The Muon Collider

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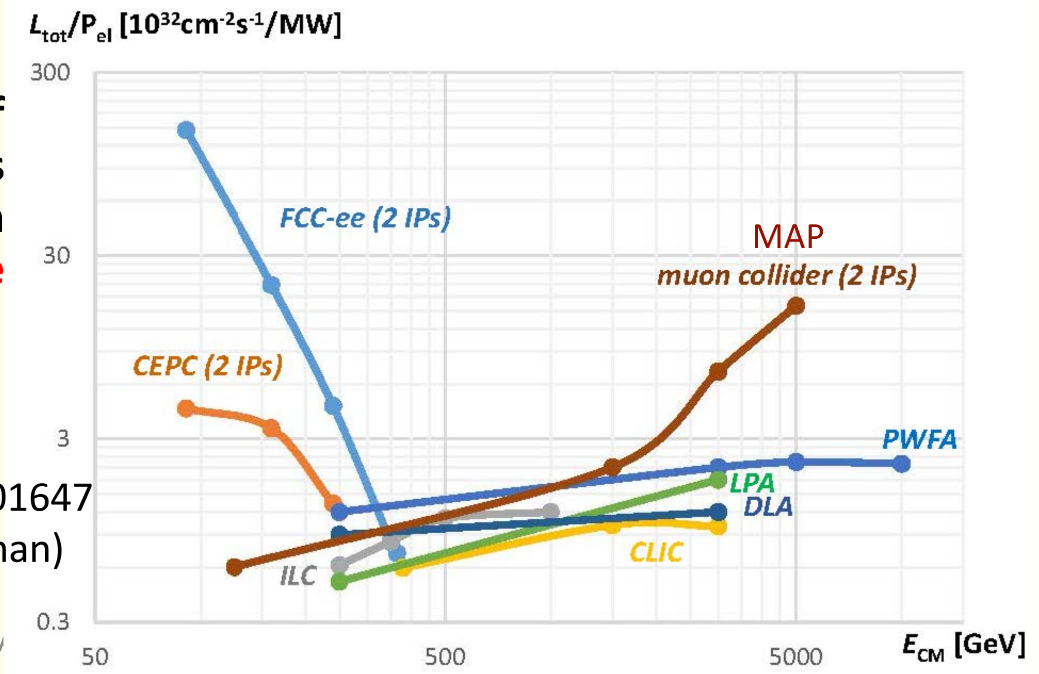
Outline

- **Introduction**
- **Muon production**
  - proton driven source: **MAP**
  - positron driven source: **LEMMA**
- **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**

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 Source

Tertiary production from **protons on target:** p + target→ π/K → μ
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 → **cooling needed**
production Rate > 10^{13} μ/sec $N_\mu = 2 \cdot 10^{12}$/bunch → **MAP**

from **direct μ pair production**:
muons produced from **$e^+e^- \to \mu^+\mu^-$** at √s around the $\mu^+\mu^-$ threshold
(√s ≈ 0.212GeV) in asymmetric collisions (to collect μ^+ and μ^-)
e^+e^- annihilation: **e+ beam on target**
→ **cooled muon** beam with **low emittance** at production
Goal: production Rate ≈ 10^{11} μ/sec $N_\mu \approx 6 \cdot 10^9$/bunch → **LEMMA**

by Gammas (γ Nuclei→$\mu^+\mu^-$ Nuclei)**: GeV-scale Compton γs** [V. Yakimenko (SLAC)]
also: (**e^-Nuclei→$\mu^+\mu^-$ e^- Nuclei**) W. Barletta and A. M. Sessler NIM A 350 (1994) 36-44

LEMMA:

Low **EM**ittance **M**uon **A**ccelerator

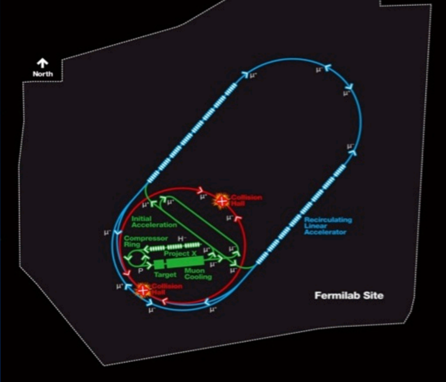
Multi-TeV Muon Collider based on a novel muon production concept

- Muons are produced in positron annihilation on e^- at rest
  $\rightarrow e^+$ 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 was proposed at Snowmass 2013 by M. Antonelli and P. Raimondi:
M. Antonelli, "*Ideas for muon production from positron beam interaction on a plasma target*", INFN-13-22/LNF Note, M. Antonelli and P. Raimondi, Snowmass Report (2013)

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}]

Challenges for a $\mu^+\mu^-$ Collider

- Pions from a MW-scale proton beam striking a target
- Efficient capture of the produced pions
  - Capture of both forward and backward produced pions loses polarization
- Phase space of the created pions is ***very large!***
  - Transverse: 20π mm-rad
  - Longitudinal: 2π m-rad
- Emittances must be cooled by factors of ~10^6-10^7 to be suitable for multi-TeV collider operation

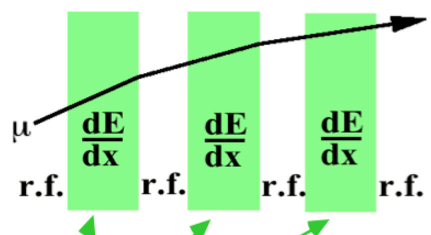
  ~1000x in the transverse dimensions
  ~40x in the longitudinal dimension
- The muon lifetime is 2.2 μs lifetime at rest

Cooling Methods

- The unique challenge of muon cooling is its short lifetime
  - Cooling must take place very quickly
  - More quickly than any of the cooling methods presently in use
  - ⇨ Utilize energy loss in materials with RF re-acceleration

Muon Ionization Cooling

- Muons cool via dE/dx in low-Z medium

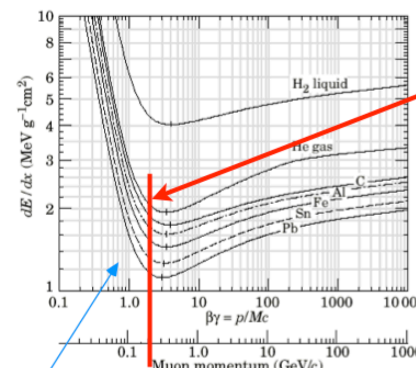


– Absorbers:

$$\begin{cases} E \to E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering



- ionization minimum is ≈ optimal working point:
  - longitudinal +ive feedback at lower p
  - straggling & expense of reacceleration at higher p

- 2 competing effects ⇒ ∃ equilibrium emittance

– RF cavities between absorbers replace ΔE

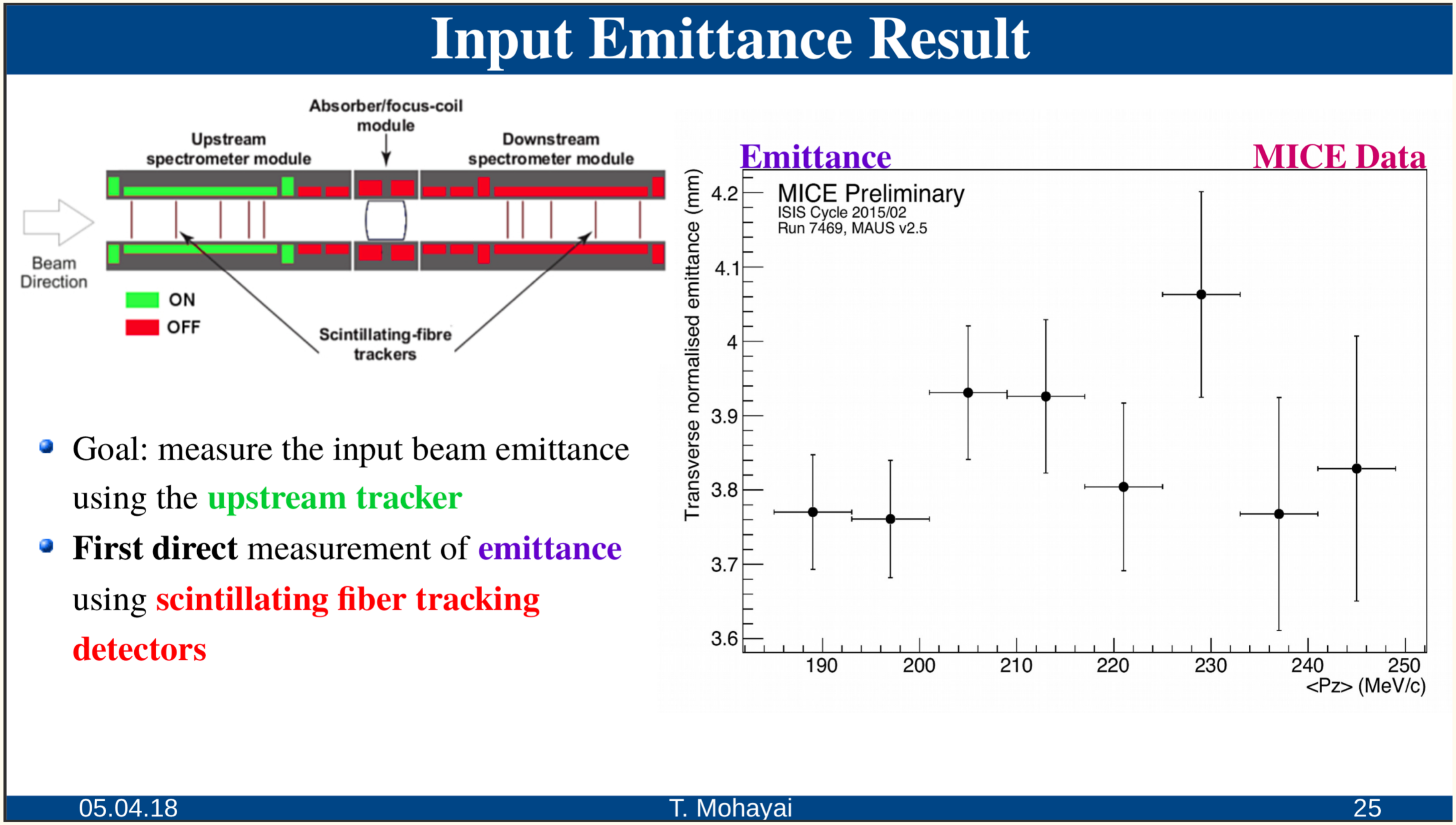
– Net effect: reduction in $p_\perp$ at constant $p_{||}$, i.e., transverse cooling

$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\text{ GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$ (emittance change per unit length)

Kaplan

BROOKHAVEN NATIONAL LABORATORY

First Demonstration of Ionization Cooling in MICE

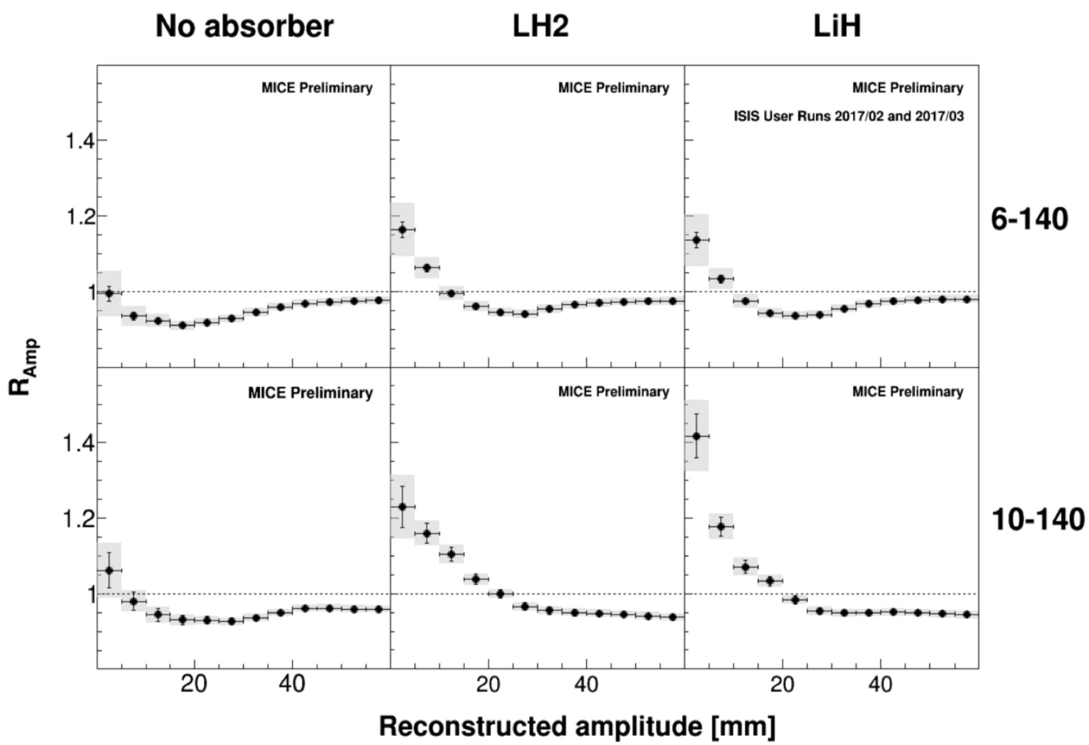


- **Reconstruction of emittance “particle-by-particle” in upstream tracker**
  - **200 MeV/c muon beam; 4T in upstream solenoid only, first ~2 hours of data taking**
- **Validates MICE measurement approach**
- **Data in hand with lithium hydride (LiH), liquid hydrogen (LH_2) and “wedge” absorbers**

First Demonstration of Ionization Cooling in MICE

Single-particle Amplitude Result

MICE Data

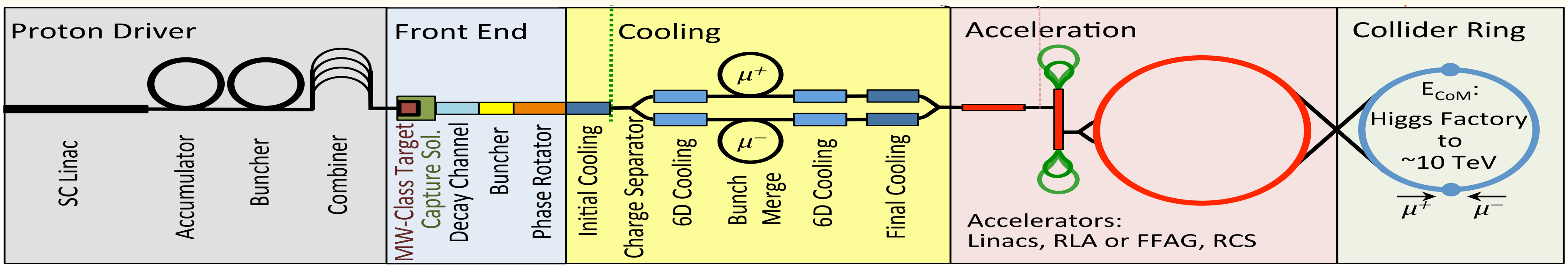


- **6-140** – $P_{reference}$ of 140 MeV/*c* and ε_{input} of 6 mm
- **10-140** – $P_{reference}$ of 140 MeV/*c* and ε_{input} of 6 mm
- R_{Amp}: ratio of downstream muon count to upstream
- **$R_{Amp} > 1 \rightarrow$ cooling:**
  - ★ Migration of high amplitude muons to low amplitude
- "No absorber" does not show cooling, agrees with Liouville's theorem

05.04.18 T. Mohayai 29

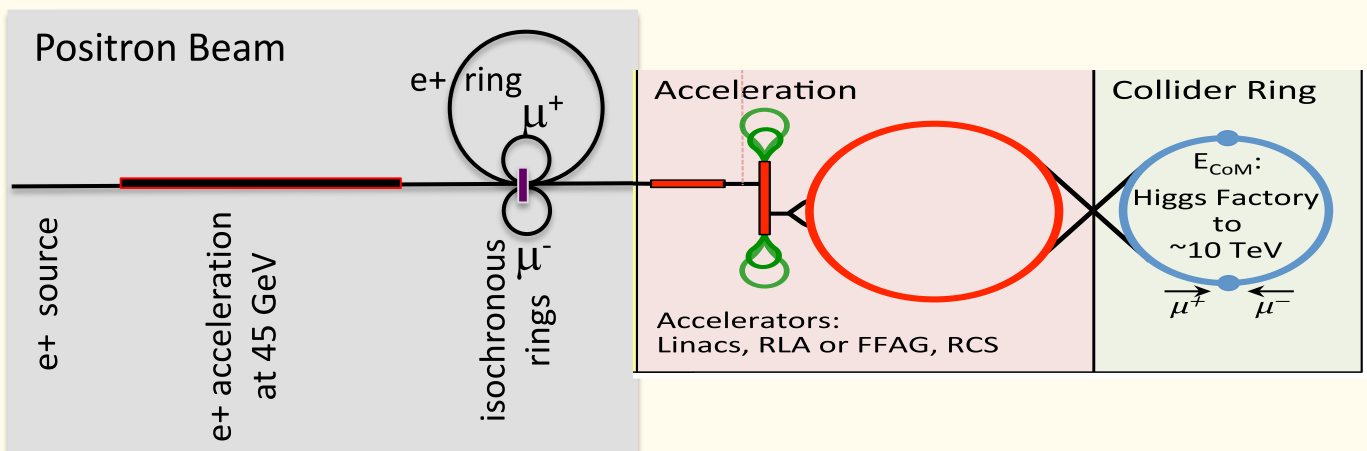
The measurements of the ratio of the uptream and downstream cumulative amplitude distributions demonstrate cooling (migration of large transverse amplitude muons to lower amplitudes after crossing the absorber).

MAP & LEMMA μ-collider Schematic Layout



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 Challenges

~10^{11} μ / sec from e+e-→$\mu+\mu-$

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

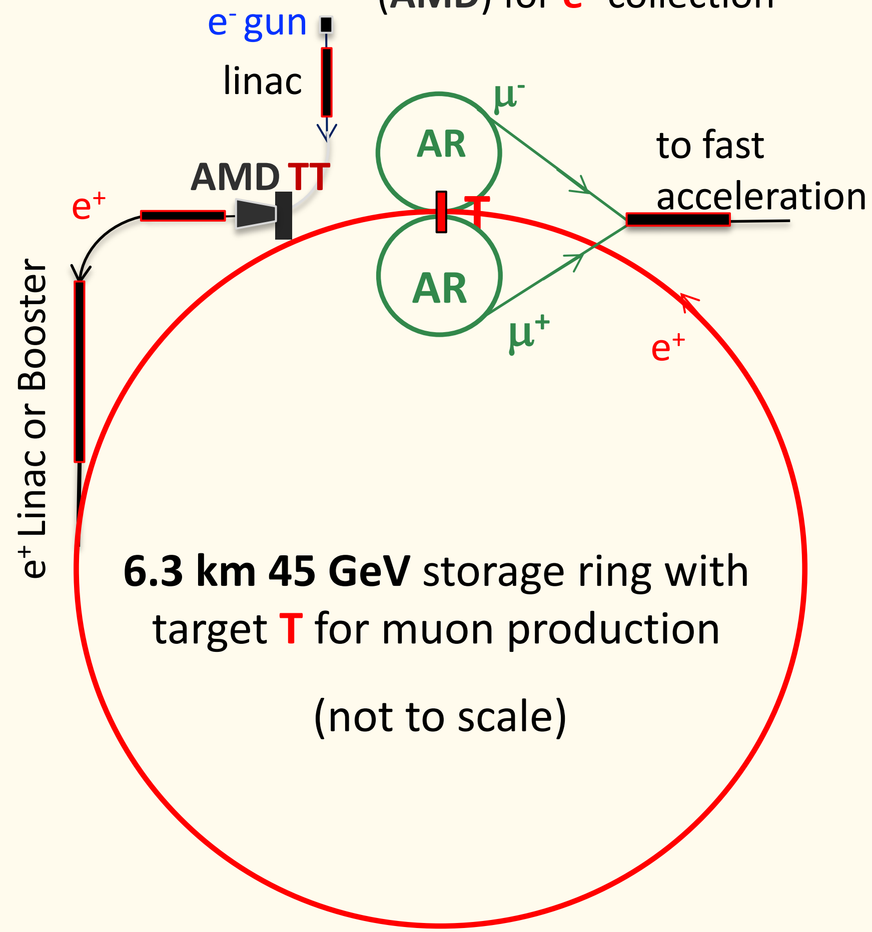
Goal: mom. aperture +/-12%

lifetime(e+) ≈ 250 turns

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

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

e^- on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.
Adiabatic Matching Device (**AMD**) for **e^+** collection



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

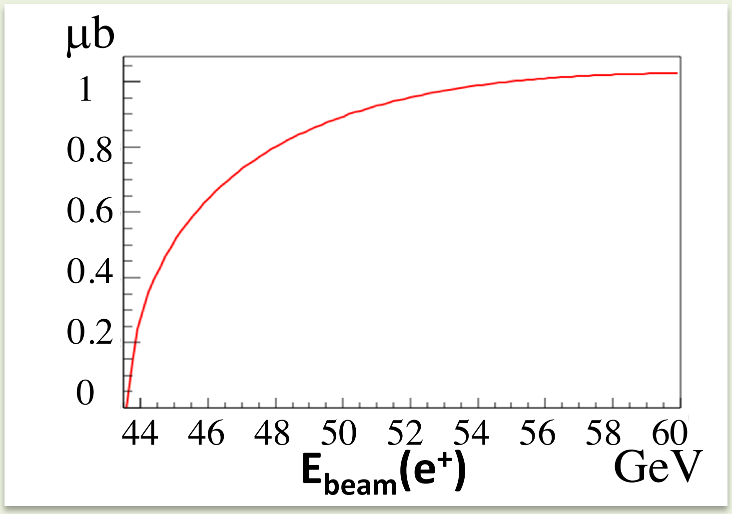
$\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx$ **1 μb** at most wrt σ(from p)$\approx$ **mb**

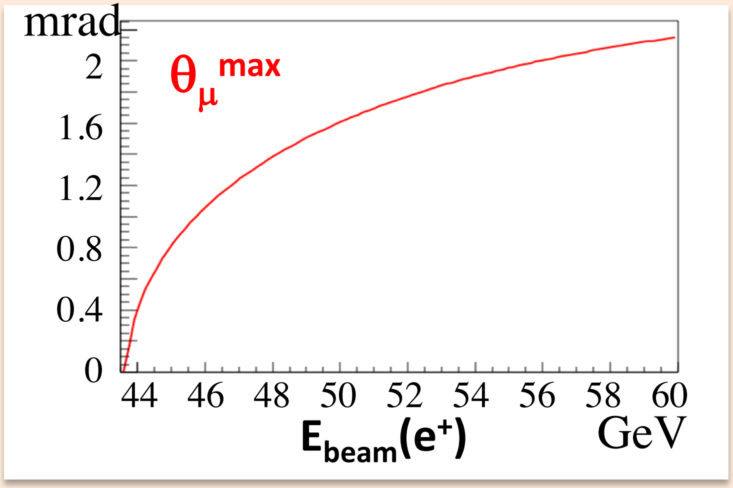
Pro LEMMA:

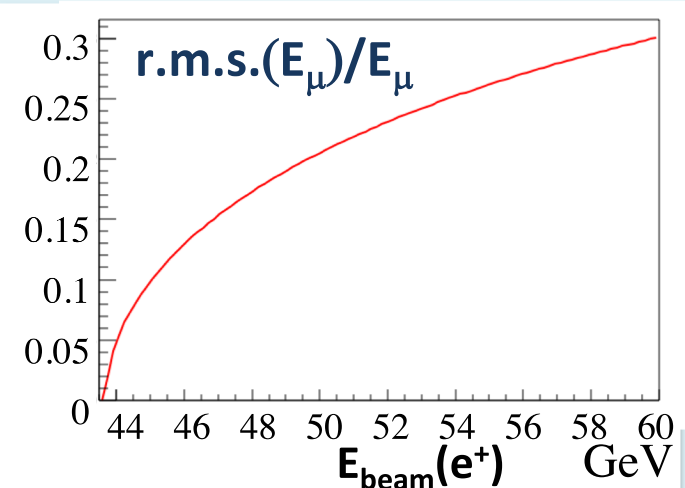
- **Reduced losses from decay:** **high collection efficiency**
- **Low background:** **Luminosity at low emittance will allow low background and low neutrino radiation → easier experimental conditions & can go to higher energies**
- **Energy spread:** muon energy spread might be **also small at threshold**,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

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

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







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

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

3×10^{13} μ/s

e^+ on target option

9×10^{10} μ/s

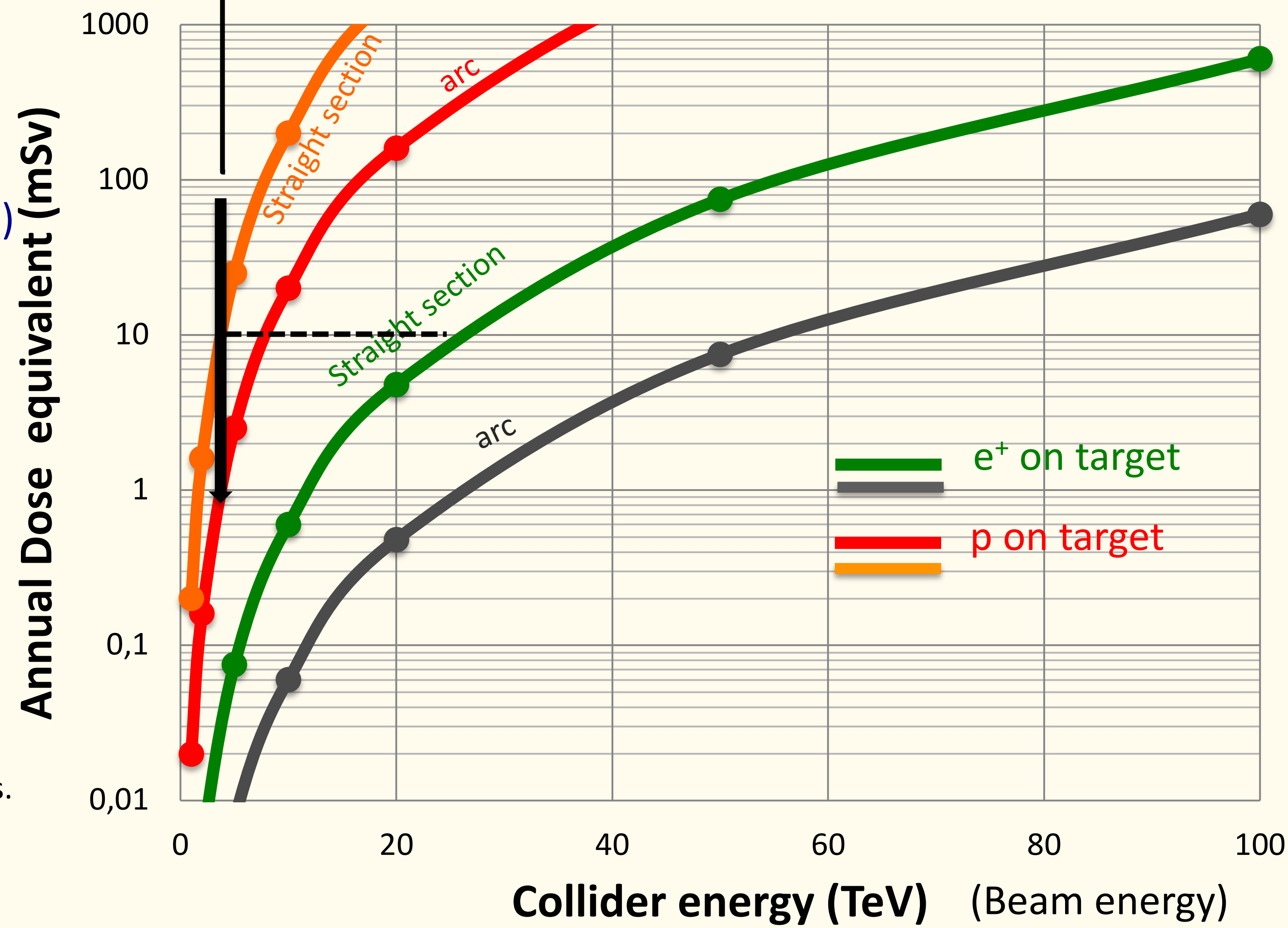
neutrino dose equivalent/fluence

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

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)



Muon collider at 6 TeV com energy

Values considered for this table:

- **$\mu^+\mu^-$ rate = 0.9 10^{11} Hz**
- **ε_N = 40 nm (as ultimate goal)**
- **3 mm Beryllium target**

Comparison with MAP:

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

Same L thanks to lower β^* (nanobeam scheme)

Considering all contributions to muon emittance, this number is larger, so we are revisiting this parameter table together with considering a different target

no lattice for the muon collider yet

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

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

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

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*" 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 Based on the Hybrid Multi Bend Achromat

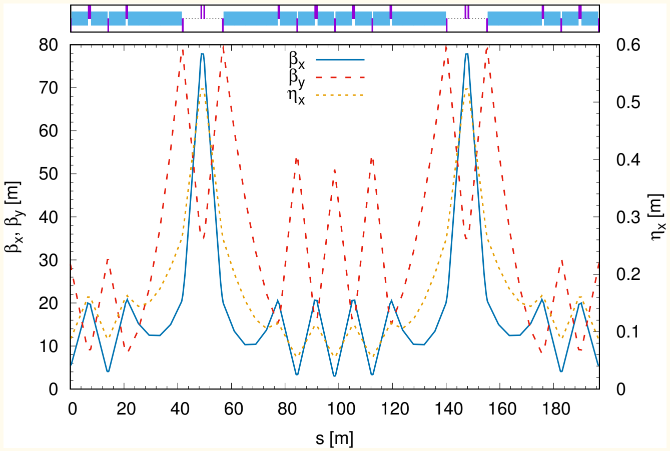
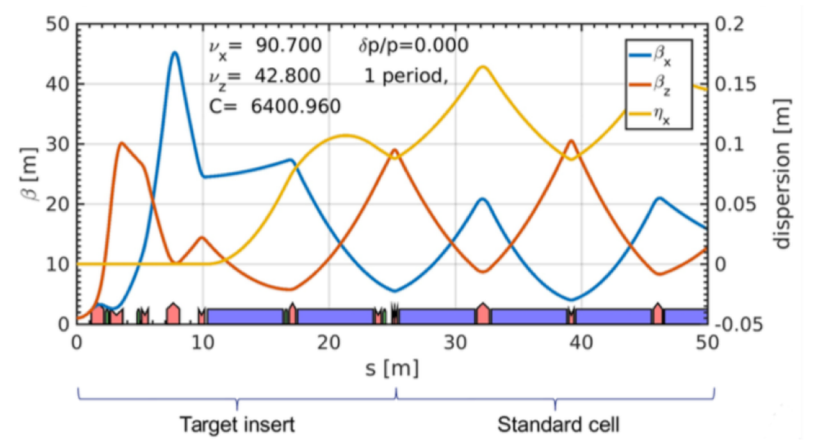


Table e+ ring parameters

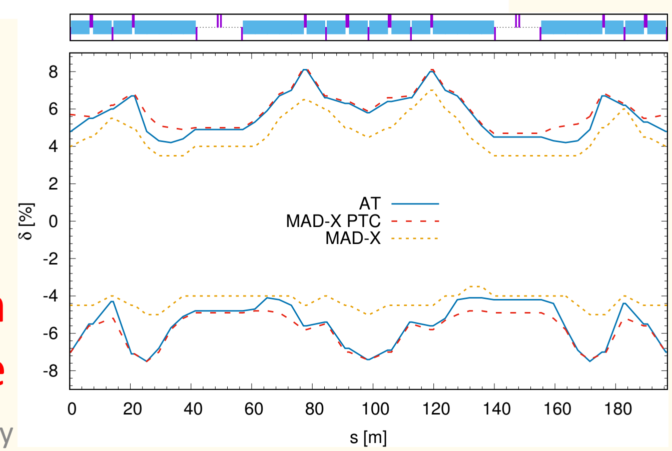
Parameter	Units	
Energy	GeV	45
Circumference	m	6300
Coupling(full current)	%	1
Emittance x	m	5.73×10^{-9}
Emittance y	m	5.73×10^{-11}
Bunch length	mm	3
Beam current	mA	240
RF frequency	MHz	500
RF voltage	GV	1.15
Harmonic number	#	10508
Number of bunches	#	100
N. particles/bunch	#	3.15×10^{11}
Synchrotron 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



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

momentum acceptance



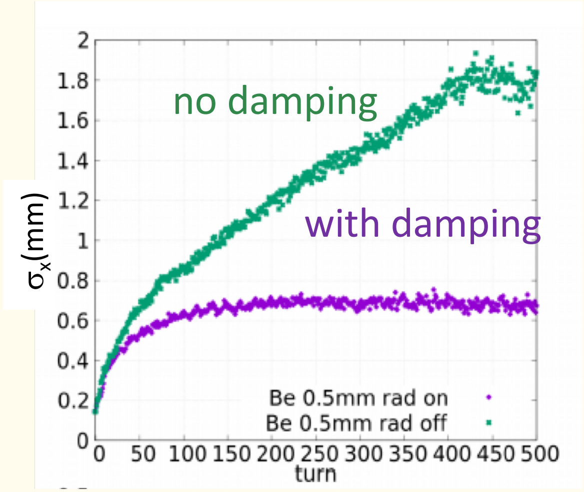
Multi-turn simulations

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)

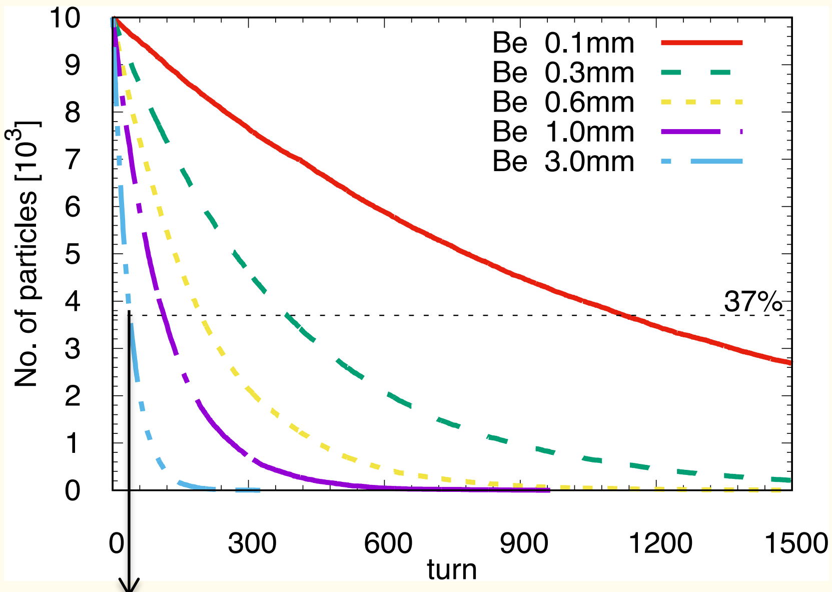


Beam dynamics e^+ beam in ring-with-target

More details in:
Arxiv. 1803.06696

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

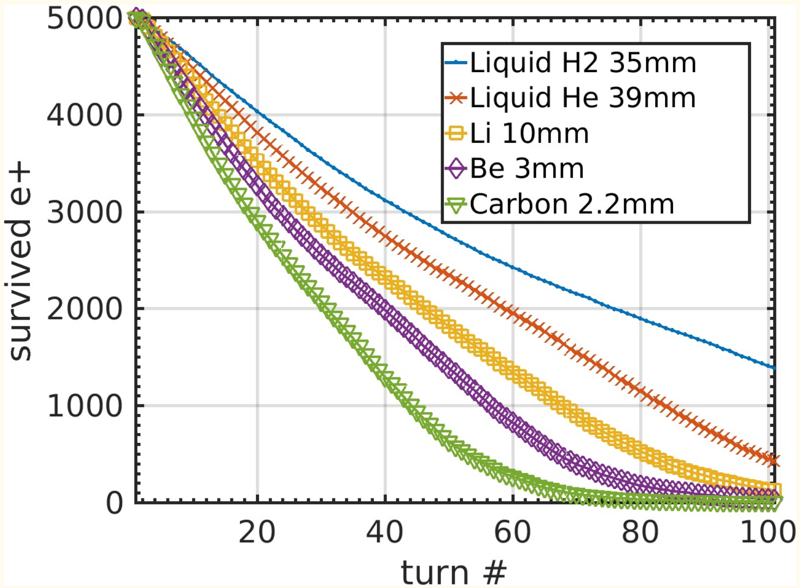
Lifetime ∝ 1/thickness as expected



Lifetime ~ 40 turns for Be 3 mm

Lifetime determined by bremsstrahlung and momentum acceptance

2-3% e+ losses in the first turn



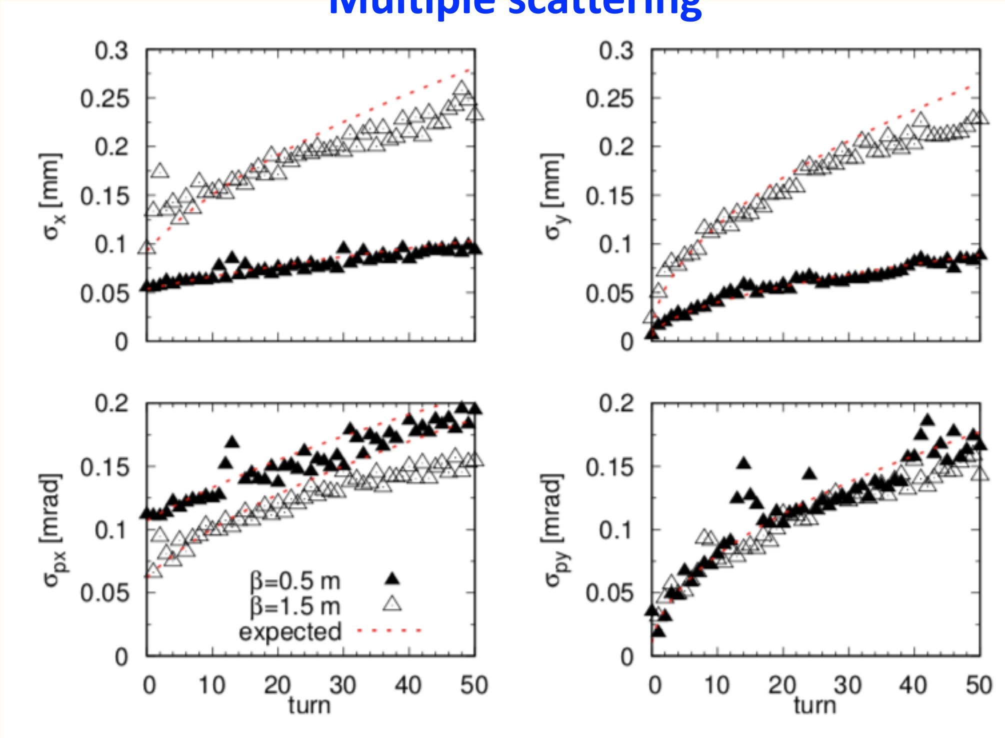
Number of e+ vs turns for different target materials.
Target thickness gives constant muon yield.

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

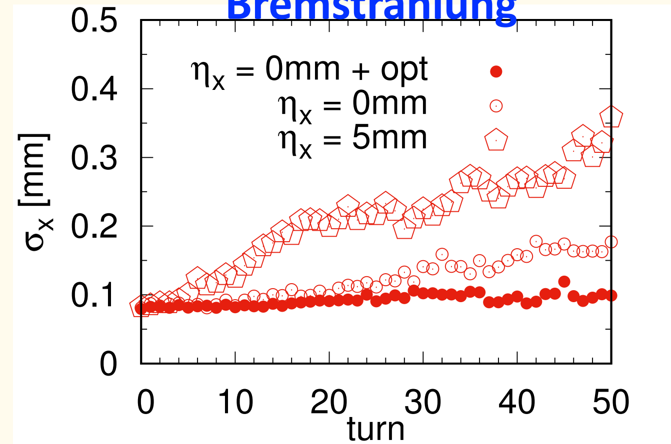
More details in:
Arxiv. 1803.06696

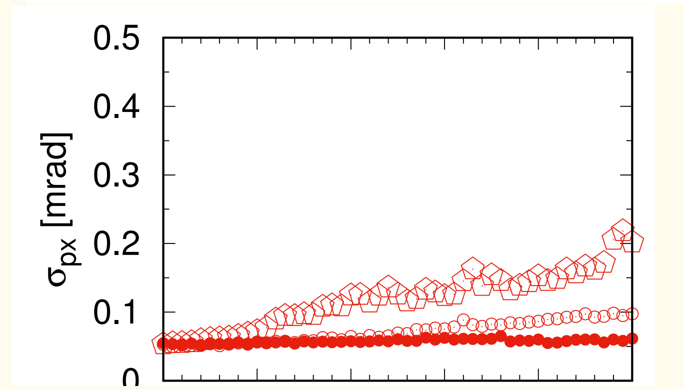
e^+ emittance growth controlled with proper β and D values @ target

Multiple scattering



Bremstrahlung





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

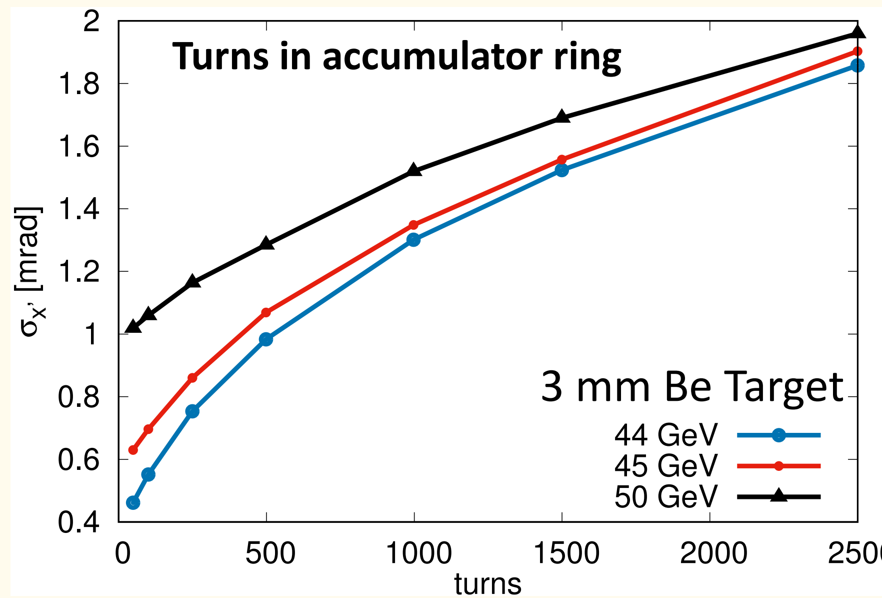
n number of turns

@Target :
linear and non-linear terms
of horizontal dispersion $\eta_x = 0$

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

More details in MOPMF087, IPAC18

Muon emittance contributions

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

Multiple scattering contribution in the target

In agreement with analytical estimate (D. Schulte)

$$\sigma_x \approx \frac{L}{\sqrt{12}}\sigma_\theta$$

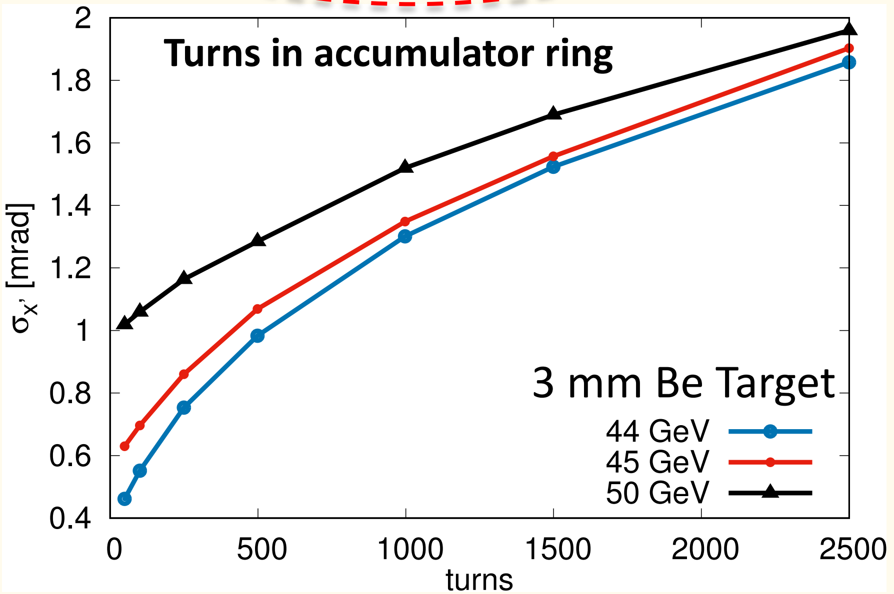
L is the target length

$$\Delta\epsilon = \sigma_\theta^2 \frac{L}{\sqrt{12}} \times \frac{E}{m_\mu c^2}$$

Norm. emittance growth for a single passage

45 GeV e+ beam, 3 mm Be, after 2500 turns:

$\sigma_{x'} = 1.85$ mrad -> norm. emittance 0.6 μm



muon production angle

muon production angle + MS contribution

Multiple scattering contribution can be strongly reduced with crystals in channeling

Muon production target

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

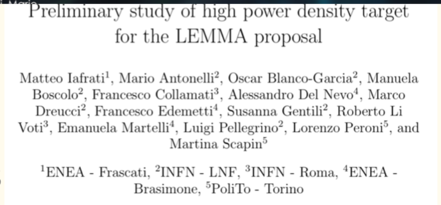
LNF has been coordinating the preliminary investigations and organizazion of the study with identification of topics, expertize and contacts for collaboration

NEWS

- collaboration with PoliTo expertize on material termo-mechanical characterization, simulations and experimental validation (L. Peroni, M. Scapin, involved in ARIES)
- Collaboration with Brasimone Expertize on Liquid Lithium (A. Del Nevo, M. Iafrati)
- Expertize on thermo-mechanical measurements (Sapienza, SBAI, R. Li Voti)
- Dedicated position ADR (INFN Rm1)

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


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

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

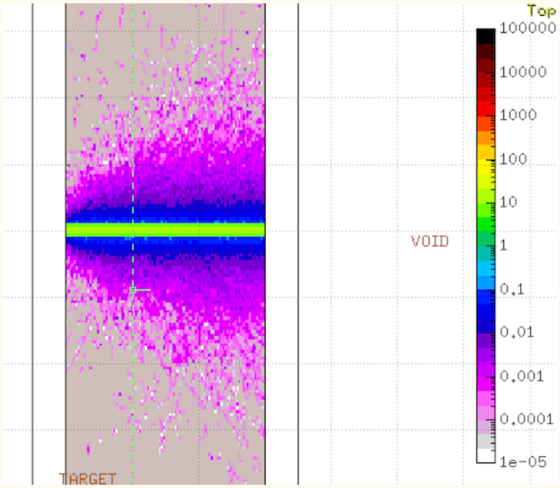
- **Solid target**: simpler and better wrt temperature rise
  - Be, C

  Be target: @HIRadMat safe operation with extracted beam from SPS, beam size 300 μm, N=1.7x10^{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

[F. Zimmermann] 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**

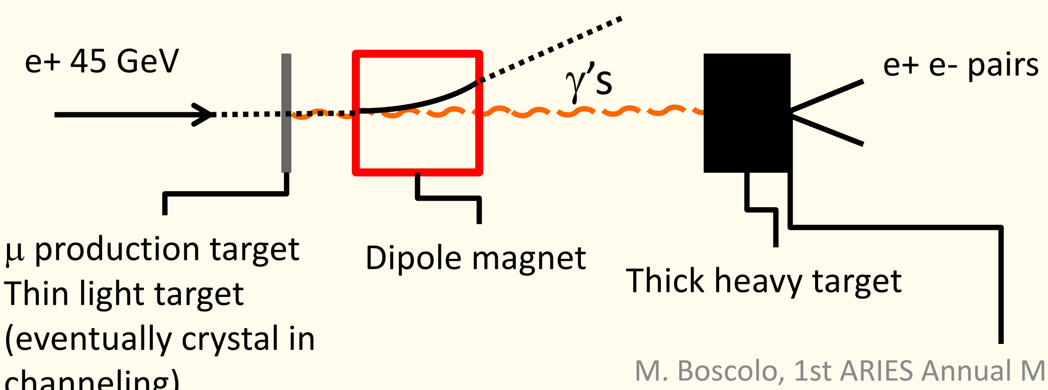
This requirement is strictly connected to the e+ lifetime and mom. acceptance

Present: 3 mm Be, 40 turns lifetime, DN/N=2.5%, DN=2.5E+16, P= 247 MW

Goal: 3 mm Be, 240 turns lifetime, DN/N=0.4%, DN=3.8E+15, P= 39 MW

Embedded e+ source idea to relax e+ source requirement

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)

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*", accepted for **IOP Conf. Series: Journal of Physics: Conf. Series** (IPAC18) also LNF-18/02(IR).

DAFNE Layout for the LEMMA Test

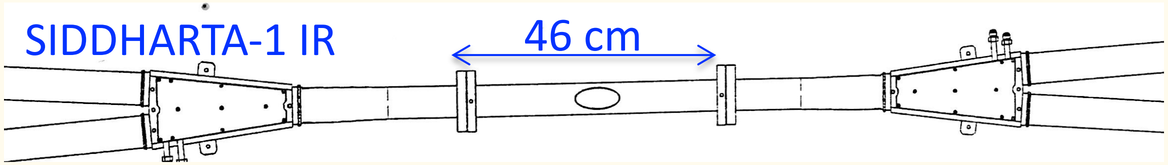
The target will be placed at the SIDDHARTA IP because:

- 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

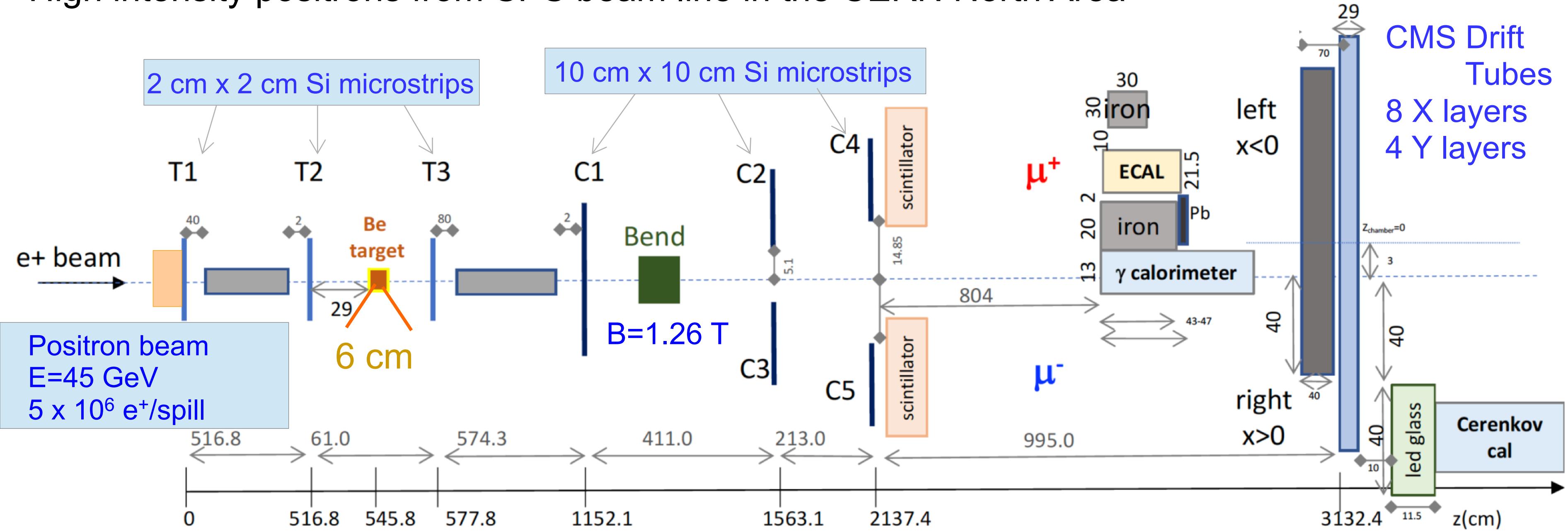
- **@H4: 1 week July 2017:**
  High intensity: up to 5 x 10^6 e+/spill with **6cm Be** target (spill ~15s)
  goal:
  measure muon production rate and muons kinematic properties
  we had 2 days at ≈ 10^6 e^+ /spill

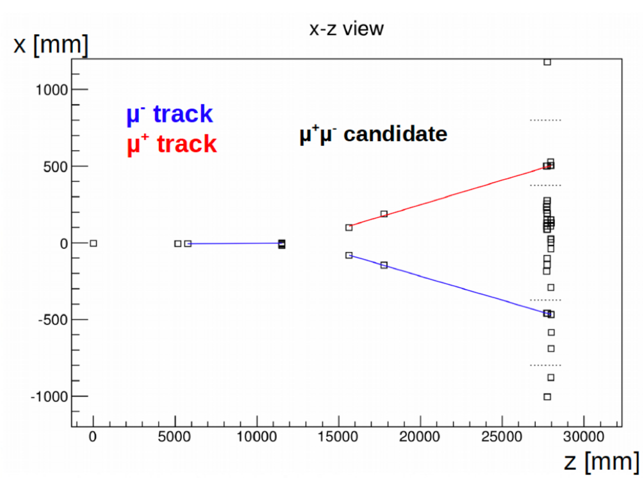
- **@H2: 15-22 August 2018 (1 week)**
  to complete original program of the 2017 experiment

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

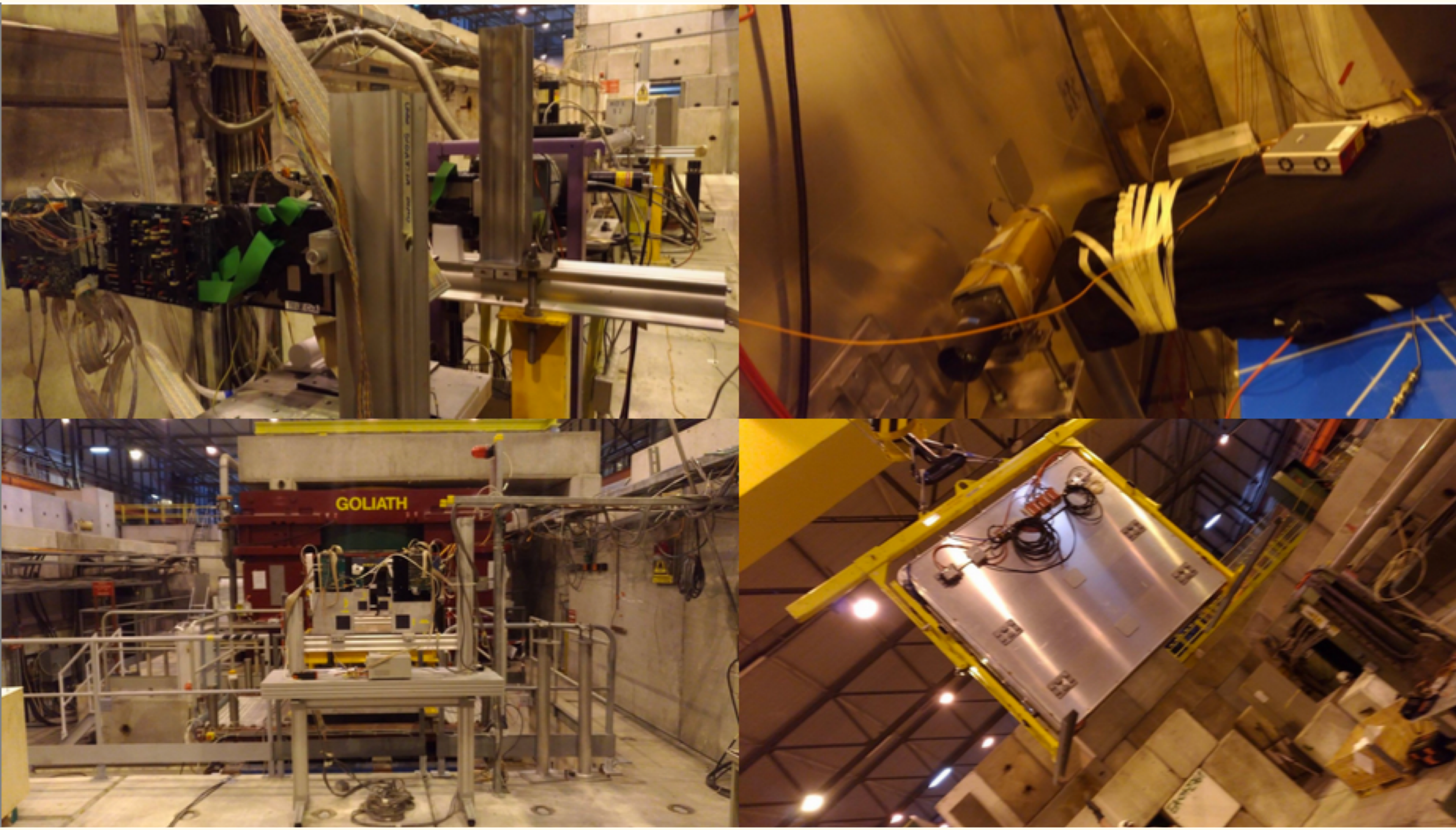




Among 620K collected events 56 $\mu^+\mu^-$ candidates
Finalization of the data analysis is on the way

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

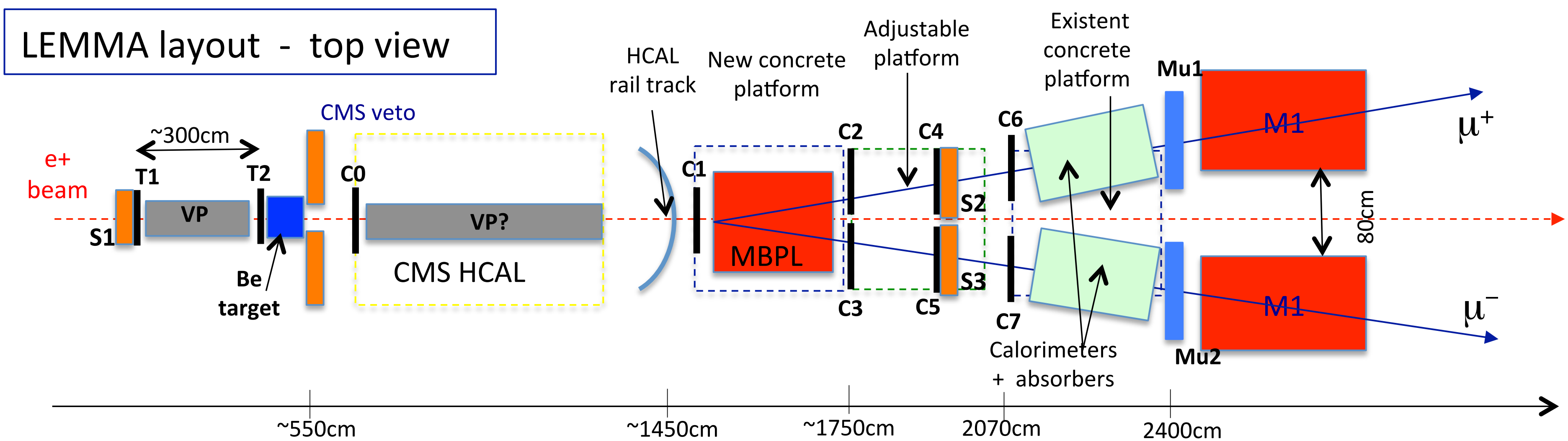
2017 Experimental set-up



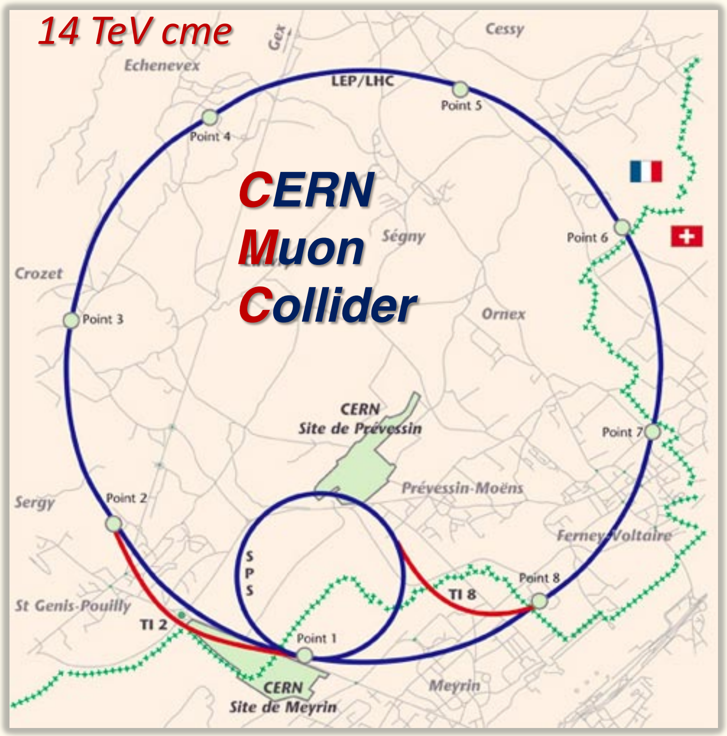
2018 Experimental layout

- 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.

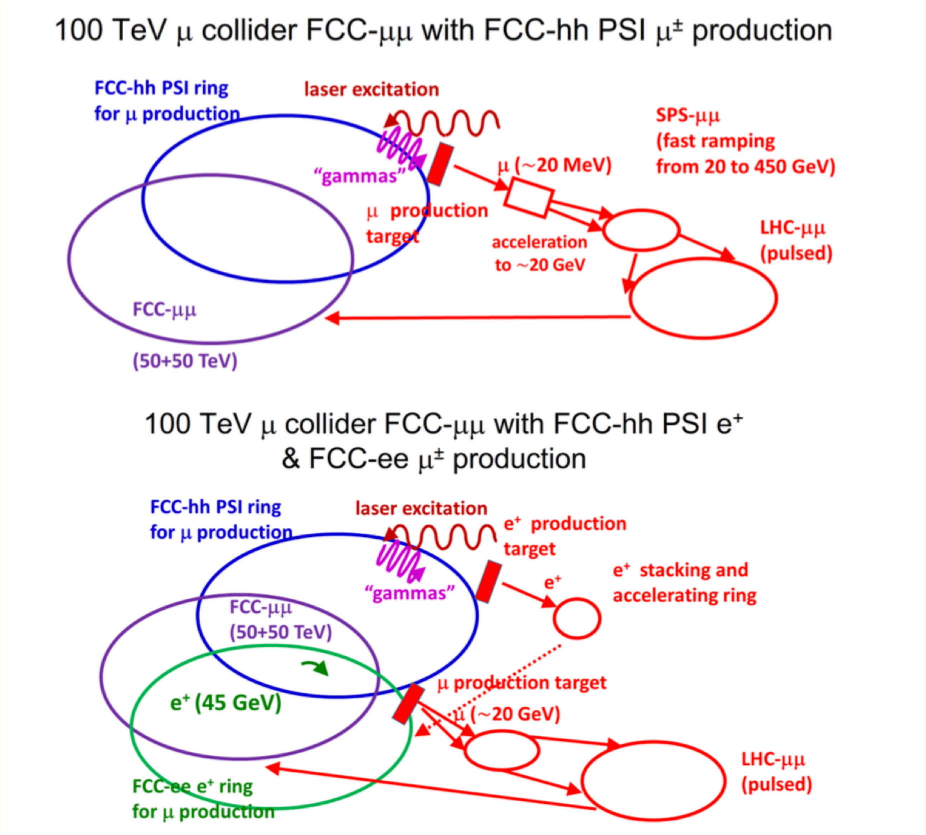
- Experimental setup modified with respect to the 2017 TB, also to account the different experimental hall (H4 -> H2)
  - additional tracking;
  - new calorimeters



Activities on high-energy muon collider



MOPMF072, IPAC18, V. Shiltzev, D. Neuffer



MOPMF065,IPAC18, F. Zimmermann

Conclusion

- LEMMA is a novel concept for muon production, , conceaved at LNF, that renewed the interest and extended the reach of Multi-TeV Muon Colliders
- Key topics for the LEMMA feasibility validation:
  - 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 Peak Energy Density Deposition
  - High positron source rate
- Preliminary studies pioneered by the INFN-LNF group are promising, progresses require to continue the design study of the accelerator complex.
- Experimental tests at DAFNE&CERN-NA for validation of some fundamental topics LEMMA are fundamental opportunities

ARIES Topical Workshop on Future Muon Colliders,

in collaboration with the WG on Muon Colliders for the ESU,

Padova, 2-3 July 2018

ARIES
Muon Collider Workshop
Padova 2-3 July 2018
https://indico.cern.ch/event/719240/

Back-up

SR Power in 45 GeV e+ ring

Circumference	**km**	**6.3**	**12.6**	**27**
SR power loss	**MW**	**123**	**61**	**29**
U_0	GeV	0.511	0.256	0.119
ρ	m	710	1419	3041
B	T	0.2	0.1	0.05
N^+/bunch	10^{11}	3.1	3.1	3.1
bunches	#	100	200	429
I_{bunch}	mA	240	240	240

[S. Guiducci]

Positron Drive Power beam

$eta_{RF} = 0.7$

3 mm Beryllium Target

Ring energy acceptance	DN/N per turn %	e+ beam lifetime (turns)	DN/sec	P/etaRF (MW)
6	2.5	39	2.40E+16	247
11	2.0	49	1.92E+16	197
20	1.4	71	1.34E+16	138
?	0.4	249	3.79E+15	39

10 mm Lithium Target

Ring energy acceptance %	DN/N per turn %	e+ beam lifetime (turns)	DN/sec	P/etaRF (MW)
5	2.2	45	2.11E+16	217
10	1.6	62	1.53E+16	157
20	1.0	99	9.53E+15	98

[S. Guiducci]

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

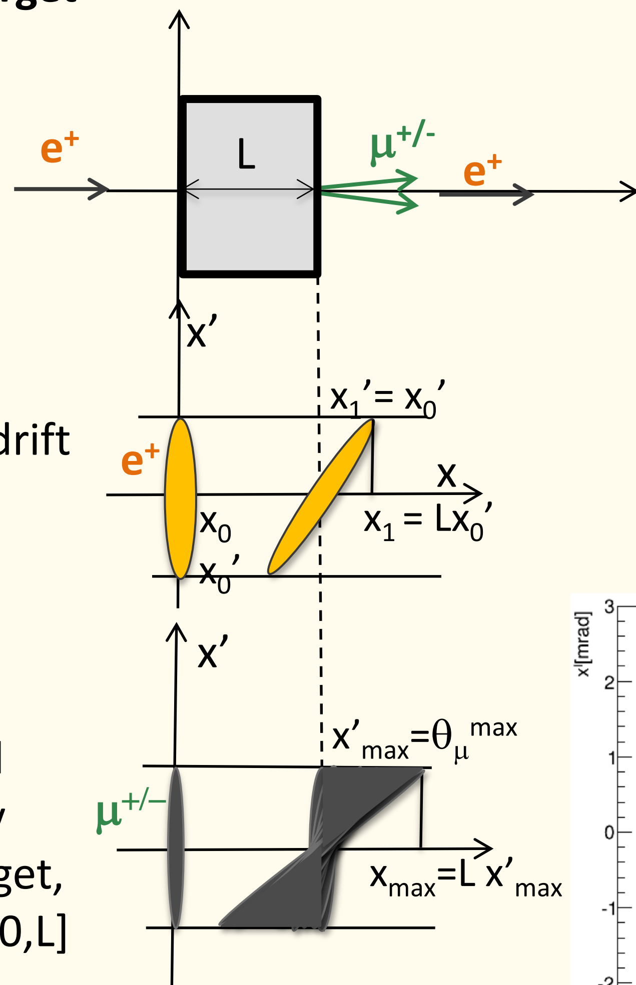
after Snowmass2013 also SLAC team investigated the idea: L. Keller, J. P. Delahaye, T. Markiewicz, U. Wienands:

- *"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

Production contribution to μ beam emittance

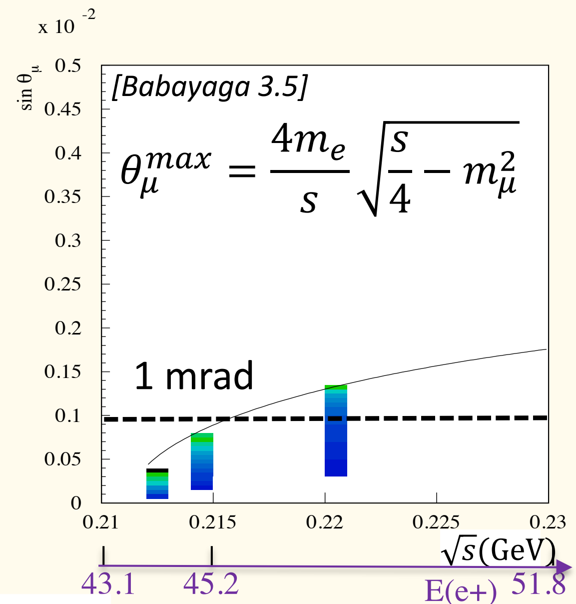
ideal e^- target

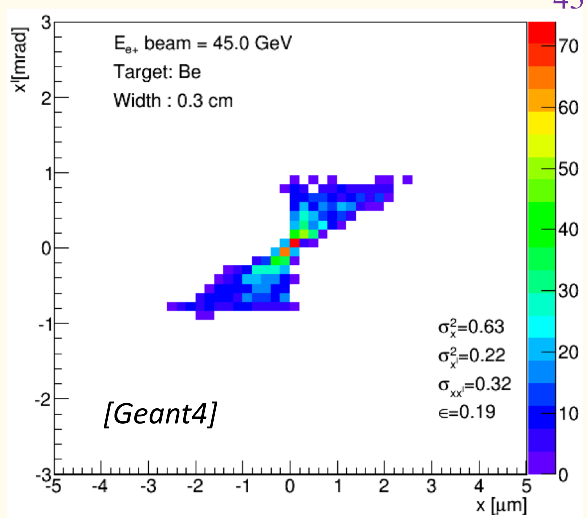
e^+ beam on target



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)

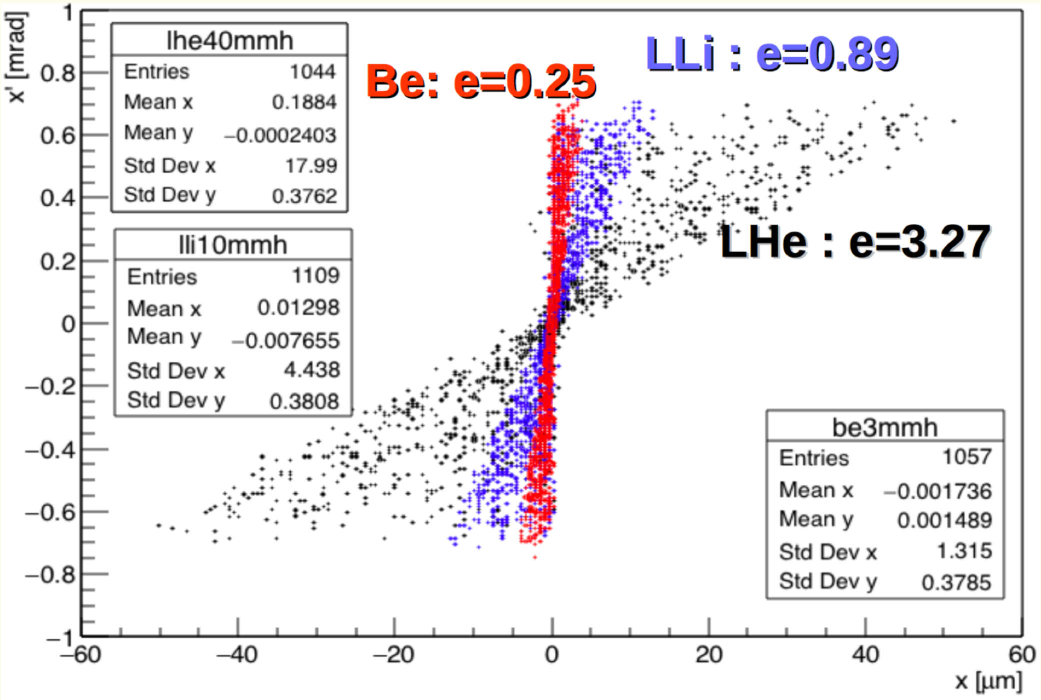
thin light materials targets have negligible multiple scattering contribution

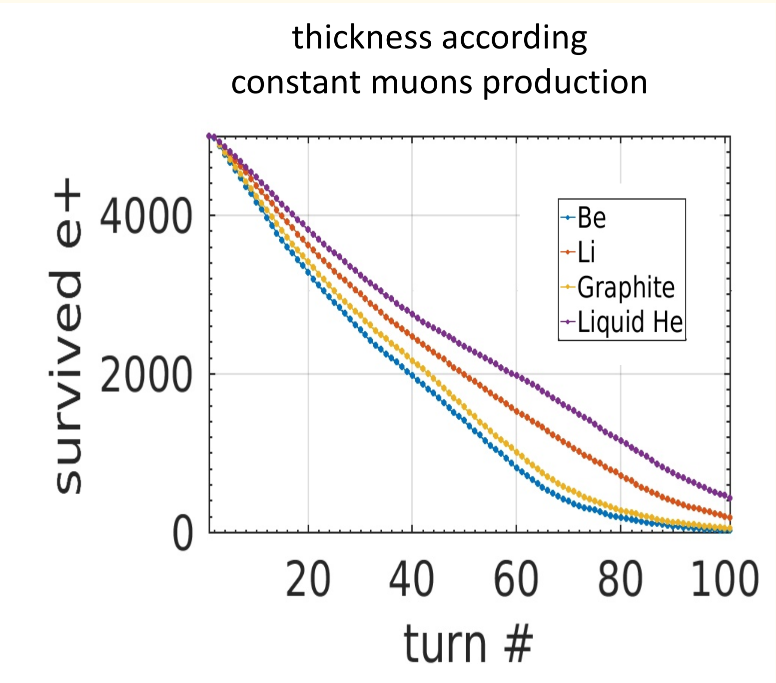
The emittance contributions due to muon production angle: $\varepsilon_\mu = x\, x'_{max}/12 = L\,(\theta_\mu^{max})^2/12$

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

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 $N_\mu^2 \quad 1/\varepsilon_\mu$

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

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.