Muon Collider Status

M. Antonelli (LNF)

Outline

- Muons case
- Muon accelerators challenges:
  - **muon production**
    - ✓ Conventional: from protons on target
      - **Cooling**
    - ✓ Unconventional: from e+e- annihilation
  - high-gradient acceleration and collider rings
  - Performances
- Conclusions

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

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

☹

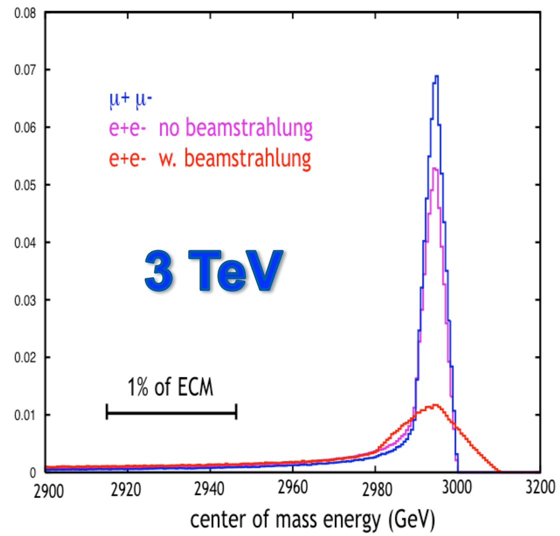
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Development of novel technologies with key accelerator and detector challenges

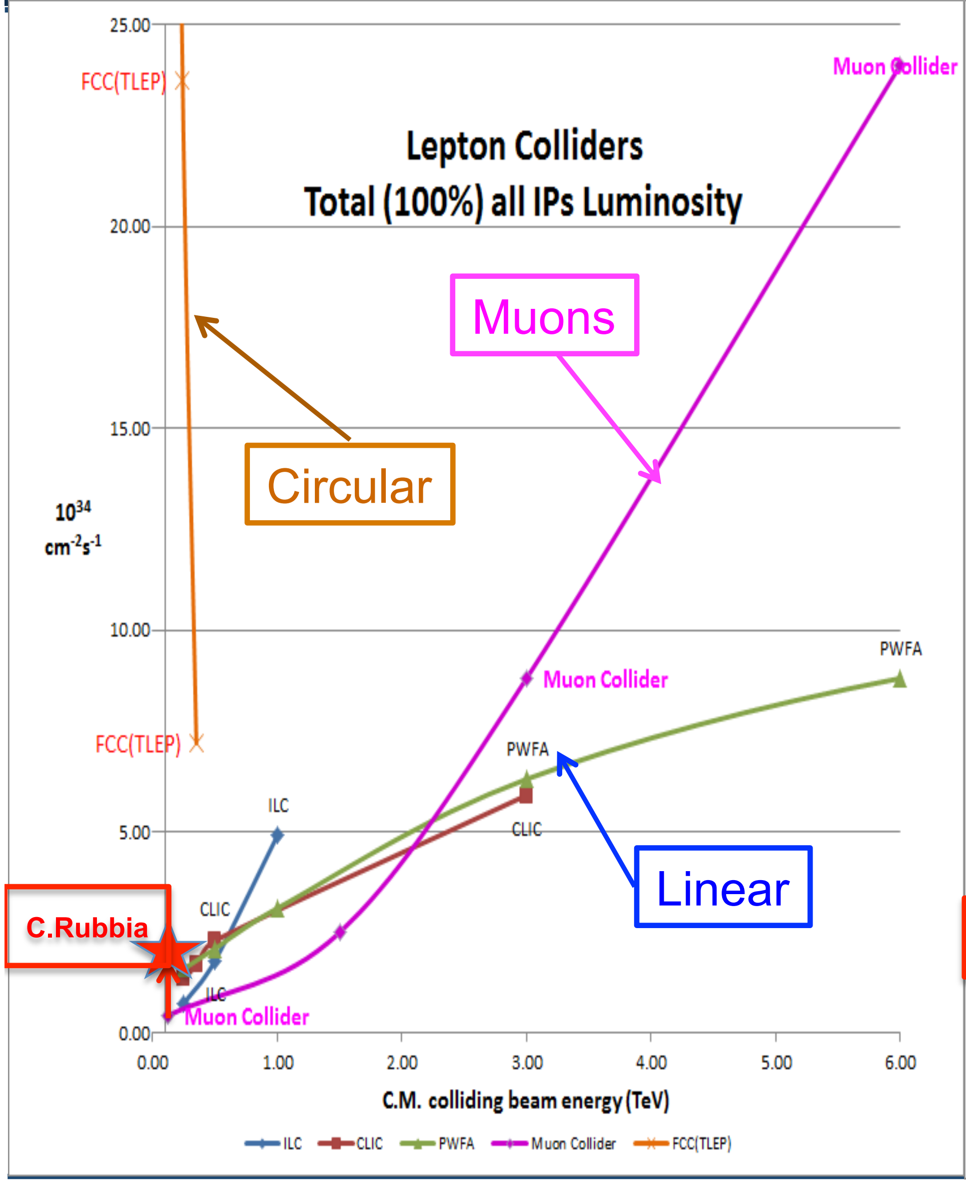
Muon beams specific properties

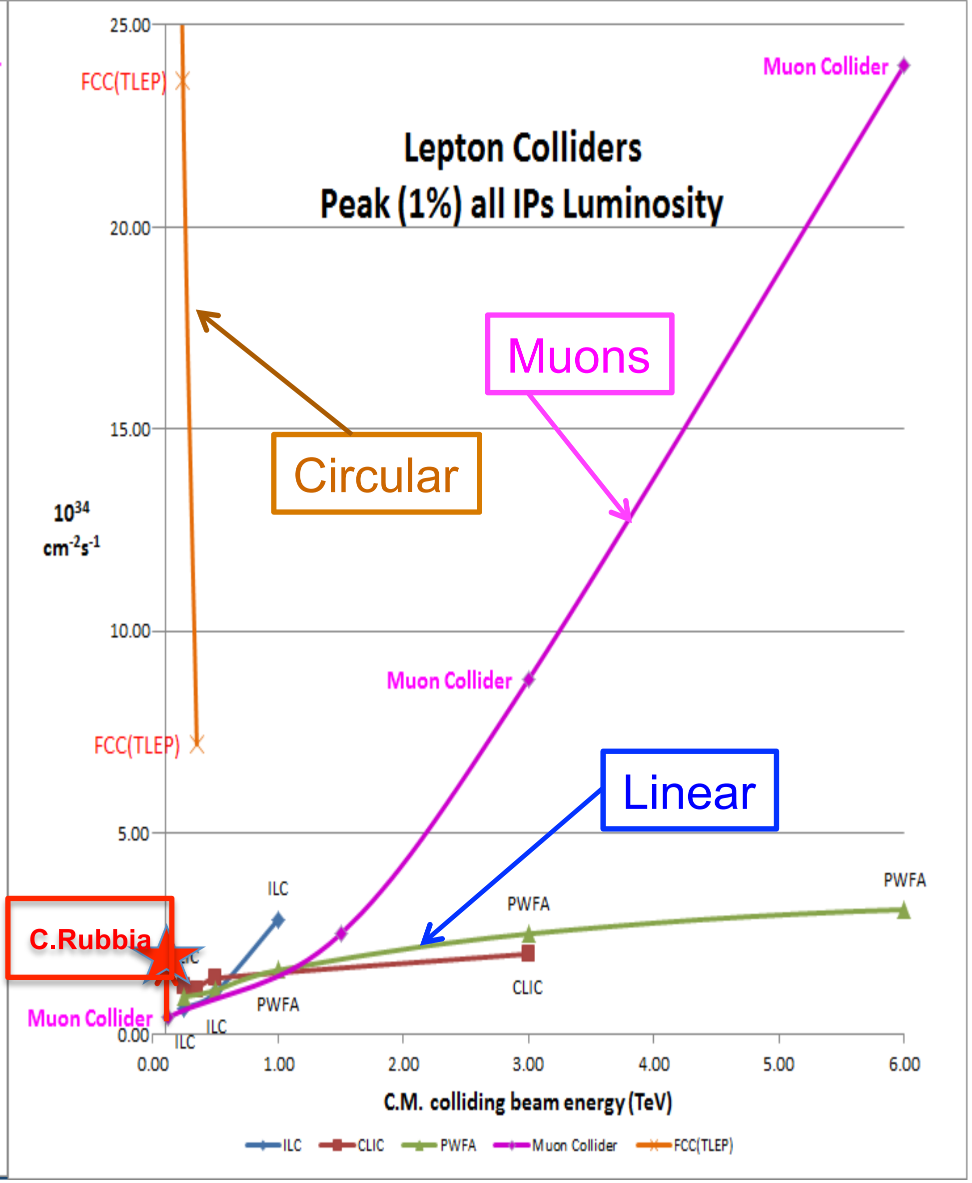
Muons are leptons like electrons & positrons but with a mass (105.7 MeV/c^2) 207 times larger

- **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**

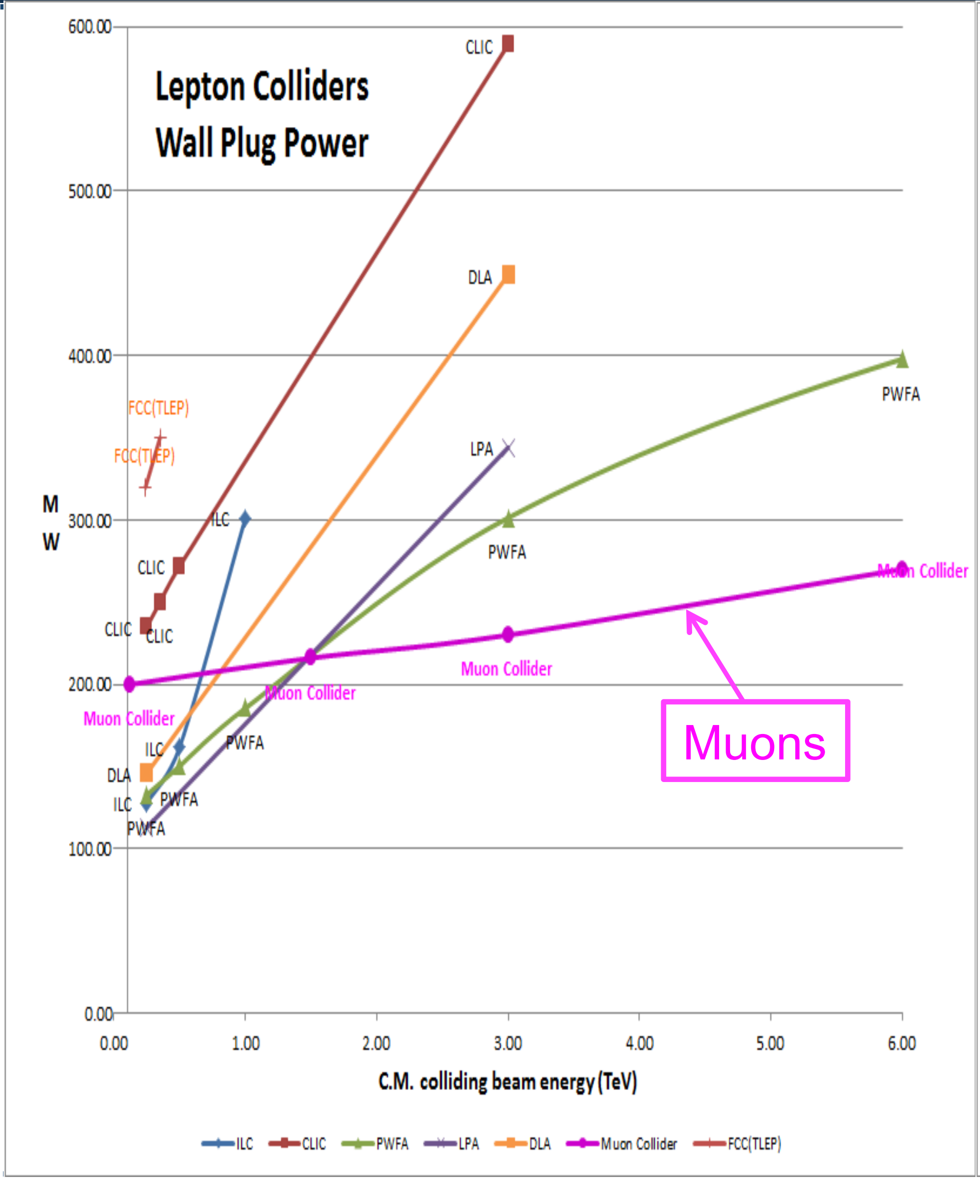


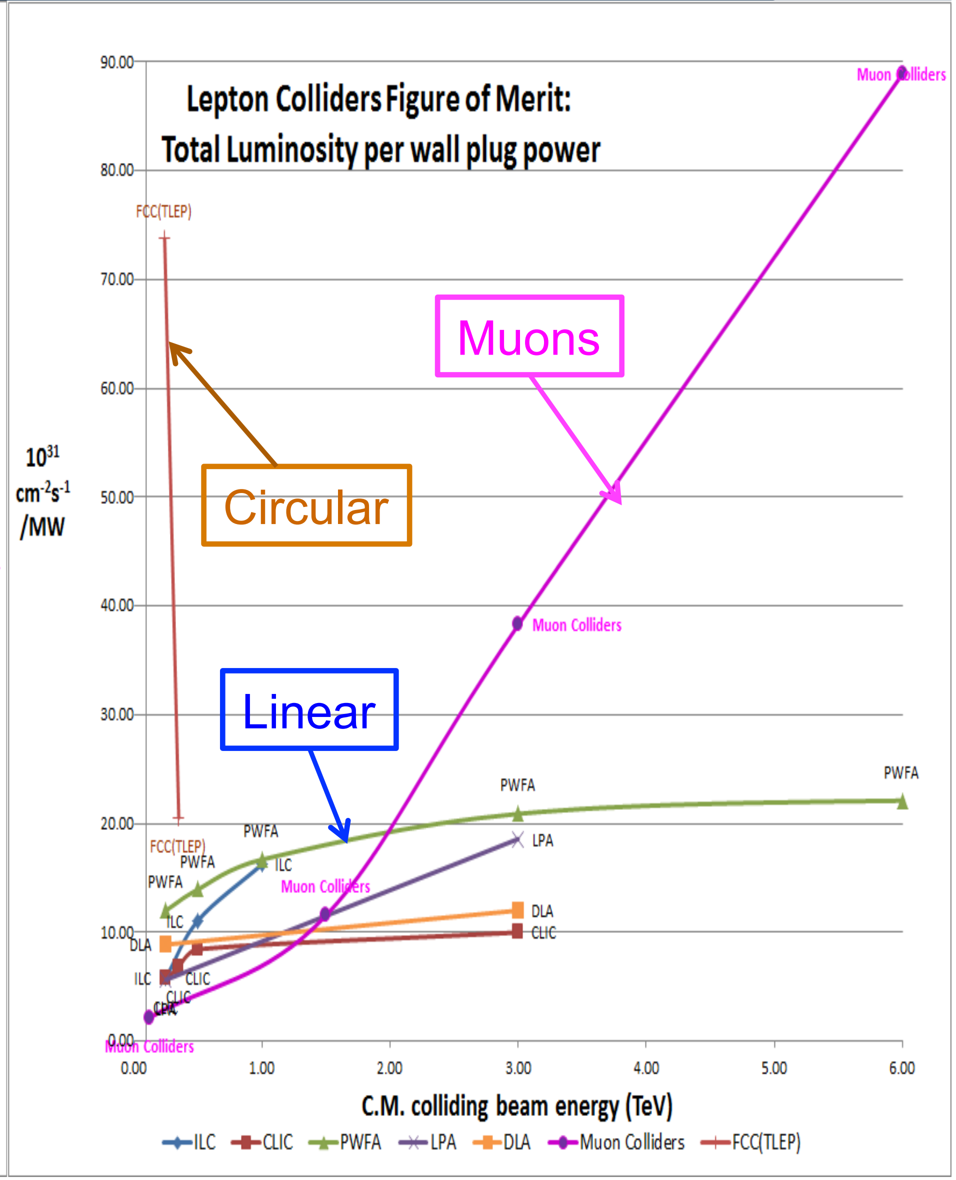
Muon Colliders potential of extending leptons high energy frontier with high performance





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 ($\sim N_\mu^2$ $1/\varepsilon_\mu$)

Options

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

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

Unconventional:

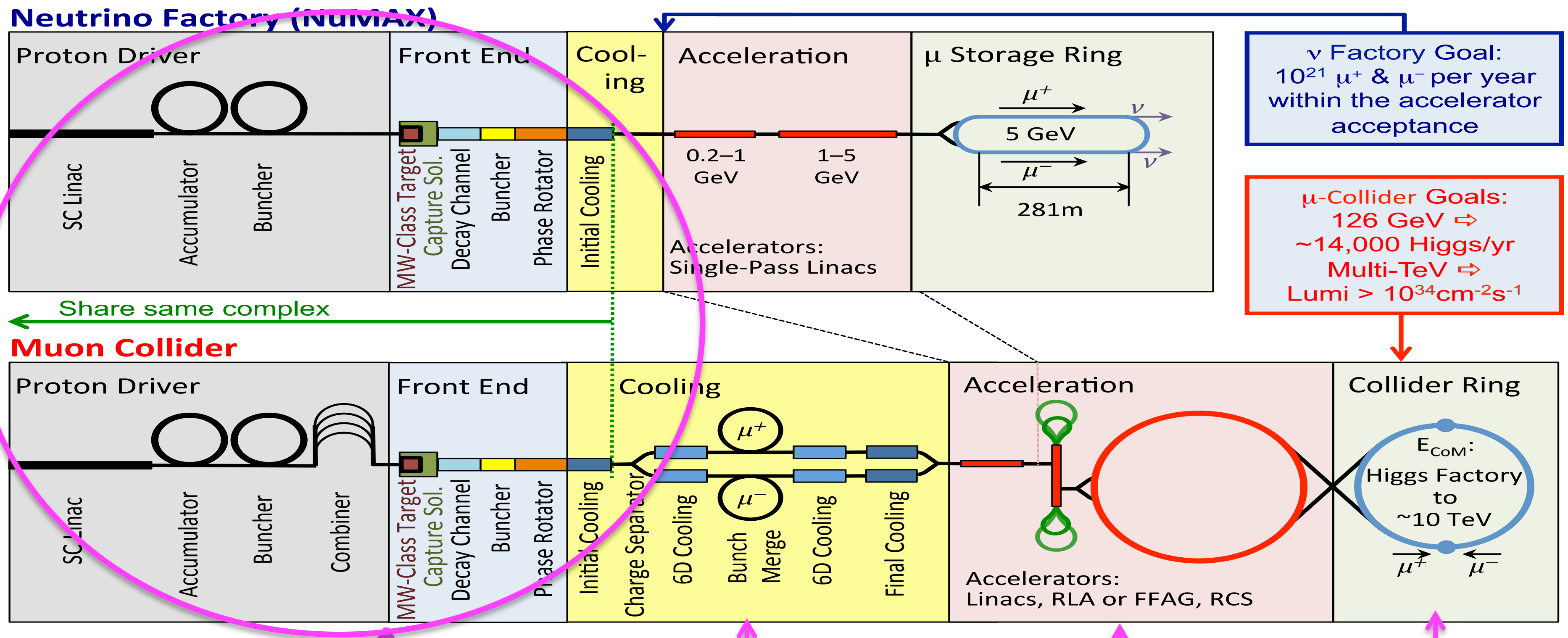
- **e^+e^- annihilation: positron beam on target** (very low emittance and no cooling needed), baseline for our proposal here
  Rate $\sim 10^{11}$ μ/sec $N_\mu \sim 5\times10^7$ /bunch

- **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

Proton-Based Source

Muon Accelerator Program (MAP)
Muon based facilities and synergies

Mark Palmer



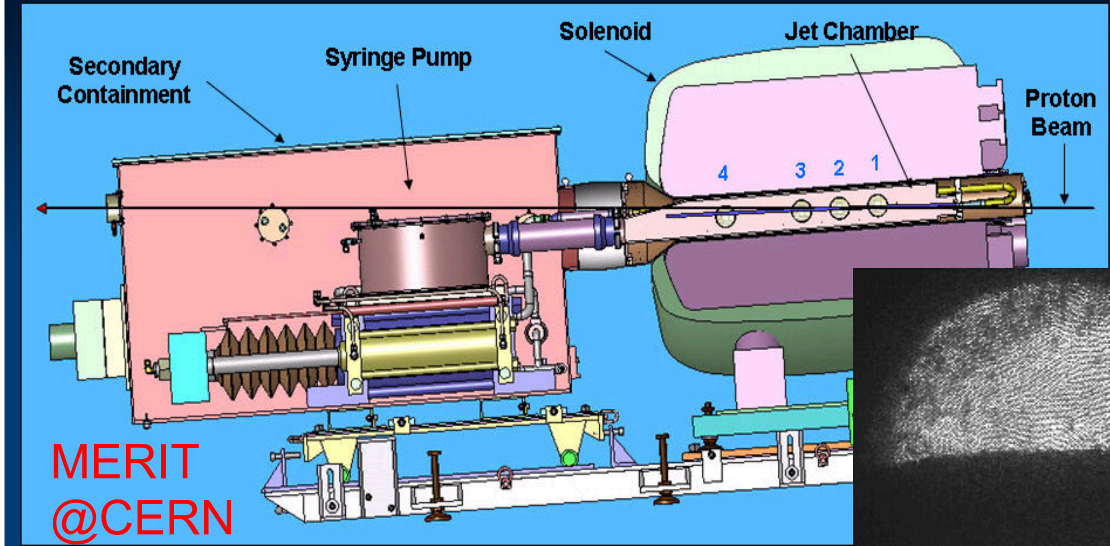
Key Challenges

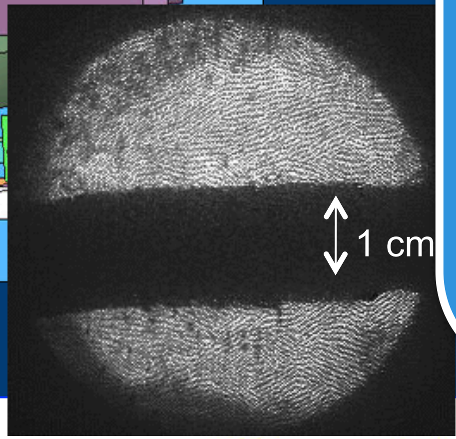
- $\sim 10^{13}$-10^{14} μ / sec — Tertiary particle $p \rightarrow \pi \rightarrow \mu$:
- Fast cooling ($\tau = 2\mu s$) by 10^6 (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay

Key R&D

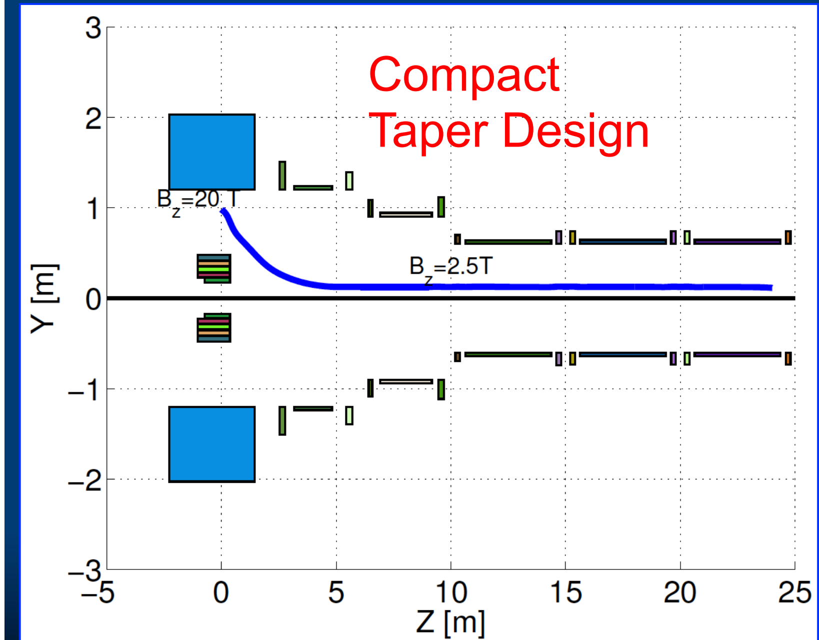
- MW proton driver; MW class target; NCRF in magnetic field
- Ionization cooling; High field solenoids (30T); High Temp Superconductor
- Cost eff. low RF SC; Fast pulsed magnet (1kHz)
- Detector/machine interface

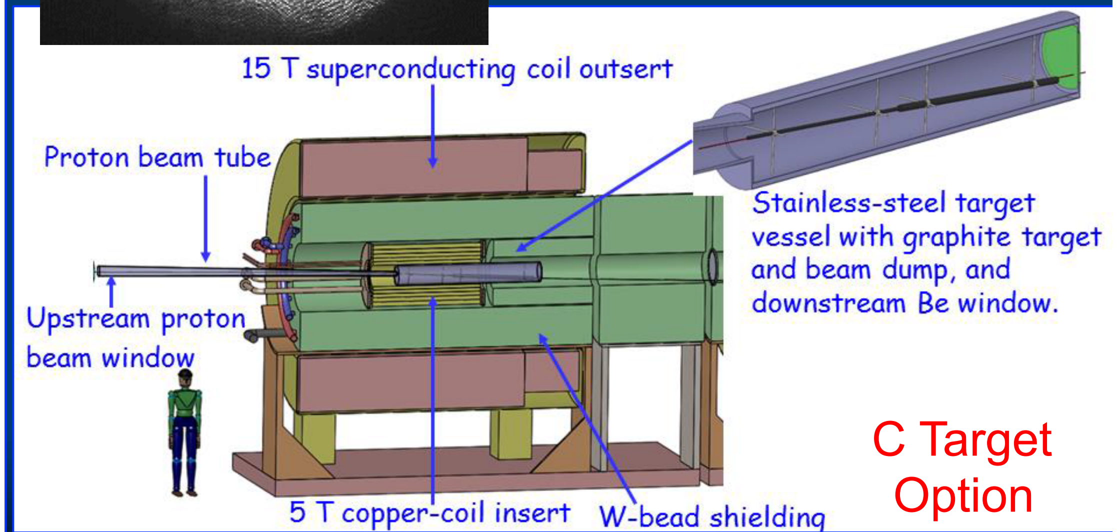
High Power Target





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





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

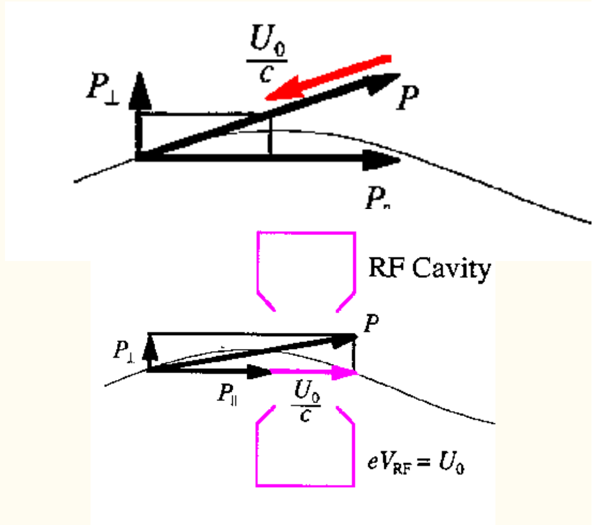
D. Neuffer

Ionization Cooling-general principle

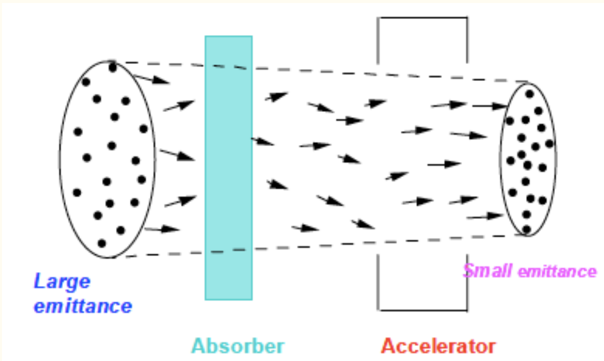
This method, called "dE/dx cooling" closely resembles to the synchrotron compression of relativistic electrons — with the multiple energy losses in a thin, low Z absorber substituting the synchrotron radiated light.

Transverse Cooling:

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



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
  - To keep multiple scattering less than beam divergence …

⇒ Quad focusing ?

⇒ Li lens focusing ?

⇒ Solenoid focusing?

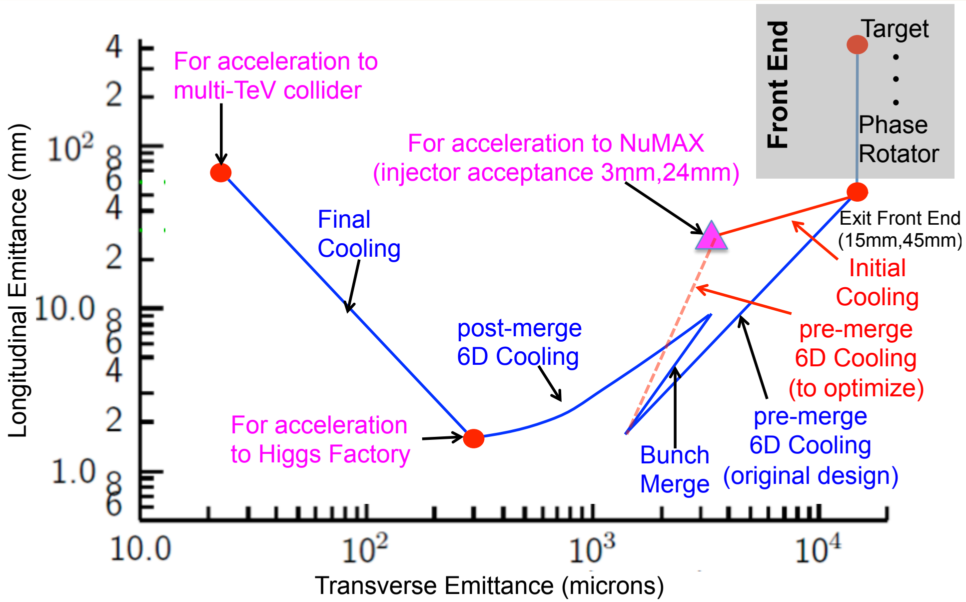
small beam size and large divergence damped by absorver + RF

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

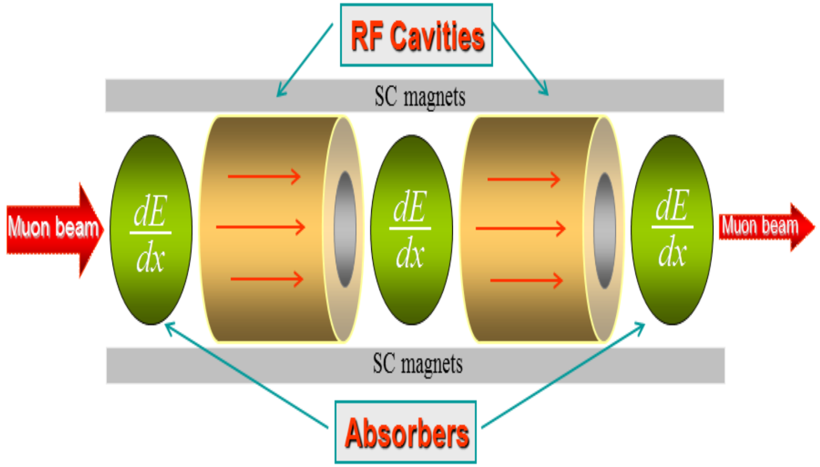
D. Neuffer

MAP Cooling scheme overview

P.Snopok (IIT)



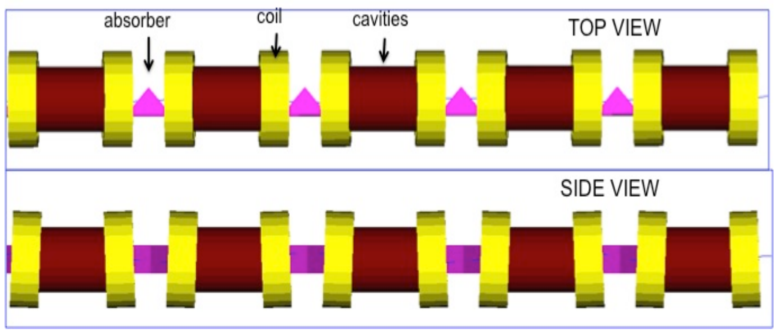
Ionization cooling

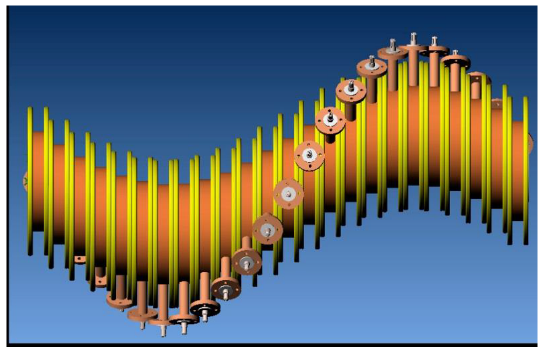


Vacuum Cooling Channel (VCC)

Helical Cooling Channel (HCC)

Two methods





Major challenges

Accelerating field limitation by magnetic field (10 T)

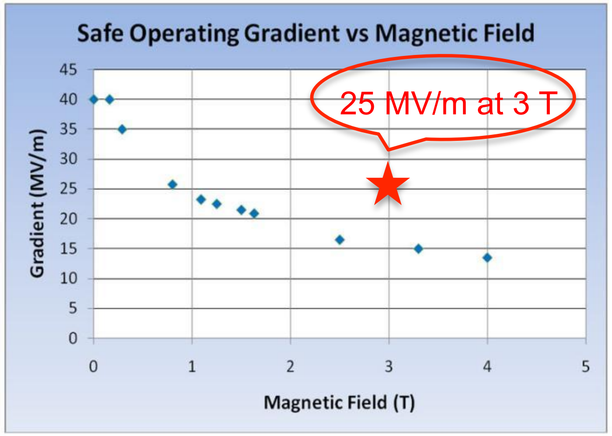
High pressure (160atm) Gas (GH2) filled RF cavities

ADVANCED Accelerator Concepts WORKSHOP

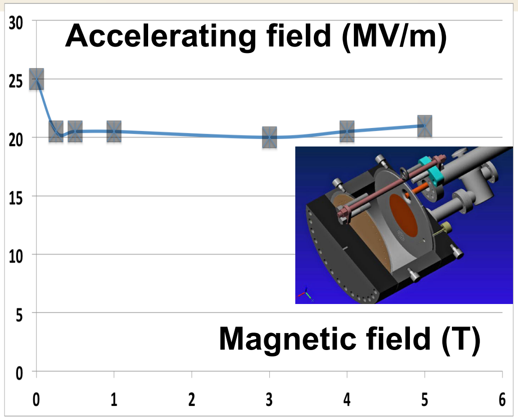
RF cavities in strong magnetic field

D.Li (LBNL)

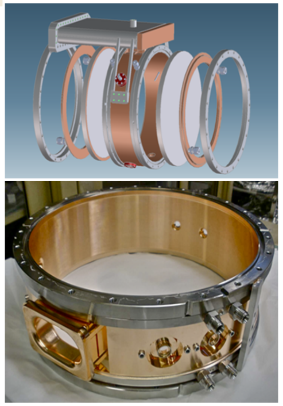
RF cavity in vacuum:

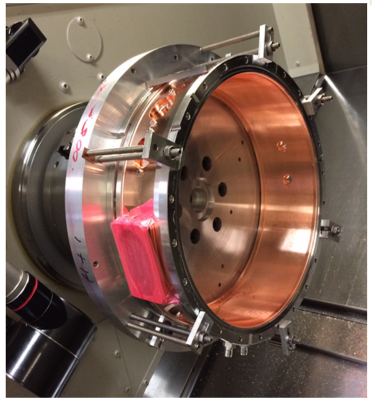


Breakdown by field emission



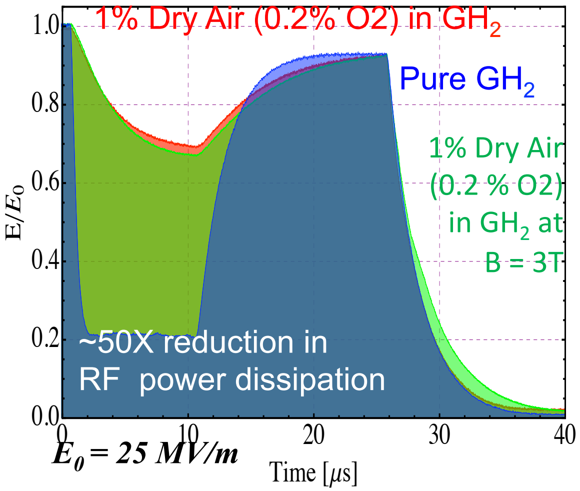
New cavity design very encouraging !





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

RF cavity filled with gas



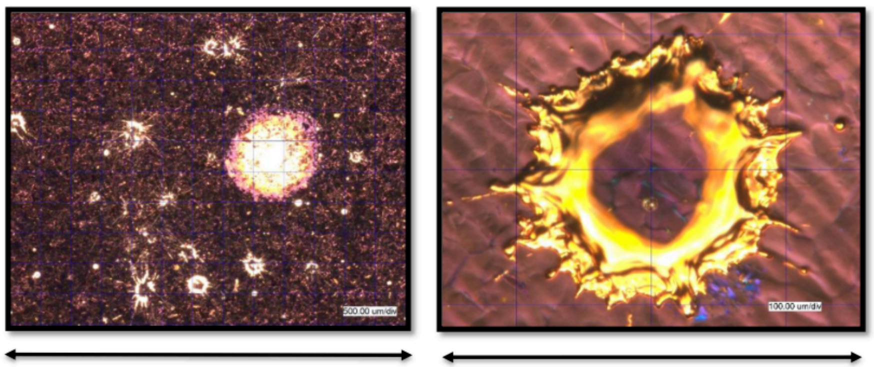
No accelerating field degradation up to 3 T

Operation with beam under heavy beam loading

Modular cavity: run history with copper endplates

- First B=0T run (baseline performance) :
  - Maximum Safe Operating Gradient of 45MV/m
  - 130 sparks detected
- First B=3T run: ← Inspection
  - Stable operation below 12MV/m
  - 55 sparks detected ← Inspection
- "Conditioning" B=0T run:
  - Conditioned up to 22MV/m inflicting 460 sparks ← Inspection
- Second B=3T run:
  - Maximum Safe Operating Gradient of 10MV/m

Splashing traces around BD damage



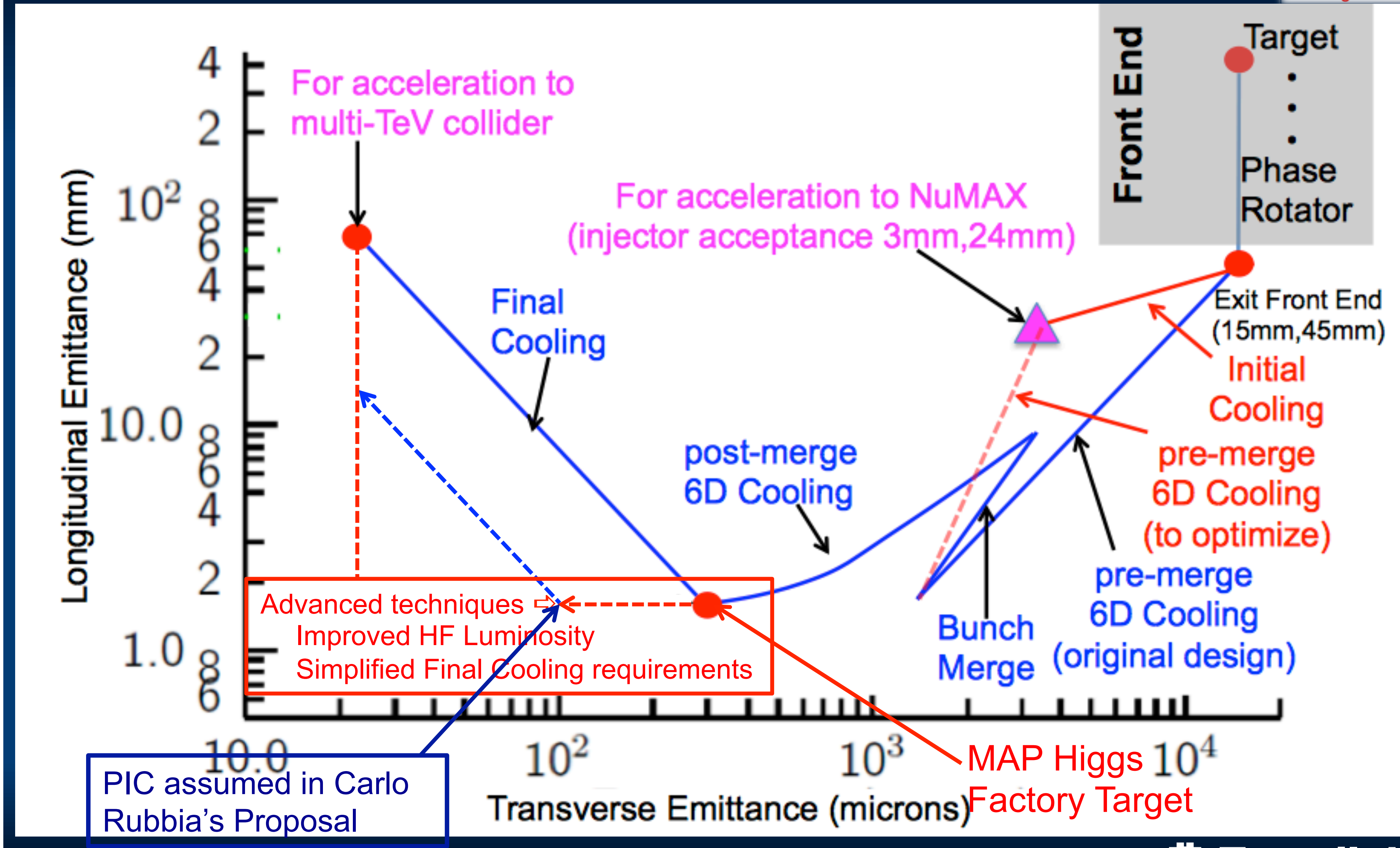
5mm *0.2mm*

A. Kochemirovskiy @ICHEP2016

- Damage is much more "violent", although stored energy was 16 times lower than in B=0 T run
- can be explained by focusing

M. Palmer

Muon Ionization Cooling

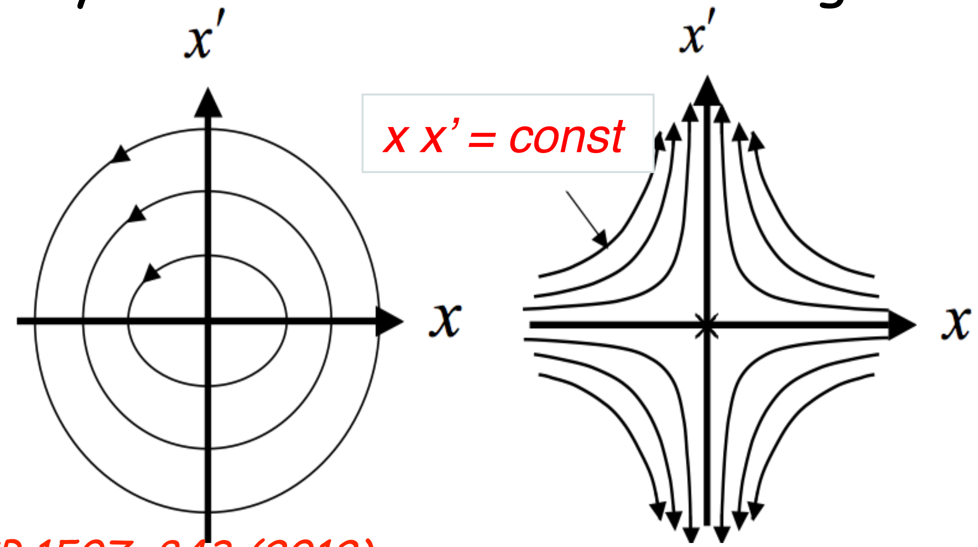


3.-PIC, the Parametric Resonance Cooling of muons

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.

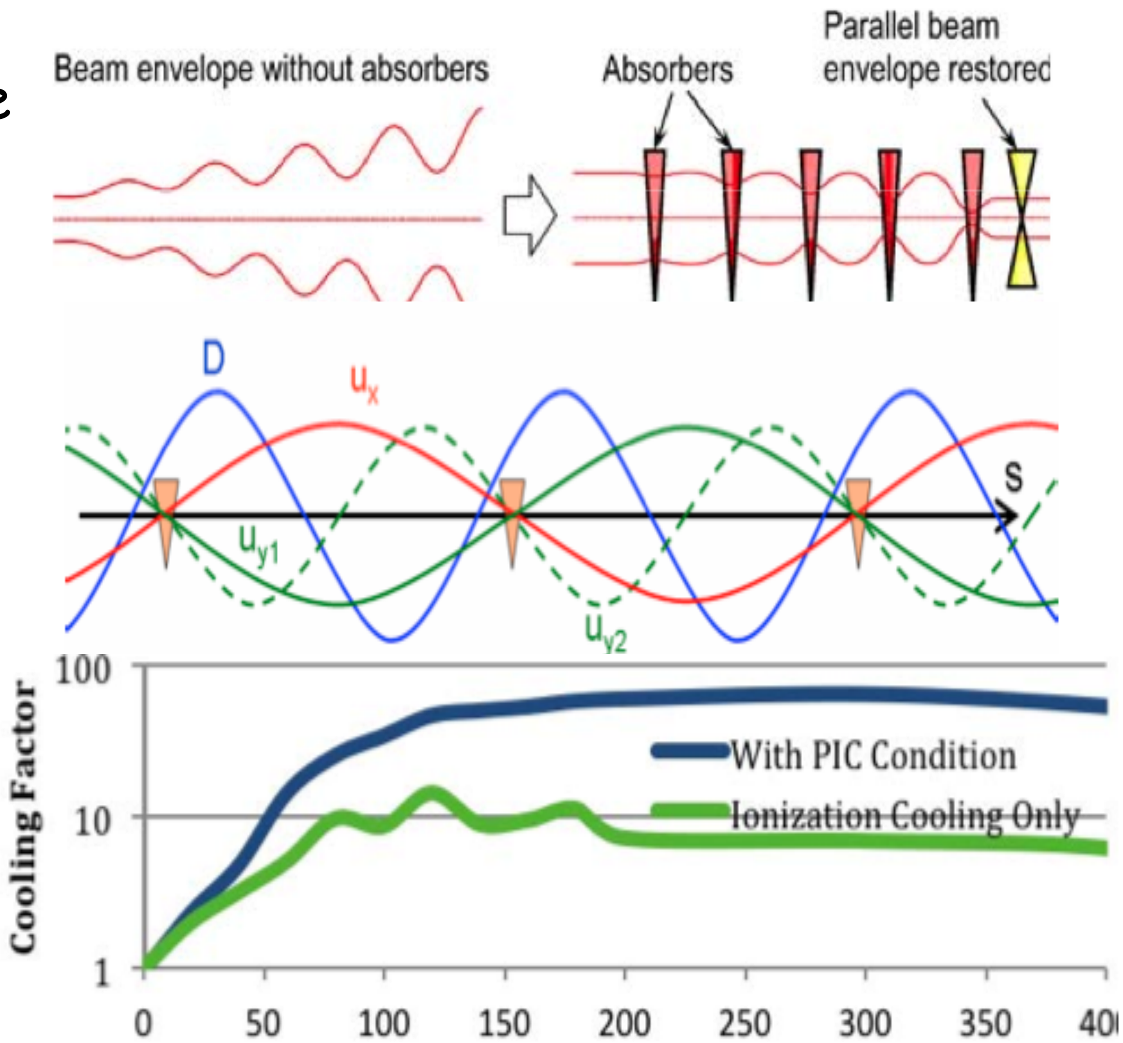


V. S. Morozov et al, AIP 1507, 843 (2012);

Details of PIC

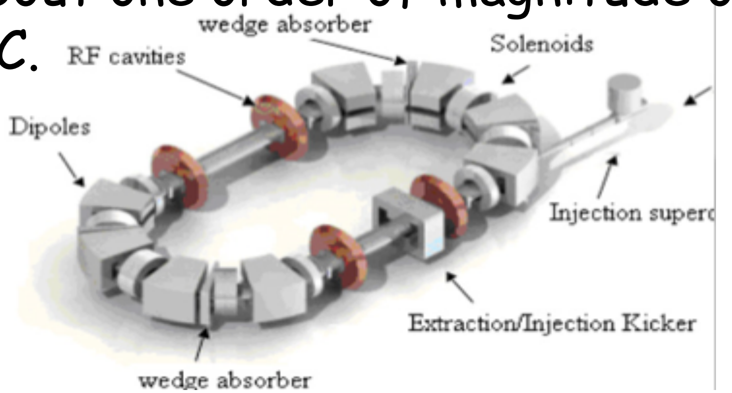
C. Rubbia

- 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

Acceleration, rings & MDI

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

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

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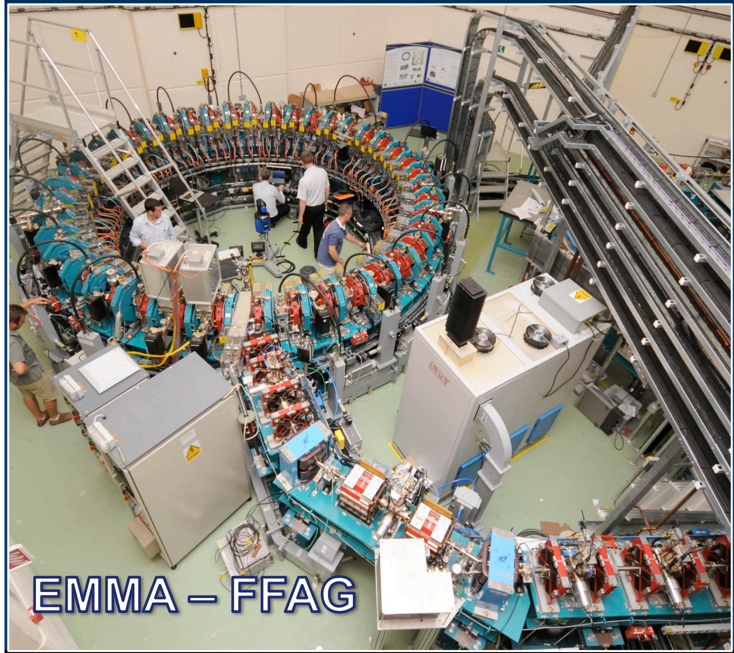
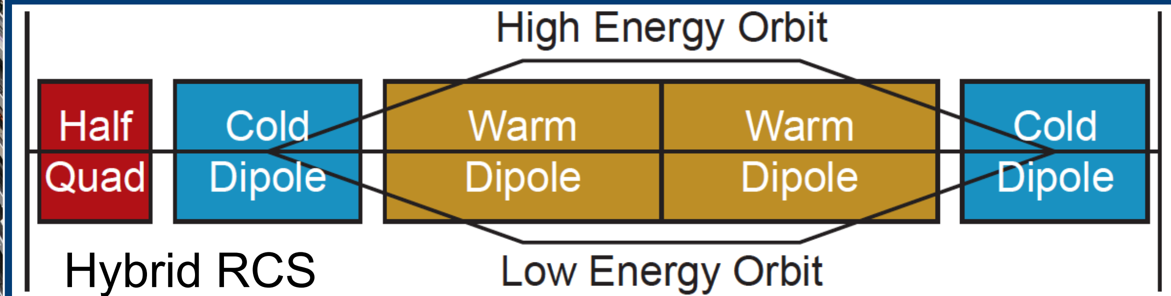
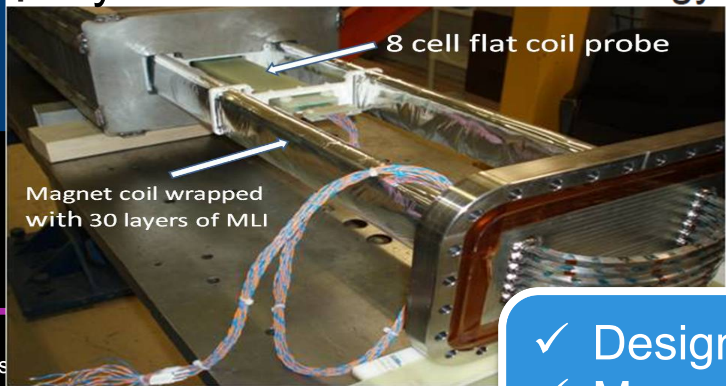
Acceleration

Technologies include:

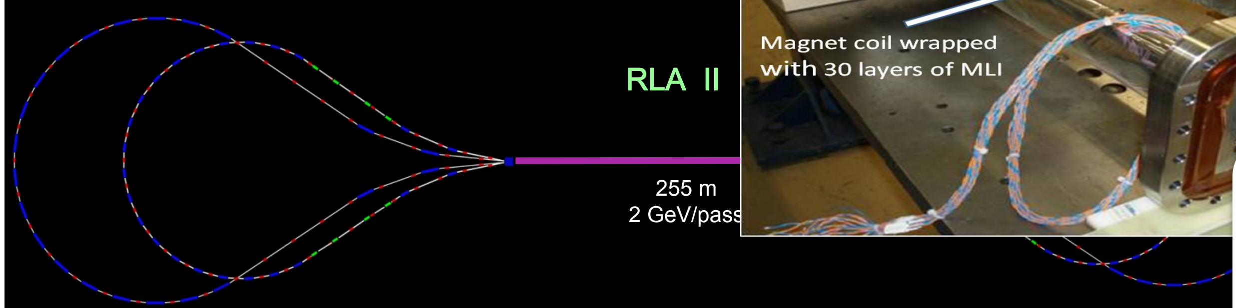
- Superconducting Linacs (NuMAX choice)
- Recirculating Linear Accelerators (RLAs)
- Fixed-Field Alternating-Gradient (FFAG) Rings
- (Hybrid) Rapid Cycling Synchrotrons (RCS) for TeV energies







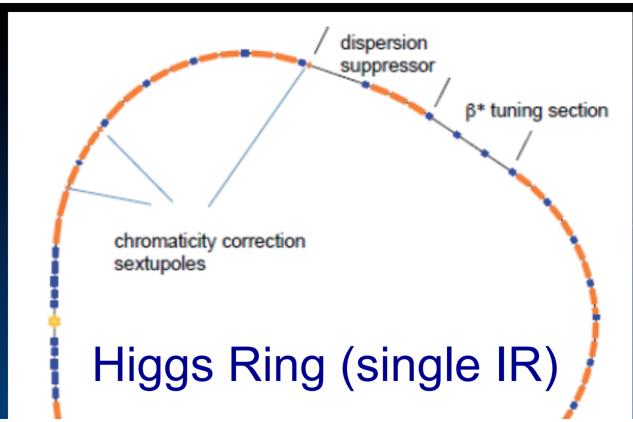
RCS requires 2 T p-p magnets at f > 400 Hz (U Miss & FNAL)



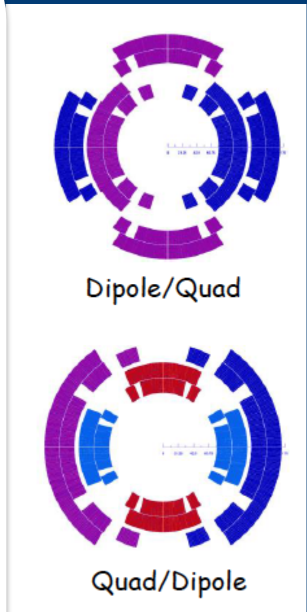
- ✓ Design concepts in hand
- ✓ Magnet R&D indicates parameters achievable

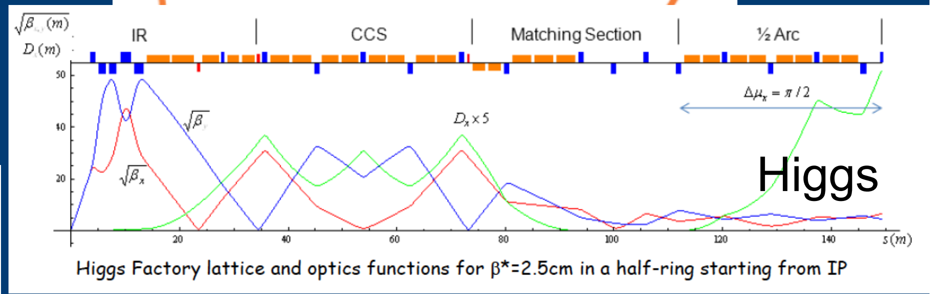
Collider Rings

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

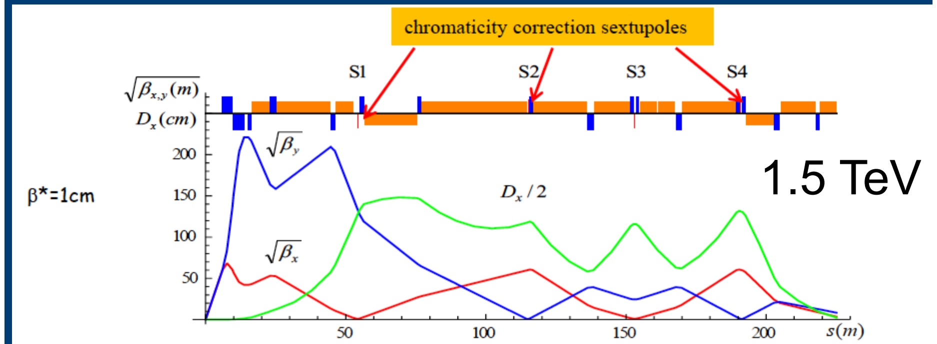


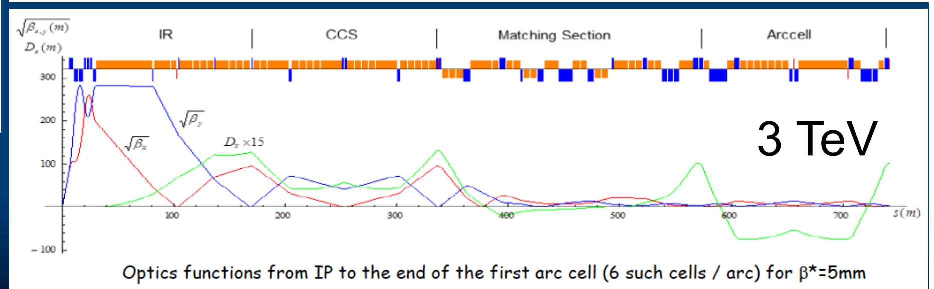
- ✓ Higgs, 1.5 TeV CoM and 3 TeV CoM Designs
  - With magnet concepts
  - Achieve target parameters
- ✓ Preliminary 6 TeV CoM design
  - Key issue is IR design and impact on luminosity
  - Utilizes lower power on target





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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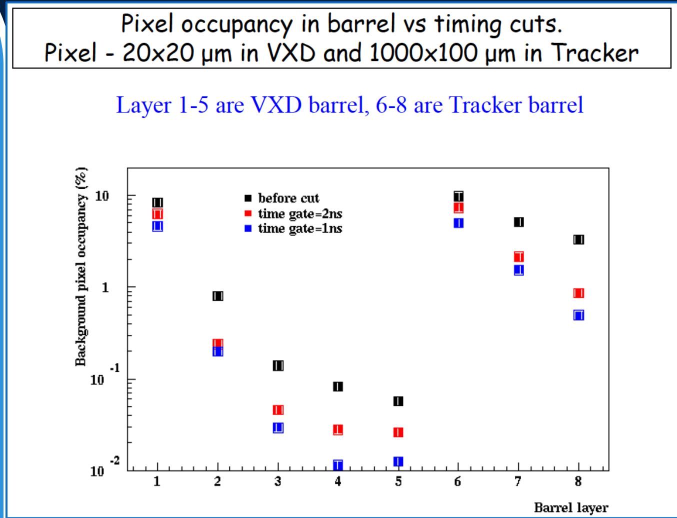
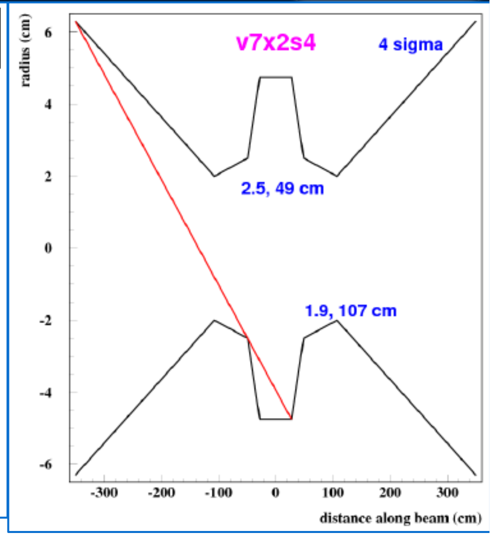
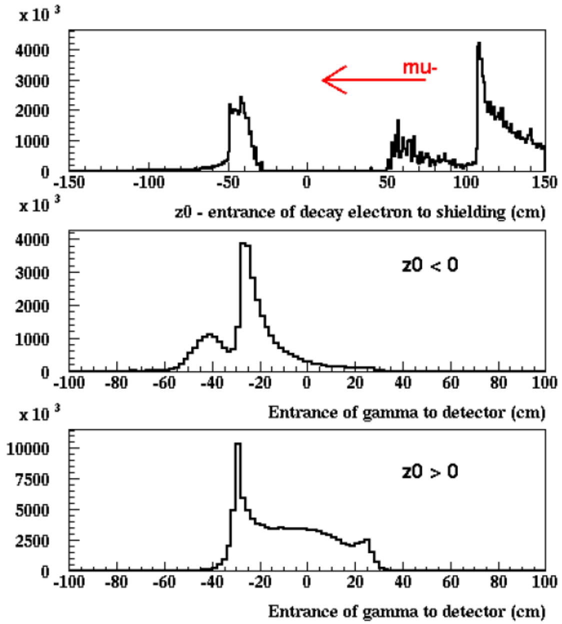
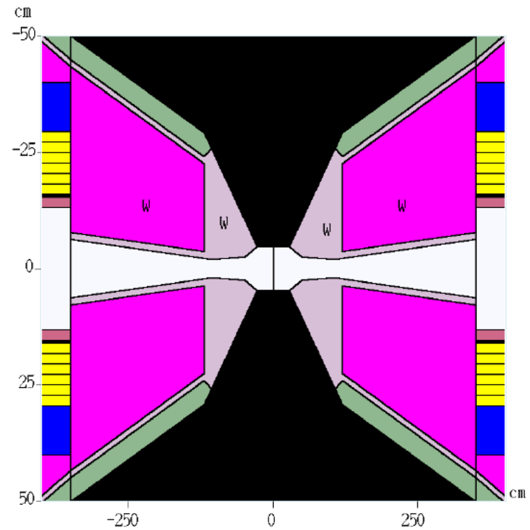
Machine Detector Interface

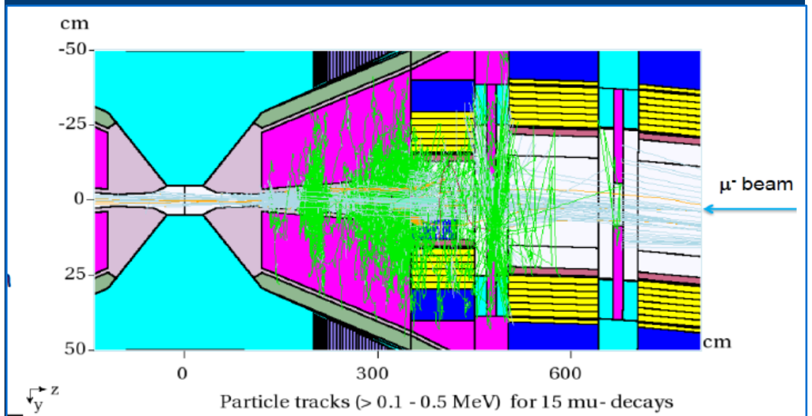
- ✓ Backgrounds appear manageable with suitable detector pixelation and timing rejection
- ✓ Recent study of hit rates comparing MARS, EGS and FLUKA appear consistent to within factors of <2
  - ⇨ Significant improvement in our confidence of detector performance











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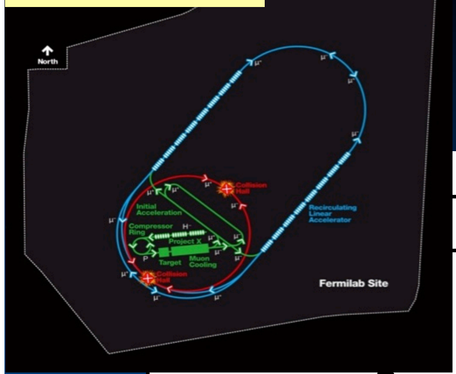


Muon Collider Parameters

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

Exploring the potential for a
Low Emittance Muon Collider

References:

- M.Antonelli, *"Very Low Emittance Muon Beam using Positron Beam on Target"*, **ICHEP (2016)**
- M.Antonelli, E.Bagli, M.Biagini, M.Boscolo, G.Cavoto, P.Raimondi and A.Variola, *"Very Low Emittance Muon Beam using Positron Beam on Target"*, **IPAC (2016)**
- M. Antonelli, *"Performance estimate of a FCC-ee-based muon collider"*, **FCC-WEEK 2016**
- M. Antonelli, *"Low-emittance muon collider from positrons on target"*, **FCC-WEEK 2016**
- 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

Also invetigated 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

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 $e^+e^- \rightarrow \mu^+\mu^-$ 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

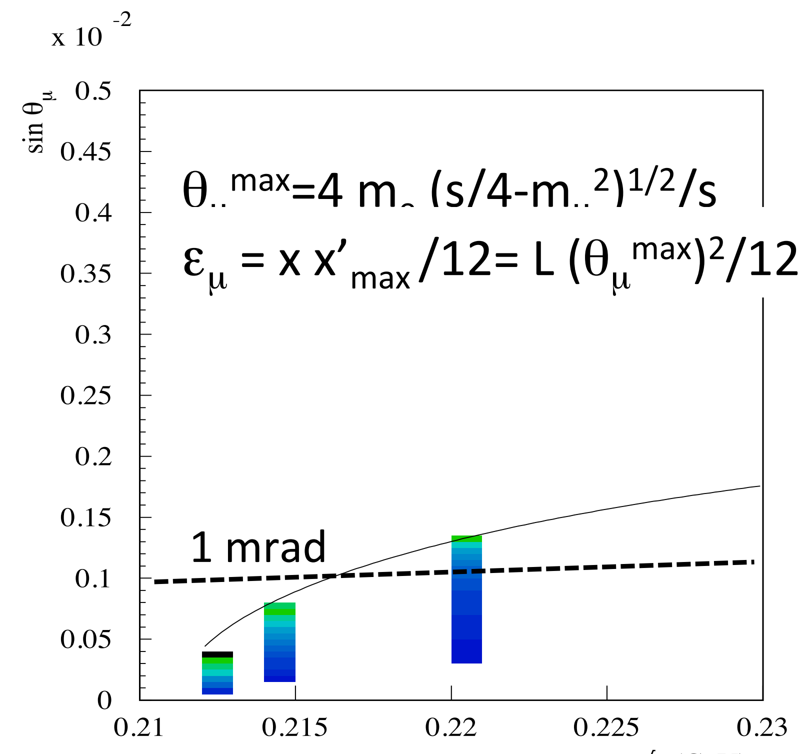
Possible Schemes

- **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
  - 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

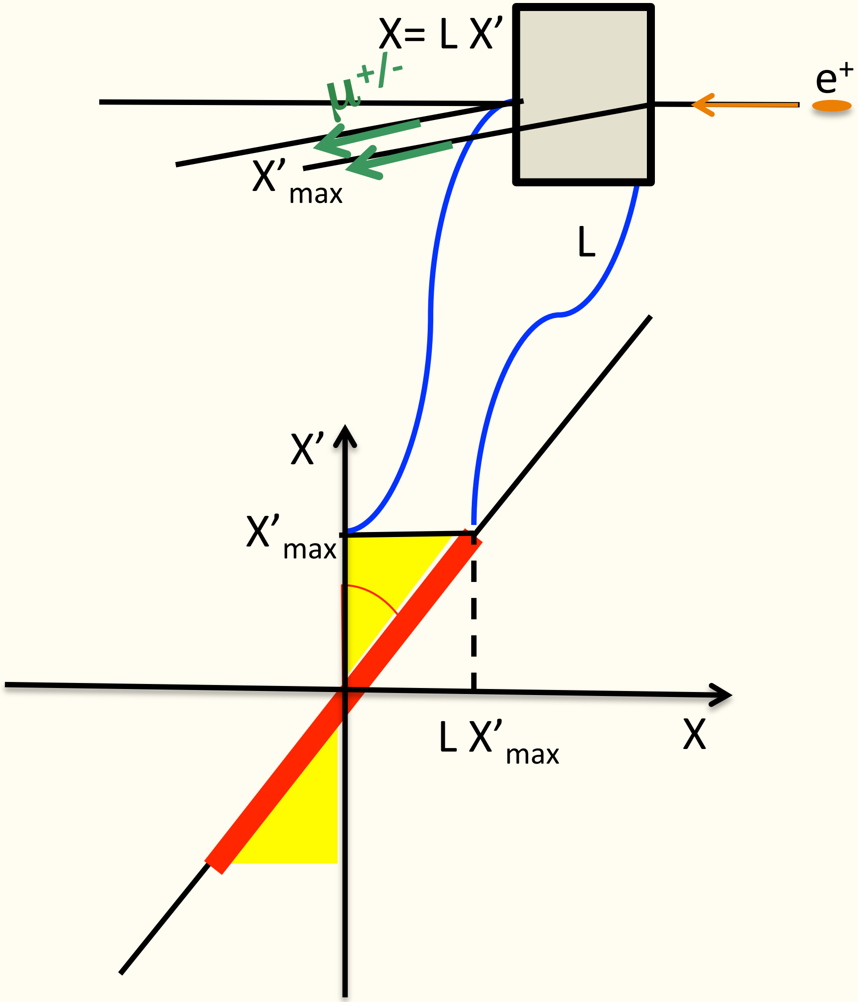
The target thickness and c.o.m. energy completely determine the emittance contributions due to muon production angle



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

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

[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

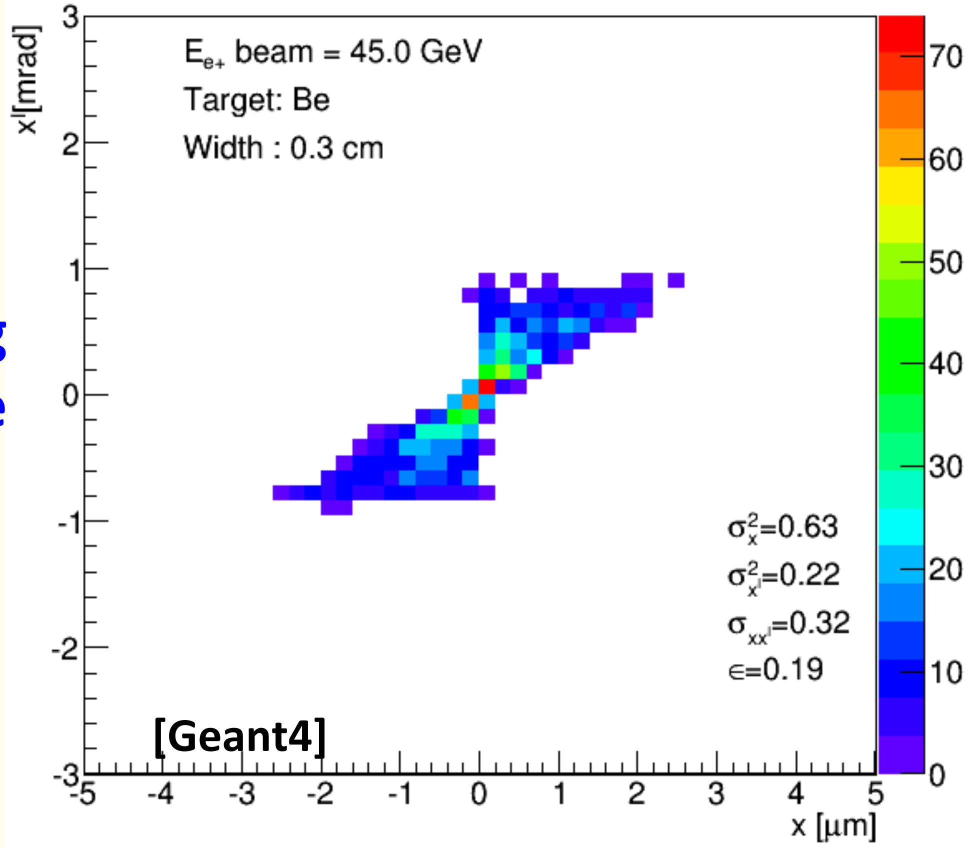
Multiple Scattering contribution is negligible

-> 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)

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

Muons at the target exit surface

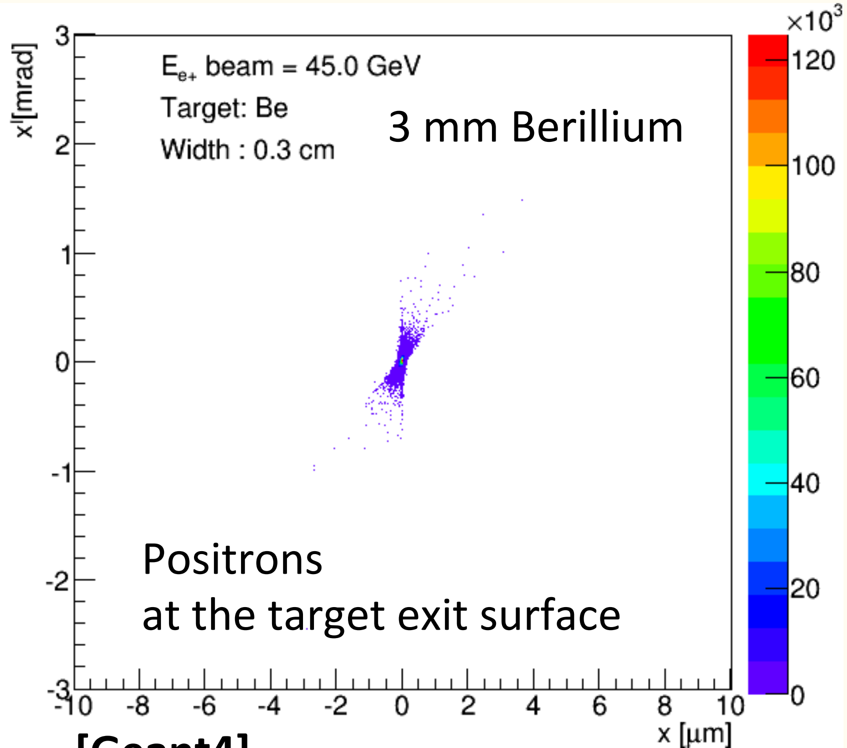


Positrons Storage Ring Requirements

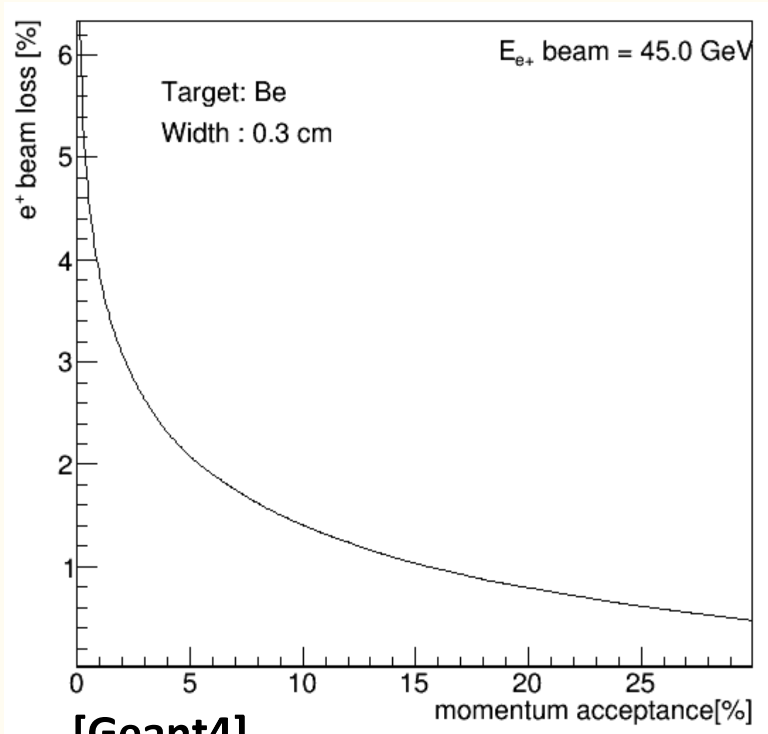
- Transverse phase space almost not affected by target
- Most of positrons experience a small energy deviation:

  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



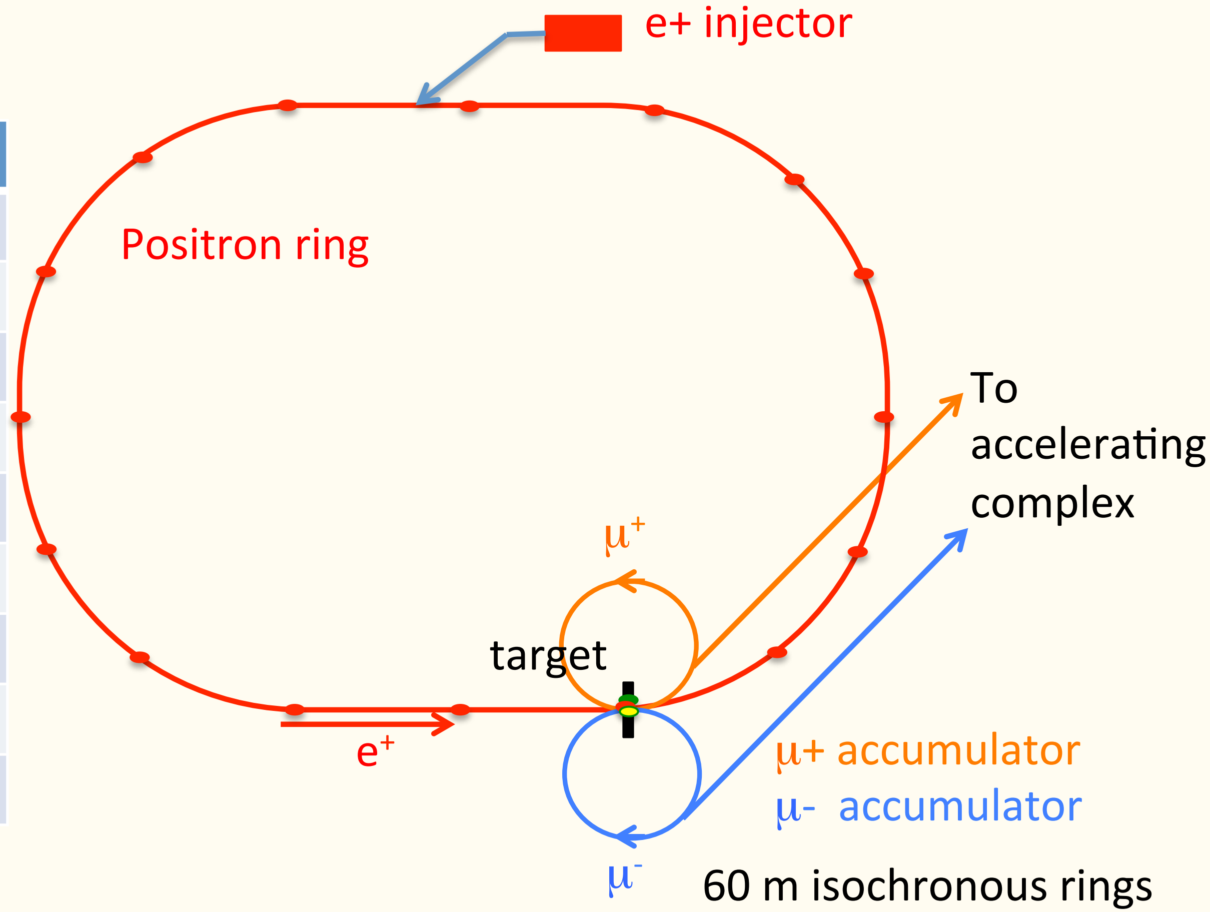
[Geant4]



[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



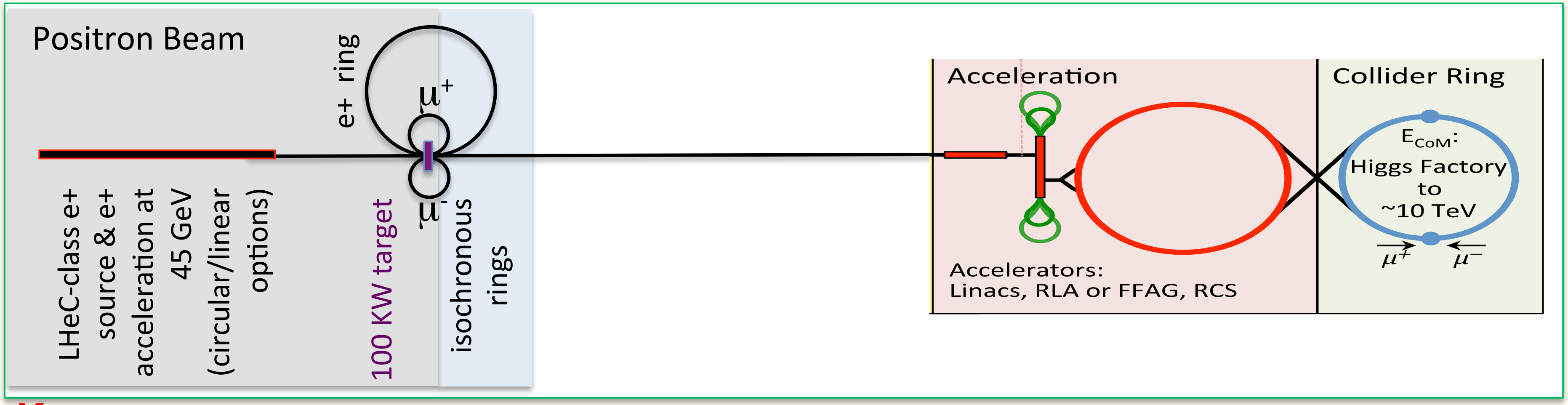
60 m isochronous rings recombine bunches

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

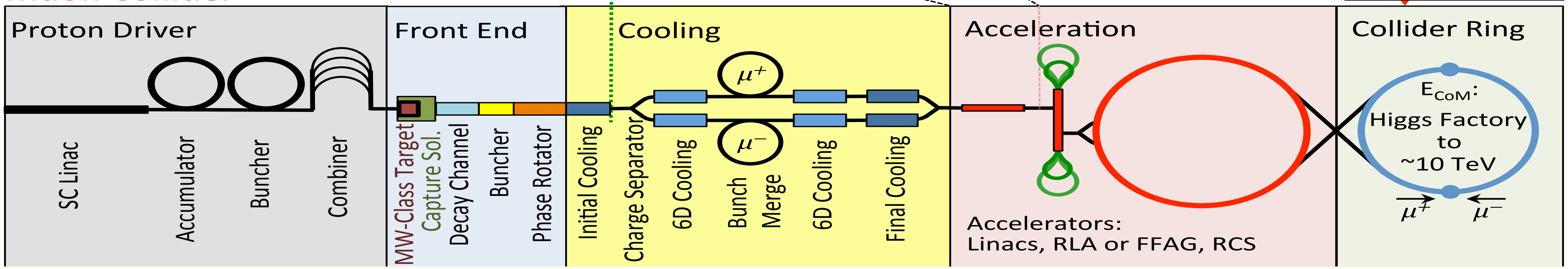
Key R&D

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

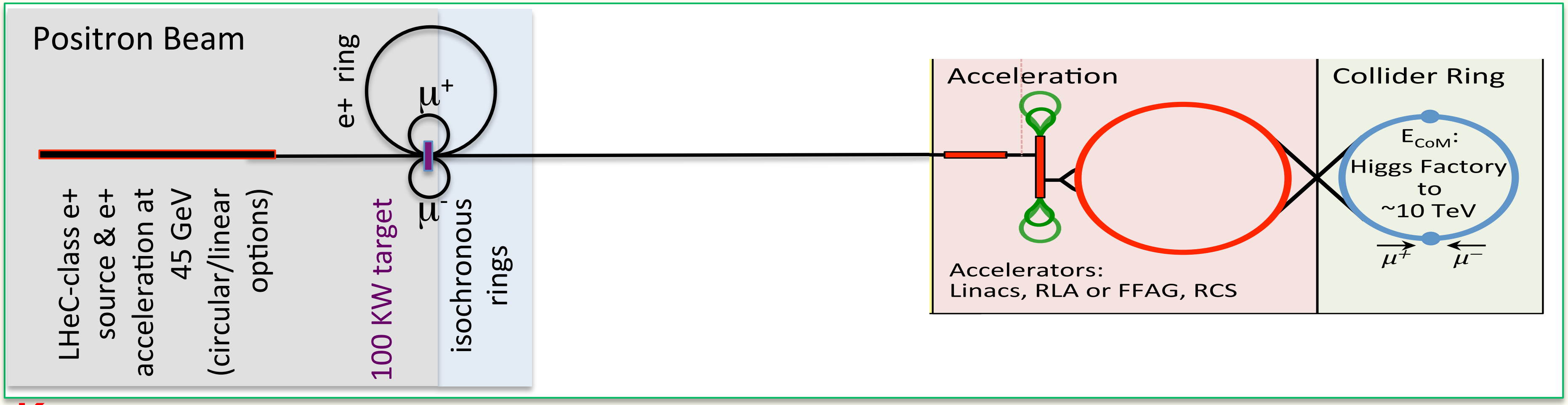
Key Challenges

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

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.

Low Emittance Mu+ Mu- Accelerator Draft Parameters

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

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

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

Radiological hazard due to neutrinos from a muon collider

Colin Johnson, Gigi Rolandi and Marco Silari

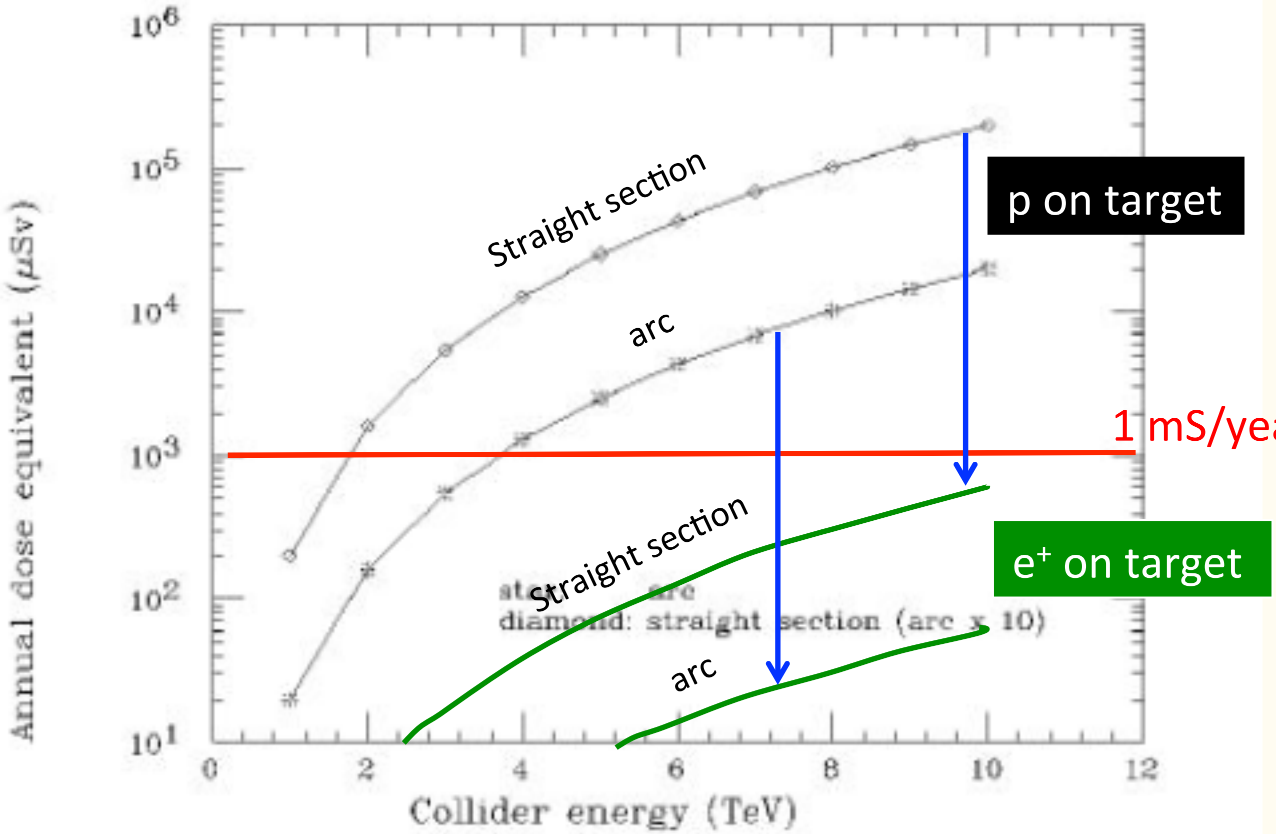


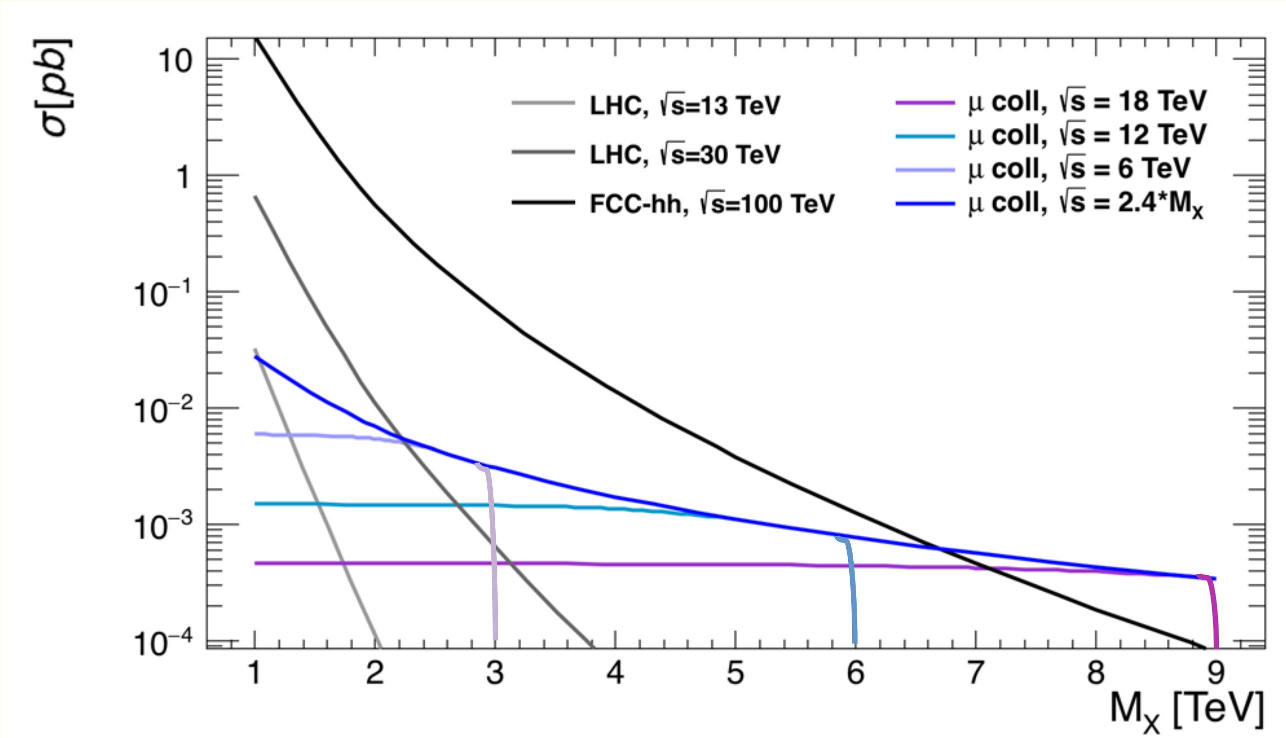
Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

muon rate: p on target option 3 10^{13} μ/s

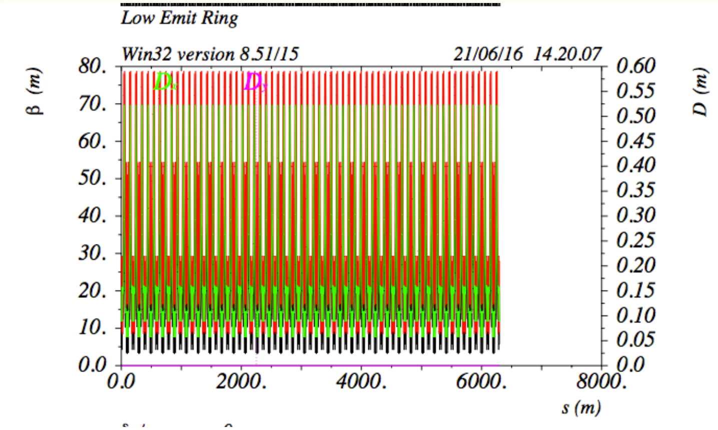
e+ on target option 9 10^{10} μ/s

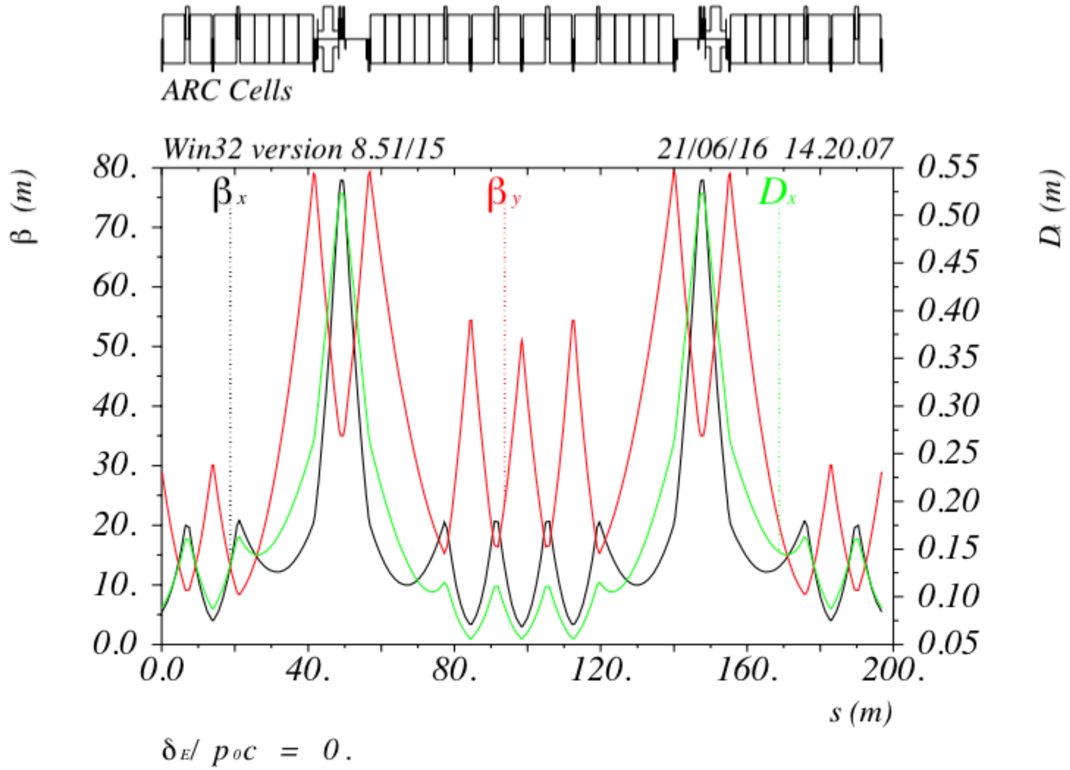
Muon collider reach: an example

- Study the same benchmark used for White Paper:
  - New heavy particles, both colored and EW charged (~vector like quarks)➔ xsec can be predicted
  - FCC reach stops at M_X = 7 TeV
- Hadron machine pays the price of the exponentially falling PDF ➔ multi-TeV muon machine can be competitive!



First Optics for e^+ ring





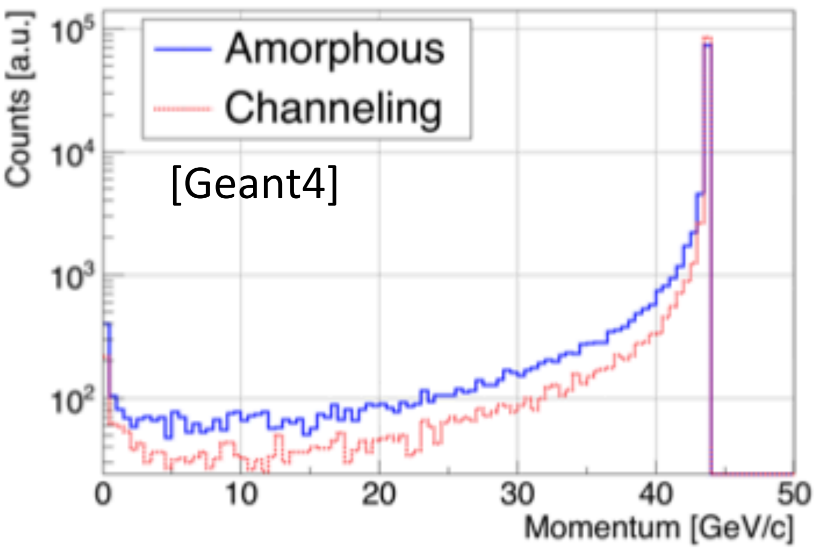
Parameter	Units	pos.
Energy	GeV	4
Circumference	m	63
Bending radius	m	70
Magnetic rigidity	T m	1
Lorentz factor		880
Coupling (full current)	%	
Emittance x (from model)	m	5.73
Emittance y	m	5.73
Bunch length (zero current)	mm	3
Beam current	mA	2
RF frequency	Hz	5.00
RF voltage	GV	0.
Revolution frequency	Hz	4.76
Harmonic number	#	10
Revolution period	s	2.10
Number of bunches	#	1
N. Particle/bunch	#	3.15
Syncronous phase	#	0.
Syncrotron frequency	Hz	241
Synchrotron tune	#	5.08
synchrotron period	turns	19
Overvoltage		1.
Transverse damping time	turns	175
Transverse damping time	s	0.0
Longitudinal damping time	turns	87
Longitudinal damping time	s	1.84
Energy Loss/turn	GeV	0.
Momentum compaction		1.21
B field	T	0.
Rf energy acceptance	%	3.
Energy spread (SR)	dE/E	1.00
SR power loss	GW	0.
SR power/Circumference	kW/m	19

Crystals as a target ?

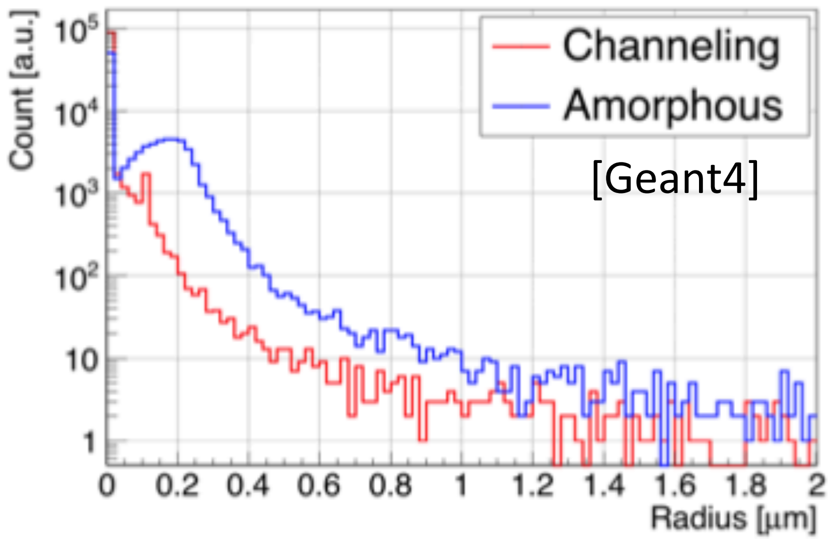
Positrons

43.8 GeV e^+
4.1 mm Si Target
Channeling plane: (110)

Momentum

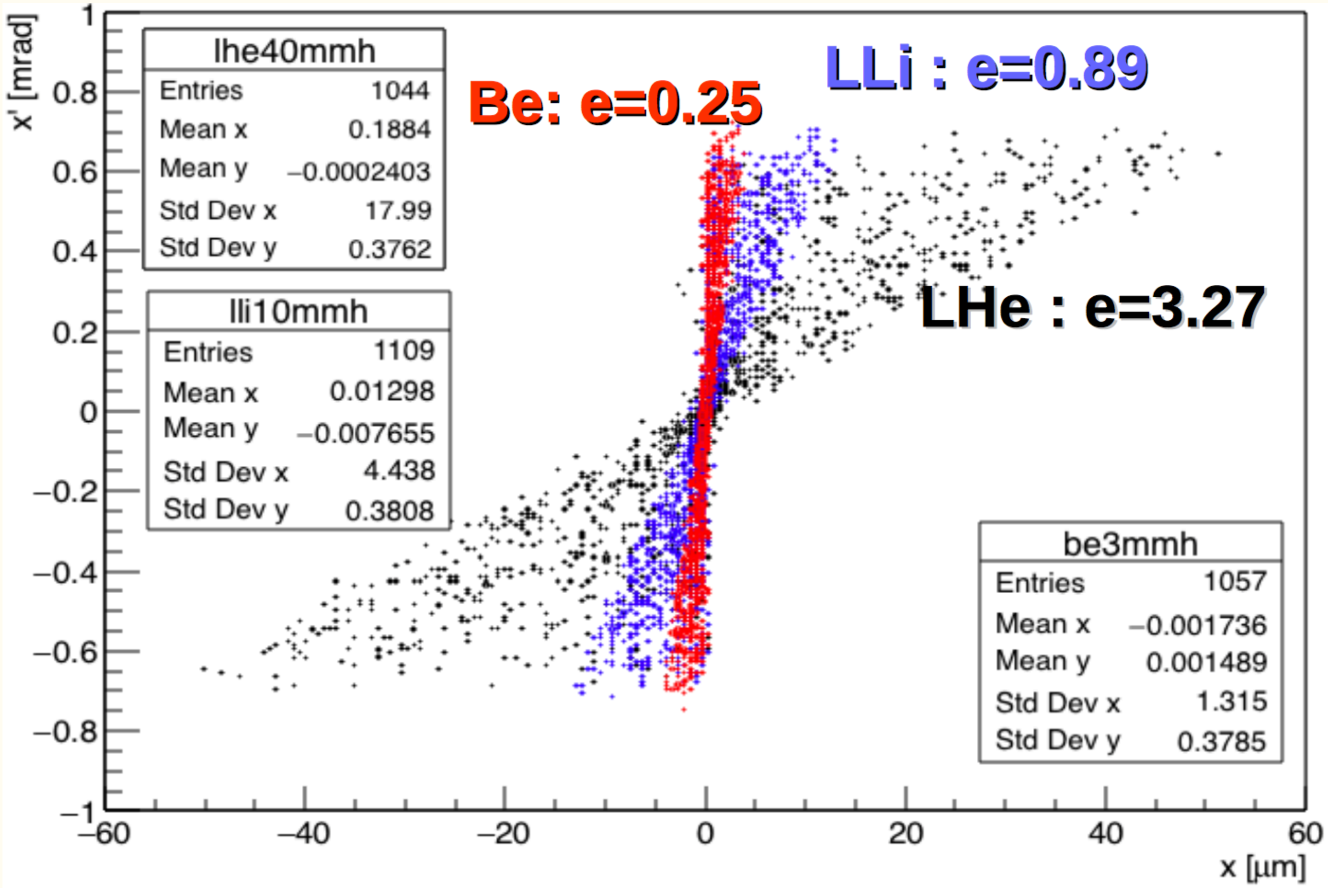


Position



Going to lighter targets for μ production

Look to light liquid targets to reduce problems of thermo-mechanical stresses



LLi might be a good option:

<factor 4 ε increase →

<2 worse In L

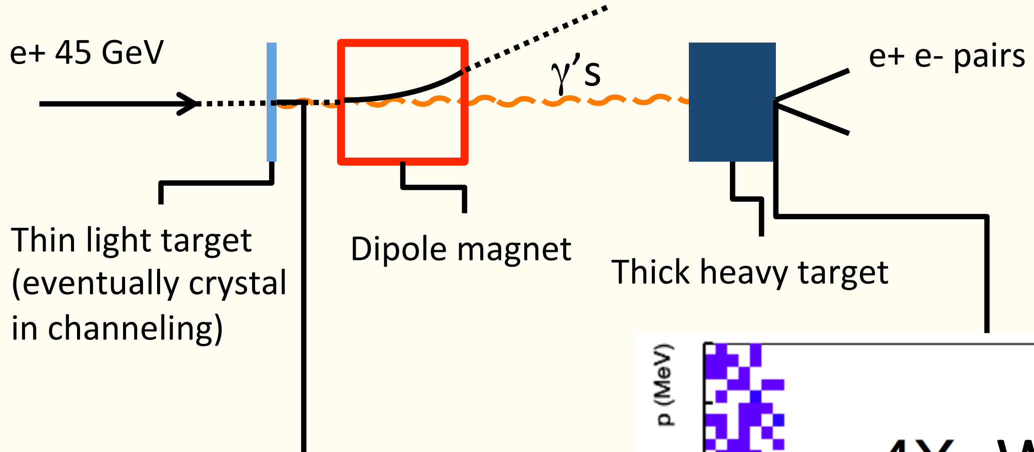
25% gain in e+ survival @ same μ production efficiency

Proposed/tested for targets for n production

High Boiling point 1615 K
Mass evaporation?
Safety?

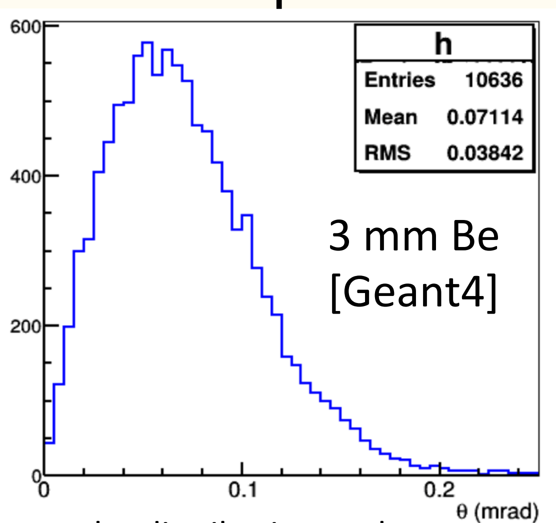
Embedded positron source?

Positron source extending the target complex?
Possibility to use the γ's from the μ production target to produce e+

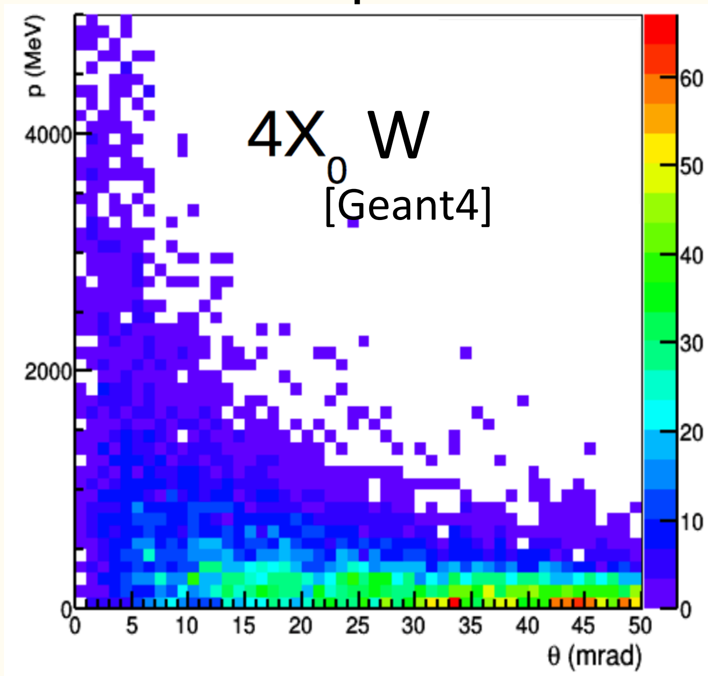


Proposed for example for CLIC

Produce a fraction of 8% e+ of the incoming positron beam



γ's angular distribution at the target exit



Assuming a 10% collection efficiency
Need to have 45 GeV e^+ loss on thin target <1%

Fast acceleration to 45 GeV (~ KHz) like μ

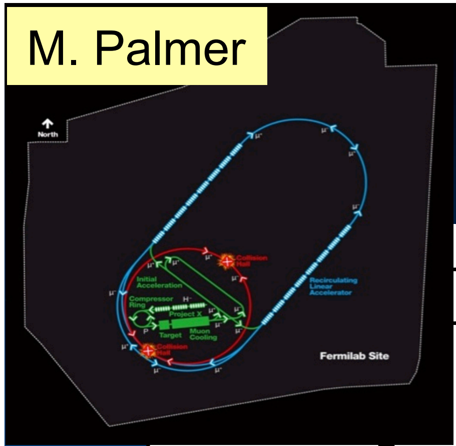
Target/s survival 100 KW (on the thin one)on small area

Low Emittance MC Draft Parameters vs $\sqrt{s}$

NEED deep investigation to be validated

		e+ ERL/LINAC	e+ STORAGE RING						
		MUFACT	MUFACT	MUFACT	MUFACT	MUFACT	MUFACT	MUFACT	MUFACT
Parameter	Units	Higgs	Higgs	ZH	Top	ILC-like	ILC-like-1000	MultiTeV	MultiTeV
LUMINOSITY/IP	$cm^{-2}\ s^{-1}$	4,15E+31	1,69E+31	7,06E+31	1,54E+32	2,94E+32	1,18E+33	5,08E+34	2,03E+35
Beam Energy spread	%	0,46	3,17	1,65	1,13	0,79	0,40	0,07	0,03
Beam Energy	GeV	62,50	62,50	120	175	250	500	3000	6000
Hourglass reduction factor		1,00	1,00	1,000	1,000	1,000	1,000	1,000	1,000
Muon mass	GeV	0,10566	0,10566	0,10566	0,10566	0,10566	0,10566	0,10566	0,10566
Lifetime @ prod	sec	2,20E-06	2,20E-06	2,20E-06	2,20E-06	2,20E-06	2,20E-06	2,20E-06	2,20E-06
Lifetime	sec	0,0013	0,0013	0,0025	0,0036	0,0052	0,0104	0,0625	0,1249
c*tau @ prod	m	658,00	658,00	658,00	658,00	658,00	658,00	658,00	658,00
c*tau	m	3,89E+05	3,89E+05	7,47E+05	1,09E+06	1,56E+06	3,11E+06	1,87E+07	3,74E+07
1/tau	Hz	7,68E+02	7,68E+02	4,00E+02	2,74E+02	1,92E+02	9,61E+01	1,60E+01	8,00E+00
Circumference	m	150,00	150,00	300	450	600	1200	6000	12000
Bending Field	T	15,00	15,00	15	15	15	15	15	15
Bending radius	m	13,89	13,89	27	39	56	111	667	1333
Magnetic rigidity	T m	208,33	208,33	400	583	833	1667	10000	20000
Gamma (Lorentz factor)		591,52	591,52	1135,72	1656,26	2366,08	4732,16	28392,96	56785,92
N turns before decay		2594,80	2594,80	2491,01	2421,81	2594,80	2594,80	3113,76	3113,76
β_x @ IP	m	0,00020	0,00020	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002
β_y @ IP	m	0,00020	0,00020	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002
Beta ratio		1,00	1,00	1,0	1,0	1,0	1,0	1,0	1,0
Coupling (full current)	%	100	100	100	100	100	100	100	100
Normalised Emittance x	m	5,90E-09	4,00E-08	4,00E-08	4,00E-08	4,00E-08	4,00E-08	4,00E-08	4,00E-08
Emittance x	m	9,97E-12	6,76E-11	3,52E-11	2,42E-11	1,69E-11	8,45E-12	1,41E-12	7,04E-13
Emittance y	m	9,97E-12	6,76E-11	3,52E-11	2,42E-11	1,69E-11	8,45E-12	1,41E-12	7,04E-13
Emittance ratio		1,00	1,00	1,0	1,0	1,0	1,0	1,0	1,0
Bunch length (full current)	mm	0,10	0,10	0,1	0,1	0,1	0,1	0,1	0,1
Beam current	mA	0,64	0,04	0,040	0,040	0,040	0,040	0,048	0,048
Revolution frequency	Hz	2,00E+06	2,00E+06	9,99E+05	6,66E+05	5,00E+05	2,50E+05	5,00E+04	2,50E+04
Revolution period	s	0,00	0,00	1,00E-06	1,50E-06	2,00E-06	4,00E-06	2,00E-05	4,00E-05
Number of bunches	#	1,00	1,00	1	1	1	1	1	1
N. Particle/bunch	#	2,00E+09	1,20E+08	2,50E+08	3,75E+08	5,00E+08	1,00E+09	6,00E+09	1,20E+10
Number of IP	#	1,00	1,00	1	1	1	1	1	1
σ_x @ IP	micron	0,04	0,12	8,39E-02	6,95E-02	5,81E-02	4,11E-02	1,68E-02	1,19E-02
σ_y @ IP	micron	0,04	0,12	8,39E-02	6,95E-02	5,81E-02	4,11E-02	1,68E-02	1,19E-02
$\sigma_{x'}$ @ IP	rad	0,00	0,00	4,20E-04	3,47E-04	2,91E-04	2,06E-04	8,39E-05	5,93E-05

M. Palmer



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}]

Key Feasibility Issues

Positron Source

Muon Target

Positron Ring

HIGH rate

Non destructive

Mom. acceptance

Targets survival

NEED
deep investigation
(design study)

- μ Acceleration
- Collider Ring
- Collider MDI
- Collider Detector

(mostly) independent on muon source
Benefit from MAP studies

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)

Key Feasibility Issues

Proton Based Source

- Proton Driver
- Target
- Front End
- **Cooling (PIC)**

Positron Based Source

- Positron Source
- Muon Target
- Positron Ring

not yet investigated

- μ Acceleration
- Collider Ring
- Collider MDI
- Collider Detector

(mostly) independent on muon source

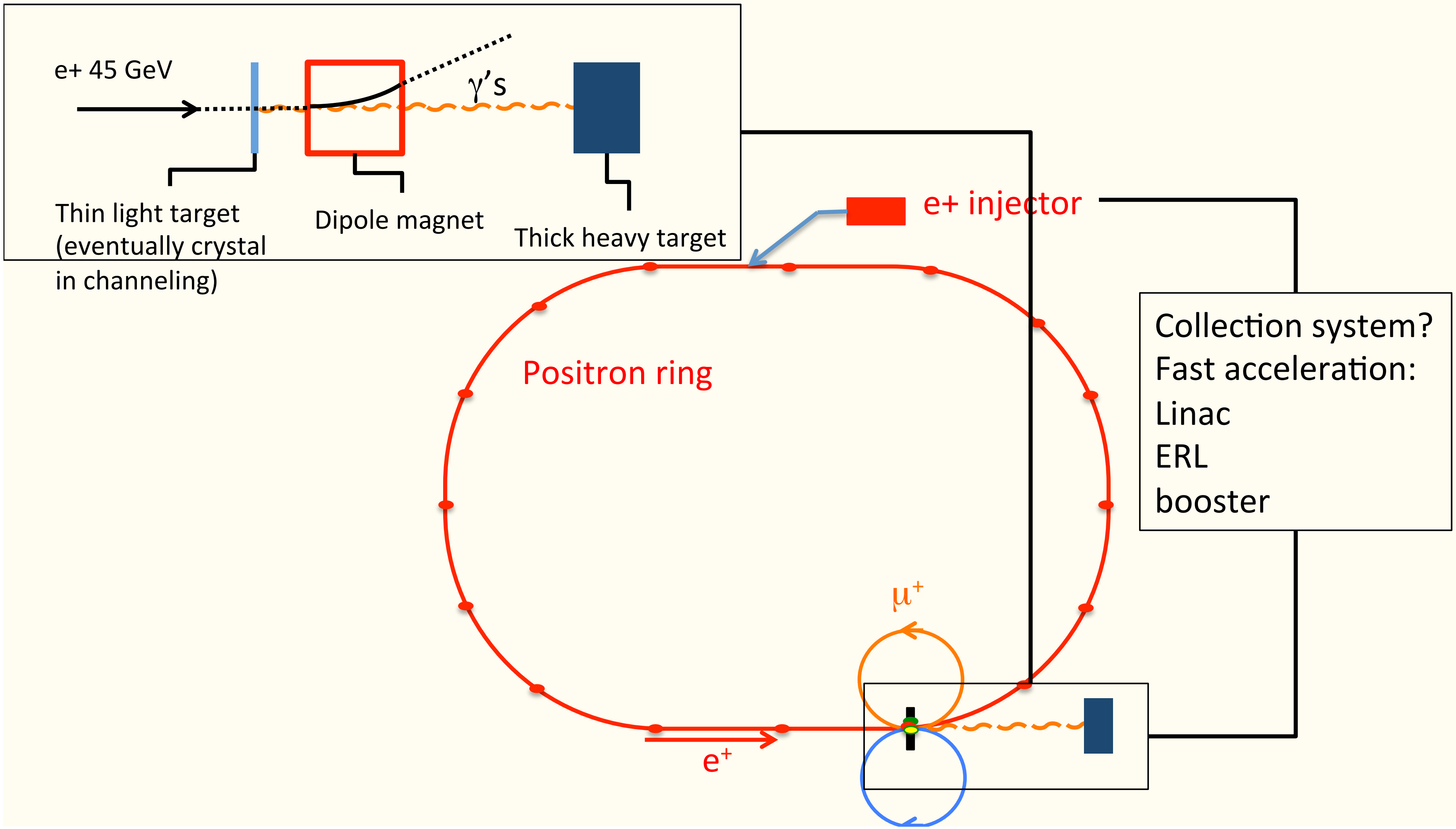
synergy with the two options

Conclusion

- Muon Colliders deeply studied by Muon Accelerator Program (R&D and tests in smooth progress)
  - Cooling experiments are ongoing (MICE) and new ideas for cooling have been proposed (PIC)
  - Need for experimental tests to proceed
- 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/FCC-eh, ILC,…)
  - Positron ring with high momentum acceptance (synergy with next generation SL sources and FCC-ee)
  - Thin targets surviving to ~100 KW
- fast muon acceleration concepts and collider rings design studied by MAP

Backup Slides

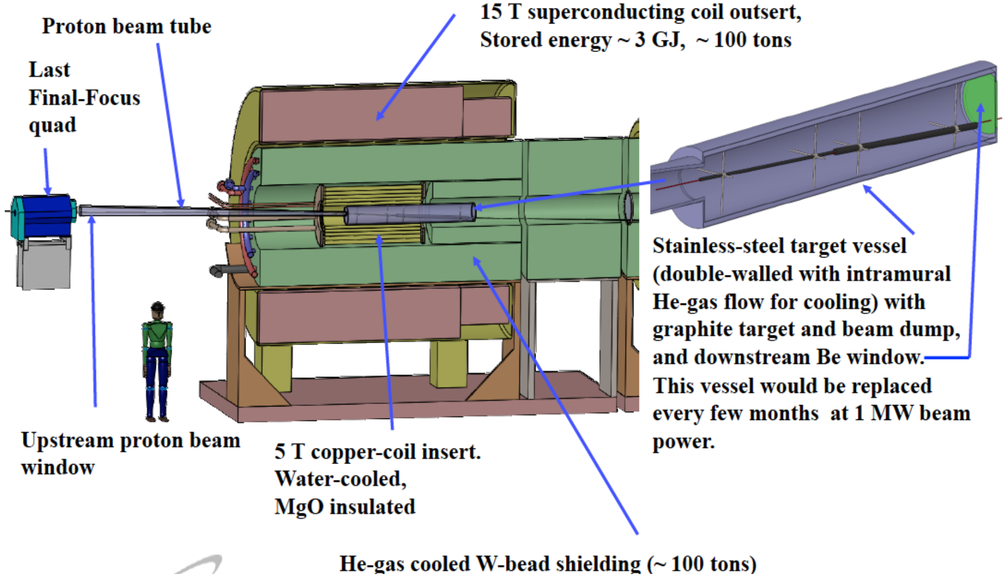
Embedded positron source?



MAP muon generation by Proton driver

H.Kirk (BNL)

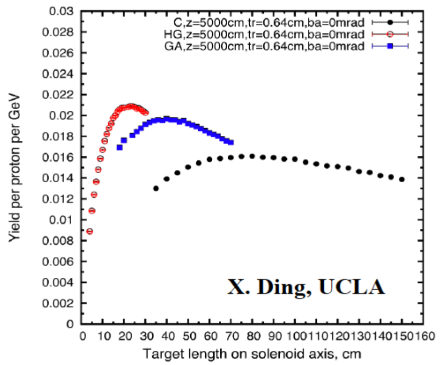
A Graphite Target Core



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

- 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)

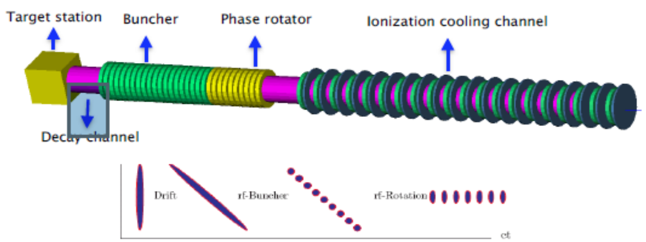
A 25% advantage of using high-Z Hg compared to low-Z Carbon

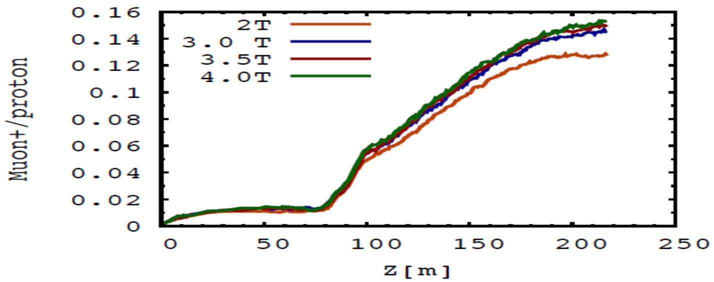
Low-z Carbon is attractive due to it's simplicity and robustness

Proton Beam: KE = 6.75 GeV

Normalization: For Hg $\Sigma(\mu^+ + \mu^-)/\text{proton} \approx 1$

H.K.Sayed (BNL)





Muon per proton production at Front End exit

Tests with e^+ beam

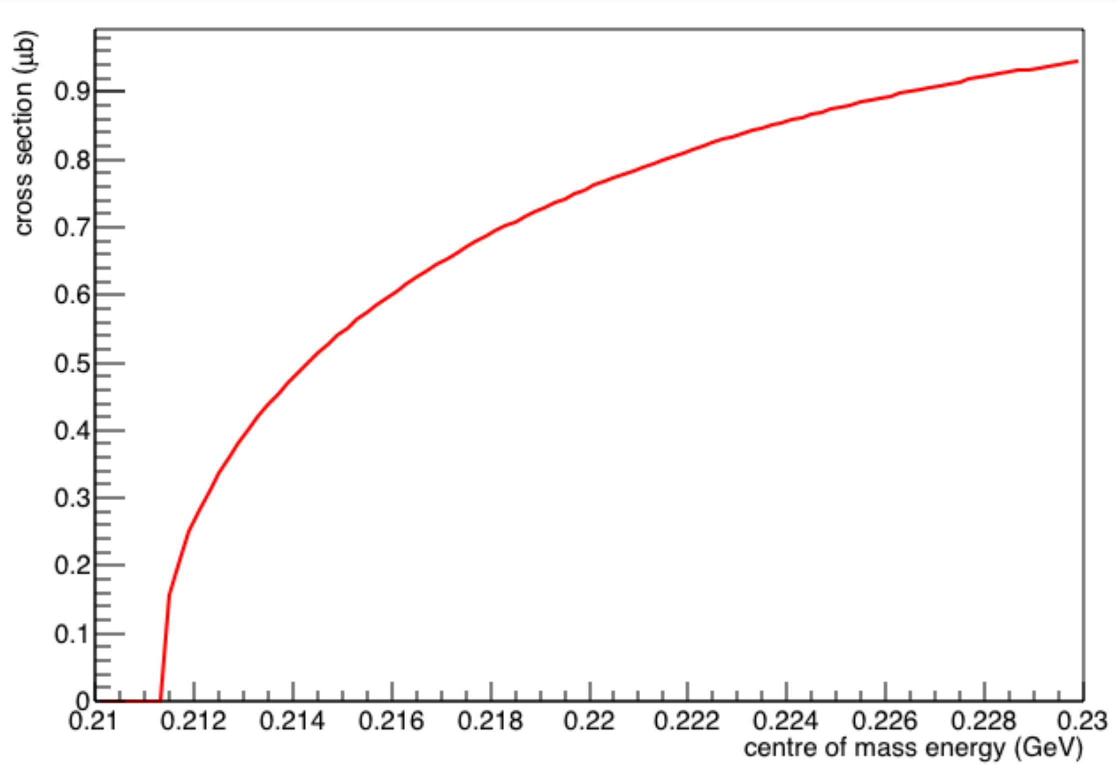
Use tertiary 45 GeV e^+ beam in CERN North area (H4)
(ask for 2 weeks of beam time for next year)

- Low intensity (one by one e^+ tracking) with crystals and amorphous targets:
  measure beam degradation (emittance energy spectrum)
  measure produced photons flux and spectrum

- High intensity (up to 5 x 10^6 /spill) with amorphous targets:
  measure muon production rate and muons kineamatic properties

Processes at √s around 0.212 GeV

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

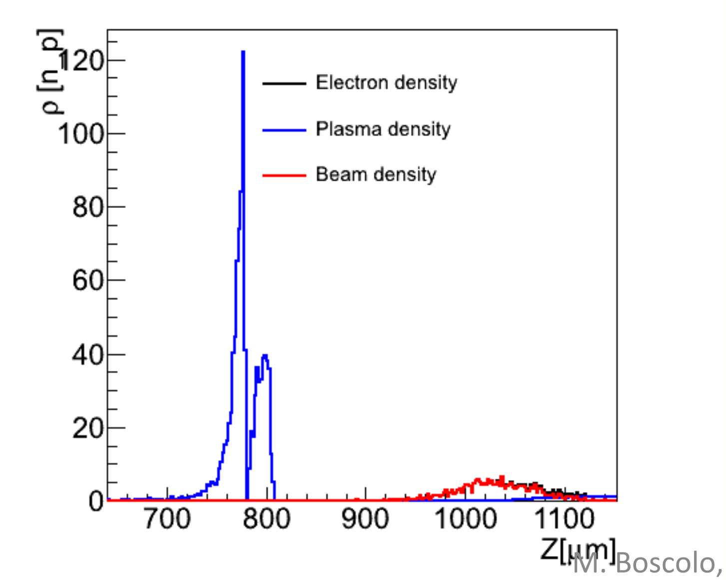


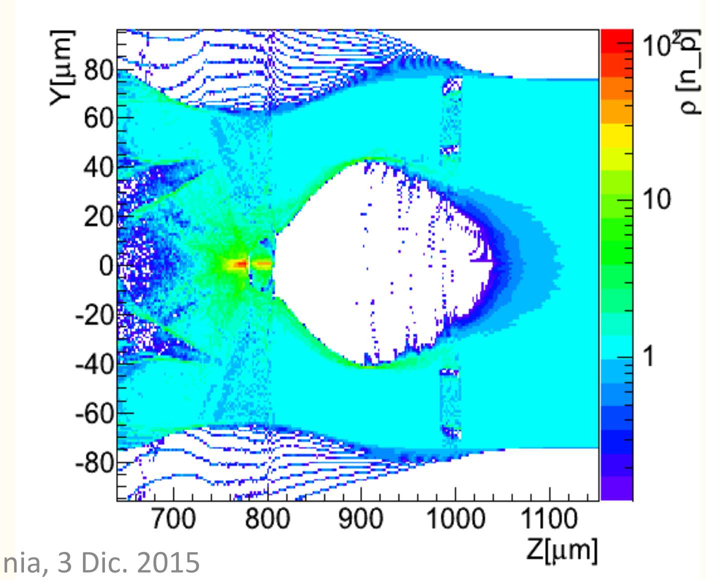
Muonium production also investigated:
huge cross section (mb range)
10^{-4} eV width

Not viable…. Deeper studies?

Few statements on the plasma option

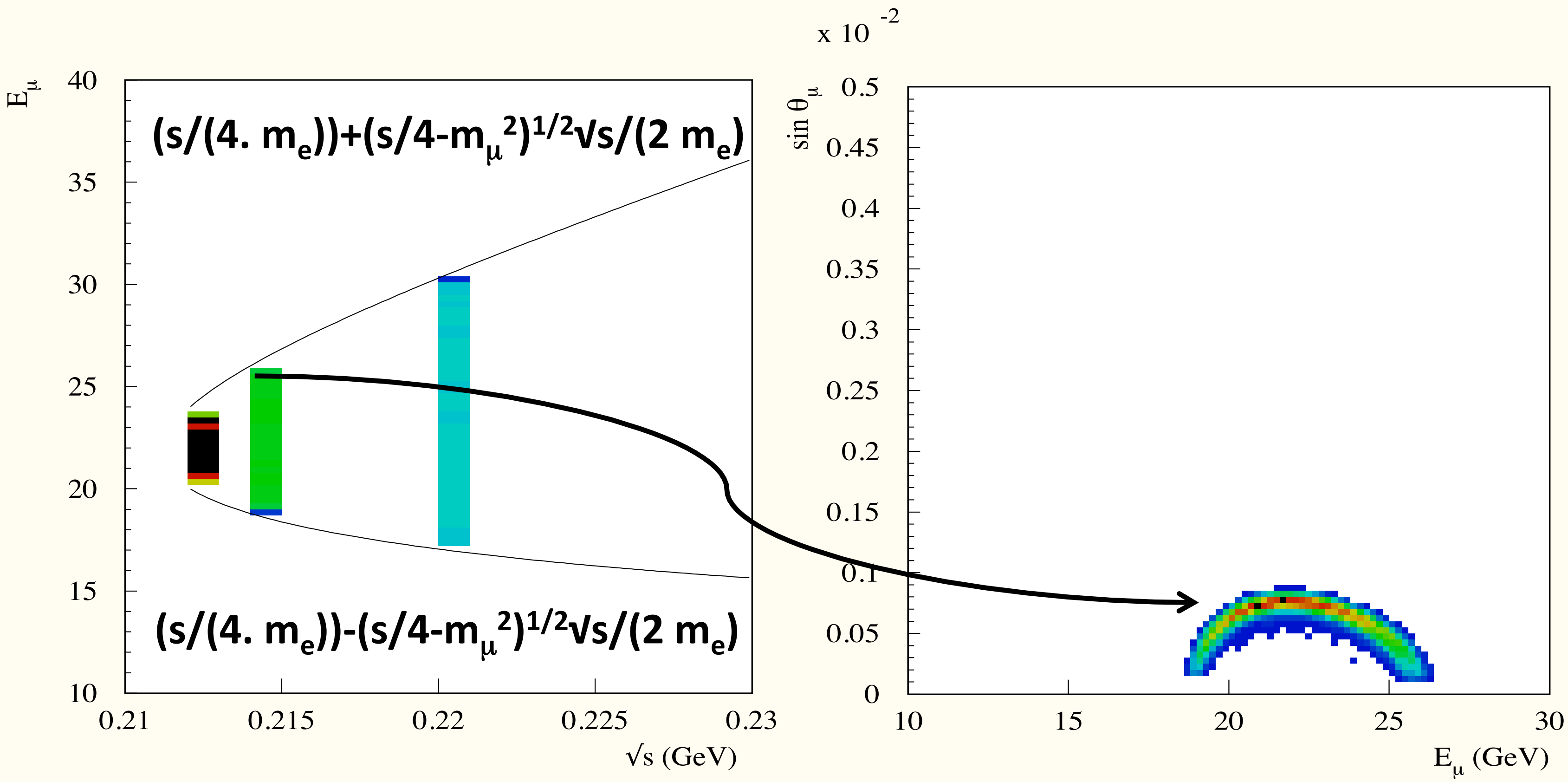
- Plasma would be a good approximation of an ideal electron target ++ autofocussing by Pinch effect
- enhanced electron density can be obtained at the border of the blow-out region (up x100)
- Simulations for $n_p=10^{16}$ electrons/cm^3 (C. Gatti, P. Londrillo)
- Region size decreases with $1/\sqrt{n_p}$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





Processes at $\sqrt{s}$ ~ 0.212 GeV e^+ on target

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



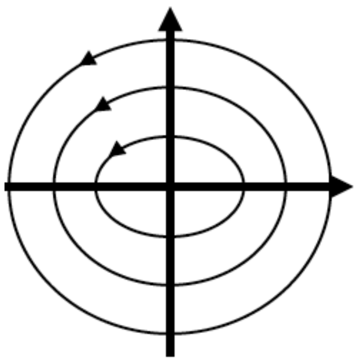
Parametric-resonance Ionization Cooling

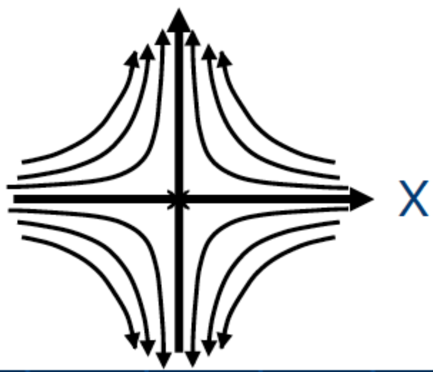
see Derbenev, Johnson, Beard

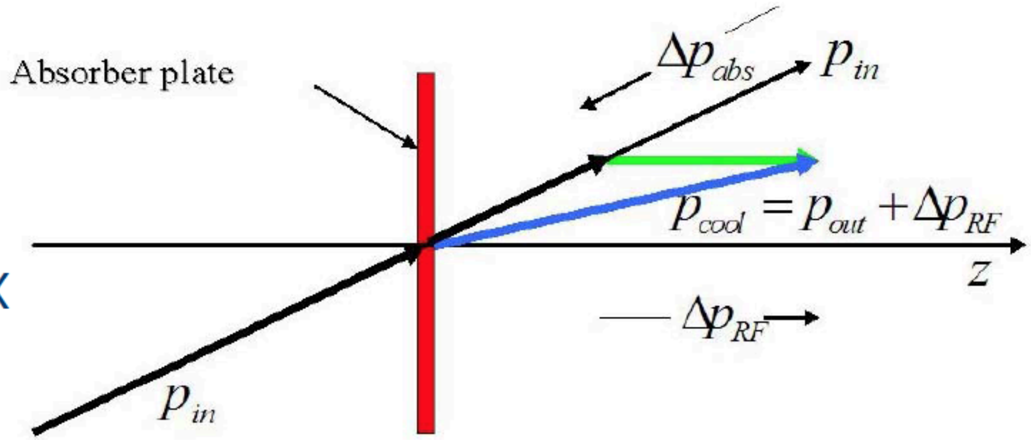
Excite ½ integer parametric resonance (in Linac or ring)

- Like vertical rigid pendulum or ½-integer extraction
- Elliptical phase space motion becomes hyperbolic
- Use xx′=const to reduce x, increase x′
- Use IC to reduce x′

Detuning issues being addressed (chromatic and spherical aberrations, space-charge tune spread). Simulations underway. New progress by Derbenev.



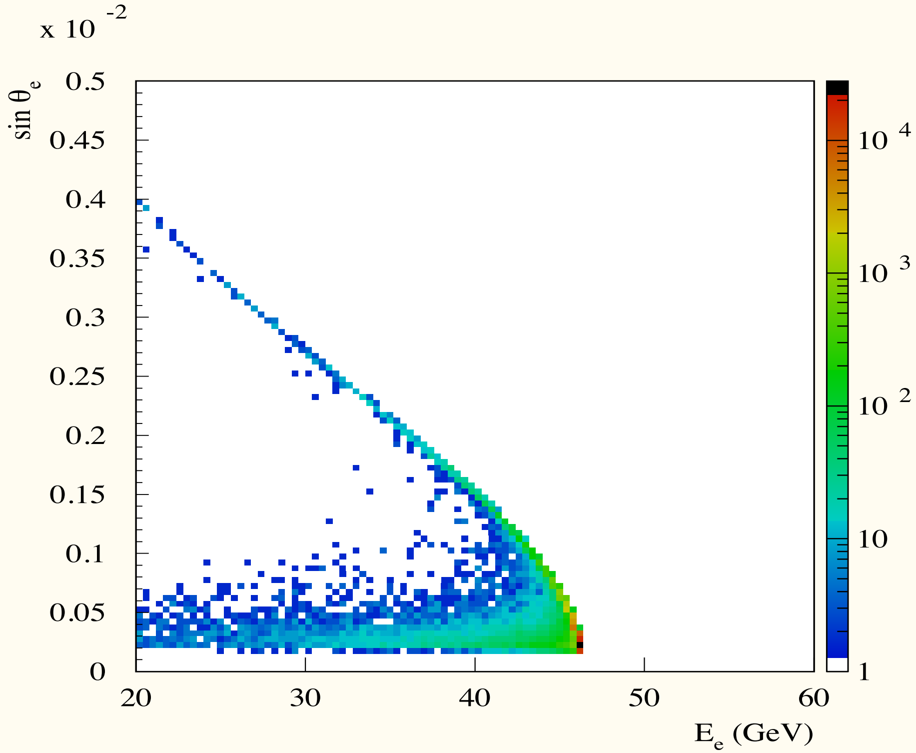




Processes at $\sqrt{s} \sim 0.212$ GeV e^+ on target

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

- Babayaga for "large" angles and
- BBBrems for collinear (dominant $\sigma \sim 150$ mb, $\delta E/E<2\%$)



Positron sources: studies on the market

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

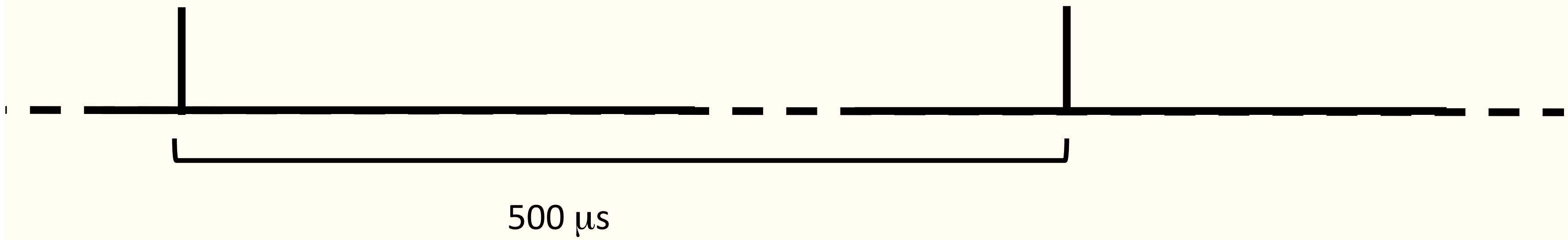
In [F. Zimmermann, et al., '**POSITRON OPTIONS FOR THE LINAC-RING LHEC'**, WEPPR076 Proceedings of IPAC2012, New Orleans, Louisiana, USA]

	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

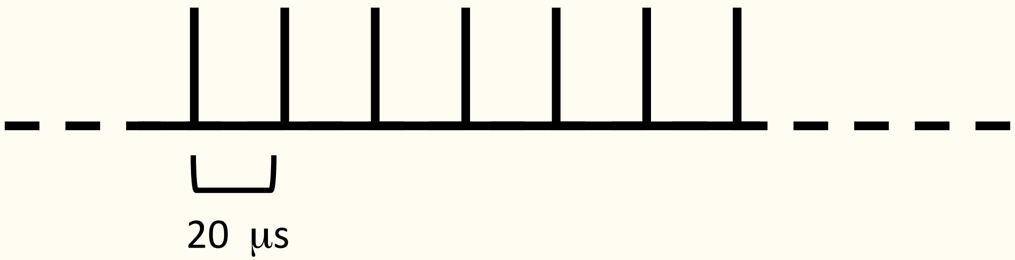
- ➢ This is the most critical issue

rebunching at 6 TeV

bunch structure from production



bunch structure at collider



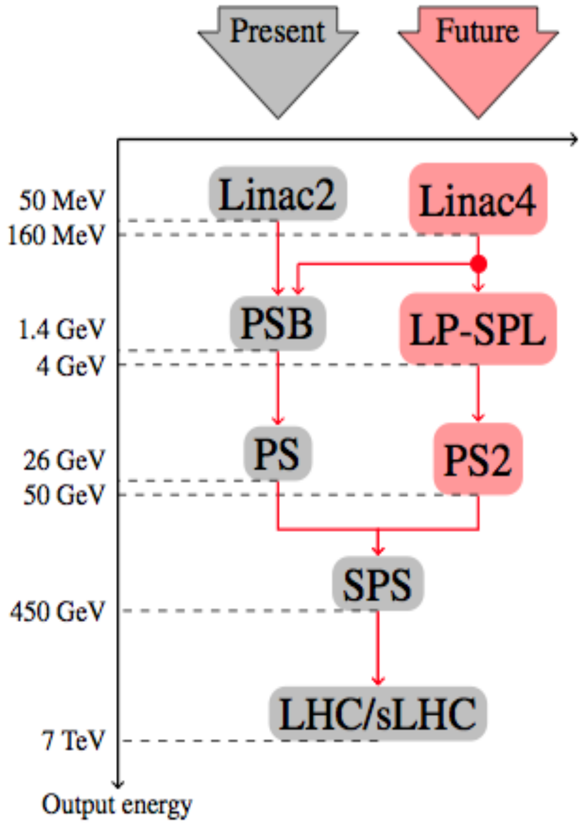
perform continuous injection every 500 μs

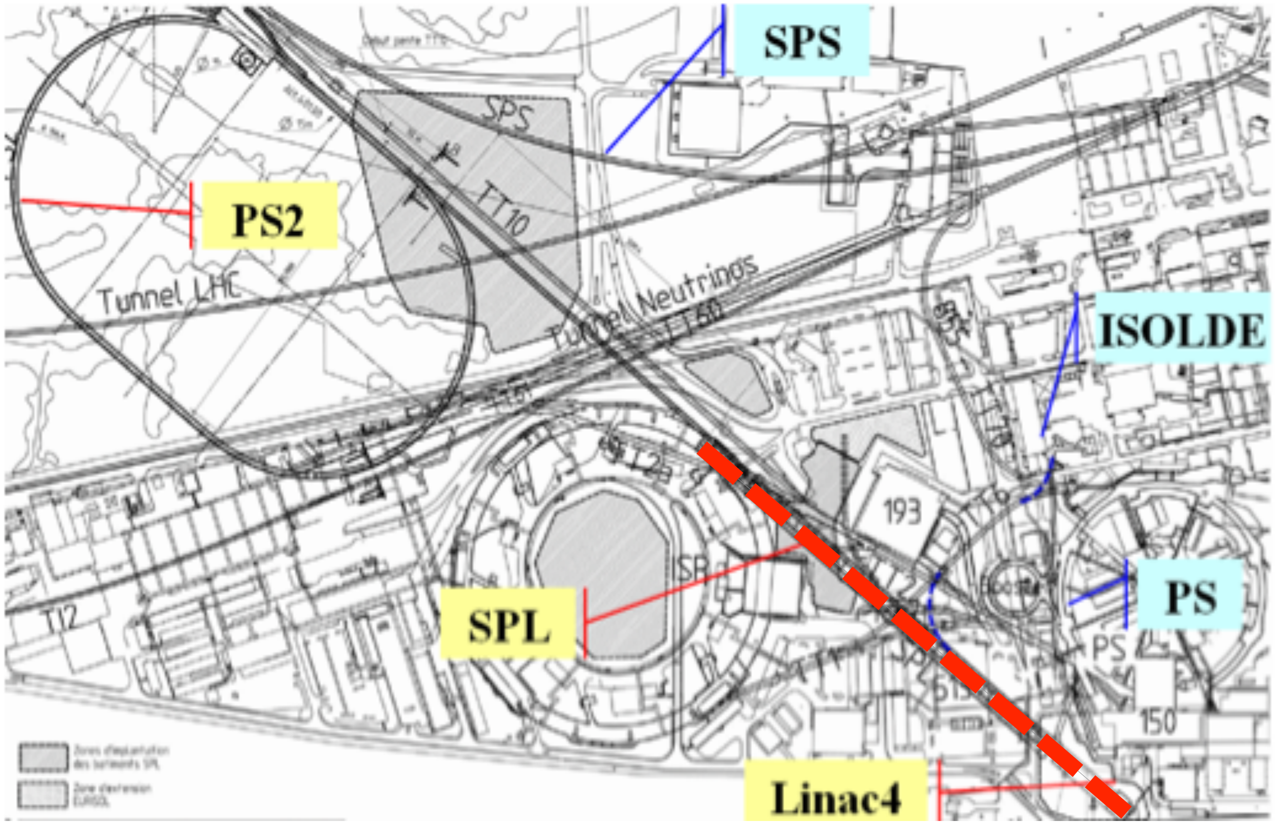
rebunch effective for ~ 1 muon lifetime 66 ms (factor 66/0.5)

no damping -> fill transverse phase space maintaining lumi increase

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,

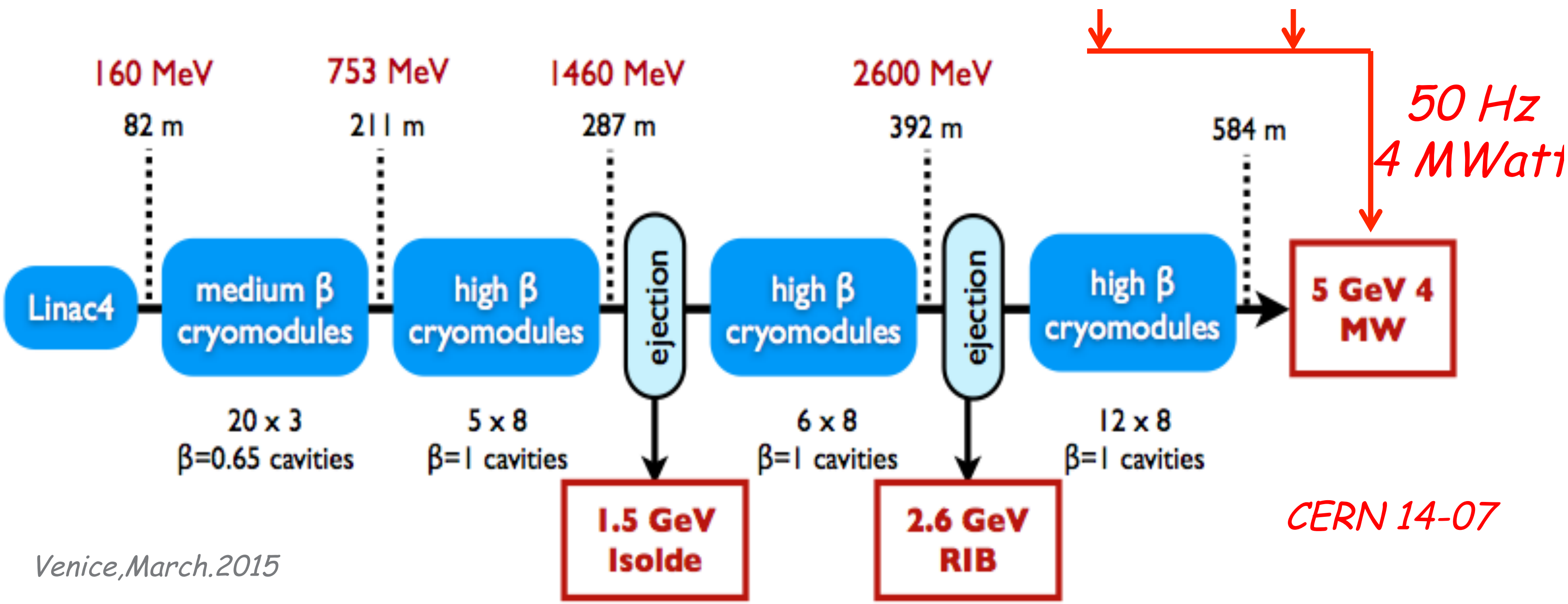




CERN-SPL parameters

- 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		LP-SPL
		Low-current	High-current	
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

Increasing complexity and challenges

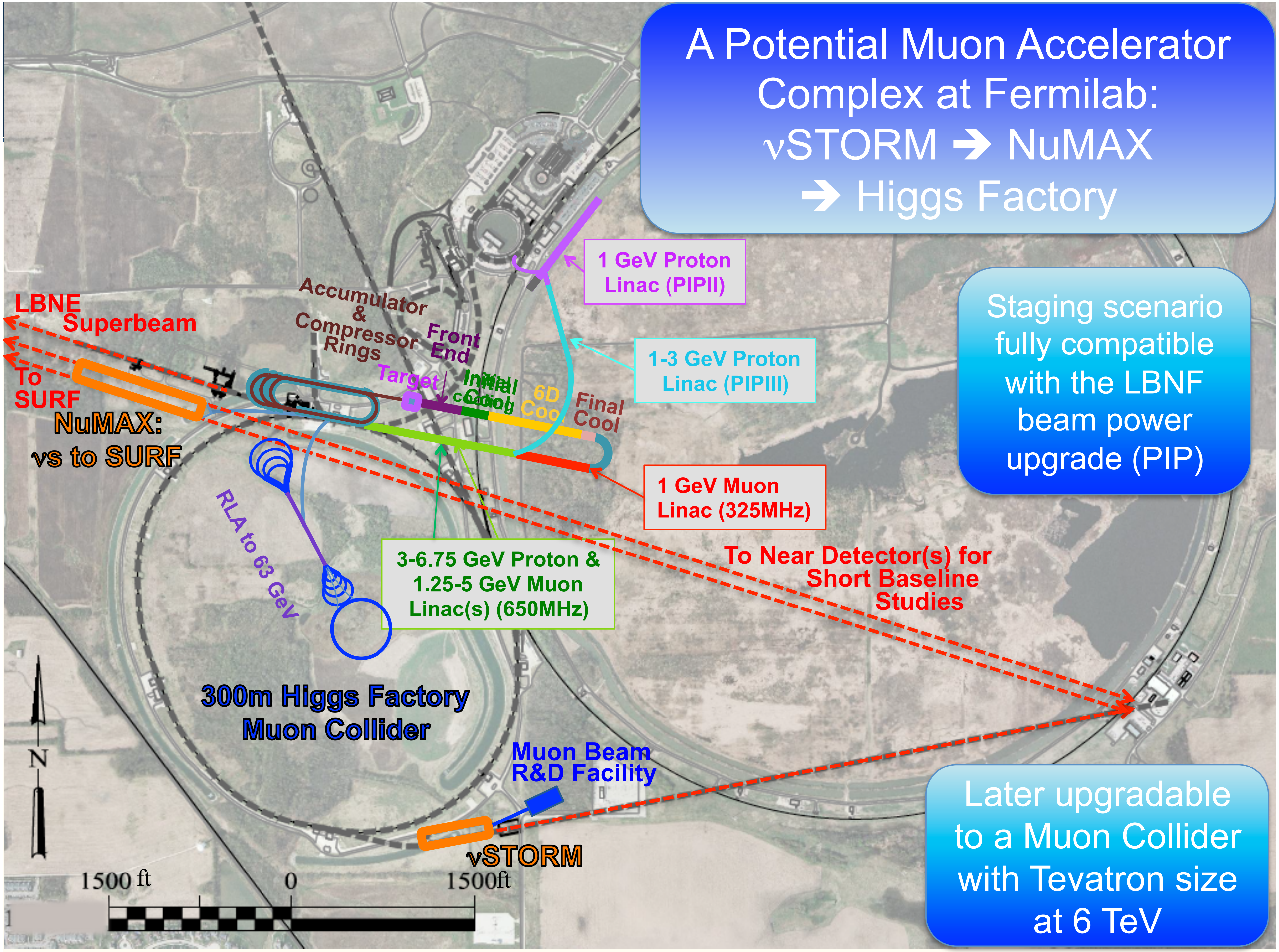
main parameters

Neutrino Factory at intensity frontier

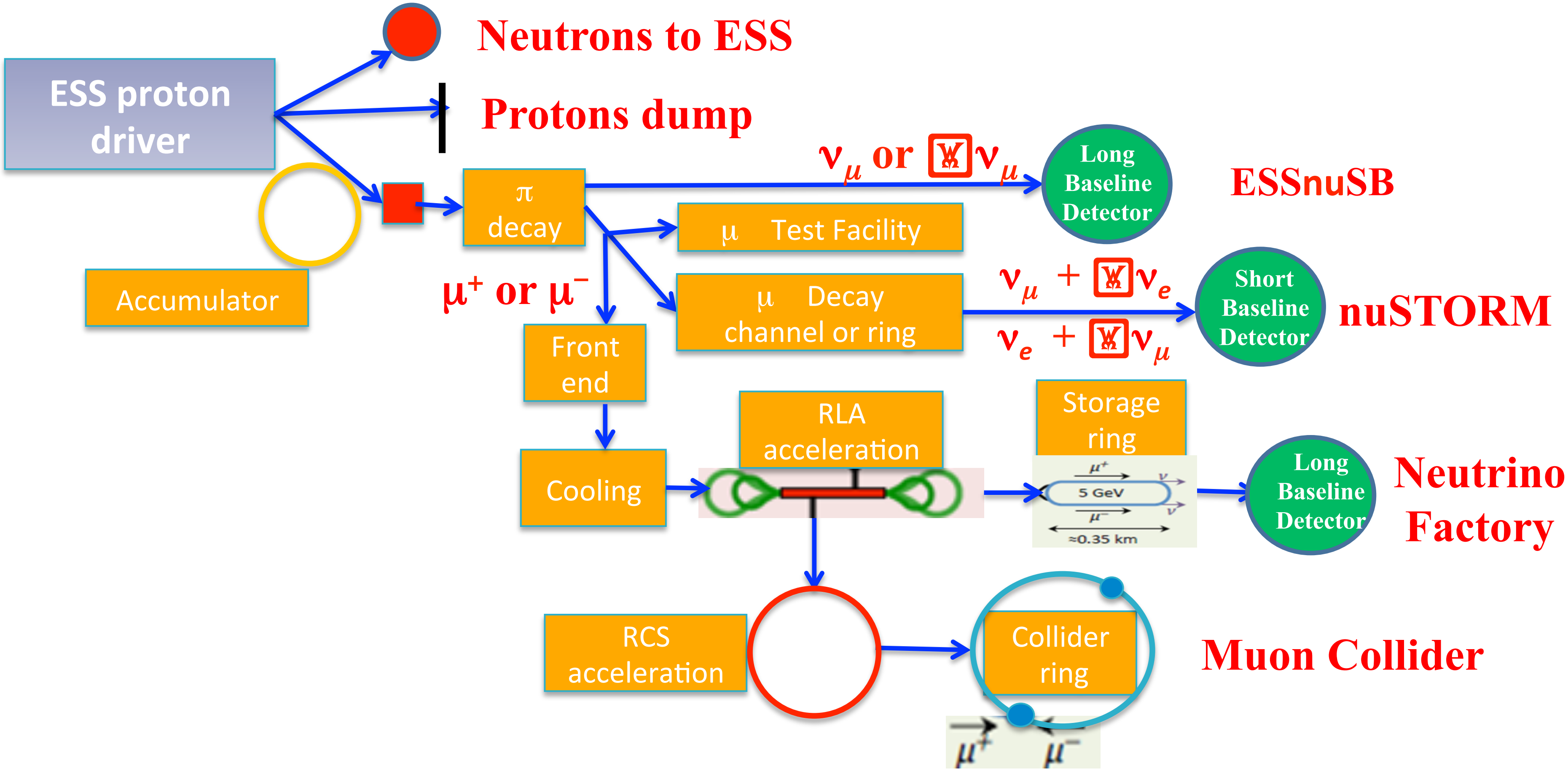
System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Perfor-mance	ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
	Stored μ+ or μ-/year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}
Detector	***Far Detector:***	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND / 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$^{\sharp}$	4	4	4	4	4	1.6
Cooling		6D no final		Full 6D				


A Potential Muon Accelerator Complex at Fermilab:
νSTORM ➔ NuMAX ➔ Higgs Factory
1 GeV Proton Linac (PIPII)
1-3 GeV Proton Linac (PIPIII)
Staging scenario fully compatible with the LBNF beam power upgrade (PIP)
LBNE Superbeam
To SURF
NuMAX: νs to SURF
Accumulator & Compressor Rings
Front End
Target
Final Cool
6D Cool
1 GeV Muon Linac (325MHz)
3-6.75 GeV Proton & 1.25-5 GeV Muon Linac(s) (650MHz)
RLA to 63 GeV
To Near Detector(s) for Short Baseline Studies
300m Higgs Factory Muon Collider
Muon Beam R&D Facility
νSTORM
N
1500 ft
0
1500ft
Later upgradable to a Muon Collider with Tevatron size at 6 TeV

ESS neutrino and muons facility



J.P.Delahaye ESS_NuSTORM

Beam characteristics

Main ESS facility parameters concerning the proton beam.

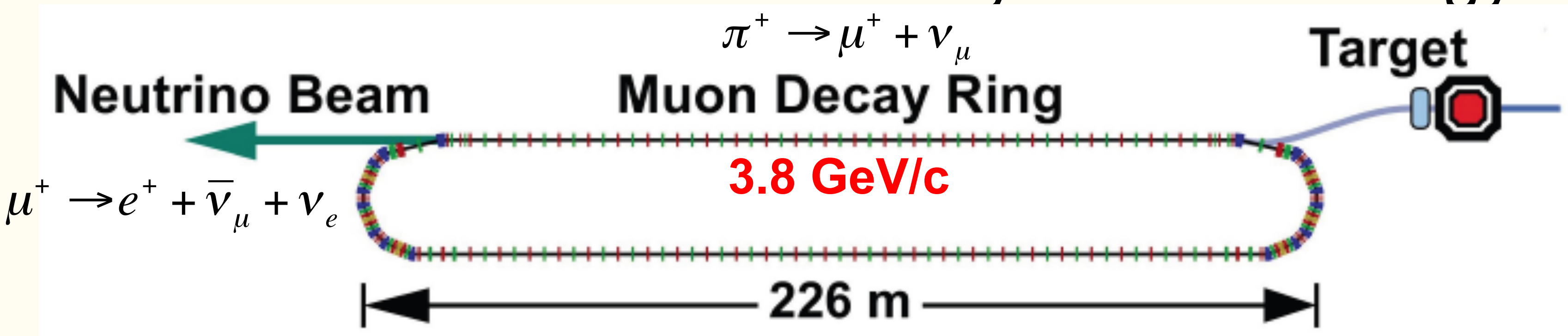
Parameter	Value
Average beam power	5 MW
Proton kinetic energy	2.0 GeV
Average macro-pulse current	62.5 mA
Macro-pulse length	2.86 ms
Pulse repetition rate	14 Hz
Maximum accelerating cavity surface field	45 MV/m
Maximum linac length (excluding contingency and upgrade space)	352.5 m
Annual operating period	5000 h
Reliability	95%

Number of neutrinos per m^2 crossing a surface placed on-axis at a distance of 100 km from the target station during 200 days for 2.0 GeV protons and positive and negative horn current polarities.

	Positive		Negative	
	N_ν $(\times 10^{10})/m^2$	%	N_ν $(\times 10^{10})/m^2$	%
ν_μ	396	97.9	11	1.6
$\bar{\nu}_\mu$	6.6	1.6	206	94.5
ν_e	1.9	0.5	0.04	0.01
$\bar{\nu}_e$	0.02	0.005	1.1	0.5

nuSTORM: Neutrinos from STORed Muons

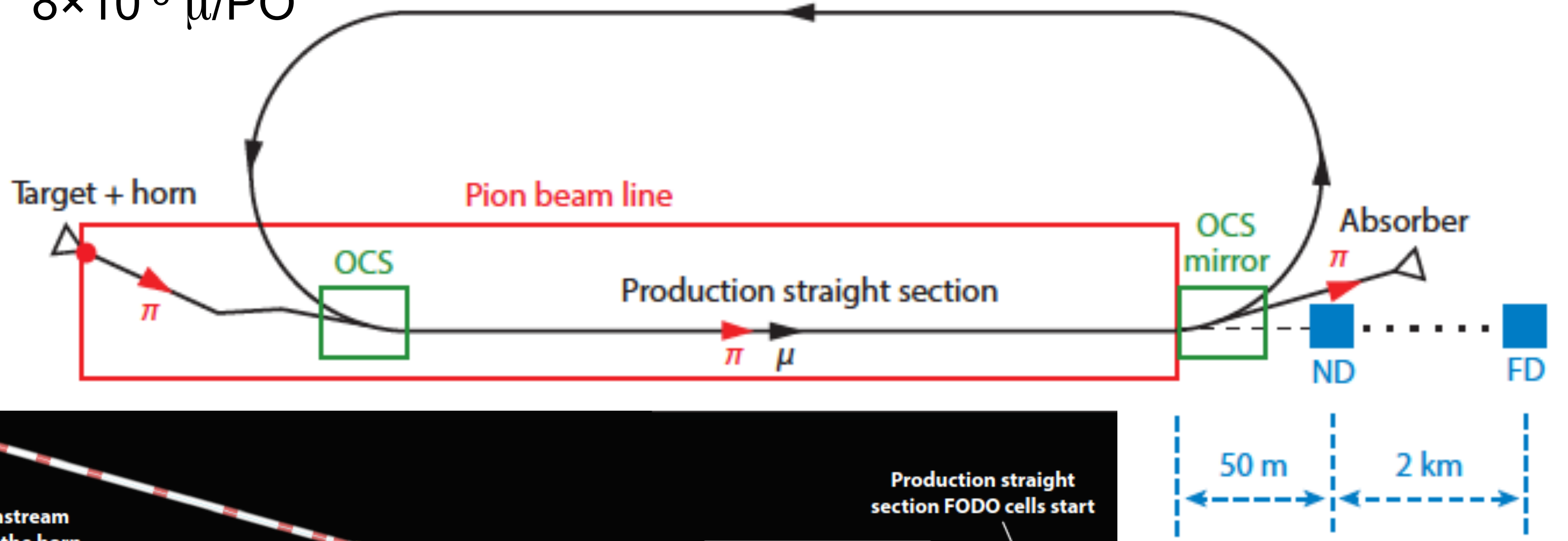
- nuSTORM: storage ring for 3.8 GeV/c muons that can be realised now without any new technology

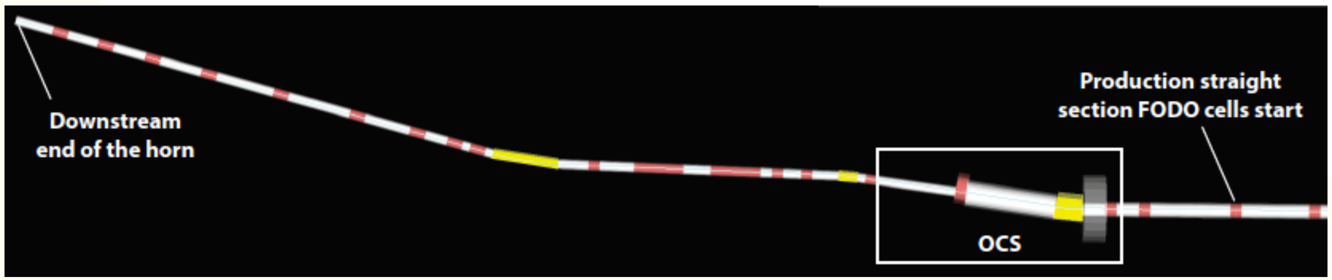


  - Pions of 5 Gev/c captured and injected into ring.
  - 52% of pions decay to muons before first turn: $\pi^+ \to \mu^+ + \nu_\mu$
  - This creates a first flash of neutrinos from pion decays
  - Ring designed to store muons with p = 3.8 GeV ± 10%
  - Muons decay producing neutrinos: $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$
  - Creates hybrid beam of neutrinos from pion & muon decay

nuSTORM Facility

- nuSTORM facility:
  - 120 GeV protons on carbon or inconel target (100 kW)
  - NuMI-style horn for pion collection
  - Injection pions (5 GeV/c ± 10%) into storage ring: 0.09 π/POT
  - Storage ring: large aperture FODO lattice (3.8 GeV/c ± 10%) muons: 8×10^{-3} μ/PO

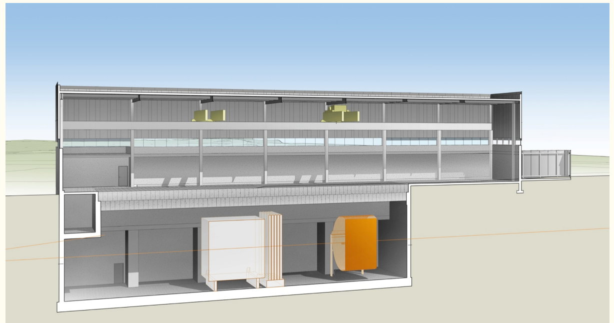




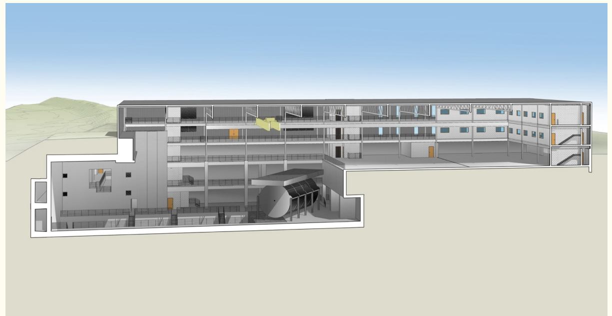
nuSTORM at Fermilab

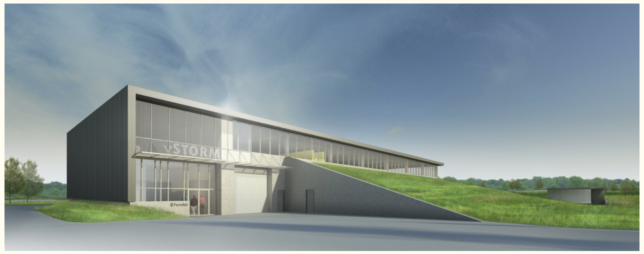
- nuSTORM could be sited at Fermilab
  Proposal to FNAL PAC: arXiv: 1308.6822

Near Detector Hall

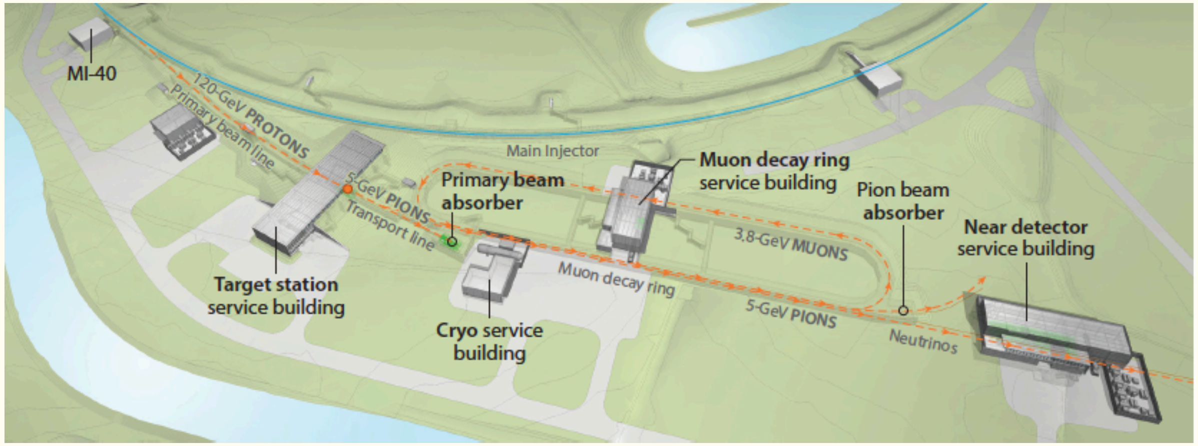


Far Detector Hall (D0)





Target building

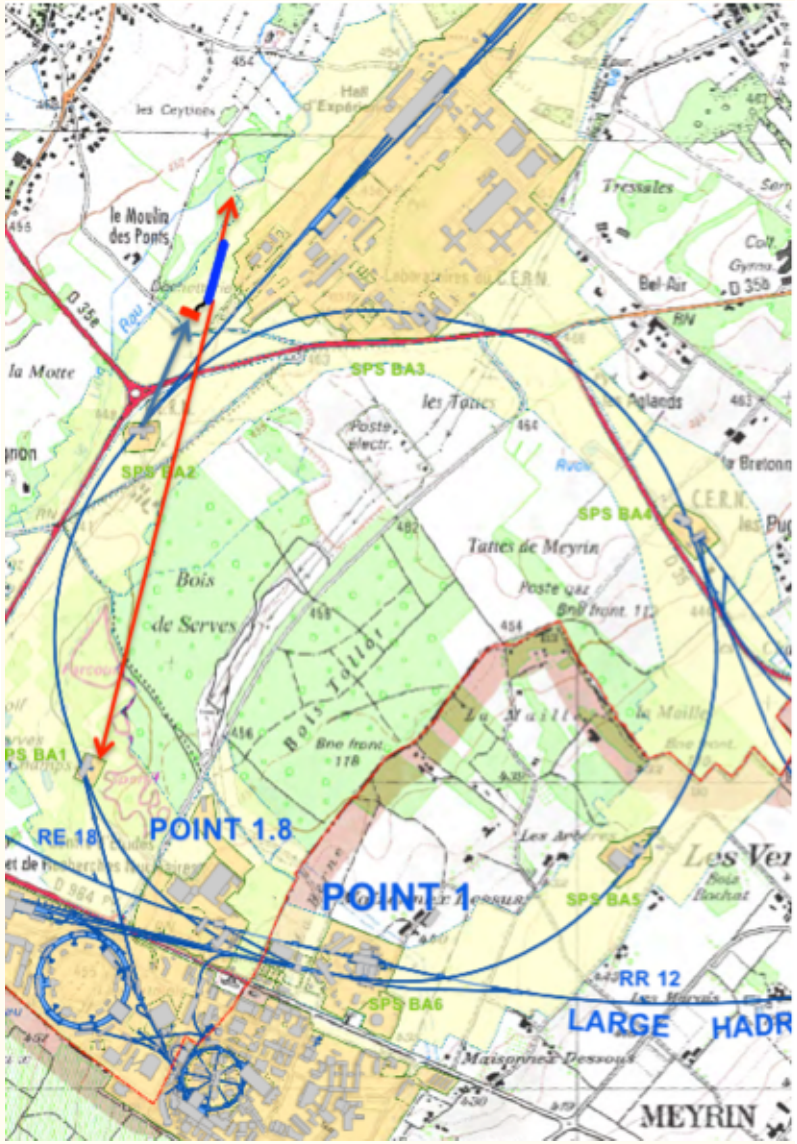


nuSTORM at CERN

- nuSTORM could be sited at CERN
- Target station in North Area

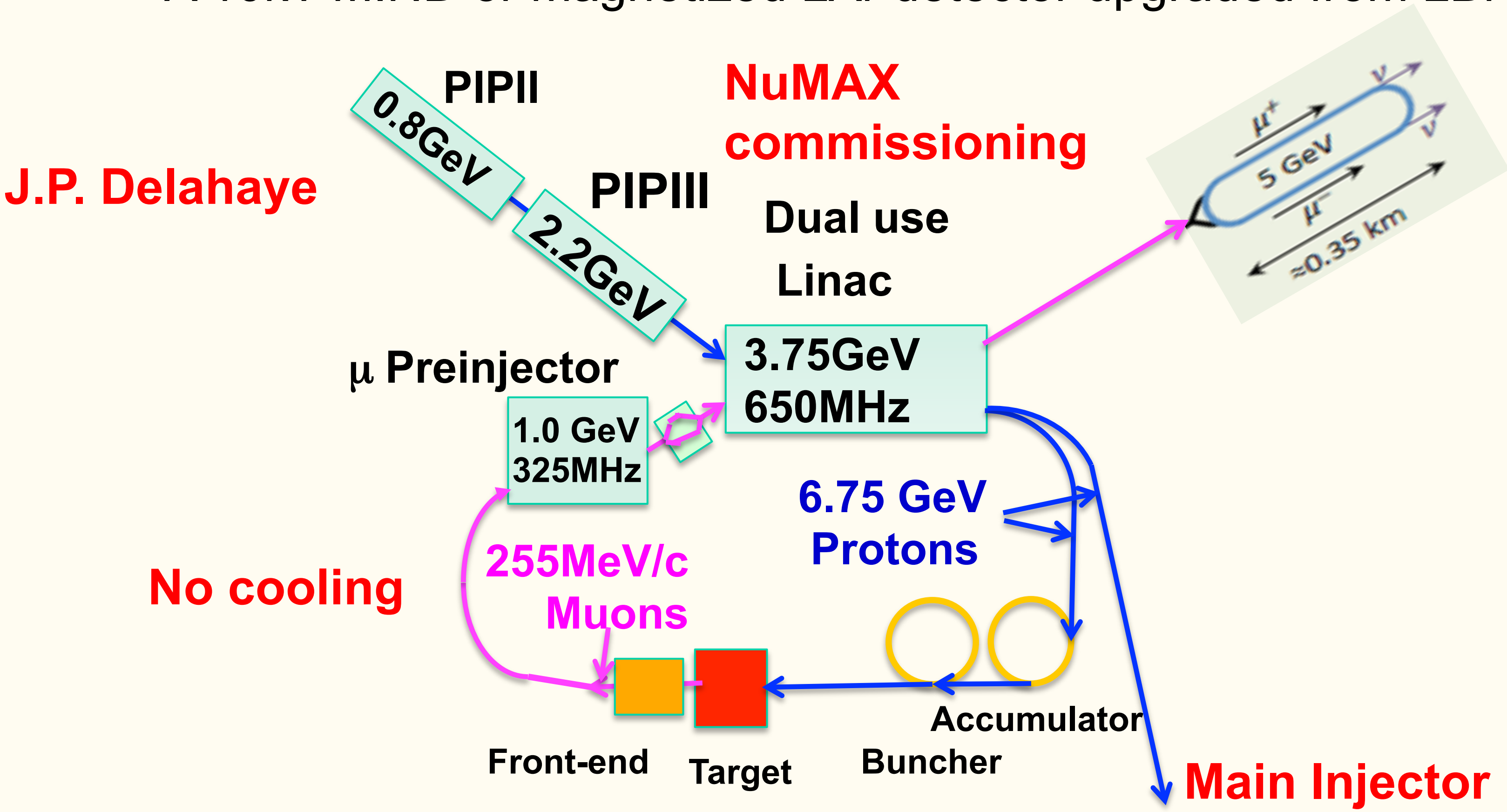
  EoI to CERN: arXiv:1305.1419

- For two detector oscillation search: near detector in North Area and far detector in Point 1.8

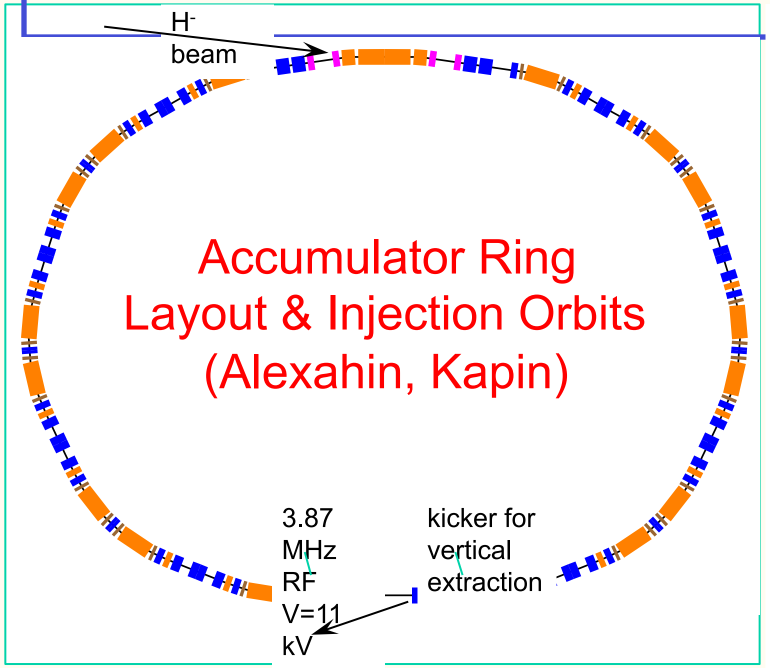


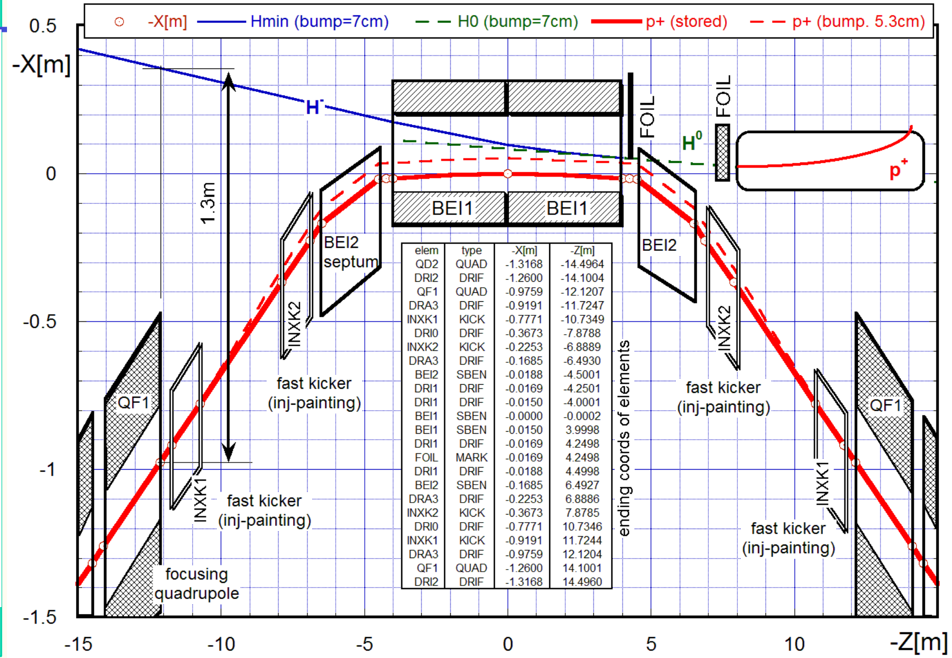
NuMAX: Neutrino Factory FNAL/Sanford

- Neutrinos from a Muon Accelerator CompleX (NuMAX)
  - Neutrino Factory with 10^{20} straight muons decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford
  - A 10kT MIND or magnetized LAr detector upgraded from LBNE

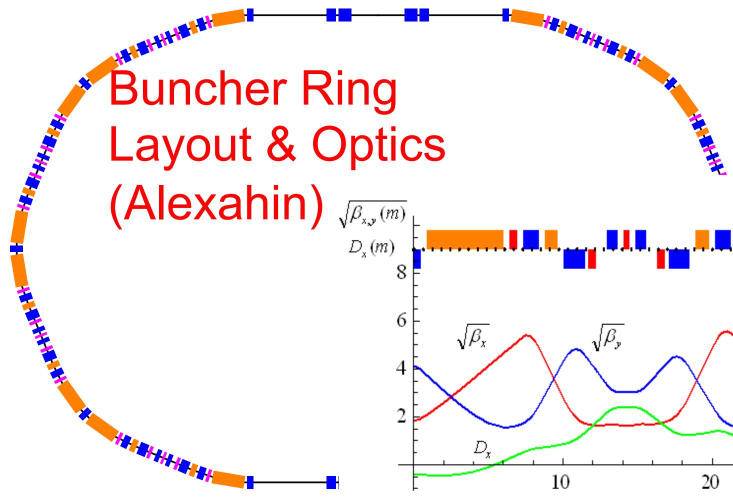


Proton Driver

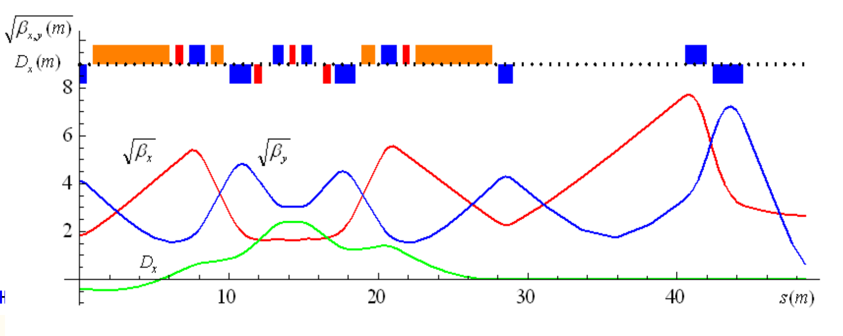




elem	type	-X[m]	-Z[m]
QD2	QUAD	-1.3168	-14.4964
DRI2	DRIF	-1.2600	-14.1004
QF1	QUAD	-0.9759	-12.1207
DRA3	DRIF	-0.9191	-11.7247
INXK1	KICK	-0.7771	-10.7349
DRI0	DRIF	-0.3673	-7.8788
INXK2	KICK	-0.2253	-6.8889
DRA3	DRIF	-0.1685	-6.4930
BEI2	SBEN	-0.0188	-4.5001
DRI1	DRIF	-0.0169	-4.2501
DRI1	DRIF	-0.0150	-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:
½ staight +
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

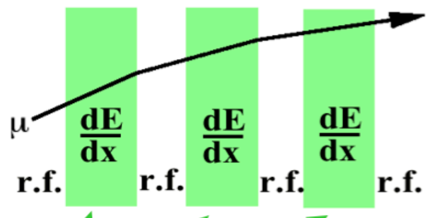
M. Palmer

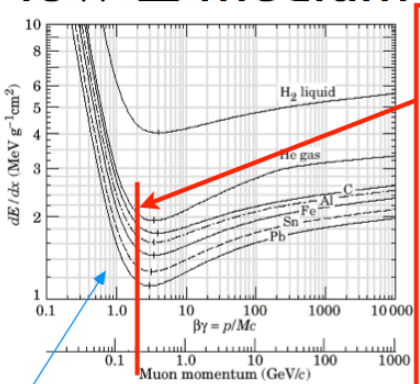
Cooling Methods

- 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:

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

ionization energy loss

multiple Coulomb scattering

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

- 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)

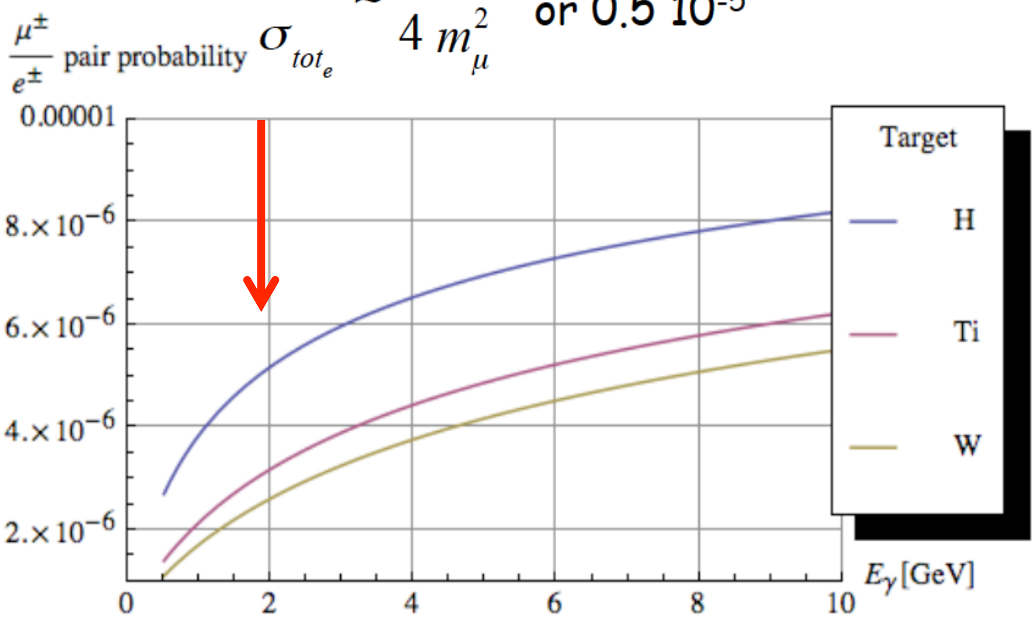
Kaplan

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)