STUDIES OF A SCHEME FOR LOW EMITTANCE MUON BEAM PRODUCTION FROM POSITRONS ON TARGET

FRANCESCO COLLAMATI (INFN-ROMA) - 8.7.2017

Outline

- Introduction: Why a muon collider
- Proposal for a novel technique for direct muon production
  - Target choice & accelerator scheme
  - Multi-turn simulations
  - Muons’ emittance
- Test beam
- Conclusion and perspectives

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    - **Physics**:
      - Higgs coupling $\propto m^2$

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

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- **CONs:**
  - **Muons decay** in *2.2μs*!
    - The whole **chain** (generation, acceleration, interaction) must be very **quick**!
  - Traditional muon production scheme leads to **large emittance** beams: $p + target \rightarrow \pi/K \rightarrow \mu$
    - Muons are produced with a variety of angles and energies (P_{μ}~100MeV/c)
    - **Cooling** needed!
      ➜ tradeoff monochromaticity/luminosity

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Novel Approach

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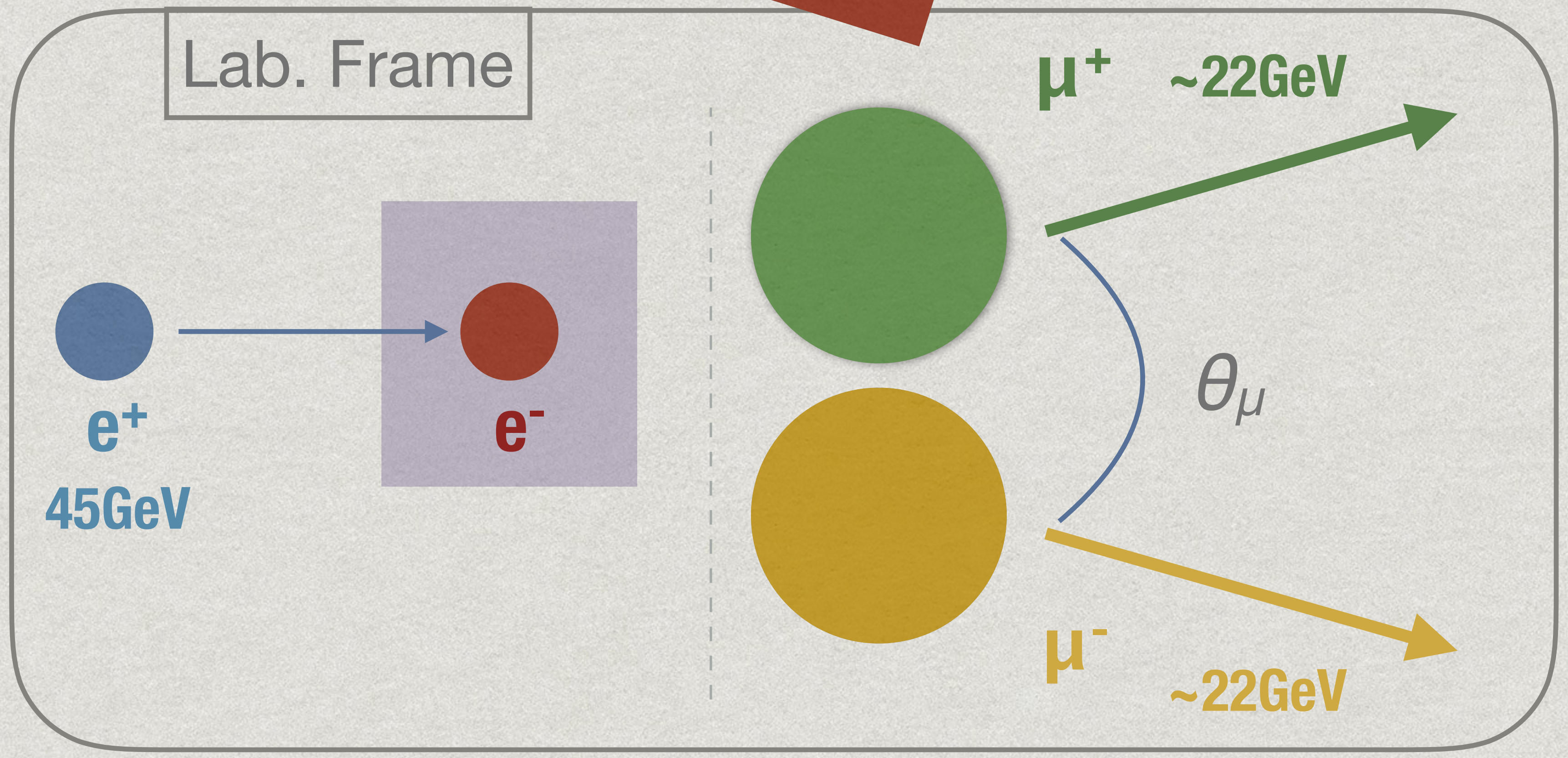

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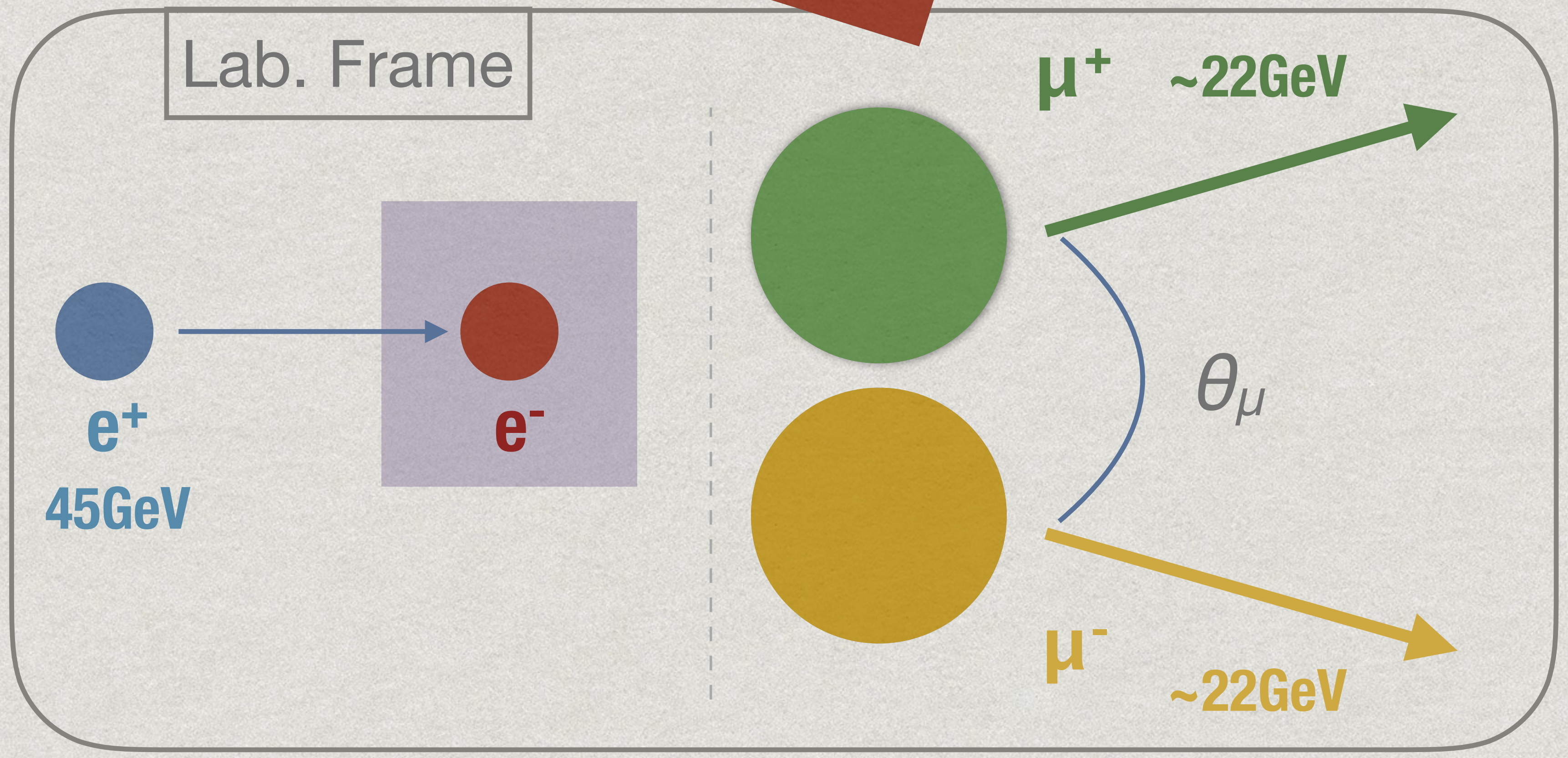

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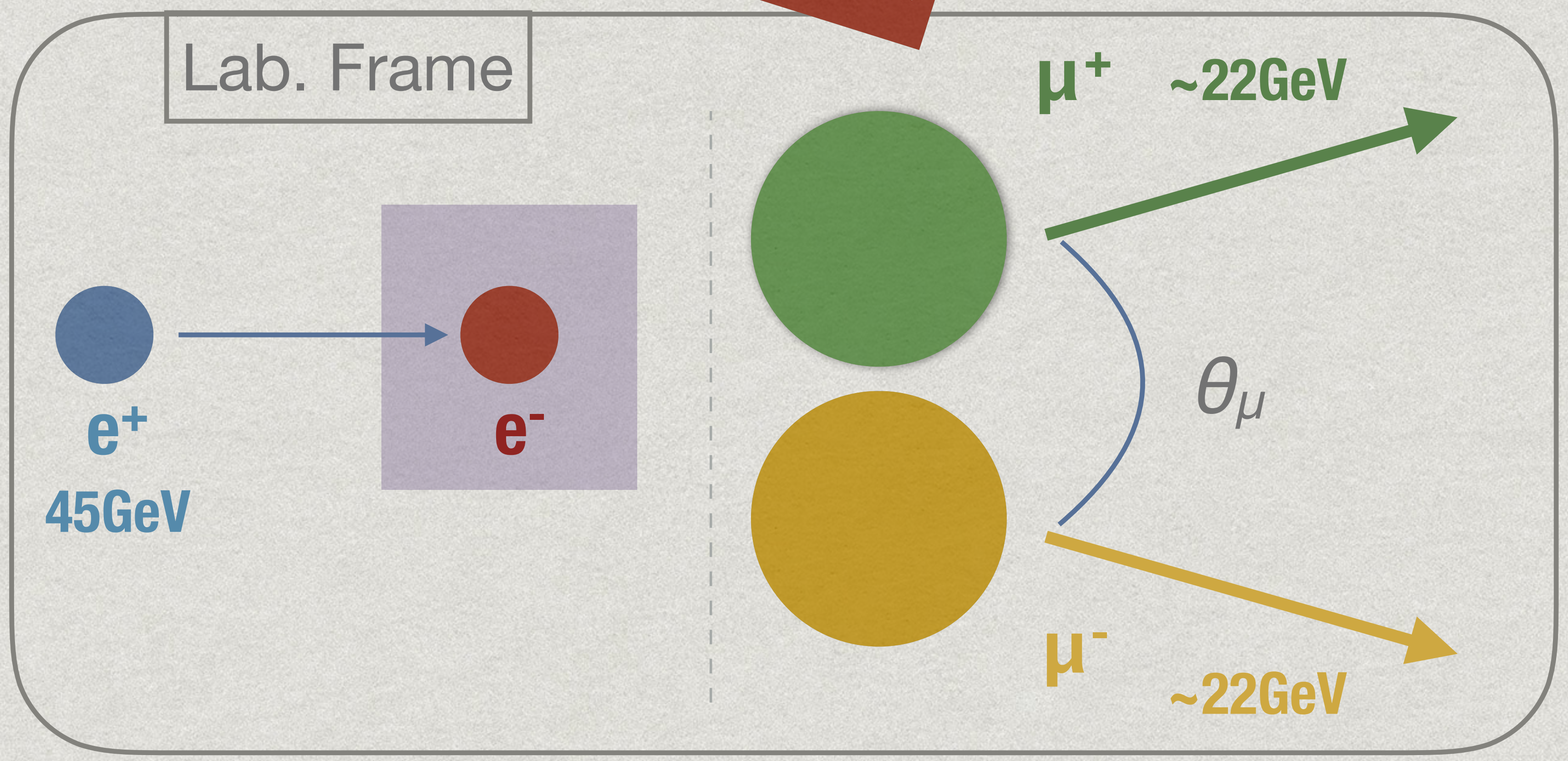

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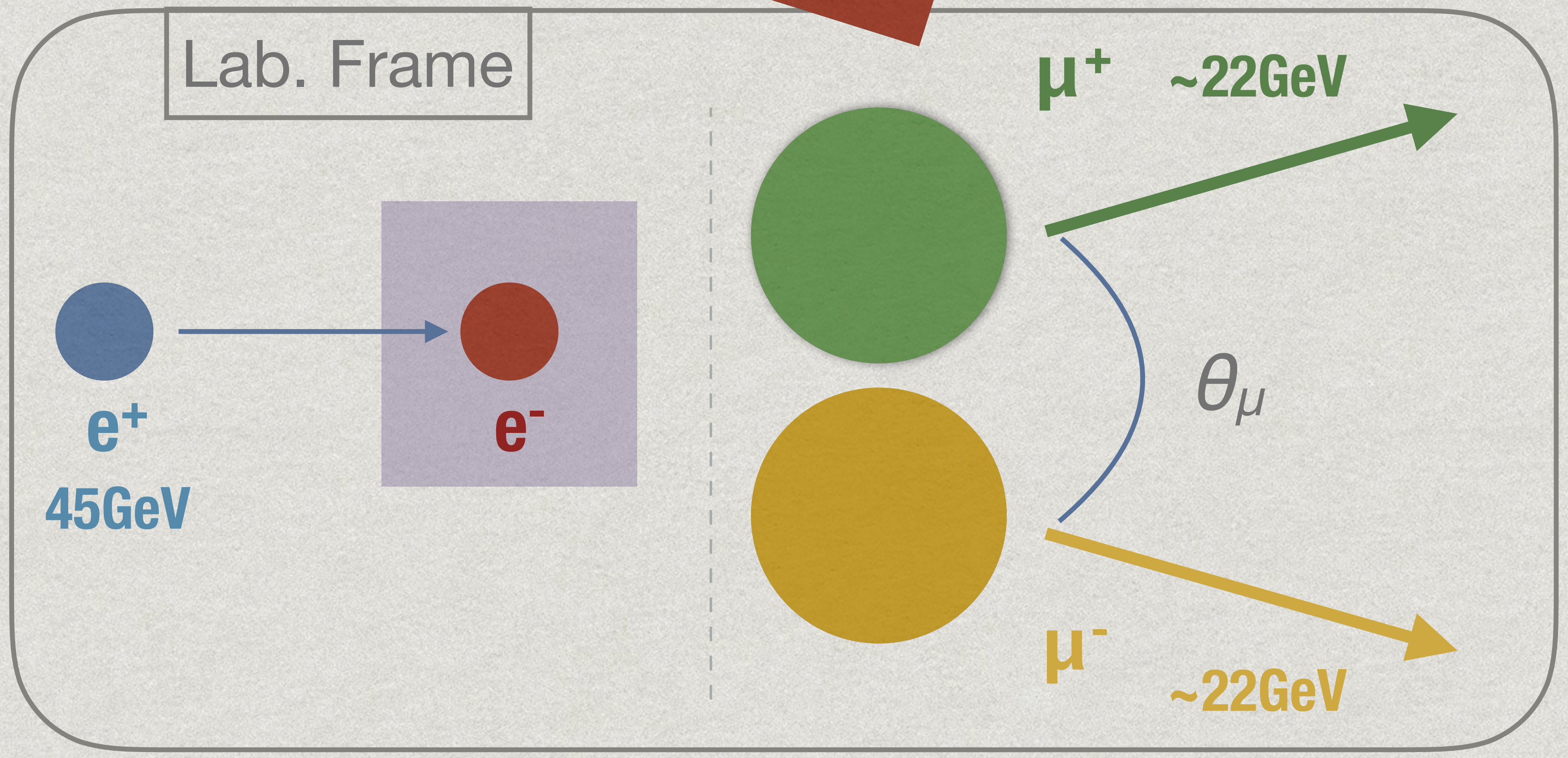

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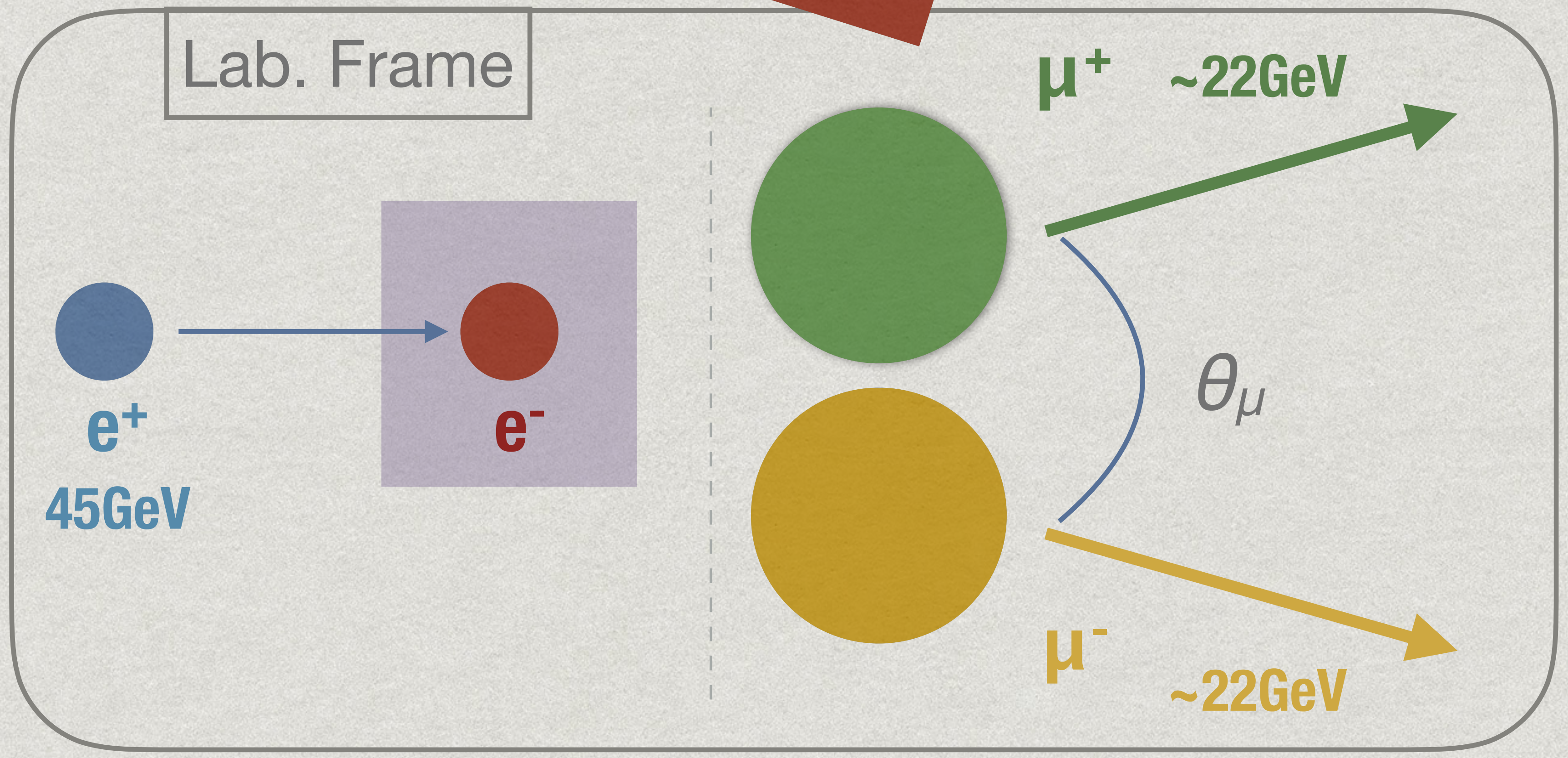

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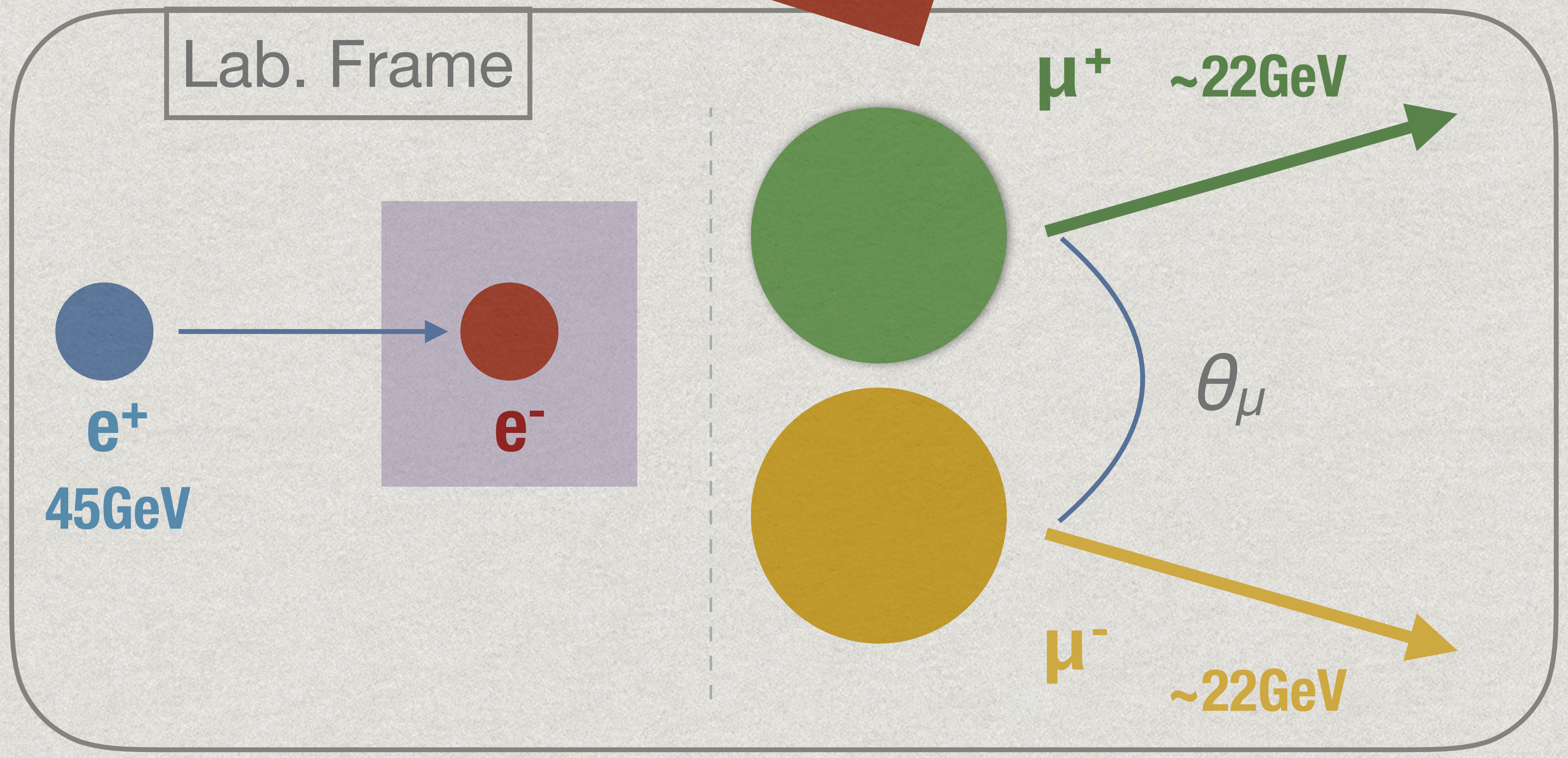

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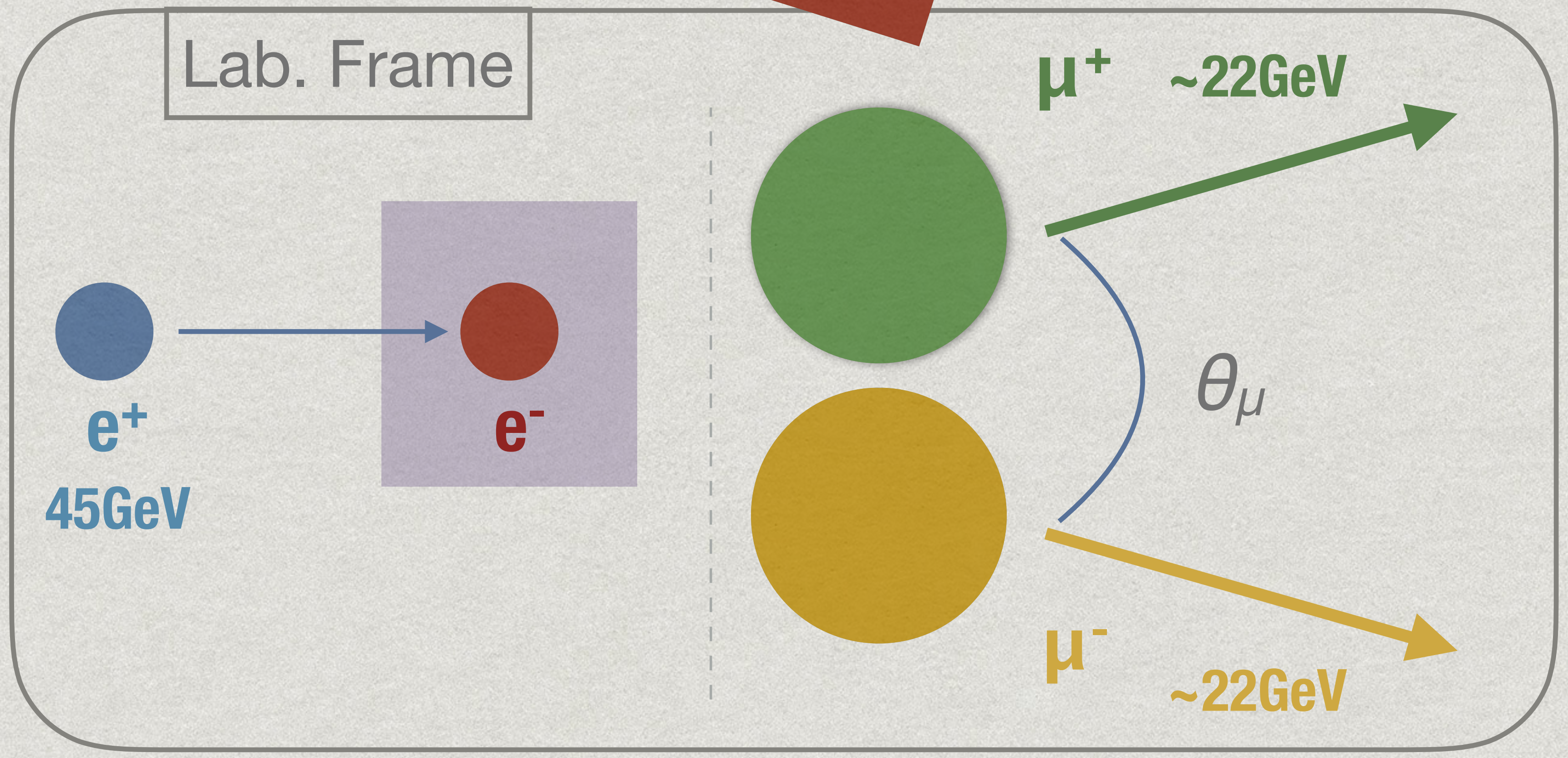

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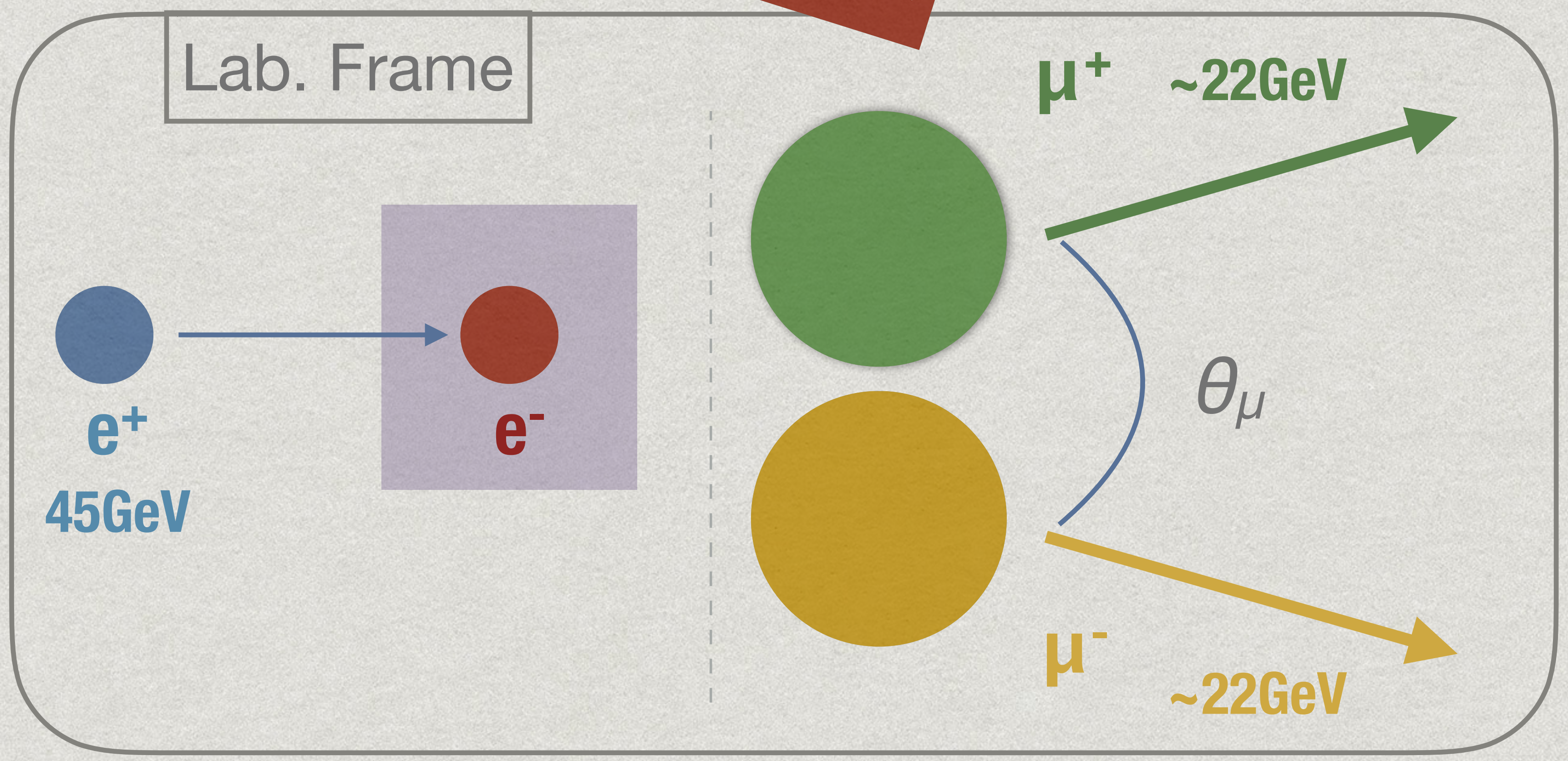
    - **Rate**: much smaller cross section wrt protons (μb vs mb)



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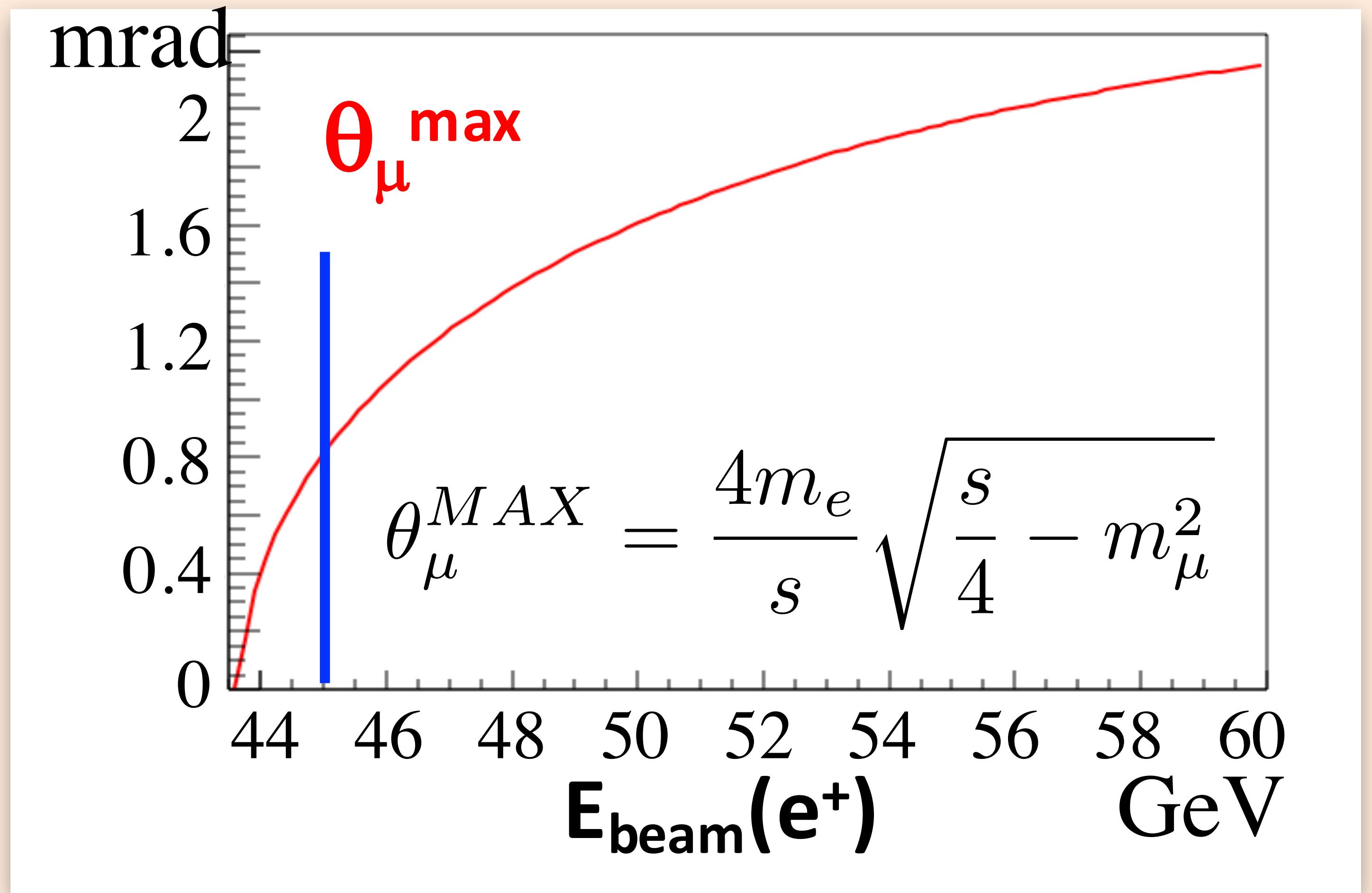
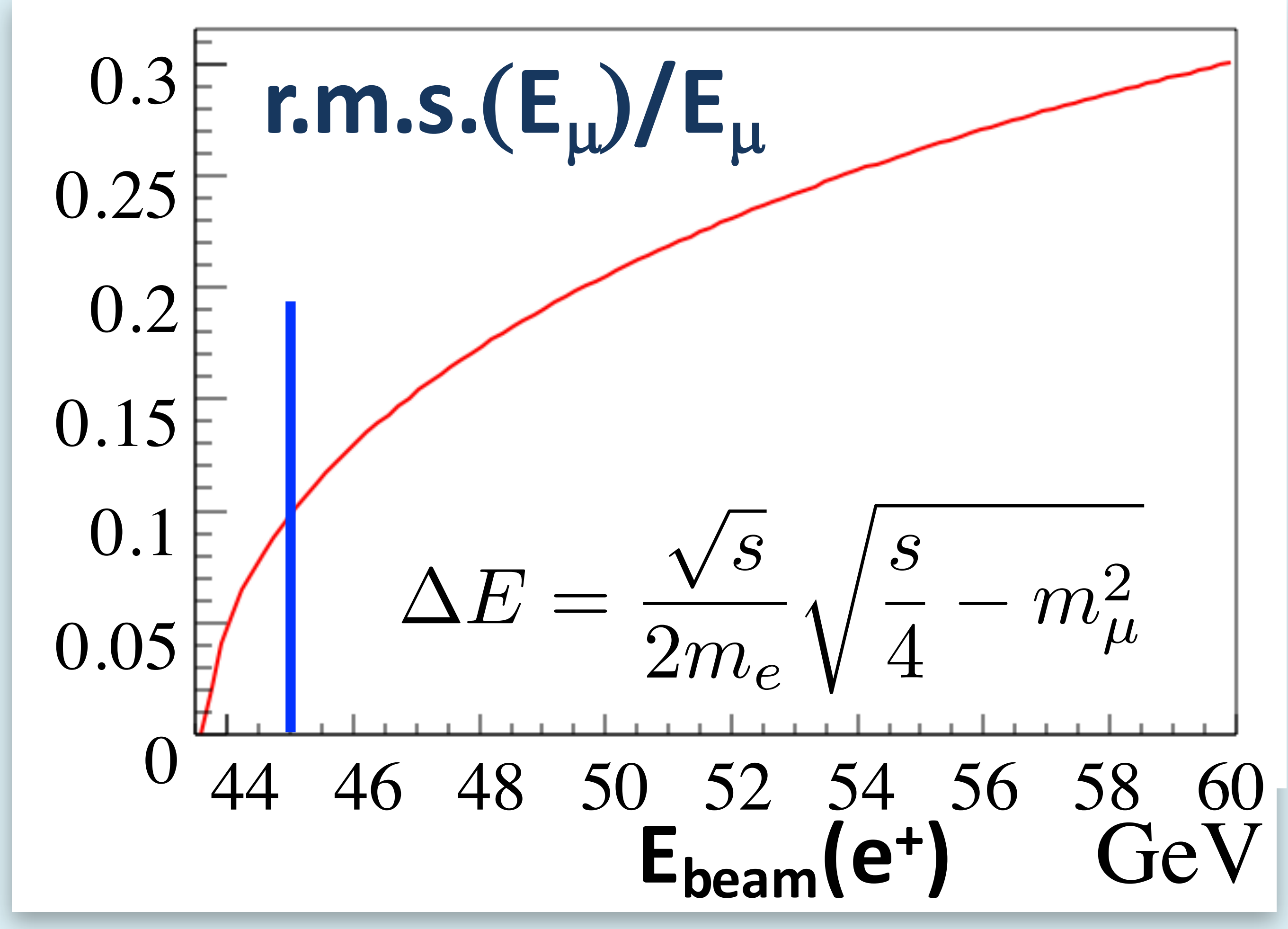
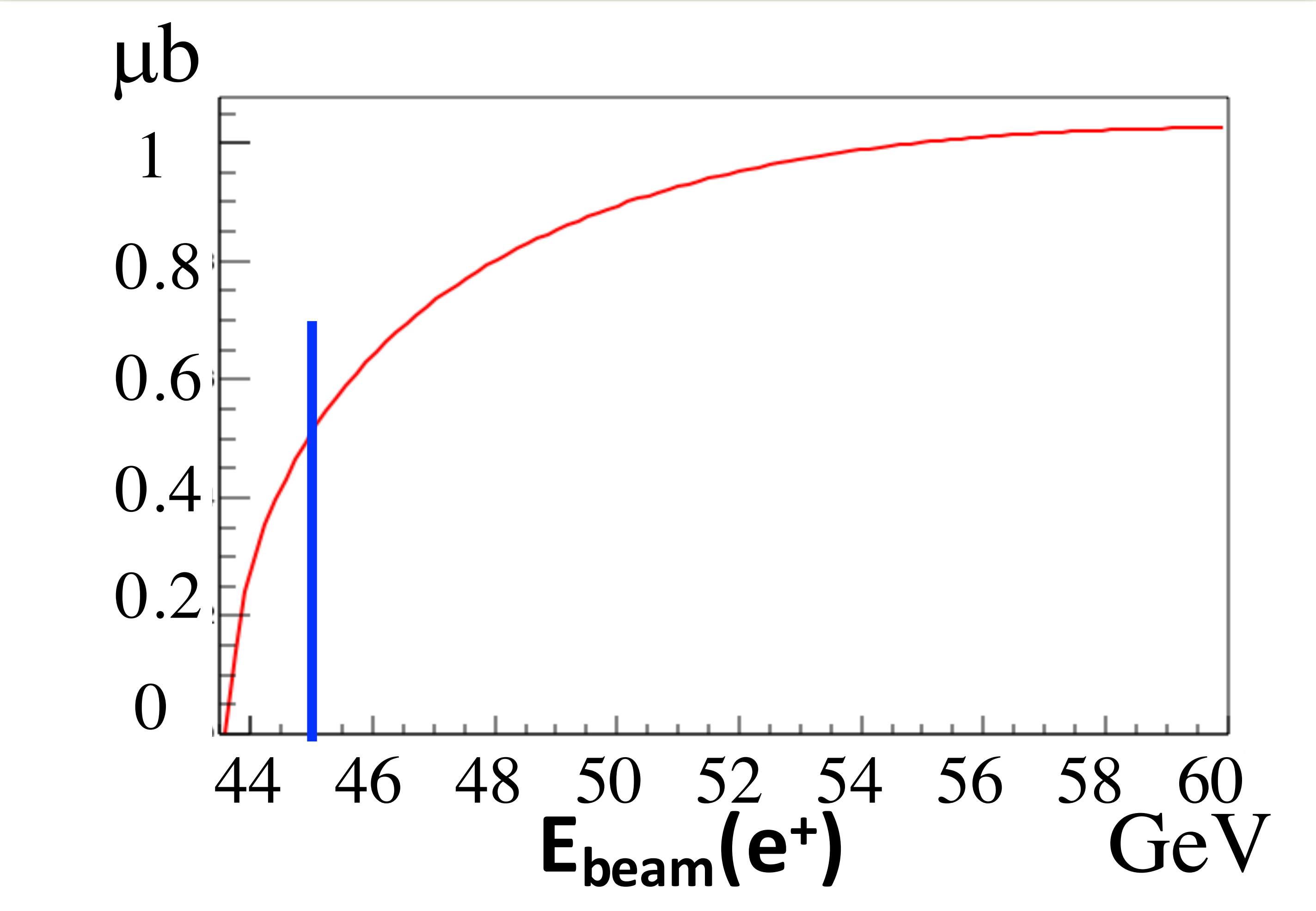




$\sigma(e^+e^- \rightarrow \mu^+\mu^-)$



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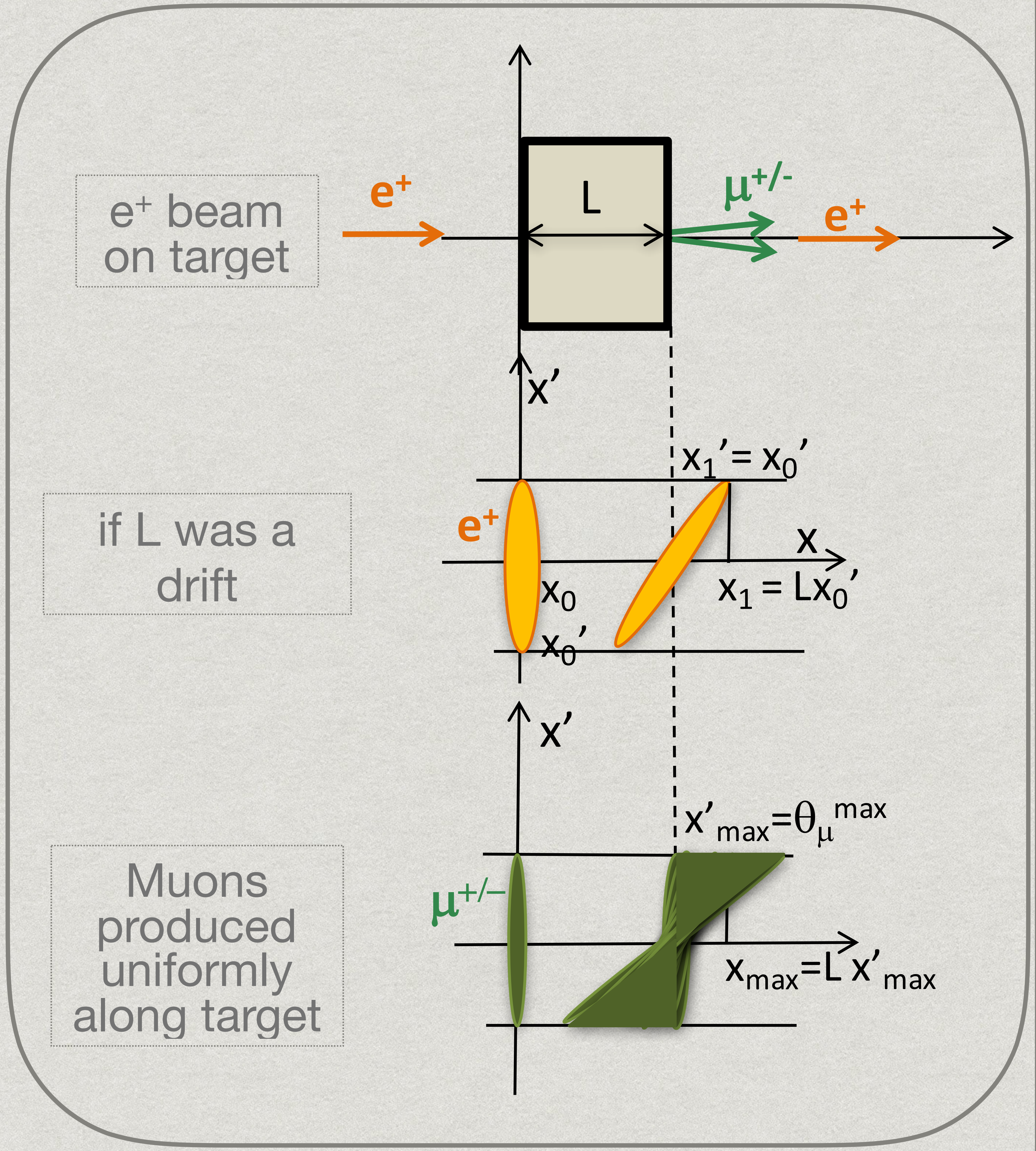

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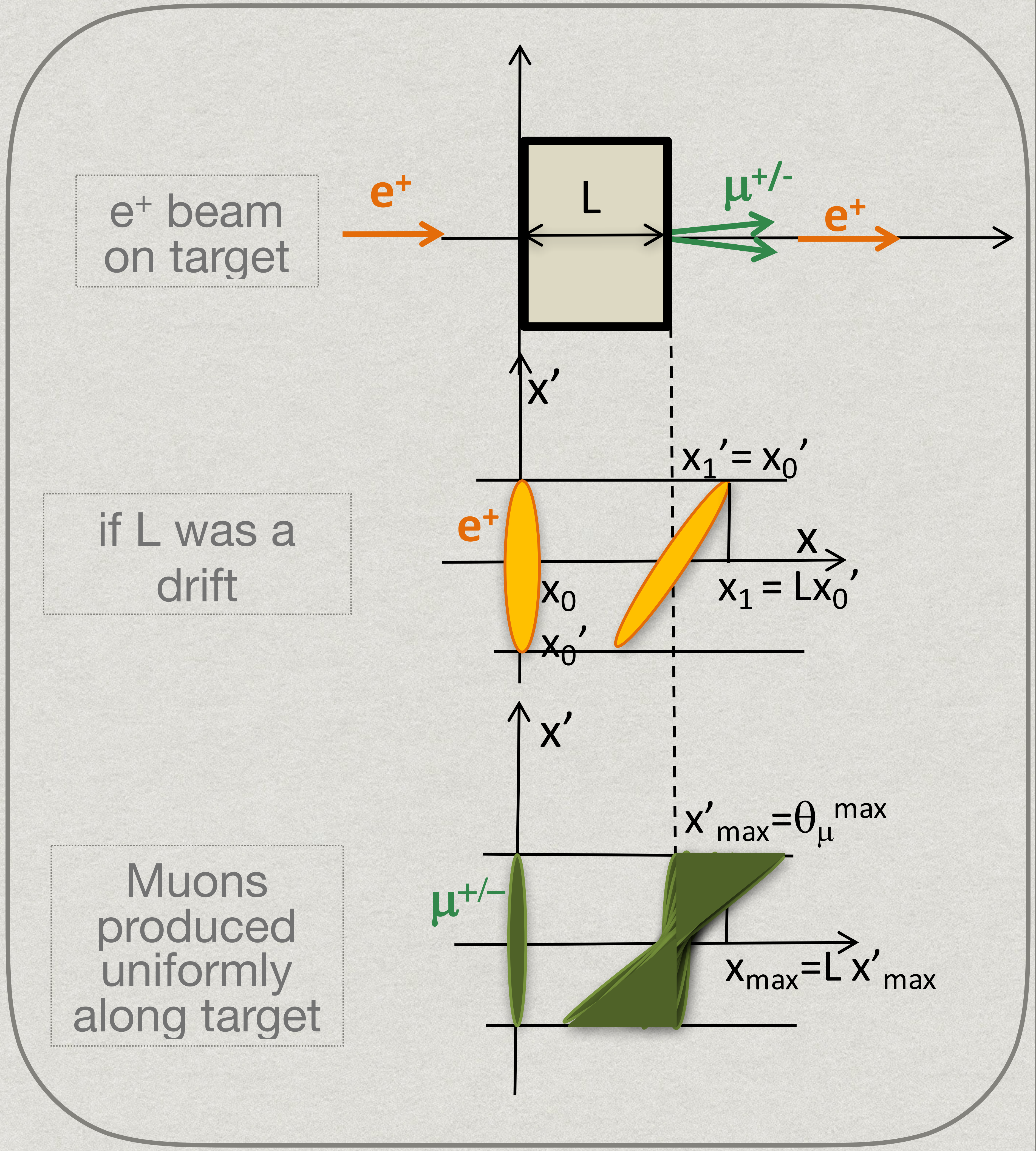

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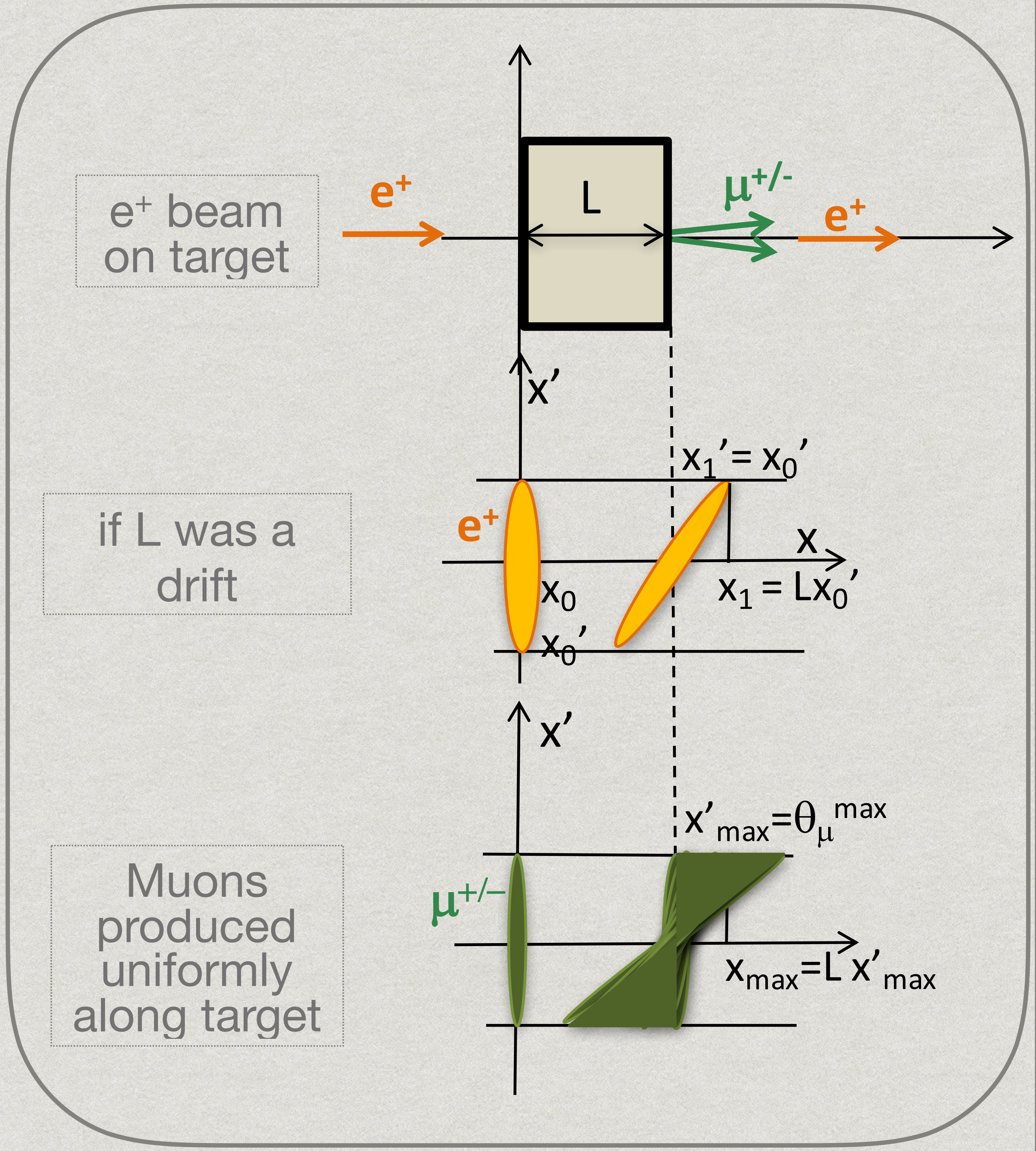

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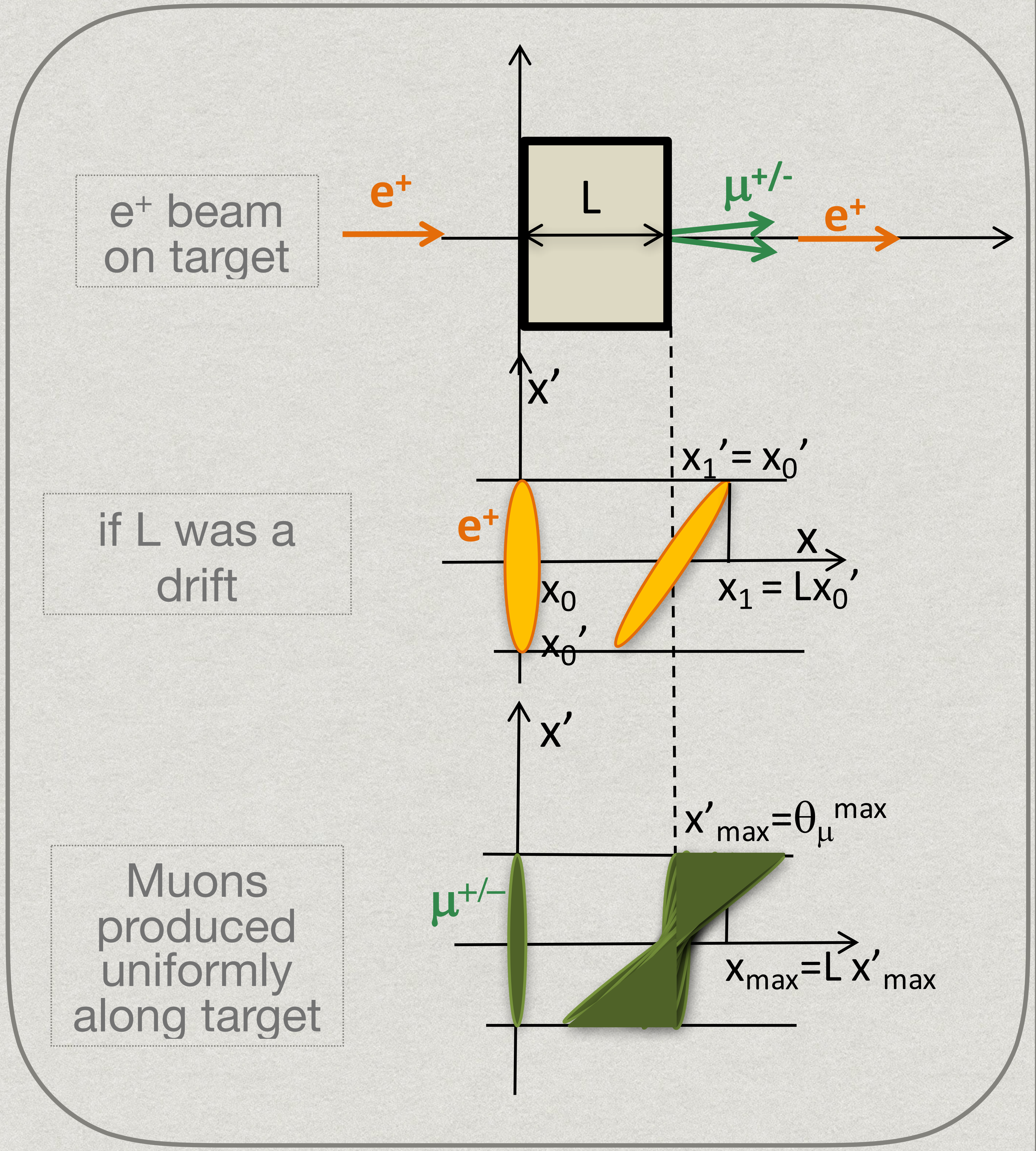

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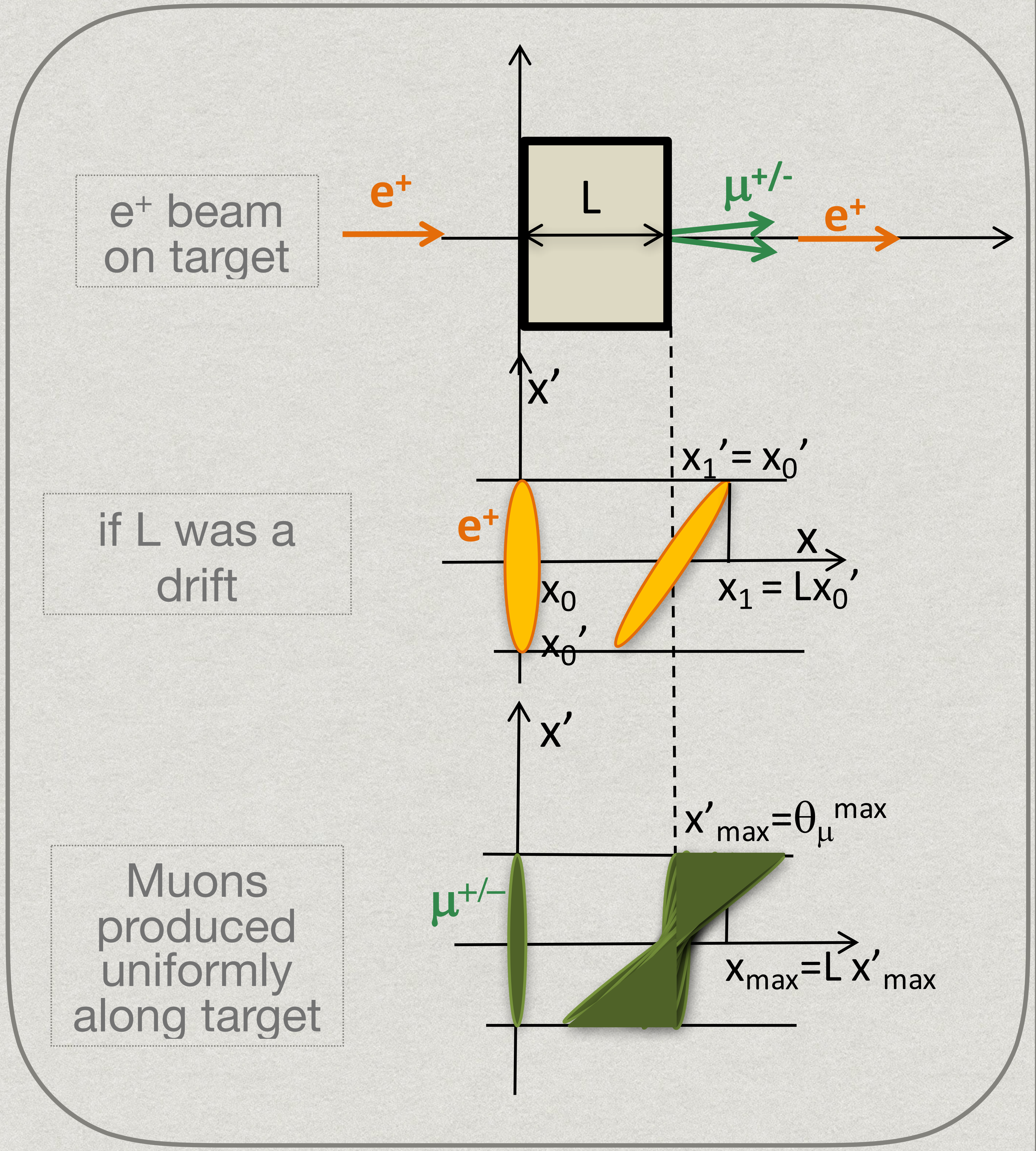

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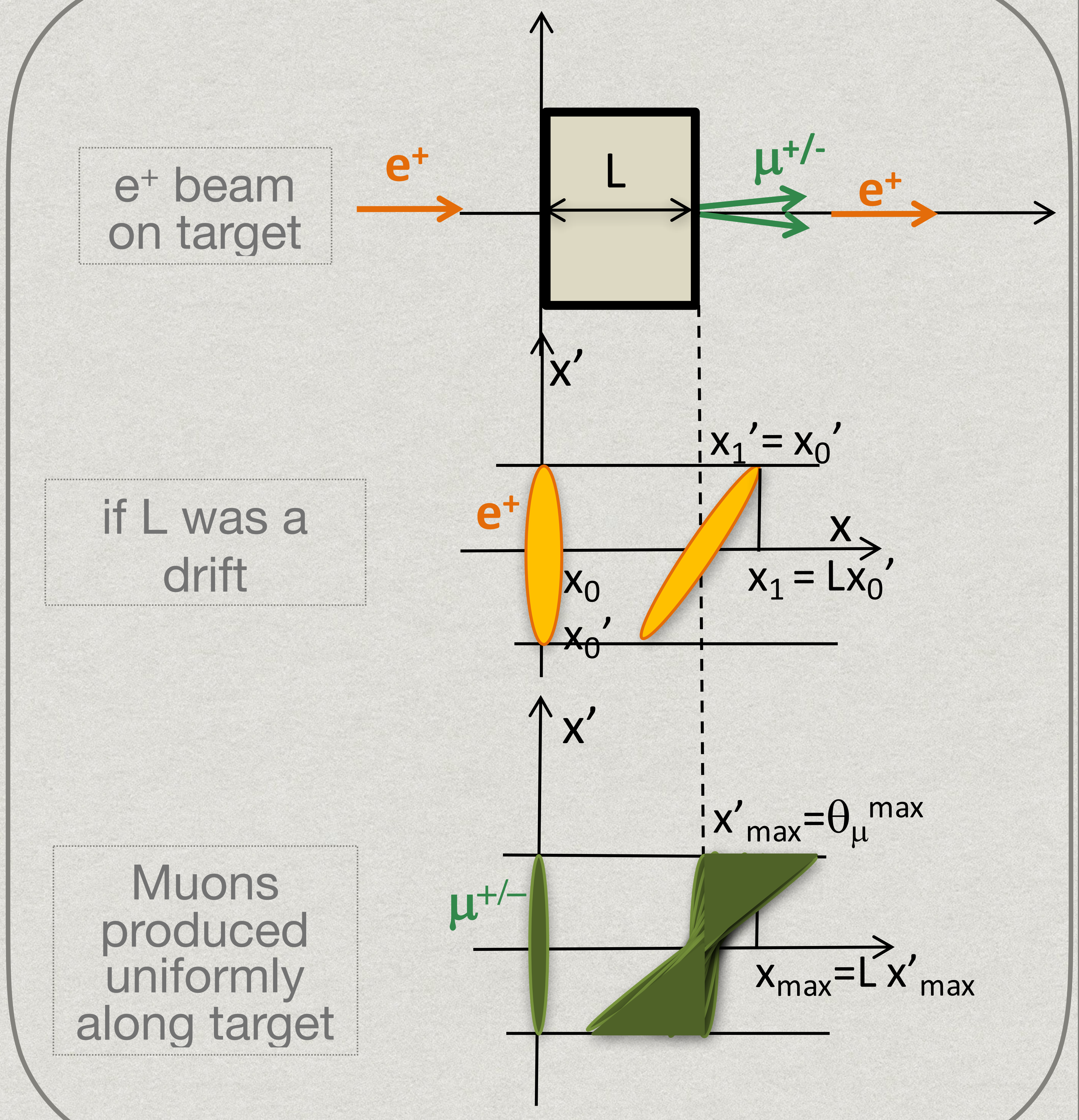

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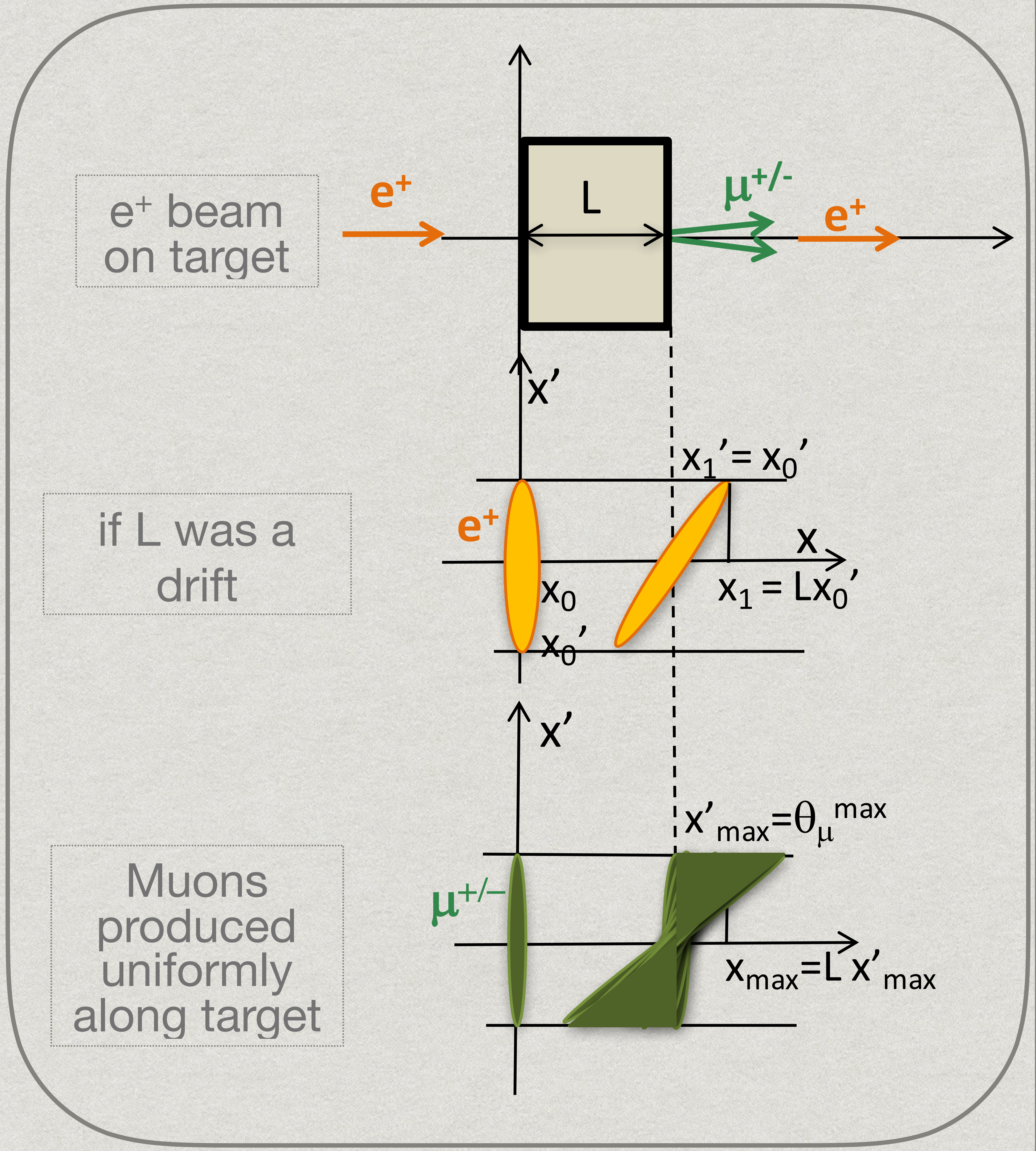

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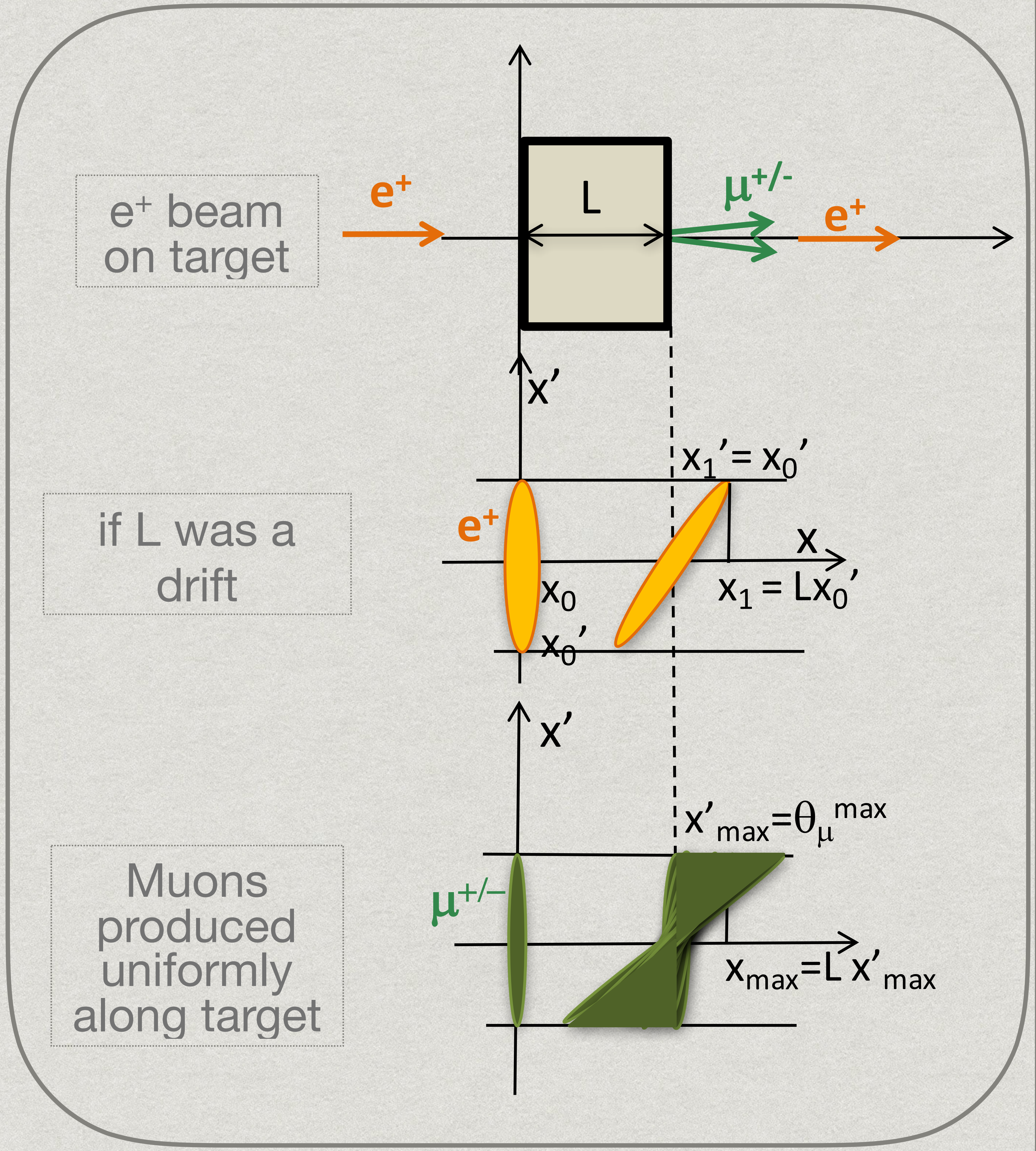
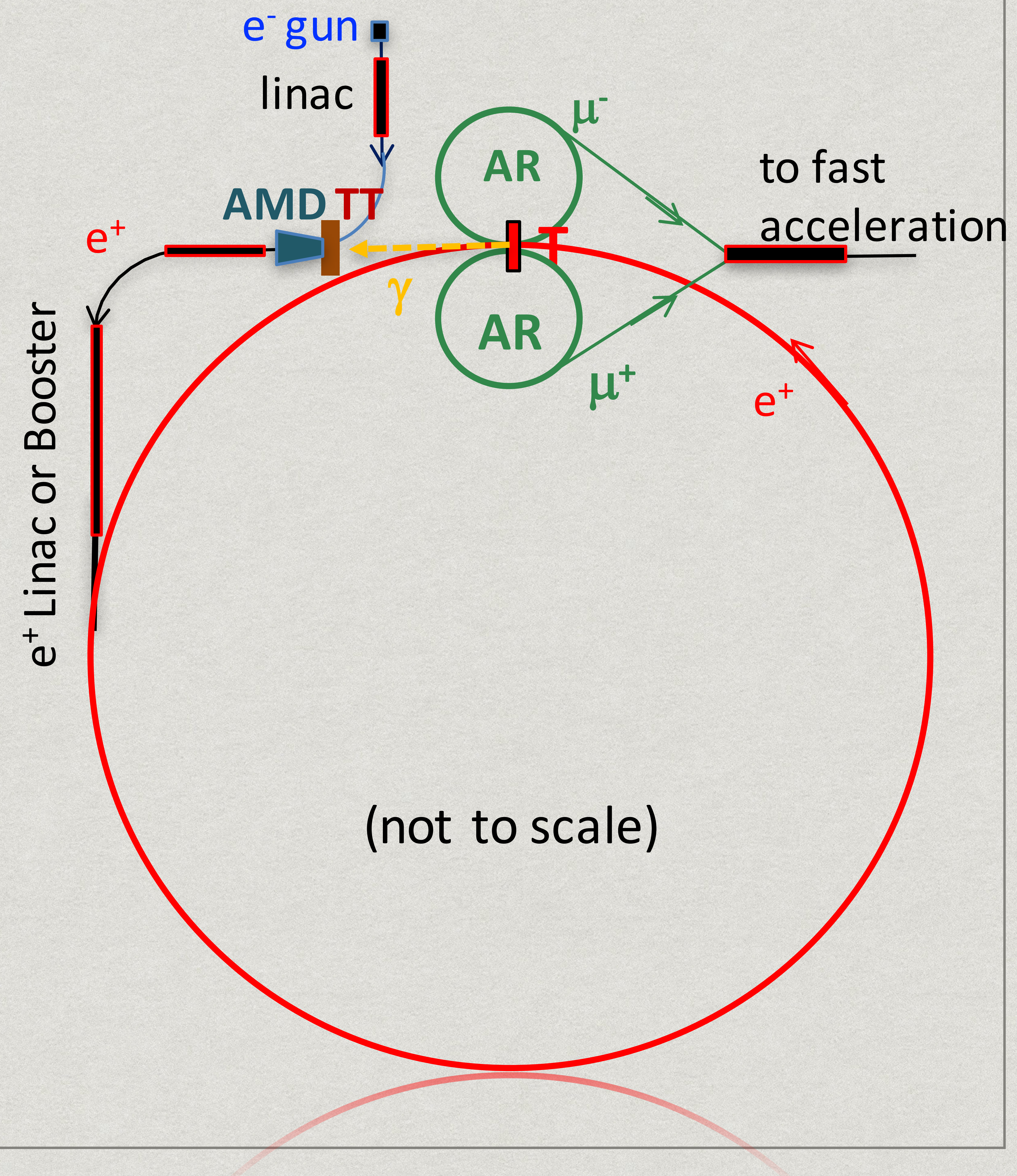
  - Possible **tradeoff**: not too heavy materials (Be, C, Li) and not to thin target

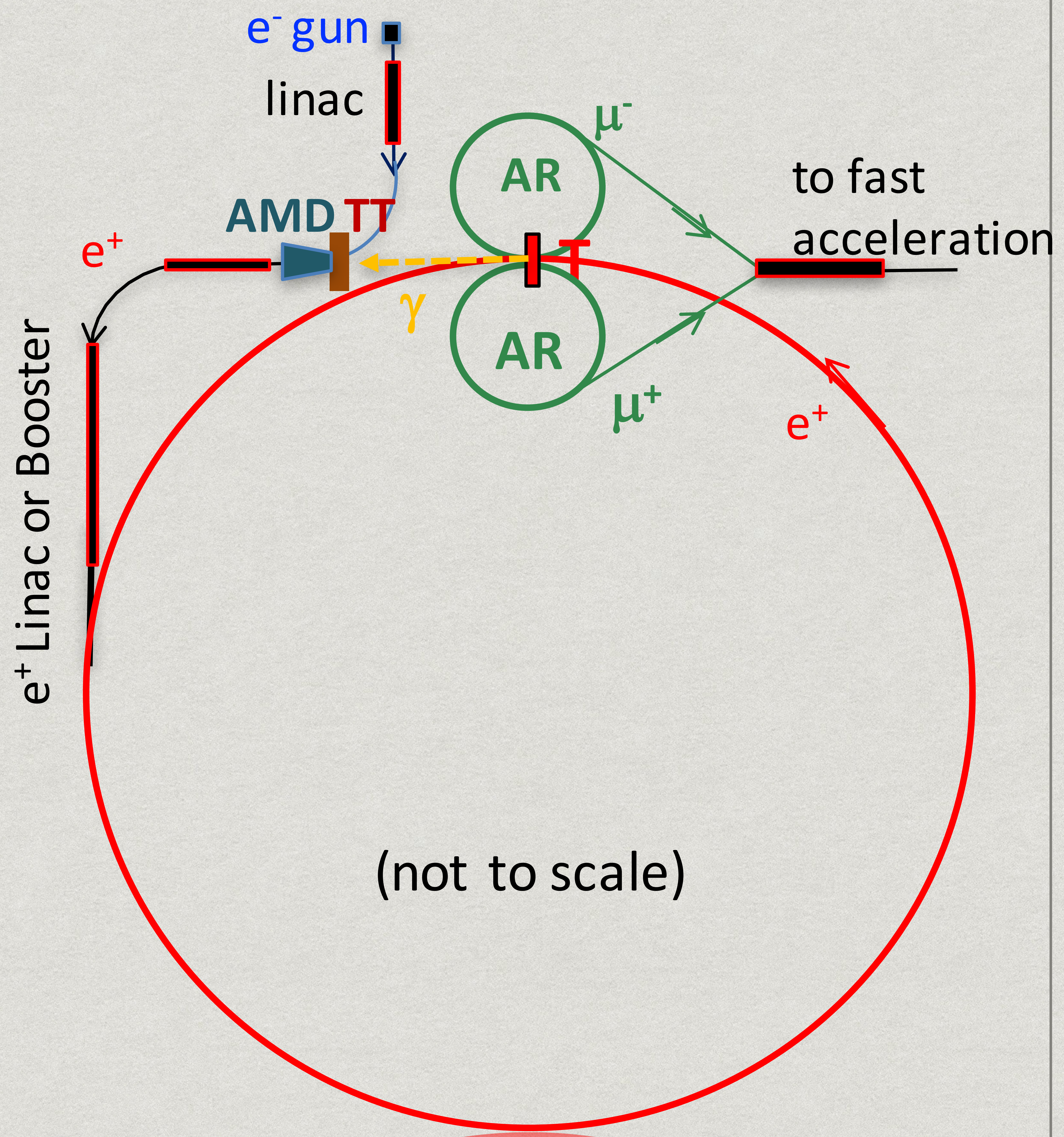


Accelerator Scheme



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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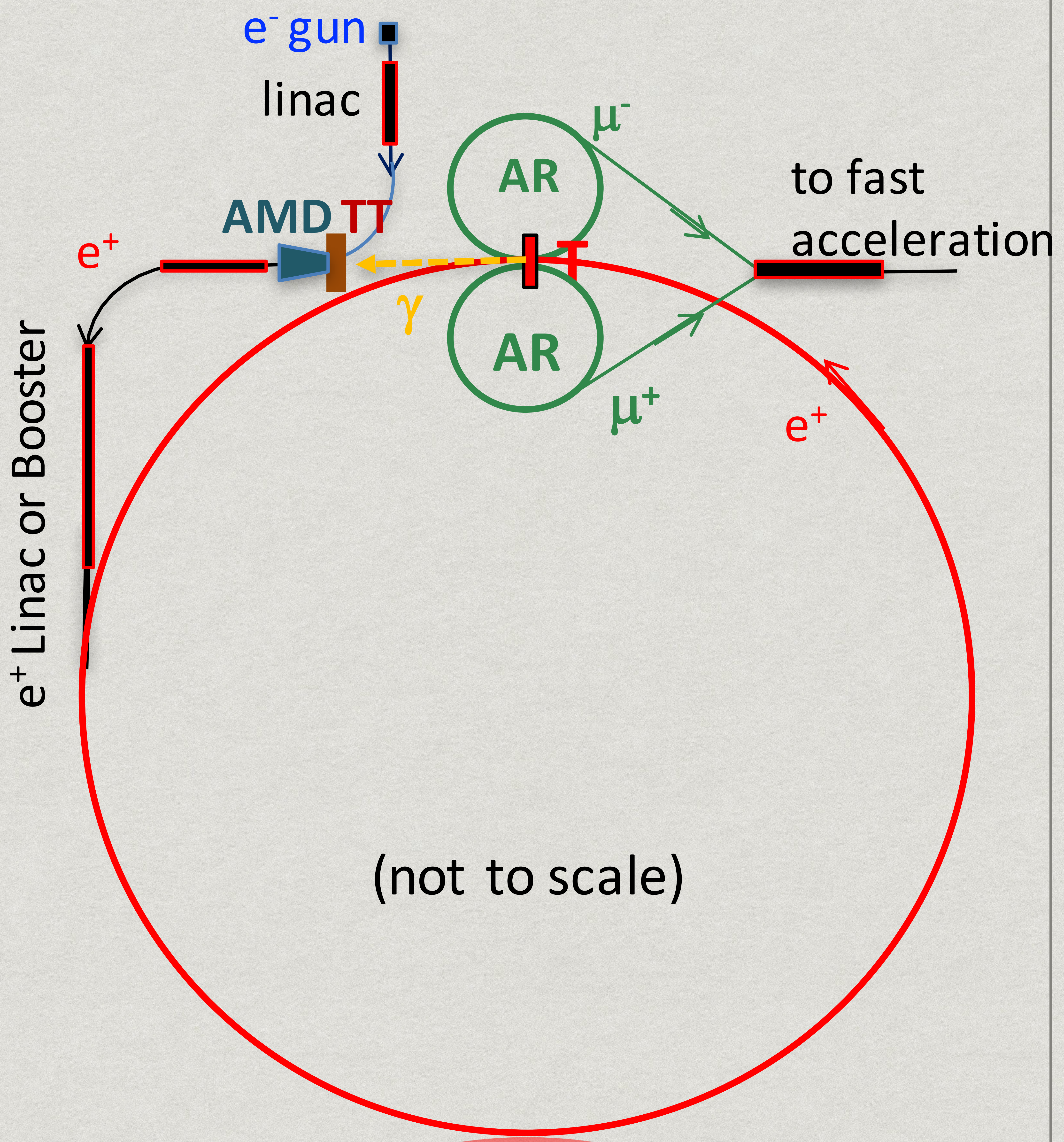

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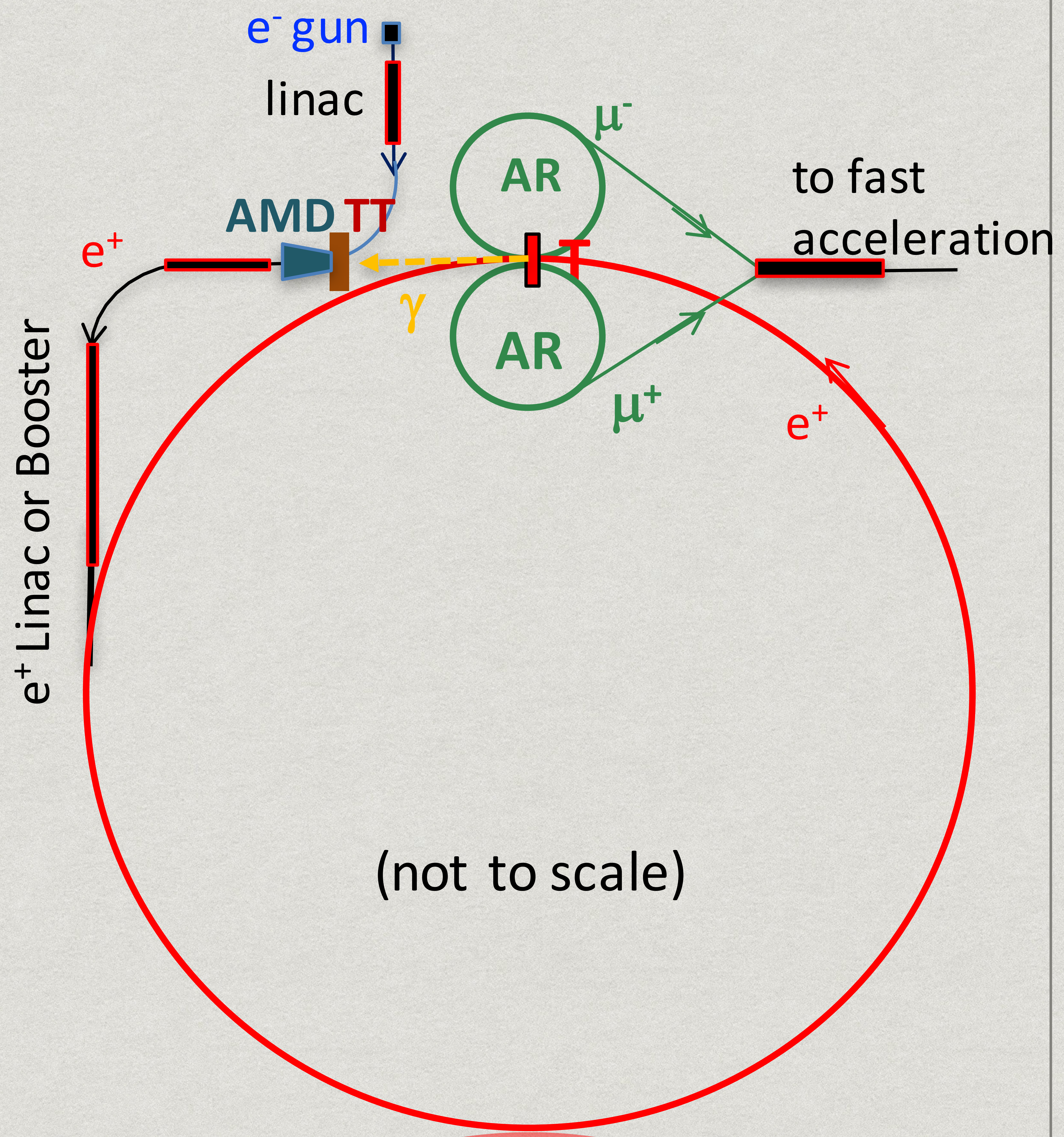
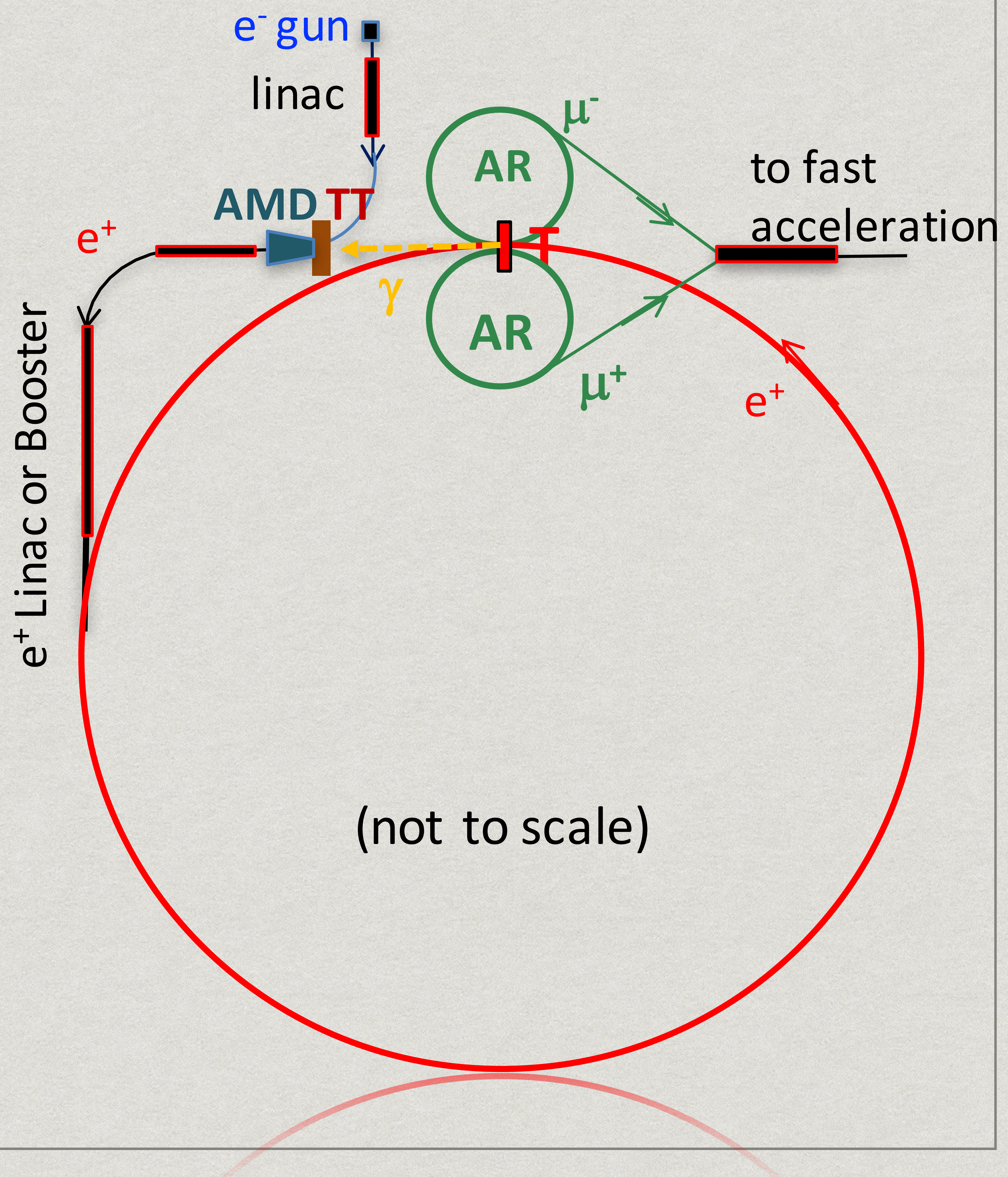
- **From $\mu^+\mu^-$ production to collider:**
  - Produced by the e^+ beam on target **T** with $E(\mu)\approx 22\text{GeV}$, $\gamma(\mu)\approx 200$ → $\boldsymbol{\tau_{LAB}(\mu)\approx 500\mu s}$
  - Accumulation Ring: 60m isochronous and high mom. accept. for μ recomb. (τ_μ^{LAB}~2500 turns)
  - 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)



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e⁺ ring parameter	unit	value
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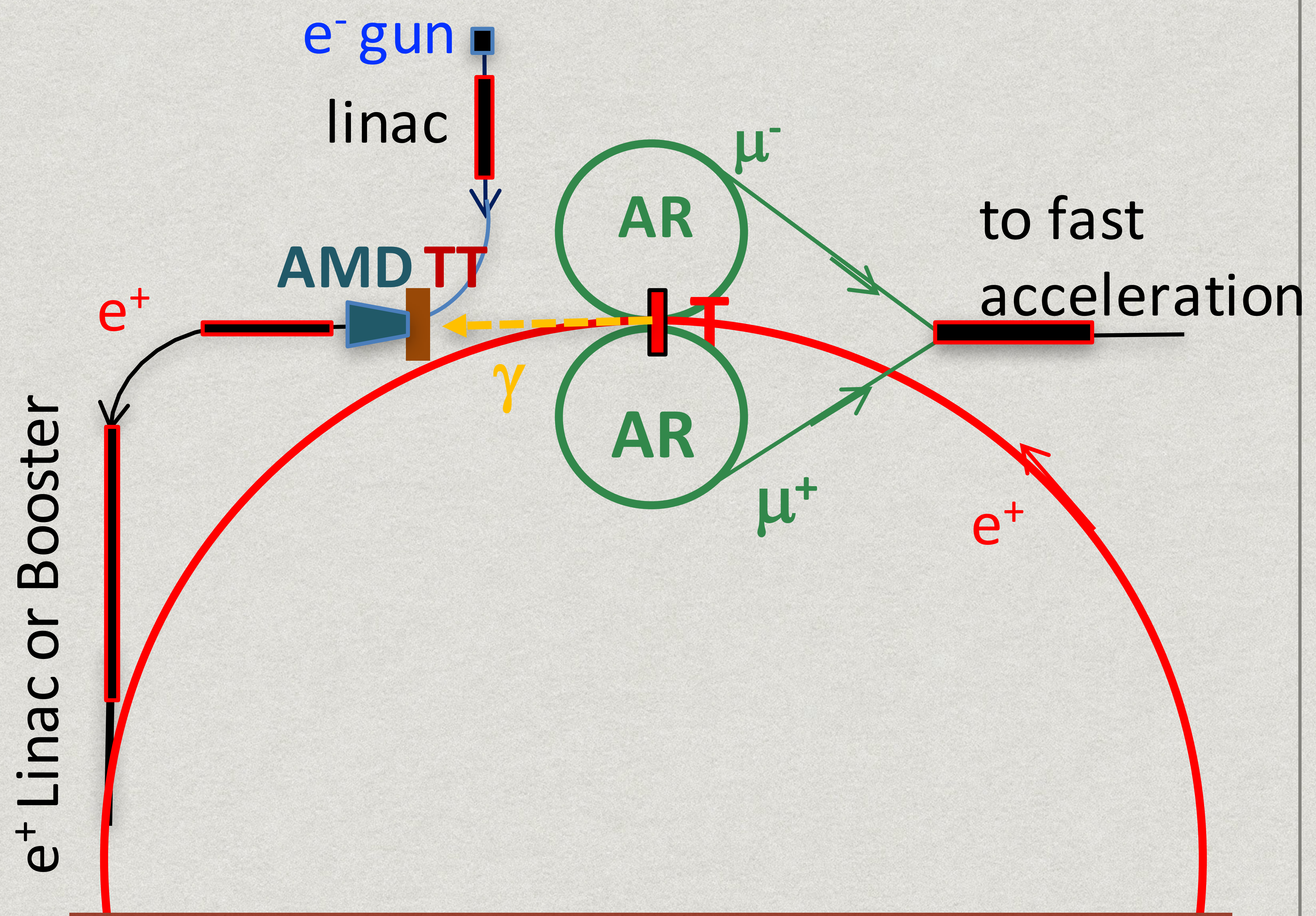


Key topics for this scheme:

➡Low emittance and high mom. acc. 45GeV e⁺ **ring**

➡O(100kW) class **target** in the e⁺ ring

➡High rate positron **source**

➡High mom. acc. μ **accumulator** rings

6TeV μ collider draft Parameters (no lattice yet)

[NIM A 807 101-107 (2016)]

$\mu^+\mu^-$ rate = 9 10^{10} Hz, ε_N = 40 nm

if: LHeC like e^+ source with 25% mom. accept. e^+ ring and ε dominated by μ production

thanks to very small emittance
(and lower beta*)
comparable luminosity with
lower N_μ/bunch
(→ lower background)

Of course, a design study is needed to have a reliable estimate of performances

		LEMC-6TeV
Parameter	Units	
LUMINOSITY/IP	cm^{-2} s^{-1}	5.09E+34
Beam Energy	GeV	3000
Hourglass reduction factor		1.000
Muon mass	GeV	0.10566
Lifetime @ prod	sec	2.20E-06
Lifetime	sec	0.06
c*tau @ prod	m	658.00
c*tau	m	1.87E+07
1/tau	Hz	1.60E+01
Circumference	m	6000
Bending Field	T	15
Bending radius	m	667
Magnetic rigidity	T m	10000
Gamma Lorentz factor		28392.96
N turns before decay		3113.76
b_x @ IP	m	0.0002
b_y @ IP	m	0.0002
Beta ratio		1.0
Coupling (full current)	%	100
Normalised Emittance x	m	4.00E-08
Emittance x	m	1.41E-12
Emittance y	m	1.41E-12
Emittance ratio		1.0
Bunch length (zero current)	mm	0.1
Bunch length (full current)	mm	0.1
Beam current	mA	48
Revolution frequency	Hz	5.00E+04
Revolution period	s	2.00E-05
Number of bunches	#	1
N. Particle/bunch	#	6.00E+09
Number of IP	#	1.00
s_x @ IP	micron	1.68E-02
s_y @ IP	micron	1.68E-02
$s_{x'}$ @ IP	rad	8.39E-05
$s_{y'}$ @ IP	rad	8.39E-05

Radiological hazard due to neutrinos

Colin Johnosn, Gigi Rolandi and Marco Silari

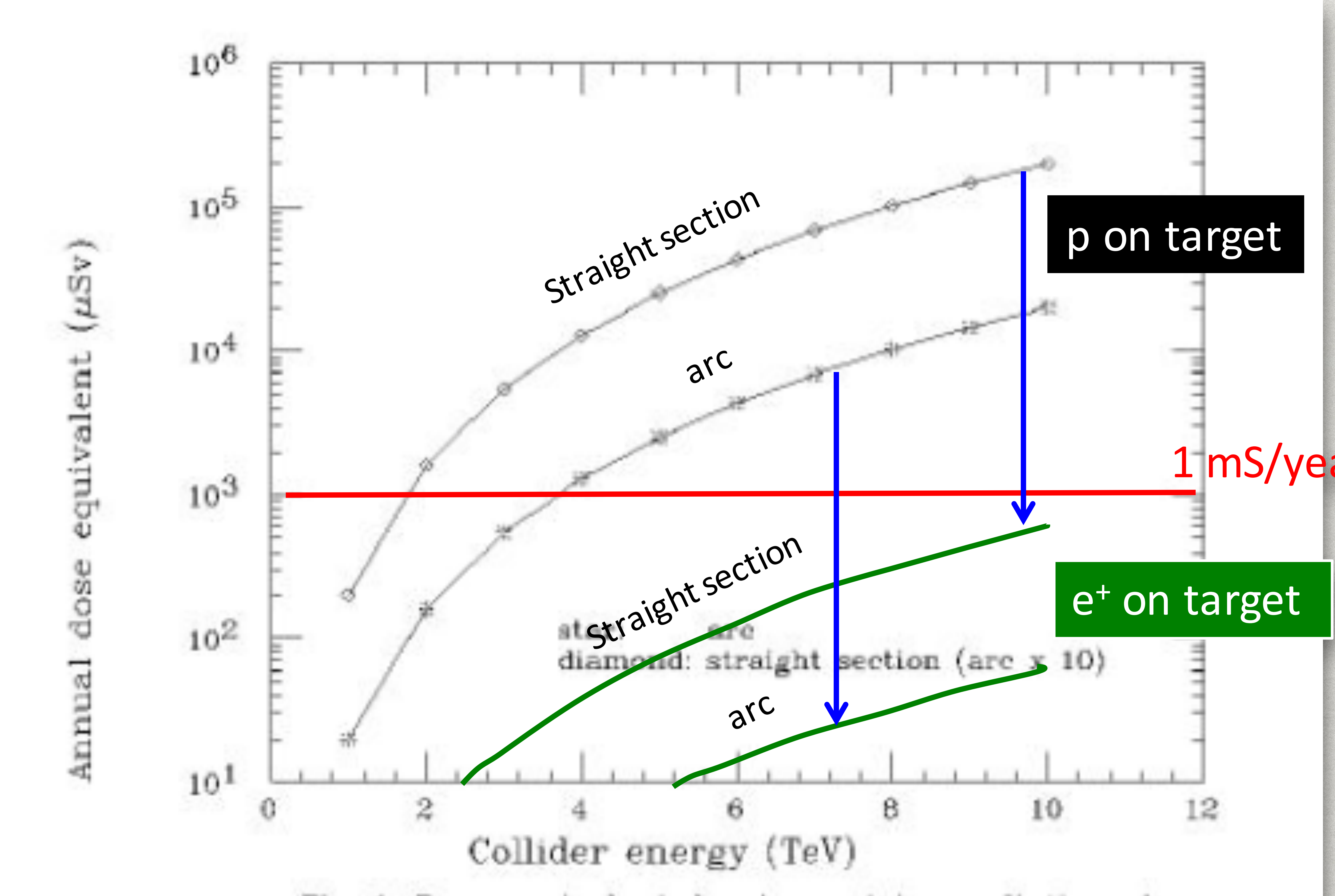
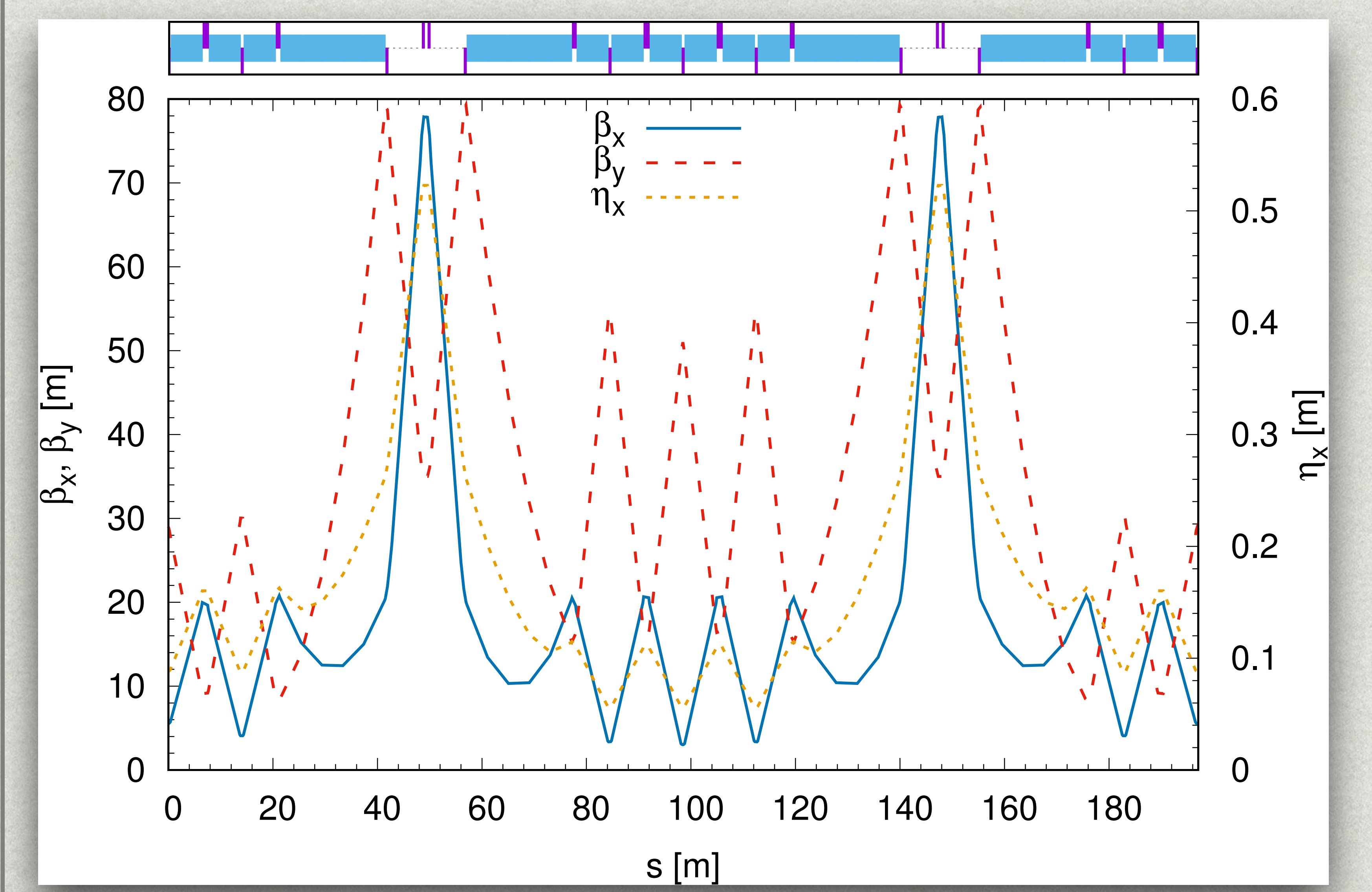


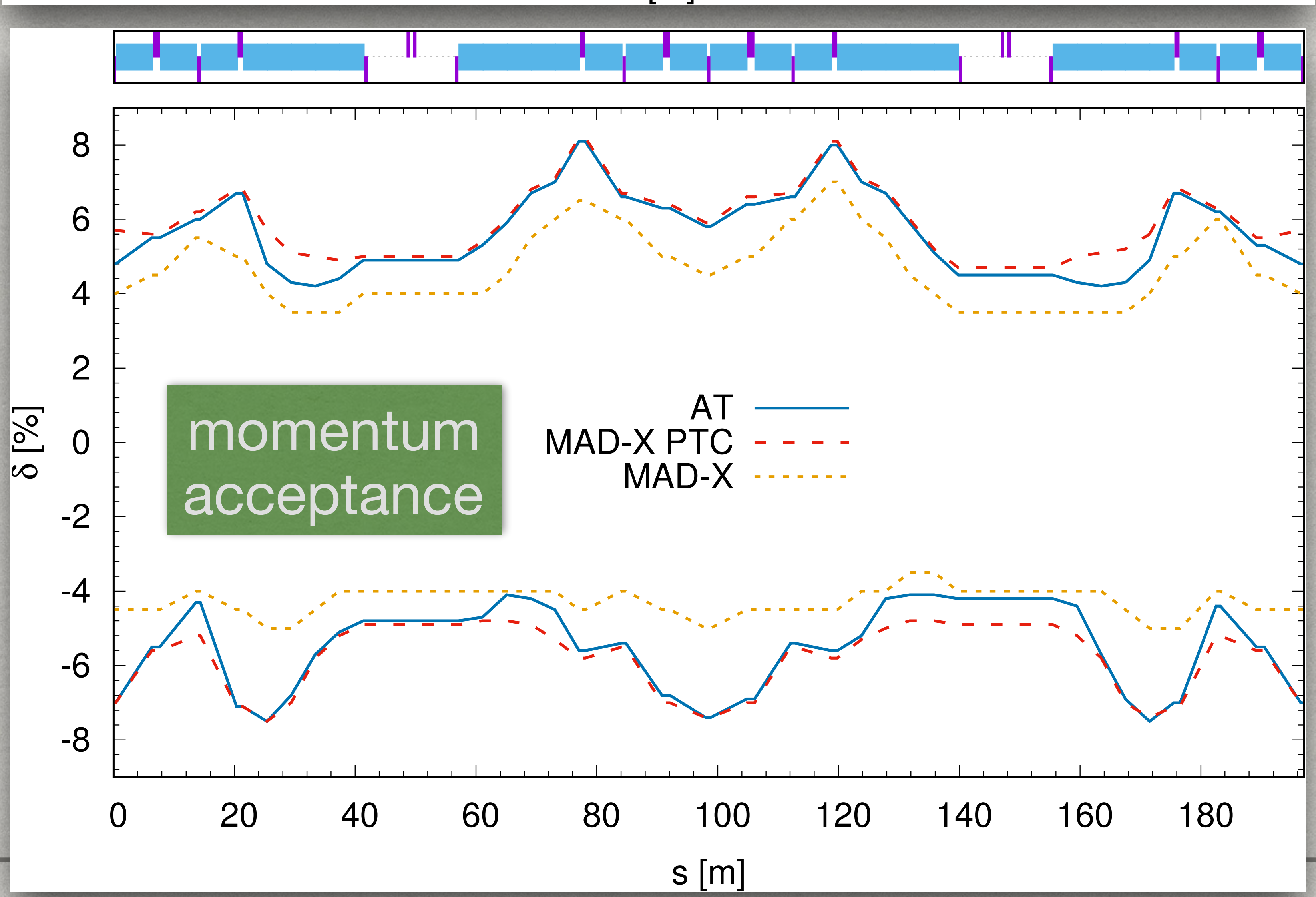
Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

muon rate: p on target option **3 10^{13}** μ/s

e+ on target option **9 10^{10}** μ/s

Low emittance 45GeV e^+ ring





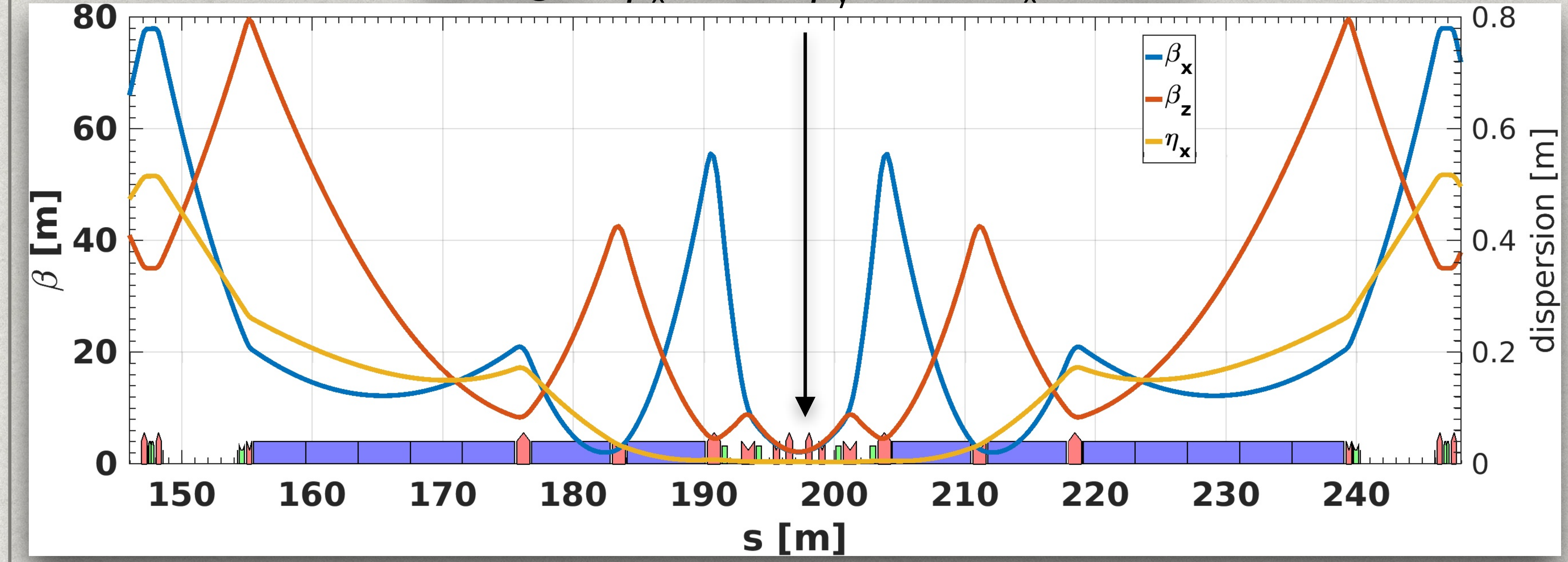
- Circumference 6.3 km: 197 m x 32 cells (no injection section yet)

Parameter	Units	
Energy	GeV	45
Circumference	m	6300
Coupling(full current)	%	1
Emittance x	m	5.73×10^{-9}
Emittance y	m	5.73×10^{-11}
Bunch length	mm	3
Beam current	mA	240
RF frequency	MHz	500
RF voltage	GV	1.15
Harmonic number	#	10508
Number of bunches	#	100
N. particles/bunch	#	3.15×10^{11}
Synchrotron tune		0.068
Transverse damping time	turns	175
Longitudinal damping time	turns	87.5
Energy loss/turn	GeV	0.511
Momentum compaction		1.1×10^{-4}
RF acceptance	%	± 7.2
Energy spread	dE/E	1×10^{-3}
SR power	MW	120

- Physical aperture=5 cm constant no errors
- Good agreement between MADX PTC / Accelerator Toolbox, both used for particle tracking in our studies

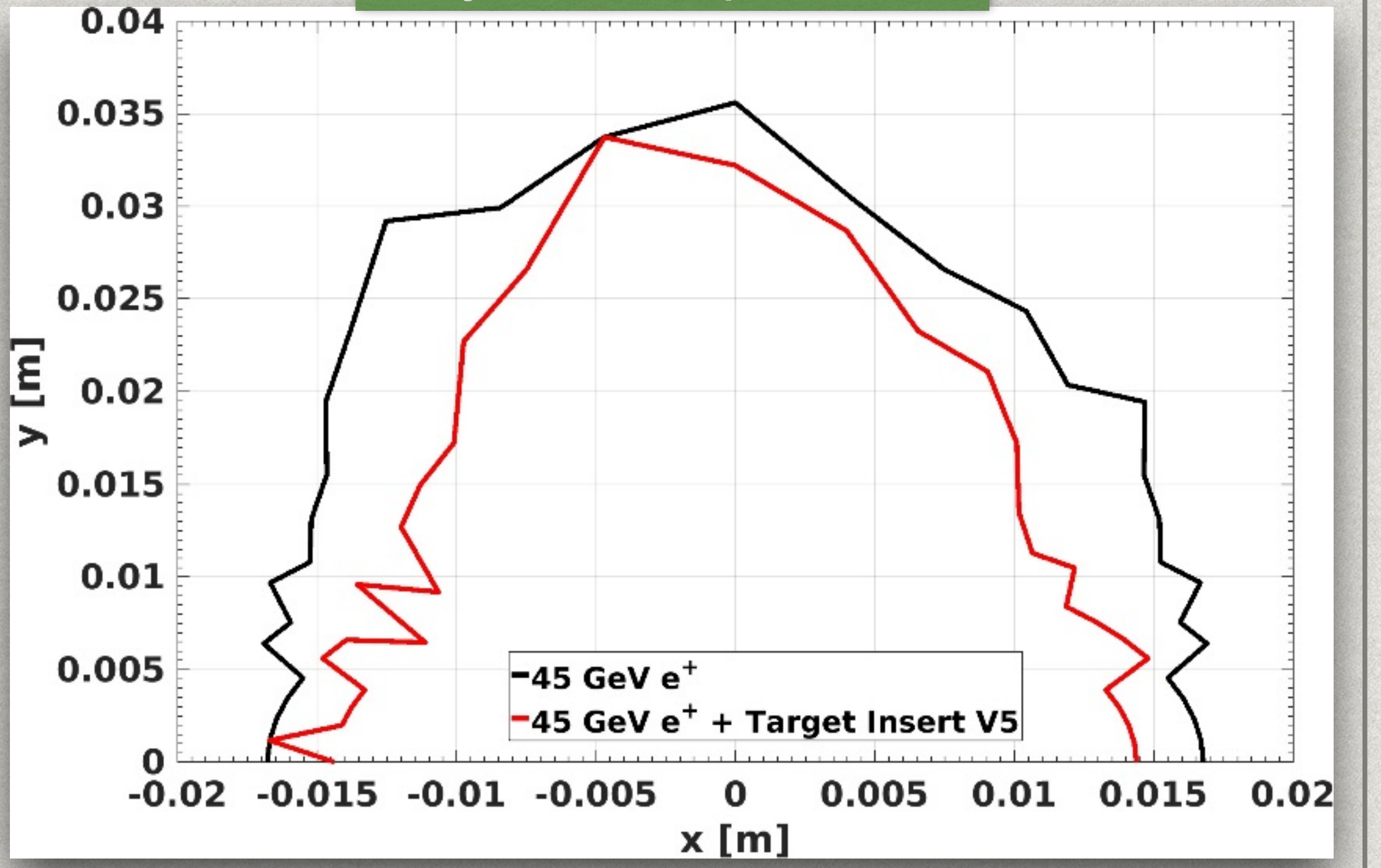
Preliminary low-β IR for muon target insertion

@target: β_x=1.6m; β_y=1.7m; D_x=5.4mm

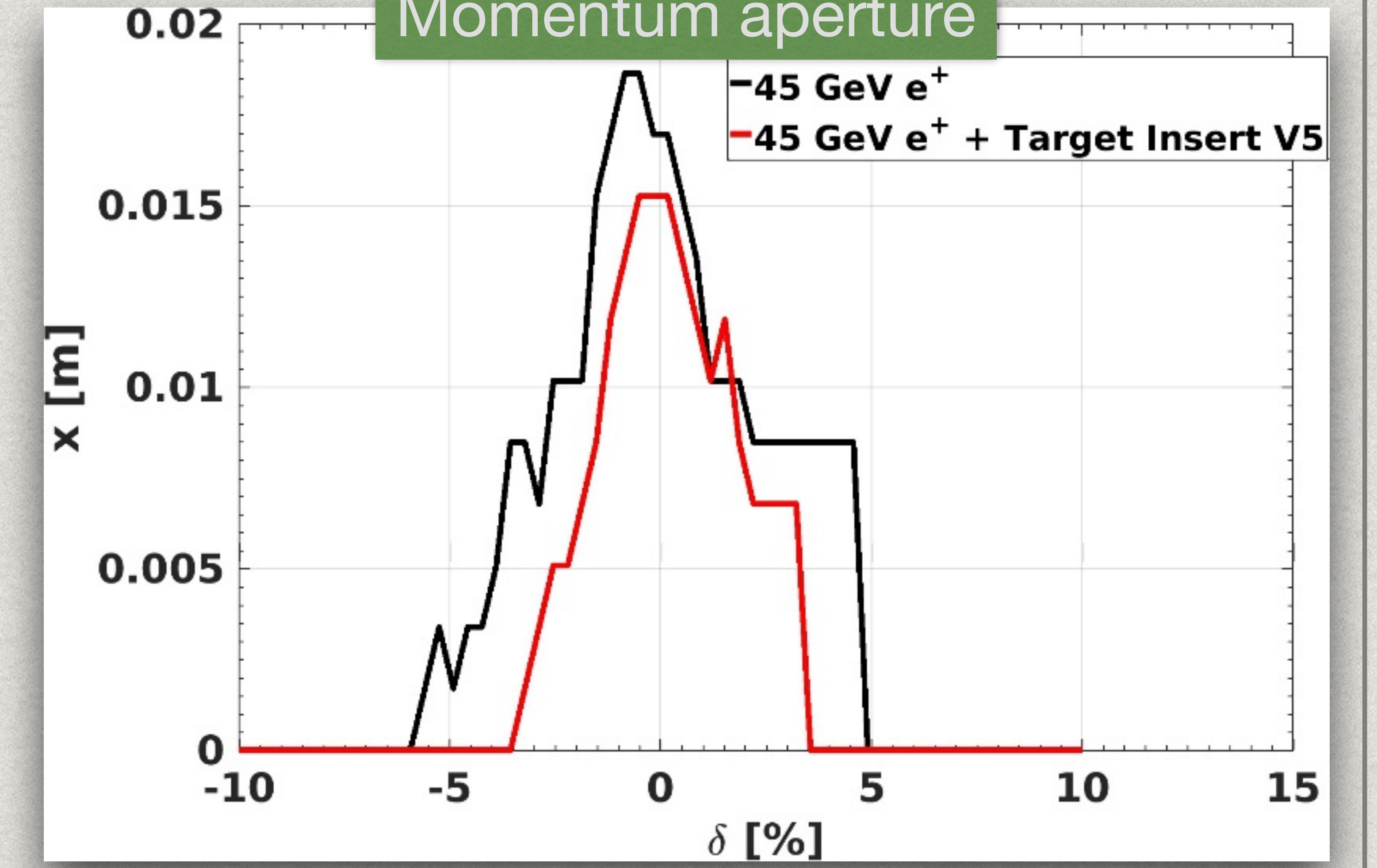


@target location:
- Dx ≈ 0
- low-β

Dynamic aperture



Momentum aperture



- Further optimisations are underway:
  - Match the transverse minimum beam size with constraints of target thermo-mechanical stress
  - Match with other contributions to muon emittance (production, accumulation)
  - Dynamic and momentum aperture can be optimised

Multi-turn simulations

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** (FLUKA/GEANT4)
4. Back to tracking code

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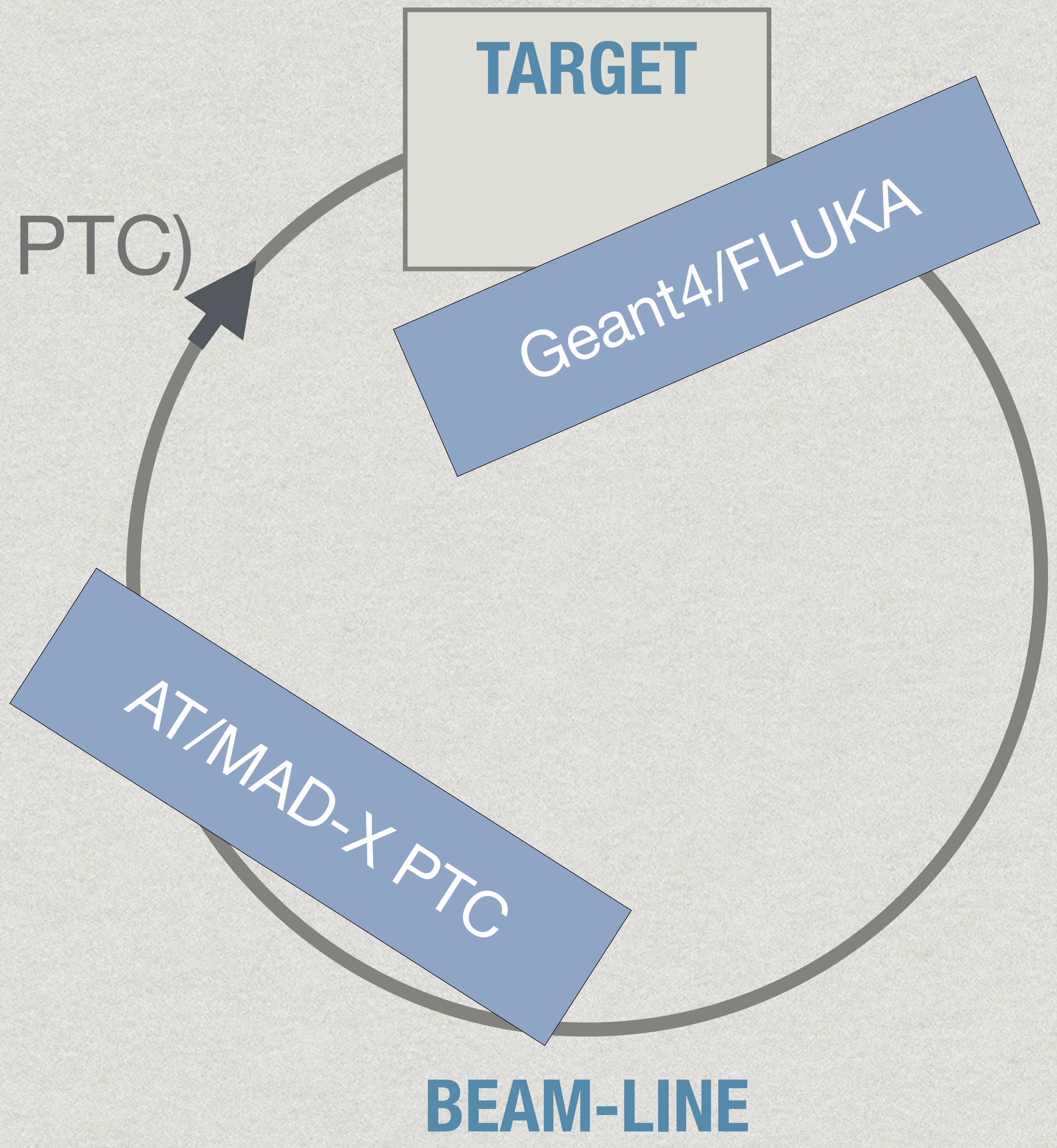

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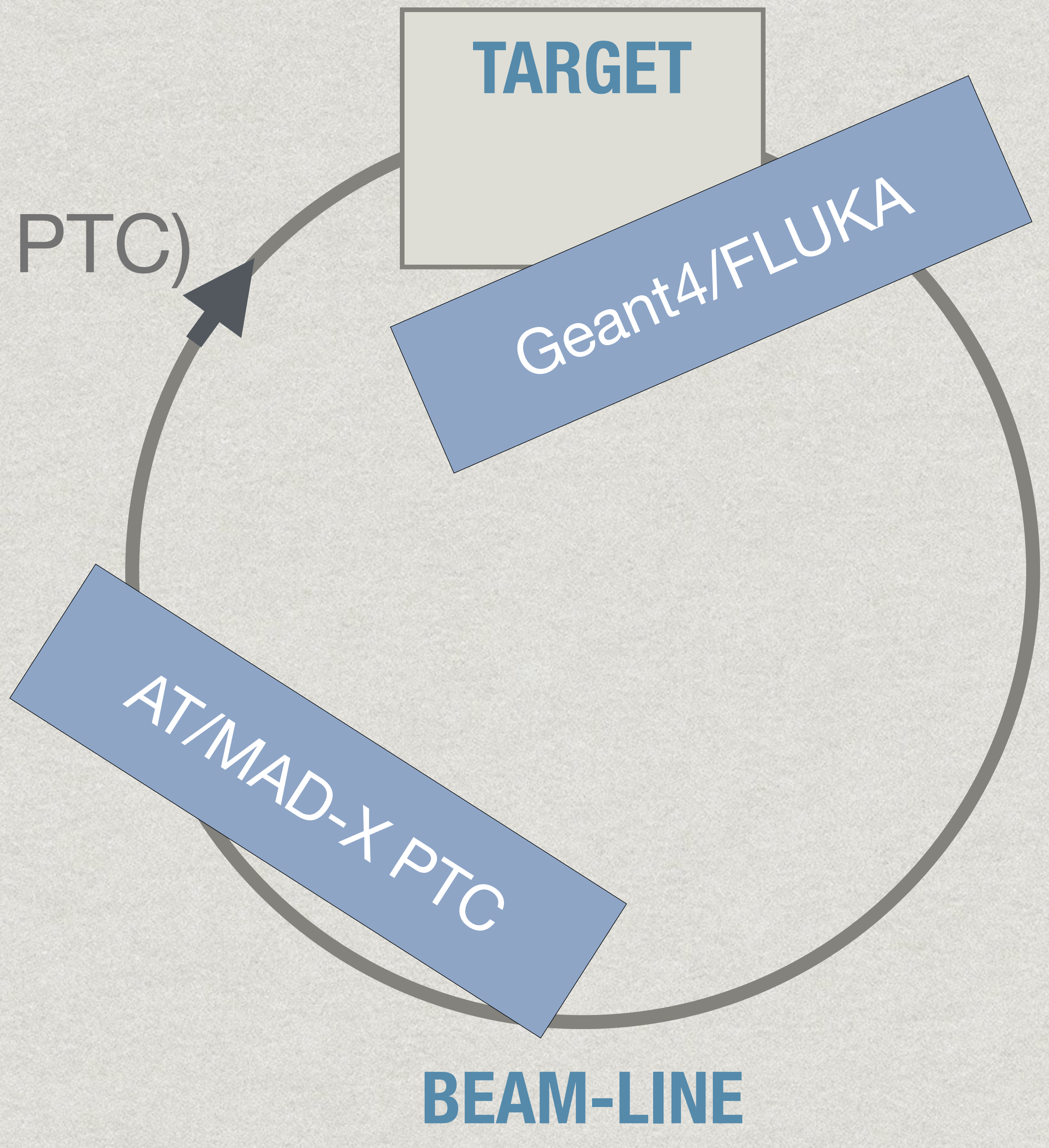

At each pass through the Target the e^+ beam:

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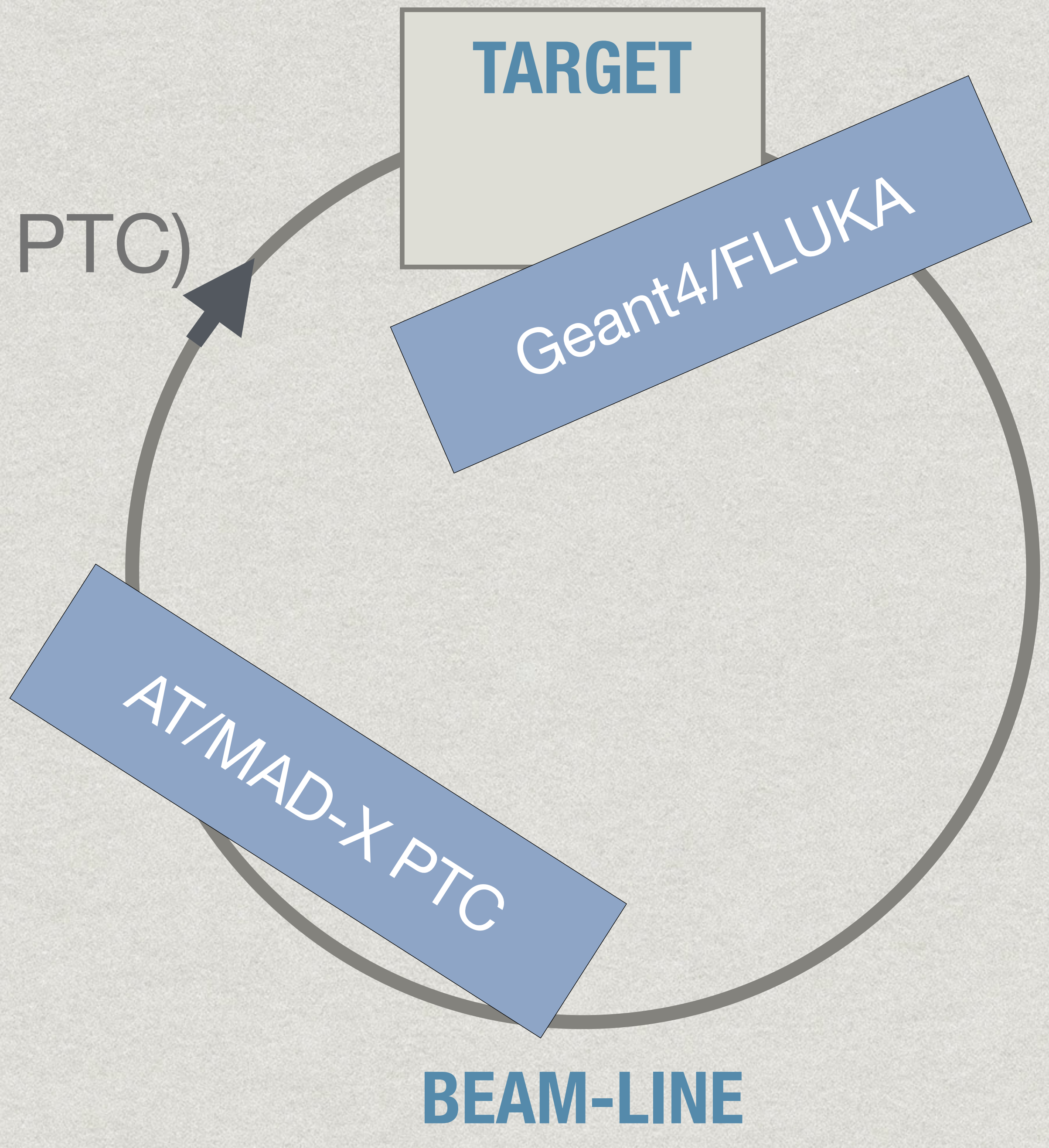

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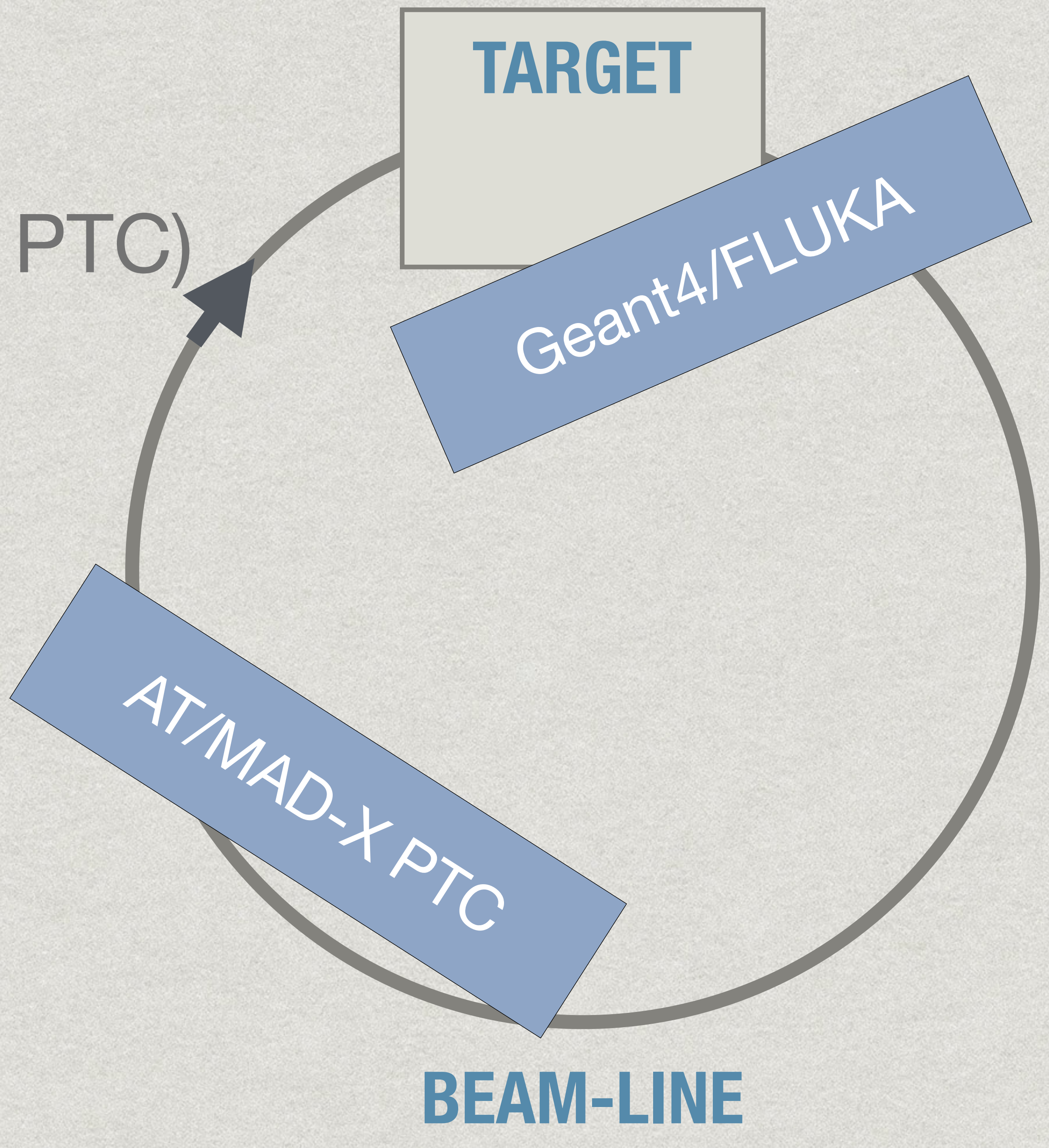

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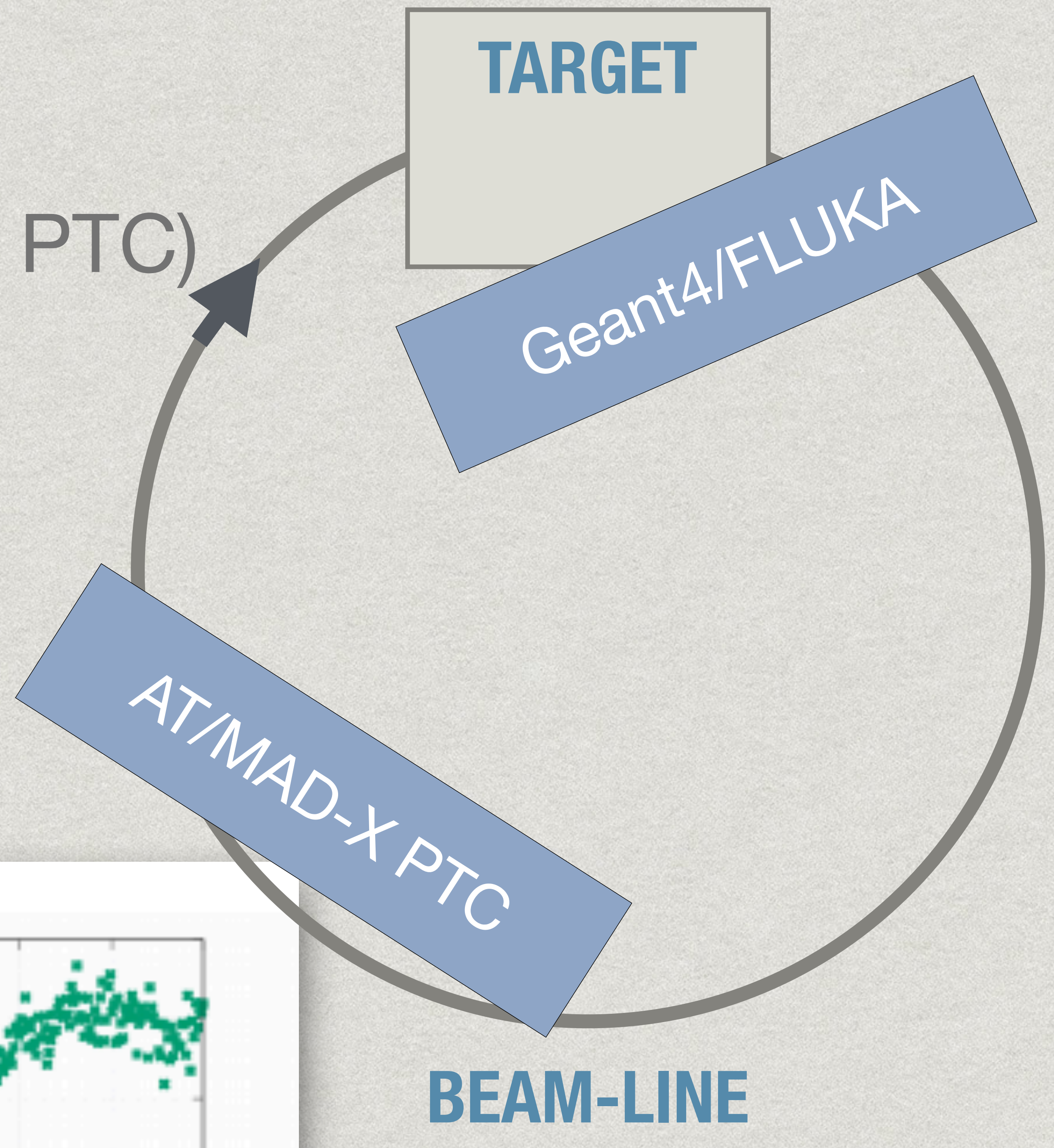

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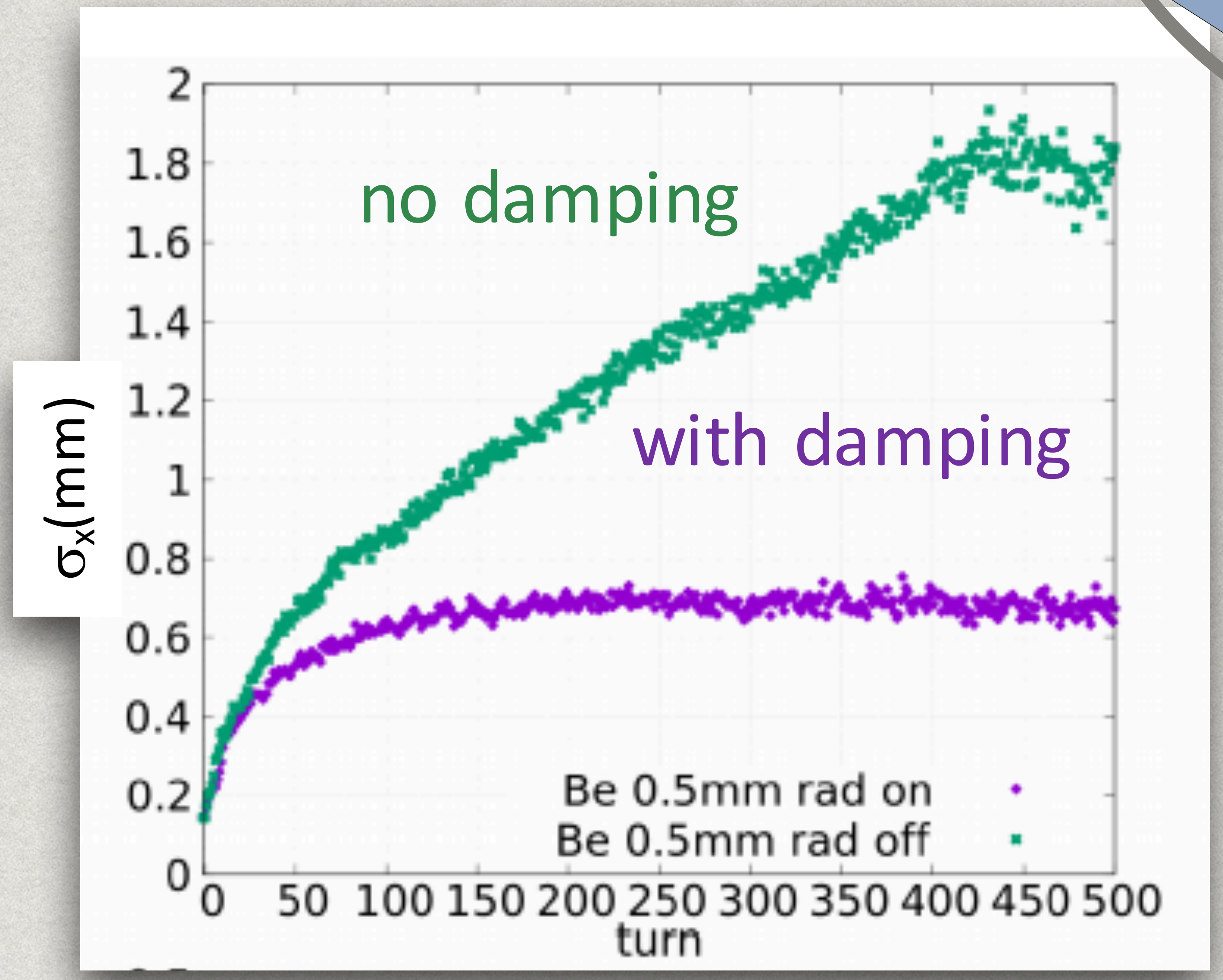
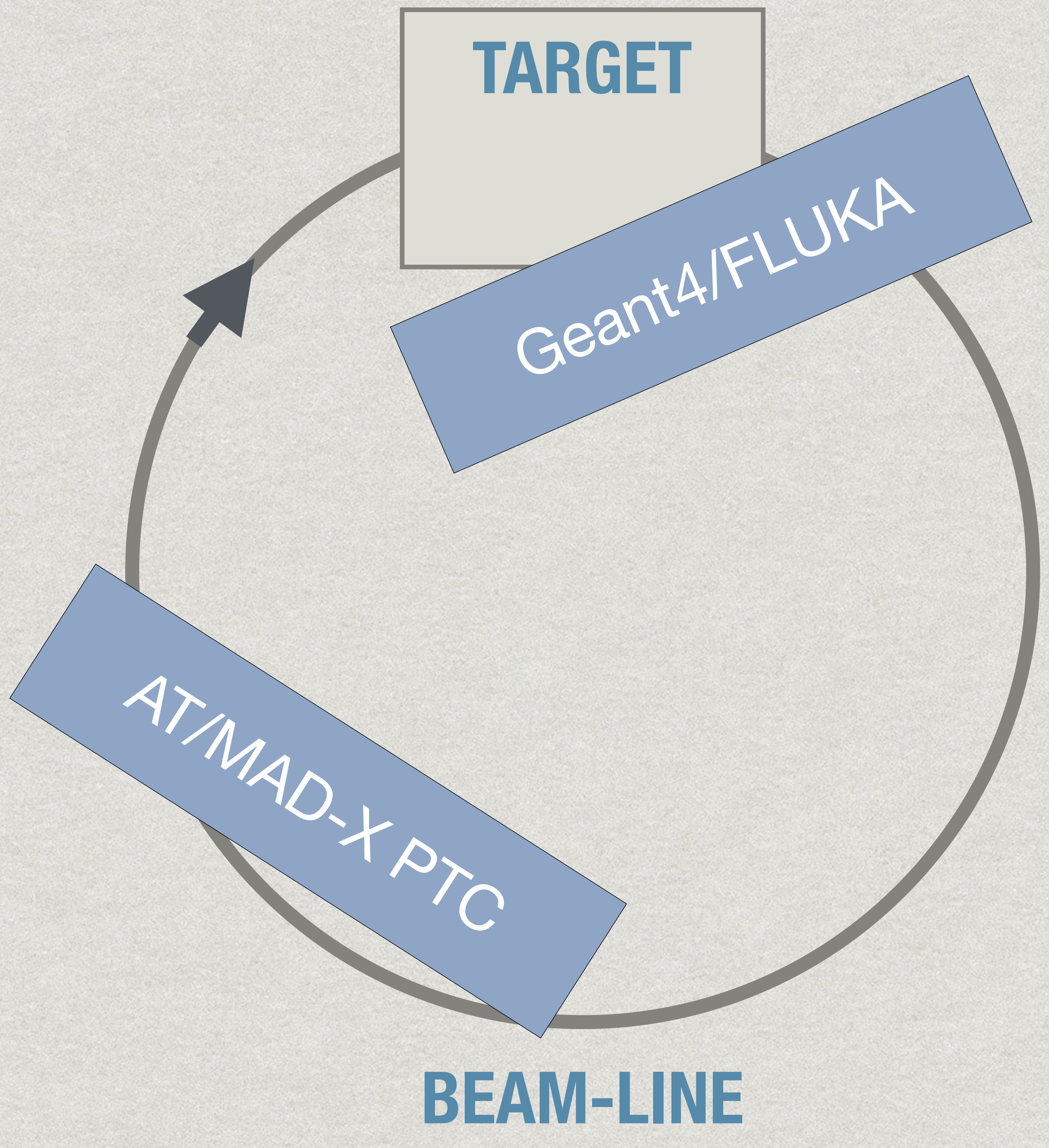
⊕ natural radiation damping

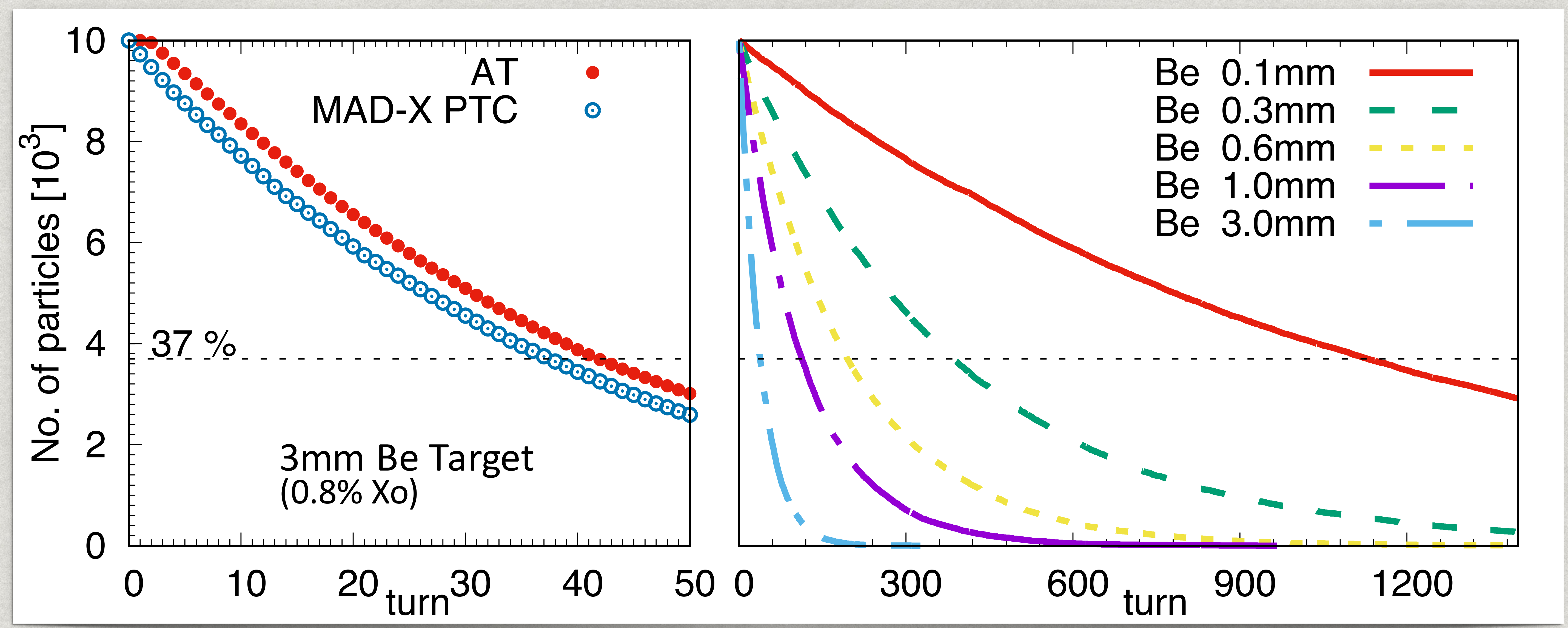


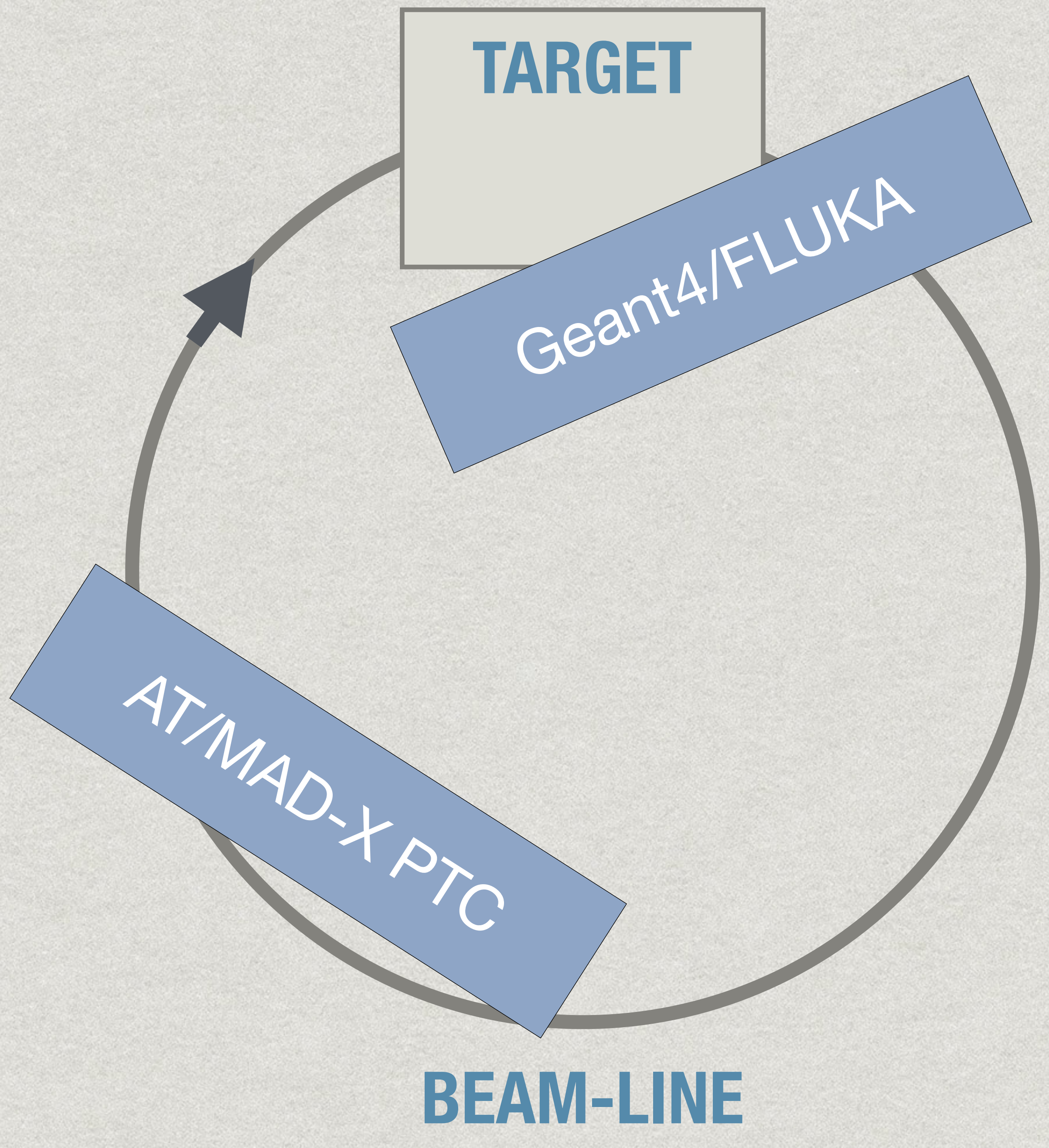
Positron lifetime with Be target



Positron lifetime with Be target

beam lifetime
~35 turns





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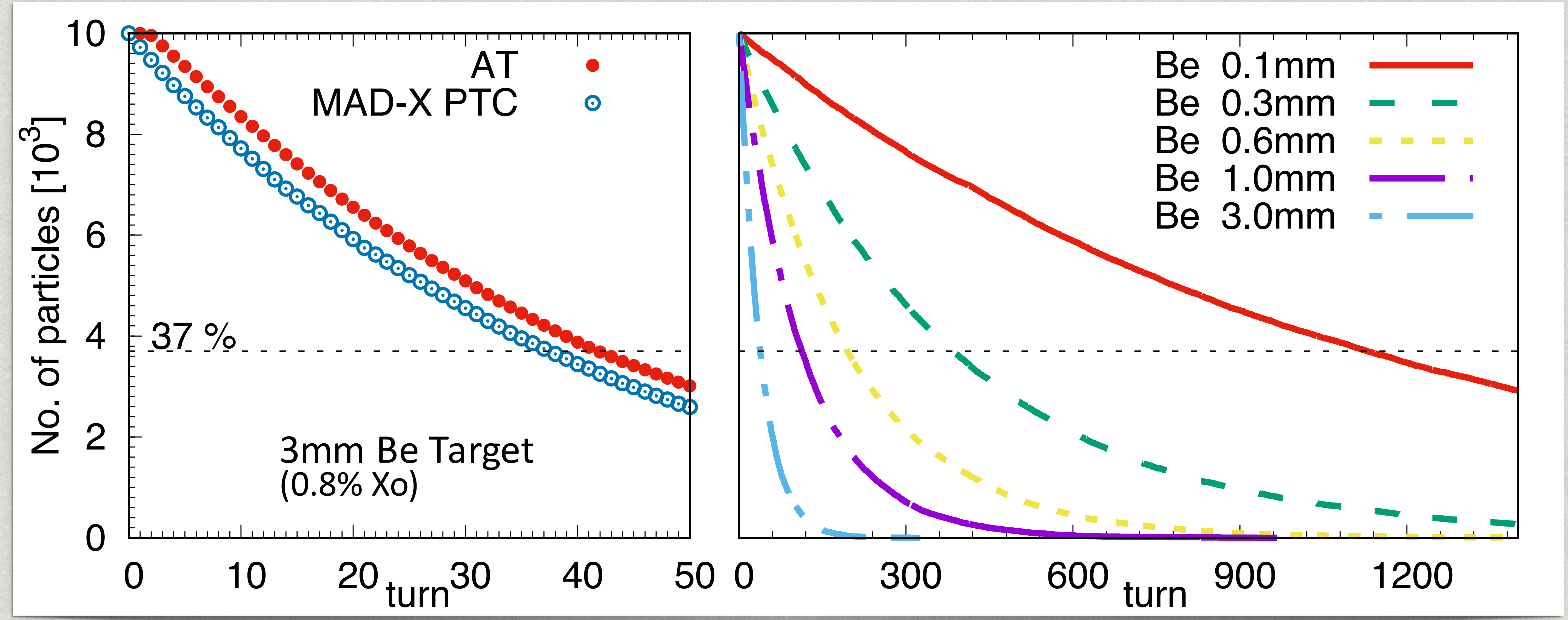
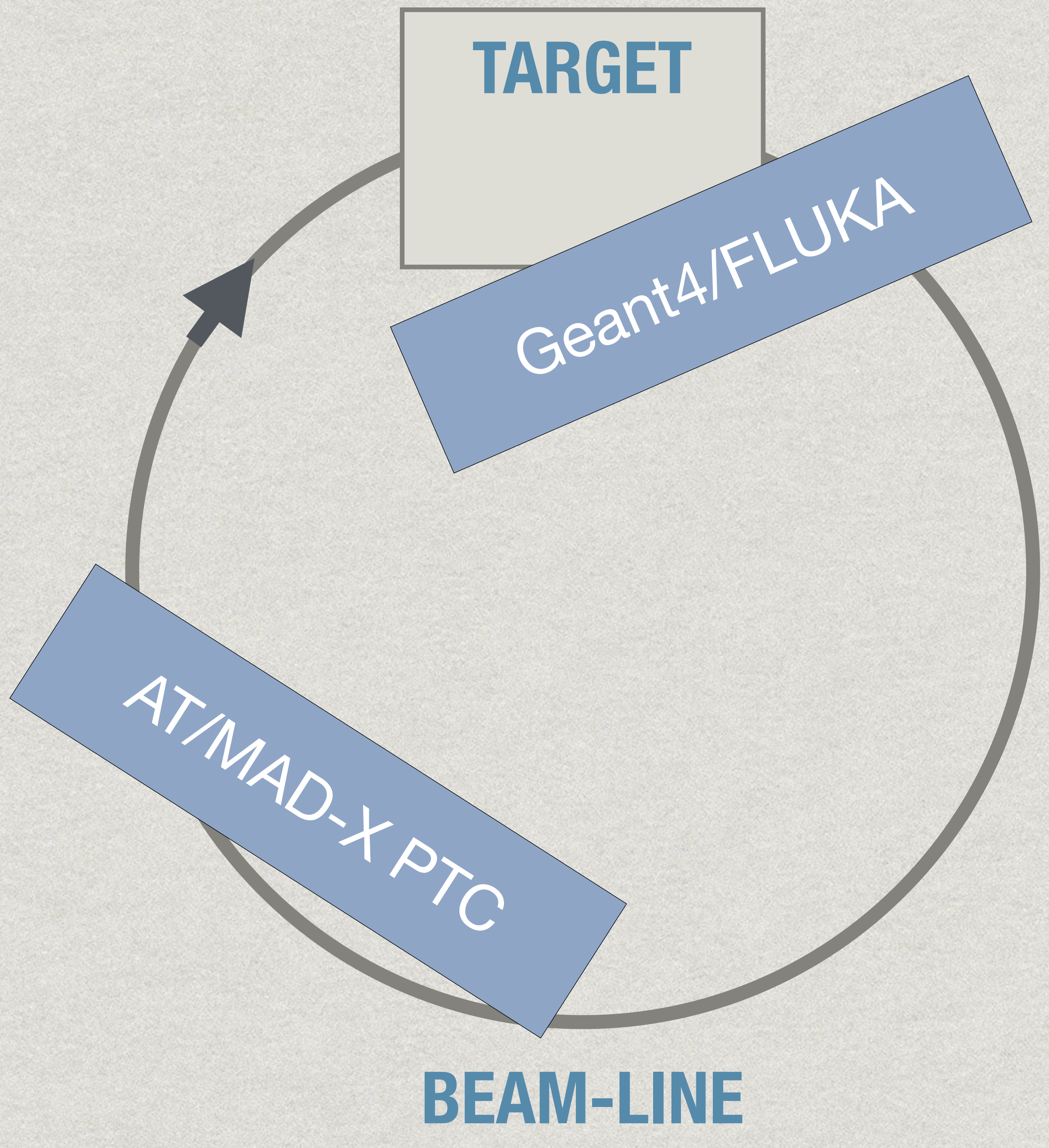
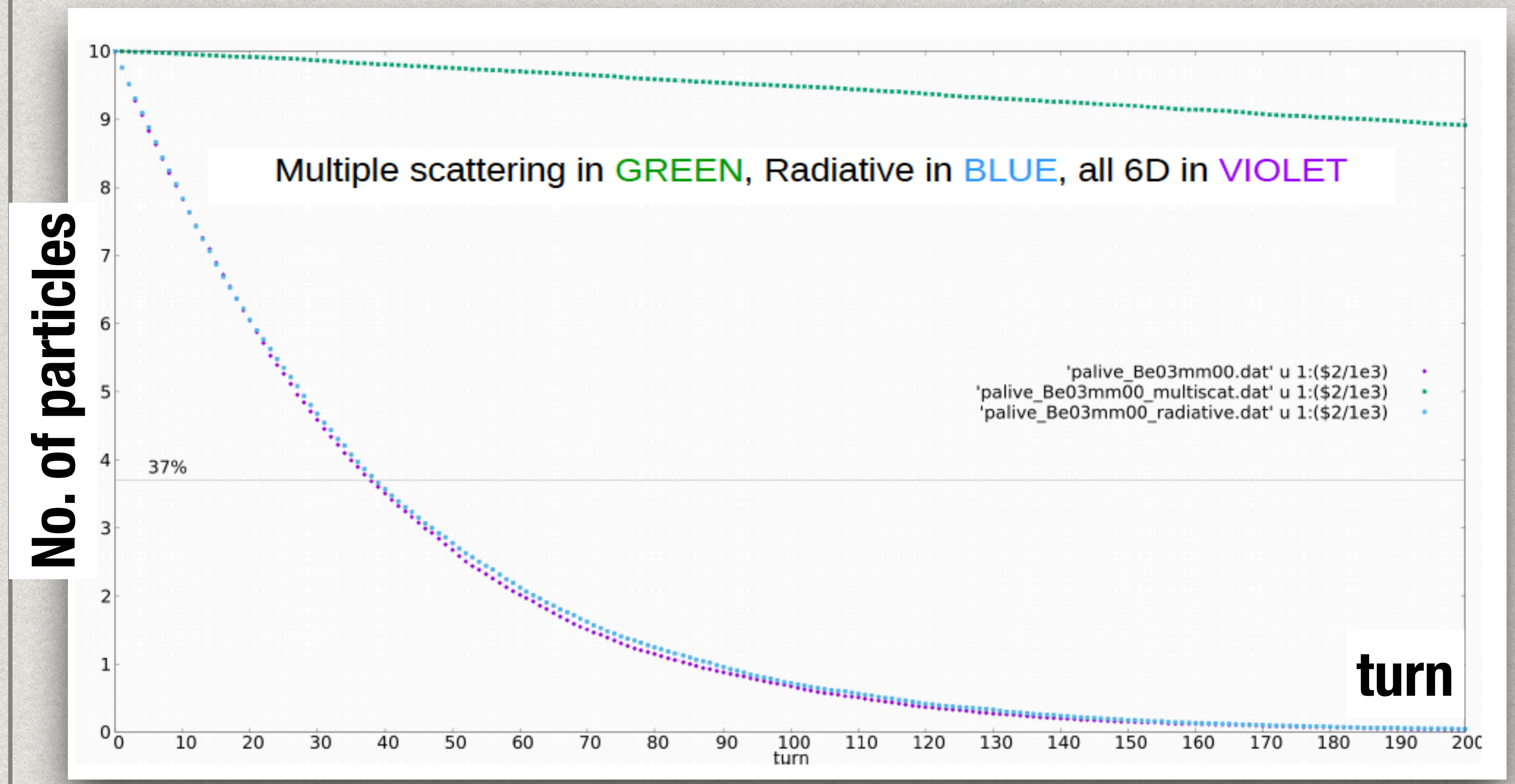


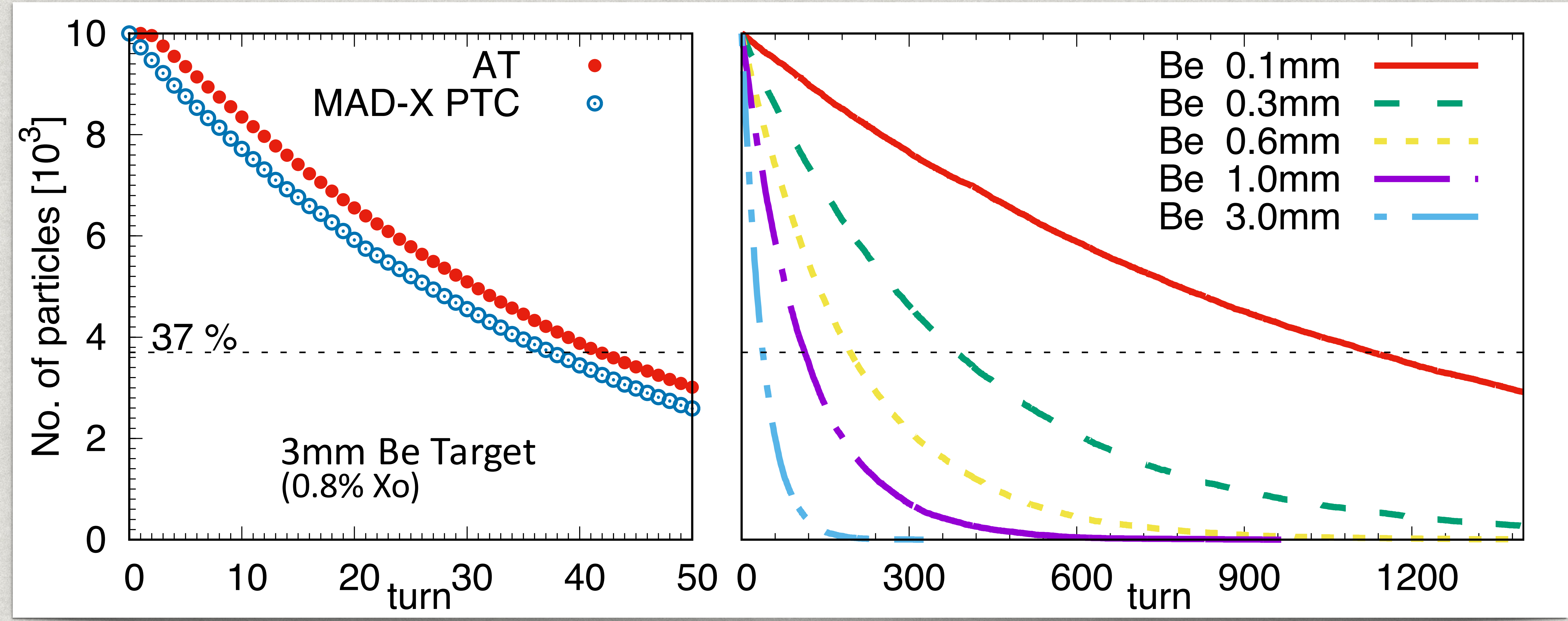


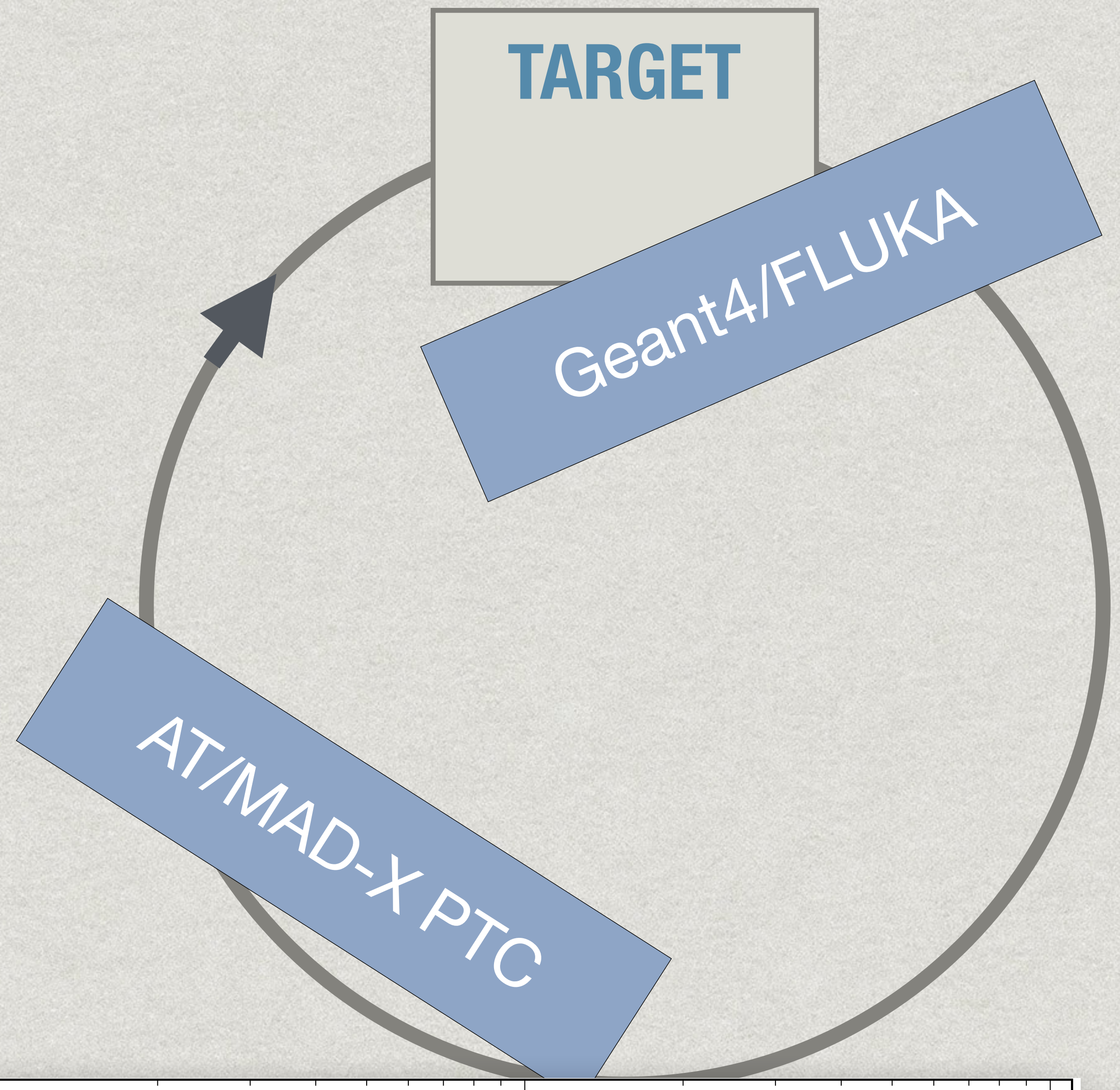


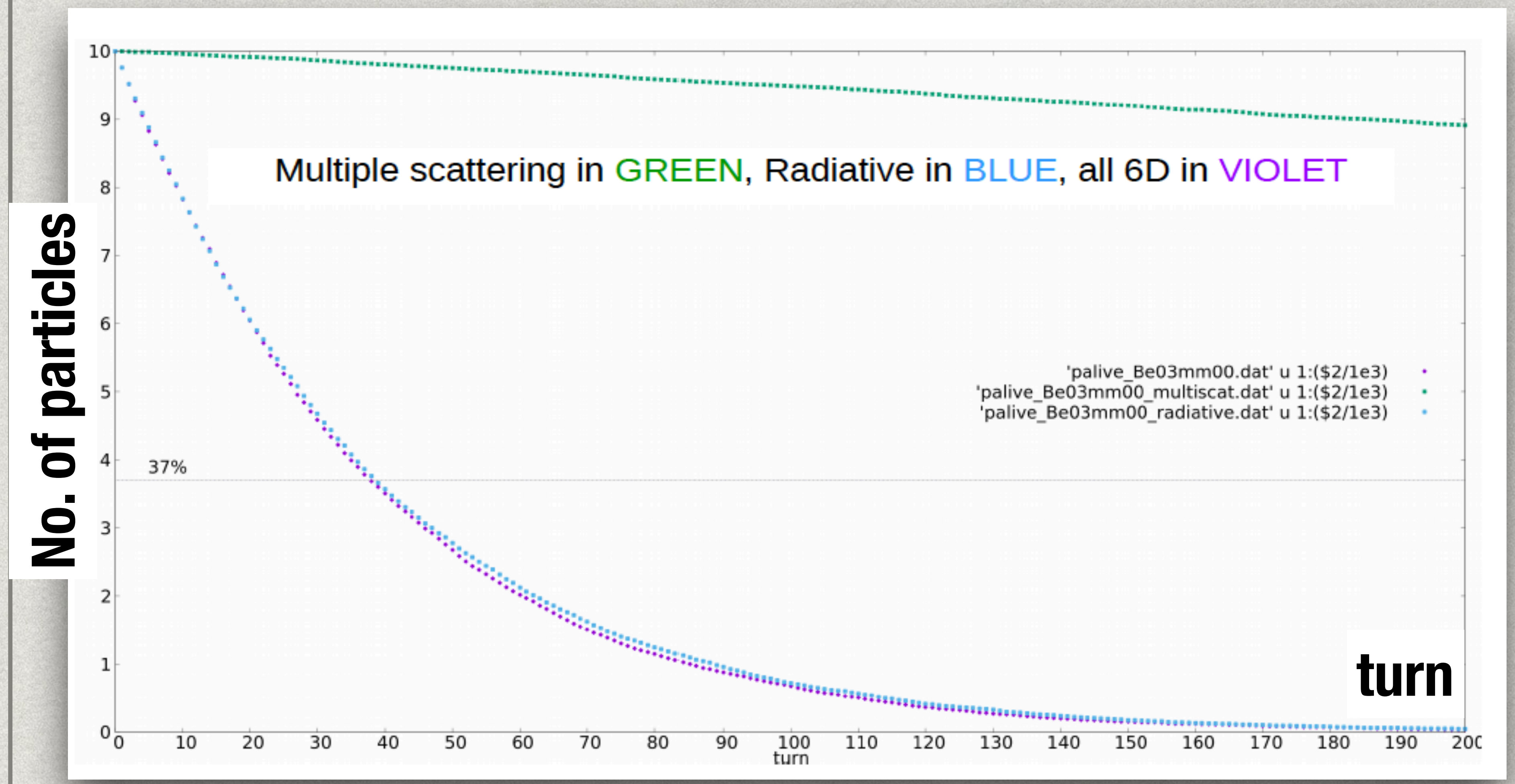
radiative loss is dominant

Positron lifetime with Be target

beam lifetime ~35 turns

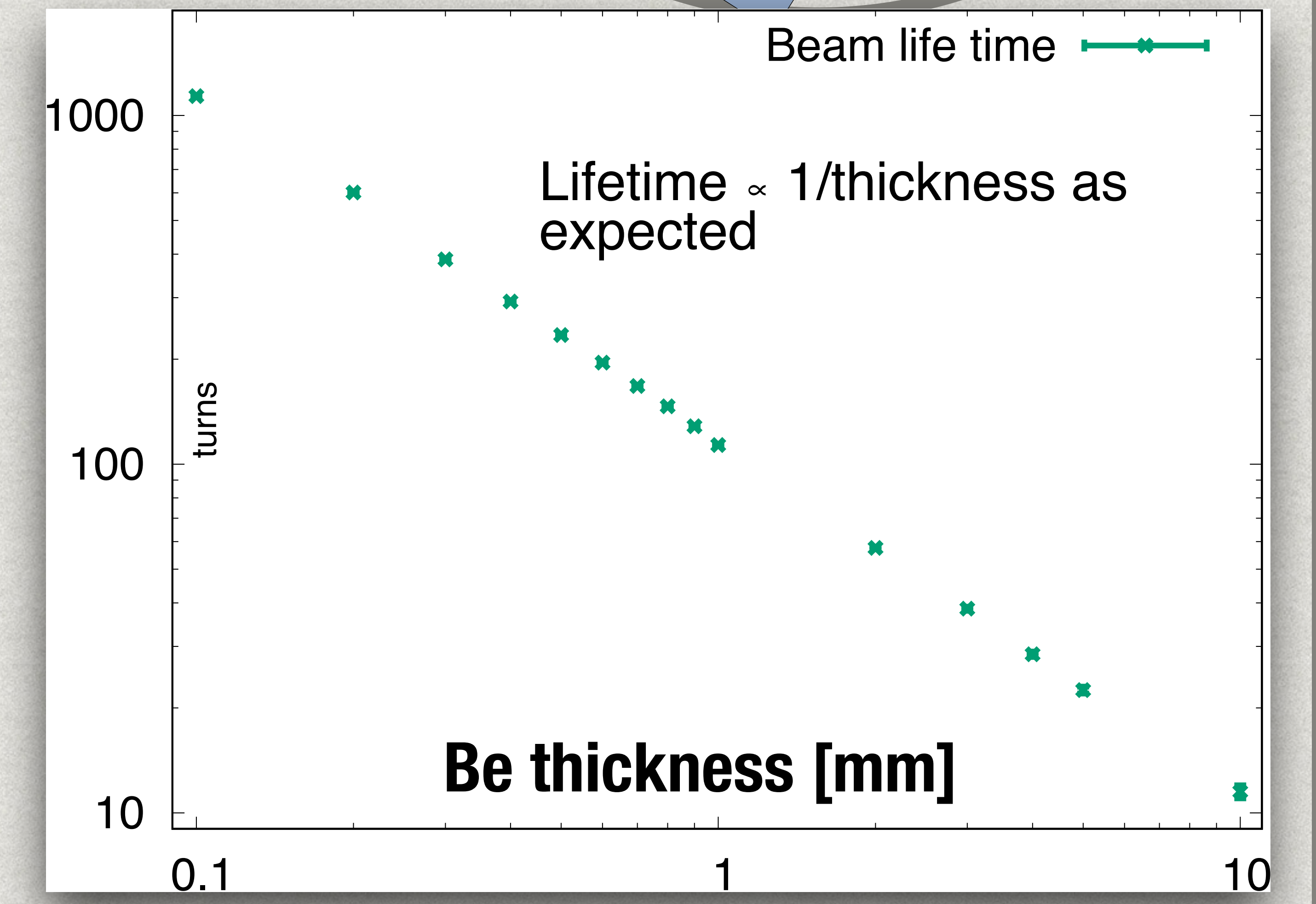




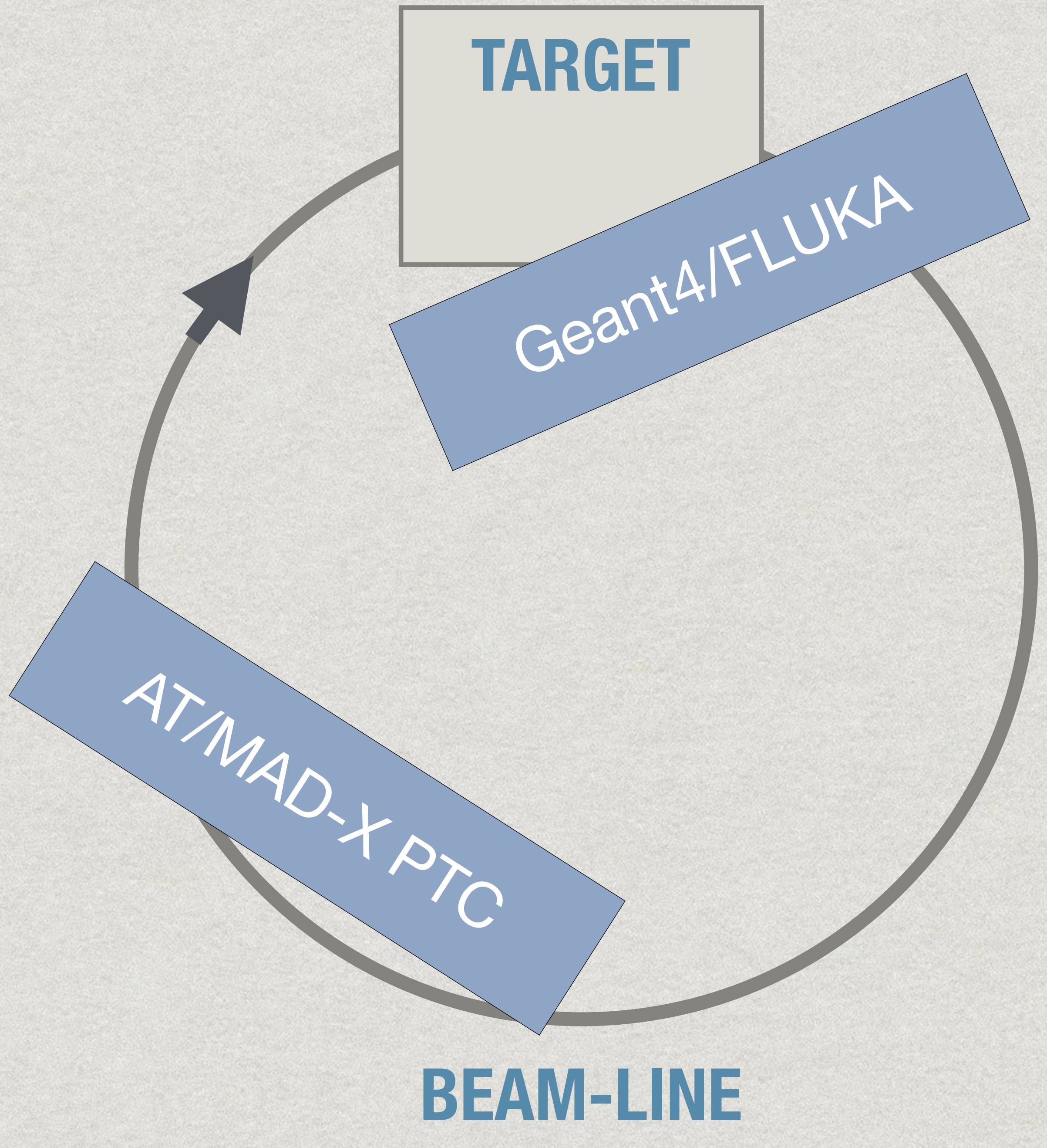


radiative loss is dominant

Lifetime ∝ 1/ thickness as expected

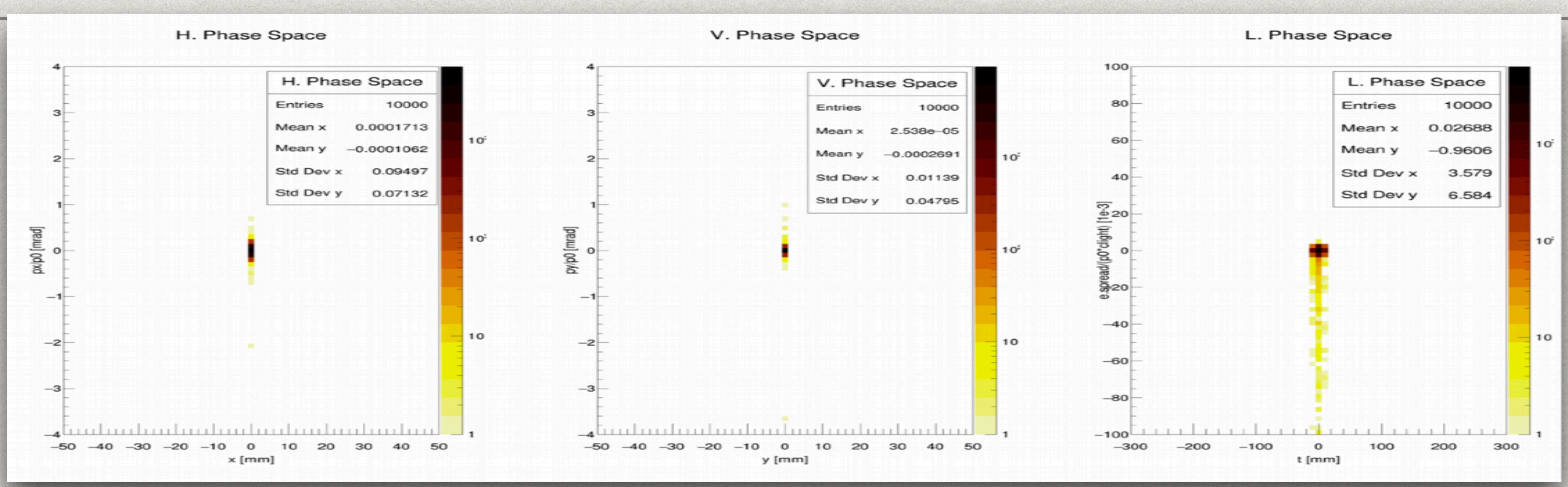


Multi-turn simulations

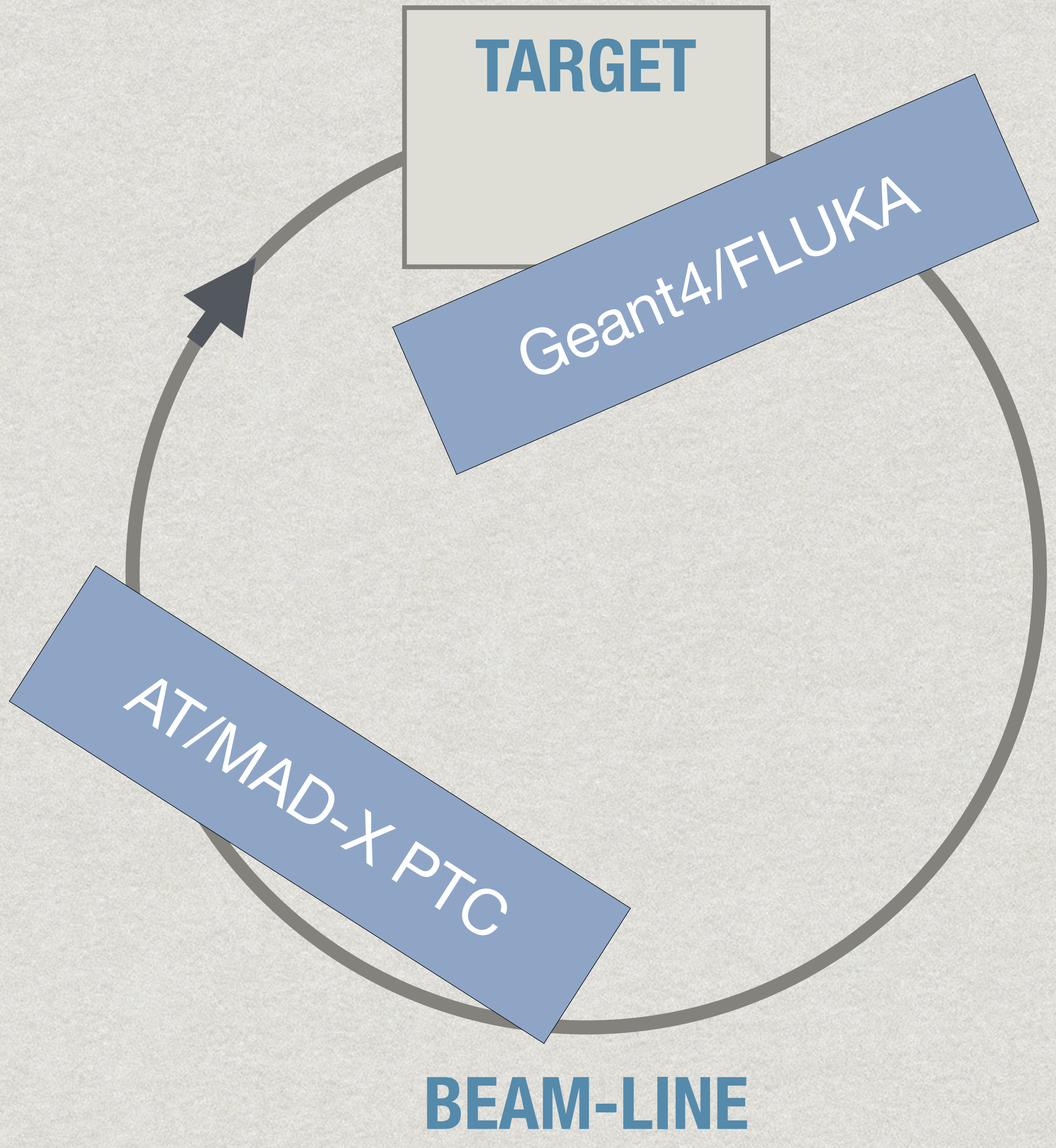


MAD-X PTC & GEANT4 6-D tracking simulation of e+ beam with **3 mm Be** target along

Multi-turn simulations



after target, before turn



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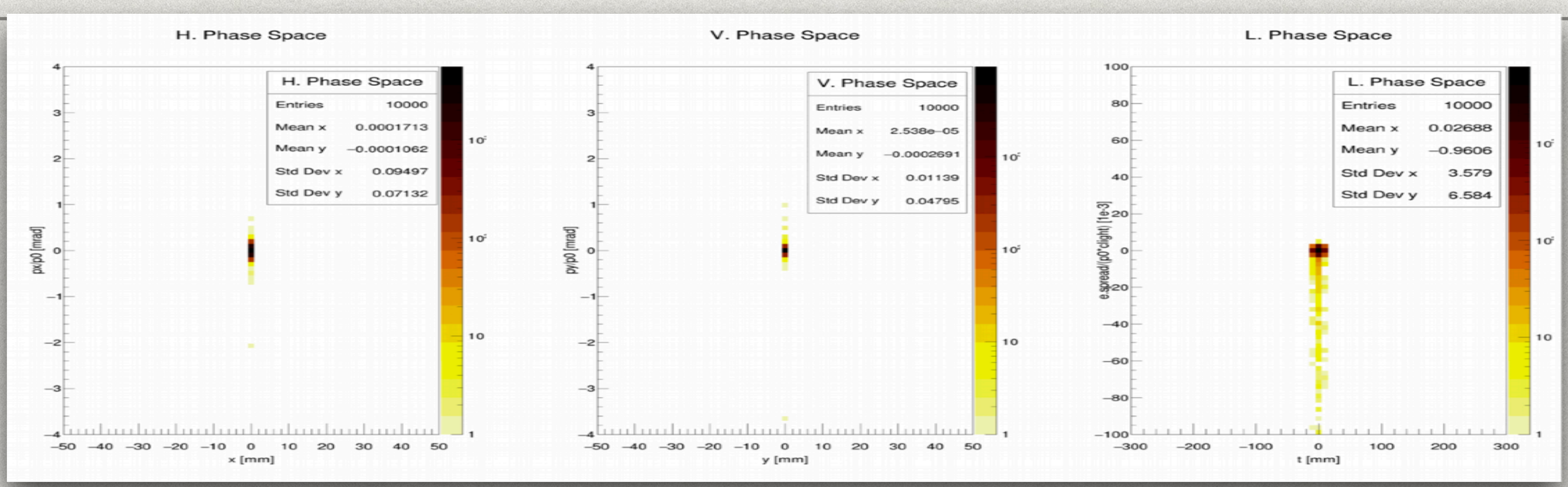

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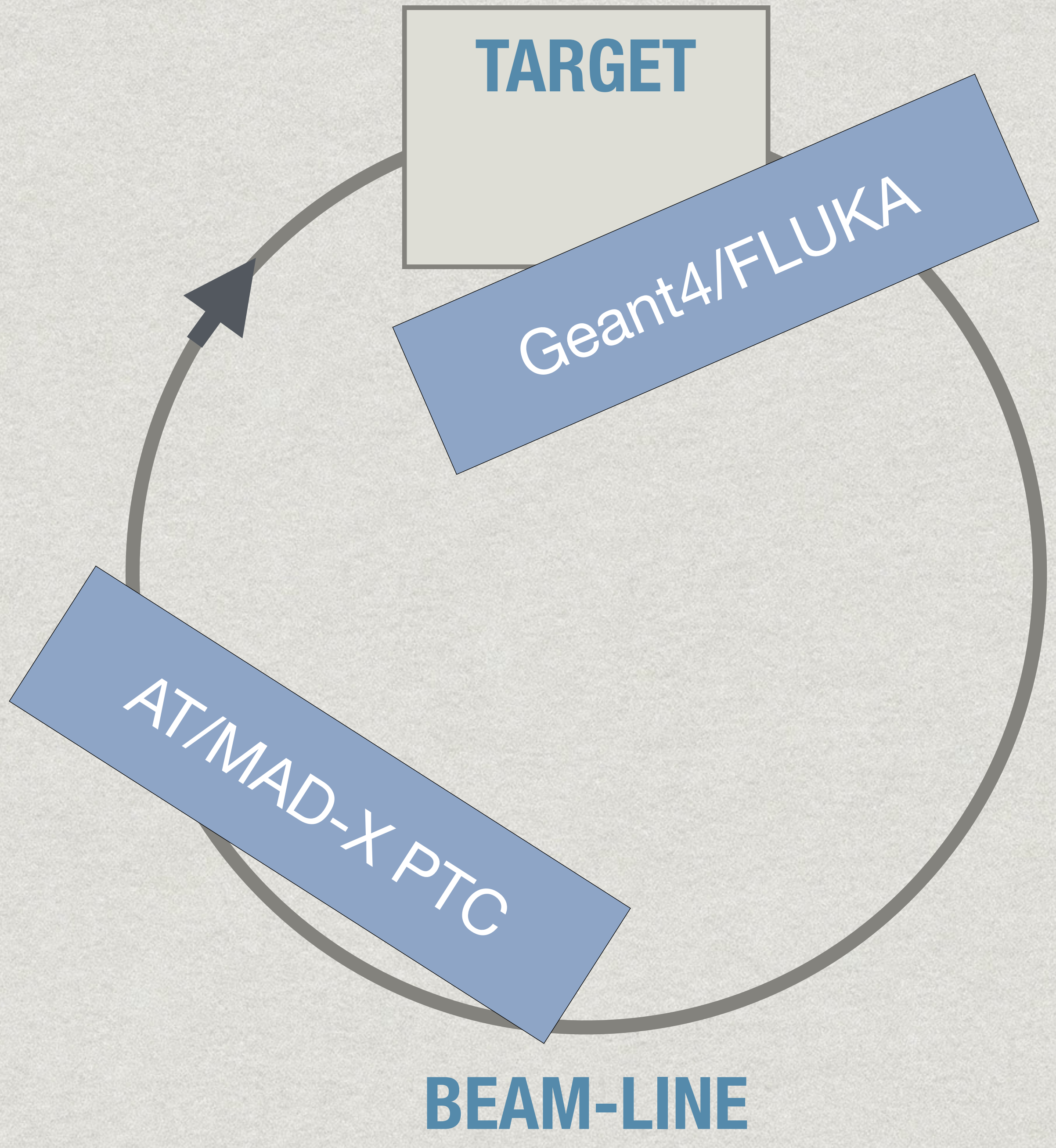
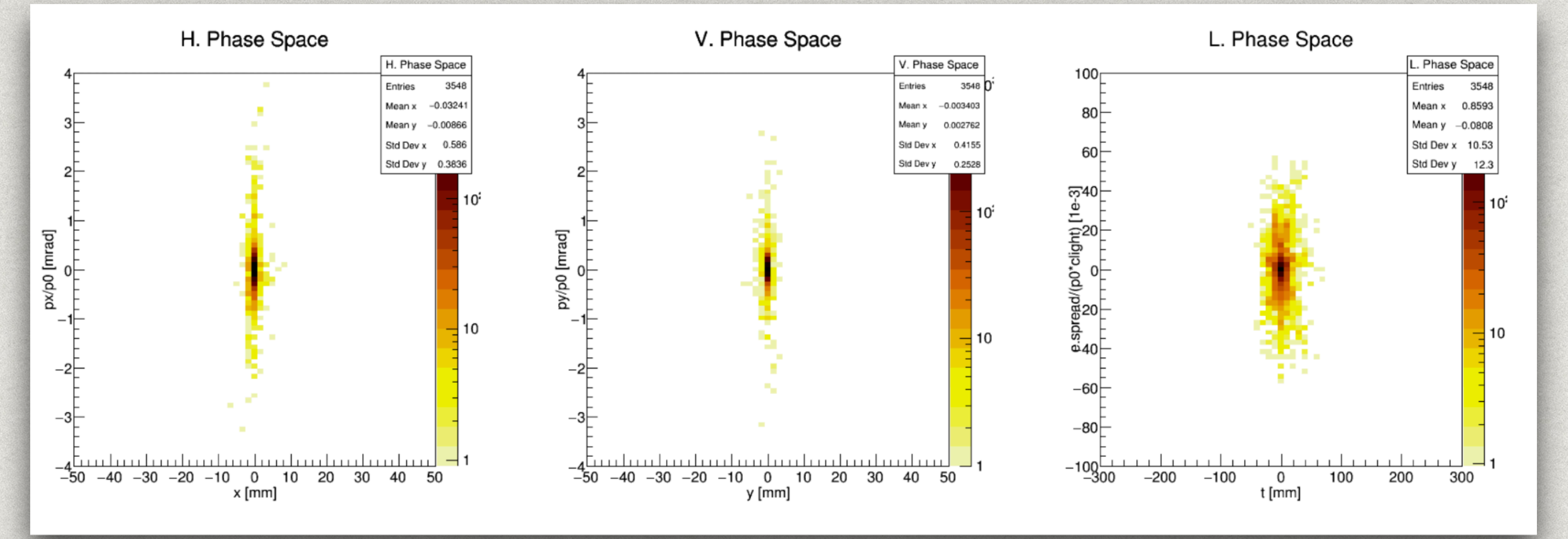
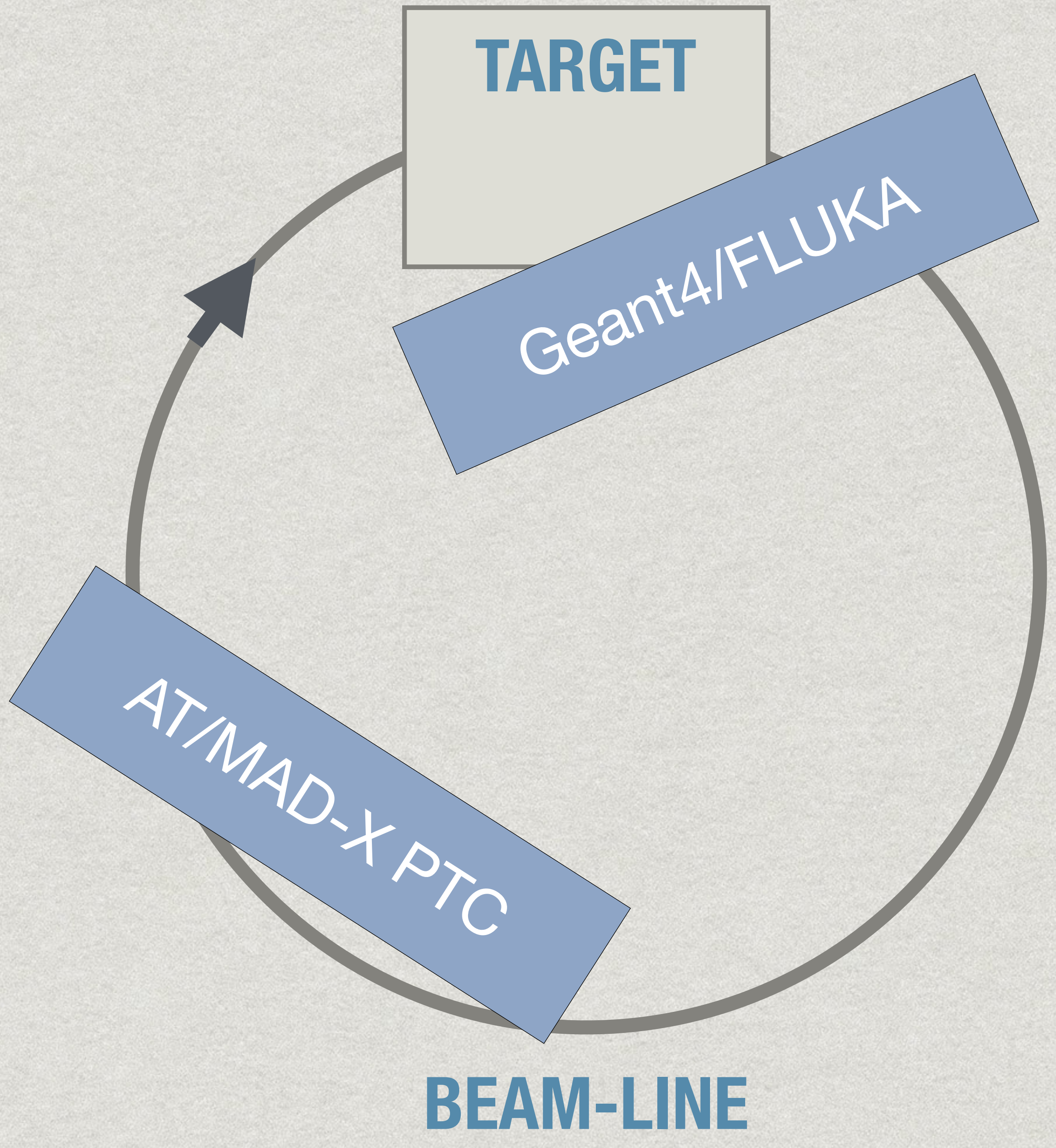




turn n 35

MAD-X PTC & GEANT4 6-D tracking simulation of e+ beam with **3 mm Be** target along

Multi-turn simulations



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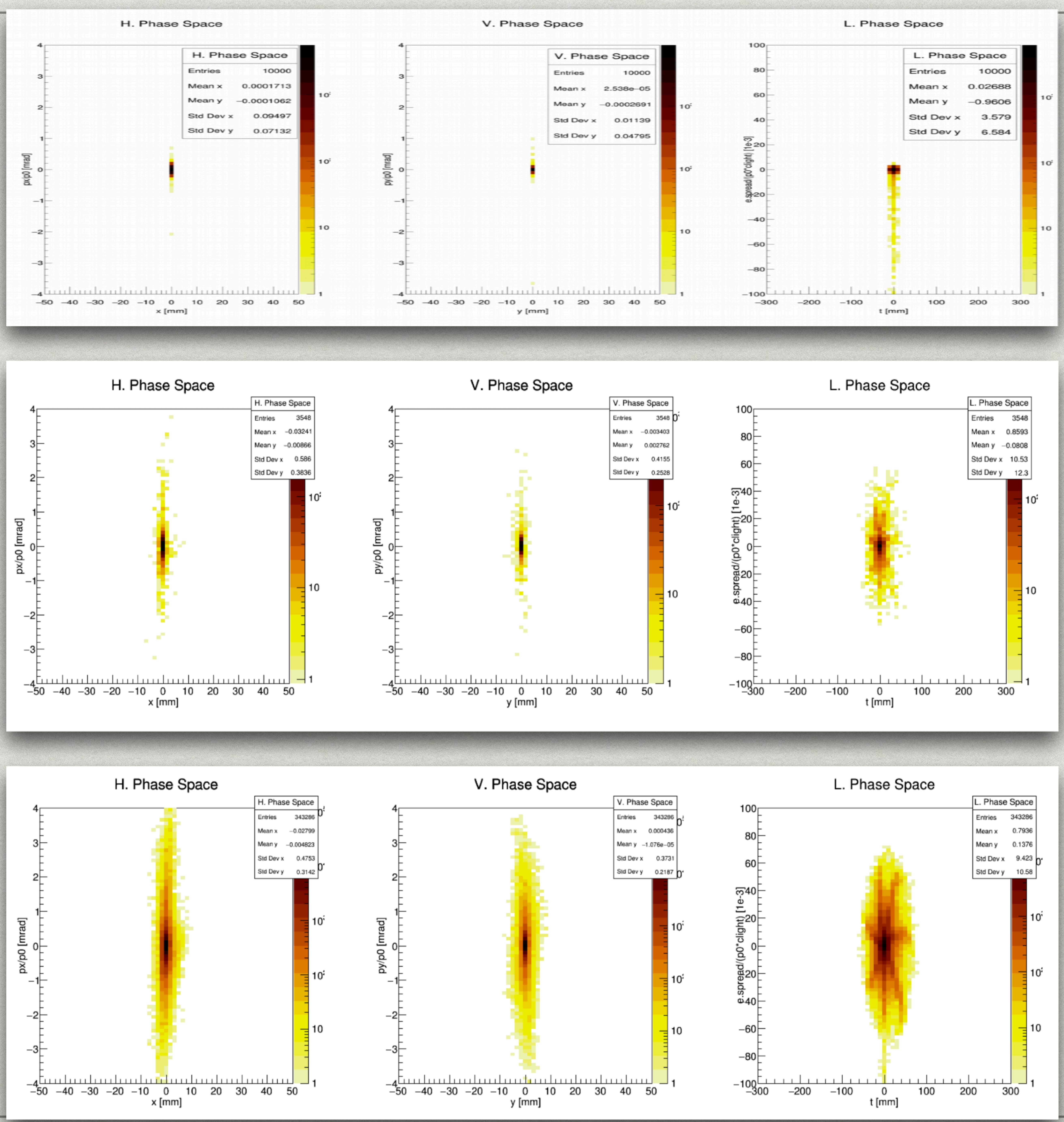
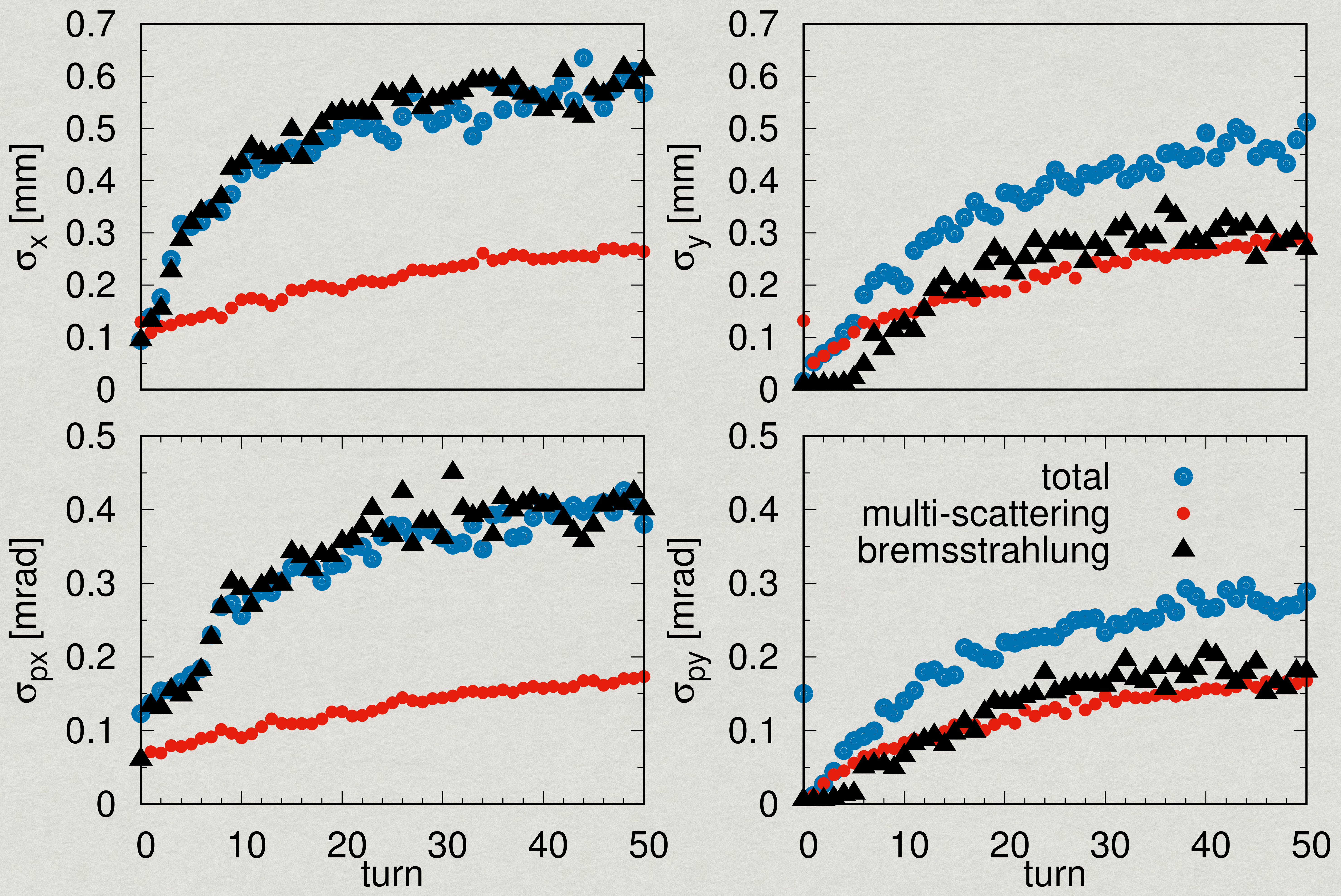


after target, before turn

turn n 35

35 turns superimposed

Evolution of e^+ beam size and divergence



bremsstrahlung and multiple scattering artificially separated by considering alternatively effects in longitudinal (dominated by **bremsstrahlung**) and transverse (dominated by **multiple scattering**) phase space due to target; in **blue** the combination of both effects (realistic target)

- Some bremsstrahlung contribution due to residual dispersion at target
- Multiple scattering contribution in line with expectation (nD= number of damping turns): $\sigma_{MS} = \frac{1}{2}\sqrt{n_D}\,\sigma'_{MS}\,\beta$
- One pass contribution due to the target: $\sigma'_{MS} = 25\ \mu\text{rad}$

Muons' emittance

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

ε(e+) = e^+ emittance
ε(MS) = multiple scattering contribution
ε(rad) = energy loss (brem.) contribution
ε(prod) = muon production contribution
ε(AR) = accumulator ring contribution

would like all contributions of same size. knobs:

β_x, β_y @target & target material
β_x, β_y, D_x @ target & target material
E(e+) & target thickness
AR optics & target

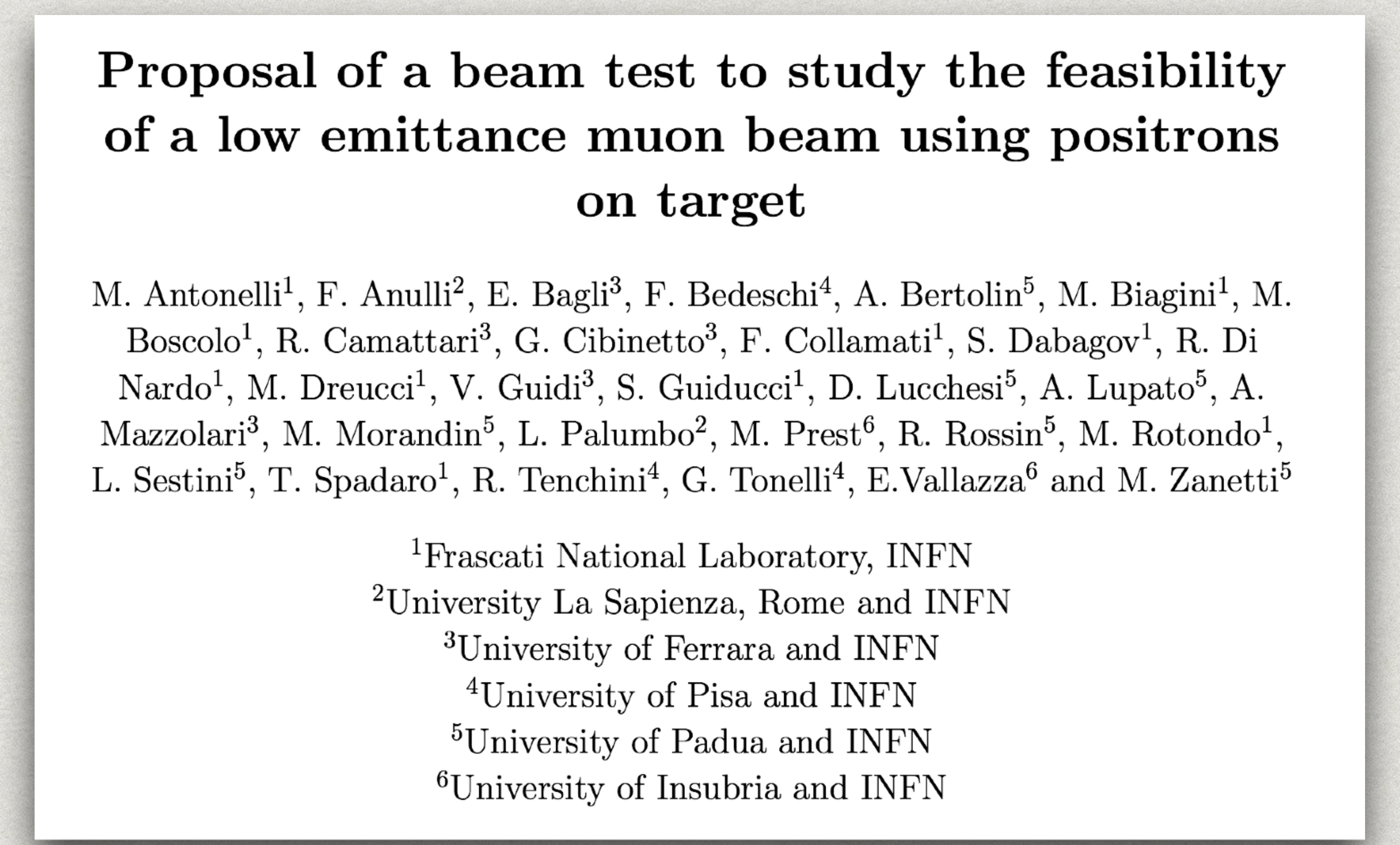
Now: **ε(μ)** dominated by **ε(MS)** ⊕ **ε(rad)** ➜ lower D & βs @ target with beam spot at the limit of target survival

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

Test Beam

- Foreseen for the last week of July 2017, **@CERN North Area** (H4) *founded by* ***CSN1-INFN***
- Use tertiary **45GeV e⁺** beam, up to $5\text{x}10^6$ /spill with amorphous targets, to:
  ➜ measure *muon production* rate, cross section..
  ➜ measure muons kinematic properties: emittance…

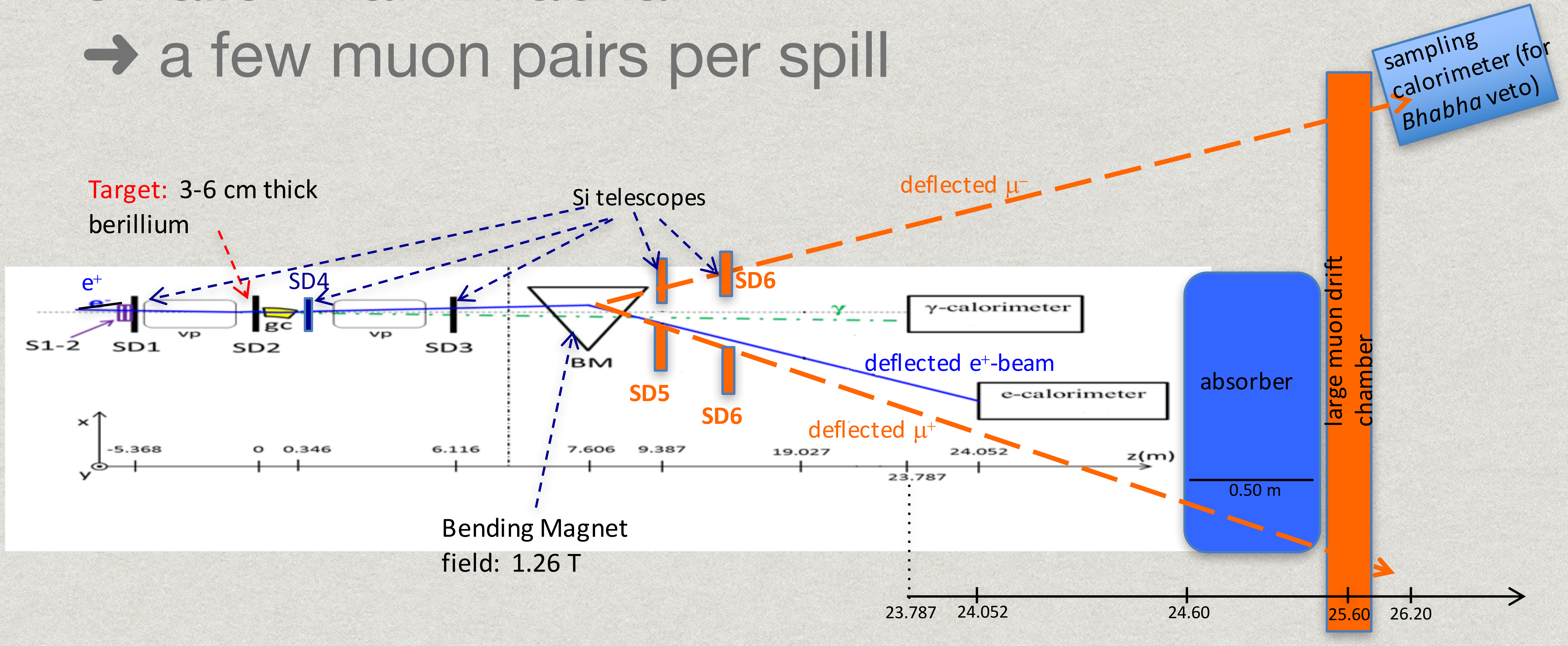


Proposal of a beam test to study the feasibility of a low emittance muon beam using positrons on target

M. Antonelli[1], F. Anulli[2], E. Bagli[3], F. Bedeschi[4], A. Bertolin[5], M. Biagini[1], M. Boscolo[1], R. Camattari[3], G. Cibinetto[3], F. Collamati[1], S. Dabagov[1], R. Di Nardo[1], M. Dreucci[1], V. Guidi[3], S. Guiducci[1], D. Lucchesi[5], A. Lupato[5], A. Mazzolari[3], M. Morandin[5], L. Palumbo[2], M. Prest[6], R. Rossin[5], M. Rotondo[1], L. Sestini[5], T. Spadaro[1], R. Tenchini[4], G. Tonelli[4], E.Vallazza[6] and M. Zanetti[5]

[1]Frascati National Laboratory, INFN
[2]University La Sapienza, Rome and INFN
[3]University of Ferrara and INFN
[4]University of Pisa and INFN
[5]University of Padua and INFN
[6]University of Insubria and INFN

- Expected $\sigma_{ee\mu\mu} < 1\ \mu b$, 5 order of magnitudes smaller than Bhabha!
  ➜ a few muon pairs per spill



Summary

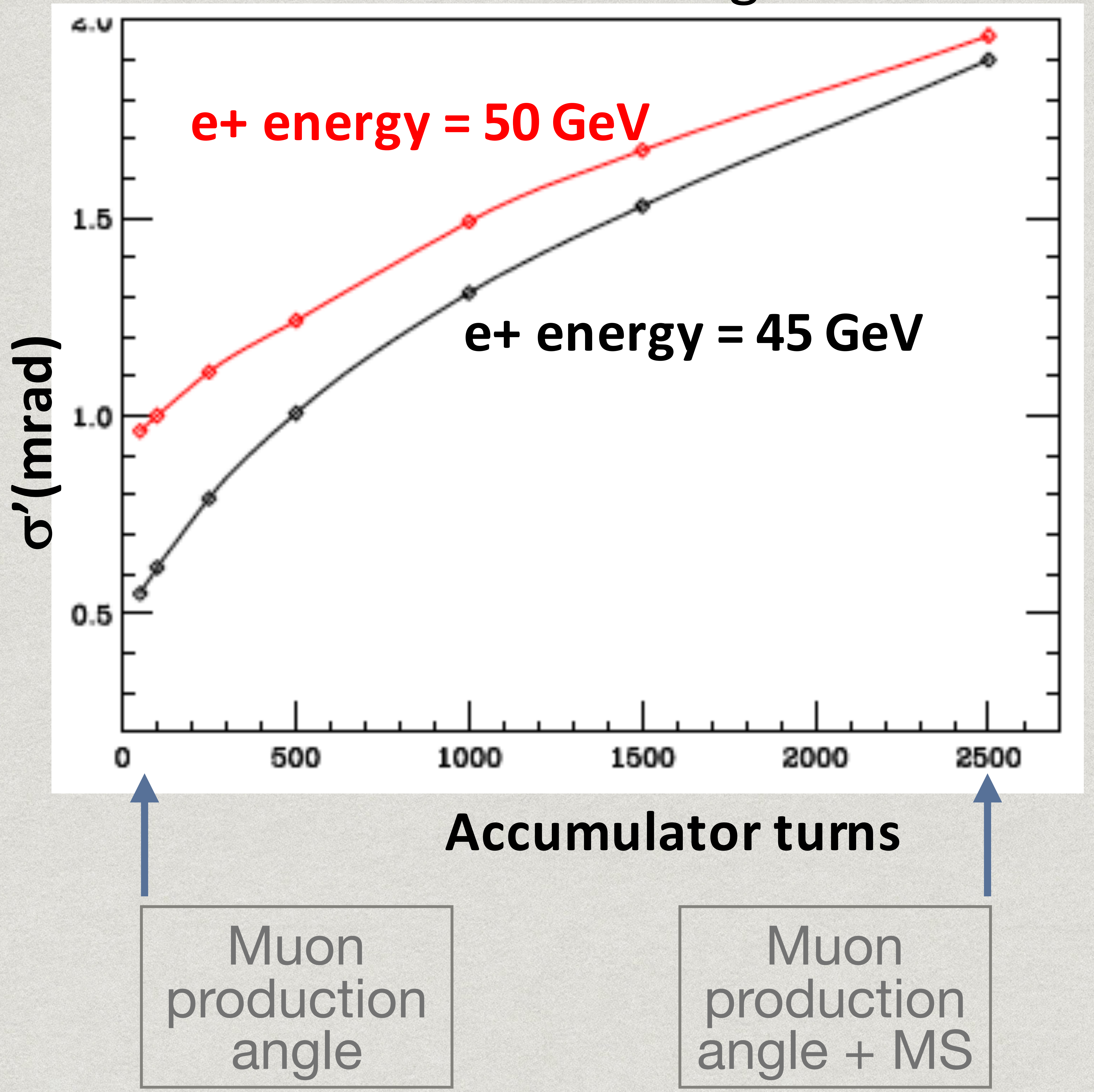
- A novel approach to muon production can allow the design of a **muon collider**:
  - **Low emittance (➜ no needing for cooling)**
  - **Low rate (➜ target load)**
- First design of low emittance e^+ ring with preliminary studies of beam dynamics
- Optimisation requires other issues to be preliminary addressed
  - Target material & characteristics
  - e^+ accelerator complex
  - Muons accumulator rings design
- **Preliminary studies are promising, we will continue to optimise all the parameters, lattices, targets, etc. in order to assess the ultimate performances of the machine**

Backup

Muon Accumulator Rings considerations

- Isochronous optics with high momentum acceptance (δ≳10%)
- Multiple pass through the target leads to emittance increase due to Multiple Scattering:
  - *Beam divergence*:
    - A **factor 3** (2) **increase** in beam divergence is expected at **45** (50)**GeV**
  - *Beam size*:
    - Depends on optics, need low-β to suppress size increase
- This contributions can be strongly reduced with crystals in channeling

3 mm Be Target



Target considerations

- The goal is to have a beam size as small as possible, but:
- Constraints for **power removal** (200kW) and **temperature rise**
  ➜ move target (for free with liquid jet)
  ➜ e+ bump every 1 munch muon accumulation
- Possibilities:
  - 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=1.7x1011 p/bunch, up to 288 bunches in one shot

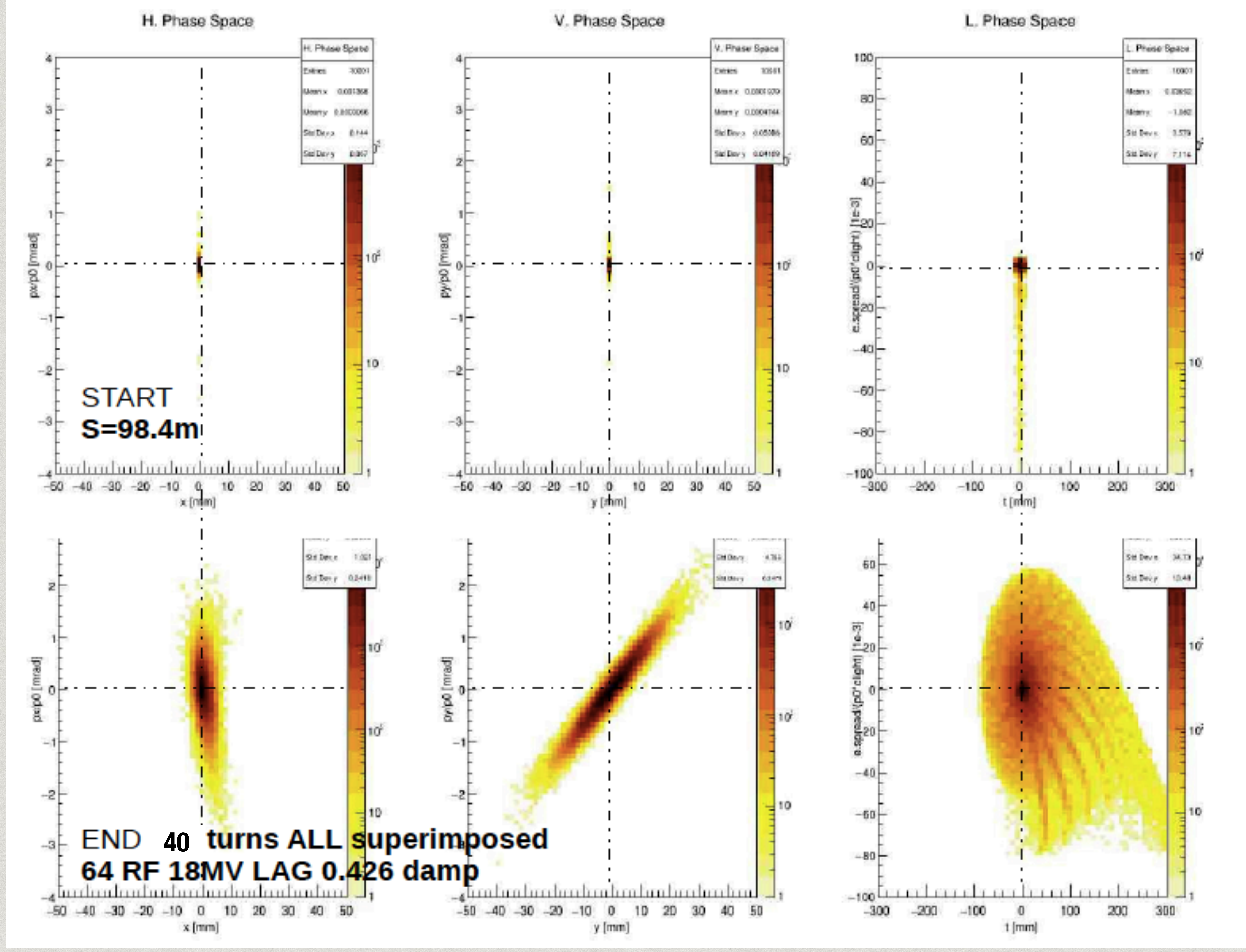
[Kavin Ammigan 6th High Power Targetry Workshop]

  - Liquid target: better wrt power removal
    - Li, difficult to handle! lighter materials (H, He)
      - Lli jets examples from neutron production (Tokamak divertor). 200kW beam power removal seems feasible, minimum beam size to be understood

Multi-turn simulations

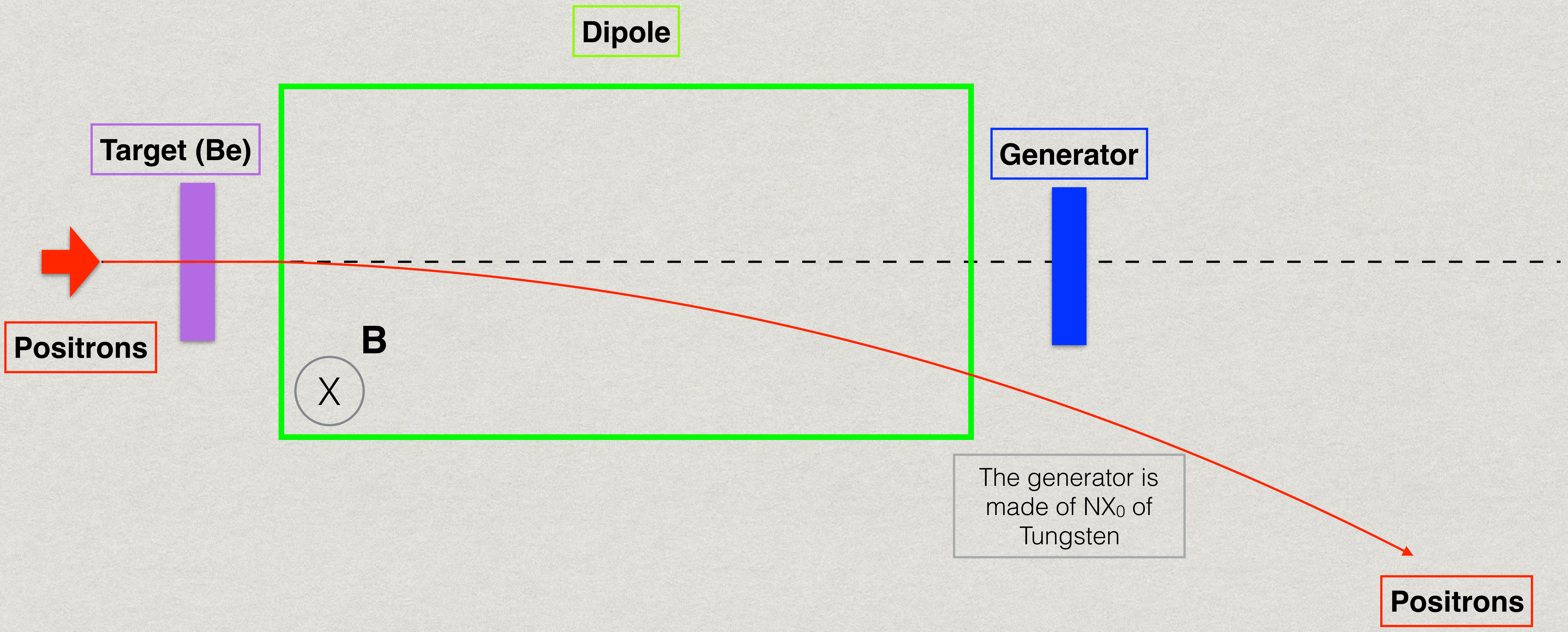
before target, starting point

after 40 turns



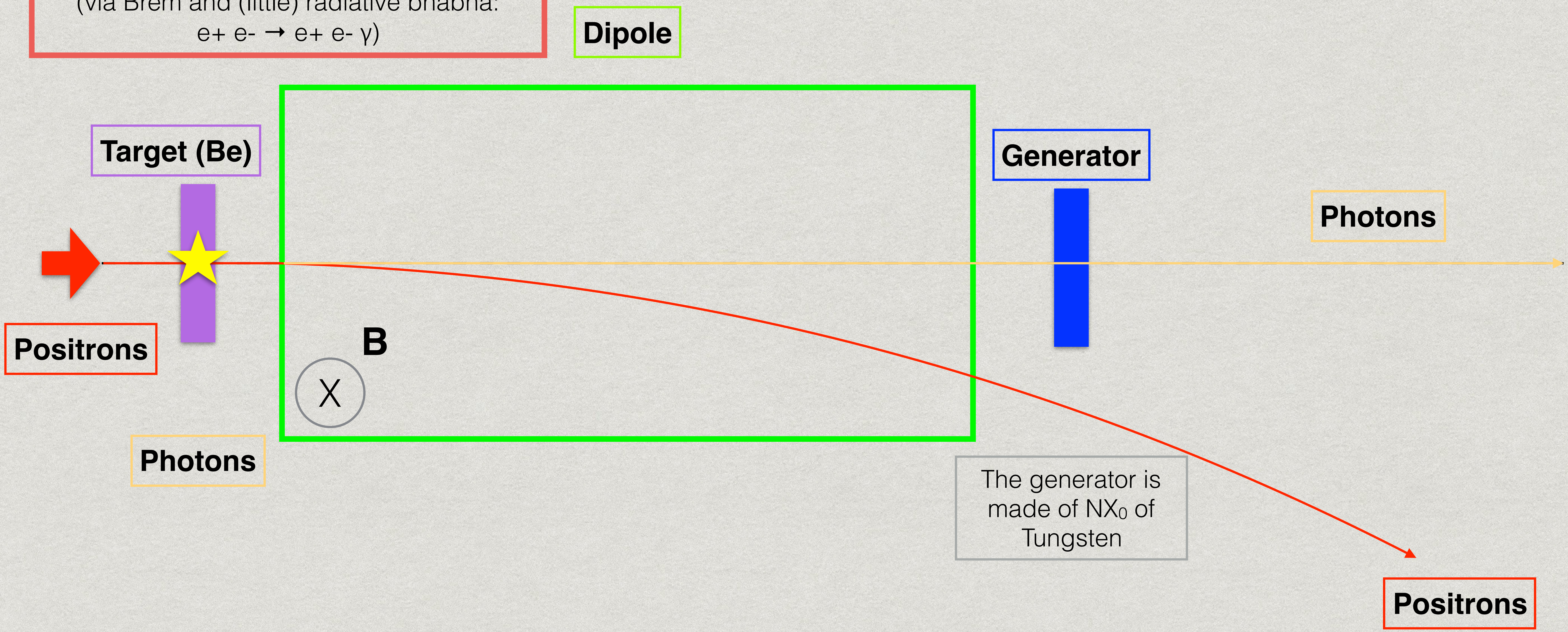
MAD-X PTC & GEANT4 6-D tracking simulation of e+ beam with **3 mm Be** target along the ring (not at IR center in this example)

Preliminary considerations on e^+ source



Preliminary considerations on e^+ source

Positrons in the target create photons at very small angles wrt to the beam
(via Brem and (little) radiative bhabha: $e+ \; e- \rightarrow e+ \; e- \; \gamma$)



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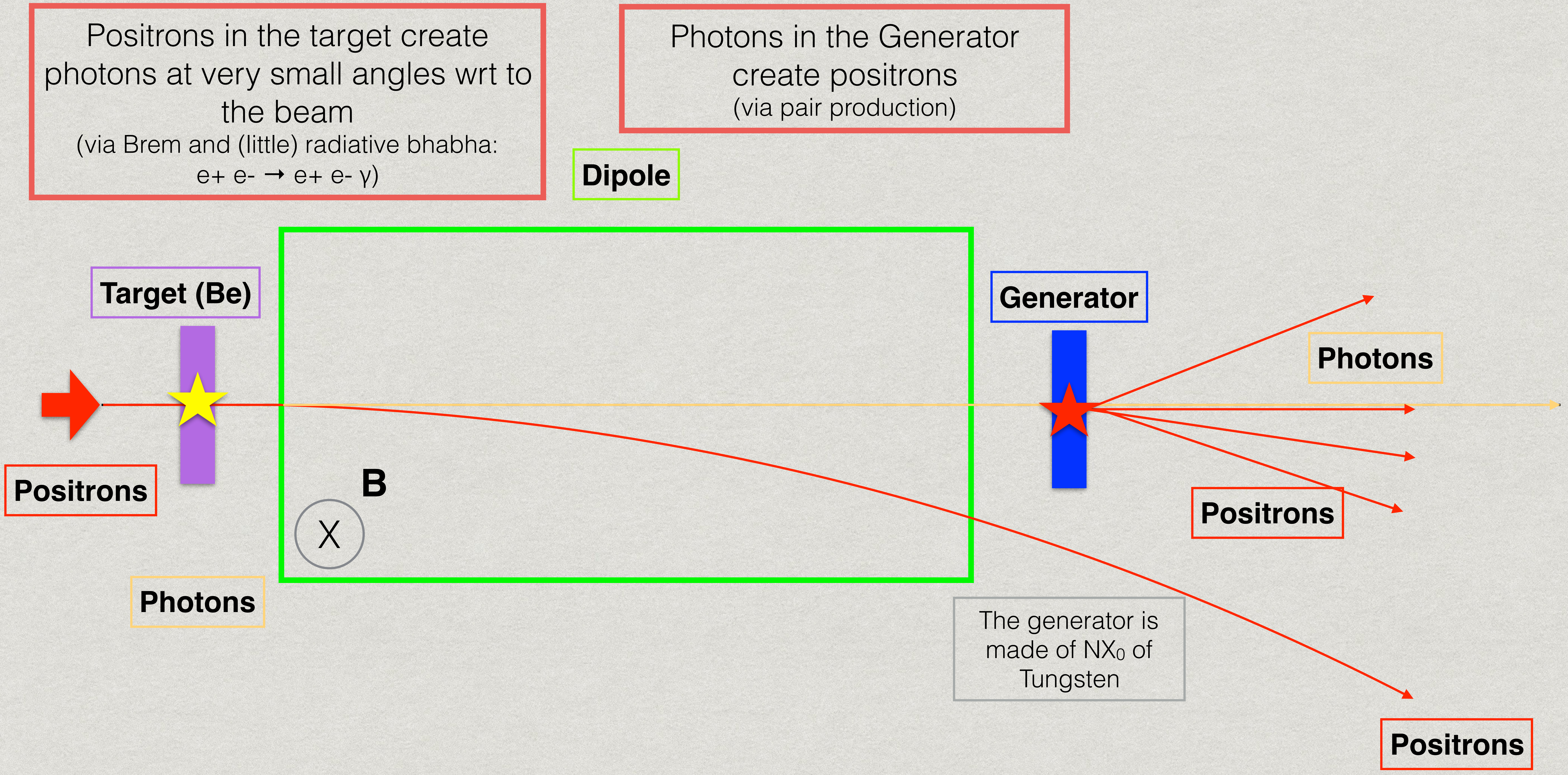

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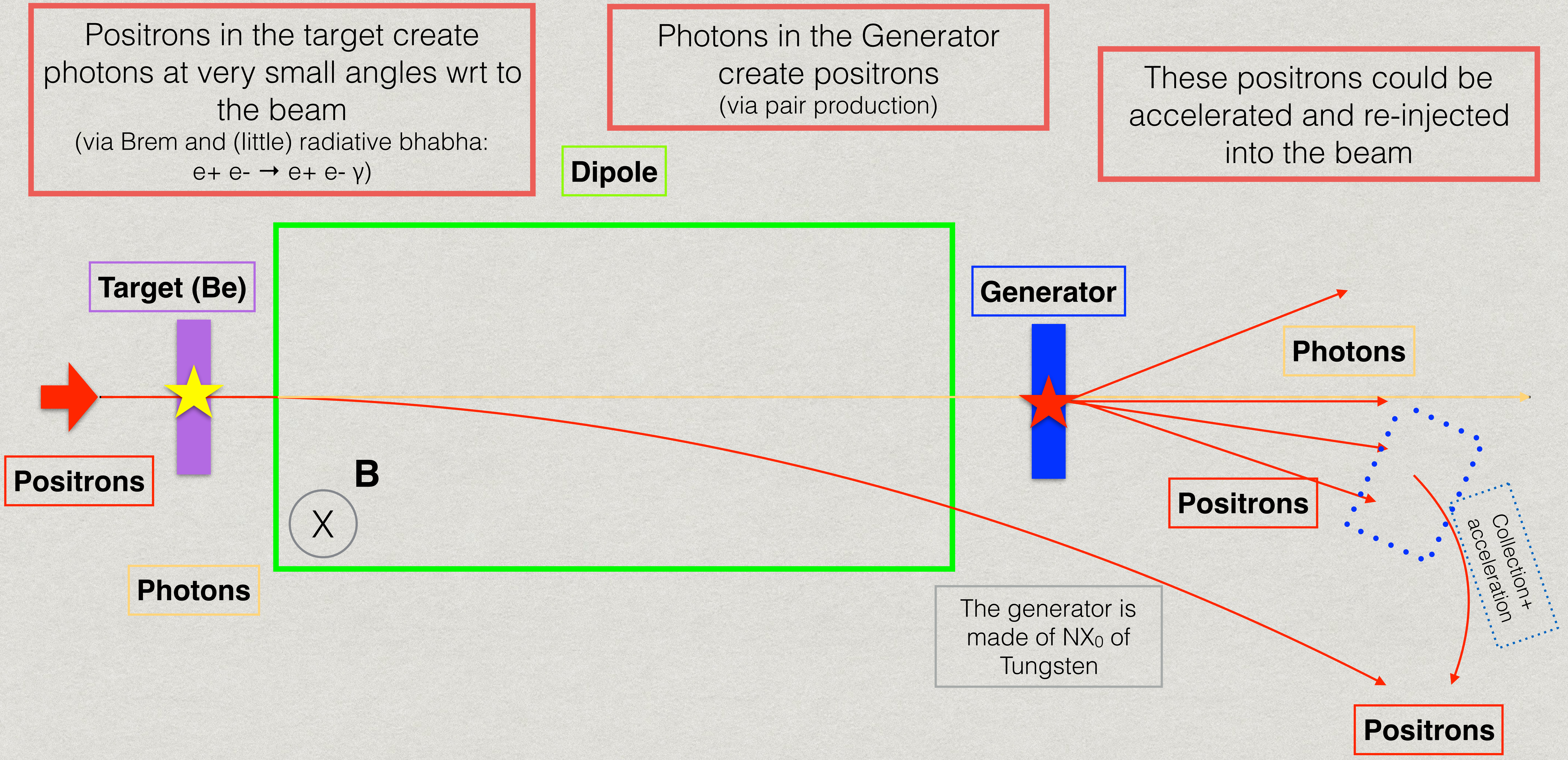
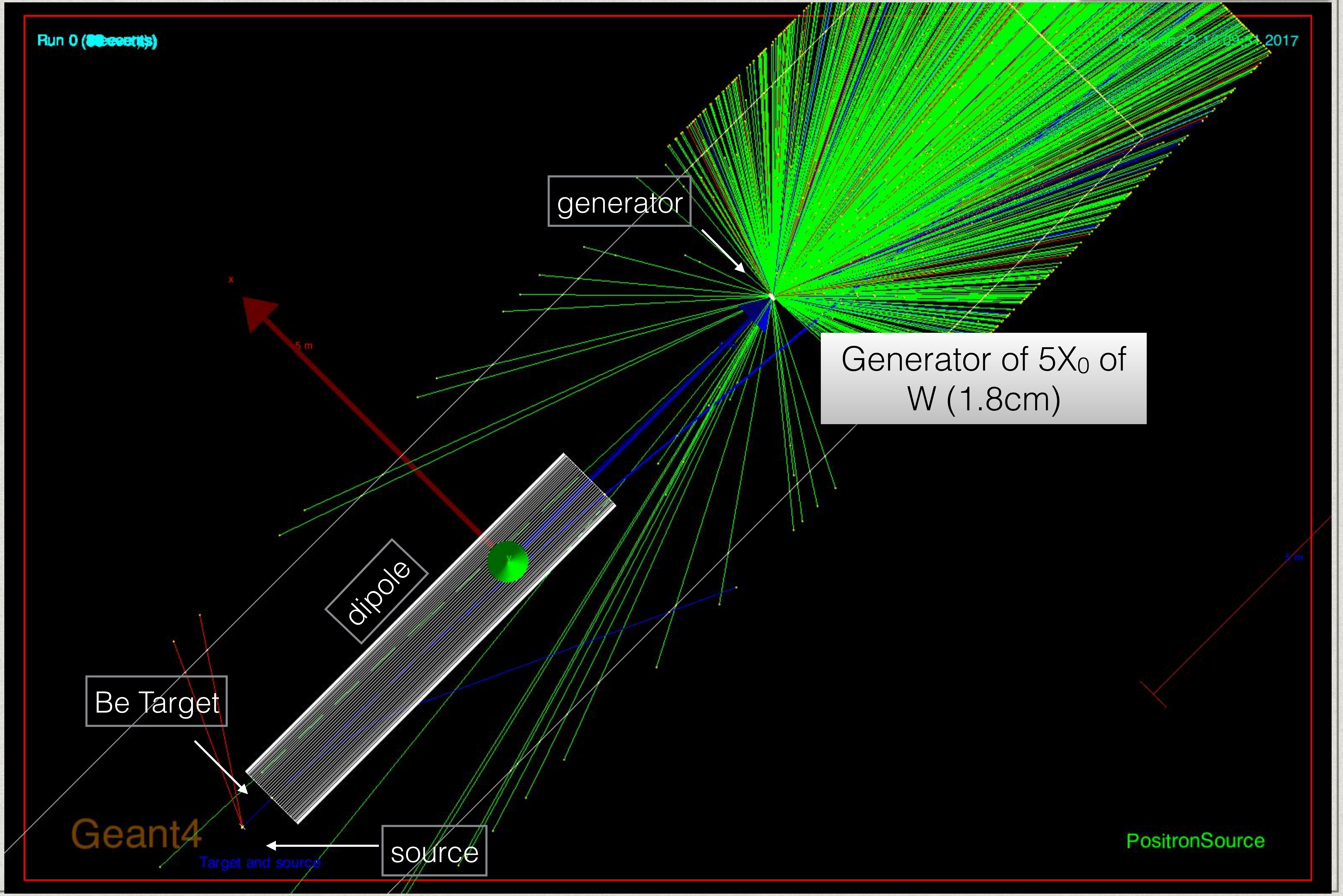


Preliminary considerations on e^+ source

Geant4 simulation

Total flux



Preliminary considerations on e^+ source

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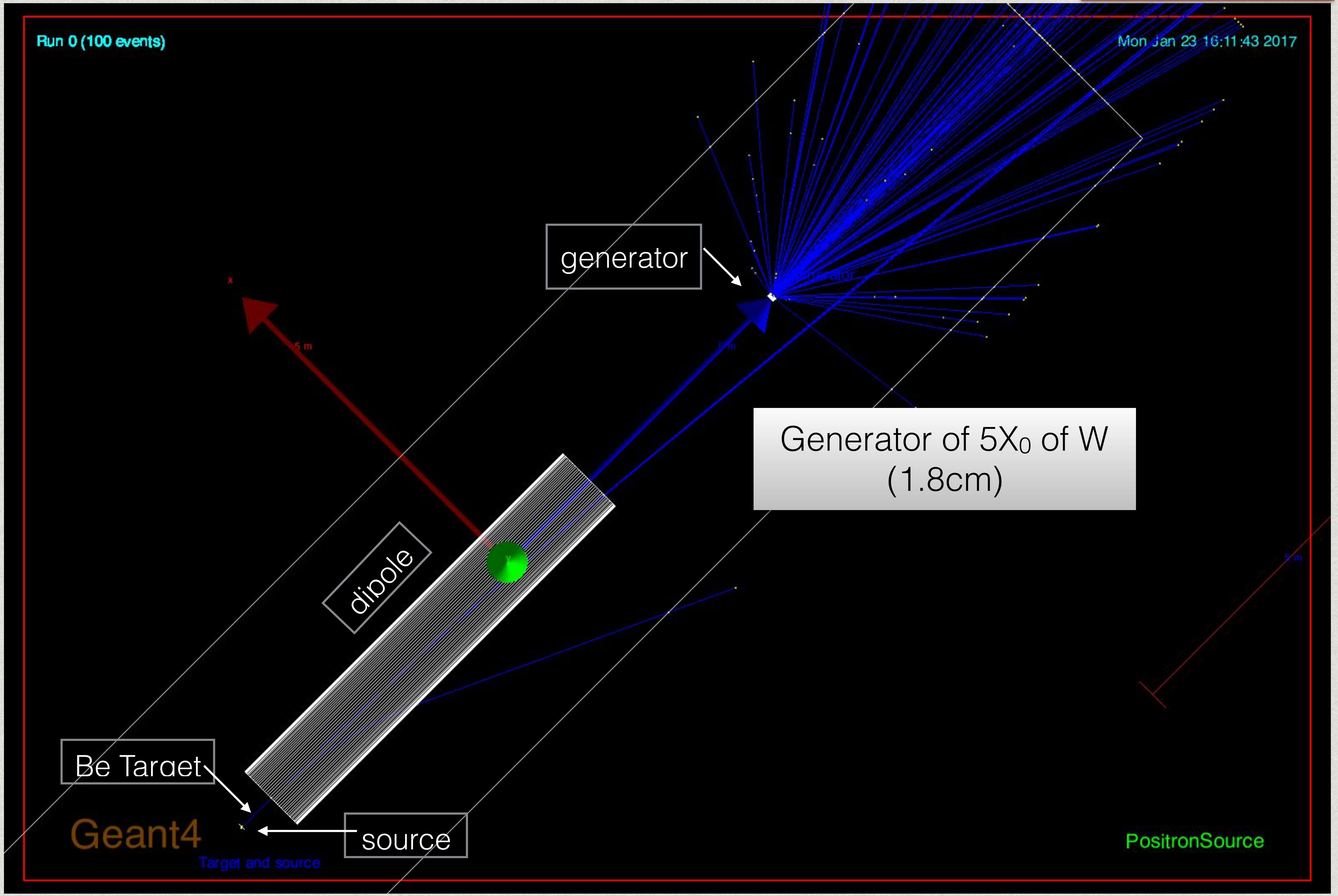

Geant4 simulation

Electron flux