Muon Colliders:
Physics and Accelerator Technology

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Acknowledgements

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

Outline

- Introduction: Why Muons?
- Physics with a Muon Collider
- The Feasibility of Building a Muon Collider
- Conclusion

INTRODUCTION: WHY MUONS?

Why Muons?

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

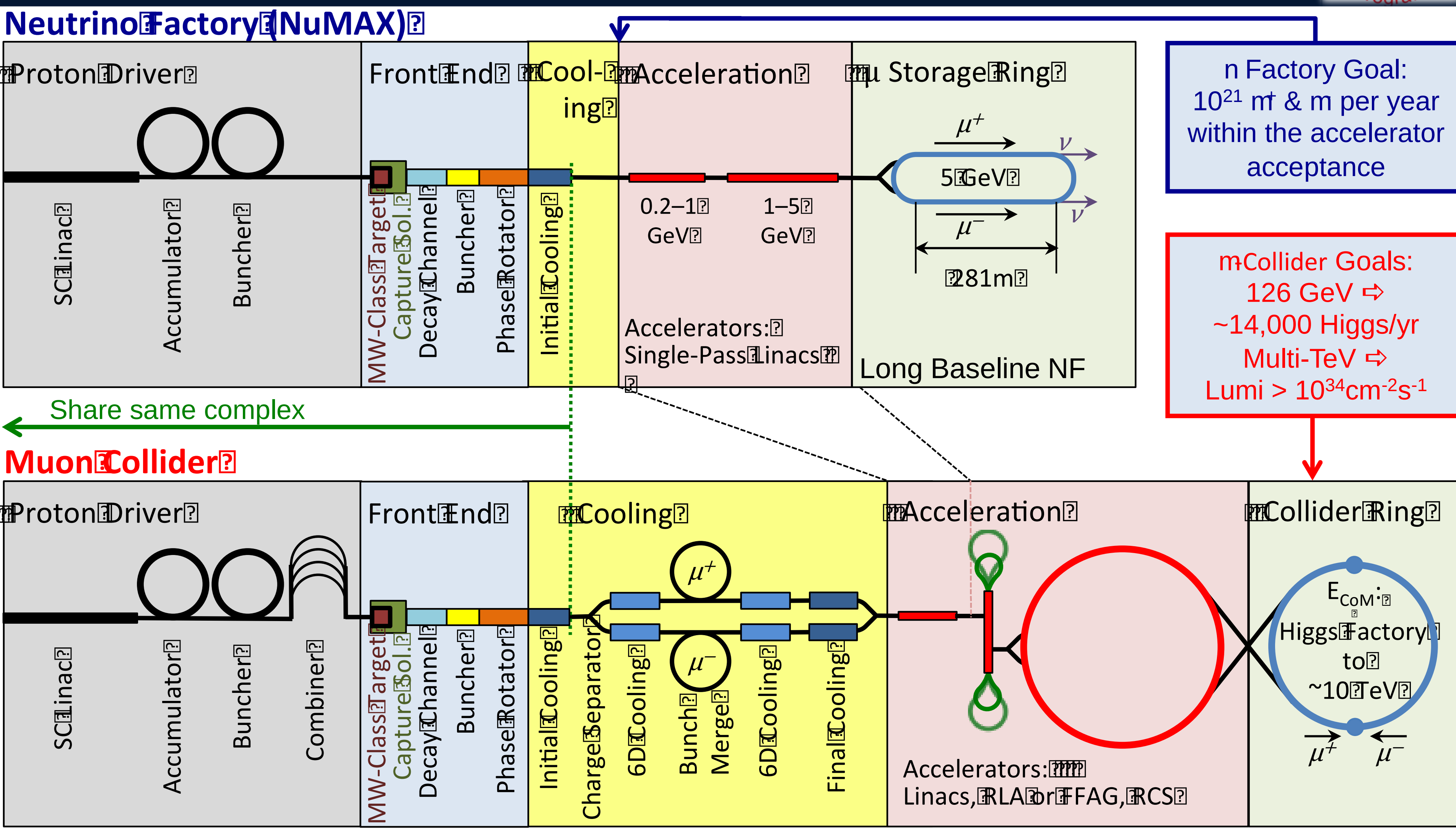
$$\tau_\mu = 2.2\, \mu s$$

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

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

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

High Energy Muon Accelerator Capabilities



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

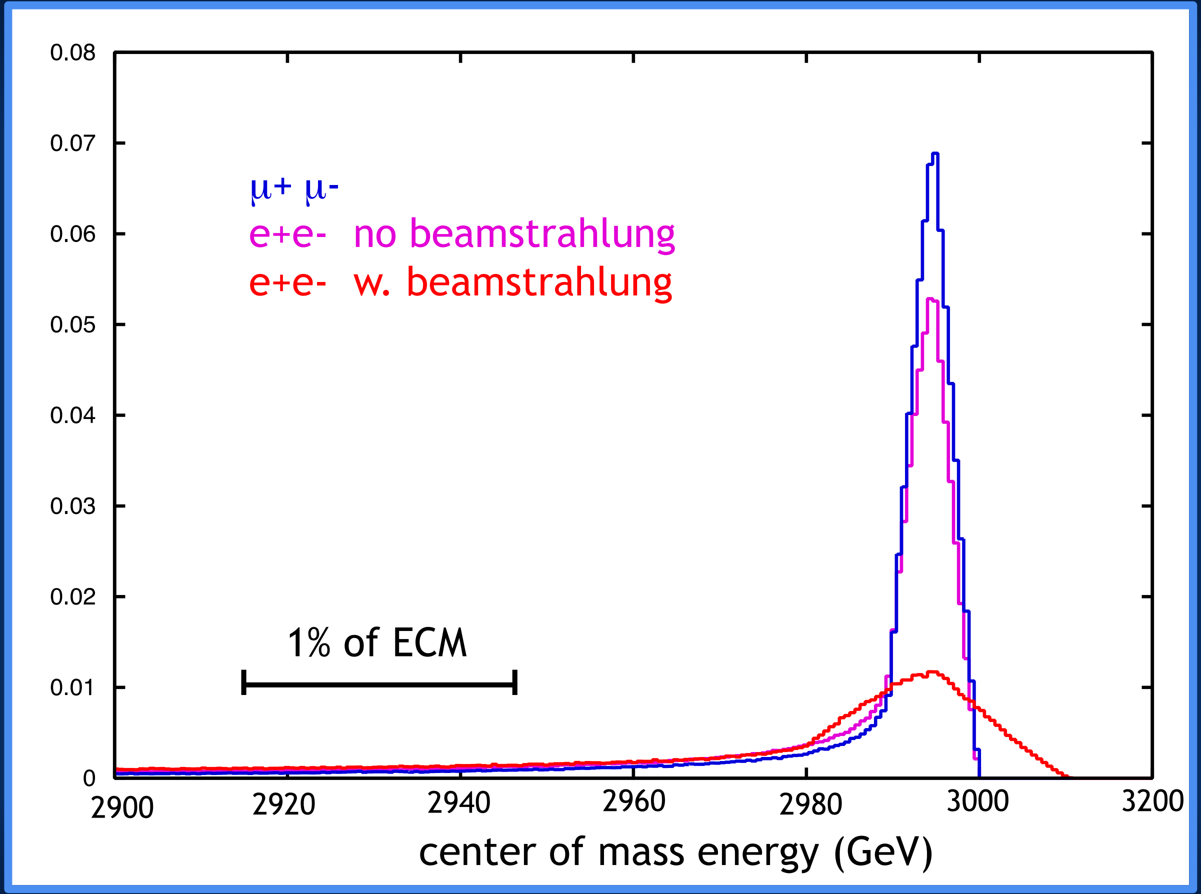
    ⇨ a ~2 TeV lepton collider probes the full energy range of fundamental processes under study at the LHC

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:

    $e^+e^- \rightarrow \mathit{Higgs}$ **OR** $\mu^+\mu^- \rightarrow \mathit{Higgs}$

  - The cross section for this process scales as m^2 of the colliding particles, so:

$$s\left(m^+m^- \rightarrow H\right) = \left(\frac{m_m}{m_e}\right)^2 \times s\left(e^+e^- \rightarrow H\right) = \left(\frac{105.7\,MeV}{0.511\,MeV}\right)^2 \times s\left(e^+e^- \rightarrow H\right)$$

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

  - 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

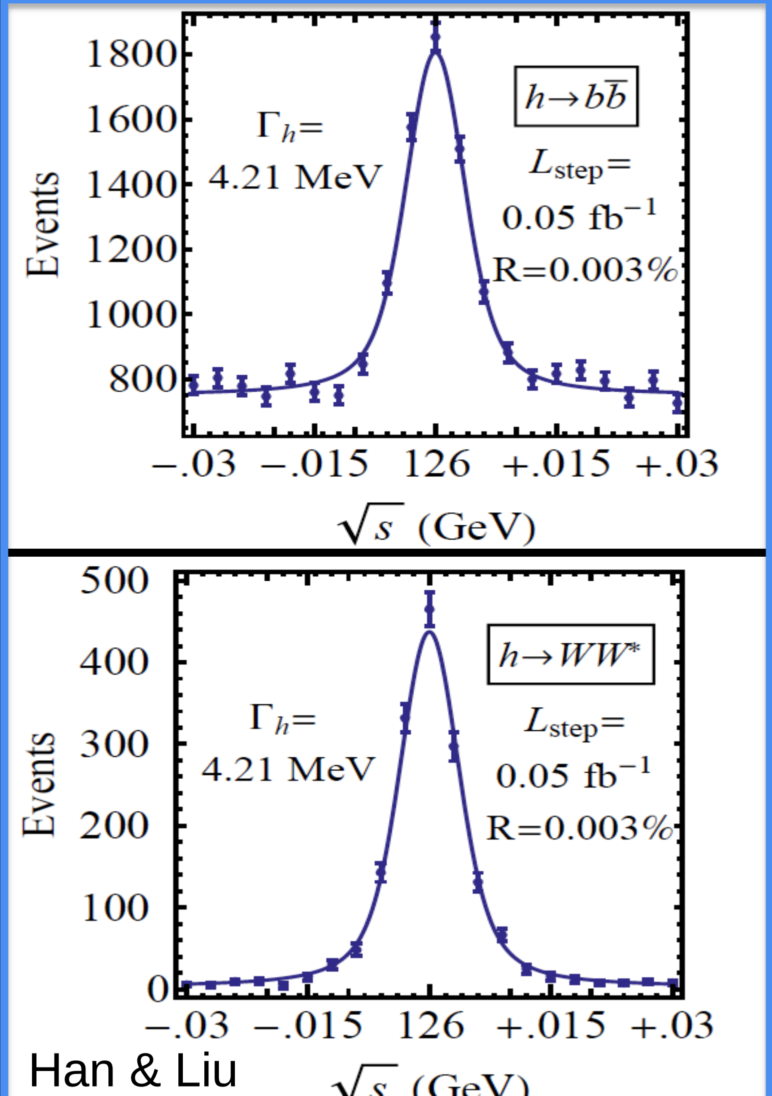
Energy Resolution

- 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

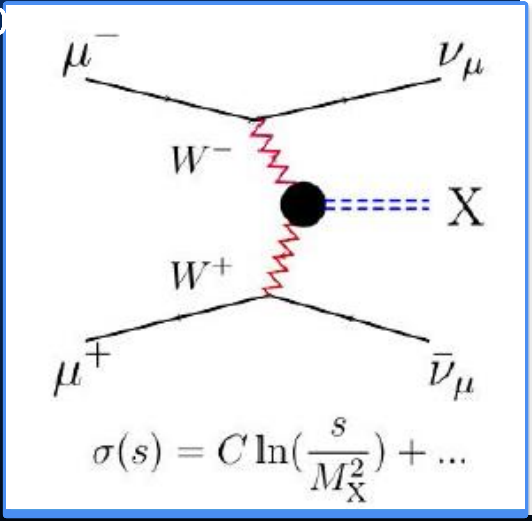


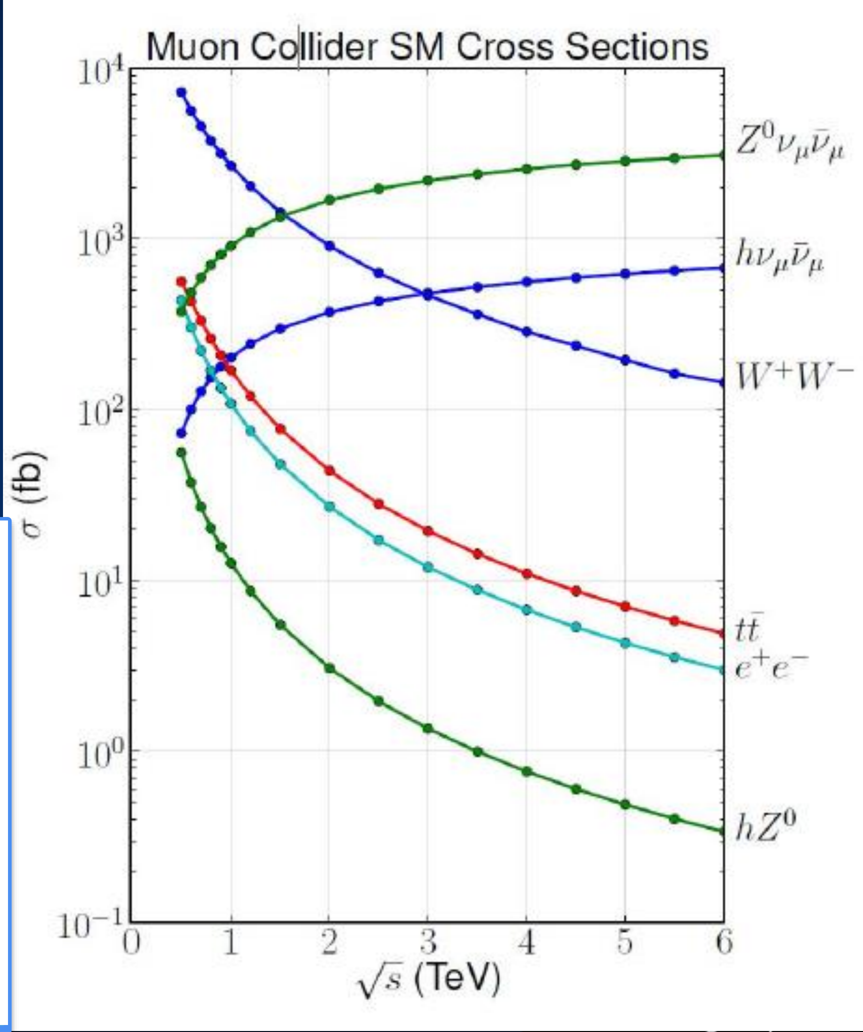
Han & Liu

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:

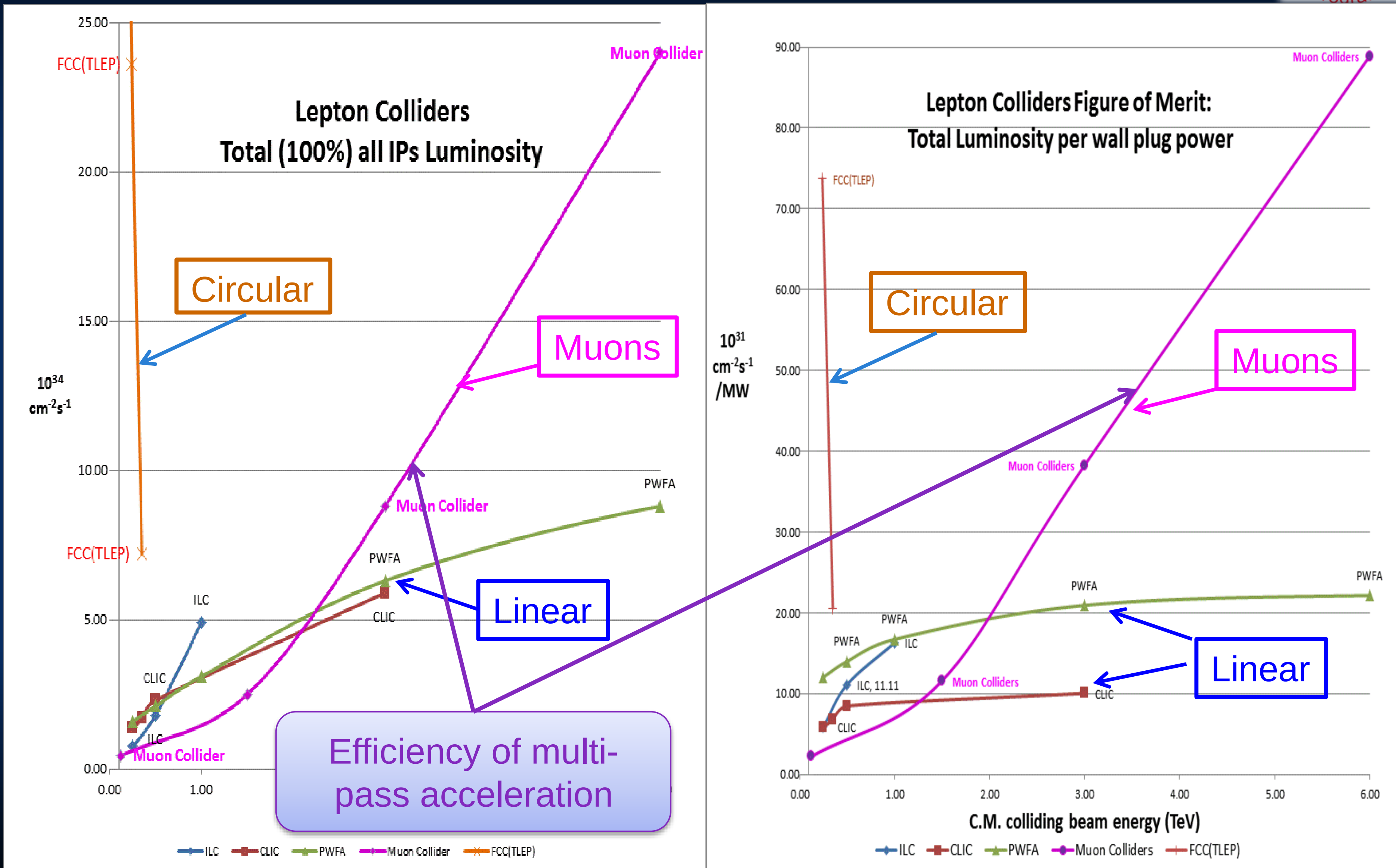
$$\Delta E_{turn} = \left(\frac{4\pi m c^2}{3}\right)\left(\frac{r_0}{\rho}\right)\beta^3\gamma^4$$

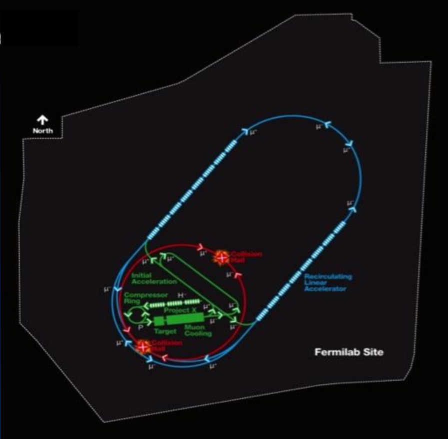
where ρ is the bending radius

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

  - 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

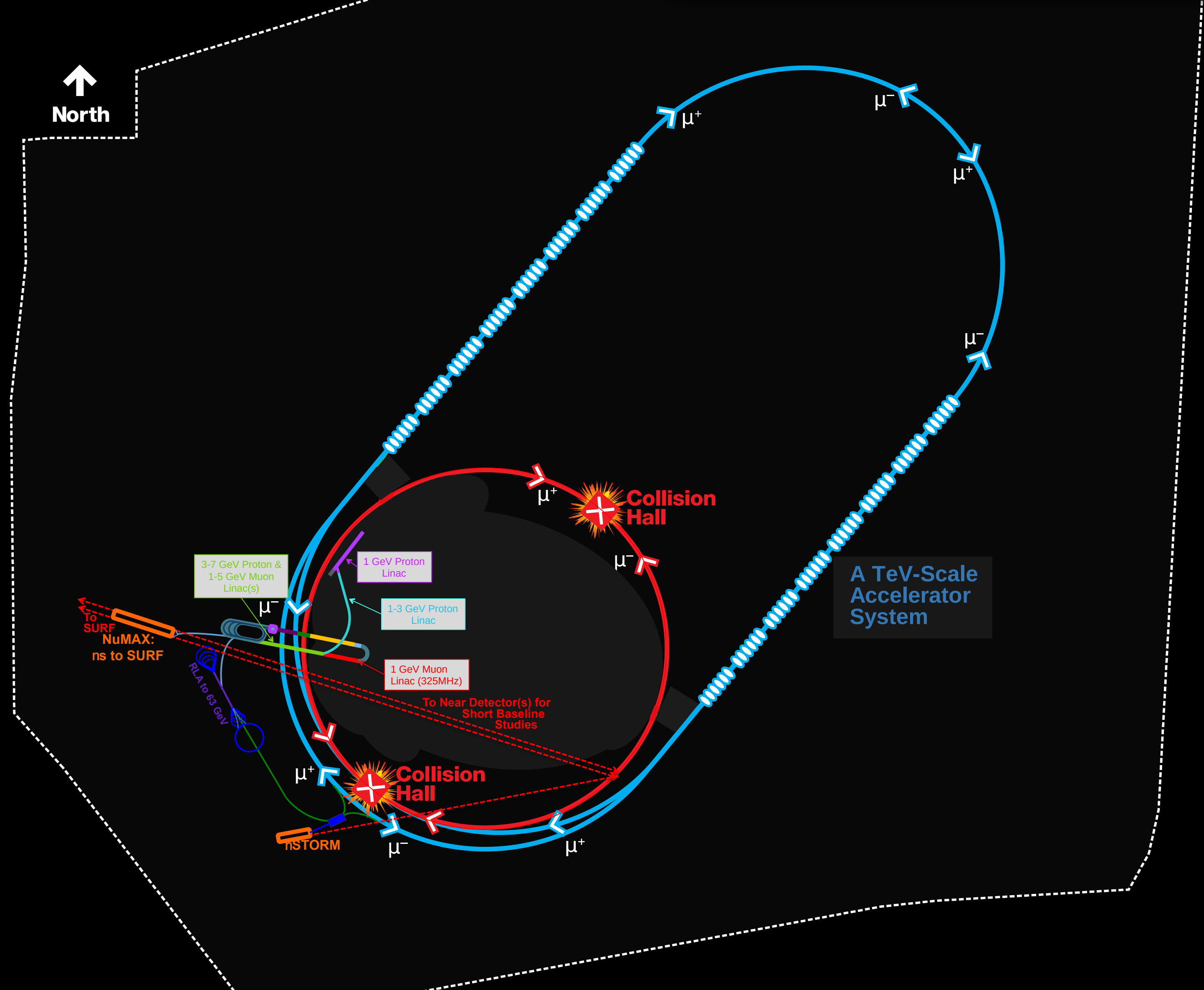
Muon Collider Parameters

Parameter	Units	Higgs	Multi-TeV		
		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
b*	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, e_{TN}	p mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1.5	70	70	70
Bunch Length, s_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 × 10^{32} [Rubbia proposal: 5×10^{32}]

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



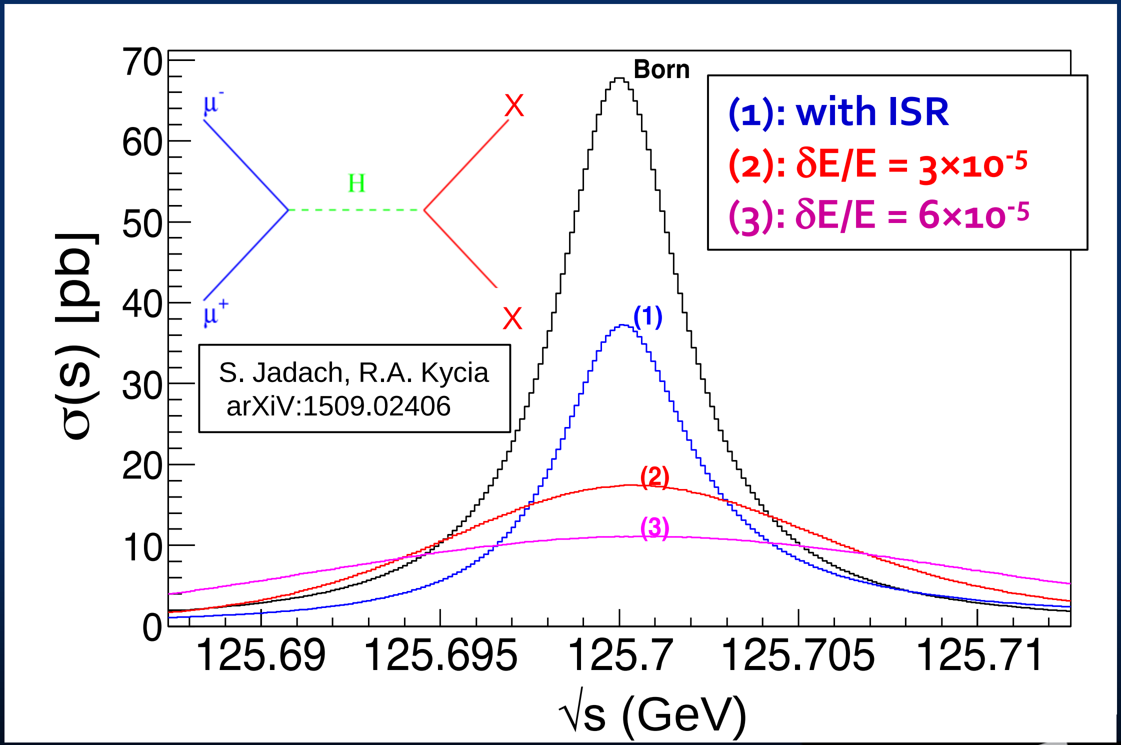
PHYSICS WITH A MUON COLLIDER

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



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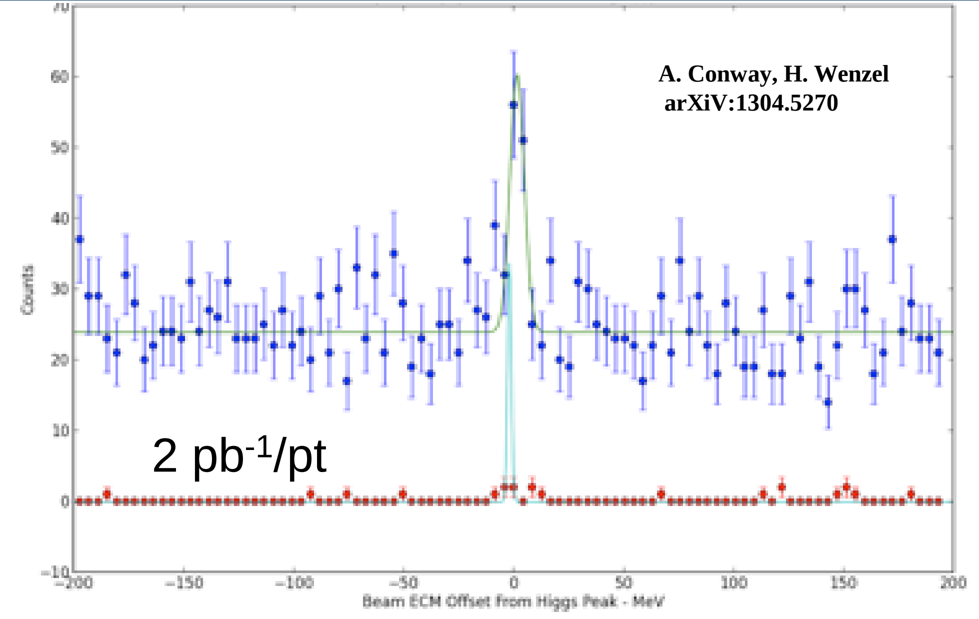
A Higgs Factory

- 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

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



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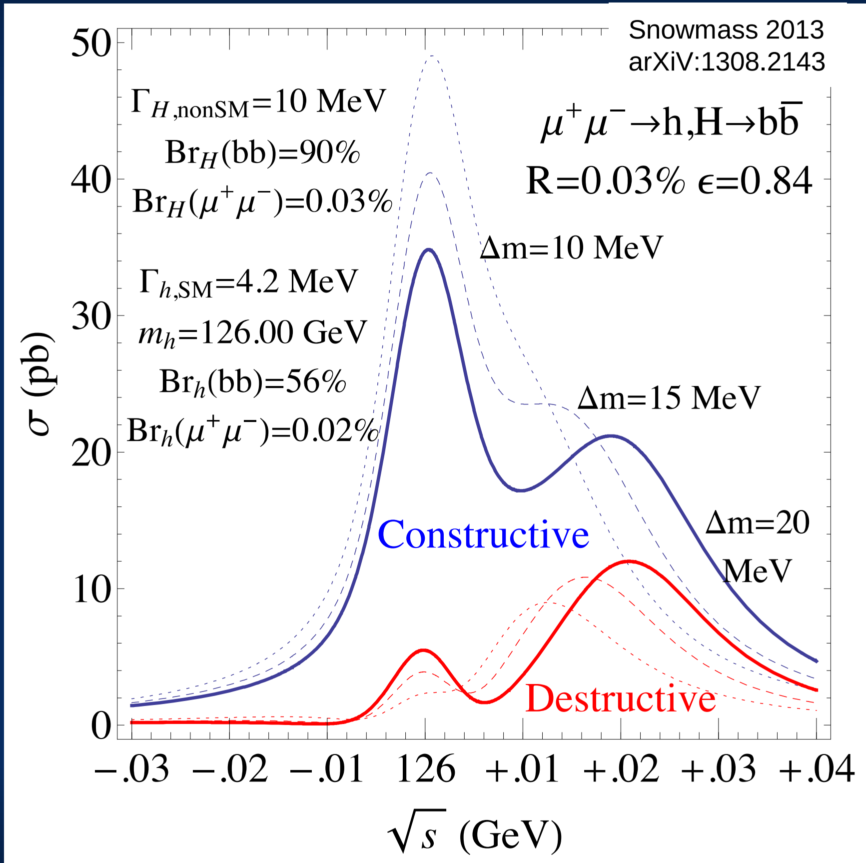
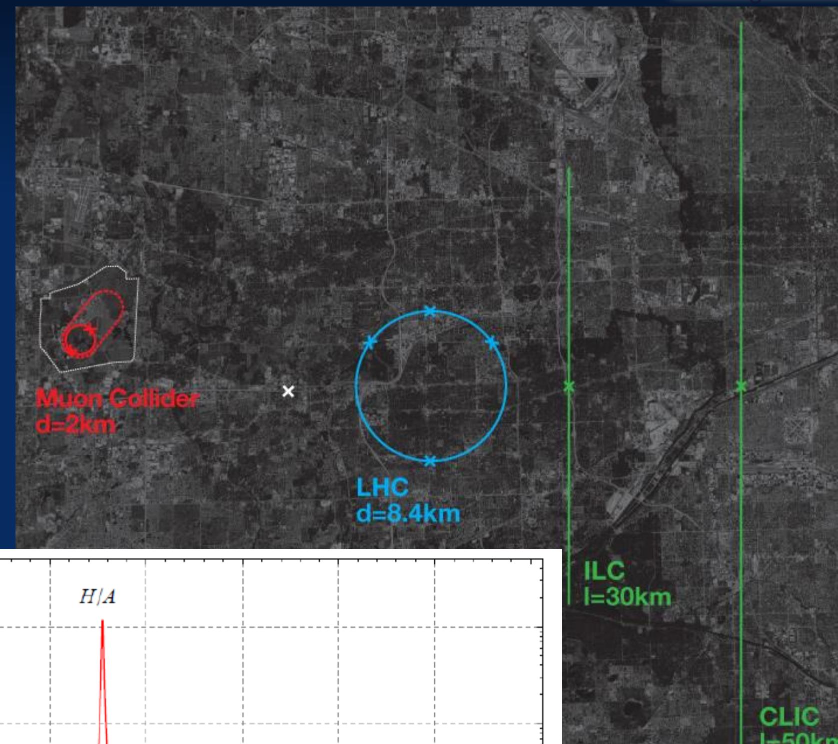
A Higgs Factory

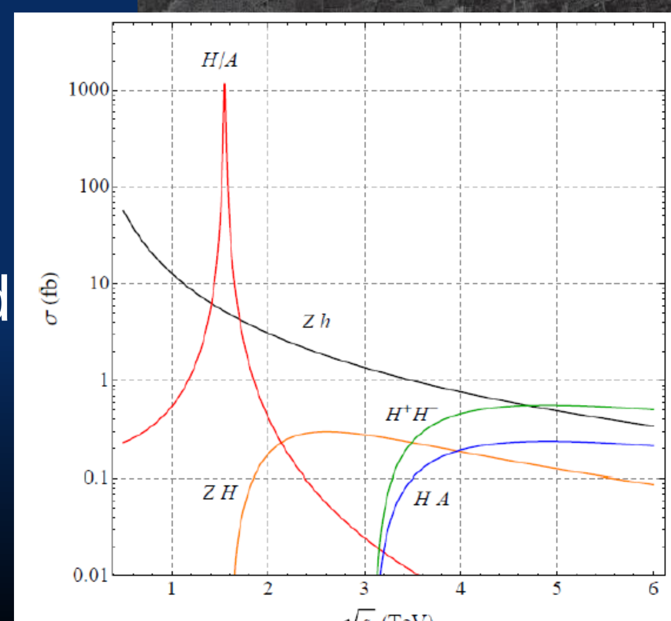
- Direct production combined with precise energy resolution
  - Ability to probe detailed structure
  - A full line-shape measurement probes:
    - The Higgs mass, m_H
    - The Higgs width, Γ_H
    - The branching ratio into $\mu^+\mu^-$, BR($H \rightarrow \mu\mu$) [and hence $g_{H\mu\mu}$]
  - Look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





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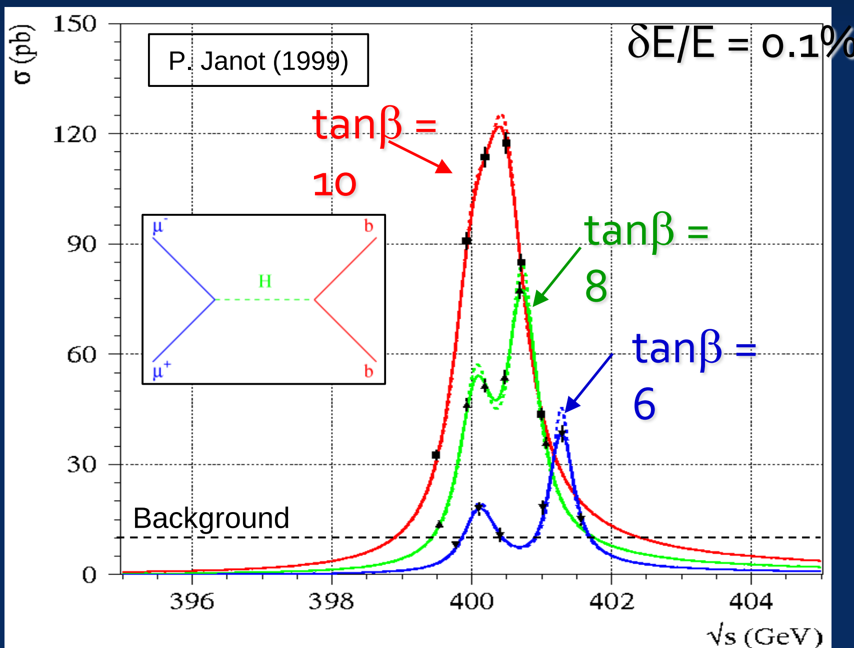
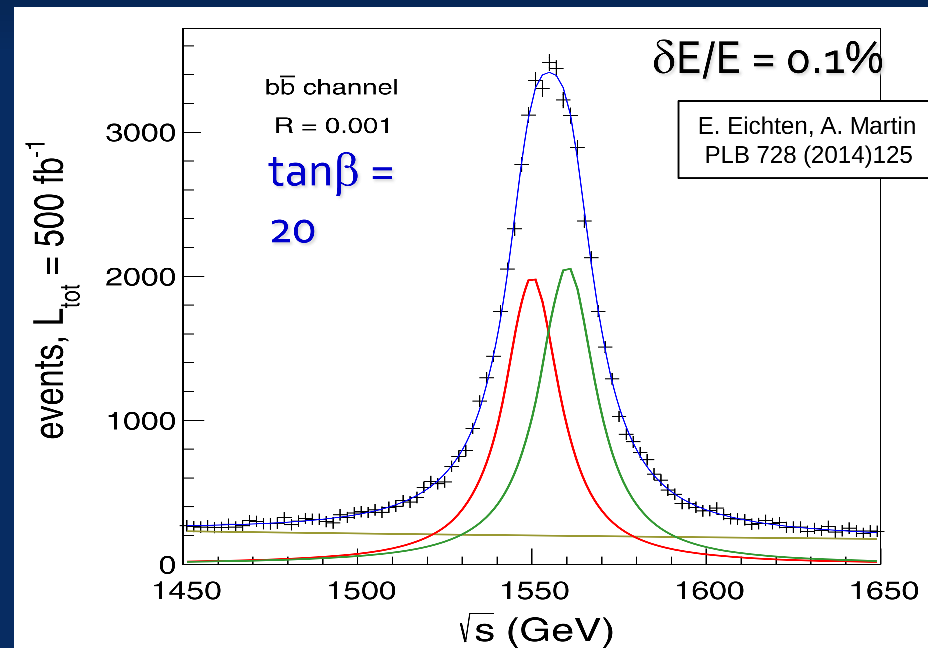
H/A Examples

- 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





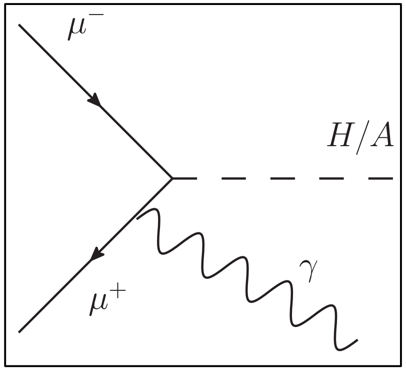
  - Best performance is ultimately obtained by optimizing the ring for operation at E_{COM} of interest

One way to proceed

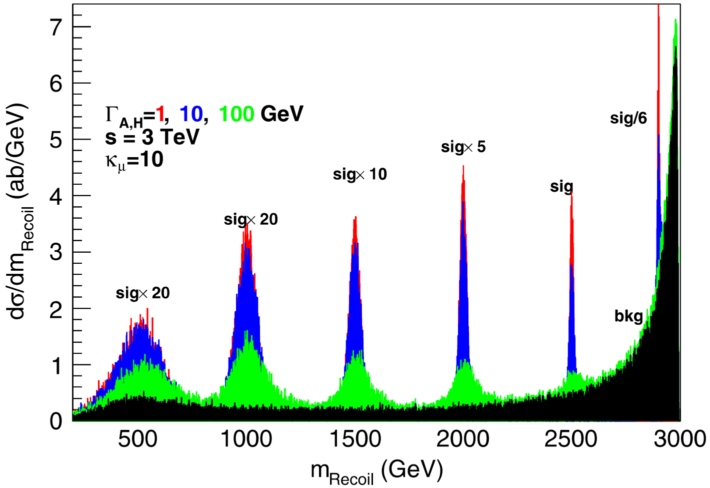
Additional Higgs bosons (3)

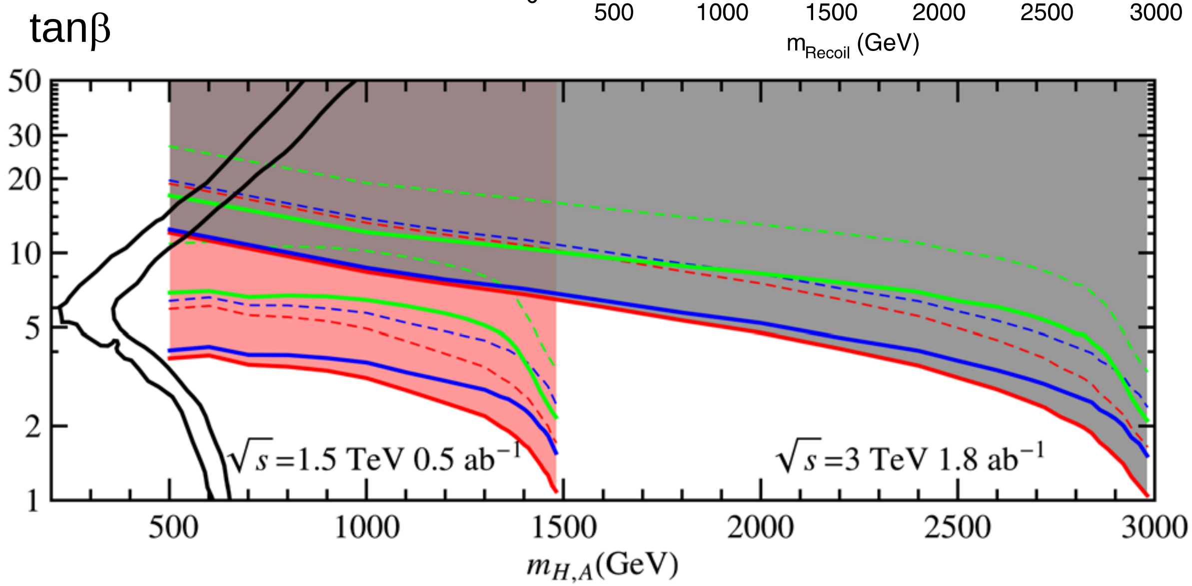
Automatic mass scan with radiative returns in μμ collisions

- 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





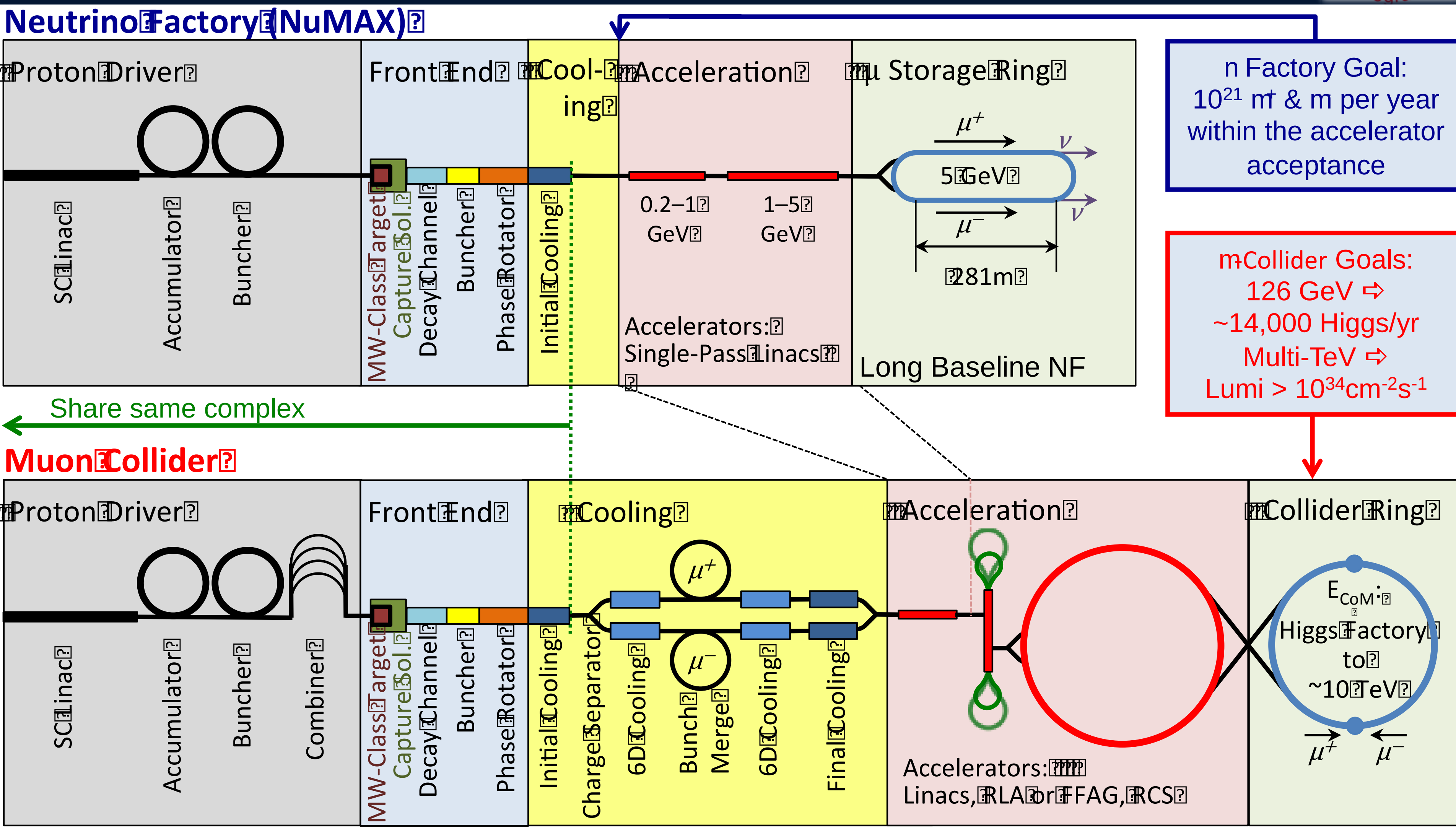
- Can "see" H and A
  - If tanβ > 5
- Build the next collider
  - At $\sqrt{s} \sim m_{A,H}$

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

ACCELERATOR TECHNOLOGY

High Energy Muon Accelerator Capabilities



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Luminosity

- The principle parameter driver is the production of luminosity at a single collision point

$$\mathcal{L} = \frac{N^2 f_{coll}}{4\pi\sigma_x\sigma_y}\mathcal{H}_D$$

Linear Collider Form

- where

  N is the number of particles per bunch (*assumed equal for all bunches*)

  f_{coll} is the overall collision rate at the interaction point (IP)

  σ_x and σ_y are the horizontal and vertical beam sizes (*assumed equal for all bunches*)

  $\mathcal{H}_D$ is the luminosity enhancement factor

- Ideally we want:
  – High intensity bunches
  – High repetition rate
  – Small transverse beam sizes

ILC Parameters at the IP

- The parameters at the interaction point have been chosen to provide a nominal luminosity of 2×10^{34} cm^{-2}s^{-1}. With

  $N = 2\times10^{10}$ particles/bunch

  $\sigma_x \sim 640$ nm $\Leftrightarrow$ $\beta_x^* = 20$ mm, $\varepsilon_x = 20$ pm-rad

  $\sigma_y \sim 5.7$ nm $\Leftrightarrow$ $\beta_y^* = 0.4$ mm, $\varepsilon_y = 0.08$ pm-rad

  $\mathcal{H}_D \sim 1.7$

$$\mathcal{L} = \frac{N^2 f_{coll}}{4\pi\sigma_x\sigma_y}\mathcal{H}_D = \left(1.4\times 10^{30}\, cm^{-2}\right)\times f_{coll}$$

- An average collision rate of ~14kHz is required.
- Beam sizes at the IP are determined by the strength of the final focus magnets and the emittance (phase space volume) of the incoming bunches.

A number of issues impact the choice of the final focus parameters. For example, the beam-beam interaction as two bunches pass through each other can enhance the luminosity, however, it also disrupts the bunches. If the beams are too badly disrupted, safely transporting them out of the detector to the beam dumps becomes quite difficult. Another effect is that of beamstrahlung which leads to significant energy losses by the particles in the bunches and can lead to unacceptable detector backgrounds. Thus the above parameter choices represent a complicated optimization.

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)

$$\mathcal{L} \approx \frac{N_0^2 n_{turns} f_{bunch}}{4\pi\sigma_\perp^2} \approx 1.4 \times 10^{34}\, cm^{-2} s^{-1}$$

- 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 ~1.2×10^{34} $cm^{-2}s^{-1}$.

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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

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

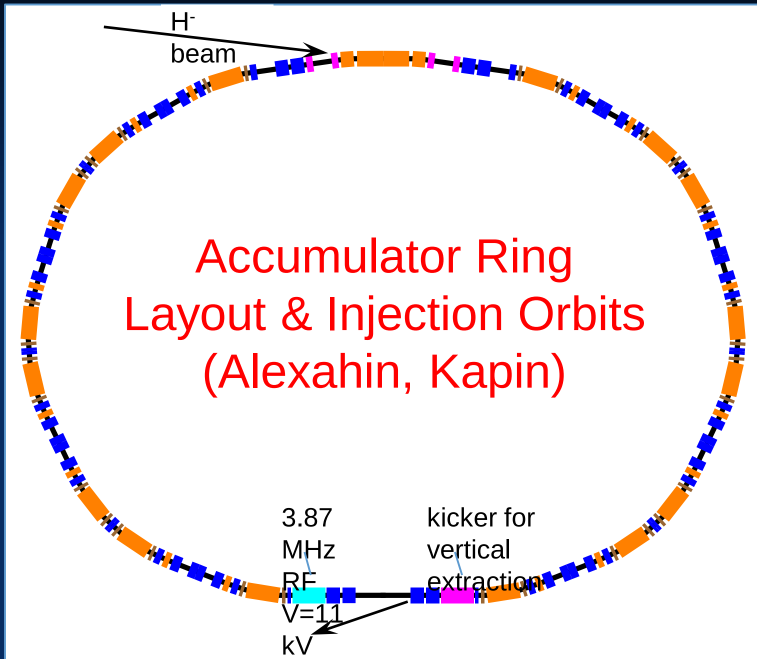
- Proton Driver
- Target
  - High Power Target Station
  - Capture Solenoid
- Front End
  - Energy Deposition
- Cooling
  - RF in Magnetic Fields
  - Magnet Needs (Nb_3Sn vs HTS)
  - Performance
- Acceleration
  - Acceptance (NF)
  - >400 Hz AC Magnets (MC)
- Collider Ring
  - IR Magnet Strengths/Apertures
- Collider MDI
  - SC Magnet Heat Loads (μ decay)
- Collider Detector
  - Backgrounds (μ decay)

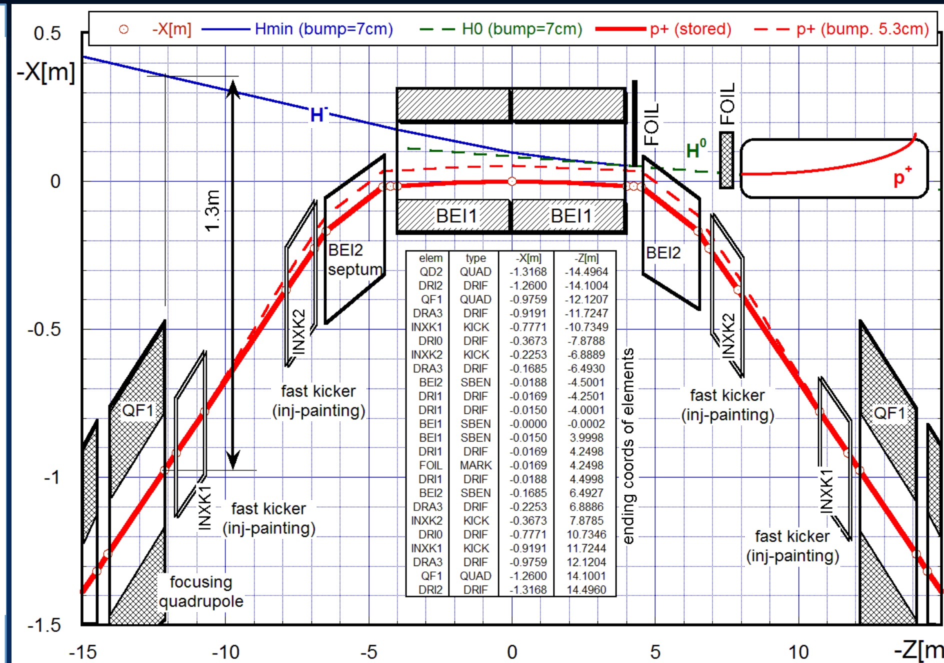
Characteristics of the Muon Source

- 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)

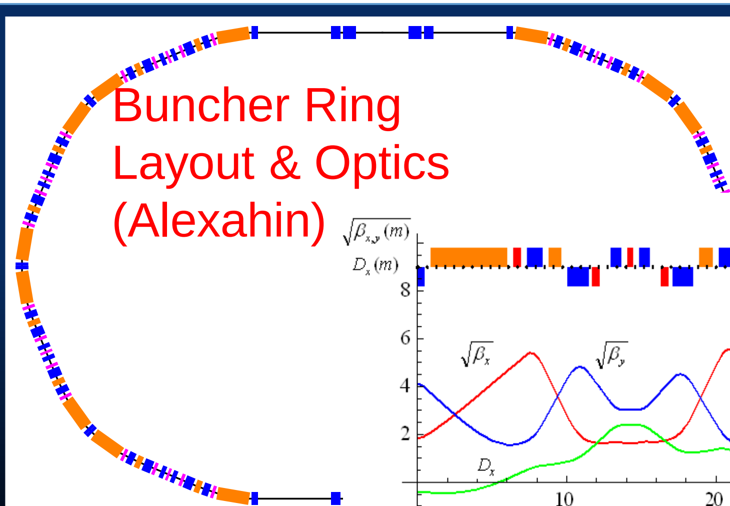
    Rate > 10^{13}/sec $n_b = 2 \cdot 10^{12}$

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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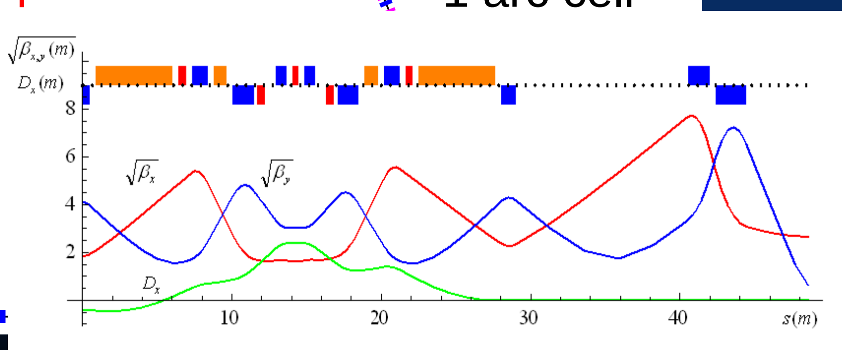
1 arc cell



- ✓ 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

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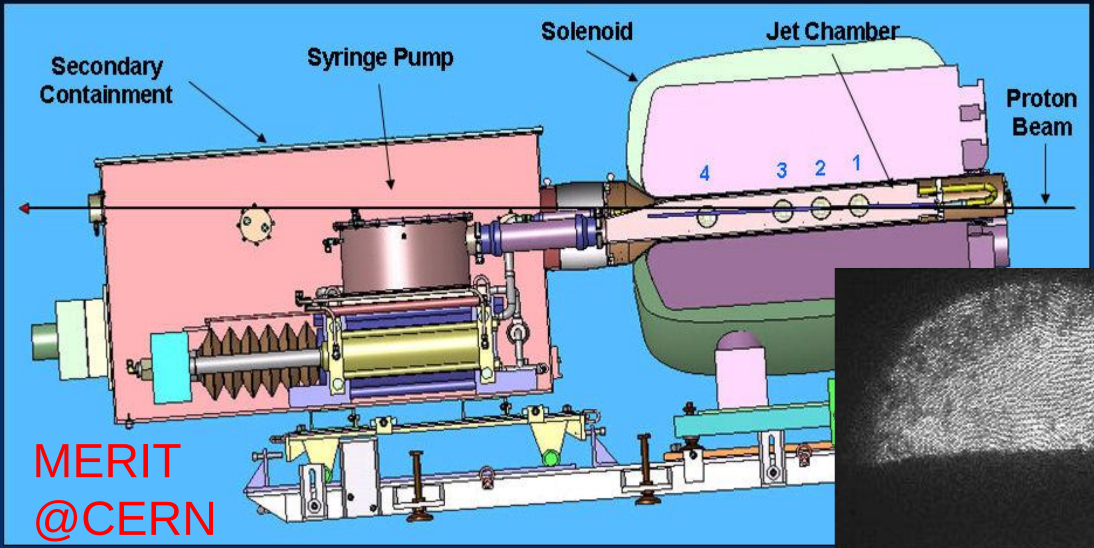
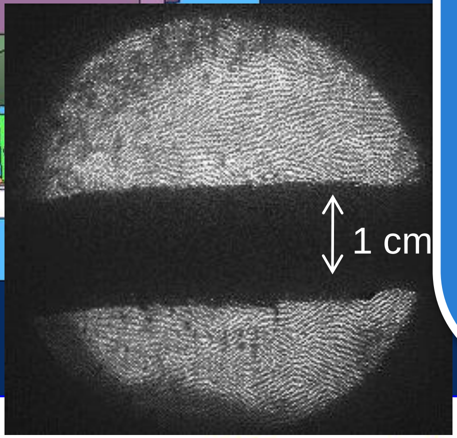
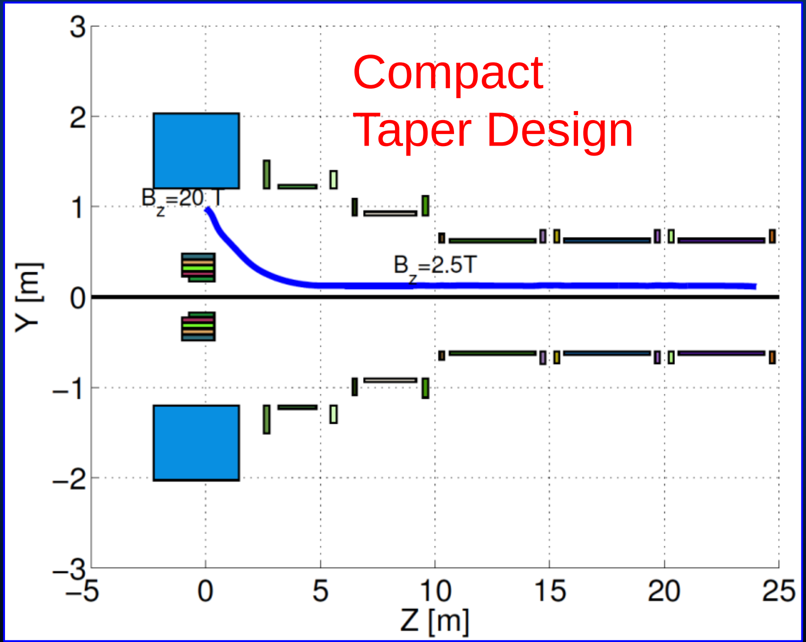
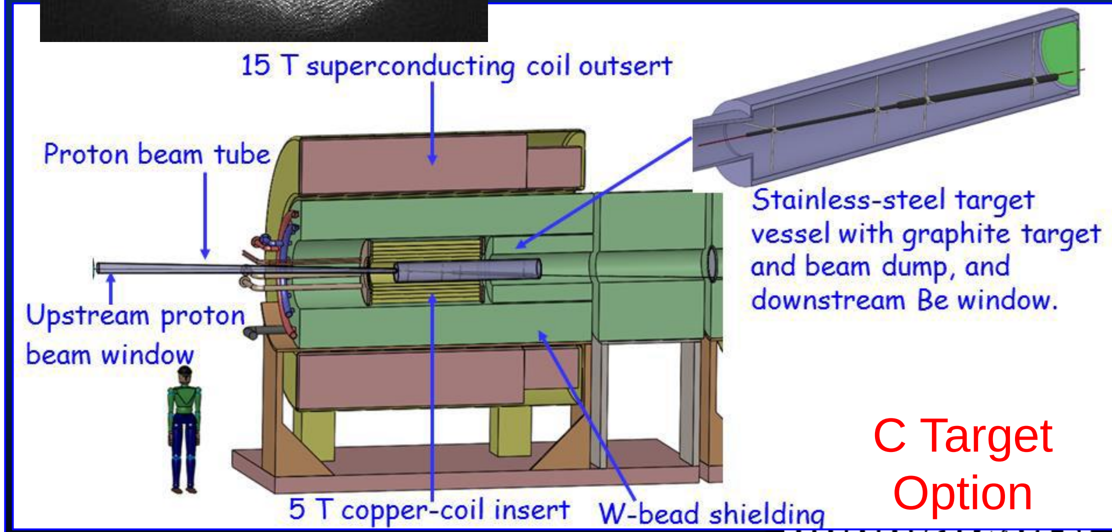
High Power Target





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





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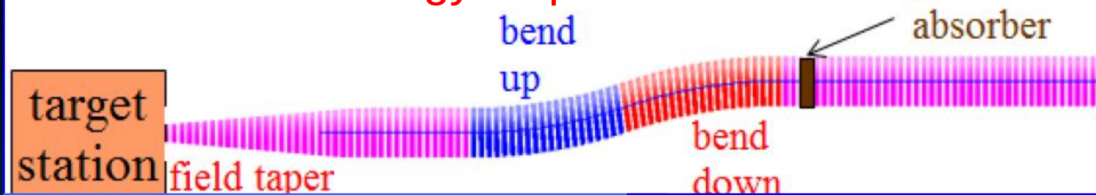
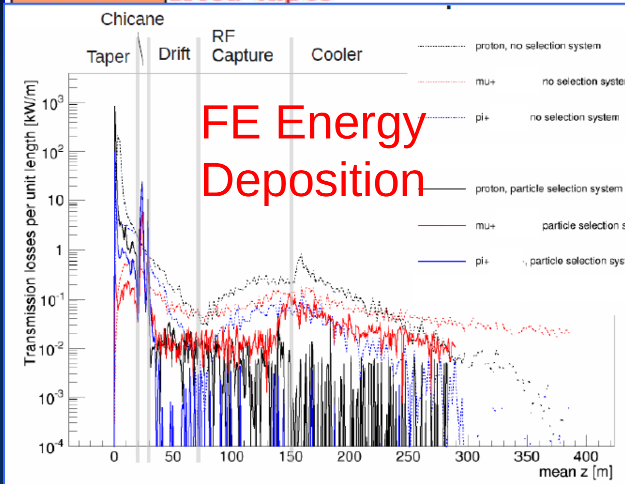
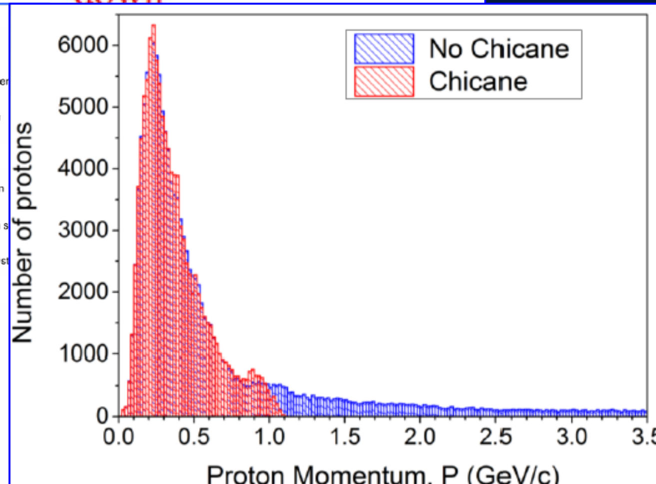
Front End

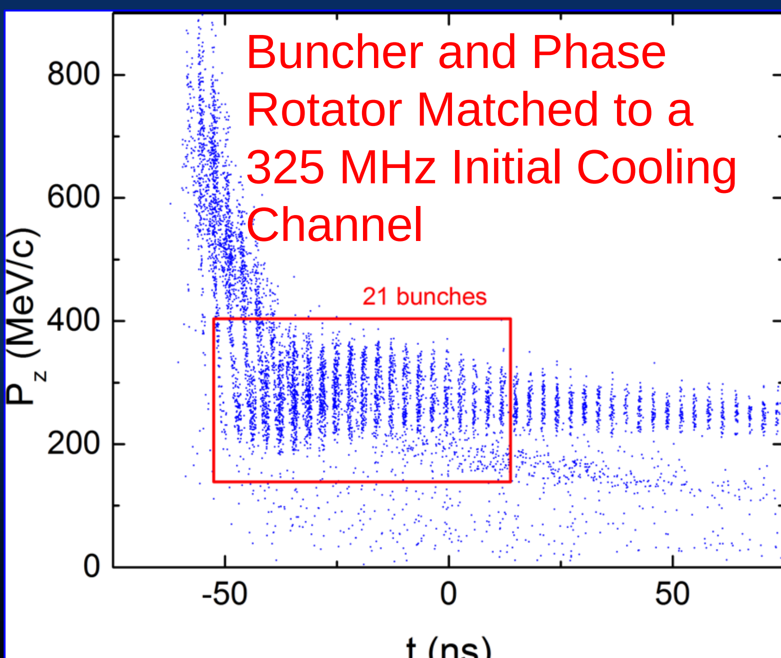
Control of FE Energy Deposition

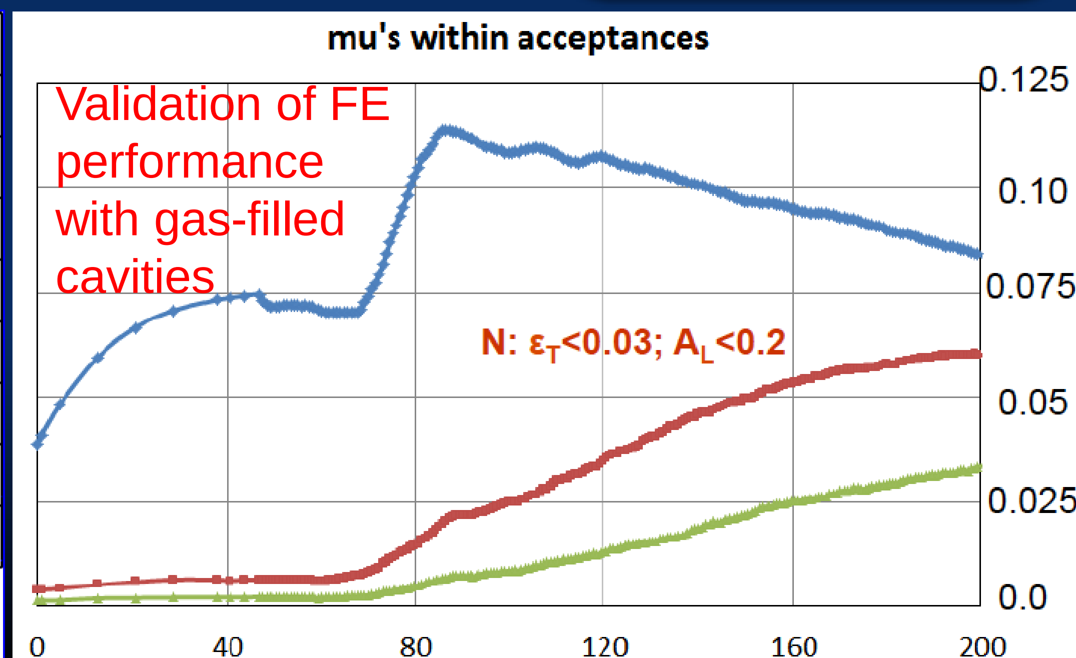






- ✓ Energy Deposition
- ✓ Full 325 MHz RF Design
- ✓ Validation of gas-filled RF cavity performance



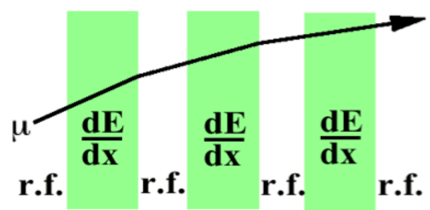


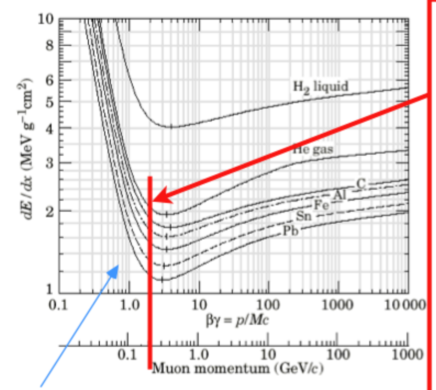
Cooling Methods

- 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





- Absorbers:

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

ionization energy loss

multiple Coulomb scattering

- RF cavities between absorbers replace ΔE
- Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

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

(emittance change per unit length)

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

- 2 competing effects ⇒ ∃ equilibrium emittance

Kaplan

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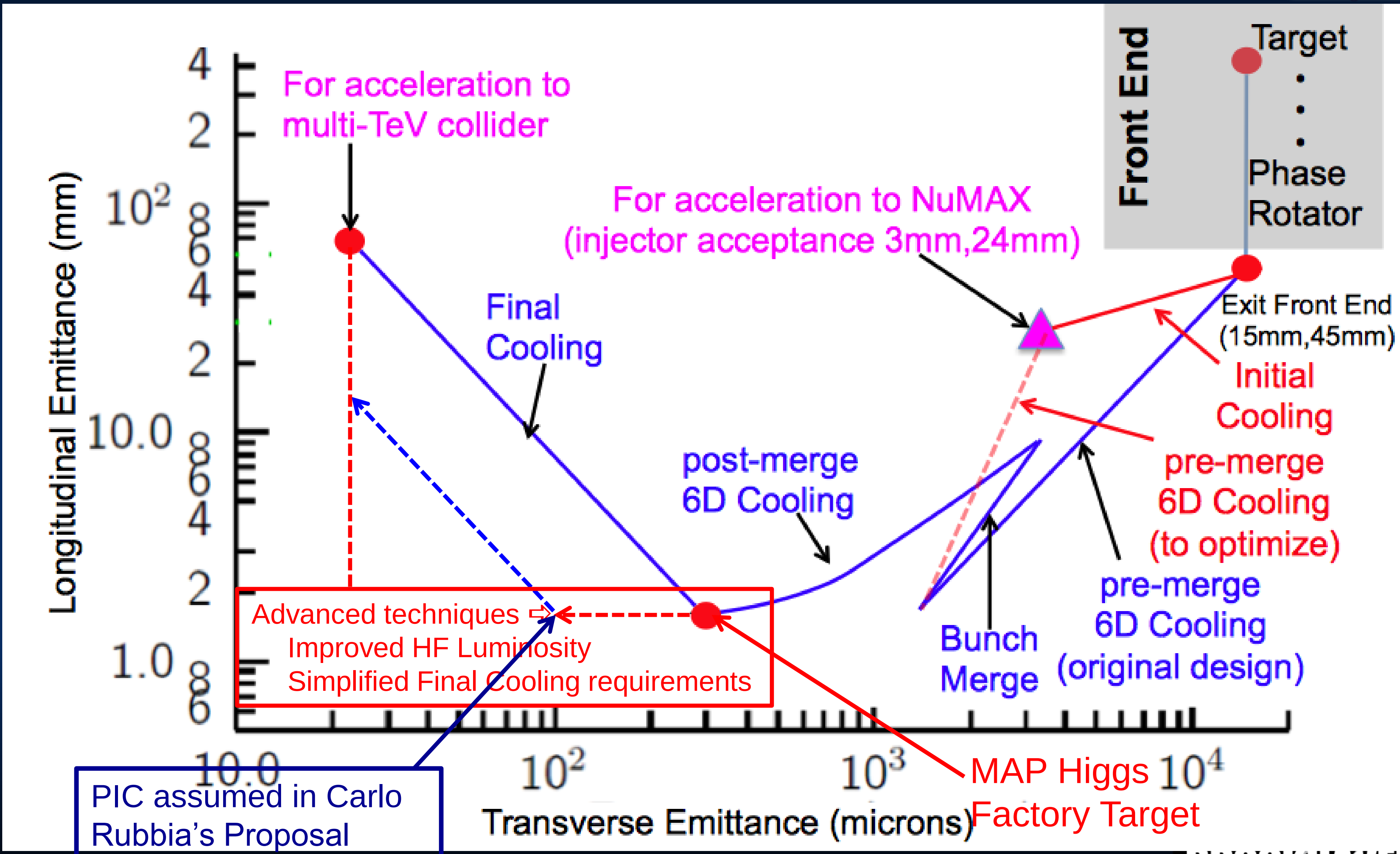
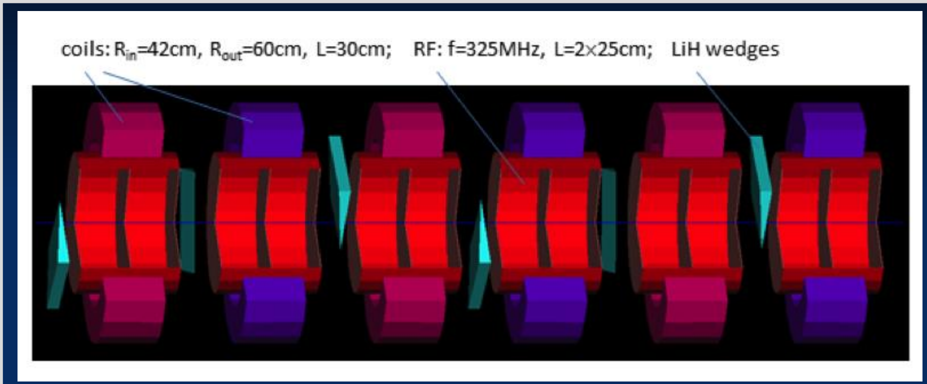
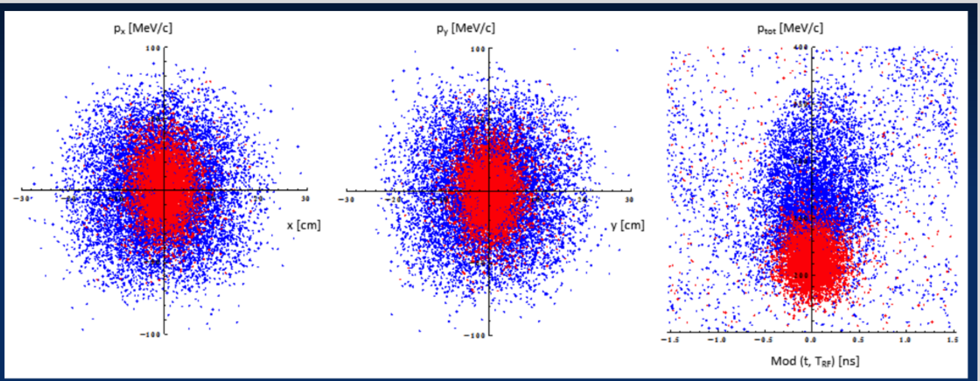
Muon Ionization Cooling

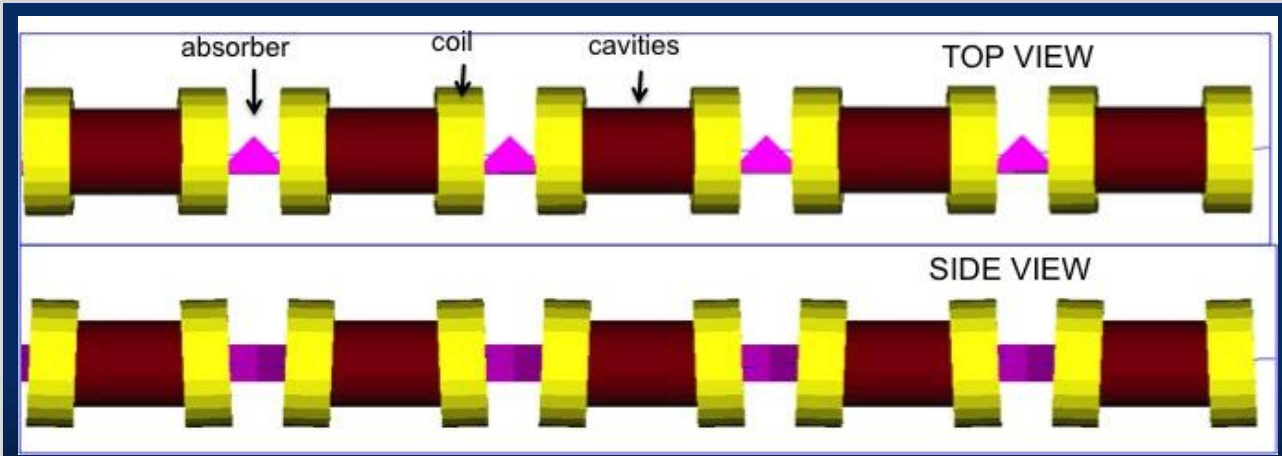


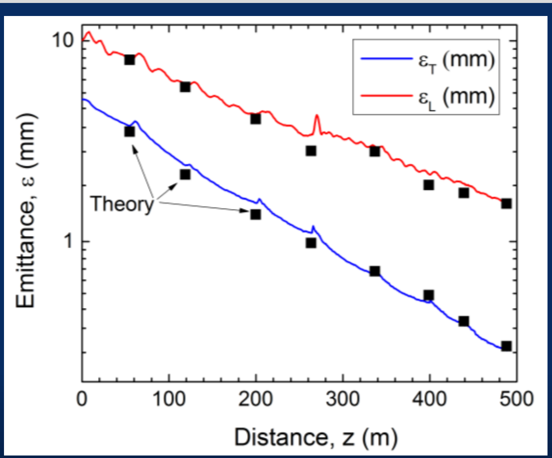
Muon Ionization Cooling (Design)





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

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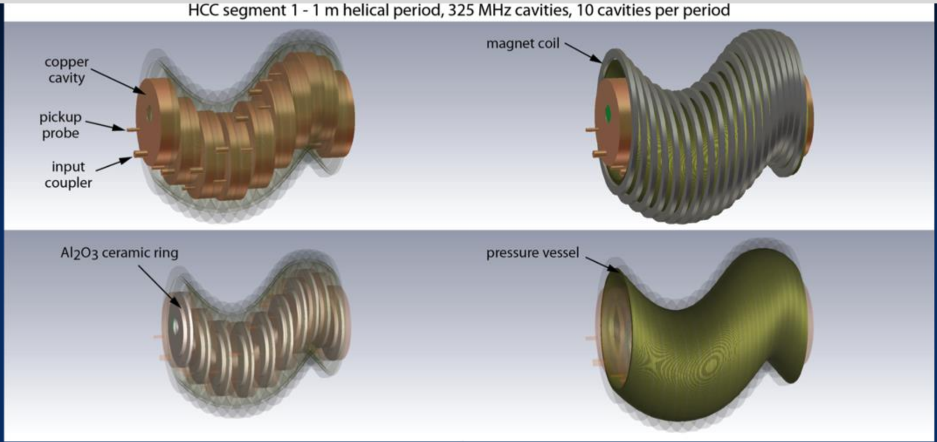
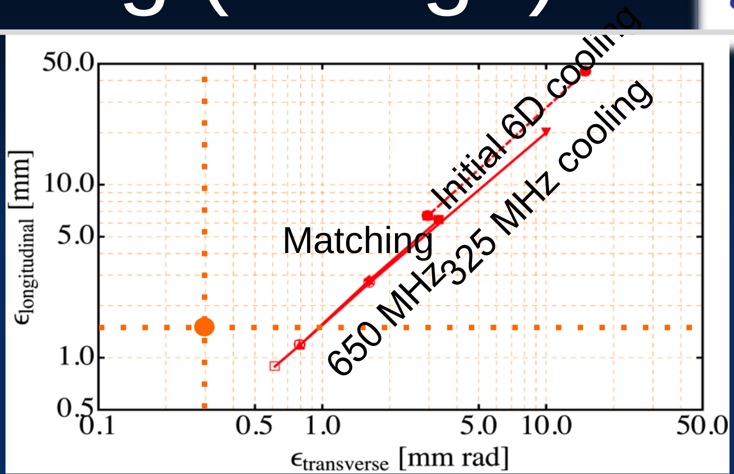
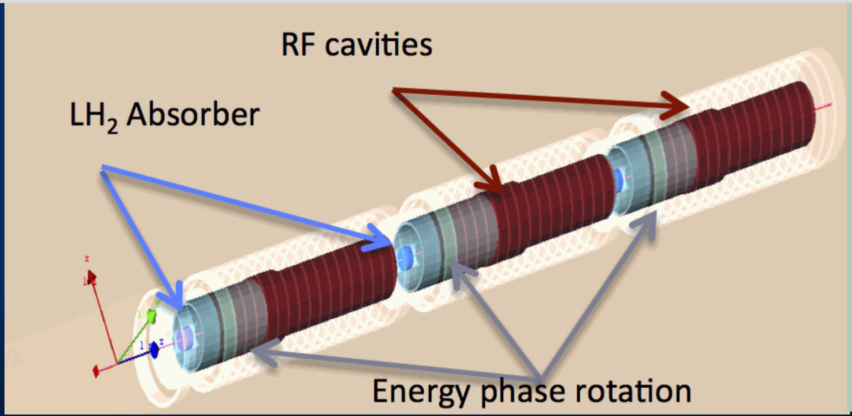
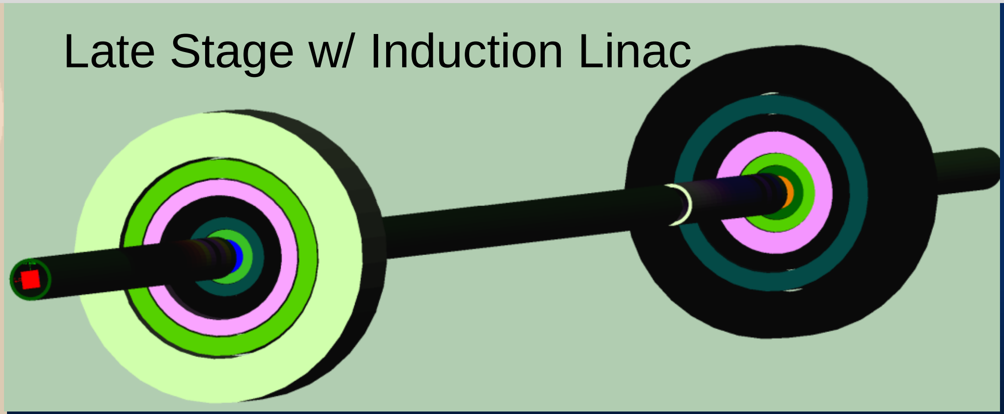
Muon Ionization Cooling (Design)





- Helical Cooling Channel (Gas-filled RF Cavities): $\varepsilon_T = 0.6$mm, $\varepsilon_L = 0.3$mm

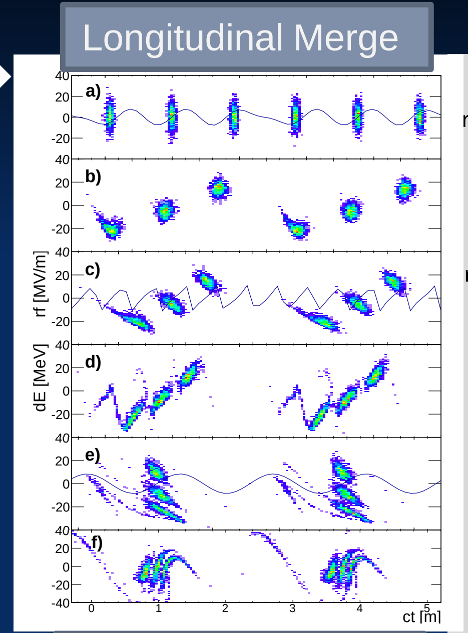




- Final Cooling with 25-30T solenoids (emittance exchange): $\varepsilon_T = 55\mu$m, $\varepsilon_L = 75$mm

Muon Ionization Cooling (Design)

Bunch Merge



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

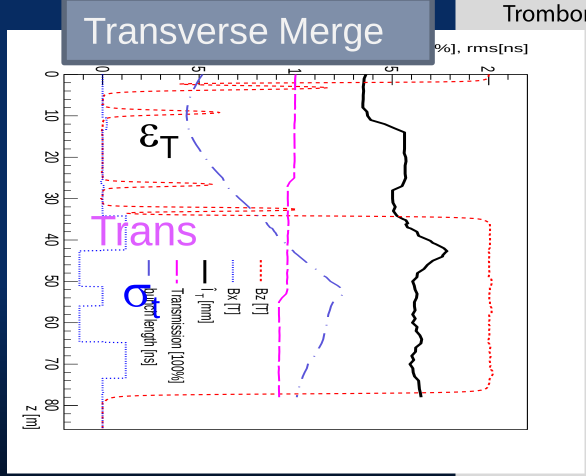
Higgs Factory

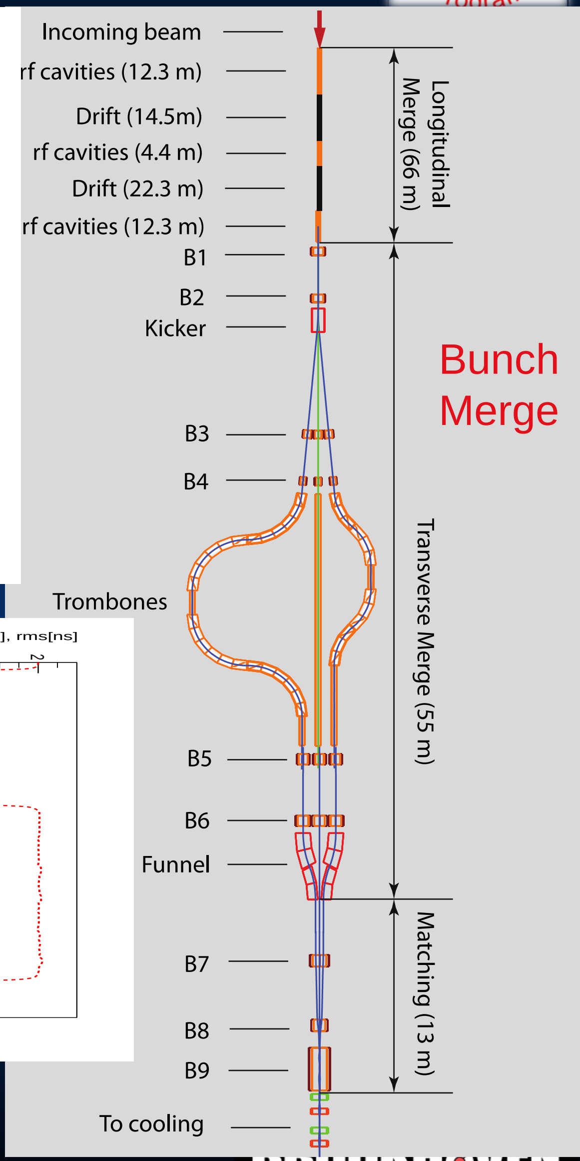
  - Hybrid Rectilinear Channel (gas-filled structures)
  - Parametric Ionization Cooling
  - Alternative Final Cooling

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*





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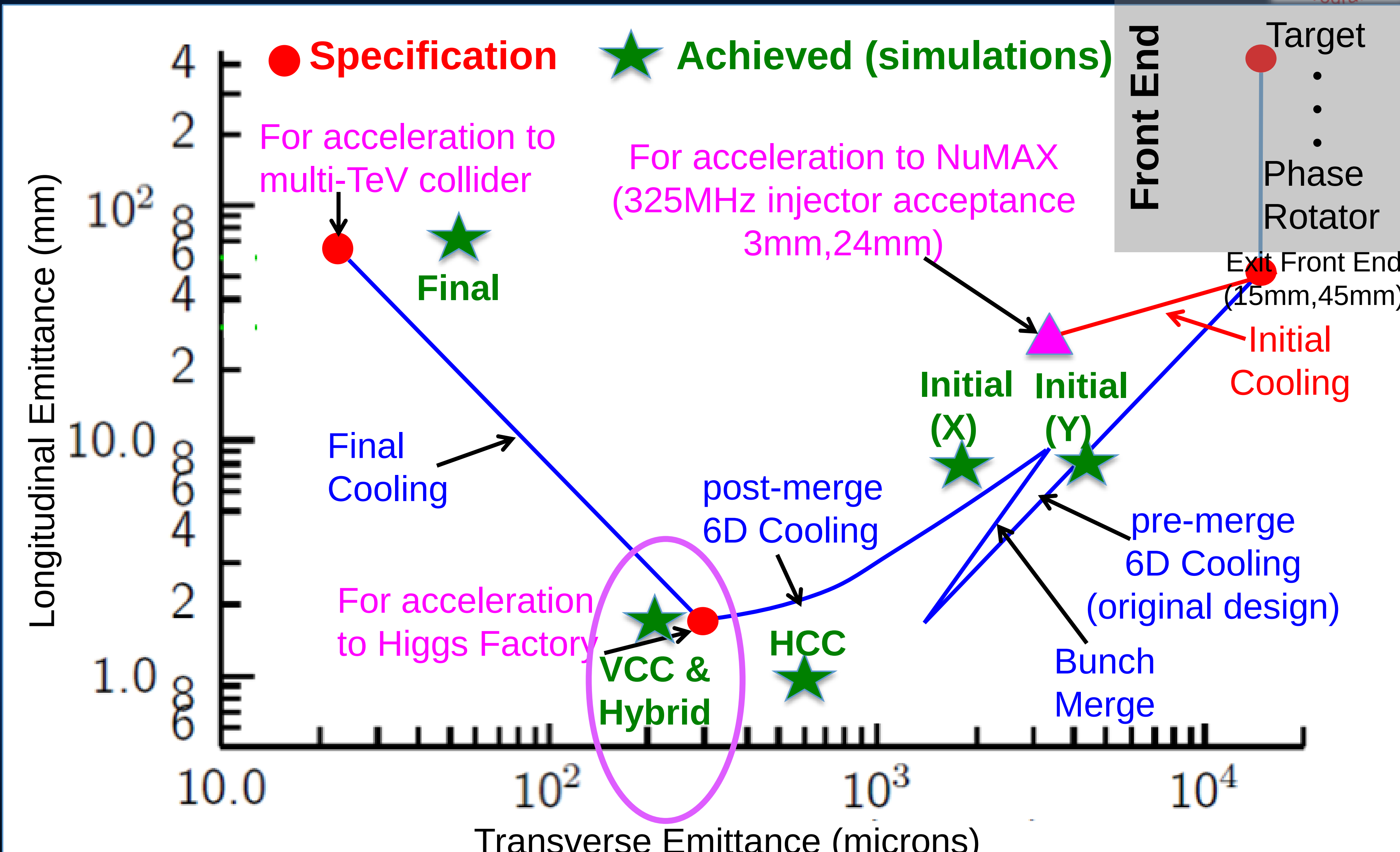
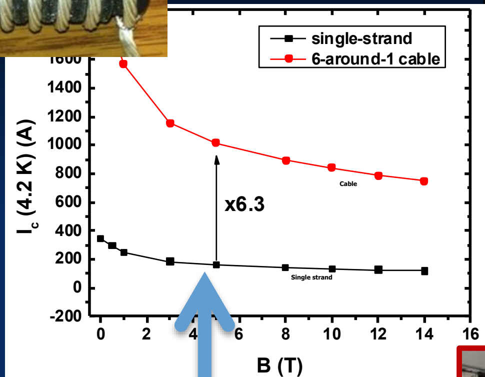
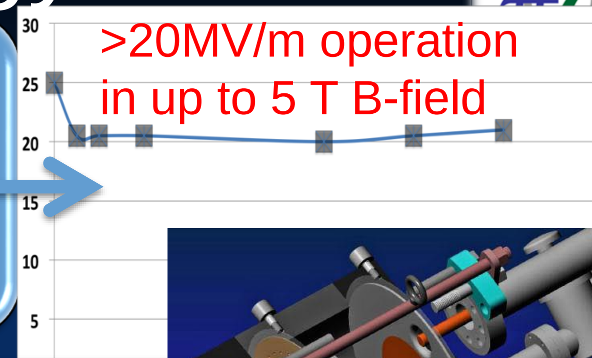
Cooling: The Emittance Path



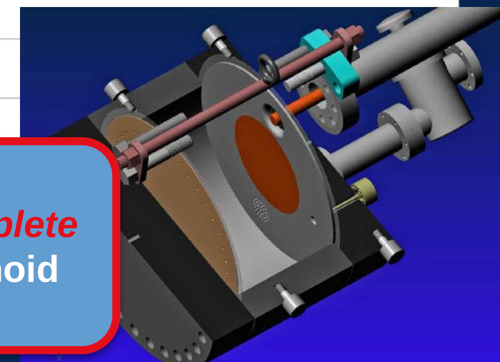
Cooling Technology R&D





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

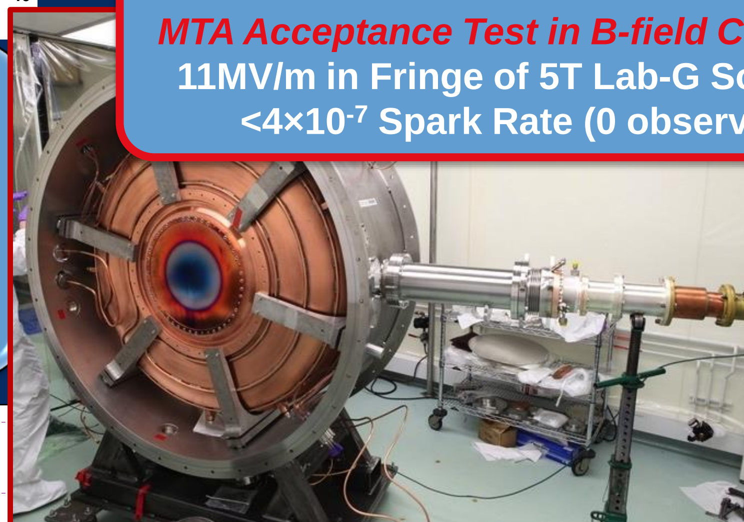
MuCool Test Area/Muons Inc



Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

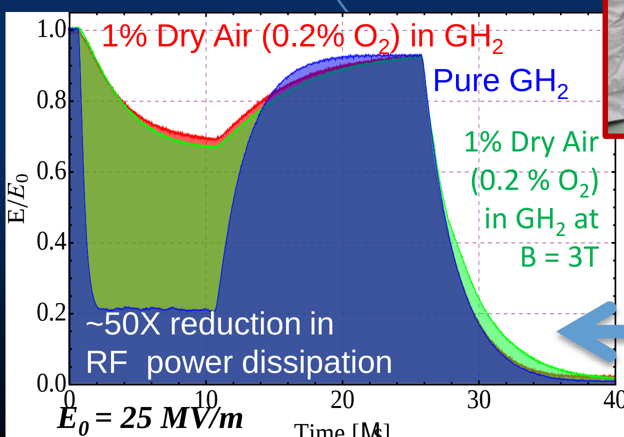
FNAL-Tech Div
T. Shen-Early Career Award

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)

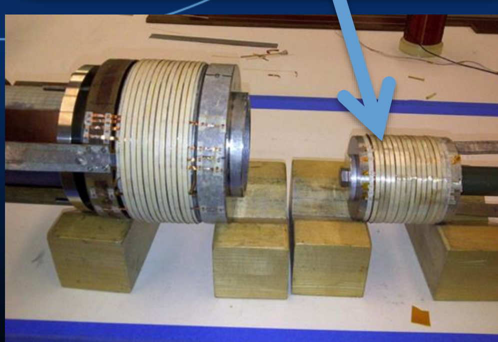
R. Gupta
PBL/BNL



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

Extrapolates to required
μ-Collider Parameters

MuCool Test Area



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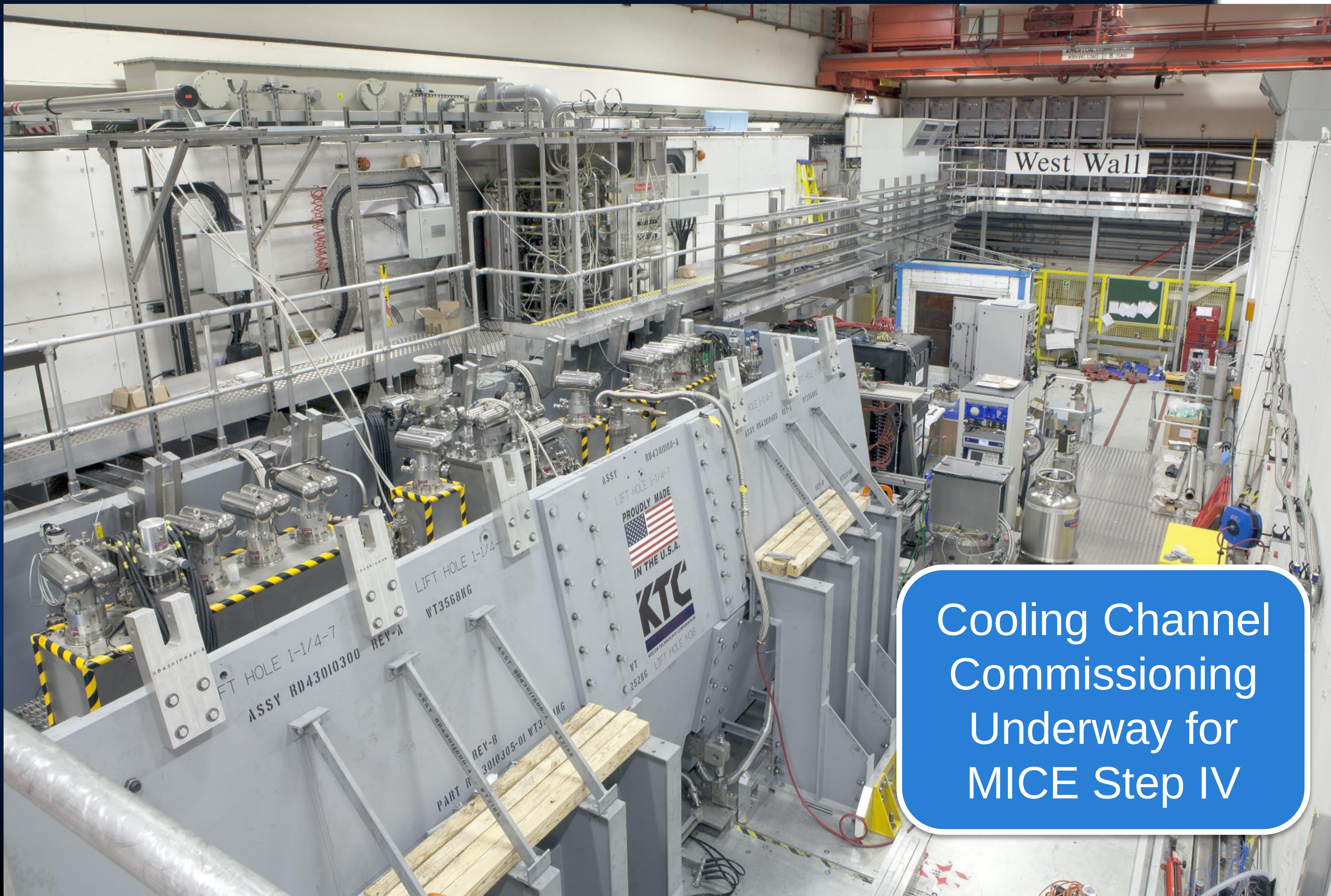
Muon Ionization Cooling Experiment



Cooling Channel Commissioning Underway for MICE Step IV

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 now in commissioning phase

~ 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

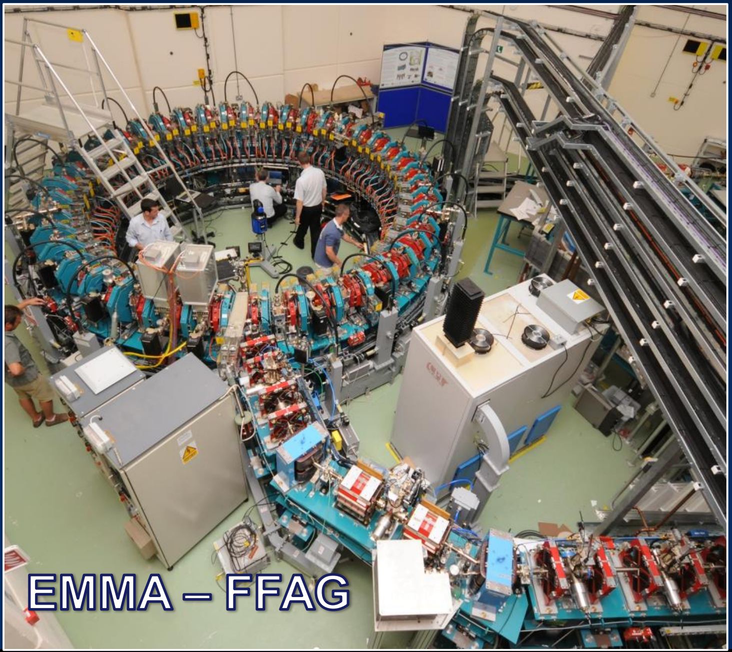
- Key Issues:
  - Muon lifetime ⇨ ultrafast acceleration chain
  - NF with modest cooling ⇨ accelerator acceptance
  - Total charge ⇨ cavity beam-loading (stored energy)
  - TeV-scale acceleration focuses on hybrid Rapid Cycling Synchrotron ⇨ requires rapid cycling magnets

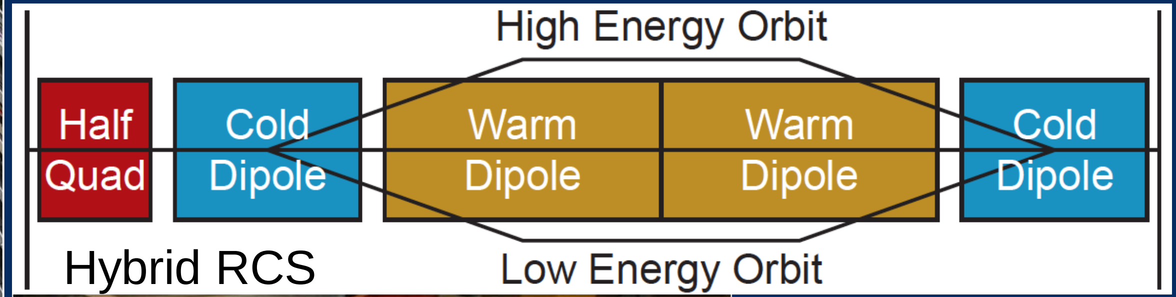
    $B_{peak} \sim 2T$ $f > 400Hz$

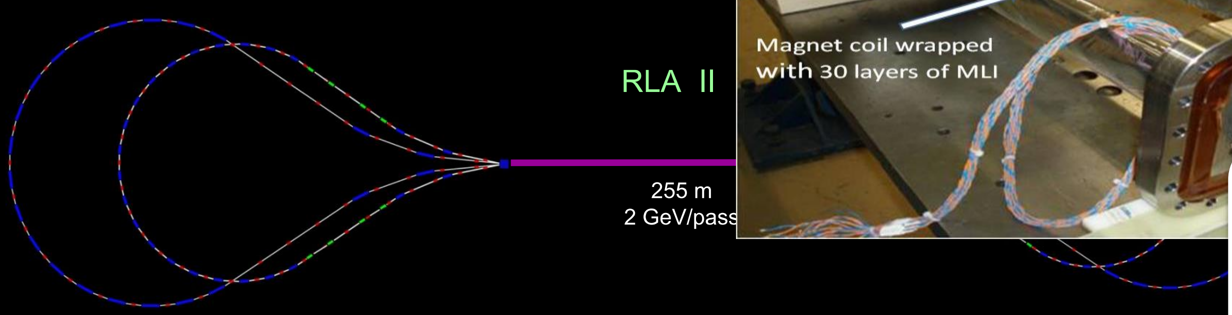
Acceleration

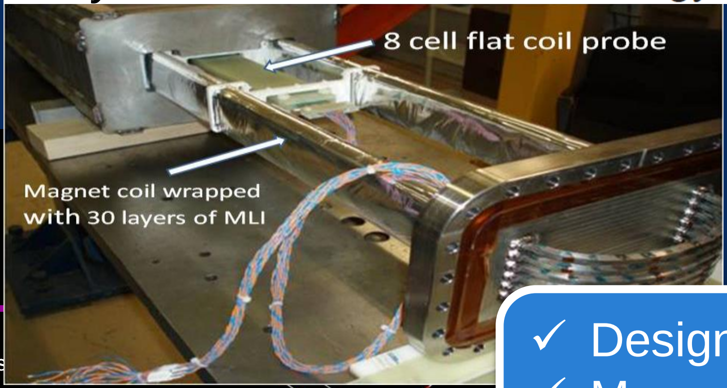
Technologies include:

- 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)

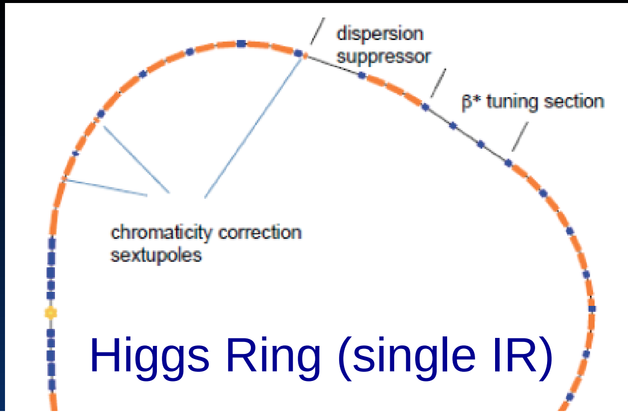
- ✓ Design concepts in hand
- ✓ Magnet R&D indicates parameters achievable

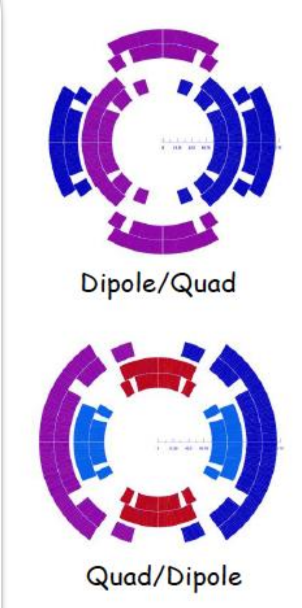
Collider Rings

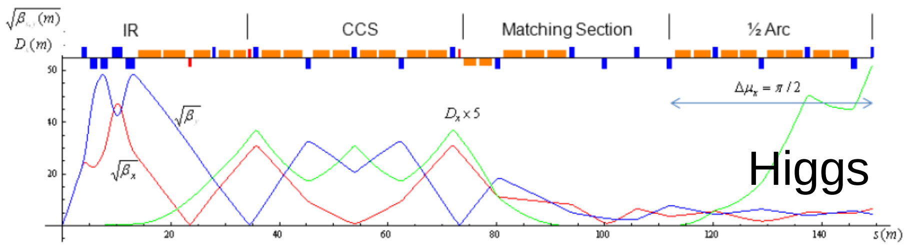
- Detailed optics studies for Higgs, 1.5 TeV, 3 TeV and now 6 TeV CoM
  - With supporting magnet designs and background studies

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

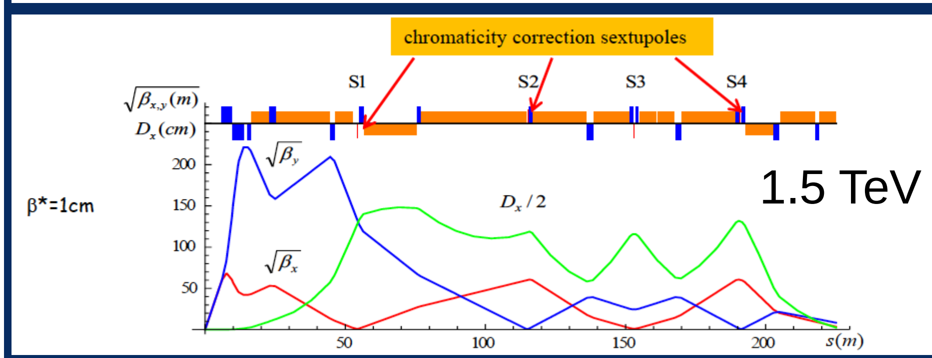
✓ Preliminary 6 TeV CoM design
  - Key issue is IR design and impact on luminosity
  - Utilizes lower power on target

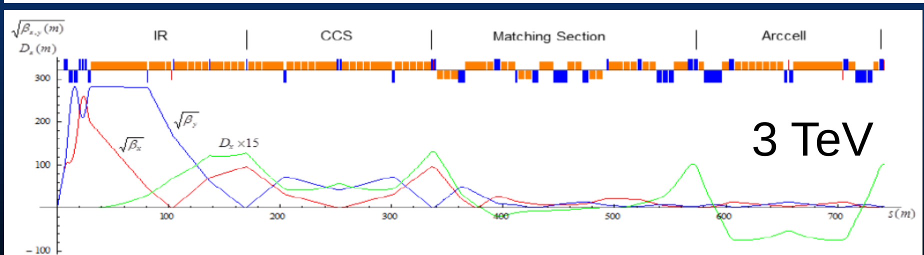






Higgs Factory lattice and optics functions for β*=2.5cm in a half-ring starting from IP

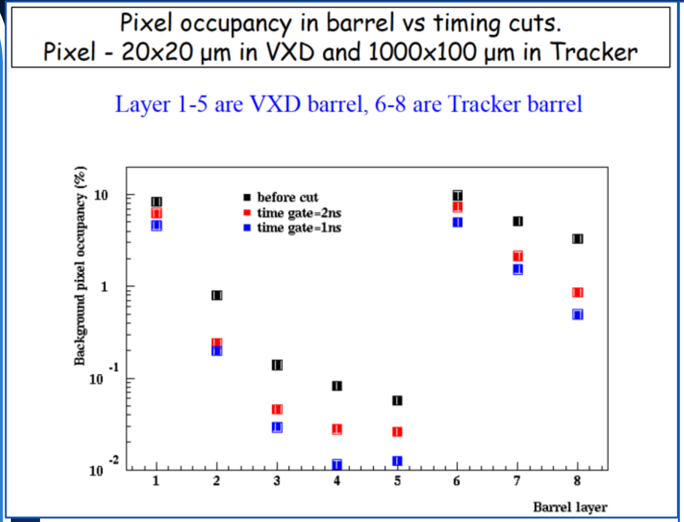


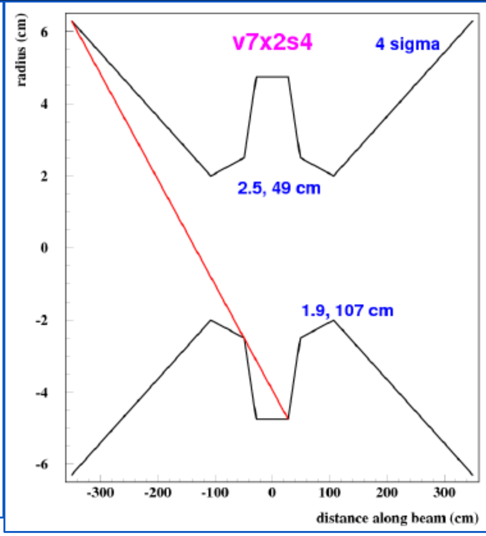


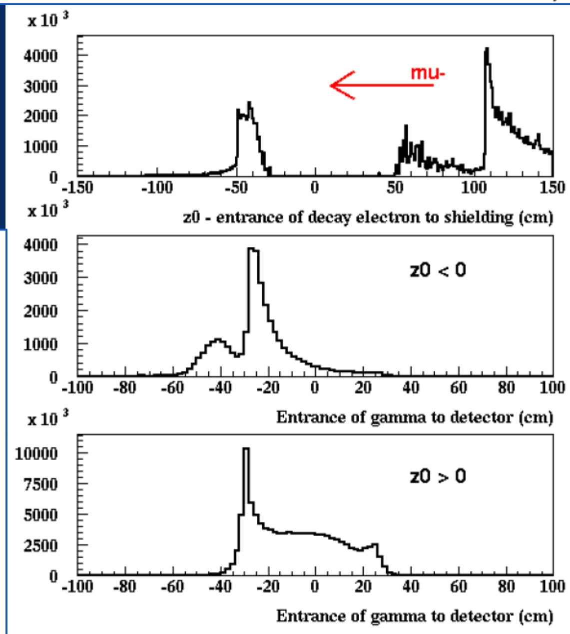
Optics functions from IP to the end of the first arc cell (6 such cells / arc) for β*=5mm

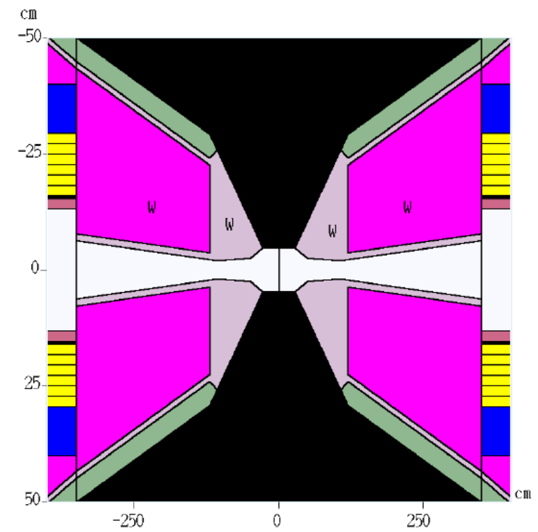
Machine Detector Interface

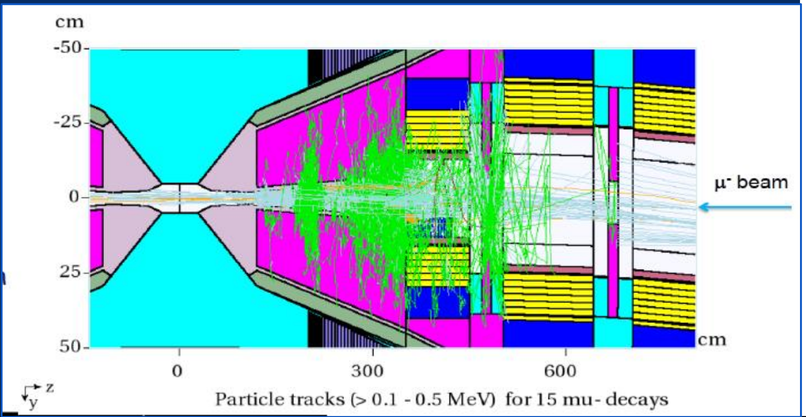
- ✓ Backgrounds appear manageable with suitable detector pixelation and timing rejection
- ✓ Recent study of hit rates comparing MARS, EGS and FLUKA appear consistent to within factors of <2
  - ⇨ Significant improvement in our confidence of detector performance





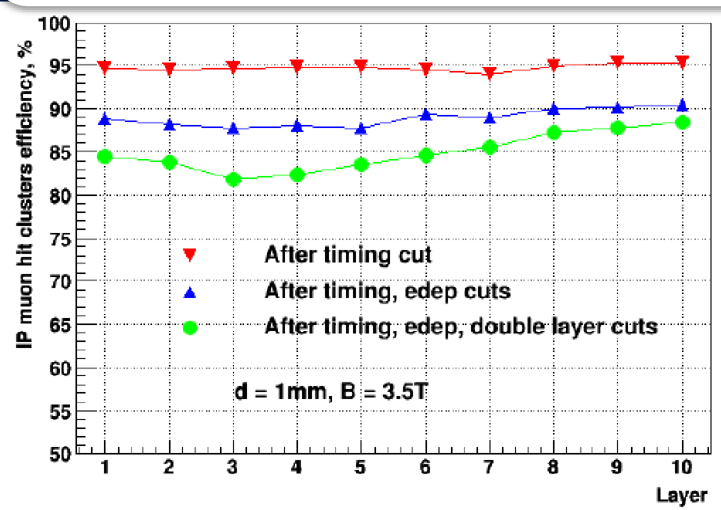




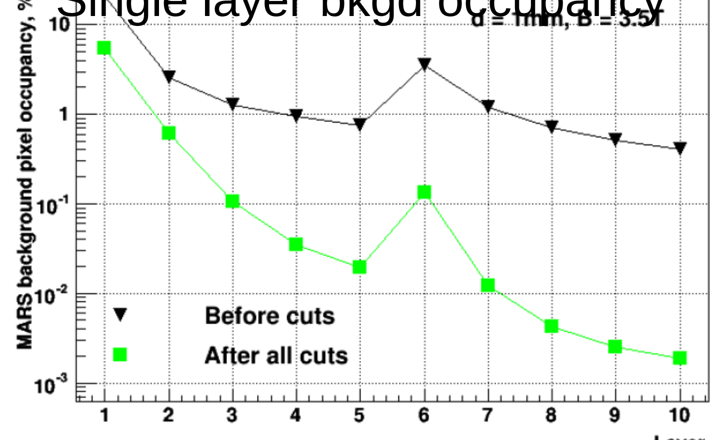


Detector Backgrounds & Mitigation

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



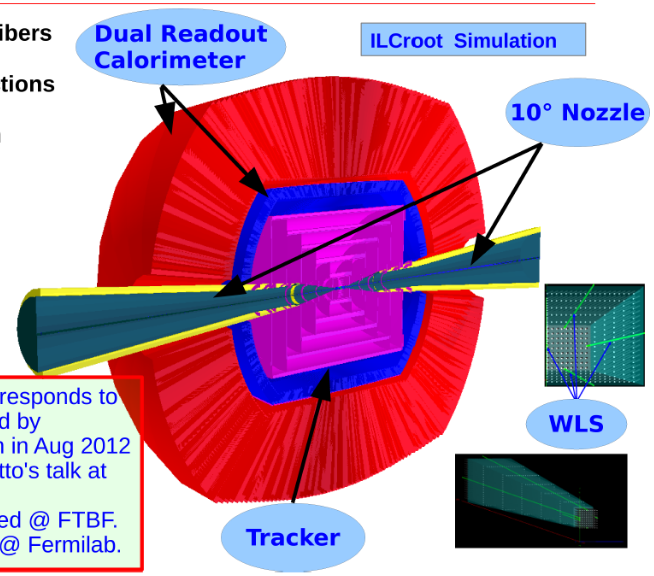
Single layer bkgd occupancy



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

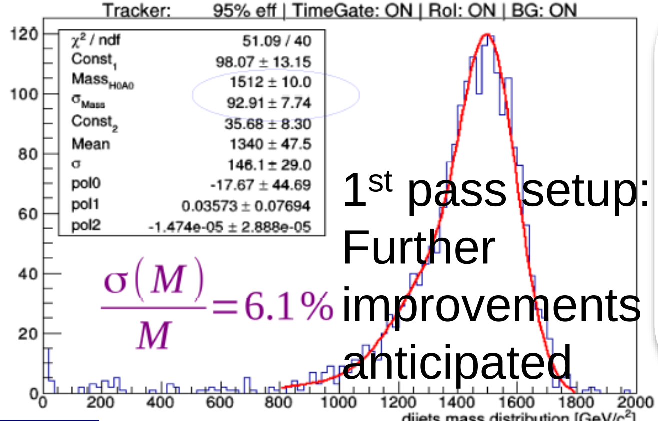


- All simulation parameters corresponds to ADRIANO prototype #9 tested by Fermilab T1015 Collaboration in Aug 2012 @ FTBF (see also T1015 Gatto's talk at Calor2012)
- Several more prototypes tested @ FTBF.
- New test beam ongoing now @ Fermilab.

- Fermilab 7

Time gate & RoI ON – BG ON

Calorimeter: 90% eff | TimeGate: ON | BG: ON
Tracker: 95% eff | TimeGate: ON | RoI: ON | BG: ON



$$\frac{\sigma(M)}{M} = 6.1\%$$

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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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