Muon collider: opzioni di macchina

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F. Bedeschi (Pi)

Gruppo 1, Catania, 2-3 dicembre 2015

Outline

- Muons case
- Muon accelerators challenges:
  - **muon production**
    - ✓ Conventional: from protons on target
    - ✓ Unconventional: from e+e- annihilation
  - emittance reduction via **cooling**
  - high-gradient acceleration
- Conclusions

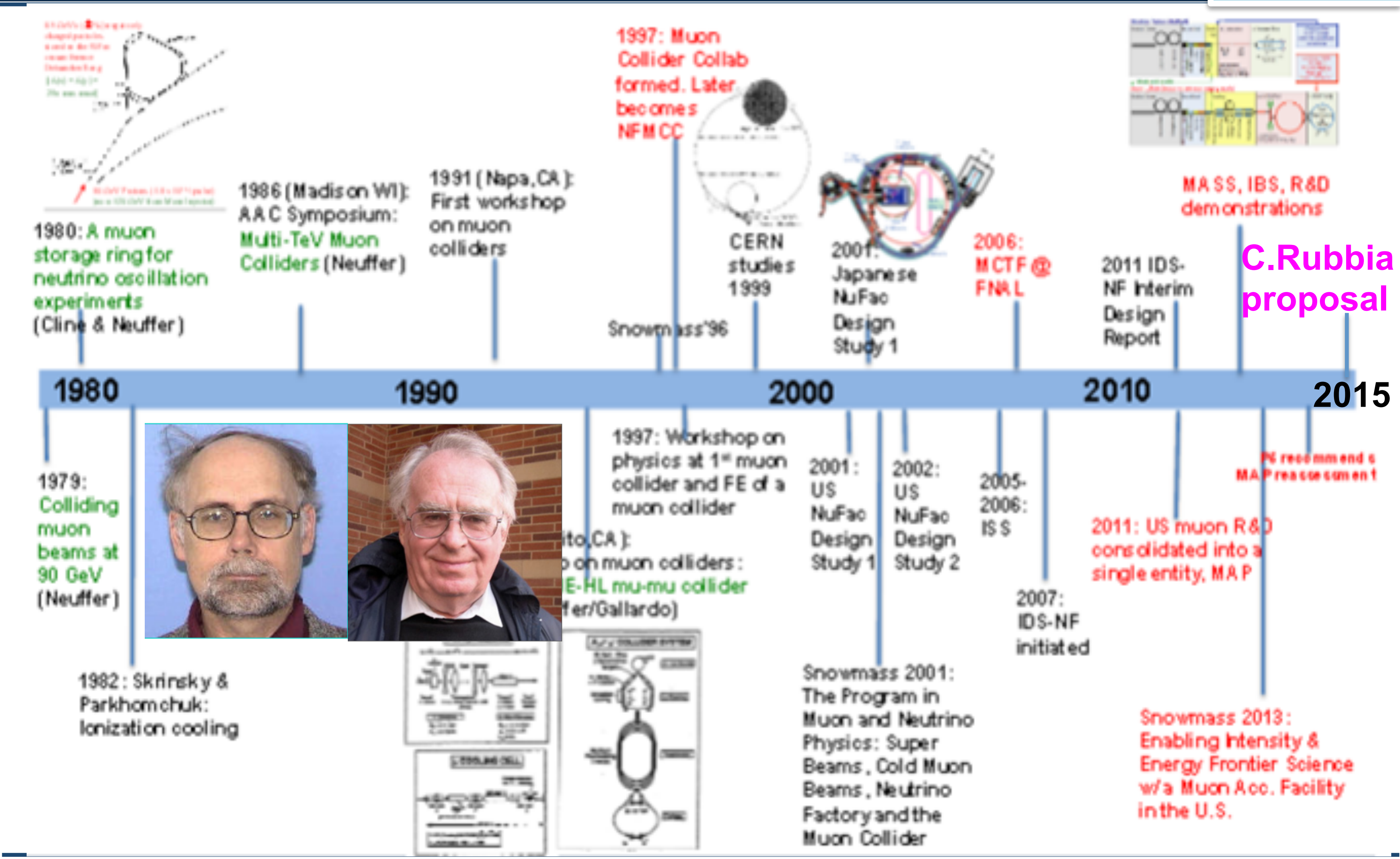
Ancora in fase di R&D o idee, ancora molto lontani rispetto al Linear Collider o Circular collider

I due approcci non sono confrontabili: per il primo c'e' uno studio, per il secondo l'idea che, appunto, proponiamo di studiare.

Ref. : "Discussion of the scientific potential of muon beams", CERN, Nov. 18th 2015
https://indico.cern.ch/event/450863/

Muons: a long history of development

Rob Ryne



Muon based colliders great potential

As with an e^+e^- collider, a $\mu^+\mu^-$ collider offers a precision probe of fundamental interactions without energy limitations

- **By synchrotron radiation (limit of e^+e^- circular colliders)**
- **By beam-strahlung (limit of e^+e^- linear colliders)**

Muon Collider is the ideal technology to extend lepton high energy frontier in the multi-TeV range with reasonable dimension, cost and power consumption

Muon based Higgs factory takes advantage of a strong coupling to Higgs mechanism by s resonance

IF THE MUON BEAM NOVEL TECHNOLOGY CAN BE DEMONSTRATED TO BE FEASIBLE

Muons: Issues & Challenges

- **Limited lifetime: 2.2 μs (at rest)**
  - Race against death: generation, acceleration & collision before decay
  - Muons decay in accelerator and detector
    - Shielding of detector and facility irradiation
    - Collider and Physics feasibility with large background environment?

      Not by beamshtrahlung as with e+/e- but by muon decay (e, ν)

      Reduced background at high energy due to increased muon lifetime
  - Decays in neutrinos:
    - Ideal source of well defined electron & muon neutrinos in equal quantities whereas Superbeams by pion decay only provide muon ν:

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

The neutrino factory concept

- **Generated as tertiary particles in large emittances**
  - powerful MW(s) proton driver and pion decay
  - novel (fast) cooling and acceleration methods

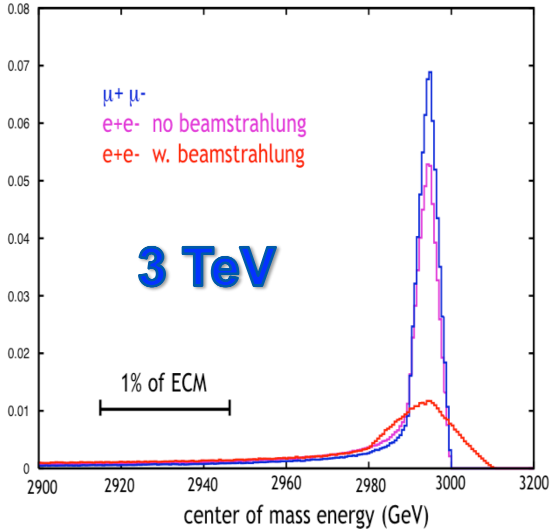
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \nu_\mu$$

Development of novel technologies with key accelerator and detector challenges

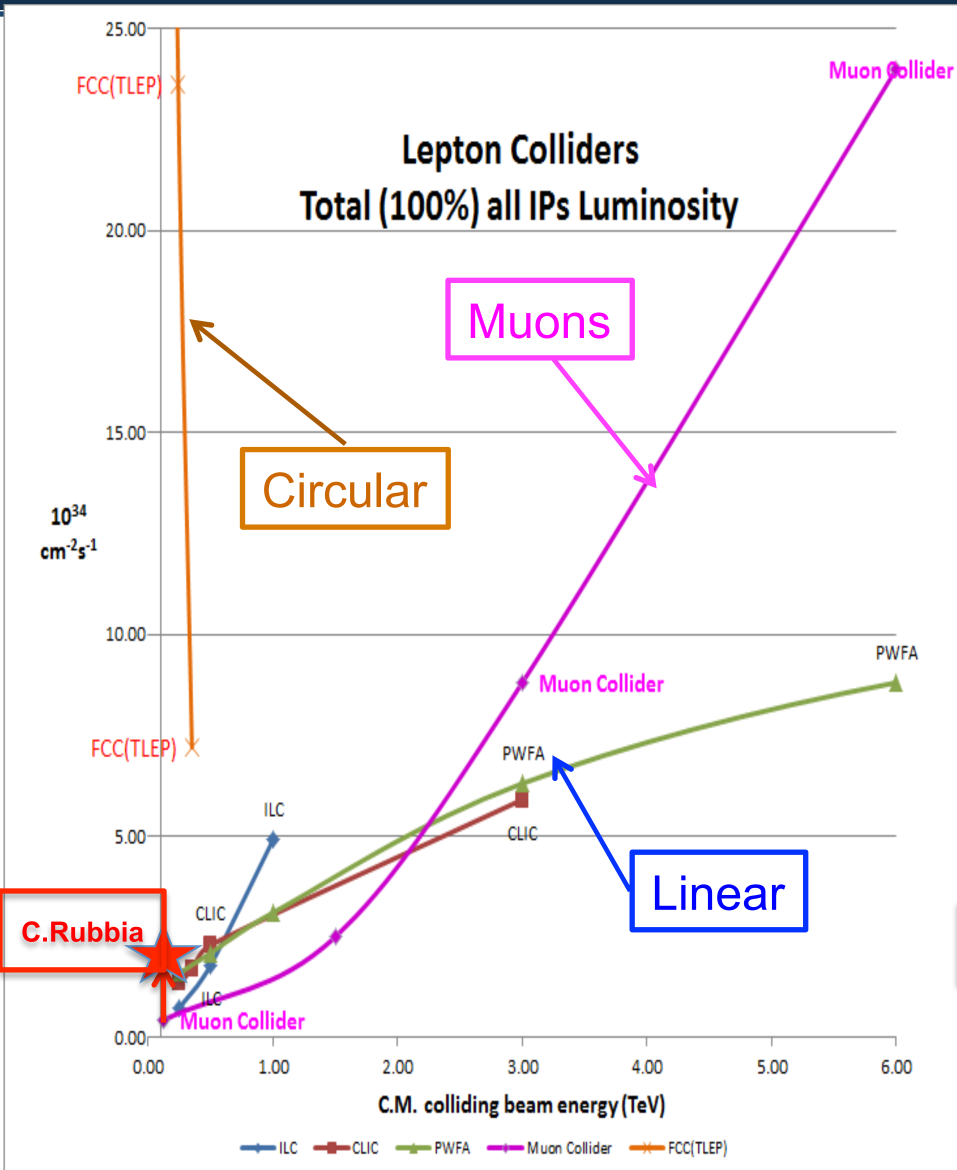
Muon beams specific properties

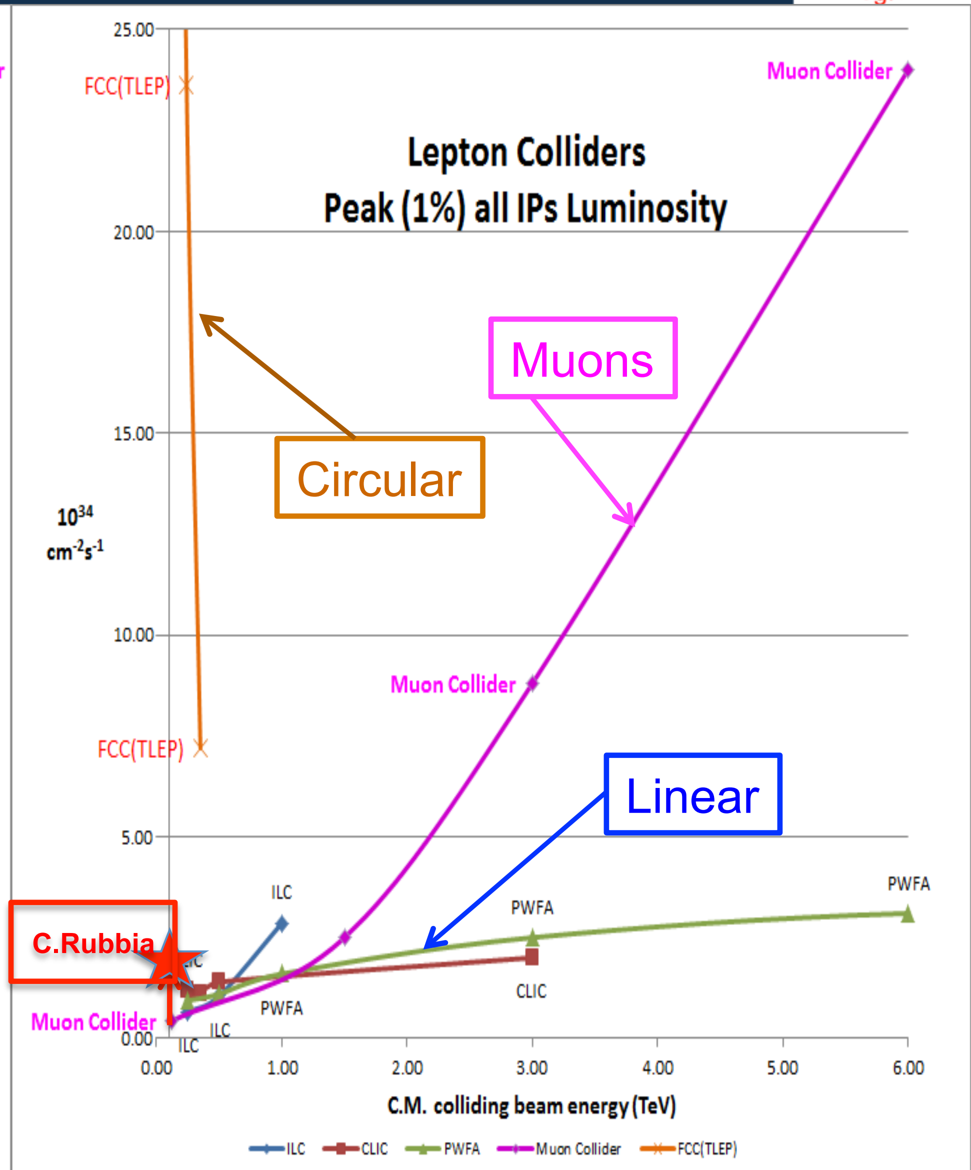
Muons are leptons like electrons & positrons but with a mass (105.7 MeV/c^2) 207 times larger

- **Negligible synchrotron radiation emission (α m^{-2})**
  - **Multi-pass collisions (1000 turns) in collider ring**
    - ☺ **High luminosity with reasonable beam power and wall plug power consumption**
      - **relaxed beam emittances & sizes, alignment & stability**
    - **Multi-detectors supporting broad physics communities**
    - **Large time (15 μs) between bunch crossings**
  - ☺ **No beam-strahlung at collision:**
    - **narrow luminosity spectrum**
  - ☺ **Multi-pass acceleration in rings or RLA:**
    - **Compact acceleration system and collider**
    - **Cost effective construction & operation**
  - ☹ **No cooling by synchrotron radiation in standard damping rings**
    - **Requires development of novel cooling method**

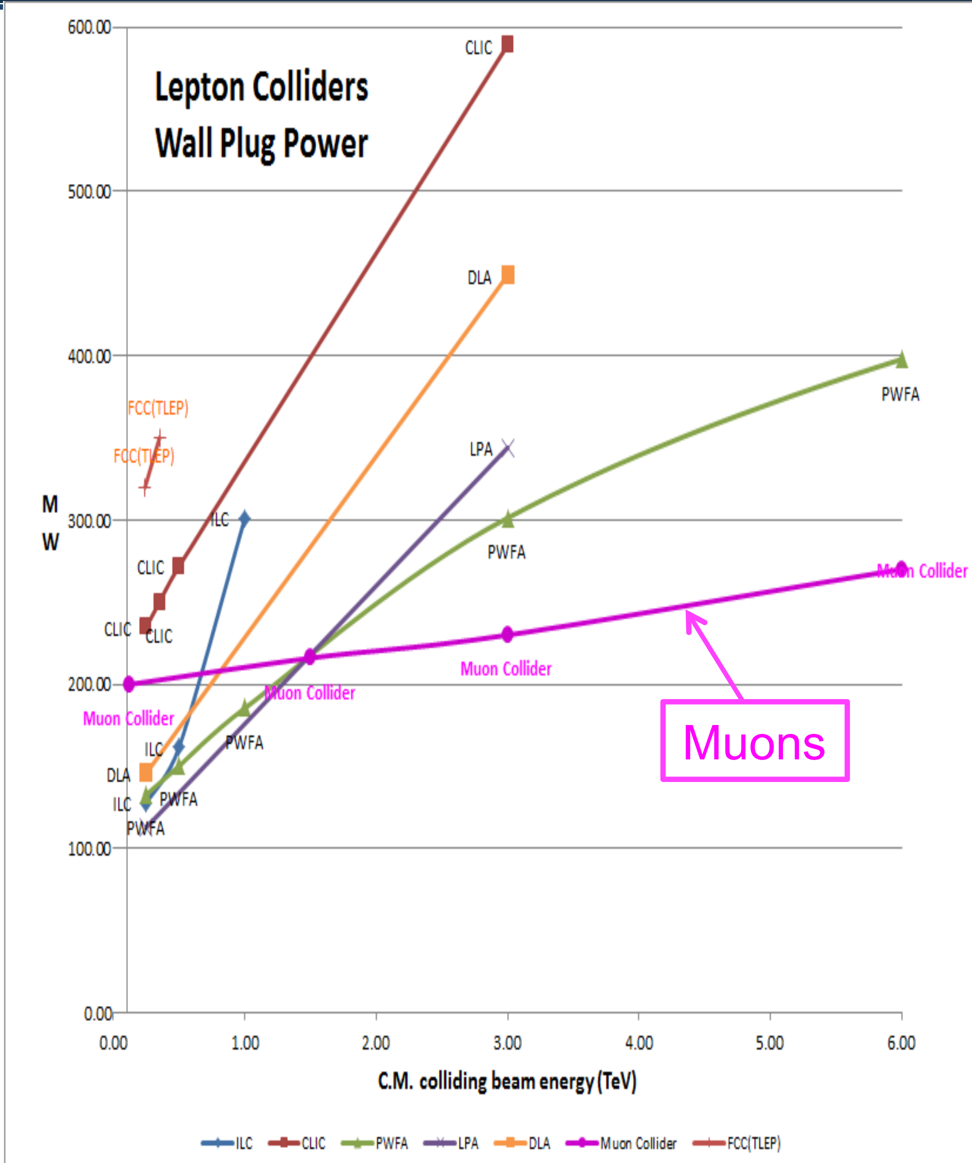


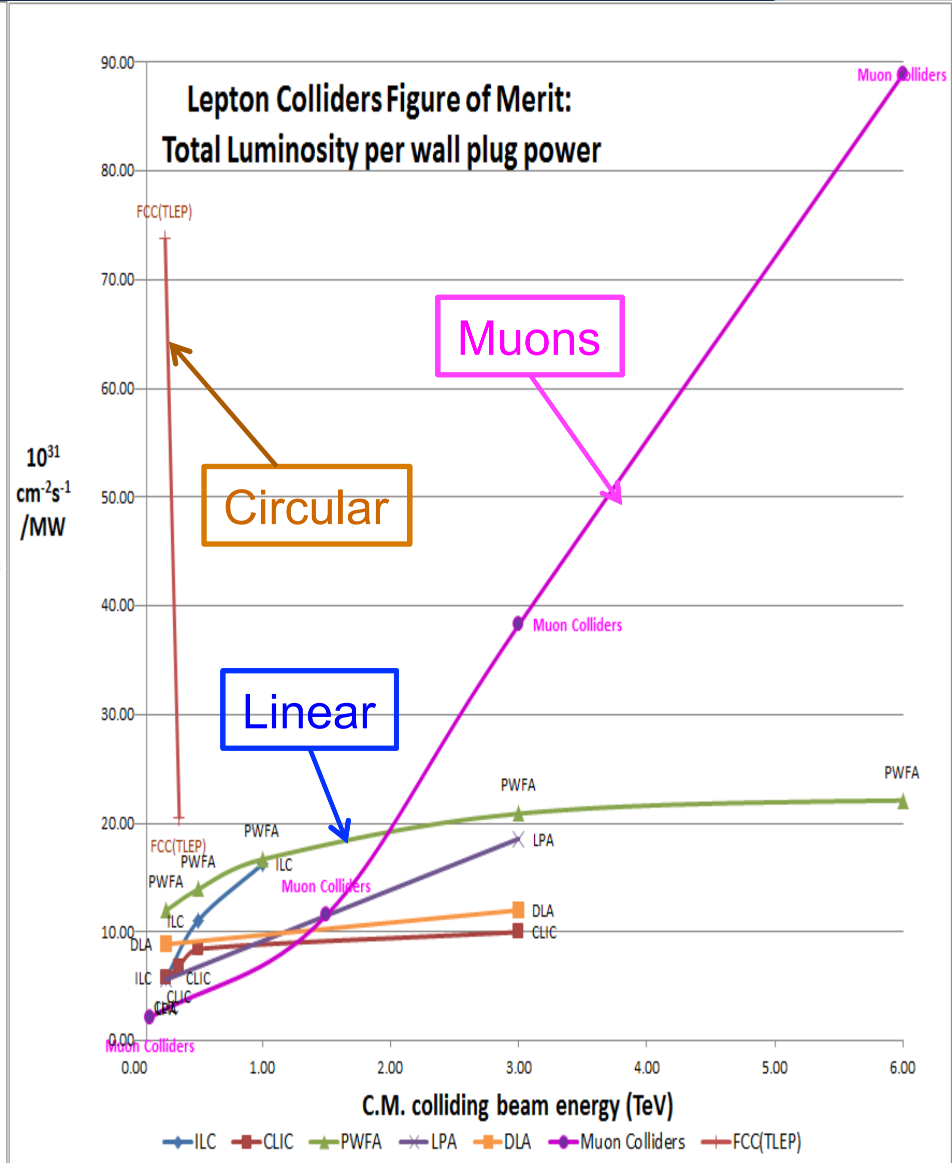
Muon Colliders potential of extending leptons high energy frontier with high performance





Muon Colliders extending leptons high energy frontier with potential of considerable power savings





Muon Source

Goals

- **Neutrino Factories**: $O(10^{21})$ μ/yr within the acceptance of a μ ring
- **Muon Collider**: luminosities $>10^{34}$/cm^{-2}s^{-1} at TeV-scale ($\sim N_\mu^2$)

Options

Conventional: Tertiary production through **proton on target** (and then cool), baseline for Fermilab design study

Rate $> 10^{13}$ μ/sec $N_\mu = 2\times10^{12}$ /bunch

Unconventional:

- **e^+e^- annihilation: positron beam on target** (very low emittance and no cooling needed), baseline for our proposal here

  Rate $\sim 10^{11}$ μ/sec $N_\mu \sim 5\text{x}10^7$ /bunch

- **by Gammas: GeV-scale Compton γs** not discussed here

  Rate $\sim 5\times10^{10}$ μ/sec $N_\mu \sim 10^6$ (Pulsed Linac) [V. Yakimenko (SLAC)]

  Rate $>$ 10^{13} μ/sec $N_\mu \sim$ few$\times10^4$ (High Current ERL)

  see also: W. Barletta and A. M. Sessler NIM A 350 (1994) 36-44

Exploring the potential for a Low Emittance Muon Collider

with muon source from e^+ beam on target

References:

- M. Antonelli, M. Boscolo, R. Di Nardo, P. Raimondi, *"Novel proposal for a low emittance muon beam using positron beam on target"*, **NIM A 807 101-107 (2016)**
- P. Raimondi, *"Exploring the potential for a Low Emittance Muon Collider"*, in **Discussion of the scientific potential of muon beams workshop**, CERN, Nov. 18th 2015
- M. Antonelli, **Presentation Snowmass 2013**, Minneapolis (USA) July 2013, [M. Antonelli and P. Raimondi, Snowmass Report (2013) also INFN-13-22/LNF Note

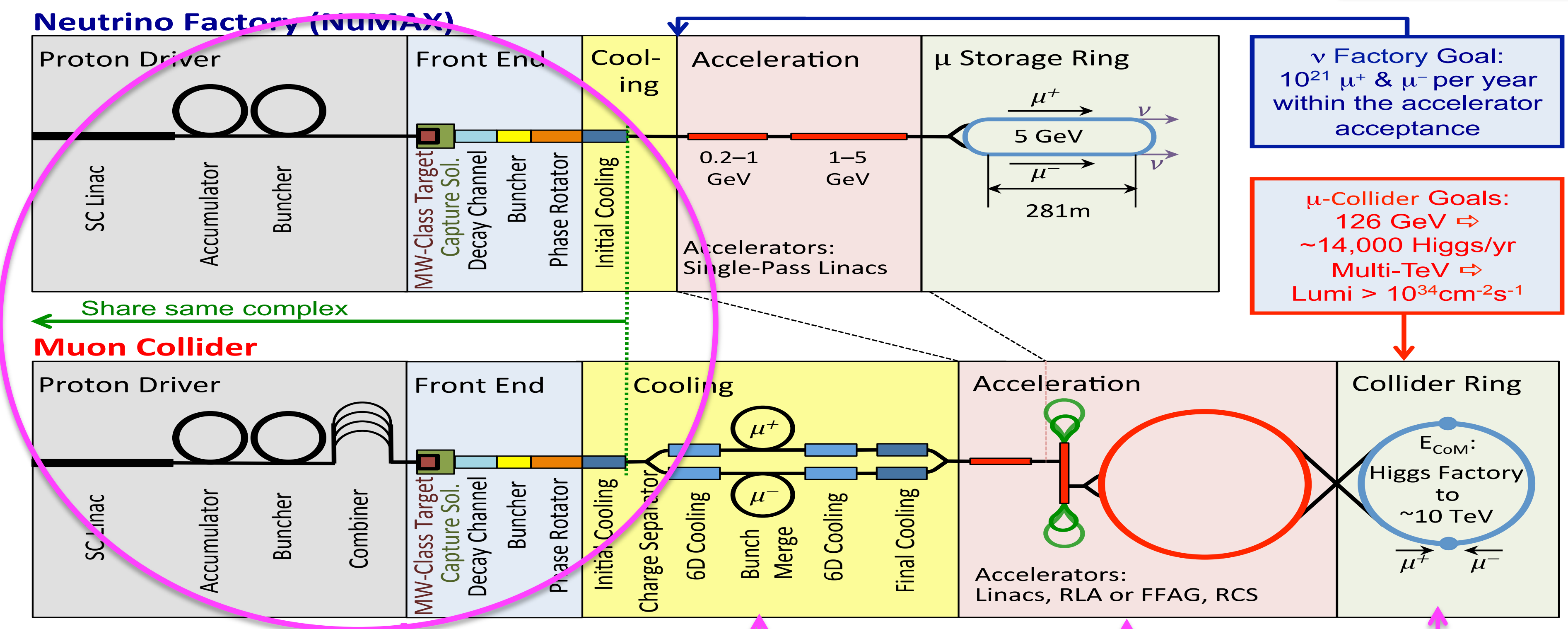
This idea has been investigated with a simulation study by SLAC team:
L. Keller, J. P. Delahaye, T. Markiewicz, U. Wienands:

- *"Luminosity Estimate in a Multi-TeV Muon Collider using $e^+e^- \rightarrow \mu^+\mu^-$ as the Muon Source"*, MAP 2014 Spring workshop, Fermilab (USA) May '14
- Advanced Accelerator Concepts Workshop, San Jose (USA), July '14

Proton-Based Source

Muon Accelerator Program (MAP)
Muon based facilities and synergies

Mark Palmer



Key Challenges

- ~10^{13}-10^{14} μ / sec Tertiary particle $p \rightarrow \pi \rightarrow \mu$:
- Fast cooling (τ=2μs) by 10^6 (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay

Key R&D

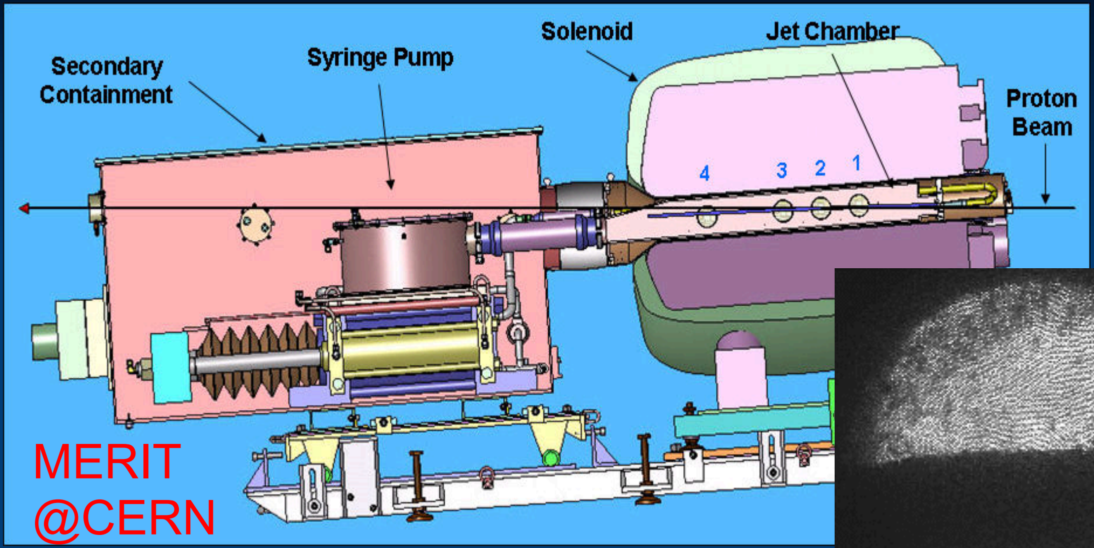
- MW proton driver; MW class target; NCRF in magnetic field
- Ionization cooling; High field solenoids (30T); High Temp Superconductor
- Cost eff. low RF SC; Fast pulsed magnet (1kHz)
- Detector/ machine interface

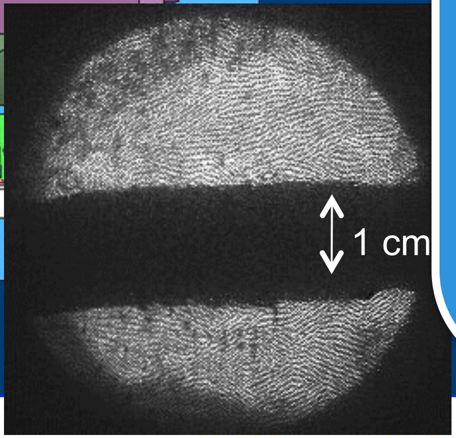
M. Palmer

Key Feasibility Issues

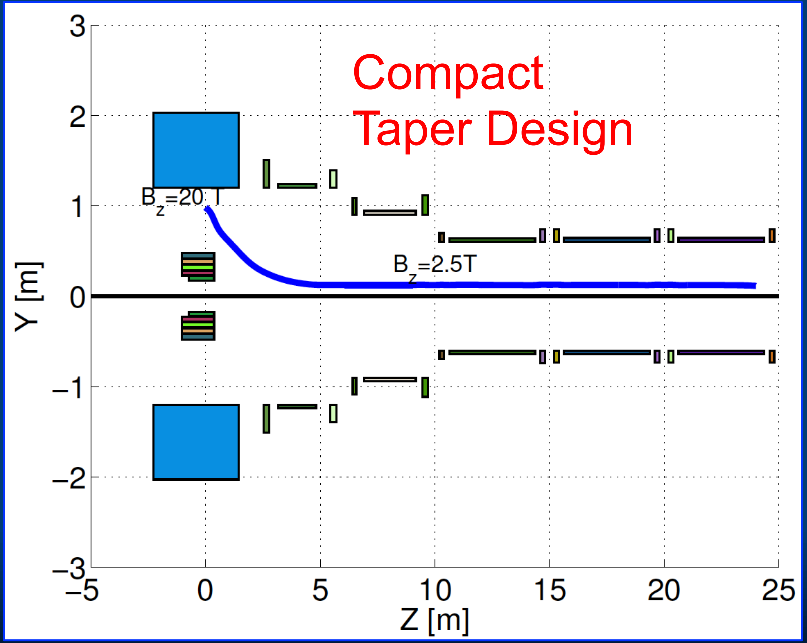
- Proton Driver
- Target
  - High Power Target Station
  - Capture Solenoid
- Front End
  - Energy Deposition
- Cooling
  - RF in Magnetic Fields
  - Magnet Needs (Nb_3Sn vs HTS)
  - Performance
- Acceleration
  - Acceptance (NF)
  - >400 Hz AC Magnets (MC)
- Collider Ring
  - IR Magnet Strengths/Apertures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

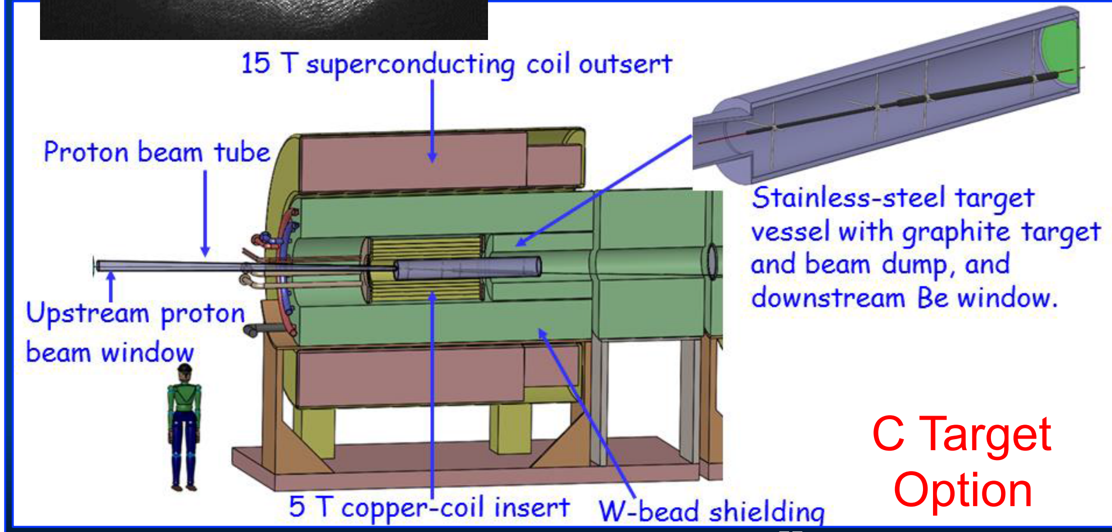
High Power Target





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

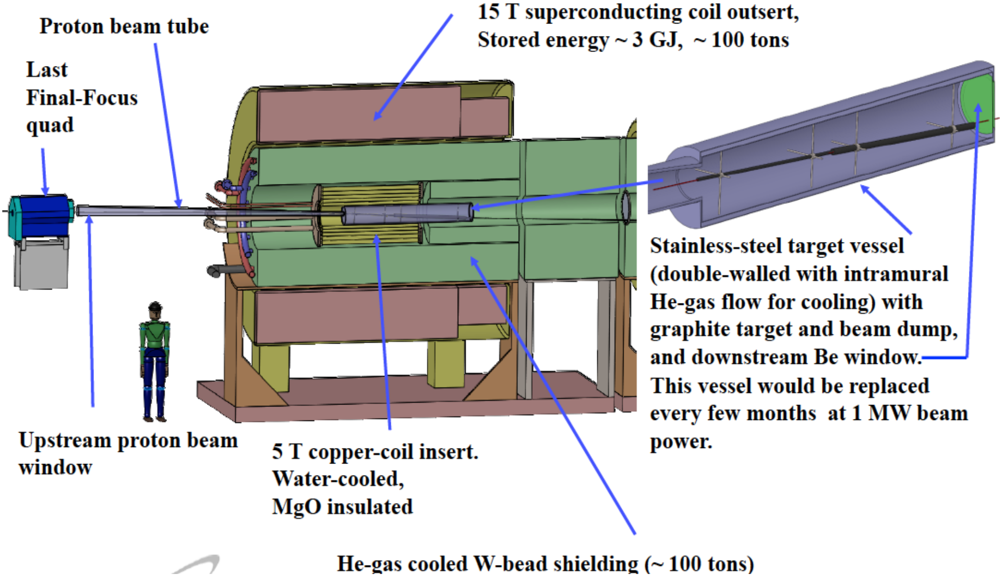




MAP muon generation by Proton driver

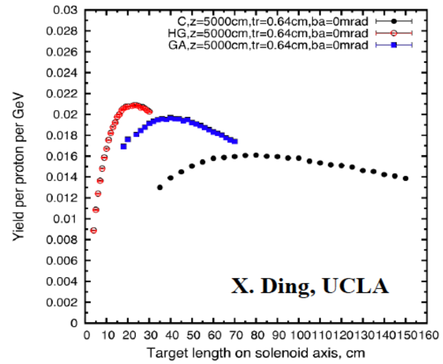
H.Kirk (BNL)

A Graphite Target Core



- MW-Class proton driver at ~5-10 GeV
- Capture solenoid system (μ^+ & μ^-)
  - 15 T outsert, 5 T insert
  - ~3GJ stored energy

Choice of Target Materials II



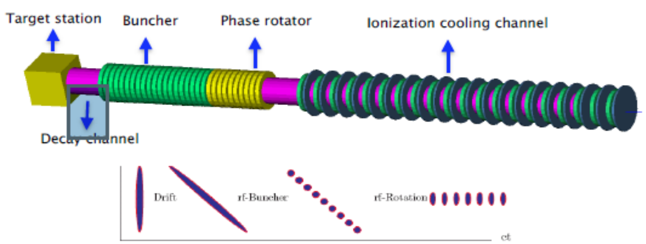
- High Z (e.g. Hg)
- Mid Z (e.g. Ga)
- Low Z (e.g. Carbon)

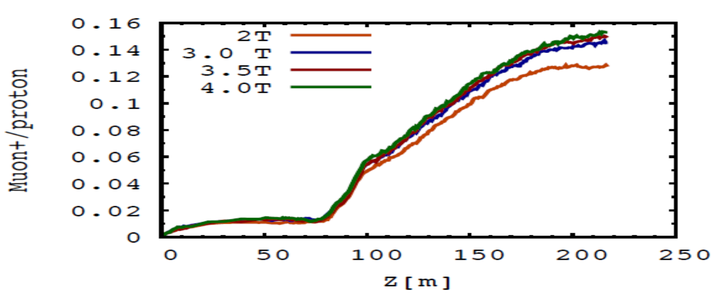
A 25% advantage of using high-Z Hg compared to low-Z Carbon
Low-z Carbon is attractive due to it's simplicity and robustness

Proton Beam: KE = 6.75 GeV
Normalization: For Hg $\Sigma(\mu^+ + \mu^-)$/proton ≈ 1

- Initial operation with 1MW carbon target
- Upgrade to multi-MW with Liquid Metal Jet Technology (demonstrated in MERIT Experim.)

H.K.Sayed (BNL)





Muon per proton production at Front End exit

Ionization Cooling

- No damping from SR ->Ionization 'dE/dx' cooling:
  - Helical 6D Cooling
  - PIC
  - …

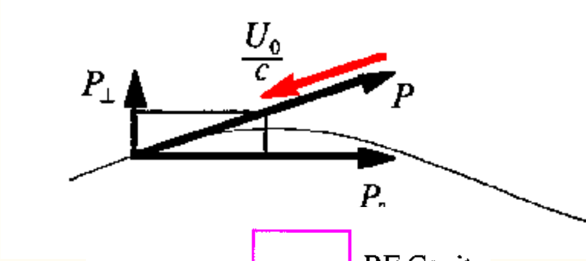
Ionization Cooling
Experimental R&D Program

- **MICE** –International Muon Ionization Cooling Experiment
  - μ-beam at RAL ISIS
  - Systems test of complete cooling system
- **MuCOOL** Program
  - Rf, absorber, magnet R&D-supports MICE
  - MuCOOL test area (Fermilab)
  - Muon Collider Task Force
- **MUONS, Inc.** (R. Johnson, et al.)
  - High-pressure rf cavities
  - Helical cooler, Parametric resonance cooler

D. Neuffer

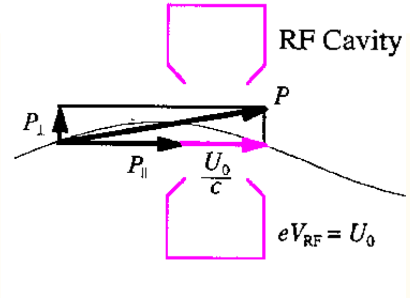
Ionization Cooling-general principle

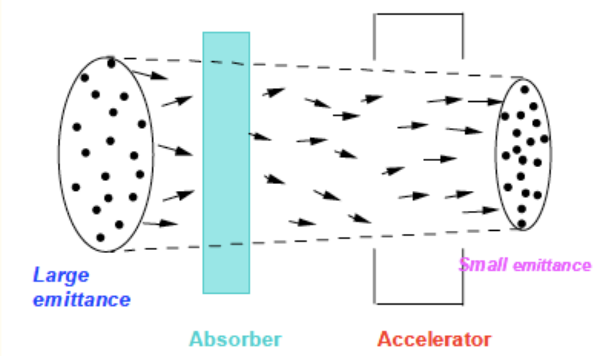
This method, called “**dE/dx cooling**" closely resembles to the synchrotron compression of relativistic electrons - with the multiple energy losses in a thin, low Z absorber substituting the synchrotron radiated light.



Transverse Cooling:

- Particle loses momentum in material
- Particle gains only $p_{||}$ in RF





On the other hand,
Multiple scattering in material increases rms emittance

Combining Cooling and Heating:

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_N + \frac{\beta\gamma\ \beta_\perp}{2}\frac{d\langle\theta_{rms}{}^2\rangle}{ds}$$

- Low-Z absorbers (H_2, Li, Be, …) to reduce multiple scattering
- High Gradient RF
  - To cool before μ-decay (2.2γ μs)
  - To keep beam bunched
- Strong-Focusing at absorbers → small beam size and large divergence then damped by absorber + RF
  - To keep multiple scattering
  - less than beam divergence …

⇒ Quad focusing ?

⇒ Li lens focusing ?

⇒ Solenoid focusing?

$$\frac{d\langle\theta_{rms}^2\rangle}{ds} = \frac{z^2 E_s^2}{\beta^2 c^2 p_\mu^2 L_R}$$

D. Neuffer

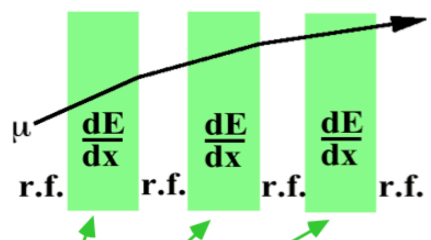
M. Palmer

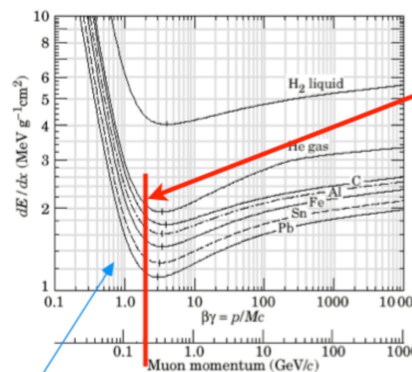
Cooling Methods

- The particular 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 $p_{||}$, 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)

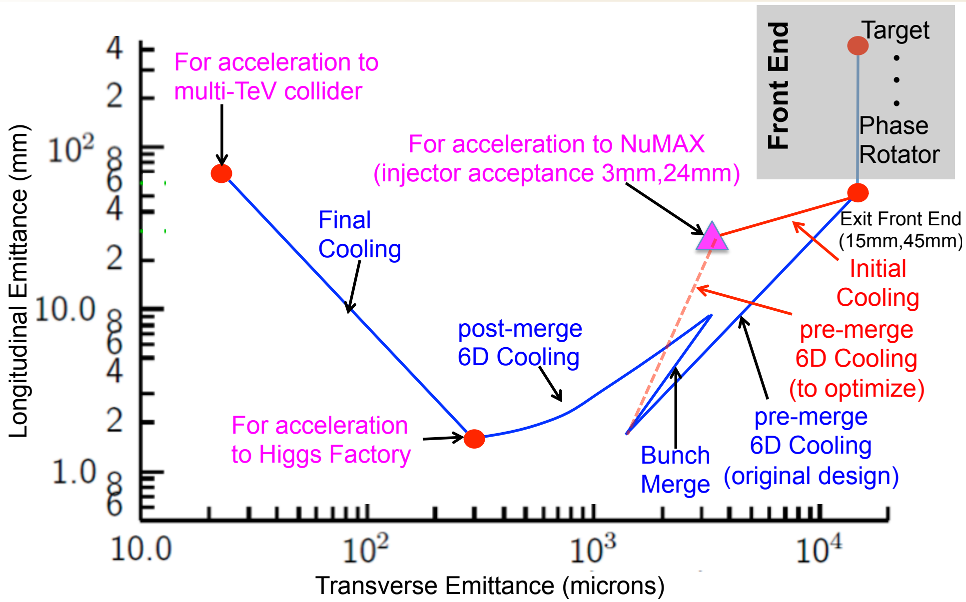
- ionization minimum is ≈ optimal working point:
  - longitudinal +ive feedback at lower p
  - straggling & expense of reacceleration at higher p

- 2 competing effects ⇒ ∃ equilibrium emittance

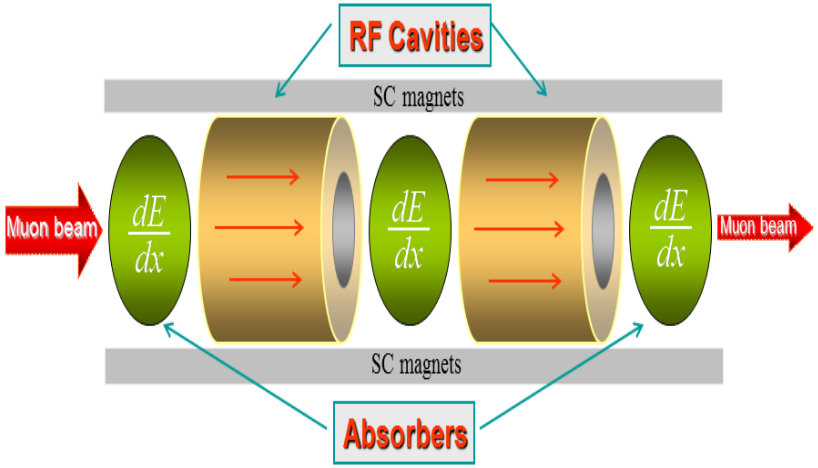
Kaplan

MAP Cooling scheme overview

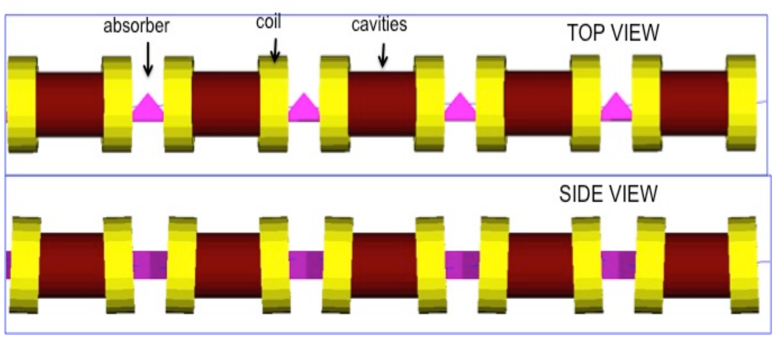
P.Snopok (IIT)



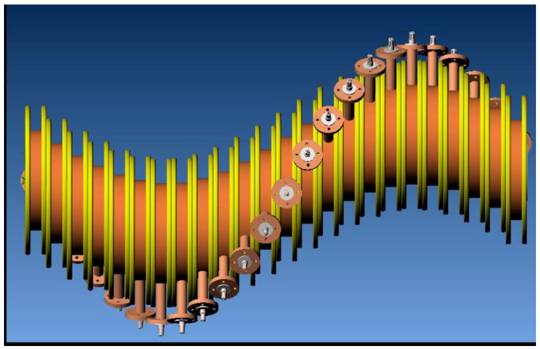
Ionization cooling



Vacuum Cooling Channel (VCC)



Helical Cooling Channel (HCC)



Two methods

Major challenges

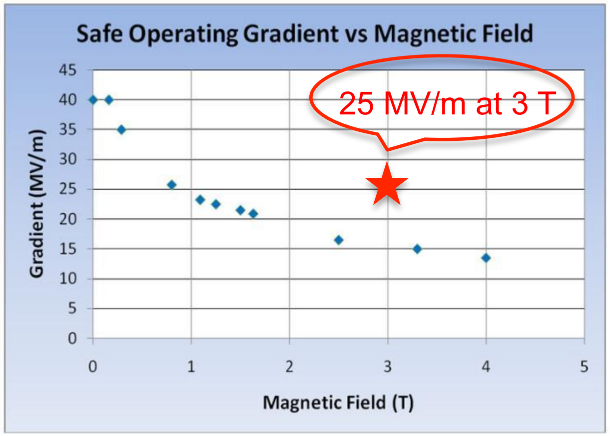
Accelerating field limitation by magnetic field (10 T)

High pressure (160atm) Gas (GH2) filled RF cavities

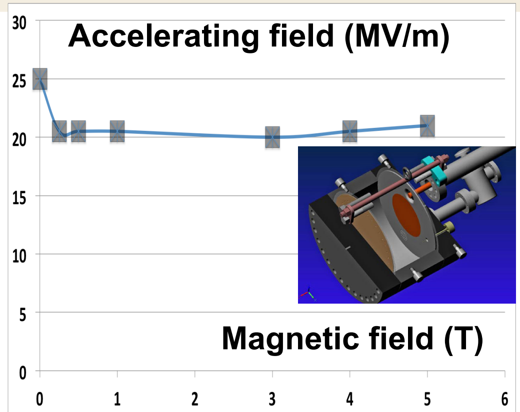
RF cavities in strong magnetic field

D.Li (LBNL)

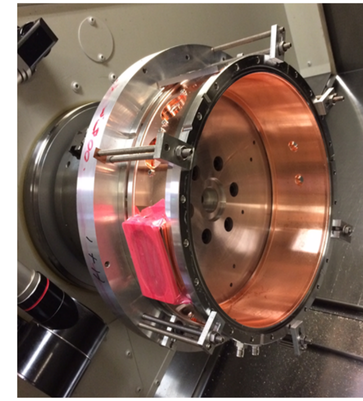
RF cavity in vacuum:



Breakdown by field emission

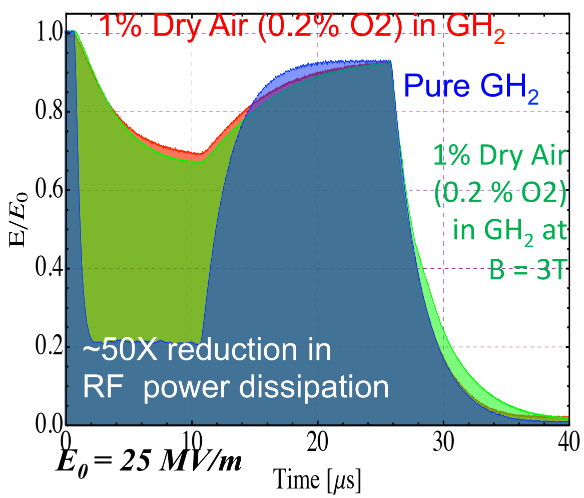


New cavity design very encouraging !



New cavity by LBNL/SLAC for tests in FNAL/MTA

RF cavity filled with gas



No accelerating field degradation up to 3 T
Operation with beam under heavy beam loading

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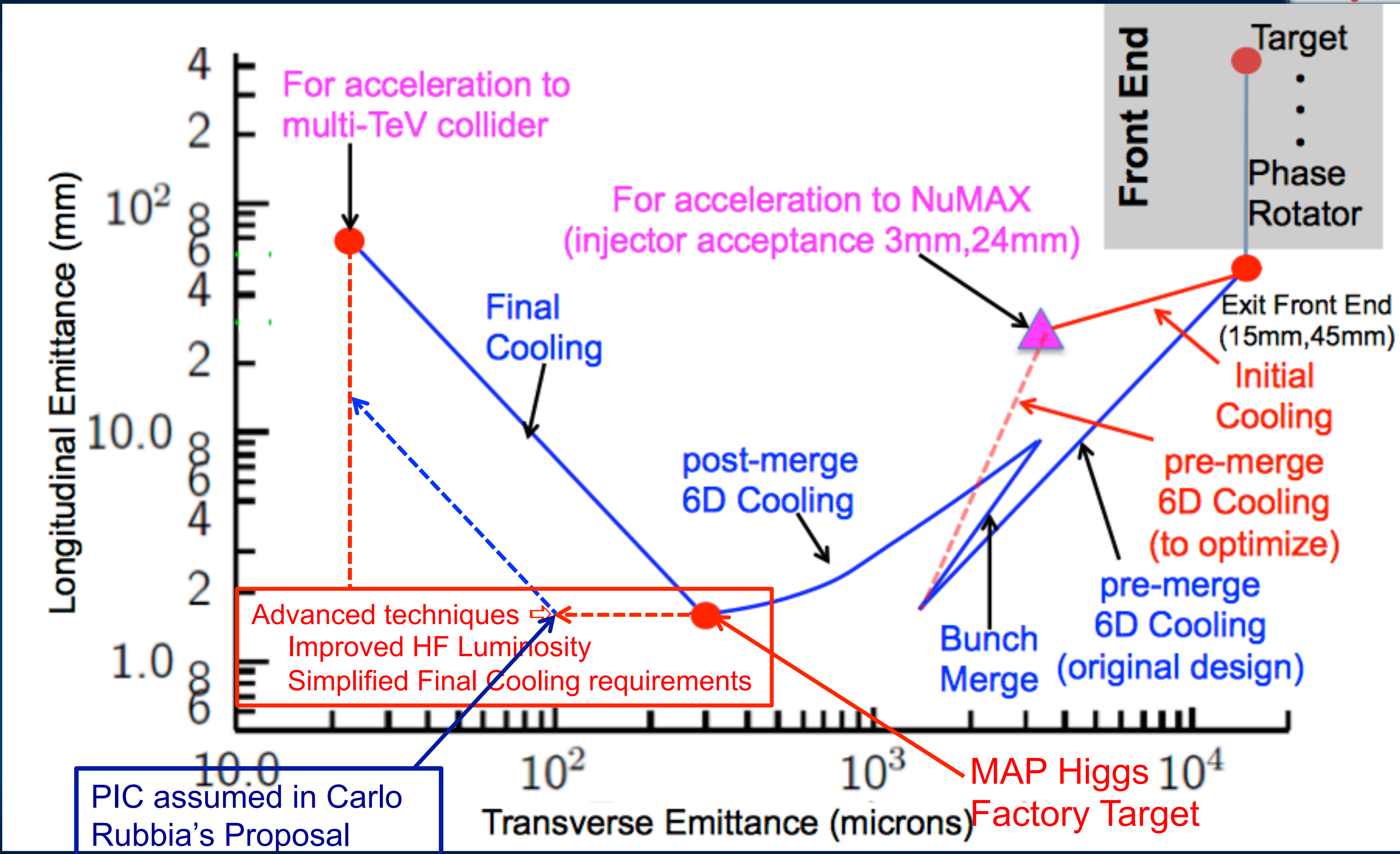
Muon Ionization Cooling

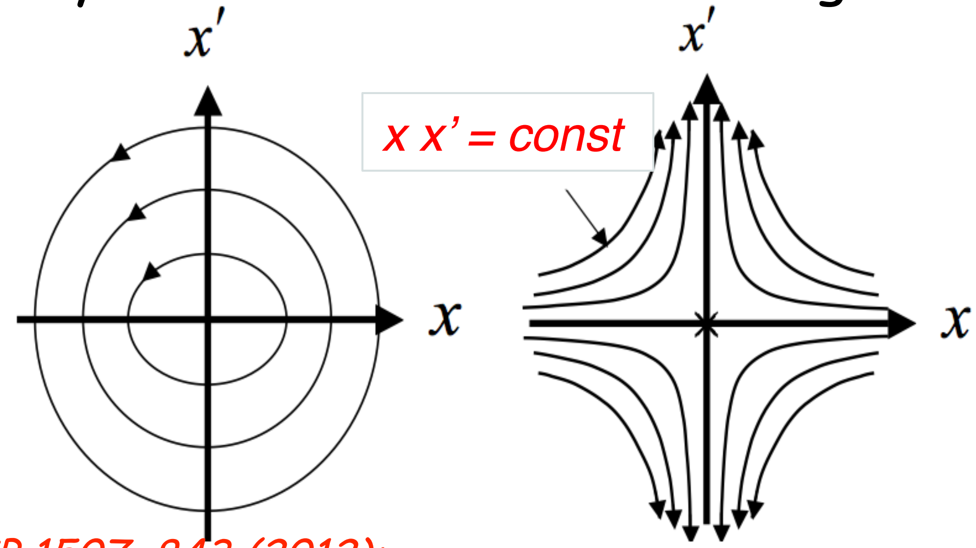


3.-PIC, the Parametric Resonance Cooling of muons

C. Rubbia

- Combining ionization cooling with parametric resonances is expected to lead to muon with much smaller transv. sizes.
- A linear magnetic transport channel has been designed by Ya.S. Derbenev et al where a half integer resonance is induced such that the normal elliptical motion of particles in x-x' phase space becomes hyperbolic, with particles moving to smaller x and larger x' at the channel focal points.
- Thin absorbers placed at the focal points of the channel then cool the angular divergence by the usual ionization cooling.

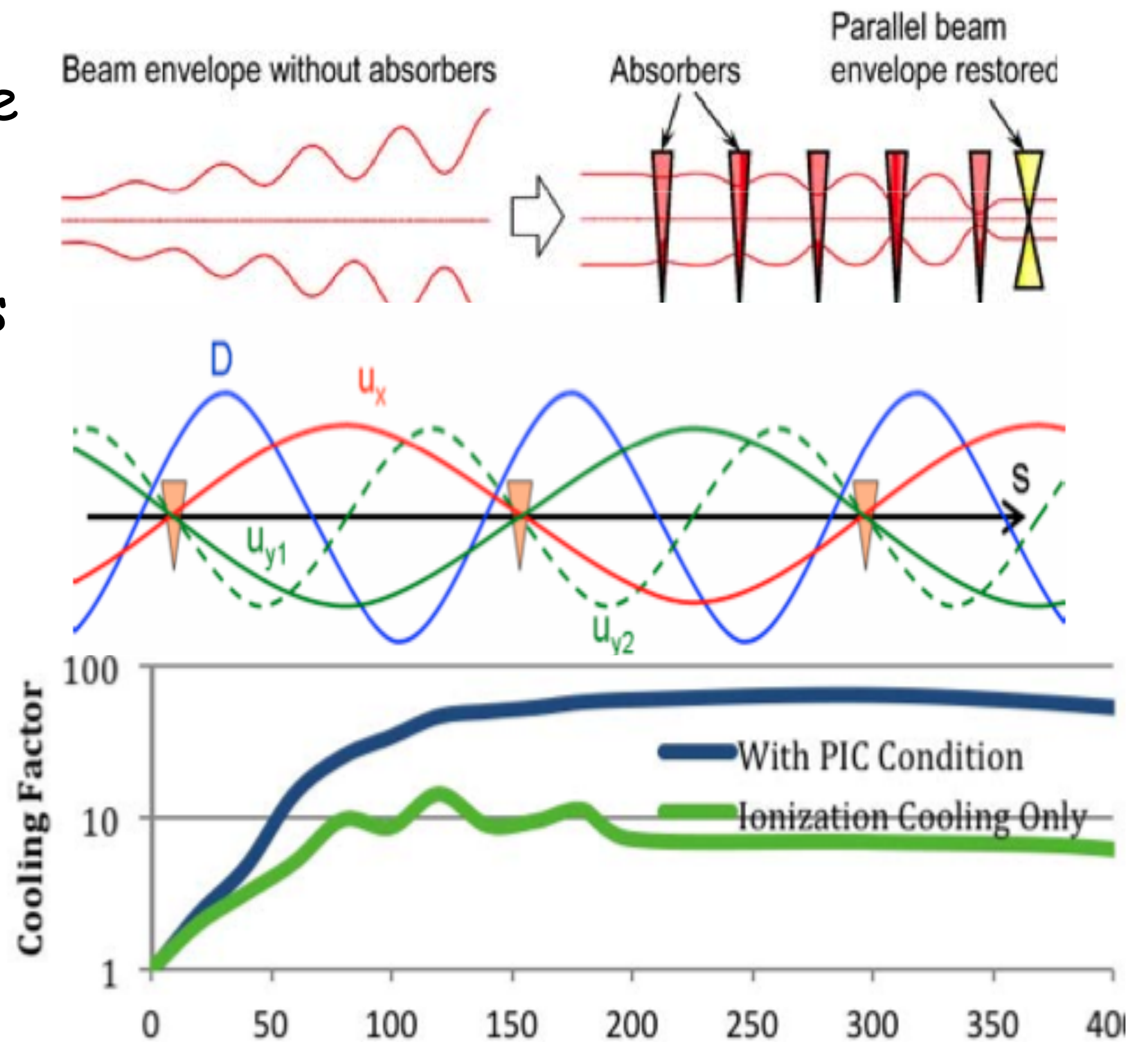
LEFT ordinary oscillations RIGHT hyperbolic motion induced by perturbations near an (one half integer) resonance of the betatron frequency.



V. S. Morozov et al, AIP 1507, 843 (2012);

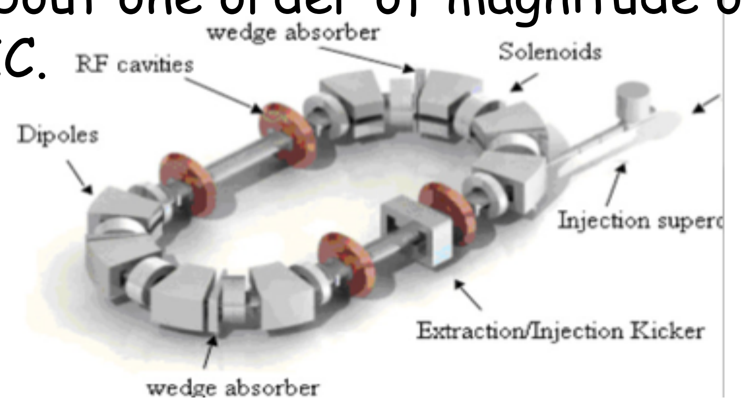
Details of PIC

- Without damping, the beam dynamics is not stable because the beam envelope grows with every period. Energy absorbers at the focal points stabilizes the beam through the ionization cooling.
- The longitudinal emittance is maintained constant tapering the absorbers and placing them at points of appropriate dispersion, vertical β and two horizontal β.
- Comparison of cooling factors (ratio of initial to final 6D emittance) with and without the PIC condition vs number of cells: more than 10x gain



Parametric Resonance Cooling

- The first muon cooling ring should present no unexpected behaviour and good agreement between calculations and experiment is expected both transversely and longitudinally
- The novel Parametric Resonance Cooling (PIC) involves instead the balance between a strong resonance growth and ionization cooling and it may involve significant and unexpected conditions which are hard to predict.
- Therefore the experimental demonstration of the cooling must be concentrated on such a resonant behaviour.
- On the other hand the success of the novel Parametric Resonance Cooling is a necessary premise for a viable luminosity of the initial proton parameters of the future CERN accelerators since the expected Higgs luminosity is proportional to the inverse of the transverse emittance, hence about one order of magnitude of increment is expected from PIC.



Carlo Rubbia – FNAL May 2015

M. Palmer

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

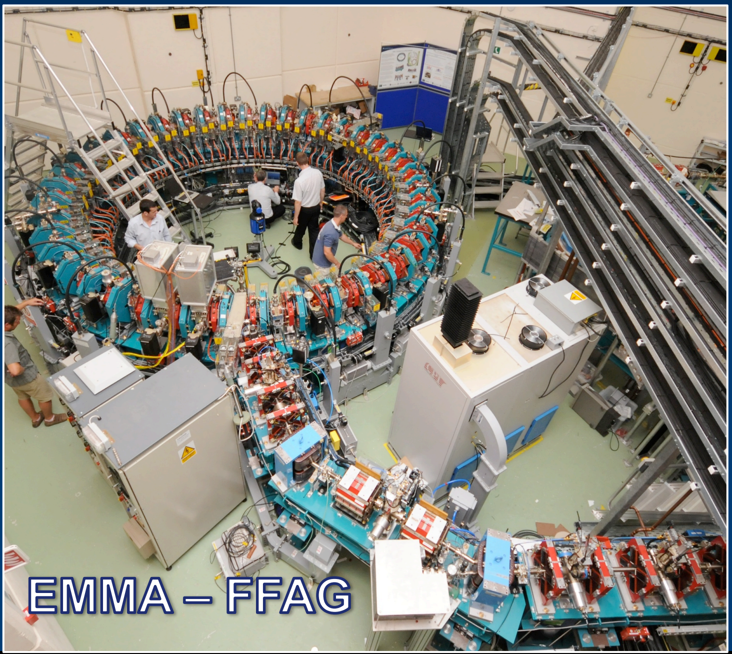
    $B_{peak} \sim 2T$ $f > 400Hz$

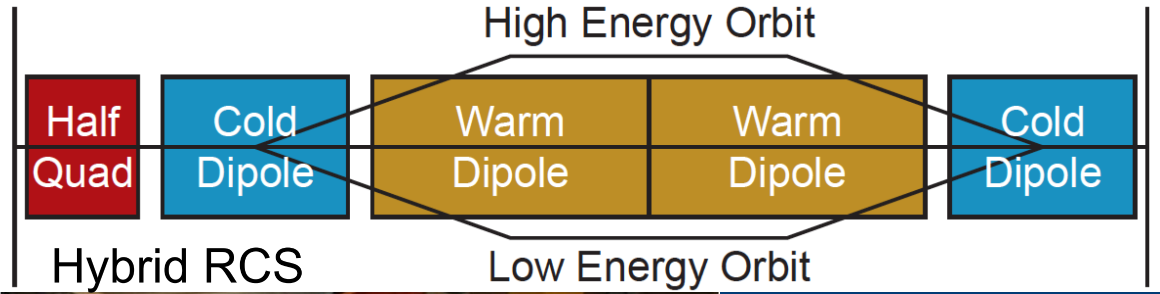
M. Palmer

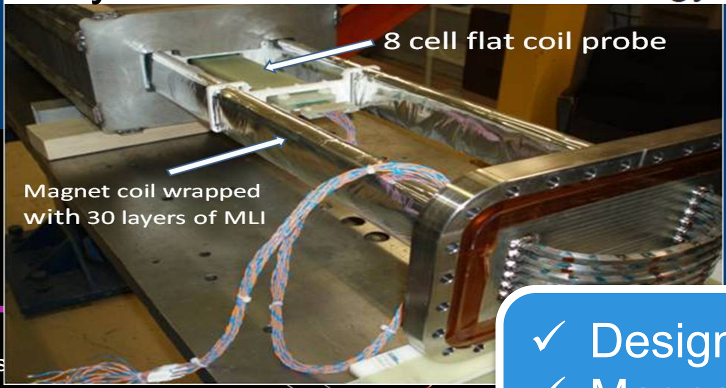
Acceleration

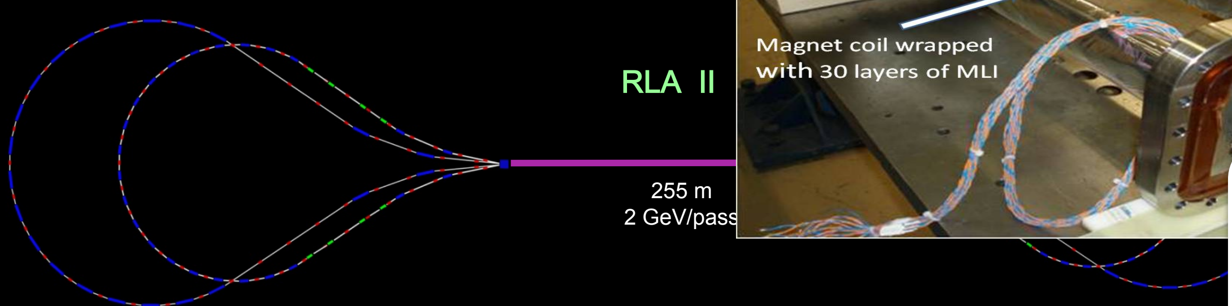
Technologies include:

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







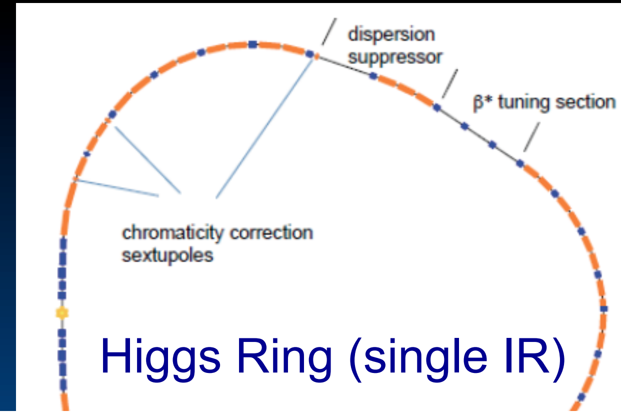


RCS requires
2 T p-p magnets
at f > 400 Hz
(U Miss & FNAL)

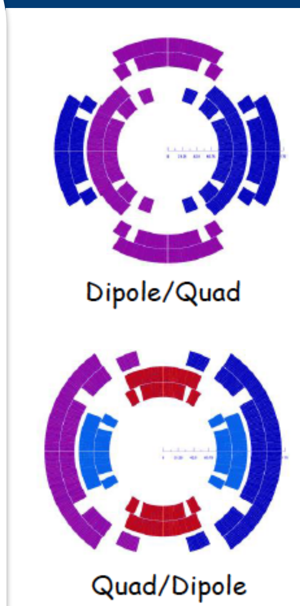
- ✓ Design concepts in hand
- ✓ Magnet R&D indicates parameters achievable

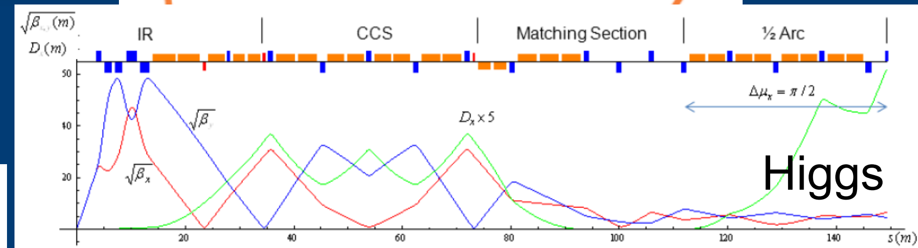
Collider Rings

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

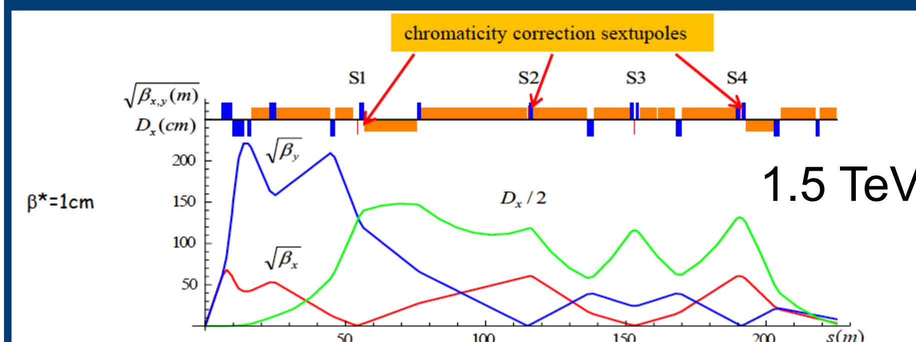


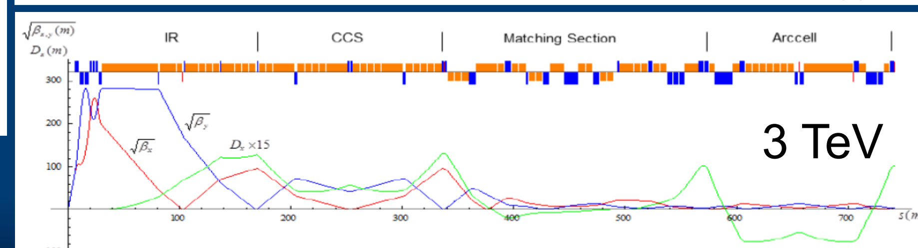
- ✓ Higgs, 1.5 TeV CoM and 3 TeV CoM Designs
  - With magnet concepts
  - Achieve target parameters
- ✓ Preliminary 6 TeV CoM design
  - Key issue is IR design and impact on luminosity
  - Utilizes lower power on target





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

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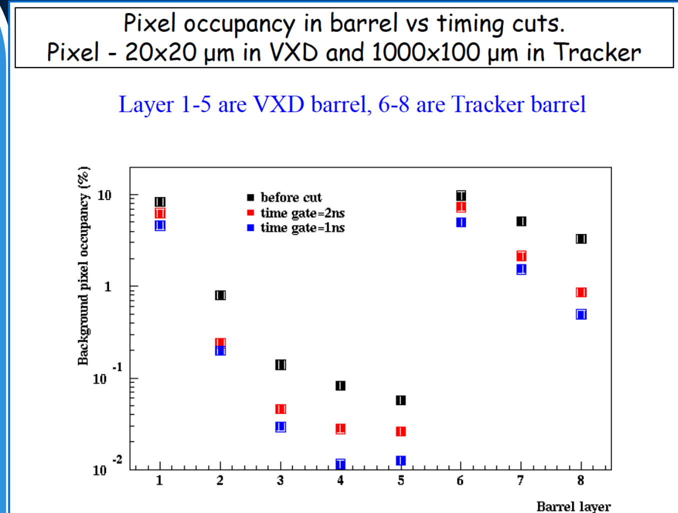
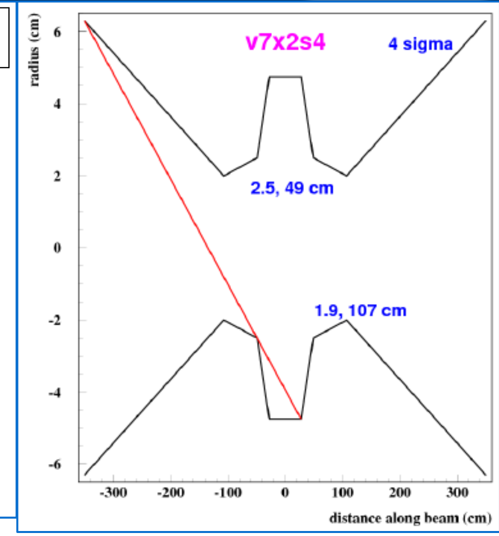
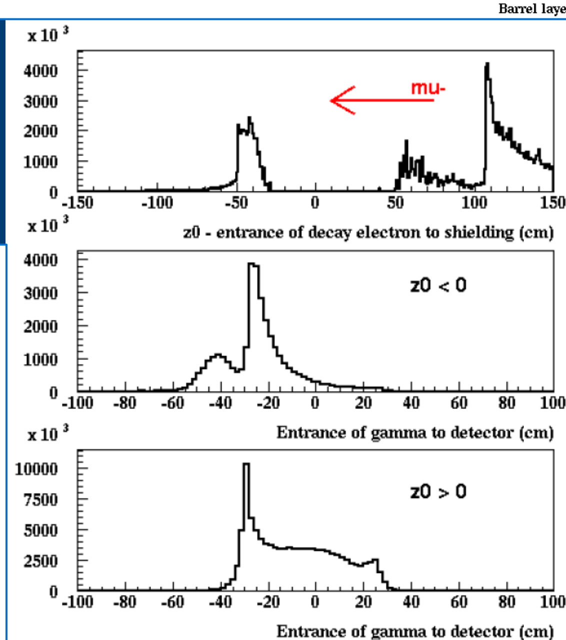
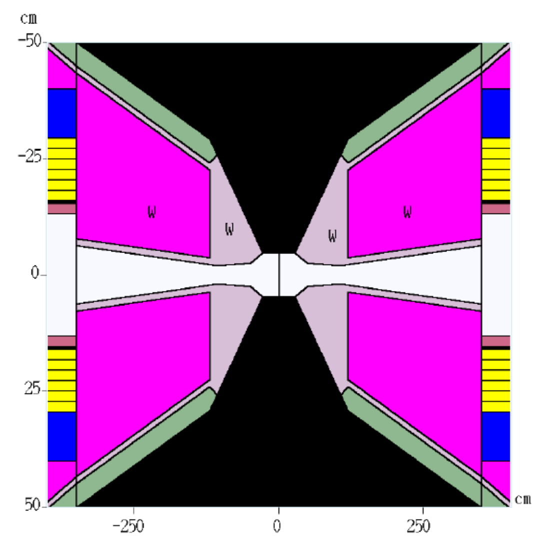
Machine Detector Interface

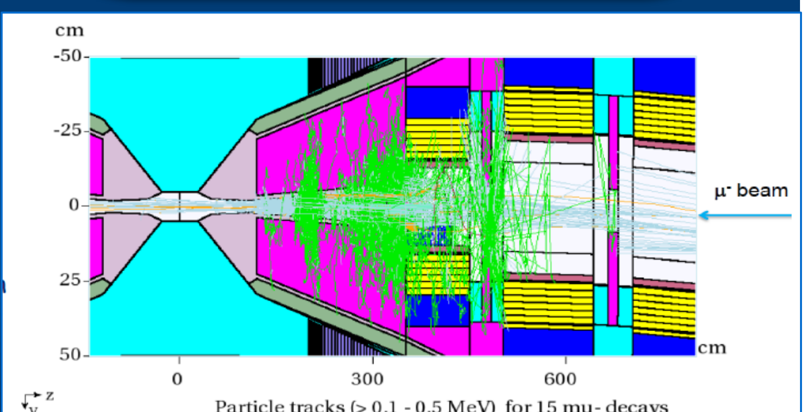
- ✓ Backgrounds appear manageable with suitable detector pixelation and timing rejection
- ✓ Recent study of hit rates comparing MARS, EGS and FLUKA appear consistent to within factors of <2
  - ⇨ Significant improvement in our confidence of detector performance











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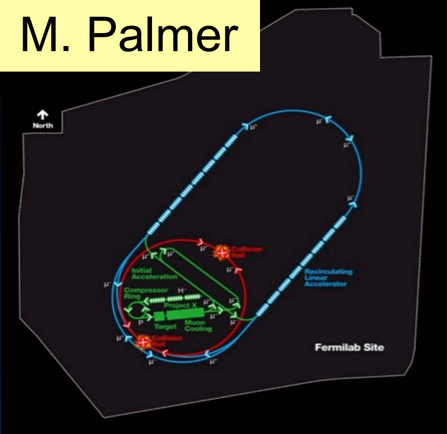


Muon Collider Parameters

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
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 × 10^{32} [Rubbia proposal: 5×10^{32}]

e+ on target muon source

Idea for low emittance μ beam

Conventional production: from **proton on target**

π, K decays from proton on target have typical **P_μ~ 100 MeV/c** (π, K rest frame)

whatever is the boost P_T will stay in Lab frame →
very high emittance at production point → **cooling needed**!

Direct μ pair production:

Muons produced from **$e^+e^- \to \mu^+\mu^-$** at √s around the $\mu^+\mu^-$ threshold **(√s~0.212GeV)** in asymmetric collisions (to collect μ^+ and μ^-)

NIM A Reviewer: ***"A major advantage of this proposal is the lack of cooling of the muons…. the idea presented in this paper may truly revolutionise the design of muon colliders … "***

Advantages:

1. **Low emittance possible:** P_μ is tunable with $\sqrt{s}$ in $e^+e^- \to \mu^+\mu^-$ P_μ can be **very small** close to the $\mu^+\mu^-$ threshold
2. **Low background:** Luminosity at low emittance will allow low background and low ν radiation (easier experimental conditions, can go up in energy)
3. **Reduced losses from decay:** muons can be produced with a relatively high boost in asymmetric collisions
4. **Energy spread:** Muon Energy spread **also small at threshold**, it gets larger as $\sqrt{s}$ increases, one can use correlation with emission angle (eventually it can be reduced with short bunches)

Disadvantages:

- Rate: much smaller cross section wrt protons

$$\sigma(e^+e \to \mu^+\mu^-) \sim 1\ \mu b \text{ at most}$$

i.e. Luminosity(e+e-)= $10^{40}\ cm^{-2}\ s^{-1}$ → gives μ rates 10^{10} Hz

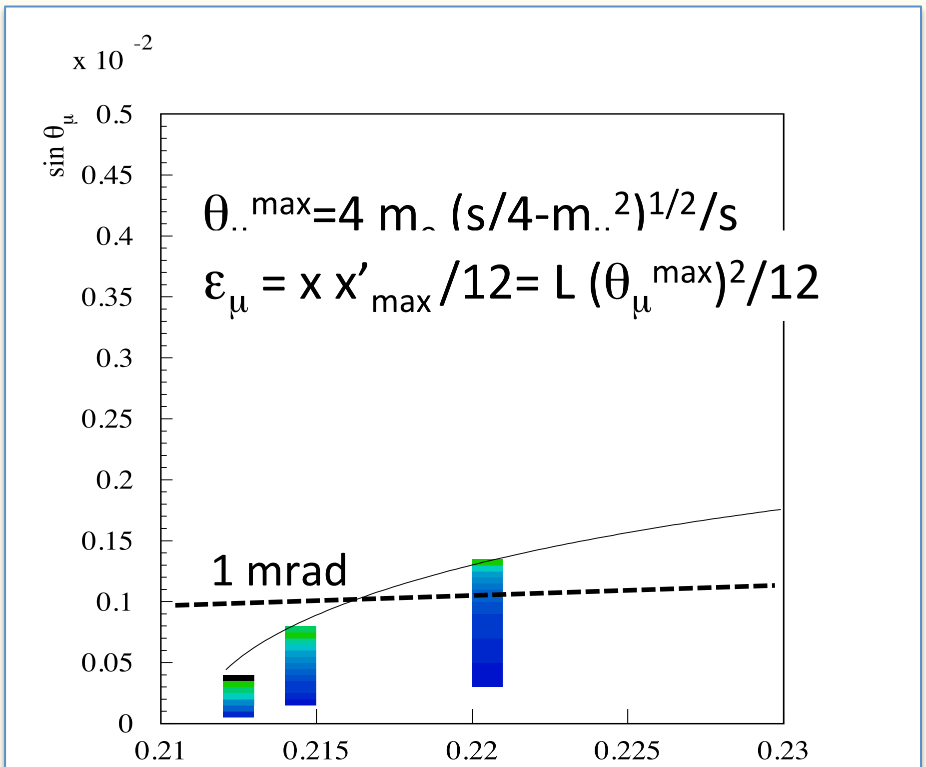
Possible Schemes

- **Low energy collider with e+/e- beam (e+ in the GeV range):**
  1. Conventional asymmetric collisions (but required luminosity is beyond current knowledge)
  2. Positron beam interacting with continuous beam from electron cooling (too low electron density, 10^{20} electrons/cm^{-3} needed to obtain an reasonable conversion efficiency to muons)
- **Electrons at rest (seems more feasible):**
  3. e+ on Plasma target
  4. e+ on standard target, including crystals with channeling
  - Need Positrons of ~45 GeV
  - $\gamma(\mu)$~200 and μ laboratory lifetime of about 500 μs

Ideally muons will *copy* the positron beam

Muons angle contribution to μ beam emittance

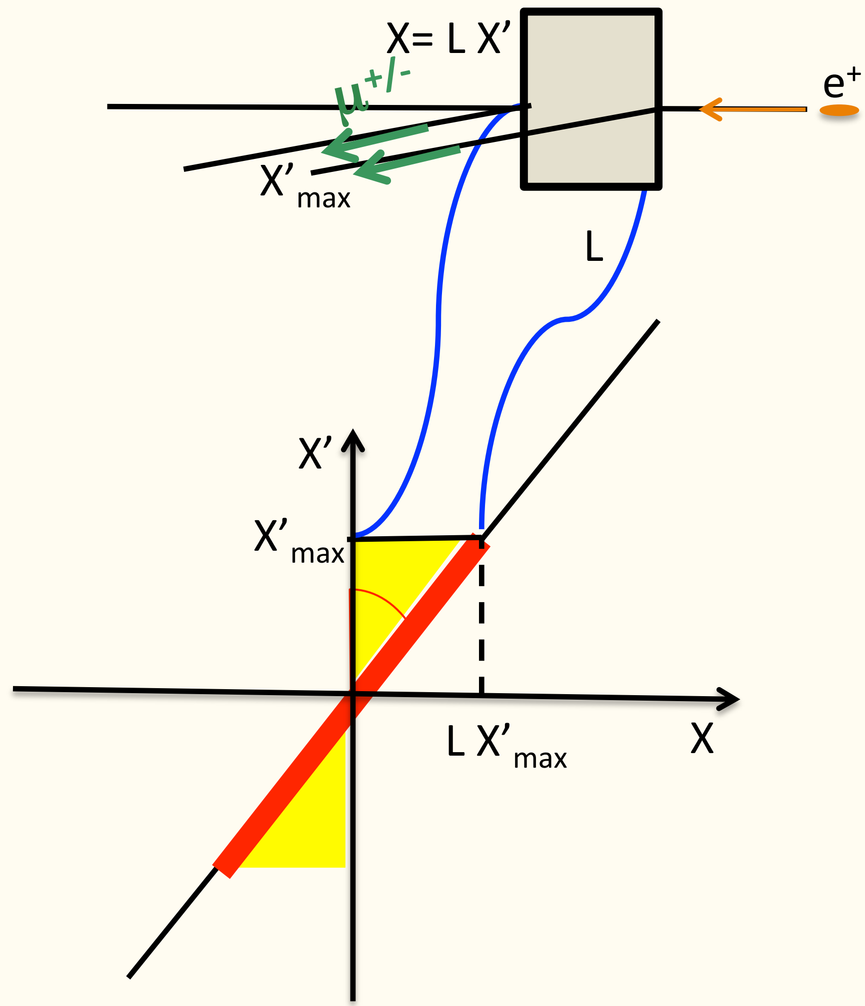
The target thickness and c.o.m. energy completely determine the emittance contributions due to muon production angle



$$\theta_\mu^{max} = 4\, m_e\, (s/4 - m_\mu^2)^{1/2}/s$$

$$\varepsilon_\mu = x\, x'_{max}/12 = L\, (\theta_\mu^{max})^2/12$$

[Babayaga 3.5]



Criteria for target design

- **Number of $\mu^+\mu^-$ pairs produced per interaction:**

$$n(\mu^+\mu^-) = n^+ \rho^- L \, \sigma(\mu^+\mu^-)$$

n^+ = number of e^+

ρ^- = target electron density

L = target length

- **ρ^- L costraints**
  - Ideal target (e^- dominated)
    $(\rho^- L)_{max} = 1/\sigma(\text{radiative bhabha}) \approx 10^{25}\ cm^{-2}$
    (beam lifetime determined by radiative Bhabha)
  - With $(\rho^- L)_{max}$ one has a maximal $\mu^+\mu^-$ production efficiency ~10^{-5}
  - Muon beam emittance increases with L (in absence of intrinsic focusing effects) ➔ increase ρ^-
  - Conventional target $(\rho^- L)_{max}$ depends on material (see next slides)

Criteria for target design

Bremsstrahlung on nuclei and multiple scattering (MS) are the dominant effects in real life… Xo and electron density will matter:

- **Heavy materials**
  - minimize emittance (enters linearly) ➔ Copper has about same contributions to emittance from MS and $\mu^+\mu^-$ production
  - high e^+ loss (Bremsstrahlung is dominant)
- **Very light materials**
  - maximize production efficiency(enters quad) ➔ H_2
  - even for liquid need O(1m) target ➔ emittance increase
- **Not too heavy materials(Be, C)**
  - Allow low emittance with small e^+ loss

optimal: not too heavy and thin

Application for Multi-TeV Muon Collider as an example

- Use thin target with high efficiency and small e^+ loss
- Positrons in storage ring with high momentum acceptance
- No need of extreme beam energy spread

Possible target: 3 mm Be

45 GeV e^+ impinging beam

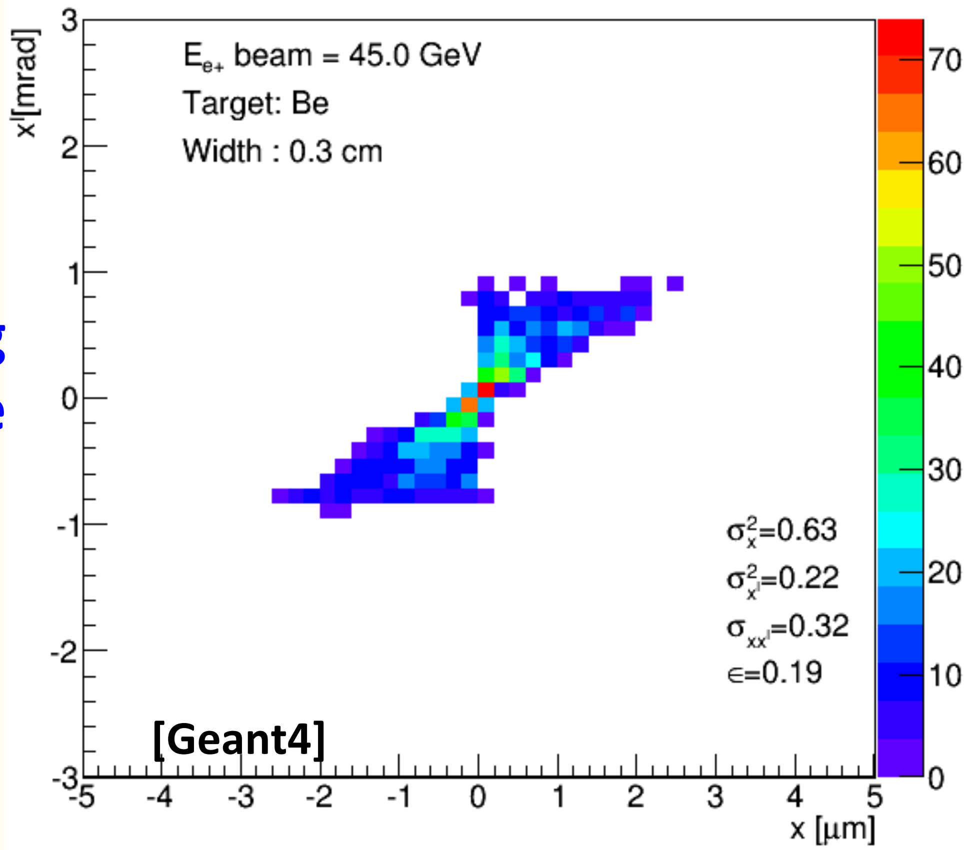
- Emittance at E_μ = 22 GeV:

  ε_x = 0.19 $\cdot 10^{-9}$ m-rad

Multiple Scattering contribution is negligible

-> μ after production is not affected by nuclei in target
-> e+ beam emittance is preserved, not being affected by nuclei in target (see also next slide)

Muons at the target exit surface



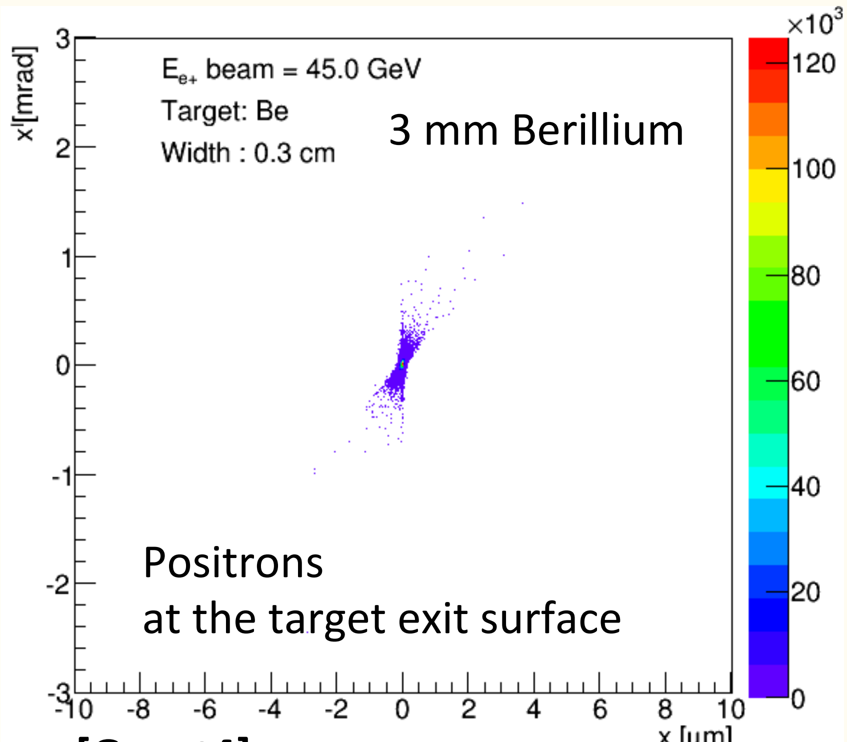
- Conversion efficiency: 10^{-7}
- Muons beam energy spread: 9%

Positrons Storage Ring Requirements

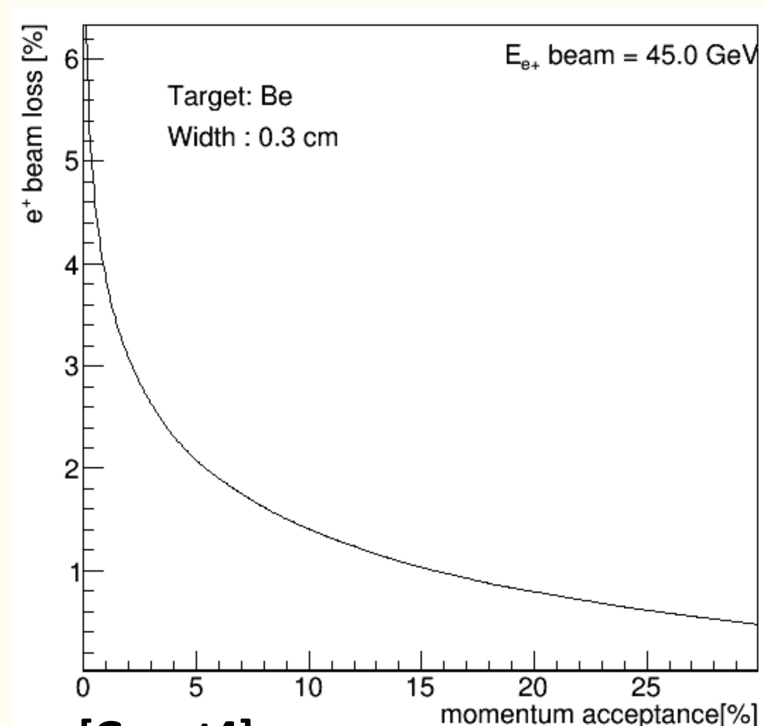
- Transverse phase space almost not affected by target
- Most of positrons experience a small energy deviation:

  A large fraction of e^+ can be stored (depending on the momentum acceptance)

  - 10% momentum acceptance will increase the effective muon conversion efficiency (produced muon pairs/produced positrons) by factor 100



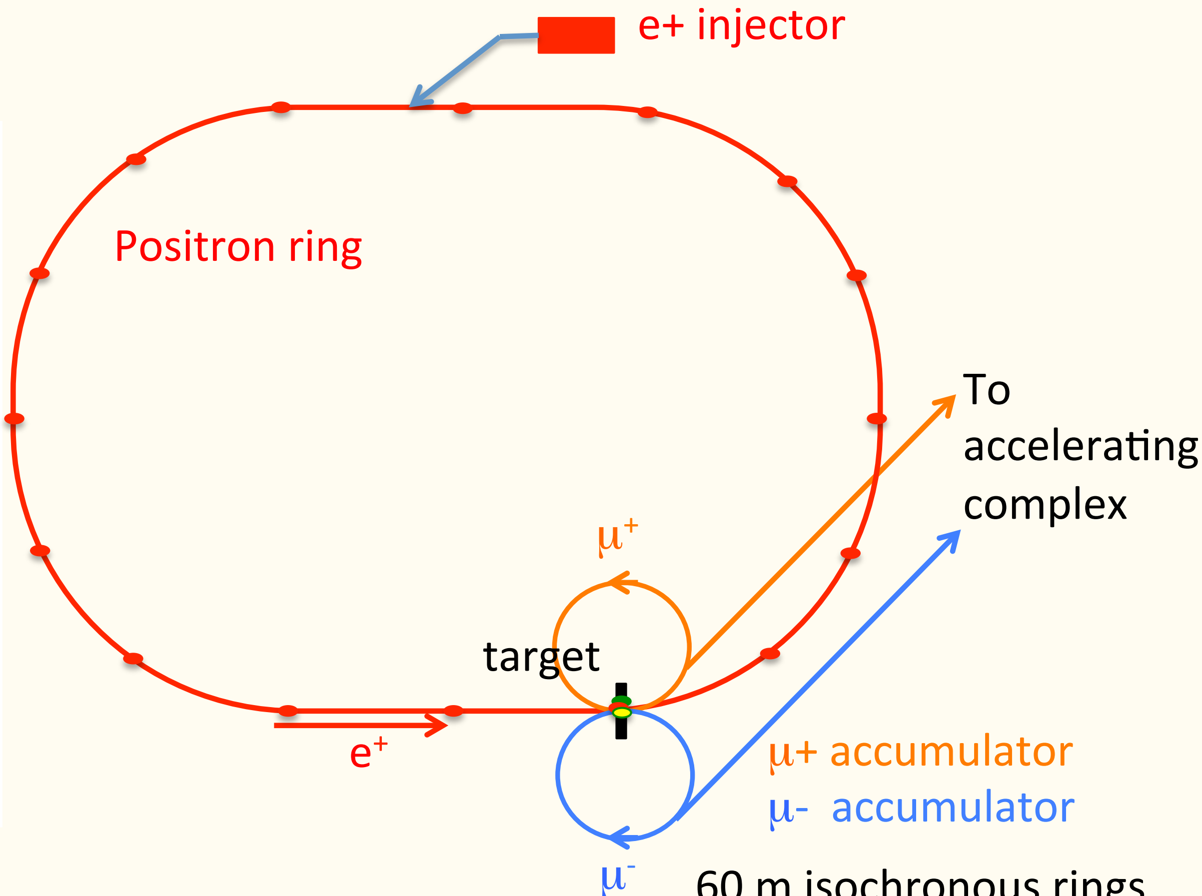
[Geant4]



[Geant4]

Schematic Layout for muon source from e+

Circumference	6 km
ρ	0.6 km
number e+ bunches	100
e+ bunch spacing	200 ns
Beam current	240 mA
e+ Particles/bunch	$3 \cdot 10^{11}$
Rate e+ on target	$1.5 \cdot 10^{18}$ e^+/s
U_0	0.58 GeV
P_{tot}	139 MW
B	0.245 T



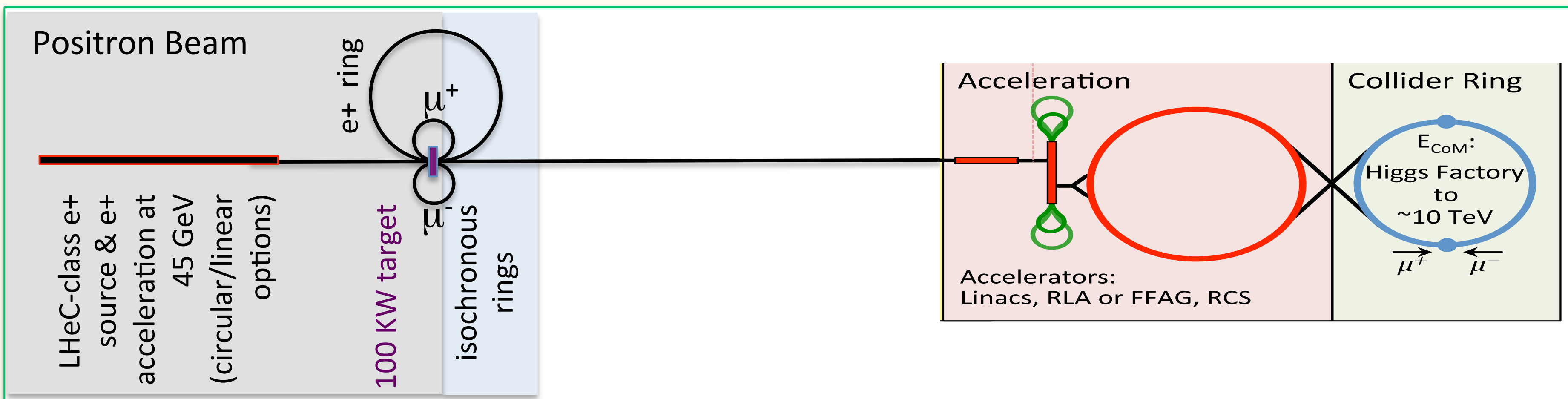
60 m isochronous rings recombine bunches for ~ 1 τ_μ^{lab} ~2500 turns

$$n_b = \sum_{i=1}^{N_T} e^{-\Delta t(N_T - i)/\tau_\mu^{lab}}$$

Key point:

Positron source requirements strictly related to the e^+ ring momentum acceptance

Muon Collider:
Schematic Layout for positron based muon source



Key Challenges

~10^{11} μ / sec from e+e-→$\mu+\mu-$

Key R&D

10^{15} e+/sec, 100 kW class target, NON distructive process in e+ ring

Key R&D

MW proton driver
MW class target
NCRF in magnetic field

Ionization cooling
High field solenoids (30T)
High Temp Superconductor

Cost eff. low RF SC
Fast pulsed magnet (1kHz)

Detector/ machine interface

Key Challenges

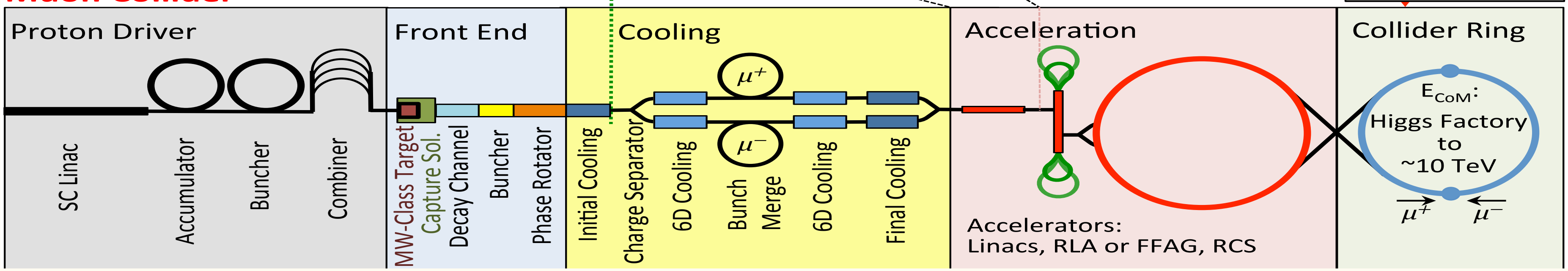
~10^{13}-10^{14} μ / sec
Tertiary particle $p \rightarrow \pi \rightarrow \mu$:

Fast cooling (τ=2μs) by 10^6 (6D)

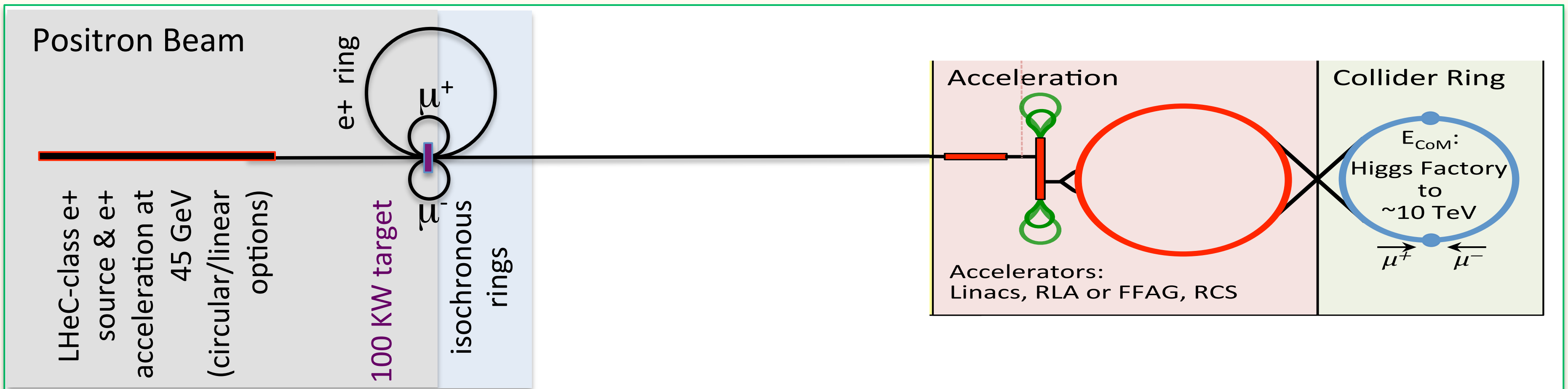
Fast acceleration mitigating μ decay

Background by μ decay

Muon Collider



share the same complex



Key Challenges

~10^{11} μ / sec from e+e-→ $\mu^+\mu^-$

Key R&D

10^{15} e+/sec, 100 kW class target, NON distructive process in e+ ring

EASIER AND CHEAPER DESIGN, IF FEASIBLE

Muon beam parameters

Assuming

- a positron ring with a total 25% momentum acceptance (10% easily achieved) and
- ~3 × LHeC positron source rate

	positron source	proton source
μ rate[Hz]	$9 \cdot 10^{10}$	$2 \cdot 10^{13}$
μ/bunch	$4.5 \cdot 10^{7}$	$2 \cdot 10^{12}$
normalised ϵ [μm-mrad]	40	25000

Very small emittance, **high muon rates** but relatively small bunch population:

➢ The actual number of μ/bunch in the muon collider can be larger by a factor ~ τ_μ^{lab}(HE)/500 μs (~100 @6 TeV) by topping up.

LEMC Draft Parameters

comparable luminosity with
lower Nμ/bunch
(lower background)
thanks to very small emittance
(and lower beta*)

much higher signal/noise ratio

Of course, a design study is needed to define this table

Parameter	Units	LEMC-6TeV	LEMC-H
LUMINOSITY/IP	$cm^{-2}\ s^{-1}$	5.09E+34	1.69E+31
Beam Energy	GeV	3000	62.5
Hourglass reduction factor		1.000	1.000
Muon mass	GeV	0.10566	0.10566
Lifetime @ prod	sec	2.20E-06	2.20E-06
Lifetime	sec	0.06	0.00
c*tau @ prod	m	658.00	658.00
c*tau	m	1.87E+07	3.89E+05
1/tau	Hz	1.60E+01	7.68E+02
Circumference	m	6000	150
Bending Field	T	15	15
Bending radius	m	667	14
Magnetic rigidity	T m	10000	208
Gamma Lorentz factor		28392.96	591.52
N turns before decay		3113.76	2594.80
β_x @ IP	m	0.0002	0.0002
β_y @ IP	m	0.0002	0.0002
Beta ratio		1.0	1.0
Coupling (full current)	%	100	100
Normalised Emittance x	m	4.00E-08	4.00E-08
Emittance x	m	1.41E-12	6.76E-11
Emittance y	m	1.41E-12	6.76E-11
Emittance ratio		1.0	1.0
Bunch length (zero current)	mm	0.1	0.1
Bunch length (full current)	mm	0.1	0.1
Beam current	mA	0.048	0.1
Revolution frequency	Hz	5.00E+04	2.00E+06
Revolution period	s	2.00E-05	5.00E-07
Number of bunches	#	1	1
N. Particle/bunch	#	6.00E+09	1.20E+08
Number of IP	#	1.00	1.00
σ_x @ IP	micron	1.68E-02	1.16E-01
σ_y @ IP	micron	1.68E-02	1.16E-01
$\sigma_{x'}$ @ IP	rad	8.39E-05	5.81E-04
$\sigma_{y'}$ @ IP	rad	8.39E-05	5.81E-04

Key Feasibility Issues

Muon Collider Study:
Proton Based Source

- **Proton Driver**
- **Target**
- **Front End**
- **Cooling (PIC)**
- **μ Acceleration**
- **Collider Ring**
- **Collider MDI**
- **Collider Detector**

(mostly) independent on muon source

synergy with the two options

Positron Based Source

Positron Source
Muon Target
Positron Ring

not yet investigated!

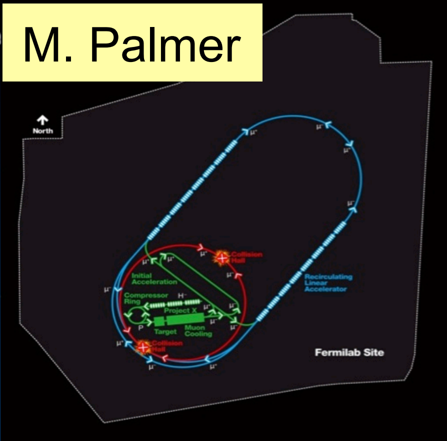
Conclusions

- **Very low emittance muon beams** can be obtained by means of positron beam on target
- Interesting **muon rates require**:
  - **Challenging positron source** (synergy with LHeC, ILC, FCC-ee…)
  - **Positron ring with high momentum acceptance** (synergy with next generation SL sources)

- Fast muon acceleration concepts deeply studied by MAP
- Final focus design can profit of studies on conventional muon studies

Backup Slides

M. Palmer



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 × 10^{32} [Rubbia proposal: 5×10^{32}]

M. Palmer

Conclusion

- NF ⇨ precision ν microscopes
- Multi-TeV MC ⇨ potentially only cost-effective route to lepton collider capabilities with E_{CM} > 5 TeV
- 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

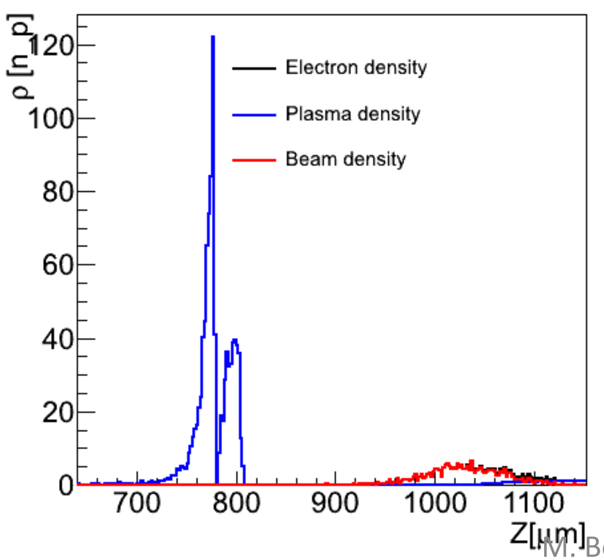
Accelerator	Energy Scale	Performance
Cooling Channel	**~200 MeV**	**Emittance Reduction**
MICE	*160-240 MeV*	*5%*
Muon Storage Ring	**3-4 GeV**	**Useable μ decays/yr***
νSTORM	*3.8 GeV*	*$3x10^{17}$*
Intensity Frontier ν Factory	**4-10 GeV**	**Useable μ decays/yr***
NuMAX (Initial)	*4-6 GeV*	*$8x10^{19}$*
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*	*$12x10^{34}cm^{-2}s^{-1}$*

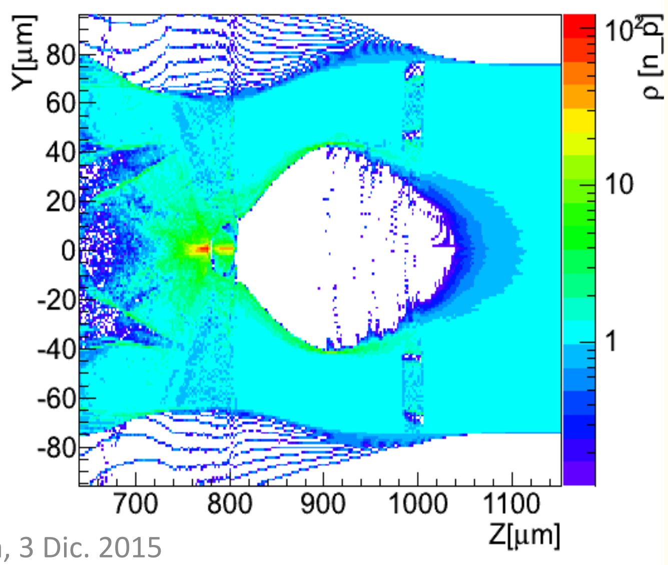
* Decays of an individual species (ie, μ^+ or μ^-)

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

Few statements on the plasma option

- Plasma would be a good approximation of an ideal electron target ++ autofocussing by Pinch effect
- enhanced electron density can be obtained at the border of the blow-out region (up x100)
- Simulations for $n_p=10^{16}$ electrons/cm^3 (C. Gatti, P. Londrillo)
- Region size decreases with $1/\sqrt{n_p}$ even don't know if blowout occurs at $n_p \sim 10^{20}$electrons/cm^3





Positron sources: studies on the market

- Summary of e^+ sources projects (all very aggressive):

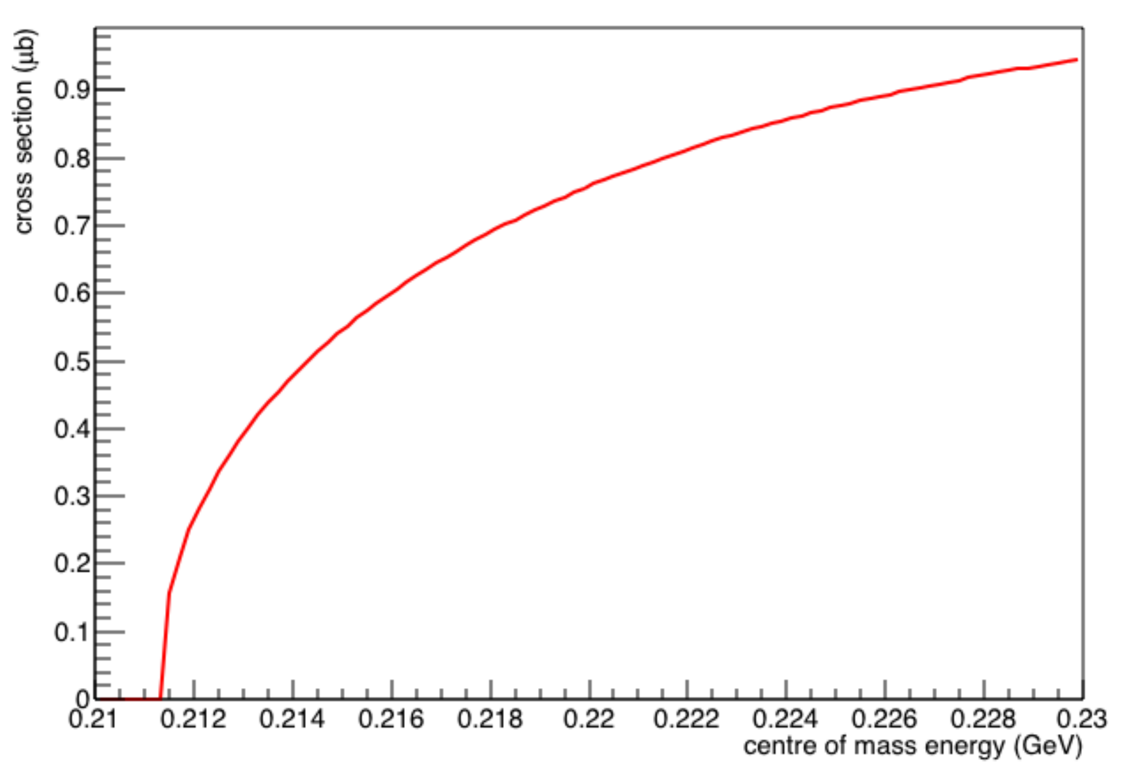
In [F. Zimmermann, et al., '**POSITRON OPTIONS FOR THE LINAC-RING LHEC**', WEPPR076 Proceedings of IPAC2012, New Orleans, Louisiana, USA]

	SLC	CLIC	ILC	LHeC pulsed	LHeC ERL
E [GeV]	1.19	2.86	4	140	60
$\gamma\epsilon_x$ [μm]	30	0.66	10	100	50
$\gamma\epsilon_y$ [μm]	2	0.02	0.04	100	50
$e^+[10^{14}\text{s}^{-1}]$	0.06	1.1	3.9	18	440

➢ <u>This is the most critical issue</u>

Processes at √s around 0.212 GeV

- Bhabha scattering, $\mu^+\mu^-$ production $\gamma\gamma$ (not relevant)
- $e^+e^-\rightarrow\mu^+\mu^-$ cross section:

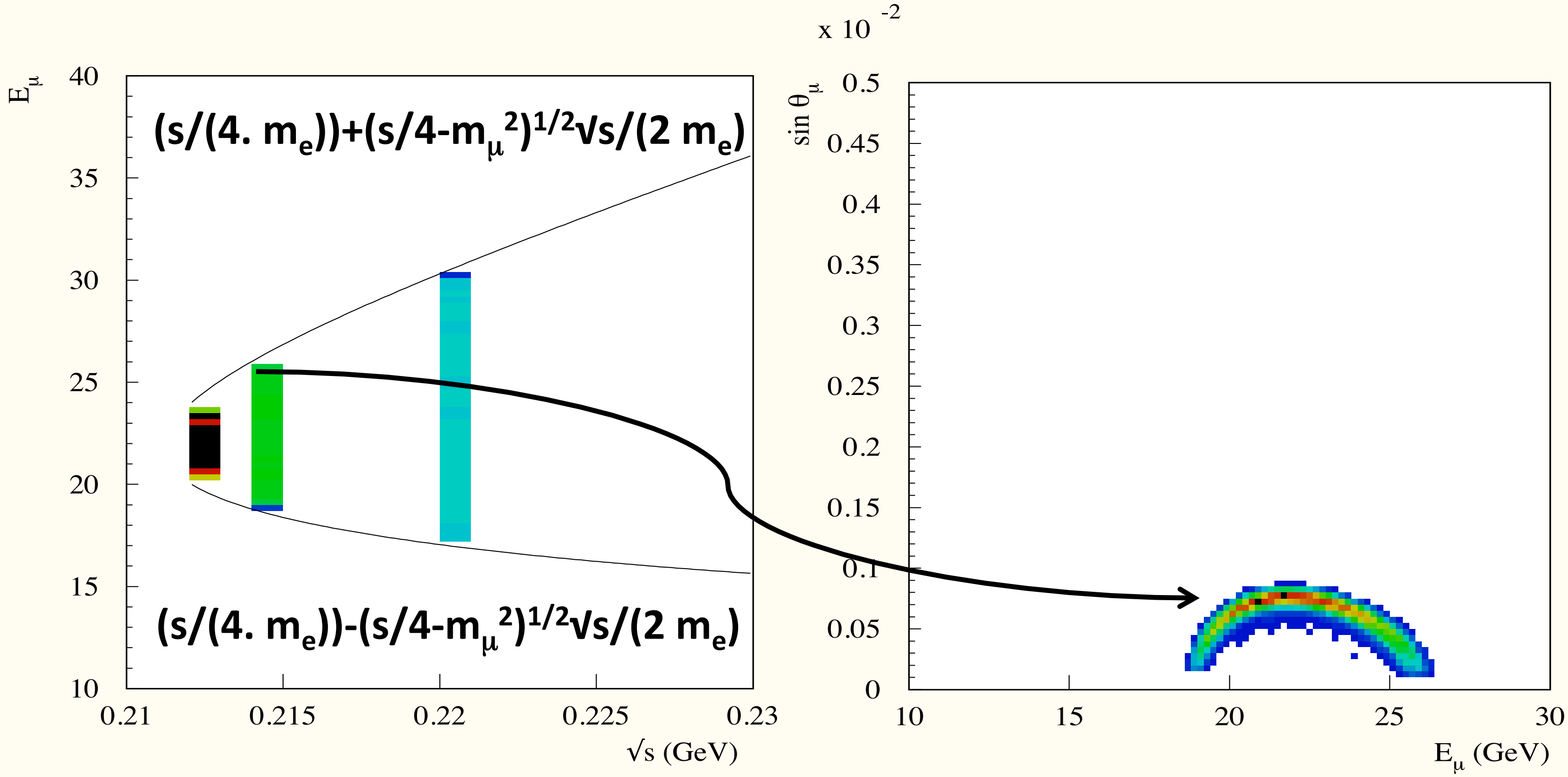


Muonium production also investigated:
  huge cross section (mb range)
  10^{-4} eV width

Not viable…. Deeper studies?

Processes at √s ~ 0.212 GeV e^+ on target

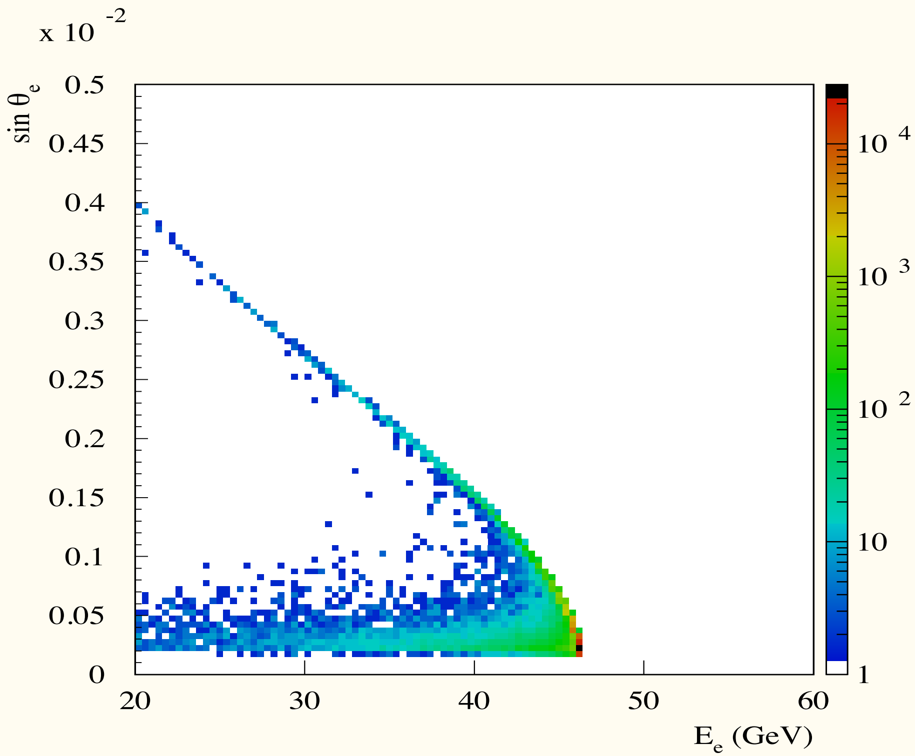
$e^+e^- \rightarrow \mu^+\mu^-$ muons energy spread:



Processes at √s ~ 0.212 GeV e^+ on target

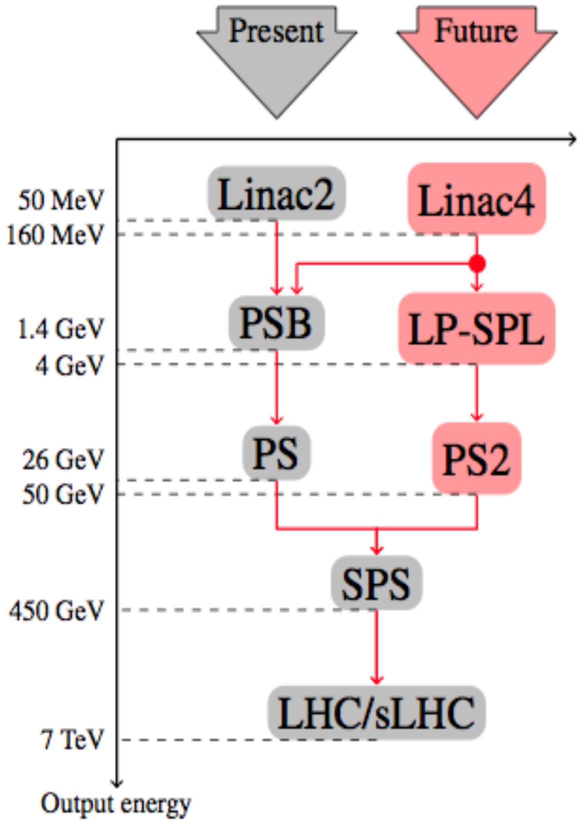
$e^+e^- \rightarrow e^+ e^-(\gamma's)$ is the dominant process

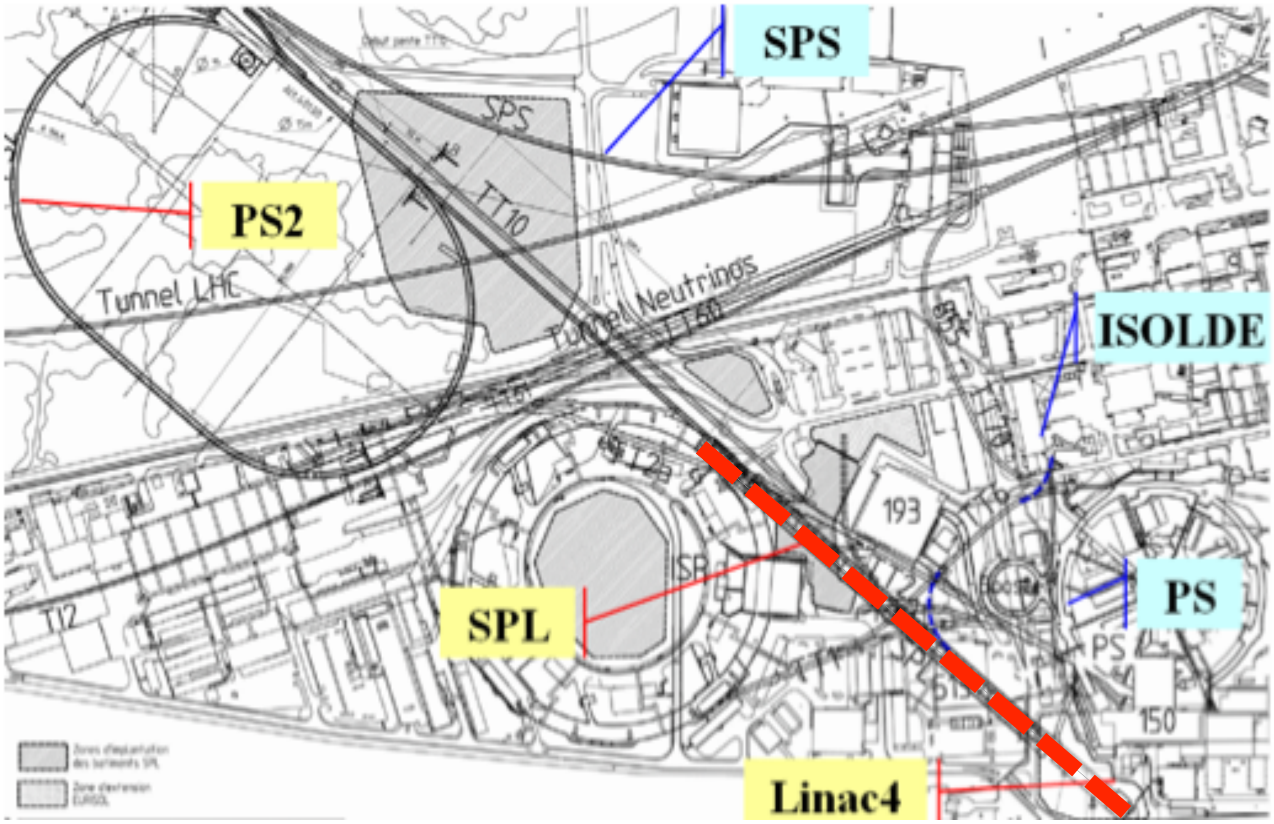
- Babayaga for “large” angles and
- BBBrems for collinear (dominant σ ~ 150 mb, $\delta E/E<2\%$)



Future accelerators programs at CERN

- A new LHC injector complex to increase the collider luminosity 10x with the High Luminosity LHC (HL-LHC)).
- Two accelerators (the LP-SPL and a new 50 GeV synchrotron, PS2) would replace the three existing ones (Linac2, the PSB, and the PS), with the injection of the SPS at 50 GeV,

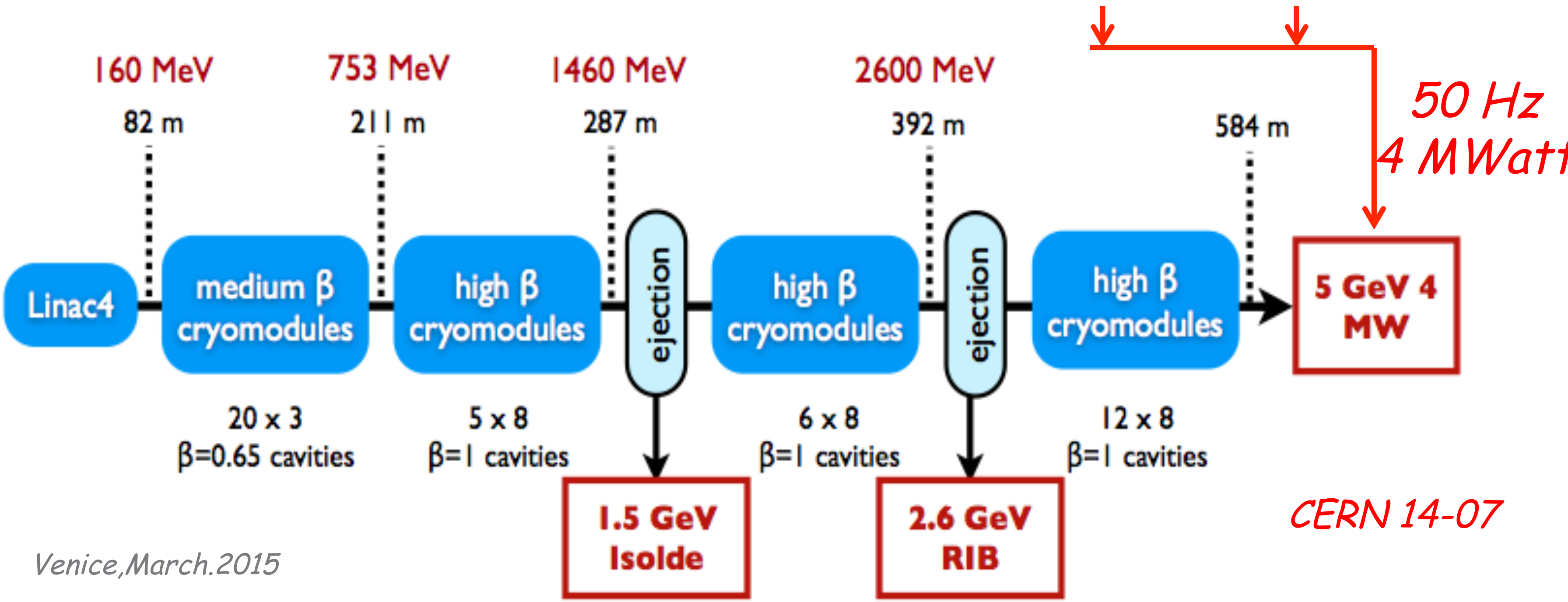




CERN-SPL parameters

- Layout of superconducting SPL with intermediate extractions.
- SPL design is very flexible and it can be adapted to the needs of many high-power proton beam applications.

Parameter	Units	HP-SPL Low-current	HP-SPL High-current	LP-SPL
Energy	GeV	5	5	4
Beam power	MW	4	4	0.144
Repetition rate	Hz	50	50	2
Average pulse current	mA	20	40	20
Peak pulse current	mA	32	64	32
Source current	mA	40	80	40
Chopping ratio	%	62	62	62
Beam pulse length	ms	0.8	0.4	0.9
Protons per pulse	10^{14}	1.0	1.0	1.13



CERN 14-07

A muon based Higgs factory at CERN

- A muon cooled Higgs factory can be easily housed within CERN
- The new 5 GeV Linac will provide at 50 c/s a multi MWatt H- beam with enough pions/muons to supply the muon factory.
- The basic additional accelerator structure will be the following:
  - Two additional small storage rings with R ≈ 50 m will strip H- to a tight p bunch and compress the LP-SPL beam to a few ns.
  - Muons of both signs are focused in a axially symmetric B = 20 T field, reducing progressively pt with a horn and B = 2 T
  - A buncher and a rotator compresses muons to ≈ 250 MeV/c
  - Muon Cooling in 3D compresses emittances by a factor 106.
  - Bunches of about 2x1012 m± are accelerated to 62.5 GeV
  - Muons are colliding in a SC storage ring of R ≈ 60 m (about one half of the CERN-PS ,1/100 of LHC) where about 104 Higgs events/y are recorded for each of the experiments.

Staged Neutrino Factory and Muon Colliders main parameters

Neutrino Factory at intensity frontier

System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Performance	ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
	Stored μ+ or μ-/year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}
Detector	*Far Detector:*	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND / Mag LAr
	Distance from Ring	km	1.9	1300	1300	1300
	Mass	kT	1.3	100 / 30	100 / 30	100 / 30
	Magnetic Field	T	2	0.5-2	0.5-2	0.5-2
	Near Detector:	Type	SuperBIND	Suite	Suite	Suite
	Distance from Ring	m	50	100	100	100
	Mass	kT	0.1	1	1	2.7
	Magnetic Field	T	Yes	Yes	Yes	Yes
Neutrino Ring	Ring Momentum	GeV/c	3.8	5	5	5
	Circumference (C)	m	480	737	737	737
	Straight section	m	184	281	281	281
	Number of bunches	-		60	60	60
	Charge per bunch	1×10^9		6.9	26	35
Acceleration	Initial Momentum	GeV/c	-	0.25	0.25	0.25
	Single-pass Linacs	GeV/c	-	1.0, 3.75	1.0, 3.75	1.0, 3.75
		MHz	-	325, 650	325, 650	325, 650
	Repetition	Hz	-	30	30	60
Cooling			No	No	Initial	Initial
Proton Driver	Proton Beam Power	MW	0.2	1	1	2.75
	Proton Beam	GeV	120	6.75	6.75	6.75
	Protons/year	1×10^{21}	0.1	9.2	9.2	25.4
	Repetition	Hz	0.75	15	15	15

Muon Collider at the energy frontier

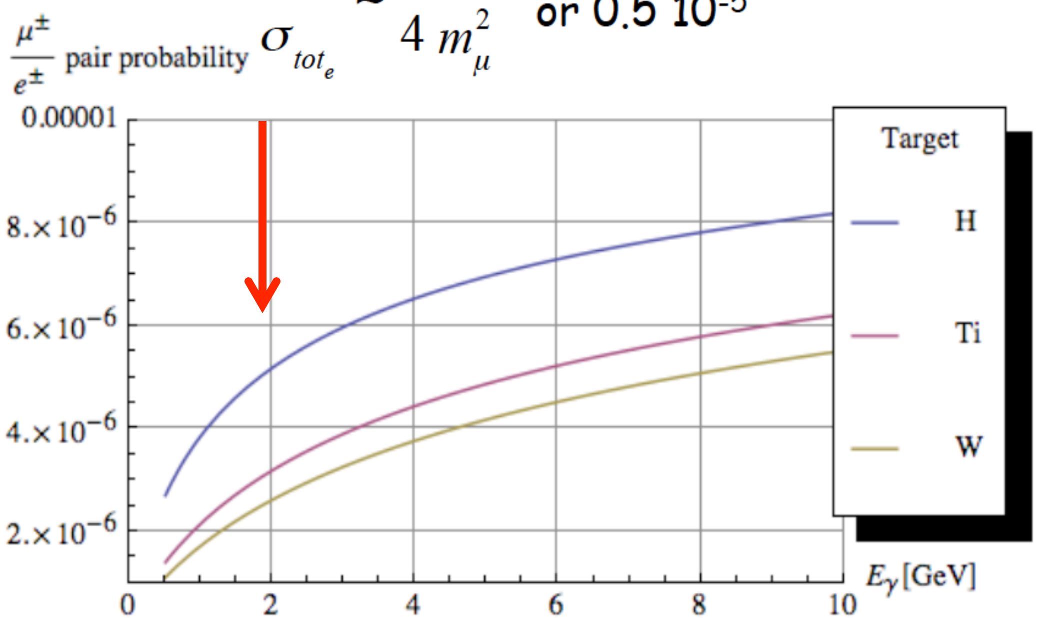
		Higgs Factory		Top Threshold Options		Multi-TeV Baselines		
Parameter	*Units*	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top^{+} Production/10^7sec		3,500*	13,500*	7,000^{+}	60,000^{+}	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	$4^{\#}$	4	4	4	4	4	1.6
Cooling		**6D no final**		**Full 6D**				

Muon generation by GeV-scale Compton γs

V.Yakimenko (SLAC)

Probability of creating μ+μ− pairs as a function of the incident photon energy

$$\frac{\sigma_{tot_\mu}}{\sigma_{tot_e}} \approx \frac{1}{4}\frac{m_e^2}{m_\mu^2}$$ or 0.5 10-5



2GeV γ beam	Pulsed Linac	ERL
e-beam energy [GeV]	36	11
Laser wavelength [μm]	10	1
Bunch charge [nC]	10	1.5
Rep. rate [kHz]	0.2	20 / 200
Bunches per beam	250	
Average current [mA]	2	30 / 300
e-beam power [MW]	18	330 / 3300
e-to-γ convers. efficiency	3	0.33
γ-beam power [MW]	3	20 / 200
Total AC-to-γ efficiency	10%	20% / 75%
Peak $\mu^+\mu^-$ [per bunch]	10^6	$3\ 10^4$
Average $\mu^+\mu^-$ [per second]	$5\ 10^{10}$	$3\ 10^{11}$ / $3\ 10^{12}$

- Brightness 10^3 larger than with proton driver
- 10^3 too low with pulsed linac
- 10^2 flux increase with high current ERL
- Approaching intensities desired for NF (but train structure not favorable for collider luminosity, N^2 issue)