Low EMittance Muon Accelerator studies

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Low EMittance Muon Accelerator team

← CSN1 team

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- L. Keller, T. Markiewicz **(SLAC)**

ARIES WP6: improving Accelerator PErformance and new Concepts task for muon collider

Task 6.6 Assessment of advanced muon-collider concepts without ionization cooling

Outline

1. **Introduction:** muon case, muon sources
2. **Physics Opportunities**
   - Very High Energy
   - Multi-TeV
3. **Low emittance muon beam production concept:** e^+ on target
   - Target options
   - Positron Source
   - Multipass scheme
4. **First study of multi-TeV MC parameters**
5. **First design of the e^+ ring**
   - Multiturn simulations
   - First considerations about target thermo-mechanical stresses
   - First considerations on e+ source
6. **Experimental tests**
   - 45 GeV e+ beam
7. **Conclusions**

The strength of a $\mu-$beam facility lies in its richness:

- Muon rare processes
- Neutrino physics
- Higgs factory
- Multi-TeV frontier

Take 1

Get 4 !

$\mu-$colliders can essentially do the HE program of e^+e^- colliders with added bonus (and some limitations)

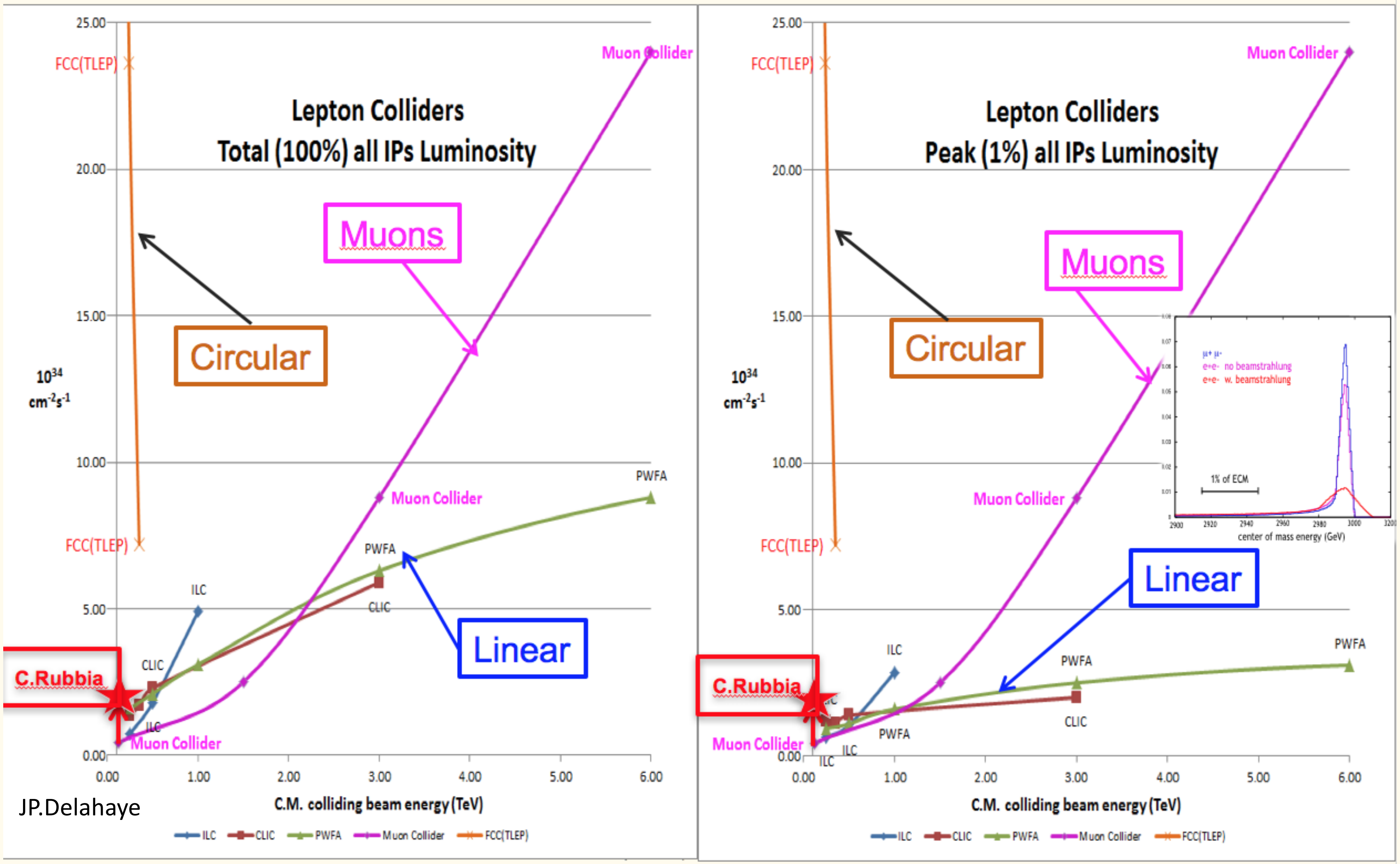
Giudice

Muon based Colliders

- A $\mu^+\mu^-$ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
  - No synchrotron radiation (limit of e^+e^- circular colliders)
  - No beamstrahlung (limit of e^+e^- linear colliders)
  - but muon lifetime is 2.2 μs (at rest)
- Best performances in terms of luminosity and power consumption

- Great potentiality if the technology proves its feasibility:
  - cooled muon source
  - fast acceleration
  - μ Collider
  - radiation Safety (muon decay in accelerator and detector)

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



JP.Delahaye

Muon Source

Goals

- **Neutrino Factories**: Rate > 10^{14} μ/sec within the acceptance of a μ ring
- **Muon Collider**: luminosities $>10^{34}/\text{cm}^{-2}\text{s}^{-1}$ at TeV-scale ($\approx N_\mu^2\ 1/\varepsilon_\mu$)

Options

- Tertiary production through **proton on target:** cooling needed, baseline for Fermilab design study

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

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

  production Rate $\approx 10^{11}$ μ/sec $N_\mu \approx 6\cdot10^{9}$/bunch

- **by Gammas** ($\gamma N\rightarrow\mu^+\mu^-N$): **GeV-scale Compton γs** not discussed here

  production Rate $\approx 5\cdot10^{10}$ μ/sec $N_\mu \approx 10^6$ (Pulsed Linac)

  production Rate $>10^{13}$ μ/sec $N_\mu \approx$ few$\cdot10^4$ (High Current ERL)

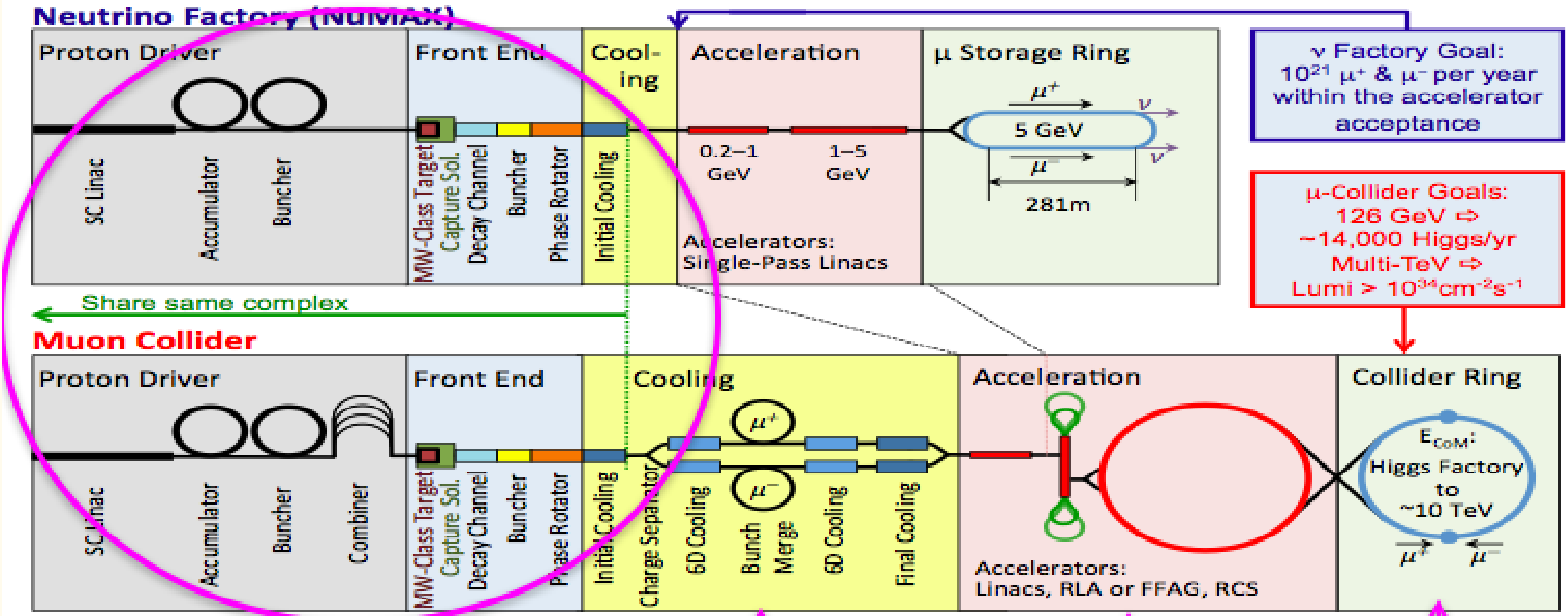
  see also: W. Barletta and A. M. Sessler NIM A 350 (1994) 36-44 ($e^-N\rightarrow\mu^+\mu^-e^-N$)

Muon source Comparison

	Physical process	Rate μ/s	normalized emittance [μm-rad]
e+ on target	**e+e-→ μ+μ-**	**0.9×10^{11}**	**0.04**
Protons on target	p N→ πX, kX→ μ X’	10^{13}	25
Compton γ on target	γ N→ μ+μ- N	5×10^{10}	2

Muon Accelerator Program (MAP)
Muon based facilities and synergies

Mark Palmer



ν Factory Goal:
10^{21} μ^+ & μ^- per year
within the accelerator
acceptance

μ-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^{34}cm^{-2}s^{-1}

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

Key R&D

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

M. Palmer

Muon Collider Parameters

Muon Collider Parameters

		Higgs	**Multi-TeV**		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts
⇨ several × 10^{32} [Rubbia proposal: 5×10^{32}]

Low emittance μ beam source

from **proton on target:** $p+\text{target}\to\pi/K\to\mu$

typically **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**!

from **direct μ pair production**:

Muons produced from **$e^+e^-\to\mu^+\mu^-$** at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold **($\sqrt{s}\approx$ 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:** θ_μ is tunable with $\sqrt{s}$ in $e^+e^- \to \mu^+\mu^-$
   θ_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

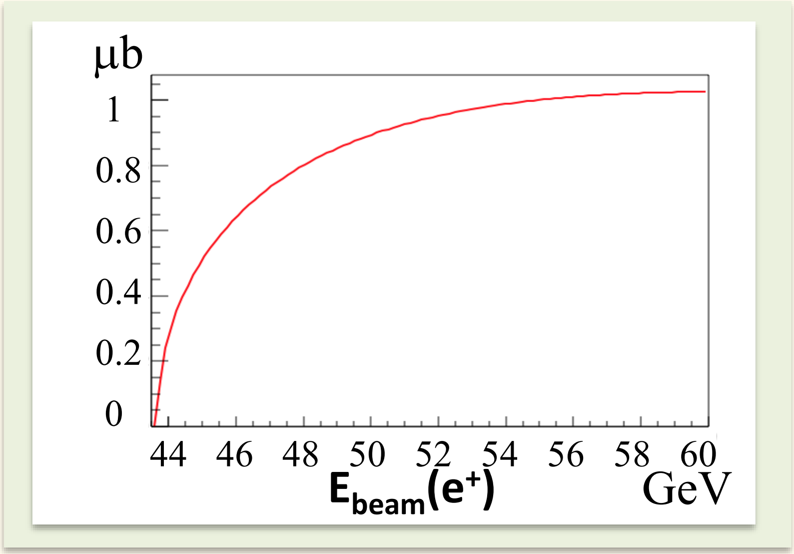
Disadvantages:

- Rate: much smaller cross section wrt protons ($\approx$ mb)

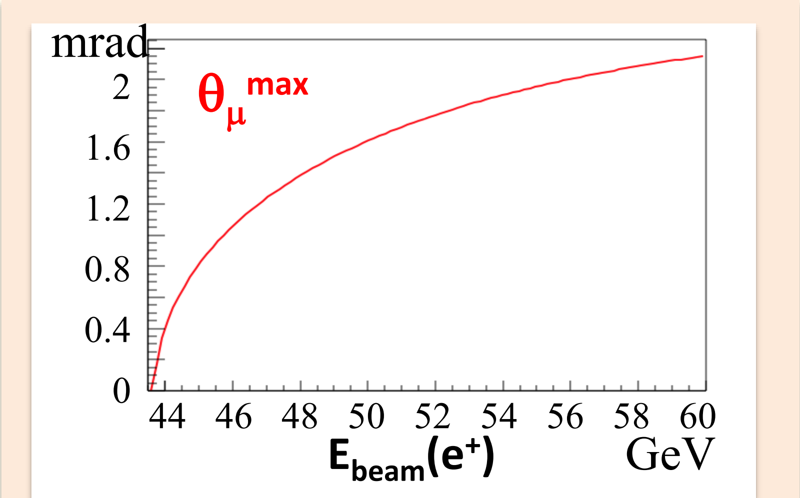
  $\sigma(e^+e^- \to \mu^+\mu^-) \approx 1\ \mu b$ at most

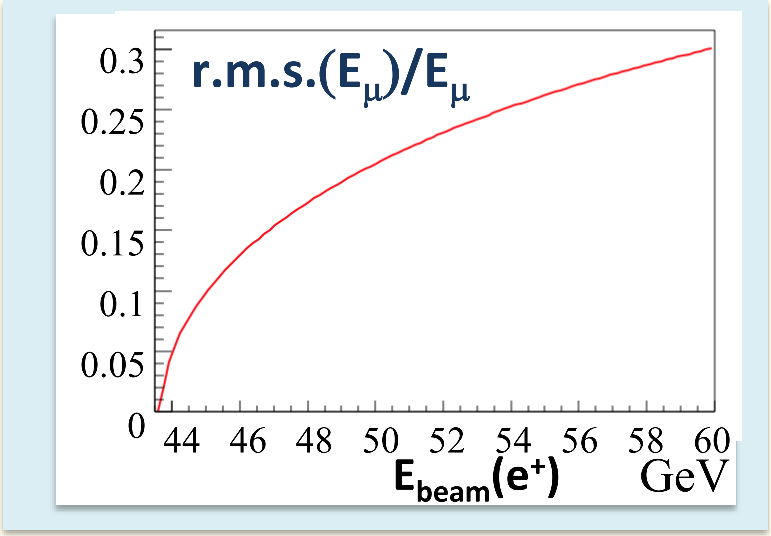
Cross-section, muons beam divergence and energy spread as a function of the e+ beam energy

$\sigma(e^+e^- \to \mu^+\mu^-)$



The value of sqrt(s) (*i.e.* E(e^+) for atomic e^- in target) has to maximize the muons production and minimize the beam angular divergence and energy spread





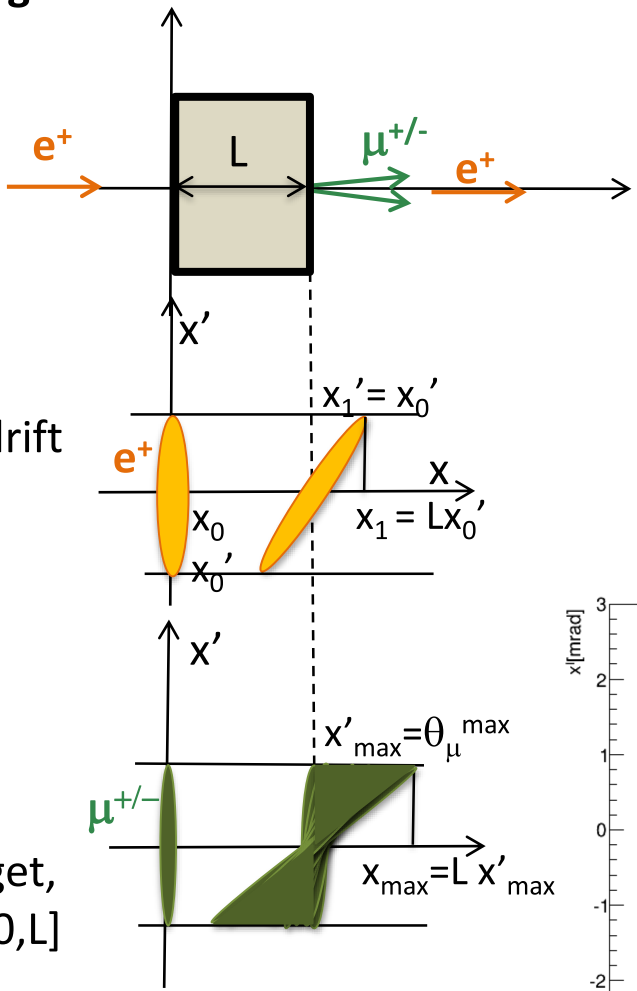
Production contribution to μ beam emittance

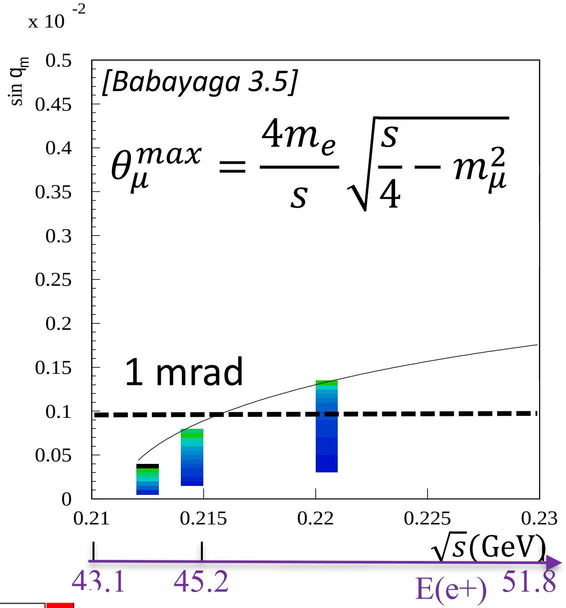
ideal e⁻ target

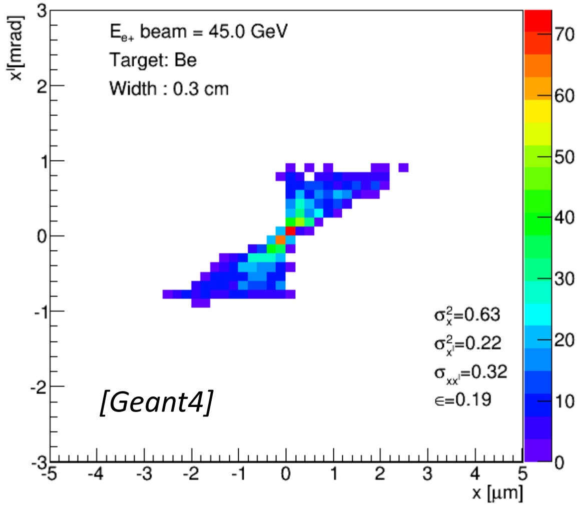
e⁺ beam
on target

If L was a drift

Muons
produced
uniformly
along target,
∞ drifts [0,L]







Muon beam at the exit of a 3 mm Be target
ε_μ=0.19 nm
(45 GeV e+ beam)

thin light materials targets have negligible multiple scattering contribution

The emittance contributions due to muon production angle: $\varepsilon_\mu = x\,x'_{max}/12 = L\,(\theta_\mu^{max})^2/12$

□ ε_μ completely determined by L and s -by target thickness and c.o.m. energy

Criteria for target design

Number of $\mu^+\mu^-$ pairs produced per e^+e^- interaction is given by

$$\boxed{N(\mu^+\mu^-) = \sigma(e^+e^- \rightarrow \mu^+\mu^-)\, \mathbf{N(e^+)}\, \boldsymbol{\rho(e^-)}\mathbf{L}}$$

$N(e^+)$ number of e^+

$\rho(e^-)$ target electron density

L target length

To maximise $N(\mu^+\mu^-)$:

- **N(e^+)** max rate limit set by e^+ source
- **$\rho(e^-)$L** max occurs for L or ρ values giving total e^+ beam loss
  - **e^- dominated target:** radiative Bhabha is the dominant e^+ loss effect, giving a maximal $\mu^+\mu^-$ conversion efficiency $$N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e^- \longrightarrow \mu^+\mu^-)/\sigma_{rb} \approx 10^{-5}$$
  - **standard target:** Bremsstrahlung on nuclei and multiple scattering are the dominant effects, Xo and electron density will matter $N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e^- \longrightarrow \mu^+\mu^-)/\sigma_{brem}$

Criteria for target design

Luminosity is proportional to N_μ^2 $1/\varepsilon_\mu$

optimal target: minimizes μ emittance with highest μ rate

- **Heavy materials, thin target**
  - to minimize ε_μ : thin target (ε_μ□L) with high density ρ

  Copper: MS and $\mu^+\mu^-$ production give about same contribution to ε_μ

  BUT high e^+ loss (Bremsstrahlung is dominant) so

  $\sigma(e^+\text{loss}) \approx \sigma(\text{Brem+bhabha}) \approx (Z+1)\sigma(\text{Bhabha}) \rightarrow$

  $N(\mu^+\mu^-)/N(e^+) \approx \sigma_\mu/[(Z+1)\sigma(\text{Bhabha})] \approx 10^{-7}$
- **Very light materials, thick target**
  - **maximize $\mu^+\mu^-$ conversion efficiency $\approx 10^{-5}$** (enters quad) → H_2

  Even for liquid targets O(1m) needed → ε_μ□L increase
- **Not too heavy materials (Be, C)**
  - Allow low ε_μ with small e^+ loss **$N(\mu^+\mu^-)/N(e^+) \approx 10^{-6}$**

not too heavy and thin in combination with stored positron beam to reduce requests on positron source

Low emittance μ beam production by positrons on target

Goal:

$@T \approx 10^{11}\ \mu/s$

Efficiency ≈ 10^{-7} (with Be 3mm)→

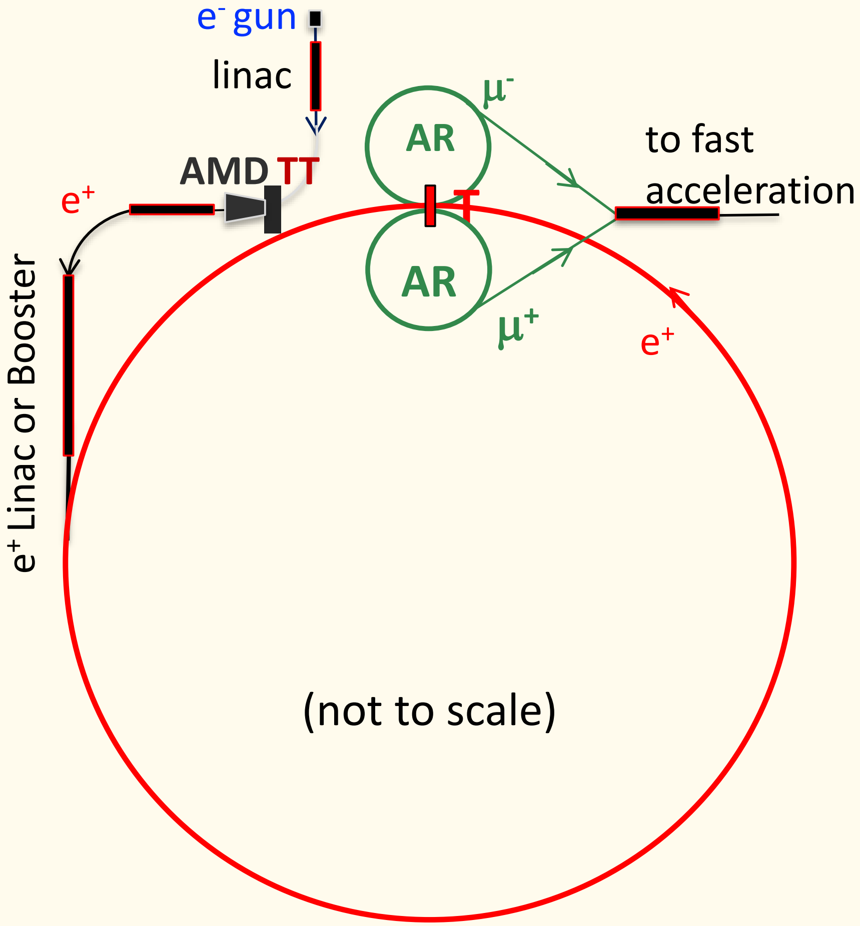
10^{18} e^+/s needed @T →

e^+ stored beam with T

need the largest possible lifetime to minimize positron source rate

LHeC like e+ source required rate with lifetime(e+) ≈ 250 turns [i.e. 25% momentum aperture (+/-12%)]

→ $n(\mu)/n(e^+\ \text{source}) \approx 10^{-5}$



Low emittance μ beam production by positrons on target

from e^+ SOURCE to RING:

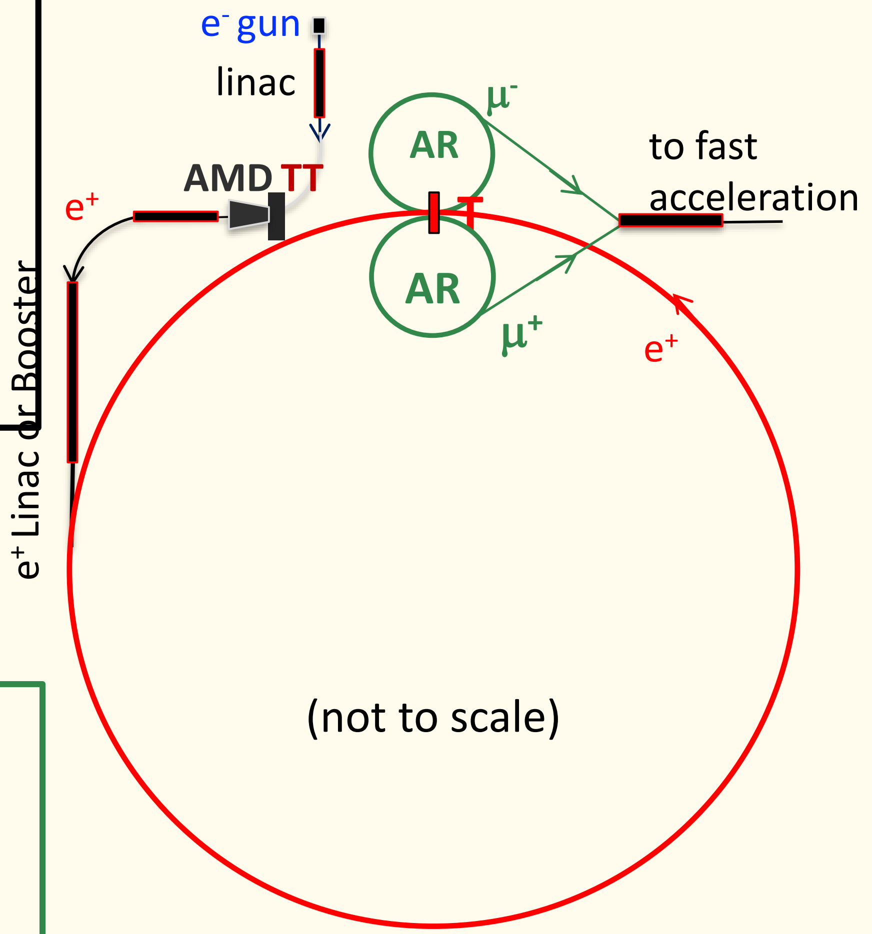
- **e^-** on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.
- Adiabatic Matching Device (**AMD**) for **e^+** collection →
- acceleration (linac / booster) , injection →

e^+ RING:

- **6.3 km 45 GeV** storage ring with target **T** for muon production

from $\mu^+ \mu^-$ production to collider

- produced by the **e^+** beam on target **T** with **$E(\mu) \approx 22$ GeV**, $\gamma(\mu) \approx 200 \rightarrow \tau_{lab}(\mu) \approx 500\mu s$
- **AR**: **60 m** isochronous and high mom. acceptance rings will recombine μ bunches for ~ 1 $\tau_\mu^{lab} \approx 2500$ turns
- fast acceleration
- muon collider



Low emittance μ beam production by positrons on target

from e^+ SOURCE to RING:

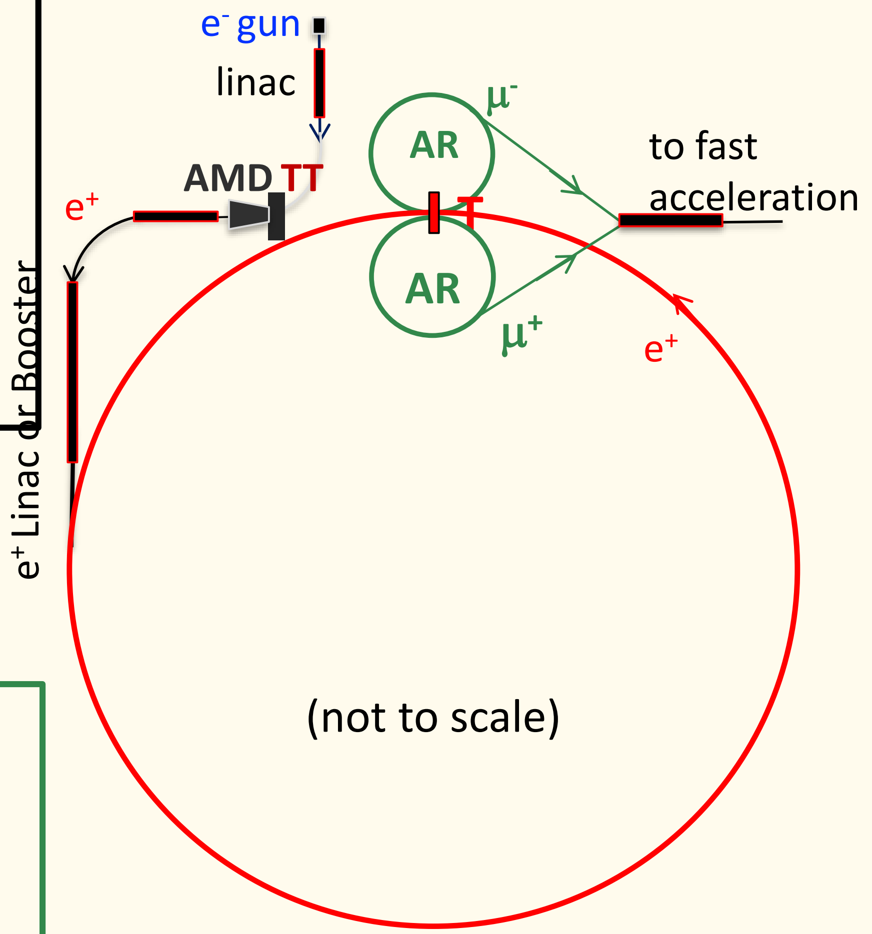
- **e^-** on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.
- possibly with
- Adiabatic Matching Device (**AMD**) for **e^+** collection
- acceleration (linac) , injection

e^+ RING:

- **6.3 km 45 GeV** storage ring with target **T** for muon production
- The ring will work as a fast cycling booster

from $\mu^+ \mu^-$ production to collider

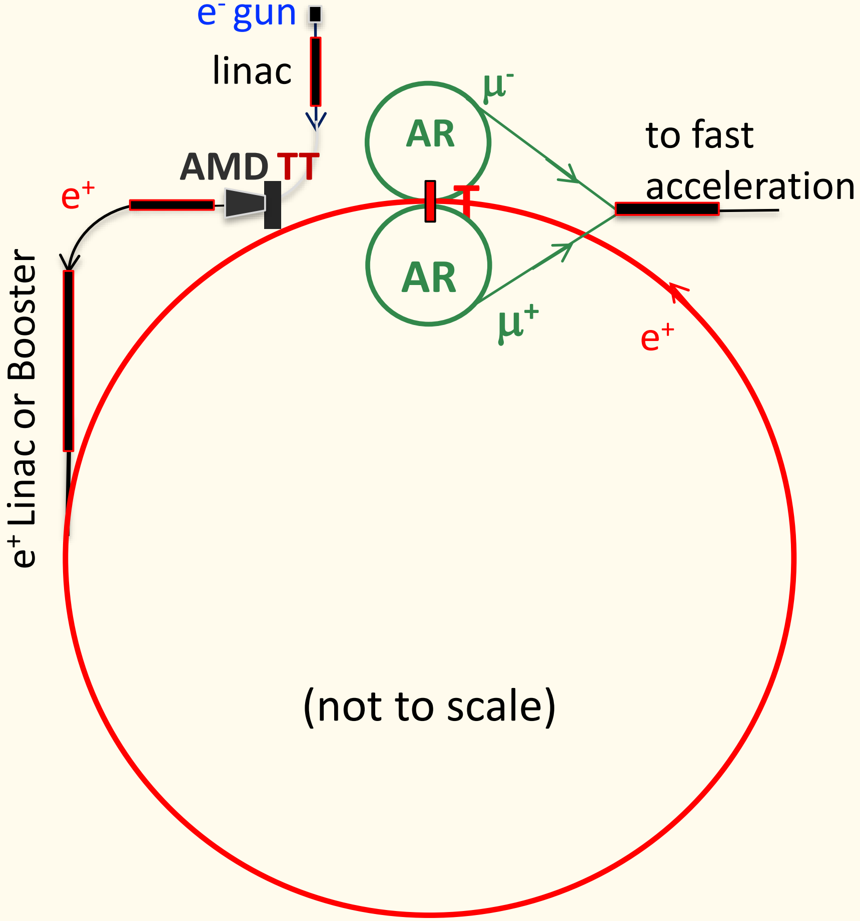
- produced by the **e^+** beam on target **T** with **$E(\mu) \approx 22$ GeV**, $\gamma(\mu) \approx 200 \rightarrow \tau_{lab}(\mu) \approx 500\mu s$
- **AR**: **60 m** isochronous and high mom. acceptance rings will recombine μ bunches for ~ 1 $\tau_\mu^{lab} \approx 2500$ turns
- fast acceleration
- muon collider



Low emittance μ beam production by positrons on target

e+ ring parameter	unit	
Circumference	km	6.3
Energy	GeV	45
bunches	#	100
e^+ bunch spacing = T_{rev} (AR)	ns	200
Beam current	mA	240
$N(e^+)$/bunch	#	$3 \cdot 10^{11}$
U_0	GeV	0.51
SR power	MW	120

(also 28 km is being studied as an option)



(not to scale)

6 TeV μ collider draft Parameters

no lattice yet

$\mu^+\mu^-$ rate = 9 10^{10} Hz

[NIM A 807 101-107 (2016)]

ε_N = 40 nm

if: LHeC like e^+ source

with 25% mom. accept. e^+ ring

and ε dominated by μ production

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

(→ lower background)

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

Parameter	Units	LEMC-6TeV
LUMINOSITY/IP	$\text{cm}^{-2}\ \text{s}^{-1}$	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

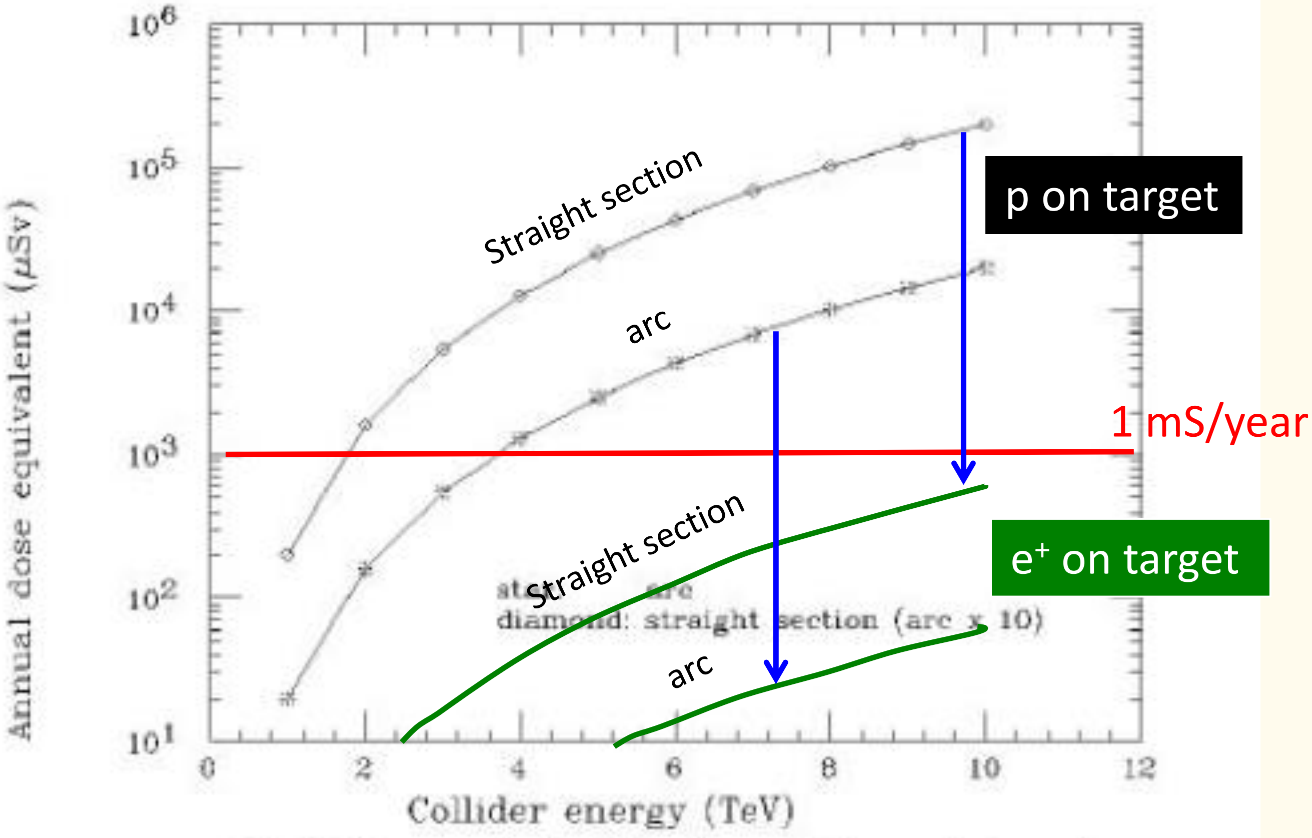


Fig. 1 Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

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

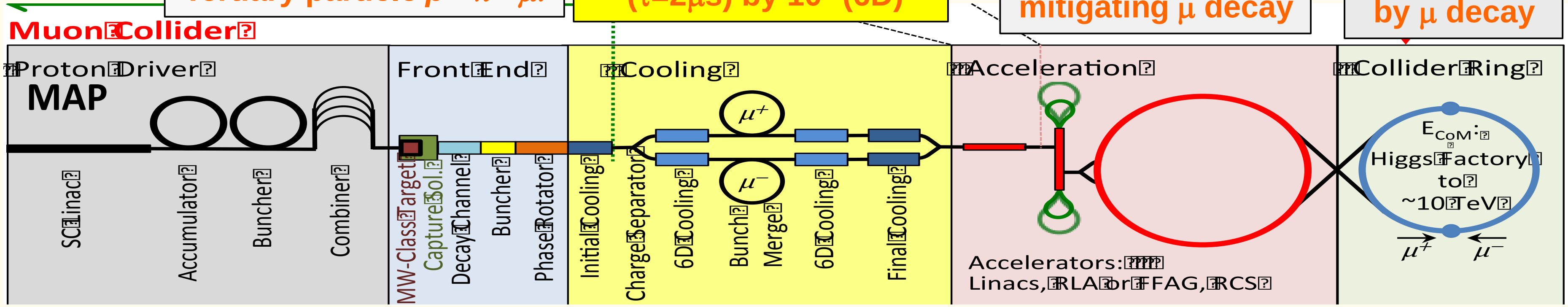
e$^+$ on target option 9 10^{10} μ/s

Key R&D

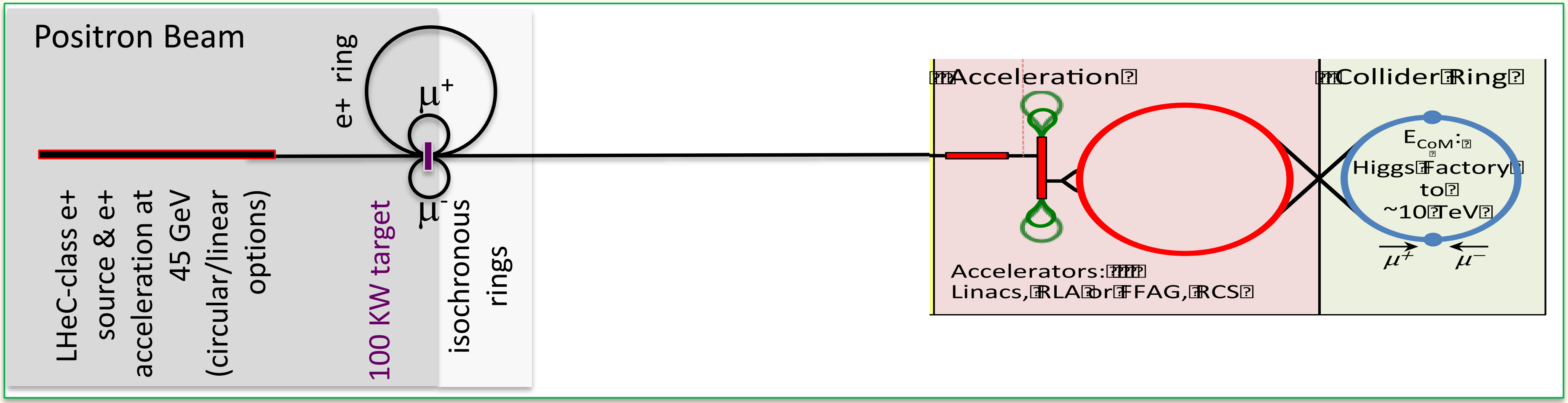
- MW proton driver
MW class target
NCRF in magnetic field
- Ionization cooling
High field solenoids (30T)
High Temp Superconductor
- Cost eff. low RF SC
Fast pulsed magnet (1kHz)
- Detector/ machine interface

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



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

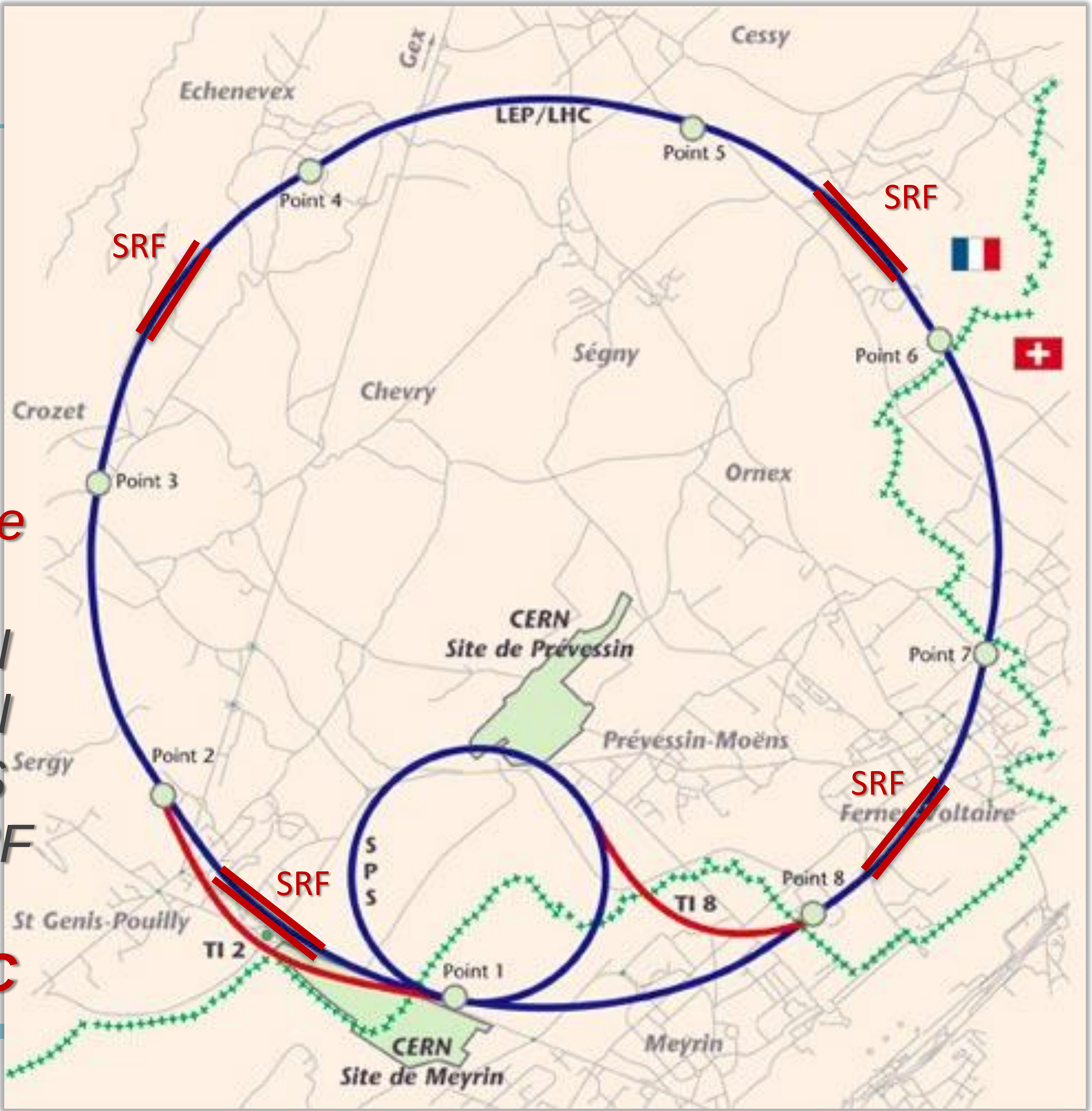
CMC

CERN Muon Collider

- *14 TeV cme*

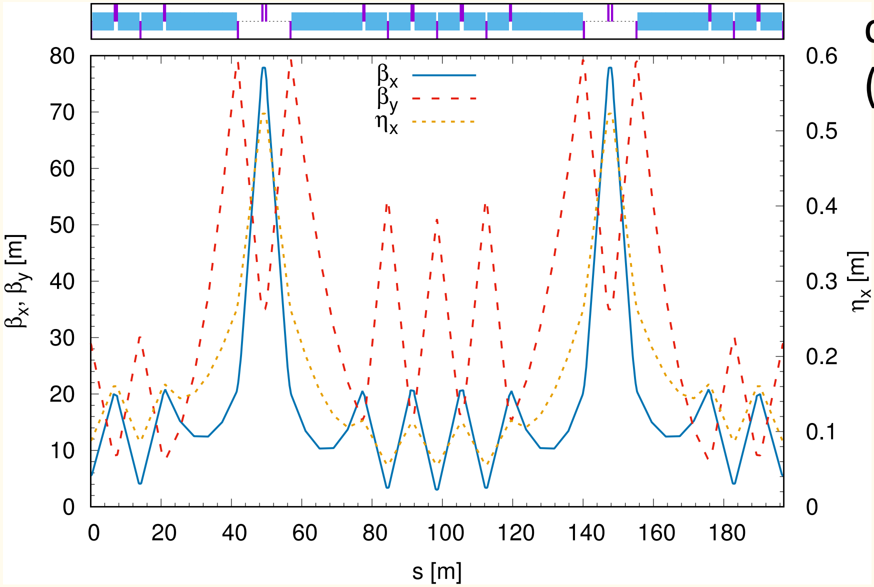
- *LHC tunnel*
- *SPS tunnel and mb PS*
- *~7GeV SRF*

- ***Cost ~LHC***



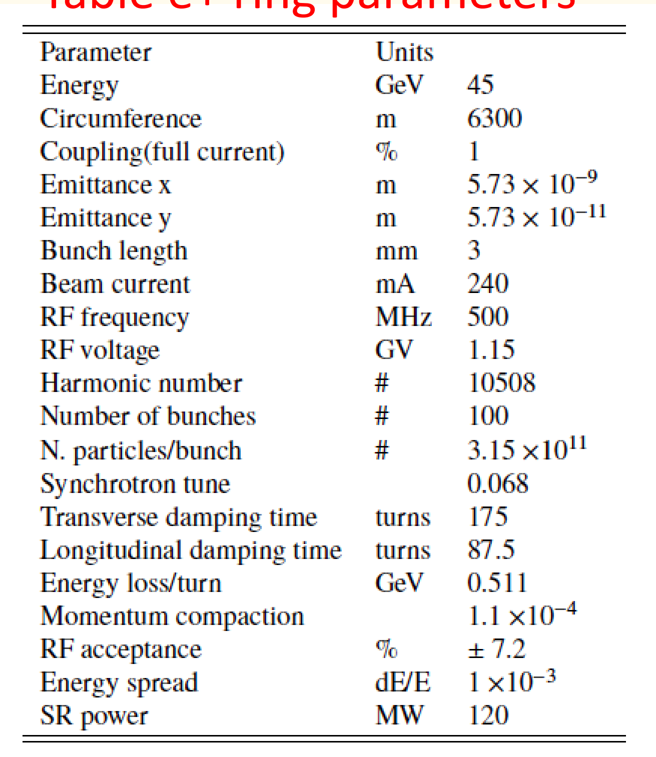
Low emittance 45 GeV positron ring

cell



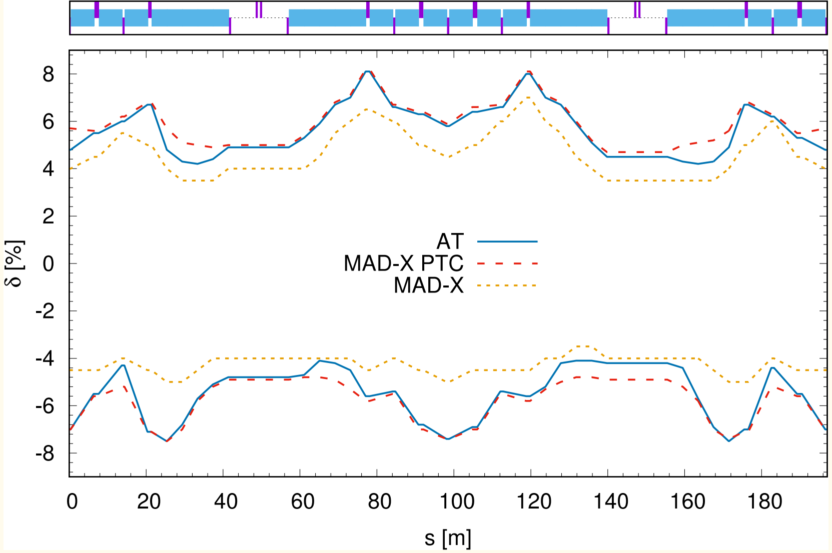
circumference 6.3 km: 197 m x 32 cells
(no injection section yet)

Table e+ ring parameters



Parameter	Units	
Energy	GeV	45
Circumference	m	6300
Coupling(full current)	%	1
Emittance x	m	5.73×10^{-9}
Emittance y	m	5.73×10^{-11}
Bunch length	mm	3
Beam current	mA	240
RF frequency	MHz	500
RF voltage	GV	1.15
Harmonic number	#	10508
Number of bunches	#	100
N. particles/bunch	#	3.15×10^{11}
Synchrotron tune		0.068
Transverse damping time	turns	175
Longitudinal damping time	turns	87.5
Energy loss/turn	GeV	0.511
Momentum compaction		1.1×10^{-4}
RF acceptance	%	± 7.2
Energy spread	dE/E	1×10^{-3}
SR power	MW	120

momentum acceptance



Physical aperture=5 cm constant

no errors

Good agreement between MADX PTC / Accelerator Toolbox, both used for particle tracking in our studies

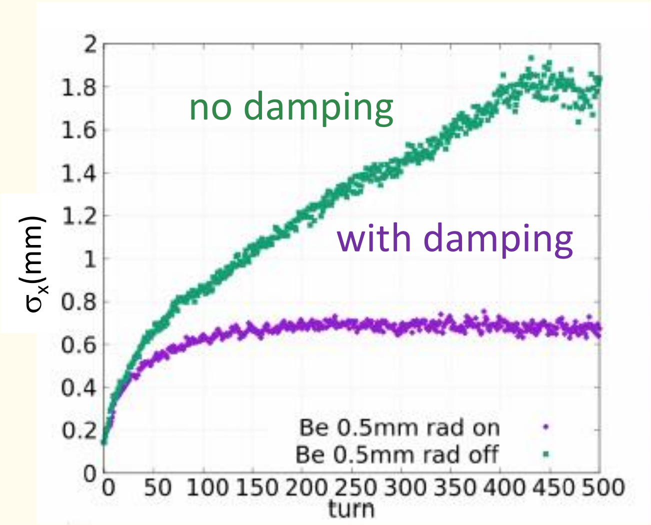
Multi-turn simulations

1. Initial 6D distribution from the equilibrium emittances
2. 6D e^+ distribution tracking up to the target (AT and MAD-X PTC)
3. tracking through the target (with Geant4beamline and FLUKA and GEANT4)
4. back to tracking code

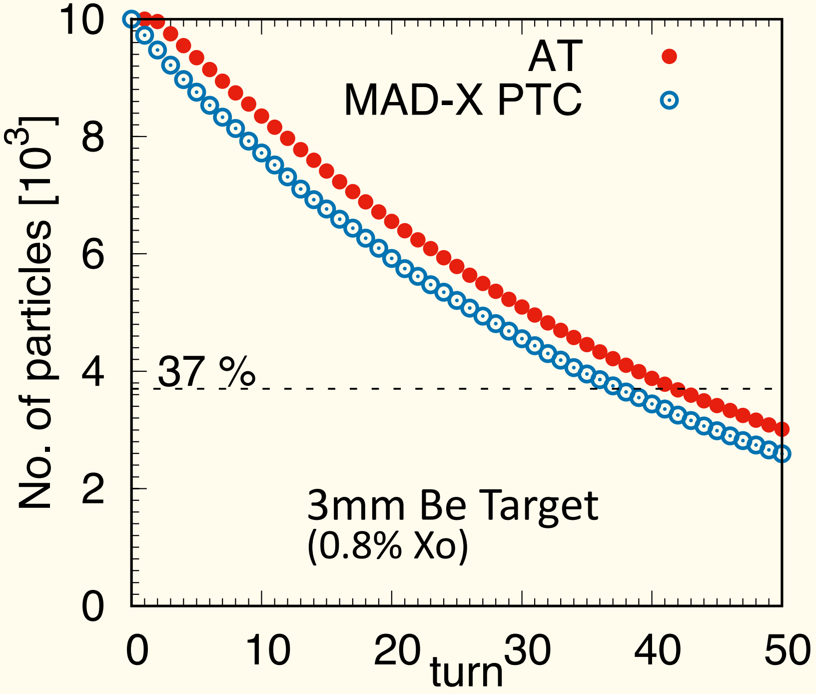
At each pass through the muon target the e+ beam

- gets an angular kick due to the **multiple Coulomb scattering**, so at each pass changes e^+ beam divergence and size, resulting in an emittance increase.
- undergoes **bremsstrahlung energy loss**: to minimize the beam degradation due to this effect, $D_x=0$ at target

- in addition there is natural radiation **damping** **(**it prevents an indefinite beam growth)

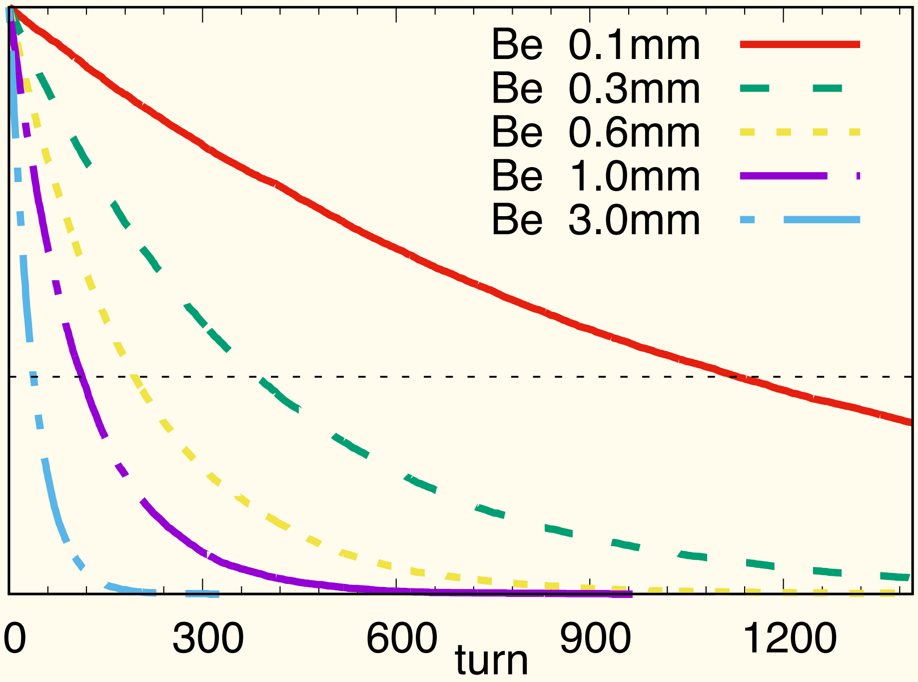


e+ lifetime with Be target



determined by **bremsstrahlung and momentum acceptance**

Lifetime with ~ 40 turns

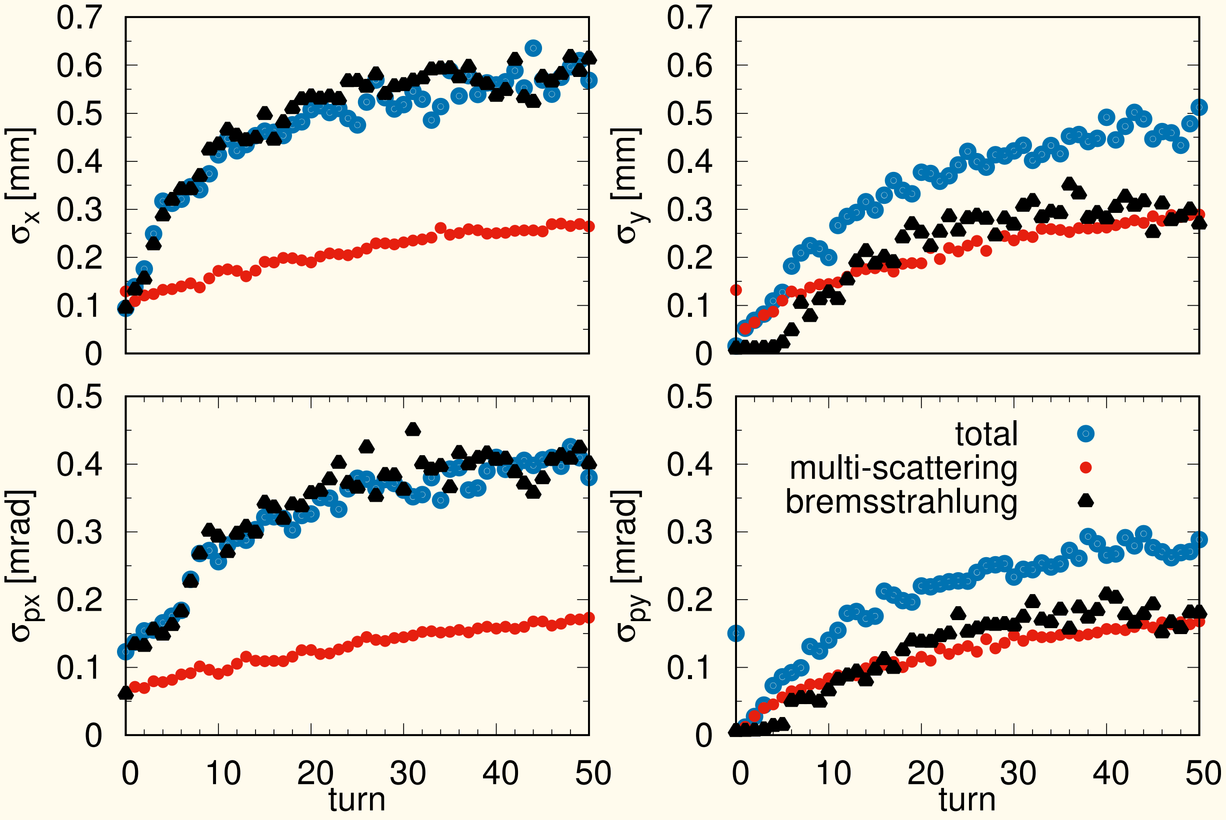


Lifetime ∝ 1/thickness as expected

2-3% e+ losses happen in the first turn

Evolution of e+ beam size and divergence

3mm Be Target (0.8% Xo) at center of IR



bremsstrahlung and multiple scattering artificially separated by considering alternatively effects in longitudinal (dominated by **bremsstrahlung**) and transverse (dominated by **multiple scattering**) phase space due to target; in **blue** the combination of both effects (realistic target)

Some bremsstrahlung contribution due to residual dispersion at target

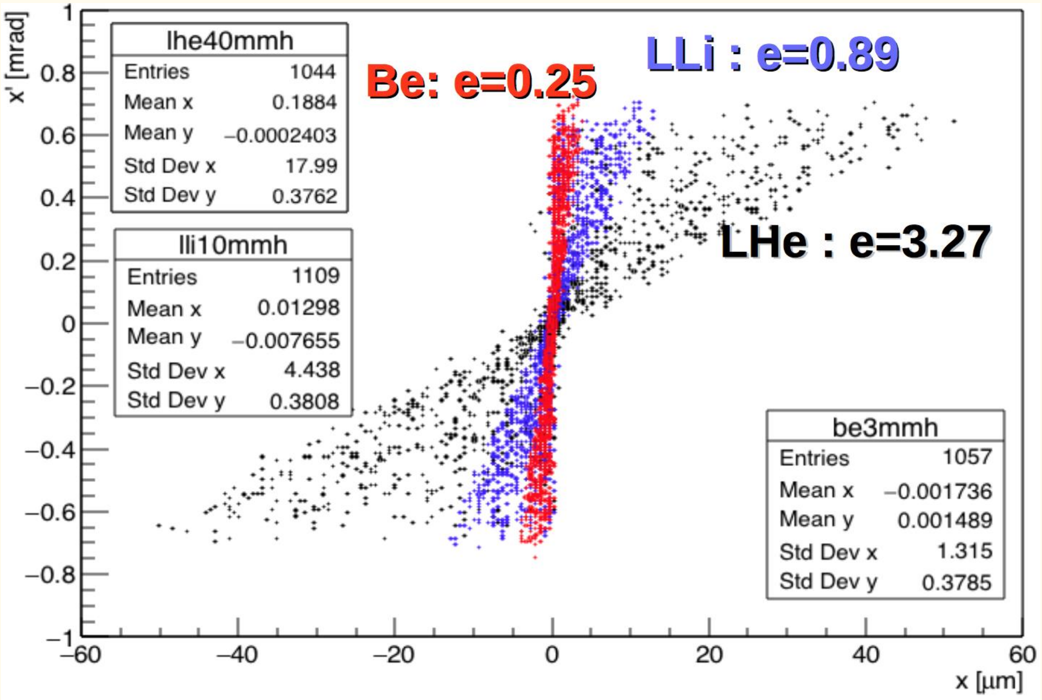
multiple scattering contribution in line with expectation: $\sigma_{MS} = \frac{1}{2}\sqrt{n_D}\,\sigma'_{MS}\,\beta$

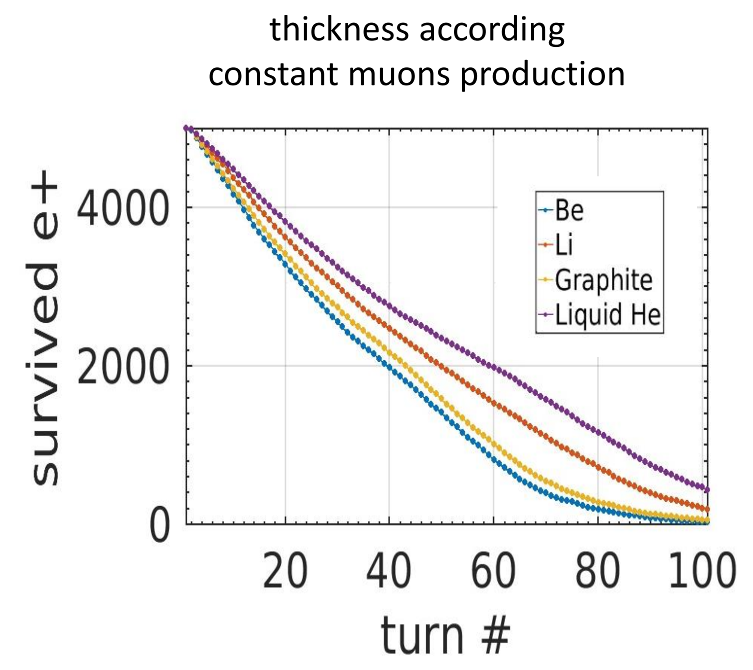
one pass contribution due to the target: $\sigma'_{MS} = 25\ \mu\text{rad}$

n_D number of damping turns

Going to lighter targets for μ production

Be Beryllium
LLi Liquid Lithium, might be a good option (Proposed/tested for targets for n production)
LHe Liquid Helium





e = muon emittance at production [10^{-9}m-rad]

E(e^+)=45 GeV

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

Target: thermo-mechanical stresses considerations

Beam size as small as possible (matching various emittance contribution), but

- constraints for power removal (200 kW) and temperature rise
- to contrast the temperature rise

  move target (for free with liquid jet) and

  e^+ beam bump every 1 bunch muon accumulation

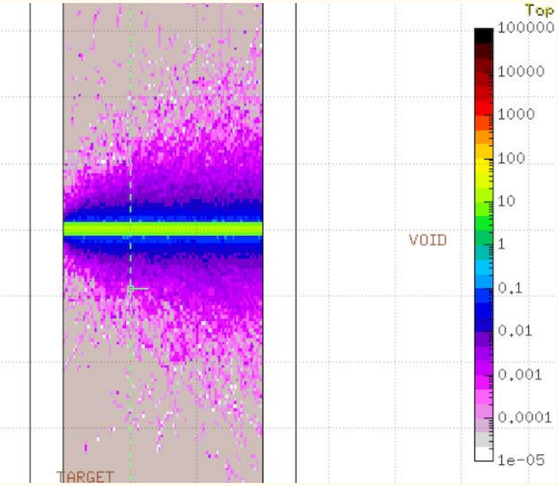
- **Solid target**: simpler and better wrt temperature rise
  - Be, C

  Be target: @HIRadMat safe operation with extracted beam from SPS, beam size 300 μm, N=1.7×10^{11} p/bunch, up to 288 bunches in one shot [Kavin Ammigan 6th High Power Targetry Workshop]
- **Liquid** target: better wrt power removal
  - Li, difficult to handle lighter materials, like H, He
    - LLi jets examples from neutron production, Tokamak divertor

(200 kW beam power removal seems feasible) , minimum beam size to be understood

Conventional options for μ target

- Aim at bunch ($3x10^{11}$ e^{+}) transverse size on the 10 μm scale: rescaled from test at HiRadMat ($5x10^{13}$p on 100μm) with **Be-based** targets and **C-based** (HL-LHC) [F. Maciariello *et al.*, IPAC2016]
- No bunch pileup → Fast rotating wheel (20000 rpm)
- Power removal by radiation cooling (see for instance PSI muon beam upgrade project HiMB) [A. Knecht, NuFact17]]
- Need detailed simulation of thermo-mechanical stresses dynamics
  - Start using FLUKA + Ansys Autodyn (collaboration with CERN EN-STI)



- Experimental tests:
  - **FACET-II** available from 2019

    10^{11} e-/bunch, 10 μm spot size, 100 Hz
  - **DAFNE** available from 2020, see later

μ Accumulator Rings considerations

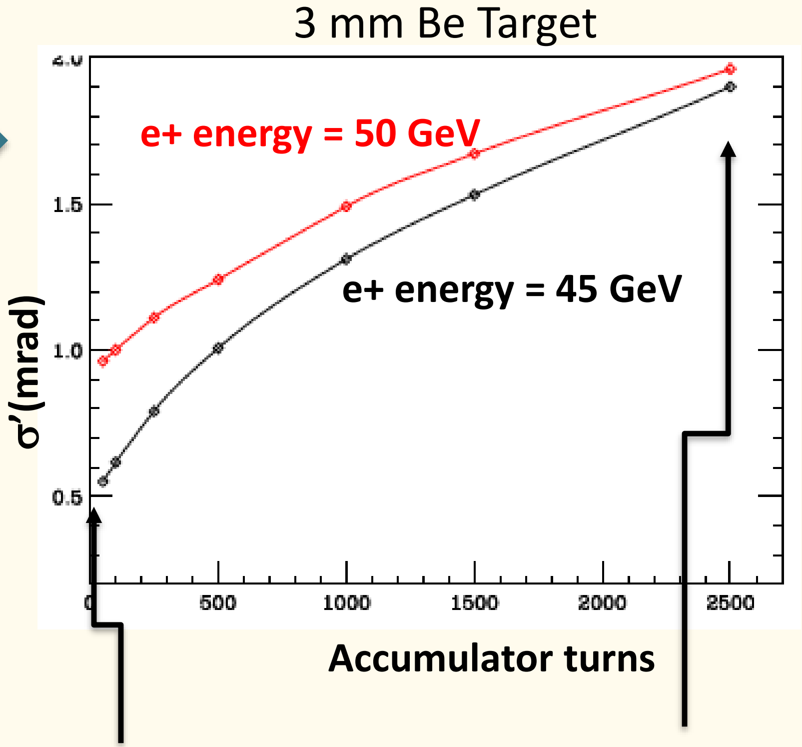
isochronous optics with high momentum acceptance (δ ≳ 10%)
optics to be designed

Multiple Scattering effect using one-turn matrix →

beam divergence:
a factor 3-2 increase at 45-50 GeV w.r.t. muon production angle contribution
beam size:
depends on optics need low-β to suppress size increase

this contribution can be strongly reduced with crystals in channeling

better performances at 50 GeV provided >15% momentum acceptance

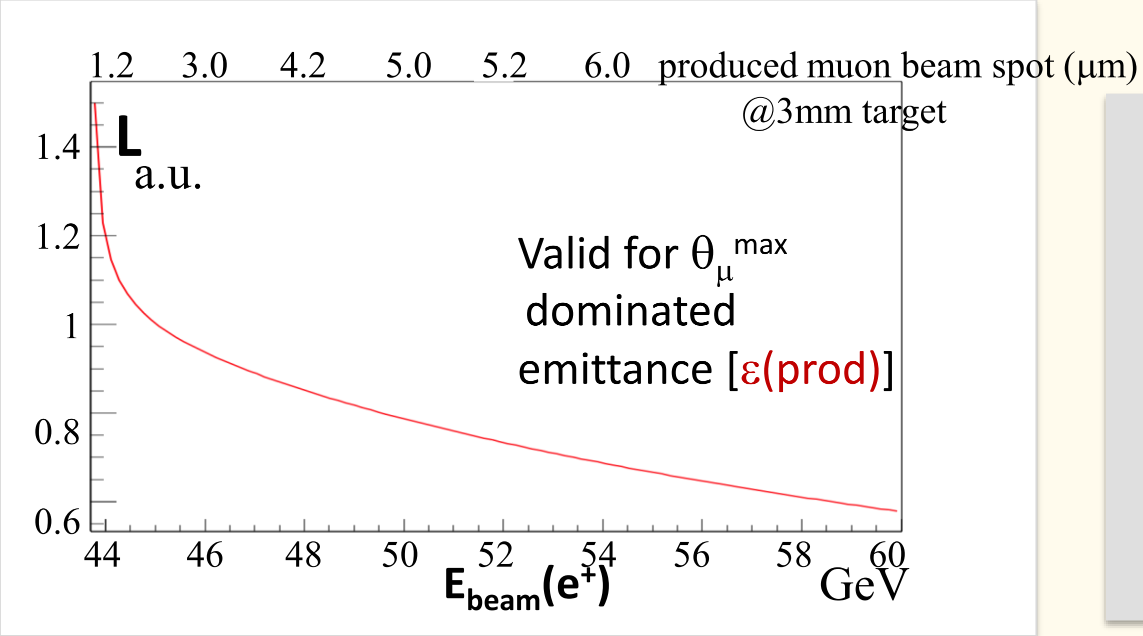


muon production angle

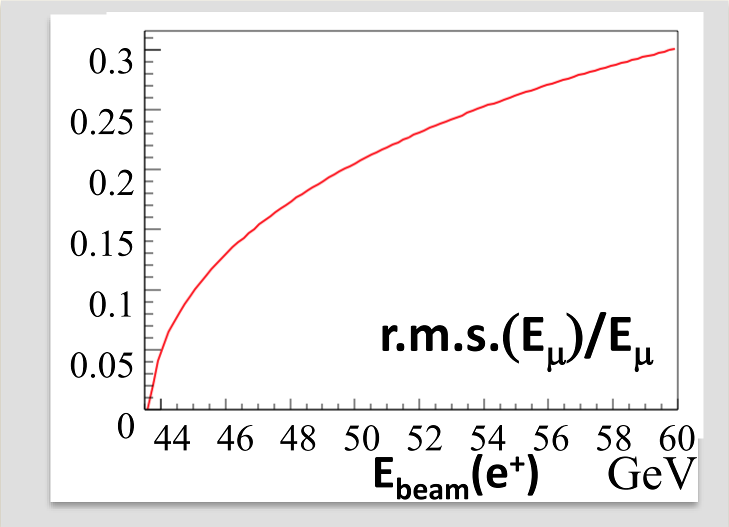
muon production angle + MS contribution

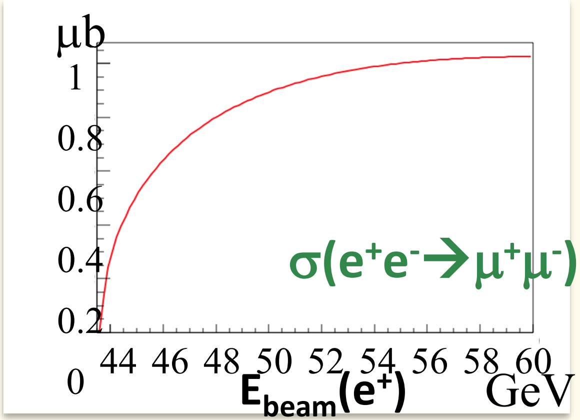
Luminosity of $\mu^+\mu^-$ Collider vs e^+ beam energy

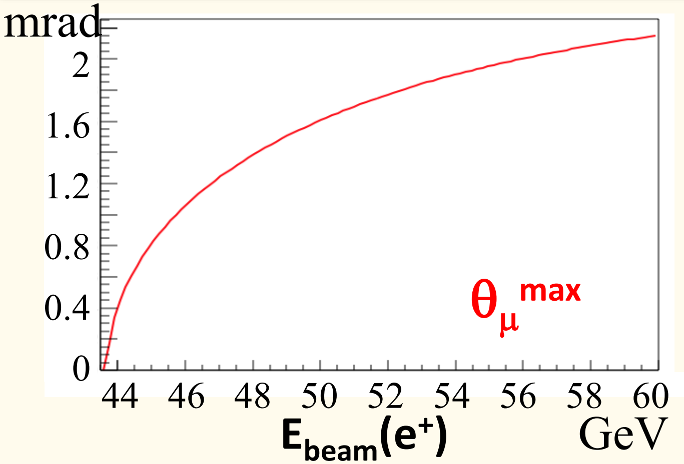
Optimal working point for $\varepsilon(e^+) \cong \varepsilon(MS) \cong \varepsilon(rad) \cong \varepsilon(prod) \cong \varepsilon(AR)$
and sustainable beam spot on target
$\varepsilon(prod)$ and μ intensity $\propto$ positron beam energy:



Valid for θ_μ^{max} dominated emittance [ε(prod)]







Test @CERN

Experiments in H4:

45 GeV e^+ on target, beam spot 2 cm, mrad divergence

High intensity (up to 5 x 10^6 e+/spill) with 6 cm Be target (spill ~15s)

goal: measure muon production rate and muons kinematic properties

Low intensity

measure beam degradation (emittance energy spectrum)

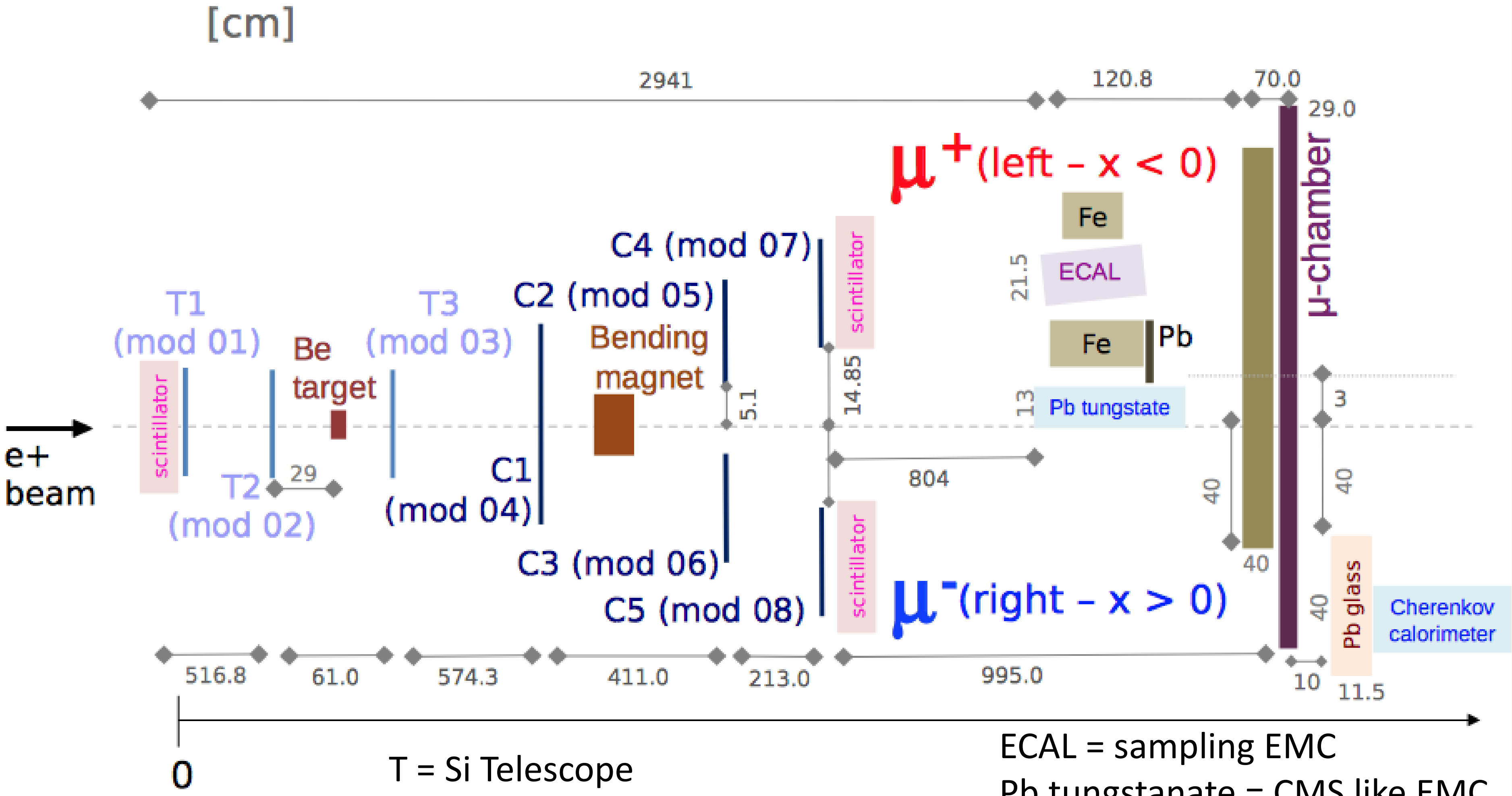
measure produced photons flux and spectrum

- 1 week assigned out of 2 requested in 2017

Priority to High intensity (had 2 days at ≈ 10^6 e^+ /spill)

- **1-(2) weeks in 2018** for:
  - Complete original program of the 2017 experiment (need 2 weeks for high and low intensity runs)
  - Attempt muon production on crystals

Experimental set-up

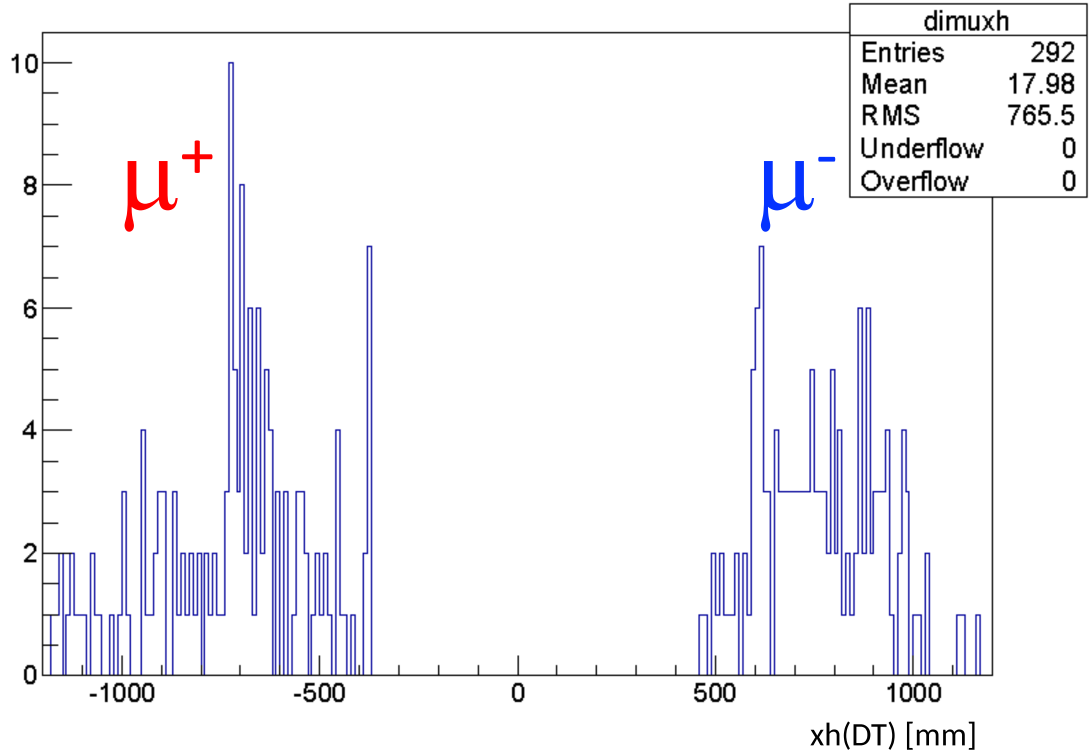


T = Si Telescope
C = Si chambers

ECAL = sampling EMC
Pb tungstanate = CMS like EMC
Pb glass = lead glass EMC

EXPERIMENTAL SETUP

Candidates events in the μ chambers



Conclusion

- The production of muons starting from e^+ beam on target is a very attractive possibility for a muon collider
- Key challenges:
  - Low emittance and high momentum acceptance 45 GeV e^+ ring
  - O(100 kW) class target in the e^+ ring for $\mu^+ \mu^-$ production
  - High rate positron source
  - High momentum acceptance muon accumulator rings

First design of low emittance e^+ ring with preliminary studies of beam dynamics

Many issues are being addressed:

target material & characteristics
e^+ accelerator complex
muon accumulator rings design
luminosity parameters optimization

We will continue to optimize all the parameters, lattices, targets, etc. in order to assess the ultimate performances of a muon collider based on this concept

Exploring the potential for a Low Emittance Muon Collider

some References:

- M. Boscolo *et al.*, **“***Studies of a scheme for low emittance muon beam production from positrons on target”,* **IPAC17 (2017)**
- M.Antonelli, *“Very Low Emittance Muon Beam using Positron Beam on Target”*, **ICHEP (2016)**
- M.Antonelli *et al.* , *“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 by SLAC team:

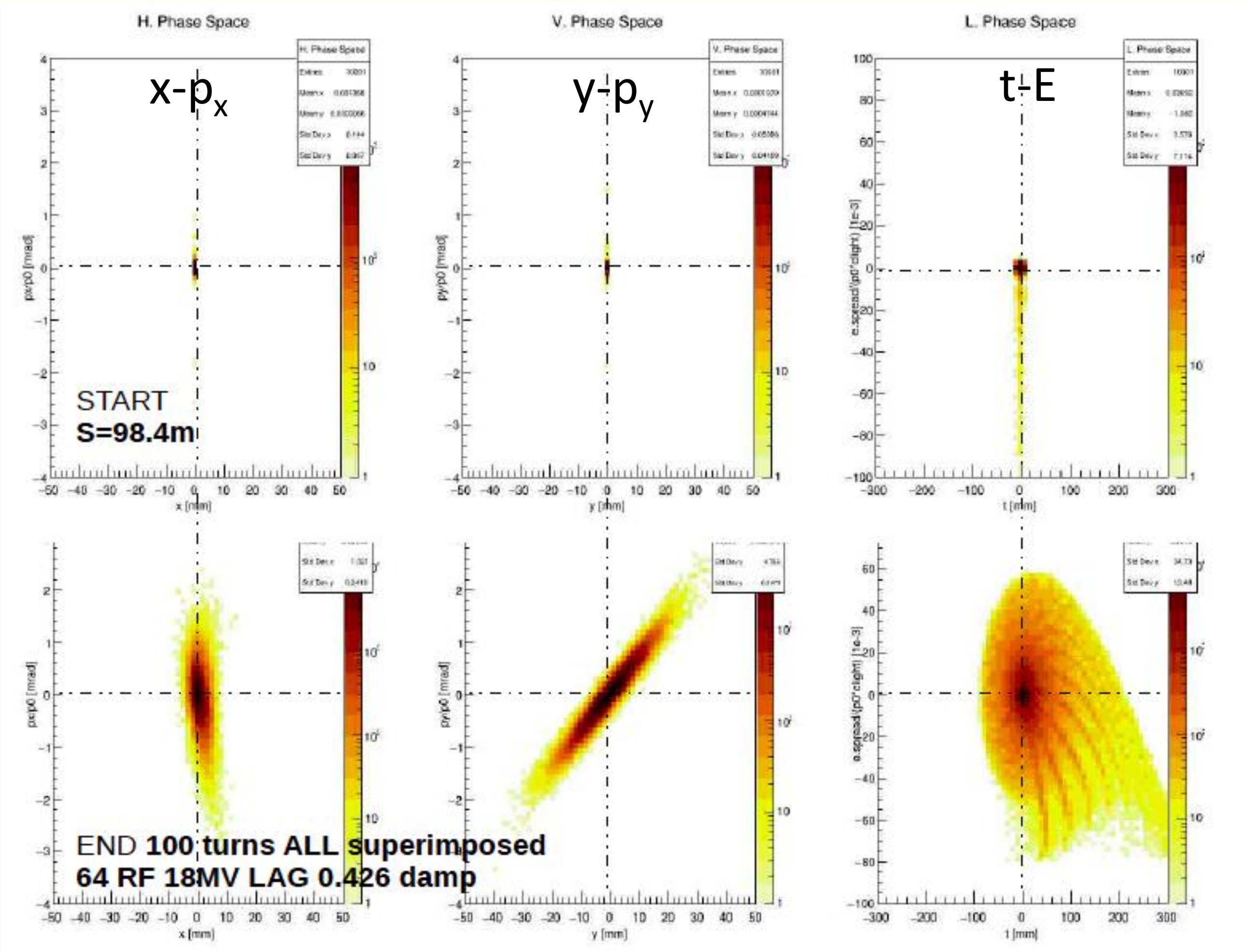
L. Keller, J. P. Delahaye, T. Markiewicz, U. Wienands:

- *“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

e+ ring with target: beam evolution in the 6D phase space

before target, starting point

after 40 turns



MAD-X PTC & GEANT4 6-D tracking simulation of
e+ beam with 3 mm Be target along the ring (not at IR center in this example)