Muon Production Challenges for High Energy Physics Applications

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Acknowledgements

- MAP Collaboration
- IDS-NF Collaboration
- MICE Collaboration
- Of special note: A. Blondel, J-P. Delahaye, E. Eichten, P. Janot, …

Outline

- Introduction: Why Muons?
- Accelerator Technology:
  The Feasibility of Building a Muon Collider
- Conclusion

INTRODUCTION: WHY MUONS?

Why Muons?

Physics Frontiers

- **Intense and cold muon beams ⇨ unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$$m_\mu = 105.7\, MeV / c^2$$
$$\tau_\mu = 2.2 \mu s$$

Colliders

- **Opportunities**
  - s-channel production of scalar objects
  - Strong coupling to particles like the Higgs →
  - Reduced synchrotron radiation ⇨ multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at IP
- ***BUT* accelerator complex/detector must be able to handle the impacts of μ decay**

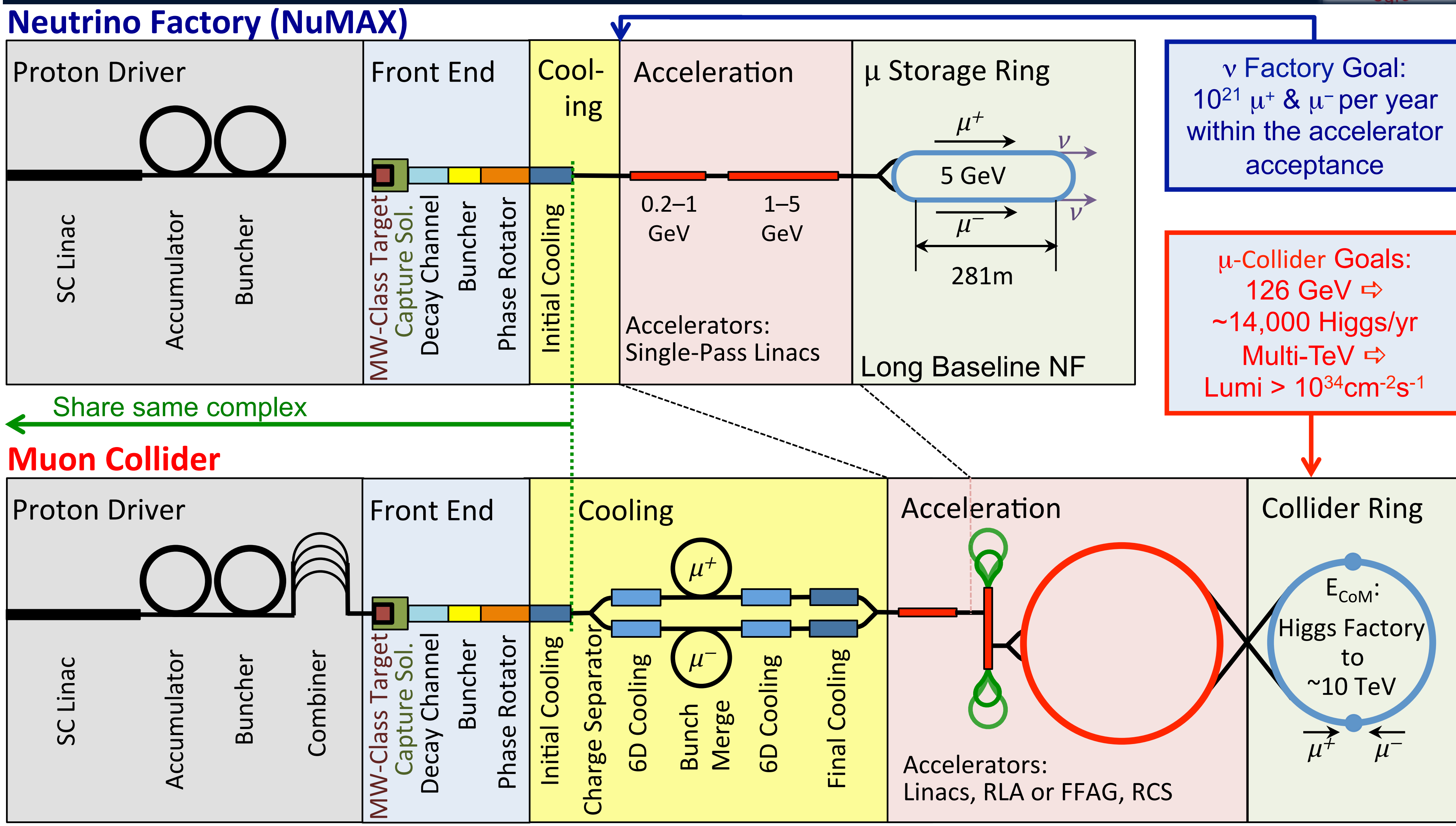
$$\sim \left(\frac{m_\mu^2}{m_e^2} \right) \cong 4 \times 10^4$$

Collider Synergies

- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

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

High Energy Muon Accelerator Capabilities



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The MAP Approach

- Pursue a path that supports the broadest possible range of high energy physics based on muon beams

- A muon source that would support:
  - Short baseline ν capabilities
  - Long baseline ν capabilities
    - With the ability to optimize the energy of the source
  - Colliders
    - A Higgs factory
      - **With the energy resolution necessary to directly probe the detailed resonance structure**
    - Colliders at the multi-TeV scale to look for new physics

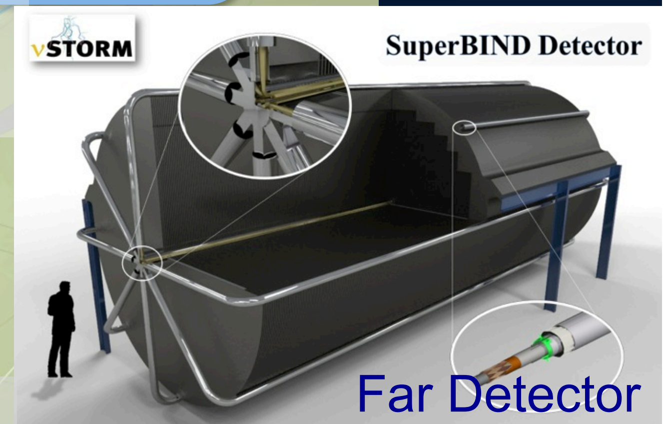
⇨ A challenging optimization focused on both production rate and luminosity issues!

Neutrino Factories

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

- νSTORM – Short Baseline ν factory



- Definitive measurement of sterile neutrinos
- Precision ν_e cross-section measurements (key systematic for LB SuperBeam experiments)
- Muon accelerator proving ground…

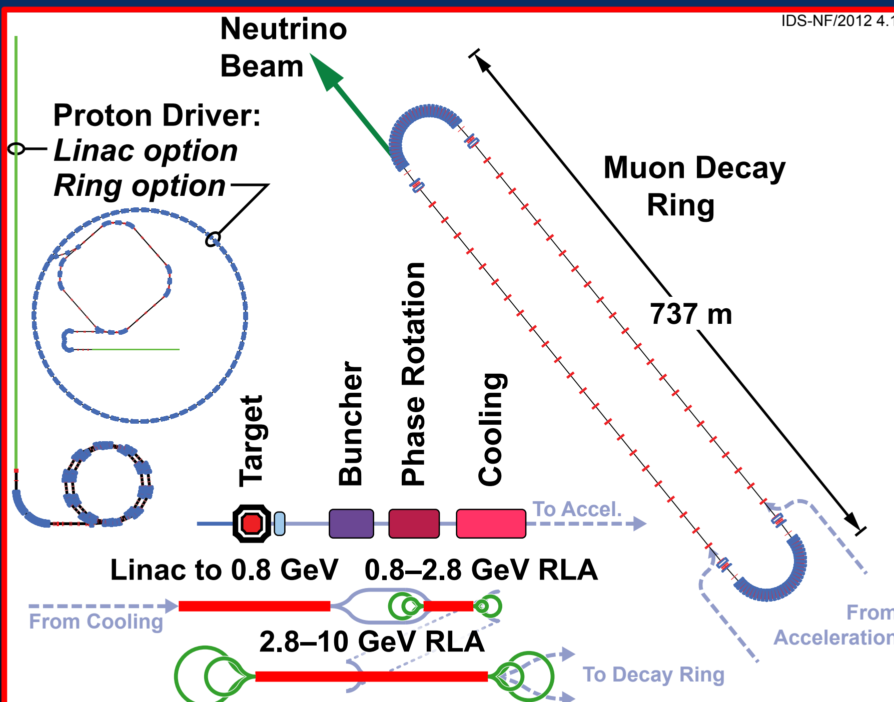
- **NuMAX** (Neutrinos from a Muon Accelerator CompleX)
  - Long baseline concept developed by MAP
    - As part of its Muon Accelerator Staging Study (MASS)
  - Evolutionary from IDS-NF Concept ⇨ FNAL to SURF baseline
    - Magnetized detector (MIND, Mag LAr?)
    - CP violation sensitivity optimal for 4-6 GeV beam energy
    - Provides ongoing short baseline capabilities

The Long Baseline Neutrino Factory

- IDS-NF: the *ideal* NF
  - Supported by MAP
- MASS working group:
  A staged approach -

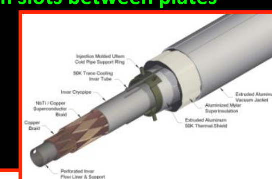
NuMAX@5 GeV⇨SURF

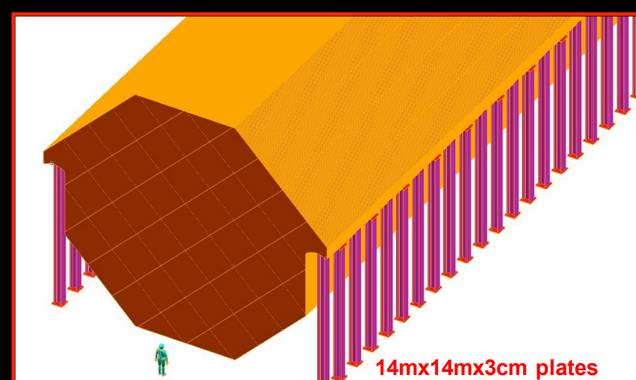
	Value
Accelerator facility	
Muon total energy	10 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Distance to long-baseline neutrino detector	1 500–2 500 km

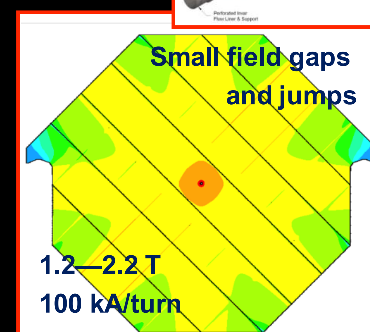


Magnetized Iron Neutrino Detector (MIND):

- IDS-NF baseline:
  - Intermediate baseline detector:
    - 100 kton at 2500—5000 km
  - Magic baseline detector:
    - 50 kton at 7000—8000 km
  - Appearance of "wrong-sign" muons
  - Toroidal magnetic field > 1 T
    - Excited with "superconducting transmission line"
  - Segmentation: 3 cm Fe + 2 cm scintillator
  - 50-100 m long
  - Octagonal shape
  - Welded double-sheet
    - Width 2m; 3mm slots between plates







Bross, Soler

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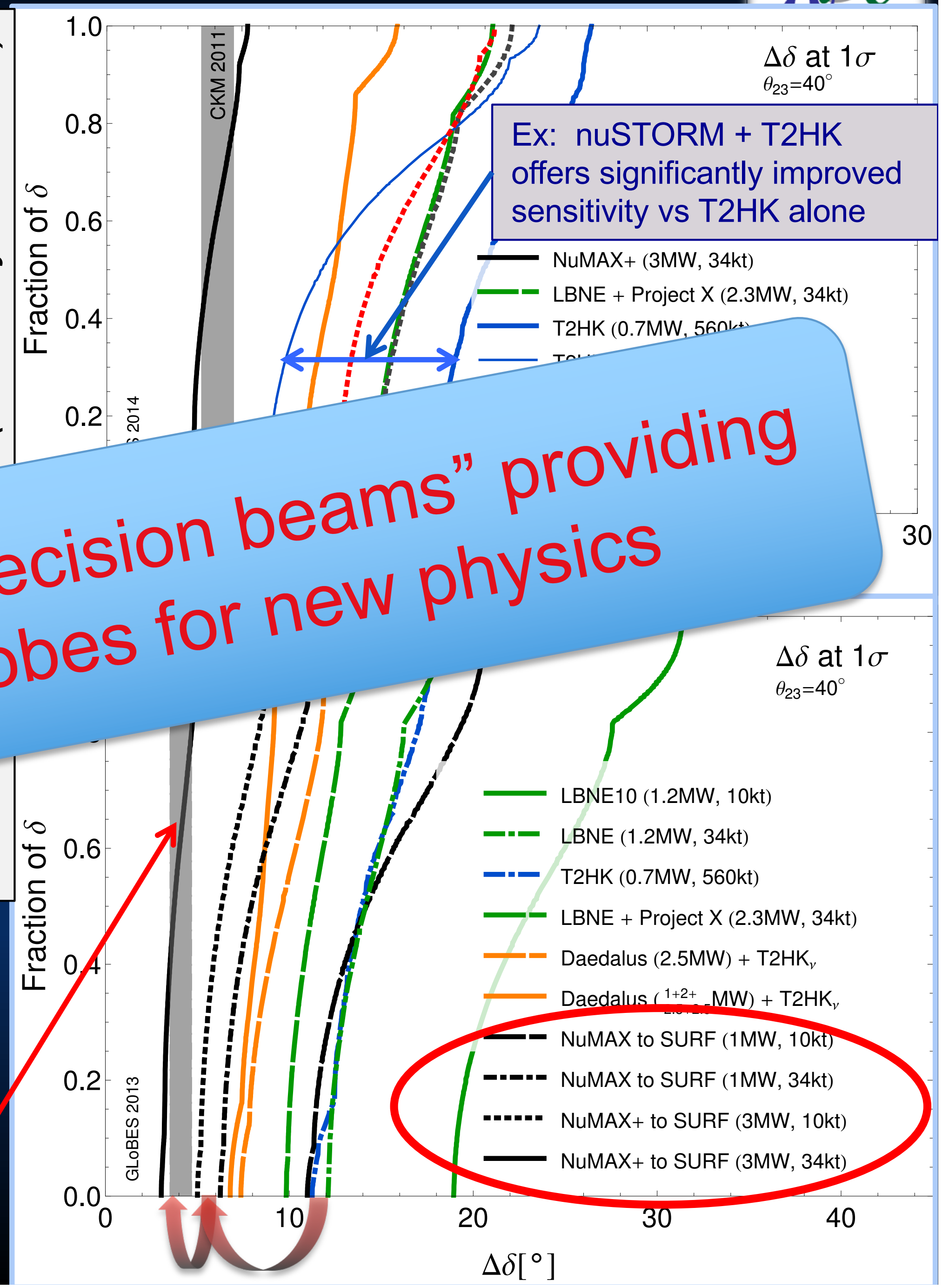
Precision Capabilities for the ν Sector

- Both short- (νSTORM) and long-baseline (NuMAX) options provide routes to high precision measurements in the ν sector with very well understood systematic[s]
- NuMAX
  - Ultimate [...] ν sector
  - Offers:
    - Well-characterized beam
    - Energy Flexibility
    - Discovery Potential!

G[...]arison of Potential [...] of the Various
Adva[...]s (courtesy P. Huber)



High intensity "precision beams" providing sensitive probes for new physics

NuMAX+ targets equivalent sensitivity to CP violation in the ν sector as has been achieved in the flavor sector

Why a Muon Collider?

- First – why a lepton collider?
  - In proton (or proton-antiproton) collisions, composite particles (hadrons), made up of quarks and gluons, collide
    - Fundamental interactions take place are between individual constituents
    - The constituents carry only a fraction of the total energy
    - p-p collisions: $E_{effective} = O(10\%\ E_{COM})$

    ⇨ LHC probes an energy scale E < 2 TeV
  - Electrons and muons are fundamental particles (leptons)
    - Point-like particles
    - Well-understood energy and quantum state at collision
    - Collision products probe the full CoM energy

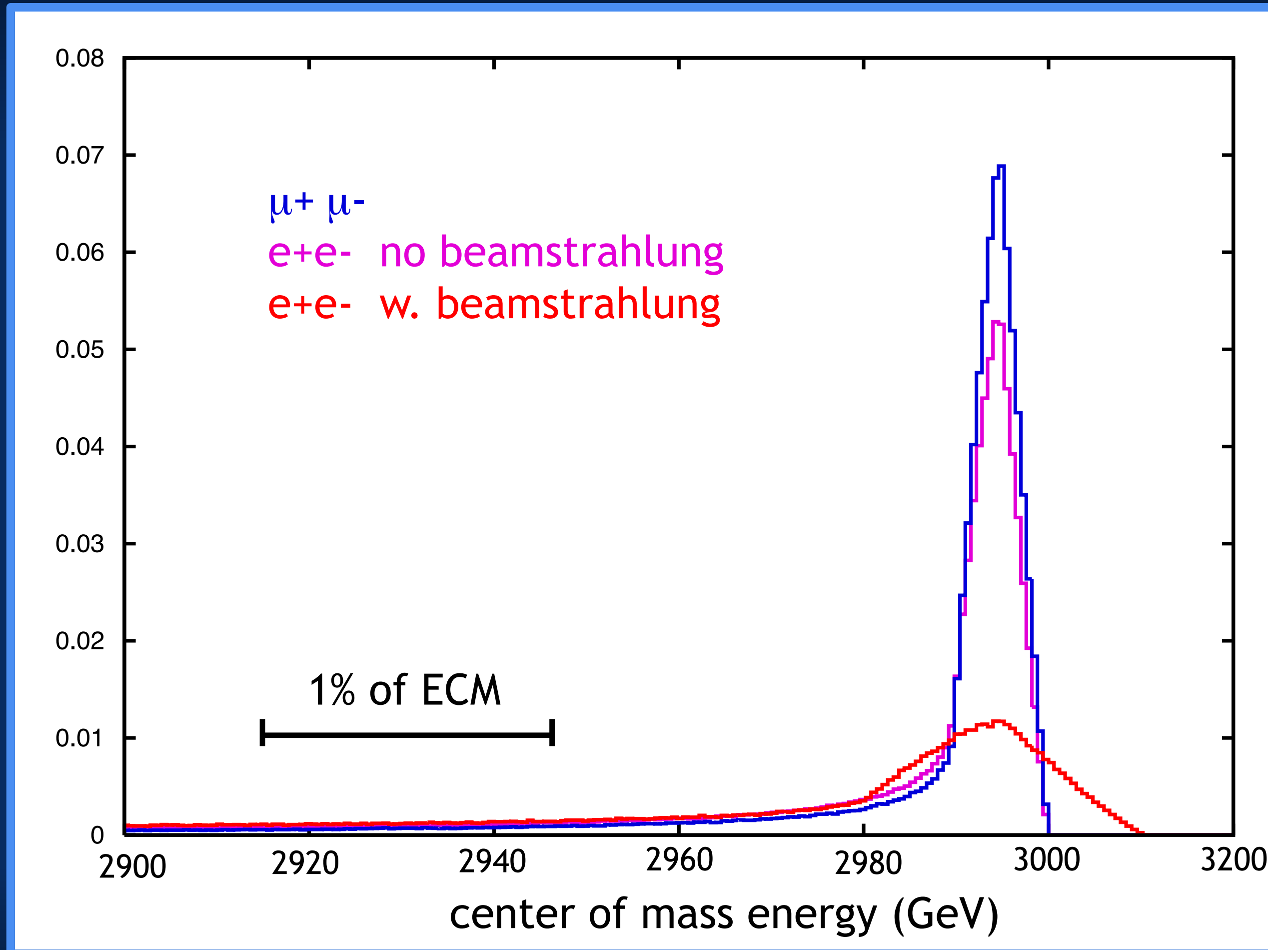
    ⇨ a ~2 TeV lepton collider probes the full energy range of fundamental processes under study at the LHC

Muon Collider Features

Beamstrahlung

- Effect of ISR and beamstrahlung at the IP for 3 TeV CoM energy

- Typical metric developed for e^+e^- LCs is the fraction of luminosity within 1% of E_{CM}



$\mu^+\mu^-$ Colliders vs e^+e^- Colliders

- s-Channel Production
  - When 2 particles annihilate with the correct quantum numbers to produce a single final state. Examples:

    $e^+e^- \rightarrow Higgs$ **OR** $\mu^+\mu^- \rightarrow Higgs$
  - The cross section for this process scales as m^2 of the colliding particles, so:

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

$$\sigma\left(\mu^+\mu^- \rightarrow H\right) = 4.28 \times 10^4\,\sigma\left(e^+e^- \rightarrow H\right)$$

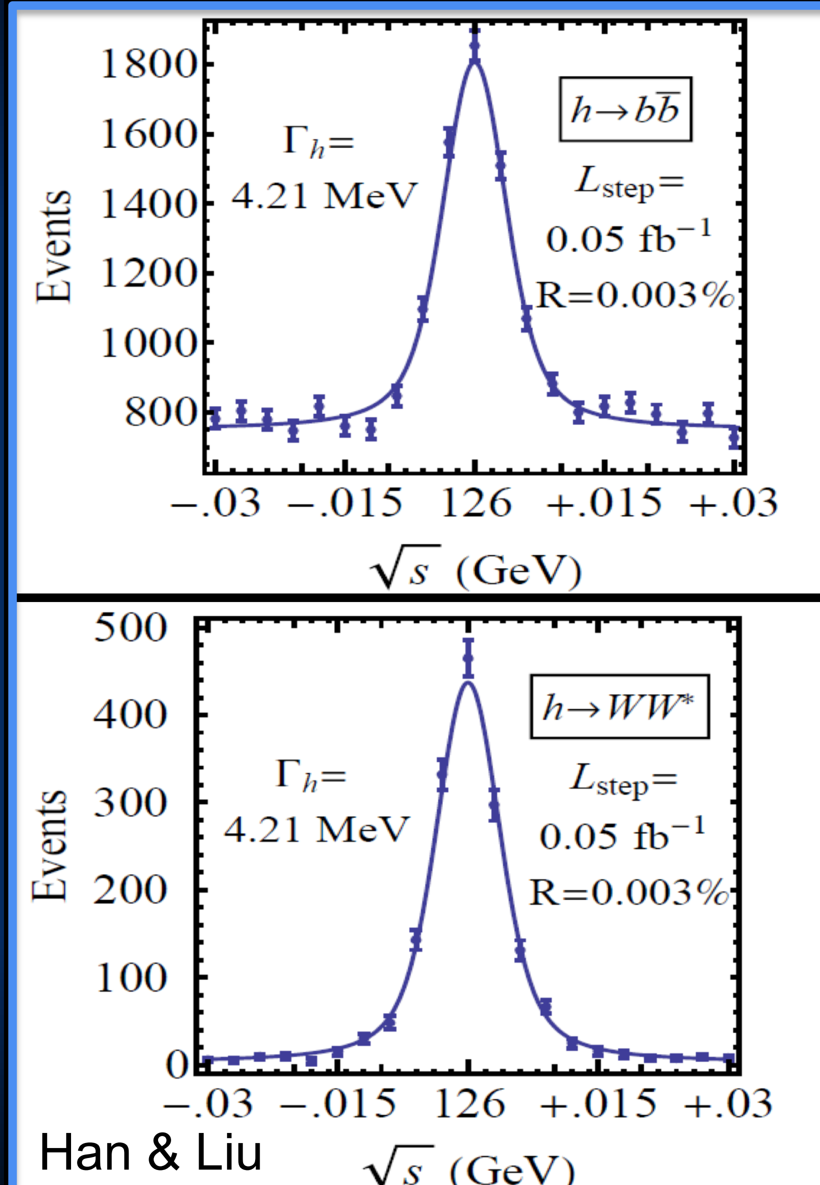
  - A muon collider can probe the Higgs resonance directly
    - The luminosity required is not so large
    - **A precision scan capability is particularly interesting in the case of a richer Higgs structure (eg, a Higgs doublet)**

Muon Collider Features

Energy Resolution

- Muon beams enable colliding beams with very small energy spread
- Of particular significance for a Higgs Factory if there were signs of a non-standard Higgs
  - Ability to directly probe the width and structure of the resonance
- Specific Cases:

$\delta E_b/E_b \sim 4\cdot 10^{-5}$ @ Higgs
$\delta E_b/E_b \sim 10^{-4}$ to 10^{-3} @ Top
$\delta E_b/E_b \sim 1\cdot 10^{-3}$ @ TeV-scale

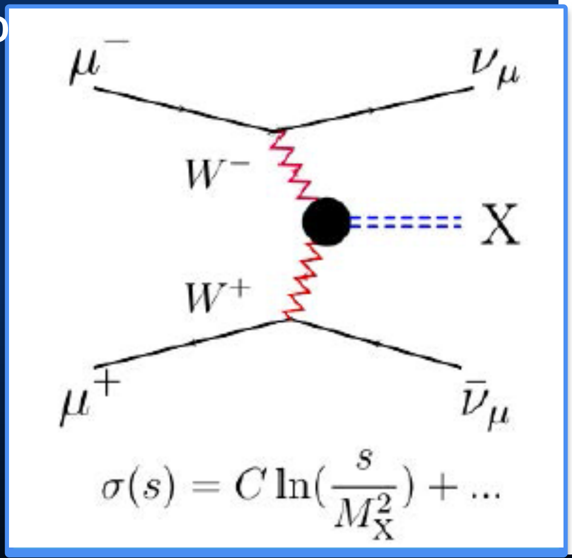


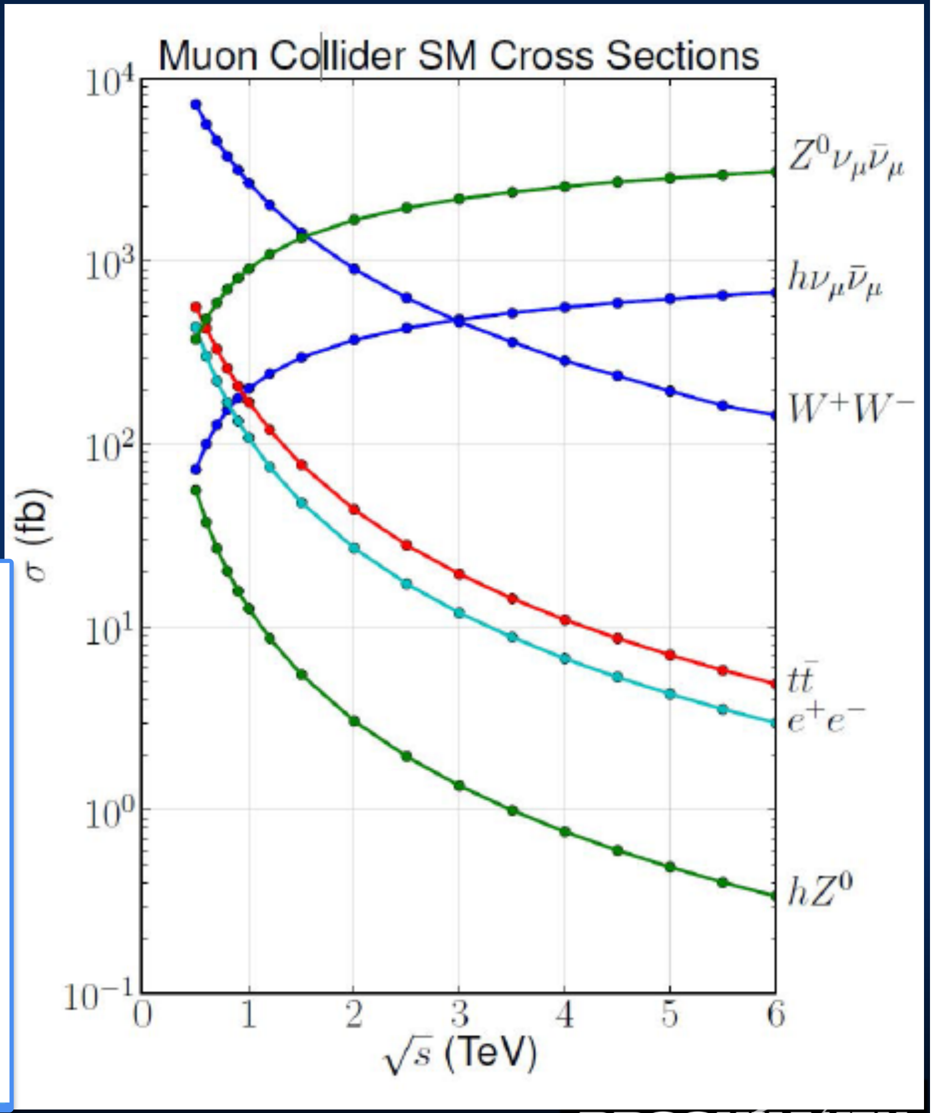
Han & Liu

Muon Collider Features

High Energy Collisions

- At √s > 1 TeV: Fusion processes dominate
  - An Electroweak Boson Collider
  - A discovery machine complementary to very high energy pp collider
- At >5TeV: Higgs self-coupling resolution <10%





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Synchrotron Radiation and Energy Reach

- Synchrotron Radiation
  - In a circular machine, the energy loss per turn due to synchrotron radiation can be written as:

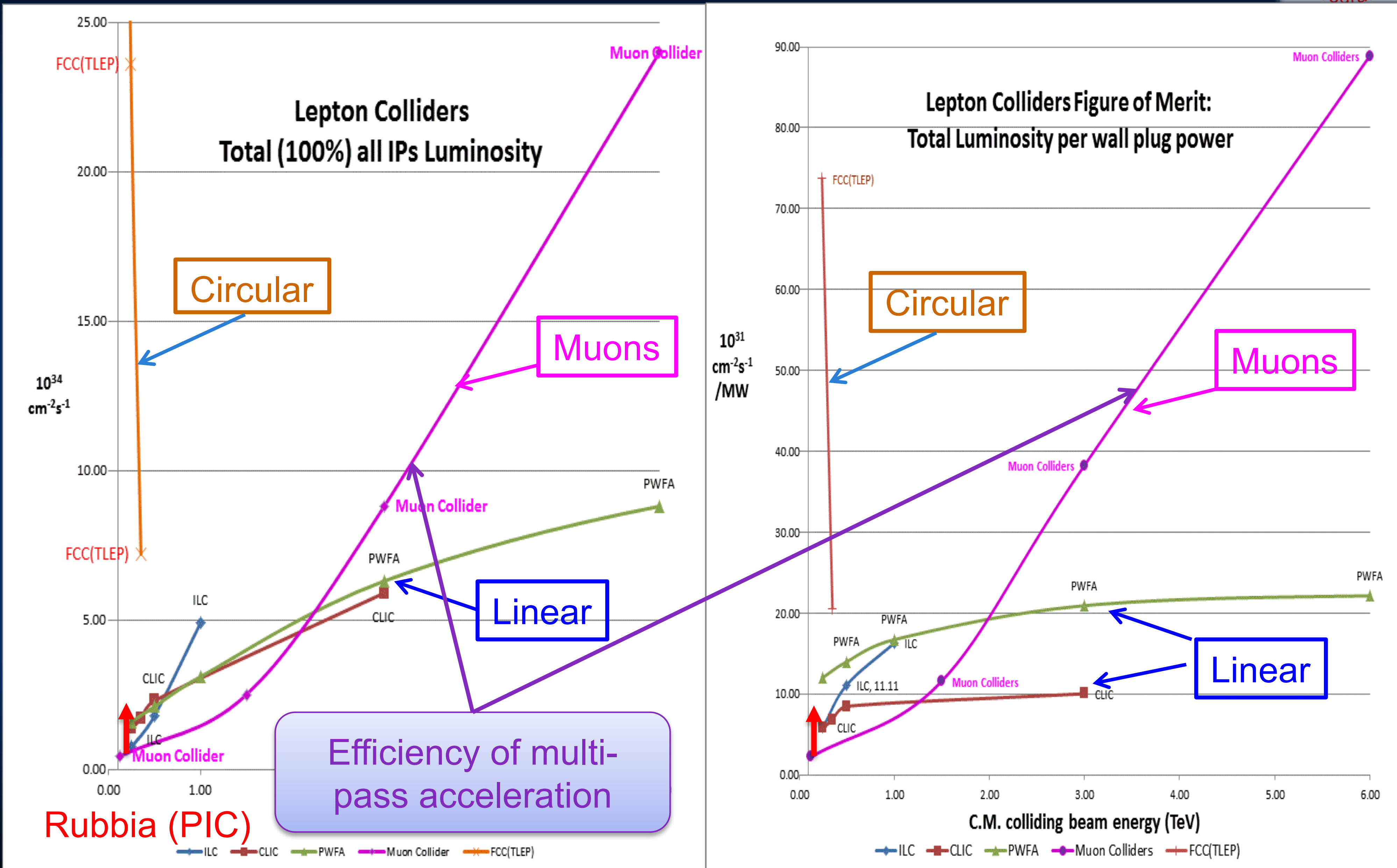
$$\Delta E_{turn} = \left(\frac{4\pi mc^2}{3}\right)\left(\frac{r_0}{\rho}\right)\beta^3\gamma^4$$

where ρ is the bending radius

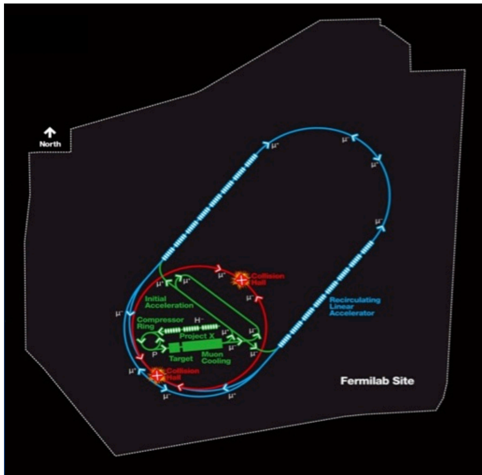
$$\rho \propto \frac{\beta\gamma}{B} \Rightarrow \boxed{\Delta E_{turn} \propto B\gamma^3}$$

  - If we are interested in reaching the TeV scale, an e^+e^- circular machine is not feasible due to the large energy losses
    Solution 1: e^+e^- linear collider
    Solution 2: Use a heavier lepton – i.e., the muon

Muon Colliders –
Efficiency at the multi-TeV scale



Muon Collider Parameters

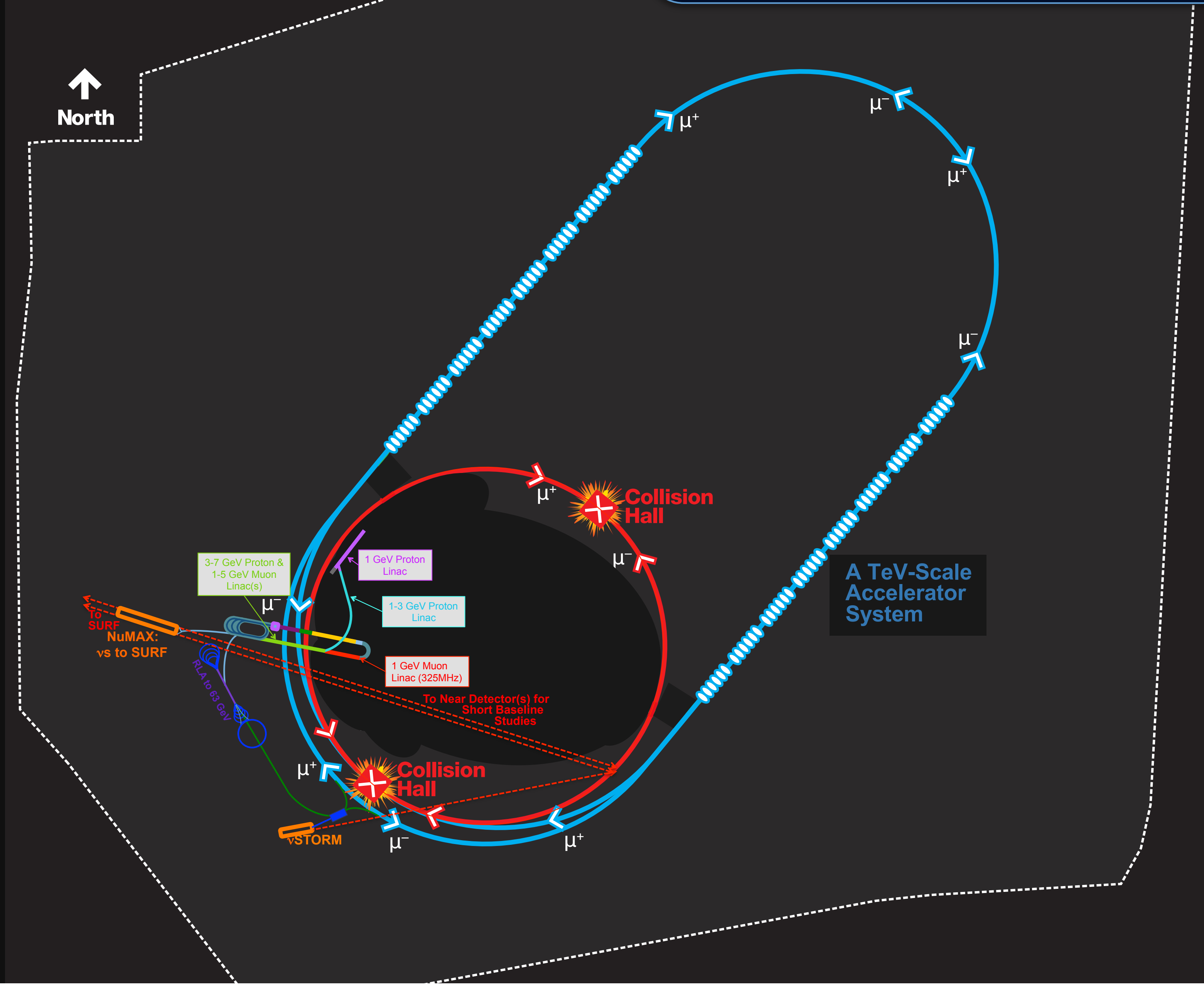


Muon Collider Parameters					
		Higgs	Multi-TeV		
Parameter	*Units*	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec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

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

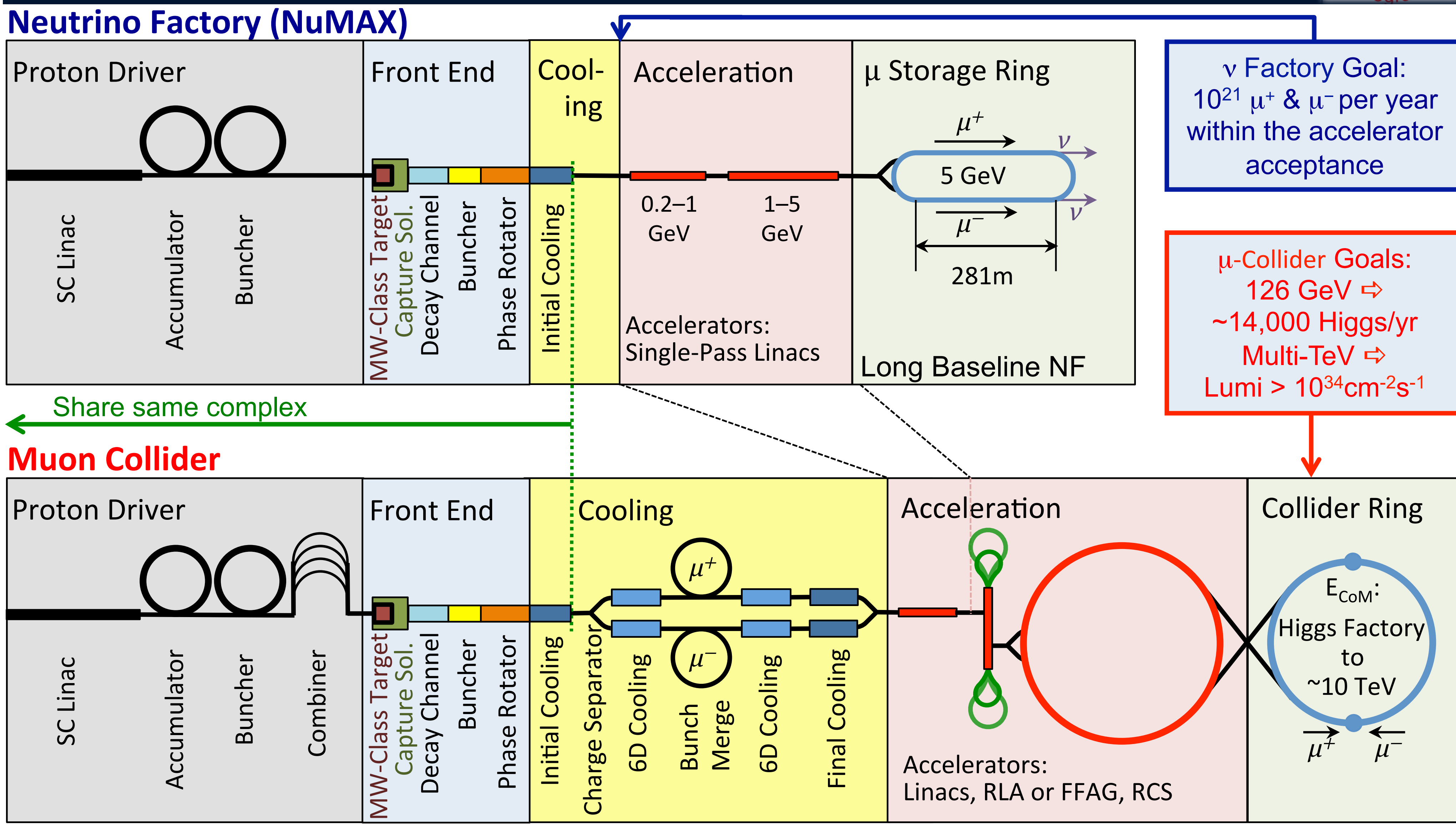
Success of advanced cooling concepts
⇨ several $\times 10^{32}$ [Rubbia proposal: 5×10^{32}]

The Scale of a Multi-TeV Collider shown on the Fermilab Site



ACCELERATOR TECHNOLOGY

High Energy Muon Accelerator Capabilities



Muon Collider Luminosity

- For a muon collider, we can write the luminosity as:

$$\mathcal{L} = \frac{N^2 f_{coll}}{4\pi\sigma_x\sigma_y} = \frac{\left\langle N^2 \right\rangle_{n_{turns}} n_{turns} f_{bunch}}{4\pi\sigma_\perp^2}$$

- For the 1.5 TeV muon collider design, we have
  - N = 2×10^{12} particles/bunch
  - $\sigma_{x,y}$ ~ 5.9 μm, β^* = 10 mm, $\varepsilon_{x,y}(norm)$ = 25 μm-rad
  - n_{turns}~1000
  - f_{bunch}=15 Hz (rate at which new bunches are injected)

$$\mathcal{L} \approx \frac{N_0^2 n_{turns} f_{bunch}}{4\pi\sigma_\perp^2} \approx 1.4\times10^{34}\, cm^{-2} s^{-1}$$

- But this is optimistic since we've assumed N is constant for ~1000 turns when it's actually decreasing. The anticipated luminosity for this case is $\sim 1.2\times10^{34}\, cm^{-2}s^{-1}$.

Challenges for a $\mu^+\mu^-$ Collider

- Pions from a MW-scale proton beam striking a target
- Efficient capture of the produced pions
  - Capture of both forward and backward produced pions loses polarization
- Phase space of the created pions is ***very large!***
  - Transverse: 20π mm-rad
  - Longitudinal: 2π m-rad
- Emittances must be cooled by factors of ~10^6-10^7 to be suitable for multi-TeV collider operation

  ~1000x in the transverse dimensions
  ~40x in the longitudinal dimension
- The muon lifetime is 2.2 μs lifetime at rest

LEMMA vs Proton Driver

- Key Features:
  - *Muons produced with much smaller transverse emittance*
  - *Significantly lower charge/bunch*
  - *Source power requirements significantly lower than proton-driver source?*
- Impacts:
  - *Acceleration requirements improved*
  - *Long Baseline NF applications appear challenging*
    - *Are there any paths to increased muon production rate?*
  - *High Energy Collider*
    - *Luminosity performance appears acceptable*
      - *Collider optimization needs further study*
      - *Higgs factory? Similar luminosity to MAP baseline but larger energy spread prevents structural scans.*
    - *Lower overall charge implies detector background issues from muon decay are greatly improved*
    - *Site radiation issues also improved ➩ even higher energies possible*

Cooling Options

- Electron/Positron cooling: use synchrotron radiation
  ⇨ For muons $\Delta E \sim 1/m^3$ (*too small!*)
- Proton Cooling: use
  - A co-moving cold e- beam
    ⇨ For muons this is too slow
  - Stochastic cooling
  ⇨For muons this is also too slow
- Muon Cooling: use
  - Use Ionization Cooling
    ⇨ Likely the only viable option
  - Optical stochastic cooling
  ⇨ Maybe, but far from clear

Key Feasibility Issues

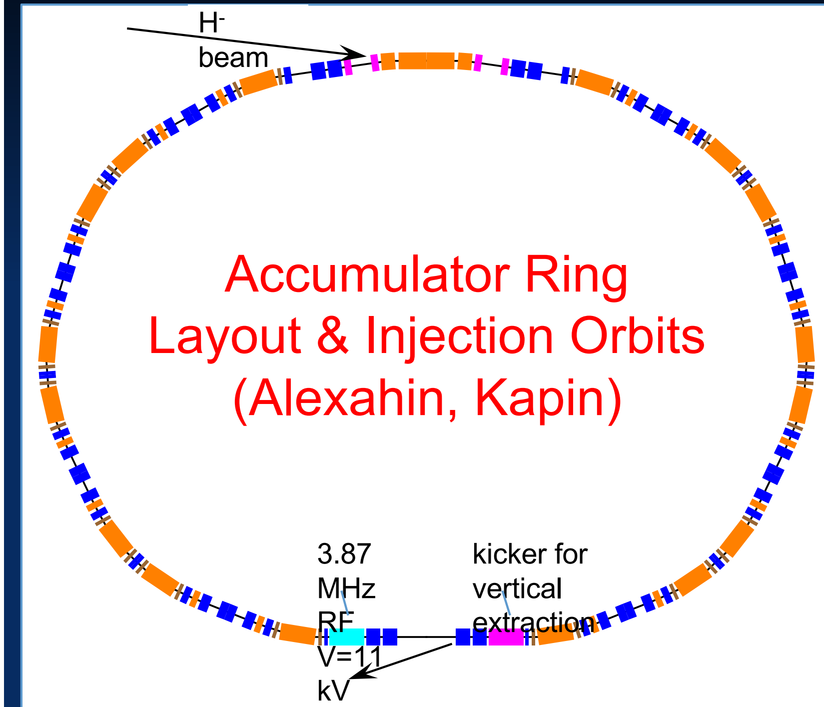
- Proton Driver
- Target
- Front End
- Cooling
- Acceleration
- Collider Ring
- Collider MDI
- Collider Detector

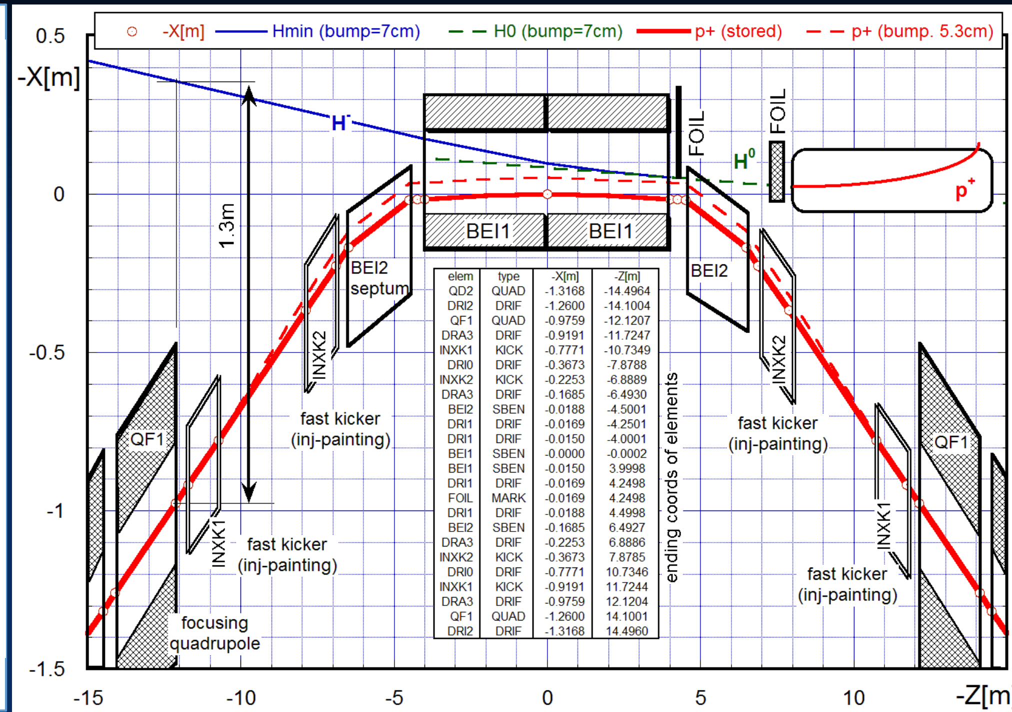
High Power Target Station
Capture Solenoid
Energy Deposition
RF in Magnetic Fields
Magnet Needs (Nb_3Sn vs HTS)
Performance
Acceptance (NF)
>400 Hz AC Magnets (MC)
IR Magnet Strengths/Apertures
SC Magnet Heat Loads (μ decay)
Backgrounds (μ decay)

Characteristics of the Muon Source

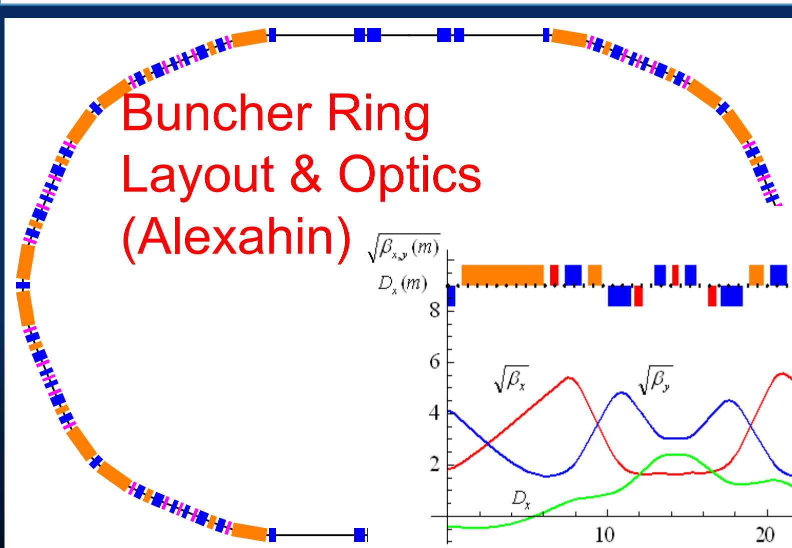
- Overarching goals
  - NF: Provide $O(10^{21})$ μ/yr within the acceptance of a μ ring
  - MC: Provide luminosities $>10^{34}/cm^{-2}s^{-1}$ at TeV-scale ($\sim n_b^2$)
    Enable precision probe of particles like the Higgs
- How do we do this?
  - Tertiary muon production through protons on target (followed by capture and cooling)
    Rate $> 10^{13}$/sec $n_b = 2 \cdot 10^{12}$

Proton Driver





elem	type	-X[m]	-Z[m]
QD2	QUAD	-1.3168	-14.4964
DRI2	DRIF	-1.2600	-14.1004
QF1	QUAD	-0.9759	-12.1207
DRA3	DRIF	-0.9191	-11.7247
INXK1	KICK	-0.7771	-10.7349
DRI0	DRIF	-0.3673	-7.8788
INXK2	KICK	-0.2253	-6.8889
DRA3	DRIF	-0.1685	-6.4930
BEI2	SBEN	-0.0188	-4.5001
DRI1	DRIF	-0.0169	-4.2501
DRI1	DRIF	-0.0150	-4.0001
BEI1	SBEN	-0.0000	-0.0002
BEI1	SBEN	-0.0150	3.9998
DRI1	DRIF	-0.0169	4.2498
FOIL	MARK	-0.0169	4.2498
DRI1	DRIF	-0.0188	4.4998
BEI2	SBEN	-0.1685	6.4927
DRA3	DRIF	-0.2253	6.8886
INXK2	KICK	-0.3673	7.8785
DRI0	DRIF	-0.7771	10.7346
INXK1	KICK	-0.9191	11.7244
DRA3	DRIF	-0.9759	12.1204
QF1	QUAD	-1.2600	14.1001
DRI2	DRIF	-1.3168	14.4960



Optics:
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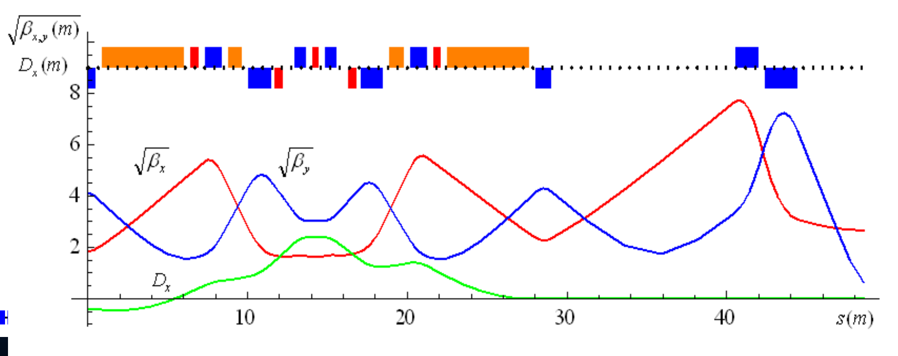
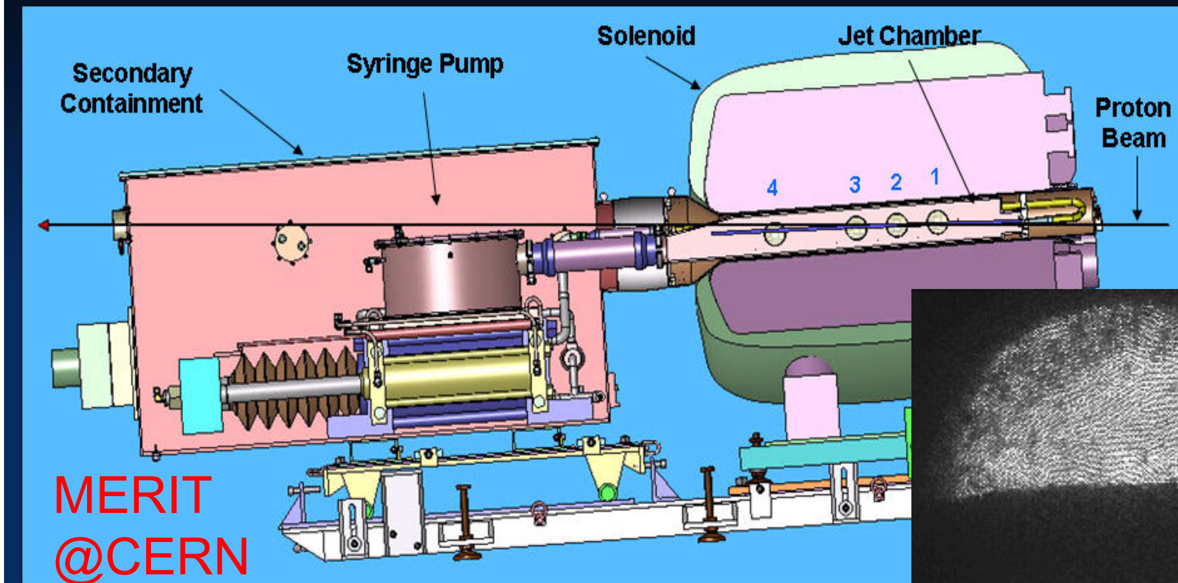
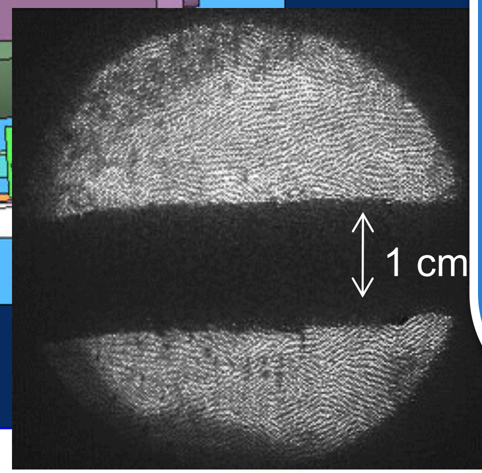
1 arc cell



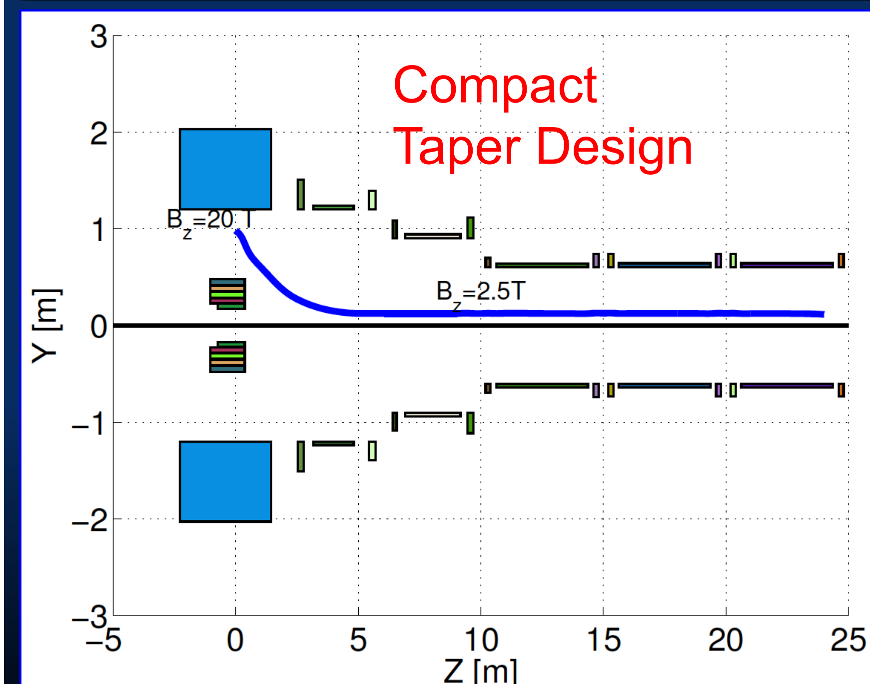
- ✓ Based on 6-8 GeV Linac Source
- ✓ Accumulator & Buncher Ring Designs in hand
- ✓ H- stripping requirements same as those established for Fermilab's Project X

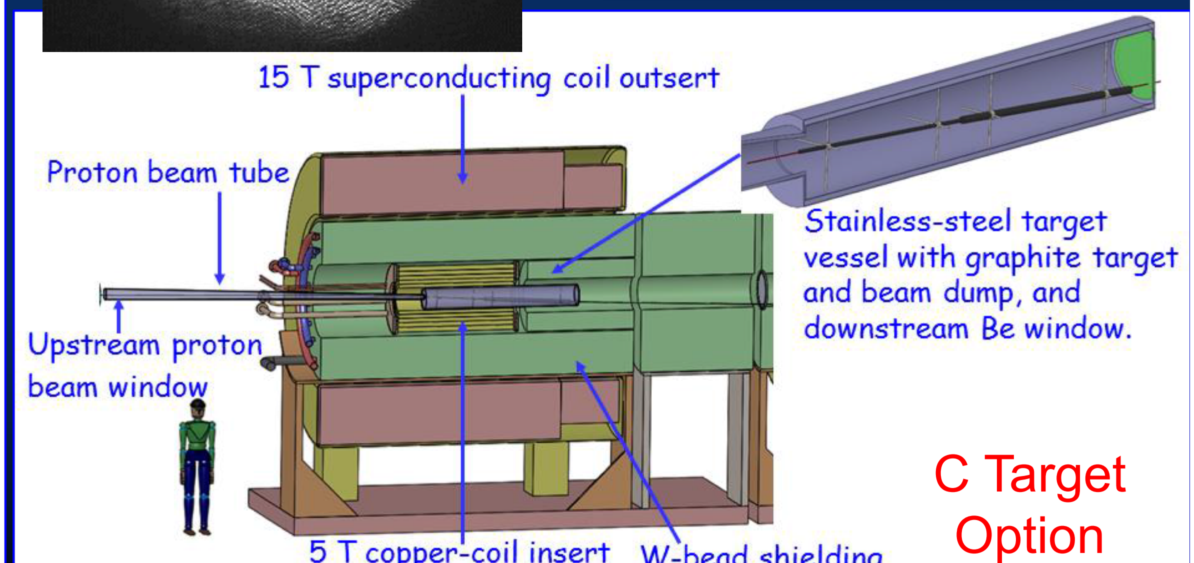
High Power Target



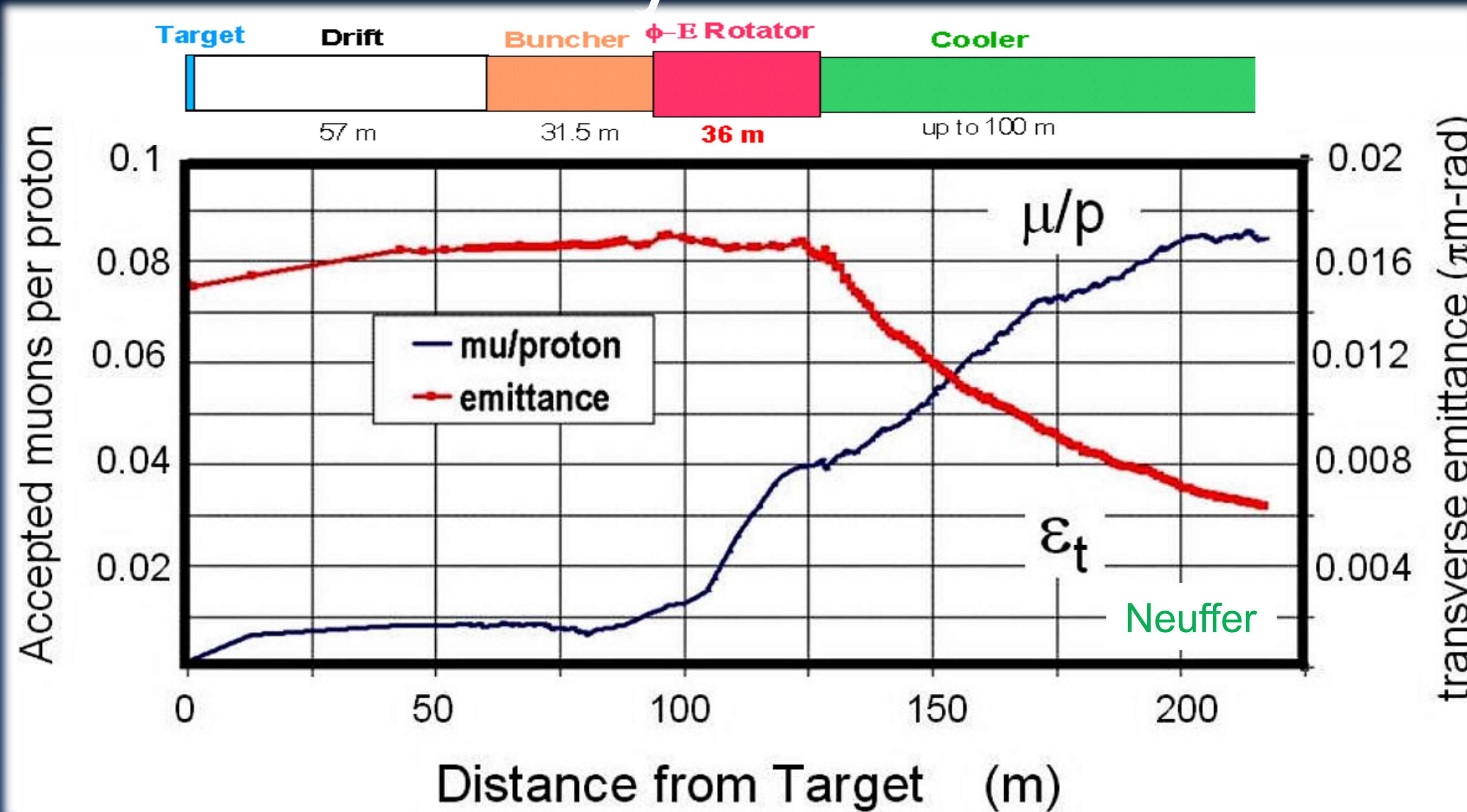


- ✓ MERIT Expt:
  - LHg Jet in 15T
  - Capability: 8MW @70Hz
- ✓ MAP Staging aims at 1-2 MW ➪ C Target
- ✓ Improved Compact Taper Design
  - Performance & Cost





Technology Challenges – Tertiary Production



- A multi-MW proton source would enable O(10^{21}) muons/year to be produced, bunched and cooled to fit within the acceptance of an accelerator.

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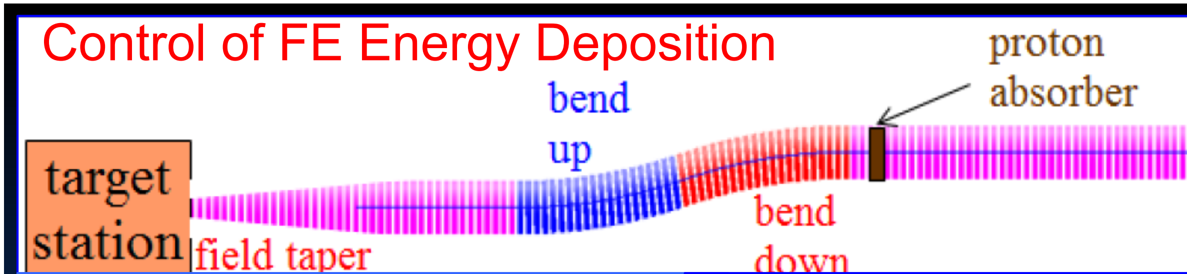
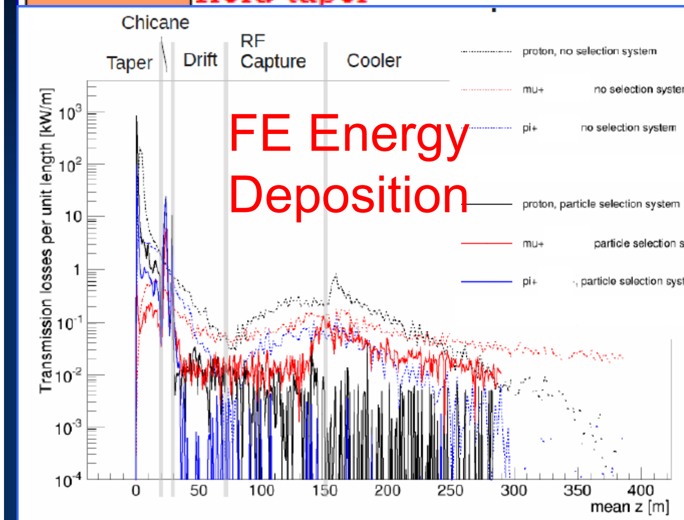
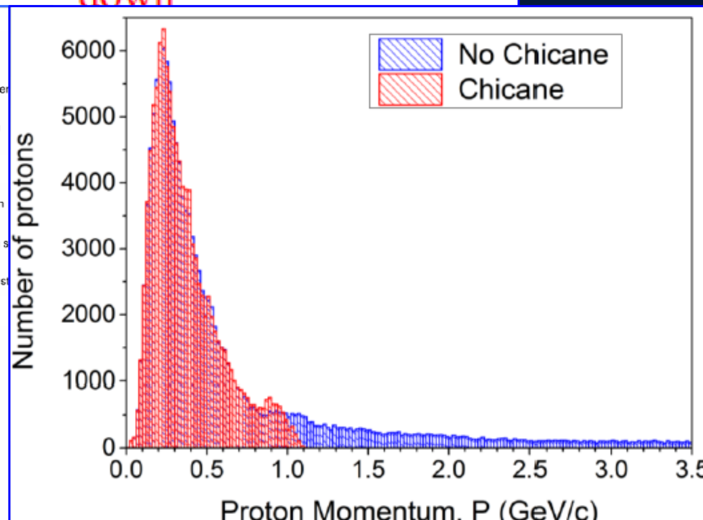
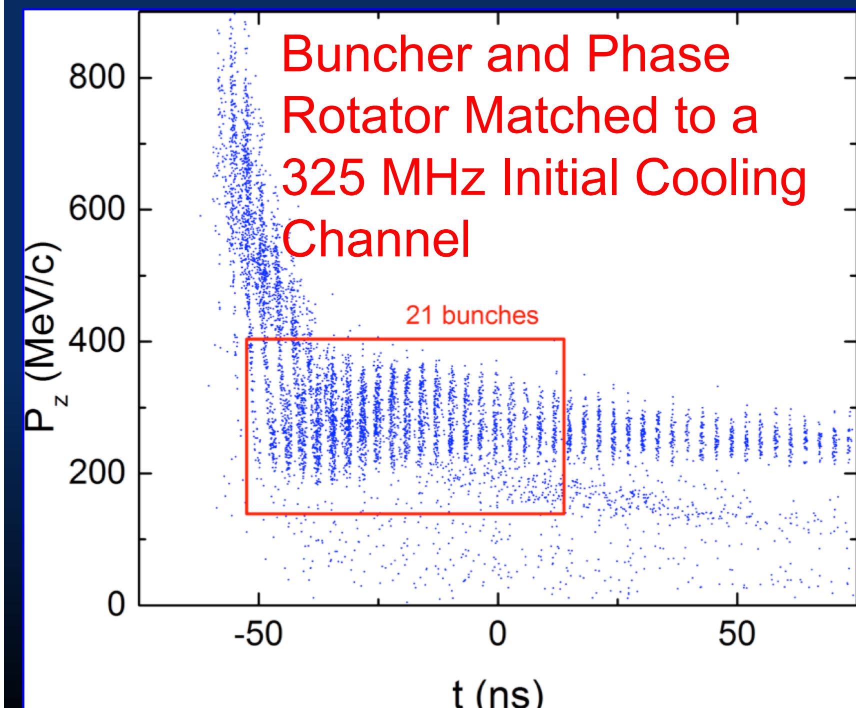
Front End

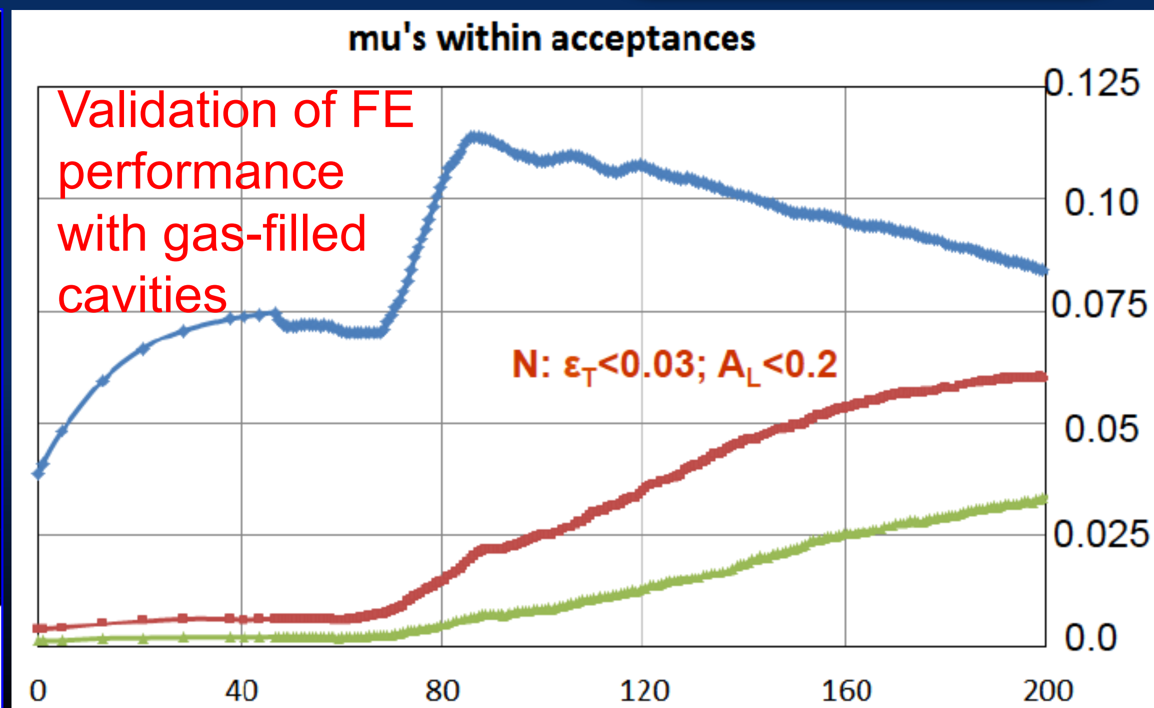






- ✓ Energy Deposition
- ✓ Full 325 MHz RF Design
- ✓ Validation of gas-filled RF cavity performance



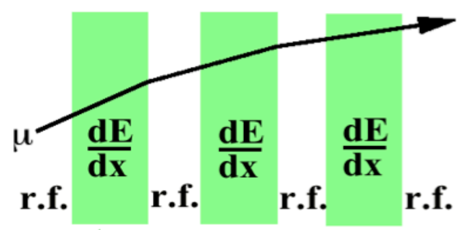


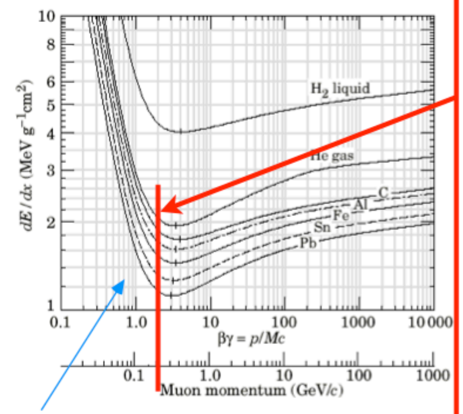
Cooling Methods

- The unique challenge of muon cooling is its short lifetime
  - Cooling must take place very quickly
  - More quickly than any of the cooling methods presently in use
  - ⇨ Utilize energy loss in materials with RF re-acceleration

Muon Ionization Cooling

- Muons cool via dE/dx in low-Z medium





- ionization minimum is ≈ optimal working point:
  - longitudinal +ive feedback at lower *p*
  - straggling & expense of reacceleration at higher *p*

– Absorbers:

$$\begin{cases} E \to E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

- 2 competing effects ⇒ ∃ equilibrium emittance

– RF cavities between absorbers replace ΔE

– Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

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

Kaplan

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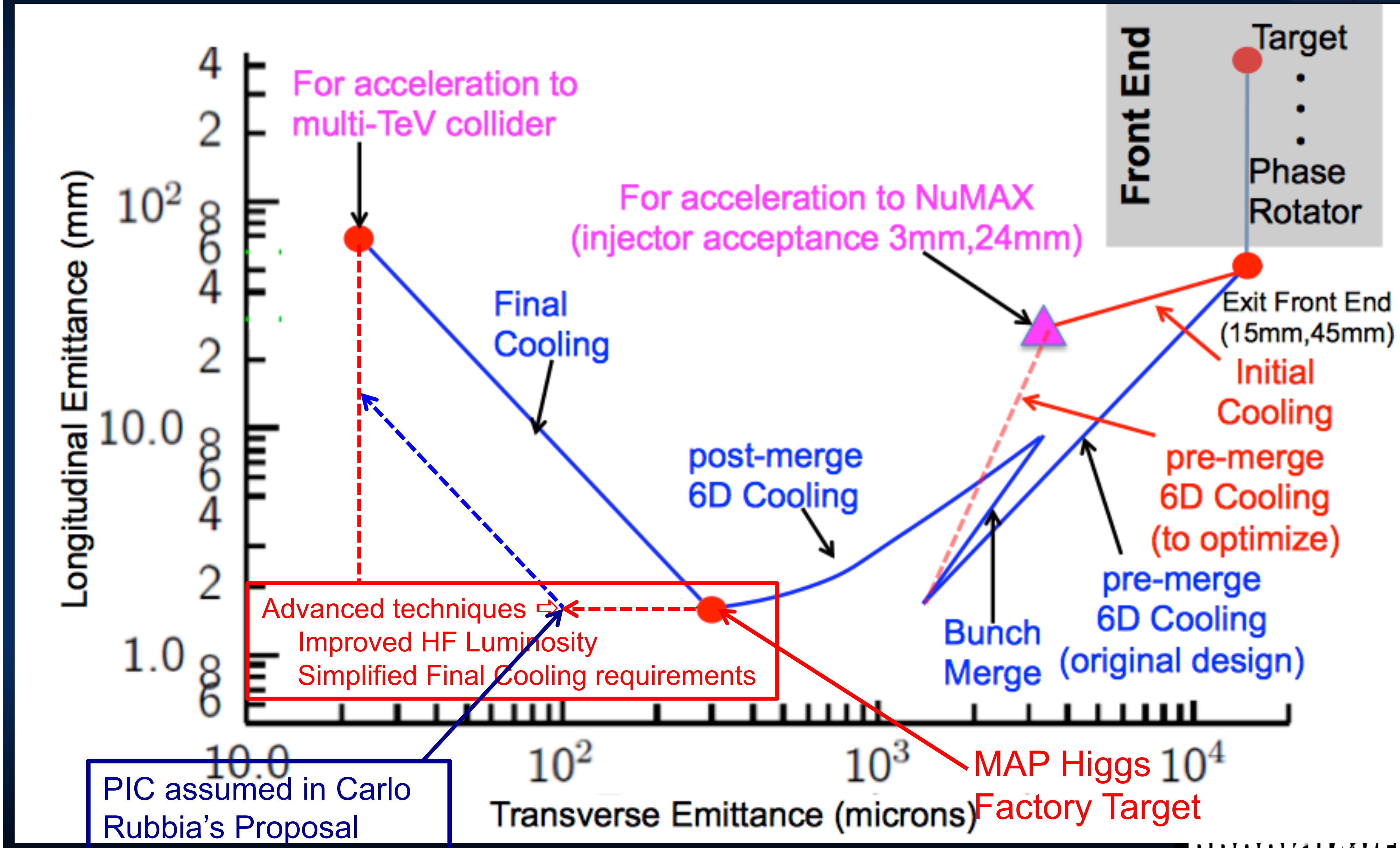
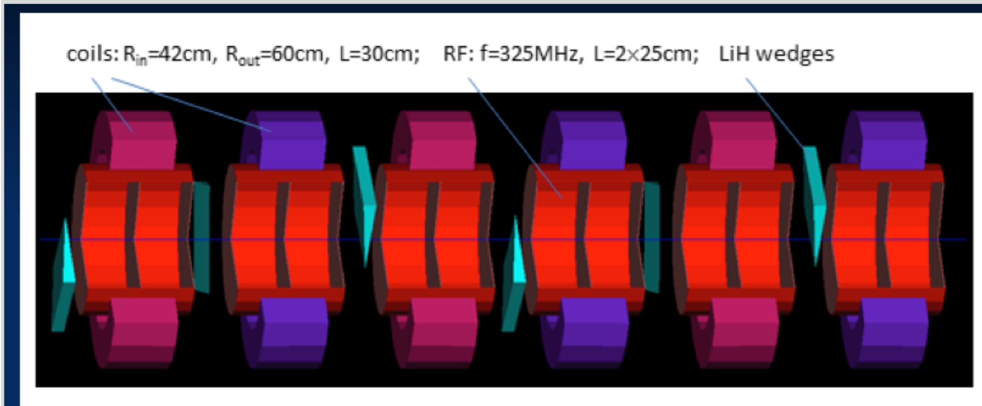
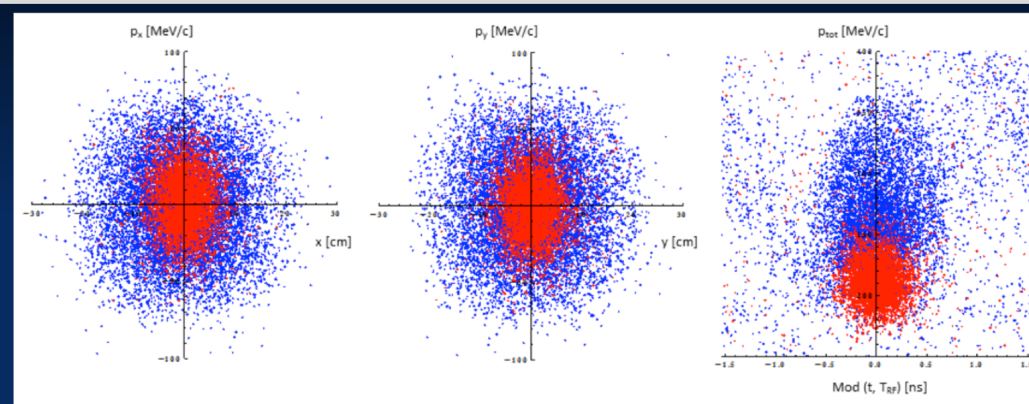
Muon Ionization Cooling

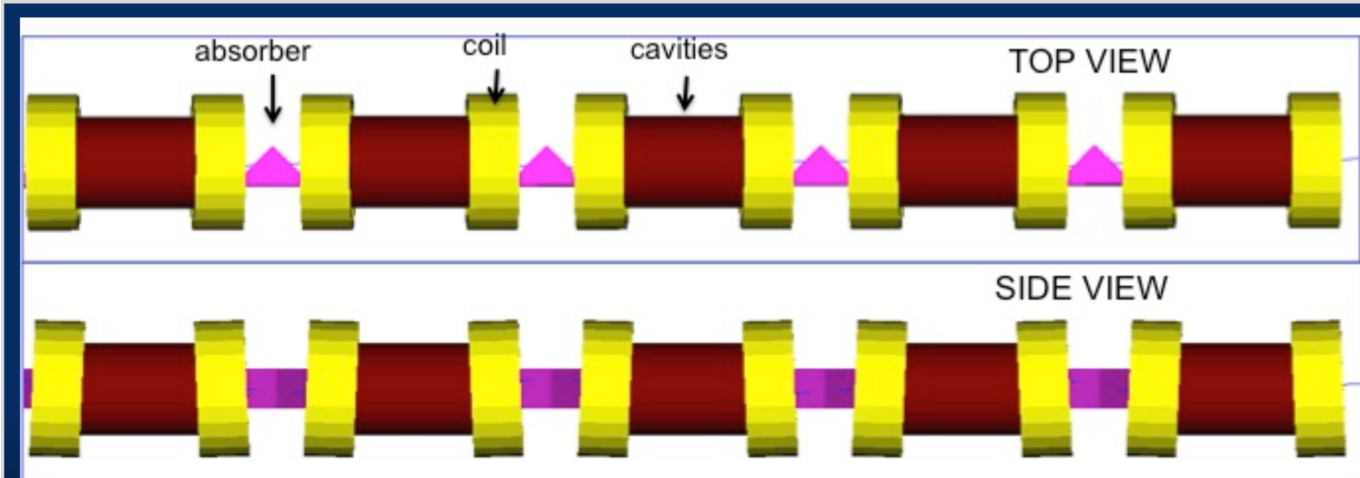


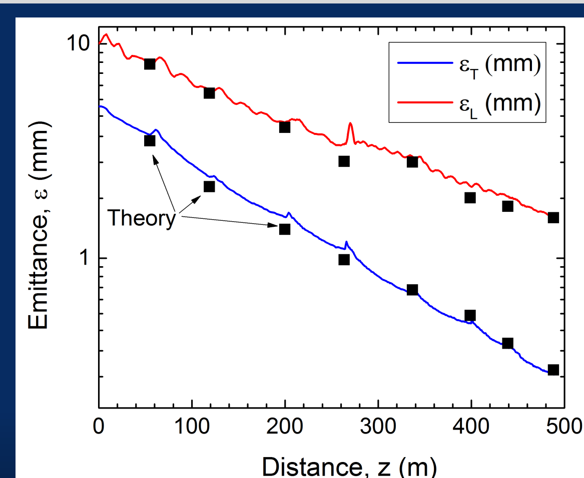
Muon Ionization Cooling (Design)





Initial 6D Cooling: ε_{6D} 60 cm^3 ⇨ ~50 mm^3; Trans = 67%



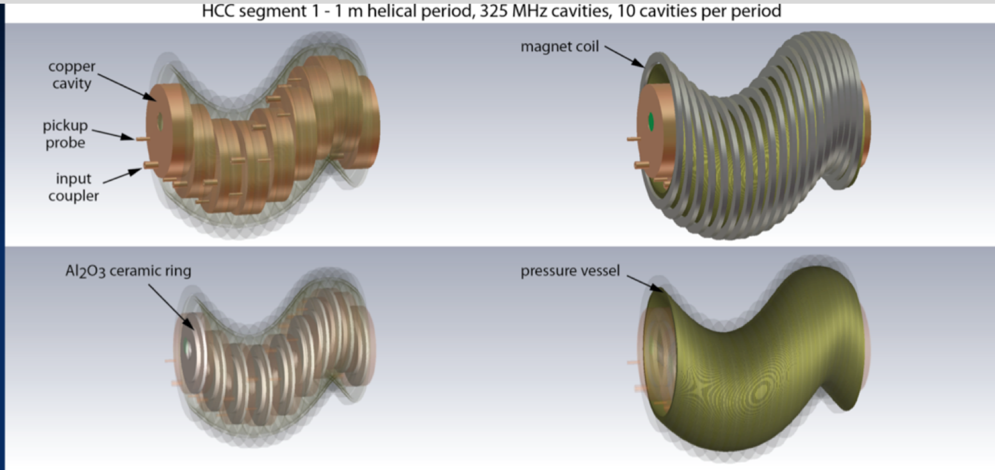


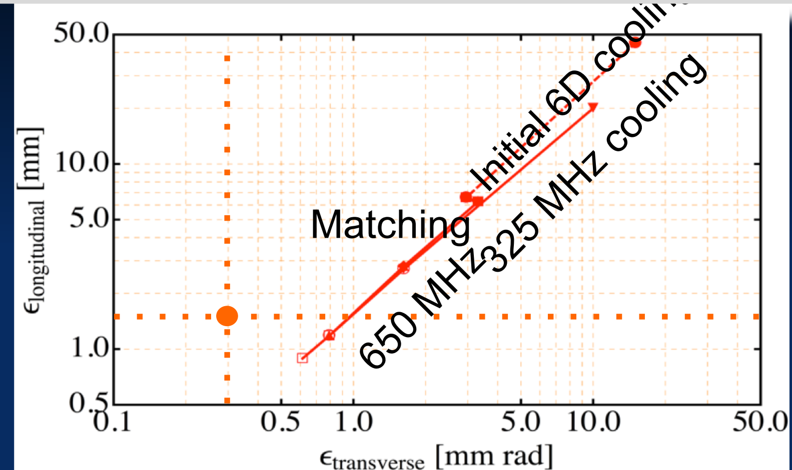
6D Rectilinear Vacuum Cooling Channel (replaces Guggenheim concept):

ε_T = 0.28mm, ε_L = 1.57mm @488m

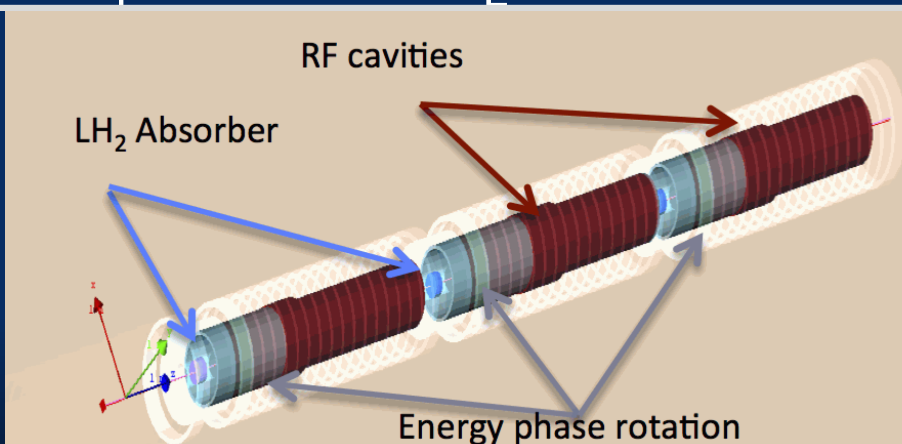
Transmission = 55%(40%) without(with) bunch recombination

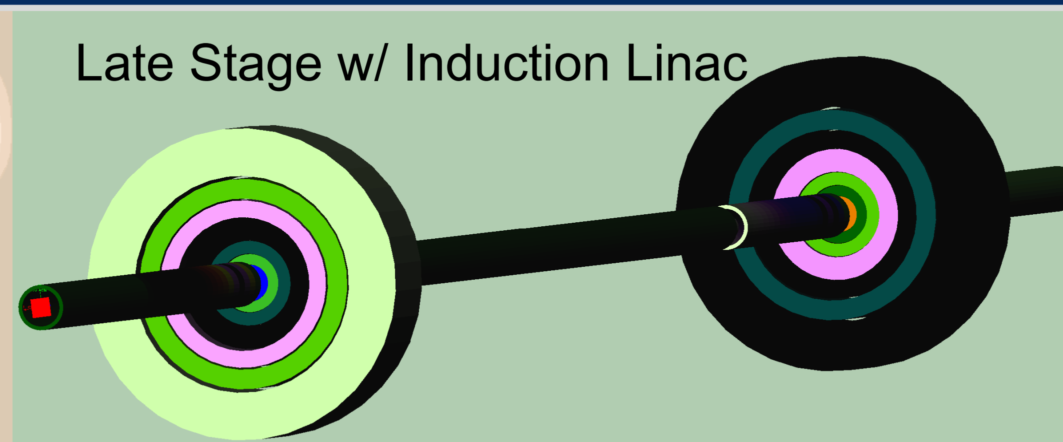
Muon Ionization Cooling (Design)





- Helical Cooling Channel (Gas-filled RF Cavities): ε_T = 0.6mm, ε_L = 0.3mm





- Final Cooling with 25-30T solenoids (emittance exchange): $\varepsilon_T = 55\mu m$, ε_L = 75mm

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Muon Ionization Cooling (Design)

Bunch Merge

- MAP Baseline Designs offer
  - Factor $>10^5$ in emittance reduction
- Alternative and Advanced Concepts

Higgs Factory

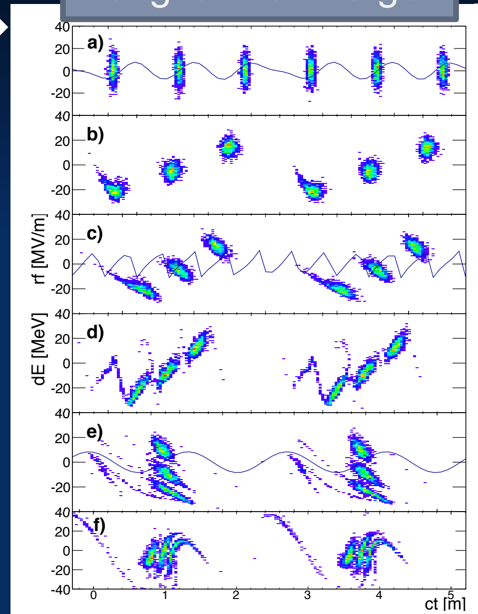
  - Hybrid Rectilinear Channel (gas-filled structures)
  - Parametric Ionization Cooling
  - Alternative Final Cooling

One example:

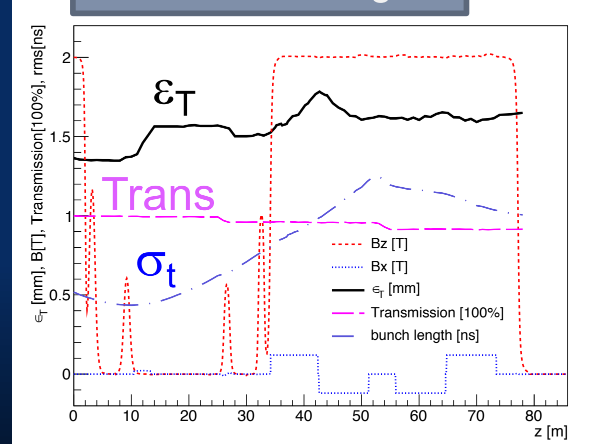
⇨ Early stages of existing scheme
⇨ Round-to-flat Beam Transform
⇨ Transverse Bunch Slicing
⇨ Longitudinal Coalescing (at ~10s of GeV)

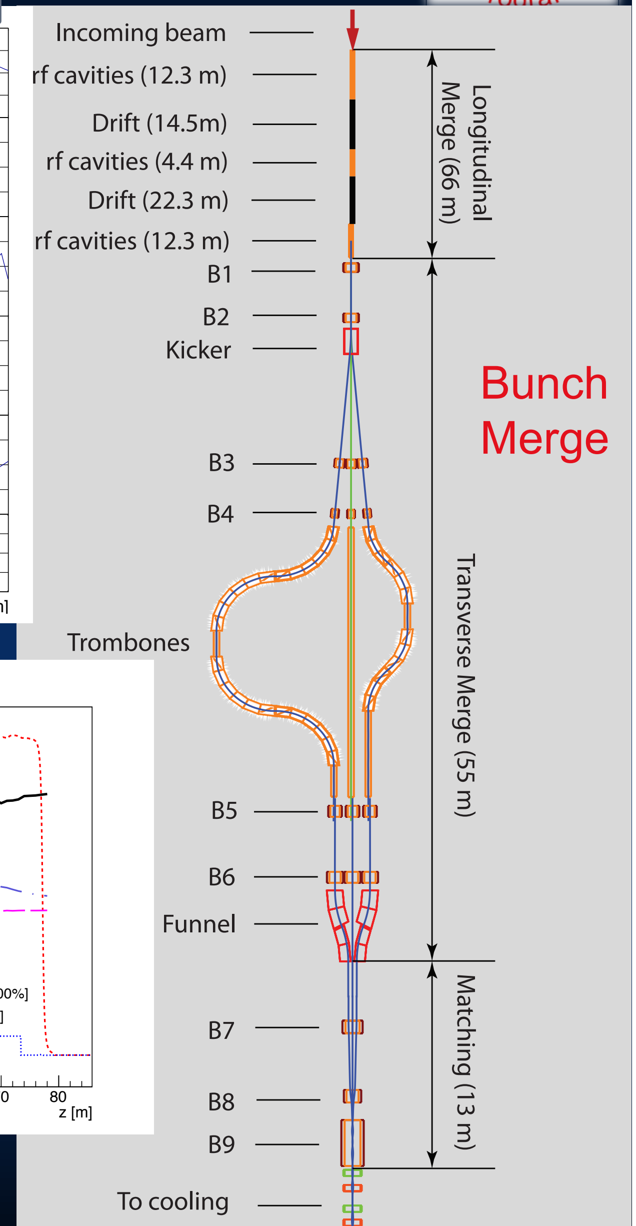
⇨ Considerable promise to exceed our original target parameters

Longitudinal Merge

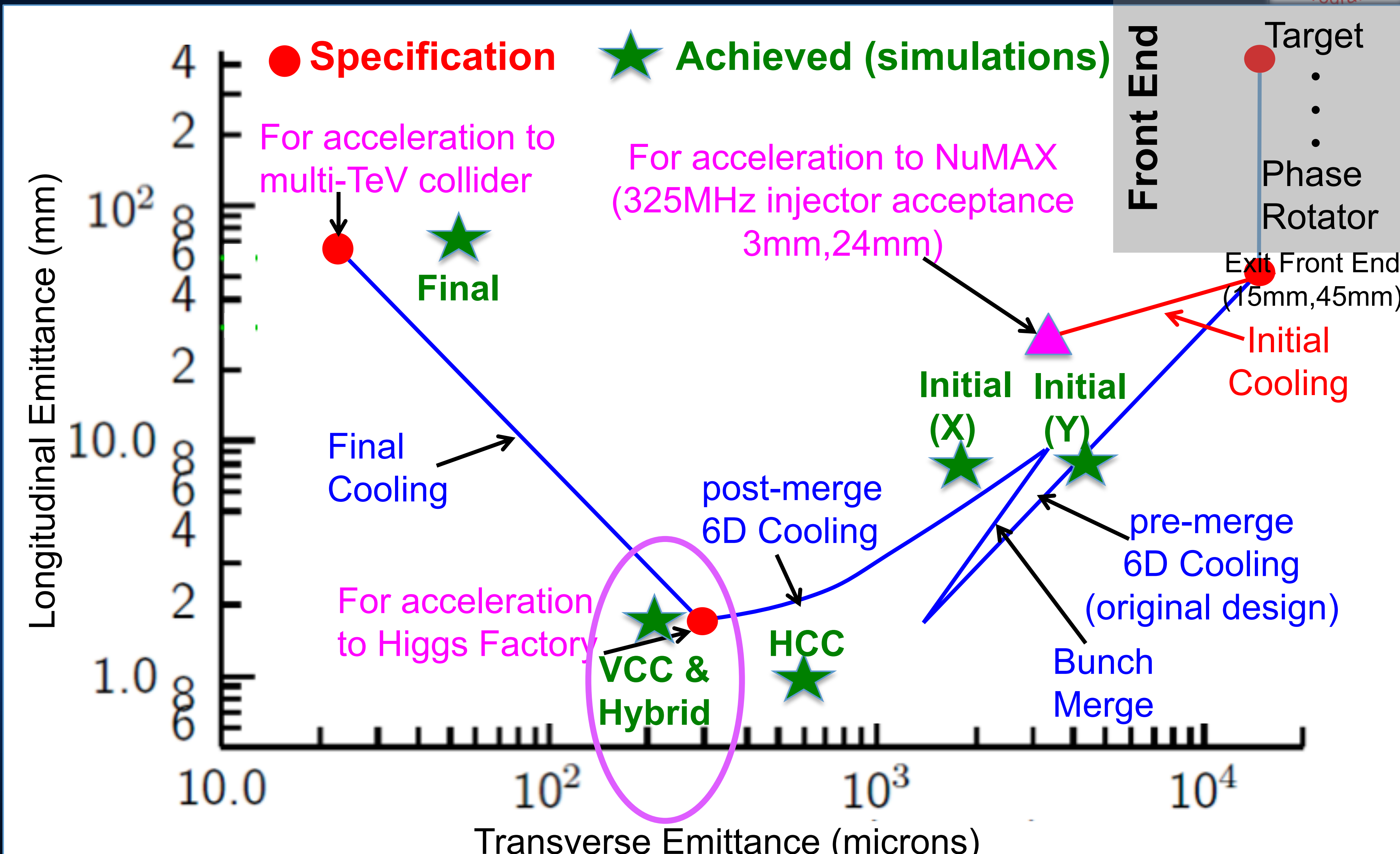


Transverse Merge

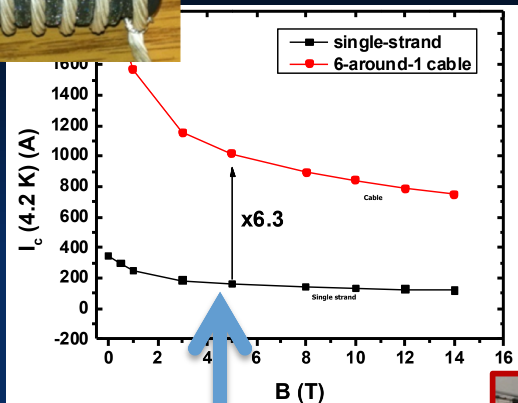




Cooling: The Emittance Path



Cooling Technology R&D

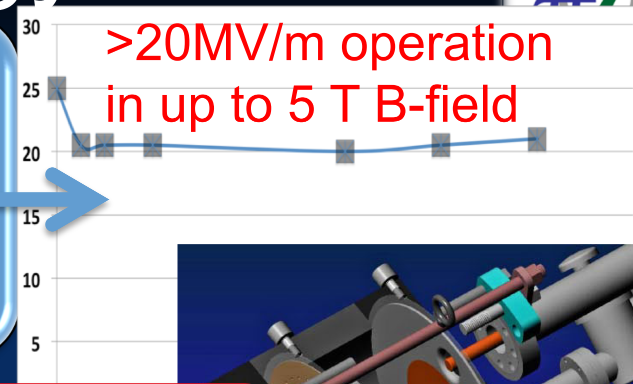


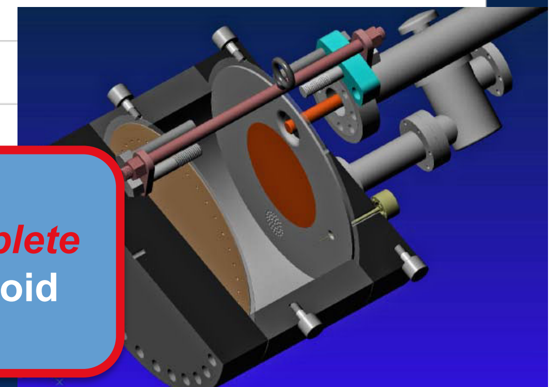
Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

FNAL-Tech Div
T. Shen-Early Career Award

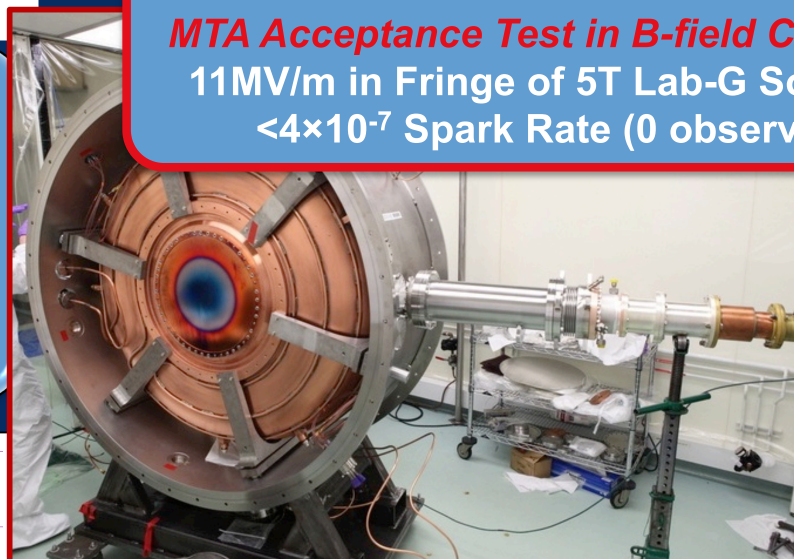
Successful Operation of 805 MHz "All Seasons" Cavity in 5T Magnetic Field under Vacuum

MuCool Test Area/Muons Inc

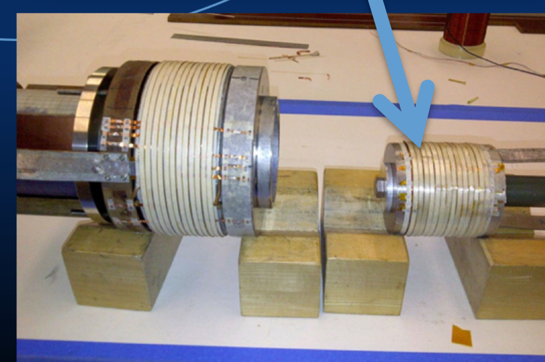


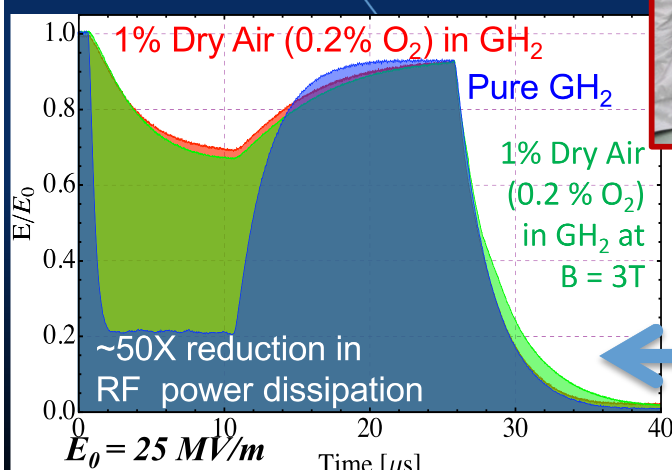


MICE 201 MHz RF Module –
MTA Acceptance Test in B-field Complete
11MV/m in Fringe of 5T Lab-G Solenoid
$<4\times10^{-7}$ Spark Rate (0 observed)



World Record HTS-only Coil
15T on-axis field (16T on coil)
R. Gupta
PBL/BNL



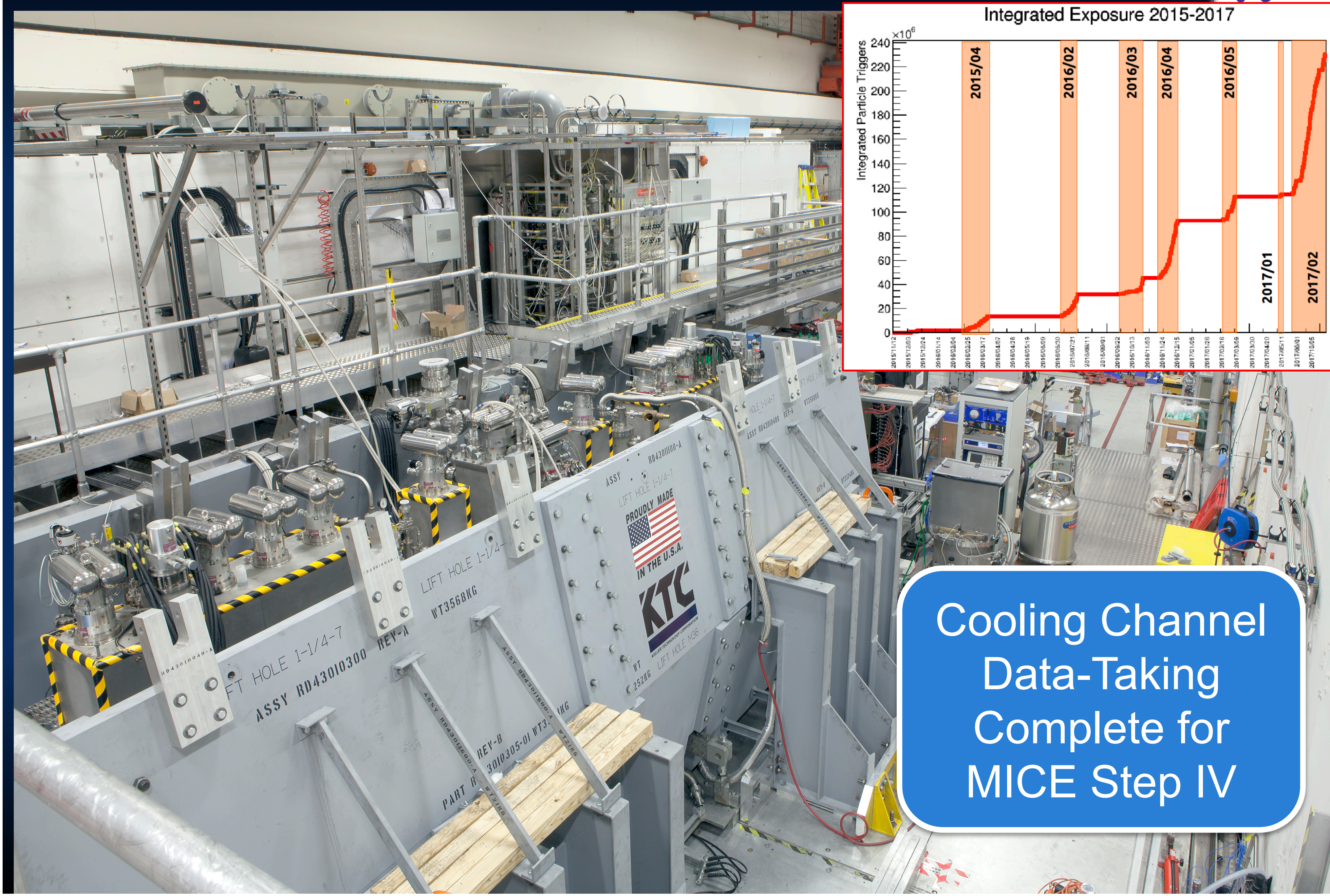


Demonstration of High Pressure RF Cavity <u>in 3T Magnetic Field with Beam</u>

Extrapolates to required μ-Collider Parameters

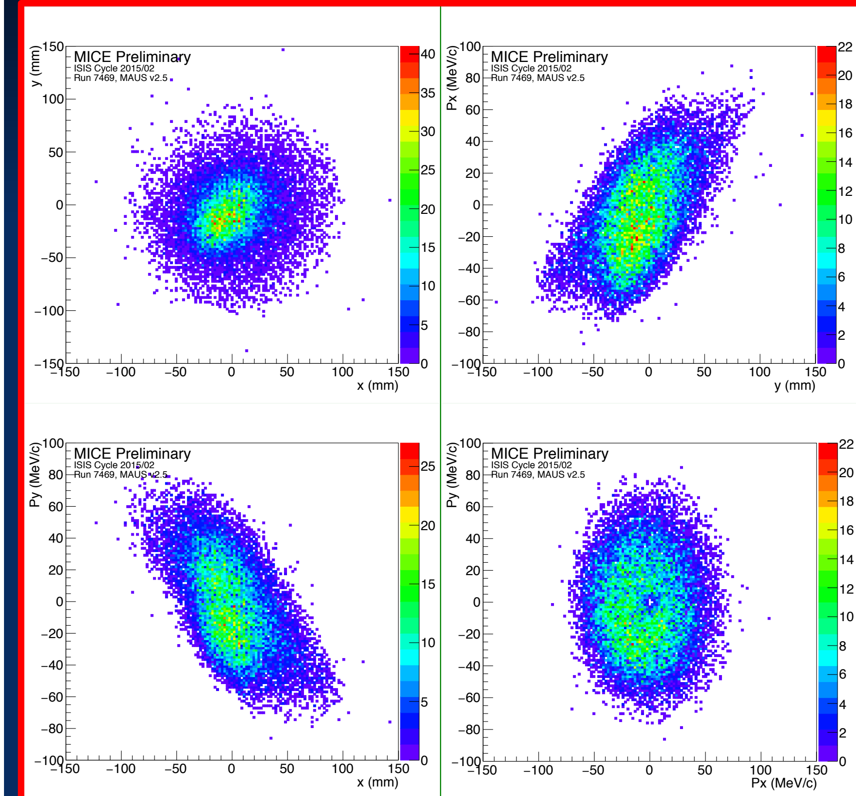
MuCool Test Area

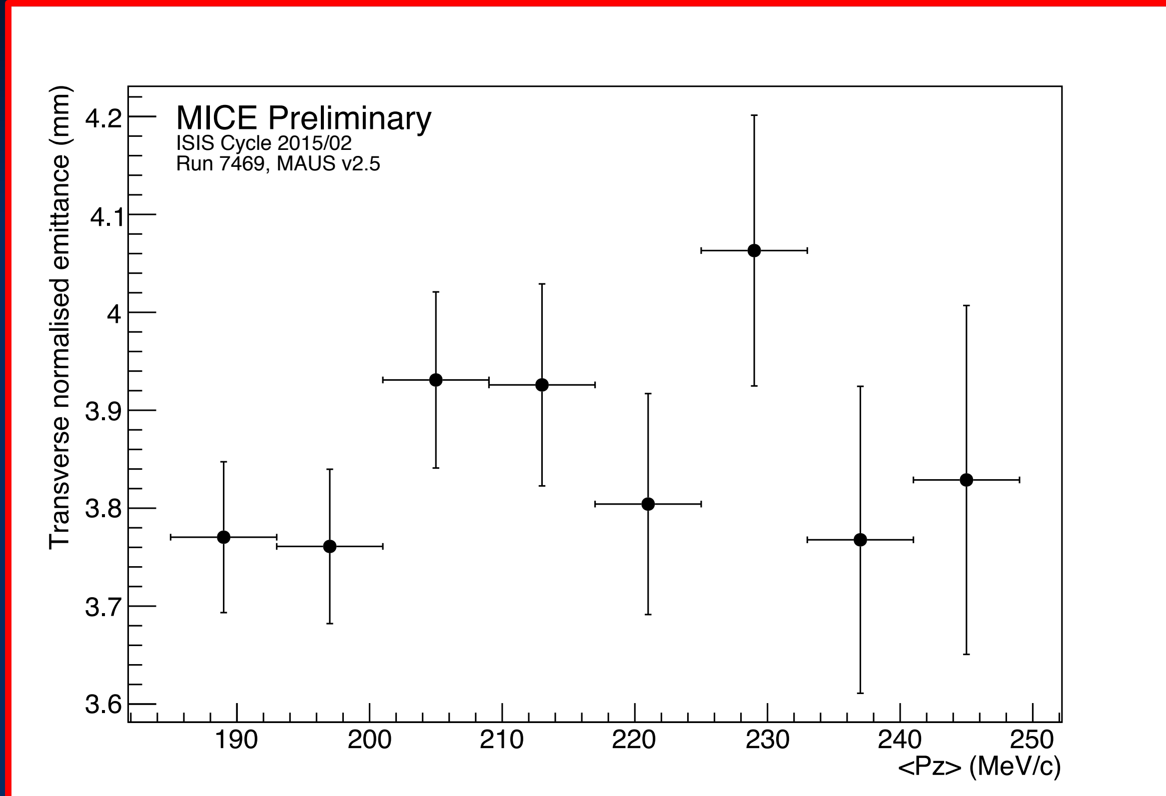
Muon Ionization Cooling Experiment



Cooling Channel Data-Taking Complete for MICE Step IV

Emittance reconstruction





- **Reconstruction of emittance "particle-by-particle" in upstream tracker**
  - **200 MeV/c muon beam; 4T in upstream solenoid only, first ~2 hours of data taking**
- **Validates MICE measurement approach**
- **Data in hand with LiH, LH_2 and "wedge" absorbers**
- **Preliminary analysis to be presented at IPAC`18**

Ionization Cooling Summary

✓ 6D Ionization Cooling Designs
- Designs in hand that meet performance targets in simulations with stochastic effects
- Ready to move to engineering design and prototyping
- Able to reach target performance with Nb_3Sn conductors (NO HTS)

✓ RF operation in magnetic field (MTA program)
- Gas-filled cavity solution successful and performance extrapolates to the requirements of the NF and MC
- Vacuum cavity performance now consistent with models
- MICE Test Cavity significantly exceeds specified operating requirements in magnetic field

✓ MICE Experiment data now in hand **(IPAC18 will provide a look at new results)**

~ Final Cooling Designs
- Baseline design meets Higgs Factory specification and performs within factor of 2.2× of required transverse emittance for high energy MC (while keeping magnets within parameters to be demonstrated within the next year at NHMFL).
- Alternative options under study

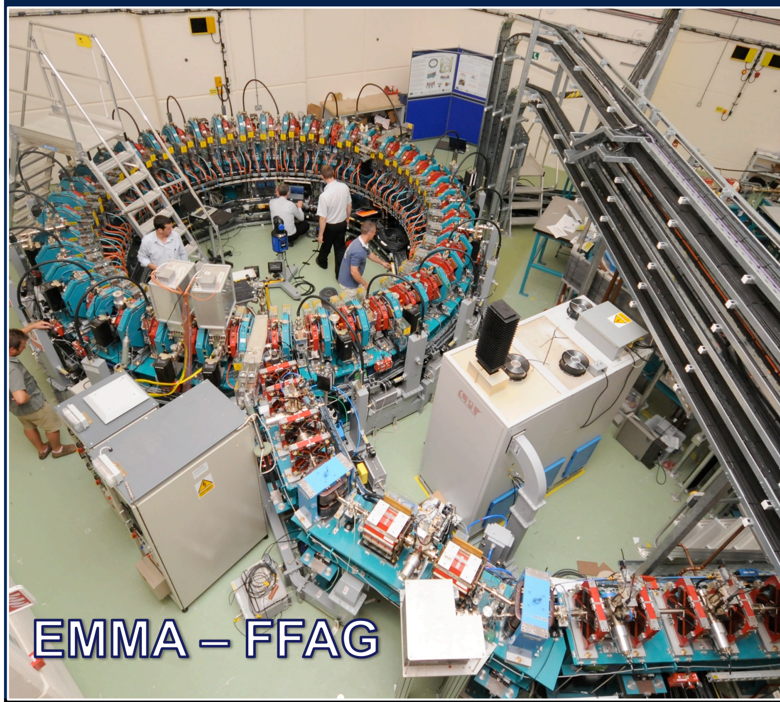
Acceleration Requirements

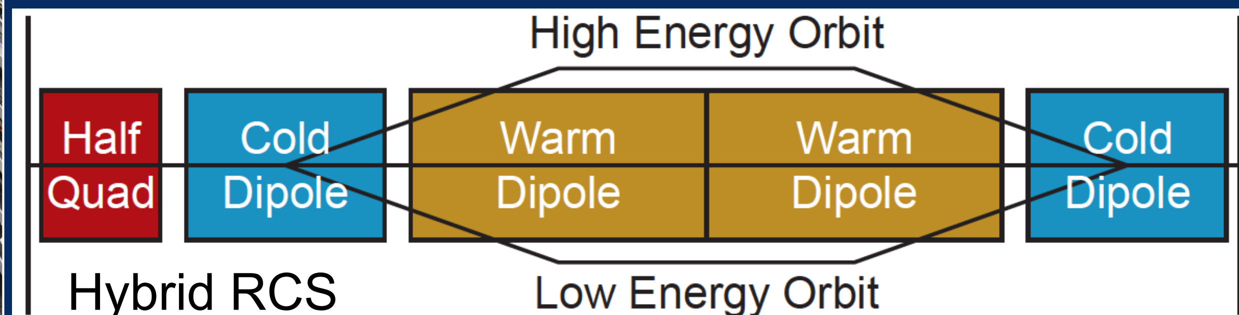
- Key Issues:
  - Muon lifetime ⇨ ultrafast acceleration chain
  - NF with modest cooling ⇨ accelerator acceptance
  - Total charge ⇨ cavity beam-loading (stored energy)
  - TeV-scale acceleration focuses on hybrid Rapid Cycling Synchrotron ⇨ requires rapid cycling magnets
    $B_{peak} \sim 2T$ $f > 400Hz$

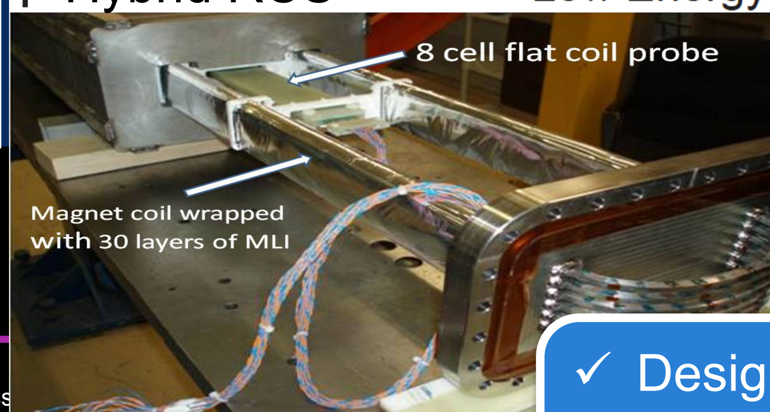
Acceleration

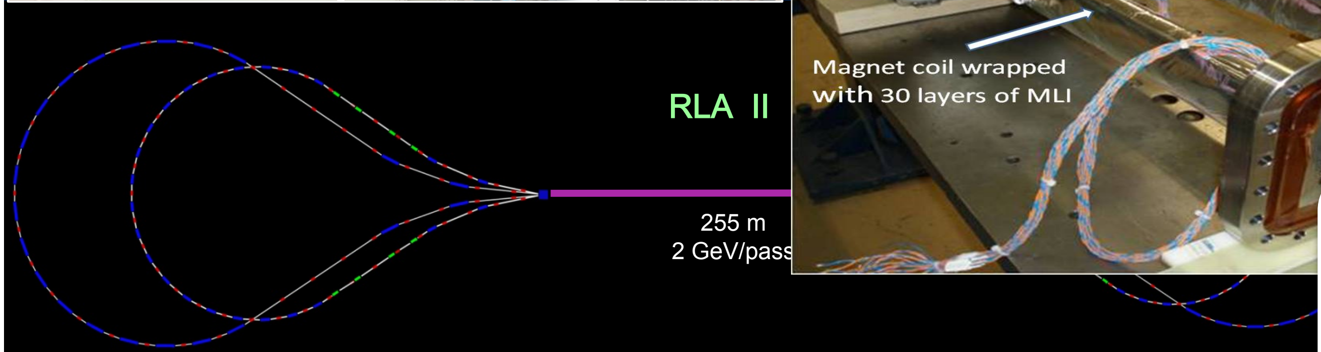
Technologies include:

- Superconducting Linacs (NuMAX choice)
- Recirculating Linear Accelerators (RLAs)
- Fixed-Field Alternating-Gradient (FFAG) Rings
- (Hybrid) Rapid Cycling Synchrotrons (RCS) for TeV energies







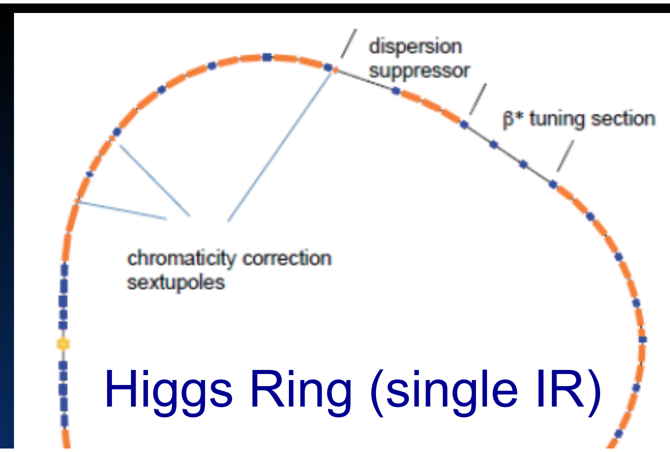


RCS requires 2 T p-p magnets at f > 400 Hz (U Miss & FNAL)

✓ Design concepts in hand
✓ Magnet R&D indicates parameters achievable

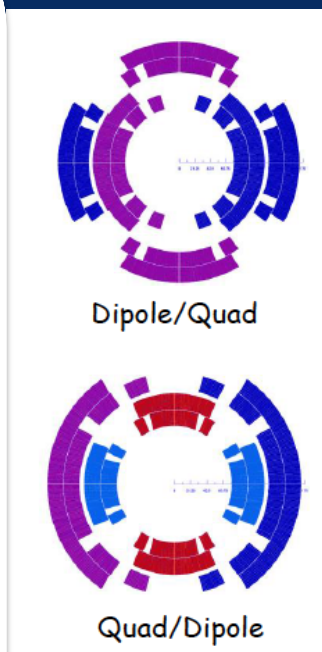
Collider Rings

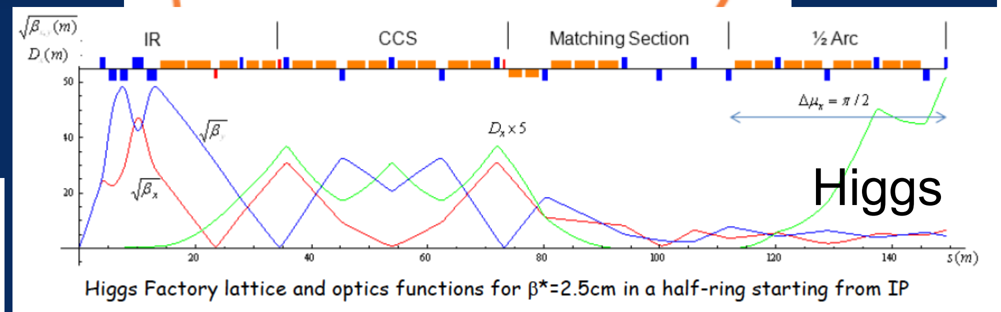
- Detailed optics studies for Higgs, 1.5 TeV, 3 TeV and now 6 TeV CoM
  - With supporting magnet designs and background studies



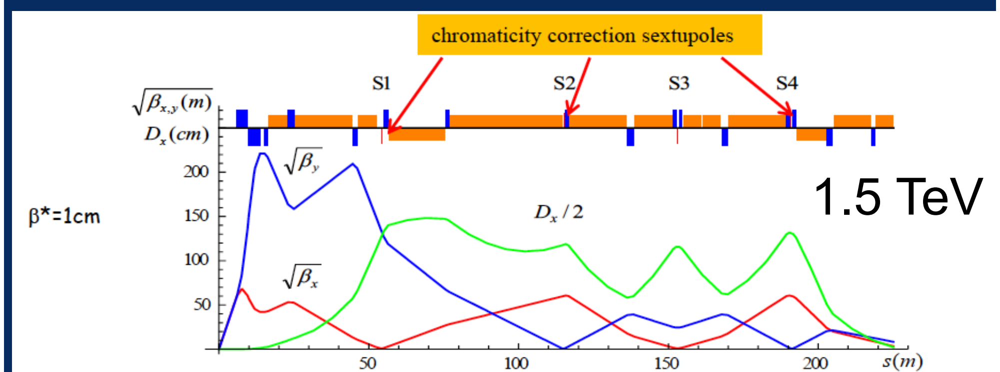
✓ Higgs, 1.5 TeV CoM and 3 TeV CoM Designs
  - With magnet concepts
  - Achieve target parameters

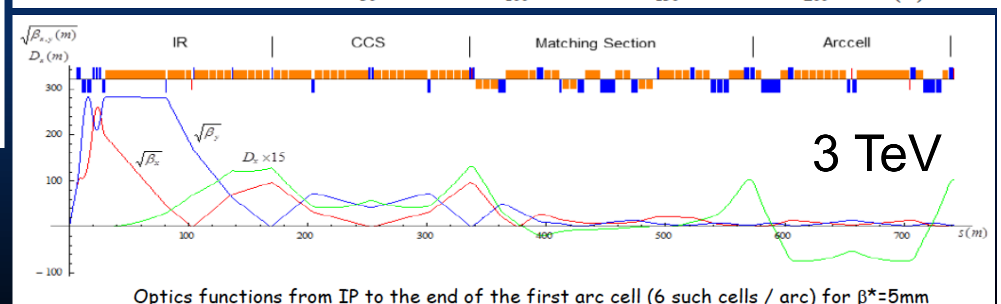
✓ Preliminary 6 TeV CoM design
  - Key issue is IR design and impact on luminosity
  - Utilizes lower power on target





Higgs Factory lattice and optics functions for β*=2.5cm in a half-ring starting from IP

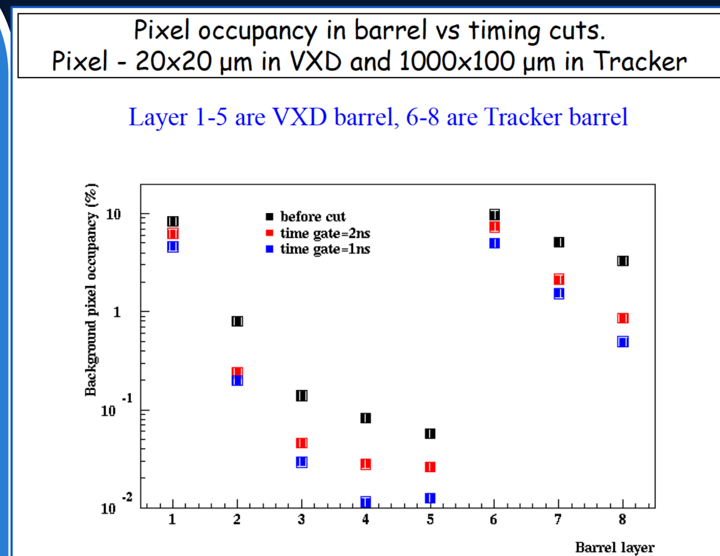


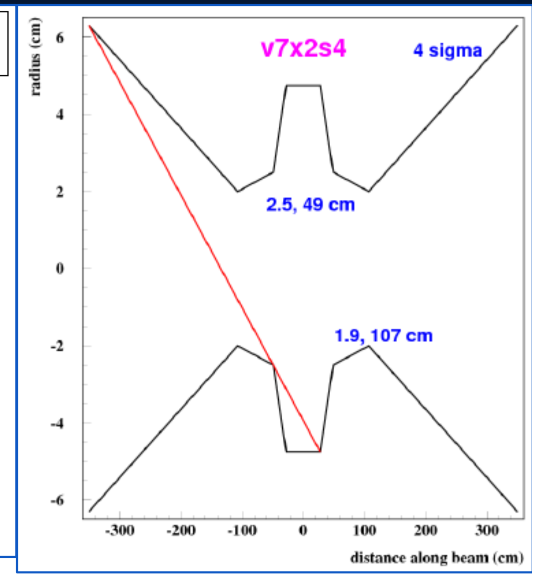


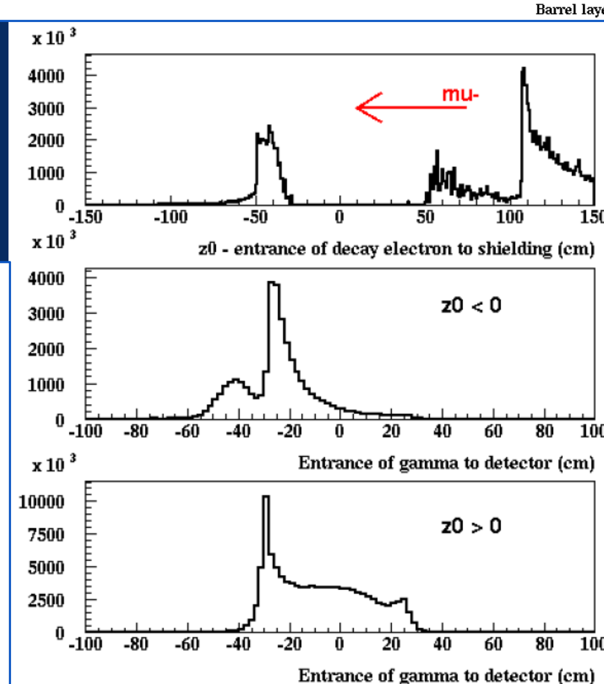
Optics functions from IP to the end of the first arc cell (6 such cells / arc) for β*=5mm

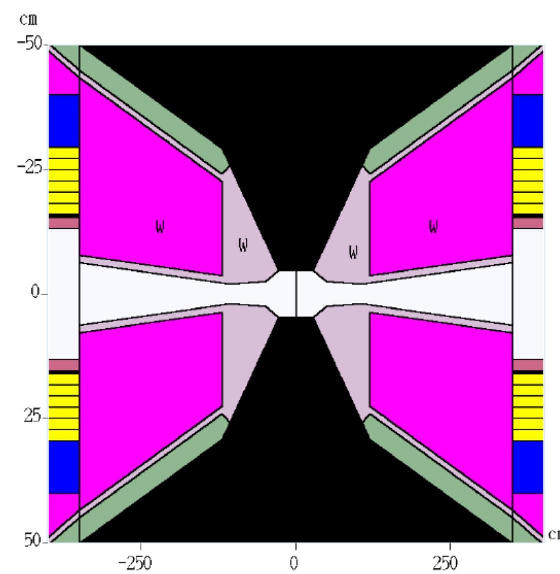
Machine Detector Interface

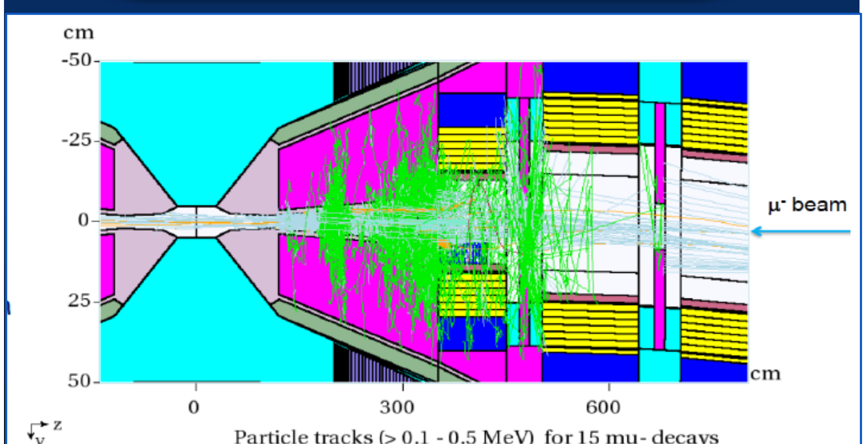
- ✓ Backgrounds appear manageable with suitable detector pixelation and timing rejection
- ✓ Recent study of hit rates comparing MARS, EGS and FLUKA appear consistent to within factors of <2
  - ⇨ Significant improvement in our confidence of detector performance





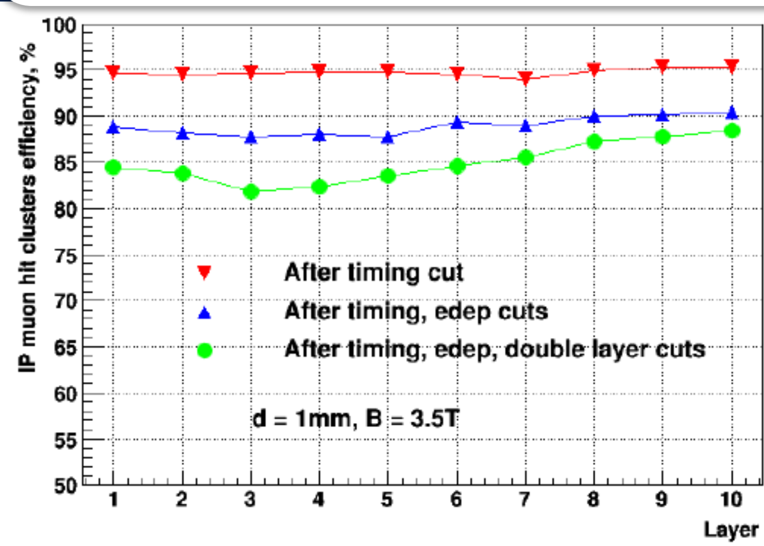




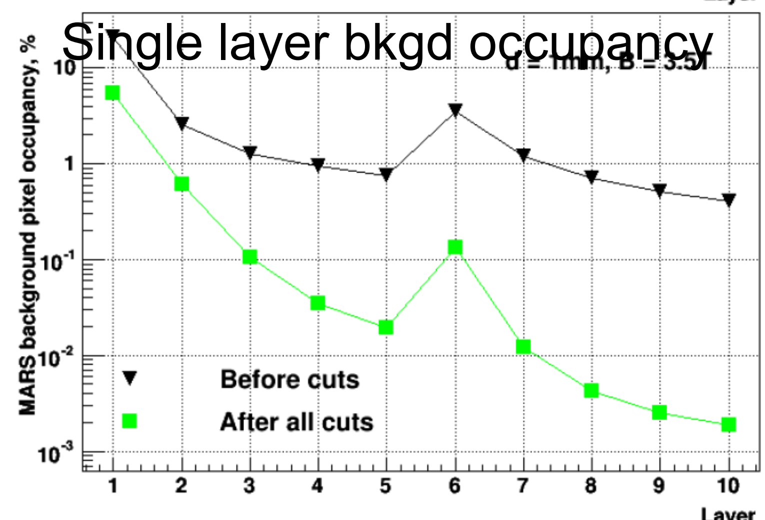


Detector Backgrounds & Mitigation

Trackers: Employ double-layer structure with 1mm separation for neutral background suppression



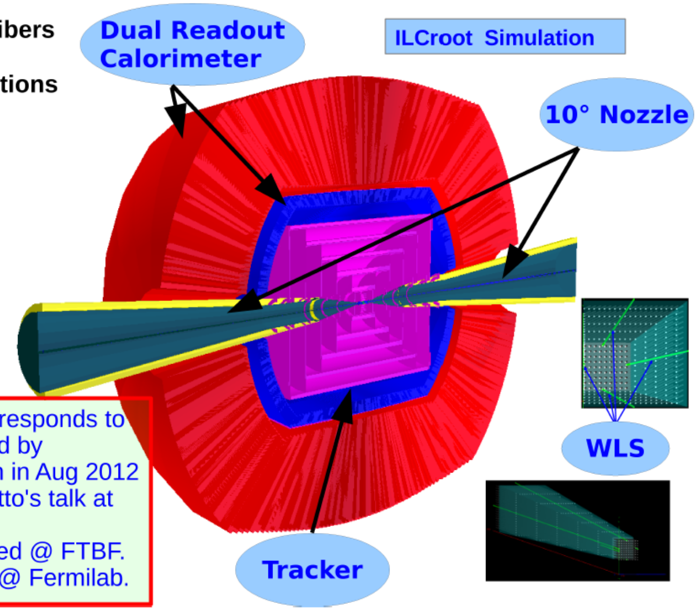
Single layer bkgd occupancy



MARS Bkgds ⇨ ILCRoot Det Model

Dual Readout Projective Calorimeter

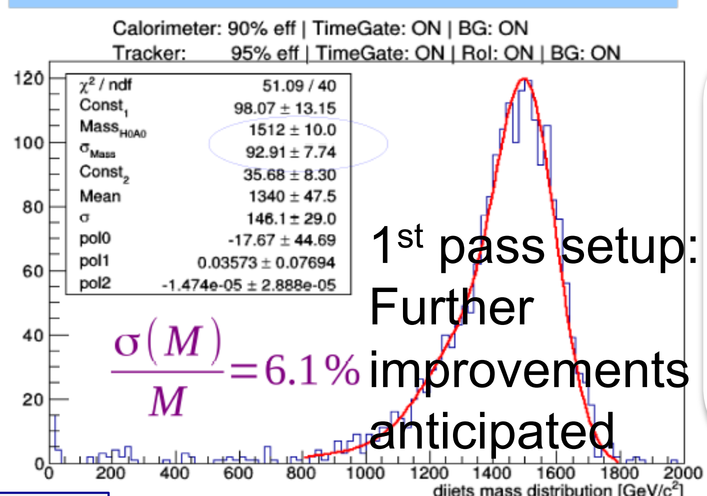
- Lead glass + scintillating fibers
- ~1.4° tower aperture angle
- Split into two separate sections
- Front section 20 cm depth
- Rear section 160 cm depth
- ~ 7.5 λ_{int} depth
- >100 X_0 depth
- Fully projective geometry
- Azimuth coverage down to ~8.4° (Nozzle)
- Barrel: 16384 towers
- Endcaps: 7222 towers



- All simulation parameters corresponds to ADRIANO prototype #9 tested by Fermilab T1015 Collaboration in Aug 2012 @ FTBF (see also T1015 Gatto's talk at Calor2012)
- Several more prototypes tested @ FTBF.
- New test beam ongoing now @ Fermilab.

- Fermilab 7

Time gate & RoI ON – BG ON



1st pass setup: Further improvements anticipated

- ✓ Preliminary detector study promising
  - Real progress requires dedicated effort, which MAP was not allowed to fund

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MAP Conclusion

- Multi-TeV MC ⇨ potentially only cost-effective route to lepton collider capabilities with E_{CM} > 5 TeV
- Capability strongly overlaps with next generation neutrino source options, i.e., the neutrino factory
- Key technical hurdles have been addressed:
  - High power target demo (MERIT)
  - Realizable cooling channel designs with acceptable performance
  - Breakthroughs in cooling channel technology
  - Significant progress in collider & detector design concepts

Accelerator		Energy Scale	Performance
Cooling Channel		**~200 MeV**	**Emittance Reduction**
	MICE	*160-240 MeV*	*5%*
Muon Storage Ring		**3-4 GeV**	**Useable μ decays/yr***
	νSTORM	*3.8 GeV*	*$3x10^{17}$*
Intensity Frontier ν Factory		**4-10 GeV**	**Useable μ decays/yr***
	NuMAX (Initial)	*4-6 GeV*	*$8x10^{19}$*
	NuMAX+	*4-6 GeV*	*$5x10^{20}$*
	IDS-NF Design	*10 GeV*	*$5x10^{20}$*
Higgs Factory		**~126 GeV CoM**	**Higgs/10^7s**
	s-Channel μ Collider	~126 GeV CoM	3,500-13,500
Energy Frontier μ Collider		**> 1 TeV CoM**	**Avg. Luminosity**
	Opt. 1	*1.5 TeV CoM*	*$1.2x10^{34}cm^{-2}s^{-1}$*
	Opt. 2	*3 TeV CoM*	*$4.4x10^{34}cm^{-2}s^{-1}$*
	Opt. 3	*6 TeV CoM*	*$12x10^{34}cm^{-2}s^{-1}$*

* Decays of an individual species (ie, μ^+ or μ^-)

Muon collider capabilities offer unique potential for the future of high energy physics research

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LEMMA

- Thank you for the opportunity to meet and discuss the LEMMA concepts in greater detail
- Clearly muon production target issues are extremely challenging – **irrespective of the production process!**
- I'm very much looking forward to discussing
  - the trade-offs and potential physics reach in greater detail
  - what concepts from MAP may be helpful to LEMMA

Thank you for your attention!

Backup Slides Follow

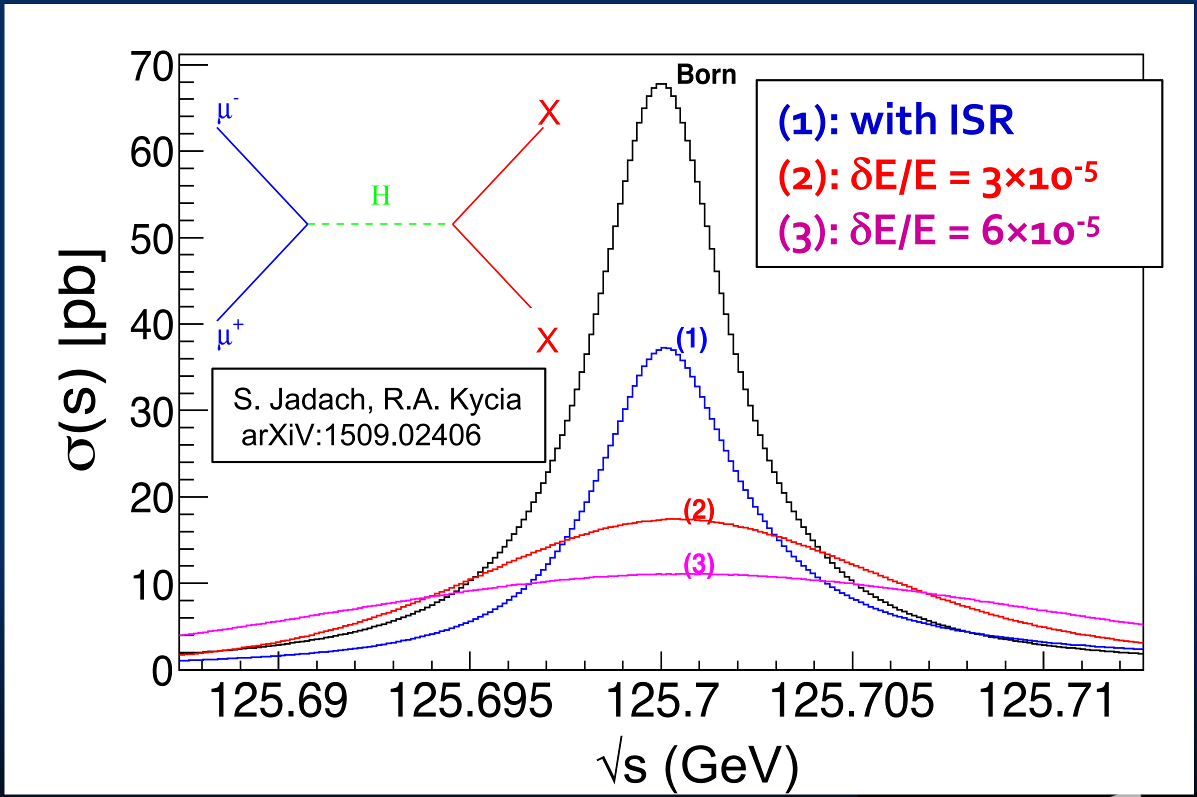
PHYSICS WITH A MUON COLLIDER

A Higgs Factory

Direct s-channel production

$$\sigma(\mu^+\mu^- \to H^0) = \frac{4\pi\Gamma_H^2 Br(H^0 \to \mu^+\mu^-)}{(\hat{s} - M_H^2)^2 + \Gamma_H^2 M_H^2}$$

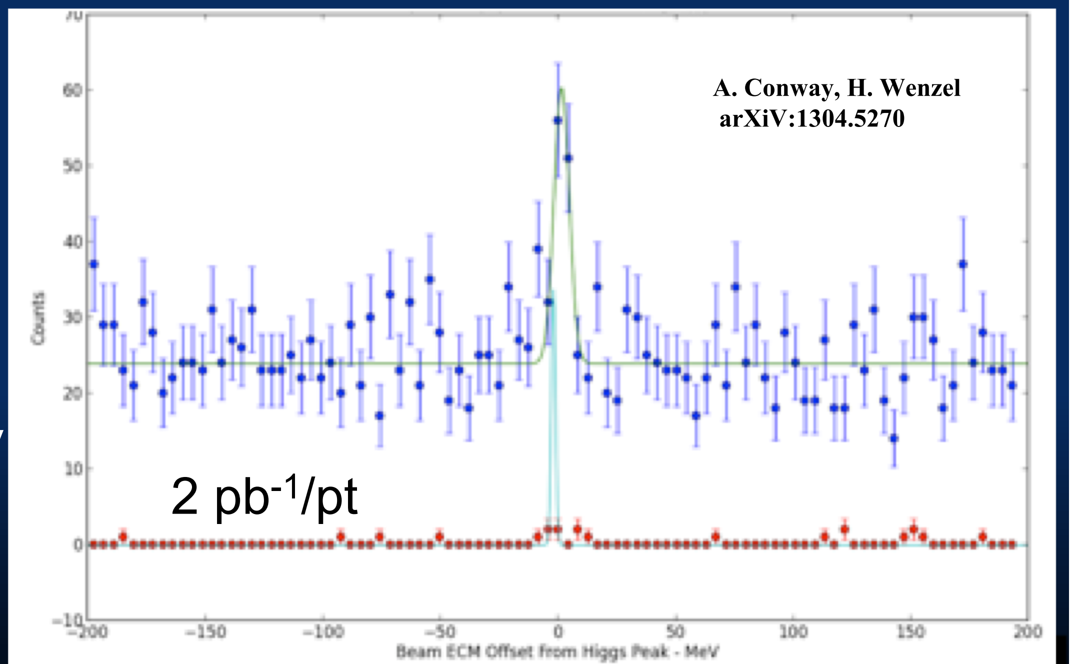
- $\sigma(\mu^+\mu^- \to H) \sim \sigma(e^+e^- \to H) \times 40{,}000$
- ~14K Higgs/yr (MAP baseline)
- Advanced muon cooling (c.f. Rubbia plan) ⇨ ~5x more rate



A Higgs Factory

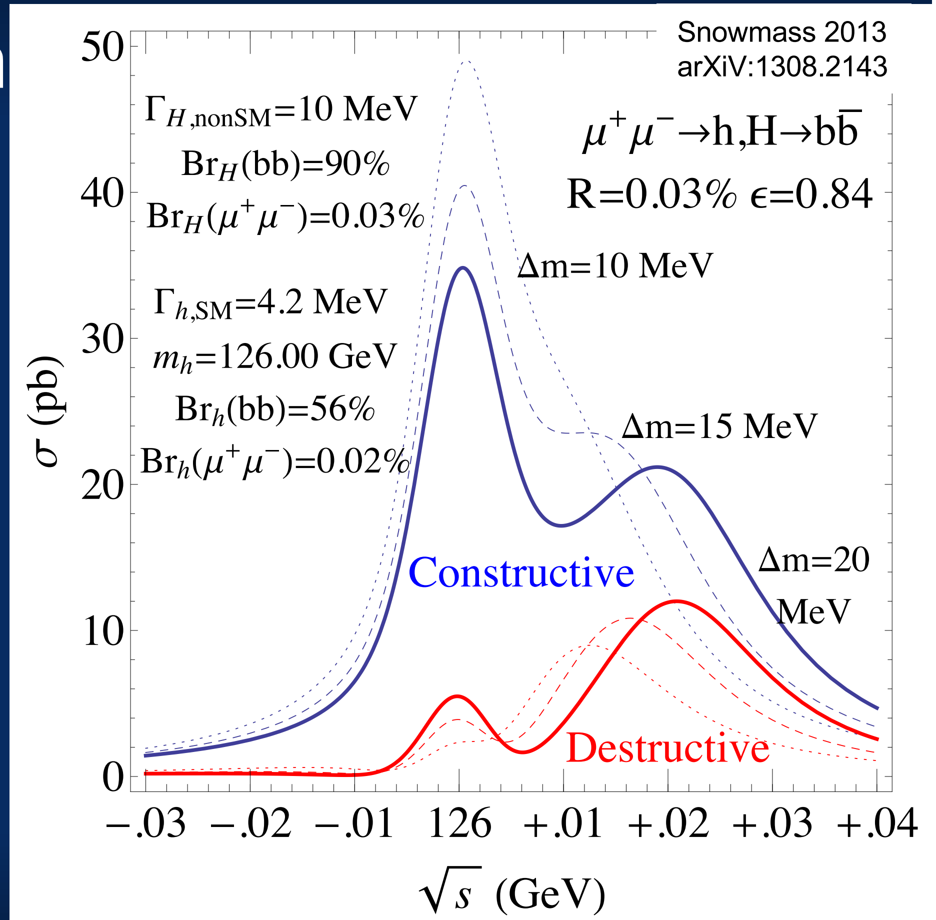
- With a beam energy spread of 0.004%, a Higgs Factory has unique operating features
  - Requires excellent machine energy stability
  - Would utilize a “g-2” technique to monitor the beam energy (Rana and Tollestrup)
    - Electron calorimeter to monitor the decay electrons as the beam polarization precesses in the dipole field of the ring
    - Precision measurement of the oscillation frequency provides the energy
  - An initial energy scan campaign required to locate the resonance
    - Presently know m_H to ±250 MeV
    - ~2 orders of magnitude smaller with a muon collider

$$\nu_0 = \frac{g_\mu - 2}{2} \times \frac{E_{\mathrm{Beam}}}{m_\mu}$$



A Higgs Factory

- Direct production combined with precise energy resolution
  - Ability to probe detailed structure
  - A full line-shape measurement probes:
    - The Higgs mass, m_H
    - The Higgs width, Γ_H
    - The branching ratio into $\mu^+\mu^-$, BR($H \to \mu\mu$) [and hence $g_{H\mu\mu}$]
  - Look for new physics features
    - Ex: Higgs doublet model

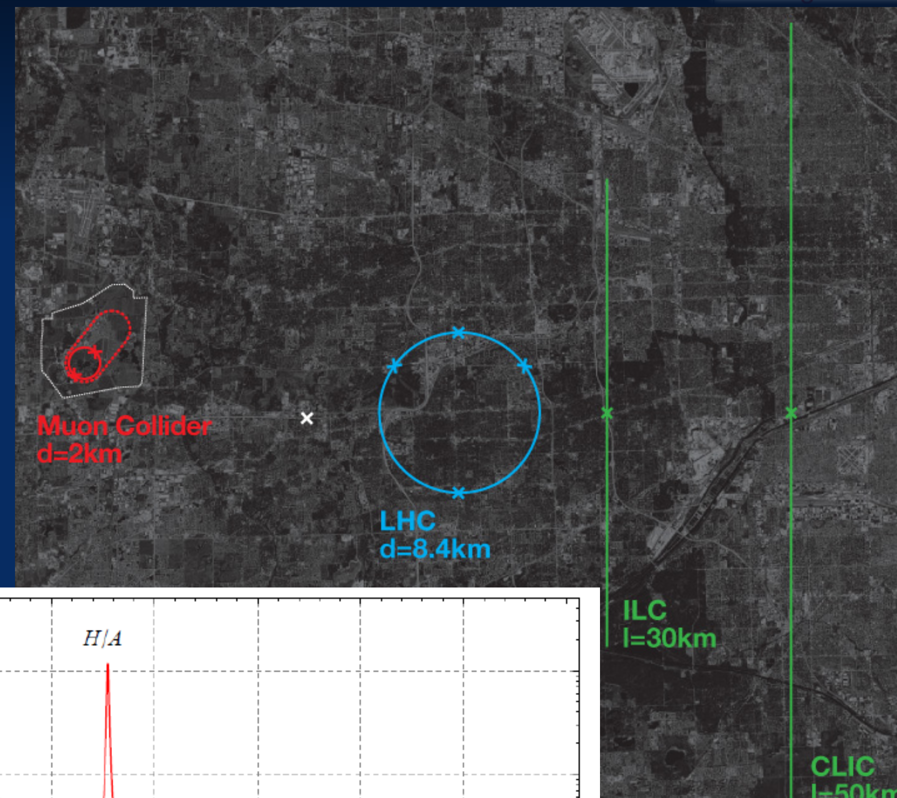


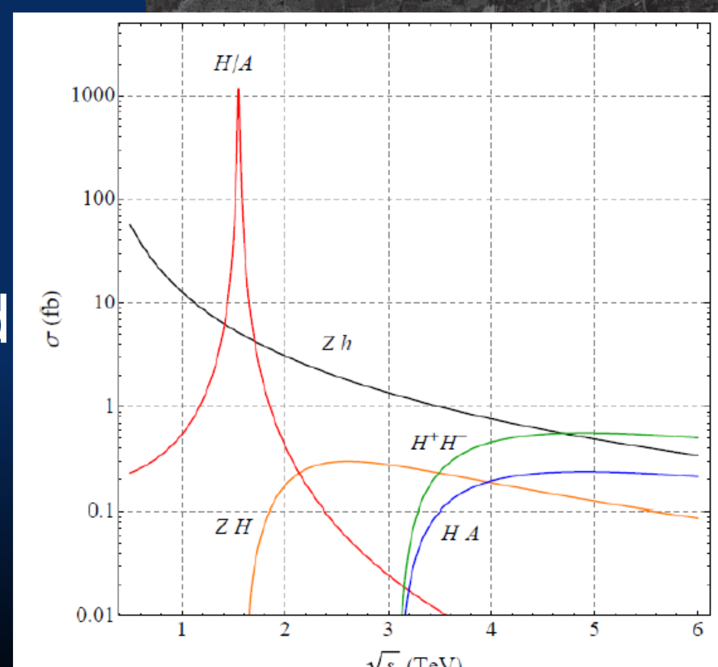
Higher Energy Colliders

- Multi-TeV lepton collider: ***required*** for a thorough exploration of Terascale physics

- Muon colliders come into their own at energies >2 TeV
  - Absolute luminosity
  - Luminosity per wall-plug power
  - Compact rings

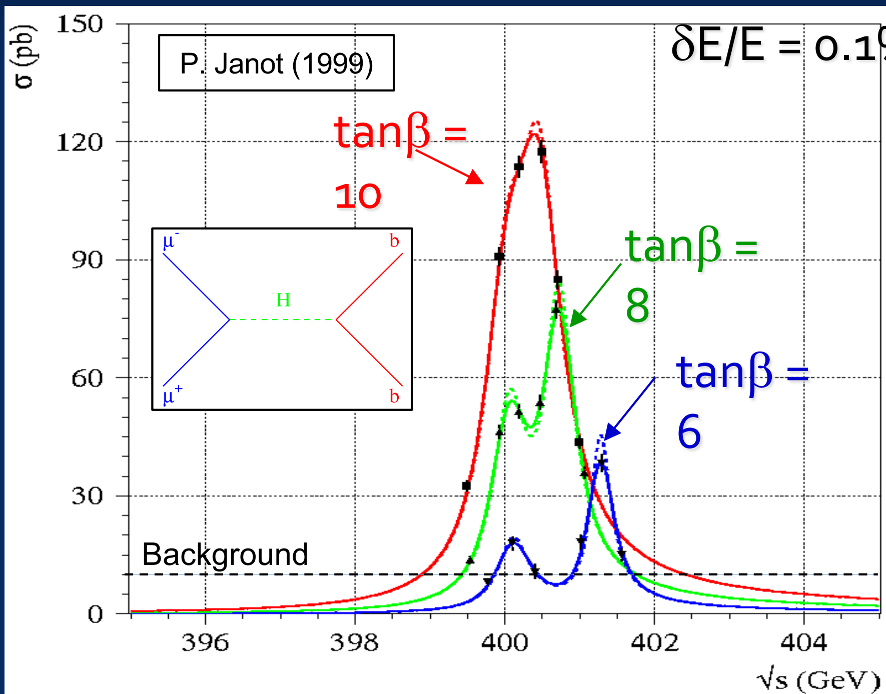
- Excellent energy resolution ⇨ disentangle closely-spaced states
  - Example: Extended Higgs Sector and the H/A resonance

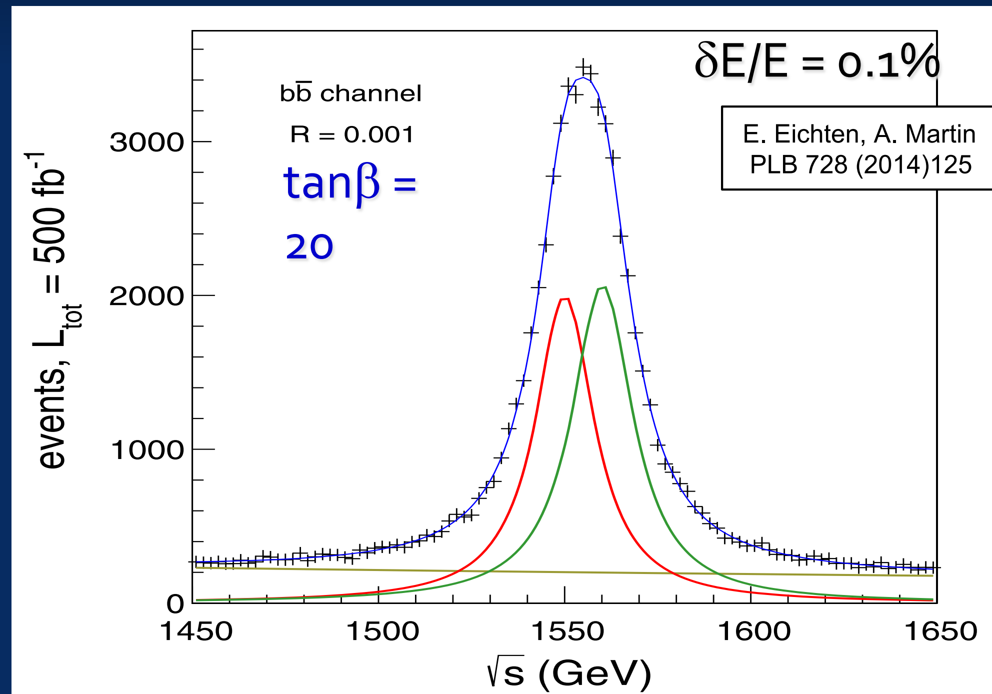




H/A Examples

- Can be applied to heavier H and A in 2HDM (e.g., from SUSY)
  - Example 1: m_A = 400 GeV Example 2: m_A = 1.55 TeV





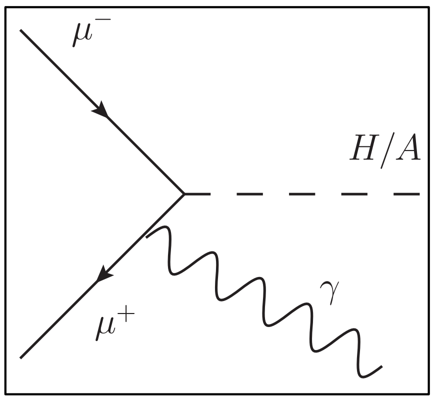
  - Best performance is ultimately obtained by optimizing the ring for operation at E_{COM} of interest

Additional Higgs bosons (3)

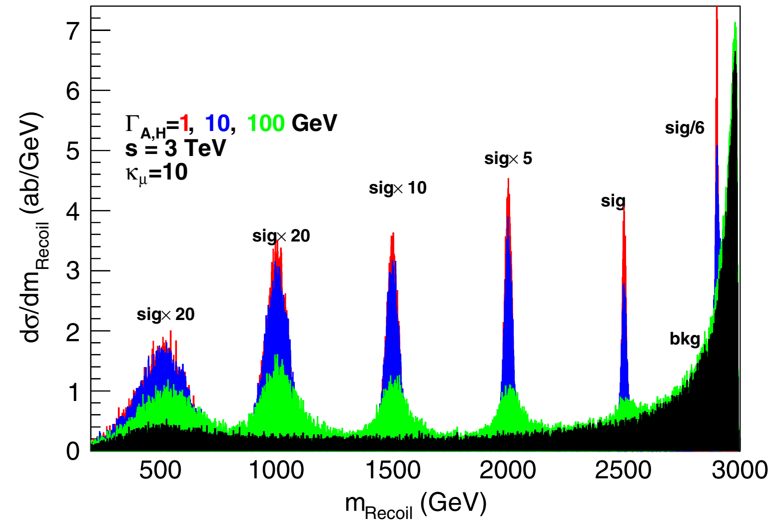
One way to proceed

Automatic mass scan with radiative returns in μμ collisions

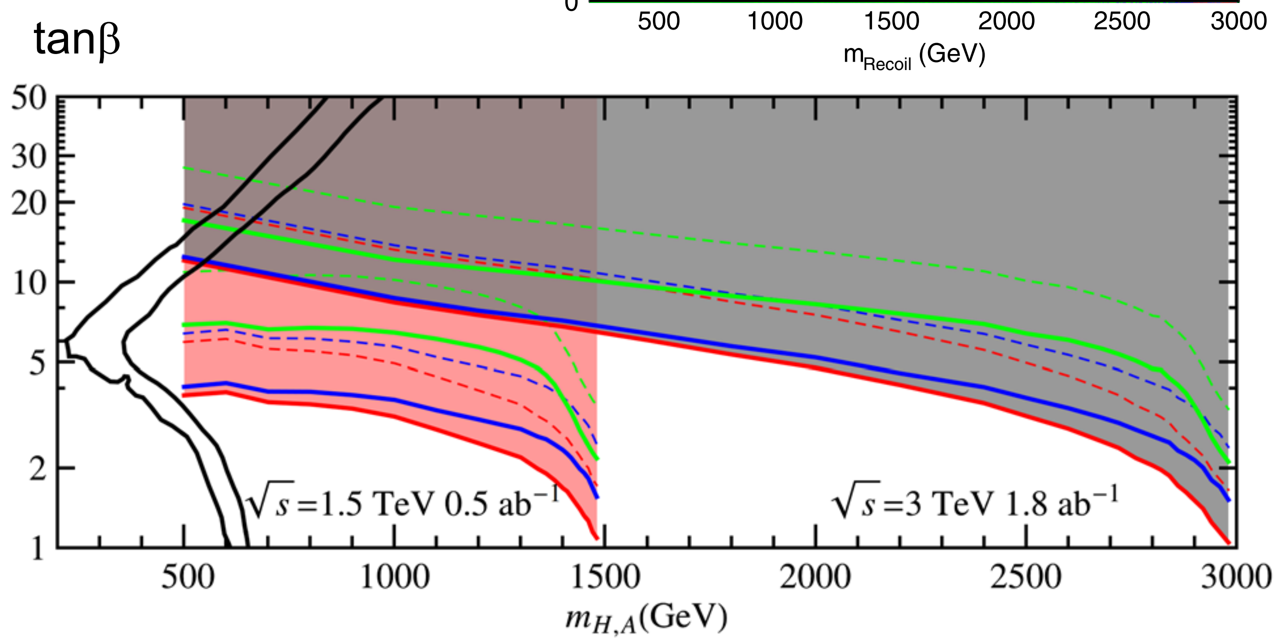
- Go to the highest energy first
  - $\sqrt{s}$ = 1.5, 3 or 6 TeV
- Select event with an energetic photon
  - Check the recoil mass $m_{Recoil} = [s - 2E_\gamma\sqrt{s}]^{1/2}$



N. Chakrabarty et al.
PRD 91 (2015)015008



- Can "see" H and A
  - If tanβ > 5
- Build the next collider
  - At $\sqrt{s} \sim m_{A,H}$



Summary

- Muon colliders offer great potential for exploration of the Terascale
  - May offer the only cost-effective route to a lepton collider operating in the several TeV range
- There are technical challenges – examples:
  - Muon cooling technology
  - Detector backgrounds from μ decays
- Let's take a quick look at some of the technology issues
  - Further work is desirable to understand the detailed physics reach given the proposed solutions to those challenges