LEMMA

M. Boscolo (LNF)
For the LEMMA Team

Istituto Nazionale di Fisica Nucleare

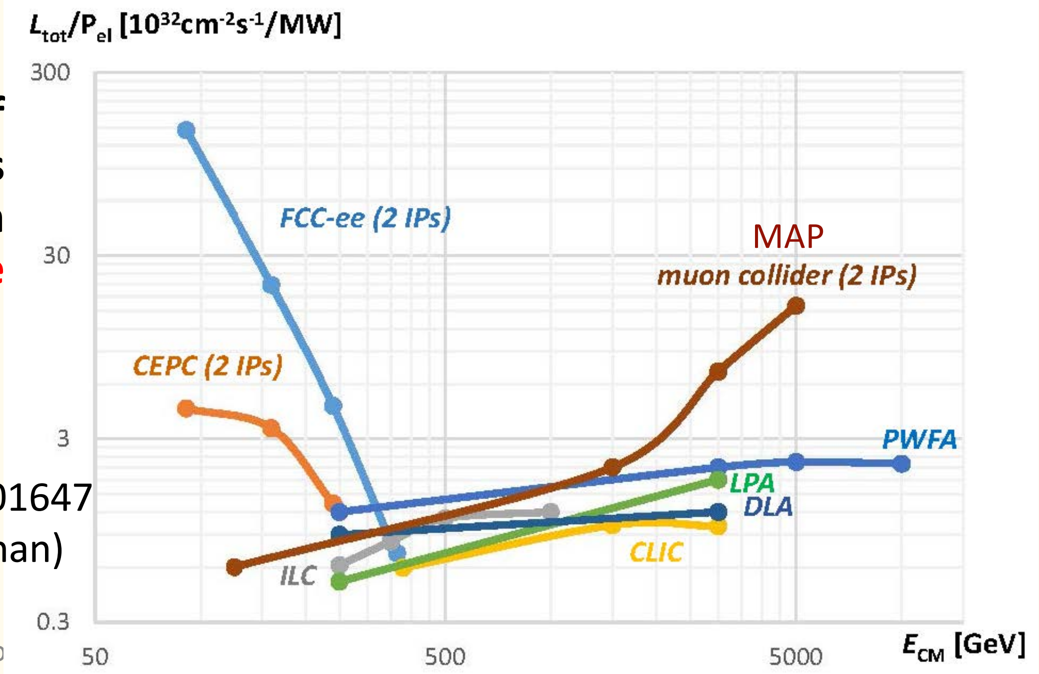
Outline

- **Introduction**
- **Muon production**
  - proton driven source (conventional MAP scheme)
  - positron driven source (alternative LEMMA scheme)
- **LEMMA accelerator concept**
  - Accelerator layout with Multi-TeV collider opportunity
  - Key issues
- **LEMMA R&D**
  - Experimental test at DAFNE after the SIDDHARTA run
  - Test beam at CERN–North Area (1 week July 2017+ 1 week August 2018)
- **Conclusion & Plan**

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
- **Great potentiality if the technology proves its feasibility**
- **Best performances in terms of luminosity and power consumption**

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



J.P. Delahaye, M. Palmer, et al., arXiv:1502.01647 (updated by A. Blondel, P. Janot, F. Zimmerman)

The strength of a μ−beam facility lies in its richness:

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

Take 1

Get 4 !

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

Giudice

Muon Colliders

A. Wulzer at last
LEMMA meeting, 20/4/18

We should remind everybody about pdf's!

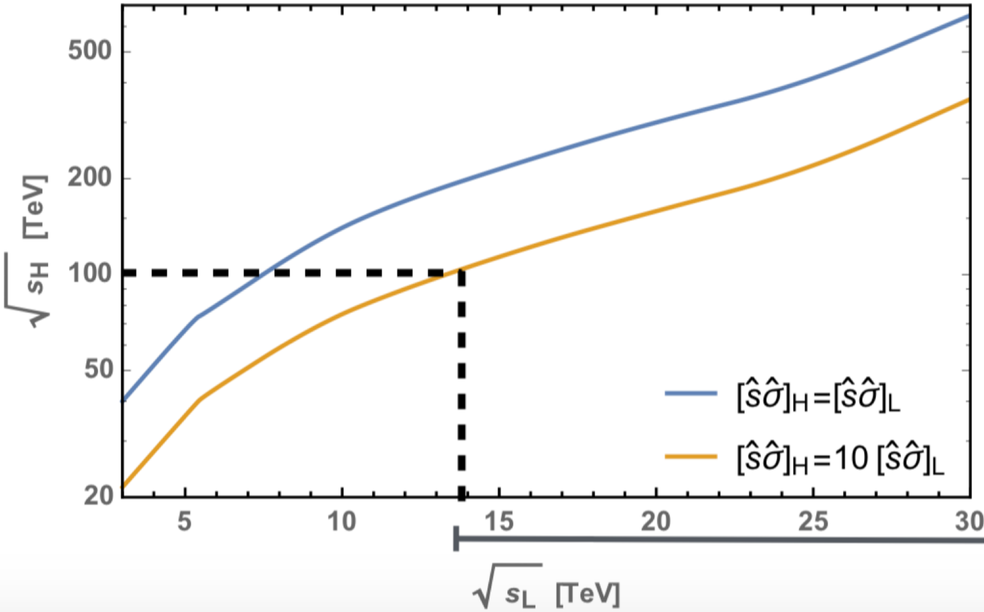
Lepton coll. operating at energy $\sqrt{s_L}$.
Cross section for reaction at $E \sim \sqrt{s_L}$
(e.g., production of BSM at M=E)

$$\sigma_L(s_L) = \frac{1}{s_L}[\hat{s}\hat{\sigma}]_L$$

Hadron coll. operating at energy $\sqrt{s_H}$.
Cross section for reaction at E.
Parton Luminosity suppression

$$\sigma_H(E, s_H) = \frac{1}{s_H}\int_{E^2/s_H}^{1} \frac{d\tau}{\tau}\frac{dL}{d\tau}[\hat{s}\hat{\sigma}]_H$$

Find **equivalent $\sqrt{s_H}$** for Had. Coll. have **same cross-section** as Lep. Coll. for reactions at $E \sim \sqrt{s_L}$. Use that $[\hat{s}\hat{\sigma}]$ is nearly constant in τ.



QCD-coloured BSM can easily have much larger partonic XS.

Comparison even more favourable for **QCD-neutral BSM**

14 TeV μ-collider nearly as good as the FCC at 100 TeV?

LEMMA:
Low EMittance Muon Accelerator

Multi-TeV Muon Collider based on a novel muon production concept

- Muons are produced in positron annihilation on e^- at rest
  → e^+ on target
- It is a low emittance muon source

- **Low emittance concept overcomes muon cooling**
- **Low emittance allows operations at very high c.o.m. energy**

LEMMA concept is proposed by M. Antonelli and P. Raimondi:

M. Antonelli, "*Ideas for muon production from positron beam interaction on a plasma target*", **Snowmass**, Minneapolis (USA) July **2013**, [M. Antonelli and P. Raimondi, Snowmass Report (2013)]
see: INFN-13-22/LNF Note

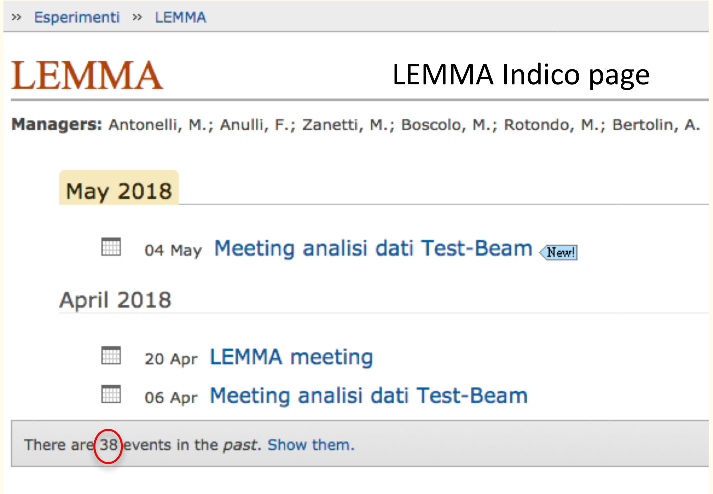
It is a LNF idea !

LEMMA activity @INFN

LEMMA is a WP within RD_FA activity (CSN1) since 2016

(resp. WP M. Antonelli, nat. resp. RD_FA F. Bedeschi)

- M. Boscolo, “*Muon collider: opzioni di macchina*”, **CSN1** Catania, Dec. 2015
- M. Boscolo, “*LEMMA”,* **MAC of INFN,** LNGS, 10 Oct. 2017
- **Document prepared for the MAC of INFN** “*Preliminary study of the definition of a white paper for a conceptual Design Study of a Low EMittance Muon Accelerator (LEMMA)”* pp58, not for distribution, Oct. 2017 **(*)**
- P. Raimondi, **CSN1**, Dec. 2017
- N. Pastrone, **INFN Board directors,** March 2018



(*) Short-term goals together with WP plan are proposed. Manpower is essential for a white paper/CDR goal. MoUs with our collaborators would help to profit from past and top level experience to progress in the accelerator key topics understanding.

Conferences and Workshops

After first presentation in Snowmass

- 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, *"Low-emittance muon collider from positrons on target"*, FCCWEEK2016
- M. Antonelli, *"Performance estimate of a FCC-ee-based muon collider"*, FCCWEEK2016
- M.Antonelli *et al.* , *"Very Low Emittance Muon Beam using Positron Beam on Target"*, IPAC16
- M.Antonelli, *"Very Low Emittance Muon Beam using Positron Beam on Target"*, ICHEP (2016)
- F. Collamati, EPS17
- F. Collamati, Nufact17
- M. Boscolo *et al., "Studies of a scheme for low emittance muon beam production from positrons on target",* IPAC17 (2017)
- M. Boscolo, "*LEMMA",* INFN MAC, LNGS, Ottobre 2017
- D. Lucchesi, FERMILAB Colloquium, 2018
- P. Raimondi, "Towards a future muon collider", La Thuile 2018
- L. Sestini, Test beam workshop 2018
- F. Anulli, Muon Collider: LEMMA proposal", XXIV Cracow EPIPHANY Conference on Advances in Heavy Flavour Physics, 2018
- Workshop on Targetry LNF mini-workshop
- M. Boscolo et al., "*Proposal of an experimental test at DAΦNE for the low emittance muon beam production from positrons on target",* Inst. of Phys. J. of Physics: Conf. Series from IPAC18
- M. Boscolo et al., IPAC18
- M. Boscolo, Invited talk at 1° ARIES annual meeting "The muon collider", May 2018
- M. Iafrati et al., "*Preliminary study of high power density target for the LEMMA proposal*", to be presented at HPTW workshop, 2018

not exhaustive list

References on LEMMA

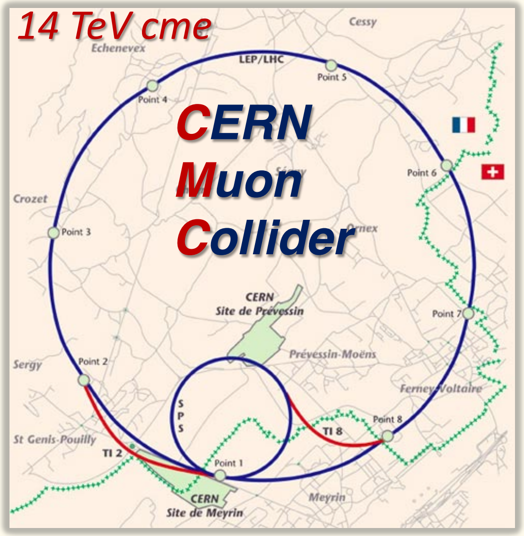
- M. Antonelli, "*Ideas for muon production from positron beam interaction on a plasma target*", Snowmass, Minneapolis (USA) July 2013, [M. Antonelli and P. Raimondi, **Snowmass Report** (**2013**)] see: INFN-13-22/LNF Note
- M. Antonelli, M. Boscolo, R. Di Nardo, P. Raimondi, "*Novel proposal for a low emittance muon beam using positron beam on target*", **NIM A 807** 101-107 (**2016**)
- M. Antonelli et al., "Very Low Emittance Muon Beam using Positron Beam on Target", in Proc. **IPAC16**
- M. Boscolo et al., "Studies of a Scheme for Low Emittance Muon Beam Production From Positrons on Target" in Proc. **IPAC17**
- F. Collamati et al., "Studies of a scheme for low emittance muon beam production from positrons on target", **PoS EPS-HEP2017** (2017) 531
- "Preliminary study of the definition of a white paper for a conceptual Design Study of a Low EMittance Muon Accelerator (LEMMA)" pp58, **document prepared for the MAC of INFN**, not for distribution, October **2017**
- M. Boscolo et al., "*Low emittance muon accelerator studies with production from positrons on target*" submitted to **Phys. Rev. Accel. Beams**, review process, Arxiv. 1803.06696, **2018**
- M. Boscolo et al, "*Proposal of an experimental test at DAΦNE for the low emittance muon beam production from positrons on target*", **Inst. of Phys. J. of Physics: Conf. Series** (IPAC18)
- M. Boscolo et al., "Muon accumulator ring requirements for a low emittance muon collider from positrons on target", in Proc. IPAC18

after Snowmass2013 also SLAC team investigated the idea: L. Keller, J. P. Delahaye, T. Markiewicz, U. Wienands:

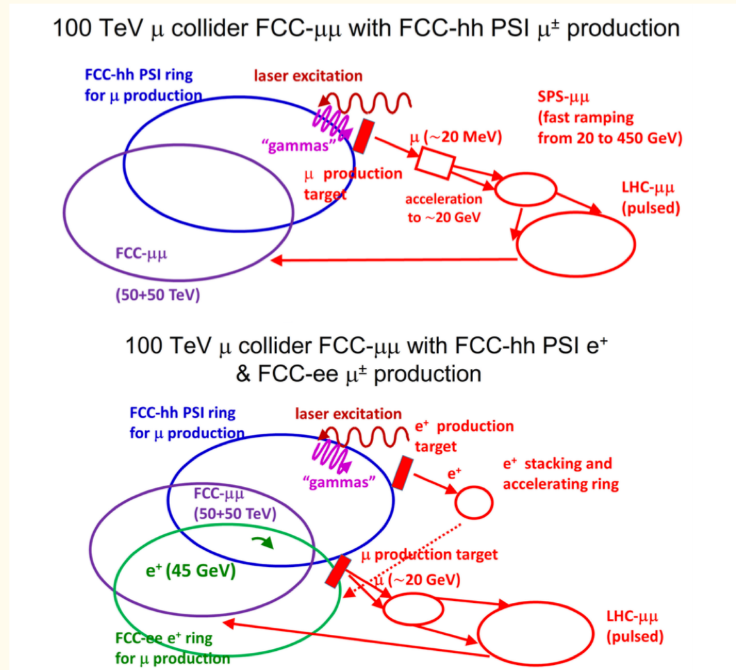
- *"Luminosity Estimate in a Multi-TeV Muon Collider using $e^+e^- \rightarrow \mu^+\mu^-$ as the Muon Source"*, MAP14 Spring worksh., Fermilab (USA)
- Advanced Accelerator Concepts Workshop, San Jose (USA), July '14

Recent activities on high-energy muon collider

Muon Collider WG for European Strategy Update: **N. Pastrone, INFN, Italy, chair**, M. Diemoz, INFN. Italy, A. Skrinsky, BINP, Russia, K. Long, Imperial College, UK, JP Delahaye, CERN, D. Schulte, CERN, A. Wulzer, CERN, B. Mansoulie, IRFU, France



MOPMF072, IPAC18, V. Shiltzev



MOPMF065,IPAC18, F. Zimmermann

Coming soon:

- M. Boscolo, M. Palmer and JP Delahaye, '*The future prospects of muon collider and neutrino factory'*, *in* **Reviews of Accelerator Science and Technology journal**
- **ARIES Topical Workshop on Future Muon Colliders,** in collaboration with the WG on Muon Colliders for the ESU, **Padova, 2-3 July 2018**

Idea for low emittance μ beam

from **proton on target:** p + target$\rightarrow \pi/K \rightarrow \mu$

typically **$P_\mu \approx$ 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 **$e^+e^-\rightarrow\mu^+\mu^-$** at √s around the $\mu^+\mu^-$ threshold **(√s ≈ 0.212GeV)** in asymmetric collisions (to collect μ^+ and μ^-)

NIM A reviewer (2016) : "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…"

PR-AB reviewer *(still in review process, April 2018):* `I believe this is an important contribution to the literature on muon colliders as a means of delivering multi-TeV lepton-anti-lepton collisions. It is also important at this time because it has re-initiated the discussion of a muon collider as a potential route to energy-frontier lepton-antilepton collisions in advance of the update to the European Strategy for Particle Physics. .... Overall, I was impressed by this paper and am convinced that it should be published.'

LEMMA scheme

Goal:

@T ≈ 10^{11} μ/s

Efficiency ≈ 10^{-7} (with Be 3mm)→

10^{18} e^+/s needed @T →

e^+ stored beam with T

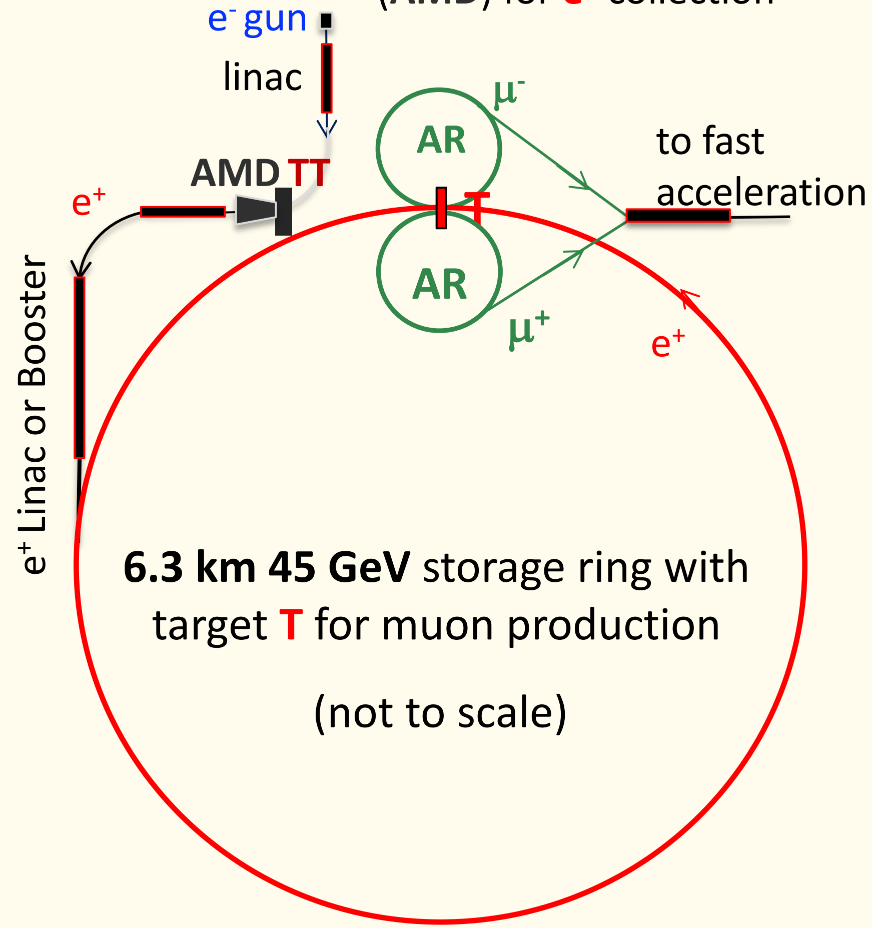
to minimize positron source rate

Goal: mom. aperture +/-12%

lifetime(e+) ≈ 250 turns

e^- on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.

Adiabatic Matching Device (**AMD**) for $\mathbf{e^+}$ collection



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

- produced by the $\mathbf{e^+}$ beam on target **T** with **E(μ) ≈ 22 GeV**, $\gamma(\mu) \approx 200 \rightarrow \tau_{lab}(\mu) \approx$ **500μs**
- **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

Pro LEMMA: Low emittance

θ_μ is tunable with $\sqrt{s}$ in $e^+e^- \rightarrow \mu^+\mu^-$

μ beam divergence can be **very small** close to the $\mu^+\mu^-$ threshold

Cons LEMMA: Low μ prod. Rate

much smaller cross section. wrt proton-driven-source

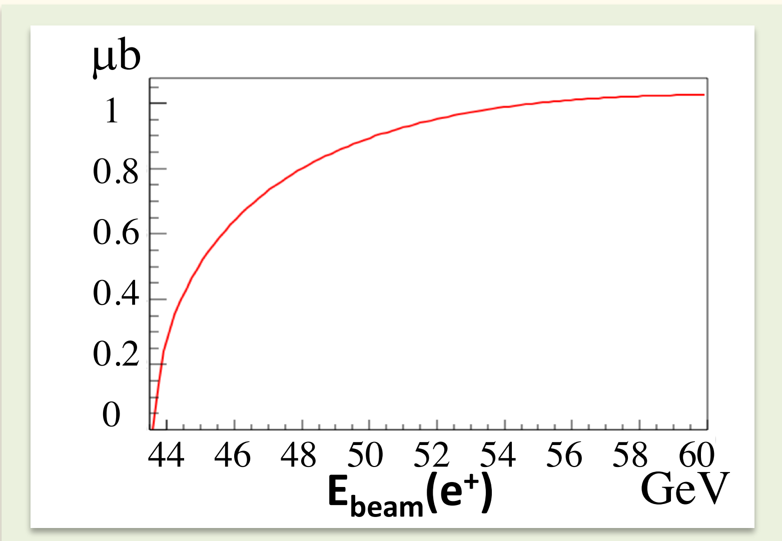
$\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx$ **1 μb** at most wrt σ(from p)$\approx$ **mb**

Pro LEMMA:

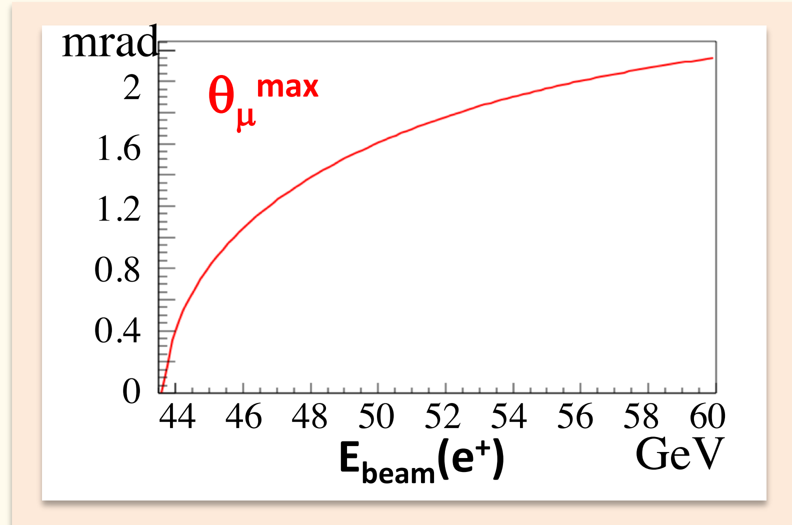
- **Reduced losses from decay:** **high collection efficiency**
- **Low background:** **Luminosity at low emittance will allow low background and low neutrino radiation → easier experimental conditions & can go to higher energies**
- **Energy spread:** muon energy spread might be **also small at threshold**, it gets larger as $\sqrt{s}$ increases

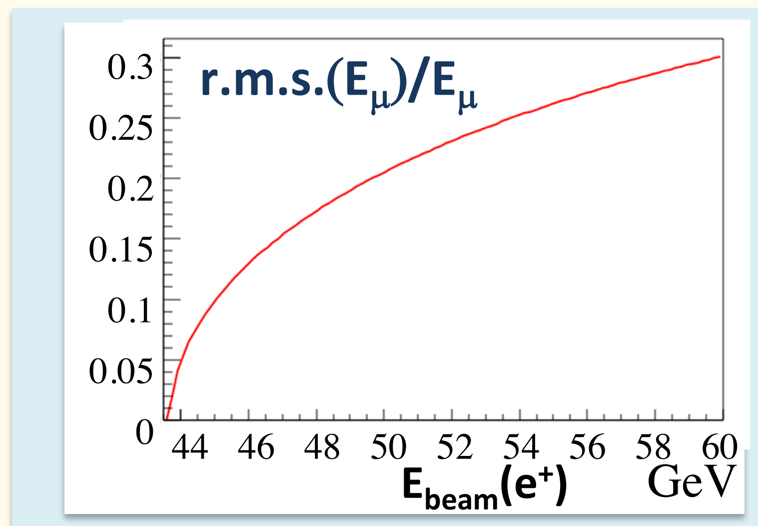
Cross-section, muons beam divergence and energy spread as a function of the e+ beam energy

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



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





Radiological hazard due to neutrinos from a muon collider

Colin Johnson, Gigi Rolandi and Marco Silari

TIS-RP/IR/98-34 (1998) (updated by M.Antonelli)

MAP design for a 6 TeV MC (500 m depth)

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

muon rate:

p on target option

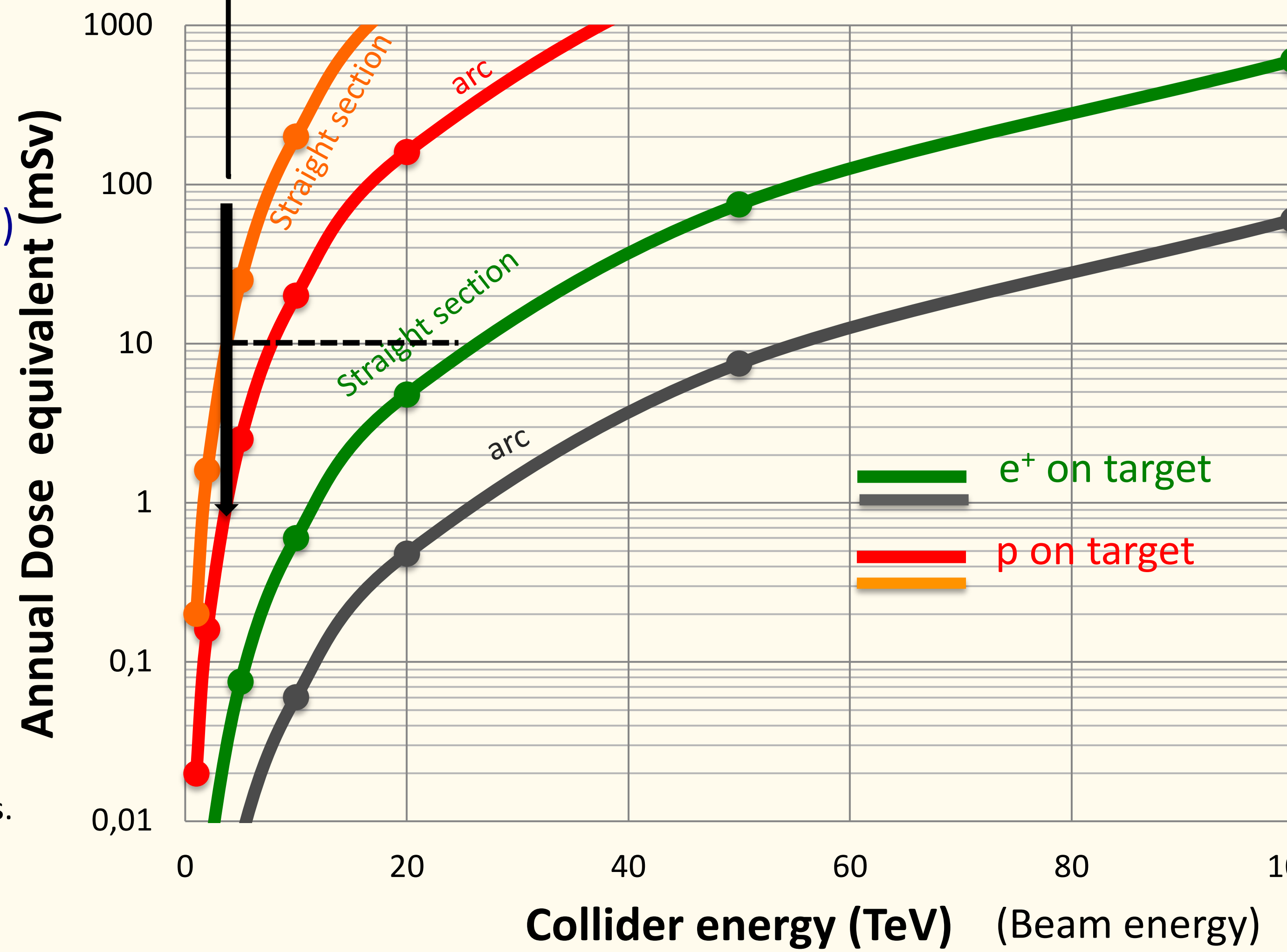
$3 \times 10^{13}\ \mu/s$

e^+ on target option

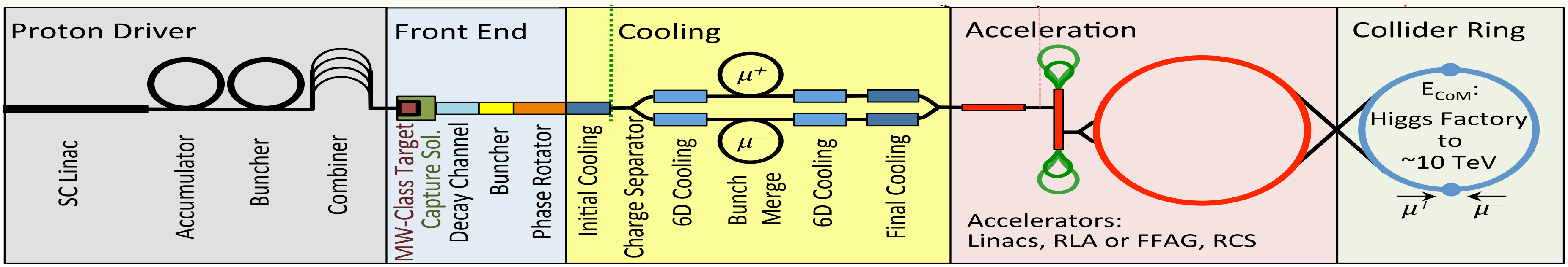
$9 \times 10^{10}\ \mu/s$

neutrino dose equivalent/fluence

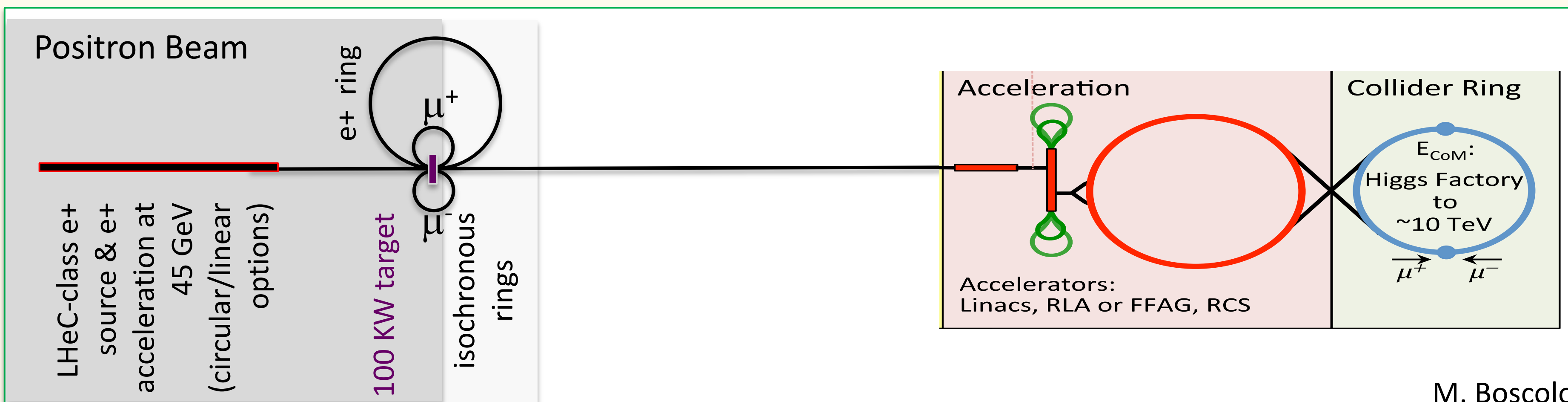
[J.D. Cossairt, N.L. Grossman and E.T . Marshall, Health Phys. 73 (1997), 894-898.]



From US-MAP to Italian-LEMMA μ-collider



Key Challenges	**~10^{13}-10^{14} μ / sec Tertiary particle *p→π→μ*:**	**Fast cooling (τ=2μs) by 10^6 (6D)**	**Fast acceleration mitigating μ decay**	**Background by μ decay**



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**

Muon collider at 6 TeV com energy

no lattice for the muon collider yet

Values considered for this parameter table:

- **$\mu^+\mu^-$ rate = 0.9 10^{11} Hz**
- **ε_N = 40 nm (as ultimate goal of our studies)**

Comparison with MAP:

muon source	Rate μ/s	ε_{norm} μm
LEMMA	0.9×10^{11}	0.04
MAP	10^{13}	25

Same L thanks to lower β*
(nanobeam scheme)

Parameter	unit	LEMMA-6 TeV
Beam energy	Tev	3
Luminosity	$cm^{-2}s^{-1}$	5.1×10^{34}
Circumference	km	6
Bending field	T	15
N particles/bunch	#	6×10^{9}
N bunches	#	1
Beam current	mA	0.048
Emittance x,y	m-rad	1.4×10^{-12}
$\beta_{x,y}$ @IP	mm	0.2
$\sigma_{x,y}$ @IP	m	1.7×10^{-8}
$\sigma_{x',y'}$ @IP	rad	8.4×10^{-5}
Bunch length	mm	0.1
Turns before decay	#	3114
muon lifetime	ms	60

Accelerator physics key topics for the feasibility LEMMA scheme

1. **Positron ring**

   Optics design & beam dynamics

   - low emittance and high momentum acceptance

2. **Muon Accumulator Rings**

   Optics design & beam dynamics

   - High momentum acceptance

3. **Positron source**

   Synergy with FCC-ee/ILC/CLIC future colliders

   - High rate

4. **$\mu^{+/-}$ production target**
   - High Peak Energy Density Deposition PEDD
   - Power O(100 kW)

   Synergy with High Power Targetry R&D, HL-LHC beam interceptors

Optics & Beam Dynamics

- **Design of the positron ring**
- **Beam dynamics studies e+ beam with target**
- **Muon Emittance: matching various contributions**
- **Muon accumulator rings first concept**

LNF: M.Boscolo, S. Guiducci, O. Blanco, M.Antonelli ; ESRF: P. Raimondi, S. Liuzzo; Rm1: F. Collamati; SLAC: L. Keller, CERN: D. Schulte (last IPAC18 paper)

Refs.

- M. Boscolo et al., "*Studies of a Scheme for Low Emittance Muon Beam Production From Positrons on Target*" in Proc. **IPAC17**
- M. Boscolo M. Antonelli, O. Blanco, S. Guiducci, , S. Liuzzo, P. Raimondi, F. Collamati "*Low emittance muon accelerator studies with production from positrons on target*" submitted to **Phys. Rev. Accel. Beams 2018** (review process), Arxiv. 1803.06696
- M. Boscolo, M. Antonelli, O. Blanco, S. Guiducci, F. Collamati, S. Liuzzo, P. Raimondi, L. Kellers, D. Schulte, "*Muon accumulator ring requirements for a low emittance muon collider from positrons on target*", in Proc. IPAC18

Optics design positron ring

More details in:
Arxiv. 1803.06696

optics cell

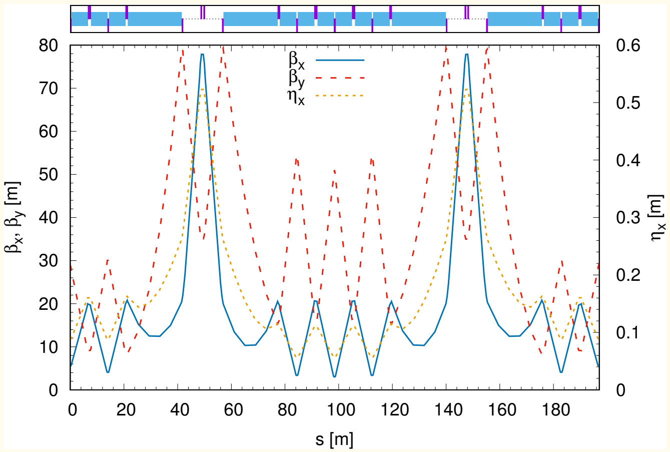
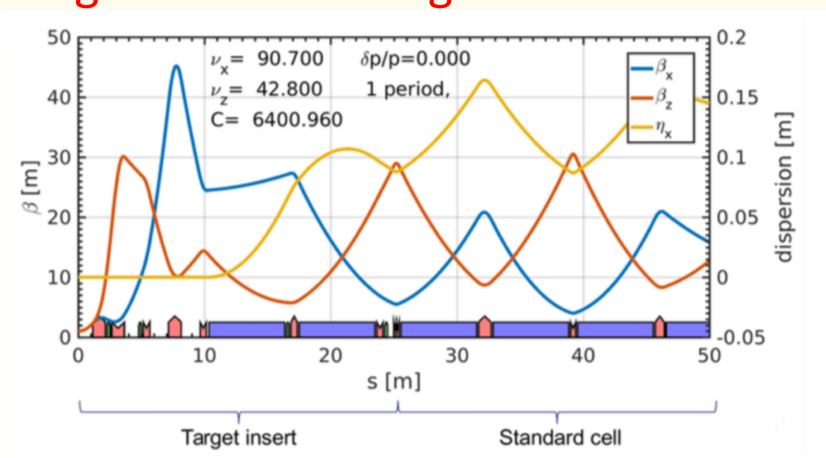


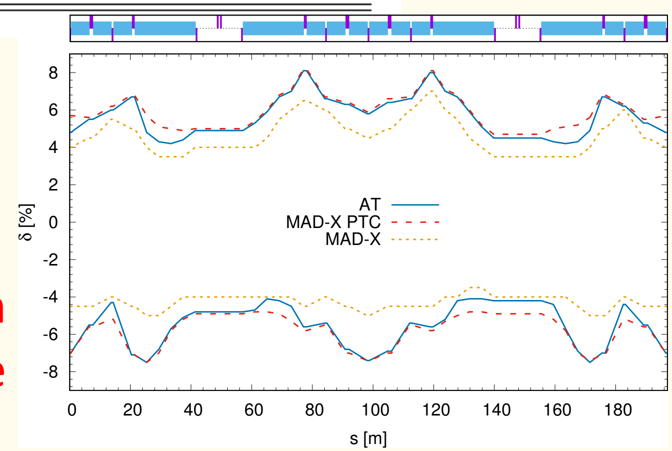
Table e+ ring parameters

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

Target Insertion Region



momentum acceptance



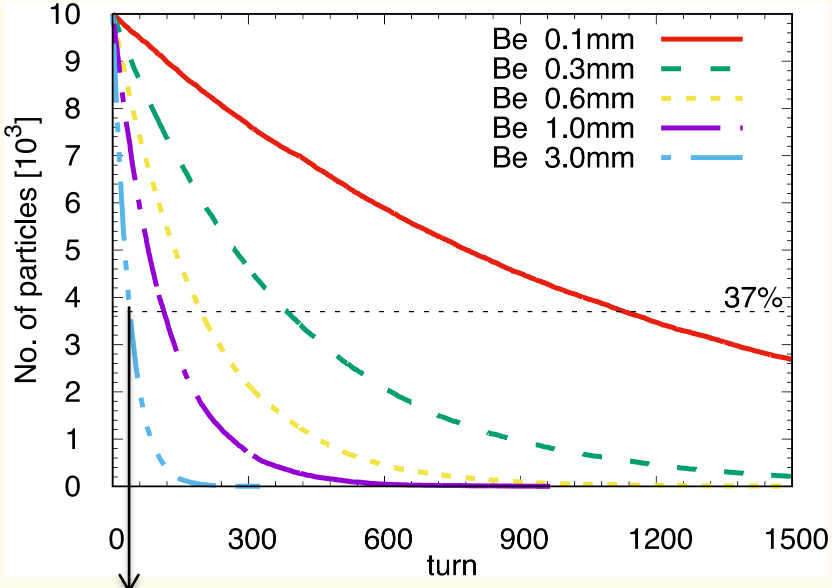
@target $\begin{cases} D_x \approx 0 \\ \text{low-}\beta\ (\beta_{x,y} = 0.5\ \text{m}) \end{cases}$

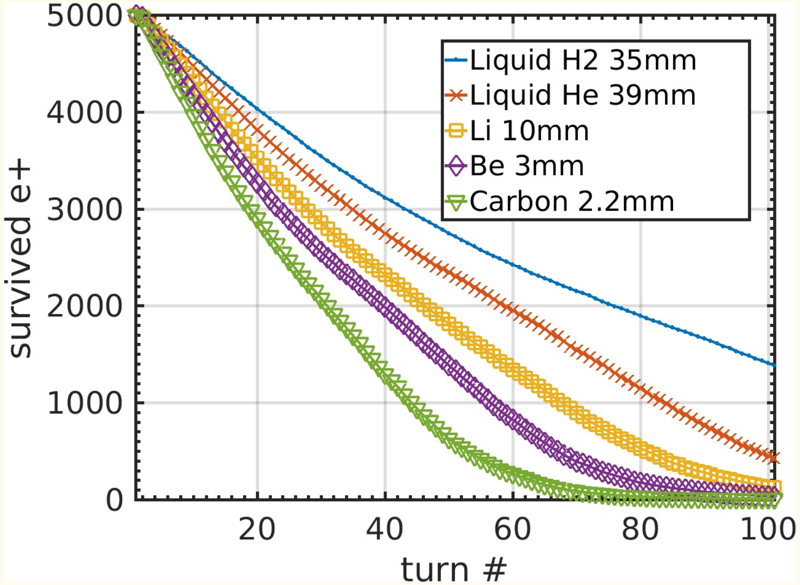
Beam dynamics e^+ beam in ring-with-target

More details in:
Arxiv. 1803.06696

Particle tracking with: MADX/ PTC/GEANT4/FLUKA & Accelerator Toolbox/G4-Beamline

Lifetime ∝ 1/thickness as expected





Lifetime ~ 40 turns for Be 3 mm

Lifetime determined by bremsstrahlung and momentum acceptance

2-3% e+ losses in the first turn

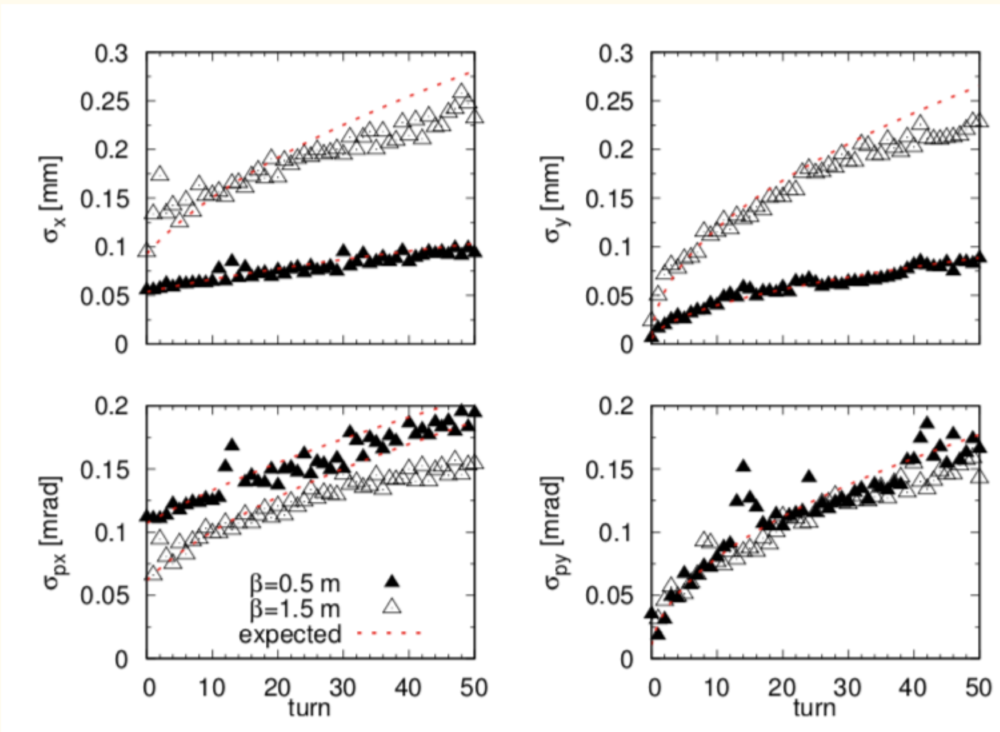
Number of e+ vs turns for different target materials.

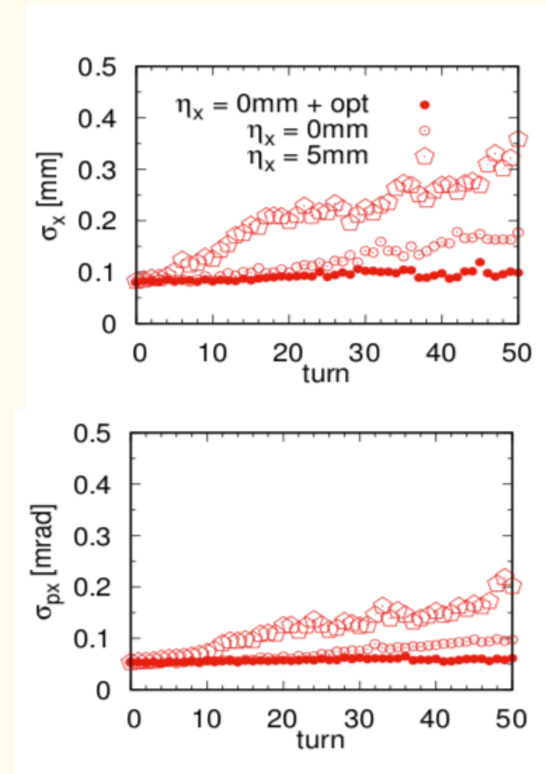
Target thickness gives constant muon yield.

Beam dynamics e^+ beam in ring-with-target

More details in:
Arxiv. 1803.06696

e^+ emittance growth controlled with proper β and D values @ target





multiple scattering contribution also explained analytically:
one pass contribution due to the target:

$$\sigma_{MS} = \frac{1}{2}\sqrt{n}\,\sigma'_{MS}\,\beta$$

After 40 turns $\sigma'_{MS} = 25\ \mu\text{rad}$

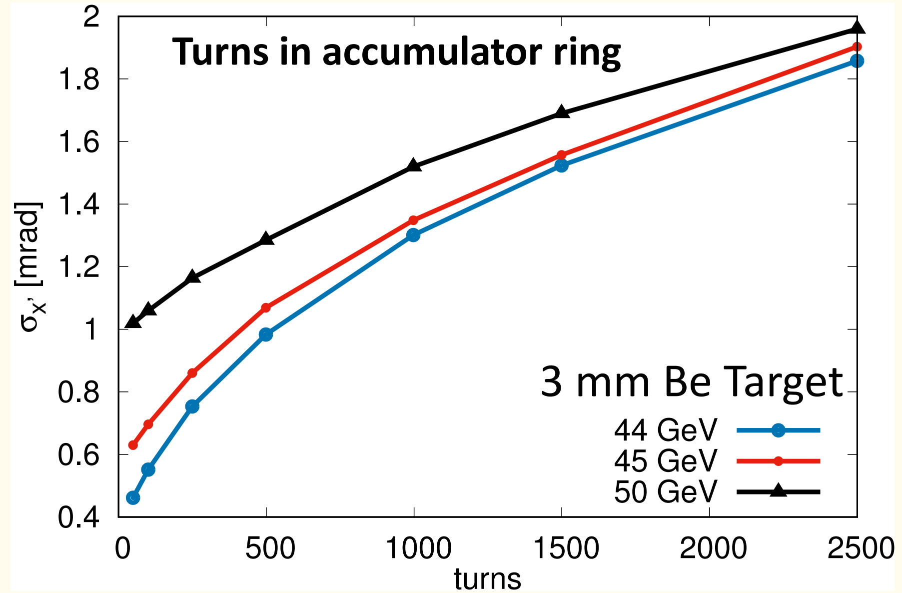
n number of turns

Several optics versions to correct dispersion effects beyond linear term

Muon emittance contributions

$$\varepsilon(\mu) = \varepsilon(e^+) \oplus \varepsilon(MS) \oplus \varepsilon(rad) \oplus \varepsilon(prod) \oplus \varepsilon(AR)$$

$\varepsilon(e^+)$ = e^+ emittance
$\varepsilon(MS)$ = multiple scattering contribution
$\varepsilon(rad)$ = energy loss (brem.) contribution
$\varepsilon(prod)$ = muon production contribution
$\varepsilon(AR)$ = accumulator ring contribution



muon production angle

muon production angle + MS contribution

All these values need to be matched to minimize emittance growth due to beam filamentation.

σ_x and $\sigma_{x'}$ and correlations of e^+ and μ beams have to be similar

In agreement with analytical estimate

Multiple scattering contribution can be strongly reduced with crystals in channeling

More details in MOPMF087, Proc. IPAC18

Muon production target

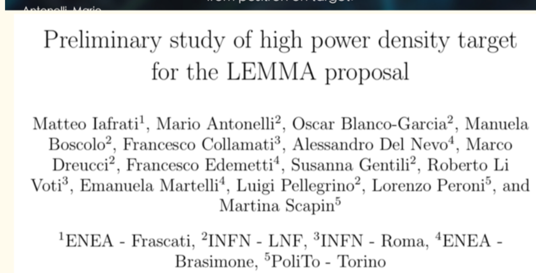
This is the core topic of LEMMA feasibility. Thermo-mechanical stress is the main issue (very high Peak Energy Density Deposition)

LNF has been coordinating the preliminary investigations and organizazion of the study with identification of topics, expertize and contacts for collaboration

NEWS

- collaboration with PoliTo expertize on material termo-mechanical characterization
  (simulations and experimental validation)
- Collaboration with Brasimone Expertize on Liquid Lithium
- Dedicated position ADR (INFN Rm1)
  Expertize on thermo-mechanical measurements

LNF: M.Boscolo, M.Antonelli, L. Pellegrino, M. Iafrati (ENEA); Sapienza SBAI: R. Li Voti
INFN-Rm1: F. Collamati, G. Cesarini
Poli-TO: M. Scapin, L. Peroni
Brasimone: A Del Nevo;
Consulenza CERN: M. Calviani, S. Gilardoni


Preliminary study of high power density target for the LEMMA proposal

Matteo Iafrati[1], Mario Antonelli[2], Oscar Blanco-Garcia[2], Manuela Boscolo[2], Francesco Collamati[3], Alessandro Del Nevo[4], Marco Dreucci[2], Francesco Edemetti[4], Susanna Gentili[2], Roberto Li Voti[3], Emanuela Martelli[4], Luigi Pellegrino[2], Lorenzo Peroni[5], and Martina Scapin[5]

[1]ENEA - Frascati, [2]INFN - LNF, [3]INFN - Roma, [4]ENEA - Brasimone, [5]PoliTo - Torino

Refs.

- LNF Mini-Workshop Series: "*Muon production and beam interceptors*", 19 April 2018
- M. Iafrati et al., "*Preliminary study of high power density target for the LEMMA proposal*", to be presented at HPTW workshop, June 2018

Target: thermo-mechanical stresses considerations

Beam size as small as possible (matching various emittance contributions), 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

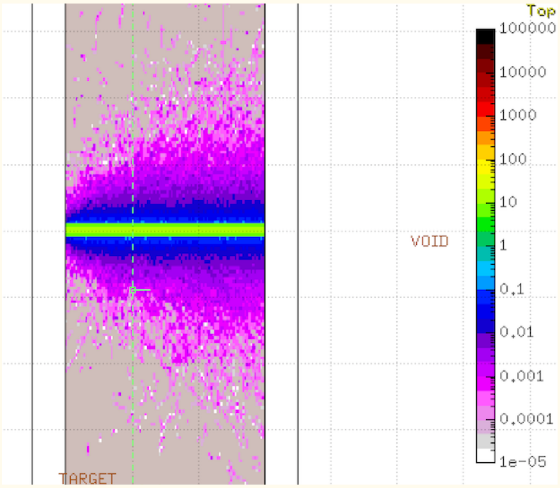
- **Solid target**: simpler and better wrt temperature rise
  - Be, C

  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:
  - **DAFNE** available from 2020, see later



Alternative options like H pellet, crystals or more exotic targets are under consideration

Positron source

e$^+$ production rates achieved (SLC) or needed

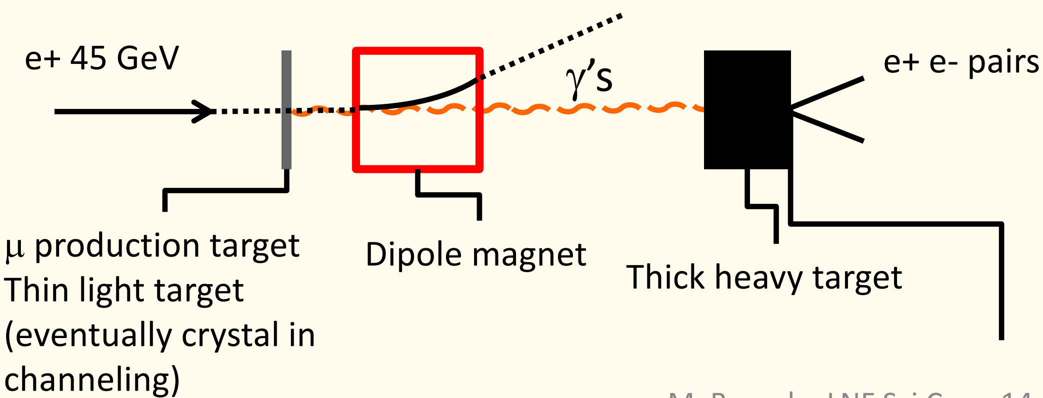
	S-KEKB	SLC	CLIC (3 TeV)	ILC (*H*)	FCC-ee (*Z*)	Italian μ collider
10^{12} e$^+$ / s	**2.5**	**6**	**110**	**200**	**5**	**1000**

[F. Zimmermann]

embedded e+ source idea

[suggested by A. Variola]

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



About 0.6 new e$^+$ produced per e$^+$ on thin target

Required collection efficiency feasible with standard design

not yet found a system able to transform the temporal structure of the produced positrons to one that is compatible with the requirement of a standard positron injection chain

LEMMA ring-plus-target Test at DAΦNE after SIDDHARTA-2 run

- **Beam dynamics study of the ring-plus-target scheme:**
  - transverse beam size / current / lifetime
- **Measurements on target:**
  - temperature (heat load) / thermo—mechanical stress

GOAL of the experiment:

- **Validation LEMMA studies**, benchmarking data/expectations
- **Target Tests**: various targets (materials and thicknesses)

Feasibility Concept study:
LNF: M.Boscolo, M.Antonelli, O.Blanco, A.Stella, A.Ghigo, D. Alesini, S.Guiducci, L.Pellegrino; Sapienza SBAI: R. Li Voti, Rm1: F.Collamati; ESRF: P. Raimondi, S. Liuzzo

Experiment Test will require technical and engineering support from LNF Acc. Div., both for the executive project, and the experiment itself

Ref. M. Boscolo, M. Antonelli, O. Blanco, S. Guiducci, A. Stella, F. Collamati, S. Liuzzo, P. Raimondi, R. Li Voti "*Proposal of an experimental test at DAΦNE for the low emittance muon beam production from positrons on target*",to be publ. in **Inst. of Phys. J. of Phys. Conf. Series** (IPAC18) also LNF-18/02(IR).

DAFNE Layout for the LEMMA Test

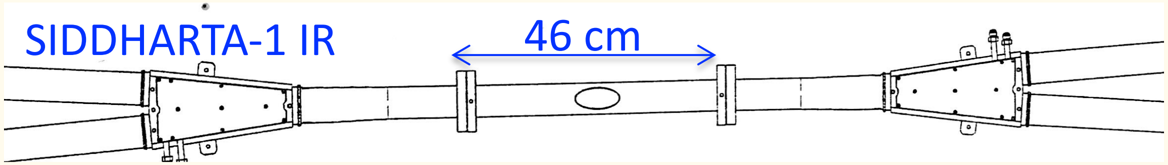
The target will be placed at the SIDDHARTA IP because:

- low-β and D_x=0 is needed (similarly to IP requirements)
- to minimize modifications of the existing configuration

Possible different locations for the target can be studied

For the preparation of this experiment we need:

1. **Full design of vacuum chamber IR and target insertion system**
2. **Target design**
3. **Diagnostics for target thermo-mechanical stress measurements**
4. **Beam diagnostics**
5. **Injection scheme (on axis)**
6. **Optics and beam dynamics**



Given the limited energy acceptance of the ring we plan to insert **light targets (Be, C)** with thickness in the range ≈ **100 μm**. Crystal targets can be foreseen too.

Diagnostics for the test at DAFNE

- **Beam characterization after interaction with target, additional beam diagnostic to be developed**:
  - **turn by turn charge measurement** (lifetime)
    - ✓ existing diagnostic already used for stored current measurement
    - ✓ need software and timing reconfiguration
  - **turn by turn beam size**
    - ✓ beam imaging with synchrotron radiation
    - ✓ DAFNE CCD gated camera provides gating capabilities required to measure average beam size at each turn.
    - ✓ software modification and dedicated optics installation required.
- **Target diagnostics:**
  - Passive Infrared Thermography
  - Infrared radiometry
  - Measurement of surface deformation

Experimental Test @CERN-North Area

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

Experimental Team: **See next slide**
INFN sections: LNF, Rm1, Pd, To, Fe, Ts
Univ.: Insubria, Sapienza, Pd

- **@H4: 1 week July 2017:**
  High intensity: up to 5 x 10^6 e+/spill with **6cm Be** target (spill ~15s)
  goal:
  measure muon production rate and muons kinematic properties
  we had 2 days at ≈ 10^6 e^+ /spill

- **@H2: 15-22 August 2018 (1 week)**
  to complete original program of the 2017 experiment

Tonelli Guido	10 PI
Benato Lisa	15 PD
Bertolin Alessandro	5 PD
Checchia Paolo	10 PD
Lucchesi Donatella	30 PD
Lujan Paul	15 PD
Lupato Anna	10 PD
Morandin Mauro	5 PD
Rossin Roberto	10 PD
Sestini Lorenzo	30 PD
Zanetti Marco	25 PD
Gonella Franco	20 PD
Anulli Fabio	20 RM1
Collamati Francesco	40 RM1
Palumbo Luigi	20 RM1
Camattari Riccardo	30 FE
Guidi Vincenzo	10 FE
Vallazza Erik	50 TS
Antonelli Mario	20 LNF
Blanco Garcia Oscar	30 LNF
Guiducci Susanna	20 LNF
Iafrati Matteo	100 LNF
Rotondo Marcello	20 LNF
Biagini Maria	20 LNF
Boscolo Manuela	60 LNF
Pellegrino Luigi	10 LNF

Low EMittance Muon Accelerator team

← CSN1 team

Additional national

- M. Ricci **(Uni. Marconi, INFN-LNF)** A. Stella **(LNF),** G. Cavoto **(La Sapienza),** E. Bagli **(INFN-Fe),** M. Prest, M. Soldani, C. Brizzolari **(Uni-Insubria&INFN),** A. Lorenzon, S. Vanini, S. Ventura, D. Dattola**(INFN-Uni. Padova),** A. Wulzer **(Uni. Pd & EPFL)**

Additional international

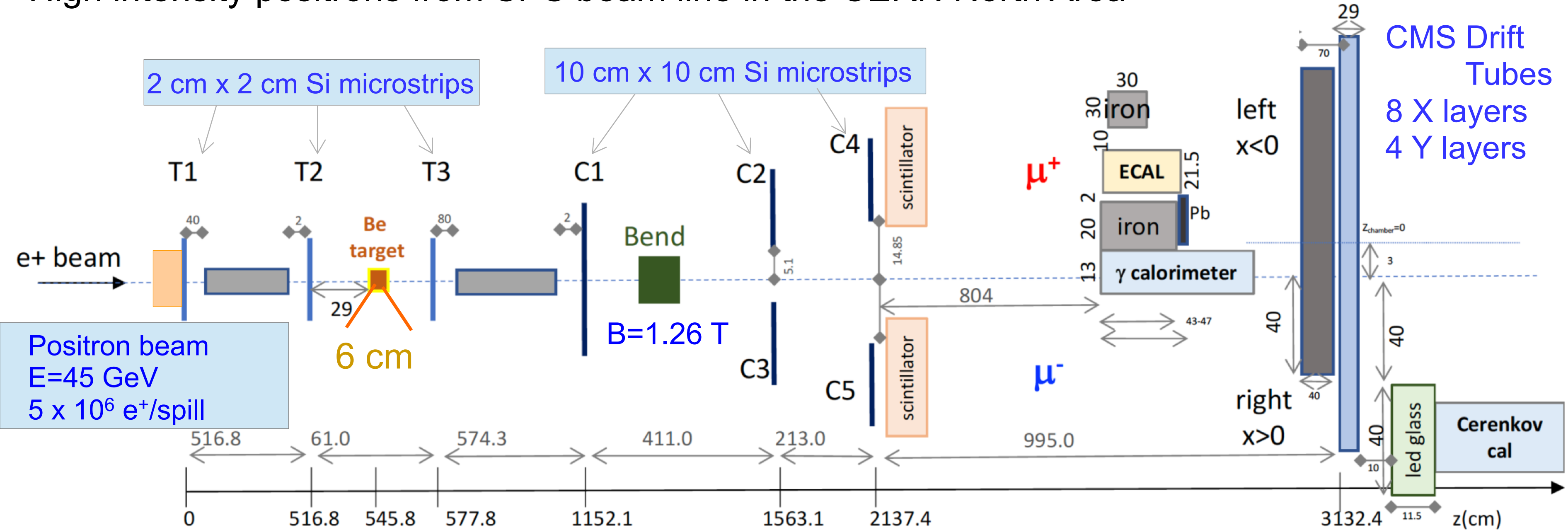
- P. Raimondi, S. Liuzzo, N. Carmignani **(ESRF)**
- R. Di Nardo, P. Sievers, M. Calviani, S. Gilardoni **(CERN)**
- I. Chaikovska, R. Chehab **(LAL-Orsay)**
- L. Keller, T. Markiewicz **(SLAC)**

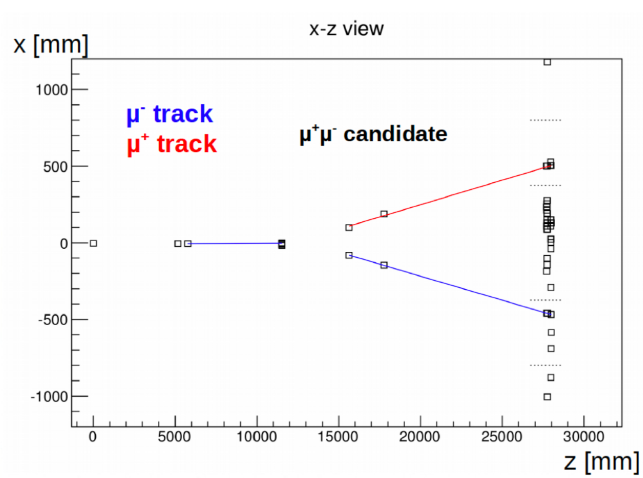
ARIES WP6: improving Accelerator PErformance and new Concepts task for muon collider
Task 6.6 Assessment of advanced muon-collider concepts without ionization cooling

2017 CERN test beam

Precision spectrometer aiming to measure $\mu^+\mu^-$ production cross section and μ^+/μ^- emittance

High intensity positrons from SPS beam line in the CERN North Area





Among 620K collected events 56 $\mu^+\mu^-$ candidates
Finalization of the data analysis is on the way

We are preparing the next TB (August 2018) exploiting all lessons learned from the 2017 TB

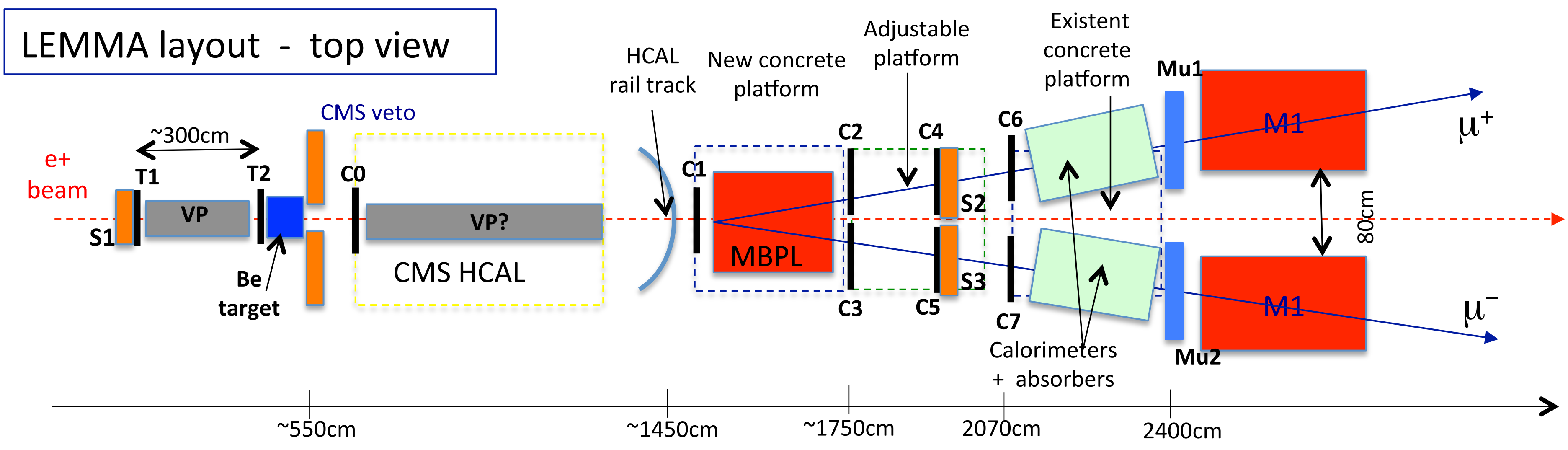
2017 Experimental set-up

2018 Experimental layout

- Study of kinematic properties of the produced muons
  - Measure the $\mu^+\mu^-$ production rate for the provided positron beam features (momentum and energy spread)
    - Use Bhabha events for normalization
  - Measure muons momentum and emittance
- Trigger for Signal and Normalization events provided by the coincidence of the 3 scintillator S1 (intercept the incoming beam) and S2 and S3 intercepting the outcoming muons.

- Experimental setup modified with respect to the 2017 TB, also to account the different experimental hall (H4 -> H2)
  - additional tracking;
  - new calorimeters

LEMMA layout - top view



Conclusion

- LEMMA is a novel concept -conceaved at LNF- for muon production that renewed the interest and extended the reach of Multi-TeV Muon Colliders
- There are few key topics for the LEMMA feasibility validation that are accelerator physics topics:
  - Positron ring-with-target: low emittance and high momentum acceptance
  - Muon Accumulator Rings: compact, isochronous and high $(\Delta p/p)_{accept}$
  - Muon production target: extreme Power Energy Density Deposition
  - High positron source rate
- Preliminary studies pioneered by the LNF group are promising, progresses require to continue the design study of the accelerator complex and experimental tests.
- Experimental test at DAFNE for validation of some fundamental topics LEMMA is a fundamental opportunity
- LNF has close contacts with the international accelerator physics community
- A conceptual design study: the investigation of the proof of principle and the assessment of the ultimate performances of this scheme can be performed on a five to ten year time scale provided an adequate support in terms of manpower and fundings for research.

M. Palmer

Proton driven source

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}]

Fermilab

Plans

- A **conceptual design study**: the investigation of the proof of principle and the assessment of the ultimate performances of this scheme can be performed on a **five to ten years time scale provided** an adequate **support in terms of manpower and fundings** for research.

- The work can be organized as:
  - **WG1: accelerator design**
  - **WG2: target design**
  - **WG3: experimental tests**

We propose to formalize our informal contacts with international labs (i.e. **CERN ESRF, LAL, SLAC, …**) to official **collaborations**, as **MoU**. The opportunity to profit from past and top level experience in some of the key topics of this project is clear, to progress in the accelerator key topics understanding.

Richieste

- **Personale extra richiesto:**
  - 2 post-doc ottica
  - 1 post-doc sorgente di positroni
  - 1 post-doc ingegnere targhetta
  - 1 post-doc misure termiche targhetta
  - 1 post-doc test dafne

- **Stima richieste finanziarie:**
  - test H4: 40 kE (da esperienza test 2017)
  - test FACETII + realizzazione
  - targhetta: 100kE (stima indicativa da meeting con gruppo EN-STI CERN)
  - test DAFNE: 200 kE (stima indicativa comprensiva di camera da vuoto, supporto per targhetta, diagnostica)

WG1: accelerator design

WG1 has to design the whole accelerator complex and to determine the ultimate parameters set to reach the required brilliance for the muon beams.

It can be sub-divided in the following main topics:

a) **45 GeV e^+ ring**, 1.5 FTE shared between ~ 3 people
b) **muon accumulator rings**, 1.5 FTE shared between ~ 3 people
c) **e^+ source and injection**, 1 FTE shared between ~ 3 people
d) **parameters optimization** (as a function of luminosity), ~1 FTE 3 people

WG2: target design

WG2 includes the issues concerning the muon and positron target, and required efficiency. Engineering study is needed to simulate thermo-mechanical stress and heat load, together with mechanical design of its support.

It can be sub-divided in the following two main topics:

a) **muon source target**, 1 FTE shared between ~ 2 people
b) **e^+ source target**, 0.5 FTE

WG3: experimental tests

WG3 is dedicated to experimental tests, it is strictly connected with WG1 and WG2.

Proper diagnostic for experimental tests must also be studied.

It can be sub-divided in the following two main topics:

a) **CERN tests with 45 GeV e^+**, 4 FTE shared between about 15 people

b) **DAFNE test of ring-plus-target scheme,** 5 FTE shared between 15 people

Timeline

- **Short-term goal:** progress report after 1.5y (beginning 2019) for the ES update report (see next slide).

- The design study progresses will follow after the ES update.
  - the test a FACET-II will be performed in 2019/2020
  - the test for DAFNE can be performed in 2020/2021

advances in all WGs are foreseen.

A conceptual design study: the investigation of the proof of principle and the assessment of the ultimate performances of this scheme can be performed on a five to ten year time scale provided an adequate support in terms of manpower and fundings for research.

Short-term plan (for the ES update)

WG1:

a) Improvement on current 45 GeV ring design in terms of energy acceptance and target region optics.
b) First design of muon accumulator rings.
c) First design of positron source scheme including the investigation of the embedded positron source.

WG2:

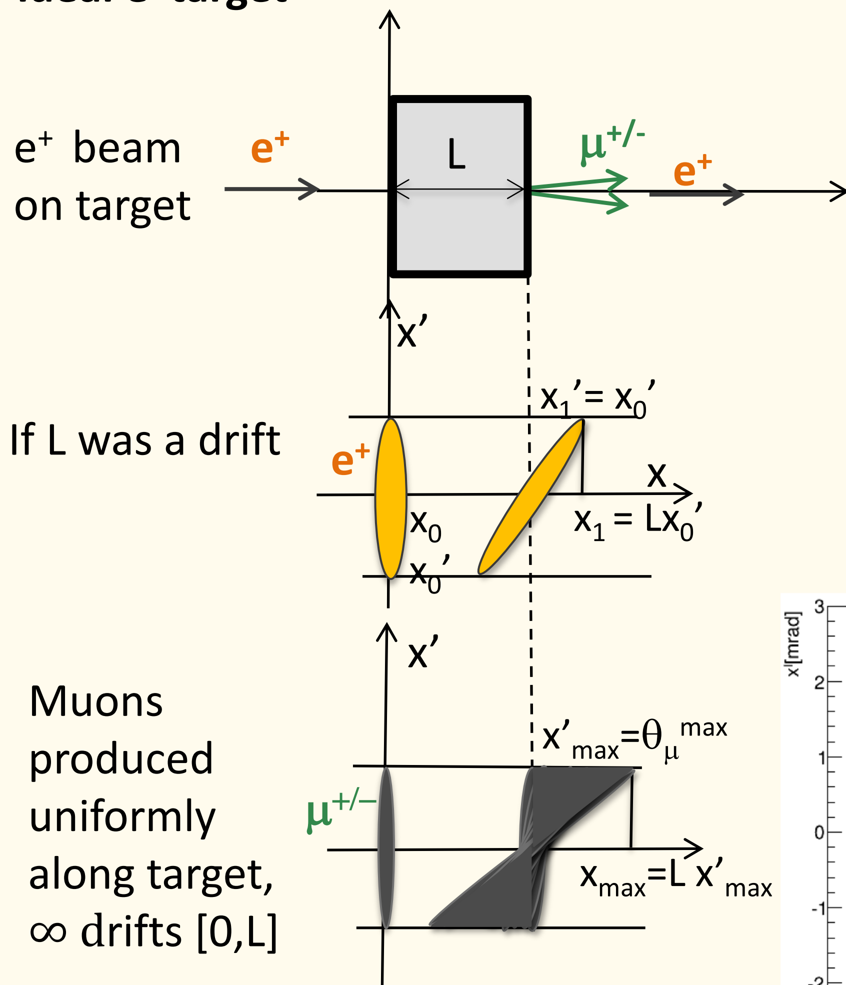
a) Preliminary target design
b) Definition of parameters necessary for the target experimental tests
c) First study of targets for positron production.

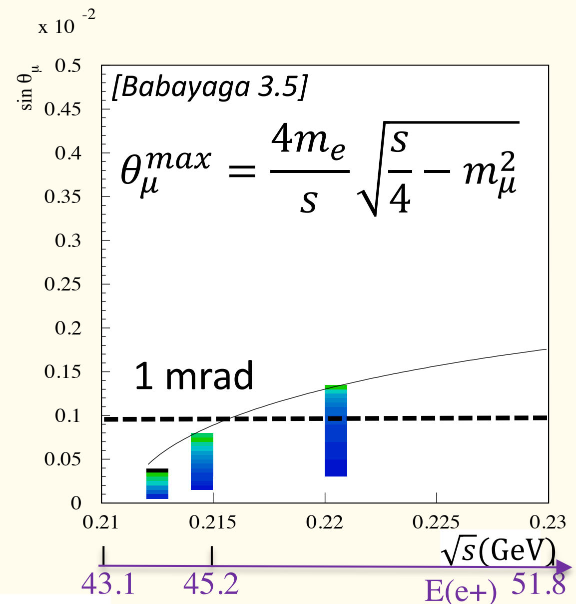
WG3:

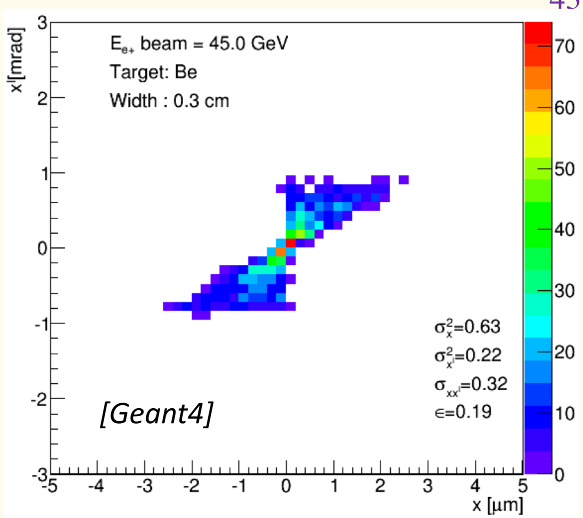
a) The characteristics of the muons produced by positron on target are planned to be measured if the request for data taking period is approved.
b) The experimental test on target thermo-mechanical stress has to be ready or performed depending on the FACETII availability.

Production contribution to μ beam emittance

ideal e^- target







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

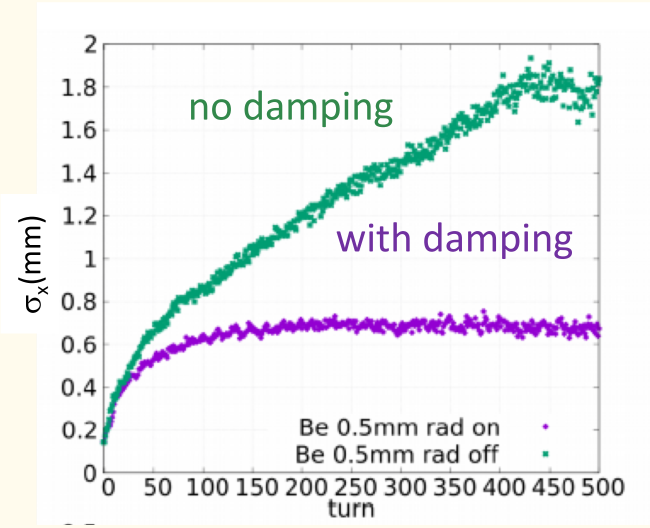
Multi-turn simulations

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)

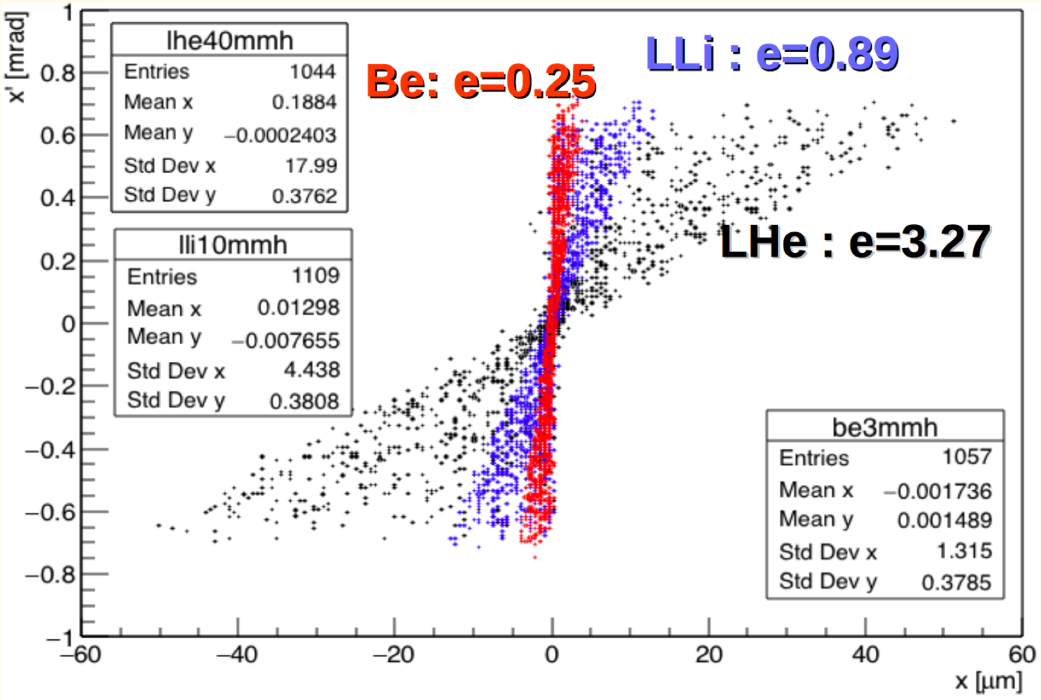


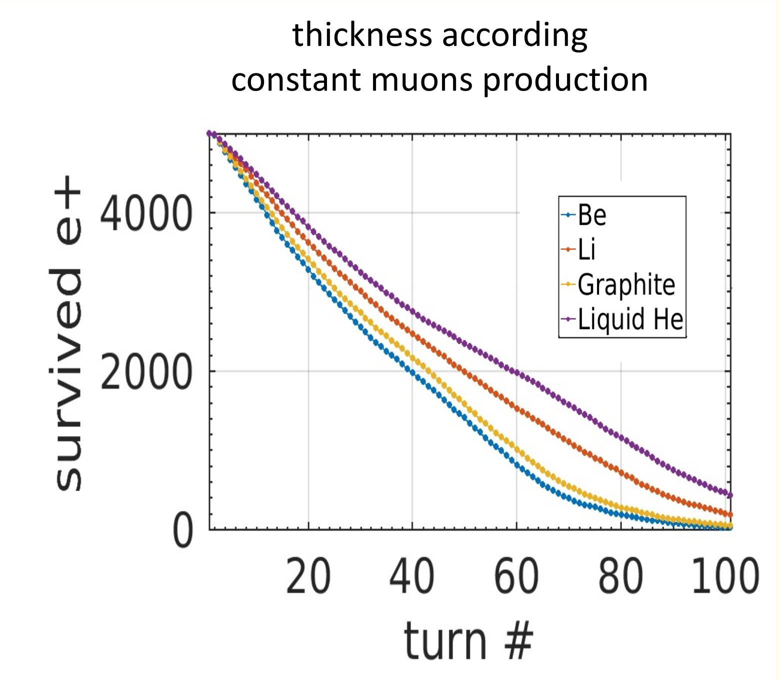
Going to lighter targets for μ production

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

Criteria for target design

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

optimal target: minimizes μ emittance with highest μ rate

- **Heavy materials, thin target**
  - to minimize ε_μ : thin target ($\varepsilon_\mu \propto L$) 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) $\rightarrow$ H_2

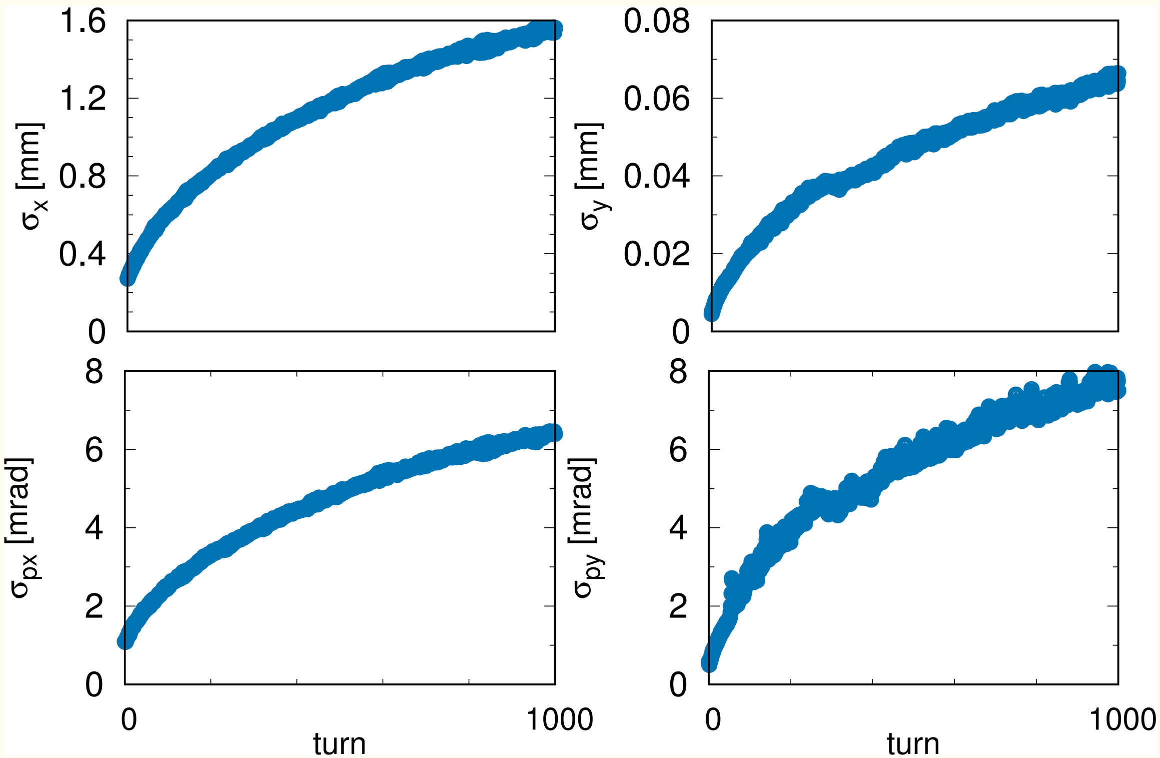
  Even for liquid targets O(1m) needed $\rightarrow$ $\varepsilon_\mu \propto L$ increase

- **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

Evolution of e+ beam size and divergence

Beam evolution in the ring with 50μm Be target at IP

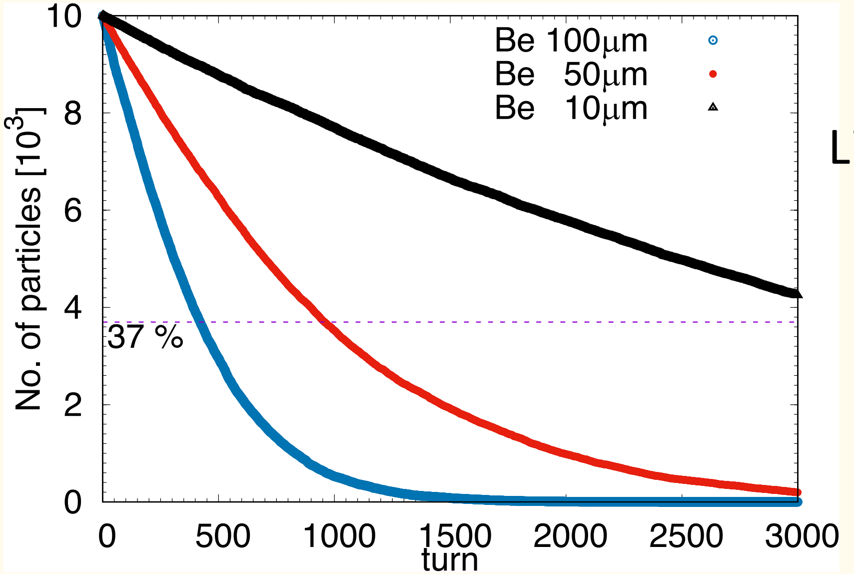


first turn, before target

σ_x^* = 0.27 mm

σ_y^*=4.4μm

e+ lifetime with Be target



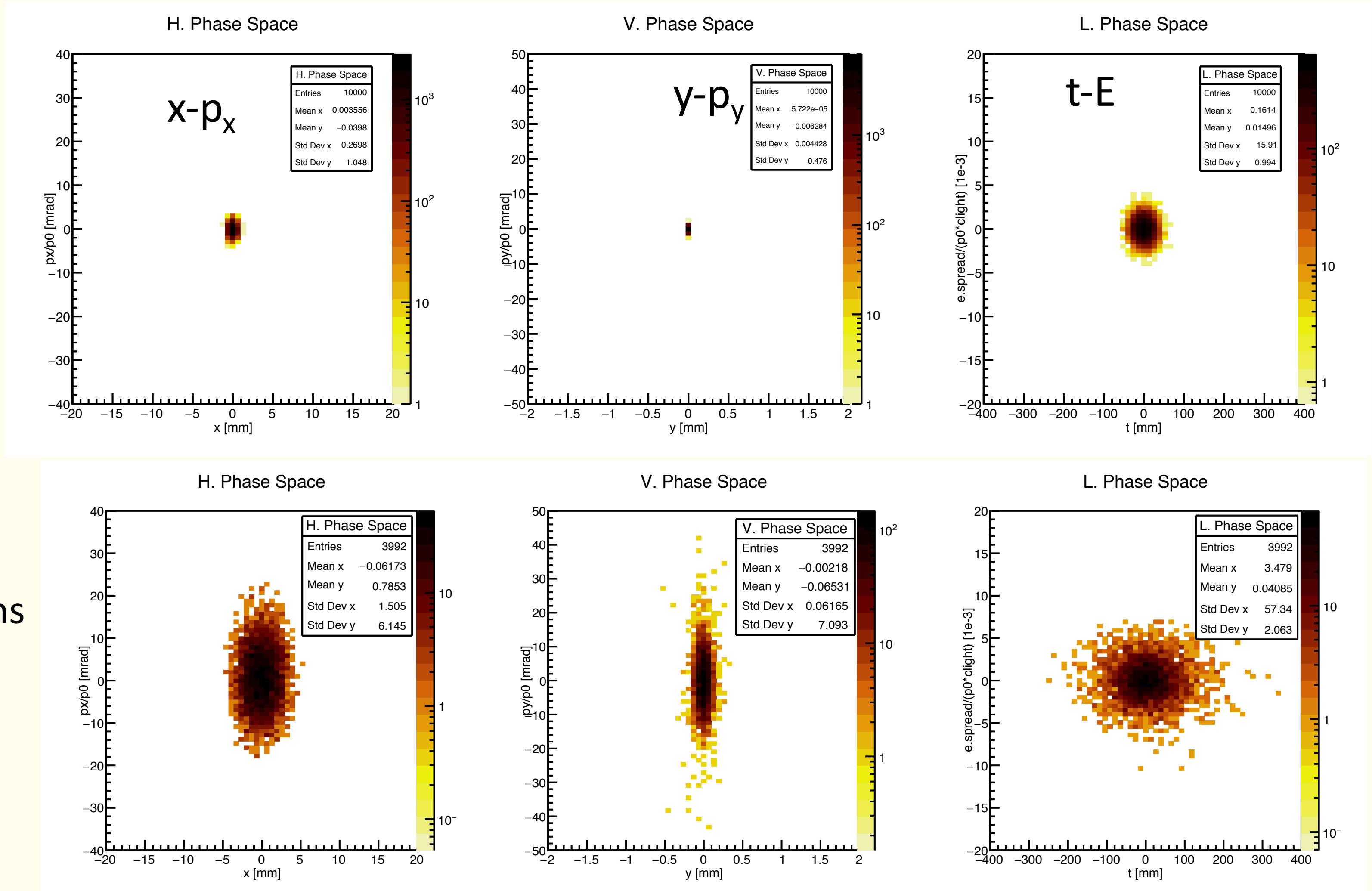
Lifetime with ~ 3500 turns for 10μm Be target
as short as 1.6 ms

- Beam will not be stored
- Injection in single bunch mode
- turn-by-turn beam size and charge measurement

DAFNE e^+ ring with 50μm Be target: beam evolution in the 6D phase space

before target, starting point

after 900 turns



MAD-X PTC & GEANT4 6-D tracking simulation