Novel ideas for further studies in Europe

Low Emittance Muon Collider (LEMMA)

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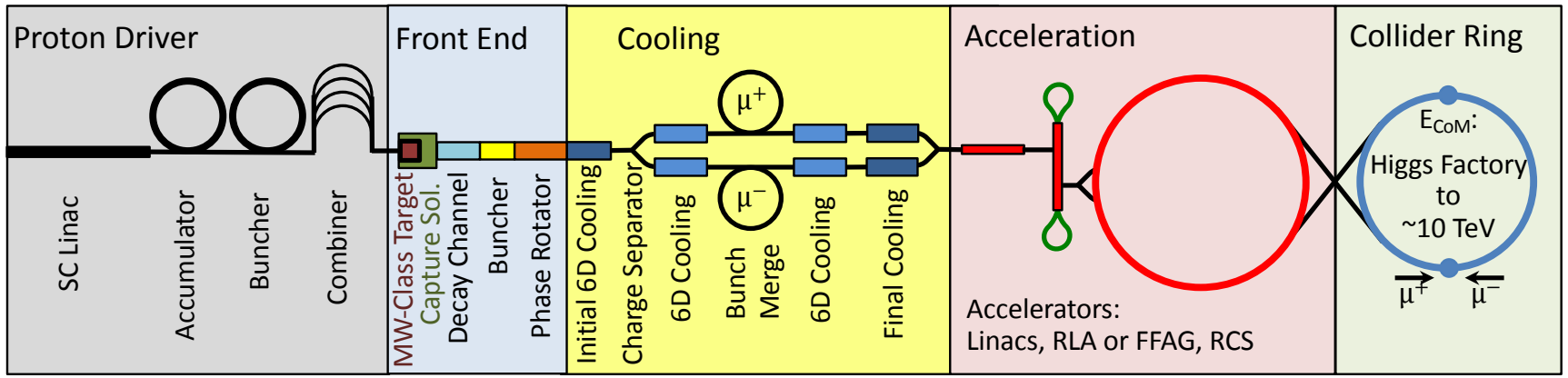
For the LEMMA team

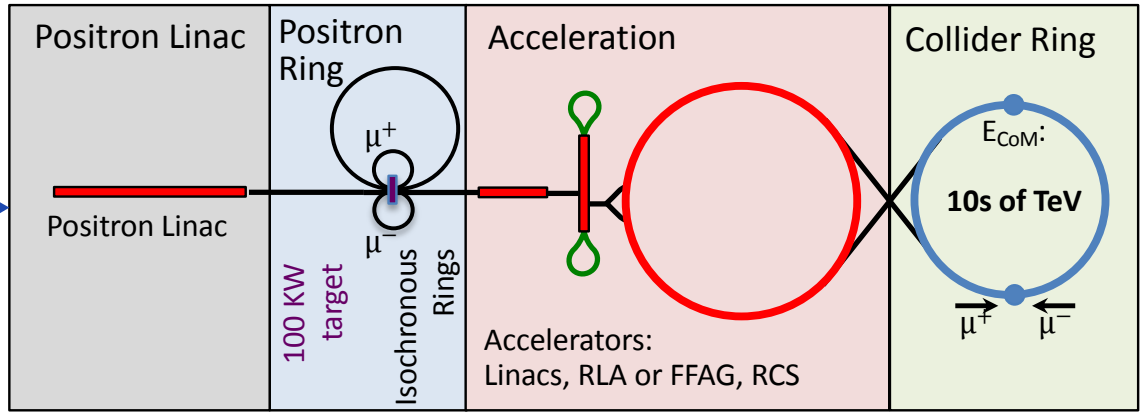
Outline

- Introduction
- Positron driven source
- LEMMA scheme
- Status
- Further studies on key topics
- Conclusion

LEMMA & MAP



Low EMmittance Muon Accelerator (LEMMA): 10^{11} ∝ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



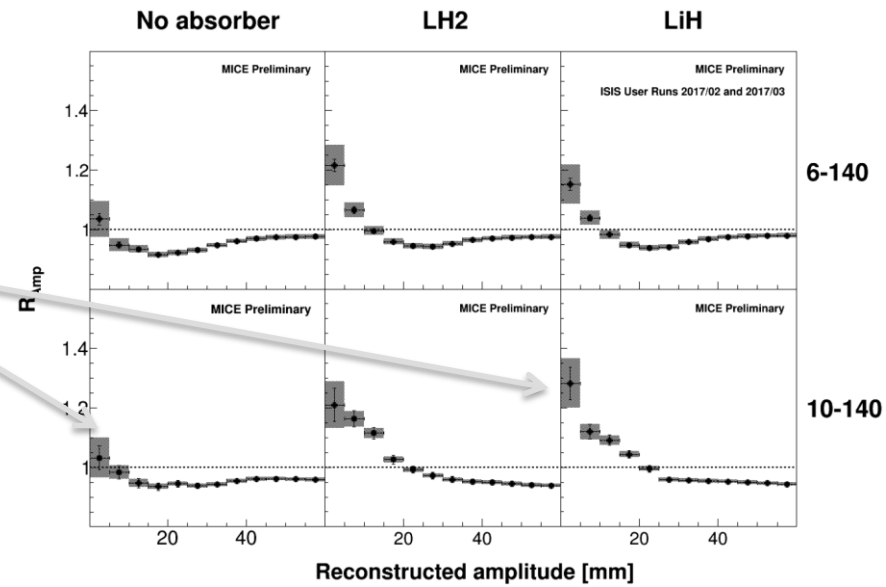
Not really a fair comparison: MAP studies much more advanced
LEMMA much simpler in principle but still many key aspects to be fully studied (this talk)

New tunnels and/or new high field magnets (e.g.HTS) and/or new acceleration could provide large benefits to both options

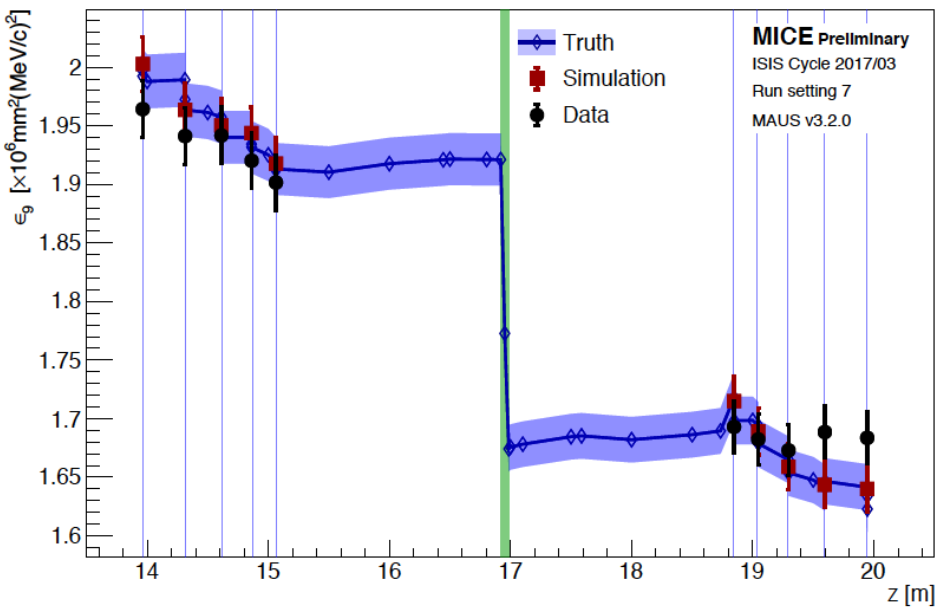
MICE selected Result

The absorber reduces the number of particle with large amplitude

They appear with smaller amplitude



Noticeable reduction of 9% emittance



But still some way to go
- 6D cooling
- Stages
- Small emittances

Muon production

from **proton on target:** p+target→π/K → μ

typically **P_μ ≈ 100 MeV/c** (π, K rest frame)

whatever is the boost P_T will stay in Lab frame →

very high emittance at production point → **cooling needed**!

from **direct μ pair production**:

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

⇩

NIM A Reviewer: ***"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 … "***

Advantages:

1. **Low emittance possible:** θ_μ is tunable with $\sqrt{s}$ in $e^+e^- \rightarrow \mu^+\mu^-$
   θ_μ can be **very small** close to the $\mu^+\mu^-$ threshold
2. **Low background:** Luminosity at low emittance will allow low background and low ν radiation (easier experimental conditions, can go up in energy)
3. **Reduced losses from decay:** muons can be produced with a relatively high boost in asymmetric collisions
4. **Energy spread:** muon energy spread **also small at threshold**, it gets larger as $\sqrt{s}$ increases

Disadvantages:

- Rate: much smaller cross section wrt protons ($\approx$ mb)

$$\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 1\ \mu b \quad \text{at most}$$

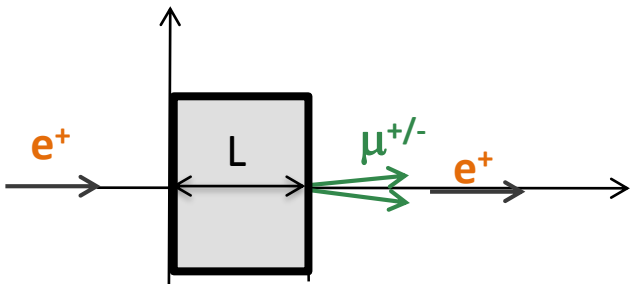
Possible implemetation

- **Low energy collider with e^+/e^- beam (e^+ in the GeV range):**
  1. Conventional asymmetric collisions (but required luminosity $\approx 10^{40}$ is beyond present capability)
  2. Positron beam interacting with continuous beam from electron cooling (too low electron density, 10^{20} electrons/cm^3 needed to obtain a reasonable conversion efficiency to muons)
- **Electrons at rest (seems more feasible):**
  3. e^+ on plasma target
  4. **e^+ on standard target** (eventually crystals in channeling)
  - **Need Positrons of $\approx$ 45 GeV**
  - $\gamma(\mu)\approx 200$ and μ laboratory lifetime of about 500 μs

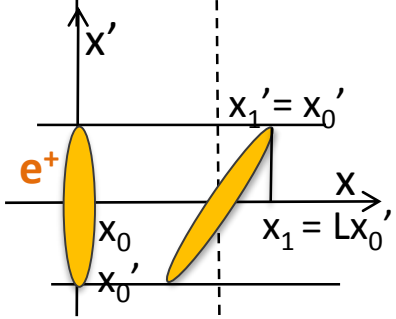
Ideally muons will *copy* the positron beam

Contribution to μ beam size due to finite target length

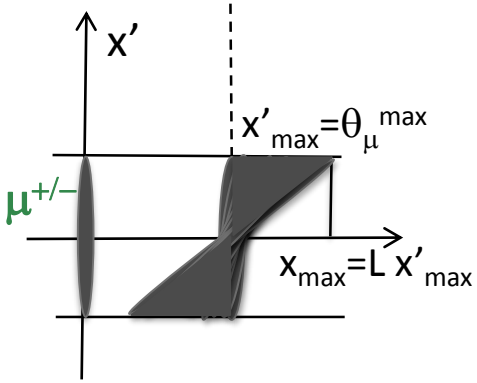
e^+ beam on target

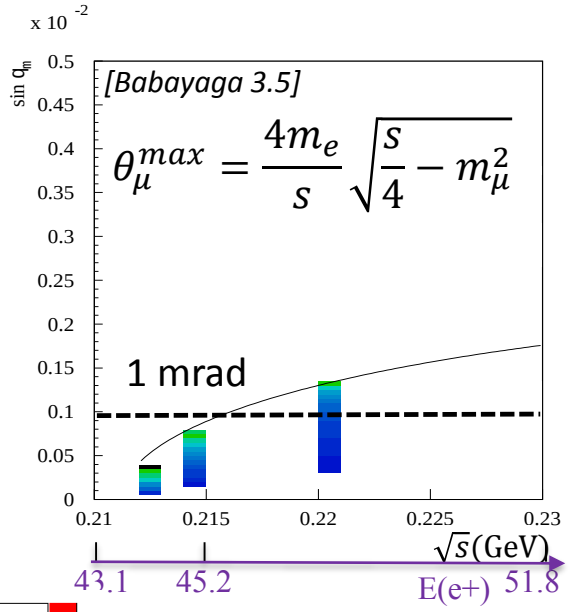


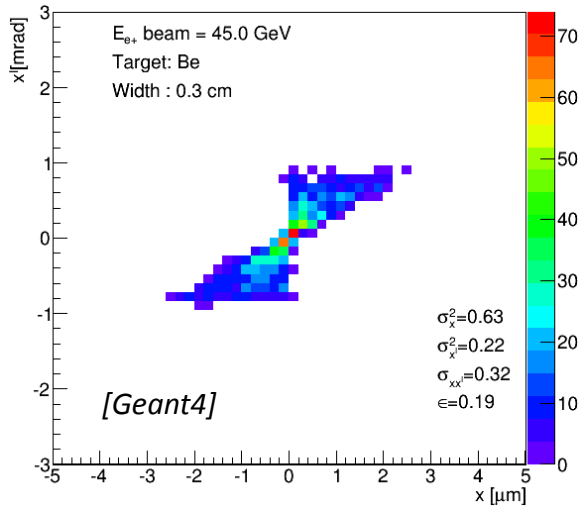
If L was a drift



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

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 (ε_μ □ 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

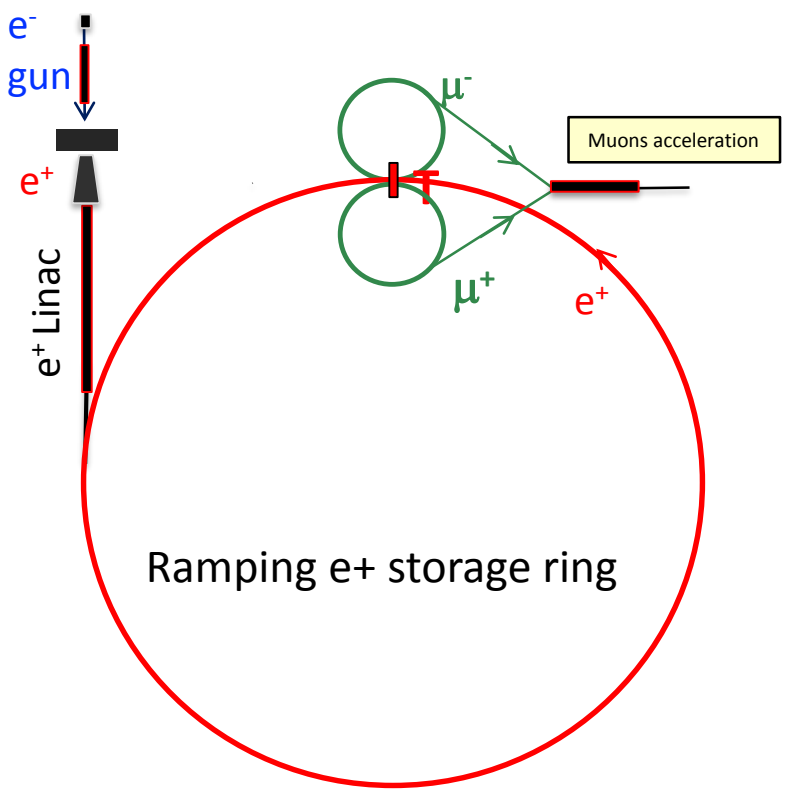
  $\sigma(e^+\text{loss}) \approx \sigma(\text{Brem+bhabha}) \approx (Z+1)\sigma(\text{Bhabha}) \rightarrow$

  $N(\mu^+\mu^-)/N(e^+) \approx \sigma_\mu/[(Z+1)\sigma(\text{Bhabha})] \approx 10^{-7}$
- **Very light materials, thick target**
  - **maximize $\mu^+\mu^-$ conversion efficiency ≈ 10^{-5}** (enters quad) → H_2

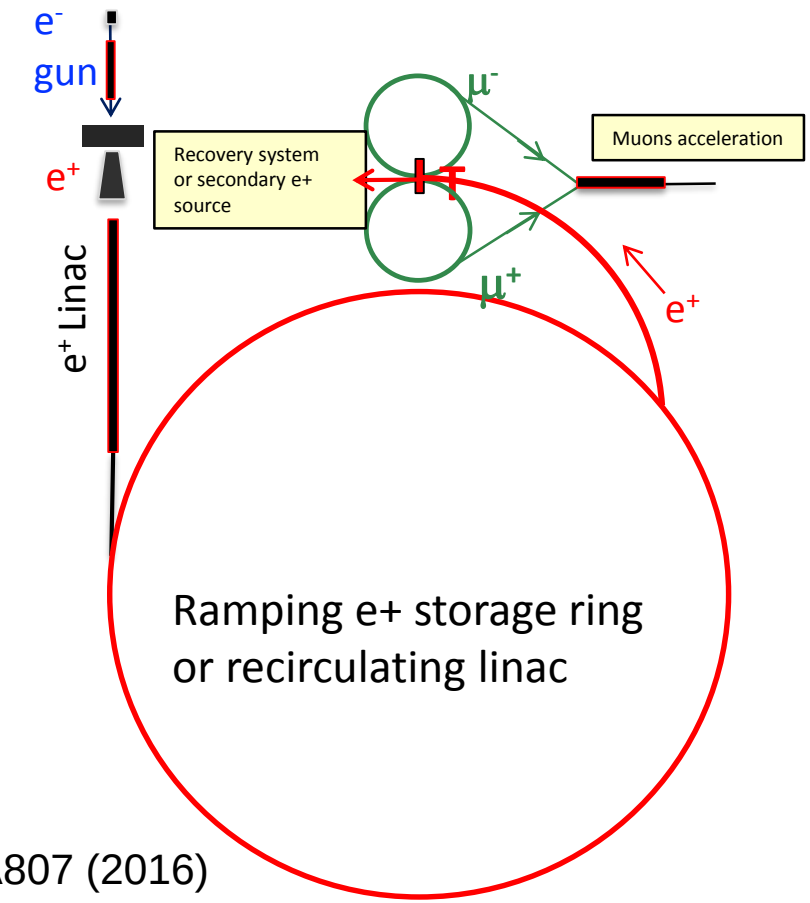
  Even for liquid targets O(1m) needed → ε_μ □ L increase
- **Not too heavy materials (Li, Be, C)**
  - Allow low ε_μ with small e^+ loss **$N(\mu^+\mu^-)/N(e^+) \approx 10^{-6}$**

Possible schemes for muon production

Multi-pass scheme



Single-pass scheme



Nucl.Instrum.Meth. A807 (2016)

Multi-pass scheme

Goal:

@T ≈ 10^{11} μ/s

Efficiency ≈ 10^{-7} (with Be 3mm)→

10^{18} e^+/s needed @T →

e^+ "stored" beam with T

need the largest possible lifetime to minimize positron source rate

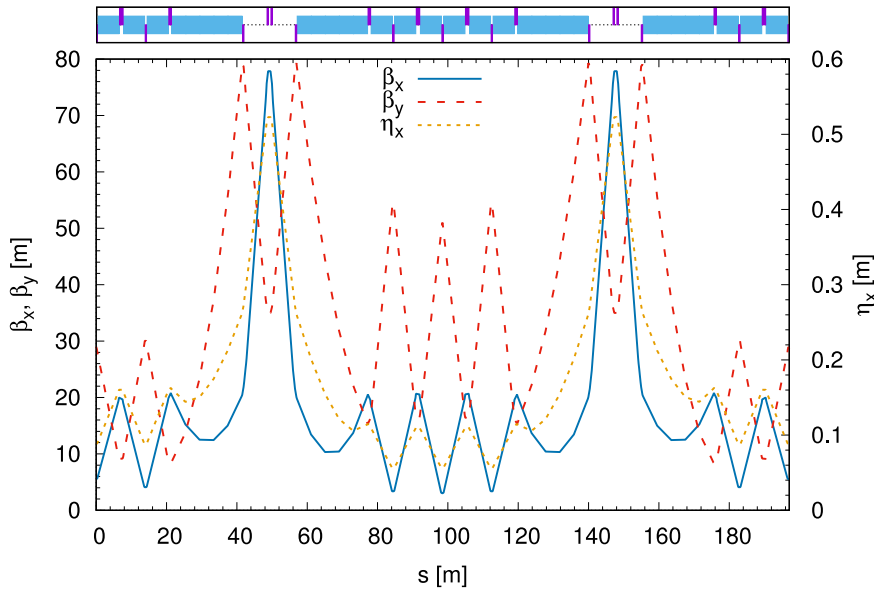
LHeC like e+ source required rate with lifetime(e+) ≈ 250 turns [i.e. 25% momentum aperture →

n(μ)/n(e^+ source) ≈ 10^{-5}

- **Low emittance and high momentum acceptance 45 GeV e^+ ring**
- **O(100 kW) class target in the e^+ ring for μ^+ μ^- production**
- **High rate positron source**
- **High momentum acceptance muon accumulator rings**

Low emittance 45 GeV positron ring

cell

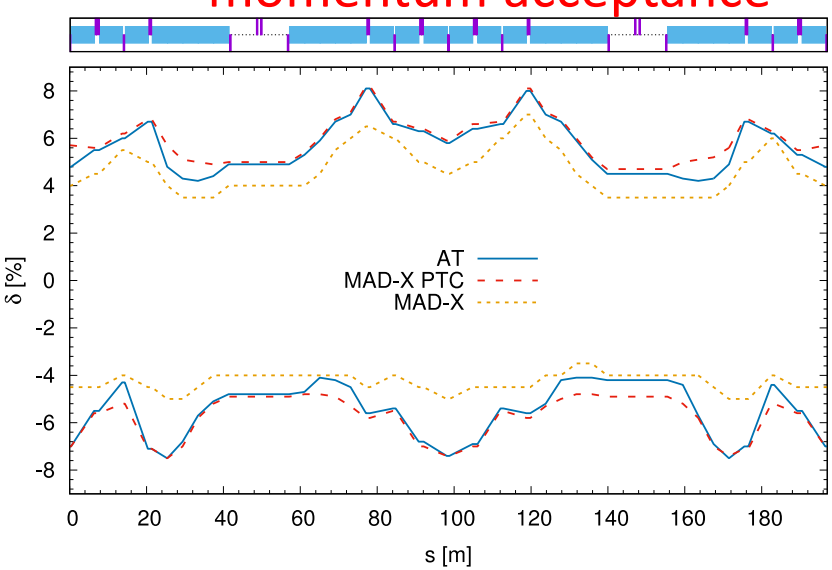


circumference 6.3/27 km: 197 m x 32 cells

Table e+ ring parameters

Parameter	0.7 nm	6 nm	10 nm
Circumference [km]	27	27	27
N. cells	64	32	32
I_b [A]	0.89	0.89	0.89
N_{part} /bunch	$5x10^{11}$	$5x10^{11}$	$5x10^{11}$
N. bunches	1000	1000	1000
E_{loss}/turn [GeV]	0.12	0.12	0.19
Nat. σ_z [mm]	1.9	3.6	3.8
α_c	$2.9x10^{-5}$	$1x10^{-4}$	$1.1x10^{-}4$
Energy spread	$7x10^{-4}$	$7x10^{-4}$	$9x10^{-4}$
$\tau_{x,y}$ [ms]	68	66	42
Energy acceptance [%]	± 8	±6	± 2
SR power [MW]	106	109	170

momentum acceptance



Physical aperture=5 cm constant

no errors

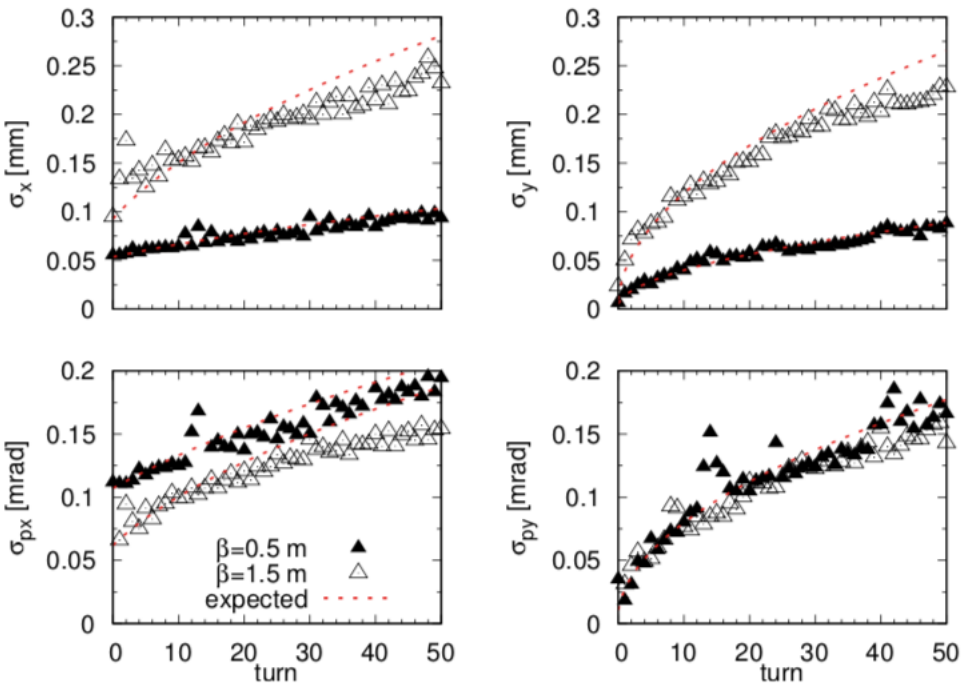
Good agreement between MADX PTC / Accelerator Toolbox, both used for particle tracking in our studies

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

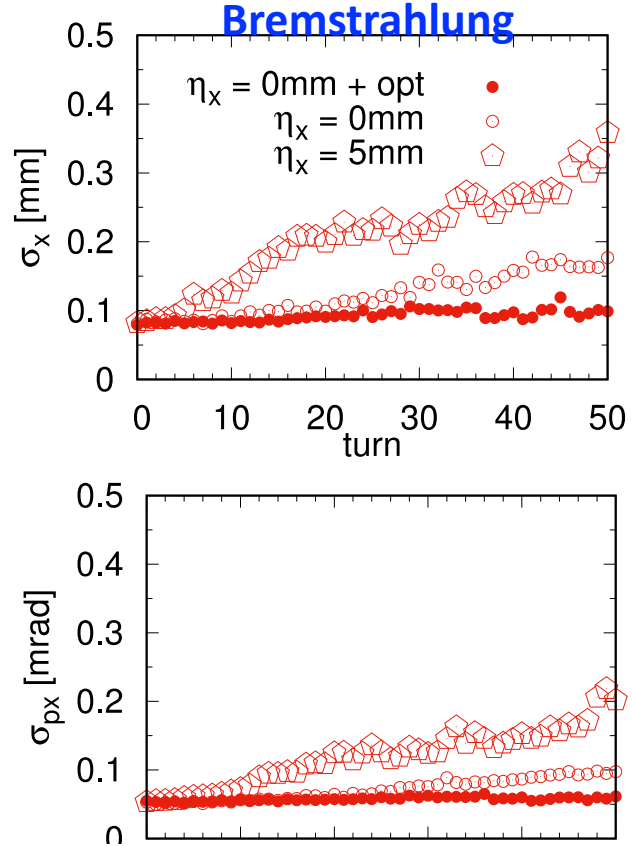
More details in: PR-AB 21, 061005 (2018)

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

Multiple scattering



Bremstrahlung



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

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

Comments on multi-pass scheme

CONS

- High power on target
- Low number of muons per bunch: do not have a realistic scheme for recombination at high energy
- Muon beam almost in CW, not compatible with acceleration by synchrotron
- The same is true for positron beam replacement (source + acceleration + injection)

PROS

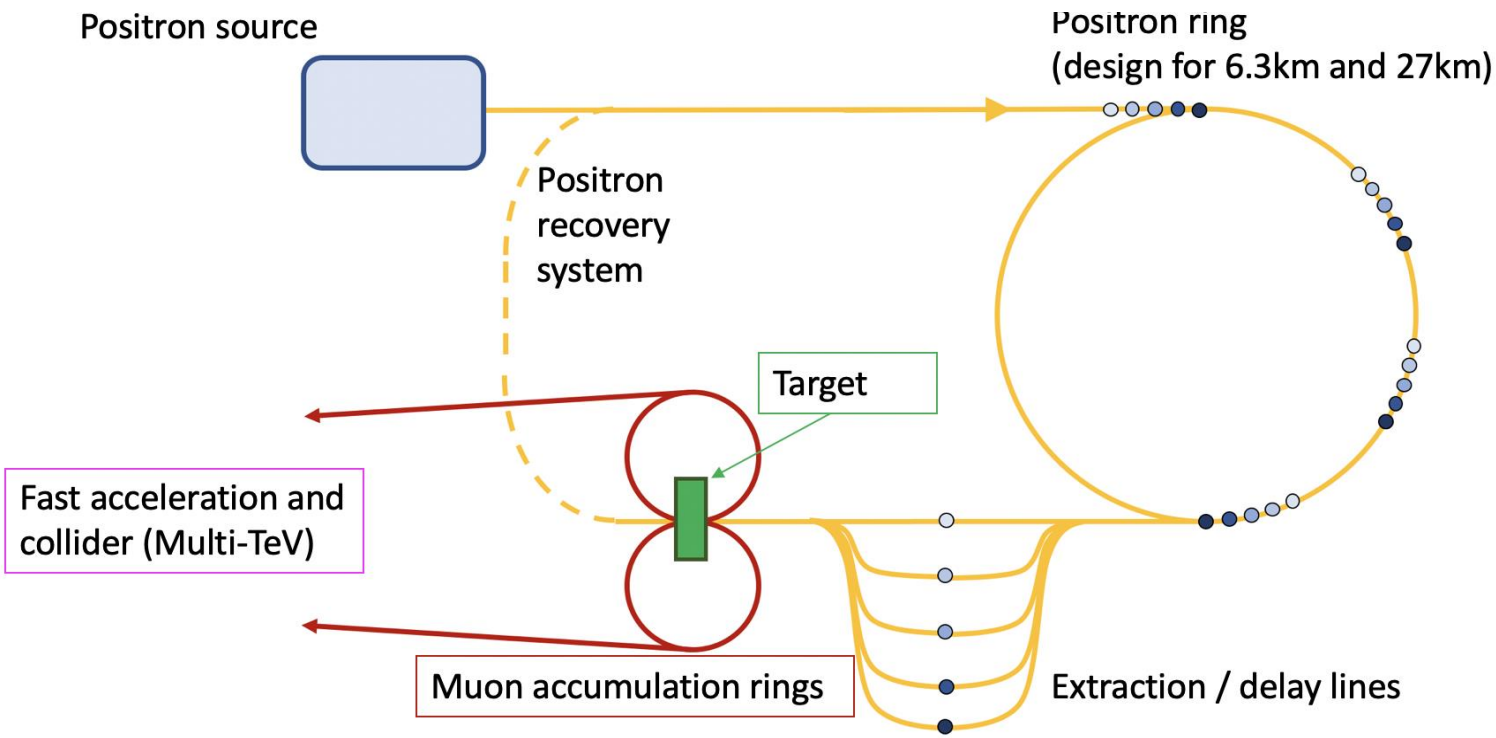
✓ muon emittance is small

Single-pass scheme

arXiv:1905.05747

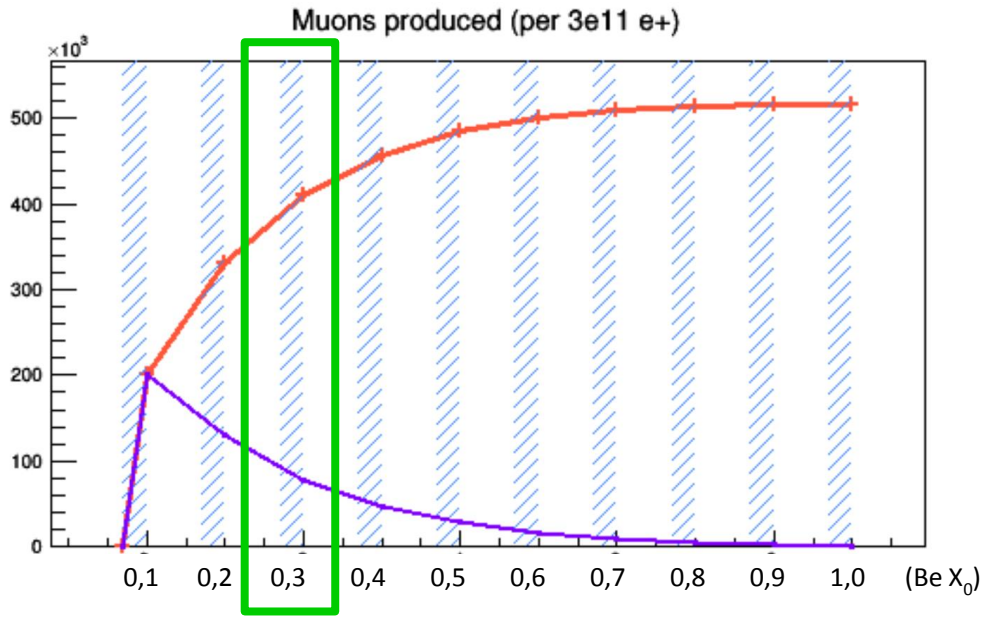
positron beam passes only once through a ~X0

- **More muons** produced per bunch
- **Power can be distributed** over a long target



- Full preliminary accelerator complex description including all subsystems in arXiv:1905.05747: e^+ sources, e^+ rings, compressor linac, target system….
  - State of the art and future R&D

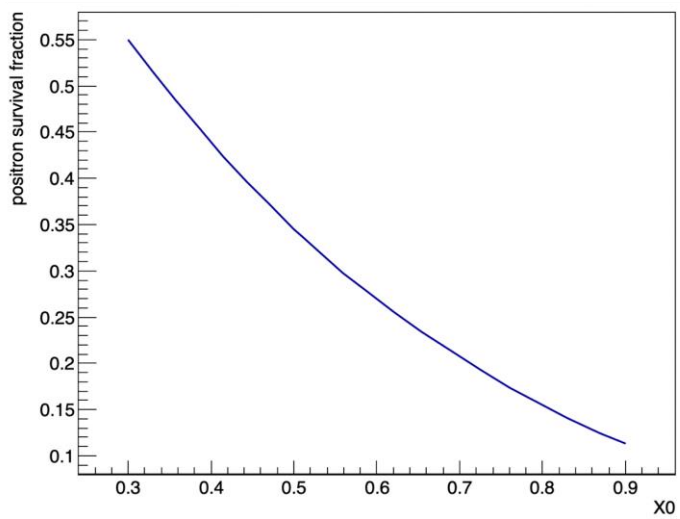
Target issues

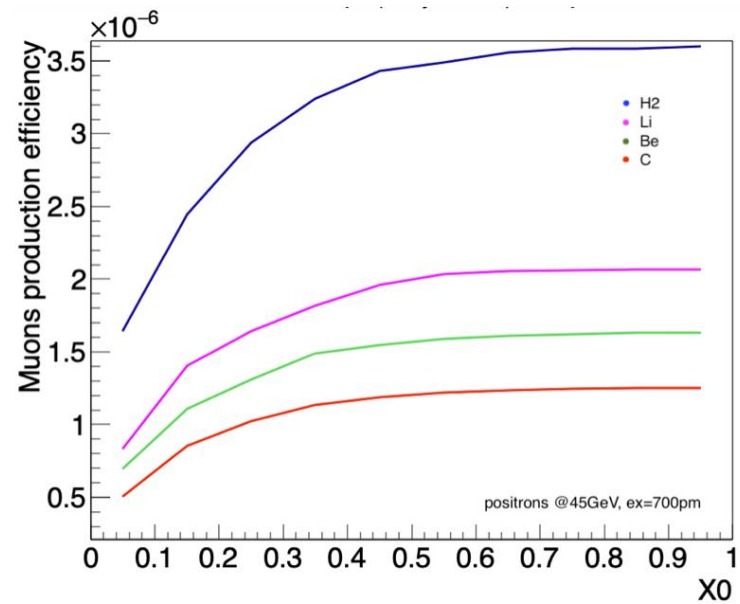


3e11 e+ @45GeV
10 x 0.1X_0 of Be

Most of the muons are produced in the first 3 targets = **0.3X0**

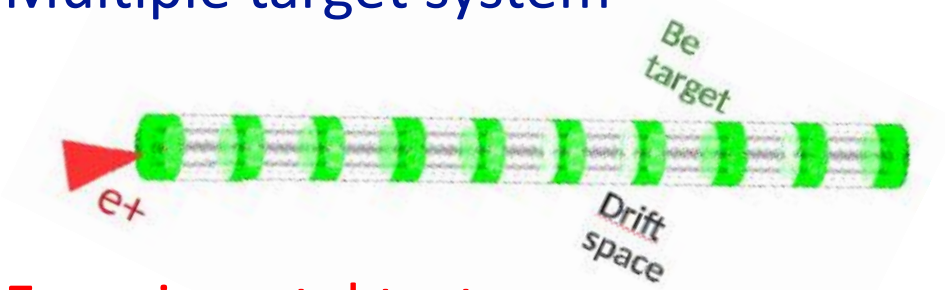
Target material plays a crucial role



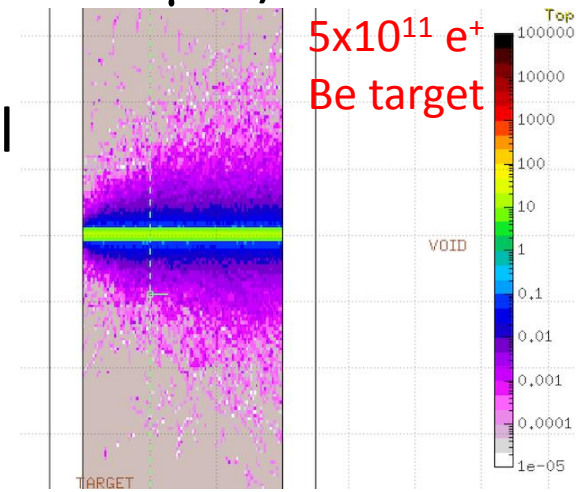


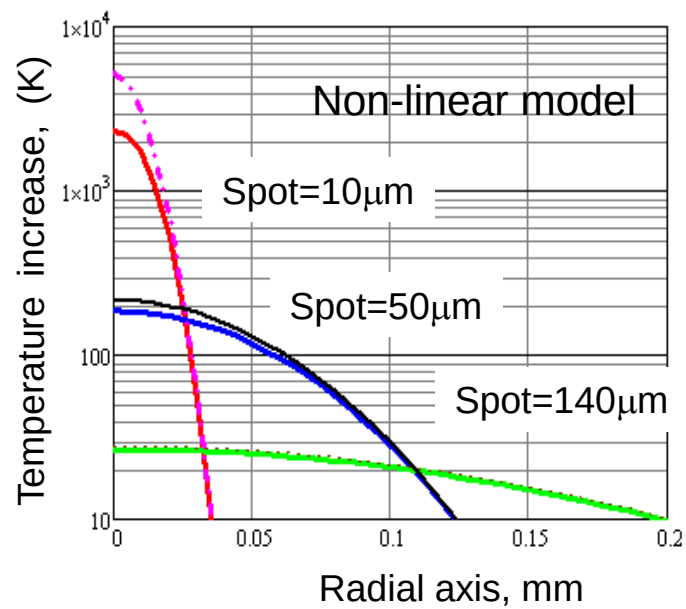
Thermo-mechanical issues

- Aim at bunch ($5x10^{11}$ e^+) transverse size on the 10-20 μm scale: rescaled from test at HiRadMat ($5x10^{13}$p on 100μm) with **Be-based** targets and **C-based** (HL-LHC)
- Detailed simulation of thermo-mechanical stresses dynamics
  - FLUKA + FTDT/Ansys Autodyn) with CERN EN-STI)
- Multiple target system



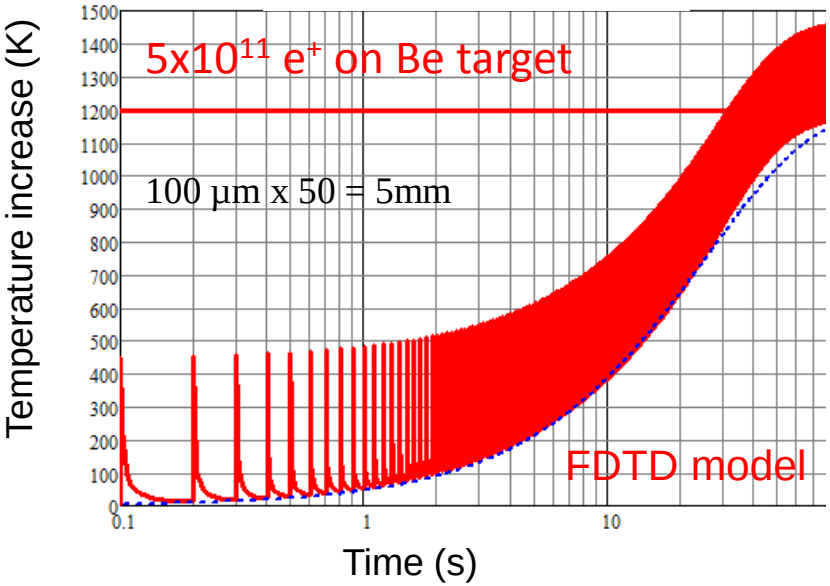
- Experimental tests:
  - **DAFNE linac**
  - **DAFNE** TF available if approved





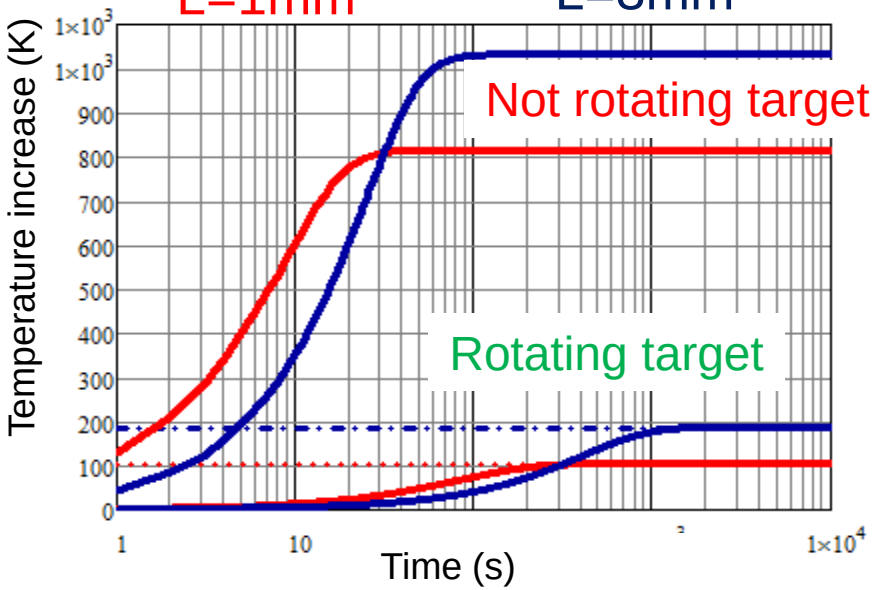
Thermal Study

Not rotating target



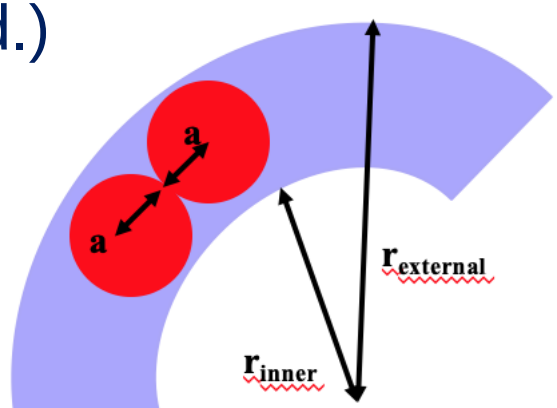
C : R=5mm, L=1mm

Be : R=5cm, L=3mm

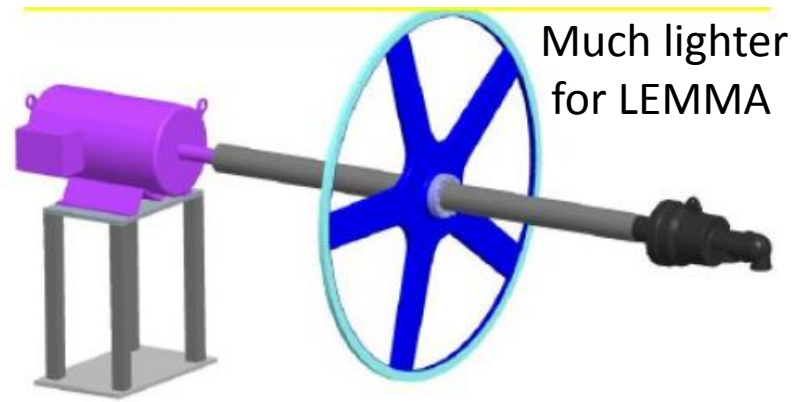


ILC(e^+ prod.) like target

- Radius 50 cm
- N ~ 2000 rpm



- Wheel rim speed 100 m/s
- Wheel diameter ~ 1 m



- No bunch pileup
- Power removal by radiation cooling (see for instance PSI muon beam upgrade project HiMB)

Considerations on μ accumulation

Accumulation must be performed in $\tau_{lab} \sim 500\mu s$

Ring must be as short as possible with the largest possible E acceptance

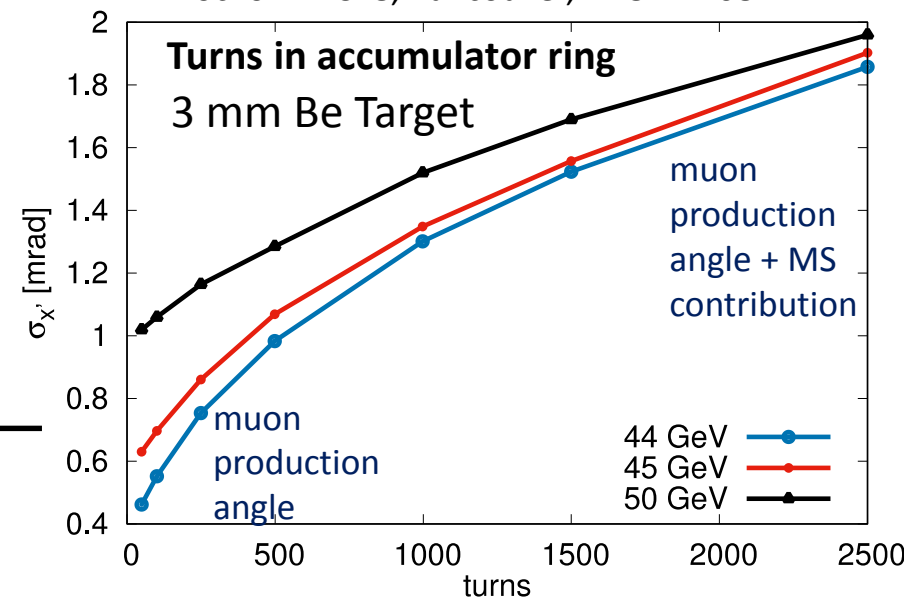
Number of muons increased by using a thick target

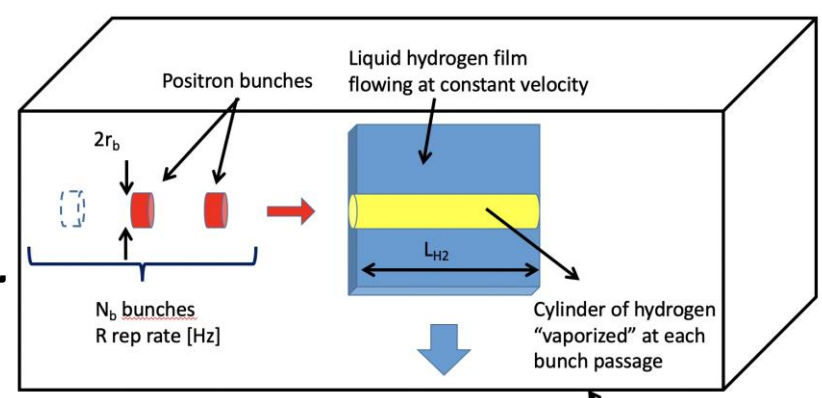
- drift contribution on beamsize ($\propto L_T$)
- MS contribution on emittance($\propto \sqrt{X_0 N_T}$)

Possible solutions:

- ✓ Multiple IP
- ✓ **Spaghetti/film-like targets** or channeling in crystals

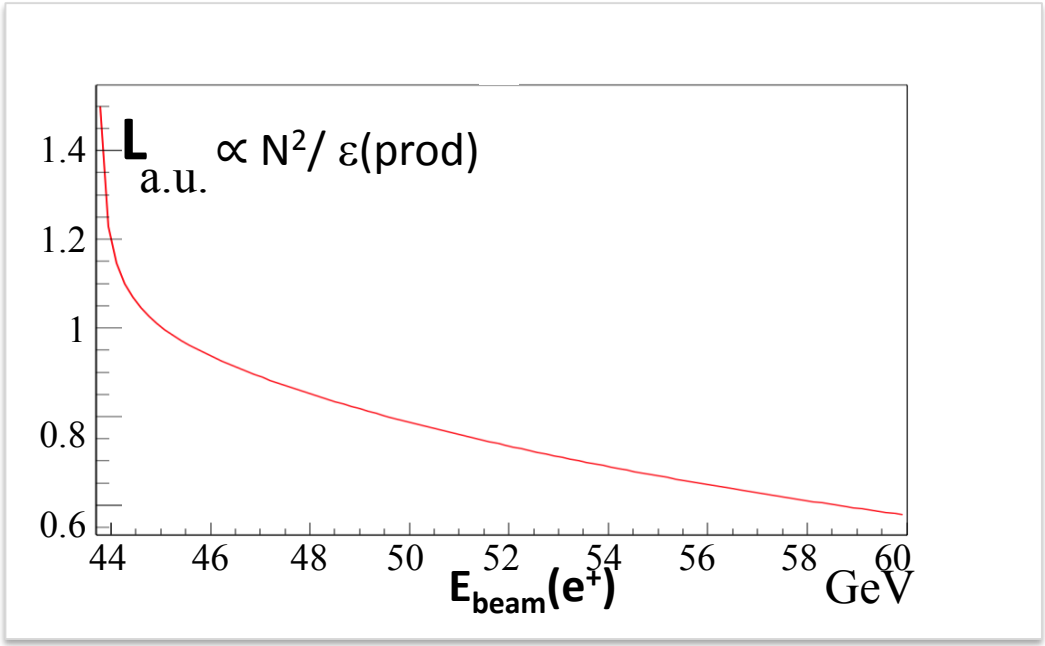
Proc. of IPAC18, Vancouver, MOPMF087



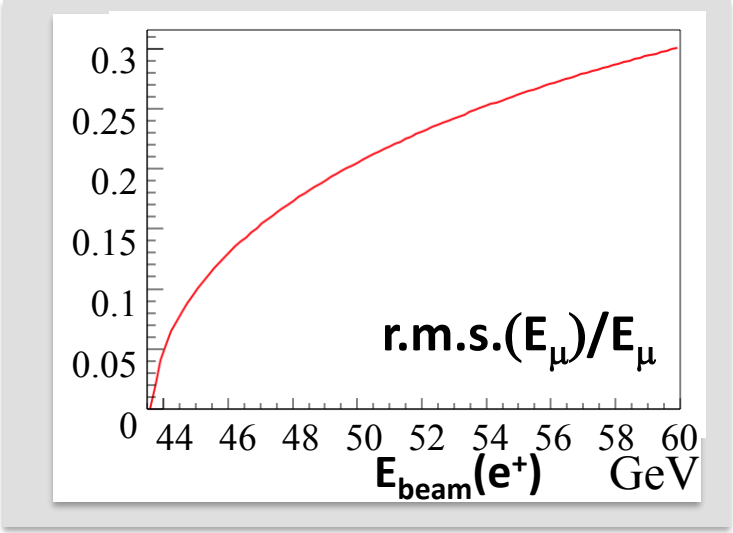


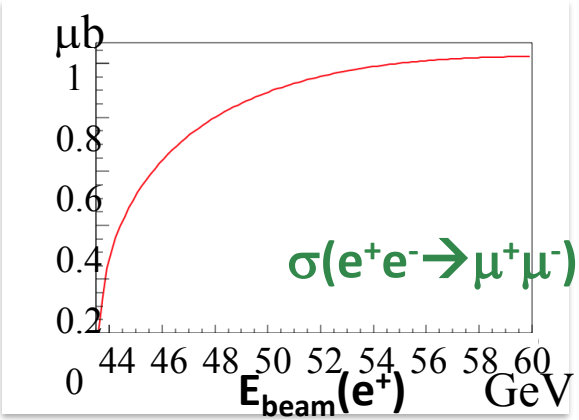
Luminosity of $\mu^+\mu^-$ Collider vs e^+ beam energy

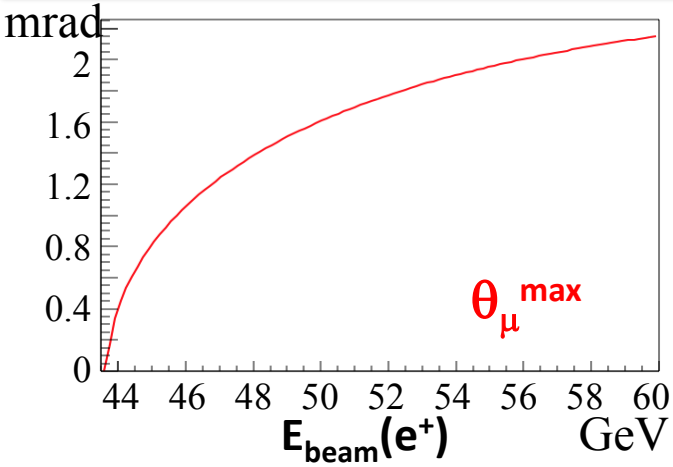
Optimal working point for $\varepsilon(e^+) \cong \varepsilon(MS) \cong \varepsilon(rad) \cong \varepsilon(prod) \cong \varepsilon(AR)$
and sustainable beam spot on target
$\varepsilon(prod)$ and μ intensity $\propto$ positron beam energy:



Need of high energy acceptance μ ring

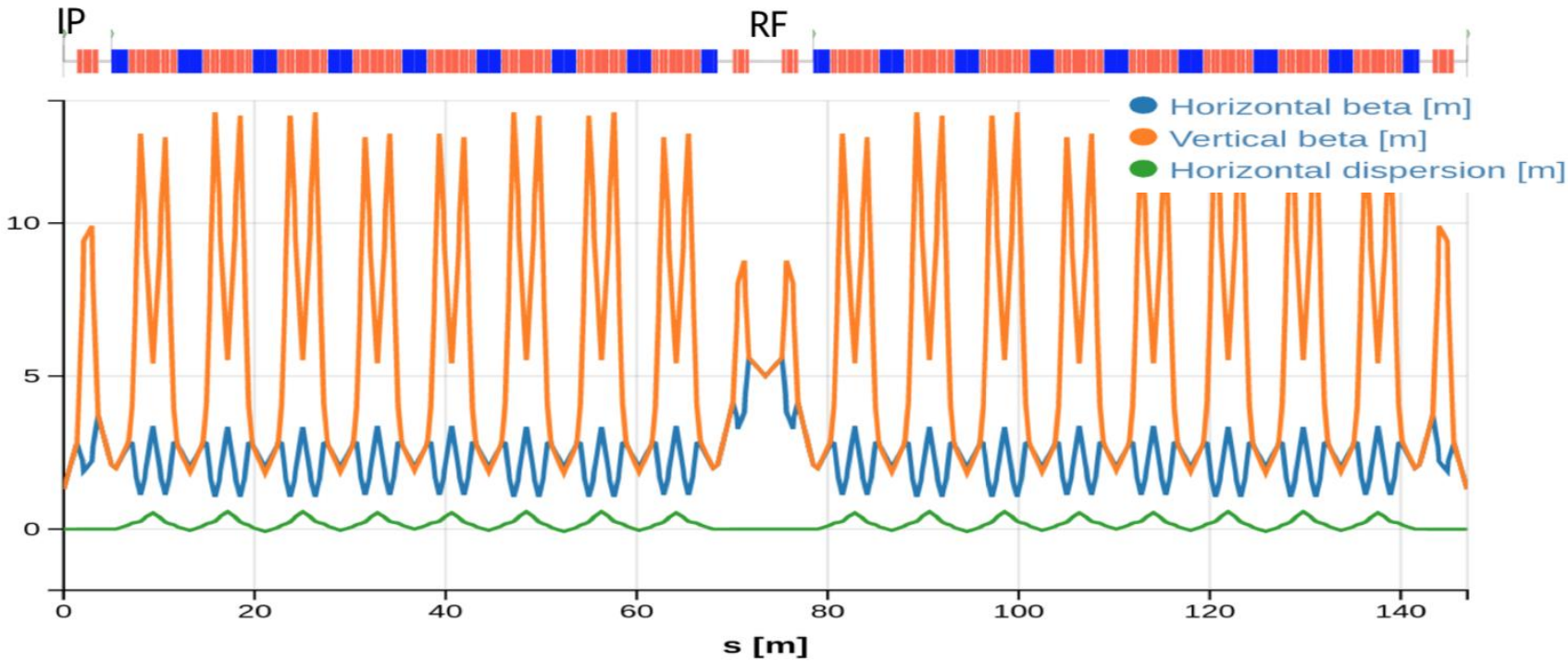


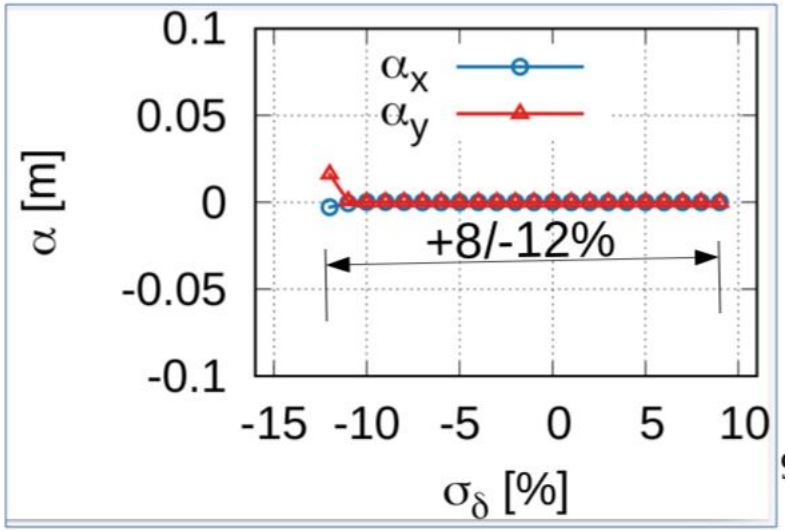


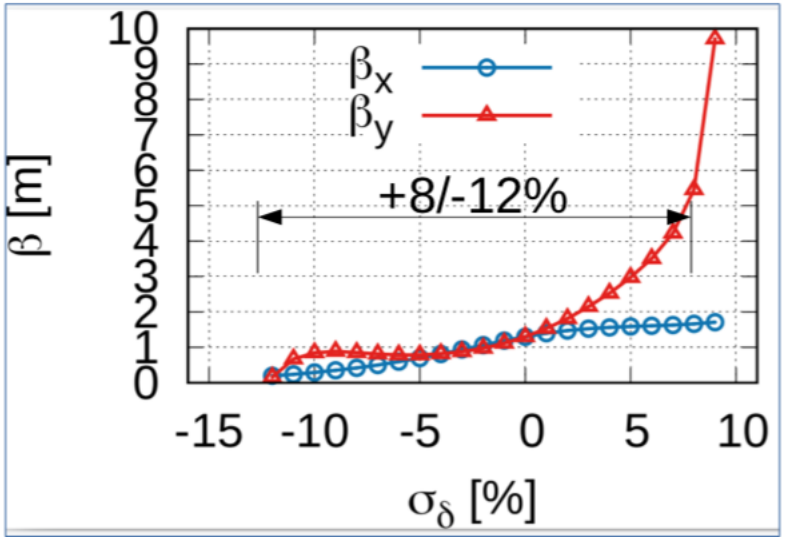


First accumulator μ ring design

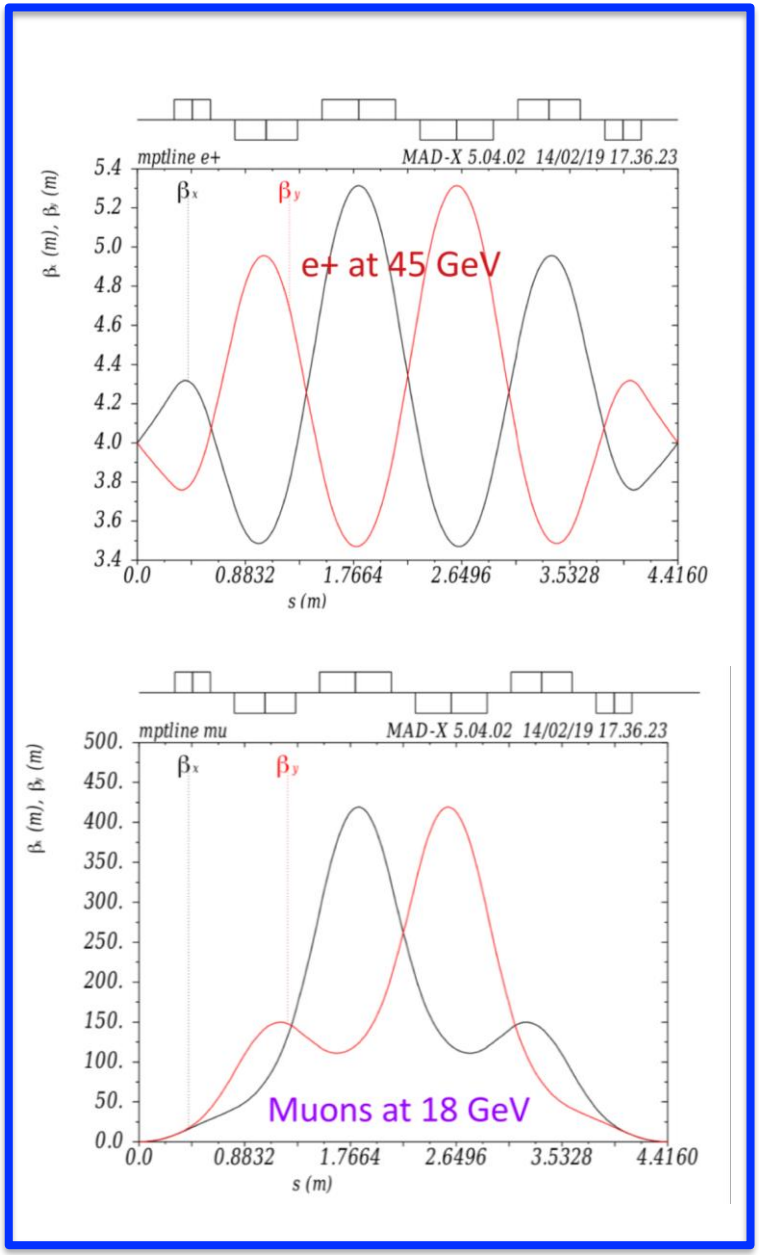
P. Raimondi







Multiple IP, multiple targets



Targets separated by a transport line where magnets are **common to the three beams** (*e*+, μ+ and μ−), focusing the beams at each IP to achieve the production of new muons with **minimal growth to the final beam emittance.**

lattice design:

- Lenght < 5 m
- magnet gradient at 200 T/m
- aperture radius 1 cm

Two triplets are used to focus the beams on both transverse planes, and they are put in asymmetry in order to **partially cancel chromaticity** at 45 GeV as in the apochromatic design

Still work to be done to benefit from this option

Positron source requirements

Positron source rate is **independent on the scheme** (multi- or single-pass)
Main dependences on **target material** and **recovery system energy acceptance**

Single-pass scheme

	Be 0.106m		LH2 2.66m		Li 0.45m	
Energy acceptance %	ΔN/sec	Power [MW]	ΔN/sec	Power [MW]	ΔN/sec	Power [MW]
5	4,89E+15	41,43	4,99E+15	42,28	4,82E+15	40,9
10	4,11E+15	34,88	4,22E+15	35,79	4,06E+15	34,4
20	3,22E+15	27,33	3,33E+15	28,24	3,23E+15	27,4

To evaluate the number of positrons per second required from the source we assume to have **1500 bunches** with **5 10^{11} e^+/ bunch** on target at **10Hz (total of 7.5 10^{15} e^+/sec)**

➢This is a key issue to be studied

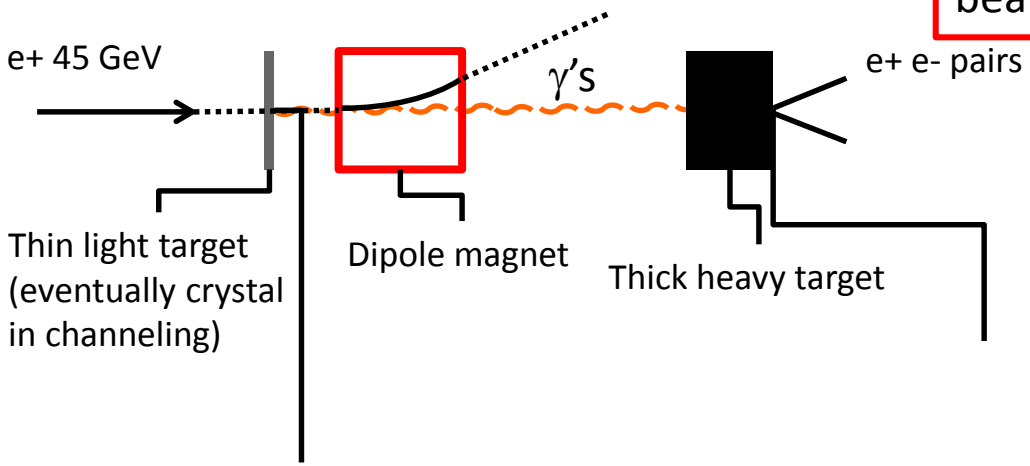
	SLC	CLIC	ILC	LHeC pulsed	LHeC ERL
E [GeV]	1.19	2.86	4	140	60
$\gamma\epsilon_x$ [μm]	30	0.66	10	100	50
$\gamma\epsilon_y$ [μm]	2	0.02	0.04	100	50
$e^+[10^{14}s^{-1}]$	0.06	1.1	3.9	18	440

Summary of e^+ sources projects (<u>all very aggressive</u>):
In [F. Zimmermann, et al., '**POSITRON OPTIONS FOR THE LINAC-RING LHeC'**, WEPPR076 Proceedings of IPAC2012, New Orleans, Louisiana, USA]

Embedded positron source

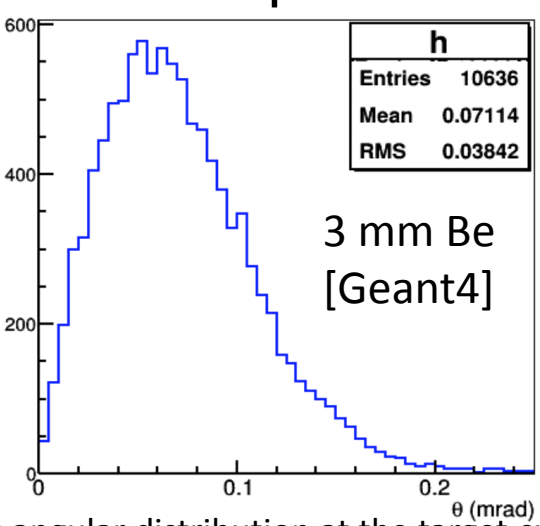
Positron source extending the target complex? Possibility to use the γ's from the μ production target to produce e+

Straightforward (in principle) to produce low energy damped accumulated e^+ with a yield>1 (SLC yield=1.1 @22GeV primary beam)

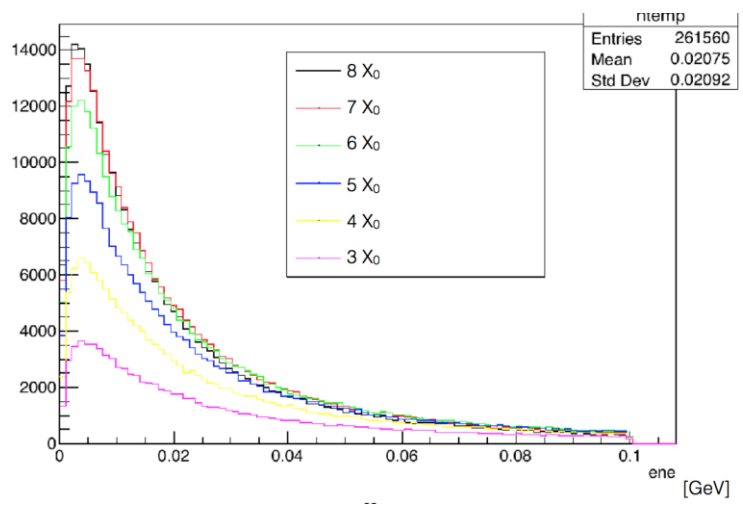


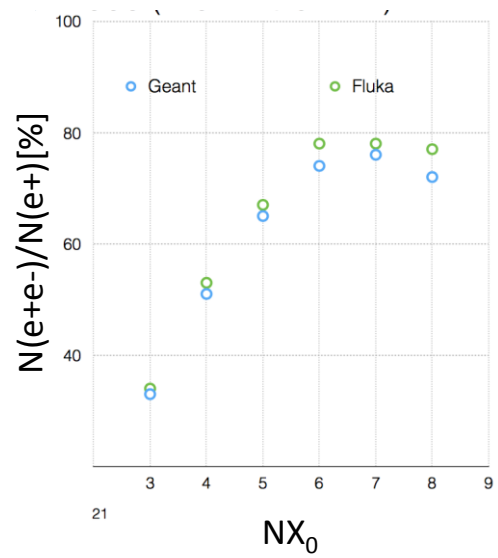
Focusing based on AMD under study promising preliminary results on collection efficiency

Produce a fraction of e+ of the incoming positron beam



γ's angular distribution at the target exit





Conclusion

Studies for a low emittance muon source are promising

We will continue to optimize all the parameters, lattices, targets, etc. in order to assess the ultimate performances of a muon collider based on this concept

Some of the key challenges:

- High rate positron source
- High momentum acceptance muon accumulator rings
- High power target

Most of them are in common with other accelerator projects

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(Be)	LEMMA(LH2)
10^{14} e^+ / s	**0.025**	**0.06**	**1.1**	**2**	**0.05**	**100**	**40**

Present: 3 mm Be, 40 turns lifetime(DP/P<6%), $\Delta N/N$=2.5%, P= 247 MW
35 mm LH2, 100 turns lifetime(DP/P<6%), $\Delta N/N$=1%, P= 98 MW

Goal: 3 mm Be, 240 turns lifetime(DP/P<25%), , $\Delta N/N$=0.4%, P=39 MW
35 mm LH2, 625 turns lifetime(DP/P<25%), $\Delta N/N$=0.1%, P= 16 MW

Low EMittance Muon Accelerator team

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Criteria for target design

Number of $\mu^+\mu^-$ pairs produced per e^+e^- interaction is given by

$$N(\mu^+\mu^-) = \sigma(e^+e \rightarrow \mu^+\mu^-)\, \mathbf{N(e^+)}\, \rho(e^-)\mathbf{L}$$

$N(e^+)$ number of e^+

$\rho(e^-)$ target electron density

L target length

To maximise $N(\mu^+\mu^-)$:

- **$N(e^+)$** max rate limit set by e^+ source
- **$\rho(e^-)L$** max occurs for L or ρ values giving total e^+ beam loss
  - **e^- dominated target:** radiative Bhabha is the dominant e^+ loss effect, giving a maximal $\mu^+\mu^-$ conversion efficiency $N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e \longrightarrow \mu^+\mu^-)/\sigma_{rb} \approx 10^{-5}$
  - **standard target:** Bremsstrahlung on nuclei and multiple scattering are the dominant effects, Xo and electron density will matter $N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e \longrightarrow \mu^+\mu^-)/\sigma_{brem}$