Performance estimate of a FCC-ee-based muon collider

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

- Involved persons:

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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^-)

Advantages:

1. **Low emittance possible:** Pμ is tunable with √s in $e^+e^- \rightarrow \mu^+\mu^-$ Pμ 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 √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

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

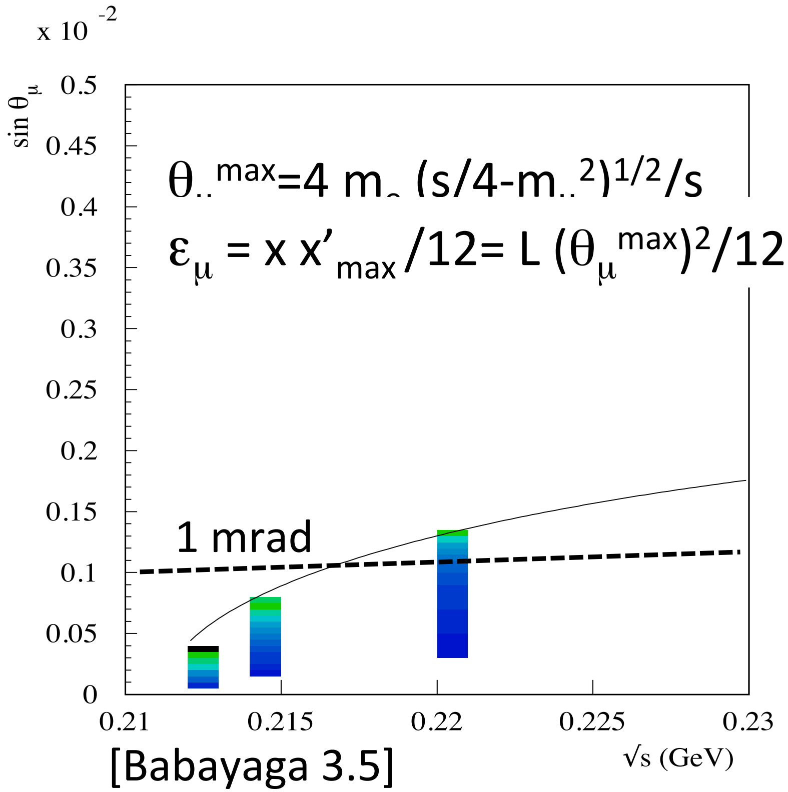
Ideally muons will *copy* the positron beam

Muons angle contribution to μ beam emittance

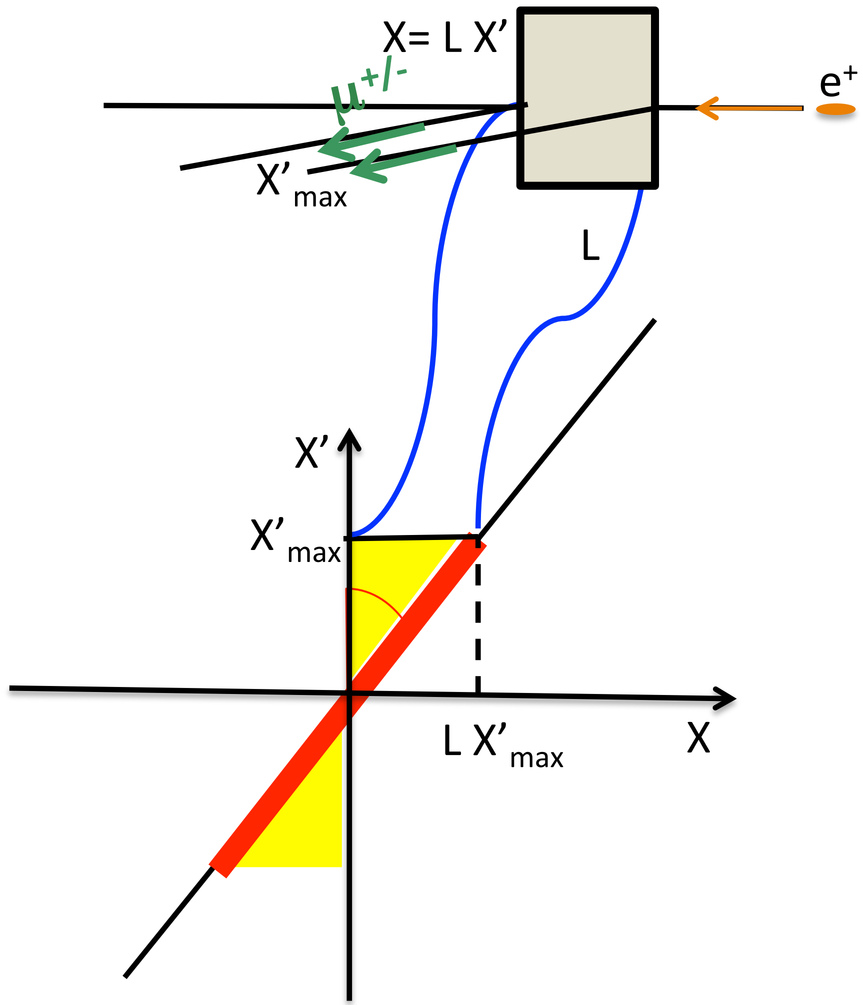
The target thickness and c.o.m. energy completely determine the emittance contributions due to muon production angle

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

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



[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 $\sim 10^{-5}$
  - 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:

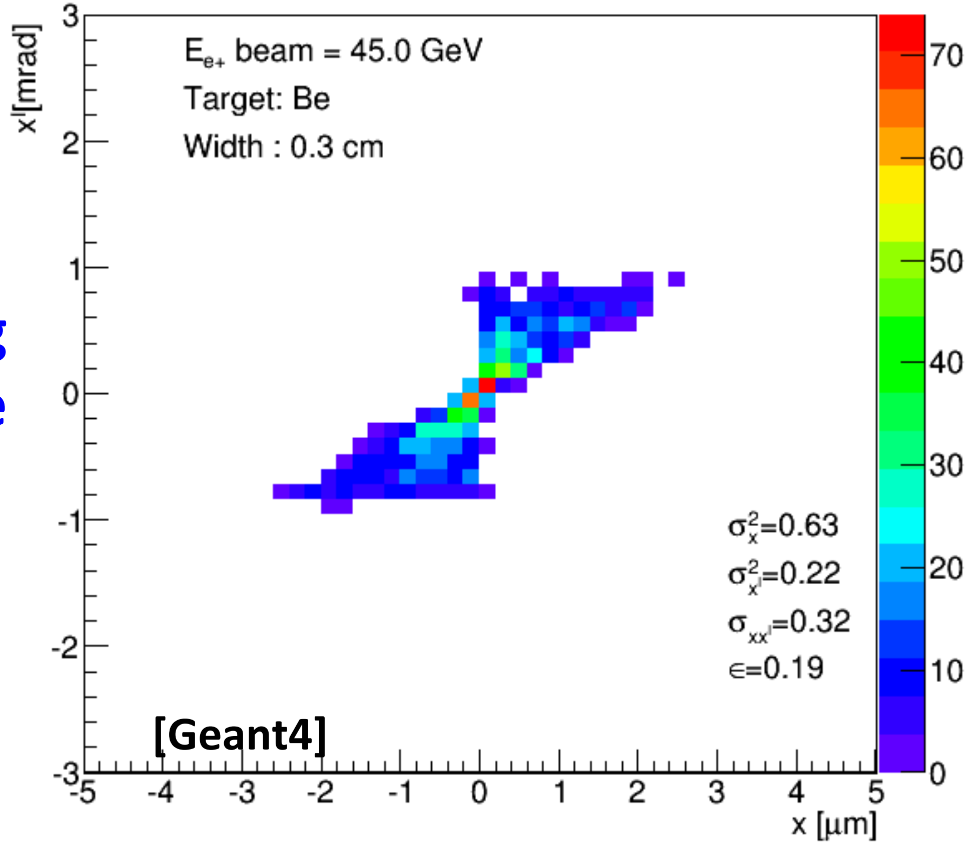
  ε_x = 0.19 $\cdot 10^{-9}$ m-rad

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

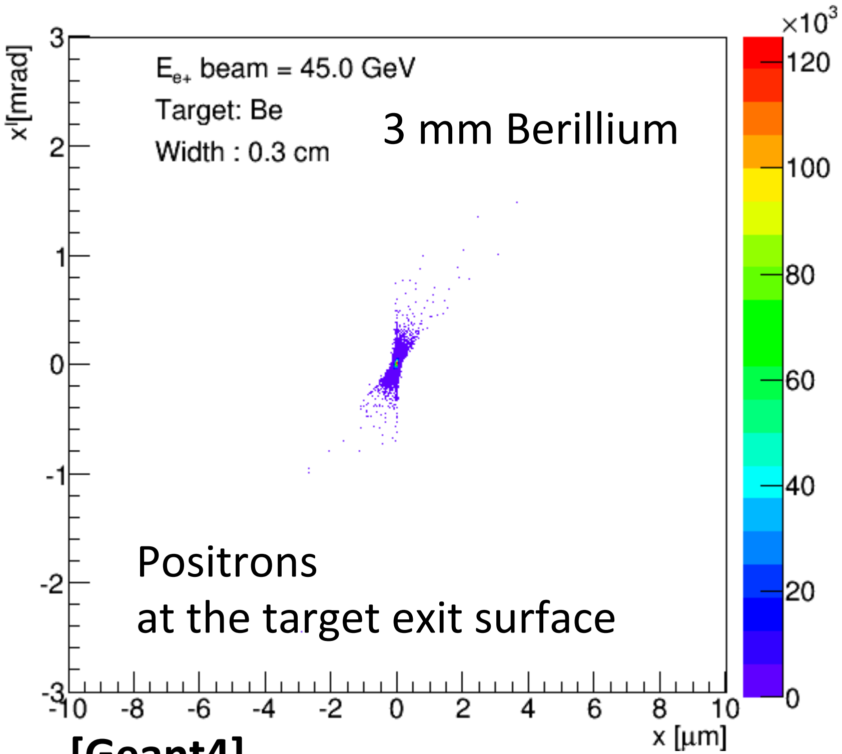


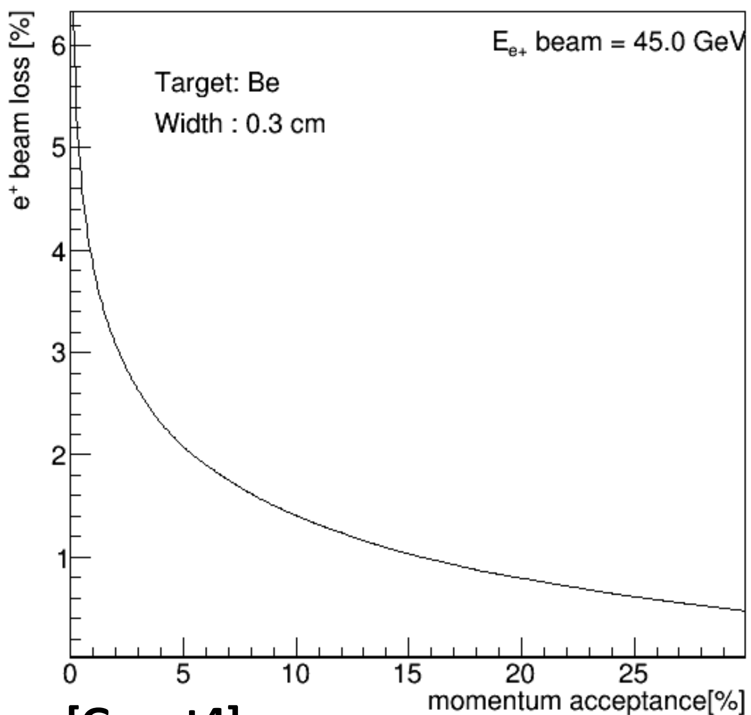
~2 mm diamond target works with similar performances (more resistant to PPDE)

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



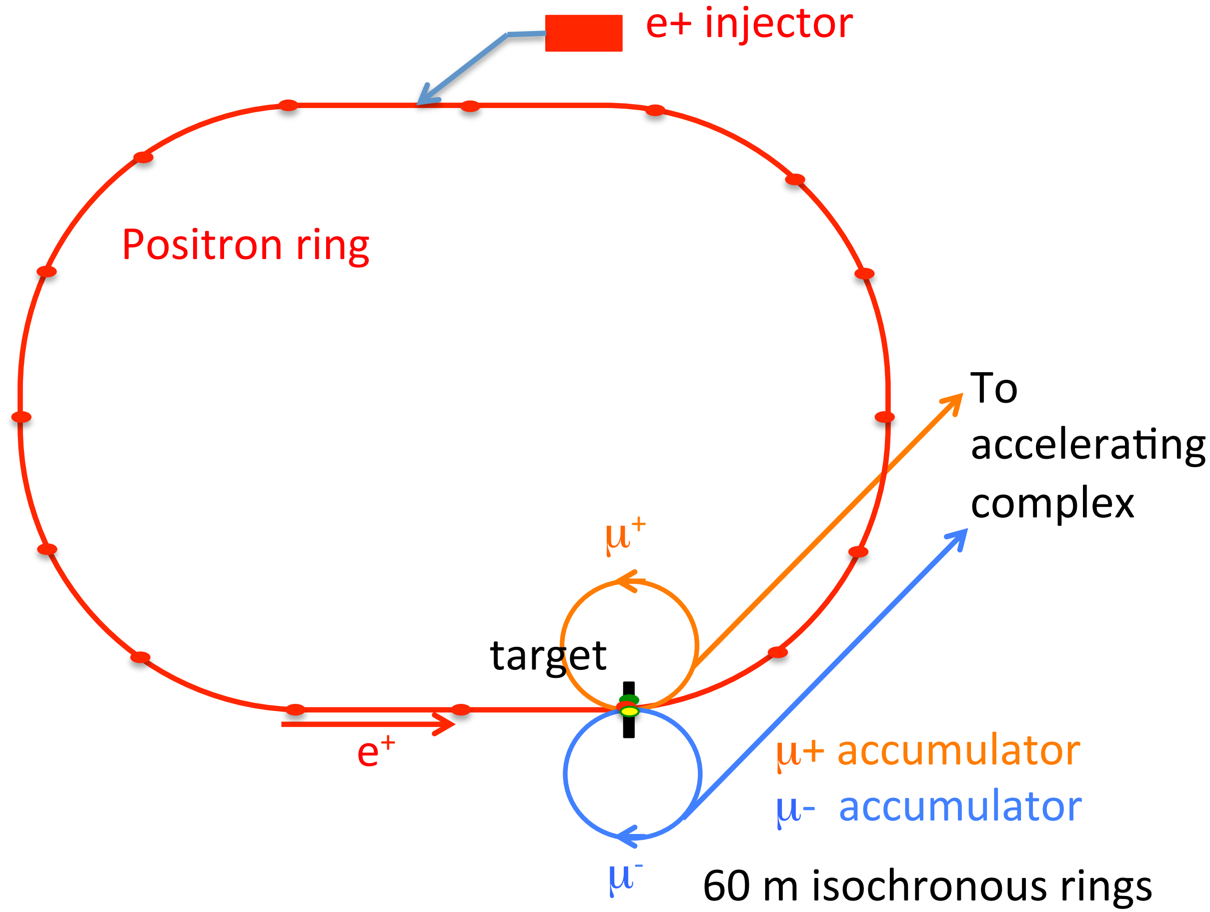


[Geant4] **[Geant4]**

Schematic Layout for muon source from e+

Positron beam parameters

	LEMMA
e+ bunch spacing	200 ns
e+/bunch	$3 \cdot 10^{11}$
Beam current	240 mA
Rate e+ on target	$1.5 \cdot 10^{18}$ e^+/s



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

parameter	FCC-ee	LEMC
energy/beam [GeV]	**45**	**45**
bunches/beam	90000	**1700**
beam current [mA]	1450	**240**
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**70**	
energy loss/turn [GeV]	0.03	**~0.4**
synchrotron power [MW]	100	
RF voltage [GV]	0.08	
rms bunch length (SR,+BS) [mm]	1.6, 3.8	
rms emittance $\varepsilon_{x,y}$ [nm, pm]	0.09, 1	**>0.1,>100**
longit. damping time [turns]	1320	
crossing angle [mrad]	30	
beam lifetime [min]	251	**>>1s**

Next slides

Muon beam parameters

Assuming

- a positron ring with a total 25% momentum acceptance
- ~3 × LHeC positron source rate

FCC

- 2% momentum acceptance? (no need of FF here)
- Requires dedicated positron source
  - **push on mom. acceptance and e^+ source performances**
  - **improve target performances (crystals?)**

	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

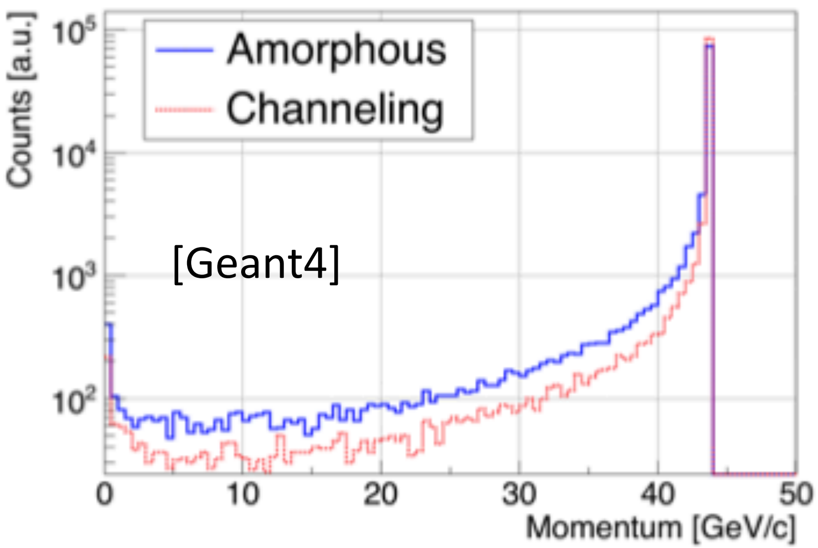
Very small emittance, **high muon rates** but relatively small bunch population:

➢ 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.

Positrons

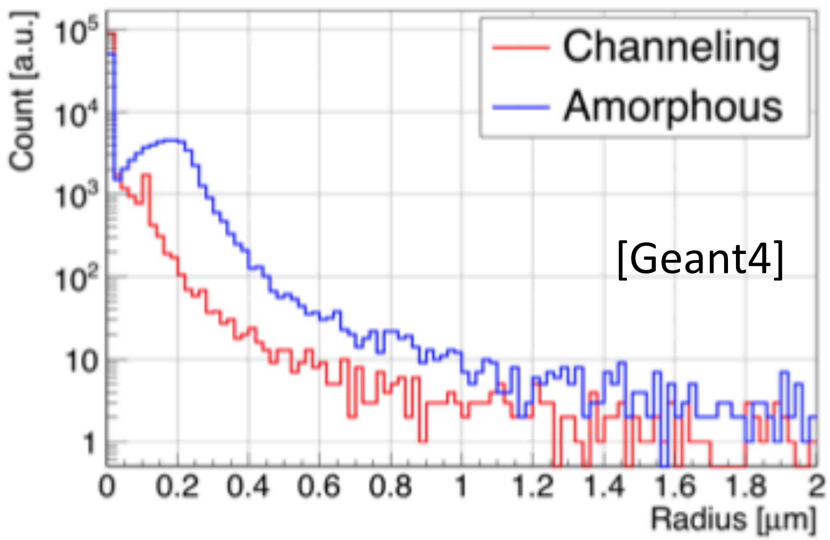
43.8 GeV e^+
4.1 mm Si Target
Channeling plane: (110)

Momentum



Position

[Bagli, Cavoto]

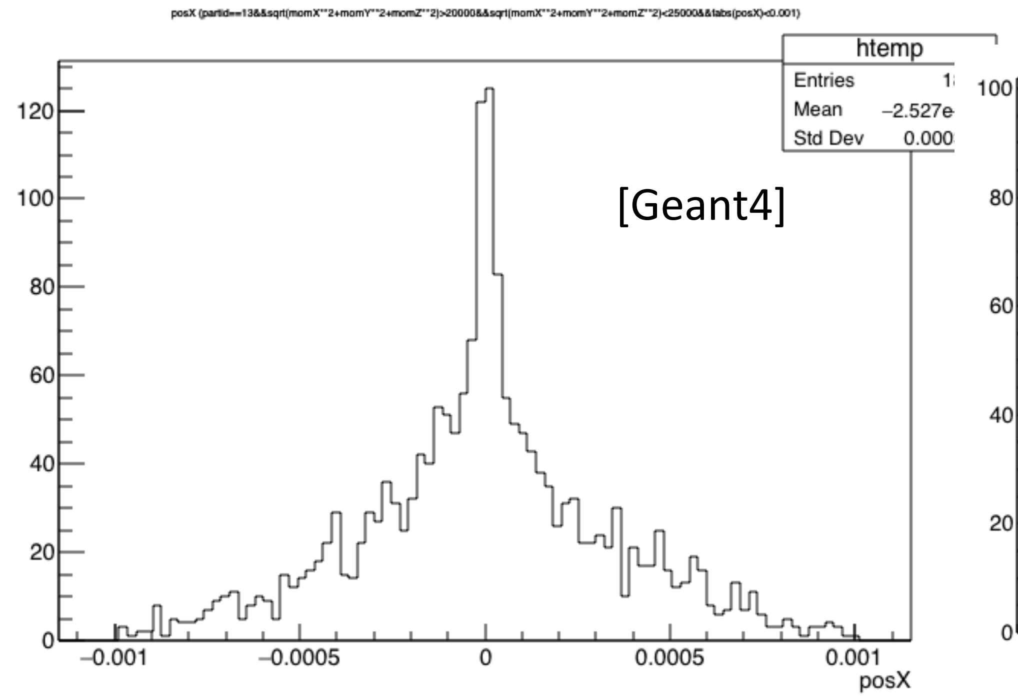


Channeling of produced muons

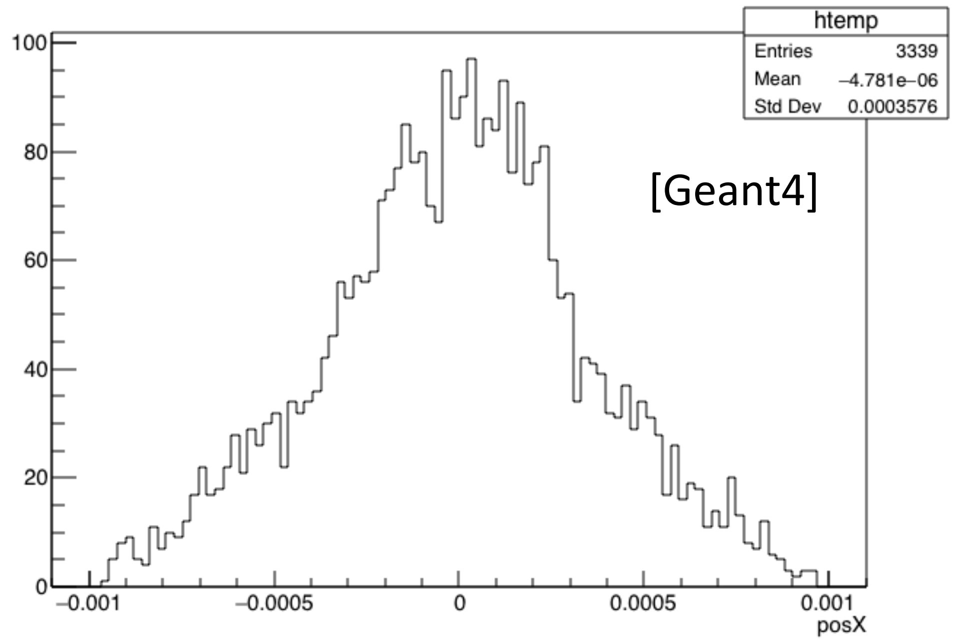
[Bagli, Cavoto]

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

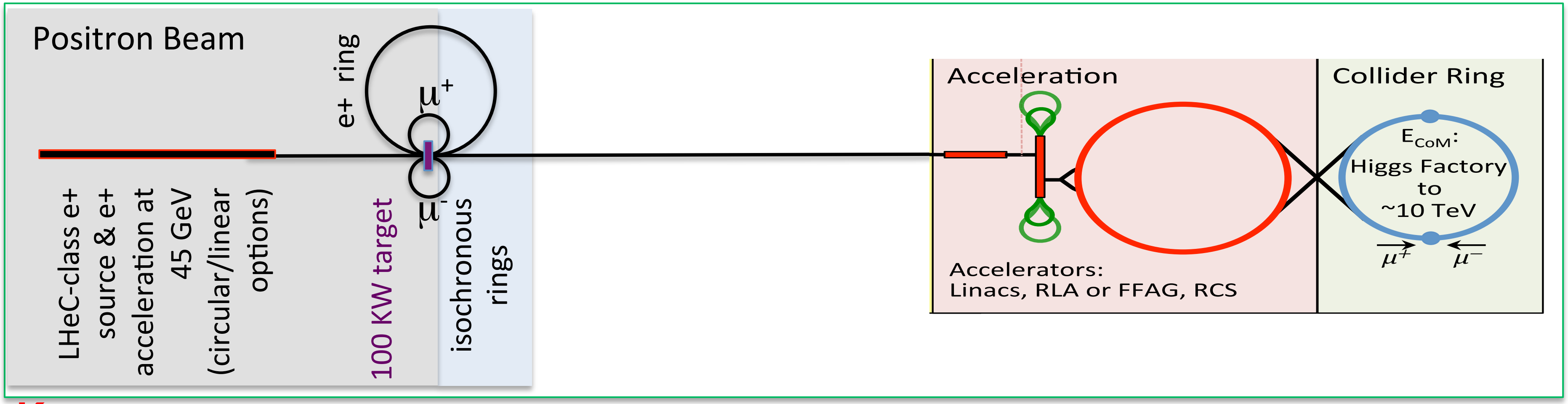
crystal



amorphous



Muon Collider:
Schematic Layout for positron based muon source



Key Challenges

~10^{11} μ / sec from e+e-→μ+μ−

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

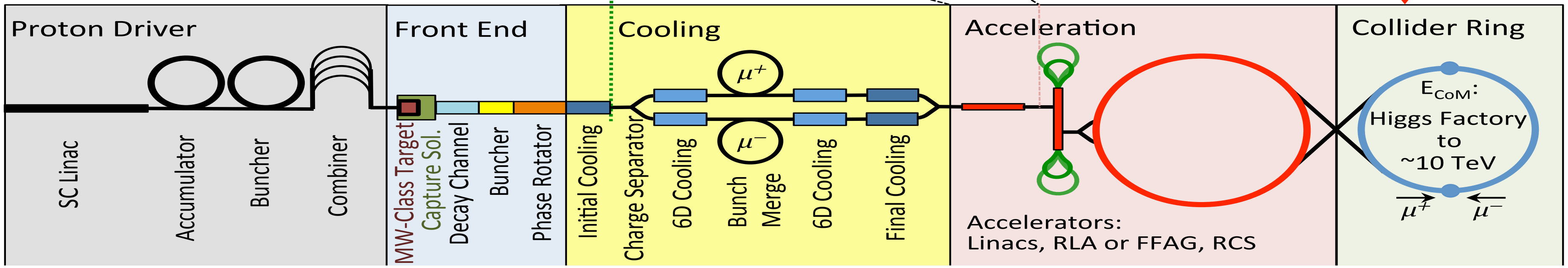
~10^{13}-10^{14} μ / sec
Tertiary particle $p \rightarrow \pi \rightarrow \mu$:

Fast cooling
(τ=2μs) by 10^6 (6D)

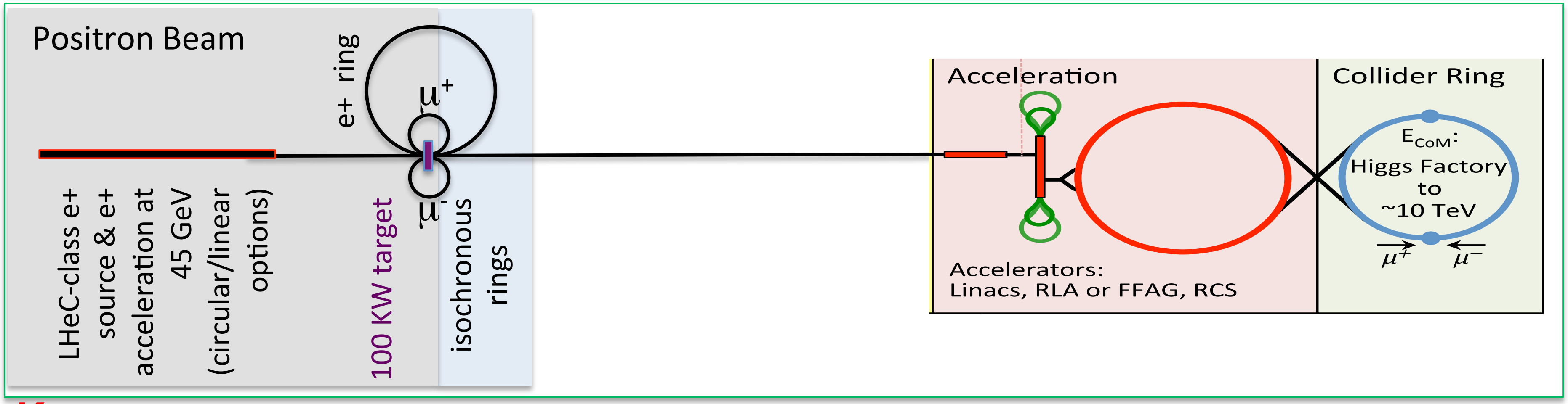
Fast acceleration
mitigating μ decay

Background
by μ decay

Muon Collider



share the same complex



Key Challenges

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

Key R&D

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

EASIER AND CHEAPER DESIGN, IF FEASIBLE

LEMC 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 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

Radiological hazard due to neutrinos from a muon collider

Colin Johnson, Gigi Rolandi and Marco Silari

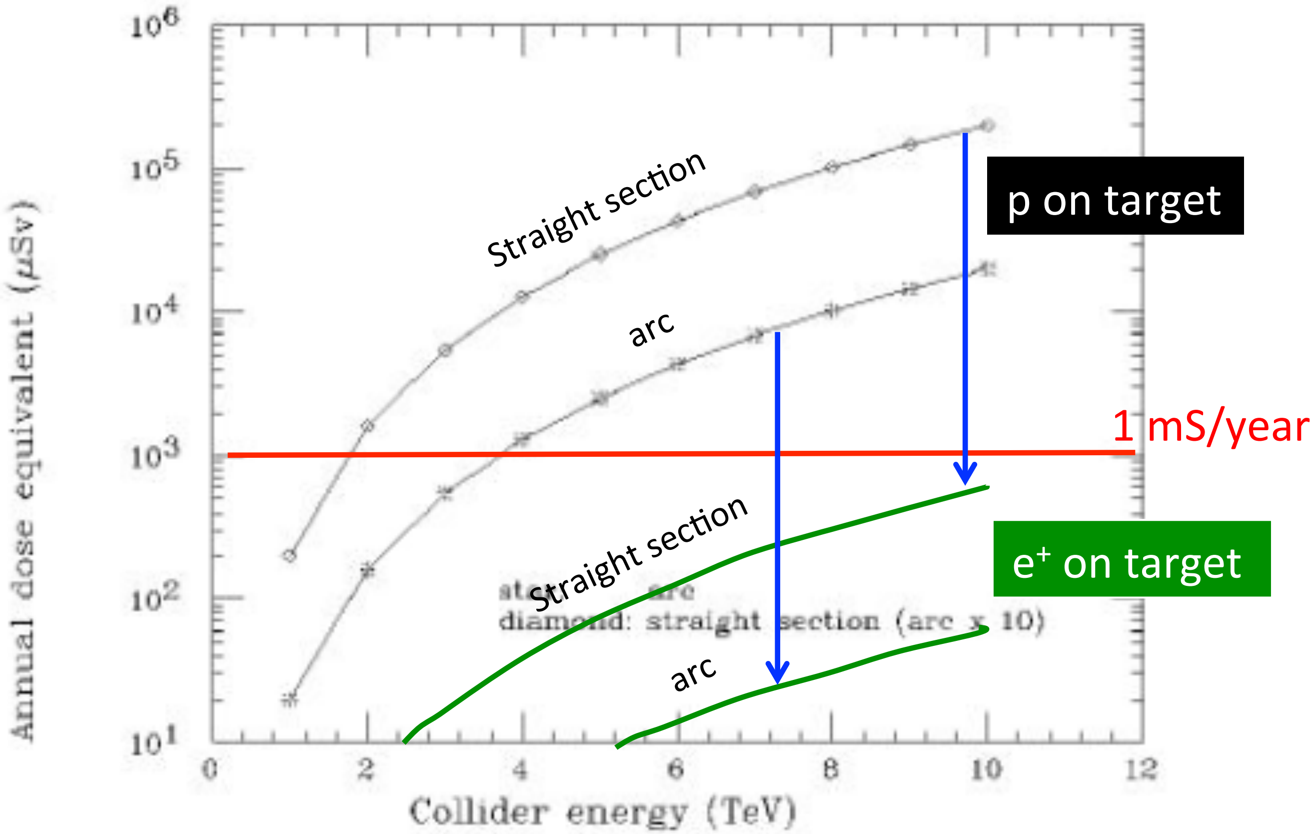


Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

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

e^+ on target option 9 10^{10} μ/s

Conclusion

- Very low emittance muon beams can be obtained by means of positron beam on target
- Some synergy with FCC-ee parameters: beam energy, emittance, bunch structure.. but
- competitive muon rates require:
  - Challenging positron source (LHeC like)
  - Positron ring with high momentum acceptance (synergy with next generation SR sources)
- fast muon acceleration concepts deeply studied by MAP