Sub-GeV dark matter search at beam dump experiments

The 3rd DMNet international symposium
27 September 2023

Daiki Ueda (Technion)

Introduction

- One of the DM candidates is thermal DM, i.e., DM is thermalized with SM particles in the early universe

Introduction

- One of the DM candidates is thermal DM, i.e., DM is thermalized with SM particles in the early universe

[attractive features]

Introduction

- One of the DM candidates is thermal DM, i.e., DM is thermalized with SM particles in the early universe

[attractive features]

- Freeze-out mechanism can yield DM abundance ⇒ DM-SM reaction cross section can be large

Introduction

- One of the DM candidates is thermal DM, i.e., DM is thermalized with SM particles in the early universe

[attractive features]

- Freeze-out mechanism can yield DM abundance ⇒ DM-SM reaction cross section can be large

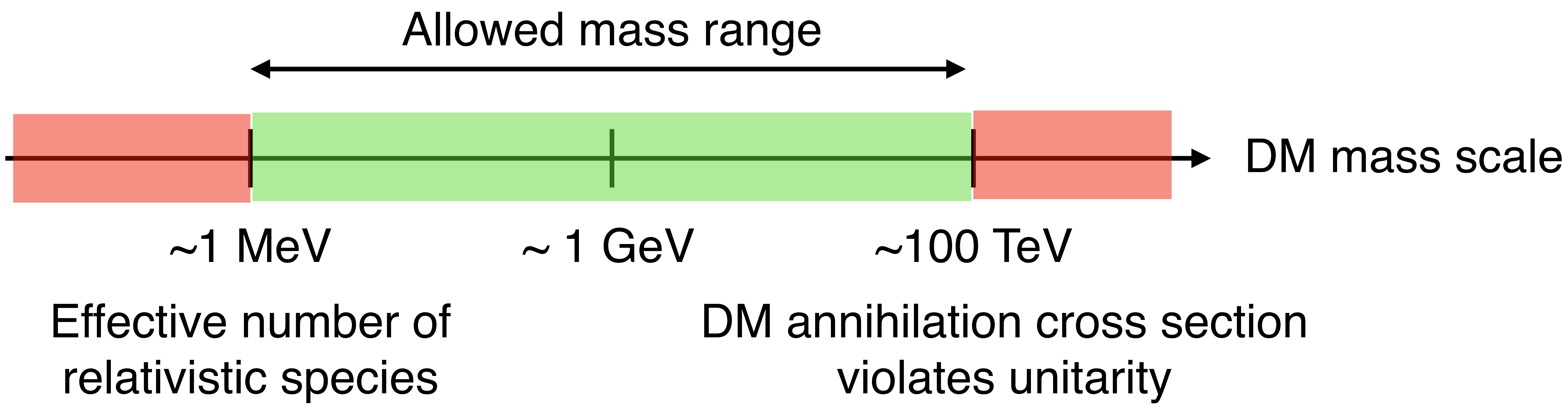
- Viable DM mass range is limited ⇒ Thermal mass window (~1 MeV to ~100 TeV)

Introduction

- One of the DM candidates is thermal DM, i.e., DM is thermalized with SM particles in the early universe

[attractive features]

- Freeze-out mechanism can yield DM abundance ⇒ DM-SM reaction cross section can be large
- Viable DM mass range is limited ⇒ Thermal mass window (~1 MeV to ~100 TeV)



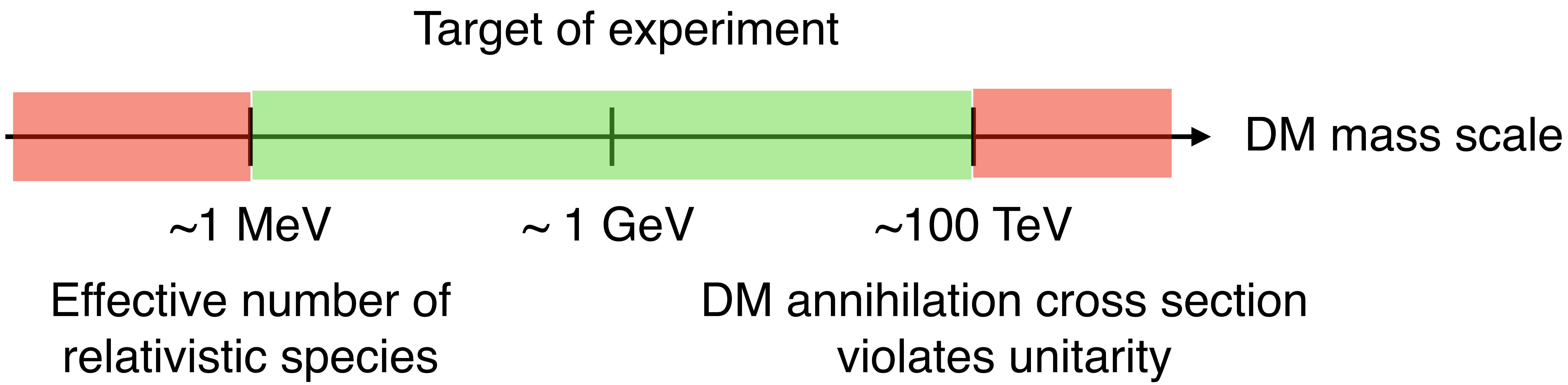
Introduction

- One of the DM candidates is thermal DM, i.e., DM is thermalized with SM particles in the early universe

[attractive features]

- Freeze-out mechanism can yield DM abundance ⇒ DM-SM reaction cross section can be large

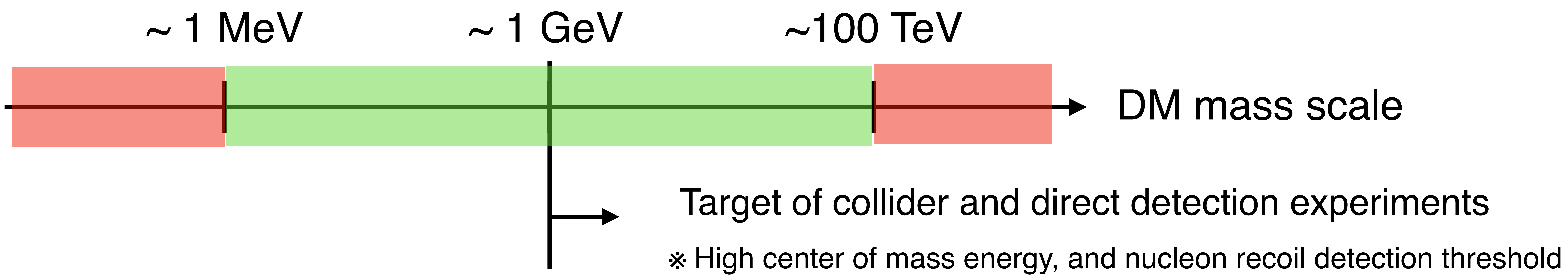
- Viable DM mass range is limited ⇒ Thermal mass window (~1 MeV to ~100 TeV)



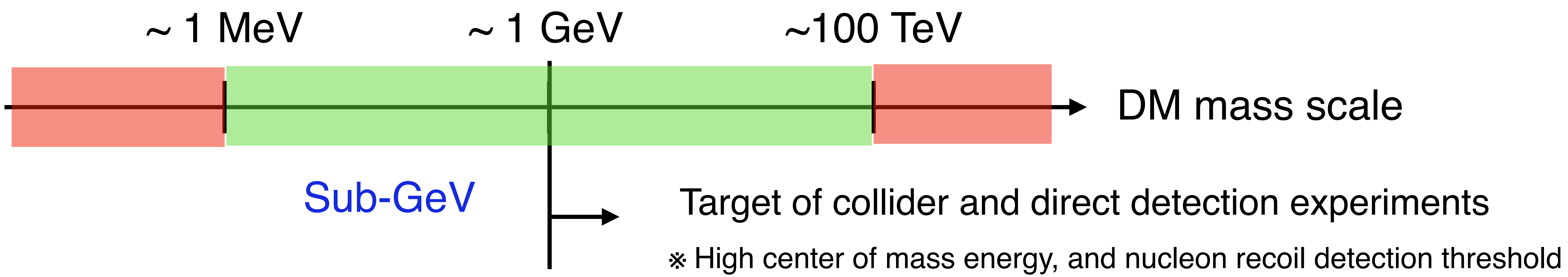
Thermal DM scenario provides target of experiment

Sub-GeV dark matter

Sub-GeV dark matter

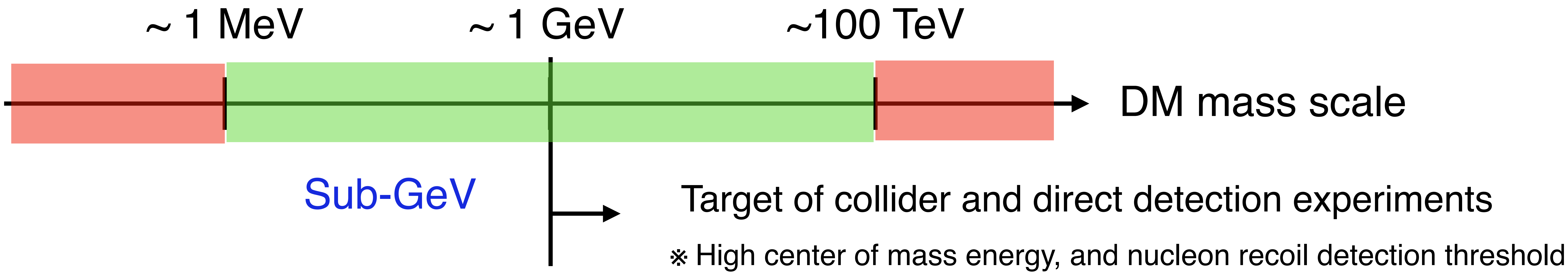


Sub-GeV dark matter



- Sub-GeV DM is also a DM candidate but is feebly coupled with SM particles

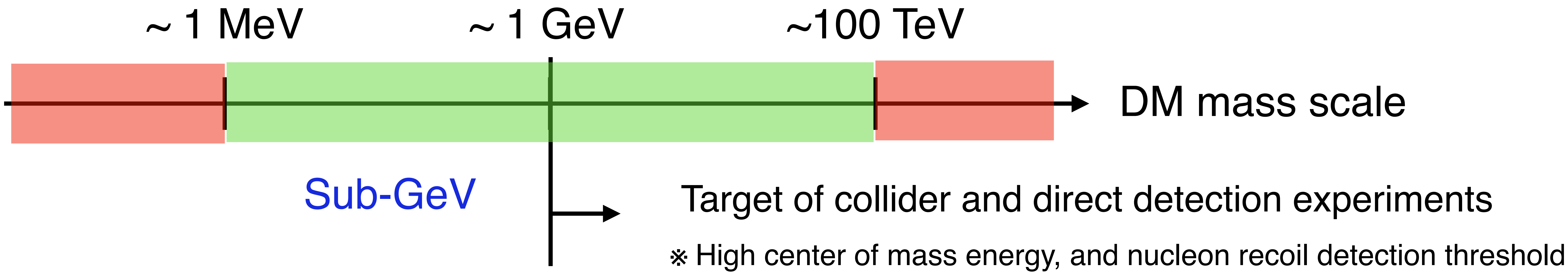
Sub-GeV dark matter



- Sub-GeV DM is also a DM candidate but is feebly coupled with SM particles

  - Benchmark model: $\mathscr{L} \supset \epsilon e A'_\mu J^\mu_{\mathrm{EM}} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + \mathrm{H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, J^μ_{EM}: SM EM current

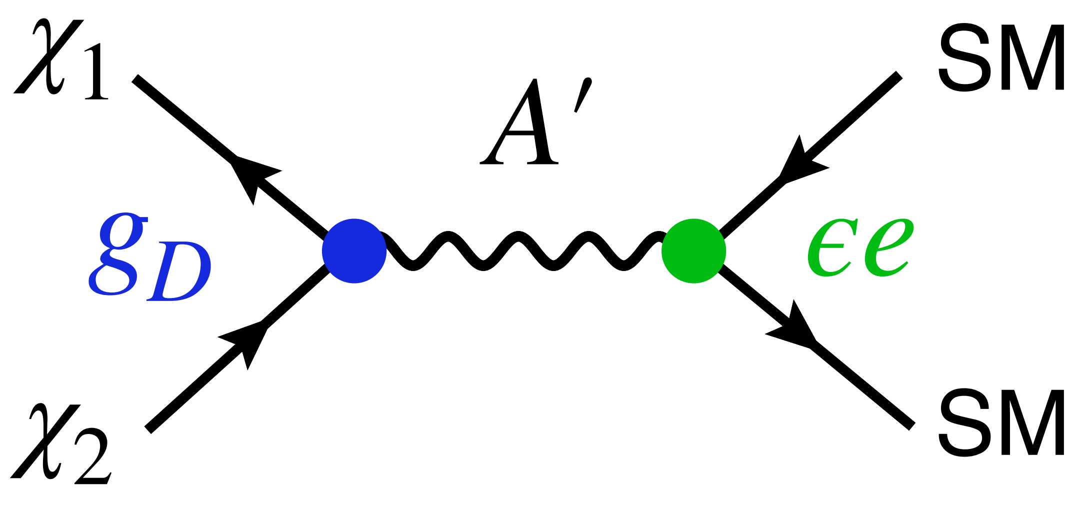
Sub-GeV dark matter



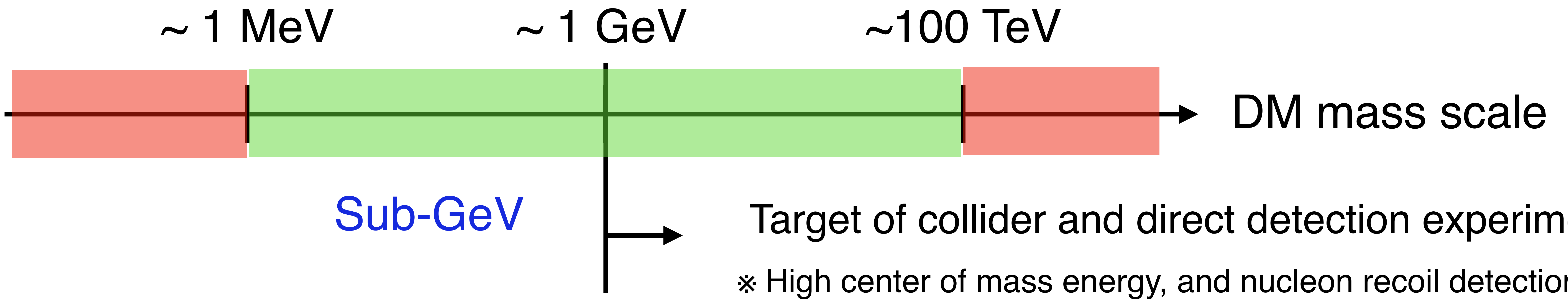
- Sub-GeV DM is also a DM candidate but is feebly coupled with SM particles

  - Benchmark model: $\mathscr{L} \supset \epsilon e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

DM annihilation cross section for $m_{\chi_1} + m_{\chi_2} < m_{A'}$



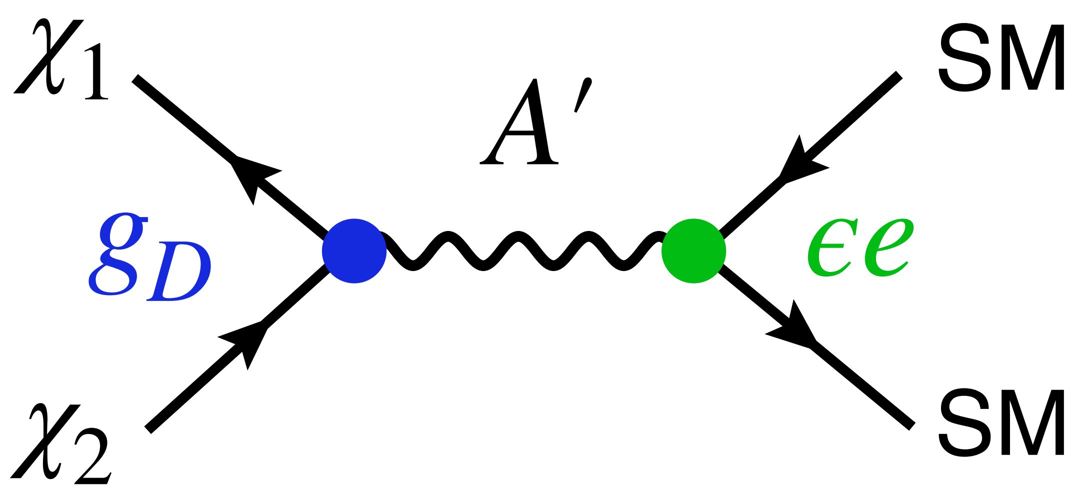
Sub-GeV dark matter



- Sub-GeV DM is also a DM candidate but is feebly coupled with SM particles

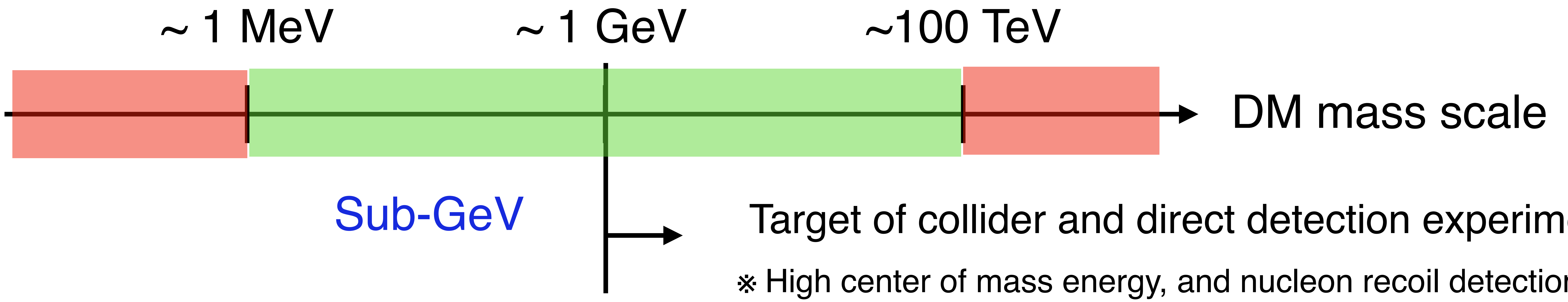
  - Benchmark model: $\mathscr{L} \supset \epsilon e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

DM annihilation cross section for $m_{\chi_1} + m_{\chi_2} < m_{A'}$



$$\langle \sigma v \rangle_{\rm ann} \propto y/m_{\chi_1}^2 \ \text{with} \ y \equiv \epsilon^2 g_{\rm D}^2 \left(m_{\chi_1}/m_{A'} \right)^4$$

Sub-GeV dark matter



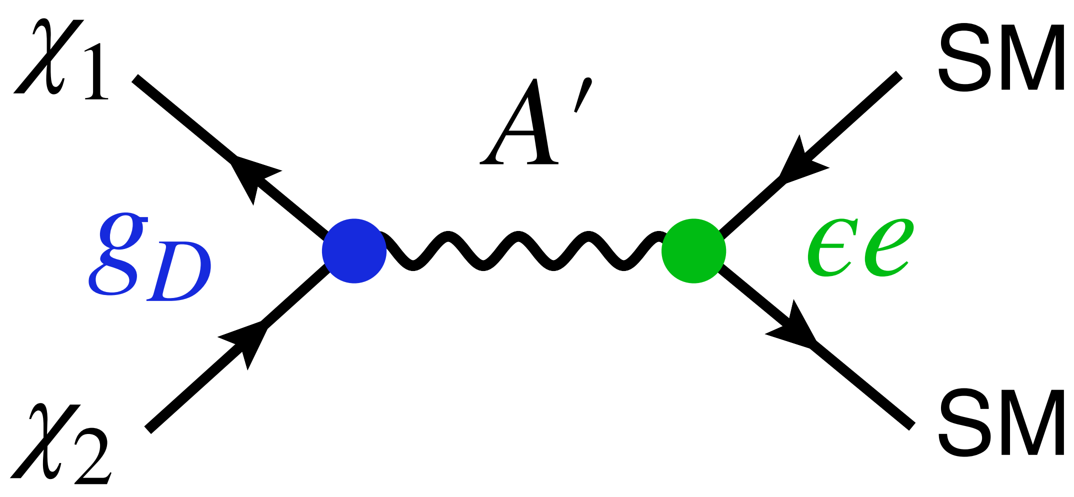
Target of collider and direct detection experiments

※ High center of mass energy, and nucleon recoil detection threshold

- Sub-GeV DM is also a DM candidate but is feebly coupled with SM particles

  - Benchmark model: $\mathscr{L} \supset \epsilon e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + \rm H.c.)$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

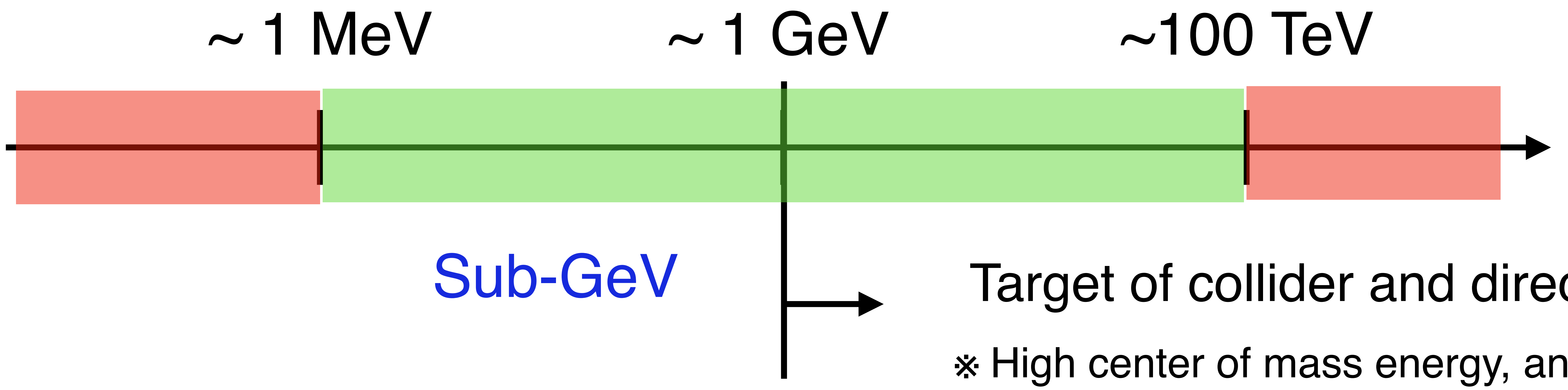
DM annihilation cross section for $m_{\chi_1} + m_{\chi_2} < m_{A'}$



$$\langle \sigma v \rangle_{\rm ann} \propto y / m^2_{\chi_1} \text{ with } y \equiv \epsilon^2 g^2_{\rm D} \left(m_{\chi_1} / m_{A'} \right)^4$$

For a fixed $\langle \sigma v \rangle_{\rm ann}$, y becomes smaller(feebly coupled) when m_χ gets smaller

Sub-GeV dark matter



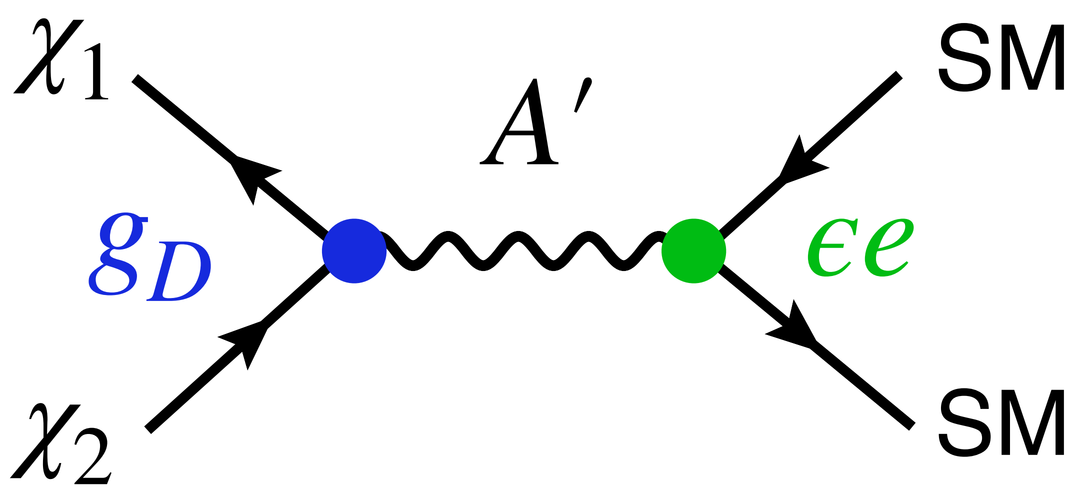
Target of collider and direct detection experiments

※ High center of mass energy, and nucleon recoil detection threshold

- Sub-GeV DM is also a DM candidate but is feebly coupled with SM particles

  - Benchmark model: $\mathscr{L} \supset \epsilon e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

DM annihilation cross section for $m_{\chi_1} + m_{\chi_2} < m_{A'}$



$$\langle \sigma v \rangle_{\rm ann} \propto y / m_{\chi_1}^2 \ \text{with} \ y \equiv \epsilon^2 g_{\rm D}^2 \left(m_{\chi_1} / m_{A'} \right)^4$$

For a fixed $\langle \sigma v \rangle_{\rm ann}$, y becomes smaller(feebly coupled) when m_χ gets smaller

Hight intensity experiments are needed to search for Sub-GeV DM

DM search at beam dump experiment

- Beam dump experiments are high-intensity experiments and are sensitive to Sub-GeV DM

DM search at beam dump experiment

- Beam dump experiments are high-intensity experiments and are sensitive to Sub-GeV DM
  - three components of beam dump experiment:

DM search at beam dump experiment

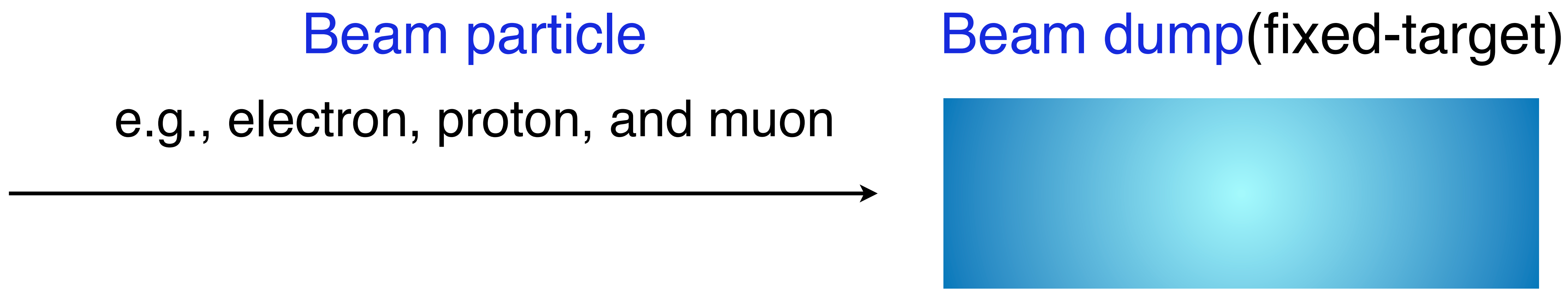
- Beam dump experiments are high-intensity experiments and are sensitive to Sub-GeV DM
  - three components of beam dump experiment:

Beam particle

e.g., electron, proton, and muon

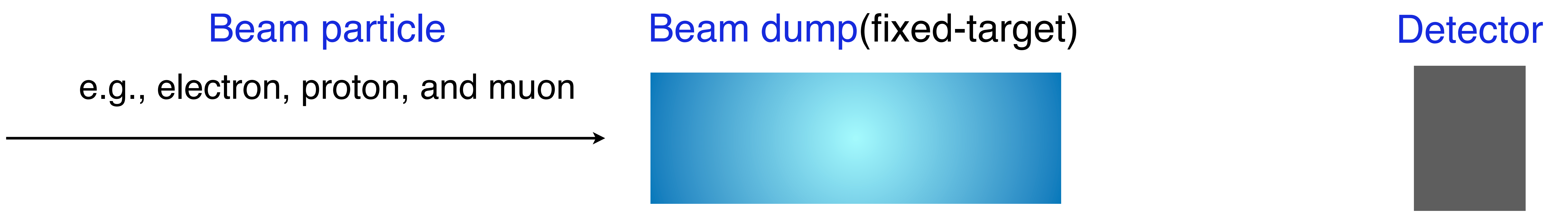
DM search at beam dump experiment

- Beam dump experiments are high-intensity experiments and are sensitive to Sub-GeV DM
  - three components of beam dump experiment:



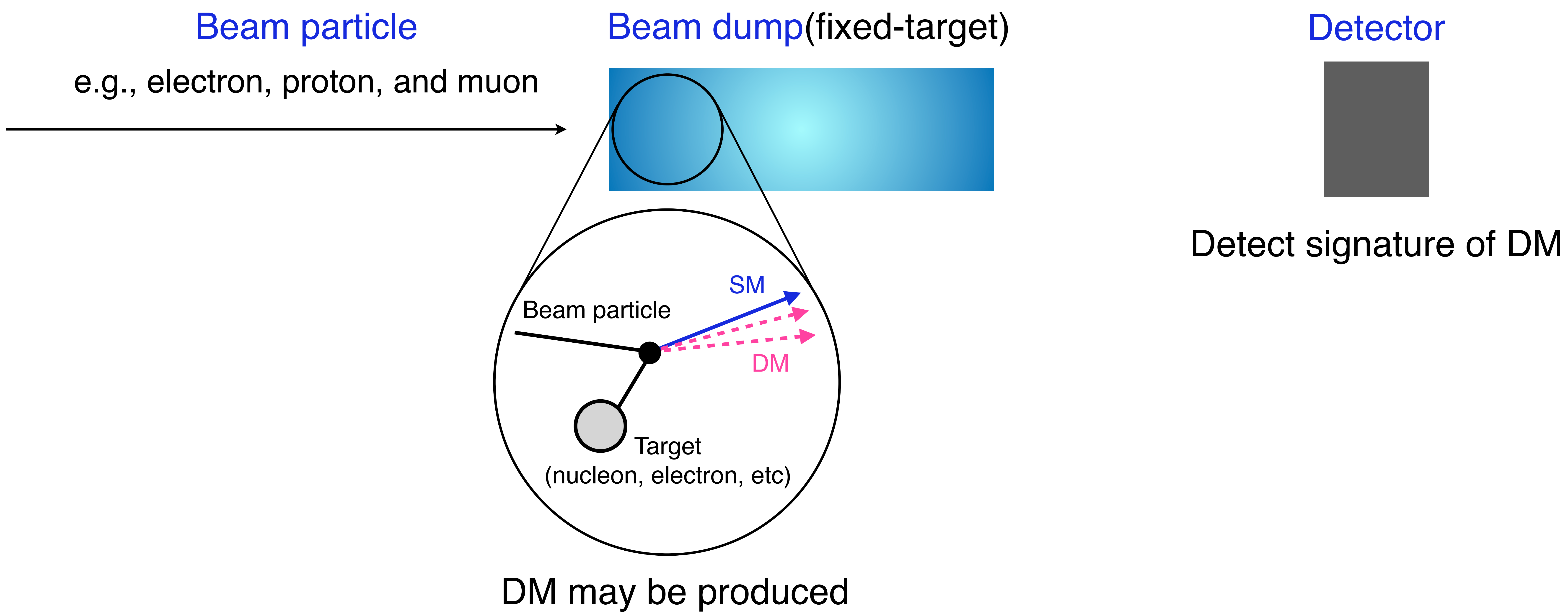
DM search at beam dump experiment

- Beam dump experiments are high-intensity experiments and are sensitive to Sub-GeV DM
  - three components of beam dump experiment:



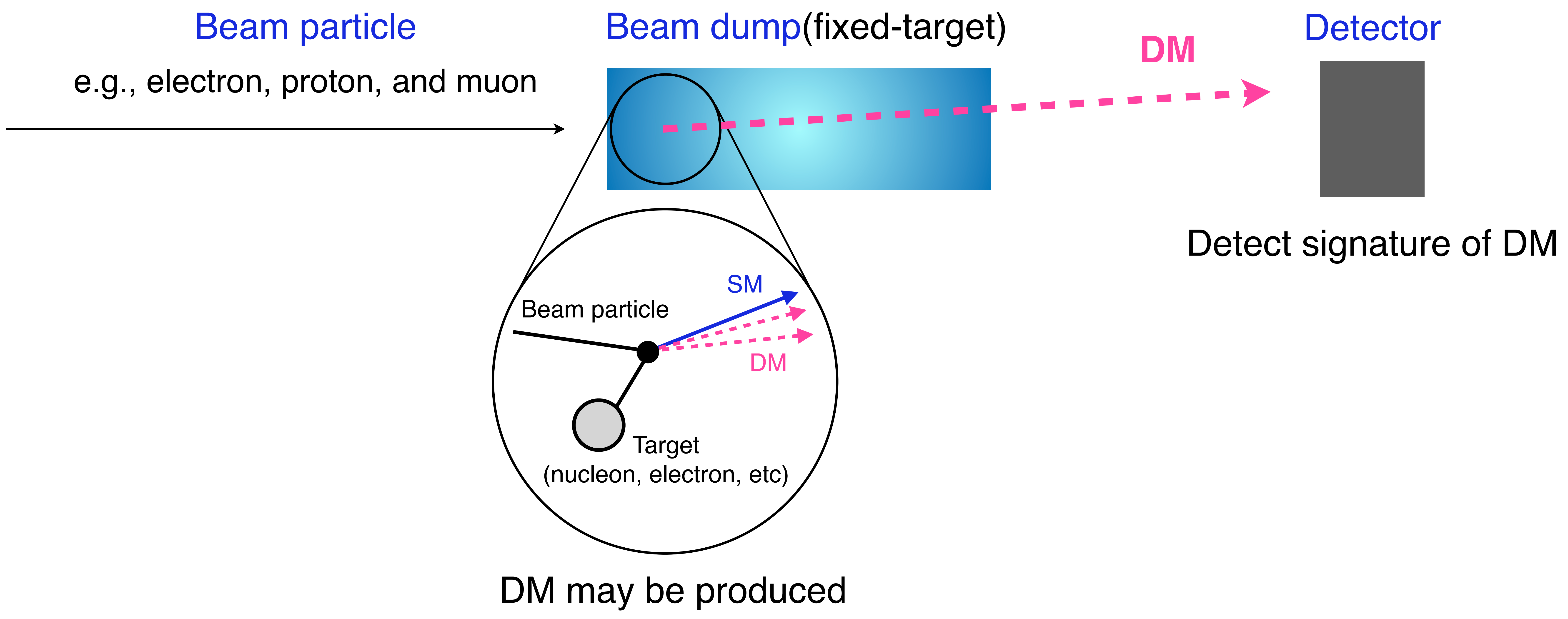
DM search at beam dump experiment

- Beam dump experiments are high-intensity experiments and are sensitive to Sub-GeV DM
  - three components of beam dump experiment:



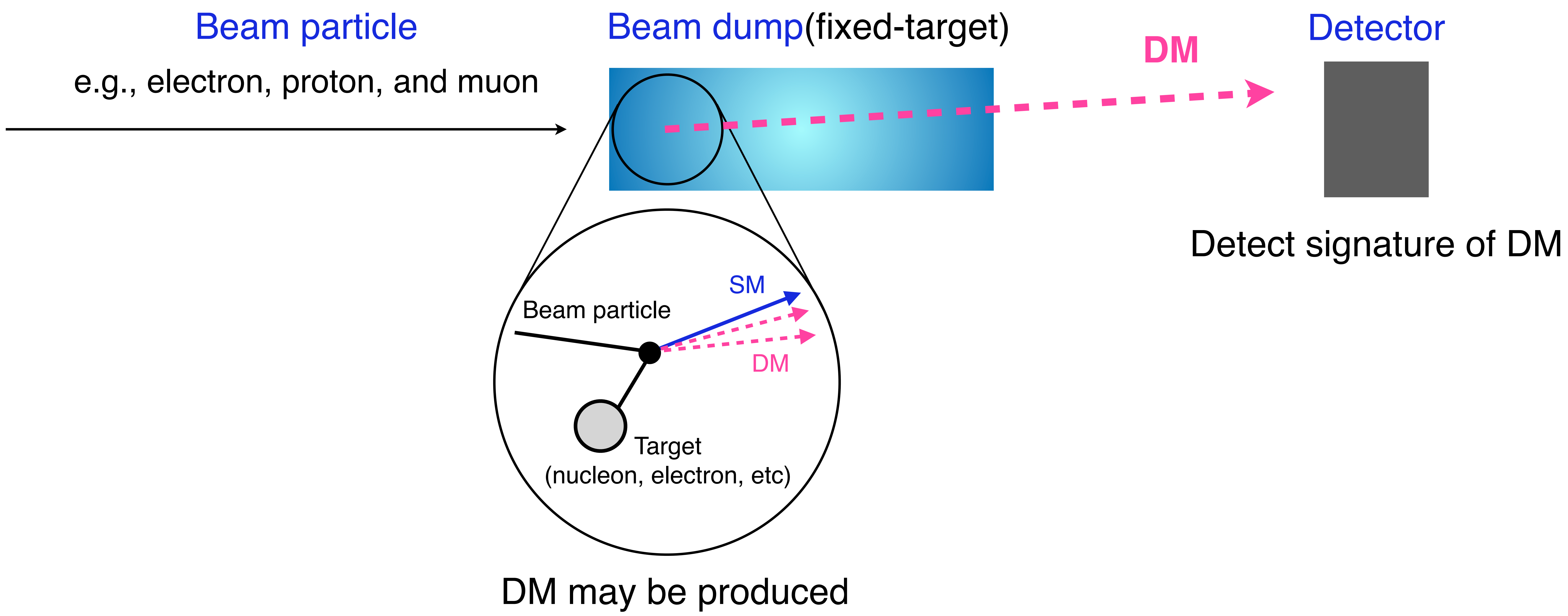
DM search at beam dump experiment

- Beam dump experiments are high-intensity experiments and are sensitive to Sub-GeV DM
  - three components of beam dump experiment:



DM search at beam dump experiment

- Beam dump experiments are high-intensity experiments and are sensitive to Sub-GeV DM
  - three components of beam dump experiment:



[Goal of beam dump experiment]

To detect DM signatures produced by beam-target collision

Key features of beam dump experiment (1)

Key features of beam dump experiment (1)

[Center of mass energy]

$$\sqrt{s} = \sqrt{m_{\text{beam}}^2 + m_{\text{target}}^2 + 2E_{\text{beam}}m_{\text{target}}}$$

where m_{beam} is mass of beam particle, m_{target} is mass of target particle, and E_{beam} is beam energy

※ This feature is determined only by beam and target properties

Key features of beam dump experiment (1)

[Center of mass energy]

$$\sqrt{s} = \sqrt{m_{\rm beam}^2 + m_{\rm target}^2 + 2E_{\rm beam}m_{\rm target}}$$

where $m_{\rm beam}$ is mass of beam particle, $m_{\rm target}$ is mass of target particle, and $E_{\rm beam}$ is beam energy

・Center of mass energy is smaller than collider energy scale, but Sub-GeV DM productions are kinematically allowed

※ This feature is determined only by beam and target properties

Key features of beam dump experiment (1)

[Center of mass energy]

$$\sqrt{s} = \sqrt{m_{\text{beam}}^2 + m_{\text{target}}^2 + 2E_{\text{beam}}m_{\text{target}}}$$

where m_{beam} is mass of beam particle, m_{target} is mass of target particle, and E_{beam} is beam energy

・Center of mass energy is smaller than collider energy scale, but Sub-GeV DM productions are kinematically allowed

Ex. Beam = electron (m_{beam} = 0.5 MeV), target = nucleon (m_{target} = 1 GeV), E_{beam} = 10 GeV

$$\sqrt{s} = \sqrt{m_{\text{beam}}^2 + m_{\text{target}}^2 + 2E_{\text{beam}}m_{\text{target}}} \simeq 5\ \text{GeV}$$

※ This feature is determined only by beam and target properties

Key features of beam dump experiment (1)

[Center of mass energy]

$$\sqrt{s} = \sqrt{m_{\rm beam}^2 + m_{\rm target}^2 + 2E_{\rm beam}m_{\rm target}}$$

where $m_{\rm beam}$ is mass of beam particle, $m_{\rm target}$ is mass of target particle, and $E_{\rm beam}$ is beam energy

・Center of mass energy is smaller than collider energy scale, but Sub-GeV DM productions are kinematically allowed

Ex. Beam = electron ($m_{\rm beam}$ = 0.5 MeV), target = nucleon ($m_{\rm target}$ = 1 GeV), $E_{\rm beam}$ = 10 GeV

$$\sqrt{s} = \sqrt{m_{\rm beam}^2 + m_{\rm target}^2 + 2E_{\rm beam}m_{\rm target}} \simeq 5\ \mathrm{GeV}$$

Boosted Sub-GeV DM can be produced in beam dump

※ This feature is determined only by beam and target properties

Key features of beam dump experiment (2)

- Beam dump experiment is high luminosity frontier

※ This feature is determined only by beam and target properties

Key features of beam dump experiment (2)

- Beam dump experiment is high luminosity frontier

(# of produced DM) = (DM production cross section [L^2])

×

※ This feature is determined only by beam and target properties

Key features of beam dump experiment (2)

- Beam dump experiment is high luminosity frontier

(# of produced DM) = (DM production cross section [L^2])

× (Beam flux [T^{-1}]) ×

※ This feature is determined only by beam and target properties

Key features of beam dump experiment (2)

- Beam dump experiment is high luminosity frontier

(# of produced DM) = (DM production cross section [L^2])

× (Beam flux [T^{-1}])× (Operation time [T]) ×

※ This feature is determined only by beam and target properties

Key features of beam dump experiment (2)

- Beam dump experiment is high luminosity frontier

(# of produced DM) = (DM production cross section [L^2])

× (Beam flux [T^{-1}]) × (Operation time [T]) × (# density of target [L^{-3}]) ×

※ This feature is determined only by beam and target properties

Key features of beam dump experiment (2)

- Beam dump experiment is high luminosity frontier

(# of produced DM) = (DM production cross section [L^2])

× (Beam flux [T^{-1}]) × (Operation time [T]) × (# density of target [L^{-3}]) × (Track length [L])

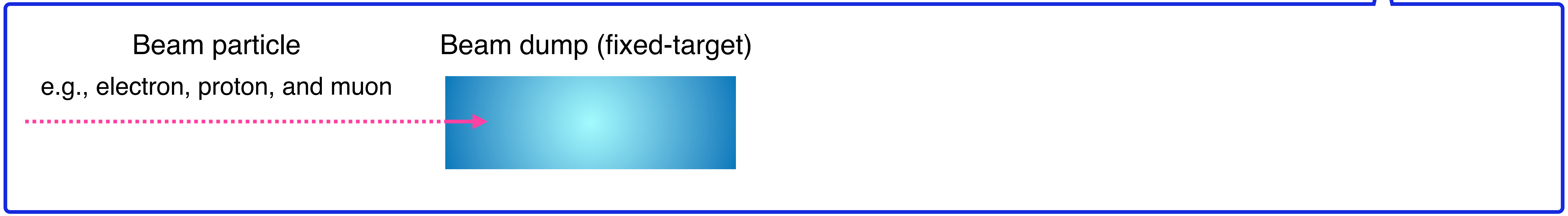
※ This feature is determined only by beam and target properties

Key features of beam dump experiment (2)

- Beam dump experiment is high luminosity frontier

(# of produced DM) = (DM production cross section [L^2])

× (Beam flux [T^{-1}]) × (Operation time [T]) × (# density of target [L^{-3}]) × (Track length [L])



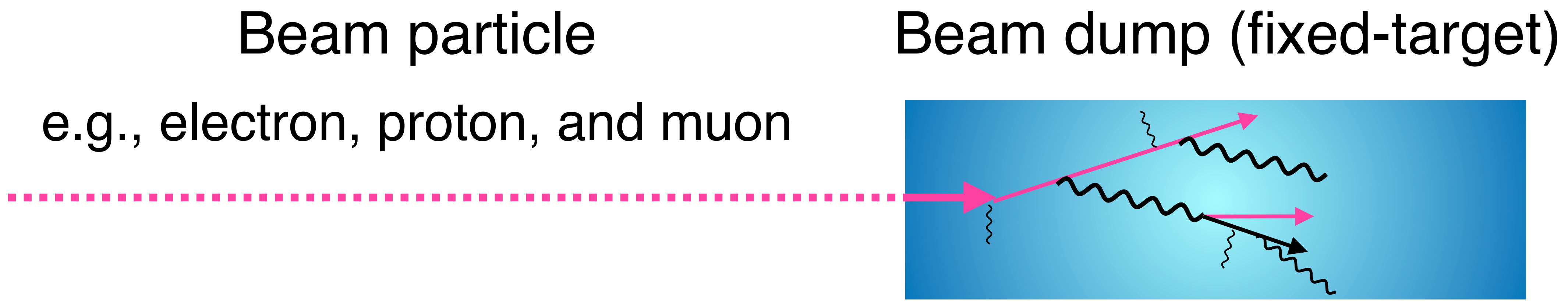
※ This feature is determined only by beam and target properties

Key features of beam dump experiment (2)

- Beam dump experiment is high luminosity frontier

(# of produced DM) = (DM production cross section [L^2])

× (Beam flux [T^{-1}]) × (Operation time [T]) × (# density of target [L^{-3}]) × (Track length [L])



※ This feature is determined only by beam and target properties

Key features of beam dump experiment (2)

- Beam dump experiment is high luminosity frontier

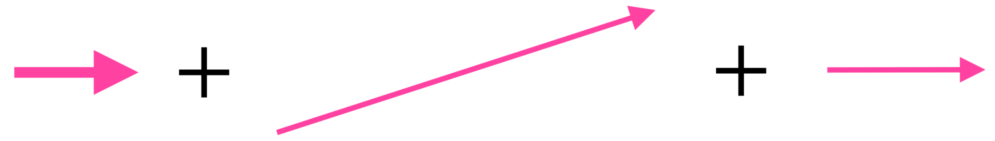
(# of produced DM) = (DM production cross section [L^2])

× (Beam flux [T^{-1}]) × (Operation time [T]) × (# density of target [L^{-3}]) × (Track length [L])

Beam particle

e.g., electron, proton, and muon

Beam dump (fixed-target)

(Track length) = 

※ This feature is determined only by beam and target properties

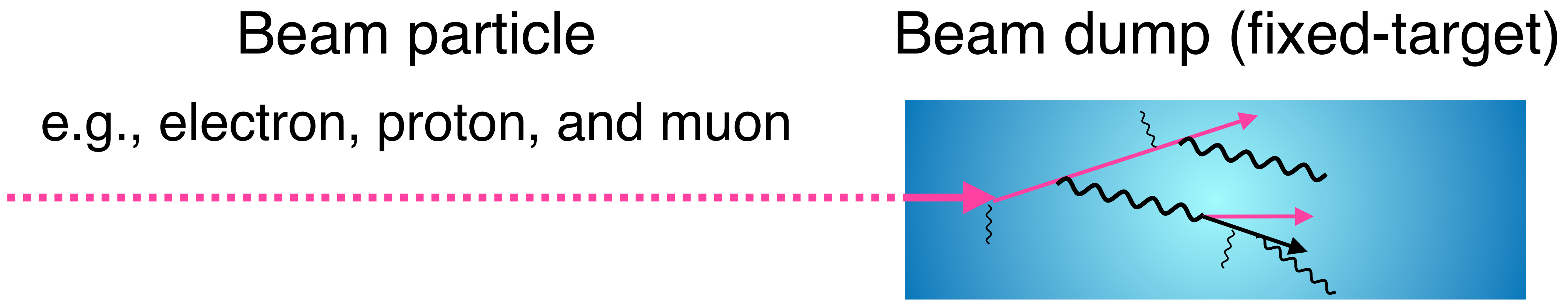
Key features of beam dump experiment (2)

- Beam dump experiment is high luminosity frontier

(# of produced DM) = (DM production cross section [L^2])

Integrated luminosity

× (Beam flux [T^{-1}]) × (Operation time [T]) × (# density of target [L^{-3}]) × (Track length [L])



(Track length) = → + → + →

※ This feature is determined only by beam and target properties

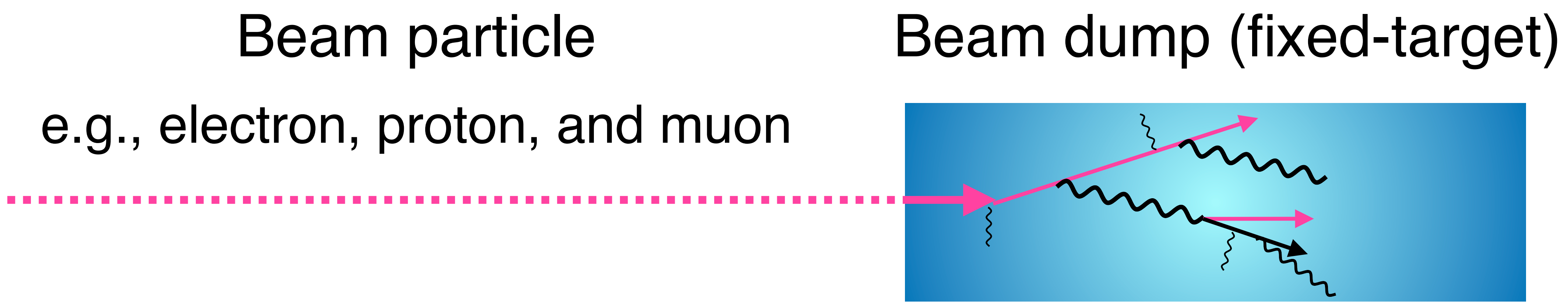
Key features of beam dump experiment (2)

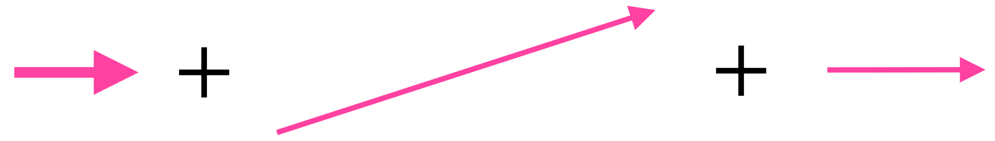
- Beam dump experiment is high luminosity frontier

(# of produced DM) = (DM production cross section [L^2])

Integrated luminosity

× (Beam flux [T^{-1}]) × (Operation time [T]) × (# density of target [L^{-3}]) × (Track length [L])



(Track length) = 

Ex. Target = Iron, # of injected proton beam = 10^{20}

※ This feature is determined only by beam and target properties

Key features of beam dump experiment (2)

- Beam dump experiment is high luminosity frontier

(# of produced DM) = (DM production cross section [L^2])

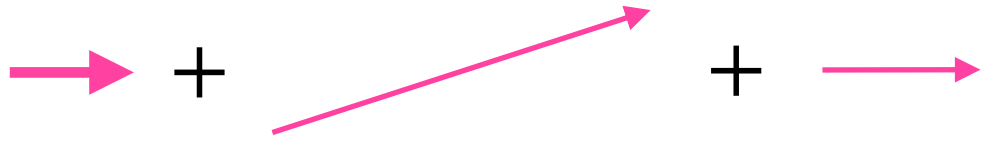
Integrated luminosity

× (Beam flux [T^{-1}]) × (Operation time [T]) × (# density of target [L^{-3}]) × (Track length [L])

Beam particle

e.g., electron, proton, and muon

Beam dump (fixed-target)

(Track length) = 

Ex. Target = Iron, # of injected proton beam = 10^{20}

(Proton luminosity) $\sim 90\ \mathrm{ab}^{-1}$ for track length of 10 cm(nuclear collision length)

※ Luminosity becomes higher for thick targets

※ This feature is determined only by beam and target properties

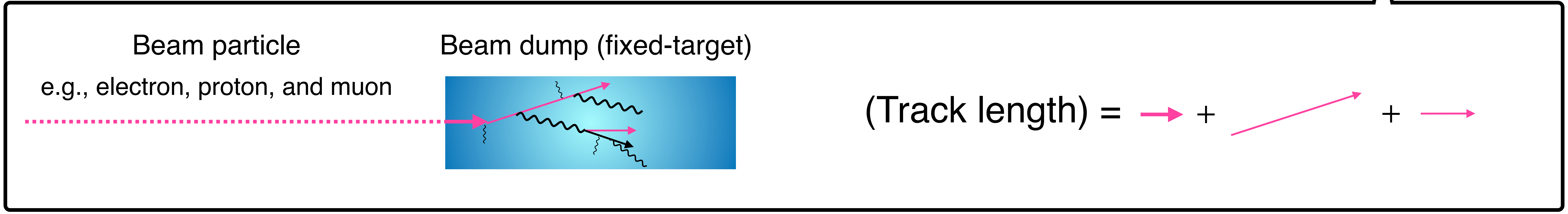
Key features of beam dump experiment (2)

- Beam dump experiment is high luminosity frontier

(# of produced DM) = (DM production cross section [L^2])

Integrated luminosity

× (Beam flux [T^{-1}]) × (Operation time [T]) × (# density of target [L^{-3}]) × (Track length [L])



Ex. Target = Iron, # of injected proton beam = 10^{20}

(Proton luminosity) $\sim 90\ \mathrm{ab}^{-1}$ for track length of 10 cm(nuclear collision length)

※ Luminosity becomes higher for thick targets

Beam dump experiment has high luminosity and is sensitive to feeble coupling DM

※ This feature is determined only by beam and target properties

Three detection approaches

- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?

Three detection approaches

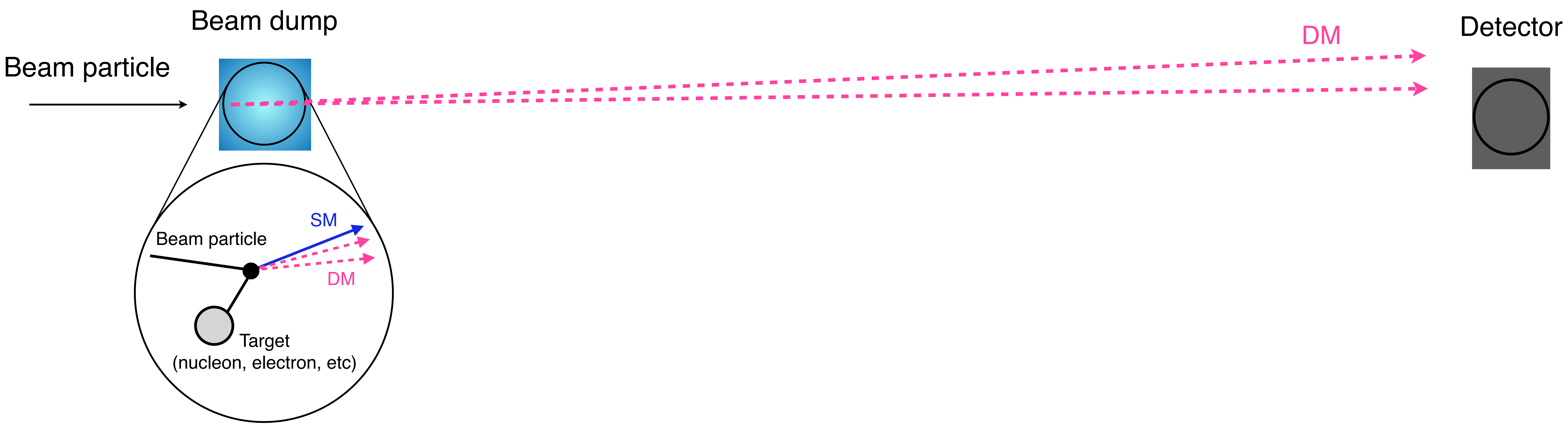
- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?

Three detection approaches

- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?

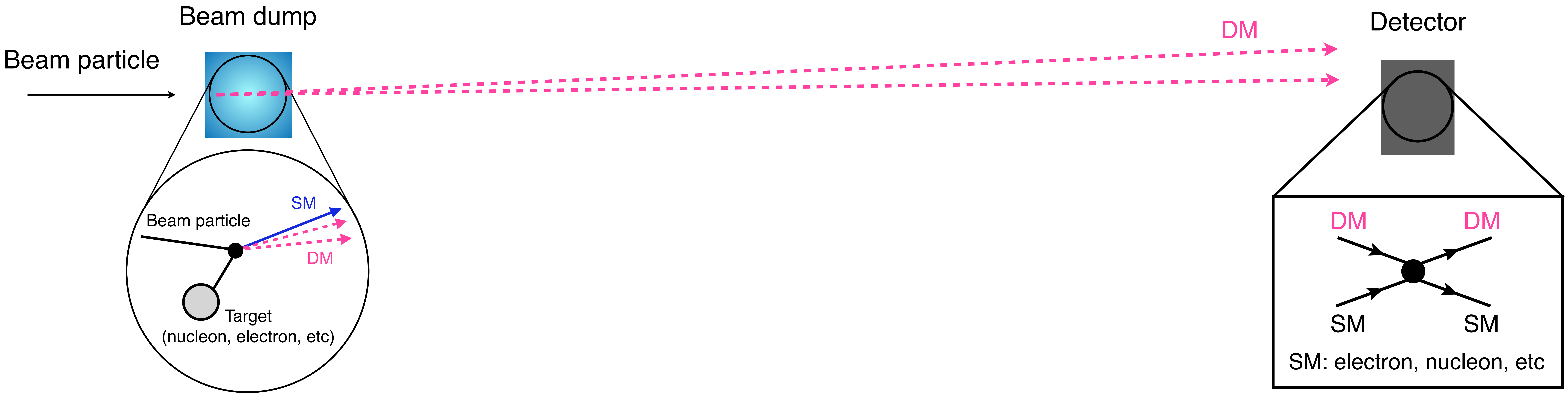
Three detection approaches

- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?



Three detection approaches

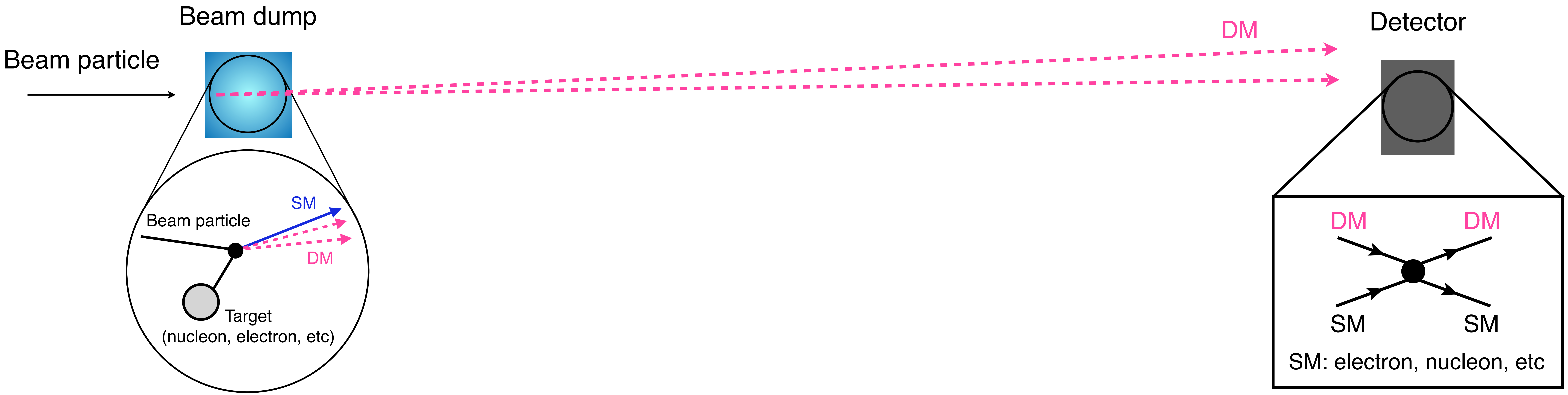
- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?



1. Recoil signal

Three detection approaches

- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?



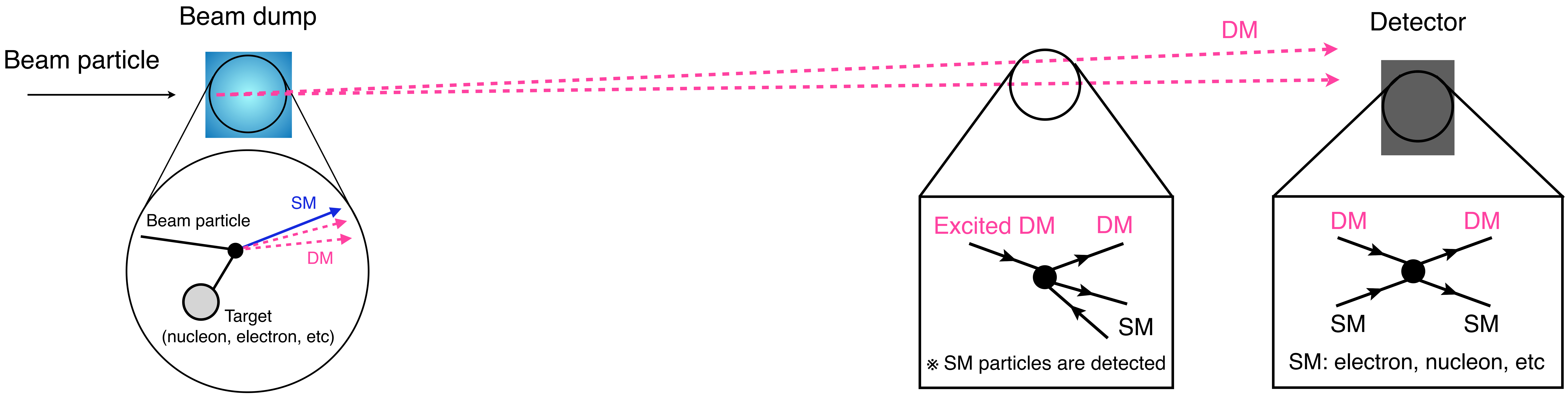
1. Recoil signal

e.g., E137, LDND, MiniBooNE, CCM120,

BDX, PIP2-BD, DUNE, CCM200, SHiP, ILC-BDX(proposed), etc

Three detection approaches

- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?



2. Visible decay signal

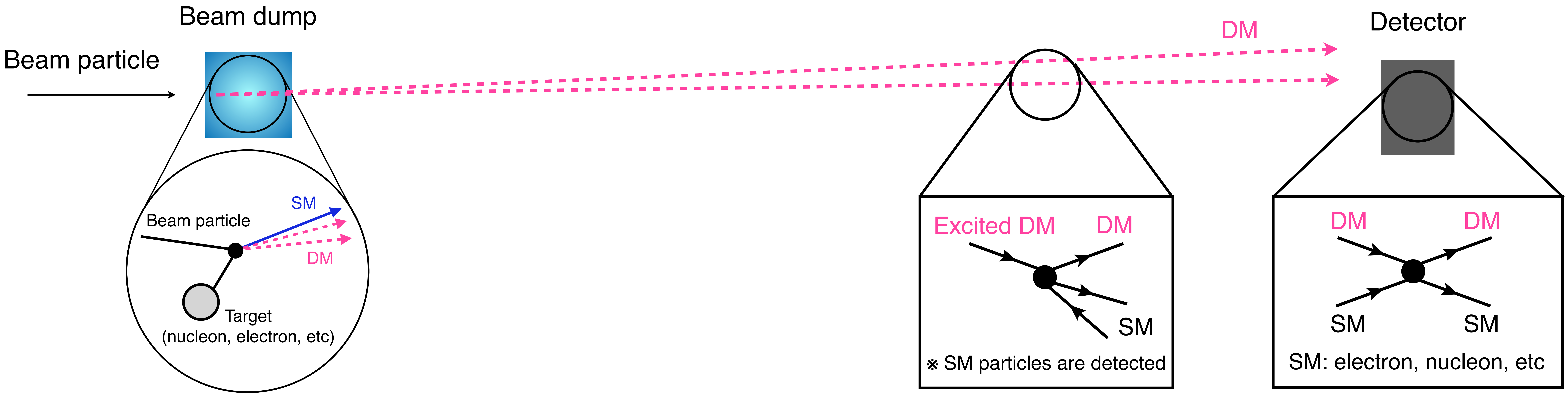
1. Recoil signal

e.g., E137, LDND, MiniBooNE, CCM120,

BDX, PIP2-BD, DUNE, CCM200, SHiP, ILC-BDX(proposed), etc

Three detection approaches

- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?



2. Visible decay signal

e.g., E137, LSND, CHARM, BDX, PIP2-BD, SeaQuest(proposed), etc

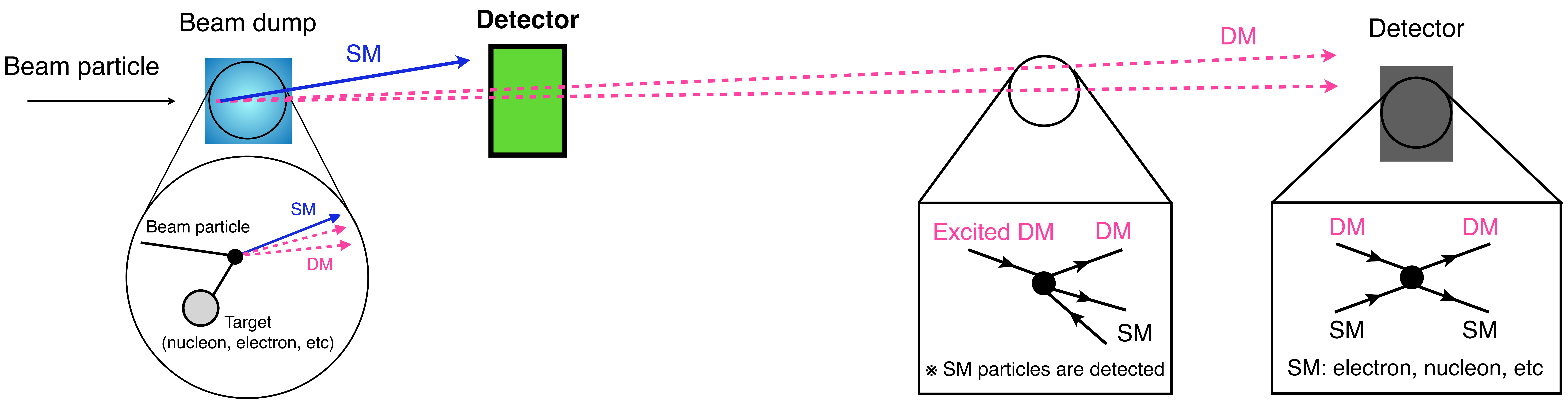
1. Recoil signal

e.g., E137, LDND, MiniBooNE, CCM120,

BDX, PIP2-BD, DUNE, CCM200, SHiP, ILC-BDX(proposed), etc

Three detection approaches

- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?



2. Visible decay signal

e.g., E137, LSND, CHARM, BDX, PIP2-BD, SeaQuest(proposed), etc

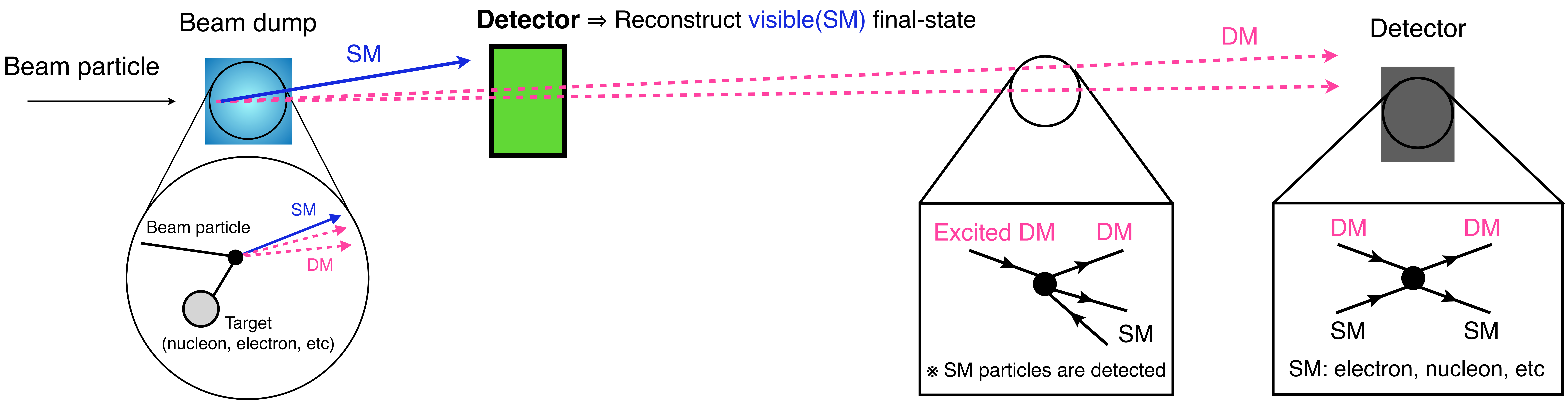
1. Recoil signal

e.g., E137, LDND, MiniBooNE, CCM120,

BDX, PIP2-BD, DUNE, CCM200, SHiP, ILC-BDX(proposed), etc

Three detection approaches

- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?



2. Visible decay signal

e.g., E137, LSND, CHARM, BDX, PIP2-BD, SeaQuest(proposed), etc

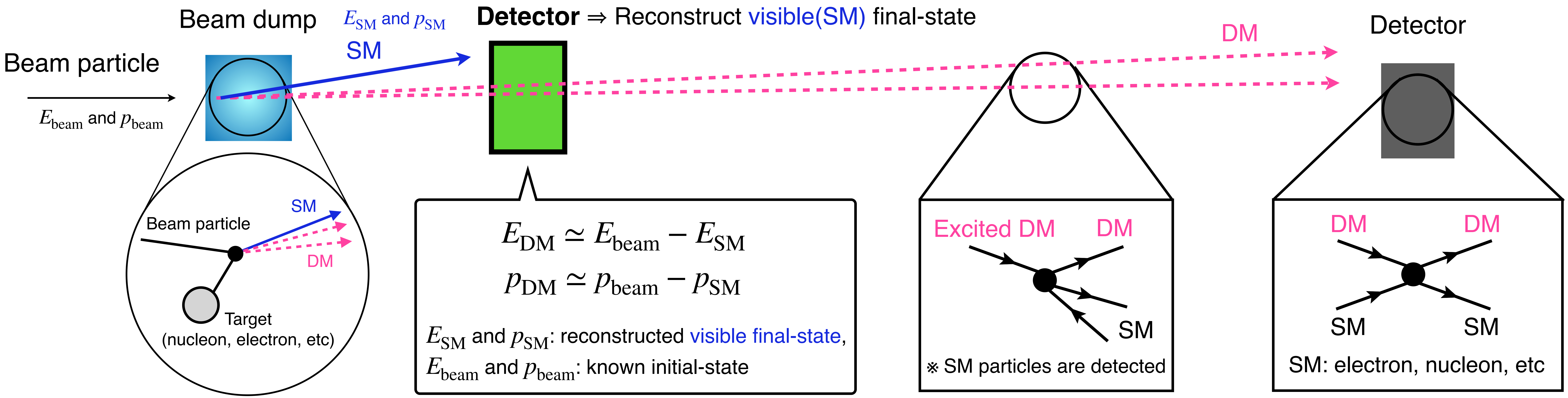
1. Recoil signal

e.g., E137, LDND, MiniBooNE, CCM120,

BDX, PIP2-BD, DUNE, CCM200, SHiP, ILC-BDX(proposed), etc

Three detection approaches

- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?



3. Missing energy/momentum signal

2. Visible decay signal

e.g., E137, LSND, CHARM, BDX, PIP2-BD, SeaQuest(proposed), etc

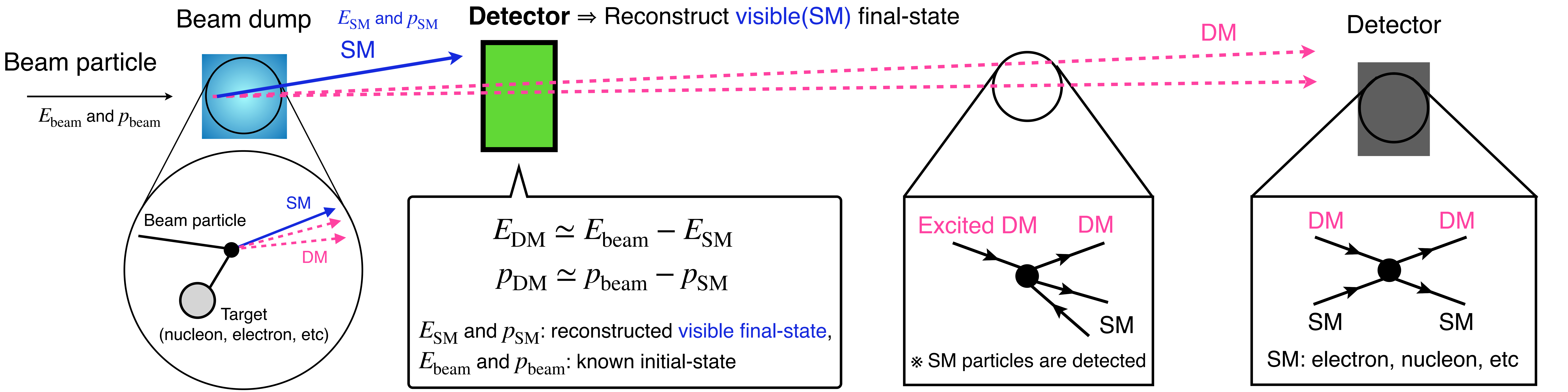
1. Recoil signal

e.g., E137, LDND, MiniBooNE, CCM120,

BDX, PIP2-BD, DUNE, CCM200, SHiP, ILC-BDX(proposed), etc

Three detection approaches

- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?



3. Missing energy/momentum signal

e.g., NA64, LDMX, M³, NA64e, NA64μ(proposed),etc

2. Visible decay signal

e.g., E137, LSND, CHARM, BDX, PIP2-BD, SeaQuest(proposed), etc

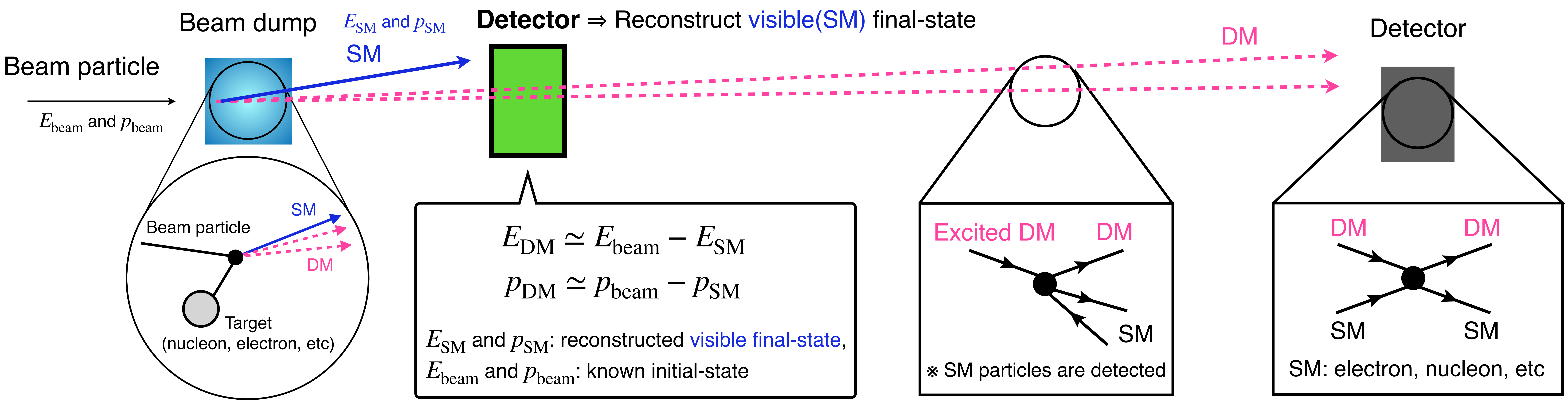
1. Recoil signal

e.g., E137, LDND, MiniBooNE, CCM120,

BDX, PIP2-BD, DUNE, CCM200, SHiP, ILC-BDX(proposed), etc

Three detection approaches

- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?



3. Missing energy/momentum signal

e.g., NA64, LDMX, M³, NA64e, NA64μ(proposed),etc

2. Visible decay signal

e.g., E137, LSND, CHARM, BDX, PIP2-BD, SeaQuest(proposed), etc

1. Recoil signal

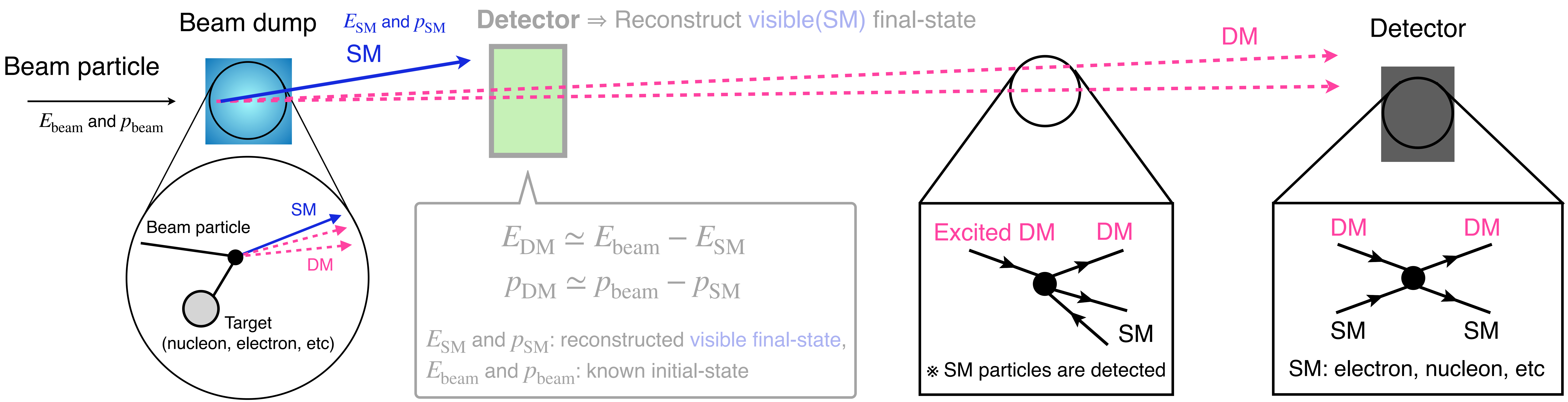
e.g., E137, LDND, MiniBooNE, CCM120,

BDX, PIP2-BD, DUNE, CCM200, SHiP, ILC-BDX(proposed), etc

Beam dump experiments are divided into three classes of experiments

Three detection approaches

- Center of mass energy and luminosity are determined by beam and target ⇒ How about detector?



3. Missing energy/momentum signal

e.g., NA64, LDMX, M³, NA64e, NA64μ(proposed),etc

2. Visible decay signal

e.g., E137, LSND, CHARM, BDX, PIP2-BD, SeaQuest(proposed), etc

1. Recoil signal

e.g., E137, LDND, MiniBooNE, CCM120,

BDX, PIP2-BD, DUNE, CCM200, SHiP, ILC-BDX(proposed), etc

Beam dump experiments are divided into three classes of experiments

Recoil and visible decay processes

- Typical setup:

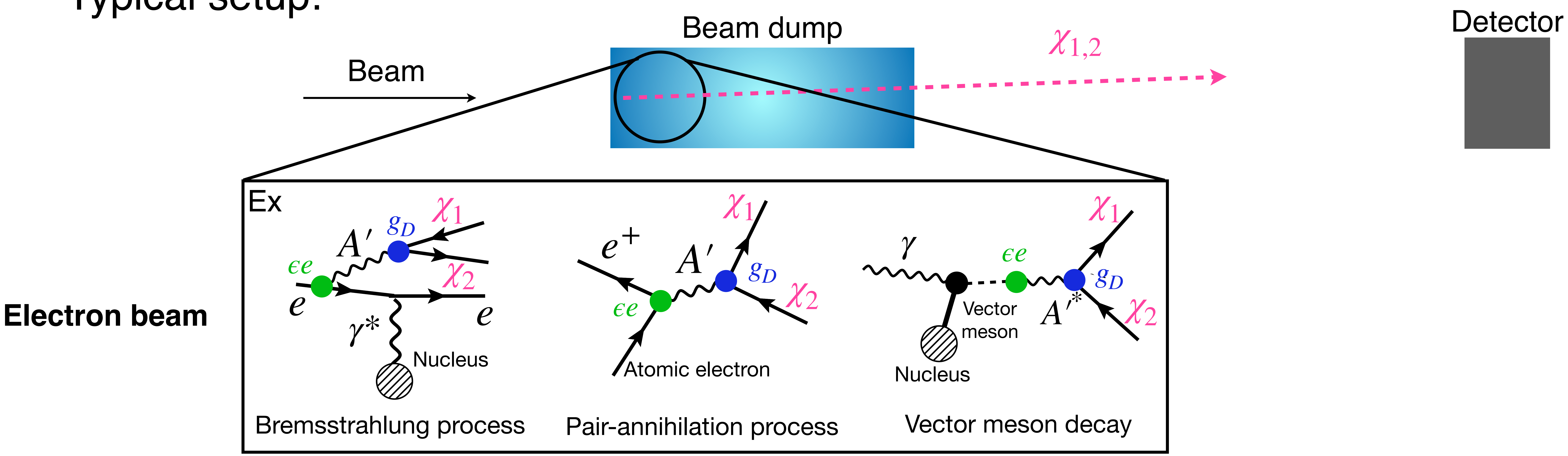
Recoil and visible decay processes

- Typical setup:

Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\mathrm{EM}} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + \mathrm{H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, J^μ_{EM}: SM EM current

Recoil and visible decay processes

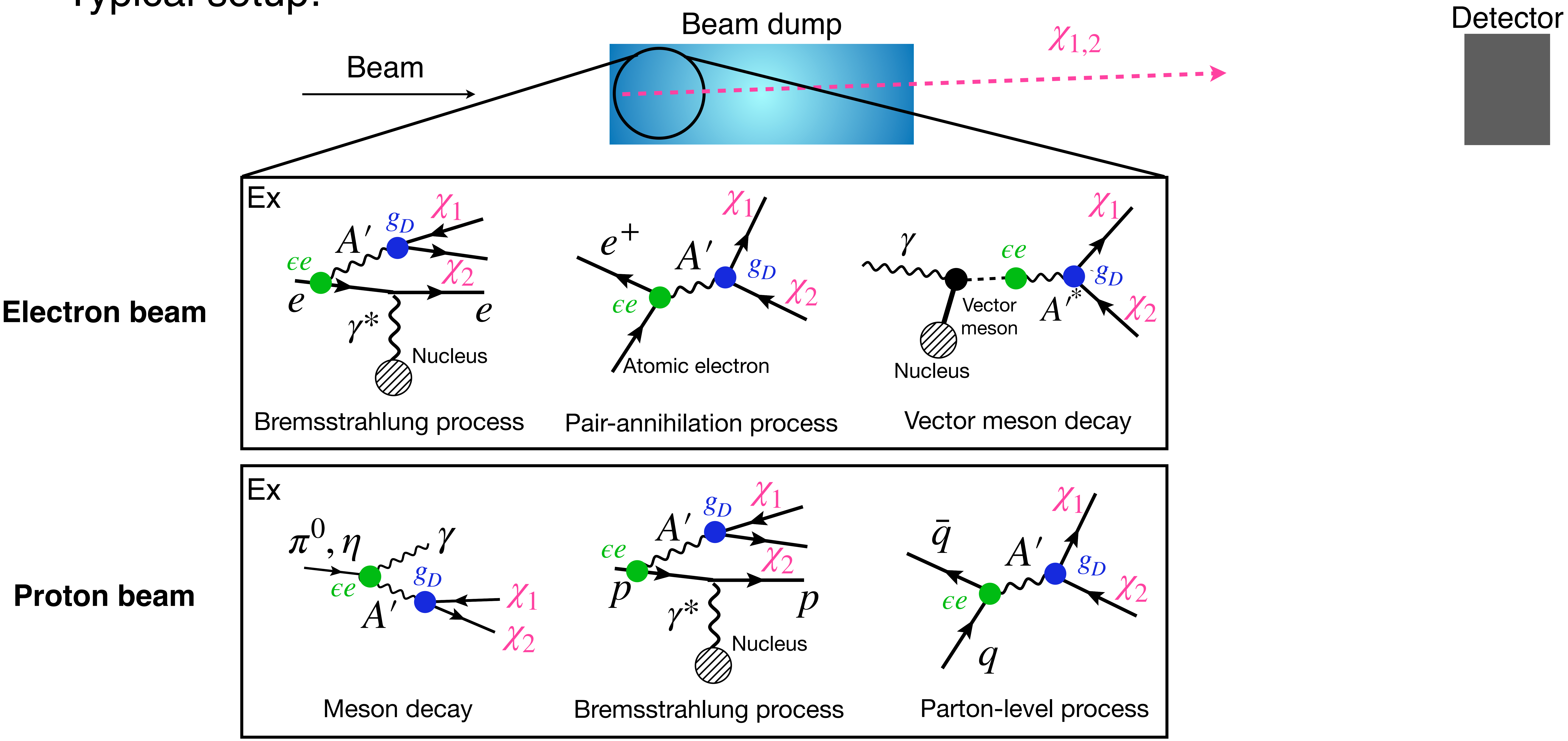
- Typical setup:



Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

Recoil and visible decay processes

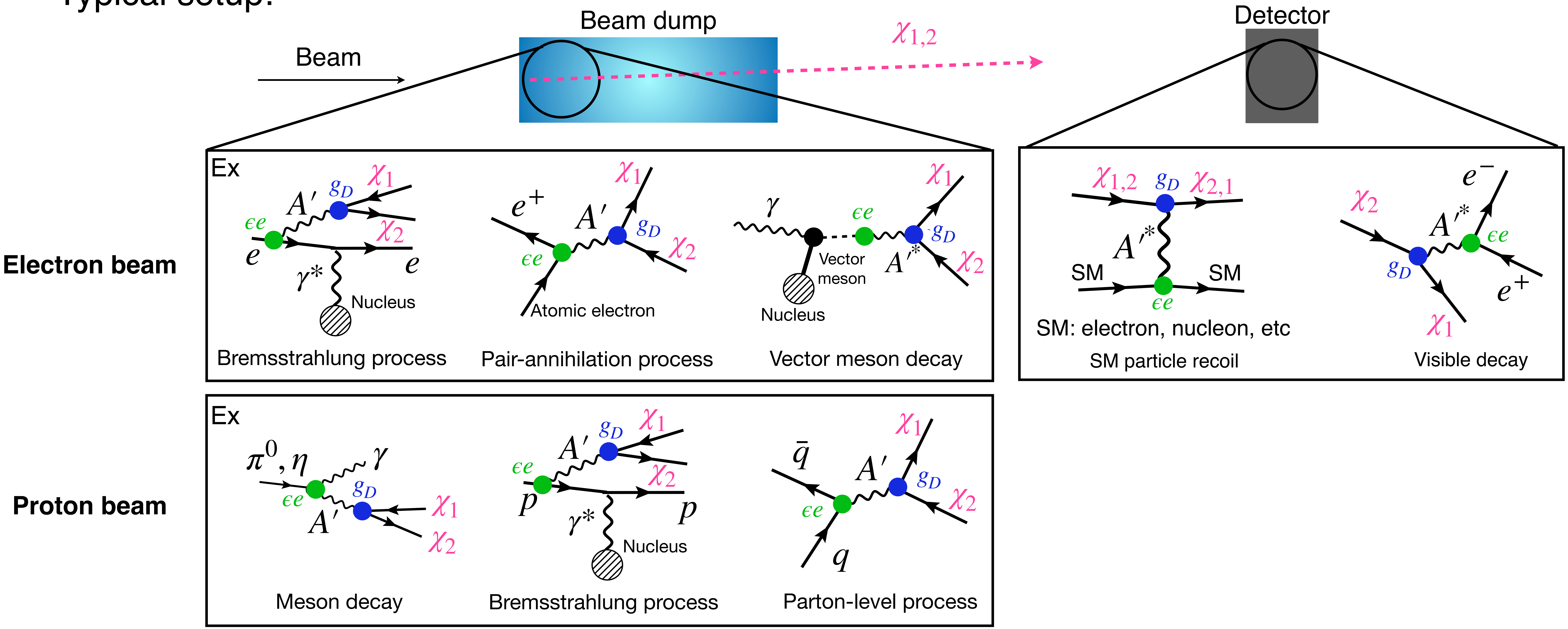
- Typical setup:



Benchmark model: $\mathscr{L} \supset \epsilon \cdot eA'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

Recoil and visible decay processes

- Typical setup:

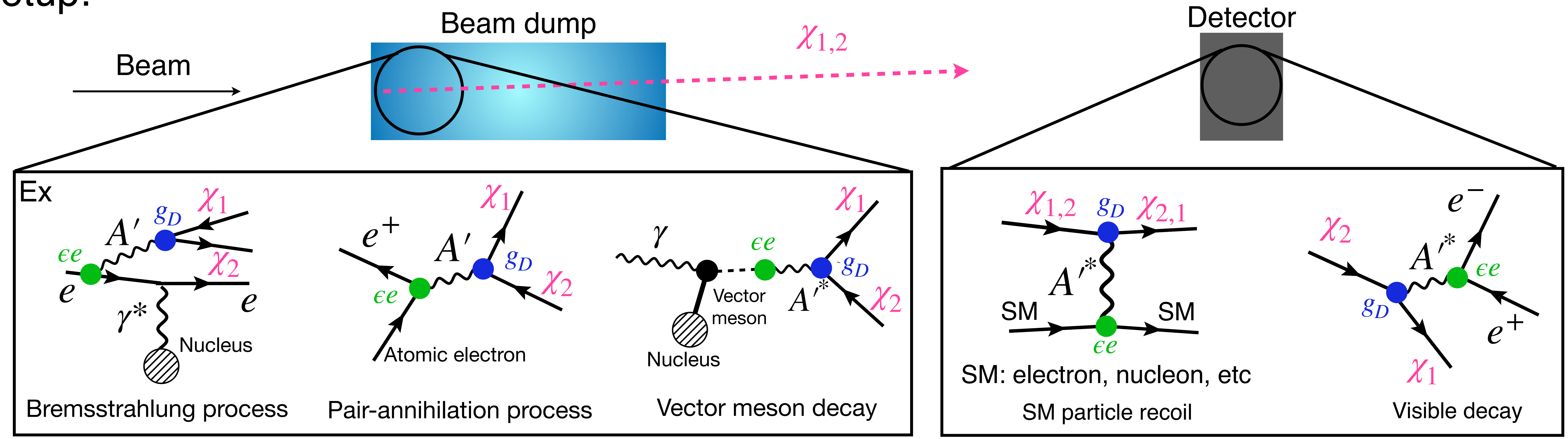


Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

Recoil and visible decay search

- Typical setup:

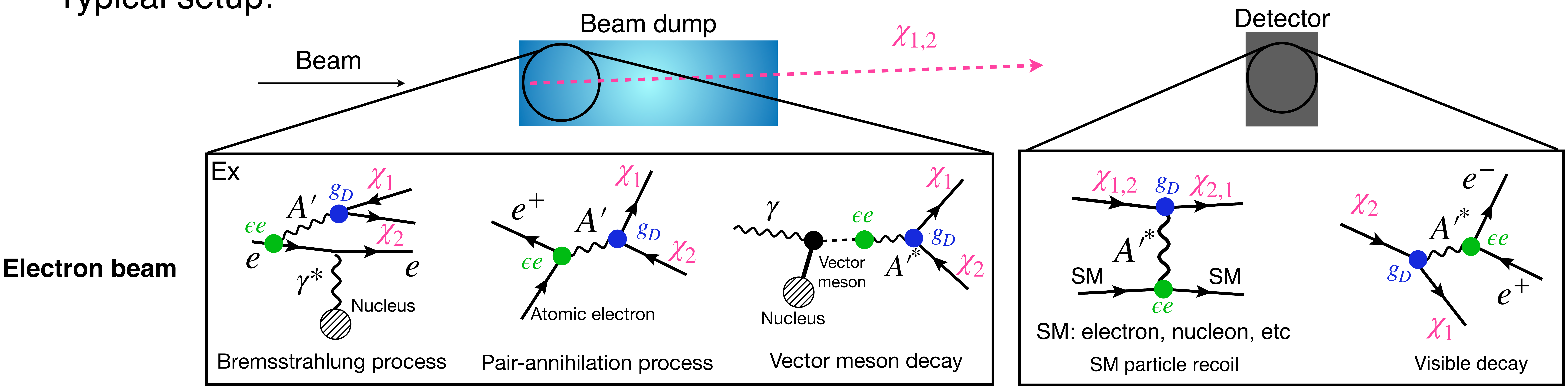
Electron beam



- # of detected DM (signal events):

Recoil and visible decay search

- Typical setup:

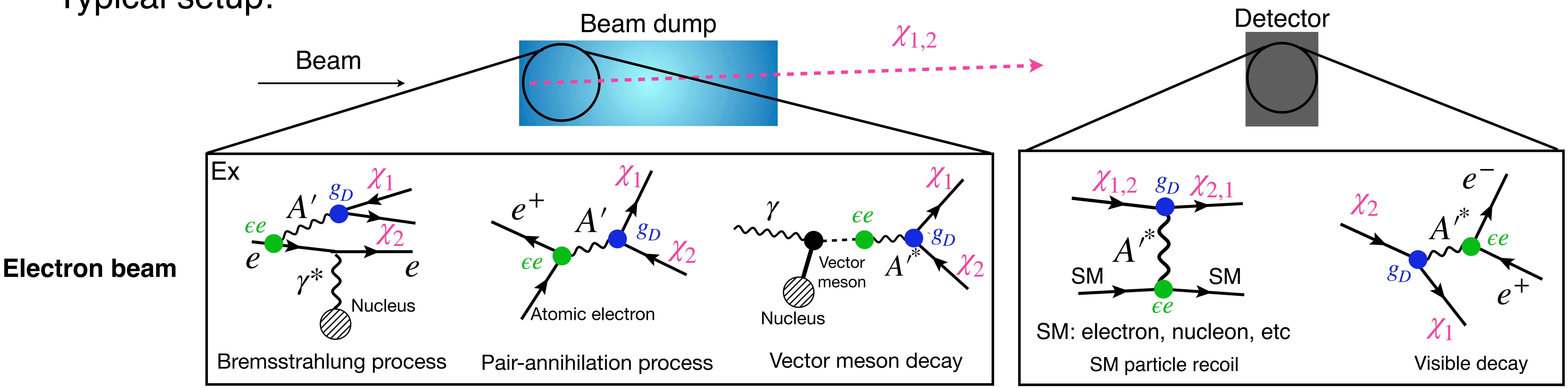


- # of detected DM (signal events):

~ (# of produced DM) ×

Recoil and visible decay search

- Typical setup:

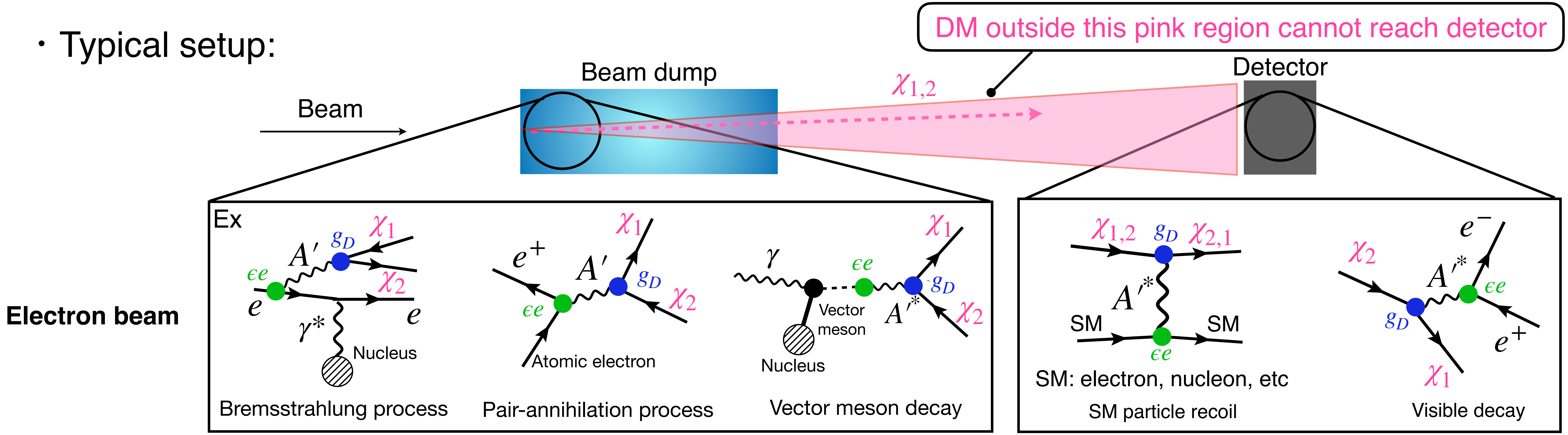


- # of detected DM (signal events):

~ (# of produced DM) × (Probability DM reaches detector) ×

Recoil and visible decay search

- Typical setup:

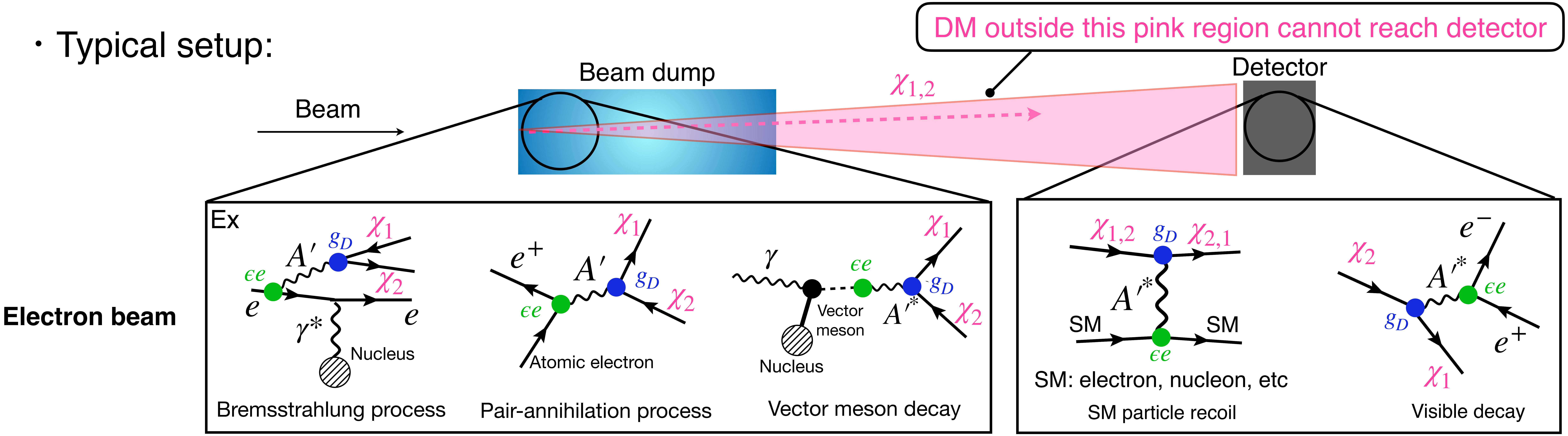


- # of detected DM (signal events):

~ (# of produced DM) × (Probability DM reaches detector) ×

Recoil and visible decay search

- Typical setup:

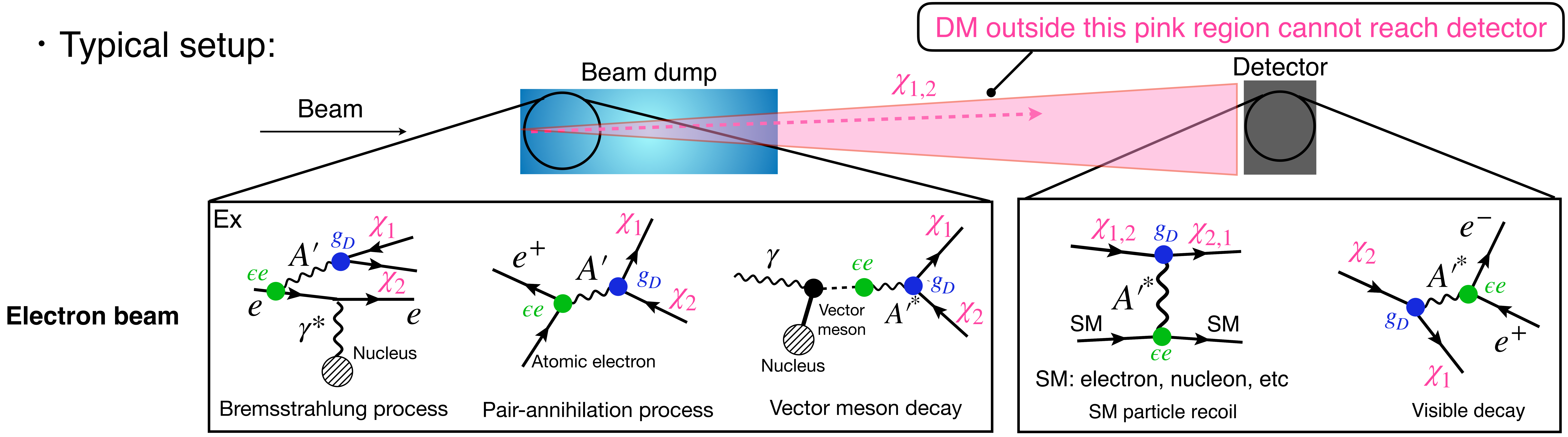


- # of detected DM (signal events):

~ (# of produced DM) × (Probability DM reaches detector) × (Probability DM is detected)

Recoil and visible decay search

- Typical setup:



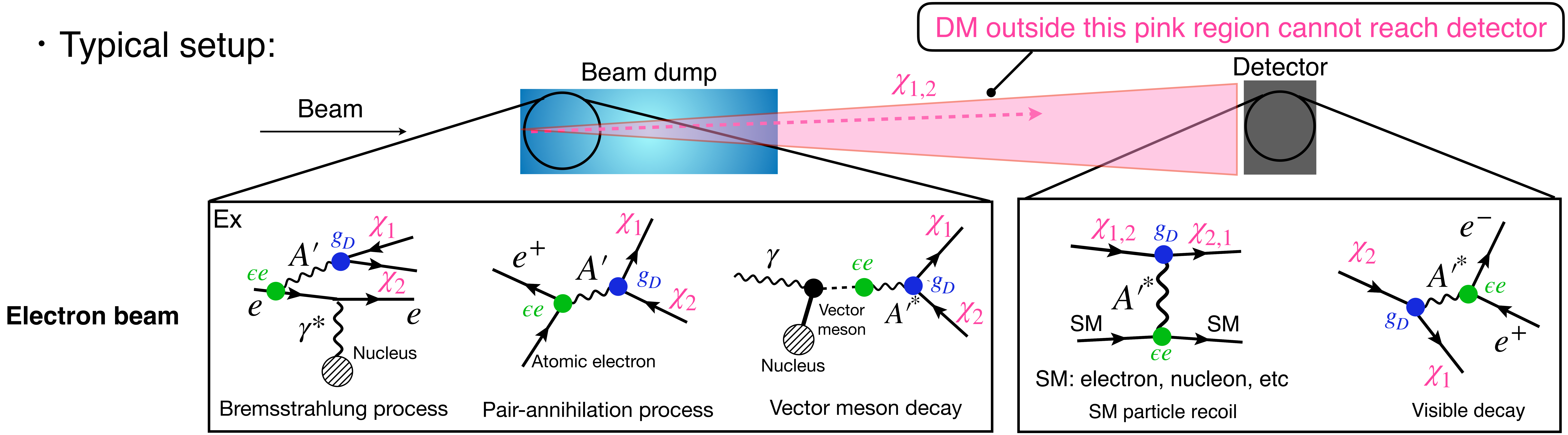
- # of detected DM (signal events):

Acceptance

~ (# of produced DM) × (Probability DM reaches detector) × (Probability DM is detected)

Recoil and visible decay search

- Typical setup:



- # of detected DM (signal events):

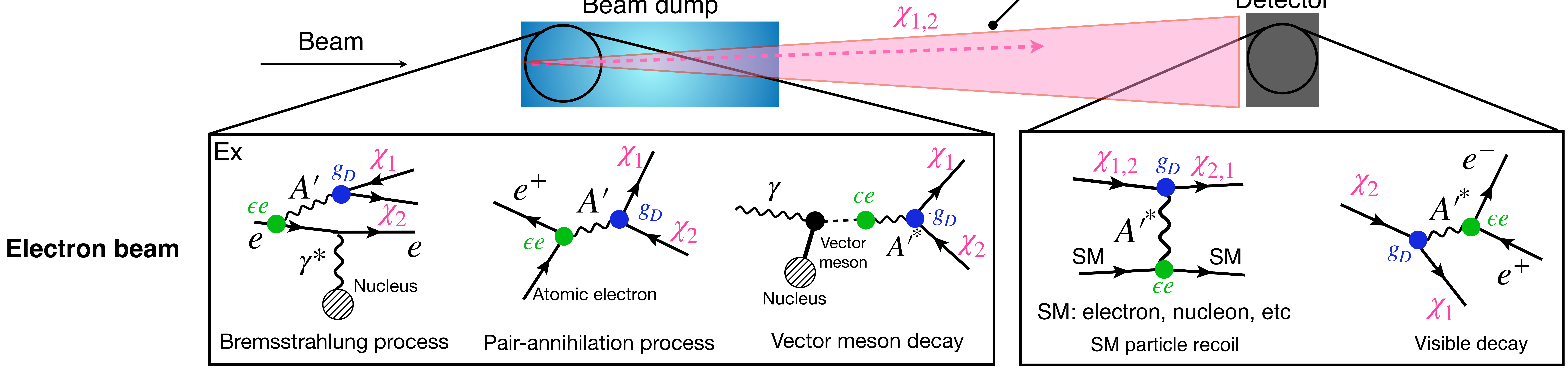
Acceptance

~ (# of produced DM) × (Probability DM reaches detector) × (Probability DM is detected)

∝ (Beam flux)×$(\epsilon e)^2$

Recoil and visible decay search

・Typical setup:



・# of detected DM (signal events):

Acceptance

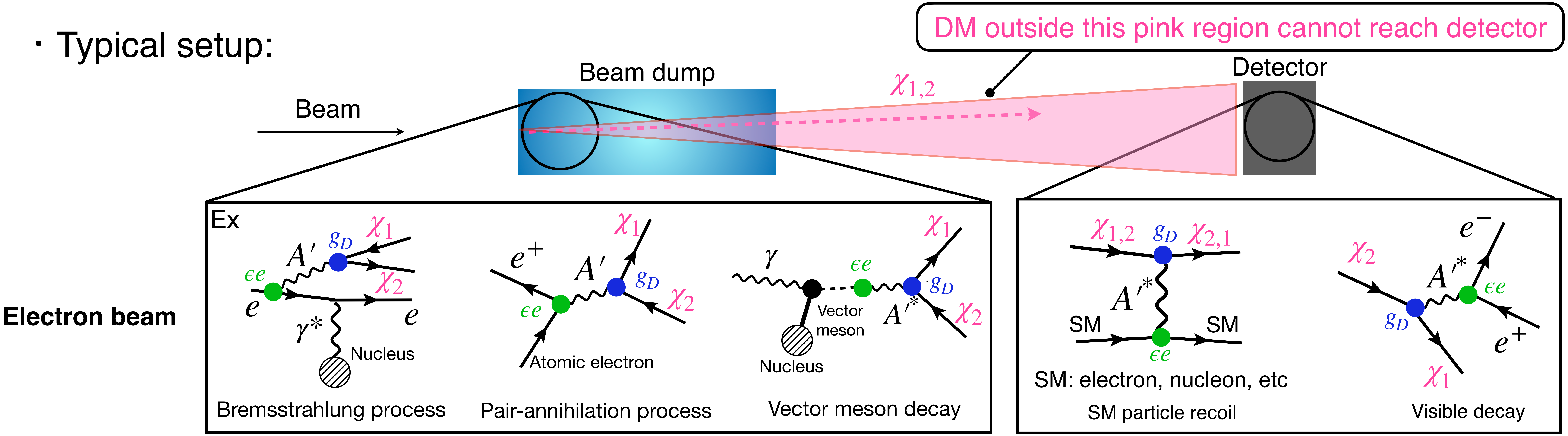
~ (# of produced DM) × (Probability DM reaches detector) × (Probability DM is detected)

∝ (Beam flux)×$(\epsilon e)^2$

∝ (height of detector)^2
× (length b/w beam dump and detector)$^{-2}$

Recoil and visible decay search

- Typical setup:



- # of detected DM (signal events):

Acceptance

~ (# of produced DM) × (Probability DM reaches detector) × (Probability DM is detected)

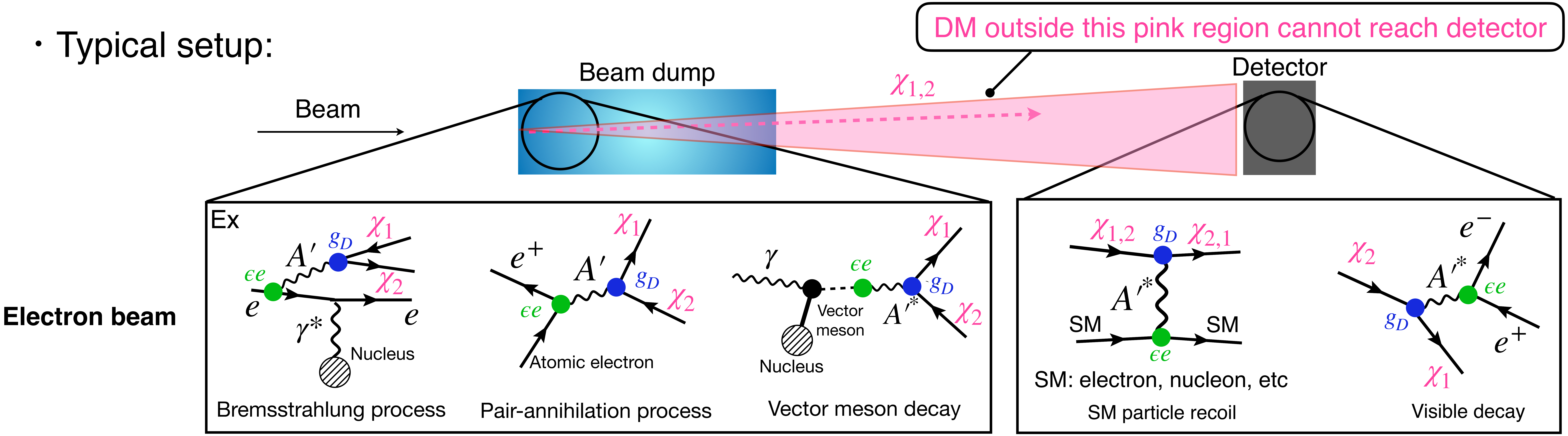
∝ (Beam flux)×$(\epsilon e)^2$

∝ (height of detector)^2 × (length b/w beam dump and detector)$^{-2}$

∝ (Length of detector)×$(\epsilon e)^2$

Recoil and visible decay search

・Typical setup:



・# of detected DM (signal events):

Acceptance

~ (# of produced DM) × (Probability DM reaches detector) × (Probability DM is detected)

∝ (Beam flux)×$(\epsilon e)^2$

∝ (height of detector)^2 × (length b/w beam dump and detector)$^{-2}$

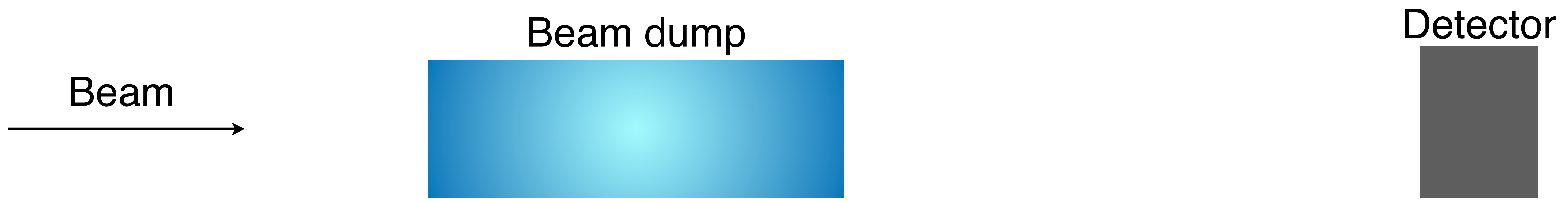
∝ (Length of detector)×$(\epsilon e)^2$

High flux beam, near※ and large detectors are suited for recoil and visible decay search

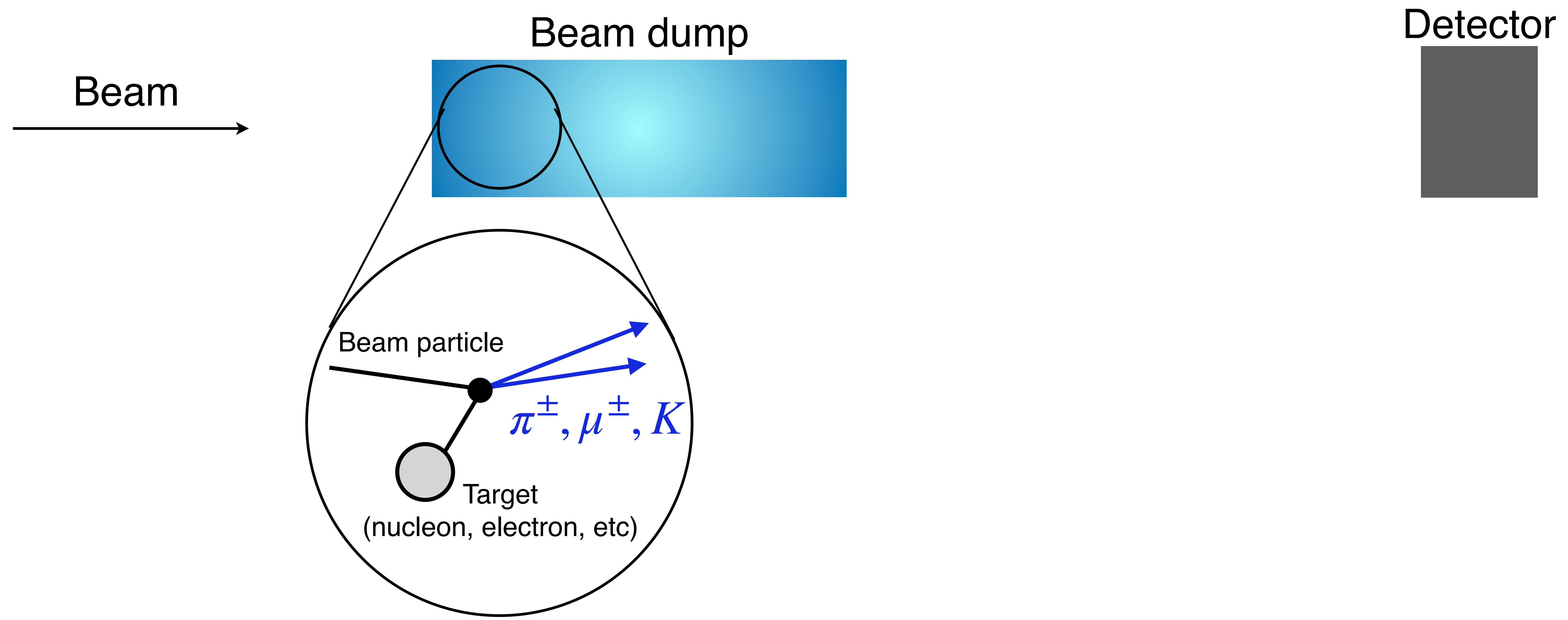
※ **Detector cannot be too near** because large beam dump or shield is needed to reduce beam-induced BG

Background events in recoil and visible decay search

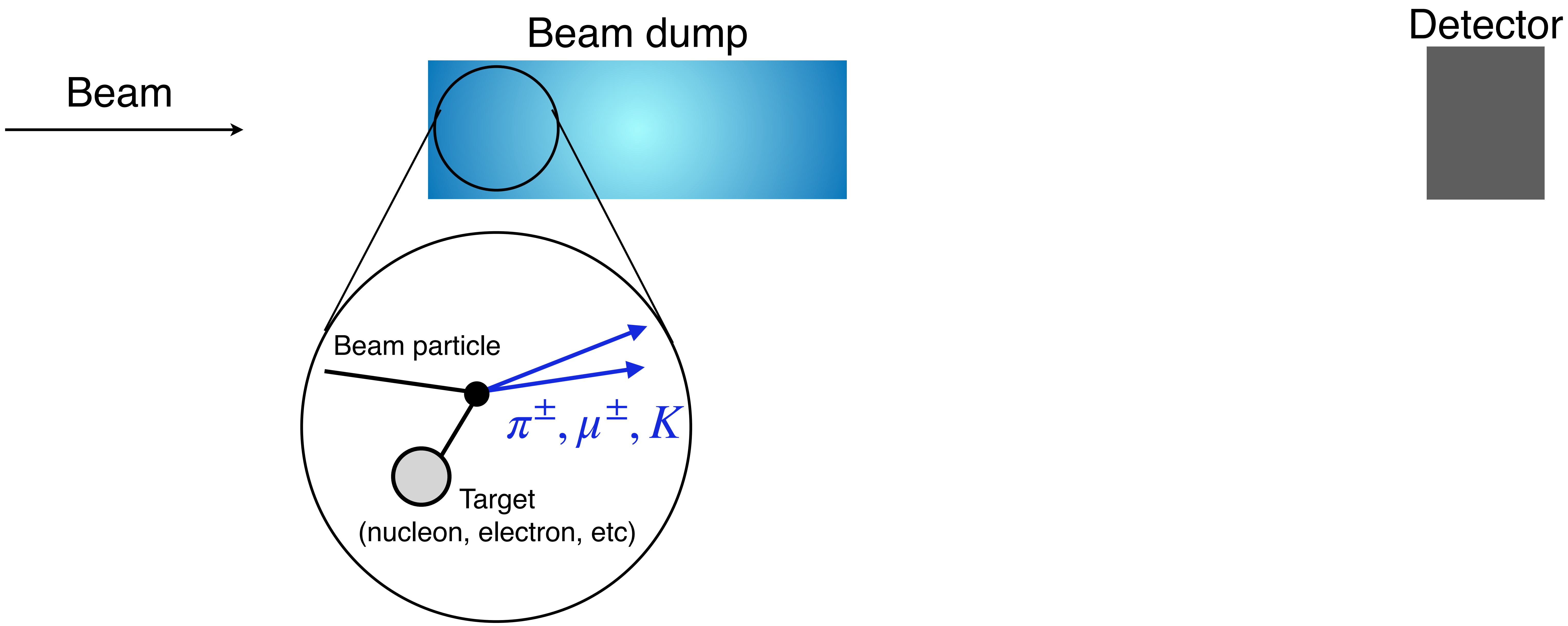
Background events in recoil and visible decay search



Background events in recoil and visible decay search

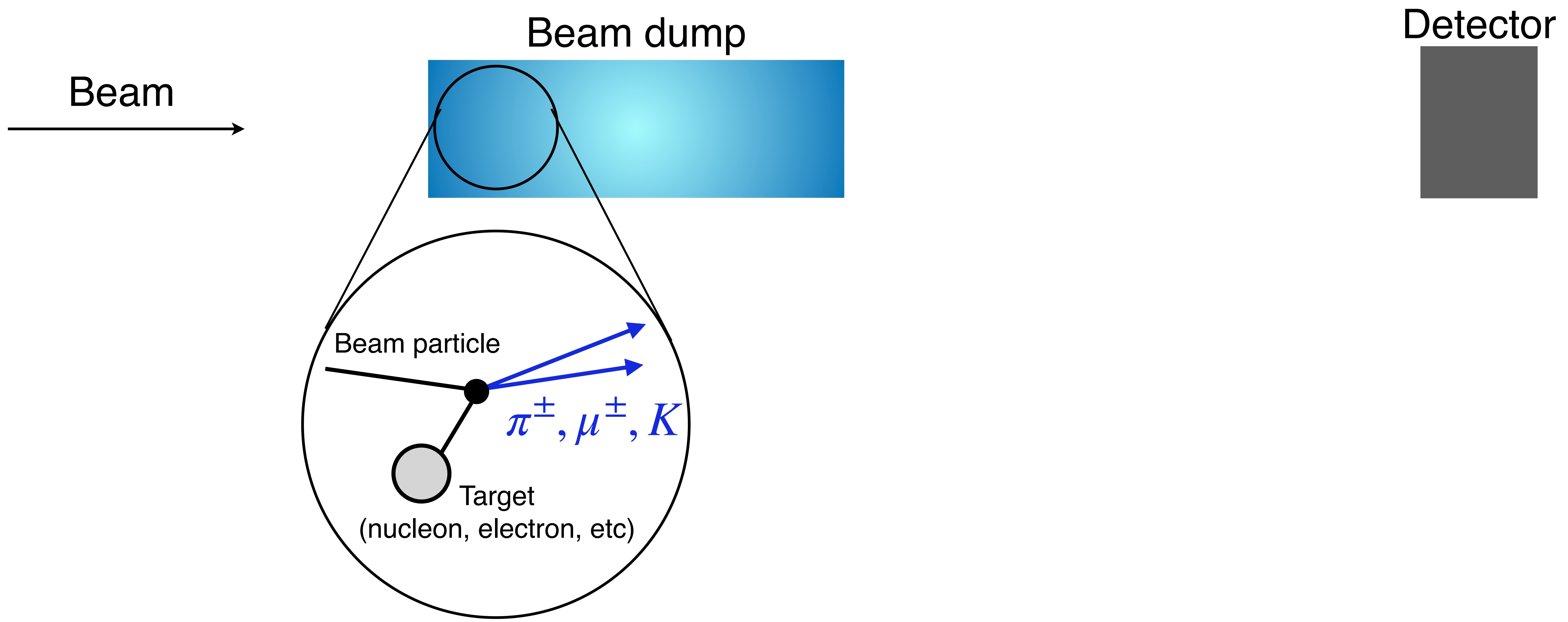


Background events in recoil and visible decay search



- Large beam dump or shield is needed to remove beam-induced particles, e.g., $\pi^{\pm}$, $\mu^{\pm}$, K

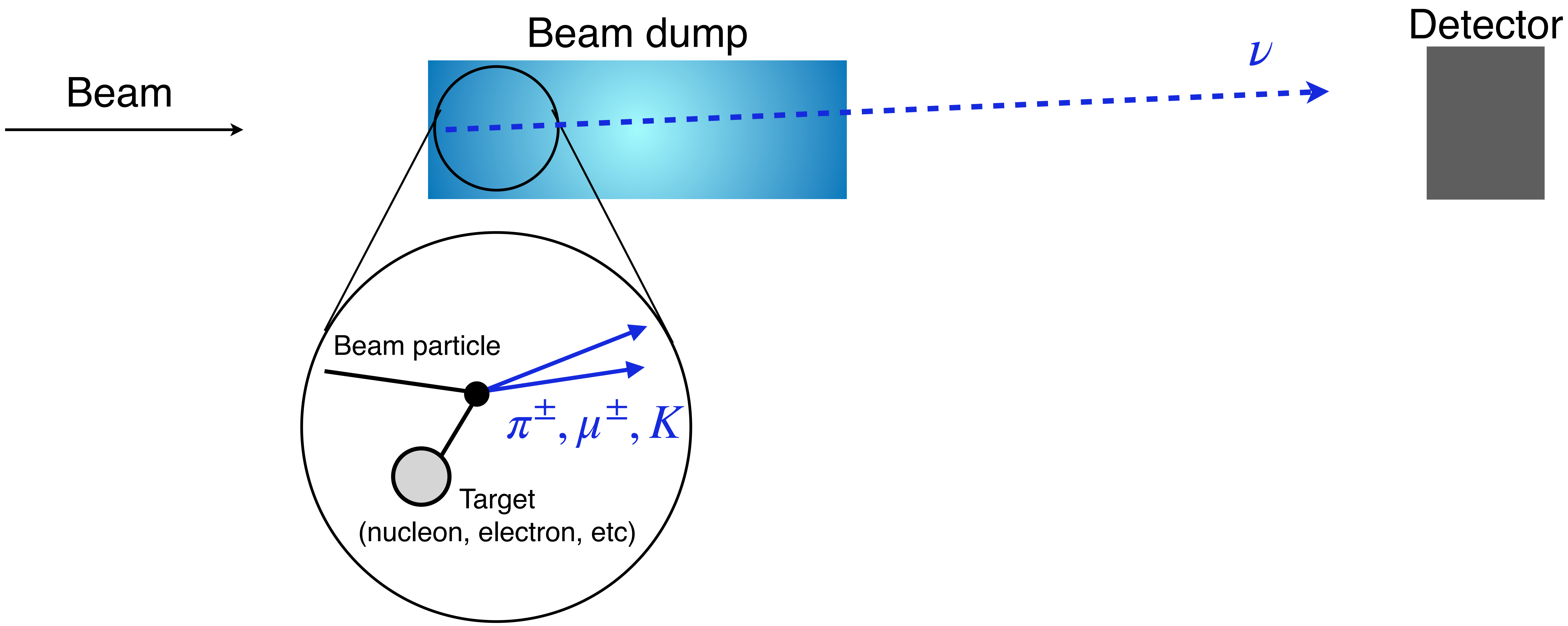
Background events in recoil and visible decay search



- Large beam dump or shield is needed to remove beam-induced particles, e.g., $\pi^{\pm}$, $\mu^{\pm}$, K

  - neutrinos are produced by decay of $\pi^{\pm}$, $\mu^{\pm}$,… in beam dump Ex. $\pi^+ \to \mu^+ + \nu_\mu$, $\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e$,…

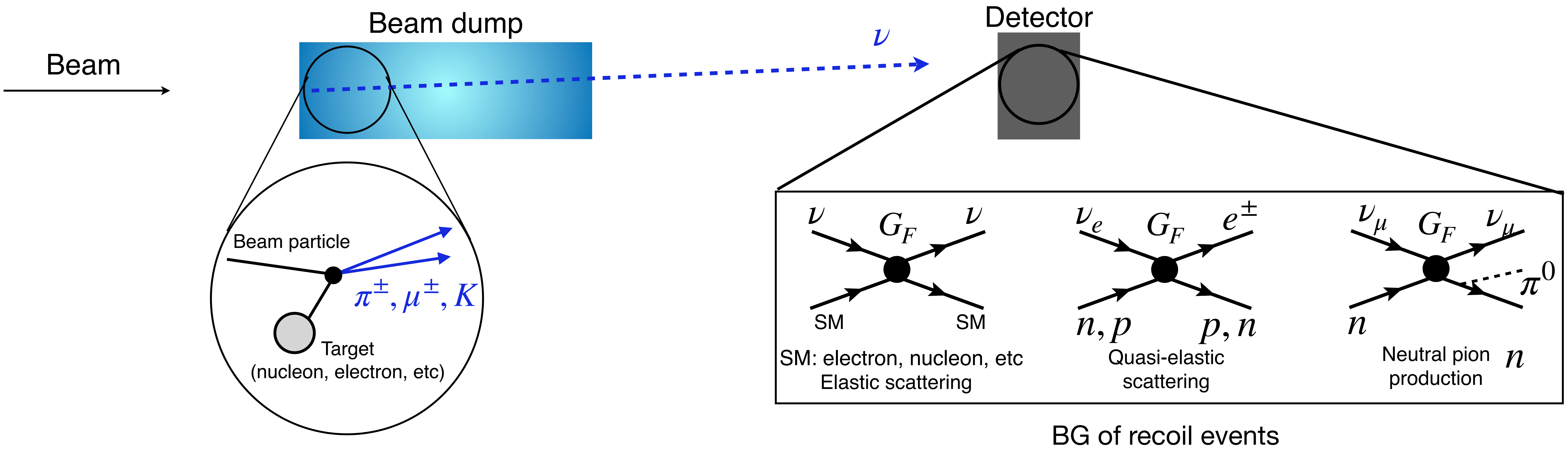
Background events in recoil and visible decay search



- Large beam dump or shield is needed to remove beam-induced particles, e.g., $\pi^\pm$, $\mu^\pm$, K

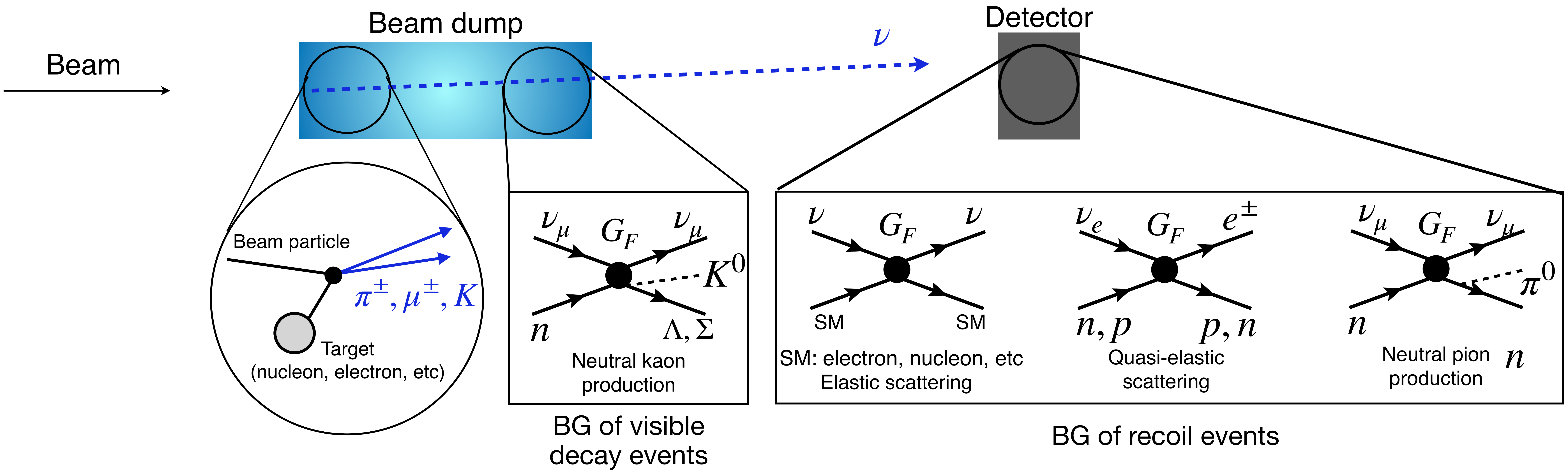
  - neutrinos are produced by decay of $\pi^\pm$, $\mu^\pm$,… in beam dump Ex. $\pi^+ \to \mu^+ + \nu_\mu, \ \ \mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e, \ldots$

Background events in recoil and visible decay search



- Large beam dump or shield is needed to remove beam-induced particles, e.g., $\pi^{\pm}$, $\mu^{\pm}$, K
  - neutrinos are produced by decay of $\pi^{\pm}$, $\mu^{\pm}$,... in beam dump Ex. $\pi^+ \to \mu^+ + \nu_\mu$, $\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e$,...

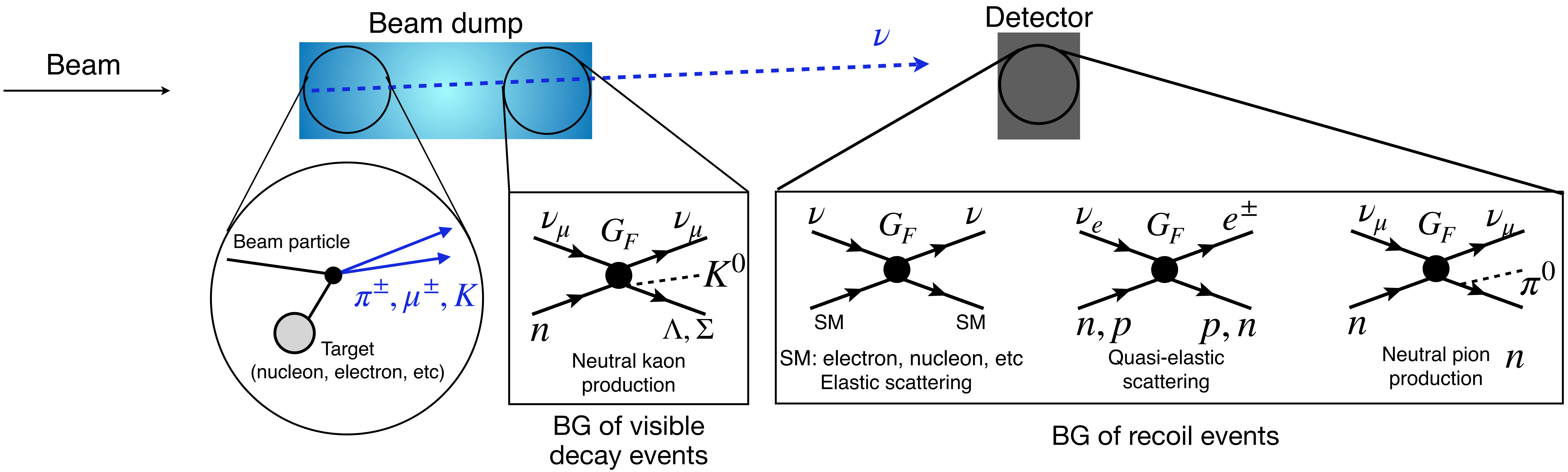
Background events in recoil and visible decay search



- Large beam dump or shield is needed to remove beam-induced particles, e.g., $\pi^{\pm}$, $\mu^{\pm}$, K

  - neutrinos are produced by decay of $\pi^{\pm}$, $\mu^{\pm}$,… in beam dump   Ex. $\pi^+ \to \mu^+ + \nu_\mu$, $\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e$,…

Background events in recoil and visible decay search

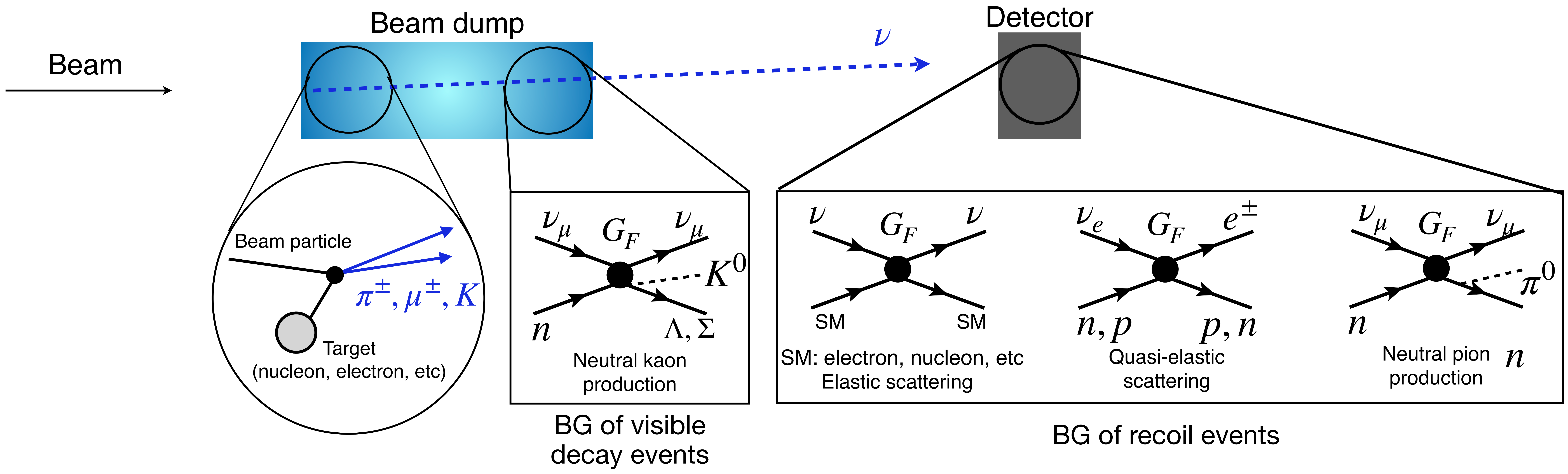


- Large beam dump or shield is needed to remove beam-induced particles, e.g., $\pi^{\pm}$, $\mu^{\pm}$, K

  - neutrinos are produced by decay of $\pi^{\pm}$, $\mu^{\pm}$,... in beam dump   Ex. $\pi^+ \to \mu^+ + \nu_\mu$, $\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e$,...

Beam-induced neutrino can be main background events

Background events in recoil and visible decay search



- Large beam dump or shield is needed to remove beam-induced particles, e.g., $\pi^\pm,\ \mu^\pm,\ K$

  - neutrinos are produced by decay of $\pi^\pm,\ \mu^\pm, \ldots$ in beam dump Ex. $\pi^+ \to \mu^+ + \nu_\mu,\ \ \mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e, \ldots$

  - $\pi^\pm,\ \mu^\pm$ are absorbed or decay at rest by large beam dump ⇒ neutrino flux is reduced

Beam-induced neutrino can be main background events

Missing energy/momentum signal processes

Missing energy/momentum signal processes

Missing energy search, e.g., NA64:

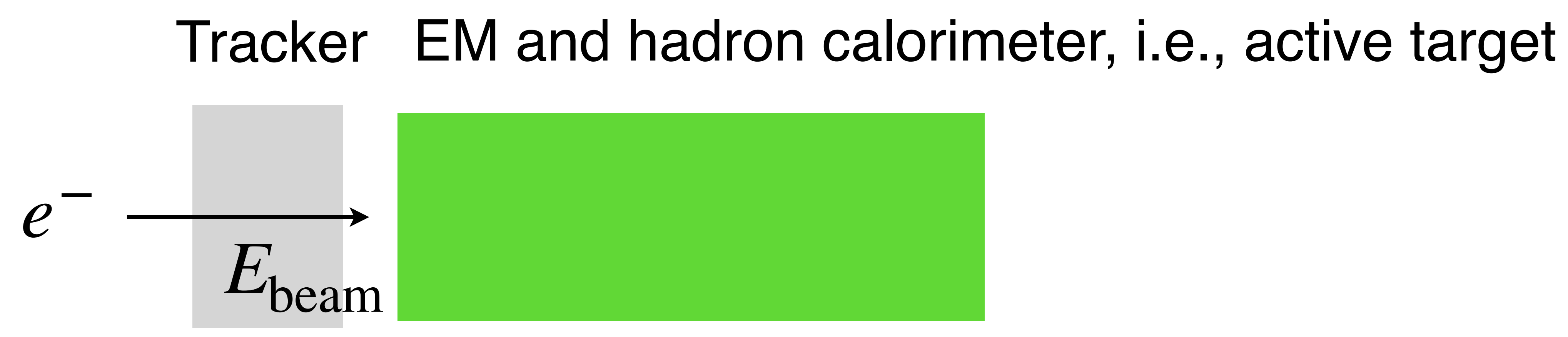
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:

EM and hadron calorimeter, i.e., active target

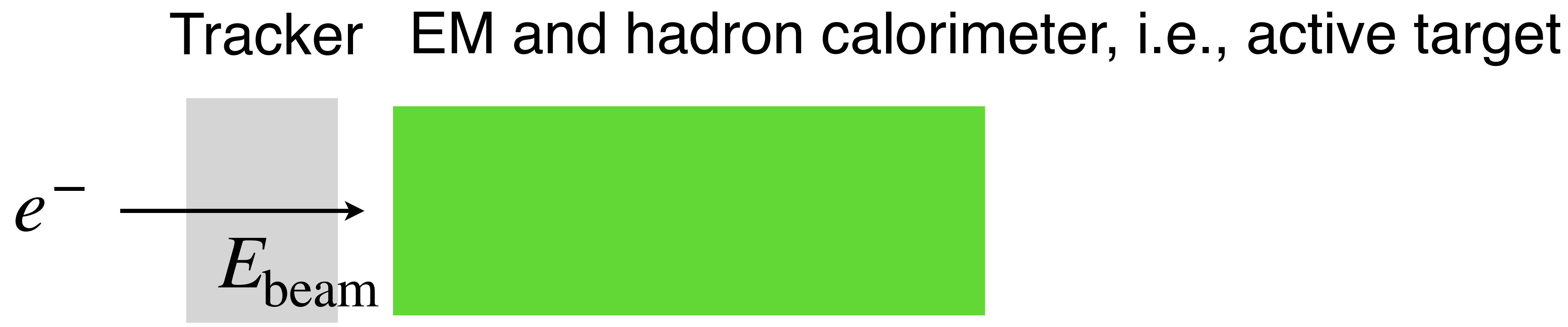
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



Missing energy/momentum signal processes

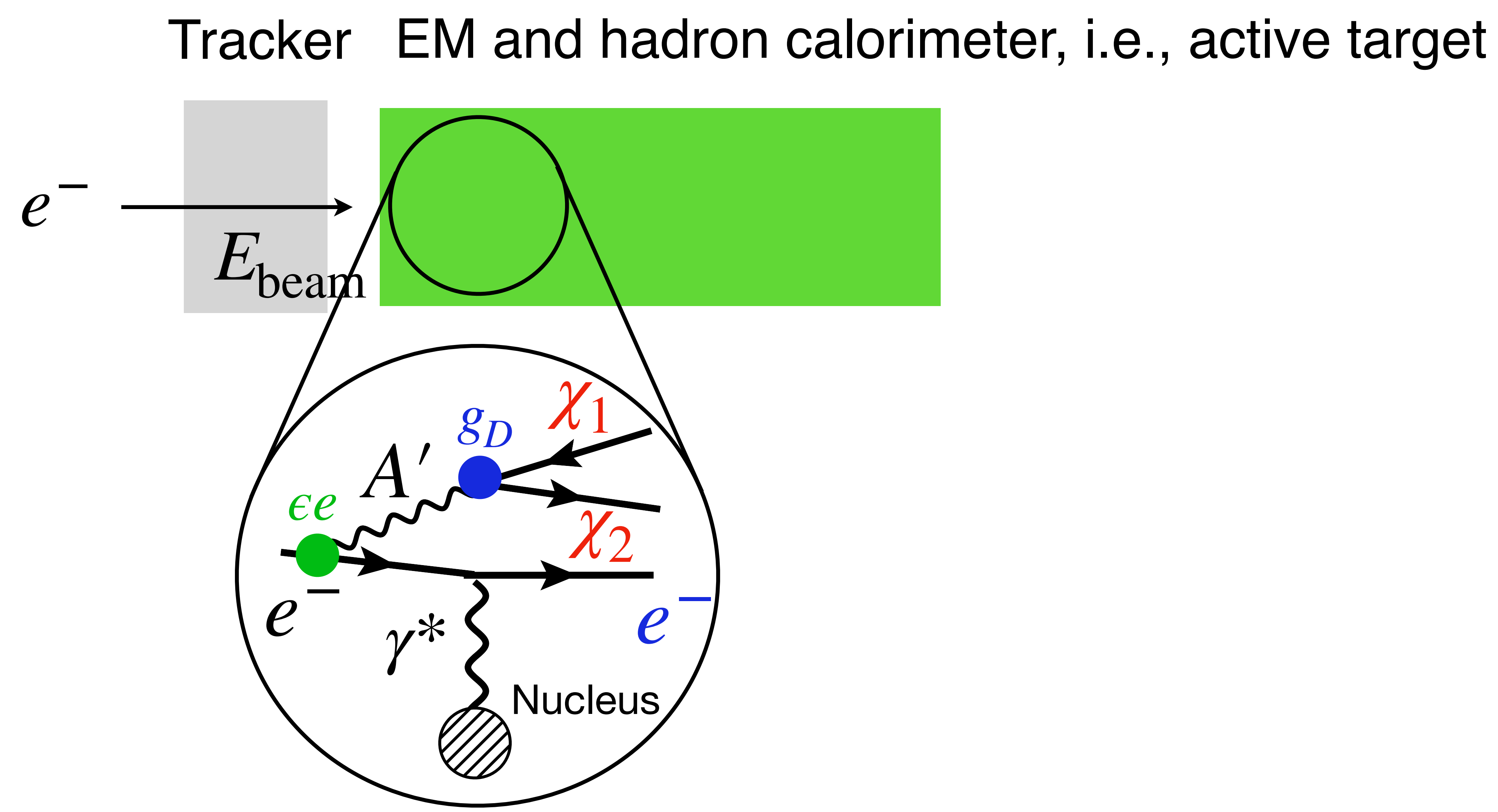
Missing energy search, e.g., NA64:



Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\text{EM}} - g_D A'_\mu (i \bar{\chi}_2 \gamma^\mu \chi_1 + \text{H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, J^μ_{EM}: SM EM current

Missing energy/momentum signal processes

Missing energy search, e.g., NA64:

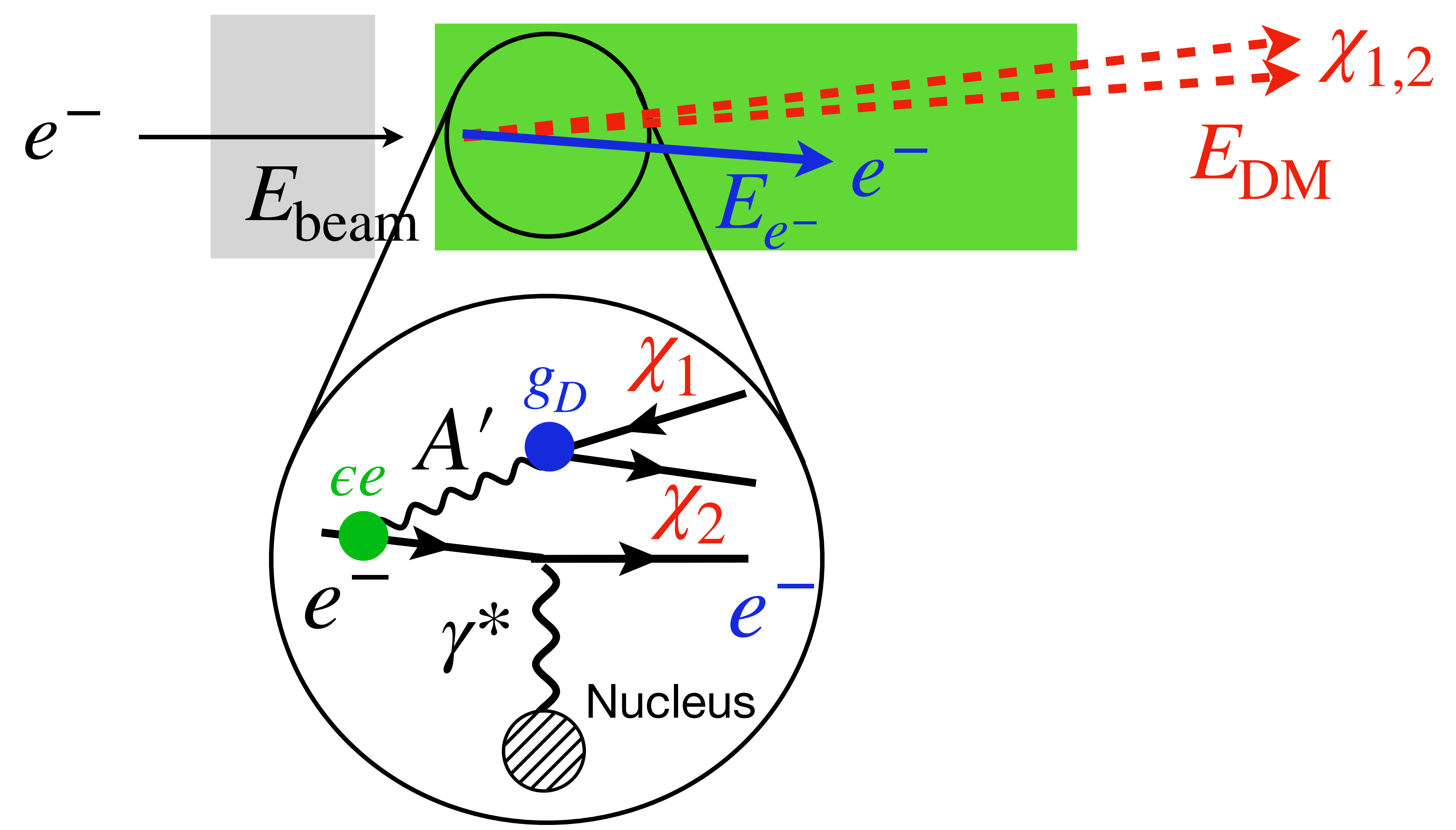


Ex. bremsstrahlung process

Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\text{EM}} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + \text{H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, J^μ_{EM}: SM EM current

Missing energy/momentum signal processes

Missing energy search, e.g., NA64:

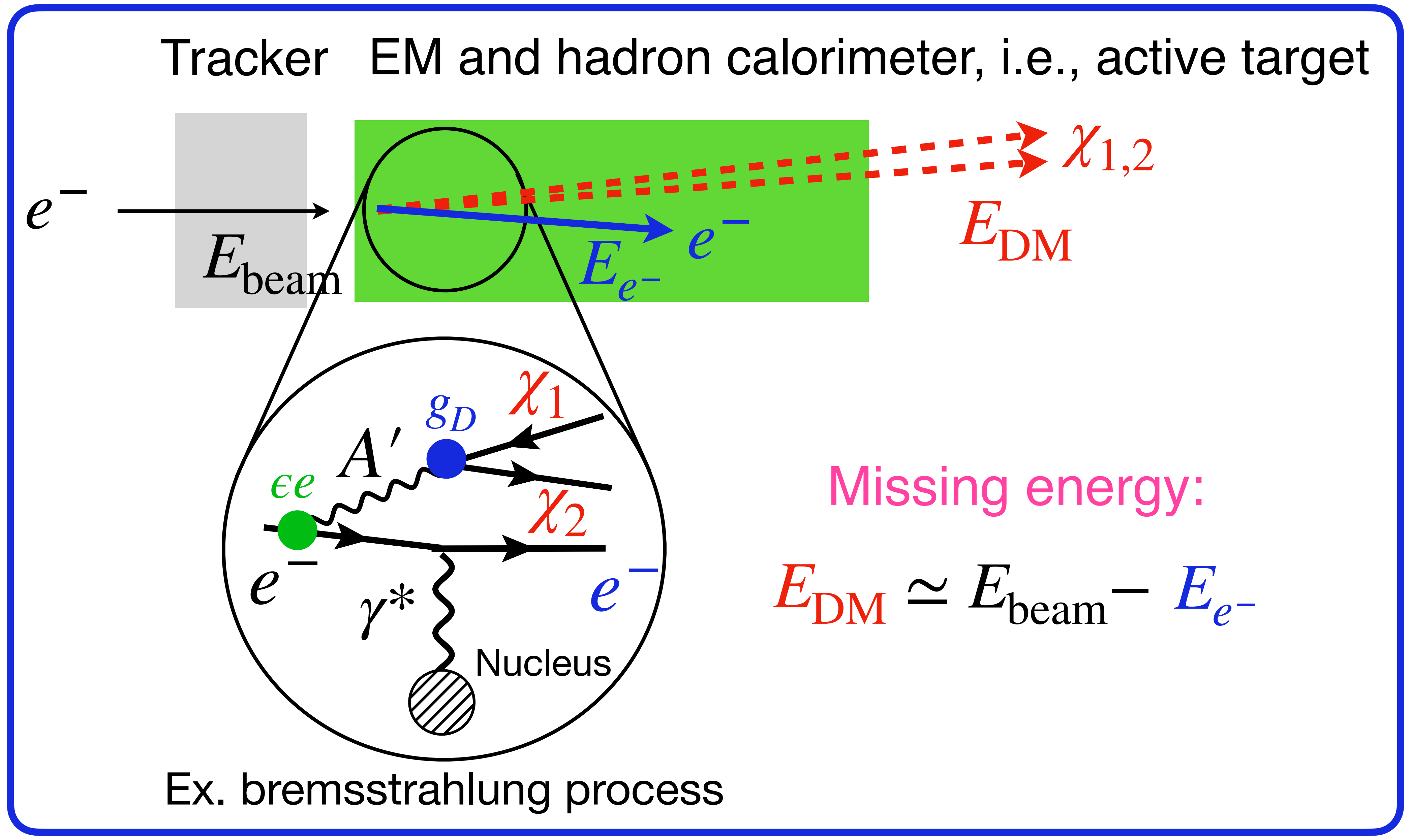


Ex. bremsstrahlung process

Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\text{EM}} - g_D A'_\mu (i \bar{\chi}_2 \gamma^\mu \chi_1 + \text{H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, J^μ_{EM}: SM EM current

Missing energy/momentum signal processes

Missing energy search, e.g., NA64:

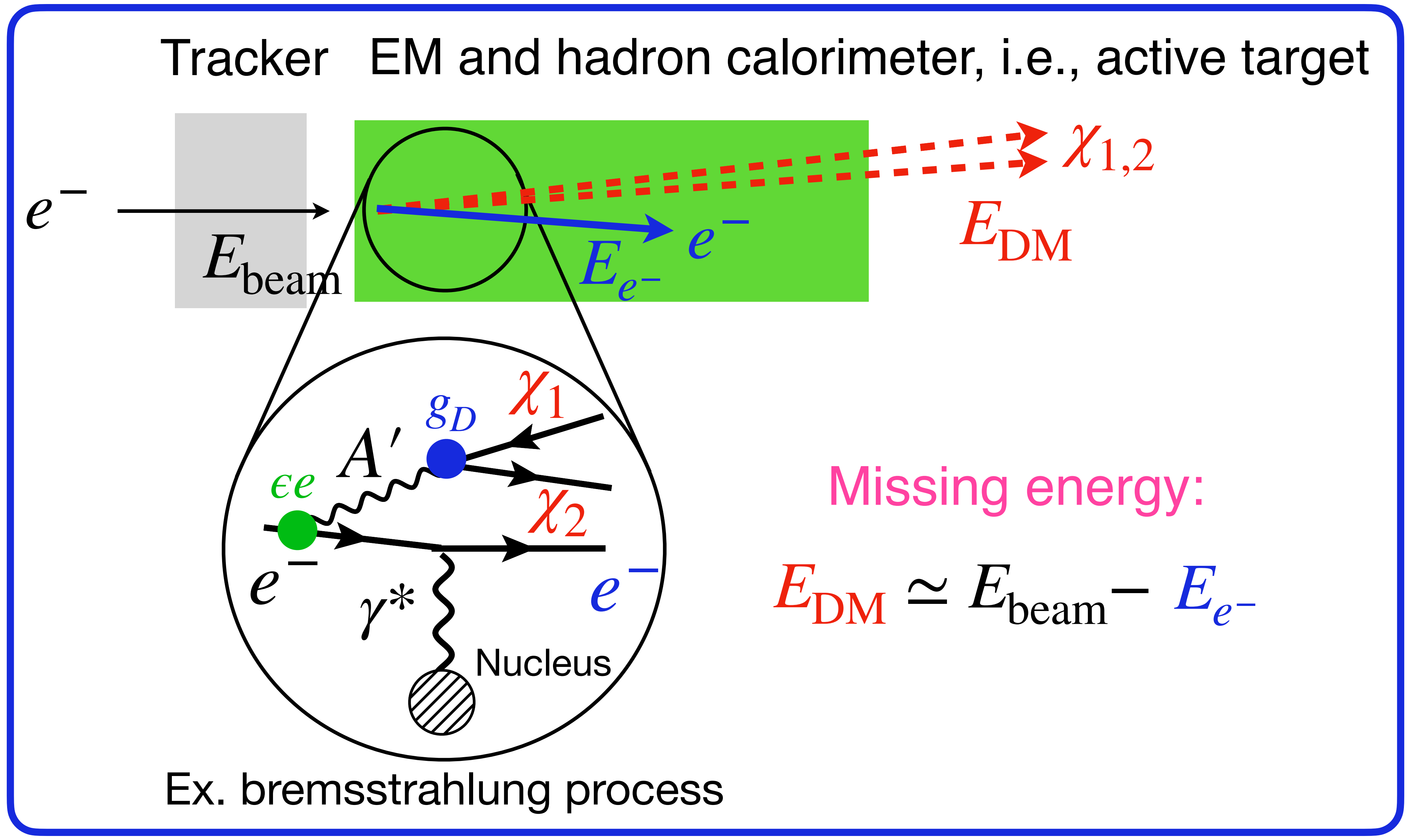


※ Energy transfer to nucleus is modest in Bremsstrahlung process

Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



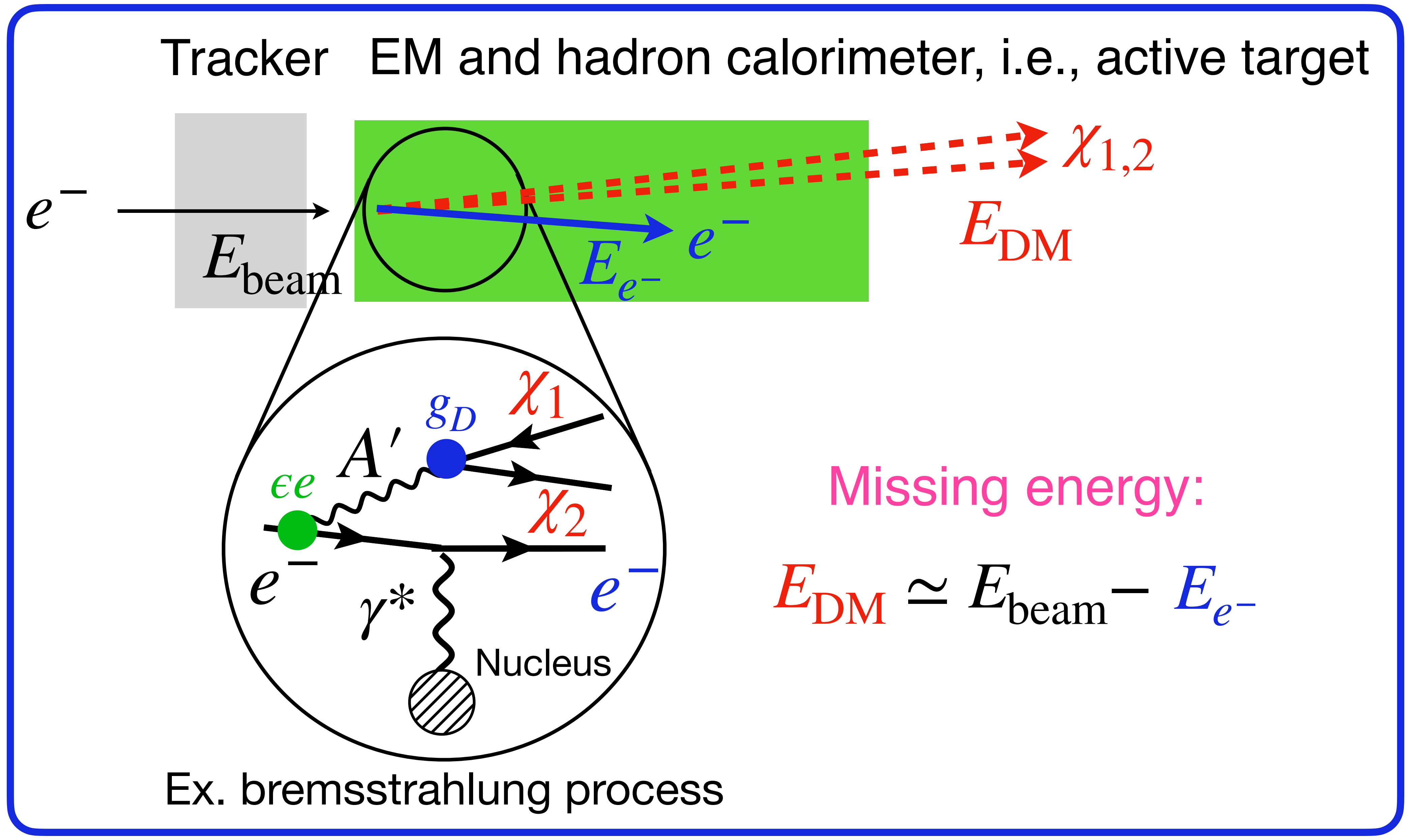
※ Energy transfer to nucleus is modest in Bremsstrahlung process

Missing momentum search, e.g., LDMX:

Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

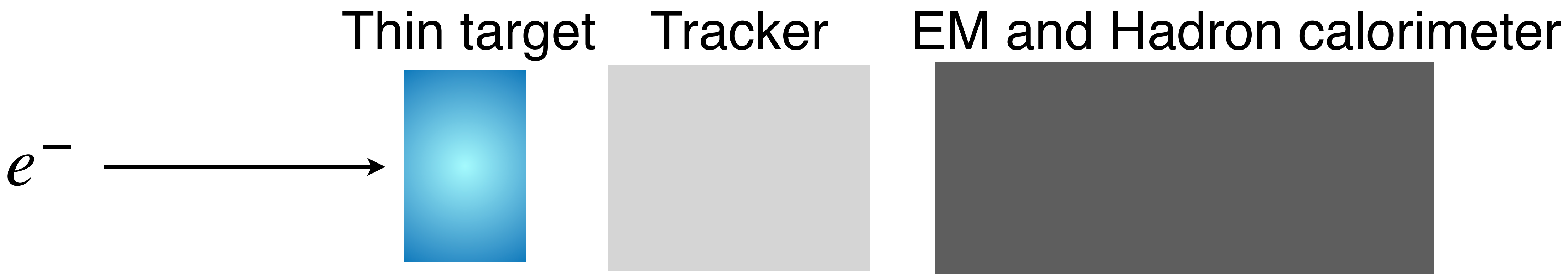
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



※ Energy transfer to nucleus is modest in Bremsstrahlung process

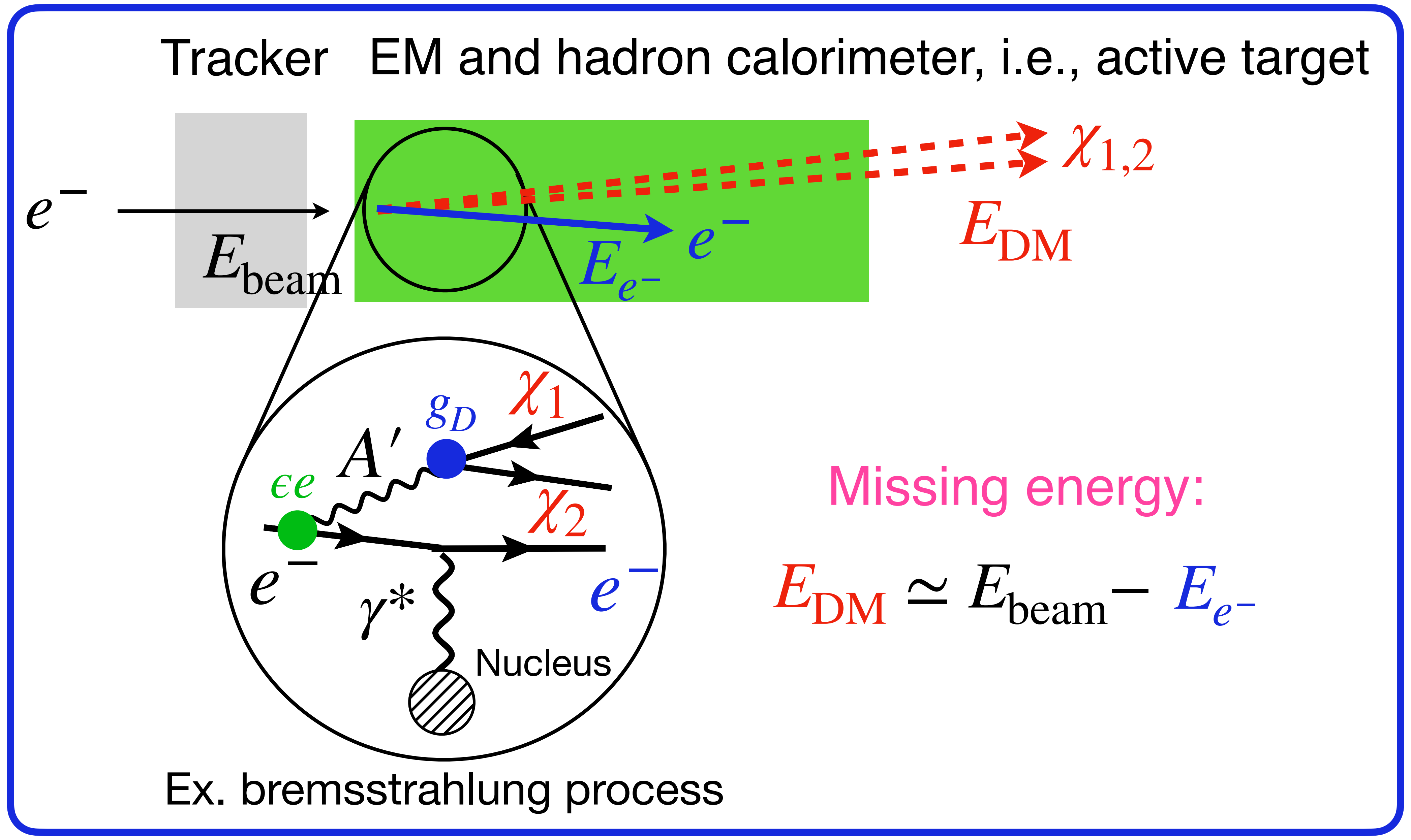
Missing momentum search, e.g., LDMX:



Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

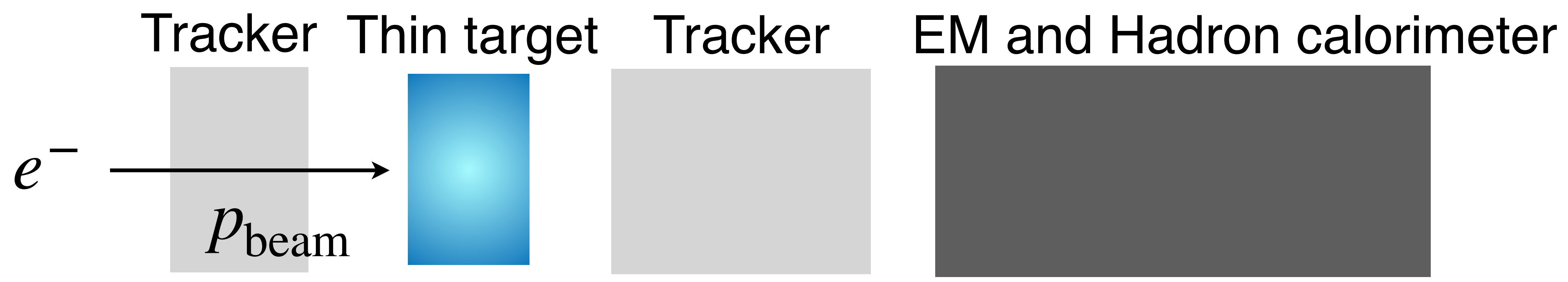
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



※ Energy transfer to nucleus is modest in Bremsstrahlung process

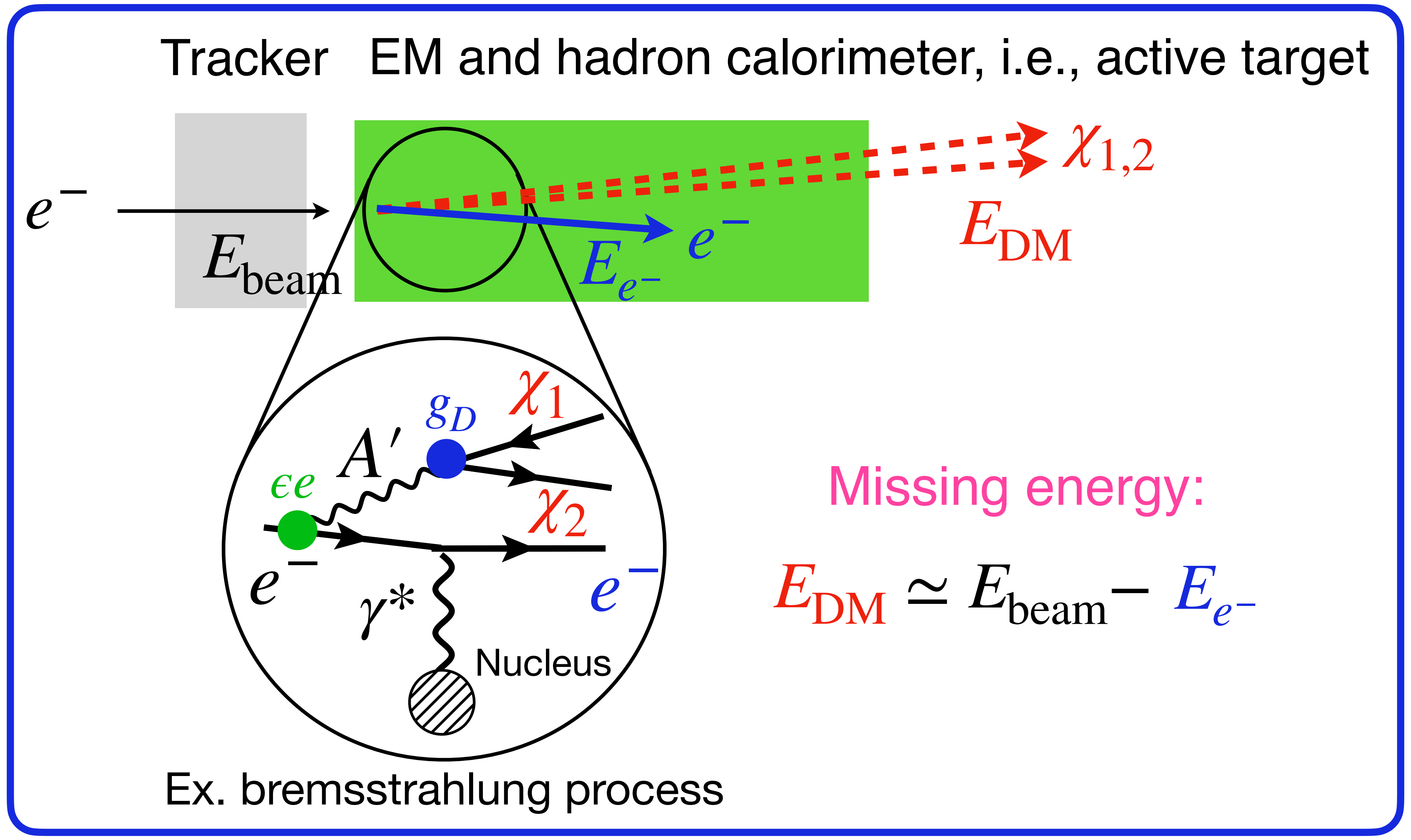
Missing momentum search, e.g., LDMX:



Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

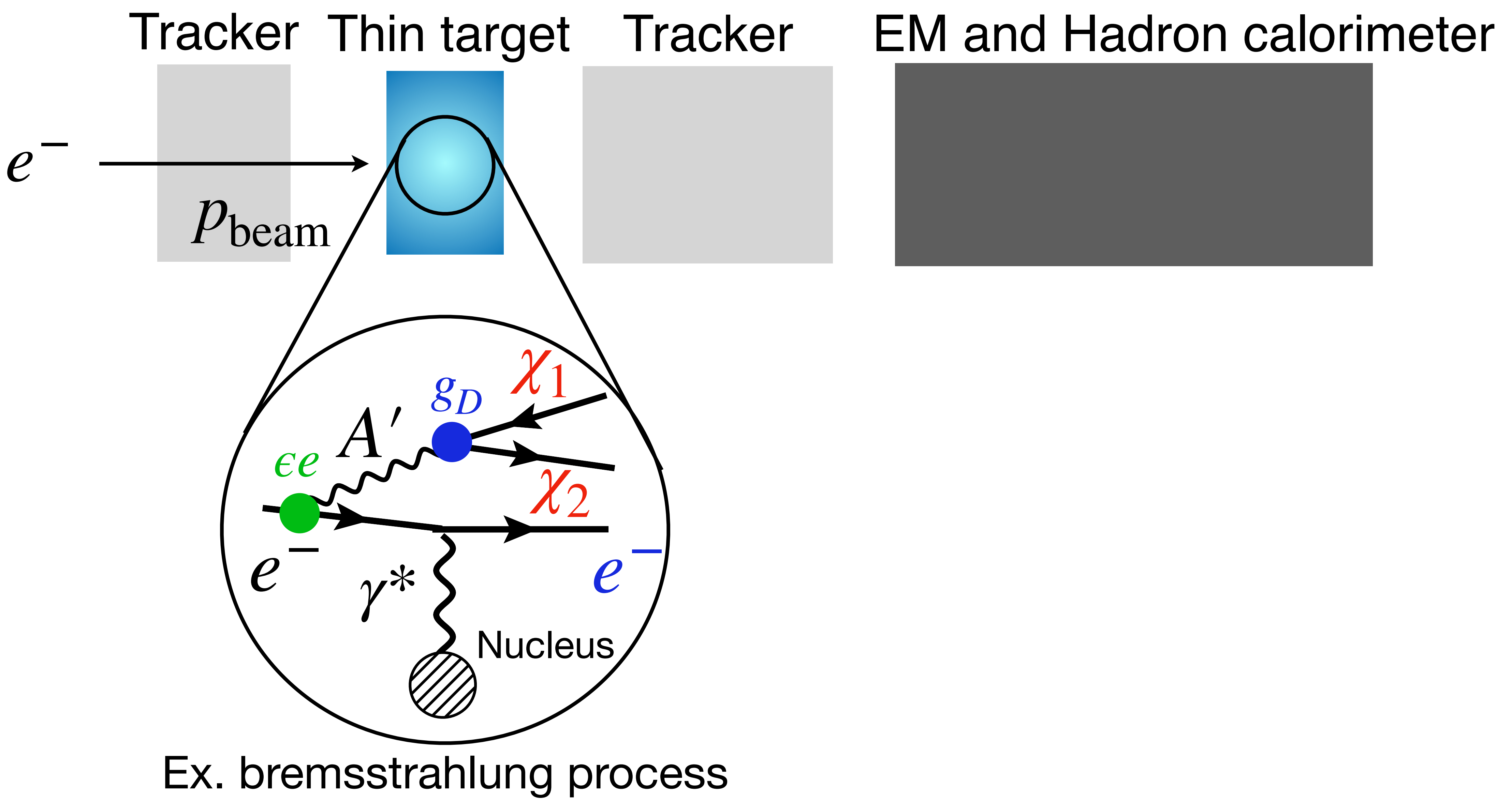
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



※ Energy transfer to nucleus is modest in Bremsstrahlung process

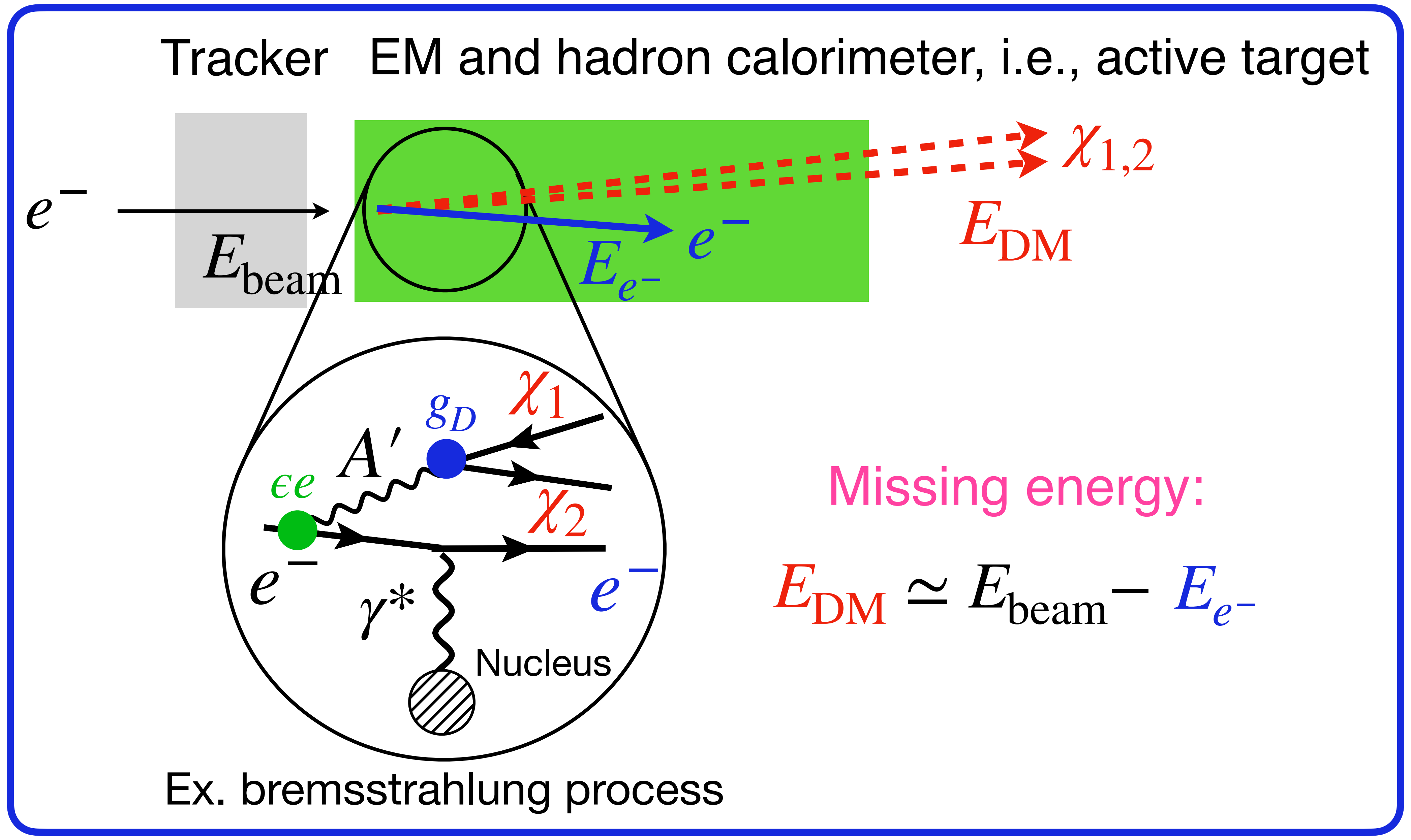
Missing momentum search, e.g., LDMX:



Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

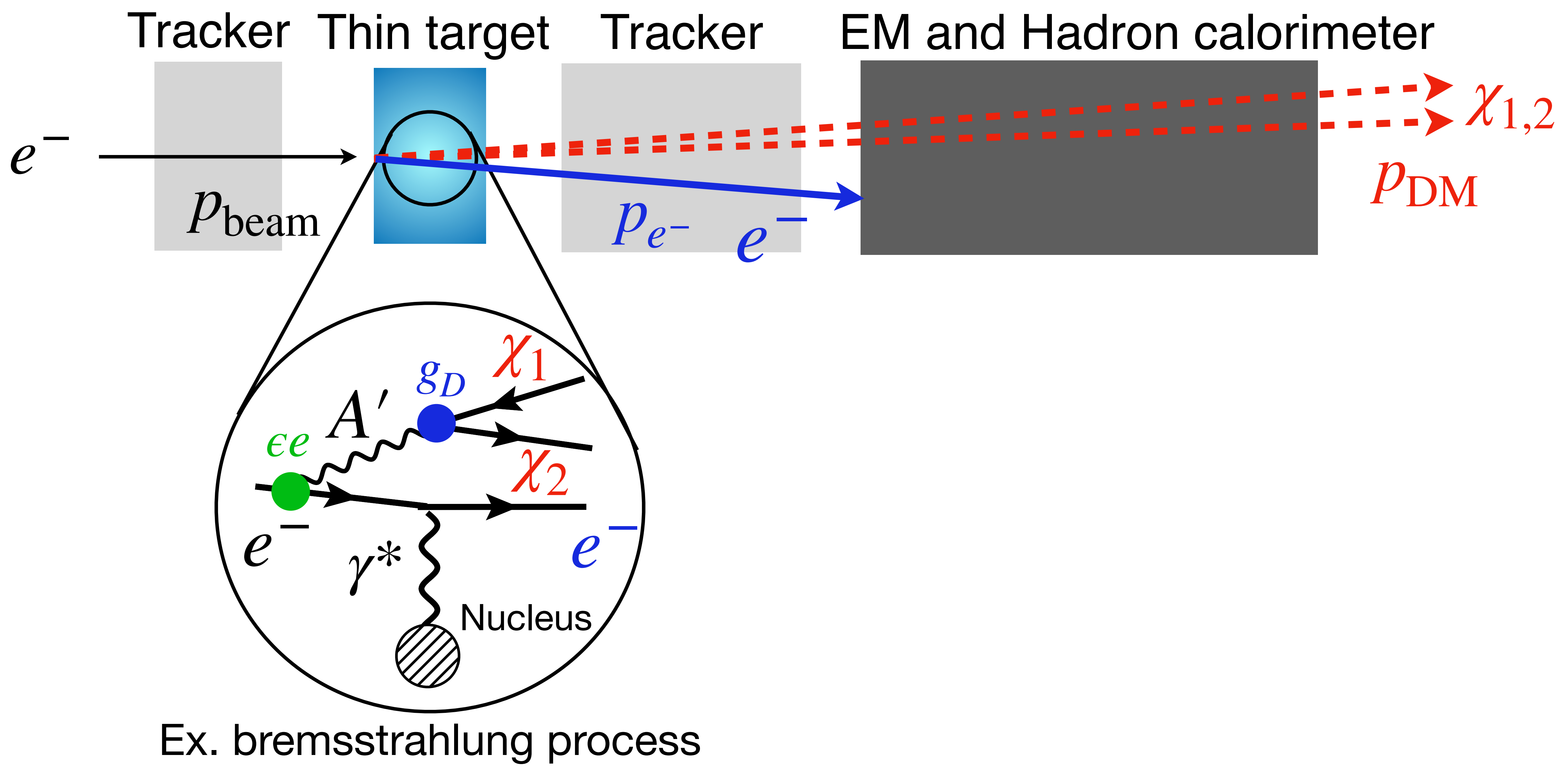
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



※ Energy transfer to nucleus is modest in Bremsstrahlung process

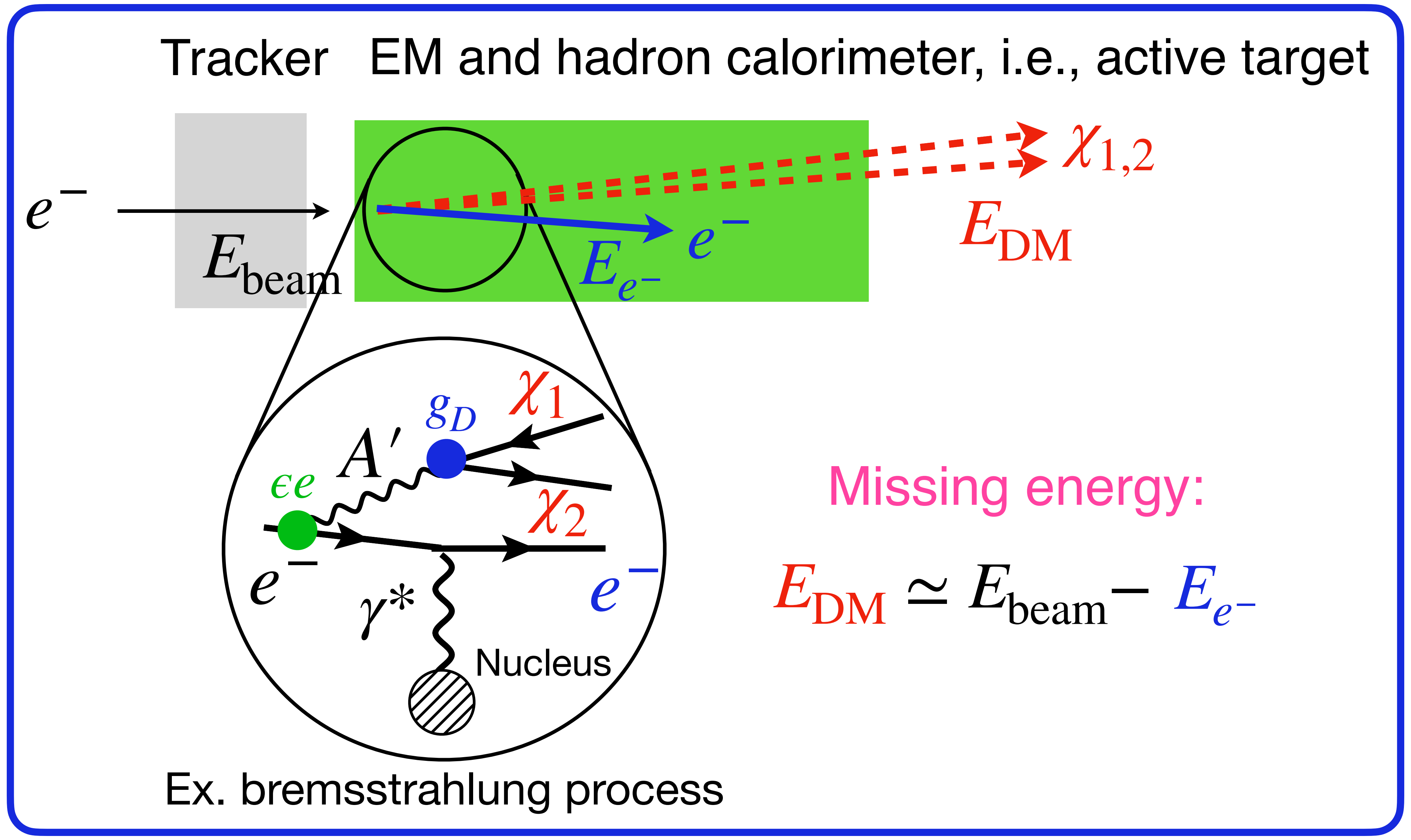
Missing momentum search, e.g., LDMX:



Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

Missing energy/momentum signal processes

Missing energy search, e.g., NA64:

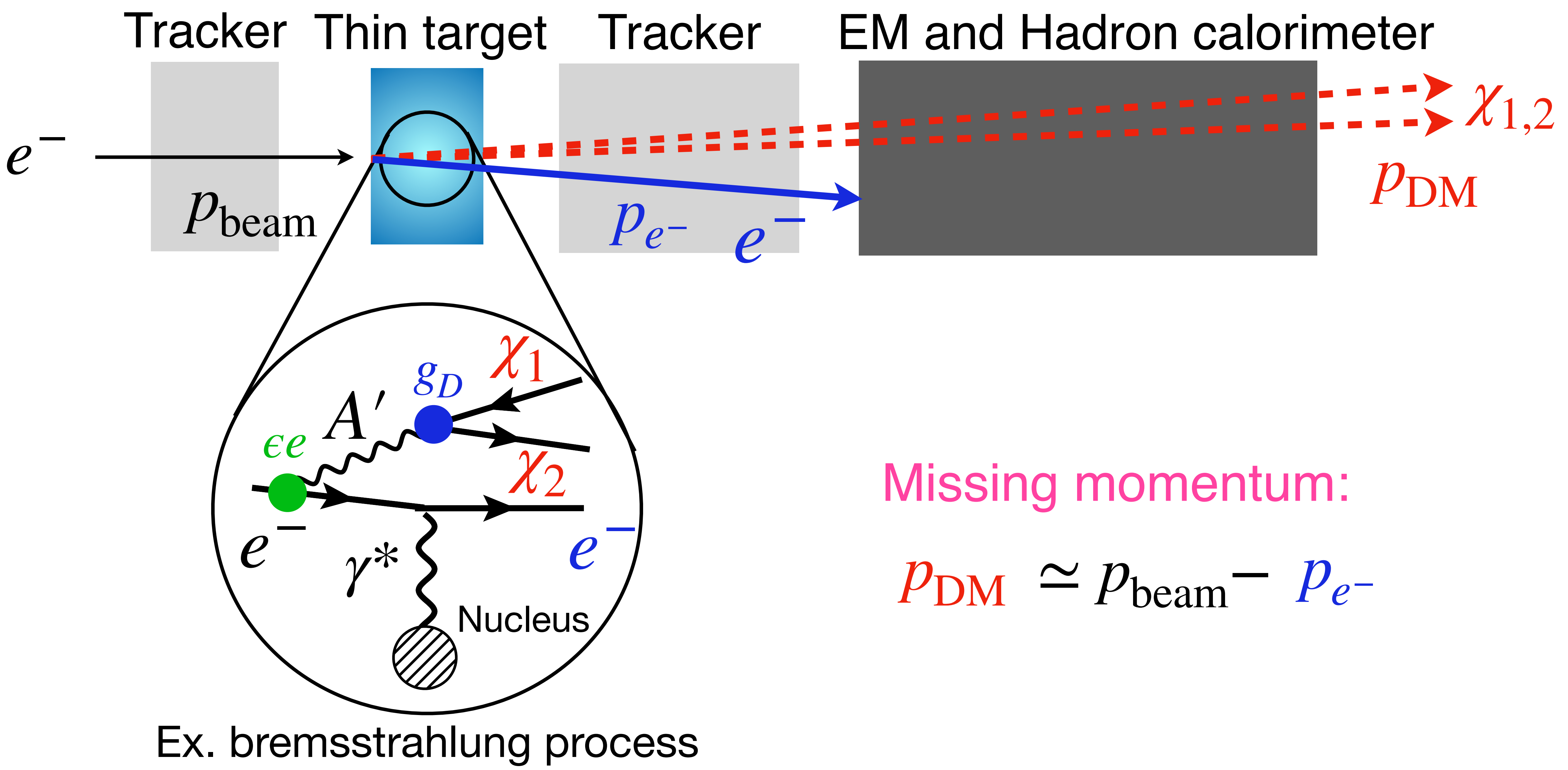


Missing energy:

$E_{\rm DM} \simeq E_{\rm beam} - E_{e^-}$

※ Energy transfer to nucleus is modest in Bremsstrahlung process

Missing momentum search, e.g., LDMX:



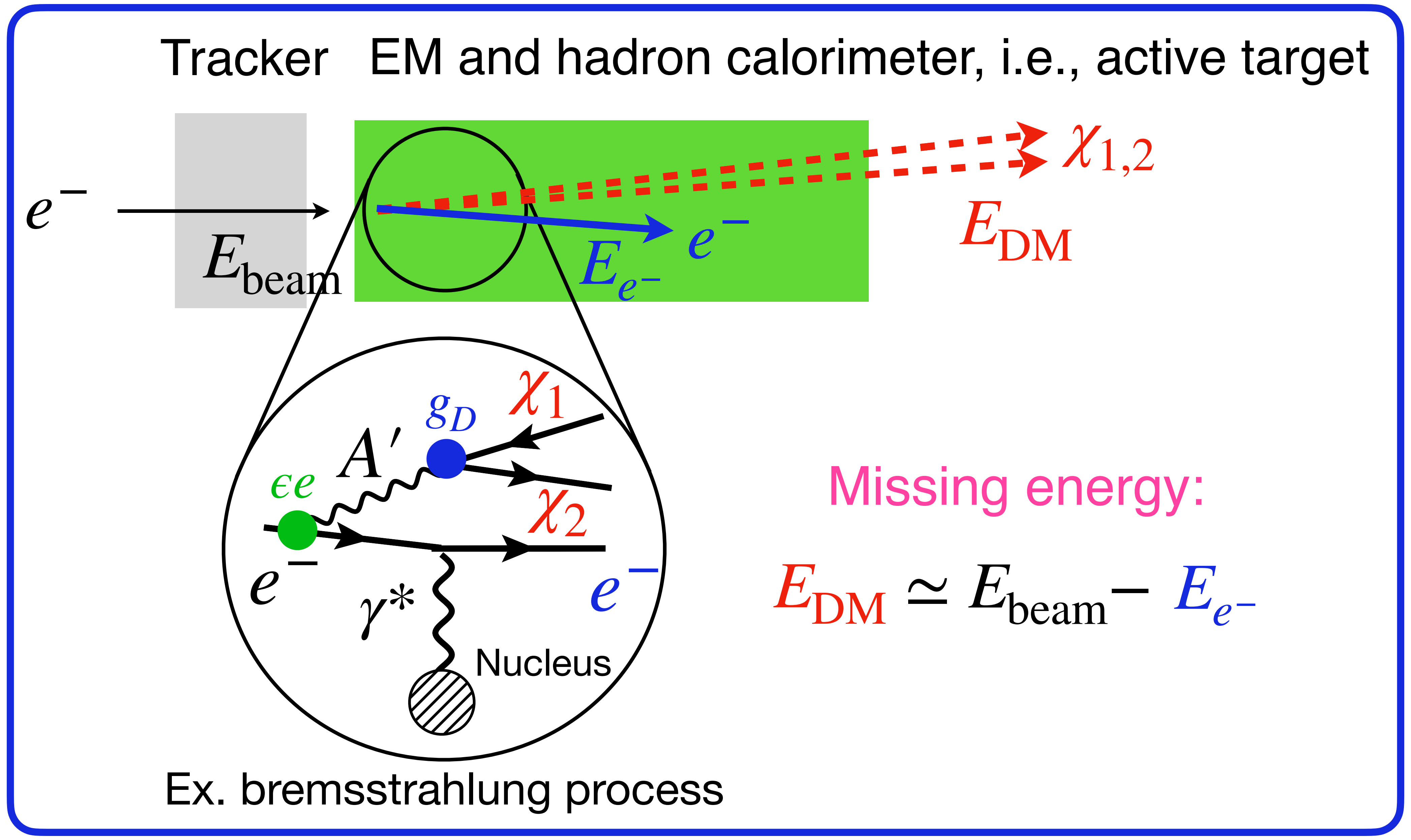
Missing momentum:

$p_{\rm DM} \simeq p_{\rm beam} - p_{e^-}$

Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

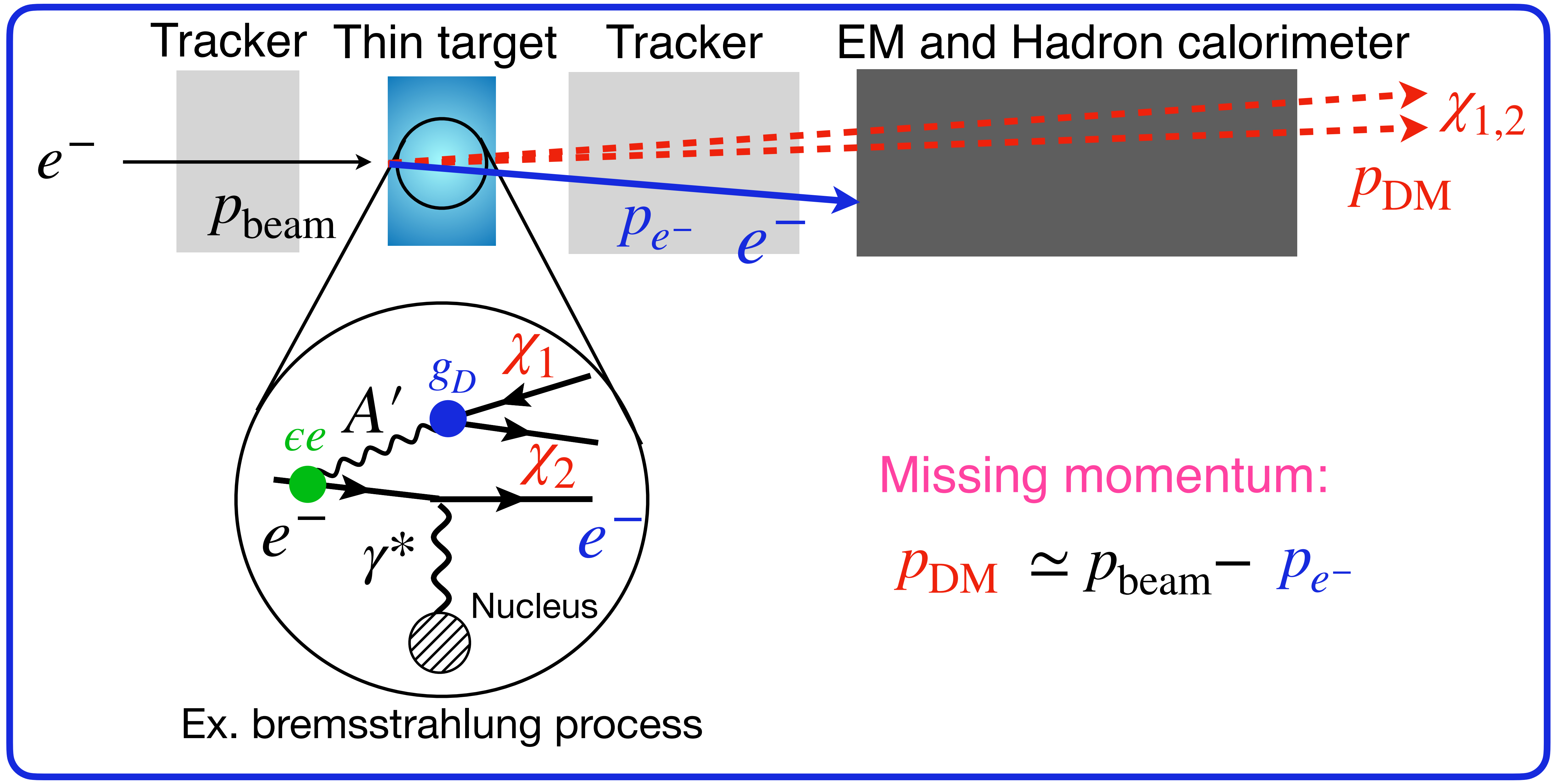
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



※ Energy transfer to nucleus is modest in Bremsstrahlung process

Missing momentum search, e.g., LDMX:

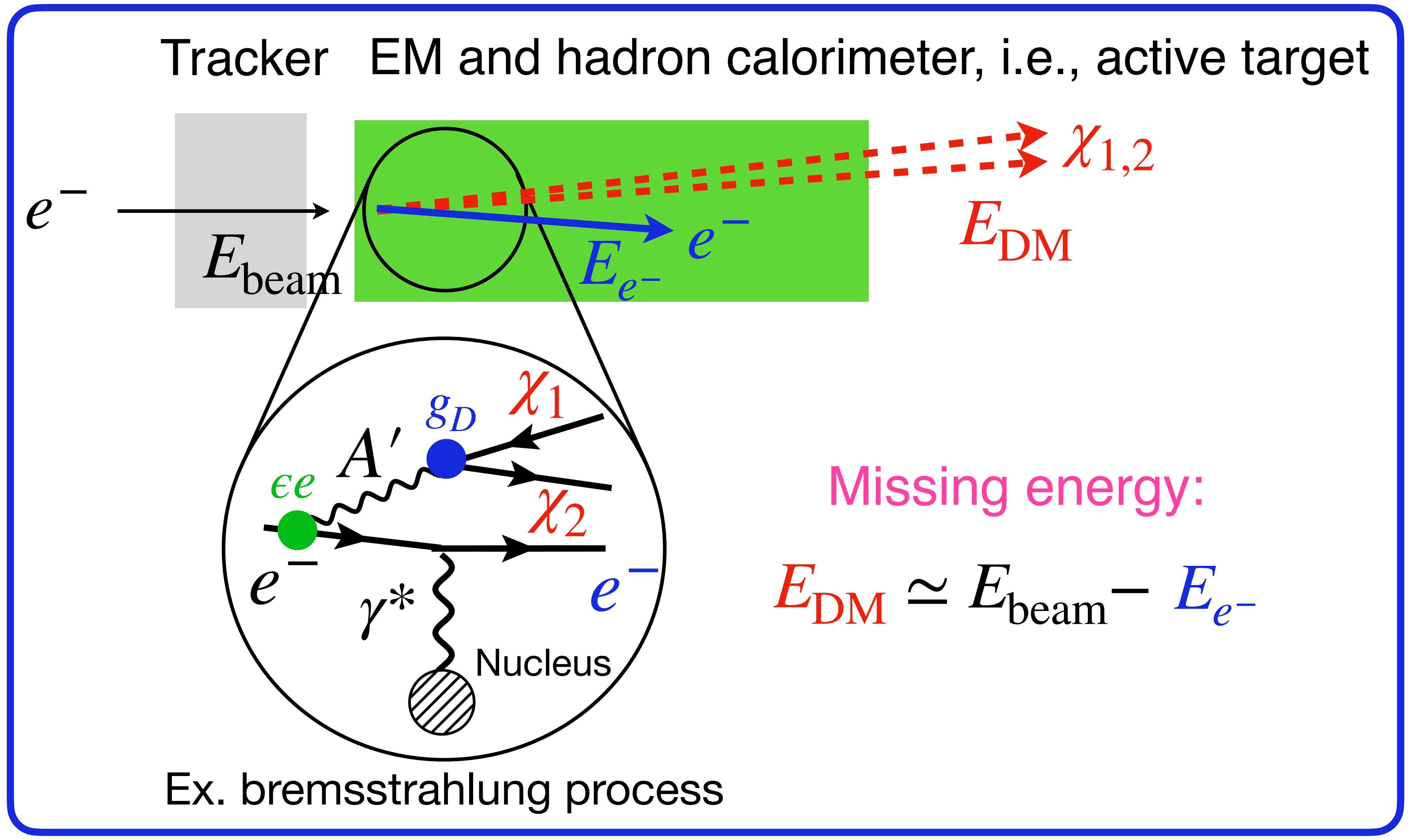


※ Target is thin to reconstruct final state electron

Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

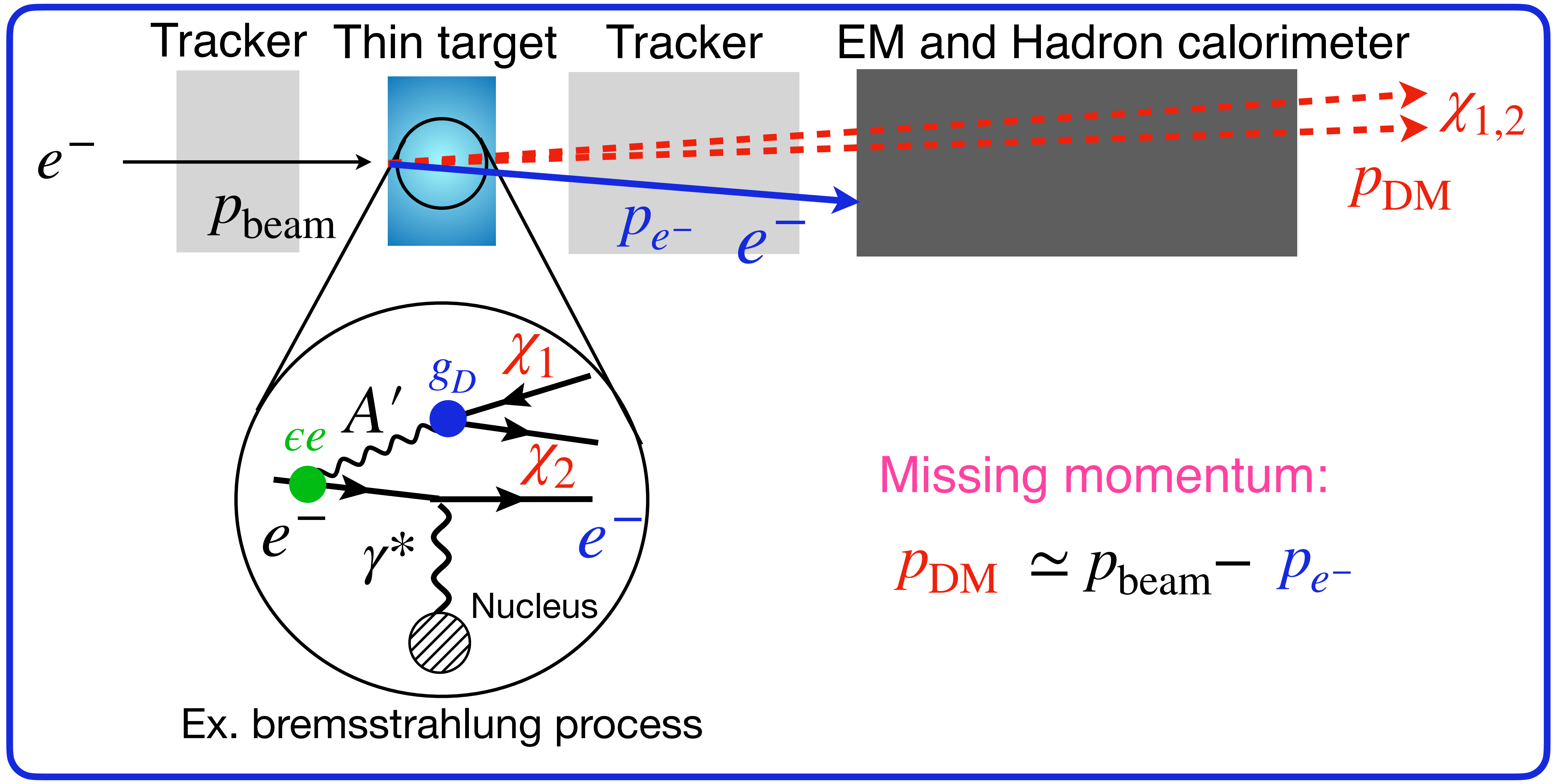
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



※ Energy transfer to nucleus is modest in Bremsstrahlung process

Missing momentum search, e.g., LDMX:



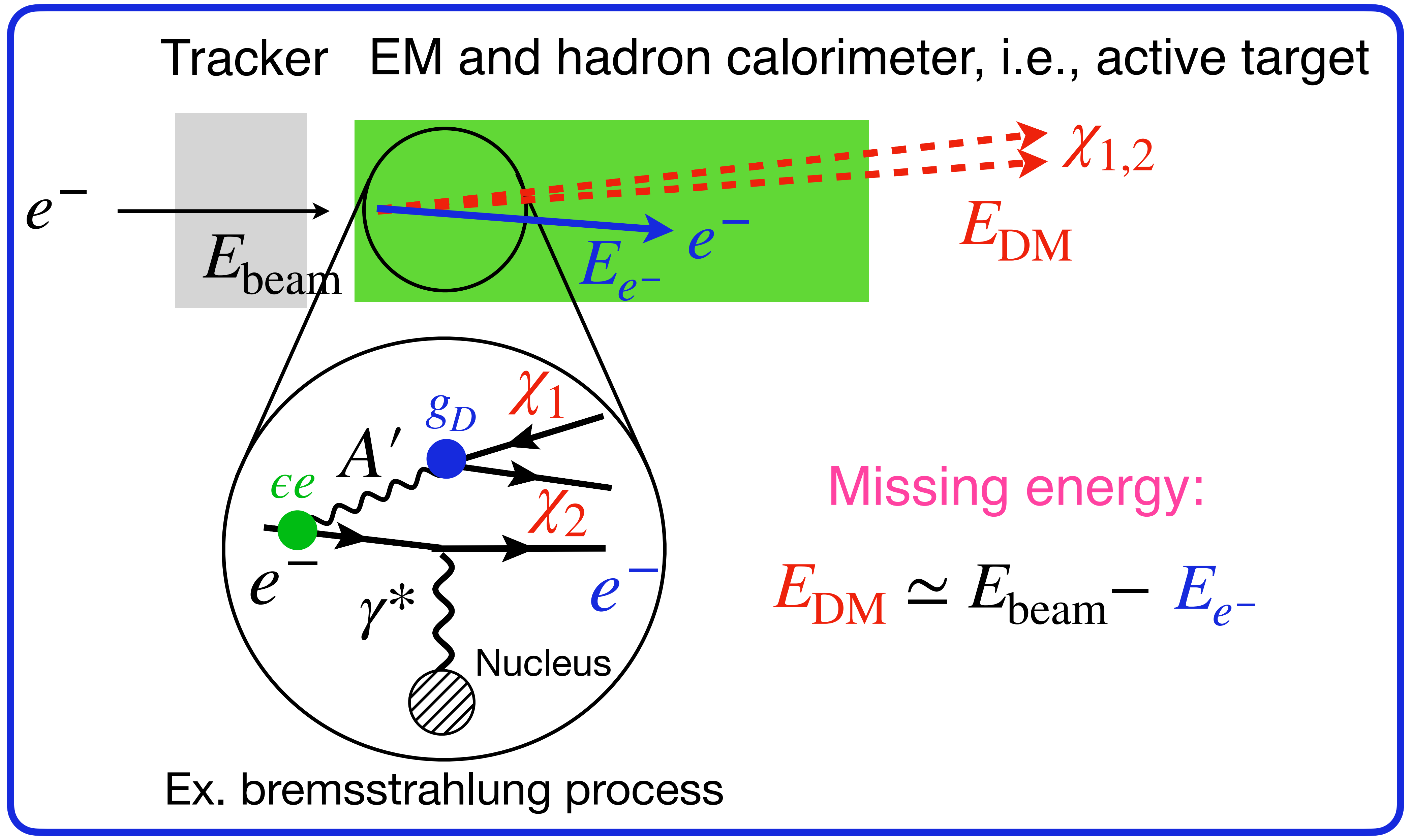
※ Target is thin to reconstruct final state electron

- \# of missing events:

Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

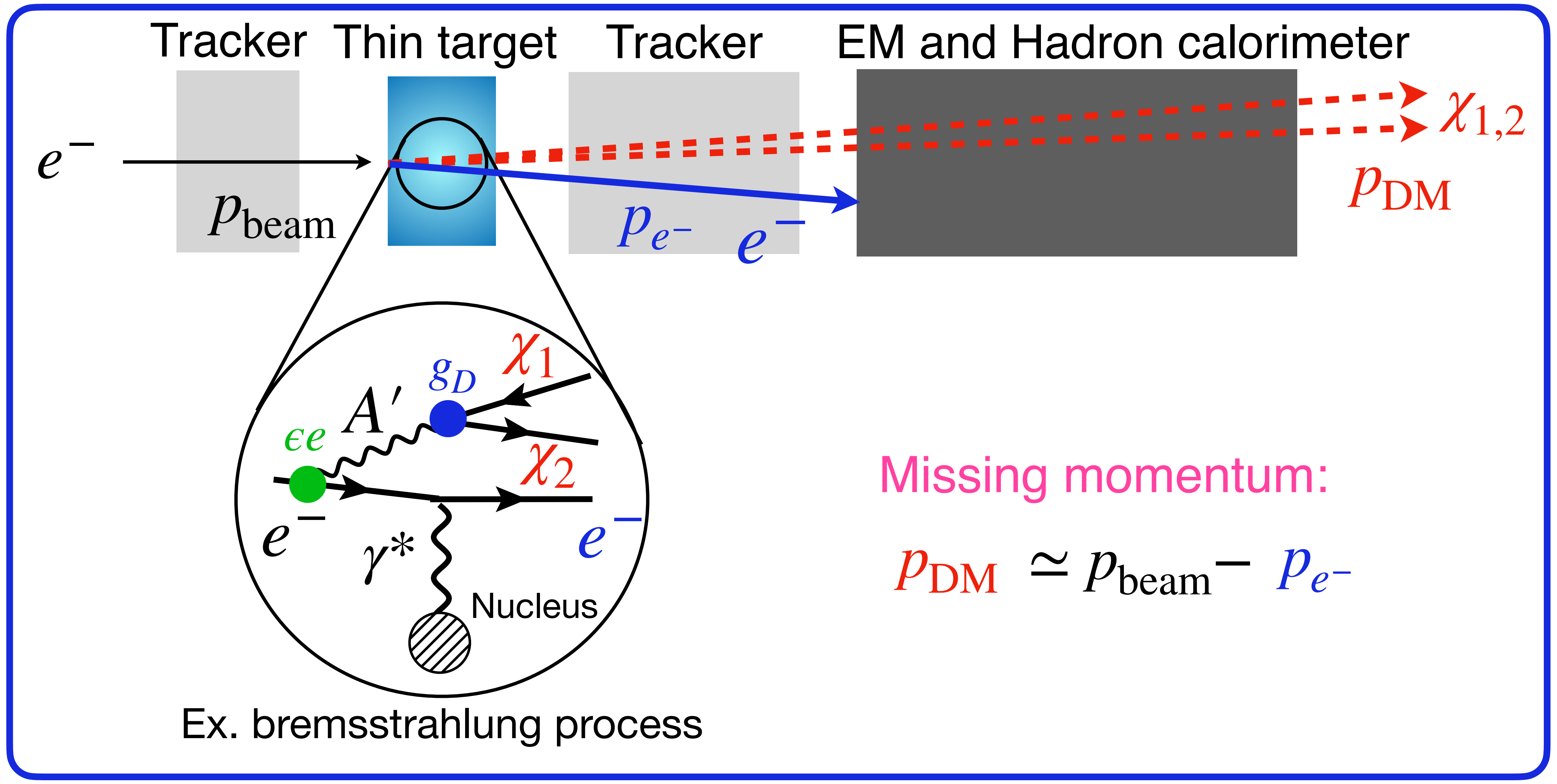
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



※ Energy transfer to nucleus is modest in Bremsstrahlung process

Missing momentum search, e.g., LDMX:



※ Target is thin to reconstruct final state electron

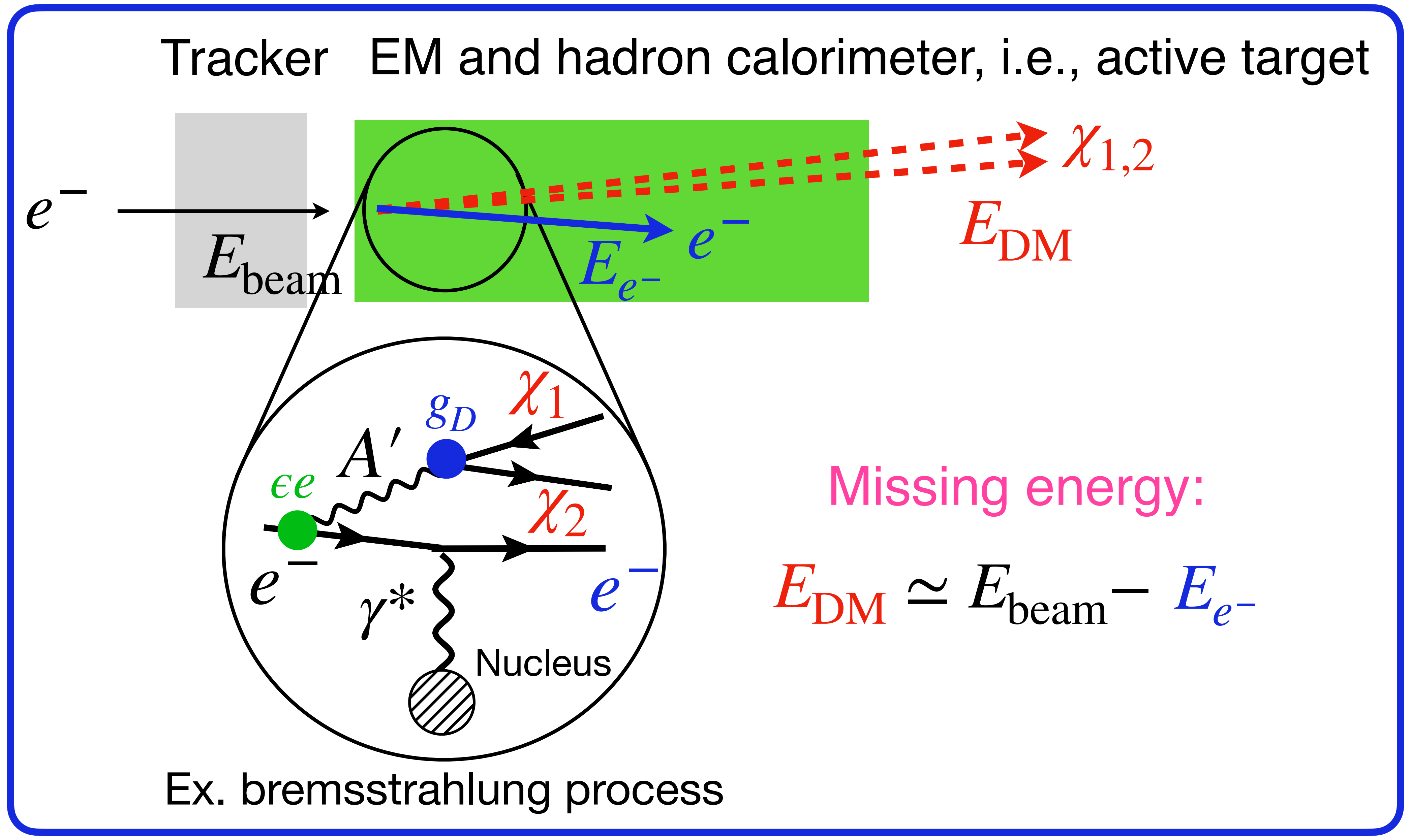
- # of missing events:

  ~ (# of produced DM)

Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

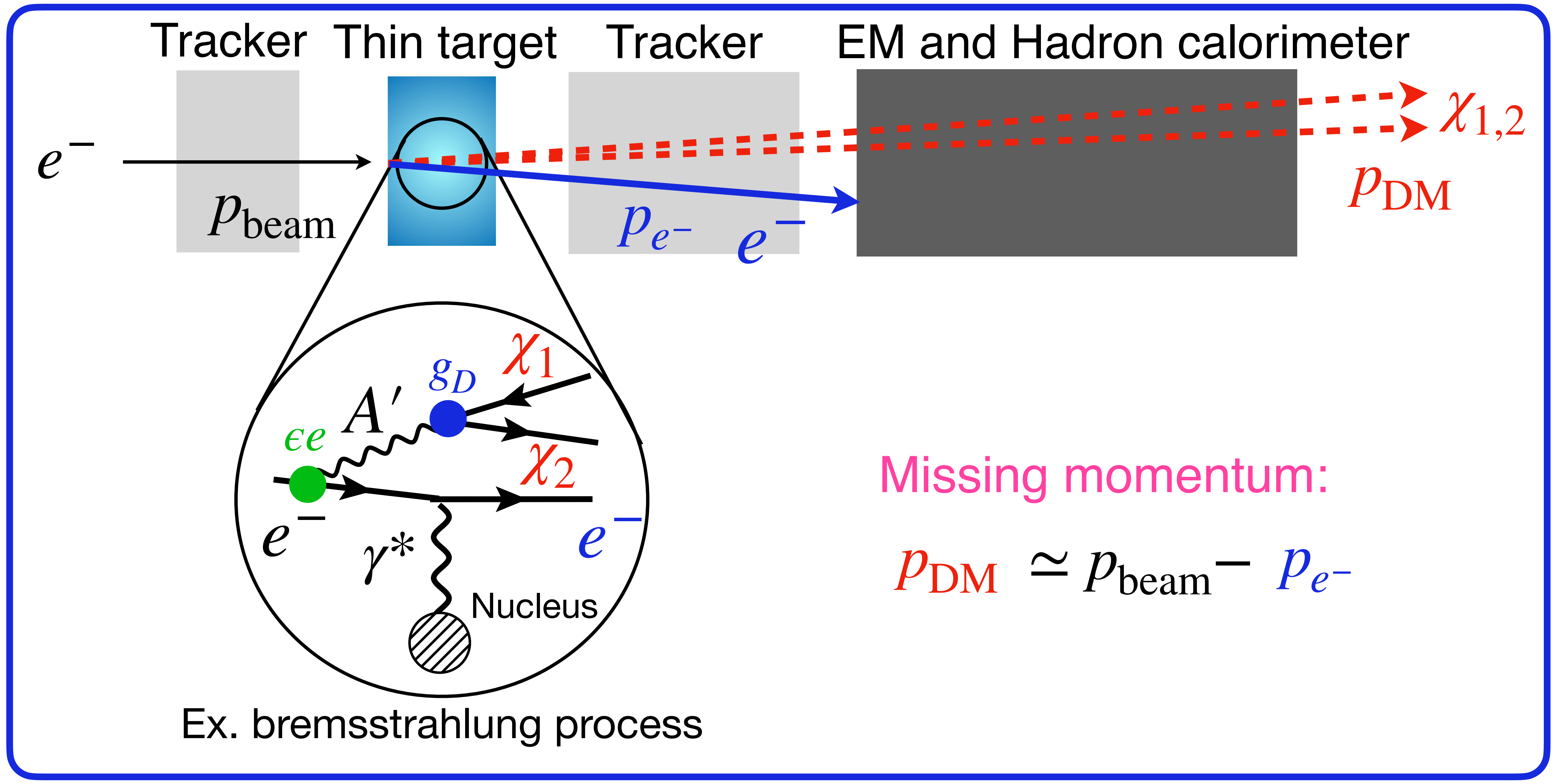
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



※ Energy transfer to nucleus is modest in Bremsstrahlung process

Missing momentum search, e.g., LDMX:



※ Target is thin to reconstruct final state electron

- # of missing events:

Acceptance

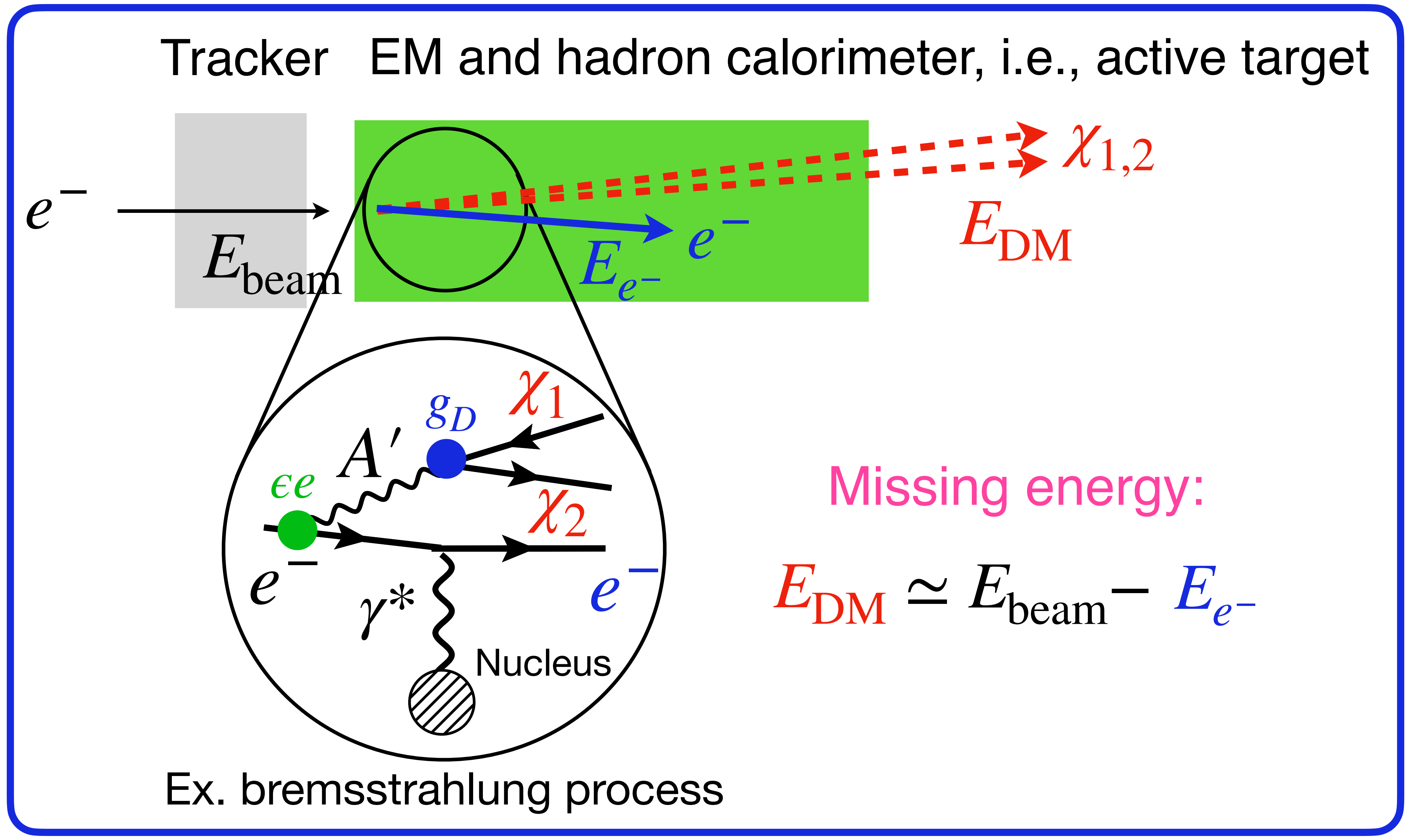
~ (# of produced DM) × (Probability DM reaches detector) × (Probability DM is detected)

~ 1

Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

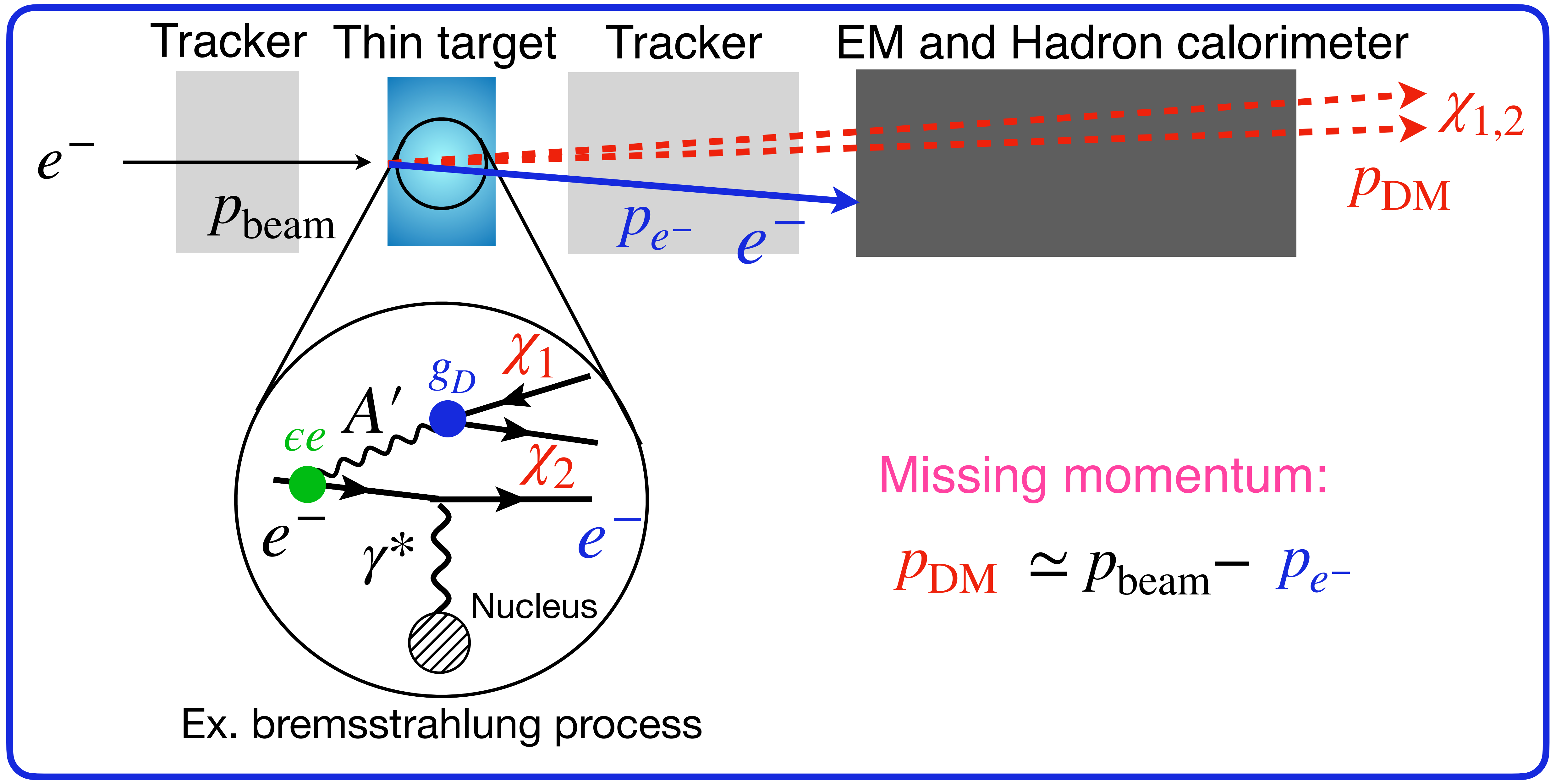
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



※ Energy transfer to nucleus is modest in Bremsstrahlung process

Missing momentum search, e.g., LDMX:



※ Target is thin to reconstruct final state electron

- # of missing events:

Acceptance

~ (# of produced DM) × (Probability DM reaches detector) × (Probability DM is detected)

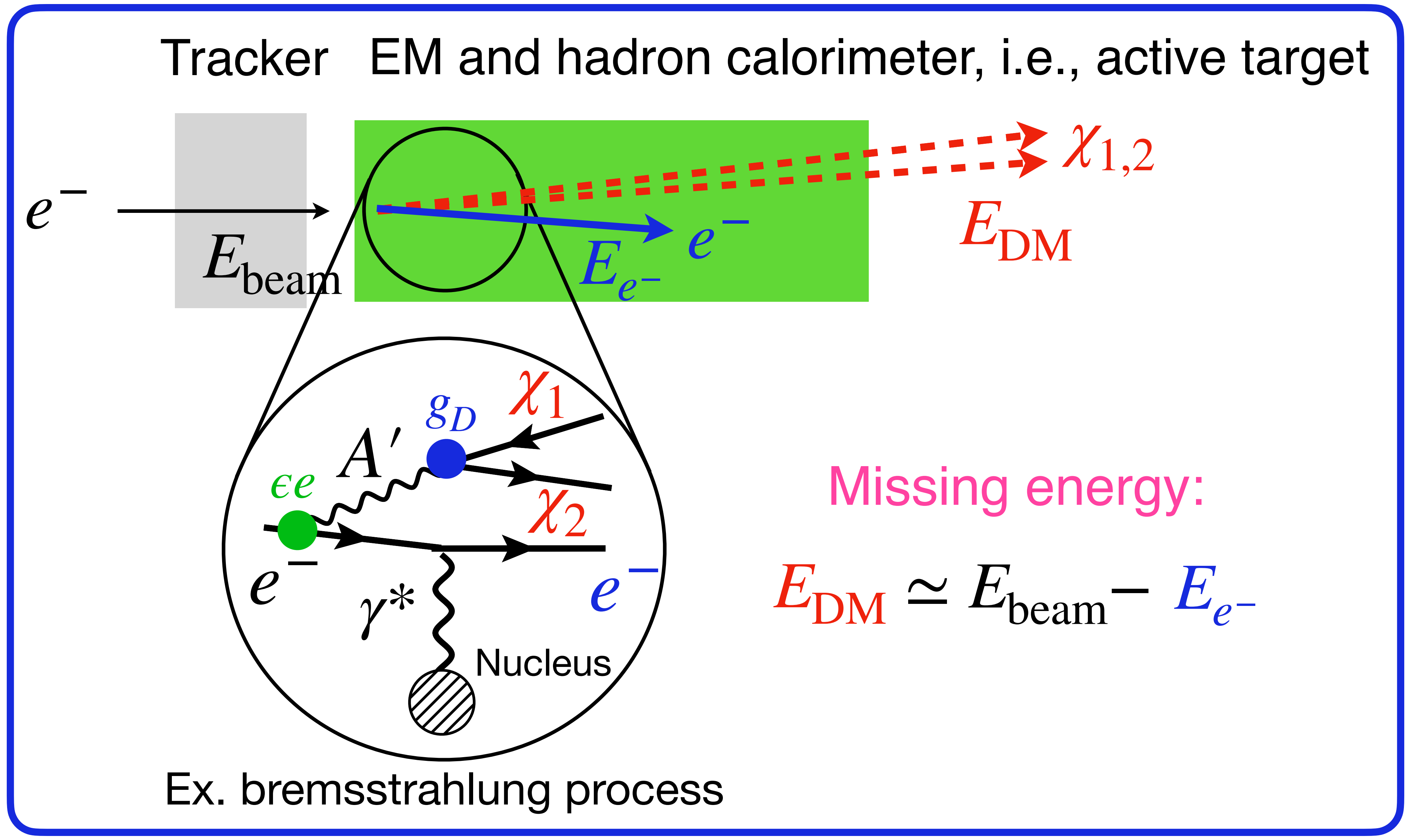
~ 1

※ not proportional to $(\epsilon e)^2$ in contrast to recoil and visible search

Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + \mathrm{H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, J^μ_{EM}: SM EM current

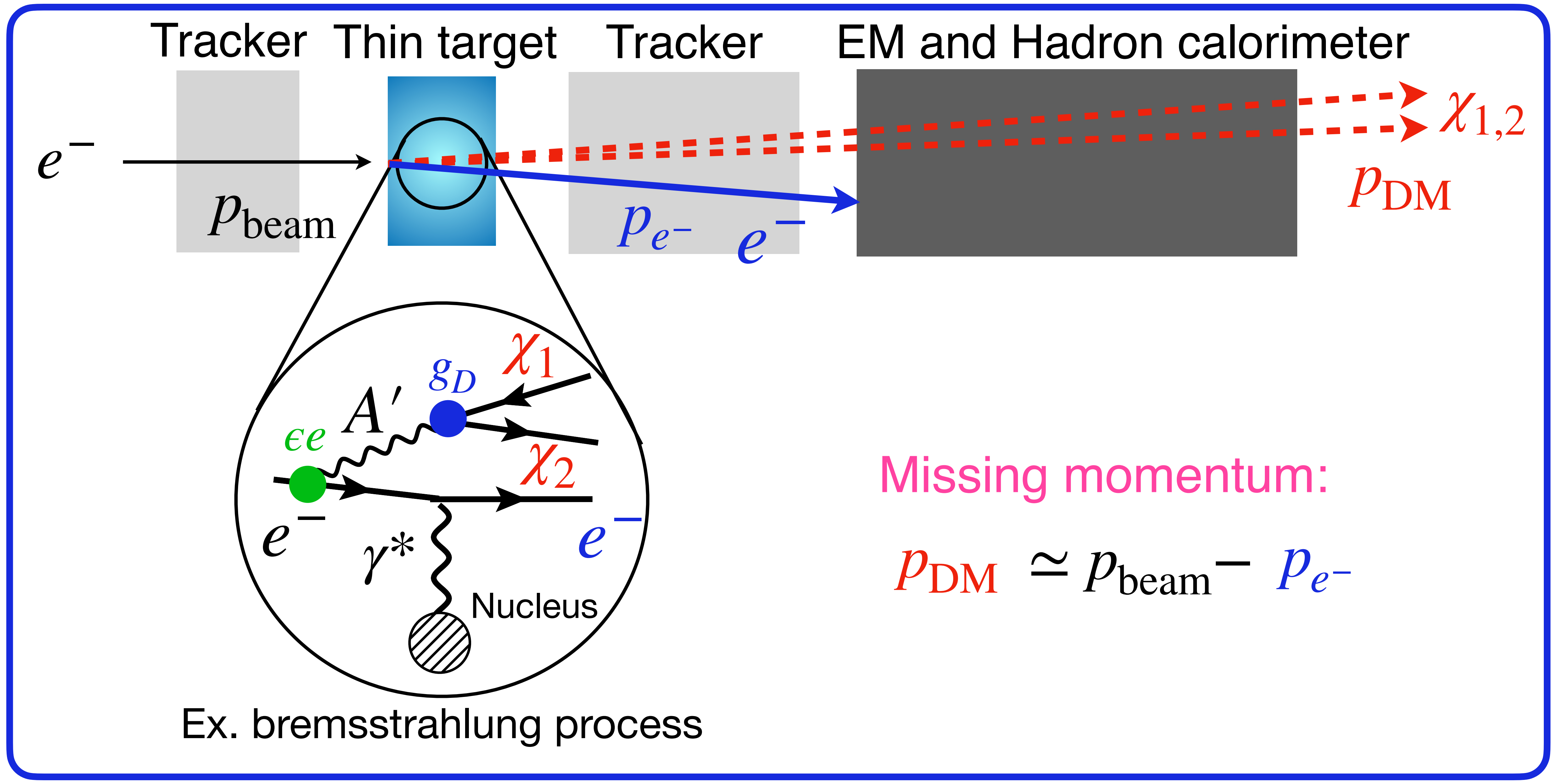
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



※ Energy transfer to nucleus is modest in Bremsstrahlung process

Missing momentum search, e.g., LDMX:



※ Target is thin to reconstruct final state electron

・# of missing events:

Acceptance

~ (# of produced DM) × (Probability DM reaches detector) × (Probability DM is detected)

∝ (Beam flux)×$(\epsilon e)^2$

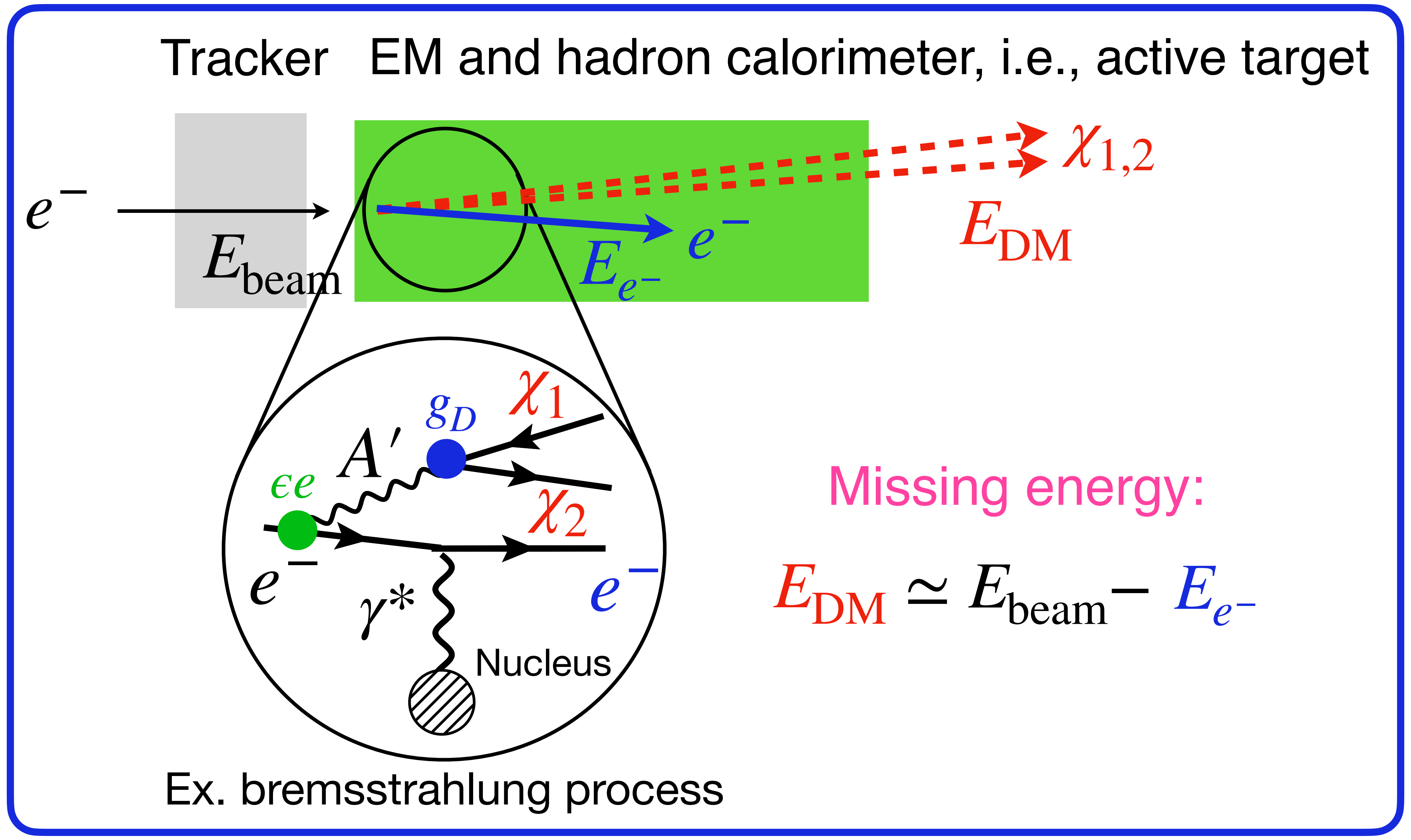
~ 1

※ not proportional to $(\epsilon e)^2$ in contrast to recoil and visible search

Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM, $J^\mu_{\rm EM}$: SM EM current

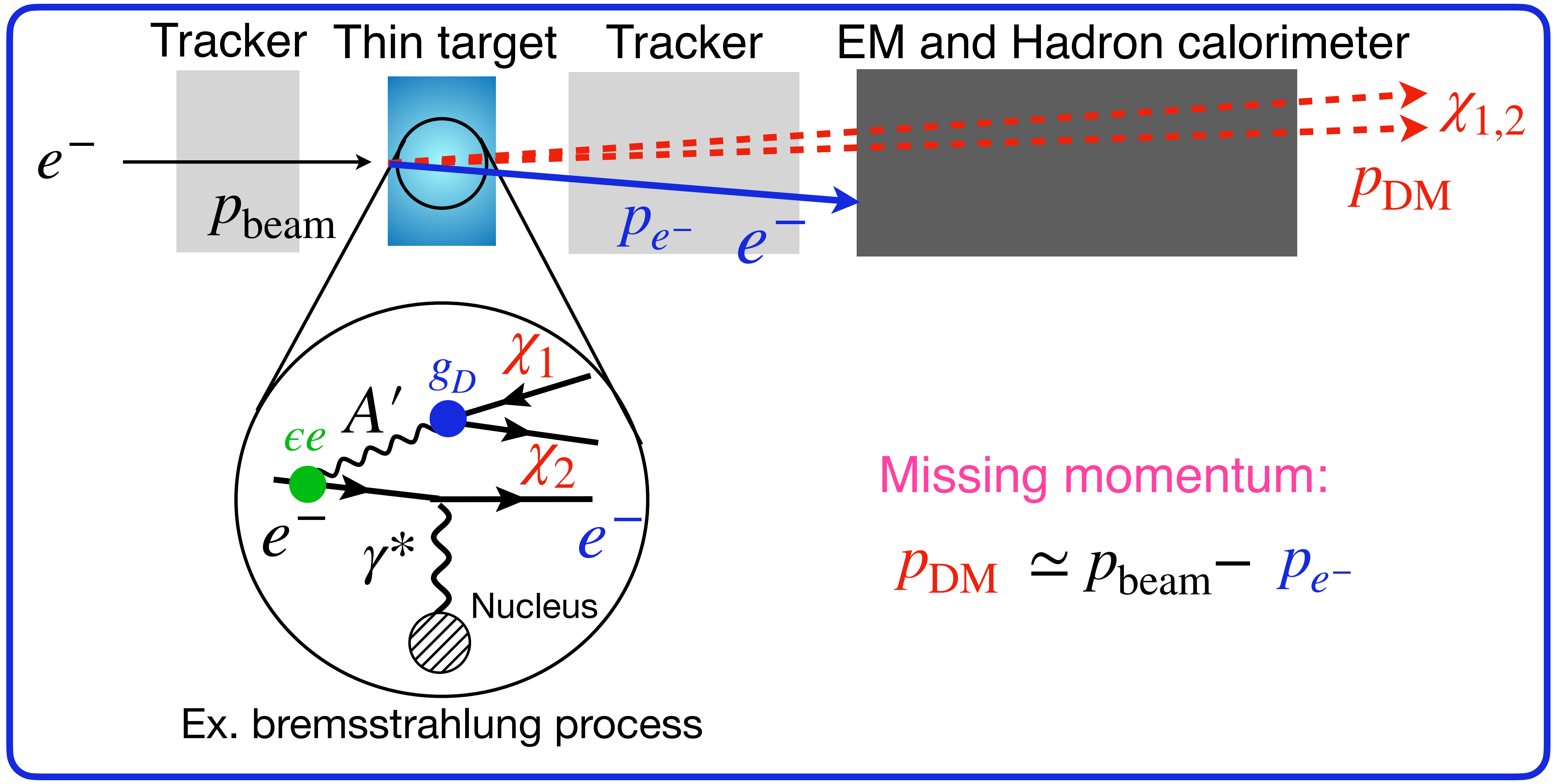
Missing energy/momentum signal processes

Missing energy search, e.g., NA64:



※ Energy transfer to nucleus is modest in Bremsstrahlung process

Missing momentum search, e.g., LDMX:



※ Target is thin to reconstruct final state electron

- # of missing events:

Acceptance

~ (# of produced DM) × (Probability DM reaches detector) × (Probability DM is detected)

∝ (Beam flux)×$(\epsilon e)^2$

~ 1

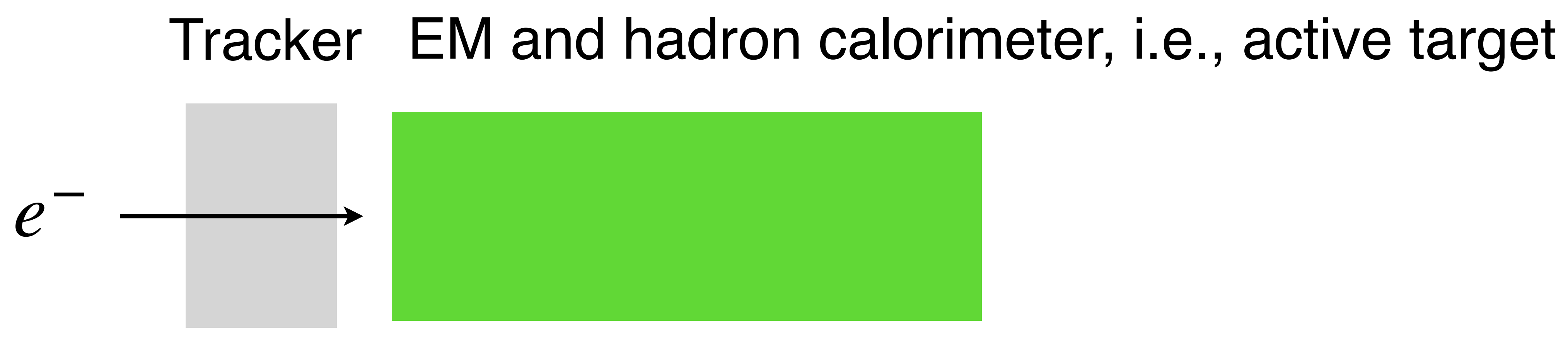
※ not proportional to $(\epsilon e)^2$ in contrast to recoil and visible search

Acceptance is good, but the continuous beam(small flux) is needed to reconstruct SM

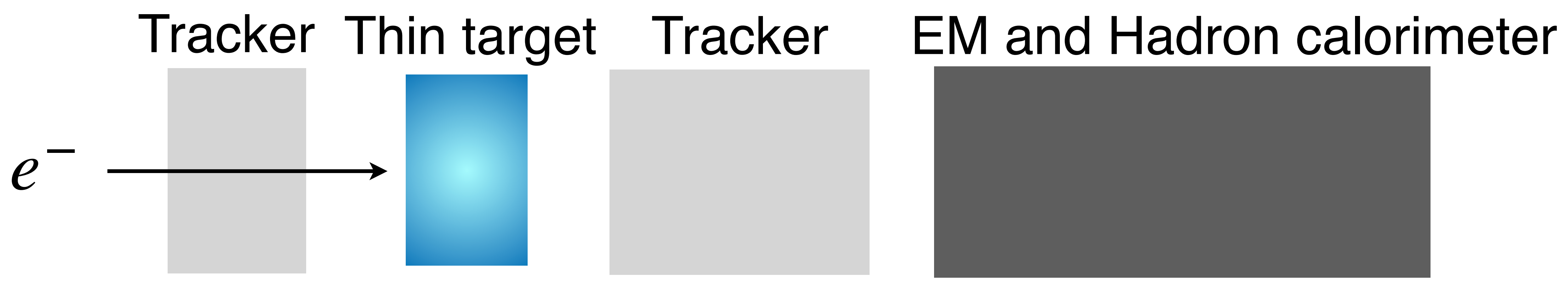
Background events in missing energy/momentum search

Background events in missing energy/momentum search

Missing energy search, e.g., NA64:

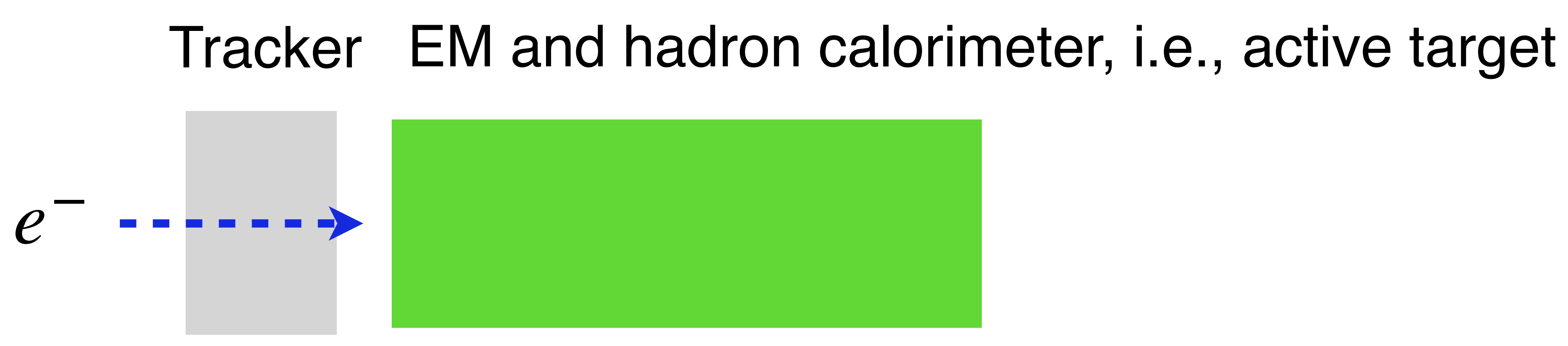


Missing momentum search, e.g., LDMX:



Background events in missing energy/momentum search

Missing energy search, e.g., NA64:



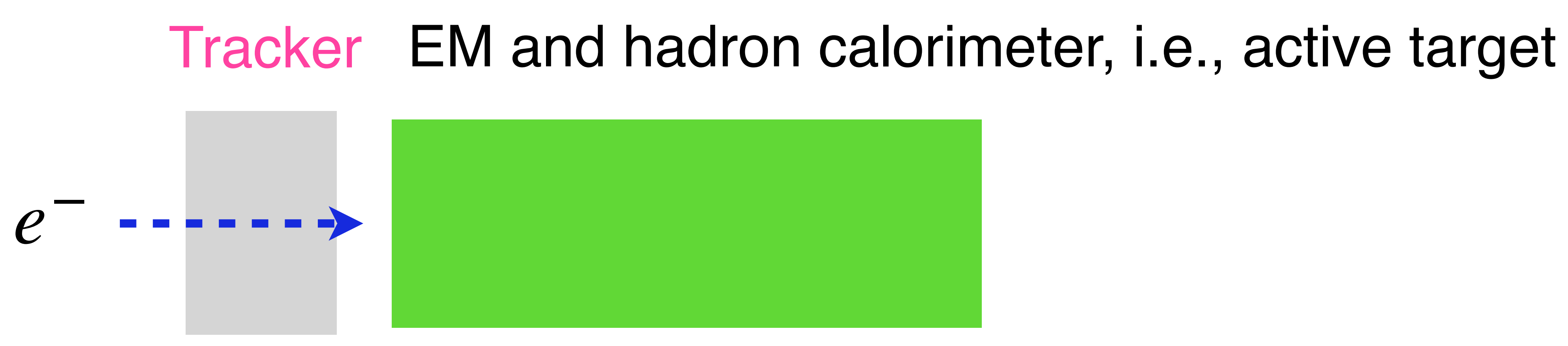
Missing momentum search, e.g., LDMX:

- Potential BG events:

  - Mistakenly tagged initial beam, e.g., incident lower energy beam

Background events in missing energy/momentum search

Missing energy search, e.g., NA64:



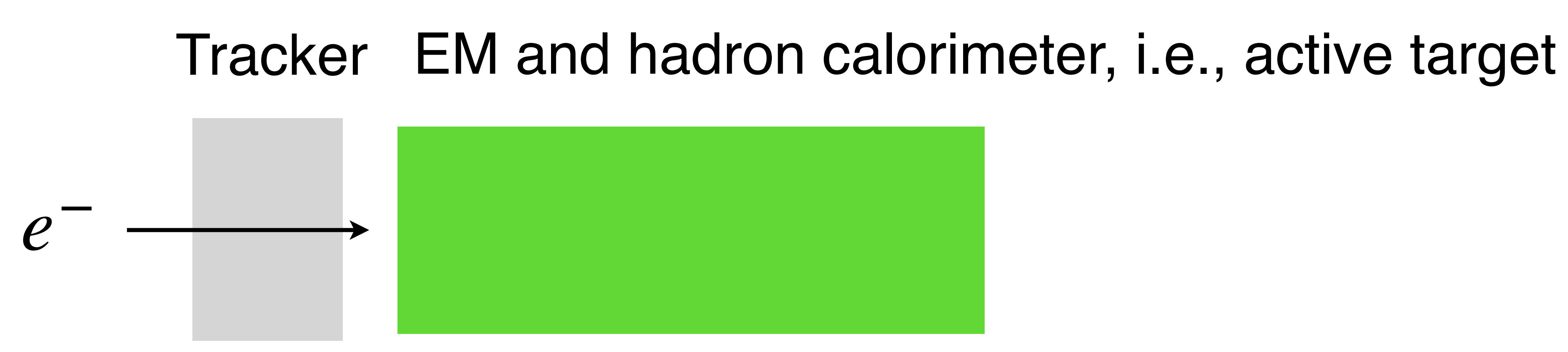
Missing momentum search, e.g., LDMX:

- Potential BG events:

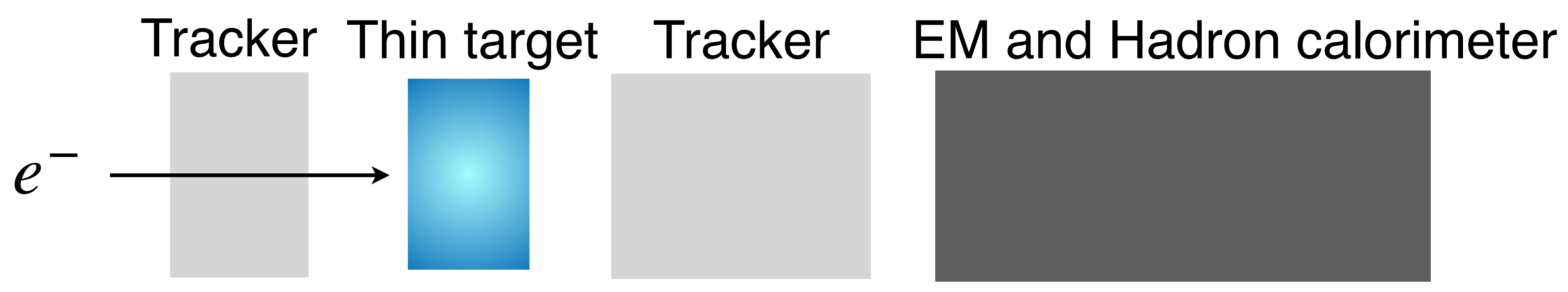
  \- Mistakenly tagged initial beam, e.g., incident lower energy beam ⇒ Reducible by tracker in front of target

Background events in missing energy/momentum search

Missing energy search, e.g., NA64:



Missing momentum search, e.g., LDMX:



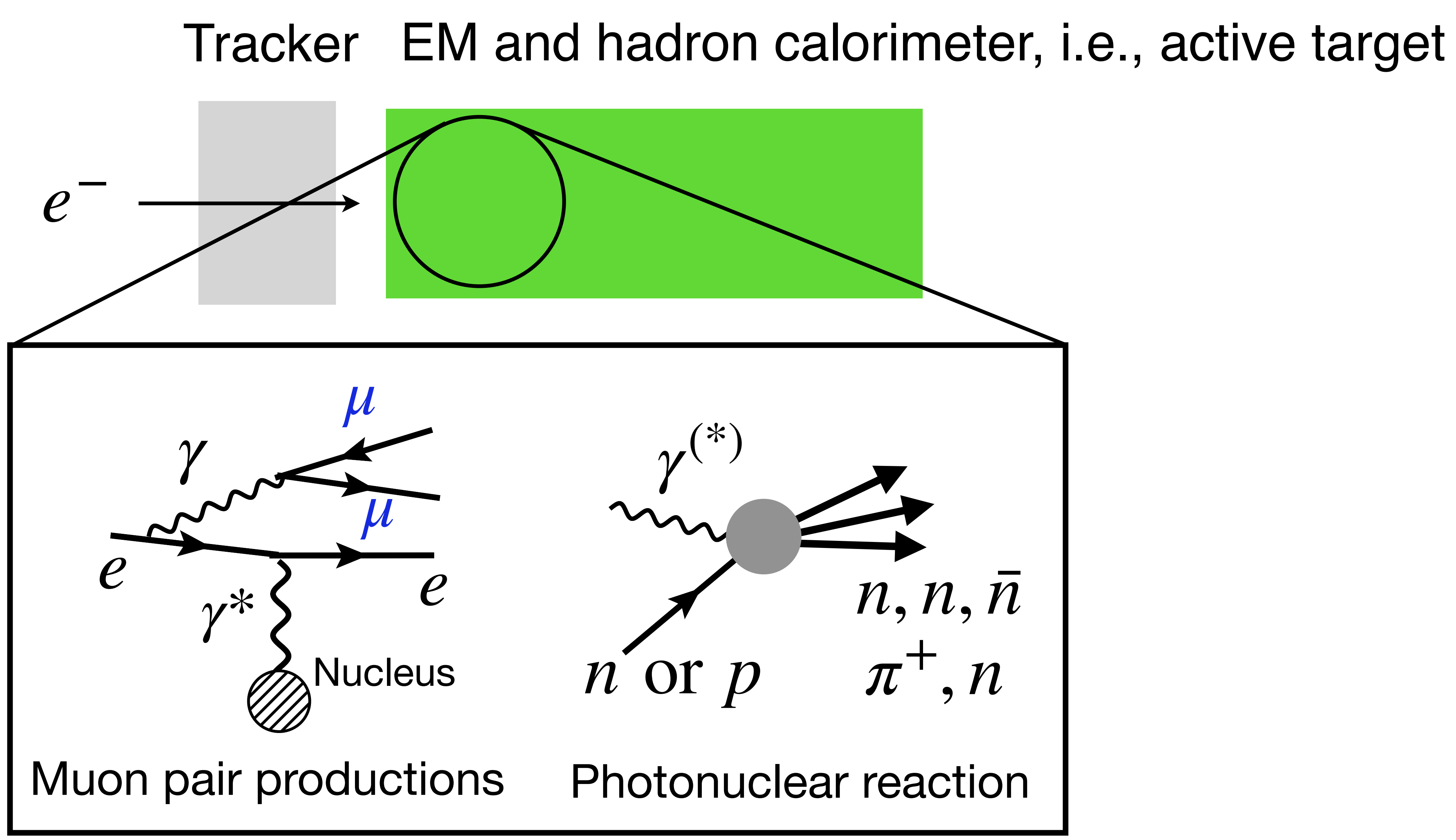
- Potential BG events:

  - Mistakenly tagged initial beam, e.g., incident lower energy beam ⇒ Reducible by tracker in front of target

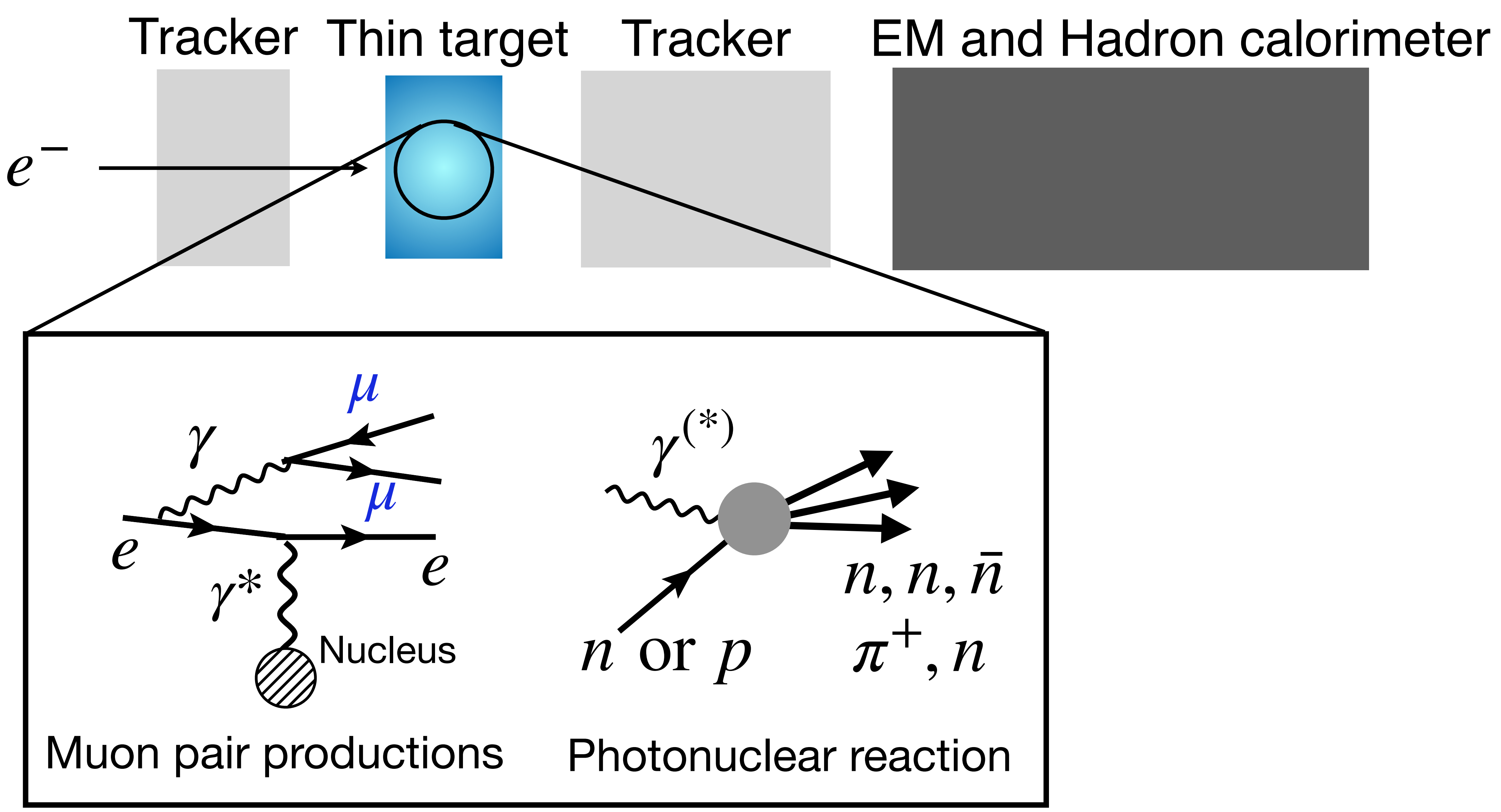
  - Photo-nuclear reaction and muon production

Background events in missing energy/momentum search

Missing energy search, e.g., NA64:



Missing momentum search, e.g., LDMX:



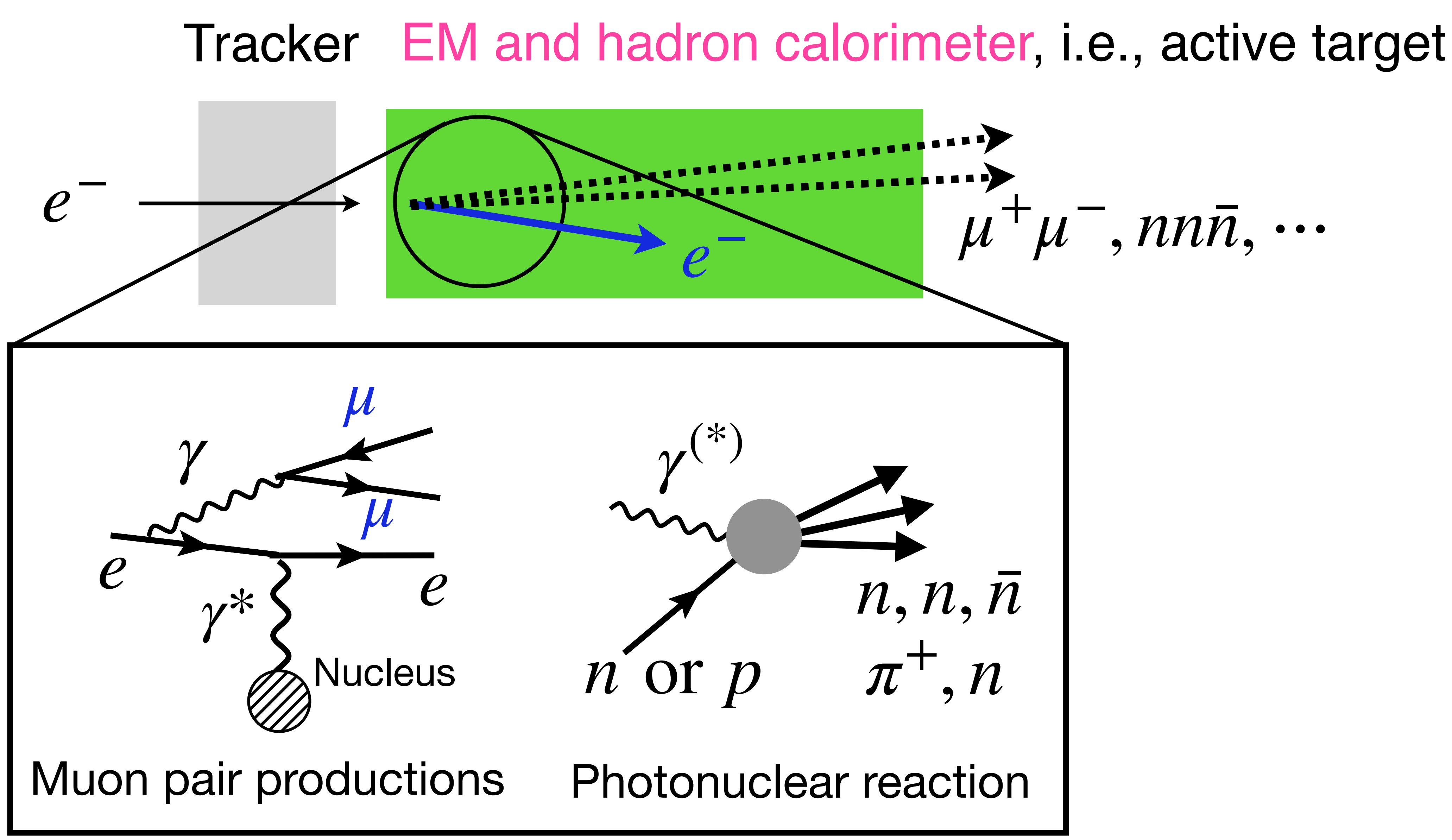
- Potential BG events:

  - Mistakenly tagged initial beam, e.g., incident lower energy beam ⇒ Reducible by tracker in front of target

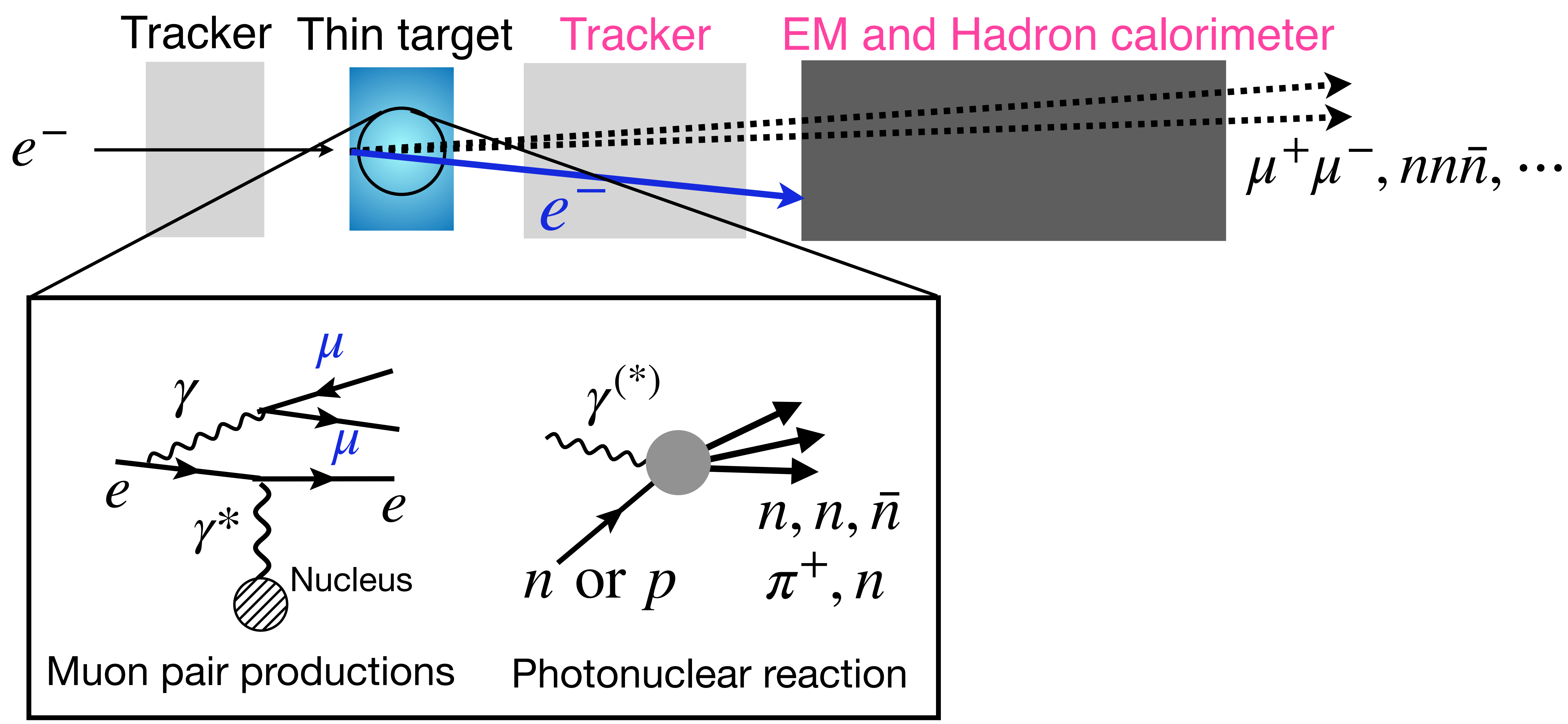
  - Photo-nuclear reaction and muon production

Background events in missing energy/momentum search

Missing energy search, e.g., NA64:



Missing momentum search, e.g., LDMX:



- Potential BG events:

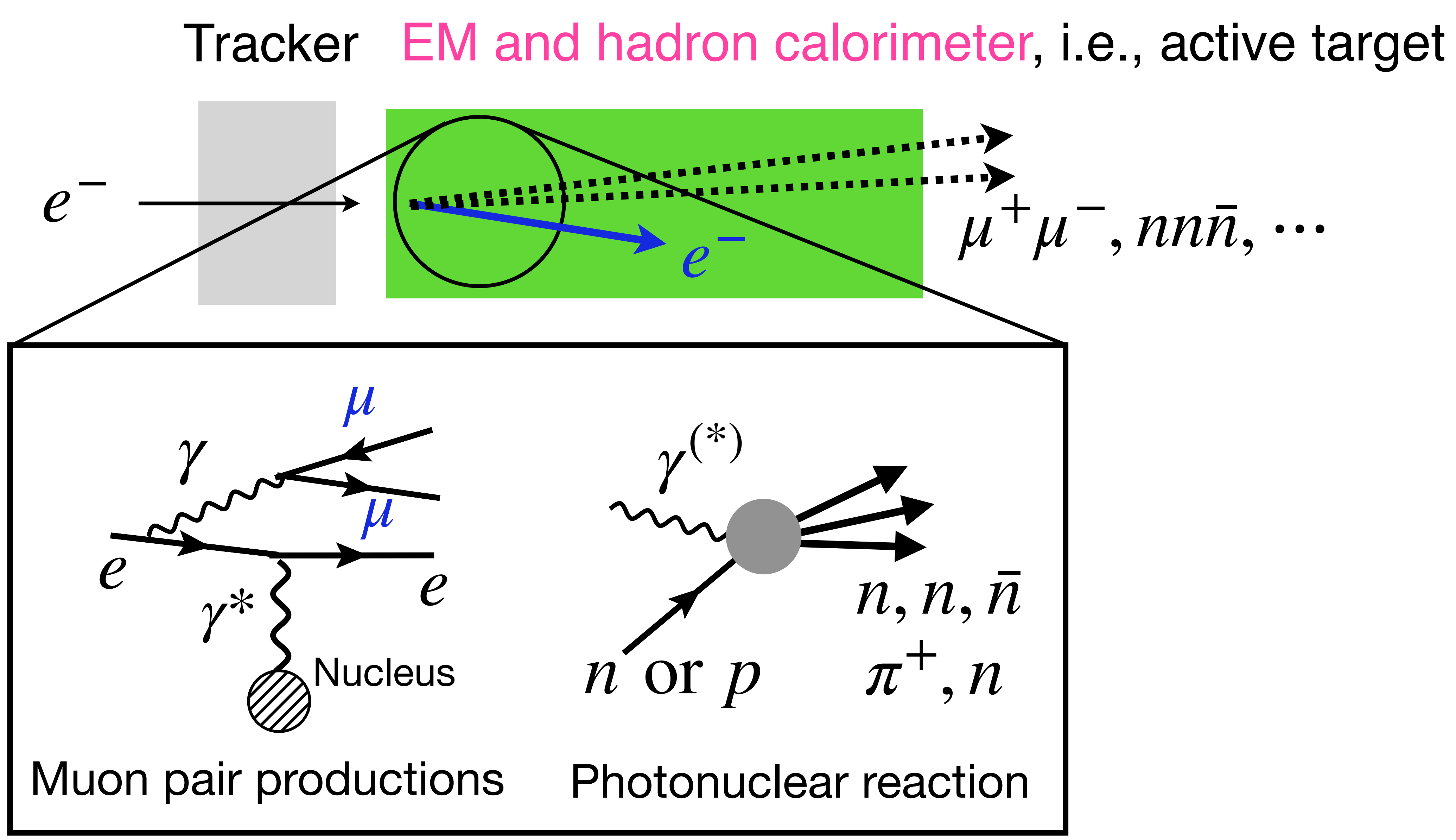
  - Mistakenly tagged initial beam, e.g., incident lower energy beam ⇒ Reducible by tracker in front of target

  - Photo-nuclear reaction and muon production

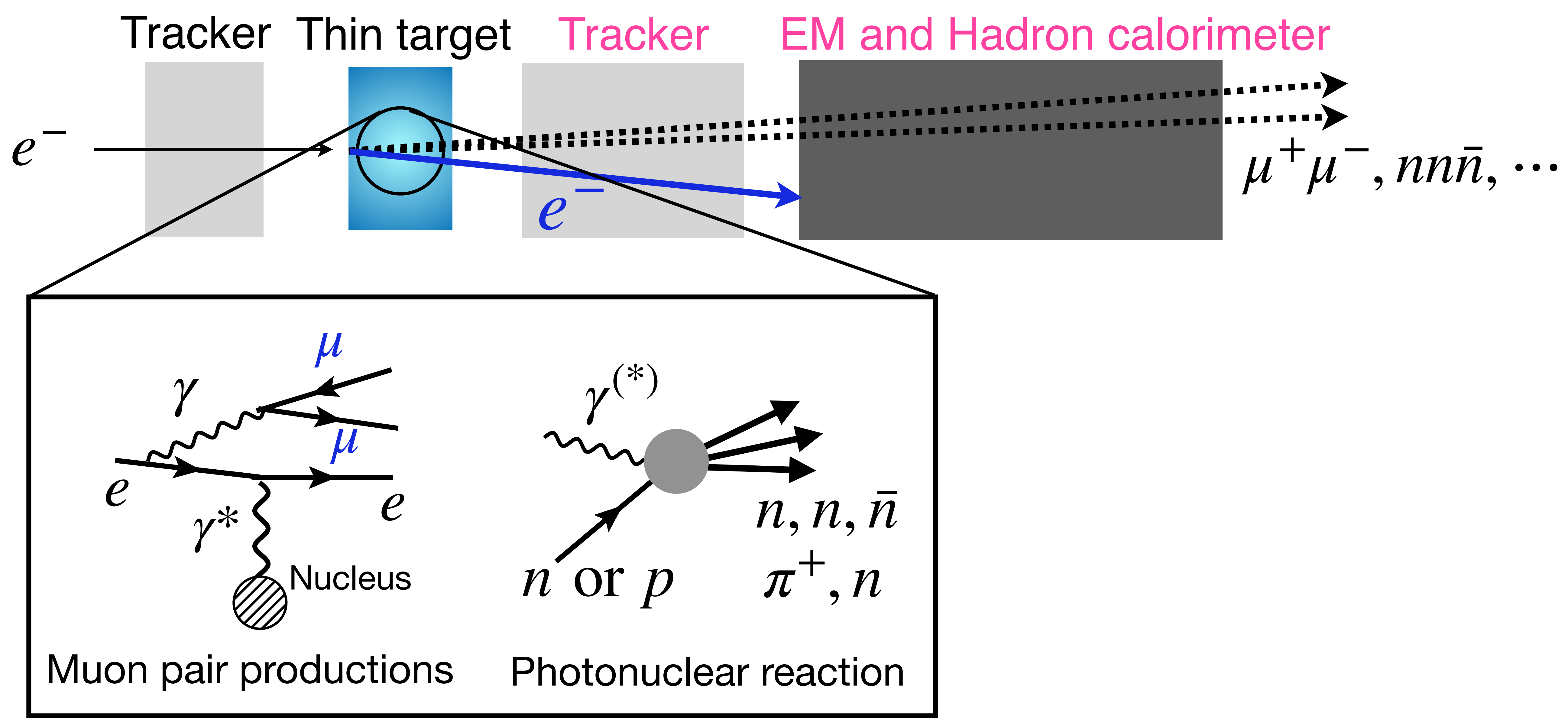
※ Here, single electron events are assumed to be selected as signal events to remove BG events

Background events in missing energy/momentum search

Missing energy search, e.g., NA64:



Missing momentum search, e.g., LDMX:



- Potential BG events:

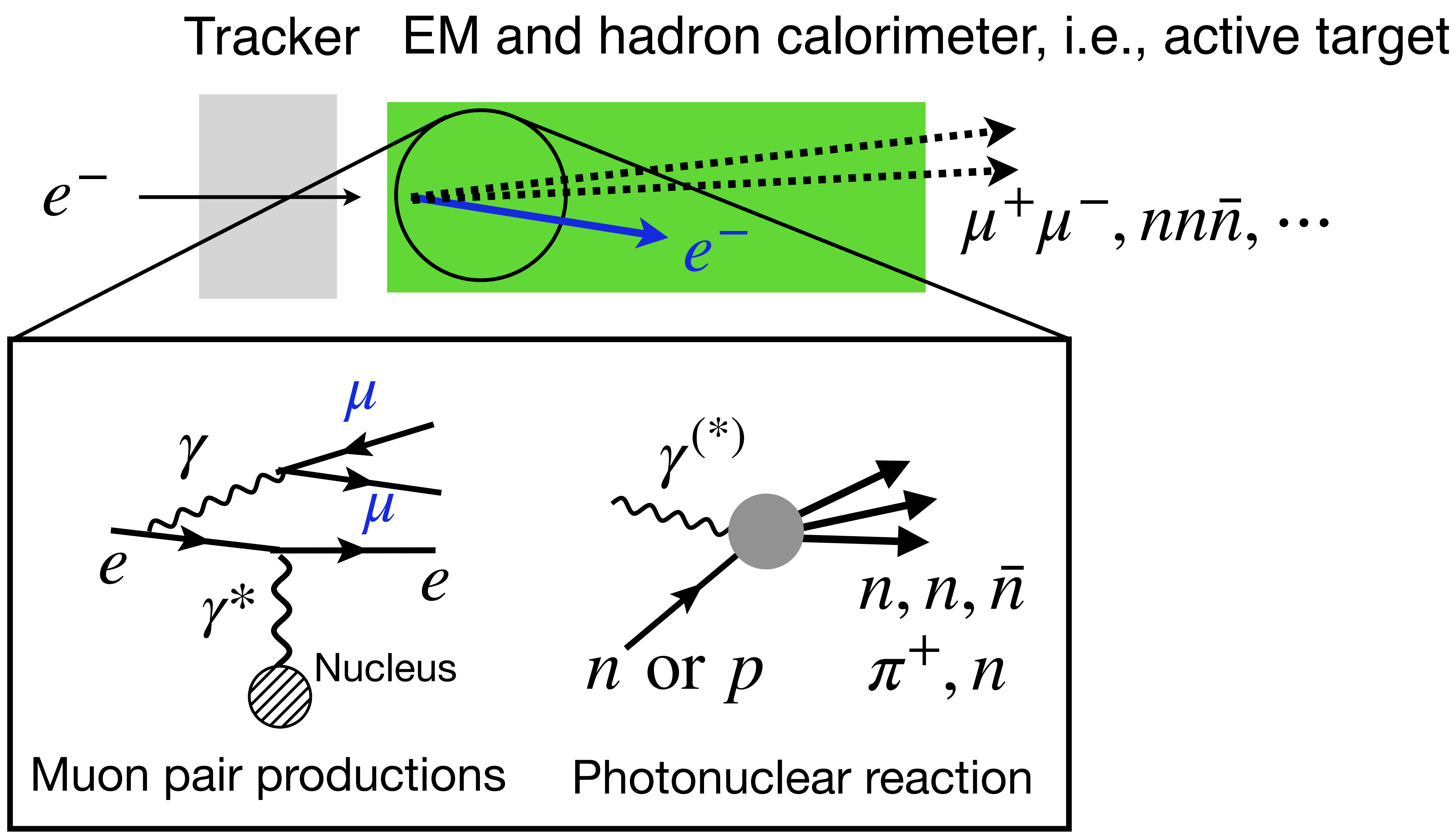
  - Mistakenly tagged initial beam, e.g., incident lower energy beam ⇒ Reducible by tracker in front of target

  - Photo-nuclear reaction and muon production ⇒ Reducible by calorimeter and tracker behind target

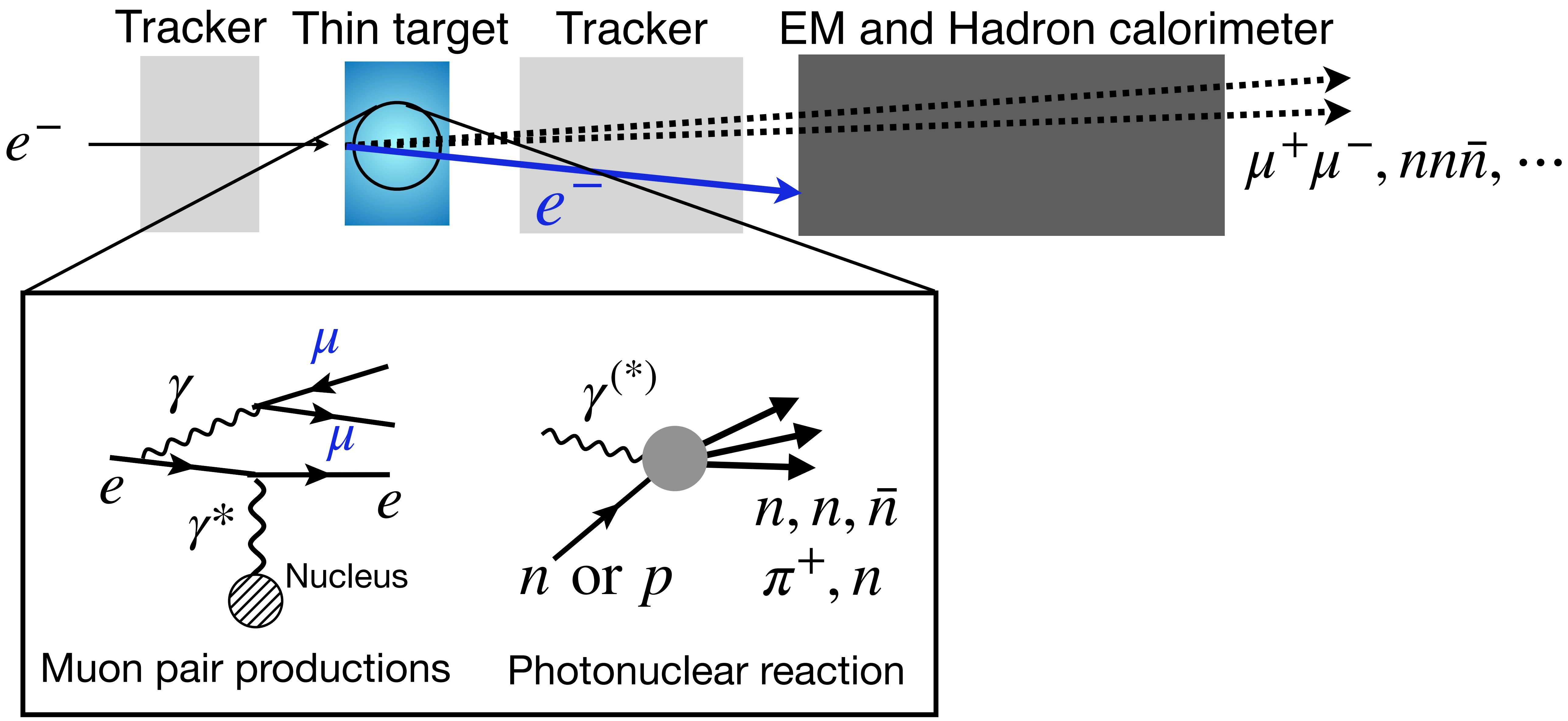
※ Here, single electron events are assumed to be selected as signal events to remove BG events

Background events in missing energy/momentum search

Missing energy search, e.g., NA64:



Missing momentum search, e.g., LDMX:



- Potential BG events:

  - Mistakenly tagged initial beam, e.g., incident lower energy beam ⇒ Reducible by tracker in front of target

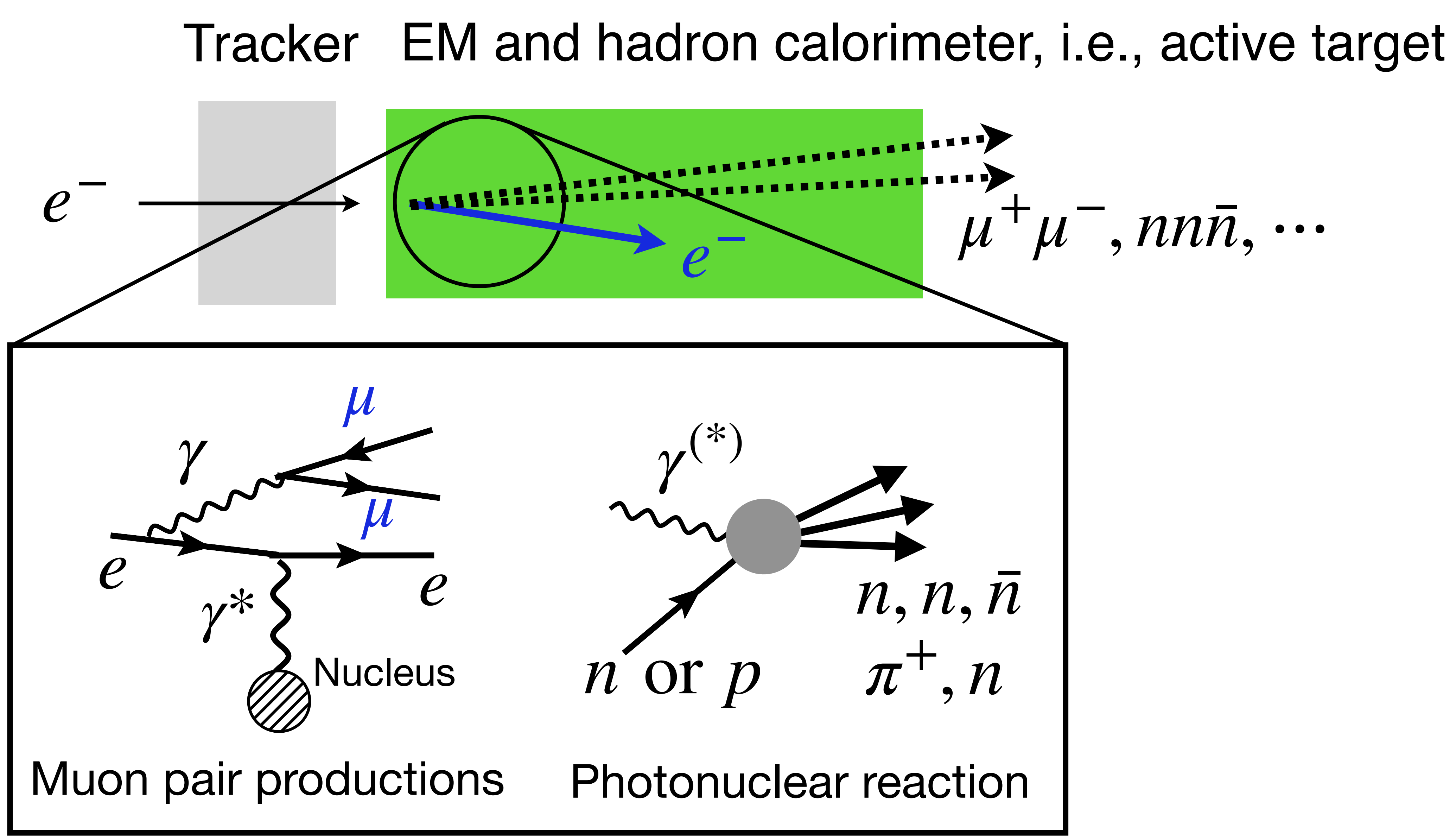
  - Photo-nuclear reaction and muon production ⇒ Reducible by calorimeter and tracker behind target

  - Neutrino background, e.g., neutrino trident process($eN \to e\nu\bar{\nu}N$)

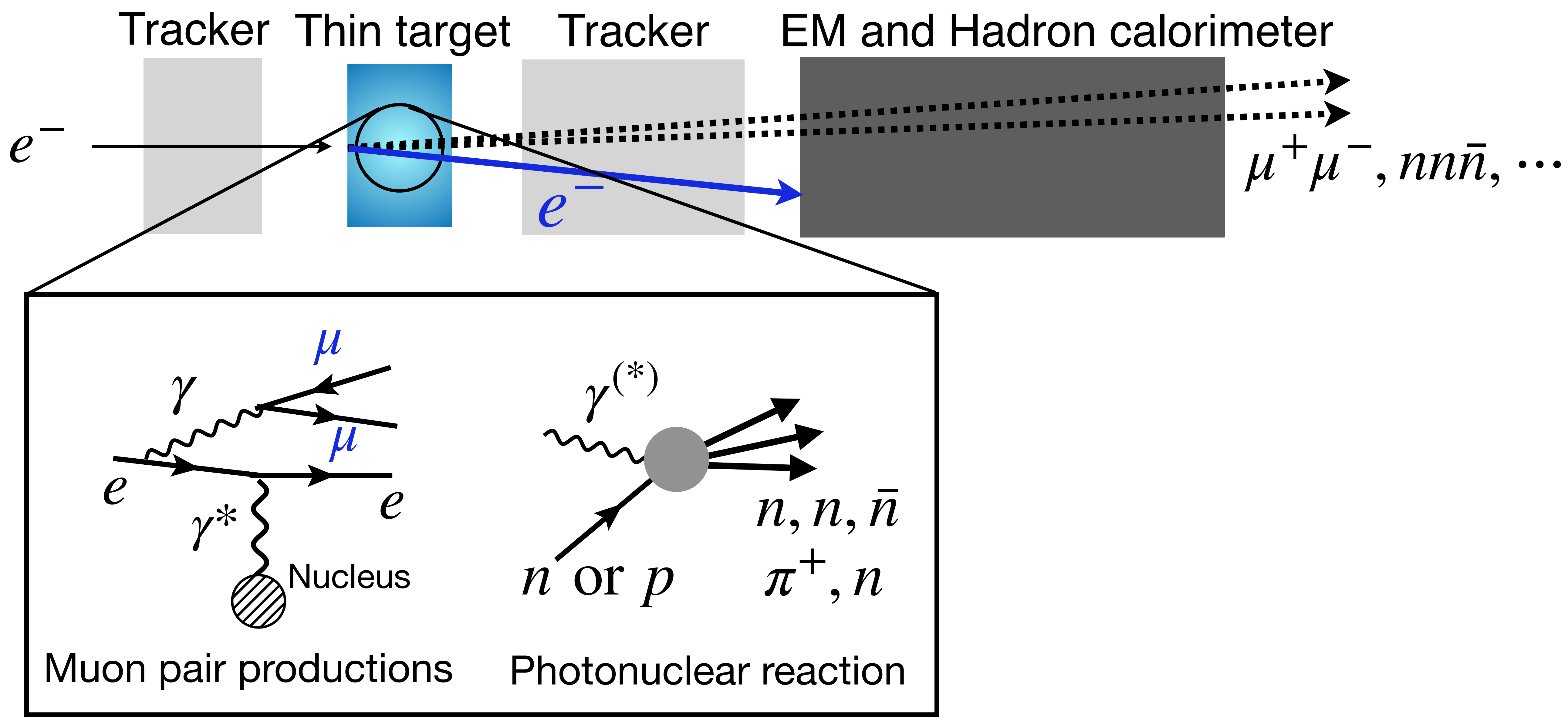
※ Here, single electron events are assumed to be selected as signal events to remove BG events

Background events in missing energy/momentum search

Missing energy search, e.g., NA64:



Missing momentum search, e.g., LDMX:

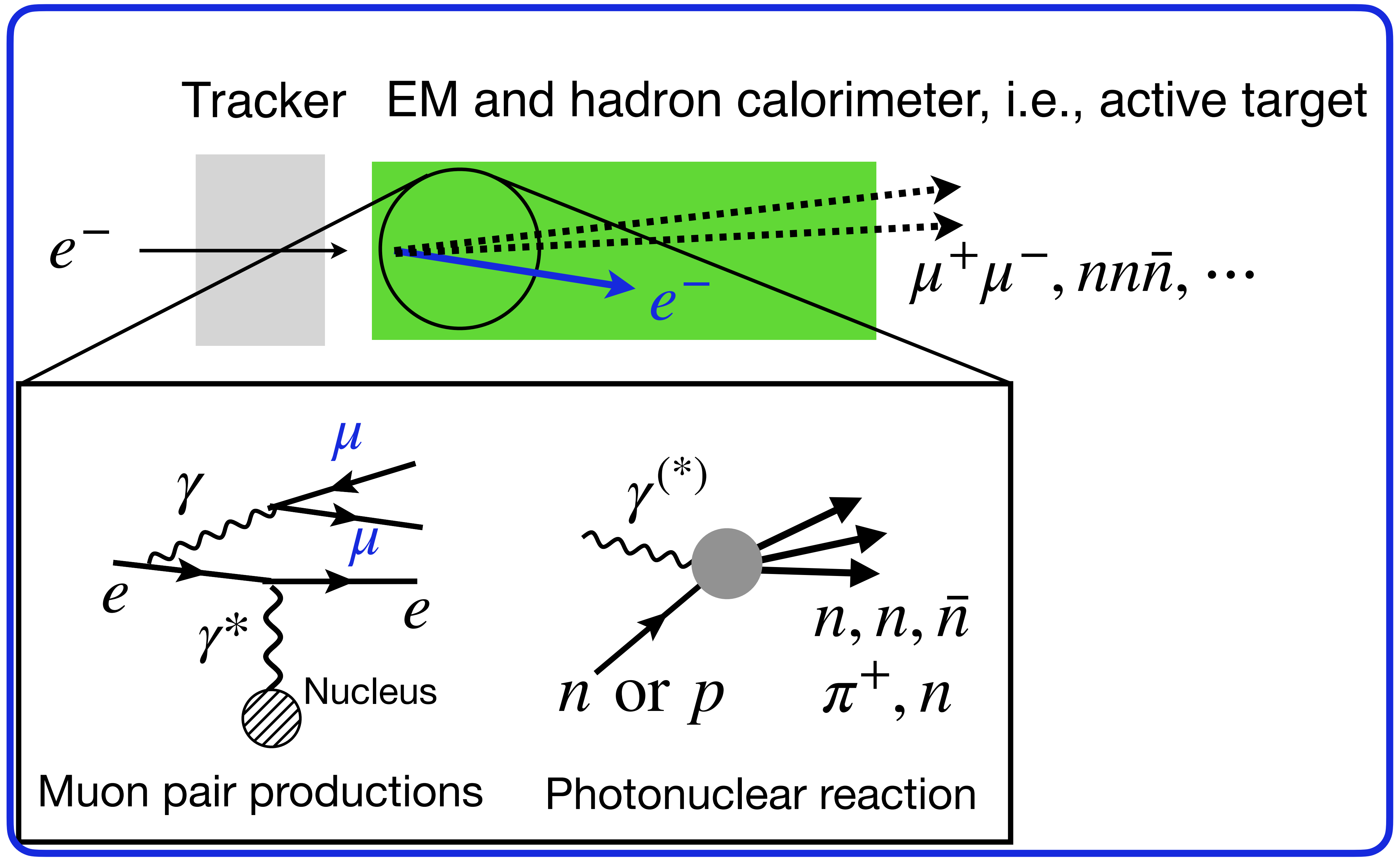


- Potential BG events:
  - Mistakenly tagged initial beam, e.g., incident lower energy beam ⇒ Reducible by tracker in front of target
  - Photo-nuclear reaction and muon production ⇒ Reducible by calorimeter and tracker behind target
  - Neutrino background, e.g., neutrino trident process($eN \to e\nu\bar{\nu}N$) ⇒ Irreducible but it's negligible

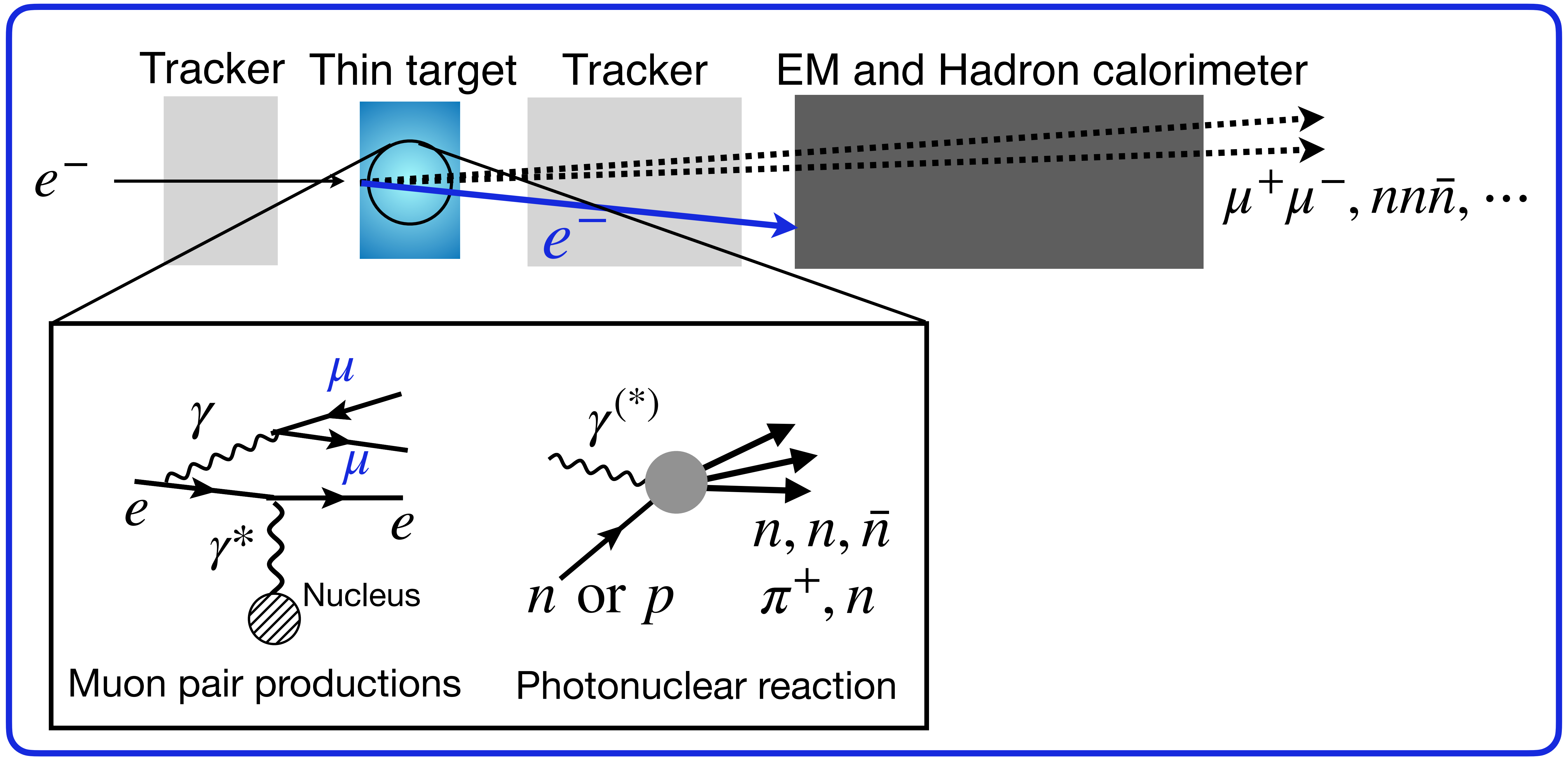
※ Here, single electron events are assumed to be selected as signal events to remove BG events

Background events in missing energy/momentum search

Missing energy search, e.g., NA64:



Missing momentum search, e.g., LDMX:



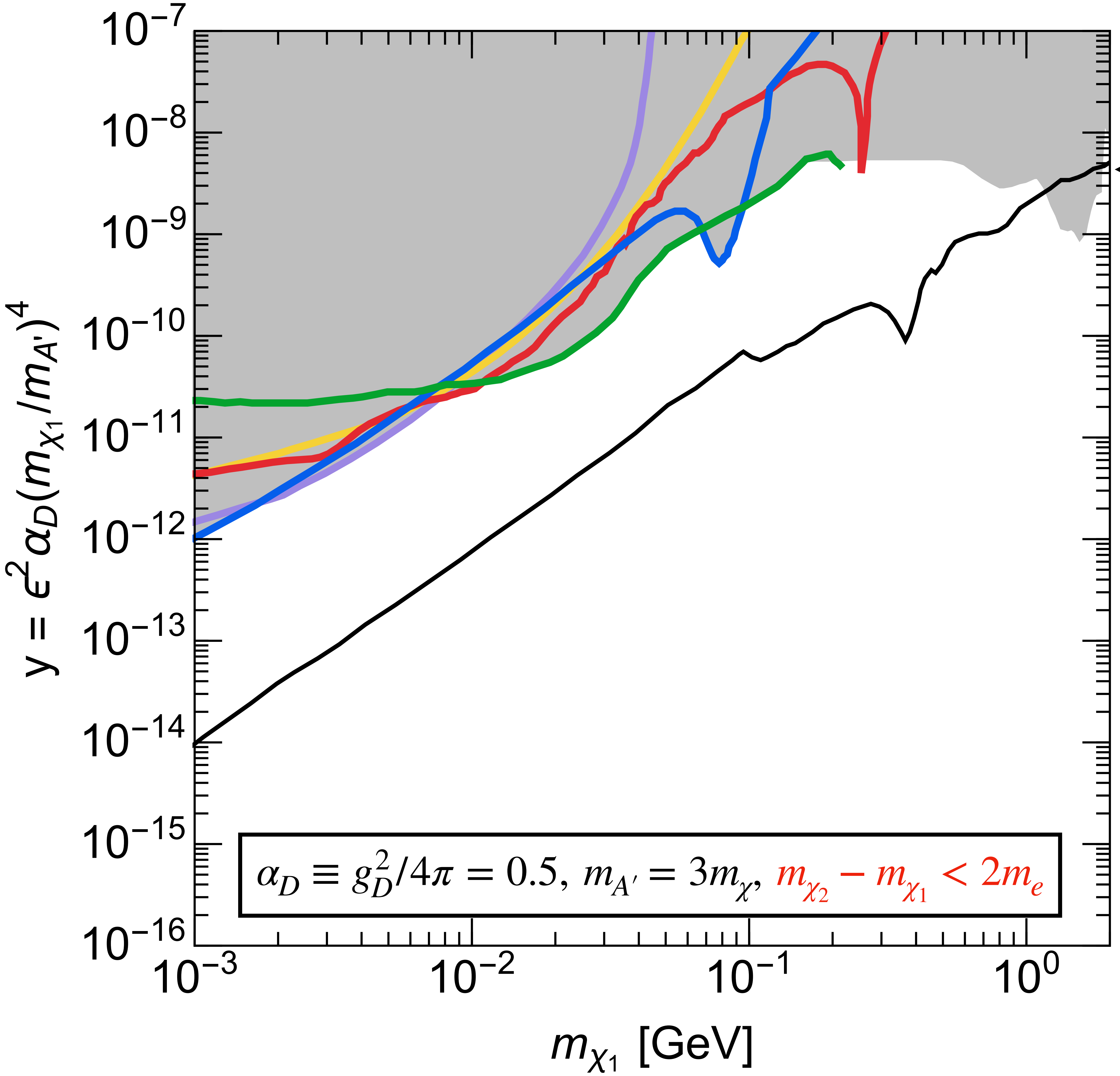
- Potential BG events:
  - Mistakenly tagged initial beam, e.g., incident lower energy beam ⇒ Reducible by tracker in front of target
  - Photo-nuclear reaction and muon production ⇒ Reducible by calorimeter and tracker behind target
  - Neutrino background, e.g., neutrino trident process($eN \to e\nu\bar{\nu}N$) ⇒ Irreducible but it's negligible

Less than one predicted BG event in both NA64 and LDMX

※ Here, single electron events are assumed to be selected as signal events to remove BG events

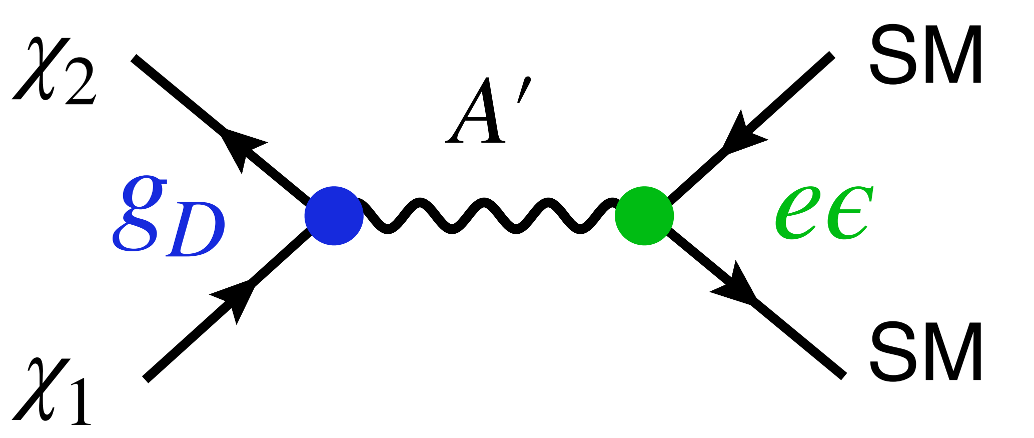
Excluded regions by beam dump experiments

- Benchmark model: $\mathscr{L} \supset \epsilon \cdot eA'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2\gamma^\mu\chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM



Pseudo-Dirac DM saturates observed DM abundance

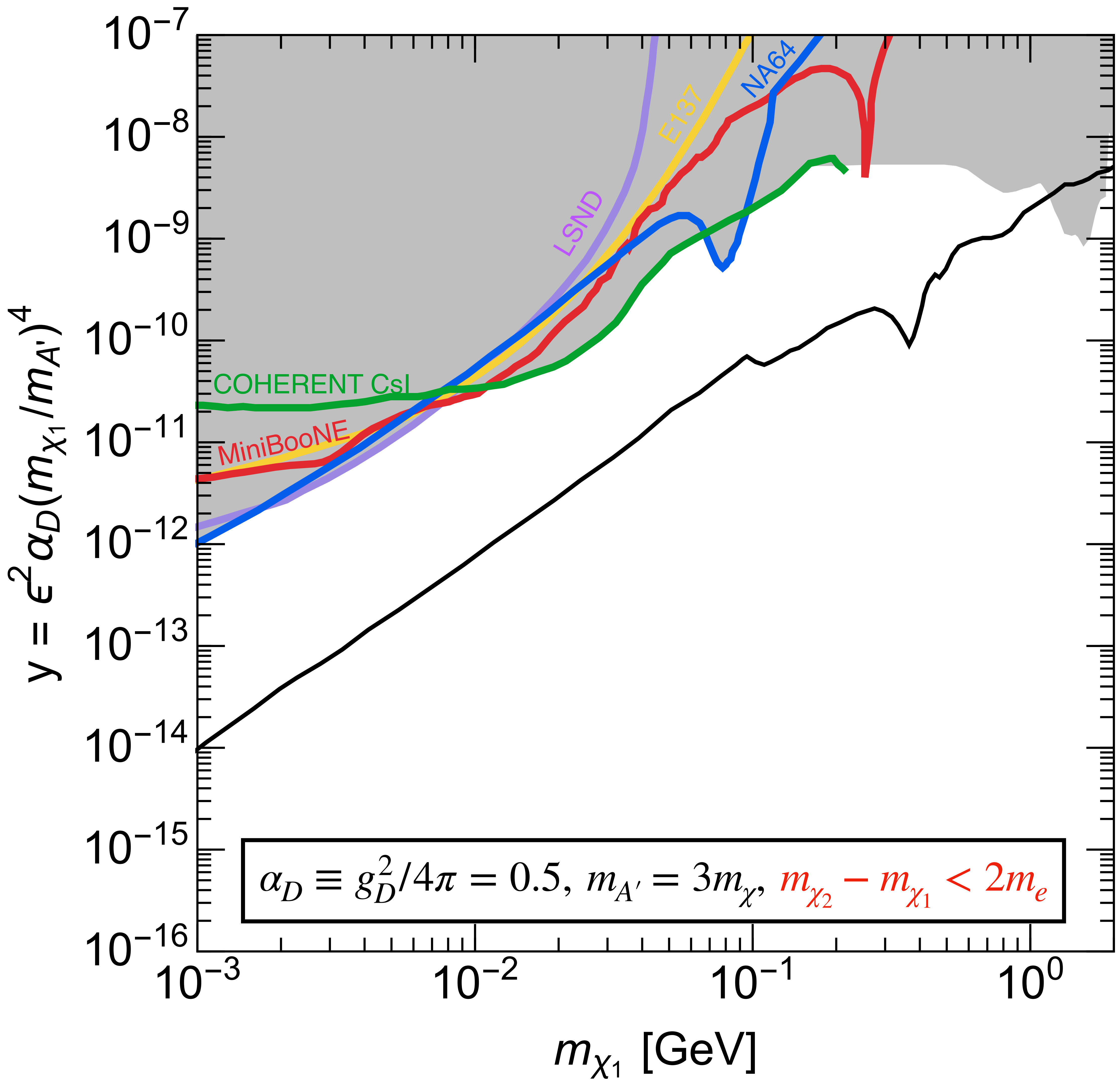
DM annihilation cross section



$$\langle\sigma v\rangle_{\rm ann} \propto y/m_{\chi_1}^2 \text{ with } y \equiv \epsilon^2\alpha_D\left(m_{\chi_1}/m_{A'}\right)^4$$

Excluded regions by beam dump experiments

- Benchmark model: $\mathscr{L} \supset \epsilon \cdot eA'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM



Rescattering	Missing signal
E137	NA64
LSND MiniBooNE COHERENT CsI	※ Limited missing signal experiments are conducted because of the severe beam condition

Electron beam: E137, NA64

Proton beam: LSND, MiniBooNE, COHERENT CsI

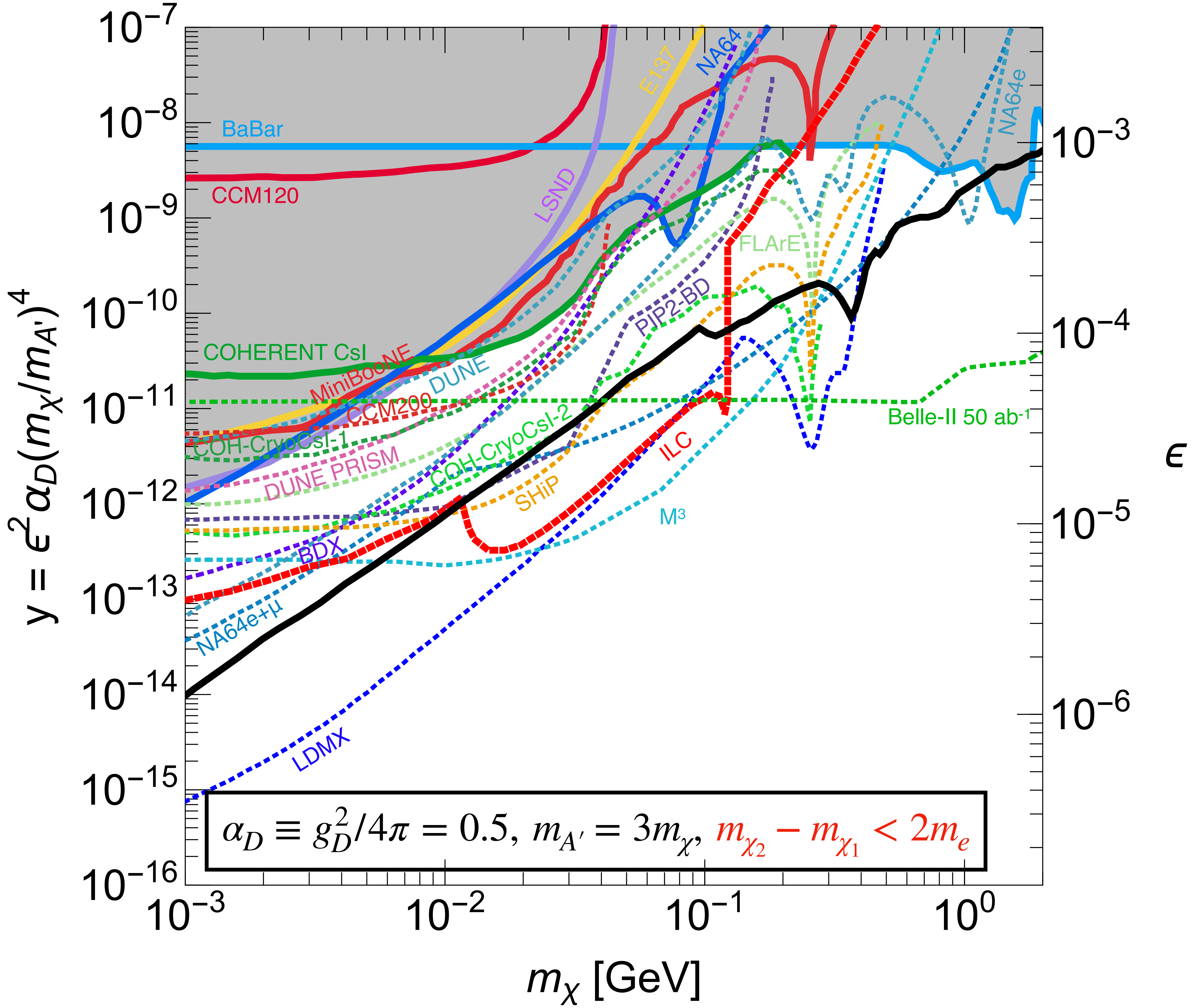
⇒ parasitic running of neutrino experiment

※ MiniBooNE is off-target running to reduce neutrino BG

※ Boosted DM productions in the beam dump are unaffected much by the spin of the DM or the Lorentz structure of its interactions

Sensitivity of future beam dump experiments

- Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM



Rescattering	Missing signal	
BDX, ILC-BDX	LDMX, NA64e	Electron beam
	M3, NA64μ	Muon beam
COH-CryoCsI-1,2, PIP2-BD, DUNE, DUNE-PRISM, CCM200, SHiP	etc	Proton beam

PIP2-BD, DUNE, DUNE-PRISM ← leverage DUNE facilities

- LDMX is highly sensitive because of good acceptance
- LDMX and CCM have been funded
- COH-CryoCsI-1,2 is an improved COHERENT
- NA64e is an improved NA64

※ Boosted DM productions in the beam dump are unaffected much by the spin of the DM or the Lorentz structure of its interactions

Summary

・The beam dump(fixed target) experiment is high luminosity experiment sensitive to Sub-GeV scale

・Several factors determine the sensitivity of the beam dump experiment (fixed target), e.g.,

beam flux, beam energy, beam particle, acceptance, detection approach,…

・There are many experiments, but these are not simply competitions to achieve the same physics

Ex. - Proton beam dump experiments are suited to leptophobic NP search

- Muon beam dump experiments are suited to muon-philic NP search

- LDMX is highly sensitive to the DM production process, but it is not sensitive to the DM detection process in contrast to recoil and visible decay searches.

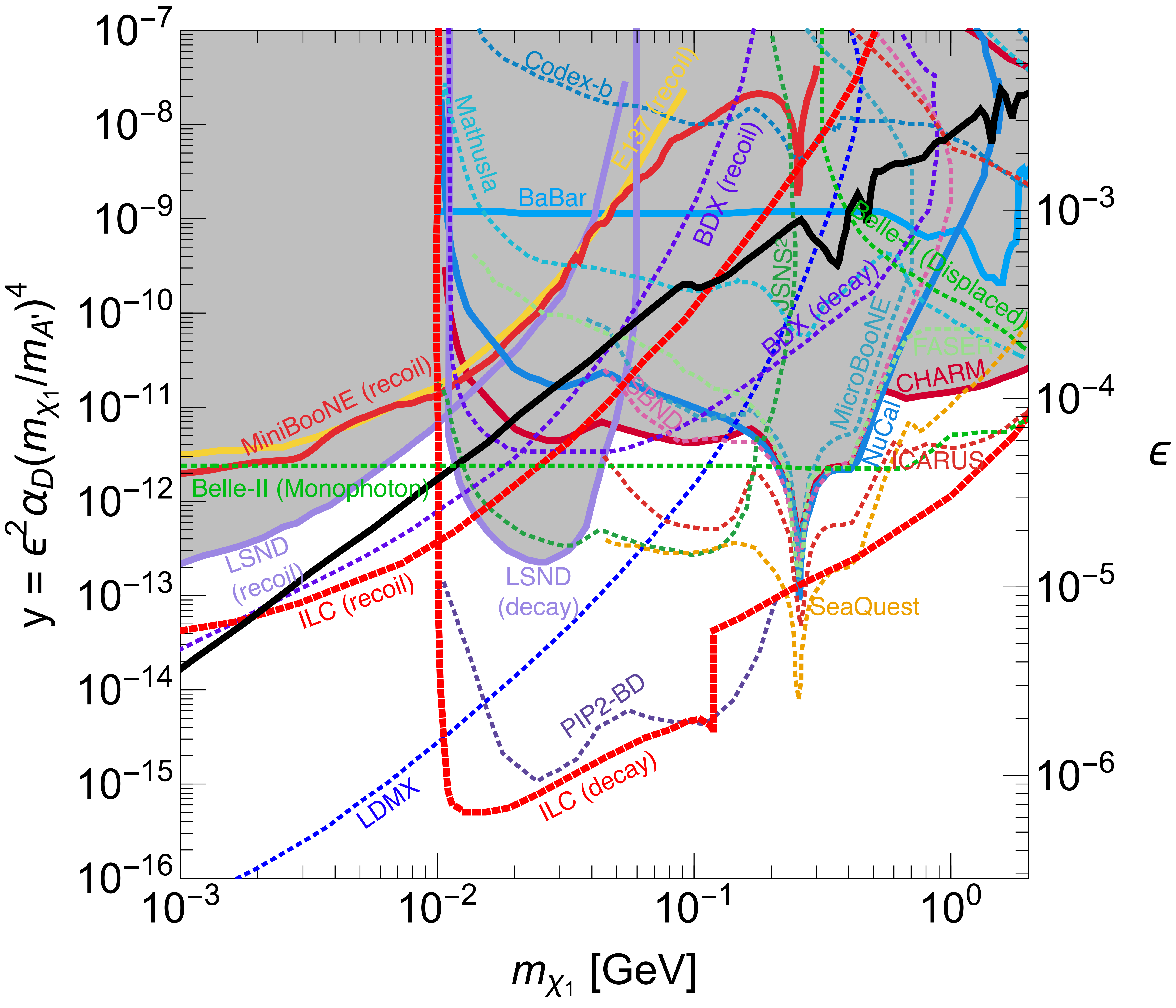
※ LDMX is missing momentum search

⇒ If a positive DM signal is observed, model distinction would be possible

・The beam dump(fixed target) experiment may play a significant role in searching for Sub-GeV DM models involving recoil, visible decay, and missing signatures

Sensitivity of beam dump experiments

- Benchmark model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$ A': Dark photon, $\chi_{1,2}$: Pseudo-Dirac DM

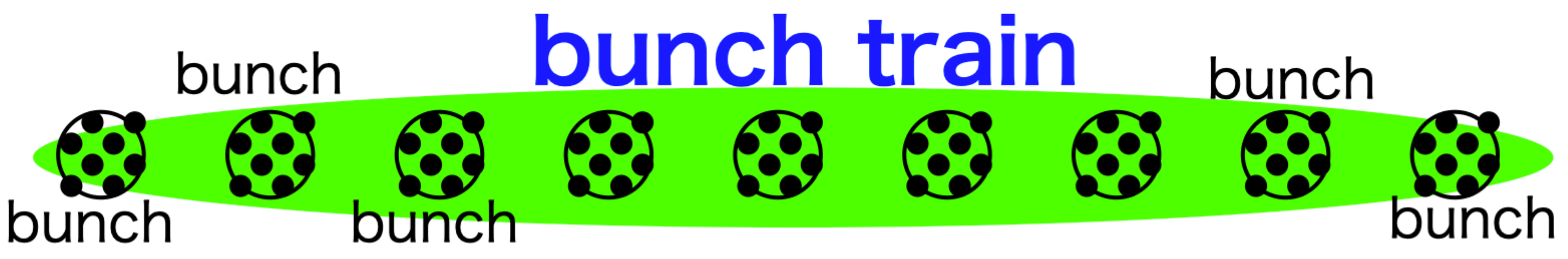


$\alpha_D \equiv g_D^2/4\pi = 0.1,\ m_{A'} = 3m_\chi,\ m_{\chi_2} - m_{\chi_1} = 0.1 m_{\chi_1}$

Visible decay
CHARM
LSND
NuCal
BDX
ILC-BDX
PIP2-BD
SeaQuest
SBND
JSNS²

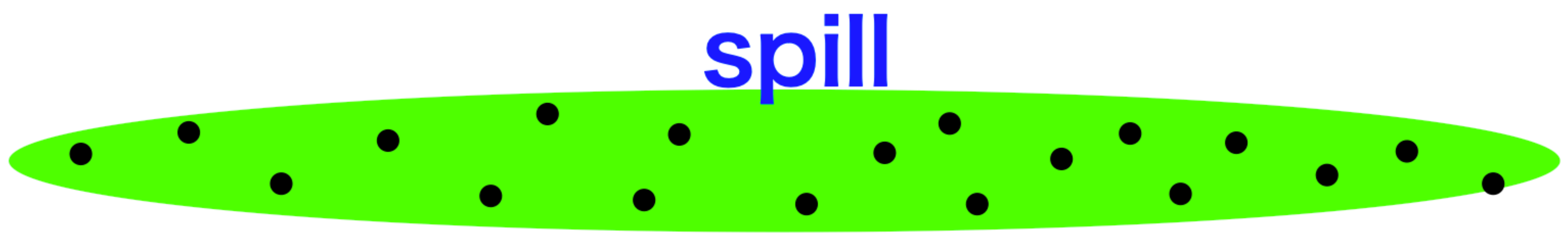
Continuous beam

- The continuous beam doesn't have beam bunches, which makes the trigger easier



Continuous beam

i.e., no bunch



e.g. NA64

Continuous beam with high flux is needed for the missing signature search

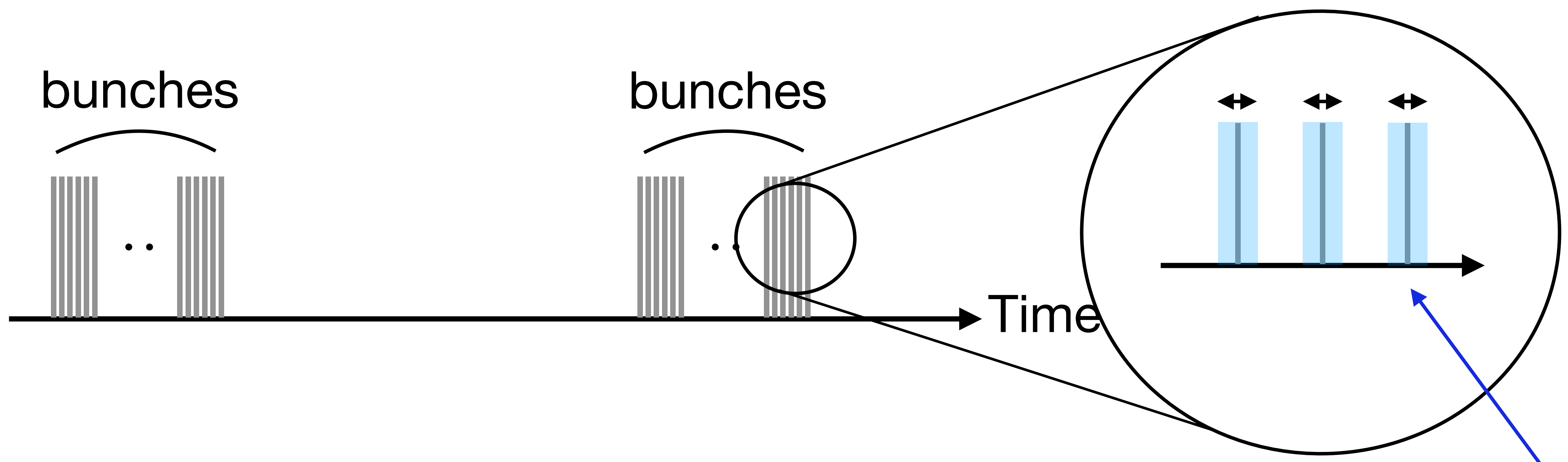
※ The missing signature search experiments are not conducted much because of this severe beam condition.

Beam unrelated background

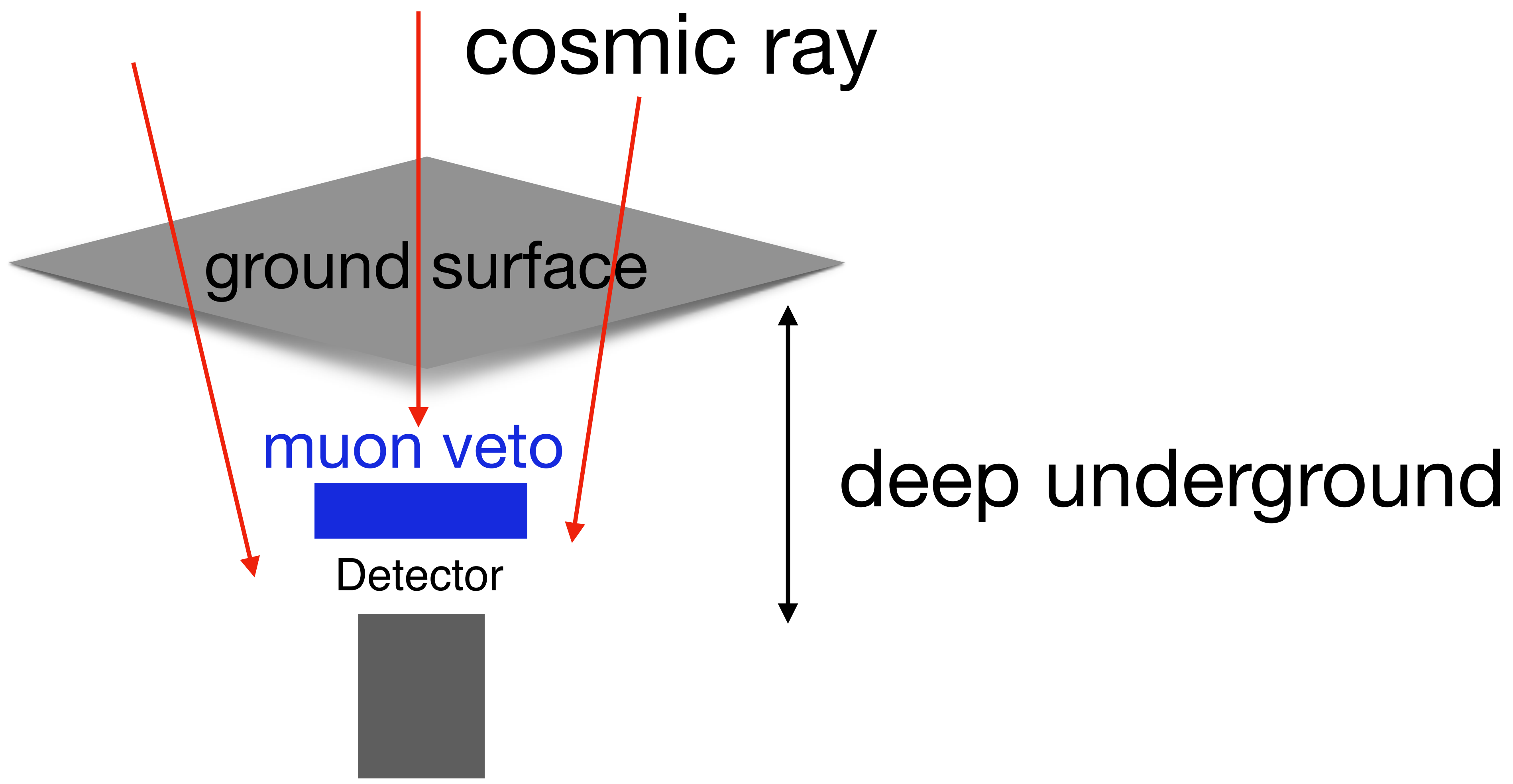
- Beam-unrelated background: cosmic muons

  - deep underground location of detector

  - time window based on pulsed beam



Signal event arises from this **time window**



  - directionality of signal events

  - muon veto

Beam-unrelated background events are reducible

Pseudo-Dirac DM mass eigenstates

$$-\mathscr{L} \supset m_D \eta\xi + \frac{1}{2} m_M(\eta^2 + \xi^2) + \mathrm{h.c.}$$

$$\psi = (\eta, \xi^c)^T,\ \xi^c = i\sigma^2 \xi *$$

$$= m_D (\xi^c)^\dagger \eta + \frac{m_M}{2}\left((\eta^c)^\dagger \eta + (\xi^c)^\dagger (\xi)\right) + \mathrm{h.c.}$$

$$\eta = \frac{1}{\sqrt{2}}(\chi_2 - i\chi_1), \quad \xi = i\frac{1}{\sqrt{2}}(\chi_1 - i\chi_2)$$

$$= \frac{1}{2}(m_D - m_M)(\chi_1^c)^\dagger \chi_1 + \frac{1}{2}(m_D + m_M)(\chi_2^c)^\dagger \chi_2 + \mathrm{h.c.}$$

$$(\chi_1^c)^\dagger \chi_2 = (\chi_2^c)^\dagger \chi_1$$

Pseudo-Dirac DM kinetic term

$$\mathscr{L} = \bar{\psi} i\gamma^\mu D_\mu \psi = i\left(\psi_L^\dagger \bar{\sigma}^\mu D_\mu \psi_L + \psi_R^\dagger \sigma^\mu D_\mu \psi_R\right)$$

$$\supset g_D \cdot \left(\eta^\dagger \bar{\sigma}^\mu A'_\mu \eta + (\xi^c)^\dagger \sigma^\mu A'_\mu \xi^c\right)$$

$$\eta^\dagger \bar{\sigma}^\mu \eta = \frac{1}{2}\left(\chi_2^\dagger \bar{\sigma}^\mu \chi_2 + \chi_1^\dagger \bar{\sigma}^\mu \chi_1 + i\chi_1^\dagger \bar{\sigma}^\mu \chi_2 - i\chi_2^\dagger \bar{\sigma}^\mu \chi_1\right)$$

$$(\xi^c)^\dagger \sigma^\mu \xi^c = \frac{1}{2}\left(-\chi_1^\dagger \bar{\sigma}^\mu \chi_1 + i\chi_1^\dagger \bar{\sigma}^\mu \chi_2 - i\chi_2^\dagger \bar{\sigma}^\mu \chi_1 - \chi_2^\dagger \bar{\sigma}^\mu \chi_2\right)$$

$$= ig_D \cdot A'_\mu \left(\chi_1^\dagger \bar{\sigma}^\mu \chi_2 - \chi_2^\dagger \bar{\sigma}^\mu \chi_1\right)$$

$$= ig_D \cdot A'_\mu \left(\chi_1^\dagger \bar{\sigma}^\mu \chi_2 + (\chi_1^c)^\dagger \sigma^\mu \chi_2^c\right)$$

$$= ig_D \cdot A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2$$

$$\bar{\chi}_1 \equiv \chi_1^\dagger \gamma^0,\ \chi_1 \equiv (\chi_1, \chi_1^c),\ \chi_2 \equiv (\chi_2, \chi_2^c)$$

$$\psi = (\psi_L, \psi_R) = (\eta, \xi^c)^T,\ \xi^c = i\sigma^2 \xi^*$$

$$\bar{\sigma}^\mu = (1, -\vec{\sigma}),\quad \sigma^\mu = (1, \vec{\sigma})$$

$$D_\mu = \partial_\mu - ig_D A'_\mu$$

$$\sigma_2 \sigma^\mu \sigma_2 = (\bar{\sigma}^\mu)^T$$