
Istituto Nazionale di Fisica Nucleare

# LOW EMITTANCE MUON BEAMS FROM POSITRONS

Francesco Collamati (INFN-Roma)
29.09.2017

# Outline

- Introduction: Why a muon collider
- Proposal for a novel technique for direct muon production
  - Target choice & accelerator scheme
  - Multi-turn simulations
  - Muons' emittance
- Experimental tests
- 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 $2.2\mu s$!
    - 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 ($P_\mu$~100MeV/c)
    - **Cooling** needed!
      ➜ tradeoff monochromaticity/luminosity

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Novel Approach

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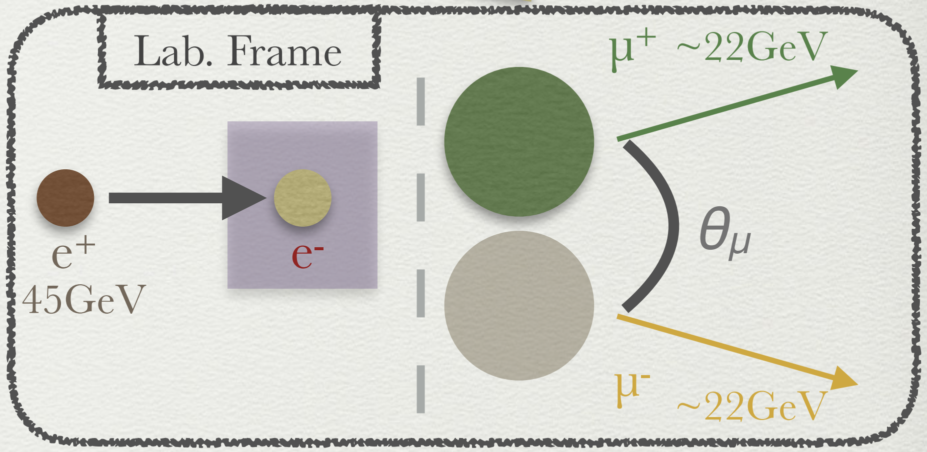

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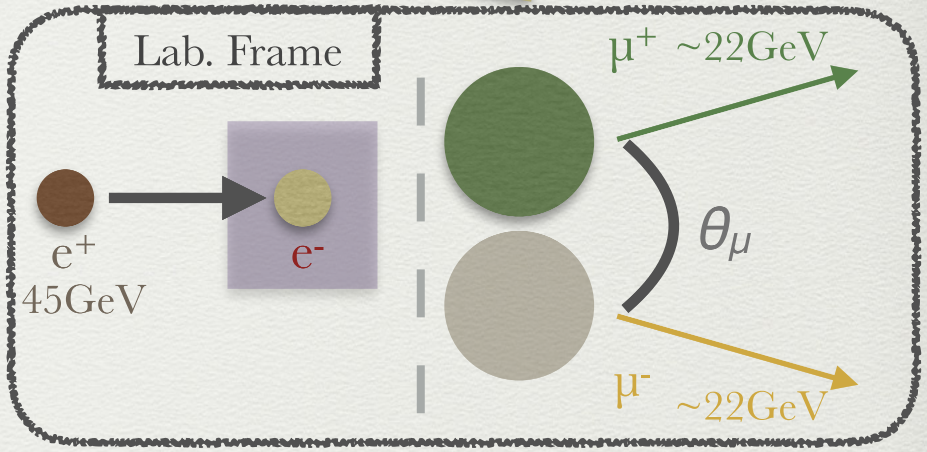

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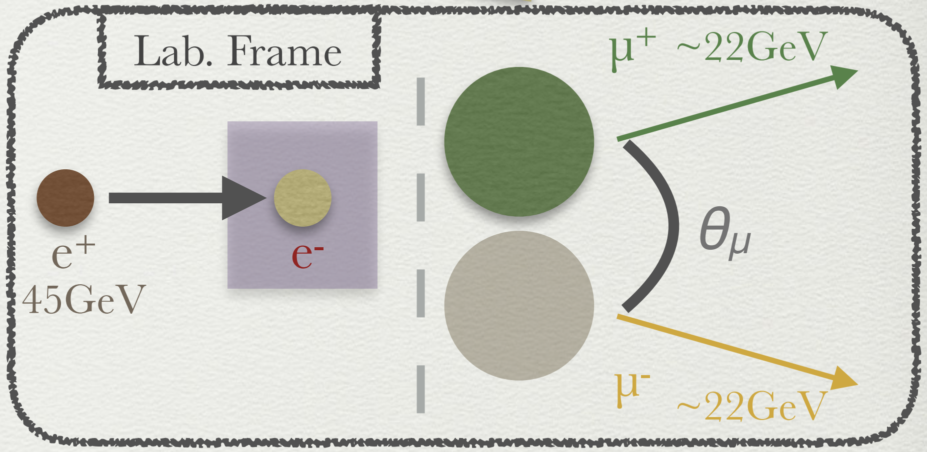


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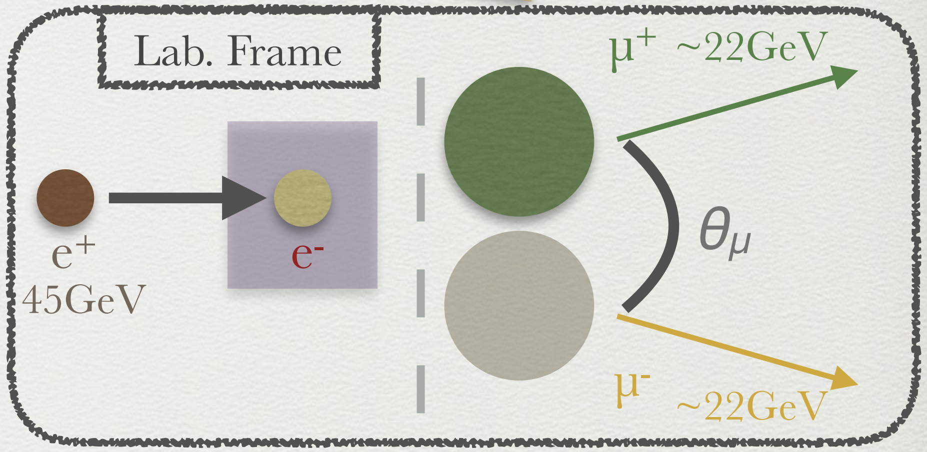

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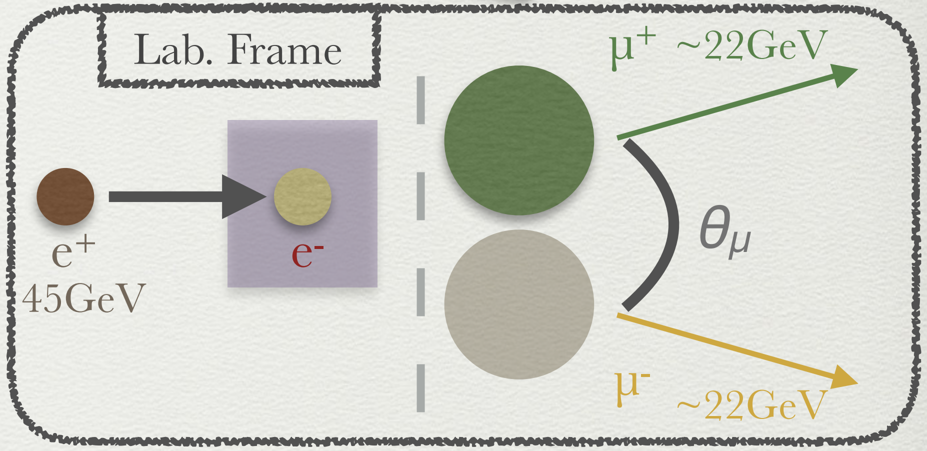


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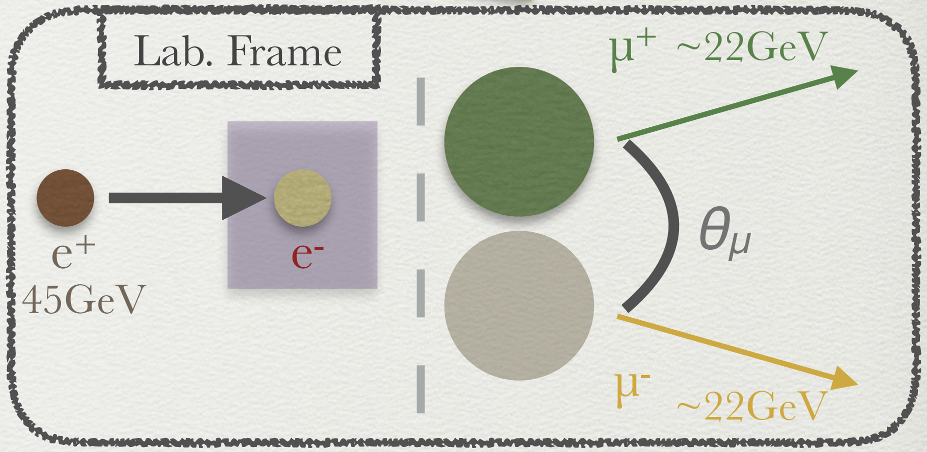


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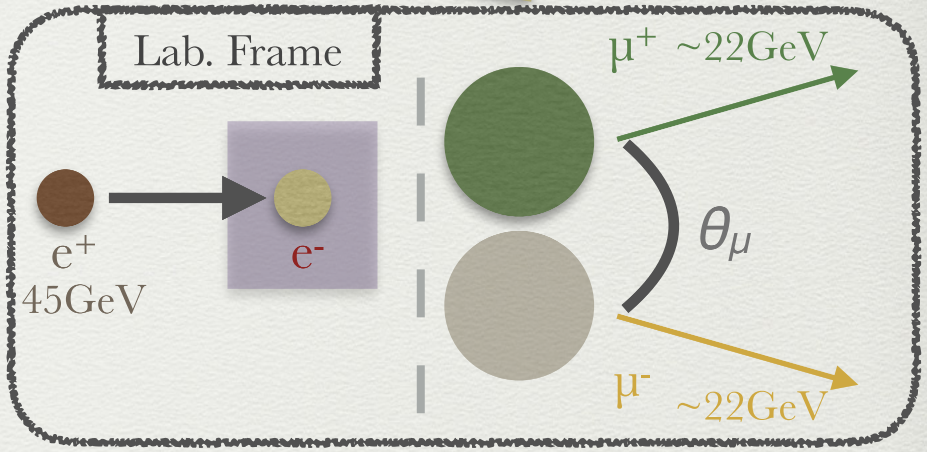


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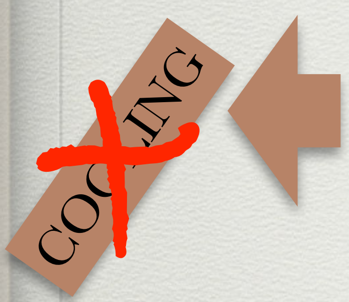


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  - **Disadvantages:**
    - **Rate**: much smaller cross section wrt protons (μb vs mb)

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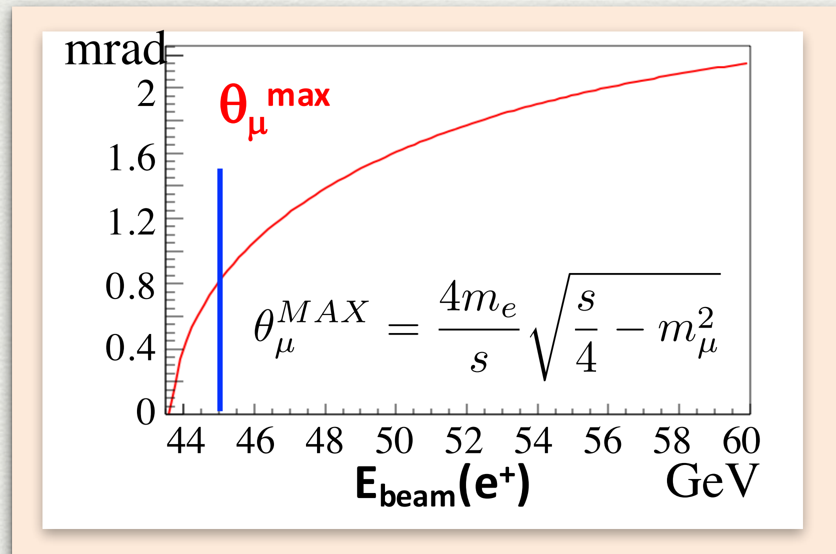
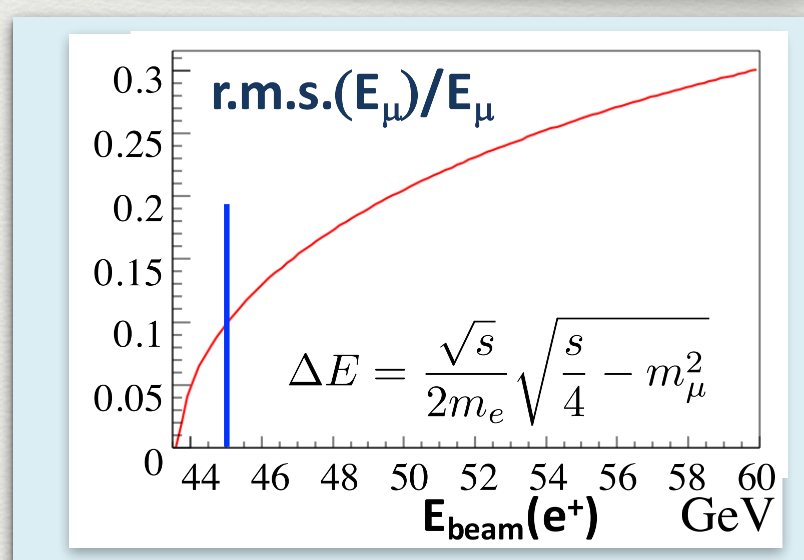
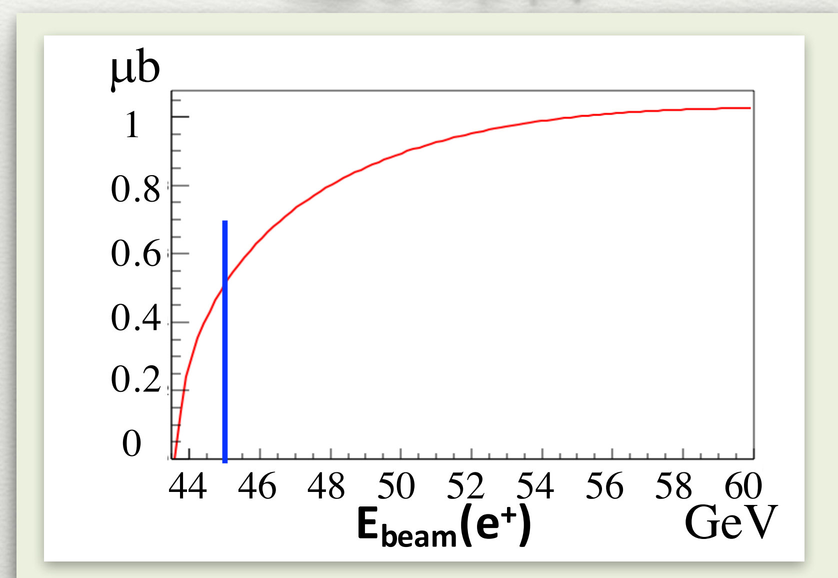



$\sigma(e^+e^- \rightarrow \mu^+\mu^-)$



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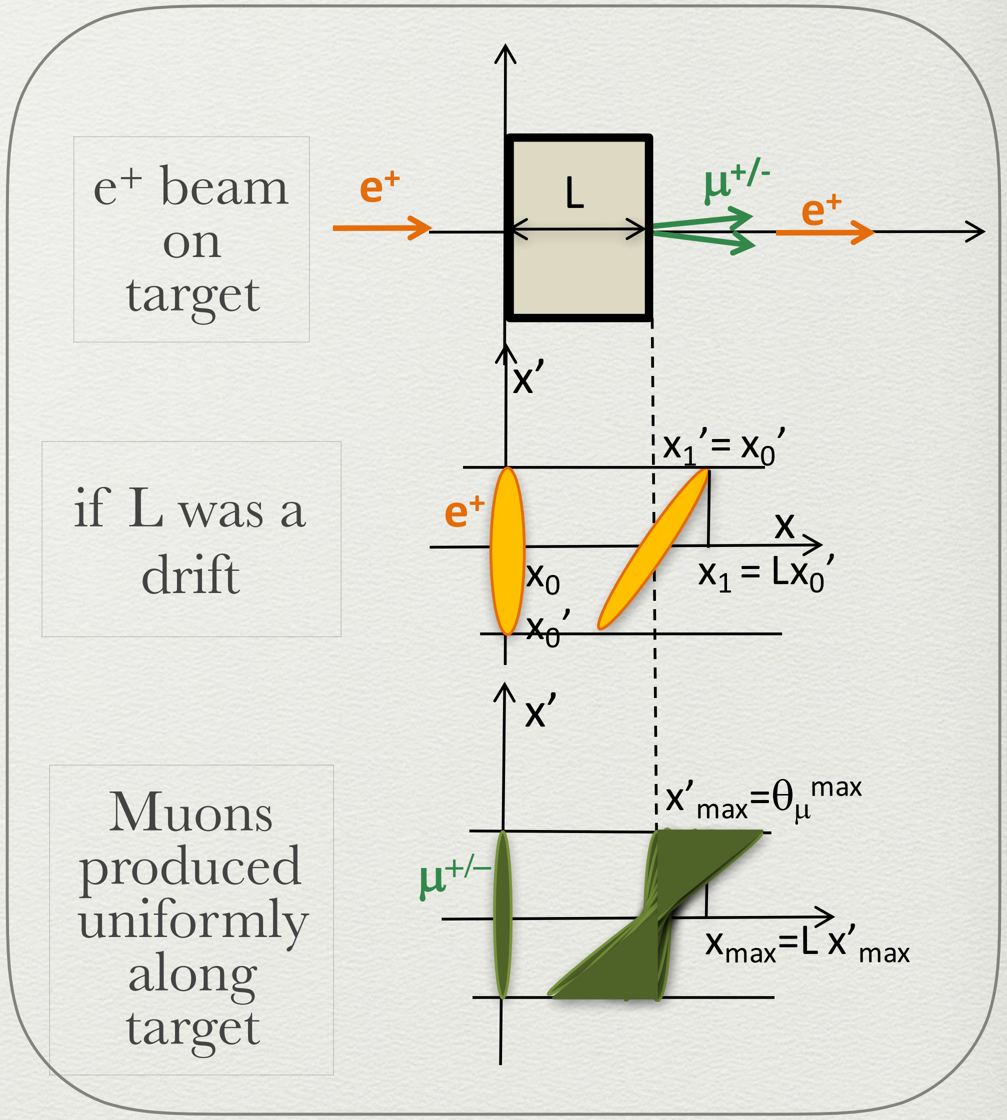

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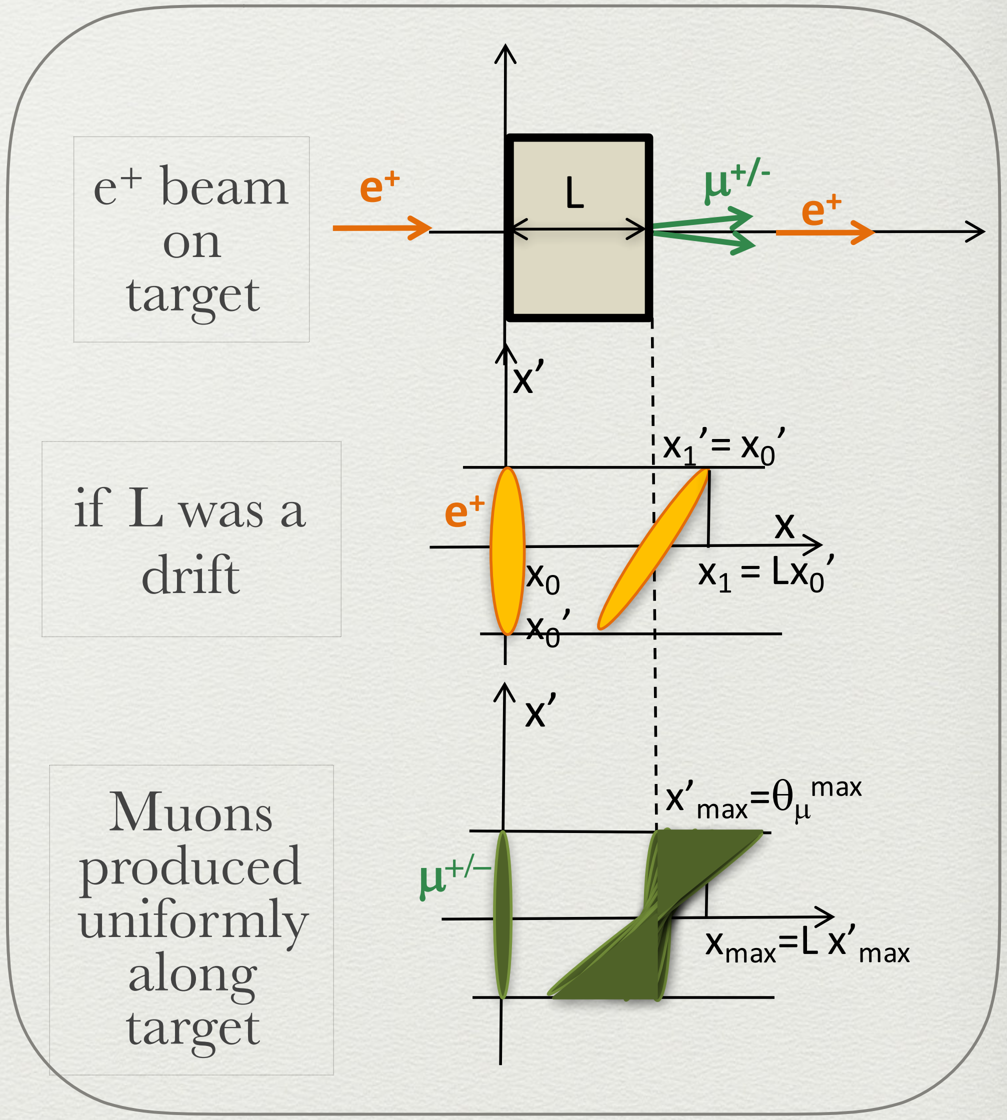

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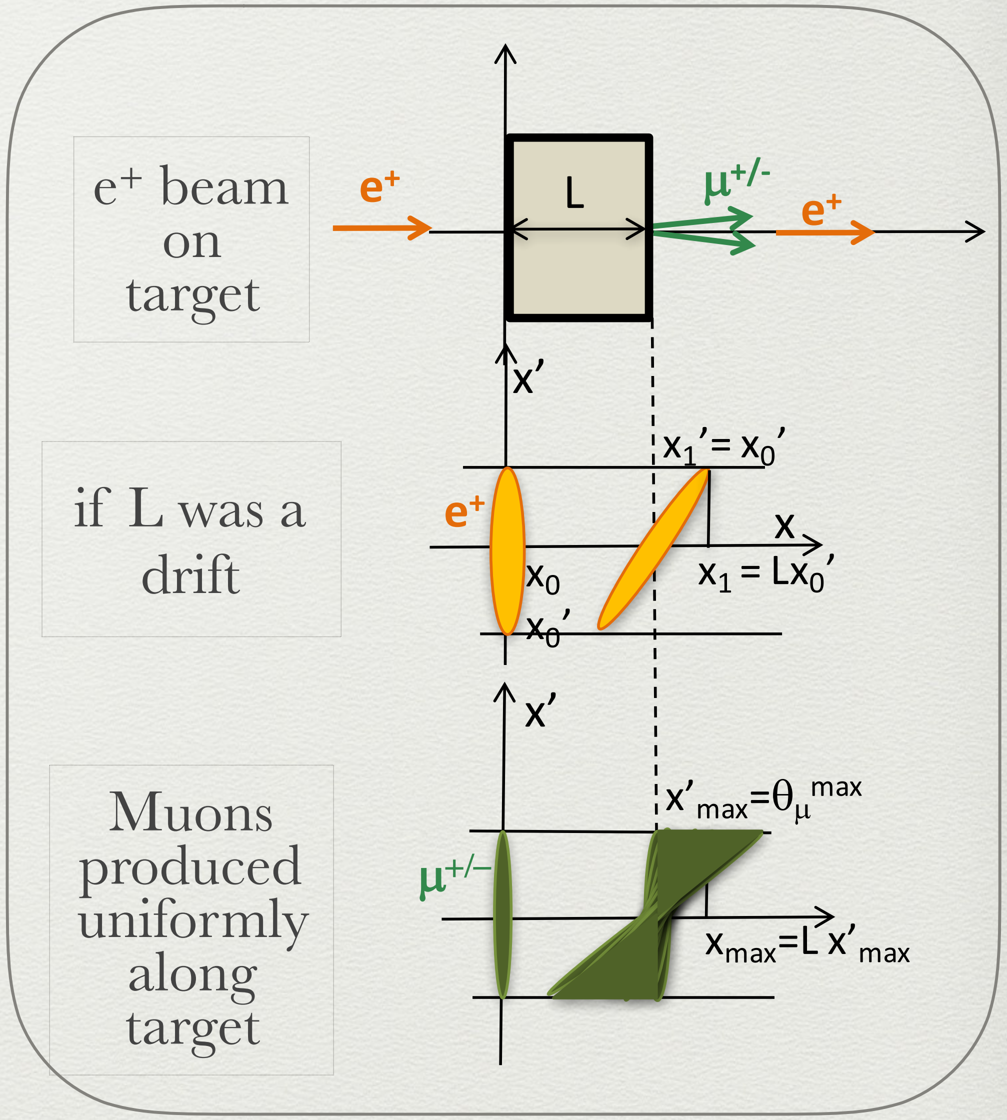

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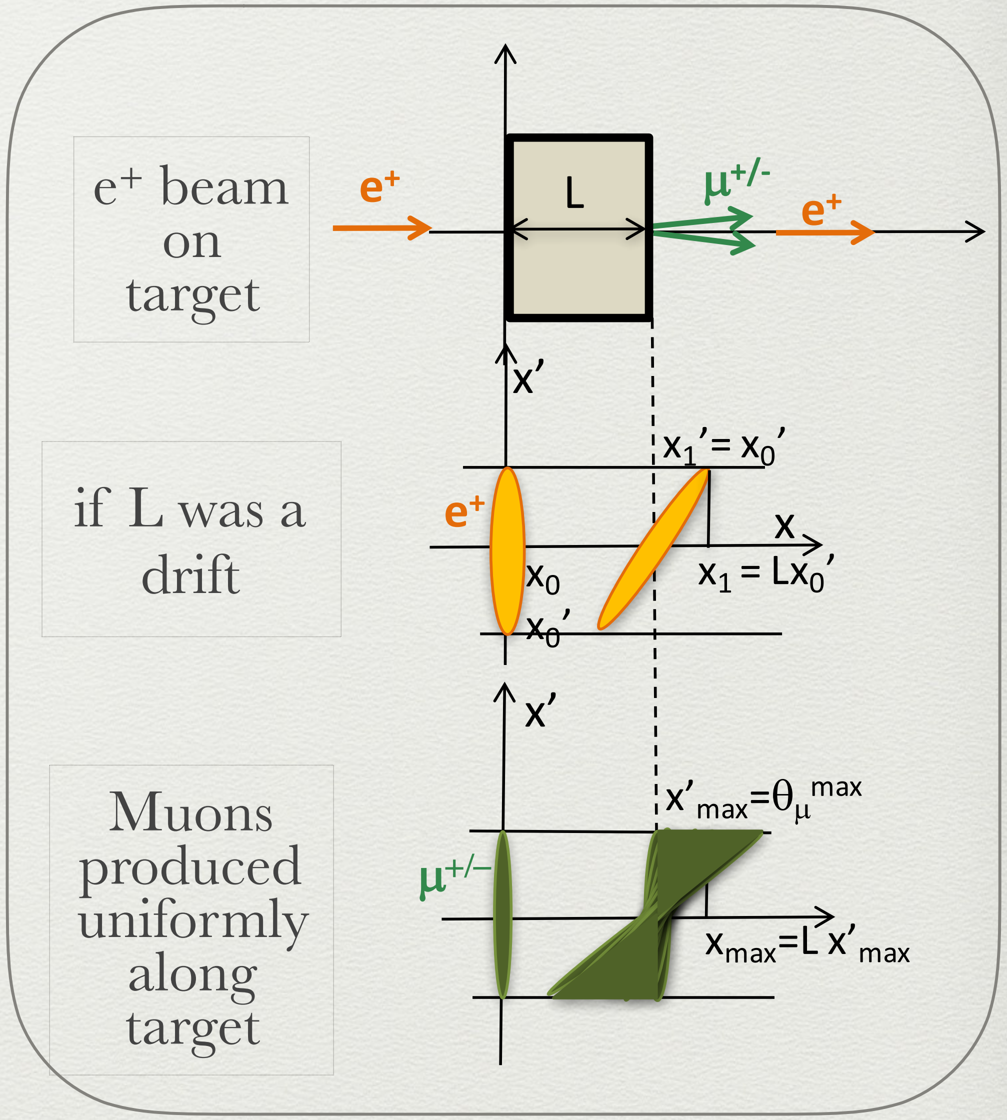

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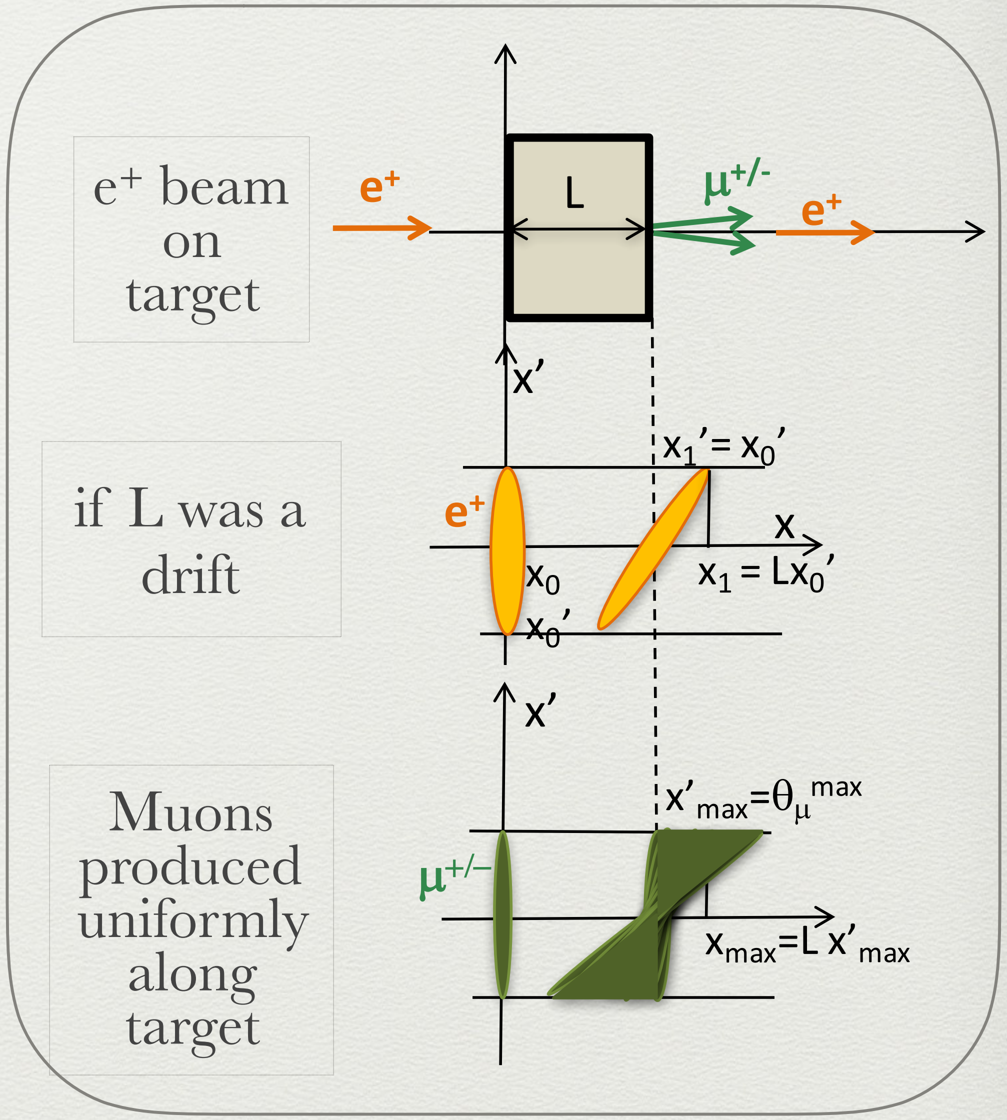

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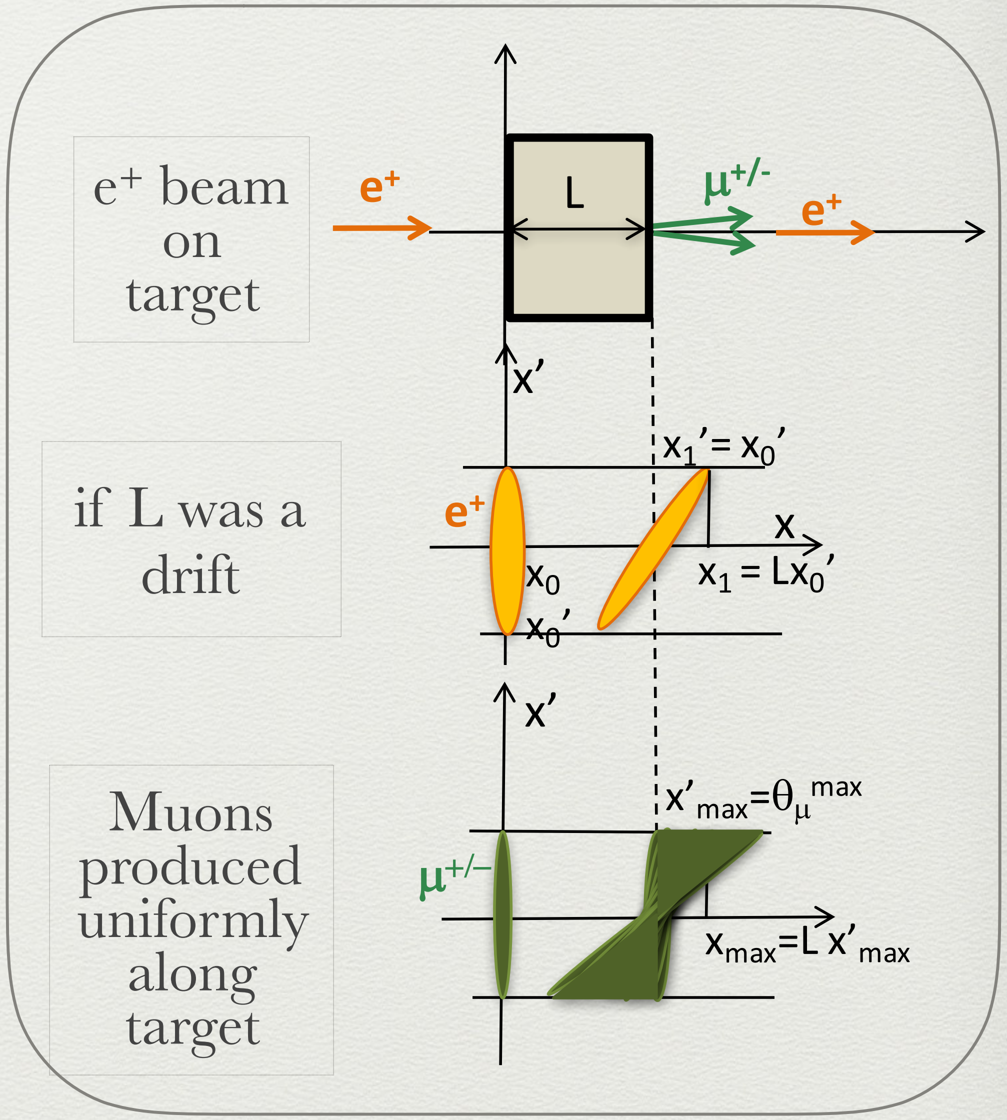

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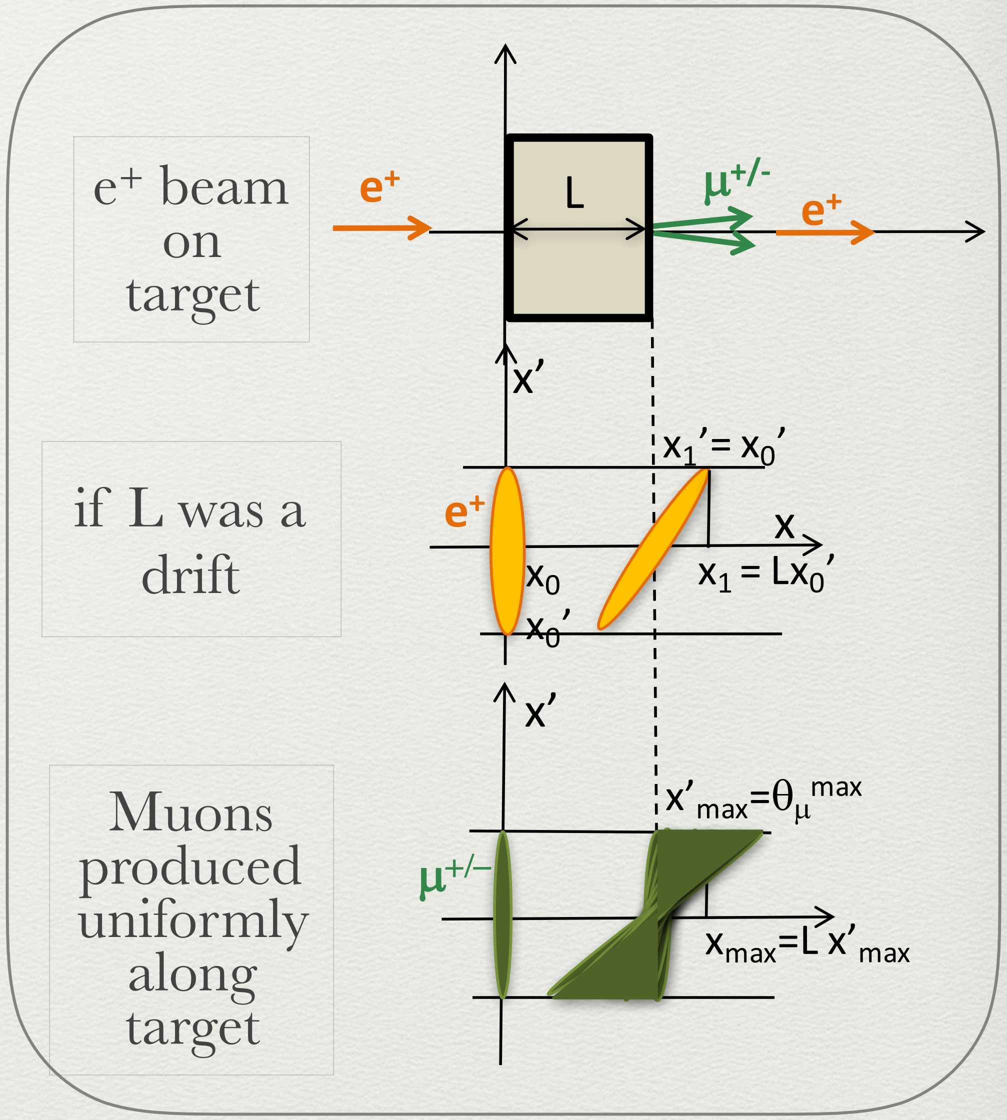

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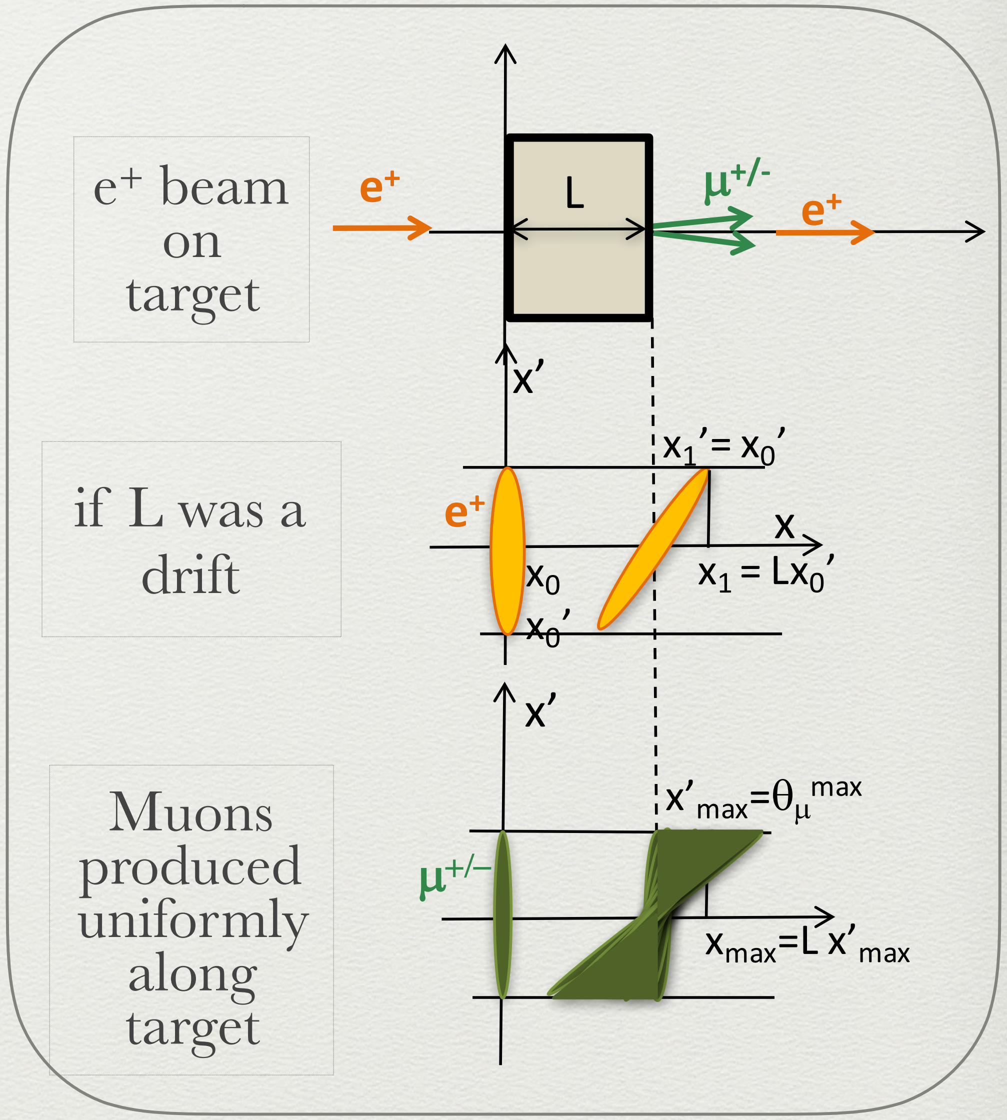
  - Possible **tradeoff**: not too heavy materials (Be, C, Li) and not too thin target



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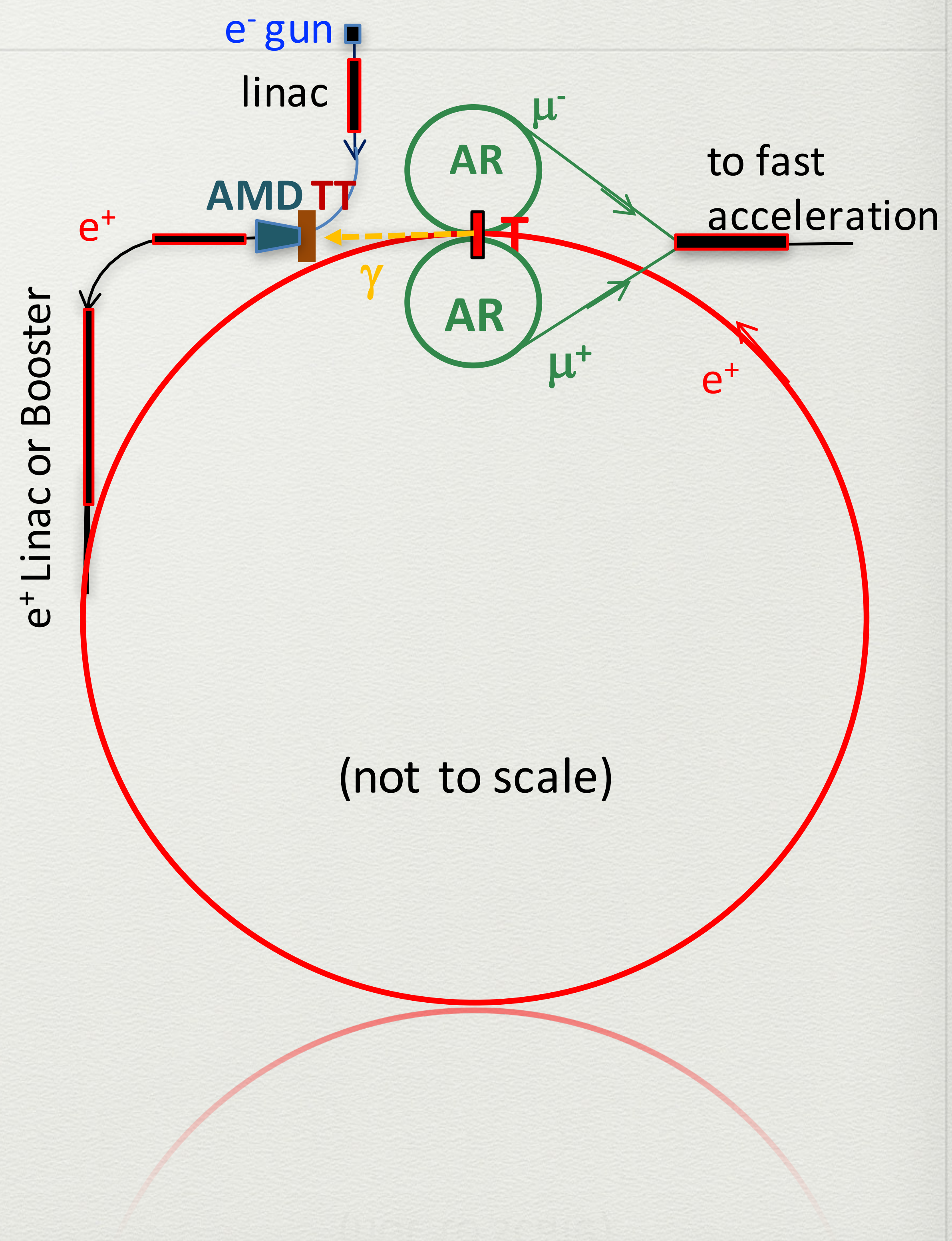

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- **<u>From $e^+$ source to ring:</u>**
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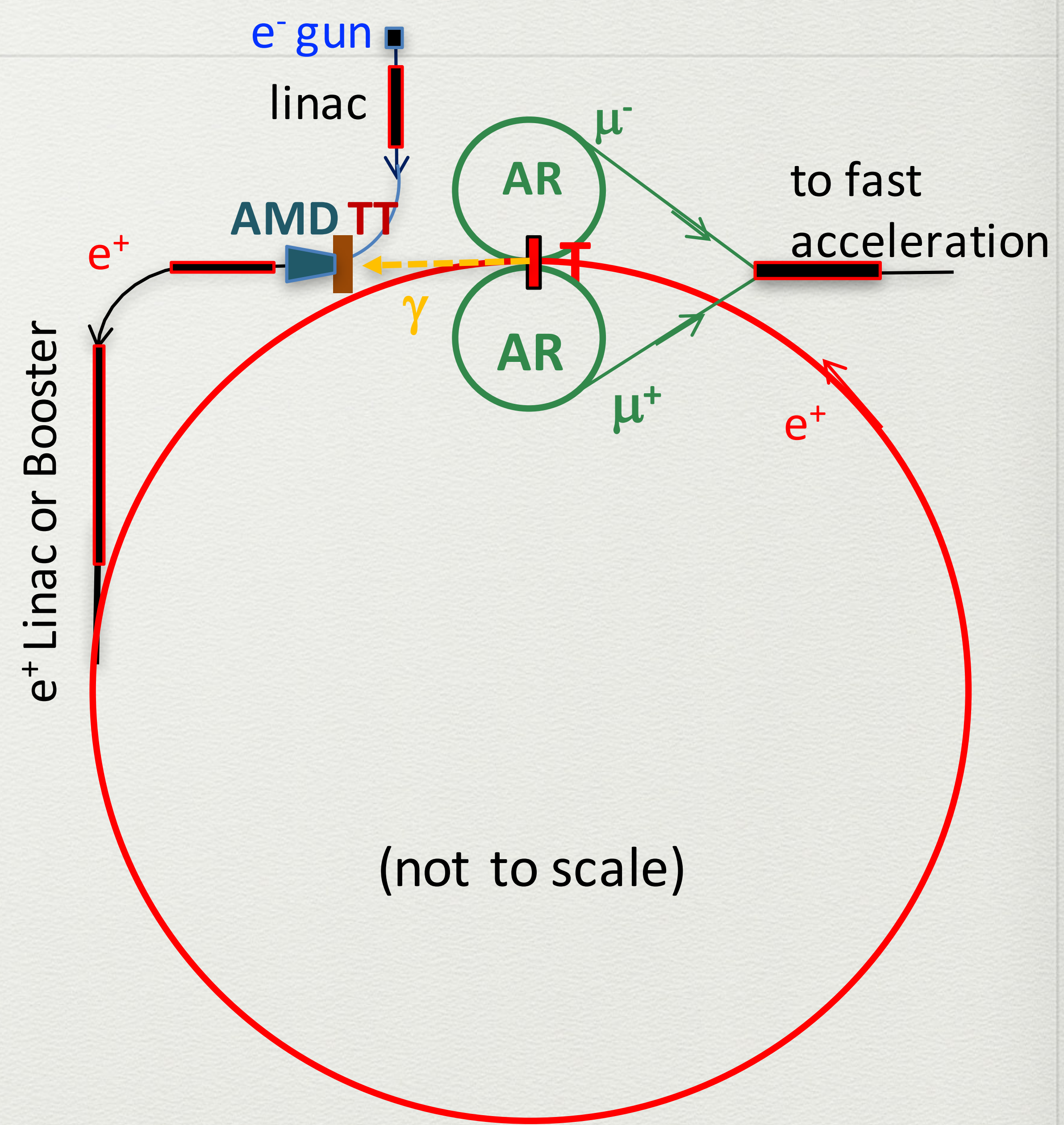
  - Acceleration (linac / booster) , injection



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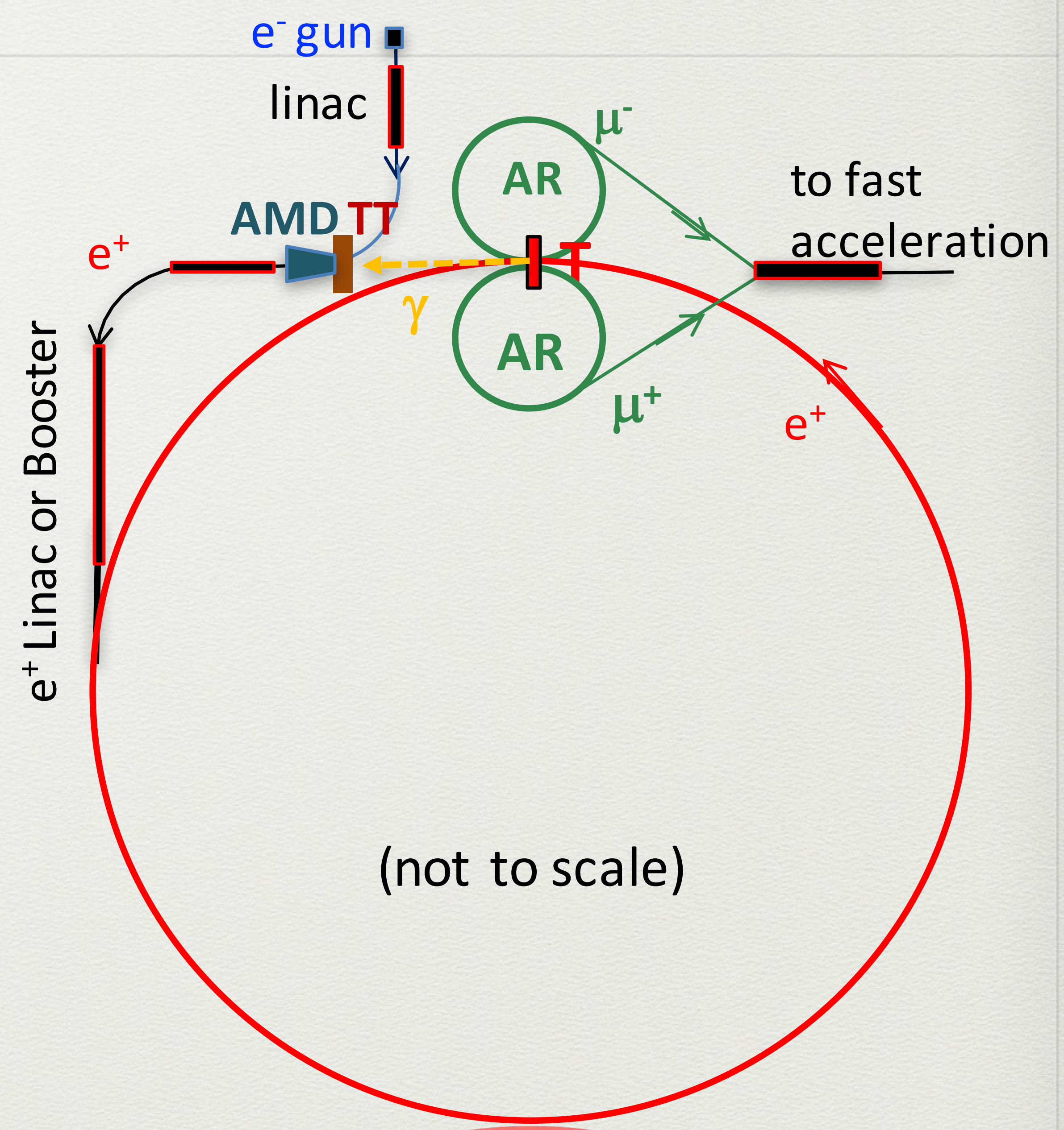

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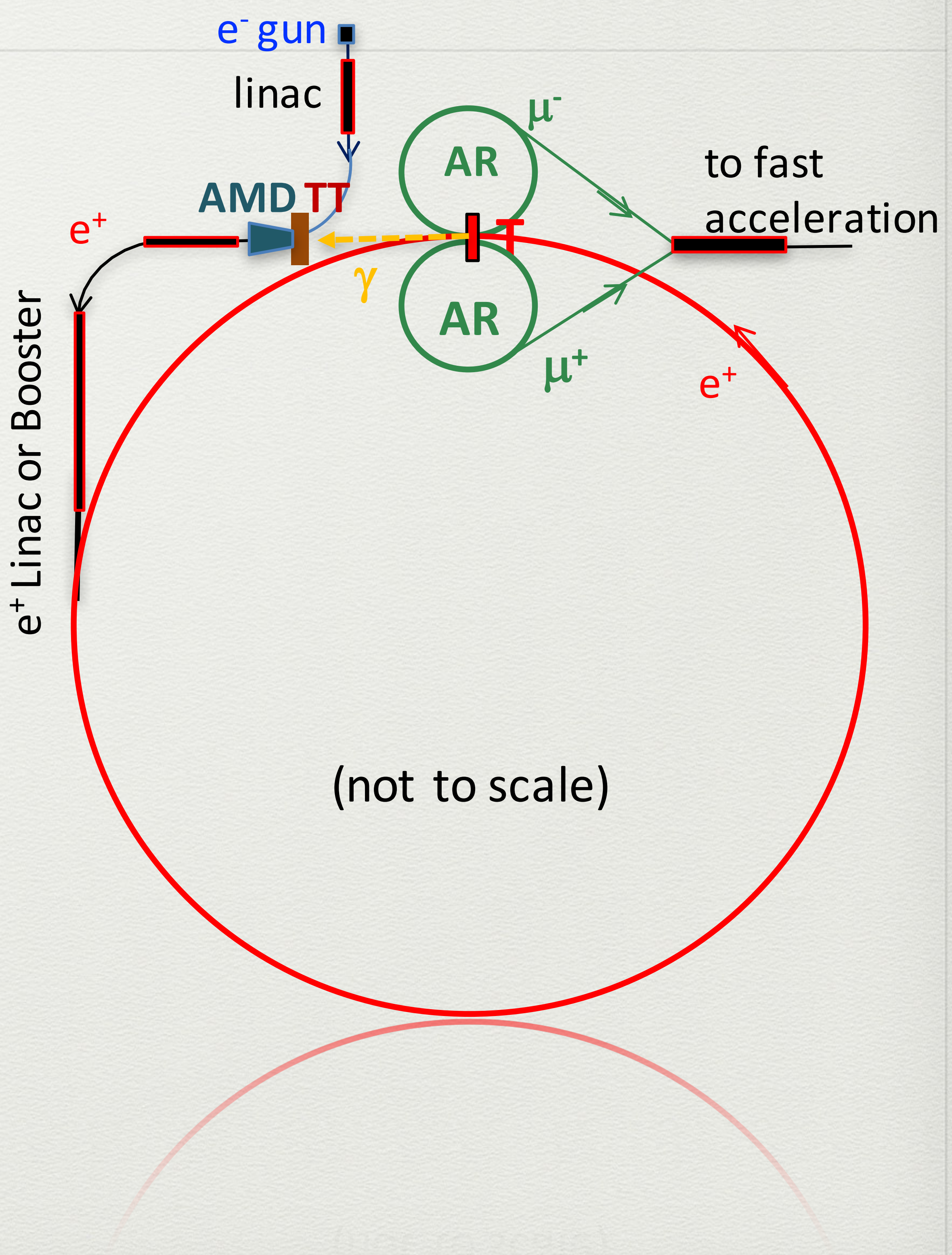
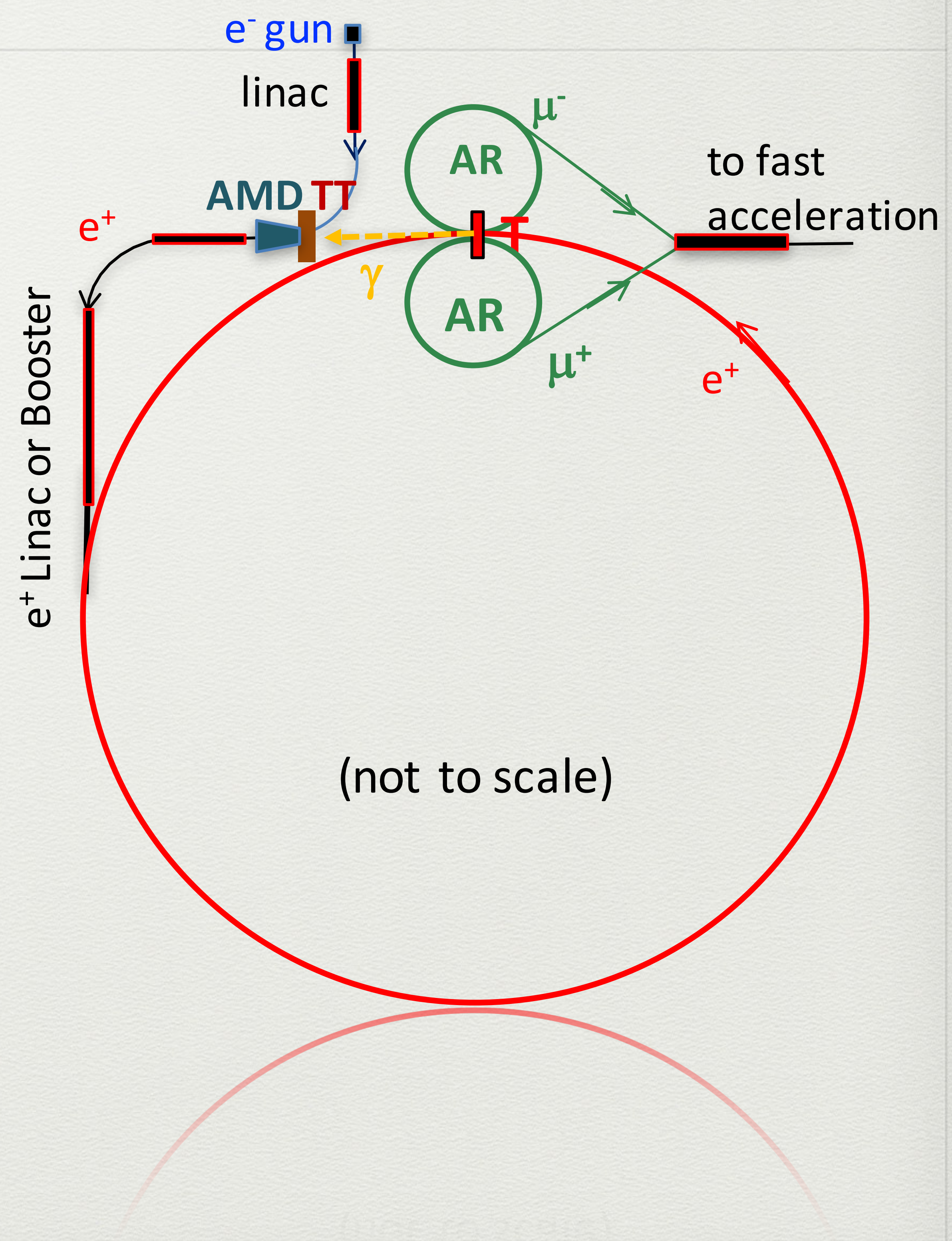
- **From $\mu^+\mu^-$ production to collider:**
  - Produced by the $e^+$ beam on target **T** with $E(\mu)\approx 22\text{GeV}$, $\gamma(\mu)\approx 200 \rightarrow \boldsymbol{\tau_{LAB}(\mu)\approx 500\mu s}$
  - Accumulation Ring: 60m isochronous and high mom. accept. for μ recomb. ($\tau_\mu^{LAB}$~2500 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 | # | $3 \cdot 10^{11}$ |
| $U_0$ | GeV | 0.51 |
| SR power | MW | 120 |

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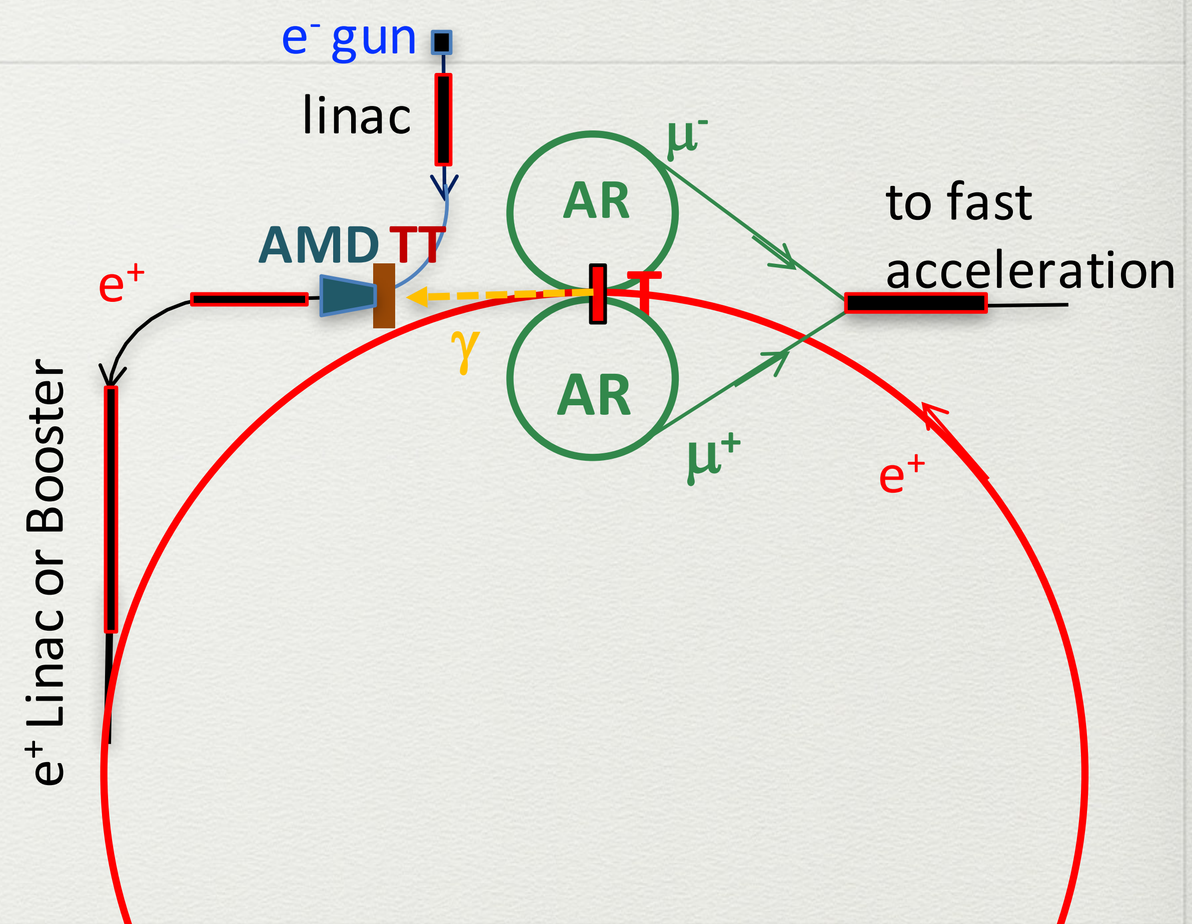



**Key topics for this scheme:**

- 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, $\varepsilon_N$ = 40 nm**

if: LHeC like $e^+$ source with 25% mom. accept. $e^+$ ring and $\varepsilon$ dominated by $\mu$ production

thanks to very small emittance
(and lower beta*)
**comparable luminosity with lower $N_\mu$/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 | 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

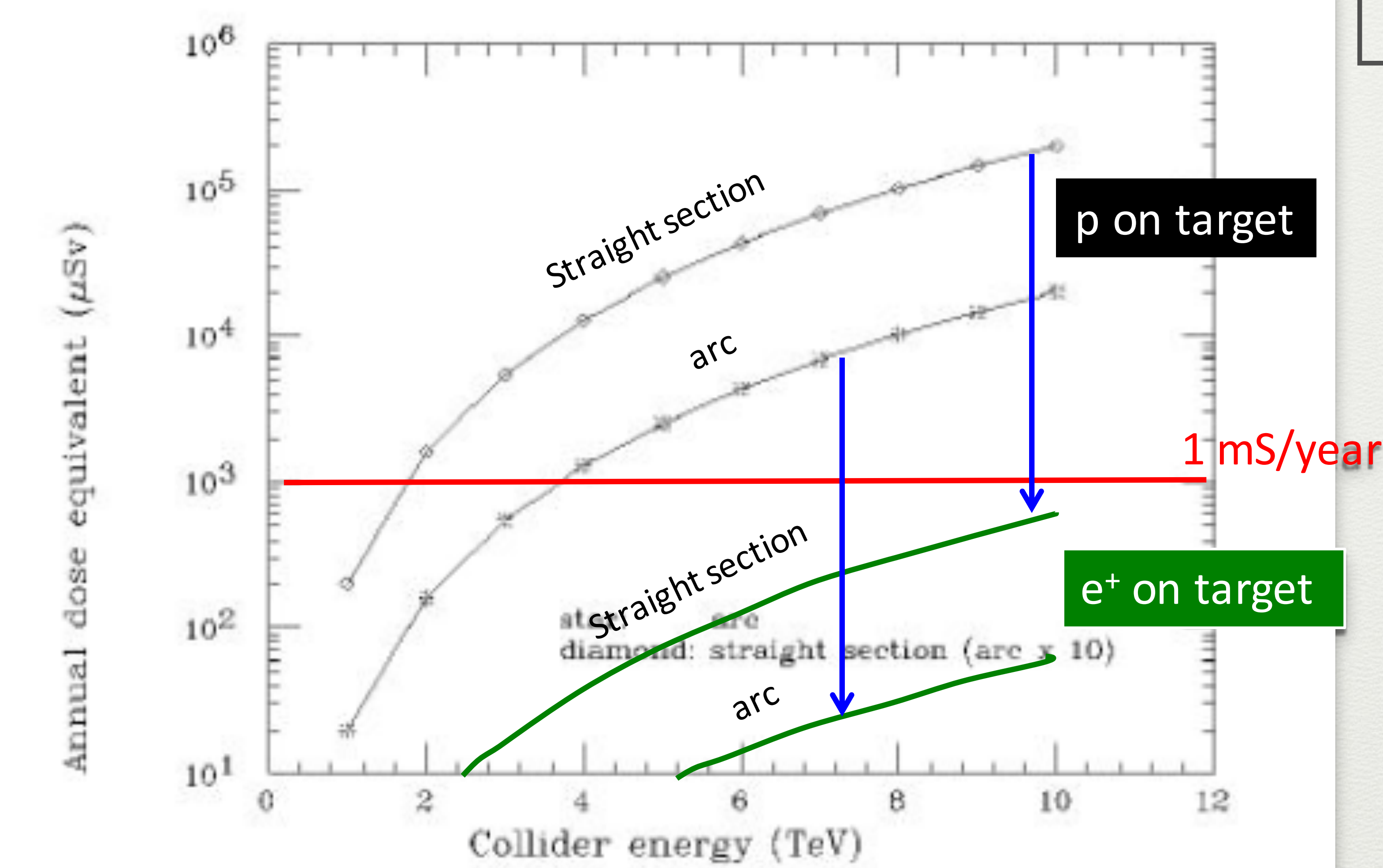
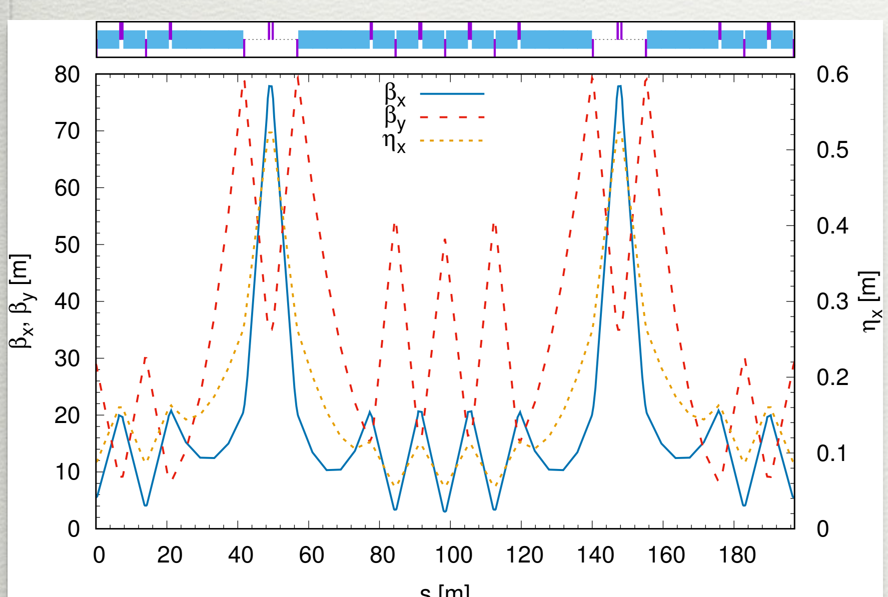


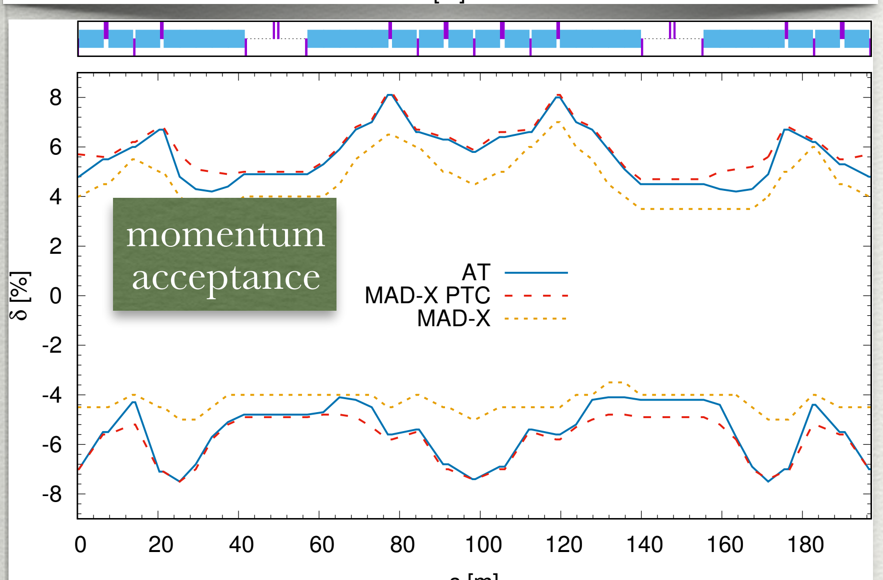

Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

*Colin Johnosn, Gigi Rolandi and Marco Silari*

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



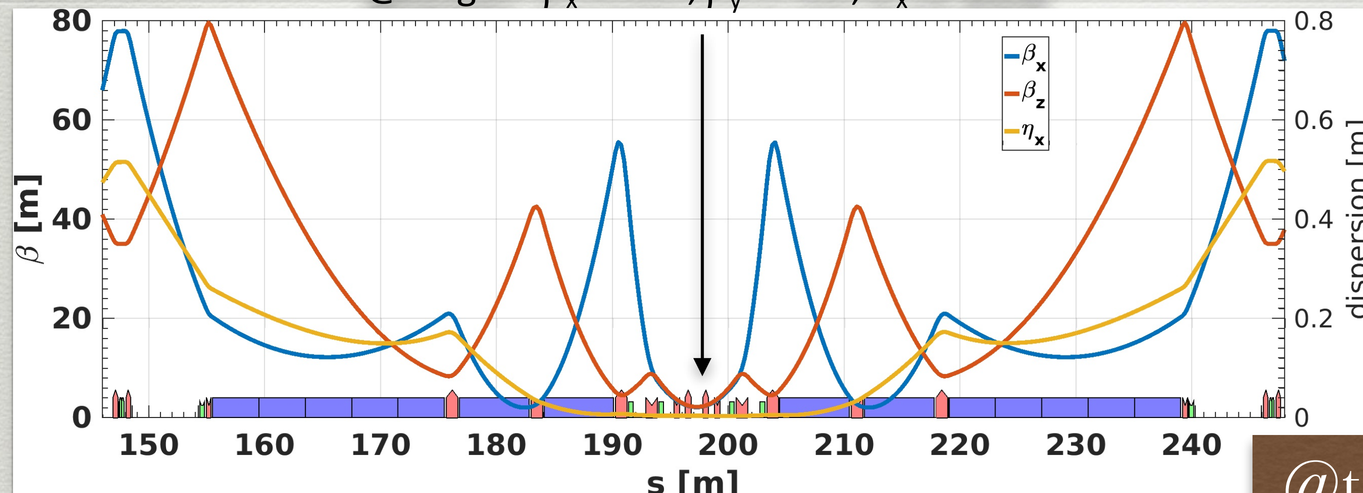

- Circumference 6.3 km: 197 m x 32 cells (no injection section yet)

| Parameter | Units | |
|---|---|---|
| Energy | GeV | 45 |
| Circumference | m | 6300 |
| Coupling(full current) | % | 1 |
| Emittance x | m | $5.73 \times 10^{-9}$ |
| Emittance y | m | $5.73 \times 10^{-11}$ |
| 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 | # | $3.15 \times 10^{11}$ |
| Synchrotron tune | | 0.068 |
| Transverse damping time | turns | 175 |
| Longitudinal damping time | turns | 87.5 |
| Energy loss/turn | GeV | 0.511 |
| Momentum compaction | | $1.1 \times 10^{-4}$ |
| RF acceptance | % | ± 7.2 |
| Energy spread | dE/E | $1 \times 10^{-3}$ |
| SR power | MW | 120 |

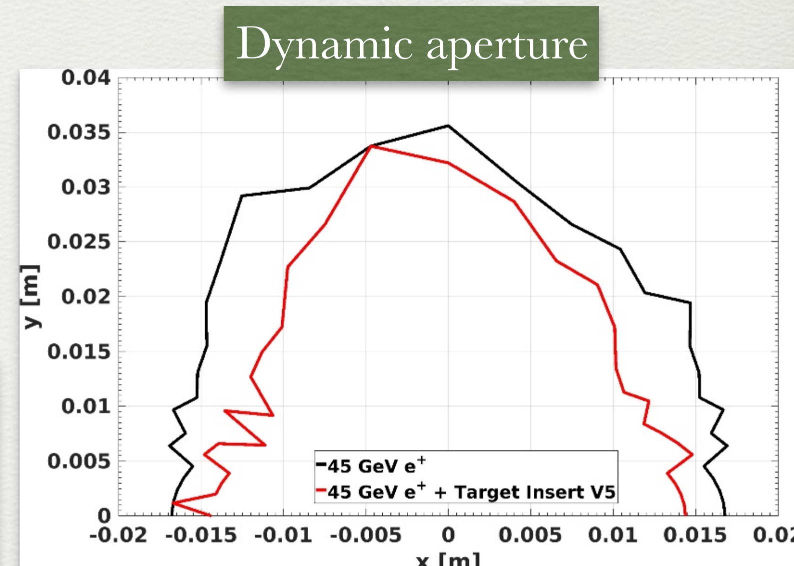
- Physical aperture=5 cm constant no errors
- Good agreement between MADX PTC / Accelerator Toolbox, both used for particle tracking in our studies

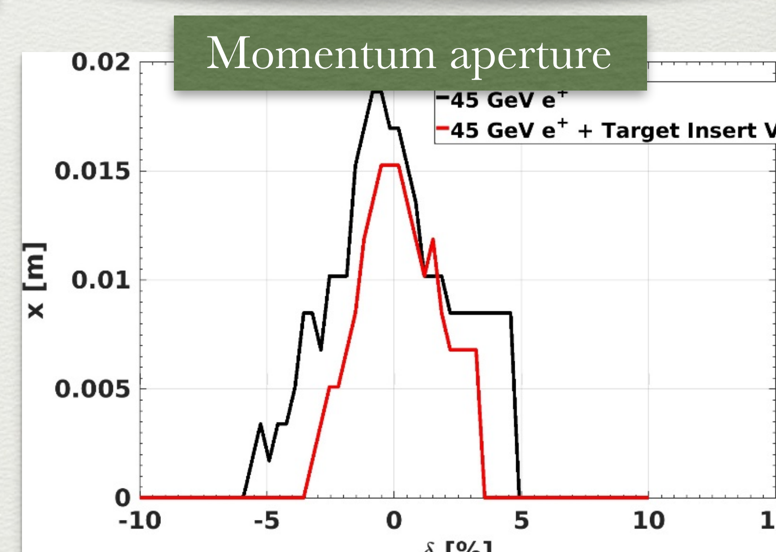
# Preliminary low-β IR for muon target insertion

@target: $\beta_x$=1.6m; $\beta_y$=1.7m; $D_x$=5.4mm




@target location:
- Dx ≈ 0
- low-β




- 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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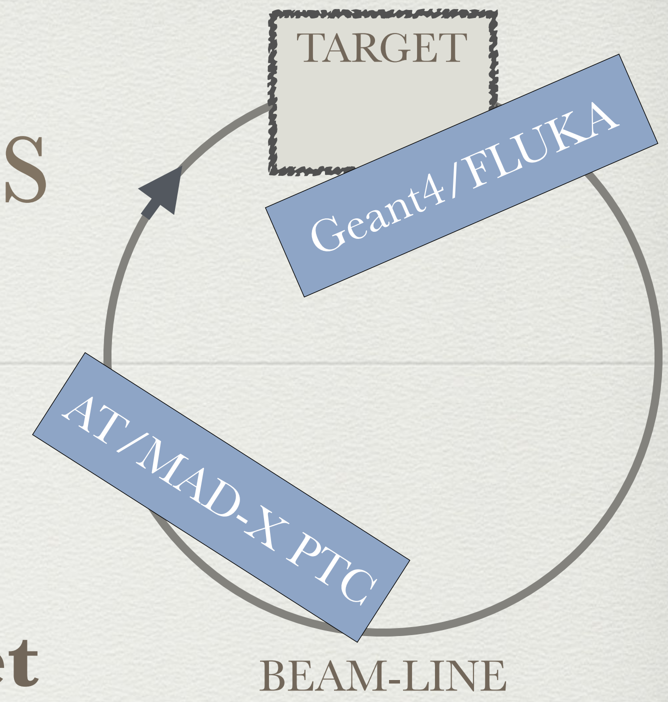


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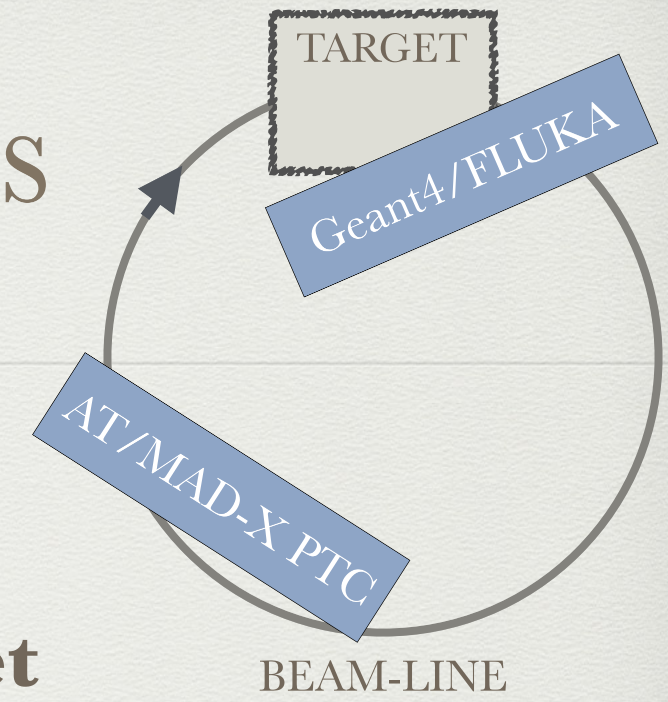


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**At each pass** through the Target the $e^+$ beam:

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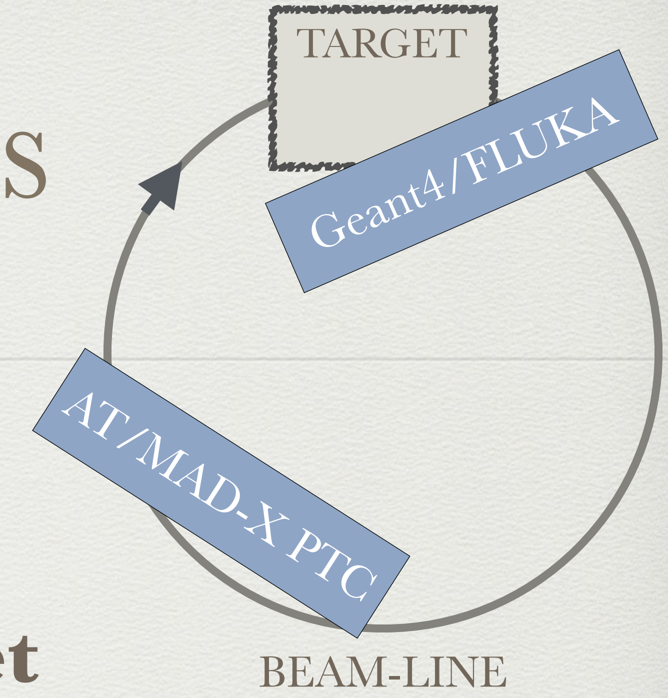


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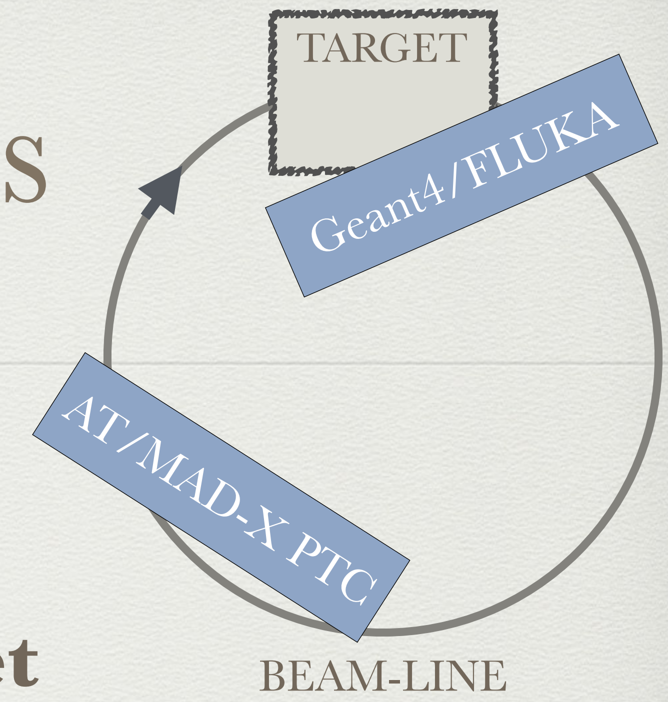


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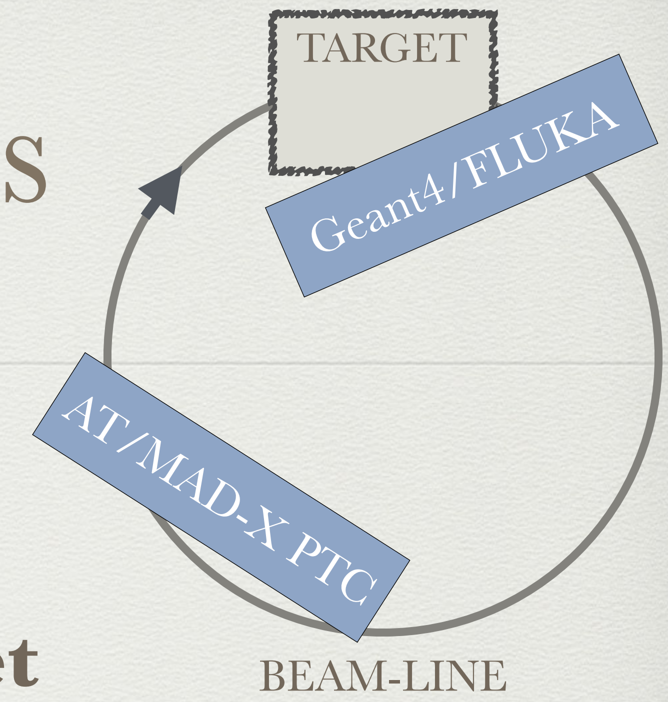


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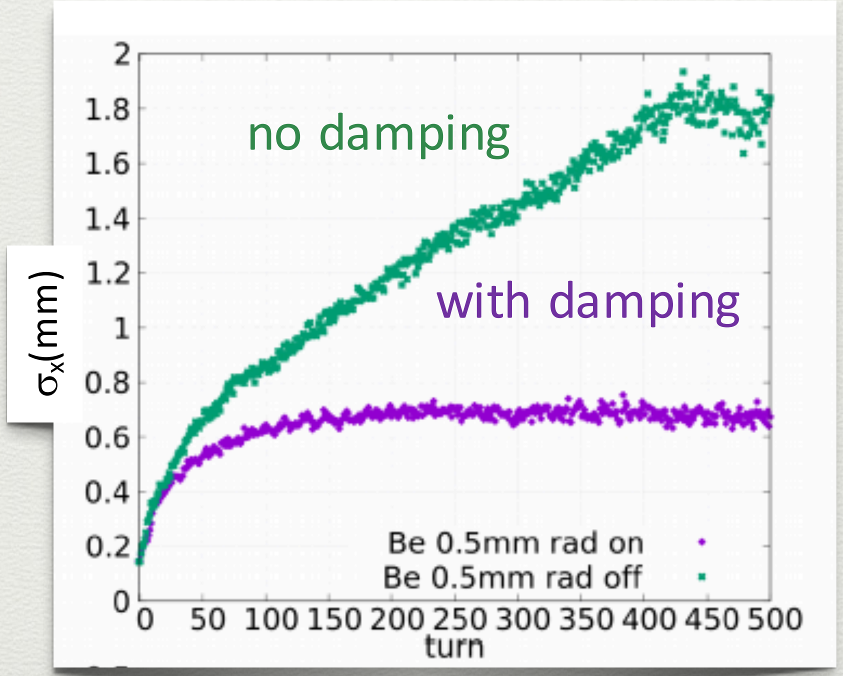
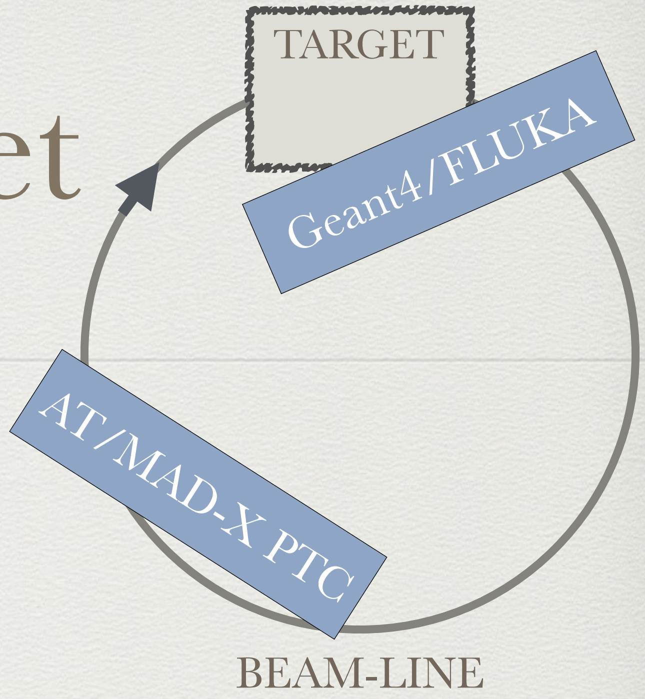
⊕ natural radiation damping



# Positron lifetime with Be target



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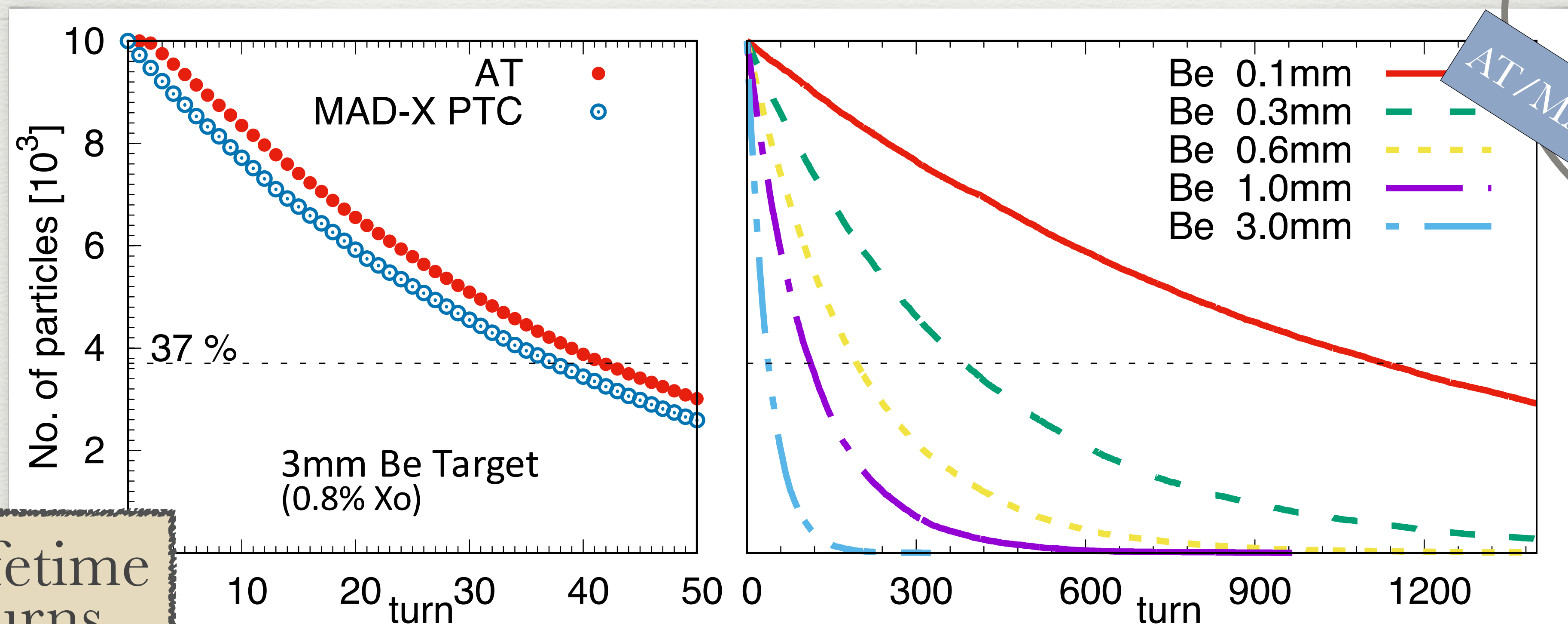
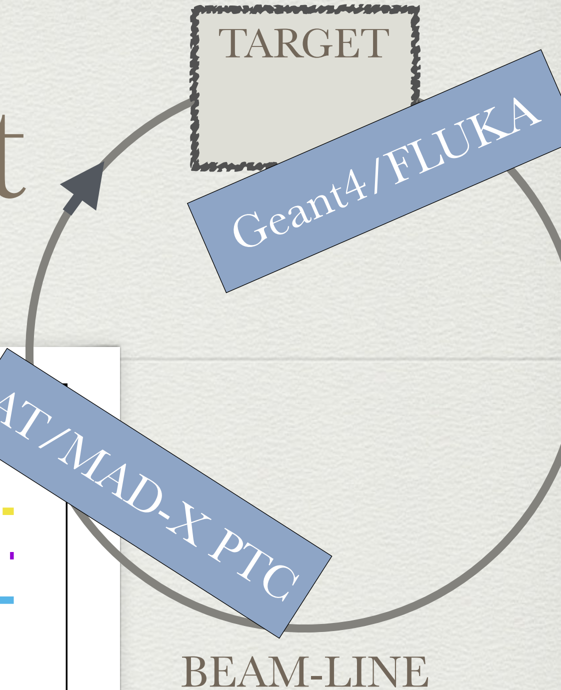
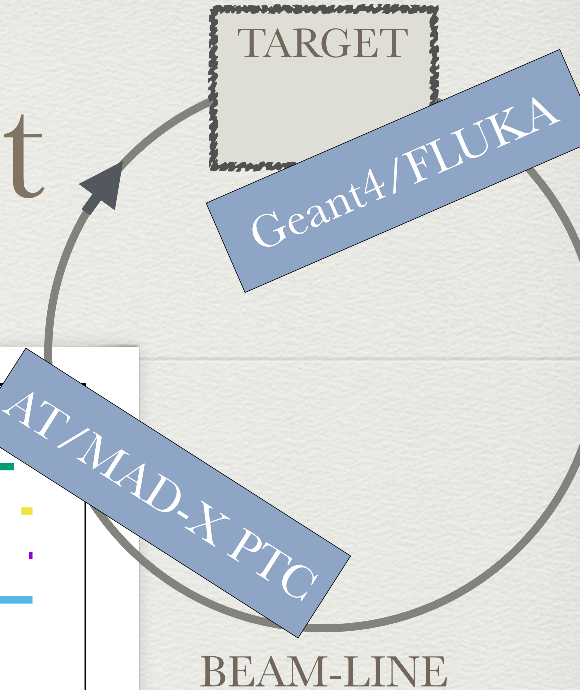
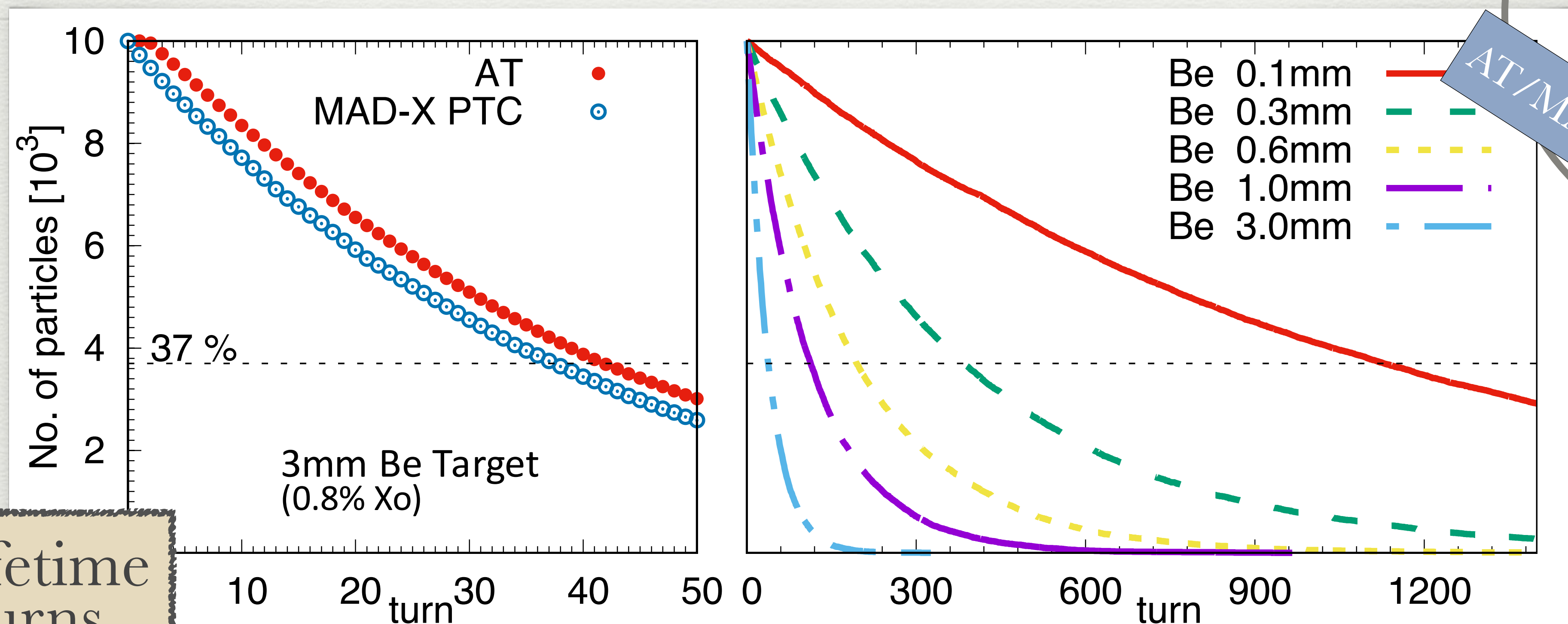



beam lifetime
~35 turns

# Positron lifetime with Be target

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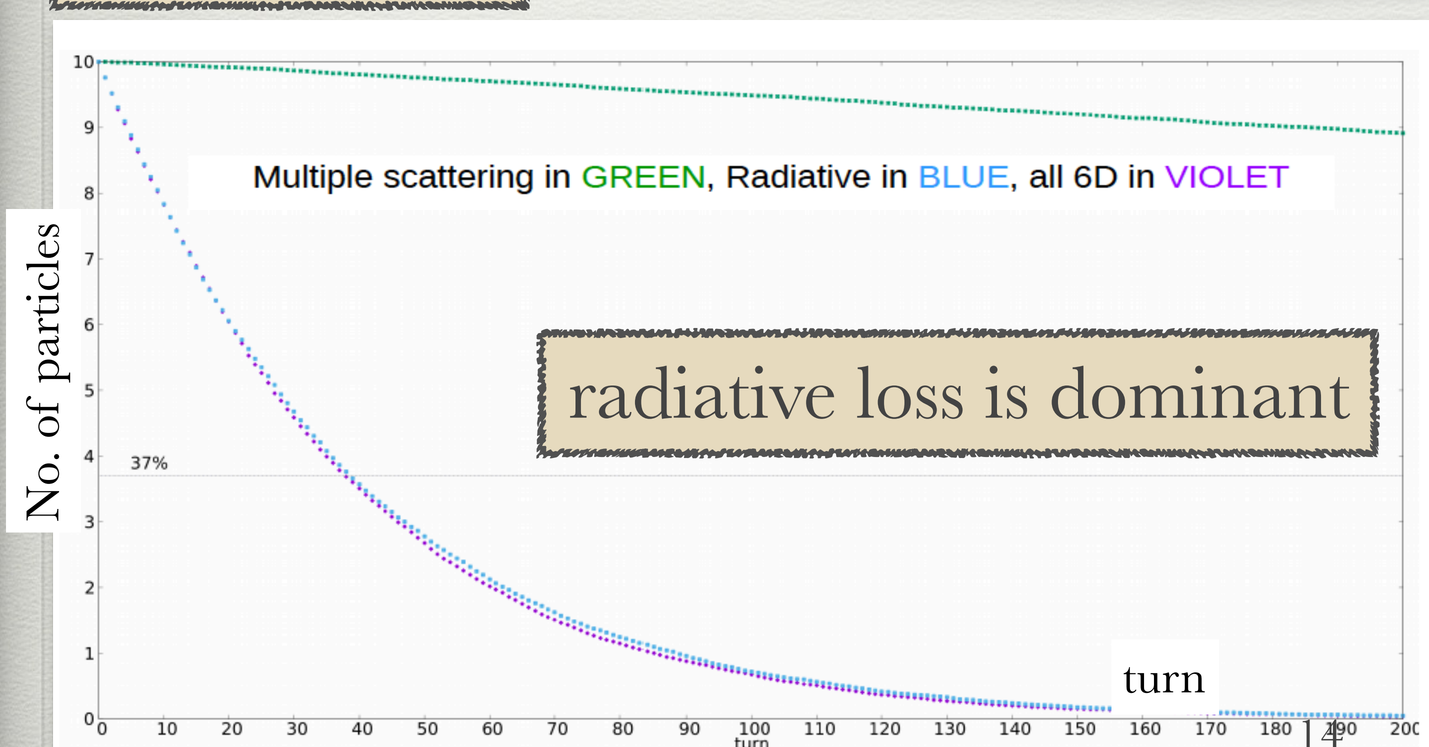
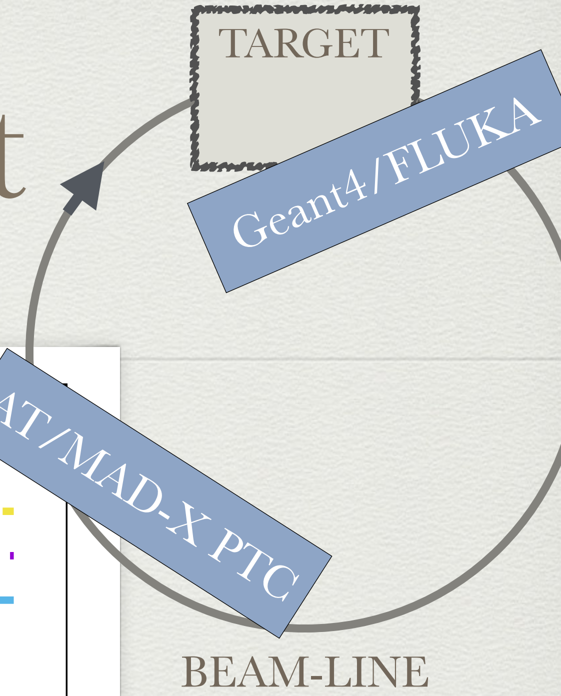
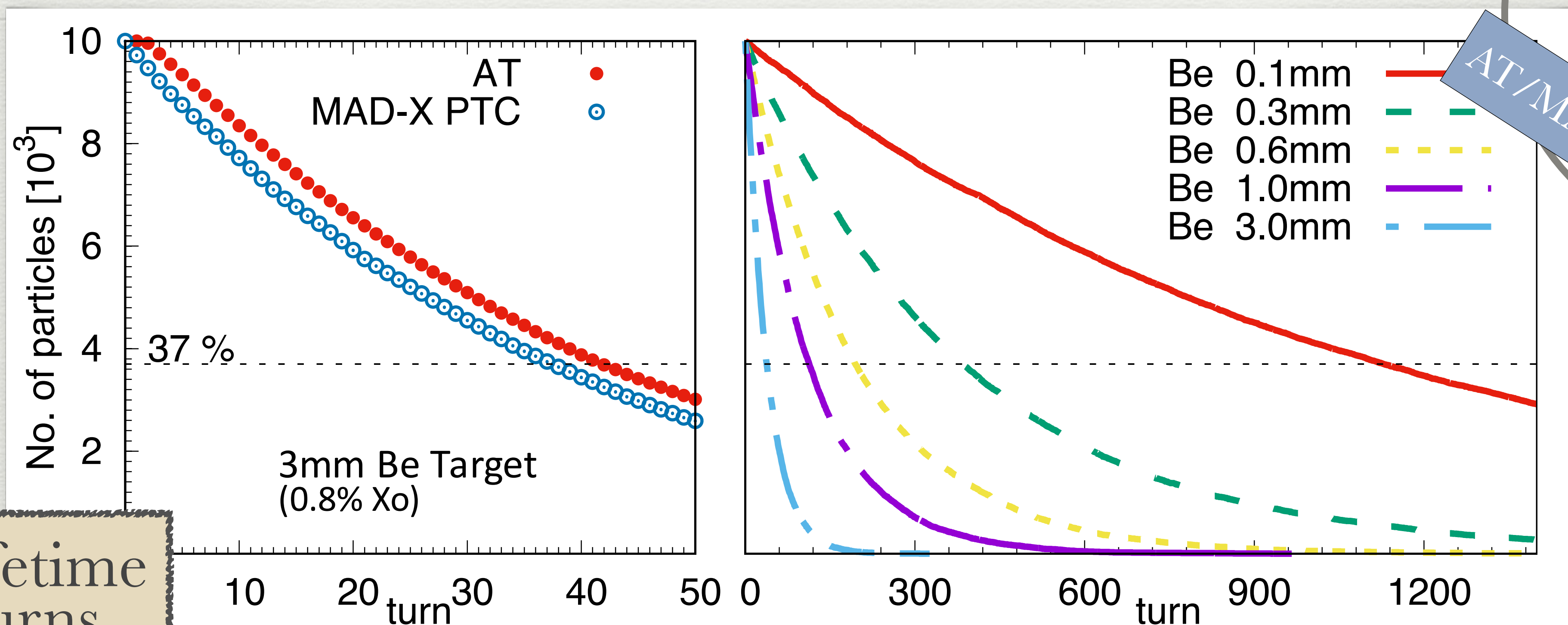



radiative loss is dominant

# Positron lifetime with Be target

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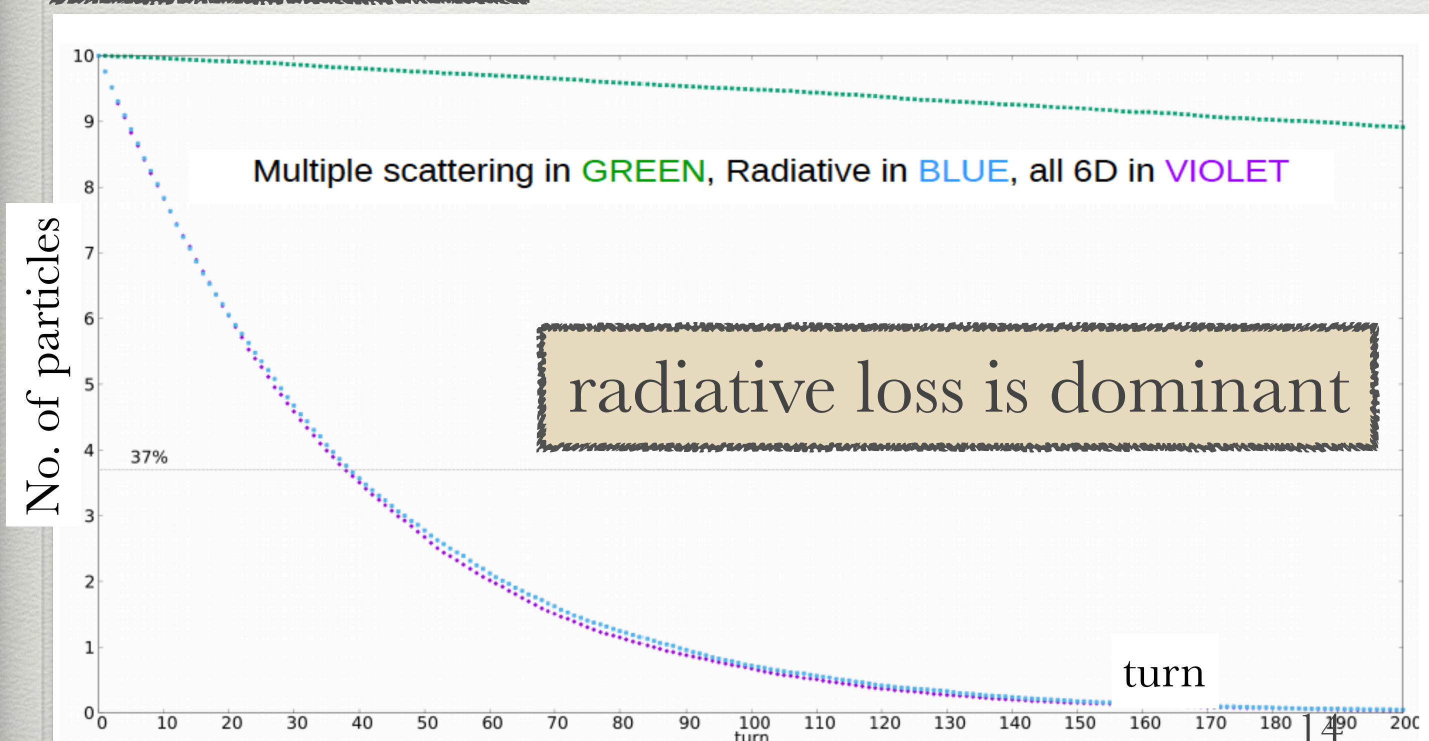


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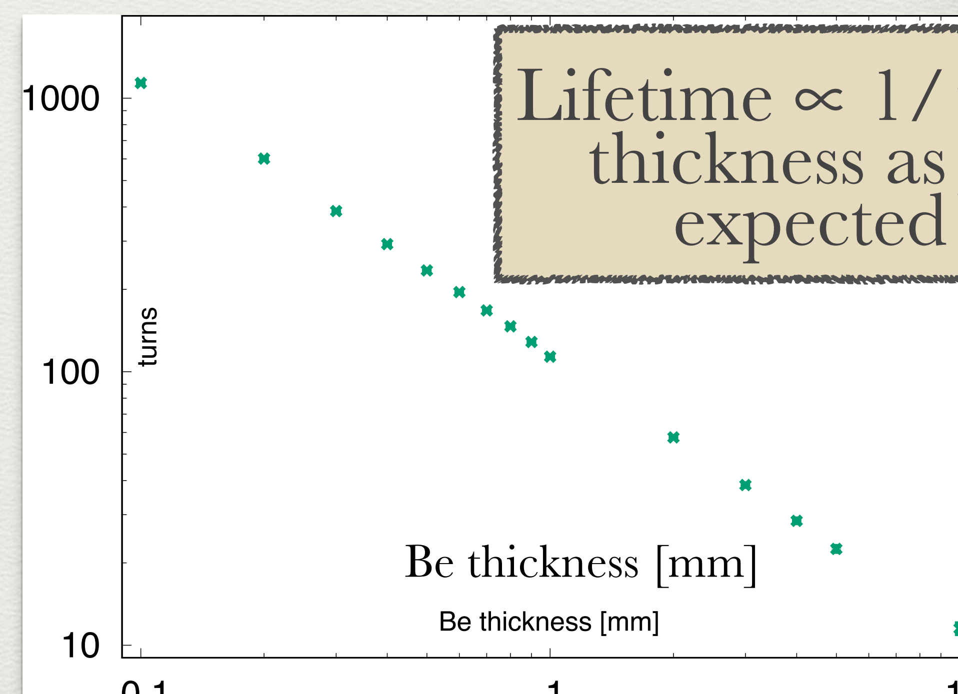
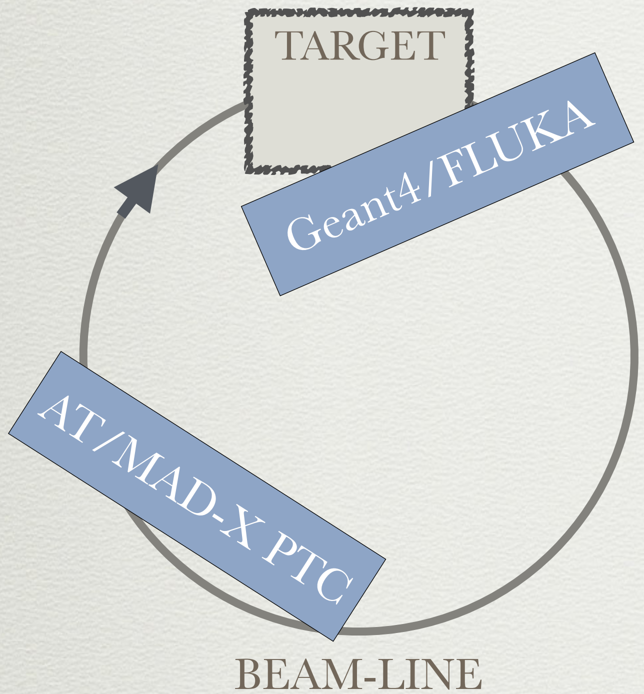


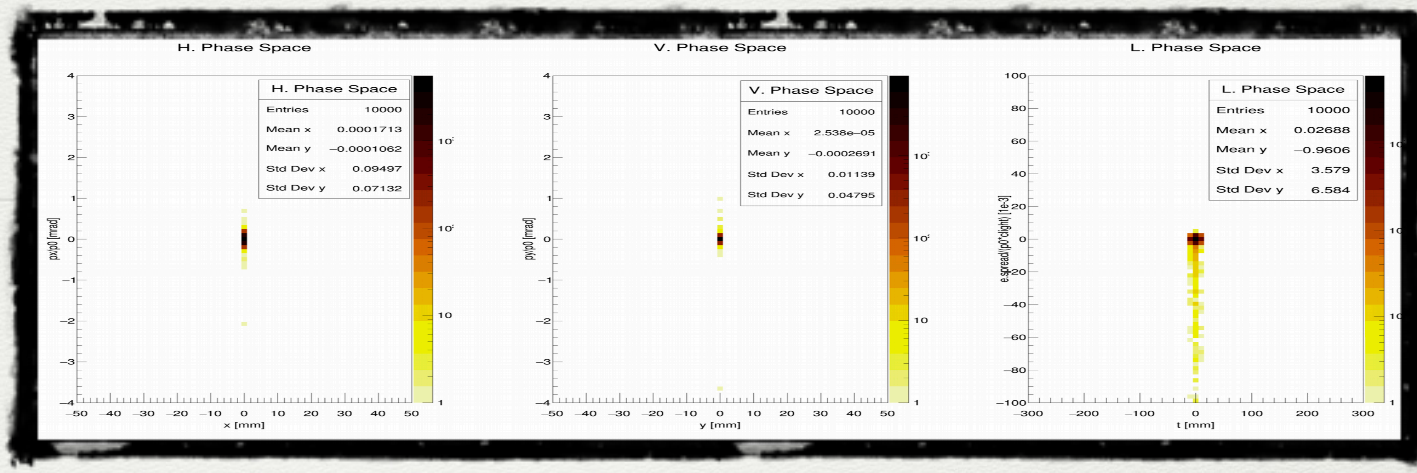

Lifetime ∝ 1/ thickness as expected

# Multi-turn simulations

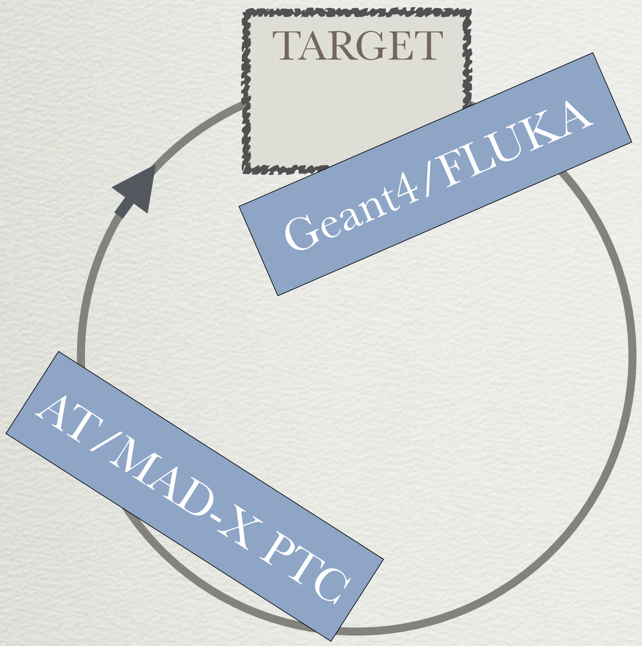



MAD-X PTC & GEANT4 6-D tracking simulation of
e+ beam with **3 mm Be** target along

# Multi-turn simulations




after target, before turn

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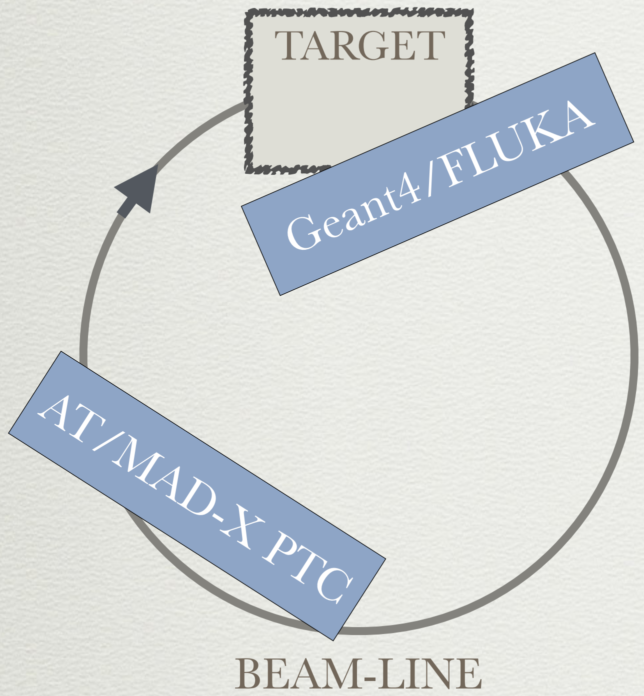
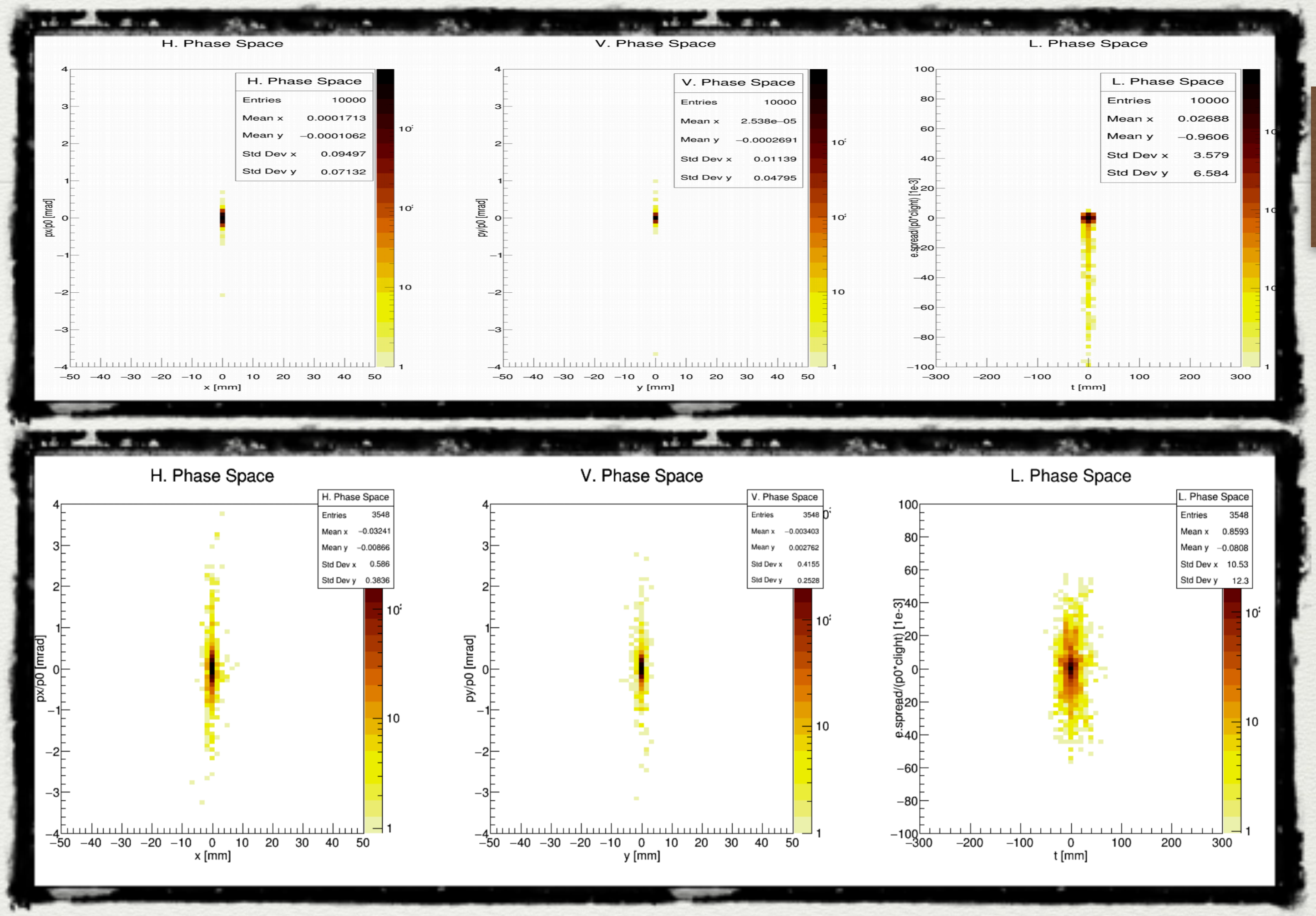


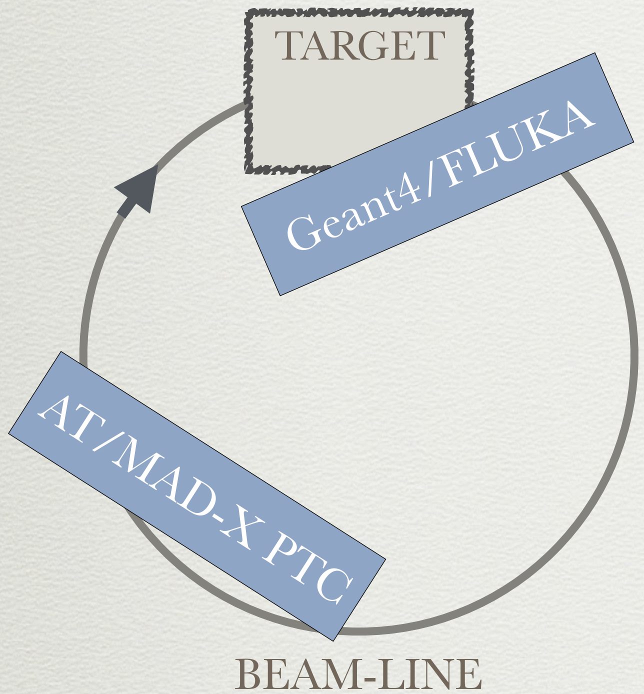



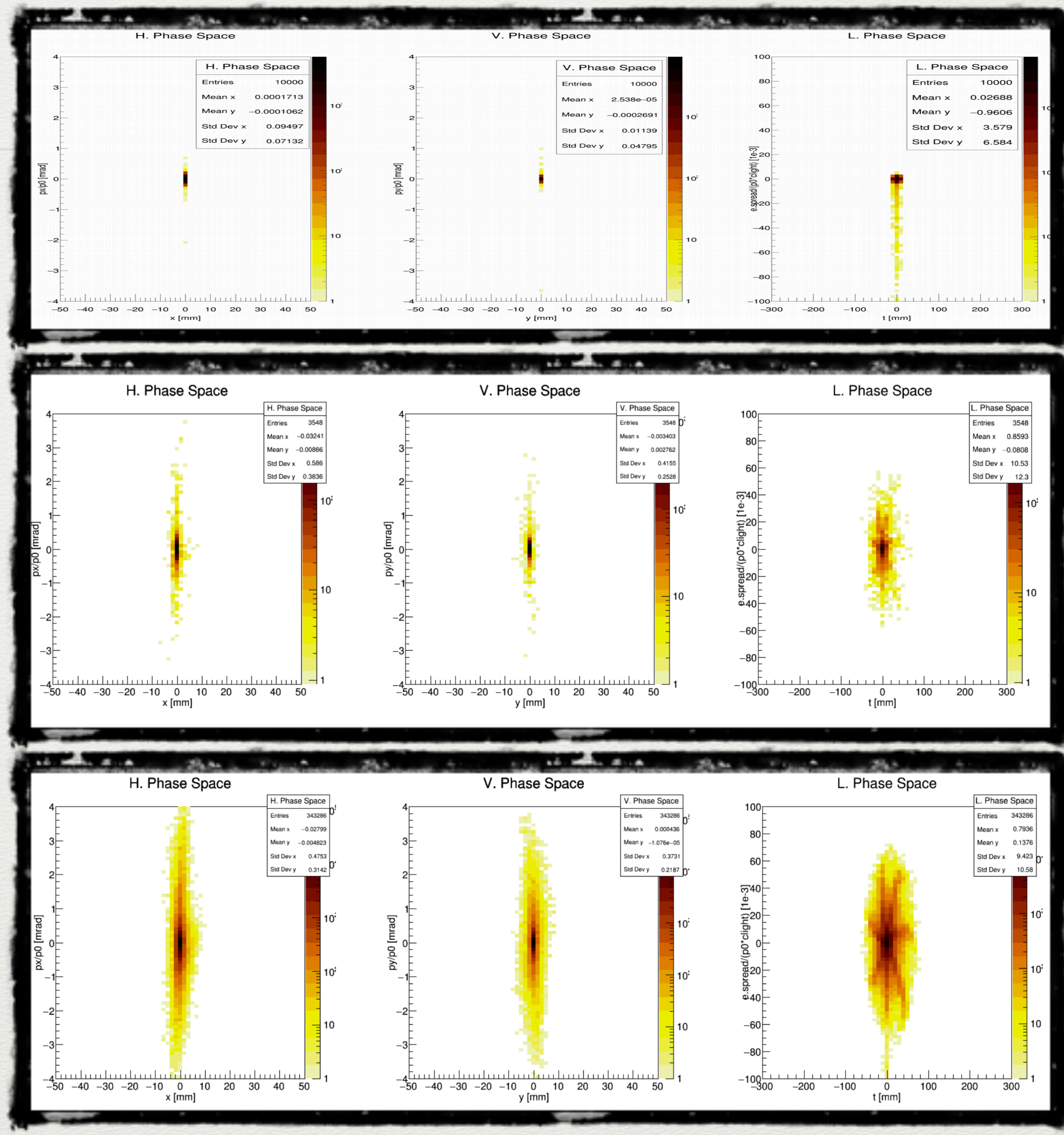

after target, before turn

turn n 35

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

# Multi-turn simulations



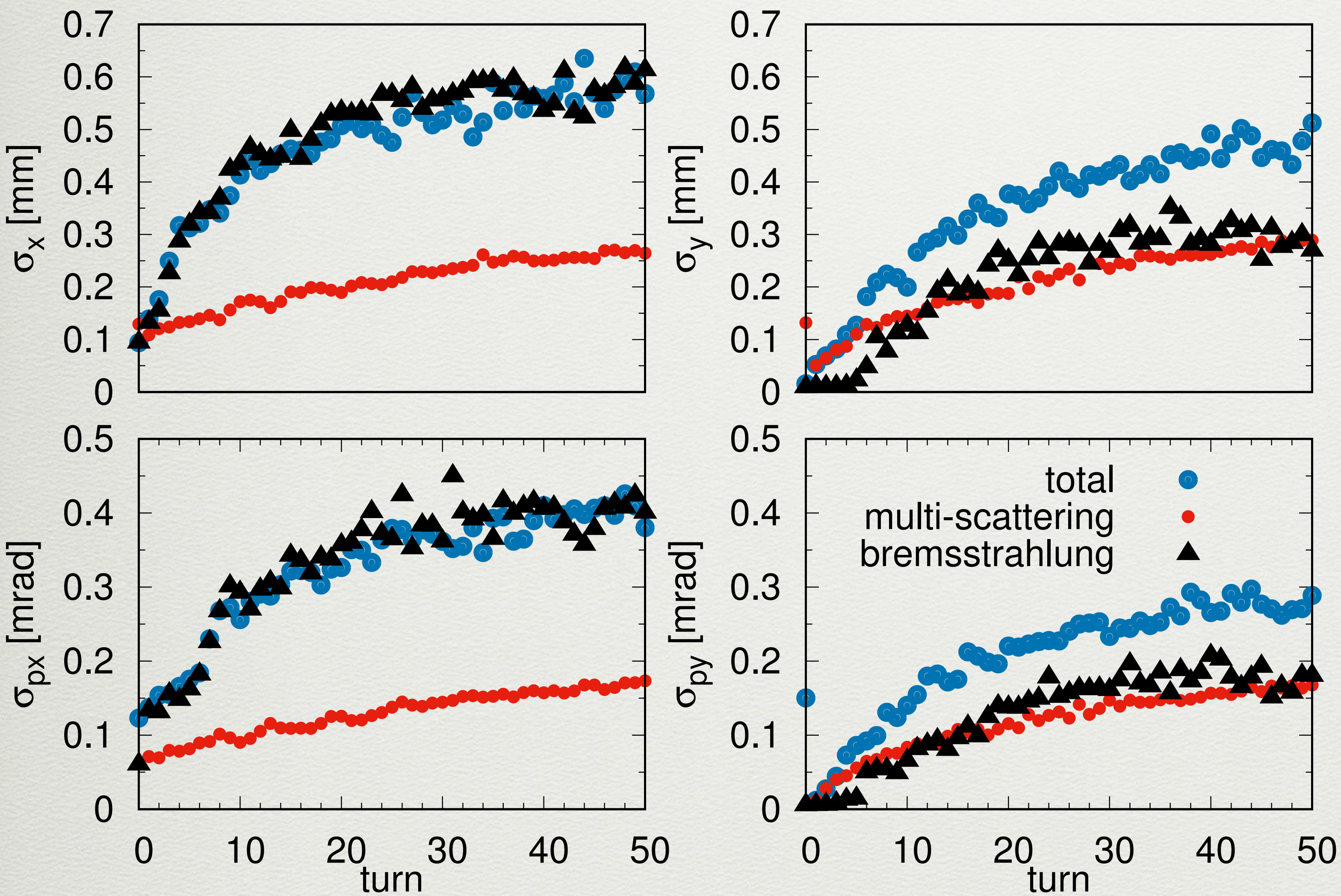

after target, before turn

turn n 35

35 turns superimposed

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

# 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

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

**$\varepsilon(e+)$ = $e^+$ emittance**

would like all contributions of same size. knobs:

**$\varepsilon(MS)$ = multiple scattering contribution** — **$\beta_x$, $\beta_y$ @target & target material**

**$\varepsilon(rad)$ = energy loss (brem.) contribution** — **$\beta_x$, $\beta_y$, $D_x$ @ target & target material**

**$\varepsilon(prod)$ = muon production contribution** — **E(e+) & target thickness**

**$\varepsilon(AR)$ = accumulator ring contribution** — **AR optics & target**

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

Also test **different materials**:

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

# Test Beam

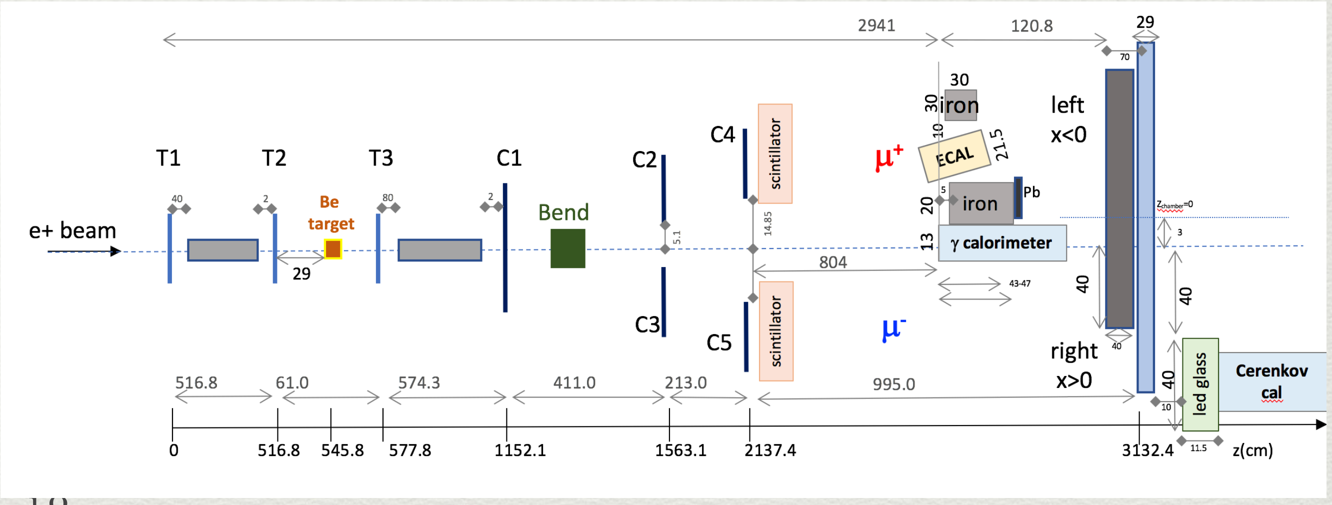
- Performed on the last week of July 2017, **@CERN North Area** (H4) *founded by* ***CSN1-INFN***
- Use tertiary **45GeV e$^+$** beam, up to 5x10$^6$ /spill with amorphous targets, to:
  ➜ measure *muon production* rate, cross section..
  ➜ measure muons kinematic properties: emittance…

**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 µb, 5 order of magnitudes smaller than Bhabha!
  ➜ a few muon pairs per spill



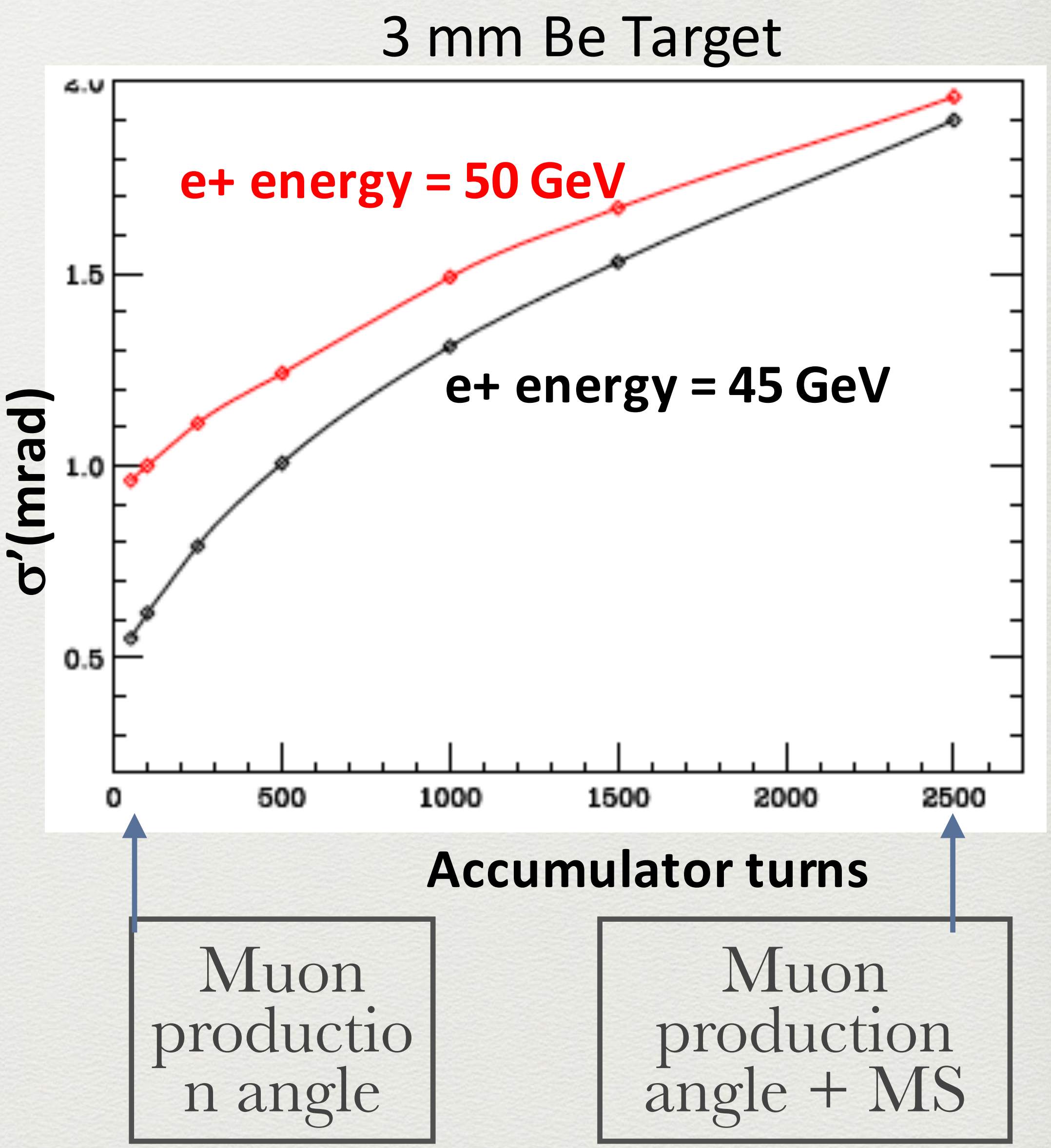
# Summary

- 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 and the feasibility of such a machine**

# Backup

# Muon Accumulator Rings considerations

- Isochronous optics with high momentum acceptance ($\delta \gtrsim 10\%$)
- 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



# Target considerations

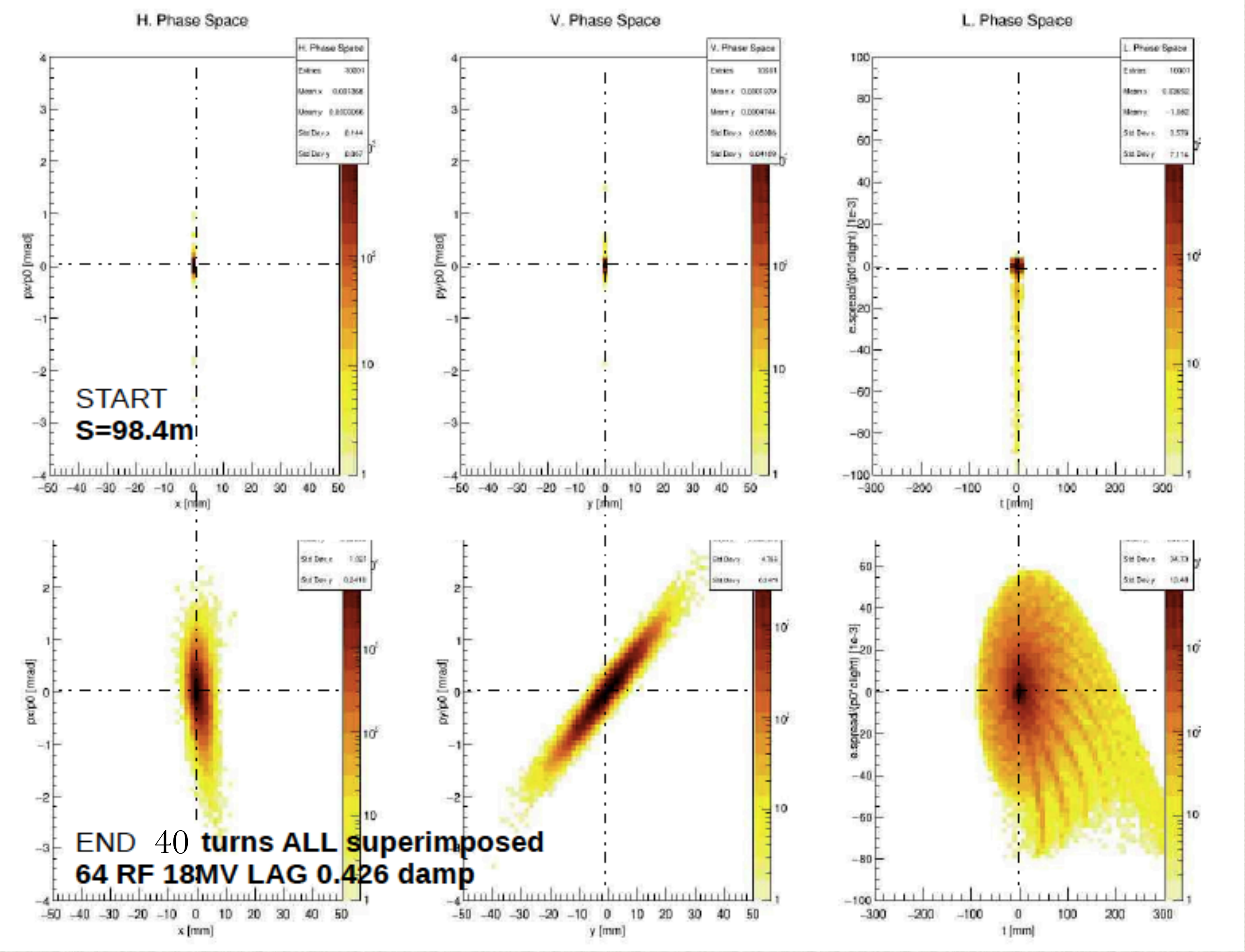
- The goal is to have a beam size as small as possible, but:
- Constraints for **power removal** (200kW) and **temperature rise**
  ➜ move target (for free with liquid jet)
  ➜ e+ bump every 1 munch muon accumulation
- Possibilities:
  - Solid target: simpler and better wrt temperature rise:
    - Be, C

      [Kavin Ammigan 6th High Power Targetry Workshop]
      - 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
  - 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

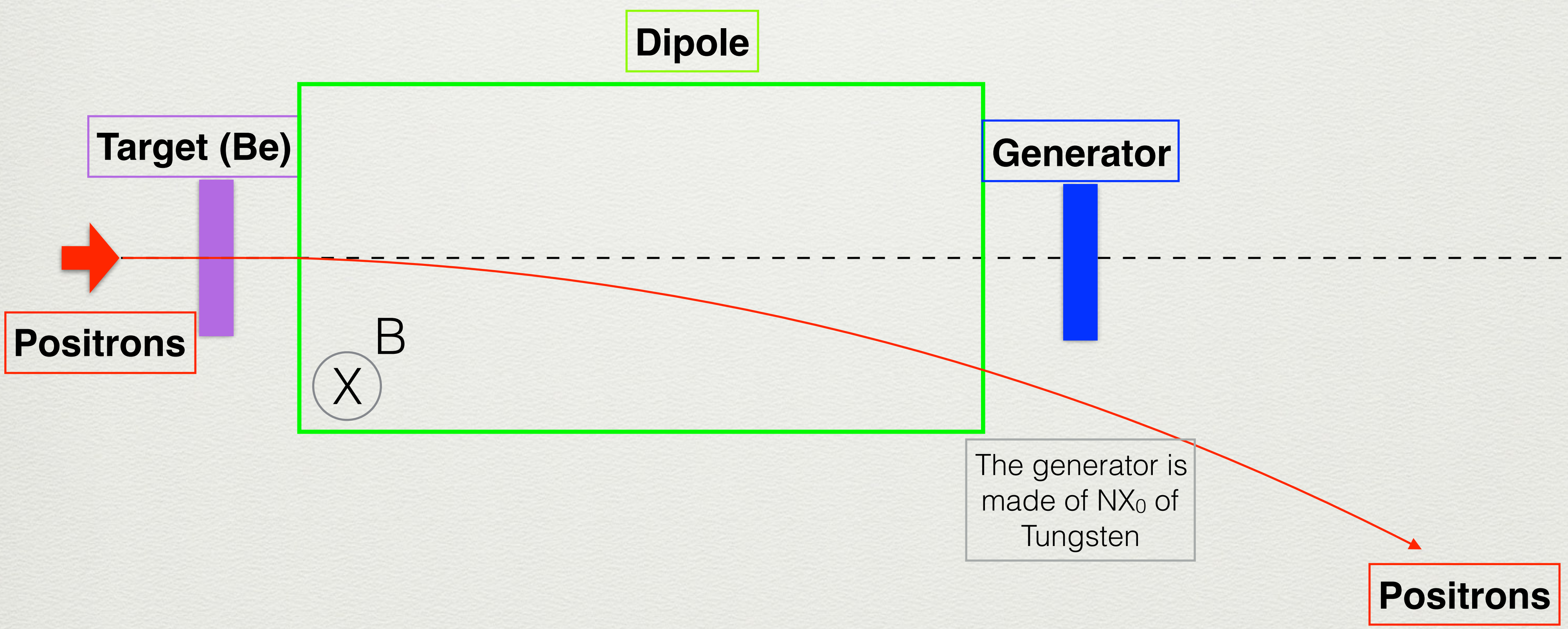
before target, starting point

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



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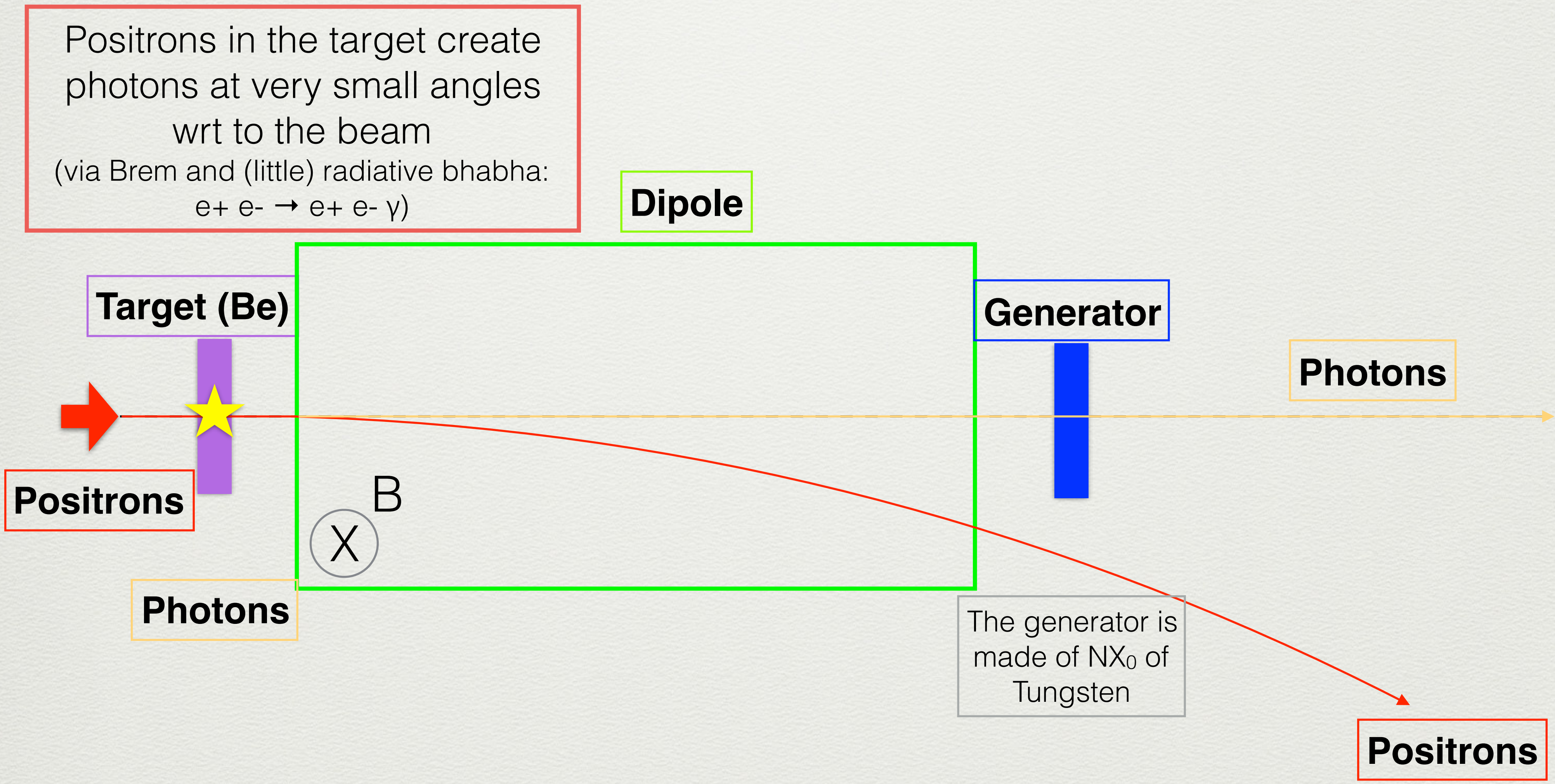

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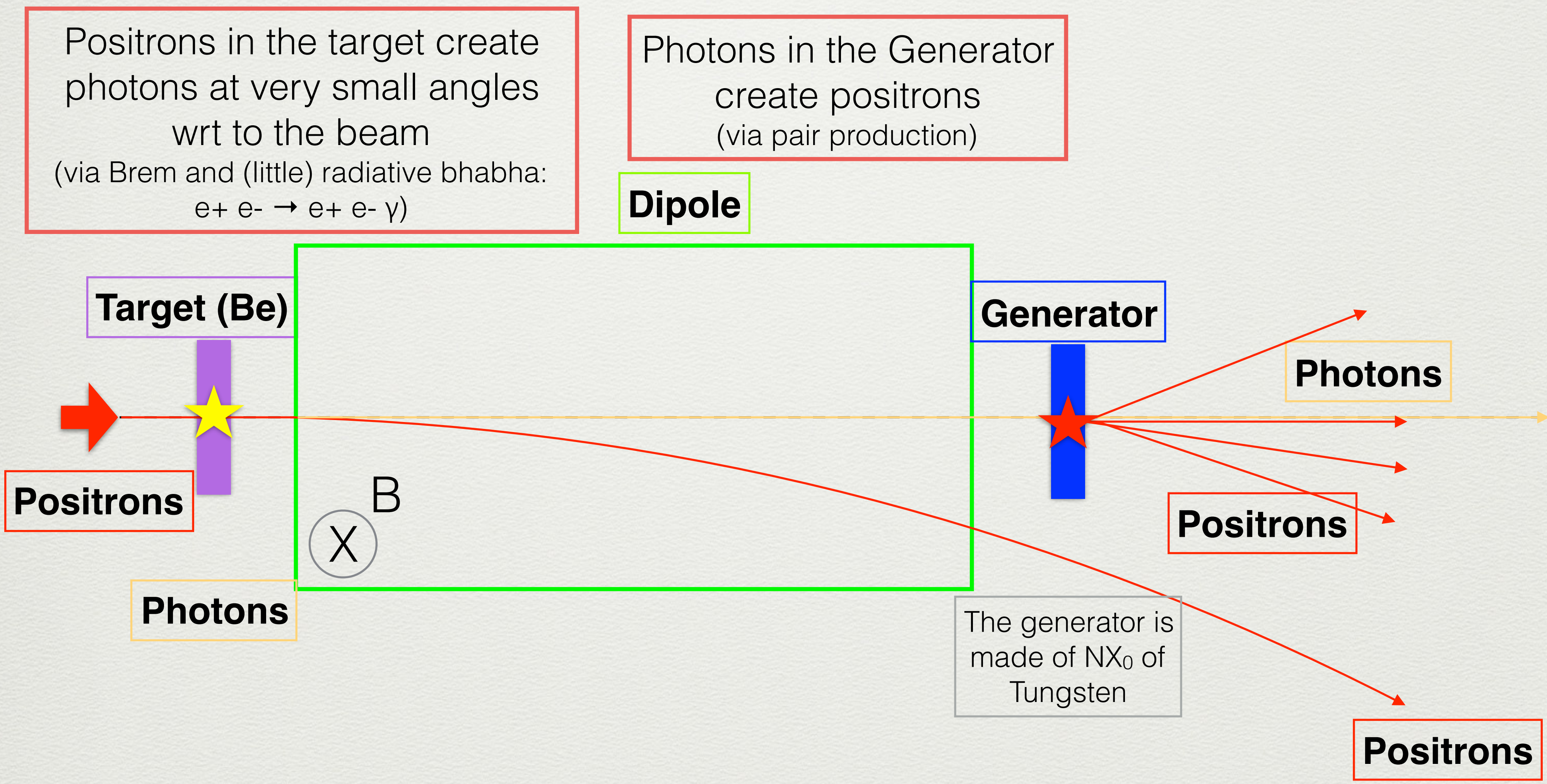

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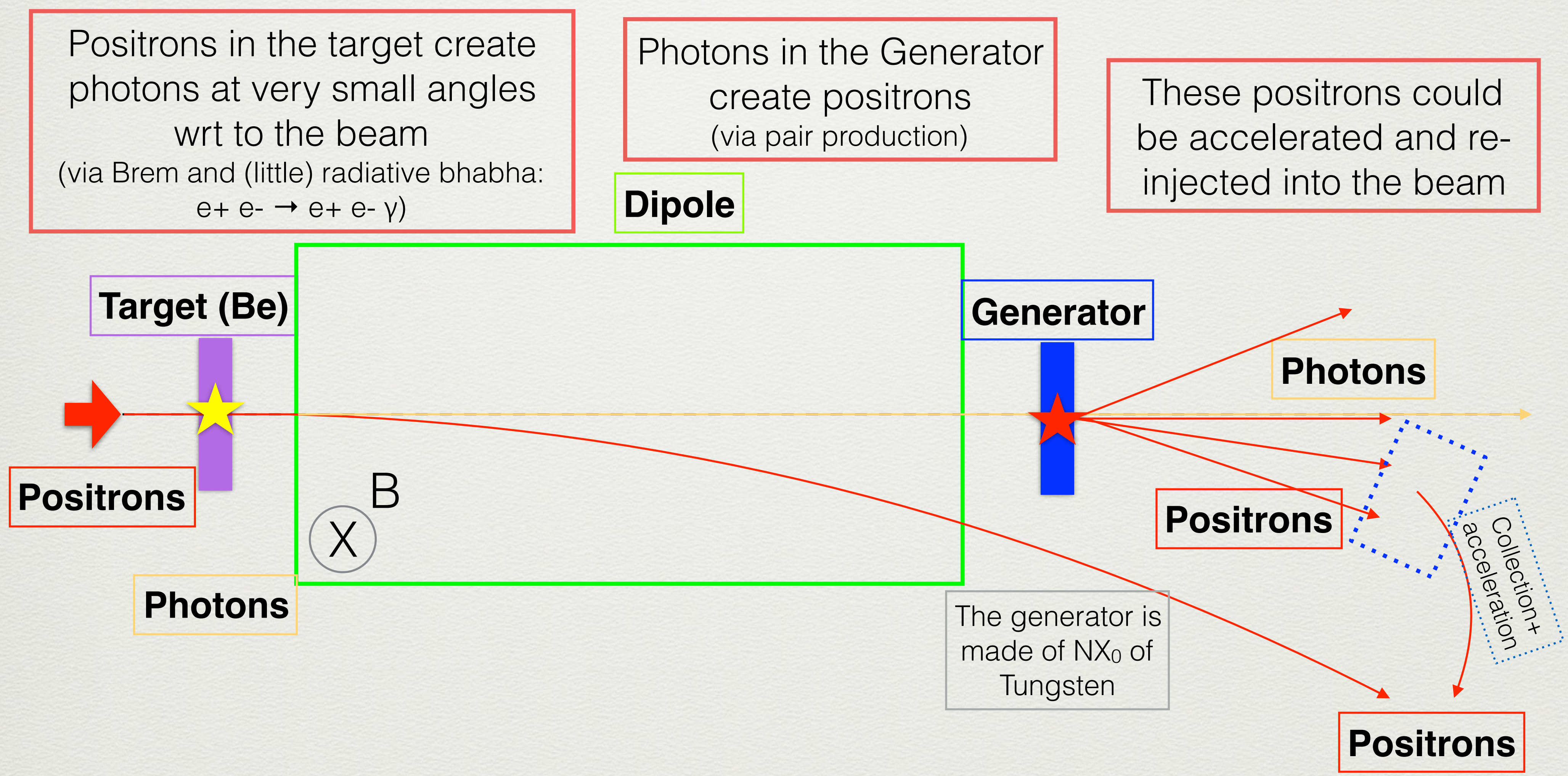
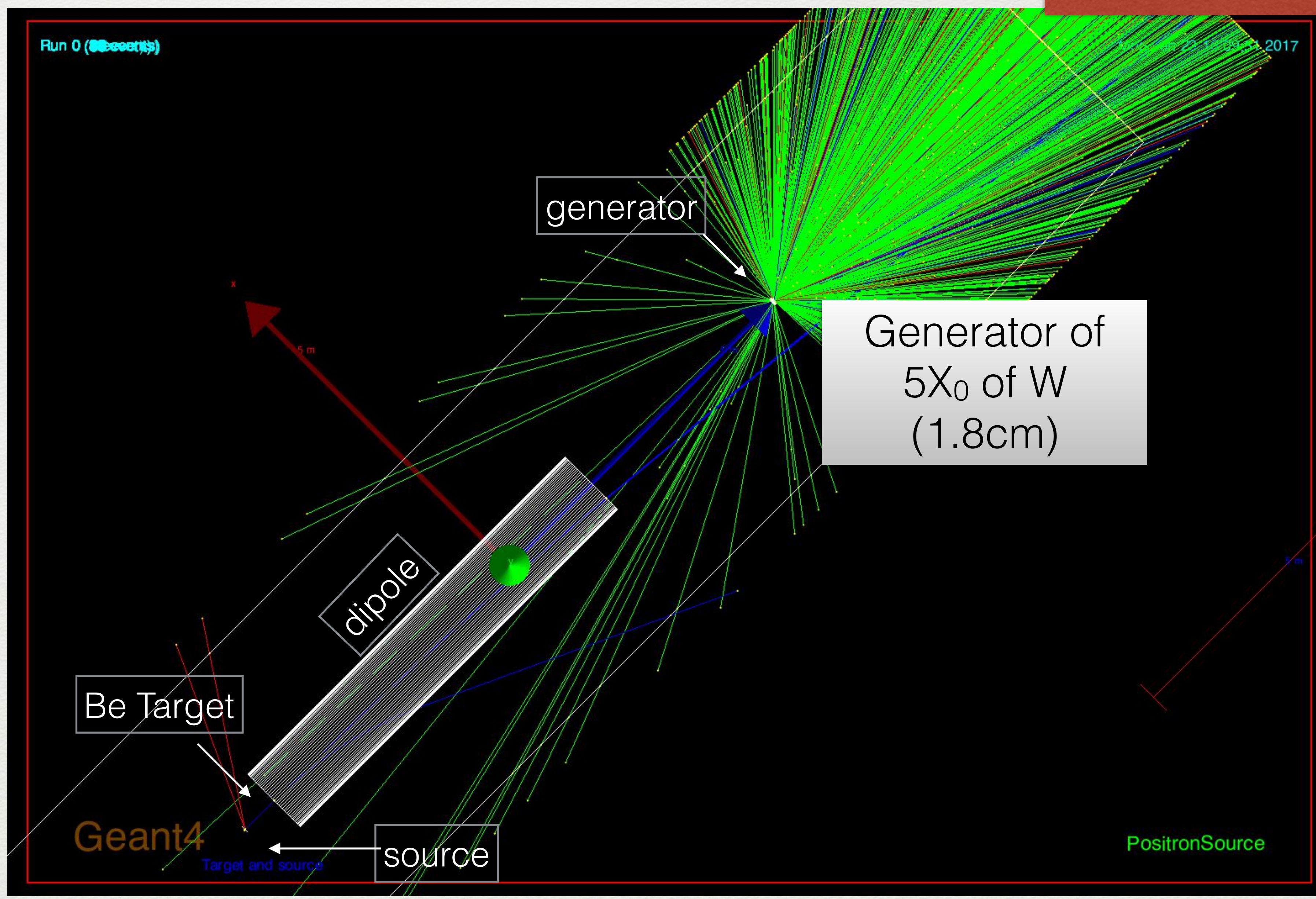


# Preliminary considerations on $e^+$ source

**Total flux**

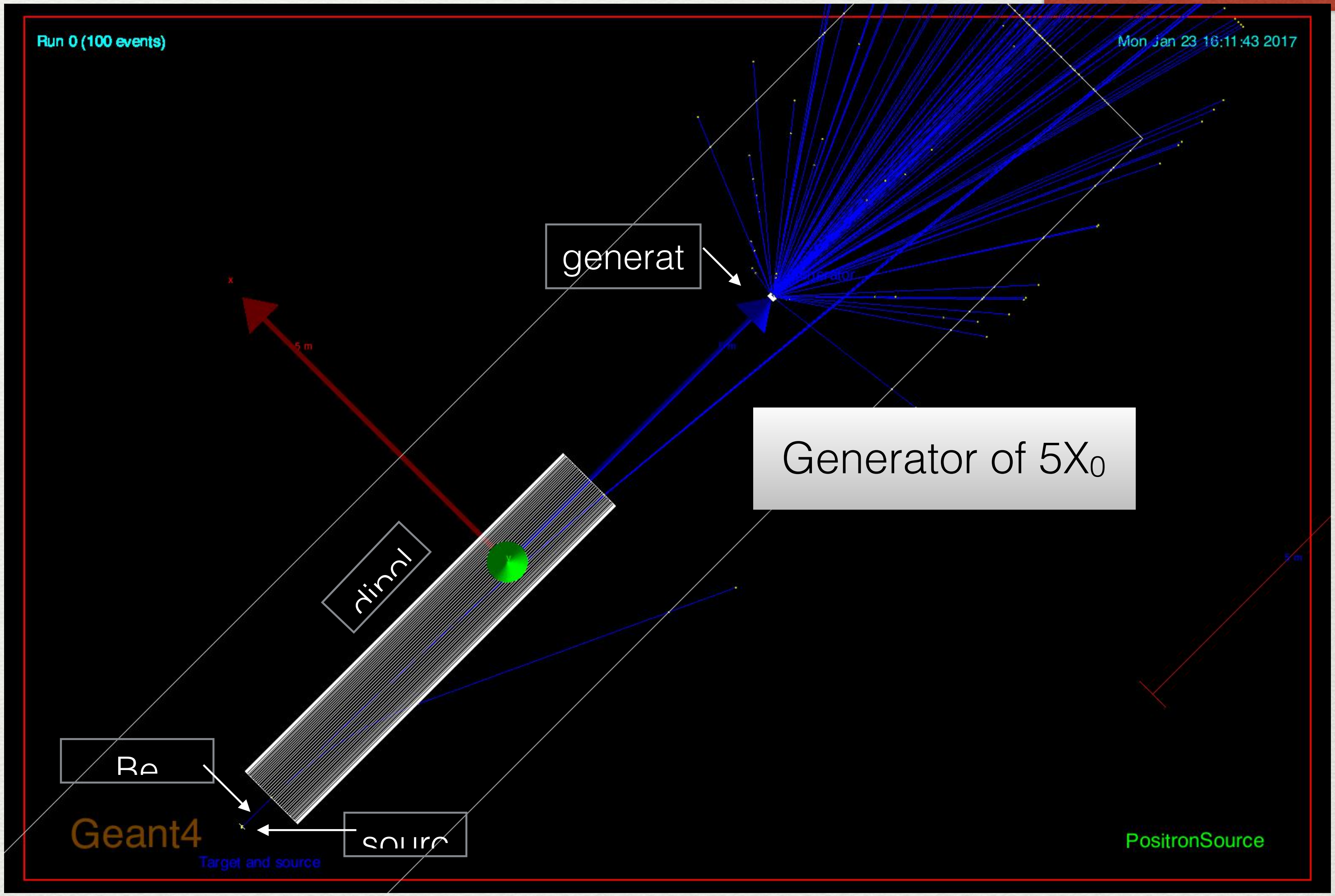
**Geant4** simulation



# Preliminary considerations on $e^+$ source

**Total flux**

**Geant4** simulation



## **Geant4** simulation

**Electron** flux