

Very low Emittance Muon Beam using positron beam on target

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References:

- 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 investigated 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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- M. Prest **(Uni-Insubria&INFN)**
- P.Raimondi **(ESRF)**
- J. P. Delahaye, P. Sievers, R. Di Nardo **(CERN)**
- I.Chaikovska, R. Chehab **(LAL-Orsay)**
- L. Keller, T. Markiewicz **(SLAC)**

Idea for low emittance μ beam

Conventional production: from **proton on target**

π , K decays from proton on target have typical $P_\mu \sim 100 \text{ MeV}/c$
(π , K rest frame)

whatever is the boost P_T will stay in Lab frame \rightarrow

very high emittance at production point \rightarrow **cooling needed!**

Direct μ pair production:

Muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at \sqrt{s} around the $\mu^+\mu^-$ threshold (**$\sqrt{s} \sim 0.212 \text{ GeV}$**) in asymmetric collisions (to collect μ^+ and μ^-)

Advantages:

1. **Low emittance possible:** P_μ is tunable with \sqrt{s} in $e^+e^- \rightarrow \mu^+\mu^-$ 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

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

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

Possible Schemes

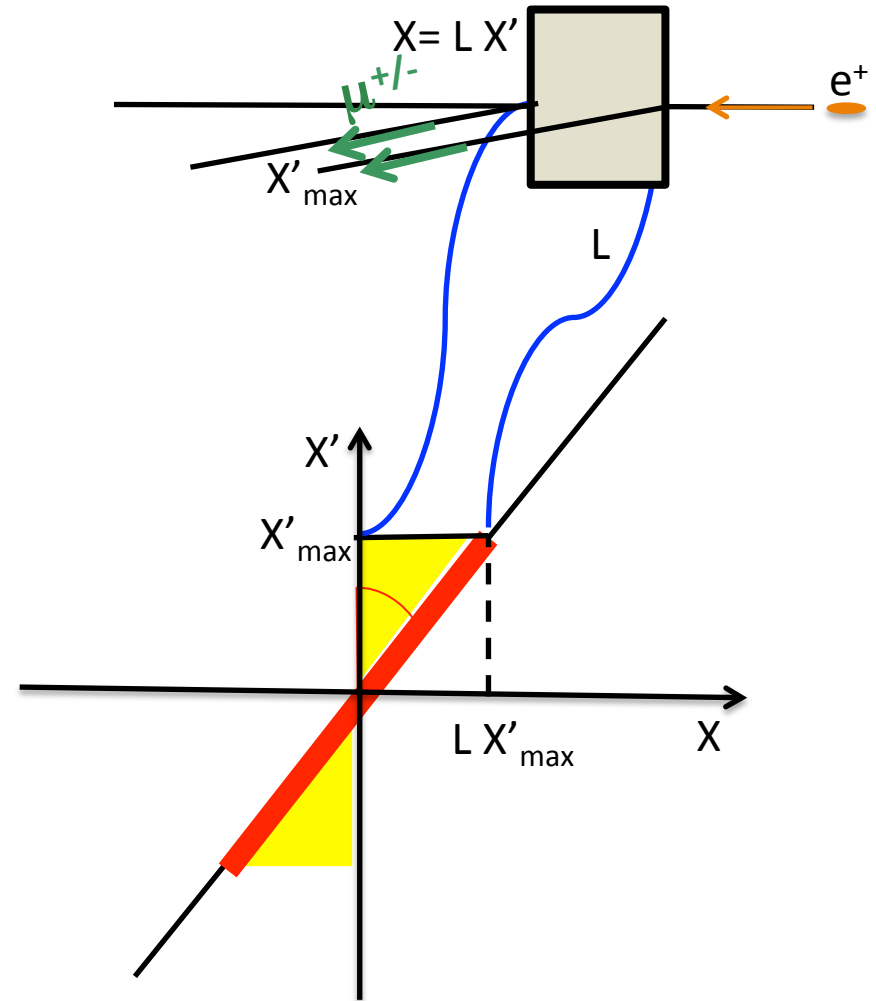
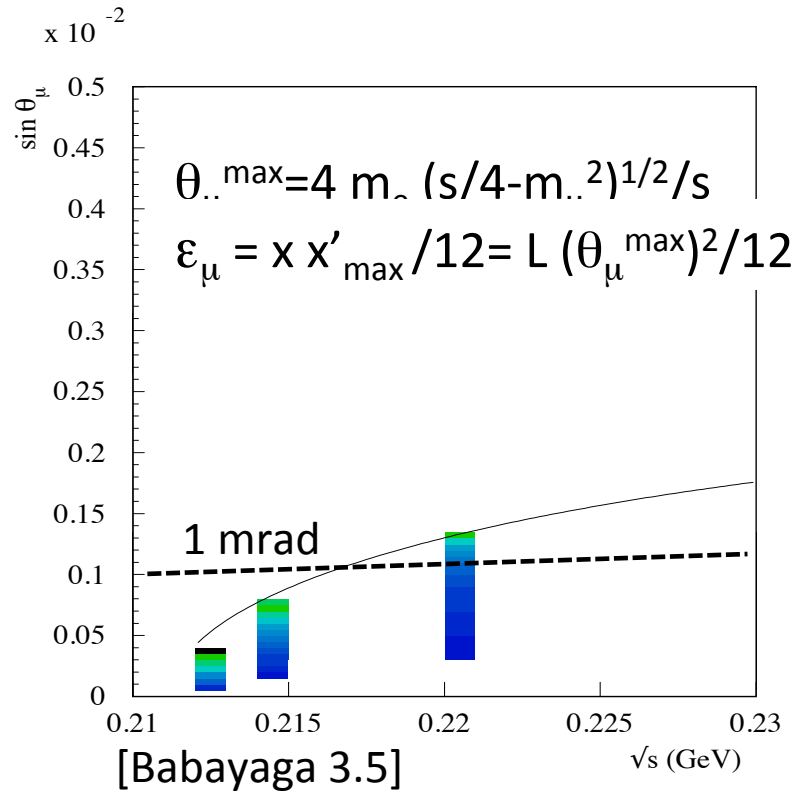
- **Low energy collider with e⁺/e⁻ beam (e⁺ in the GeV range):**
 1. Conventional asymmetric collisions (but required luminosity is beyond current knowledge)
 2. Positron beam interacting with continuous beam from electron cooling (too low electron density, 10^{20} electrons/cm⁻³ needed to obtain an 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
 - $\gamma(\mu) \sim 200$ and μ laboratory lifetime of about 500 μ s



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



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

- **$\rho^- L$ constraints**

- Ideal target (e^- dominated)

$$(\rho^- L)_{\max} = 1/\sigma(\text{radiative bhabha}) \approx 10^{25} \text{ cm}^{-2}$$

(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) \rightarrow 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... X_0 and electron density will matter:

- **Heavy materials**

- minimize emittance (enters linearly) \rightarrow 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) \rightarrow H_2
- even for liquid need $O(1m)$ target \rightarrow 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 $E_\mu = 22$ GeV:

$$\varepsilon_x = 0.19 \cdot 10^{-9} \text{ m-rad}$$

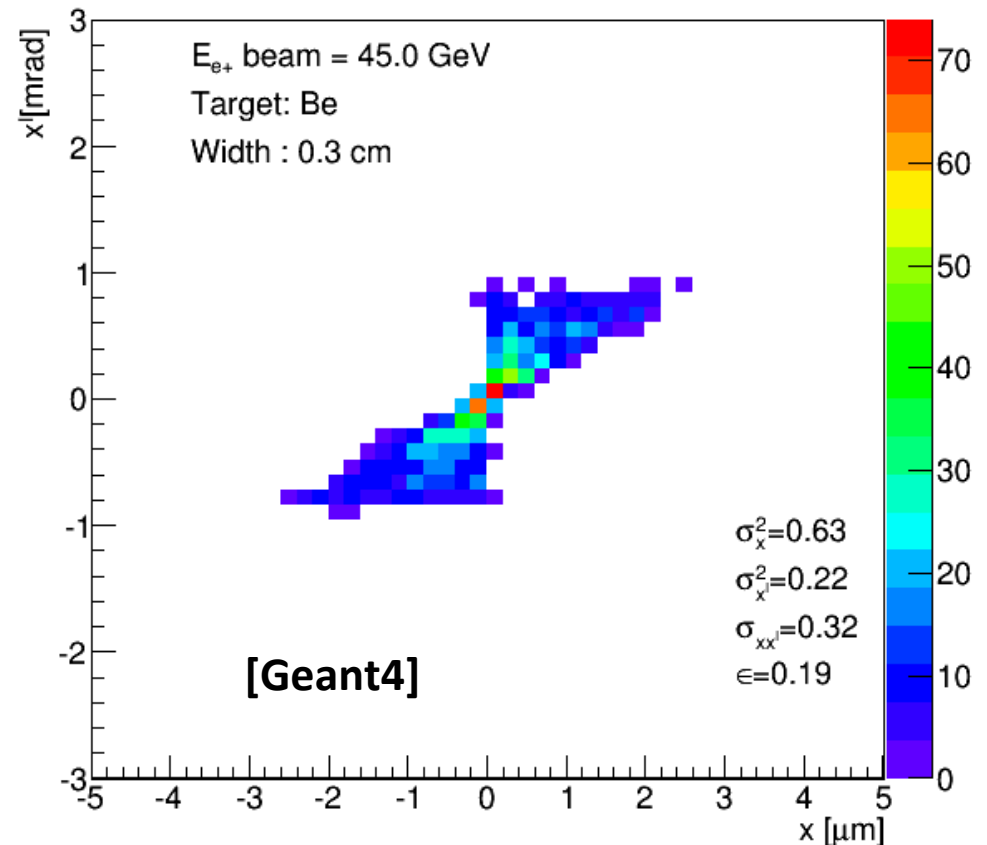
**Multiple Scattering
contribution is negligible**

-> 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%

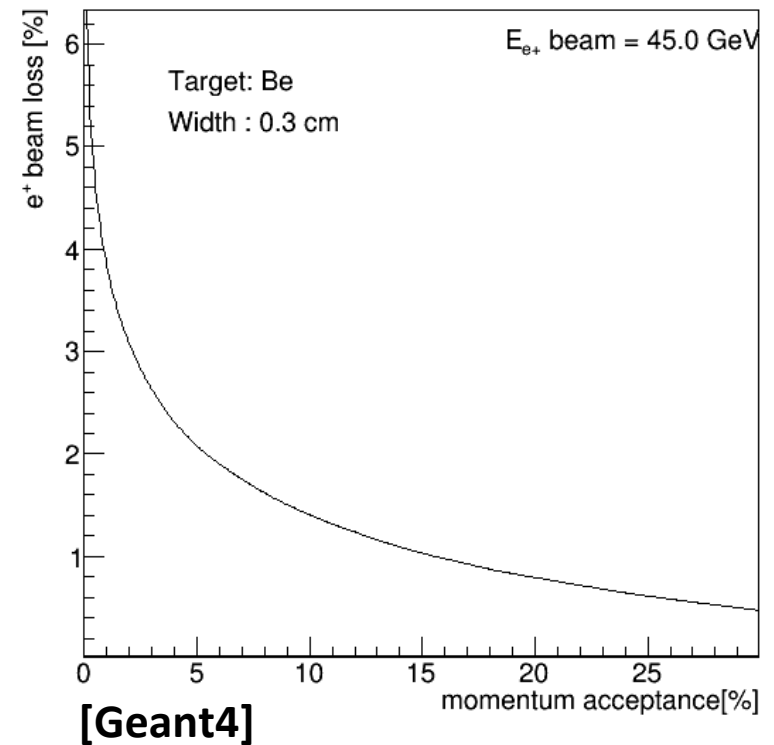
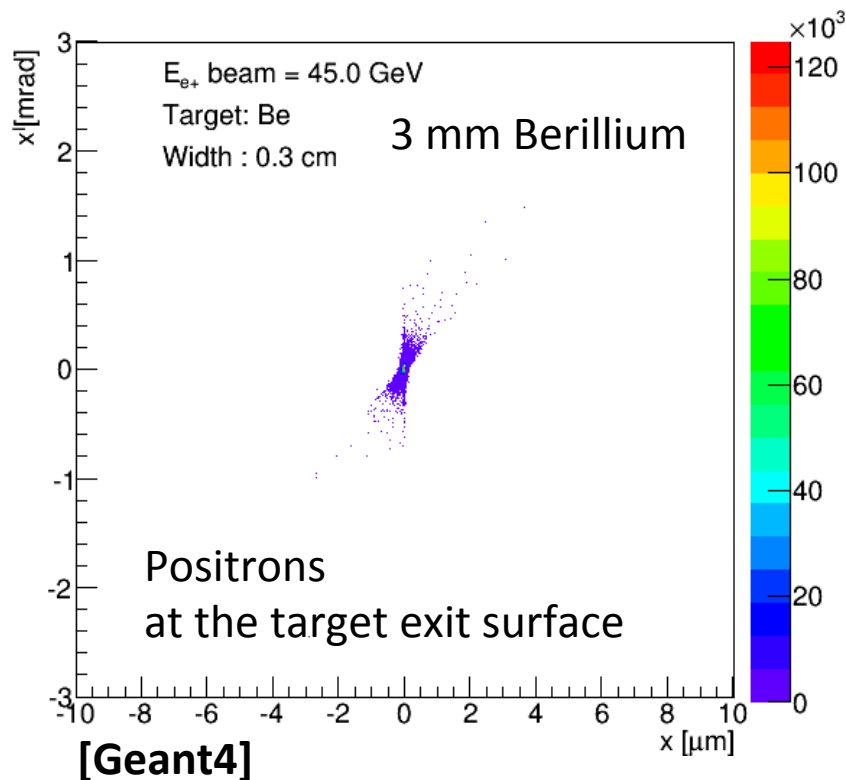
Muons at the target exit surface



~1 mm diamond target works with similar performances (more resistant to PEDD)

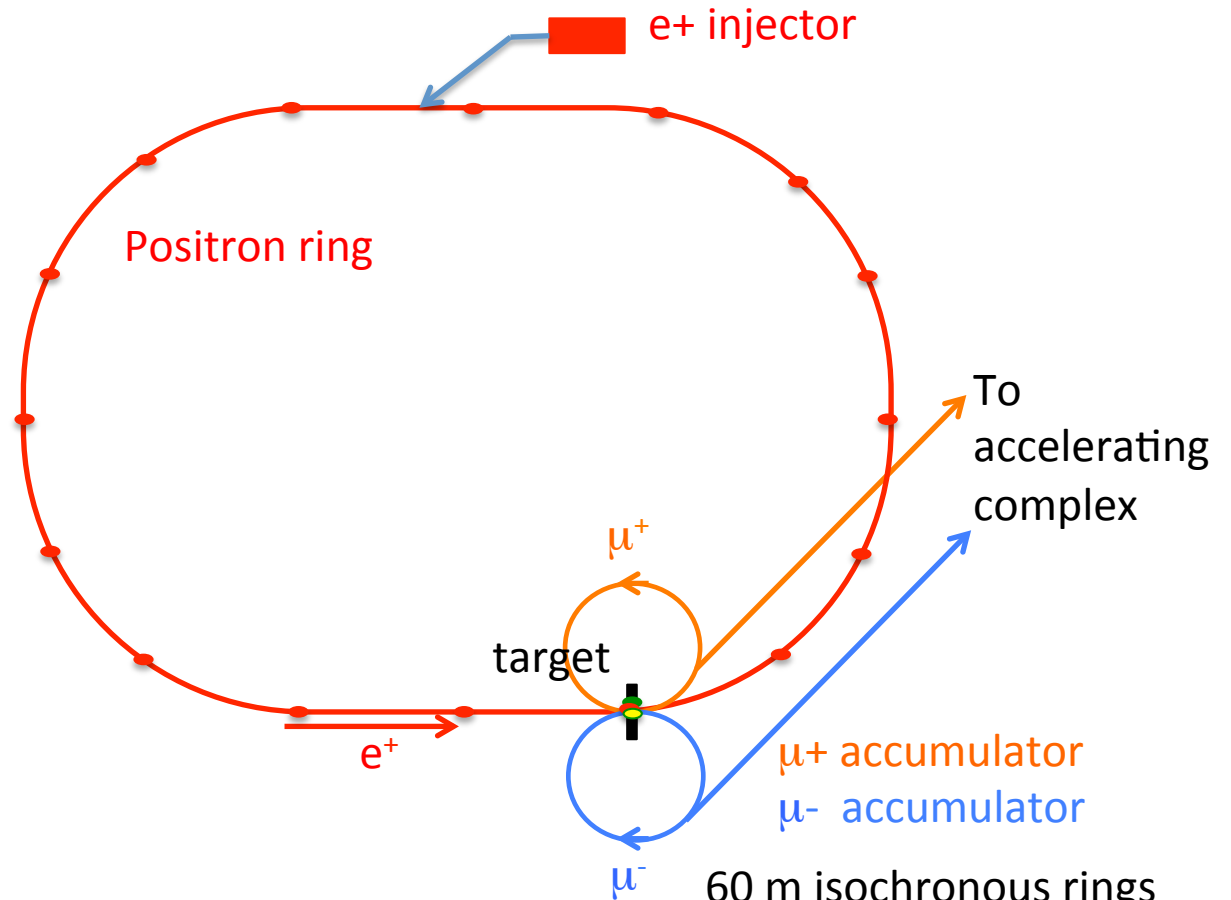
Positrons Storage Ring Requirements

- 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



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	$1.5 \cdot 10^{18} \text{ e}^+/\text{s}$
U_0	0.58 GeV
P_{tot}	139 MW
B	0.245 T



Key point:
Positron source requirements strictly related to the e+ ring momentum acceptance

60 m isochronous rings recombine bunches for $\sim 1 \tau_{\mu}^{\text{lab}} \sim 2500$ turns

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

Muon beam parameters

Assuming

- a positron ring with a total 25% momentum acceptance
- $\sim 3 \times$ FCC-he positron source rate



- **push on mom. acceptance and e^+ source performances**
- **improve target performances**

	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 [$\mu\text{m-mrad}$]	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 $\sim \tau_{\mu}^{\text{lab}}(\text{HE})/500 \mu\text{s}$ (~ 100 @6 TeV) by topping up.

Low Emittance Muon Muon Accelerator Draft Parameters

comparable luminosity with
lower $N\mu$ /bunch
(lower background)
thanks to very small
emittance (and lower beta*)

Of course, a design
study is needed to
have a reliable
estimate of
performances

		LEMC-6TeV
Parameter	Units	
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

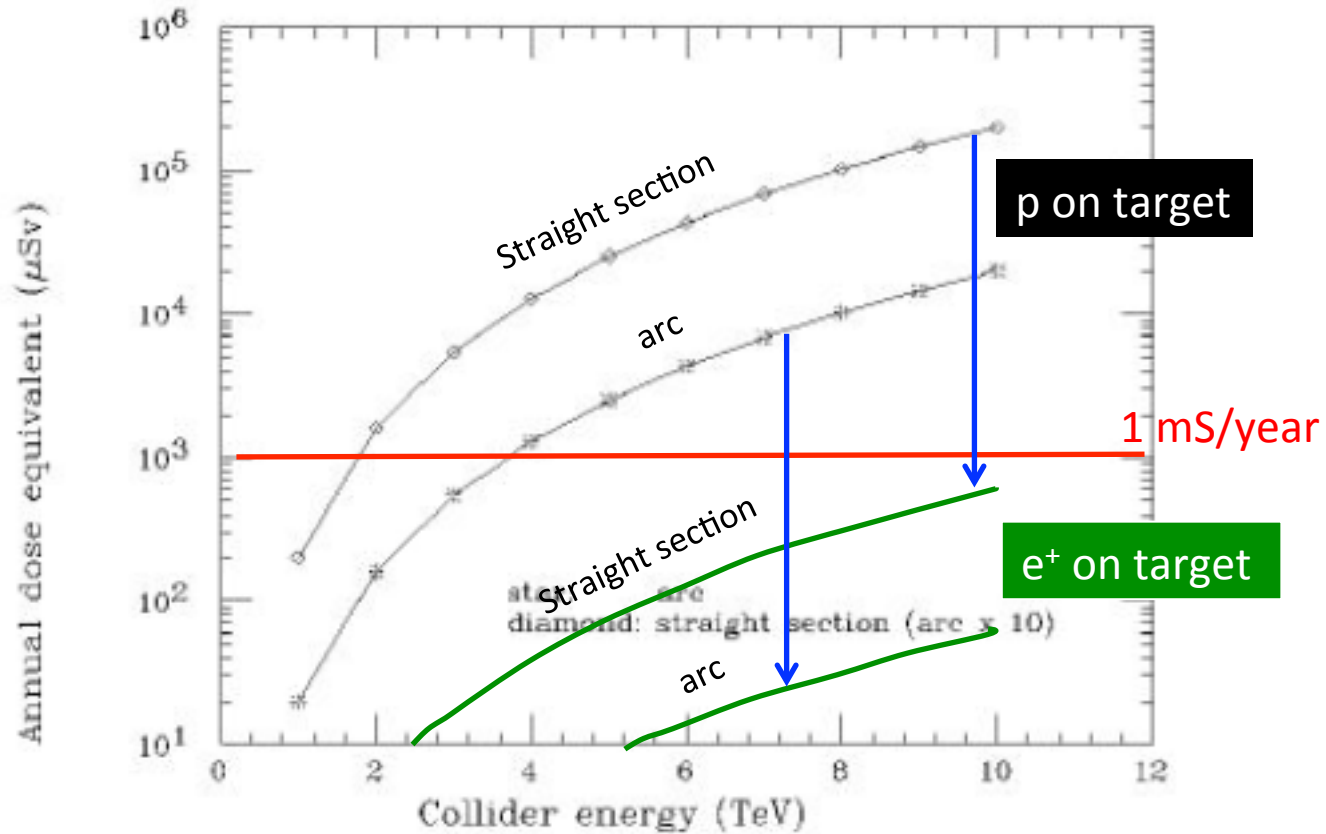


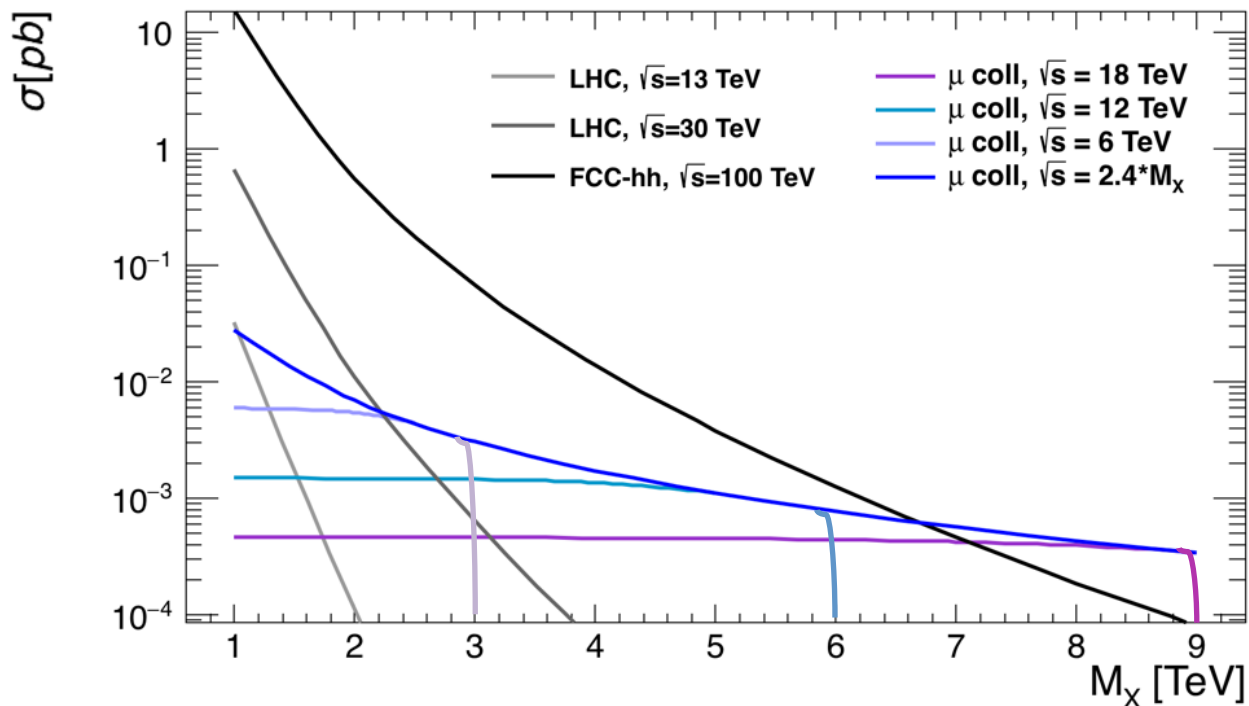
Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

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

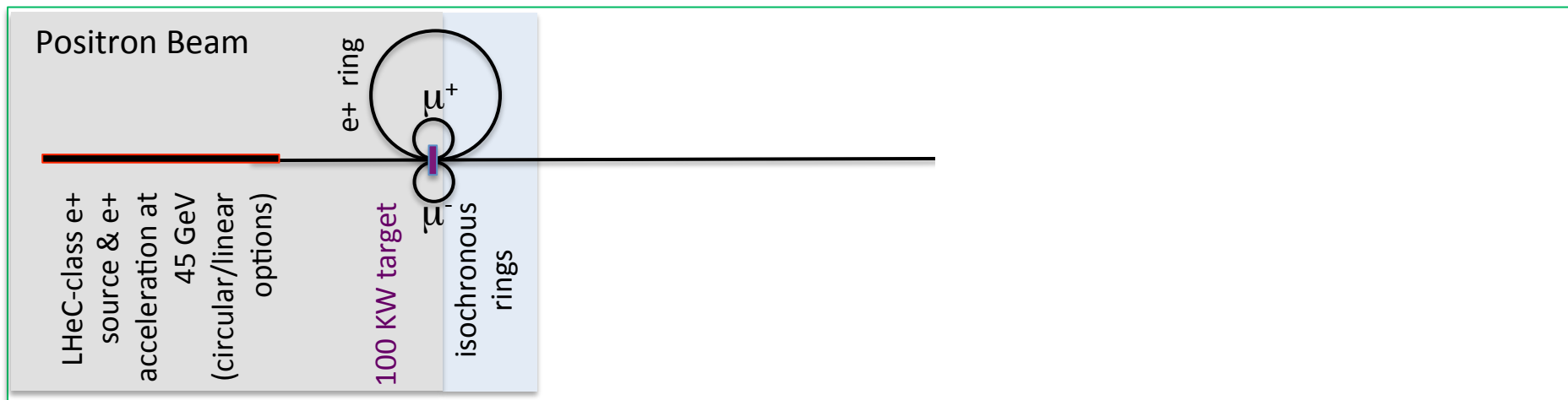
e+ on target option $9 \cdot 10^{10}$ μ/s

Muon collider reach: an example

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



Muon Collider: Schematic Layout for positron based muon source

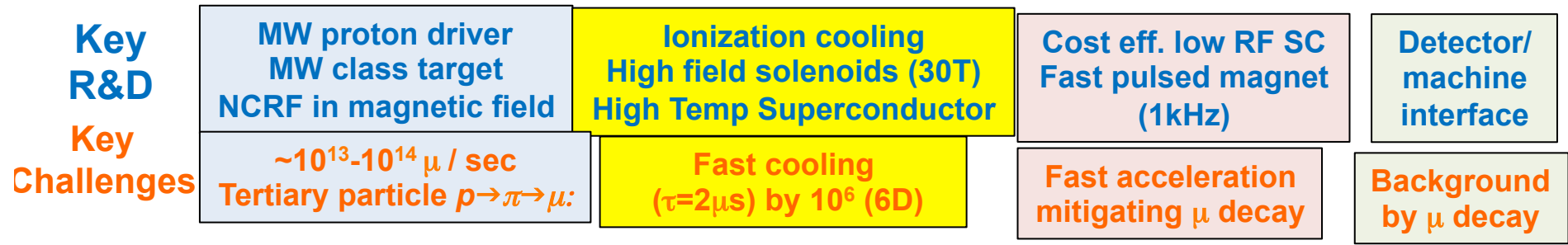


Key Challenges

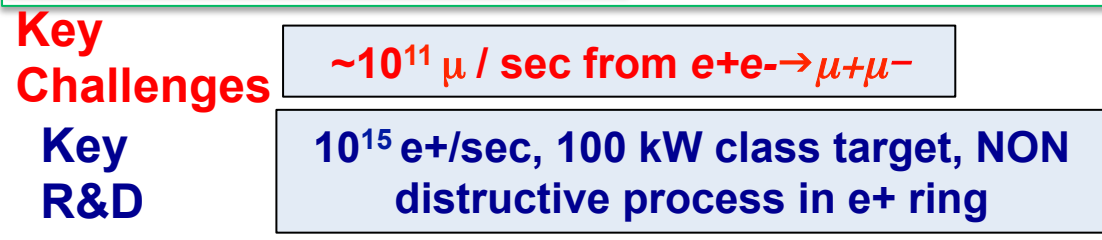
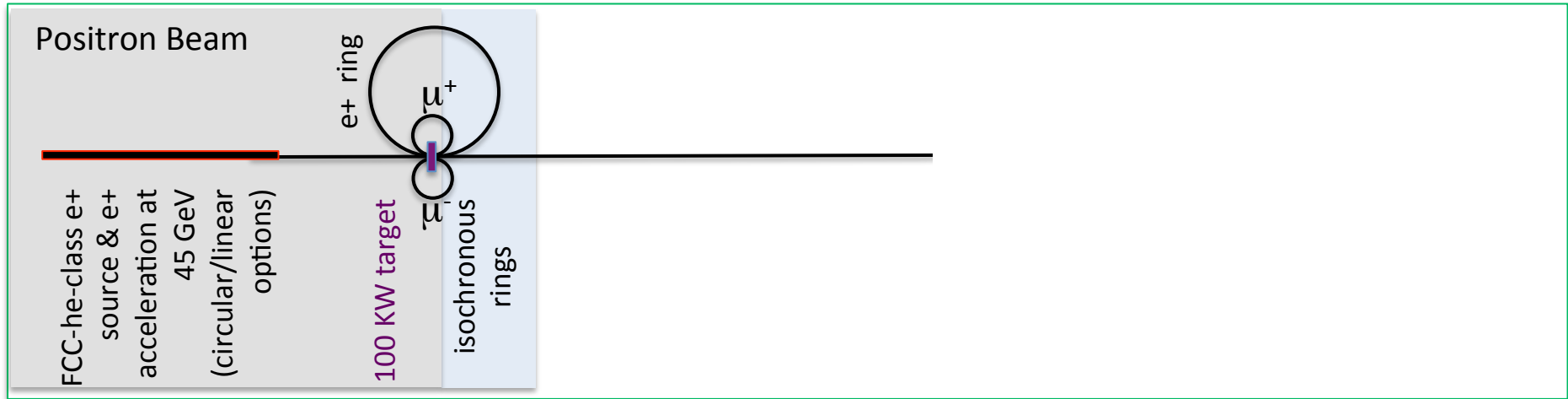
$\sim 10^{11} \mu / \text{sec}$ from $e^+e^- \rightarrow \mu^+\mu^-$

Key R&D

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



share the same complex



Key Feasibility Issues

Positron Source

Muon Target

Positron Ring

HIGH rate

Non destructive

Mom. acceptance

Targets survival

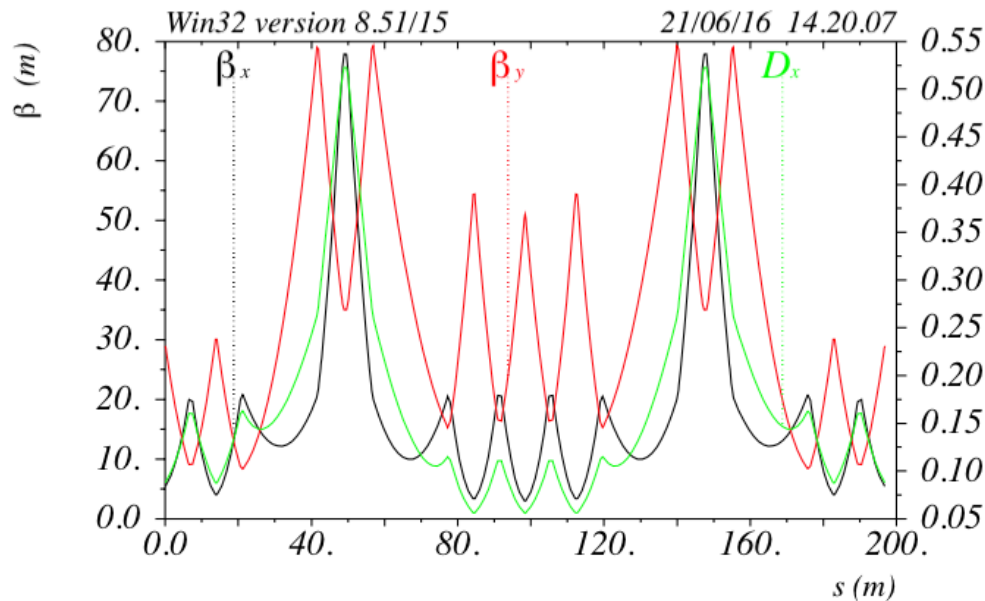
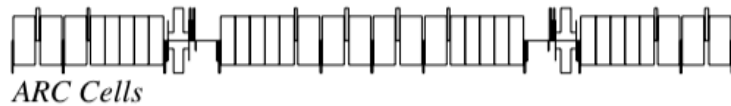
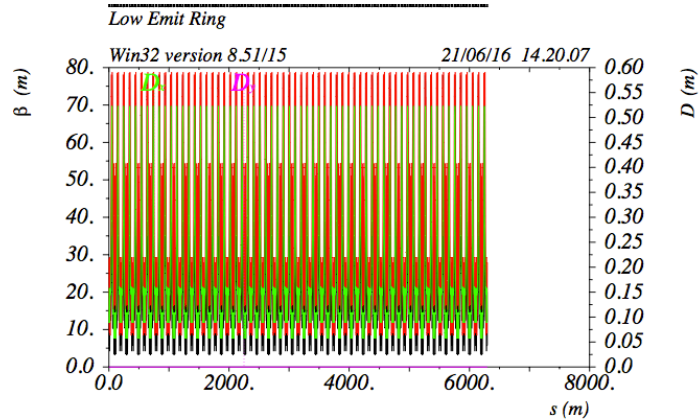
NEED

deep investigation
(design study)

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

(mostly) independent on muon source
Benefit from MAP studies

First Optics for e⁺ ring



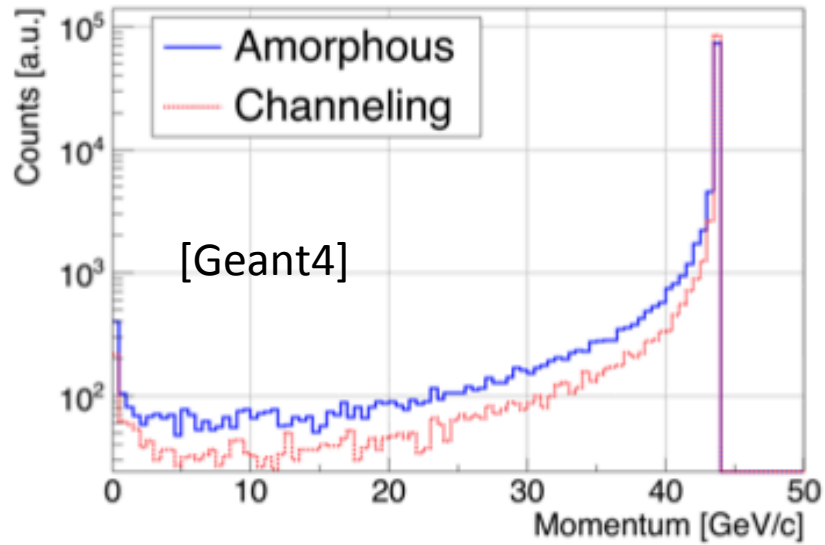
$$\delta_E / p_{oc} = 0.$$

Parameter	Units	pos_Ring
Energy	GeV	e+
Circumference	m	45
Bending radius	m	6300
Magnetic rigidity	T m	709.6
Lorentz factor		150
Coupling (full current)	%	88062.62
Emittance x (from model)	m	1
Emittance y	m	5.73E-09
Bunch length (zero current)	mm	5.73E-11
Beam current	mA	3.6
RF frequency	Hz	240
RF voltage	GV	5.00E+08
Revolution frequency	Hz	0.768
Harmonic number	#	4.76E+04
Revolution period	s	10508
Number of bunches	#	2.10E-05
N. Particle/bunch	#	100
Synchronous phase	#	3.15E+11
Synchrotron frequency	Hz	0.73
Synchrotron tune	#	2415.31
synchrotron period	turns	5.08E-02
Overvoltage		19.70
Transverse damping time	turns	1.50
Transverse damping time	s	175.00
Longitudinal damping time	turns	0.0037
Longitudinal damping time	s	87.50
Energy Loss/turn	GeV	1.84E-03
Momentum compaction		0.511
B field	T	1.21E-04
Rf energy acceptance	%	0.211
Energy spread (SR)	dE/E	3.98
SR power loss	GW	1.00E-03
SR power/Circumference	kW/m	0.12
		19.48

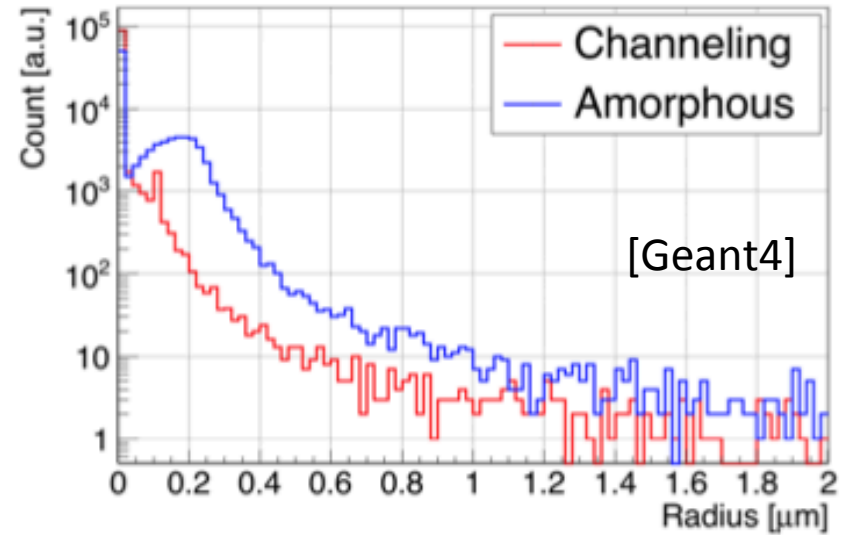
Positrons

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

Momentum

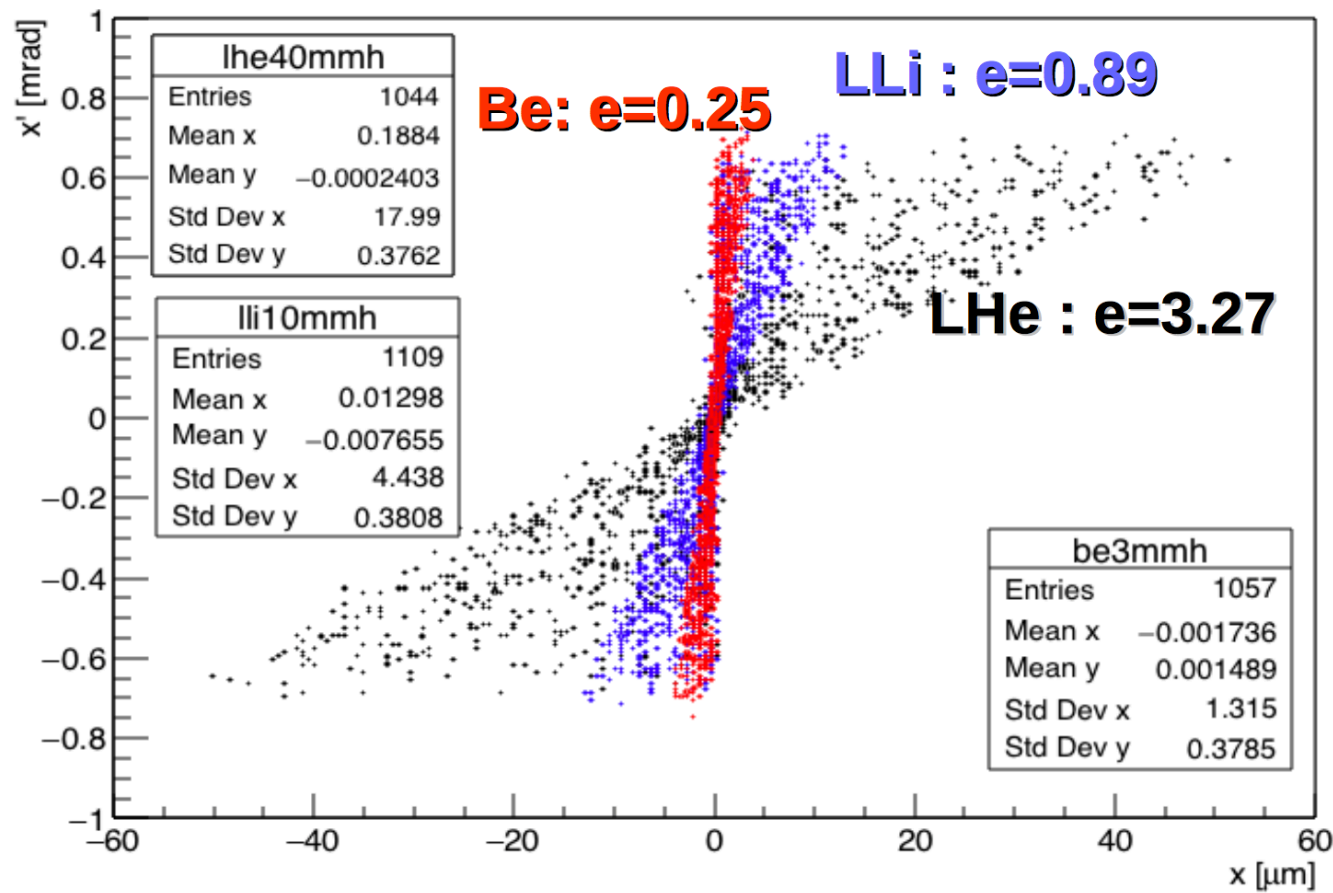


Position



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 \rightarrow
<2 worse In L

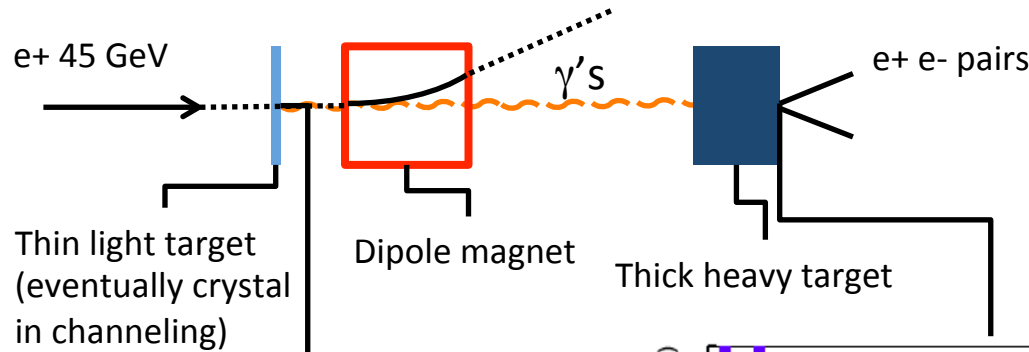
25% gain in e^+ survival @ same μ production efficiency

Proposed/tested for targets for n production

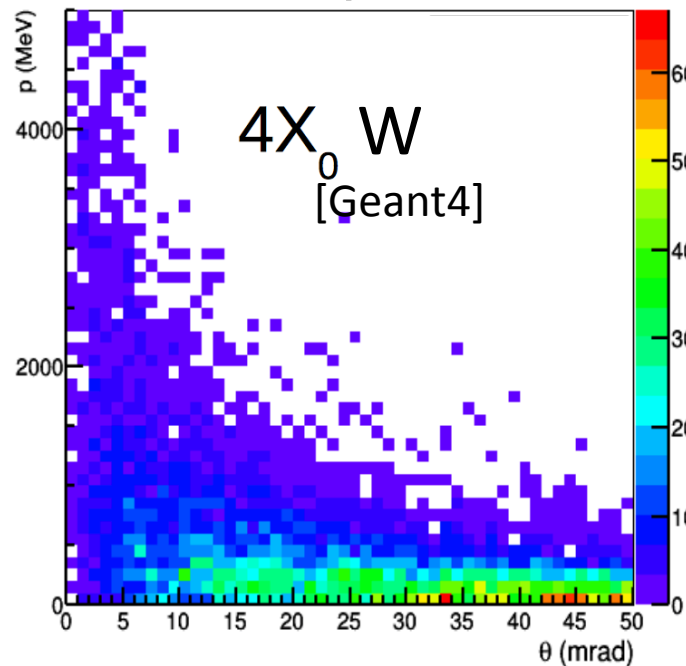
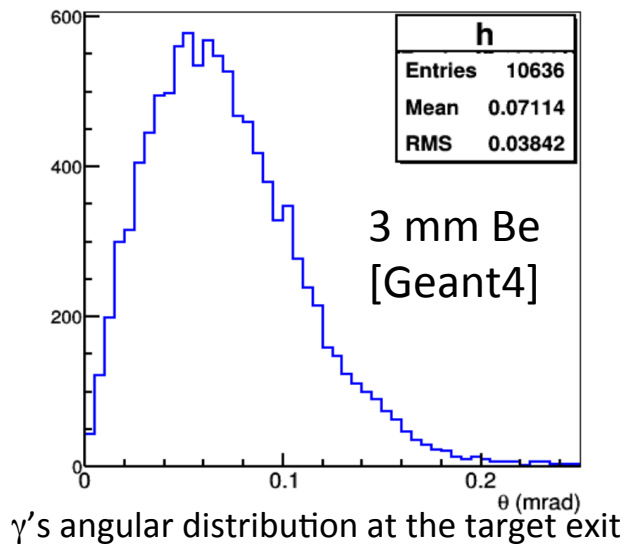
High Boiling point 1615 K
Mass evaporation?
Safety?

Embedded positron source?

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



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

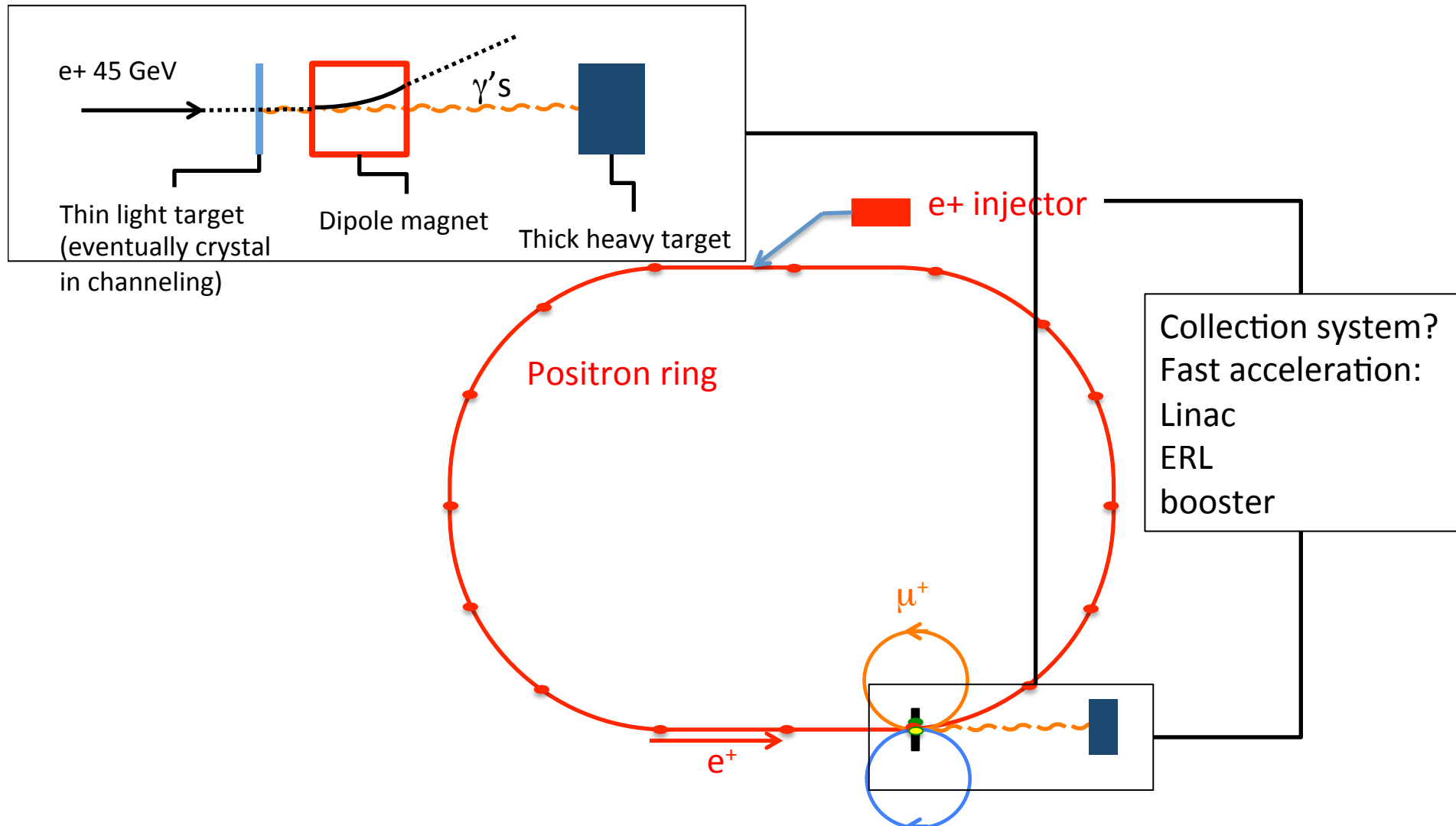


Assuming a 10% collection efficiency
 Need to have 45 GeV e^+ loss on thin target <1%

Fast acceleration to 45 GeV (\sim KHz) like μ

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

Embedded positron source?



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 5×10^6 /spill) with amorphous targets:
 - measure muon production rate and muons kinematic properties

Conclusion

- Very low emittance muon beams can be obtained by means of positron beam on target
- High Luminosity at Multi-TeV with much reduced radiological risks
- Some synergy with future e^+e^- collider parameters: beam energy, emittance, bunch structure.. But
- Competitive muon rates require:
 - Challenging positron source (FCC-eh like)
 - Positron ring with high momentum acceptance (synergy with next generation SR sources)
- Design study and tests to address Key issues

parameter	FCC-ee	LEMC
energy/beam [GeV]	45	45
bunches/beam	90000	1700
beam current [mA]	1450	240
luminosity/IP x $10^{34} \text{ cm}^{-2}\text{s}^{-1}$	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

Channeling of produced muons

43.8 GeV e^+

4.1 mm Si Target

Channeling plane: (110)

crystal

amorphous

