Hydrid Methods for Muon Accelerator Simulations with Ionization Cooling

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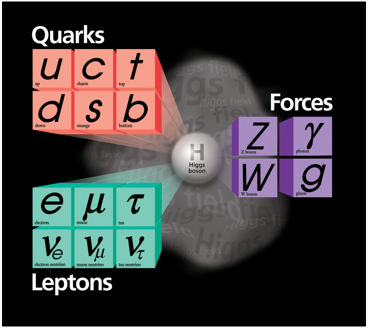
Why muons?



- Muons are ≈200 times heavier than electrons ⇒ can be accelerated in circular channels, synchrotron radiation is negligible, CoM energy is not limited by radiative effects, compact footprint, Higgs production advantages.
- Muons are elementary particles in the framework of the Standard Model ⇒ clean collisions, particle energy is utilized fully.
- Muons decay ⇒ neutrino beam via $\mu^- \to e^- \nu_\mu \bar{\nu}_e$, $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$.
- Muons provide a unique tool for addressing fundamental questions in physics, or for exploring the properties of materials.

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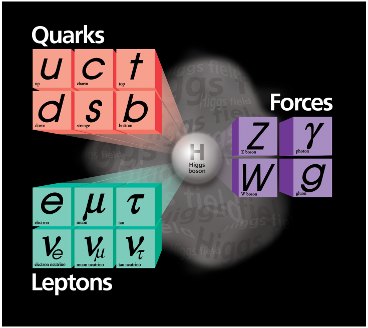

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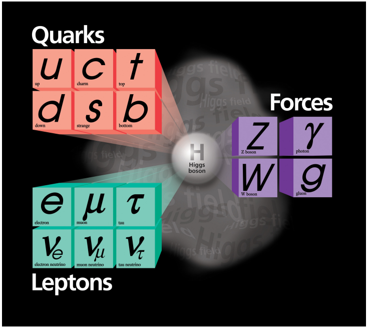

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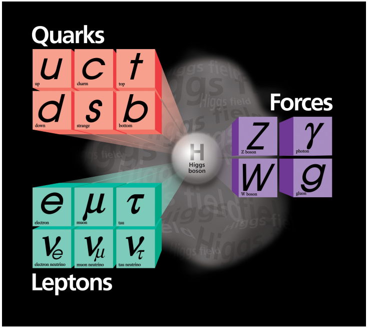

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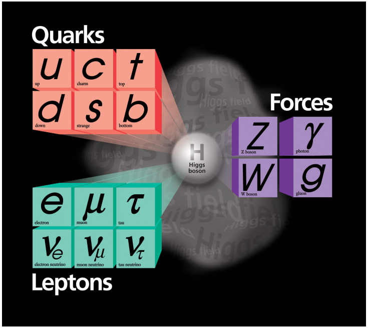

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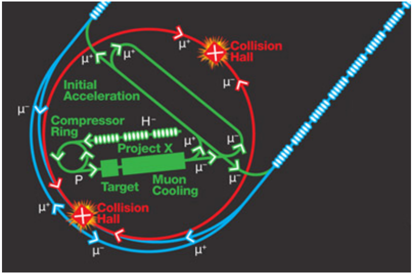

- Muons are unstable, $\tau = 2.2\ \mu$s at rest (relativity helps: at 2 TeV $\tau = 0.044$ s), rule of thumb: 1000 turns in the storage ring.
- Challenge: collect them, form them into a beam, and either accelerate them to high energy or stop them in a target.
- Challenge: get enough muons to do the job, and concentrate them within a small target, or within a very bright beam.
- Challenge: decay products heat magnets and other components, create backgrounds in the detector.

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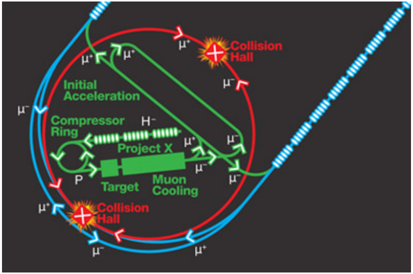

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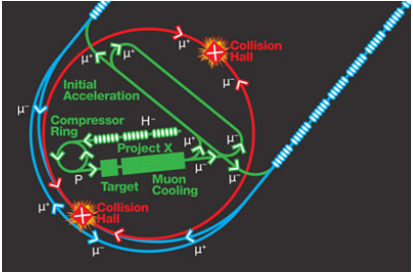

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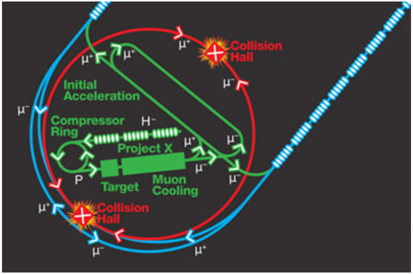

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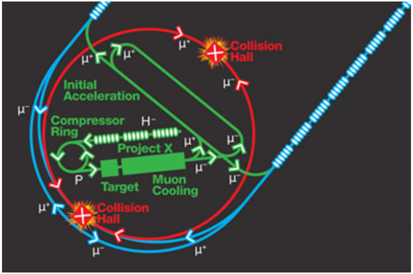

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Muon Accelerator R&D

The Muon Accelerator R&D program focuses on:

- developing the concepts and technologies needed to make vast quantities of muons (of order 10^{14} per second),
- reducing muon energy spread so that they can be captured within bunches (intense muon source),
- form muons into a very bright beam that can be either stopped or accelerated (bright muon source),
- developing applications using bright muon beams: Neutrino Factories and Muon Colliders,
- informing the HEP community regarding the feasibility of new Energy and Intensity Frontier machines,
- ensuring the accelerator complex can be built up in stages with useful physics extracted at each stage (Muon Accelerator Staging Study).

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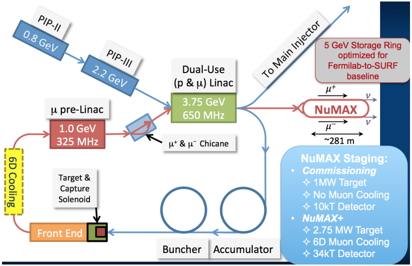
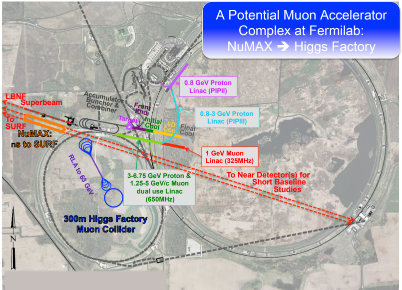
Why do we need muon accelerators?





Concept developed by MAP as part of its Muon Accelerator Staging Study (MASS)

- Neutrino Factory capabilities offer a precision microscope that will likely be needed to fully probe the physics of the neutrino sector.
- A multi-TeV muon collider may be the only cost-effective route to lepton collider capabilities at energies > 5 TeV.
- Muon accelerator capabilities offer unique potential for the future of high energy physics research.
- Bright muon sources can be used for other applications.

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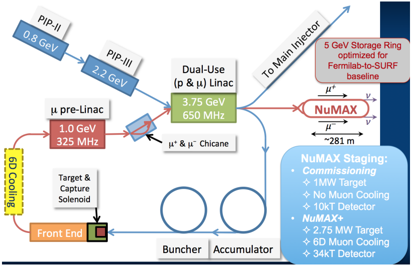

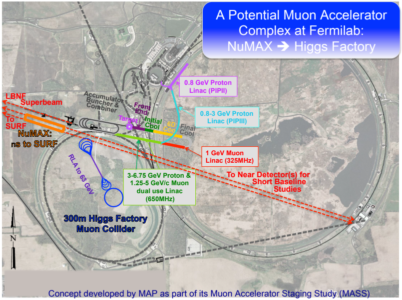

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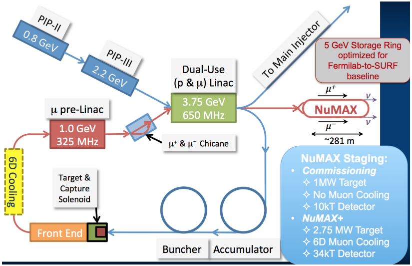

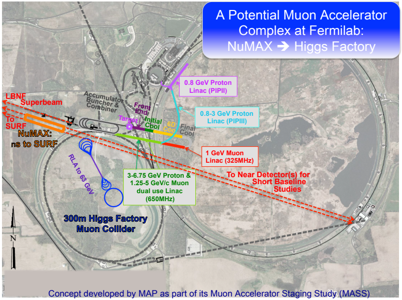

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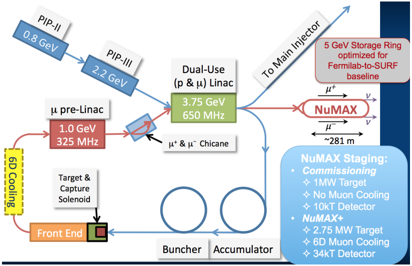

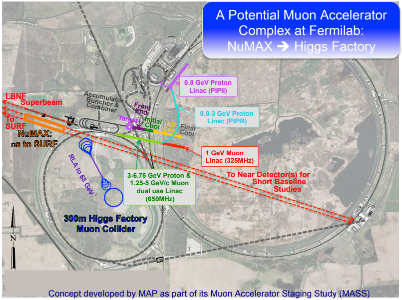

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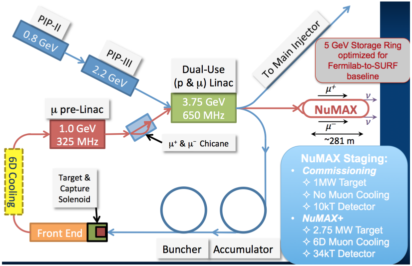

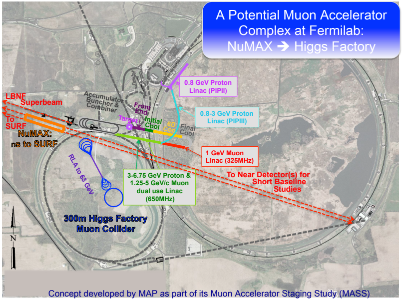

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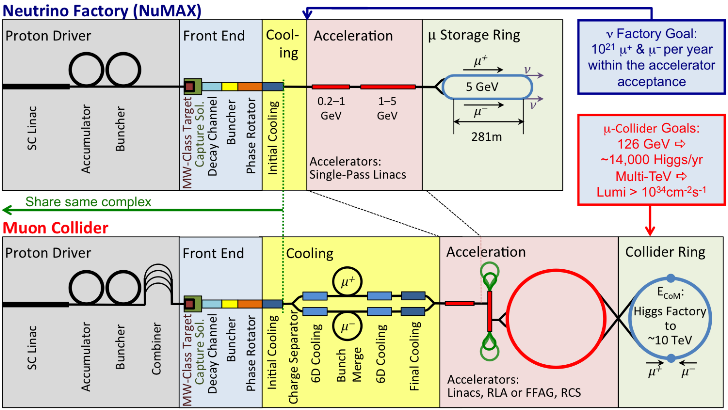
Synergies between NF and MC



- Large part of the front end is common to NF and MC, common technologies down the accelerator chain.
- R&D for both could be staged, and each stage can be used as an R&D platform for the subsequent one.

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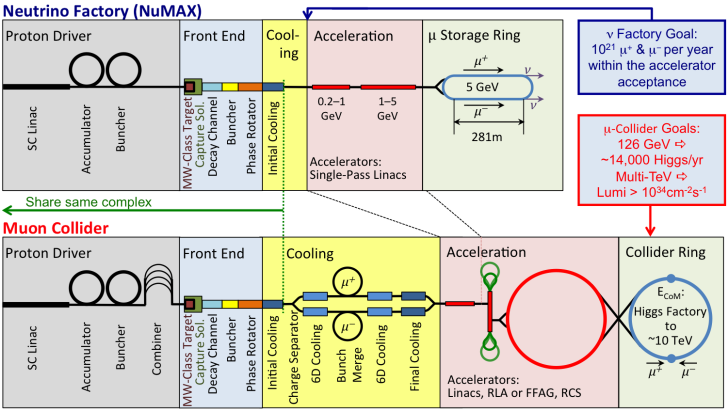

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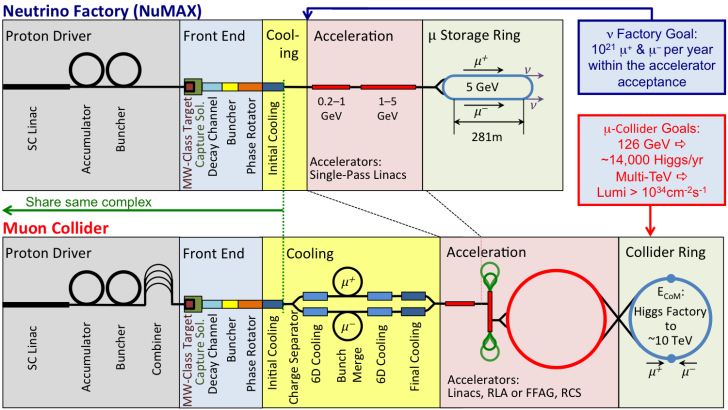

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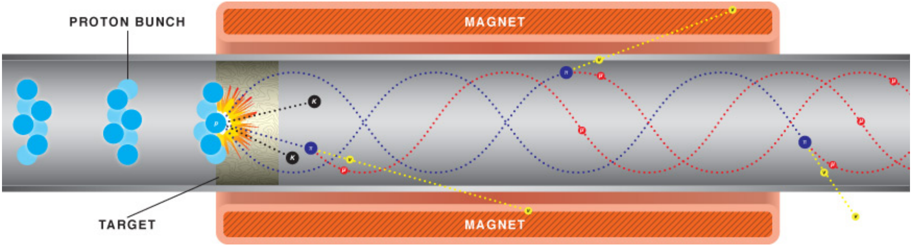
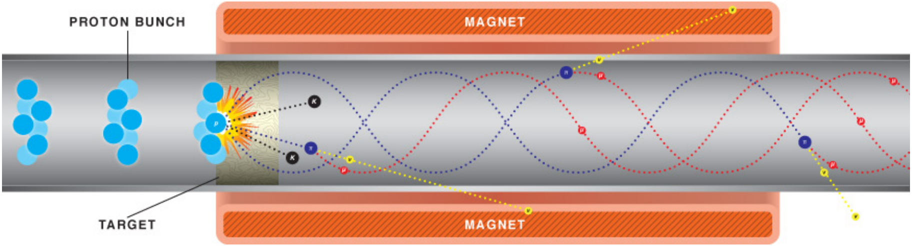
Muon Ionization Cooling: Why Cool?



- Intense muon source: p $\to \pi \to \mu$. Very large initial emittance.
- Need to capture as much as possible of the initial large emittance.
- Large aperture acceleration systems are expensive $\Rightarrow$ for cost-efficiency need to reduce emittances prior to accelerating ("cool the beam").
- Cooling requirements range from modest, predominantly transverse, to very ambitious ($O(10^6)$) six-dimensional cooling for the ultimate MC.
- Need to act fast since muons are unstable. The only feasible option is ionization cooling.



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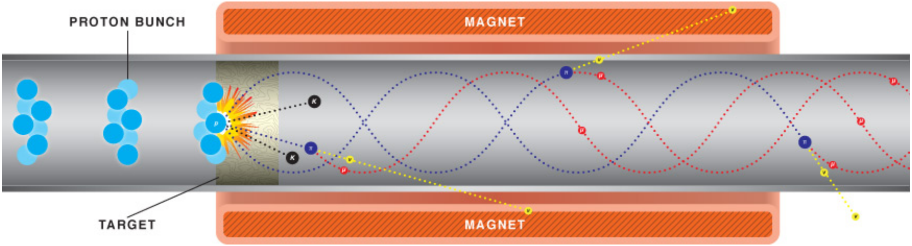

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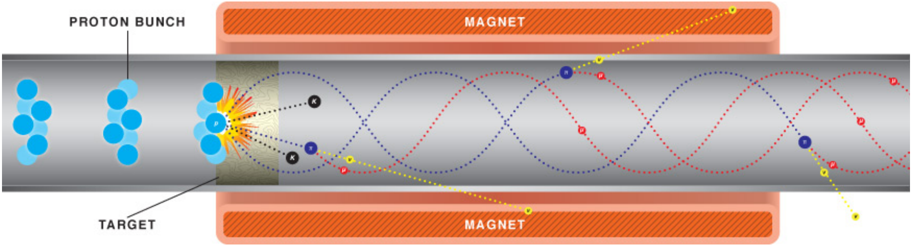

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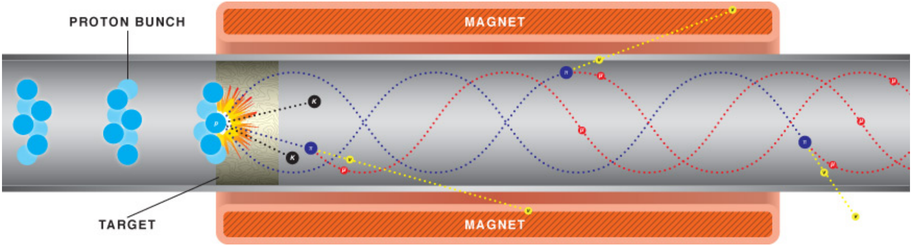

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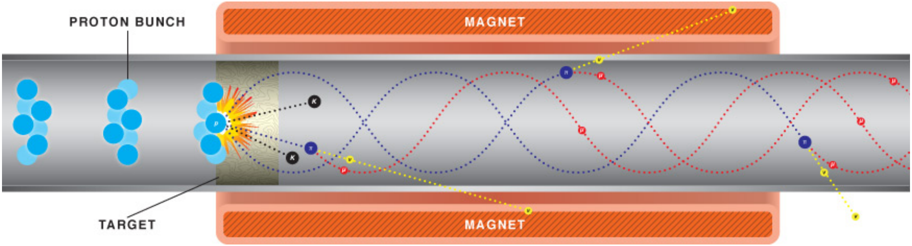

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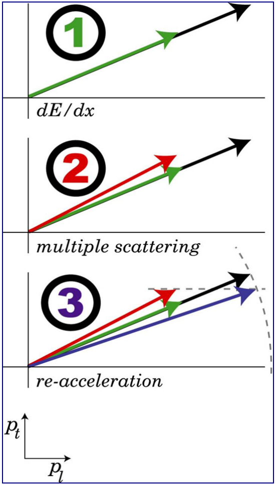
Ionization cooling principle



$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014 GeV)^2}{2\beta^3 E_\mu m_\mu X_0},$$

where $d\epsilon_N/ds$ is the rate of normalized emittance change within the absorber; βc, E_μ, and m_μ are the muon velocity, energy, and mass; $\beta_\perp$ is the lattice betatron function at the absorber; and X_0 the radiation length of the absorber material. Need low $\beta_\perp$, large X_0.

1. Energy loss in material (all three components of the particle's momentum are affected).
2. Unavoidable multiple scattering (can be minimized by choosing the material with large X_0, hence, low Z).
3. Re-acceleration to restore energy lost in material. Only the longitudinal component of momentum is affected.

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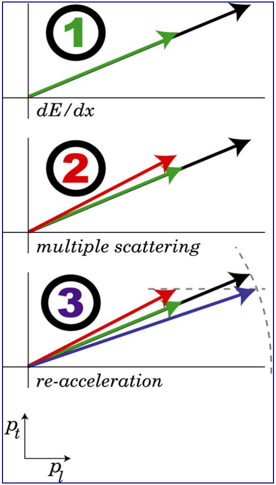

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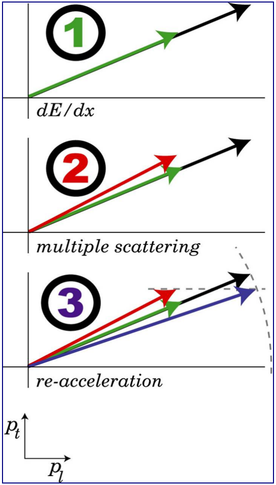

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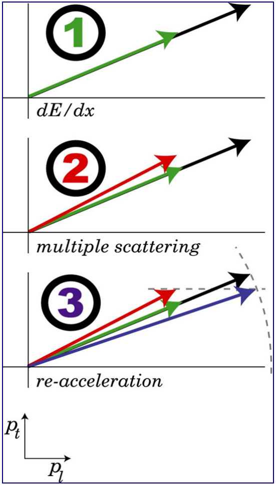
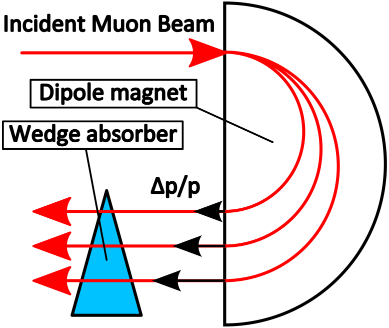


$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp(0.014GeV)^2}{2\beta^3 E_\mu m_\mu X_0},$$

where $d\epsilon_N/ds$ is the rate of normalized emittance change within the absorber; βc, E_μ, and m_μ are the muon velocity, energy, and mass; $\beta_\perp$ is the lattice betatron function at the absorber; and X_0 the radiation length of the absorber material. Need low $\beta_\perp$, large X_0.

1. Energy loss in material (all three components of the particle's momentum are affected).
2. Unavoidable multiple scattering (can be minimized by choosing the material with large X_0, hence, low Z).
3. Re-acceleration to restore energy lost in material. Only the longitudinal component of momentum is affected.

Emittance exchange or "How to cool in 6D"



Emittance exchange principle:

- instead of letting the beam with zero dispersion through a flat absorber,
- introduce dispersion and
- let the particles with higher momentum pass through more materials,
- thus reducing the beam spread in the longitudinal direction.

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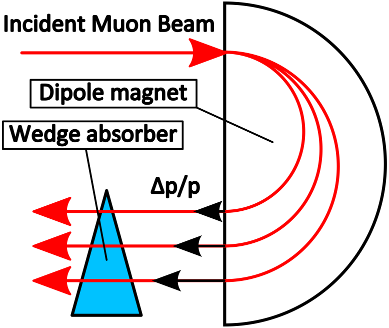

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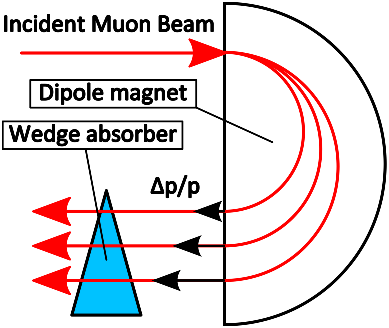

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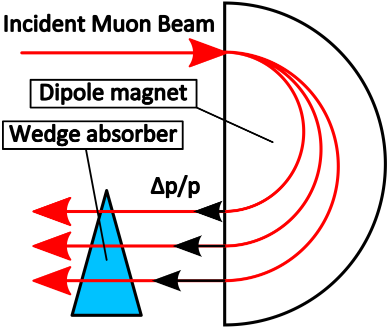

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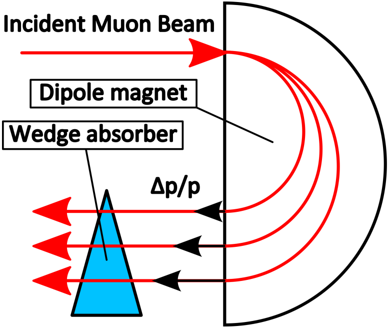

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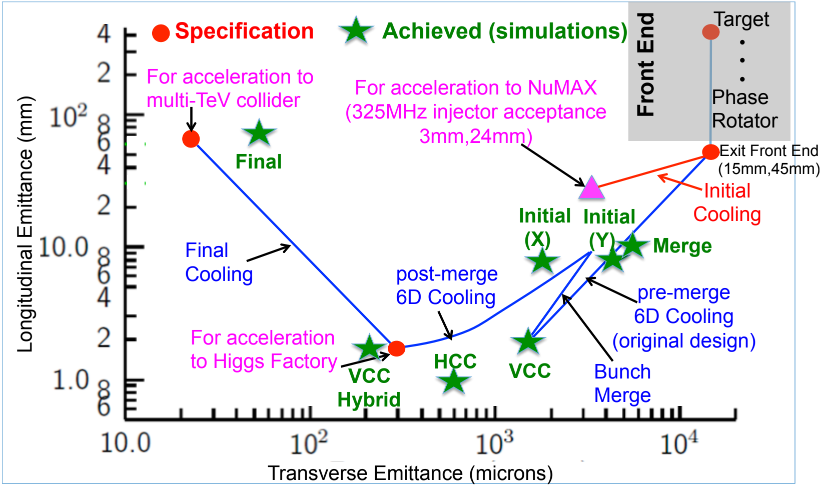
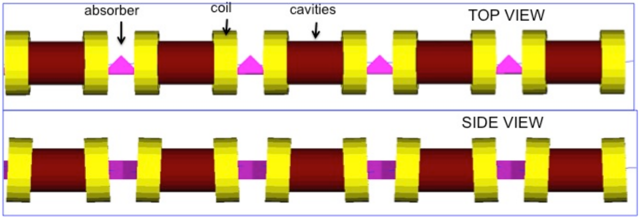
Cooling channels

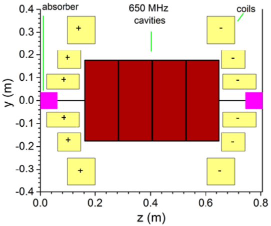
Emittance evolution diagram



Cooling channels for different applications

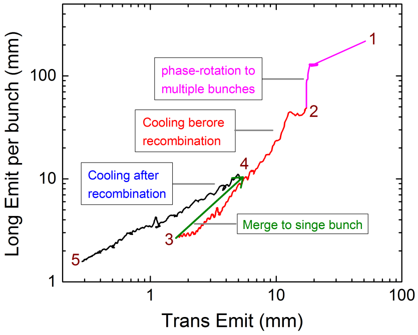
Vacuum RF cooling channel (VCC)

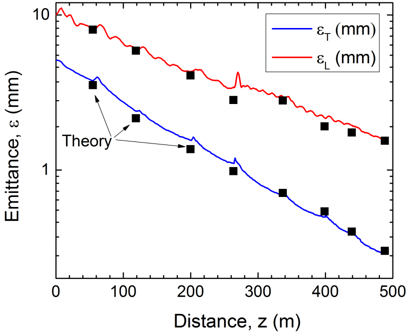




- Vacuum RF cooling channel (VCC):
  - Lattices + start-to-end simulations.
  - Lattices optimized and achieved emittance goals specified by MAP.
  - Progress on bunch merge.
  - Investigation of window effects.
  - Thermal & mechanical analysis of RF windows.
  - Magnet design.
  - Significant improvement in the final stage of 6D cooling.

VCC, contd.





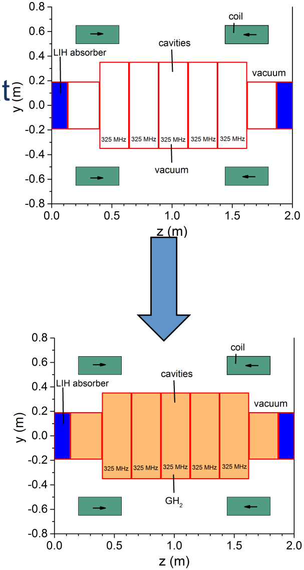
Emittance evolution plot: reaching 0.28 mm in transverse emittance and 1.57 mm in longitudinal emittance

Emittance evolution after bunch recombination: black markers are theoretical predictions

- RF: f=325 & 650 MHz; field: B_z=2.3-13.6 T; cooling section length, L=490 m.
- Transmission: 55% before recombination, 40% after recombination.

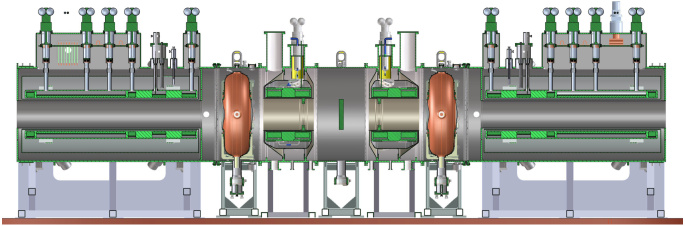
Hybrid cooling channel

- One area of concern: breakdown of RF cavities in high magnetic fields.
  - Experiments at MTA have demonstrated that using cavities filled with high-pressure gas can prevent breakdown.
- An important recent conceptual development: reconsideration of a hybrid cooling channel
  - rectilinear channel beam line components,
  - external absorbers,
  - cavities filled with medium pressure gas.
- Potential: control RF breakdown in high magnetic fields while maintaining the relative simplicity of rectilinear channel designs.



MICE: Muon Ionization Cooling Experiment

MICE and its objectives



- Design, engineer and fabricate a section of cooling channel.
- Place the cooling apparatus in a muon beam and measure its performance in various modes of operation and beam conditions, thereby investigating the limits and practicality of ionization cooling.
- Measure a reduction in transverse beam size with a precision of 1%.
- Develop and thoroughly test simulation and data analysis software.
- Step IV: demonstrate transverse emittance reduction (2015-2016).
- Cooling demonstration configuration (shown in the figure): demonstrate sustainable transverse cooling with re-acceleration (2017-2018).

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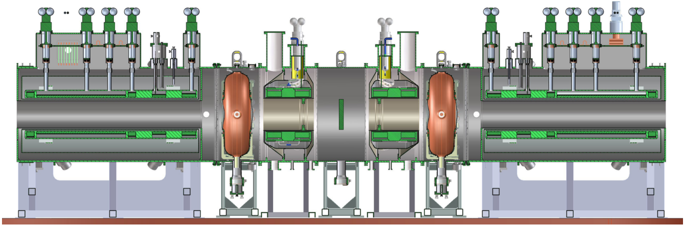

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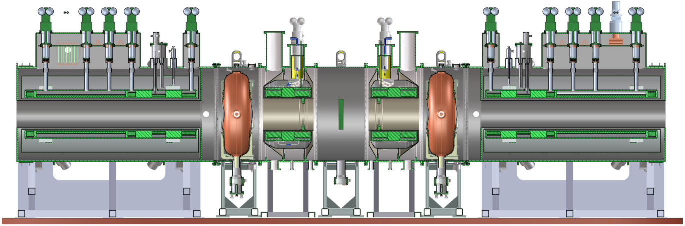

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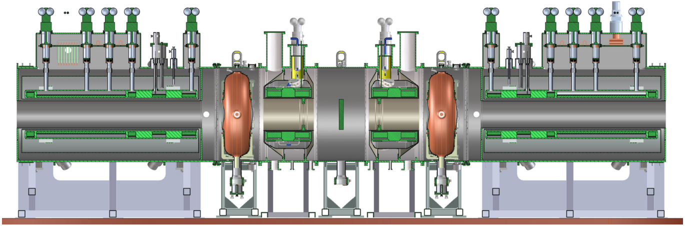

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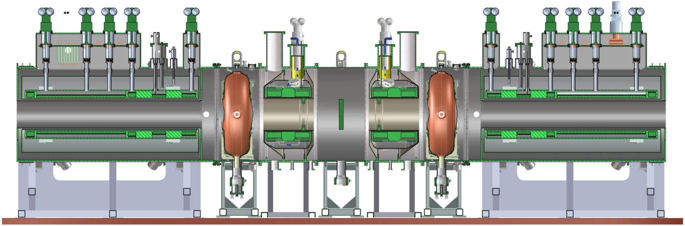

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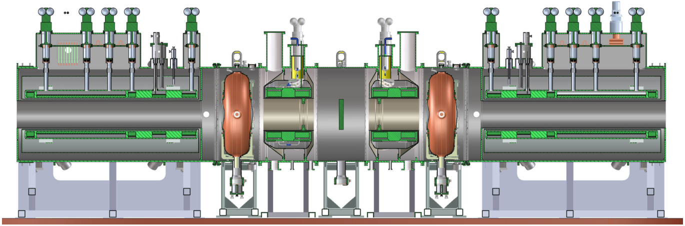

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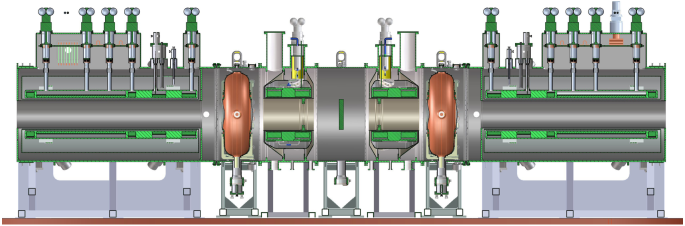

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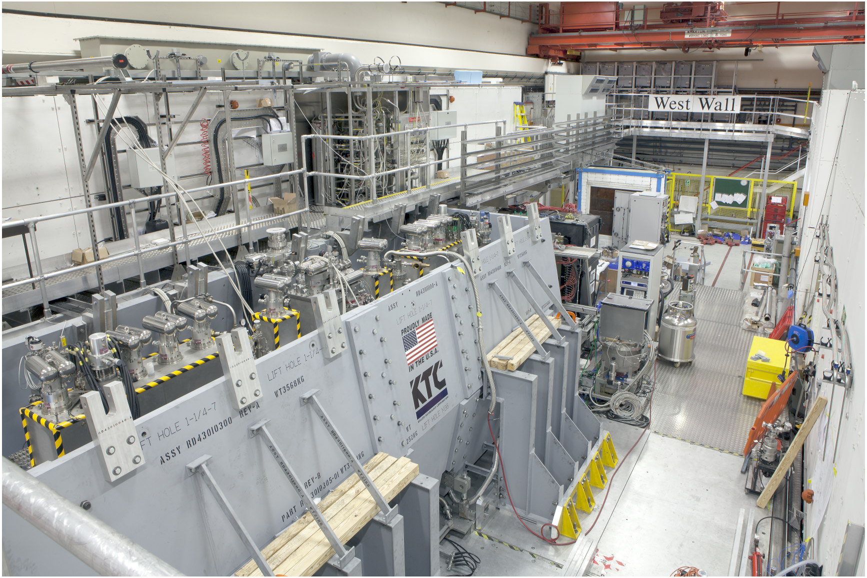
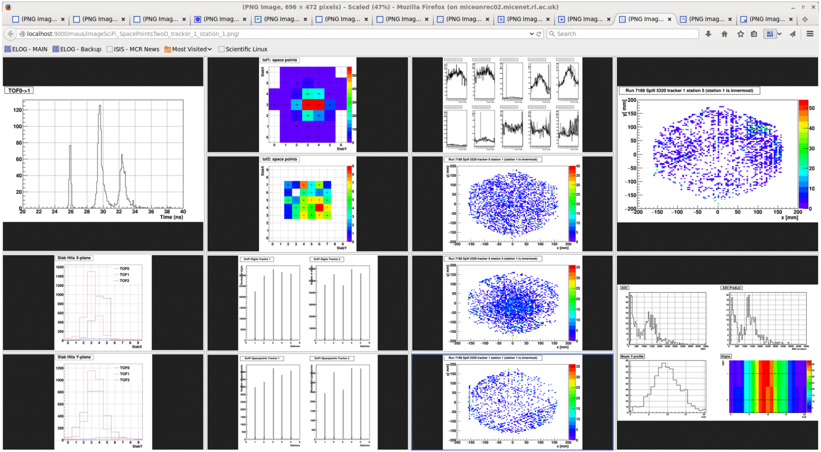
MICE Step IV on the floor



MICE online reconstruction of data



- MICE has multiple detectors for particle localization and identification: Time-of-Flight, Cherenkov, sci-fi trackers, KL calorimeter, Electron Muon Ranger.

COSY Infinity

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- COSY Infinity (COSY) is a simulation tool for design, simulation and optimization of particle accelerators.
- COSY is a transfer map code: the overall effect of the optics on a beam of particles is evaluated using differential algebra.
- Let initial phase space vector Z_0 at s_0 describe relative position of a particle with respect to the reference particle.
- Assume the future evolution of the system is uniquely determined by Z_0.
- Define a function called *transfer map* relating initial conditions at s_0 to the conditions at s via $Z(s) = \mathcal{M}(s_0, s) * Z(s_0)$ and summarizes the entire action of the system.
- The composition of two maps yields another map: $\mathcal{M}(s_0, s_1) \cdot \mathcal{M}(s_1, s_2) = \mathcal{M}(s_0, s_2)$, so that transfer maps of systems can be built up from the transfer maps of the individual elements.
- Computationally this is advantageous because once calculated, it is much faster to apply a single transfer map to a distribution of particles than to track individual particles through multiple lattice elements.

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COSY Infinity, contd.

- COSY supports a large array of lattice elements and fringe fields.
- Among the elements are *deterministic* absorbers of complex shapes described by polynomials of arbitrary order.
- Polynomial absorber acts like a drift with the average (Bethe-Bloch) energy loss.
- This element only takes into account deterministic effects producing the same final result every time for a given initial condition, not stochastic effects (such as multiple scattering and energy straggling).
- Stochastic effects do not fit well within the transfer map paradigm, so it needs to be augmented by implementing the corrections from stochastic effects directly into the fabric of COSY.

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Hybrid
transfer map–Monte-Carlo method

Hybrid method

- Designing, simulating and optimizing performance of cooling channels usually involves high-performance clusters and multi-objective genetic optimizers (multiple stages, many parameters to vary).
- Typically, particle-by-particle tracking codes are used.
- That takes toll on optimizers, especially with a large number of particles per run.
- Transfer map methods could solve this problem: map of the system is calculated once, and then applied to any number of particles at very low computational cost.
- Need to implement hybrid transfer map–Monte-Carlo approach:
- Majority of the dynamics are represented by fast application of the high-order transfer map of an entire element

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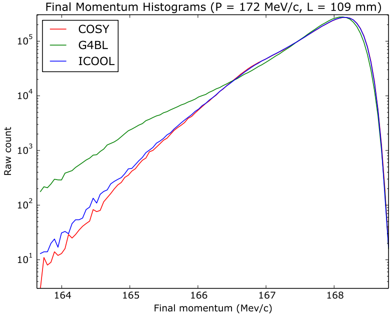
Stochastic processes

Energy straggling



- Comparison between COSY, ICOOL, and G4beamline for a pencil beam with initial momentum of 172 MeV/*c* passing through 109 mm of liquid hydrogen.

- Momentum range of interest is 50–400 MeV/*c* through low *Z* materials,
- Landau theory accurately describes ionization energy loss spectra.
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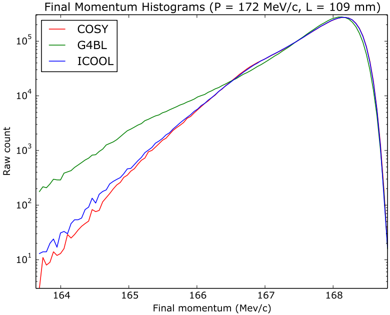

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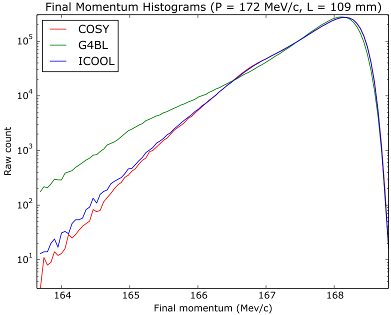

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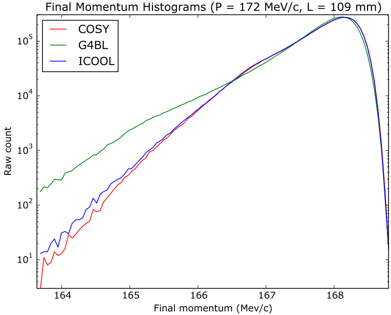

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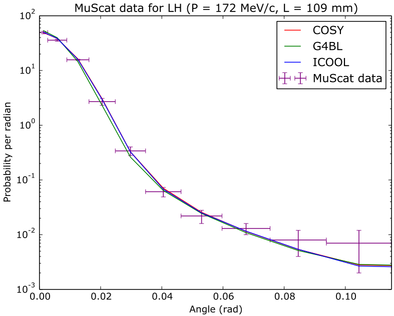

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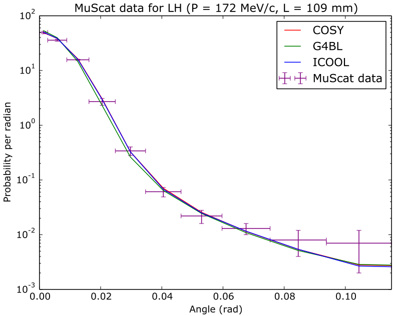

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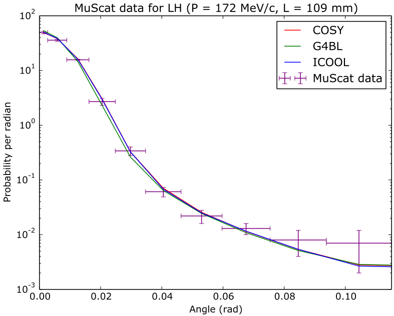

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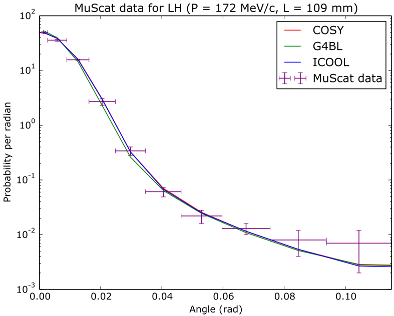

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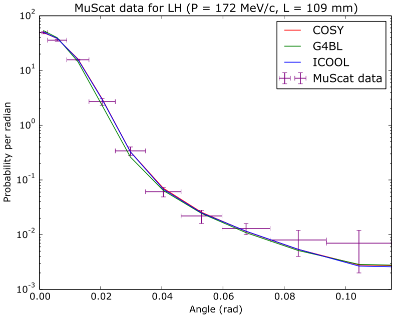

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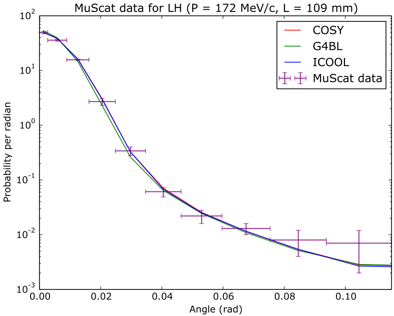

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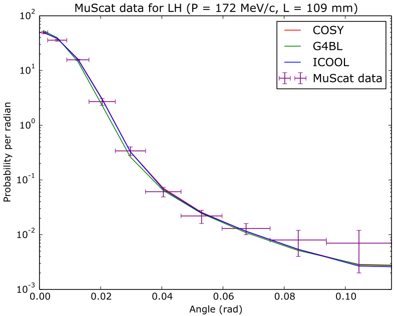

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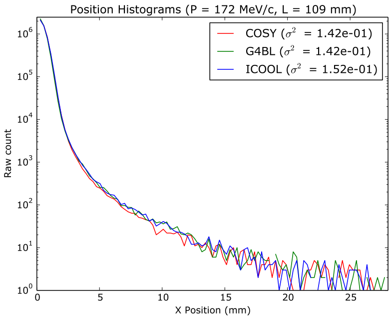

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- Multiple scatterings in medium: must account for transverse position correction.
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- This correction assumes incoming straight track, hence must be rotated accordingly and added to the mean transverse position deflection.

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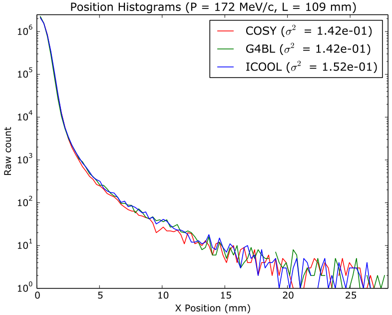

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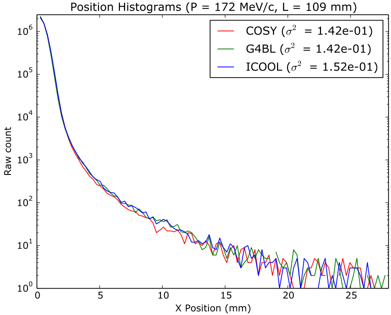

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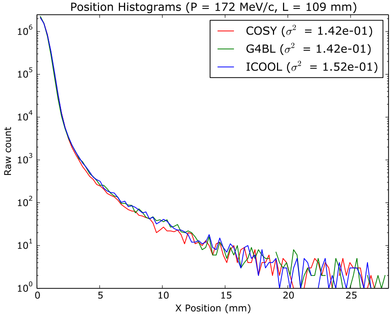

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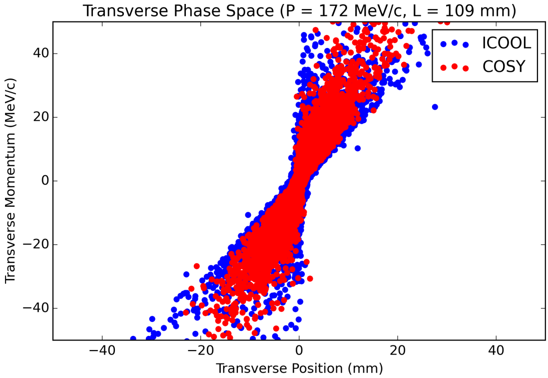

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- Illustrates scattering angle dependence.

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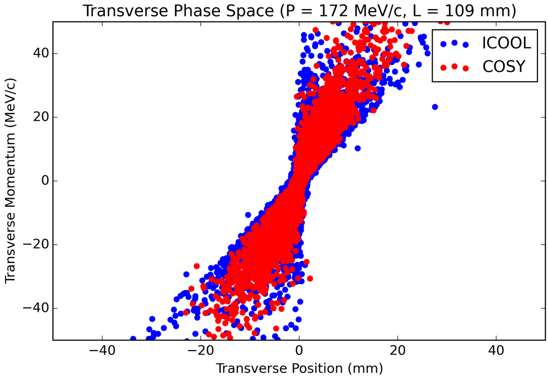

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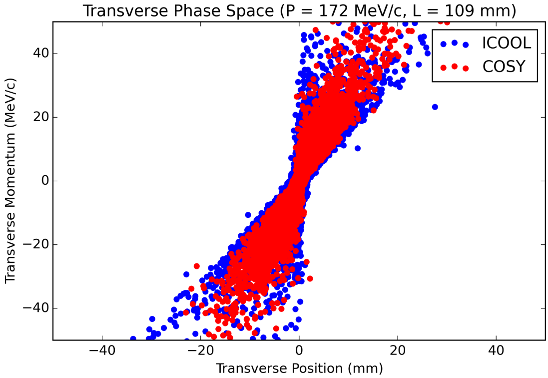

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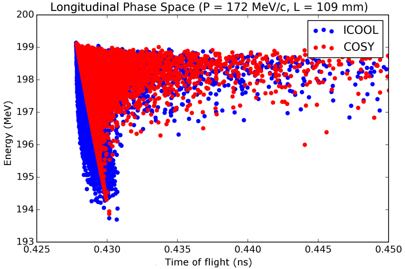

- Longitudinal phase space comparison between COSY (red) and ICOOL (blue) for muons with the initial momentum of 172 MeV/*c* passing through 109 mm of liquid hydrogen.

- Multiple scattering in material: deterministic 'straight' path length differs from the 'true' path length.
- All previous corrections are largely insensitive to this.
- Since time of flight through absorber is on the order of 1 ns, pathlength correction must be taken into account.
- ToF discrepancy between COSY and ICOOL is on the order of 0.002 ns (roughly 0.5% of the mean time-of-flight), will be improved further.

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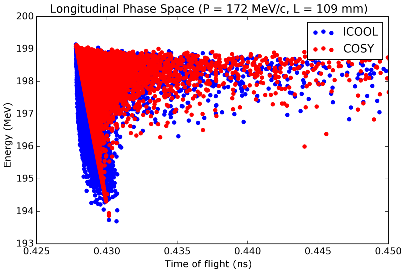

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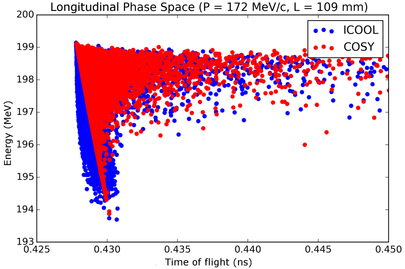

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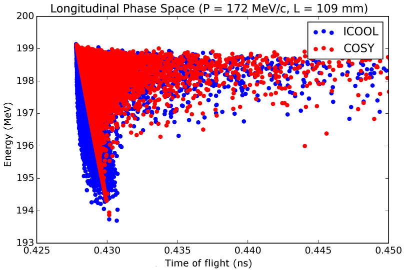

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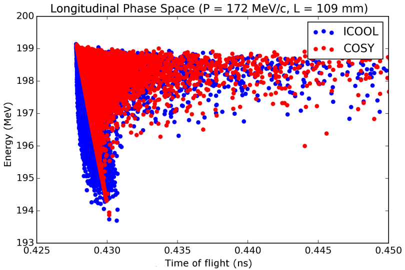

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Summary

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