LDMX at S30XL and Future Upgrades

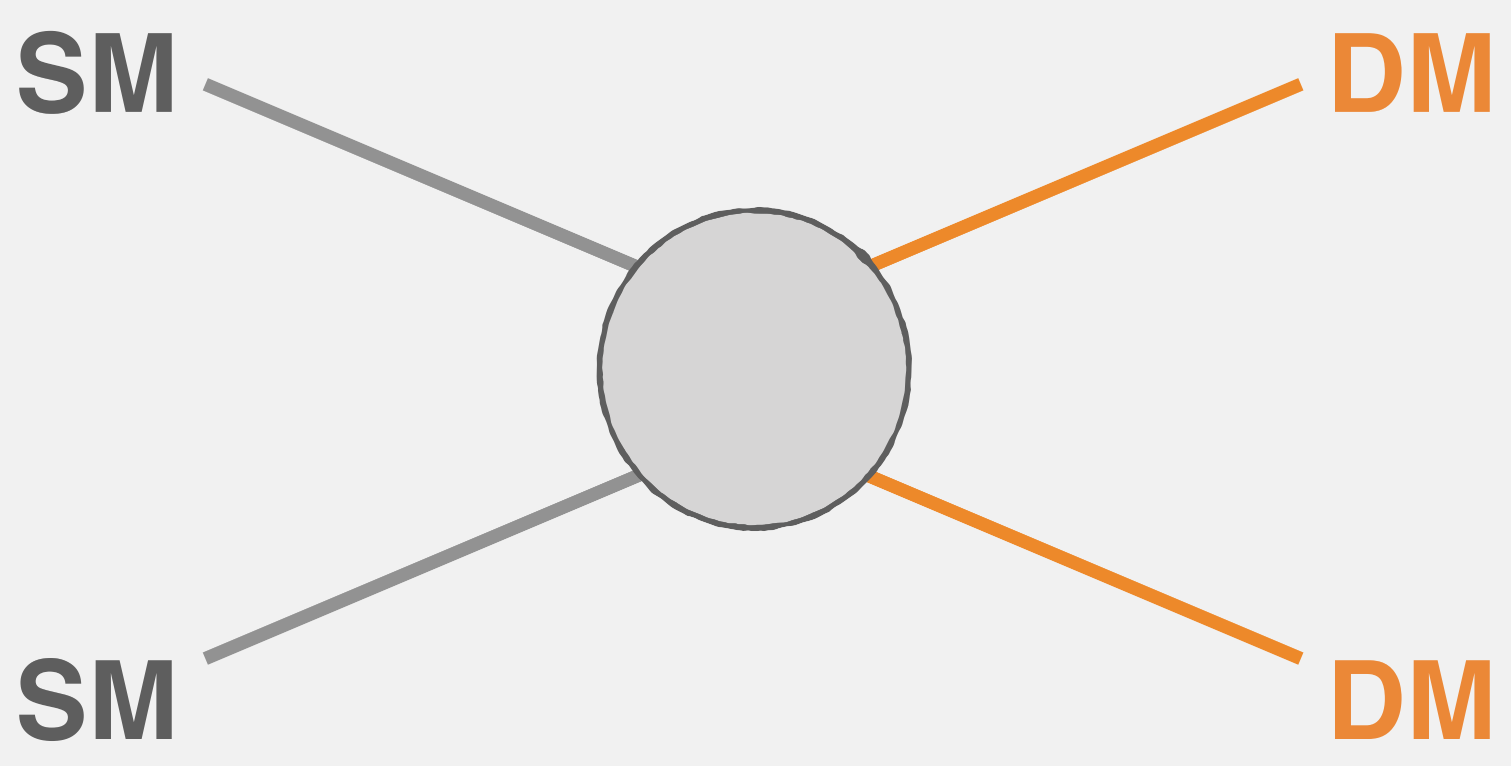
Light Dark Matter at Accelerators

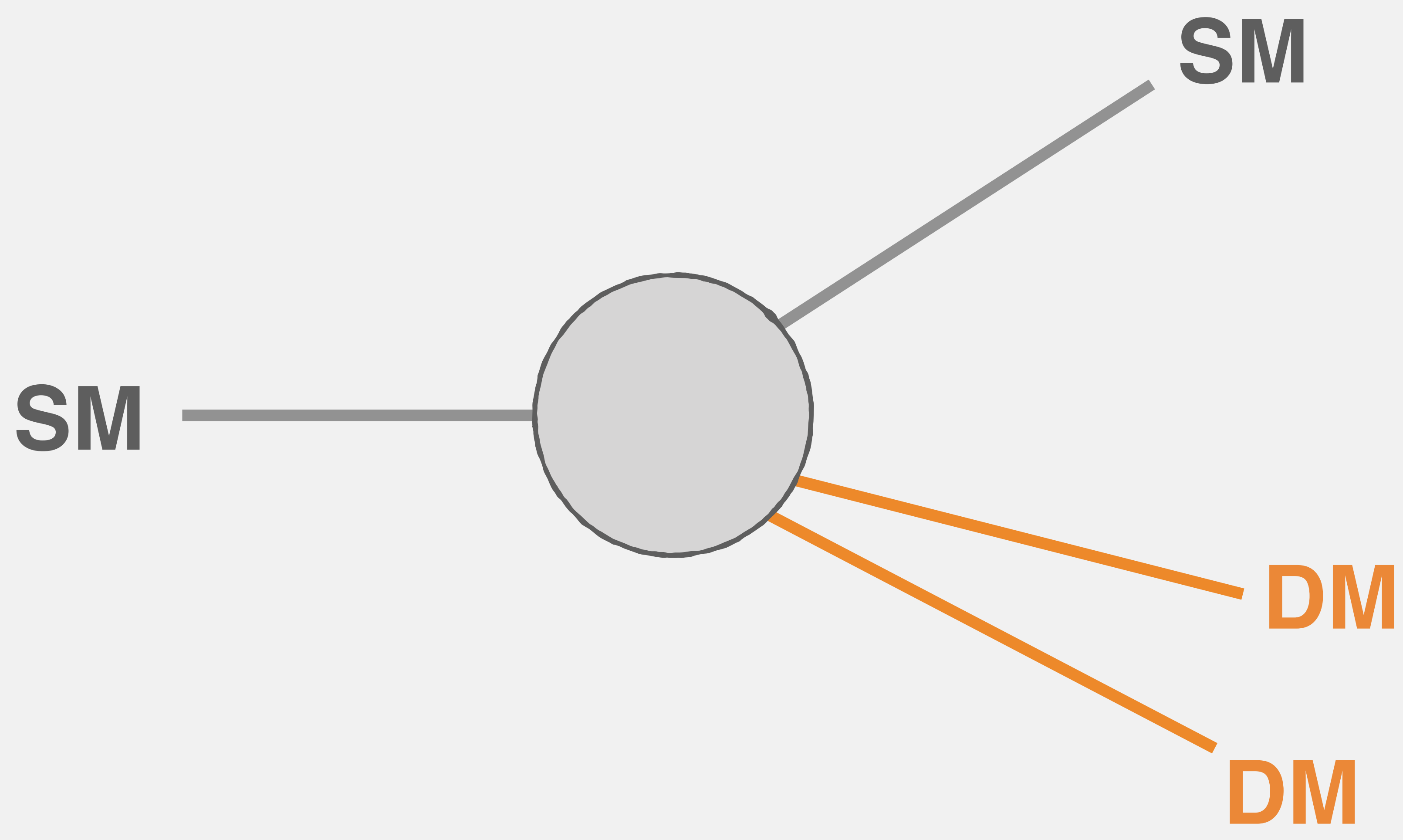
Venice, November 2019

Ruth Pöttgen, on behalf of LDMX

Main Motivation: Light Dark Matter

Thermal origin of Dark Matter —> production mechanism at accelerators/colliders



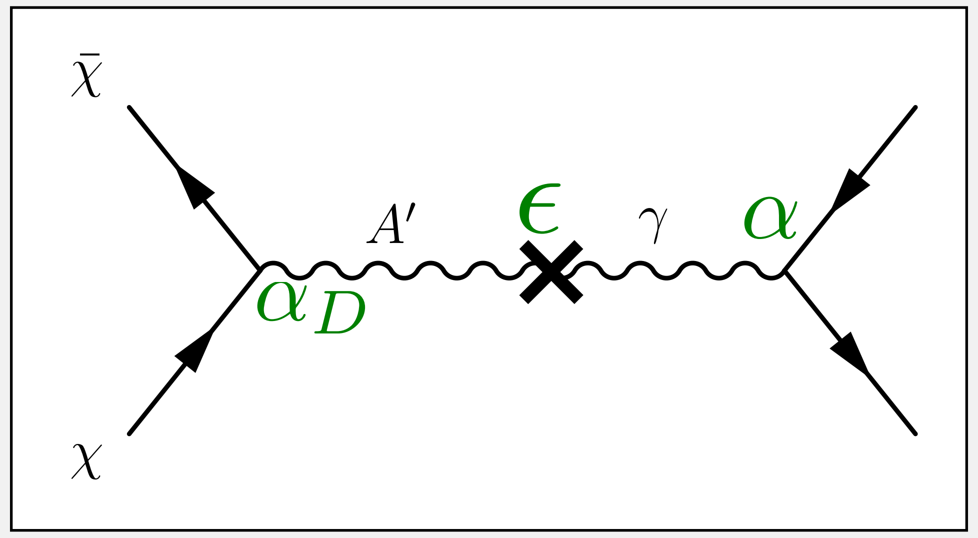


Sub-GeV thermal relic DM requires *new light mediator* to avoid overproduction of DM

Benchmark Model

Dark Photon (A')

- vector mediator
- kinetically mixes with photon (ε)
- dark sector coupling α_D

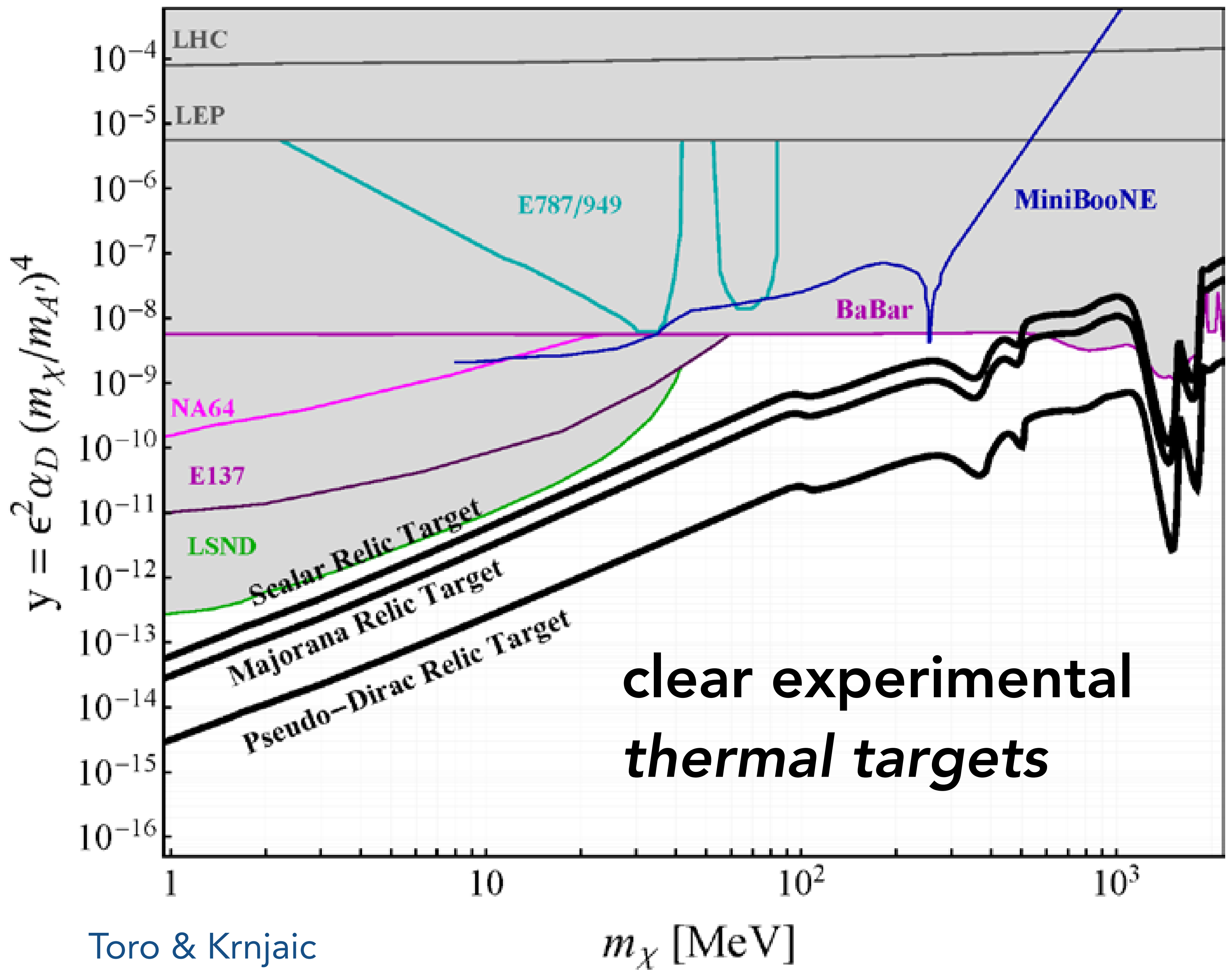


Annihilation cross section:

$$\sigma v \sim \alpha_D \varepsilon^2 \frac{m_\chi^2}{m_{A'}^4} \sim \alpha_D \varepsilon^2 \frac{m_\chi^4}{m_{A'}^4} \frac{1}{m_\chi^2} \sim y \frac{1}{m_\chi^2}$$

$$y = \alpha_D \varepsilon^2 \frac{m_\chi^4}{m_{A'}^4}$$

conservative: $\alpha_D = 0.5 \quad \frac{m_\chi}{m_{A'}} = \frac{1}{3}$



Toro & Krnjaic

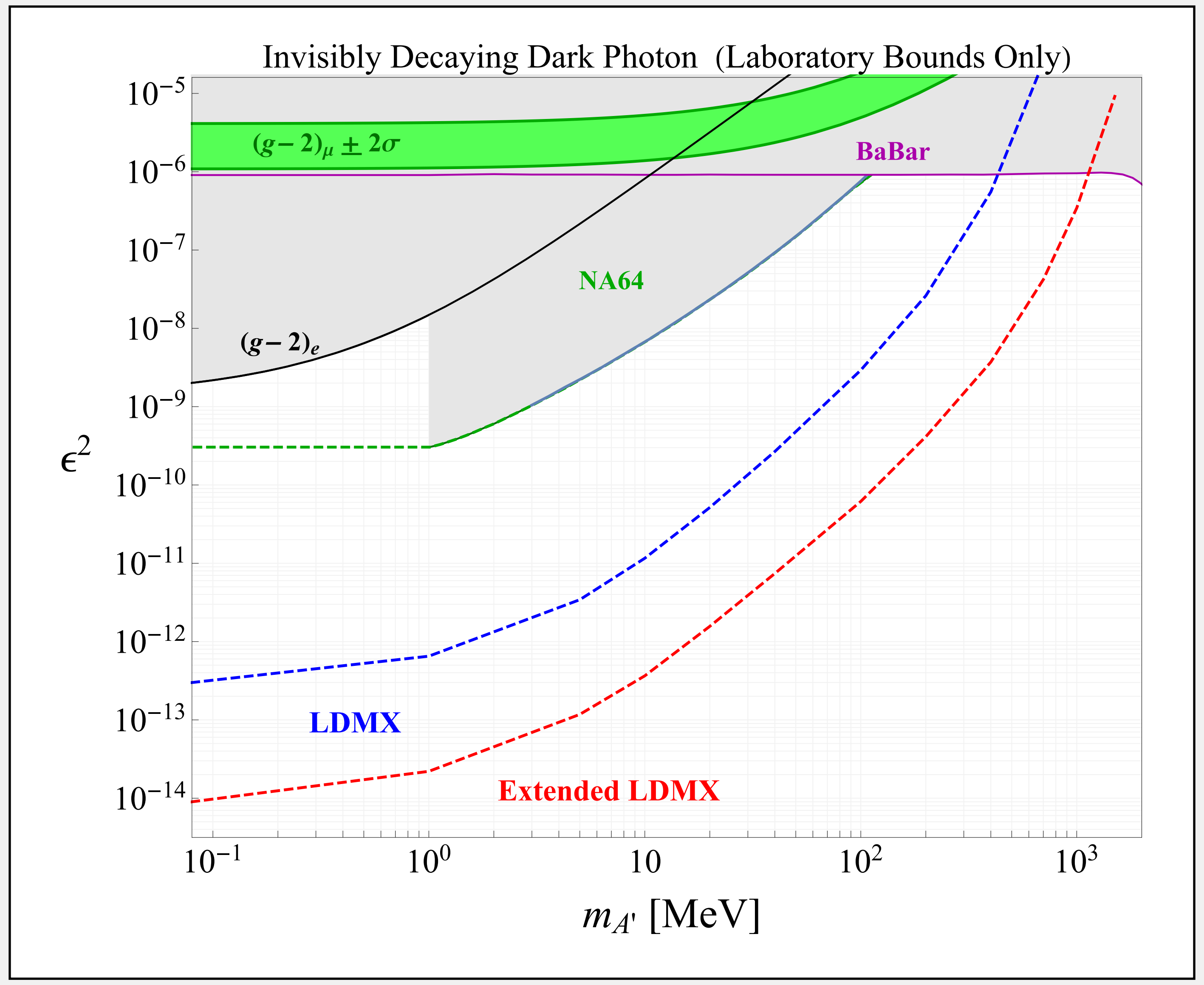
Broader Physics Potential

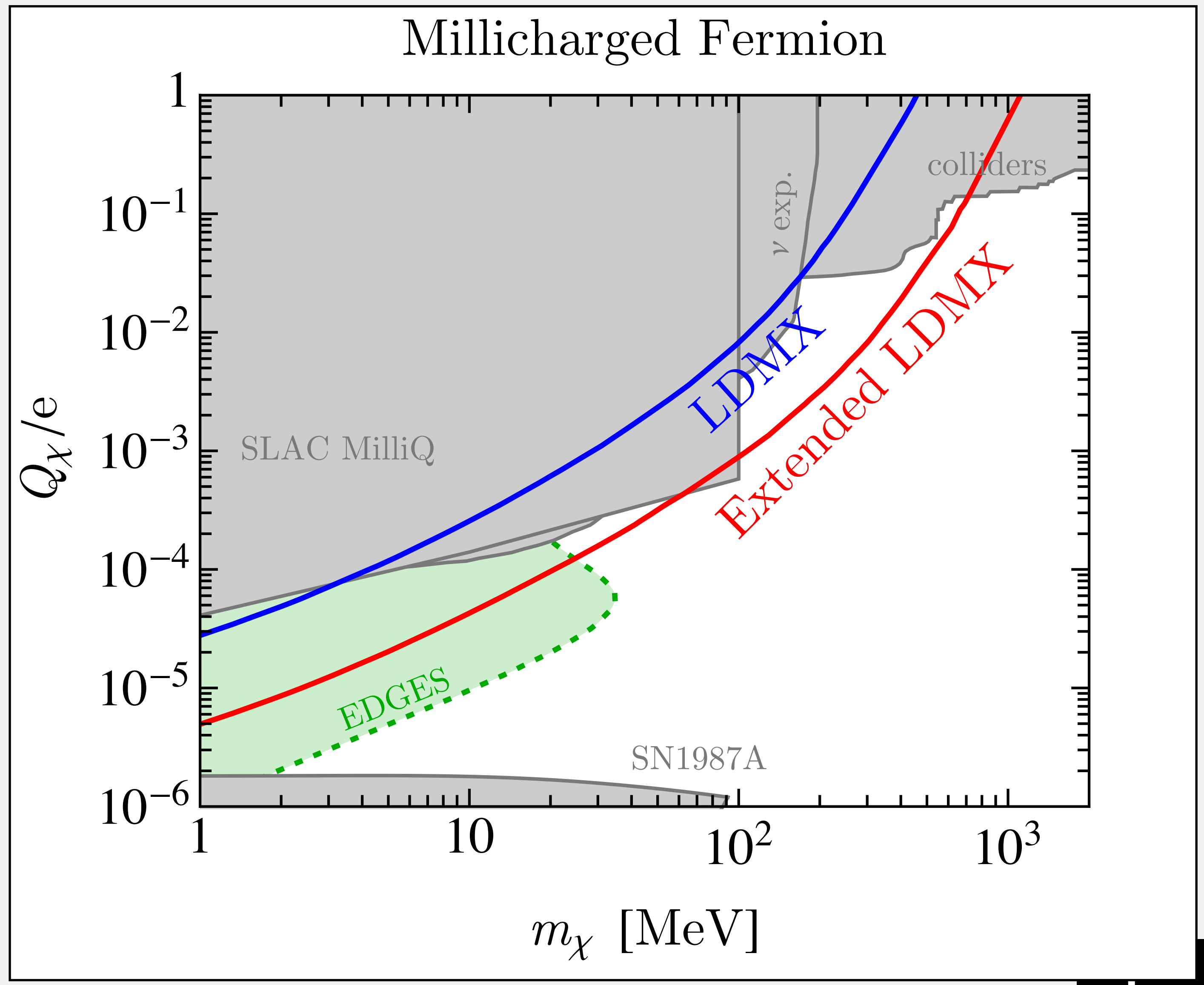
also sensitive to

- DM with quasi-thermal origin (asymmetric, SIMP/ELDER scenarios)
- new invisibly decaying mediators in general (A' one example)
- displaced vertex signatures (e.g. co-annihilation, SIMP)
- milli-charged particles

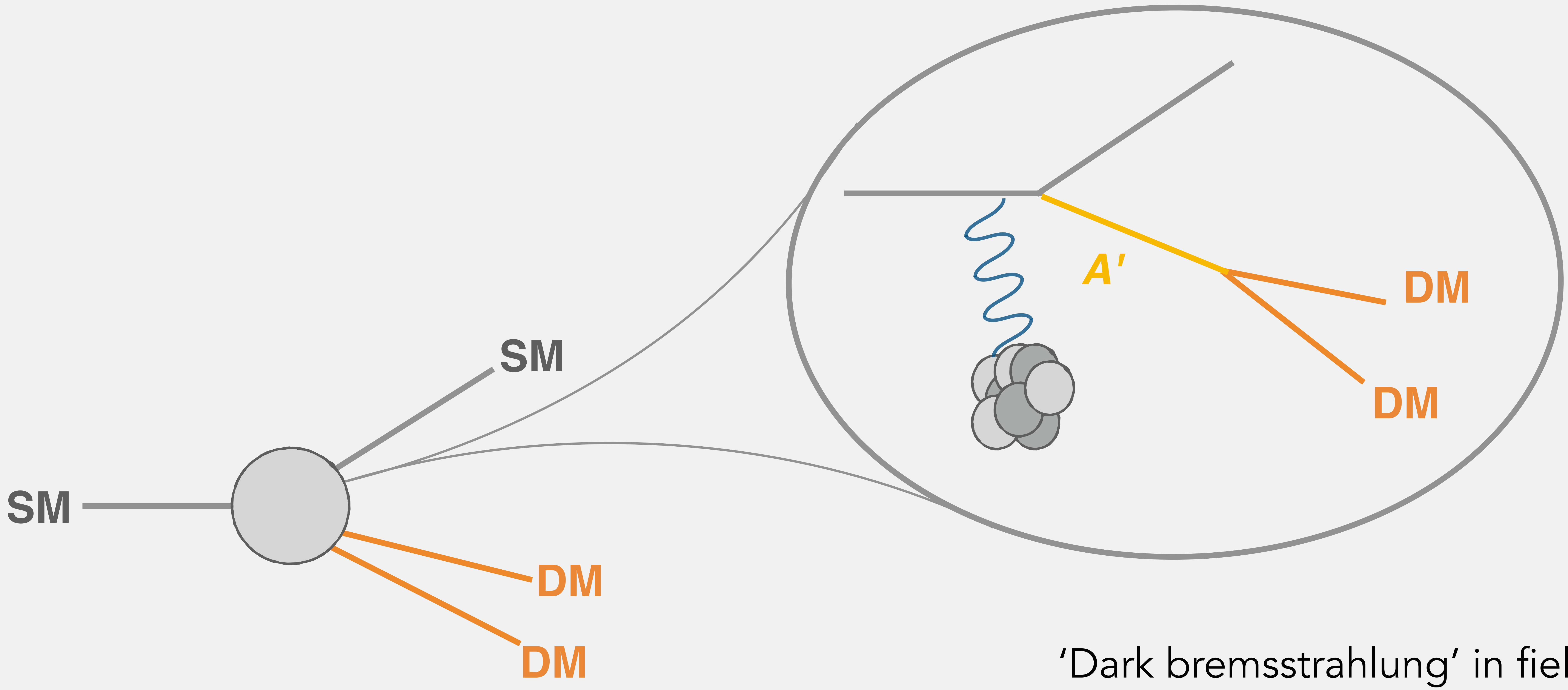
(more in Berlin, Blinov, Krnjaic, Schuster, Toro [arxiv:1807.01730](https://arxiv.org/abs/1807.01730))

in addition: *measurement* of photo- and electro-nuclear processes (for neutrino experiments)





LDM Production at Accelerators

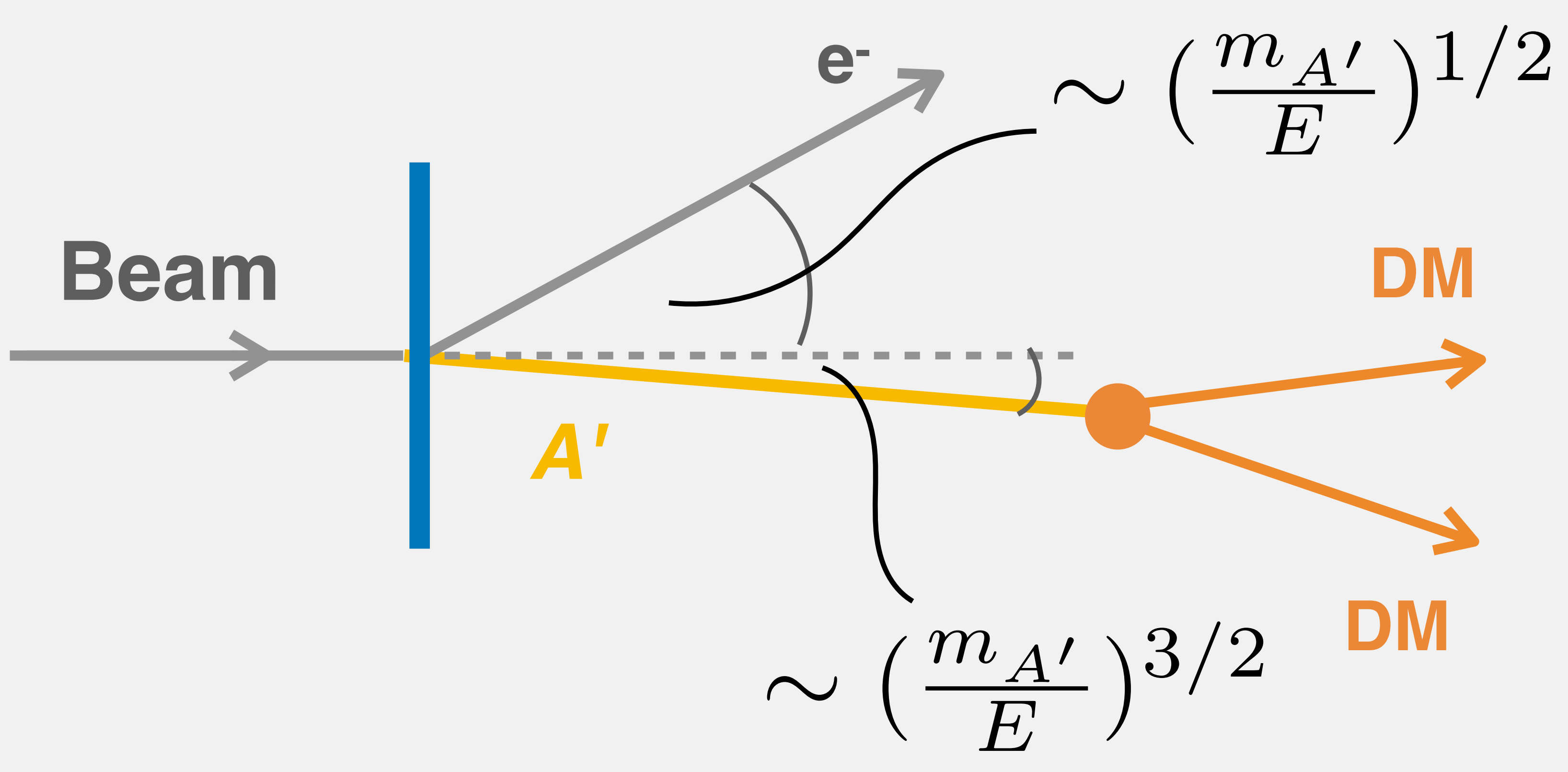


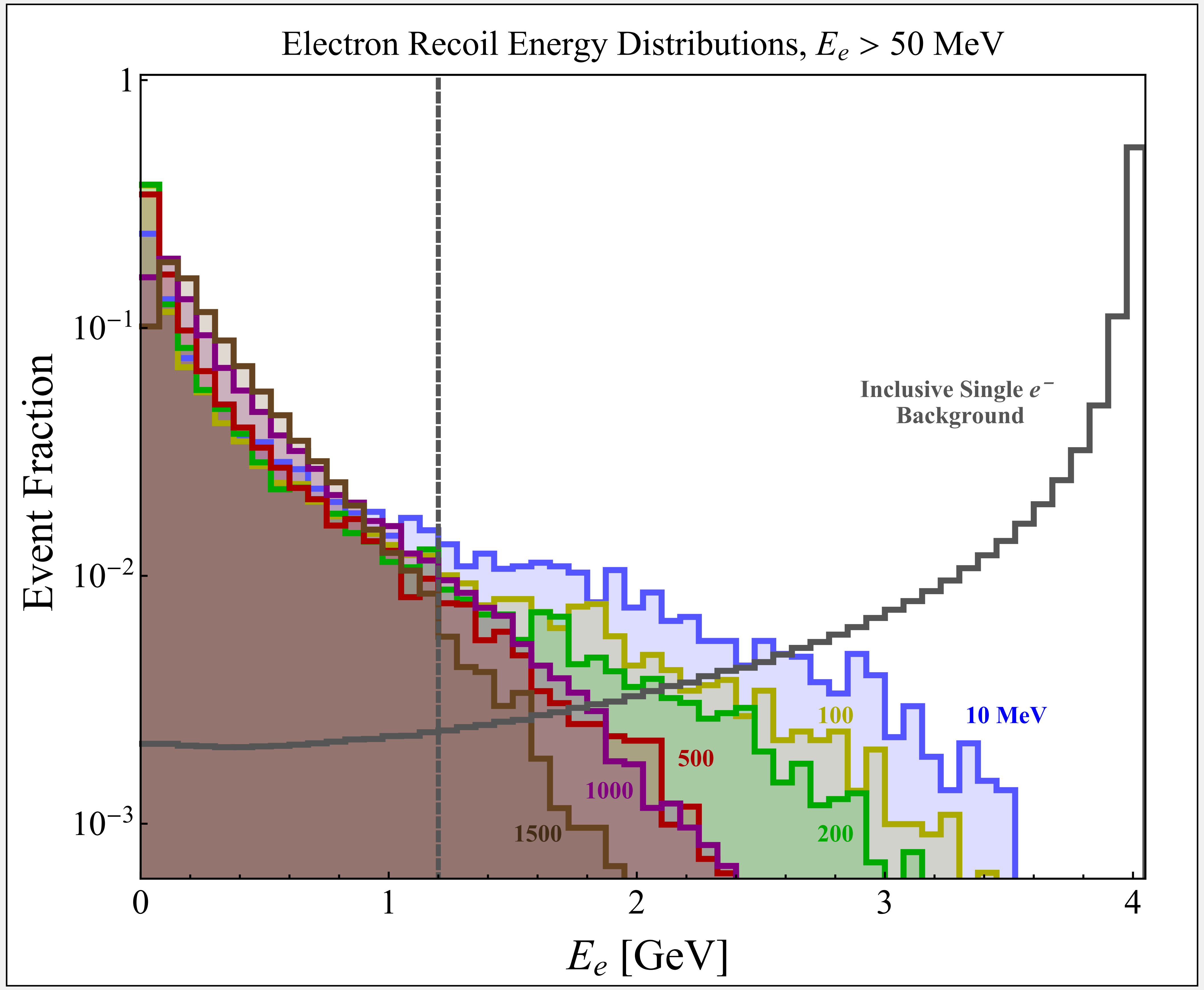
'Dark bremsstrahlung' in field of a nucleus

Main background: 'ordinary' bremsstrahlung of a SM photon

Kinematics

very different from SM bremsstrahlung (main background)



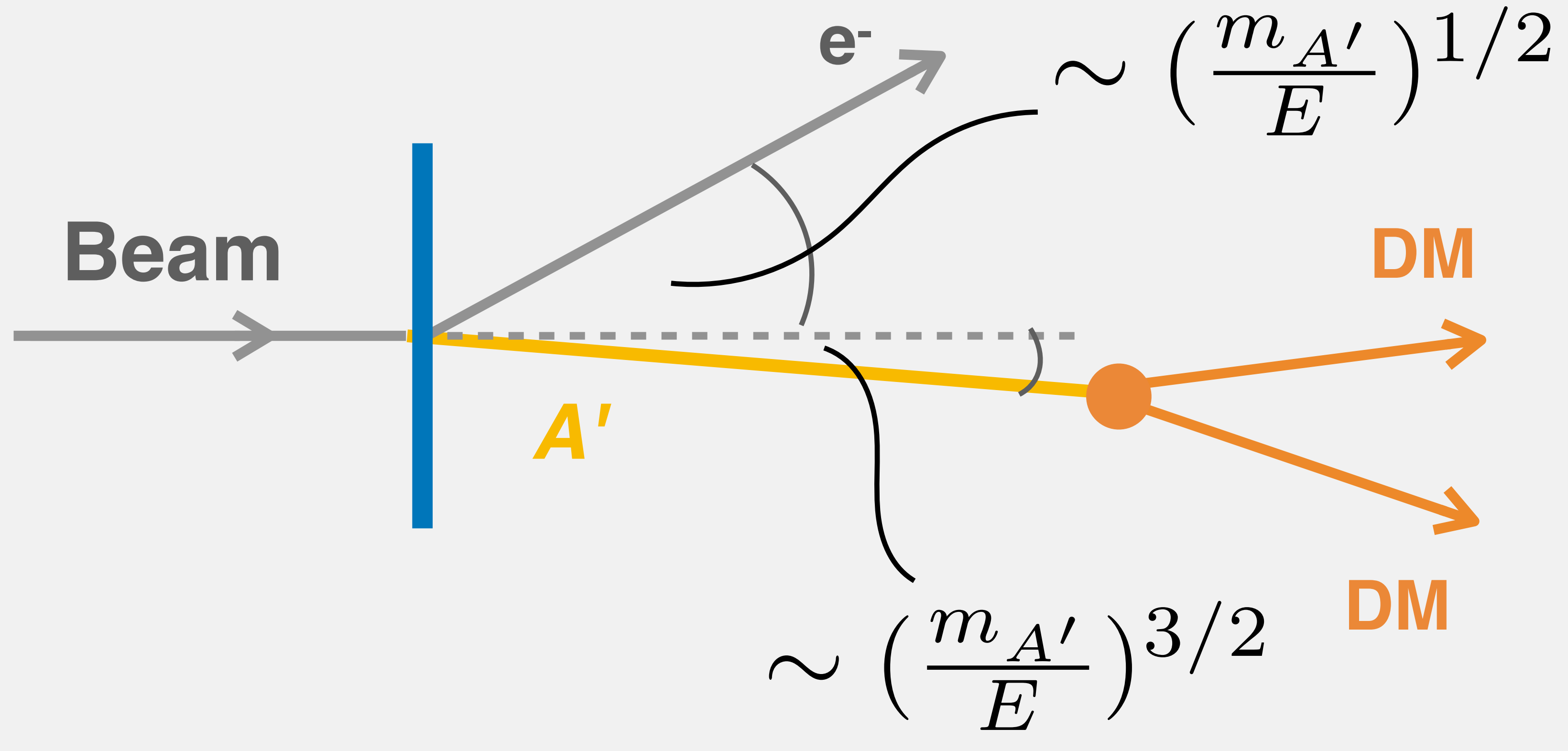


Mediator carries most of the energy

—> soft recoil electron, large missing energy

Kinematics

very different from SM bremsstrahlung (main background)

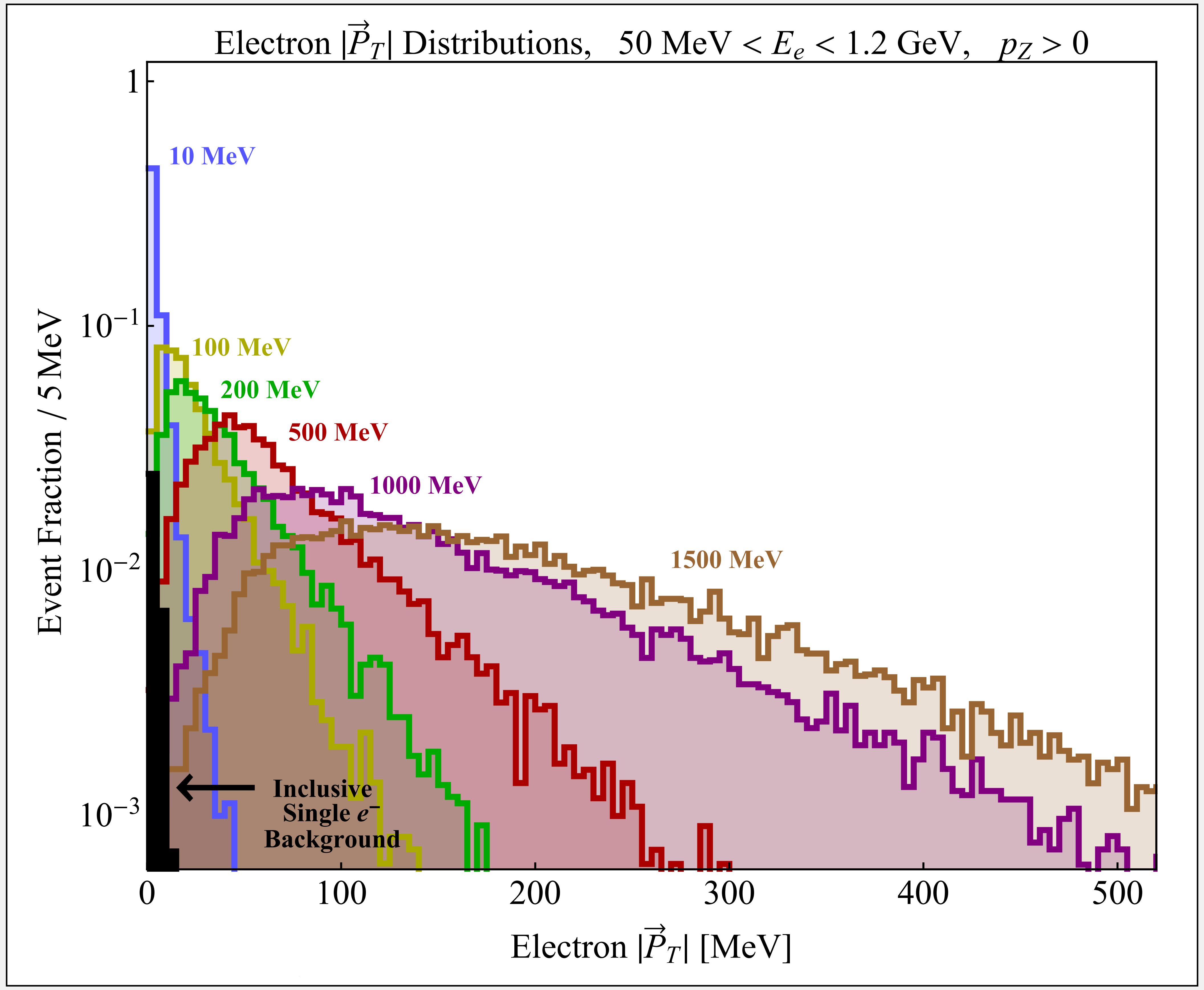


Mediator carries most of the energy

—> soft recoil electron, large missing energy

Recoil electron gets transverse 'kick'

—> large missing transverse momentum

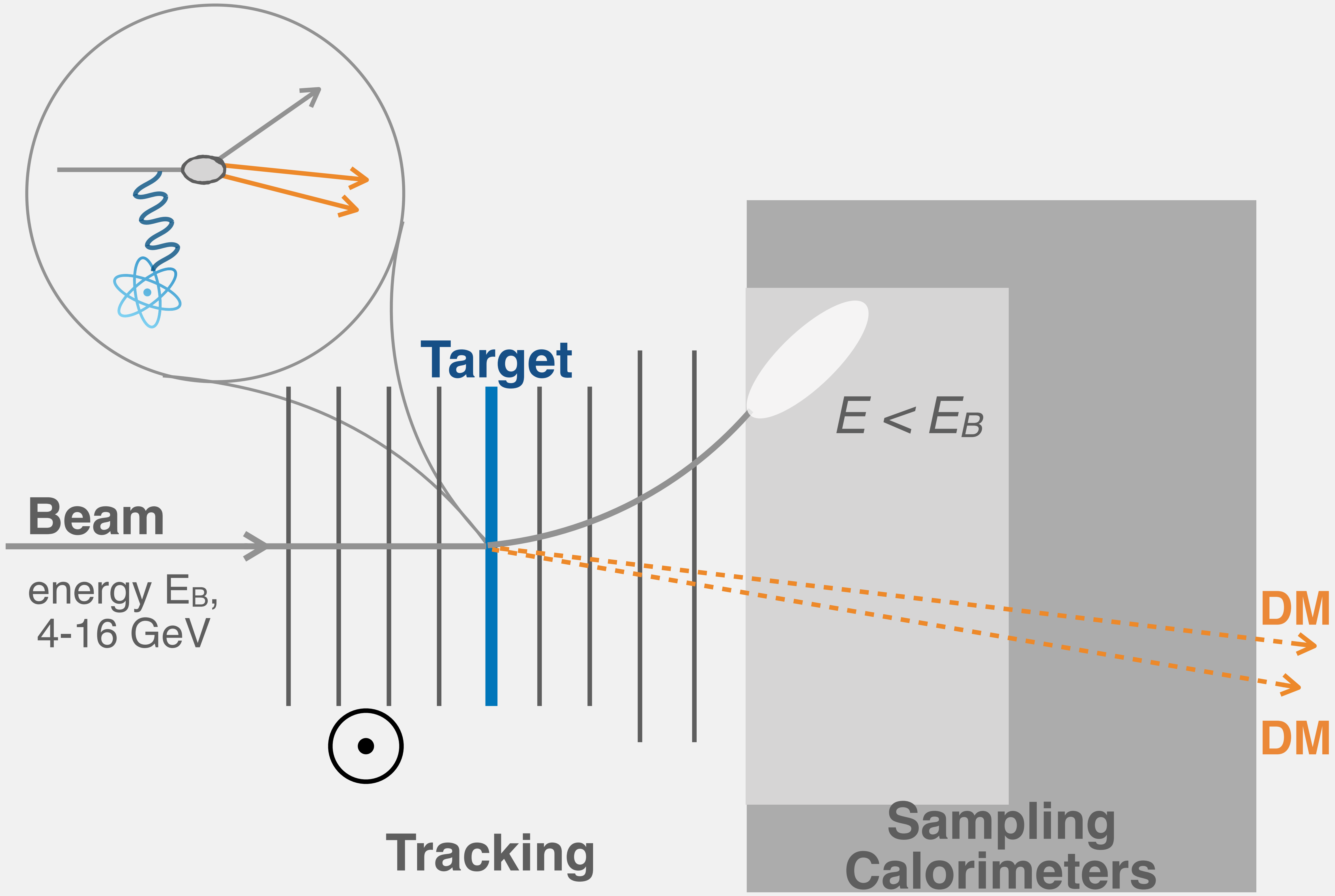


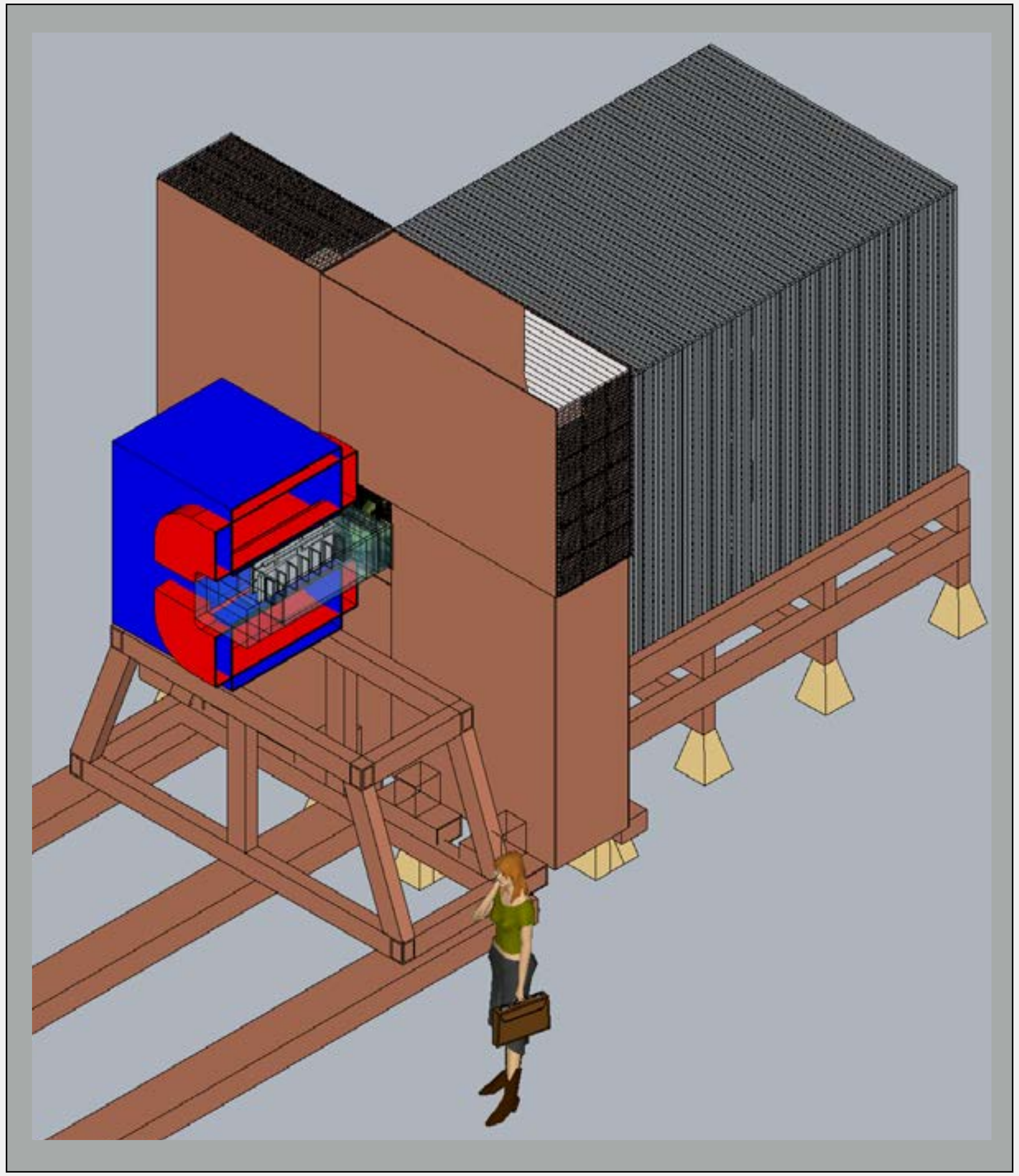
measurement of p_T: strong discriminator AND information about (missing) mass!

LDMX

design paper arxiv:1808.05219

Light Dark Matter eXperiment





individually measure up to 10^{16} electrons on target (EoT),
missing energy & *missing (transverse) momentum*

small-scale experiment

The Beam

A special beam

beam **energy** ideally 4 GeV < E_B < 20 GeV

looking for extremely rare signal
—> need very large statistics

goal: 10^{14} - 10^{16} electrons in few years

—> beam with **high duty-cycle**

resolve individual particles
—> **low number** of electrons per bunch (≤10)
—> **large beam spot**

Currently preparations for LDMX at **S30XL**:
dedicated transfer line for a 4 (8) GeV electron beam from LCLS-II at **SLAC**
(Linac Coherent Light Source)

Upgrades:
higher intensity with 8 GeV electrons at S30XL,
proposed 3.5 - 16 (20) GeV electron beam from eSPS at CERN
(Super Proton Synchrotron)

S30XL @ LCLS-II @ SLAC

https://confluence.slac.stanford.edu/display/MME/Publications+and+Presentations

(Sector 30 Transfer Line)

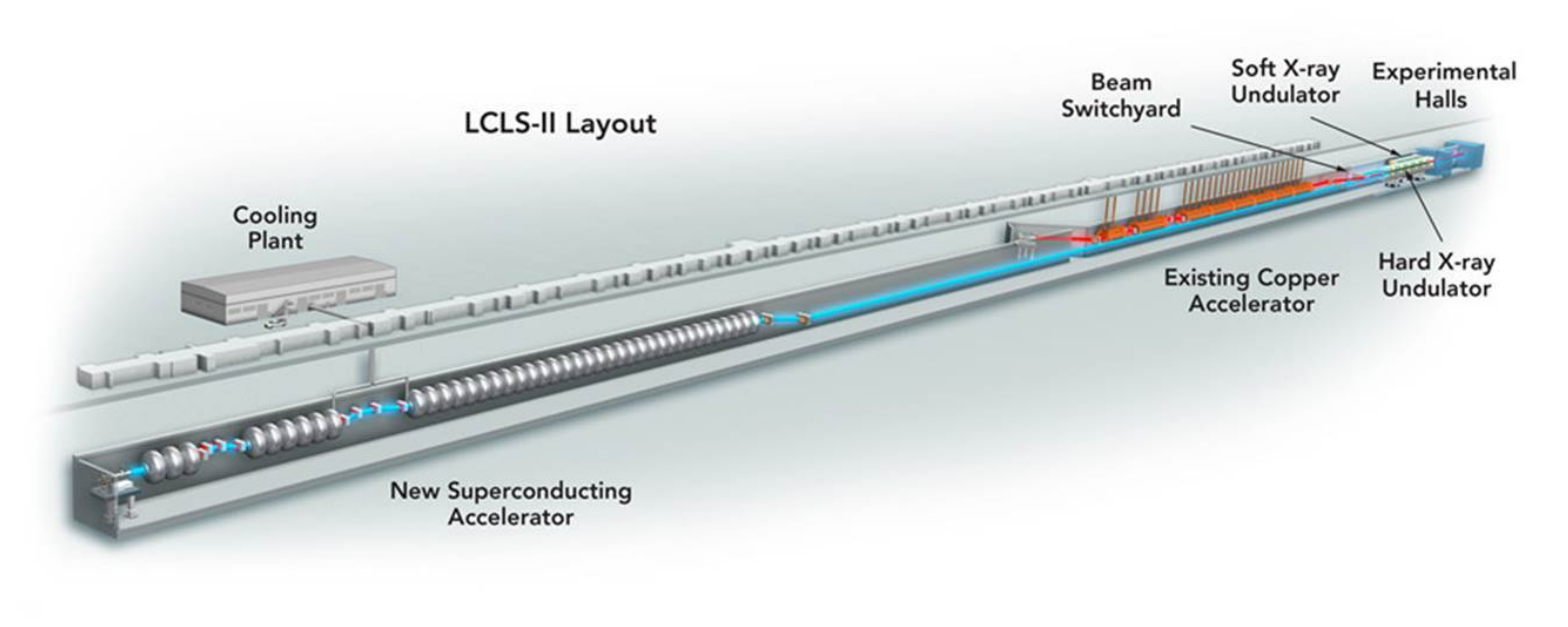
Goal: Parasitically extract low-current, high-rate electron beam from LCLS-II linac

Physics program spans dark matter physics (LDMX), neutrino physics (electro-nuclear scattering as reference), test beam program…

energy: 4 (8) GeV

bunch frequency: 46 MHz (186 MHz)

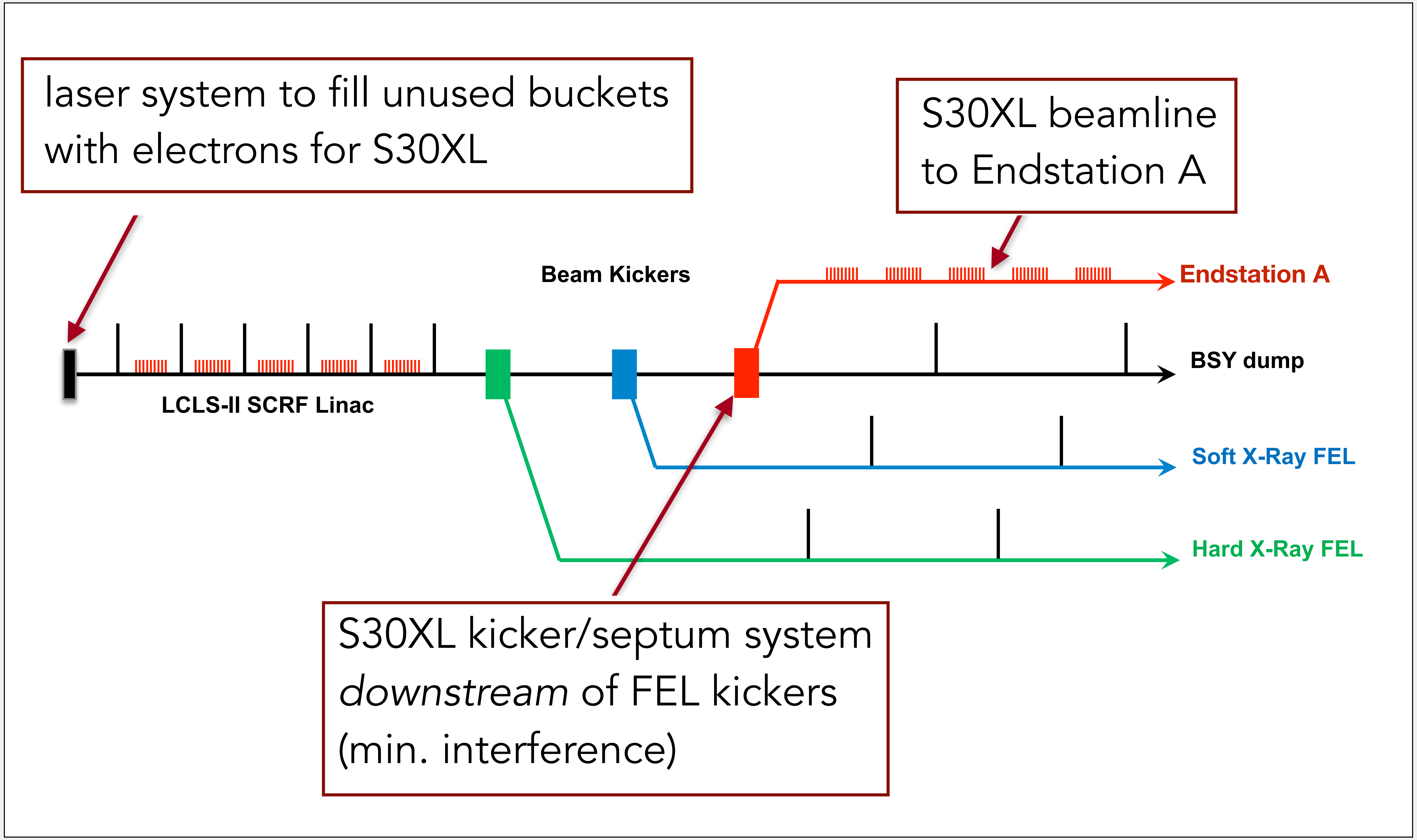
$4x10^{14}$ EoT year 1



S30XL @ LCLS-II @ SLAC

https://confluence.slac.stanford.edu/display/MME/Publications+and+Presentations

(Sector 30 Transfer Line)

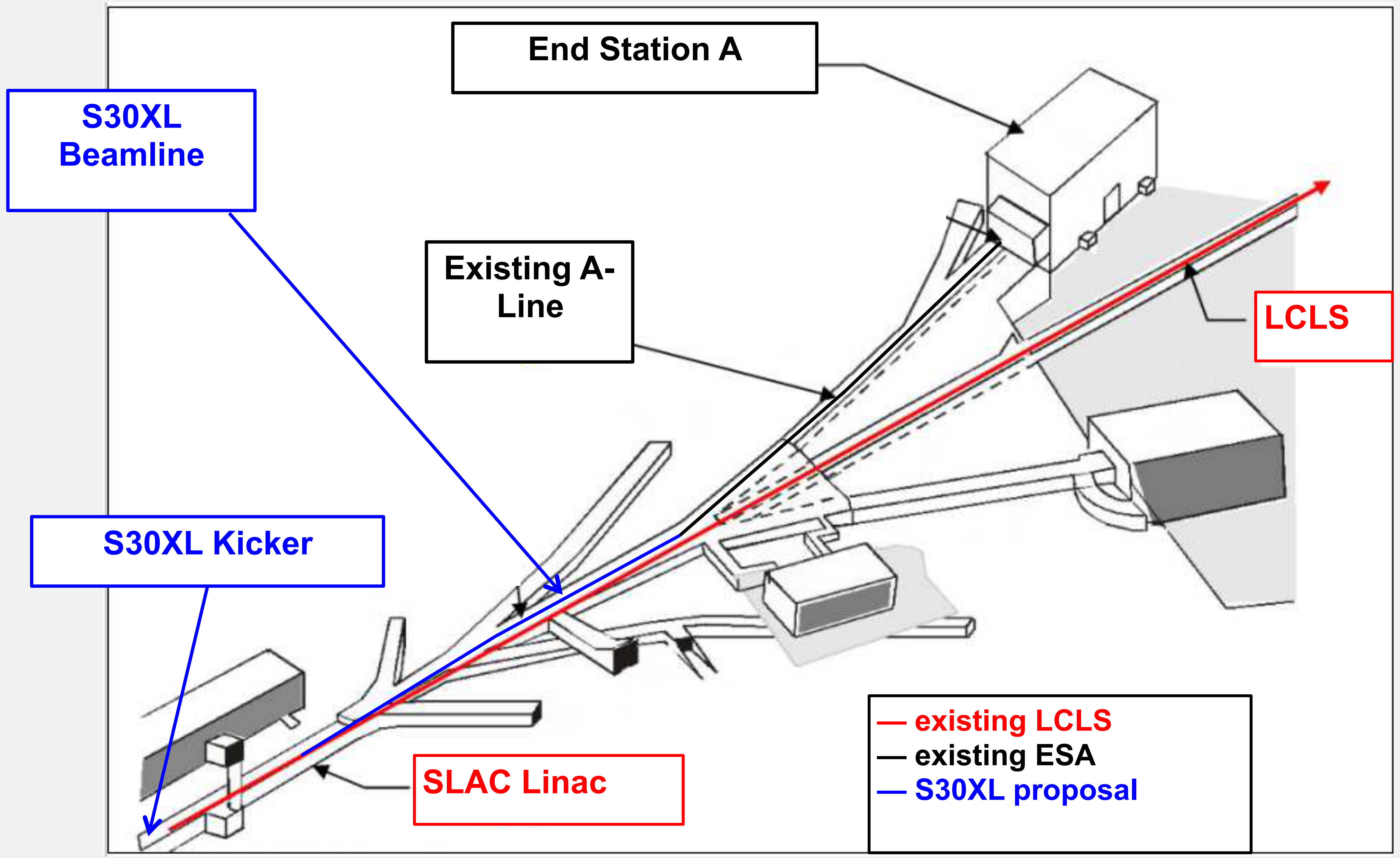


S30XL @ LCLS-II @ SLAC

(Sector 30 Transfer Line)

Staged approach:

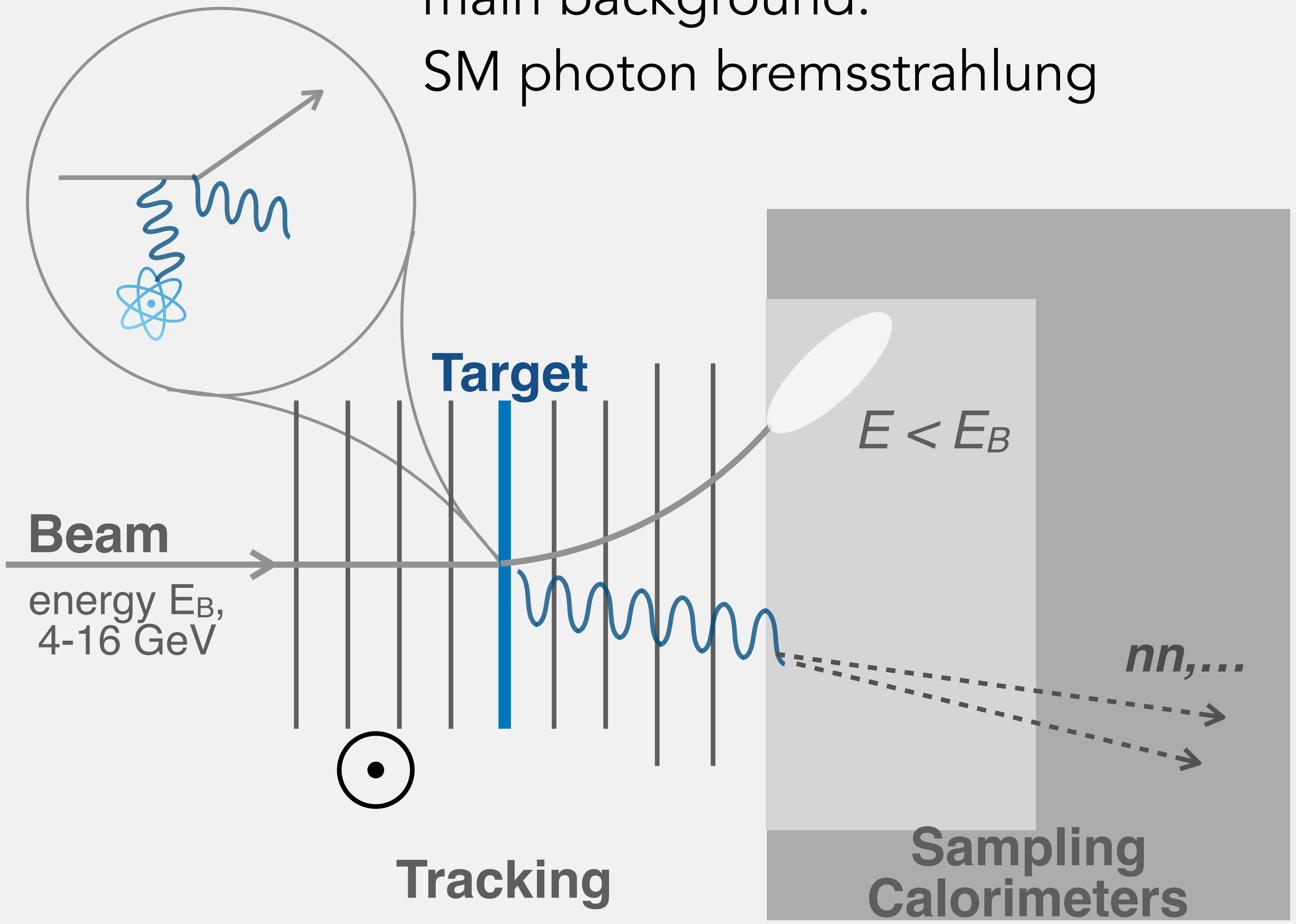
- first: S30 Accelerator Improvement Project (kicker & ~100m beamline – ending in beam switchyard)
  - Design underway following funding in FY19; release of construction funding expected after successful review (~early January)
  - Installation timeframe: depends on LCLS-II downtime schedule
  - Enable characterization of dark current, long-pulse kicker demonstration, single-electron QED tests, and high-rate single electron test beam
- second: additional ~100m beamline to connect to existing End Station A line, potentially laser system



The Experiment

Background Challenges

main background:
SM photon bremsstrahlung



particularly challenging:

photo-nuclear reactions producing *neutral final states* (relative rate: ~10^{-9})

—> most design work recently on HCal to optimise rejection power

Tracking

simplified copy of Silicon Vertex Tracker (SVT) of HPS experiment@JLab (visible Dark Photon search)

- fast (2ns hit time resolution)
- radiation hard
- technology well understood

tagging tracker

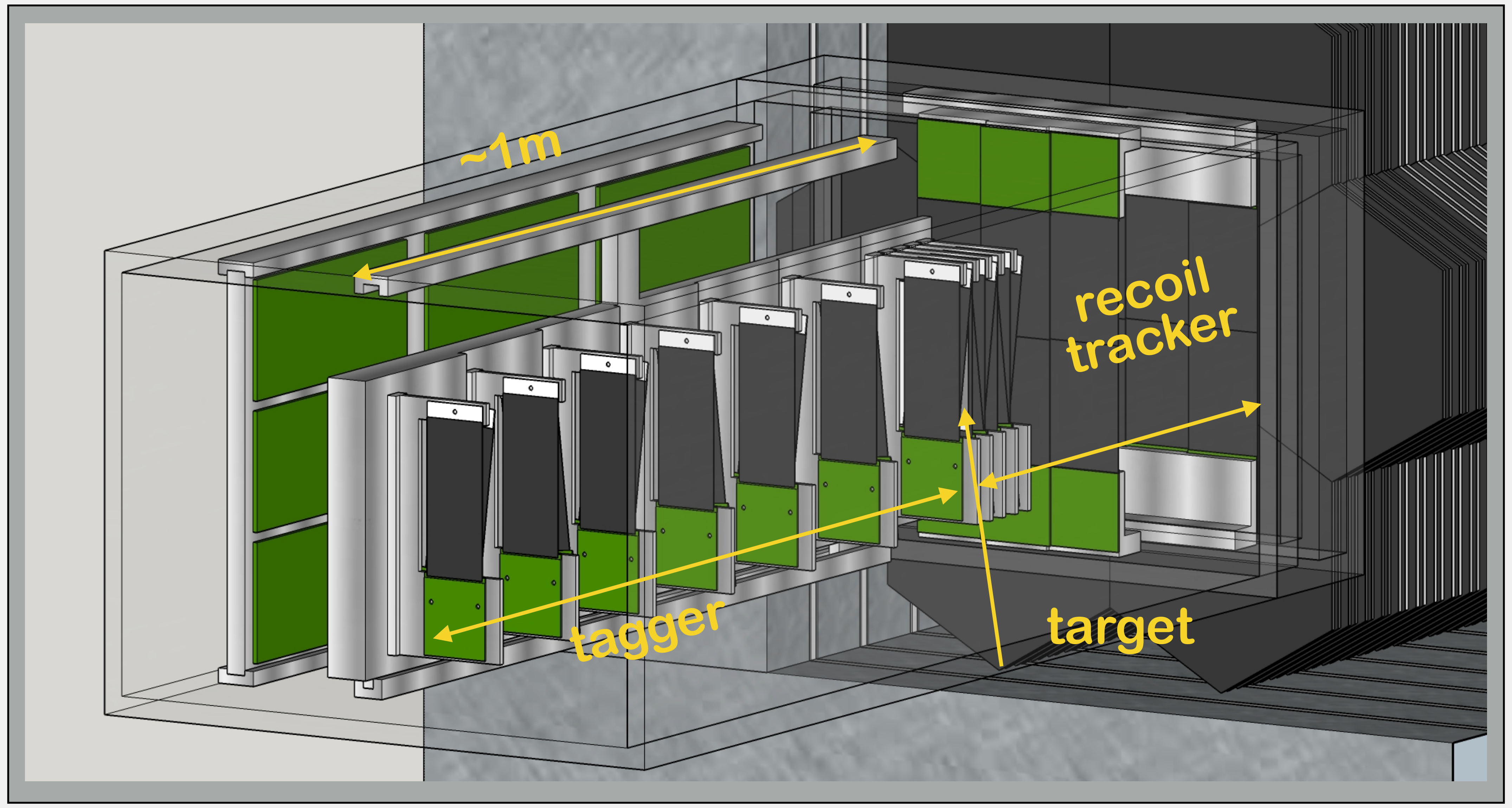
- in 1.5T dipole field
- measure incoming electron
  - momentum filter
  - impact point on target

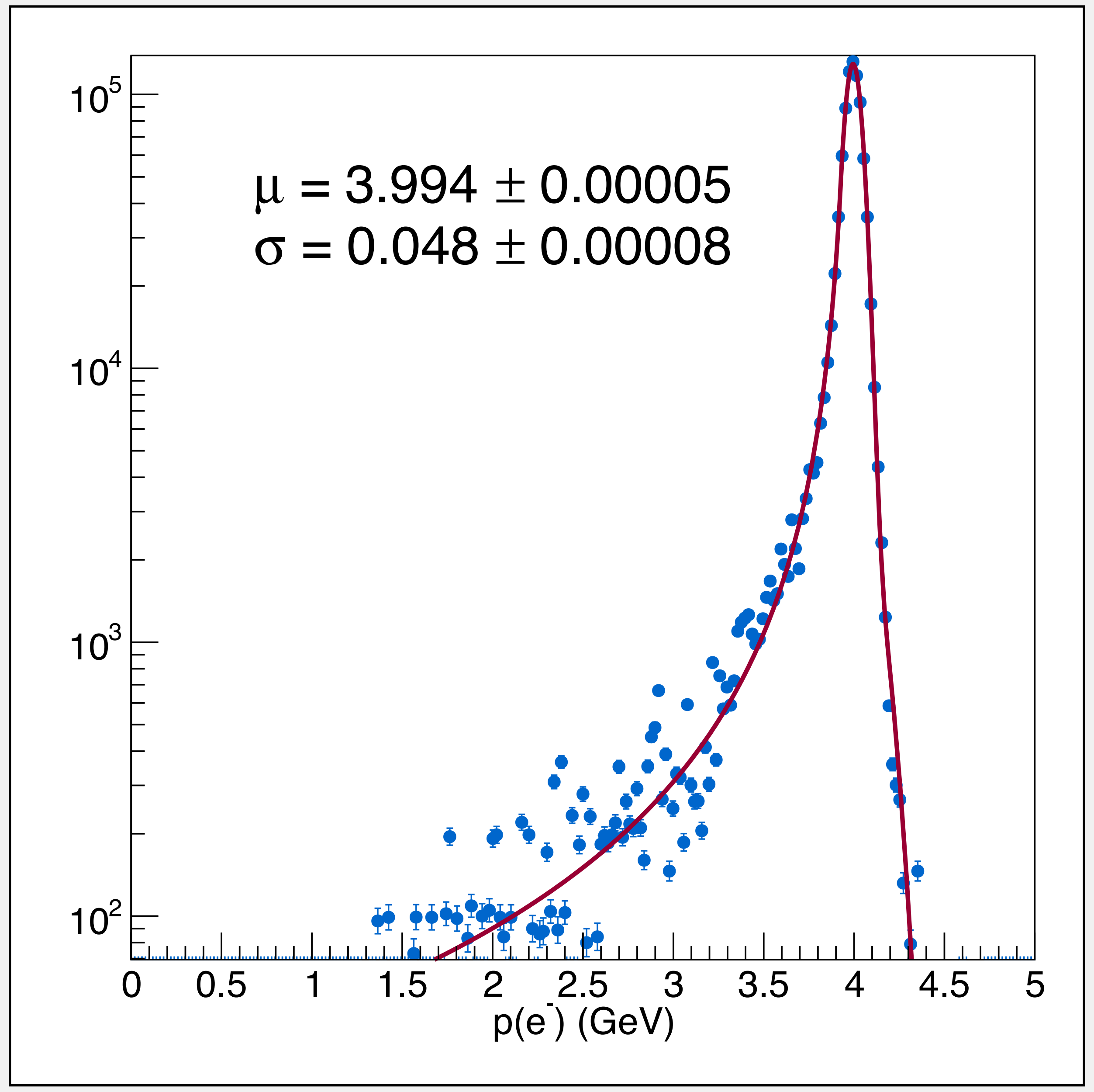
recoil tracker

- in fringe field
- measure recoil electron

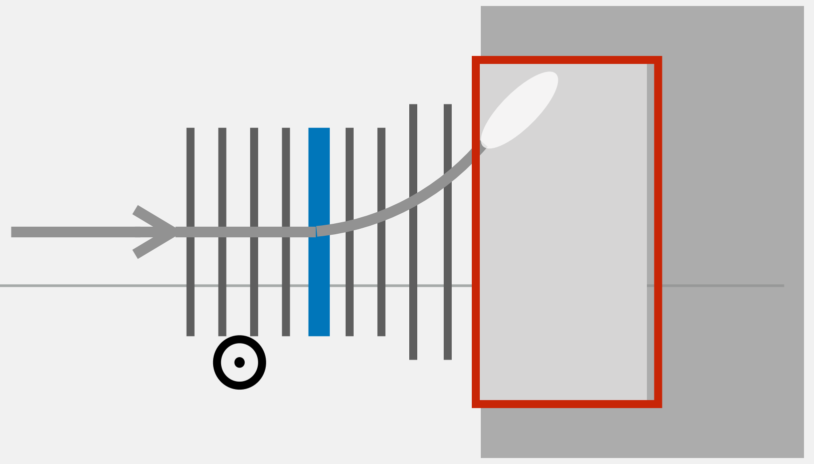
target

- ~0.1 - 0.3 X_0 tungsten
- balance signal rate & momentum smearing



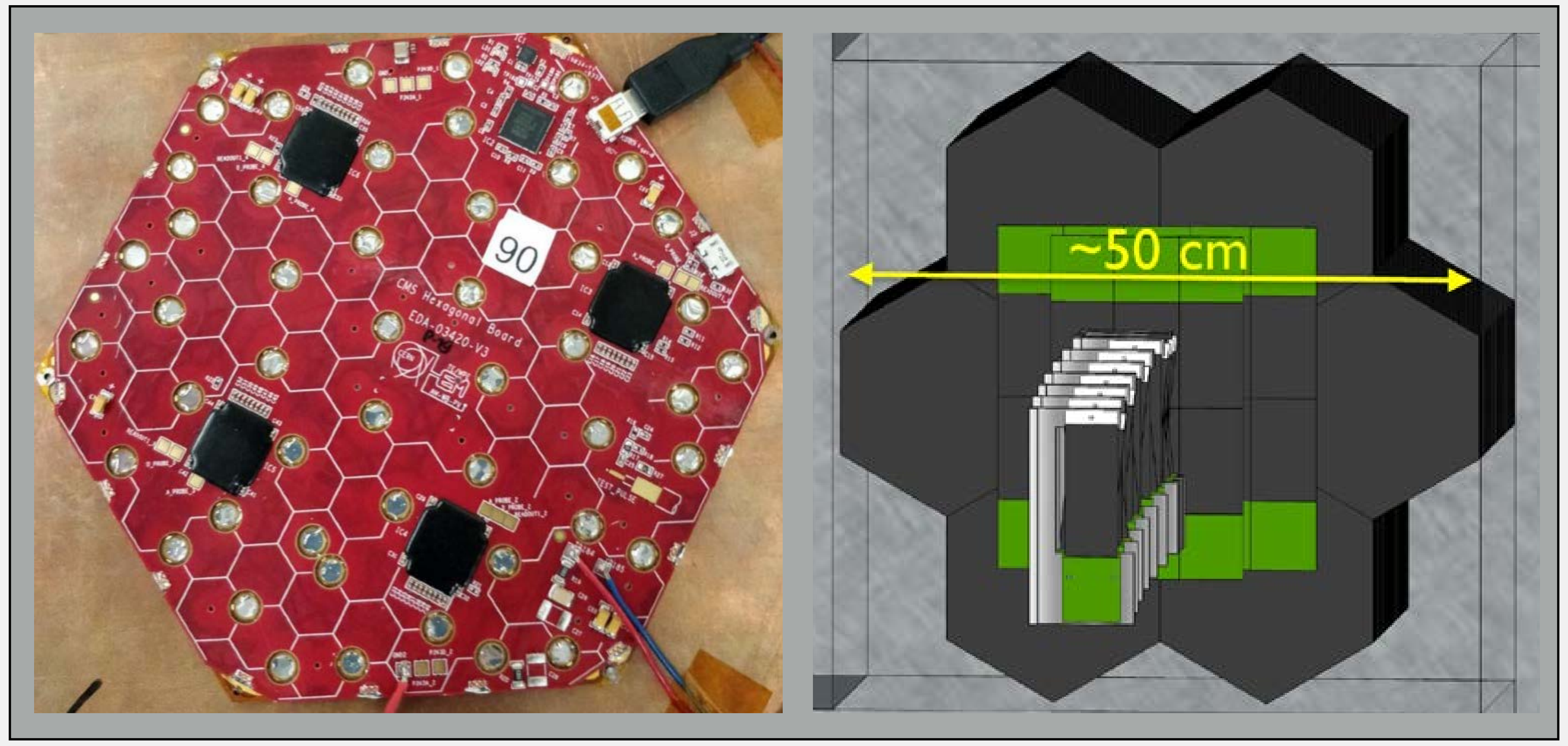


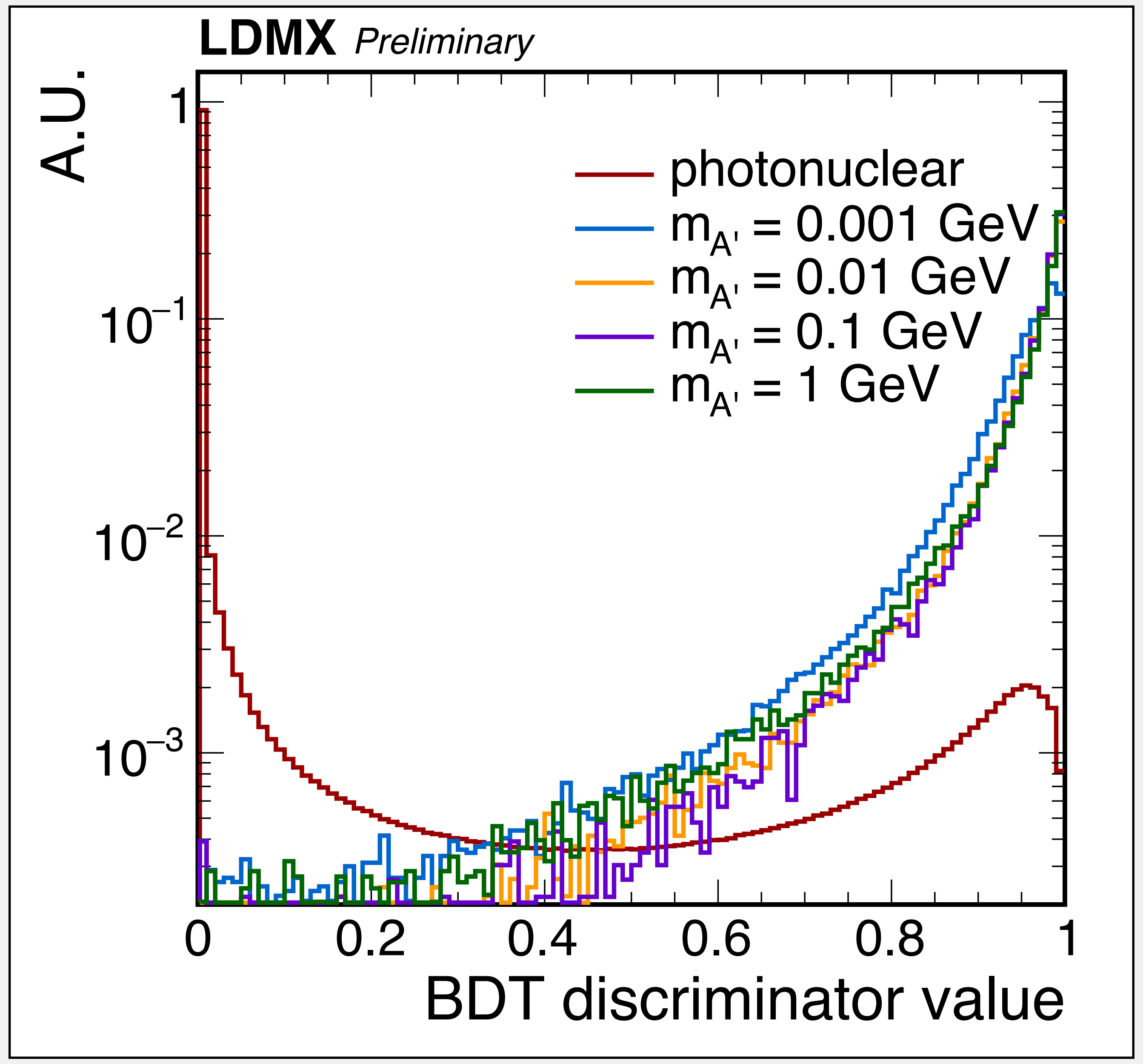
Electromagnetic Calorimeter

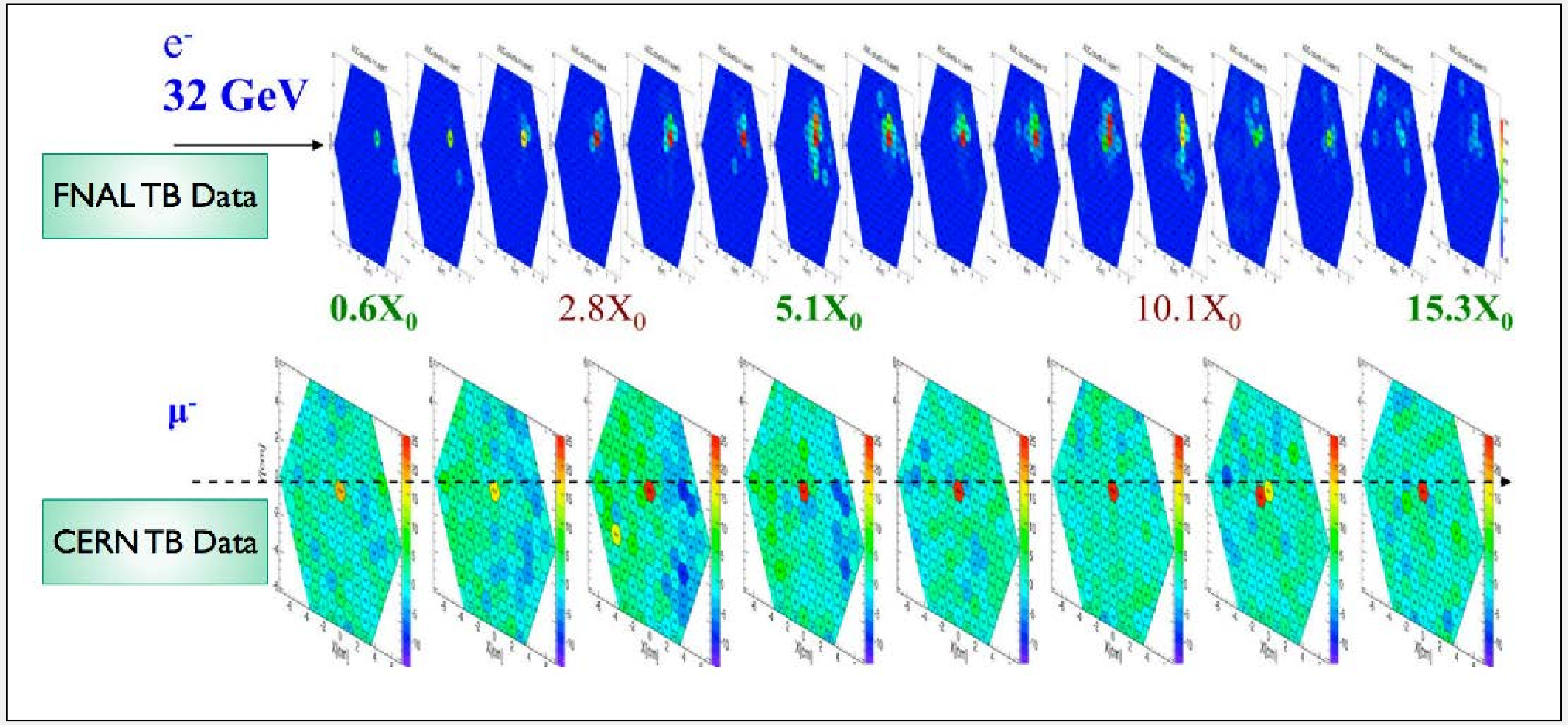


ECal

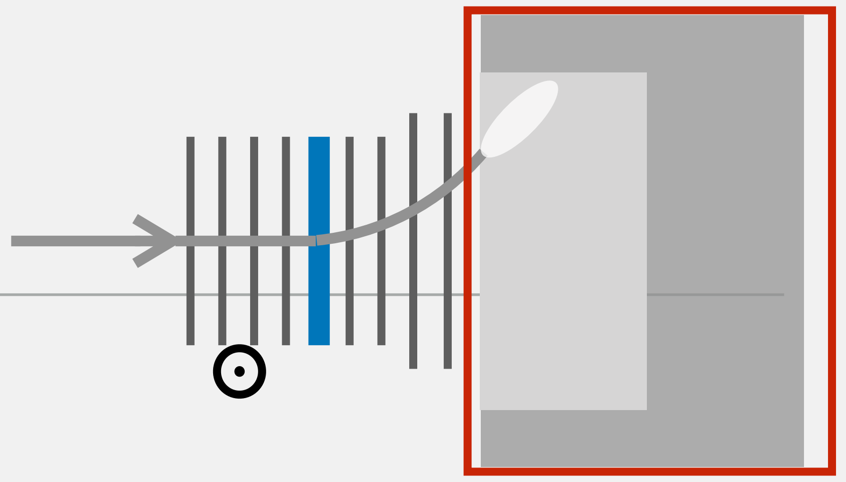
- draw on design of CMS@LHC forward SiW calorimeter upgrade
  - fast, radiation hard, dense
  - 40 radiation lengths (>30 layers)
  - high granularity ('tracking' of MIPs)
    - potentially increase granularity in central module





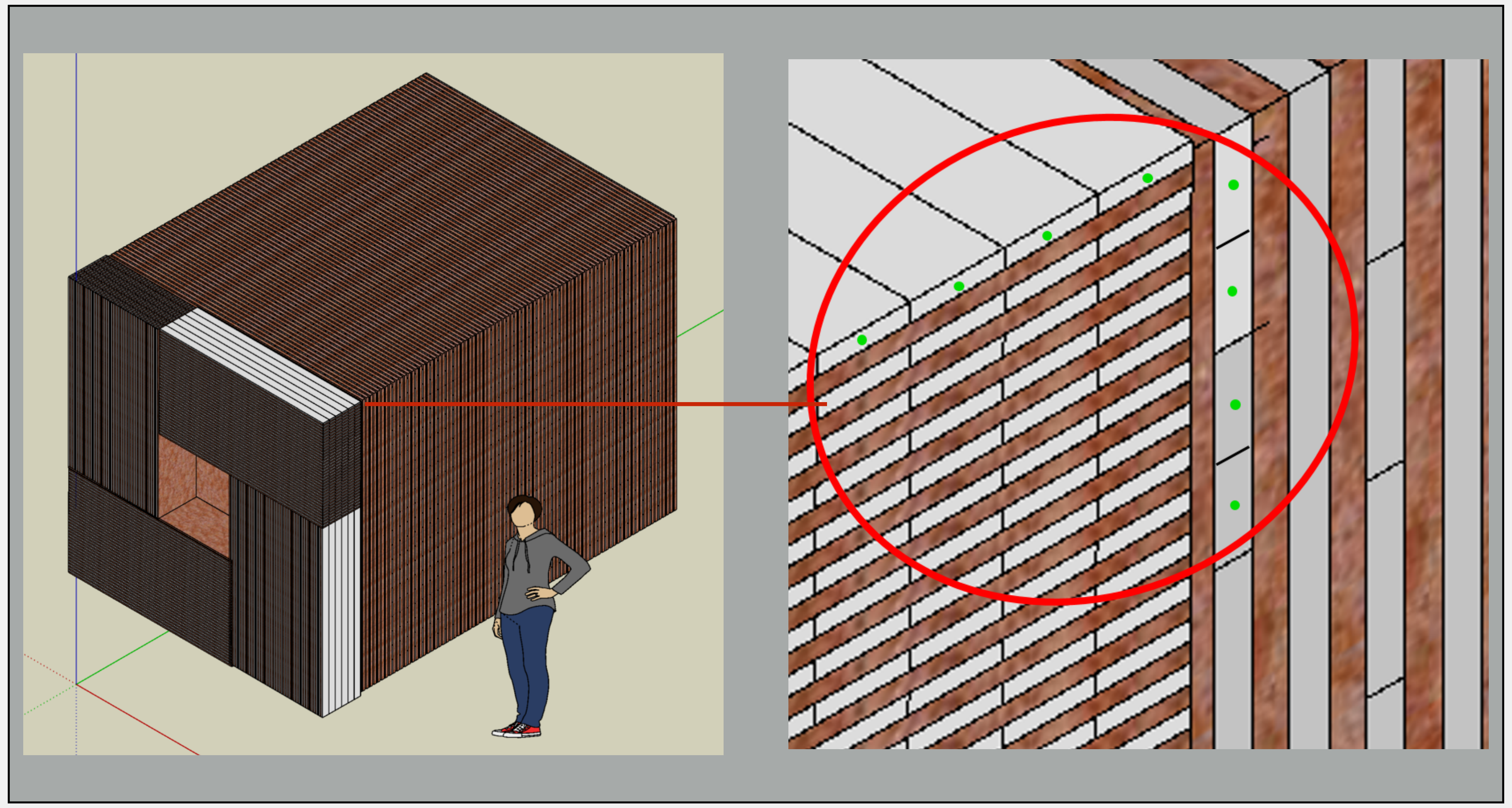


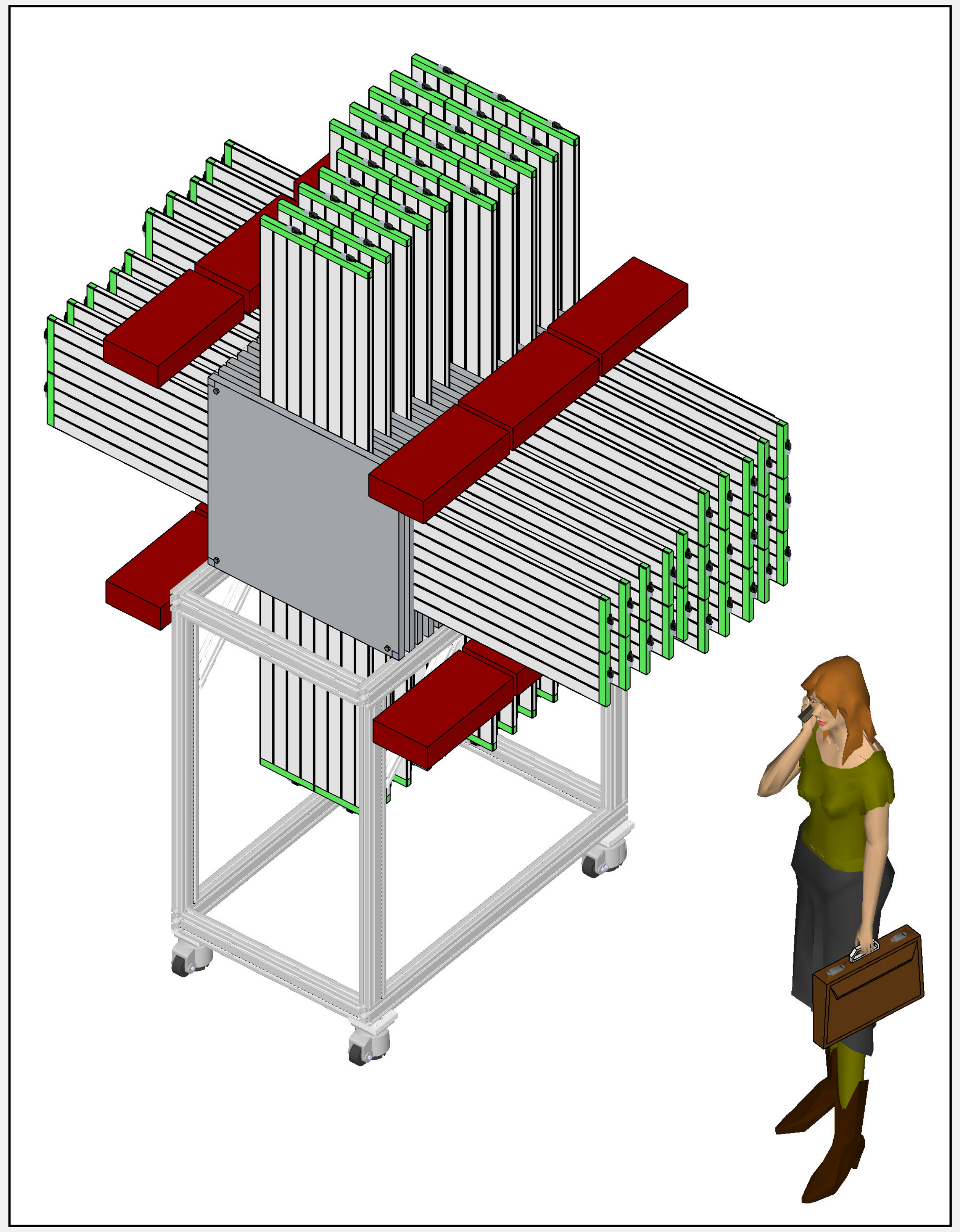
Hadronic Calorimeter



HCal

- highly efficient **veto** of low- and high-energy neutrons
- surround ECal as much as possible (back and side)
- plastic scintillator with steel absorber (inspiration from Minos/Mu2e/CMS)





Testbeam

- obtained first funding for R&D/prototype
- planned for fall 2020
- prototype layout coming together

Hadronic Calorimeter

Benchmark example:

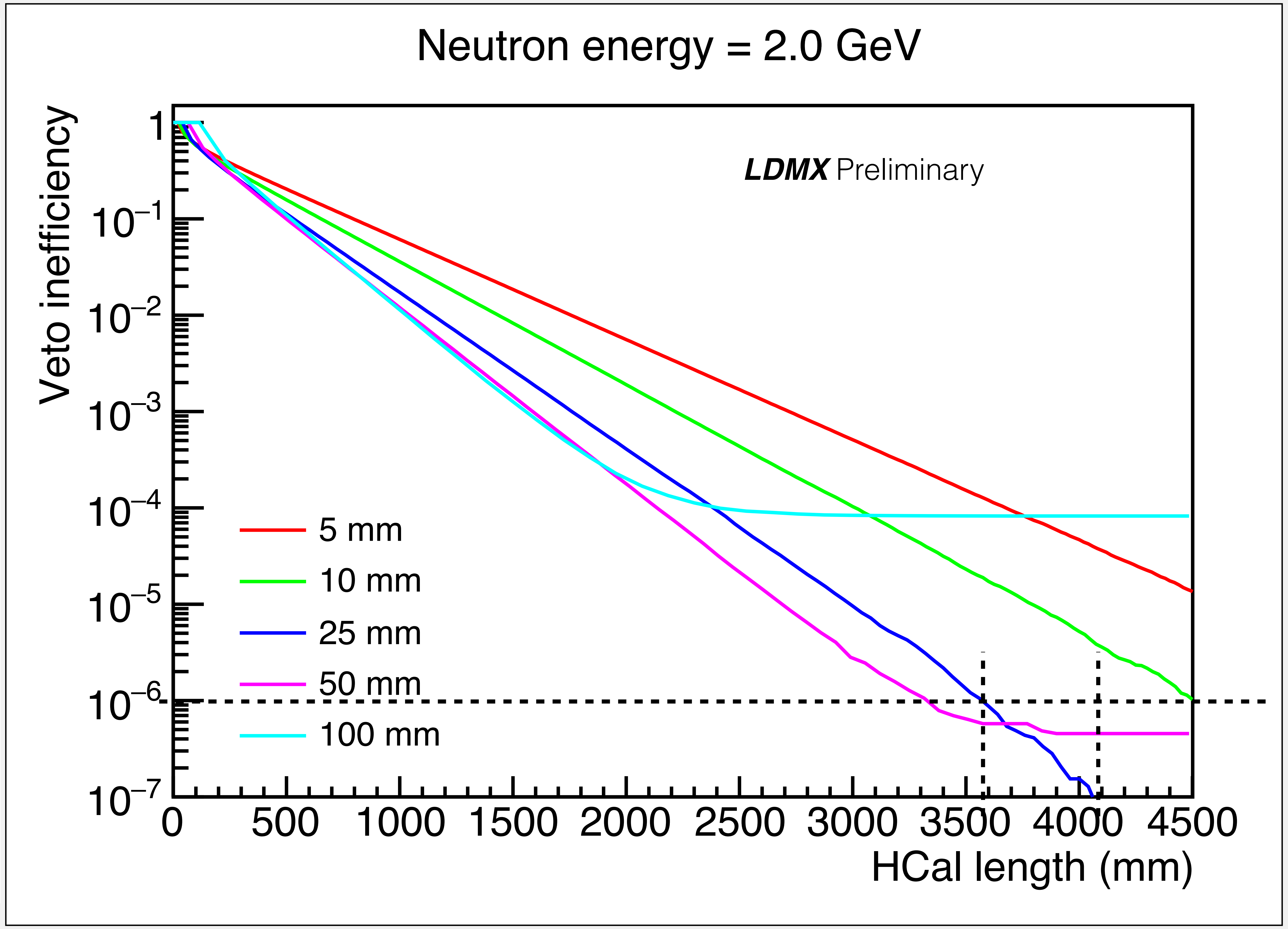
veto inefficiency of at most 10^{-6} for single neutrons (~15λ)

Absorber thickness?

- too thick: neutrons 'get stuck'
  —> no signal in scintillator
- too thin: detector needs to be very large

Currently assuming 25mm, 4m deep, transverse size 2-3m

"Side HCal" around the ECal: Similar configuration, few λ deep



Finalisation of design parameters ongoing

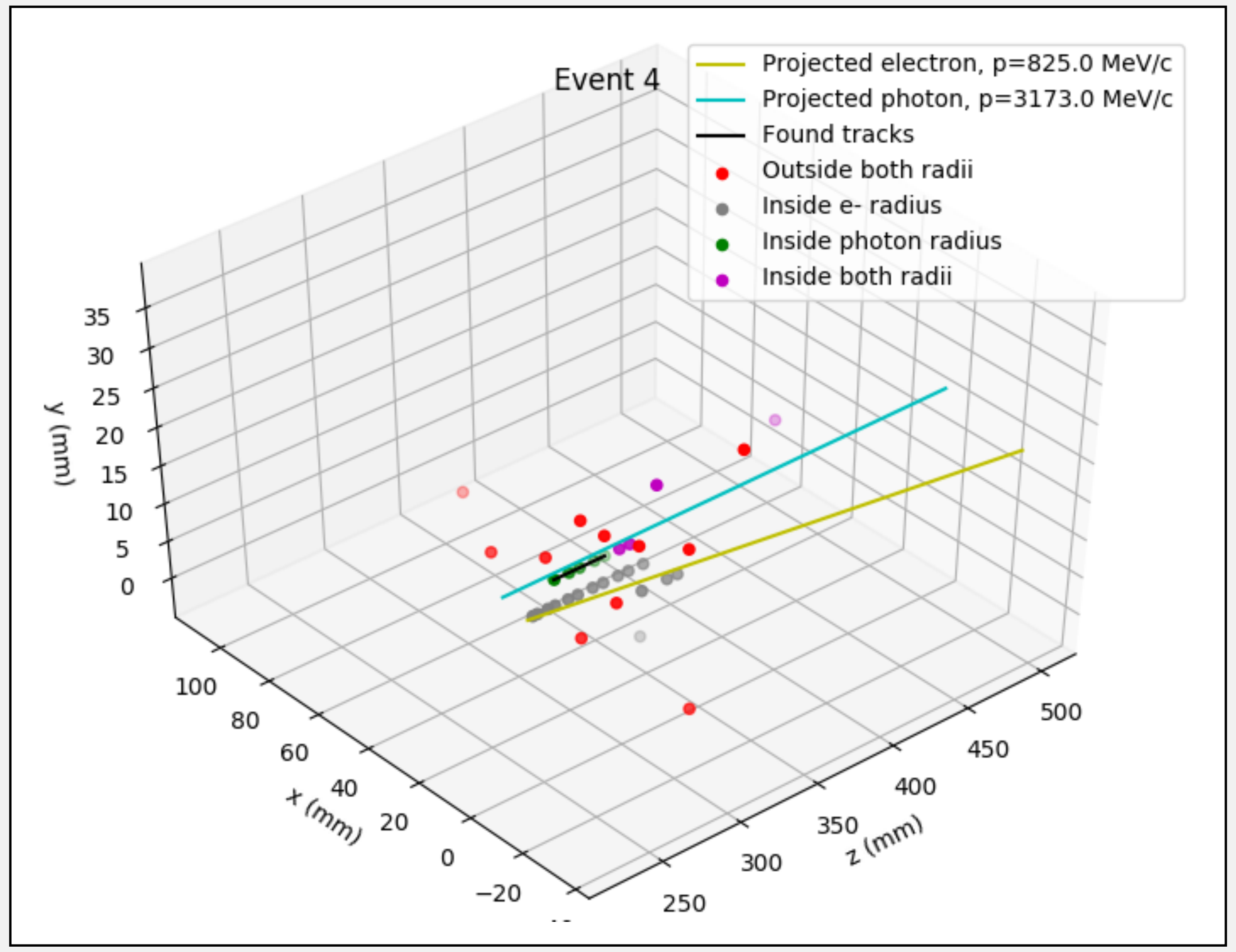
Analysis Strategy

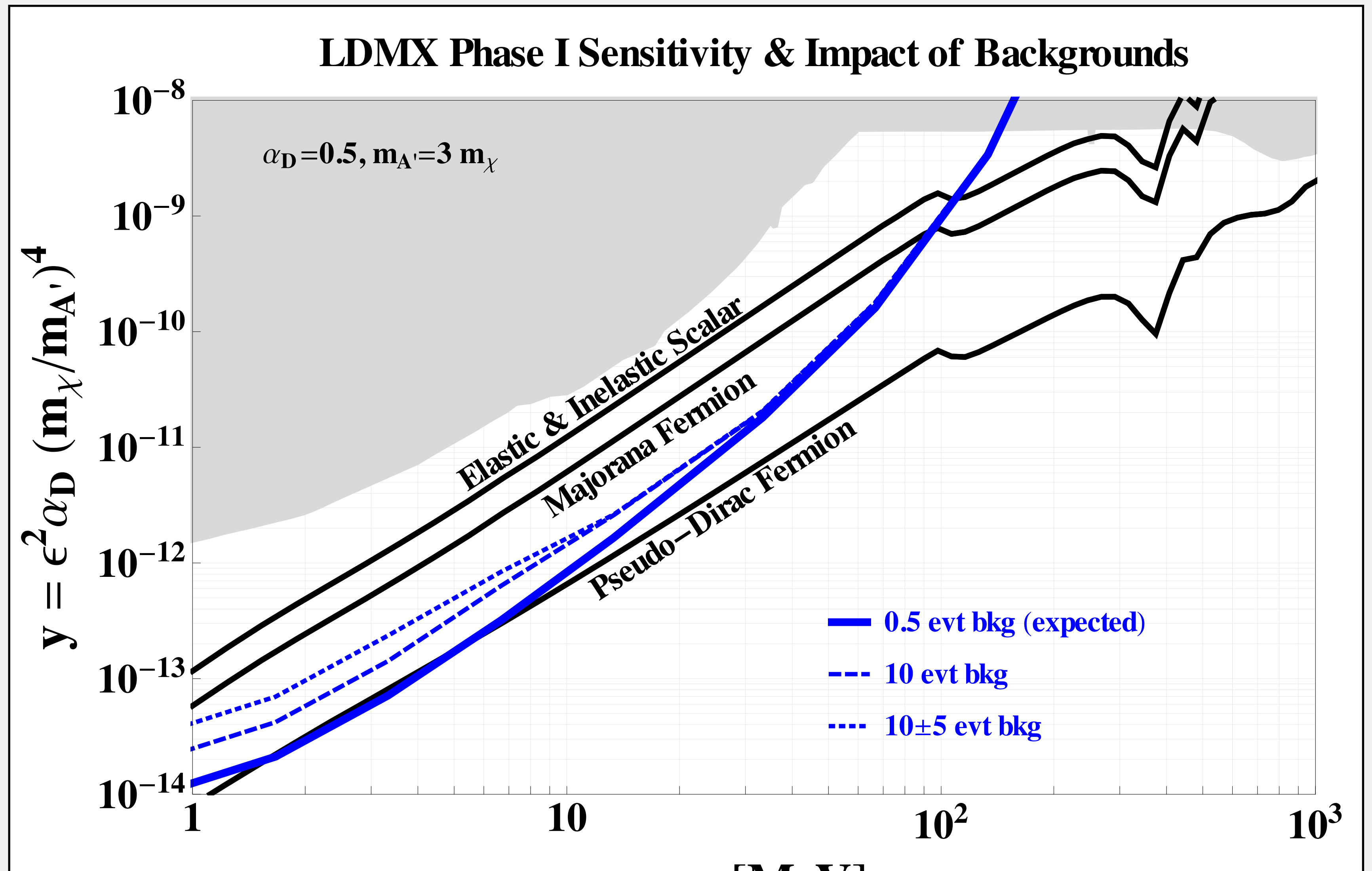
trigger on missing energy

+ combine ECal features into a BDT
+ veto on activity in HCal
+ MIP tracking in ECal (**new!**)

---

at 4 GeV: **close to 0-background** for 4e14 EoT
based on simulation studies





arxiv:1808.05219

Analysis Strategy

trigger on missing energy

+ combine ECal features into a BDT

+ veto on activity in HCal

+ MIP tracking in ECal (**new!**)

---

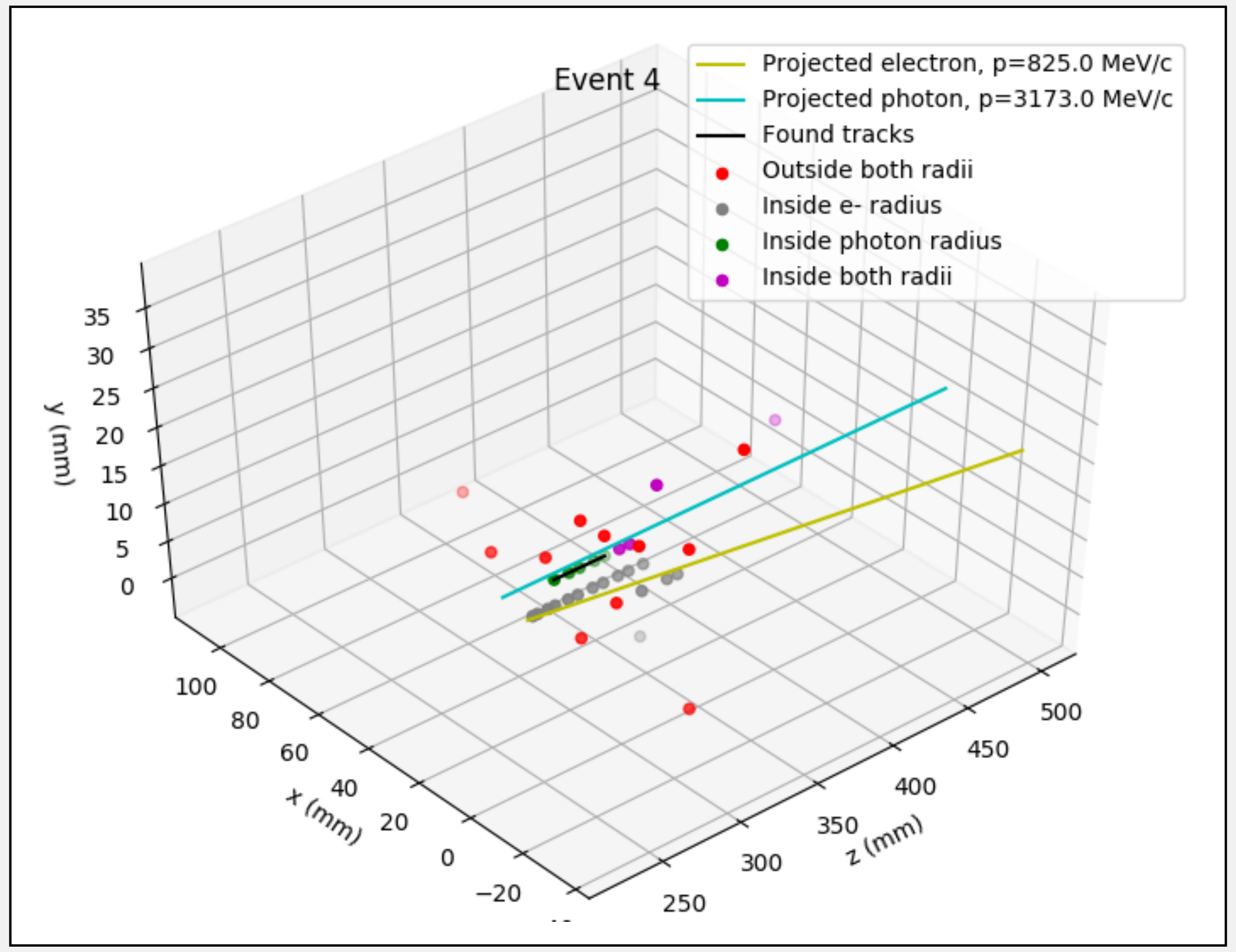
at 4 GeV: **close to 0-background** for 4e14 EoT
based on simulation studies

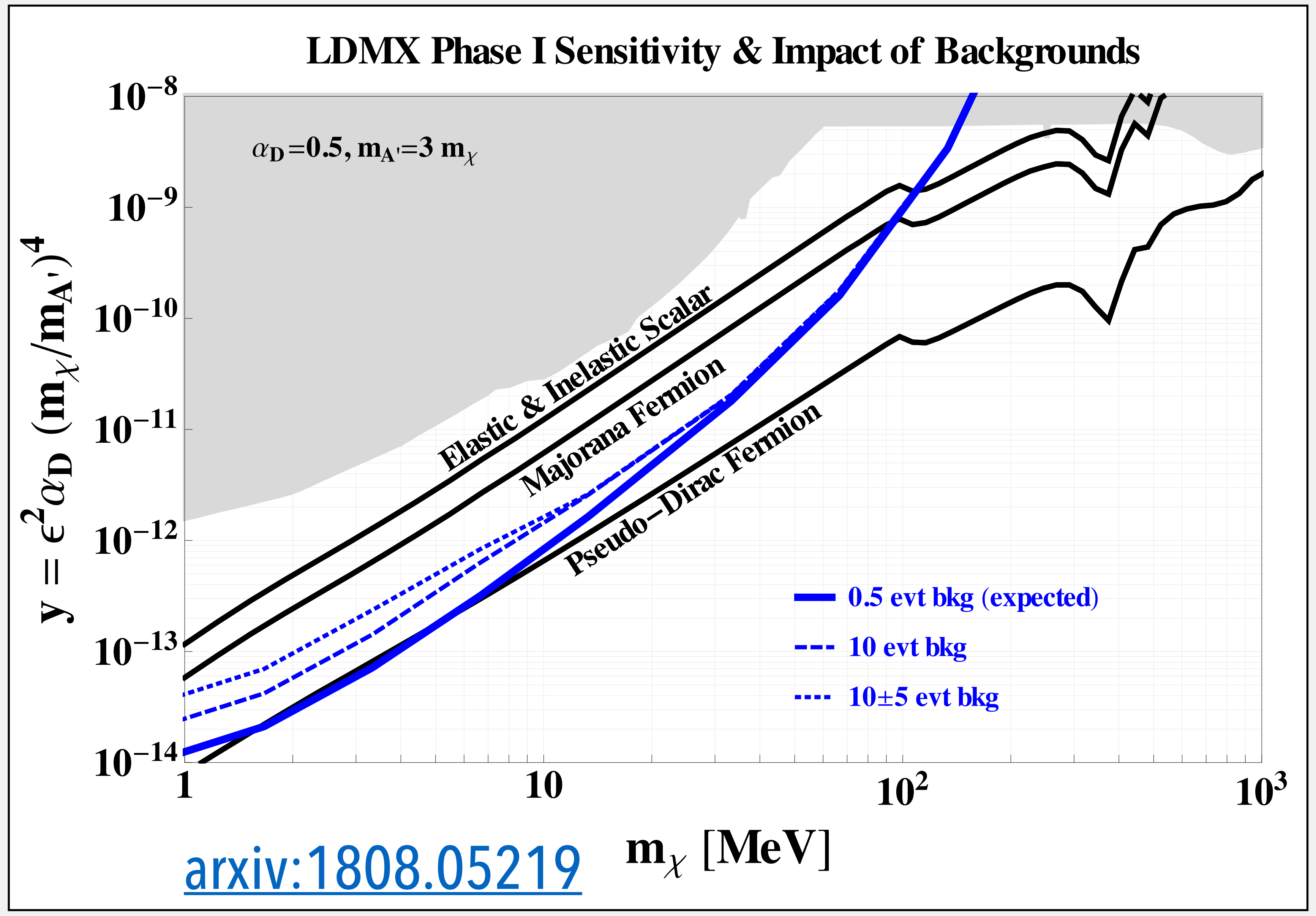
important:

several handles not exploited yet, in particular p_T!

HCal optimisation ongoing

things get easier at higher energy!





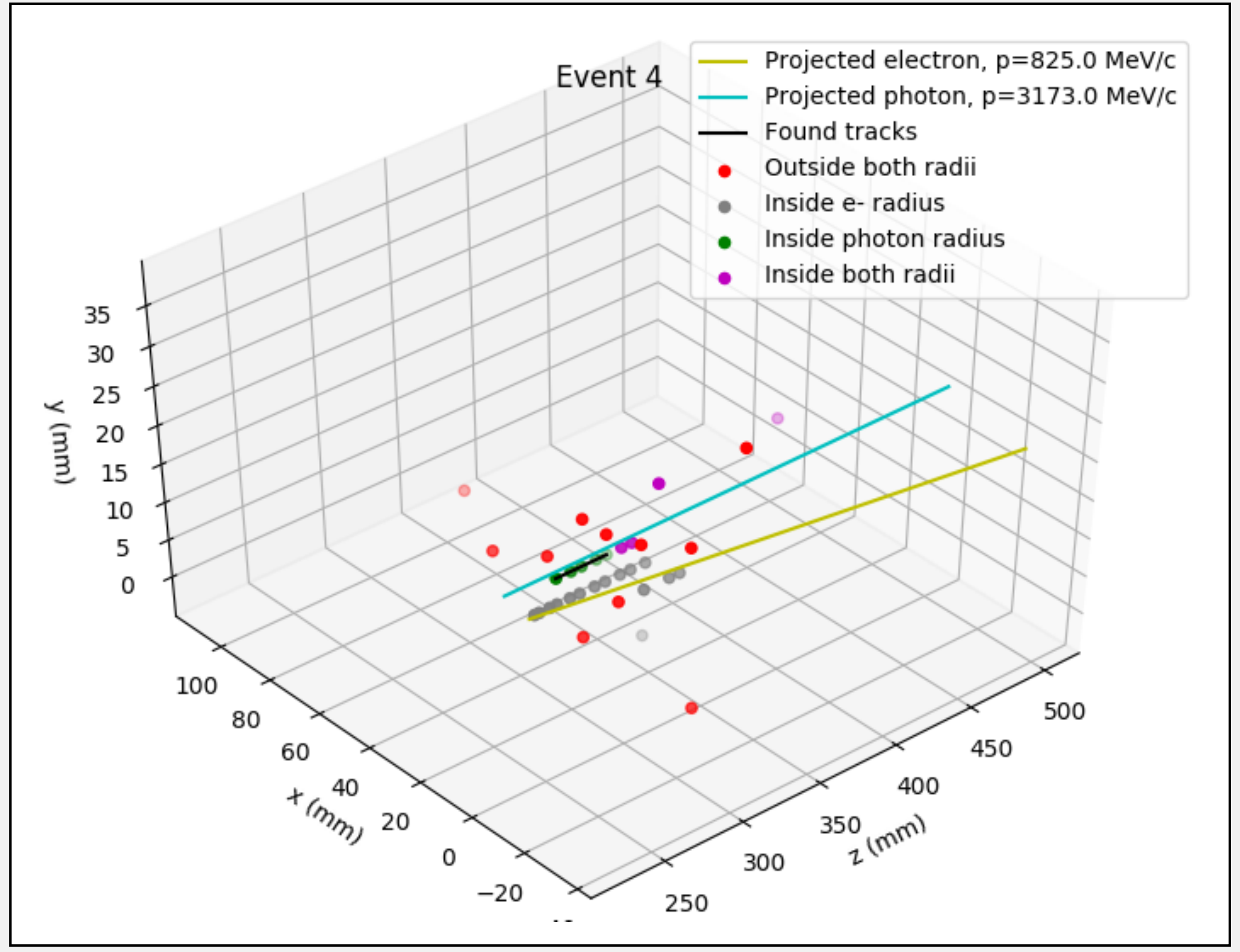
Analysis Strategy

trigger on missing energy

+ combine ECal features into a BDT

+ veto on activity in HCal

+ MIP tracking in ECal (**new!**)



---

at 4 GeV: **close to 0-background** for 4e14 EoT
based on simulation studies

important:

several handles not exploited yet, in particular p_T!

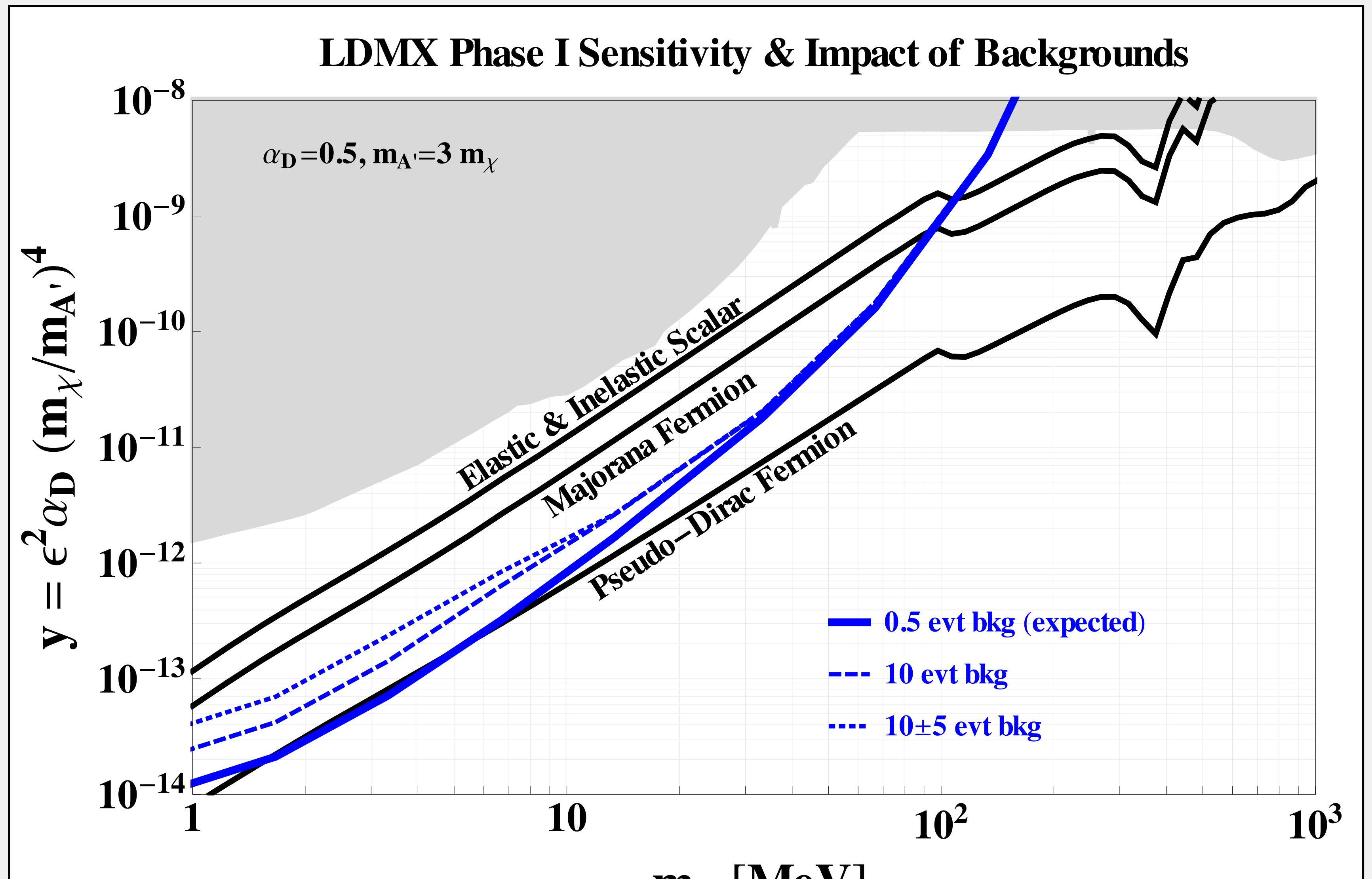
HCal optimisation ongoing

things get easier at higher energy!

with data:

redundancy in vetoes —> data control samples, verify rejection

comprehensive kinematic information —> establish signal-likeness



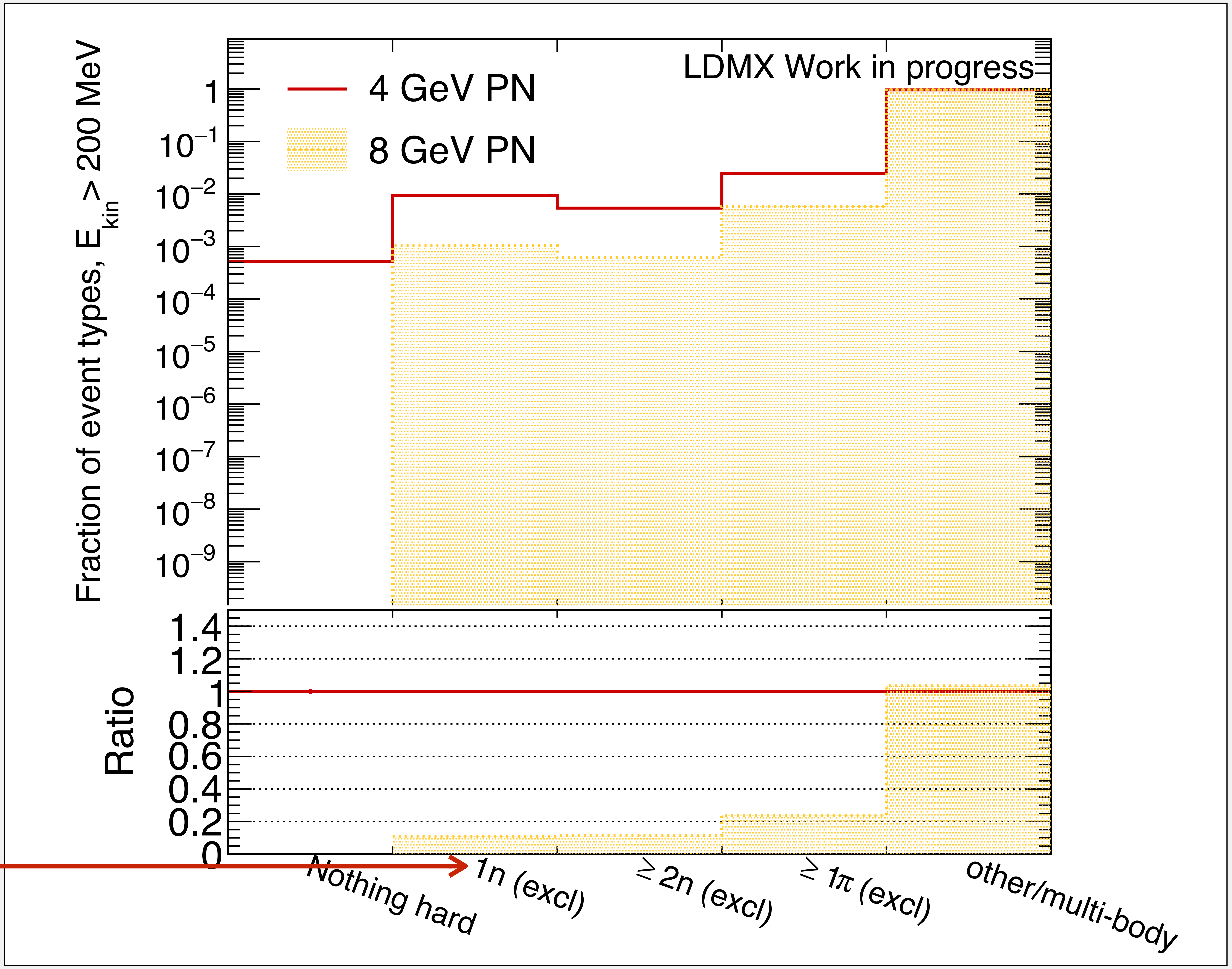
arxiv:1808.05219

Going Beyond

Why higher energy?

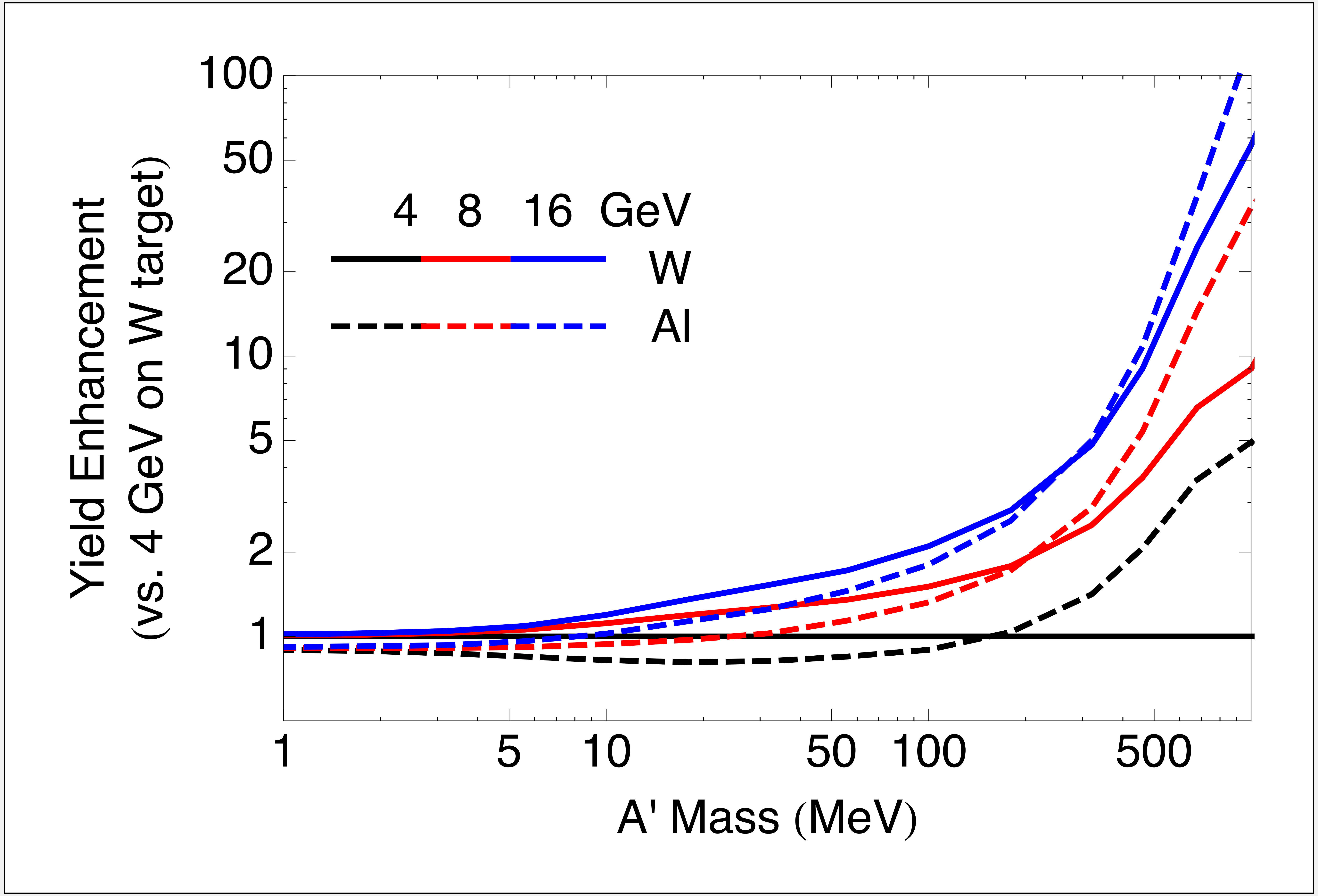
improved background rejection possibilities

particularly critical



Why higher energy?

increased signal yield



eSPS at CERN

arxiv:1805.12379 arxiv:1905.07657

Get e- back in CERN accelerators, next step for X-band linac developed for CLIC, accelerator R&D

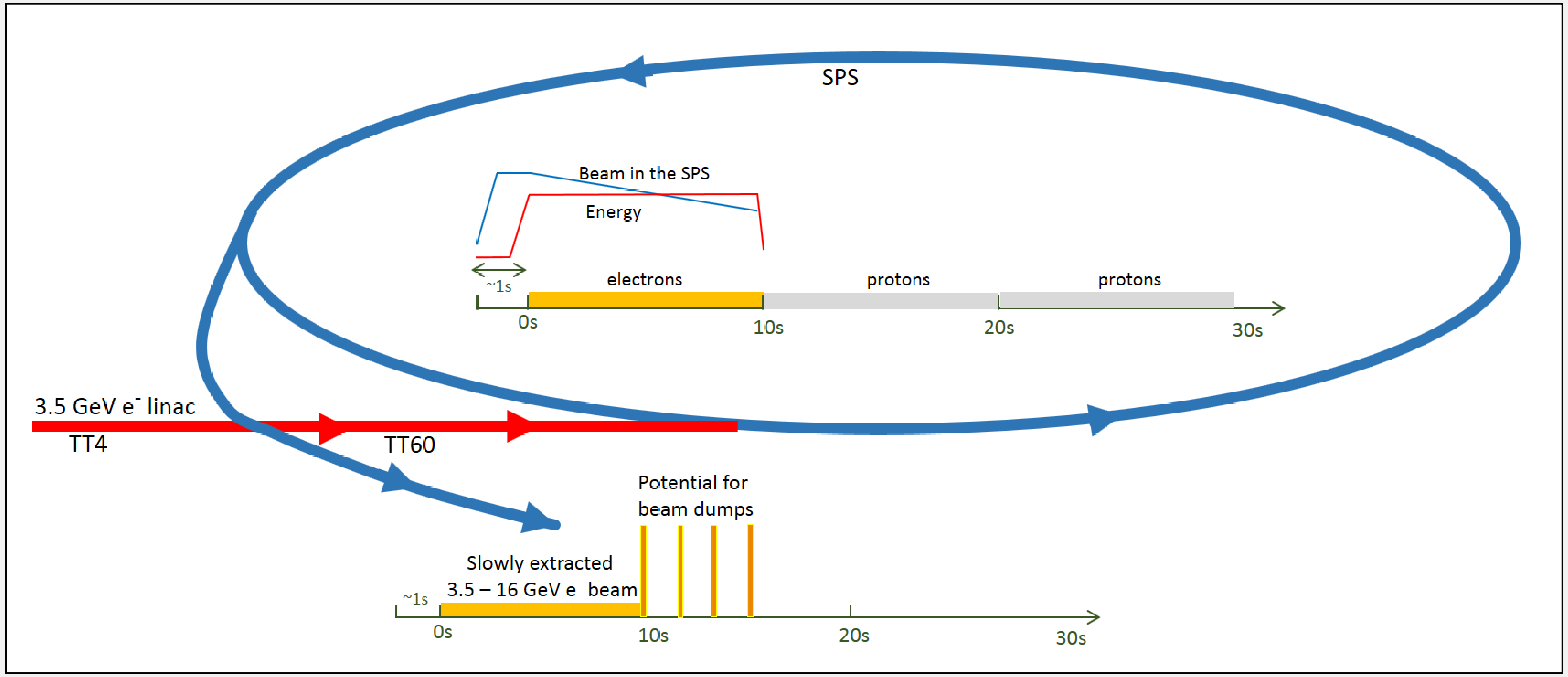
Idea ~2 years ago, quickly picked up momentum

Expression of interest to SPSC in October 2018 https://cds.cern.ch/record/2640784 Input to Strategy Update (#36)

- 3.5 GeV Linac as injector to SPS
- large number of electrons can be filled within 2s
- slow extraction over e.g. 10s
- could run in parallel with other SPS programme or in dedicated runs (depending on how cavities will be arranged)

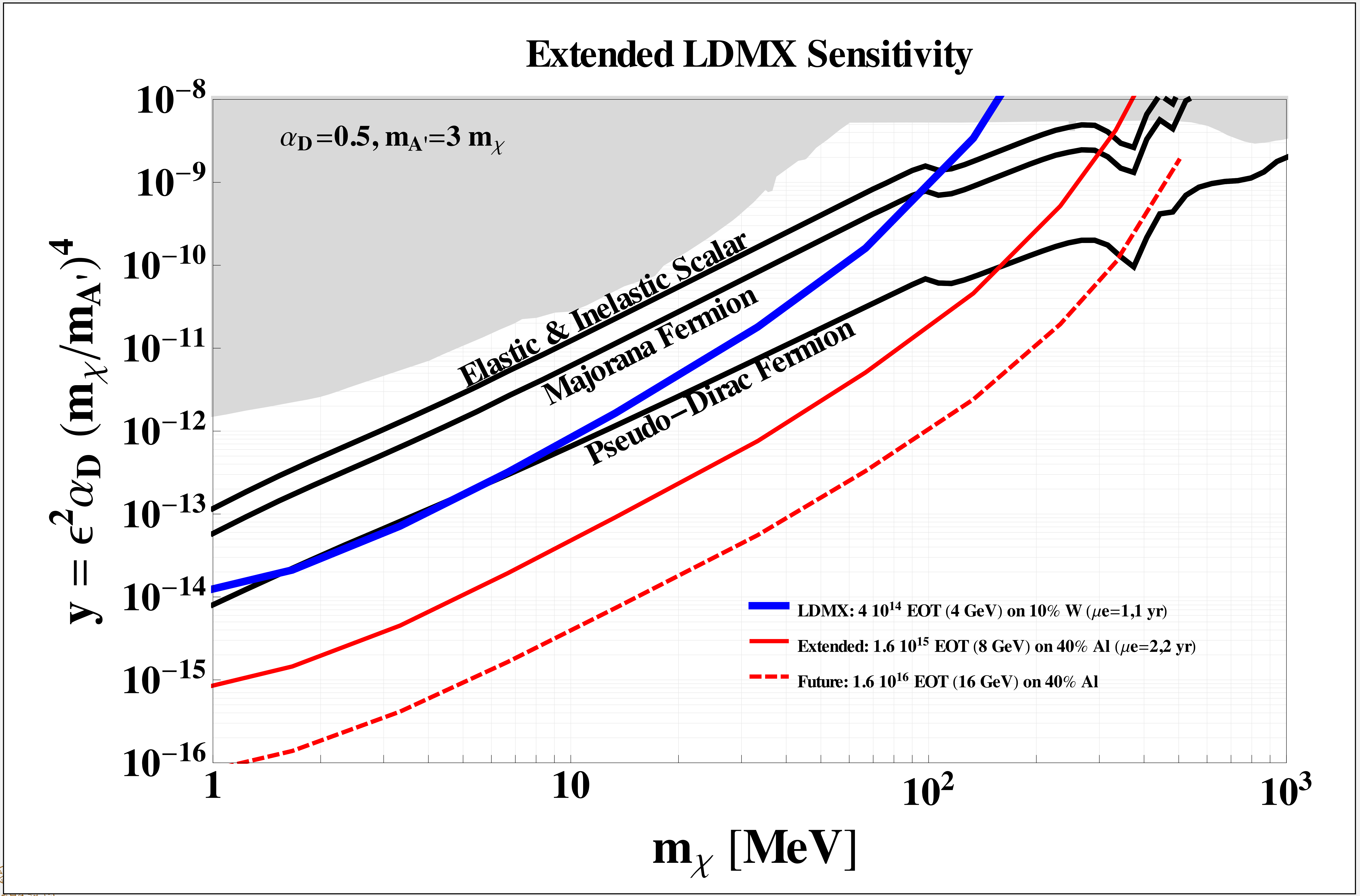
flexible parameters:

- energy: 3.5 - 16 (20) GeV
- electrons per bunch: 1 - 40
- bunch spacing: multiples of 5 ns
- adjustable beam size



optimal catering for LDMX-like experiment

Projected Sensitivity



LDMX can explore a lot of new parameter space

sensitive to various thermal targets already with "pilot run"

ultimately potential to probe all thermal targets up to a few hundred MeV

Funding Status

US: Awaiting outcome of application for R&D funding submitted in spring

Europe: Some funding awarded during summer/fall

- support for HCal prototype/testbam
  - Crafoord Foundation + Royal Physiographic Society Lund
- project grant for research programme on LDMX from Knut and Alice Wallenberg Foundation
- individual support from Swedish Research Council

—> Things are moving along!

Summary

- Light, thermal relic Dark Matter well motivated
- LDMX can achieve outstanding sensitivity (within a few years)
- Potential to probe thermal targets in MeV - GeV range
- Generally sensitive to broad range of sub-GeV physics
- First funding coming in

The next few years will be exciting!

Summary

- Light, thermal relic Dark Matter well motivated
- LDMX can achieve outstanding sensitivity (within a few years)
- Potential to probe thermal targets in MeV - GeV range
- Generally sensitive to broad range of sub-GeV physics
- First funding coming in

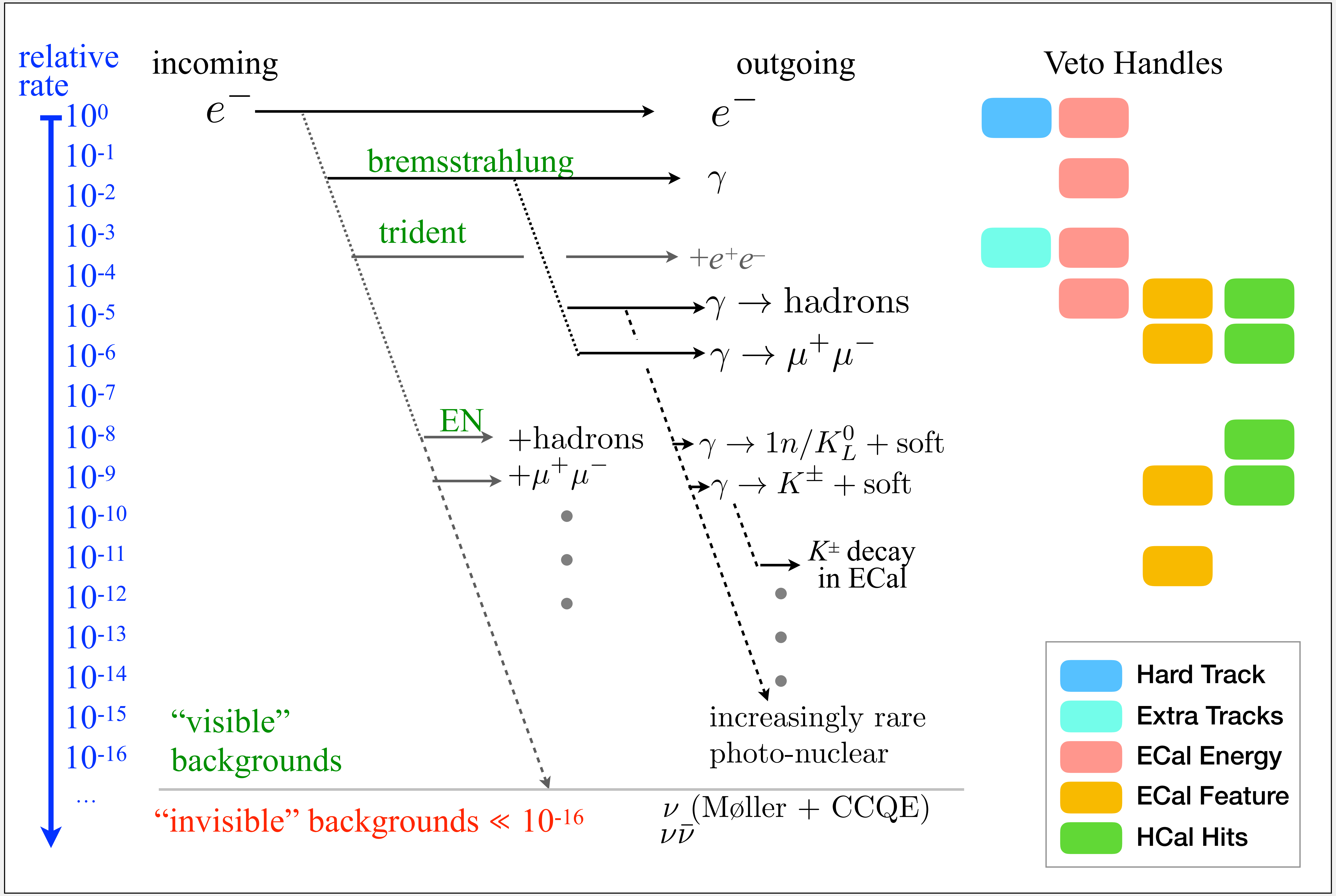
The next few years will be exciting!

Thank you!

[Craig Group & Son]

Additional Material

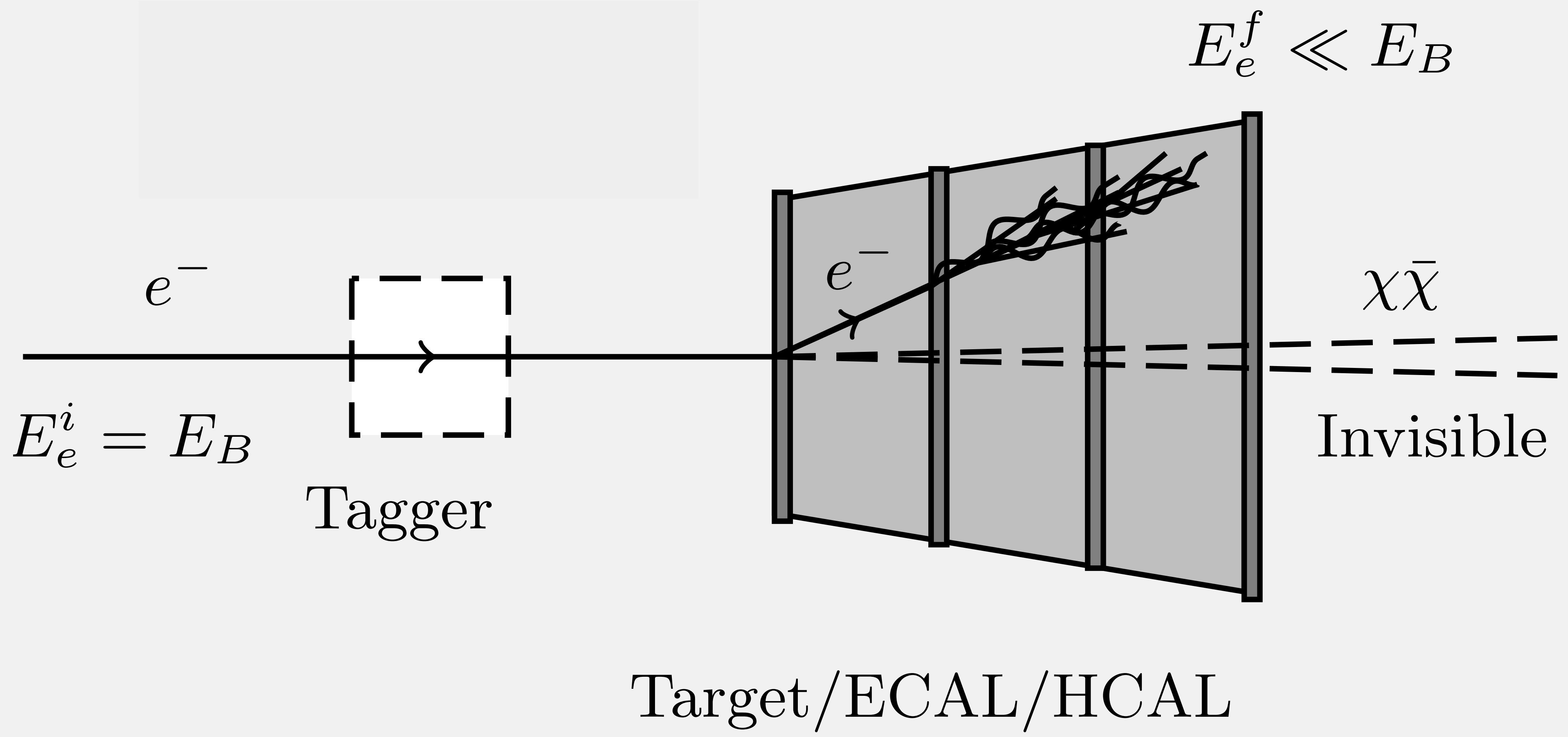
Backgrounds



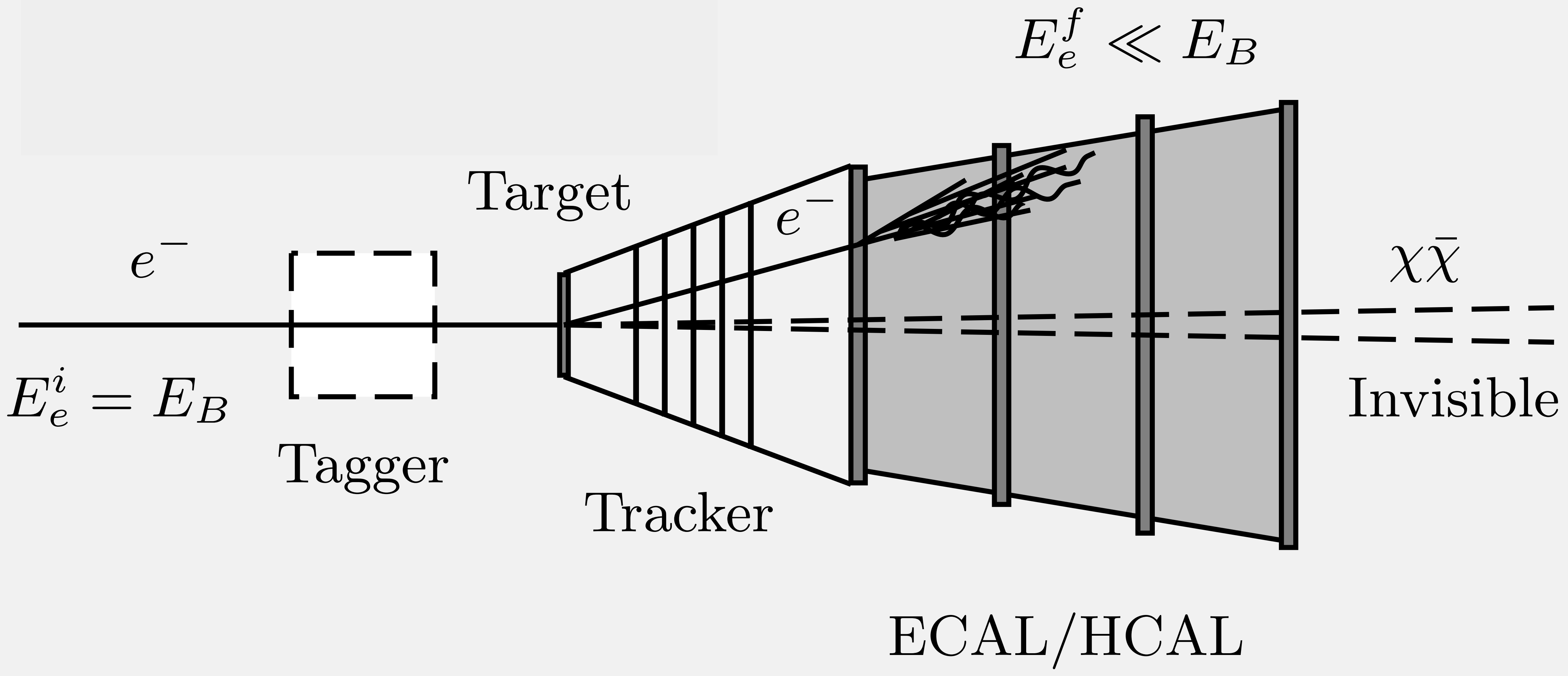
essentially only instrumental backgrounds

Two Approaches

missing energy



missing momentum



higher signal yield/EoT (thicker target)

greater signal acceptance

no e-γ particle ID

includes missing energy

p_T as discriminator & *signal identifier*

e-γ particle ID

Why not only direct detection?

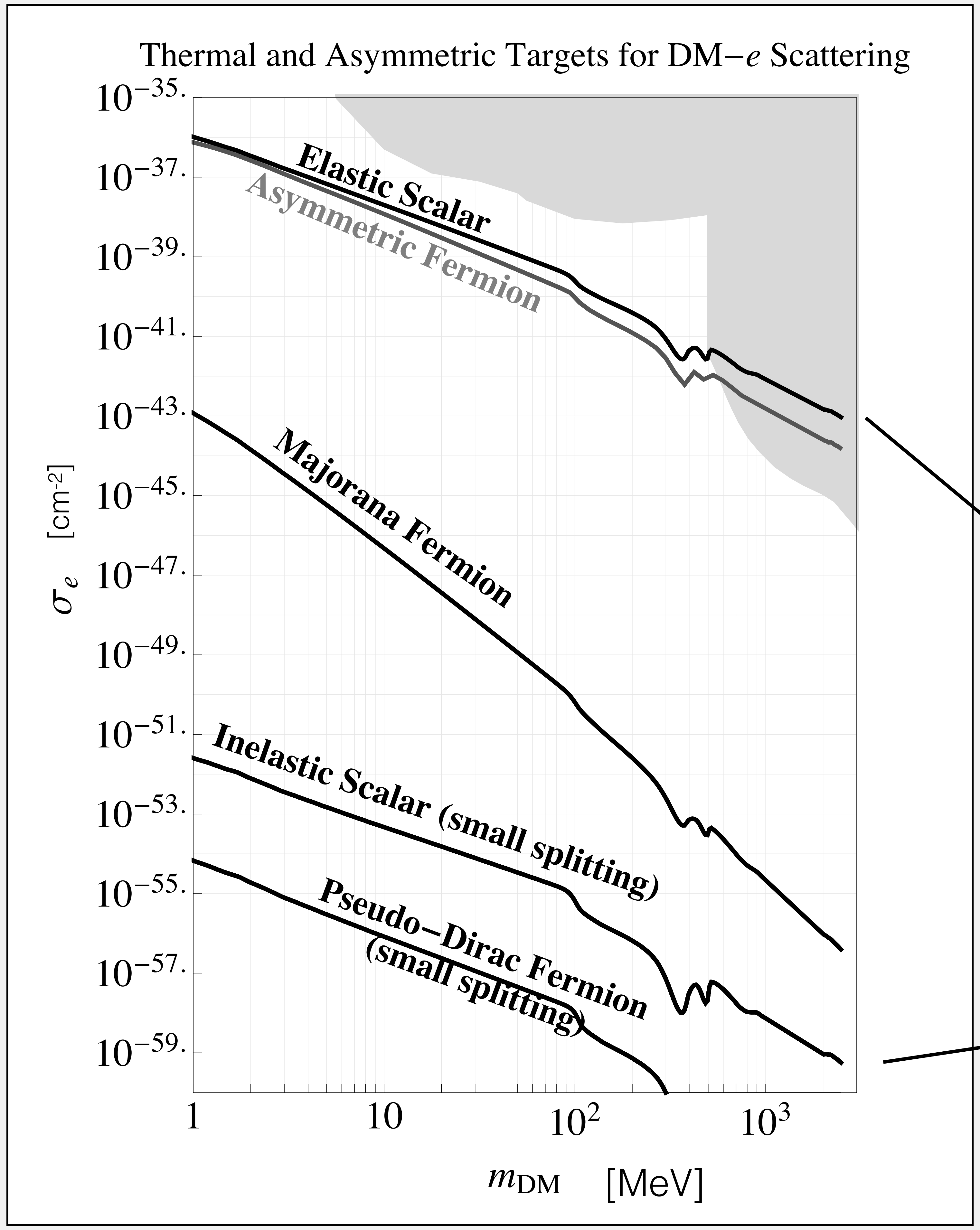
direct detection:

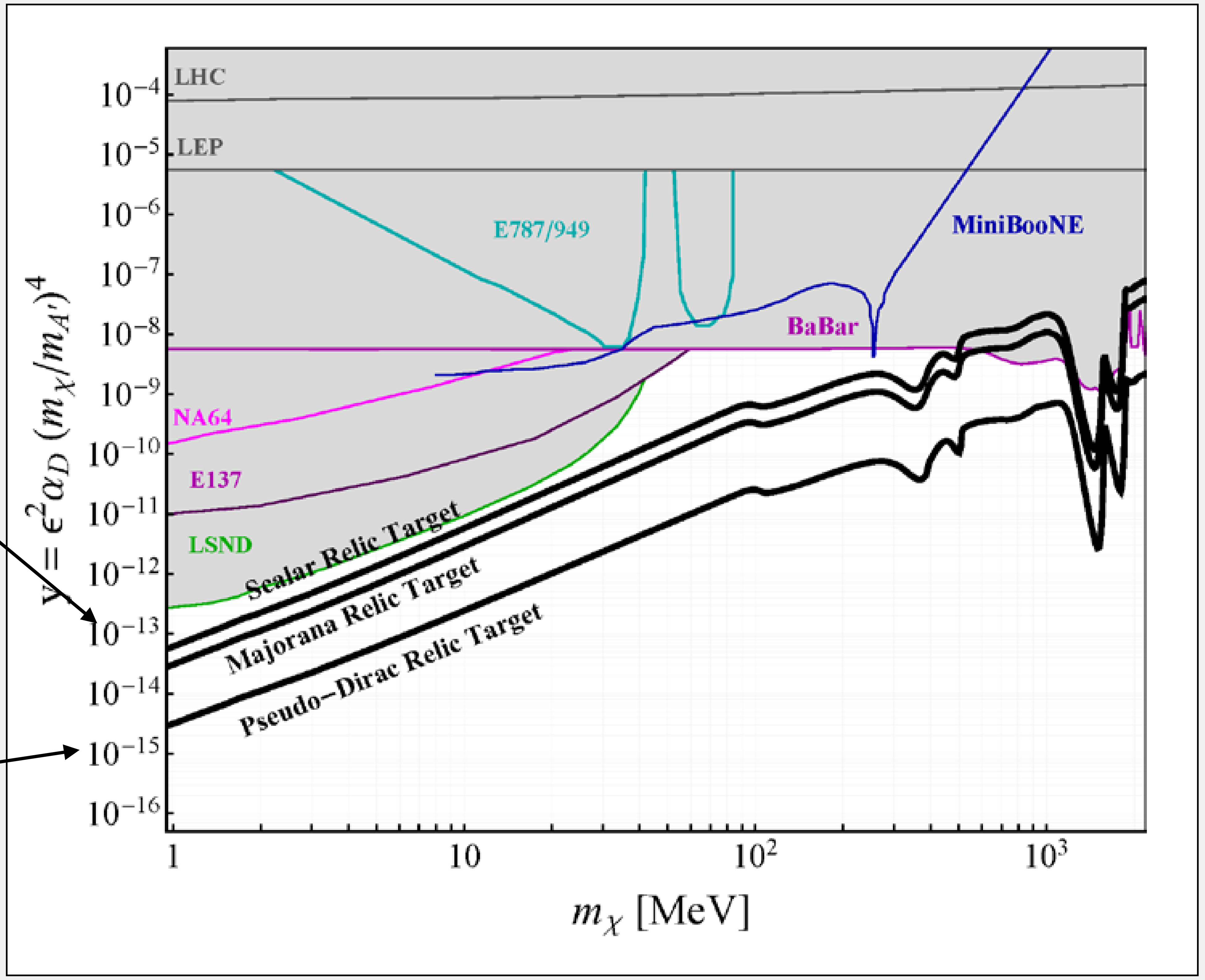
strong spin/velocity dependency

at accelerators: relativistic production

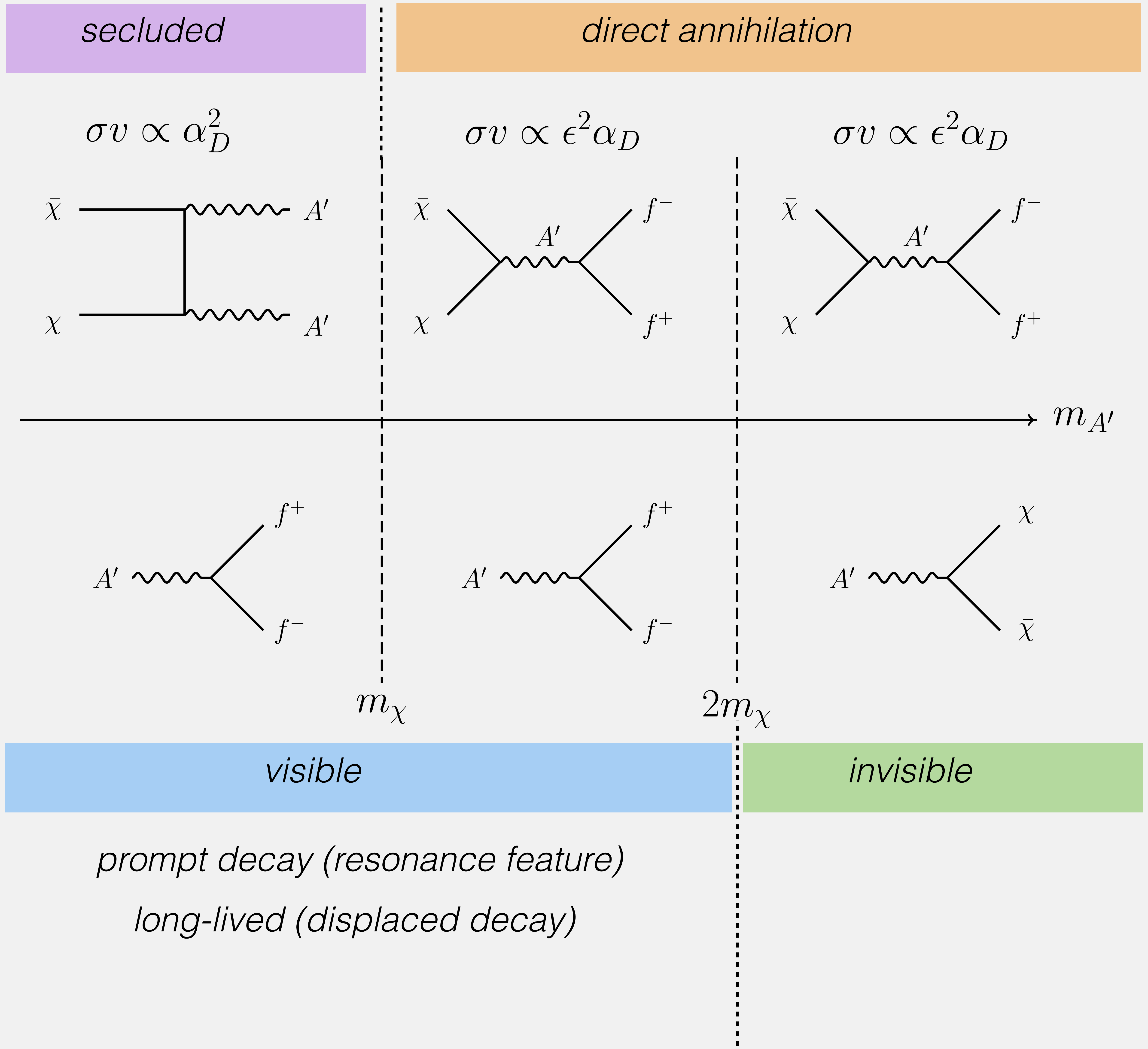
—> spin/velocity dependency reduced

all thermal targets in reach!



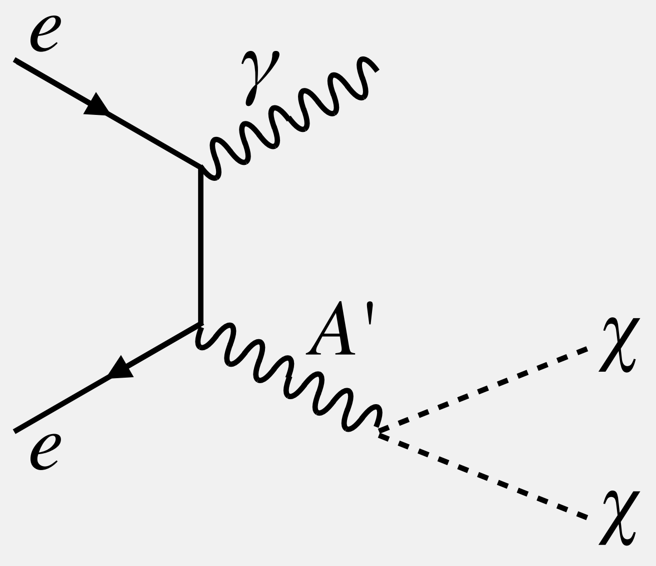


Signatures

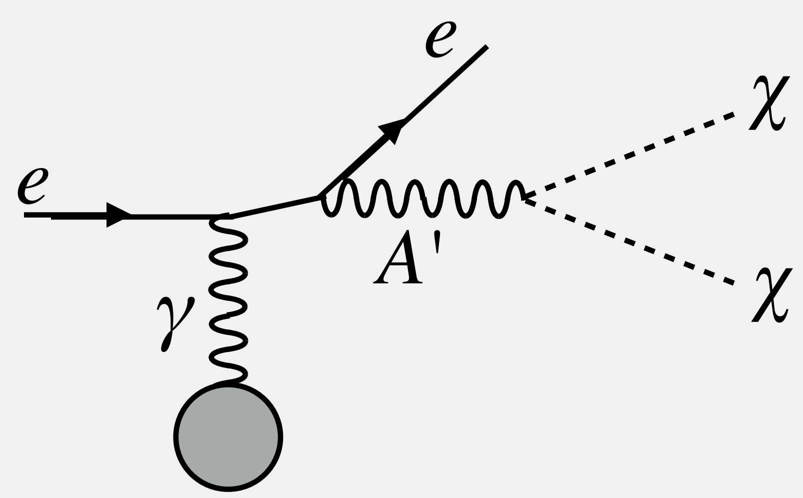

secluded
direct annihilation
$\sigma v \propto \alpha_D^2$
$\sigma v \propto \epsilon^2 \alpha_D$
$\sigma v \propto \epsilon^2 \alpha_D$
$\bar{\chi}$ A'
χ A'
$\bar{\chi}$ f^- A' χ f^+
$\bar{\chi}$ f^- A' χ f^+
$m_{A'}$
A' f^+ f^-
A' f^+ f^-
A' χ $\bar{\chi}$
m_χ
$2m_\chi$
visible
invisible
prompt decay (resonance feature)
long-lived (displaced decay)

Complimentary Approaches

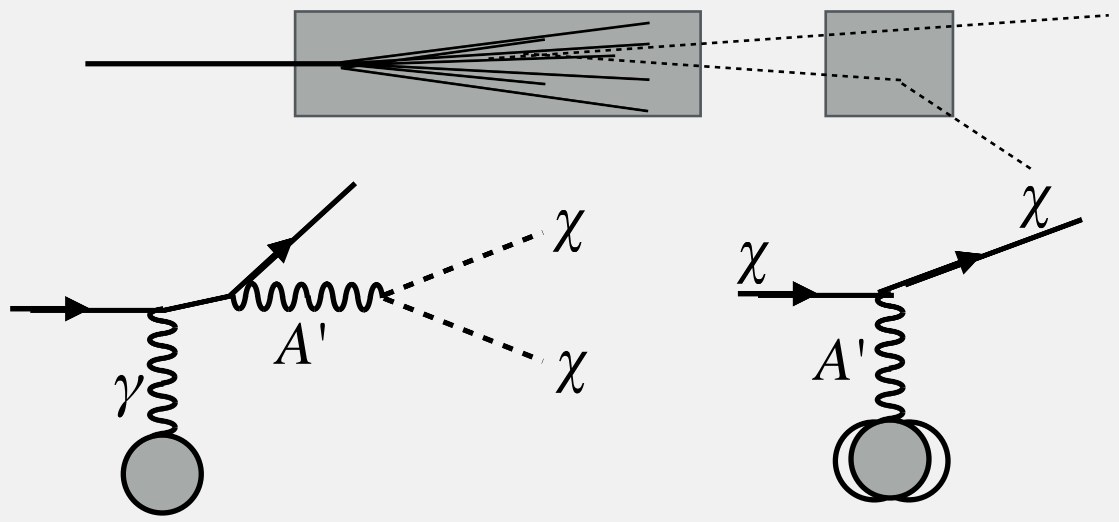
collider



fixed target



beam dump



$\sigma_{\text{coll}} \propto \frac{\varepsilon^2}{E_{\text{cm}}^2}$ $\ll$ $\sigma_{\text{FT}} \propto \frac{Z^2\varepsilon^2}{m_{\text{A'}}^2}$ $N \propto \varepsilon^2(1-\varepsilon^2) \approx \varepsilon^2$ $\gg$ $N \propto \varepsilon^4$

but **"direct DM detection"**

examples (existing or planned)	BaBar Belle II LHC	PADME MMAPS NA64 VEPP3 **LDMX** DarkLight (II)	E137 SBNe/pi LSND MiniBooNE BDX SHiP
mass range	0.1 - 10 GeV	MeV - GeV	

Various Future Projections