Physics potential of beam dump experiments at future accelerators

Corfu Workshop on Future Accelerators
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Daiki Ueda (Technion)

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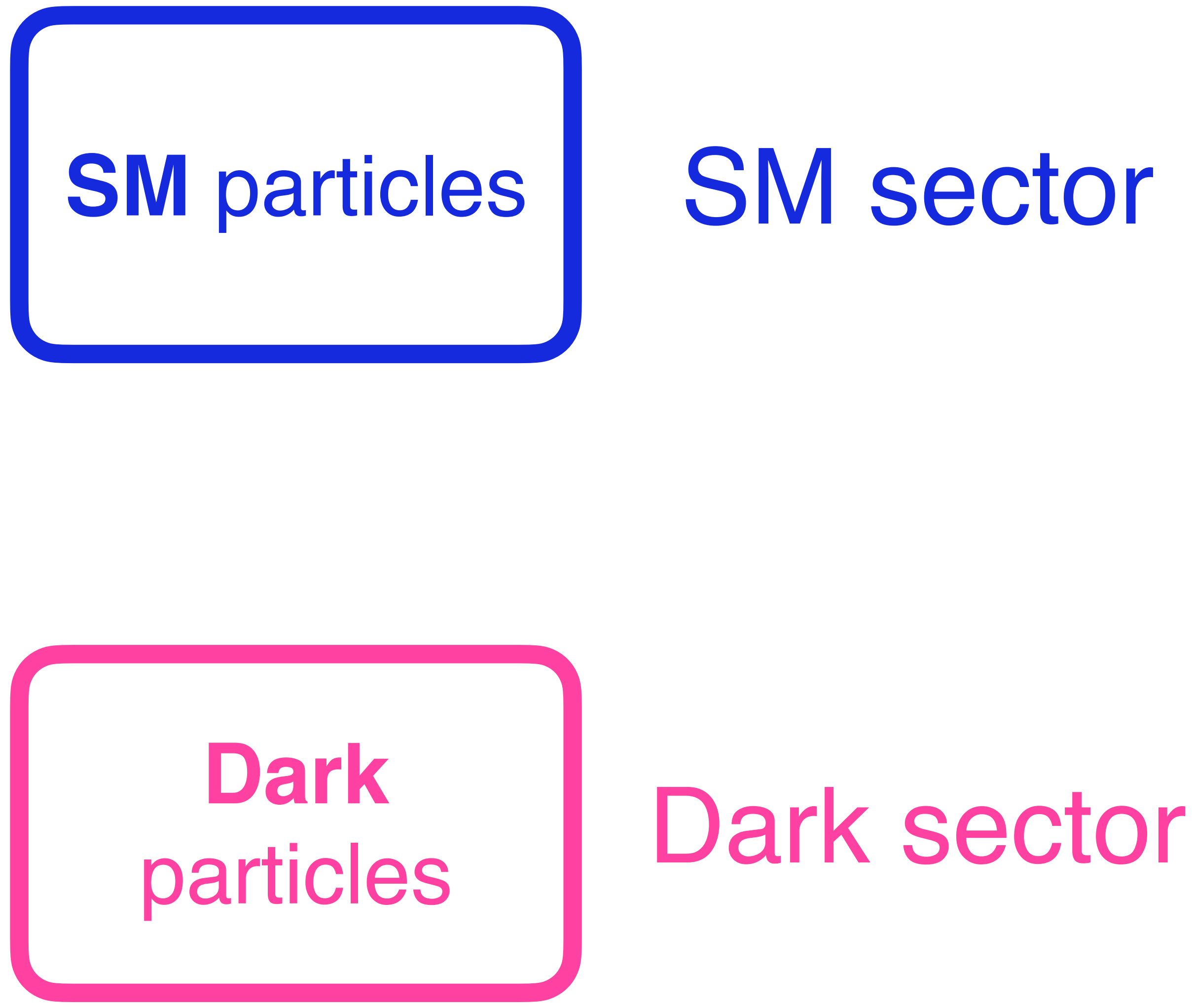

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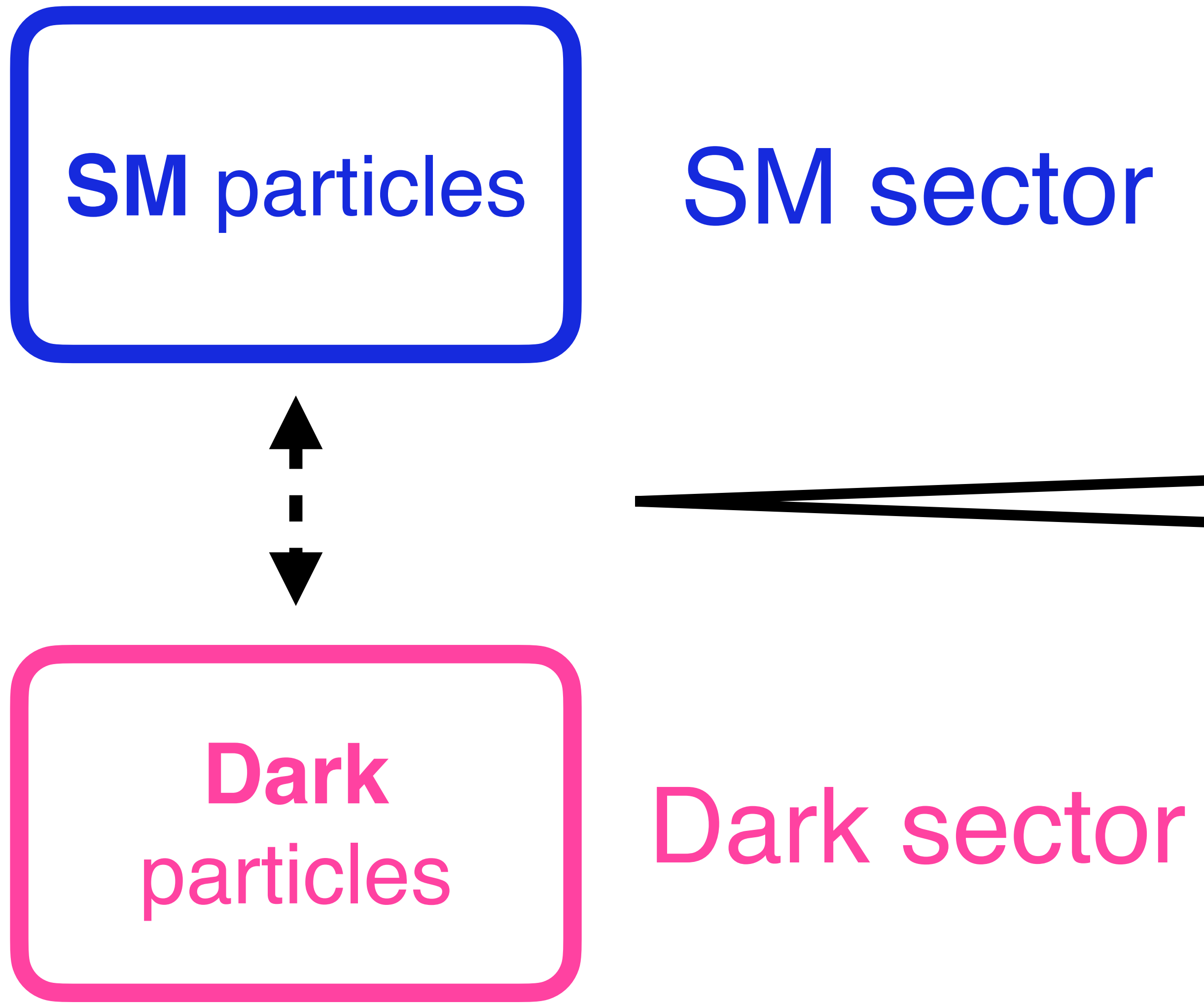

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$$\mathscr{L}^{d=4}_{\text{vector portal}} = -\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'_{\mu\nu}$$

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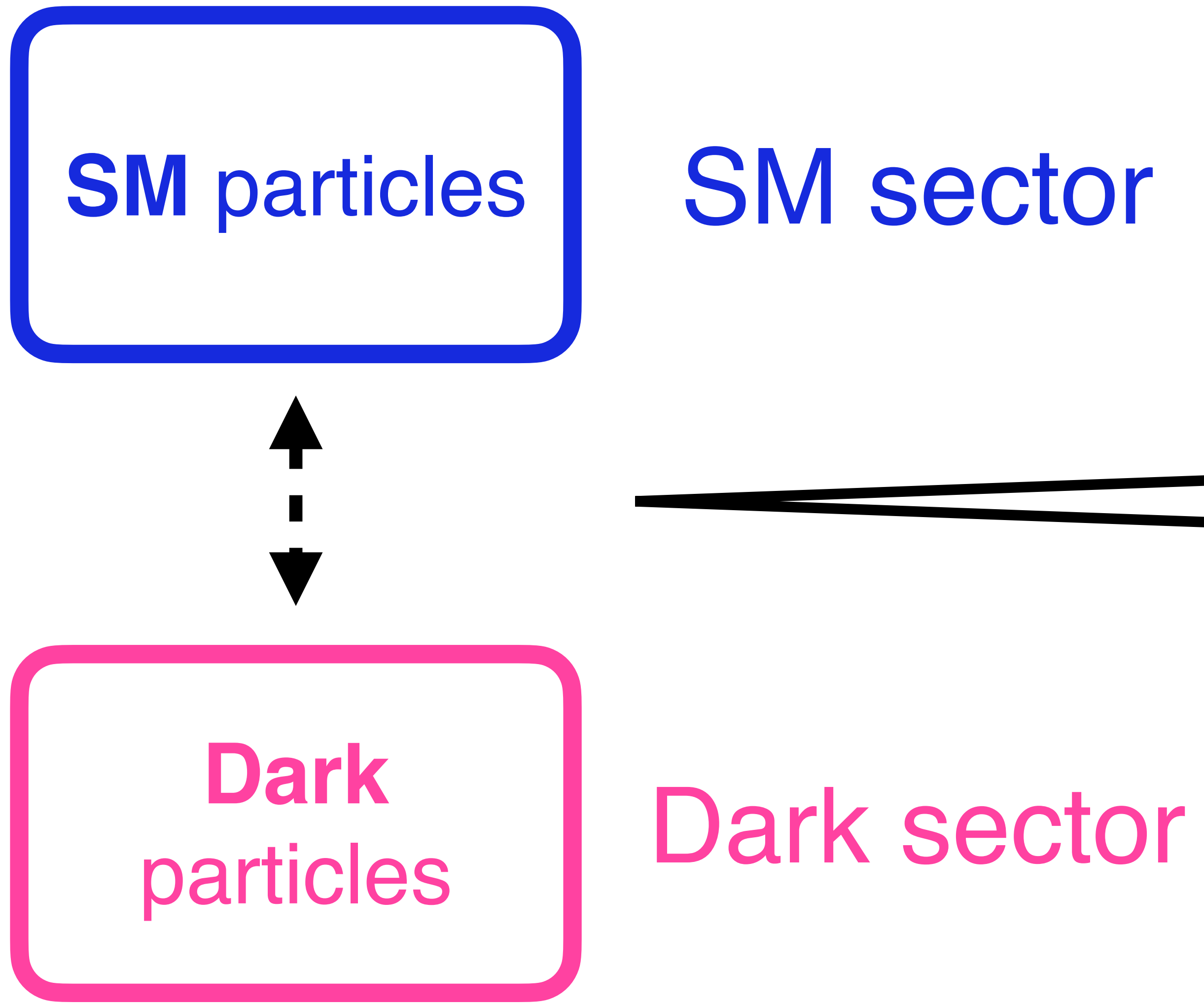

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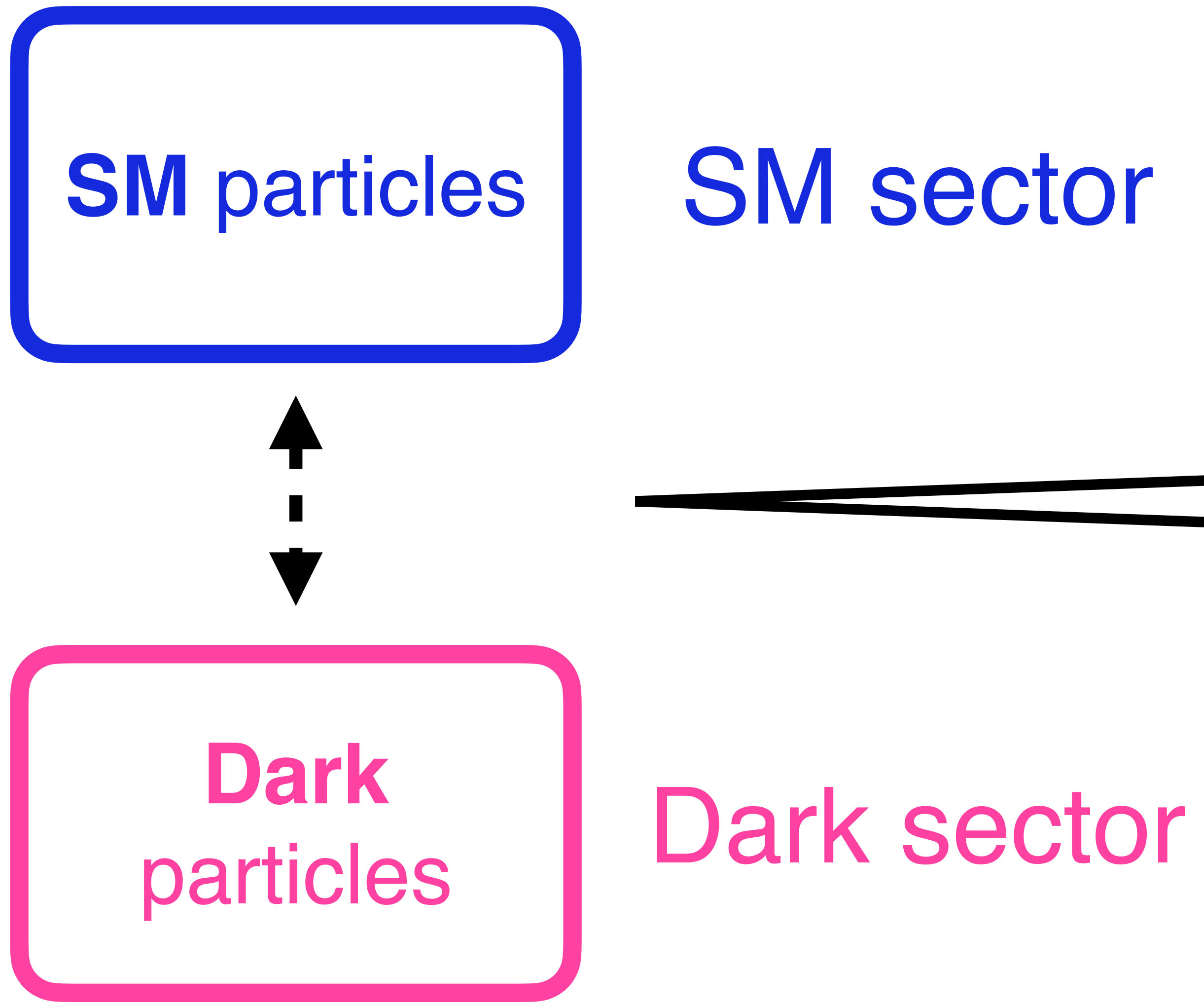

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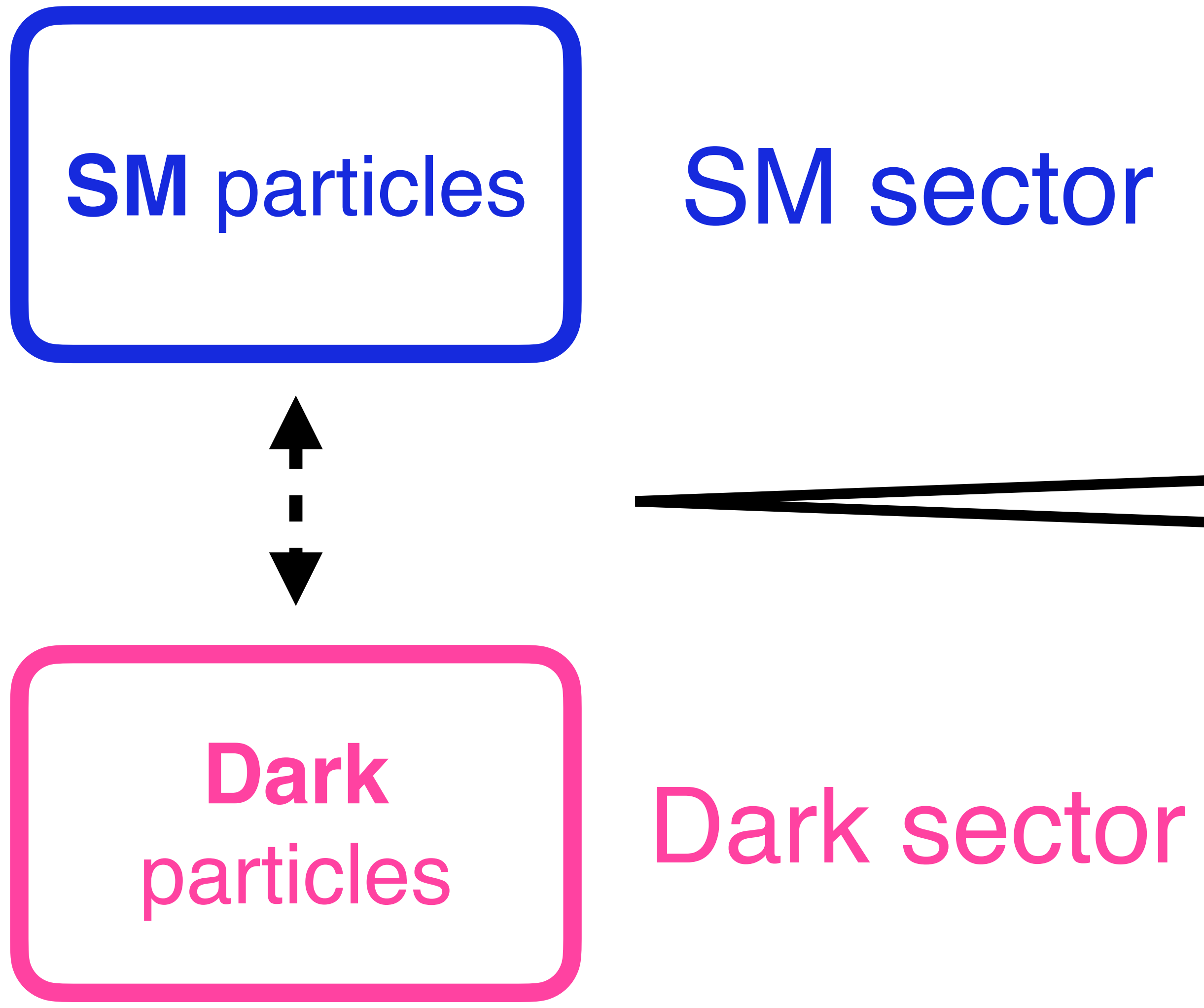

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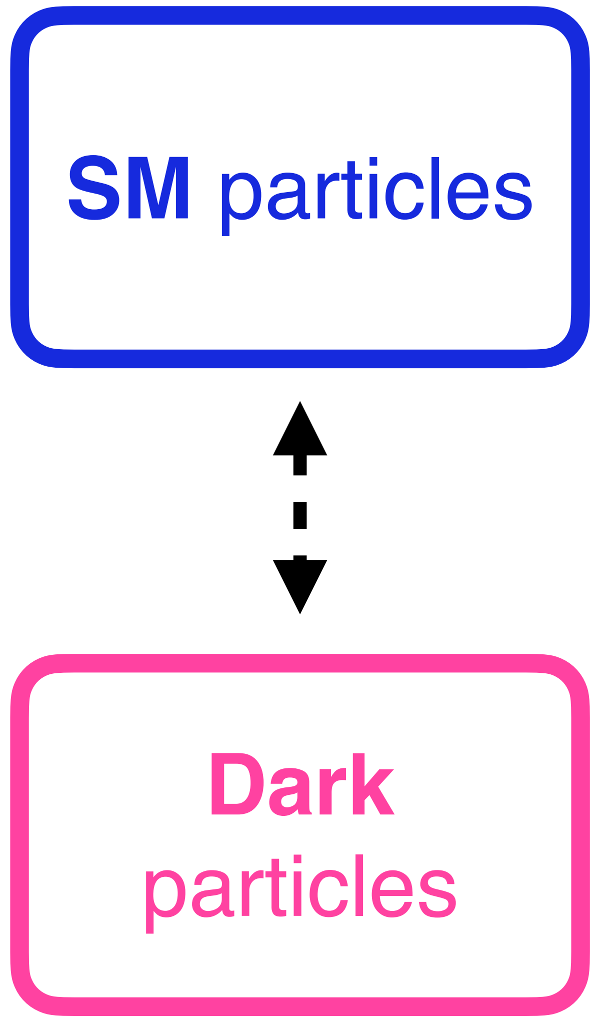

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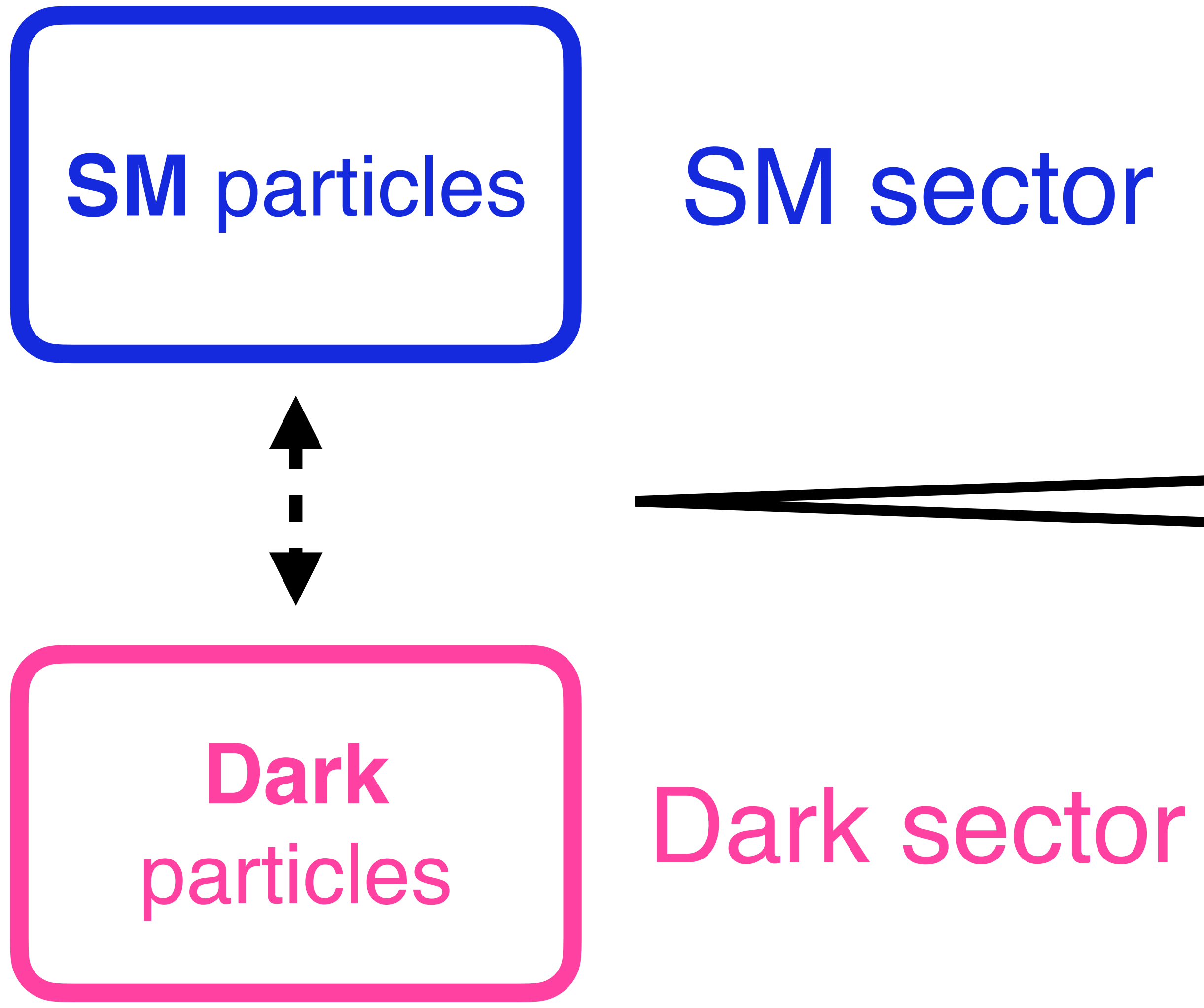

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Dark sector potentially includes DM candidates

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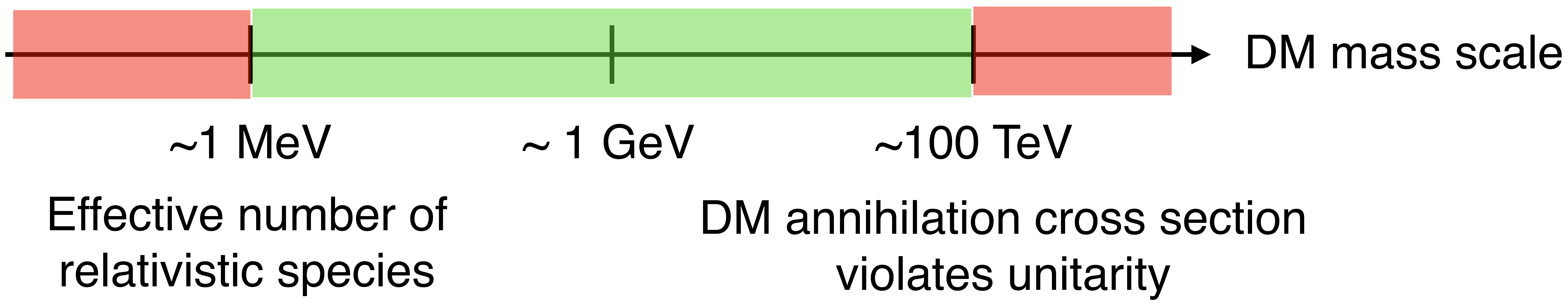

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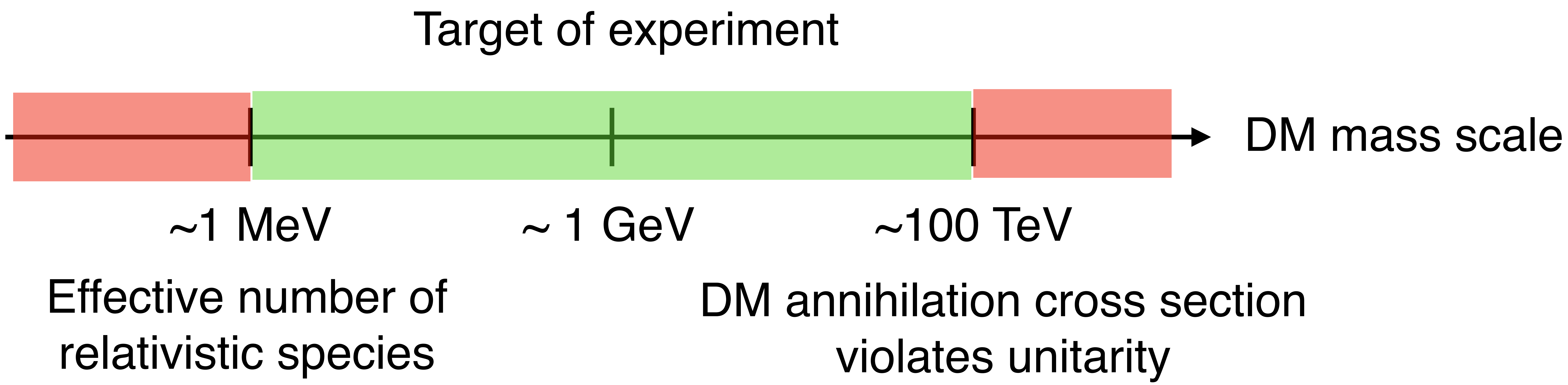

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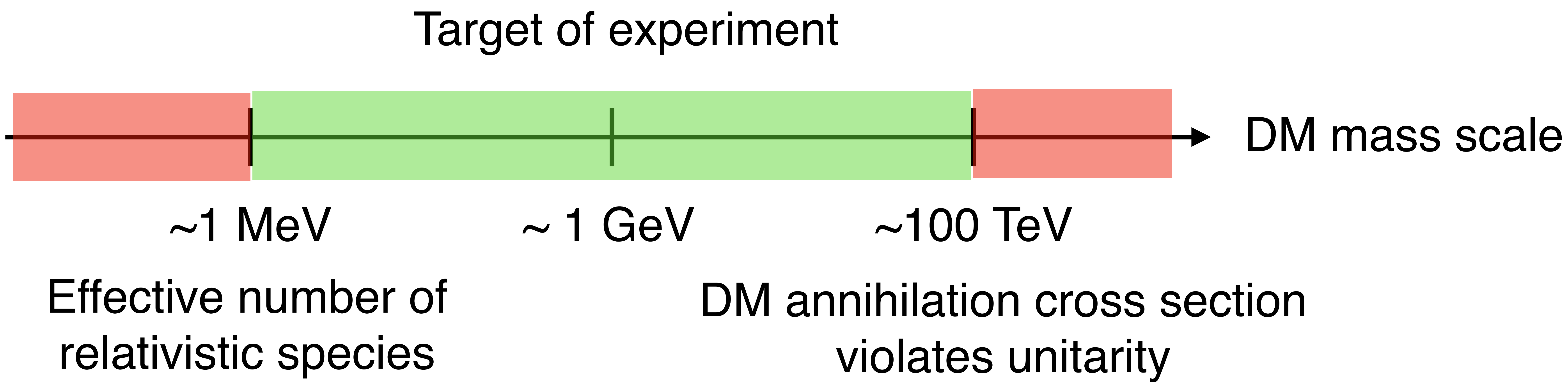
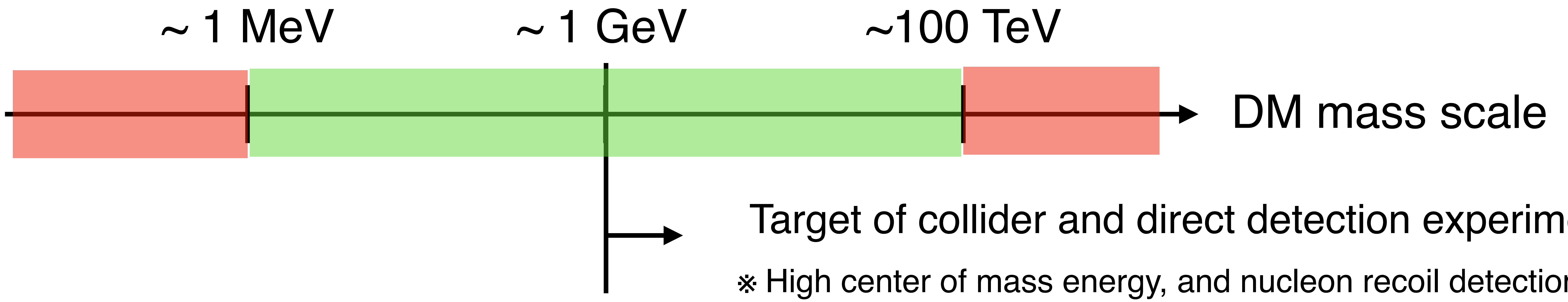


Thermal DM scenario provides target of experiment

Sub-GeV dark matter



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

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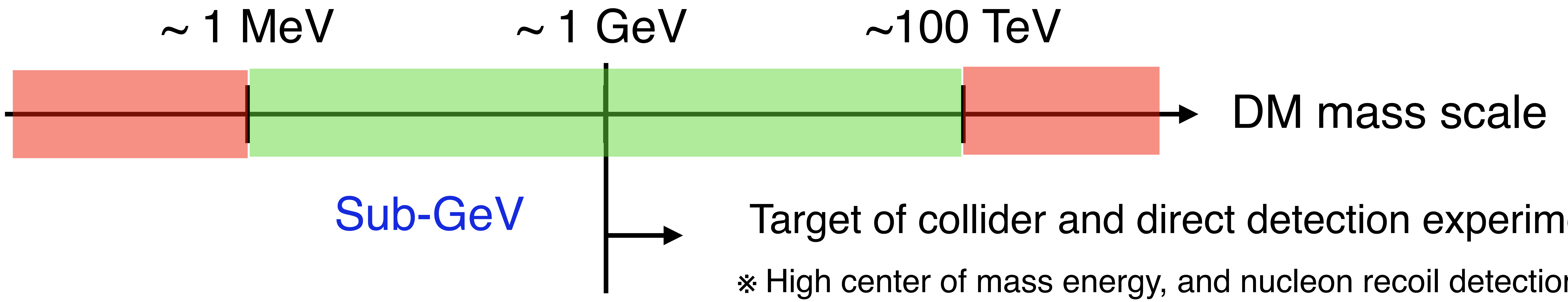

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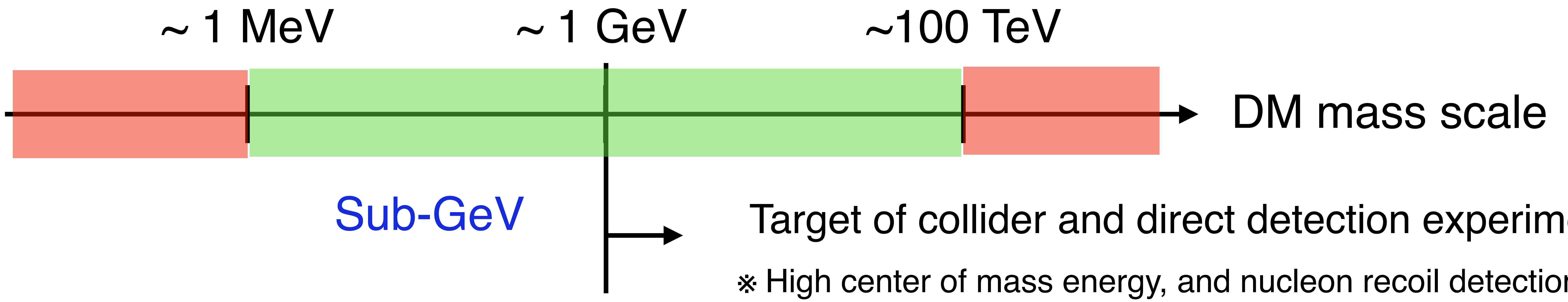

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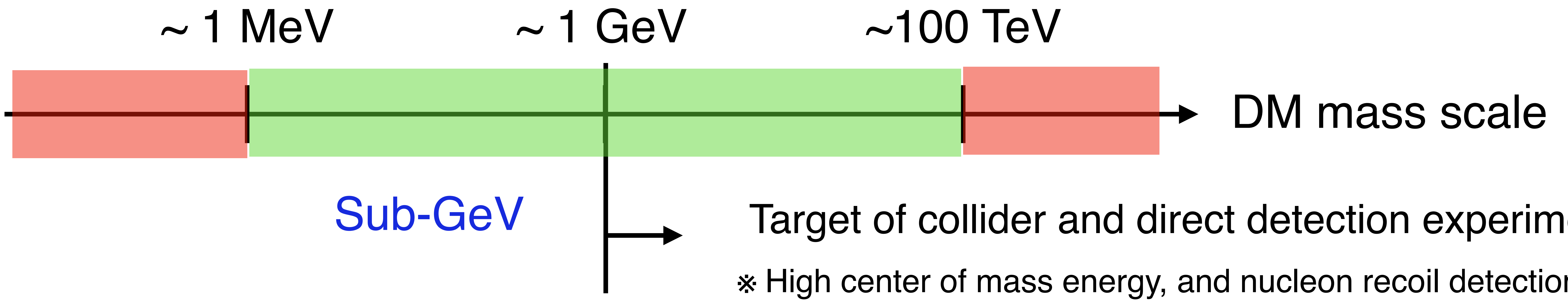

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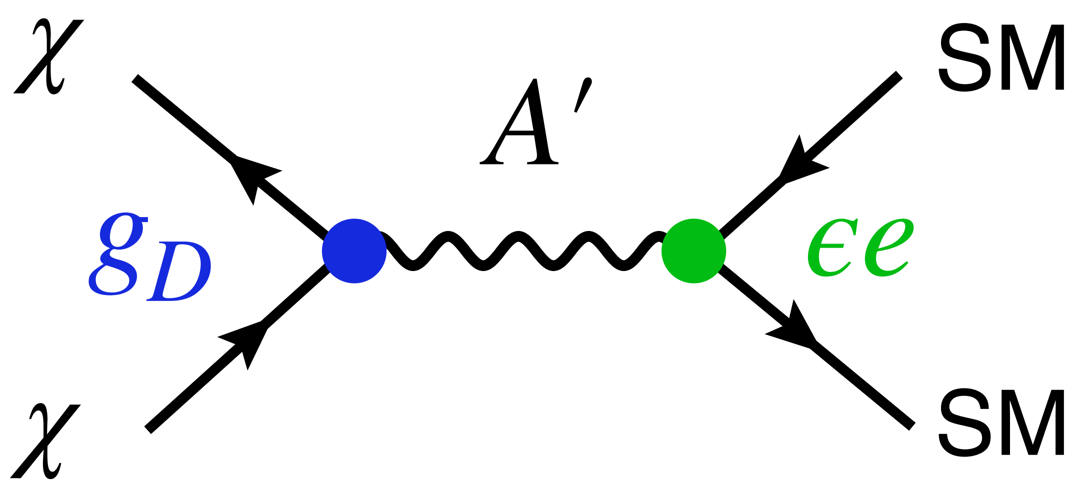

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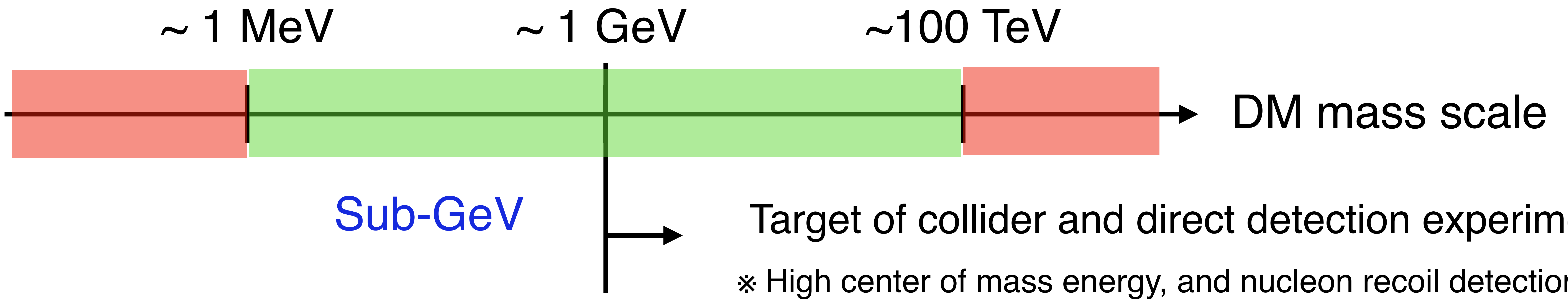

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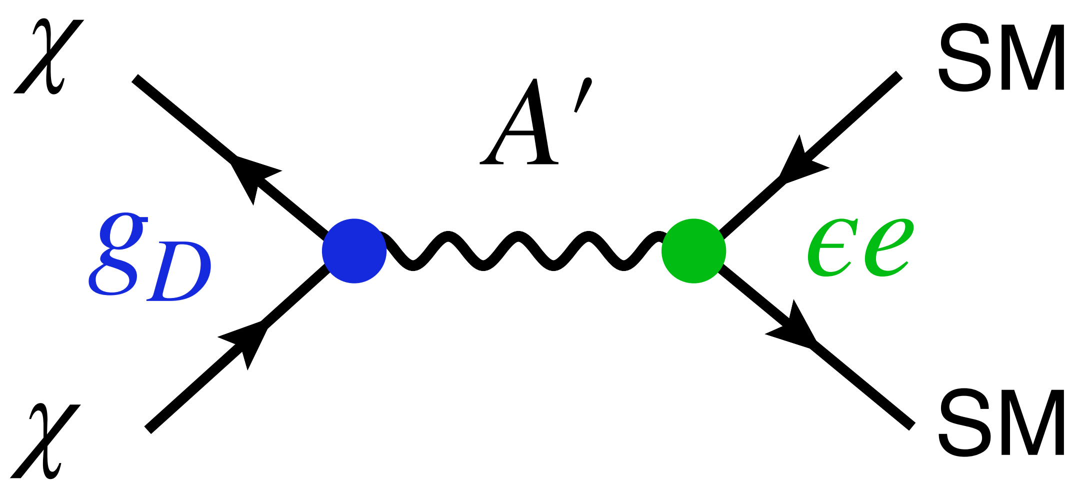

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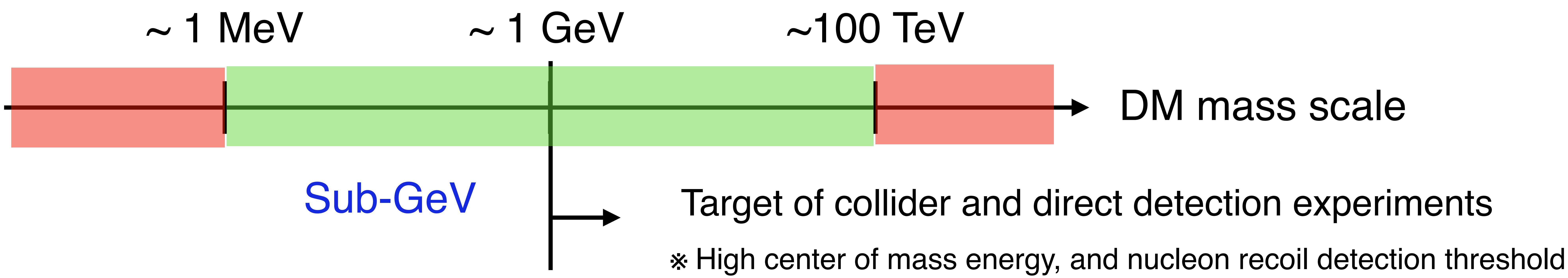

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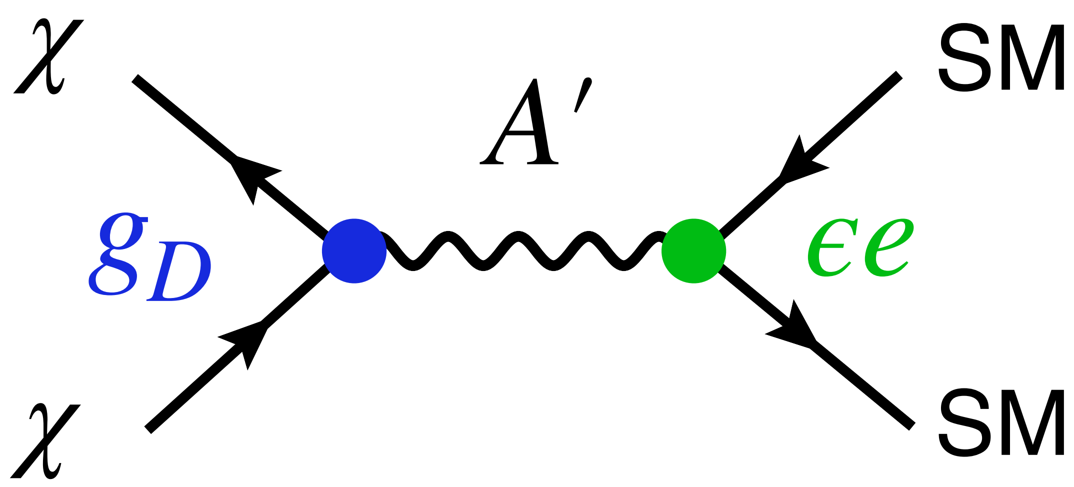

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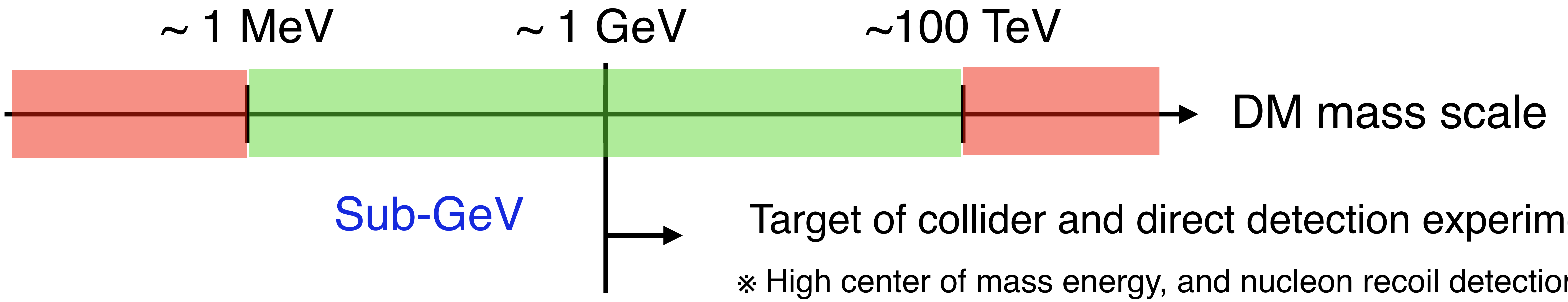

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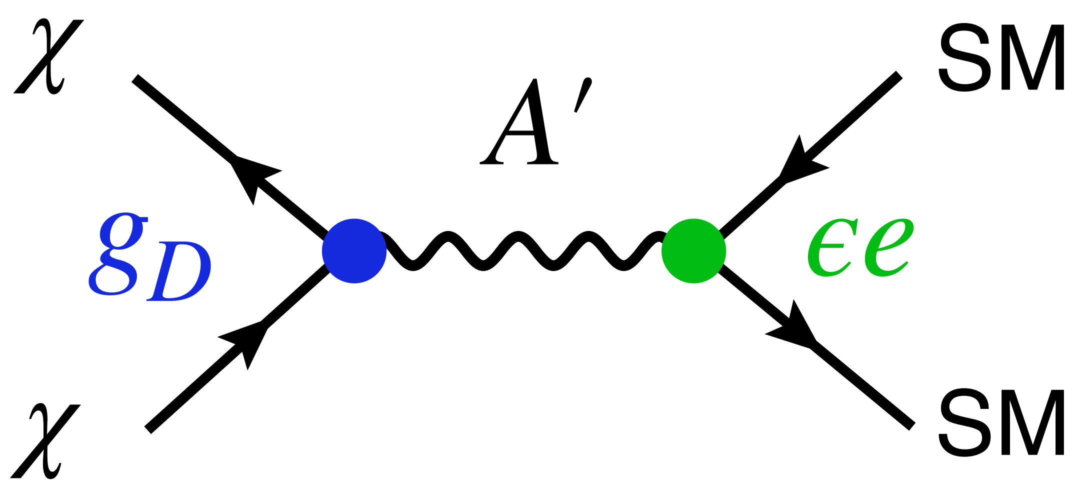

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Hight intensity experiments are needed to search for Sub-GeV dark states

Beam dump(fixed-target) experiment

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e.g., electron, proton, and muon

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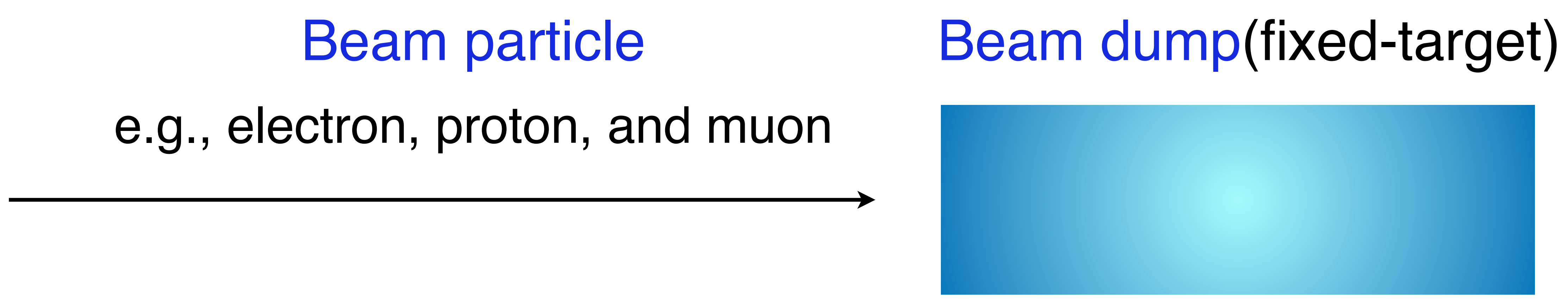

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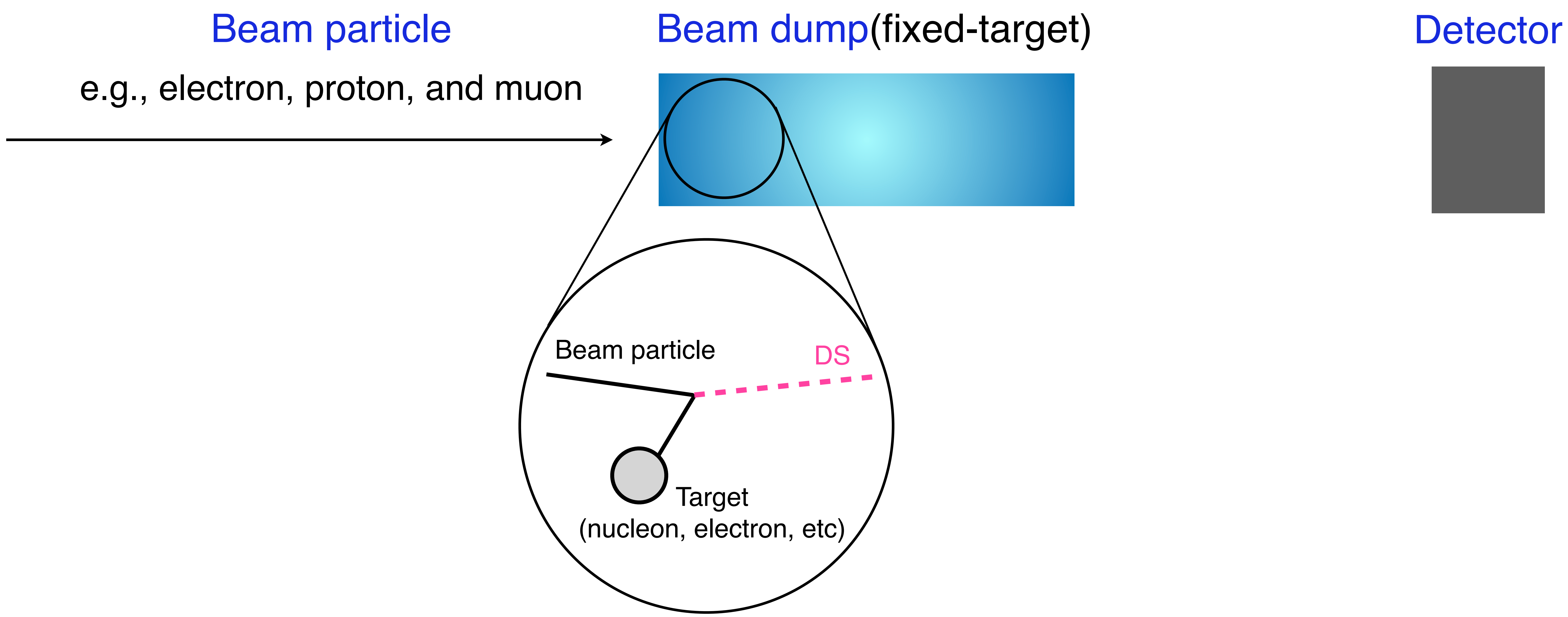

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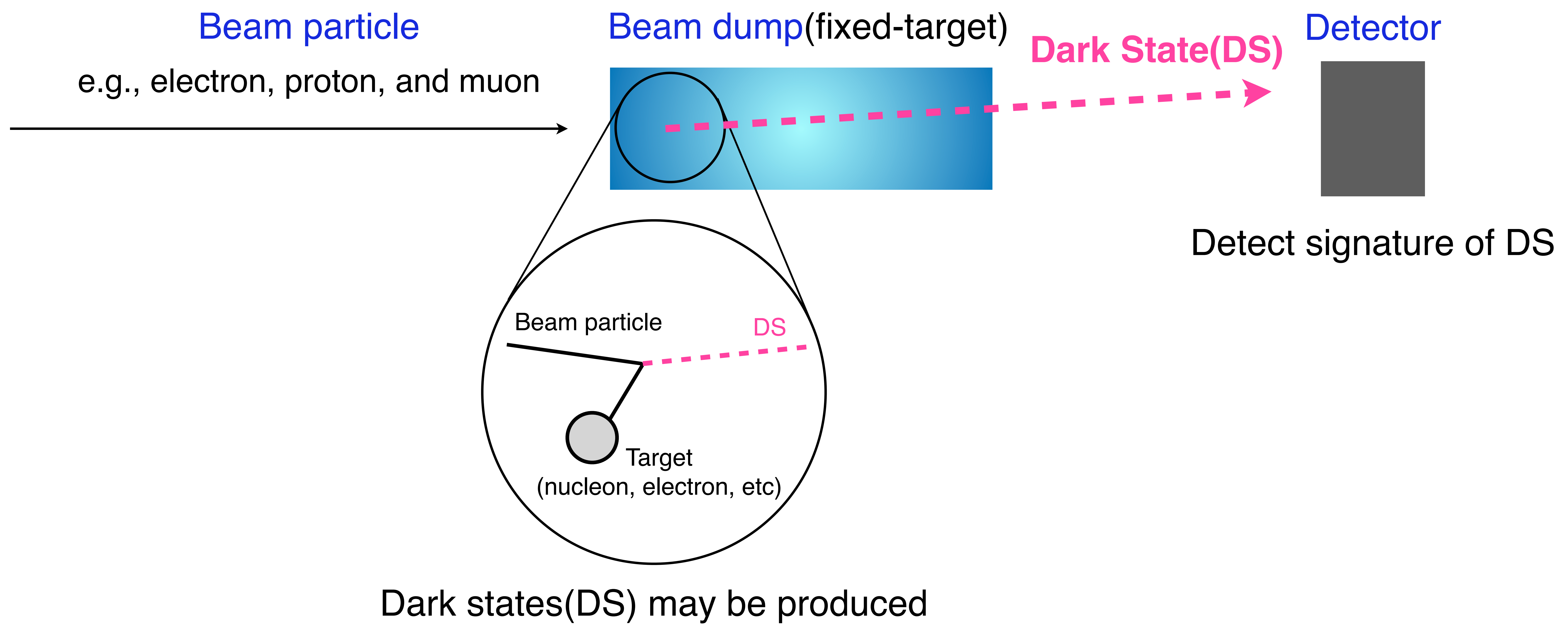

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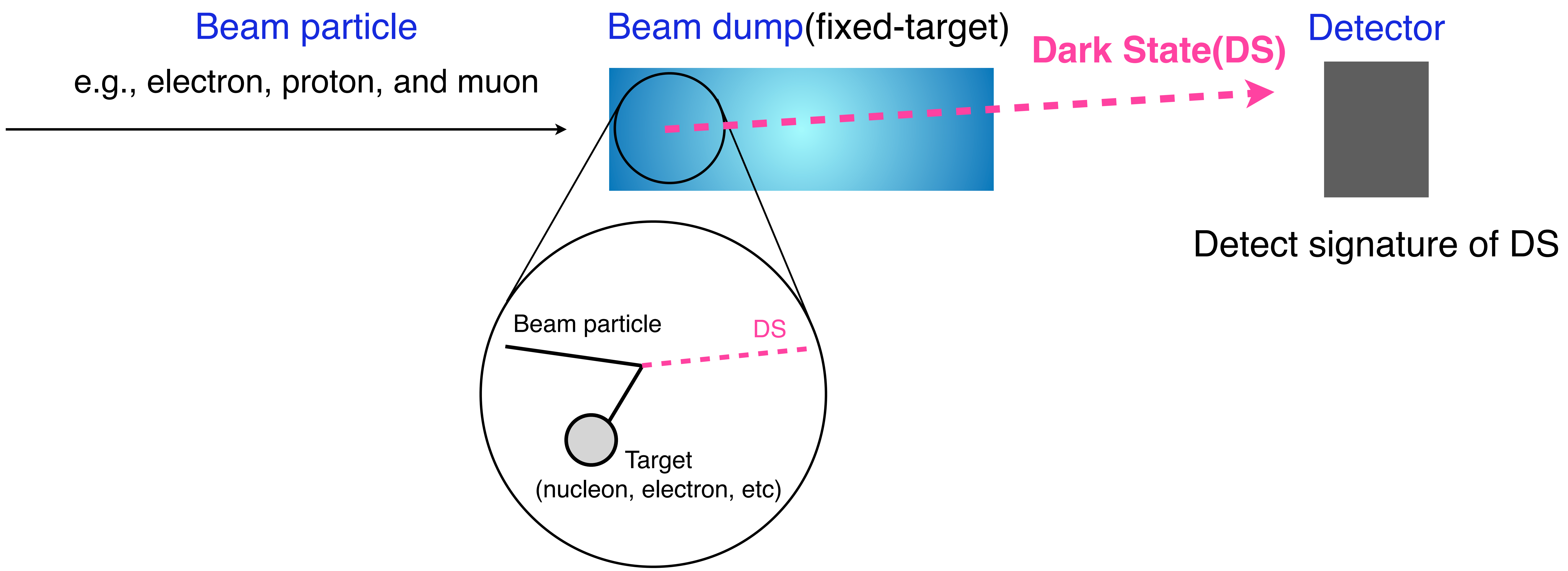

Dark states(DS) may be produced

[My talk's focus]

Detection of dark state signatures produced by beam-target collision

Outline

- Introduction
  - dark sector and Sub-GeV dark matter
  - beam dump(fixed-target) experiment
- Key features of beam dump experiment
- A classification of beam dump experiment
- Sensitivity of beam dump experiments at future accelerators
- Summary

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

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Boosted Sub-GeV particles can be produced in beam dump

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Key features of beam dump experiment (2)

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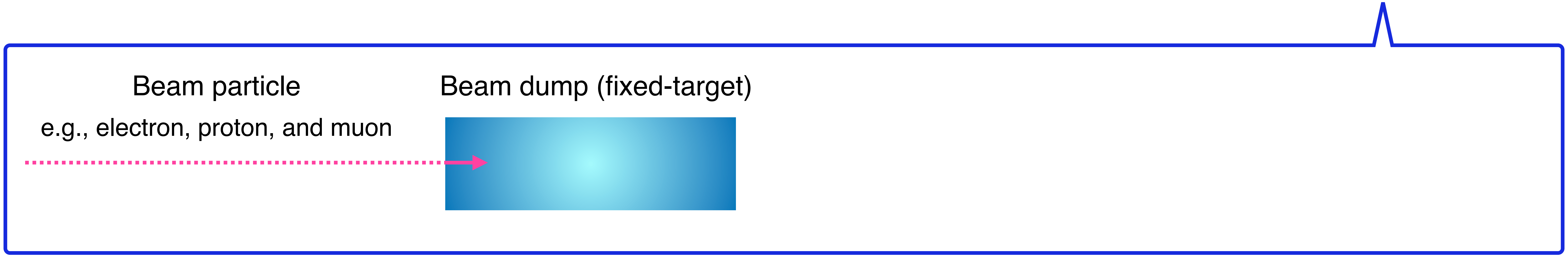

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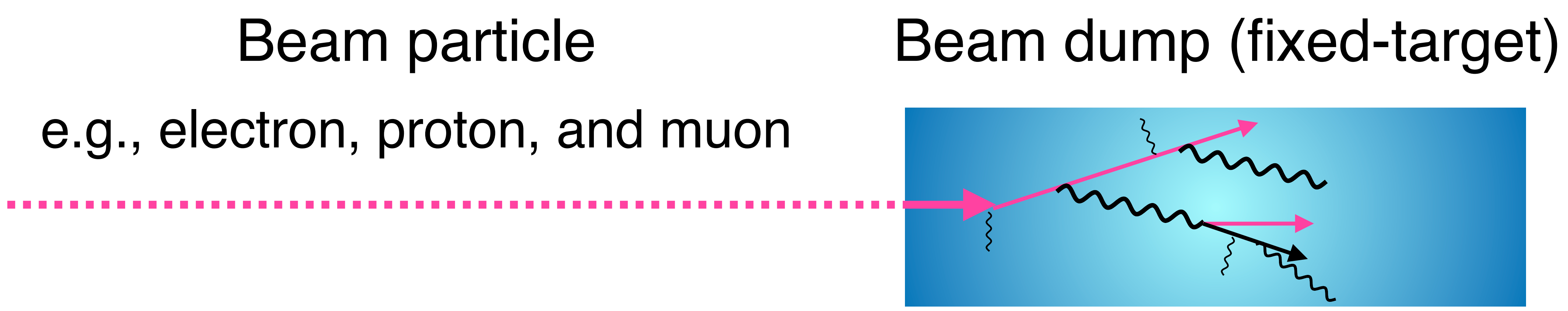

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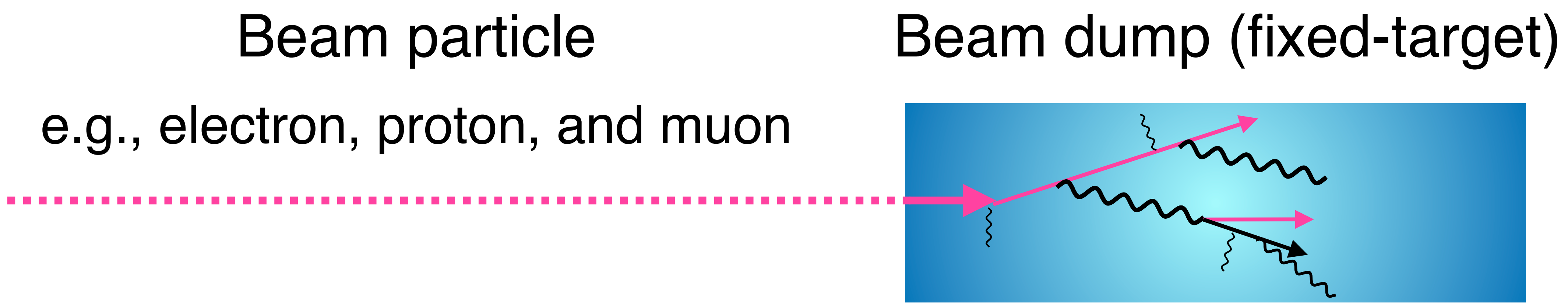

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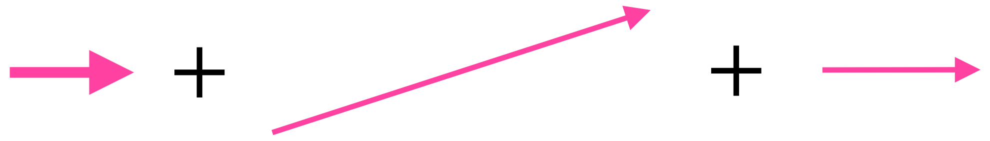
Beam dump (fixed-target)

(Track length) = 

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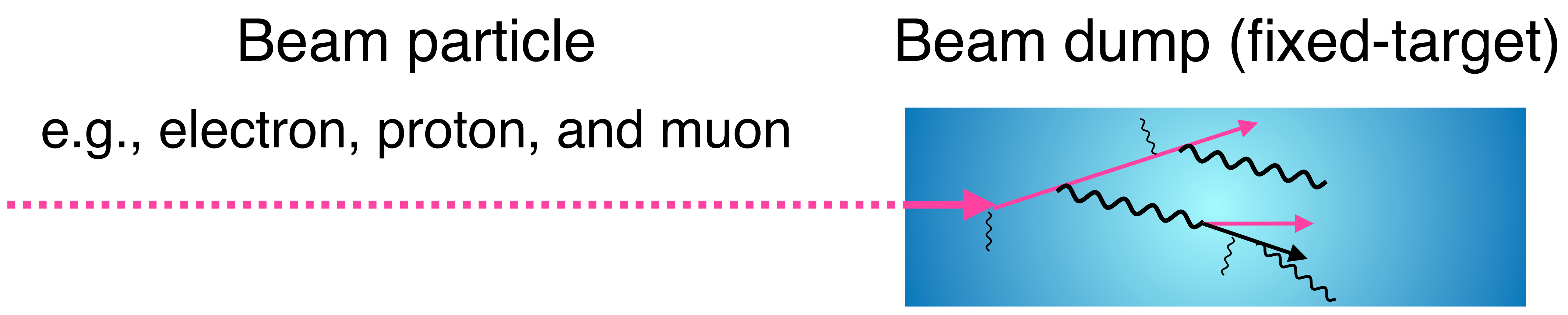
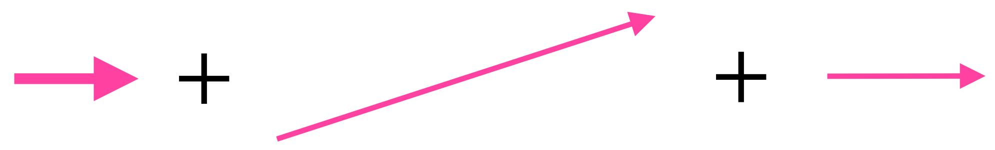
× (Beam flux [T^{-1}]) × (Operation time [T]) × (# density of target [L^{-3}]) × (Track length [L])



(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

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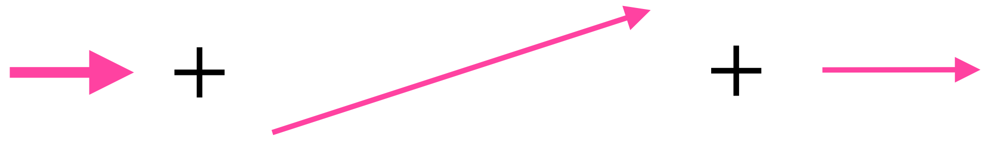
Beam particle

e.g., electron, proton, and muon

Beam dump (fixed-target)

(Track length) = 

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

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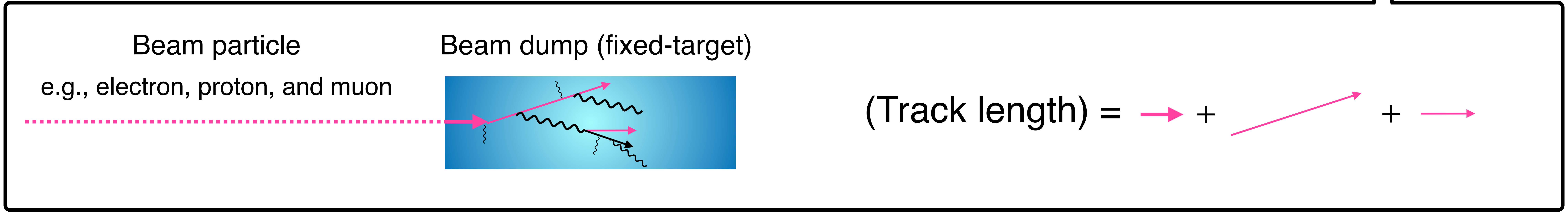

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Key features of beam dump experiment (3)

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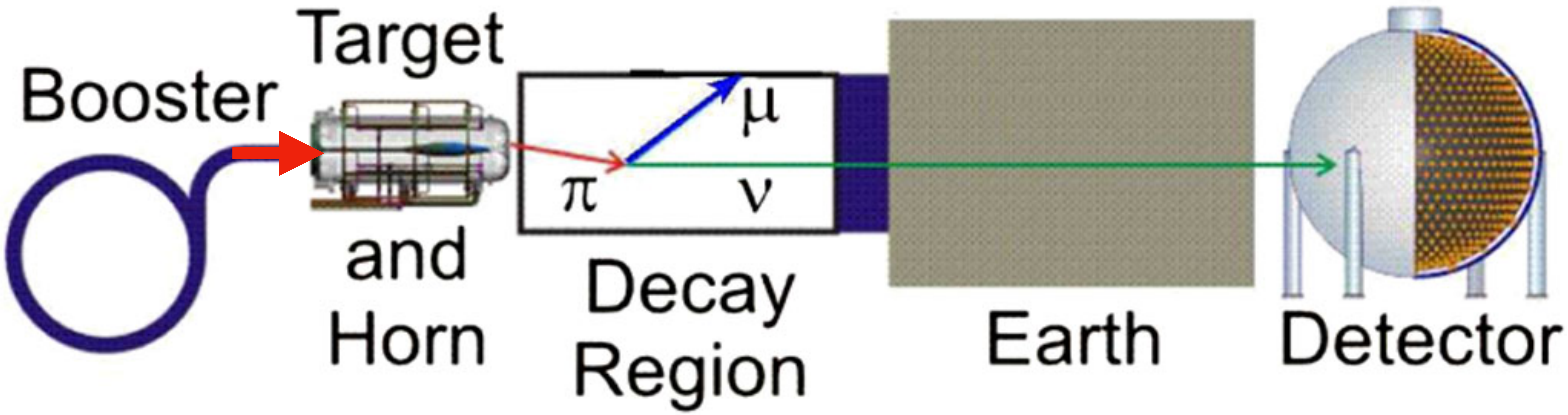
  Ex. MiniBooNE experiment



[1807.06137]

proton beam

Fixed-target
(beam dump)

Neutrino detector

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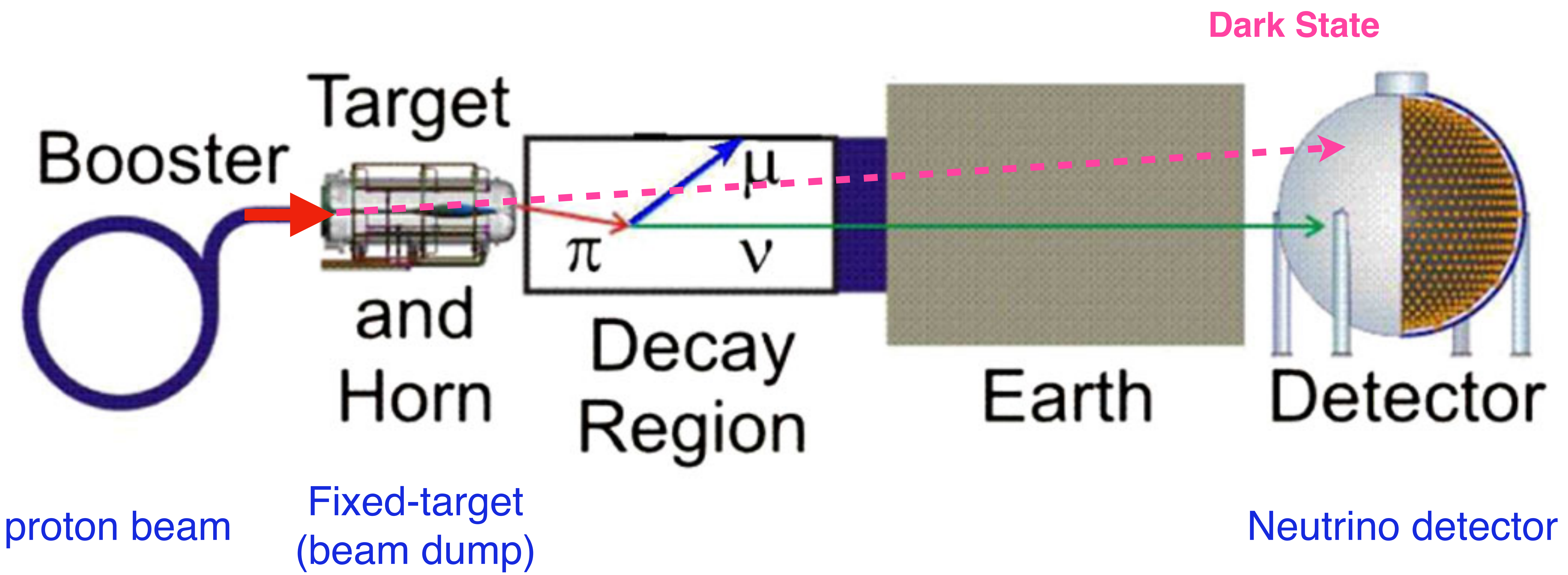

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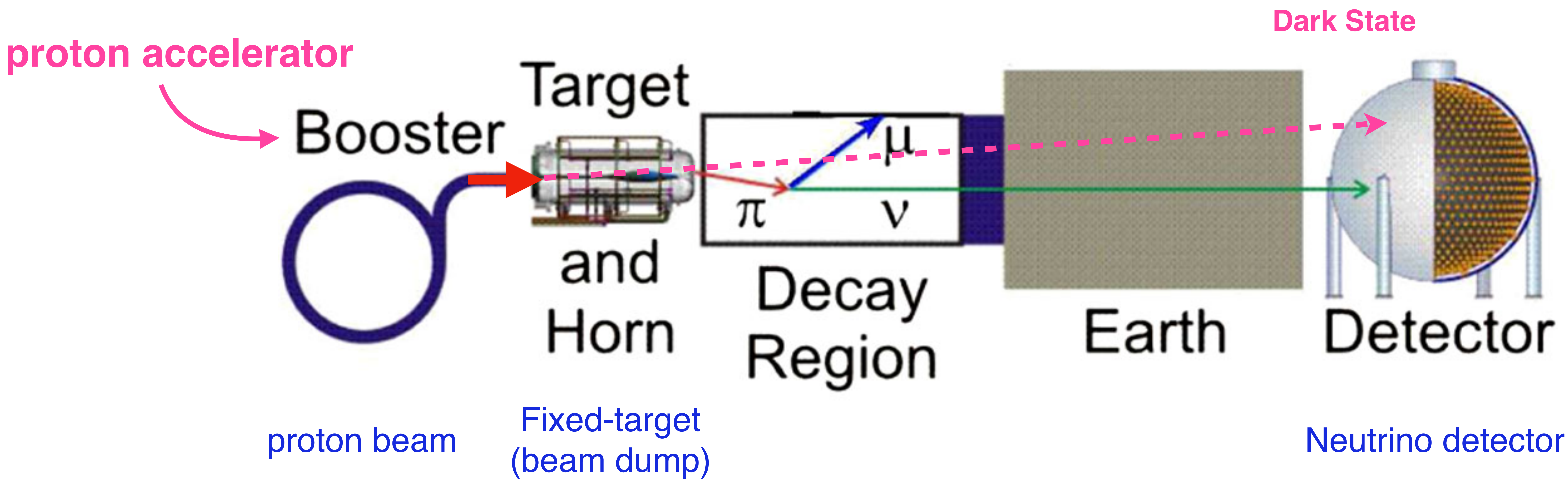

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Beam dump experiments can use accelerator facilities of neutrino experiments

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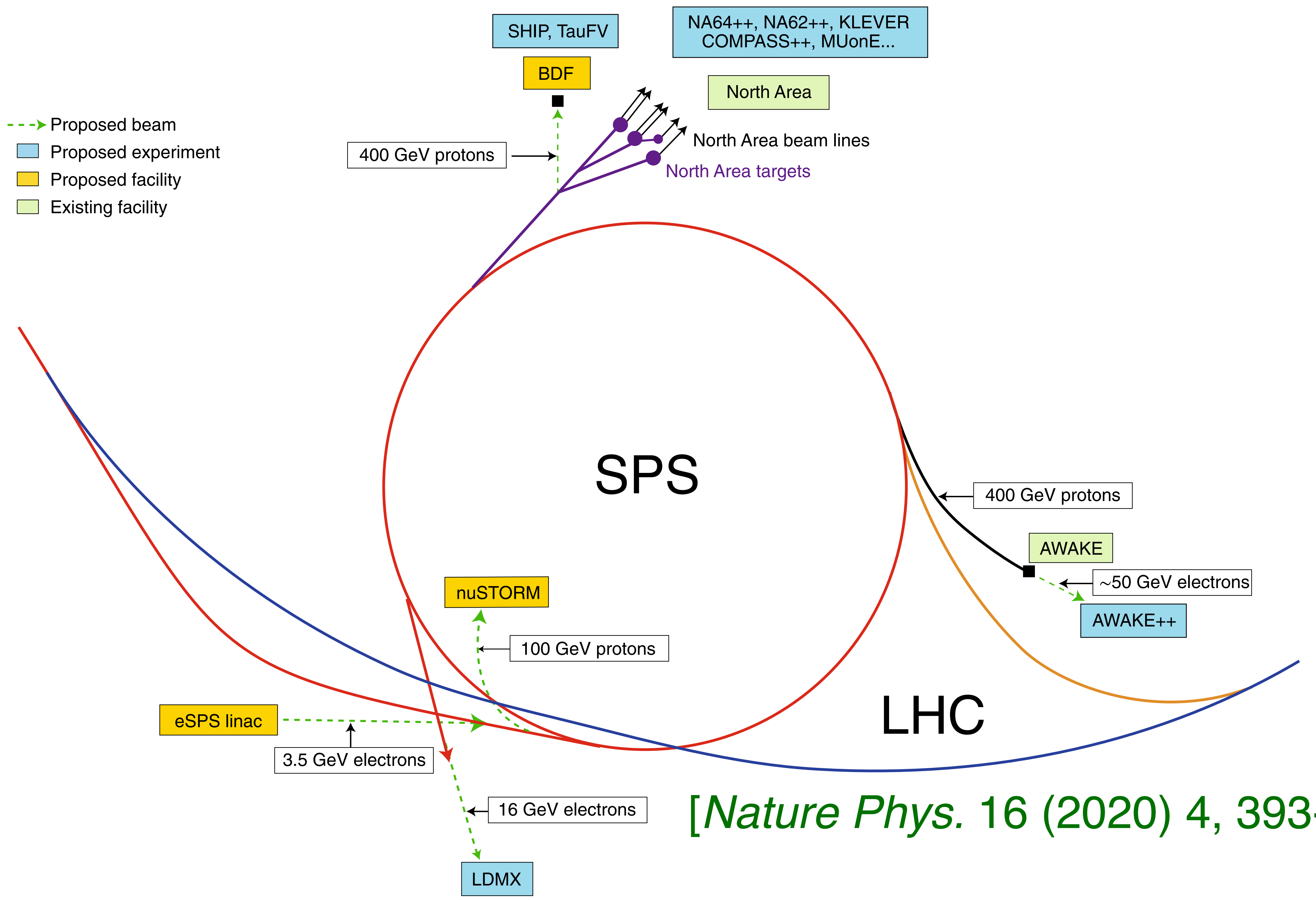

[*Nature Phys.* 16 (2020) 4, 393-401]

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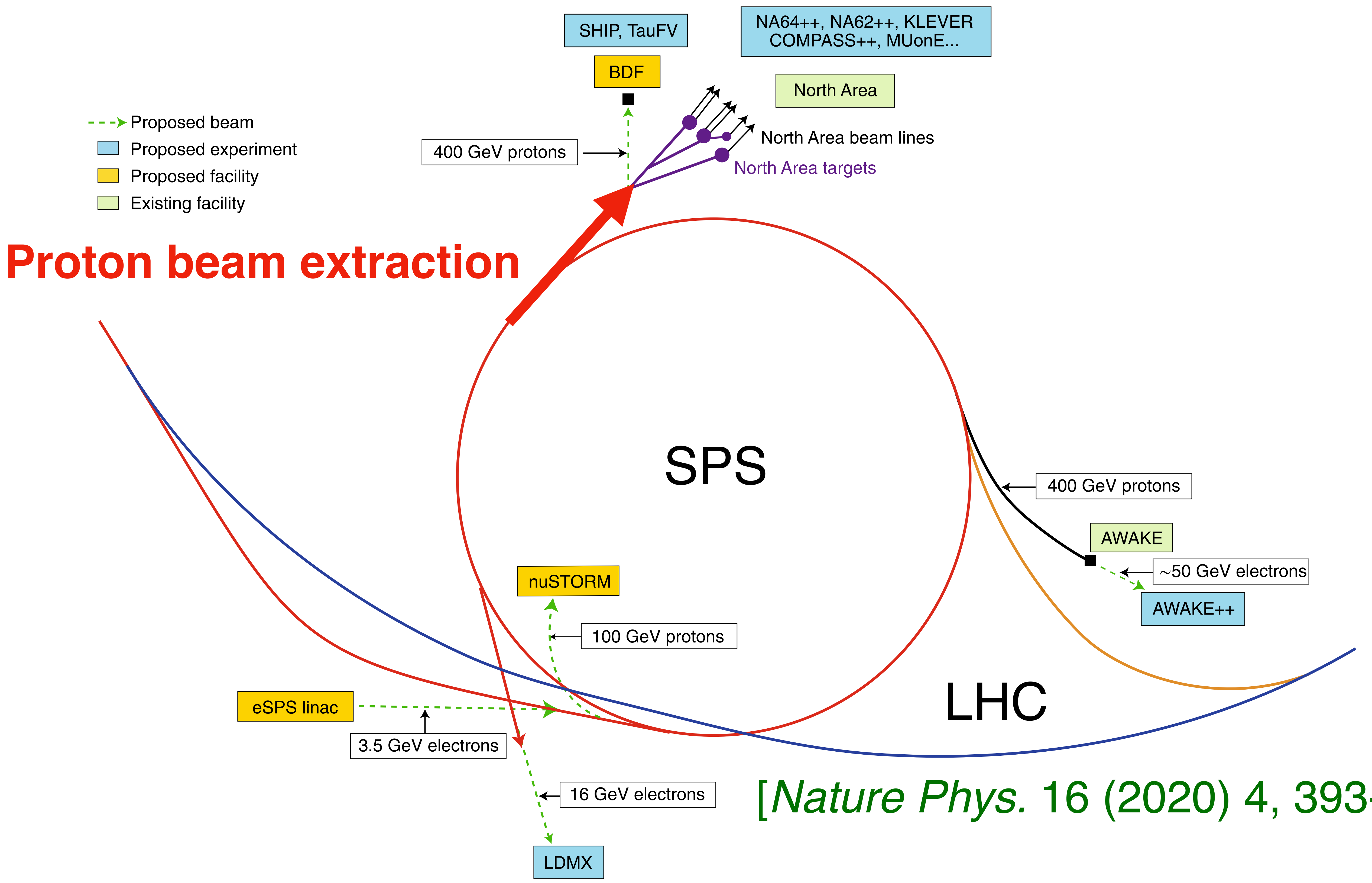

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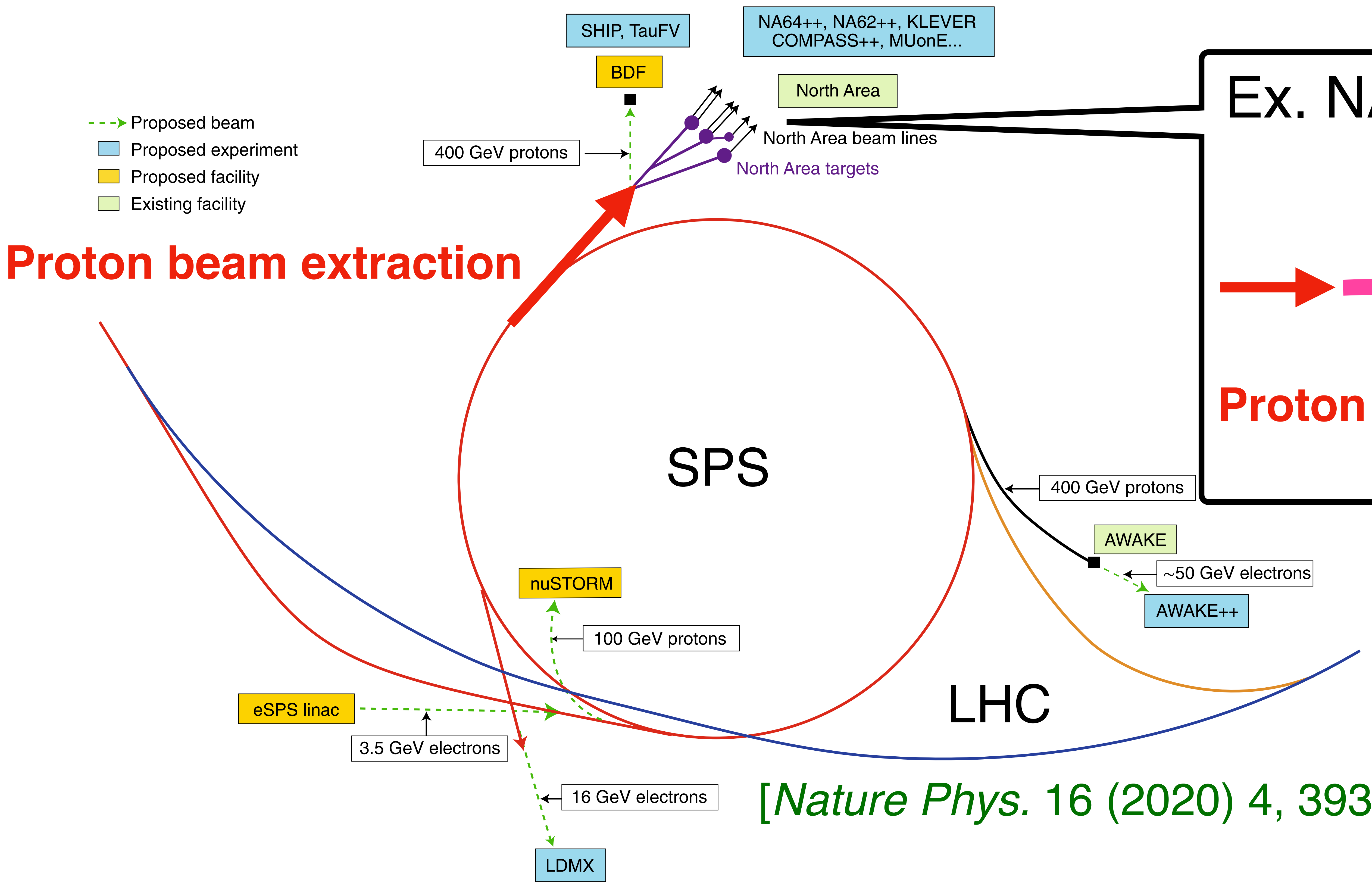

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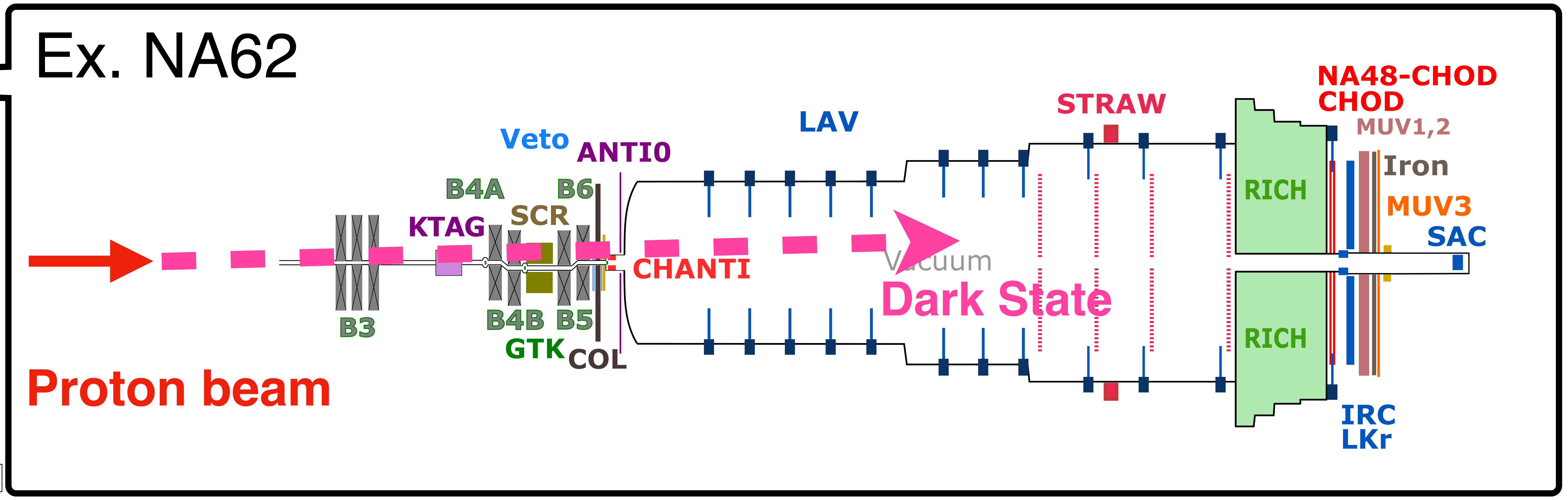

[2312.12055]

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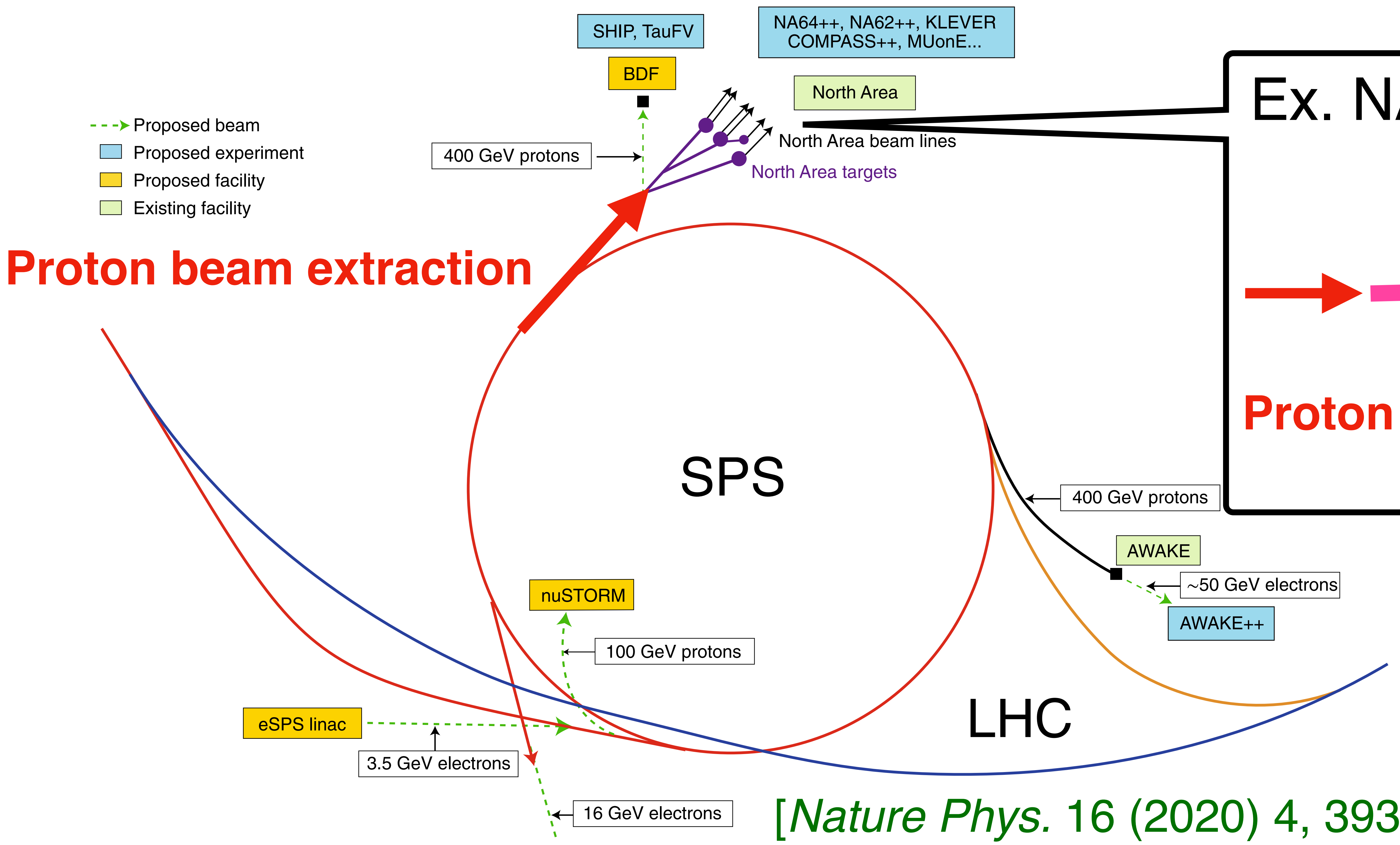

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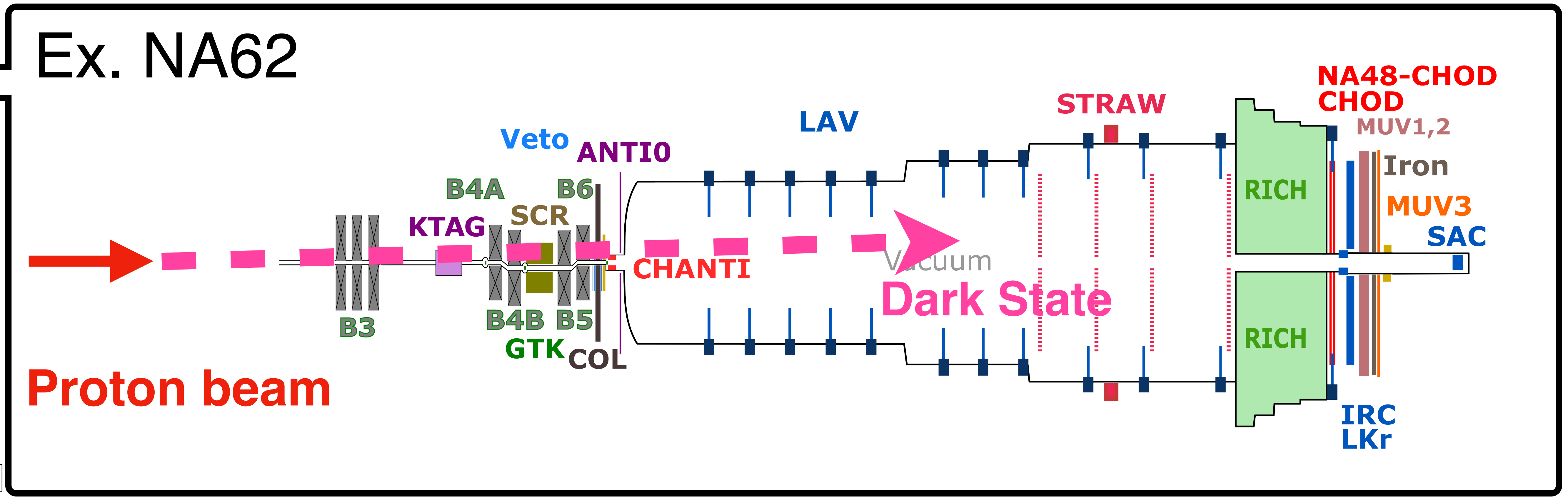

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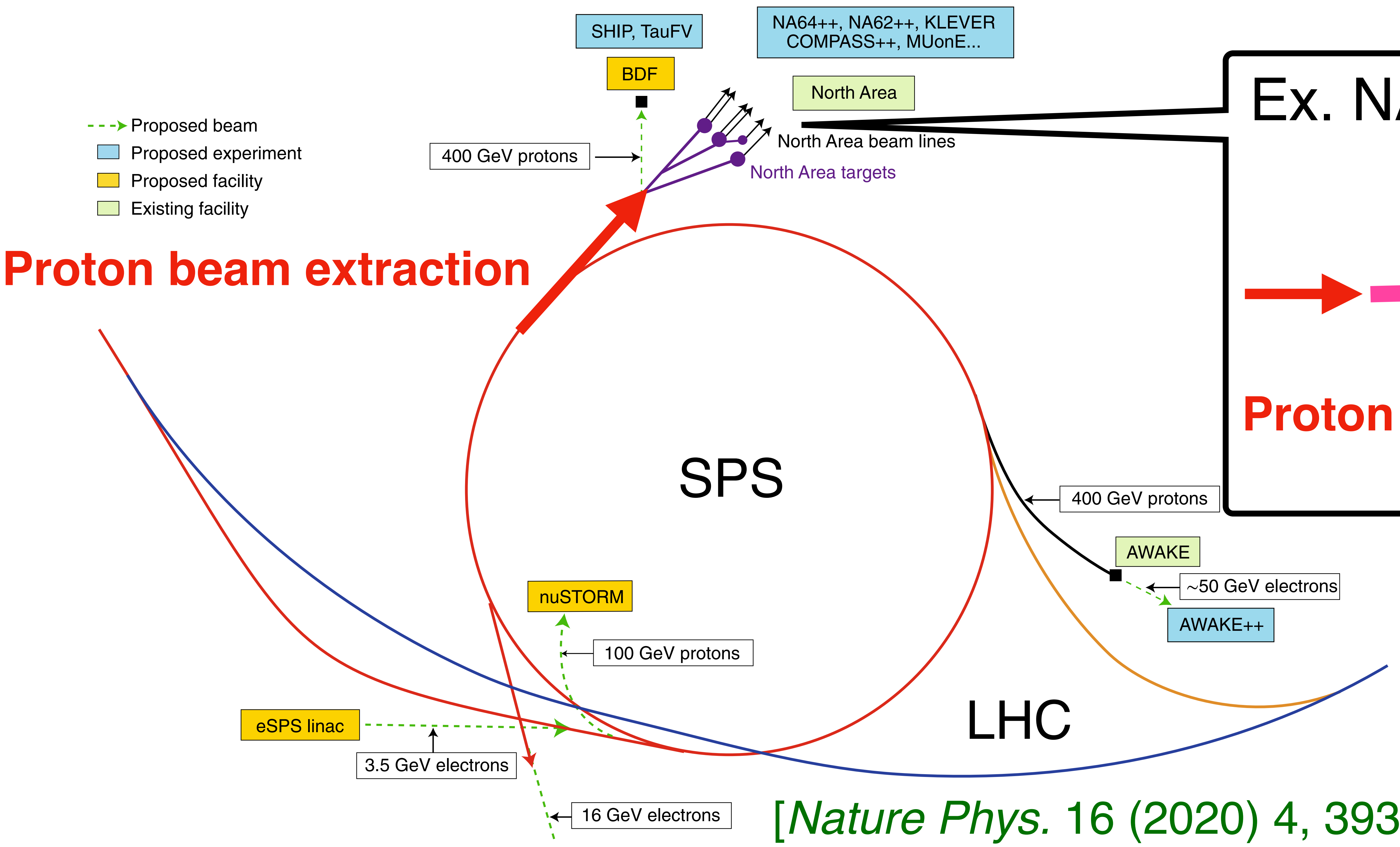

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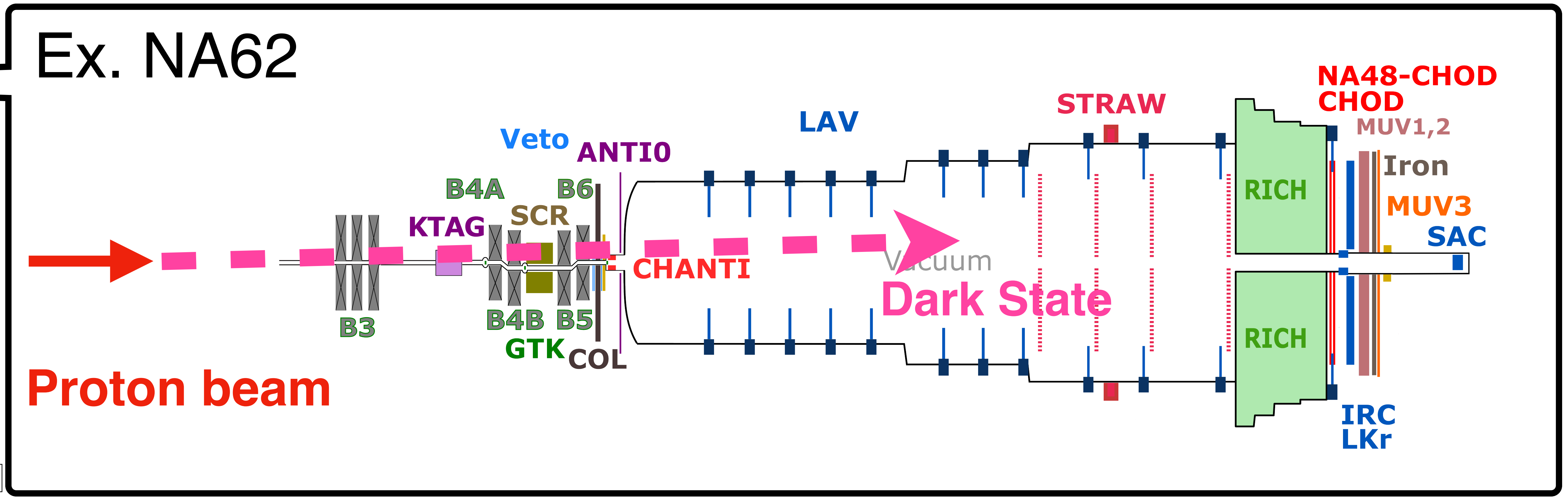

[2312.12055]

Beam dump experiments can be parasitic runnings of accelerator experiments

⇒ beam dump experiments will be conducted at **future accelerators**

Beam dump experiments at future accelerators

Ex. ILC-BDX ⇒ parasitic running of International Linear Collider(ILC) experiment

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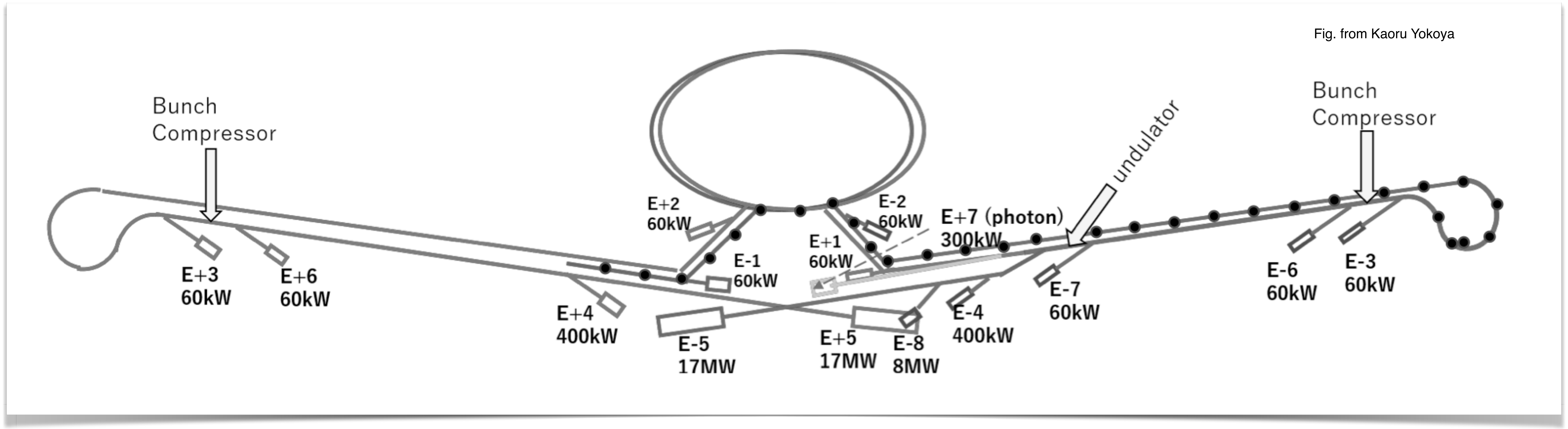

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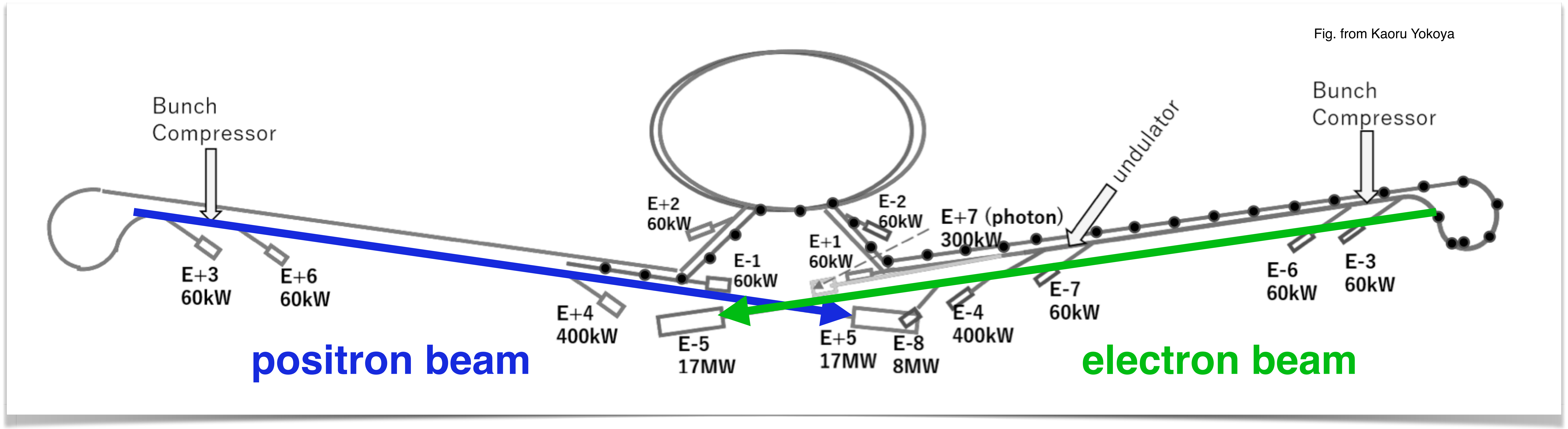

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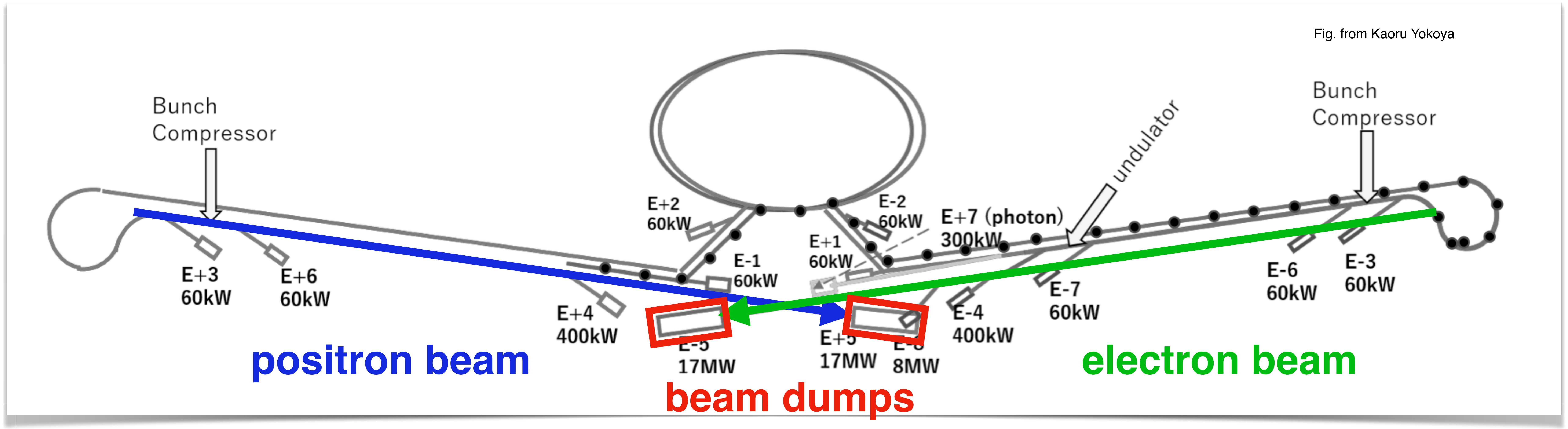

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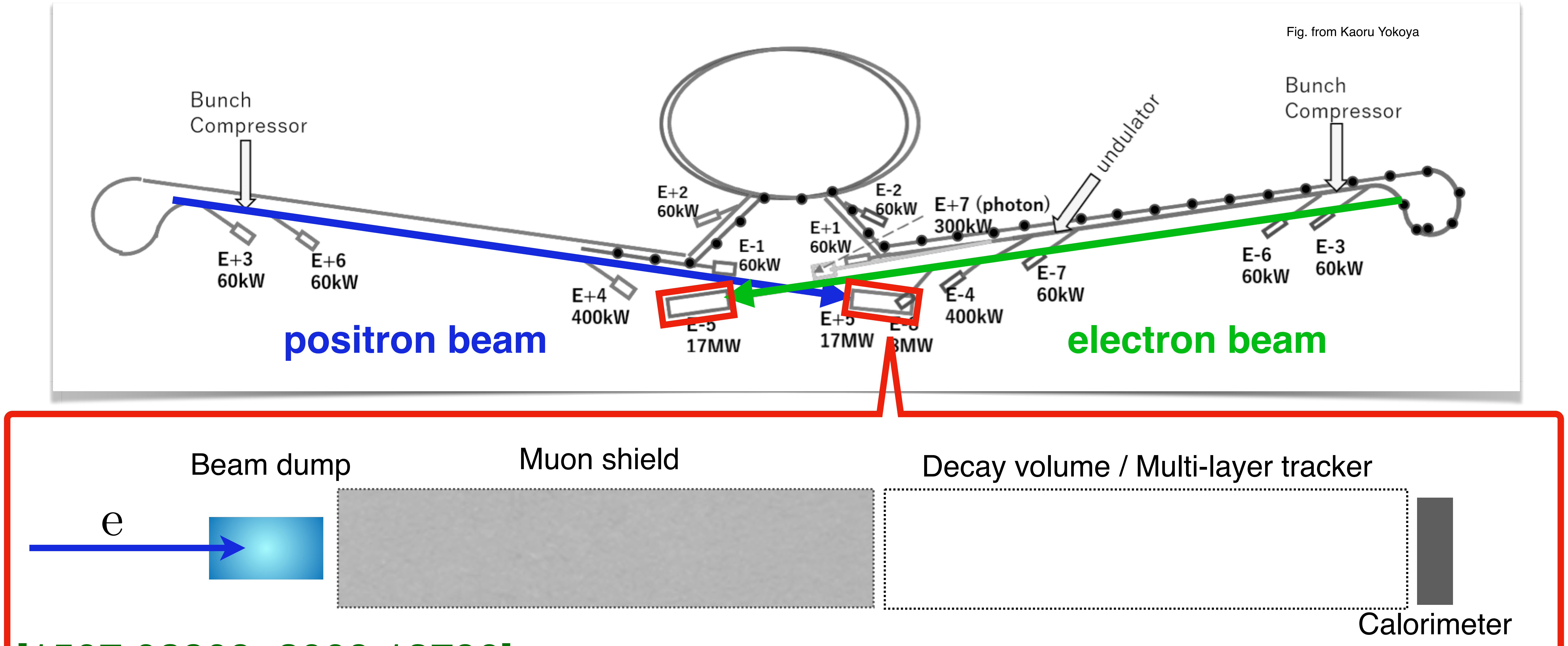

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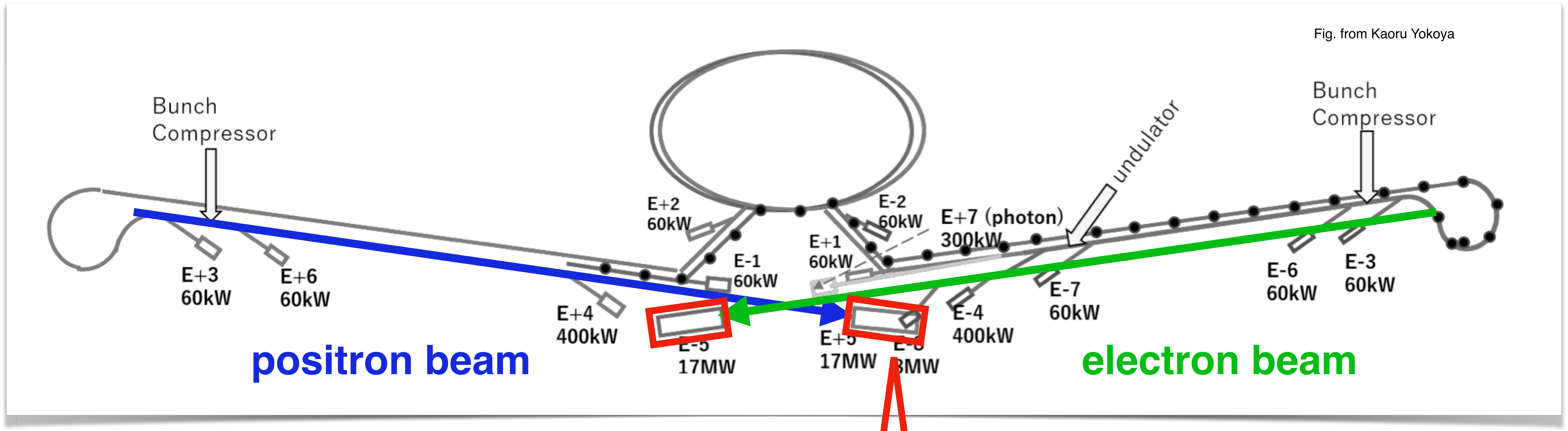

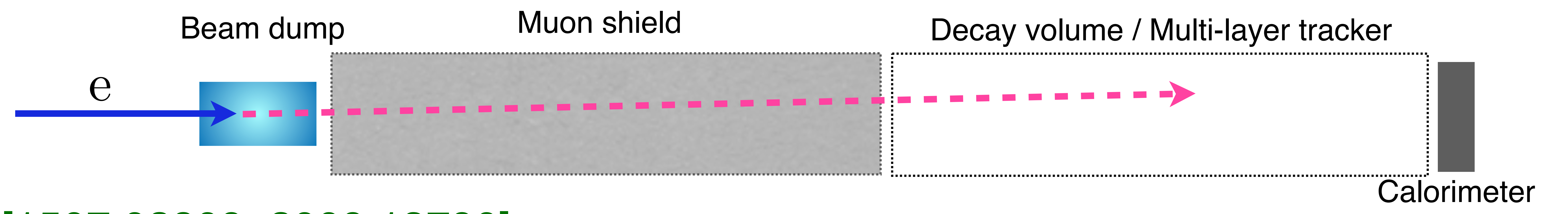

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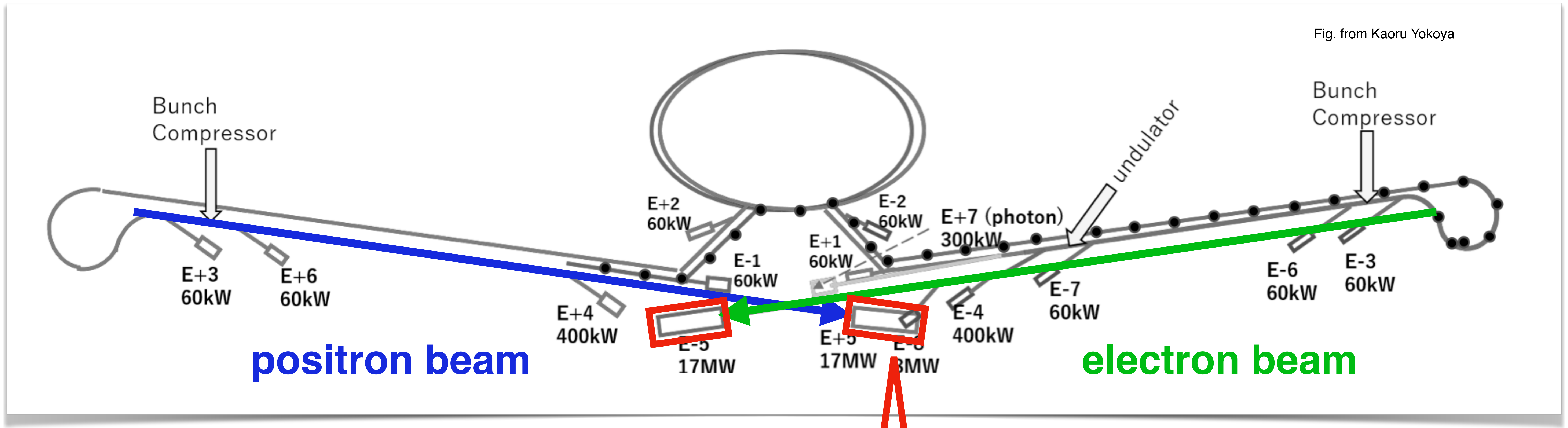

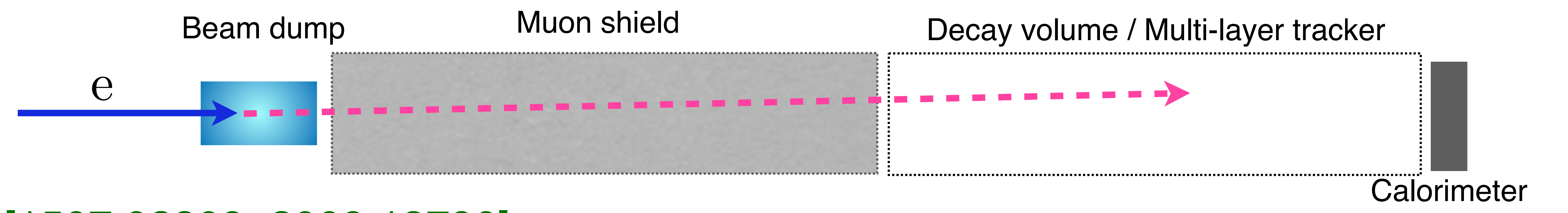

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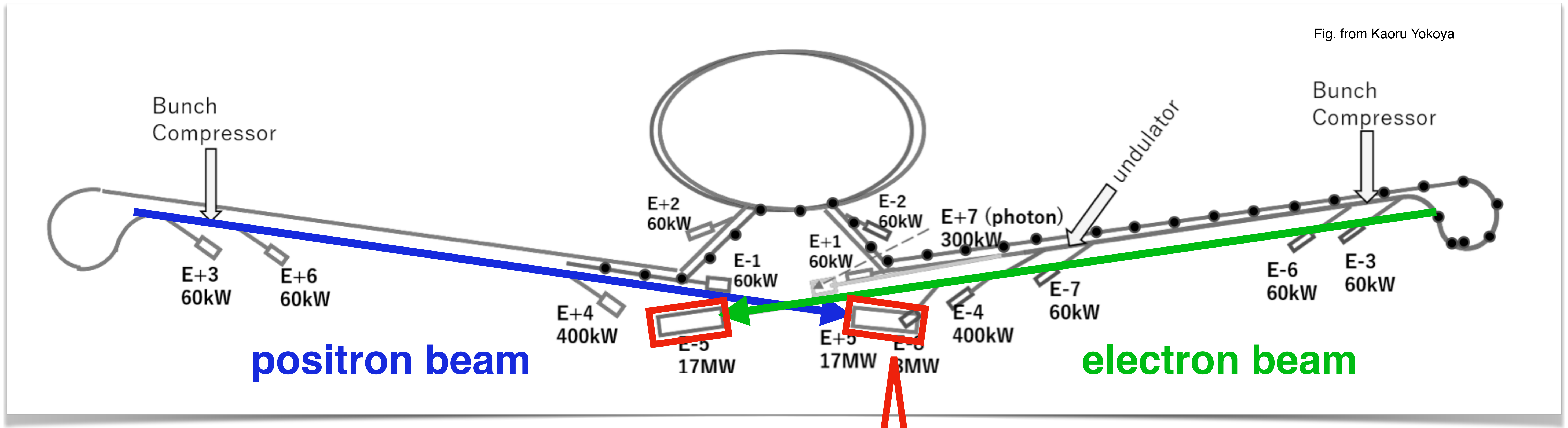

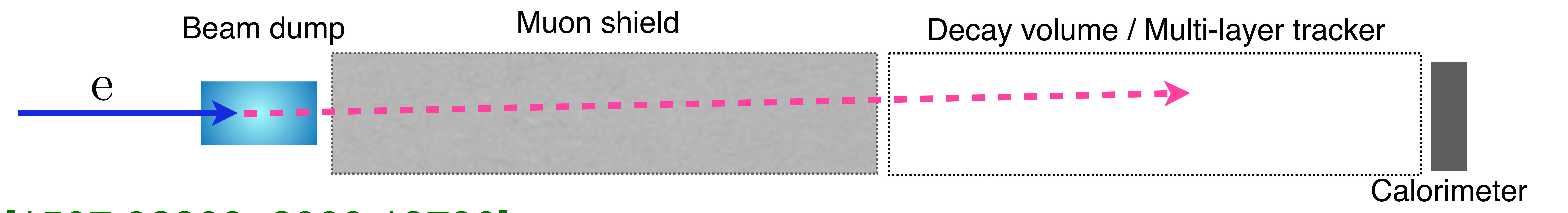

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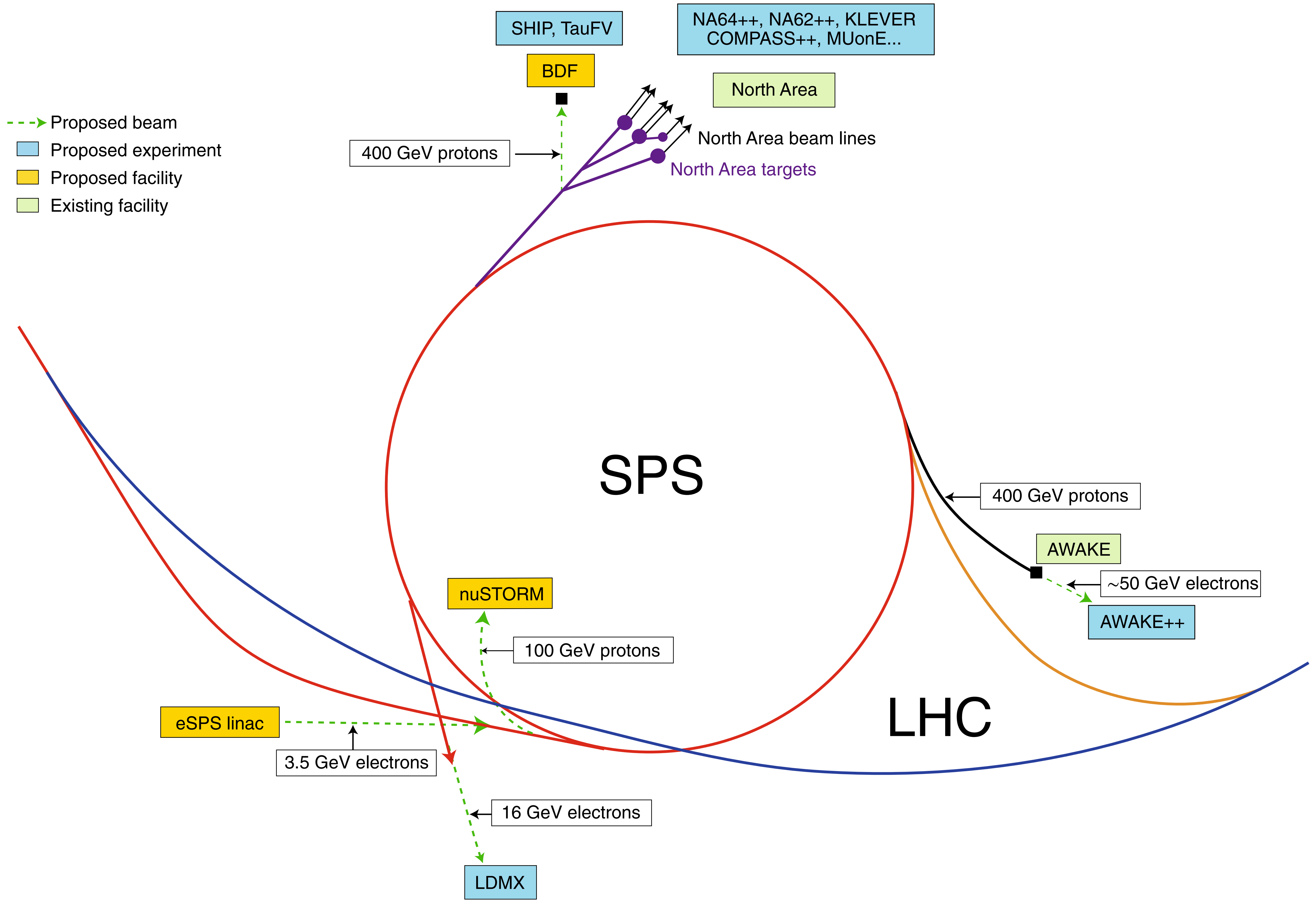

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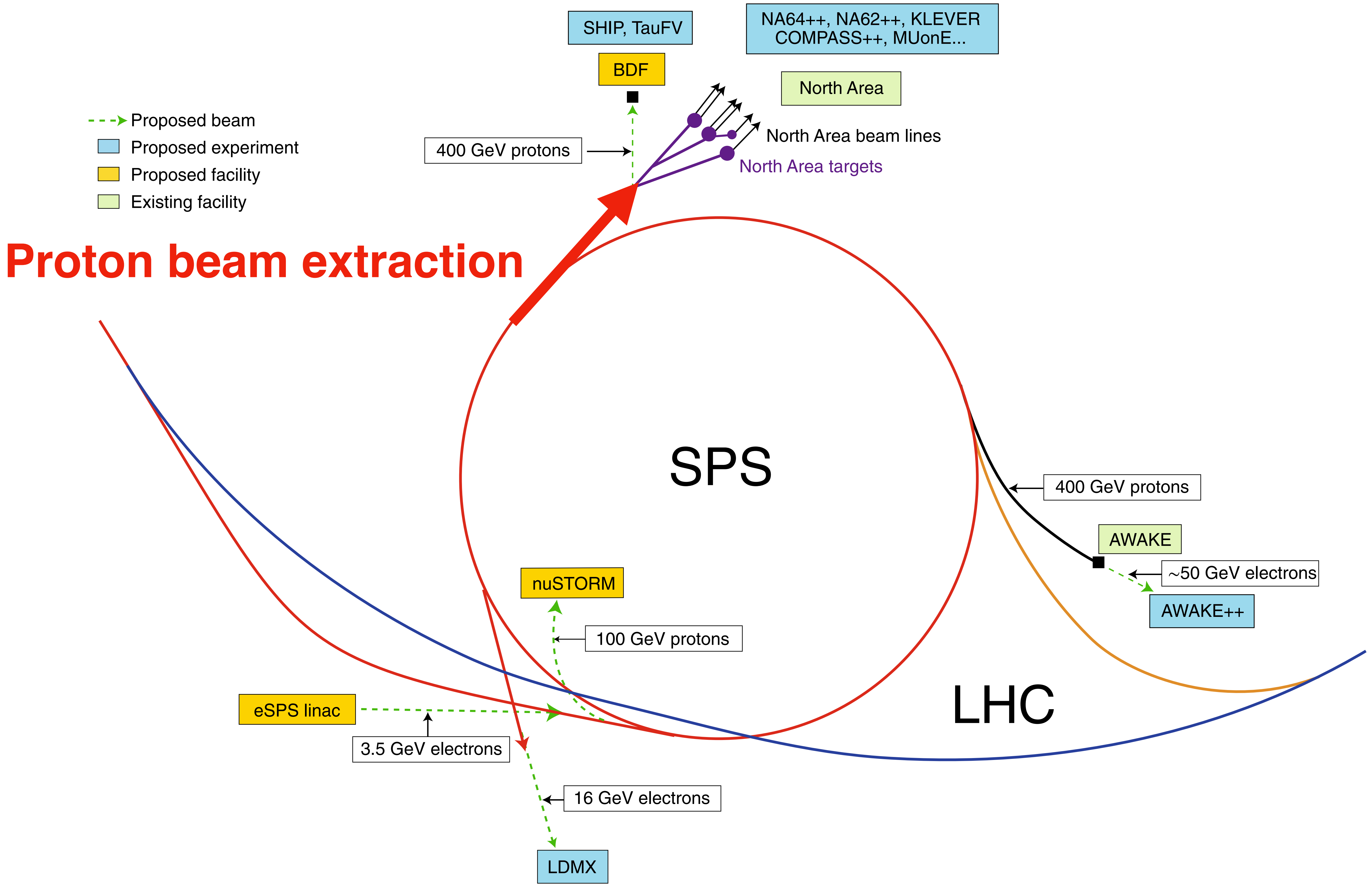

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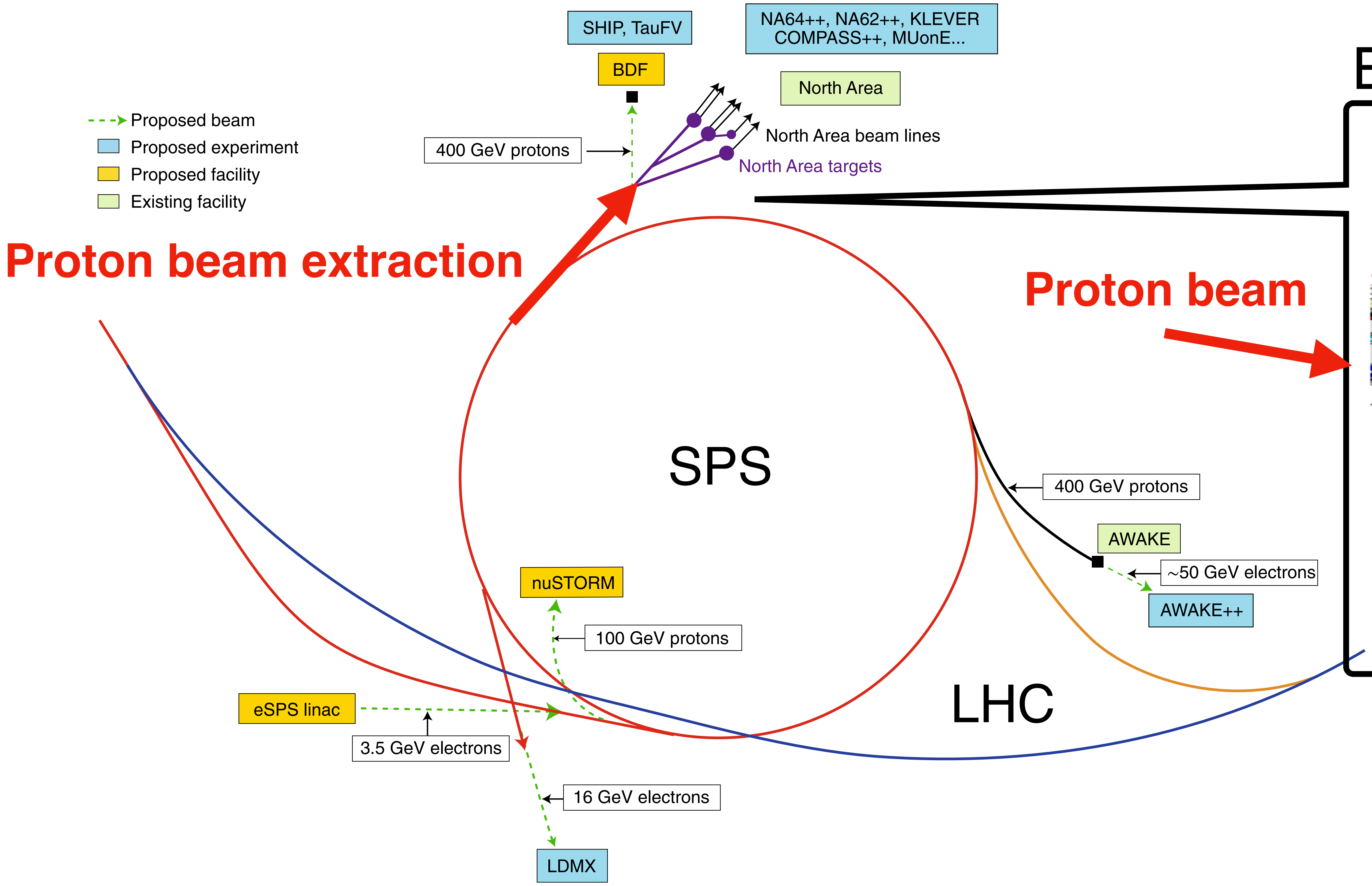

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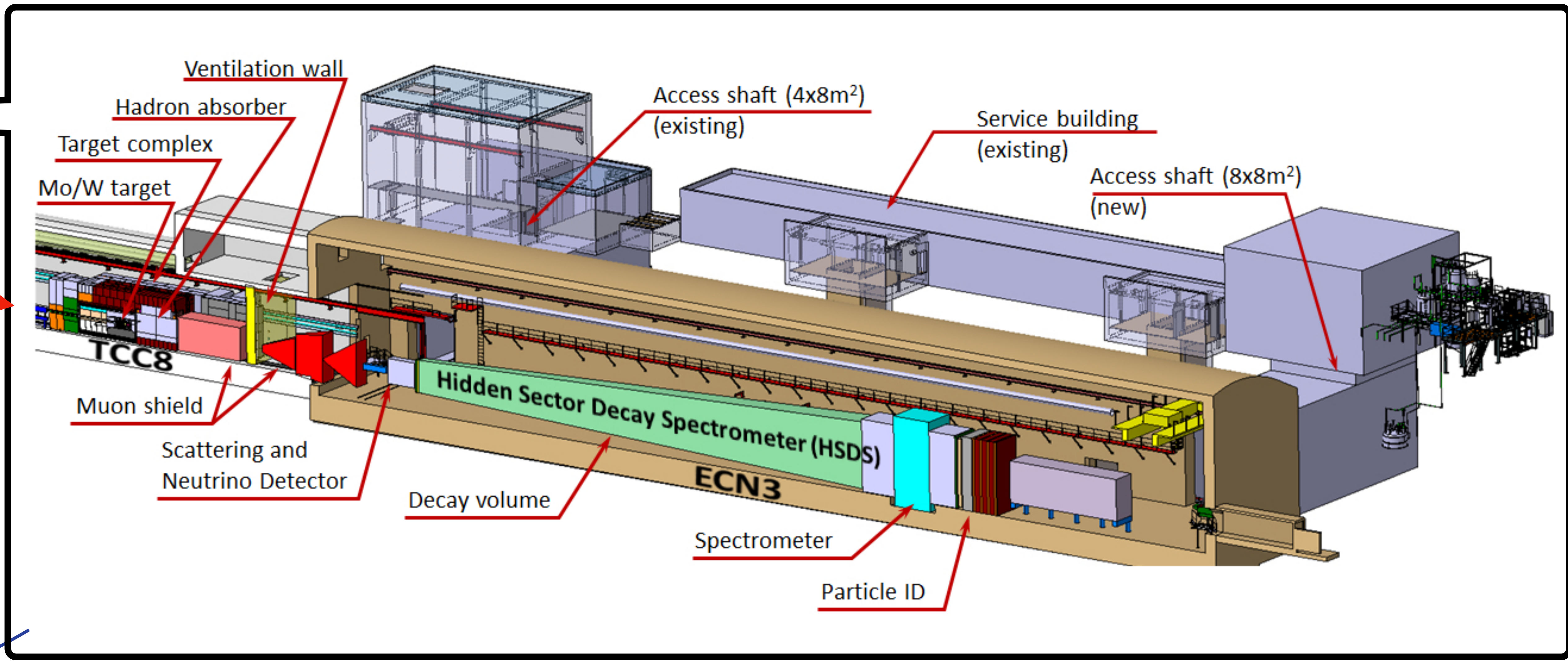

[https://home.web.cern.ch/news/news/experiments]

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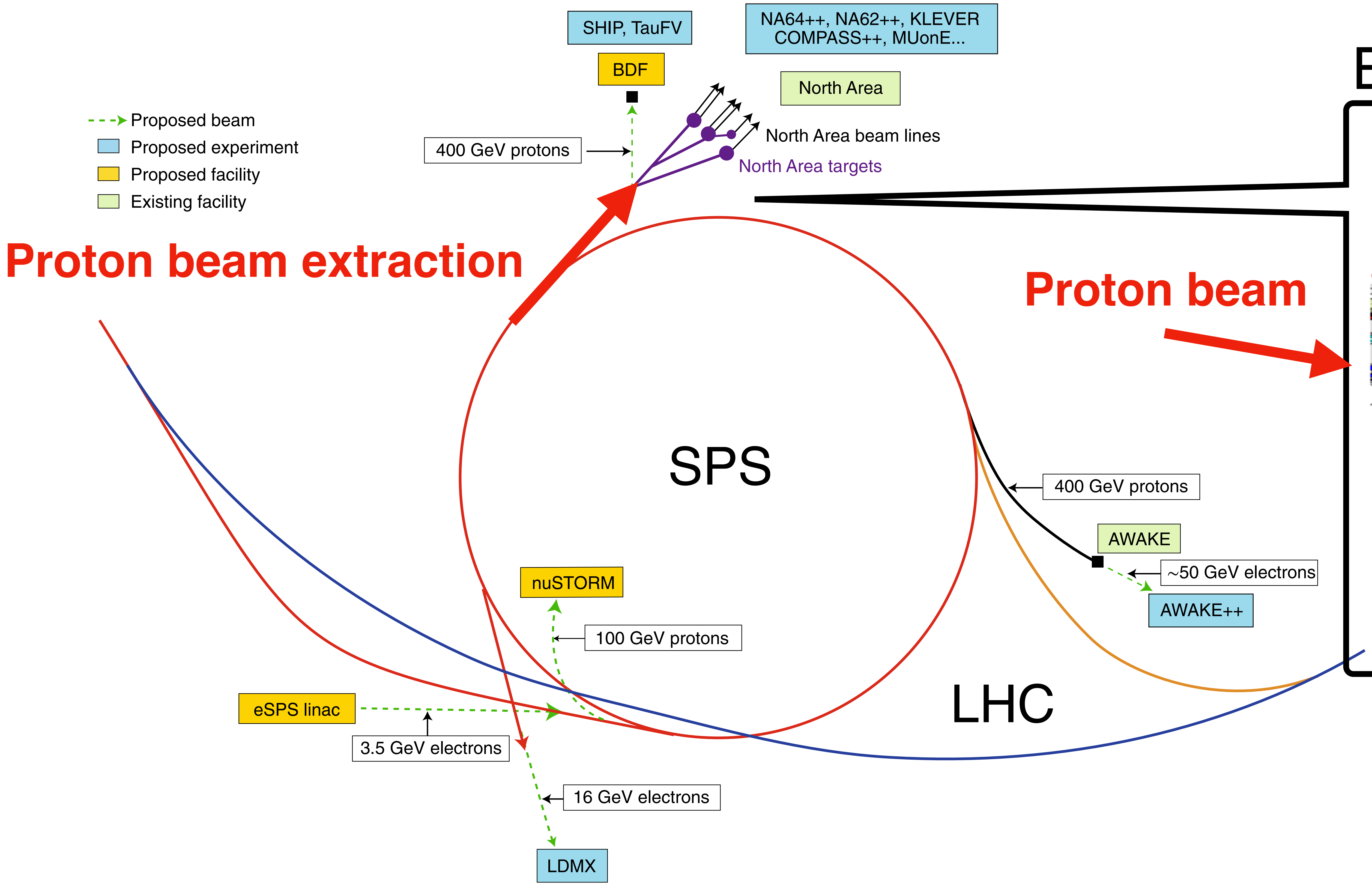

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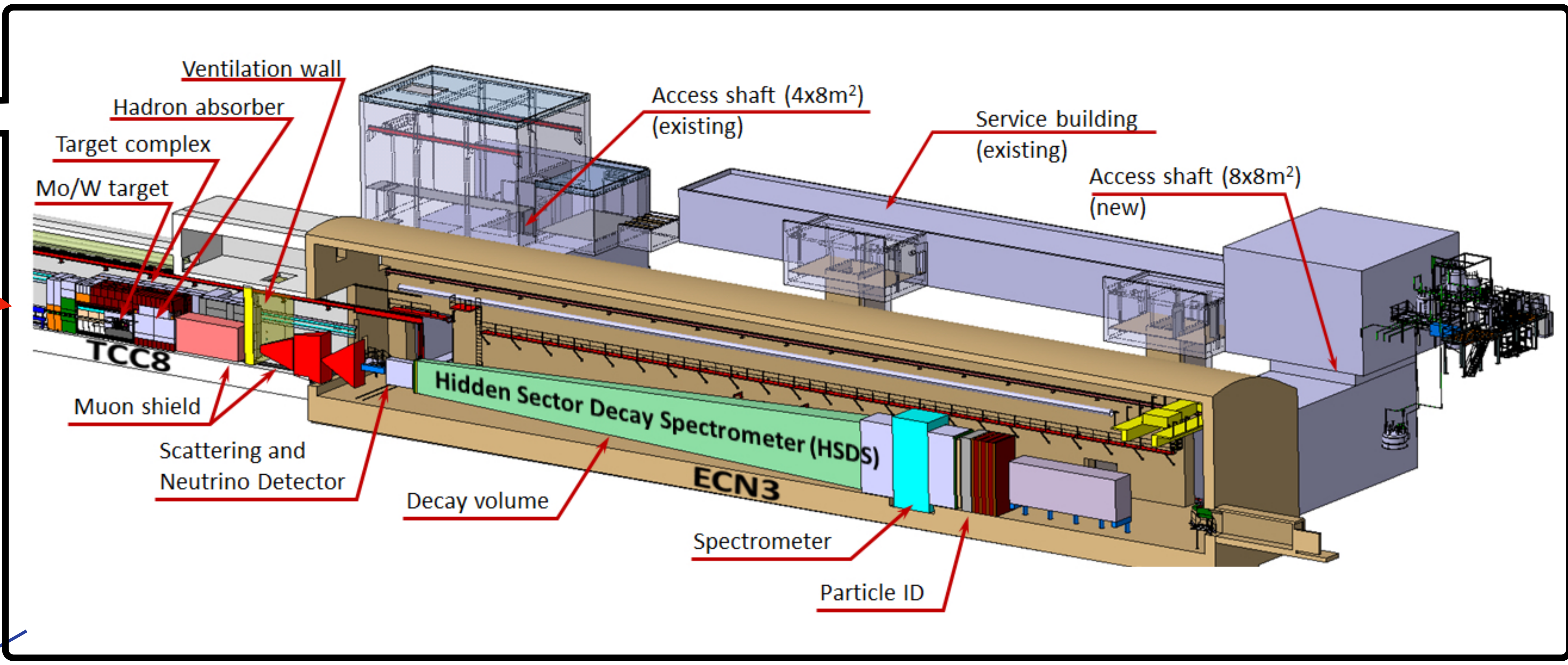

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- SHiP has been **approved** recently by CERN and will start to explore in 2031 in the North Area's ECN3 hall
- LDMX@eSPS, HIKE, SHADOWS, etc are proposed at CERN

Beam dump experiments will run in parallel with future accelerator facilities

Beam dump experiments at future accelerators

- Examples of proposed beam dump experiments at future accelerator

  - SHiP, LDMX*, HIKE, SHADOWS, etc [1901.09966, 2211.16586, etc]

    ⇒ parasitic running of HL-LHC, etc

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Beam dump experiments will run in parallel with future accelerator facilities

Outline

- Introduction
  - dark sector and Sub-GeV dark matter
  - beam dump(fixed-target) experiment
- Key features of beam dump experiment
- A classification of beam dump experiment
- Sensitivity of beam dump experiments at future accelerators
- Summary

A classification of beam dump experiments

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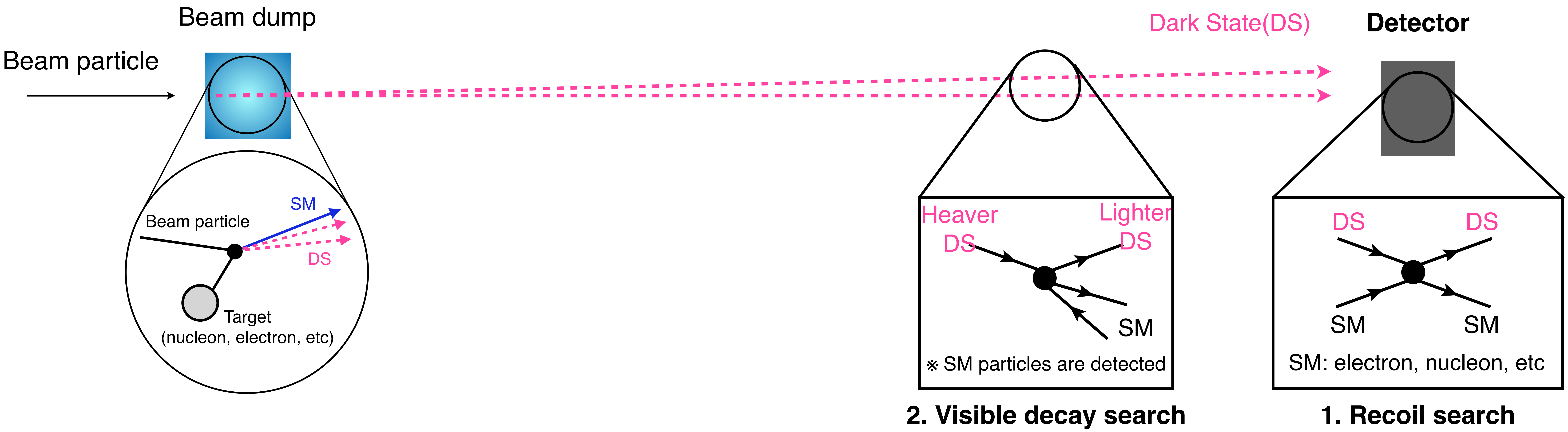

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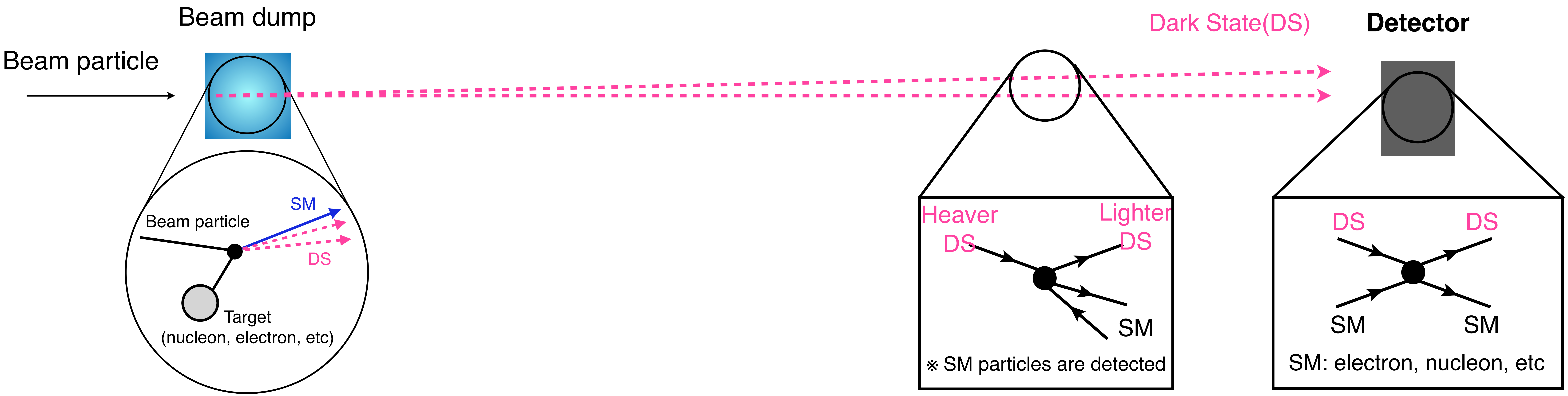

2. Visible decay search **1. Recoil search**

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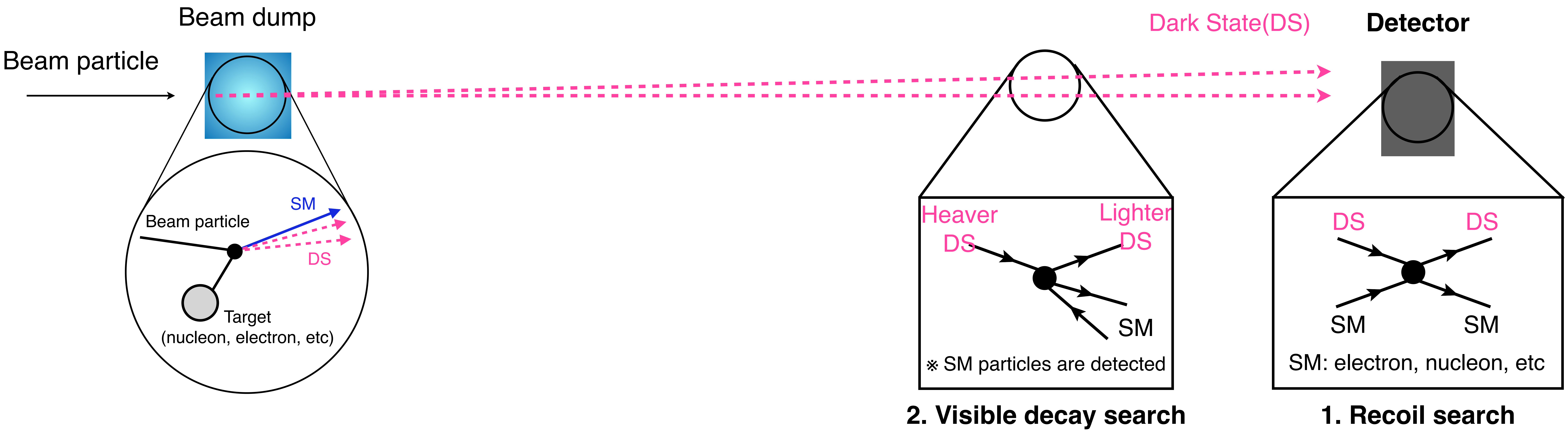

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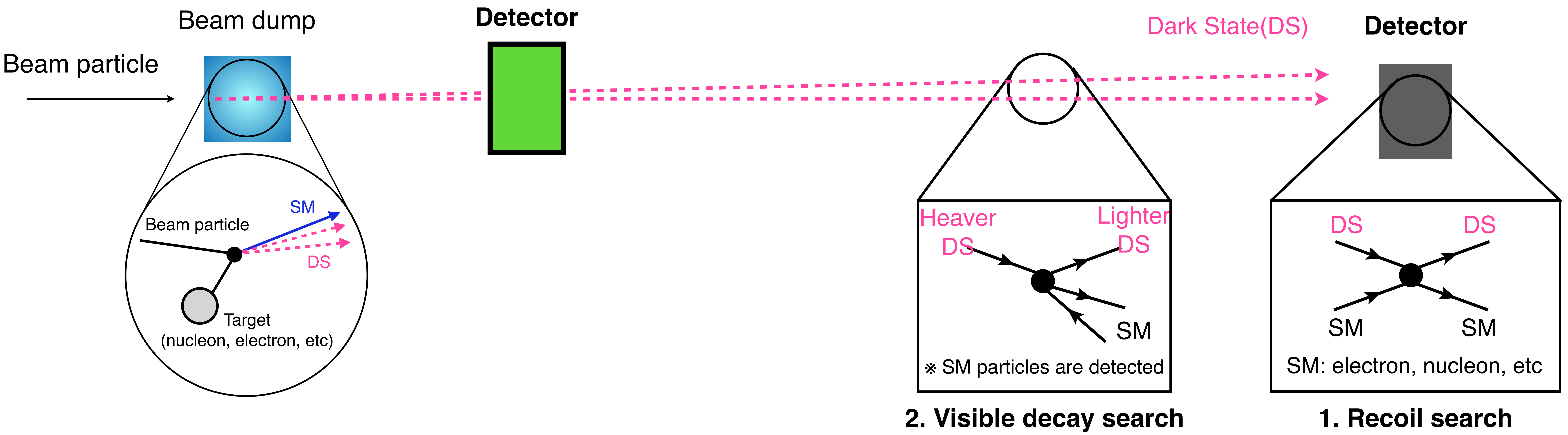

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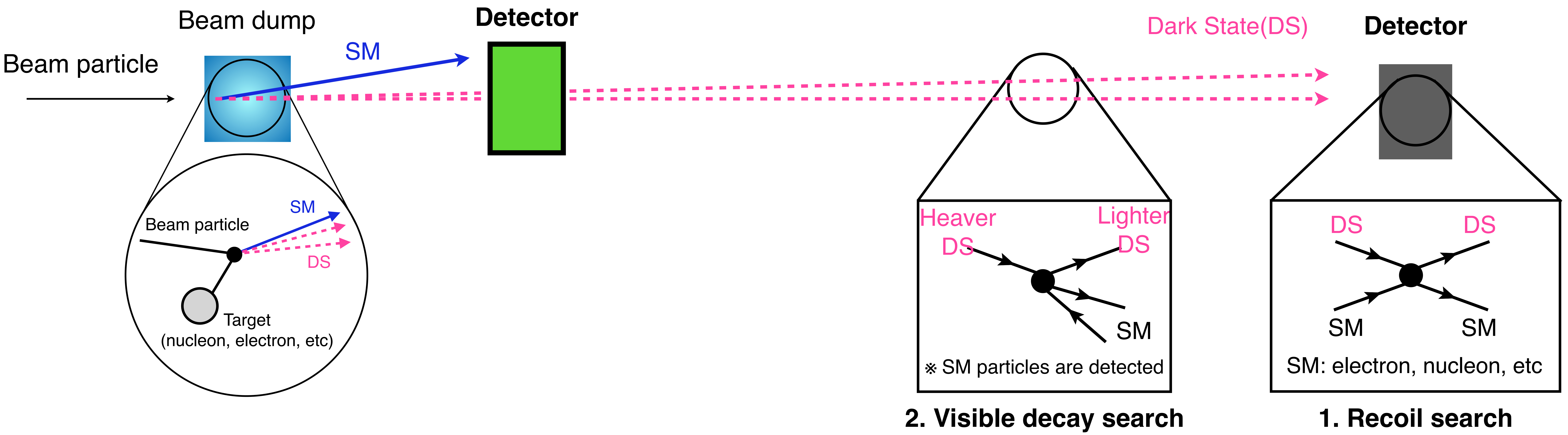

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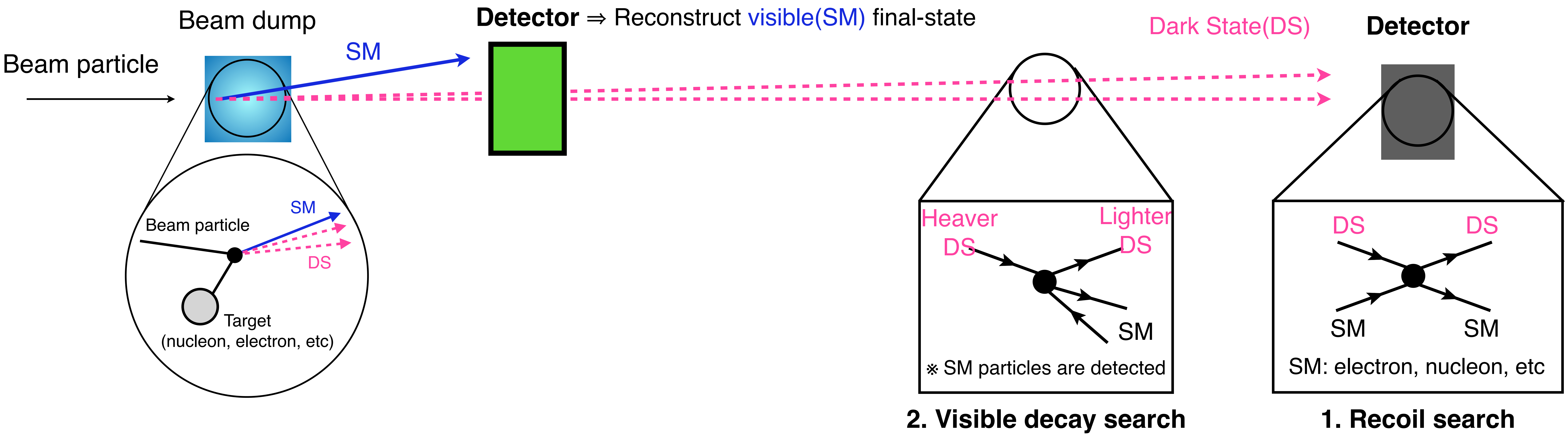

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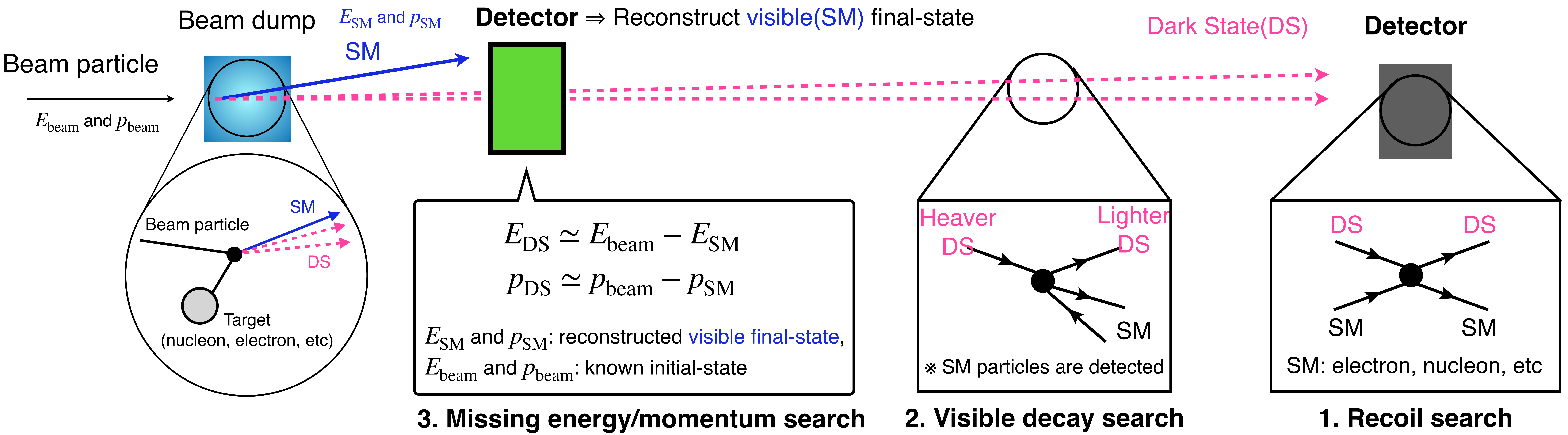

Past and current experiments		E137, LSND, CHARM, NA62, NA64, HPS, etc	E137, LSND, MiniBooNE, COHERENT CsI, etc
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A classification of beam dump experiments

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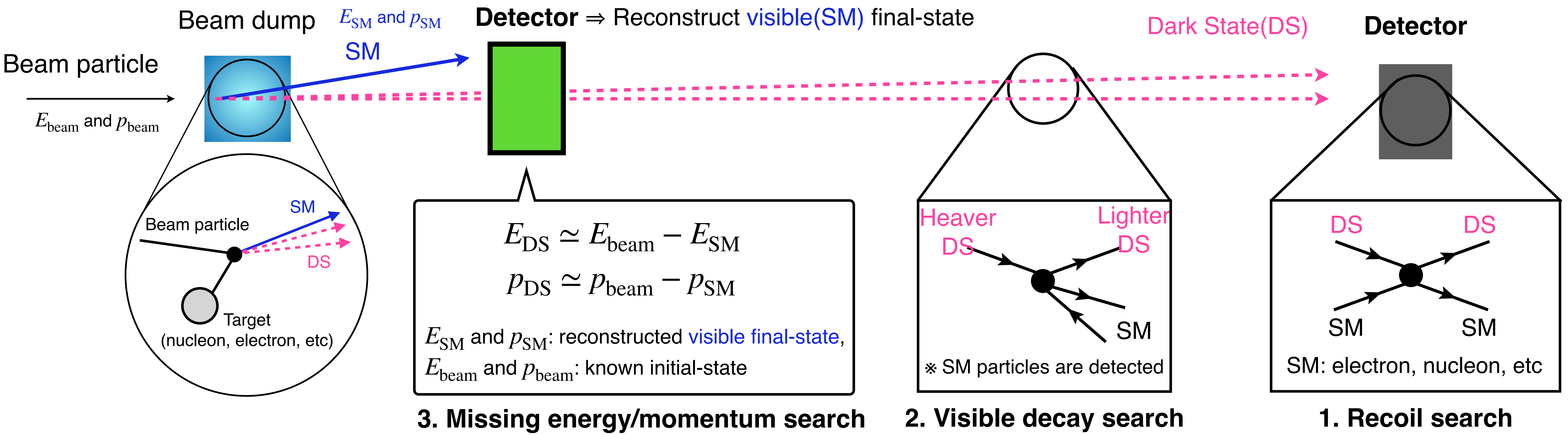

	3. Missing energy/momentum search	2. Visible decay search	1. Recoil search
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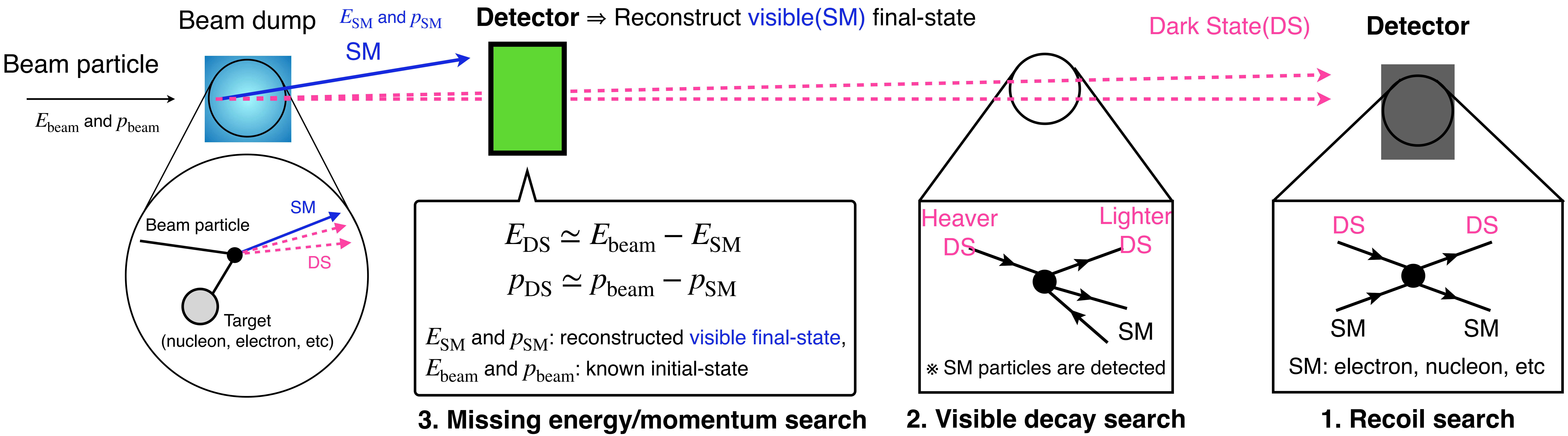

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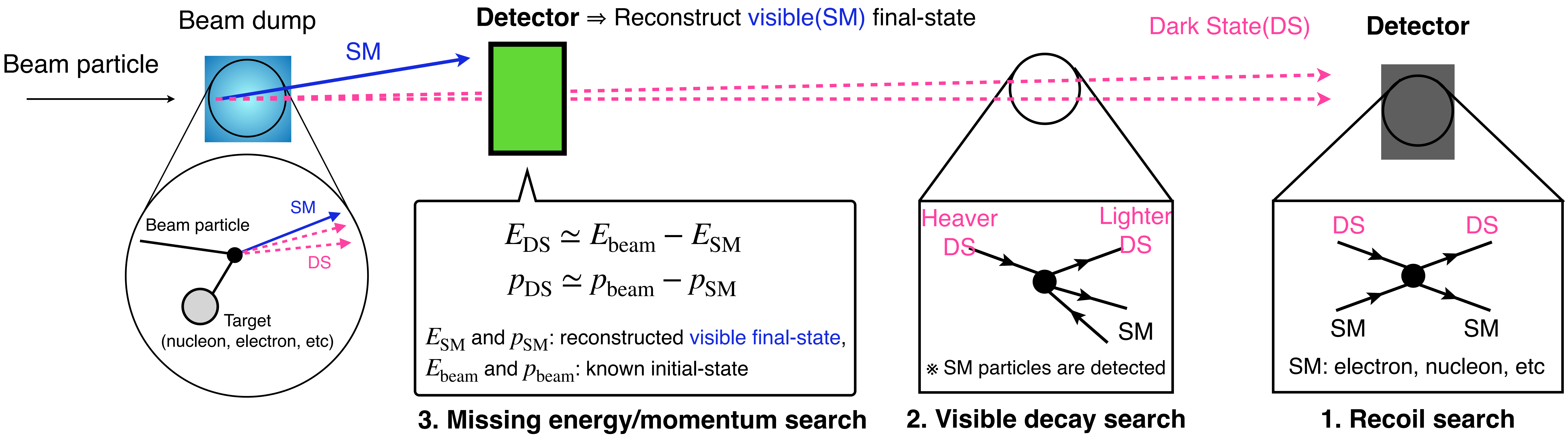

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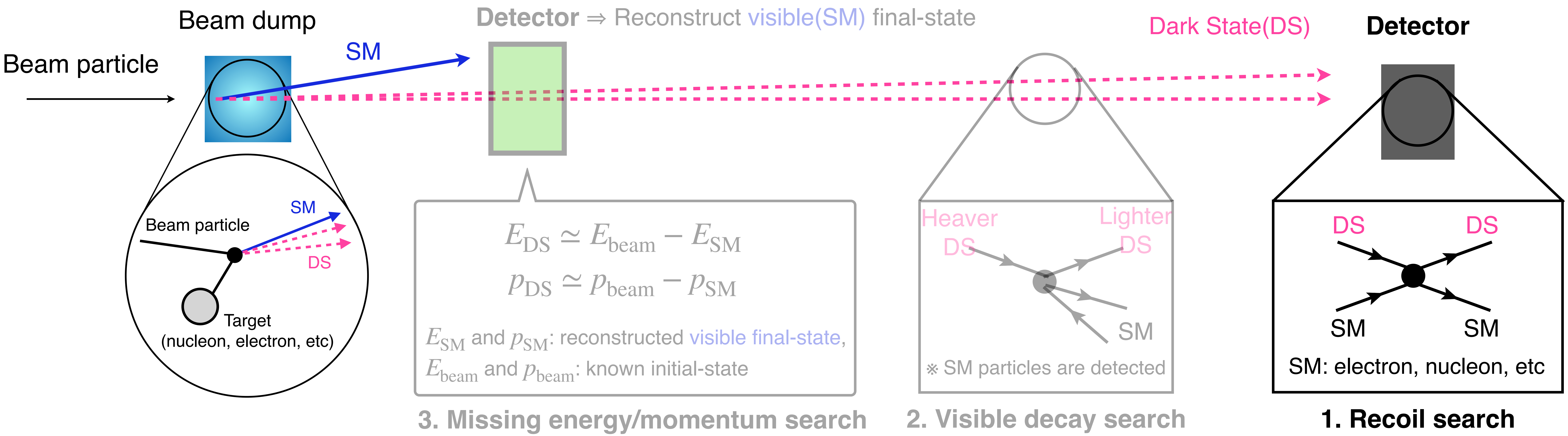

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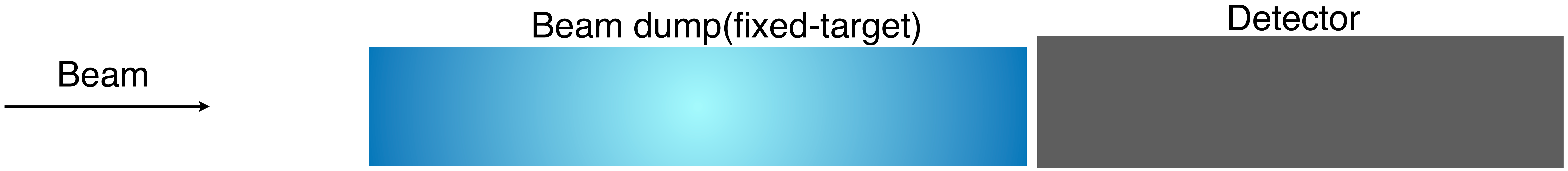
Beam dump experiments are divided into three detection approaches

Recoil search (1)

- Typical setup:



Recoil search (1)

- Typical setup:

Benchmark model: $\mathscr{L} \supset \epsilon e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu \bar{\chi}\gamma^\mu \chi$ A': Dark photon, χ: Dark Matter, $J^\mu_{\rm EM}$: SM EM current

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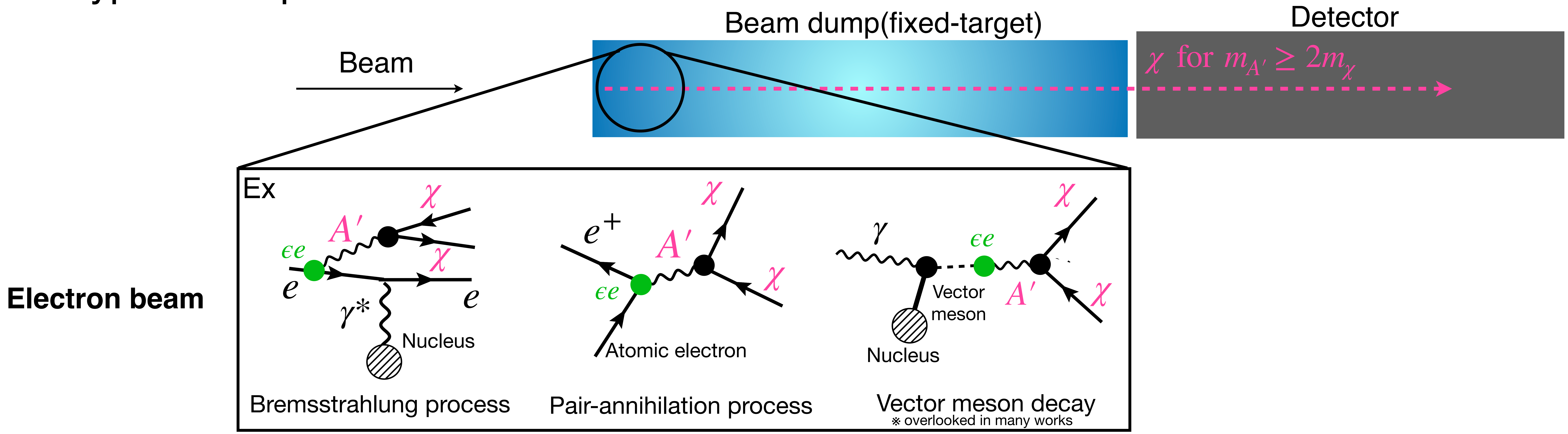

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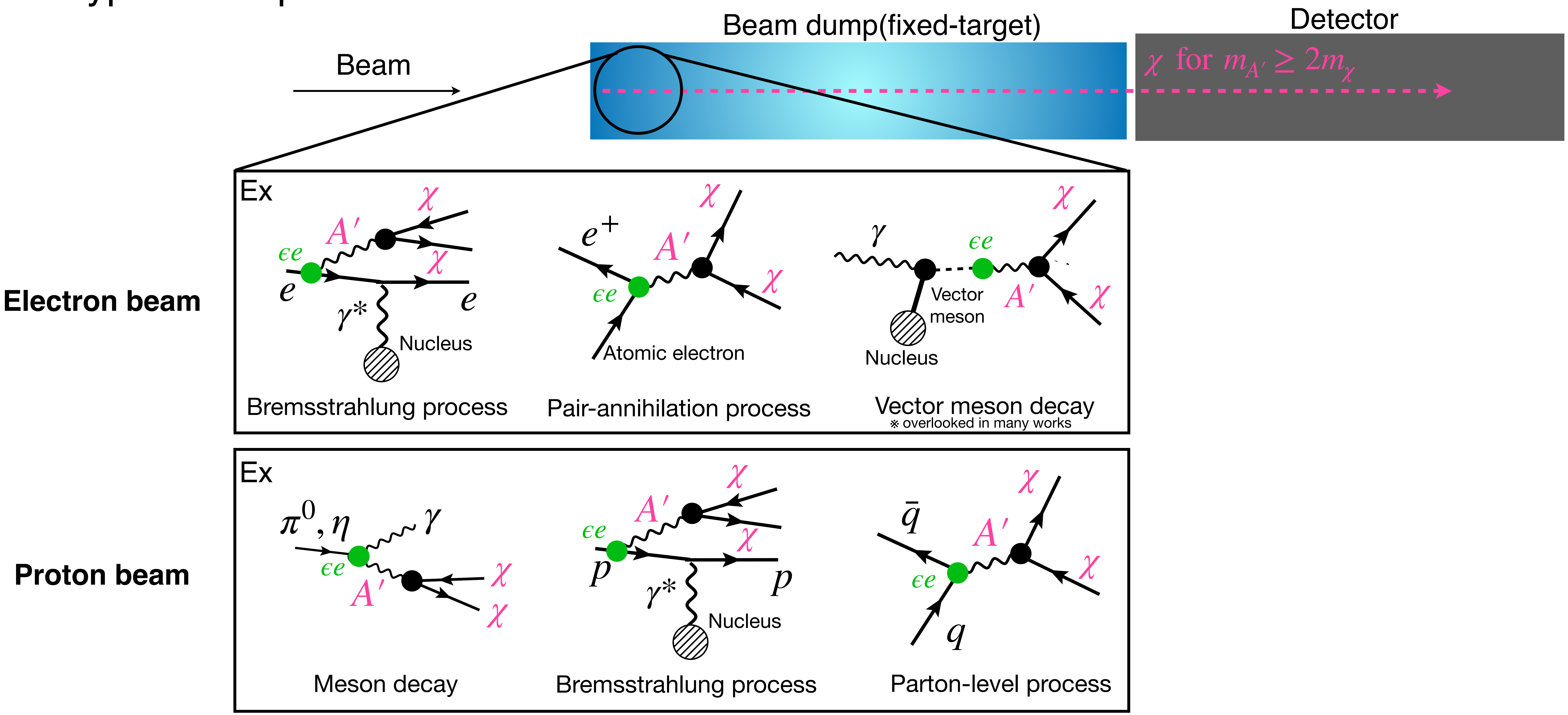

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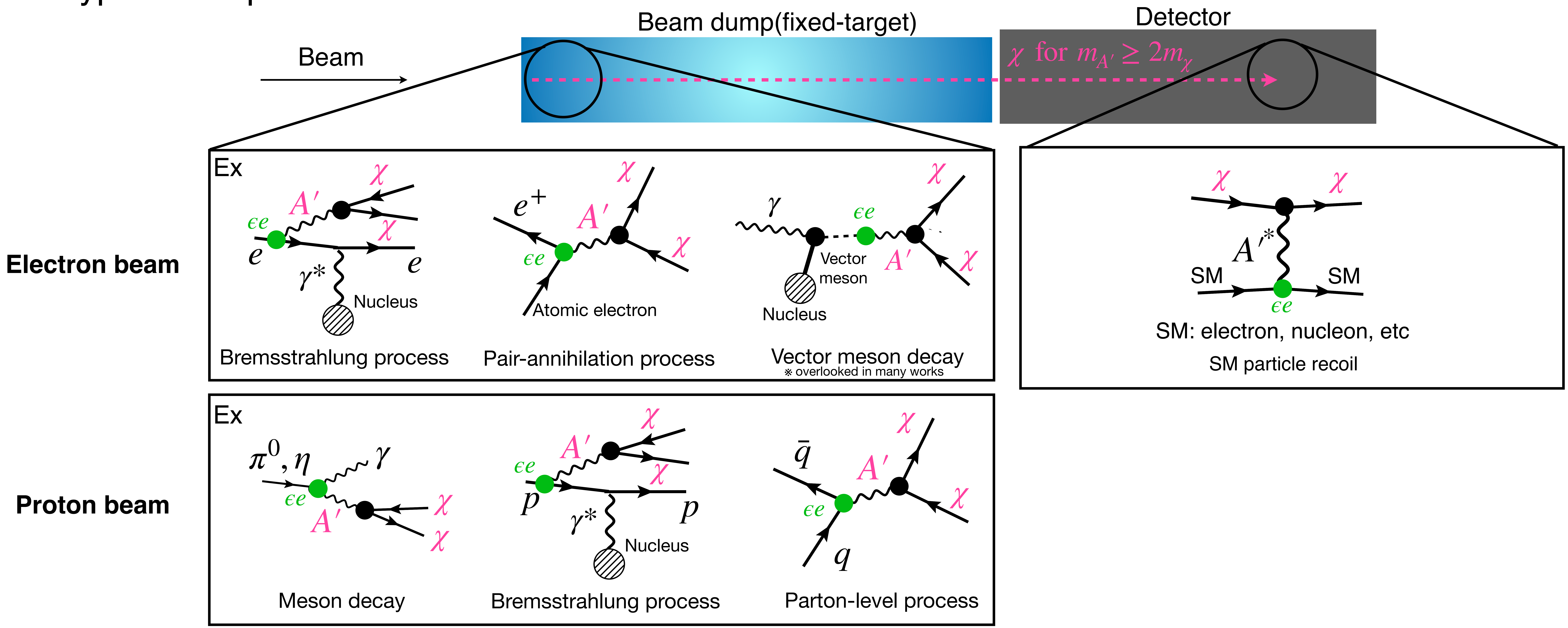

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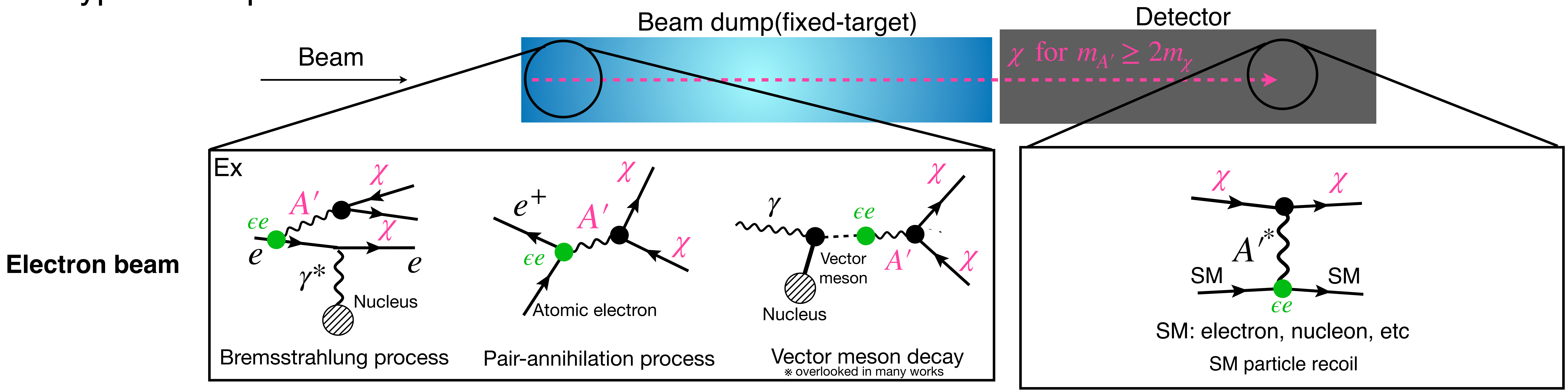

- # of detected DS signature (signal events):

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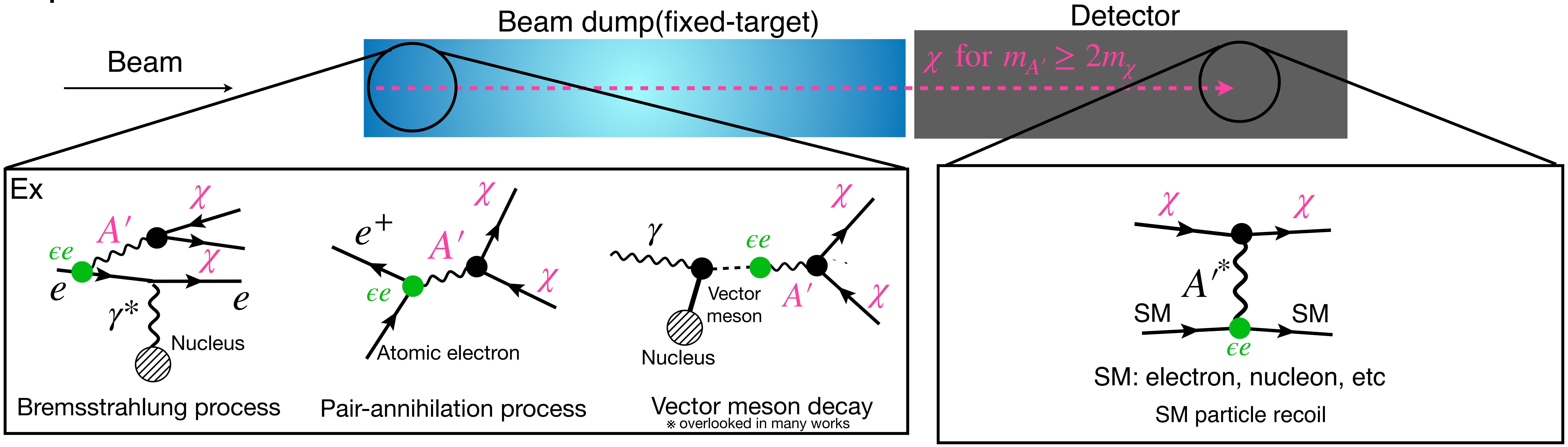

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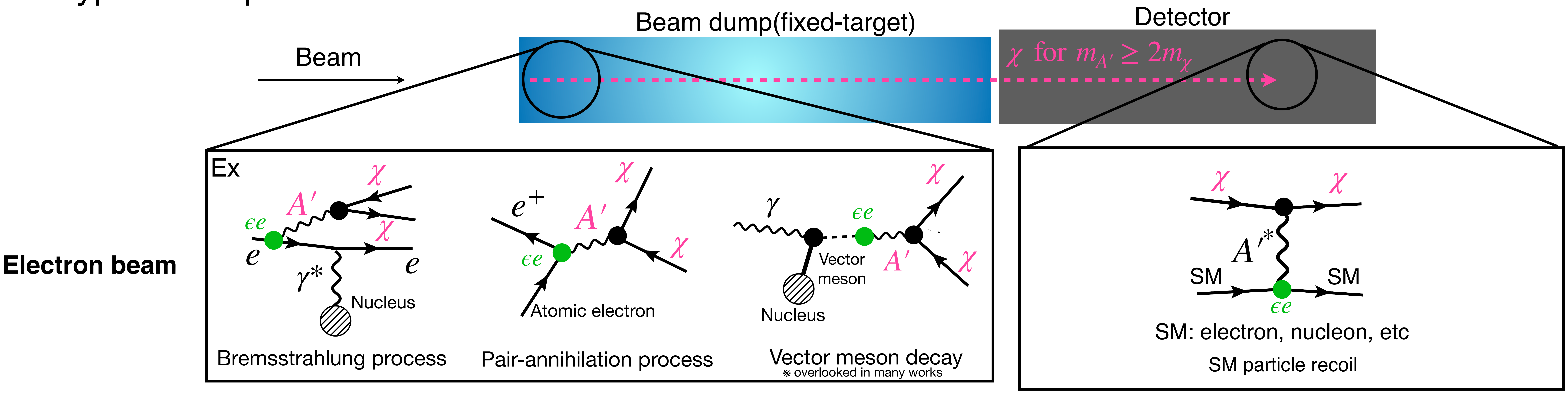

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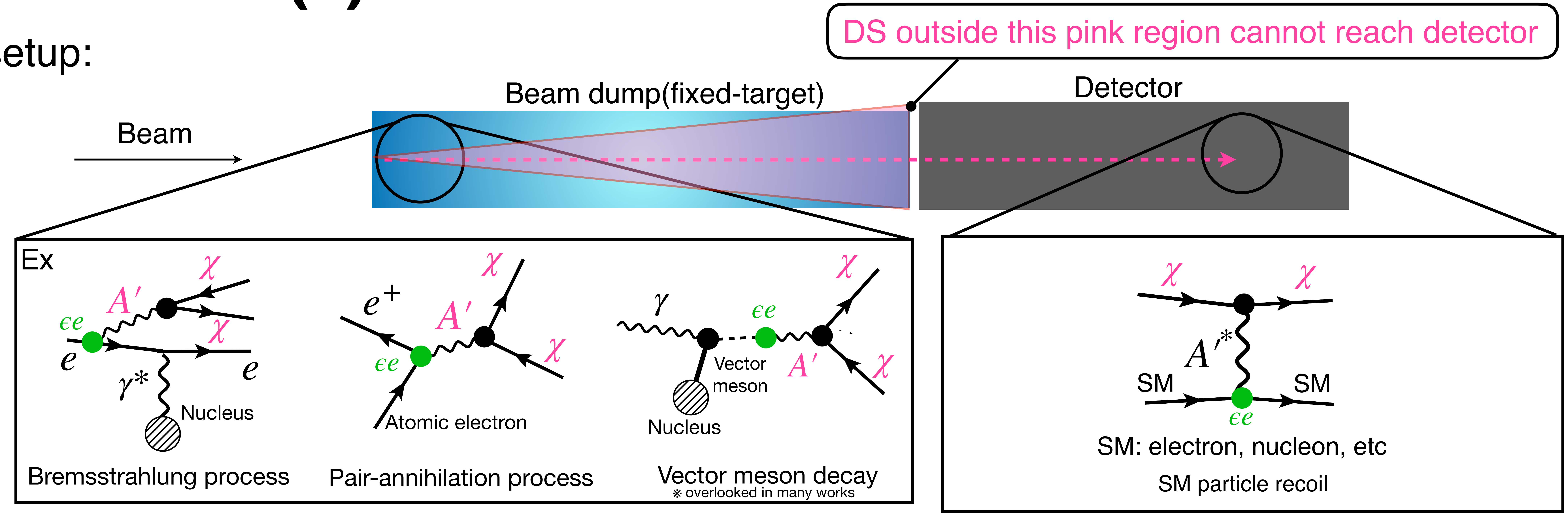

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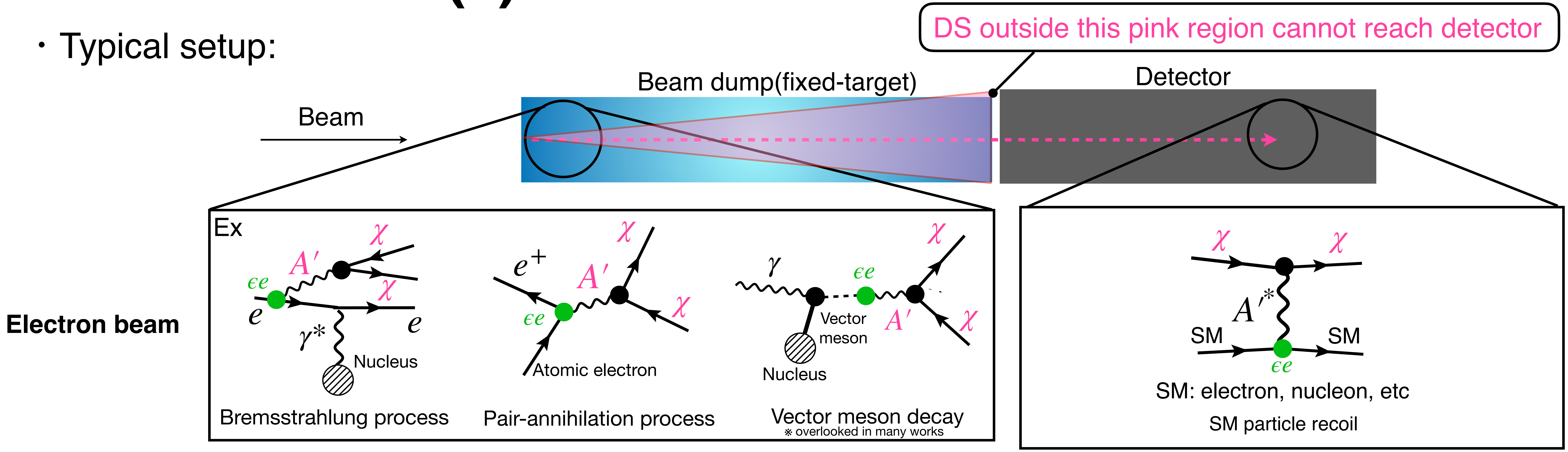

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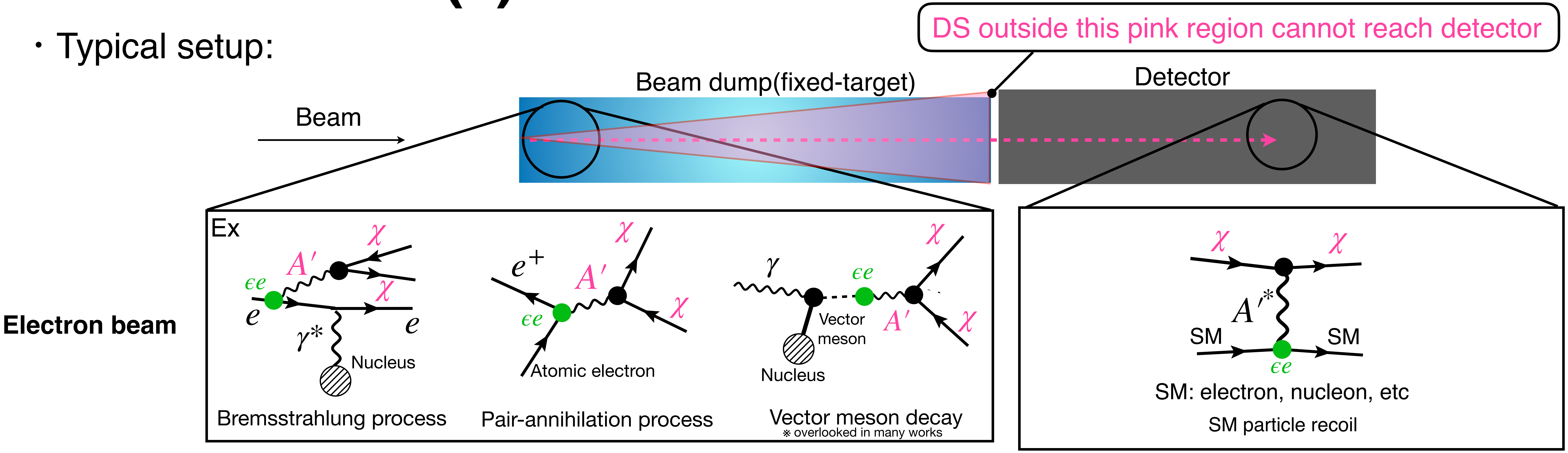

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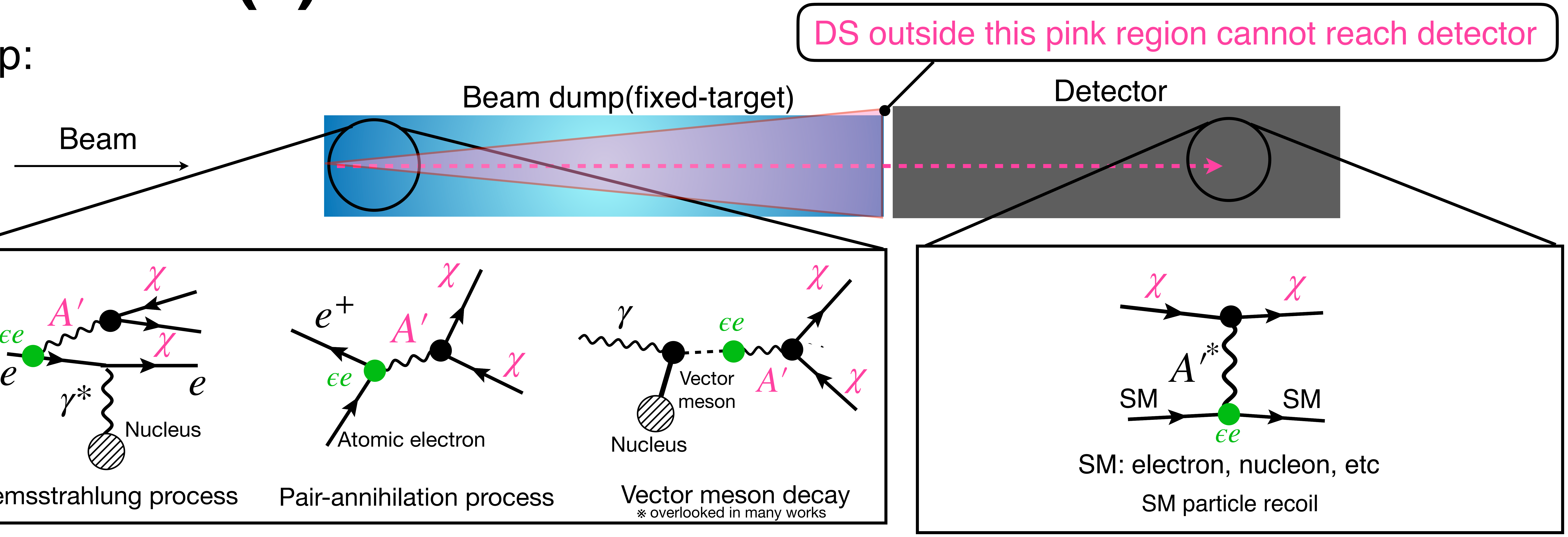

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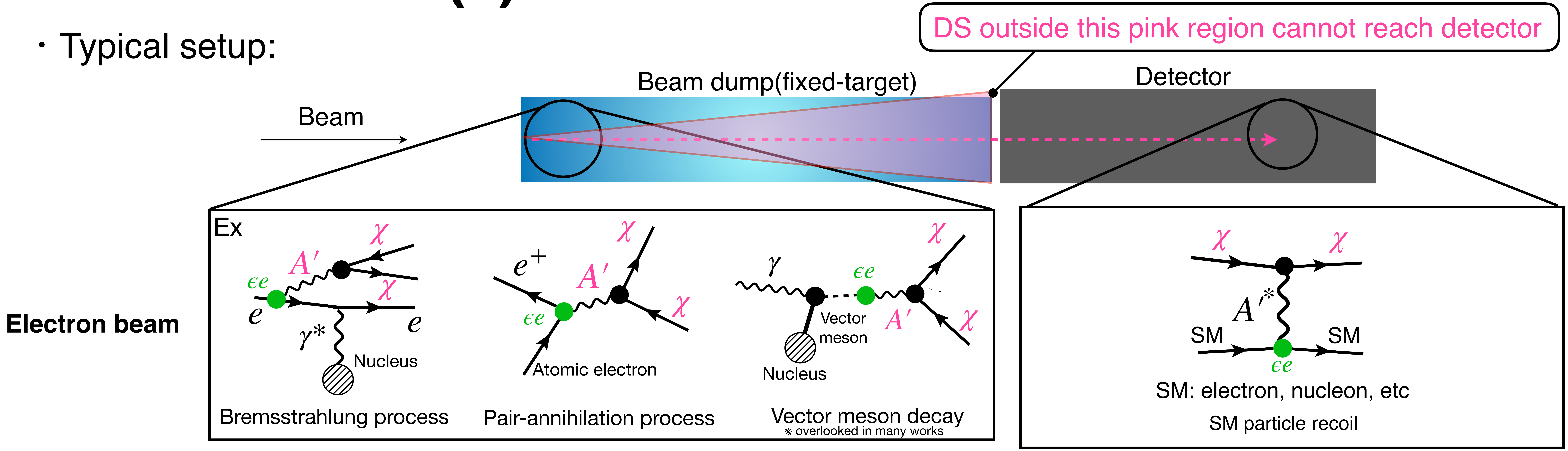

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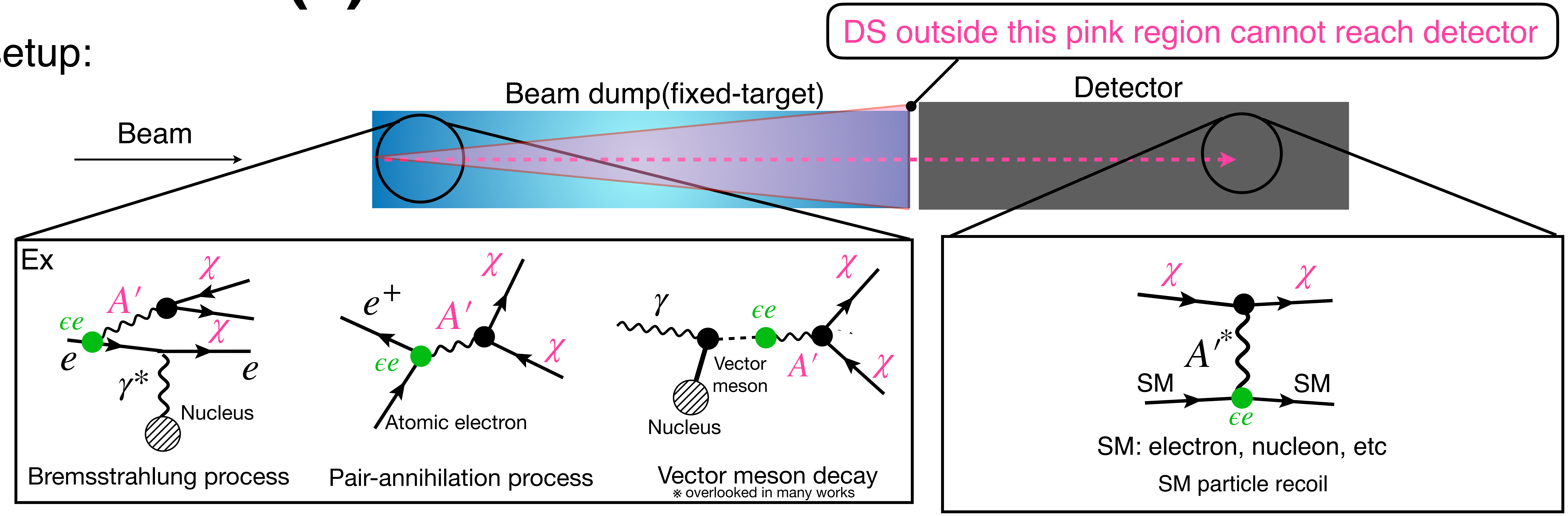

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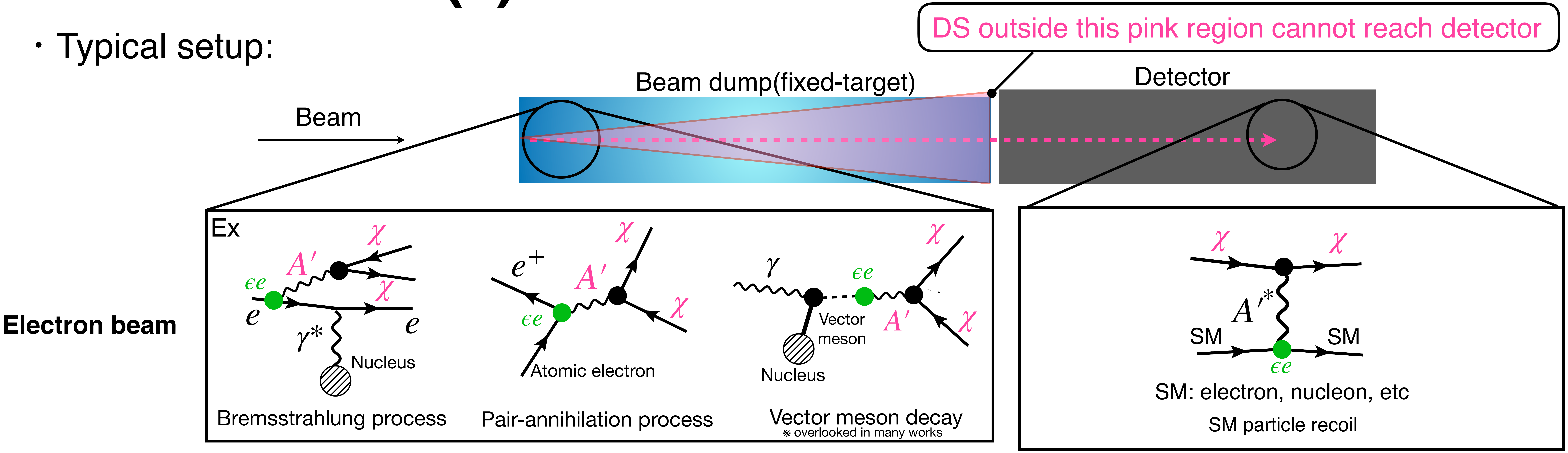

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High flux beam, near※ and large detectors are suited for recoil search

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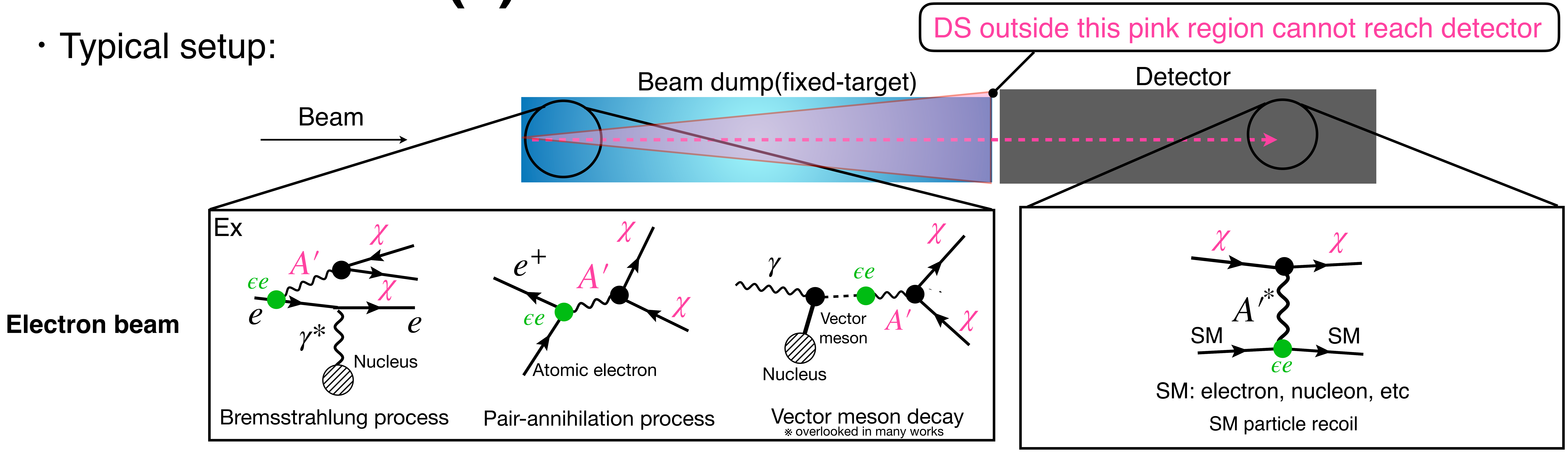

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High flux beam, near※ and large detectors are suited for recoil search

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

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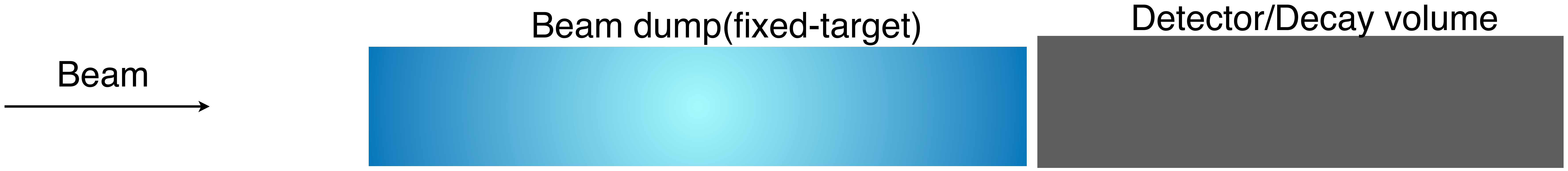

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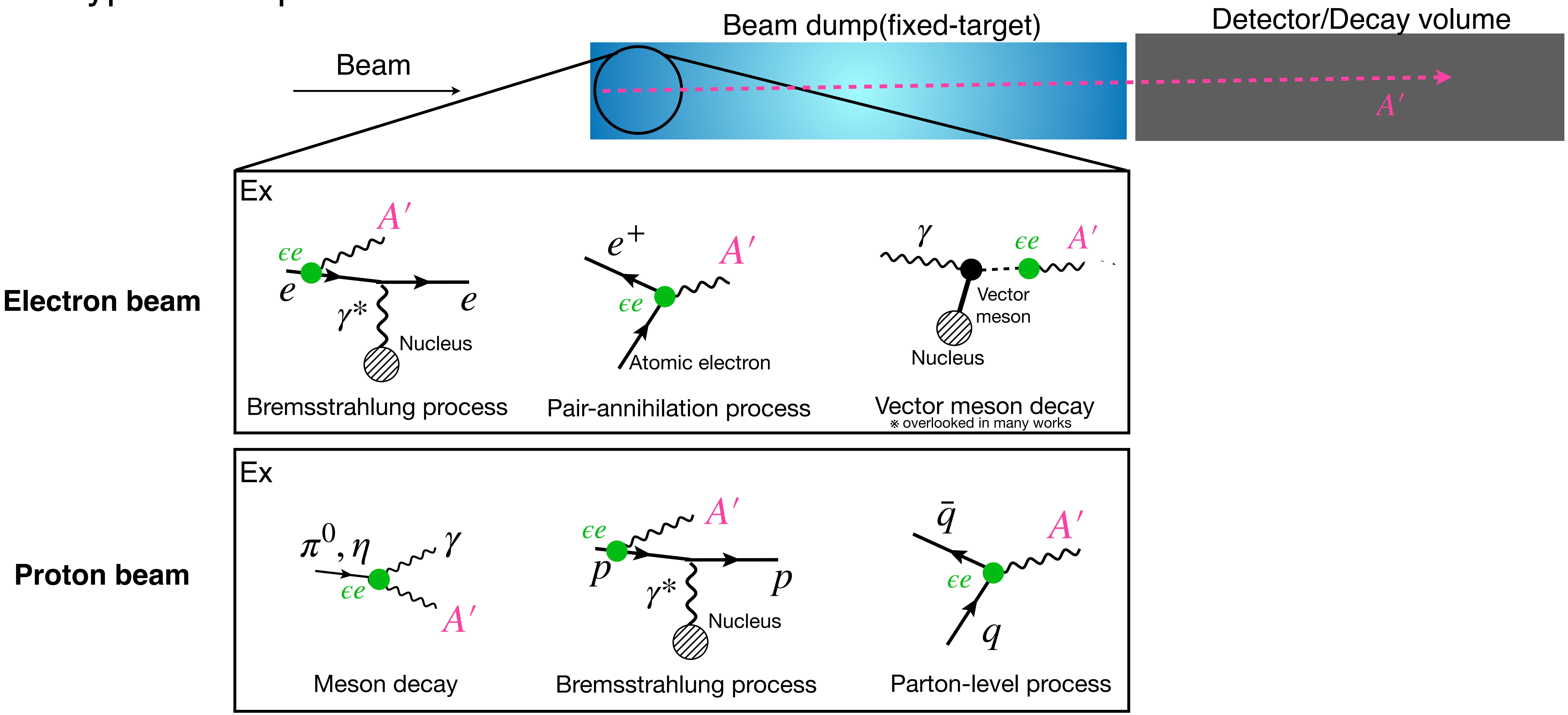

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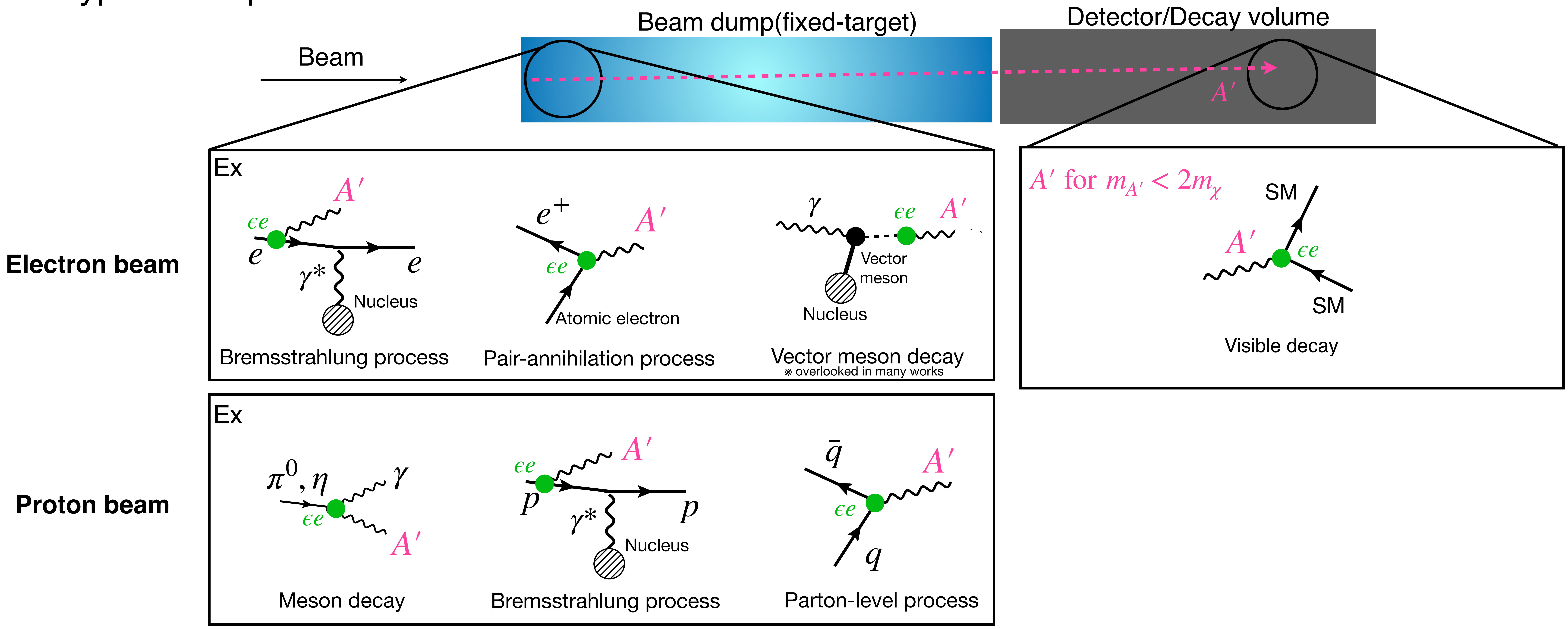

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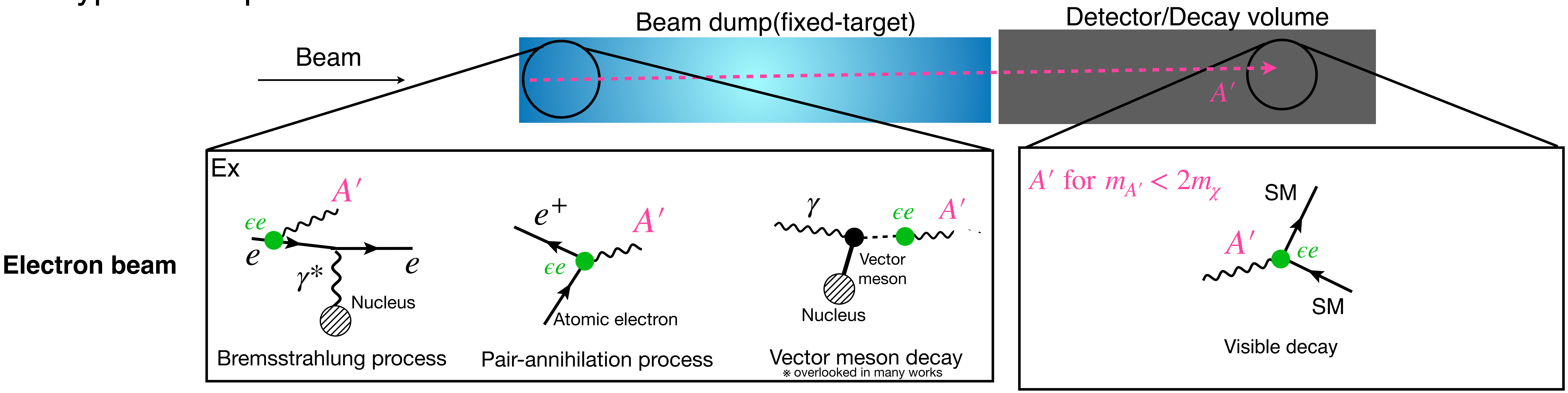

- # of detected dark state(DS) signature:

Visible decay search (2)

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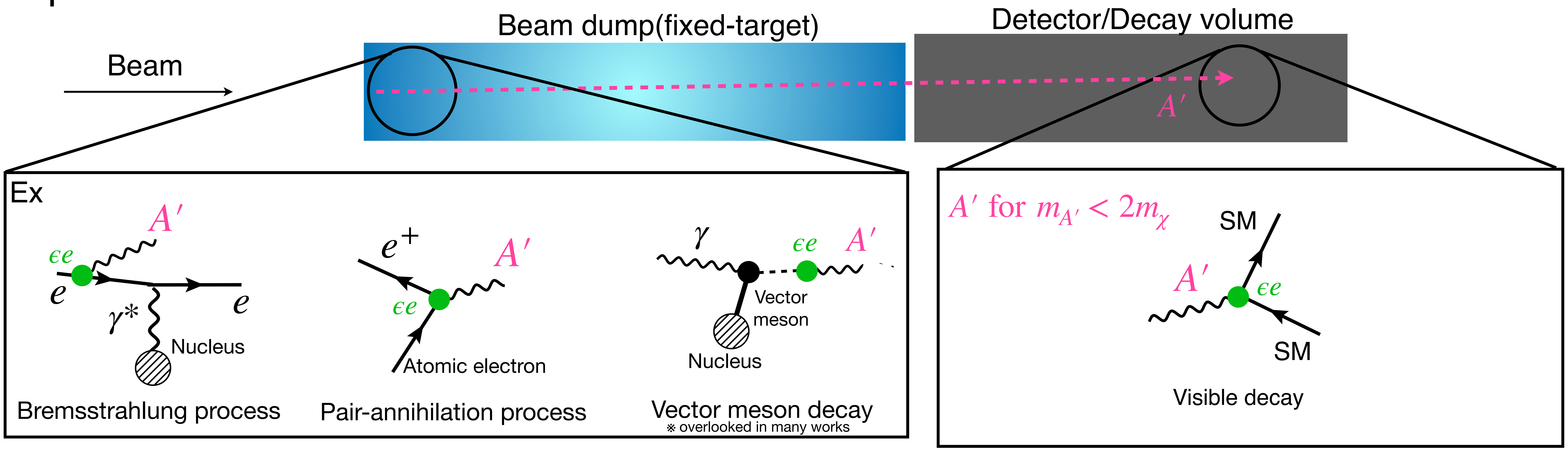
Electron beam



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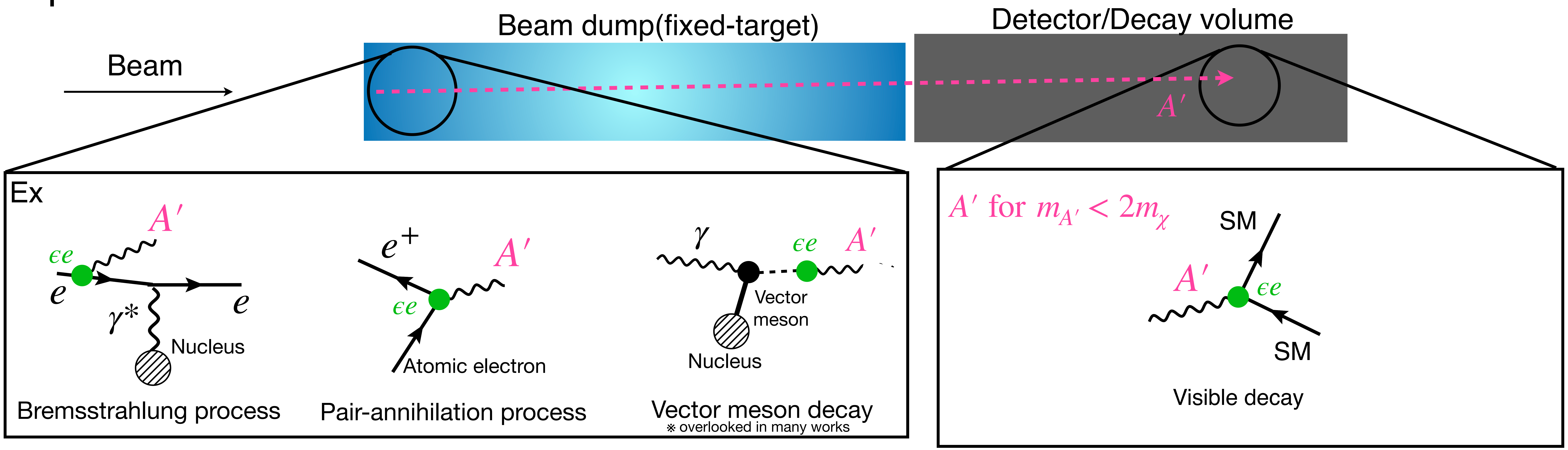

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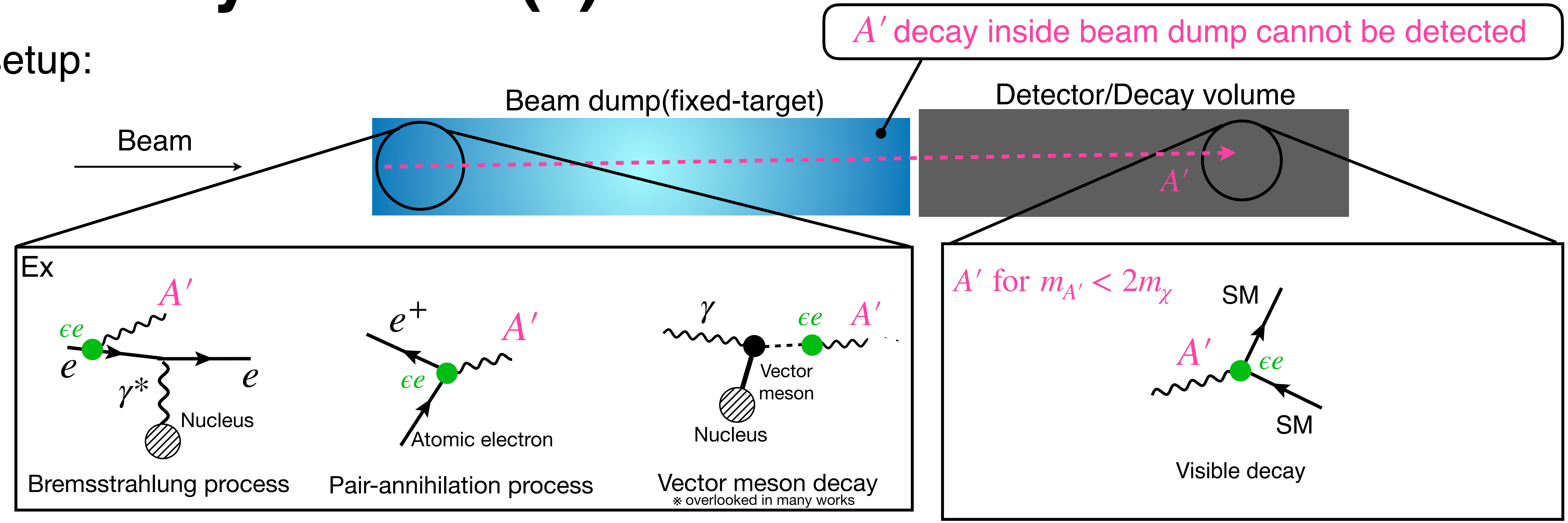

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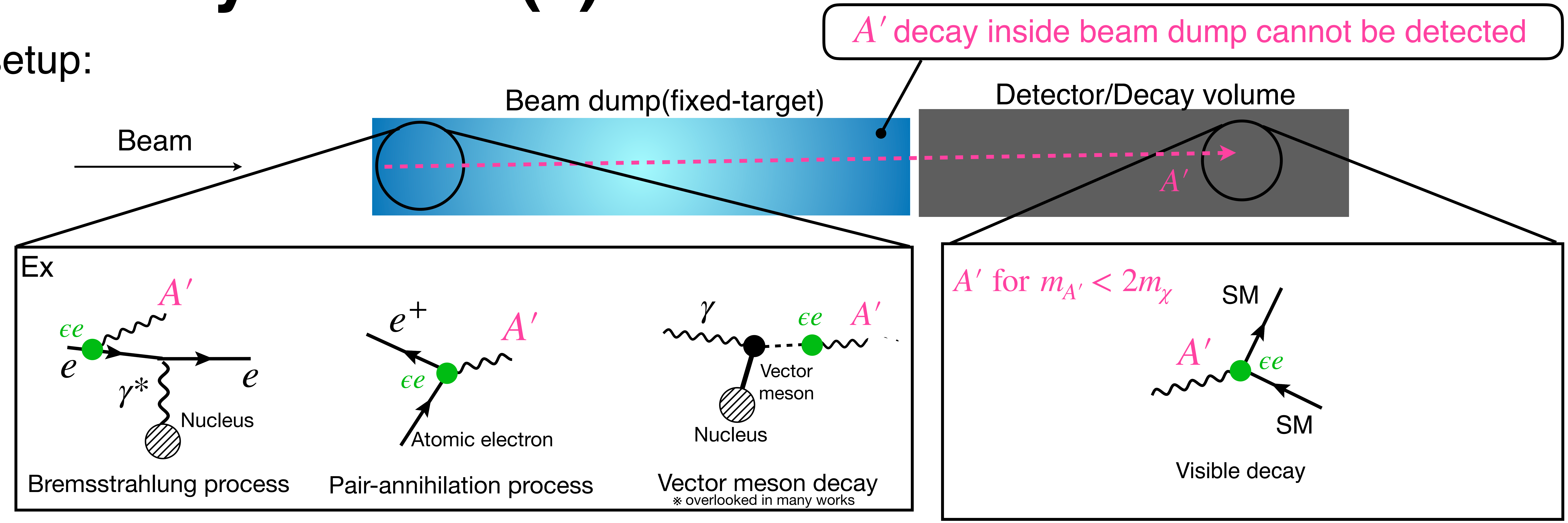

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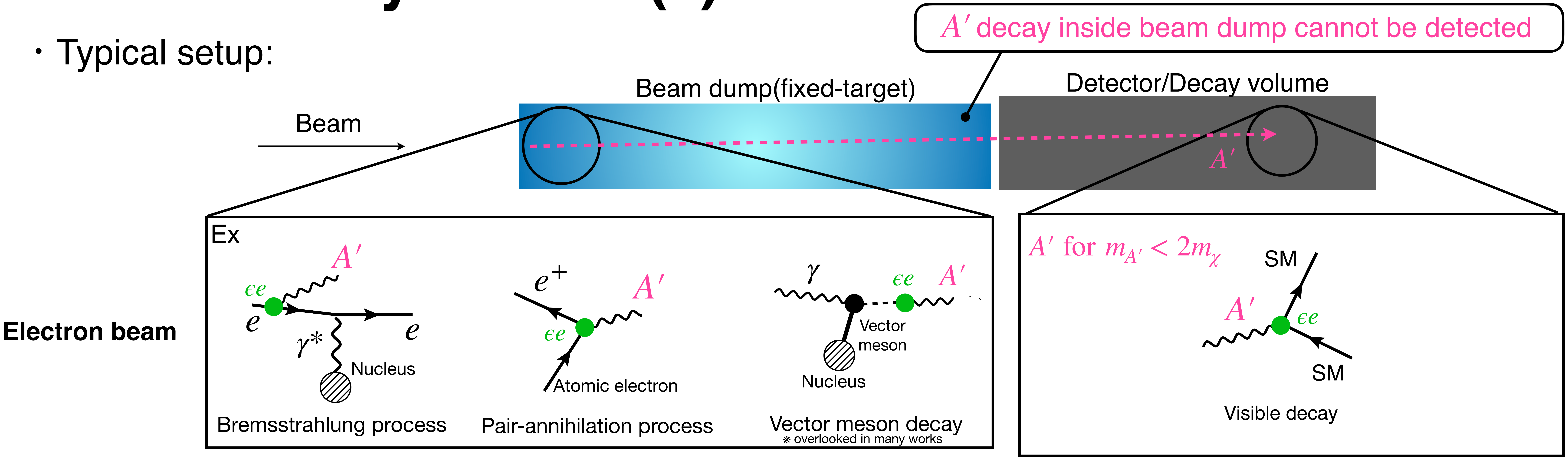

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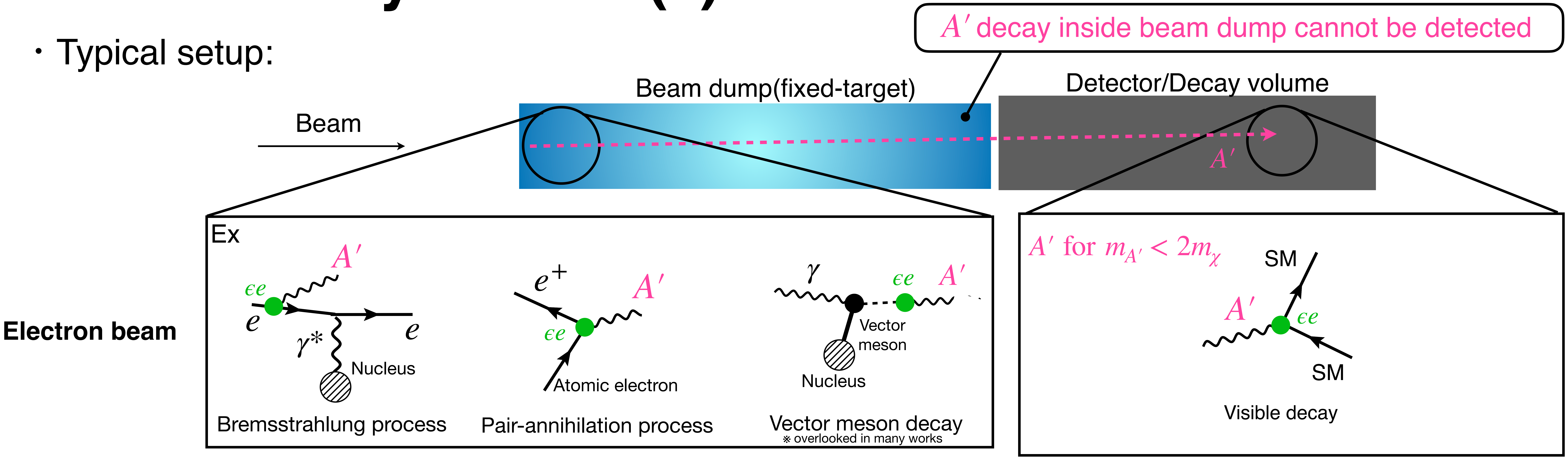

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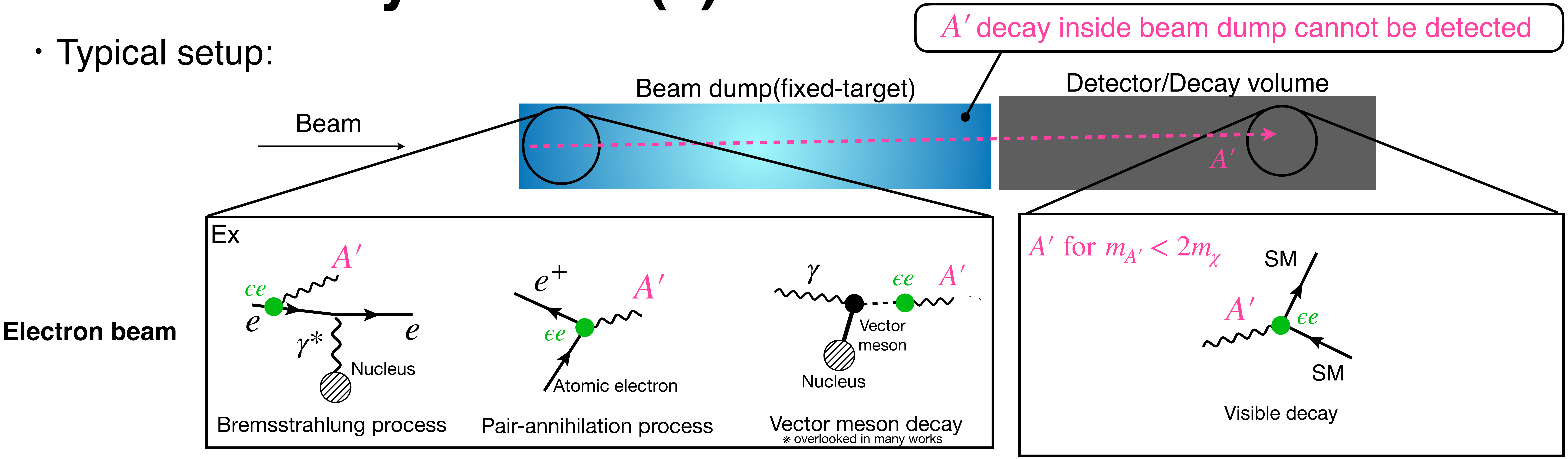

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Thick(Thin) target experiments can be sensitive to long(short) lifetime dark states

※ In thin target experiments, e.g, HPS, NA64(visible decay search), continuous beam(low-intensity) is used to distinguish signal signatures

Missing energy/momentum signal processes

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Missing energy search, e.g., NA64:

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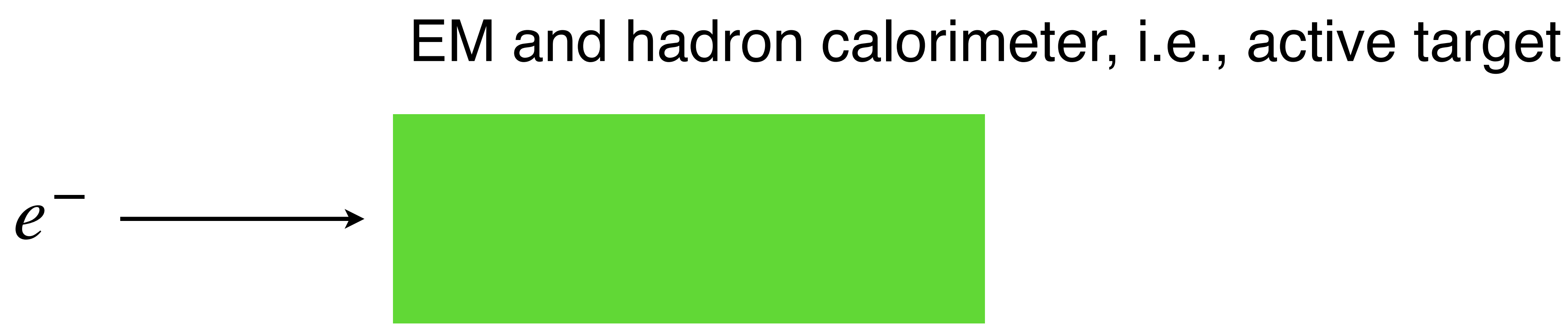

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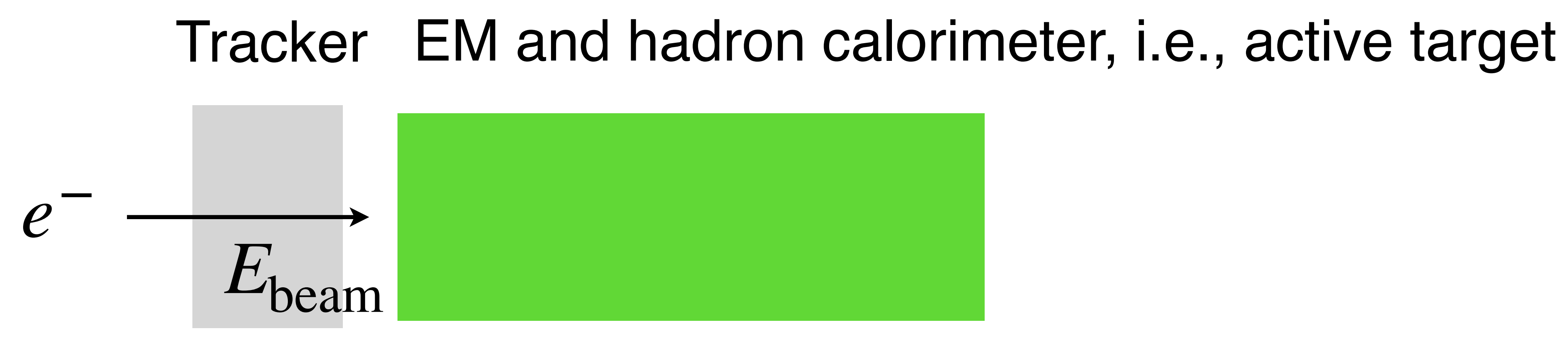
Missing energy search, e.g., NA64:



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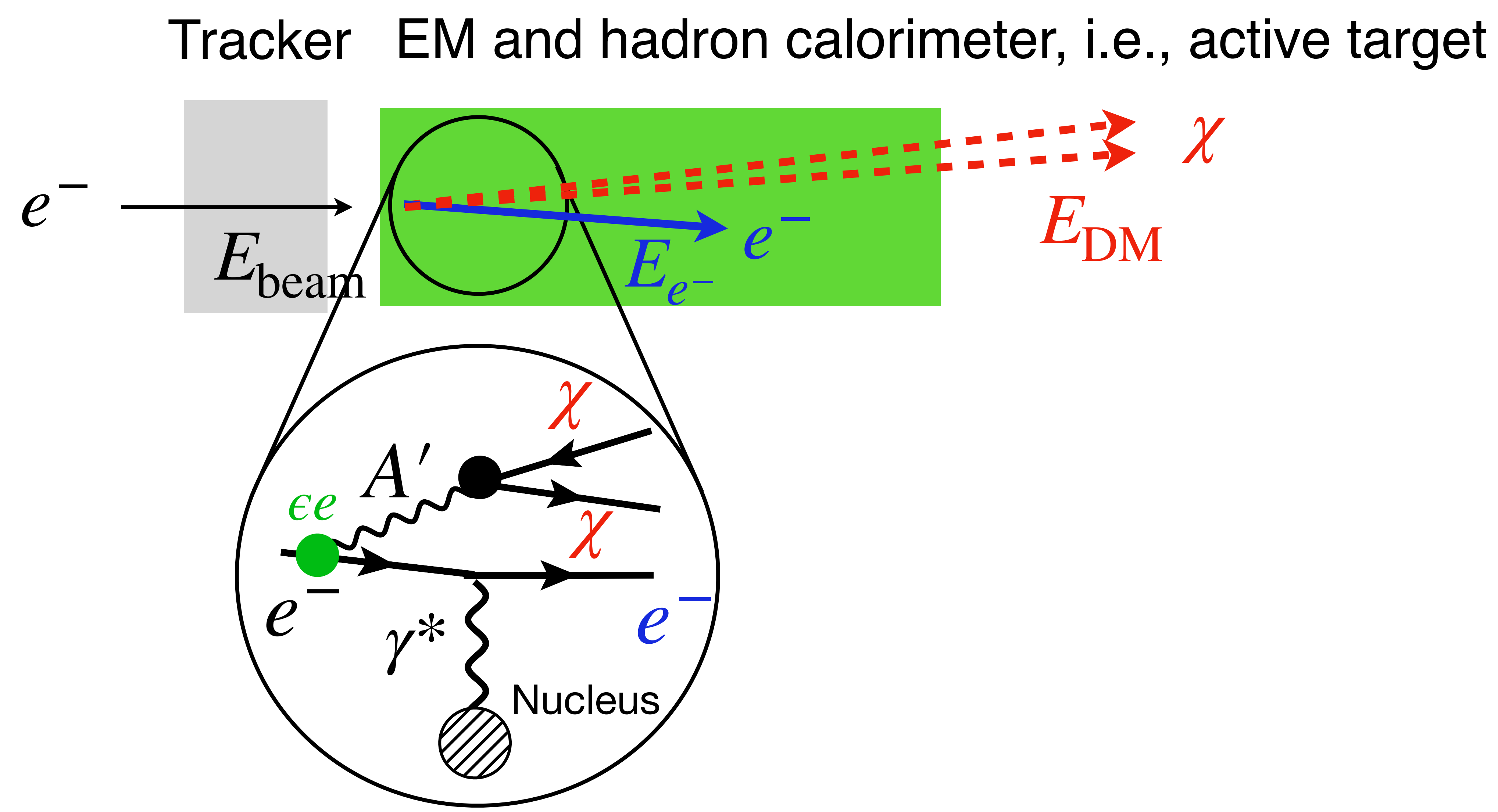

Bremsstrahlung process

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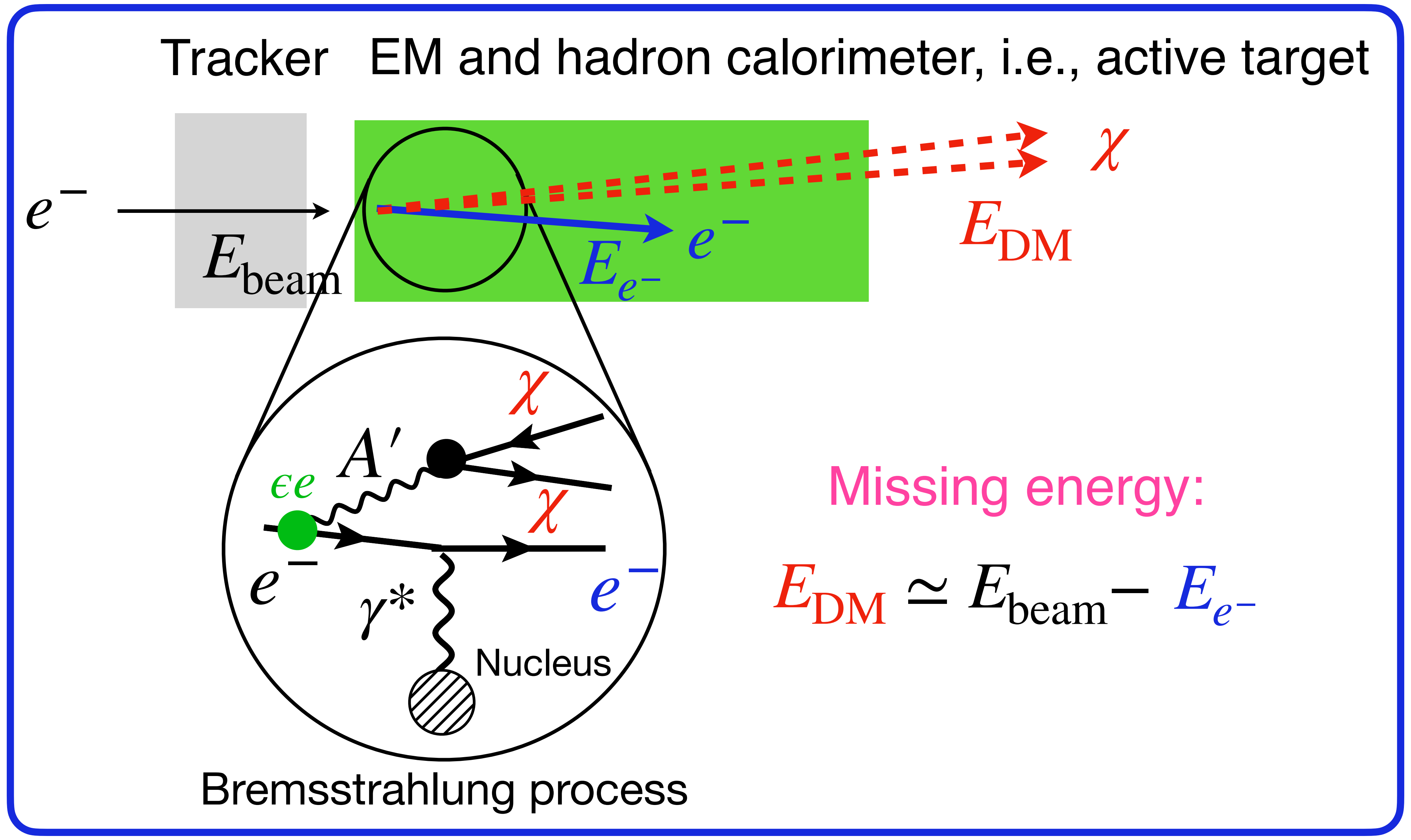

Missing energy:

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

※ Energy transfer to nucleus is modest in Bremsstrahlung process

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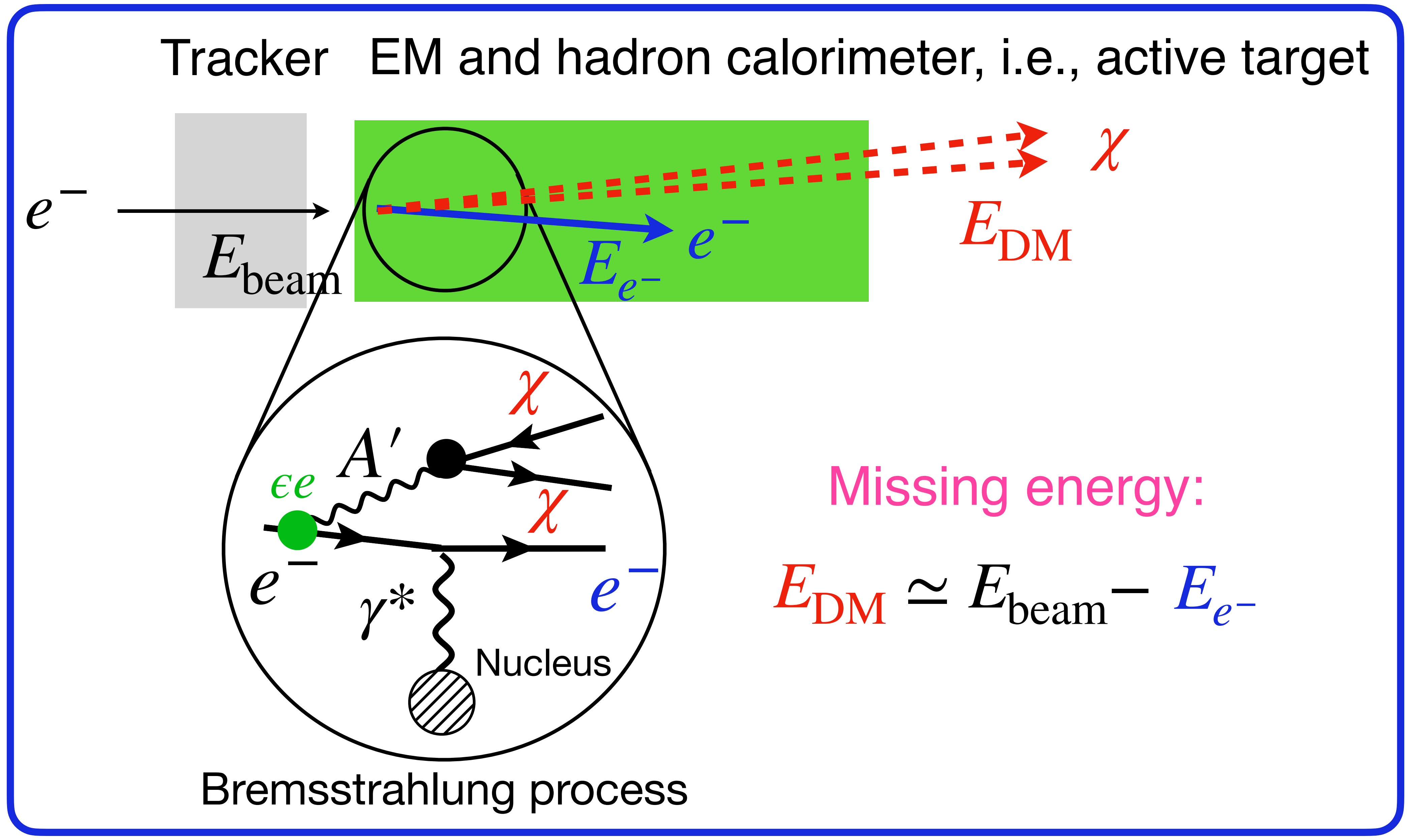

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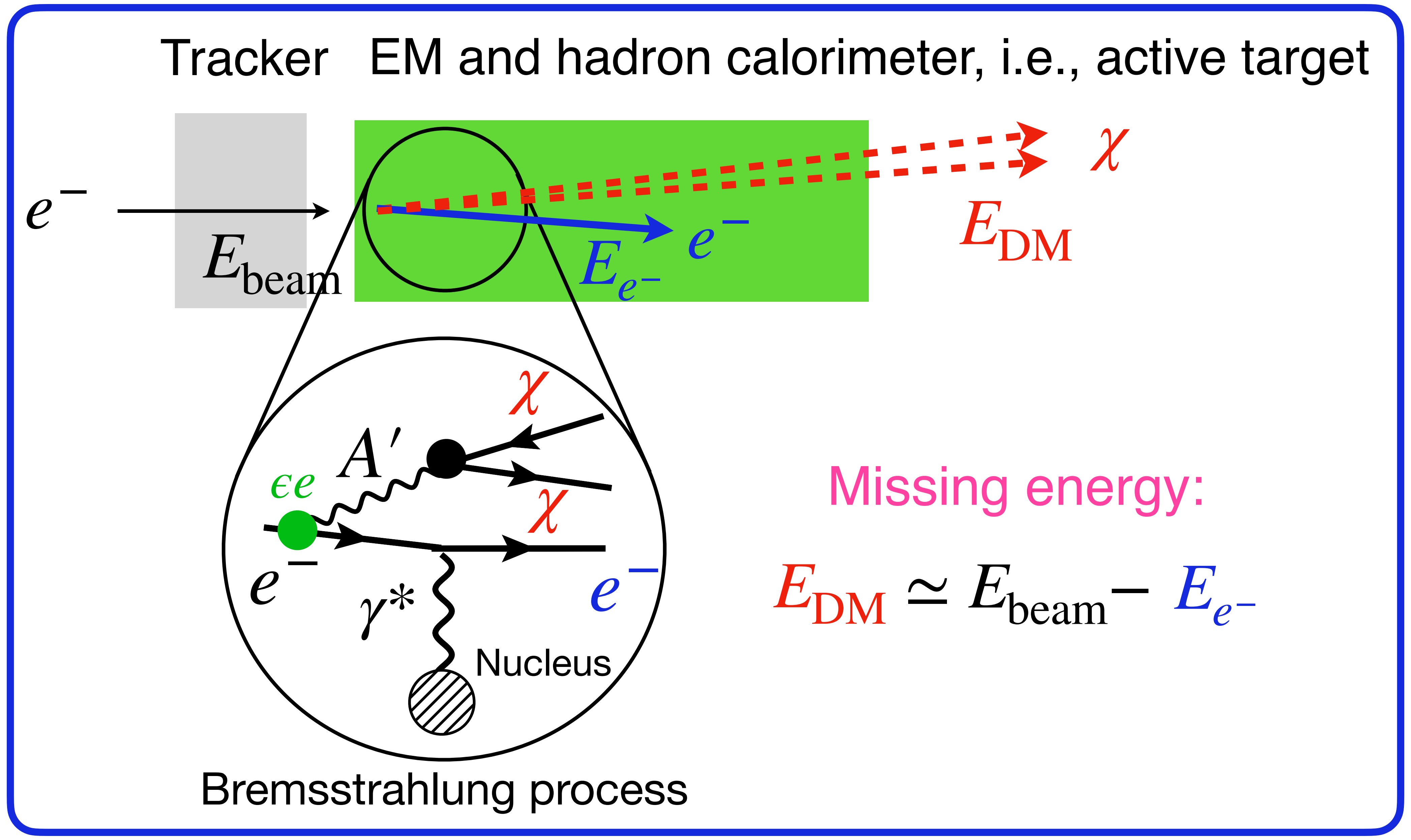

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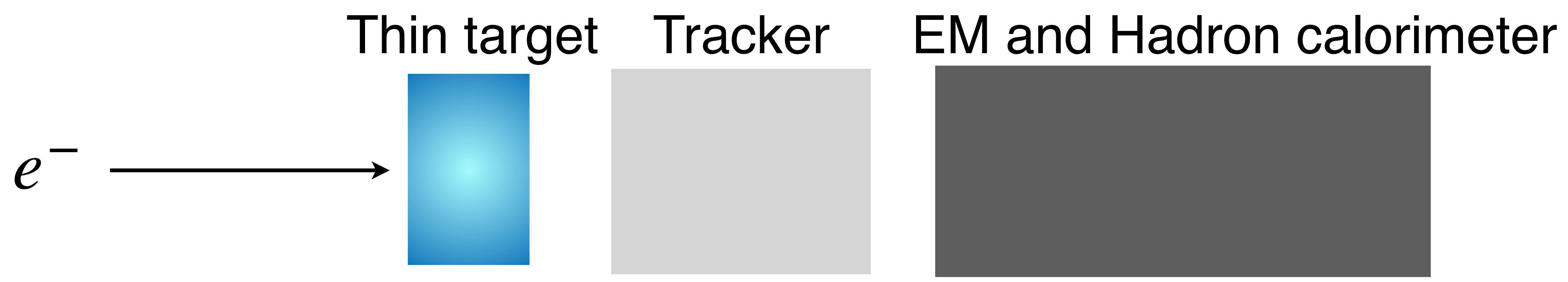

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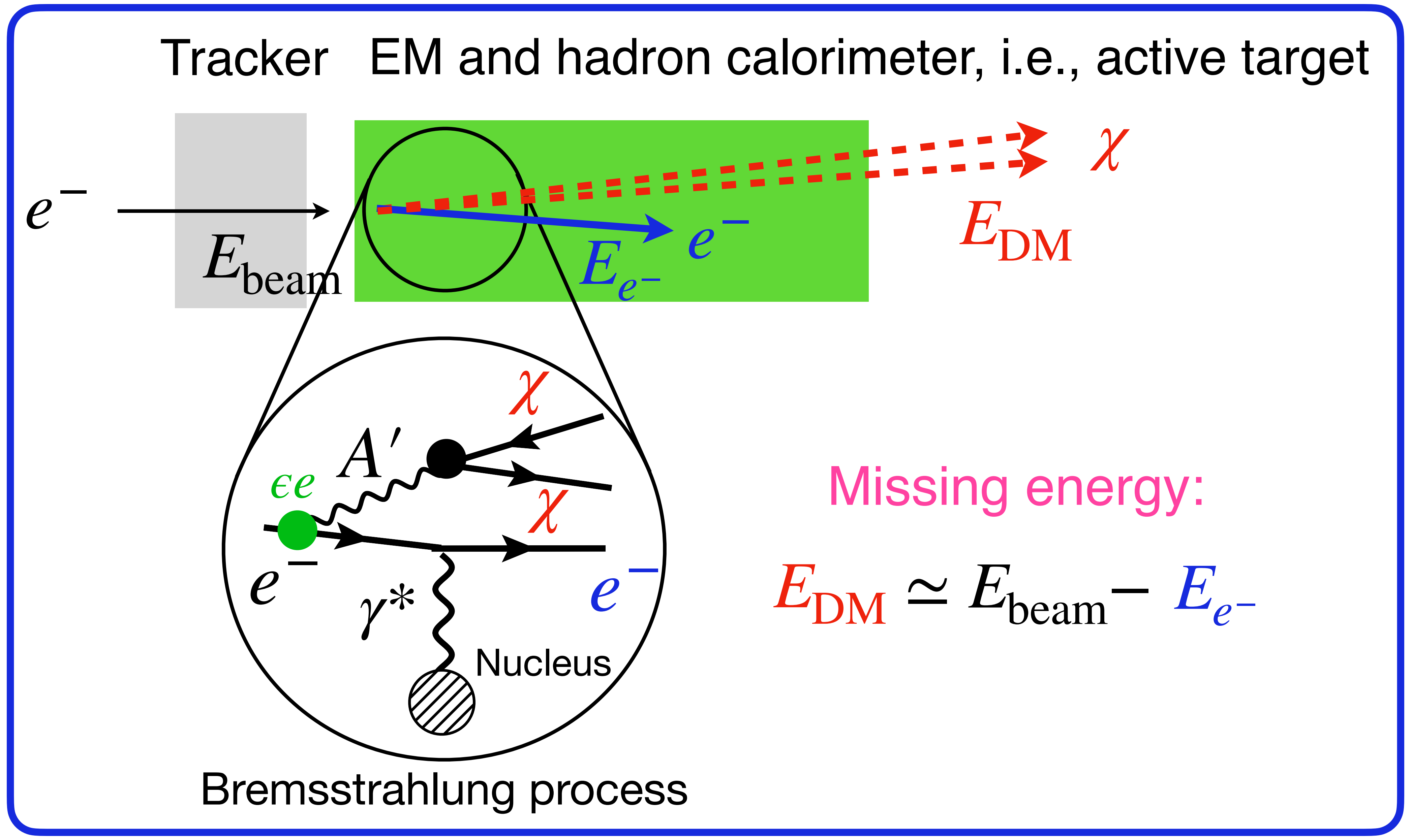

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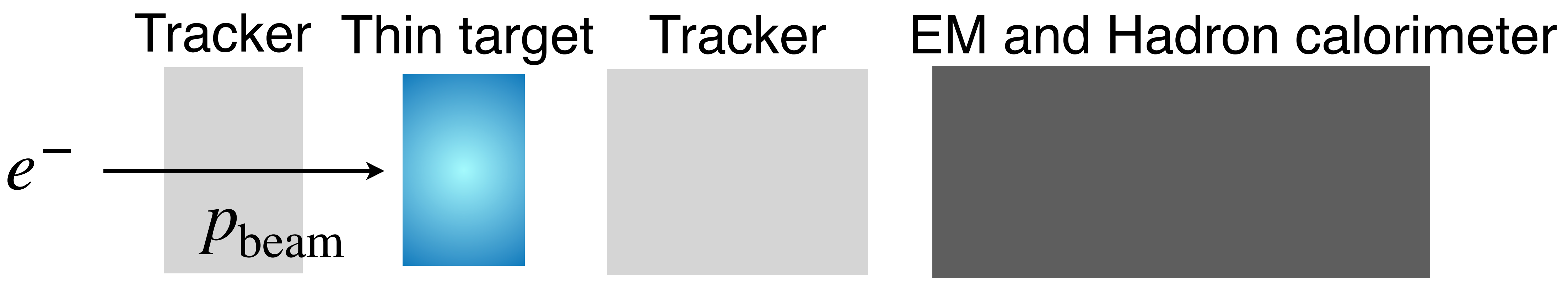

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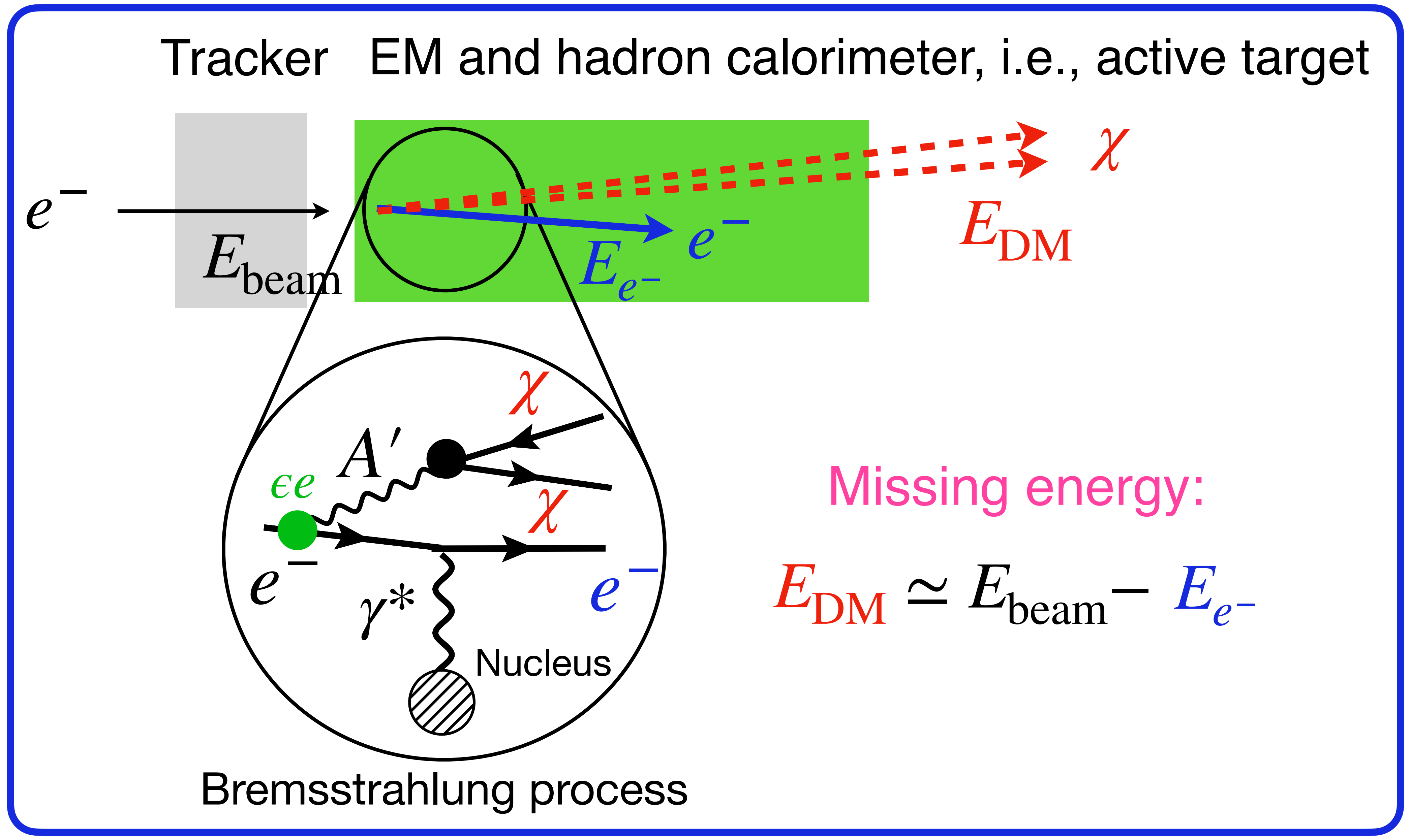

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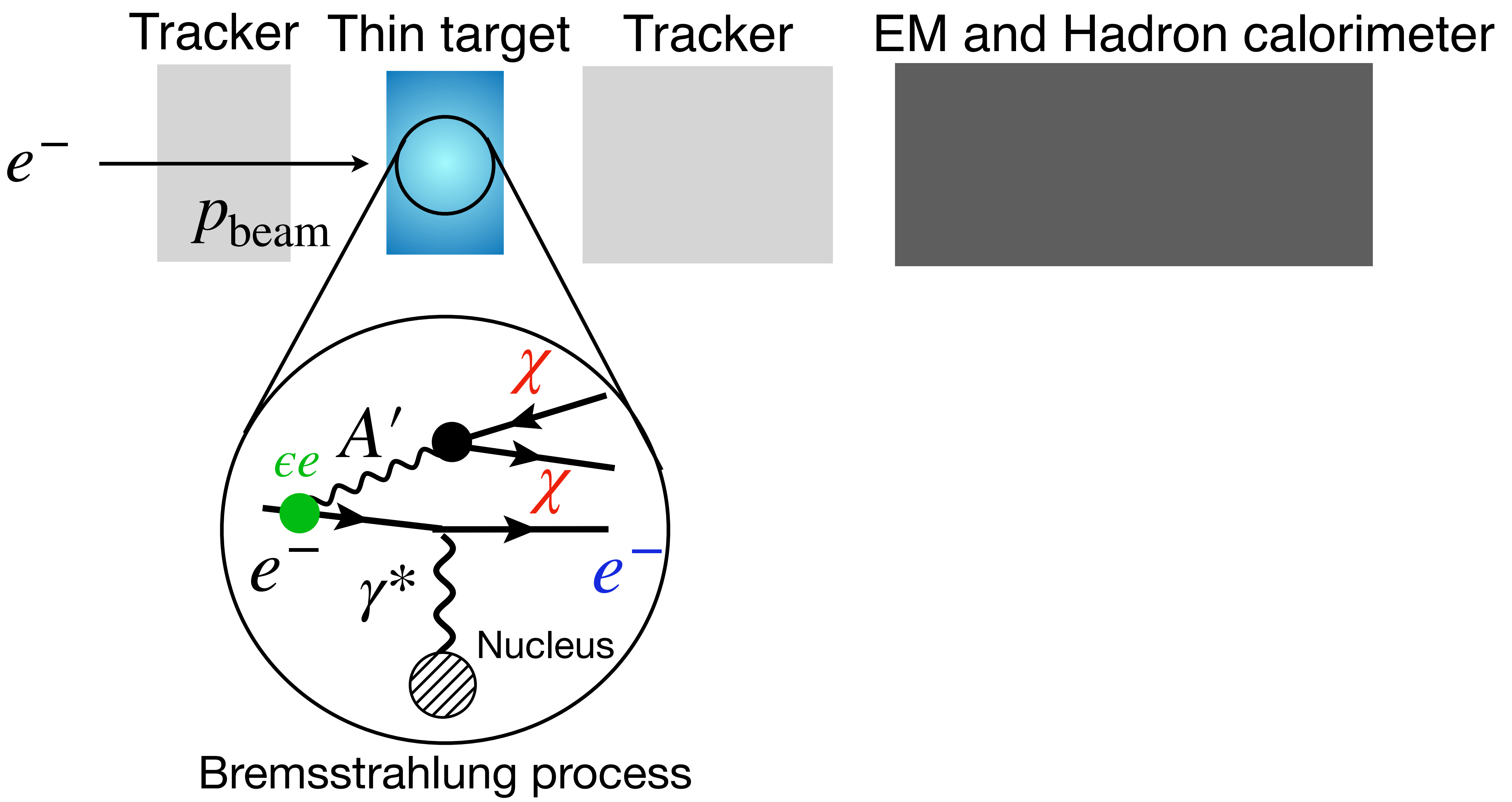

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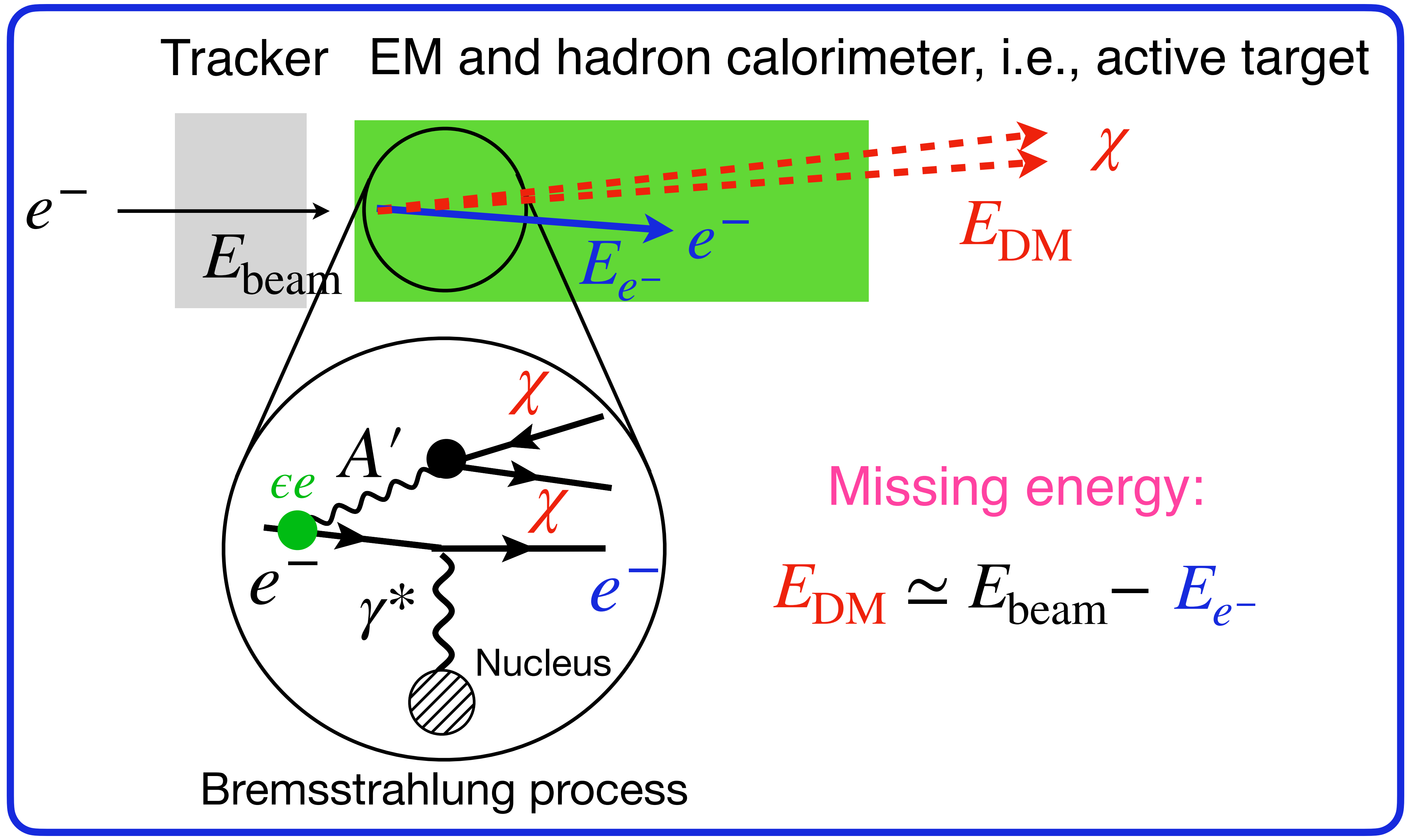

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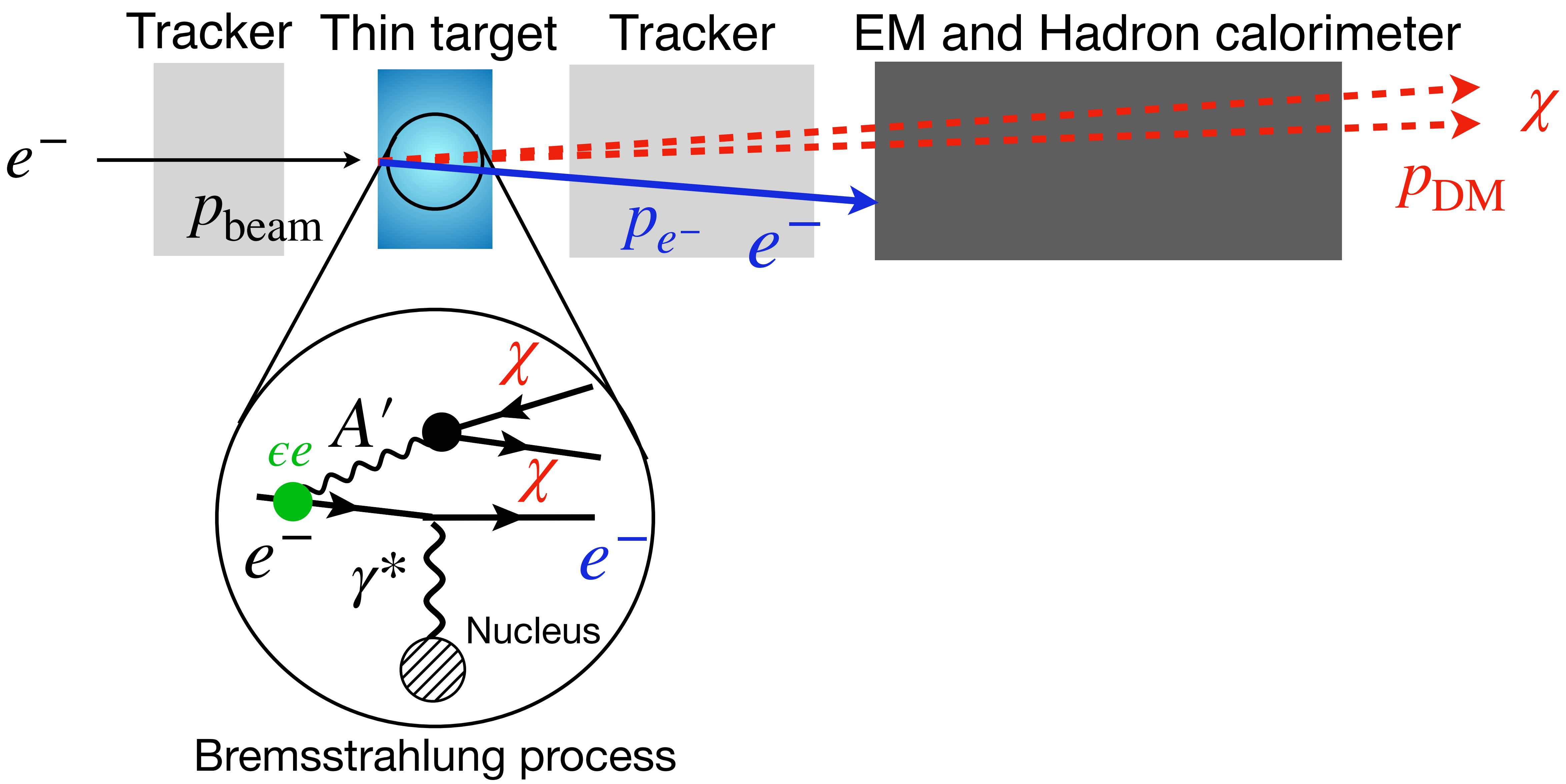

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Missing energy/momentum signal processes

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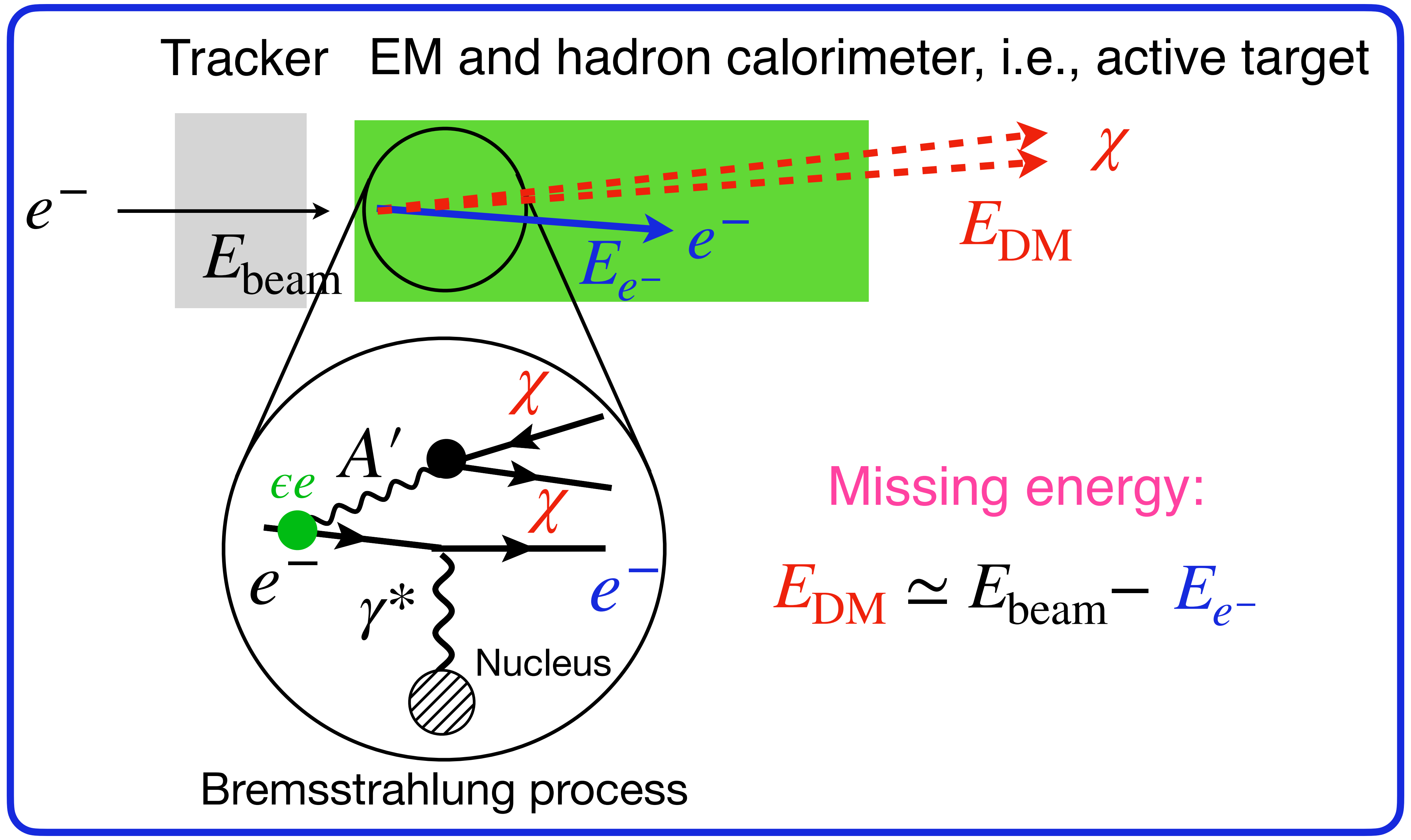

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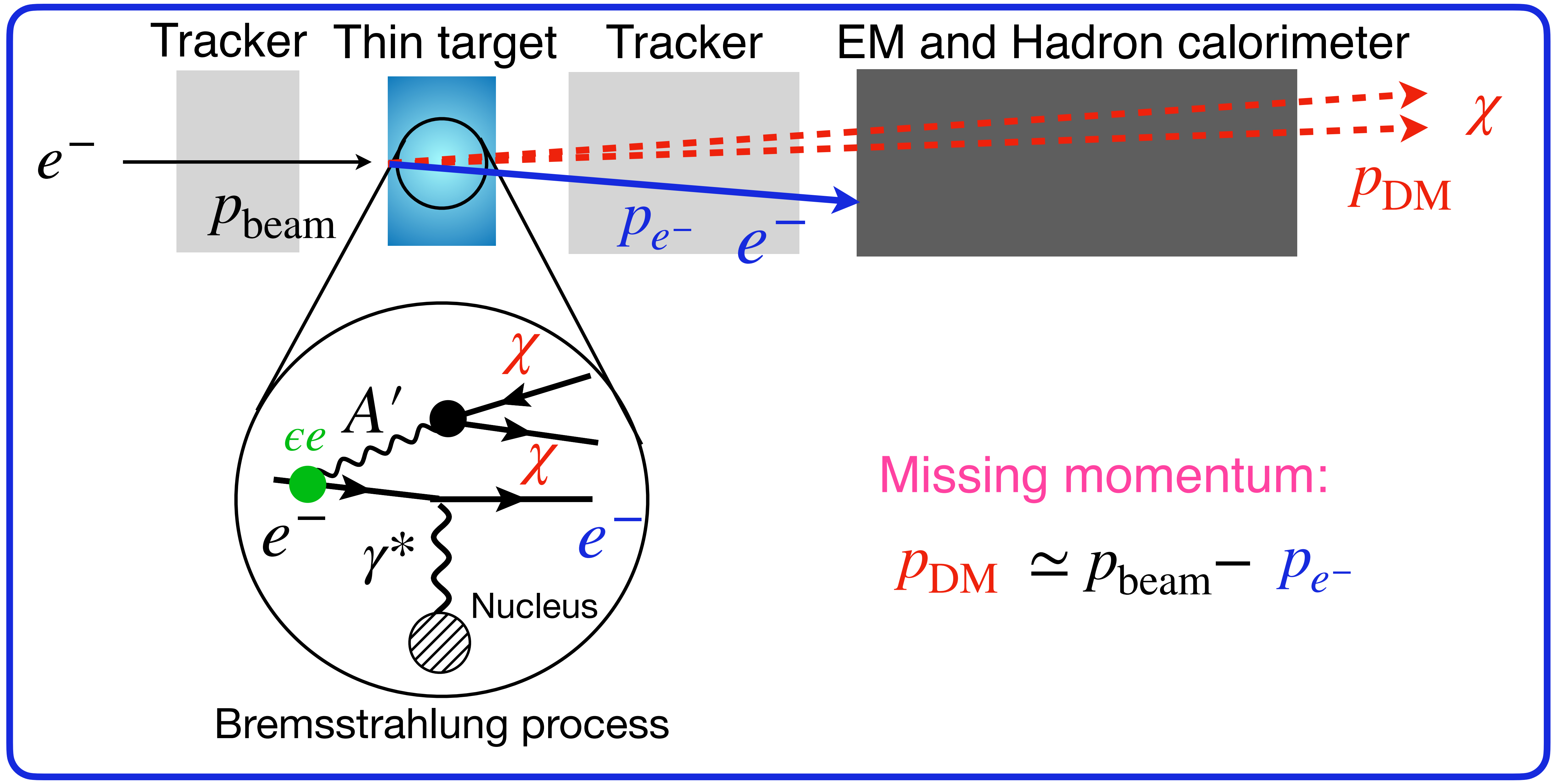

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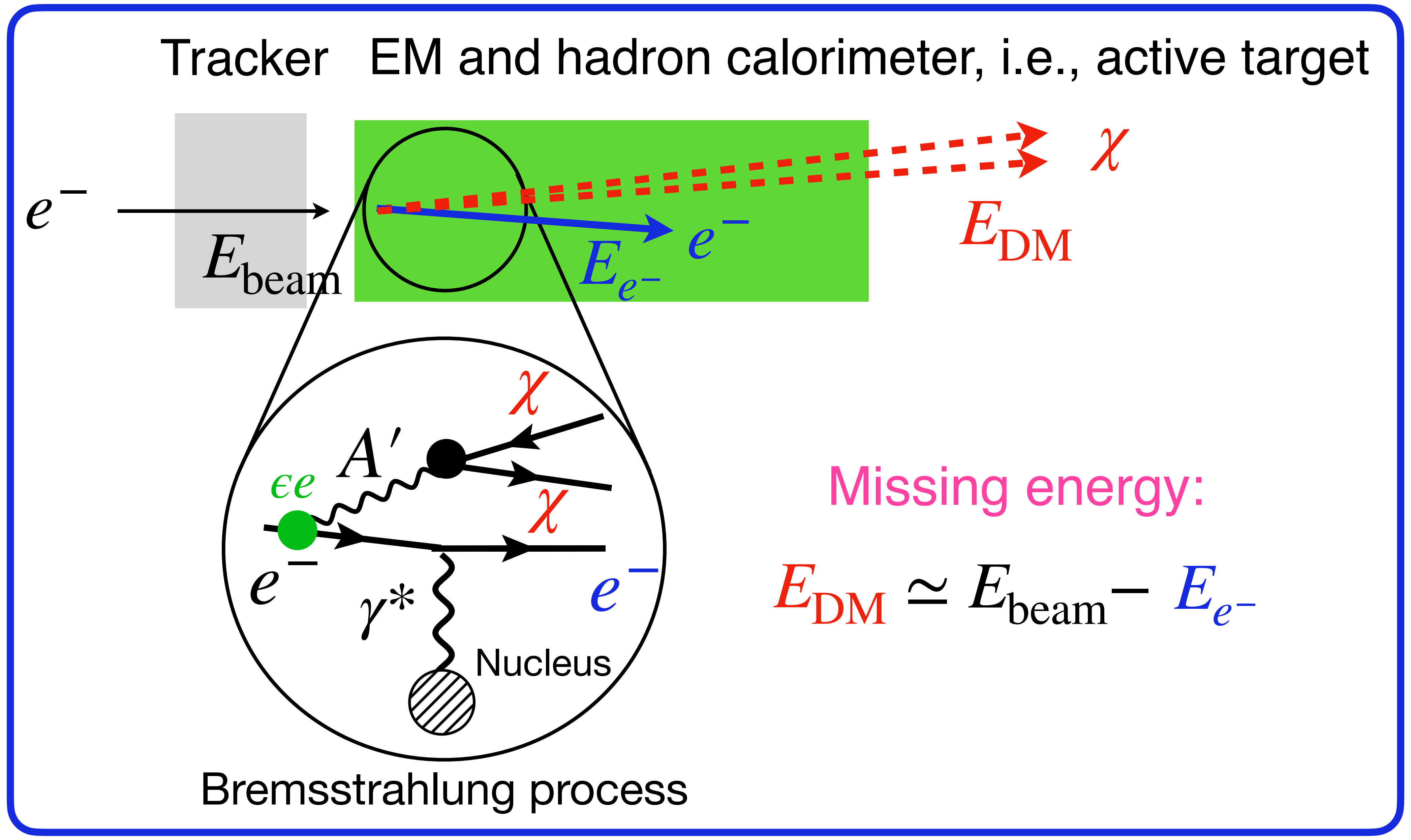

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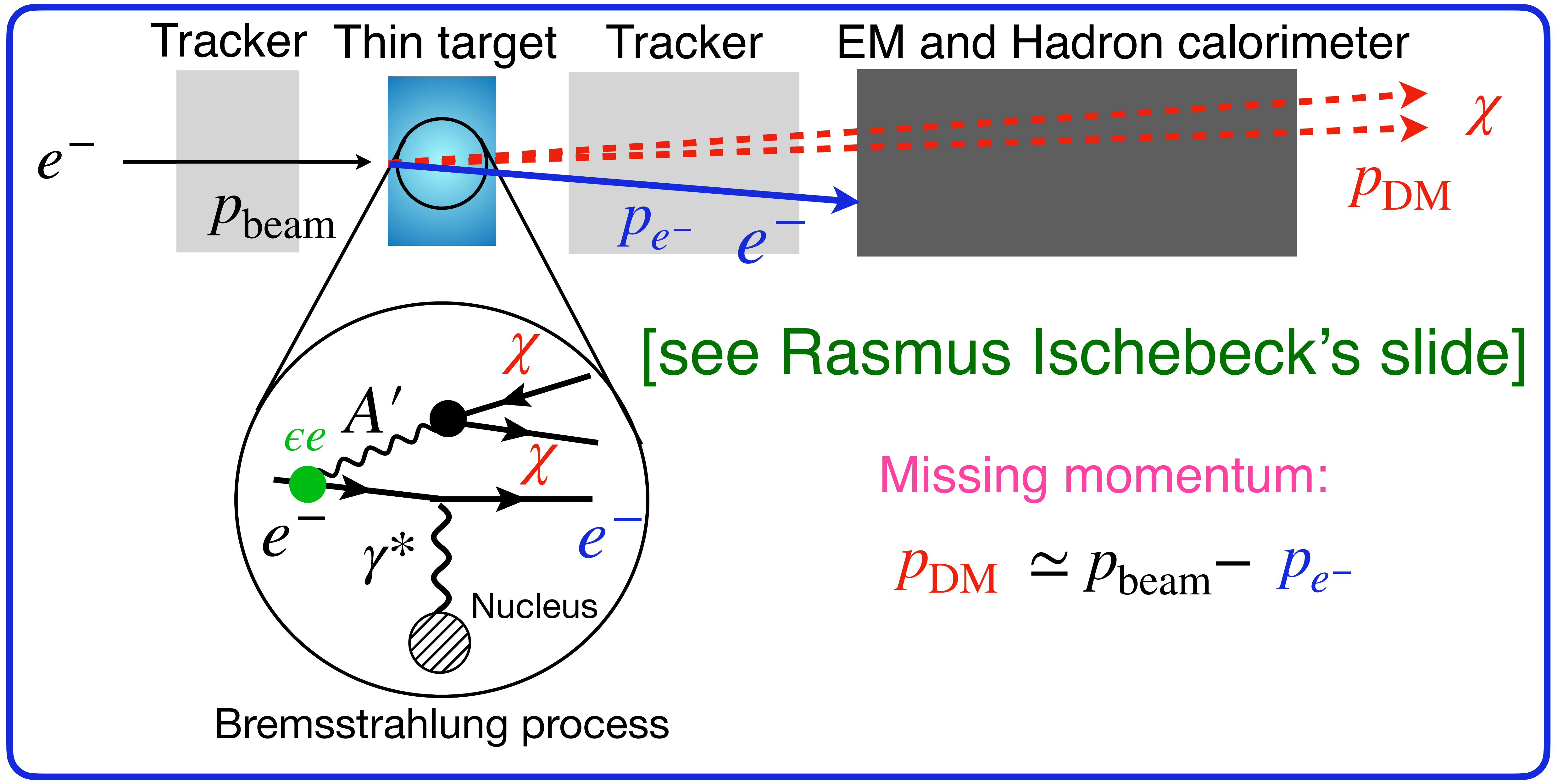

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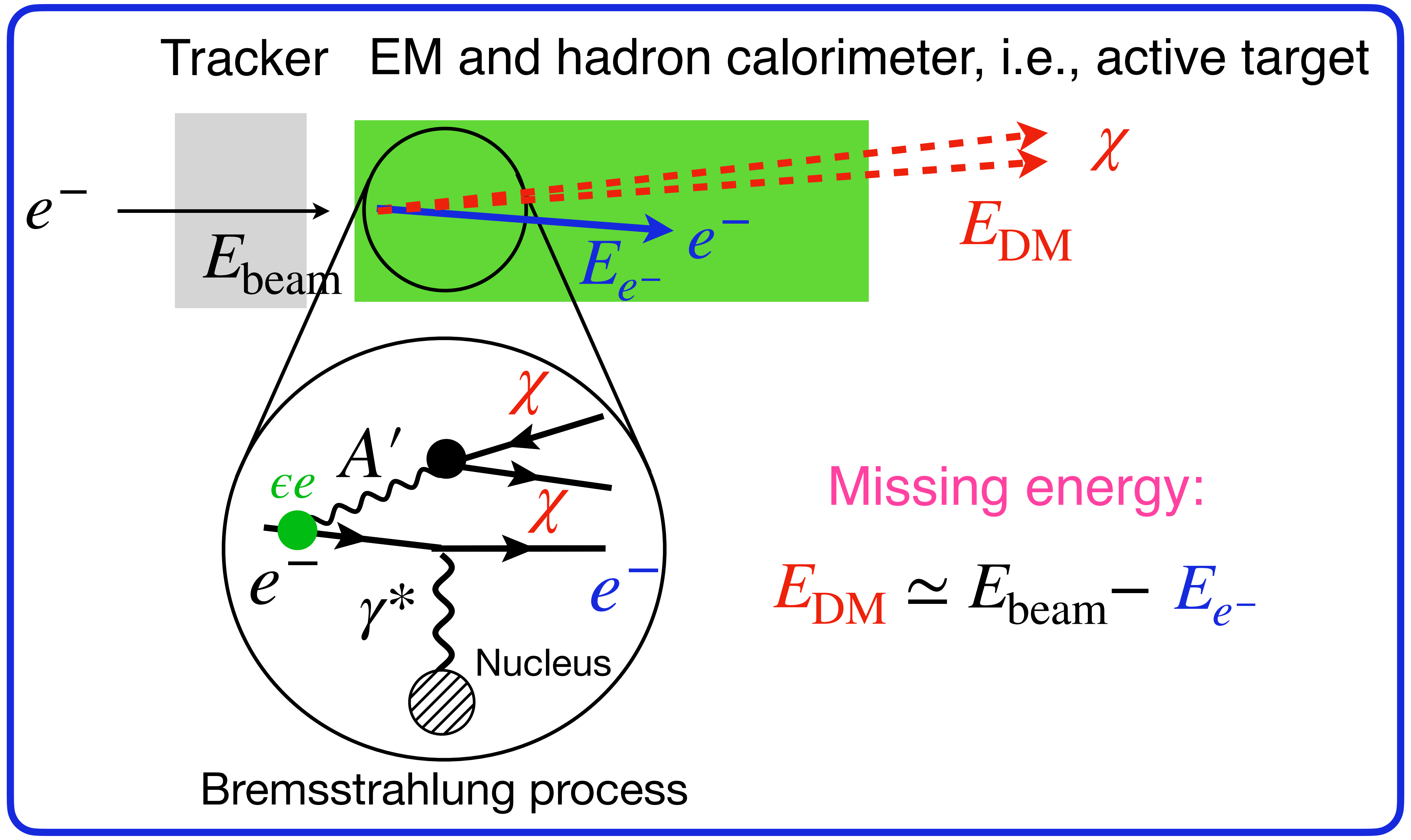

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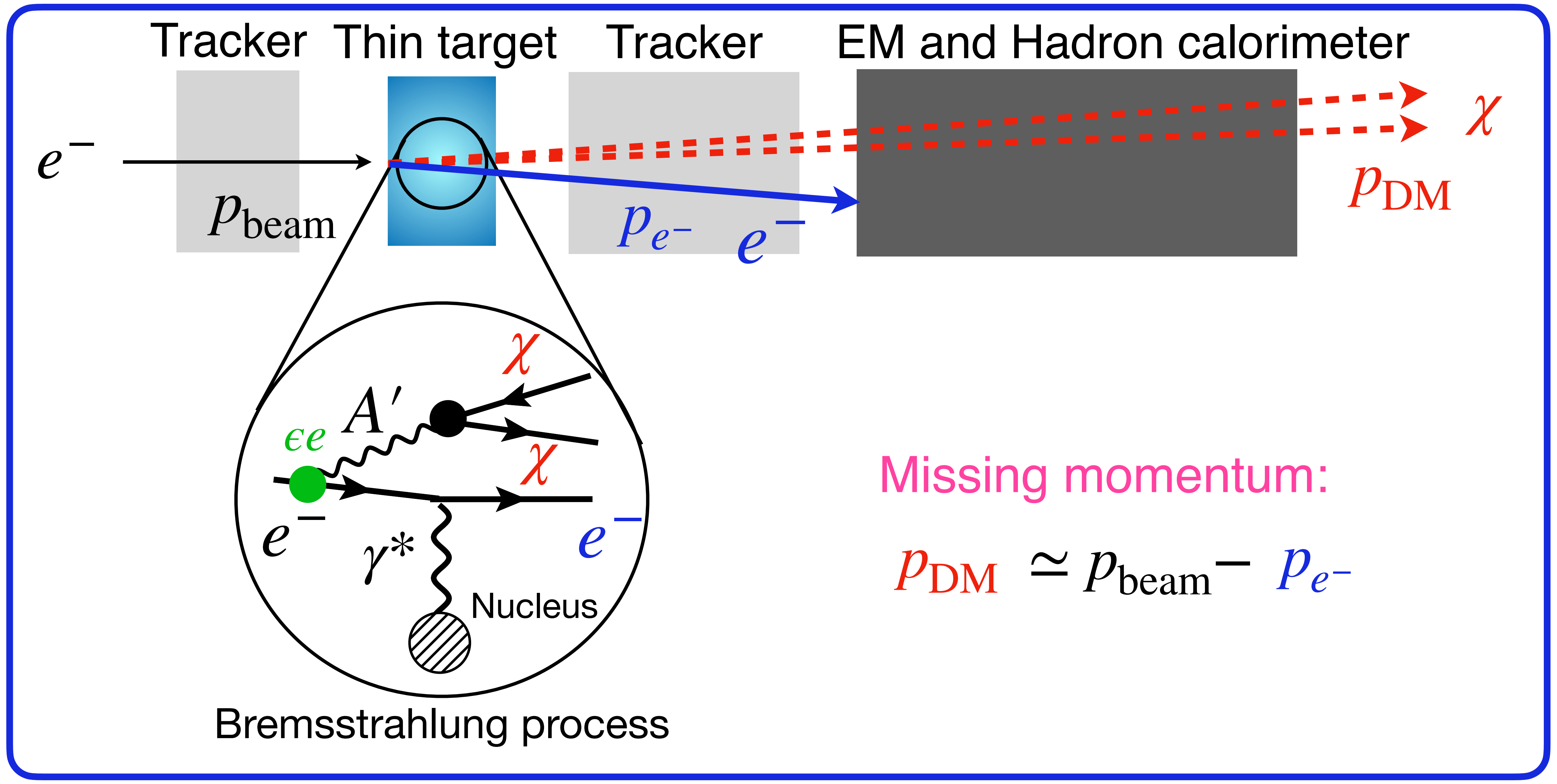

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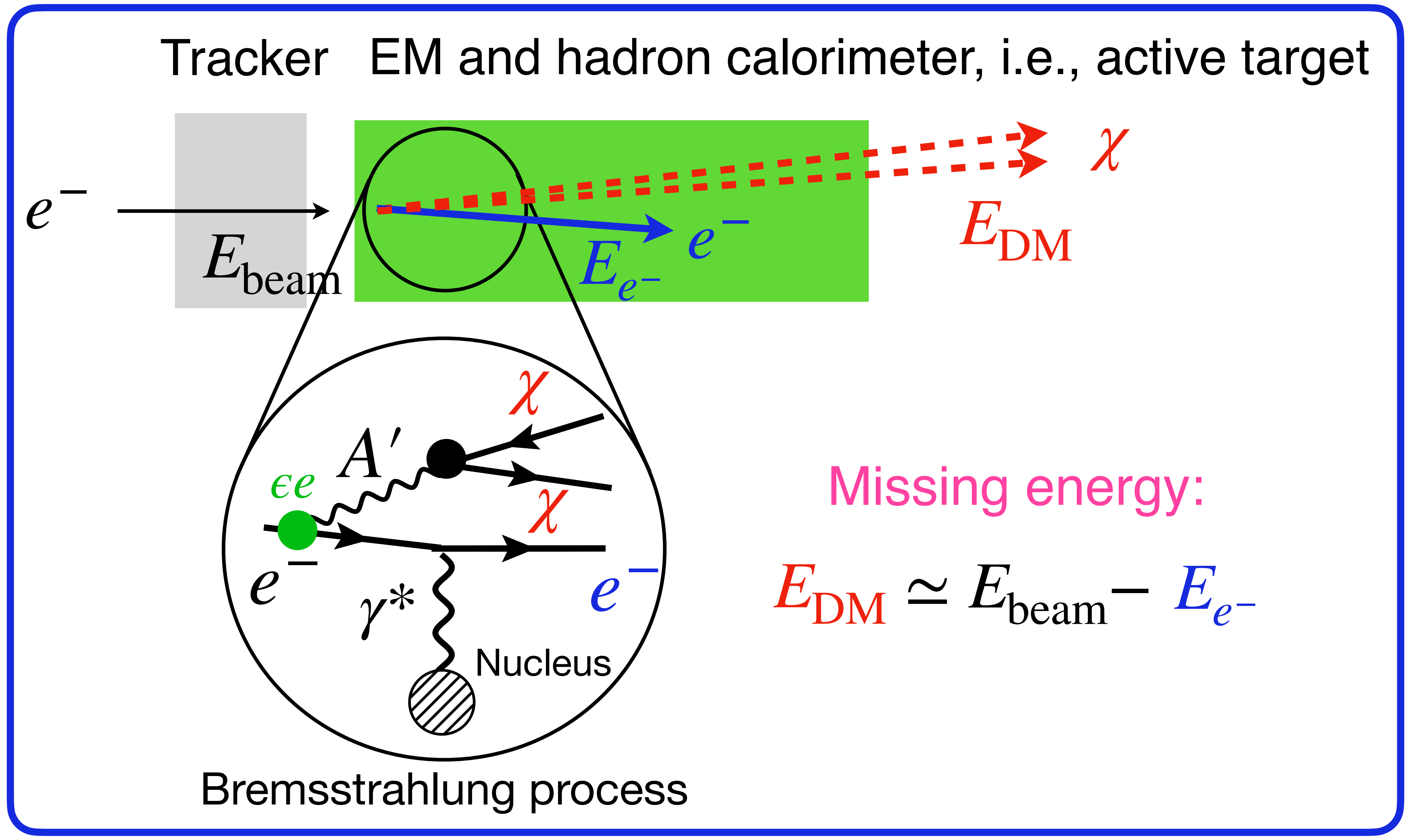

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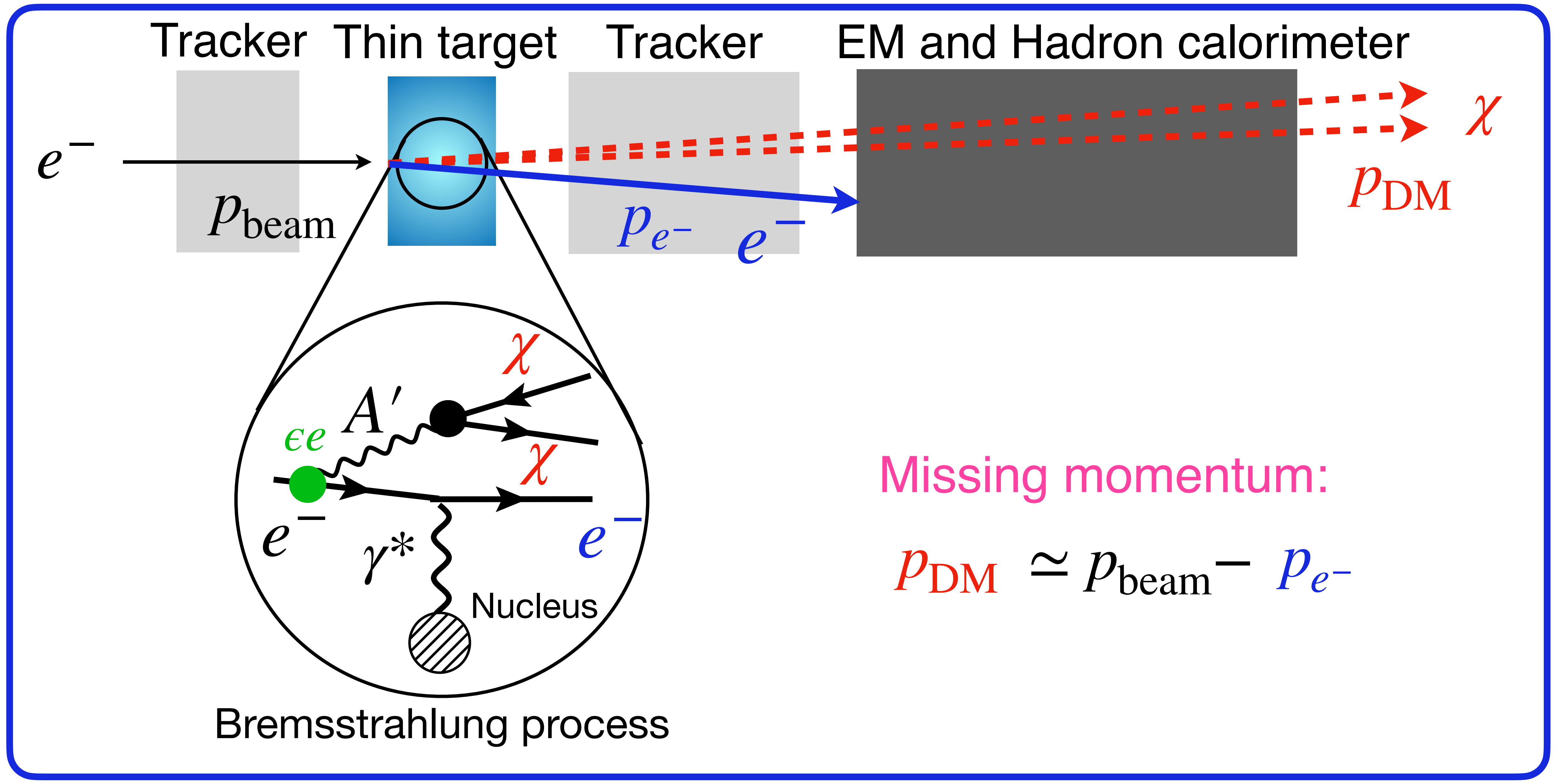

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  ~ (# of produced DM)

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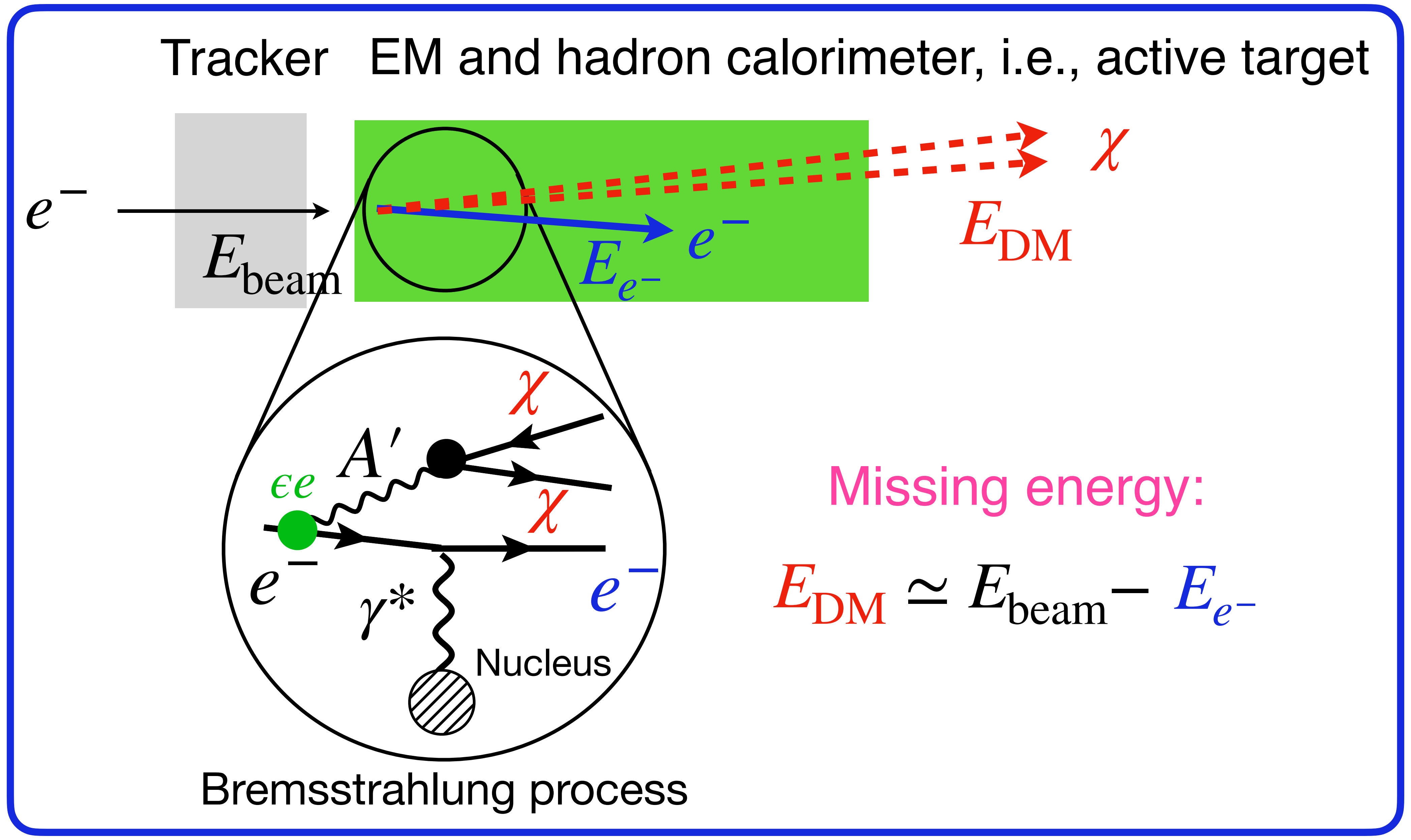

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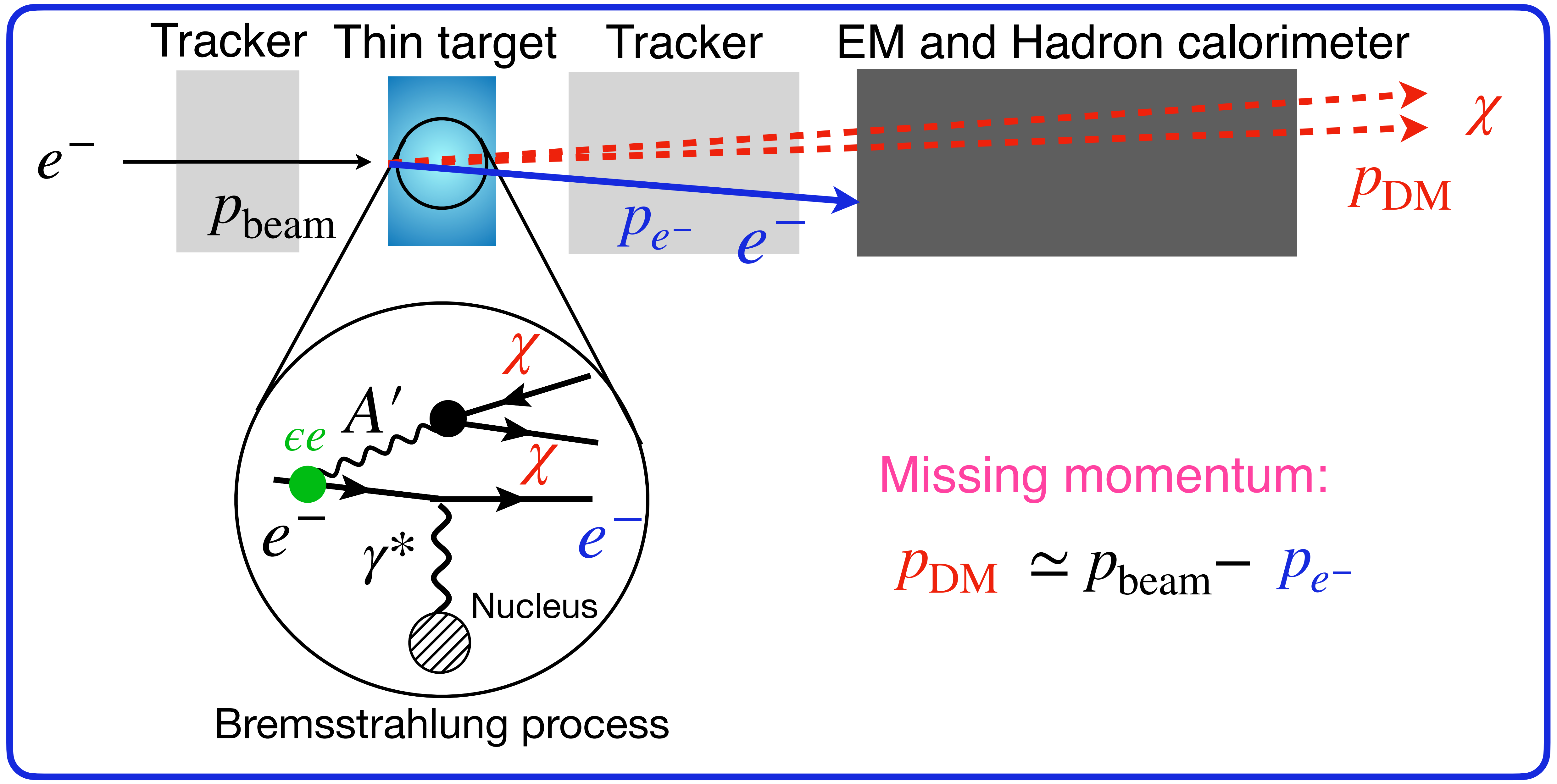

※ Target is thin to reconstruct final state electron

- # of missing events:

Acceptance

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

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

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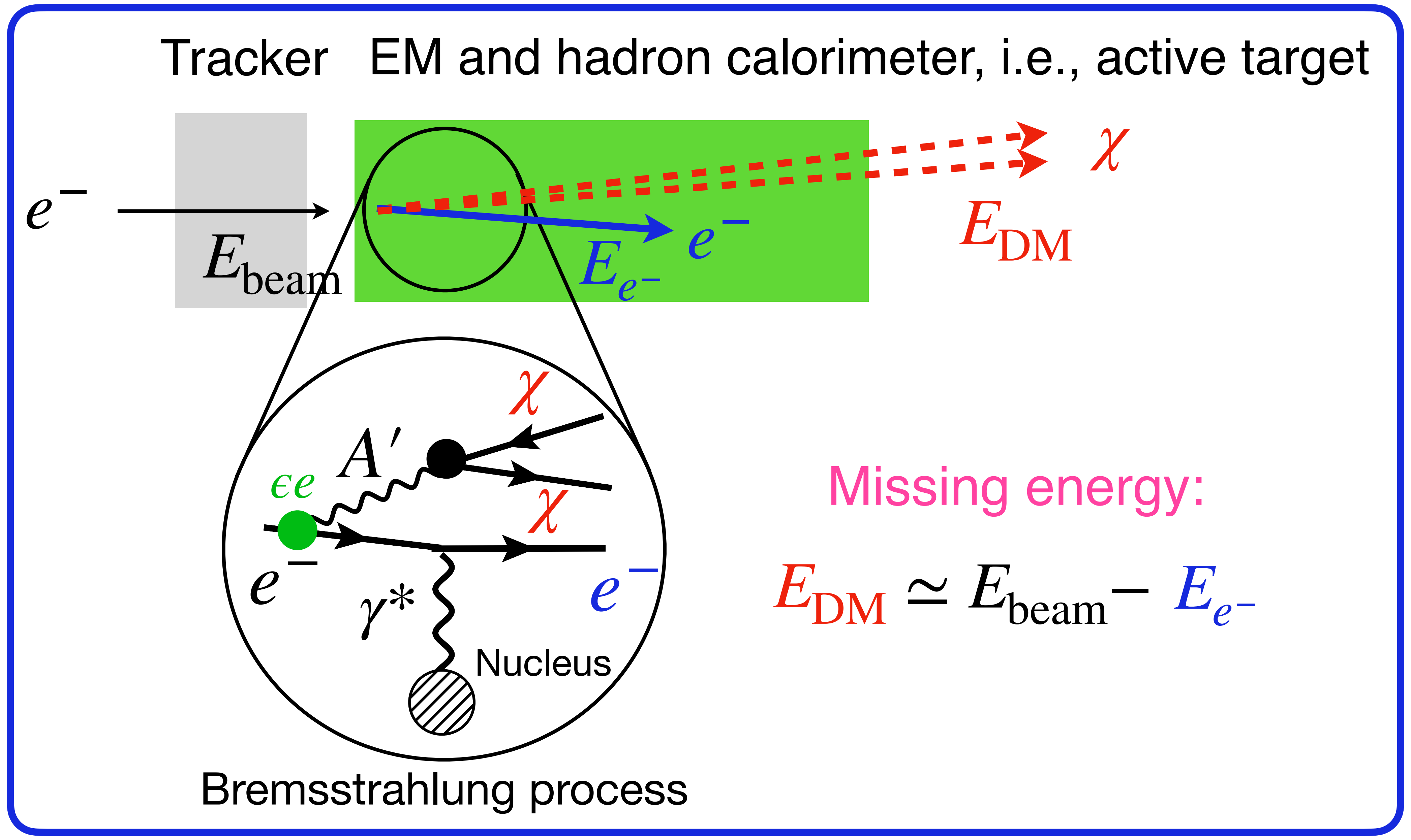

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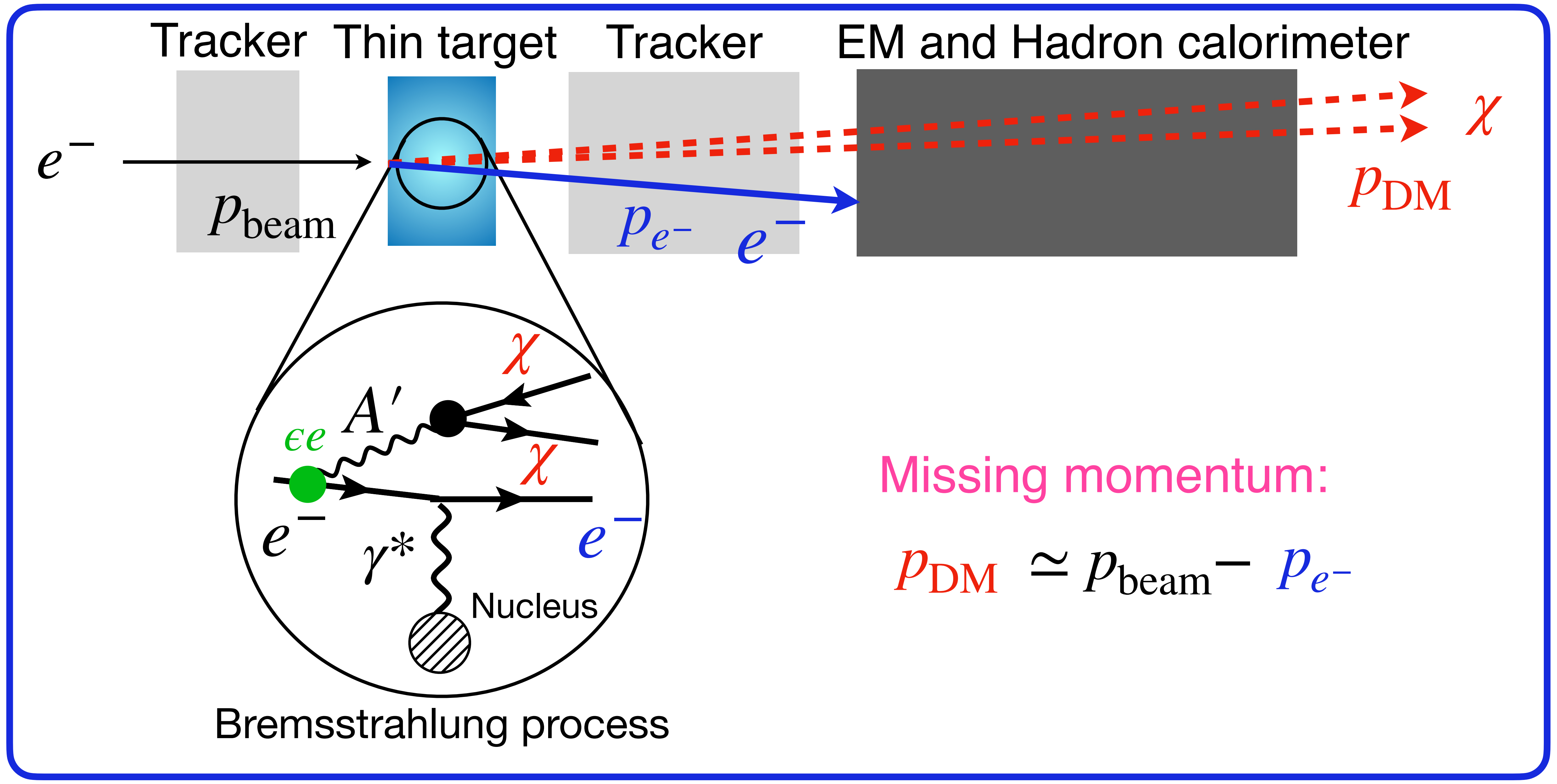

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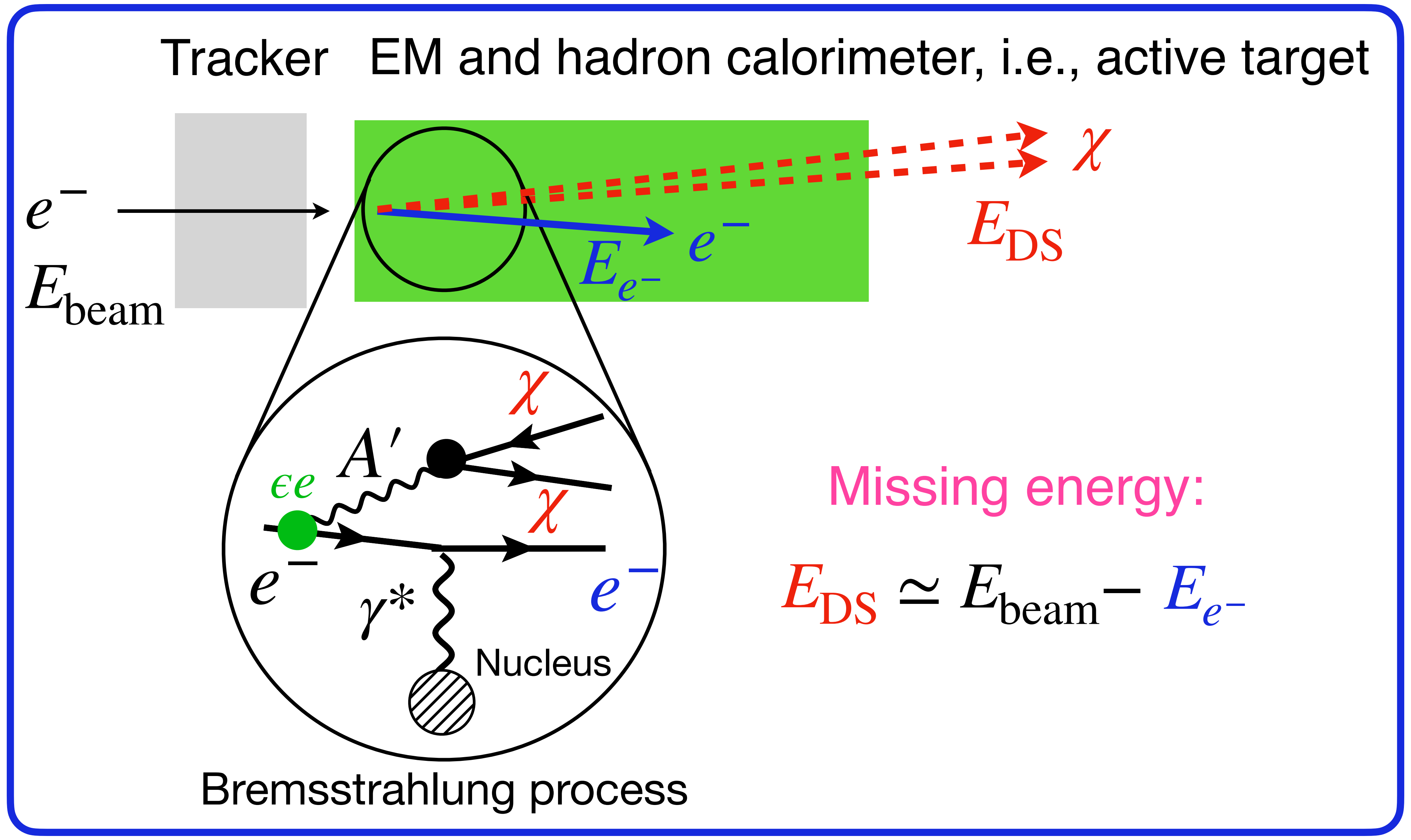

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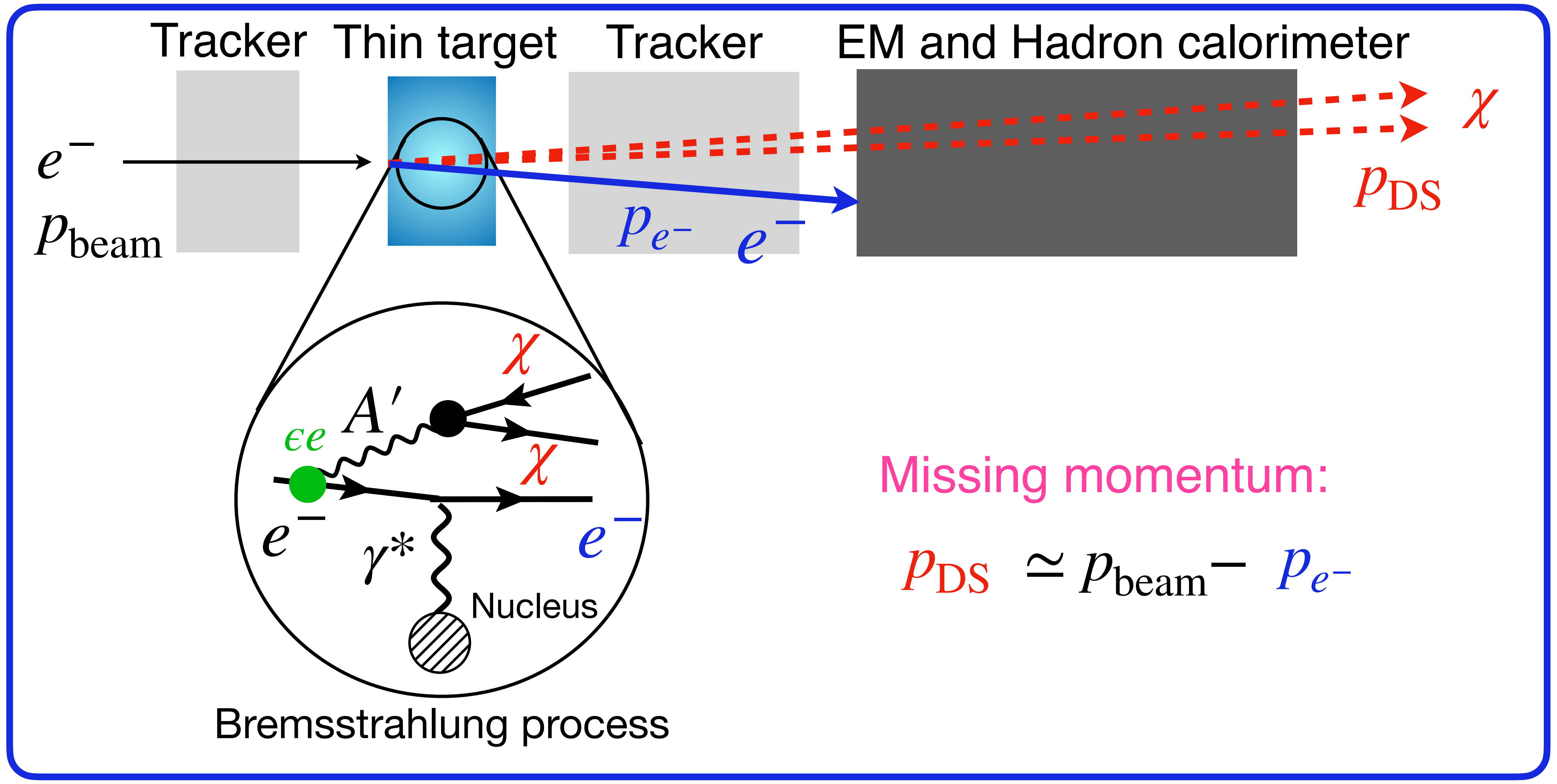

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Acceptance is good, but the continuous beam(low-intensity) is needed to reconstruct final state

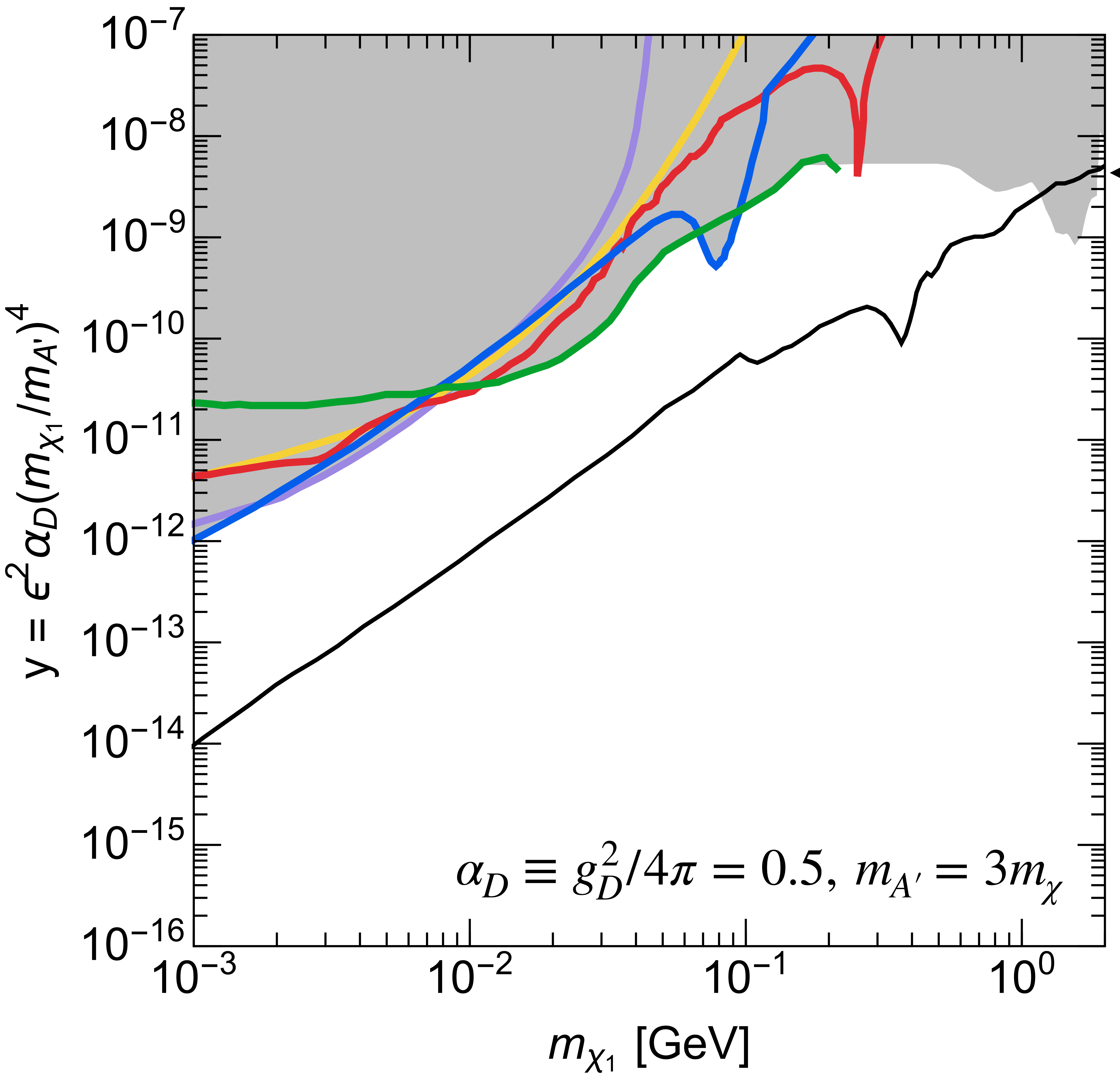
Benchmark model: $\mathscr{L} \supset \epsilon e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu \bar{\chi}\gamma^\mu\chi$ A': Dark photon, χ: Dark Matter, $J^\mu_{\rm EM}$: SM EM current

Outline

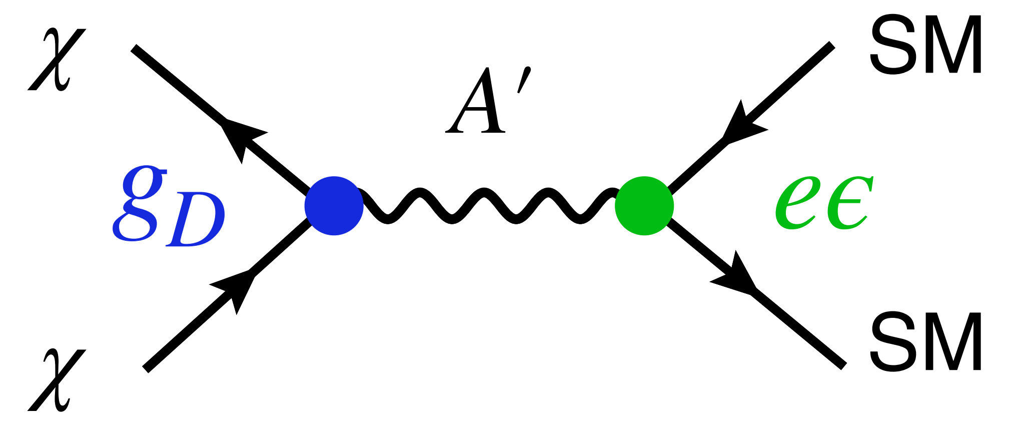
- Introduction
  - dark sector and Sub-GeV dark matter
  - beam dump(fixed-target) experiment
- Key features of beam dump experiment
- A classification of beam dump experiment
- Sensitivity of beam dump experiments at future accelerators
- Summary

Excluded regions by beam dump experiments (1)

- Benchmark model (1): $\mathscr{L} \supset \epsilon \cdot eA'_\mu J^\mu_{\rm EM} - g_D A'_\mu \bar{\chi}\gamma^\mu \chi$ where A': dark photon, and χ: DM



DM annihilation cross section



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

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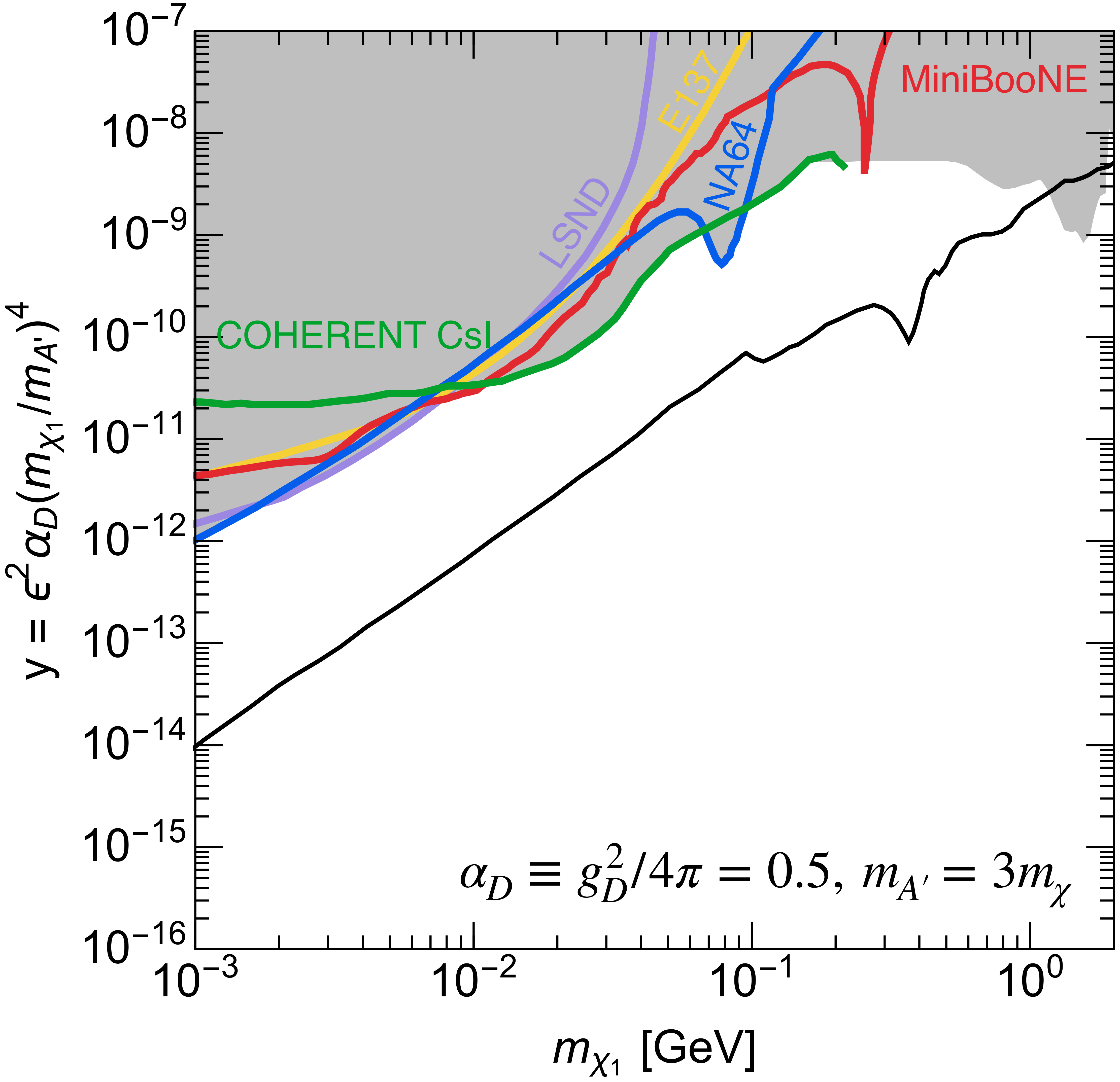


Rescattering	Missing signal
E137	NA64
LSND MiniBooNE COHERENT CsI	※ Limited missing signal experiments are conducted because of the severe beam condition

Electron beam: E137, NA64

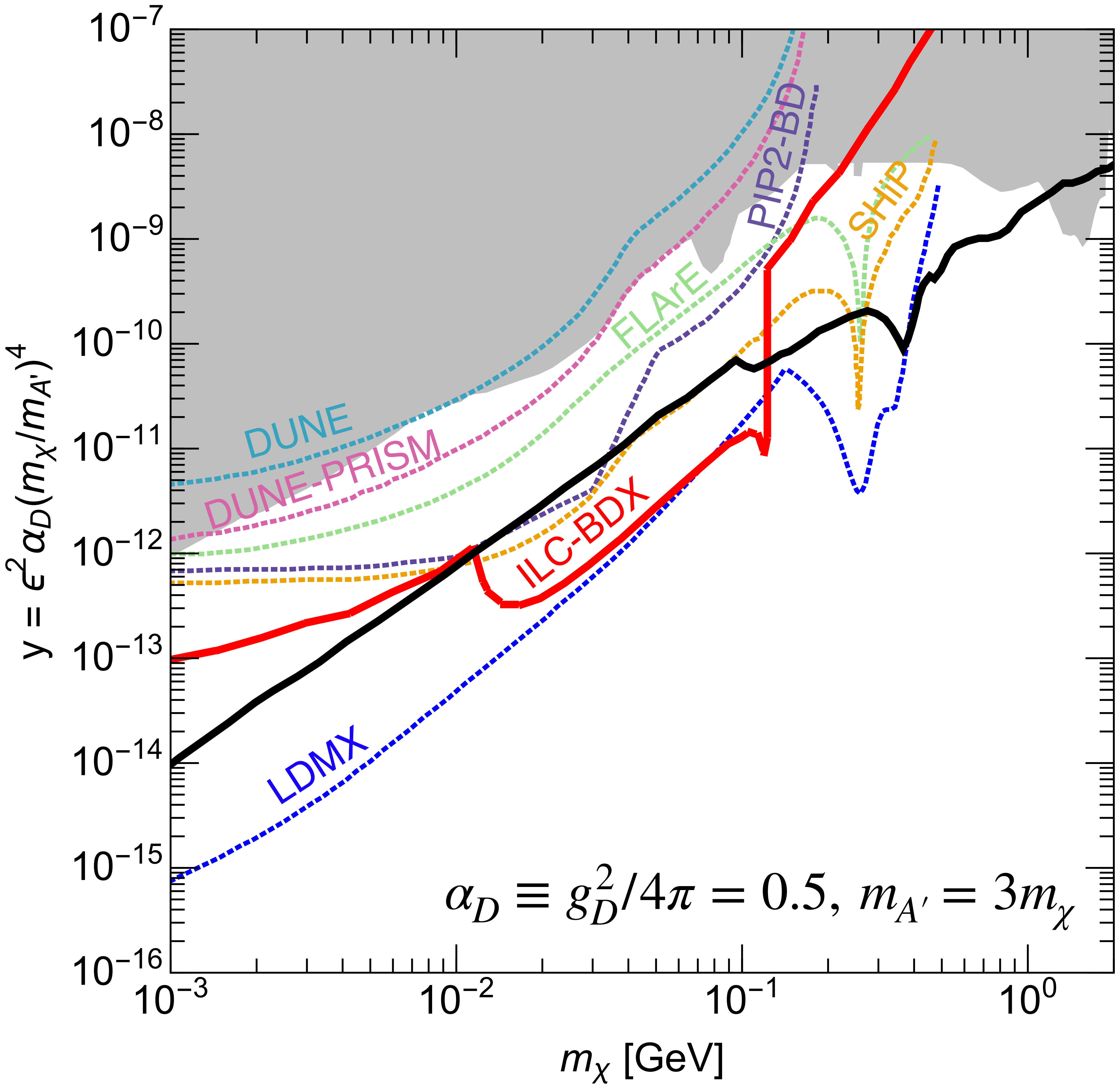
Proton beam: LSND, MiniBooNE, COHERENT CsI

⇒ parasitic running of neutrino experiment

※ MiniBooNE is off-target running to reduce neutrino BG

Sensitivity of beam dump experiments at future accelerators (1)

・Benchmark model (1): $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu \bar{\chi}\gamma^\mu \chi$ where A': dark photon, and χ: DM



Examples of BD at future accelerators

Rescattering	Missing signal	
ILC-BDX	LDMX	Electron beam
SHiP PIP2-BD DUNE DUNE-PRISM	← leverage DUNE facilities	
Proton beam		

- LDMX is highly sensitive because of good acceptance

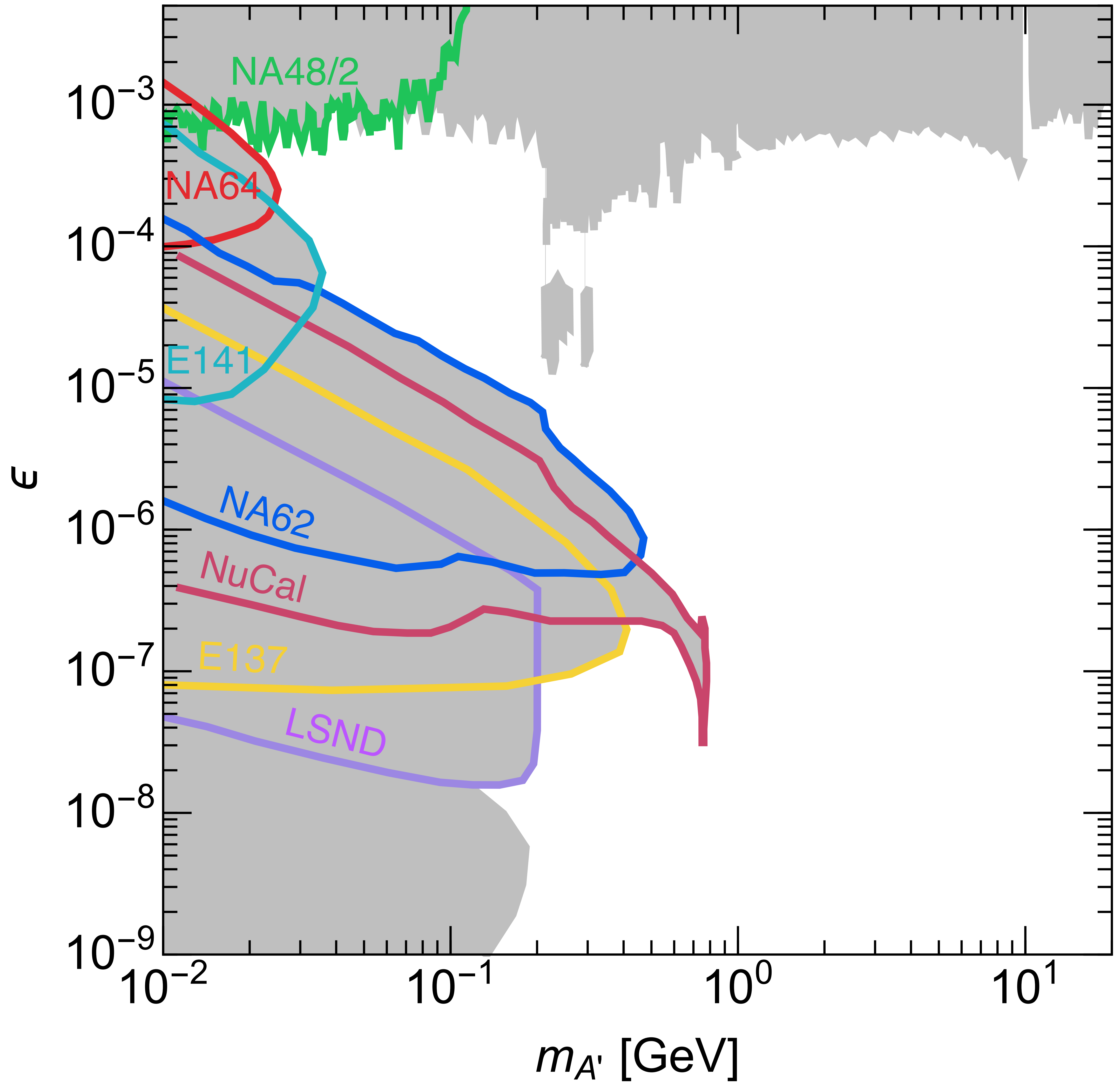
- ILC is sensitive because of high energy positron annihilation

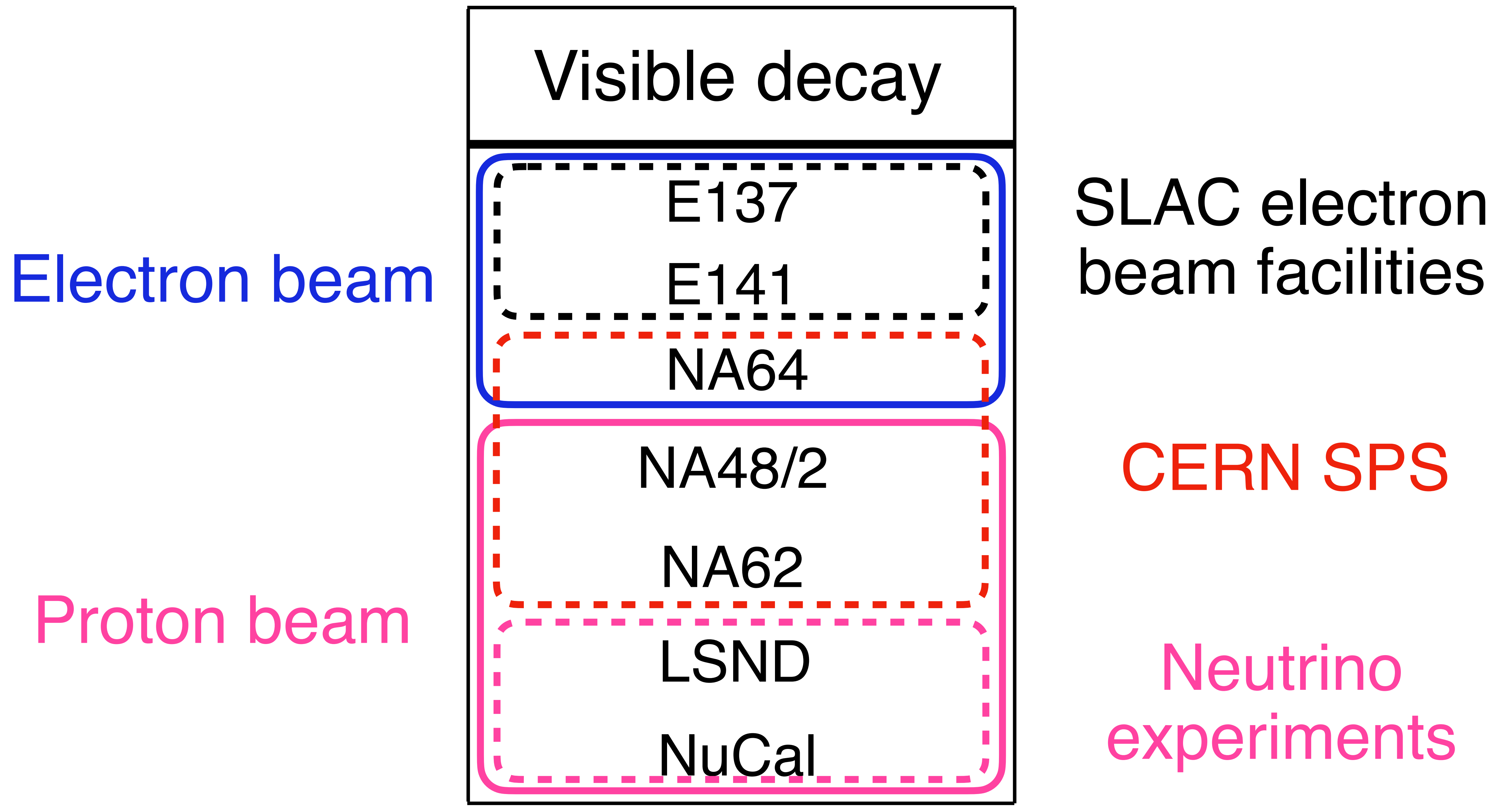
- DUNE-PRISM(off-axis detector) is more sensitive than DUNE(on-axis detector) because of neutrino BG reductions

※ FLArE is LHC auxiliary detector experiments in HL-LHC phase

Excluded regions by beam dump experiments (2)

- Benchmark model (2): $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM}$ where A': dark photon





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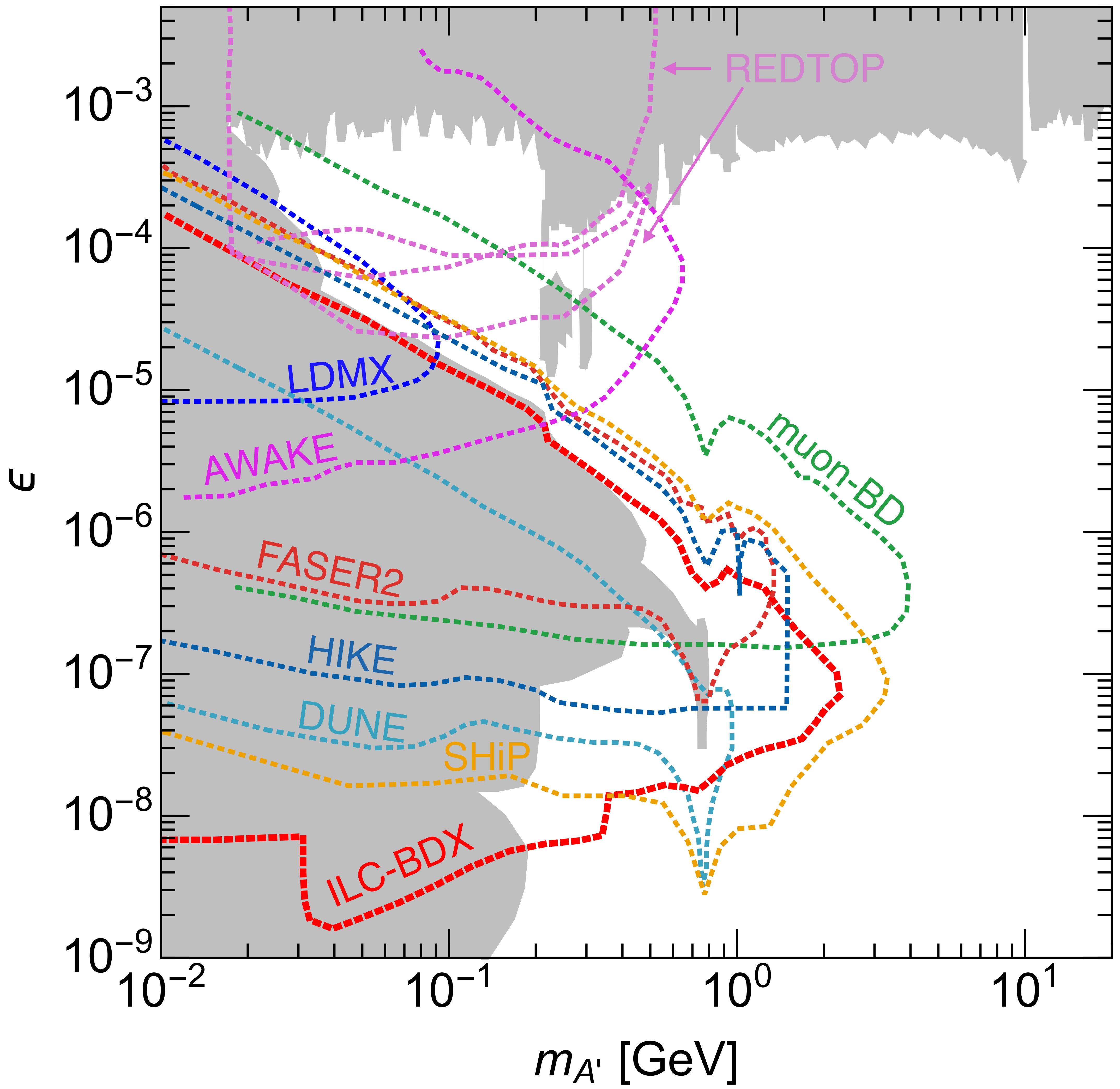

Examples of BD at future accelerators

	Visible decay	
Electron beam	ILC-BDX LDMX AWAKE	ILC, SLAC, and CERN
Muon beam	muon-BD	muon collider
Proton beam	SHiP HIKE REDTOP DUNE	SPS, neutrino experiments, etc

- ILC can be sensitive to small ϵ because of positron annihilation
- AWAKE and muon-BD can be sensitive to large ϵ because of thick target and high beam energy, respectively
- REDTOP is η meson factory and can perform prompt decay search(sensitive to large ϵ)

※ FASER2 is LHC auxiliary detector experiments in HL-LHC phase

Summary

・Key features of beam dump(fixed target) experiments:

- The beam dump experiment is high luminosity experiment sensitive to Sub-GeV scale

  ⇒ The physical potential is complemental to the other experiments, e.g., collider experiments, direct detection experiments

- The beam dump experiment can run in parallel with accelerator-based experiments

  ⇒ The beam dump experiments are economical and would also run with future accelerators, e.g., HL-LHC, ILC, and muon collider.

  ⇒ High energy and high flux beams in the future accelerator lead to high sensitivity of the parasitic beam dump experiments

・Regarding the dark sector search, the physical potential of the beam dump experiment depends on various factors, e.g., beam flux, beam energy, beam particle, acceptance, detection approach,…

・The beam dump experiment tandems with the future accelerators and potentially sheds light on the beyond the SM