Brilliant muon beam production at the ILC

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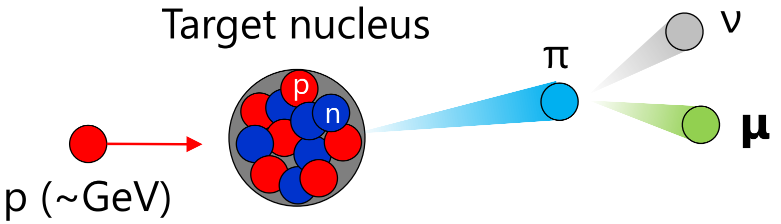
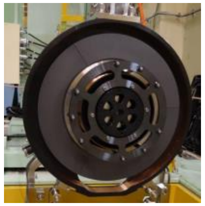
Overview

- Conventional way to produce a muon beam from a proton beam

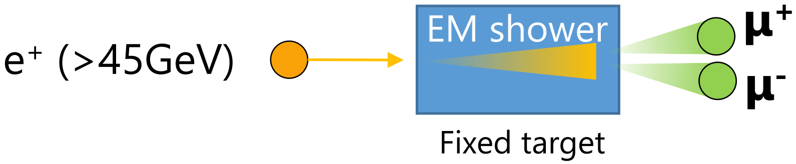


$T = O(1\sim10)$ MeV
$I = O(1e8)\ \mu^+/s$
$\varepsilon = O(10^3)$ mm*mrad

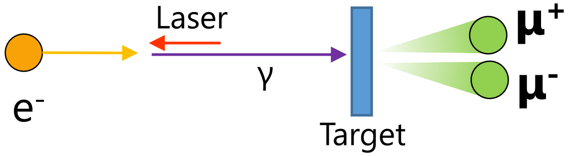


@J-PARC MLF
- Graphite, t=2mm
- Rotating target

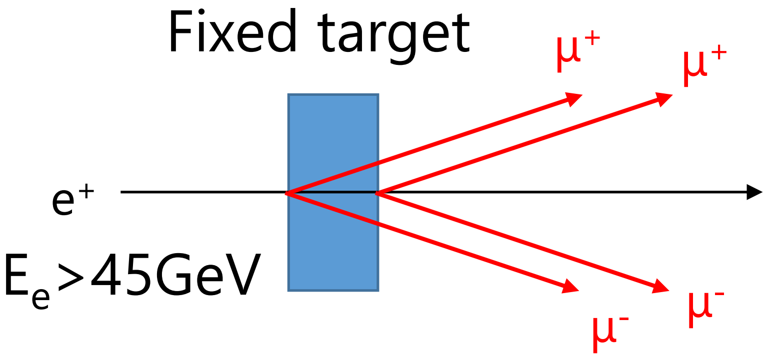
- From a positron/electron beam, a low emittance and high energy muon beam can be produced.
  1. 45GeV positron beam on a fixed target

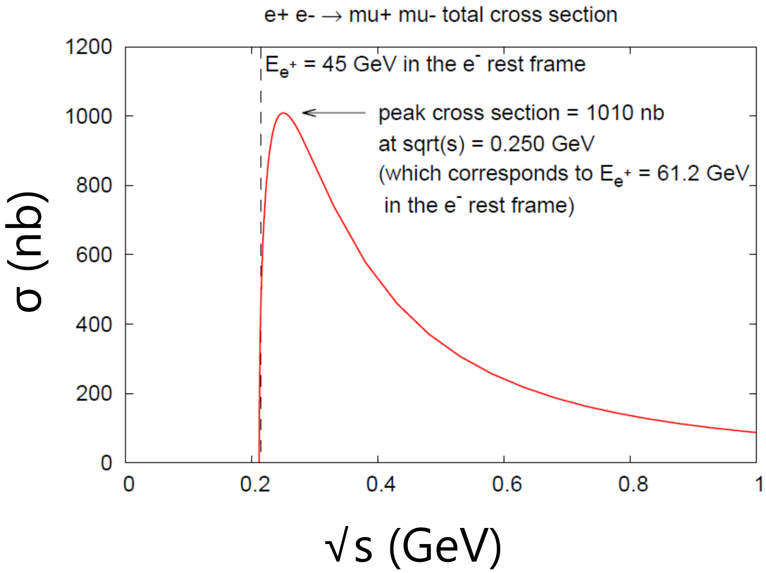


  2. $\gamma A \rightarrow \mu^+\mu^- A$, γ is generated via Laser Compton Scattering (LCS)



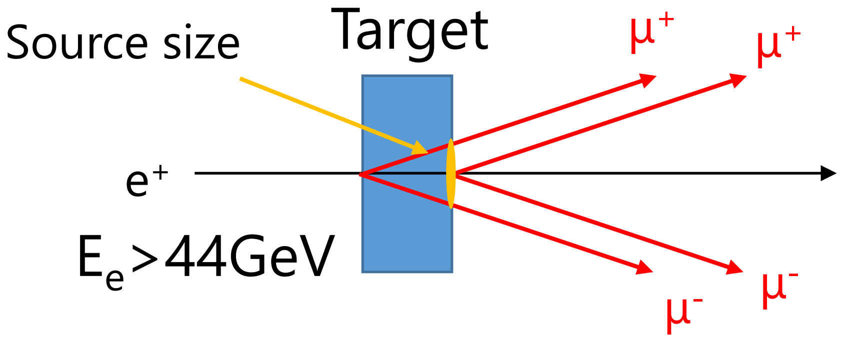
1. Muon beam from e^+





- Production process
  - A positron beam generates electromagnetic showers in a fixed target. Then $e^+ + e^- \rightarrow \mu^+ + \mu^-$ or $\gamma + e^- \rightarrow e^- + \mu^+ + \mu^-$ happens.
  - $E_e > 44$GeV because a fixed target is used
  - The cross section of $e^+ + e^- \rightarrow \mu^+ + \mu^-$ のbecomes maximum ($\sigma \sim 1\mu b$) just above the energy threshold.

Target material



- A thinner target is better to produce a low emittance beam.

- Small Z material has a larger muon production efficiency, because interaction length $\lambda(\mu^+\mu^-)$ divided by radiation length X_0 gets smaller.

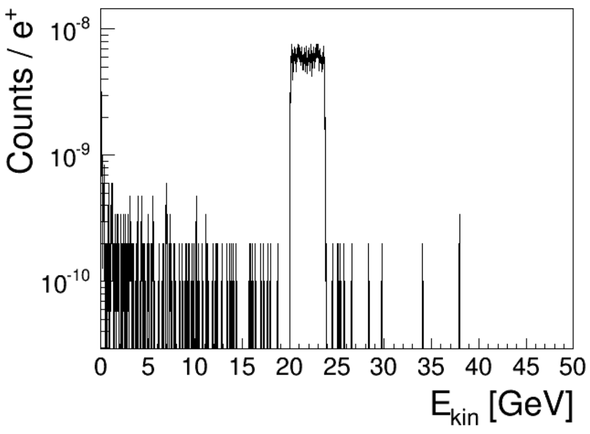
	Z	X_0 (cm)	$\lambda(\mu^+\mu^-)$ (cm)	$\lambda(\mu^+\mu^-)/X_0$
Be	4	35.2	2.0e6	**5.7e4**
Cu	29	1.4	4.1e5	**2.8e5**
W	74	0.4	2.1e5	**6.1e5**

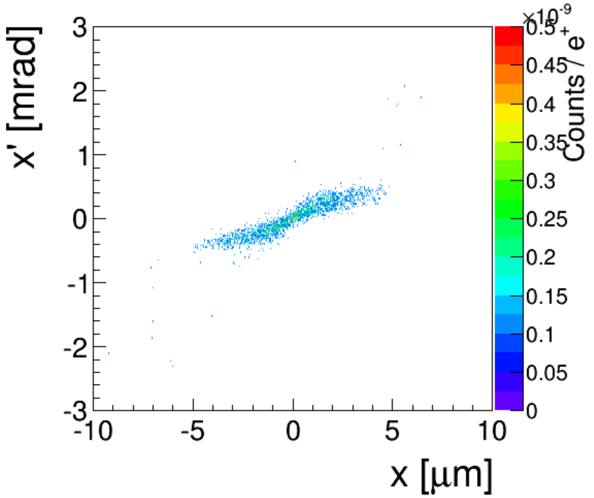
c.f. NIM A 807 (2016) 101-107, Table 1

Case study: 45GeV e^+ beam on Be 1cm

- Geant4 simulation: Reference physics list (FTFP_BERT_EMV) plus
  - ✓ **G4AnnihiToMuPair** ($e^+ + e^- \rightarrow \mu^+ + \mu^-$)
  - ✓ **G4GammaConversionToMuons** ($\gamma + e^- \rightarrow e^- + \mu^+ + \mu^-$)
  - ✓ G4eeToHadrons ($e^+ + e^- \rightarrow$ hadrons)

- Be 1cm = $0.03X_0$ (thin target)
- Peak of $e^+ + e^- \rightarrow \mu^+ + \mu^-$ @22.5GeV
- Low energy tail from $\gamma + e^- \rightarrow e^- + \mu^+ + \mu^-$
- Eff.($\mu^+\mu^-$) = 1e-7 → 3e7 $\mu^+\mu^-$/s given e^+ intensity of ILC



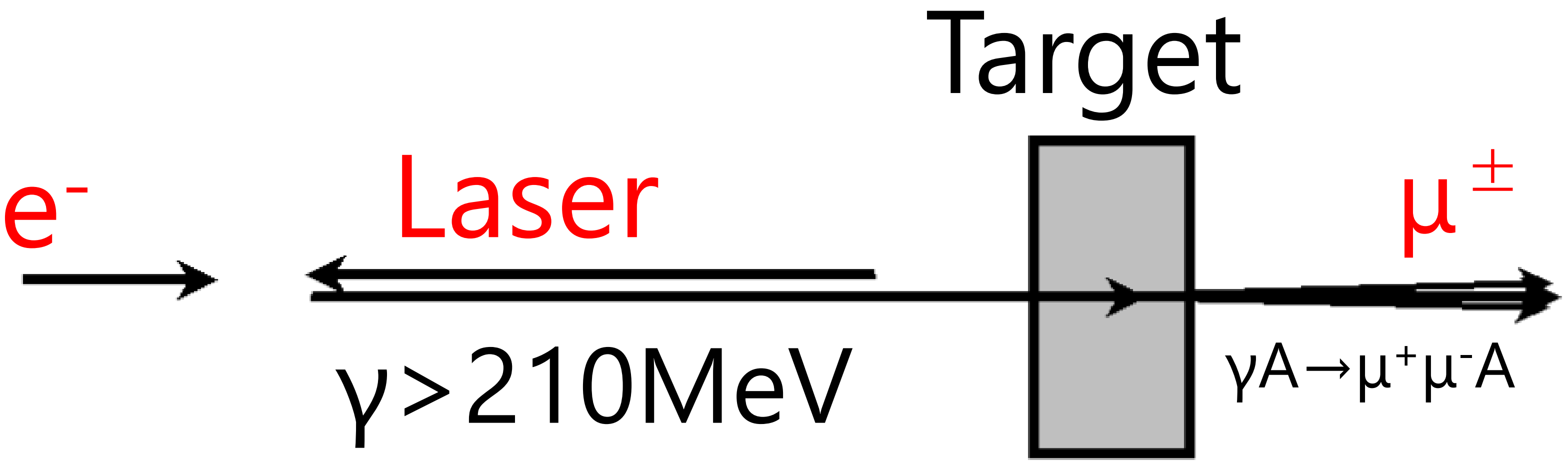


σ_x=2μm, $\sigma_{x'}$=0.3mrad

$\varepsilon_x = 2 \times 10^{-4}$ mm*mrad

Not intense,
but very luminous
and high energy

2. Use Laser Compton Scattering



Target

e^-

Laser

$\mu^\pm$

$\gamma > 210\text{MeV}$

$\gamma A \rightarrow \mu^+\mu^- A$

- O(GeV) e^- is available

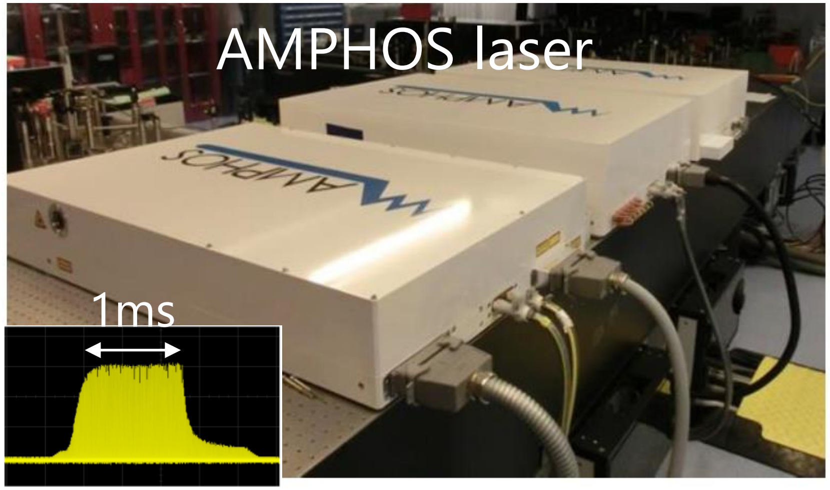
$$E_\gamma = \frac{4\gamma^2 E_L}{1+(\gamma\theta)^2+4\gamma E_L/m_e}$$

$$F_\gamma = 2f\frac{\sigma}{A}N_e N_L \propto f N_L/A \propto P\lambda/A \propto P/\lambda$$

γ ： γ-factor of e^-
E_L [eV] ： laser photon energy
θ [rad] ： Scattering angle ~**1/γ**
m_e [eV] ： elecron mass
f [/s] ： collision rate
σ [m^2] ： Thomson cross section
A [m^2] ： beam size of laser
N_e ： # of electrons/pulse
N_L ： # of photons/pulse
P [W] : average laser power
λ [m] : laser wavelength

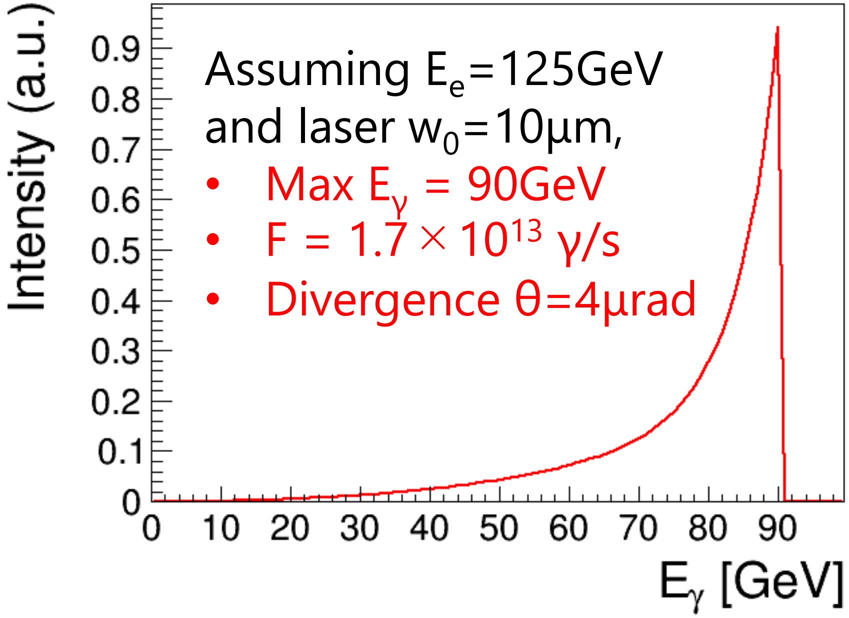
- A high average power & short wavelength laser is better.

Flux of LCS



- AMPHOS laser is best suited to the ILC bunch structure.
  - ✓ λ=1μm
  - ✓ Average power 200W
  - ✓ Burst Mode : 20J macro pulse in which 20mJ pulse, width~1ps, ~1MHz), width =1ms, 10Hz

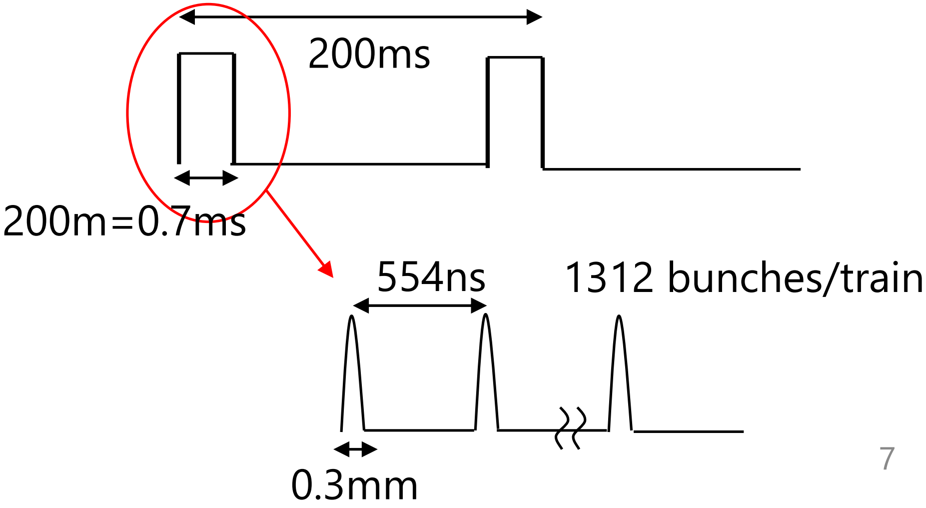
Energy spectrum of LCS γ



Assuming E_e=125GeV and laser w_0=10μm,

- Max E_γ = 90GeV
- F = 1.7×10^{13} γ/s
- Divergence θ=4μrad

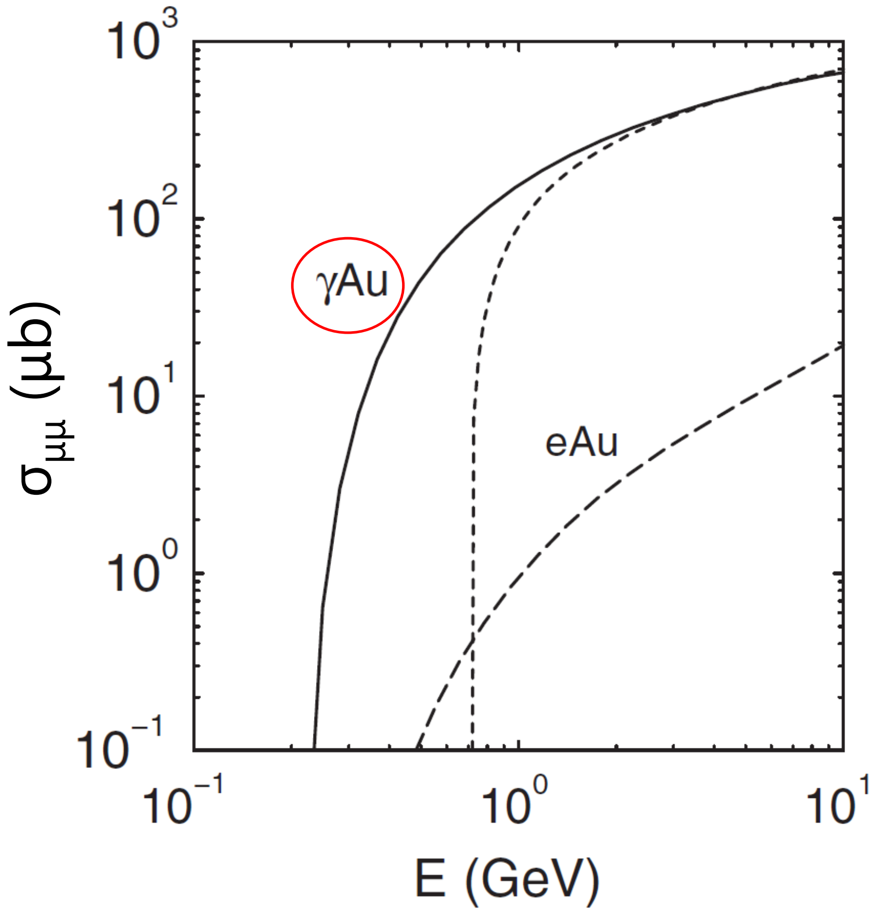
Bunch structure of the ILC



Muon production via γA→$\mu^+\mu^-$A

Total cross section of γA→$\mu^+\mu^-$A

c.f. Phys. Rev. ST Accel. Beams **12**, 111301 (2009)



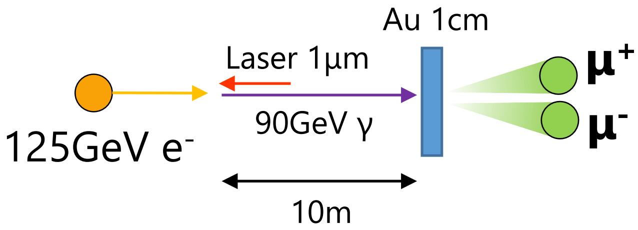
- High energy γ is better
  - ✓ High energy e^- → 125GeV
  - ✓ Short wavelength laser
- If target thickness L is set equal to the attenuation length of LCS γ and the energy of LCS γ is high enough, the muon flux is

$$\boxed{F_{\mu\mu} = \frac{\sigma_{\mu\mu} N_A}{A} \rho L F_\gamma = \frac{\sigma_{\mu\mu}}{\sigma_{ee}} F_\gamma}$$

N_A : Avogadro constant
A : mass number, ρ : density, L : target thickness
σ_{ee} : Total cross section of e-pair production

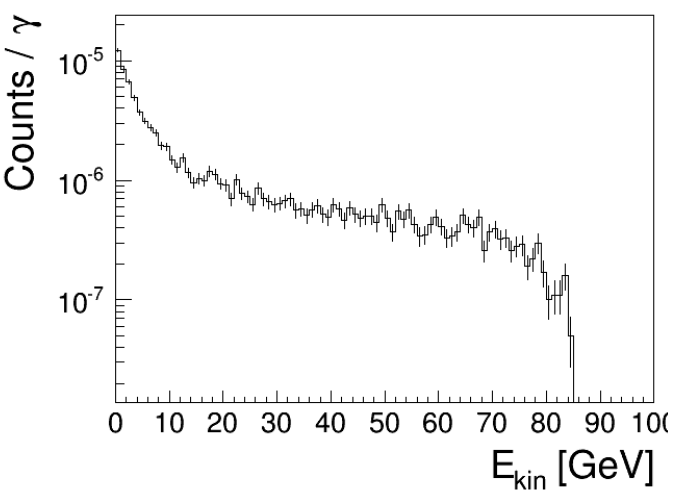
- But large Z target is a little better because σ_{ee} becomes smaller than Z^2 dependence due to the effect of electron cloud screening.

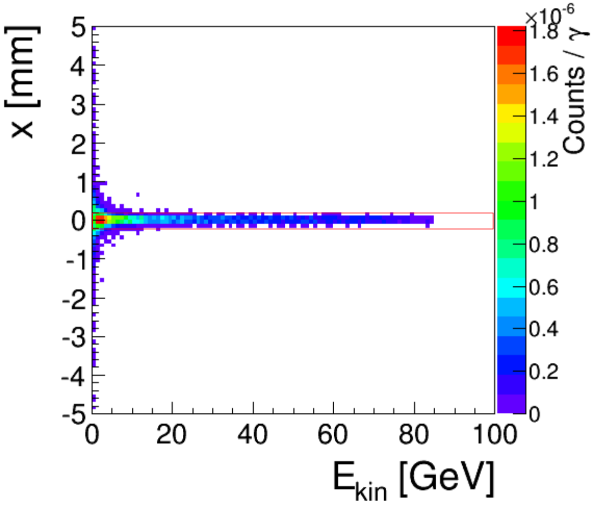
Case study: 90GeV LCS γ, Au 1cm

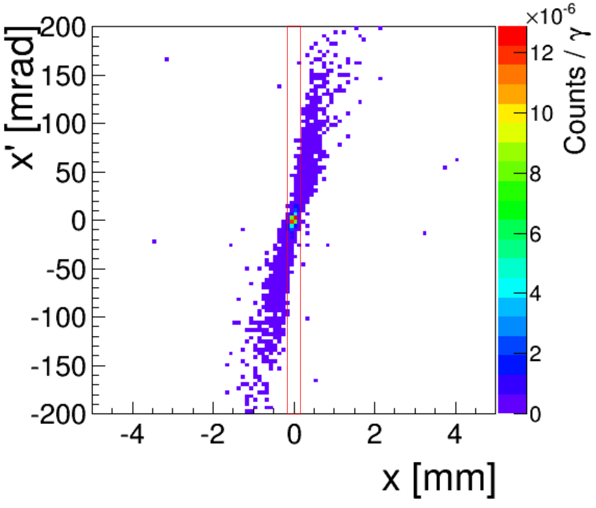


- The size of a muon source is determined by the distance from the LCS IP and the fixed target. 10m → 40μm (θ=4μrad)

- G4 simulation using monochromatic 90GeV γ
- If a collimator selecting |x|<0.1mm,
  - ✓ Eff.($\mu^+\mu^-$) = 2.7e-5 → **4.6e8 $\mu_+\mu_-$/s**
  - ✓ σ_x=45μm, $\sigma_{x'}$=6.9mrad, ε_x=0.27 mm*mrad
- **Intense, luminous, and high energy** (but broad energy spectrum)







Comparison

	~1GeV p	**45GeV e^+**	**LCS γ**
Kinetic energy (GeV)	10^{-3}	22.5	0~85GeV
Energy width (%)	10	20	broad
Emittance (mm*mrad)	$O(10^3)$	$O(10^{-4})$	O(0.1)
Flux (/s)	10^8	3×10^7	5×10^8
Others		$\mu^+\mu^-$対	$\mu^+\mu^-$対

- Conventional method is suitable for material sciences like μSR or element analysis using muonic X rays which needs muons to stop in a sample.
- A low emittance and high energy muon beam is suitable for radiography of large structure, which is currently conducted using cosmic ray muons. And input to muon collider?
- "e^+&fixed target" is best to generate a low emittance beam, but "LCS method" is better in intensity.

Summary

- We considered two methods to generate a muon beam from a $e^{\pm}$ beam.
  - ✓ 45GeV positron on fixed target ($e^+ + e^- \rightarrow \mu^+ + \mu^-$)
    - E=22.5 GeV, F=3×10^{7} $\mu^+\mu^-$/s, ε~2×10^{-4} mm*mrad
  - ✓ LCS γ from e- and laser on fixed target ($\gamma + A \rightarrow \mu^+ + \mu^- + A$)
    - E=0~85 GeV, F=5×10^{8} $\mu^+\mu^-$/s, ε~0.3 mm*mrad

- These beams have much higher energy and much lower emittance compared to the conventional muon beams generated from proton beams. Applications like radiography and large structure analysis are promising.