Light dark matter searches at (Super) B-Factories.

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721. WE-Heraeus-Seminar: Light Dark Matter Searches

11.06.2021

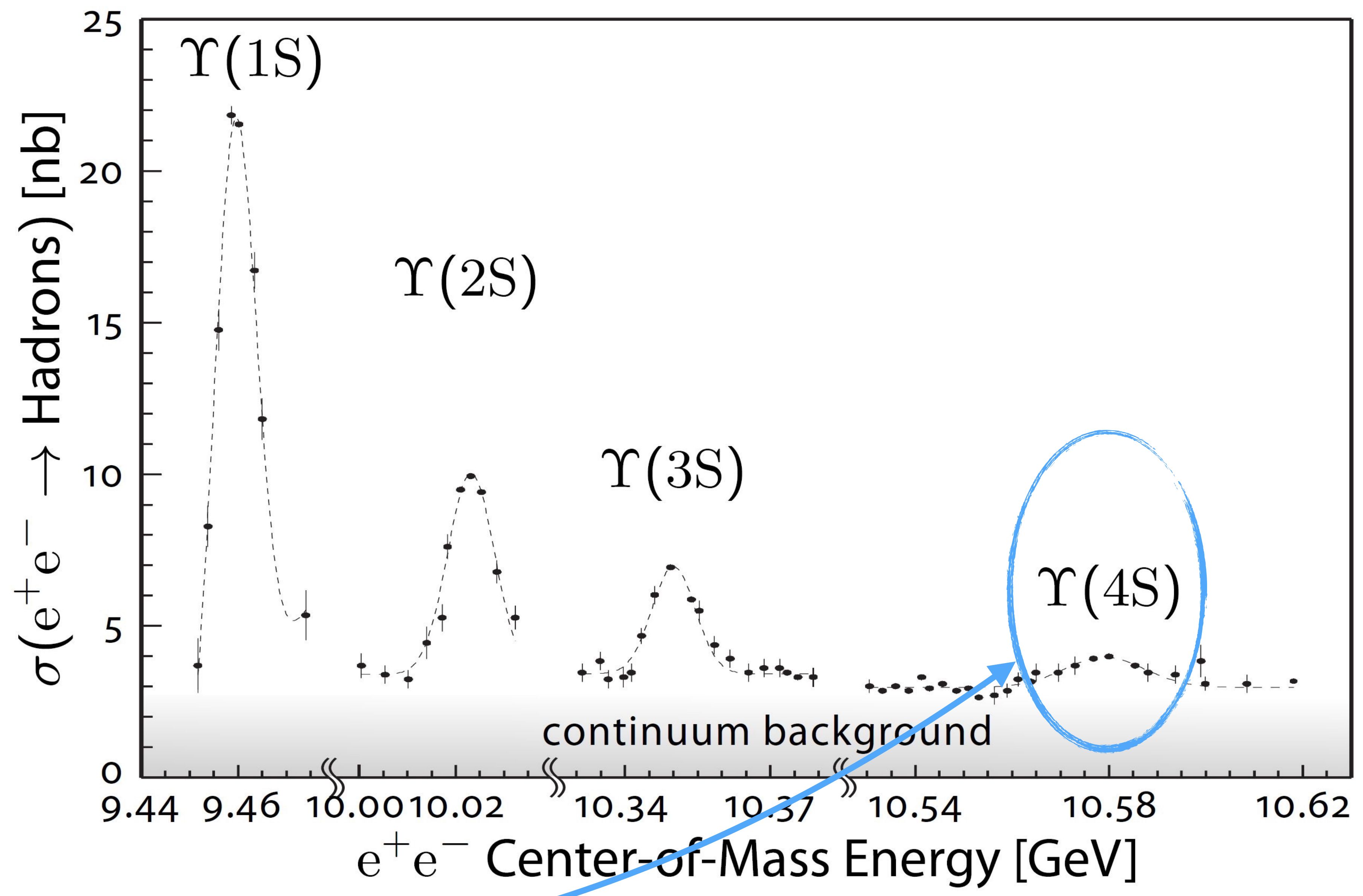
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

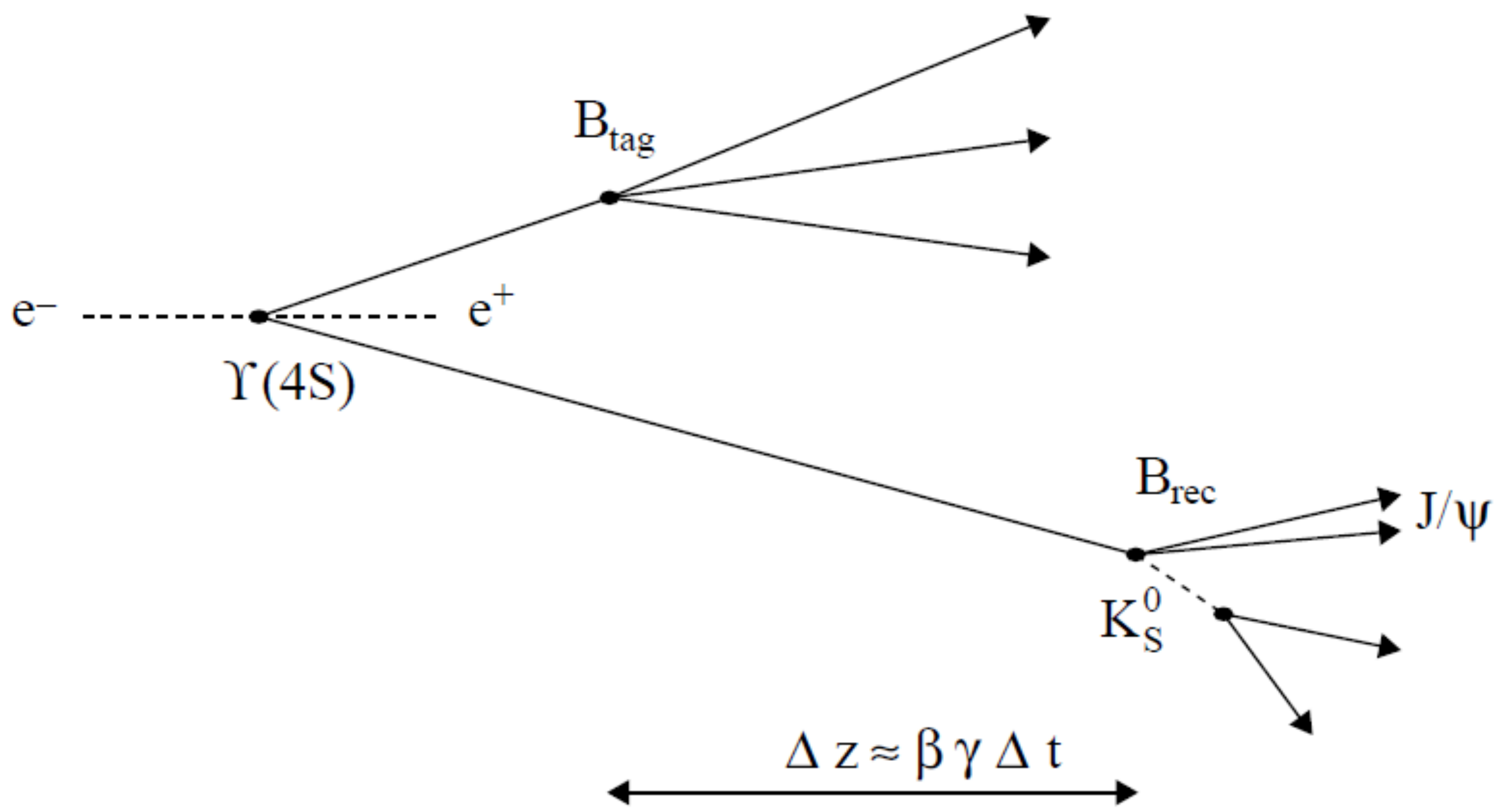
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

B-factories: Belle@KEKB and BaBar@PEP-II

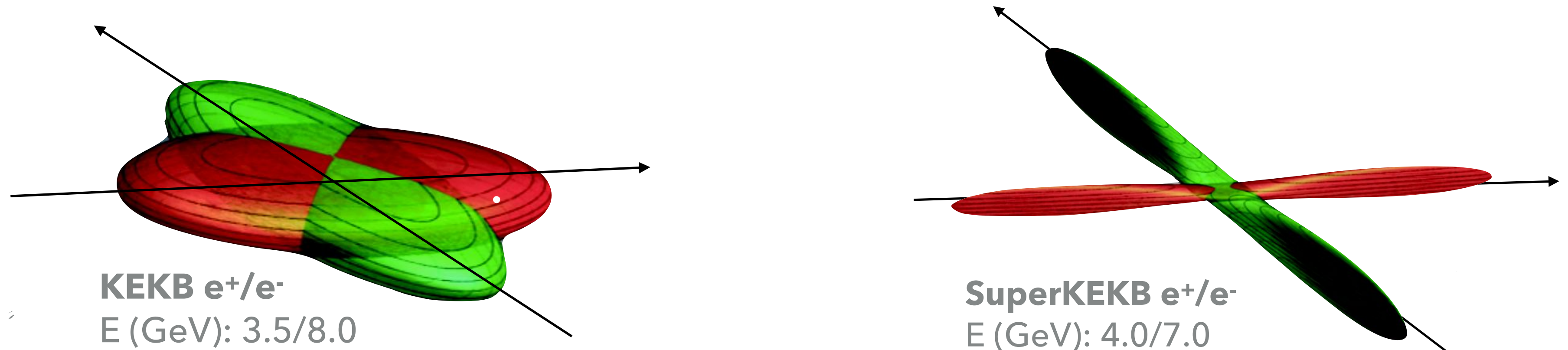
- Very high luminosity: ~$2{\times}10^{34}$ /cm²/s (Belle)
- Collision energy at Υ(nS):
  Mainly at $\sqrt{s} = 10.58$ GeV
  BF(Υ(4S)→ $B\bar{B}$) > 96%
- Asymmetric beam energies:
  e.g. 8.0 GeV (e⁻) / 3.5 GeV (e⁺) (Belle)
  → Boosted $B\bar{B}$ pairs
- Many analysis still statistically limited





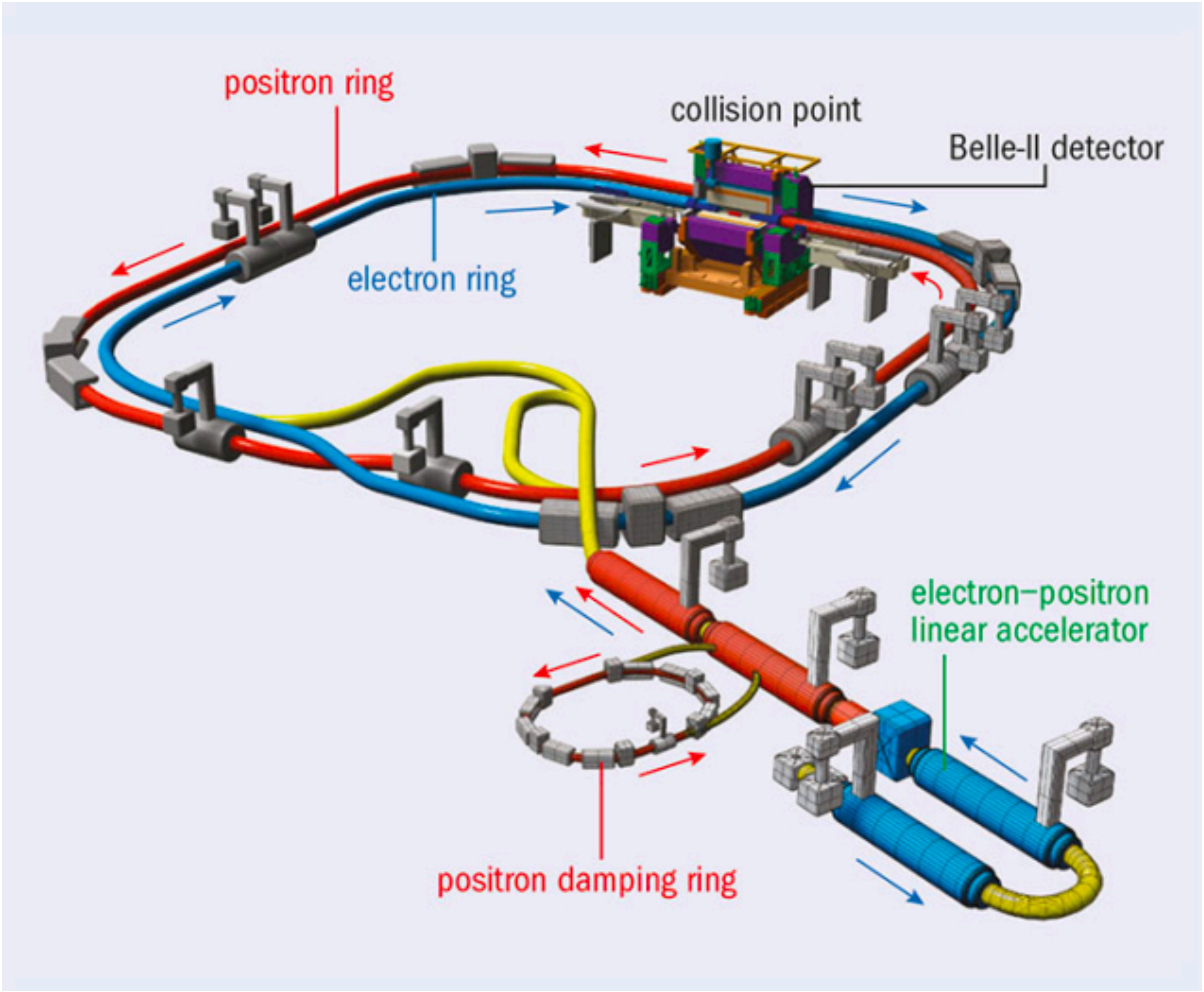
Super B-factory accelerator: SuperKEKB

- Asymmetric beam energies:
  e.g. 7.0 GeV (e^-) / 4.0 GeV (e^+)
- Large crossing angle of 83 mrad
- Major upgrade to the accelerator with 30× the KEKB design luminosity ($6x10^{35}$ $cm^{-2}s^{-1}$)
  - 1.5× higher beam currents
  - 20× smaller beam spot (σ_y=50 nm): "Nano-beam scheme"
  - Ultimate goal: 50 ab^{-1} (50× Belle)



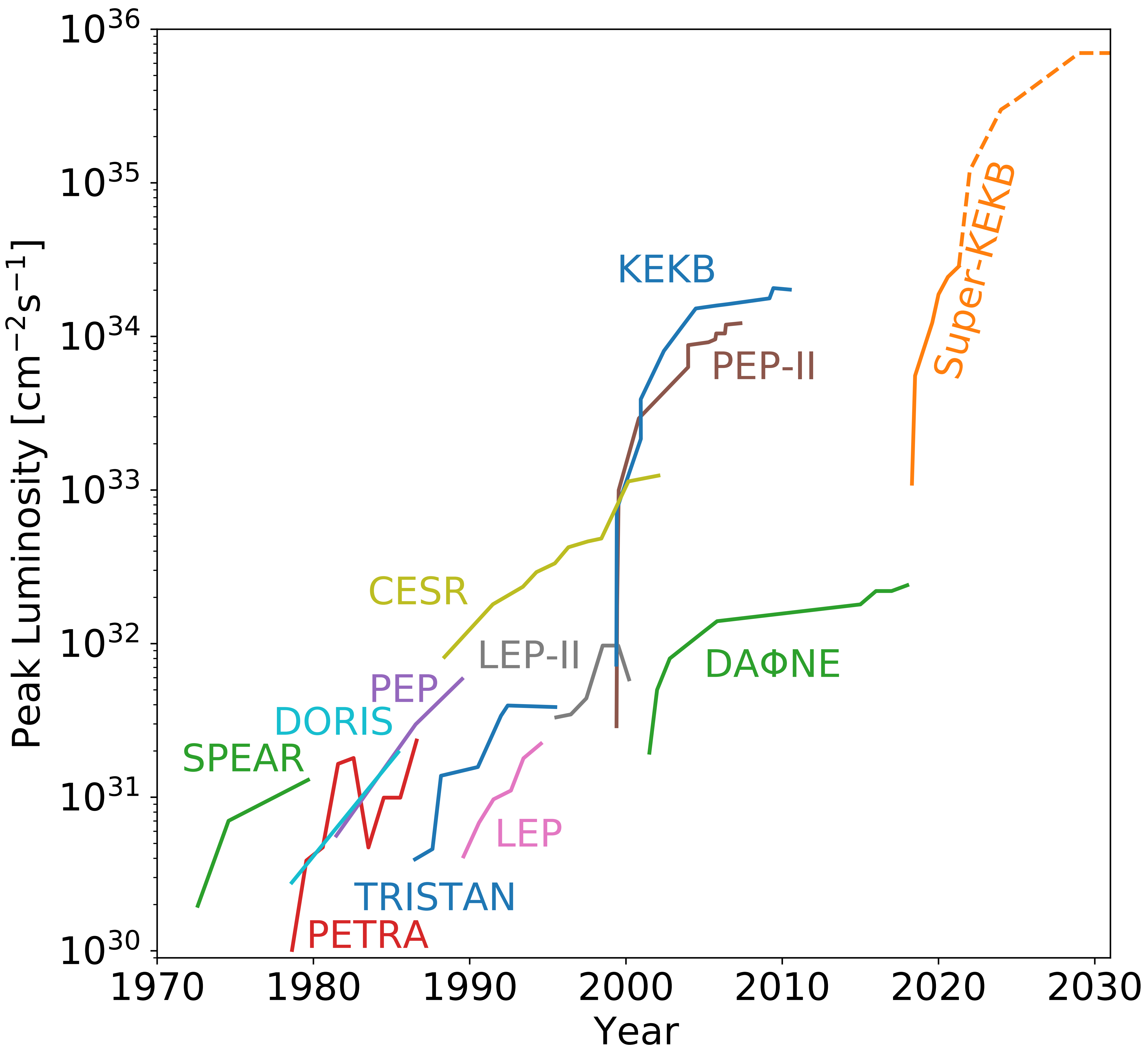
KEKB e^+/e^-
E (GeV): 3.5/8.0
I (A): ~ 1.6/1.2
β^*_y (mm): ~5.9/5.9
Crossing angle (mrad): 22

SuperKEKB e^+/e^-
E (GeV): 4.0/7.0
I (A): ~ 3.6/2.6
β^*_y (mm): ~0.27/0.3
Crossing angle (mrad): 83

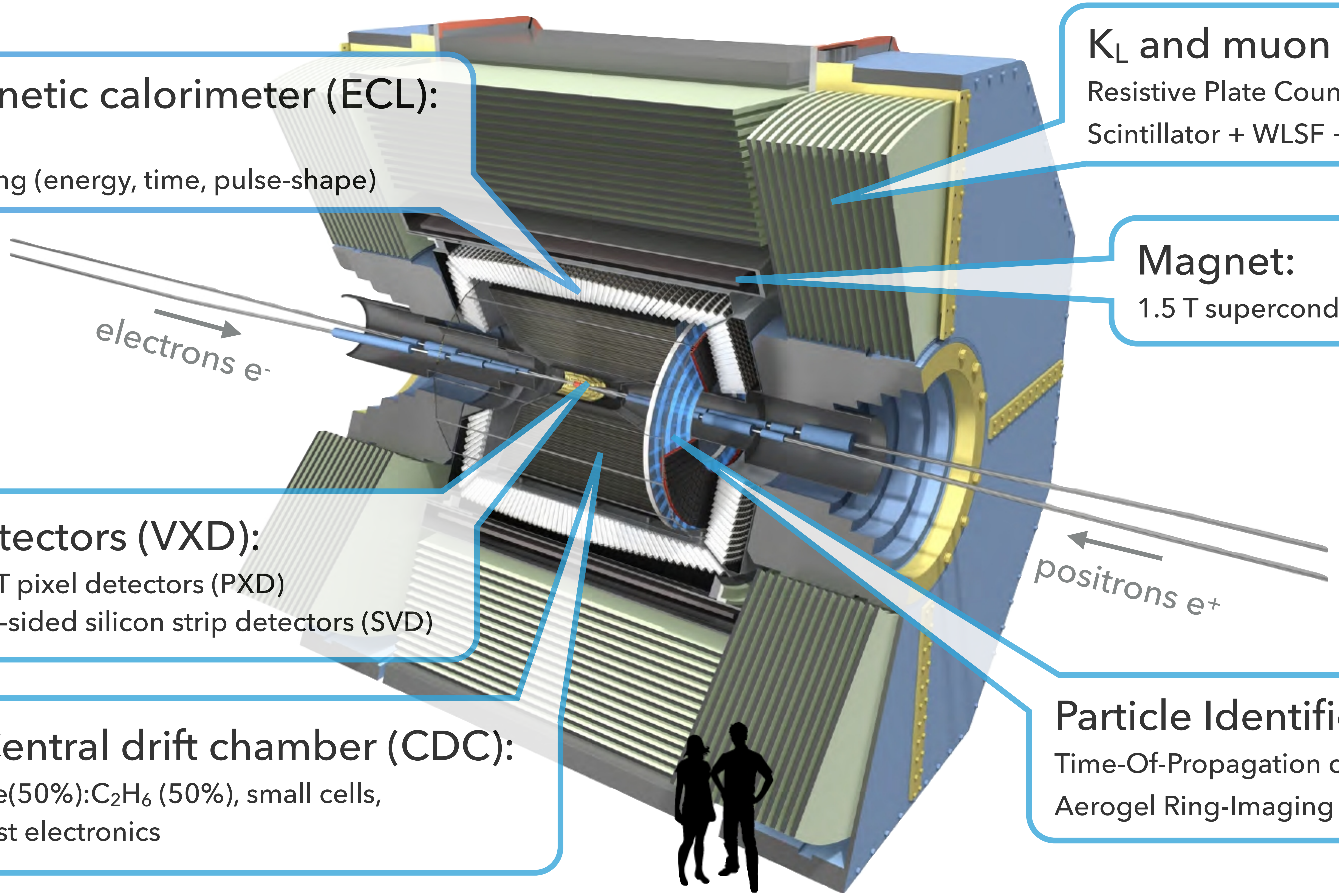


KEK in Tsukuba (Japan)

Luminosity


Peak Luminosity [cm^{-2}s^{-1}]
Year
10^{30}
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
10^{36}
1970
1980
1990
2000
2010
2020
2030
KEKB
PEP-II
Super-KEKB
CESR
LEP-II
DAΦNE
PEP
DORIS
SPEAR
LEP
TRISTAN
PETRA

Super B-factory detector: 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

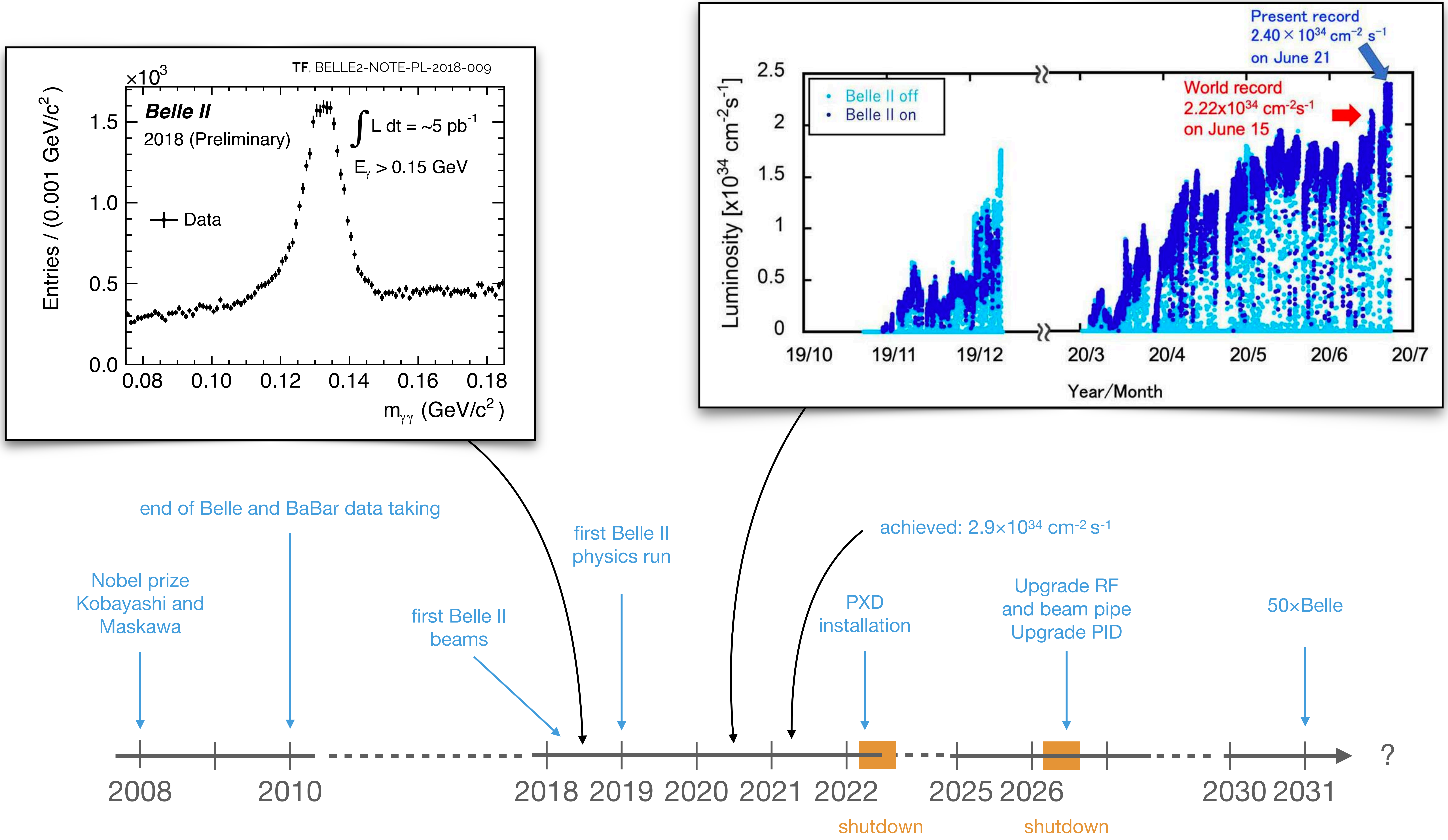
Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

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)

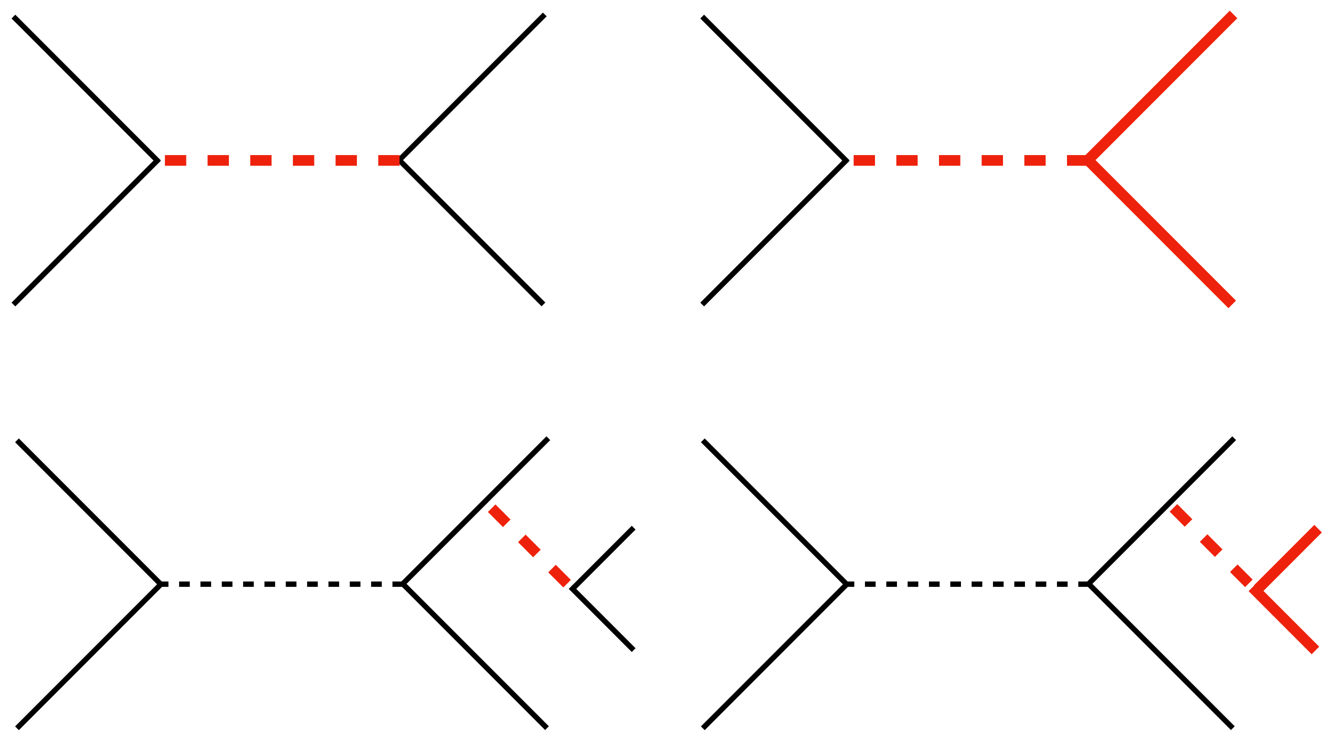
DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

Timeline


TF, BELLE2-NOTE-PL-2018-009
Belle II
2018 (Preliminary)
∫L dt = ~5 pb⁻¹
Eγ > 0.15 GeV
Data
Entries / (0.001 GeV/c²)
×10³
1.5
1.0
0.5
0.0
0.08
0.10
0.12
0.14
0.16
0.18
mγγ (GeV/c²)
Present record
2.40 × 10³⁴ cm⁻² s⁻¹
on June 21
World record
2.22x10³⁴ cm⁻²s⁻¹
on June 15
Belle II off
Belle II on
Luminosity [x10³⁴ cm⁻²s⁻¹]
2.5
2
1.5
1
0.5
0
19/10
19/11
19/12
20/3
20/4
20/5
20/6
20/7
Year/Month
end of Belle and BaBar data taking
Nobel prize
Kobayashi and
Maskawa
first Belle II
beams
first Belle II
physics run
achieved: 2.9×10³⁴ cm⁻² s⁻¹
PXD
installation
Upgrade RF
and beam pipe
Upgrade PID
50×Belle
2008
2010
2018
2019
2020
2021
2022
2025
2026
2030
2031
?
shutdown
shutdown

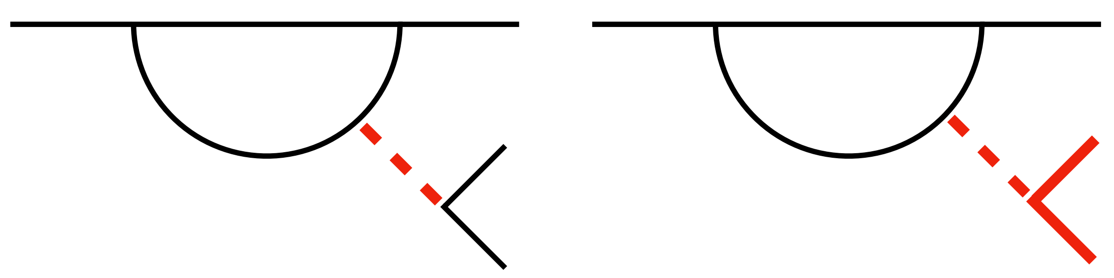
Dark matter at B-factories

direct production



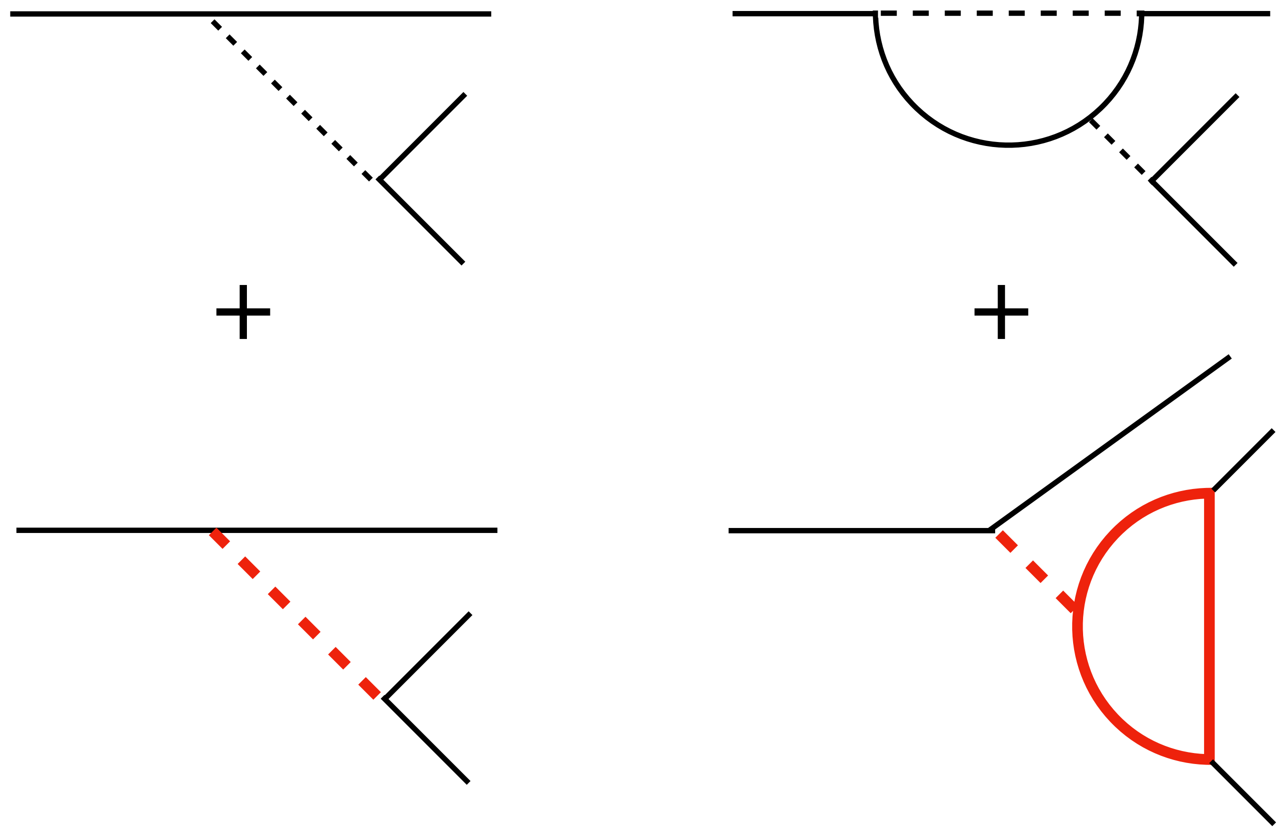
- mediators coupled to e, μ, τ, hadrons ('g-2 anomaly')
- visible or invisible final states
- probe light mediator masses up to ~10 GeV

meson decays



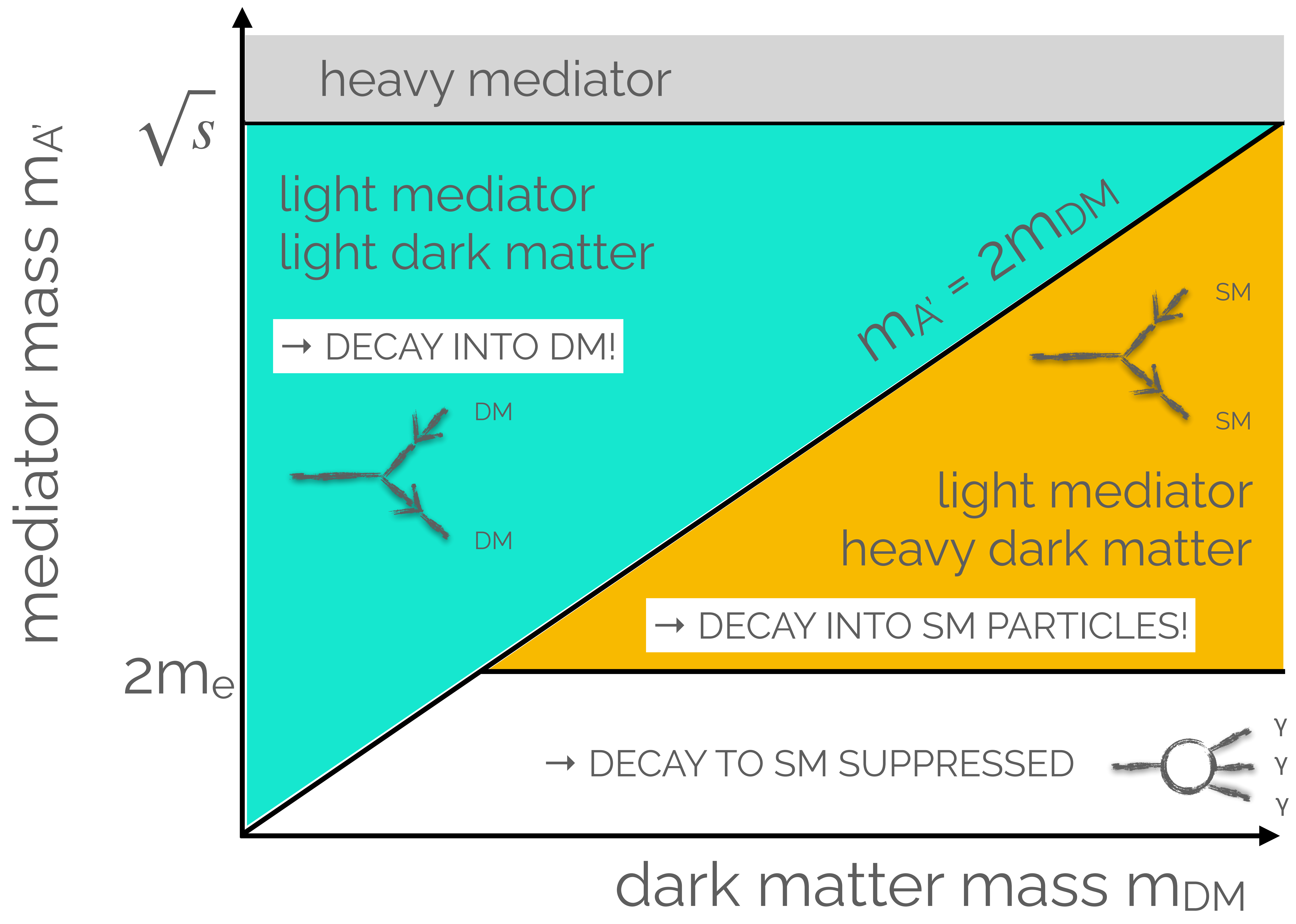
- mediators coupled D, B, or ϒ
- visible (incl. LFV) or invisible final states
- probe light mediator masses up to respective meson mass

precision physics



- loop induced effects or LFU at tree level ('B-anomalies')
- probe (only) very high mediator masses

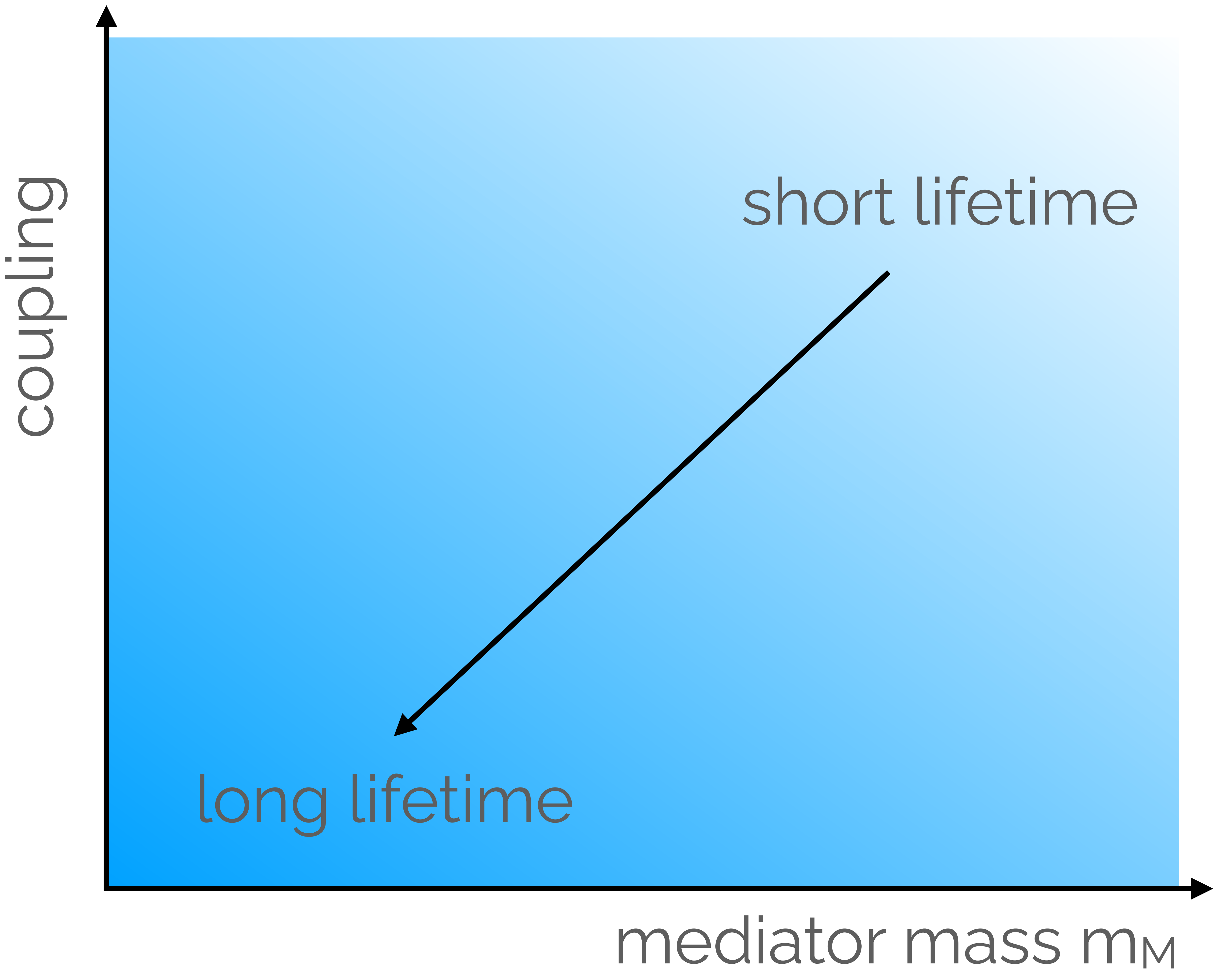
Mediator mass vs DM mass



Lifetime (simplified)

“brute force” probe tiny couplings → displaced decay vertices

very long lifetimes: decays are invisible (and SM backgrounds often small)

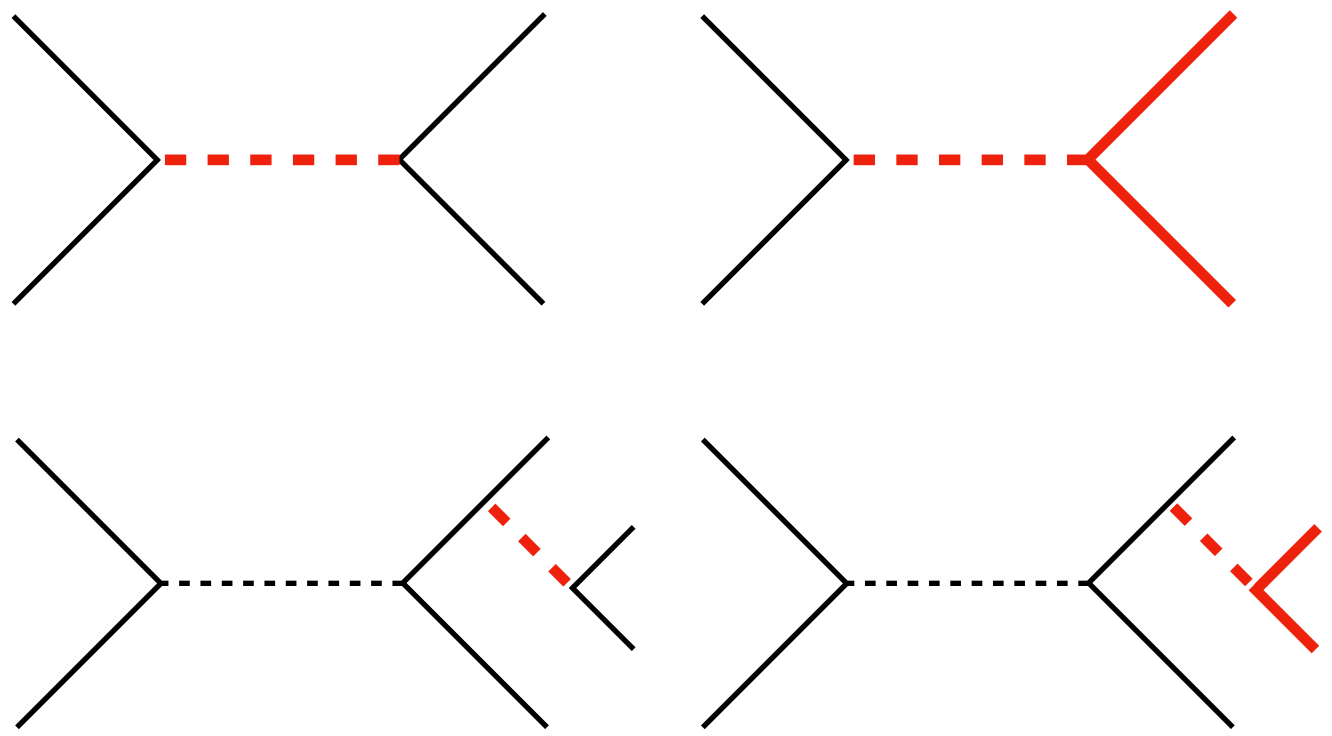


“decouple” production (large couplings → high rate) and decay (small coupling→ long lifetime)

Model dependency

- Most (if not all) searches and studies at Belle II are performed for simplified "benchmark" models
- Recasting limits to account for different angular distributions (e.g. A' vs. ALPs) is usually rather straight forward
- Trigger and selections (accept and veto) for low multiplicity final states are very sensitive to the presence or absence of additional particles
- Generally: The more model-dependent a search, the more free parameters and the stronger the limits

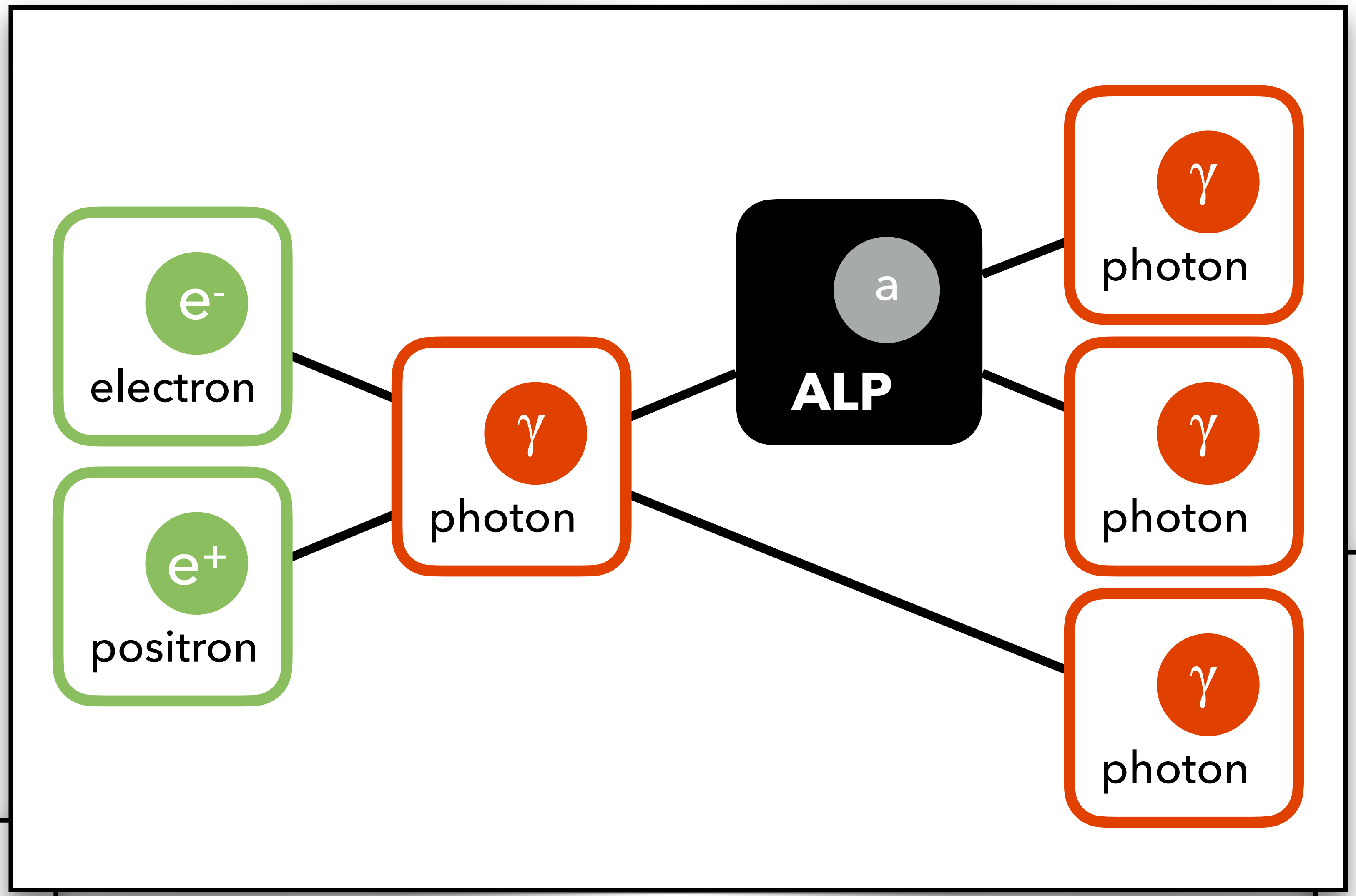
direct production

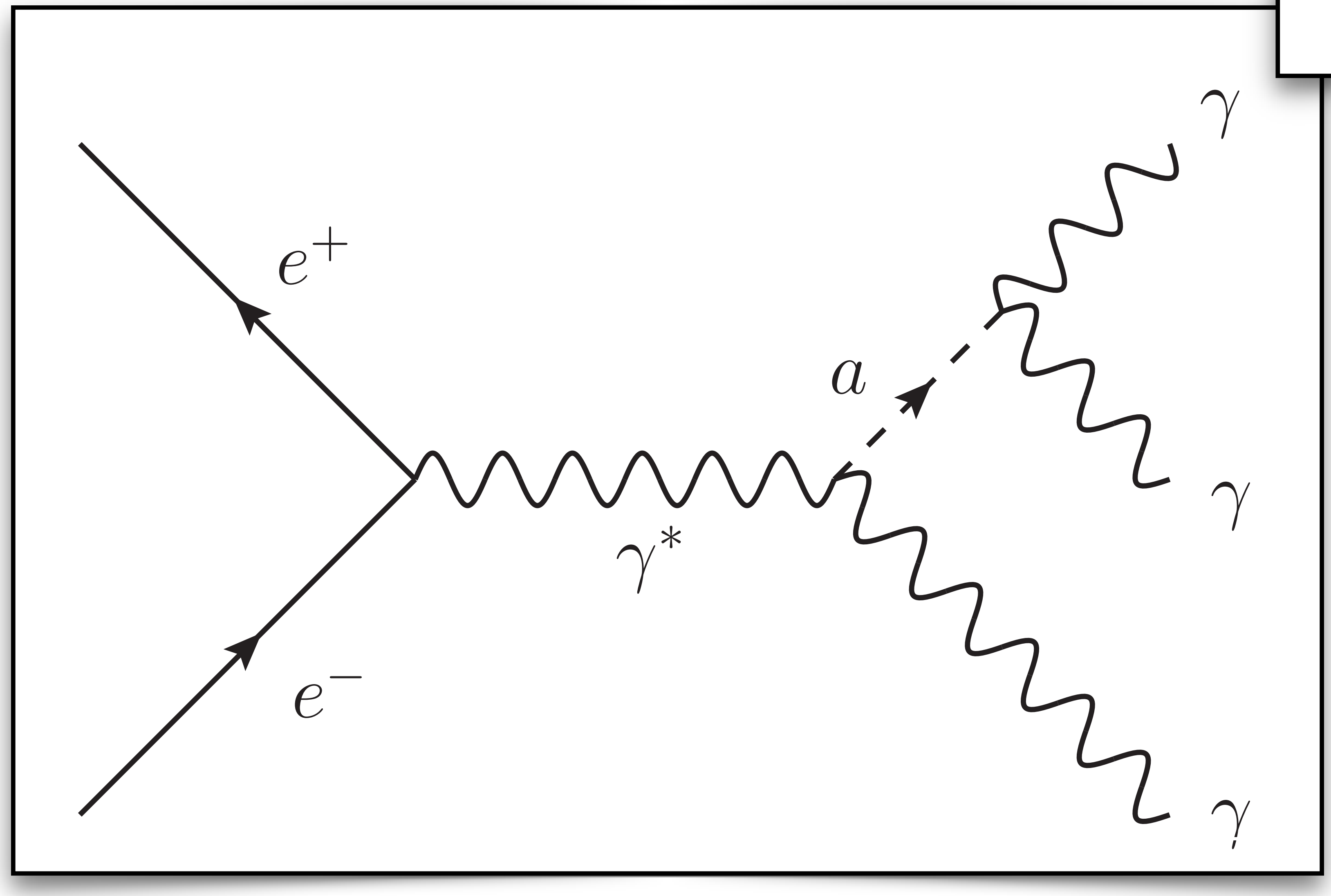


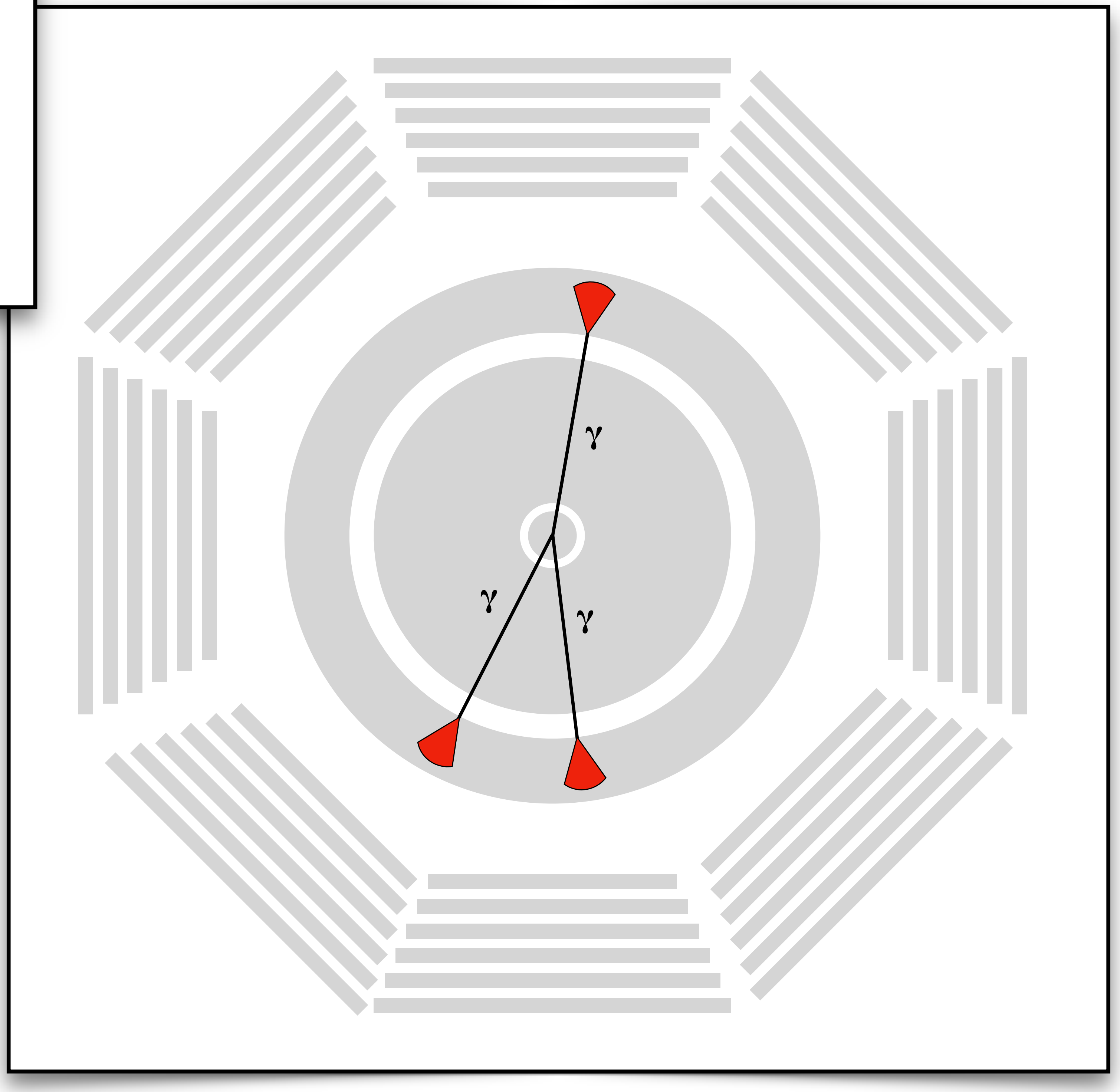
- mediators coupled to e, μ, τ, hadrons ('g-2 anomaly')
- visible or invisible final states
- probe light mediator masses up to ~10 GeV

- Typically "bump-hunts" on locally smooth, but large QED backgrounds
- Very few particles in the final state
  - Challenging to trigger these events, especially with electron or photon final states (Bhabha background at e^+e^- colliders)
- World-leading sensitivity for vanilla dark photons (A'), flavour-sensitive dark mediators (Z'), and axion-like particles (ALPs)

Axion-like Particles (ALPs) at Belle II

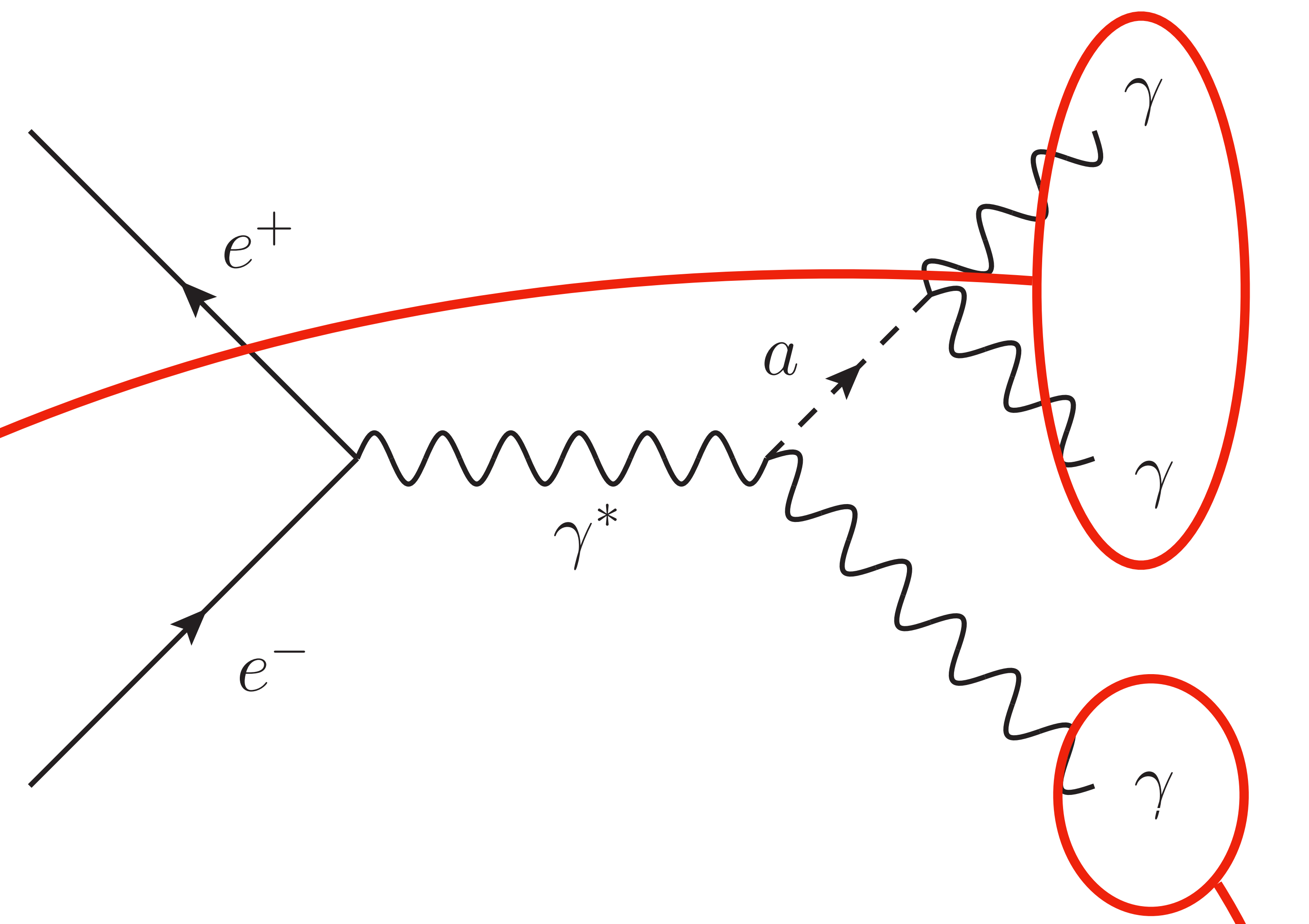




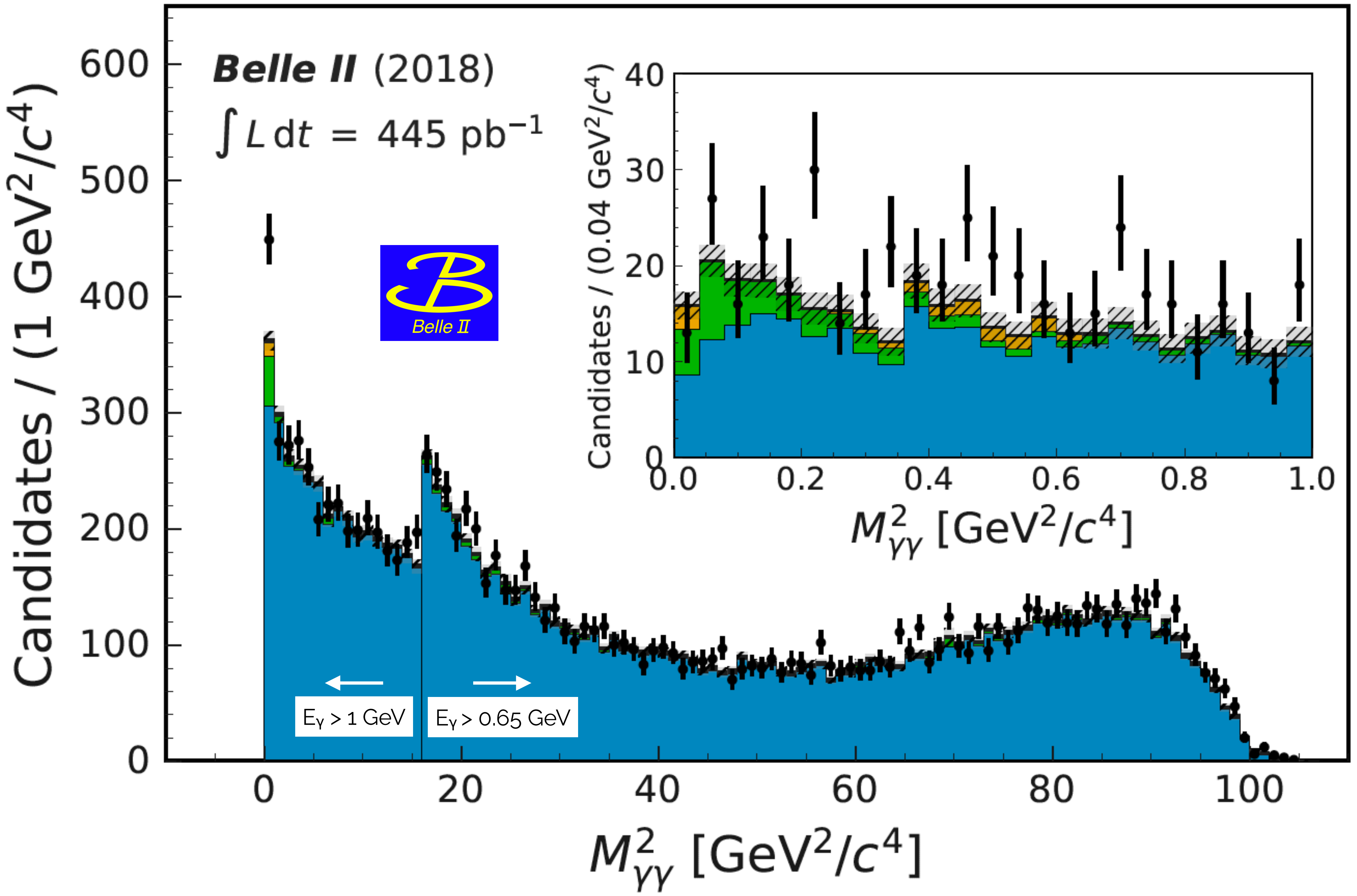


Belle II collaboration, "Search for Axion-Like Particles produced in e⁺e⁻ collisions at Belle II", Phys. Rev. Lett. 125, 161806 (2020)

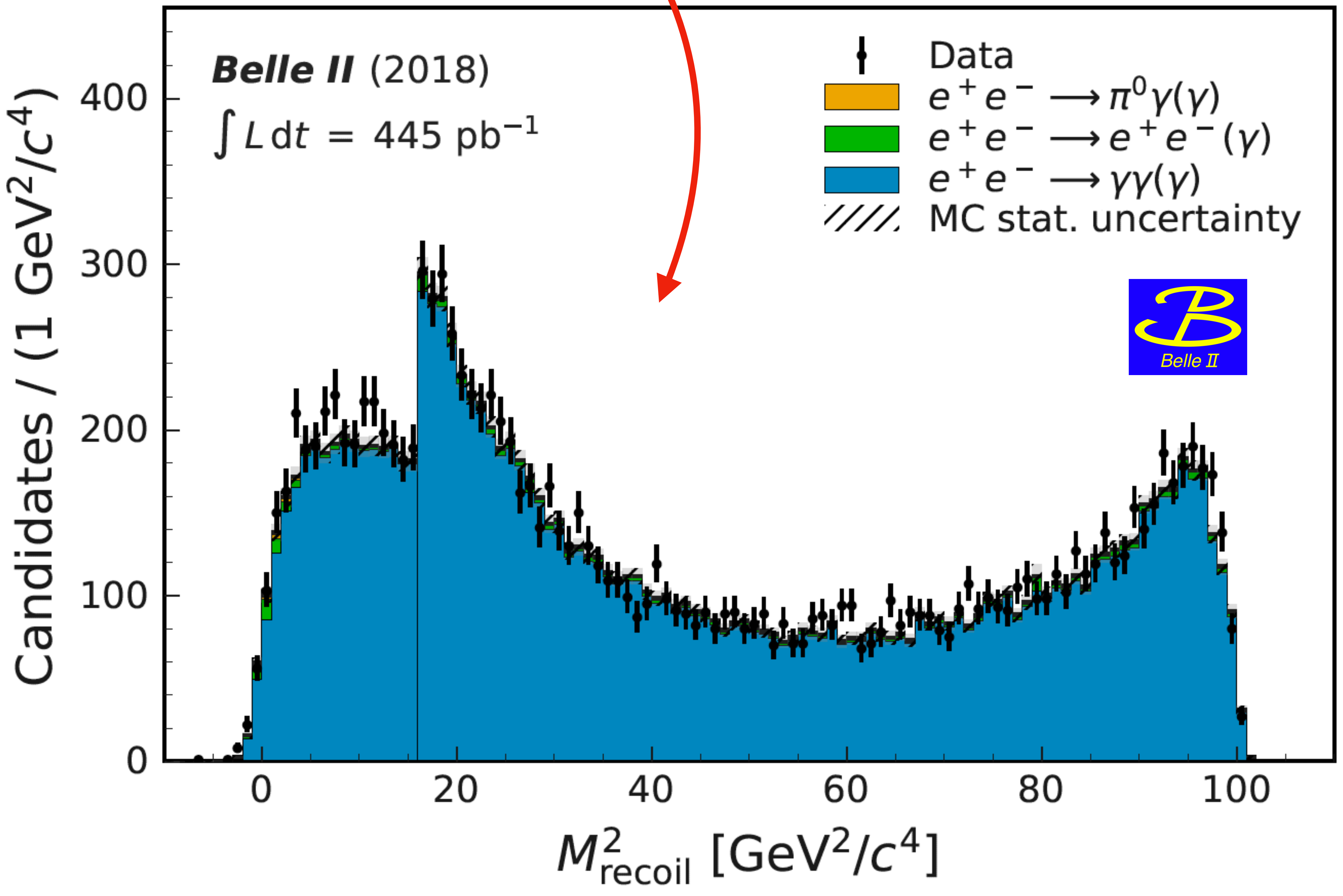
ALPs at Belle II



$m_a < 6.85$ GeV/c²

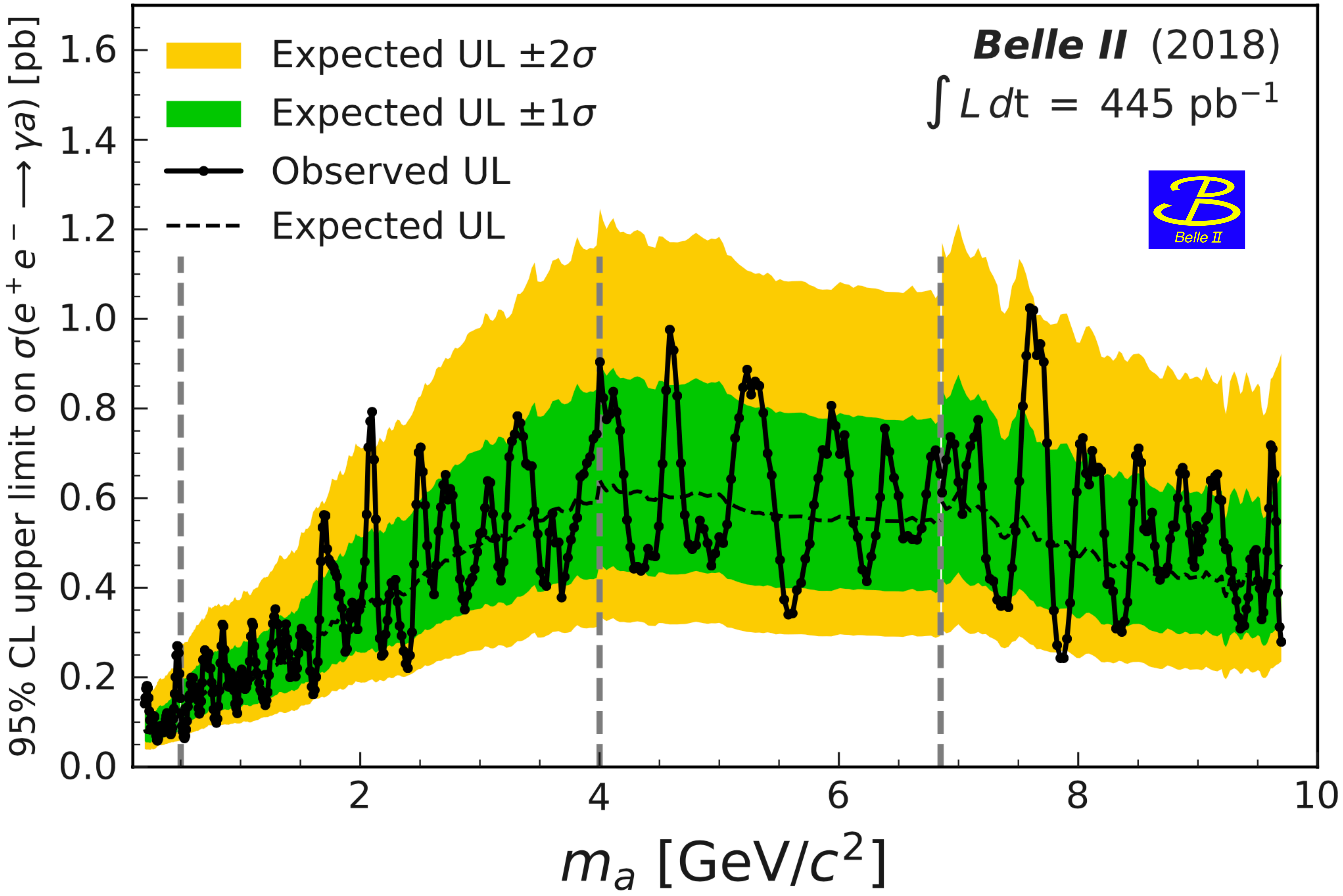


$m_a \geq 6.85$ GeV/c²



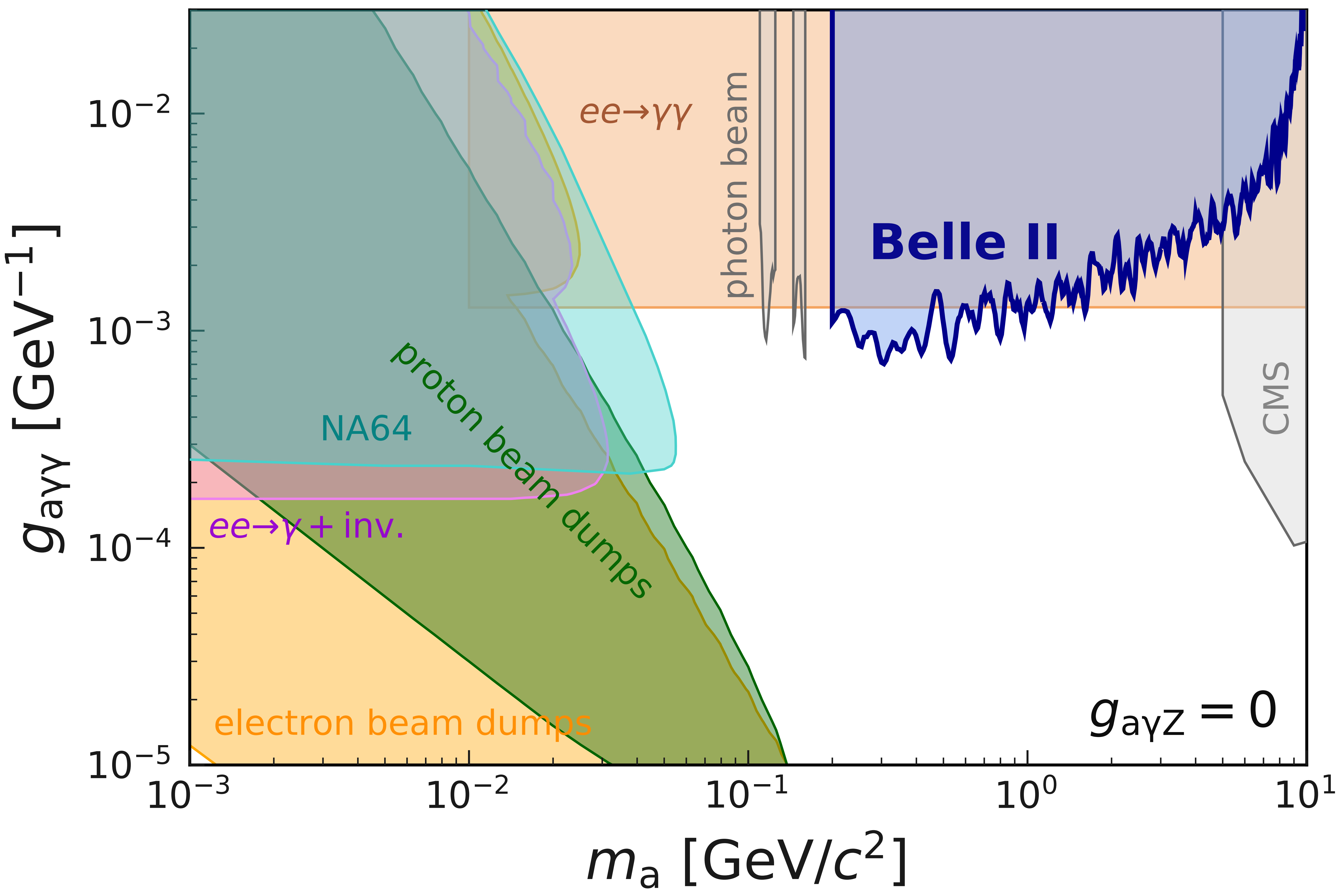
Belle II collaboration, "Search for Axion-Like Particles produced in e^+e^- collisions at Belle II", Phys. Rev. Lett. 125, 161806 (2020)

ALPs at Belle II



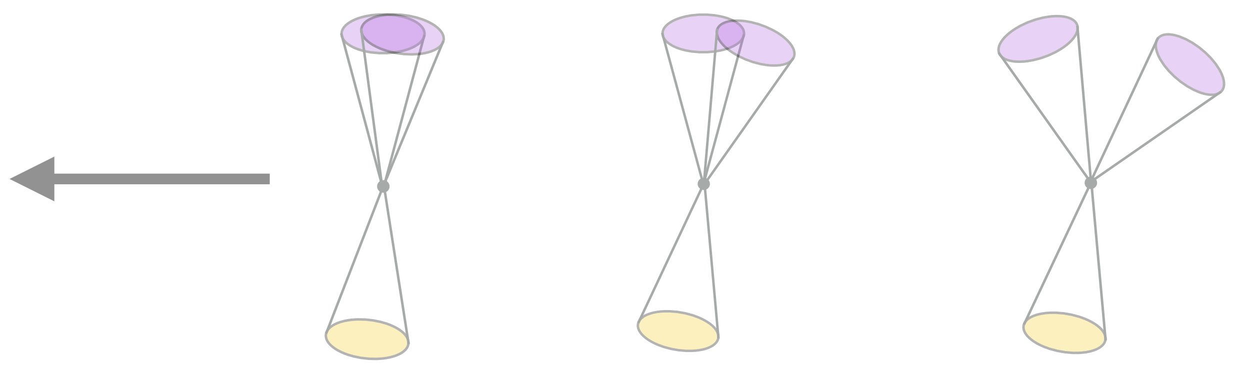
Belle II collaboration, "Search for Axion-Like Particles produced in e⁺e⁻ collisions at Belle II", Phys. Rev. Lett. 125, 161806 (2020)

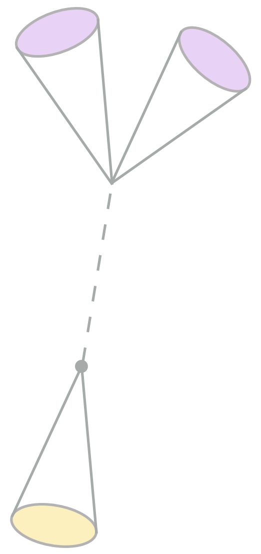
ALPs at Belle II



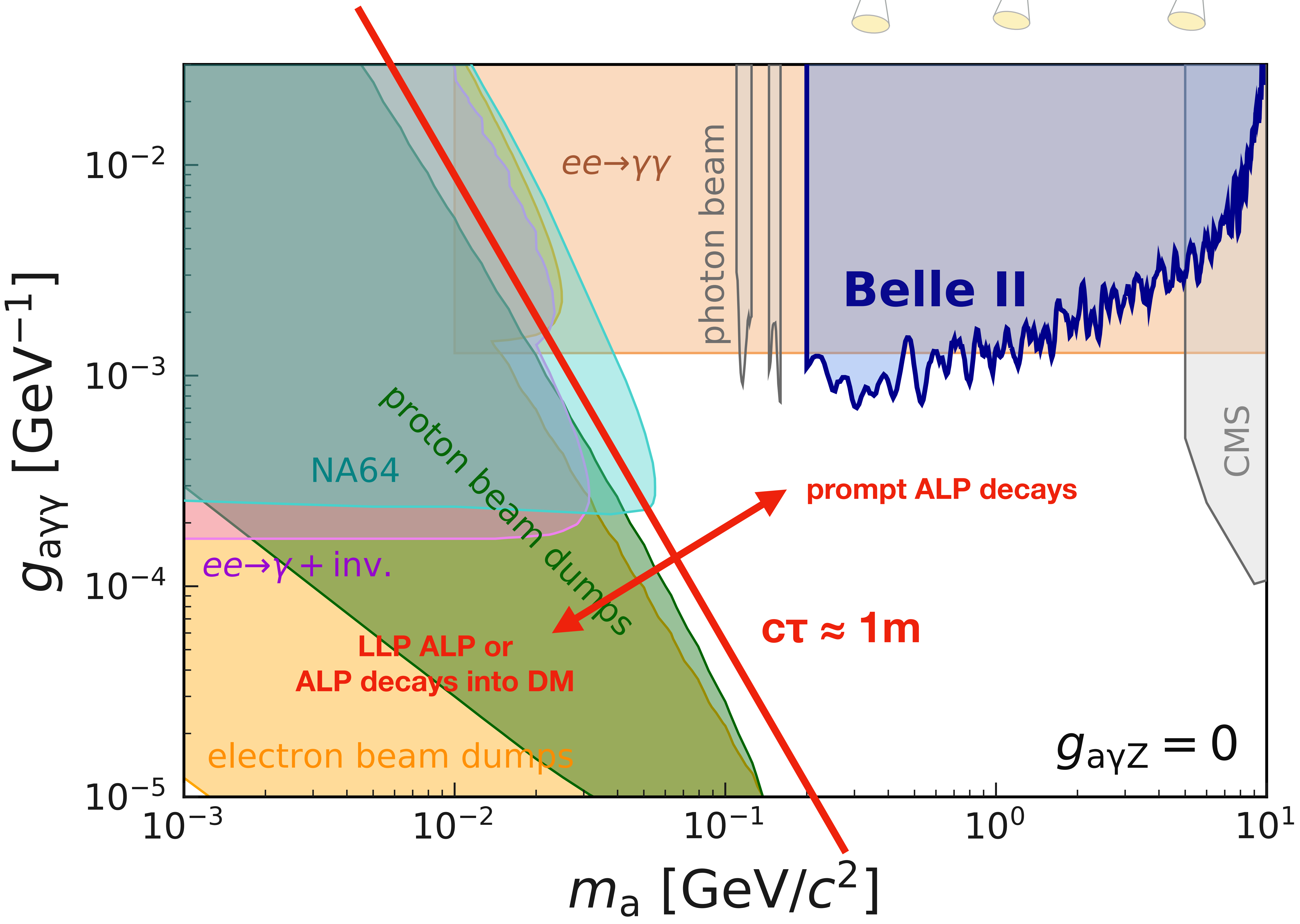
Belle II collaboration, "Search for Axion-Like Particles produced in e+e- collisions at Belle II", Phys. Rev. Lett. 125, 161806 (2020)

ALPs at Belle II

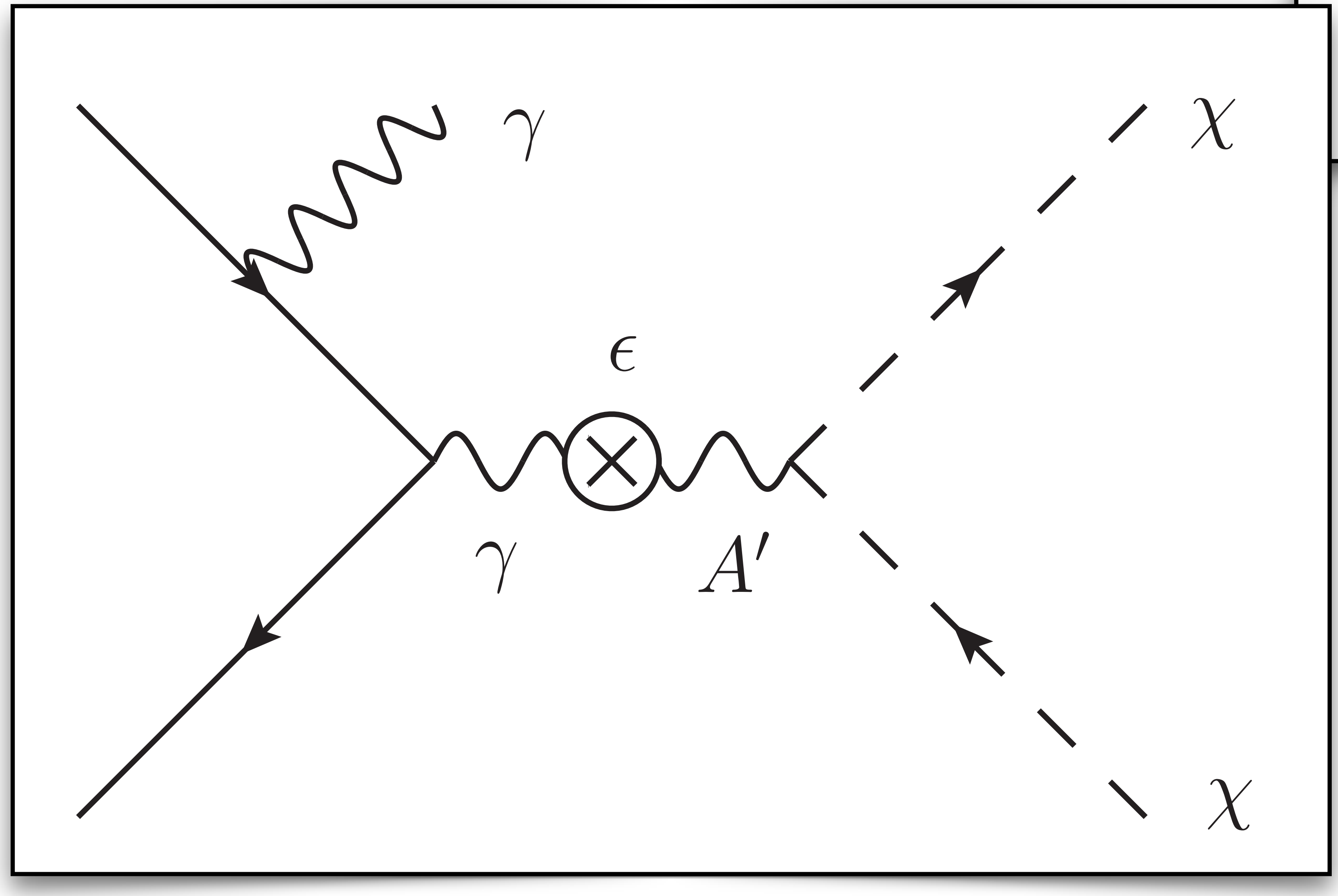


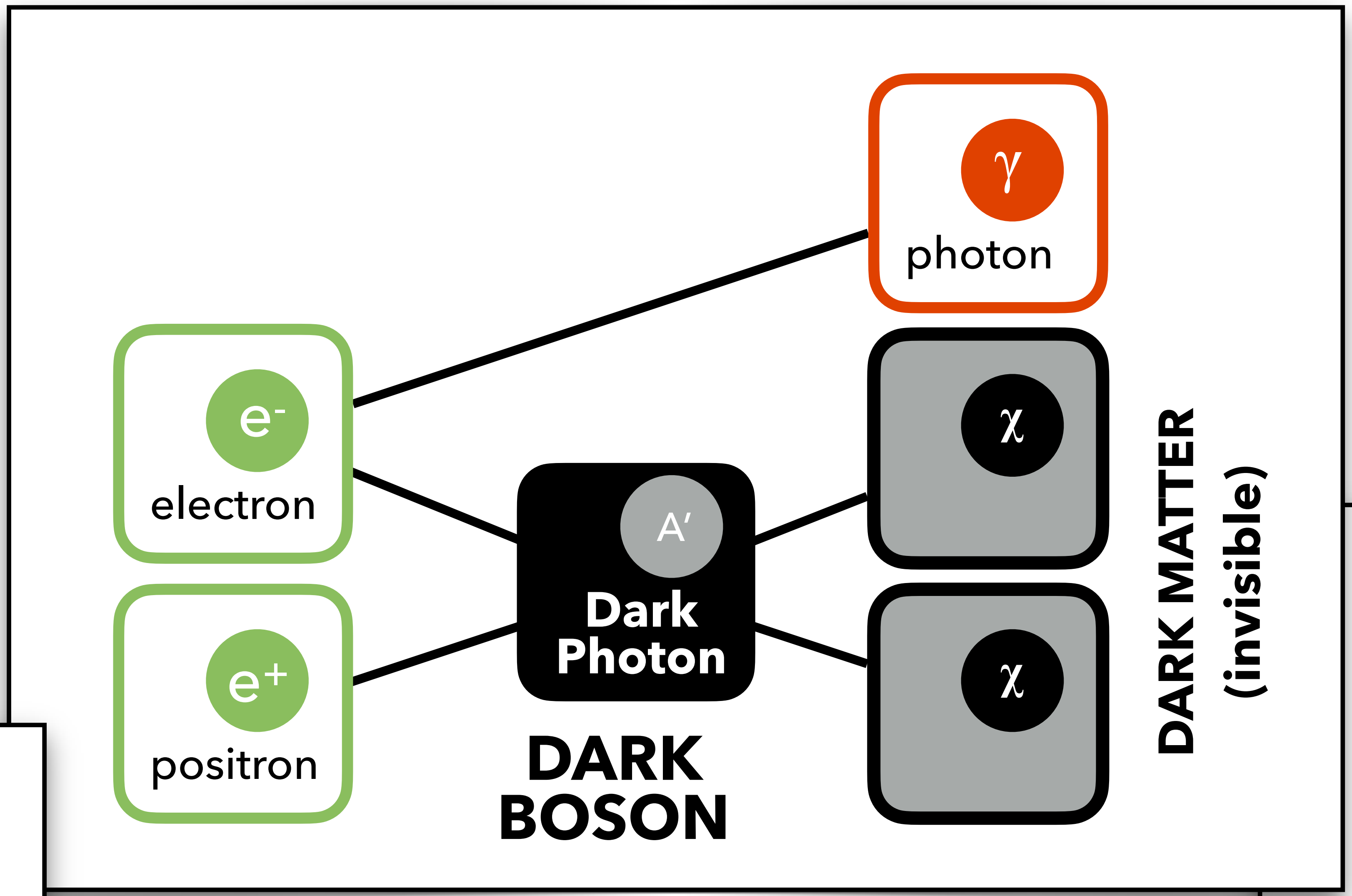


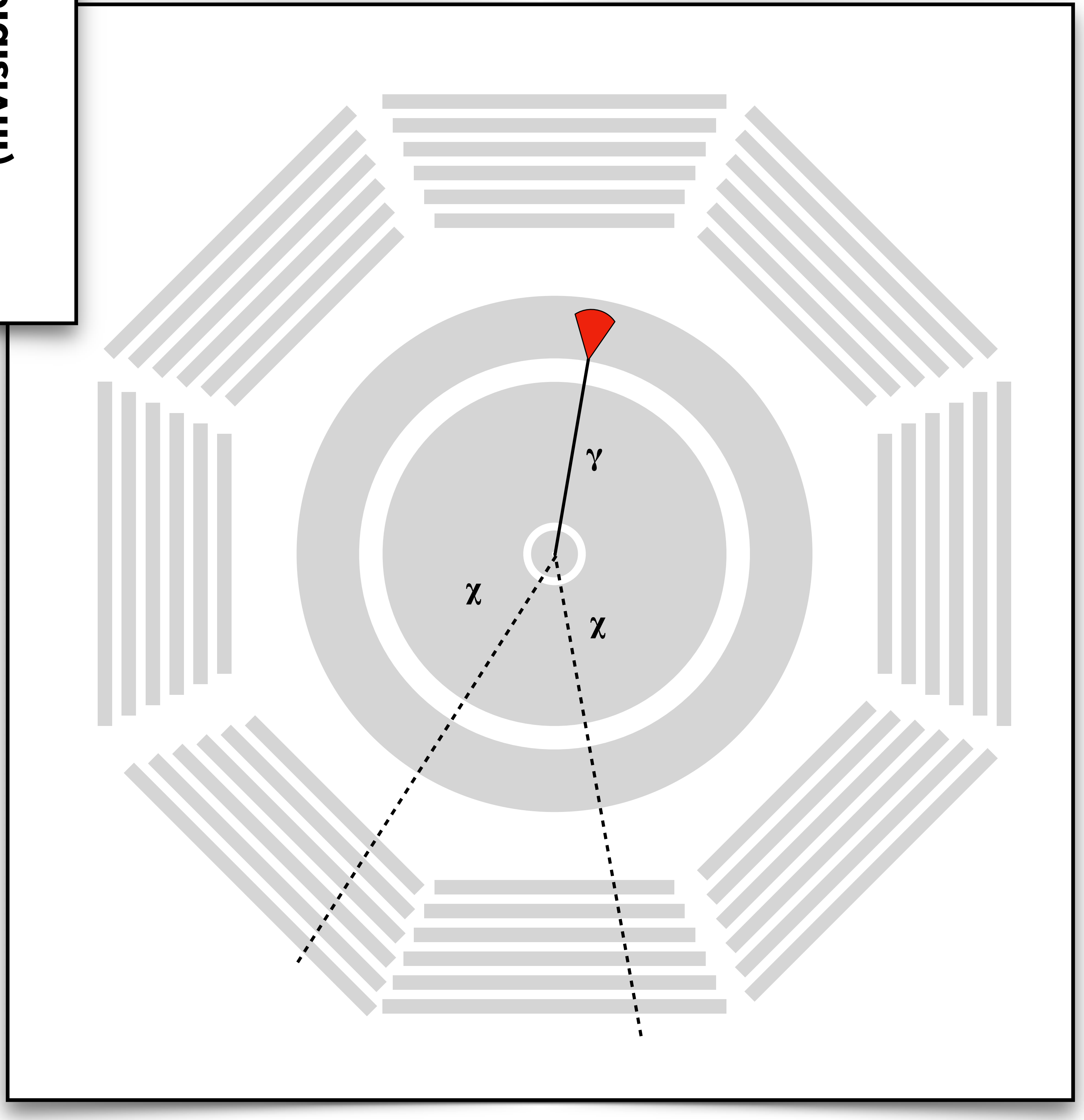
single photon final state (ALP decay outside of Belle II)



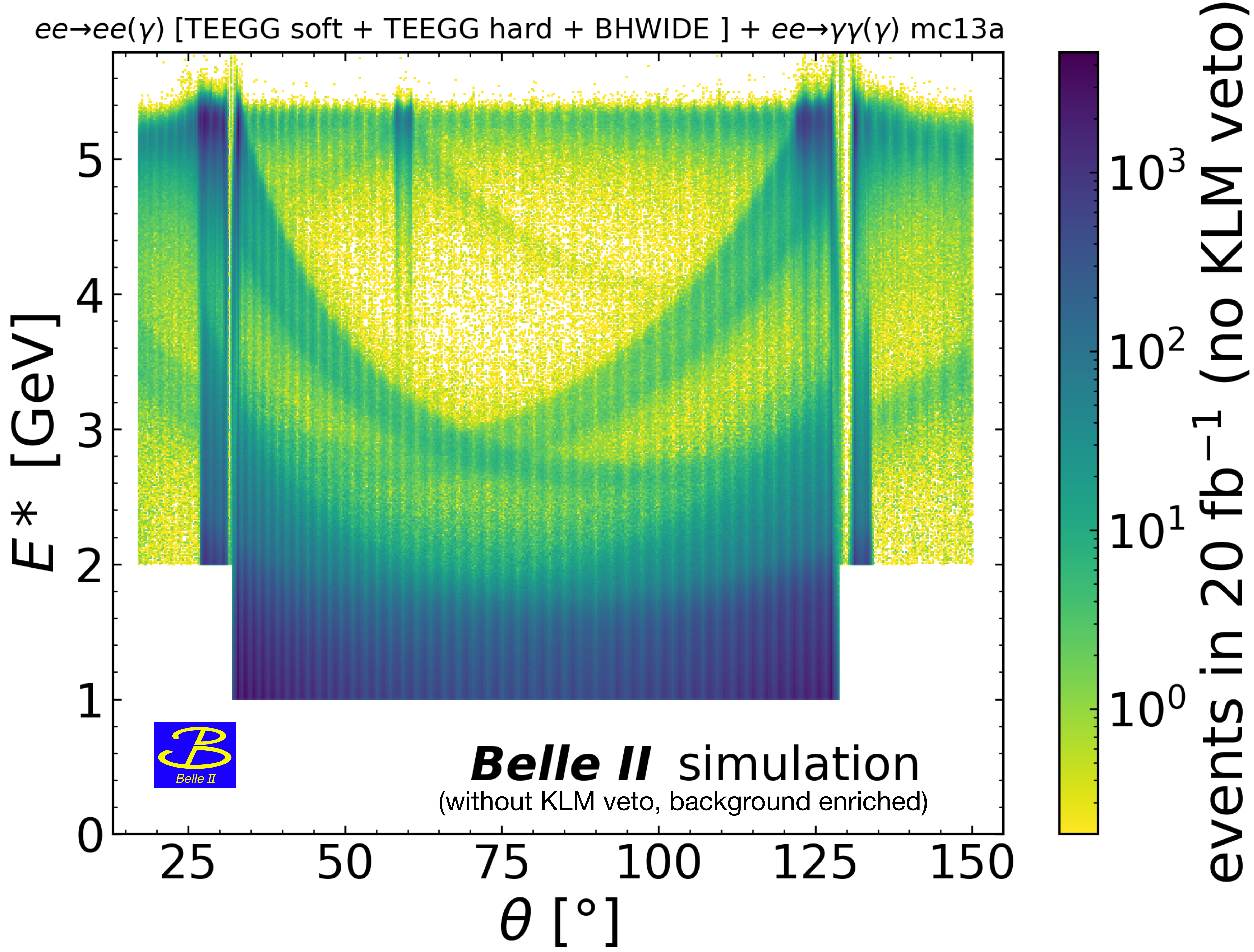
Invisible Dark Photon (A') decays





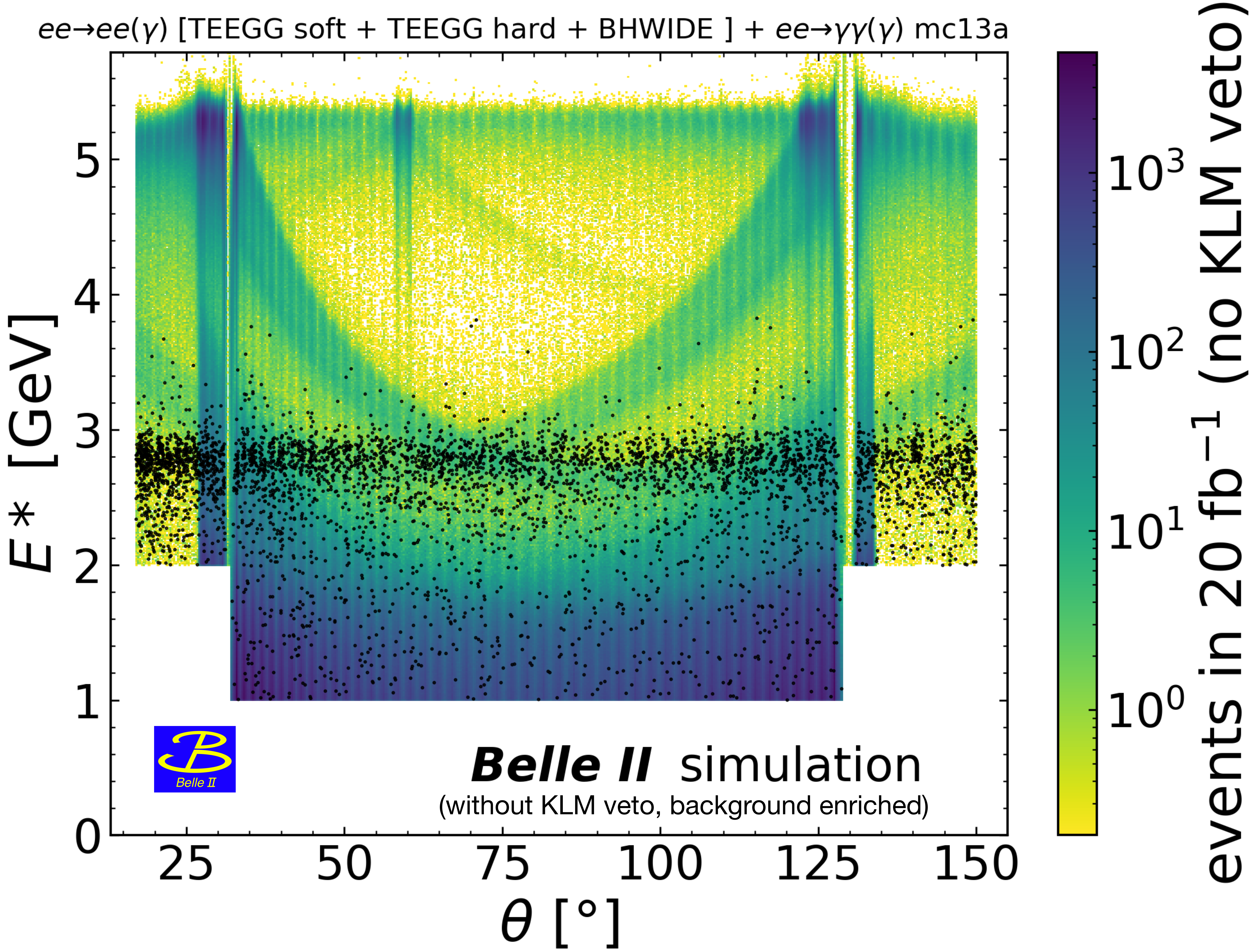


A'→invisible at Belle II

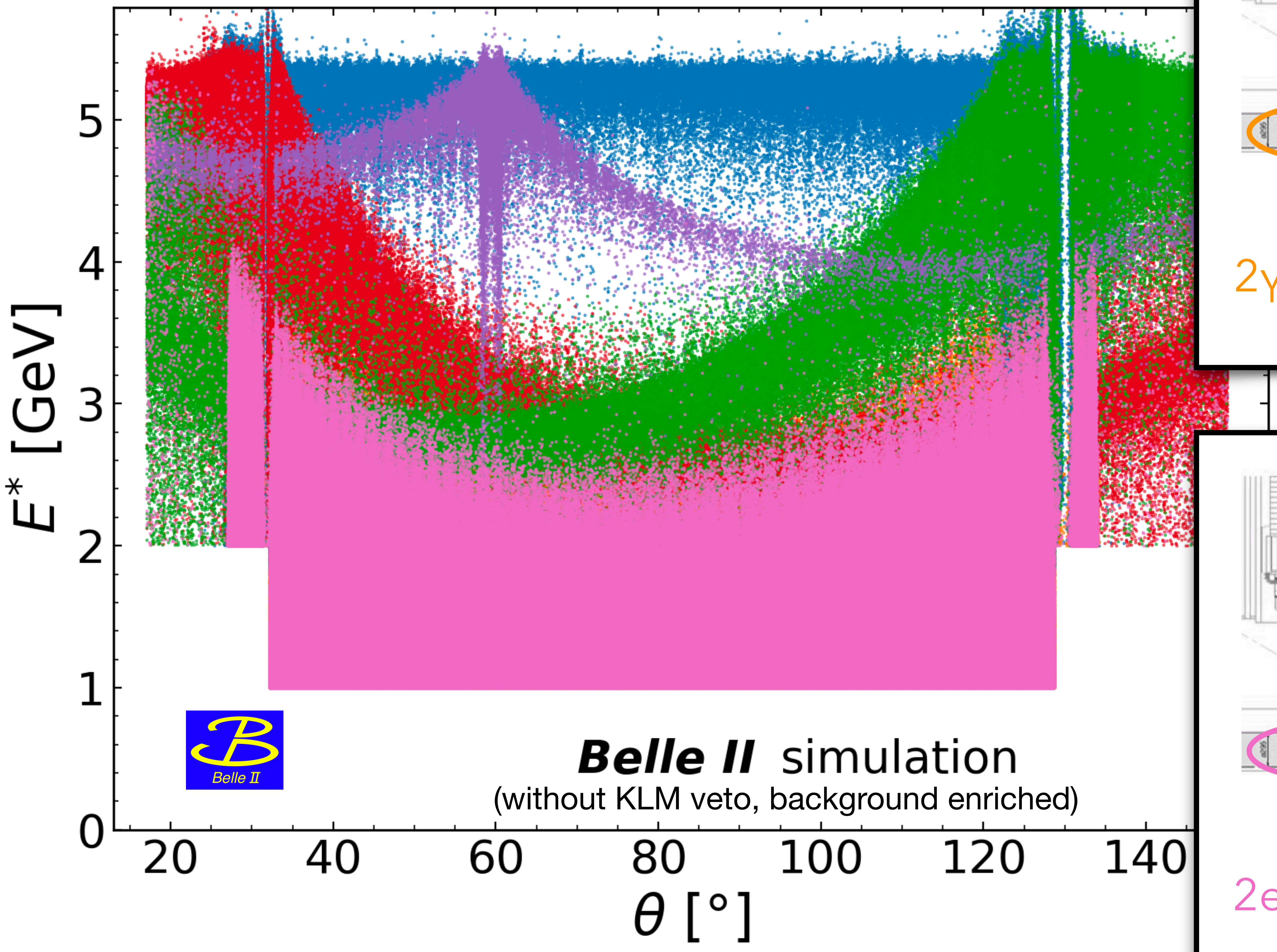


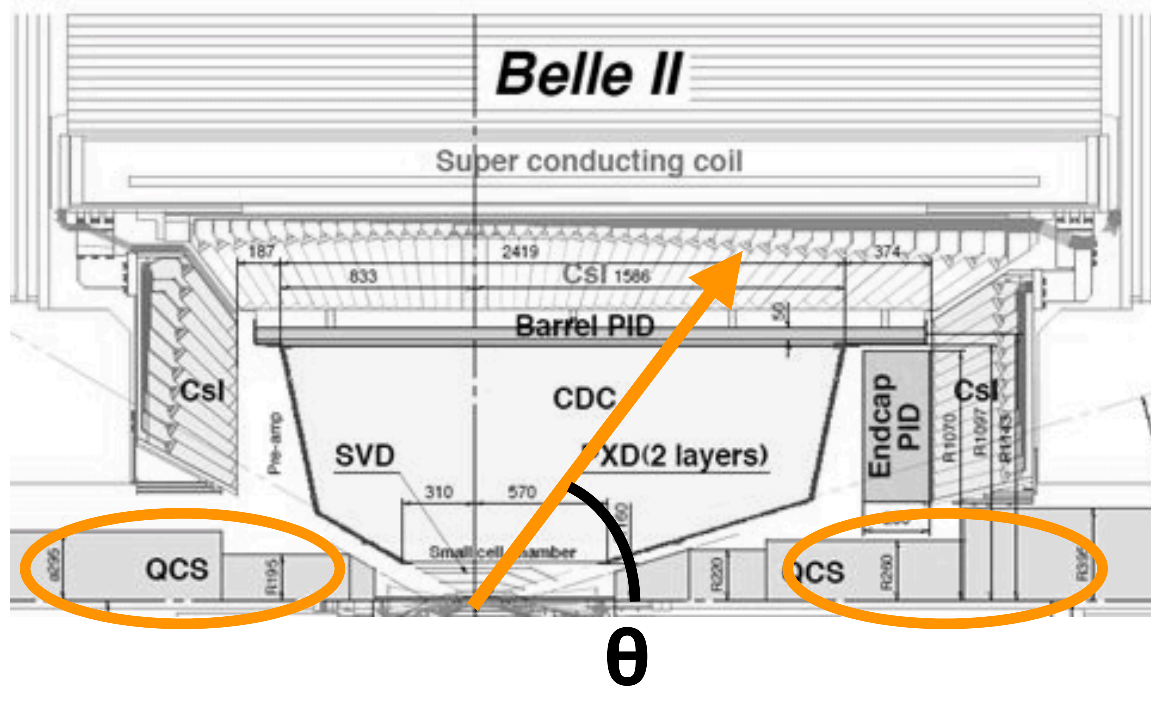
A'→invisible at Belle II

Simulated signal m=7.2 GeV/c²

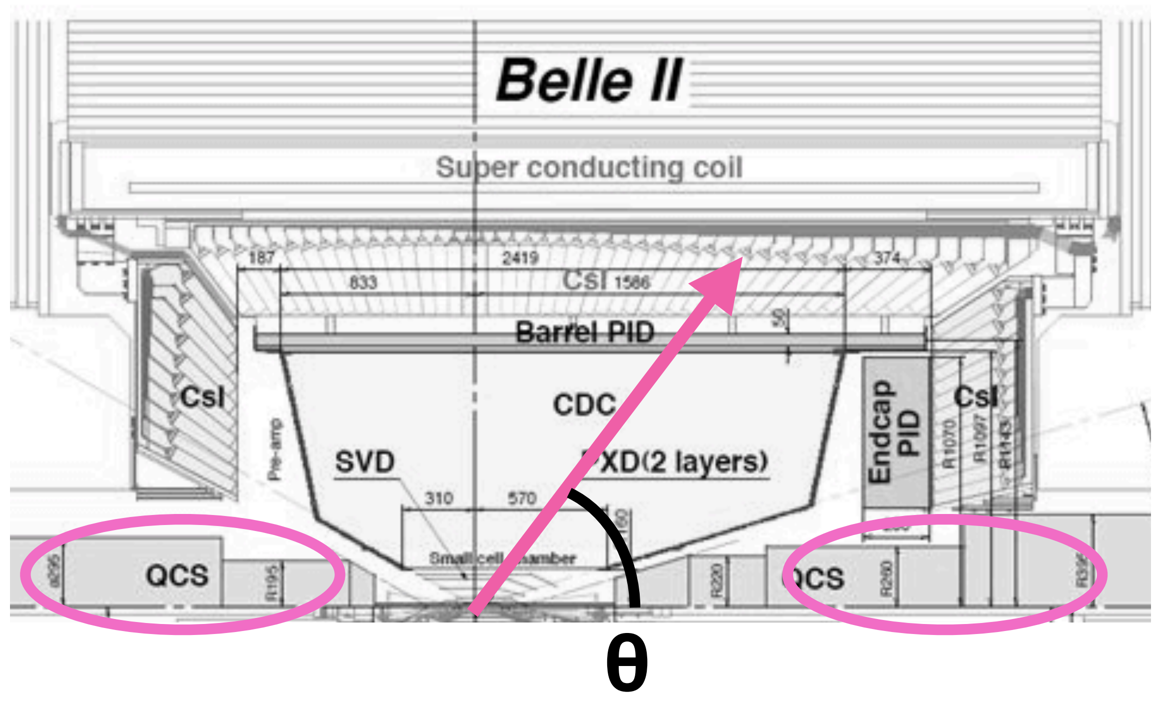


A'→invisible at Belle II



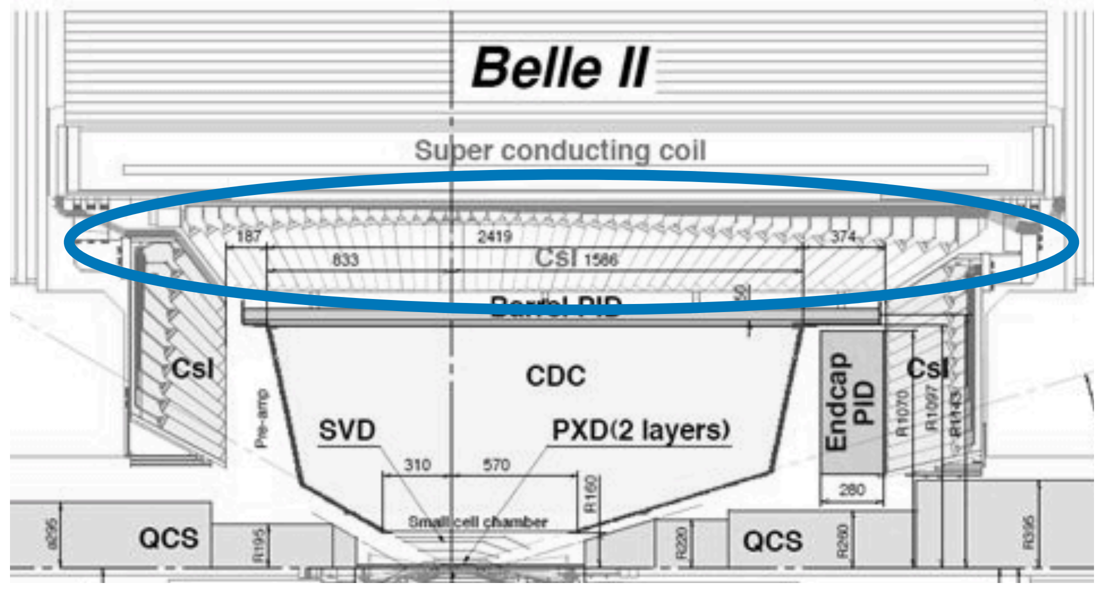


ee→γγγ
2γ out of ECL acceptance

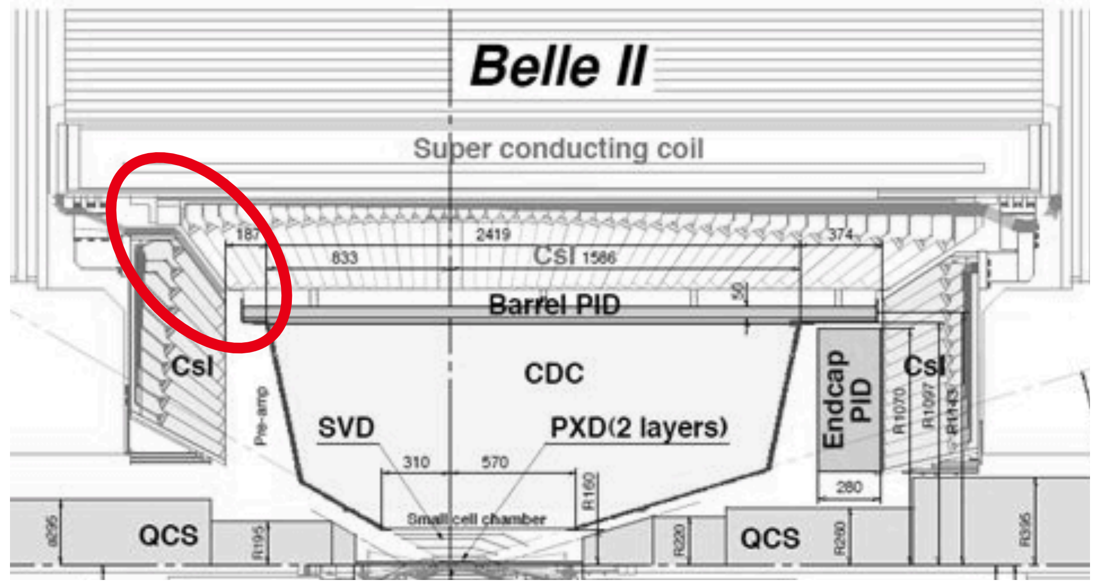


ee→eeγ
2e out of ECL acceptance

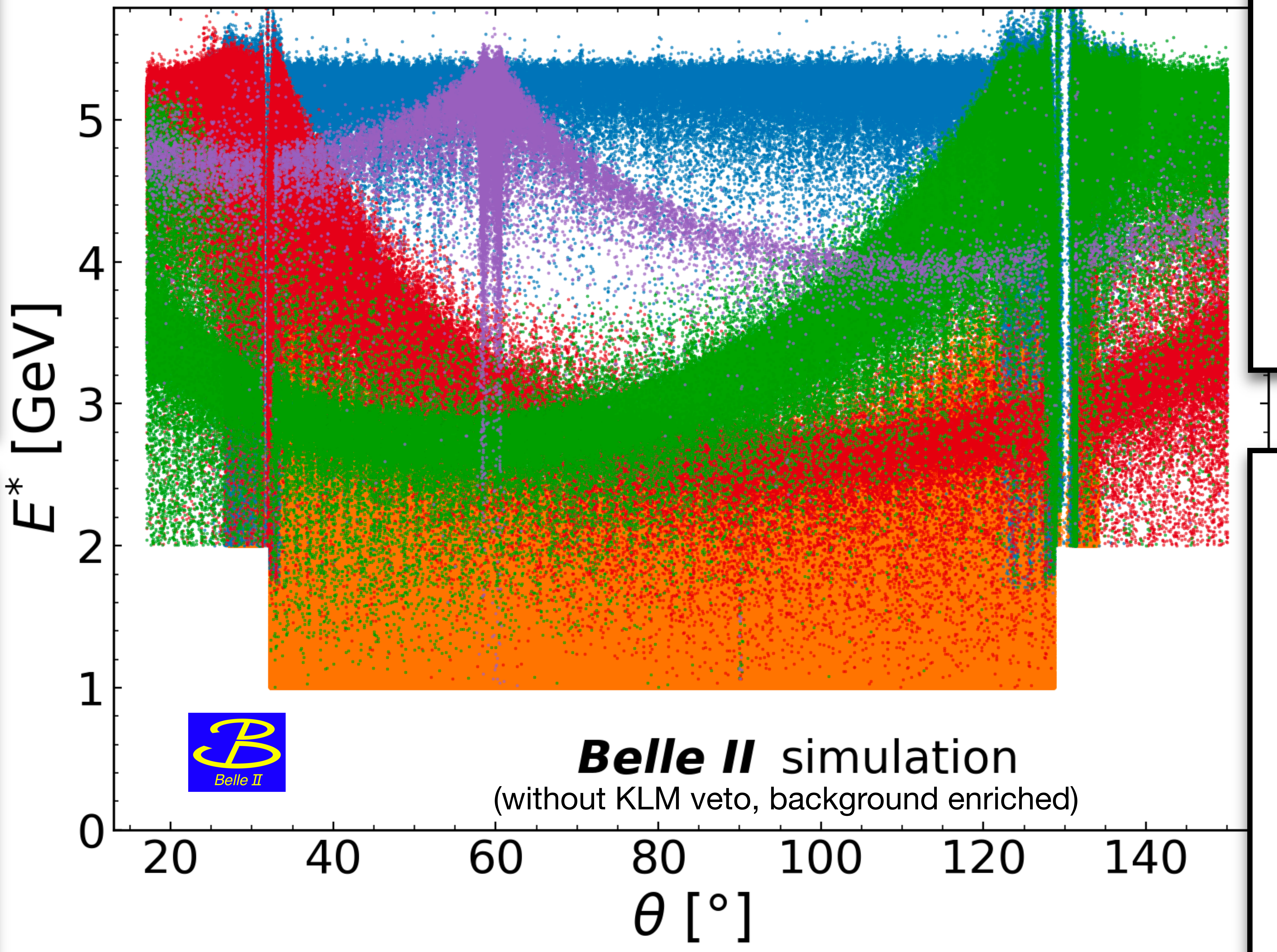
A'→invisible at Belle II

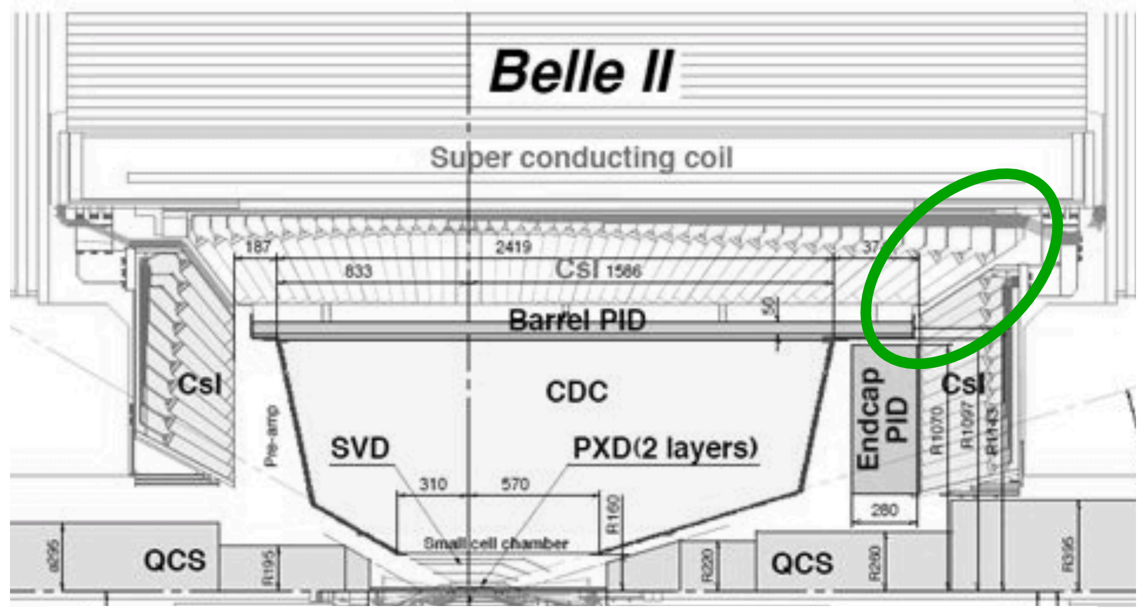


ee→2γ
1γ "punchthrough"

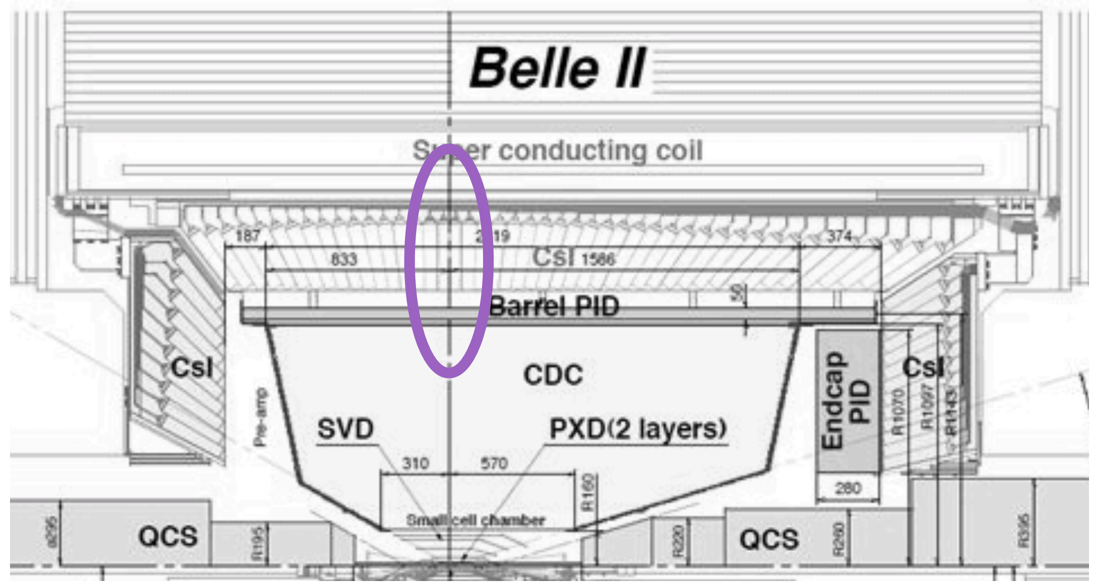


ee→2γ and 3γ
1γ in ECL BWD gap
(1γ out of ECL acceptance)





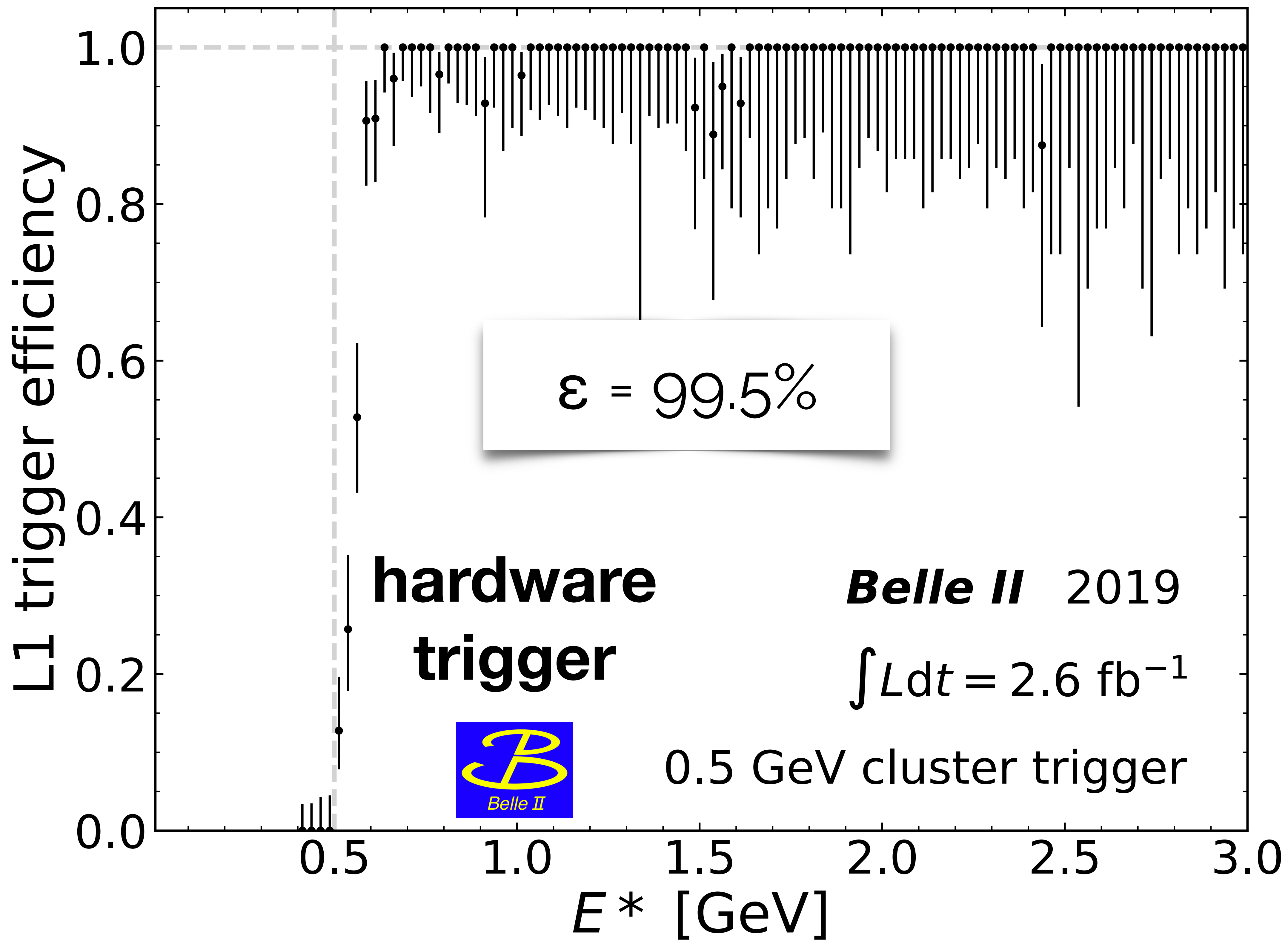
ee→2γ and 3γ
1γ in ECL FWD gap
(1γ out of ECL)acceptance

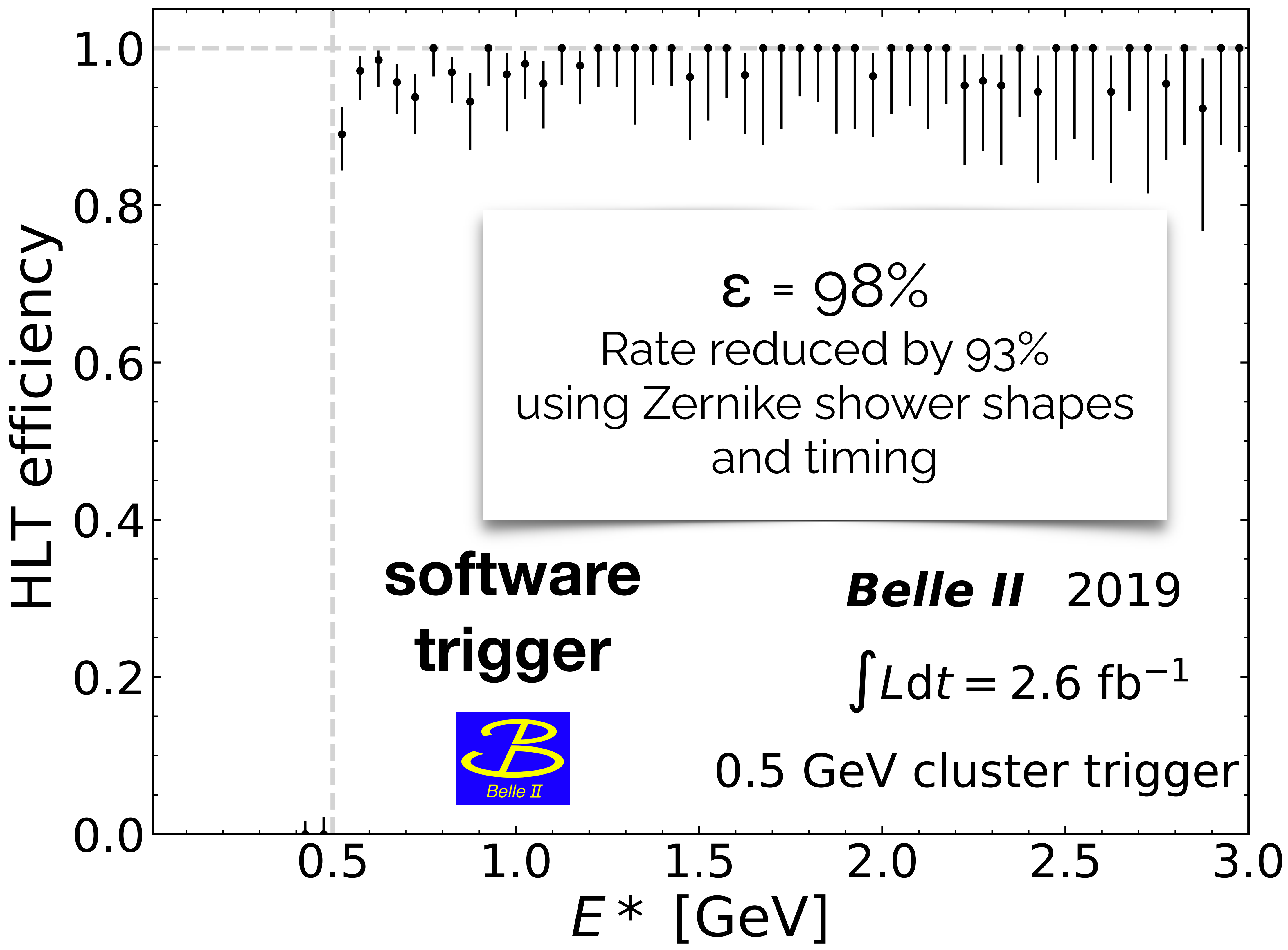


ee→2γ and 3γ
1γ in ECL 90° gap
(1γ out of ECL acceptance)

BaBar collaboration, "Trigger efficiencies for single photon events", BELLE-NOTE-PL-2020-0 (2020)

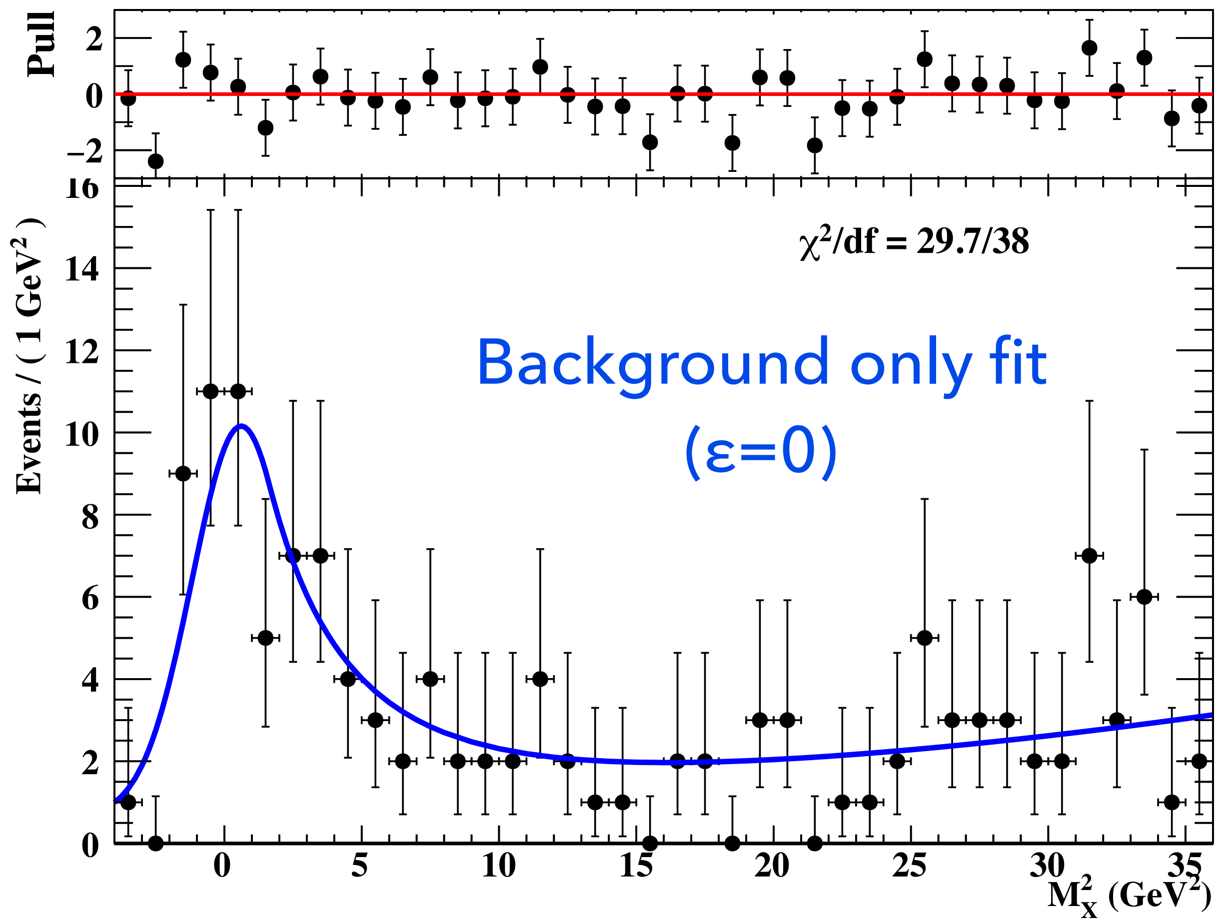
A'→invisible at Belle II: Triggers

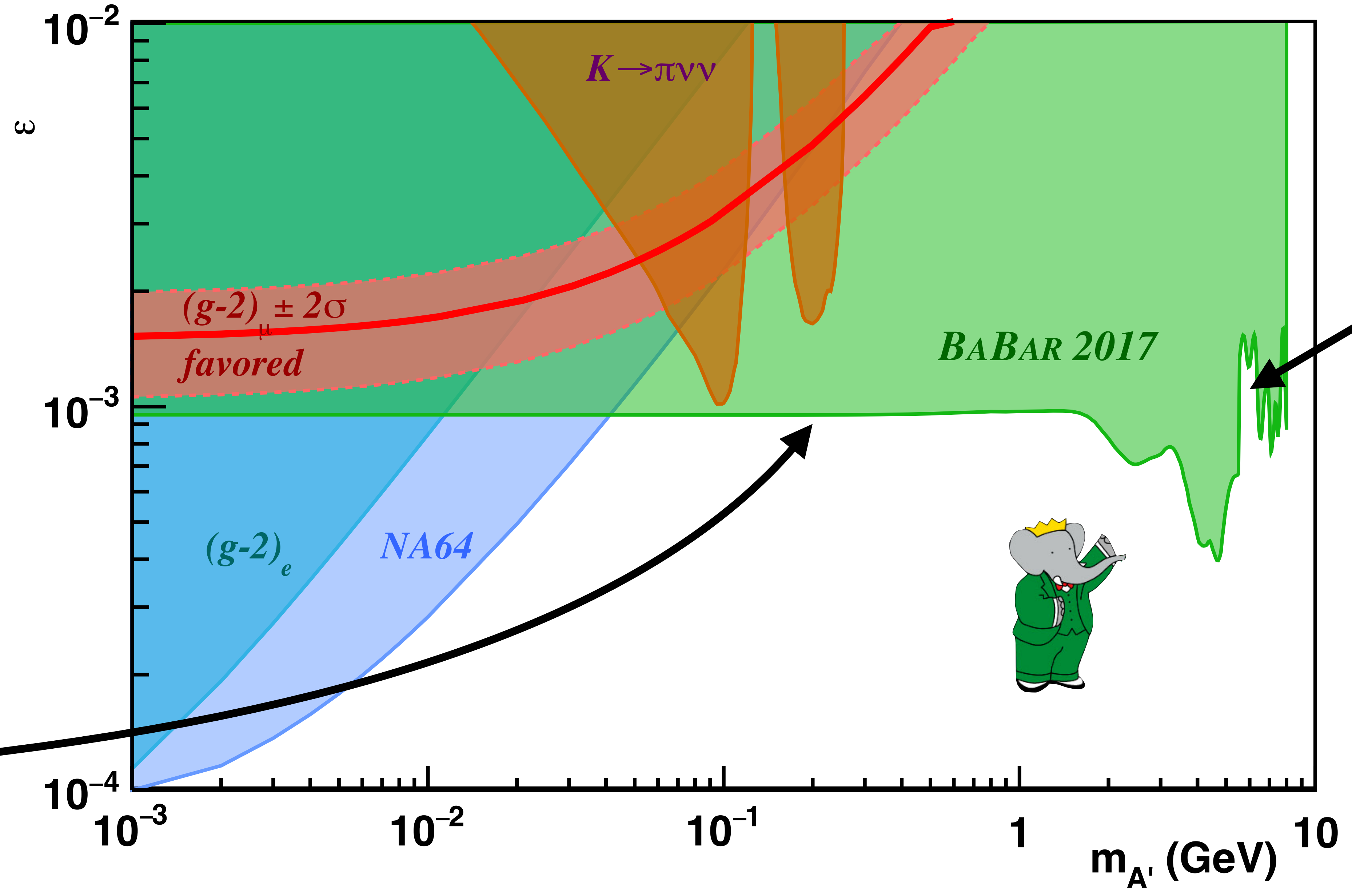


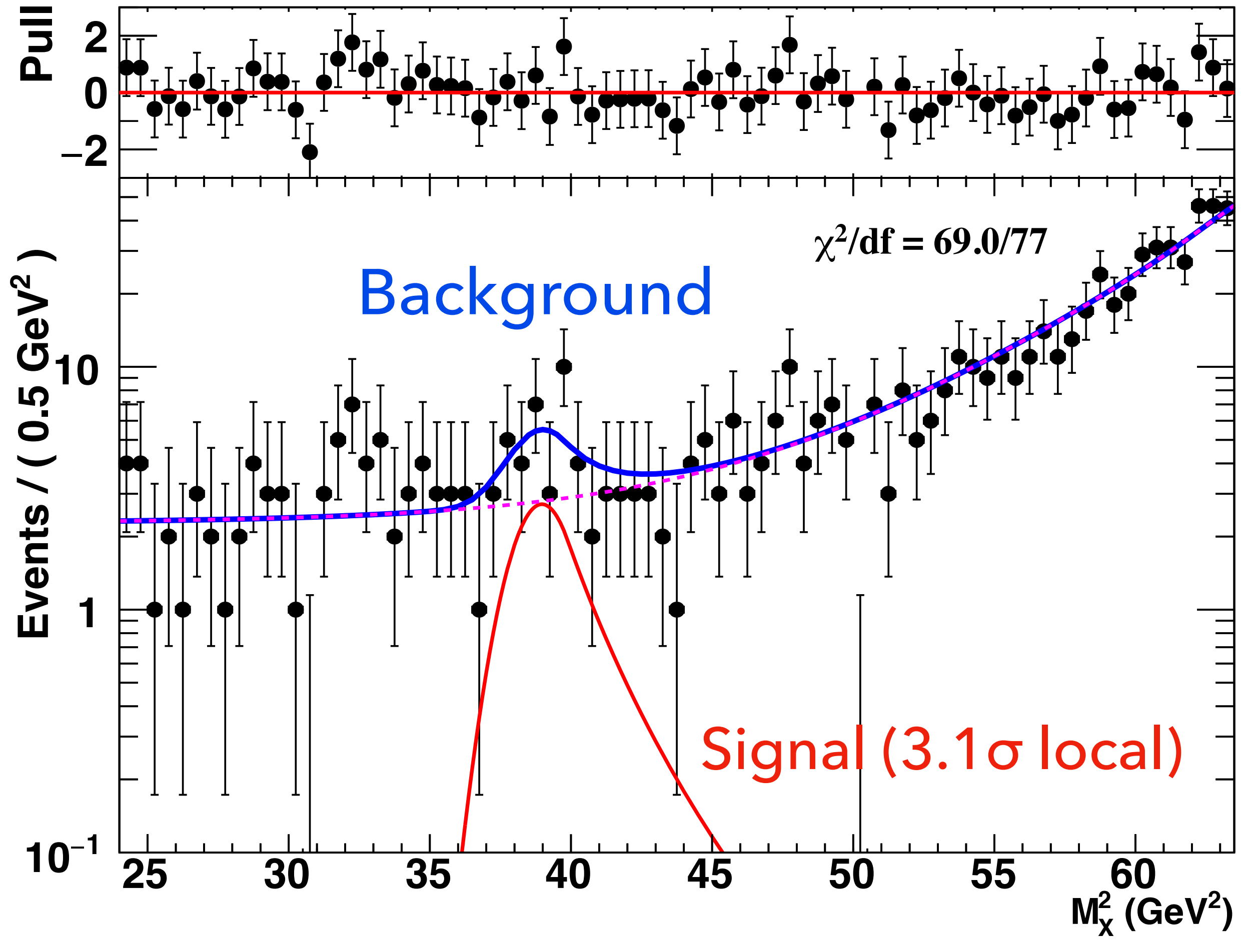


BaBar collaboration, "Search for Invisible Decays of a Dark Photon Produced in e+e- Collisions at BaBar", Phys. Rev. Lett. 119, 131804 (2017)

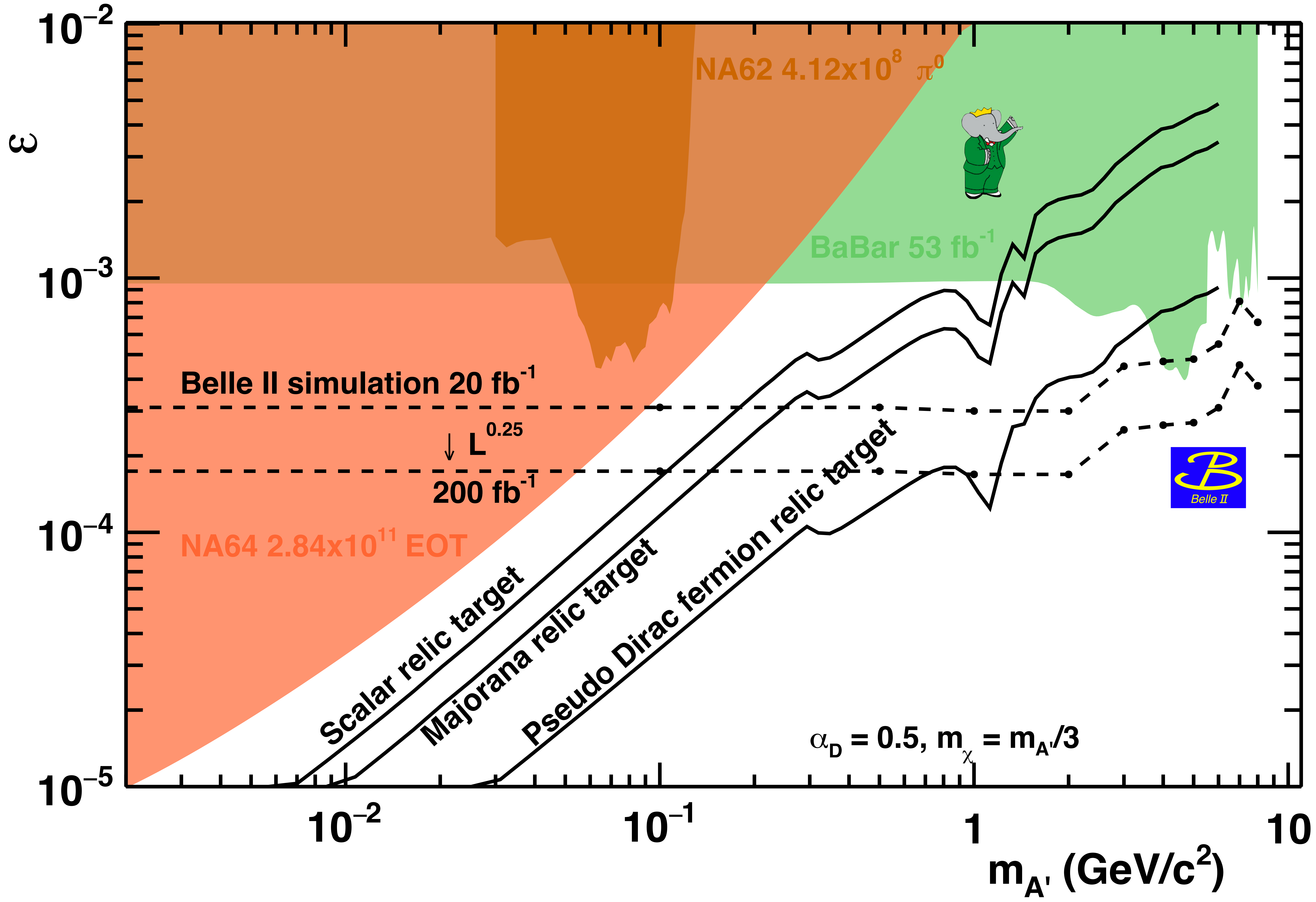
A'→invisible at BaBar



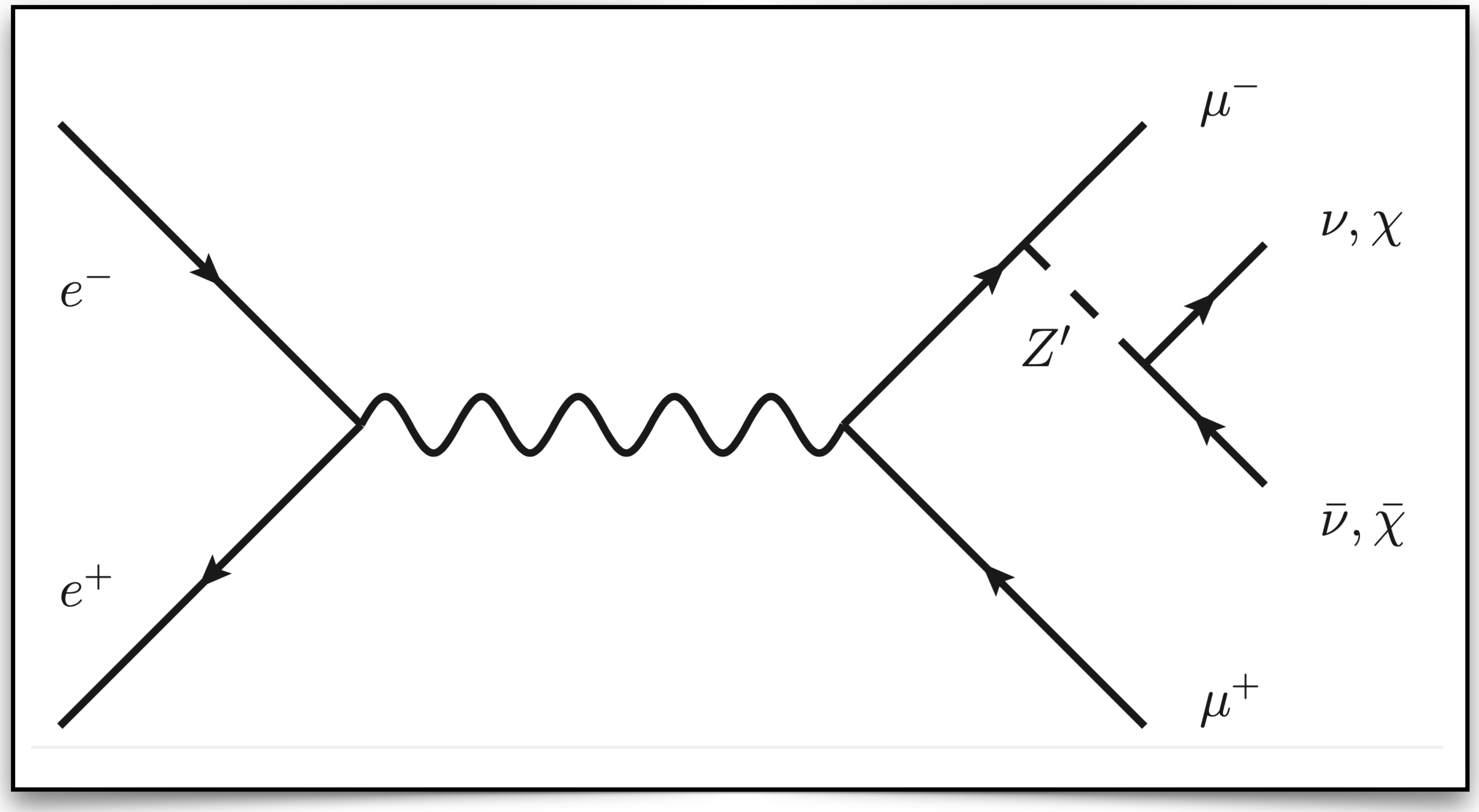


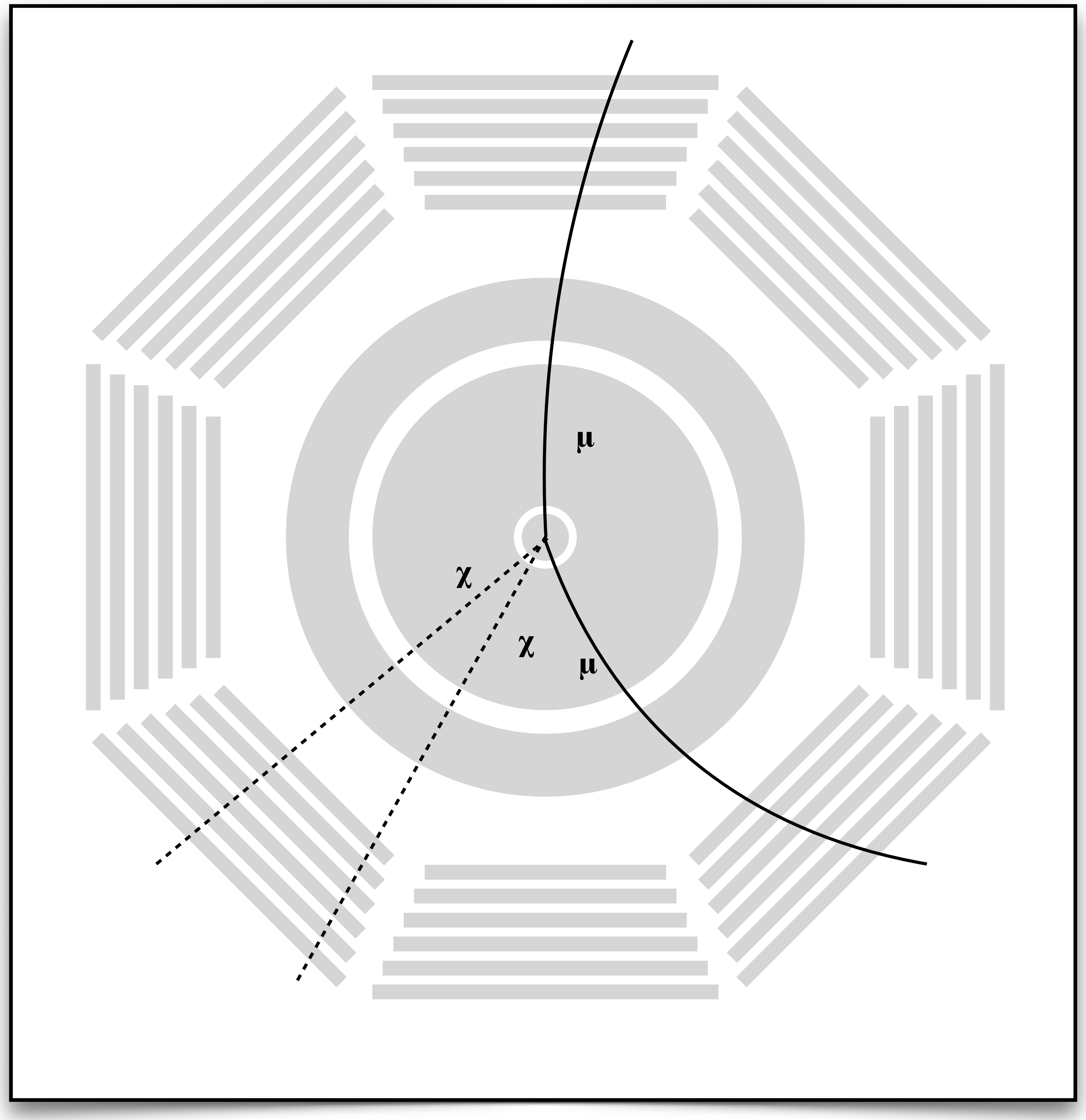


A'→invisible at Belle II: Sensitivity



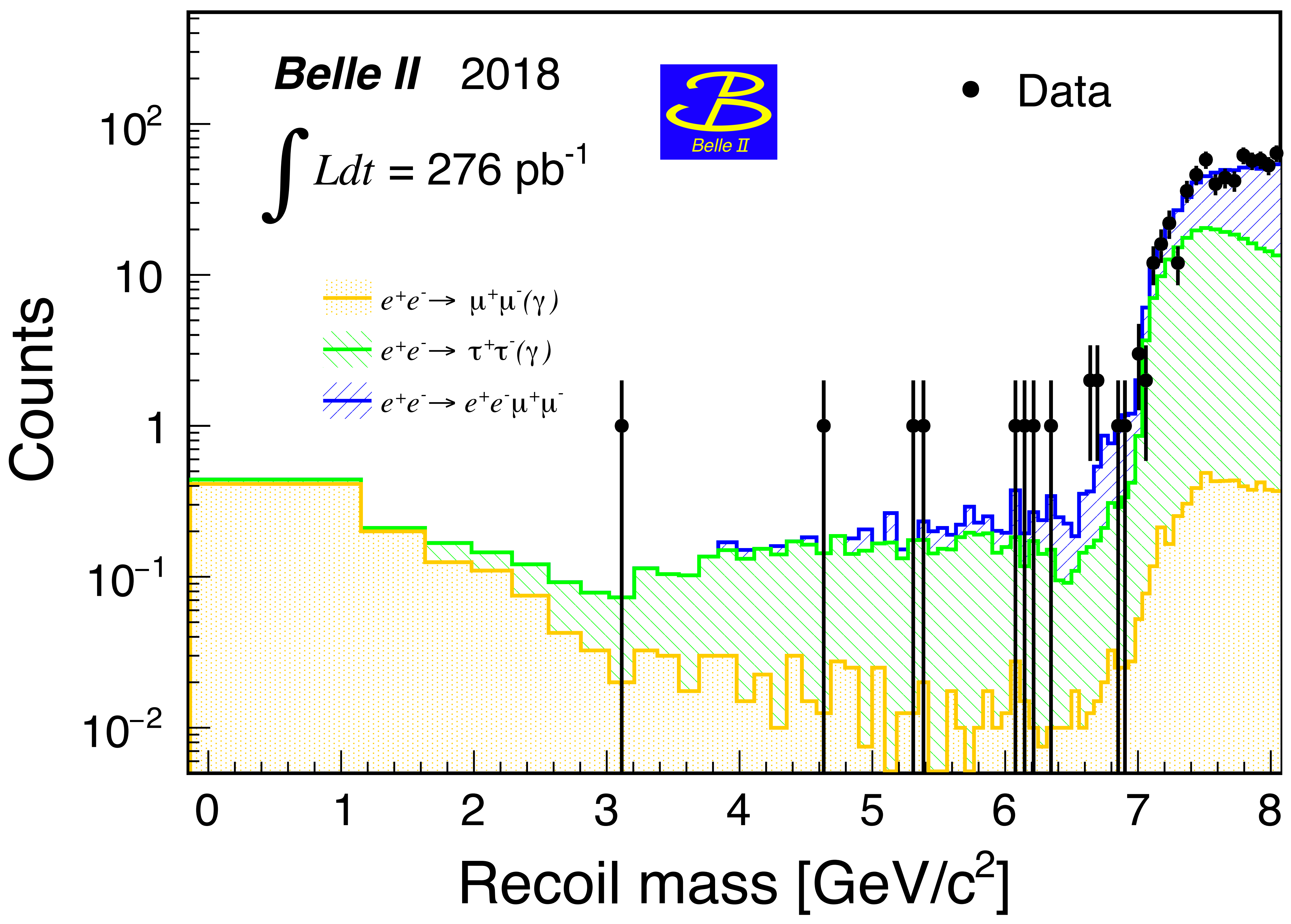
Invisible Z' decays

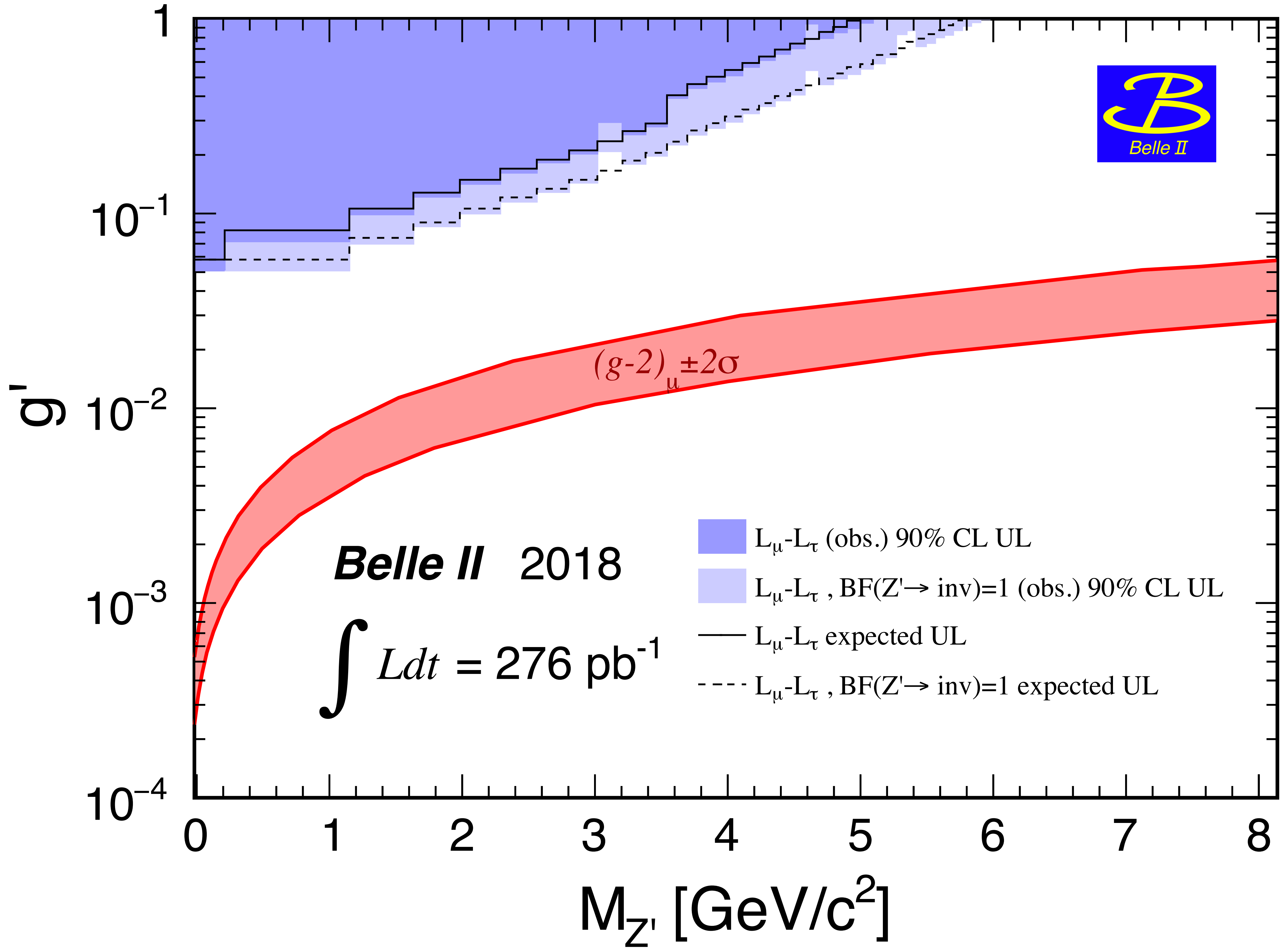




Belle II collaboration, "Search for an invisibly decaying Z' boson at Belle II in $e^+e^- \to \mu^+\mu^-$ ($e^\pm\mu^\mp$) plus missing energy final states", Phys. Rev. Lett. 124, 141801 (2020)

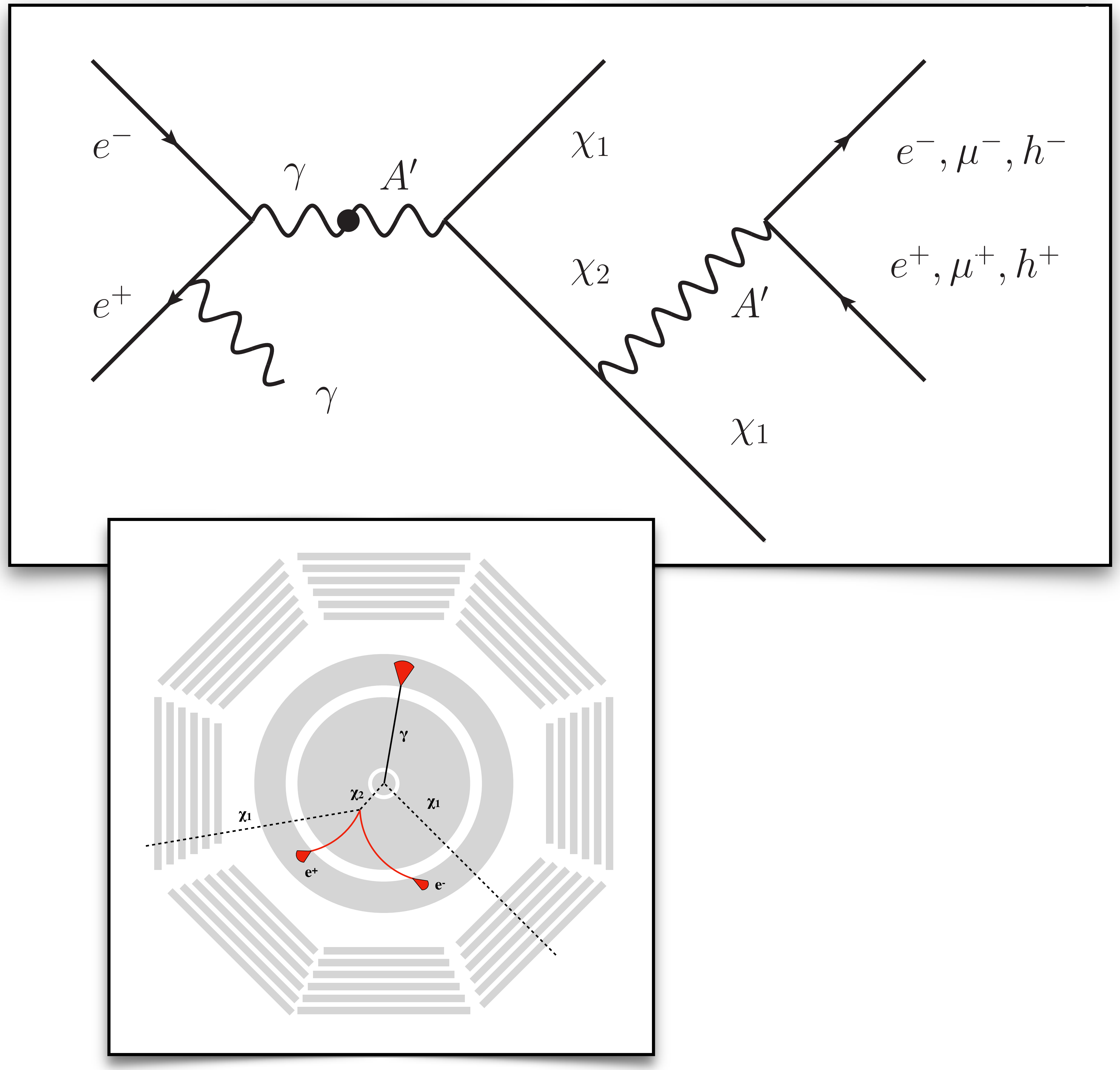
Z'→invisible at Belle II



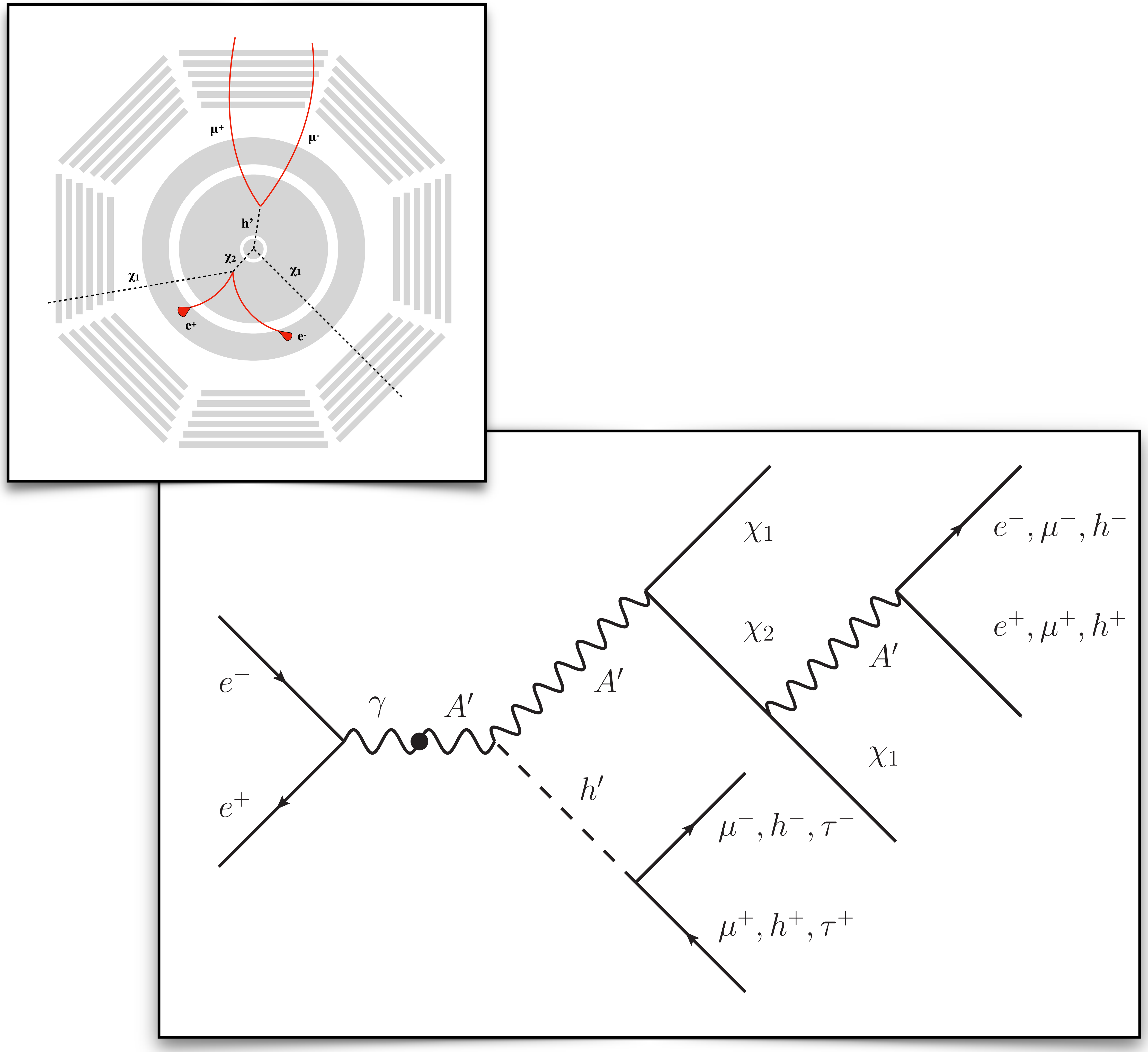


Long-lived particles

M. Duerr, **TF**, C. Garcia-Cely, C. Hearty, K. Schmidt-Hoberg, J. High Energ. Phys. 2021, 146 (2021)

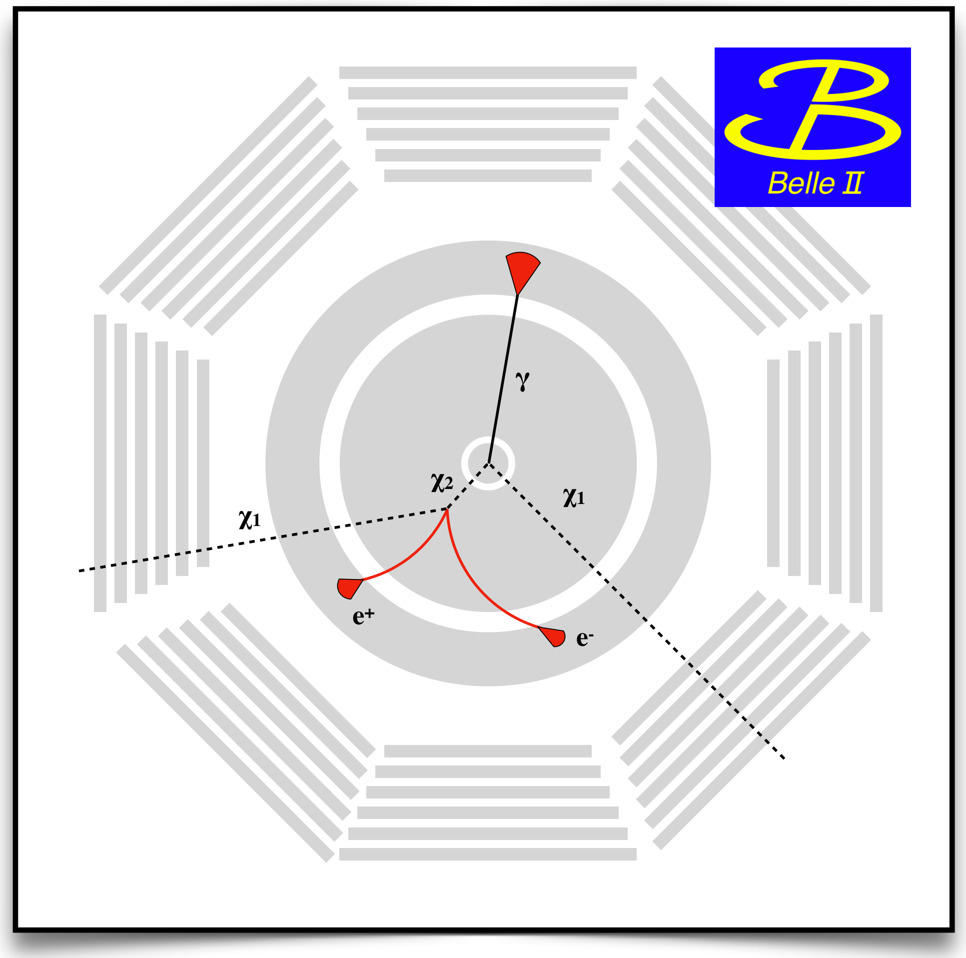


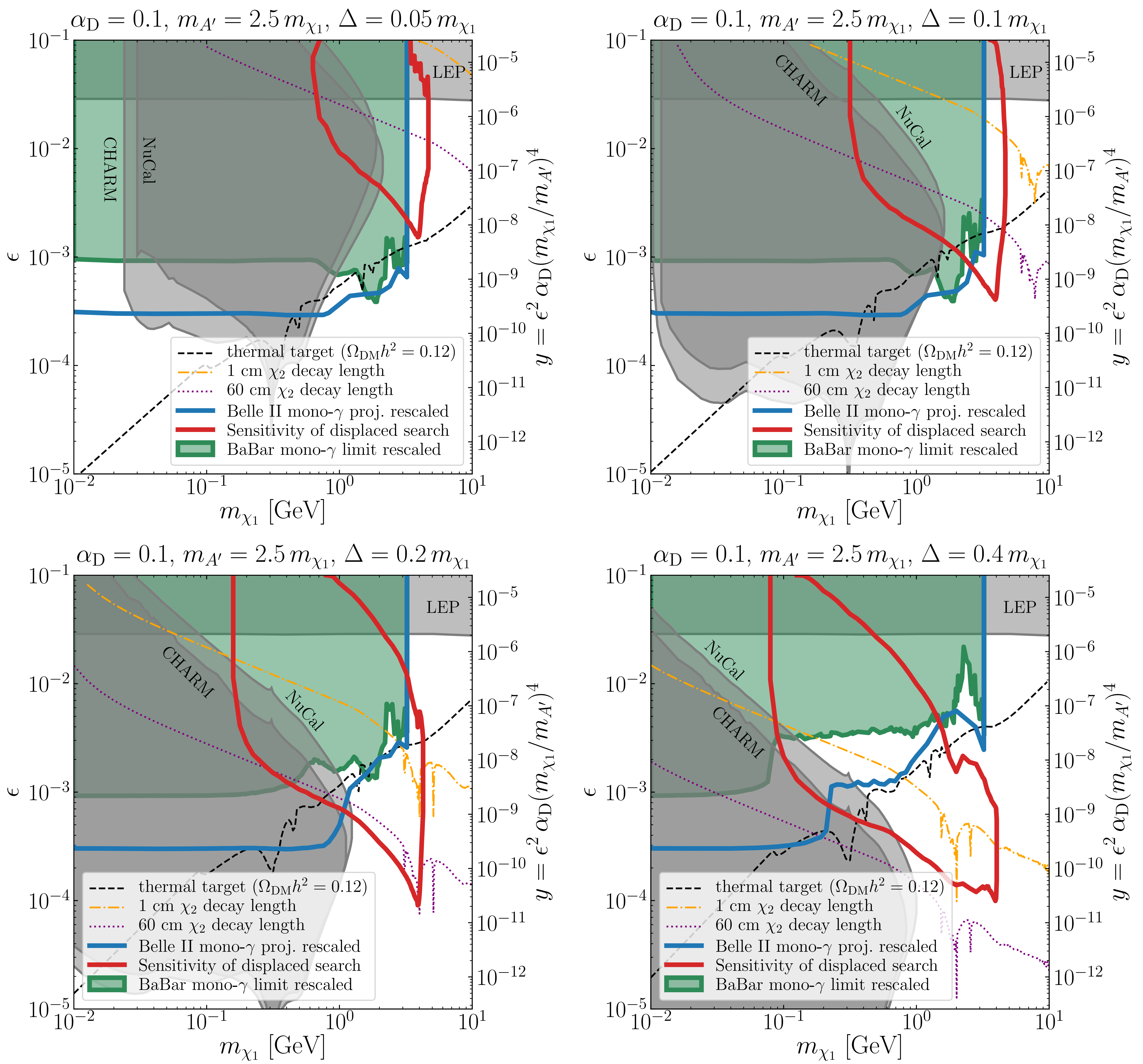
M. Duerr, **TF**, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg, P. Tunney, J. High Energ. Phys. 2020, 39 (2020)

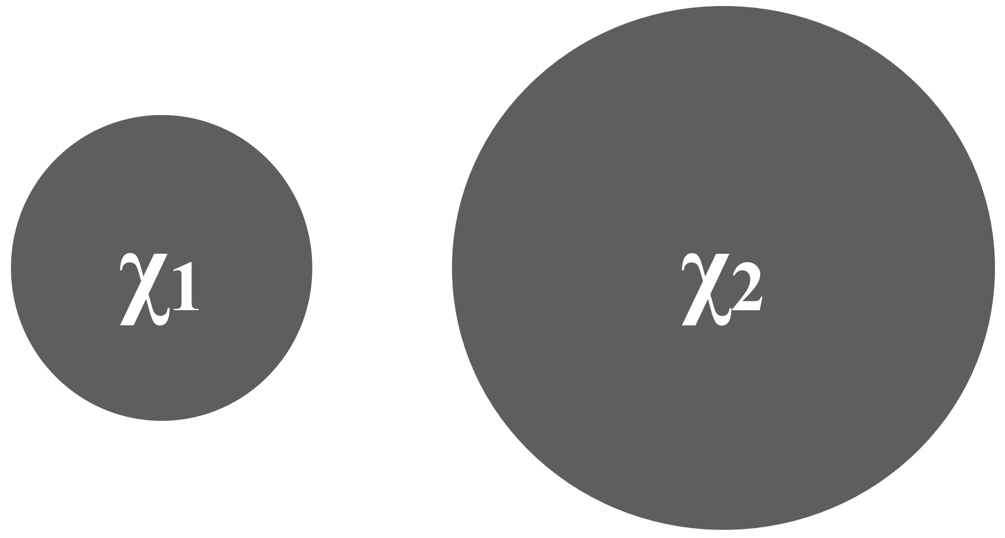


M. Duerr, **TF**, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg, P. Tunney, J. High Energ. Phys. 2020, 39 (2020)

Long-lived particles: Inelastic Dark Matter

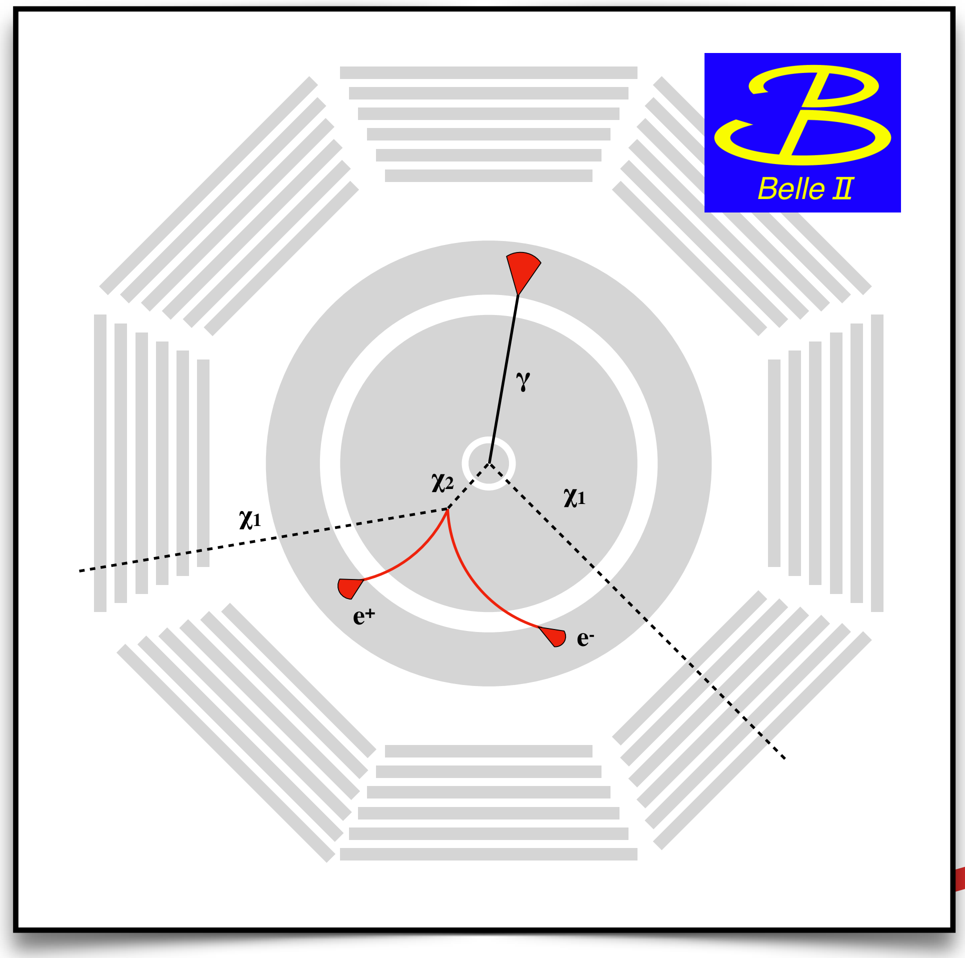


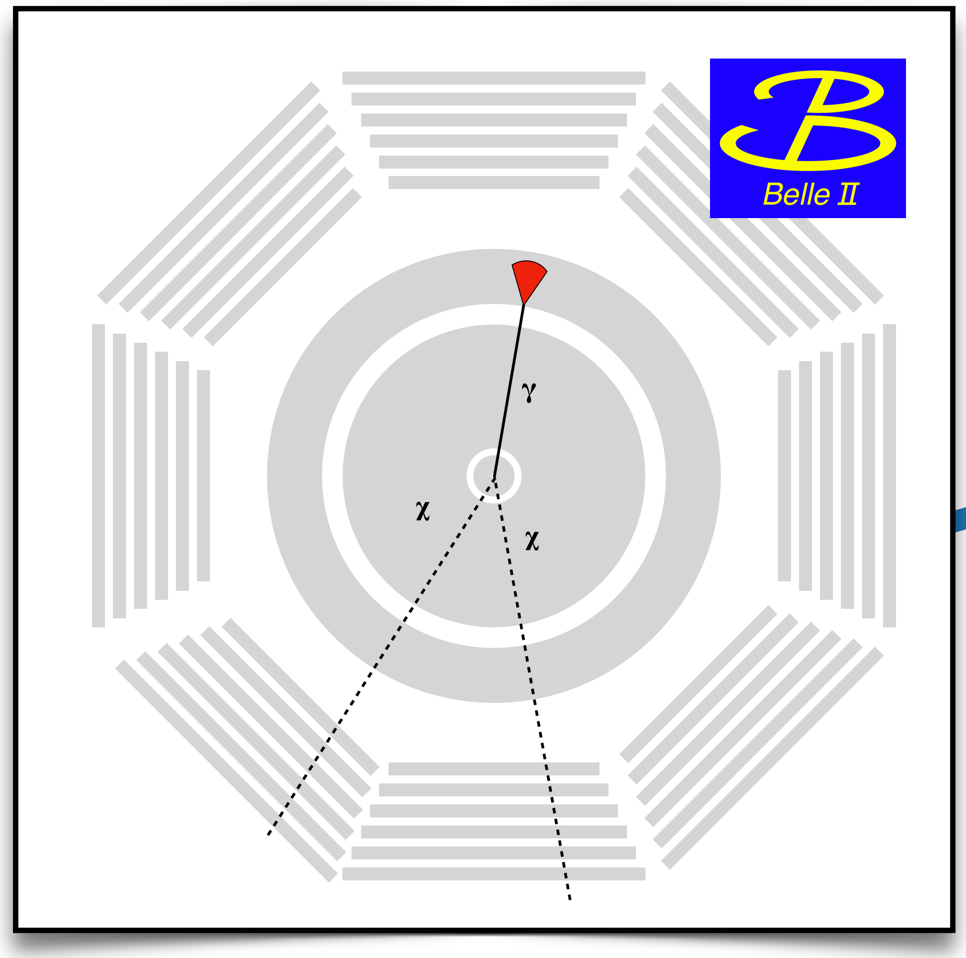


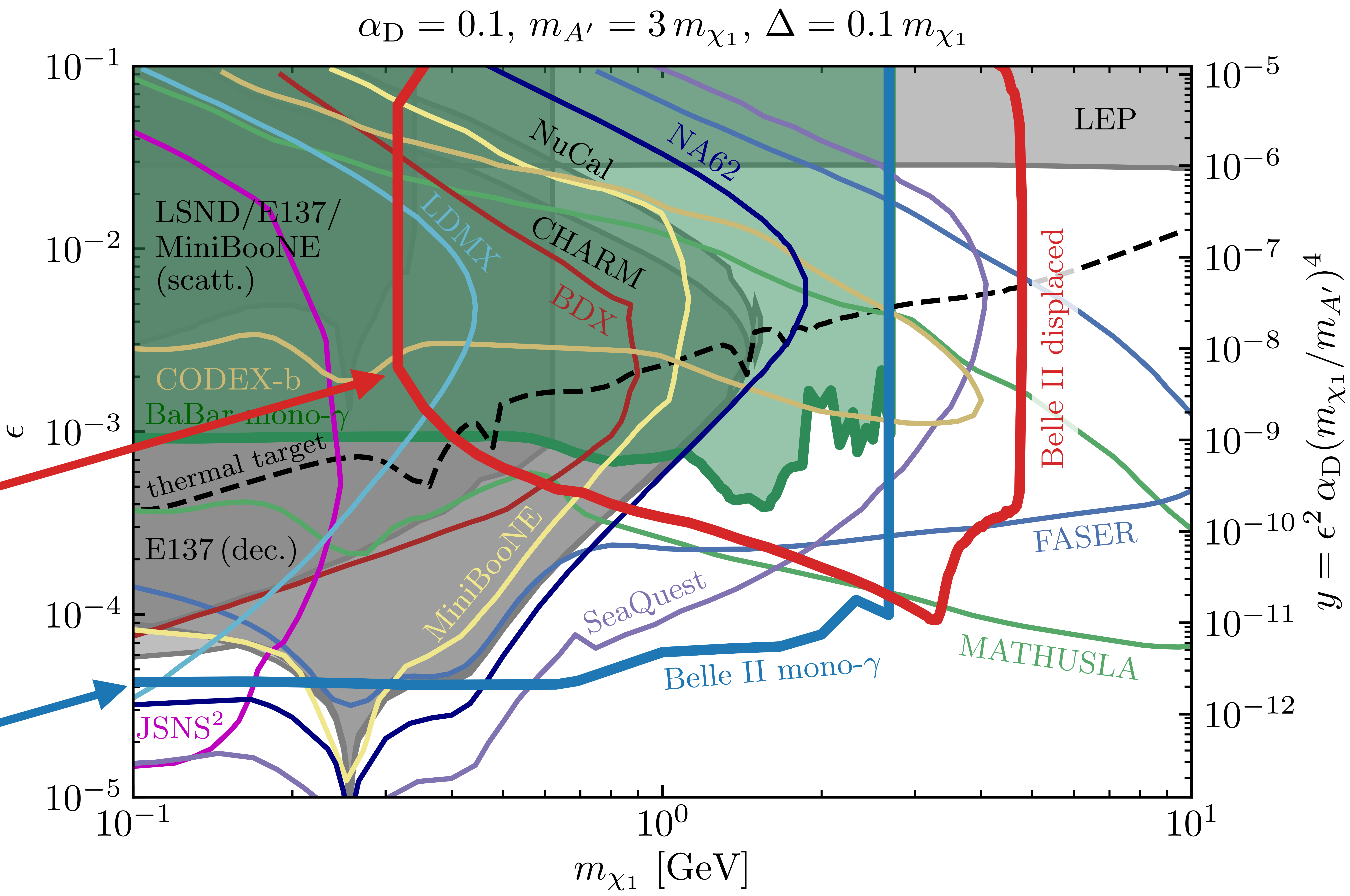


M. Duerr, **TF**, C. Hearty, F. Kahlhoefer, K. Schmidt-Hoberg, P. Tunney, J. High Energ. Phys. 2020, 39 (2020)

Long-lived particles: Inelastic Dark Matter

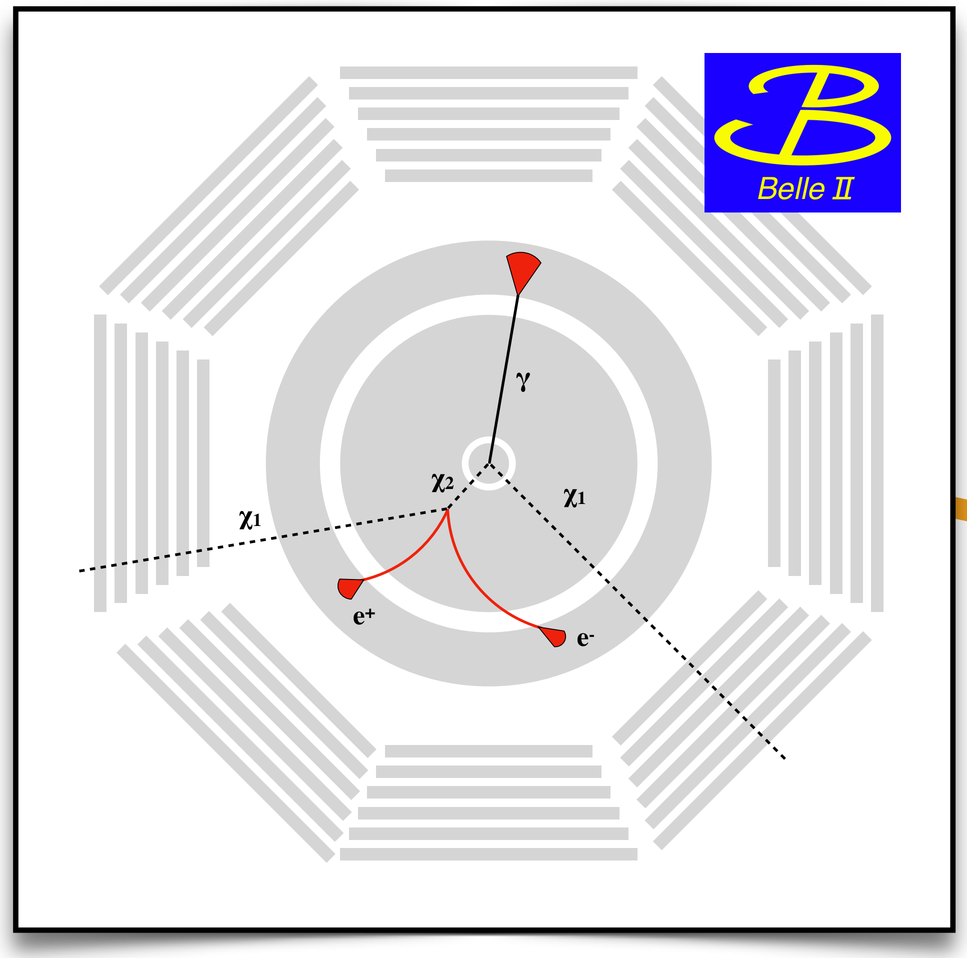


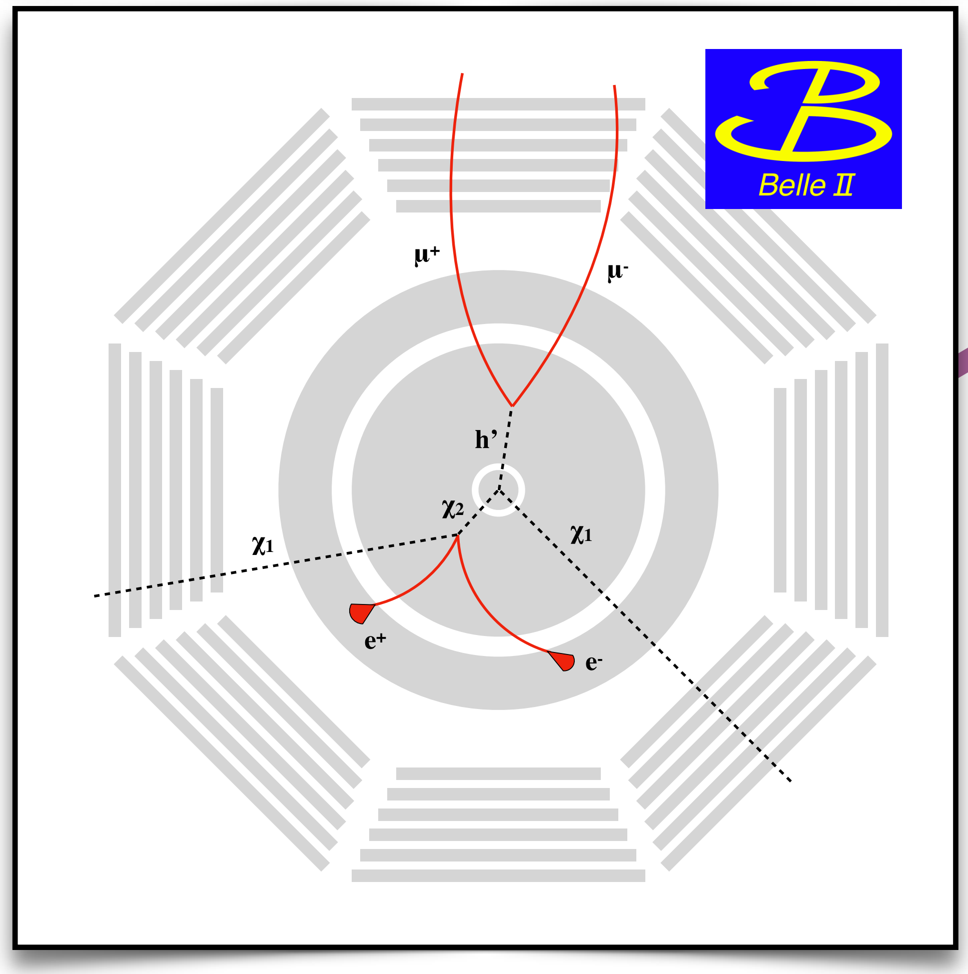


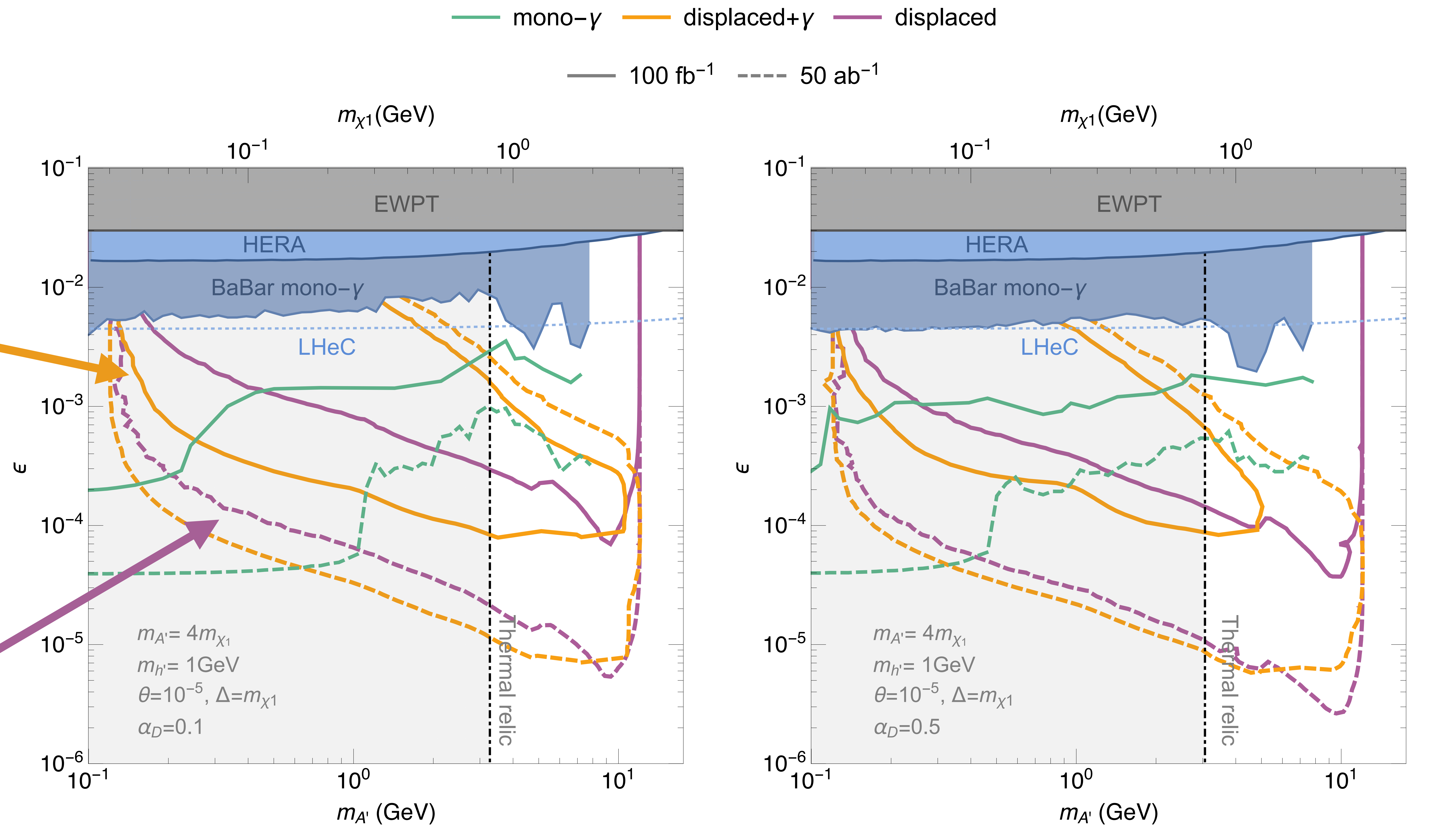


M. Duerr, **TF**, C. Garcia-Cely, C. Hearty, K. Schmidt-Hoberg, J. High Energ. Phys. 2021, 146 (2021)

Long-lived particles: Inelastic Dark Matter with Dark Higgs

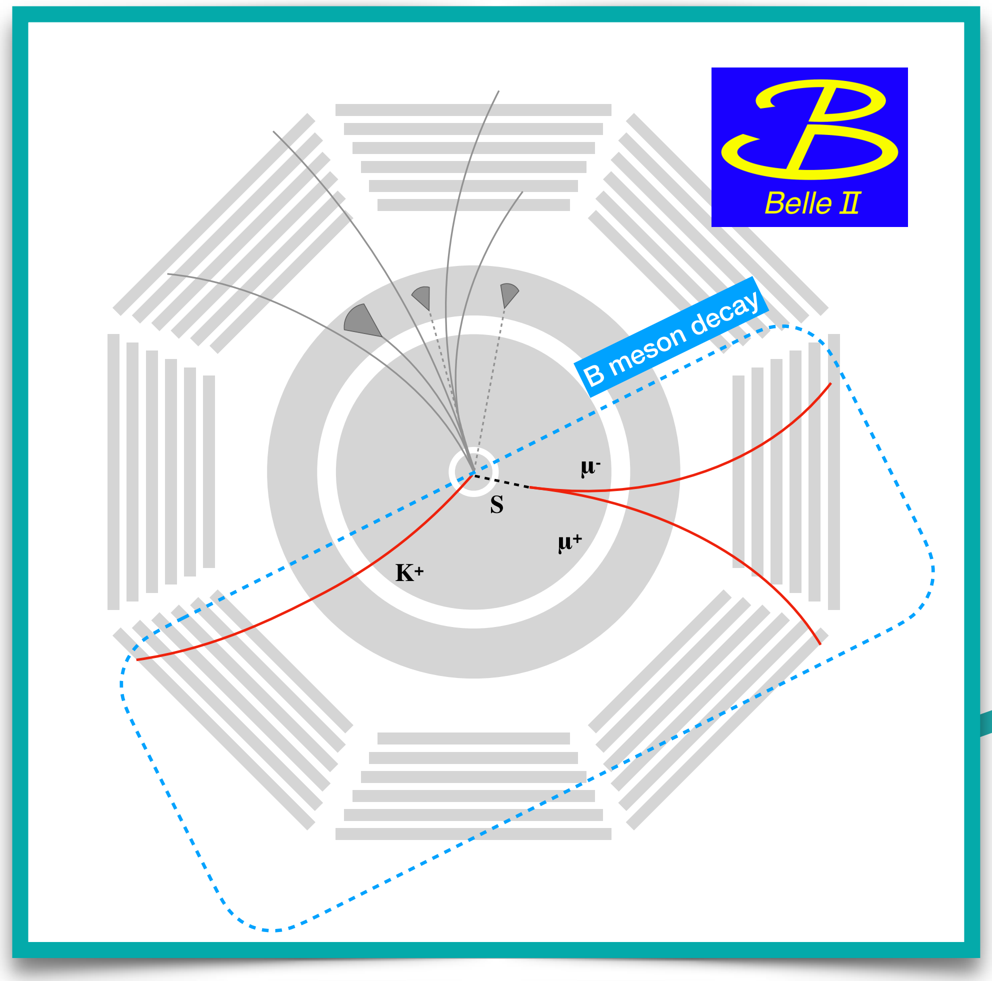


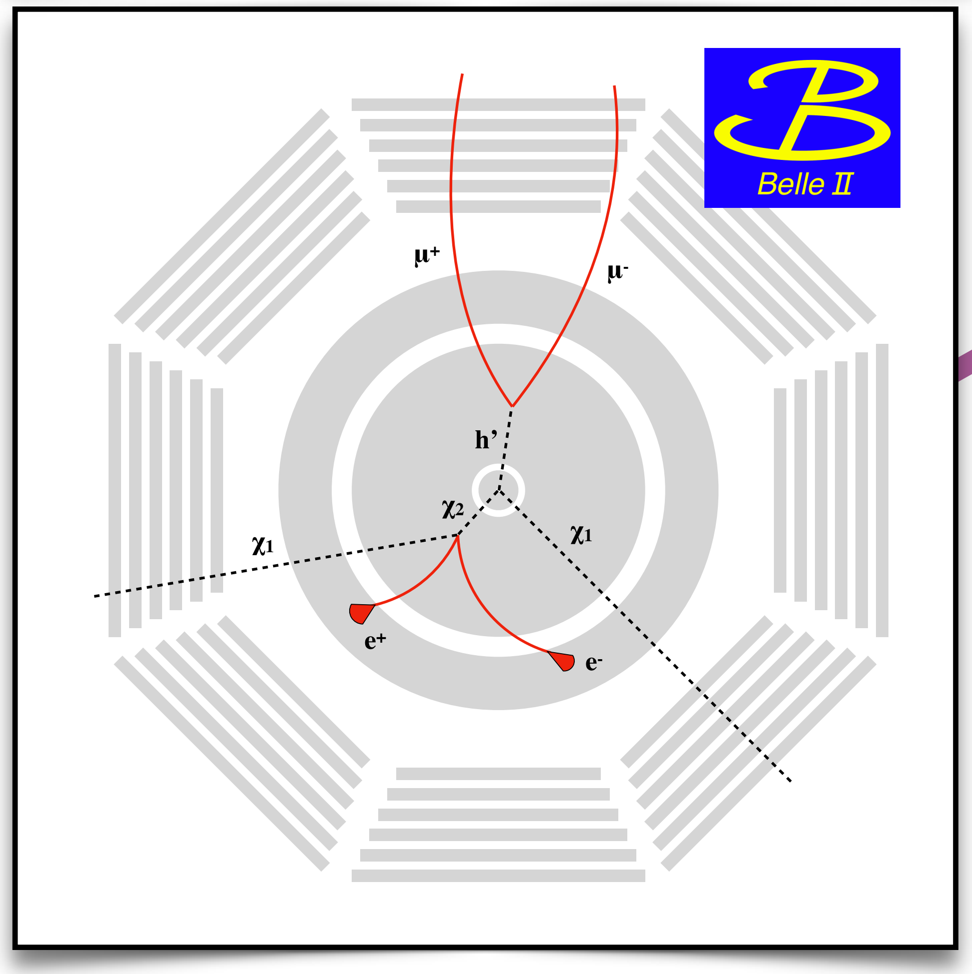


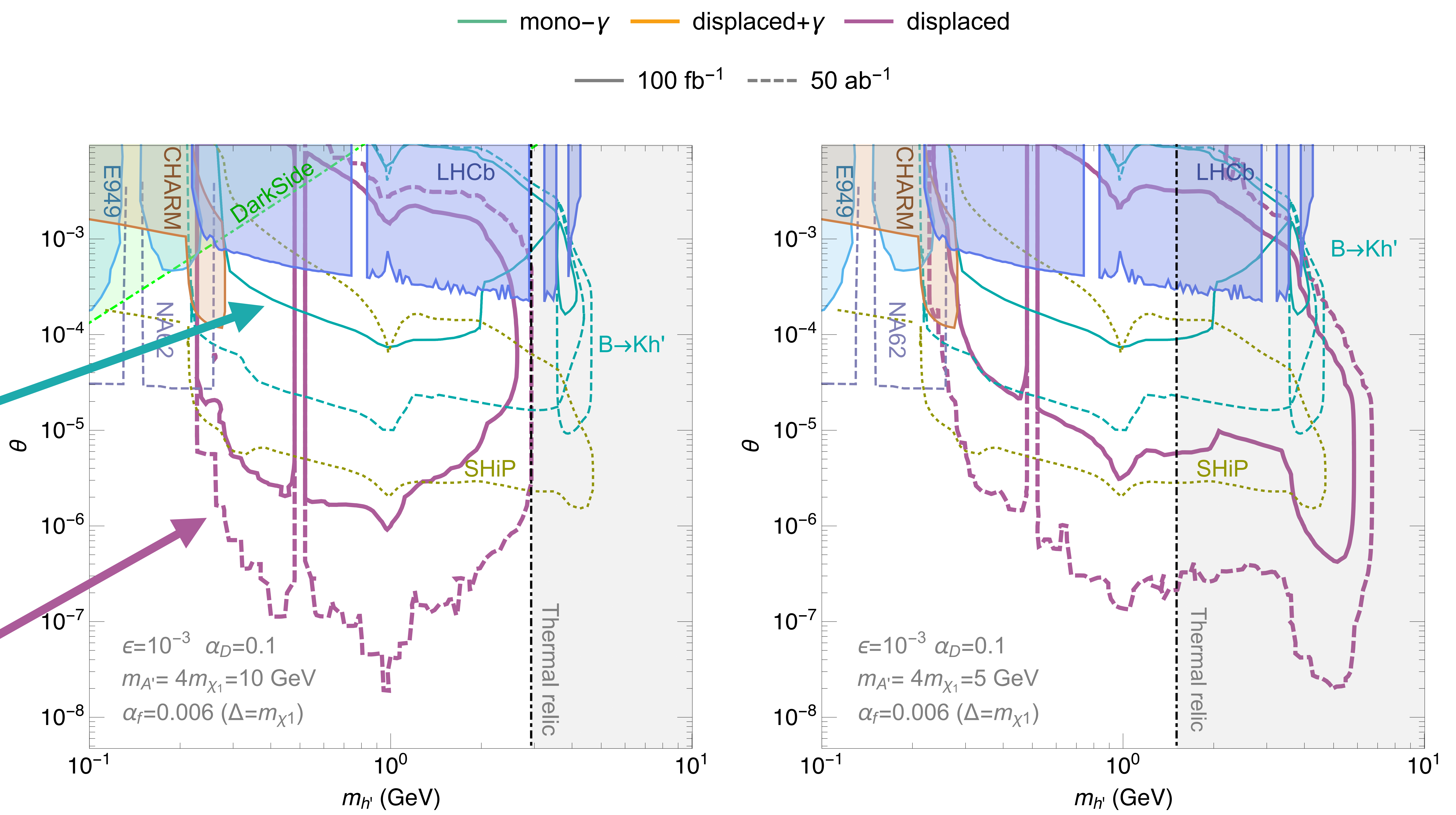


M. Duerr, **TF**, C. Garcia-Cely, C. Hearty, K. Schmidt-Hoberg, J. High Energ. Phys. 2021, 146 (2021)

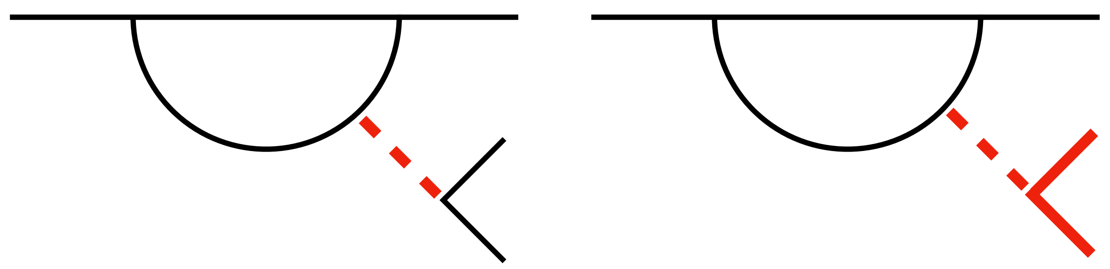
Long-lived particles: Inelastic Dark Matter with Dark Higgs







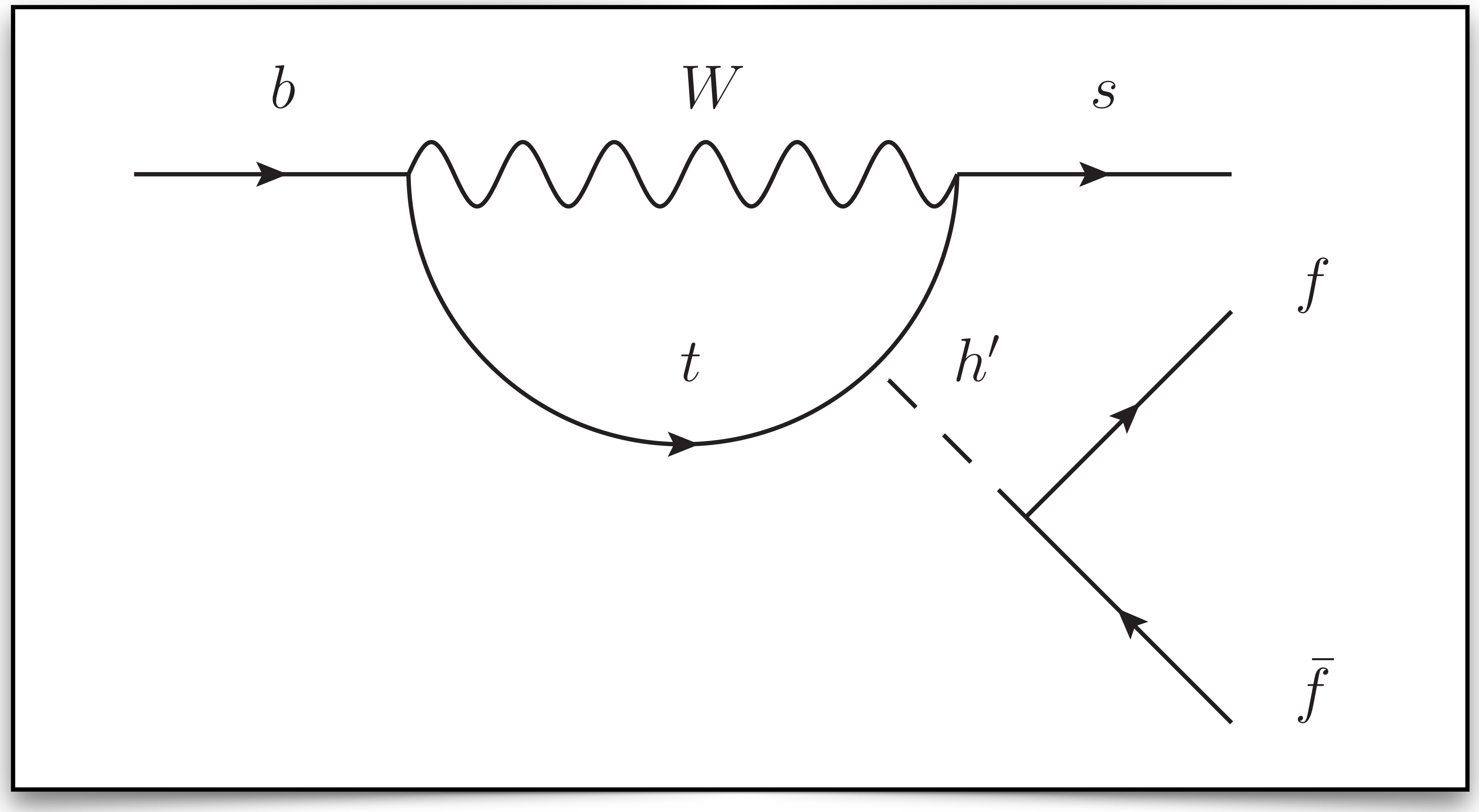
meson decays

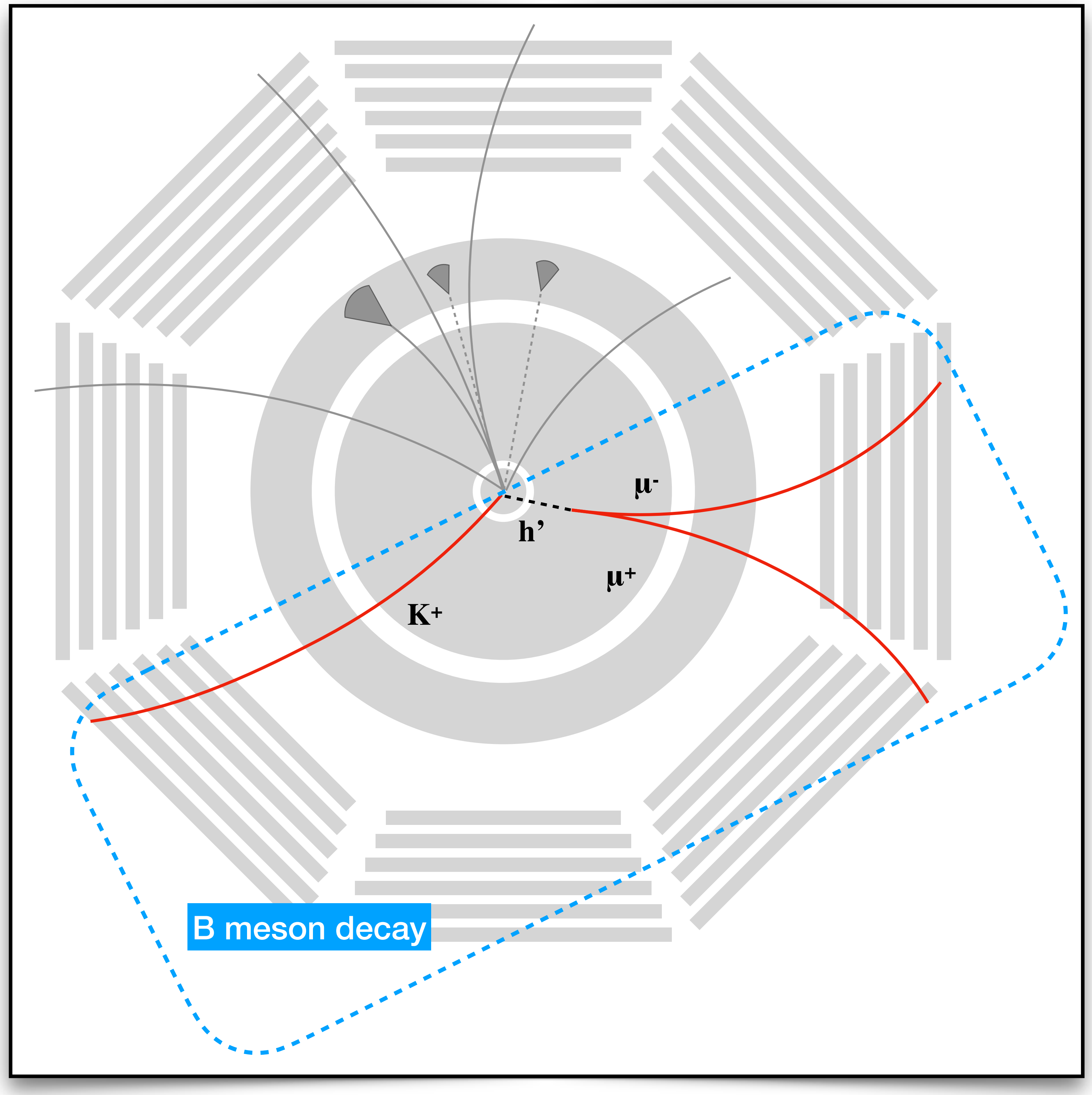


- mediators coupled D, B, or Υ
- visible (incl. LFV) or invisible final states
- probe light mediator masses up to respective meson mass

- Typically "bump-hunts" on low backgrounds
- Production and decay decoupled: LLPs!
- Many particles in the final state:
    - **There always is another B in the event** that can be used to constrain the total energy, to tag the B flavour, or just ignored (it still helps triggering the event)
- World-leading sensitivity for light scalars and ALPs with coupling to b-quarks

B→Kh' decays



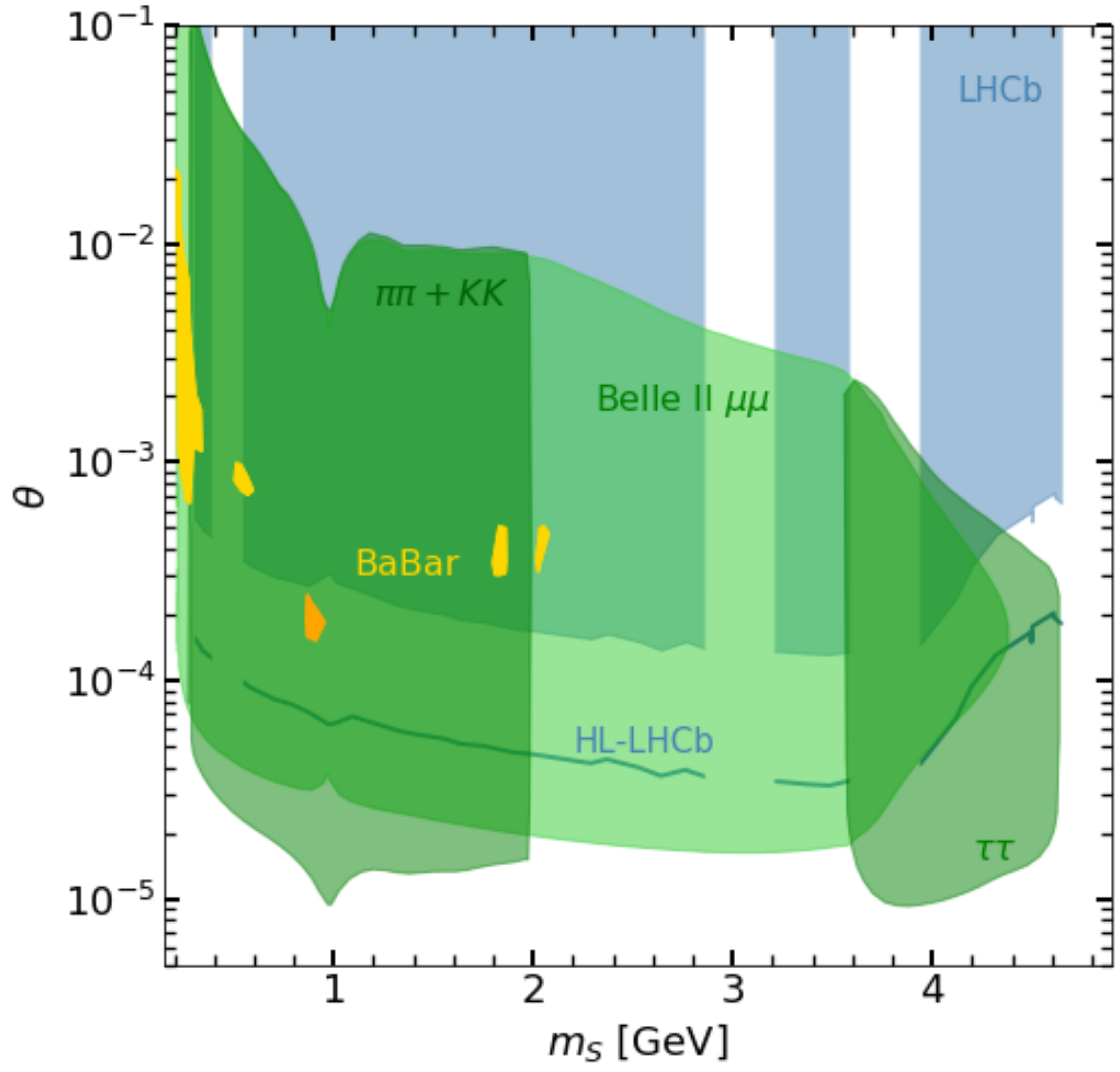


A. Filimonova, R. Schäfer, S. Westhoff, Phys. Rev. D 101, 095006 (2020)

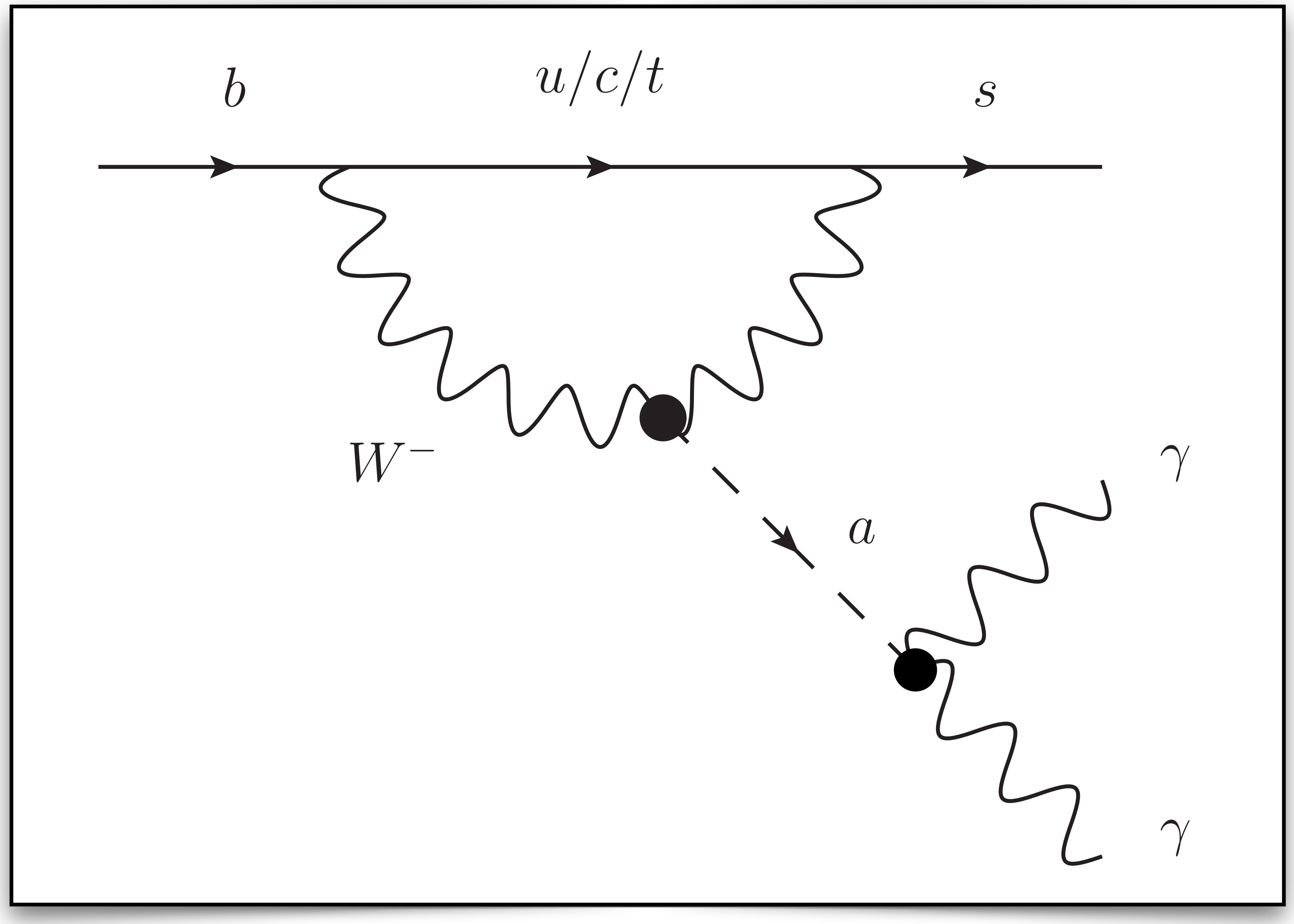
B→Kh' decays

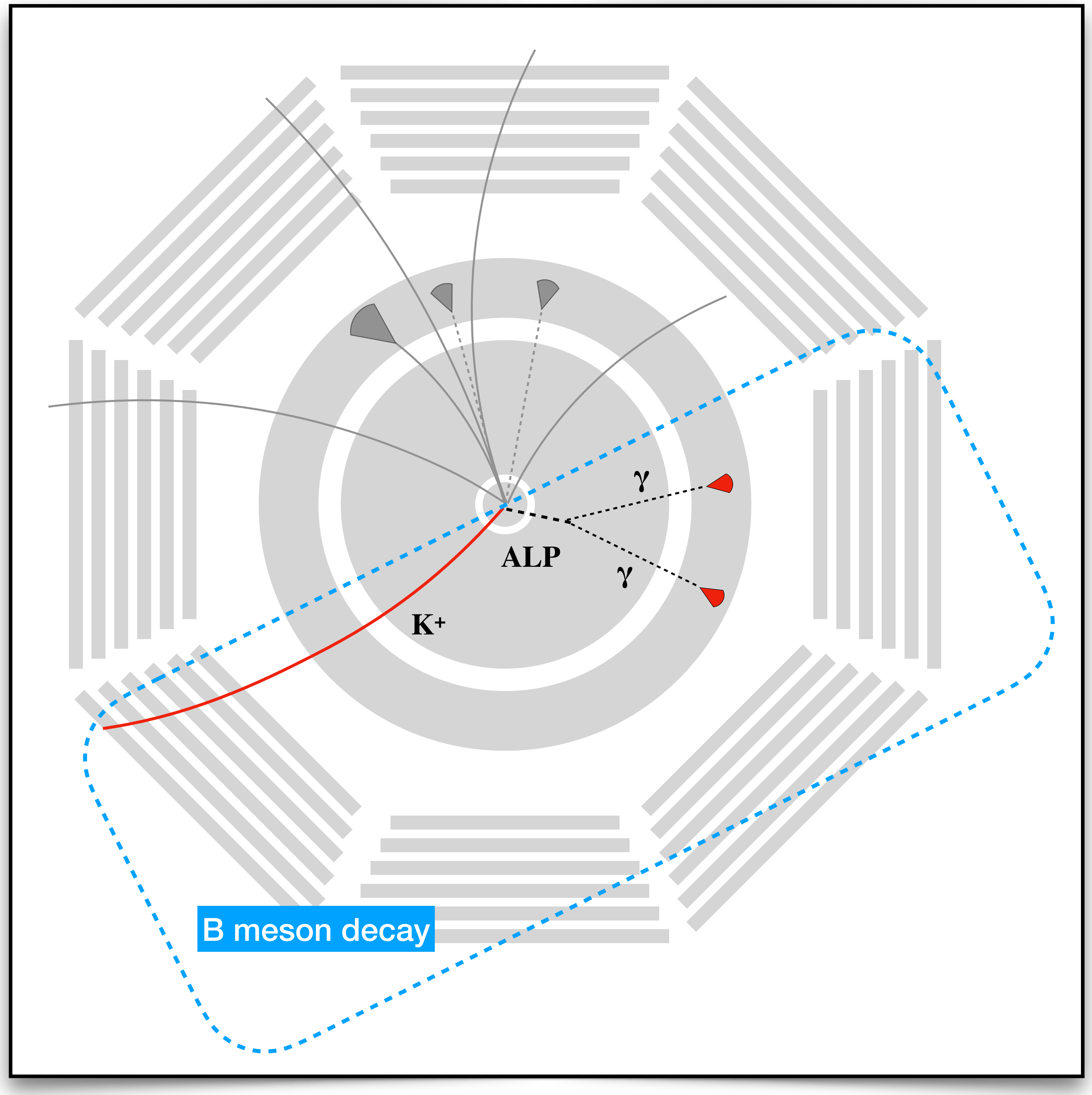
- h' is long-lived
- LHCb and Belle II complementary due to very different B momenta
- BaBar search is inclusive and recast is not competitive
- Reach towards even smaller θ by searching for B→K+invisible
    - Recasting B→Kνν SM limits untrivial (3-body vs 2-body final state)

Belle II collaboration, "Search for B+→K+νν decays using an inclusive tagging method at Belle II" (arXiv:2104.1262)



B→Ka decays





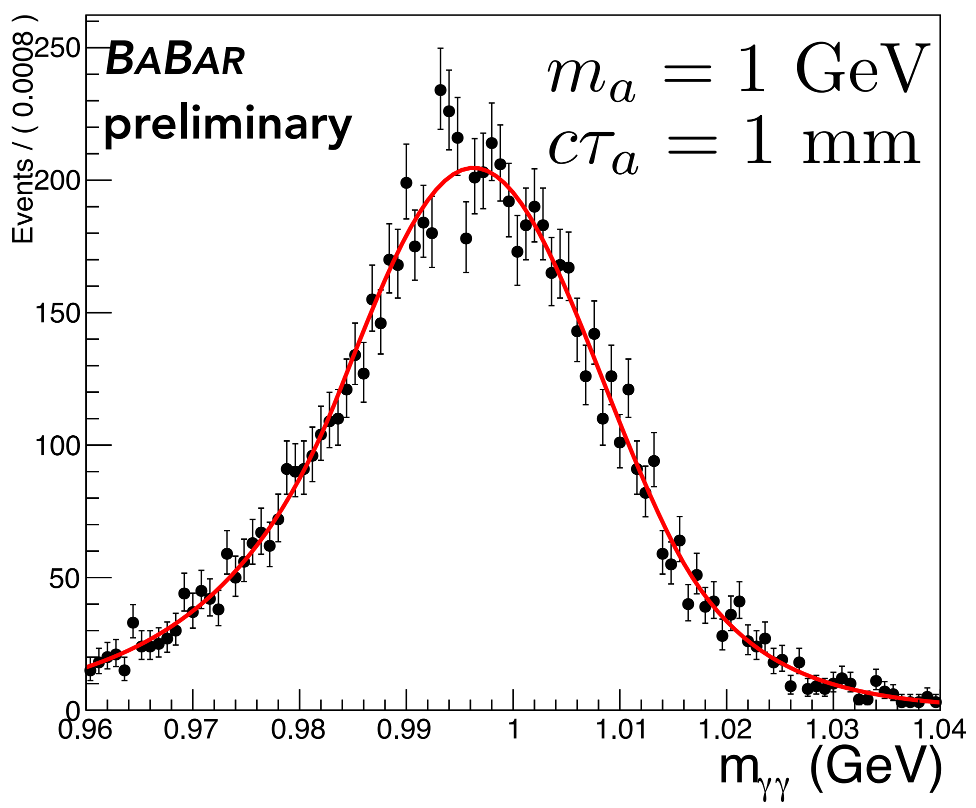
B→Ka decays

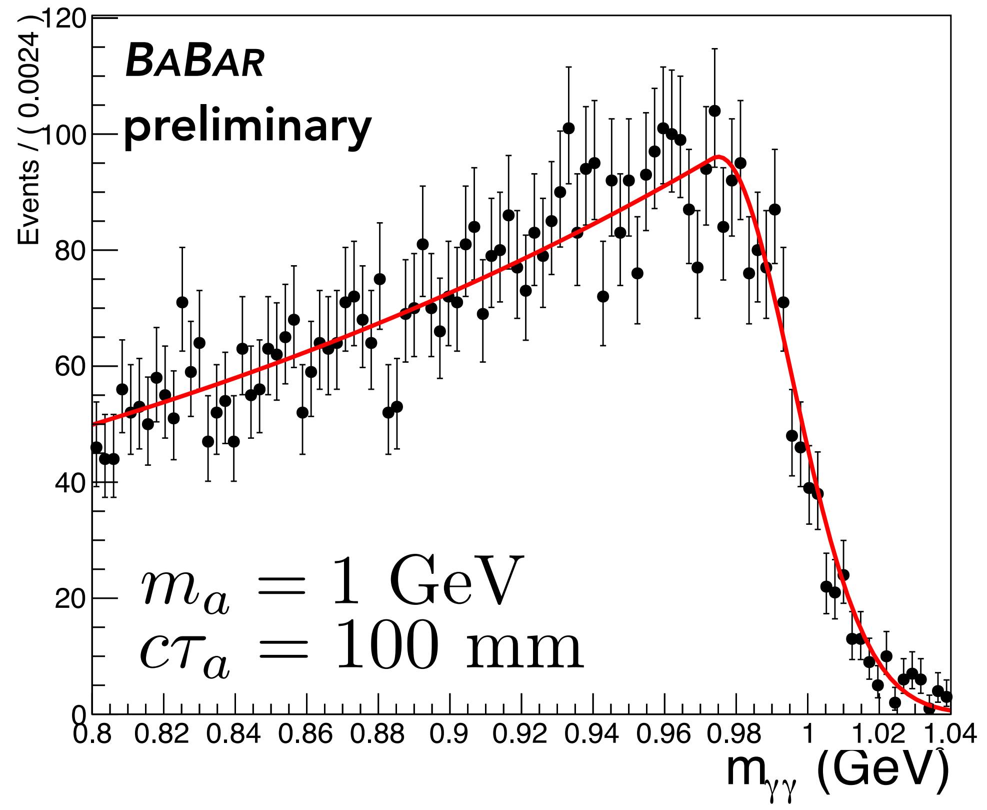
- Search for ALPs that predominantly couple to electroweak gauge bosons

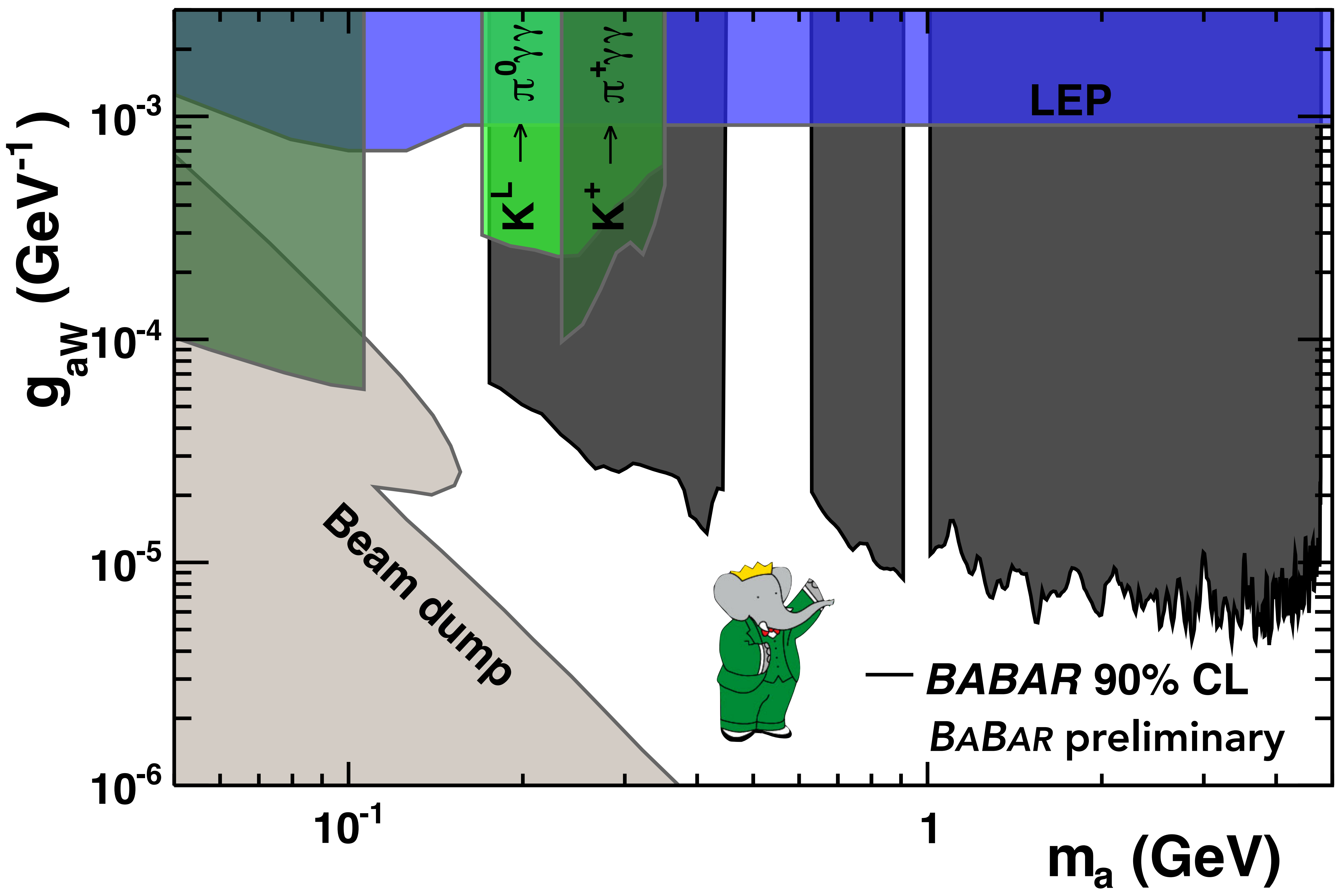
- Dominant decay for $m_a \ll m_W$ into photons

$$\Gamma(a \to \gamma\gamma) = \frac{g_{aW}^2 \sin^4\theta_W M_a^3}{64\pi}$$

- Light ALPs naturally long-lived, but decay in general model-dependent







Summary

☆ discussed today

	Belle	BaBar	Belle II	recasts
$A' \to$ invisible ☆	–	$\epsilon < 10^{-3}\,(53\,\mathrm{fb}^{-1})$ [1]	–	–
$A' \to \ell\ell$	–	$\epsilon < 5 \times 10^{-4}\,(514\,\mathrm{fb}^{-1})$ [2]	–	–
$a \to \gamma\gamma$ ☆	–	–	$g_{a\gamma\gamma} < 10^{-3}\,\mathrm{GeV}^{-1}\,(0.45\,\mathrm{fb}^{-1})$[3]	–
$A' \to \chi_1\chi_2$ ☆	–	–	–	[4]
$A' \to A'h', A' \to \chi_1\chi_2$ ☆	–	–	–	[5]
$A' \to A'h', h' \to A'A'$	$\alpha_D\epsilon < 10^{-9}\,(977\,\mathrm{fb}^{-1})$ [6]	–	–	–
DM bound states	–	–	–	[7]
$Z'_\mu \to$ invisible ☆	–	–	$g' < 10^{-1}\,(0.27\,\mathrm{fb}^{-1})$ [8]	–
$Z'_\mu \to \mu\mu$	–	$g' < 10^{-3}\,(514\,\mathrm{fb}^{-1})$ [9]	–	–
$Z'_\tau \to \ell\ell$	–	$\xi < 1\,(514\,\mathrm{fb}^{-1})$ [10]	–	–
$B \to Kh', h' \to \ell\ell/hh$ ☆	–	–	–	[11]
$B^\pm \to K^\pm a, a \to \gamma\gamma$ ☆	–	$g_{aWW} < 10^{-5}\,(424\,\mathrm{fb}^{-1})$ [12]*	–	–
$B^0 \to A'A'$	BF $< 10^{-7}$ [13]	–	–	–
$B \to X\ell\nu_H$ (HNL)	$\|U\|^2 < 5 \times 10^{-5}\,(711\,\mathrm{fb}^{-1})$ [14]	–	–	–
$\Upsilon(2S,3S) \to S\bar{\Lambda}\bar{\Lambda}$	–	BF $< 10^{-7}\,(90\times10^6\,\Upsilon(2S),\ 110\times10^6\,\Upsilon(3S))$ [15]	–	–
$\Upsilon(2S) \to \Upsilon(1S)\pi\pi, \Upsilon(1S) \to \gamma$ invisible	BF $< 10^{-6}\,(157\times10^6\,\Upsilon(2S))$ [16]	BF $< 10^{-6}\,(98\times10^6\,\Upsilon(2S))$ [17]	–	–

+many more (ref. in backup)

- Belle is often not very competitive due to trigger limitations
- BaBar is still producing DM-related papers (data taking ended 2010)
- Belle II has just started with a huge DM program

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