Accelerator Prospects for Sub-GeV DM.

June 07 2019, New Directions in the Search for LDM Particles, Fermilab

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

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DESY.

Overview

- Types of accelerator searches
- Types of DM signatures at accelerators
- Benchmark searches: Visible and Invisible Dark Photons
- Beyond simple models: iDM, DM bound states, Z'

New mediators

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Vector Portal: Massive A' mixes with SM γ via strength parameter ε

Scalar Portal: Additional dark Higgs

Neutrino Portal: Sterile neutrinos, heavy neutral leptons

e.g. Axion Portal: Massive ALP couples to SM bosons

Accelerator landscape

Collider

Beam dumps

Fixed target

Specialized (e.g. g-2, EDM)

Accelerator landscape

Collider

e^+e^- (intensity frontier, e.g. Belle II)
pp (energy frontier, LHC)
future e^+e^- (energy frontier, e.g. ILC)

Multi-purpose detectors
(tracking, calorimeters,
particle identification, …)

Beam dumps

Electrons
Protons

Passive target

Fixed target

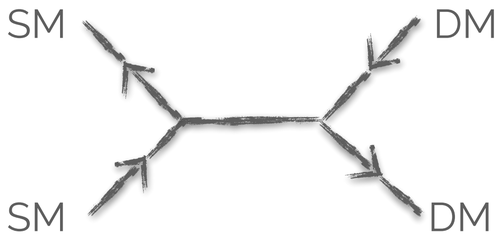
Electrons

Active target

Specialized
(e.g. g-2, EDM)

Accelerator landscape

Direct (new) mediator production



Missing energy or resonance searches, e.g.

A→Invisible (Dark Photon)

a→γγ (ALP)

+ maximum mass reach, high rate
- high backgrounds, difficult trigger

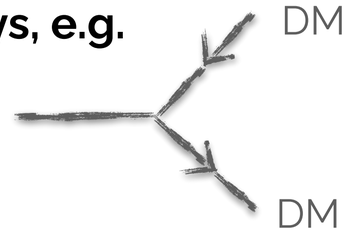
Particle decays

Resonances in meson decays, e.g.

$\pi^0 \to A'\gamma$ (Dark Photon)

$B \to K^{(*)}a$ (ALP)

$B \to K\chi\chi$



+ clean, efficient trigger, different couplings
- kinematics limited by meson mass

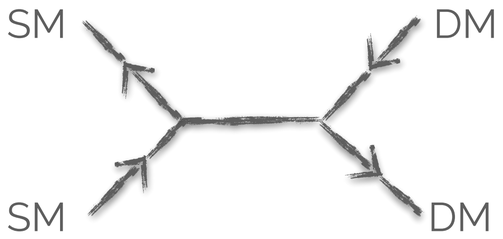
Precision measurements

Precision observables modified by DM, e.g.

Differential cross section $B \to K\mu\mu$

Accelerator landscape

Direct (new) mediator production



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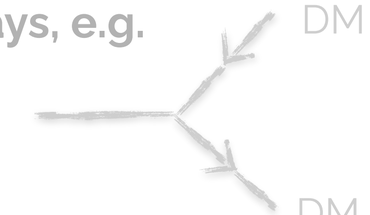

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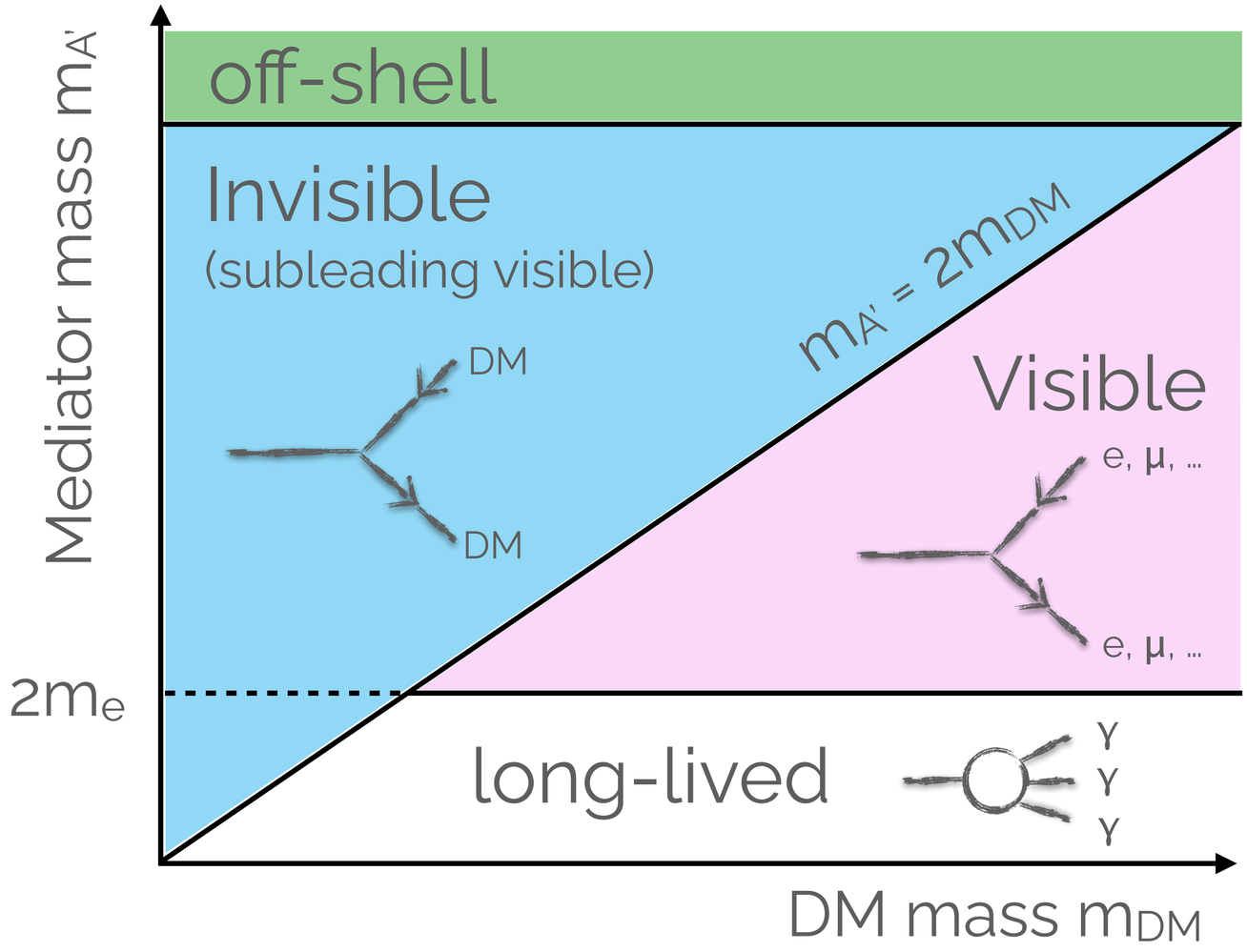
- kinematics limited by meson mass

Precision measurements

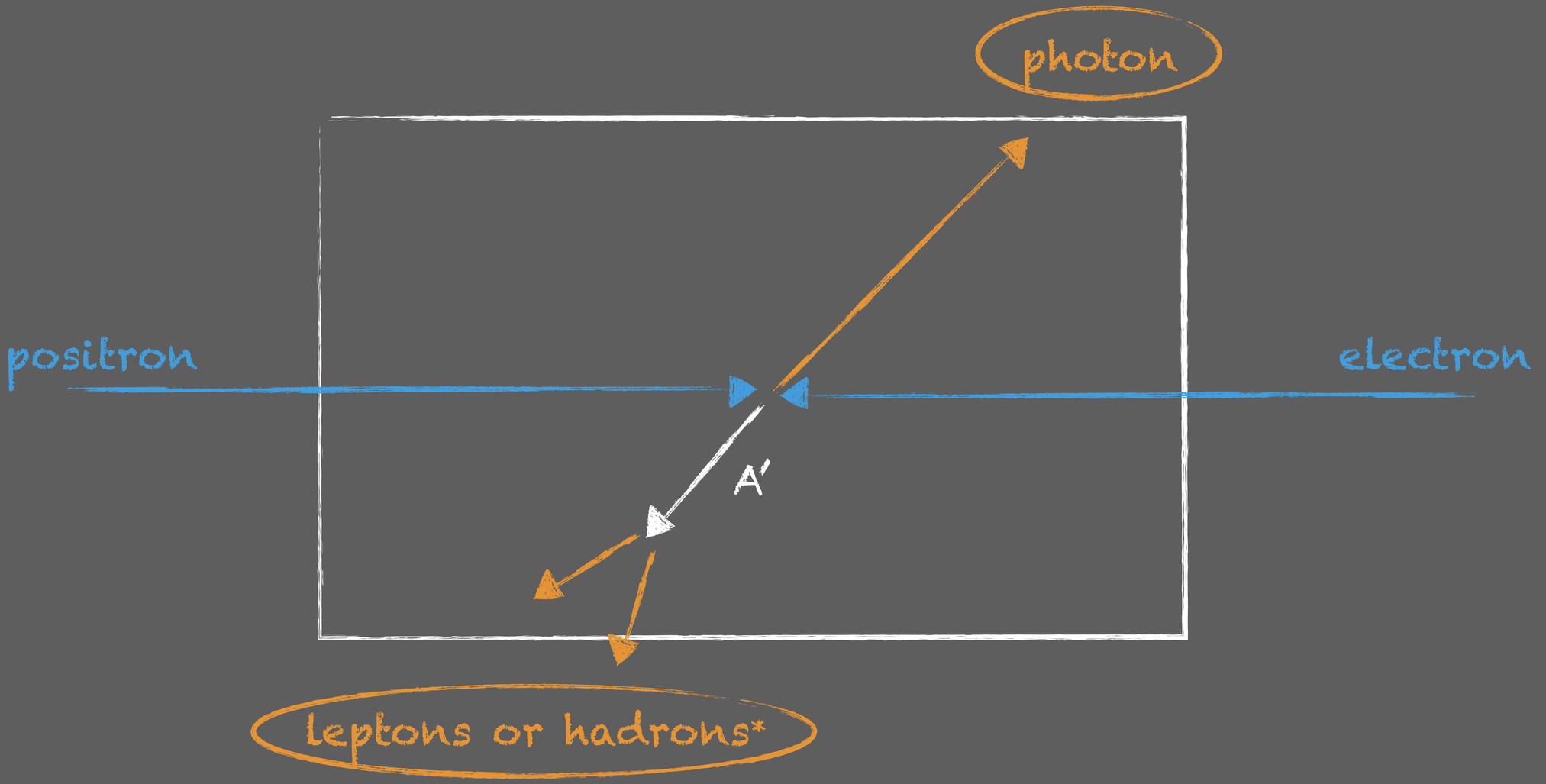
Precision observables modified by DM, e.g.

Differential cross section $B \to K\mu\mu$

New mediator production and decay



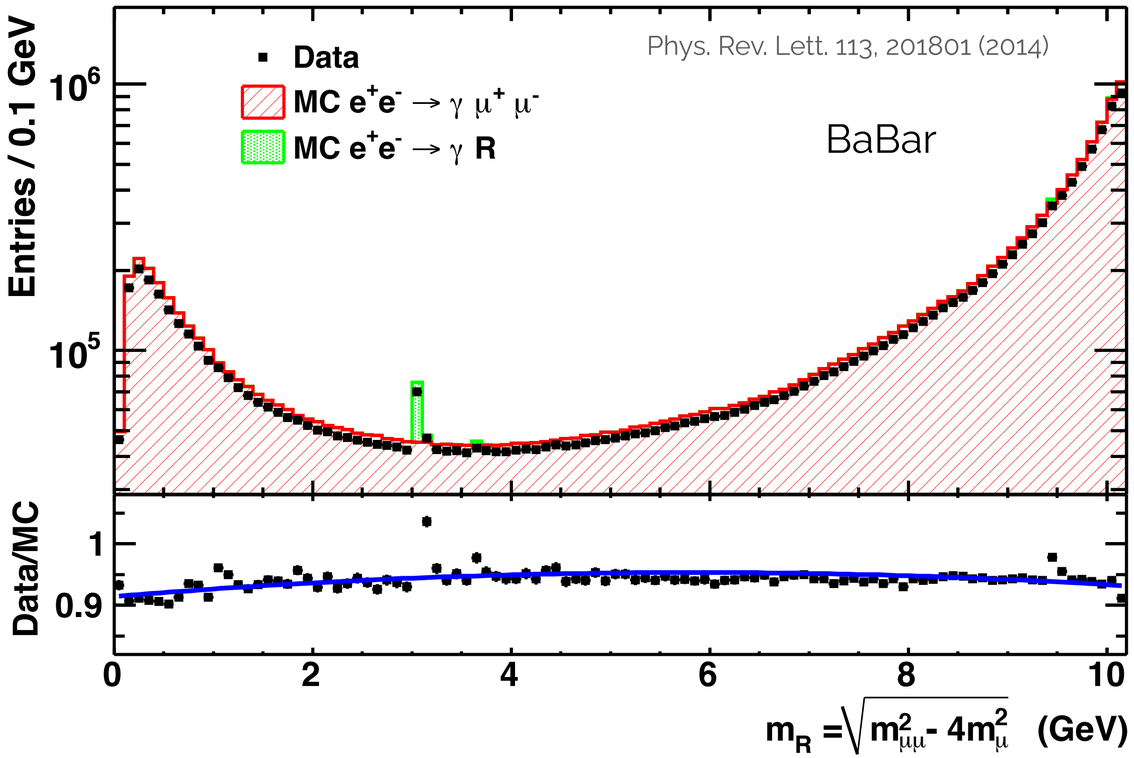
Visible Dark Photon decays: e^+e^- collider



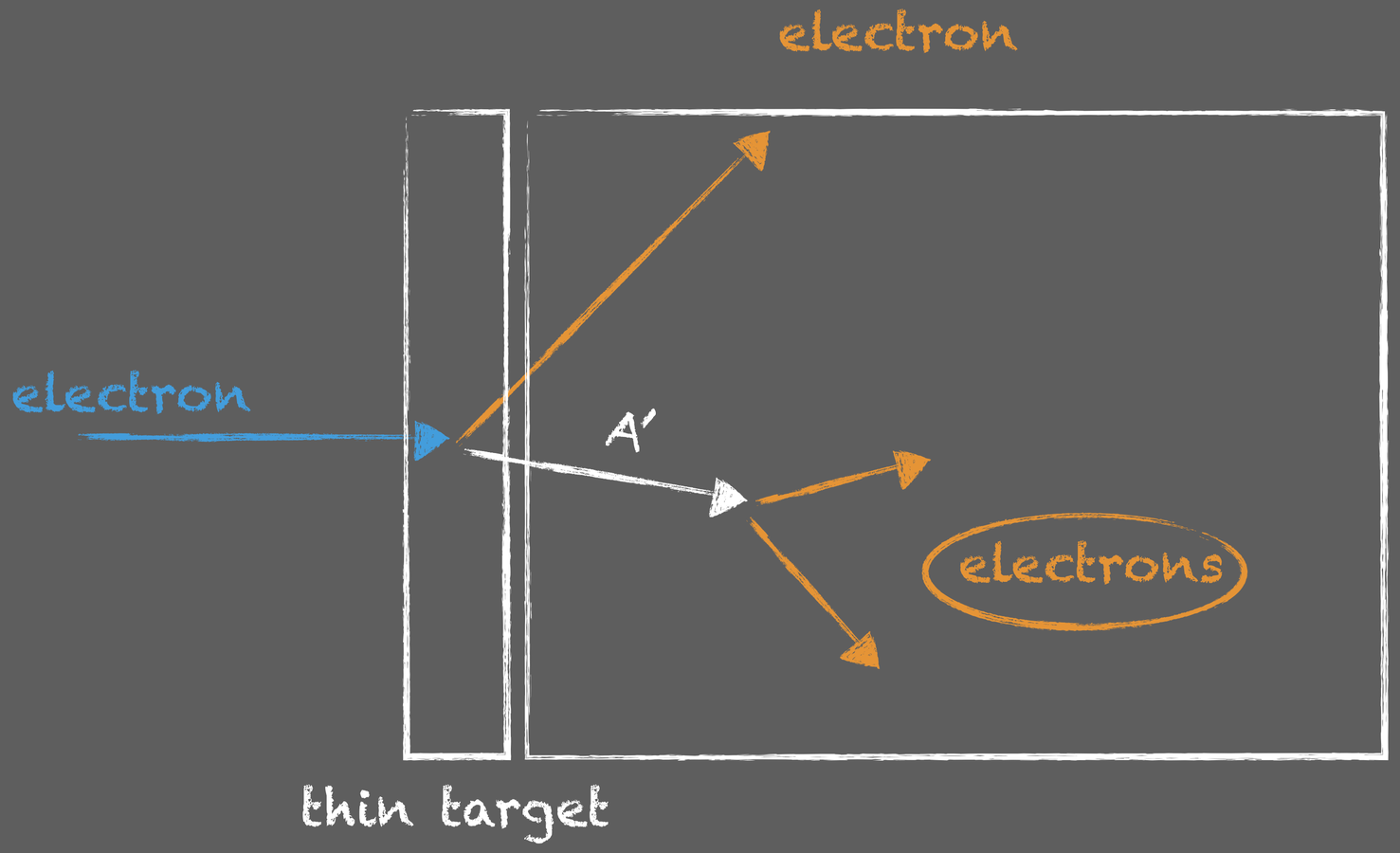
*prompt or displaced

Visible Dark Photon decays: e^+e^- collider (e.g. BaBar, Belle II)

- Bump hunts over smooth, large SM backgrounds
- Sensitivity scales only very slowly with integrated luminosity: $\sim \mathscr{L}^{1/4}$
- Hadronic final states are more challenging but possible
- $\tau\tau$ channels have not been exploited yet (missing energy from neutrinos)

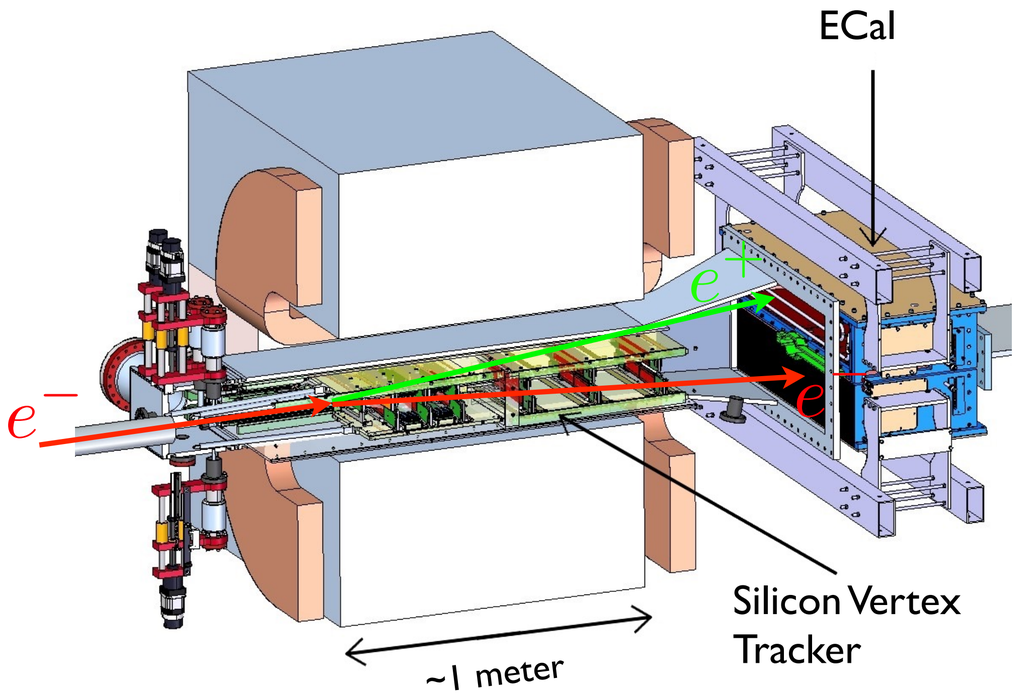


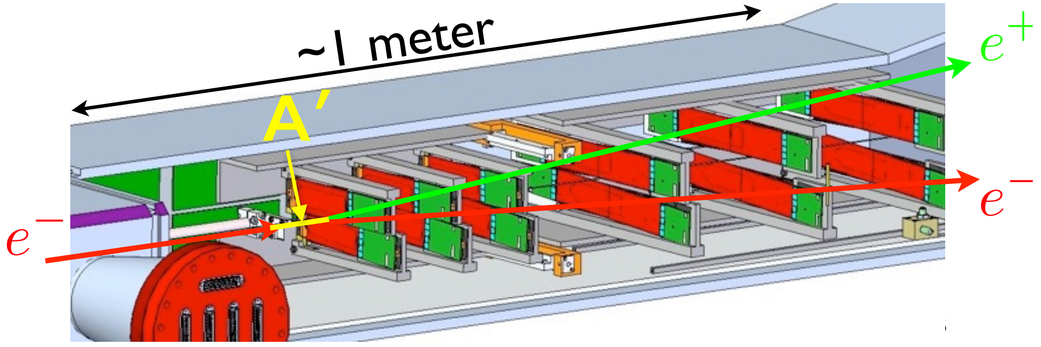
Visible Dark Photon decays: Fixed target



Visible Dark Photon decays: Fixed target (e.g. HPS@JLab)

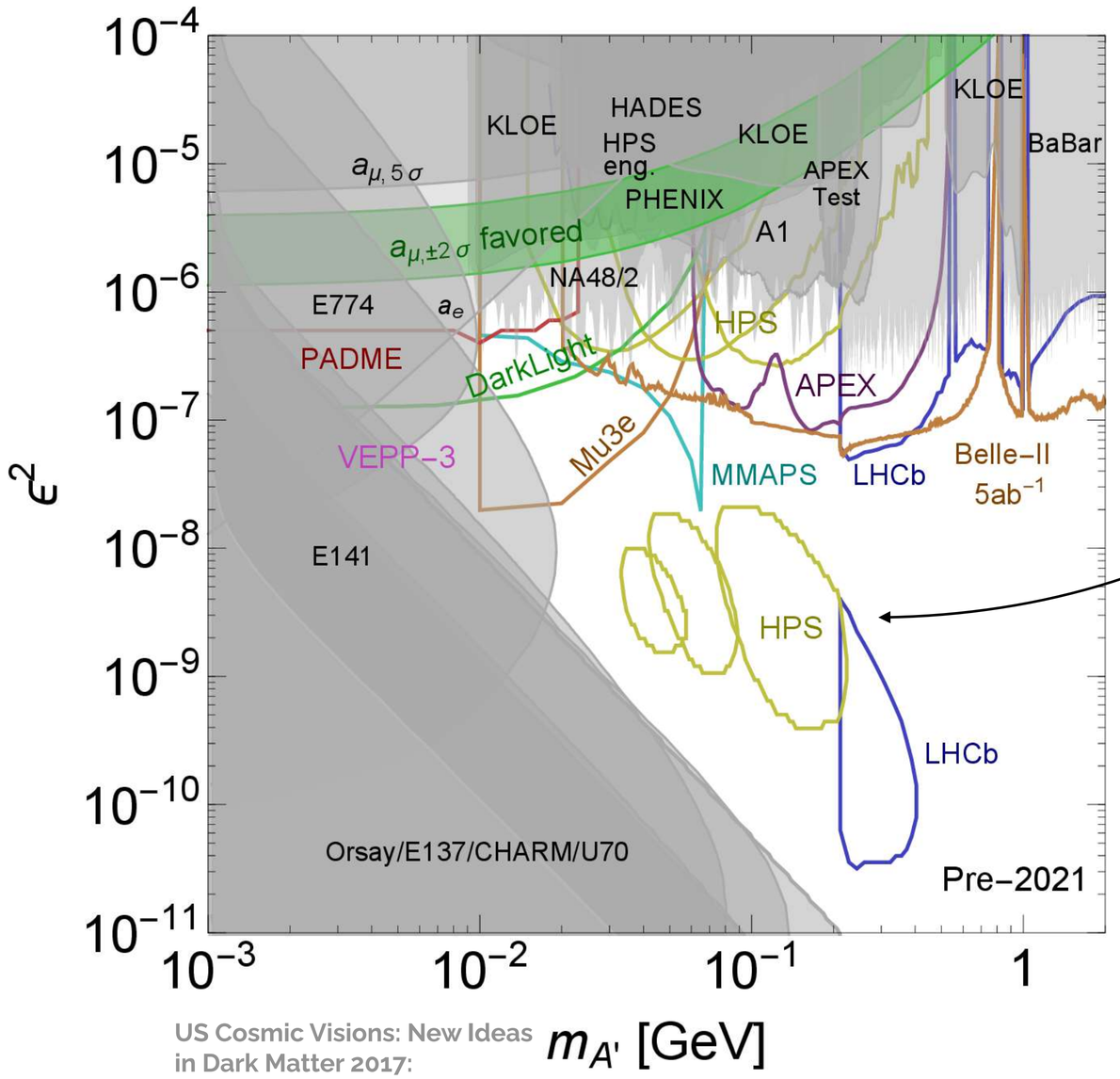
- Thin O(0.1X_0) W target
- Compact spectrometer
- PbWO4 ECal to withstand ultra high single electron rate
- SM background from radiative electron pairs (tridents: eZ → eee)
- "Dead zone" in spectrometer from passing beam (extremely high rate)
- Short commissioning runs in 2015/16, physics runs in 2018 (4.4 GeV) and 2019 (2.2 GeV)





Limits for visible Dark Photon decays

Visible Dark Photon decays: Limits (and expectations until 2021)



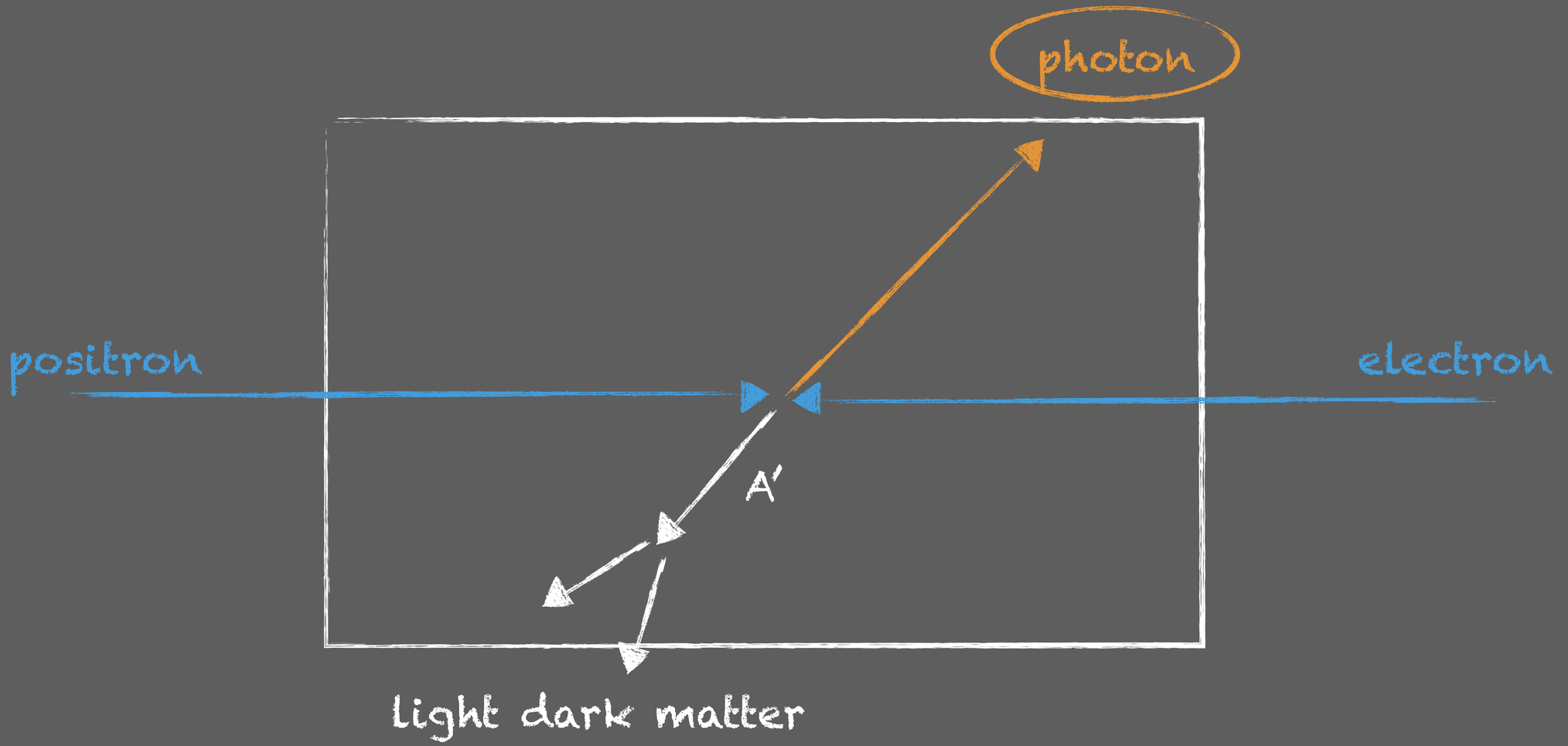
US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report

Displaced decays

beyond 2021:

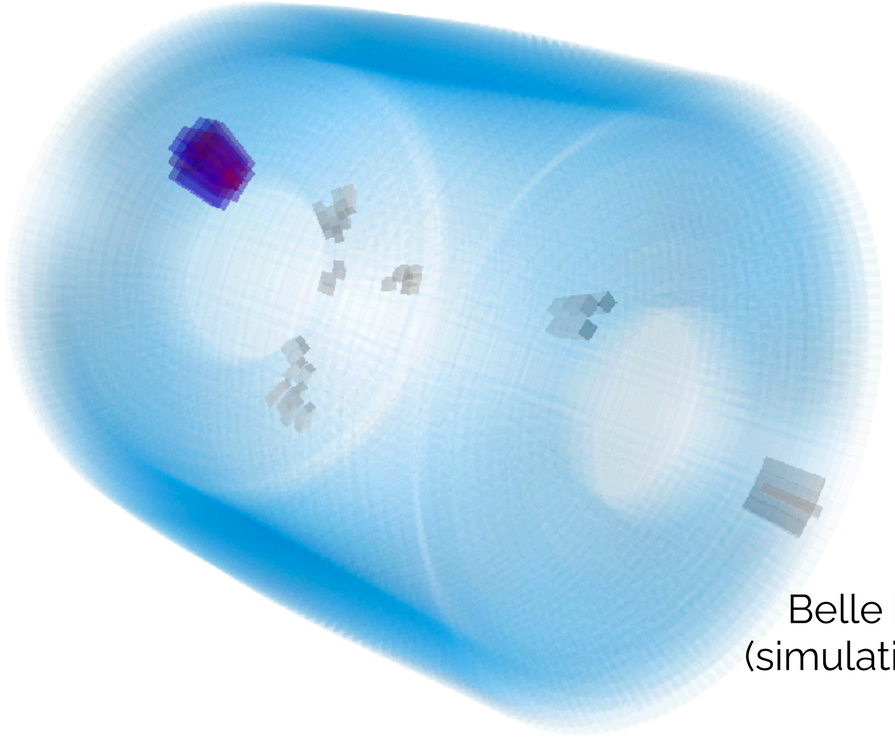
- NA62, SHiP, SeaQuest, …
- Belle II 50ab^{-1}
- LHCb e^+e^-

Invisible Dark Photon decays: e^+e^- collider



Invisible Dark Photon decays: e^+e^- collider (e.g. BaBar, Belle II)

- Requirement:
  - Single photon trigger ($E_{th} \approx 1$GeV at a B-factory)
  - Efficient outer detector to veto ECAL gaps
  - BaBar's Achilles heel: projective calorimeter crystals → large backgrounds

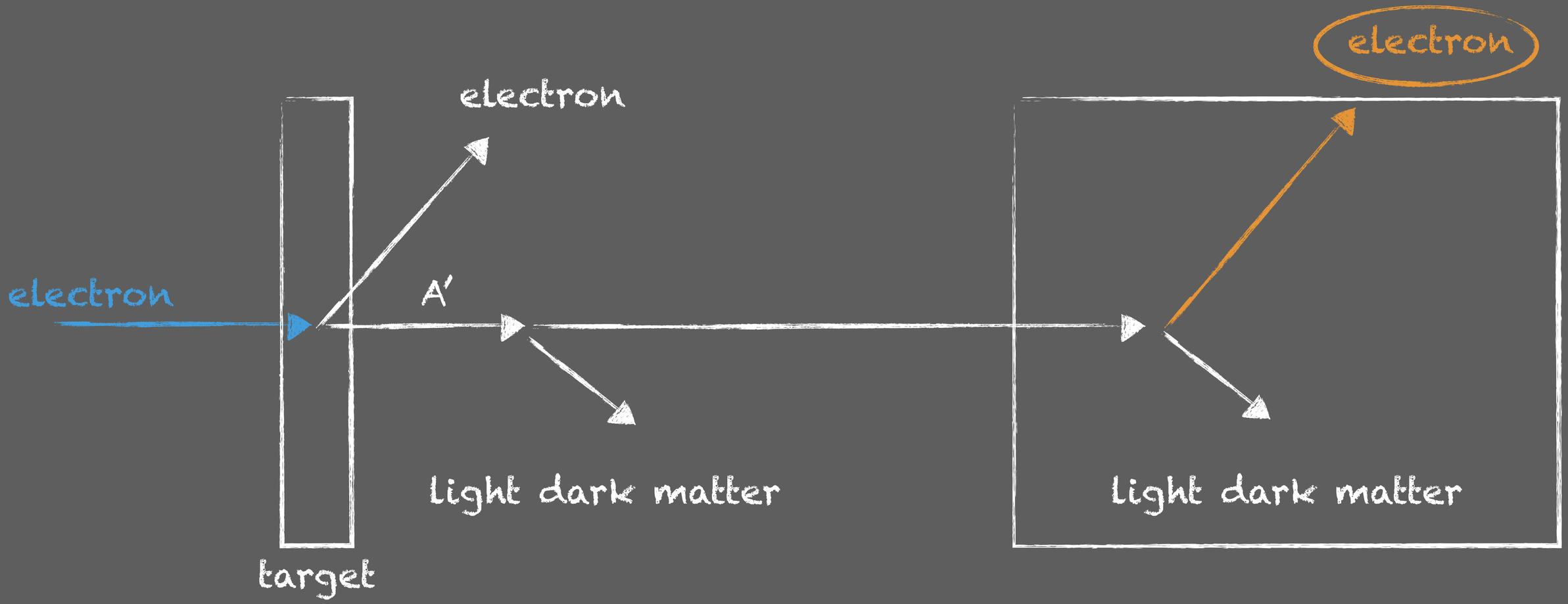


Belle II (simulation)

- SM background if one misses all but one γ:
  - Low mass A' (= high energy single γ): ee→γγ(γ)
  - High mass A' (= low energy single γ): ee→ ee(γ)

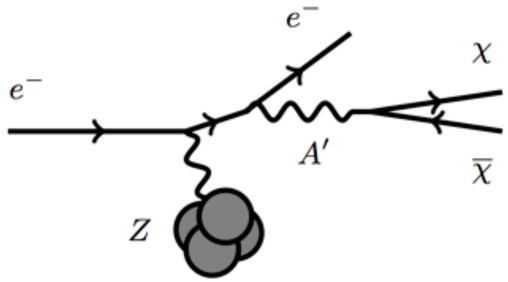
$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$

Invisible Dark Photon decays: beam dumps (e.g. BDX@MESA)

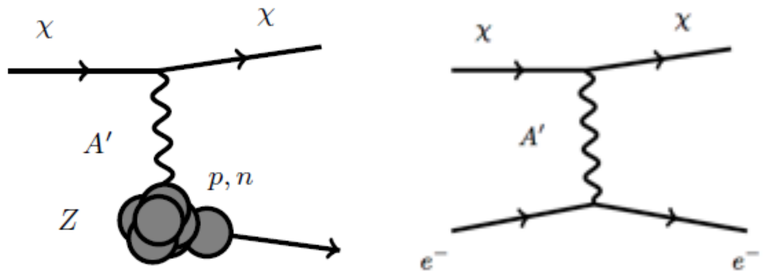


Invisible Dark Photon decays: beam dumps (e.g. BDX@MESA (planned))

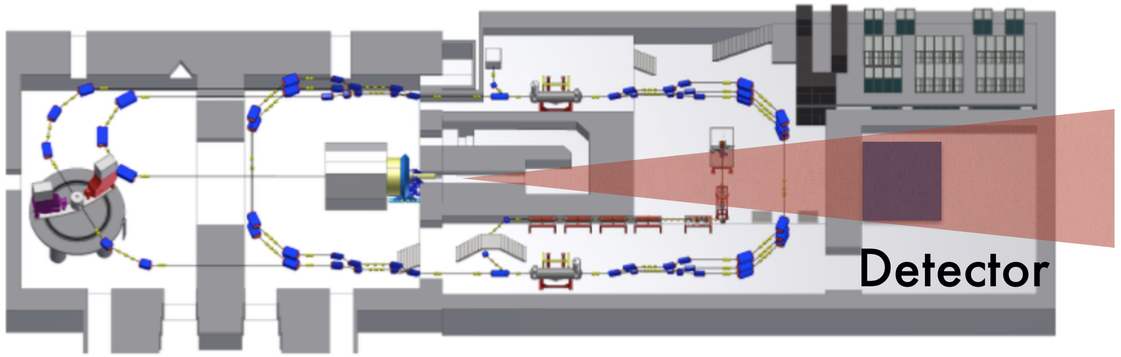
- Thick target O(20X_0)
- Thick shielding O(100X_0)
- ECAL O(10m) away from source plus cosmic veto
- One possibility:
  BDX at the Mainz Energy-Recovering Superconducting Accelerator (MESA).
  135 MeV beam (below pion threshold),
  10^{22} EOT, ~2020+



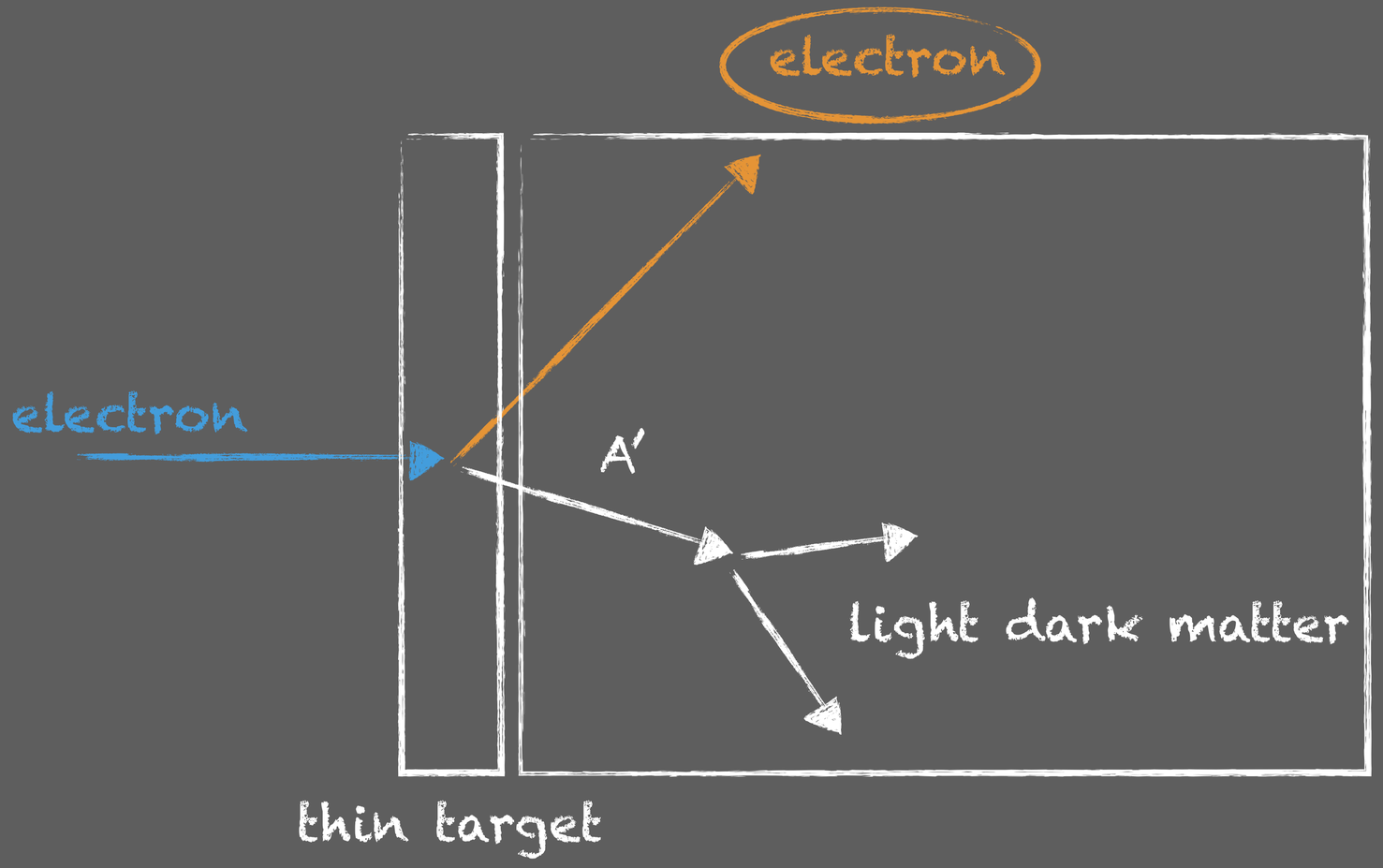
$$Y_{Prod} \sim \epsilon^2/m_A^2$$



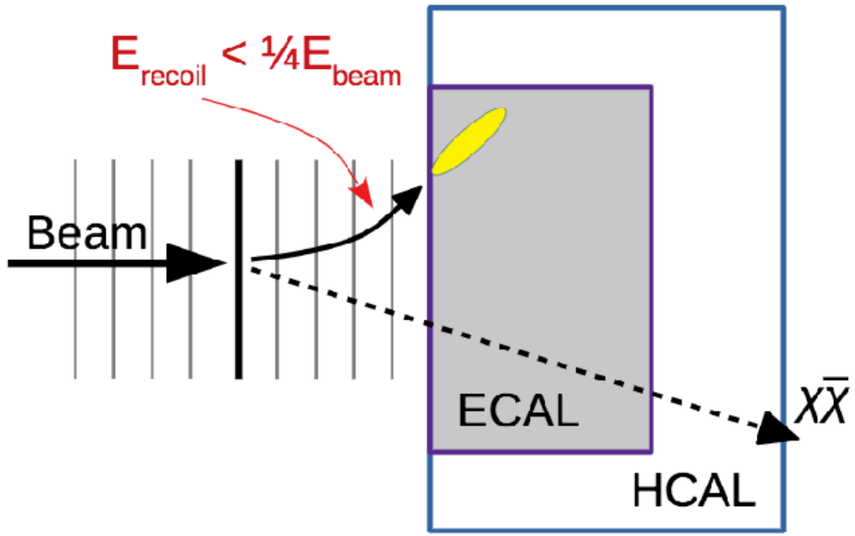
$$Y_{Det} \sim \epsilon^2 \alpha_D/m_A^2$$

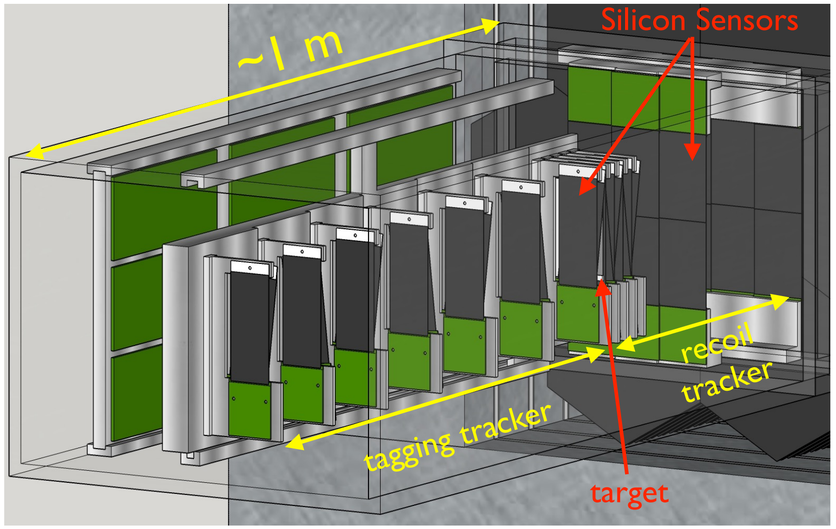


Invisible Dark Photon decays: Fixed targets (e.g. LDMX)



Invisible Dark Photon decays: Fixed targets (e.g. LDMX (planned))



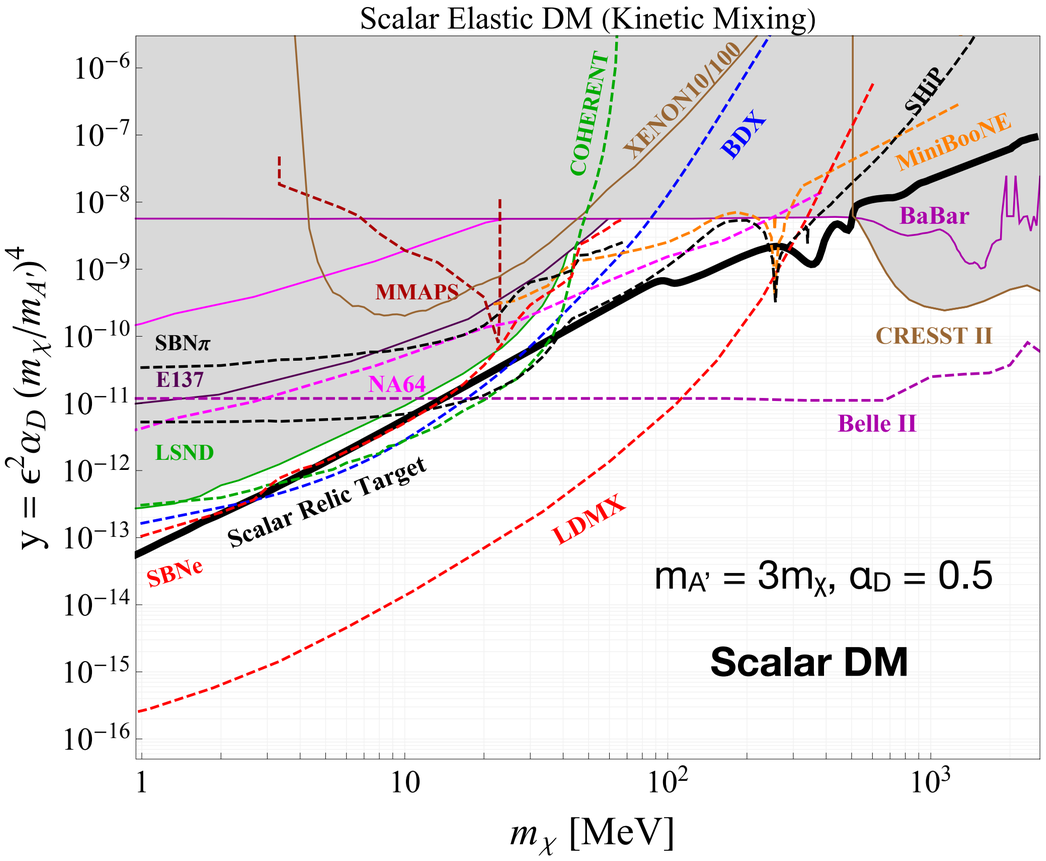


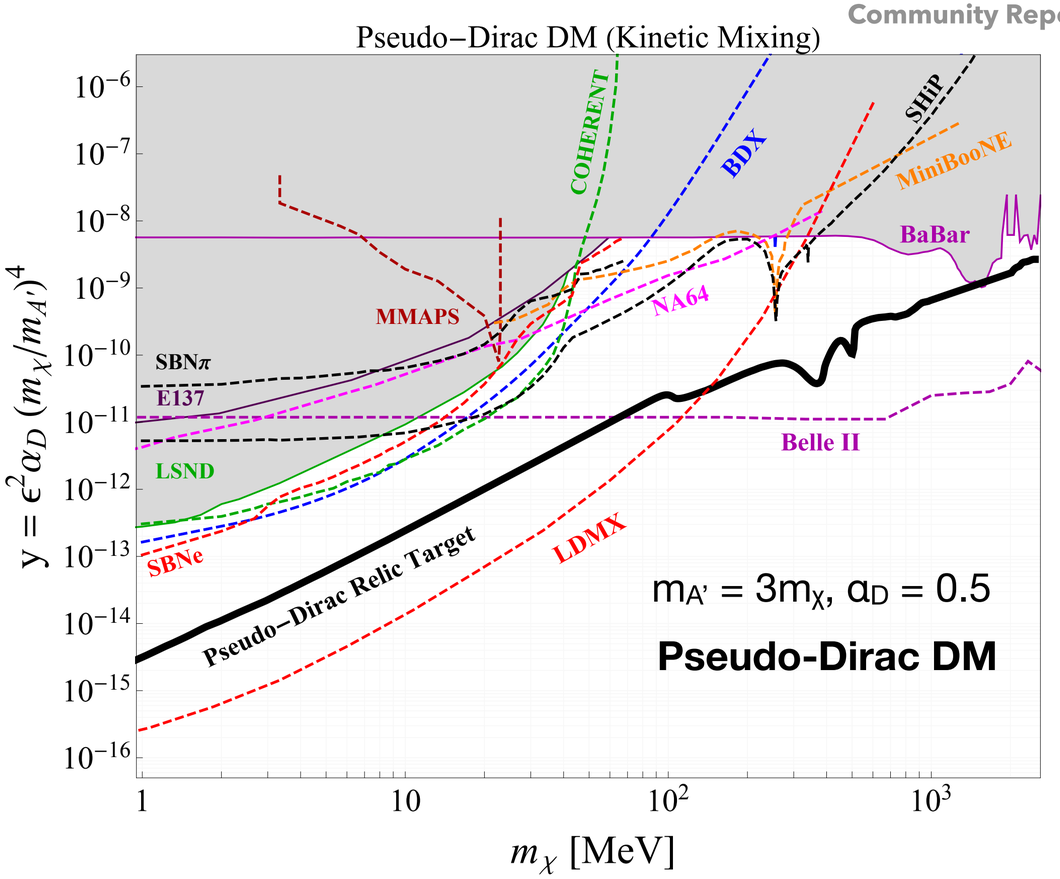
- Thin $O(0.1X_0)$ W target
- Similar tracker than HPS before and after target
- Fast, granular, radiation hard, deep $O(40X_0)$ ECAL (e.g. CMS HGCAL)
- Deep HCAL to veto rare photonuclear events and wide angle bremsstrahlung
- Electron beam O(10 GeV) at SLAC, JLab, or CERN (eSPS) under discussion

Limits for invisible Dark Photon decays

Invisible Dark Photon decays: Limits (and expectations until 2025)

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

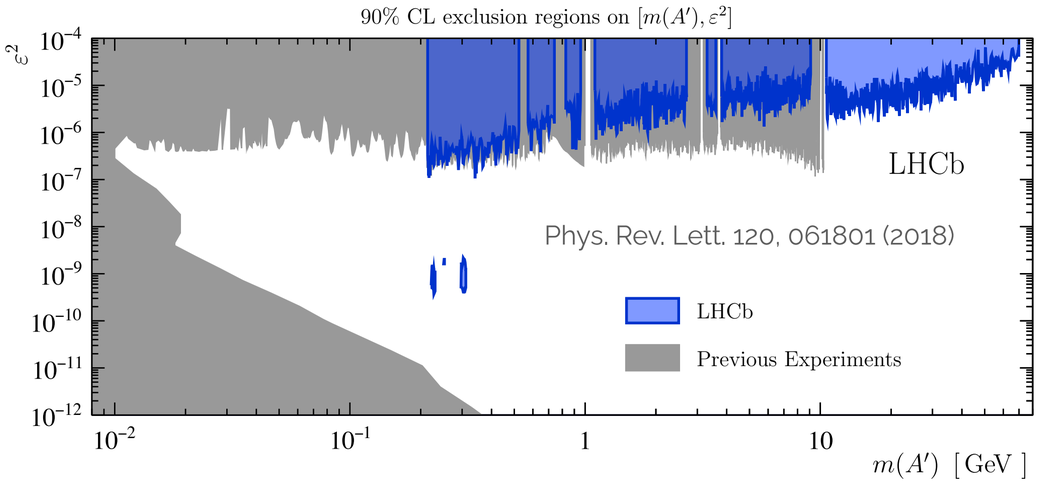




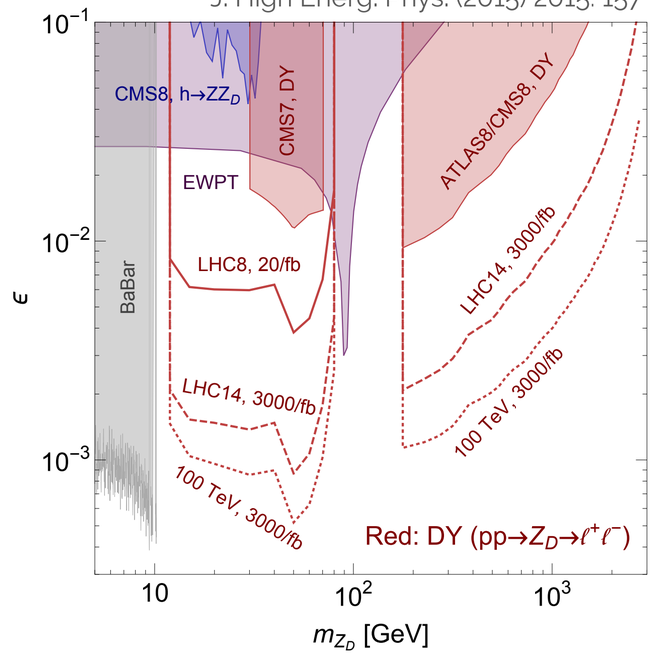
BDX and **LDMX** have different beam option with different sensitivity.
Plot for BDX@CEBAF(A), JLab and LDMX@DASEL, SLAC.
not in the plots: BESIII (low energy e+e- near charm threshold) has (some) data with single photon triggers.

Dark Photons at the LHC?

- Drell-Yan production pp→A'→μμ (some mild model-dep. near Z peak)
  - Dedicated LHCb analysis of 13TeV data (incl. meson decays). A future analysis of A'→ee from D* is a potential game-changer
- h→Z*Z_D (kinetic mixing) is complementary but not very sensitive
- EW global fits



Phys. Rev. D 90, 075016
J. High Energ. Phys. (2015) 2015: 157



Accelerator strategies, next steps

- Belle II and LDMX are at the intensity frontier: No clear path to improve sensitivity beyond ~2027 by just continue with searches for “simple” models
  - Complex final states from specific models are more predictive and more powerful
  - Avoid existing bounds to explain anomalies like g-2:
    - Search for explicit couplings to muons or taus
  - Avoid direct detection bounds:
    - Search for inelastic DM
  - Lifetime frontier: Long-lived particles
  - …

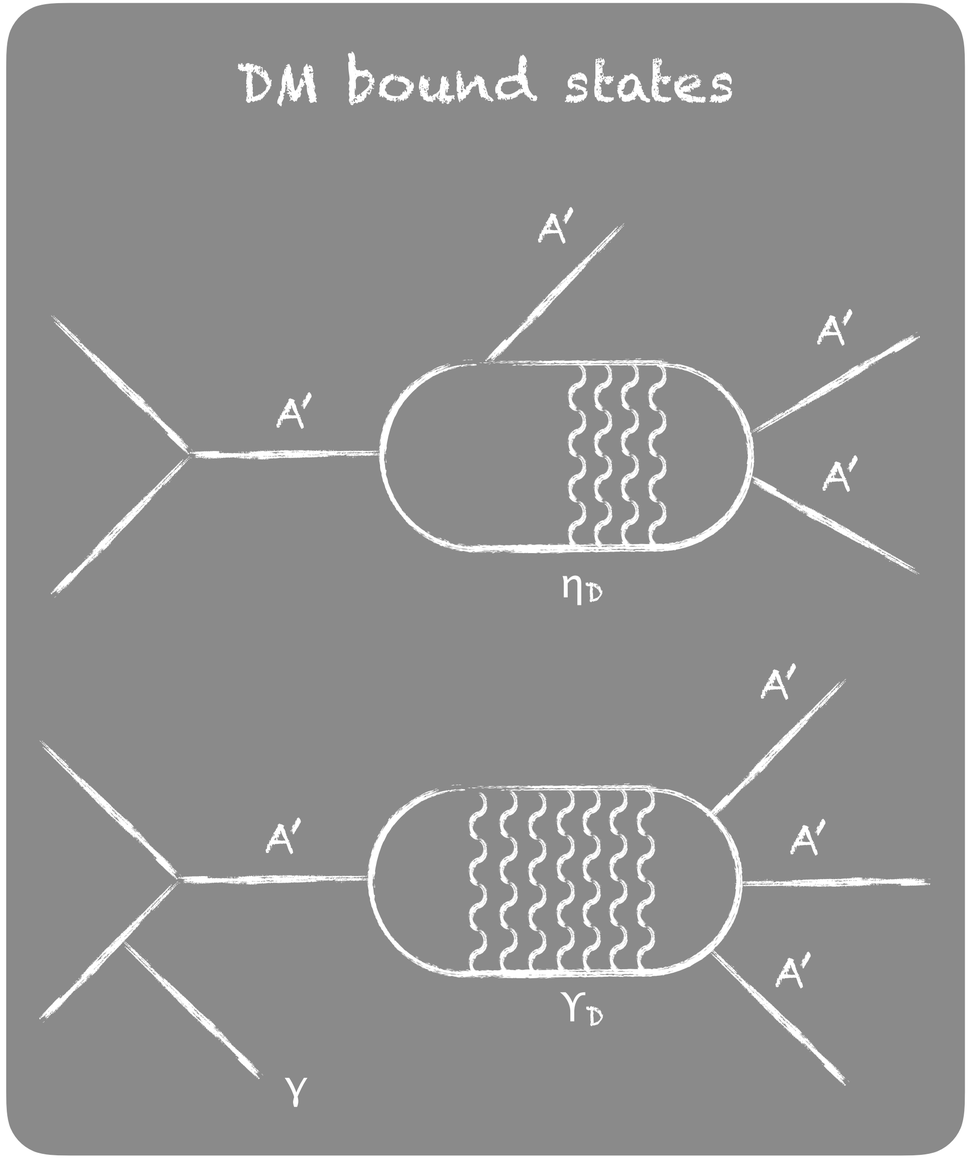
Example: Complex final state from SIDM at Belle II

PRL 116, 151801 (2016)

free parameters:
m(A'), ε, m(χ), g_D

$^1S_0$ $(J^{PC} = 0^{-+})$

$^3S_1$ $(J^{PC} = 1^{--})$



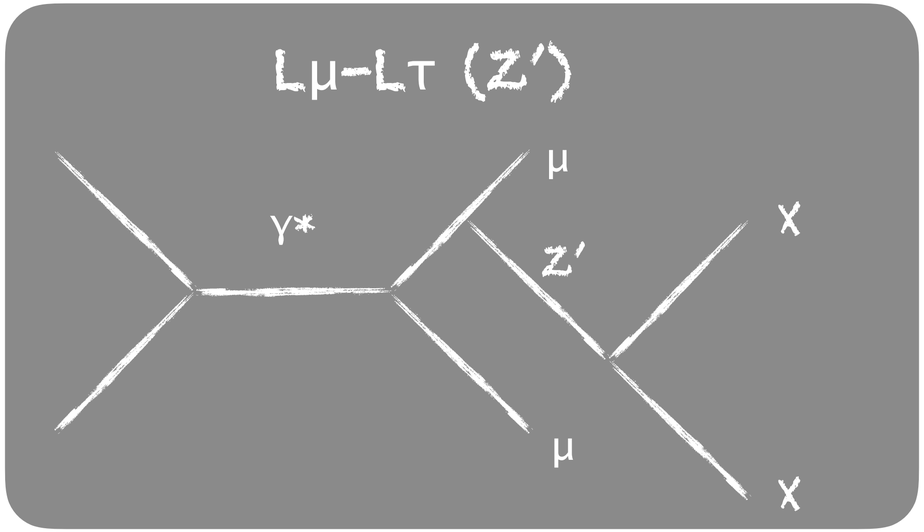
- 2 on-shell A' decaying into electrons
- 1 off-shell A' decaying into leptons/hadrons

- 3 on-shell A' decaying into leptons/hadrons
- 1 γ (→ on-shell A')

Example: Explicit coupling to muons at Belle II

Belle II analysis with 2018 data ongoing.

free parameters:
m(Z'), g(Z')



Two muons +
Missing energy

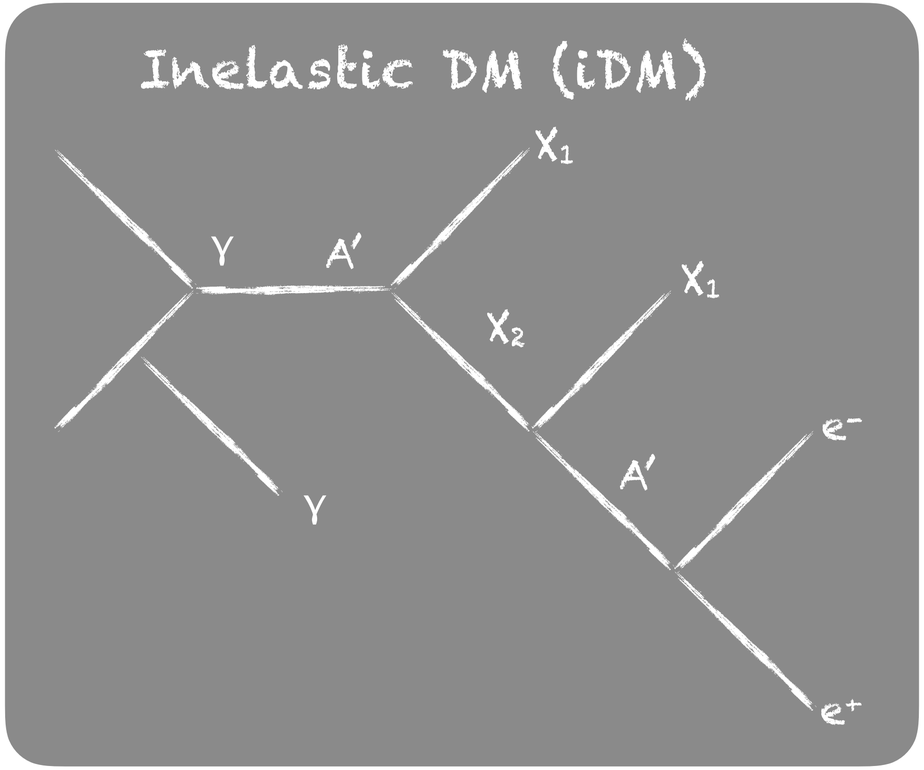
Z' does not couple to electrons

Example: Inelastic Dark Matter at Belle II

arXiv:1508.03050v2

free parameters:
m(A'), ε, m(χ_1), Δ(m), g_D

DM coupling via Dark Photon A' (kinetic mixing ε) on-shell



Cascade decay with two χ_1 (missing energy)

A' must ultimately decay back to SM particles (e, μ, hadrons, …)

χ_2 lifetime can be long
A' lifetime very short (for not too small ε)

Summary

- Accelerator searches for LDM…
  - …are usually mediator searches. LDM generally appears as missing energy.
  - …do not rely on LDM history
  - …do not rely on LDM being a scalar particle
- Belle II started data taking some weeks ago, first results this year. Together with LDMX it will be able to cover simple relic targets for vector mediators
- The collider searches are moving into more model dependency in exchange for more predictive final states (including long lived particles (LLPs))

Contact

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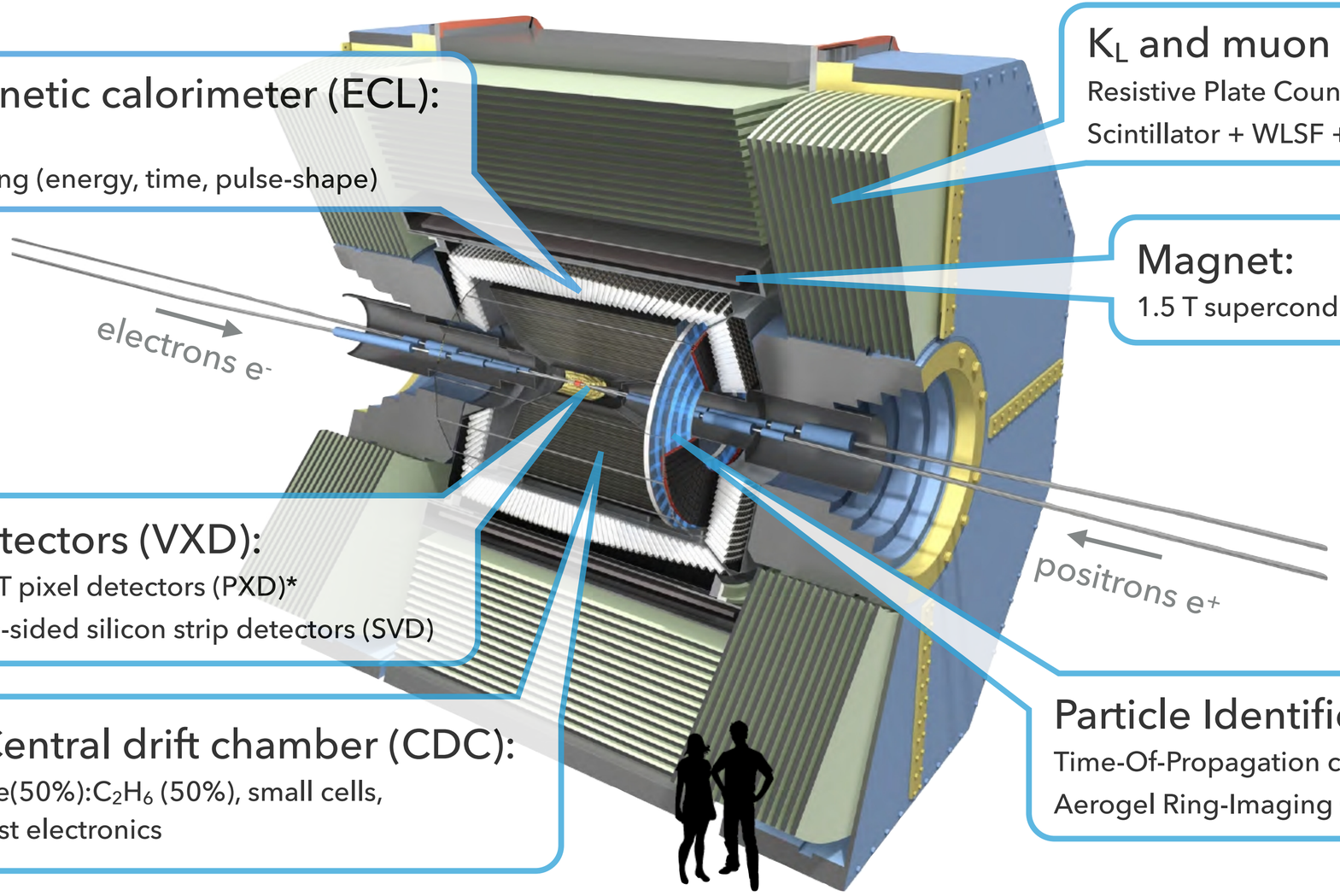
The e^+e^- collider flagship: Belle II

Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
waveform sampling (energy, time, pulse-shape)

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting



Trigger*:
Hardware: < 30 kHz
Software: < 10 kHz

Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)*
4 layer double-sided silicon strip detectors (SVD)

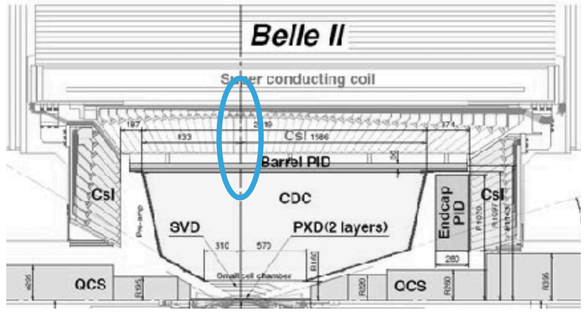
Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells,
fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

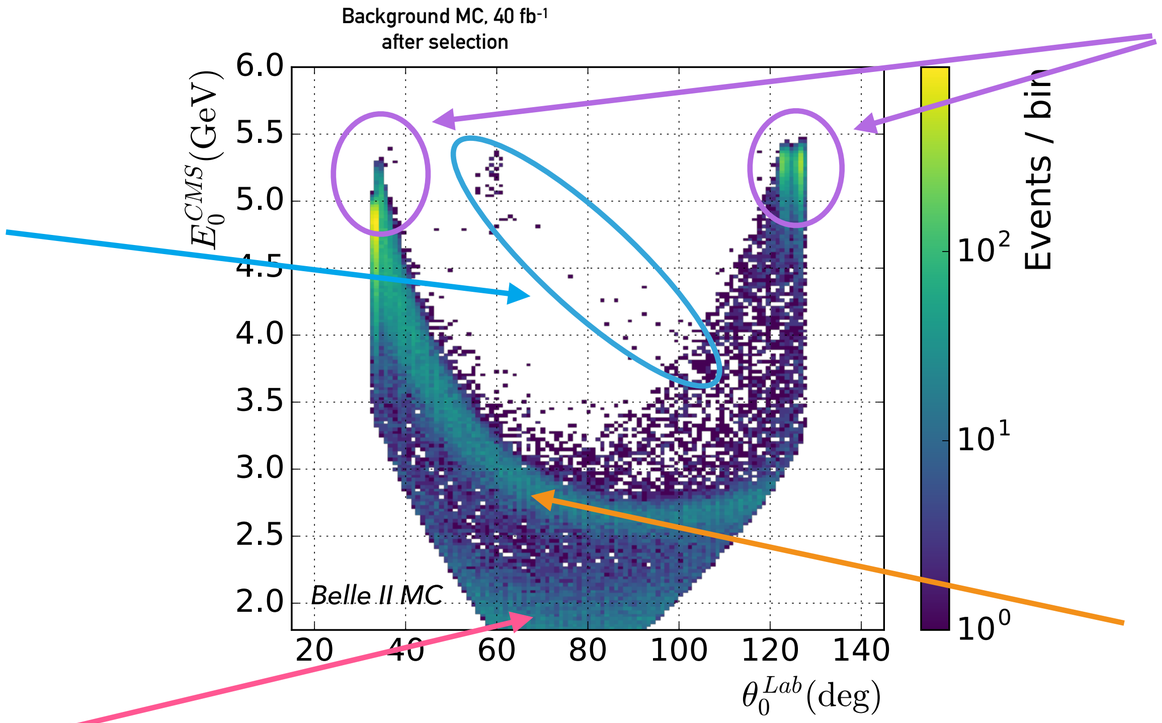
* Some modifications for early data taking

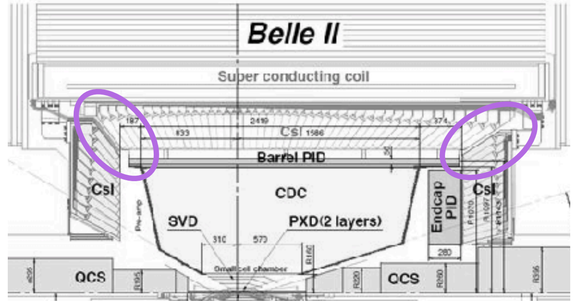
Invisible Dark Photon decays: Belle II



ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance

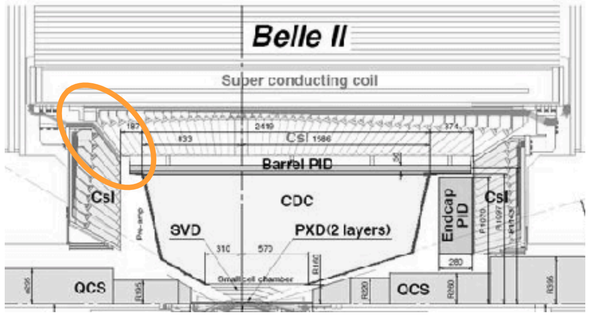
$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$





ee→2γ
1γ in ECL BWD or FWD gap

ee→eeγ
both electrons
out of tracking acceptance



ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance