Lemma muon collider

HEP before the LHC

HEP before the F.C.

Particle physics is not **validation** anymore, rather it is **exploration of unknown territories** *

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        ➜ much **higher energies** are reachable
        (~3TeV in 4km circ.)

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      - Much smaller energy spread of the beam ➜ much higher energy **resolution**
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    - **Physics**:
      - Higgs coupling $\propto m^2$

        ➜ Much bigger production of Higgs boson (also s-channel)

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  - **Cooling** needed!

The idea

* Conventional muon production scheme:

The idea

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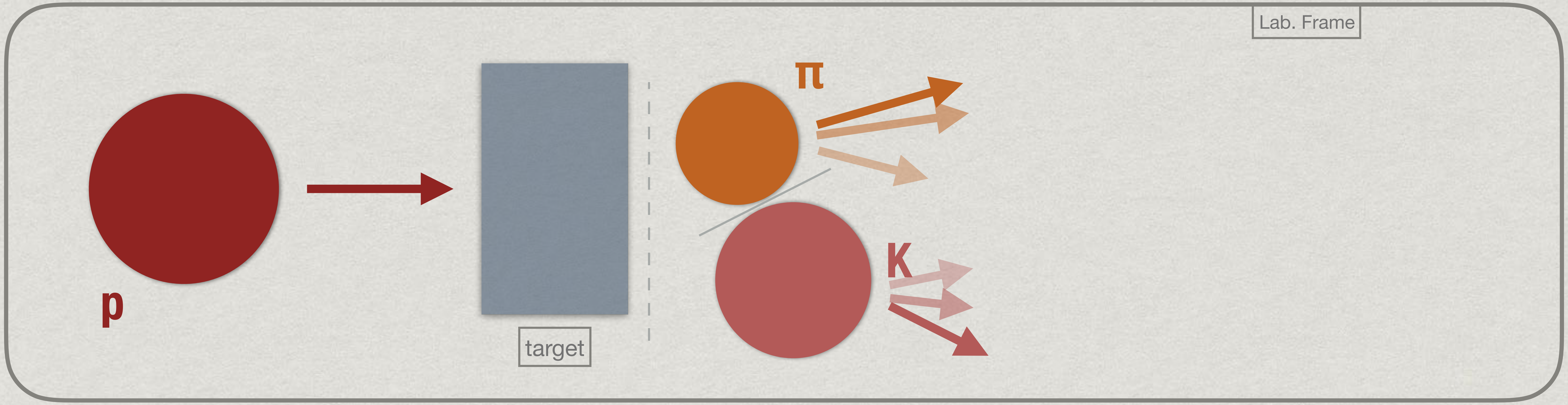

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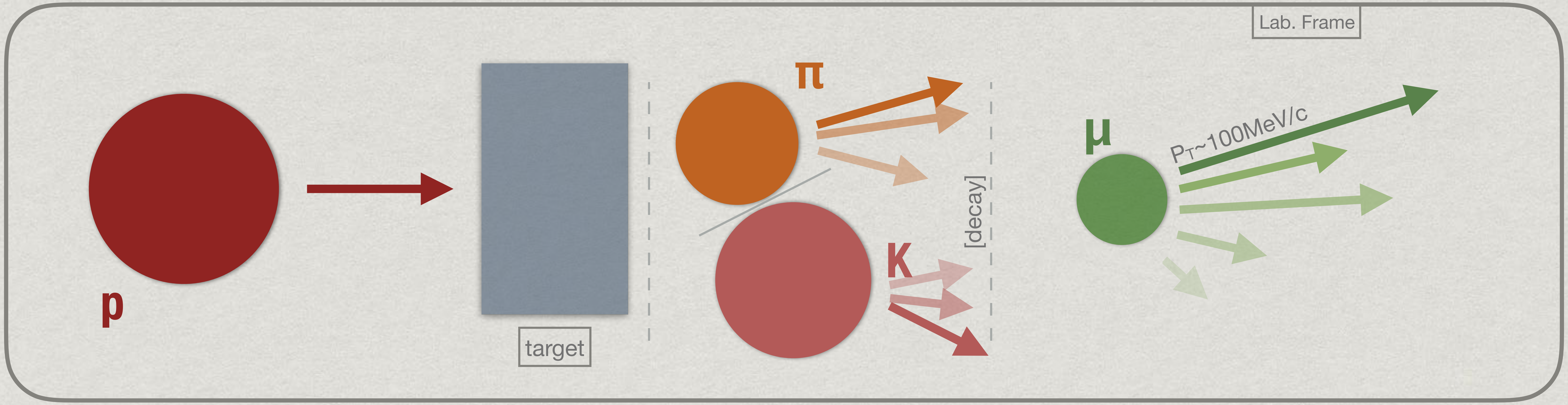

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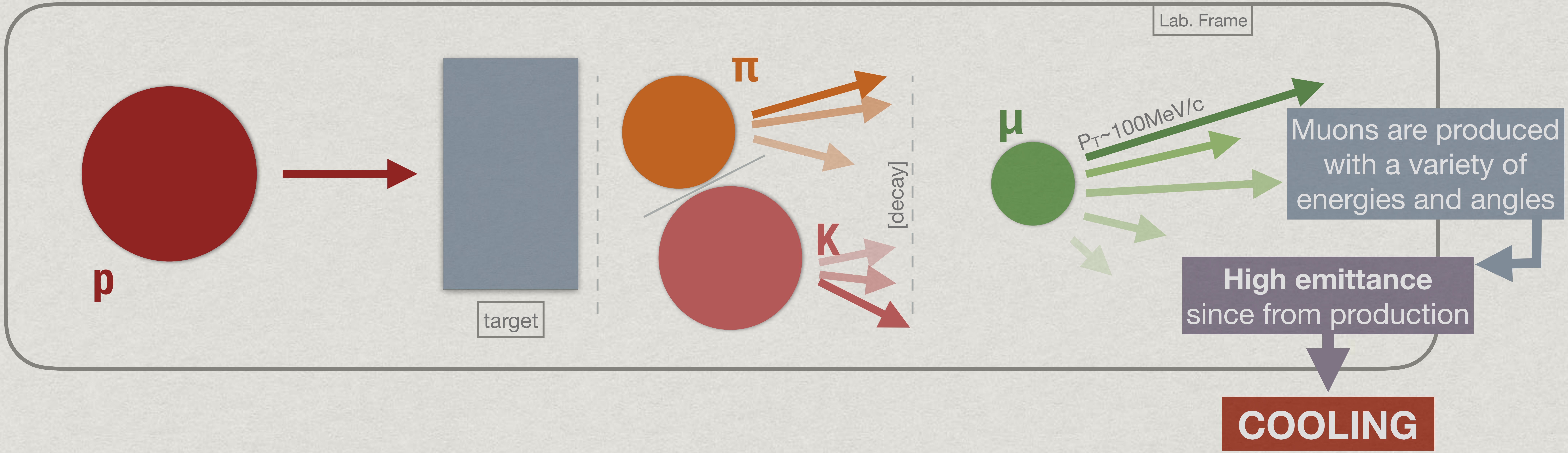

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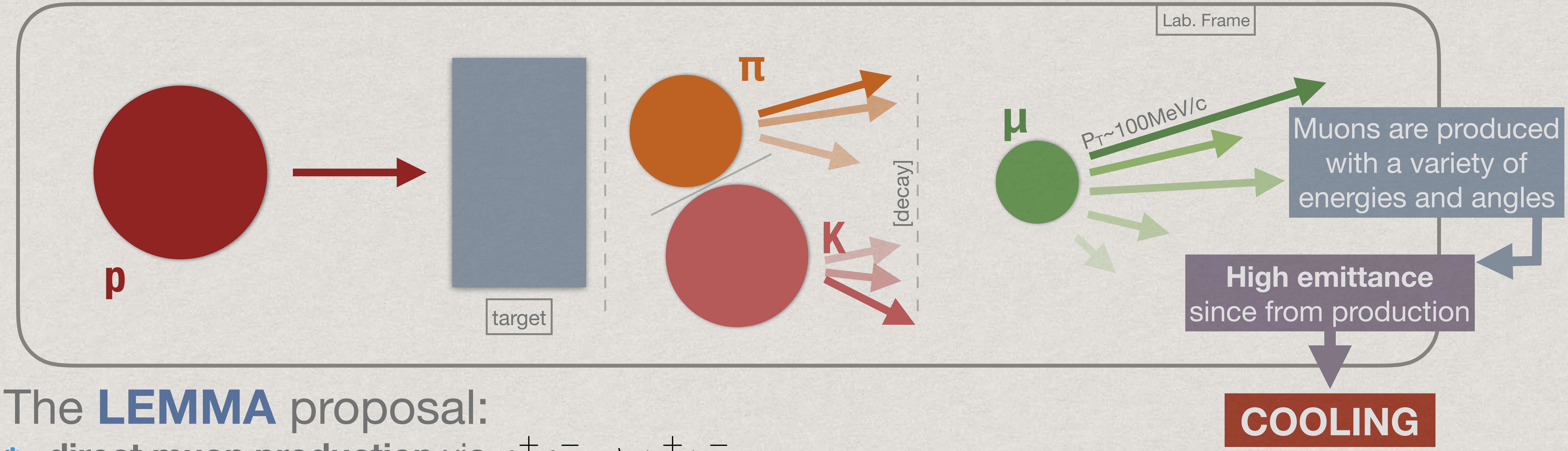

- The **LEMMA** proposal:
    - **direct muon production** via $e^+e^- \to \mu^+\mu^-$

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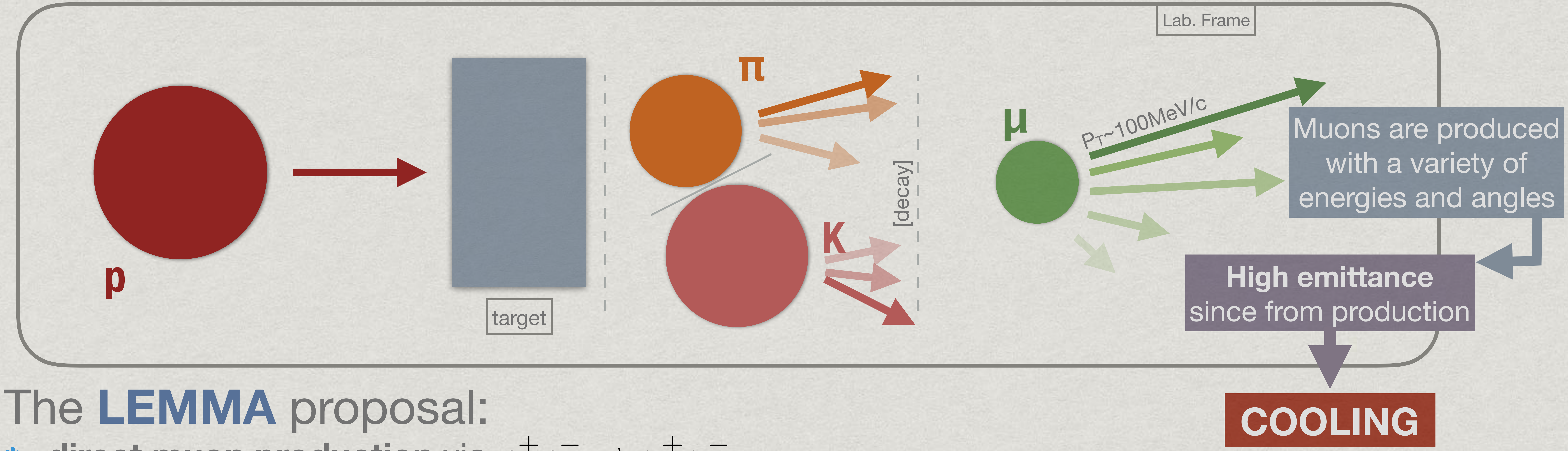

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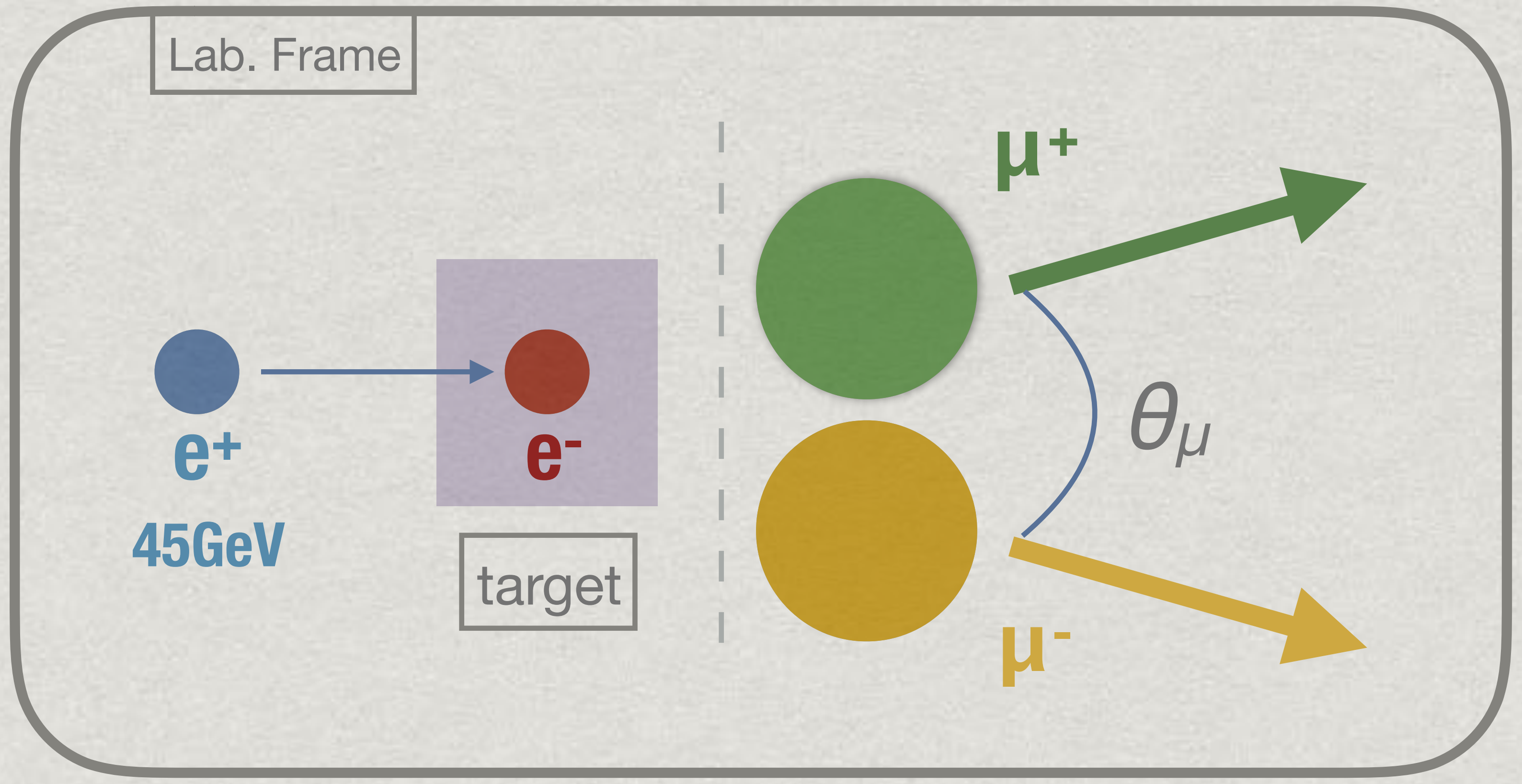

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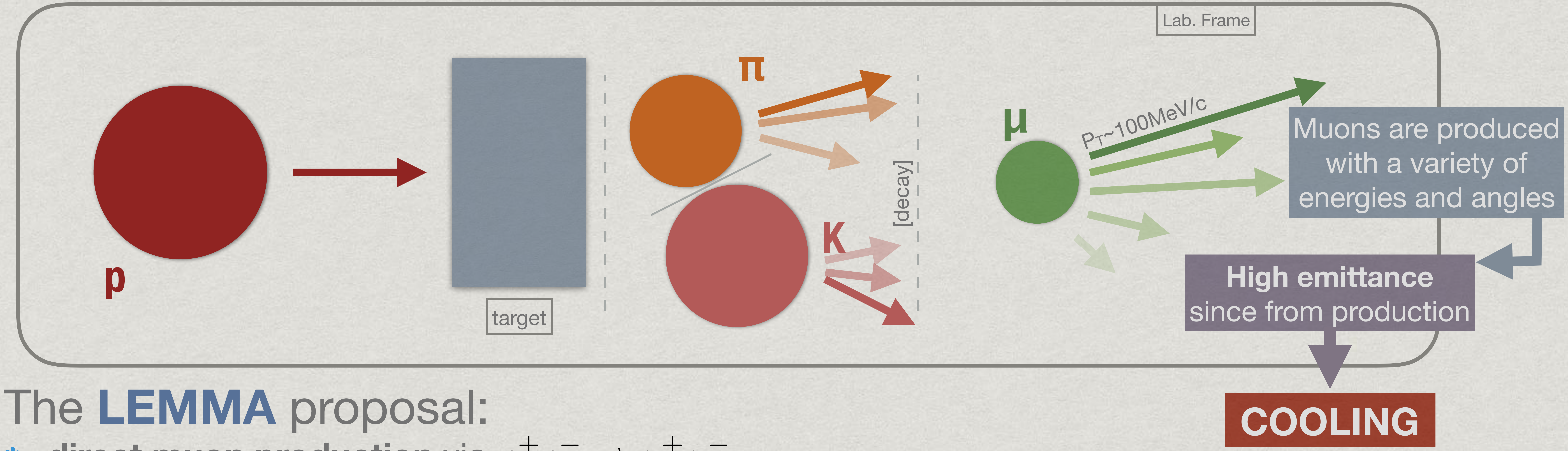

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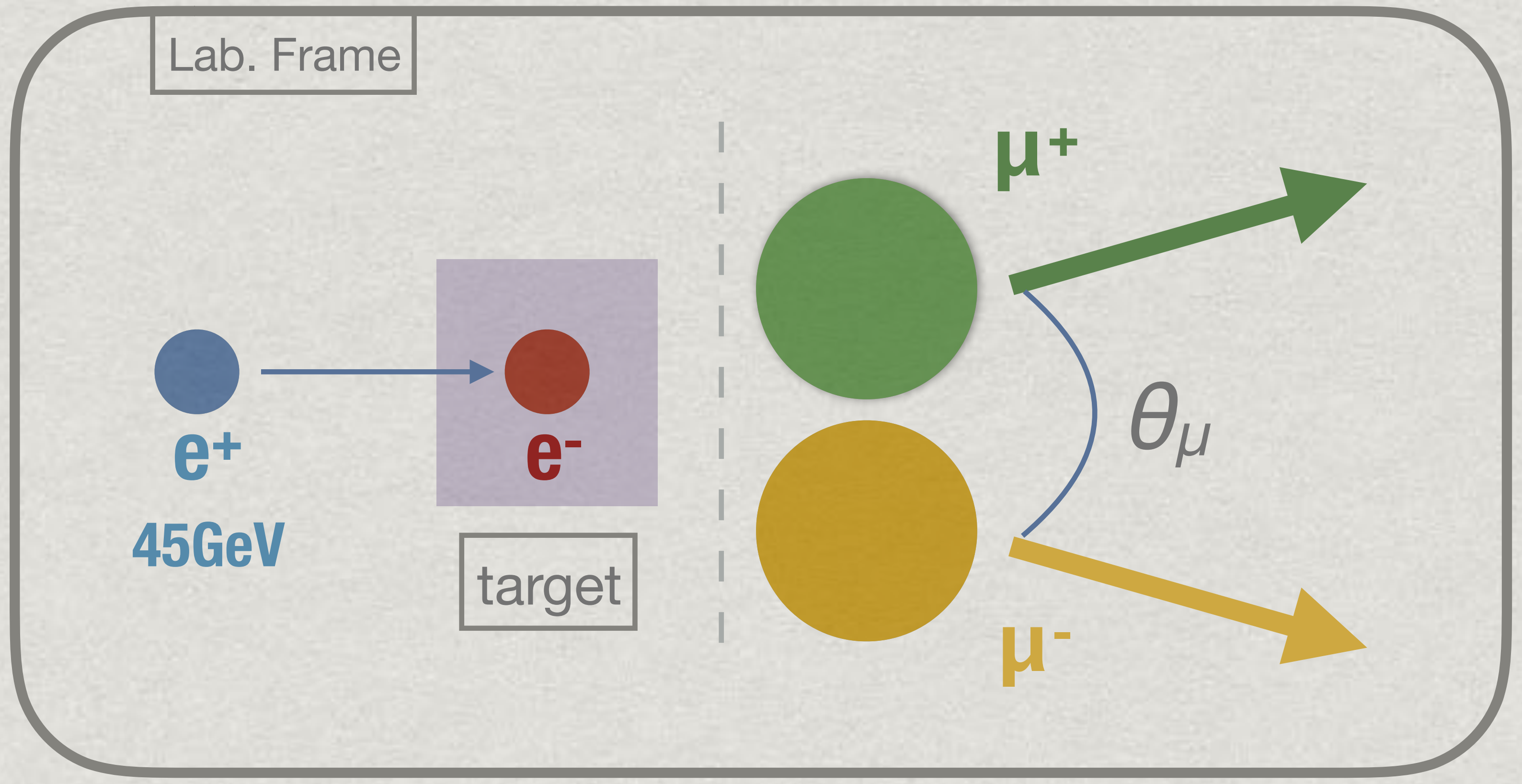

👍 - **Low emittance** possible *θ_μ and ΔE tunable with √s, and very small close to the threshold*

👍 - Small **energy spread**

👍 - Low **background** *low emittance allows good luminosity with reduced μ flux*

👍 - Reduced **losses** from decay *high boost + asymmetric scheme*

👎 - **Rate**: much smaller cross section wrt protons (μb vs mb)

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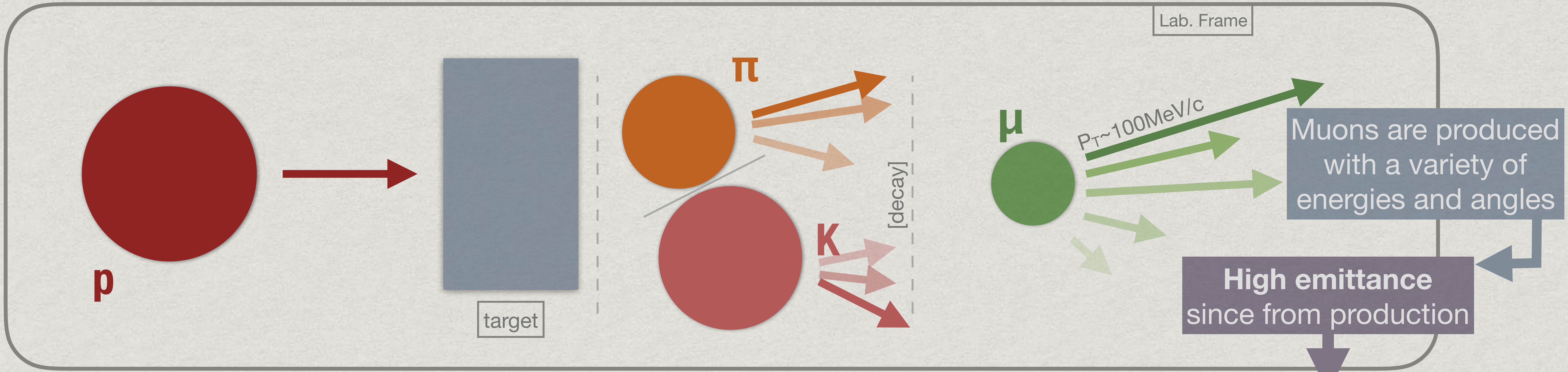

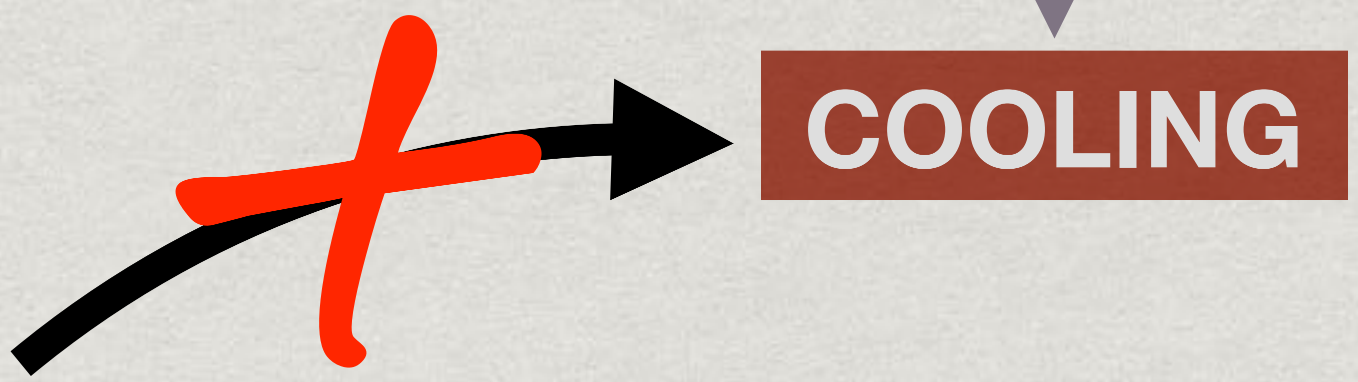

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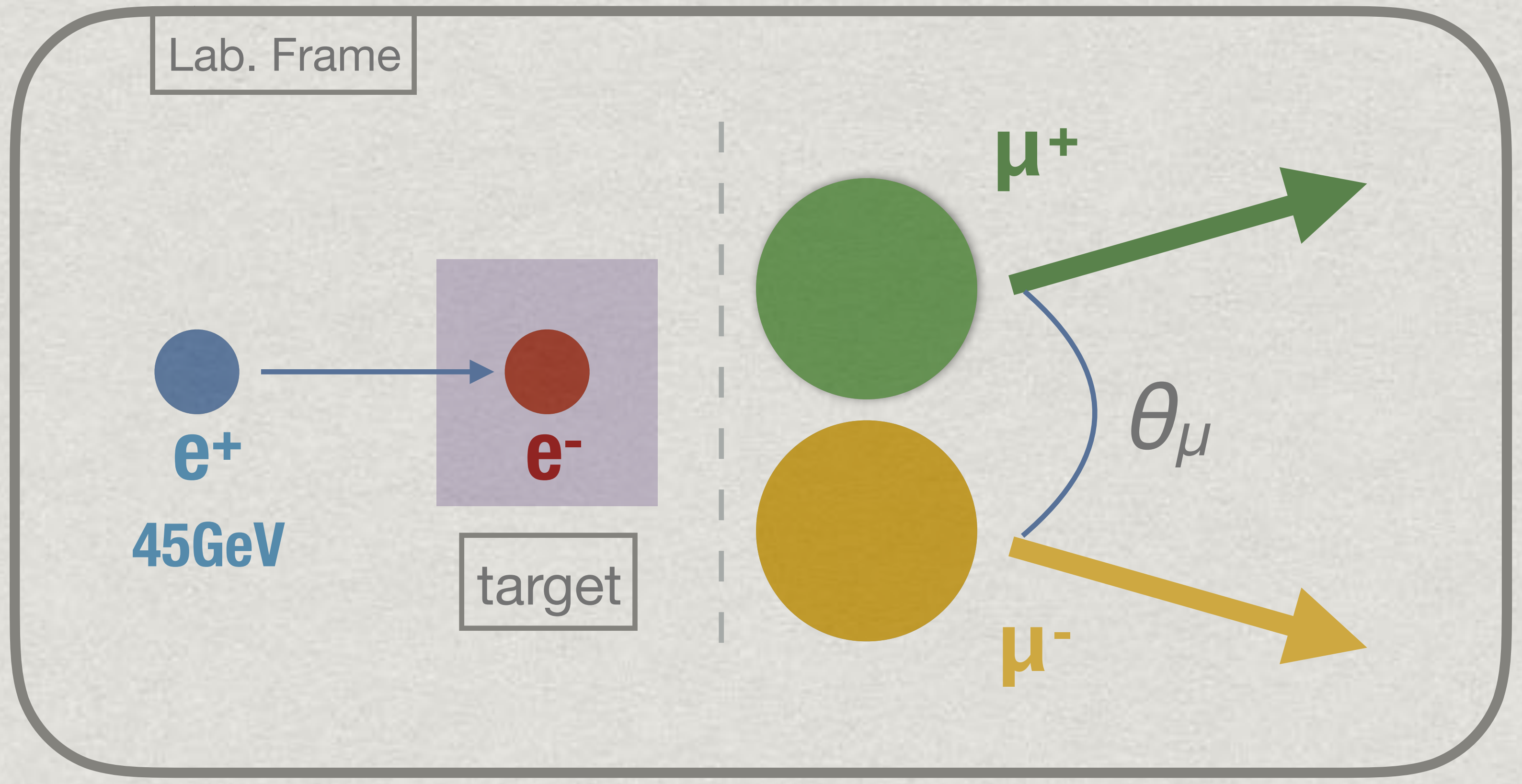

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- 👍 - Reduced **losses** from decay *high boost + asymmetric scheme*
- 👎 - **Rate**: much smaller cross section wrt protons (μb vs mb)

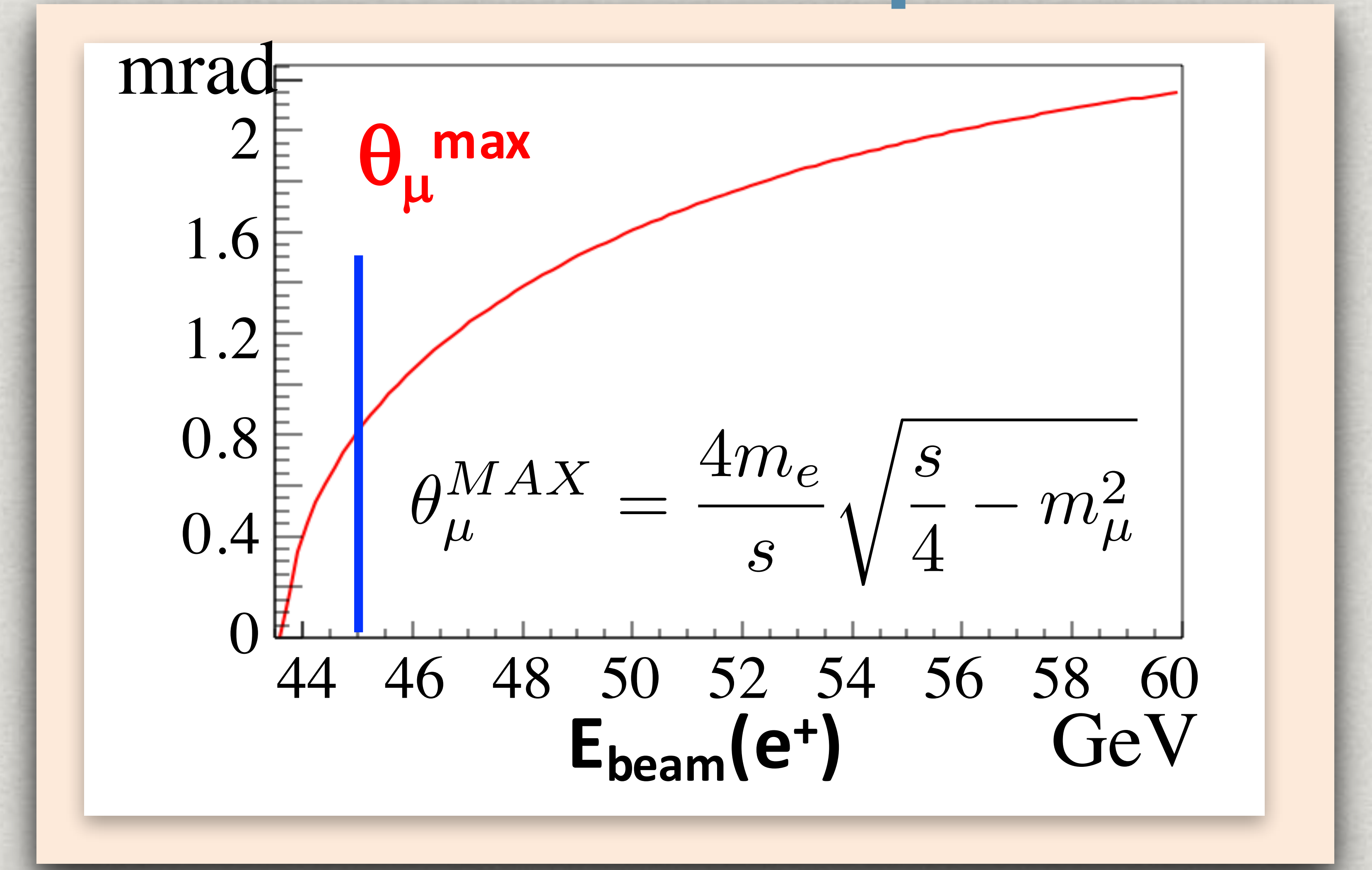
- **Main idea :** muons from **direct m pair production**:

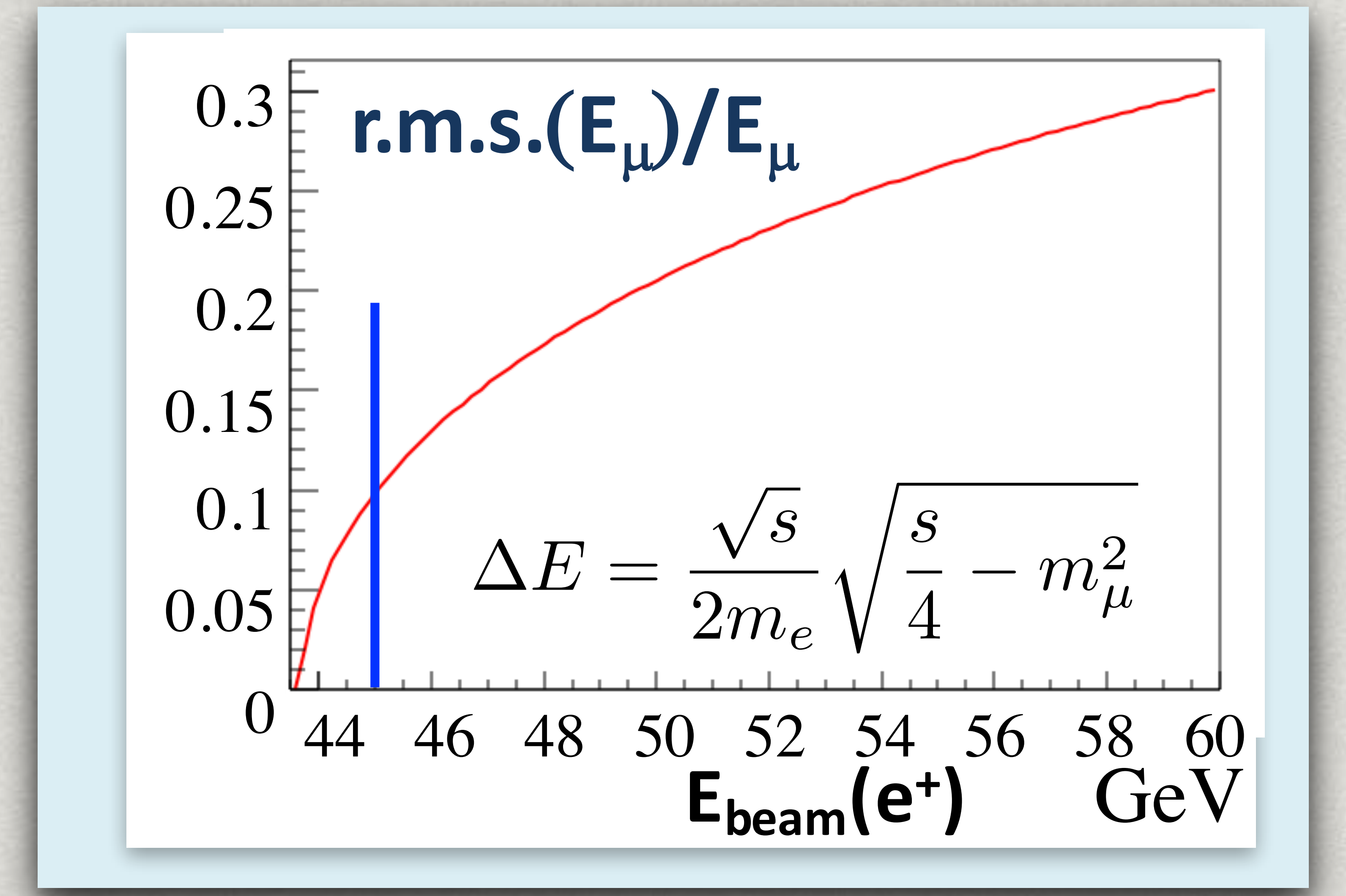
Muons produced from **e^+e^-**$\rightarrow\mu^+\mu^-$ at $\sqrt{s}$ around the m^+m^- threshold **($\sqrt{s}$ ≈ 0.212GeV)** in asymmetric collisions (to collect m^+ and m^-)

M. Antonelli and P. Raimondi, Snowmass Report (2013) also INFN-13-22/LNF Note

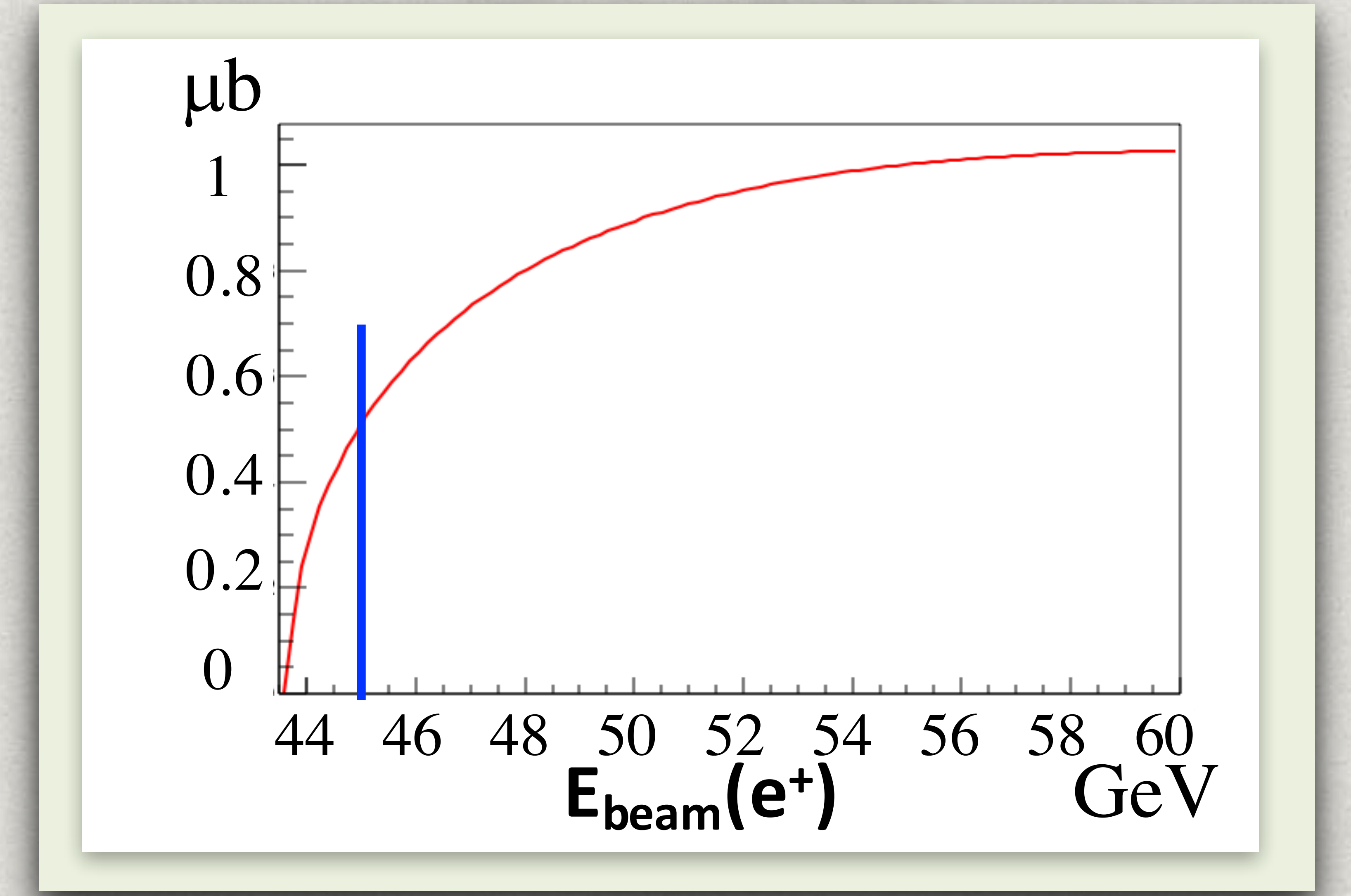
Direct muon production

Novel Approach

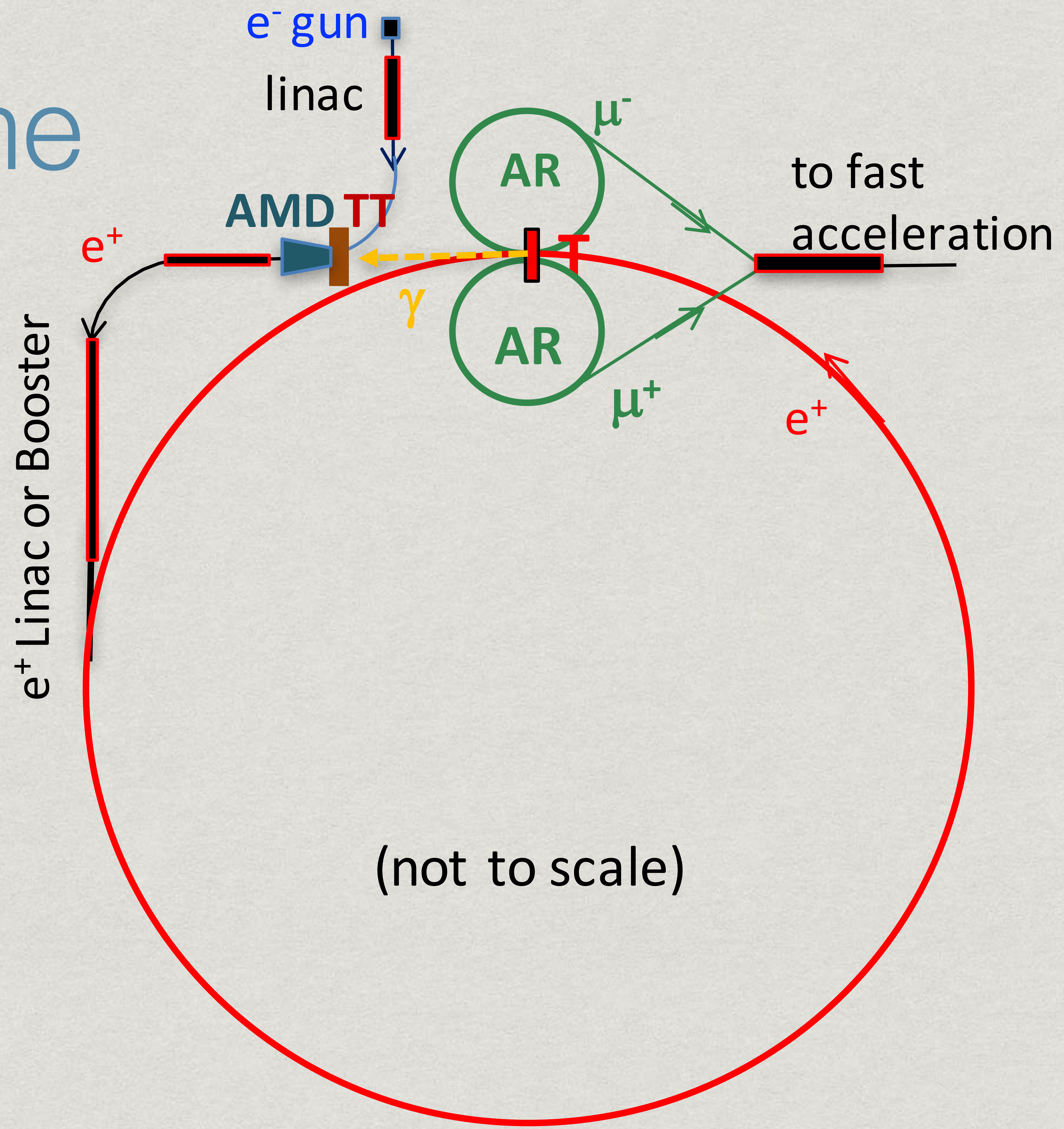




$\sigma(e^+e^- \rightarrow \mu^+\mu^-)$

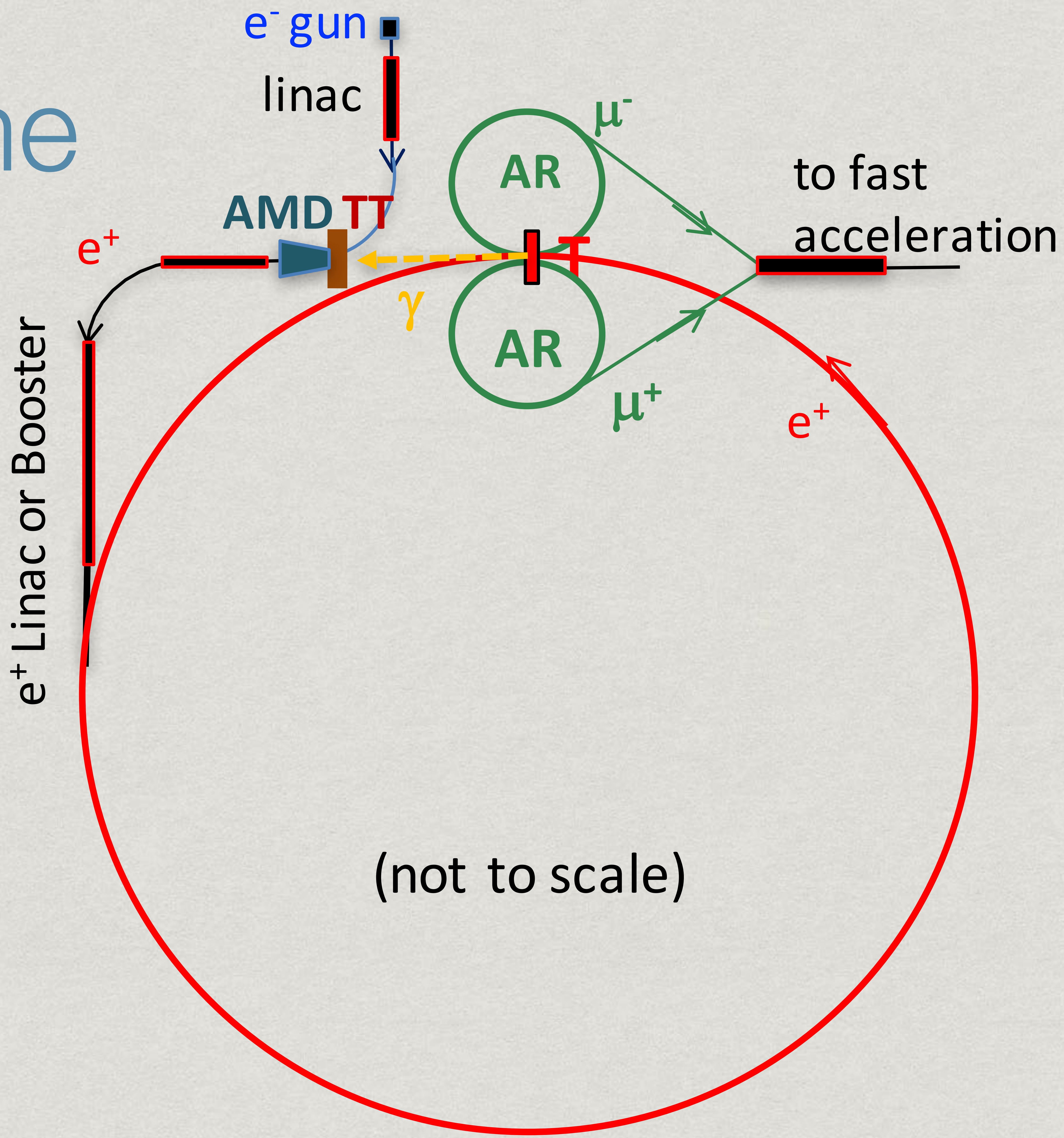


Accelerator Scheme



Accelerator Scheme

- **From e^+ source to ring:**
  - e^- on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production
    - possibly with γ produced by e+ stored beam on T
  - Adiabatic Matching Device (**AMD**) for e+ collection
  - Acceleration (linac / booster) , injection



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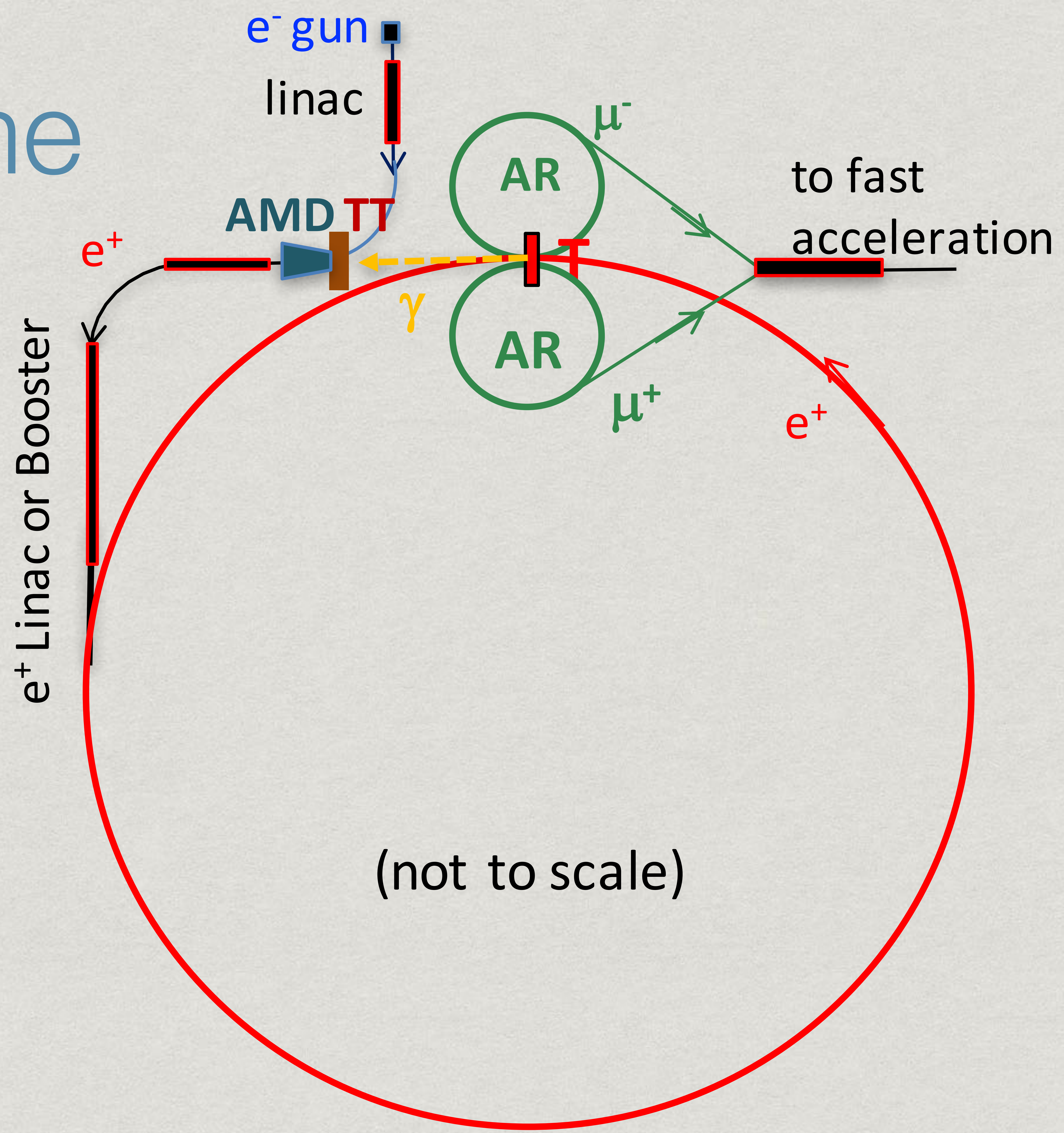
- <u>**e^+ ring:**</u>
  - A 6.3 km **45 GeV** storage ring with target T for muon production



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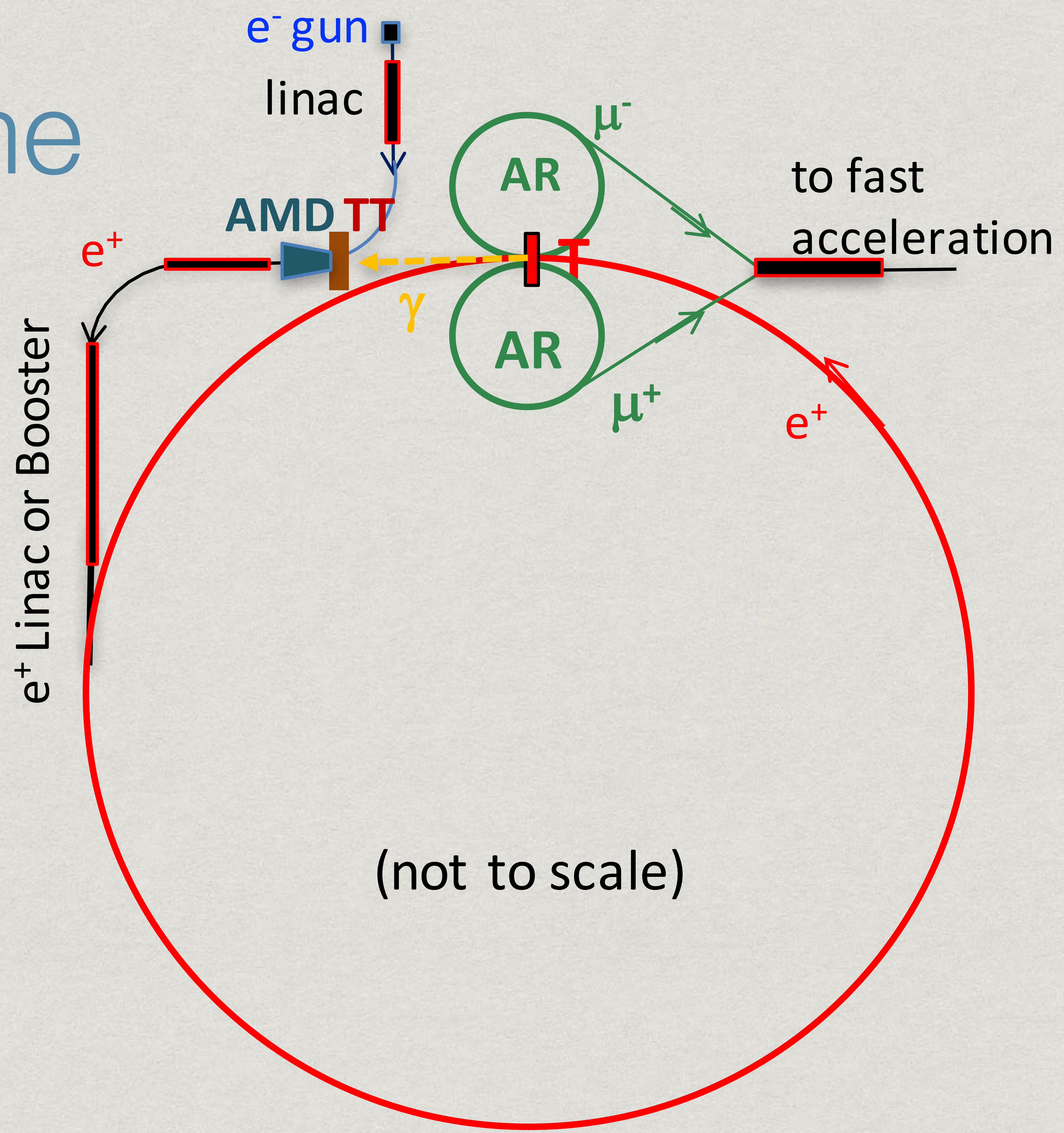
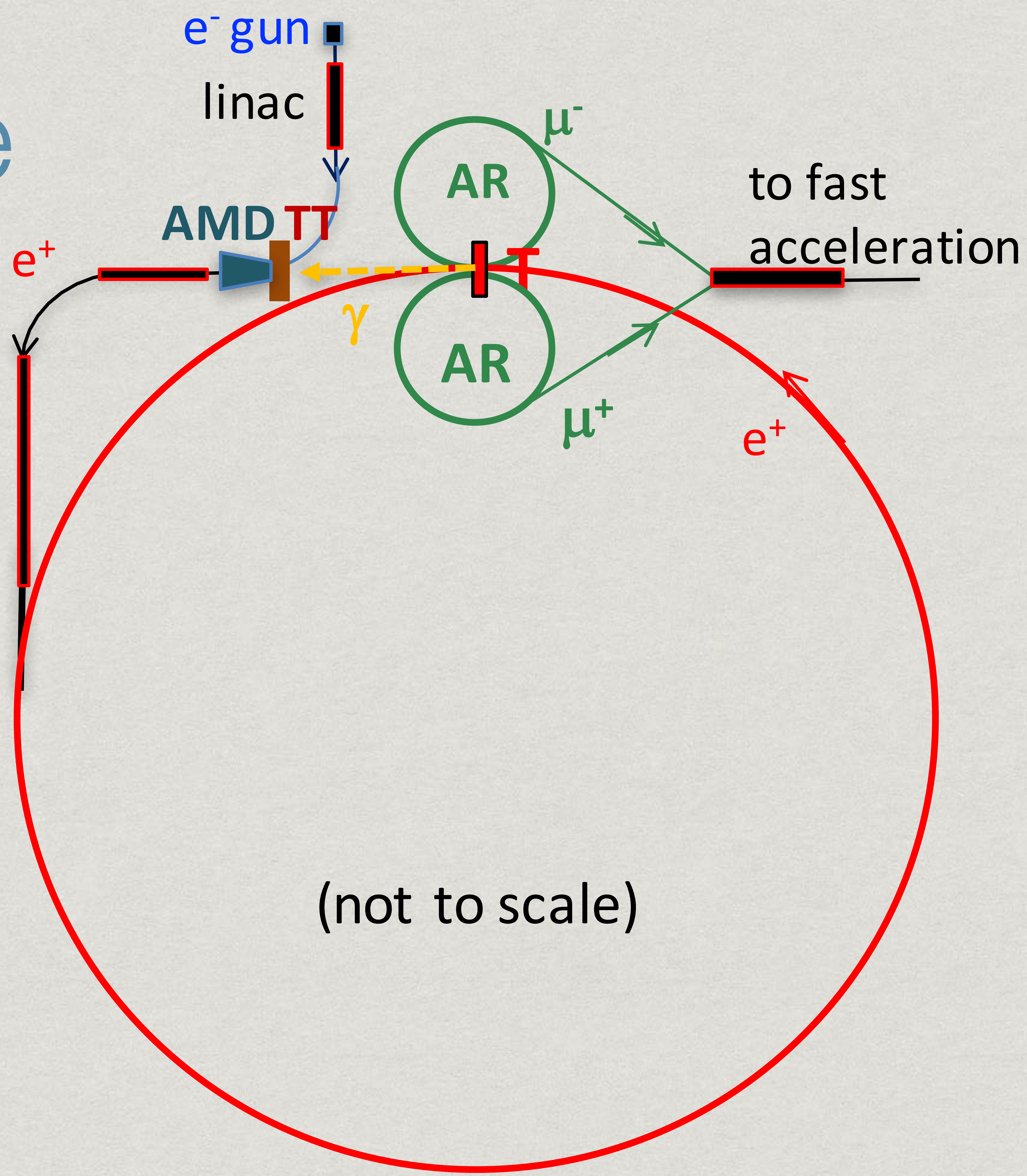
- **From μ+μ- production to collider:**
  - Produced by the e+ beam on target **T** with E(μ)≈22GeV, γ(μ)≈200 → **τ_{LAB}(μ)≈500μs**
  - Accumulation Ring: 60m isochronous and high momentum acceptance for μ recombination
  - Fast acceleration
  - Muon collider



Accelerator Scheme

e+ ring parameter	unit	value
Circumference	km	6.3
Energy	GeV	45
bunches	#	100
e+ bunch spacing = Trev (AR)	ns	200
Beam current	mA	240
N(e+)/bunch	#	3 · 1011
U_0	GeV	0.51
SR power	MW	120

(also 28 km foreseen to be studied as an option)



NOT FOR FREE

muon production by positron beam impinging on a target.

Why it is difficult….

1) Cross section , not enough (max 1μb)

2) bremsstrahlung, high Z->Z^2

3) multiple scattering in target (Sqrt (X0))

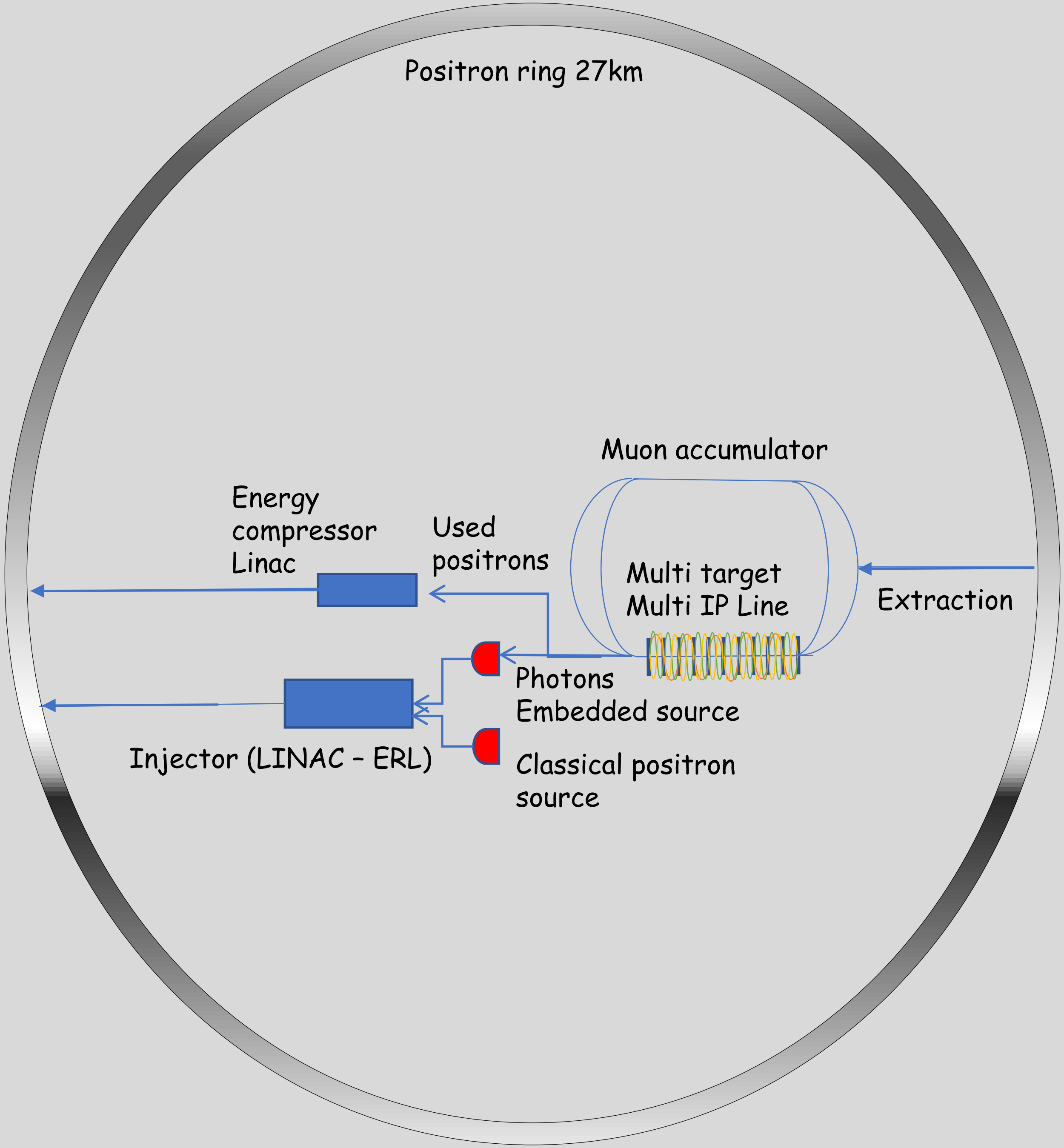
4) PEDD and target heating

5) Available positron sources

6) 45 GeV positrons – Sync Power

KEY ISSUES

	Challenges	Solutions
μ **production**	**Target average power** [material, shape, heat matching, average e^+ current on target]	Multiply N of targets to distribute average deposited energy
	Instantaneous PEDD [material, shape, bunch charge, e^+ spot on target]	Increase σ on target (increase ε_m!). Develop solid R&D program
	Integrated PEDD [material and shape, thermo-mechanical wave evacuation and matching, bunch charge and σ on target, time interval between bunches]	Increase σ on target (increase ε_m!). Increase interval between 2 e^+ beam passages (μ lifetime!)
μ **beam**	μ **emittance** [e^+ emittance and energy on target, target material and thickness (multiple scattering), μ production angle]	Preserve e^+ beam 6D characteristics @ targets. Optimize target thickness and material
	μ **bunch intensity** [cross section, material, e^+ beam energy and charge, target thickness]	Increase N of μ bunches produced/cycle and/or multiple μ production lines. Multivariable optimization of effect of the target (thickness, material, spacing, number)
	μ **beam recombination** [recombination scheme, μ lifetime, e^+ beam charge]	
e^+ **beam**	**Intensity and losses [**interaction with target, ring acceptance, injection, positron source intensity]	Use of "fresh" bunches. Re-use of "spent" bunches. Embedded e^+ source
	Source [target, N of sources, injection cycles for e^+ damping]	Re-use of "spent" bunches. Multiply embedded e^+ source. Damping Ring
	Emittance at the target [interaction with target, storage ring and cooling time]	Minimize N of bunch-target interactions per production cycle before cooling. Use "fresh" bunches
	Ring synchrotron power [very high energy]	Increase ring circumference, reduce beam current or reduce e^+ ring energy



Positron ring 27km
Muon accumulator
Energy
compressor
Linac
Used
positrons
Multi target
Multi IP Line
Extraction
Photons
Embedded source
Injector (LINAC – ERL)
Classical positron
source

Cycles

		2 damping time 80ms		300 µs		20ms		2 damping time 80ms
Positron source	Stand by		Stand by		Positron generation	1000 bunch, 3 exp 10/bunch, 0,24 mA	Target cooling	
Injection Linac	Stand by		Injection from the embedded source	1000 bunch, 2 exp 10/bunch, 10 mA	Injection from the natural source	1000 bunch, 3 exp 10/bunch, 0,24 mA	Stand by	
Positron ring	Cooling	1000 bunch, 5 exp 11/bunch, 11kHz, 0.88 A	Extraction to the muon production lines		Top up injection	1000 bunch, 4,5 exp 11/bunch,	Cooling	1000 bunch, 5 exp 11/bunch, 11kHz, 0.88 A
Muon accumulator	Stand by		Muon generation	1 bunches mu+/-, 10exp9/bunch,~1MHz, 300mA	Extraction to post acceleration		Target cooling	
Recuperation LINAC	Stand by		Positron beam energy compression	1000 bunch, 4.5 exp 11/bunch, 240 mA	First post acceleration	2 bunches mu+/-, 10exp9/bunch,	Stand by	
Embedded source	Stand by		Positron generation	1000 bunch, 2 exp 10/bunch, 10 mA	Target cooling		Target cooling	

	Positron Ring	1000 bunch, 5 exp 11/bunch, 11kHz, 0.88 A, 90-110 MW@ 2 damping time
	Injection LINAC	5 10exp14/s@45GeV. 80mA - 3,5 MW
AVERAGE	Positron source	3 10exp14/s@300MeV. 48mA - 14,5kW
	Embedded source	2 10exp14/s@300MeV. 32mA - 9,5kW
	Muon Accumulator	2 10exp9/bunch,~3MHz, 1mA x 0,003 = 3mA 22.5 GeV. No damping
	Recuperation LINAC	4.5 exp 15/s, ~720mA@3GeV, 2,15 MW

Multi-IP Beamline

- Many different **multi-IP beamline optics** (need to split the power on target)
- **Multi-IP beamline optics** is made of regular unit cells where targets are placed at the beginning and at the end of each cell.
- Three beams will pass through this beamline: e^+, μ^+, μ^-

e^+ beam:
$e(e^+)$=5.7 nm, E(e+) = 45 GeV

$\beta^*(e^+)$= 3.8m

E(e+) = 18 GeV

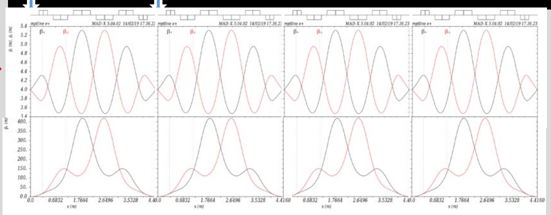
e^+ →

... → e^+ μ^+ μ^-

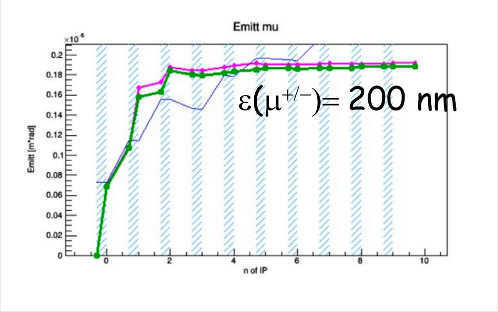
10.5 GeV < **E($\mu^{+/-}$)** < 26.2 GeV

e+

μ^+

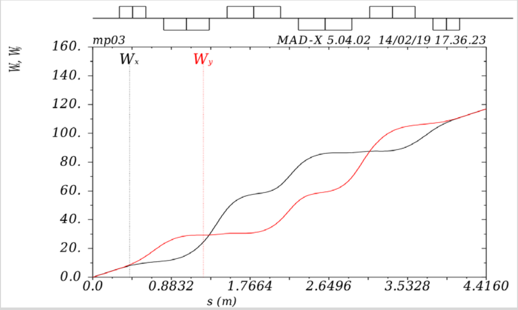


10 targets, 0.3 mm Be targets ->
0.3 X_0(Be) = 10.5 cm (efficiency = 1.3 10^{-6} μ/e^+)



$\varepsilon(\mu^{+/-})$= 200 nm

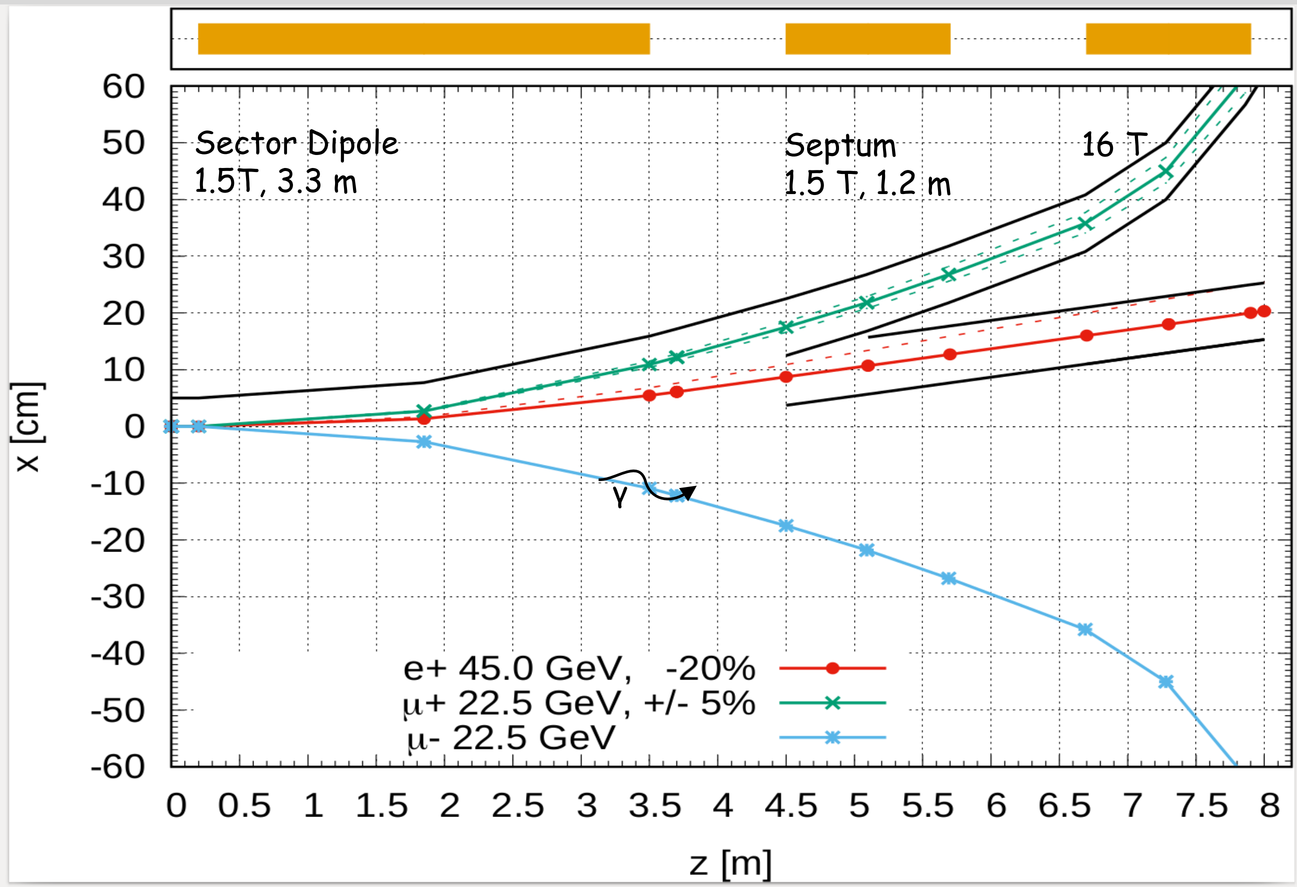
Emittance increase due to chromaticity



- Beamline has to maximize the muon production → constraint @target for e+ spot size and divergence
- Beamline has to preserve the e+ beam (to relax the e+ source requirements) → constraint to the target but also to the energy acceptance of the beamline
- Beamline as short as possible due to the short lifetime of muons

[O.Blanco, P.Raimondi, M Boscolo]

Beam Separation-Combination, Mar/2019



5cm of aperture radius
around μ+ and e+ beam trajectory

<u>μ ± 20% in energy occupy all the aperture when they reach the septum</u>

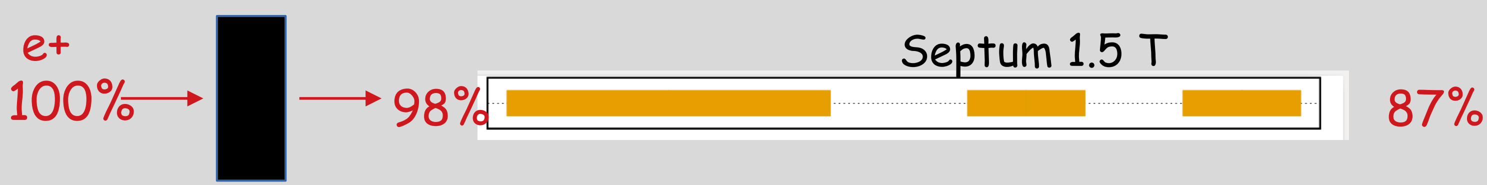
e+ above 36 GeV (-20% Energy) pass through

About 10 cm of separation between beam pipes at the 16 T magnet entrance, to give space to separated magnets.

1.5 T , 3.3 m long dipole

e+ E. Loss = 20 MeV

γ E. Crit = 2 MeV



[P.Raimondi, O.Blanco, M.Boscolo]

Single-IP: Carbon and Hydrogen vs Beryllium

Hydrogen:

- Additional factor 2 muons produced for the same X_0 with Hydrogen
- reduced multiple scattering
- Issue: target feasibility

Carbon:

- For the same fraction of radiation length, Carbon produces -25% muon pairs
- Increased multiple scattering
  - much suppressed with crystal in channeling
- Easier from target point of view

Ee+	N	L	Ltot		Mat	eff
GeV		mm	mm	X0		10^{-7} μ/e+
45	10	3	30	0,085	Be	5,1
45	5	3,2	16	0,085	C	3,8
45	7	3,2	22,4	0,089	C A412	4,0

Positron Ring

- The 45 GeV positron ring has a small emittance, mostly round beams, and should accommodate the 1000 bunches/5×10^{11} e^+ needed for the muon production
- The present layout is for a 27 Km long ring
- Several lattices have been designed with emittance ranging from 700 pm to 20 nm for a 27 Km ring
- The choice of the final lattice will be based on the larger energy acceptance since it is mandatory that possibly all the "spent" beam from the muon production be successfully re-injected in the PR to be later decelerated and re-injected in the DR for cooling.
- 100 km solution will increase the luminosity of at least a factor 3.5

A possible accelerating structure as taken from XFEL TDR

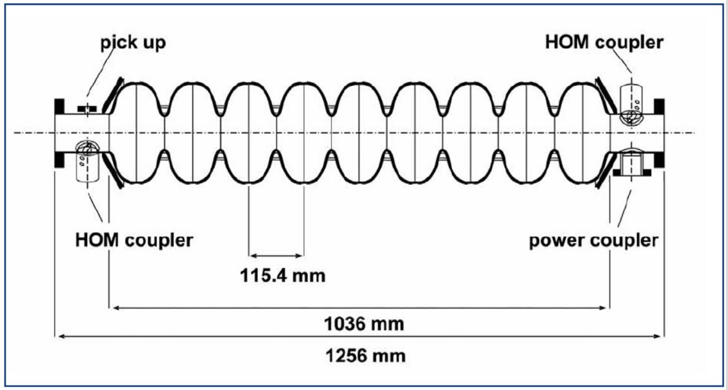
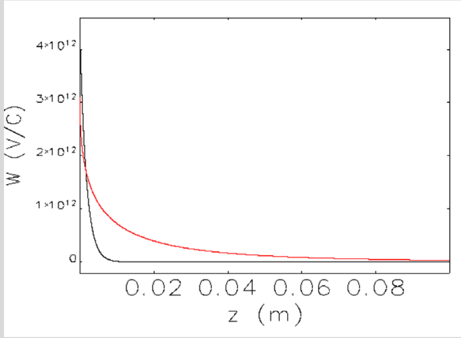


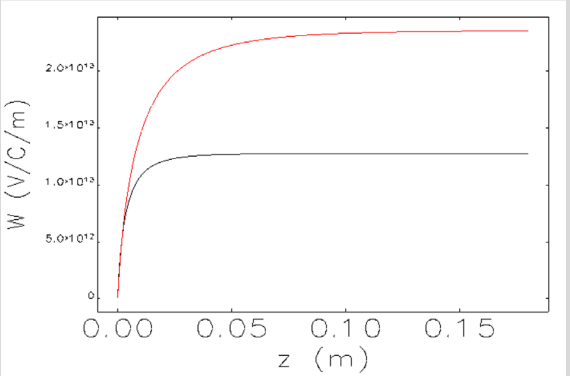
Figure 4.2.1: *Side view of the nine-cell cavity with the main power coupler port (right), the pick up probe (left), and two HOM couplers.*

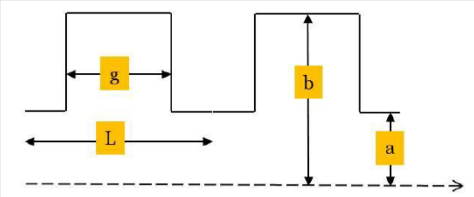
Eacc=20 MV/m
SW short range wf should be ok as TW
1 cavity=9 cells
1 cryomodule= 8 cells

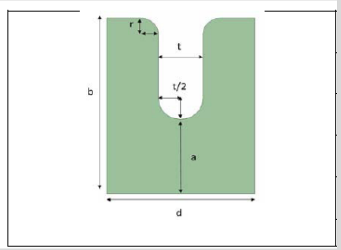
From L3 Xfel.xls= 2cryomod-quad-2cryomod



-- pure pill box
-- Xfel multistructure (2014)







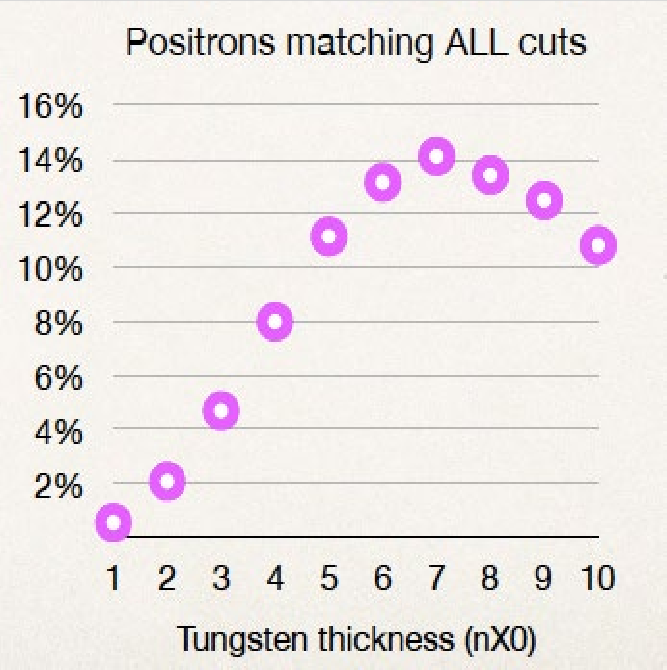
Pill box cavity model considered for the wake feld calculations: a is the iris radius, L is the cell length. The asymptotic values of the longitudinal and transverse wake functions have been calculated according to K. Bane SLAC{PUB{7862 (Revised) November 1998 with a=3.2 mm)

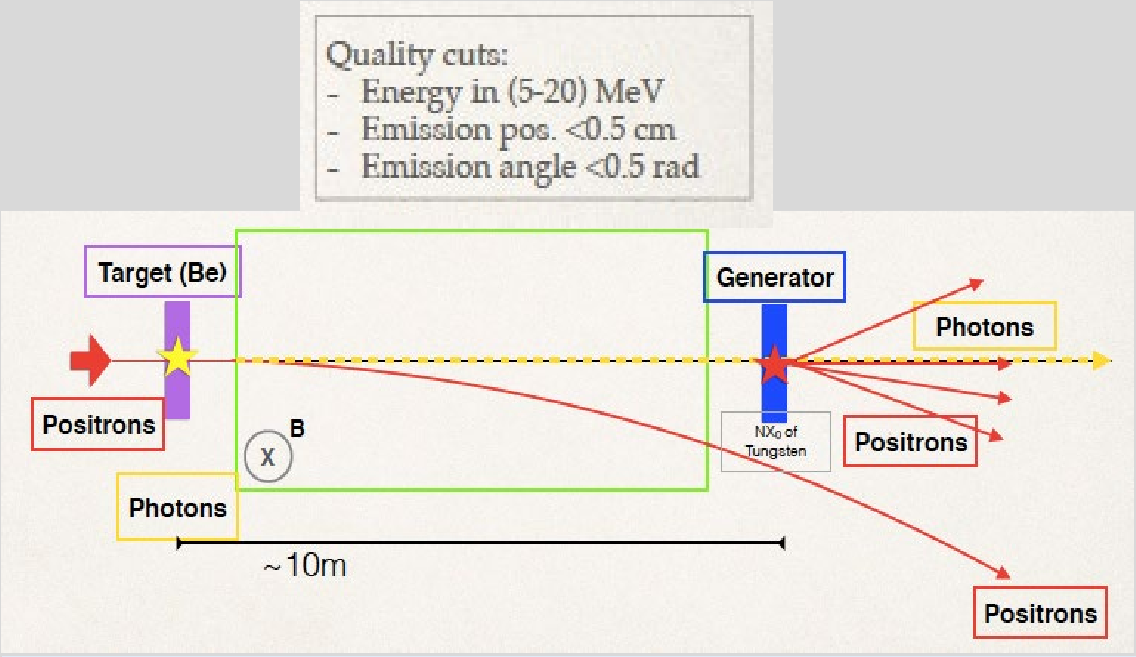
Geometrical paramaters	
a (mm)	35
g (mm)	90
L (mm)	105.4

C.Vaccarezza, D.Alesini

Embedded source

- For each positron on the primary Be target there are:
  - 0.11 photons hitting the tungsten target
  - 0.65 e+ coming out of the 5 X0 tungsten target
- To estimate the number of collected positrons the number of e+ within the following cuts have been evaluated
- For 5 X_0 target thickness 11% of the positrons are within the cuts, corresponding to a yield of 0.07
- Giotto simulation 15%.

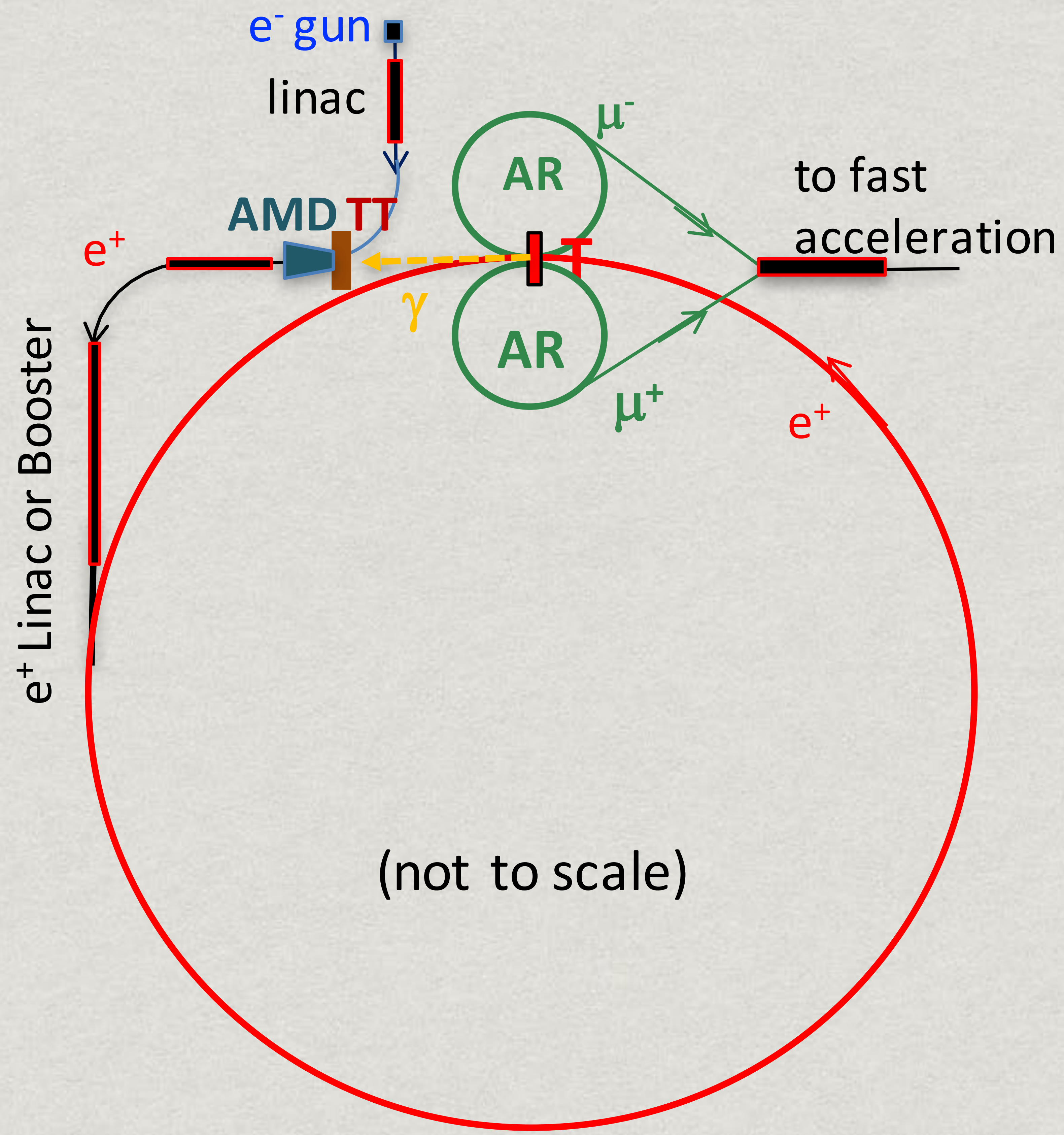




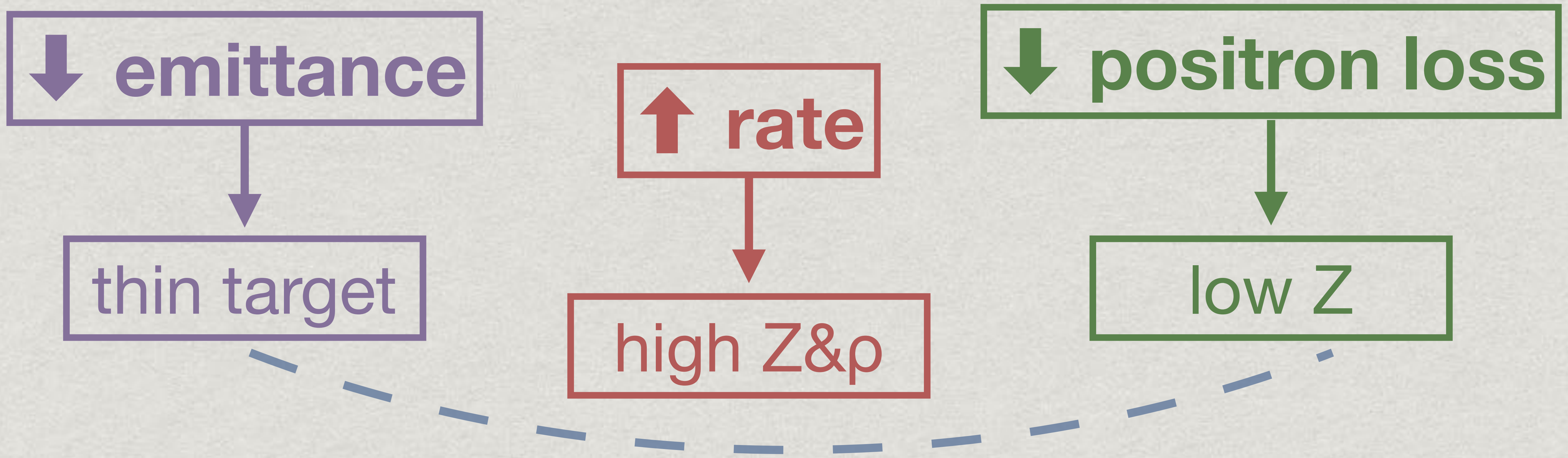
F. Collamati, Posipol 2018
https://indico.cern.ch/event/727621/timetable/#20180905

F.Collamati

The Production Target



* Criteria to follow to choose the target:

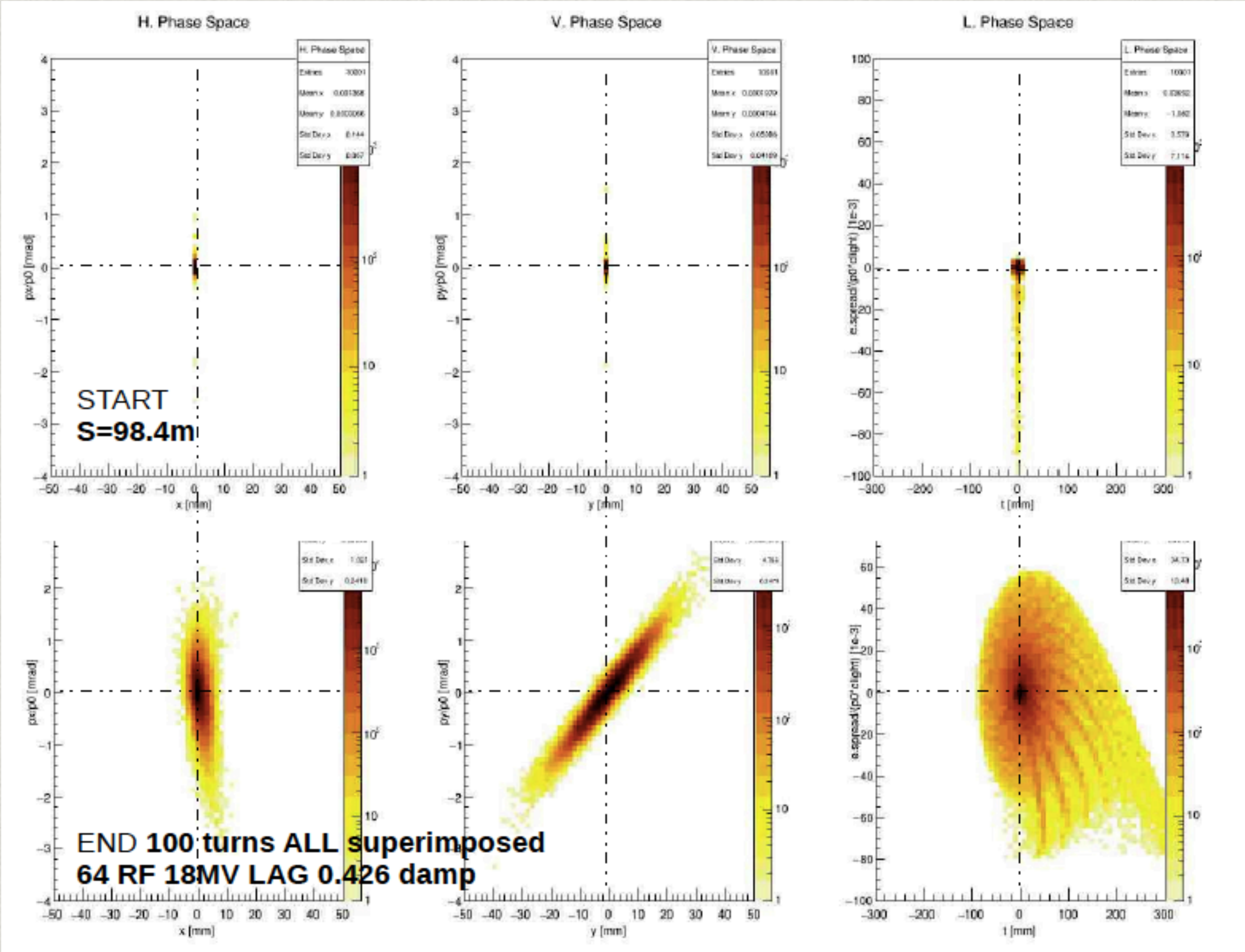


* Possible tradeoff:
  not too heavy materials and not too thin target: e.g. few mm of Be
  ✚The target has to be able to sustain huge **power load** O(100KW)
* Strategy:
  * Thermo-mechanical studies and simulations ongoing (FLUKA+Autodyn)
  * Other target options are being considered (liquid jets, crystals…)

Multi-turn simulations

before target, starting point

after 40 turns



MAD-X PTC & GEANT4 6-D tracking simulation of
e+ beam with **3 mm Be** target along the ring (not at IR center in this example)

Muons' emittance

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

would like all contributions of same size. knobs:

ε(e+)	**= e+ emittance**	
ε(MS)	**= multiple scattering contribution**	**βx, βy @target & target material**
ε(rad)	**= energy loss (brem.) contribution**	**βx, βy, Dx @ target & target material**
ε(prod)	**= muon production contribution**	**E(e+) & target thickness**
ε(AR)	**= accumulator ring contribution**	**AR optics & target**

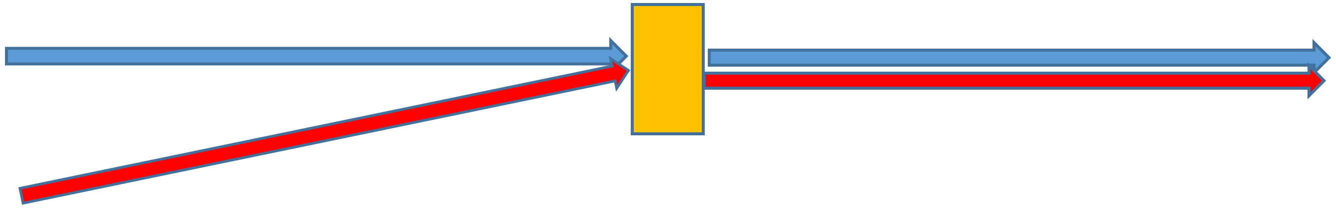
Now: ε(μ) dominated by ε(MS) ⊕ ε(rad) ➜ lower D & βs @ target with beam spot at the limit of target survival

Also test **different materials**:

- **Crystals** in channeling: better ε(MS), ε(rad), ε(prod)
- **Light** liquid **jet** target: better ε(MS), ε(rad) and gain in lifetime & target thermo-mechanical characteristics

- How we can recombine same charge muons beams in the same phase space?

- 1) We must ‘defeat’ the Liouville theorem
- ARE WE BEATING LIOUVILLE'S THEOREM? A.G.Ruggiero :
- If the beam is made of a finite number of particles, there are large empty regions surrounding the image points of the space). There is no reason and no limitation in principle why one cannot fill up these empty regions with more particles if one can find a way. The Liouville theorem would certainly not be contradicted..The question is how it is technically possible to add more particles without perturbing the motion of those that are already there.
- WE NEED an angular filter. An element that in the same point deflect particles arriving at an angle and leave unperturbate particles arriving with a different angle



- Curved Crystal (at net of the diffusion terms)

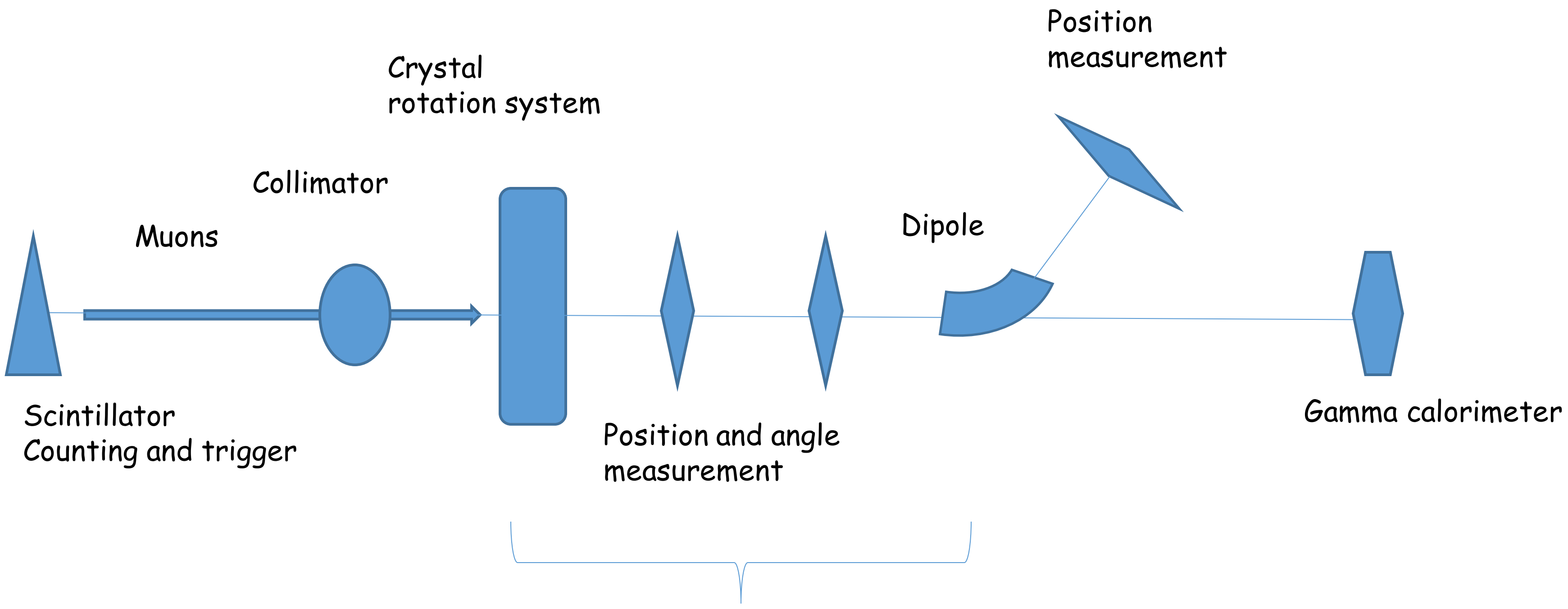
Main Idea

- We need to measure the muon dynamical state (Energy and Transverse momentum) before and after interaction with the crystals.
- 1) Curved crystal. Not possible to work with two syncro muons beams, so work with a single beam moving the crystal.

measurement – Bent crystal

- - Deflection efficiency for μ^+ and μ^-. Initial and final P_t and E for channeled and unchanneled particles. Initial and final P_t and E for the unchanneled mode (crystal rotated).

LAYOUT



System to be replicated before the crystal if the muons characteristics at z_0 are not well defined

This is an experiment not concerning only muons. It takes into account violation of the fundamental theorem of accelerator (and statistical) physics