SLAC Experimental Seminar

First Observation of Ionization Cooling

A Milestone in the Development of High Brightness Muon Accelerators

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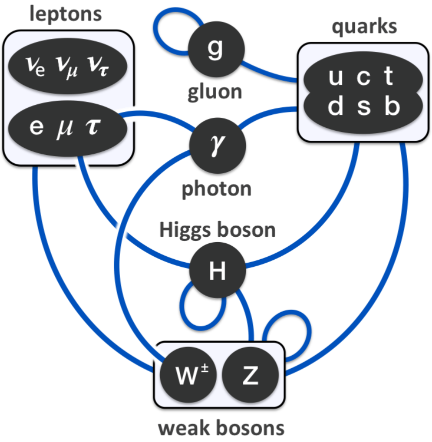
State of the art



Standard Model (SM)

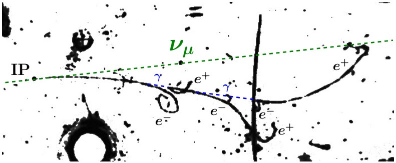
Most successful and predictive theory in the history of particle physics

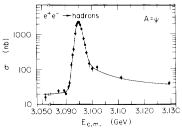
Ties in **all fundamental forces** relevant to small scale: EM, weak and strong

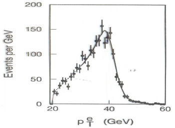
Synergistic development of accelerator technologies and SM. Chronology:

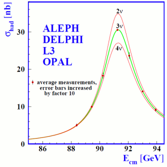
- Neutral current (CERN PS, 1973)
- Charm, J/ψ (**SLAC** and BNL, 1974)
- W and Z boson (CERN S$p\bar{p}$S, 1983)
- Z width (CERN LEP, 1989-1994)
- Top (FNAL Tevatron, 1995)
- Higgs bosons (CERN LHC, 2012)

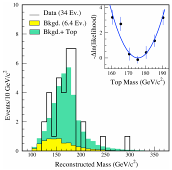
Predictions of cross section for particle production and decay processes with unprecedented accuracy

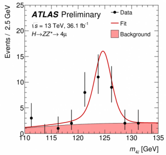


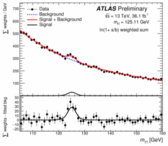












Beyond the Standard Model

The Standard Model is finally complete... with some caveats:

- **Neutrino masses**
- No cold dark matter
- No matter/antimatter asymmetry

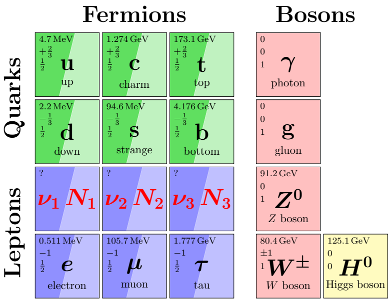
→ The theory must be extended to account for these experimental observations

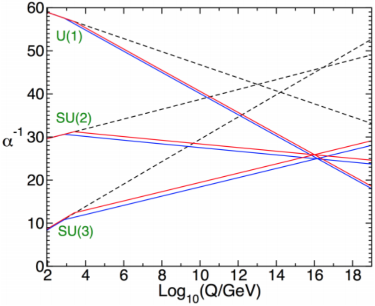
The **neutrino minimal SM** (νMSM) is an attractive first extension:

- Adds heavy sterile RH neutrinos
- Provides DM candidate
- Gives lead on M/AM asymmetry

Other possible extensions:

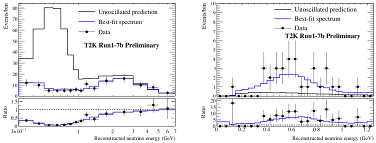
- SUSY (gauge coupling unification)
- Theory of Everything (add gravity)





Neutrino oscillations

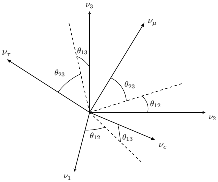
Most compelling evidence of extension of SM in many channels. E.g. T2K ⟶



Neutrinos have mass, flavour states ≠ mass states, mix through PMNS matrix:

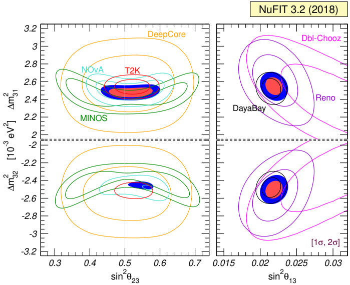
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$.

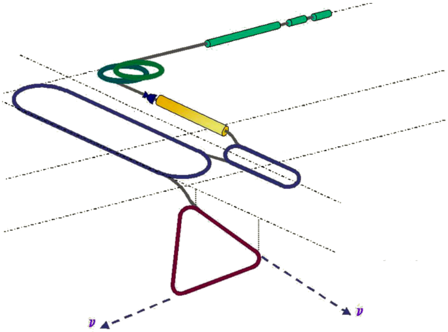


What are we missing ?

- CP violating phase, δ (violation ?)
  - Violation preferred at 2–3 σ
- Mass ordering (normal/inverted ?)
  - Normal preferred at $3.5\,\sigma$
- Nature of neutrino mass (Majorana and/or Dirac ?)
- Heavy sterile neutrinos ?



Muon accelerators



Neutrino Factory

Simple idea: use muon decays as an exquisitely clean source of neutrinos

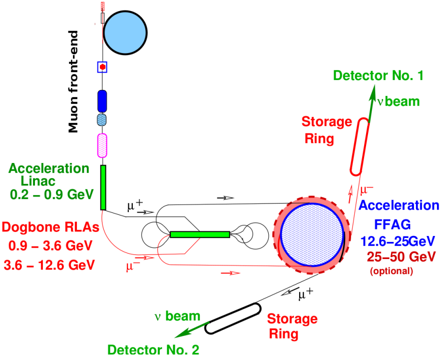
$$\mu^+ \to e^+ + \boldsymbol{\nu_e} + \boldsymbol{\bar{\nu}_\mu}$$
$$\mu^- \to e^- + \boldsymbol{\bar{\nu}_e} + \boldsymbol{\nu_\mu}$$

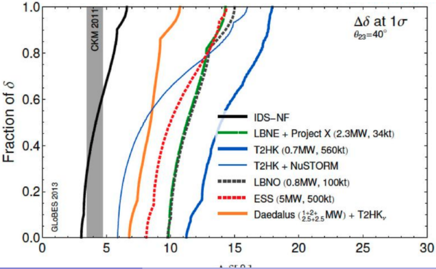
Advantages over “super-beams”:

- No wrong sign background
- Well known flux (Michel spectrum)
- Unprecedented $\nu_e/\bar{\nu}_e$ flux ($10^{21}\nu_e$/yr)

Precision era of neutrino physics:

- 0.5 % on Δm^2_{13}
- Guaranteed CPV ($\pm 5^\circ$ on δ, = CKM)
- Guaranteed mass hierarchy at $5\,\sigma$
- Test PMNS unitarity ($\nu_e \to \nu_\tau$)
- **Cross-section better than 1 %**





Muon Collider, energy frontier

Circular e^+e^- colliders limited by synchrotron radiation. Radiated power:

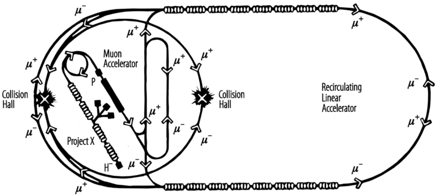
$$P = \frac{1}{\boldsymbol{m^4}} \frac{e^2 \boldsymbol{p^4}}{6\pi\epsilon_0 c^3 \boldsymbol{r^2}}.$$

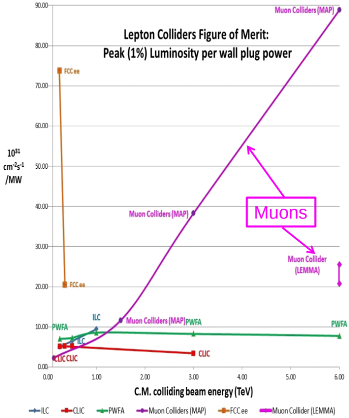
Muons are $200\times$ heavier than $e^\pm$, loose energy $\sim \mathbf{10^9}$ **times** less:

- Higher energy reach (frontier)
- Higher luminosity/MW for > 1 TeV
- Smaller footprint, easier staging

Energy frontier ($\rightarrow$10 TeV?):

- Higher energy and unprecedented precision tests of the SM
- Extend search for supersymmetry
- Running of coupling constants
- Discovery of dark matter





Muon Collider staging: Higgs factory

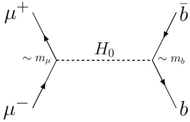
SM Higgs candidate at the LHC:

- Mass of $125.09 \pm 0.24\,\text{GeV}/c^2$
- Width < 0.013 GeV$/c^2$ at 2σ C.L.
- Z, W, b, τ, γ couplings to 10-24 %
- Even integer spin

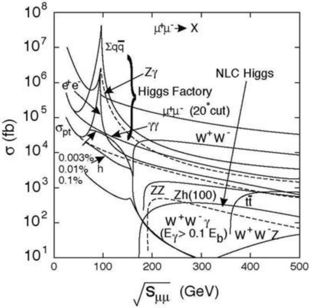
$\rightarrow$ Need **lepton machine** to improve resolution on couplings and width, may hint at BSM physics

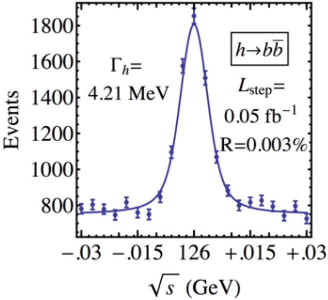
Muon Collider:

- Larger muon coupling allows for Higgs production through s-channel



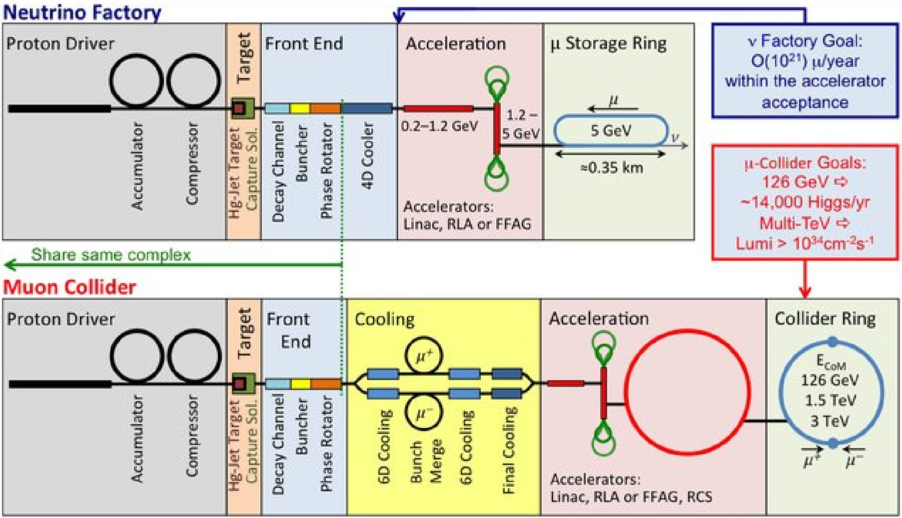
- $\sigma \simeq 40\,$pb, same as LHC at 14 TeV
- $\sim$MeV resolution on Higgs width





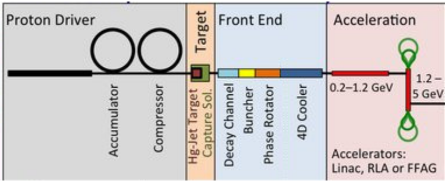
Neutrino Factory and Muon Collider front-ends

Both facilities share the same front-end:

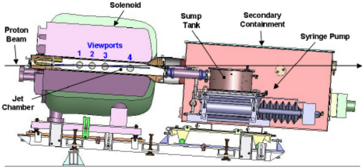


Status of R&D

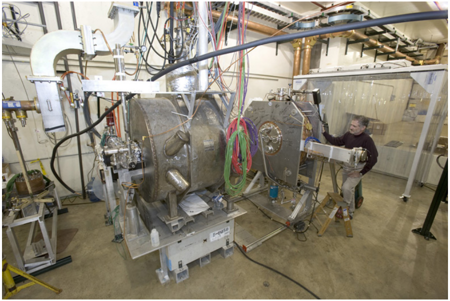
Muon facility front-end



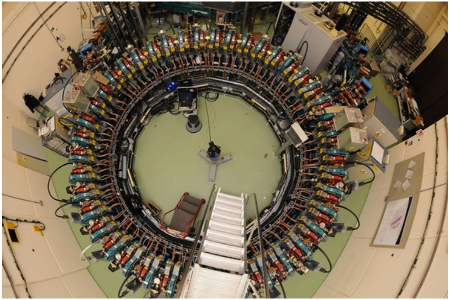
MERIT (MW-class target)



MuCool Test Area (RF in high B)



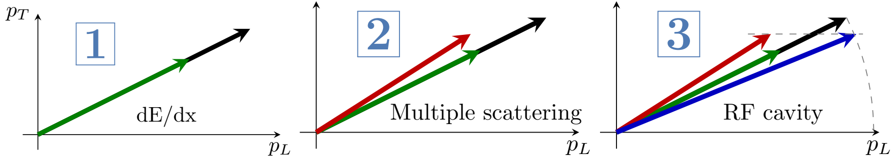
EMMA (Non-Scaling FFAG)



→ **Cooling only missing piece of the puzzle...**

Ionization cooling

Only viable method to cool a muon beam within muon lifetime ($\sim 2.2\,\mu$s)



1. energy loss, dE_μ/dz, reduces p_L and p_T;
2. multiple scattering simultaneously increases the angular spread;
3. RF cavities restore p_L only, effectively reducing the angular spread.

Rate of transverse normalised emittance change approximated by:

$$\frac{d\epsilon_\perp}{dz} \simeq \underbrace{-\frac{1}{\beta^2}\frac{\boldsymbol{\epsilon_\perp}}{E_\mu}\left|\frac{dE_\mu}{dz}\right|}_{\textbf{Cooling}} + \underbrace{\frac{(13.6\,\text{MeV})^2}{2\beta^3 E_\mu m_\mu c^2}\frac{\boldsymbol{\beta_\perp}}{\boldsymbol{X_0}}}_{\textbf{Heating}}$$

$\rightarrow$ Minimize $\boldsymbol{\beta_\perp/X_0}$ by placing a **low Z absorber at a tight focus**.

Muon Ionization Cooling Experiment (MICE)

Ionization cooling has **never been observed experimentally**.

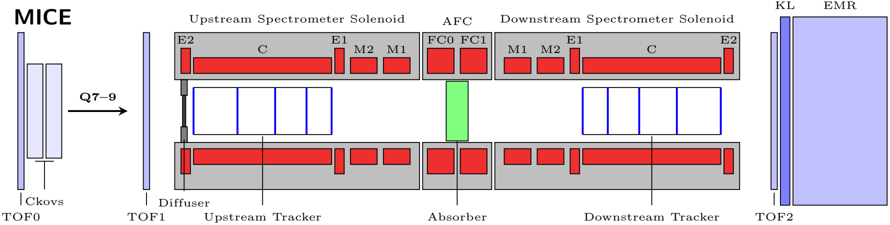
MICE designed as a **proof-of-principle** of ionization cooling. Goals:

- build and operate a realistic section of a cooling channel;
- measure a significant increase in phase space density of a muon beam.

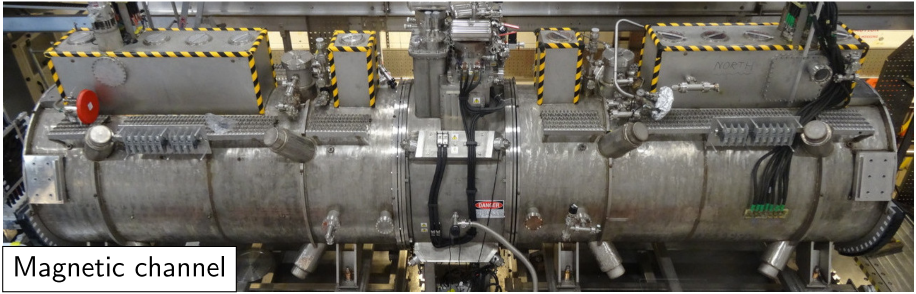
Comprehensive set of instruments:

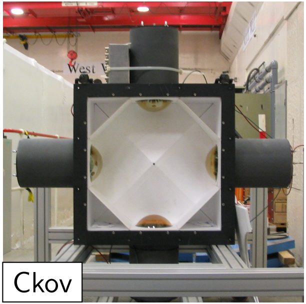
- Thorough particle identification system to select muons
  - Time-of-flight detectors, Cherenkov threshold counters and calorimetry
- Scintillating fibre trackers to reconstruct phase space of muons

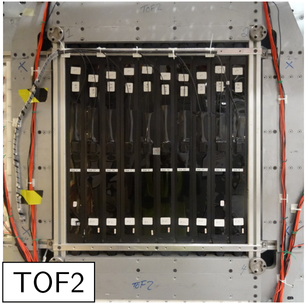
Cooling channel section comprises a single low-Z absorber module (LiH or LH_2) placed at the focal point of a pair of superconducting magnets.

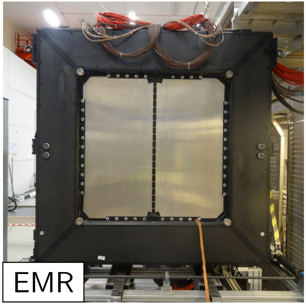


MICE in pictures









Muon beam

MICE operates parasitically on the 800 MeV ISIS p^+ synchrotron at RAL

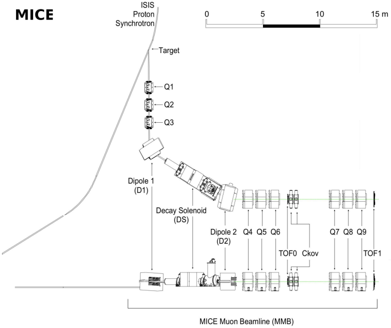
- Ti target dipped in p^+ beam halo
- π^+ momentum selected at D1
- $\pi^+ \to \mu^+ + \nu_\mu$ decays between D1 and D2
- μ^+ momentum selected at D2

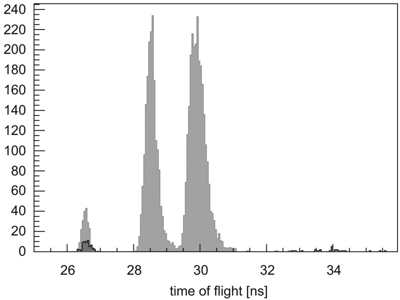
Beam line typically set to select same momentum at D1 and D2 (*pionic*)

At momenta of 140–240 MeV/c, time-of-flight very strong identification variable:

$$\frac{t_\mu}{t_\pi} = \frac{E_\mu}{E_\pi} = \frac{\sqrt{1+m_\mu^2c^2/p^2}}{\sqrt{1+m_\pi^2c^2/p^2}}$$

EMR rejects muon decays in flight (JINST 10 (2015) P12012)





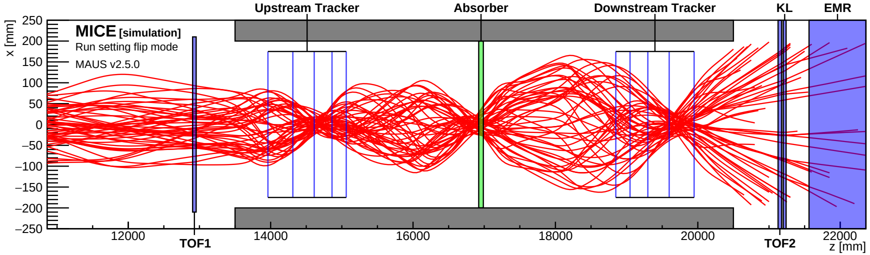
Single-particle experiment

MICE is a single-particle experiment, i.e.

- No "beam" going down the beam line, particles pass through the experiment "one-by-one" ($f \sim 200$ kHz for 1 ms every 1 s $\rightarrow \sim 30$ fA)
- At each DAQ cycle, a **single particle track** is recorded
- Particle tracks are bunched at the analysis level to create an **ensemble** of which to reconstruct the phase space distribution

$\rightarrow$ Allows for resolution at the $1\,\%$ level

$\rightarrow$ First particle-by-particle measurement of emittance (arXiv:1810.13224)



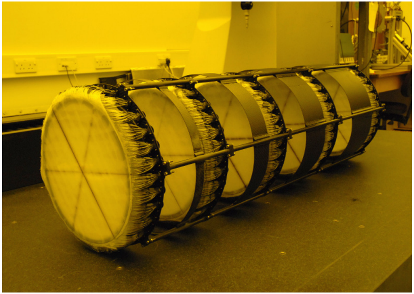
Particle track reconstruction

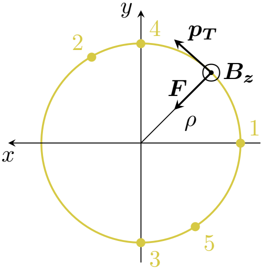
Coordinates of muon, (x, y, p_x, p_y, p_z), reconstructed by fitting helix to muon path inside a uniform solenoid field:

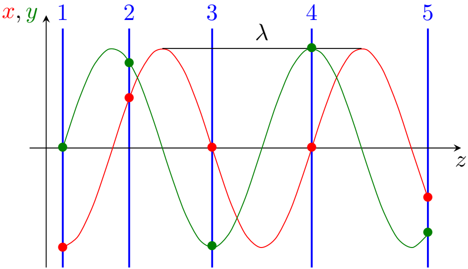
$$p_T = qB_z\rho$$
$$p_z = qB_z\lambda/(2\pi)$$

Resolution in each tracker:

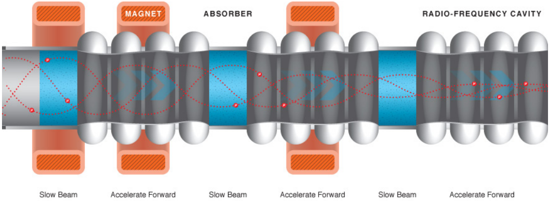
- $\sigma_{x,y} = 467 \pm 2\,\mu$m
- $\sigma_{p_T} \simeq 1.3\,MeV/c$, $\sigma_{p_z} \simeq 4\,$MeV$/c$







Cooling measurement



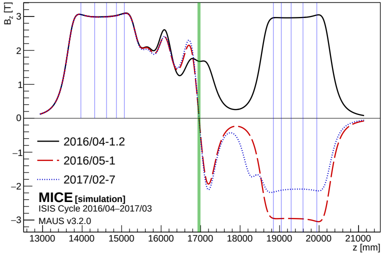
Cooling channel settings under consideration

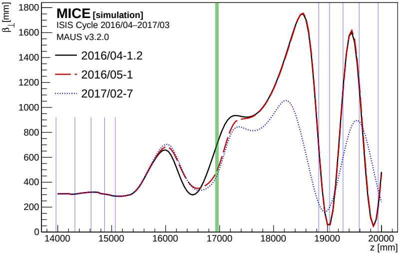
MICE recorded data in a broad set of configurations:

- 4 input $\epsilon_\perp$, 4 momenta, 8 magnet settings (> 100 configurations)

Analysis focused on the **140 MeV/c** data sets taken with the **LiH** absorber

	2016/04-1.2	2016/05-1	**2017/02-7**
Mode	Solenoid	Flip	**Flip**
Momentum [MeV/c]	140	140	**140**
Emittances [mm]	3, 6, 10	3, 6, 10	**3, 6, 10**
$\beta^*_\perp$	~ 800 mm	~ 550 mm	**~520 mm**





Beam selection

Monochromatic muon beam selection:

- Particle time-of-flight compatible with muon;
- Muon track in the upstream tracker and upstream PID system;
- Total momentum upstream in the range $p \in [135, 145]$ MeV/c.

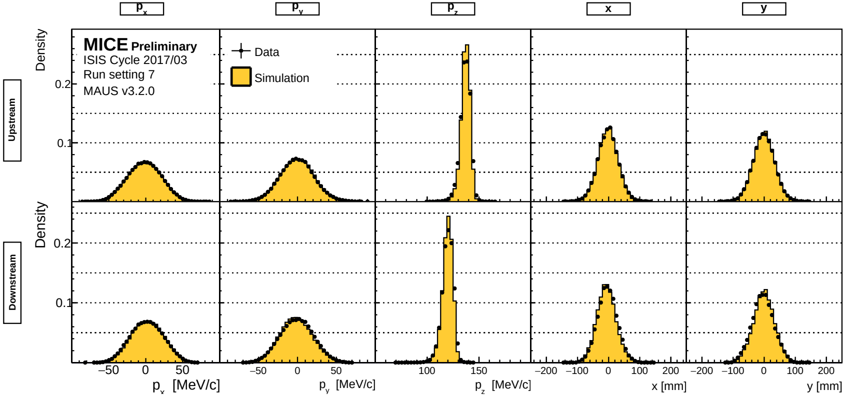


Figure: Phase space profiles of the $\epsilon_\perp = 6$ mm beam the LiH absorber present.

Transverse normalised RMS emittance

Transverse normalised RMS emittance defined as

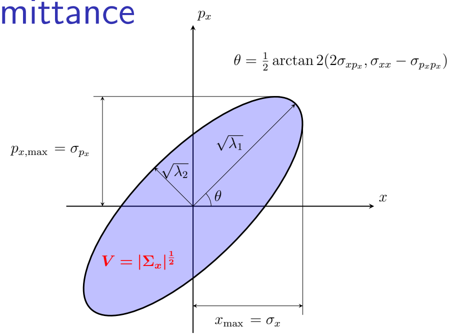
$$\epsilon_\perp = \frac{1}{mc}|\mathbf{\Sigma}_\perp|^{\frac{1}{4}},$$

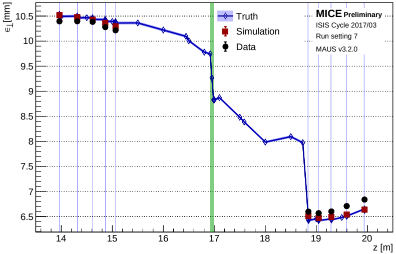
with $|\mathbf{\Sigma}_\perp|$ the determinant of the transverse covariance matrix:

$$\Sigma_\perp = \begin{pmatrix} \sigma_{xx} & \sigma_{xp_x} & \sigma_{xy} & \sigma_{xp_y} \\ \sigma_{xp_x} & \sigma_{p_xp_x} & \sigma_{p_xy} & \sigma_{p_xp_y} \\ \sigma_{xy} & \sigma_{yp_x} & \sigma_{yy} & \sigma_{yp_y} \\ \sigma_{xp_y} & \sigma_{p_xp_y} & \sigma_{yp_y} & \sigma_{p_yp_y} \end{pmatrix}$$

RMS emittance related to the **volume of the RMS ellipsoid** through $\epsilon_\perp = \sqrt{2V_{\text{RMS}}}/(mc\pi)$.

Limitation: Poor estimate if low transmission or non-linearities





Transverse single-particle amplitude

Single-particle amplitude defined as

$$A_\perp = \epsilon_\perp \mathbf{u}^T \mathbf{\Sigma}_\perp^{-1} \mathbf{u} \equiv \epsilon_\perp R^2,$$

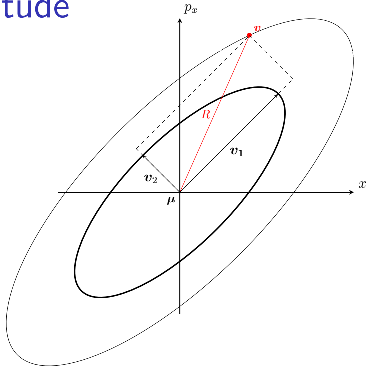
with $\mathbf{u} = \mathbf{v} - \boldsymbol{\mu}$, the centered phase-space vector of the particle.

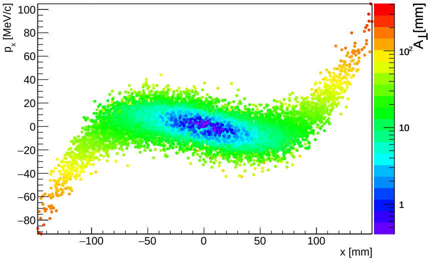
It is the emittance, scaled by the squared Mahalanobis distance, R^2

High amplitudes **iteratively removed** from ensemble to prevent bias by outliers

Particle amplitude closely related to density in a Gaussian beam:

$$\rho(\boldsymbol{v}) = \rho_{\text{max}} \exp\left[-R^2/2\right].$$





Projections (6 mm, LiH absorber)

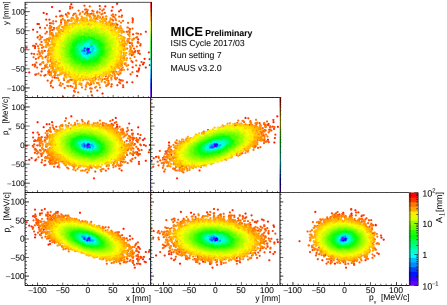
Transverse amplitude, $A_\perp$, reconstructed for each particle in the sample

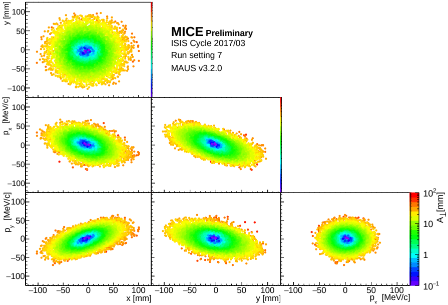
The 4×4 covariance matrix has six off-diagonal elements

- Each element represented by 2D projection of phase space
- Point color represents its amplitude (blue = low)

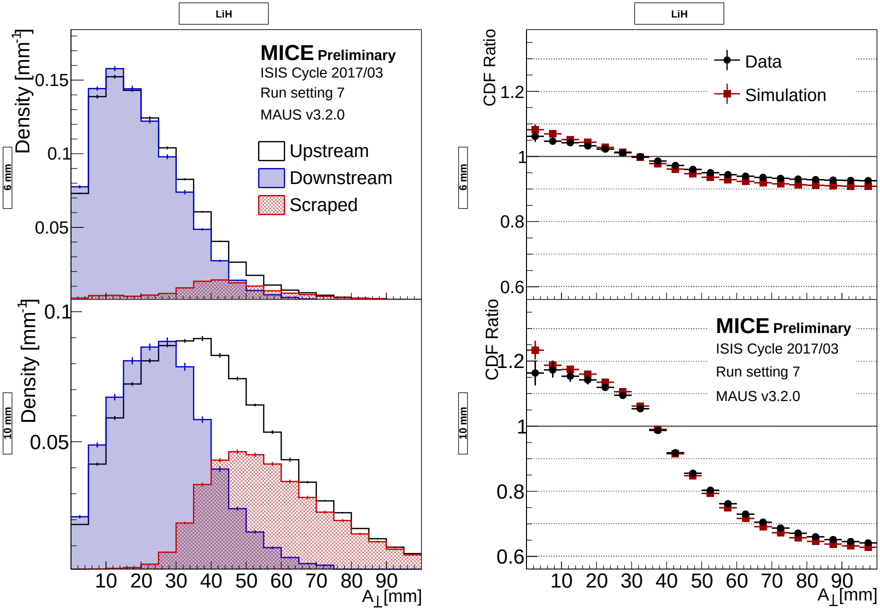
$\rightarrow$ **Allows for the identification of core particles**

$\rightarrow$ **More low-$A_\perp$ particles = Higher core density**





Amplitude distributions



Summary statistics

Several summary statistics studied and viable

	A_α	e_α	ϵ_α
Name	α-amplitude	α-subemittance	α-emittance
Meaning	Quantile of $A_\perp$ dist.	$\epsilon_\perp$ of core	Volume of core
Value $\alpha = 9\,\%$	$\boldsymbol{\epsilon}_\perp \chi_4^2(\alpha)$ $\boldsymbol{\epsilon}_\perp$	$\boldsymbol{\epsilon}_\perp P(3, \chi_4^2(\alpha)/2)/\alpha$ $\sim 0.16\boldsymbol{\epsilon}_\perp$	$V_{\text{RMS}} \chi_4^2(\alpha)$ $\boldsymbol{V}_{\textbf{RMS}}$
σ_x/x $\alpha = 9\,\%$	$g(\alpha)\sqrt{\alpha(1-\alpha)/n}$ $\sim 1.9/\sqrt{n}$	$1/\sqrt{2\alpha n}$ $\sim 2.4/\sqrt{n}$	$2g(\alpha)\sqrt{\alpha(1-\alpha)/n}$ $\boldsymbol{\sim 3.8/\sqrt{n}}$
$\Delta x/x$	δ	δ	$(\delta+1)^2 - 1 \simeq \boldsymbol{2\delta}$

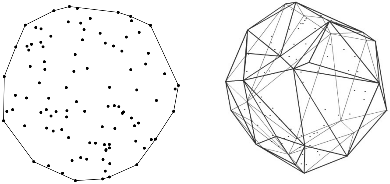
- $P(n, x)$ the regularized Gamma function;
- $g(\alpha)$ a complicated function of α (see dissertation);
- $\delta = \Delta\epsilon_\perp/\epsilon_\perp^u$ is the relative normalised emittance change.

A fraction of $\boldsymbol{\alpha = 9\,\%}$ **is chosen** as it represents the RMS ellipse in 4D.

Fractional emittance evolution

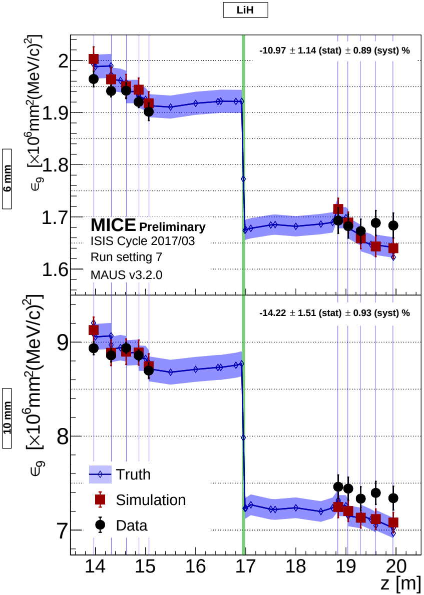
How to reconstruct the volume occupied by set of points? **Convex hull**.

The convex hull of a set of points $\boldsymbol{X}$ is the smallest convex set that contains the set $\boldsymbol{X}$



For Gaussian, relative change:

$$\frac{\epsilon_\alpha^d - \epsilon_\alpha^u}{\epsilon_\alpha^u} = (\delta+1)^2 - 1 \simeq \mathbf{2}\delta.$$



Nonparametric density estimation

Amplitude methods work well for beams with a **Gaussian core**.
Nonparametric DE removes prior assumption on underlying distribution.

Three classes of estimators considered for this measurement

	Histograms	k-Nearest Neighbor	PBATDE
$\rho(\boldsymbol{x})$	$n_i(\boldsymbol{x})/(n\Delta_i)$	$k/(n\kappa_d R_k^d)$	$\frac{1}{M}\sum_{i=1}^{M} \upsilon_i^{-1}$
MISE	$\mathcal{O}(\Delta^{2/d} + 1/(n\Delta))$	$\mathcal{O}((k/n)^{4/d} + 1/k)$	$\mathcal{O}(J^{-4/d} + J/n)$
$d = 4$	$\mathcal{O}(\Delta^{1/2} + 1/(n\Delta))$	$\mathcal{O}(k/n + 1/k)$	$\mathcal{O}(1/J + J/n)$
Convergence	$n^{-2/(2+d)}$	$n^{-4/(4+d)}$	$n^{-4/(4+d)}$
$d = 4$	$n^{-1/3}$	$\boldsymbol{n^{-1/2}}$	$\boldsymbol{n^{-1/2}}$
Speed	**Fast**	**Fast**	Slow

***k*-Nearest Neighbour** (kNN) estimator has highest rate of convergence (on par with the PBATDE) and is the least computationally intensive.

Systematic studies on a broad array of distribution classes showed robustness of the kNN algorithm (see dissertation).

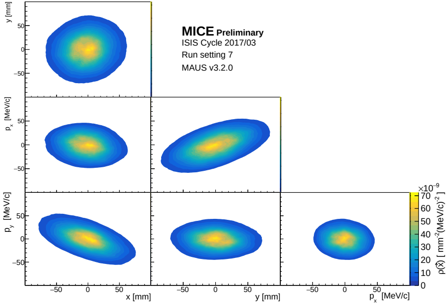
kNN Poincaré sections (6 mm, LiH)

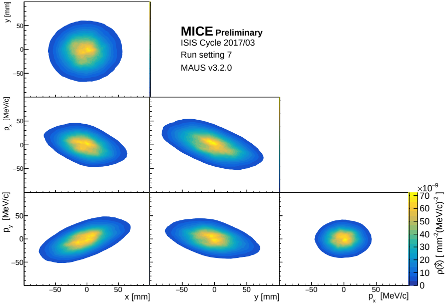
kNN density estimate, $\rho(\boldsymbol{v})$, evaluated over the whole phase space

The 4×4 covariance matrix has six off-diagonal elements

- Each element represented by 2D ‘slice’ of phase space that intersects the origin of the space (Poincaré section);
- Color represents the local density (yellow = high)

→ **Higher density = More muons in that region**





Contour levels

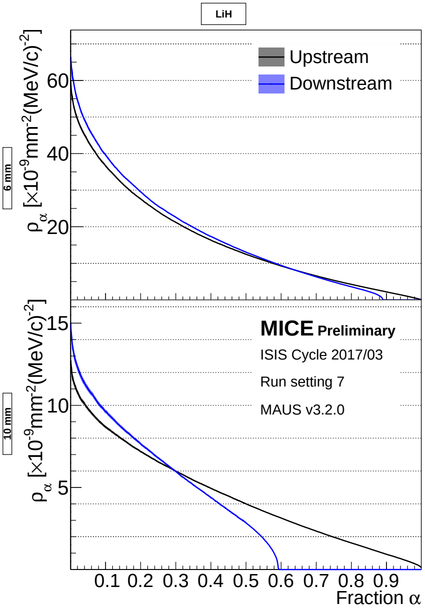
Goal: Need a 1D density profile of the a 4D phase space to compare the output to the input.

Challenge: The probability density function is unknown; the concept of radius is meaningless. Must find a different quantity.

Solution: Contour levels. For a core fraction α, find the level of the corresponding contour. If the level has raised at a given α, the density of particles has increased.

With F^{-1} the inverse CDF,

$$\rho_\alpha = \rho(F^{-1}(\alpha)).$$



Density level evolution

As a summary statistic, represent evolution of arbitrary contour level → **9 % as it corresponds to the RMS ellipse contour**, ρ_9.

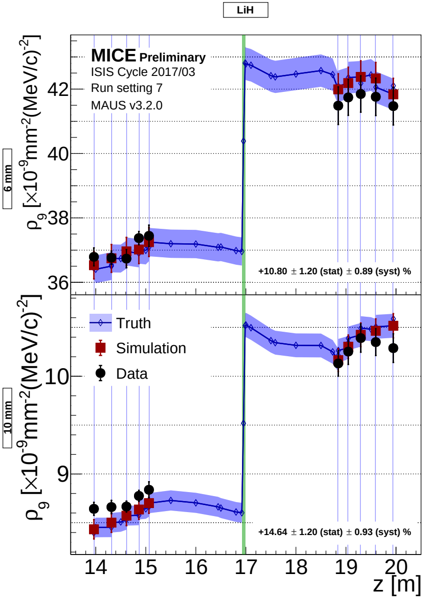
If beam core Gaussian, ratio reads

$$\frac{\rho_\alpha^d}{\rho_\alpha^u} = \frac{|\Sigma_\perp^u|^{\frac{1}{2}}}{|\Sigma_\perp^d|^{\frac{1}{2}}} = \left(\frac{\epsilon_\perp^u}{\epsilon_\perp^d}\right)^2 .$$

and the relative change

$$\frac{\rho_\alpha^d - \rho_\alpha^u}{\rho_\alpha^u} = \frac{1}{(\delta+1)^2} - 1 \simeq \mathbf{-2}\delta,$$

with δ the relative RMS emittance change. If emittance decreases by δ, density increases twice as much.

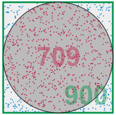


Contour volume evolution

Alternative is to compute the **volume of phase space** that contains the particles above ρ_9, V_9, the generalised fractional emittance.

Pick n points inside 4D box, particle for which $\rho > \rho_\alpha$ inside contour. Contour volume:

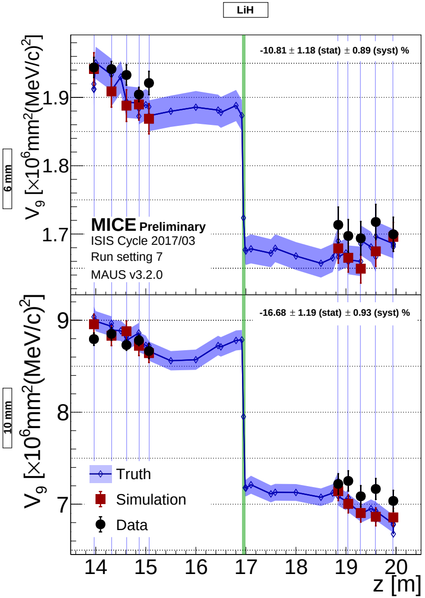
$$V_\alpha = \frac{n(\rho > \rho_\alpha)}{n} V_{box}$$



For Gaussian, relative change:

$$\frac{V_\alpha^d - V_\alpha^u}{V_\alpha^u} = (\delta + 1)^2 - 1 \simeq \mathbf{2}\delta$$

$\rightarrow$ Same as fractional emittance.



Summary of cooling measurement

1. **First measurement** of the increase of phase space density of a muon beam through ionization cooling.
2. **Consistent measurements** achieved using the concept of particle amplitudes and nonparametric density
3. **Excellent agreement** between the observed phase space volume reduction, the simulations and the models

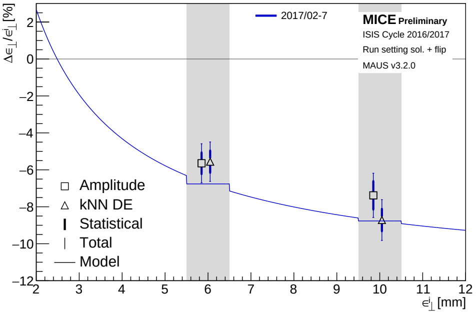
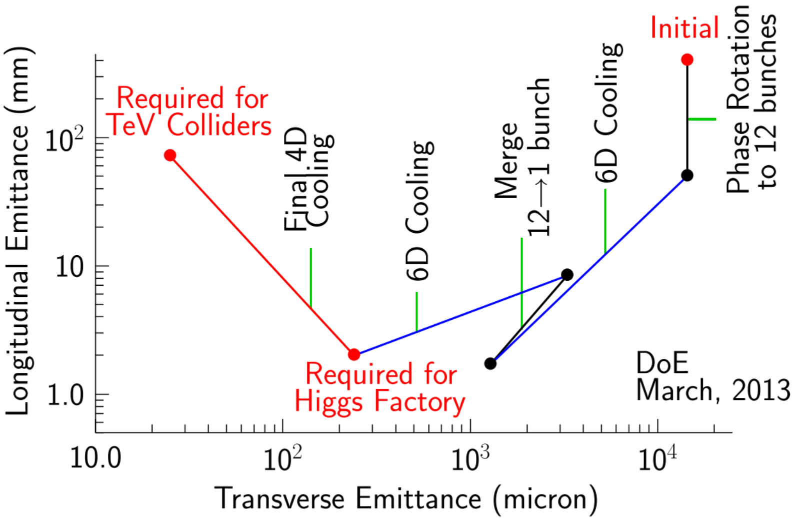


Figure: *Relative emittance change of muon beams through a 65 mm-thick LiH absorber disk, as reconstructed from the volume of the transverse RMS ellipsoid.*

Outlook

The emittance path

Still a long way to go to achieving the necessary cooling for a muon collider



→ Need a **staged approach** to its development

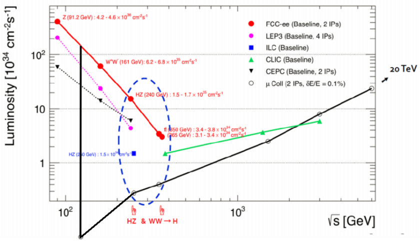
Muon Collider status

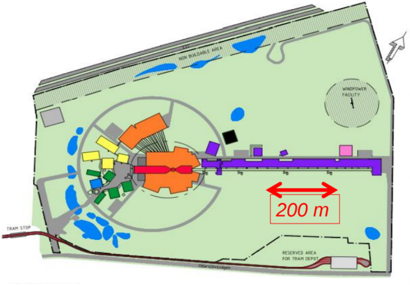
Observations at the **2018 workshop**:

- Need l^+l^- coll. to study Higgs:
  - Muons provide best resolution (line shape / width)
  - Parametric cooling may improve L to 4×10^{32}
- Best option for energy frontier:
  - Smaller footprint / cost
  - Higher reach than hh, ee

Way(s) forward:

- Build a 6D cooling demonstrator
- Proposals for several sites:
  - FNAL (MAP)
  - ESS (5MW proton driver, already have a ν osc. program)
  - CERN (Use LHC ring)





Neutrinos From STORed Muons (νSTORM)

Neutrino factory *lite*:

- 5 GeV pions injected into ring
- Muon decays for ~ 100 turns
- Could use existing facility (MI / SPS / ESS)

Beam characteristics:

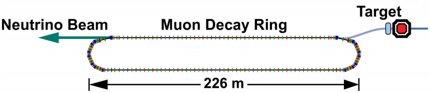
- $\sim 10^{-3}\mu^+$/POT
- Abundant ν_e beam

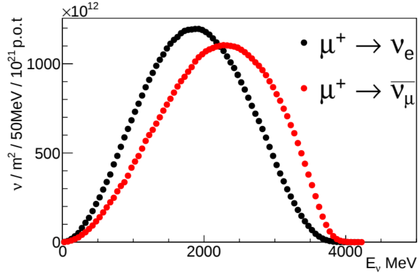
Physics motivations:

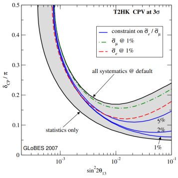
- **Cross section ratio at 1 %**

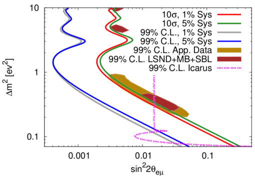
$$\frac{R^{\text{far}}_{\alpha\beta}}{R^{\text{near}}_{\alpha\beta}} \propto \frac{N^{\text{far}}}{N^{\text{near}}}\frac{\boldsymbol{\sigma_\beta}}{\boldsymbol{\sigma_\alpha}}\frac{\epsilon_\beta}{\epsilon_\alpha}P_{\alpha\to\beta}$$

- Study of sterile neutrinos
- Muon accelerator staging









Conclusions

1. **Muon cooling** is (was) the last "in-principle" obstacle for the realisation of a neutrino factory or muon collider
2. **MICE** made the **first observation** of ionization cooling; demonstrating the principle and that simulations at hand agree well with the data
3. Small but **important step** towards the realization of high-brightness muon accelerators.

Thank you to all for your attention!

Backup slides

Neutrino Factory 4D cooling section

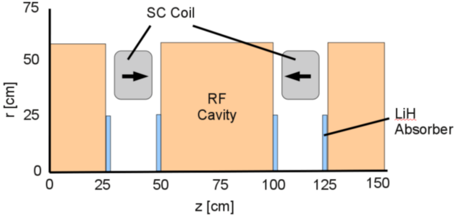
The **80 m cooling section** in the design study (arXiv:1112.2853) contains **fifty 1.5 m cooling cells** of

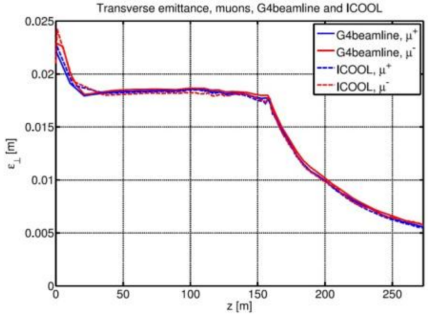
- $4\times$ 1.5 cm-thick LiH absorbers;
- $4\times$ 25 cm RF cavities;
- $2\times$ 2.8 T solenoids in flip mode.

The LiH absorbers provide the energy loss and the RF cavities restore p_L.

The solenoids provide a ~ 0.8 m $\beta_\perp$ function focus at the absorbers.

Overall, the front-end increases the capture rate of muons in the accelerator acceptance **by a factor 10**.





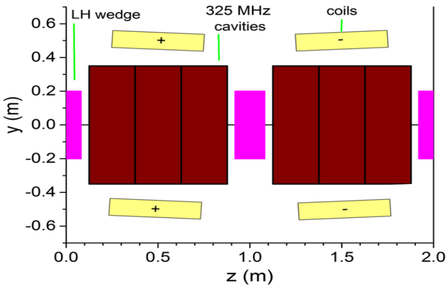
Muon Collider 6D cooling section

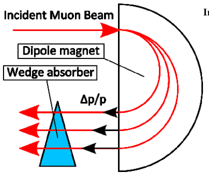
The 6D cooling section in the numerical study (PhysRevSTAB.18.031003) has an initial four stages over 380 m, followed by a bunch merger and eight additional stages over 500 m.

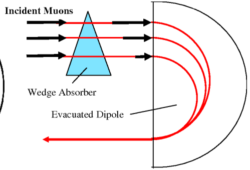
Each stage incrementally decreases its equilibrium emittance. The first stage consists of 66 cells of

- $2\times$ LH_2 wedge absorbers;
- $6\times$ 25.5 cm RF cavities;
- $2\times$ 2.4 T solenoids in flip mode.

Finally, reverse emittance exchange may be used to reach the luminosity required for a multi-TeV collider.







Low EMittance Muon Accelerator

Front-end concept:

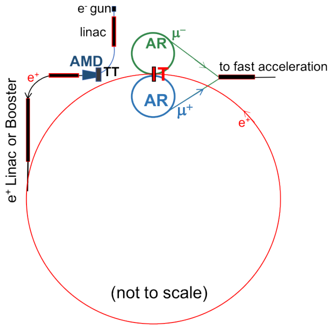
- Accelerate e^+ on target to $\mu^+\mu^-$ production threshold (45 GeV)
- Use thin, low-Z target to limit $\epsilon_\perp$ growth (e.g. 3 mm Be target)

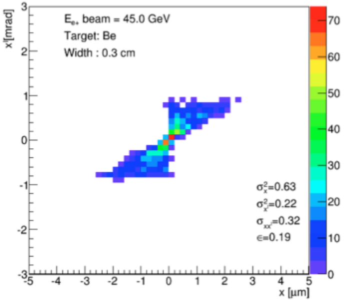
Advantages over MAP approach:

- Does not require cooling
- Low muon losses (multi-GeV muons at production)

Strong limitations:

- Low production rate ($1\,\mu$b XS, $10^{11}\,\mu$/s at best, 100 times lower)
- Higher $\epsilon_{||}$ ($\delta E/E \sim 0.4\,\%$), no opportunity to cool (GeV muons)

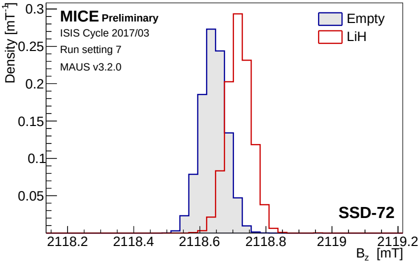


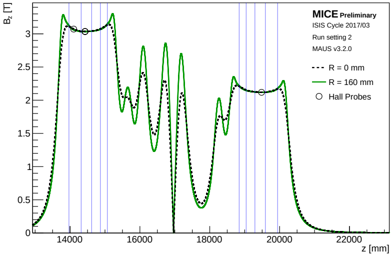


Simulations

Using the MAUS 3.2.0 simulations (latest, thanks DR, DM and PF)

- ~ 100k particles per setting, D2 tuned up to match observed;
- High ρ glue in trackers, matched within the tracker reconstruction;
- Fields scaled up by $1.8\,\%$ in SSU and $1.55\,\%$ in SSD to match the hall probe measurements;
- Hall probe readings stable at the 10^{-4} level between runs.



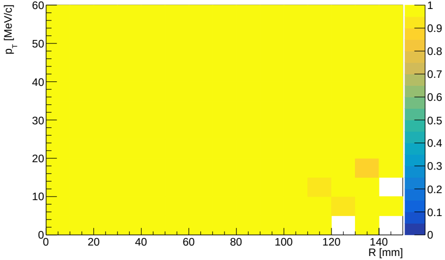


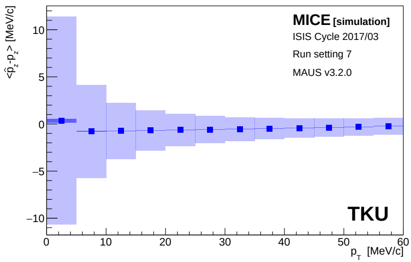
Tracker p_z resolution

The trackers are highly efficient. If a muon goes through their fiducial volume, they almost certainty record a track.

At low p_T, however, the p_z resolution decreases

- → If one applies a momentum cut to preserve monochromaticity, one will inevitably **loose more low p_T tracks**;
- → It creates a **hole** at the centre of the phase space which hinders any hope of recovering an unbiased phase space density.





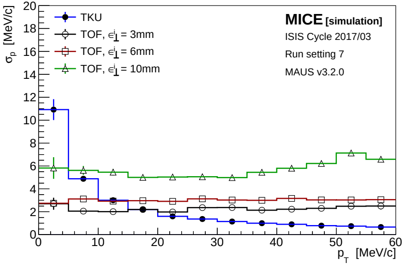
Combined p_z reconstruction

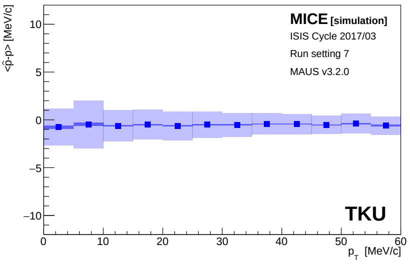
The low p_z resolution is an **inherent limitation** of the tracker technology. If the radius is too small, the uncertainty diverges.

ToF of $\sim 140\,\text{MeV}/c$ particles offers exquisite estimate of p ($\sim 1\,\%$):

- $\rightarrow$ Use it to recover the phase space of low p_T tracks;
- $\rightarrow$ Energy straggling dominant, worse for large $\epsilon_\perp$ beams;
- $\rightarrow$ Use the weighted momentum estimate, scale accordingly.

For the downstream section, propagate the total momentum downstream. Once again, use the weighted average.

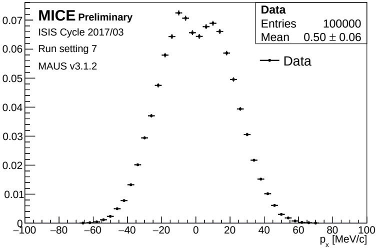


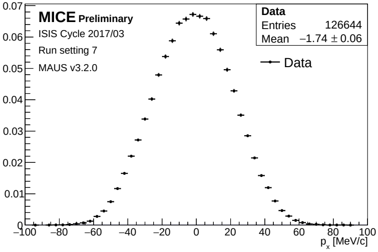


Comparison of the 6 mm beam, TKU S1

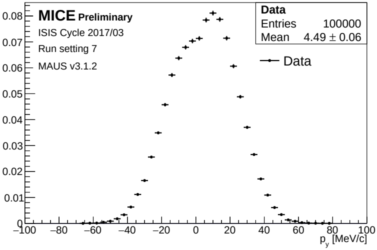
Before fix | After fix

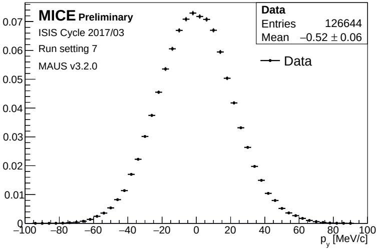
p_x





p_y

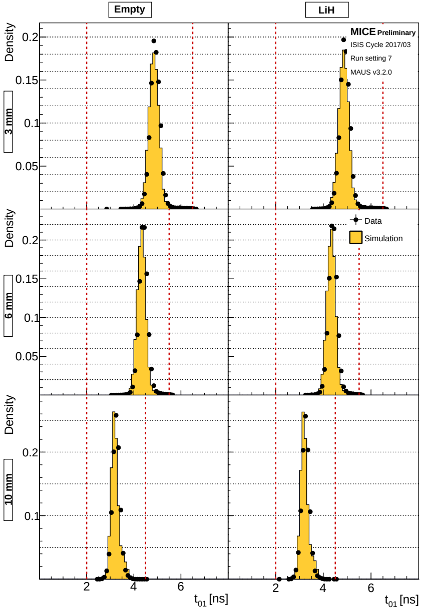




Sample selection

Series of selection criteria applied to the data and the simulation:

- 1 SP in TOF0
- 1 SP in TOF1
- ToF01 compatible with μ
- 1 tracker track (**TKU+TKD**)
- χ^2/ndf < 10 (**TKU+TKD**)
- Fiducial radius $< 150\,$mm (**TKU+TKD**)
- TKU total momentum $\in [135, 145]$ MeV/c
- Energy loss between TOF1 and TKU compatible with μ and true diffuser thickness



2017/02-7 data samples

Each number in the table below represents the amount of tracks that pass the row's cut and that cut alone. **All the data available is included**.

Cuts	No absorber			LiH absorber		
Input $\epsilon_\perp$	3 mm	6 mm	10 mm	3 mm	6 mm	10 mm
None	719334	1458158	1212980	677811	857507	1024734
TOF0 SP	613401	1216732	963969	569998	708432	802106
TOF1 SP	687660	1396488	1126896	646037	820382	946978
Time-of-flight	293958	563262	429728	272118	327895	355393
TKU track	271421	969672	623020	257795	576315	529450
TKU χ^2/ndf	252299	891481	574656	239333	527072	487189
TKU fiducial	268867	962979	595927	255364	572451	506443
TKU Momentum	81103	288399	132168	76067	168826	111180
Energy loss	119744	463164	266932	111700	269547	219638
All US	**54884**	**219146**	**87197**	**50602**	**126644**	**71213**
TKD track	53656	204415	60326	49056	118088	48193
TKD χ^2/ndf	52760	201679	59464	48361	116683	47676
TKD fiducial	53227	195329	51847	47928	114054	42774
All DS	**52368**	**192864**	**51203**	**47271**	**112777**	**42375**

Optical functions

Transversal size of the beam characterized by its **betatron function**:

$$\beta_\perp = \frac{\sigma_{xx} + \sigma_{yy}}{2\epsilon_\perp},$$

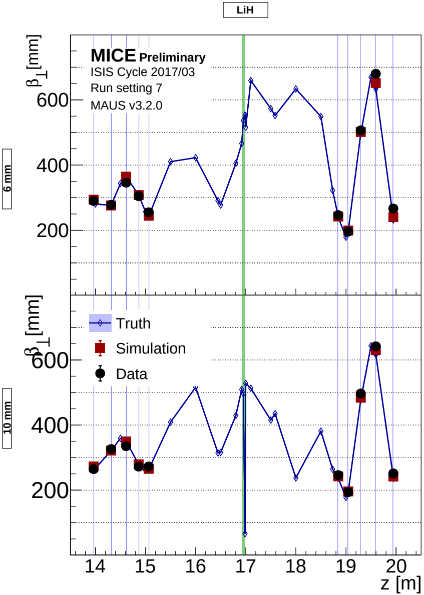
with σ_{xx} and σ_{yy} the variance in the x and y directions.

If the size of the beam is above the aperture, the beam loses particles:

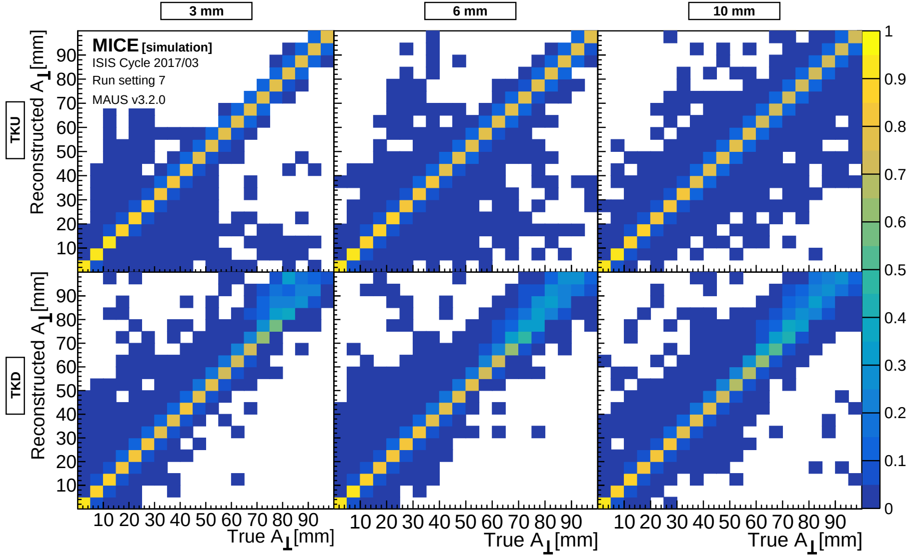
$$\sigma_x \simeq \sqrt{\epsilon_\perp \beta_\perp}.$$

Simulations show:

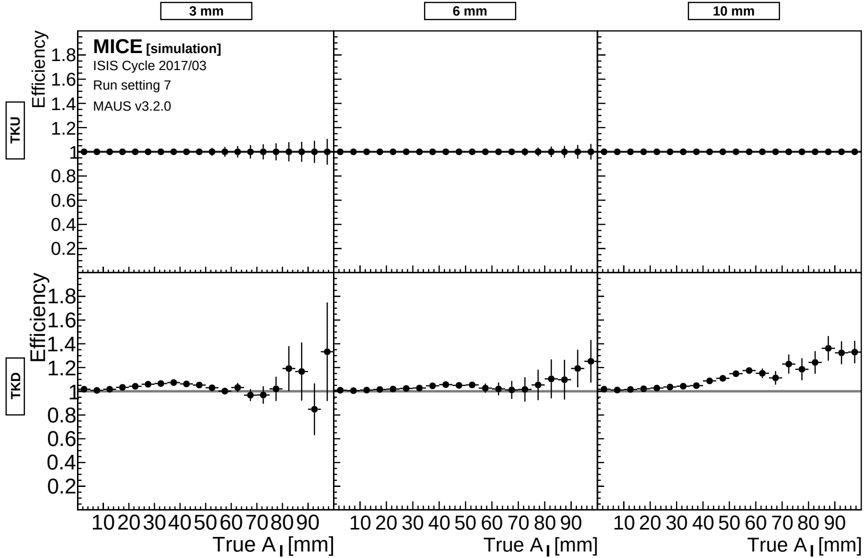
- $\beta_\perp$ well understood
- Absorber beam size as expected



Amplitude reconstruction migration matrix



Amplitude reconstruction efficiency



Systematic uncertainties on the cooling measurement

Main sources of systematic uncertainty:

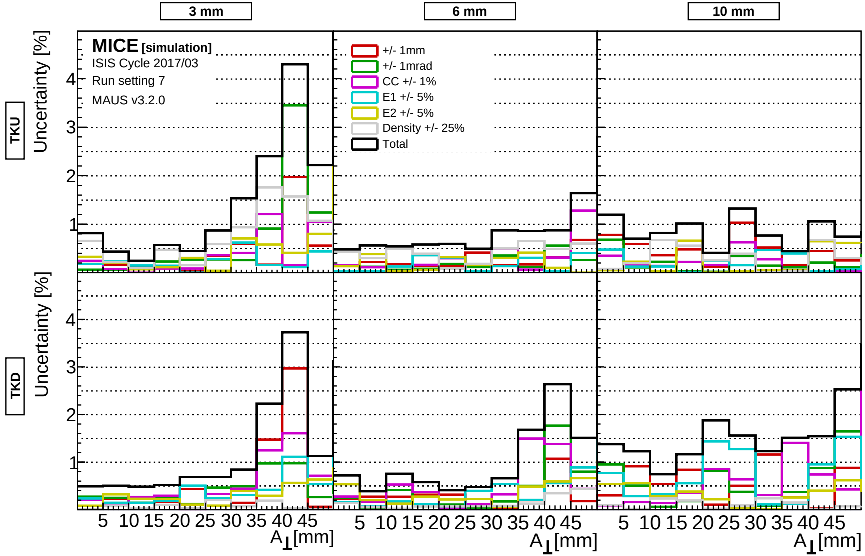
- tracker position offset (± 1 mm);
- tracker rotation offset (± 1 mrad);
- Deviation in CC current (± 1 %);
- Deviation in E1/E2 current (± 5 %);
- Unknown tracker glue density (± 25 %).

For each source, 10^6 muons resampled from the measured distribution. Same cuts applied to the so-produced simulation.

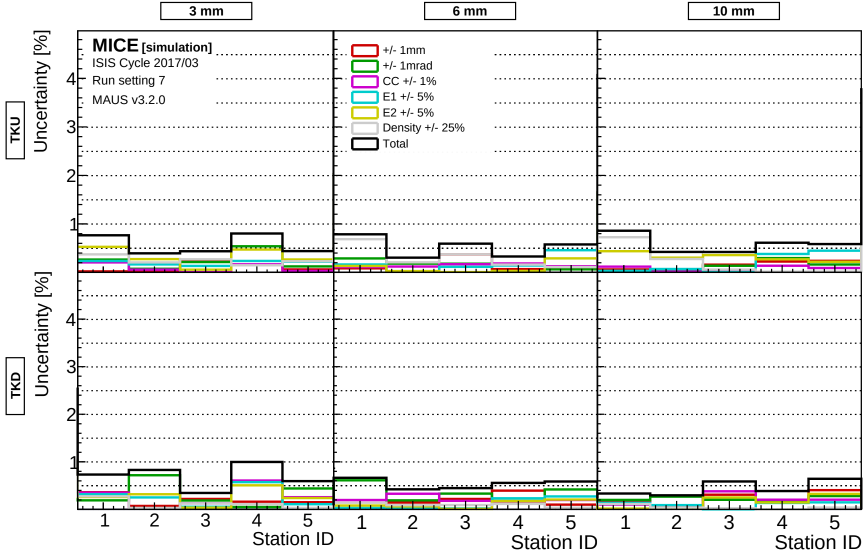
Each quantity represented is computed in each case and a systematic study of the uncertainty is produced.

Next slides show the effect on the amplitude distributions, the fractional emittance and the density estimation for 2017/02-7.

Amplitude distribution systematics



9 % fractional emittance systematics



Density levels systematics