Future muon colliders

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Lepton colliders most performing technology

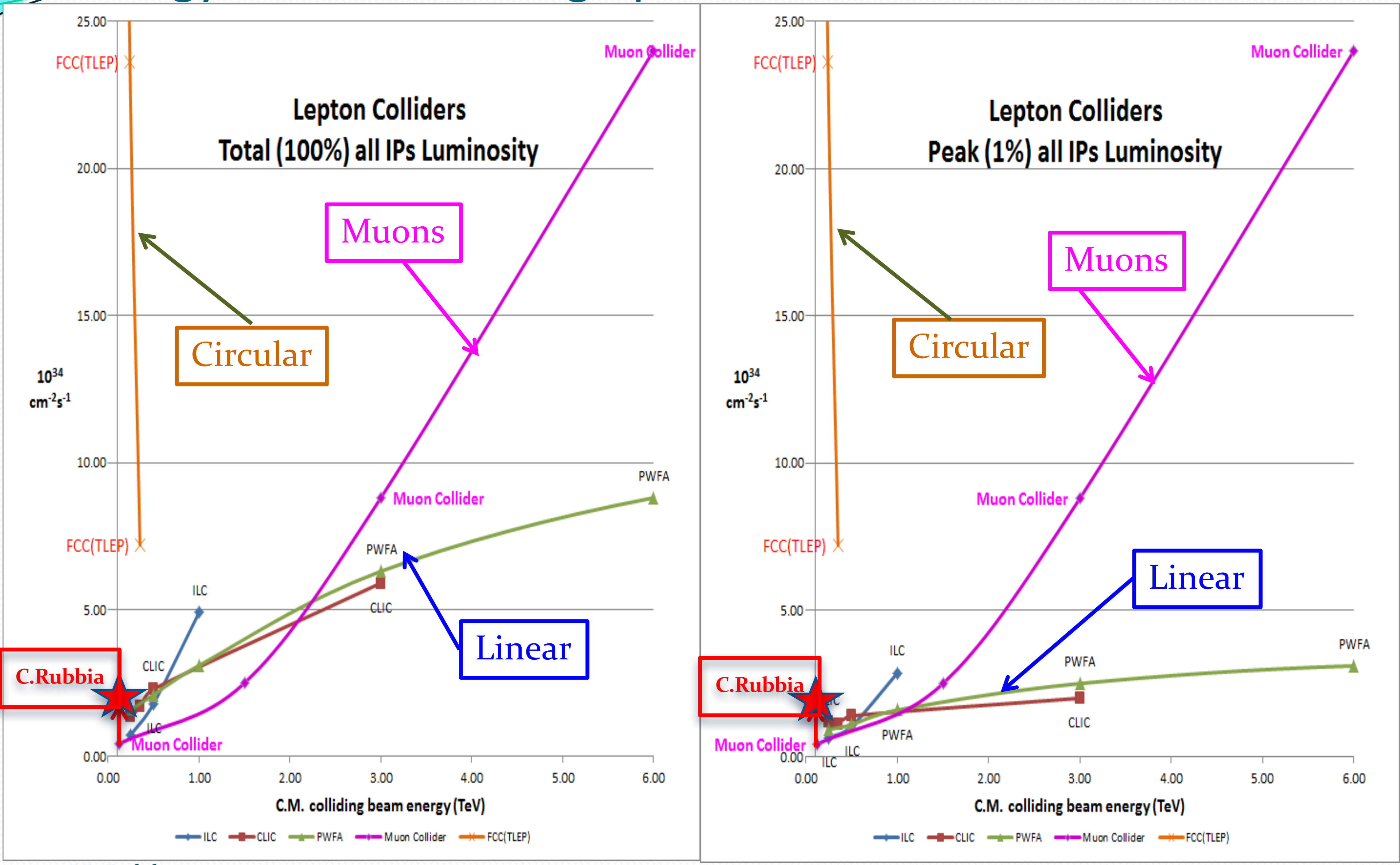
- Up to 350 GeV: Large Circular Colliders (if affordable)
- From 350 GeV to 1.5-2 TeV: Linear Colliders
  - Plasma acceleration (feasibility being addressed)
  - ILC most mature technology (up to 0.5 TeV ext. to 1 TeV)
  - CLIC only demonstrated technology in multi-TeV (up to 2TeV)
- Above 2 TeV: Muon Colliders (if feasible)

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

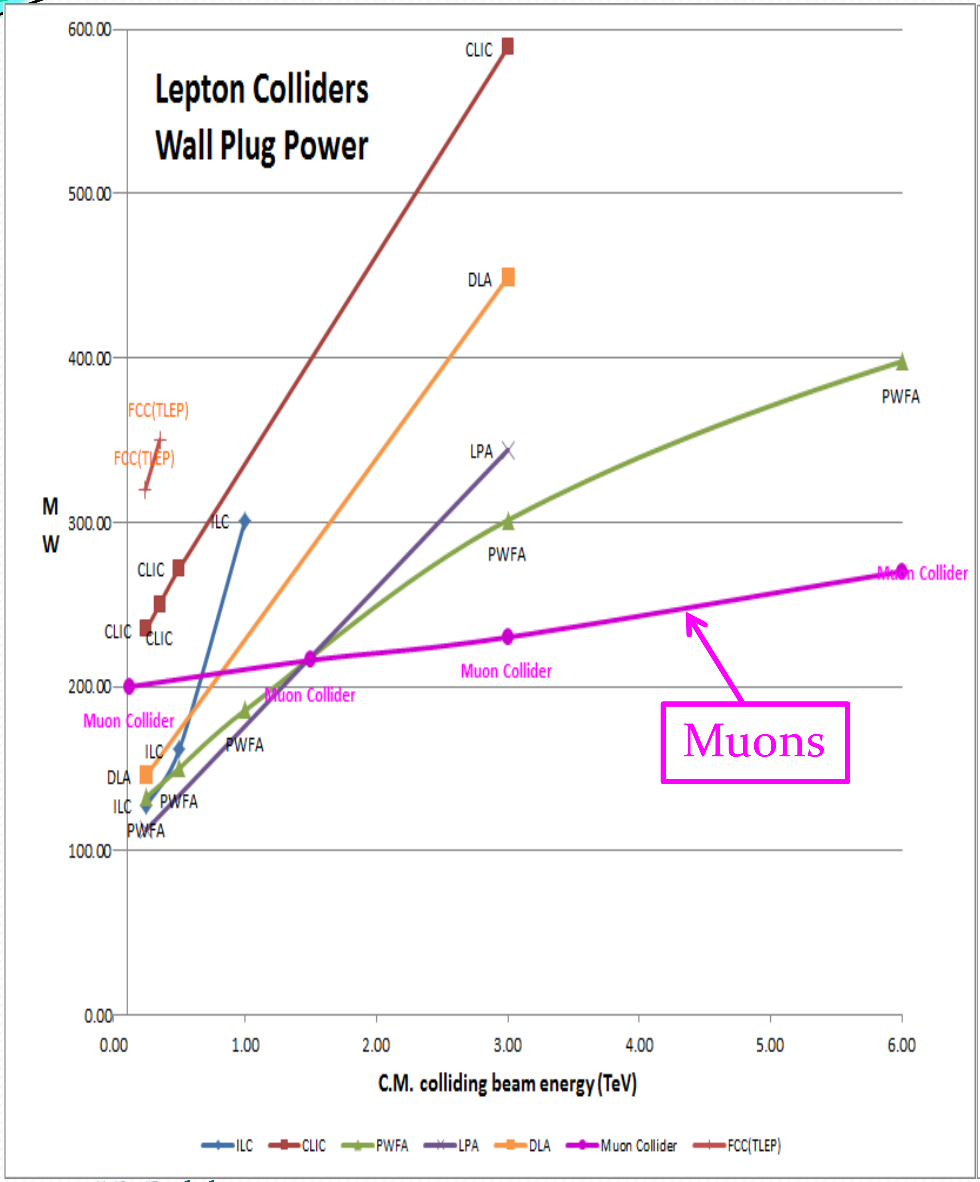
- **By synchrotron radiation as e^+e^- circular colliders**
- **By beamstrahlung as e^+e^- linear colliders**

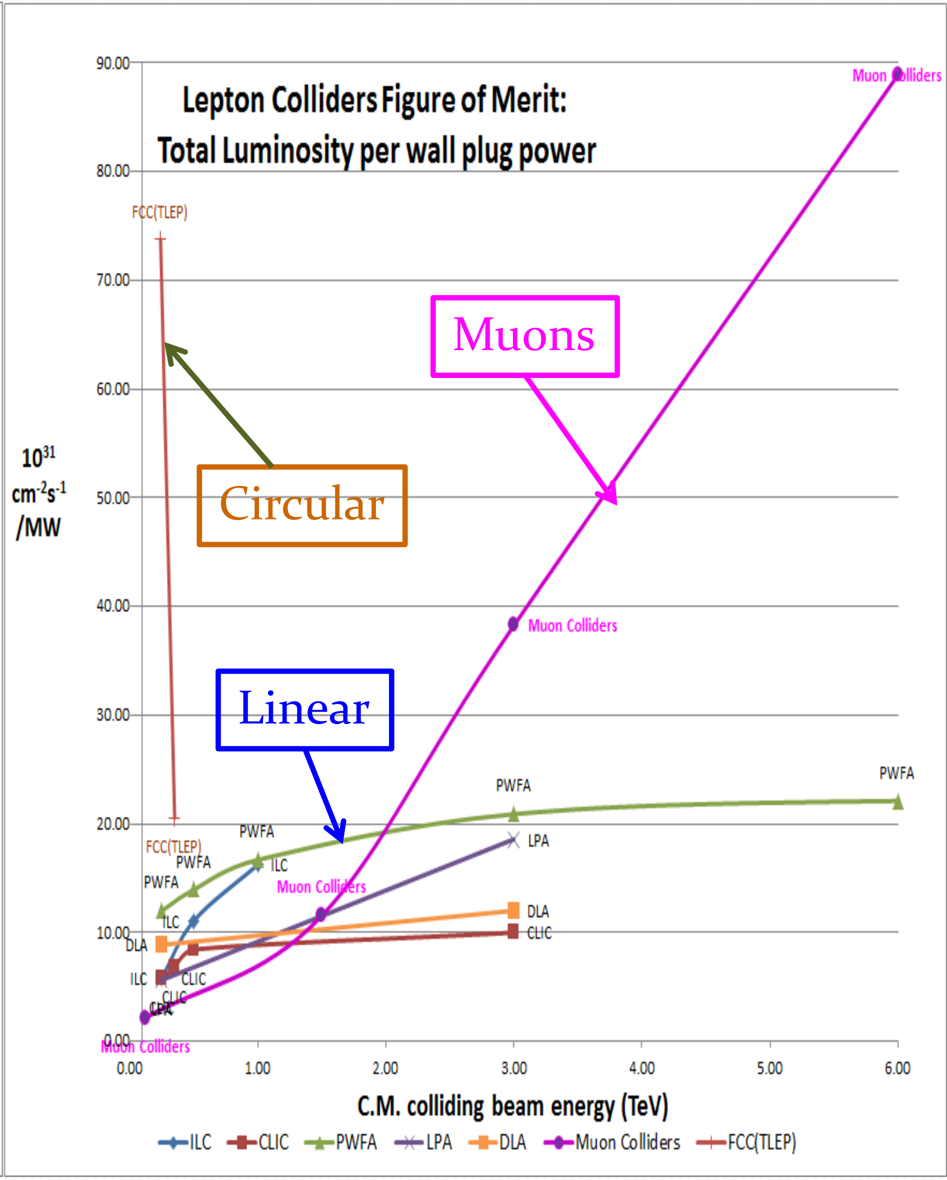
Muon Collider the ideal technology to extend lepton high energy frontier in the multi-TeV range with reasonable dimension, cost and power consumption

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 Collider

D. Schulte this morning!

- Many issues exist
  - Neutrino radiation, muon cooling, background in the detector and machine, …
  - Can they be overcome?

- Largest power in production of muons
- For fixed beam current, luminosity increases with γ^2
  - Geometric emittance shrinks and shorter bunches allow smaller betafunctions
  - At lower energies, almost the same power for stringly increasing luminosity
  - Even at highest energies luminosity increases with energy for the same power
- Maybe even better solutions to produce muons can be considered?
- Reuse of old proton colliders might be possible

$\Rightarrow$ Still feels an attractive option to be discussed for high energies and long timescales

Muon Sources

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 (~N_μ^2)

Options

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

Rate > 10^{13}μ/sec $N_\mu = 2\cdot10^{12}$ /bunch

Unconventional:
e^+e^- annihilation: positron beam on target (very low emittance and no cooling needed)

Rate ~ 10^{11} μ/sec N_μ~ 5x10^7 /bunch

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

Rate ~ $5\cdot10^{10}$ μ/sec $N_\mu \sim 10^6$ (Pulsed Linac)
Rate > 10^{13} μ/sec $N_\mu \sim$ few$\cdot10^4$ (High Current ERL)   [V. Yakimenko (SLAC)]

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

M. Palmer

Key Feasibility Issues

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

High Power Target Station

Capture Solenoid

Energy Deposition

RF in Magnetic Fields

Magnet Needs (Nb_3Sn vs HTS)

Performance

Acceptance (NF)

>400 Hz AC Magnets (MC)

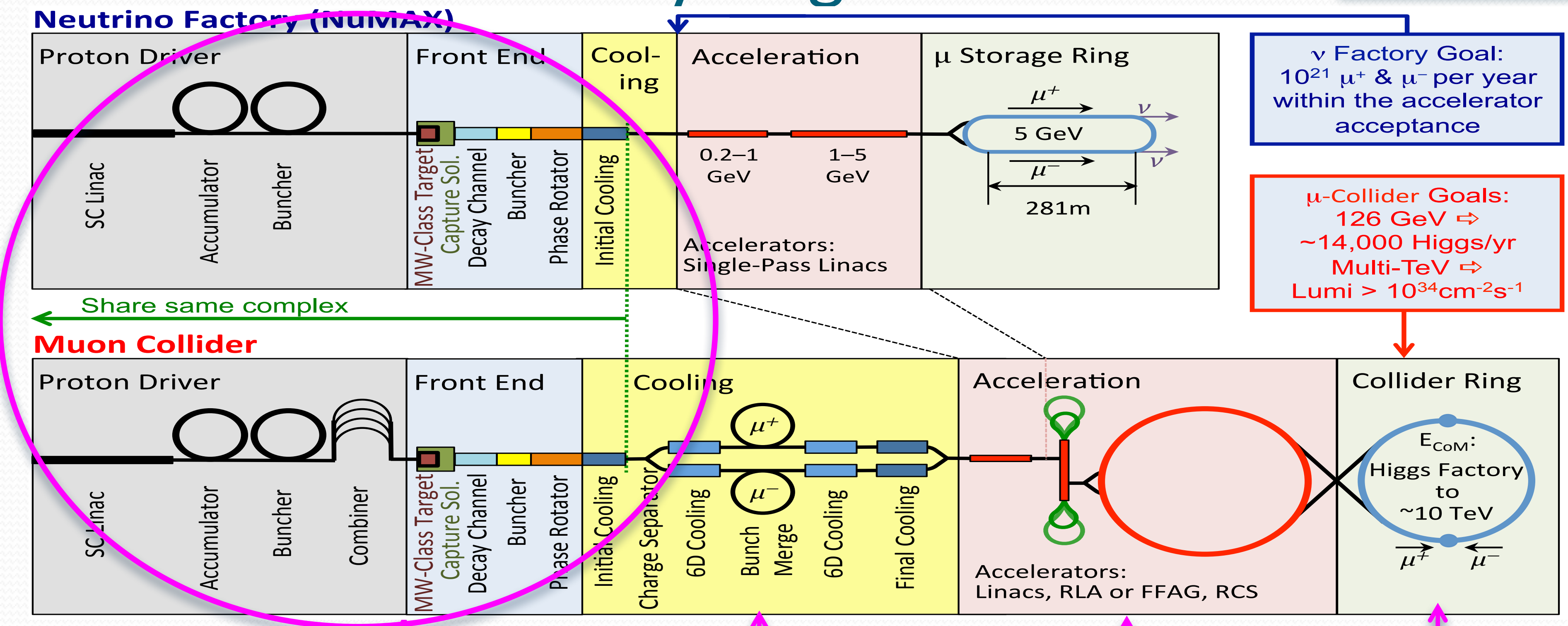
IR Magnet Strengths/Apertures

SC Magnet Heat Loads (μ decay)

Backgrounds (μ decay)

Muon Accelerator Program (MAP) Muon based facilities and synergies

Mark Palmer



Key Challenges

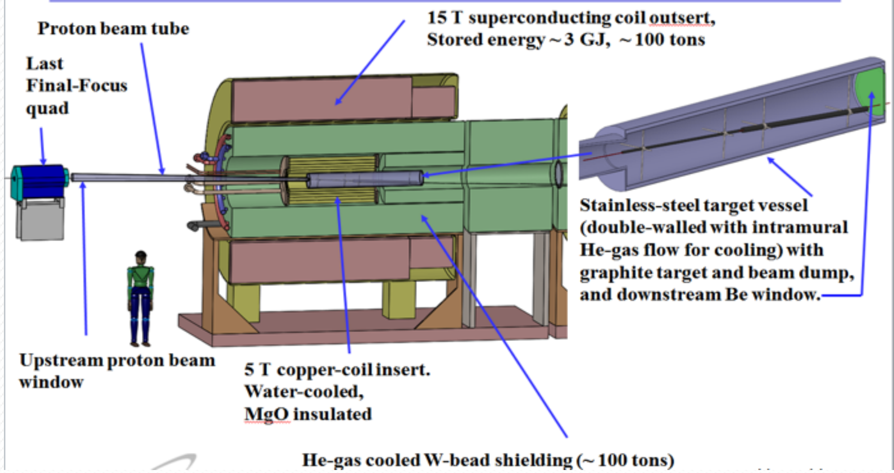
- ~10^{13}-10^{14} μ / sec Tertiary particle $p \rightarrow \pi \rightarrow \mu$:
- Fast cooling (τ=2μs) by 10^6 (6D)
- Fast acceleration mitigating μ decay
- Background by μ decay

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

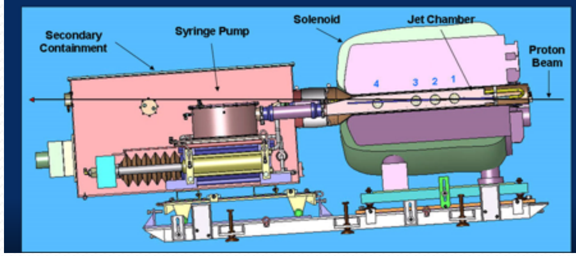
Technical challenges
Muon production as tertiary particle

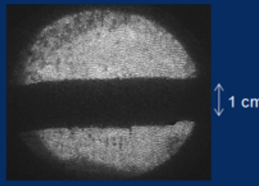
A MW class Target with Graphite Core



Multi-MW class liquid HG target

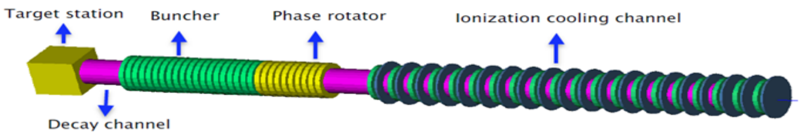
- The MERIT Experiment at the CERN PS
  - Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid and hit with a 115 KJ/pulse beam!
  - ⇨ Jets could operate with beam powers up to **8 MW** with a repetition rate of 70 Hz
- MAP staging aimed at initial 1 MW target

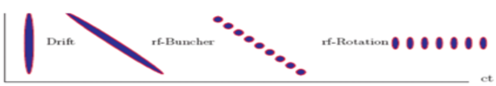


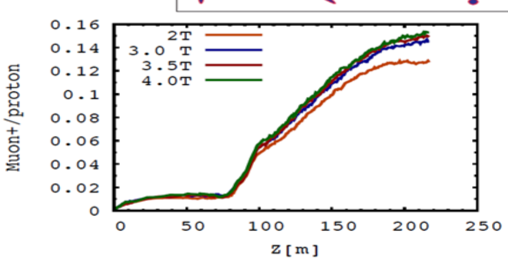


Hg jet in a 15 T solenoid with measured disruption length ~ 28 cm

An Efficient Front End for Tertiary Particle Production







A MW class proton source enables muons from pions decay to be produced, captured and bunched in a front end with an overall efficiency of 0.15 muon / proton before being cooled to fit within the acceptances of an accelerator

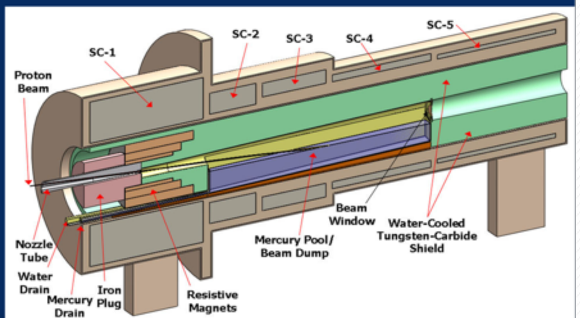
Technology Challenges – Capture Solenoid

- A Neutrino Factory and/or Muon Collider Facility requires challenging magnet design in several areas:
  - Target Capture Solenoid (15-20T with large aperture)

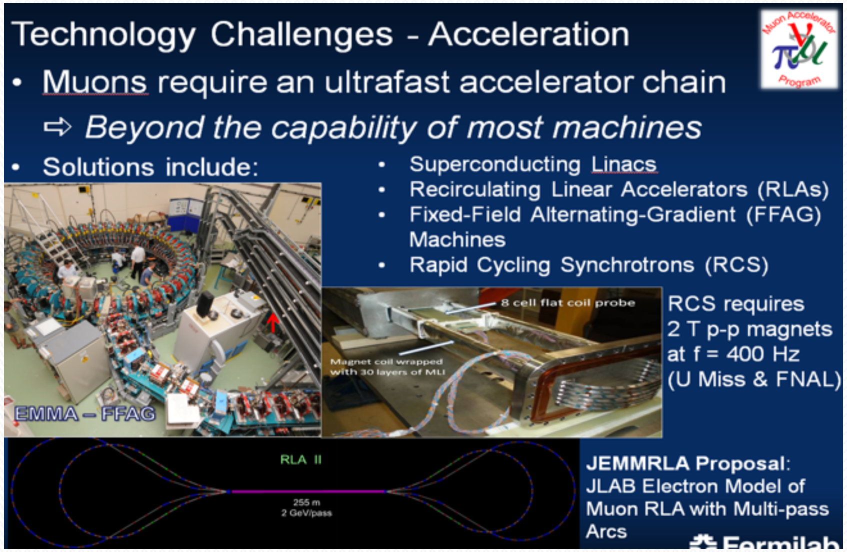
E_{stored} ~ 3 GJ

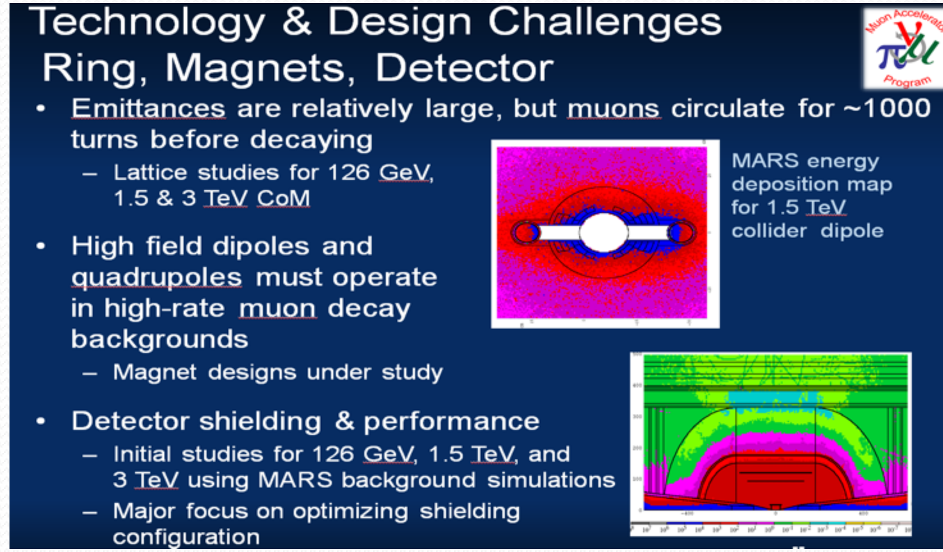
O(10MW) resistive coil in high radiation environment

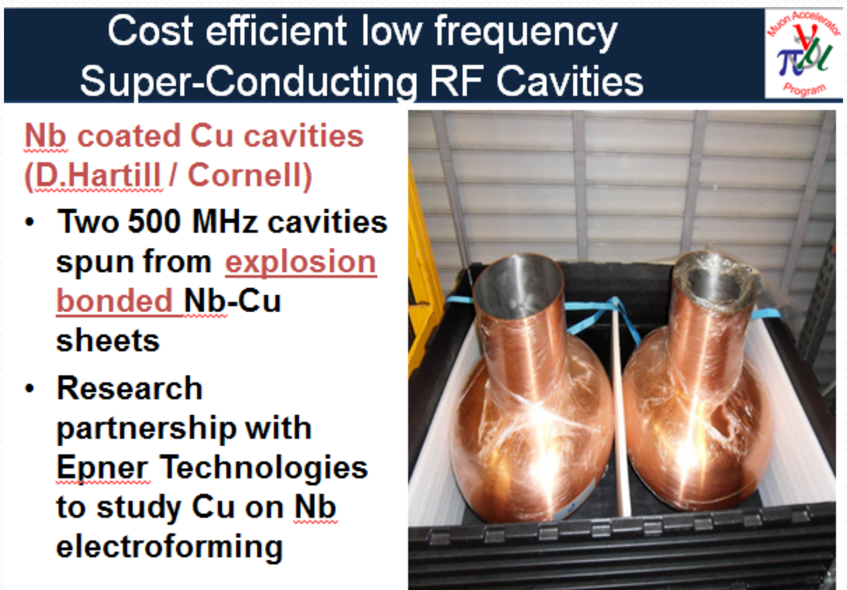
Possible application for High Temperature Superconducting magnet technology

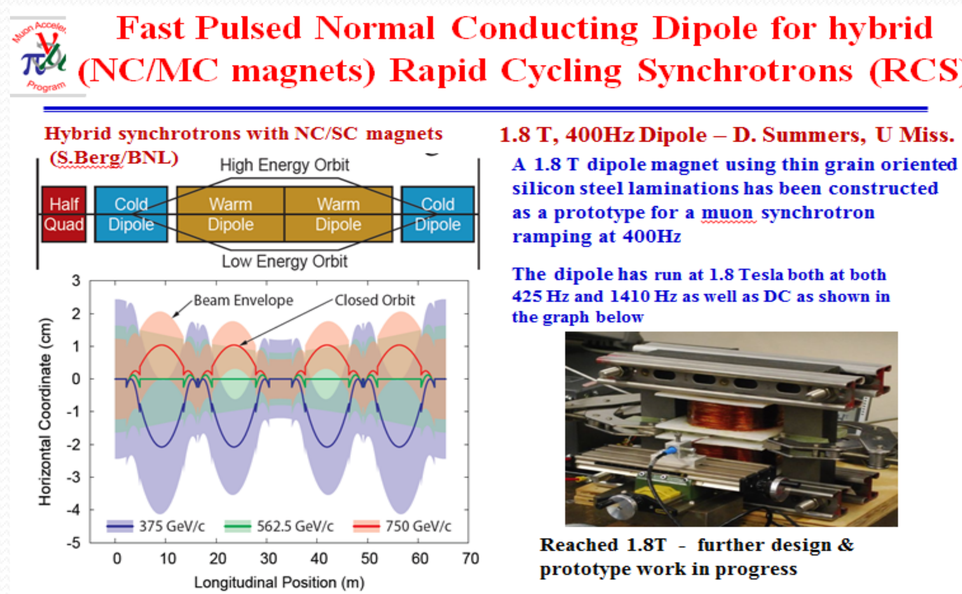


Technical challenges
Cost efficient and fast acceleration









Very low emittance muon beam by e^+ beam on target (LEMMA)

- Produce low emittance muon beams from e^+e^- collisions at c.o.m. energy just above the $\mu^+\mu^-$ production threshold with maximal beam energy asymmetry: ~ 45 GeV positron beam interacting on an electron target
- The large boost γ~200 of the c.o.m. allows for final state muons to be very collimated
- Muons produced with high energy with an average laboratory lifetime of about 500 μs, and a "minor" degradation of the positron beam emittance from Bhabha scattering
- $e^+e^- \to \mu^+\mu^-$ cross section is about 1 μb just above threshold, requires a target with very high electron density of the order of 10^{20} electrons/cm^{-3} to obtain an reasonable muon production efficiency

Ingredients

- Positron source producing a very high number of positrons
- 45 GeV positrons on a target → $\mu^+\mu^-$ produced at threshold
- Ring allows for high “collision” frequency on target
- Very low emittance positron beam
- Muons collected after production, 22.5GeV, small emittance and energy spread, in two rings
- Positrons after collision re-collected if ring energy acceptance at least >10%
- Ideally muons will ”copy” positrons

Advantages

- Muons produced at high Energy:
  - longer lifetime
  - small emittance: $P\mu$ is tunable with $\sqrt{s}$ in $e^+e^- \to \mu^+\mu^-$, $P\mu$ can be very small close to the $\mu^+\mu^-$ threshold
  - energy spread small at threshold, gets larger as $\sqrt{s}$ increases
  - no cooling needed
- Due to small emittance:
  - more Luminosity with fewer muons
- Lower muon emittance and muon flux in the collider
  - less backgrounds in detector
  - low ν radiation (easier experimental conditions, can go up in energy)
- “Simpler” scheme

Disavantages

- Rate: much smaller cross section wrt protons:

  $\sigma(e^+e \rightarrow \mu^+\mu^-) \sim 1\ \mu b$ at most

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

- Muon production efficiency per positron on target:

  $Eff(\mu^+\mu^-) < 10^{-5}$

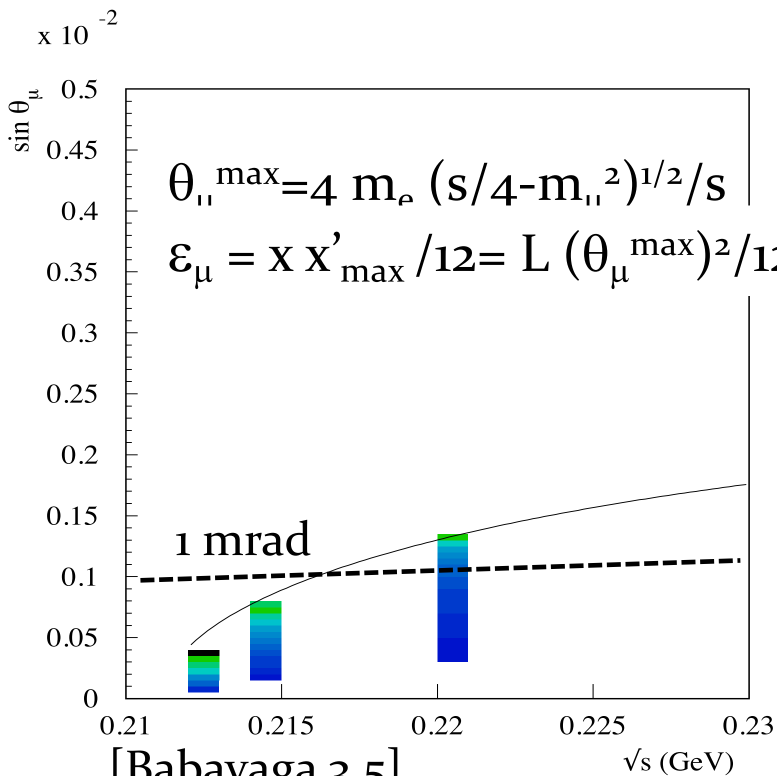
  (due to collinear radiative Bhabha scattering cross section)

Challenges

- Positron source with very high number of e^+
- Positrons after target lose energy → large energy acceptance in e^+ ring (>10%)
- Small positron beam spot on target
- Target material/design →the lighter and thinner the better for muons production efficiency, muons emittance, positrons survival probability
- Power on target (temperature), mechanical stress
- Muons collecting rings design
- Collider design

Muons angle contribution to μ beam emittance

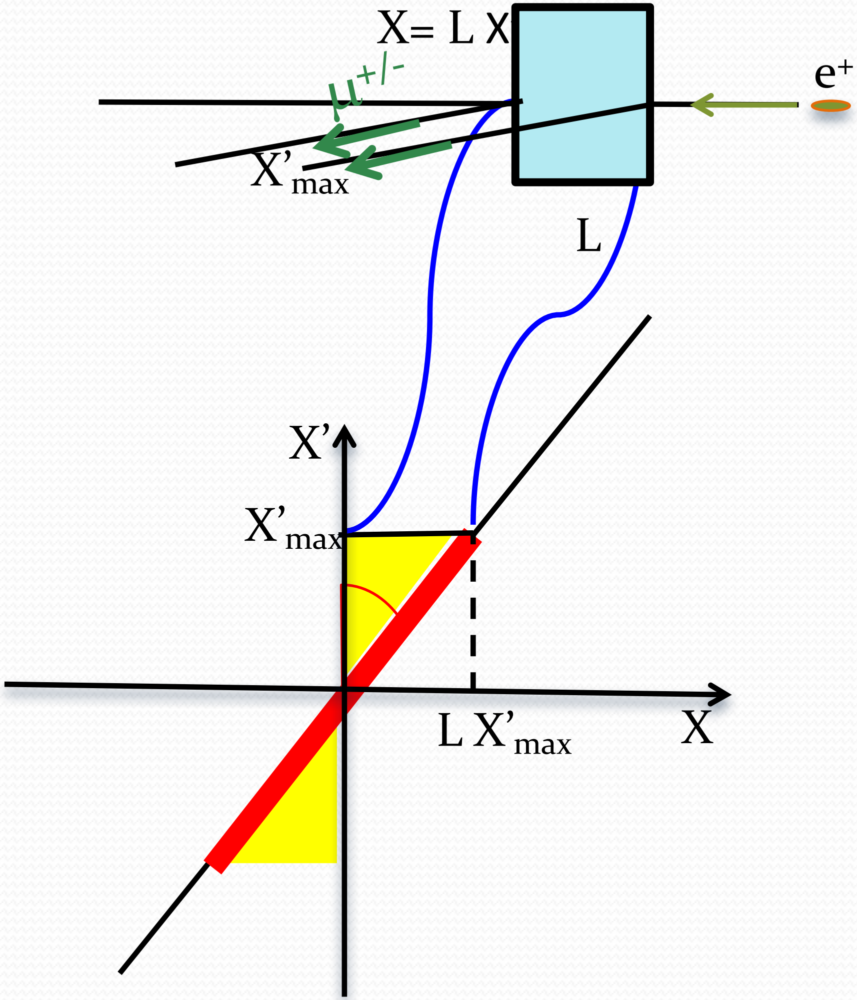
Target thickness and c.m. energy completely determine the emittance contributions due to muon production angle



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

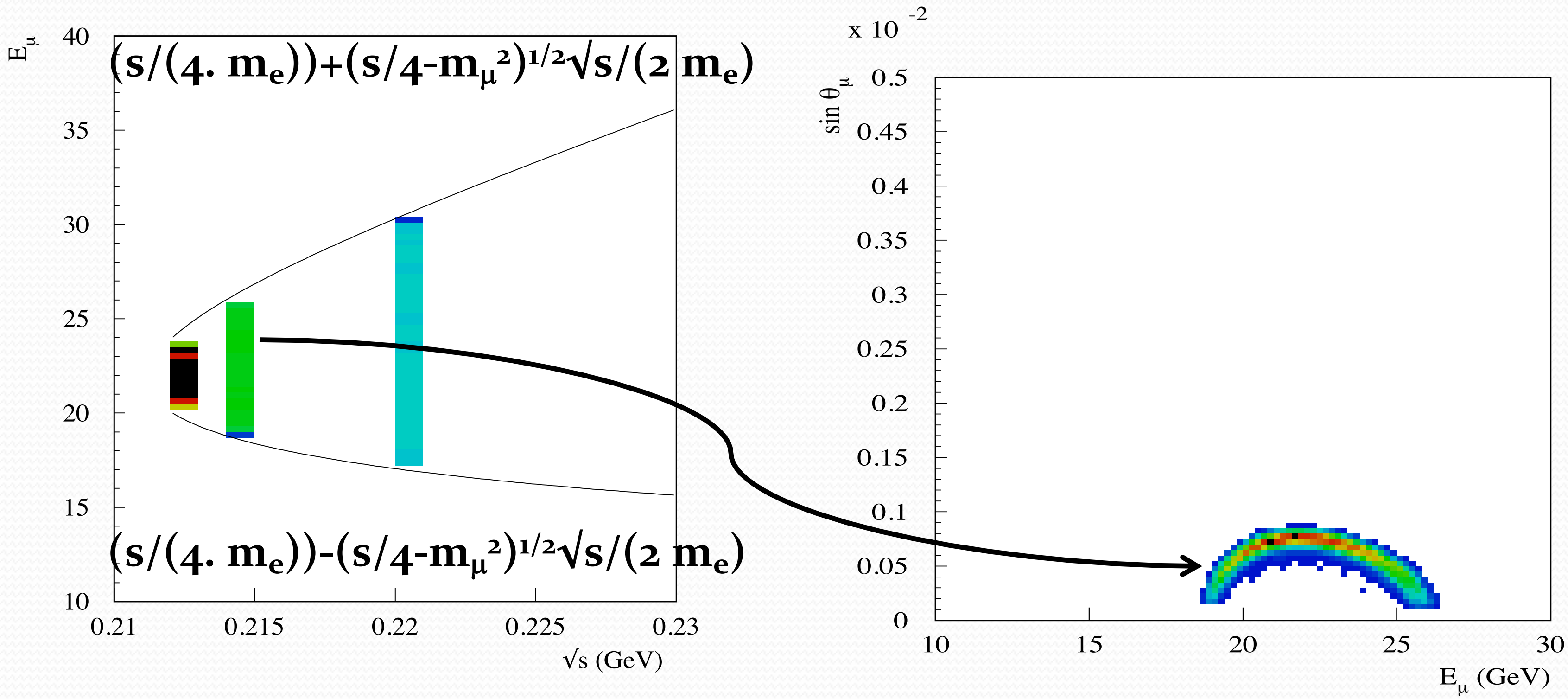
$\varepsilon_\mu = x\, x'_{max}/12 = L\, (\theta_\mu^{max})^2/12$

[Babayaga 3.5]



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

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



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

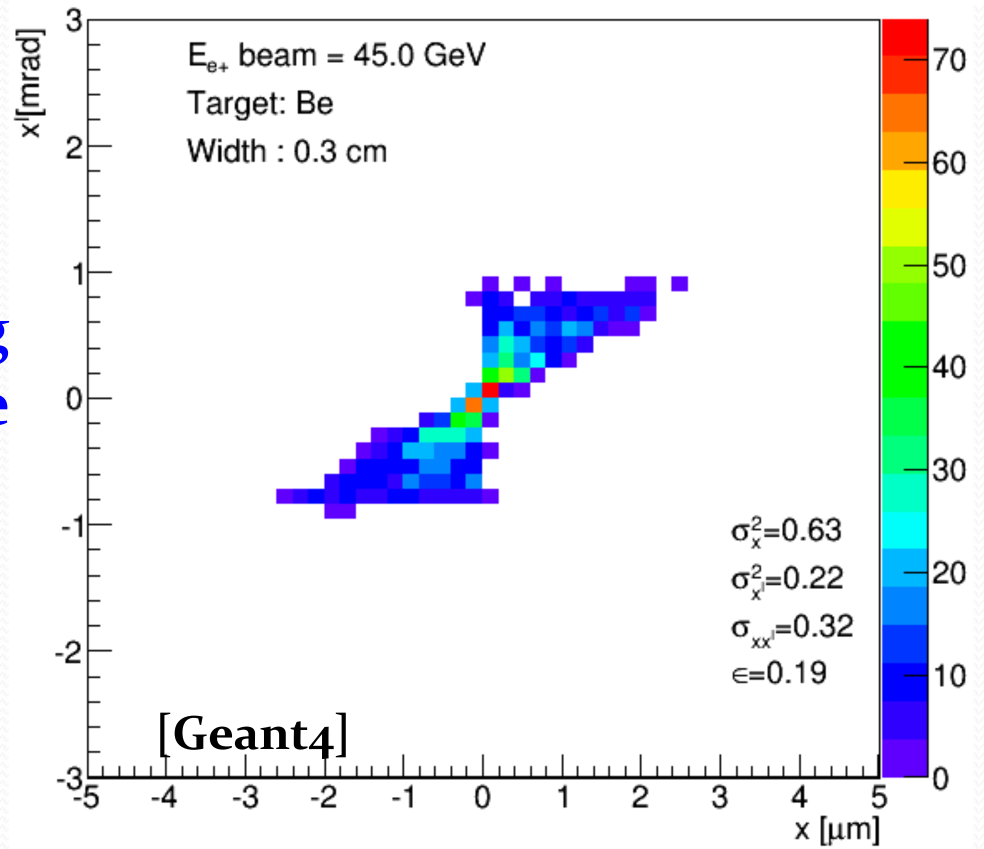
Optimal: light, thin

Possible target: 3 mm Be

Study in progress

45 GeV e^+ impinging beam

Muons at the target exit surface



- Emittance at E_μ = 22 GeV:

  $\boldsymbol{\varepsilon_x = 0.19 \cdot 10^{-9}}$ **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

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

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]

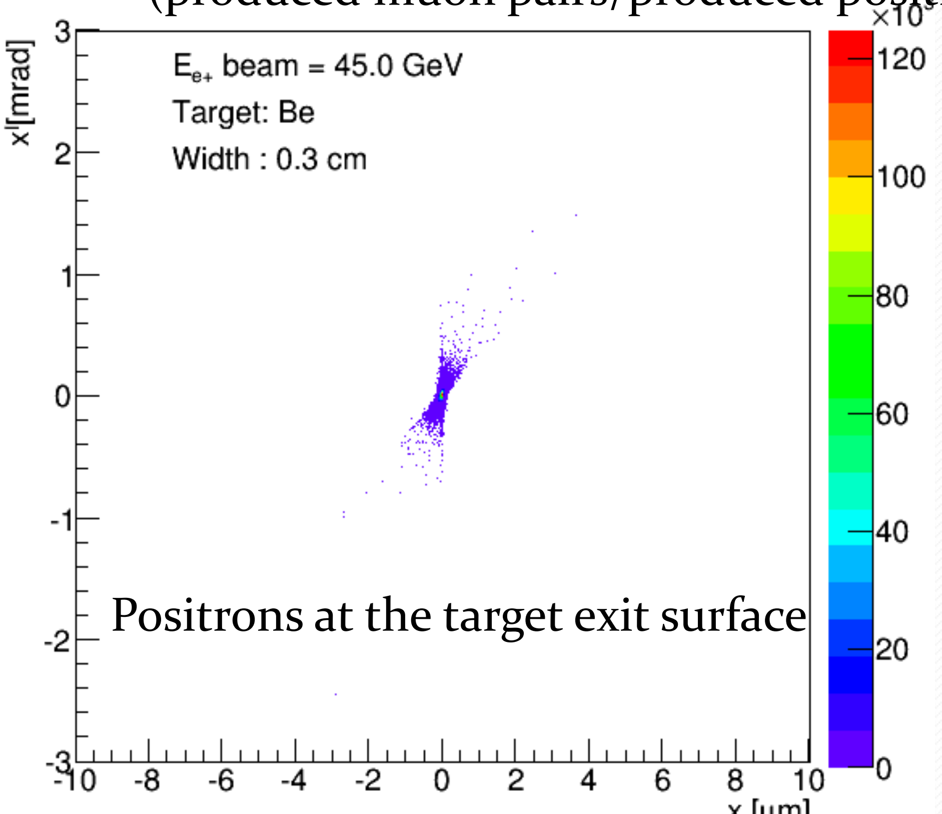
	SLC	CLIC	ILC	LHeC pulsed	LHeC ERL
E [GeV]	1.19	2.86	4	140	60
$\gamma\epsilon_x$ [μm]	30	0.66	10	100	50
$\gamma\epsilon_y$ [μm]	2	0.02	0.04	100	50
$e^+[10^{14}\mathrm{s}^{-1}]$	0.06	1.1	3.9	18	440

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

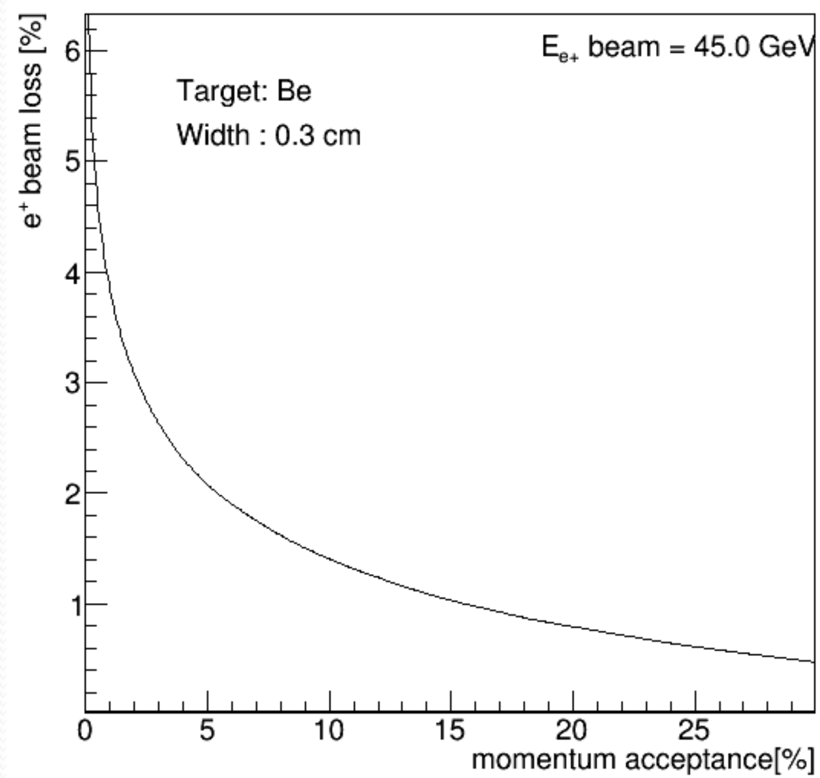
Positrons storage ring requirements

Study in progress

- Transverse phase space almost not affected by target
- Most of positrons experience a small energy deviation
- A large fraction of e⁺ can be re-collected (depending on the momentum acceptance)
  - 10% momentum acceptance will increase the effective muon conversion efficiency (produced muon pairs/produced positrons) by factor 100

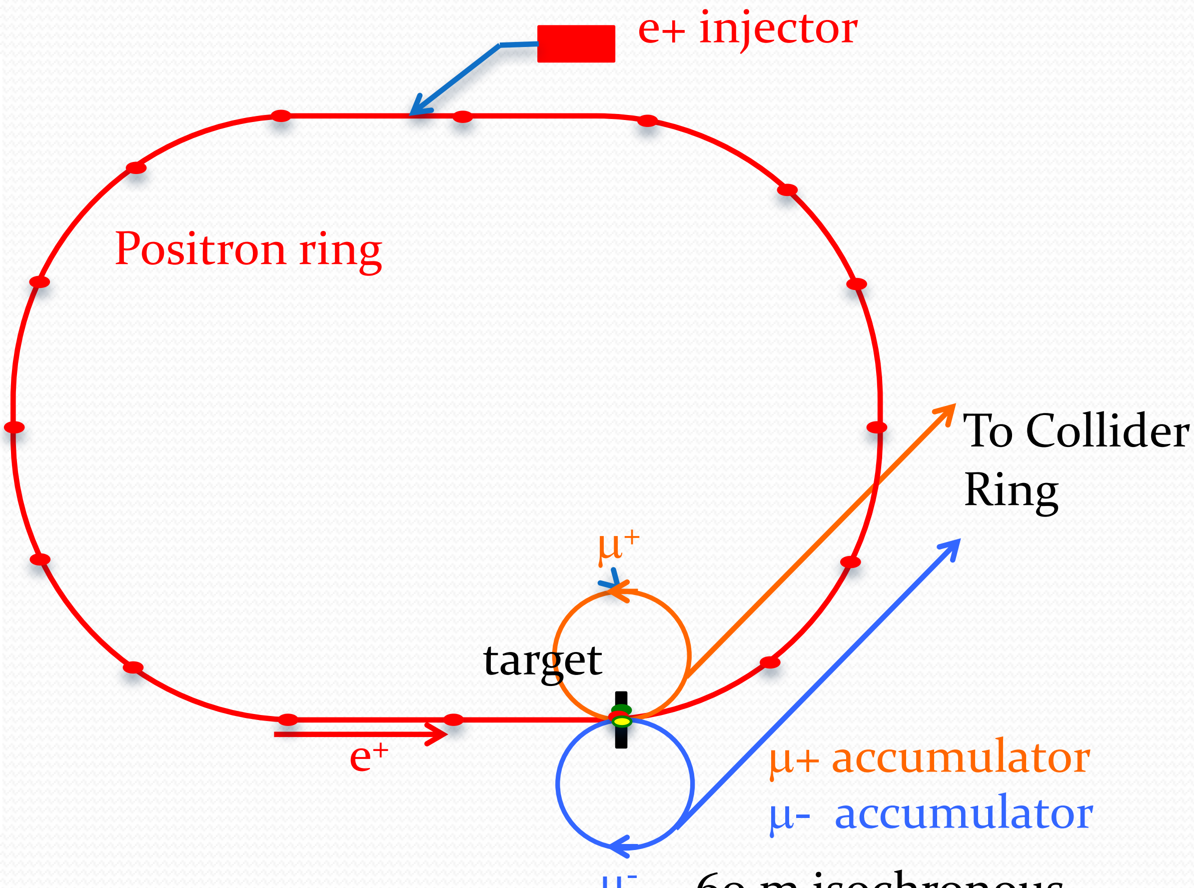


Positrons at the target exit surface



Schematic Layout for muon source from e+

Circumference	6.3 km
ρ	0.6 km
e^+ bunches n.	100
e^+ bunch spacing	200 [ns]
Beam current	240 [mA]
e^+/bunch	$3 \cdot 10^{11}$
e^+ rate on target	$1.5 \cdot 10^{18}$ [e^+/s]
U_0	0.58 [GeV]
P_{tot}	139 [MW]
B	0.245 [T]
$E_{critical}$	35 [keV]



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 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

LEMMA Draft Parameters

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

Design study needed to define 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

Key R&D

- MW proton driver
- MW class target
- NCRF in magnetic field

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

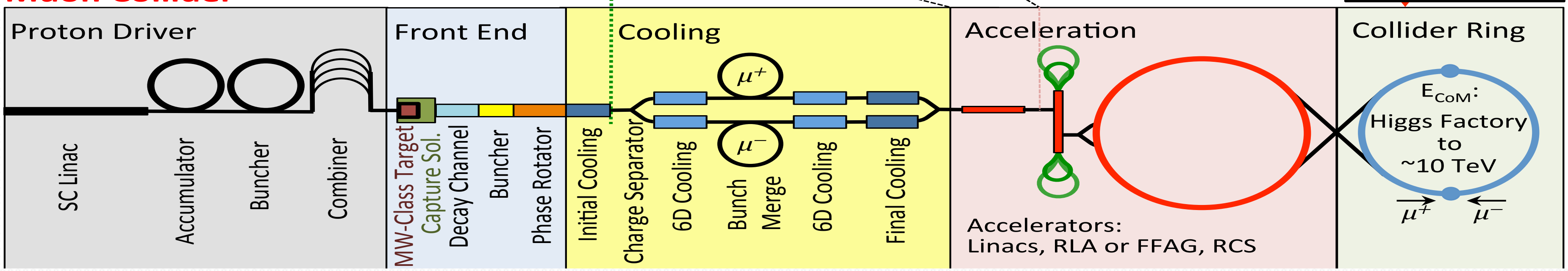
- Cost eff. low RF SC
- Fast pulsed magnet (1kHz)

- Detector/ machine interface

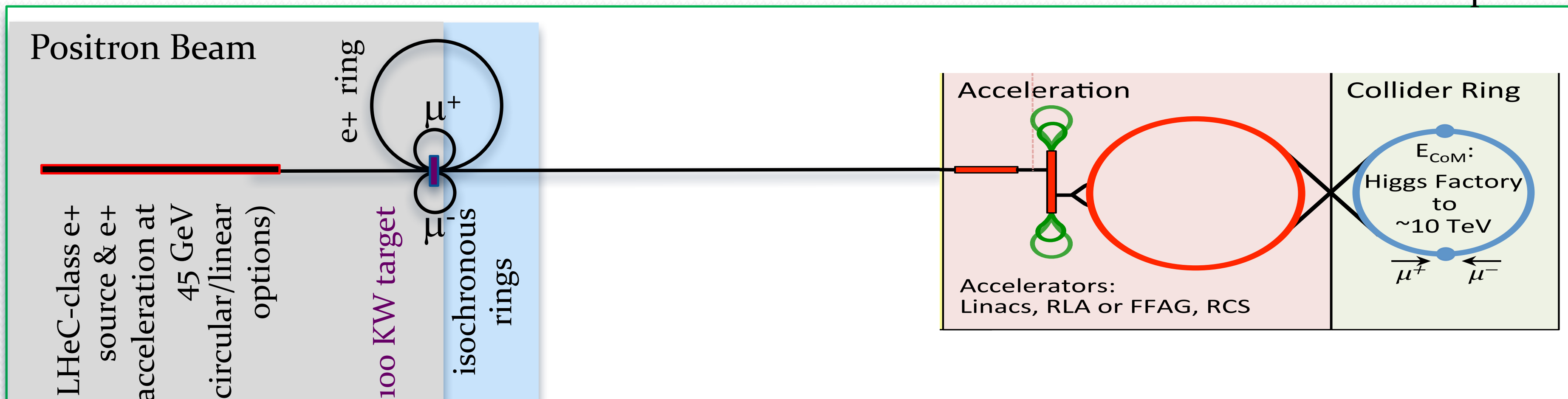
Key Challenges

- ~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

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

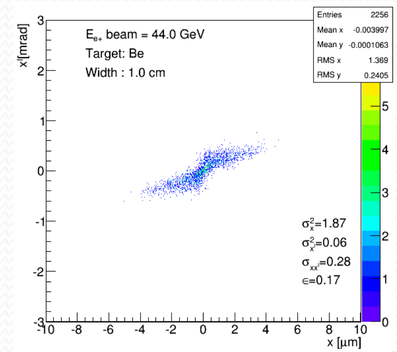
- μ Acceleration
- Collider Ring
- Collider MDI
- Collider Detector

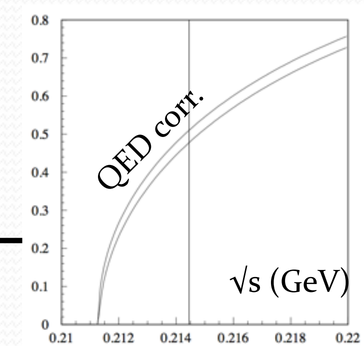
(mostly) independent on muon source

synergy between the two options

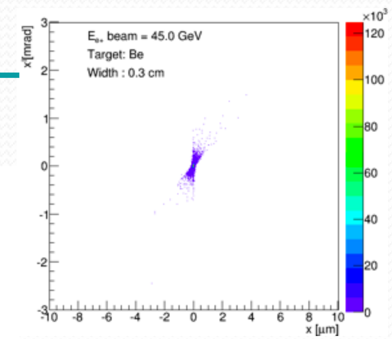
Possible experimental tests

- Muon production:
  - low muon emittance
  - Intensity
    - Measurement of cross section at threshold

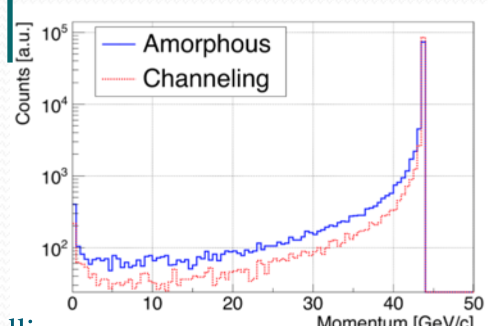




- Positron beam degradation:
  - Measurement of e+ emittance after target
  - Positron spectrum after target



- Positron source:
  - Gamma produced spectrum



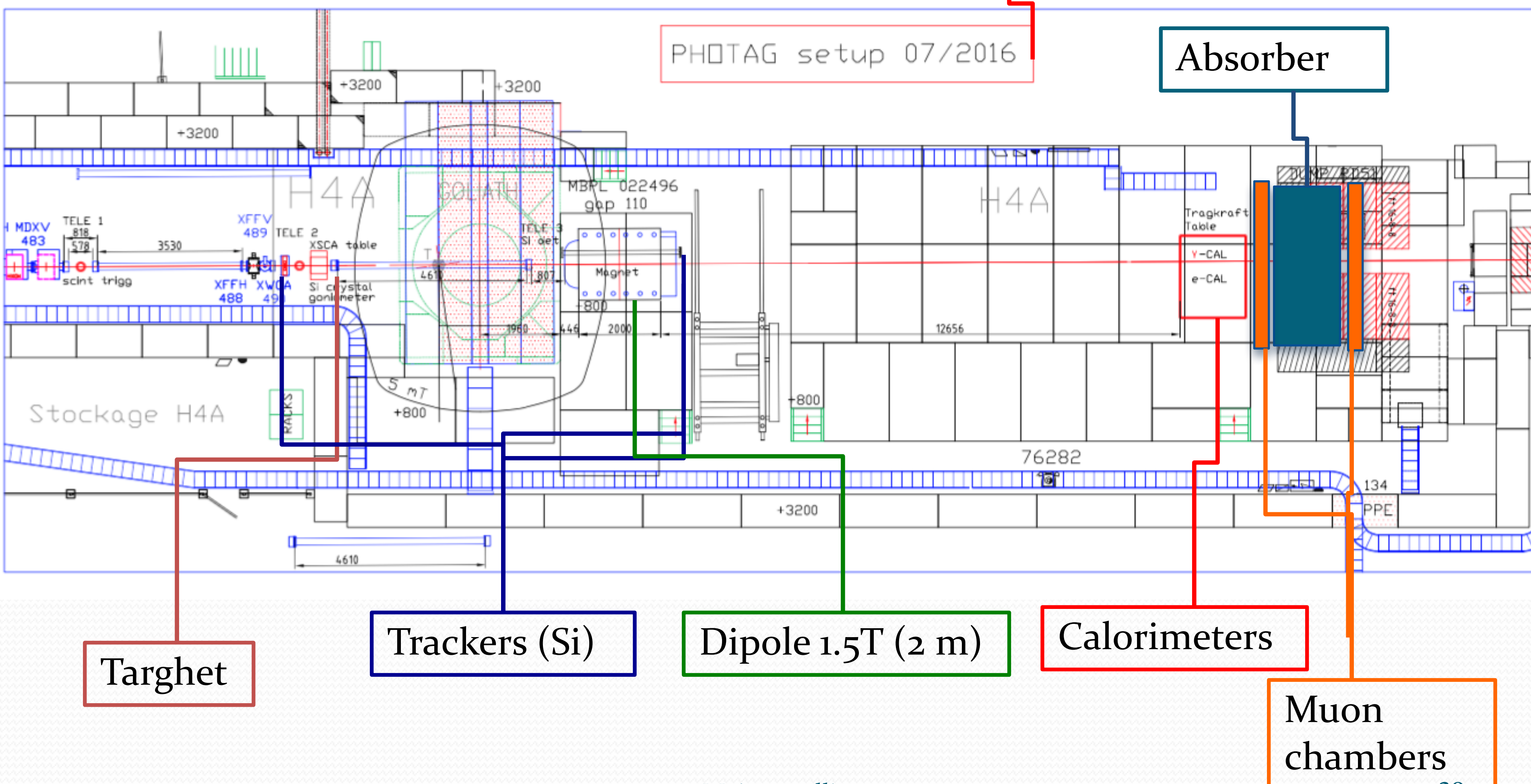
Proposal for CERN H4 experiments

- Two experiments with different scopes:
  - One week measurements at low intensity
    - Channelling on crystals (MC tuning)
    - Amorphous beam degradation
    - Gamma emitted spectrum
  - One week measurements at high intensity
    - Properties of produced muons (emittance,…)
    - Other ideas…

H4 Beam line for high intensity

45 GeV, beam energy spread ~ 1%, contamination ~ 1%
rate up to 5×10^6 e+ per spill (2/33 sec)

Modified Setup for Crystals test by Ferrara/Como



Conclusions

- Muon factories can be the future of particle physics at very high energy if the technical challenges are solved
- Studies on proton driven muon beams have been carried out and a scheme has been developed, still several issues need to be solved
  - fast muon acceleration concepts deeply studied by MAP
- A novel scheme with positron driven muon beams has been proposed, with technical challenges to be studied
- 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)
- Simulations for several types of targets are in progress
- Experimental tests at CERN H4 are foreseen
- A dedicated workshop will be held in Frascati June/July 2017

LEMMA study group (at present)

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- Un. Roma1: F. Anulli, L. Palumbo, Marongiu, G. Campogiani
- LAL-Orsay: I. Chaikovska, R. Chehab

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