MICE Step 1:
First Emittance Results with Particle Physics Detectors

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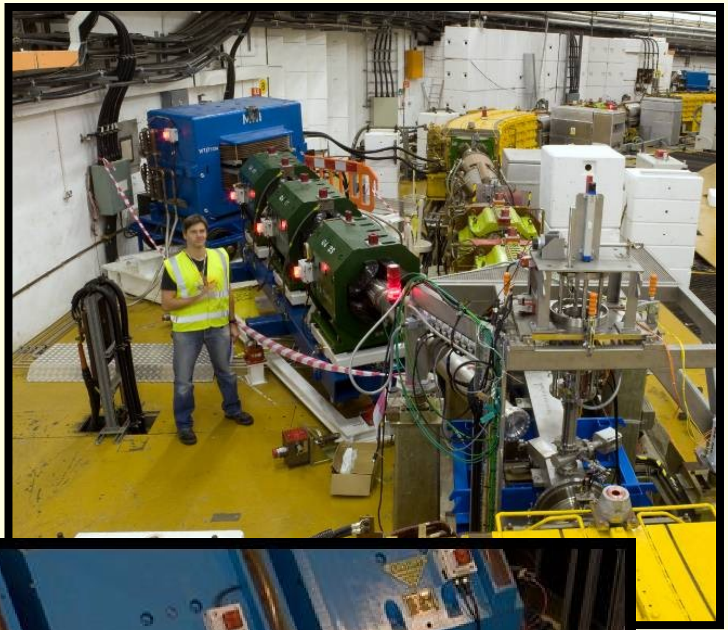
Outline

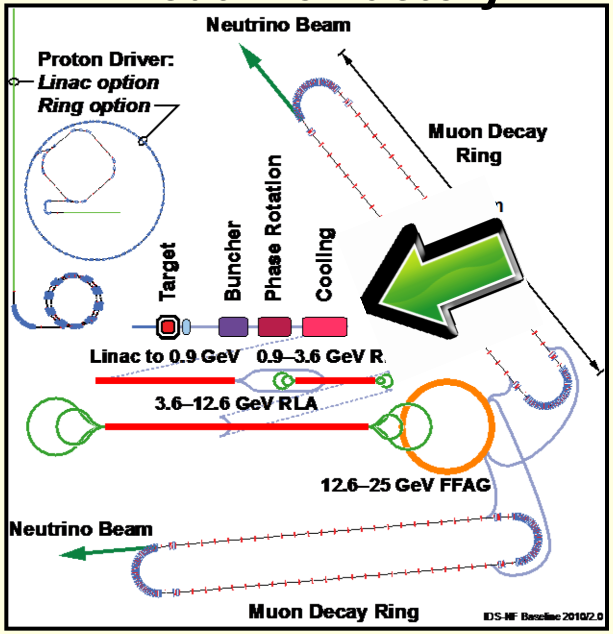
- *Introduction*
- *MICE Description*
- Step 1
- First Emittance Measurement
- Conclusions



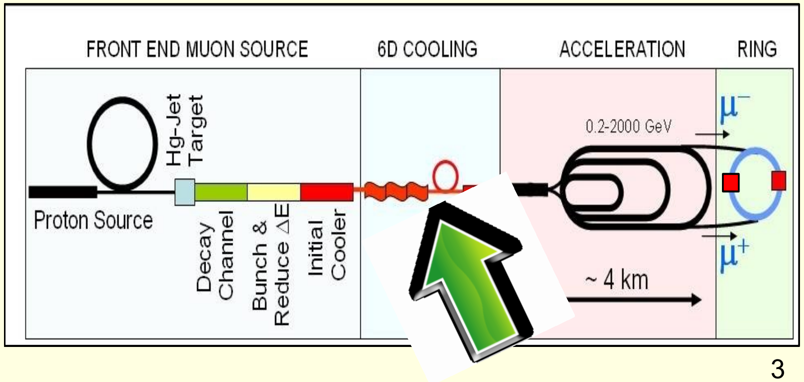
Neutrino Factory and Muon Collider R&D

- Challenges:
  - Intense proton driver
  - Complex target
  - Accelerate muon beams
    - From pion decay
    - Large phase space
      - → ie. High emittance
      - → Need to cool beam
- What do we need?
  - MICE
    - Proof of ionization cooling
  - Target studies (MERIT)
  - RF in magnetic field (MUCOOL)

Neutrino Factory



Muon Collider



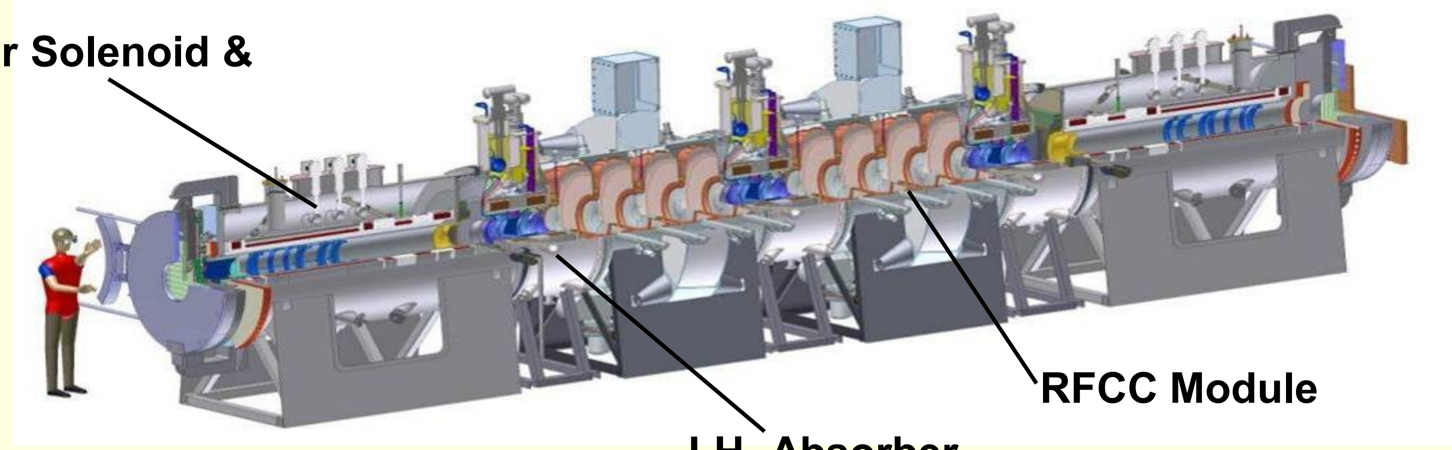
Muon Cooling

- Reduction in normalized emittance (without scraping) is needed for efficient μ beam acceleration & luminosity
- Conventional beam cooling techniques require relatively long time (muon lifetime 2 μs)
- A new solution is required…

- Ionization Cooling
  - Energy loss by ionization (dE/dX)
  - Forward re-acceleration by RF cavities

Cooling is achieved only for low Z material -> Liquid Hydrogen

MICE:
Muon Ionization Cooling Experiment



- **<u>MICE Goals</u>:**
  - Design, build, commission and operate a realistic section of cooling channel
  - Measure its performance in a variety of modes of operation and beam conditions…

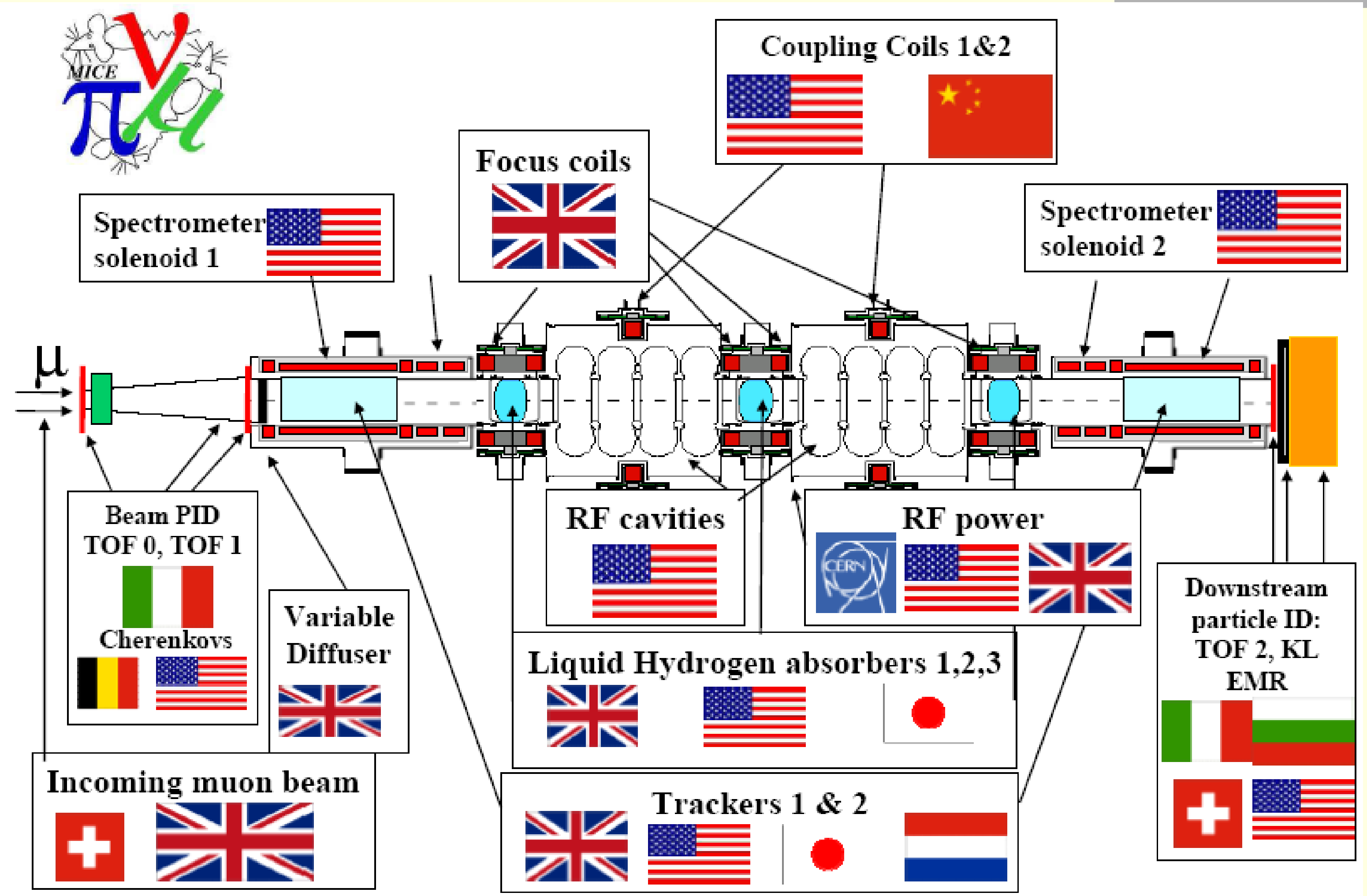
… results will be used to optimize Neutrino Factory and Muon Collider designs.

MICE: Design & Goals

- MICE is designed to produce a 10% cooling effect on the muon beam
- Use particle detectors to measure the cooling effect to ~1%
- Measurements done with muon beams with momentum 140 – 240 MeV/c

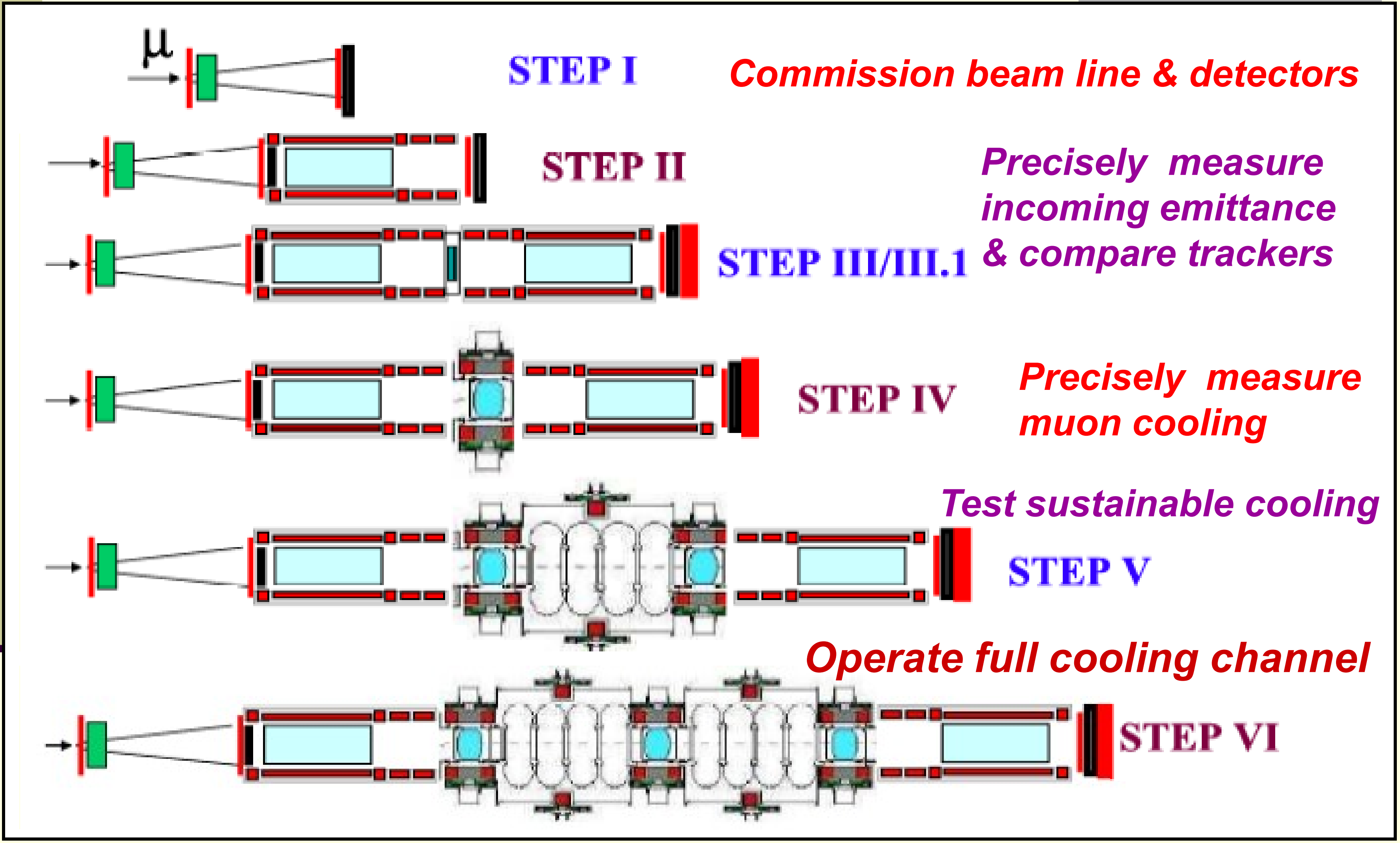
- Method:
  - Create beam of muons
  - Identify muons and reject background
  - Measure single particle parameters x, p_x, y, p_y, p_z
  - Cool muons in absorber
  - Restore longitudinal momentum component with RF cavities
  - Identify outgoing particles to reject electrons from muon decay

MICE: International Involvement



Institutions worldwide contributing to the demonstration of muon ionization cooling at MICE

MICE: Steps

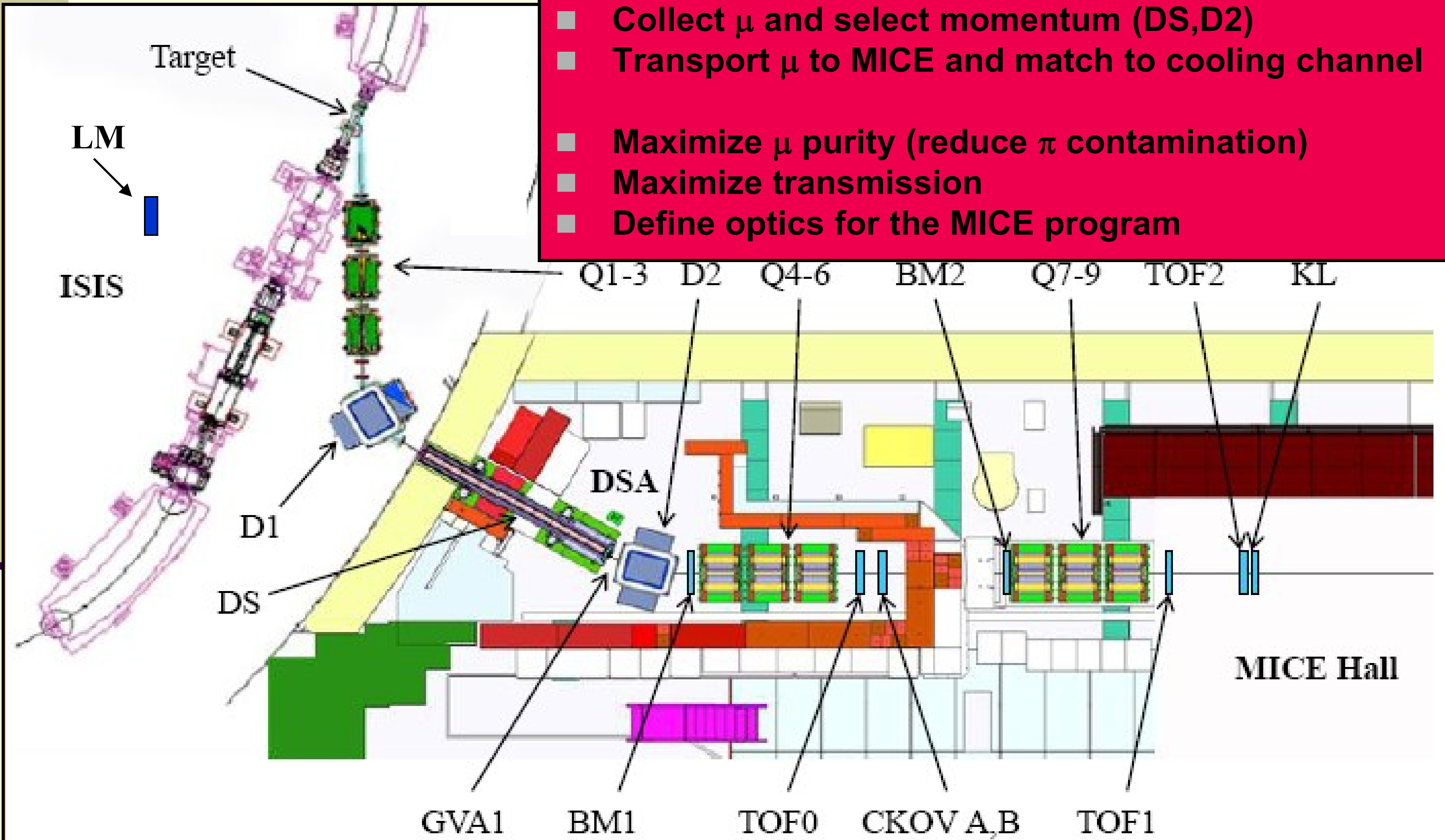


- Step 1 is now complete

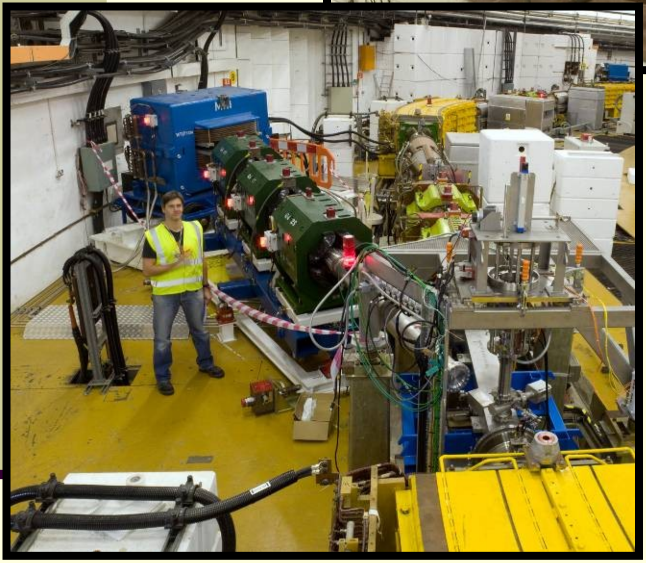
MICE: Step 1 Beam Line

- Produce π from p interactions with a titanium target
- Transport π (Q123) and select momentum (D1)
- Collect μ and select momentum (DS,D2)
- Transport μ to MICE and match to cooling channel

- Maximize μ purity (reduce π contamination)
- Maximize transmission
- Define optics for the MICE program

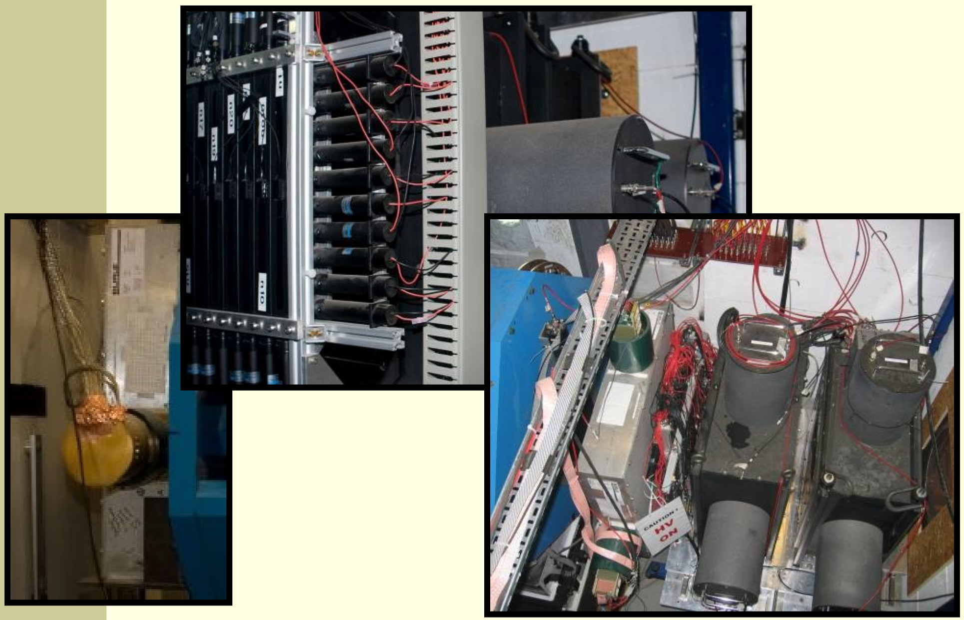


MICE: Beam Line



- Target, Q123, D1 inside ISIS synchrotron enclosure
- Decay Solenoid, Q456, TOF0, CKOVa/b
- Q789, TOF1, TOF2, KL in MICE Hall

MICE:
Particle Identification Detectors

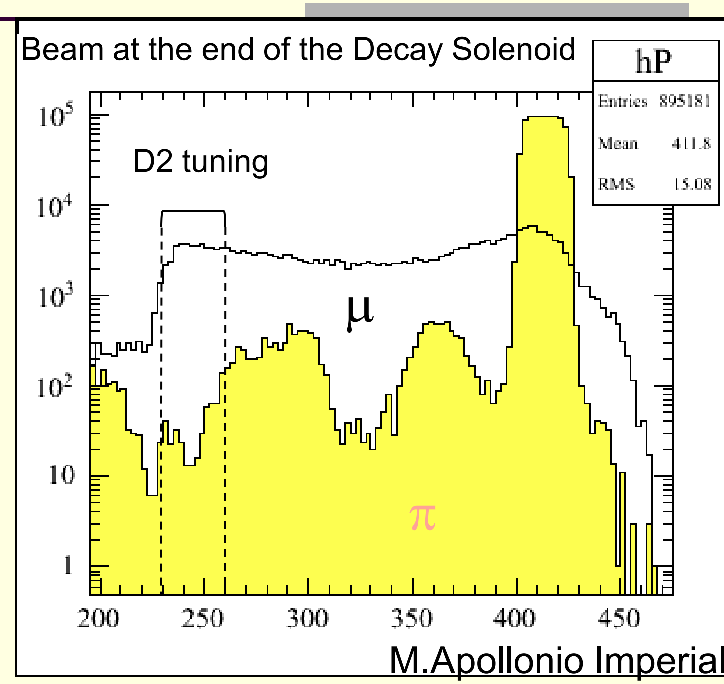


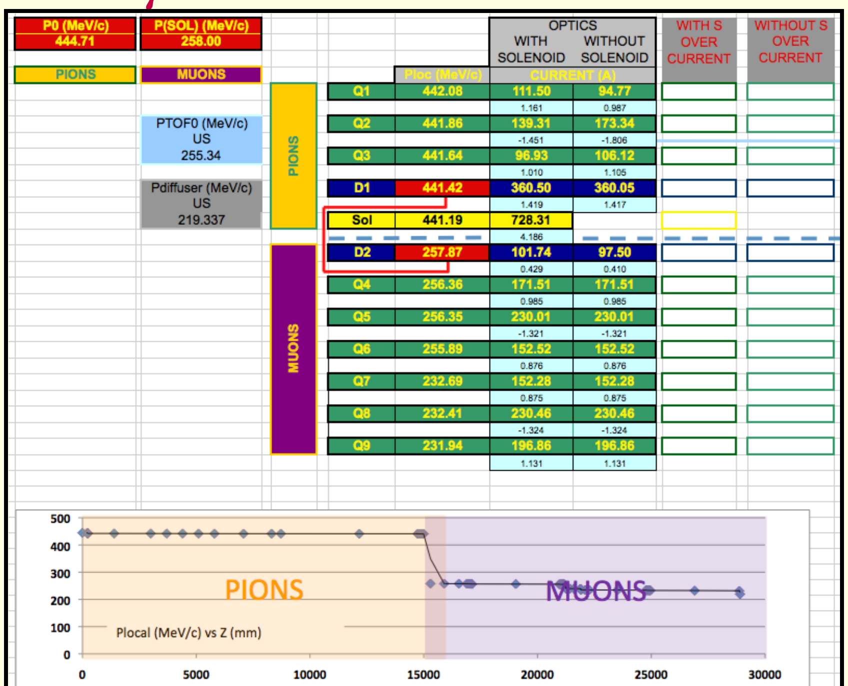
- **Upstream PID: discriminate between p, π, μ**
  - Beam Profile Monitors (FNAL)
  - Threshold Cerenkovs (UMiss/Belgium)
  - Time of Flight – TOF0 & TOF1 (Italy/Bulgaria)

- **Downstream PID: reject decay electrons**
  - Time of Flight – TOF2 (Italy/Bulgaria)
  - Kloe-Light Calorimeter – KL (Italy)
  - Electron-Muon Ranger – EMR (UGeneva)

Step 1: Creating the Muon Beam

- **Need good μ purity**
- **Use interplay between D1-D2**
  - **Tune D1 to fix π-peak**
  - **Tune D2 to select momentum fraction downstream beam line**
- **Select *backward-going μ at D2***
  - ***π/μ ratio for 238±24 MeV/c < 2%***



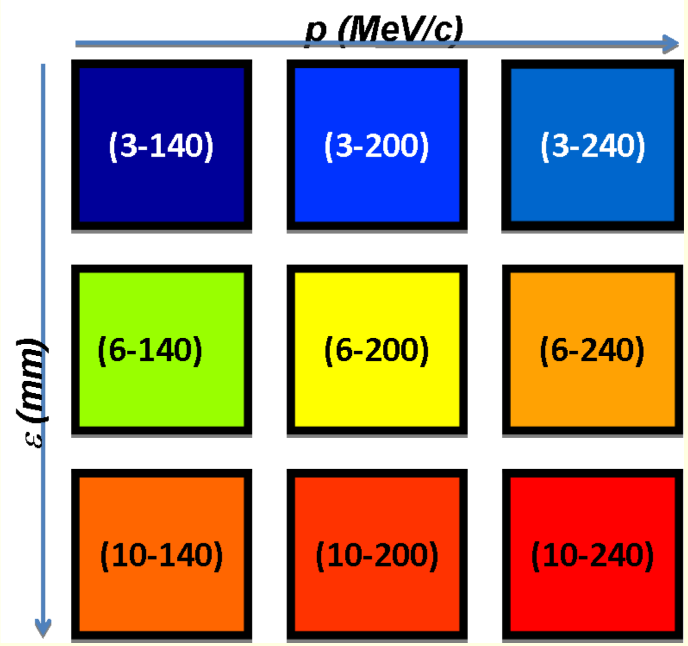


	Ploc (MeV/c)	OPTICS WITH SOLENOID CURRENT (A)	OPTICS WITHOUT SOLENOID CURRENT (A)	WITH S OVER CURRENT	WITHOUT S OVER CURRENT
Q1	442.08	111.50	94.77		
		1.161	0.987		
Q2	441.86	139.31	173.34		
		-1.451	-1.806		
Q3	441.64	96.93	106.12		
		1.010	1.105		
D1	441.42	360.50	360.05		
		1.419	1.417		
Sol	441.19	728.31			
		4.186			
D2	257.87	101.74	97.50		
		0.429	0.410		
Q4	256.36	171.51	171.51		
		0.985	0.985		
Q5	256.35	230.01	230.01		
		-1.321	-1.321		
Q6	255.89	152.52	152.52		
		0.876	0.876		
Q7	232.69	152.28	152.28		
		0.875	0.875		
Q8	232.41	230.46	230.46		
		-1.324	-1.324		
Q9	231.94	196.86	196.86		
		1.131	1.131		

- **Defining a beam line: magnet current rescaling by momentum**
- **Choose π or electron beam for calibration**

Step 1: Defining Muon Beam Optics

- MICE will need μ beam with variable momentum (140-240 MeV/c) and emittance (3-10 mm)
- Matrix of 9 optics points is defined
  - Start at hydrogen absorber
  - Find α,β,t at upstream face of diffuser → energy loss
  - Determine momentum at upstream face of diffuser
  - Define 9 initial (M0) muon beam configurations
- Baseline beam is (6-200)



Step 1: Data-Taking

- ***Goals***
  - *Calibrate beam line detectors*
    - *Luminosity Monitor, Beam Profile Monitors*
    - *TOF0, TOF1, TOF2, CKOVs, KL*
  - *Understand the beam*
    - *Composition*
    - *Rates*
    - *Momentum scale*
    - *First phase-space reconstruction*
    - *Take data for each point in (ε-p) matrix*
      - *MICE beam designed to be tunable*
      - *Understand beam parameters for each configuration*
    - *Compare data to beam line model*
  - *Prepare for Steps with cooling*
- ***Successful 2 month data-taking summer 2010***

Meant to be done using precise spectrometer
→ Necessary to improvise

Step 1: Data

Machine Physics [15/6, 16/6] 2010

- Beam Rate vs Tgt depth studies
- max. beam loss: 4V

maximize μ production while operating in a parasitic mode

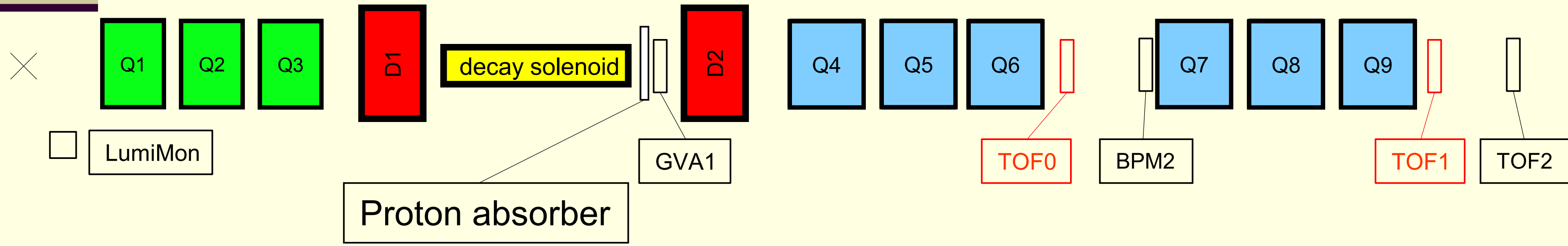
ISIS Users Run [19/6, 12/8] 2010

Over 340000 target actuations / 11M triggers / 917 runs
- upstream triplet scan
- dipoles scan & decay solenoid scan
- downstream triplets scan
- downstream single quadrupole scan
- beam composition studies
- optics data-taking: (ε,p) matrix
- DAQ tests
- Controls systems tests
- On Line Monitoring

Machine Physics [13/8, 15/8] 2010

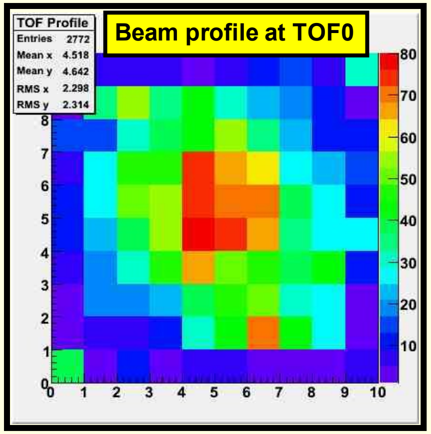
- Beam Rate vs Tgt depth studies
- max beam loss: 10V

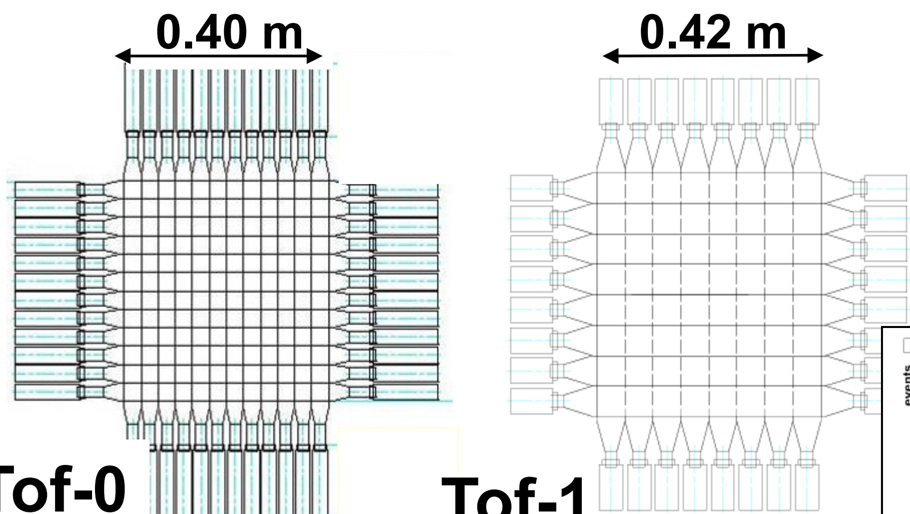
- Beam line configuration with detectors used for analysis



Step 1: TOF Commissioning

- *Two planes of 1 inch thick orthogonal scintillator slabs in x and y*
  - *Timing information & beam profile data*
  - *2D grid provides spatial information*
- *Used to Calculate Optical Parameters*





Tof-0

10 x 4cm scintillator bars

σ_x = 1.15 cm

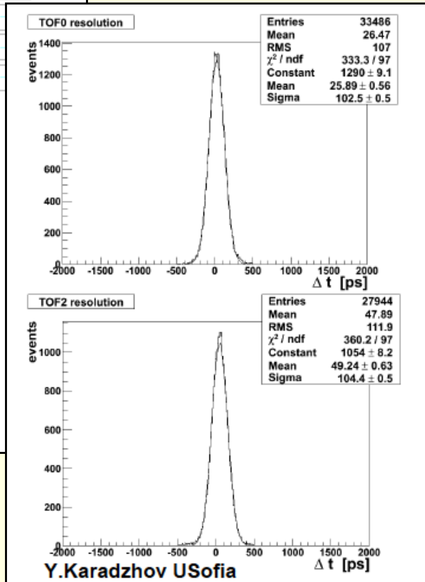
σ_t = 50 ps

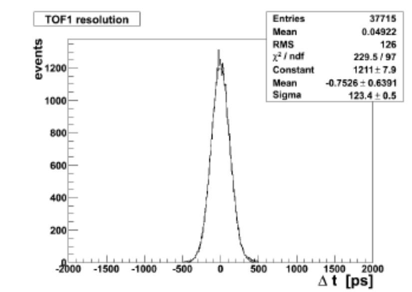
Tof-1

7 x 6cm bars

σ_x = 1.73 cm

σ_t = 50 ps





- *Time resolution after calibration:*
- *TOF0 – 51ps*
- *TOF1 – 62ps*
- *TOF2 – 52ps*
- *Resolution meets design goals for TOFs*

[The design and commissioning of the MICE upstream time-of-flight system,
R. Bertoni et al. , NIM-A 615 (2010) 14-26]

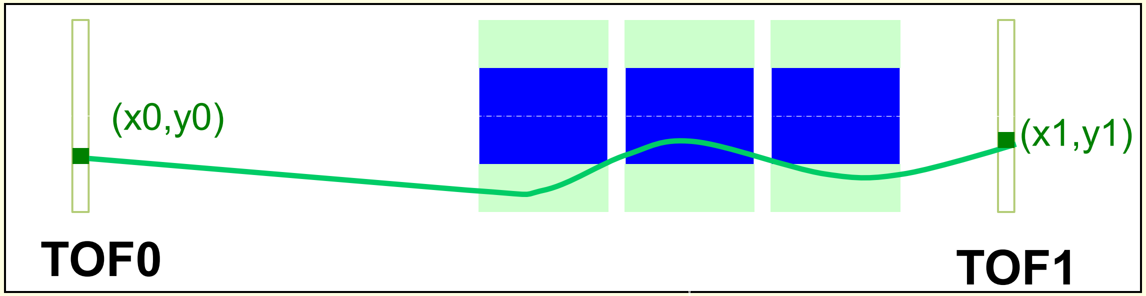
Step 1: Analyses

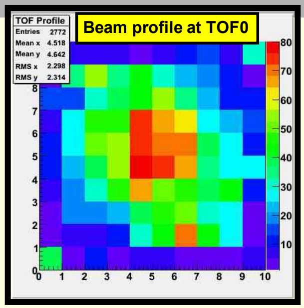
- **Particle Rate vs. Losses in ISIS**
  - **Maximize μ rate – want hundreds/spill**
- **Beam Composition**

- ***First emittance measurement in MICE***

- **Target operation studies**
  - **Depth, delay, acceleration**
- **Proton absorber**
  - **Eliminate protons in μ^+ beam**
- **Data quality**
  - **daily reference runs to verify stability**

How MICE Measures ε in Step 1



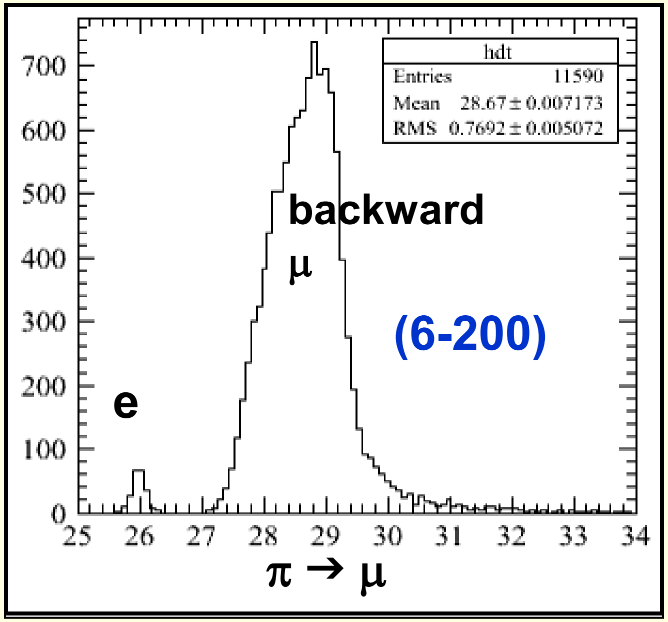


Use TOF0 and TOF1 particle detectors to determine phase space parameters of the muon beam

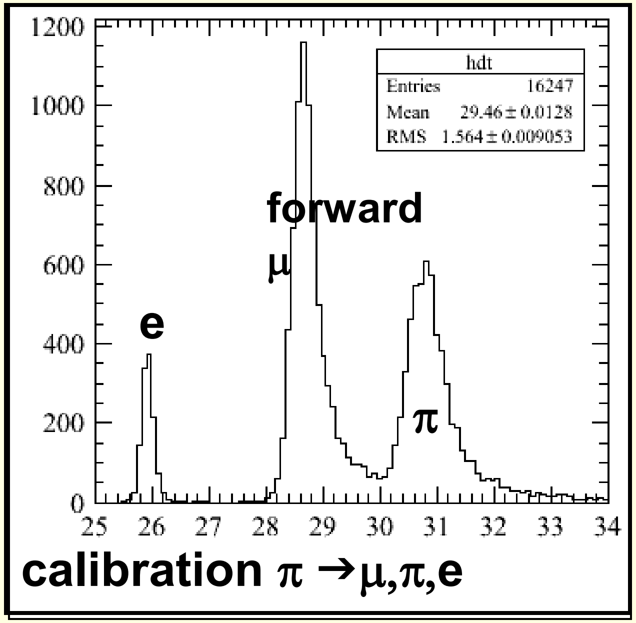
- **For each particle: know time-of-flight and position (x,y) at each detector**
- **Momentum-dependent transfer matrices map particle motion from TOF0 to TOF1 through drifts and quad triplet**
  - **G4MICE used to simulate beam, determine energy loss along path, and estimate detector effects**
- **Estimate initial path length and momentum**
- **Using transfer map:**
  - **Iterate and improve calculation of path length and momentum**
- **Calculate initial and final momentum at TOF0 and TOF1**
- **Determine phase space of beam at TOF planes, x,y, p_x, p_y**

ε Measurement: Particle Timing

- **Timing information used for both particle ID and position measurement (x,y) at TOF0 and TOF1**
  - **Selection of good muon**
  - ***Identified using time-of-flight measurement with 71 ps resolution***



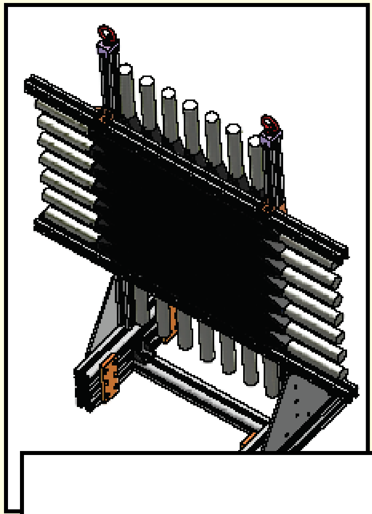
Baseline MICE muon beam setting

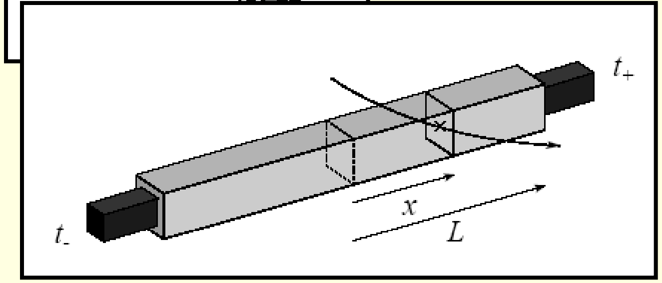


Pion beam for detector calibration (also contains e and μ)

ε Measurement: TOF Position

- **Transverse Position Determination with TOF detectors**
  - Start with size of slab crossing (4x4cm, 6x6cm)
  - *Use difference in arrival time of signals at PMTs in each slab to improve position measurement*
  - Calibration corrected for time walk and cable lengths
  - Effective propagation speed of light in the scintillator slab is measured by comparing $(t_{+} - t_{-})$ with position information given by orthogonal slab.
  - c_{eff} = 14 cm/ns; $\sigma_x \sim 1.0$ cm



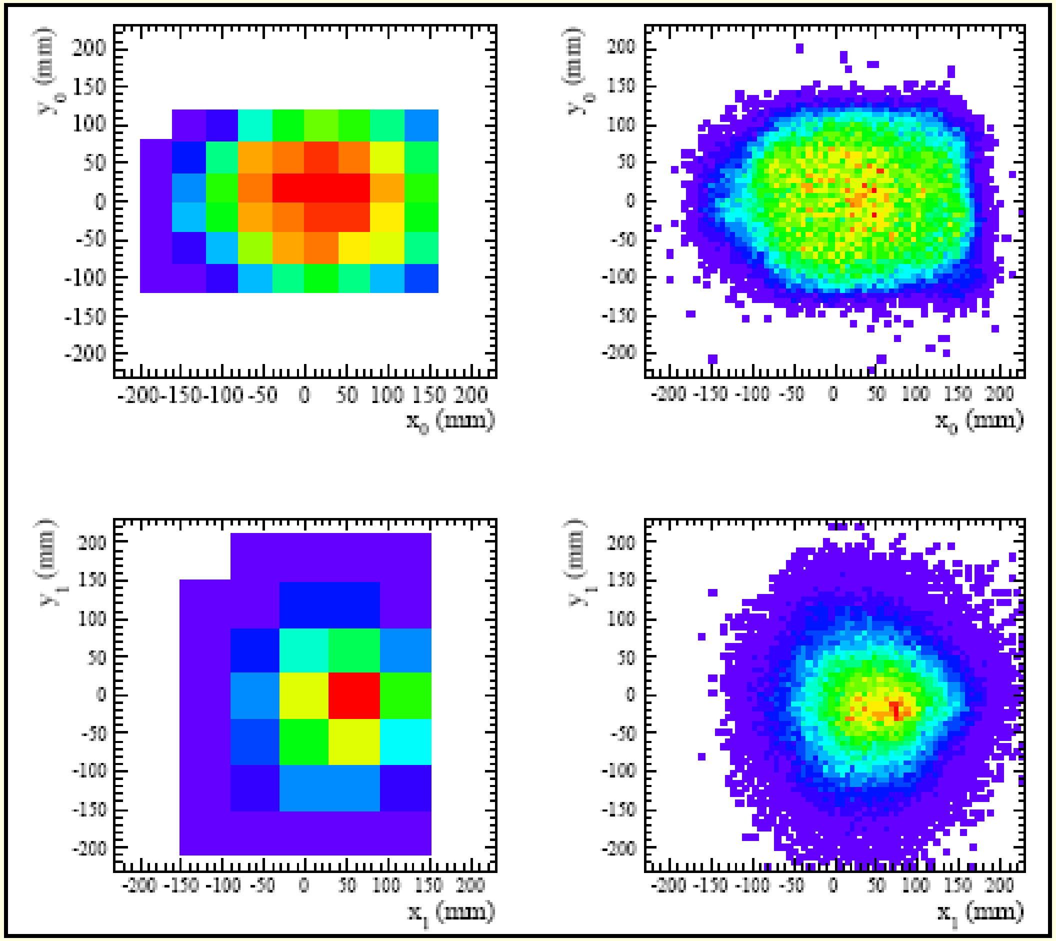


$$x = \frac{-c_{\text{eff}}(t_+ - t_-)}{2}$$

$$\sigma_x = \frac{c_{\text{eff}}\sigma_{\text{PMT}}}{\sqrt{2}}$$

ε Measurement: Beam Profile in TOF Detectors

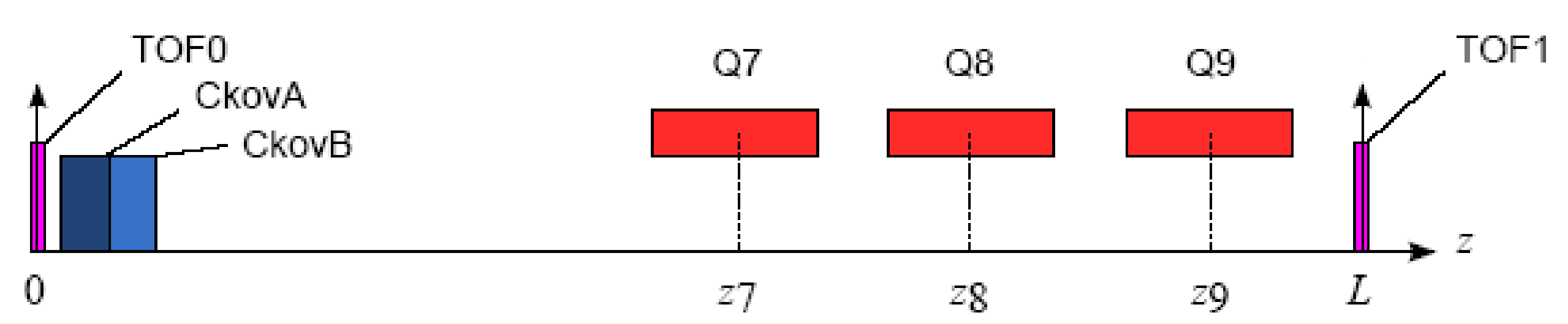
- Beam profiles in TOF0 and TOF1
  - Position using only slab width (left) and position determined by using signal arrival time in PMTs (right)



TOF0

TOF1

ε Measurement: Particle Path & Momentum



- Good muon selected & particle positions measured ✓
- Use product of transfer matrices $M(p_z)$ through the drifts and quadrupole magnets to map trace space from TOF0 to TOF1 (with det M ≡ 1).

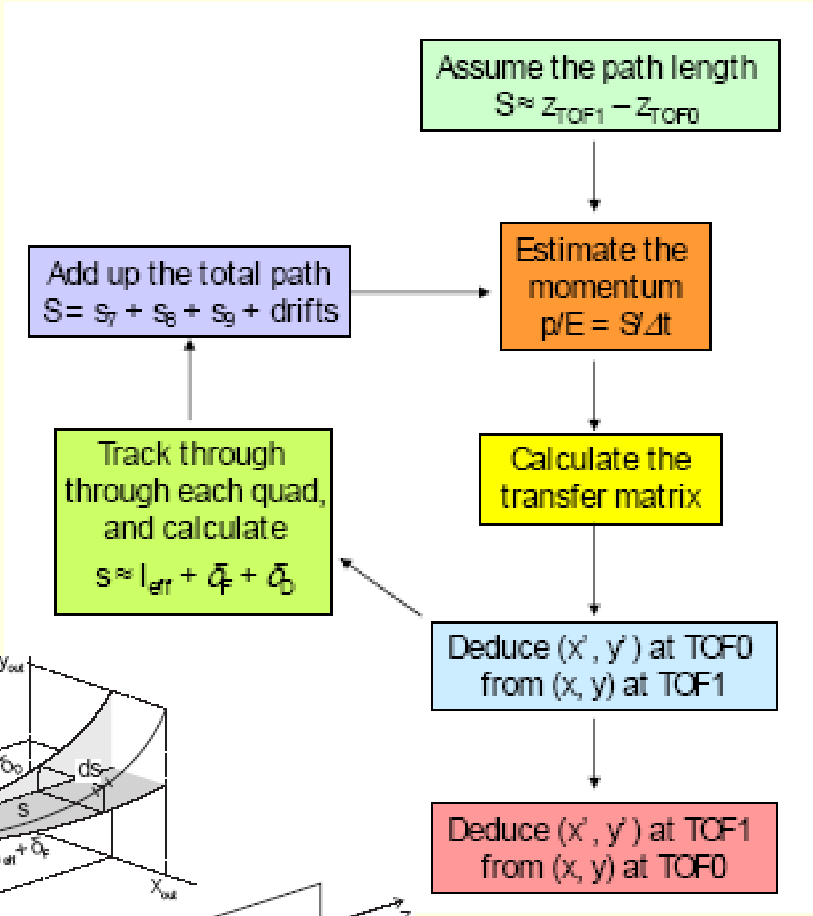
$$\begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}$$

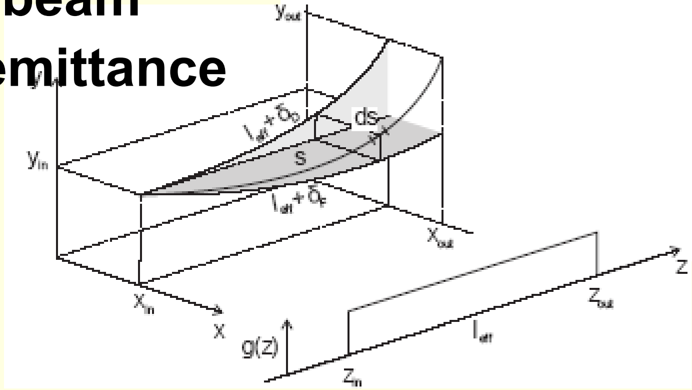
- The angles are deduced from the positions

$$\begin{pmatrix} x_0' \\ x_1' \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix}$$

ε Measurement: Path & Momentum Reconstruction

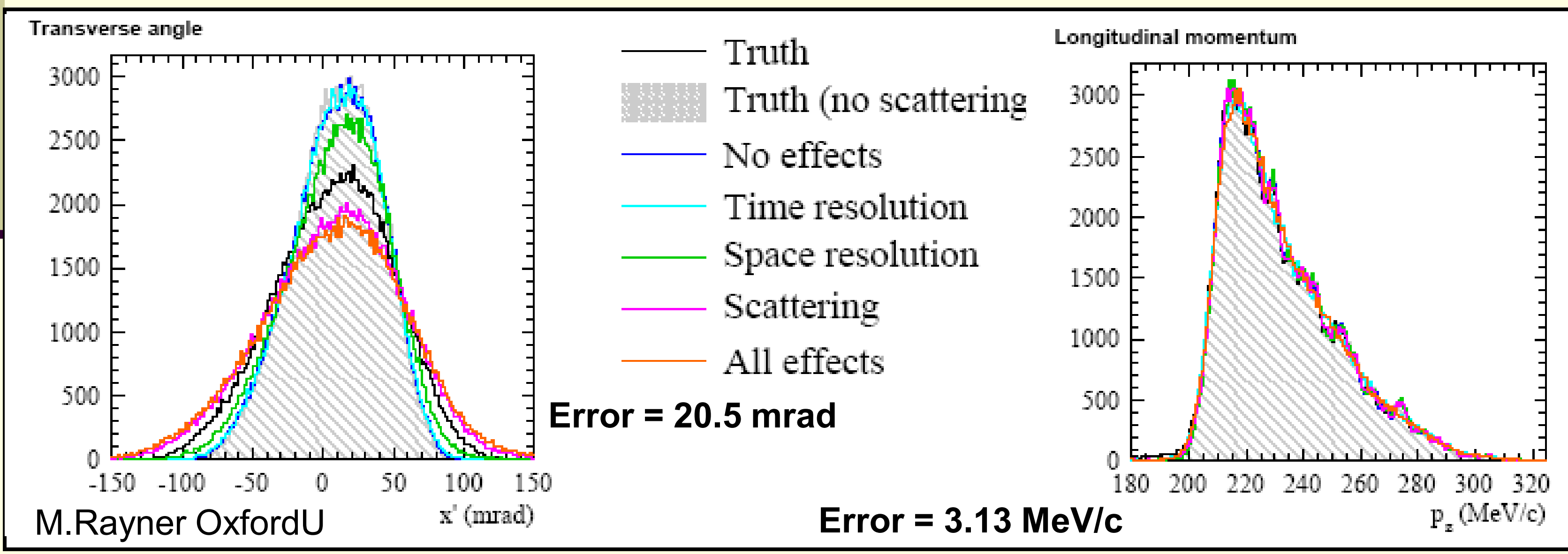
- Initial path length assumed to be straight line
- Iterate to remove bias in path length
  - Momentum calculated given path length and time-of-flight from TOFs
- Particles tracked using thick edge quadrupole model
- Compared to MC using G4MICE to simulate beam
- Calculate x′, y′ and emittance





ε Measurement: Reconstruction of x′= dx/dz and p_z

- *G4MICE simulates muons through beam line*
- **Input beam created with G4BeamLine simulation from target to upstream face of TOF0**
- **Optics tuned to baseline 6-200 beam**
  - **6 mm transverse emittance in first tracker plane**
  - **Mean p_z = 200 MeV/c in first absorber**
- **Energy loss in TOFs, CKOVS, air**
- **Detector effects varied**



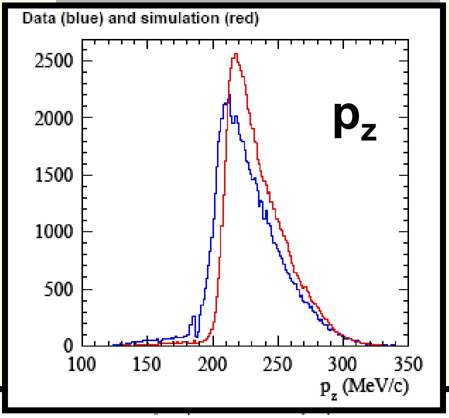
εMeasurement : Compare Data and MC

- **Emittance measurement:**
  - **Good muon selected ✓**
  - **Muon positions measured ✓**
  - **Momentum reconstructed ✓**
  - **x'_0 and x'_1 determined ✓**
  - **Calculate emittance**

- **G4MICE used to simulate TOF0 → TOF1 beam line**

- **For baseline (6-200) μ^- beam**

- **Promising agreement observed between data (blue) and Monte Carlo (red) at TOF1 for momentum and x,y,x′,y′**



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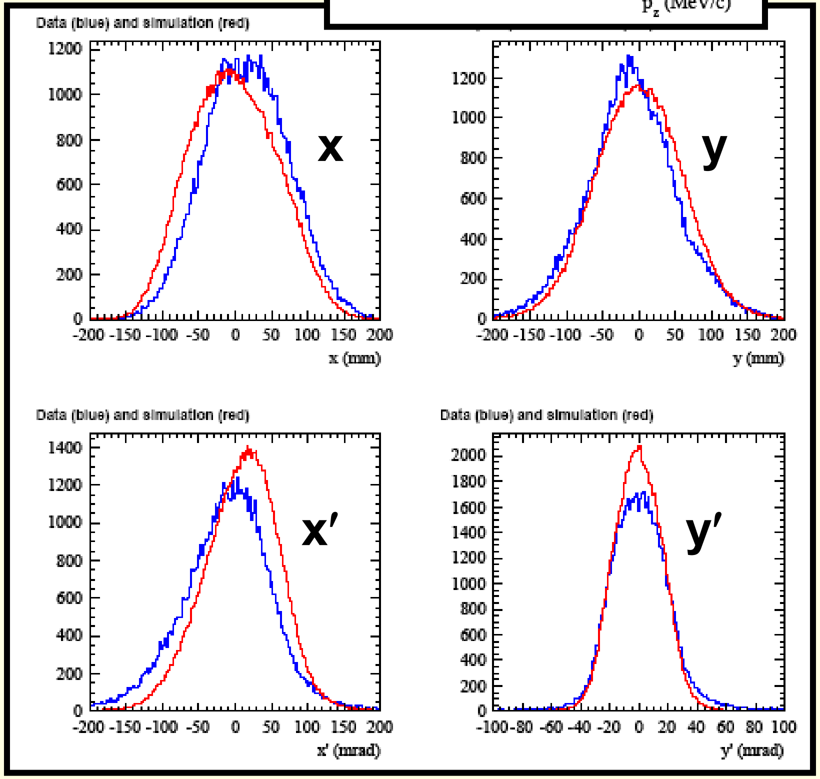
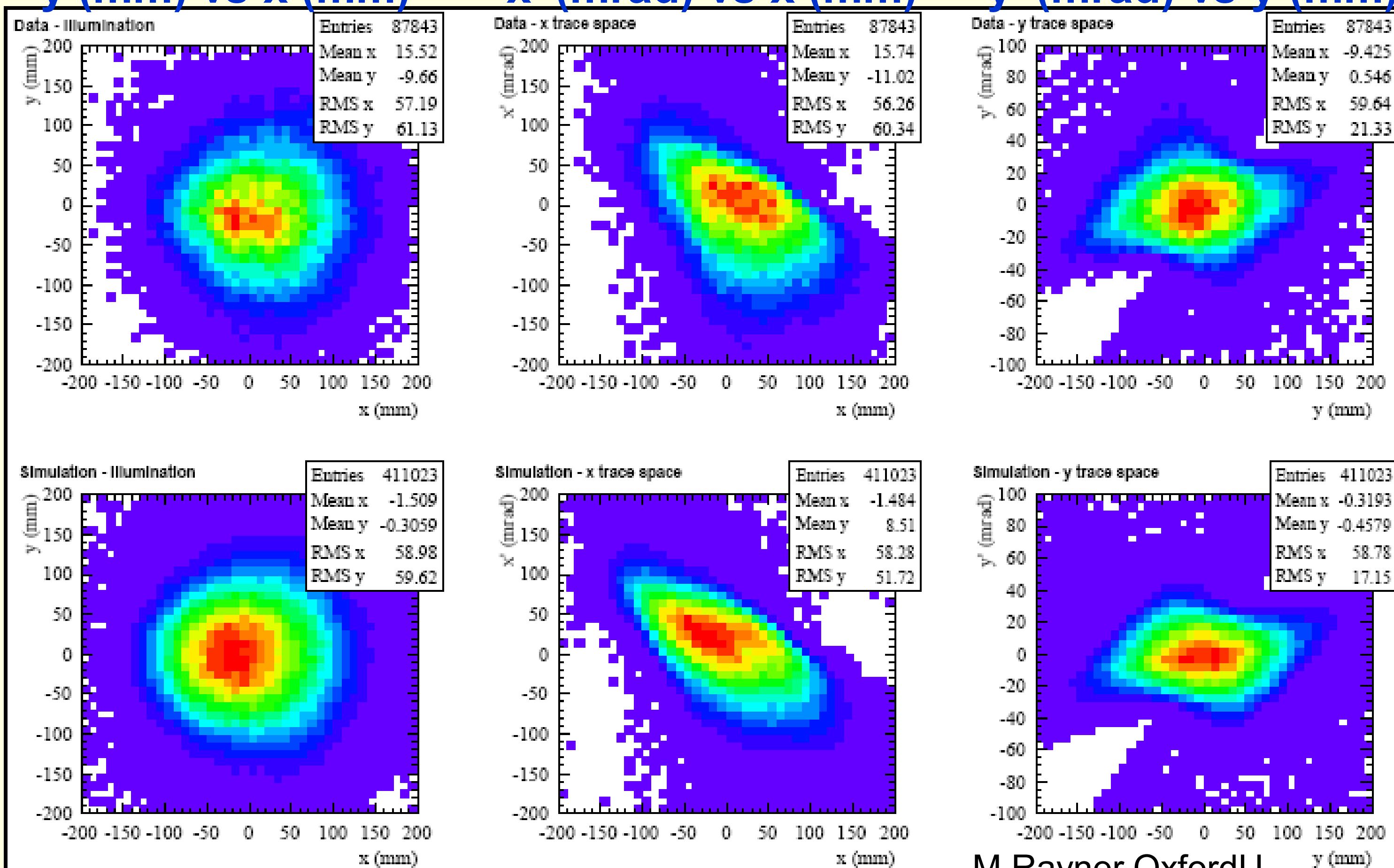


ε Measurement Result: Data vs MC

- **Reconstructed transverse phase space of the baseline MICE beam (6-200) at TOF1**

y (mm) vs x (mm) | x′ (mrad) vs x (mm) | y′ (mrad) vs y (mm)



Data

MC

M Rayner OxfordU

MICE: Conclusions

- MICE data-taking for Step 1 is complete
- Innovative method used to make first measurements of beam emittance using time-of-flight detectors
- MICE muon beam is understood and ready for the arrival of the cooling channel

MICE: Muon Rate

- **Reconstructed muon tracks/(Vms)/(3.2 ms spill)**
- **Muon track rates for both MICE beam polarities**
  - ****Emittance referred to 1rst spectrometer**
  - **†Momentum referred to MICE central absorber**
- **Counts are normalized to the V ms units used to characterize the target depth**
- **Errors primarily due to time-of-flight cuts used to define a muon**

M0		μ^- rate * P_z †(MeV/c)			μ^+ rate P_z (MeV/c)		
		140	200	240	140	200	240
ε_N **(mm·rad)	3	4.1 ±0.2	6.3 ±0.2	4.9 ±0.2	16.8 ±1.8	33.1 ±3.2	33.0 ±2.6
	6	4.1 ±0.4	4.8 ±0.2	4.5 ±0.2	17.8 ±1.8	31.0 ±2.0	31.7 ±2.0
	10	4.6 ±0.2	5.4 ±0.2	4.4 ±0.1	21.6 ±2.2	34.0 ±2.5	26.1 ±1.5

A.Dobbs Imperial College