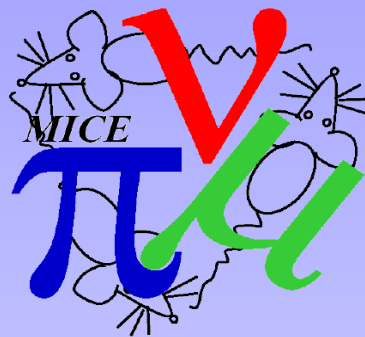




NOW 2018



&



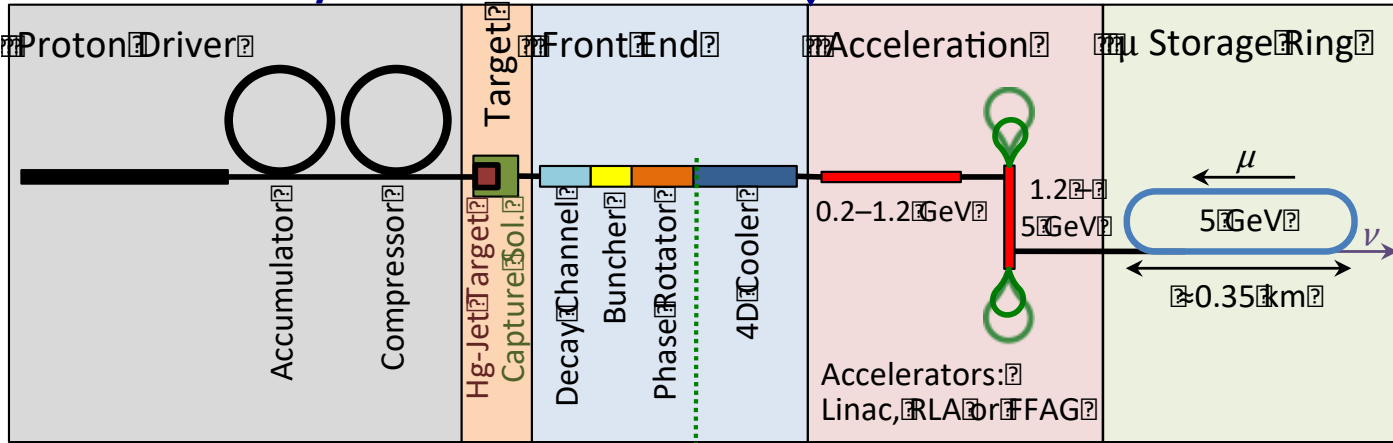
M. Bonesini

INFN, Sezione di Milano Bicocca

Milano Italy

From Neutrino Factory to Muon Collider (MAP)

Neutrino Factory



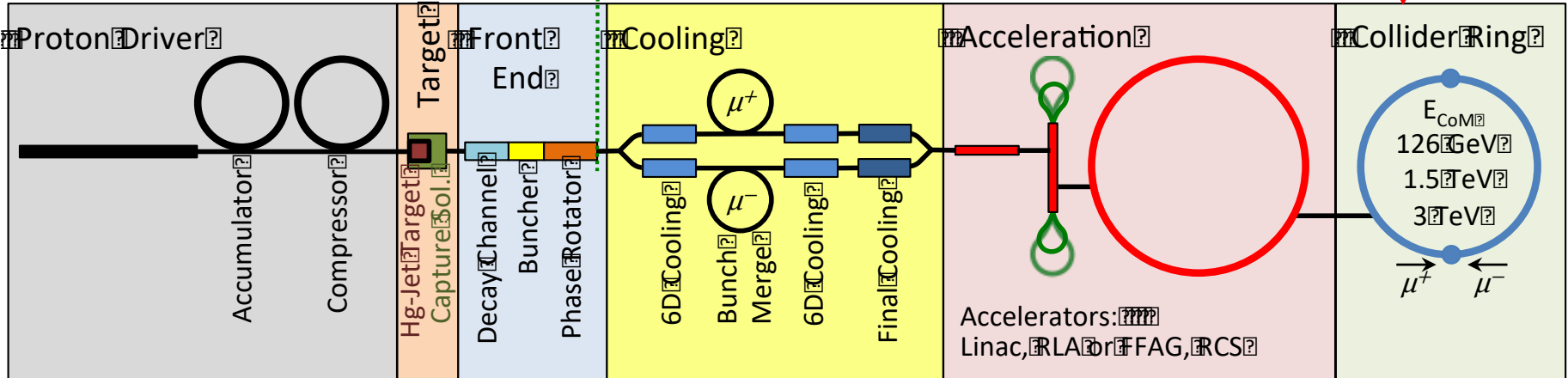
Neutrino Factory Goal:
 $O(10^{21})$ m/year
 within the accelerator acceptance

Muon Collider Goals:
 126 GeV \Rightarrow
 $\sim 14,000$ Higgs/yr
 Multi-TeV \Rightarrow
 Lumi $> 10^{34}$ cm $^{-2}$ s $^{-1}$

Share same complex

NF and MC share the same initial steps

Muon Collider



Muon Ionization Cooling: why and how

- Muons produced with large phase space (emittance) as tertiary particles
- Emittance must be reduced before injection into accelerator
 - Implications for performance (e.g. luminosity) & cost
- Lifetime of muon (2.2 μ s) requires **ionisation cooling**.
 - Muons pass through material – lose transverse and longitudinal momentum (p_T & p_L)
 - Accelerated in RF cavity – restores p_L only.

Initial motion

Absorber

Accelerated



As normal cooling methods are too slow, need for novel method: ionization cooling

$$\frac{d\varepsilon_n}{dz} \sim -\frac{1}{\beta^2} \left\langle \frac{dE_\mu}{dz} \right\rangle \frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3} \frac{\beta_\perp (0.014 \text{ GeV})^2}{2E_\mu m_\mu X_0}$$

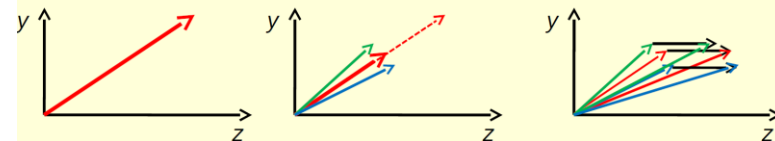
where:

- BUT – also get scattering in material:

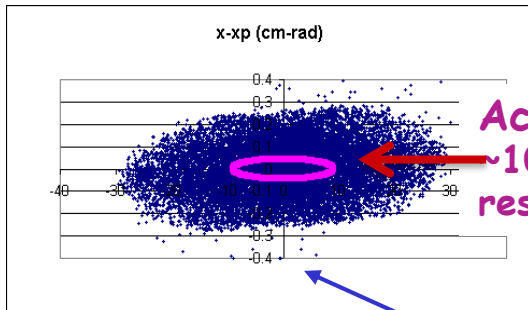
Initial motion

Absorber

Accelerated



- Need to minimise multiple Coulomb scattering
- Energy loss $\propto Z$, atomic number
- Scattering $\propto Z^2$
- Need low Z material:
 - Liquid hydrogen (liq. H_2) plus beryllium windows
 - Lithium hydride (LiH)
- Also need powerful magnetic focussing



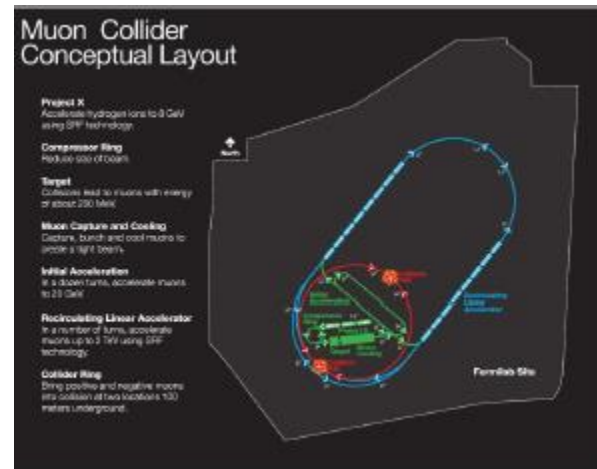
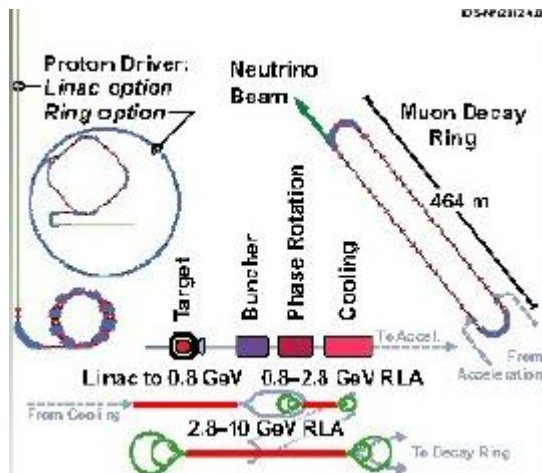
Accelerator acceptance R
~10 cm, $x' \sim 0.005$ rad
rescaled @ 200 MeV

π and μ after focalization

MICE motivations

MICE goals:

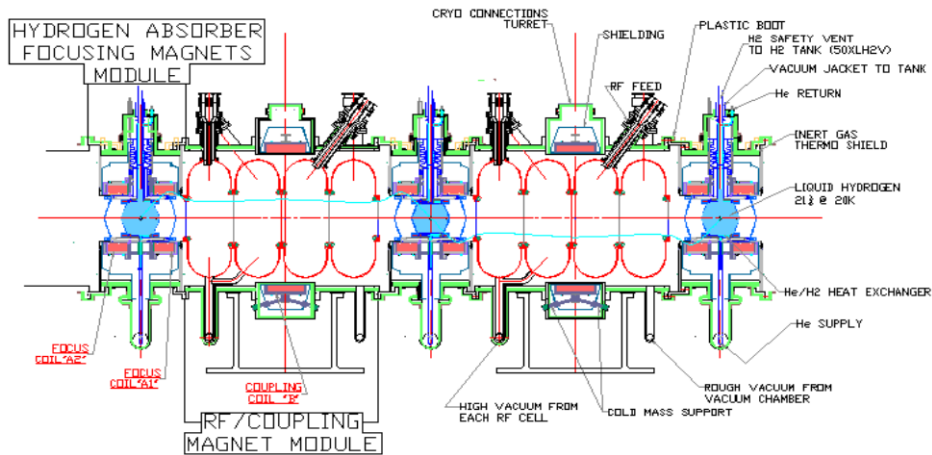
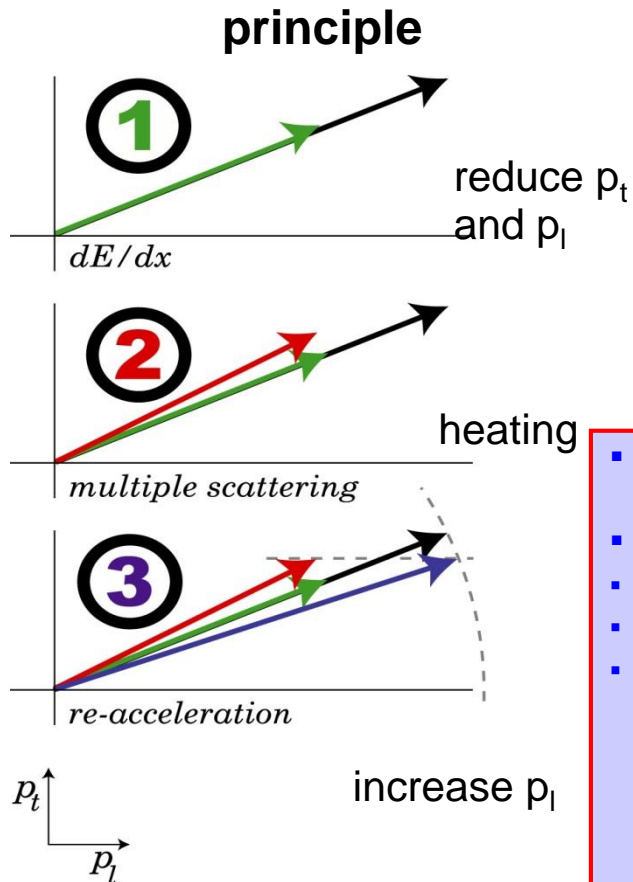
- Demonstrate the feasibility of ionization cooling, in a variety of mode of operations and beam conditions
- Measure material properties of potential absorbers (LiH and liquid H)
- Design, build, commission & operate a realistic section of cooling channel (with RF)



... results will be used to optimize Neutrino Factory, Muon Collider and future high brightness muon beam designs

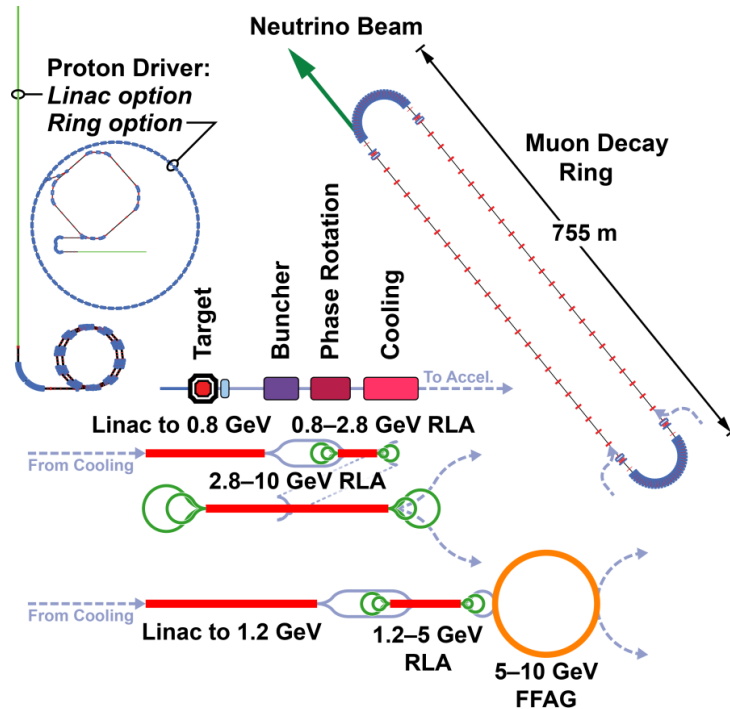
Muon ionization cooling

reality (simplified)

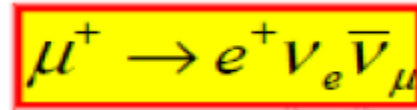


- Build a section of cooling channel long enough to provide measurable cooling (10%) and short enough to be affordable and flexible
- Wish to measure this change to 1%
- Requires high precision measurement of beam emittance into and out of cooling channel
- Cannot be done with conventional beam monitoring device
- Instead perform a single particle experiment:
 - High precision measurement of each track (x,y,z,p_x,p_y,p_z,t,E)
 - Build up a virtual bunch offline
 - Analyse effect of cooling channel on many different bunches
 - Study cooling channels parameters over a range of initial beam momenta and emittances

Neutrino Factory (NF) a closer look



neutrino factory:
accelerate muons and store to
produce neutrinos



- Flux known to 1% or better
- High energy electron neutrinos

Golden Channel:

long baseline oscillation manifests
itself by wrong sign muons:



Large (100 kton) magnetized iron
detector

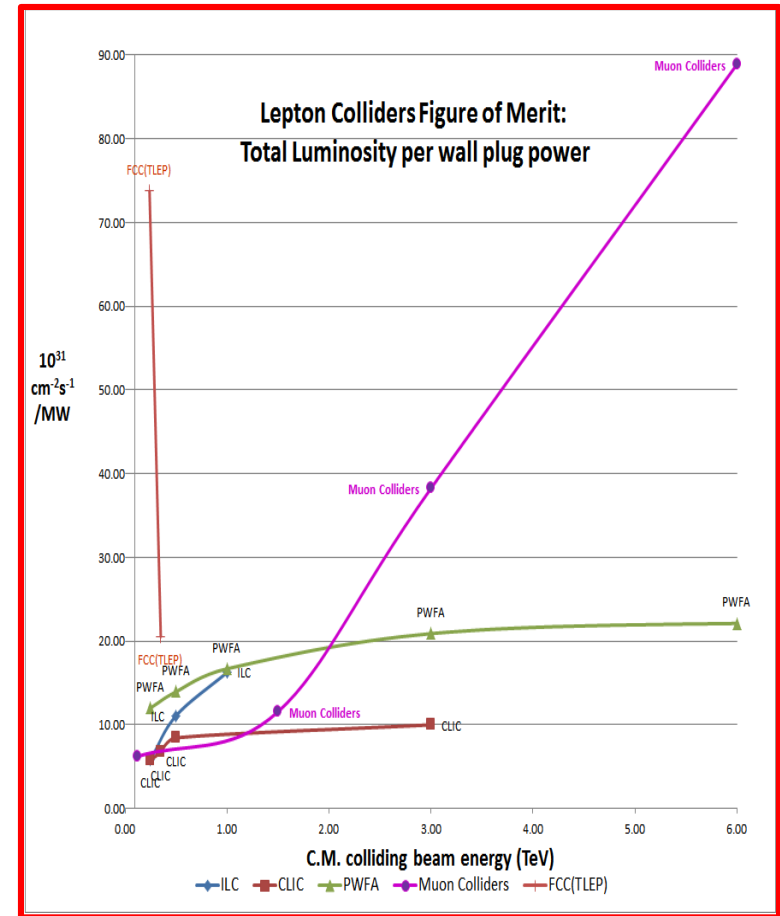
Unique ability to test $\nu_e \rightarrow \nu_\tau$

NF may be considered technology
ready: MERIT, MuCool, MICE, EMMA

- ❑ Study 1 (US-Fermilab) [2000]
- ❑ Study 2 (US-BNL) [2001]
- ❑ CERN NF study [2002]
- ❑ Study 2a (APS Neutrino Study) [2004]
- ❑ ISS (first international study) [2006]
- ❑ International Design Study for a Neutrino Factory (IDS-NF) (arXiv:1112.2853) [2013]

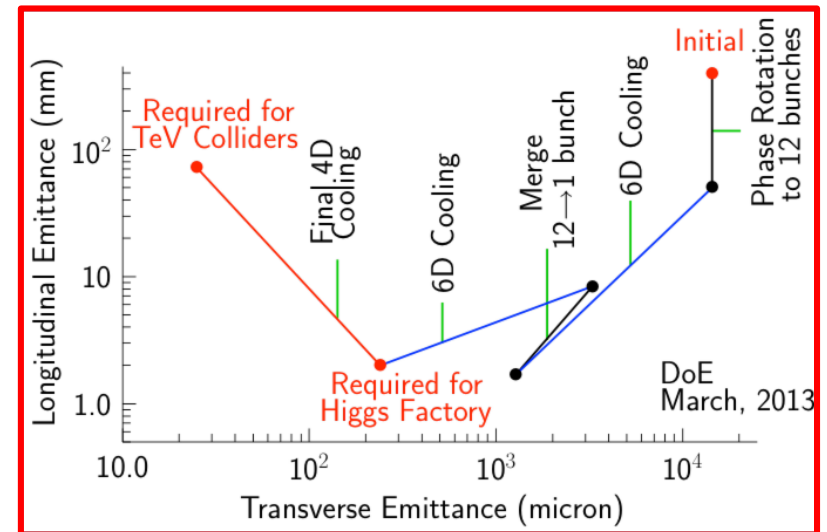
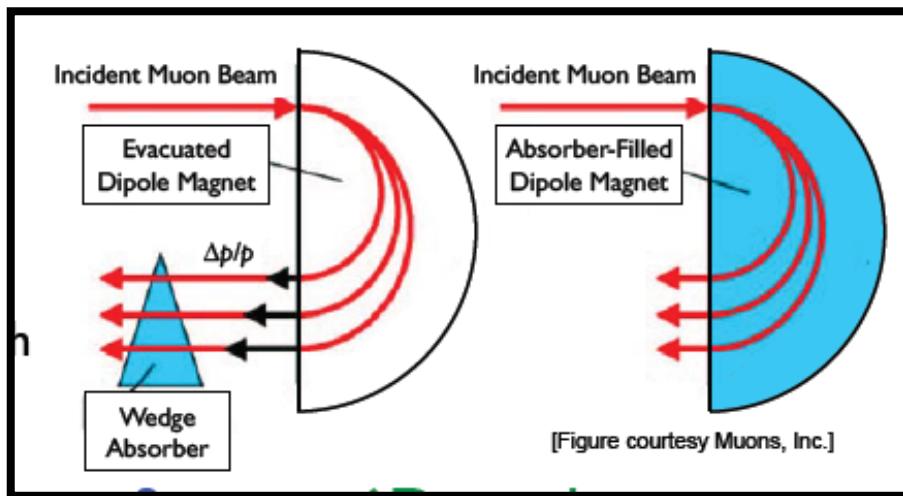
Muon Colliders

- Optimised Higgs Factory:
 - Muon mass; Higgs production rate 10^4 times larger than e^+e^-
- Optimum route to multi-TeV lepton-anti-lepton collisions:
 - Muon mass; 200 times that of the electron mitigates:
 - Synchrotron radiation;
 - Beamsstrahlung
 - Muon rigidity allows efficient acceleration
 - Results in cost-efficient acceleration to very high energy
- Luminosity critical:
 - Muon-beam cooling essential



Cooling requirements.

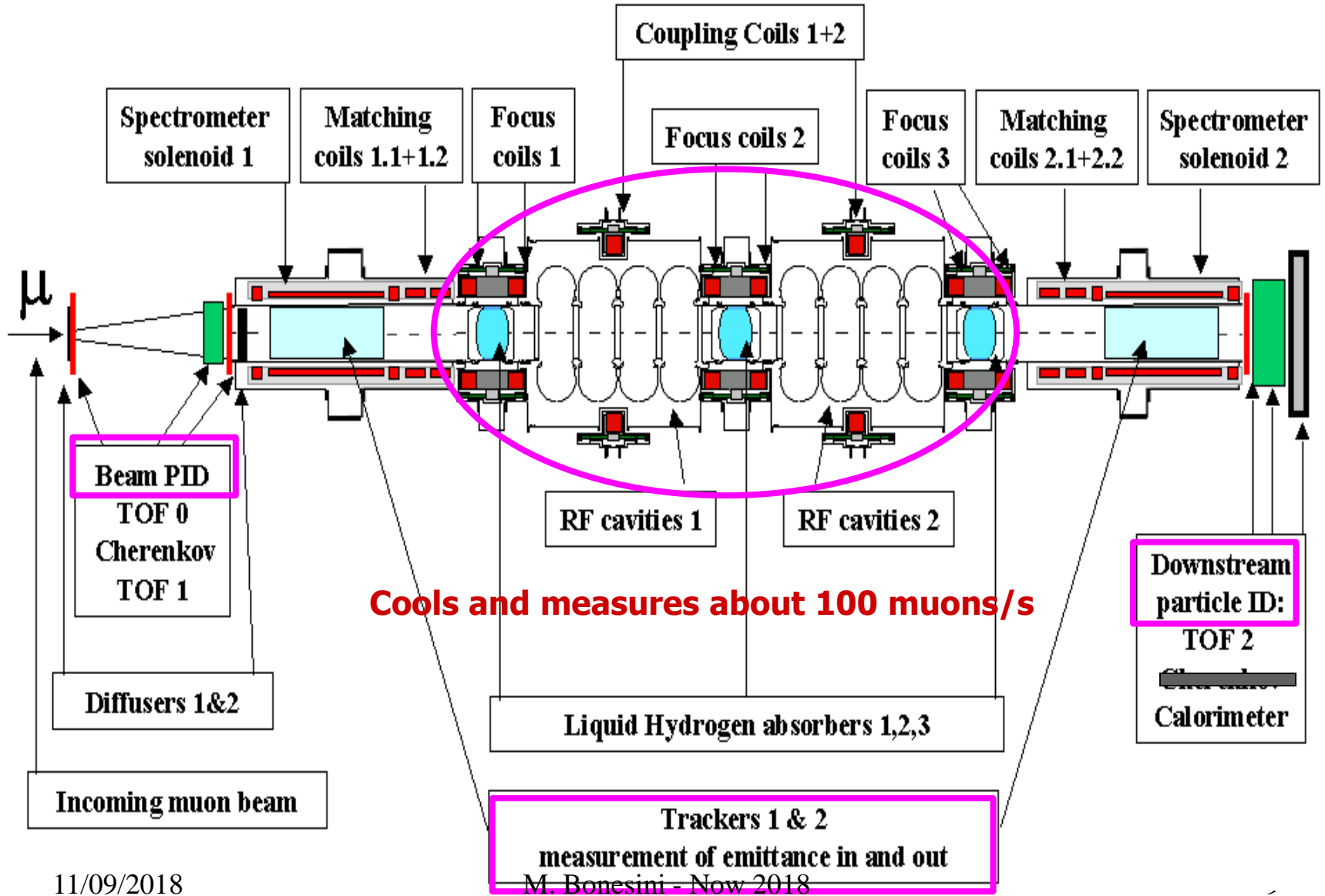
- ❑ Cooling important to deliver Neutrino Factory performance (increase by a factor 2-10), but needs only 4D (transverse)
- ❑ Cooling essential for Muon Collider performances (a factor $\sim 10^6$ needed)
- ❑ 6D cooling via emittance exchange



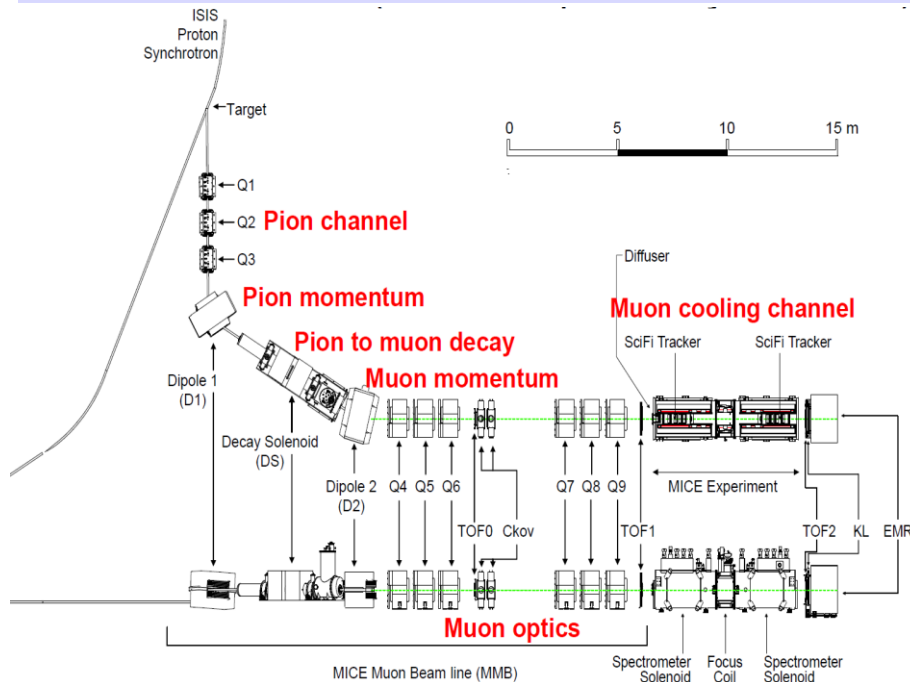
- Ionization cooling is not directly effective for longitudinal emittance
- Two approaches to longitudinal cooling via emittance exchange (cool ε_{\parallel} , exchange ε_{\perp} & ε_{\parallel})
- A wedge shaped dE/dx absorber is introduced, to increase (decrease) ionization losses for faster (slower) particles



Original MICE setup



MICE Beamline




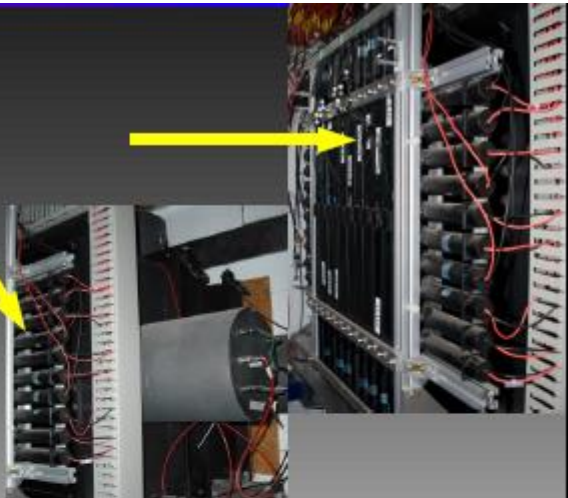

- ❑ ISIS 800 MeV proton synchrotron at RAL
- ❑ Titanium target, grazing ISIS beam
- ❑ π captured by quad triplet and momentum selected by dipole (D1)
- ❑ Followed by 5T decay solenoid (DS)
- ❑ Second dipole (D2) select muons momentum



Beam PID instrumentation



Upstream PID:
discriminate p , π , μ

- Time of Flight - ToF0 & ToF1
- Threshold Cerenkov

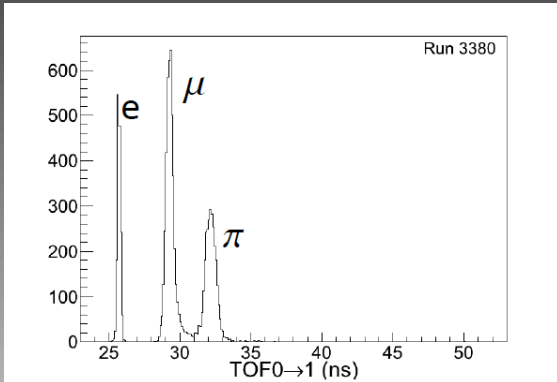


Downstream PID:
reject decay electrons

- Time of Flight - ToF2
- Kloe-light Calorimeter - KL
- Electron-Muon Ranger -EMR



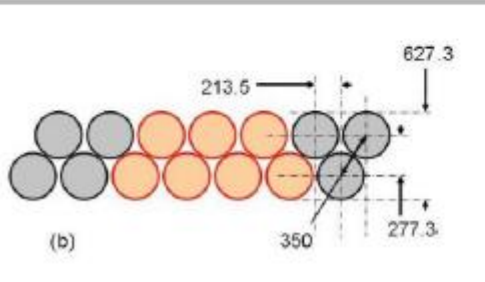
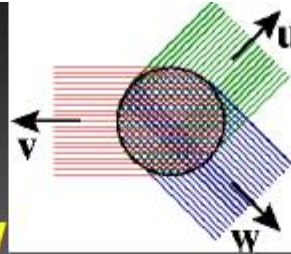
Run 3380



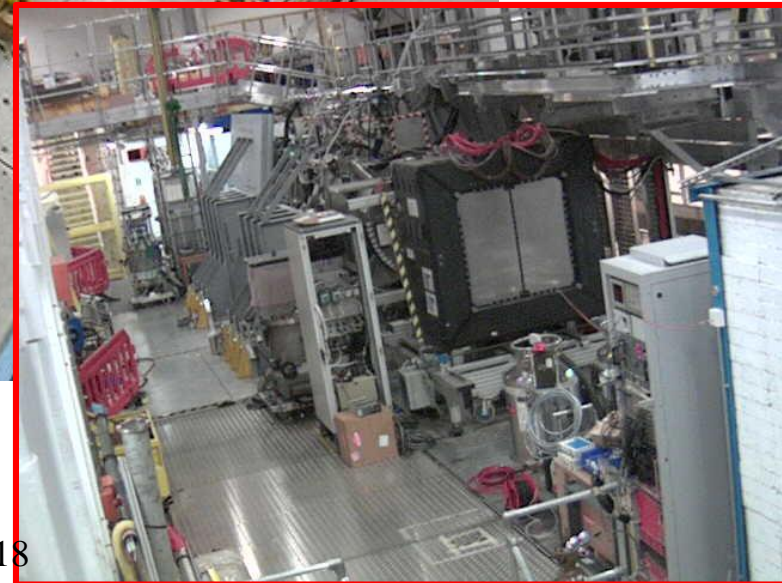
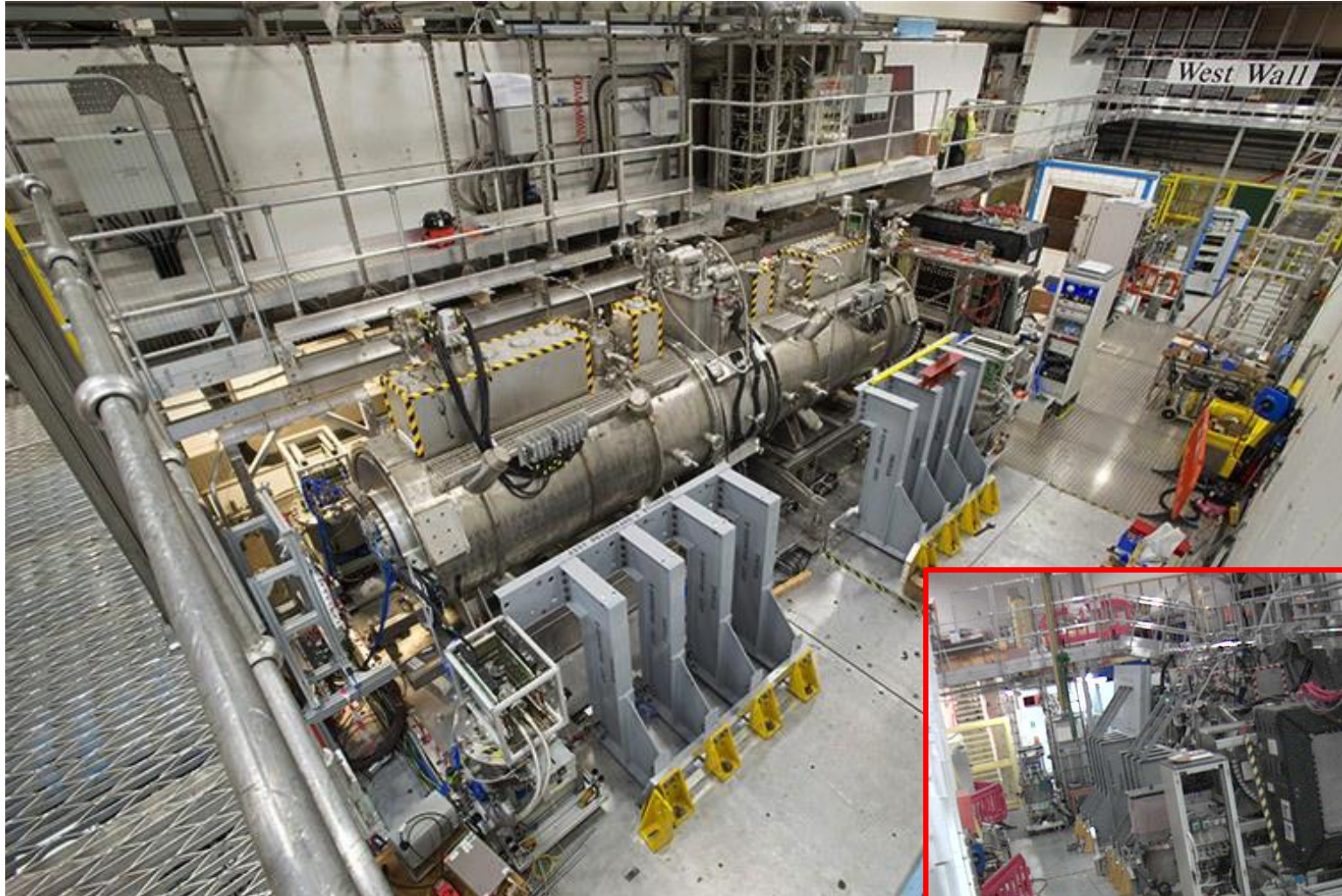
Particle Type	TOF (ns)	Count
e	25	550
μ	30	600
π	35	300

MICE trackers

- Two trackers – before/after
- Measures x, y, x', y', z
- 5 stations/tracker
- 3 stereo planes/station – U/V/W
- 1400 350 μm fibers/plane
- double layer, 7 fibers/group
- <0.2% dead channels
- >10.5 photoelectrons/MIP
- 470 μm RMS position resolution



Cooling channel with PRY (MICE STEP IV)



11/09/2018

M. Bonesini - Nov 2018

MICE Science Goals: study factors that affect cooling

• Emittance:

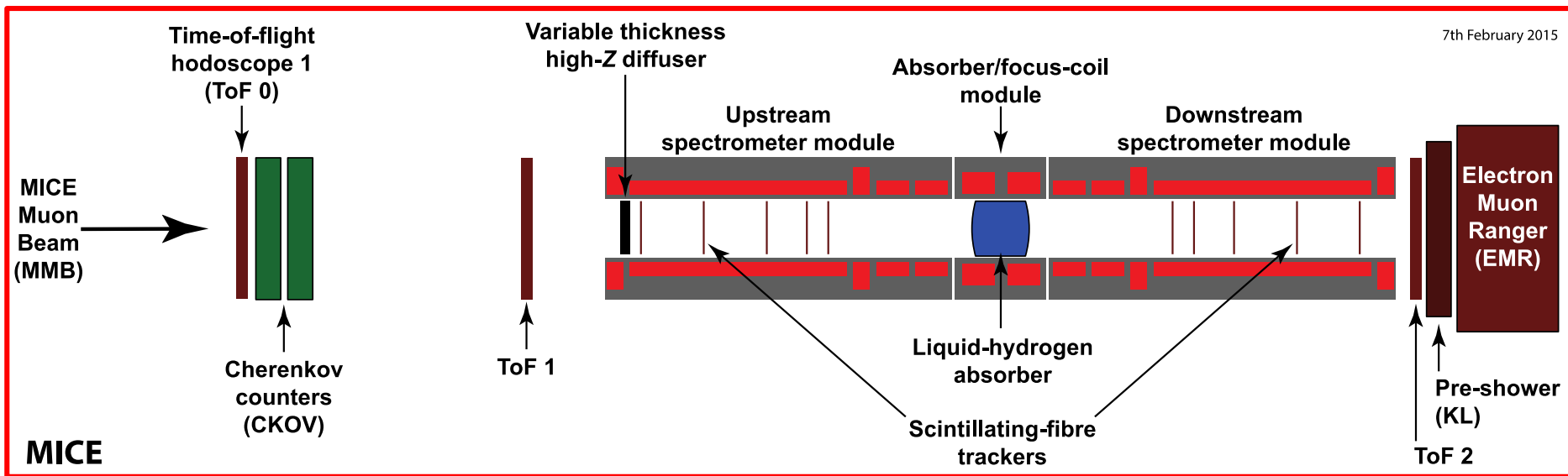
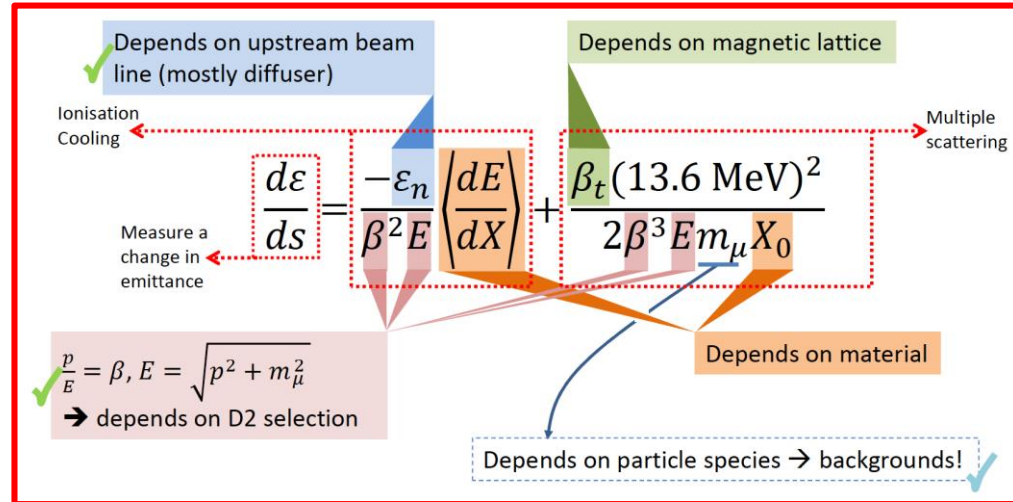
- MICE Muon Beam optics and diffuser settings

• Material:

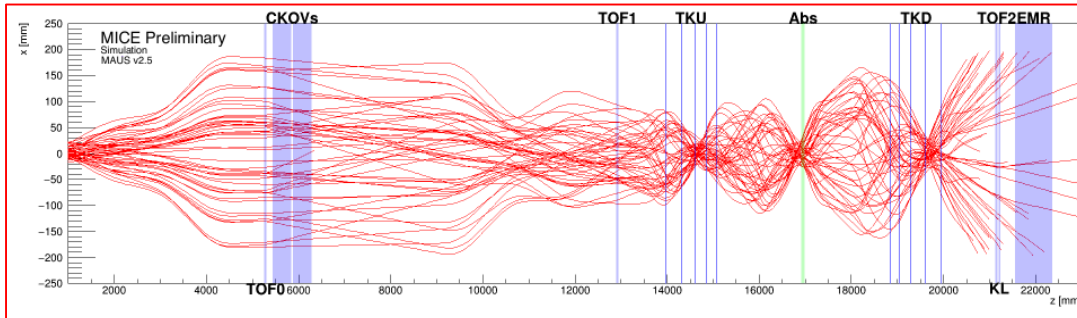
- Absorber change (LH₂; LiH);

• p , E and β :

- Vary beam momentum, optics



Data taking



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**

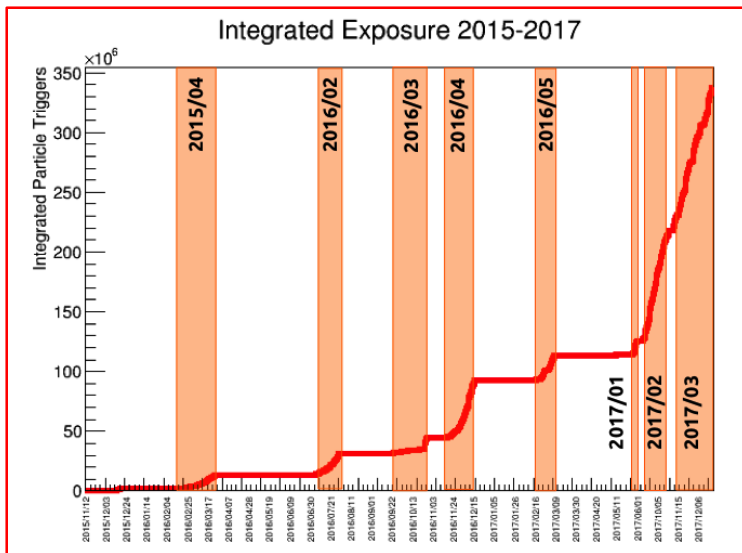
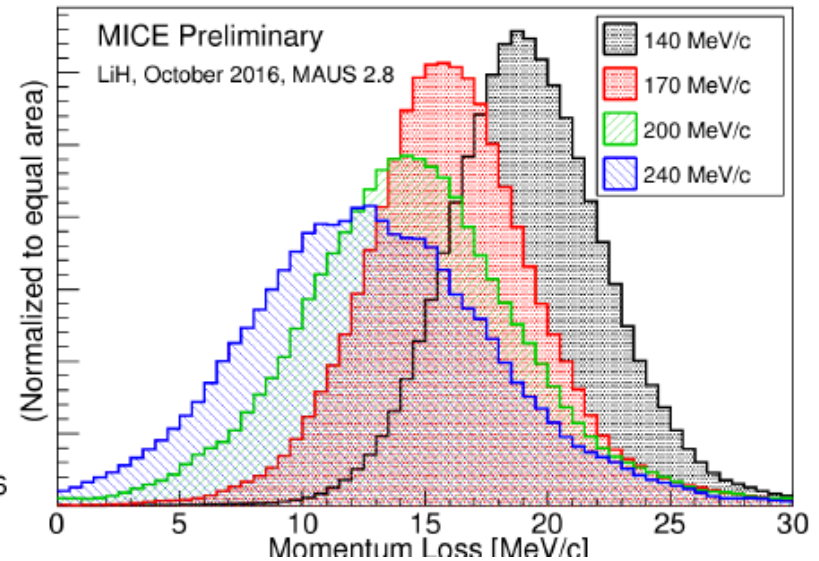
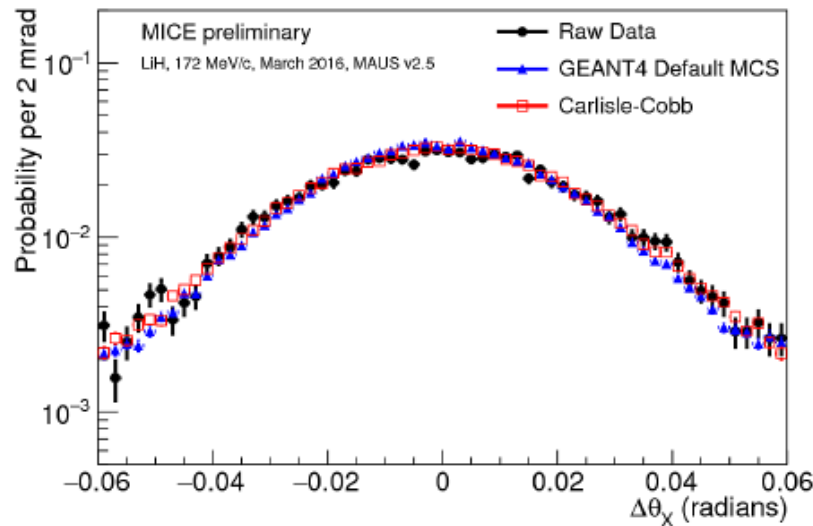


Table 2: Summary of data-taking over the Step IV period.

User cycle	Target	Channel mode	Motivation	Triggers $\times 10^6$
2015/01	-	No field	Commissioning and development	-
2015/02	-	No field	Commissioning and development	-
2015/03	Xe	No field	Commissioning / Initial data-taking	1.9
2015/04	Empty/LiH	No Field	Data-taking without decay solenoid	11.9
2016/01	Empty	-	Hall infrastructure development	-
2016/02	Empty	No field	Commissioning	17.9
2016/03	Empty/LiH	Solenoid	Data-taking	13.2
2016/04	LiH	Solenoid	Data-taking	47.6
2016/05	LiH	Flip	Data-taking	20.4
2017/01	Empty	No field	Hall Infrastructure development	12.5
2017/02	LH2	Mixed	Data-taking	105.2
2017/03	LiH/LH2/Wedge	Mixed	Data-taking	107.2

Multiple Coulomb Scattering

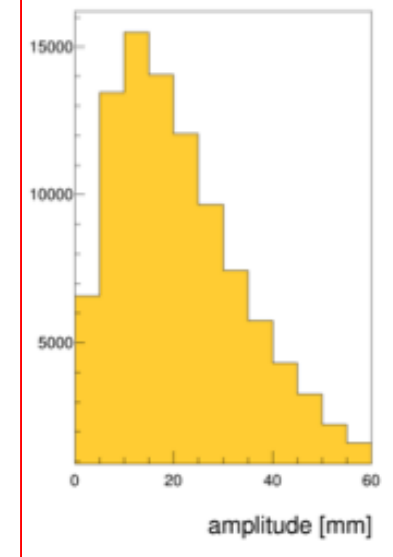
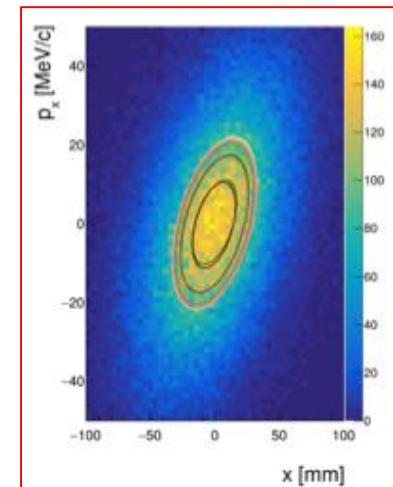


- Emittance is increased by multiple scattering
- Scattering in low-Z materials not well modelled in MCs
- First measurement of muon MCS in lithium hydride at 140-240 MeV/c
- Validation of Moliere scattering model and GEANT4
- Validation of energy loss model

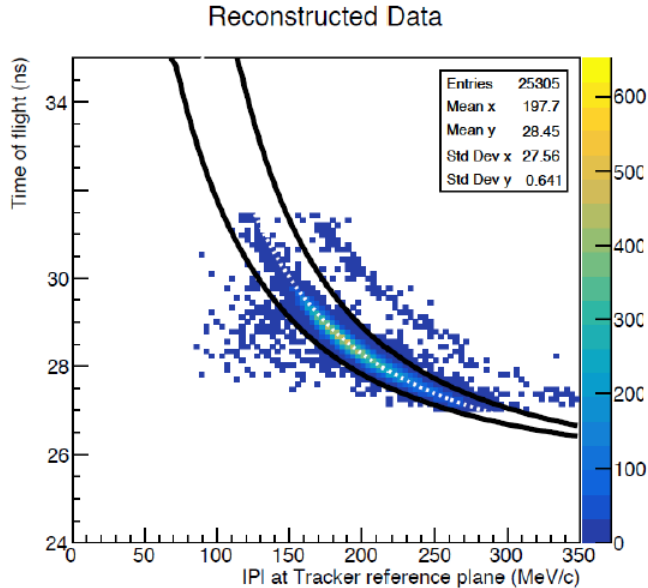
Emittance and amplitude

- 4D-phase space of particles: x, p_x, y, p_y
- Normalized emittance: $\varepsilon_T = \frac{\sqrt[4]{\Sigma_{4D}}}{mc}$; 4D cov matrix Σ_{4D}
- Transverse single-particle amplitude; phase-space distance of muon from beam core
 $A_{\perp} = \varepsilon_T \mathbf{u}^T \Sigma^{-1} \mathbf{u}$ with $\mathbf{V} = (x, p_x, y, p_y)$ and $\mathbf{u} = \mathbf{v} - \langle \mathbf{v} \rangle$

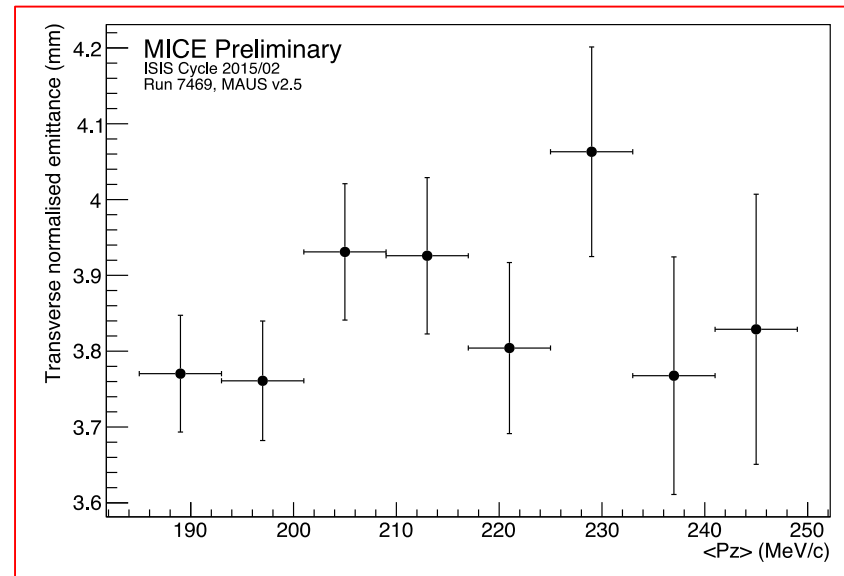
- Mean amplitude \sim RMS emittance
- Ionization cooling reduces amplitude in the core of the beam



Precise emittance measurement



Time-of-flight between TOF0 and TOF1 vs p measured in TKU. Black lines border the events considered muons.

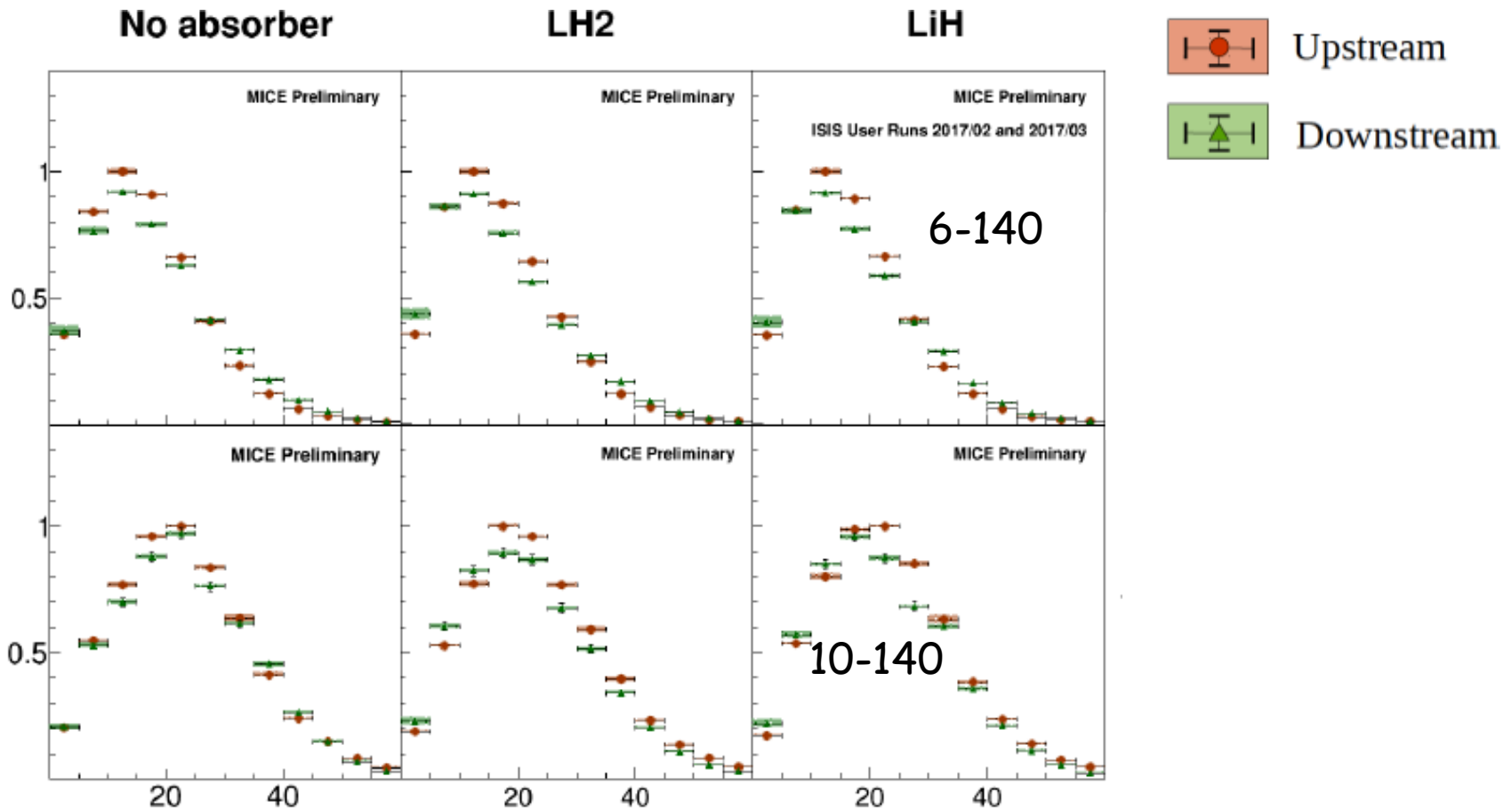


Transverse normalized emittance measured in upstream solenoid using single particle method

- flat emittance vs p
- total error between 2 and 4 %

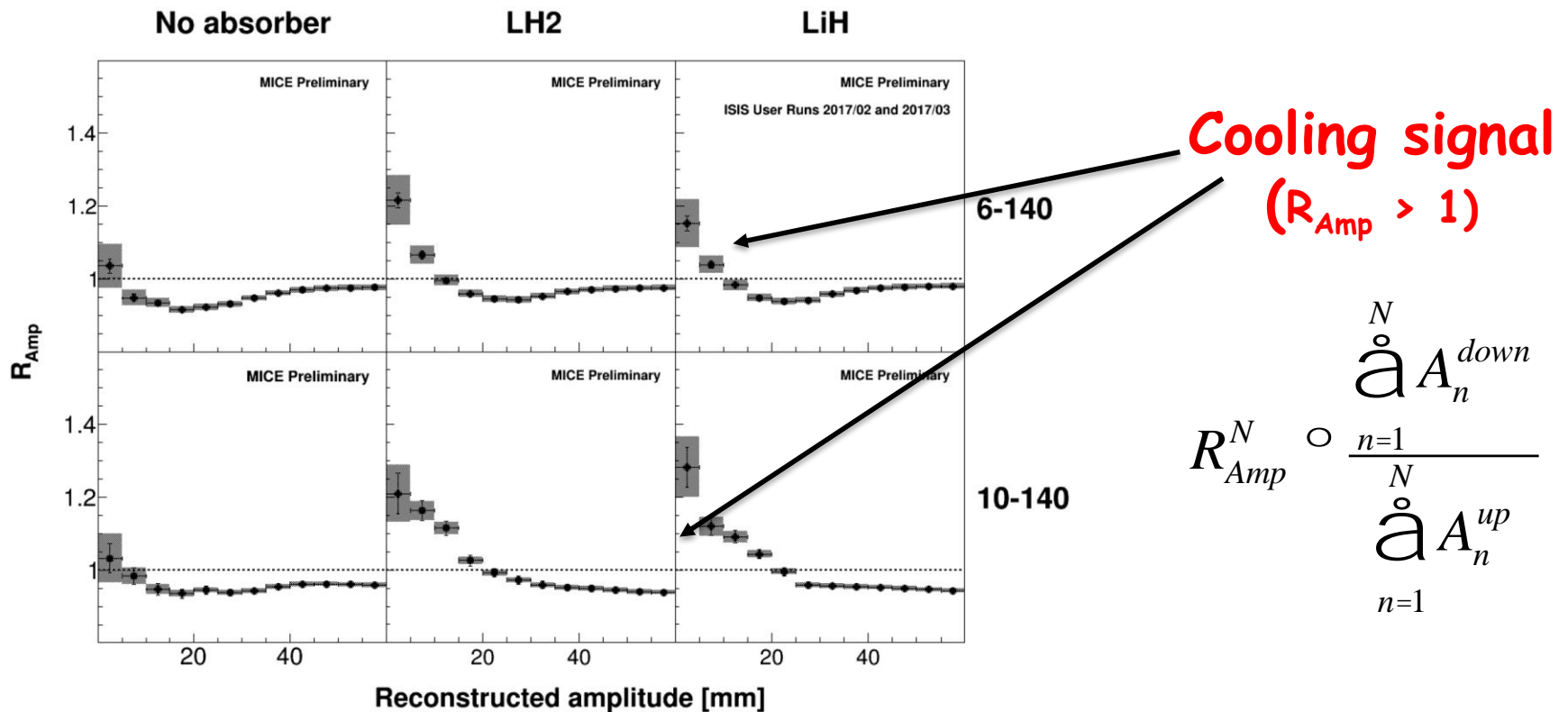
Emittance evolution: amplitude change

- No absorber: decrease in number of core muons
- Absorber: increase in number of core muons (**cooling signal**)



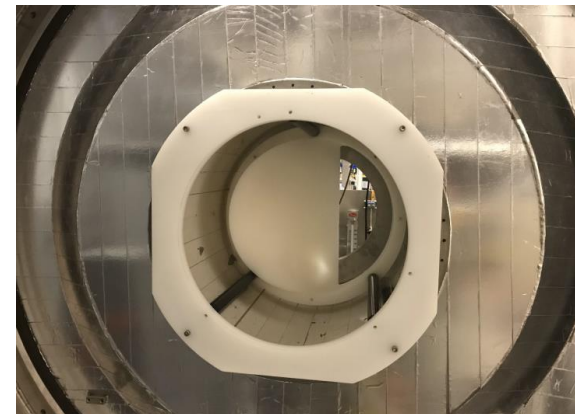
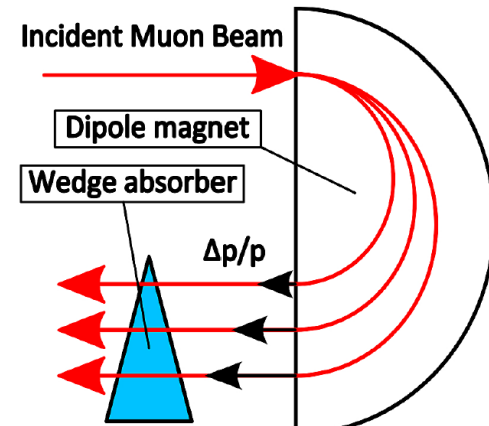
Emittance evolution: ratio of cumulative core densities

- Cumulative core density increase for LH2 and LiH absorbers
- More cooling ($R_{Amp} > 1$) at higher input emittances



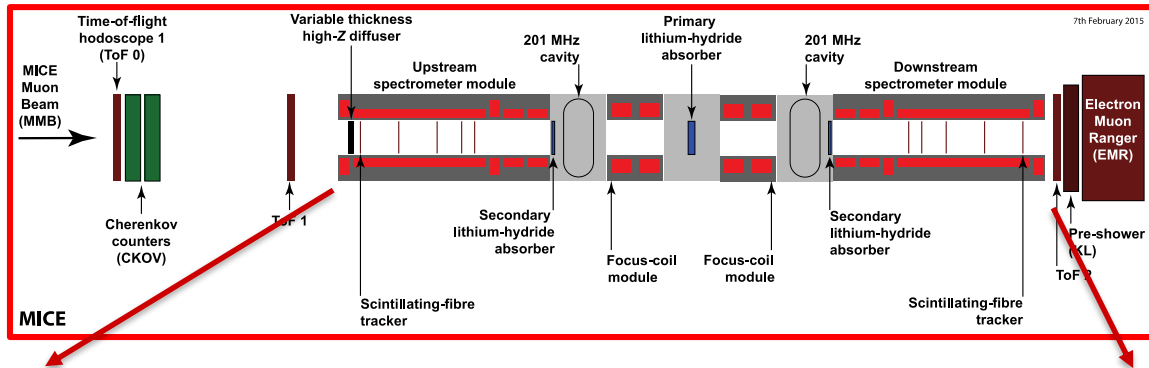
Study of emittance exchange

- Data taken in 2017 for both direct emittance exchange (ε_L decreases) and reverse emittance exchange (ε_T decreases)
- Reverse emittance exchange lengthens bunch and increases luminosity in MC
- Polyethylene wedge absorber

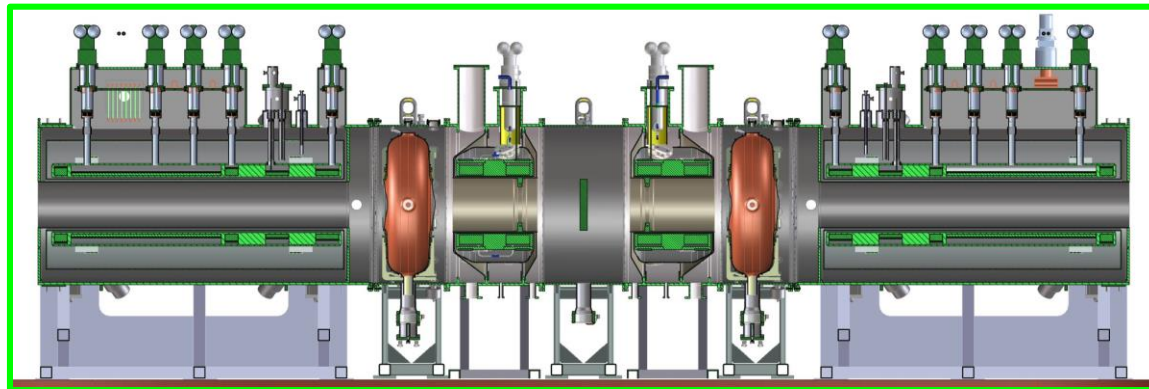


Wedge installed in MICE

Going forward: demo cooling design study

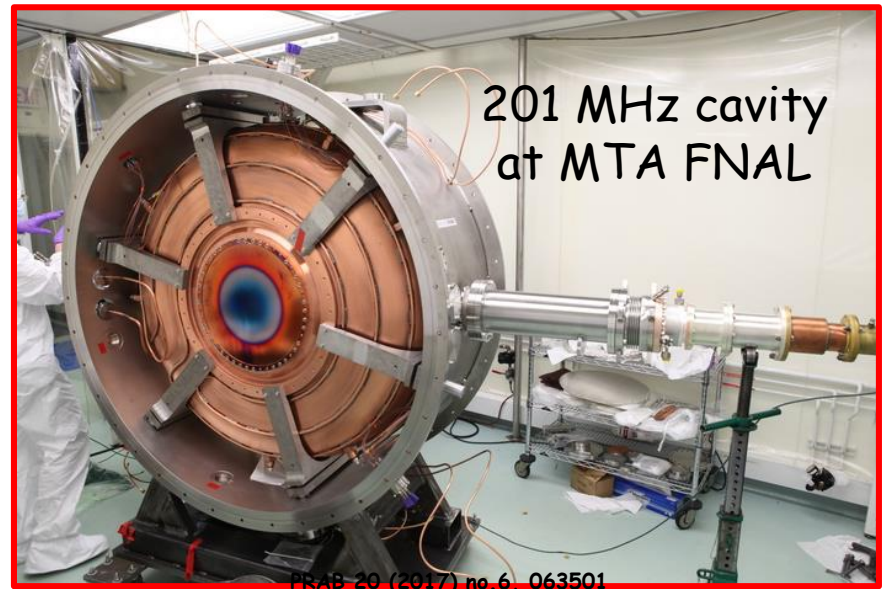
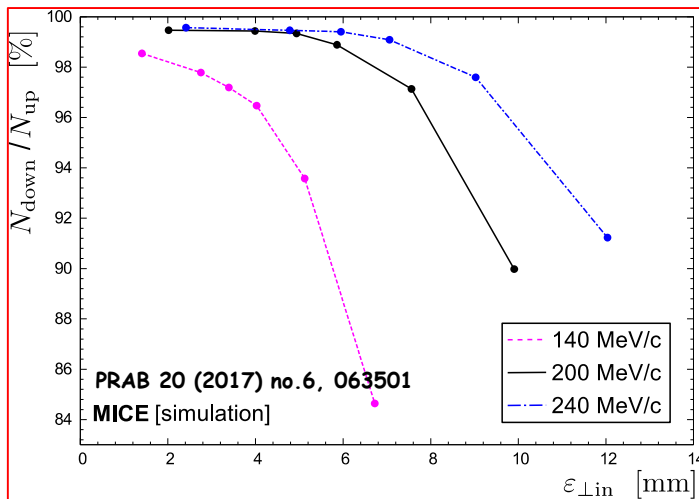
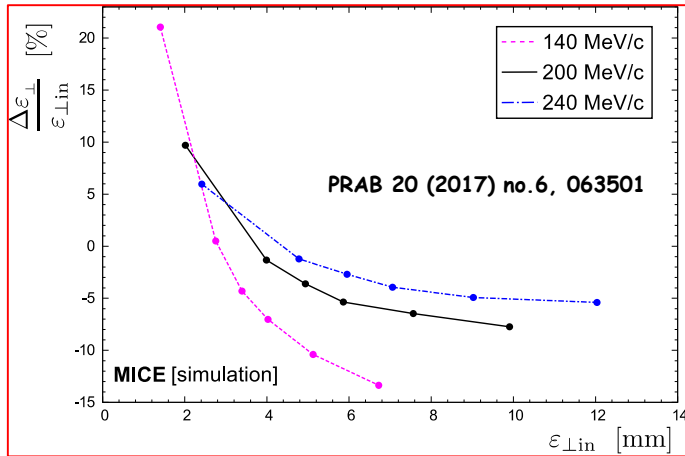


- Possible next steps: add acceleration to MICE lattice, study 4D cooling with acceleration. Upgrade to DEMO fully designed:



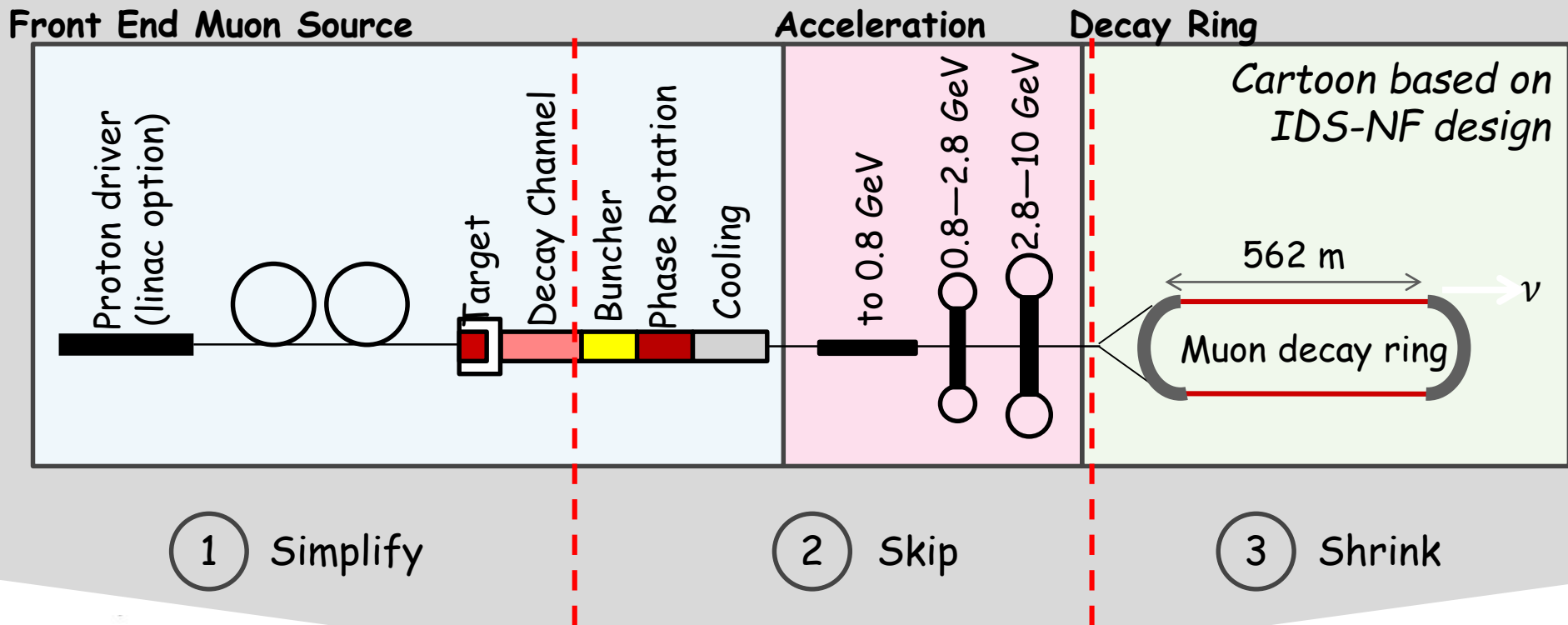
- Good performances: $\frac{\Delta \varepsilon_{\perp}}{\varepsilon_{\perp}} \approx 15\%$ (6%) at 140 (200) MeV/c to be compared with 10% at 200 MeV/c of proposal
- RF cavities tested and constructed
- Power sources available and tested

Demo cooling performances



Design achieves required cooling at large emittances; But ... not funded

For the impatient physicist: an entry level NF



nuSTORM

- nuSTORM is entry-level neutrino factory and can be realized **now without any new technology.**
- Up to π production: conventional neutrino beam
- Store time $2 \times \tau_\mu \sim 160 \mu\text{s}$ (87% of stored muons will decay)
- 0.008 μ/POT
- Delivers beams of $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$ from the decay of 3.8 GeV stored μ^\pm
- Known flavour composition and $<1\%$ neutrino flux precision
- Precise CP-conjugate beams from storing μ^+ and μ^-
- Can access **all** of these channels with % or better accuracy:

$$\nu_\mu \rightarrow \nu_\mu$$

$$\nu_e \rightarrow \nu_e$$

$$\nu_\mu \rightarrow \nu_e$$

$$\nu_e \rightarrow \nu_\mu$$

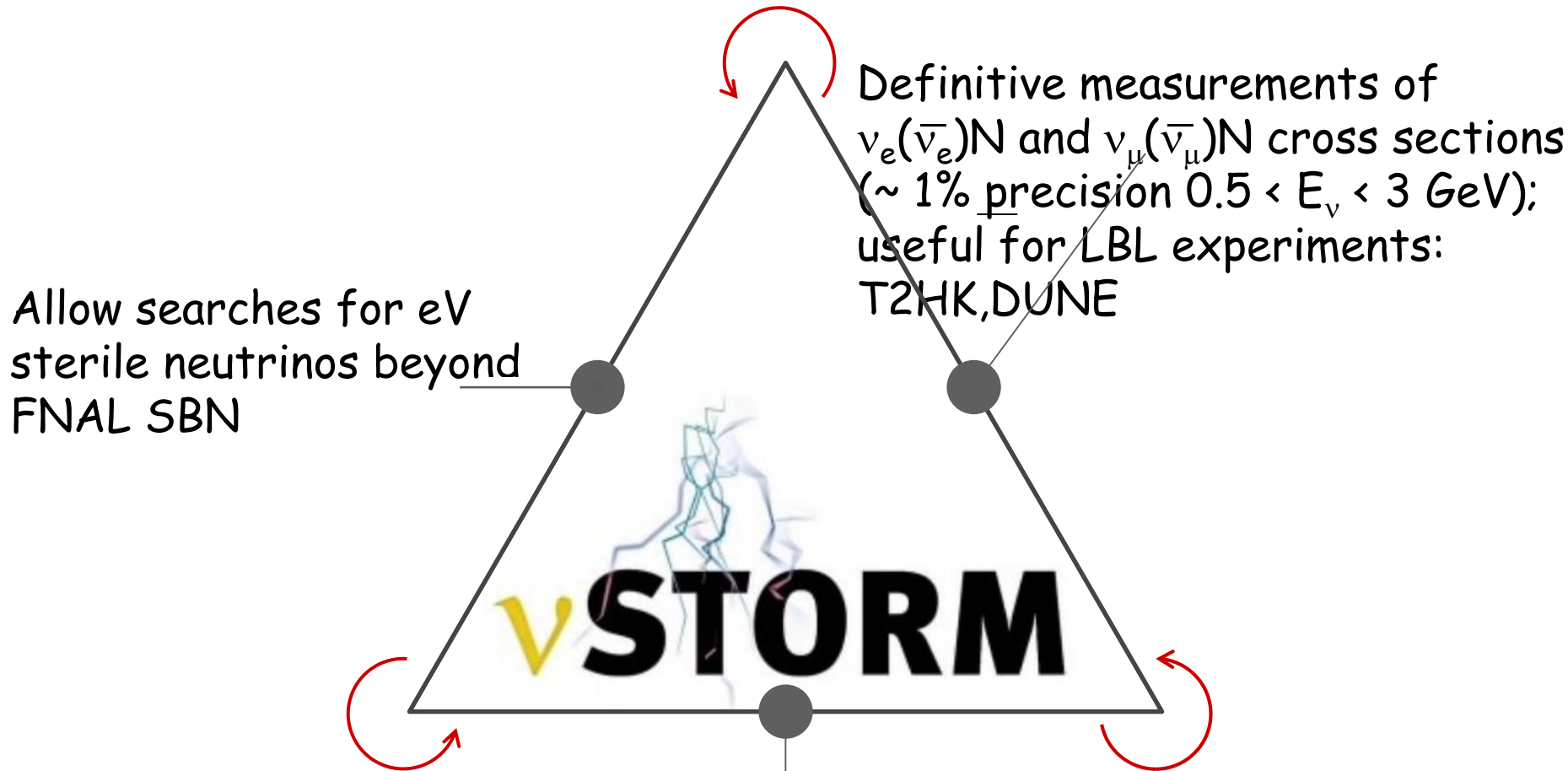
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$

$$\bar{\nu}_e \rightarrow \bar{\nu}_e$$

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$$

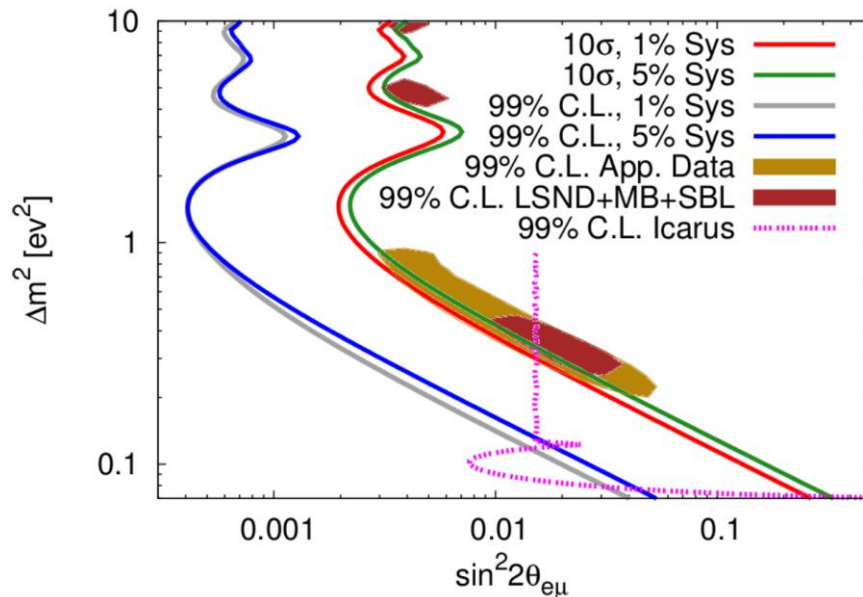
The nuSTORM Triangle



NF/HEP muon accelerator proving ground: first operational use of a muon storage ring as a ν source; testbed for 6D cooling experiment beyond MICE ($10^{10} \mu/\text{pulse}$ 100-300 MeV/c beam)

Sterile neutrino search

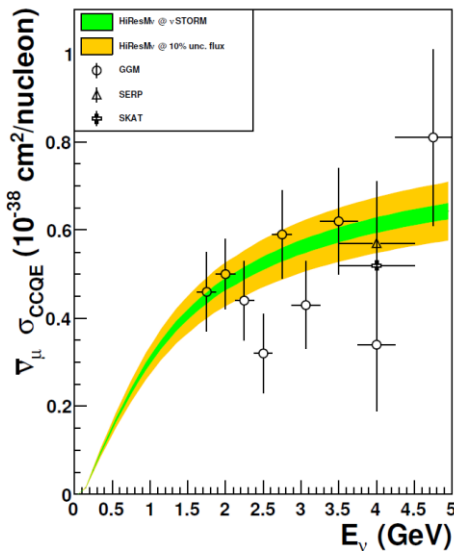
An example: $\nu_e \rightarrow \nu_\mu$ appearance search



- Very good discovery potential
- 3+1 model for sterile neutrinos
- 10^{21} POT + SuperBind detector

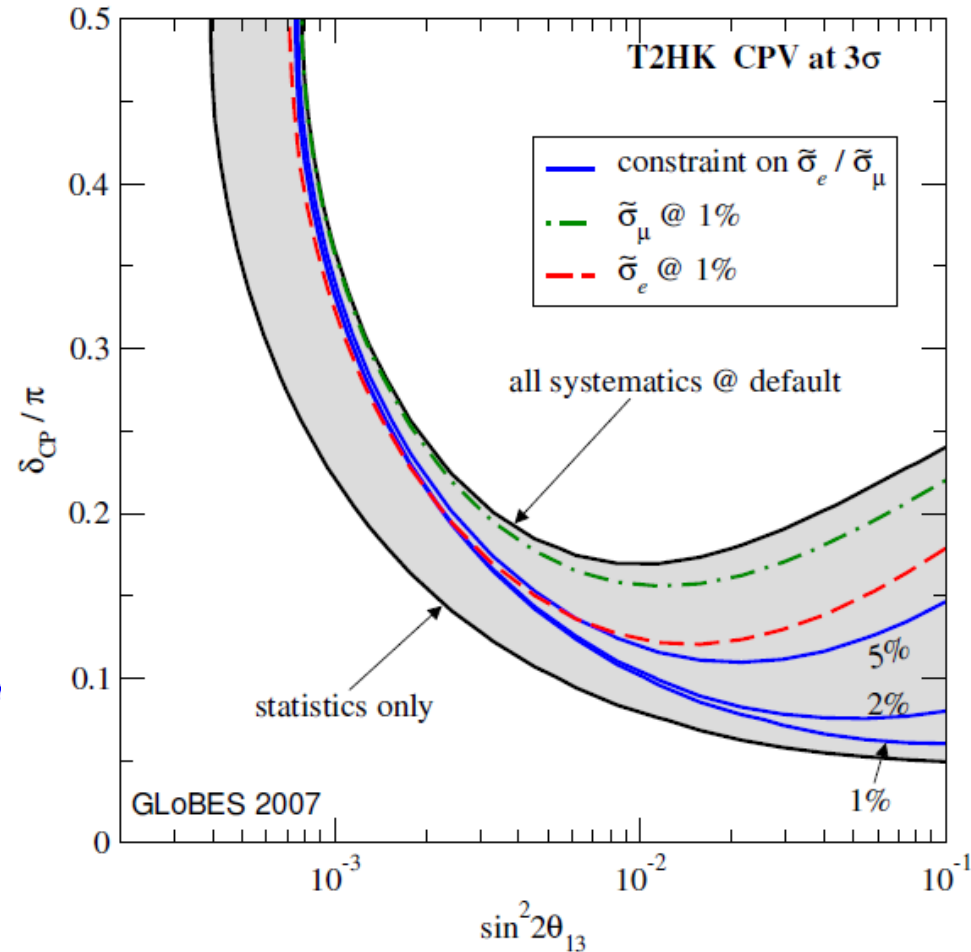
ν cross-sections at nuSTORM

- Negligible ν_e cross-section measurements at accelerator energy regimes



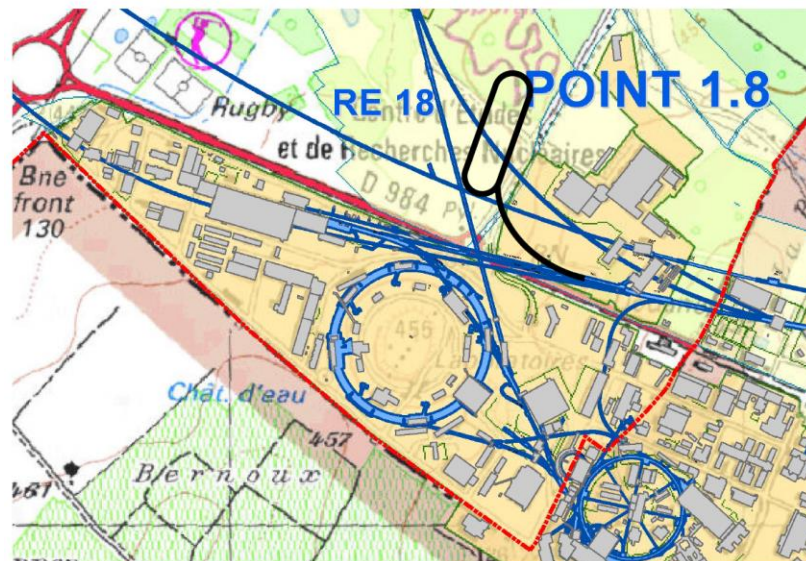
- $\nu, \bar{\nu}$ cross-sections are essential for CP sensitivity in appearance experiments
- Only nuSTORM can provide 1% level of precision
 - Intense ν_e source
 - Well known fluxes
 - $\nu, \bar{\nu}$ sources
 - ν_μ and ν_e

P. Huber, M. Mezzetto, T. Schwetz



nuSTORM AT CERN

- **Blue solid** lines existing tunnels and transfer lines serving CERN WA
- **Black solid** lines: transfer line+storage ring location for nuSTORM
- Principal issue: SPS spill is 10 μ s \rightarrow FAST extraction



nuSTORM at CERN: exploratory study including:

- SPS requirements
- Beam-line
- Target complex
- Horn
- Siting
- Civil engineering
- Radio-protection implications (similar studies also at FNAL)

Conclusions

- The Muon Ionization Cooling Experiment (MICE) was constructed at RAL and collected 350 million triggers to fully characterise ionization cooling
- **MICE** is studying ionization cooling in detail: evolution transverse emittance beam amplitudes, multiple Coulomb scattering, energy loss, reverse emittance exchange
- All main technologies required for neutrino factory and muon collider have now been demonstrated: ionization cooling (MICE), liquid mercury target (MERIT), Fixed Field Alternating Gradient accelerators (EMMA)
- **NuSTORM** will create a neutrino beam from a stored μ^{\mp} beam and will
 - Allow searches for sterile neutrinos
 - Measure scattering cross sections at per-cent level
 - Represents the simplest implementation of the Neutrino Factory concept & way to 6D cooling exp after MICE

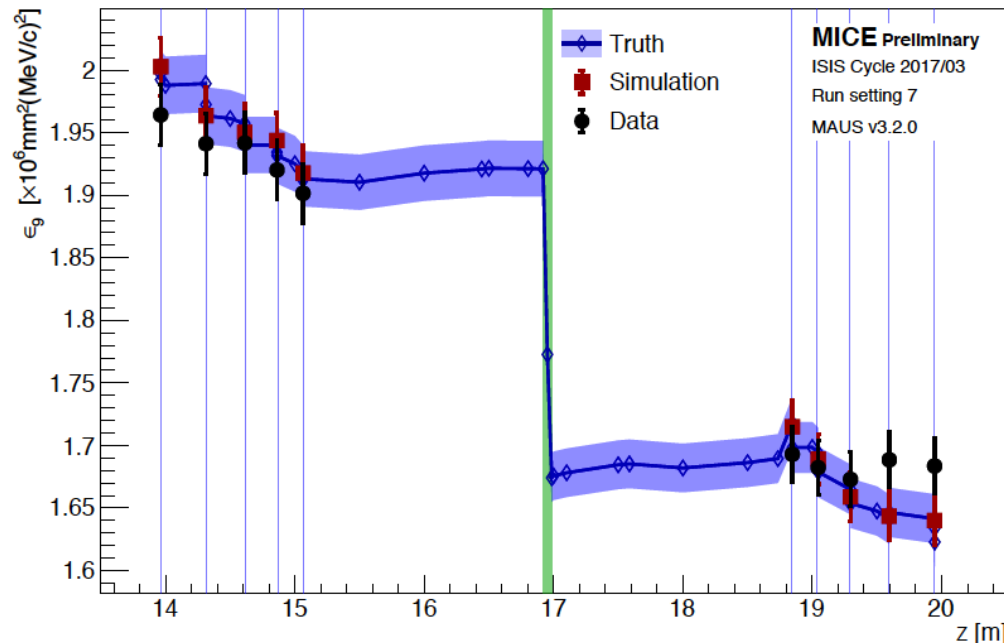


Emittance evolution: demonstration of ionization cooling via frac emittance

- Fractional emittance is phase-space volume occupied by fraction α of beam ($\alpha=9\%$ is 1σ of 4D phase space)

$$e_a = \frac{1}{2} (pmce_T)^2 \Rightarrow \frac{De_a}{e_a} \approx \frac{2De_T}{e_T}$$

- Fractional (9%) emittance evolution 6 mm, 140 MeV/c, LiH, flip

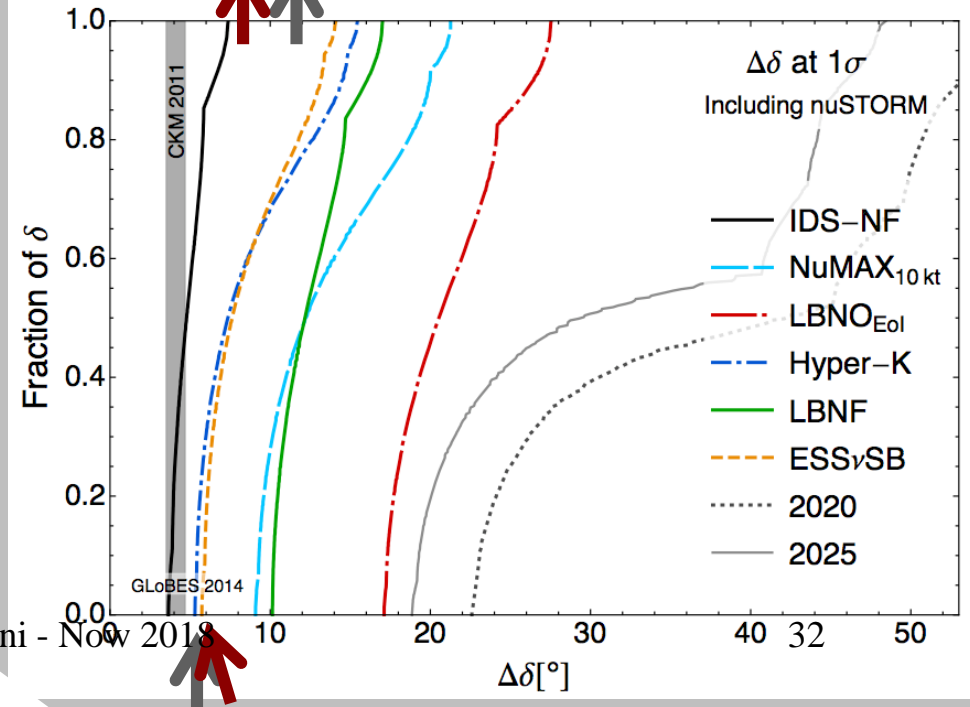
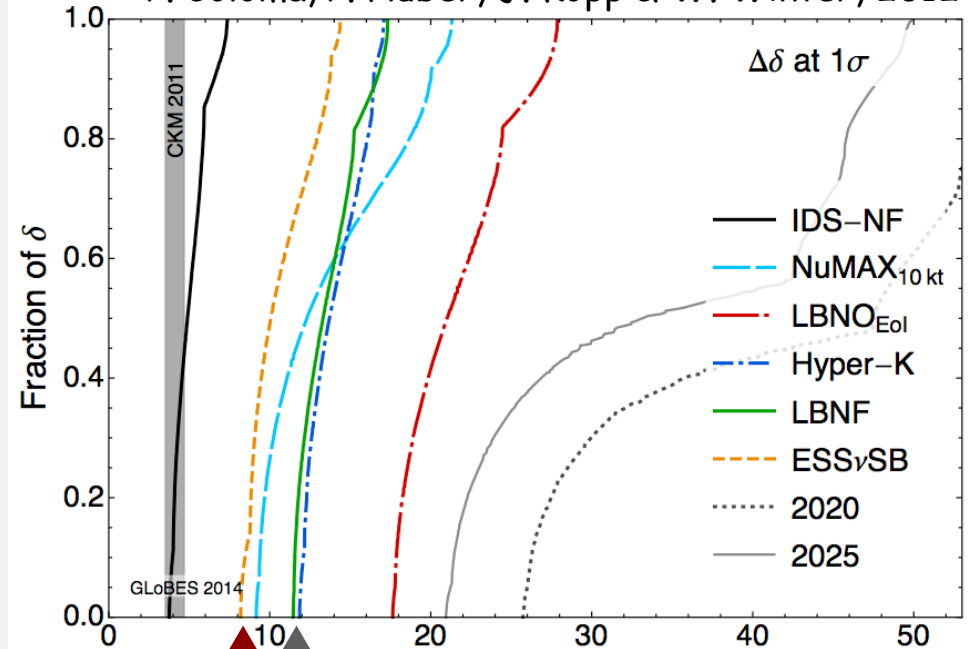


**Also shows
ionization
cooling!**

Performance with nuSTORM

Without cross-section measurements from nuSTORM

With cross-section measurements from nuSTORM



Superbeams close in on CKM-level precision