New proposal for low-emittance muon collider

INFN

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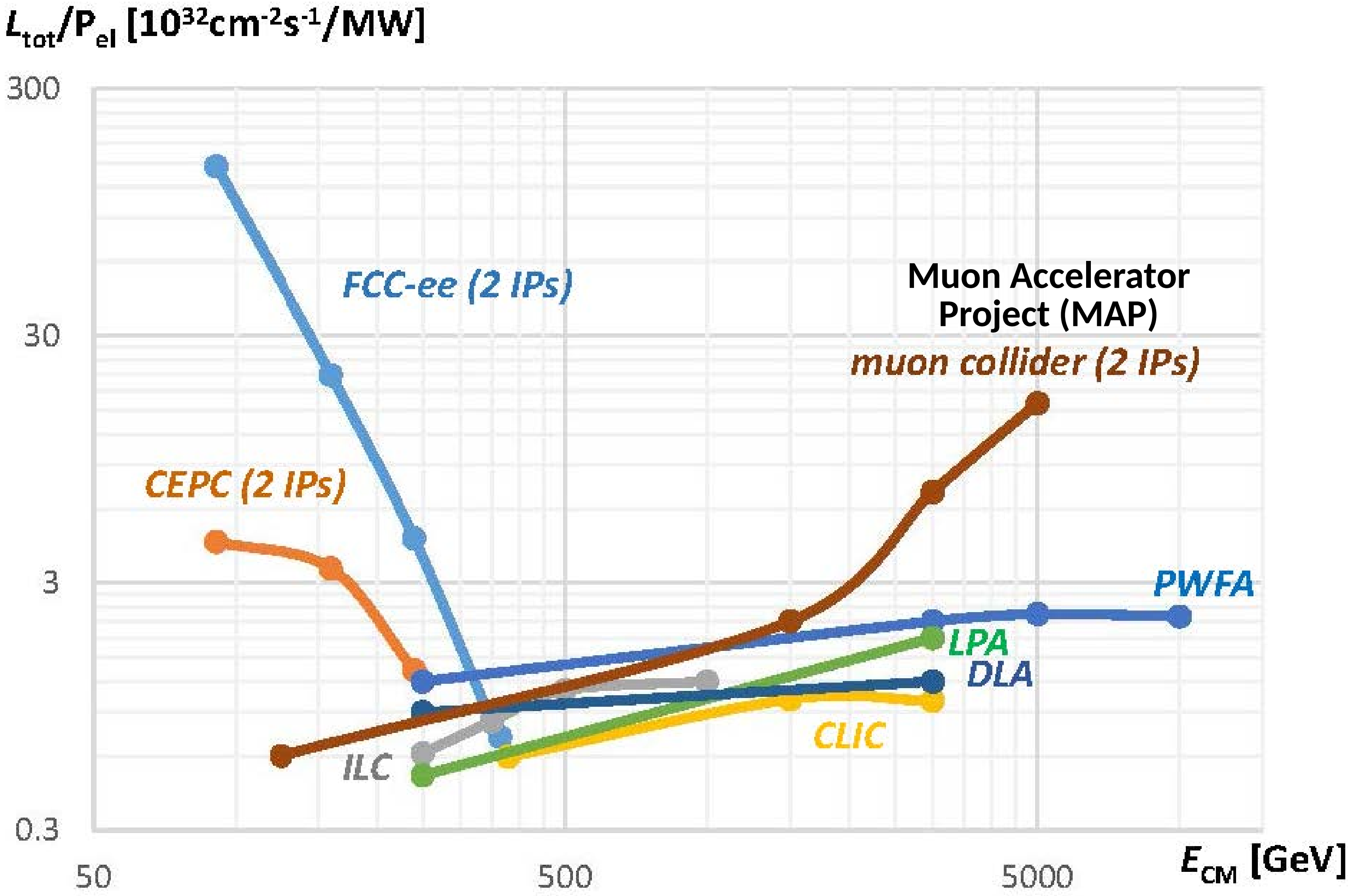
Oscar BLANCO on behalf of :
The LEMMA team

Bologna, June 7/2018
The Sixth Annual Large Hadron Collider Physics Conference LHCP 2018

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

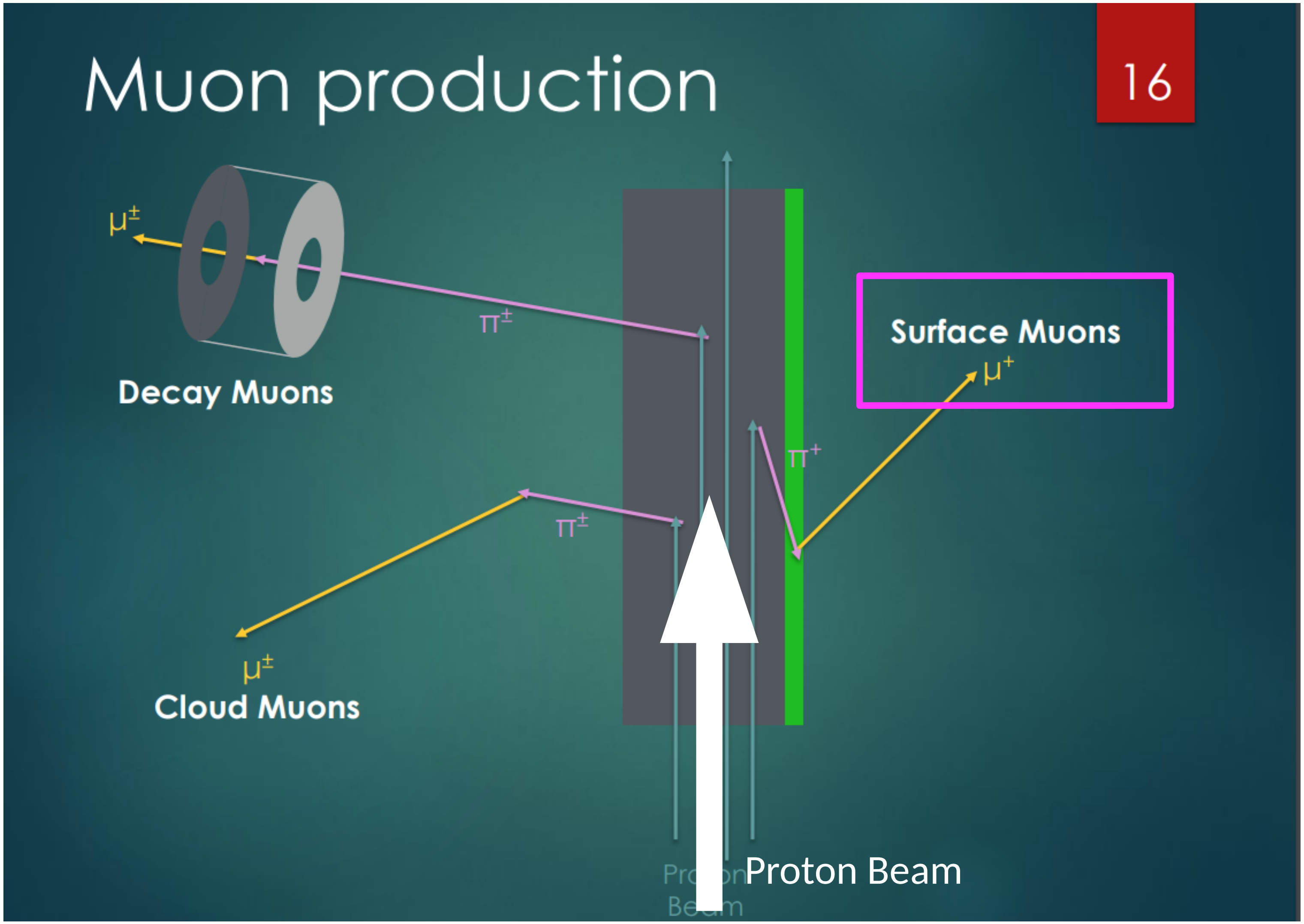
luminosity per wall-plug power vs c.m. energy

F. Zimmerman, Future Colliders for Particle Physics — "Big and Small"
arXiv:1801.03170v1



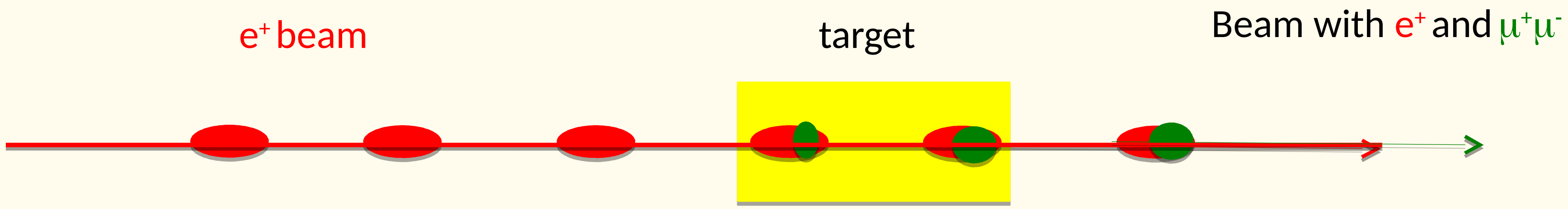
CONVENTIONAL MUON SOURCE

Surface muons as secondaries from proton-target interaction



BERG. Development of next generation High-intensity Muon Beam at the Paul Scherrer Institute
LNF Mini-Workshop Series : Muon production and beam interceptors. INFN/LNF 2018/Apr/19
https://agenda.infn.it/getFile.py/access?contribId=9&resId=0&materialId=slides&confId=15405

The alternative for a low emittance μ beam production



Ideally muons will *copy* the positron beam

Direct μ pair production:

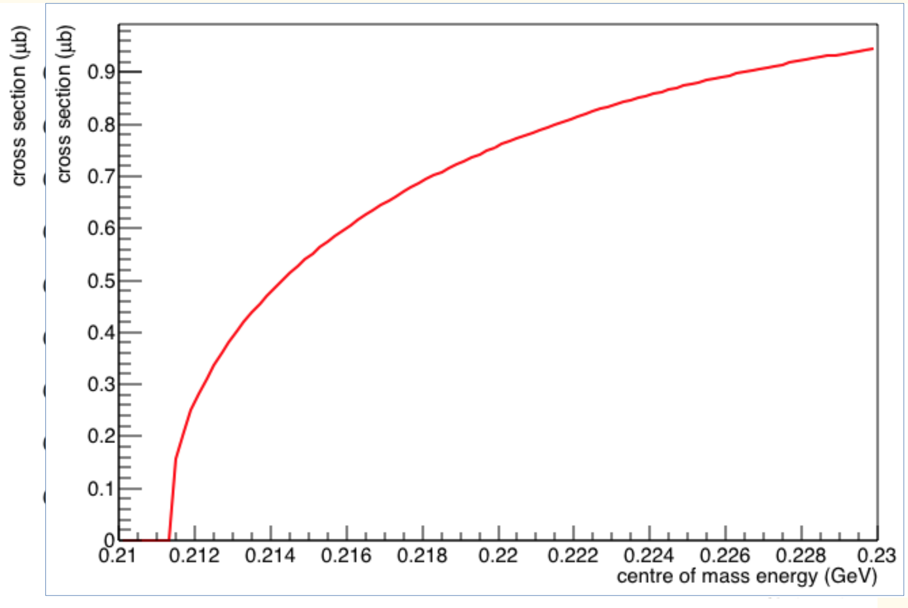
Muons produced from e+e- → $\mu^+\mu^-$ at √s around the $\mu^+\mu^-$ threshold **(√s~0.212GeV)** in asymmetric collisions (to collect μ^+ and μ^-)

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 … "*

M. Antonelli, M. Boscolo, R. Di Nardo and P. Raimondi,
"Novel proposal for a low emittance muon beam using positron beam on target,"
Nucl. Instrum. Meth. A 807 (2016) 101

Muon production at √s around 0.212 GeV c.o.m.

- Positron beam at 45GeV impinging on a target = ~0.2 GeV c.o.m.
- $e^+e^- \rightarrow \mu^+\mu^-$ cross section: 0.1~1 μbarn



Muon LEMMA

	SLC	CLIC	ILC	LHeC pulsed	LHeC ERL
E [GeV]	1.19	2.86	4	140	60
$\gamma\epsilon_x$ [μm]	30	0.66	10	100	50
$\gamma\epsilon_y$ [μm]	2	0.02	0.04	100	50
$e^+[10^{14}\text{s}^{-1}]$	0.06	1.1	3.9	18	440

F. Zimmermann, et al., '**POSITRON OPTIONS FOR THE LINAC-RING LHEC'**, WEPPR076 Proceedings of IPAC2012, New Orleans, Louisiana, USA

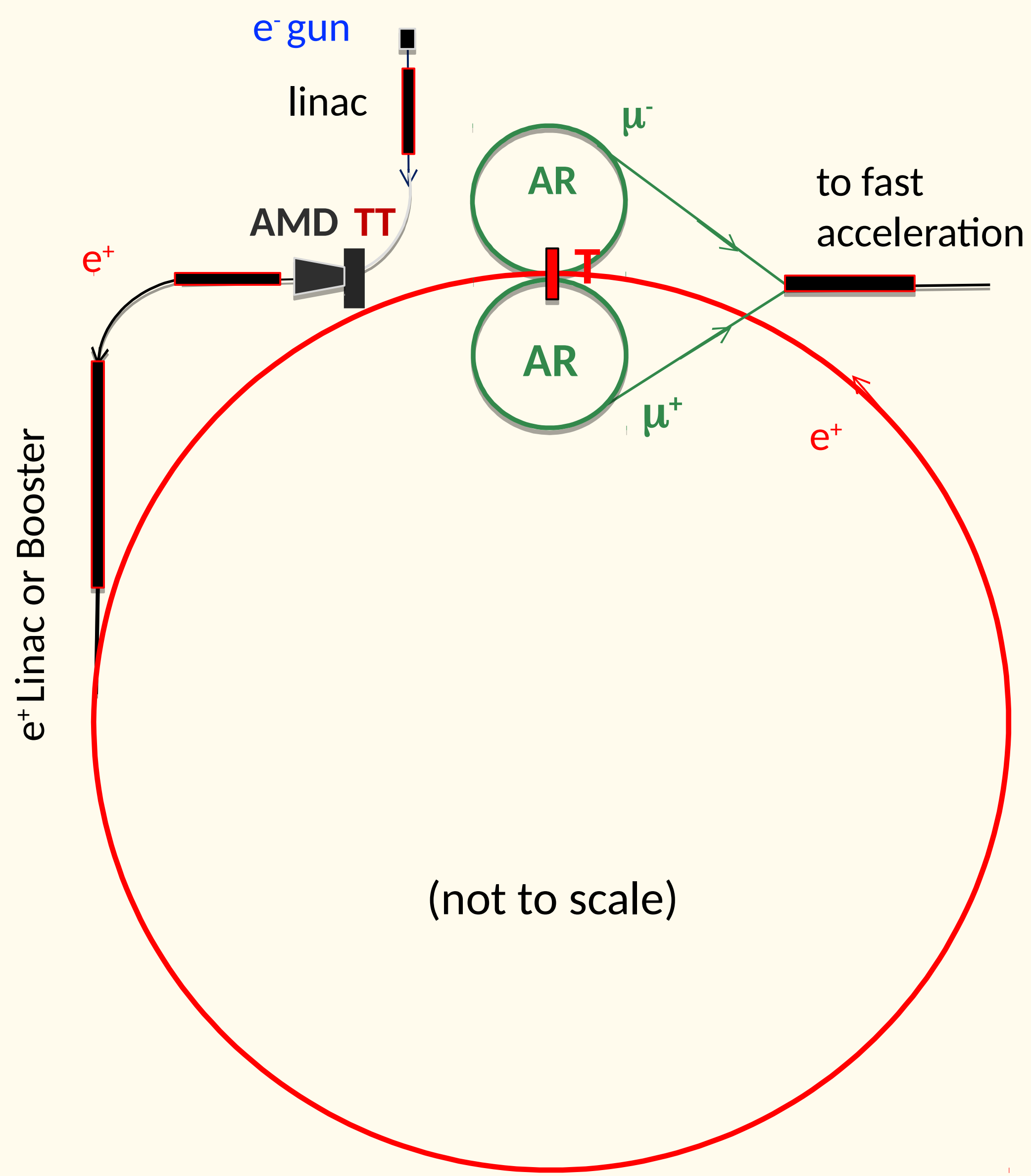
The small muon production cross section could be of interest with a large number of positrons crossing the target

GOAL ≈ 10^{18} e^+

WE CONCEIVED TO RECIRCULATE THE POSITRON BEAM FOR ABOUT 100 TURNS

SCHEME FOR LOW EMITTANCE MUON BEAM PRODUCTION FROM POSITRONS ON TARGET

M. BOSCOLO. Studies of a scheme for Low EMittance Muon Accelerator with production from positrons on target
arXiv:1803.0669



The desired Muon Production rate, requires the recirculation of the positron beam strongly affected by the target

Muon emittance

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

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

would like all contributions of same size

knobs:

- β_x β_y @target & target material
- β_x β_y D_x @target & target material
- $E(e^+)$ & target thickness
- AR optics & target

with constraints from target survival

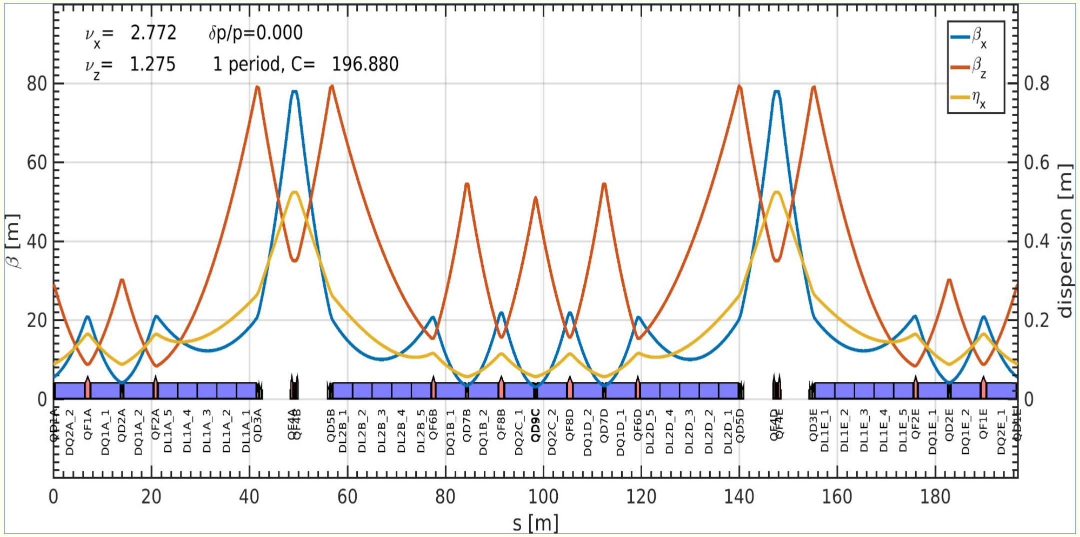
now: $\varepsilon(\mu)$ dominated by $\varepsilon(MS) \oplus \varepsilon(rad)$ -> lower dispersion & lower β-functions at target with beam spot at the limit of the target survival

The positron ring and the target contribute to the first three components of muon emittance growth

The current positron ring lattice

one cell = 200 m
Total length = 6300 m **(31 cells + 2 IR)**

Cell by P. Raimondi
Based on the Hybrid Multi Bend Achromat (ESRF upgrade)

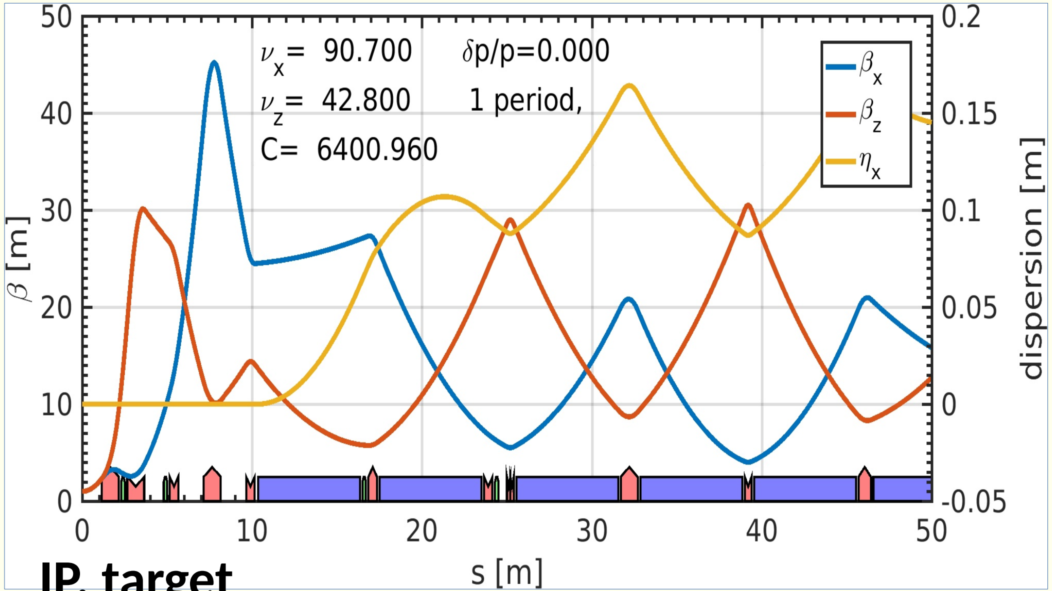


Particle = e+
Energy = 45GeV
Uloss = 1%/turn

Lifetime : 35~40 turns with Be 3mm

Longitudinal Damping t.:
88 turns (1.8 ms)
Transverse Damping t.:
178 turns (3.6 ms)

Interaction Region v11 by S. Liuzzo et. al.



IP, target

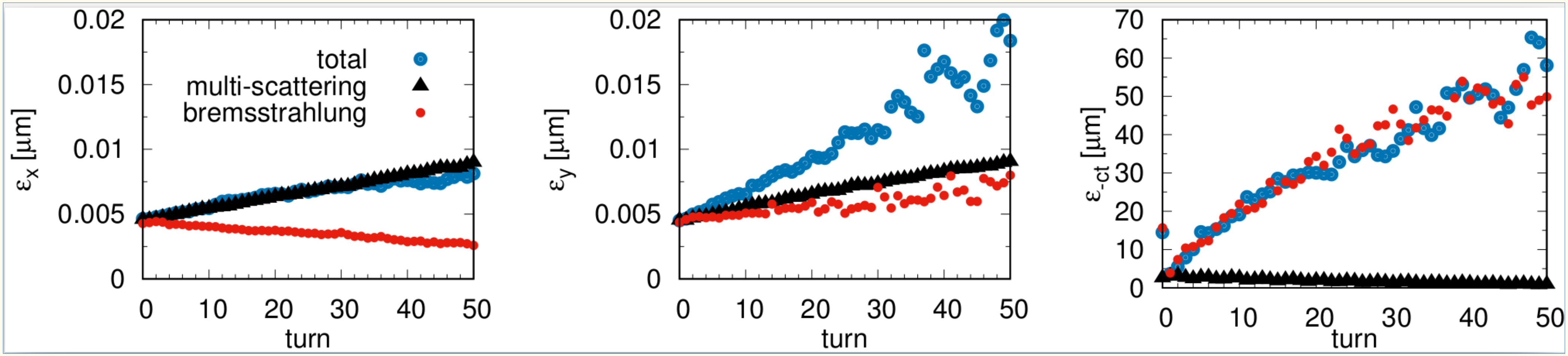
RFVoltage : 18MV * 64
Energy acceptance : ± 7%

βx(IP) = βy(IP)= 0.5m
ηx(IP) = 0mm

EMITTANCE over 50 turns

Beam matched with target multiple scattering → knob : low β at the IP

εx_0 = 5.73e-3 um, εy_0 = 5.73e-3 um, εt_0 = 3.6 um



Now the beam emittance growth due to the target is under control
→ two fold increase in the horizontal plane
→ three/four fold increase in the vertical plane

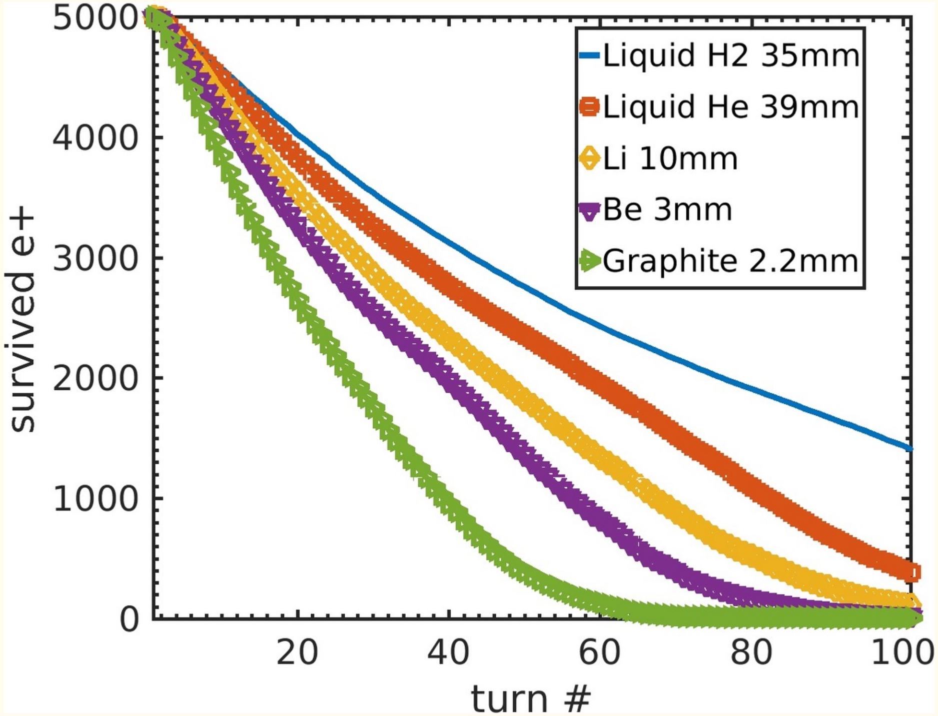
Horizontal emittance growth is smaller due to damping in the ring

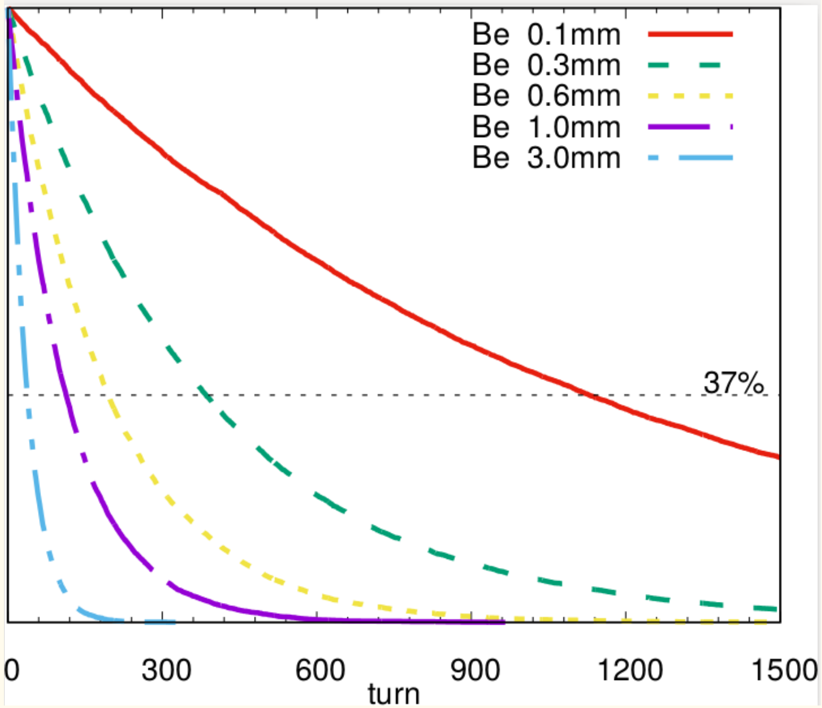
Emittance calculated from 95% of the particles remaining in the track

Turn-by-turn through the target

Several simulations with :
Beryllium, Liquid Lithium, Graphite, Liquid Helium and Carbon regarding beam degradation

A target of Be 3mm thickness seems to be the right balance between beam degradation and muon production





Beam lifetime mostly limited by energy acceptance of the lattice

… many options for a target to study

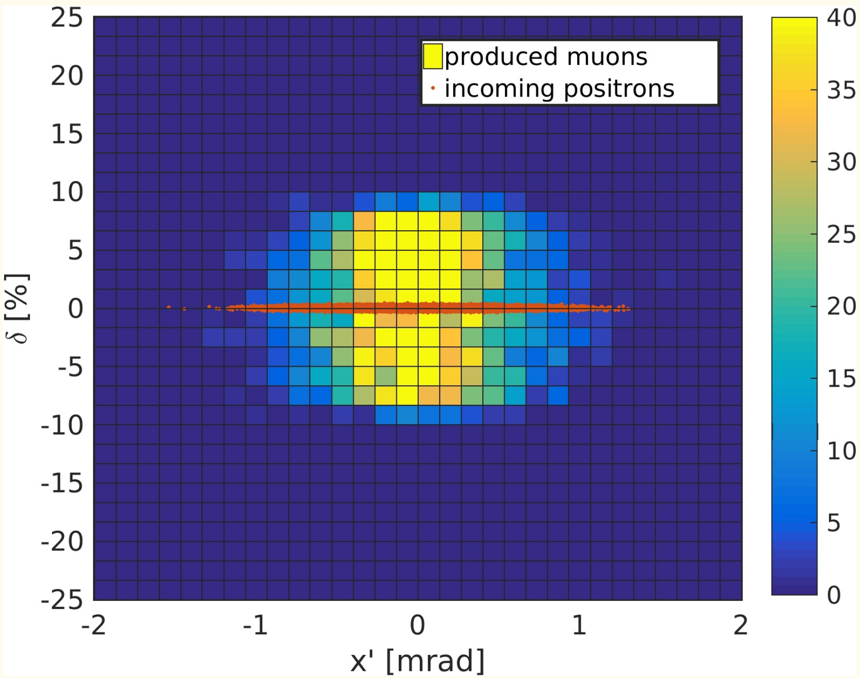
Bremsstrahlung on nuclei and multiple scattering (MS) are the dominant effects in real life… Xo and electron density will matter:

- **Heavy materials**
  - minimize emittance (enters linearly) → Copper has about same contributions to emittance from MS and $\mu^+\mu^-$ production
  - high e^+ loss (Bremsstrahlung is dominant)
- **Very light materials**
  - maximize production efficiency(enters quad) → H_2
  - even for liquid need O(1m) target → emittance increase
- **Not too heavy materials(Be, C)**
  - Allow low emittance with small e^+ loss

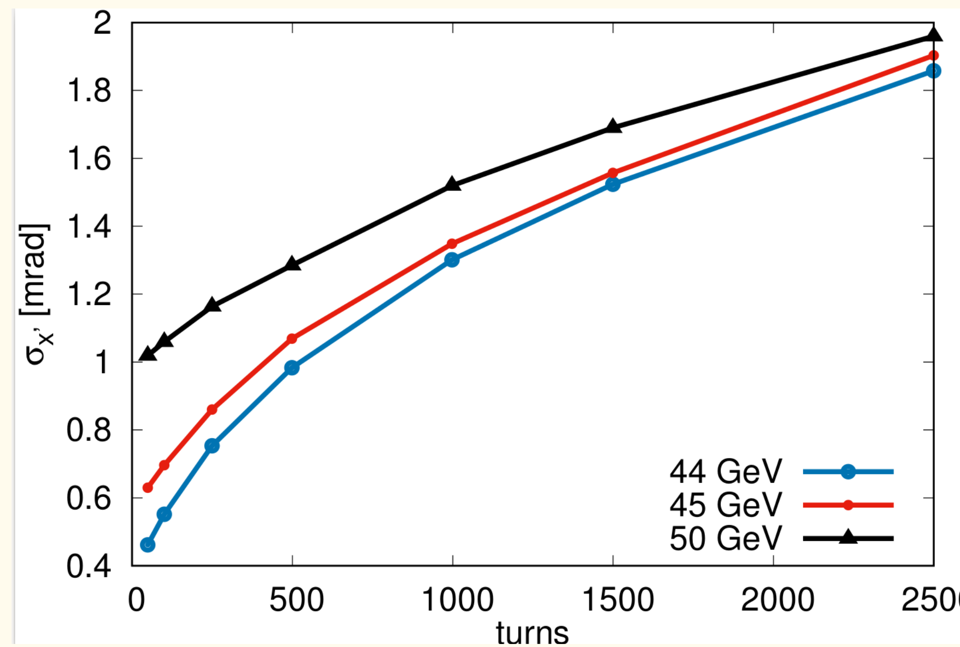
optimal: not too heavy and thin

The muon production and accumulation

Simulations from a 3 mm thick Beryllium target, and a positron beam at 44 GeV.



Muon beam divergence as a result of the interaction with the target over several turns



The muon accumulator ring will need an energy acceptance close to 5%

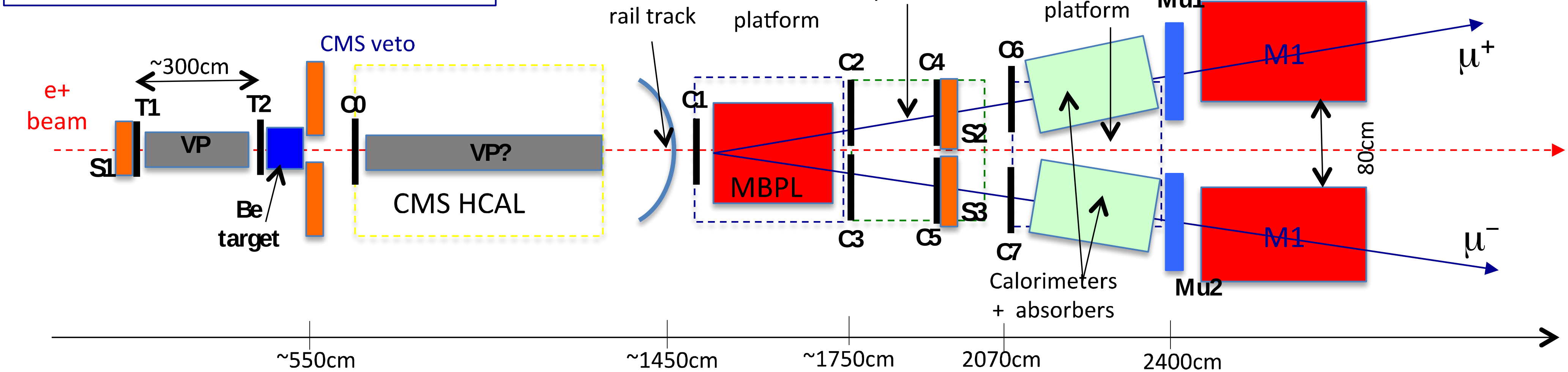
The muon accumulator optics will need to be matched with the divergence due to the target

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

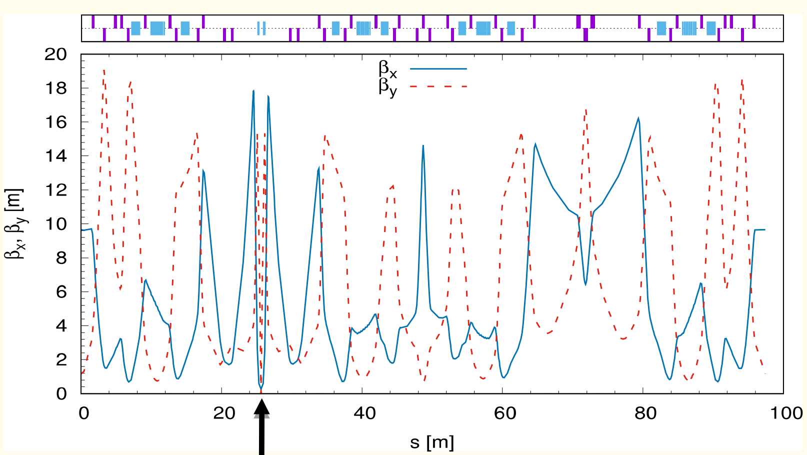


A. Bertolini, L. Sestini, T. Tabarelli, et. al.

Possible Target Test at DAFNE

b) Initial studies to propose a beam dynamics test of positron recirculation at DAFNE (DAFNE is 1 GeV c.o.m. collider at INFN/LNF Frascati, Italy) M. Boscolo. MOPMF086, IPAC18.

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)



IP, target

100 m ring, 1% Energy acceptance, 0.5 GeV e+ beam

β_x^*=26cm; β_y^*=0.9cm

σ_x^*=0.27mm; σ_y^*=4.4μm

ε_x = 0.28 μm

CONCLUSIONS

LEMMA is studying the low emittance muon production from positrons on a target, an innovative idea that could lead to new accelerators.

The muon production relies in a high rate of positrons, thus, we have considered the recirculation of a 45 GeV beam. An initial ring+IR design has been done, where we keep the emittance growth under control.

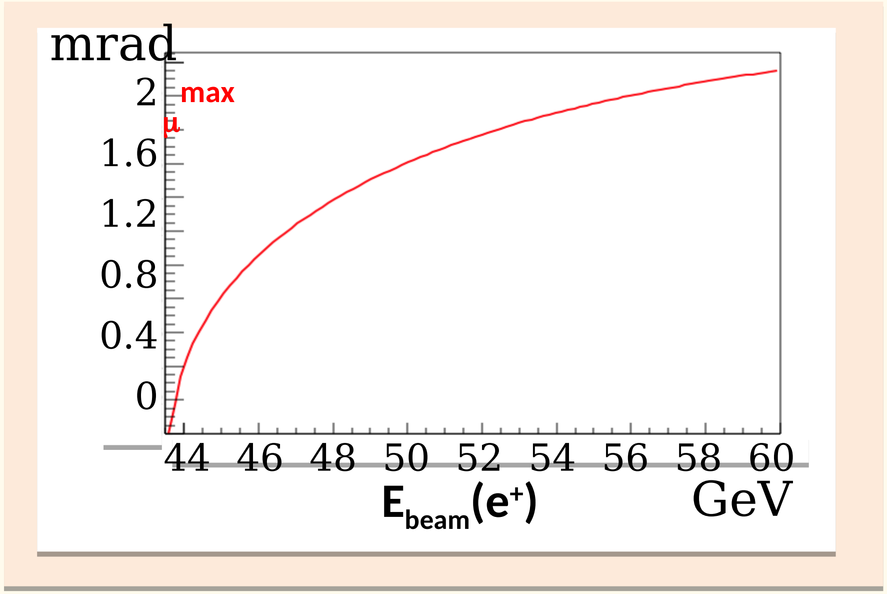
Beam lifetime is limited to 30~40 turns in simulations due to energy acceptance. This will need to be pushed further.

We have started the design of the muon accumulator rings.

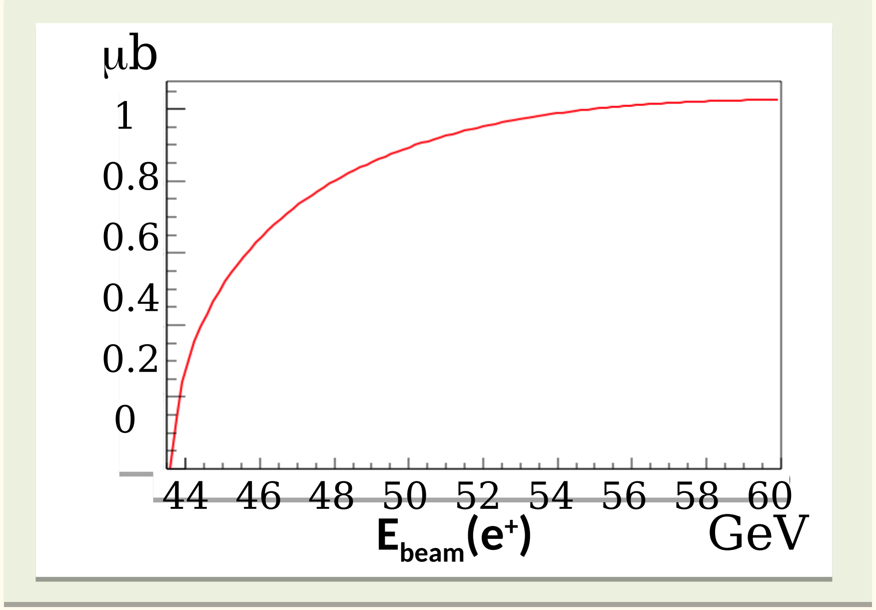
However, there is a need of experimental tests of the idea :
a) A test beam with positrons impinging on a Beryllium target is under preparation, August/2018 at CERN
b) Initial simulations for a positron recirculation test proposal at DAFNE

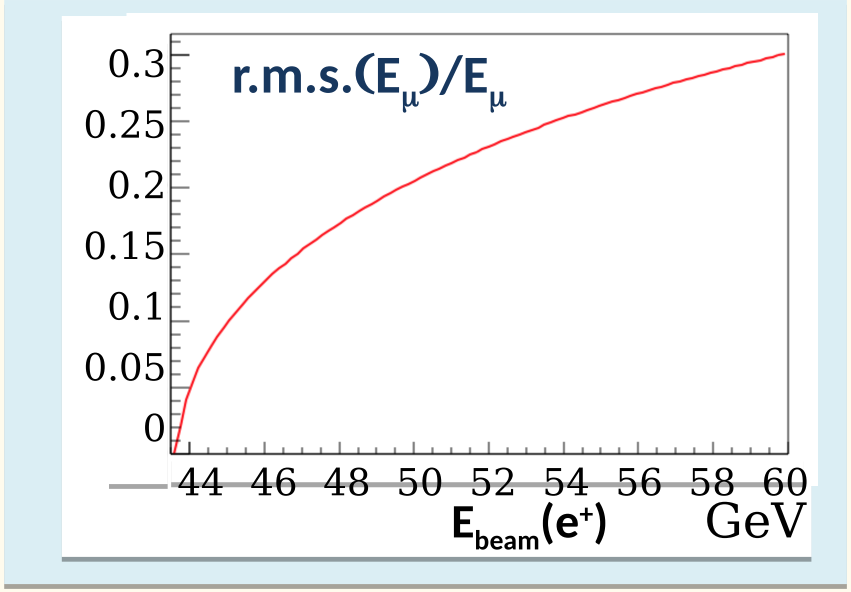
Backup Slides

Parametric behaviours



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





Low EMittance Muon Accelerator team:

(Italy) **INFN institutions involved: LNF, Roma1, Pd, Pi, Ts, Fe**

Universities: Sapienza, Padova, Insubria

(International) **Contributions from: CERN, ESRF, LAL, SLAC**

This new proposal covers different areas of research:

accelerator physics, high energy, theory, engineering material science, …

Many colleagues are interested to collaborate,

informal contacts with international experts has started

We believe in the potential of this idea, but key challenges need to be demonstrated to prove its feasibility.

I will show the work done up to now <u>on the positron ring for low emittance muon production</u>

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