LEMMA

M. Boscolo (INFN-LNF)

for the LEMMA Team

ARIES Muon Collider Workshop
Padova, 2-3 July 2018

Outline

- **Positron driven source**
- **LEMMA scheme**
- **Optics & Beam dynamics**
- **R&D**
- **High Energy Collider: preliminary parameters**
- **Conclusion**

Muon Source

Proton driven

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

Positron driven

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 EMittance Muon Accelerator

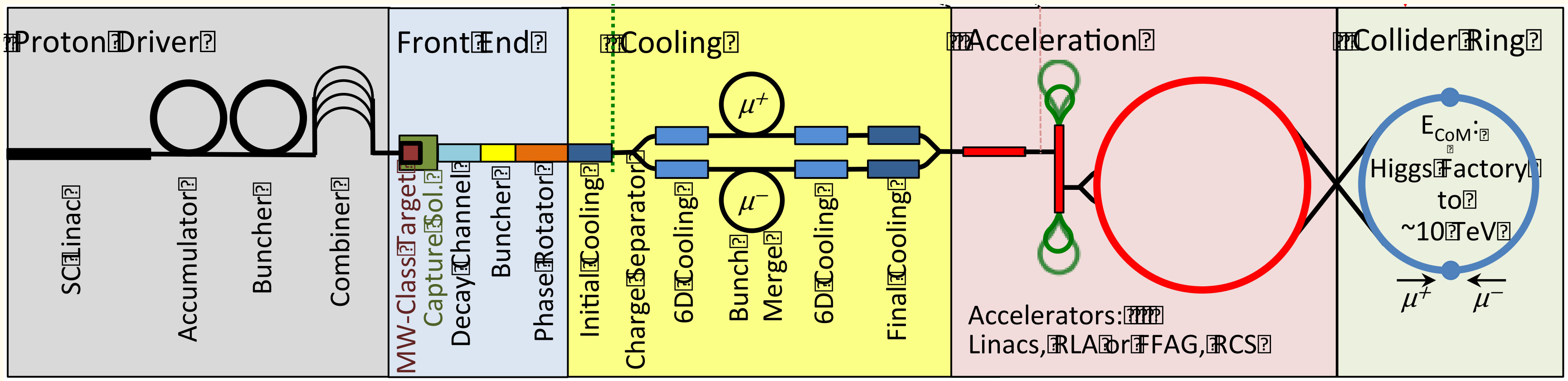
Multi-TeV Muon Collider based on a novel muon production concept

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

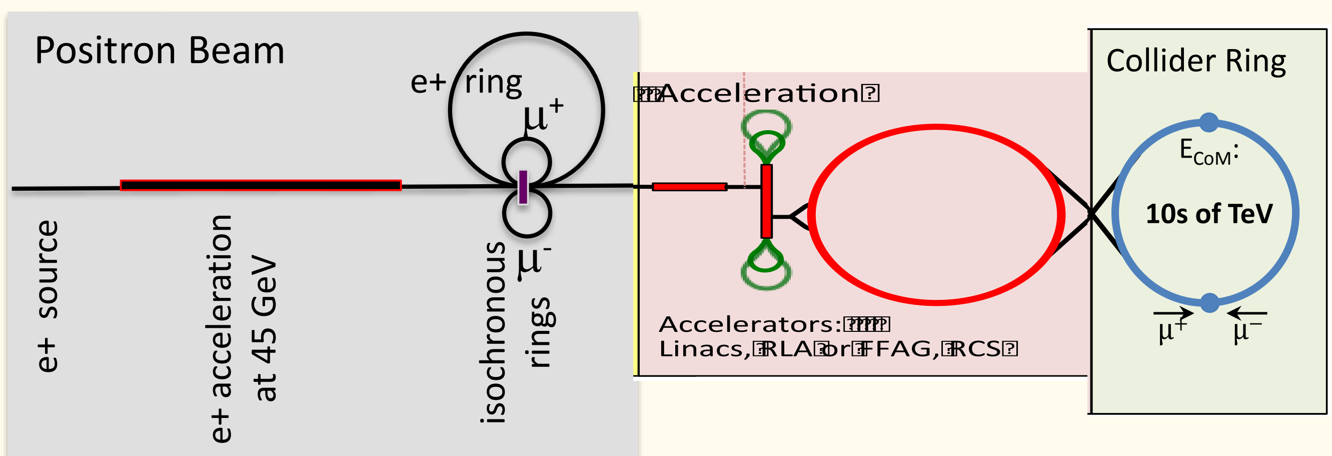
- **Low emittance concept overcomes muon cooling**
- **Low emittance allows operations at very high c.o.m. energy**

LEMMA concept 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)

MAP & LEMMA μ-collider Schematic Layout



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–***

Pro: 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

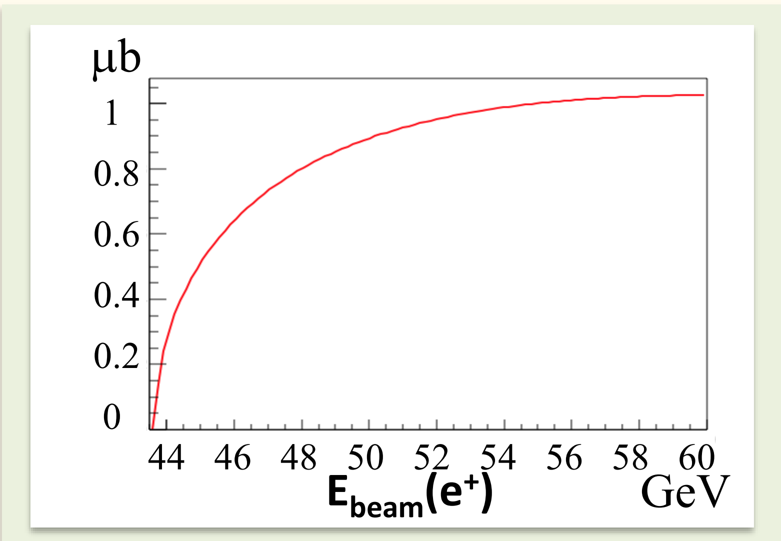
$\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx$ **1 μb** at most wrt σ(from p) $\approx$ **mb**

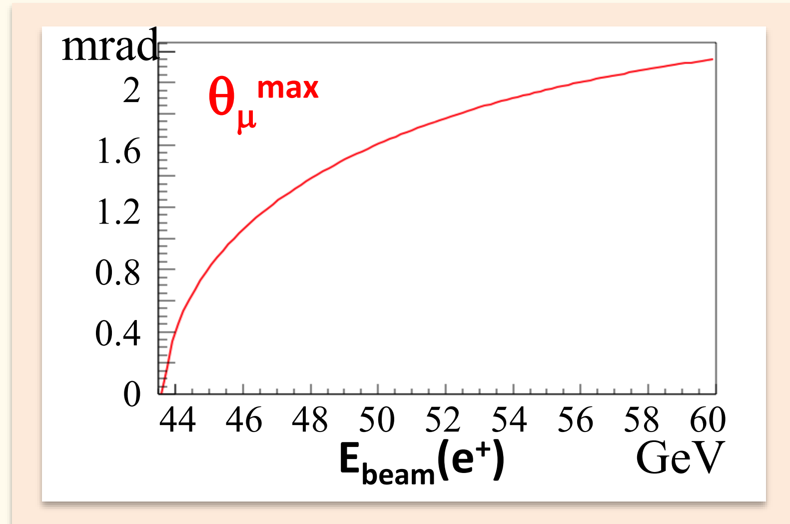
Pro LEMMA:

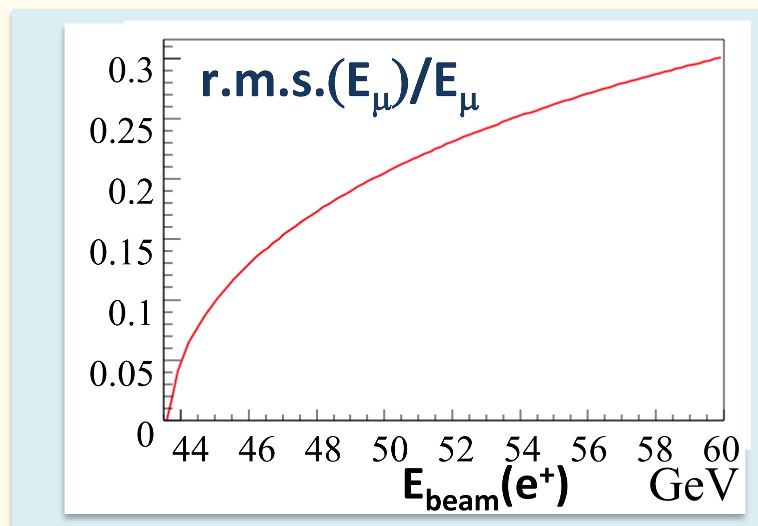
- Reduced losses from decay: **high collection efficiency**
- Low background: **Luminosity at low emittance will allow low background and low neutrino radiation → easier experimental conditions & can go to higher energies**
- Energy spread: muon energy spread might be **also small at threshold**, it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

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

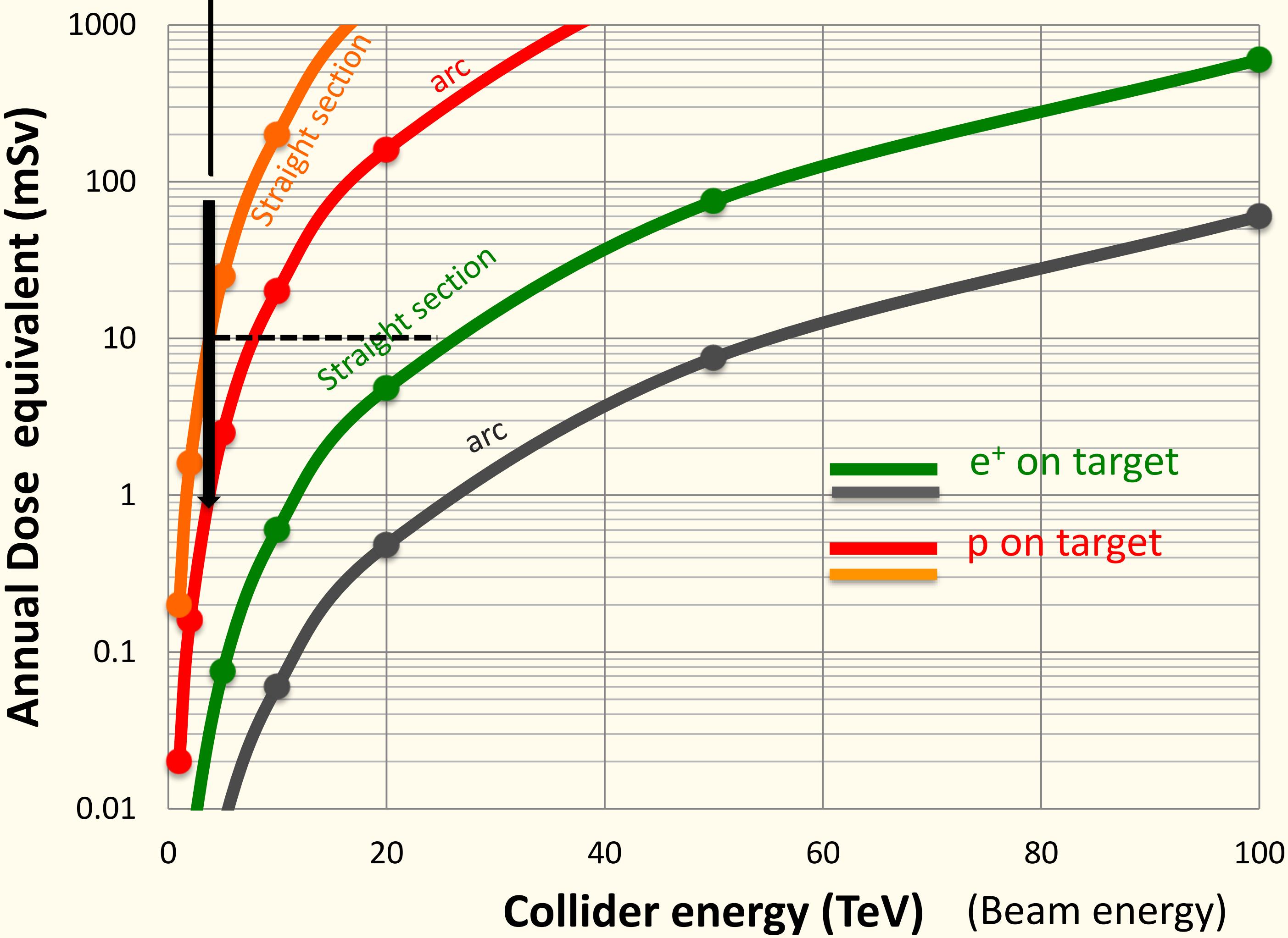
3×10^{13} μ/s

e^+ on target option

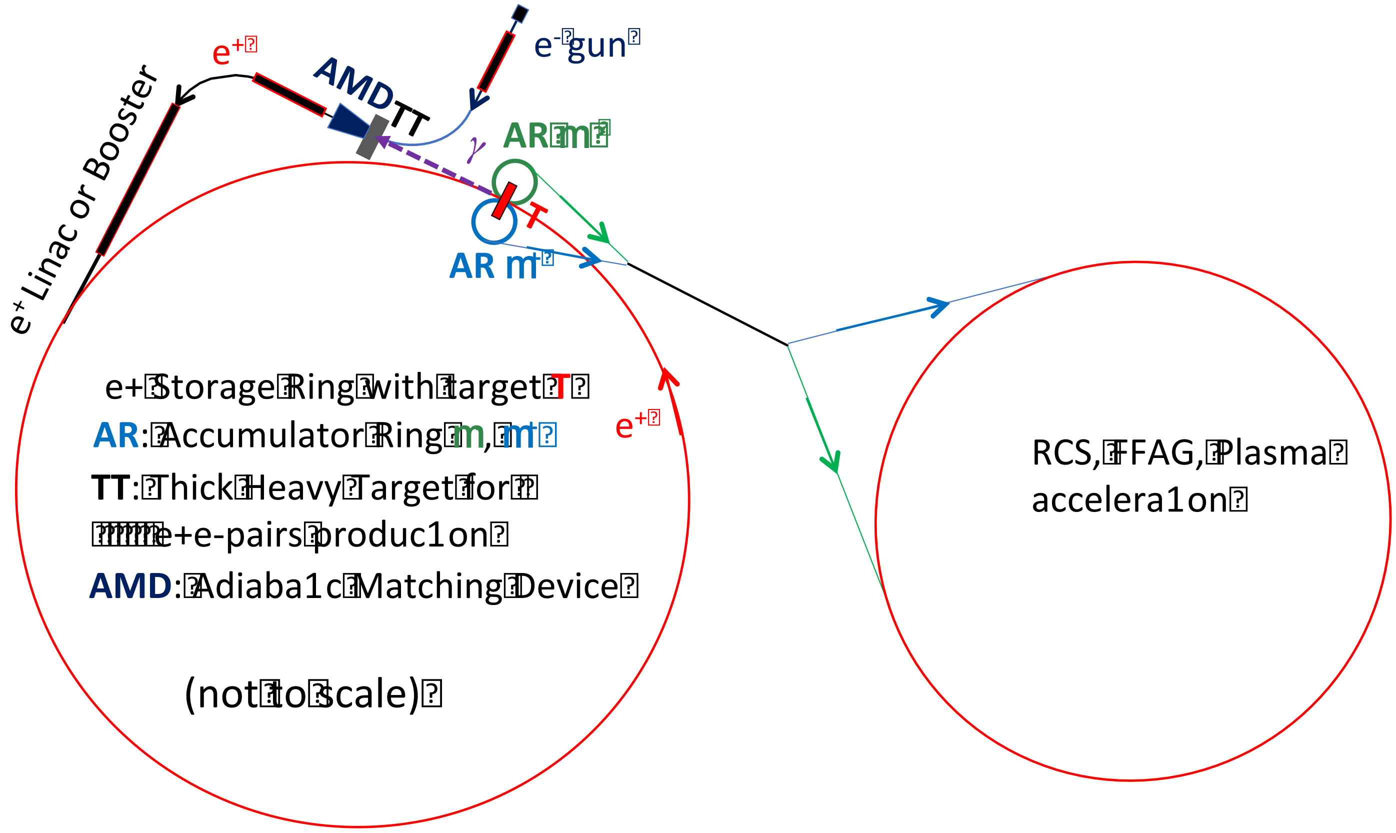
9×10^{10} μ/s

neutrino dose equivalent/fluence

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



LEMMA scheme



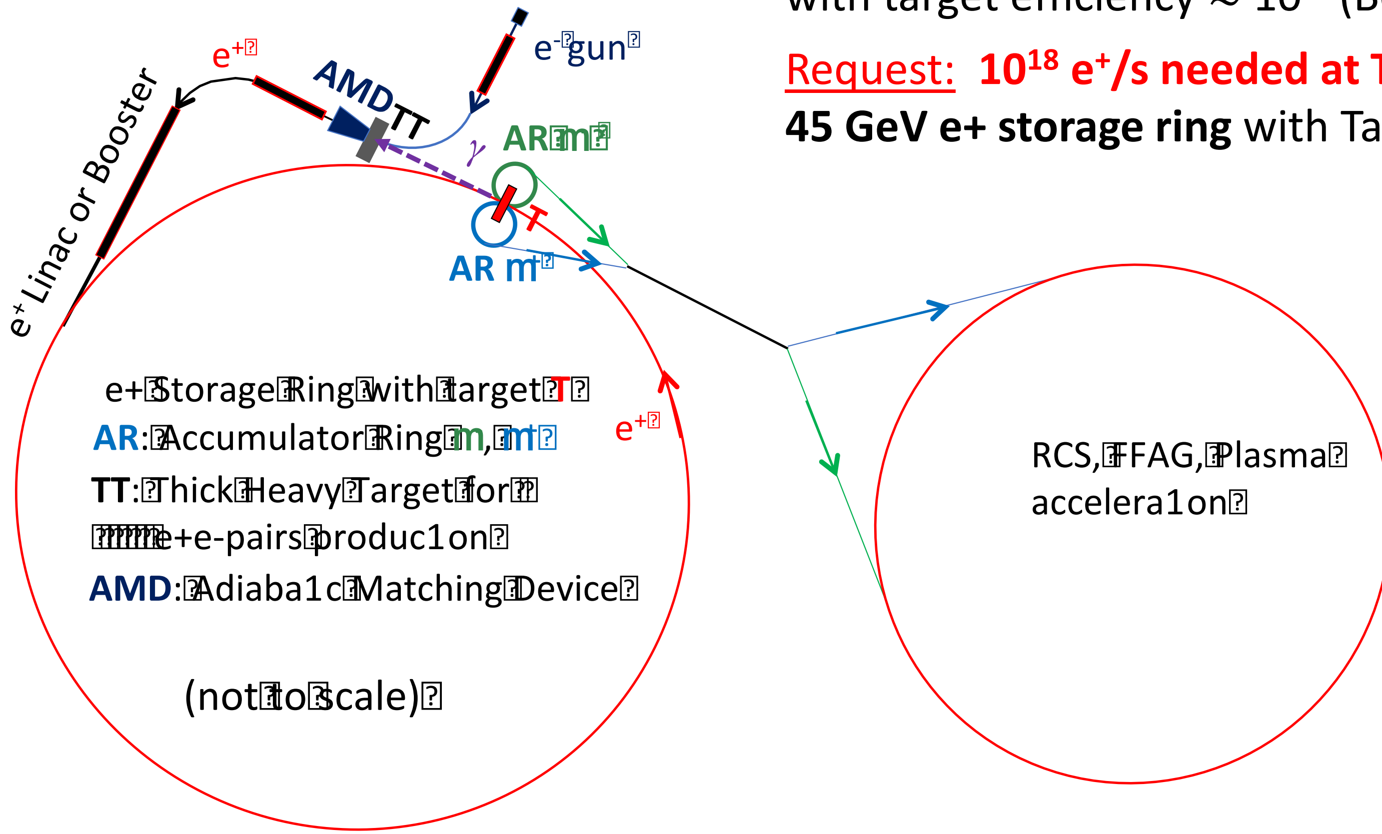
LEMMA scheme

Goal: ≈ $\mathbf{10^{11}}$ **μ/s** produced at Target

with target efficiency ≈ 10^{-7} (Be 3mm)

Request: **$\mathbf{10^{18}}$ $\mathbf{e^+}$/s needed at Target** →

45 GeV e+ storage ring with Target insertion



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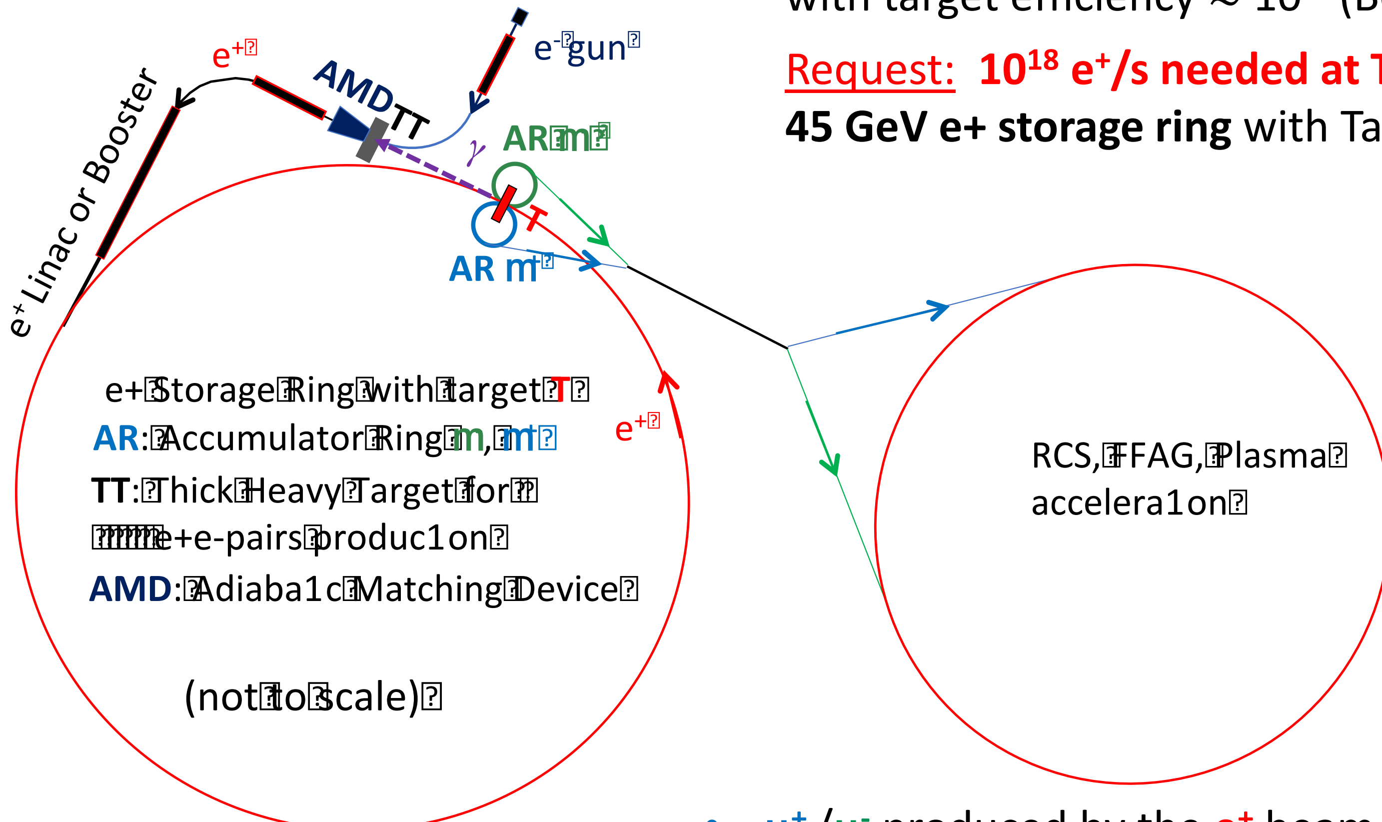


- μ^+ / μ^- produced by the e^+ beam on target **T** at about **22 GeV** → $\tau_{lab}(\mu)$ ≈ **500μs** ($\gamma(\mu)$ ≈ 200)
- Accumulator Rings (**AR**) isochronous with high momentum acceptance, they recombine μ bunches for ~ 1 τ_μ^{lab} ≈ 2500 turns
- fast acceleration and to collider

<u>from μ^+ μ^- production to collider</u>

Accelerator physics key topics for the feasibility LEMMA scheme

1. **Positron ring**
   - low emittance and high momentum acceptance

Optics design & beam dynamics

2. **Muon Accumulator Rings**
   - High momentum acceptance

Optics design & beam dynamics

3. **Positron source**
   - High rate

Synergy with FCC-ee/ILC/CLIC future colliders

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** **talk by S. Liuzzo** Optics design & beam dynamics
   - low emittance and high momentum acceptance
2. **Muon Accumulator Rings** Optics design & beam dynamics
   - High momentum acceptance **talk by O. Blanco**
3. **Positron source** Synergy with FCC-ee/ILC/CLIC future colliders
   - High rate **talk by S. Guiducci and F. Collamati**
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

talks by M. Iafrati, F. Carra and F. Nuiry

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**

Ref.

- "**Low emittance muon accelerator studies with production from positrons on target** , M. Boscolo M. Antonelli, O.Blanco, S. Guiducci, , S. Liuzzo, P. Raimondi, F. Collamati, **Phys. Rev. Accel. Beams 21, 061005 (2018)**
- "*Muon accumulator ring requirements for a low emittance muon collider from positrons on target*" M. Boscolo, M. Antonelli, O. Blanco, S. Guiducci, F. Collamati, S. Liuzzo, P. Raimondi, L. Kellers, D. Schulte, Proc. IPAC18, MOPMF087

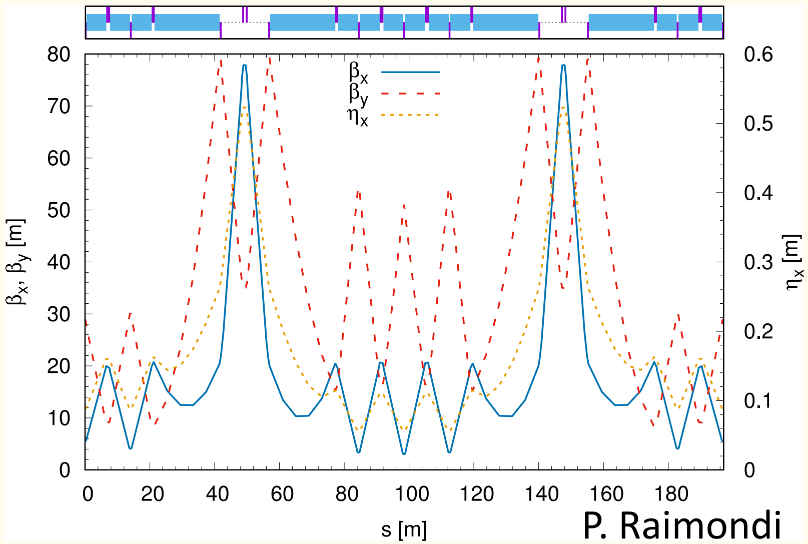
Optics design positron ring

More details in talk by S. Liuzzo

e+ ring parameter	unit	MAP option	LHC tunnel (NEW!)
Energy	**GeV**	**45**	**45**
Circumference	**km**	**6.3**	**27**
No.part./bunch	**#**	**$3 \cdot 10^{11}$**	
bunches	#	100	
e^+ bunch spacing = T_{rev} (AR)	ns	200	
Beam current	mA	240	
Emittance	nm	6	
U_0	GeV	0.51	
SR power	**MW**	**120**	**29**

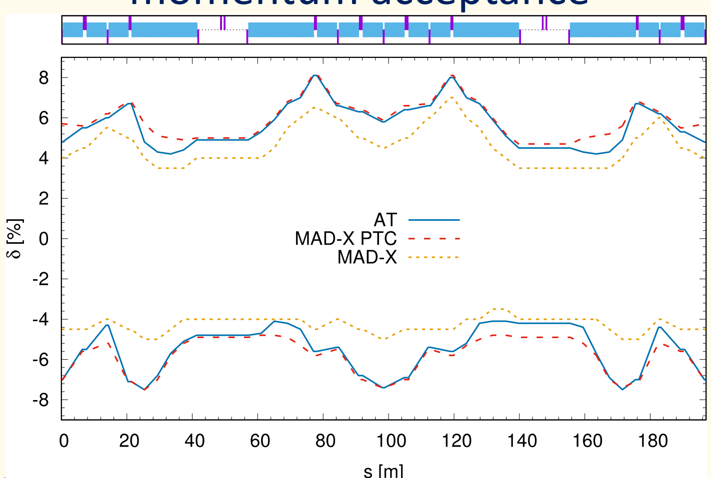
Details in specific talk on the Positron ring

Cell based on the Hybrid Multi Bend Achromat



P. Raimondi

momentum acceptance



Optics design positron ring

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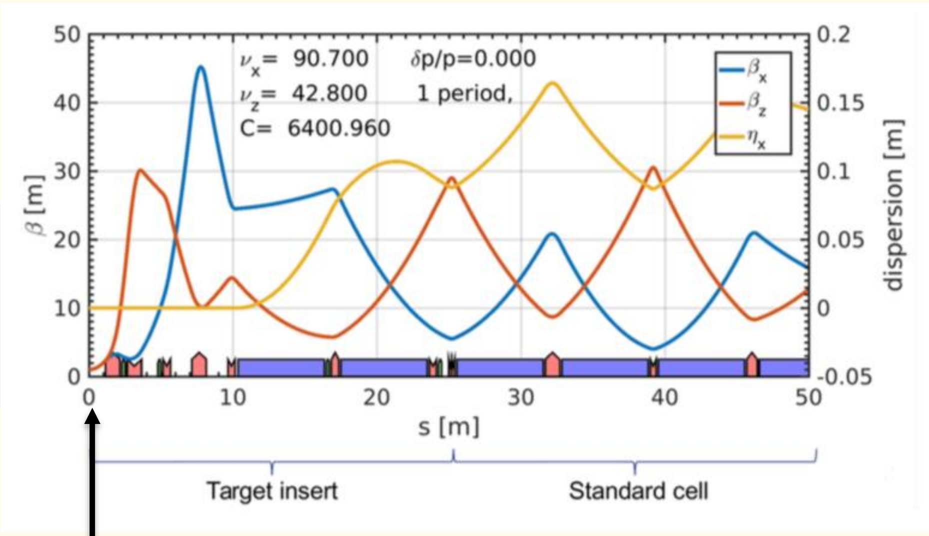
Target Insertion Region



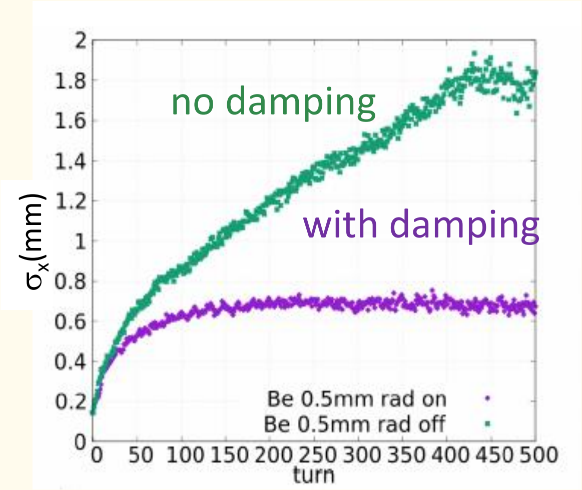
@target $\begin{cases} D_x \approx 0 \\ \text{low-}\beta\ (\beta_{x,y} = 0.5\ \text{m}) \end{cases}$

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)

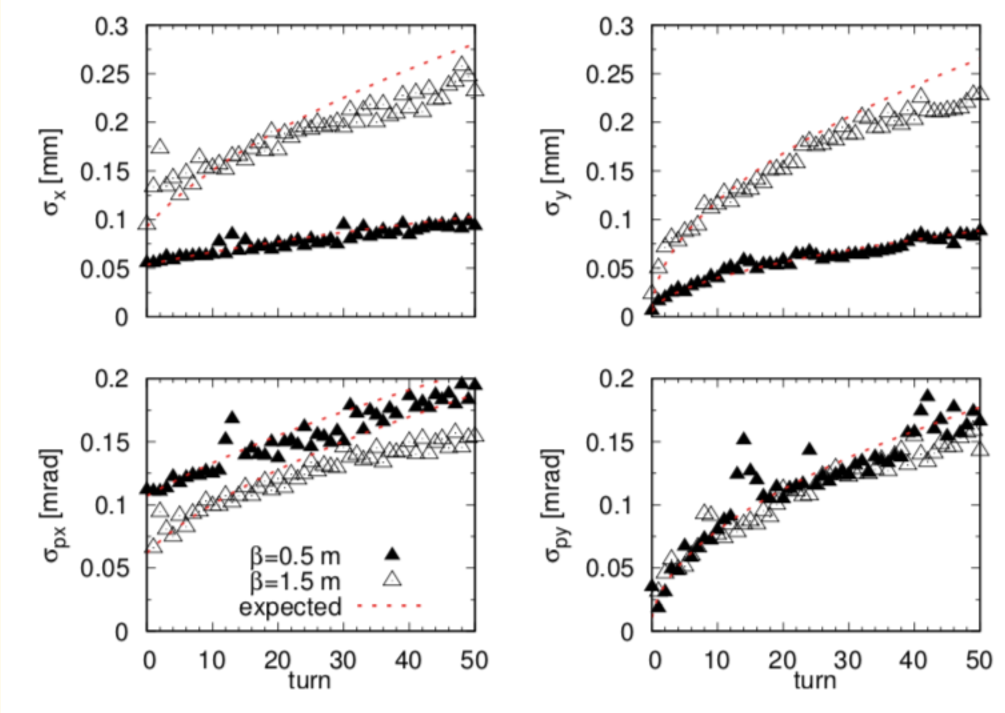


Beam dynamics e^+ beam in ring-with-target

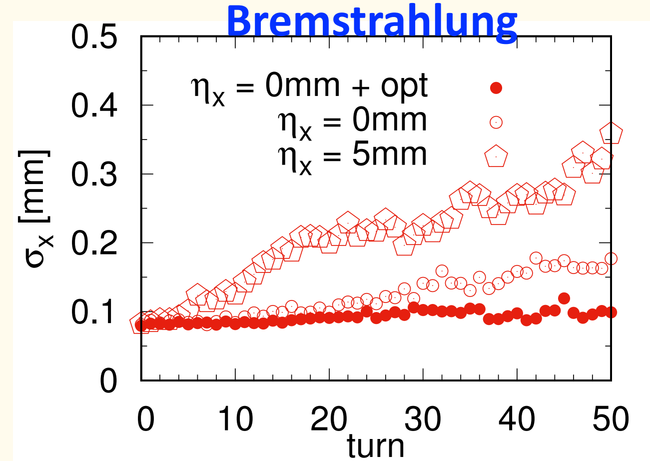
More details in: PR-AB 21, 061005 (2018)

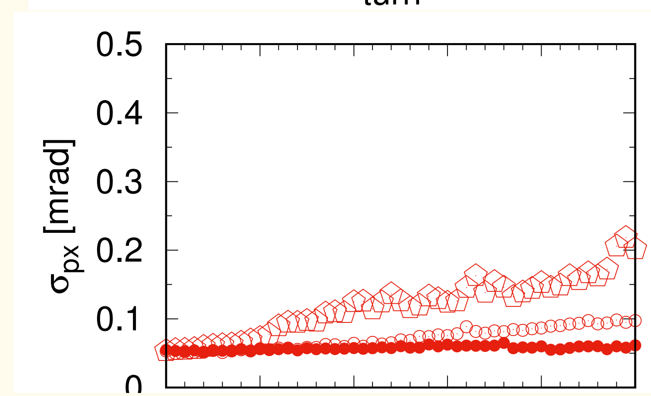
e^+ emittance growth controlled with proper β and D values @ target

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

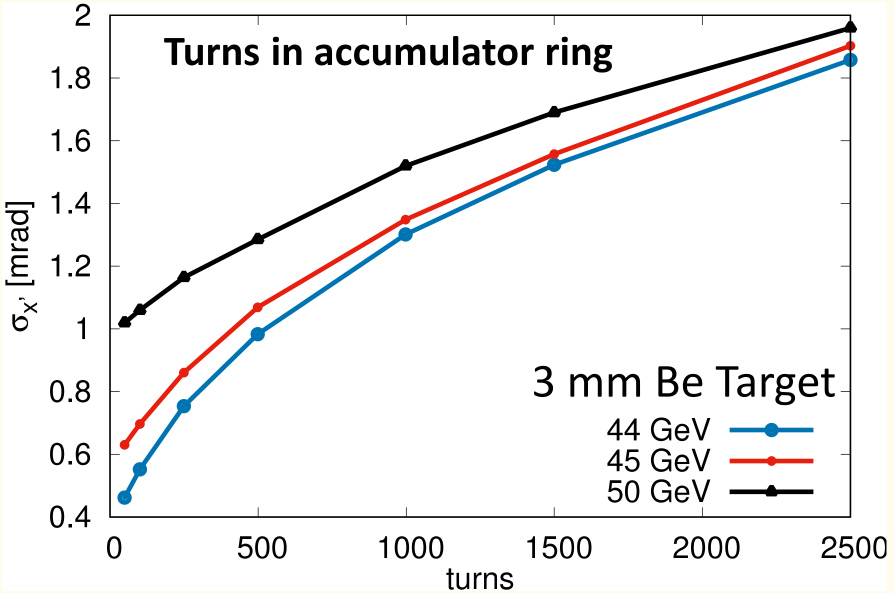
@Target :
linear and non-linear terms of horizontal dispersion η_x =0

Muon emittance contributions

More details in talk by O. Blanco

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

$\varepsilon(e^+)$ = 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

See also Proc. of IPAC18, Vancouver, MOPMF087

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)

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

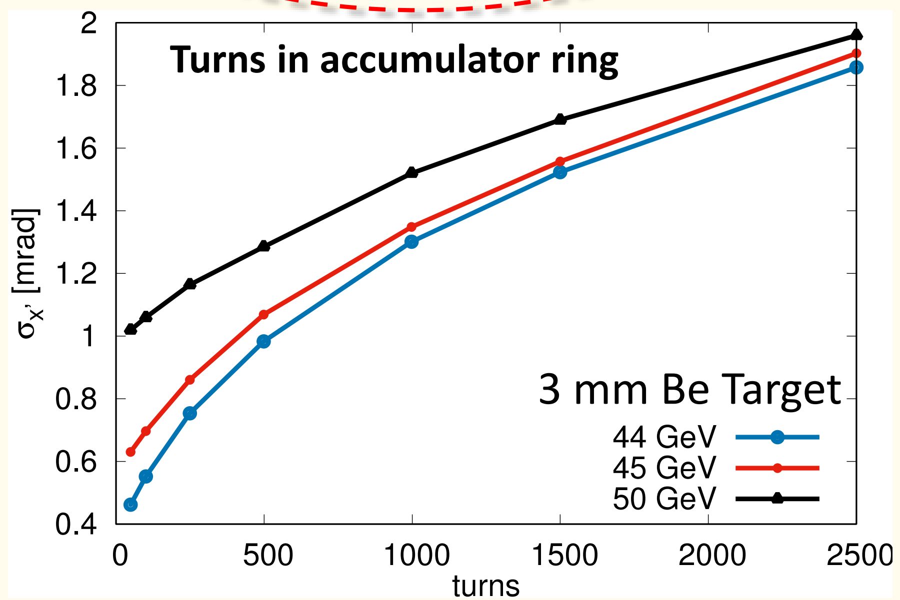
L is the target length

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

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)

More details in talks by M. Iafrati, F. Carra, F. Nuiry

Activity

- collaboration with PoliTo expertize on material termo-mechanical characterization, simulations and experimental validation, L. Peroni, M. Scapin, involved in ARIES
- Contact with ARIES PowerMat work package WP17
- Contact with CERN-STI (Sources Targets Interaction) group, S. Gilardoni, M. Calviani
- collaboration with Sapienza SBAI, R. Li Voti for their expertize on thermo-mechanical measurements
- Collaboration with Brasimone Expertize on Liquid Lithium, A. Del Nevo, M. Iafrati

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

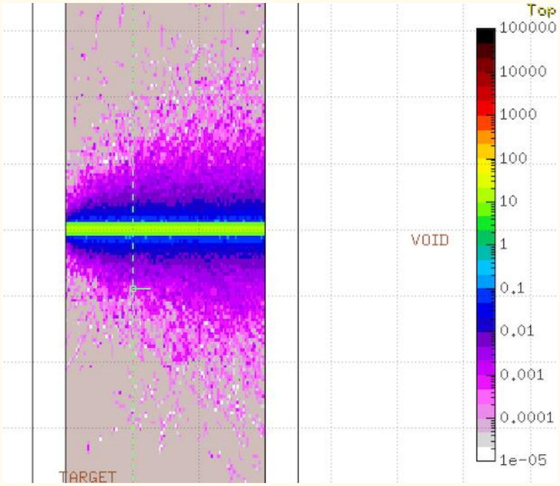
- **Solid target**: simpler and better wrt temperature rise
  - Be, C

  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

More details in talk by S. Guidducci

e^+ production rates achieved (SLC) or needed						
	S-KEKB	**SLC**	**CLIC (3 TeV)**	**ILC (*H*)**	**FCC-ee (*Z*)**	**LEMMA**
10^{14} e^+ / s	**0.025**	**0.06**	**1.1**	**2**	**0.05**	**100**

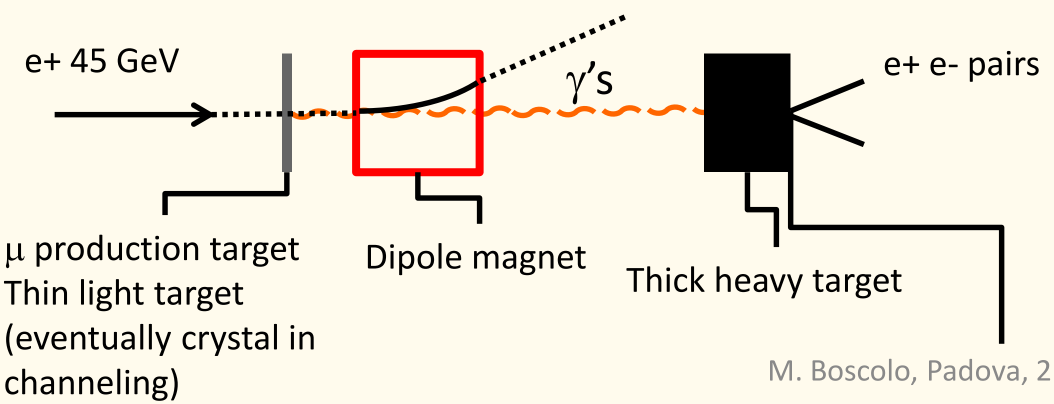
This requirement is strictly connected to the e+ lifetime and mom. acceptance

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 to relax e+ source requirement

More details in talk by F. Collamati

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

DAFNE Layout for the LEMMA Test

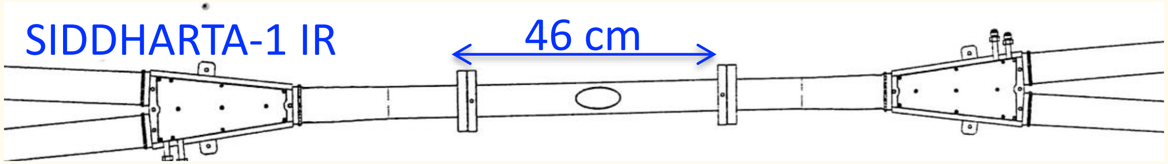
The target will be placed at the SIDDHARTA IP because:

- 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

More details in talk by F. Anulli

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**

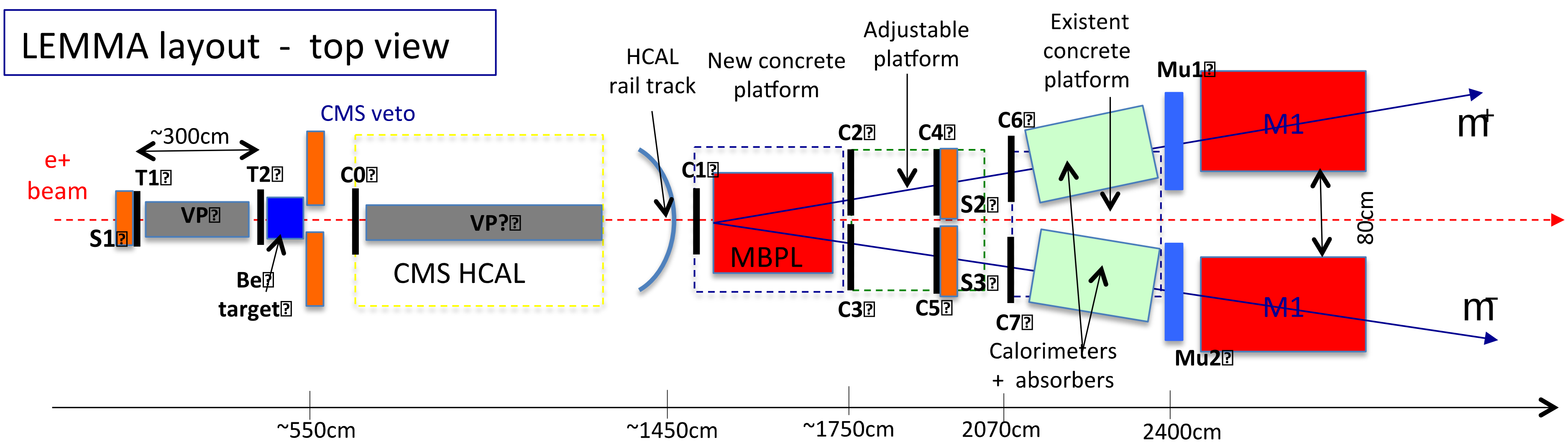
  to complete original program of the 2017 experiment

2018 Experimental layout

More details in talk by F. Anulli

- Study of kinematic properties of the produced muons
  - Measure the mm 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



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)

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

Comment on the parameters table

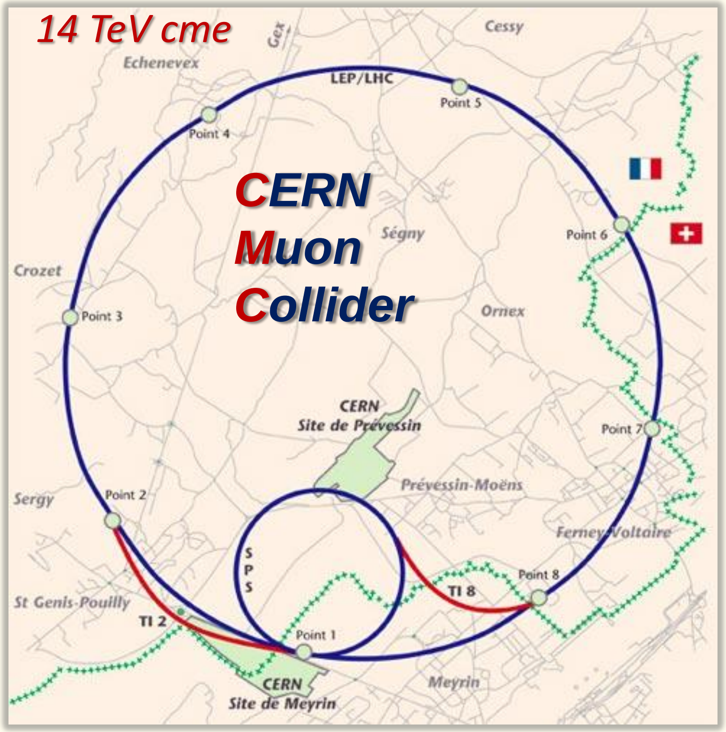
This is not a LEMMA parameter table coming out of the design study, but it gives the goal parameters that we would like to reach as closely as possible at the end of the design study

- **Low Emittance:** is the core of LEMMA idea, the greatest benefit of the positron driven source. The ultimate value has to be determined by R&D studies, we know that it will be given by the convolution of different contributions. Our goal is to reduce multiple scattering to a negligible value and have the best possible matching at target [with 3 mm Be target the multiple scattering contributes for a factor 15 in emittance increase]

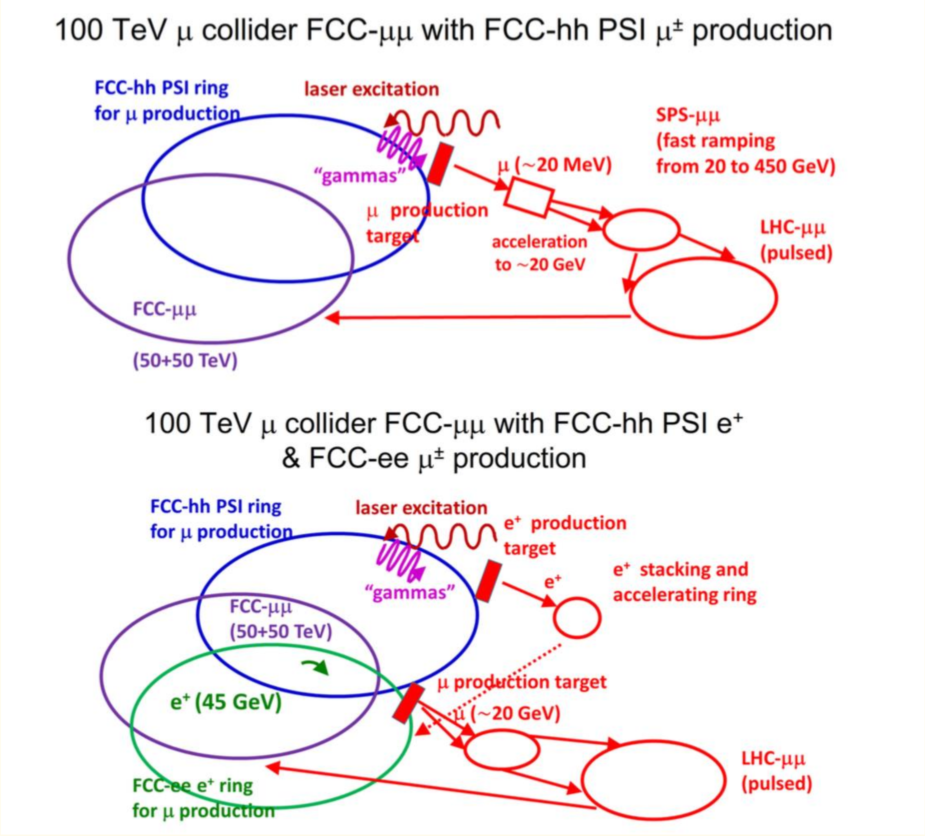
- **Bunch intensity $6x10^9$:** this value is possible only if a trick is applied to have multibunch collisions at IP in the transverse plane. P. Raimondi is proposing to investigate this possibility, requiring also half integer betatron tunes.
[w/o trick we have $4.5x10^7$]

- **β^*=0.2 mm:** aim is nano-beam scheme, final focus lattice not designed yet

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.

Back-up

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*” **Phys. Rev. Accel. Beams**, 21, 061005 (**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:

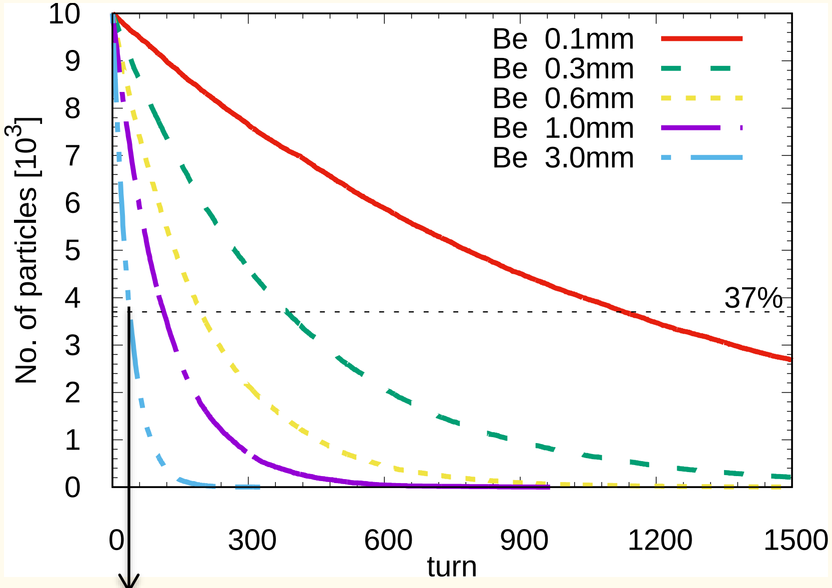
- *“Luminosity Estimate in a Multi-TeV Muon Collider using $e^+e^- \rightarrow \mu^+\mu^-$ as the Muon Source”*, MAP14 Spring worksh., Fermilab (USA)
- Advanced Accelerator Concepts Workshop, San Jose (USA), July 14

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

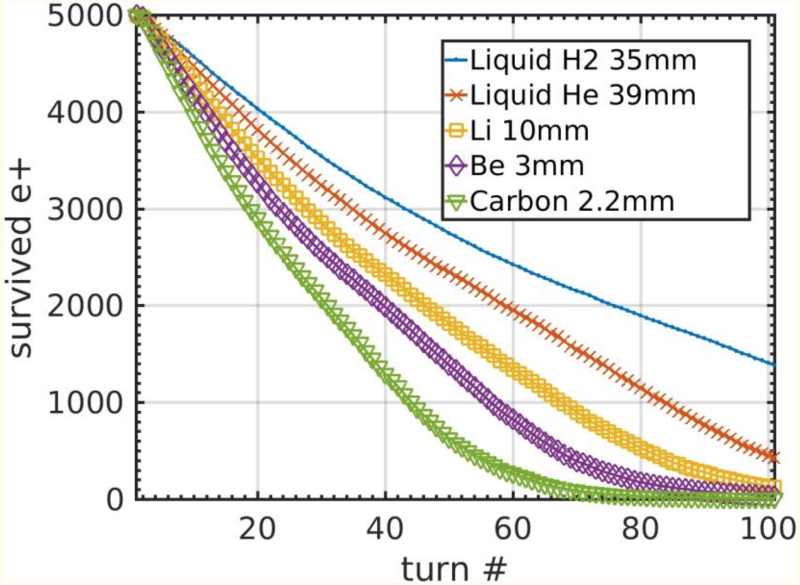
Lifetime ∝ 1/thickness as expected



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.