University of Rome La Sapienza
XXXIV Ph.D. in Accelerator Physics (2nd year)

Ph.D. Advancement Report
October 21st 2020

Muon production from positron beam on target for high energy muon collider

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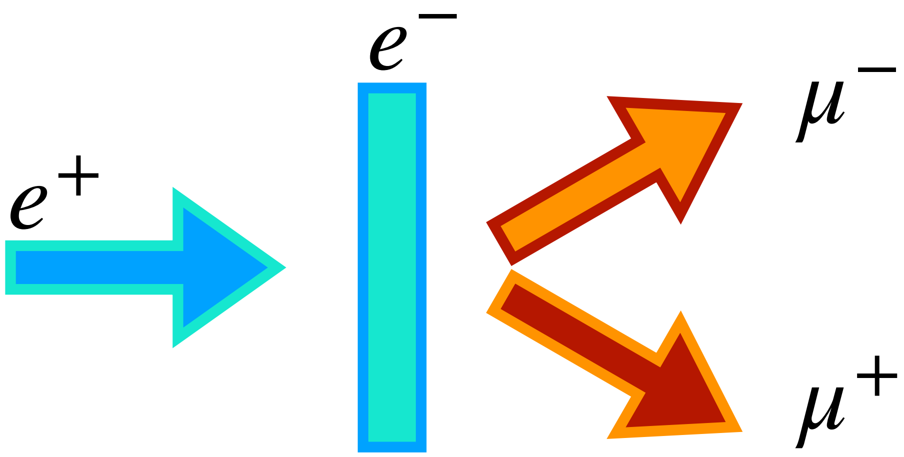
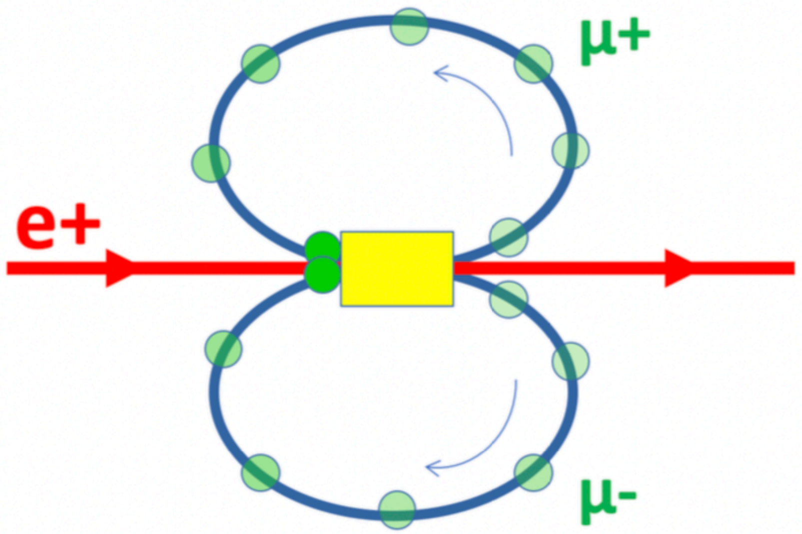
Low EMittance Muon Accelerator - LEMMA

Investigate the possibility of a **positron-driven** muon collider in the Multi-TeV range.



✓ Low production emittance
✓ Muons produced with high boost due to asymmetric collision
X Low production cross-section ($\sim 1\mu b$)

A dedicated muon **production** and **accumulation system** is one of the most important features of the LEMMA design.



Two rings are necessary in order to accumulate the muons over several iterations of positron bunches impinging on the target.

Muons are **recirculated** and arrive back to the target together with a new positron bunch, so that the new muons get produced in the same phase space of the accumulated bunch.

Muon Production and Accumulation Simulation with **MUFASA**

The design of a realistic optics for the muon accumulator allowed for a full study on the **muon beam dynamics** during the accumulation process. To this extent a dedicated simulation tool named **MUFASA** has been developed.

This tool is a C++ based **MonteCarlo** which includes the most relevant processes of muon and electron interaction with matter, and it is interfaced with **MADX** for the 6D particle tracking.

This code is essential for a **start-to-end simulation** and to determine the best target for LEMMA, allowing the study of the **dynamics of the stored beam** passing hundreds of times through the target during the accumulation process.

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10 Giugno 2020

MUFASA: MUon FAst Simulation Algorithm

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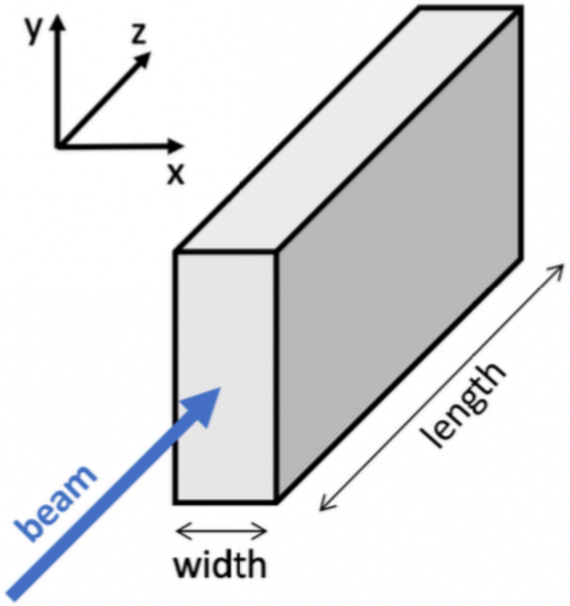
This note contains the description of the code and the results of its Benchmark against Geant4



Target features are width, length and material.

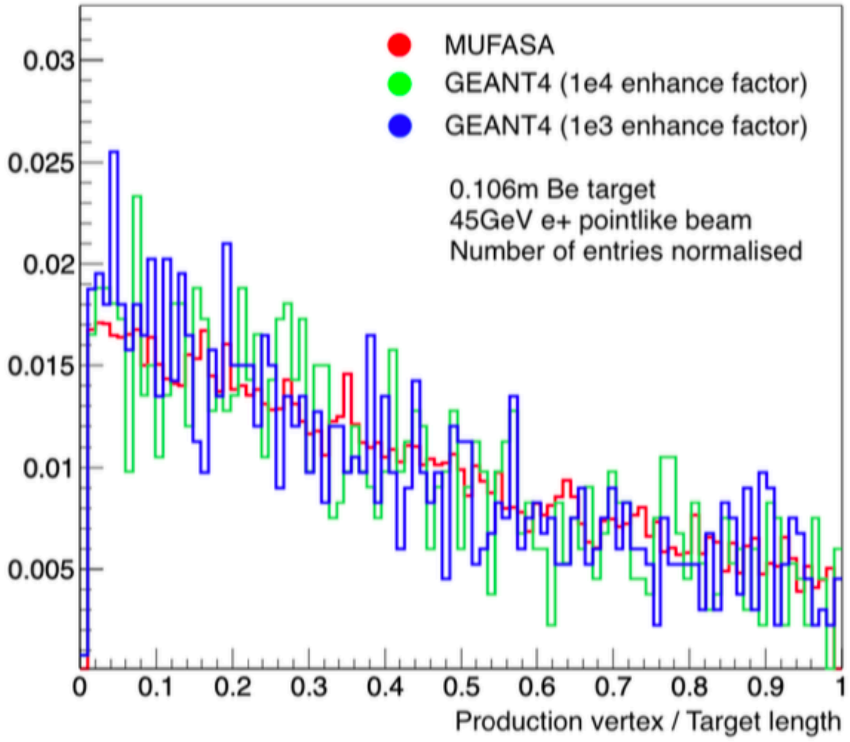
```
// material[] = {X0, rho, A, Z, dE/dx};
double beryllium[] = {65.19,1.848,9.01218,4,0.2947};
```

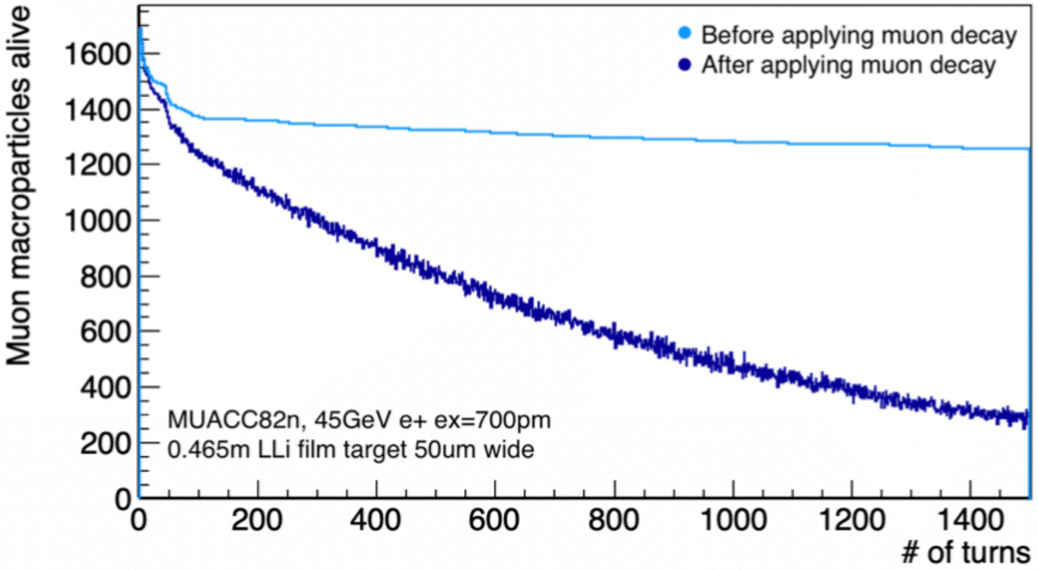
The simulations starts with e+ macroparticles at the beginning of the target. **Multiple scattering** and **energy loss** are evaluated at each step.

The **production vertex z** is extracted from the exponential distribution $f(z) = e^{-z/X_0}$

The positron is tracked *step-by-step* to z. Then if the positron energy is above threshold $E \geq 43.8GeV$ a muon is produced and a **weight** is associated to it.

Muons are tracked *step-by-step* through the target, then tracked with MADX-PTC in the accumulator optics back to the target. This **cycle** is repeated for the whole accumulation process



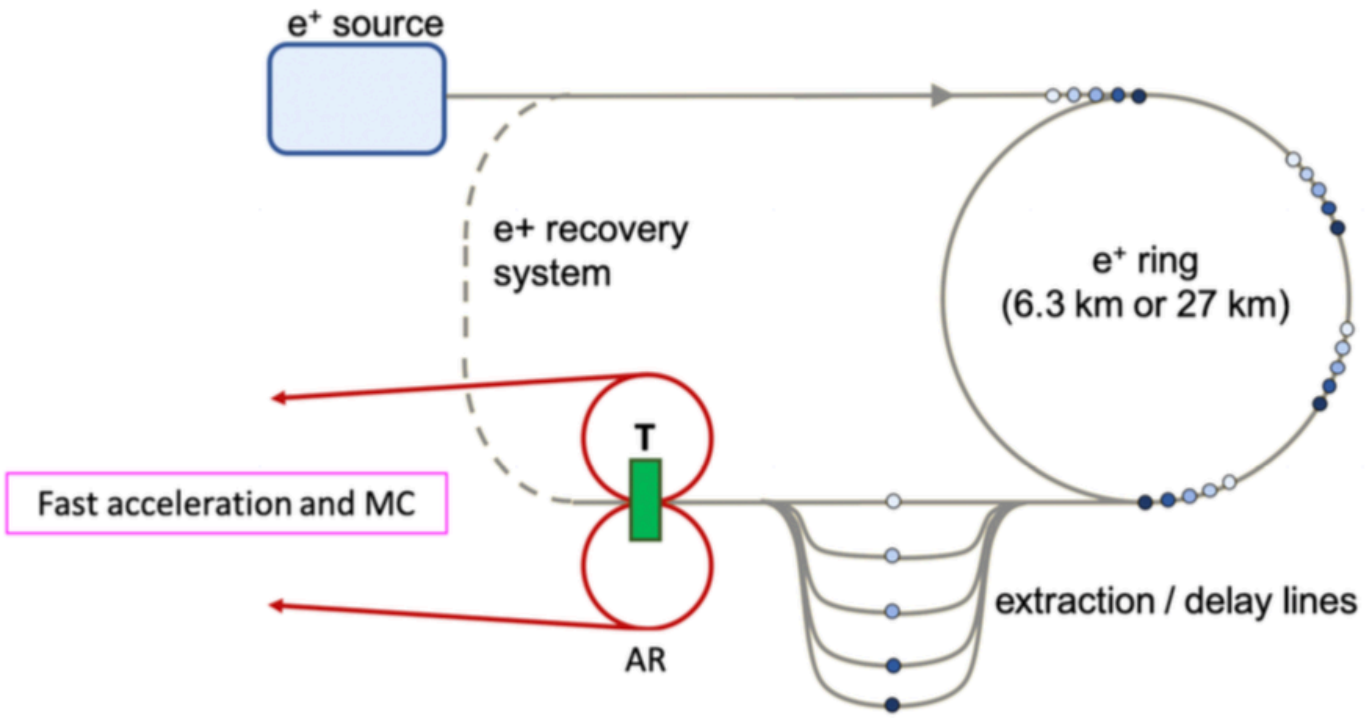


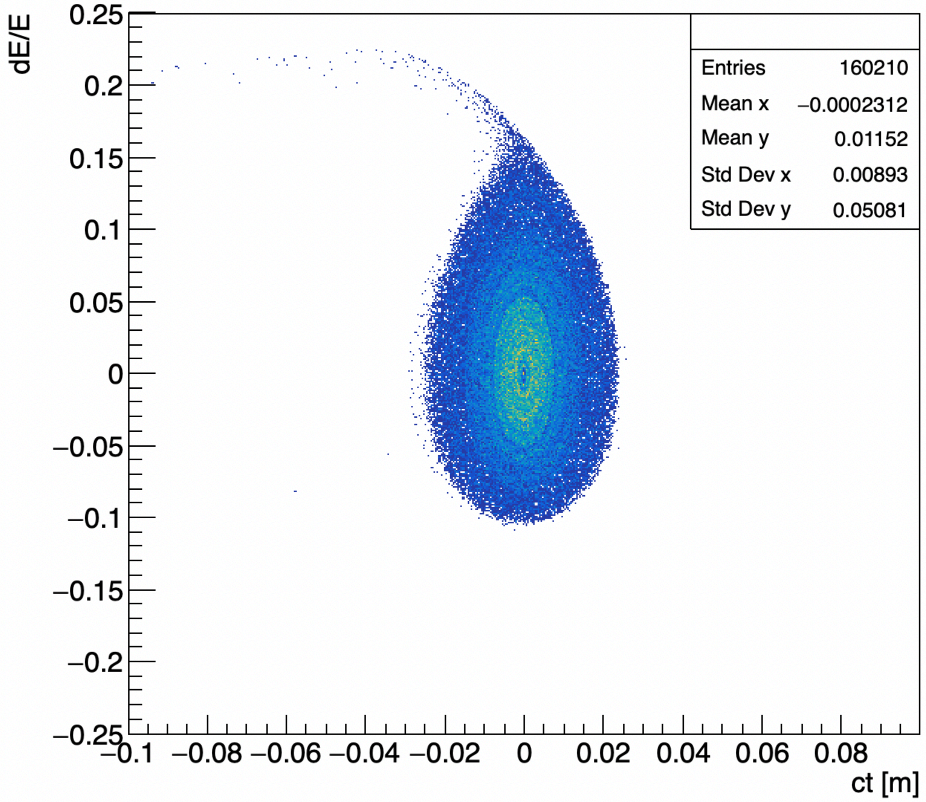
At the end of the accumulation process, **muon survival probability** is evaluated by:

$$P = e^{-L/\tau\beta c}$$

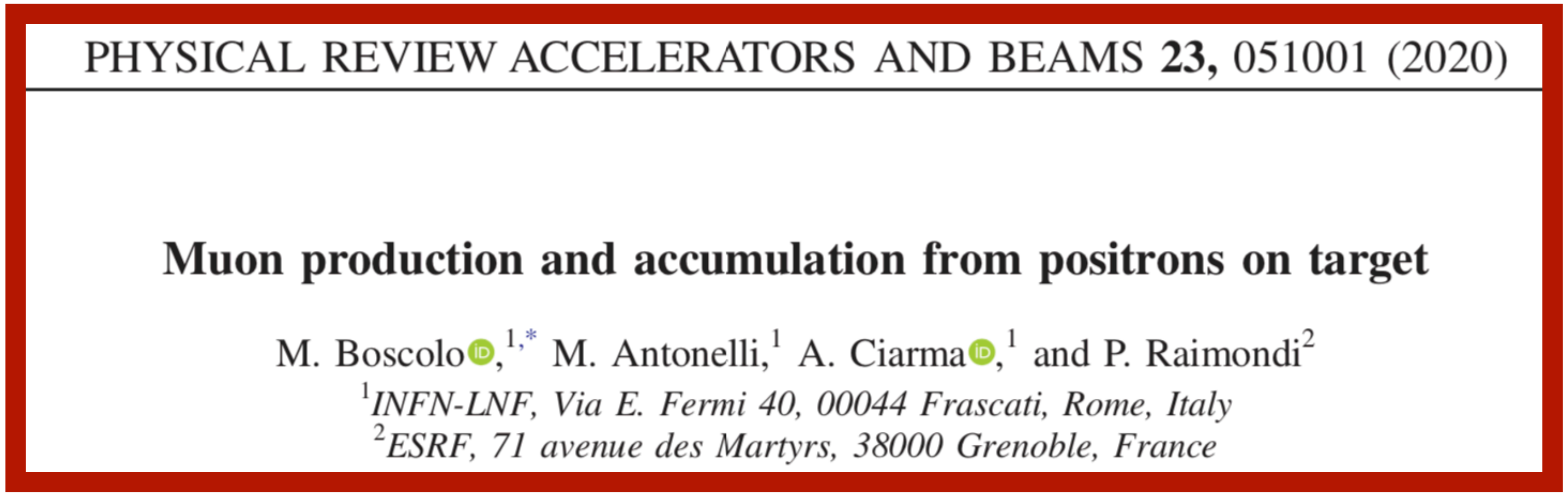
where $\tau = \gamma \cdot 2.2\mu s$ and $L = L_{accumulator} \times N_{turns}$

Dedicated study on the muon production in the LEMMA "single-pass" scheme





- Muon accumulator rings design **very large energy acceptance** (-10%/+15%)
- Full simulation of the accumulation process allowing targets optimisation:
  - Solid target
  - Liquid jet film
  - Compound target



PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 051001 (2020)

Muon production and accumulation from positrons on target

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We found that the optimised positron beam energy is **45GeV** and the low-Z targets thickness is **~0.3 radiation lengths (X_0)**

Muon Accumulator Ring Optics

A novel design for the Muon Accumulators has been developed. The **140m compact circumference** is obtained with **15T** dipoles

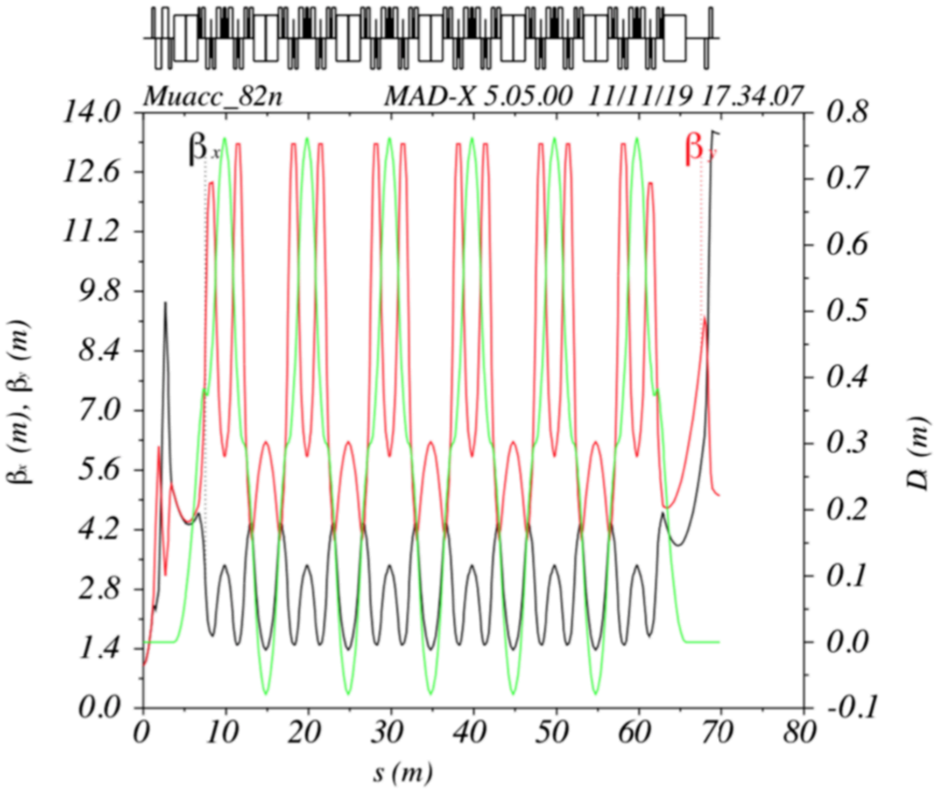
Chromaticity and high order momentum compaction correction is achieved by dedicated families of sextupoles, resulting in a **very large energy acceptance** of **-10%/+15%**

Since the **target region is in common** for the positrons and the two muon beams, a septum in the first bending magnet is used to separate the beams

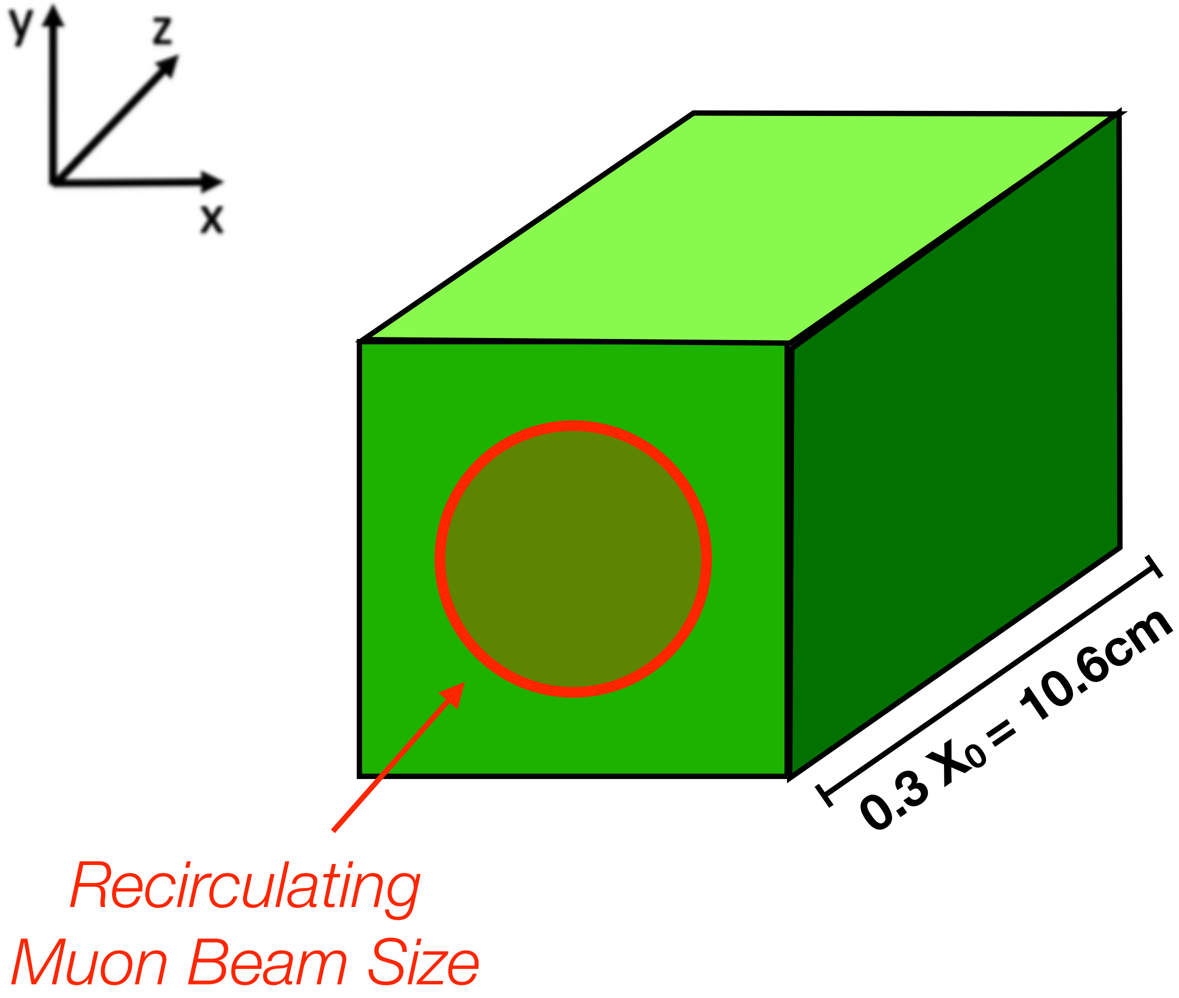
The ring is composed by two symmetric arcs and two straight sections, one for the **target insertion** and one for the **RF**

Muon beam energy	GeV	22.5
Circumference	m	140
Number of cells		12
rf frequency	GHz	3.9
rf voltage	MV	200
Harmonic number		2100
Number of bunches		1
Horizontal betatron tune		8.84
Vertical betatron tune		3.73
Longitudinal tune		0.015
Momentum compaction		-7.12×10^{-5}
Natural horizontal chromaticity		−8.28
Natural vertical chromaticity		−10.37
Bunch length	cm	0.9
Ring energy acceptance		−10%, +15%

Half ring optics



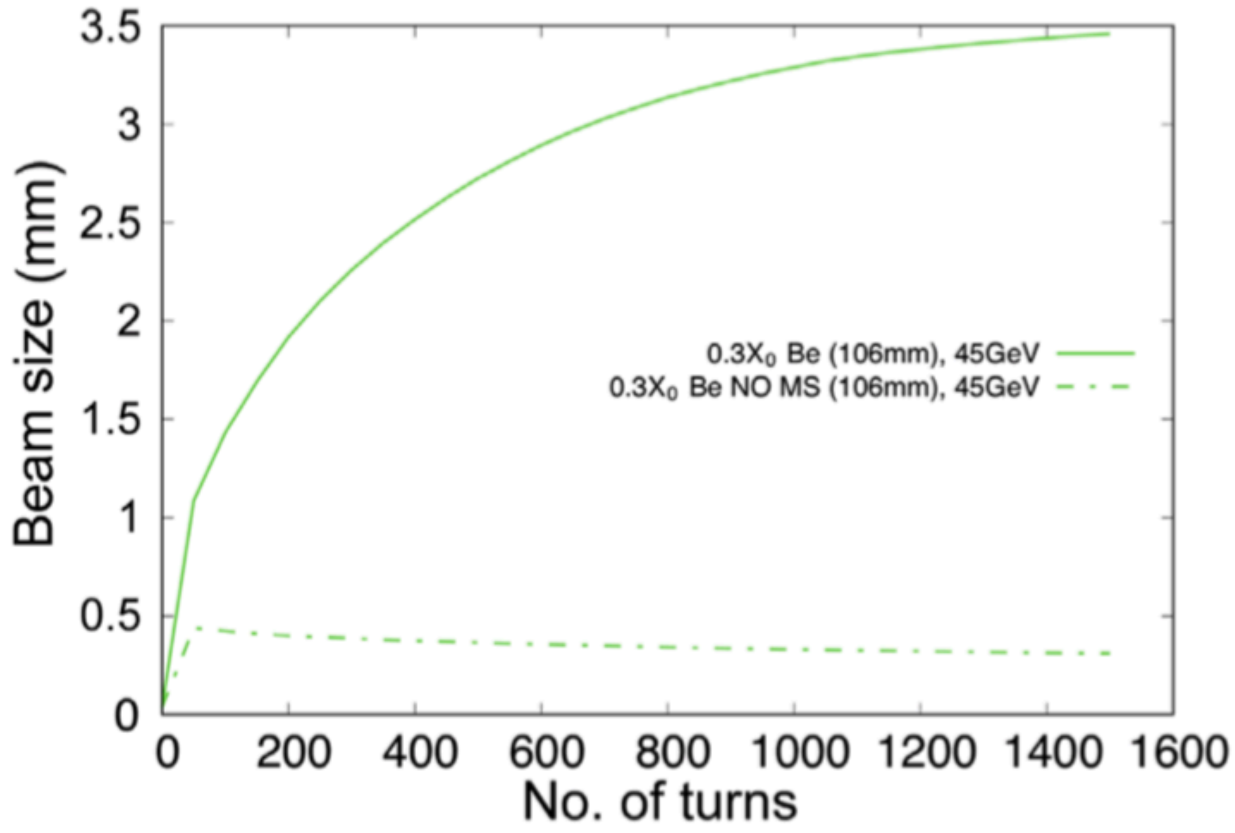
Beryllium Target

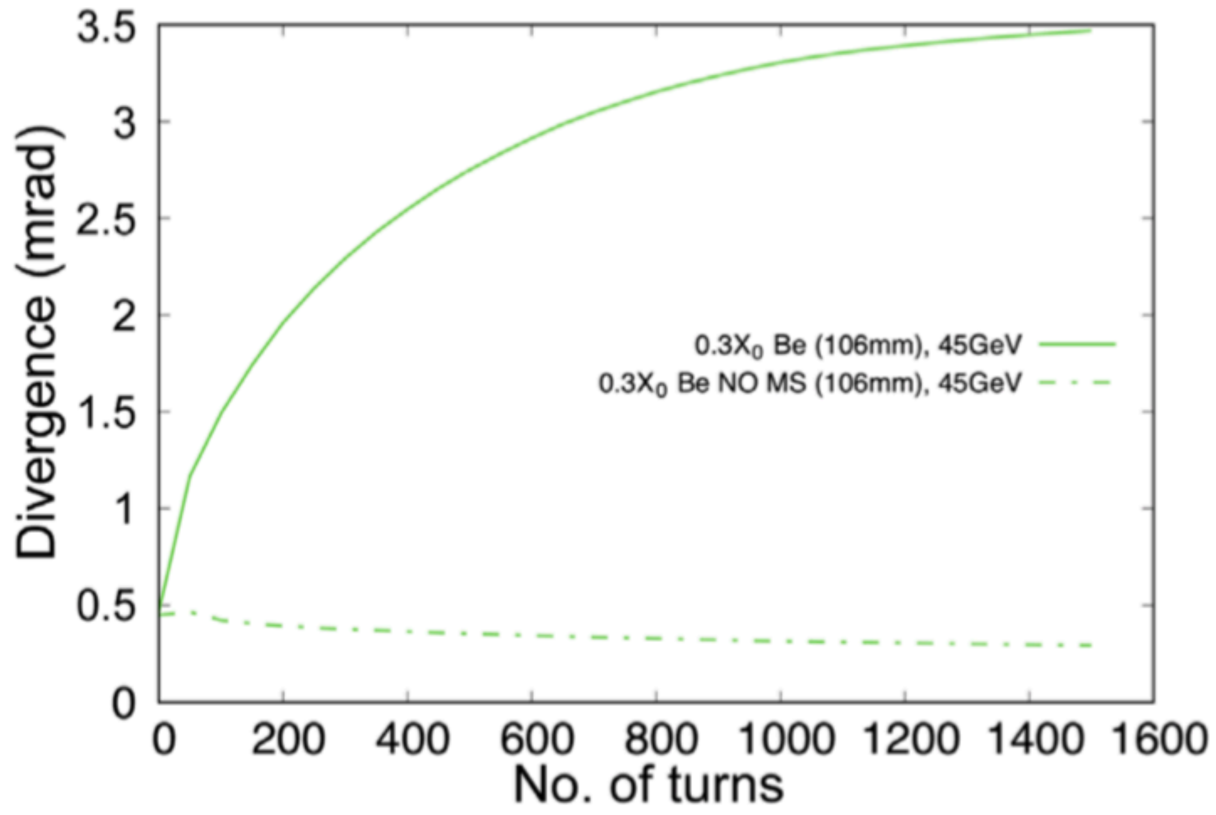


Beryllium is the **most efficient solid target** for muon pair production.

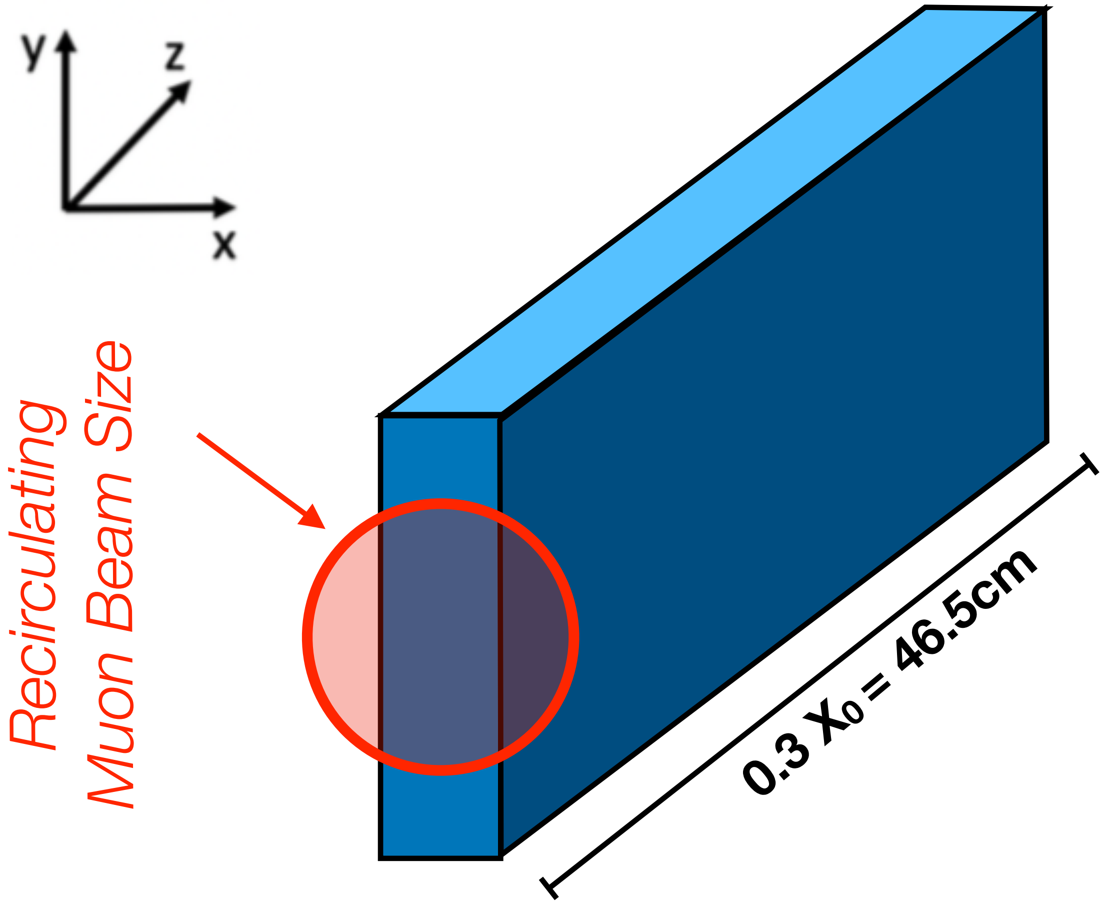
After 1500 turns (~1.5 lifetimes), **$3.5\text{x}10^8$ muon pairs** accumulated considering 1500 impinging positron bunches of $5\text{x}10^{11}$ positrons per bunch.

Due to the repeated passes through the target, the accumulated muon beam size and divergence increase because of the **Multiple Scattering**.





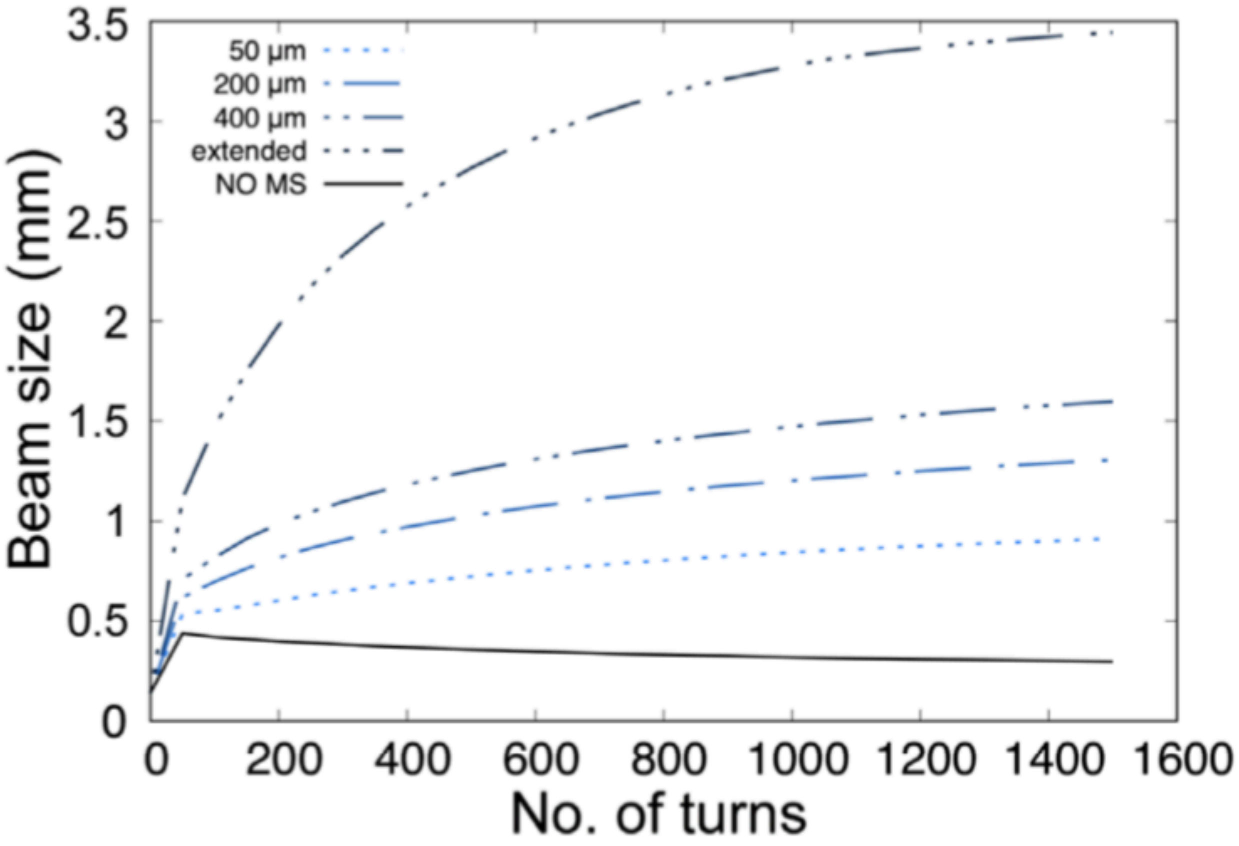
Liquid Lithium Target

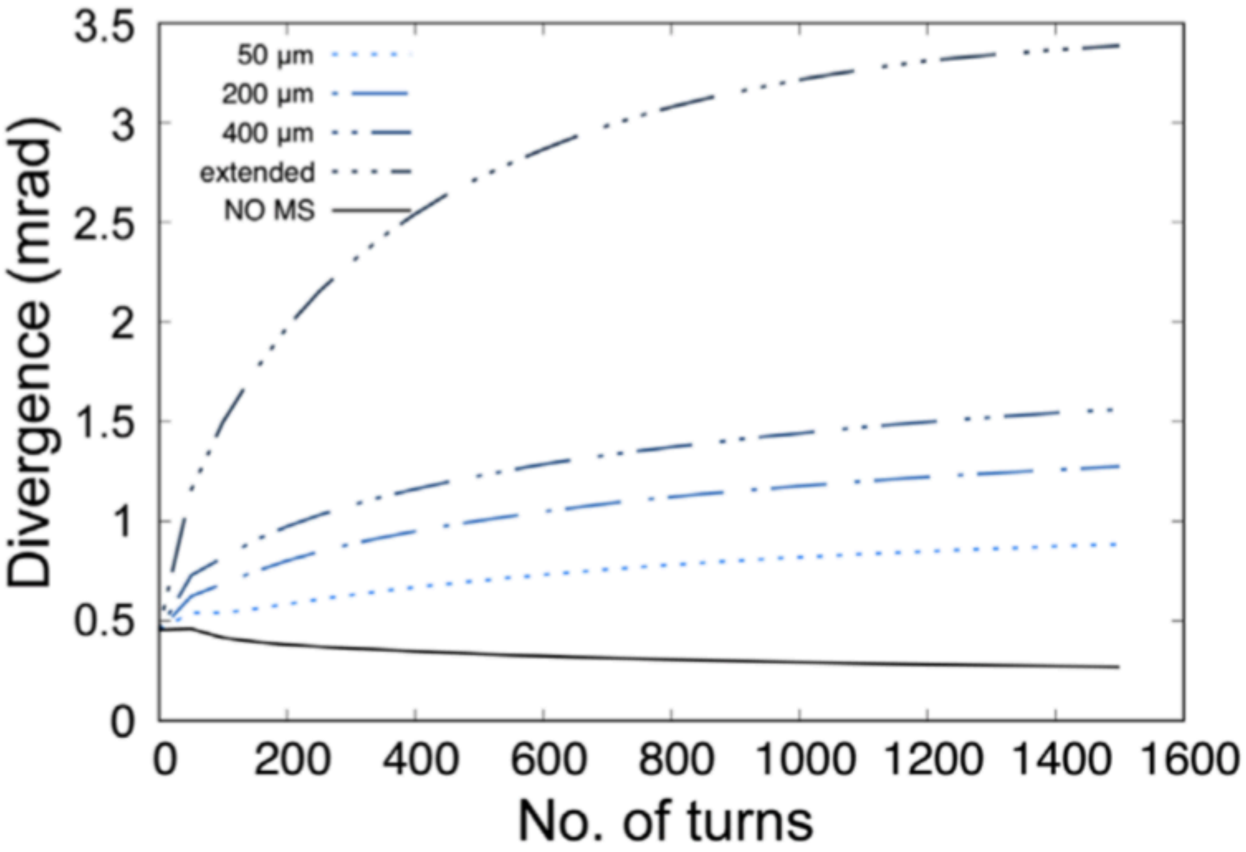


To **mitigate the effect of multiple scattering** during the accumulation a **thin film target** can be obtained using a jet of liquid Lithium.

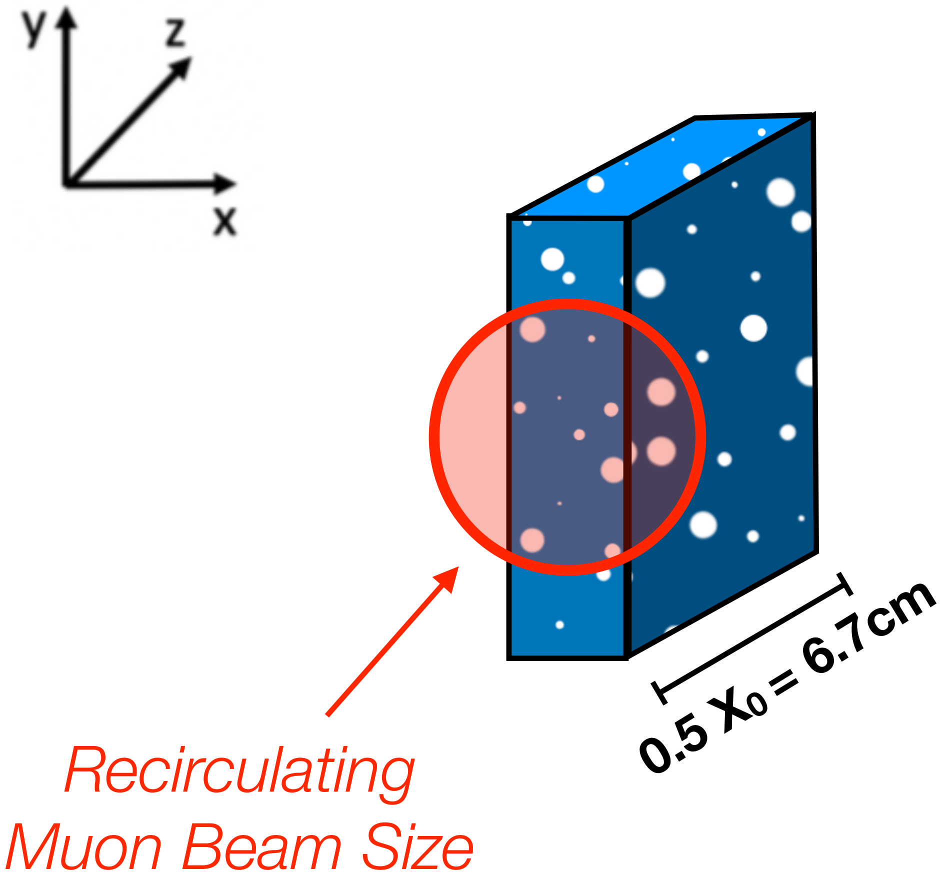
If the transverse size of the target is much **smaller than the stored beam size** (but bigger than the positron beam size!), muons will mostly not interact with matter.

On the other hand Lithium has a low X_0 so the target would be quite **long** and difficult to build





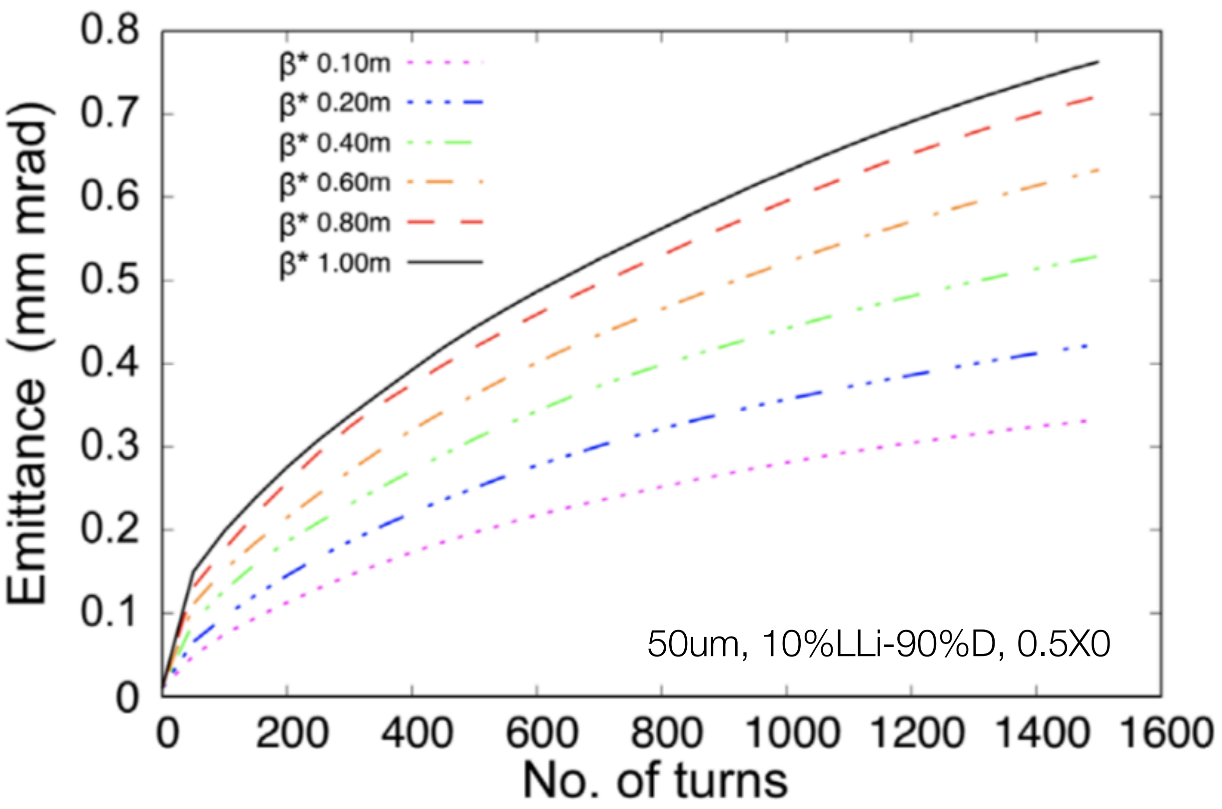
Liquid Lithium Target with Diamond dust

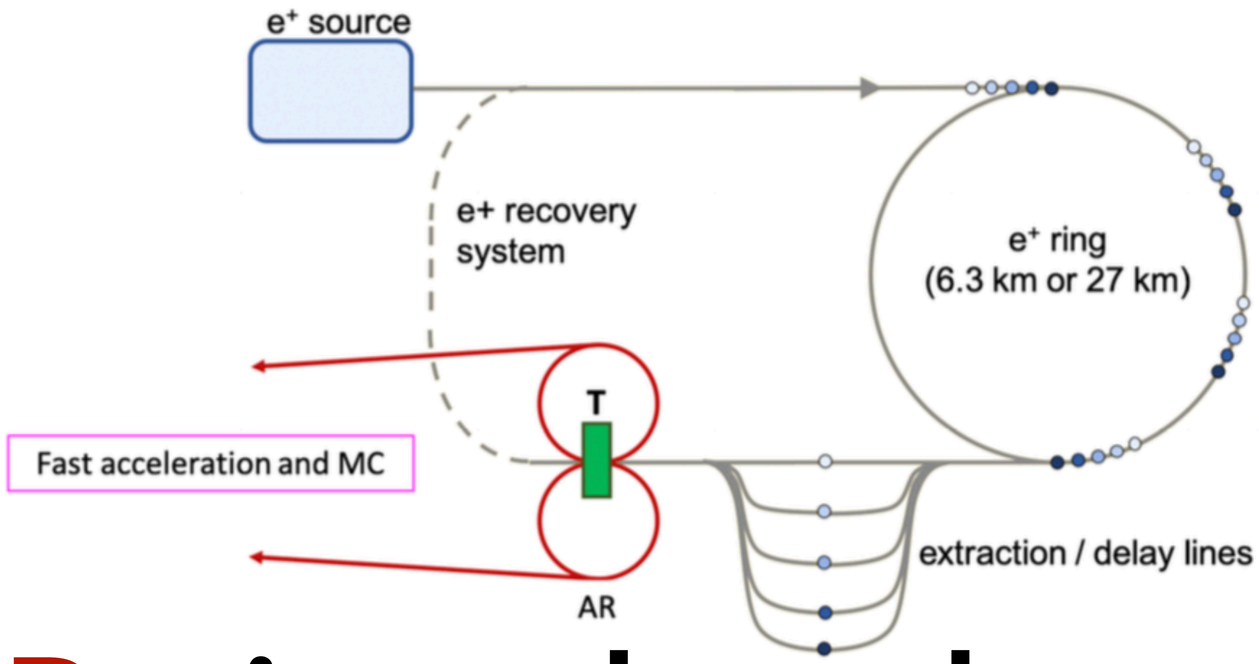


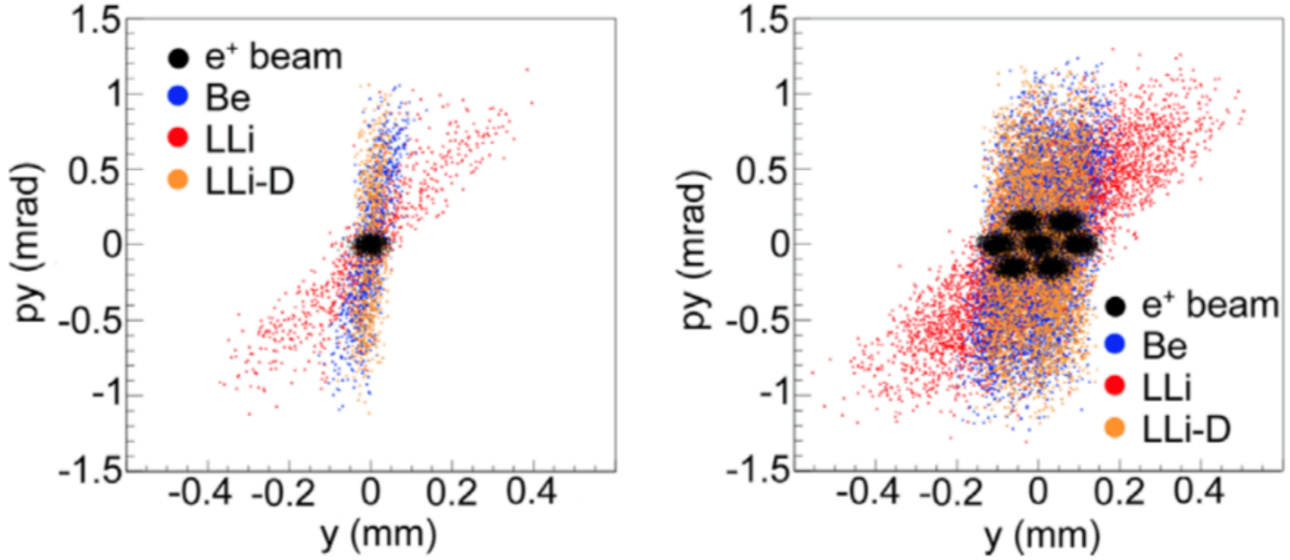
The film jet target length can be reduced by mixing **diamond powder** to the liquid Lithium.

By doing so the multiple scattering contribution to emittance is strongly suppressed, and the target has a reasonable length.

Using this target, a preliminary study on the effect of a **lower beta function** at the target location has been performed and it showed that a lower beta would **further reduce** the final muon beam emittance.



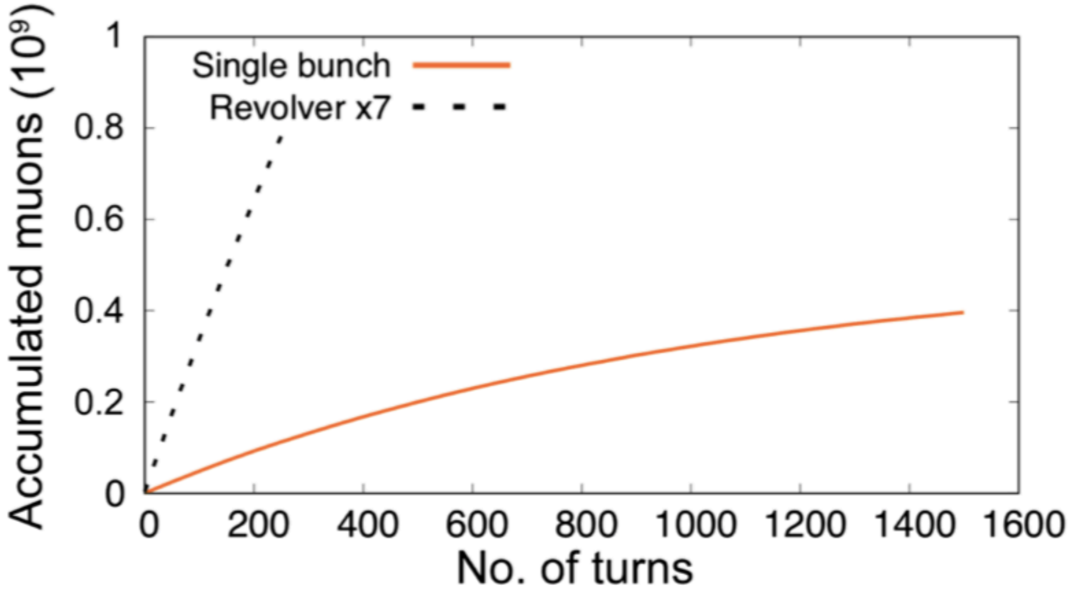


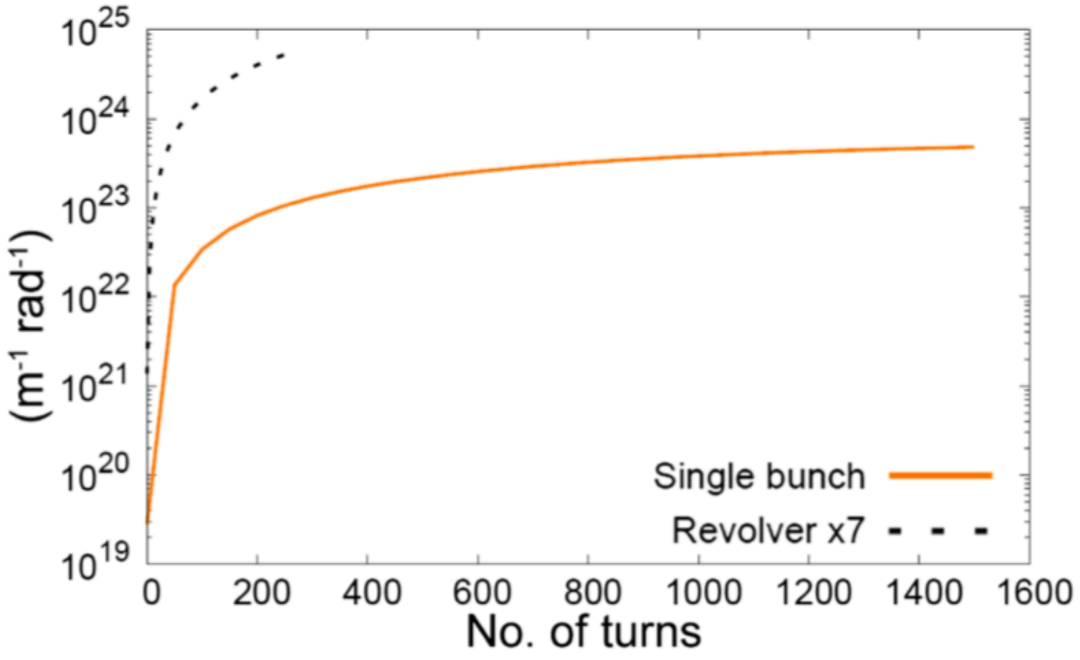


Positron bunch recombination at the target

Thanks to the small positron emittance it could be possible to simultaneously inject **multiple positron bunches** on the target by using a dedicated system of **delay lines**, spacing them on the vertical phase space.

The advantage of this configuration is the faster accumulation process, reducing the MS contribution to emittance and also preventing a lot of muons from decaying.

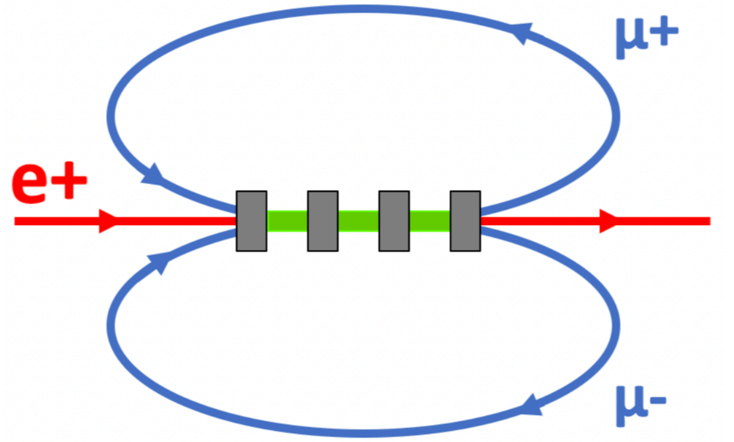


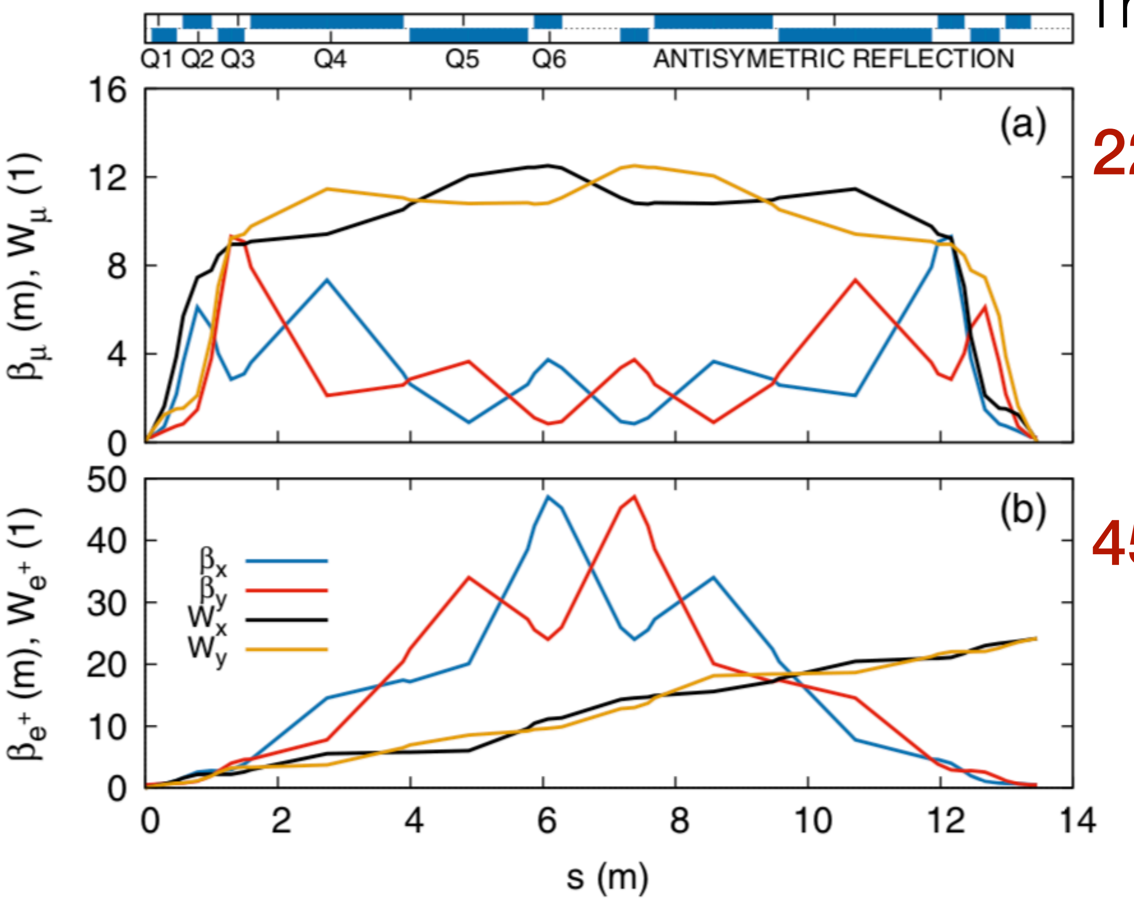


Transport lines for Multi-Target LEMMA option

Multiple thin targets $\mathcal{O}(0.01X_0)$ connected by a **transport line**:

- ✓ Reduced power per target
- ✓ Focusing the beams (instead of drift through thick target)
- X Longer production system





Only quadrupoles - max 525 T/m (CLIC 500 T/m)

The line must be able to **transport 3 beams** (e^+, μ^+, μ^-)

22.5GeV $\mu^+\mu^-$ beams

First order apochromatic line

$\beta* = 20cm$

$\pm 5\,\%$ energy acceptance

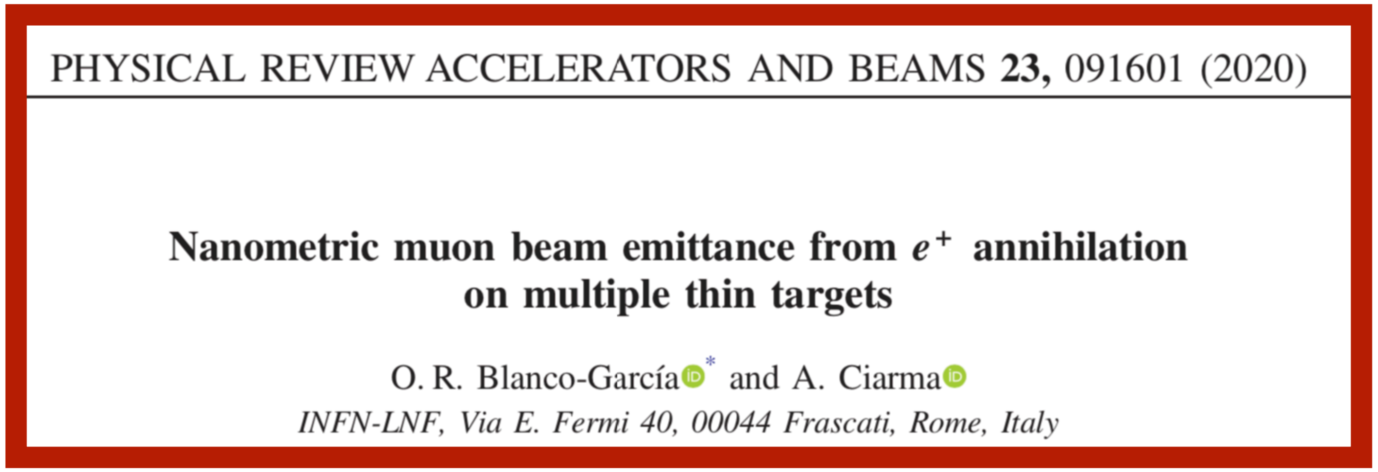
45GeV e^+ beams

$\beta* = 50cm$

Chromaticity not corrected

Positron beam $\delta E = 0.1\,\%$

A dedicated lattice for the accumulator ring has not been yet designed. In this paper the performances of the transport lines in use with thin targets have been studied.



PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 091601 (2020)

Nanometric muon beam emittance from e^+ annihilation on multiple thin targets

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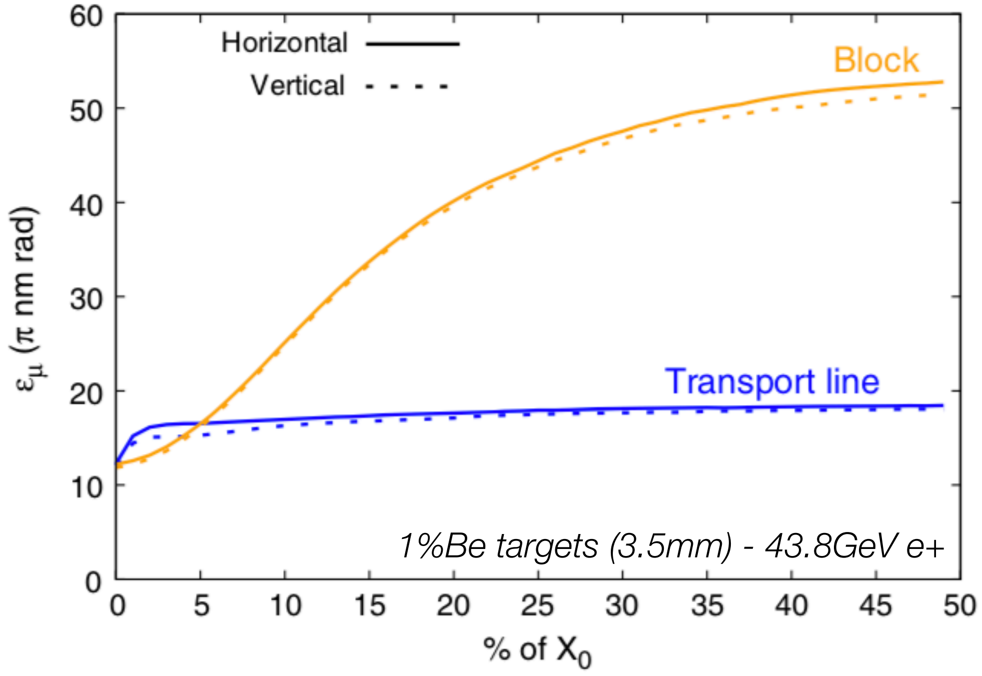


The line proves **very effective** in transporting the muon beam through several targets while keeping the **emittance constant**.

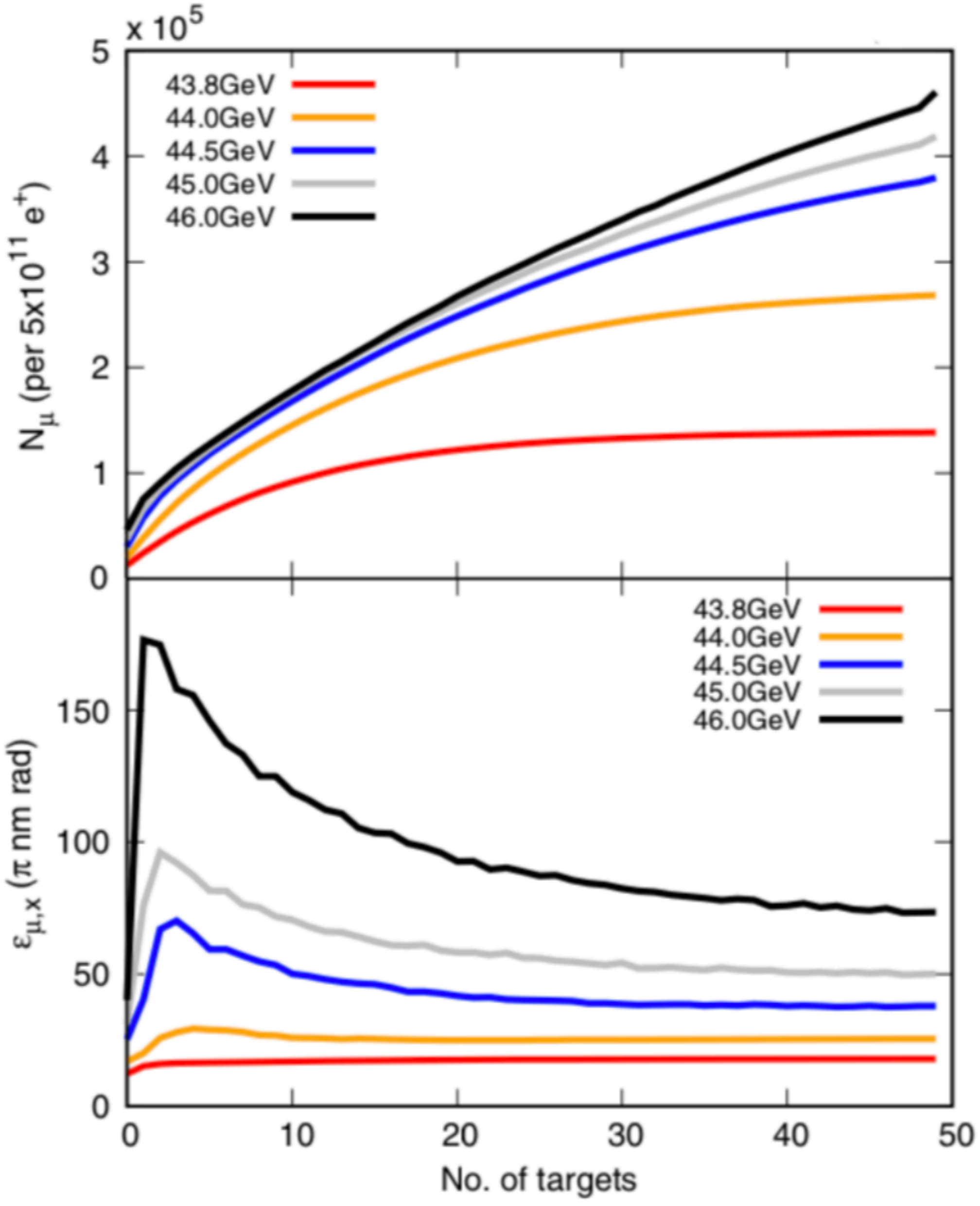
Changing the **target material** does not influence the trend as a function of the % of X_0

Small emittance increase (~30%) is due to higher order terms in the chromatic functions not corrected

Positron beam **energy scan** has been performed to find the optimised working point for this transport line.

Above 44.0GeV emittance starts to be degraded due to the **higher muon energy spread** at production, and increasing even more the energy saturates the population because muons are produced already outside the line energy acceptance.

The working point is set to 44.0GeV achieving a production efficiency of 50×10^{-8} muon pairs per positron and an emittance of $25\pi\ nm\ rad$ after 50 Beryllium targets of $1\%X_0$



Conclusions

- MUFASA, a tool for **start-to-end simulations** for the LEMMA muon production system has been developed and benchmarked

- The optics for a compact muon accumulator with **-10%/+15%** energy acceptance and a proper **low-beta interaction region** for target insertion has been presented

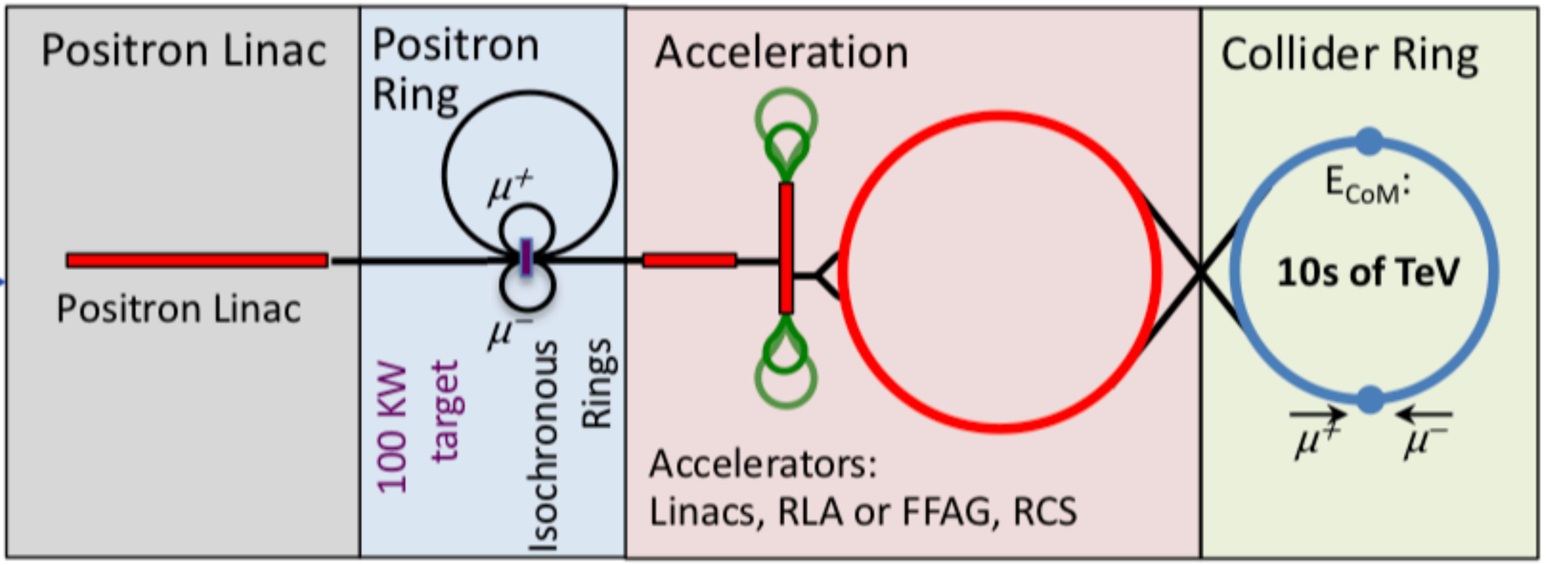
- Several ideas for the suppression of the multiple scattering contribution to the final emittance have been studied, the best solution being a 50μm LLi-D film jet target of about 0.5X_0 using a $\beta* = 0.1m$, producing a muon beam with **0.3x10^{-6} m rad** emittance after 1000 accumulation turns with **0.4x10^9 muons per bunch**

- It was also shown that the number of turns in the accumulator can be reduced using the **Revolver Configuration** resulting in an increase of the muons survival with smaller muon bunch perturbation. In this case an emittance of about **0.1x10^{-6} m rad** and a number of muons per bunch of about **10^9** have been obtained

- A 13.45m **apochromatic transport line** for multi-target configuration with $\pm 5\,\%$ energy acceptance has been presented. Emittance is preserved up to 44.0GeV positron beam energy, allowing a production efficiency of 50×10^{-8} muon pairs per positron and an emittance of $25\pi\ nm\ rad$ after 50 Beryllium targets of 1%X_0. The downside of this line is its length, reducing the possible number of iteration in the accumulation process.

Backup

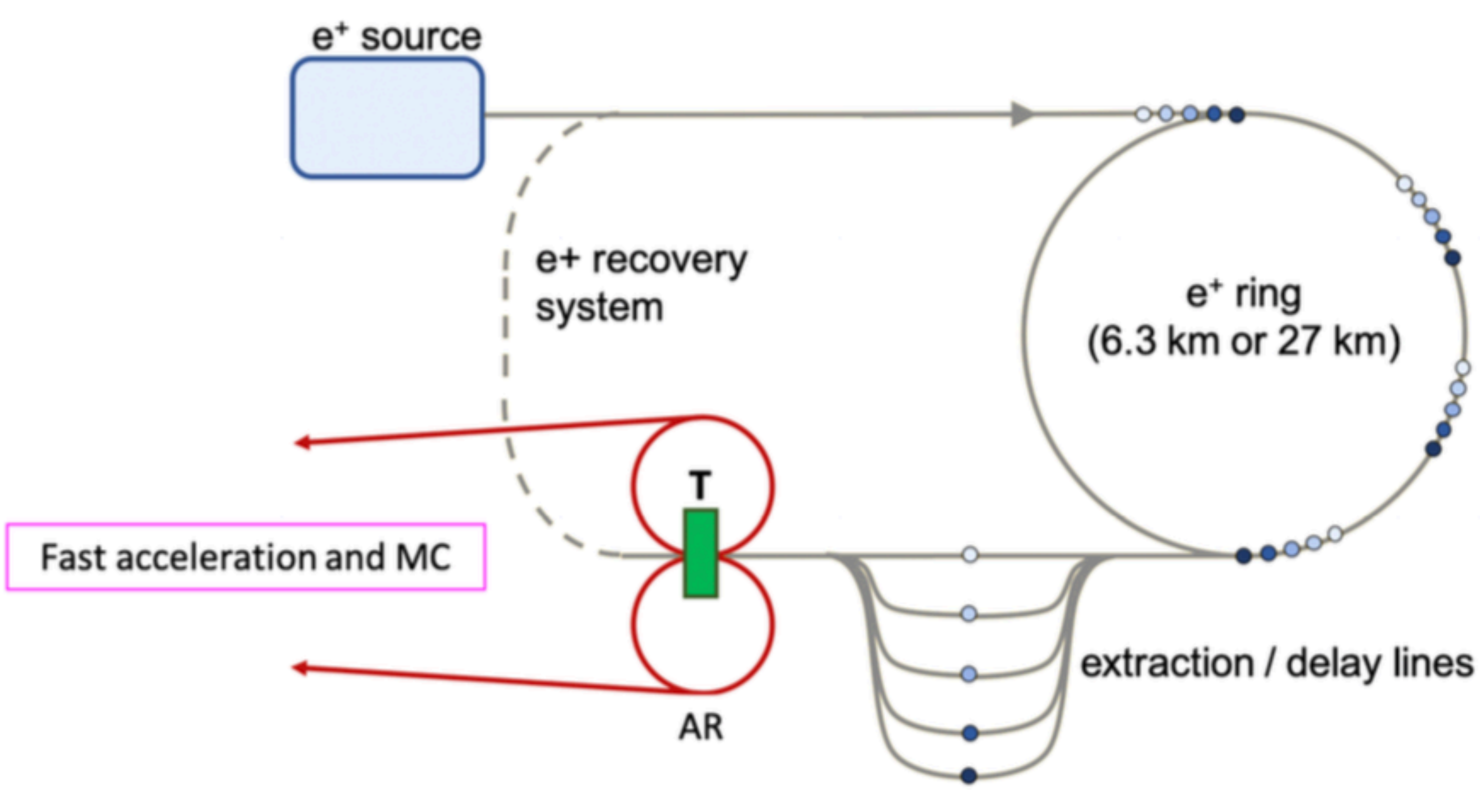
Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



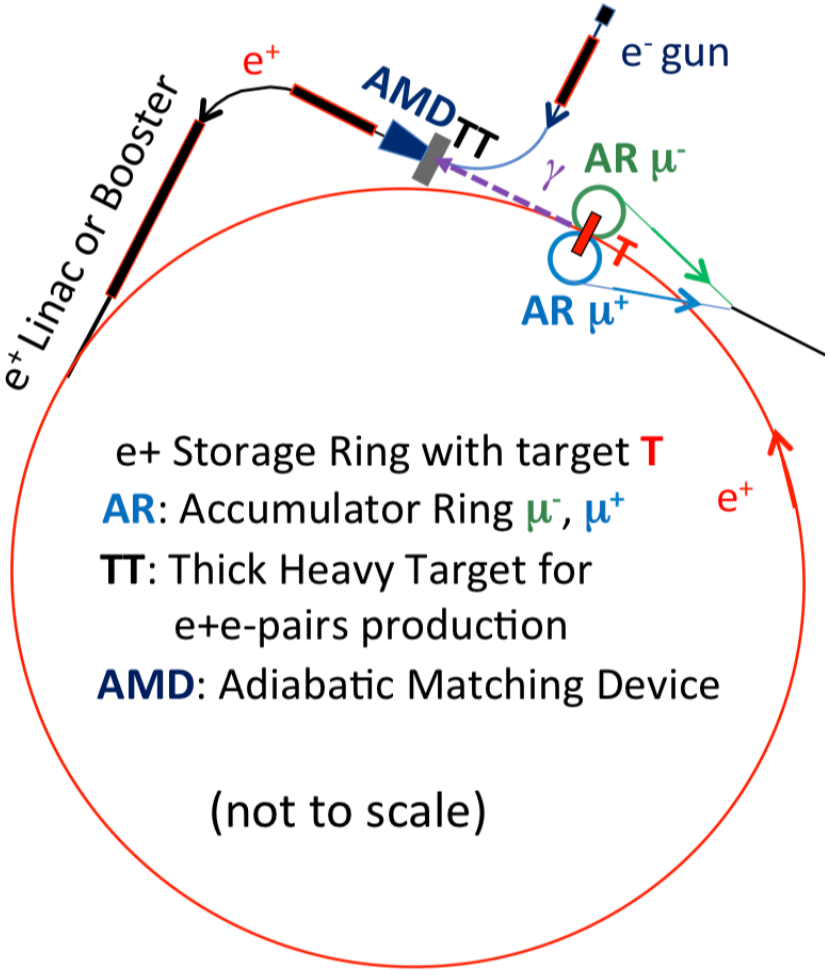
LEMMA
positron
driven

Ref. M. Boscolo, J.-P. Delahaye, M. Palmer, "*The future prospects of muon colliders and neutrino factories*", Review of Accelerators Science and Technology, Vol. 10 (2019) 189-214 ArXiv.1808.01858

Single-pass scheme



Multi-pass scheme



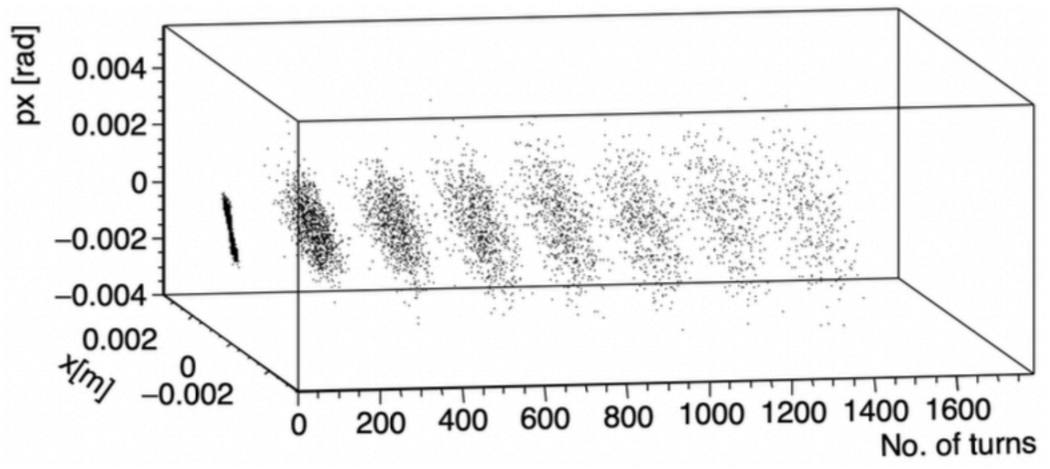
e+ Storage Ring with target **T**
AR: Accumulator Ring μ^-, μ^+
TT: Thick Heavy Target for
e+e-pairs production
AMD: Adiabatic Matching Device

(not to scale)

Multiple Scattering

$$\sigma_\theta[rad] = \frac{0.0136}{E[GeV]}\sqrt{\frac{L[m]}{X_0[m]}}$$

```
rnd = gRandom->Gaus(0,1);
x = x + L_step*px/2;
px = px + sigma_theta*rnd;
x = x + L_step*px/2;
```



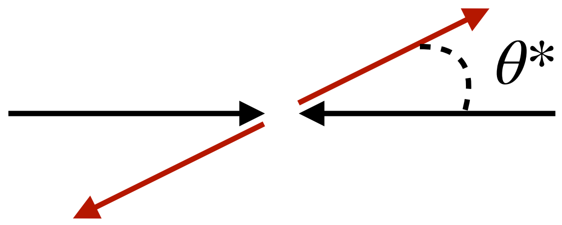
Bremsstrahlung

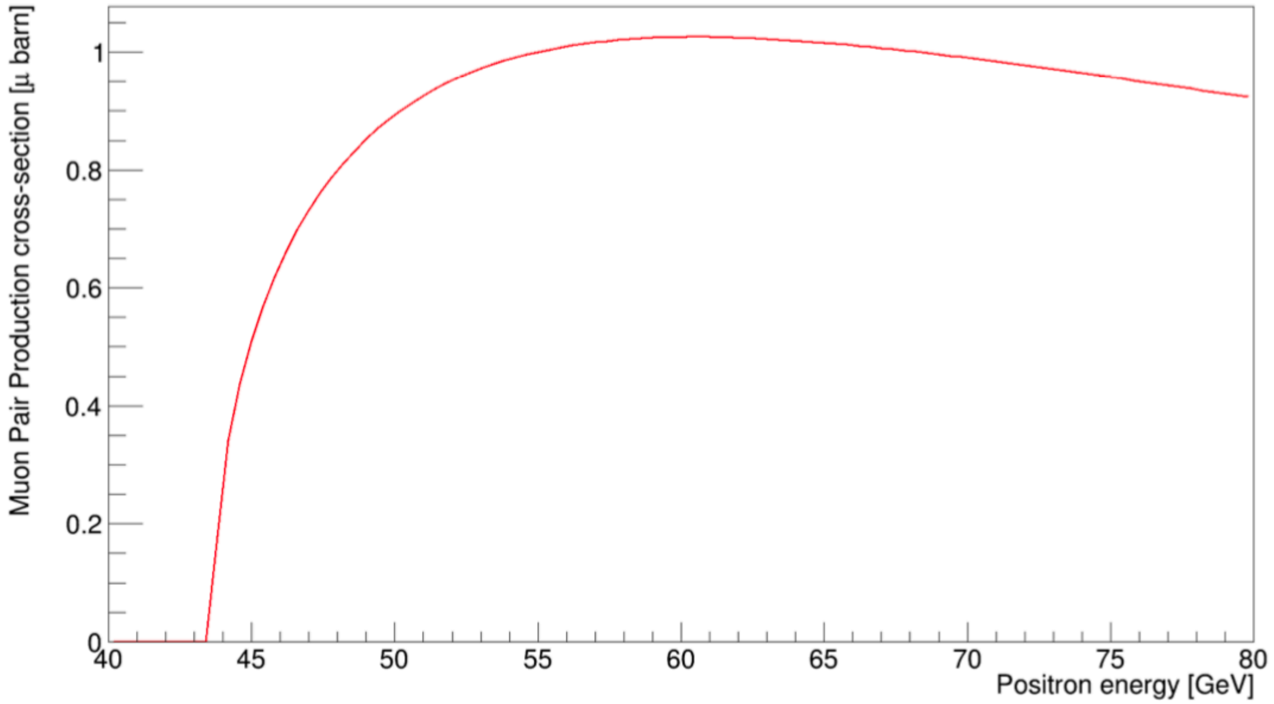
$$\frac{d\sigma}{dk} = \frac{A}{X_0 N_A k}\left(\frac{4}{3} - \frac{4}{3}y + y^2\right) \qquad P = \frac{N_A\rho}{A}L_{step}\sigma_{tot} \sim \frac{L_{step}[m]}{X_0[m]}\frac{4}{3}log\left(\frac{k_{max}}{k_{min}}\right)$$

Muon Production

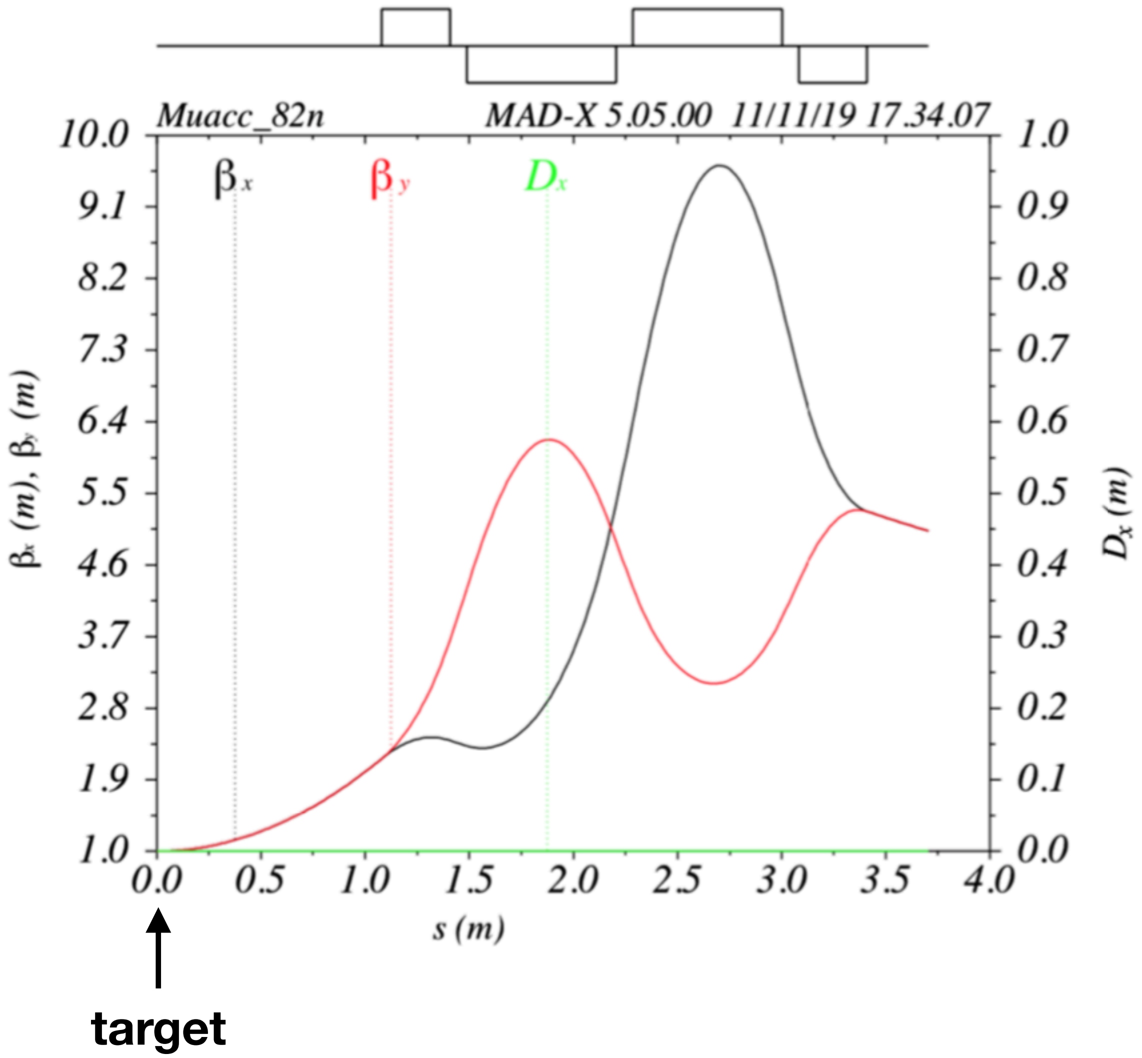
$$w = \frac{N_{e+}^{true}\ \rho N_A Z/A\ l_{tgt}\ \sigma_{e^+e^-\to\mu^+\mu^-}}{N_{e+}^{macro}}$$

$$f(\theta^*) = \left[1 + \frac{E_{th}}{E} + \left(1 - \frac{E_{th}}{E}\right)cos^2\theta^*\right]sin\theta^*$$

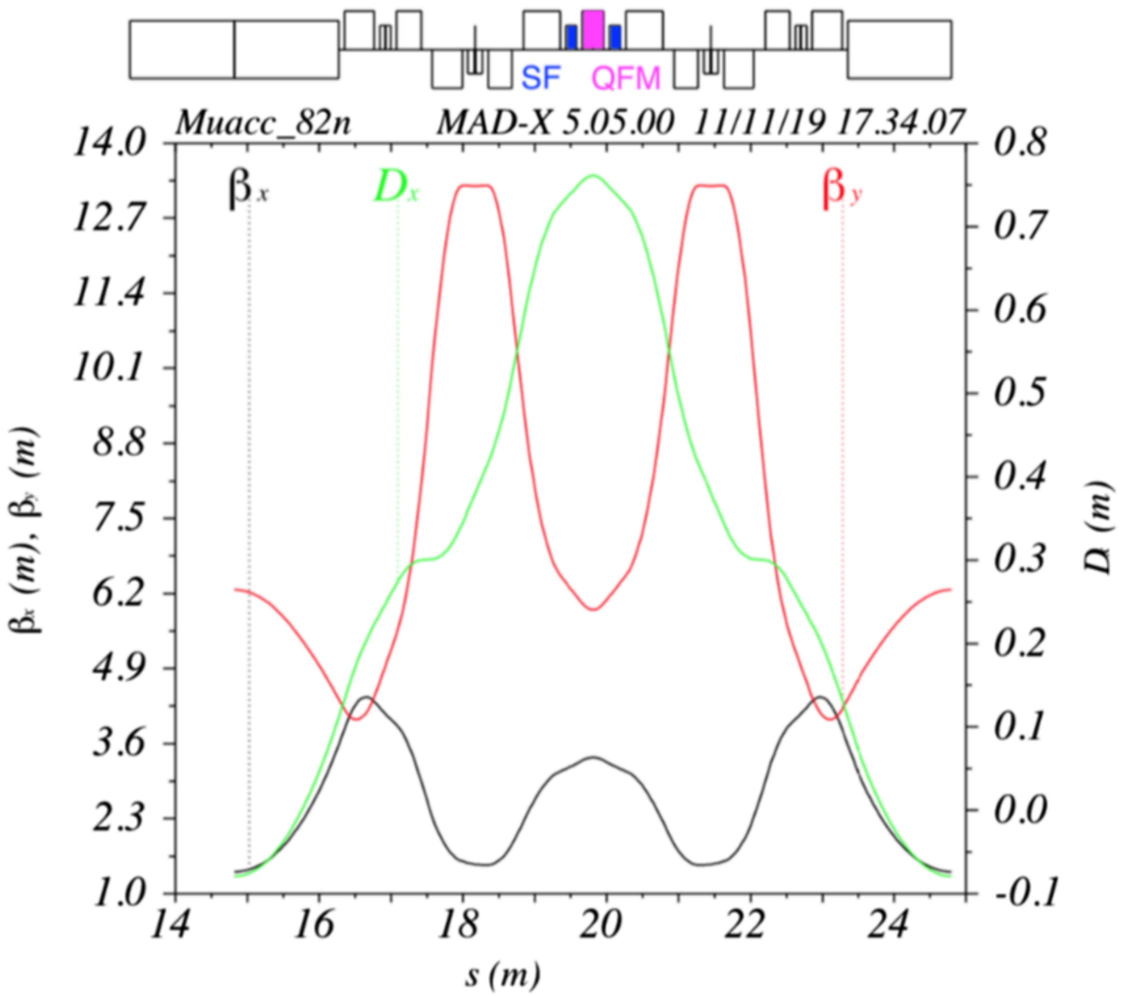


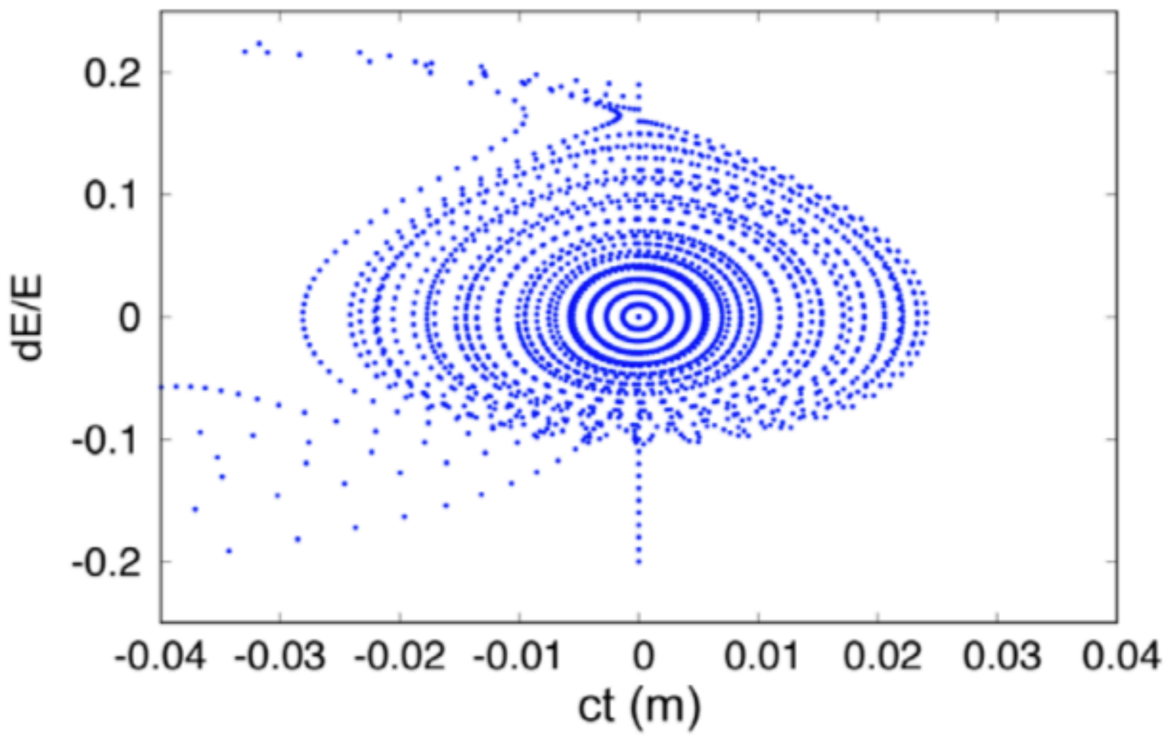


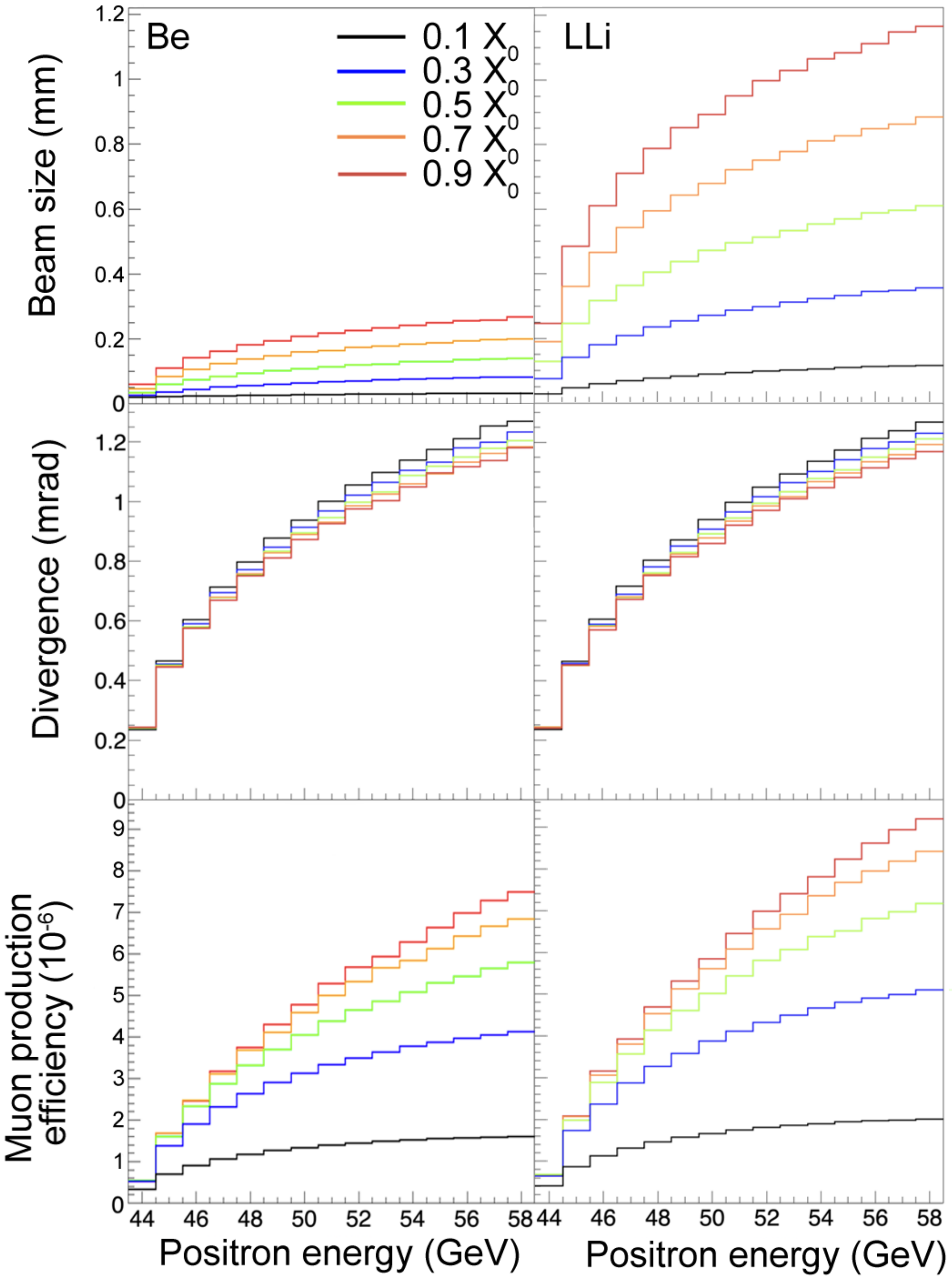
First Cell



Central Cell







$$\frac{\rho}{X_0} = f(\mathrm{LLi})\,\frac{\rho\mathrm{LLi}}{X_0^{\mathrm{LLi}}} + f(\mathrm{D})\,\frac{\rho^{\mathrm{D}}}{X_0^{\mathrm{D}}}$$

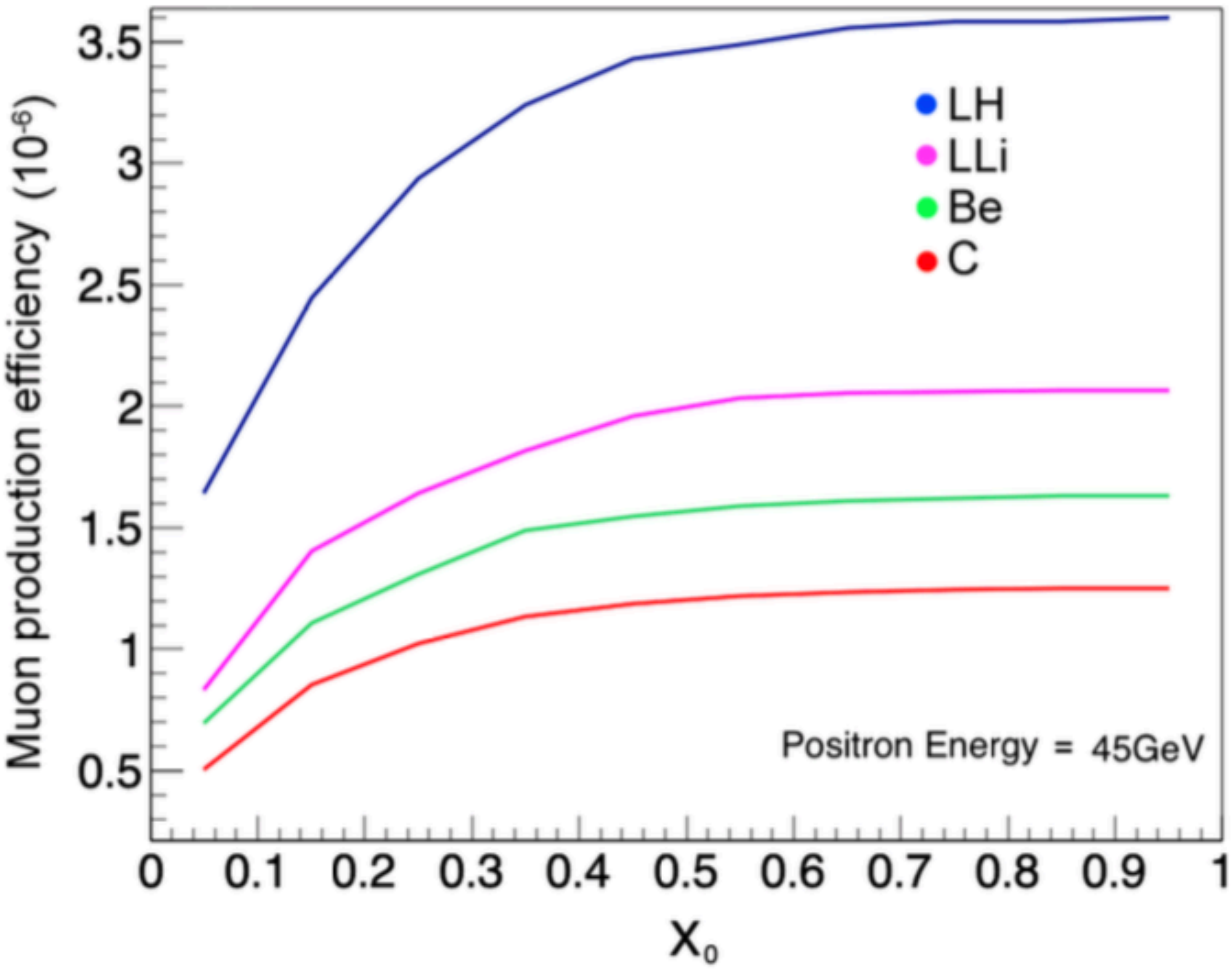
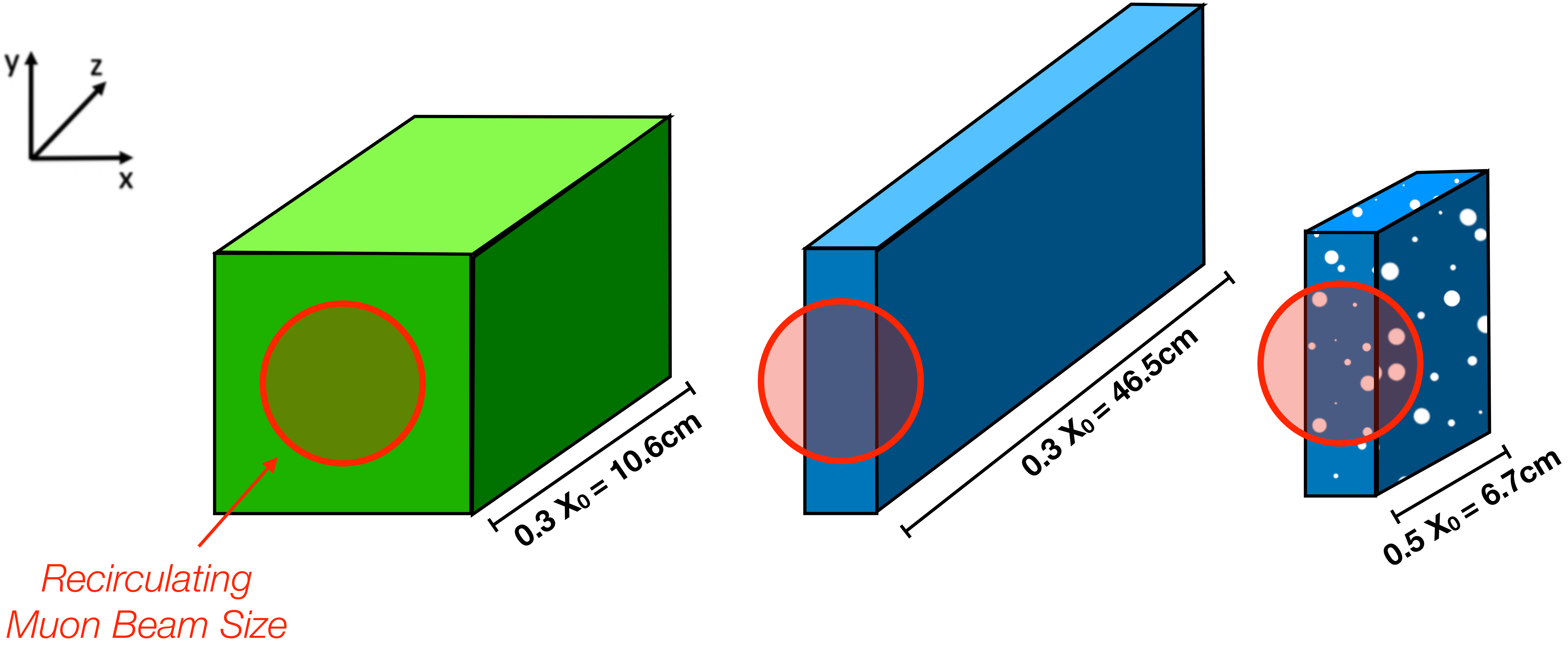


TABLE III. Properties of LLi–D compounds, for different fractions of liquid lithium $f(\mathrm{LLi})$, and diamond powder $f(\mathrm{D})$.

$f(\mathrm{LLi})$	$f(\mathrm{D})$	$\rho[\mathrm{g\ cm^{-3}}]$	$X_0\ [\mathrm{g\ cm^{-2}}]$	X_0 [cm]
1.0	0.0	0.534	82.78	155.02
0.9	0.1	0.833	59.26	71.18
0.7	0.3	1.430	48.89	34.19
0.5	0.5	2.027	45.61	22.50
0.3	0.7	2.624	44.00	16.77
0.1	0.9	3.221	43.04	13.36
0.0	1.0	3.520	42.70	12.13



Recirculating Muon Beam Size