Fixed target experiments using electron and positron beams

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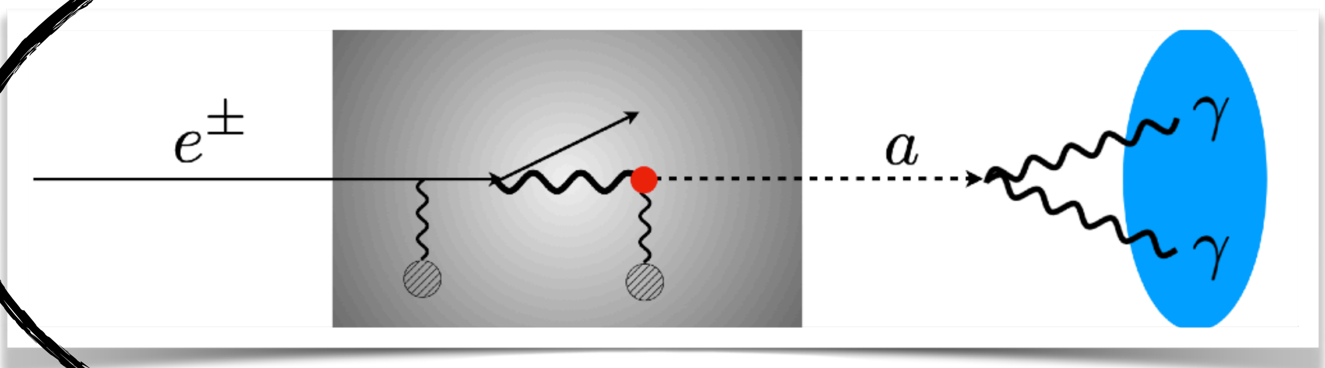
阪大素粒子セミナー, *8 June 2021*

Non-collider experiments (for particle physics)

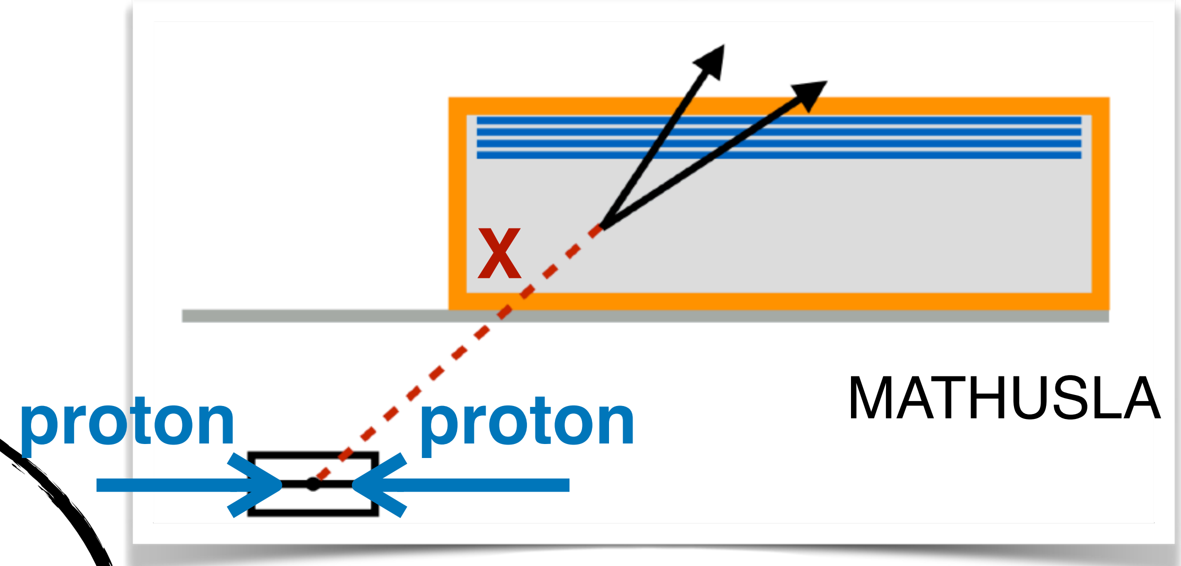
This talk

Fixed-target / Beam dump



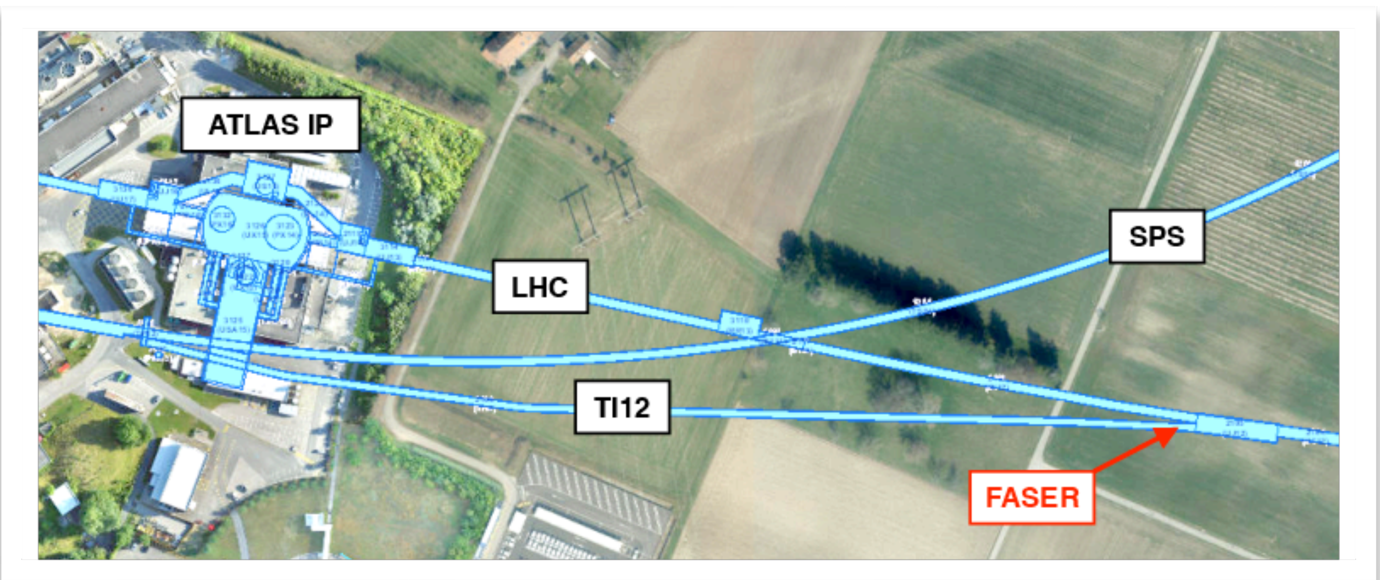
etc…

Off-axis detector



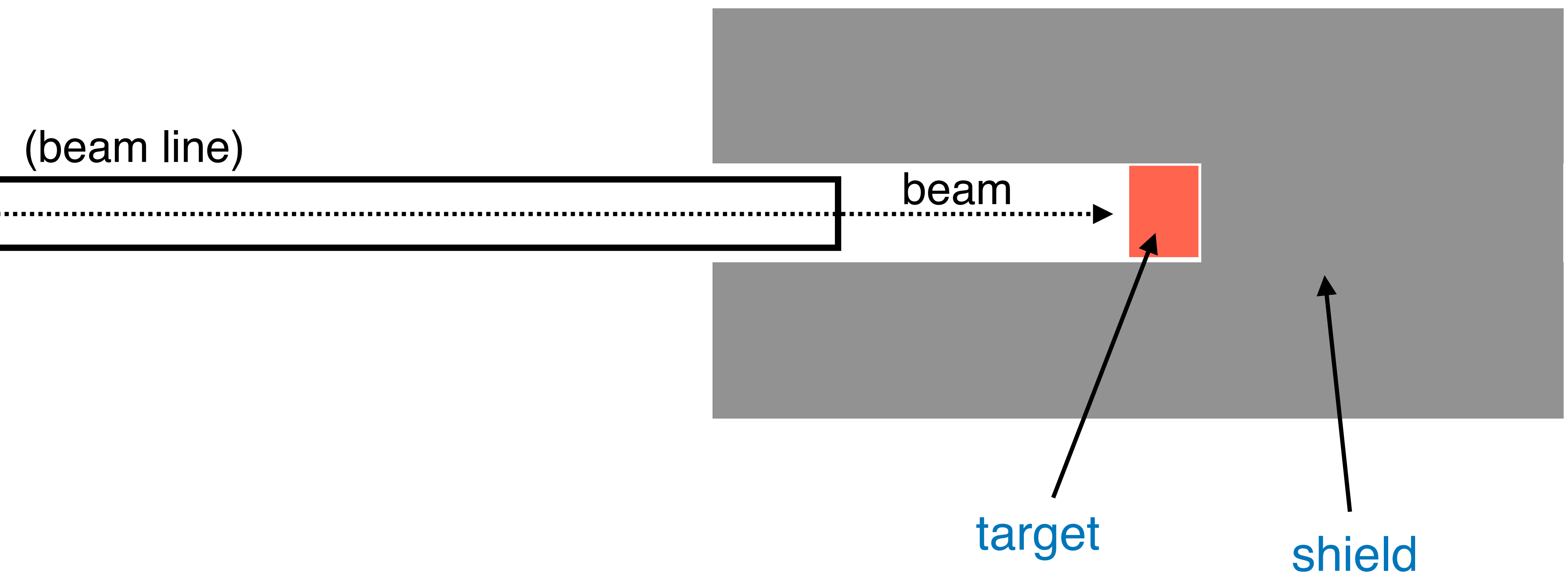
Pic. from David's slide

Forward detector



Pic. from arXiv:1901.04468

(one page for very basic terms…)



Made of C (Z=6), Cu (Z=29), Pb (Z=82), H_2O, Concrete, …

If this kind of system is used for discarding beams, this is called beam dump.

Contents

(1) Basics of fixed target experiments using e+/e- beam

- This will help you calculate the sensitivity of your favorite model from the beginning by yourself without any input.

(2) Introducing some fixed target experiments and their features

- This will help you consider an experimental setup by yourself.

(3) What can we do at ILC and KEK?

Fixed target vs Collider

- Center of mass

(High) $$\sqrt{s}\ (\text{Collider}) = 2E_{\text{beam}}$$

(Low) $$\sqrt{s}\ (\text{Fixed-target}) = \sqrt{m_{\text{beam}}^2 + m_{\text{target}}^2 + 2E_{\text{beam}} m_{\text{target}}}$$

- Luminosity

$$\mathcal{L}(\text{LHC}) = 3000\ \text{fb}^{-1}$$

$$\mathcal{L}(\text{Fixed-target}) \sim \frac{N_{\text{beam}}}{10^{13}} \frac{1}{Z^2} \frac{(\text{thickness of target})}{X_0}\ \text{fb}^{-1}$$

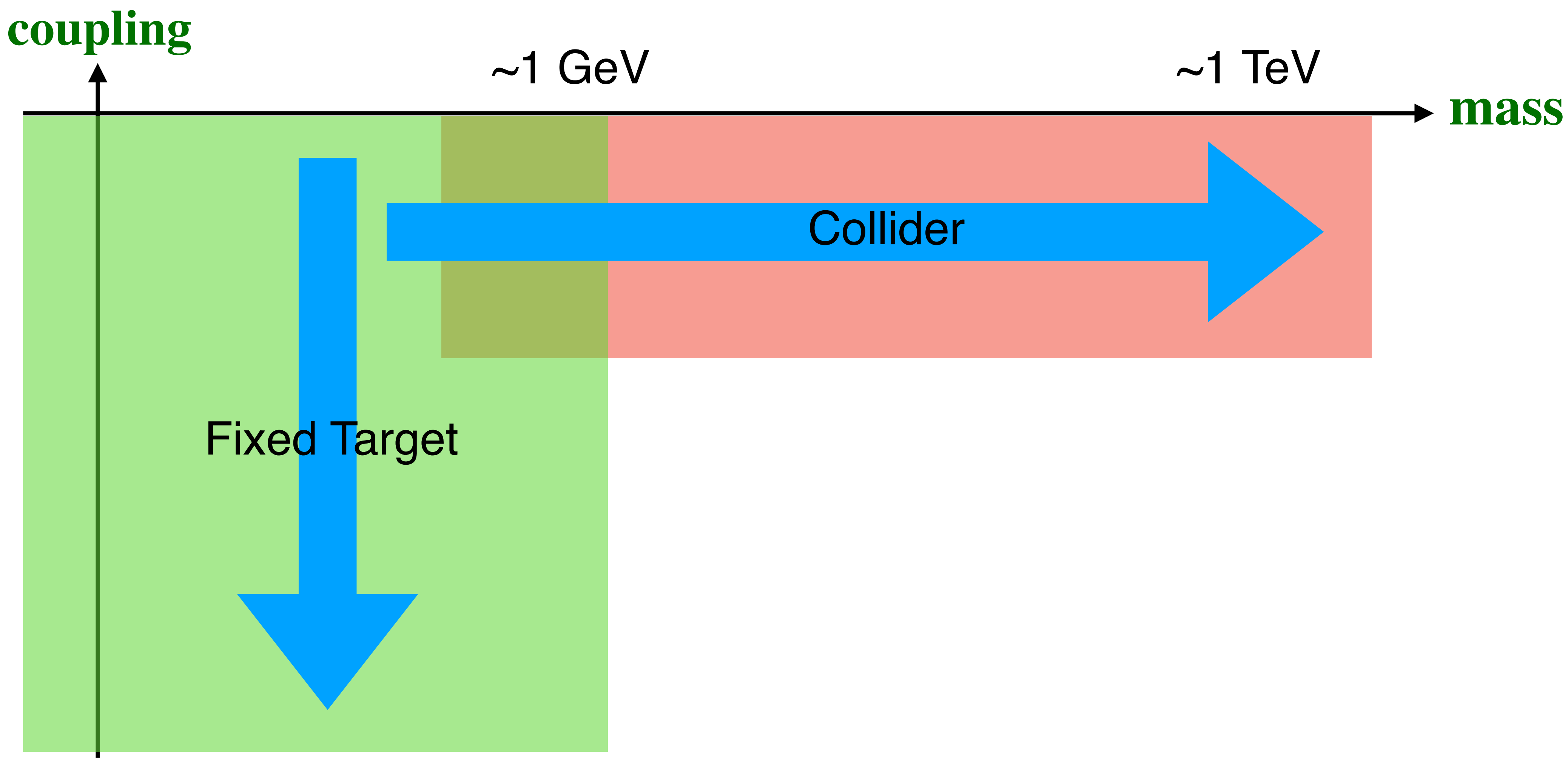
(X_0 is radiation length of target (later pages))

(N_{beam} ~10^{21}/ year @ILC)

Fixed target experiment is Luminosity frontier

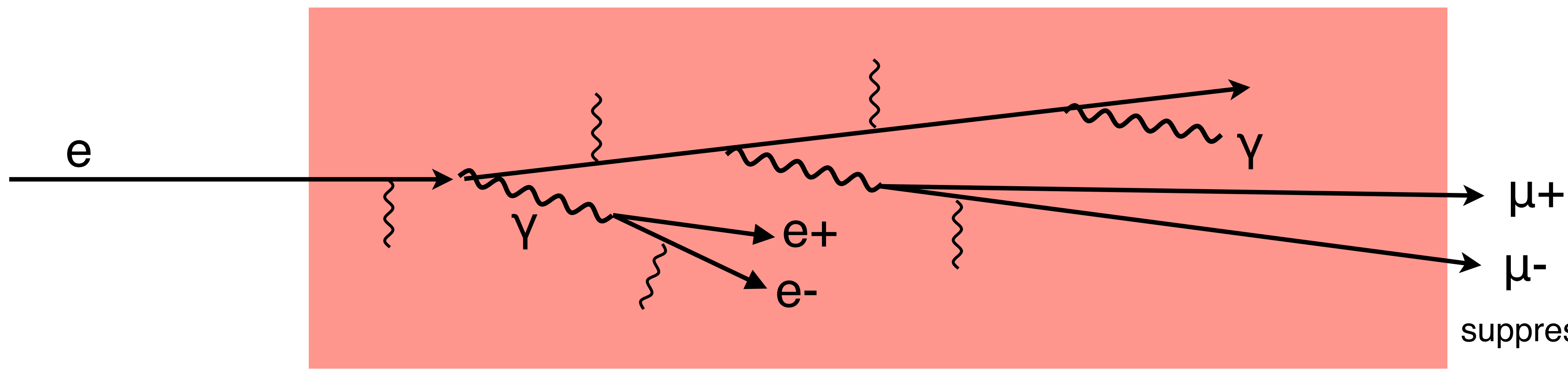
Fixed target vs Collider

- Complementary to Collider experiments
- It can coexist with a collider facility and is relatively low cost.



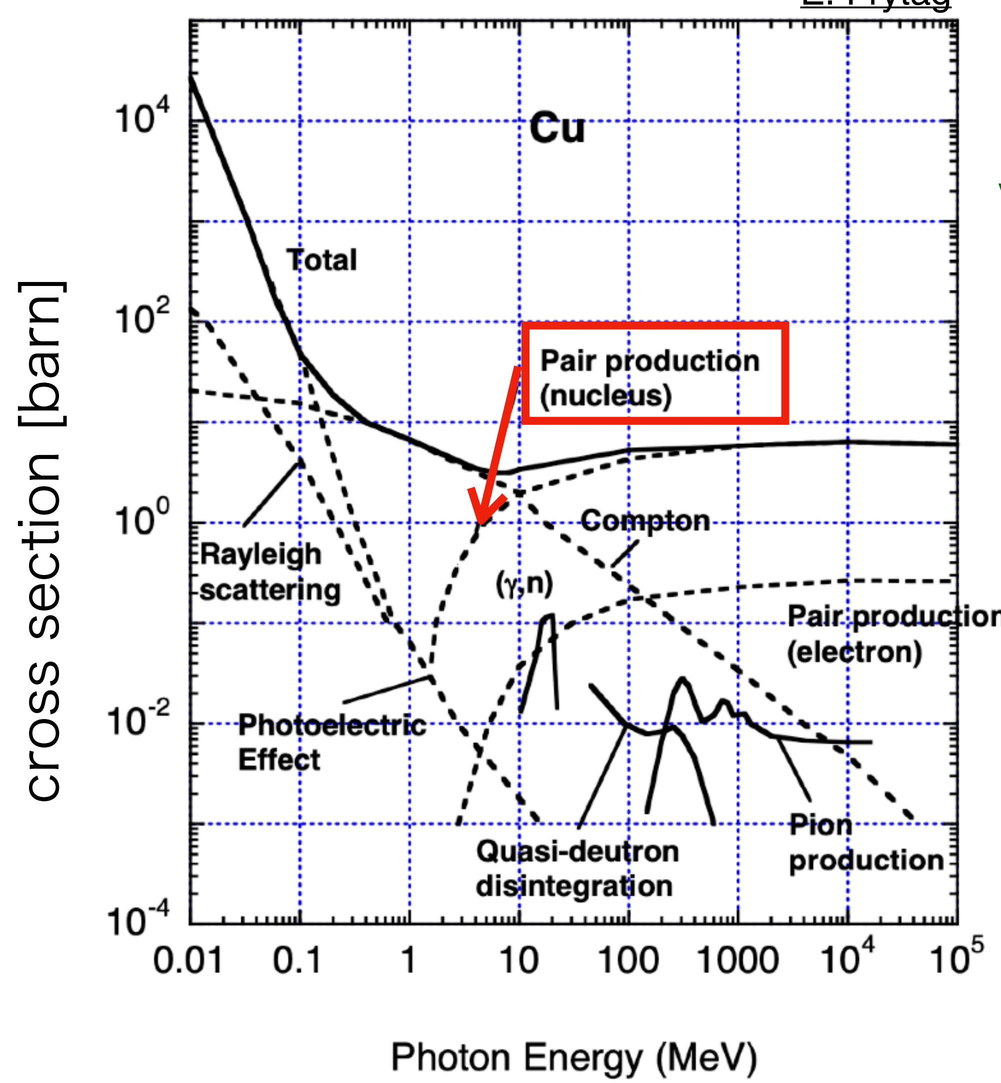
Physical processes

Electromagnetic shower: Leptons and photons are produced



suppressed by $(m_e/m_\mu)^2 \sim 1/40000$

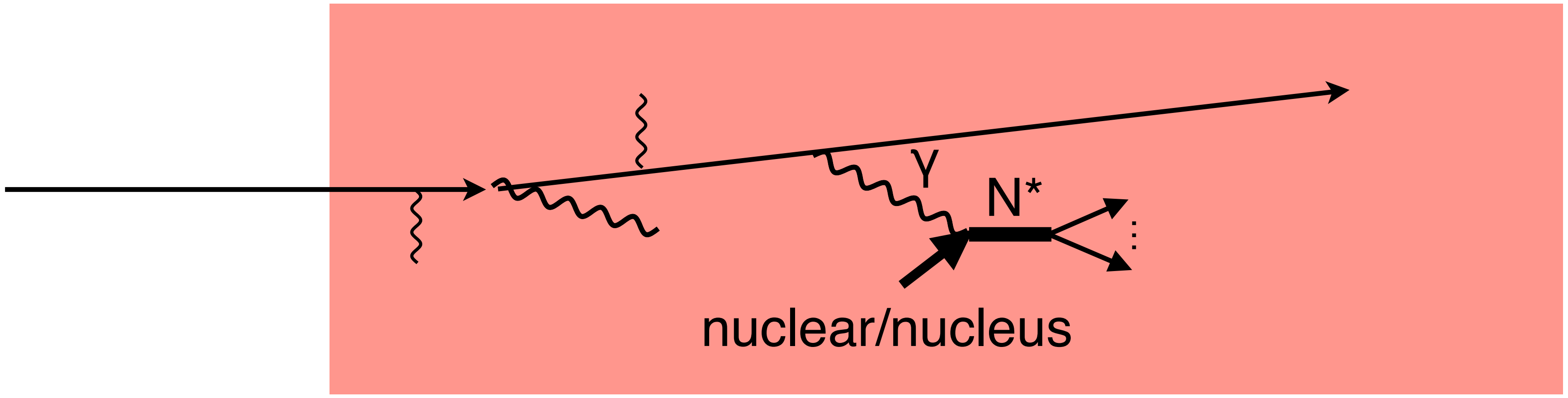
E. Frytag

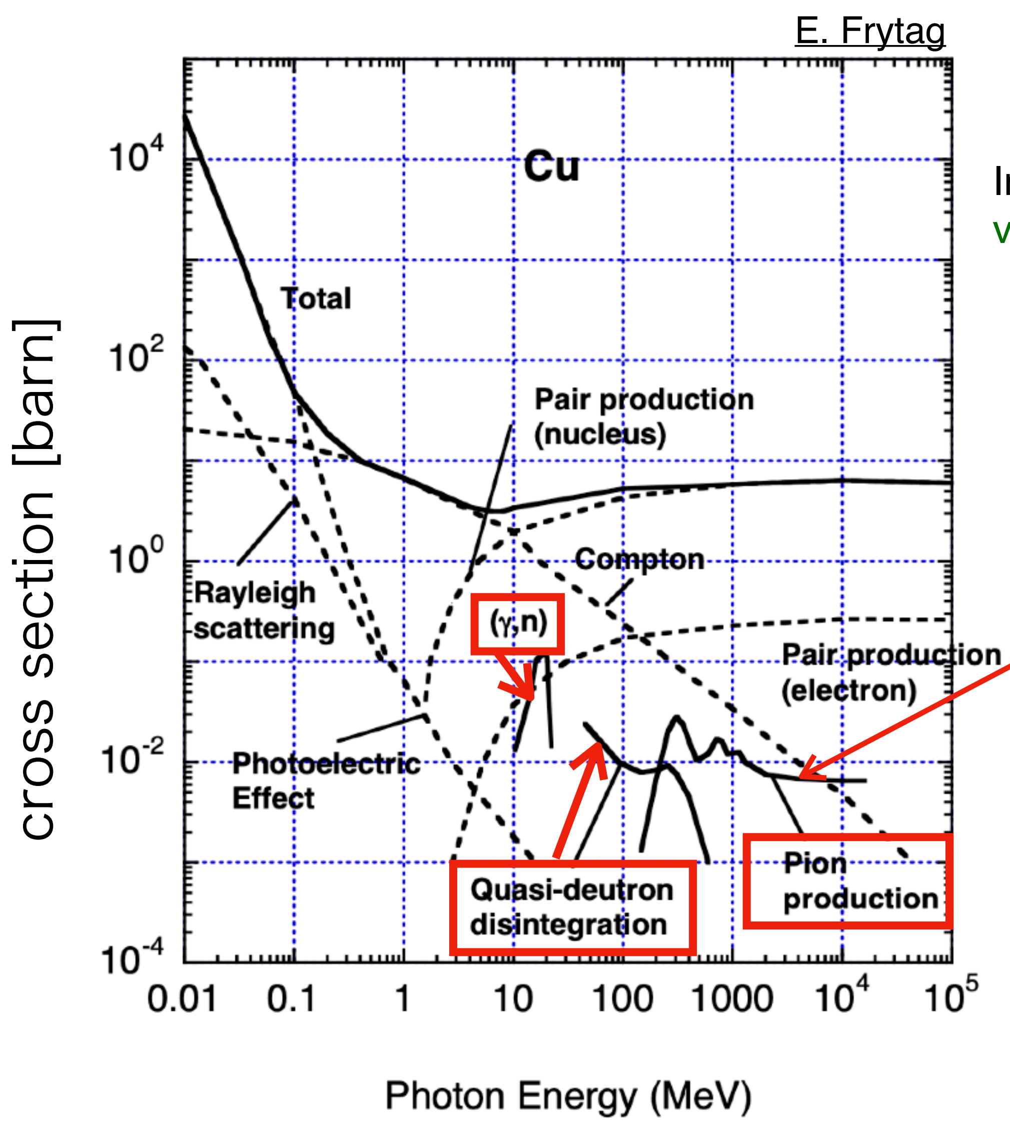


Interactions via real photon is dominant. Those via virtual photon is important only for very thin target.

Physical processes

Photonuclear interaction: Mesons and baryons are produced





Interactions via real photon is dominant. Those via virtual photon is important only for very thin target.

(N=p,n)

γ N → π p (+X)

γ N → π n (+X)

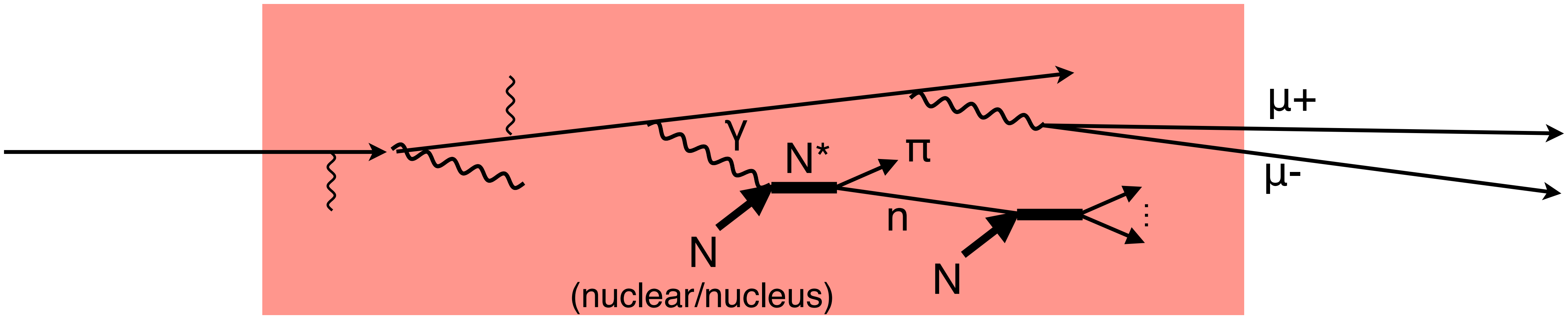
γ N → K Λ (+X)

γ N → K Σ (+X)

γ N → rho p (+X)

…

Physical processes



(e.g., n n → n n π^0, π^0 → γγ)

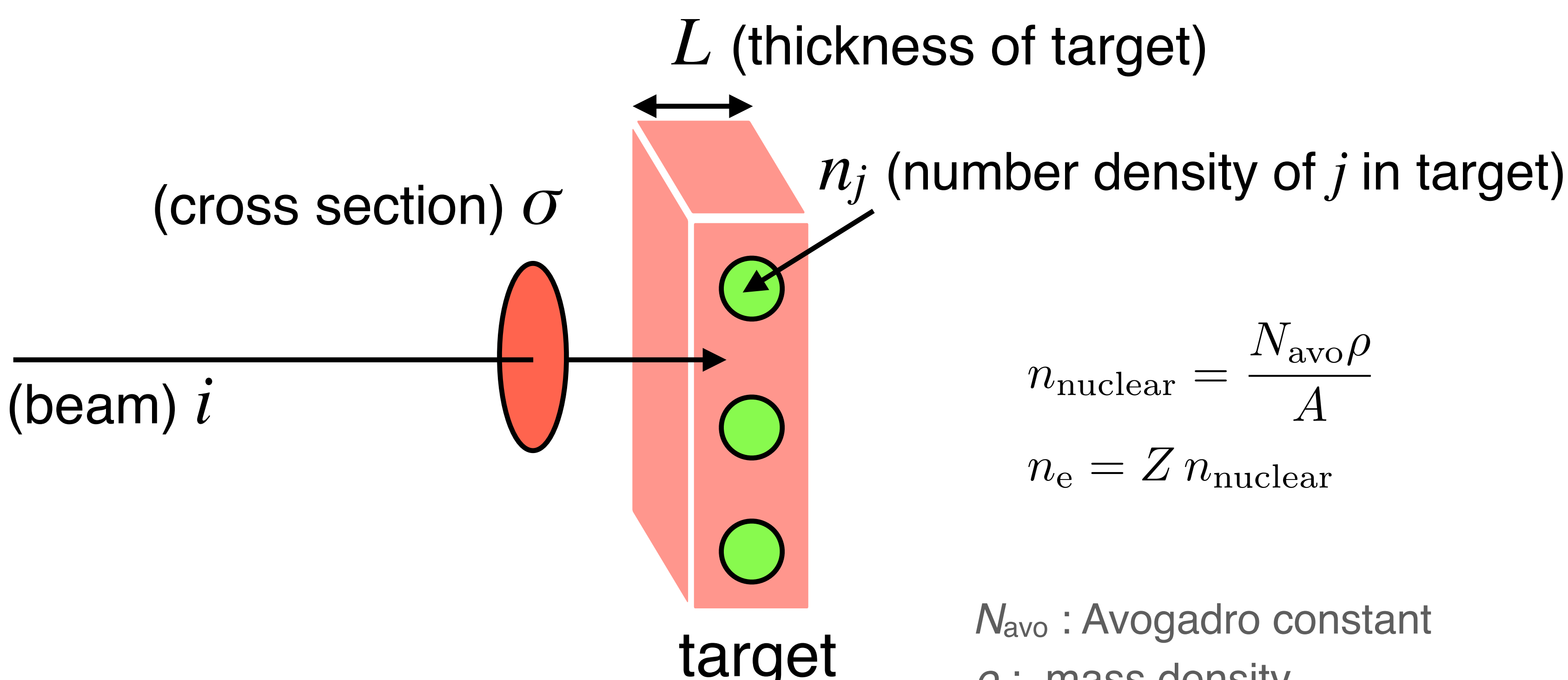
Secondary hadron interaction / decay / capture

Secondary lepton …

Number of interaction

Beam i interacts with j in target

$$N(\text{interaction}) = N(\text{beam})\ n_j\ L\ \sigma(E)$$

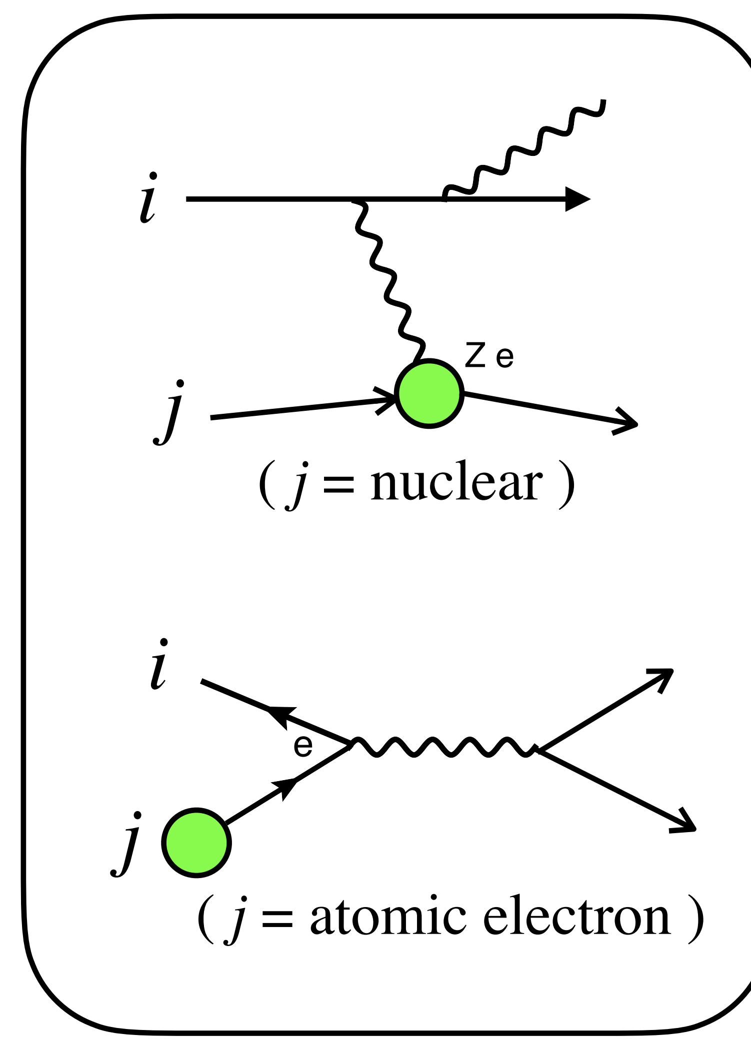


$$n_{\text{nuclear}} = \frac{N_{\text{avo}}\rho}{A}$$

$$n_{\text{e}} = Z\, n_{\text{nuclear}}$$

N_{avo} : Avogadro constant
ρ : mass density
Z : atomic number
A : mass number
(Aluminium: ρ=2.7g/cm^3, Z=13, A=27)

j depends on process



Luminosity

Thin target $L < \mathcal{O}(0.1) X_0$

$$N(\text{interaction}) = \underbrace{N(\text{beam})\; n_j\; L}_{\text{Luminosity}}\, \sigma(E)$$

$$\text{Luminosity} \sim \frac{N(\text{beam})}{10^{13}} \frac{1}{Z^2} \frac{L}{X_0}\ \text{fb}^{-1}$$

(This is for j=nuclear. Z^2 is replaced to Z for j=atomic electron.)

ex) N(beam) ~ $4*10^{21}$ / year @ILC

X_0 : radiation length (You will see this in any literature)

$$X_0 \simeq \frac{m_e^2 A}{4\,\alpha^3 Z^2 N_{\text{avo}} \ln(183\, Z^{-1/3})}$$

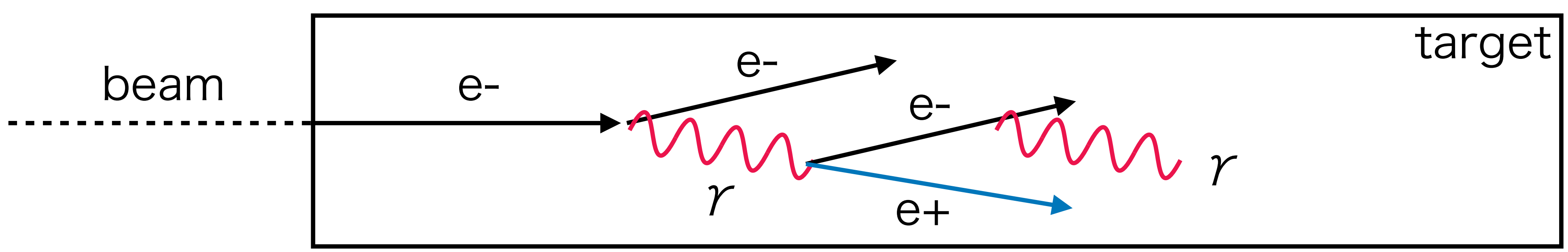
- Characteristic length of EM shower
- The length that the electron energy becomes $E_{beam}/e \sim 0.36\ E_{beam}$.
- $(9/7)*X_0$ = Photon's mean free path
- X_0 (Cu) = 1.4 cm, ….

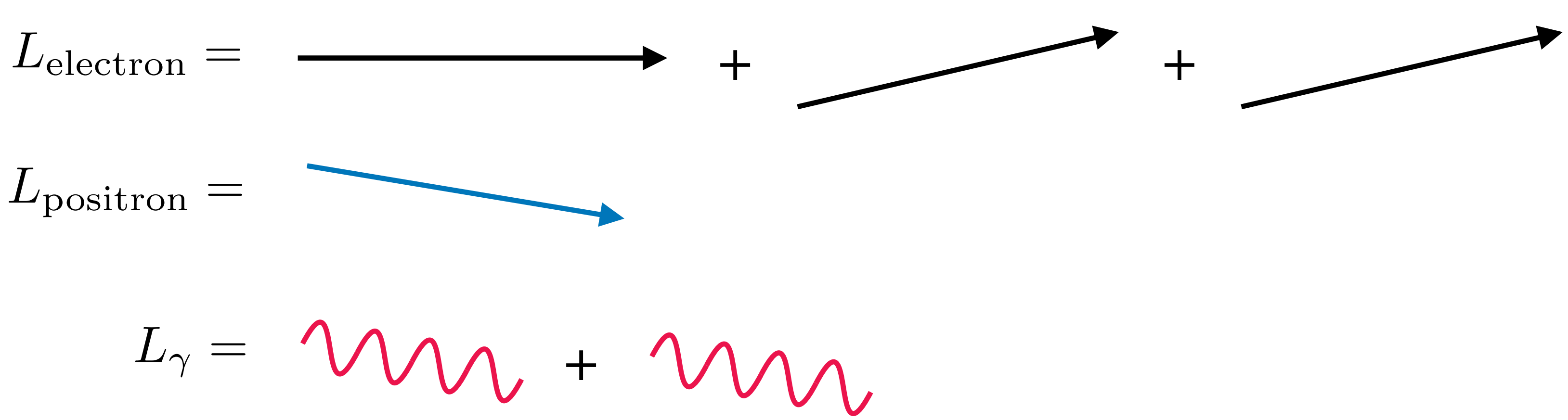
Luminosity

Thick target $L > \mathcal{O}(1)X_0$

$$N(\text{interaction}) = \int_0^{E_\text{beam}} dE_{i'} \underbrace{N(\text{beam})\ n_j \frac{dL_{i'}}{dE_{i'}}}_{\text{Luminosity}} \sigma(E_{i'})$$

$\frac{dL_{i'}}{dE_{i'}}$: Track length = (Averaged total flight length of i' in target with energy range $[E, E{+}dE]$)





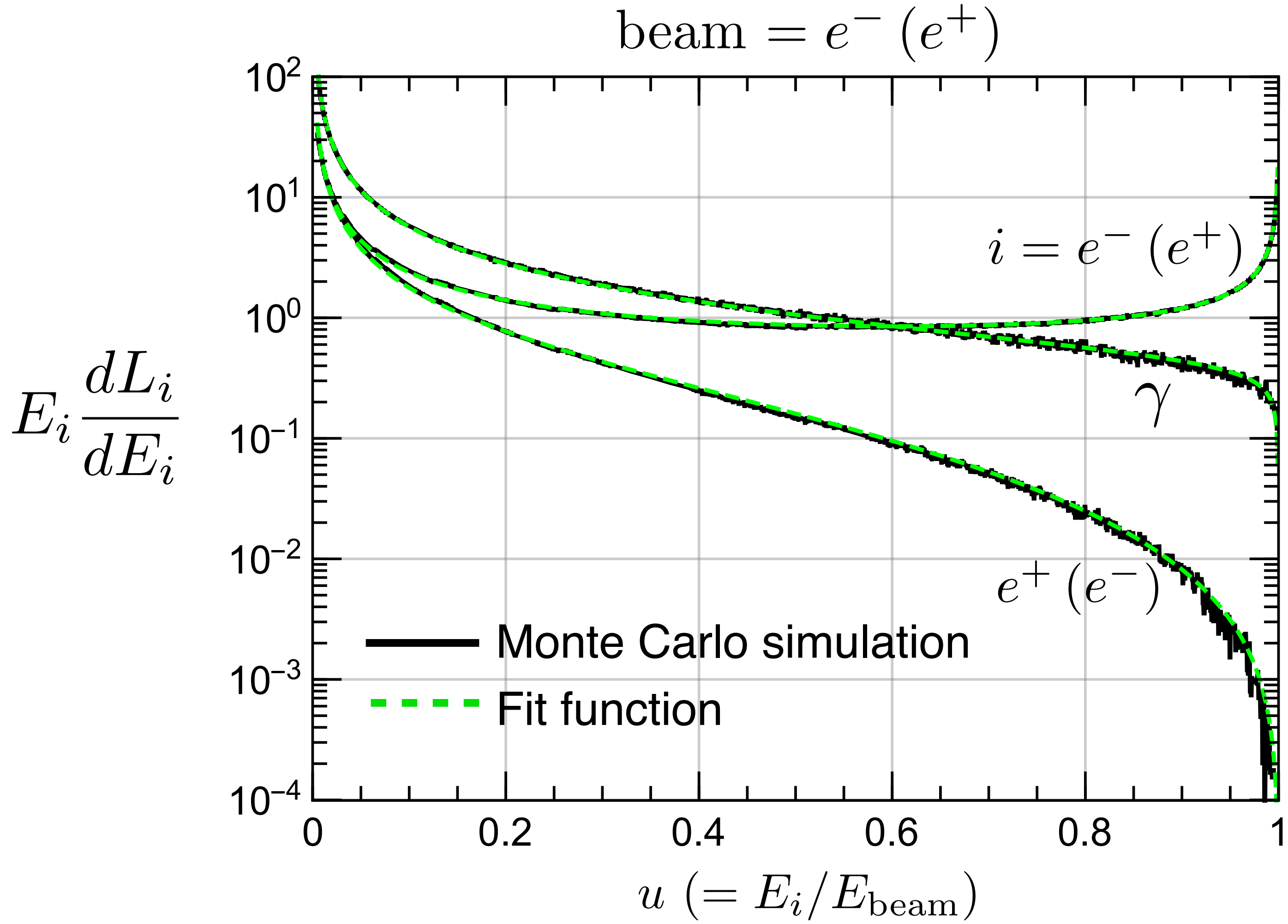
Luminosity

Thick target $L > \mathcal{O}(1)X_0$

$$N(\text{interaction}) = \int_0^{E_\text{beam}} dE_{i'} \, N(\text{beam}) \, n_j \frac{dL_{i'}}{dE_{i'}} \sigma(E_{i'})$$

Luminosity

$\frac{dL_{i'}}{dE_{i'}}$: Track length = (Averaged total flight length of i' in target with energy range $[E, E{+}dE]$)



L = 30 X_0

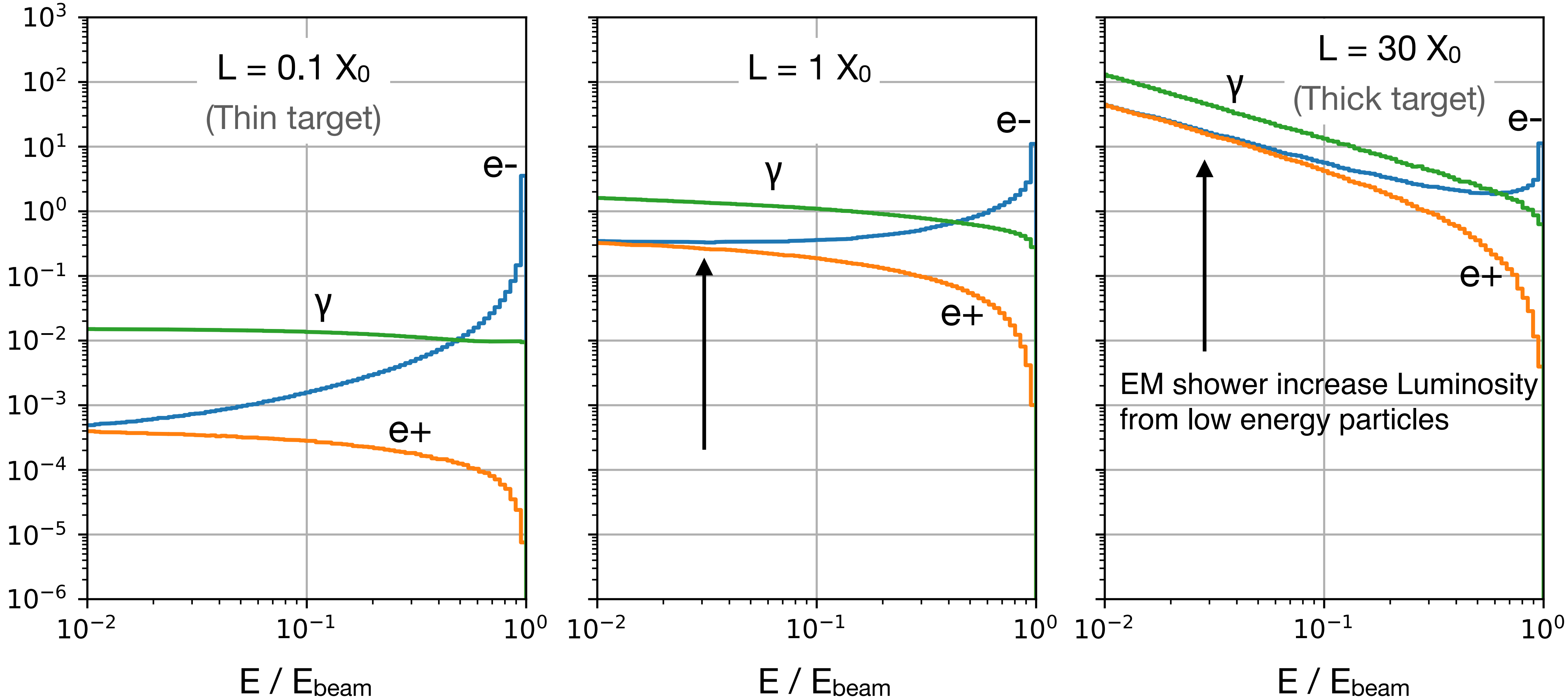
Luminosity

Thick target $L > \mathcal{O}(1) X_0$

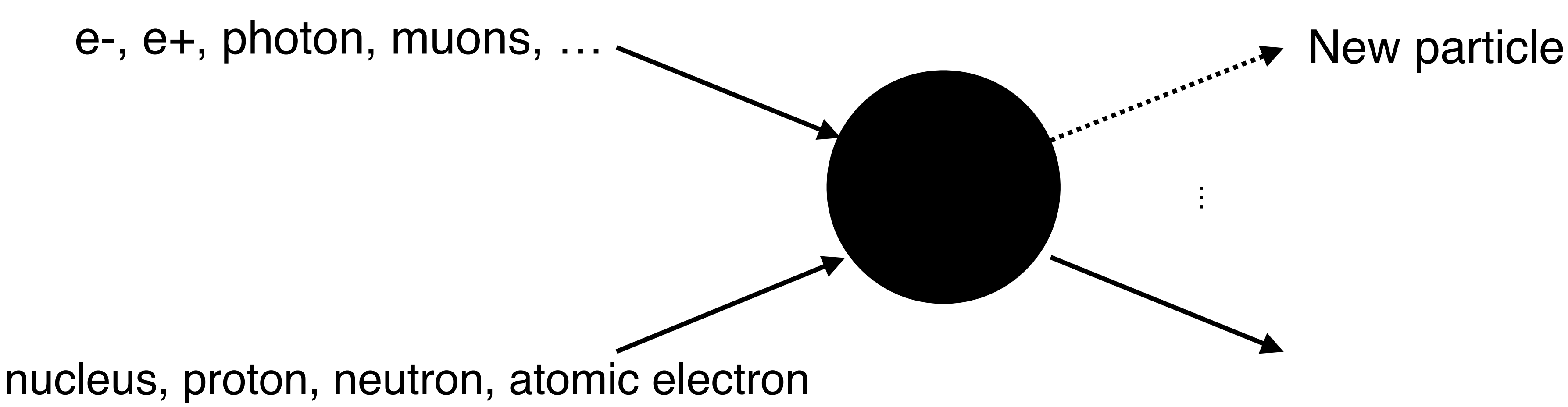
$$N(\text{interaction}) = \int_0^{E_\text{beam}} dE_{i'} \, N(\text{beam}) \, n_j \frac{dL_{i'}}{dE_{i'}} \sigma(E_{i'})$$

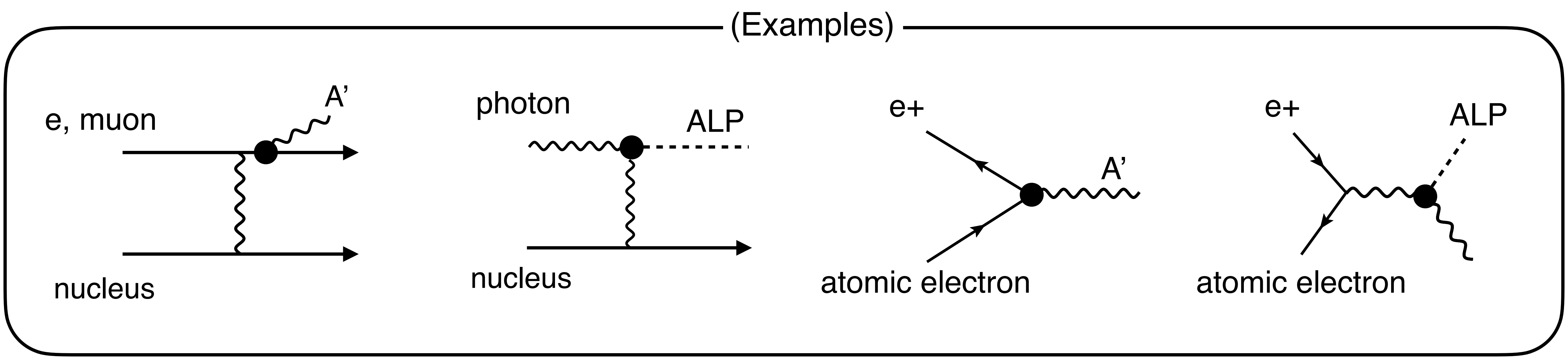
Luminosity

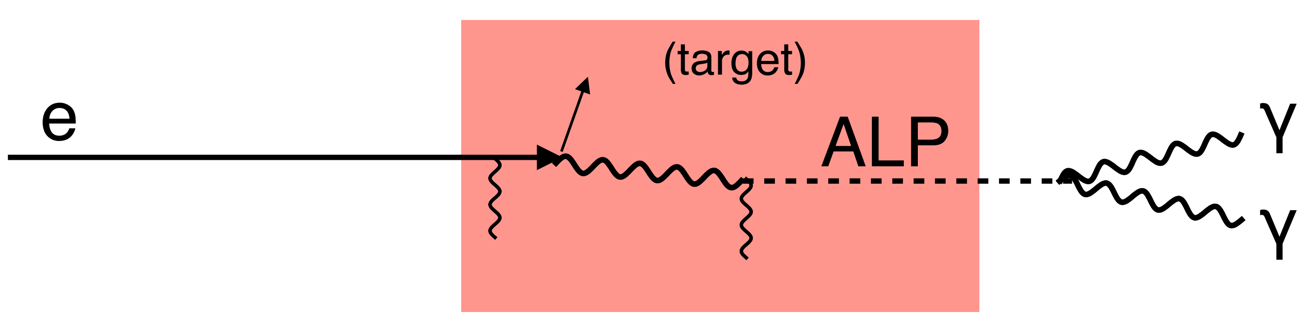
$\frac{d(\text{Luminosity})}{d\log_{10}(E/E_\text{beam})} \times Z^2 \times \text{fb}^{-1}/\text{s}$ N(beam) = 10^{13} /s



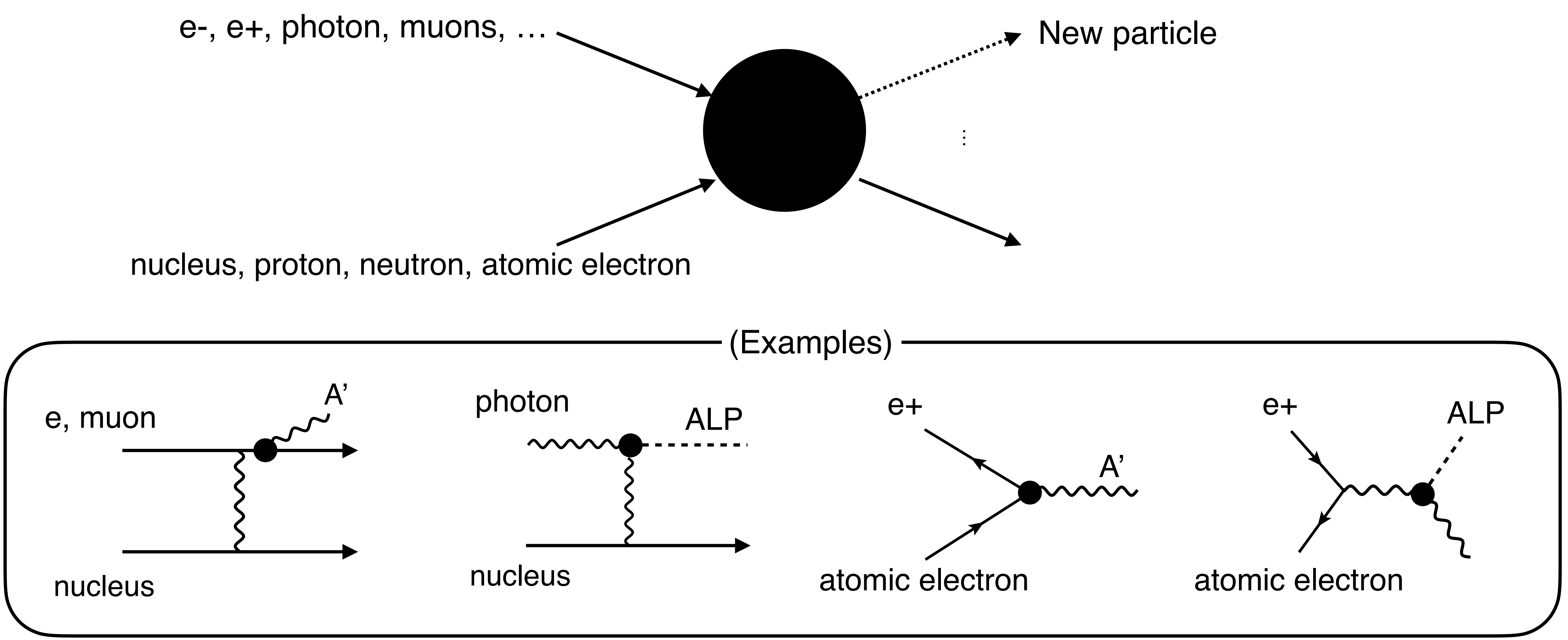
New particle production

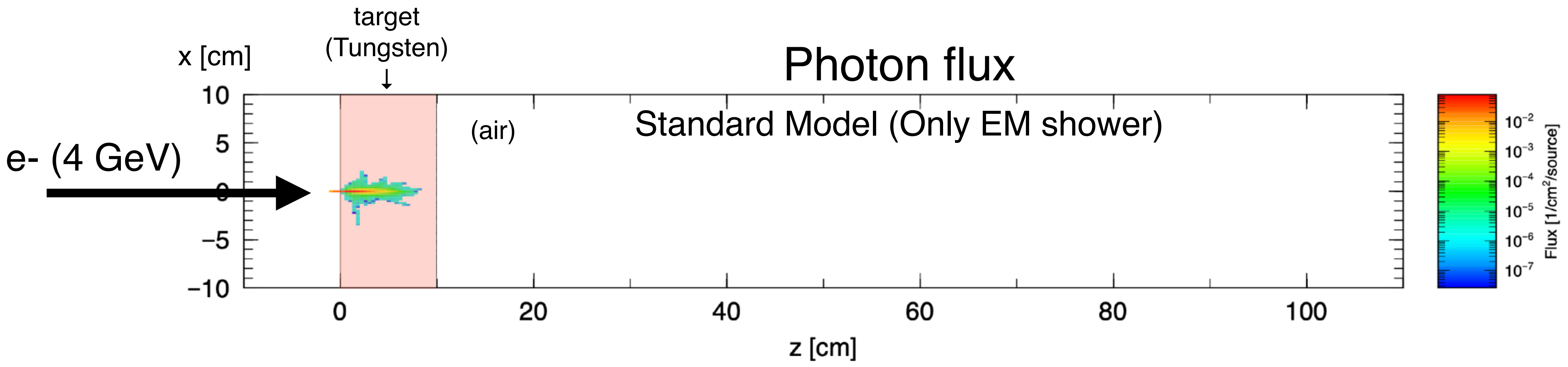




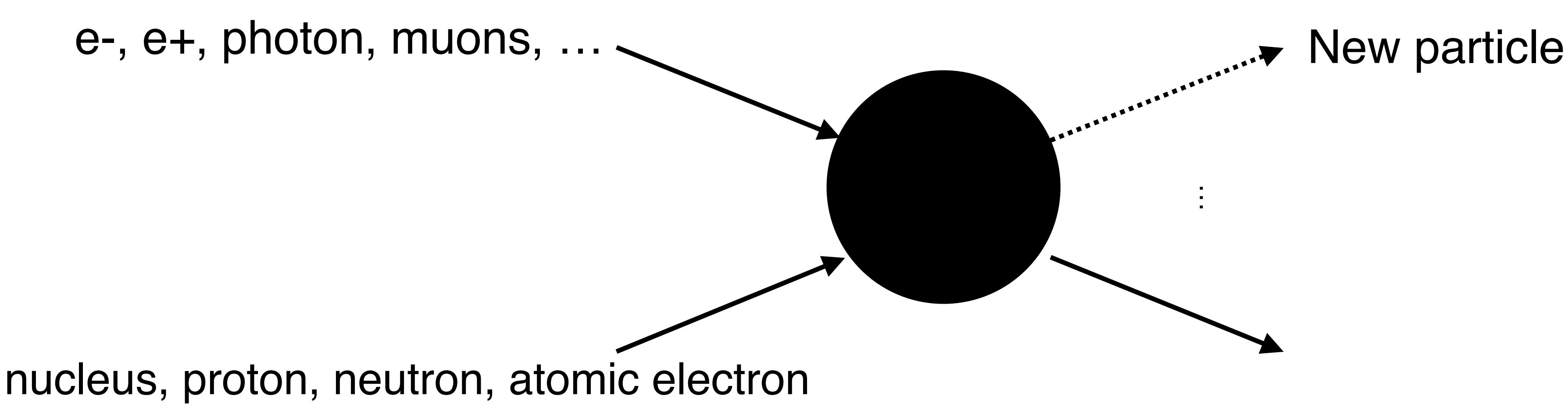


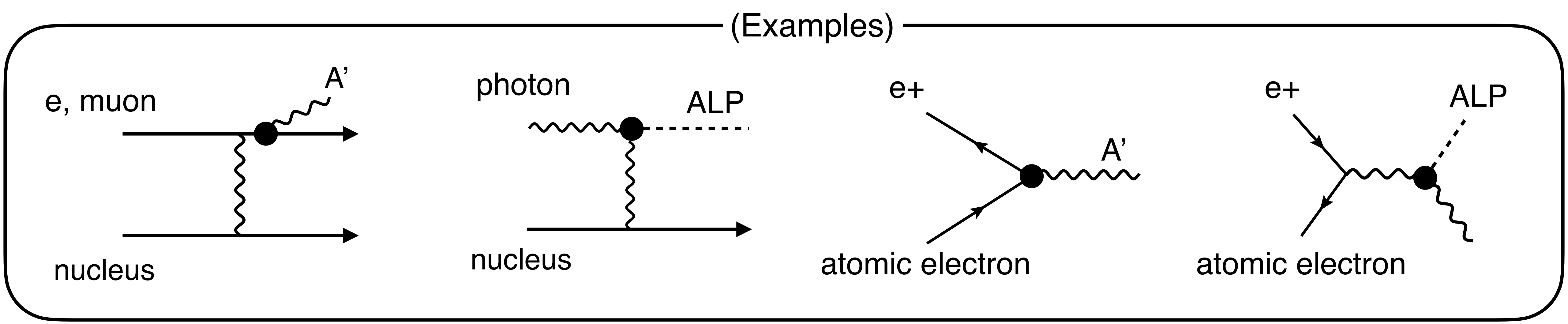
New particle production

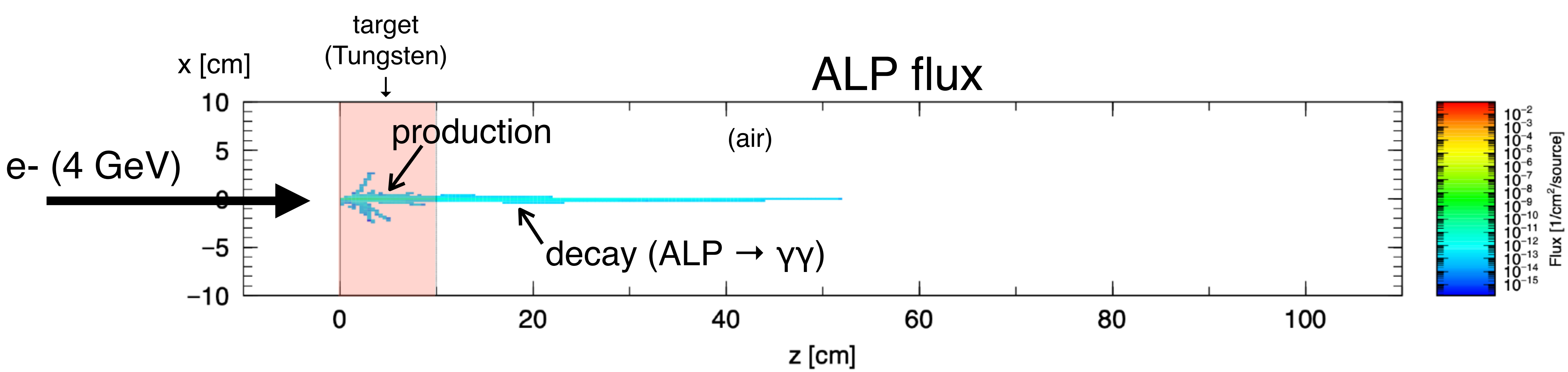




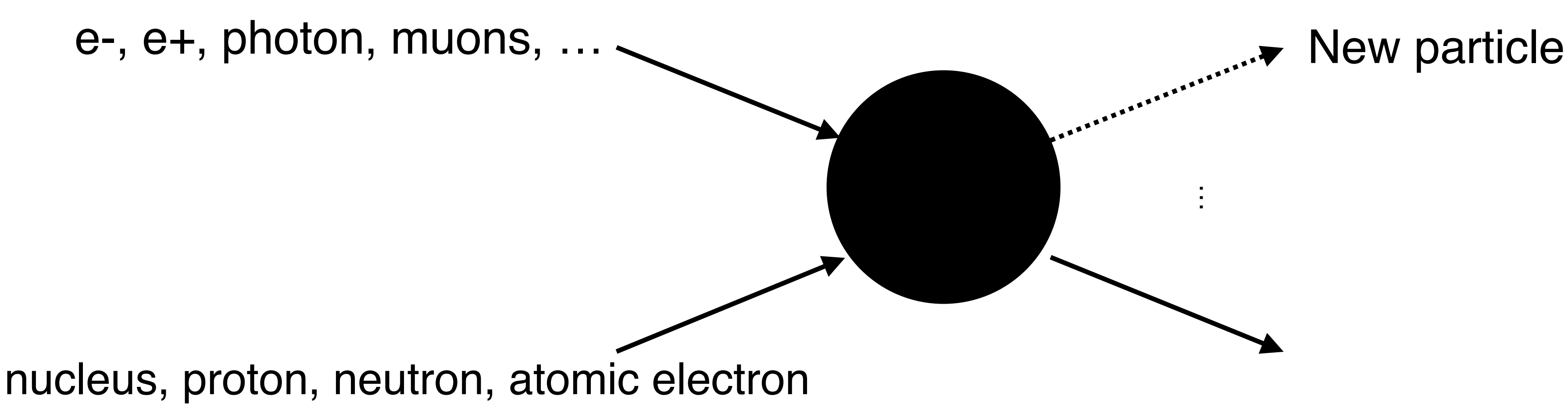
New particle production

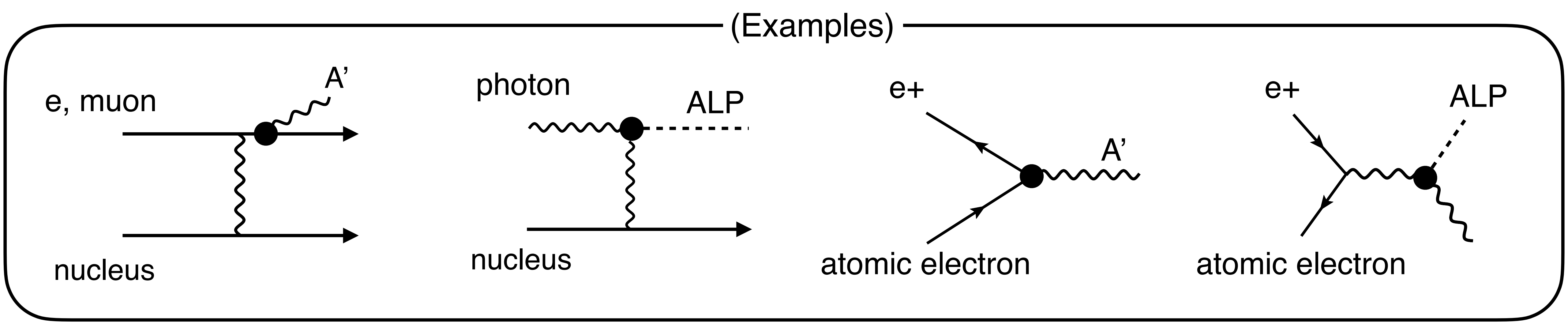


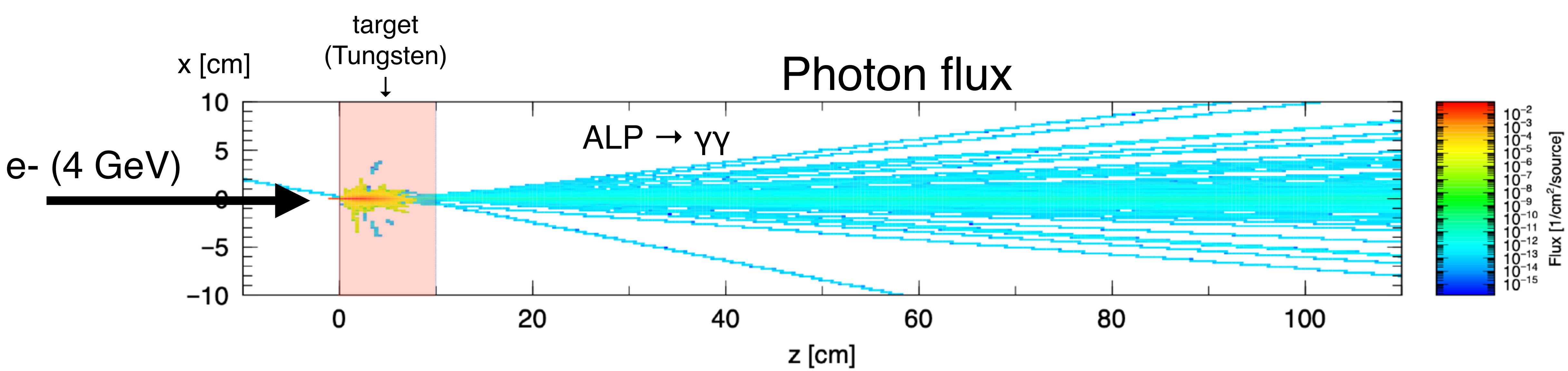




New particle production







How to calculate the number of signals

(Thin target) $$N(\text{total}) = N(\text{beam})\ n_j\ L\ \sigma_{\text{NP}}(E_{\text{beam}})$$

(Thick target) $$N(\text{total}) = \int_0^{E_{\text{beam}}} dE_i\ N(\text{beam})\ n_j\ \frac{dL_i}{dE_i}\ \sigma_{\text{NP}}(E_i)$$

Formulae of track length

(1) Analytic

Thick-Target Bremsstrahlung and Target Considerations for Secondary-Particle Production by Electrons
Yung-Su Tsai, Van Whitis
Phys.Rev. 149 (1966) 1248-1257

$$I_\gamma^{(n)}(t,k) = \frac{1}{k}\int_0^t e^{-(7/9)(t-t')}dt' \int_k^{E_0} I_e^{(n)}(t',E) \times \left[\frac{4}{3}\left(1-\frac{k}{E}\right)+\left(\frac{k}{E}\right)^2\right]dE$$

$$I_e^{(n+1)}(t,k) = \int_0^t dt' \int_E^{E_0} dE' G(t-t', E, E') \int_{E'}^{E_0} 2I_\gamma^{(n)}(t',k) \times \left[\frac{4}{3}\left(1-\frac{k}{E'}\right)+\left(\frac{k}{E'}\right)^2\right]\frac{E'^2}{k^3}dk, \quad (12)$$

or

(2) Fitting
(for thick target)

See appendix for arbitrary beam energy and target material:
arxiv: 2105.13768

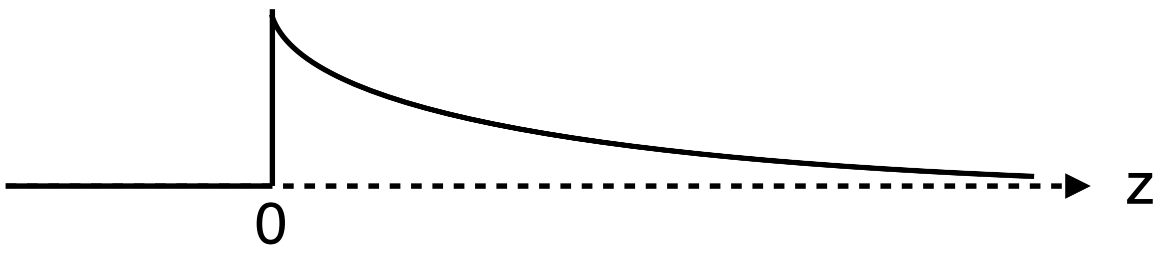
or

(3) Monte Carlo simulation

(Possible to calculate for arbitrary experimental geometry.)

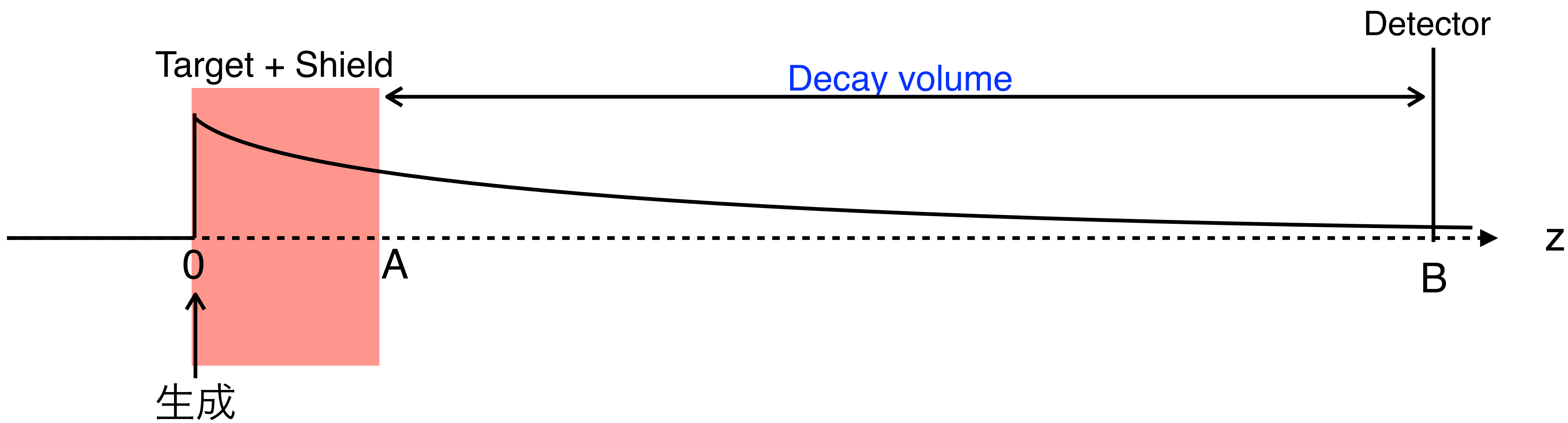
Decay probability

$$\frac{dN}{dz}(X \text{ decays at } z) = N(\text{total}) \times \frac{1}{l} e^{-z/l}, \quad l = \frac{p_X}{m_X} \frac{1}{\Gamma_X}$$

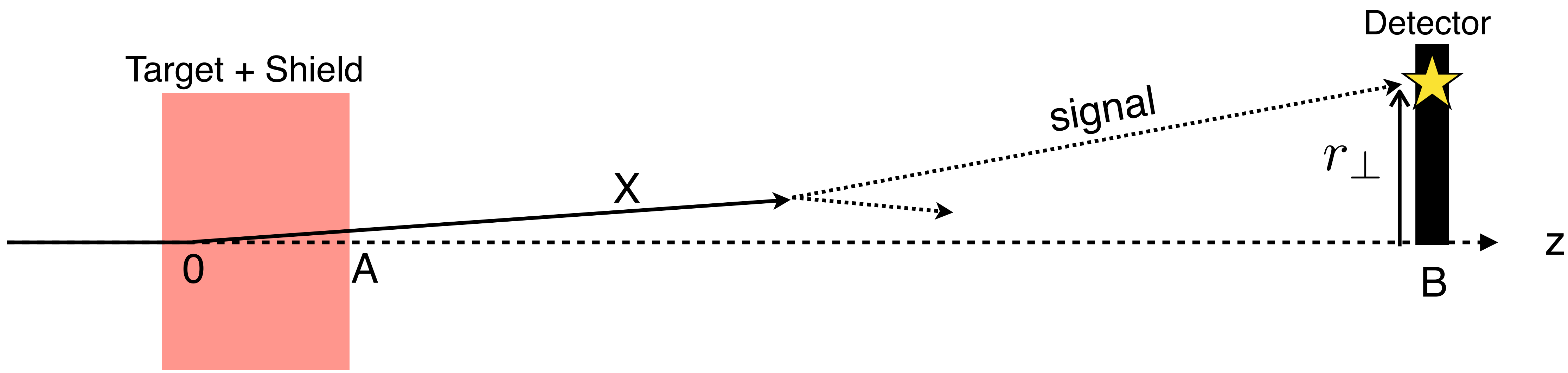


(X is produced at z=0.)

$$N(X \text{ decays on decay volume}) = N(\text{total}) \times e^{-A/l} \times (1 - e^{-(B-A)/l})$$



Angular acceptance



<u>Check if decay particles enter the detector</u>

<u>X induced by e+, e-, photon</u>

(1) EM shower's angle

(2) X production angle

(3) X decay angle

<u>X induced by muons</u>

(1) EM shower's angle

(2) Muon pair production angle

(3) Multiple coulomb scattering angle

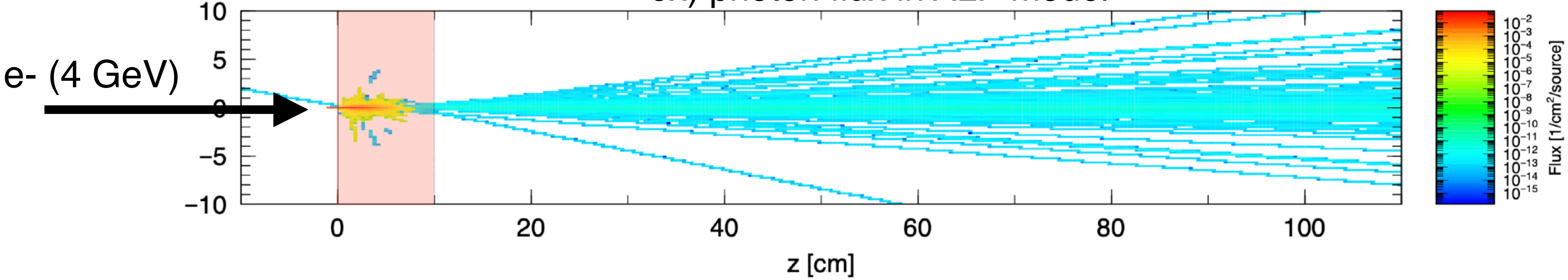
(4) X production angle

(5) X decay angle

[See details: YS, D.Ueda, arXiv:2009.13790](https://arxiv.org/abs/2009.13790)

Simulation tool

ex) photon flux in ALP model



- MC simulations give more precise results.
- If you often use MC tools in your study, you will choose Geant4 which is a de-fact standard code in HEP. But, the learning cost is high.
- **PHITS** is very easy to use and has comparable accuracy of particle transportation compared to Geant4.

  https://phits.jaea.go.jp/indexj.html

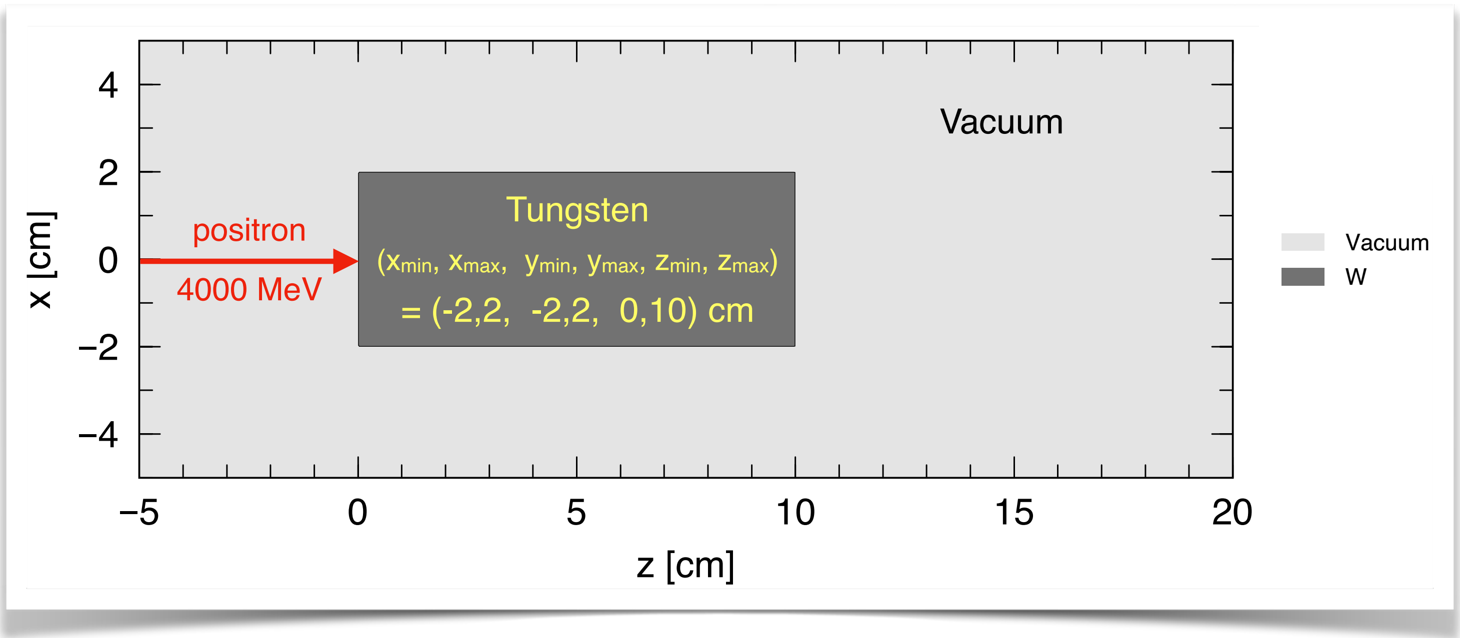
  https://phits.jaea.go.jp/ (English)
- **PHITS for BSM** is under construction, in which we can easily implement BSM and non-BSM processes. (Please contact me if you want now.)

PHITS

How to use:

Write **input file** and send it to an executable file

(Similar to Herwig, Madgraph,…)



test.txt

Number of event →
Beam particle →
Beam energy [MeV] →
Beam position [cm] →
Target shape → $(x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max})$
Target Material (Tungsten) →
Define cell → (Fill the material in the surface with a density [g/cm^3])
User Defined Parameters →
ALP Mass [GeV] →
ALP-photon coupling[1/GeV] →

```
[ parameters ]
  maxcas  =  10000

[ source ]
  proj = positron
    e0 = 4000
     z0 = -5

[ surface ]
  10  RPP    -2 2    -2 2    0 10

[ material ]
 mat[1] W 1

[ cell ]
  101     1  -19.25 -10
  102     0         -99 #101

[ userdefined ]
  udtvar(1)=1.4e-1
  udtvar(2)=1.0e-4
  udtvar(3)=1.0e+10
```

PHITS

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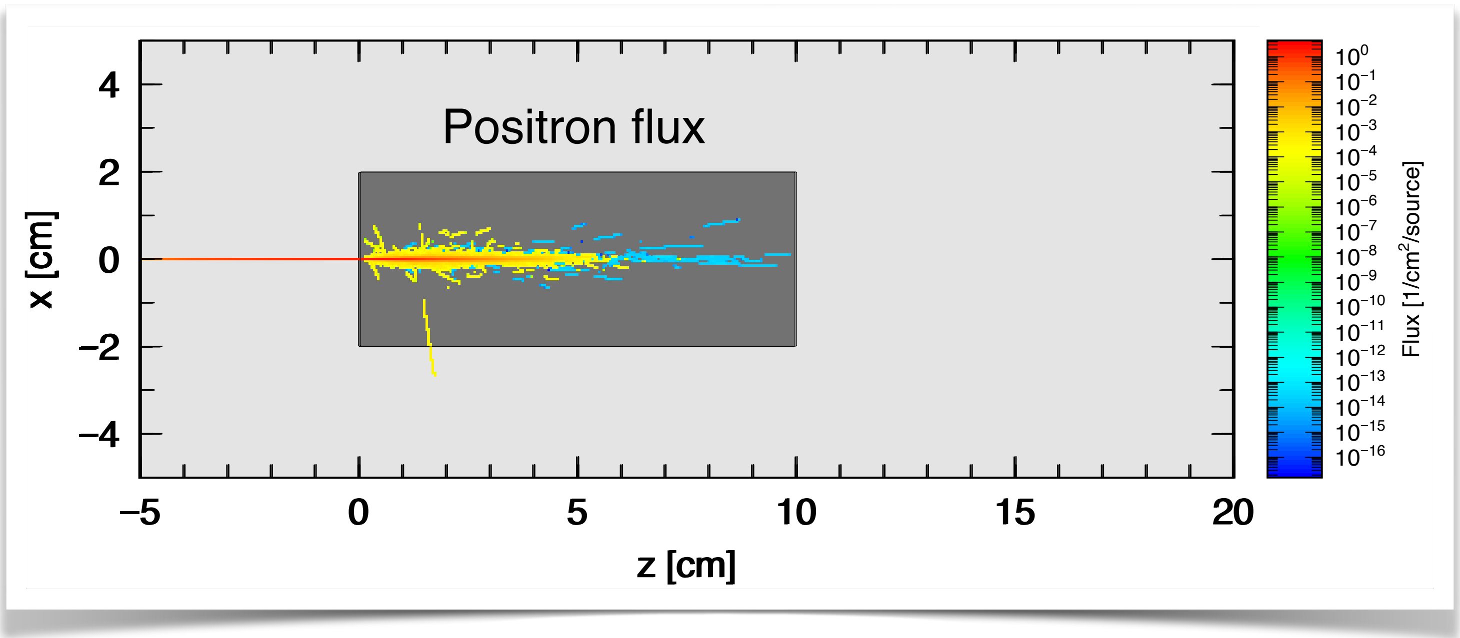

Easy to write down particle information

(p_x, p_y, p_z, E, x, y, z, time, PID, weight, ….)

test.txt

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(x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max})

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Output information →

1: Flux [1/cm2/source]
4: Track length [cm/source]
Observable type →
Axis-type →

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[ userdefined ]
  udtvar(1)=1.4e-1
  udtvar(2)=1.0e-4
  udtvar(3)=1.0e+10

[ t-track ]
   mesh =  xyz

   xmin =  -5
   xmax =   5
     nx =   100

   ymin =  -5
   ymax =   5
     ny =   1

   zmin =  -5
   zmax =   20
     nz =   300

   unit =    1
   axis =   xz
```

PHITS

How to use:

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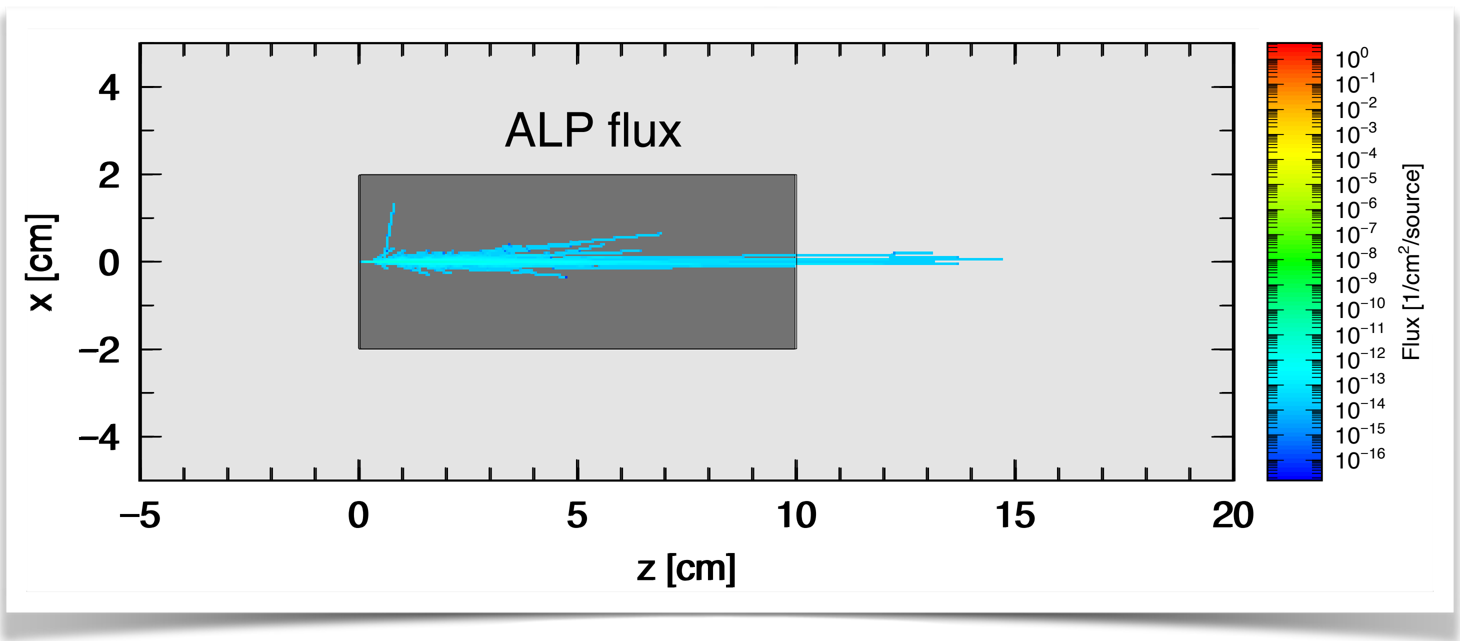
(Similar to Herwig, Madgraph,…)



Easy to write down particle information

(p_x, p_y, p_z, E, x, y, z, time, PID, weight, ….)

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[ parameters ]
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   zmax =   20
     nz =   300

   unit =    1
   axis =   xz
```

Contents

(1) Basics of fixed target experiments using e+/e- beam

- This may help calculate the sensitivity of your favorite model from the beginning by yourself without any input from the experimentalist.

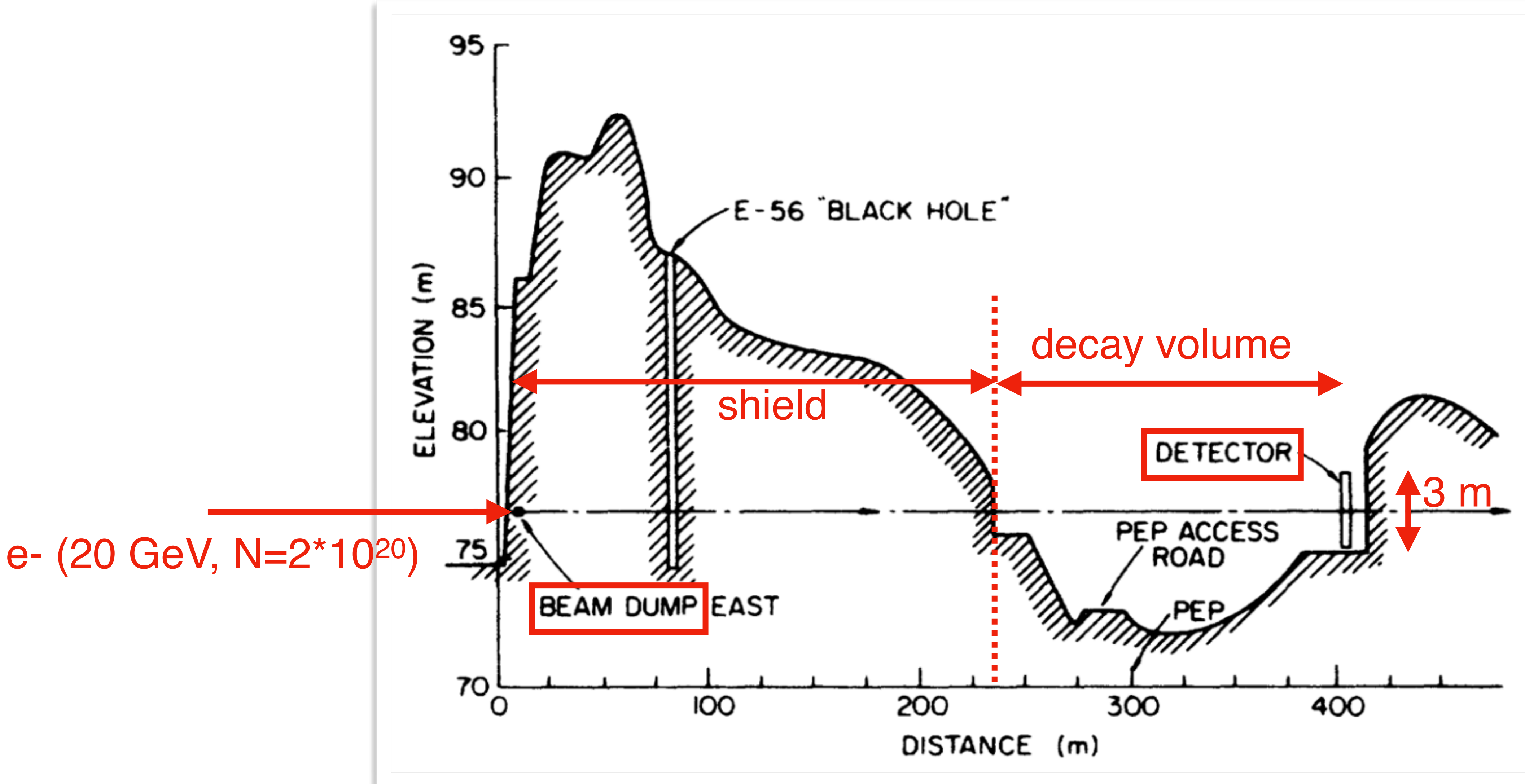
(2) Introducing some fixed target experiments and their features

- This may help you consider an experiment setup by yourself.

(3) What can we do at KEK and ILC? (not only main beam dump)

E137 experiment

J.D. Bjorken, S. Ecklund, W.R. Nelson, A. Abashian, C. Church
Phys.Rev.D 38 (1988) 3375



✓ SLAC

✓ Electron beam dump experiment

✓ Zero background setup (Shield is long)

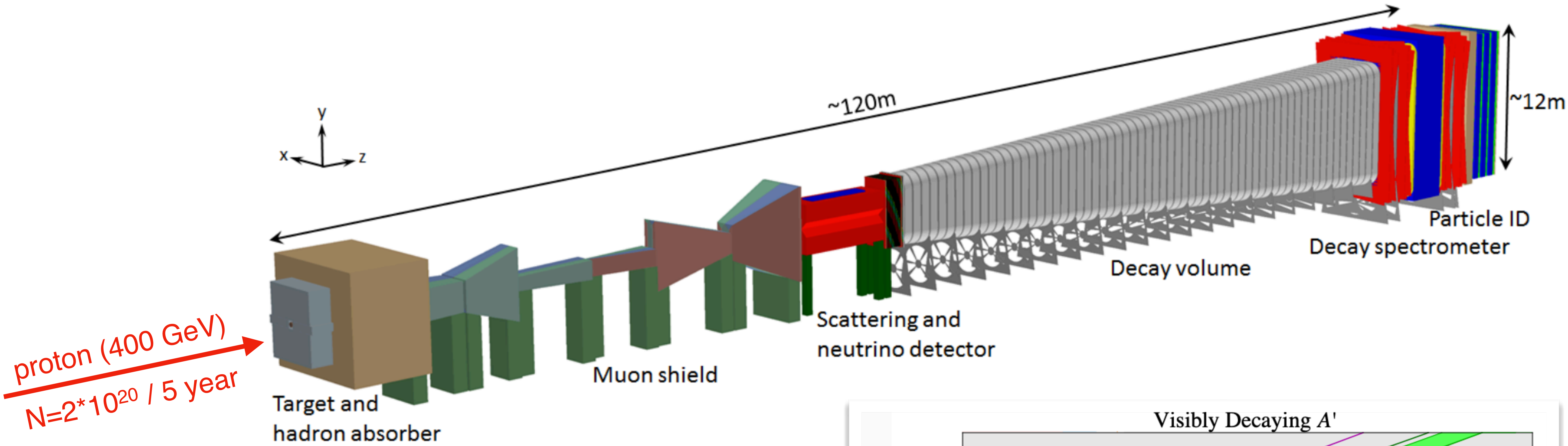
✓ (Mainly) Visible decay search

✓ Integrated injection power (E_{beam} * N) is very high and decay volume is long.

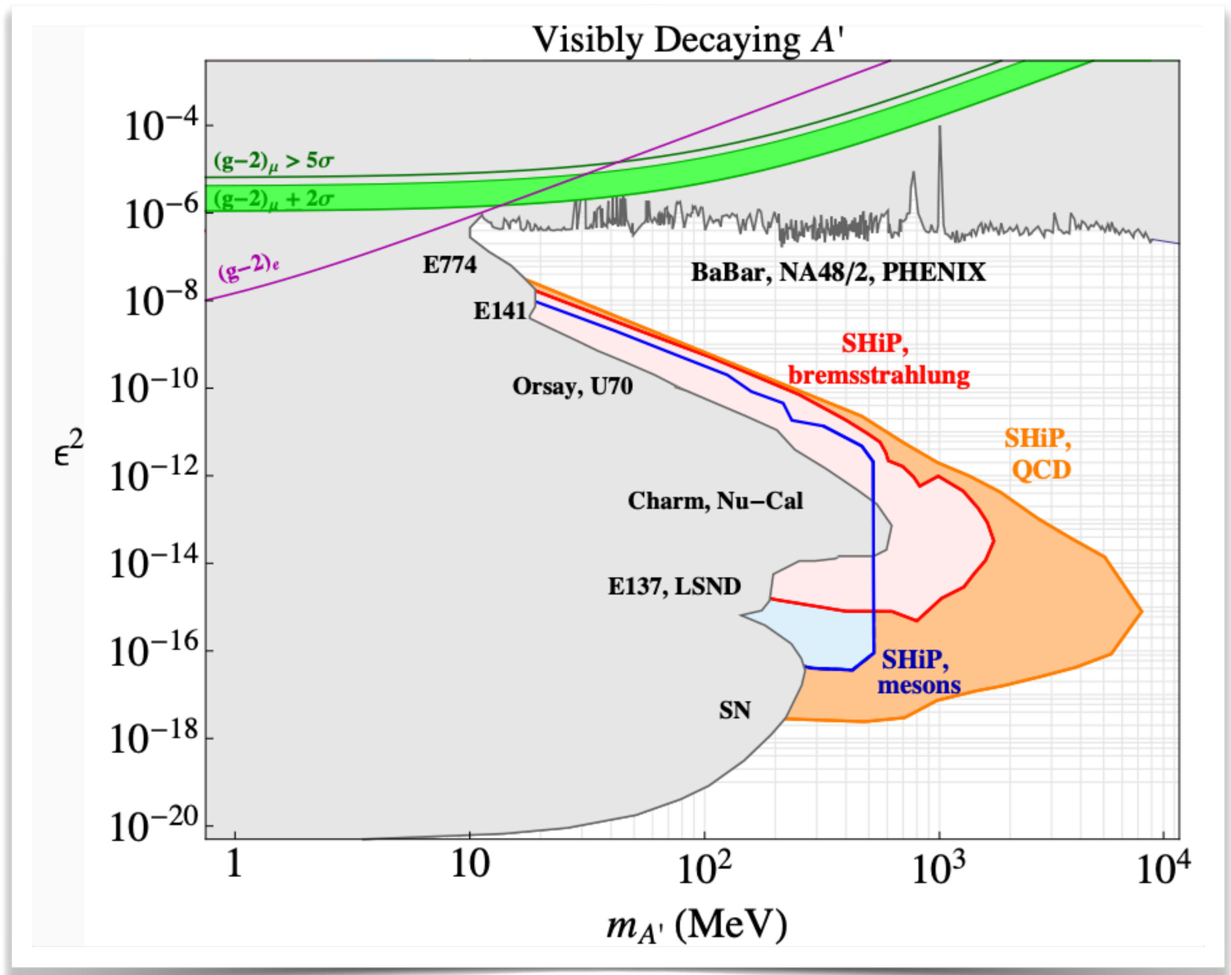
➡ High sensitivity to small coupling region (Long life time region)

➡ Weak to short lifetime region (relatively large couple region)

SHiP



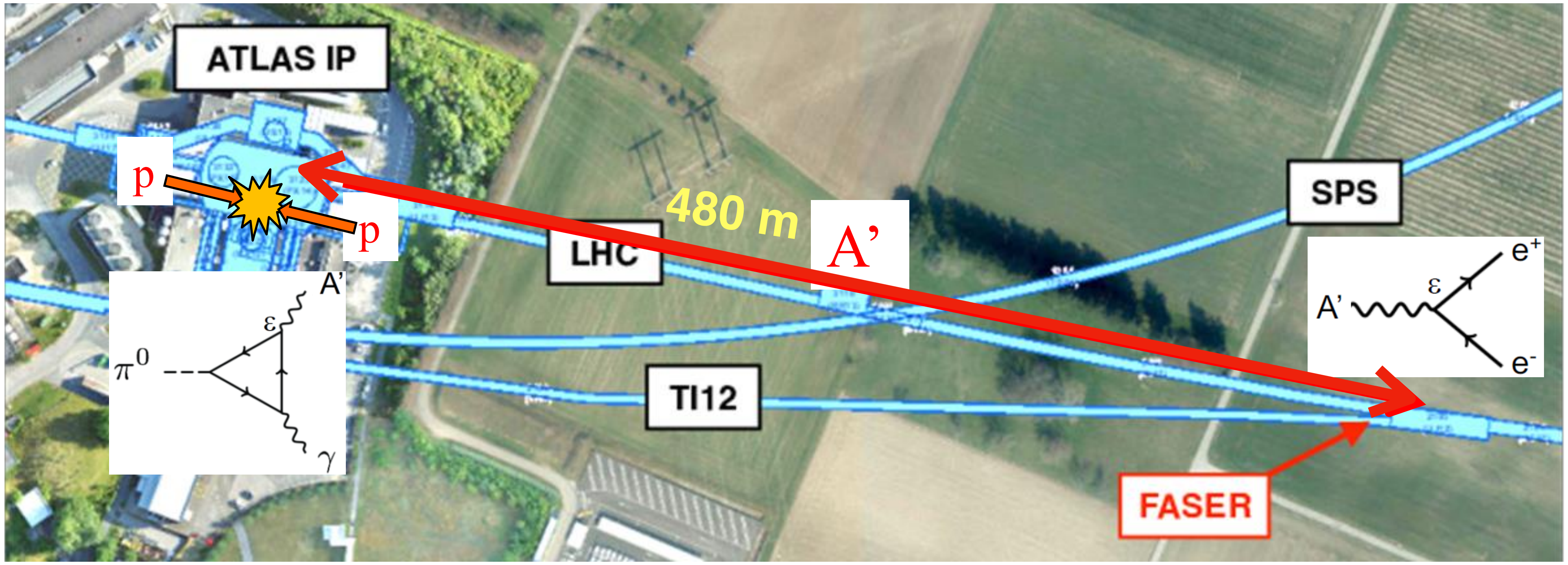
- ✓ SPS@CERN
- ✓ Proton fixed target experiment
- ✓ (Mainly) Visible decay search
- ✓ High injection power (E*N)
- ✓ Zero background experiment
  - Muon active shield
  - Surrounding Veto detectors
- ✓ Difficult to build due to higher cost



SHiP Collaboration: CERN-SHiP-NOTE-2016-004

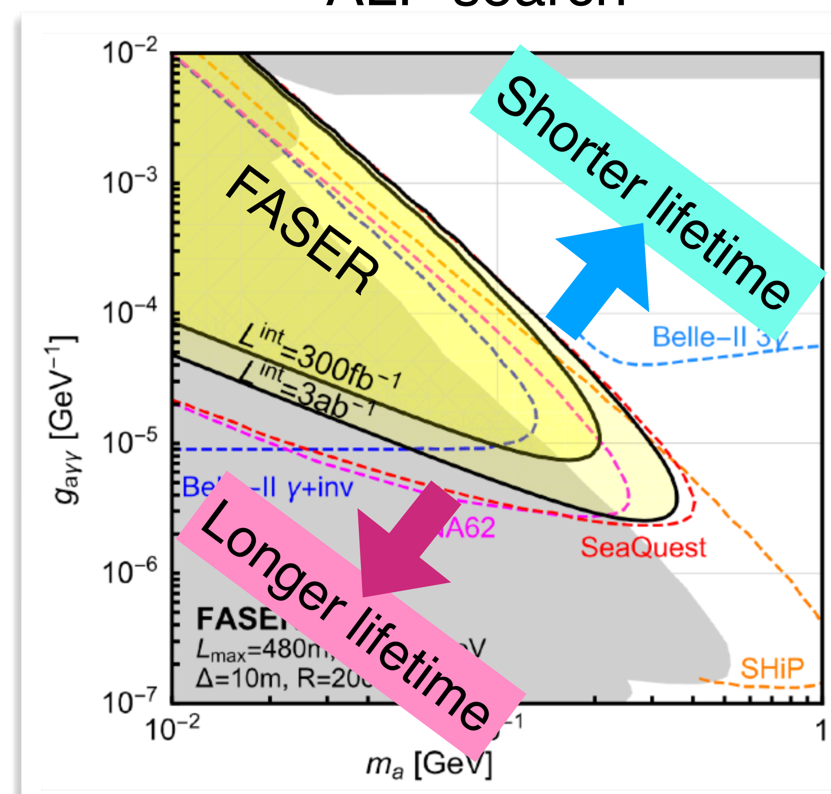
FASER

(From Y. Takubo's slide)



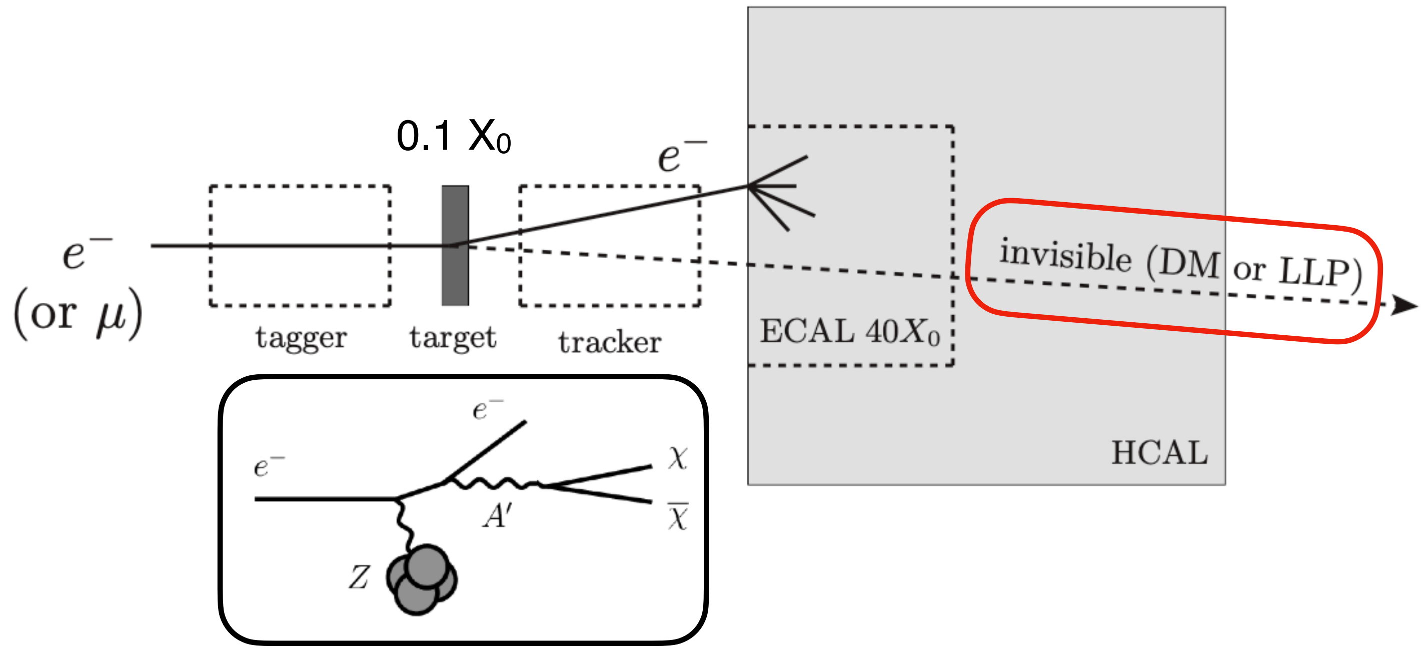
- ✓ LHC@CERN
- ✓ Proton forward experiment (Approved)
- ✓ (Mainly) Visible decay search
- ✓ $N_\pi = 2*10^{17}$ / 150 fb^{-1} (less sensitivity to small coupling)
- ✓ Due to large small-t cross section of high energy proton collision, very boosted particles along to beam direction are produced.
- ✓ High sensitivity to short lifetime region.
- ✓ Non-zero BG
- ✓ Decay particles of very-high energy must be resolved. Challenging for neutral particles (e.g., ALP→γγ)

ALP search

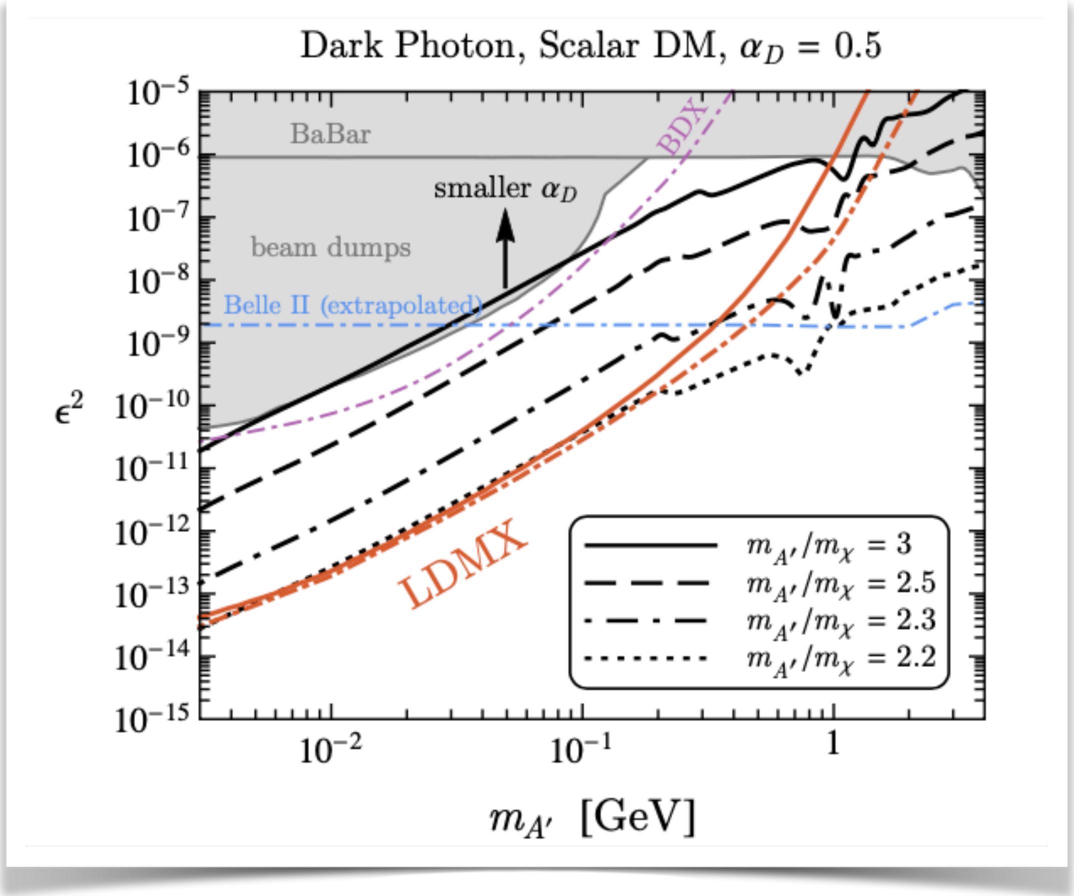


J. L. Feng, I. Galon, F. Kling, S. Trojanowski, arXiv:1806.02348

LDMX



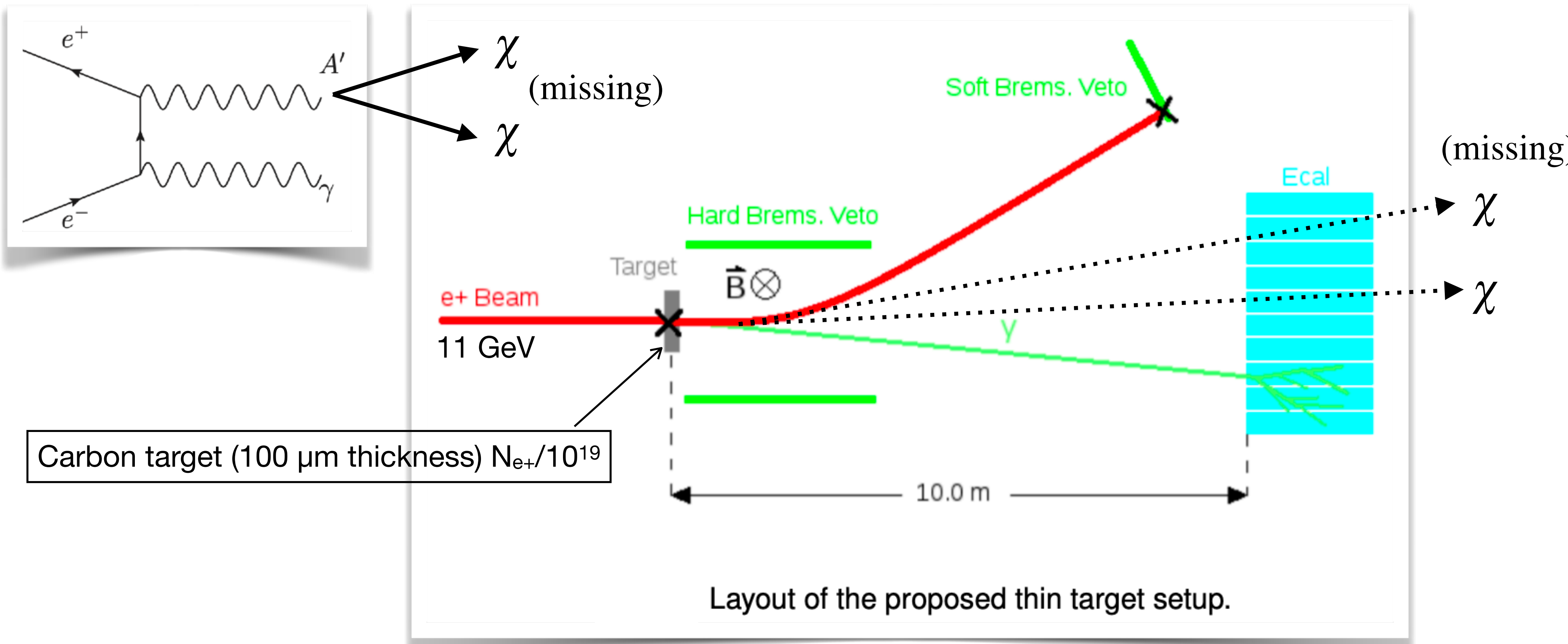
A. Berlin, N. Blinov, G. Krnjaic, P. Schuster, N. Toro, arXiv: 1807.01730



- ✓ LCLS-II beam line @SLAC ?
- ✓ (Mainly) Invisible decay search (Missing momentum measurement)
- ✓ High sensitivity to dark sector
  (ILC: ~10^{10} e/bunch)
- ✓ Low-bunch density (1-10 e/bunch), High repetition rate (>46 MHz) is key technologies (CW mode of Superconducting cavities)
- ✓ Each electrons are tagged
- ✓ N=4*10^{14} (phase-1), ~10^{16} (phase-2)
- ✓ Background
  - γp→π n, (backward pion and missing forward neutron)
  - ...

e+@JLab (Very thin target)

A. Accardi et.al., 2007.15081

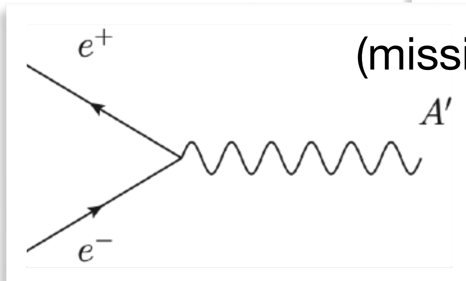


Layout of the proposed thin target setup.

- ✓ CEBAF @JLab
- ✓ Experiment using positron
- ✓ Invisible decay search
- ✓ Missing mass search: $M^2_{\rm miss} = (p_{\rm beam} + p_{\rm target} - p_\gamma)^2$
- ✓ High quality positron beam and high resolution measurement of recoiled photon is required
- ✓ Very thin target (eliminate BG from EM shower)
- ✓ Background: e+e- → γγ, e+e- → γγγ

e+@JLab (Thick target)

A. Accardi et.al., 2007.15081



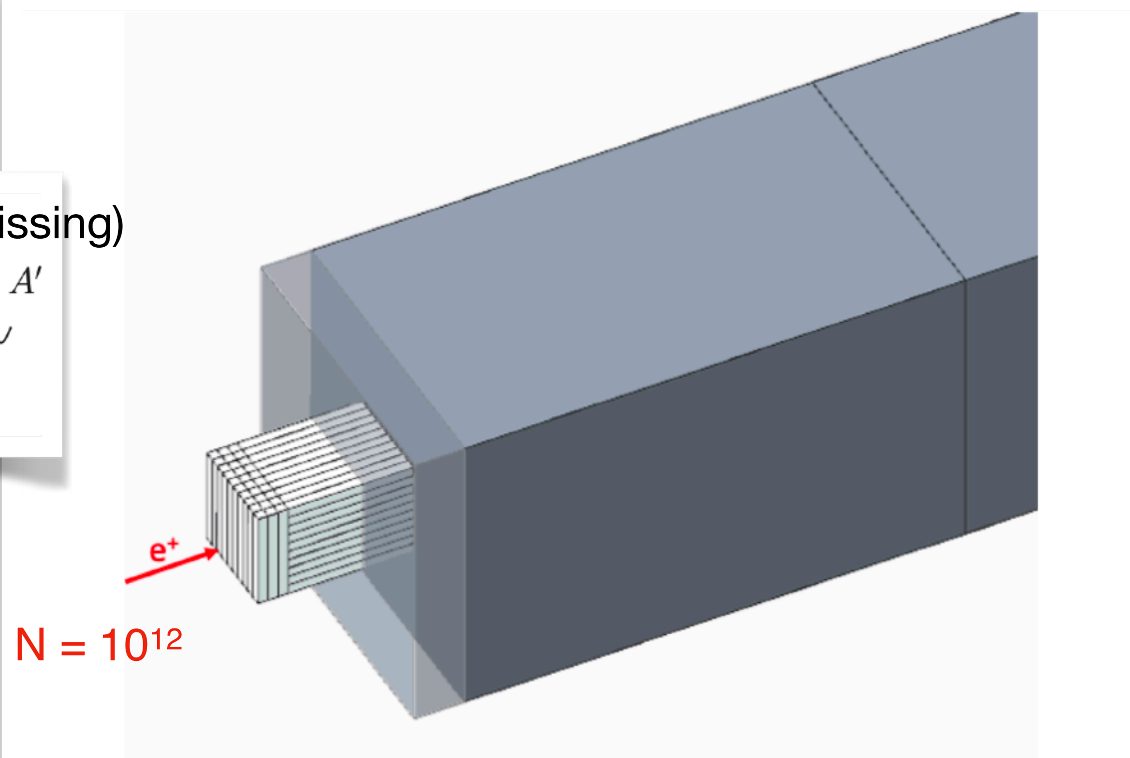


Fig. 3. Schematic layout of the active thick-target experimental setup, with the ECAL (white) followed and surrounded by the HCAL (gray). The semi-transparent portion of the HCAL in front is that installed all around the ECAL.

- ✓ Using thick active detector
- ✓ Experiment using positron
- ✓ Invisible decay search
- ✓ Low bunch density
- ✓ Missing mass search
- ✓ High quality positron beam and high resolution measurement of recoiled photon is required
- ✓ Background: ???

e+@JLab

A. Accardi et.al., 2007.15081

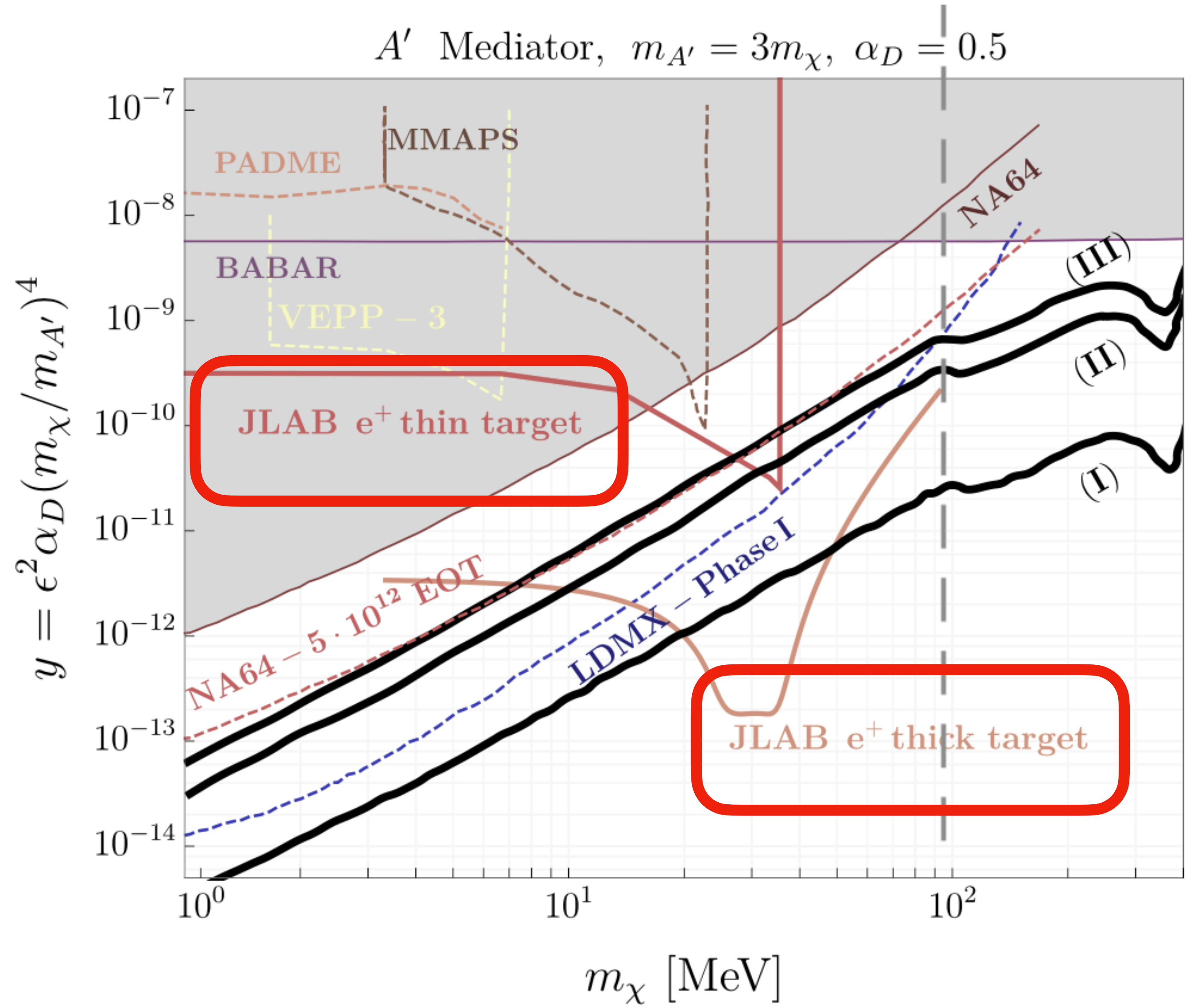
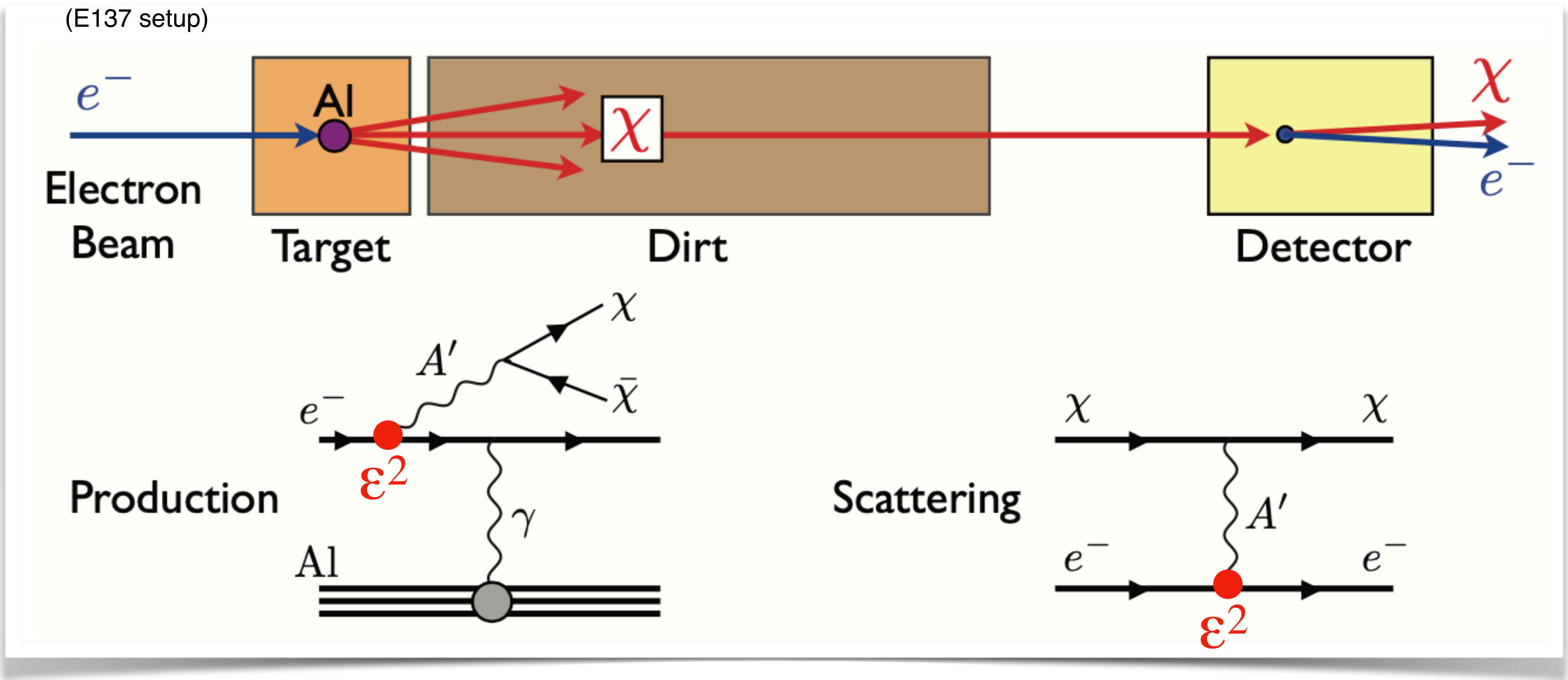


Fig. 4. The expected sensitivity for the thin-target (red) and thick-target (orange) measurements, compared to existing exclusion limits (gray area) and projections for future efforts (dotted lines). The black lines are the thermal targets for elastic and inelastic scalar LDM (I), Majorana fermion LDM (II), and pseudo-Dirac fermion LDM (III).

Invisible particle search using visible search setup

B. Batell, R. Essig, Z. Surujon, arXiv:1406.2698



✓ Visible search can do invisible search like

✓ However, it has large suppression ($N_{signal} \propto \varepsilon^4$) compared to invisible search ($N_{signal} \propto \varepsilon^2$)

✓ A half-invisible case like $\chi_2 \rightarrow \chi_1 A'$, $A' \rightarrow ee$ is searchable in visible setup

Contents

(1) Basics of fixed target experiments using e+/e- beam

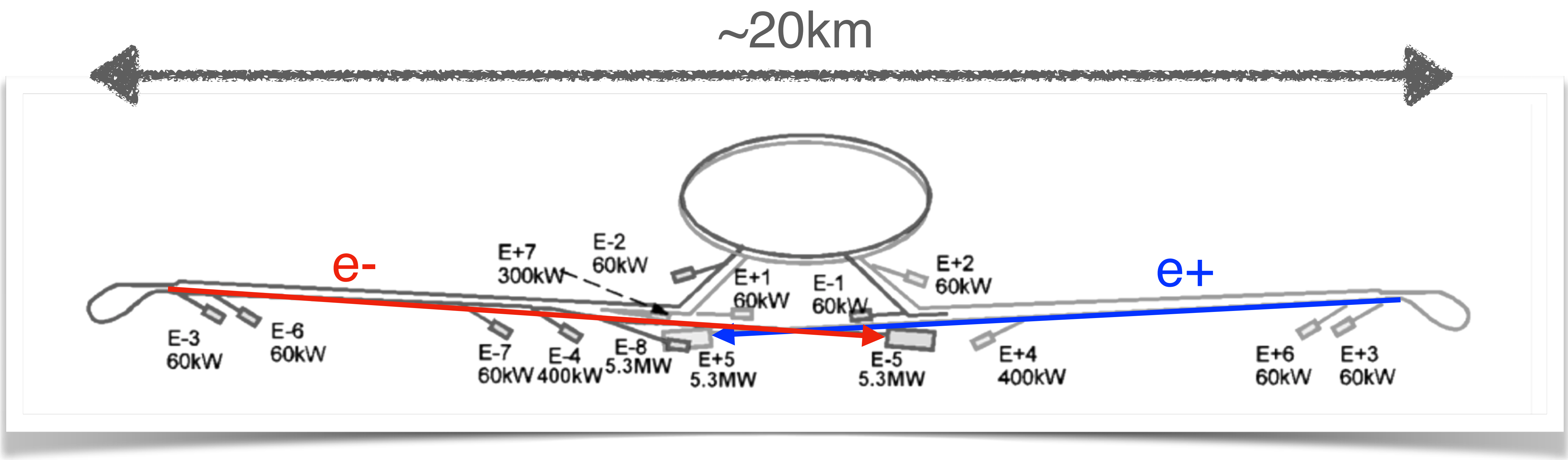
- This may help to calculate the sensitivity of your favorite model from the beginning by yourself without any input from the experimentalist.

(2) Introducing some recent fixed target experiments and its features

- This may help to think an experiment on your own.

(3) What can we do at ILC and KEK ?

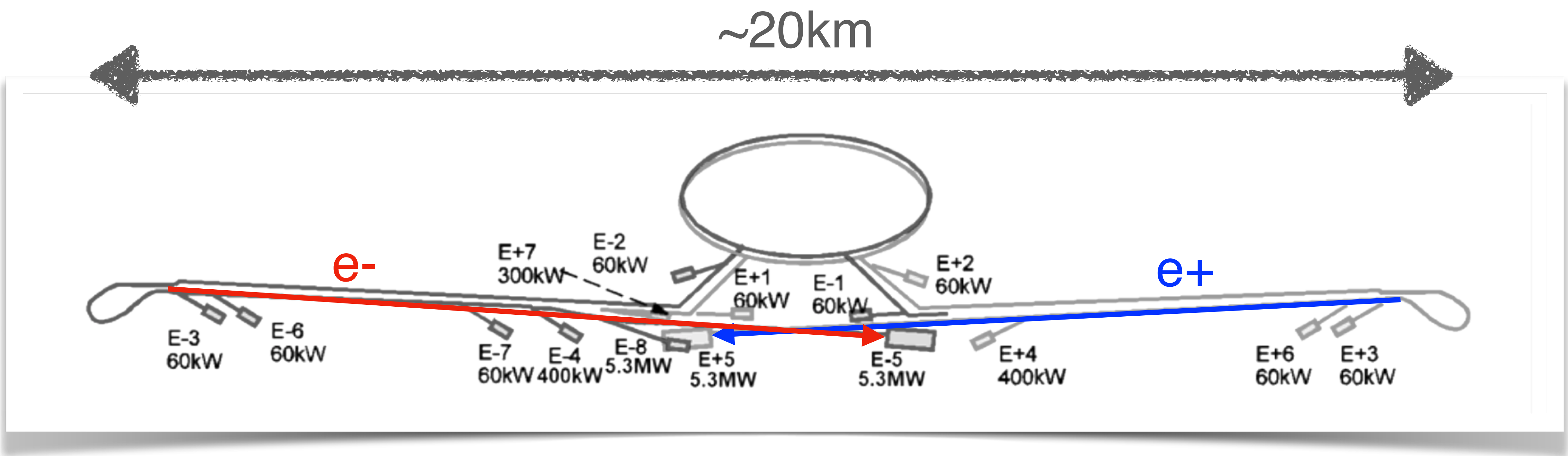
ILC



ILC site becomes more attractive, if we can do many physics programs there.

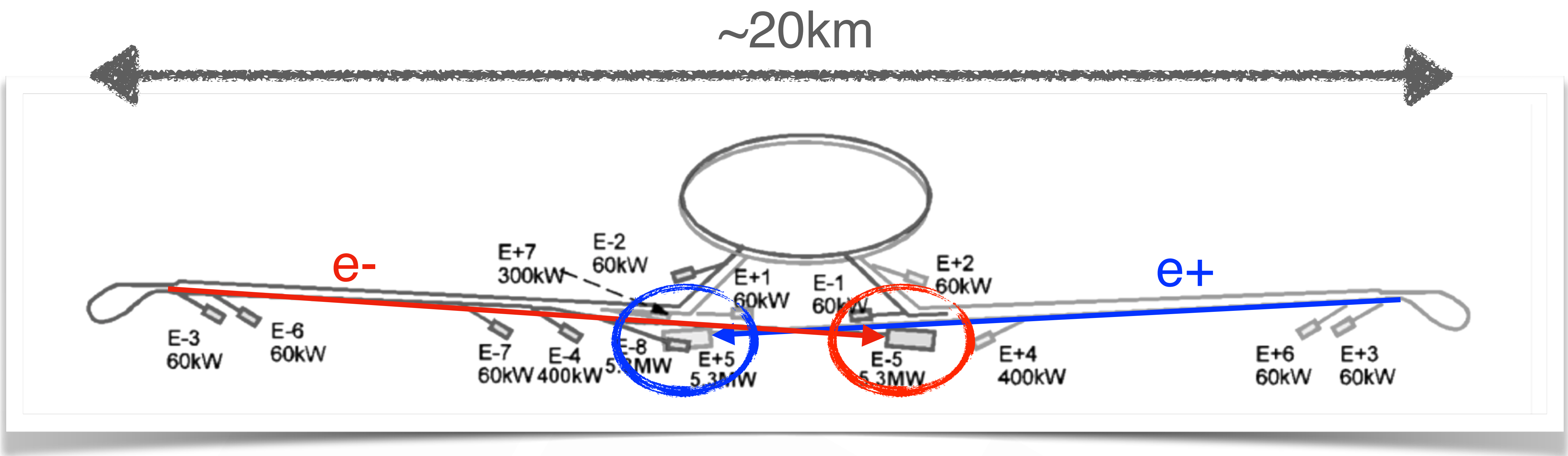
Here, let's consider some possibilities of fixed target experiment at ILC.

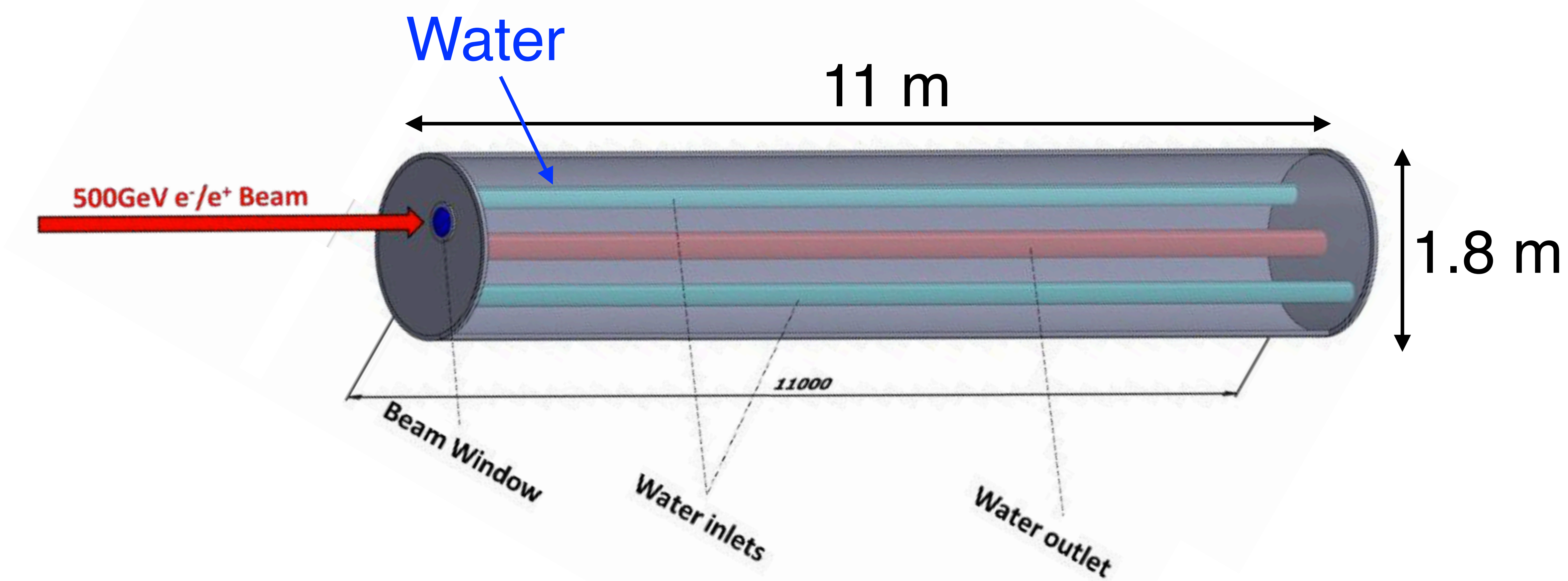
(1) Main beam dumps for e+ and e-



- Almost all e+ and e- do not collide at the center.
- These are just discarded in main beam dumps (E+5 and E-5).
- Main beam dump experiment can be performed in parallel with the collider experiment.
- Statistics are not limited by the collider experiment.

(1) Main beam dumps for e+ and e-

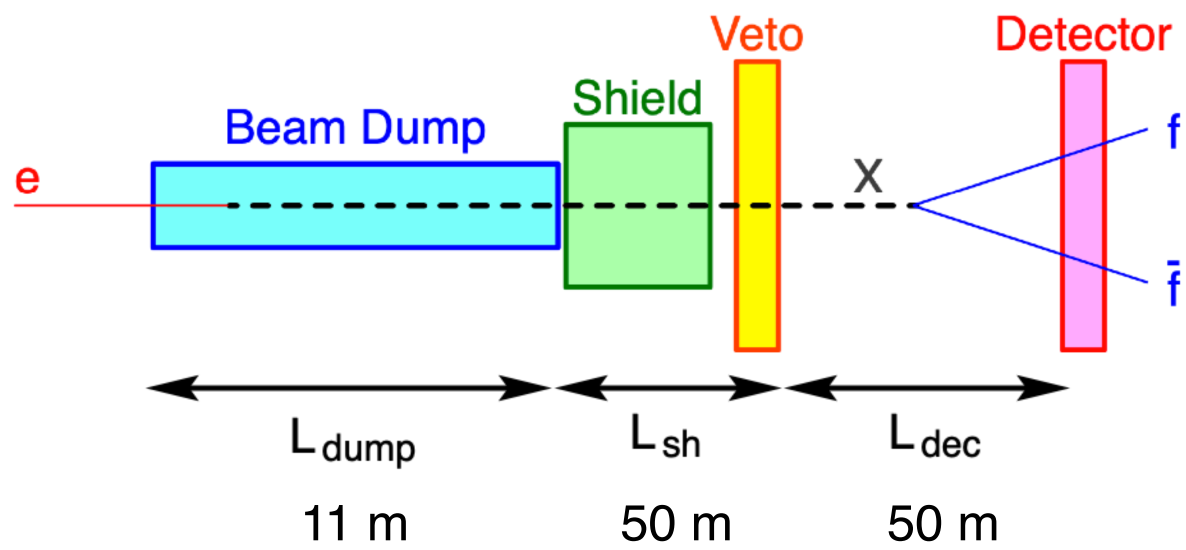


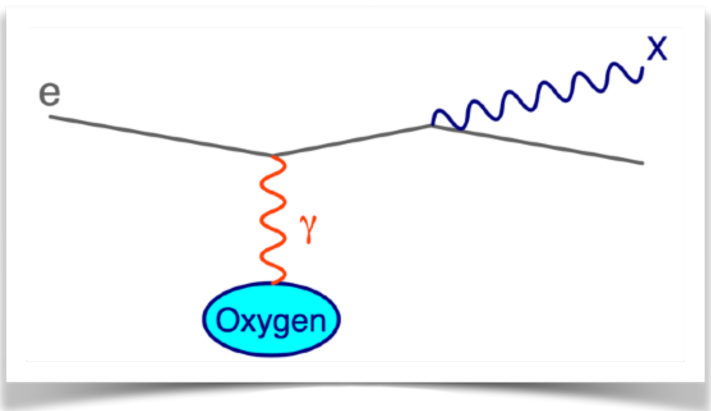


(Base design) P. Satyamurthy, et.al., NIM A 679 (2012)

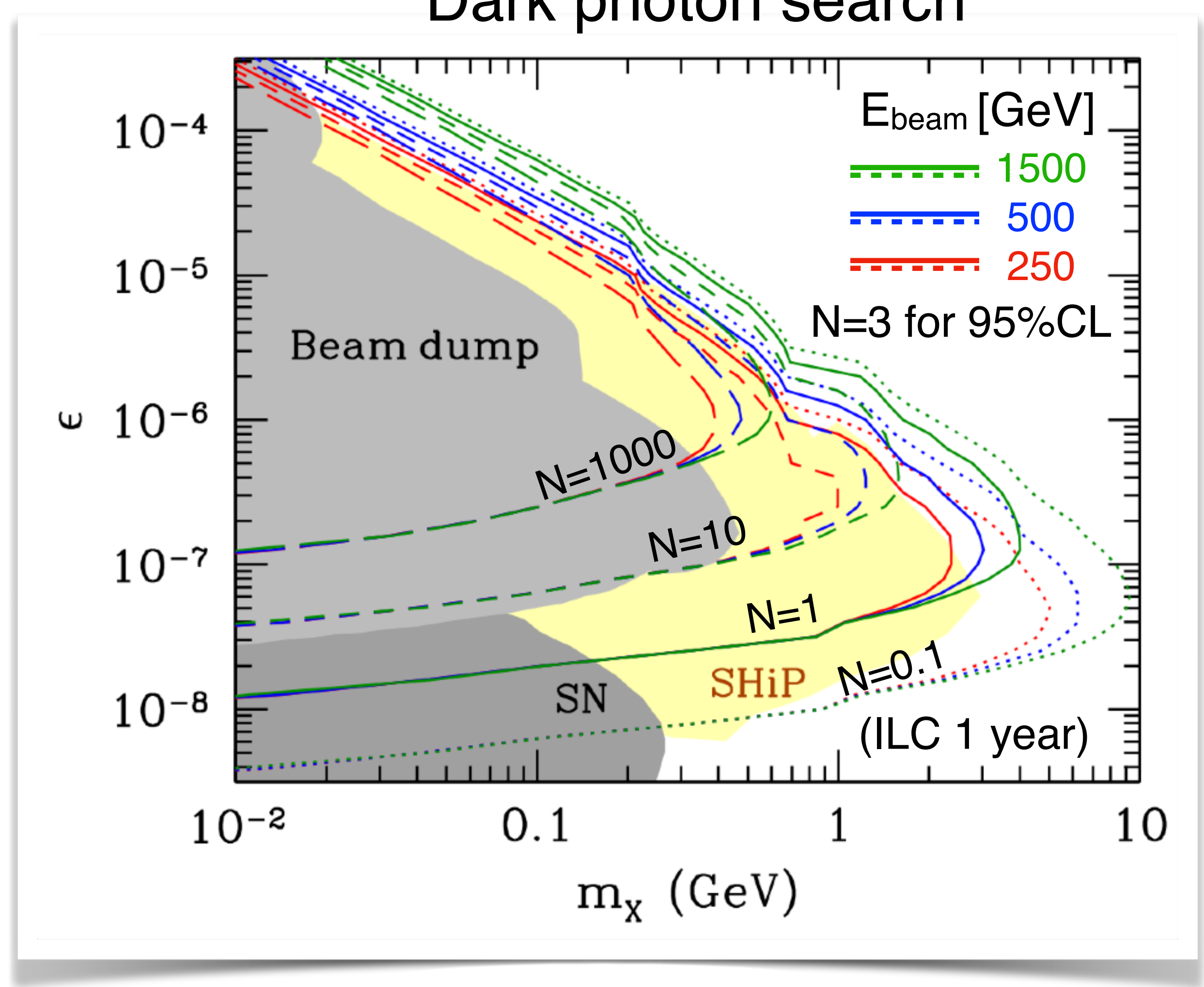
ILC / Future Linear Collider

S.Kanemura, T.Moroi, T.Tanabe. arXiv:1507.02809





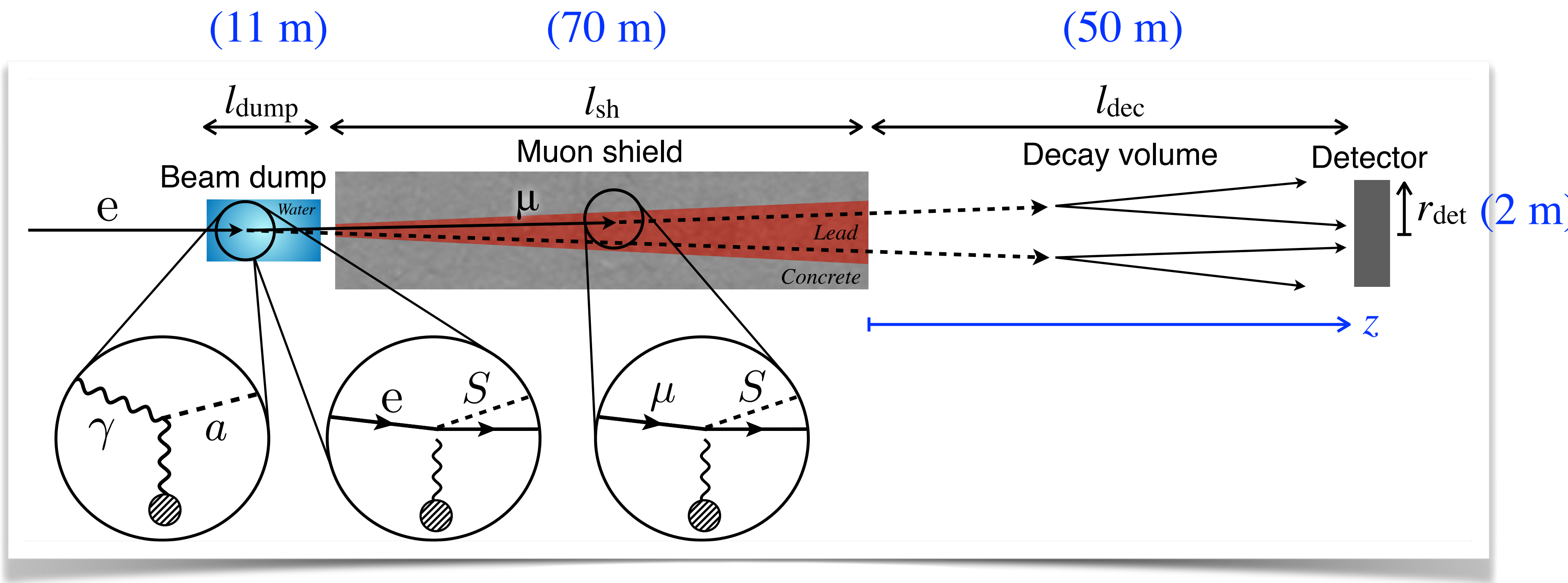
Dark photon search



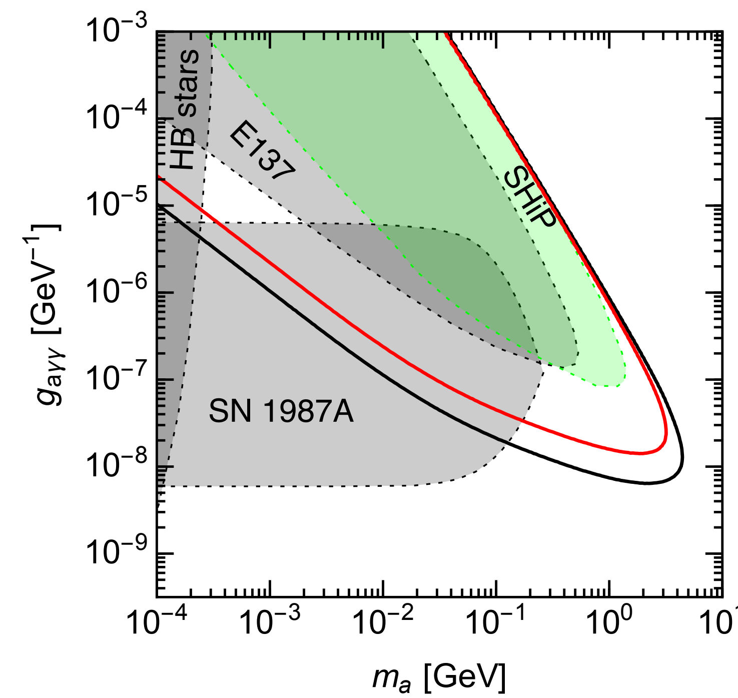
- ✓ Zero background experiment
  - SHiP-like magnetic muon shield is assumed
- ✓ ILC can search on the large unexplored region.
- ✓ ILC beam dump experiment is attractive since the SHiP would be difficult to build.

ILC-250

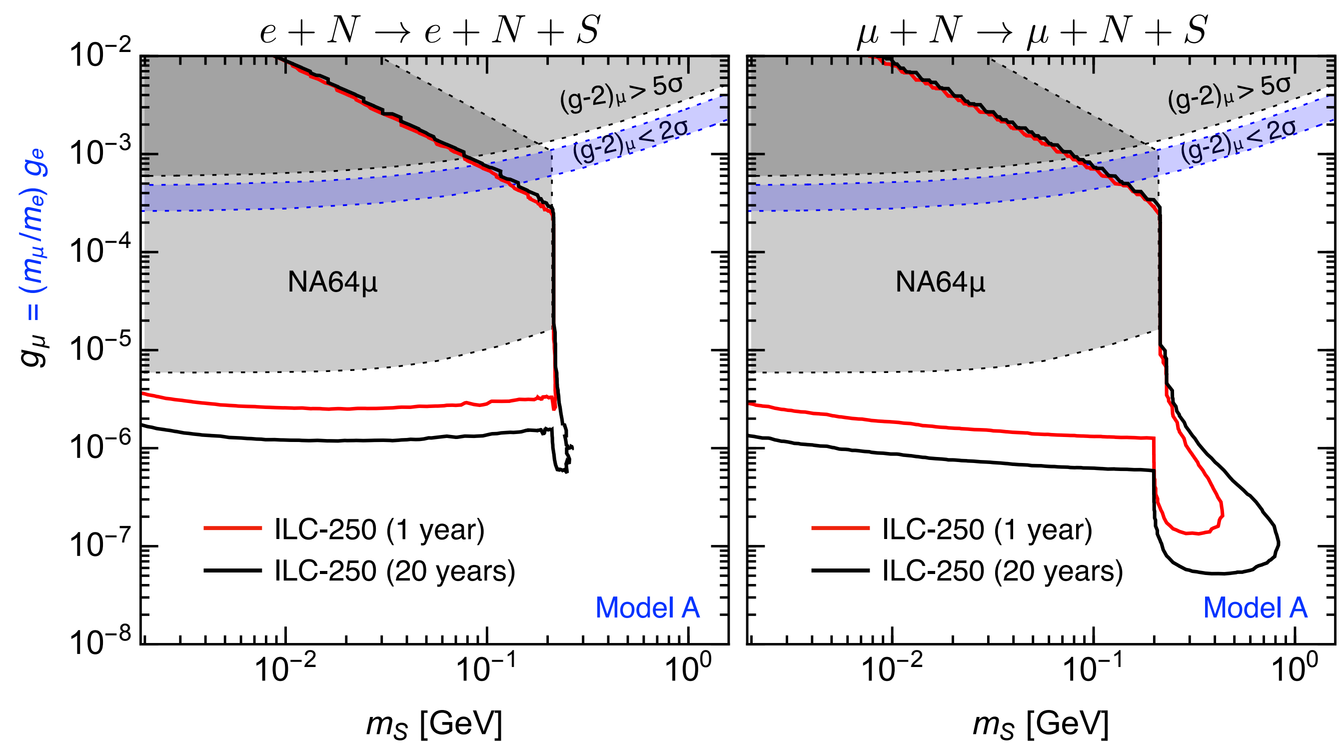
YS, D.Ueda, arXiv:2009.13790
K.Asai, S.Iwamoto, YS, D.Ueda, arXiv:2105.13768



ALP search

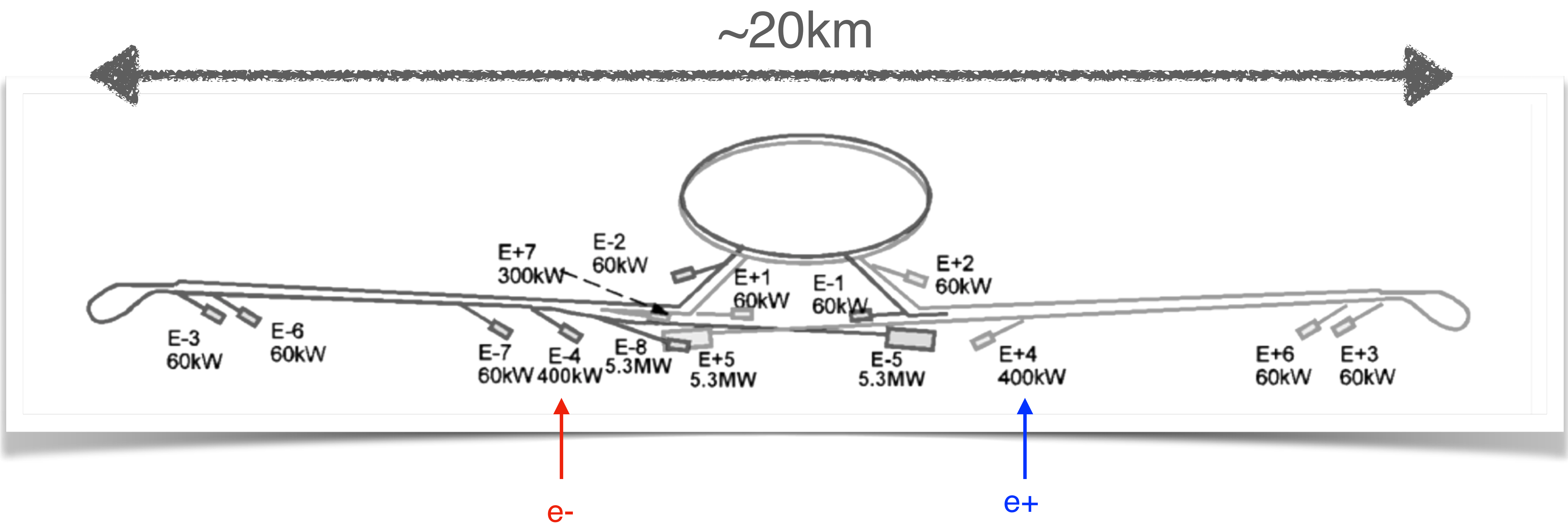


Light Scalar search



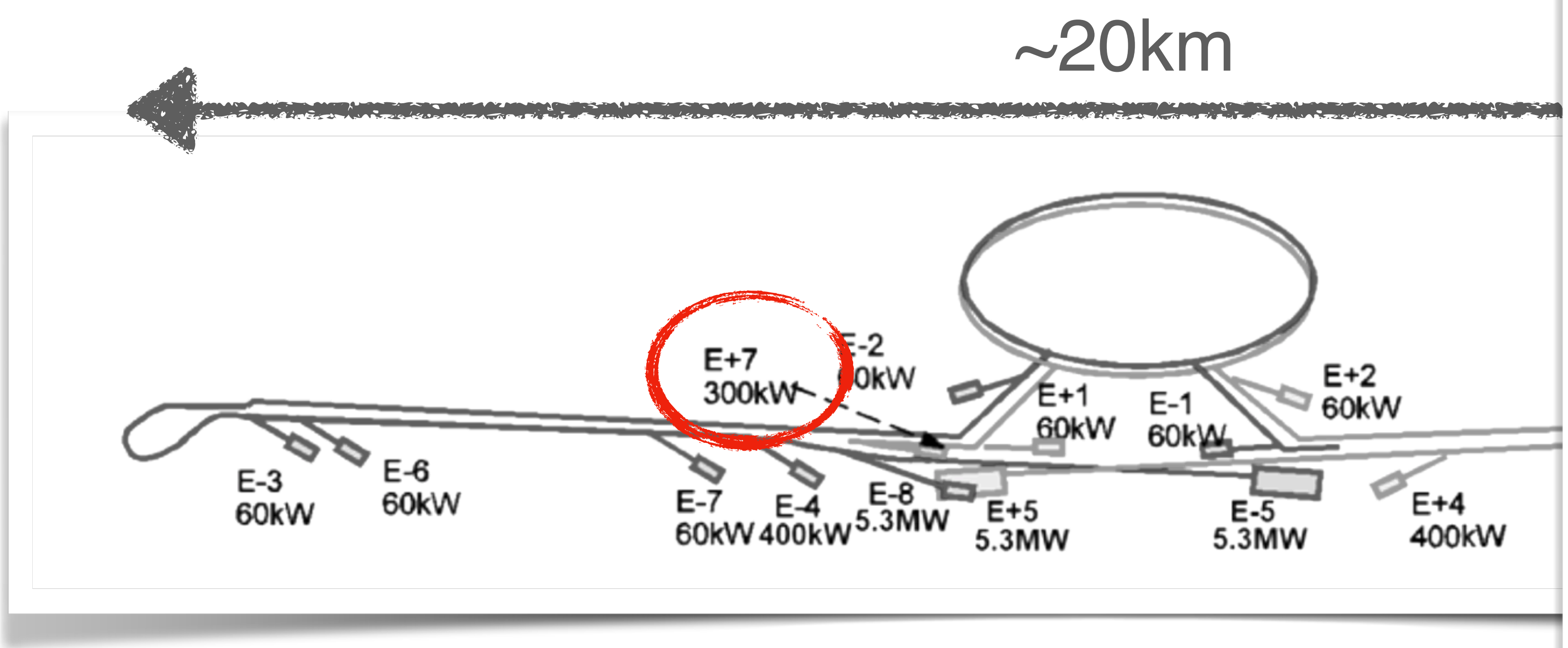
- ✓ Zero background experiment
  - Cheep passive (Lead) muon shield
- ✓ e, γ and μ are useful to search several BSM
- ✓ ILC can search on the large unexplored region.

(2) Other beam dumps

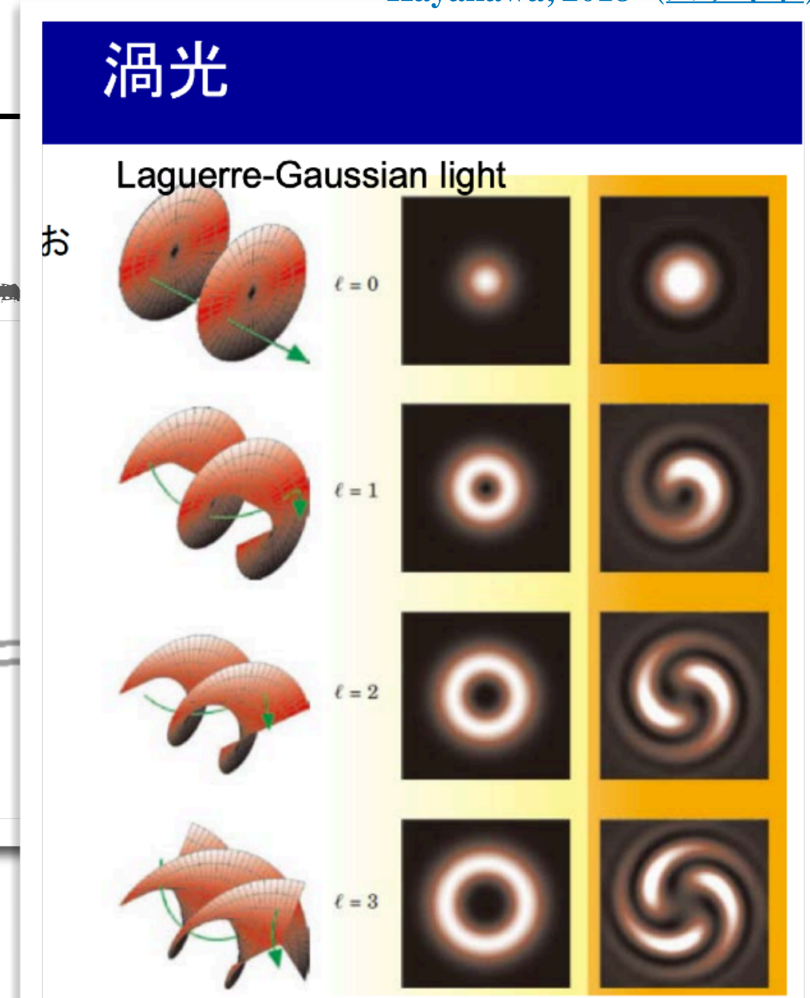


- メインビームダンプ以外でもビームは利用でできる
- 設計が固まる前に使いみちを考えたほうがいい
- 北上山地の ILC 部は花崗岩（すごく硬い）が主なので、後から追加でトンネルを掘るのはかなり大変かも

(2) Other beam dumps

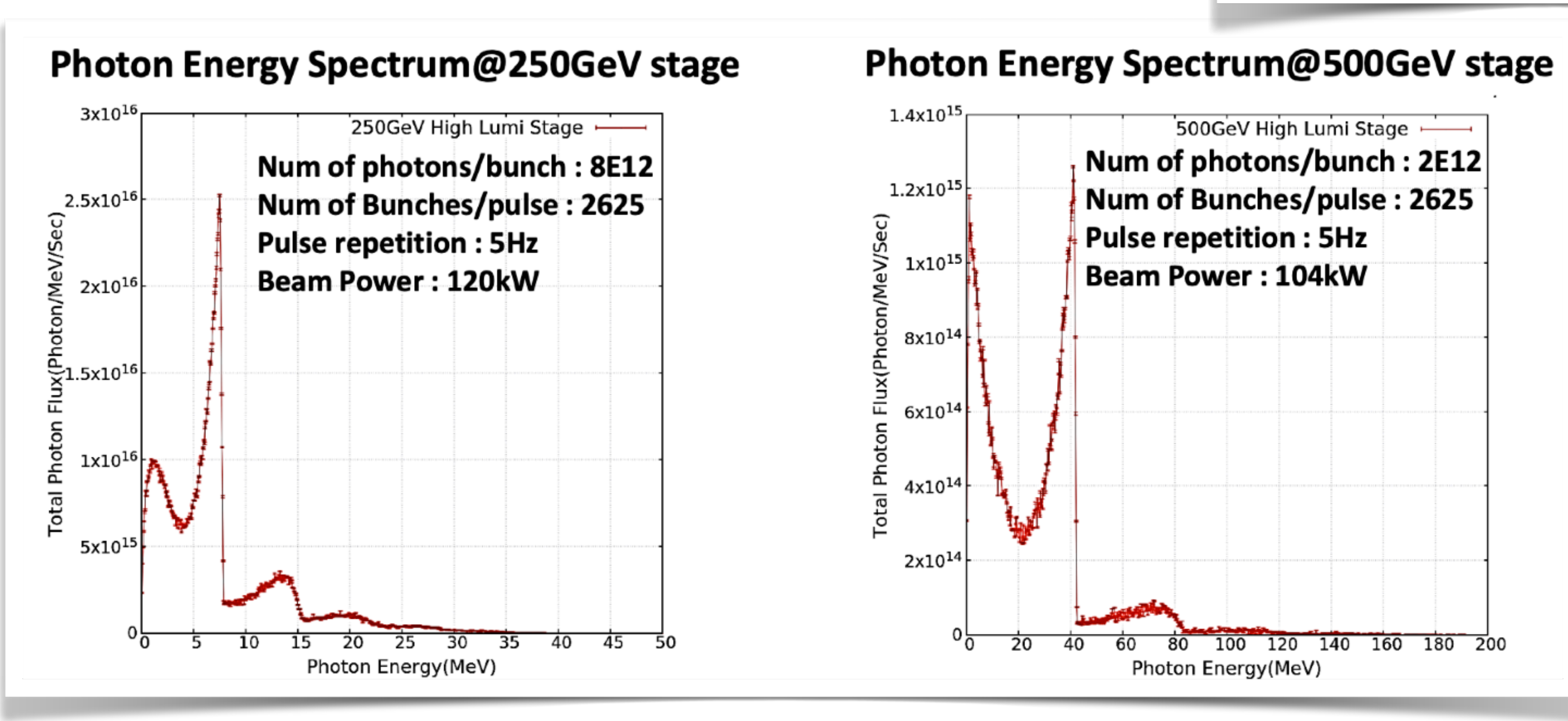


Hayakawa, 2018（スライド）



M. Padgett et al., Phys. Today 57 (2004) 35

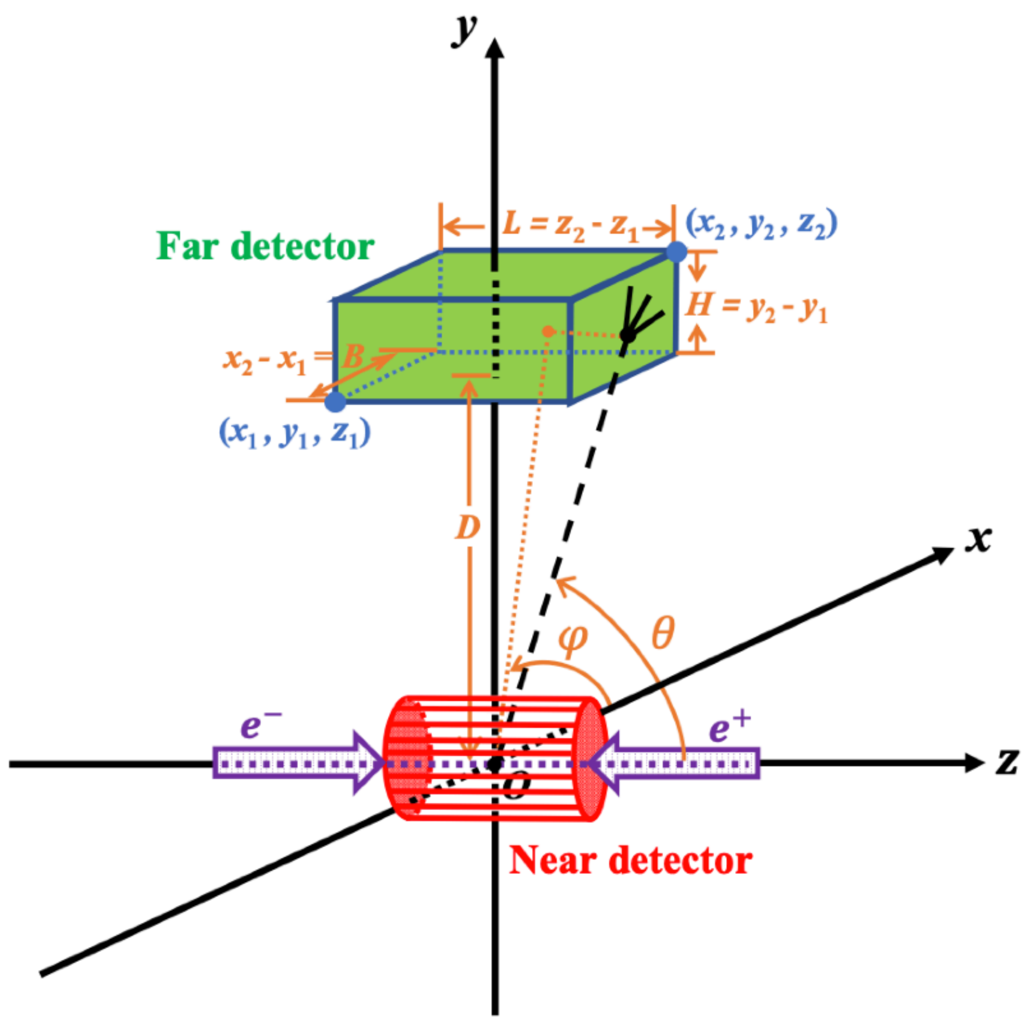
High intensity (undulator) photon source

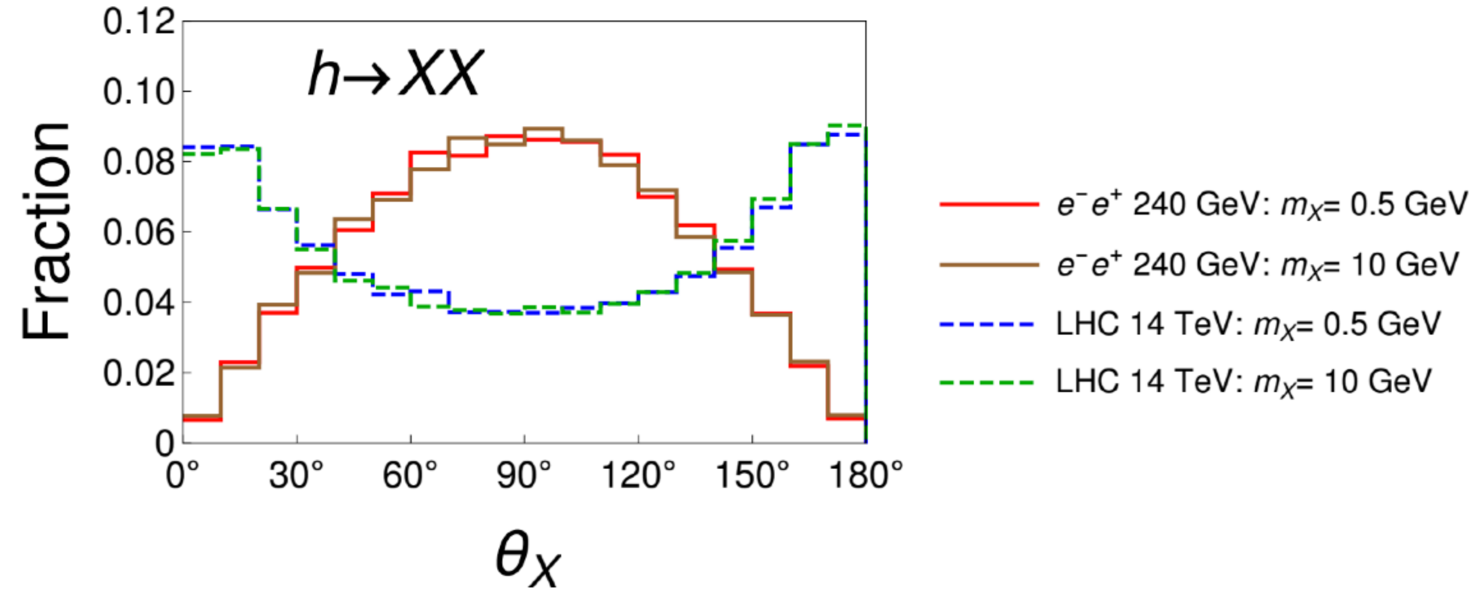


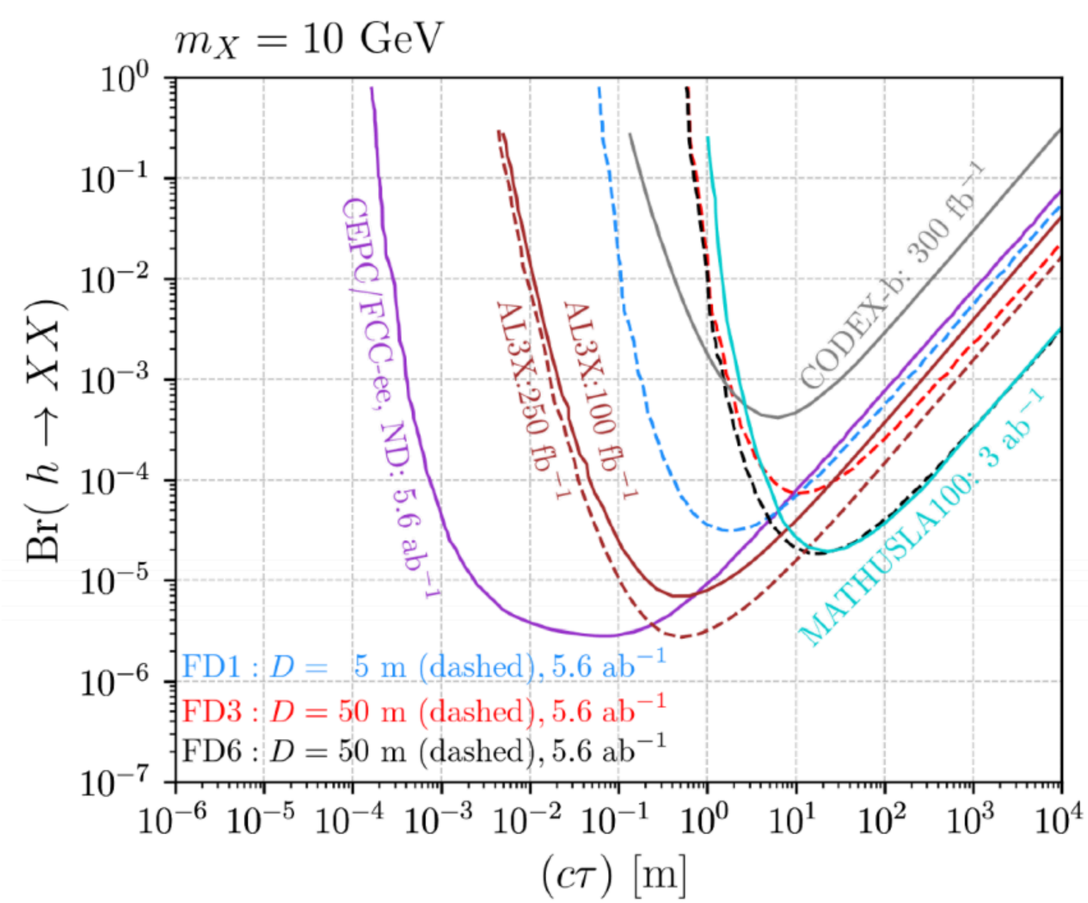
Yu morikawa, Kaoru Yokoya

(3) Off-axis detector (Far detector) @e+e- collider

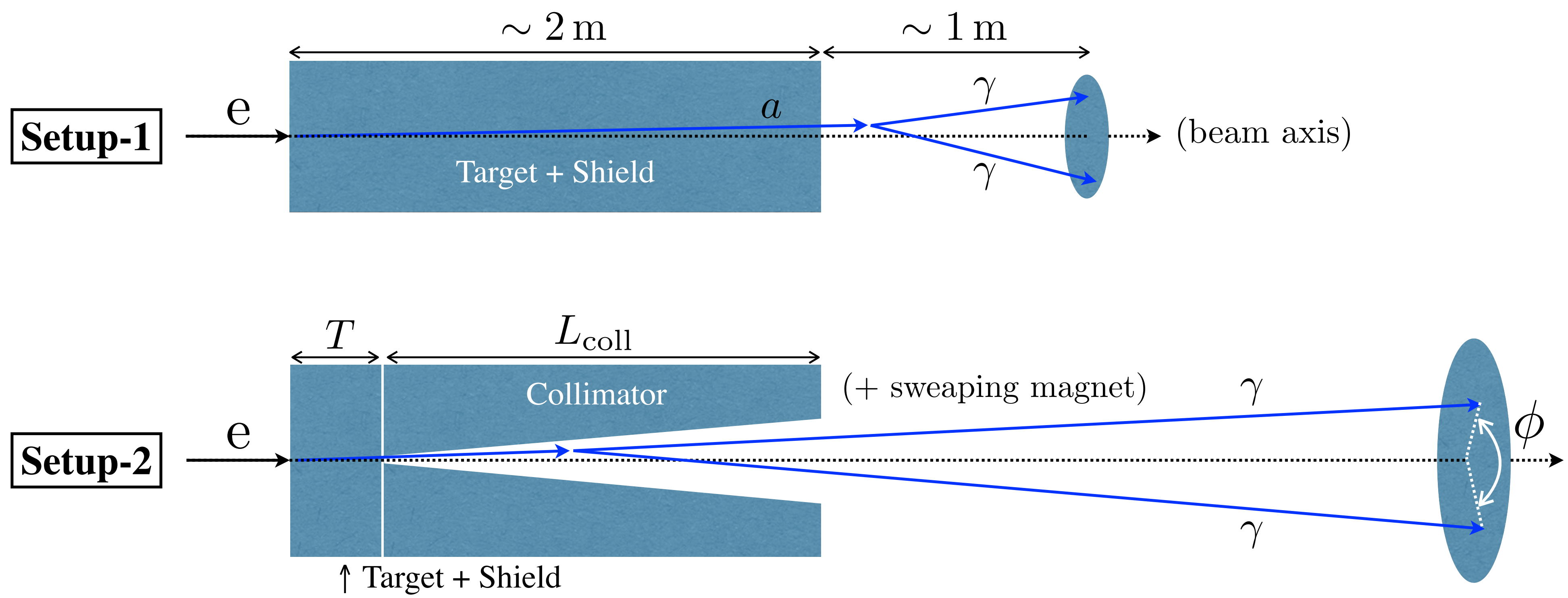
Z.S.Wang, K.Wang, arxiv:1911.06576

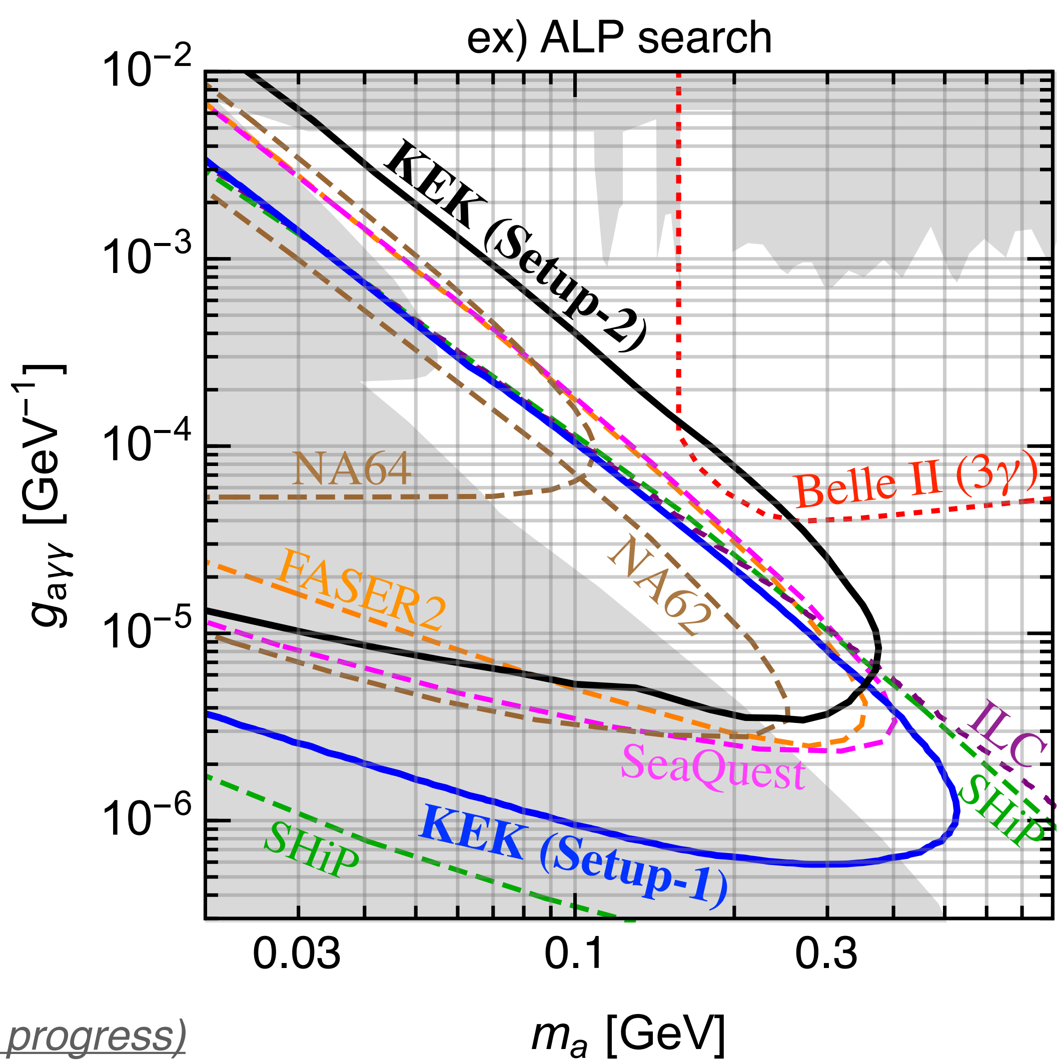






KEK Fixed-target experiment





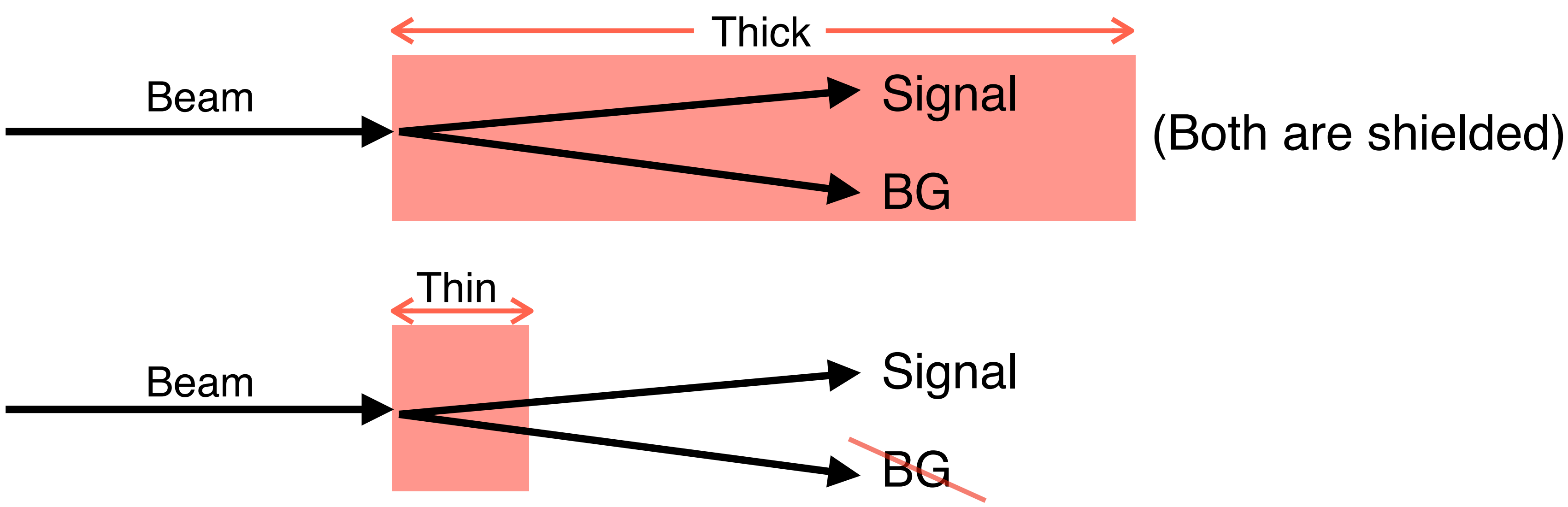
A. Ishikawa, YS, Y. Takubo (work in progress)

Summary

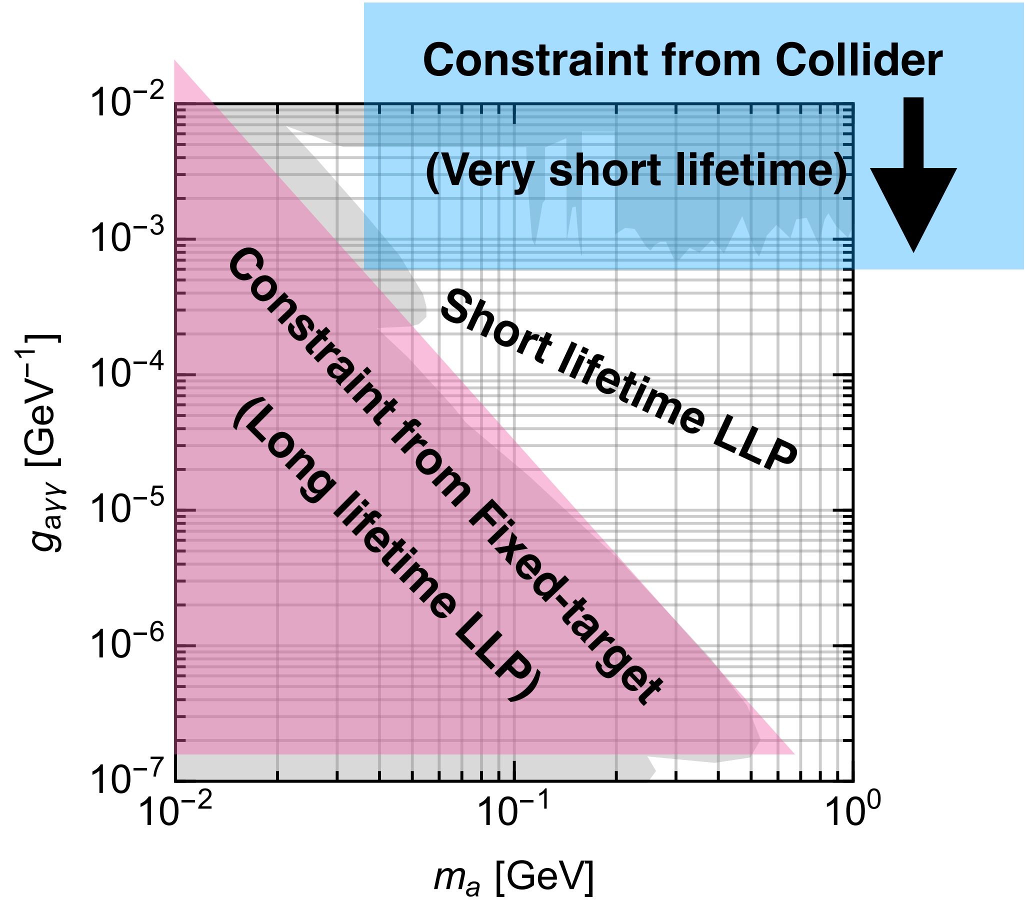
- Fixed target experiment is suitable to LLP searches due to the high Luminosity and forward directivity.
- It plays a complementary role with collider experiments, and can perform in parallel with a collider experiment.
- We learned and discussed:
  - how to calculate the number of signal at fixed target experiments using e+/e- beams.
  - several fixed target experiments, and their features.
  - possibilities of fixed target experiments at ILC and KEK.
- ILC site becomes more attractive, if we can do many physics programs there.

Extra

(2) Non-zero BG setup ?
(Thin target / shield)



- Thick shield setup can reduce ~100% BG and gives high significance with a small number of signals. This experimental setup is good at searching for long lifetime region.
- However, it is poor at searching short lifetime LLP, because the signals can not reach a detector.
- Such region can be explored by clean experiments (LEP, Belle II,…). Limited by statistics.
- The short range experiment could cover the gap between the collider and the thick shield experiment to some extent. (Later slide)
- Using positron beams may contribute to increasing the number of signals more.



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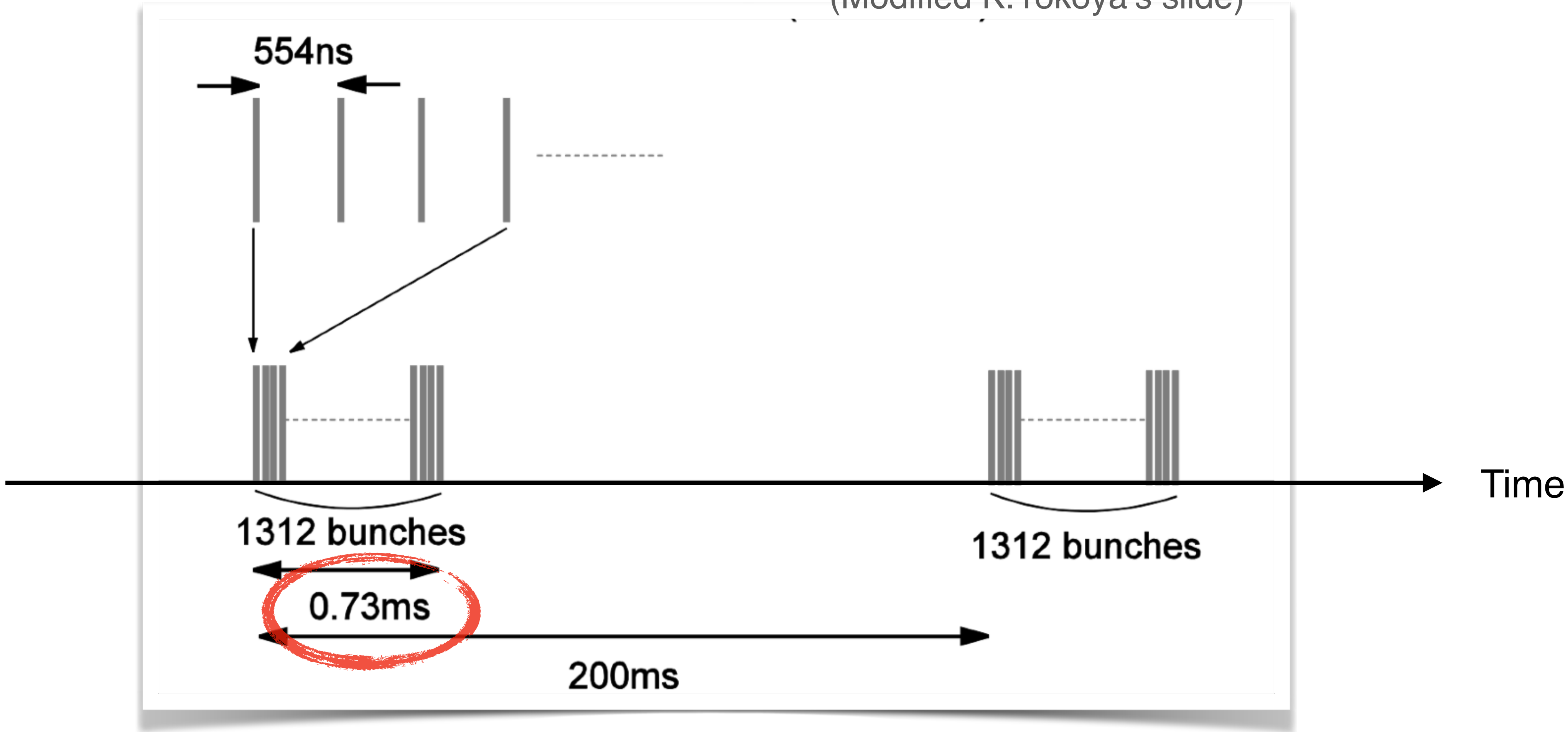
- Using positron beams may contribute to increasing the number of signals more.

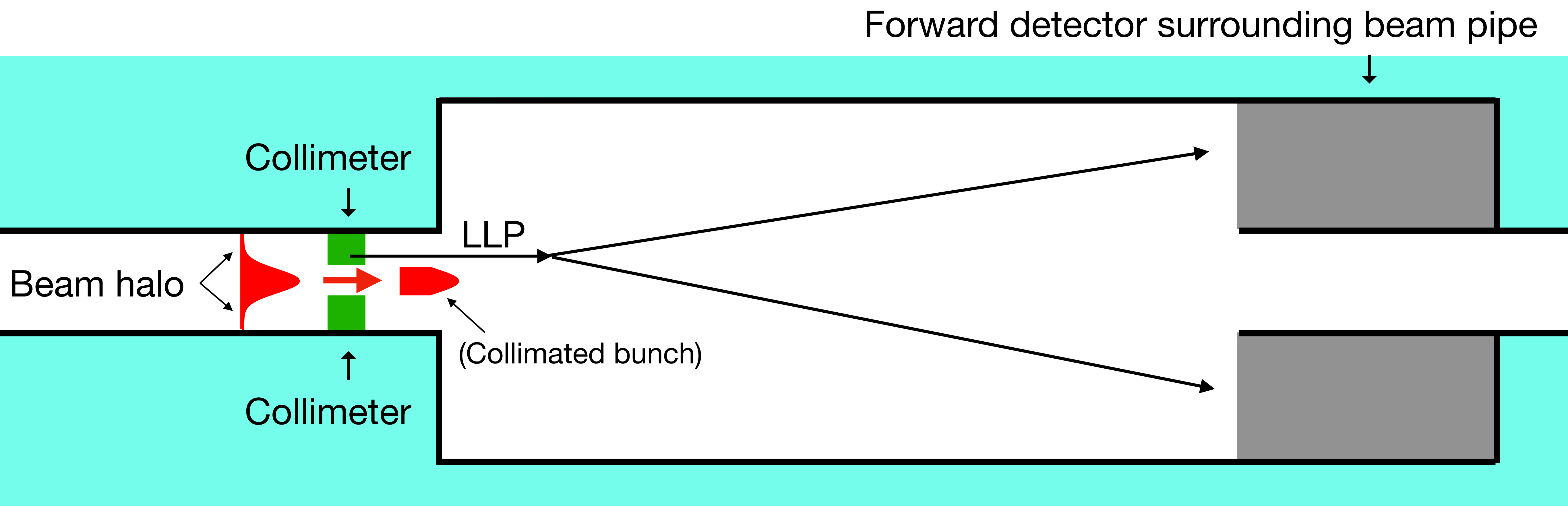
(3) Missing momentum/mass search @ILC Fixed Target Exp

(Modified K.Yokoya's slide)



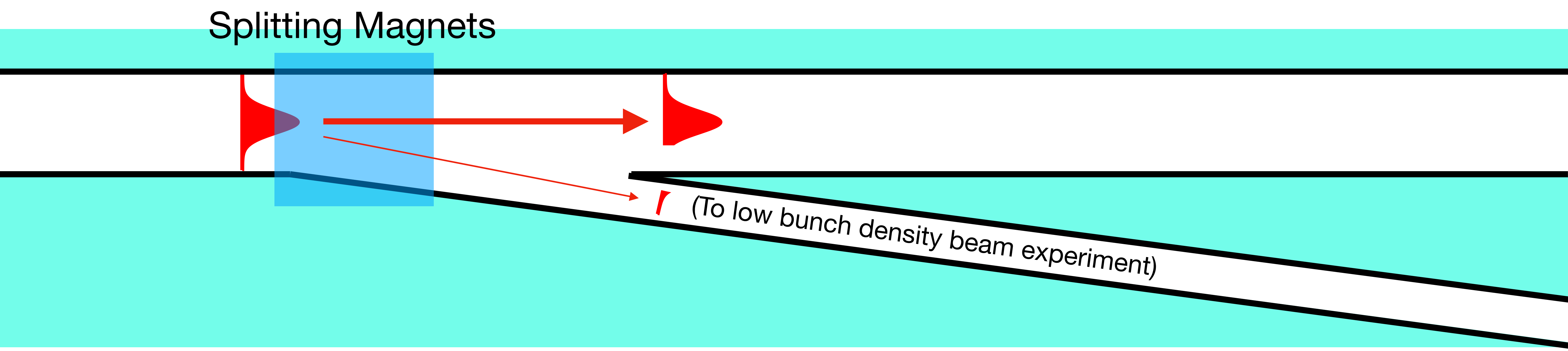
- Low bunch density and High repetition rate are required for missing measurement.
- The ILC default beam condition is not suitable to missing measurement due to its high bunch density and low repetition rate.
- However, it is principally possible to transport low-density-bunch during 0.73 ms at 1.3 GHz Radio-frequency (Therefore repetition rate is 5 Hz * 0.73 ms * 1.3 GHz ~ 5 MHz).
- LDMX@SLAC (8 GeV,> 46 MHz) vs LDMX@ILC (125 GeV, 5 MHz (Max))

(4) Collimator as Fixed target ?

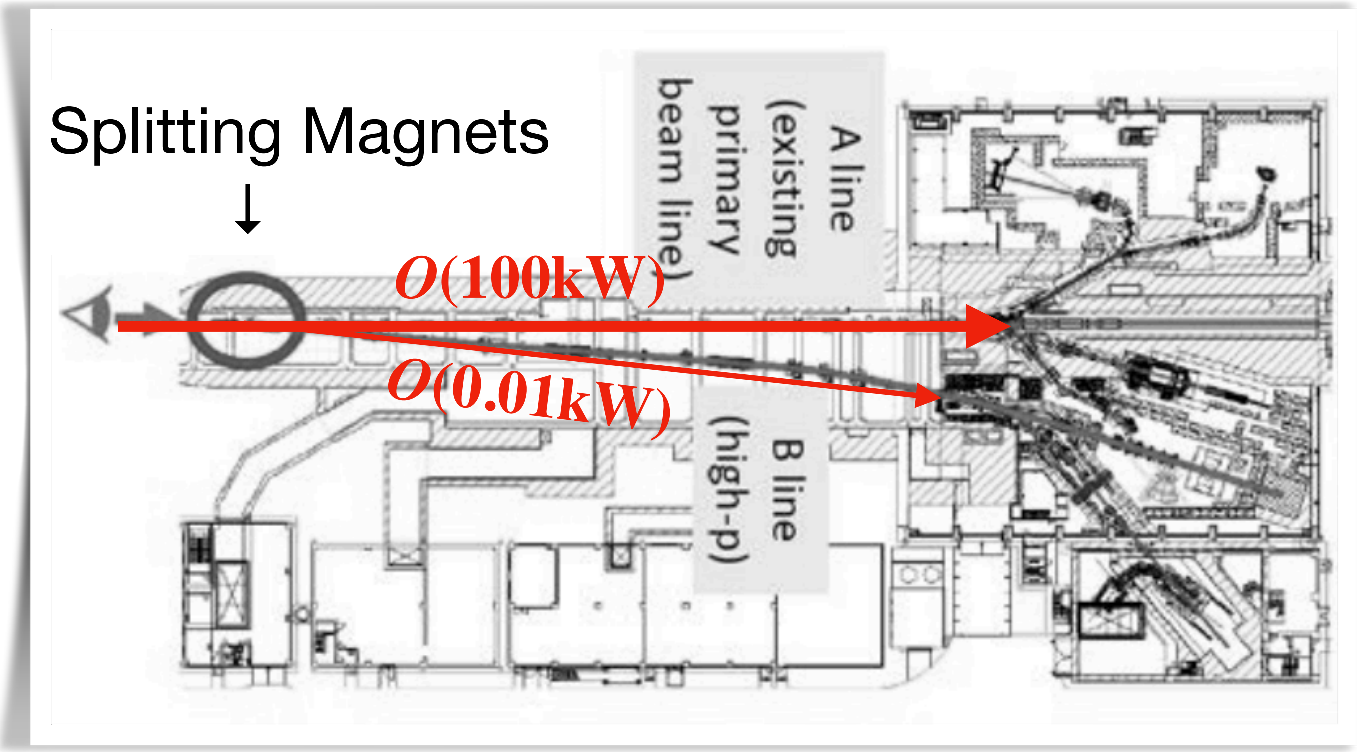


- Particles on beam halo hit collimators, in which LLP could be produced.
- Good points of collimator experiment:
  - It can be performed in parallel with a collider experiment. (Applicable to not only ILC)
  - small number of particles hit collimator, so pileup may be avoidable to some extent.
- This kind of setup might improve the sensitivity to short lifetime region.

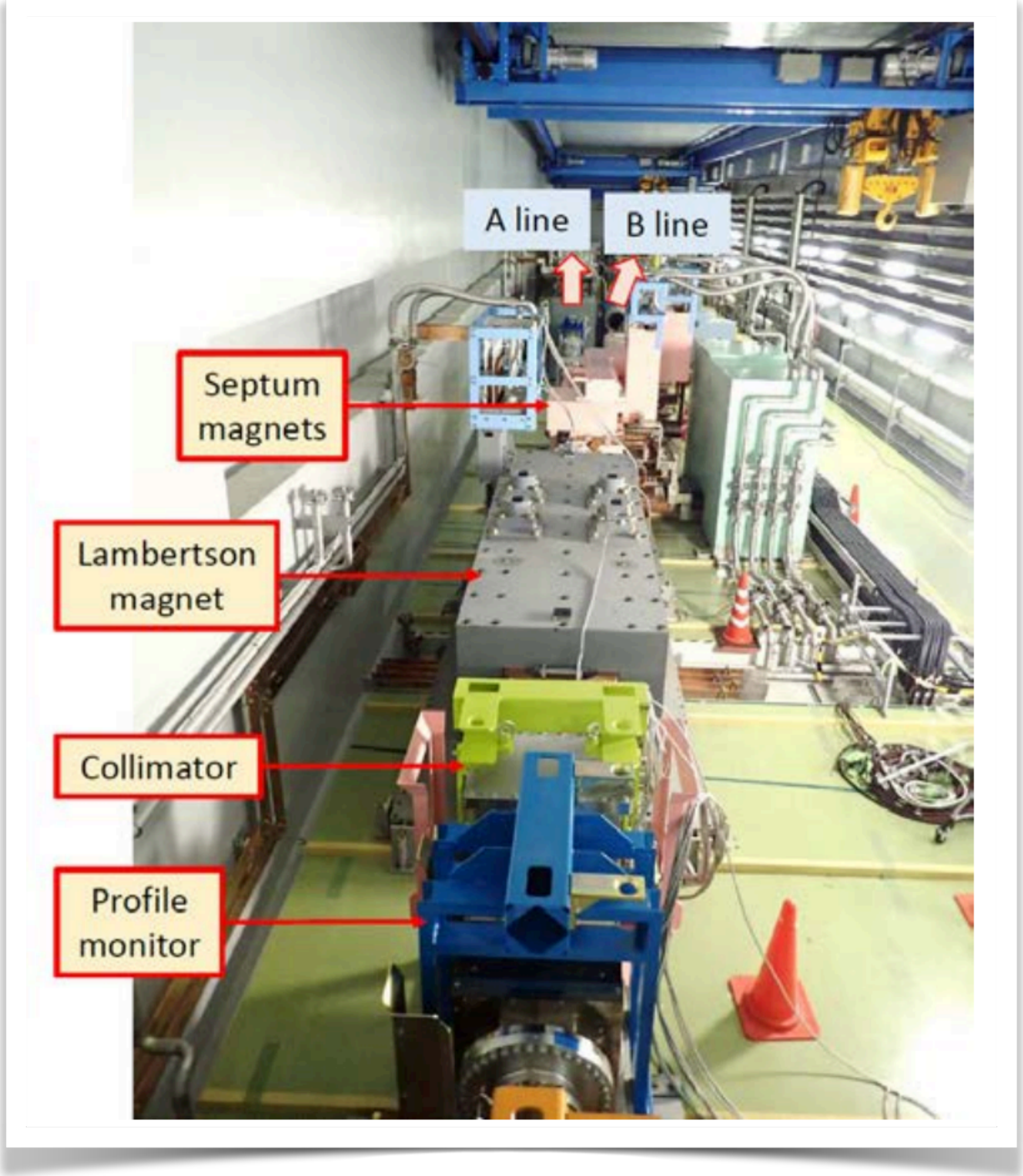
(5) Low bunch density beam with splitting magnets?



- Is it possible to take out and use a part of beam like the high-p beam line at J-PARC?

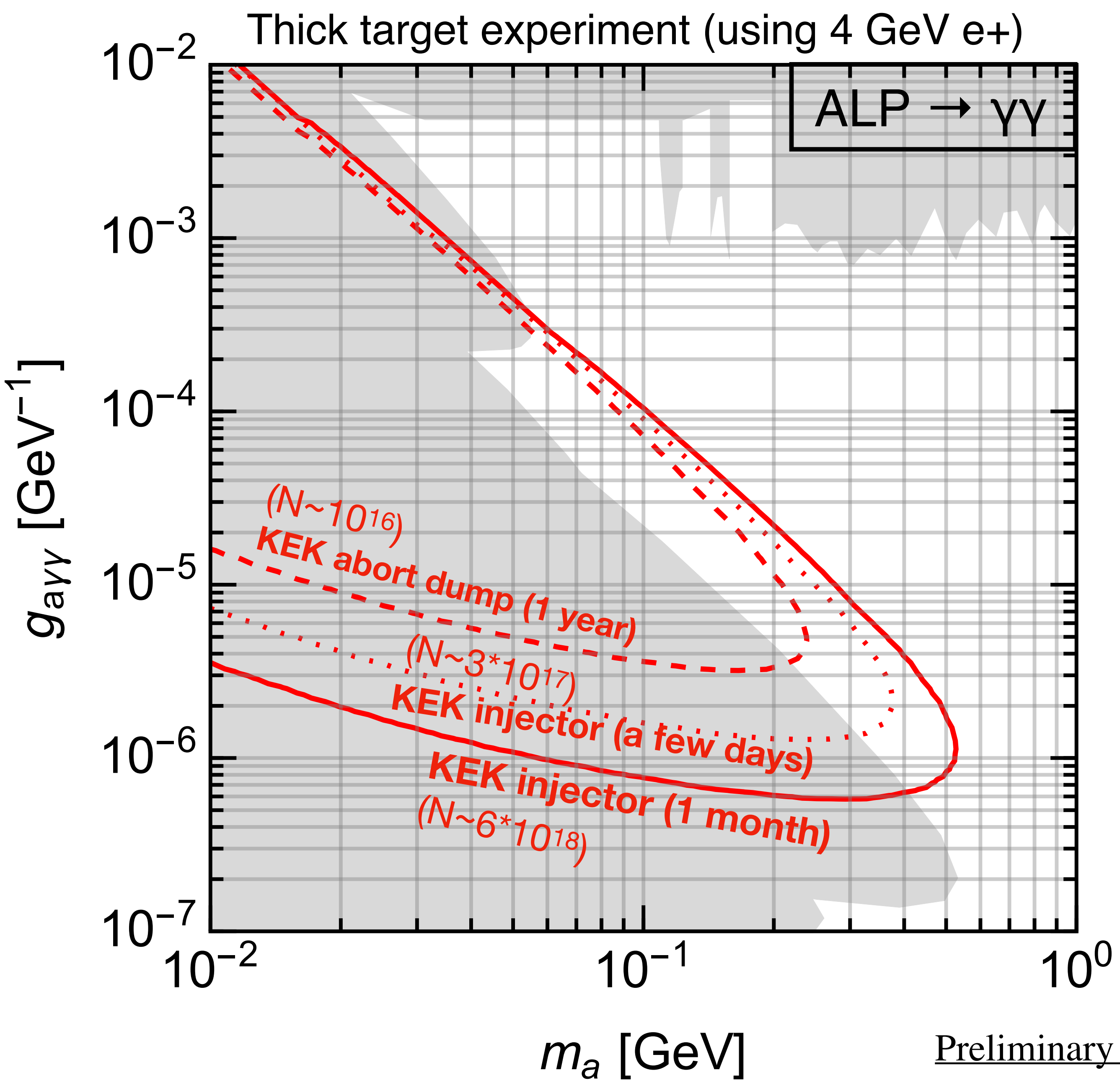


high-p @J-PARC



Fixed target experiments @ KEK ?

- Experimentalists would want to know what we can do soon.
- Consideration of Fixed target experiments at KEK could have a positive effect to the ILC fixed target program.



With thick target (Tungsten)

Preliminary results (with Y. Takubo, A.Ishikawa)

Fixed target experiments @ KEK

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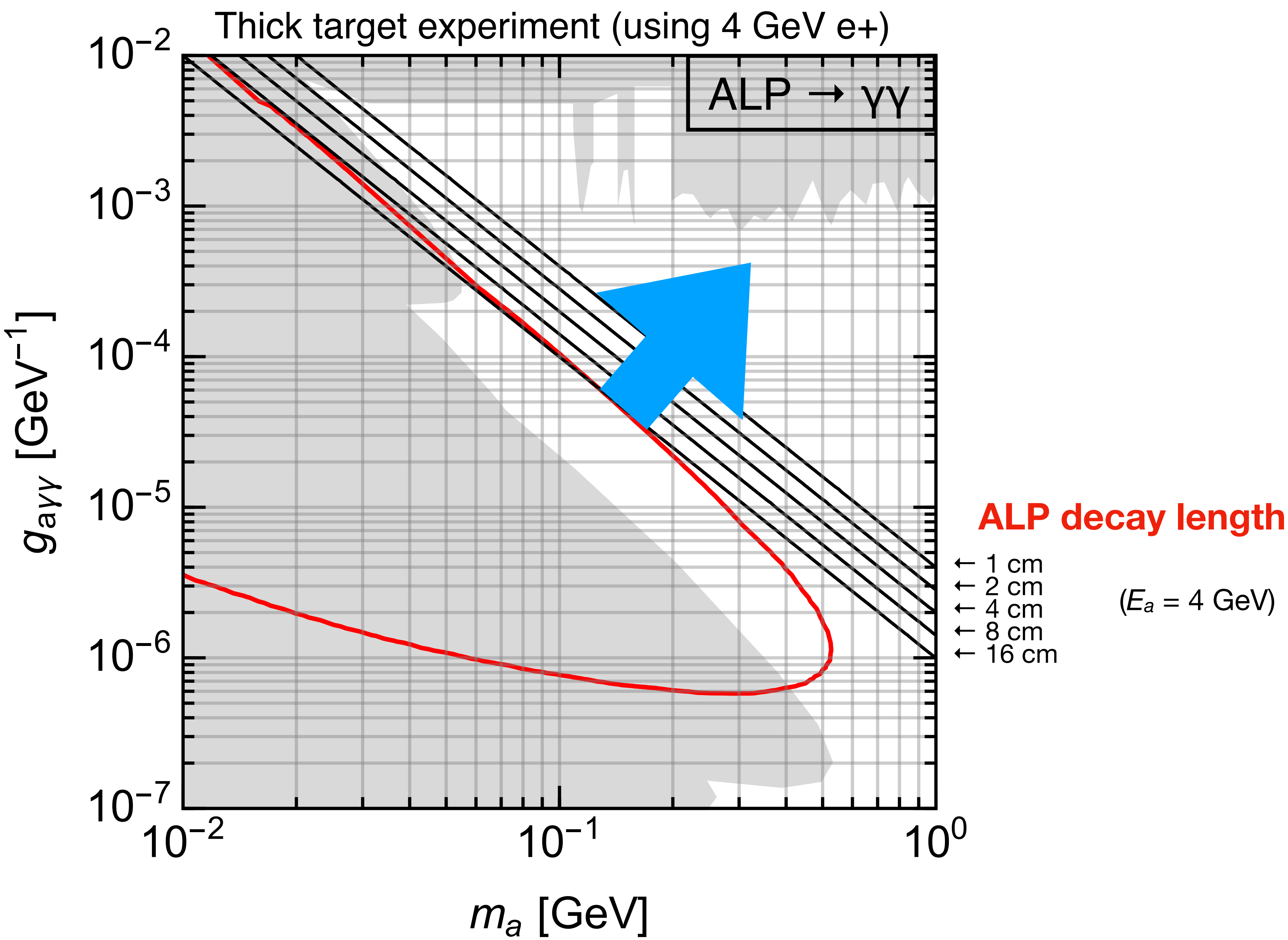


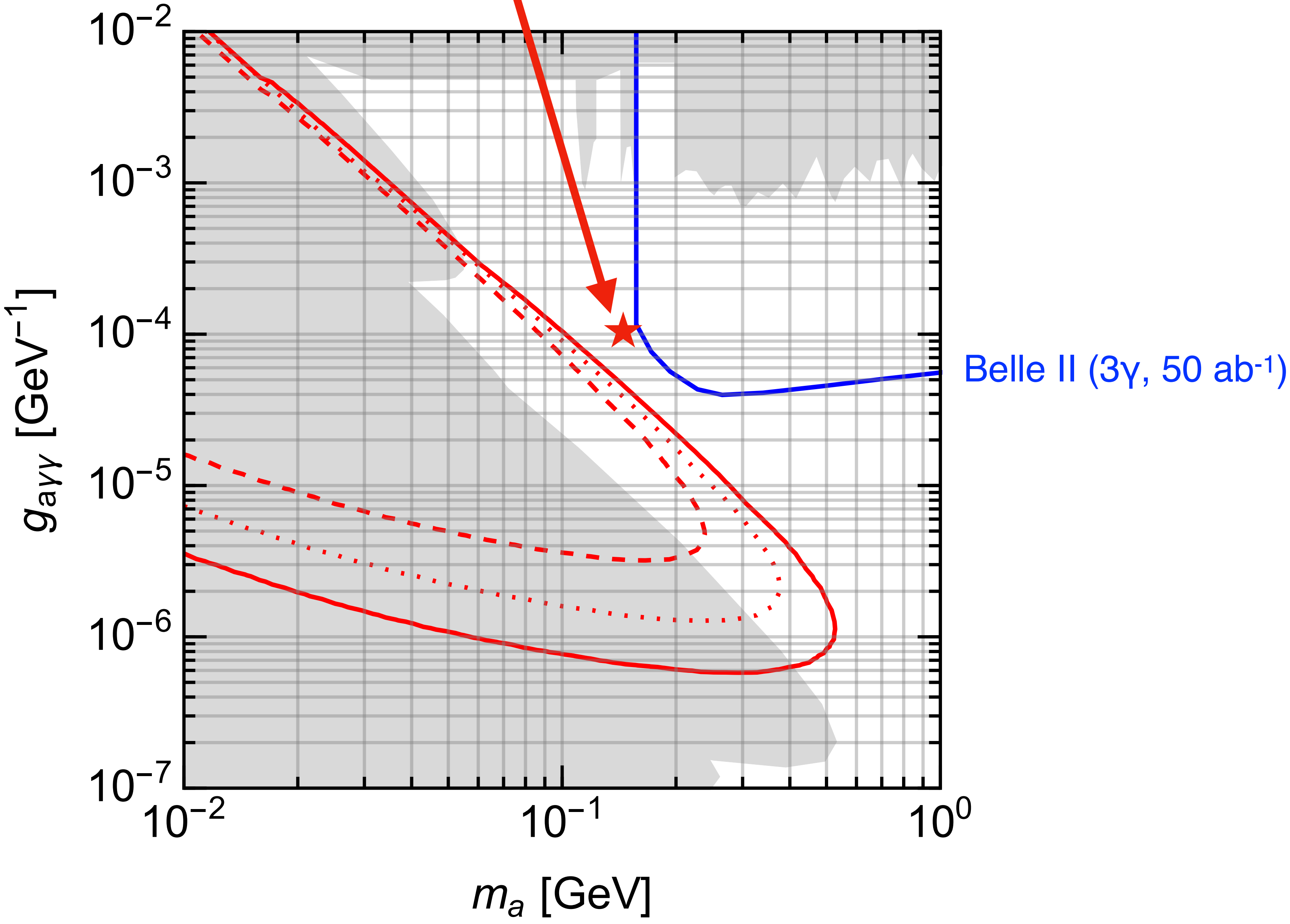
Fixed target experiments @ KEK

[Benchmark]

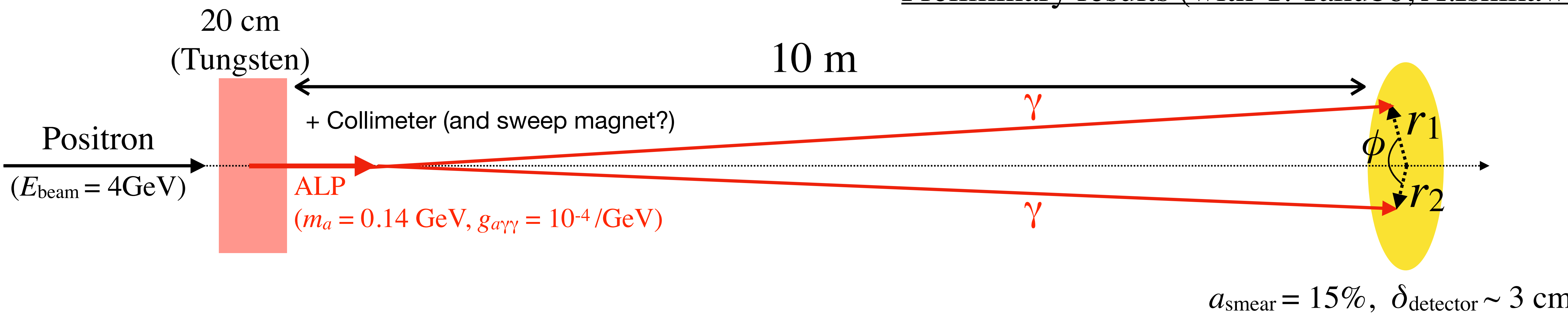
N_{signal} = $O(10^{-16})$ with thick target setup (N_e=6.5*10^{18})

Impossible to search with thick shield setup (Zero-BG setup)

Thin shield setup could search gap between *Collider* and *Thick-experiment*



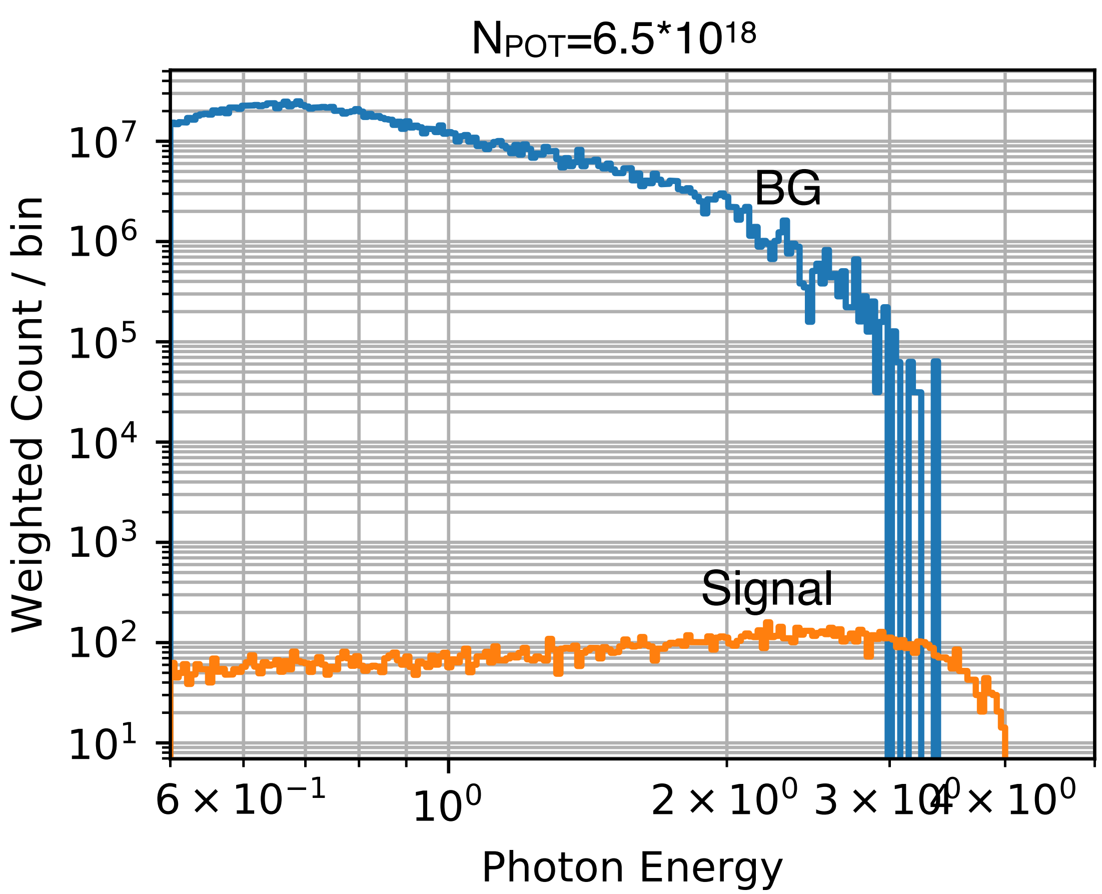
<u>Preliminary results (with Y. Takubo, A.Ishikawa)</u>

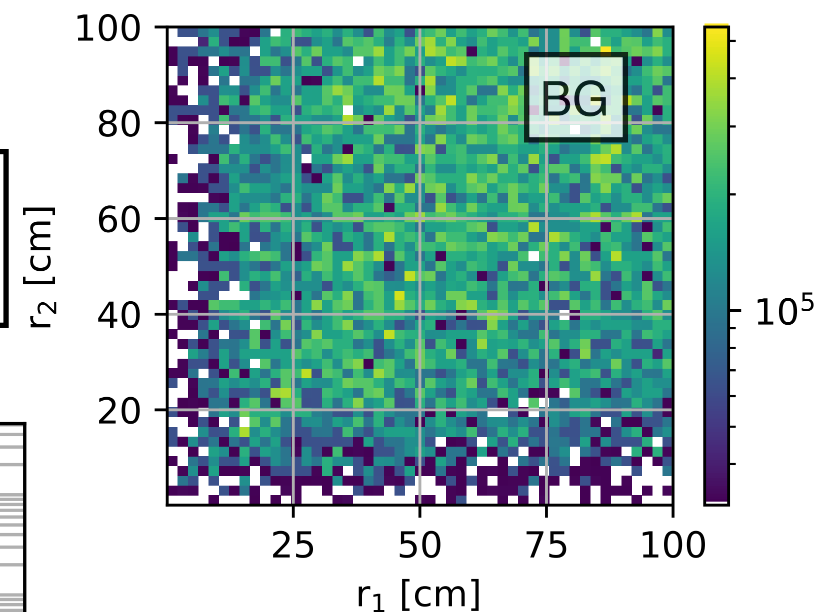


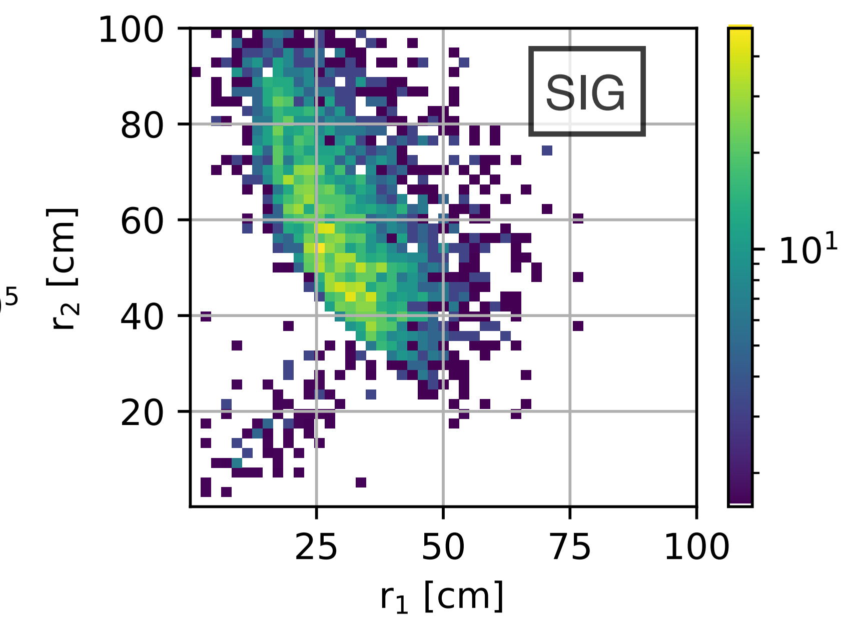
BG:
γN→n +…, nn→nnπ⁰, π⁰→γγ
γN→K⁰ Σ(Λ), K⁰→π⁰+…, π⁰→γγ
…

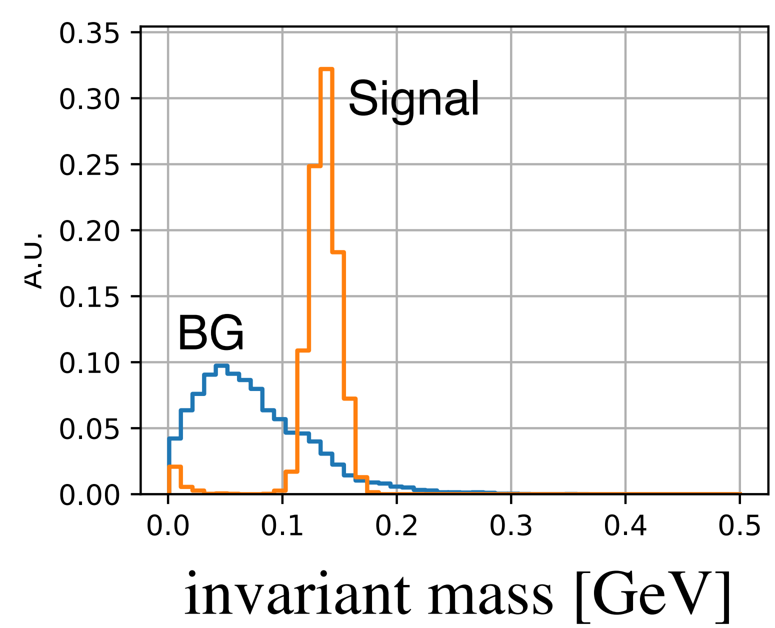
Different shape between Signal and BG.

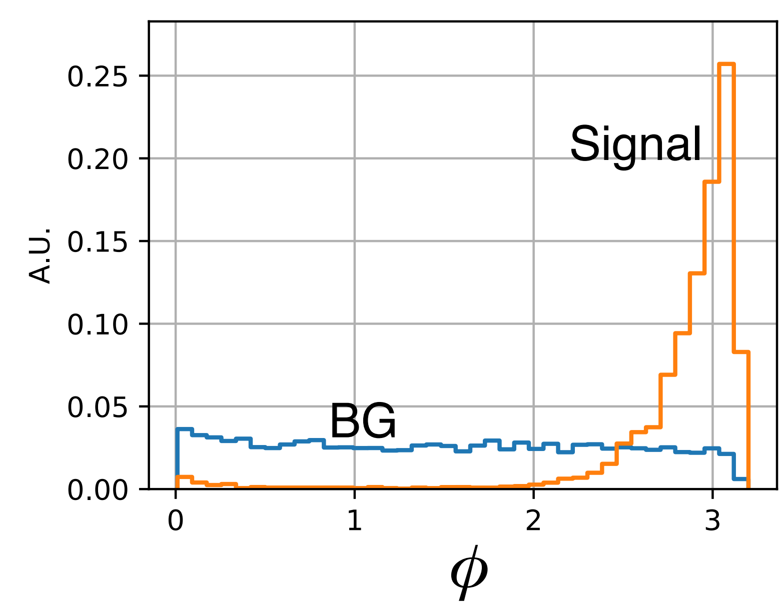
We could catch signal at high energy tail.



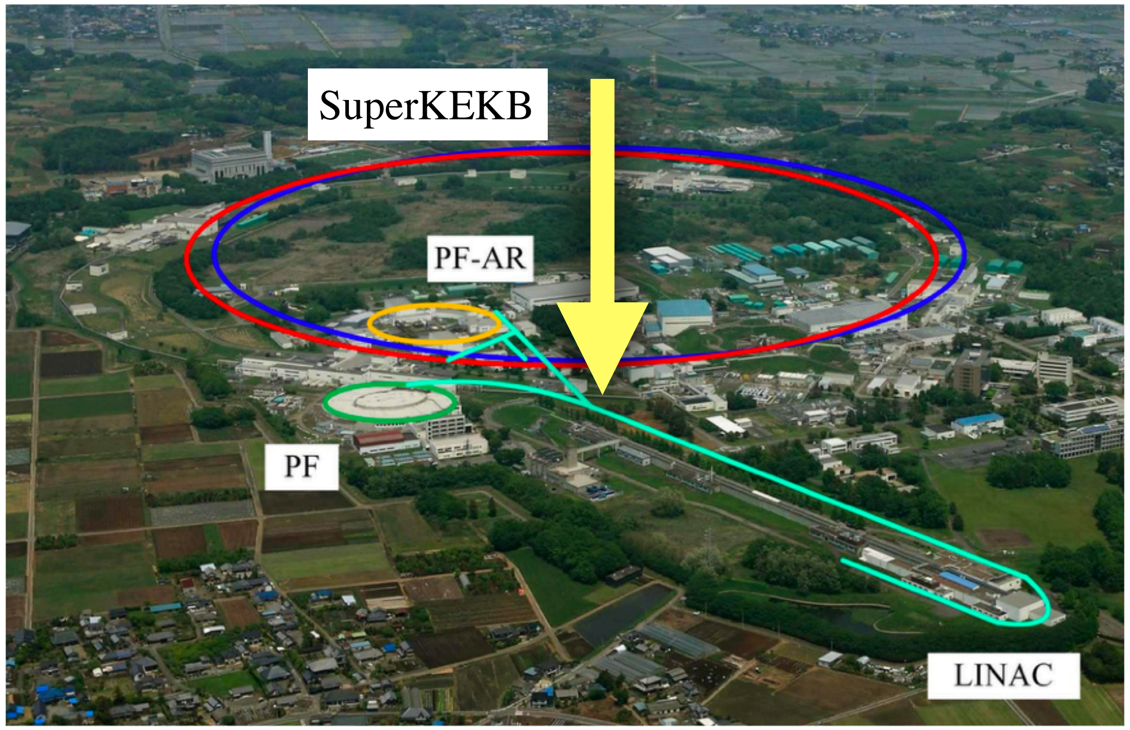


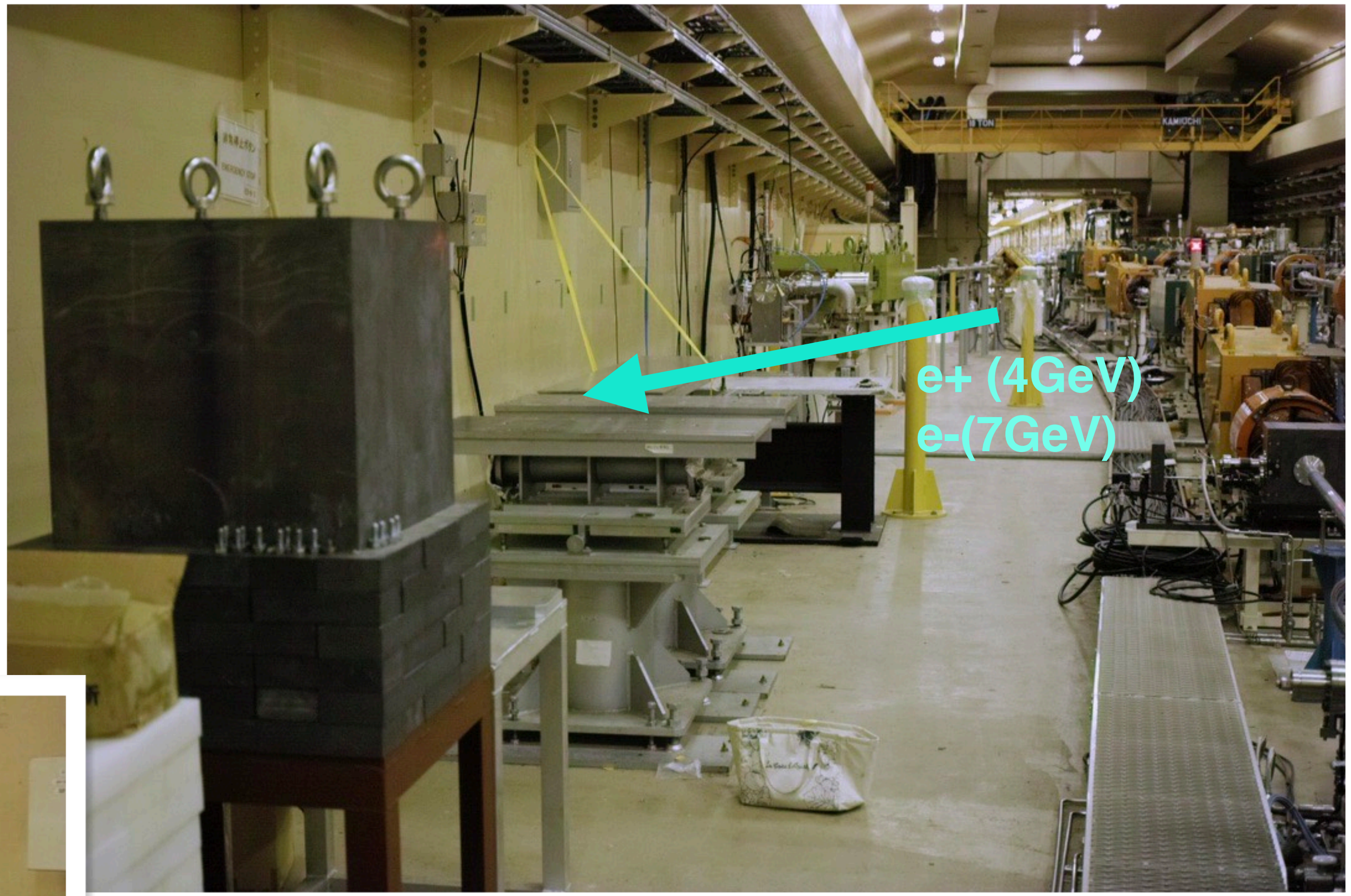






Good place to experiment ?





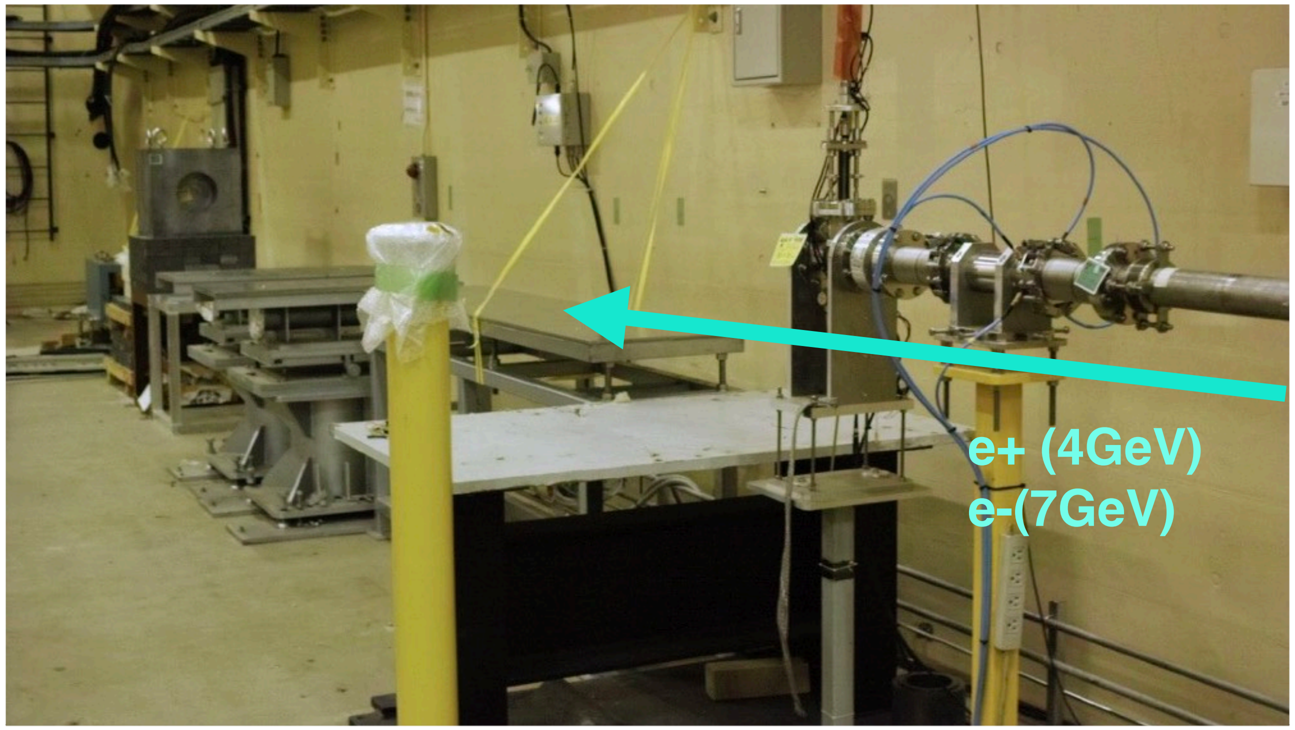


Photo by Hiroshi Iwase