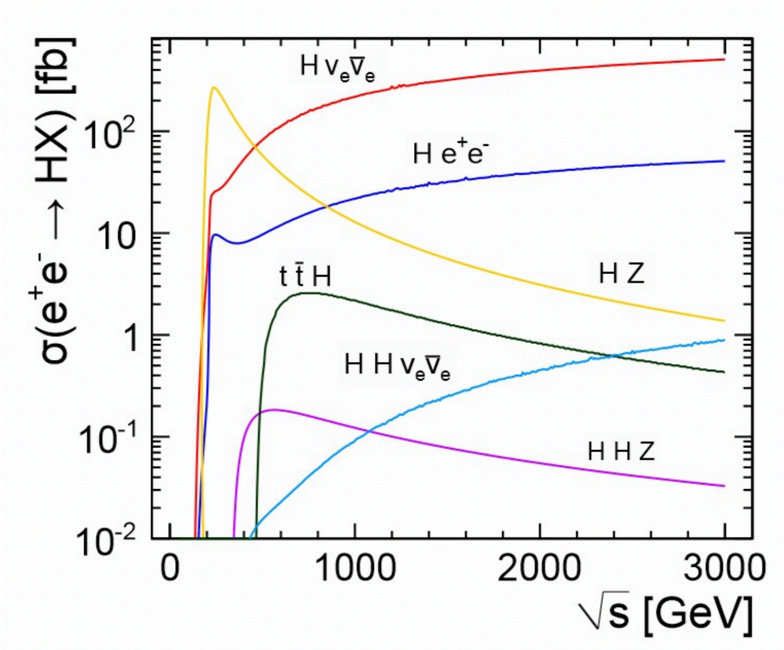
R: percentage beam energy resolution, key parameter

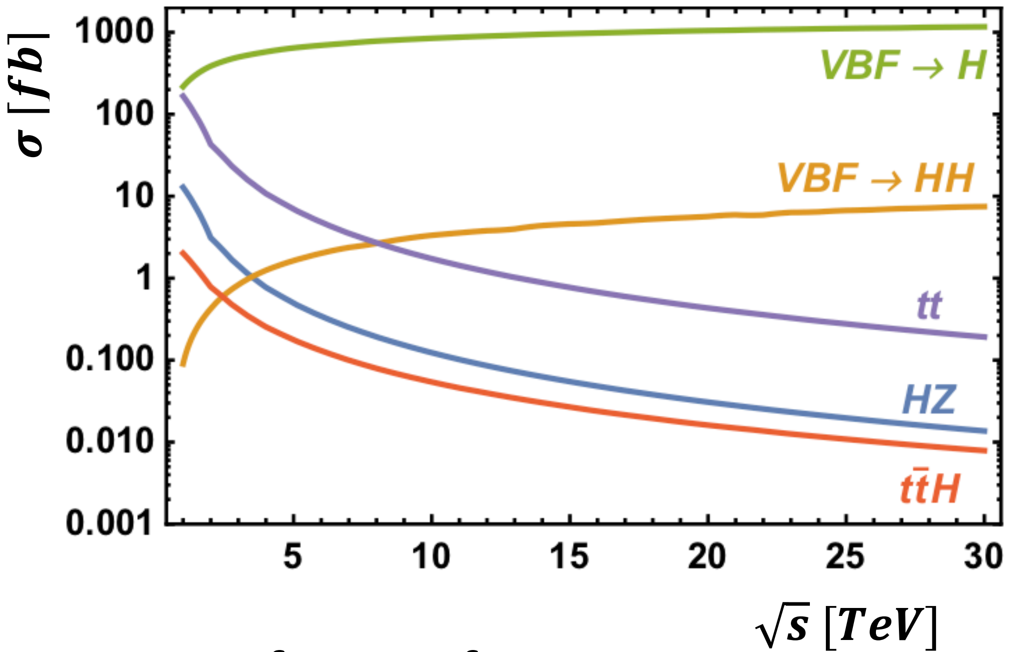
σ(BW)	ISR alone	R (%)	BES alone	BES+ISR
$\mu^+\mu^-$: 71 **pb**	37	0.01	17	10
		0.003	41	22
e^+e^-: 1.7 **fb**	0.50	0.04	0.12	0.048
		0.01	0.41	0.15



Higgs width 4.2 MeV
Beam energy spread ~ 10^{-5}

Higgs production at Lepton Collider





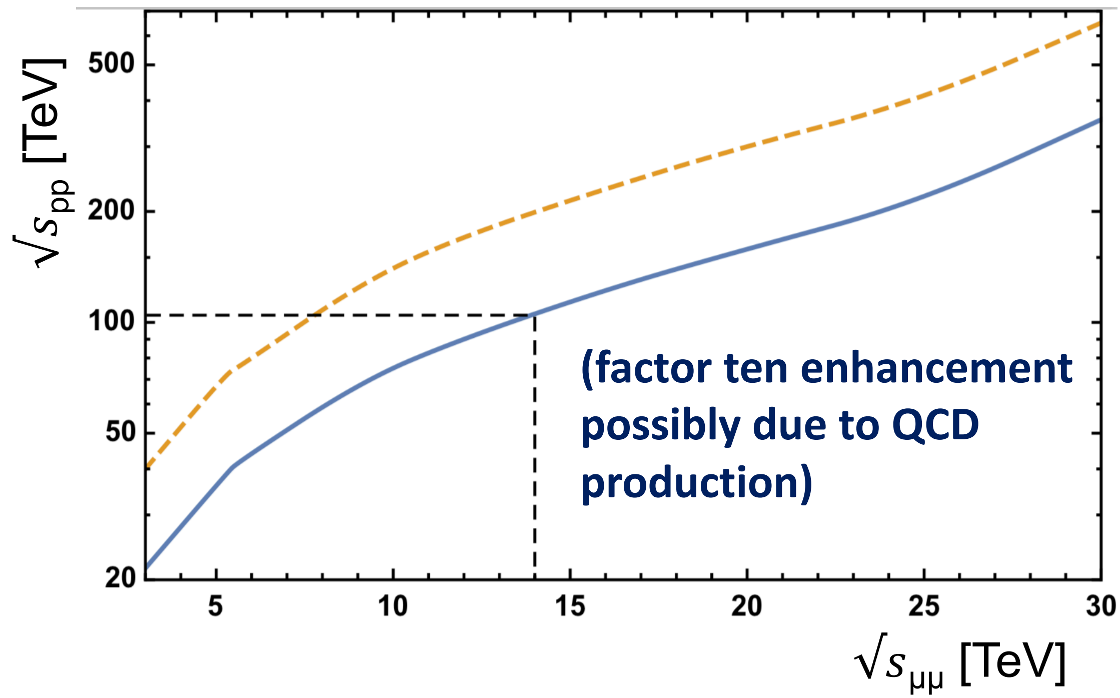
Circular muon colliders

might reach center-of-mass energies of tens of TeV thanks to the limited amount of synchrotron radiation compared to ee colliders

Proton vs Muon Colliders

Cross section comparison for pair production of heavy particles with M ~ ½ $\sqrt{s_{\mu\mu}}$

Muon collider energy $\sqrt{s_{\mu\mu}}$ is entirely available, while proton constituents collide carrying only a fraction of $\sqrt{s_{pp}}$



Equal muon and proton collider cross-sections obtained for $\sqrt{s_{\mu\mu}} \ll \sqrt{s_{pp}}$

➔ **discovery machine for complete exploration of multi-TeV energy scale**

Machine challenges

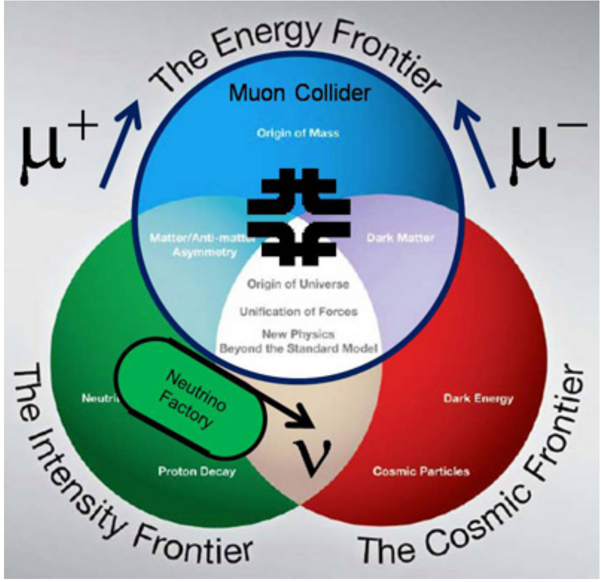
- A $\mu^+\mu^-$ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
  - No synchrotron radiation (limit of e^+e^- circular colliders)
  - No beamstrahlung (limit of e^+e^- linear colliders)
  - but muon lifetime is 2.2 μs (at rest)
- Best performances in terms of luminosity and power consumption

CRUCIAL PARAMETERS:

- luminosity
- energy
- energy spread
- wall power
- cost
- background
- radiological hazard
- technical risks

Physics reach

- Muon rare processes
- Neutrino physics
- Higgs factory
- Multi-TeV frontier



U.S. Muon Accelerator Program (MAP)

- Recommendation from 2008 Particle Physics Project Prioritization Panel (P5)
- Approved by DOE-HEP in 2011
- Ramp down recommended by P5 in 2014

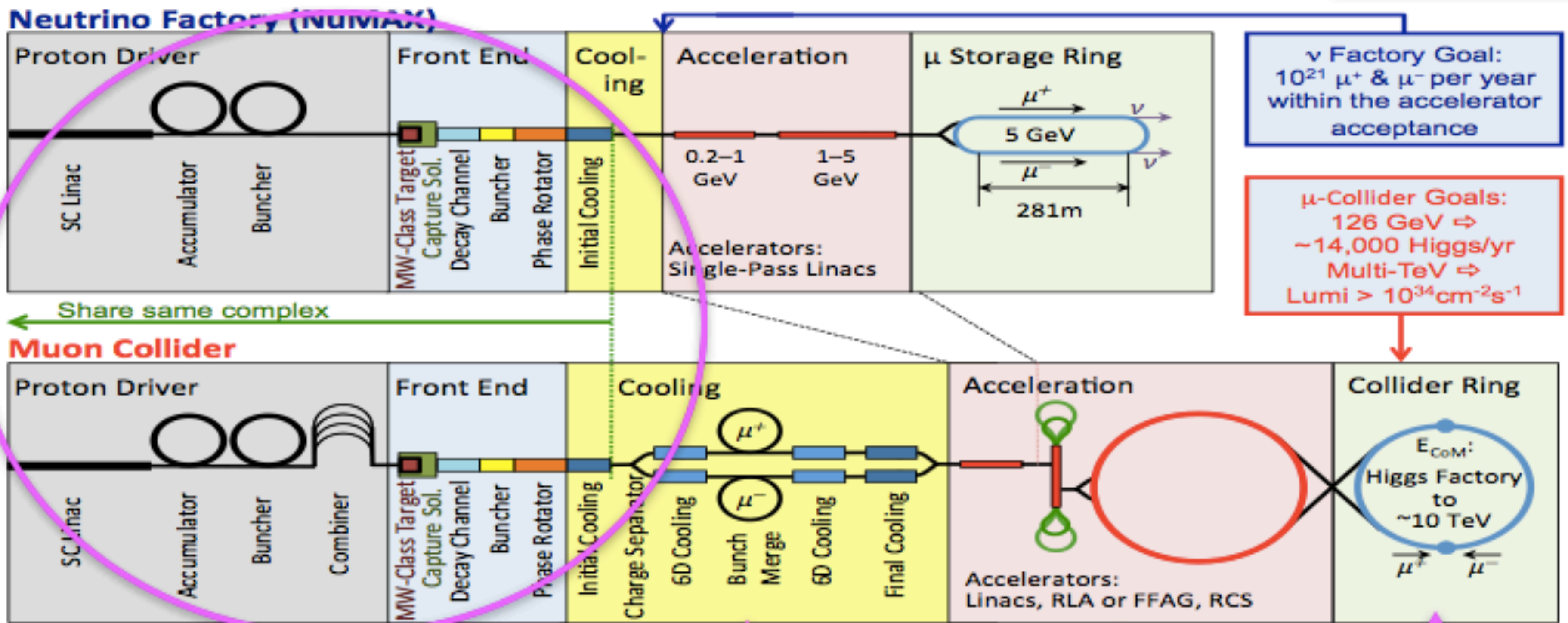
http://map.fnal.gov/

AIM: to assess feasibility of technologies to develop muon accelerators for the Intensity and Energy Frontiers:

- Short-baseline neutrino facilities (nuSTORM)
- Long-baseline neutrino factory (nuMAX) with energy flexibility
- Higgs factory with good energy resolution to probe resonance structure
- TeV-scale muon collider

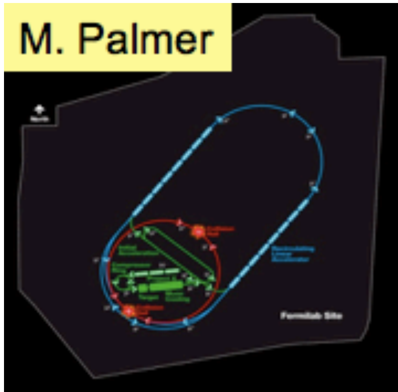
Muon Accelerator Program (MAP)
Muon based facilities and synergies

Mark Palmer



Key Challenges	~10^{13}-10^{14} μ / sec Tertiary particle $p \rightarrow \pi \rightarrow \mu$:	Fast cooling (τ=2μs) by 10^6 (6D)	Fast acceleration mitigating μ decay	Background by μ decay
Key R&D	MW proton driver MW class target NCRF in magnetic field	Ionization cooling High field solenoids (30T) High Temp Superconductor	Cost eff. low RF SC Fast pulsed magnet (1kHz)	Detector/ machine interface

M. Palmer



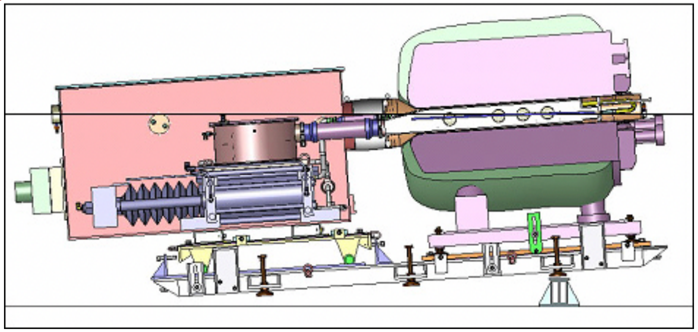
Muon Collider Parameters

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

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

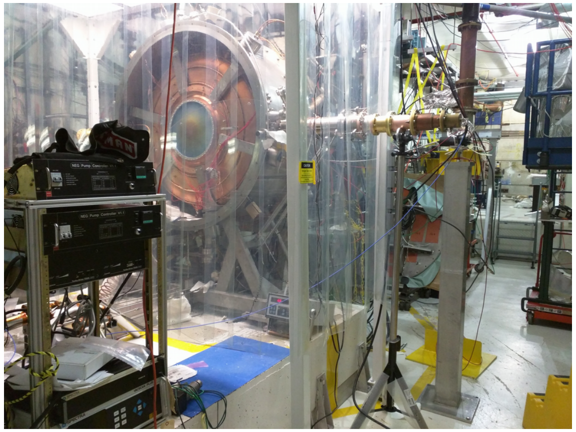
Success of advanced cooling concepts
⇨ several × 10^{32} [Rubbia proposal: 5×10^{32}]

International R&D program



MERIT - CERN

Demonstrated principle of liquid Mercury jet target

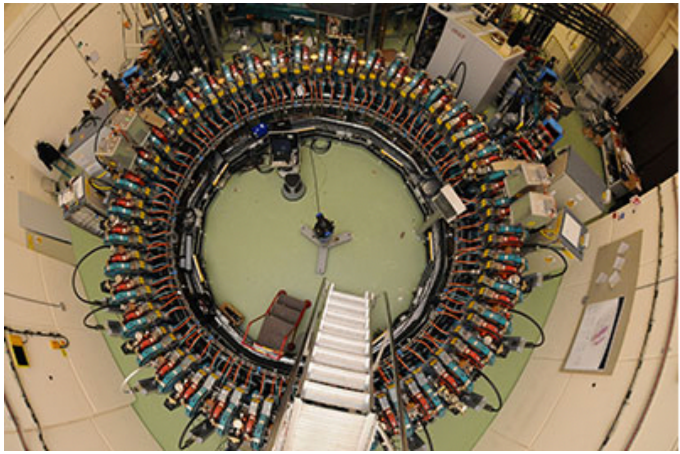


MuCool Test Area - FNAL

Demonstrated operation of RF cavities in strong B fields

EMMA - STFC Daresbury Laboratory

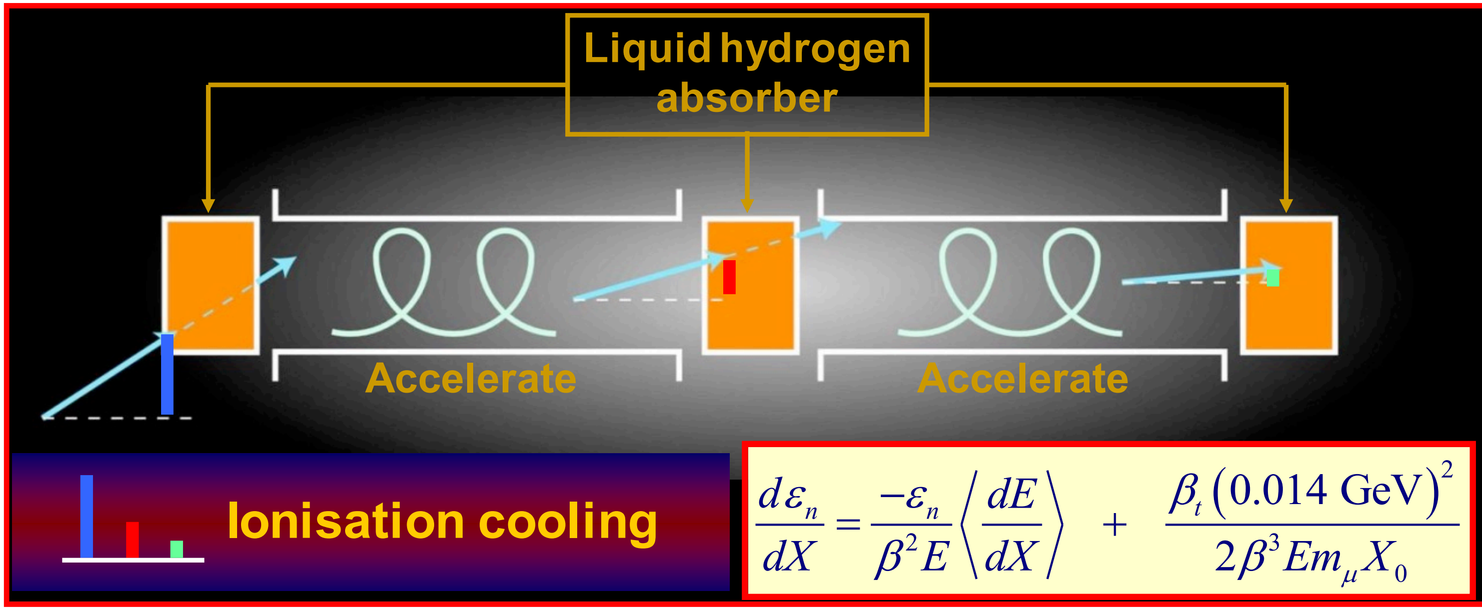
Showed rapid acceleration in non-scaling FFA



MICE - RAL

Demonstrate ionization cooling principle
Increase inherent beam brightness
→ number of particles in the beam core
“Amplitude”

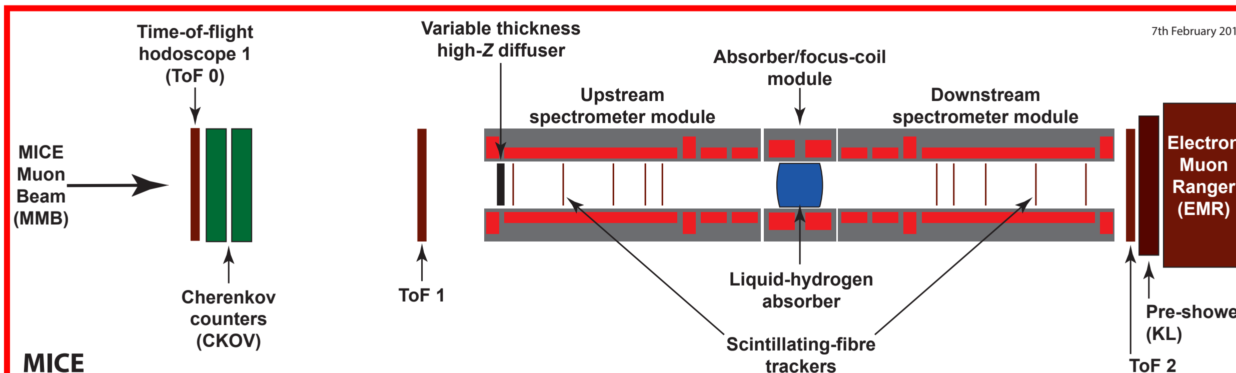
Ionization cooling – MICE experiment



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

Realistic cooling cell

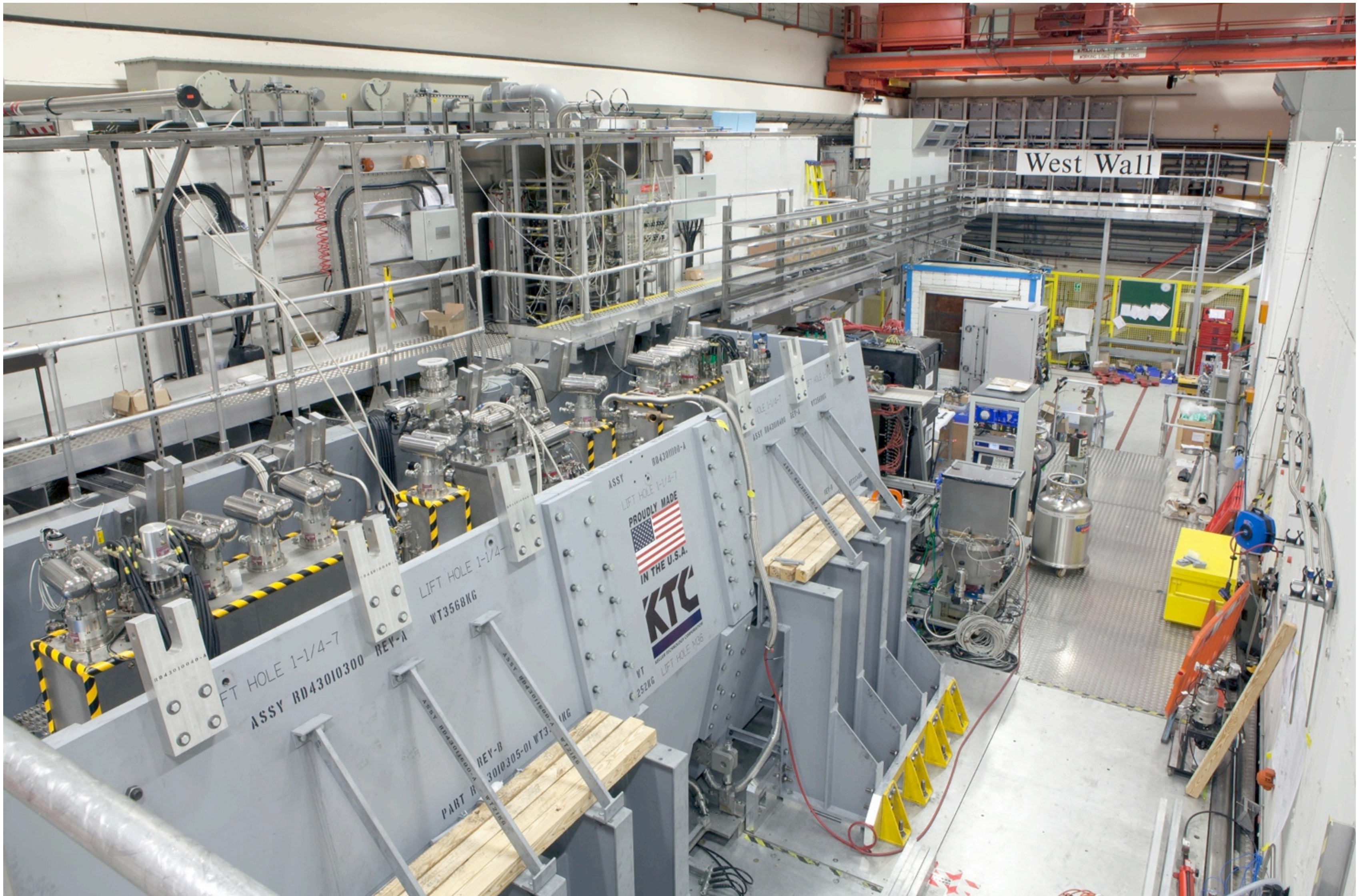
- Competition between:
  - dE/dx [cooling]
  - MCS [heating]
- Optimum:
  - Low *Z*, large X_0
  - Tight focus
  - H_2 gives best performance



He	2	182.9	0.524
Li	3	130.8	0.268
C	6	76.0	0.091
Al	13	38.8	0.024

http://mice.iit.edu/publications/

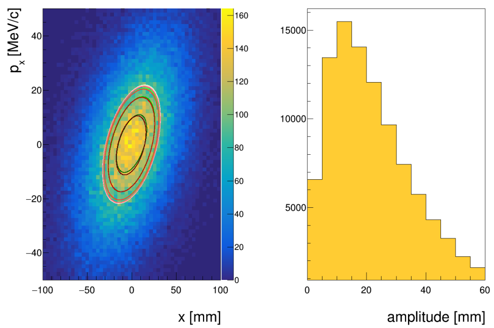
MICE experiment @ RAL

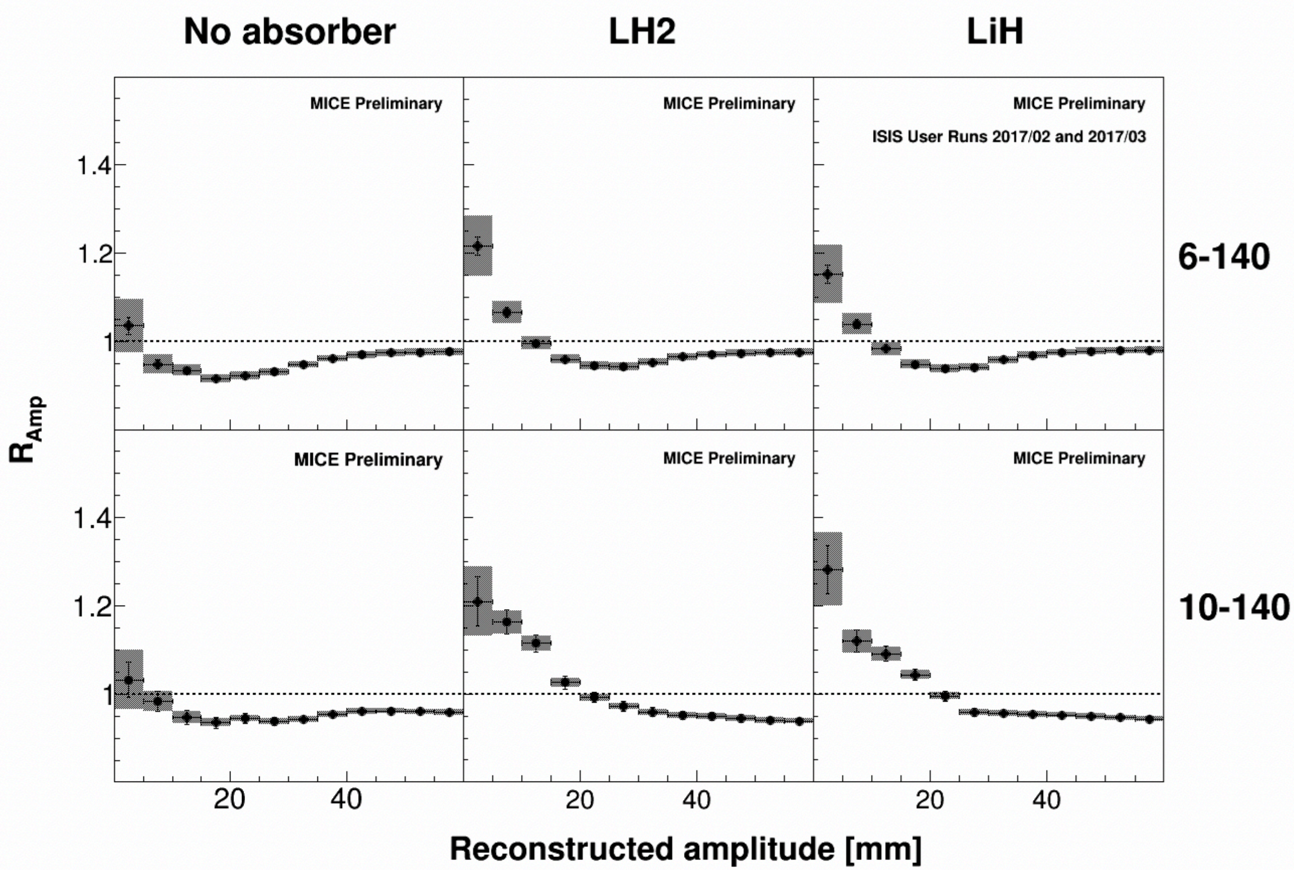


MICE: first results

IPAC2018 – FRXGBE3

Ionization cooling observed: using LiH and LH_2 absorbers





MICE has measured the underlying physics processes that govern cooling

Low EMittance Muon Accelerator

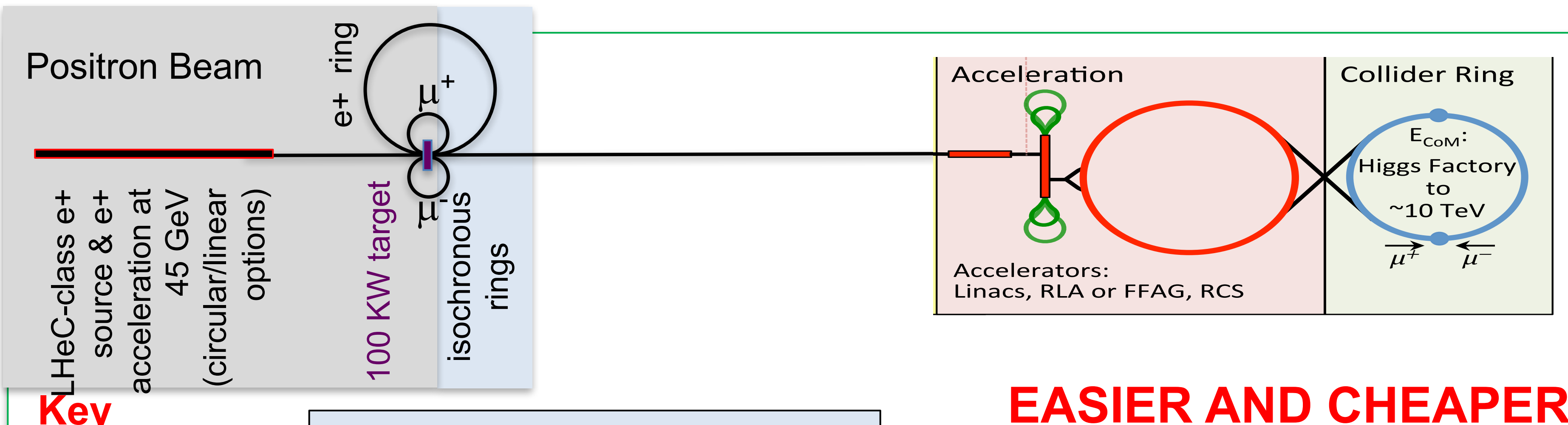
Snowmass 2013 - M. Antonelli e P. Raimondi

Direct μ pair production: muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at √s around the $\mu^+\mu^-$ threshold **(√s~0.212GeV)** in asymmetric collisions (to collect μ^+ and μ^-)

Potential of this idea, but key challenges need to be demonstrated to prove its feasibility ➔ a new proposal for machine studies and measurements

Advantages: **Low emittance possible** **Low background**
Reduced losses from decay **Energy spread**

Disadvantages: **Rate:** $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 1\ \mu b$ at most



Key Challenges

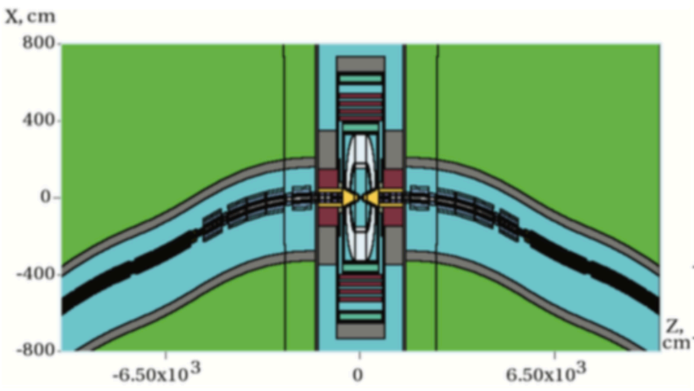
~10^{11} μ / sec from e+e-→μ+μ−

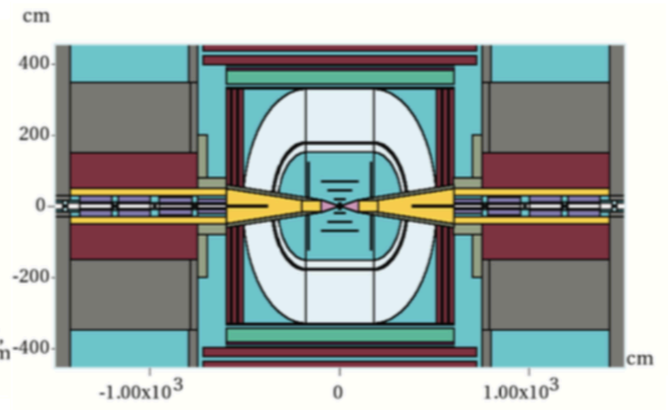
EASIER AND CHEAPER DESIGN, IF FEASIBLE

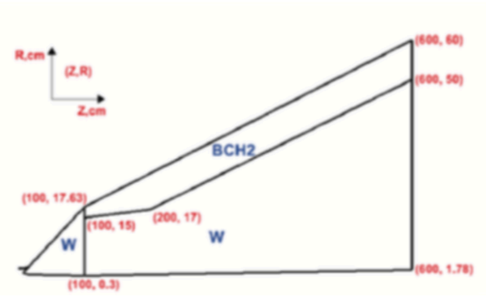
Key R&D

10^{15} e+/sec, 100 kW class target, NON distructive process in e+ ring

Detector and interaction region



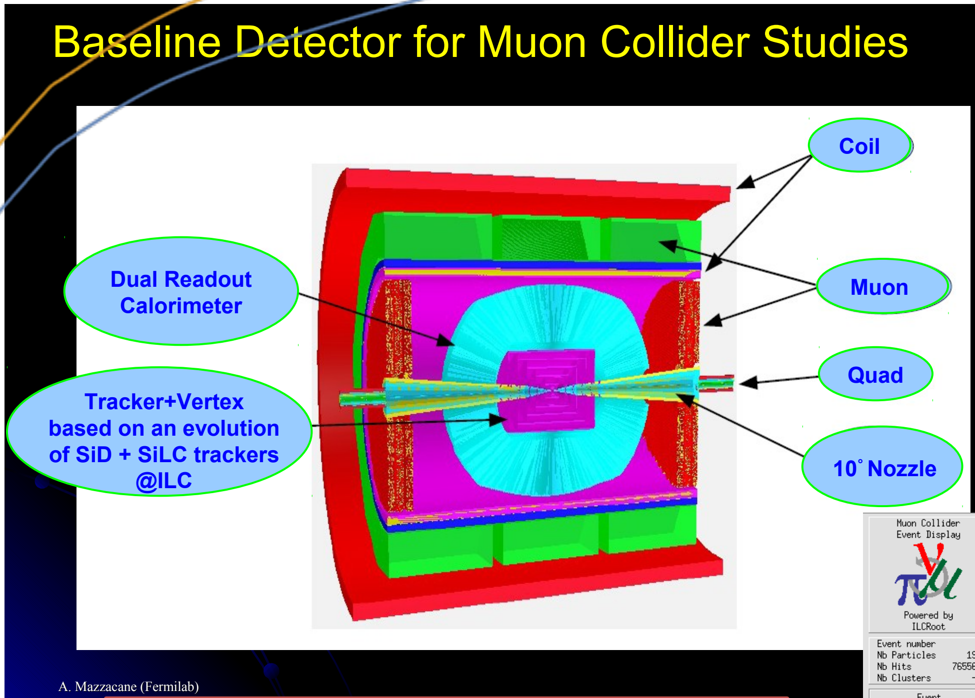




Detailed studies performed by MAP Collaboration for √s=1.5 TeV collider using MAR15 simulation of particle transport and interactions in accelerator, detector and shieldings

N.V. Mokhov, S.I. Striganov *Detector Backgrounds at Muon Colliders*, TIPP 2011, Physics Procedia 37 (2012) 2015 – 2022
N.K. Terentiev, V. Di Benedetto, C. Gatto, A. Mazzacane, N.V Mokhov, S.I. Striganov *ILCRoot tracker and vertex detector hits response to MARS15 simulated backgrounds in the muon collider*, TIPP 2011, Physics Procedia 37 (2012) 104 – 11

Detector challenges



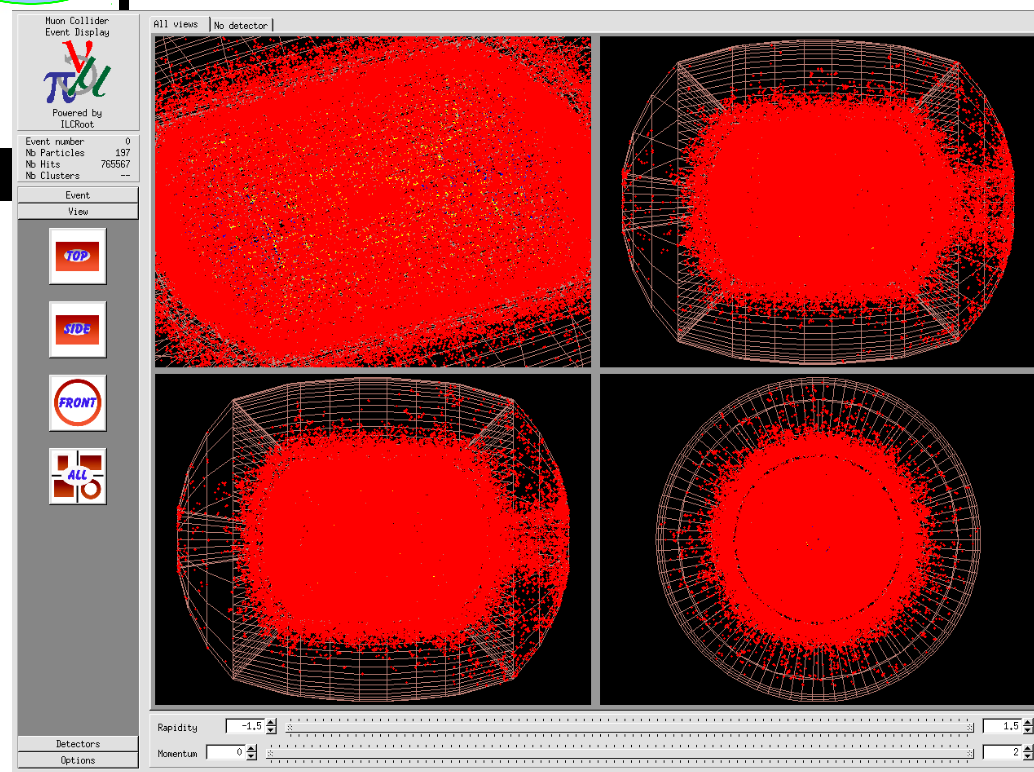
Muon Collider simulation: MAP package

$\mu^+\mu^- \longrightarrow H \longrightarrow b\bar{b}$ Pythia @ √s=125 GeV

Background (MARS somulation)

from muon decays and interaction with machine elements included

No cuts: all hits



Background @ √s=125 GeV is the worst possible case

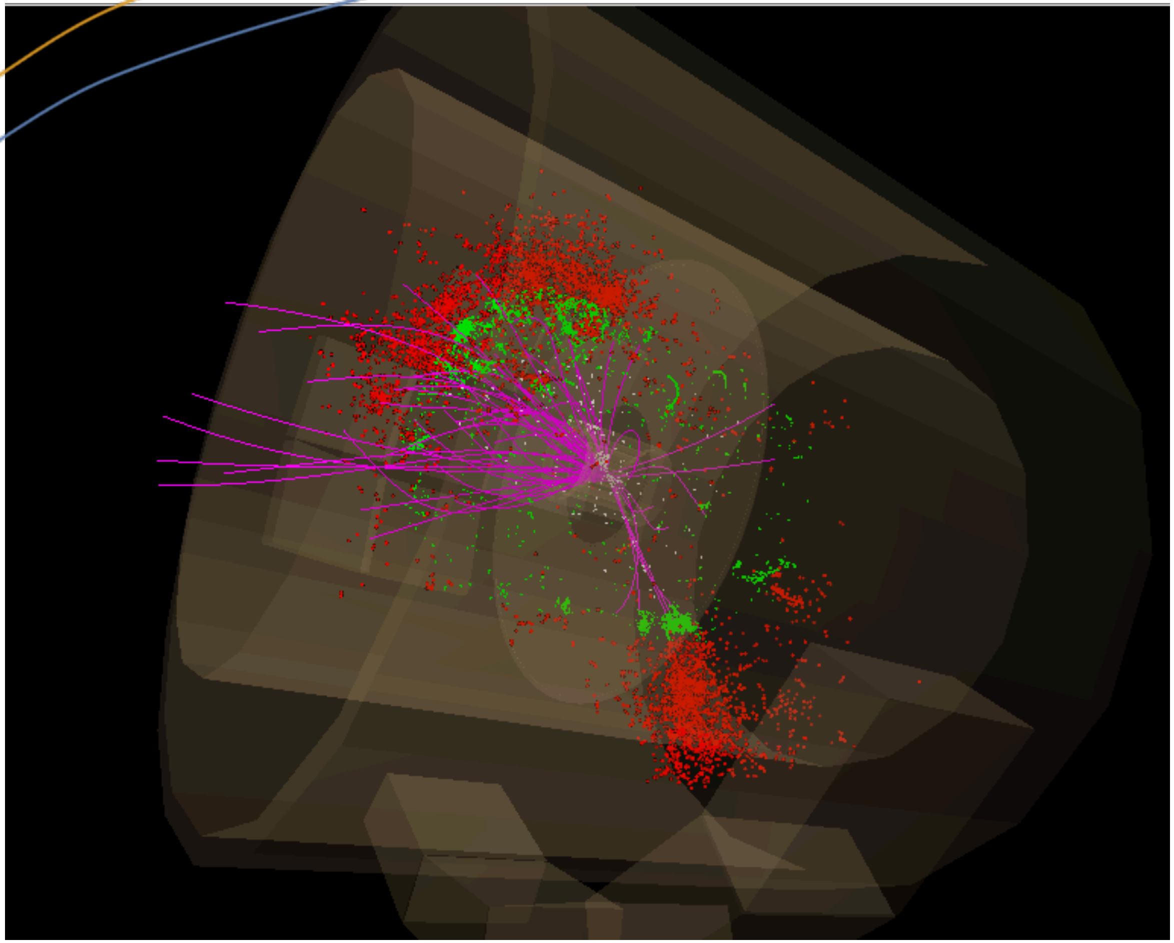
Muon decays background:

beam @ 0.75 TeV $\lambda = 4.8 \times 10^6$m

with $2 \times 10^{12}\,\mu$/bunch

➔ 4.1×10^5decay per meter of lattice

Timing powerful to remove background



Tools are in place!
work just started....

- ✓ higher energies need to be studied
- ✓ a new detector must be designed based on more recent R&D effort

Neutrino induced hazard

Neutrino radiation imposes major design and siting constraints on multi-TeV muon colliders
or inventing smart solutions!

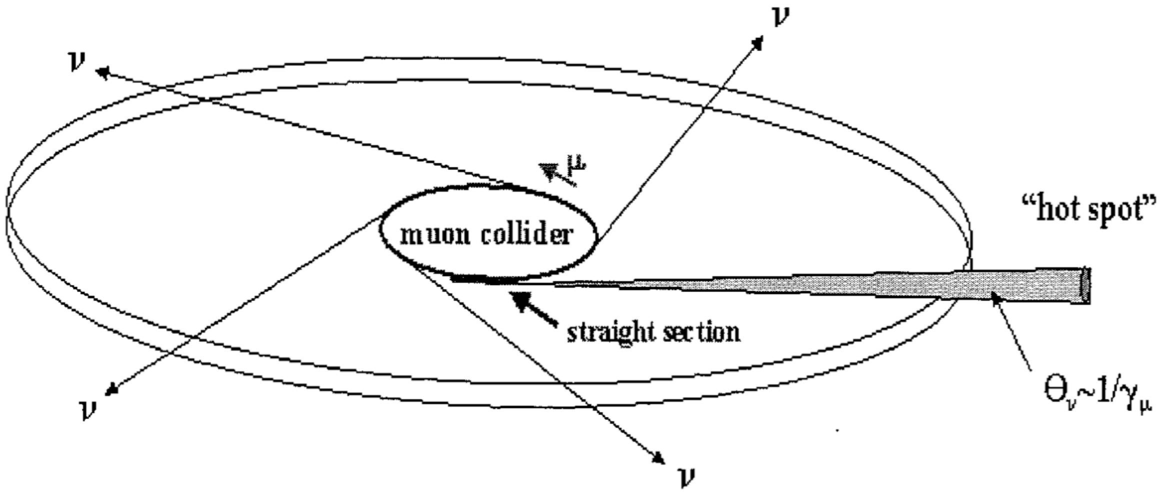


Table 4. Constraints on lattice designs to limit neutrino radiation.

E	B(min)	L(max)	$\mathscr{L}$
TeV	T	m	10^{34} cm^{-2} s^{-1}
1.5	0.25	2.4	0.008
3.0	1.5	0.28	0.6
6.0	1.5	0.28	12*

* constrained by ν radiation

One concept

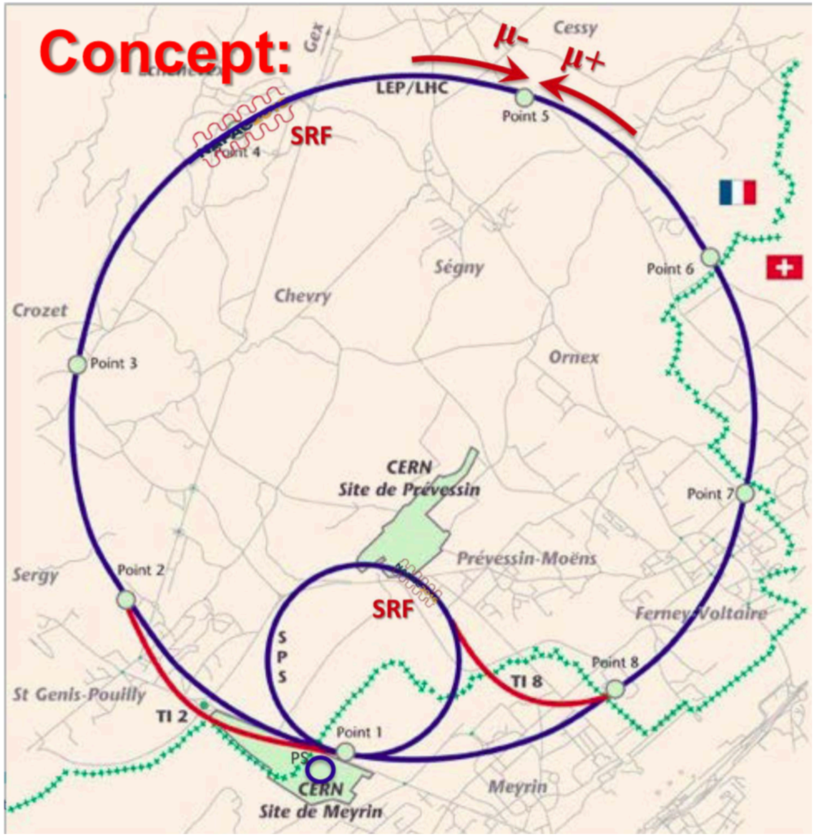
- Solution beyond 10 TeV unclear at present†

D. M. Kaplan   Muon Collider '18, U Padova 7/1–3, 2018   12/17

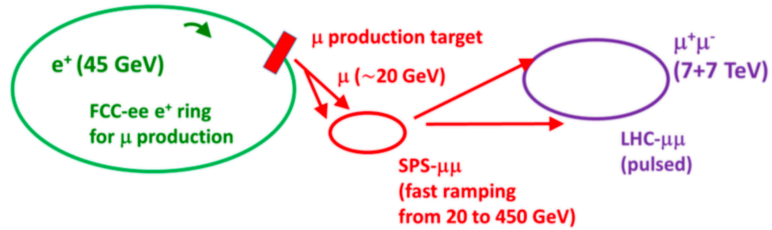
† although cf. AIP Conf. Proc. 1507 (2012) 860

New background generation with new neutrino cross sections planned with FLUKA

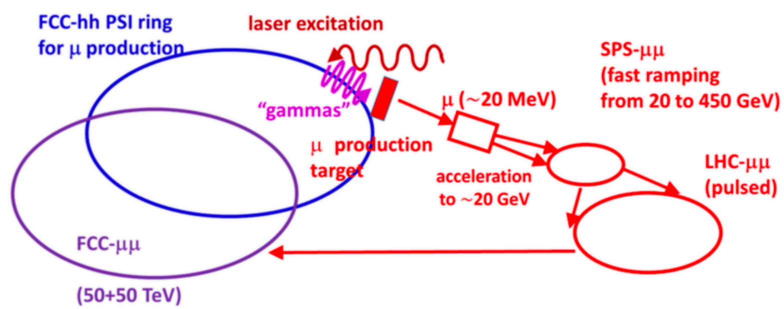
Dream or possibility?



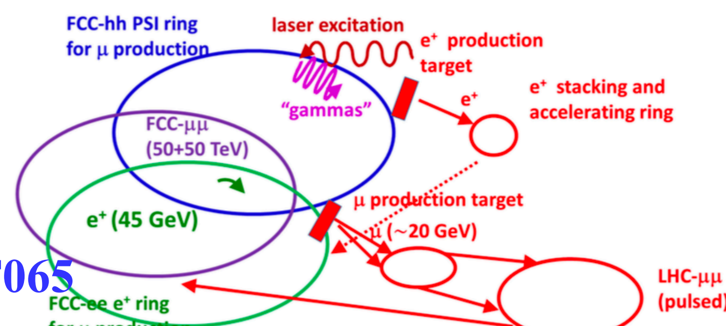
14 TeV μ collider LHC-μμ with FCC-ee μ± production



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

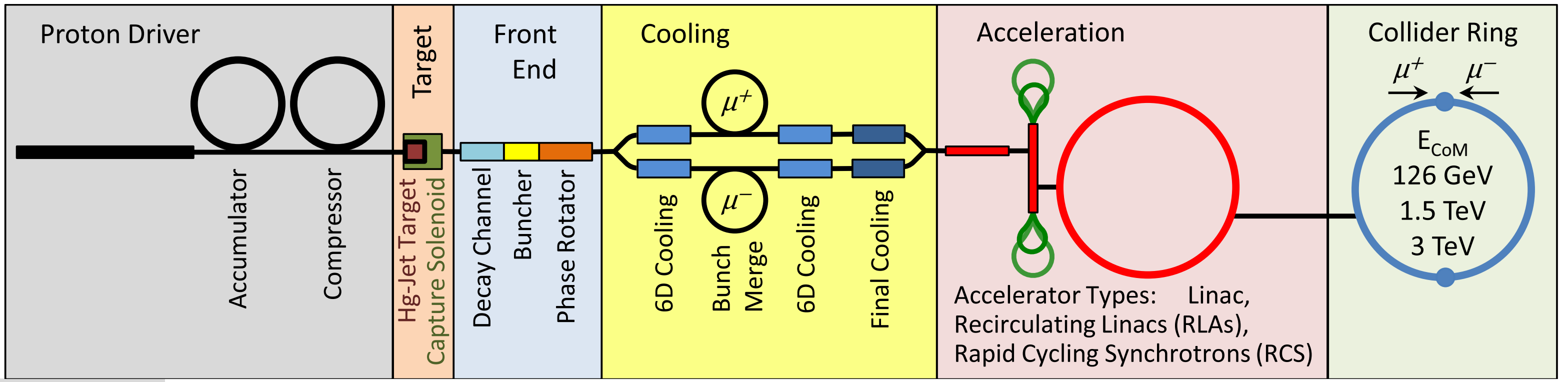


100 TeV μ collider FCC-μμ with FCC-hh PSI e+
& FCC-ee μ± production



IPAC2018 - MOPMF065

MAP Proposal R&Ds



- Based on 6-8 GeV Linac Source
- H- stripping requirements same as those established for neutrino

- MERIT@CERN studied high power target
- π production in high-field solenoid

solenoid π→μ decay channel RF cavities bunch & phase rotate $\mu^\pm$ into bunch train

- Fast ionization 6D cooling ($\tau = 2\mu s$)
- MICE
- Rubbia demonstrator proposal

- Fast acceleration
- Use RF and SC

$\mu^\pm$ decay background Tungsten shielding or bending magnets to avoid issues from e

- Critical Detector Machine Interface

A lot of material from – *JINST Special Issue MUON*

http://iopscience.iop.org/journal/1748-0221/page/extraproc46

MAP Budget/Effort Overview

Mark Palmer

- Overview of FY12-FY17
  - Full program in FY12-14 (funding includes fully burdened labor)
  - Ramp-down with focus on MICE completion during FY15-17

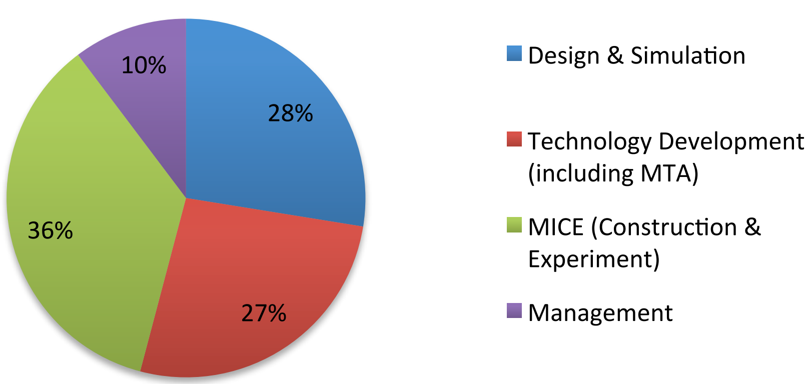
	FY12	FY13	FY14	FY15	FY16	FY17
US Funding (M$)	12.0	11.8	12.7	9.0	6.0	1.0

Reduced scope of effort (FY15–FY17)

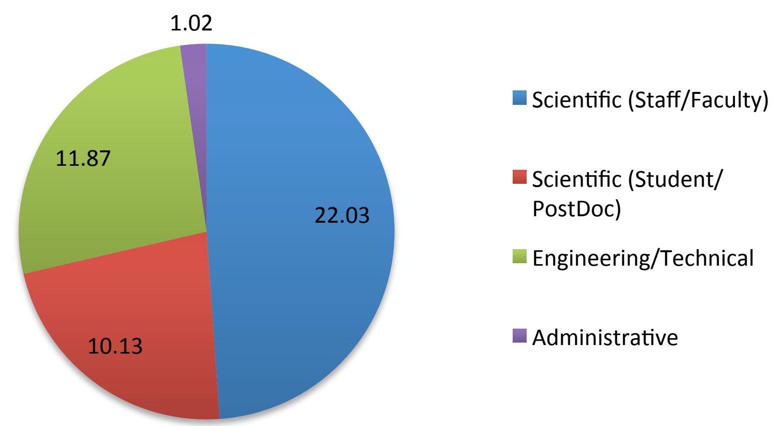
Snapshot of Effort Distribution During "full" program operation in FY13

- 23 Institutions Participating
- ~45 FTEs

MAP FY13 Funding Distribution (%)



Breakdown of Directly Supported MAP FTEs (FY13 Accelerator R&D)



Conclusions

- Muon Collider is an appealing solution as the HEP future accelerator
- U.S. Muon Accelerator Program (MAP) provides a well documented set of studies and measurements on the proton-driven option
- First results on ionizing cooling from MICE experiment now available
- A novel scheme to produce very low emittance muon pairs using a positron beam needs to be further investigated to became vialable
- Detailed studies and R&Ds, required to design a feasible solution for a Muon Collider, must be planned and pursued at international level
- The Update to the European Strategy for Particle Physics is the fly-wheel and the perfect opportunity to revise previous work and launch new studies

Seed of a renewed international effort

Muon Collider Working Group

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

appointed by CERN Laboratory Directors Group
to prepare the Input Document to the European Strategy Update
see related material @ muoncollider.web.cern.ch *soon*

A lot of past experiences and new ideas discussed at the joint ARIES Workshop

July 2-3, 2018

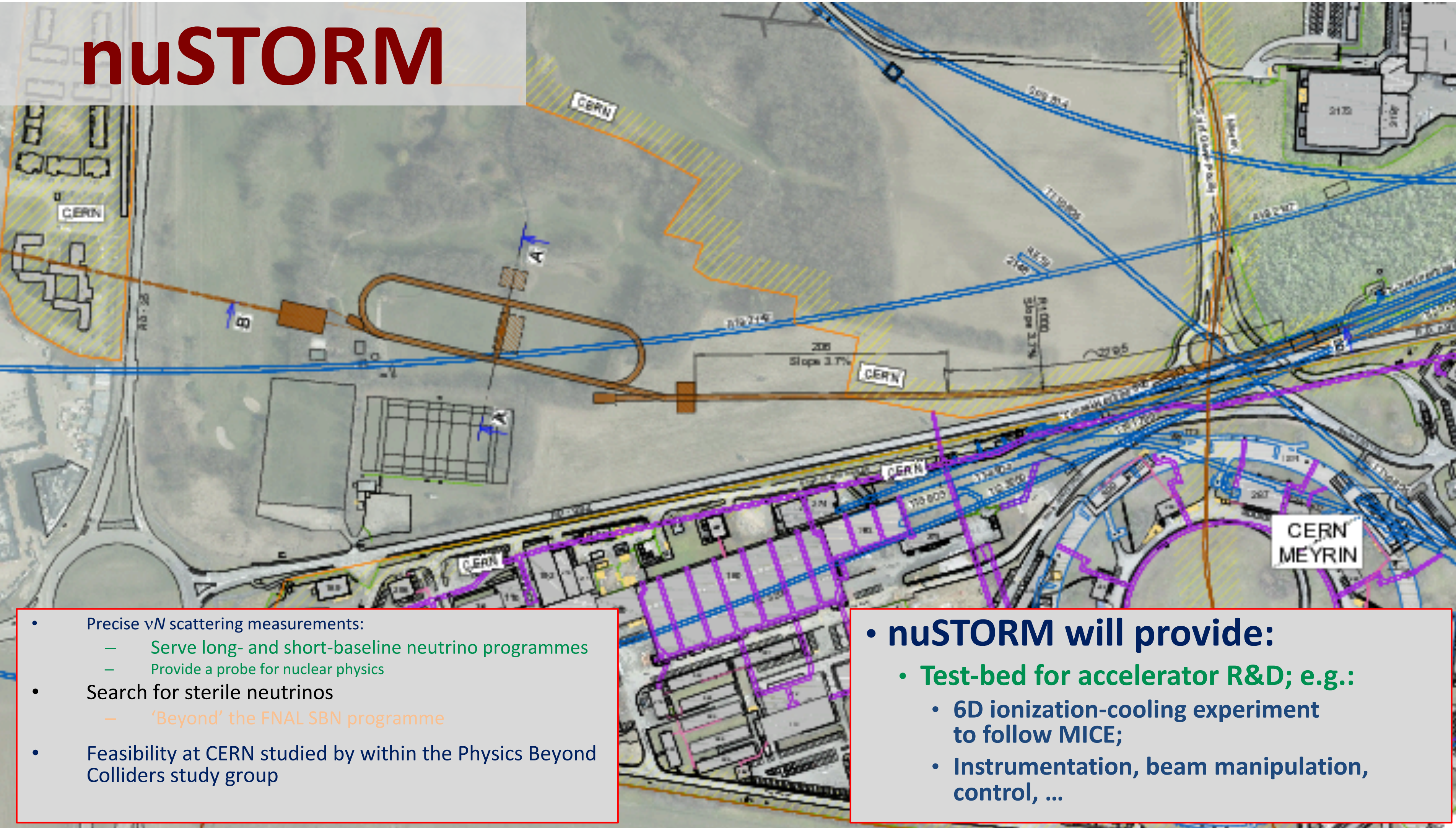
Università di Padova - Orto Botanico

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

Personal acknowledgement to Mark Palmer

extras

nuSTORM



- Precise νN scattering measurements:
  - Serve long- and short-baseline neutrino programmes
  - Provide a probe for nuclear physics
- Search for sterile neutrinos
  - 'Beyond' the FNAL SBN programme
- Feasibility at CERN studied by within the Physics Beyond Colliders study group

- **nuSTORM will provide:**
  - **Test-bed for accelerator R&D; e.g.:**
    - **6D ionization-cooling experiment to follow MICE;**
    - **Instrumentation, beam manipulation, control, …**