Low Emittance Muon Collider (LEMMA)

M. Boscolo (INFN-LNF)

Thanks to *the LEMMA collaboration and in particular to*
J. P. Delahaye, L. Keller, M. Palmer, N. Pastrone, P. Raimondi, D. Schulte, ...

gratefully acknowledging input from all contributors

INFN LNF
Istituto Nazionale di Fisica Nucleare

20th International Workshop on Neutrinos for Accelerators

Virginia Tech, Blacksburg, VA (USA) 12-18 August 2018

Outline

- Introduction
- Positron driven source
- LEMMA scheme
- Optics & Beam dynamics
- R&D on key topics
- Goal parameter table for Multi-TeV muon collider
- 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 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 > $10^{13}\mu$/sec $N_\mu = 2\cdot10^{12}$/bunch

MAP

Positron driven

from **direct μ pair production**:
muons produced from **$e^+e^-\rightarrow\mu^+\mu^-$** at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold
($\sqrt{s}\approx$ 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 $N_\mu \approx 6\cdot10^9$/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

Concept based on a positron driven source

- Muons are produced in positron annihilation on e^- at rest
  → e^+ beam impinging 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 opening the perspective to a Multi-TeV Muon Collider (MC)**

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)

Summary of LEMMA pro&cons features

Pro LEMMA:

- **μ beam divergence** can be **very small** close to the $\mu^+\mu^-$ threshold
  θ_μ is tunable with $\sqrt{s}$ in $e^+e^- \rightarrow \mu^+\mu^-$
- **Reduced losses from decay:** **high collection efficiency**
- **Low background:** **Luminosity at low emittance** will allow low background and low neutrino radiation $\rightarrow$
  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

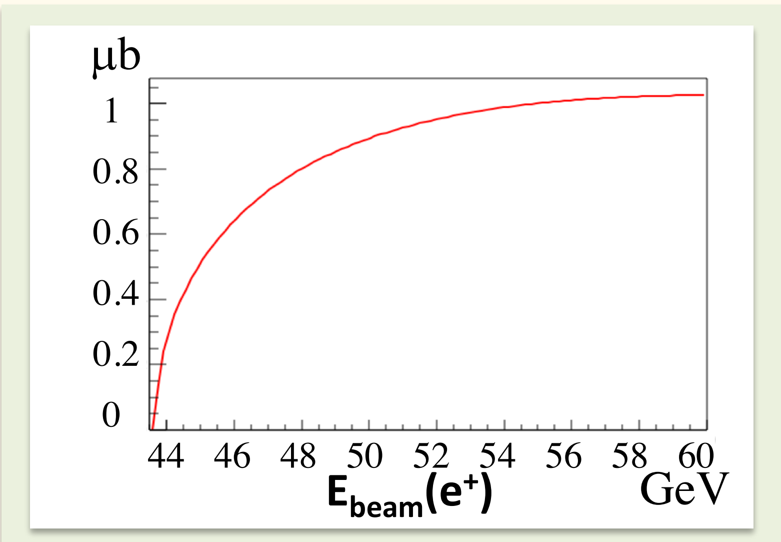
Cons LEMMA: Low μ prod. Rate

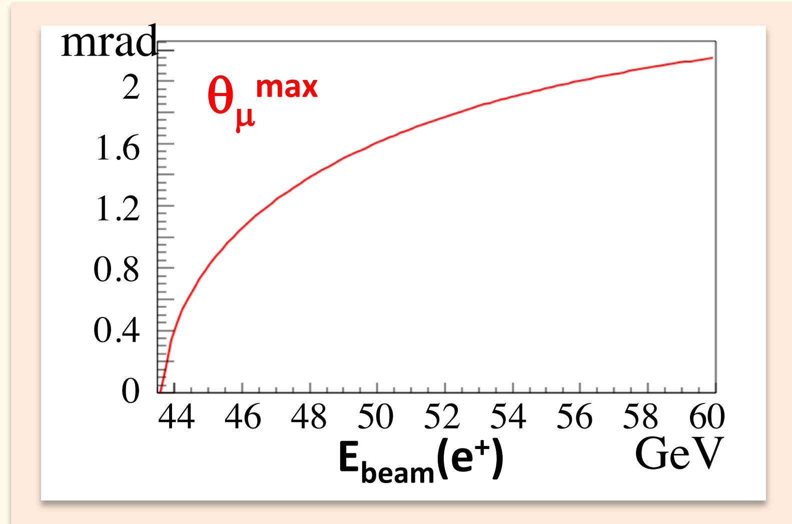
much smaller cross section wrt proton-driven-source

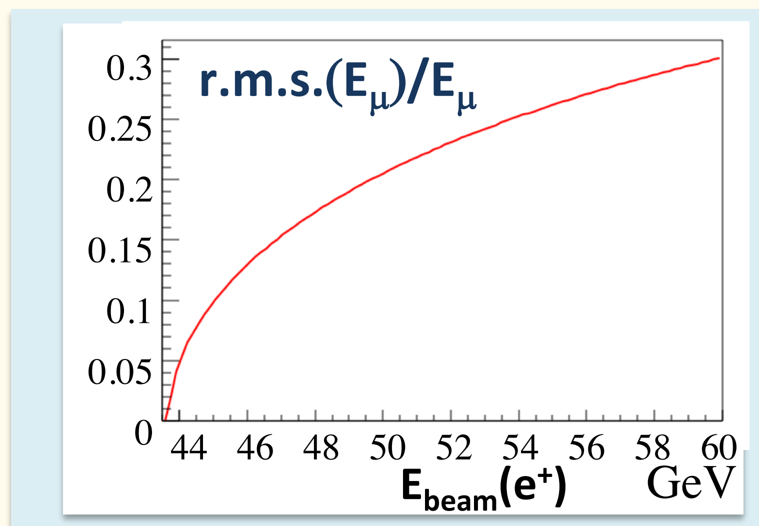
$\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx$ **1 μb** at most wrt σ(from p) $\approx$ **mb**

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 the energy spread

Radiological hazard due to neutrinos from a MC

- First studies by B.J.King in Proc. EPAC98, p. 841-843 and Proc. 1999 PAC p. 319
- C. Johnson, G. Rolandi and M. Silari, TIS-RP/IR/98-34 (1998)
- J.D. Cossairt, N.L. Grossman and E.T . Marshall, Health Phys. 73 (1997), 894-898 (on neutrino dose equivalent/fluence)
- see also D. Neuffer, MC workshop, Padova. 2-3 July 18 sl.9-10

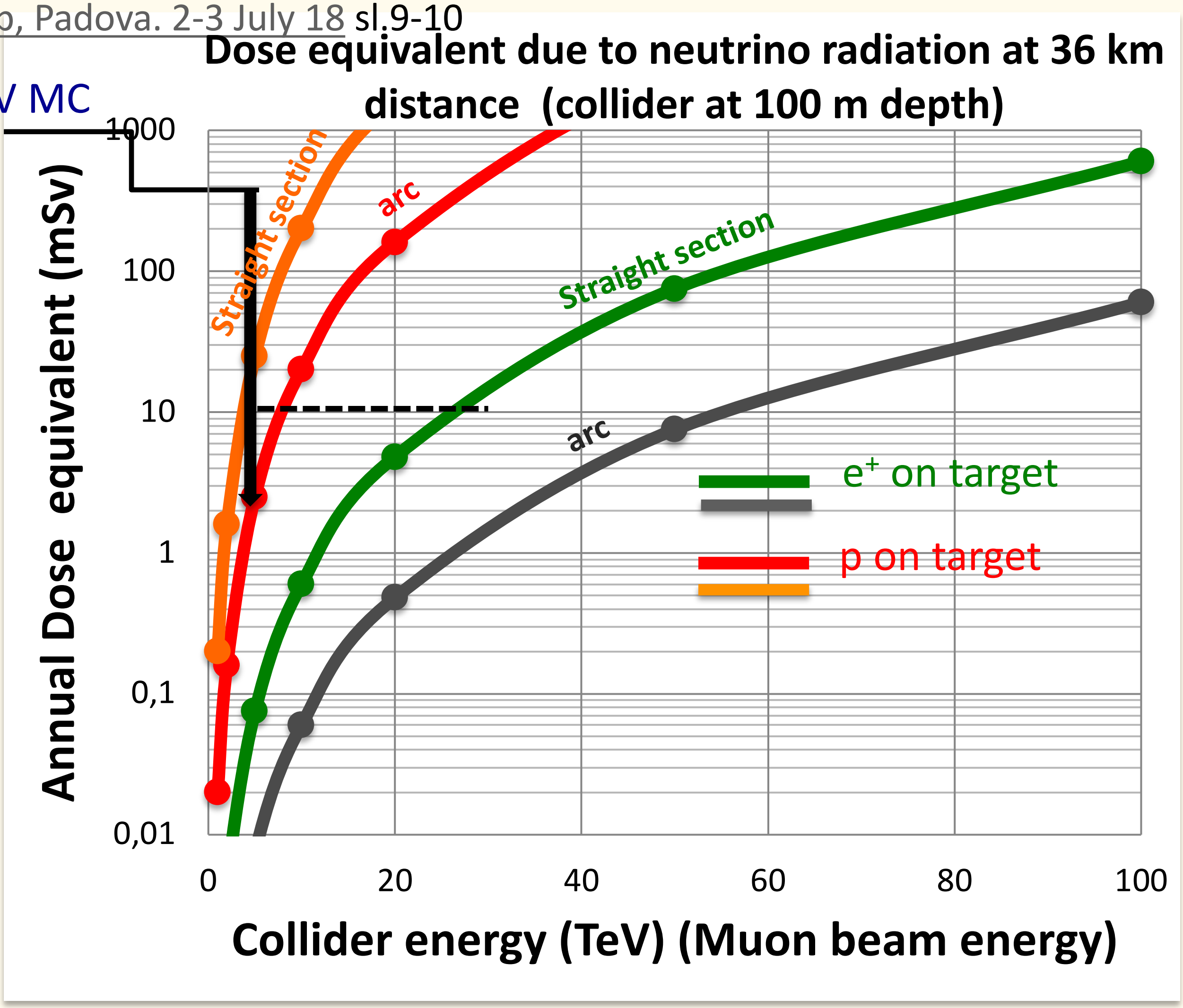
MAP design for a 6 TeV MC (500 m depth)

muon rate:

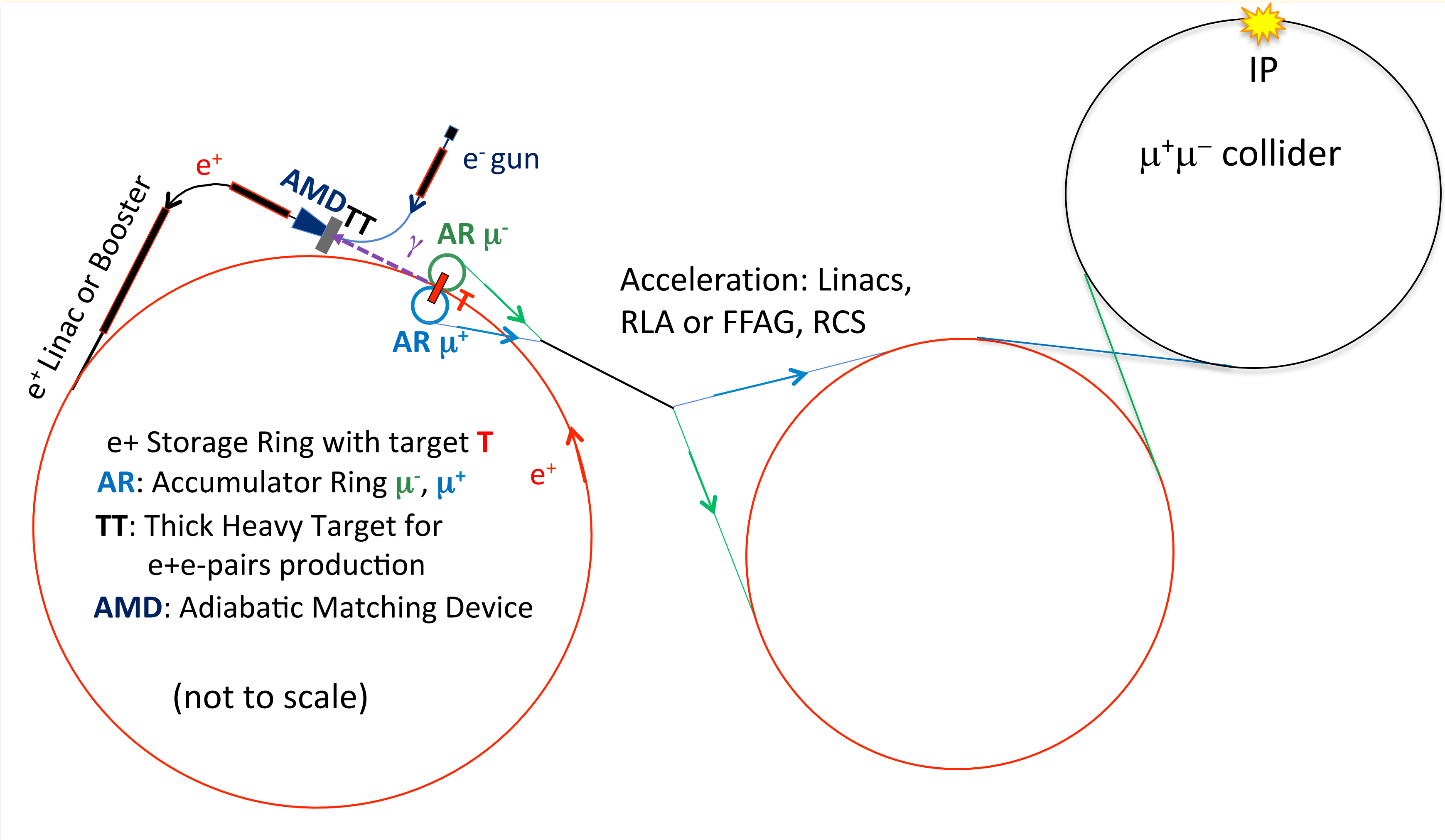
p on target option
3×10^{13} μ/s

e^+ on target option
9×10^{10} μ/s

This plot is based on numbers reported in C. Jonhson et al adding Lemma, M.Antonelli



LEMMA scheme



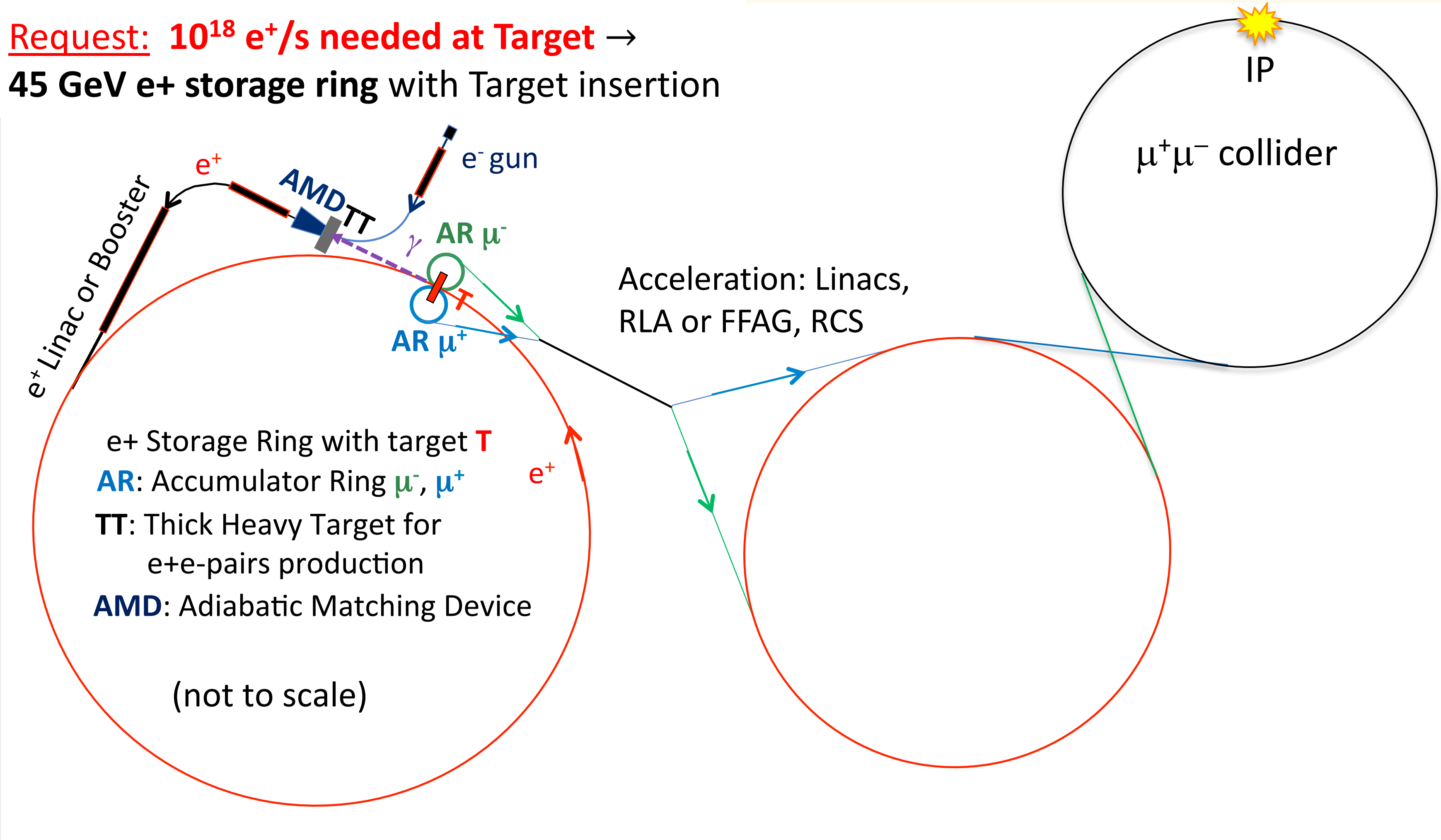
LEMMA scheme

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

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

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

45 GeV e+ storage ring with Target insertion



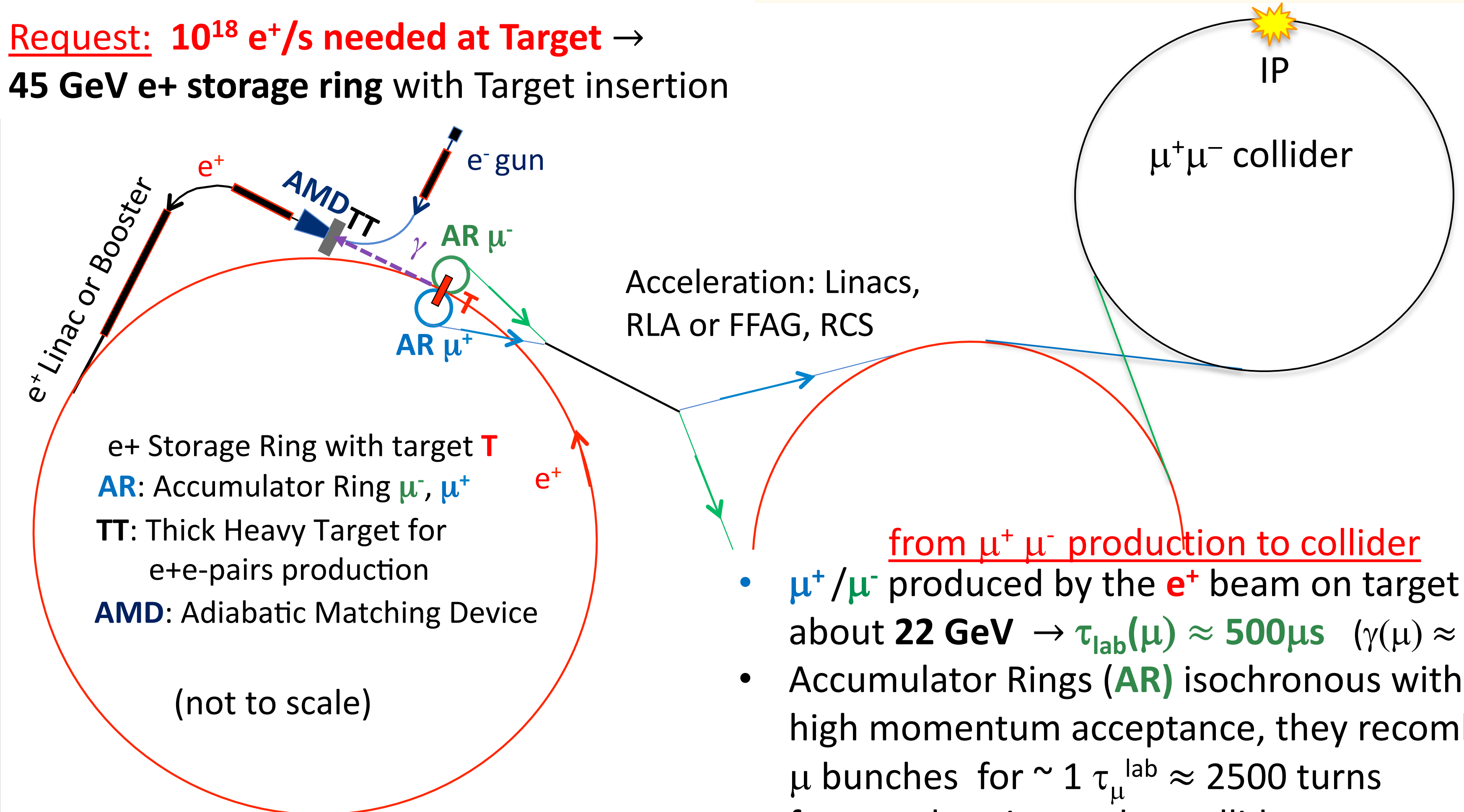
LEMMA scheme

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

with target efficiency $\approx 10^{-7}$ (Be 3mm)

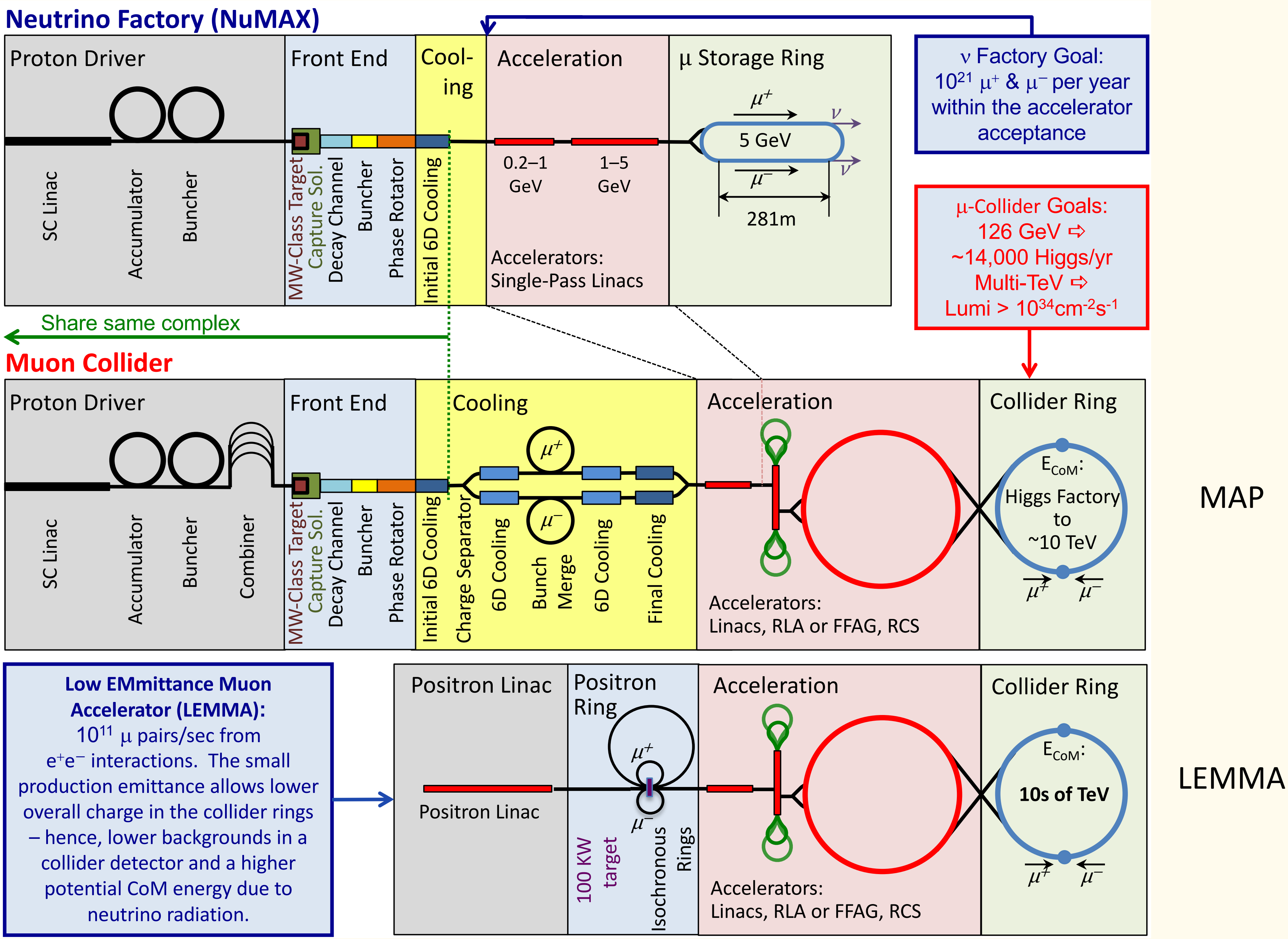
Request: **10^{18} e^+/s needed at Target** →

45 GeV e+ storage ring with Target insertion



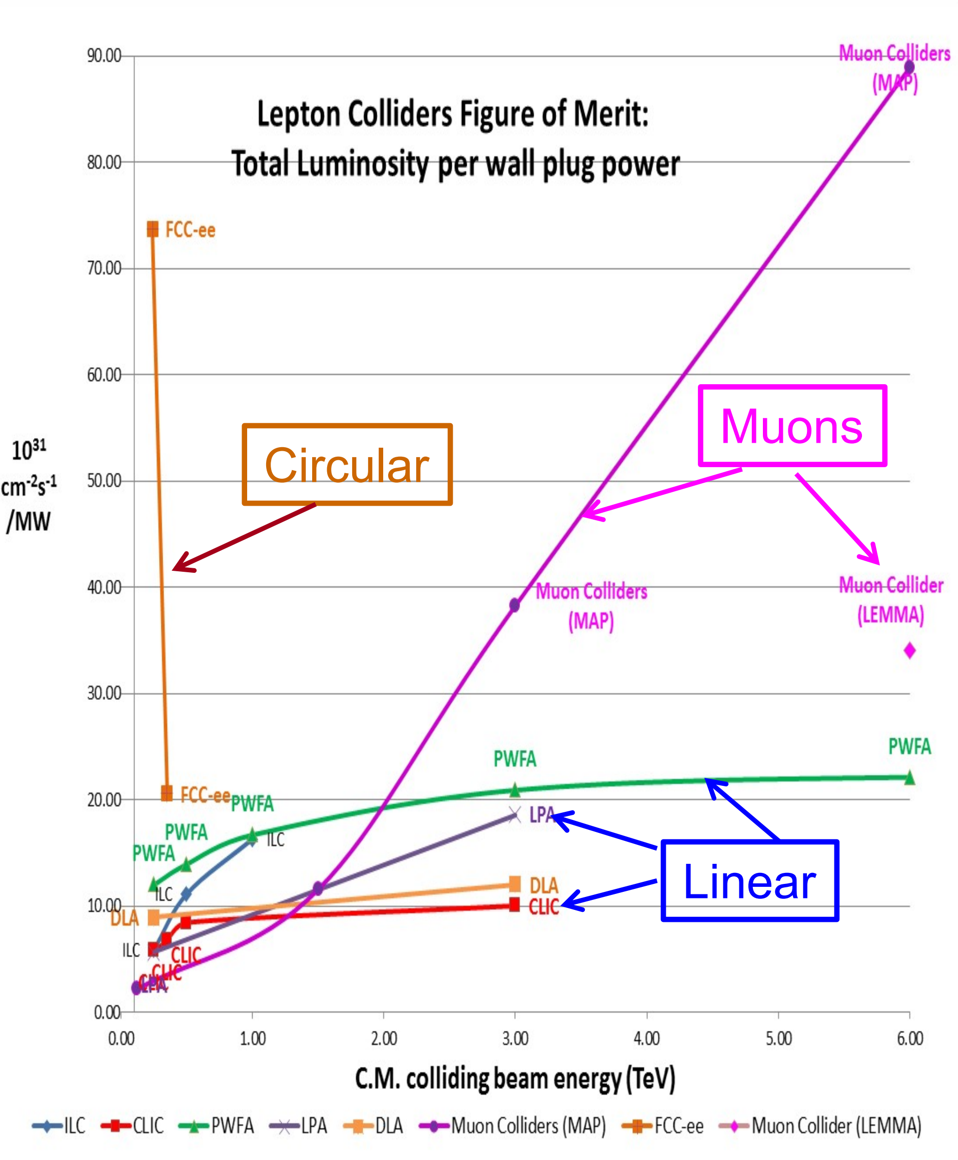
from $\mu^+ \mu^-$ production to collider

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



ArXiv: 1808.01858

Figure of merit: Luminosity per wall plug power



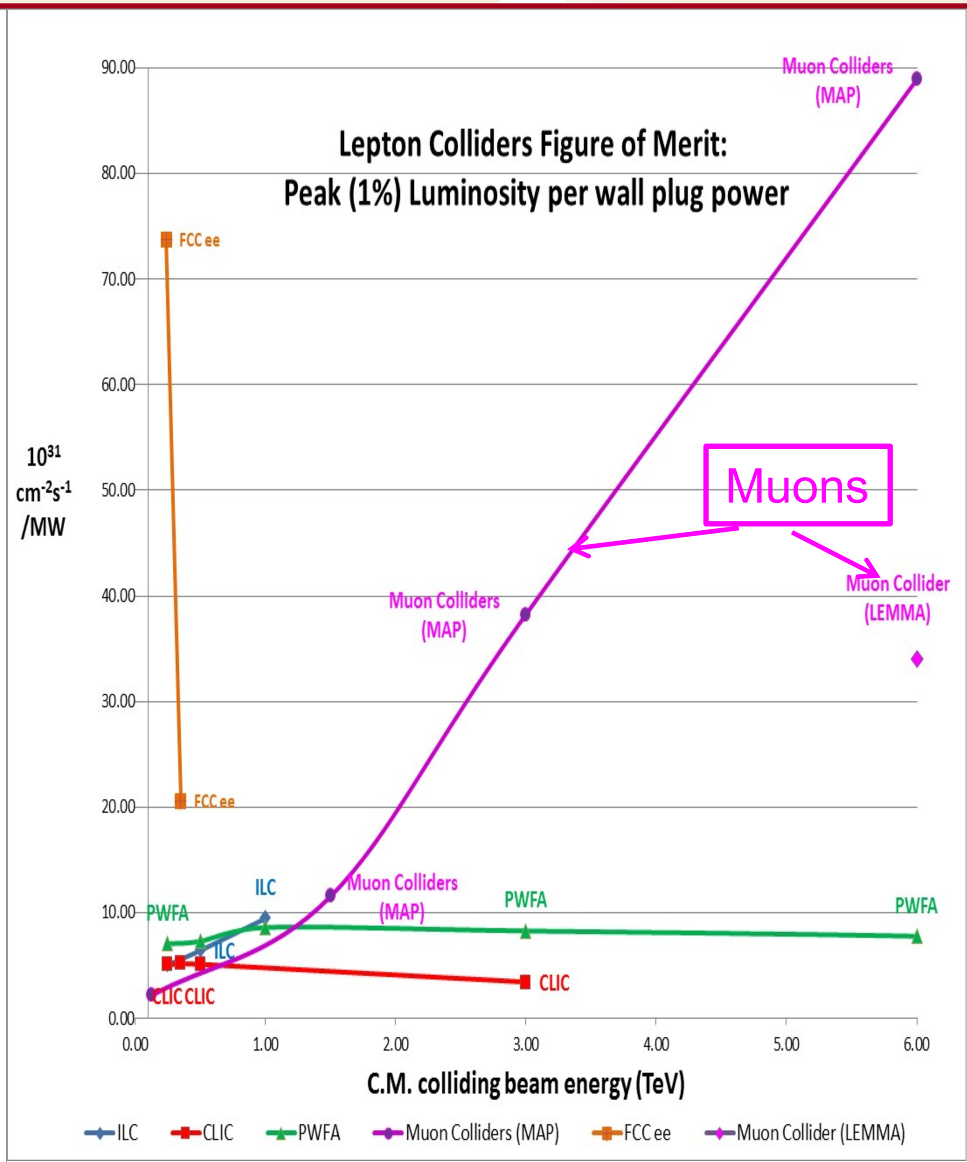
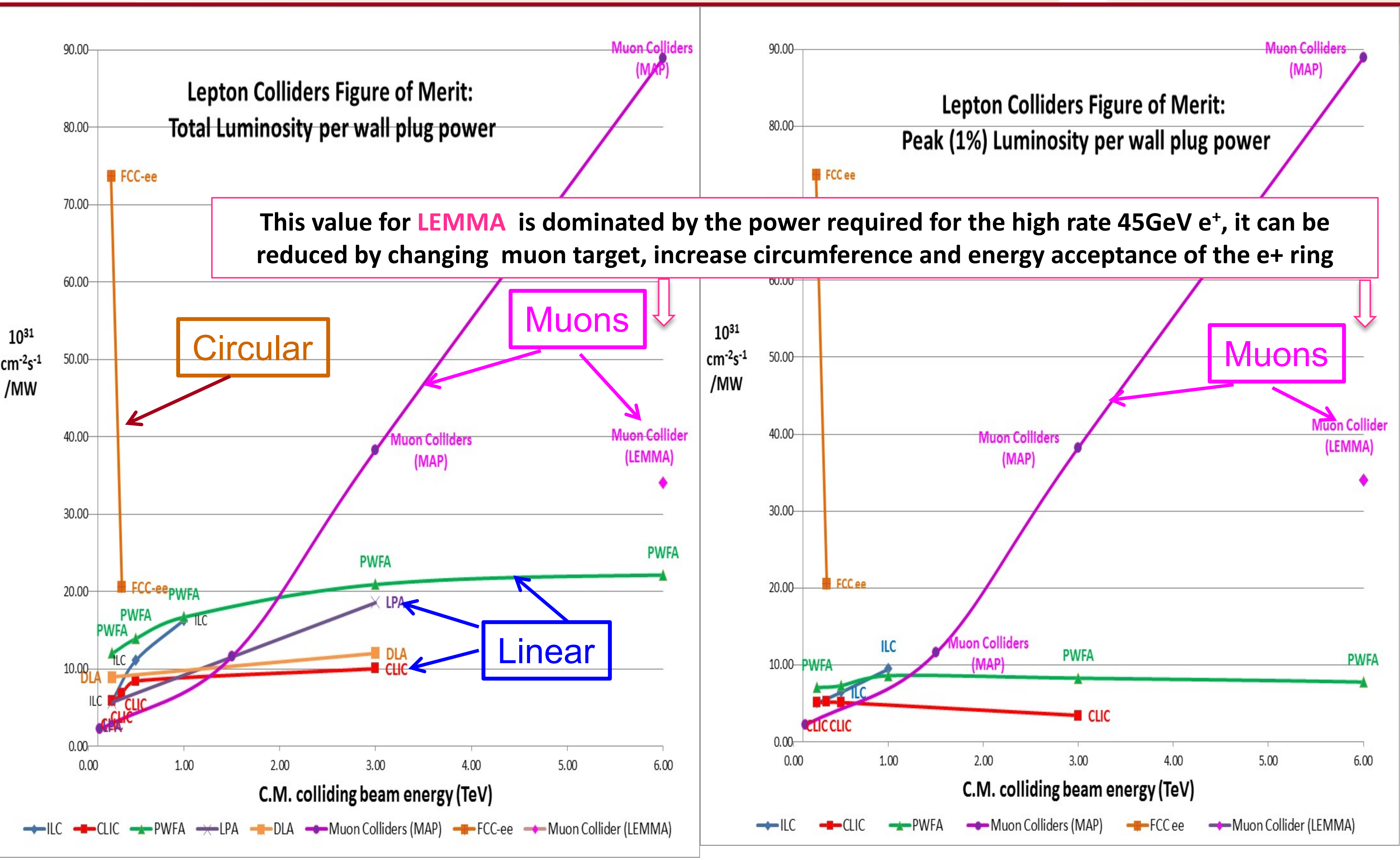


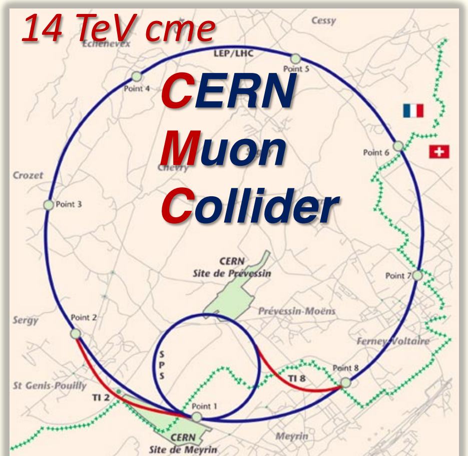
Figure of merit: Luminosity per wall plug power

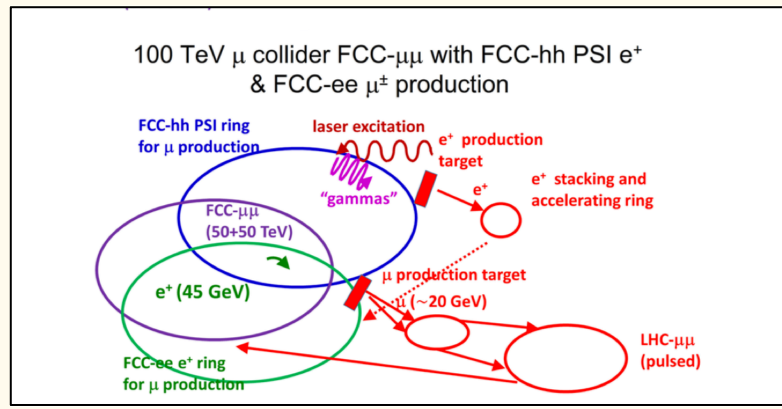


LEMMA concept and MC prospects

The LEMMA concept renewed the interest and extended the reach of Multi-TeV Muon Colliders

- Two interesting recent proposals:
  - **CERN Muon Collider @14 TeV c.m.e.** V. Shiltzev, D. Neuffer, Proc. IPAC18, MOPMF072
  - **LHC/FCC based MC** F. Zimmermann, Proc. IPAC18, MOPMF065





- In view of the **European Strategy Update** an international WG has been established last September 2017 to prepare the input on muon colliders.
- Recent updates discussed recently at : **ARIES Muon Collider Workshop**, Padova 2-3 July 2018 https://indico.cern.ch/event/719240/
- ***"The future prospects of muon colliders and neutrino factories"*** ArXiv: 1808.01858 M. Boscolo, J.P.Delahaye and M. Palmer, 6 August 2018

On going activity on the LEMMA proposal

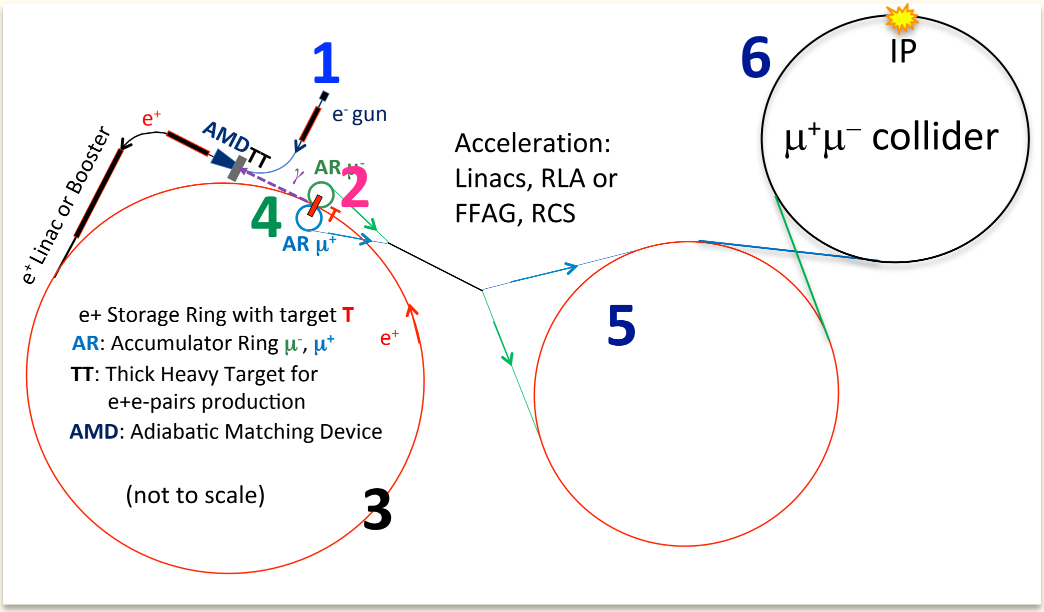
- **Our goal is to define the potentiality of this concept for a multi-TeV MC:**
  - **in terms of luminosity and beam power**
  - **design the optics for the accelerator complex**
  - **identify and possibly start with the necessary key R&D**

- **Updates** of our studies can be found in **Refs.:**
  - "***The future prospects of muon colliders and neutrino factories***", M. Boscolo, J.P.Delahaye and M. Palmer, ArXiv: 1808.01858, 6 August 2018
  - "***Low emittance muon accelerator studies with production from positrons on target***", Phys. Rev. Accel. and Beams 21, 061005 (June 2018)
  - "***Muon accumulator ring requirements for a low emittance muon collider from positrons on target***", M. Boscolo et al., in Proc. IPAC18, MOPMF087 (May 2018)
  - "***Proposal of an experimental test at DAΦNE for the low emittance muon beam production from positrons on target***", in Proc. IPAC18, MOPMF086 (May 2018)

Key steps of the study for LEMMA

1. High rate **e⁺ source**
2. **μ⁺/⁻ production target** (high peak energy density deposition (PEDD), power O(100 kW))
3. **e⁺ ring** (low ε and high momentum acceptance)
4. **Muon Accumulator Rings** (high momentum acceptance)
5. **Fast acceleration**
6. **Muon Collider**

All steps require R&D studies and raise challenges

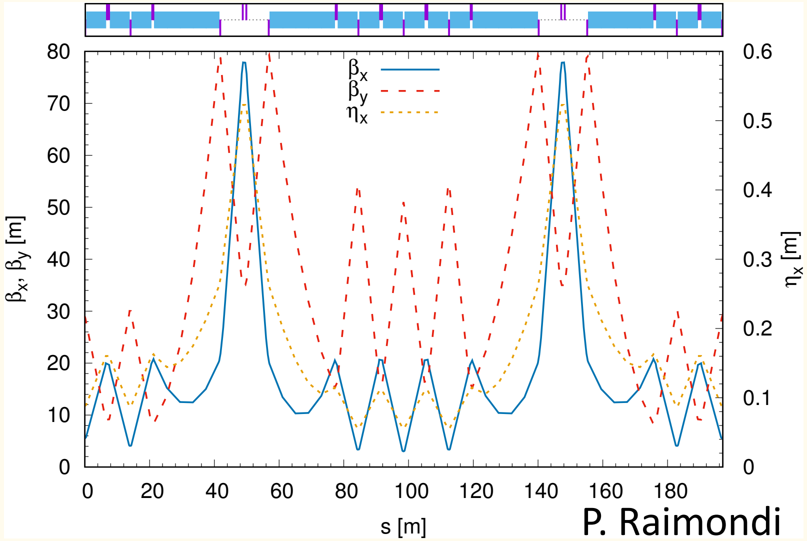


Optics design positron ring

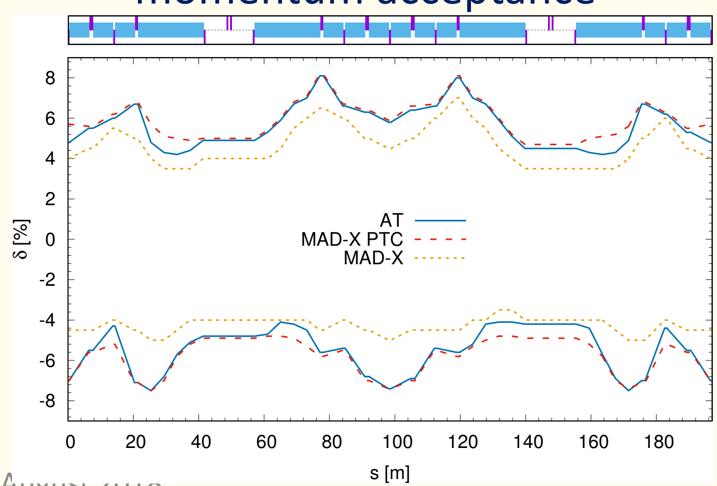
e+ ring parameter	unit	MAP option	LHC tunnel
Energy	**GeV**	**45**	**45**
Circumference	**km**	**6.3**	**27**
No.part./bunch	**#**	**$3 \cdot 10^{11}$**	
bunches	#	100	
e^+ bunch spacing = T_{rev} (AR)	ns	200	
Beam current	mA	240	
Emittance	nm	6	0.7
U_0	GeV	0.51	0.12
SR power	**MW**	**120**	**29**

S. Liuzzo, Padova workshop, 2-3 July 2018

Cell based on the Hybrid Multi Bend Achromat



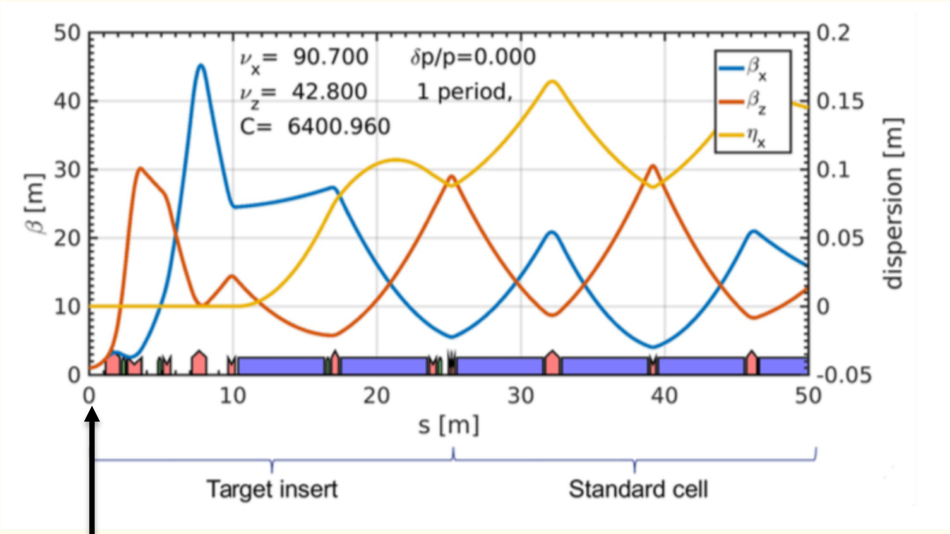
momentum acceptance



Optics design positron ring

e+ ring parameter	unit	MAP option	LHC tunnel
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	0.7
U_0	GeV	0.51	0.12
SR power	**MW**	**120**	**29**

Target Insertion Region



@target { $D_x \approx 0$; low-β ($\beta_{x,y}$=0.5 m) }

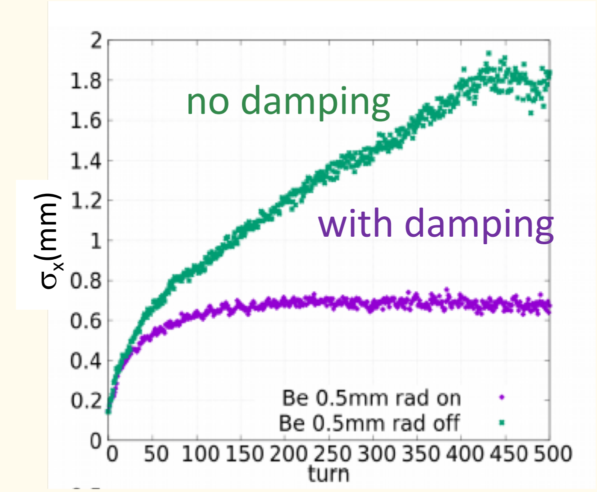
S. Liuzzo, Padova workshop, 2-3 July 2018

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)

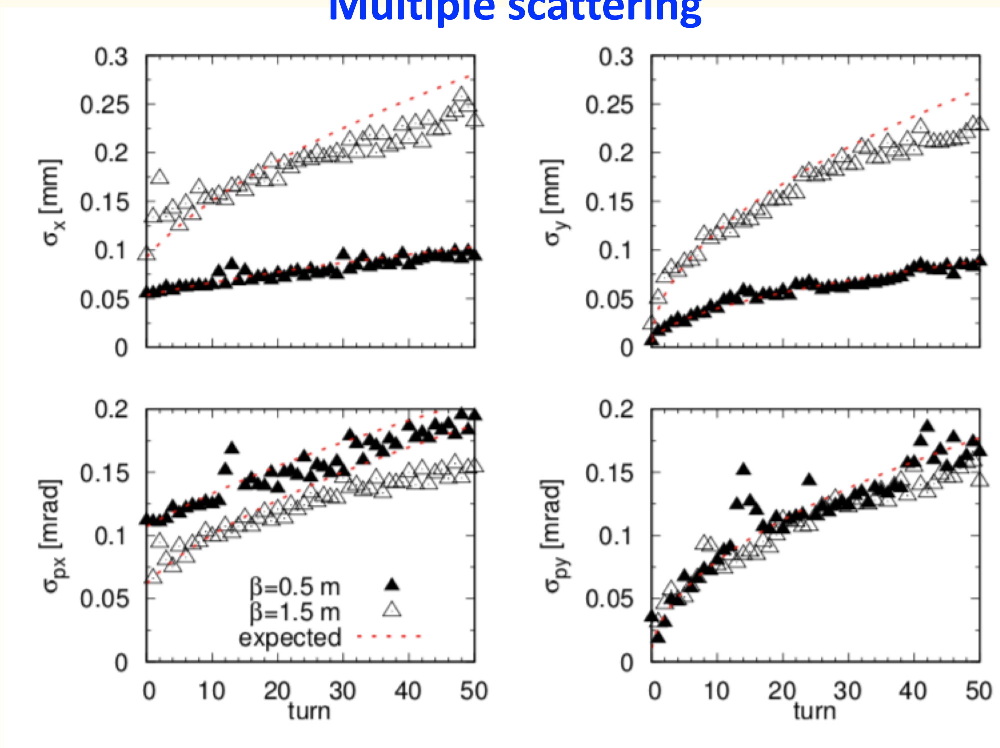


Beam dynamics e^+ beam in ring-with-target

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

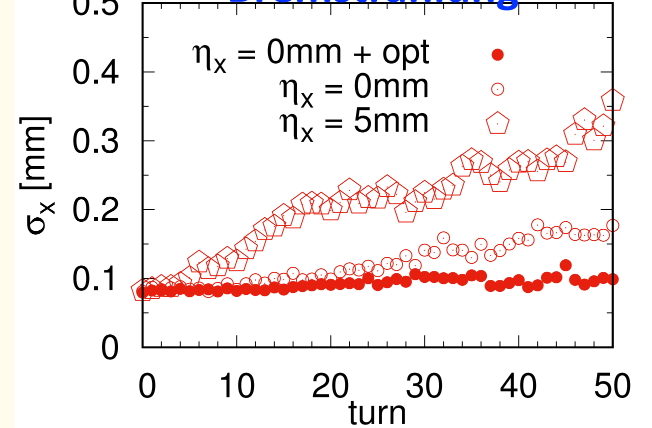
e^+ emittance growth controlled with proper β and D values @ target

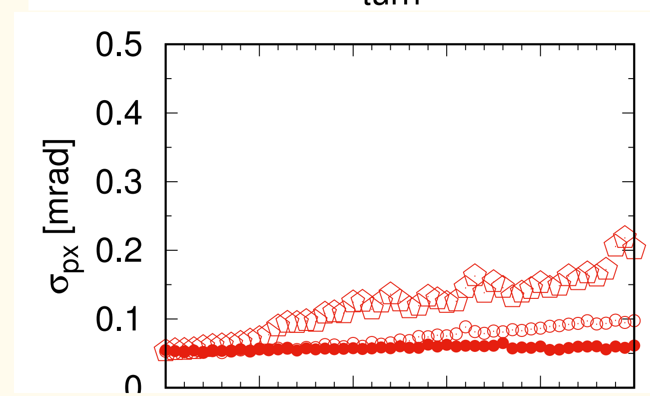
Multiple scattering



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

Bremstrahlung



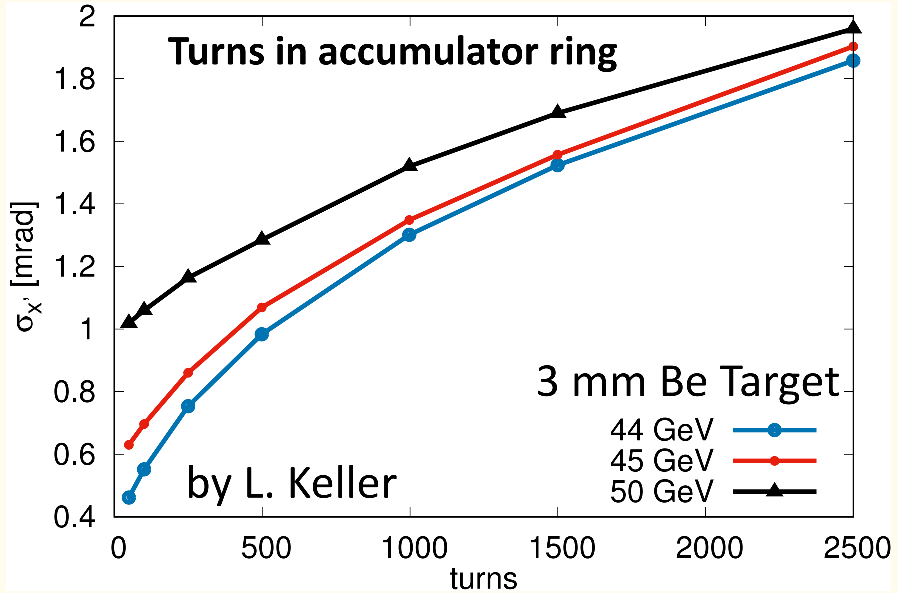


@Target :
linear and non-linear terms
of horizontal dispersion $\eta_x = 0$

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

Proc. of IPAC18, Vancouver, MOPMF087

R&D for the muon production target

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

- Engineering simulations and experimental tests will be required to find the optimal target material, considering mechanical stress and heat load resistance properties.
- We are considering now:
  - Beryllium seemed optimal from first MADX-/Geant-4 simulations
  - Carbon composites
  - Liquid Lithium
  - Hydrogen pellet
  - Crystals or more exotic targets

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

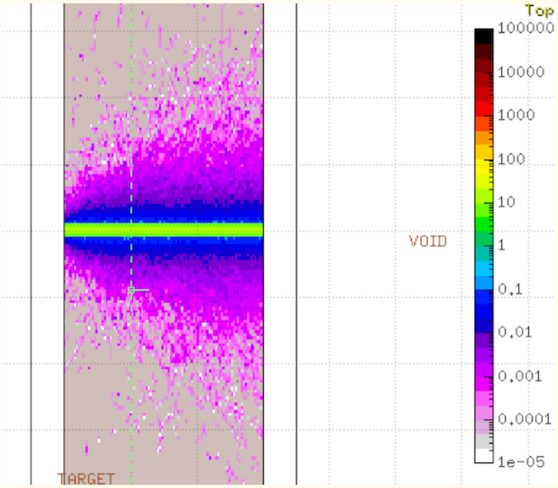
- **Solid target**: simpler and better wrt temperature rise
  - Be, C

  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



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

R&D on high rate positron source

- R&D on this topic can take advantage of significant synergies with future collider studies as FCC-ee, ILC and CLIC.
- The required intensity for LEMMA is strongly related to the beam lifetime, determined by the momentum acceptance and the target material.
- So, also optics and beam dynamics optimization is necessary.

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**

Present: 3 mm Be, 40 turns lifetime, $\Delta N/N$=2.5%, ΔN=2.5E+16, P= 247 MW
Goal: 3 mm Be, 240 turns lifetime, $\Delta N/N$=0.4%, ΔN=3.8E+15, P= 39 MW

R&D on Fast Acceleration for LEMMA

- Muon beams must be accelerated to high energy in a very short period of time to account for their short lifetime.
- Synchrotron radiation is not a limiting factor in accelerating muons at the TeV-scale, so multi-pass acceleration is preferred for cost considerations.
- LEMMA scheme utilizes a **natural cycle time of 2.2 KHz and cannot be matched to** the slower ramp rate of the MAP hybrid **Rapid Cycling Synchrotron**.
- For LEMMA two acceleration options to study are:
  - the Recirculating Linear Accelerator (**RLA**)
  - fixed-field alternating gradient (**FFAG**) machines with large energy acceptance
- Also accelerator technologies developed for the e+e- linear collider could be of benefit.

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

This table summarizes the goals of the LEMMA design study

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 (geo)	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

- **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 $6x10^9$:** a muon bunch charge of $4.5x10^7$ is provided by the AR, an enhancement by a factor 120 can be obtained by a combination scheme either in the longitudinal [D. Schulte] or in the transverse [P.Raimondi] plane. Feasibility needs to be studied, also to verify impact on emittance.

- **β^*=0.2 mm:** aim is nano-beam scheme, final focus lattice not designed yet, permanent quads might be used.

Conclusion

- **LEMMA is a novel concept for muon production, 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**
  - **Fast acceleration**
  - **Final focus at MC**

- Preliminary studies pioneered by the INFN-LNF group are promising, progresses require to continue the design study of the accelerator complex

- **More details this afternoon in parallel talk in WG3**

Back-up

Positron source requirements for LEMMA

	Be 3mm			LI 10mm			H2 lIquid 35mm		
Ring energy acceptance %	e^+ beam lifetime (turns)	ΔN/sec	P e^+ drive beam (MW)	e^+ beam lifetime (turns)	ΔN/sec	P e^+ drive beam (MW)	e^+ beam lifetime (turns)	ΔN/sec	P e^+ drive beam (MW)
5	35	2.69E+16	277	45	2.11E+16	217	78	1.21E+16	125
10	47	2.01E+16	207	62	1.53E+16	157	107	8.86E+15	91
20	71	1.34E+16	39	99	9.53E+15	98	163	5.80E+15	60

To evaluate the number of positrons per second required from the source we assume to have **100 bunches** with **3 10^{11} e^+/ bunch** stored in the ring for one beam lifetime

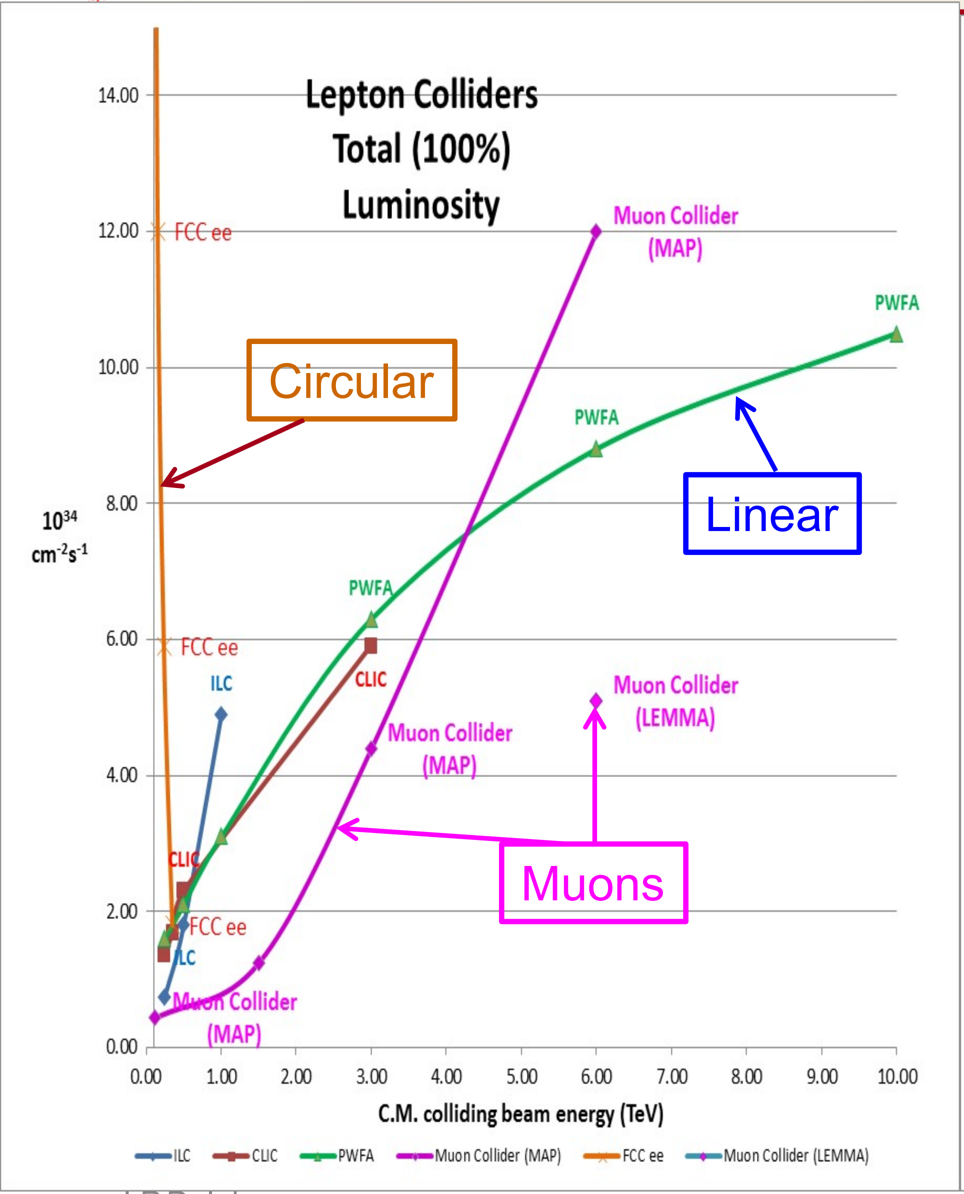
The drive beam power is given by the number of positrons accelerated per second up to 45 GeV

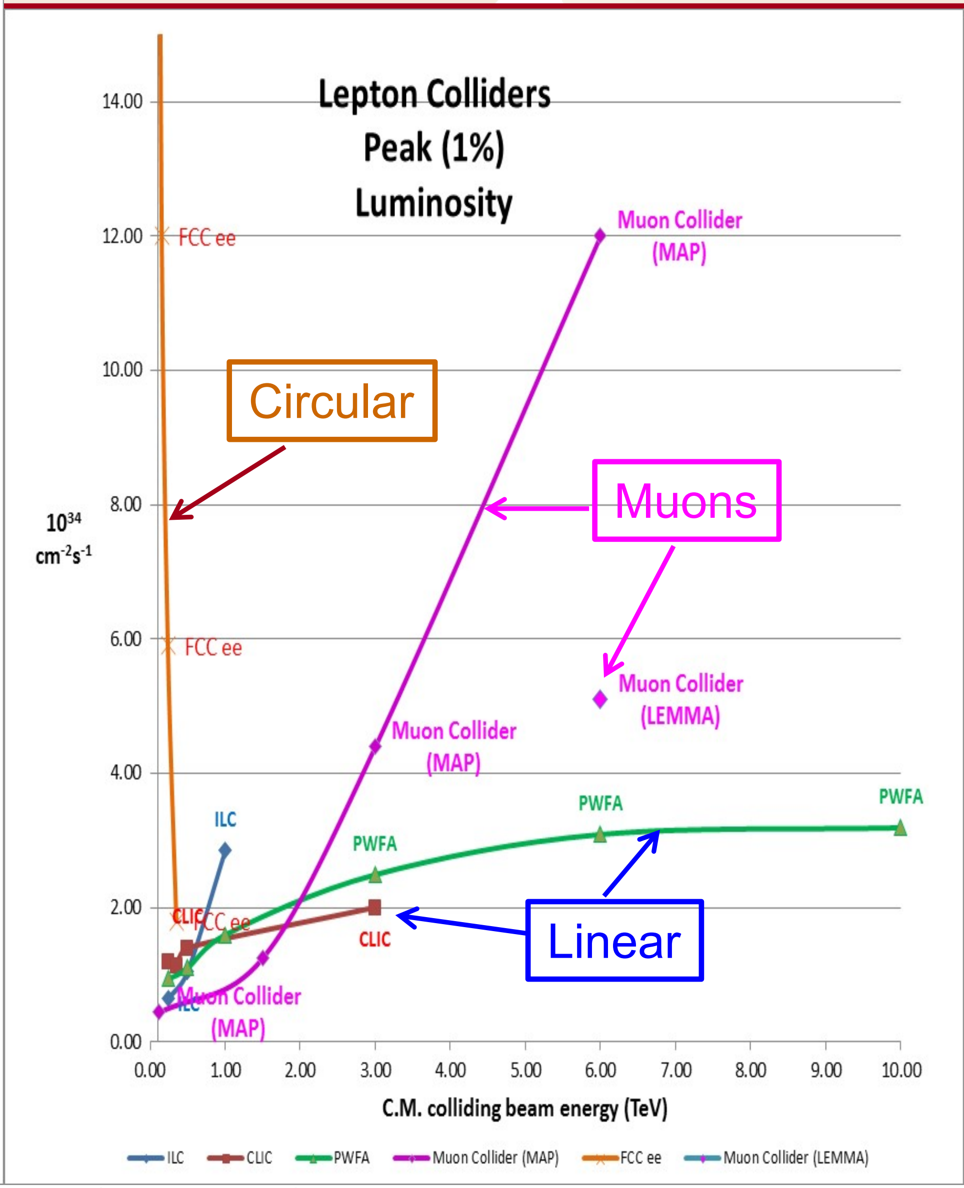
One of the objectives of the studies on the positron ring is to increase the ring energy acceptance in order to reduce the requirements on the positron source

Present ring: Dp/p = 6%, tau = 40 turns, e^+/s = 2.4e16, P= 250 MW

Target: tau> 100 turns, e+/s < 1e16, P < 100 MW

Lepton Colliders Luminosity





Conferences and Workshops

After first presentation in Snowmass

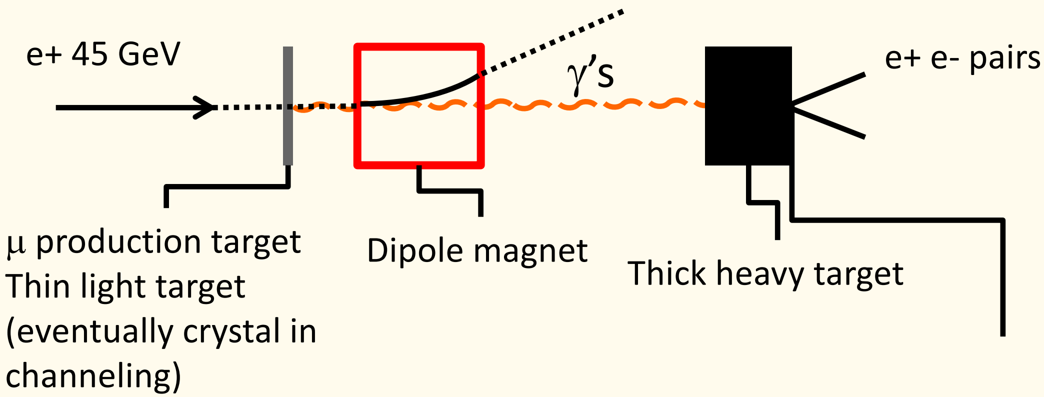
- P. Raimondi, *"Exploring the potential for a Low Emittance Muon Collider"*, in Discussion of the scientific potential of muon beams workshop, CERN, Nov. 18th 2015
- M. Antonelli, *"Low-emittance muon collider from positrons on target"*, FCCWEEK2016
- M. Antonelli, *"Performance estimate of a FCC-ee-based 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
- ARIES Muon Collider workshop, Padova 2-3 July 2018

not exhaustive list

R&D on high rate positron source

Embedded e+ source 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