Probing Dark Photons and ALPs at B-factories.

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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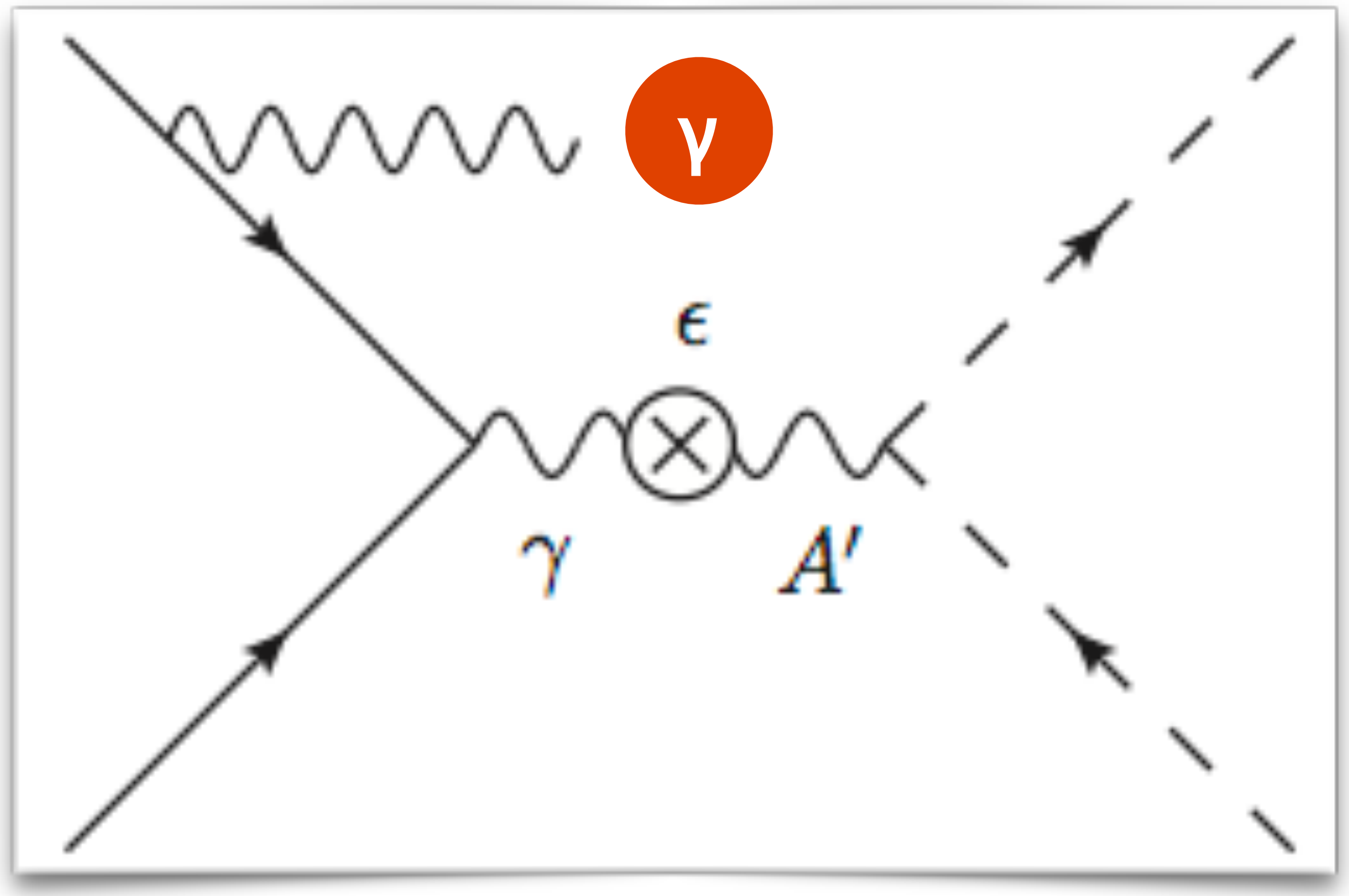
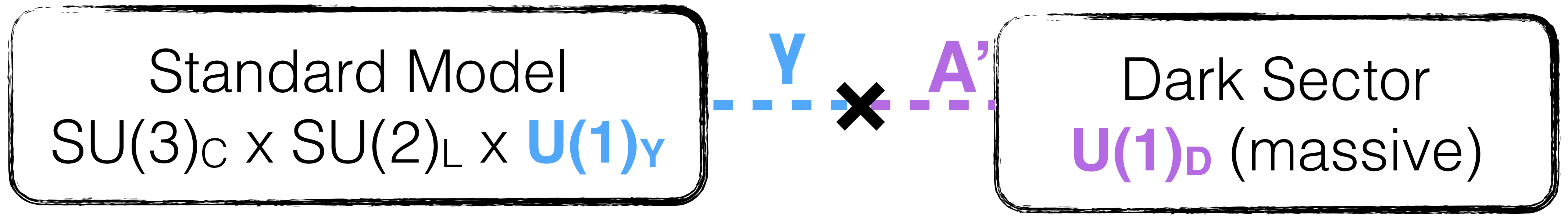
DESY.

Searches for Dark Photons at B-factories

- In the Vector Portal, a (massive) Dark Photon A′ can mix with the SM photon with strength ε.
- Searches so far always assume on-shell A′ decays ($m_{decay} \leq m_{A'}/2$).
- Signal: Peaking ISR photon energy, peaking invariant mass of decay products.
- If A′ is the lightest Dark Sector (DS) particle: A′ → SM particles dominates (“visible”). Conceptually straight forward.
- If A′ is the not the lightest Dark Sector particle: A′→ Dark Matter dominates (“invisible”).



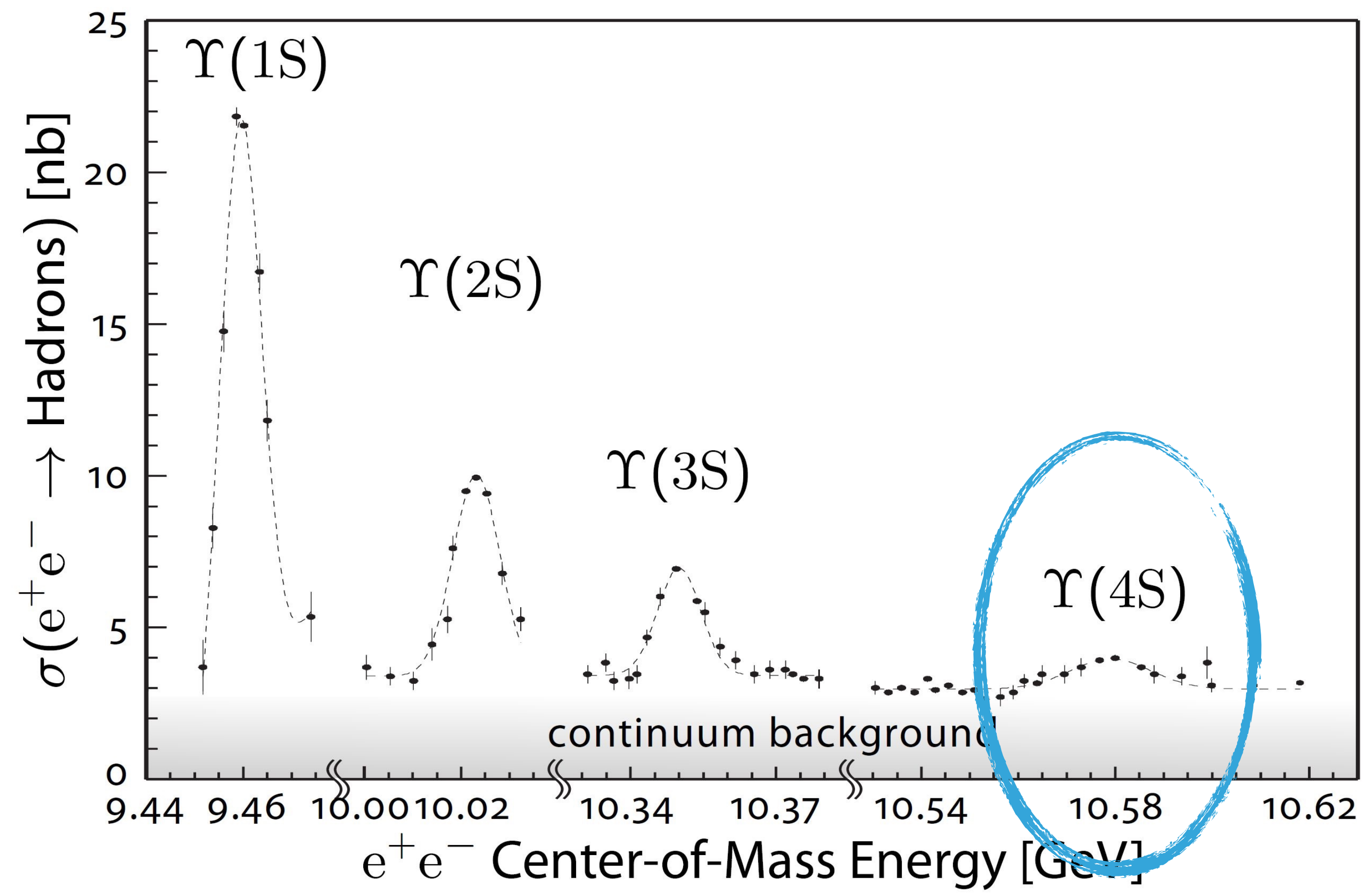
SM leptons (visible)
or
Dark Matter (invisible)

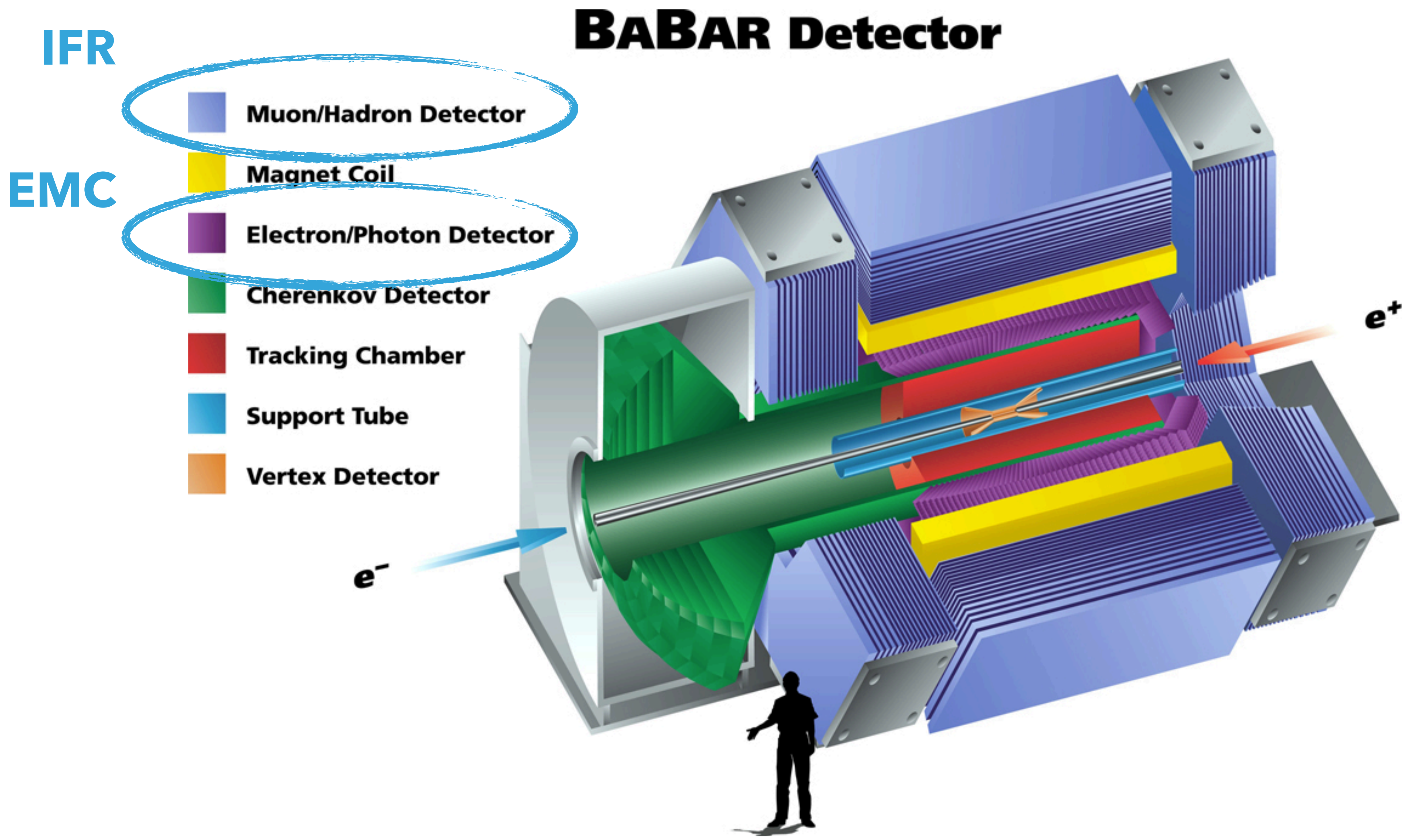


*Holdom, Phys. Lett B166, 1986

BaBar

- First generation B-factory: BaBar at PEP-II, USA, took data until 2008.
- Very high luminosity: ~1.2×10^{34} /cm²/s
- Collision energy at Y(nS): Mainly at E_{CM} = 10.58 GeV. BR(Y(4S)→BB) > 96%
- Asymmetric beam energies: 9 GeV (e^-) / 3.1 GeV (e^+) → Boosted B$\bar{B}$ pairs.





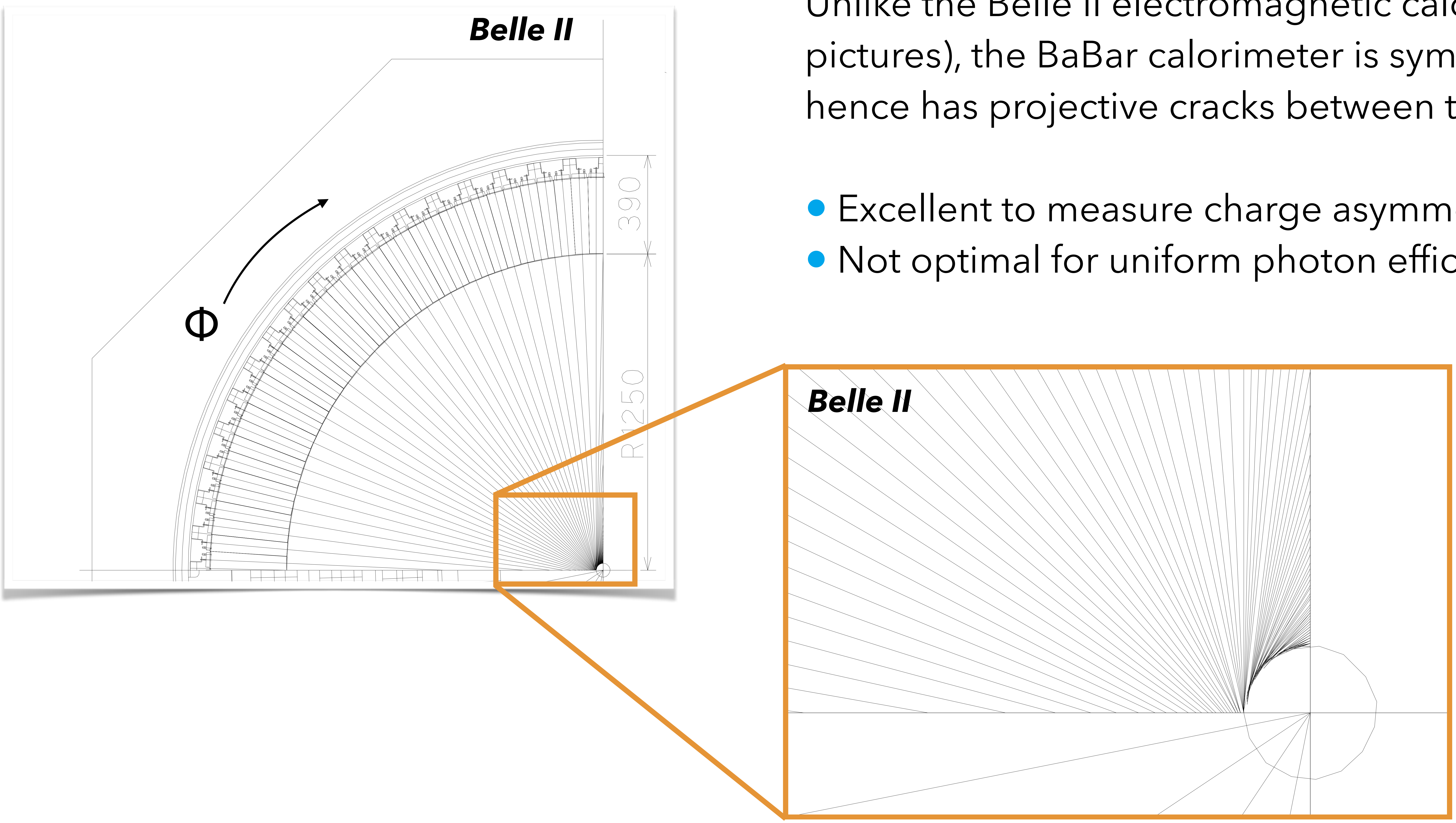
BaBar: Invisible Dark Photon decays, analysis

- Single photon trigger was implemented for final BaBar running period (~10% of all data):
  - 48 fb^{-1} for high $m_{A'}$ (low E_γ), mostly at $E^{CM}=\Upsilon(2S)$ and $E^{CM}=\Upsilon(3S)$
  - 53 fb^{-1} for low $m_{A'}$ (high E_γ), (additional 5 fb^{-1} at $E^{CM}=\Upsilon(4S)$).
- Trigger threshold: $E_\gamma^* > 1.5$ GeV. Usable at analysis level: $E_\gamma^* > 1.8$ GeV (calibration issues).
- Signal selection using a BDT with 12 variables, e.g.:
  - Energies and polar angles of highest two energetic γ's.
  - Distance of missing momentum vector to EMC crystal edges.
  - Additional clusters in muon system (IFR).
- Trained on 3 fb^{-1} $\Upsilon(3S)$ data and simulated signal samples uniform in $m_{A'}$.

BaBar: Invisible Dark Photon decays, backgrounds

Unlike the Belle II electromagnetic calorimeter (see pictures), the BaBar calorimeter is symmetric in Φ (and hence has projective cracks between the crystals):

- Excellent to measure charge asymmetries.
- Not optimal for uniform photon efficiency.

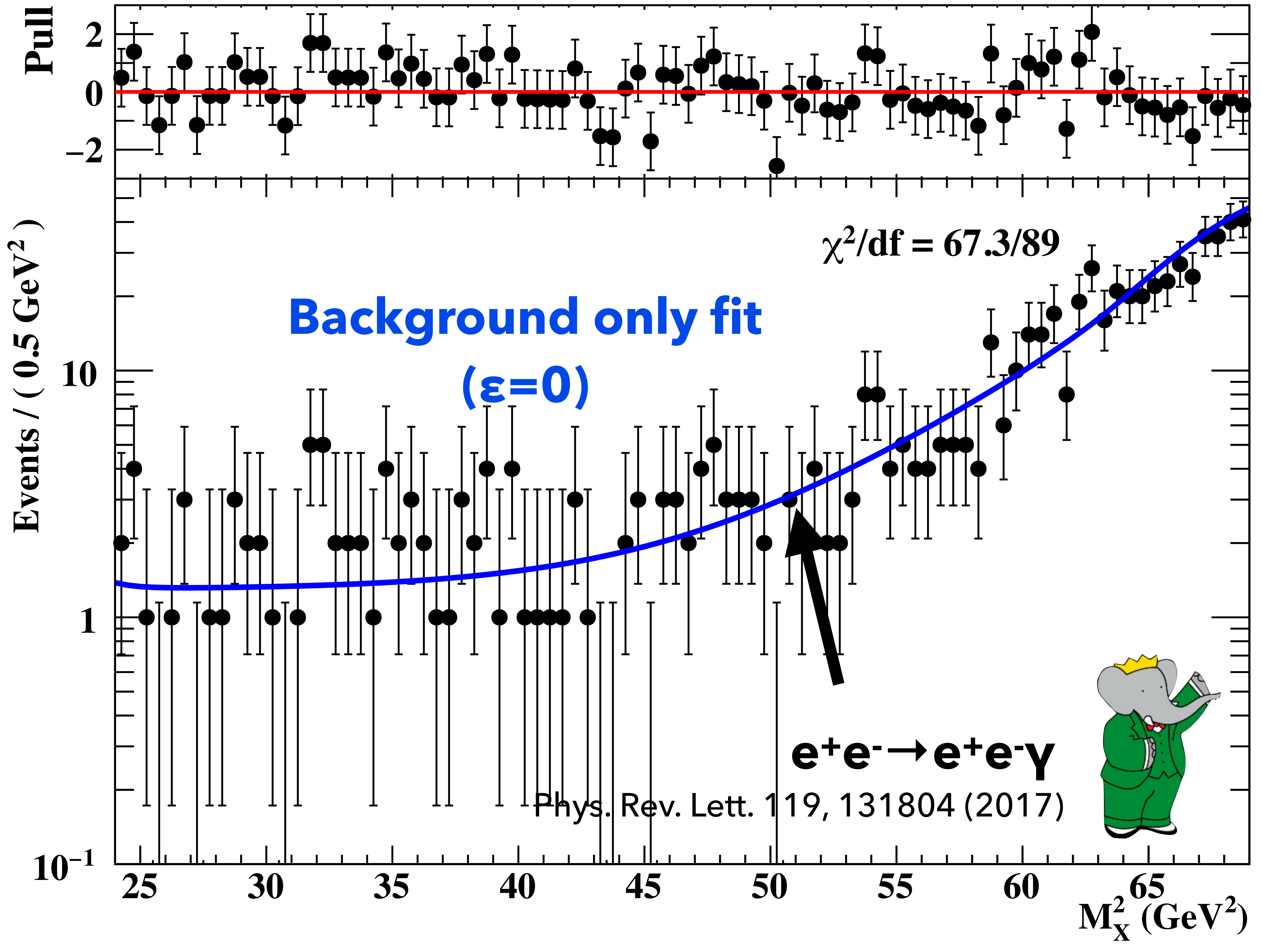


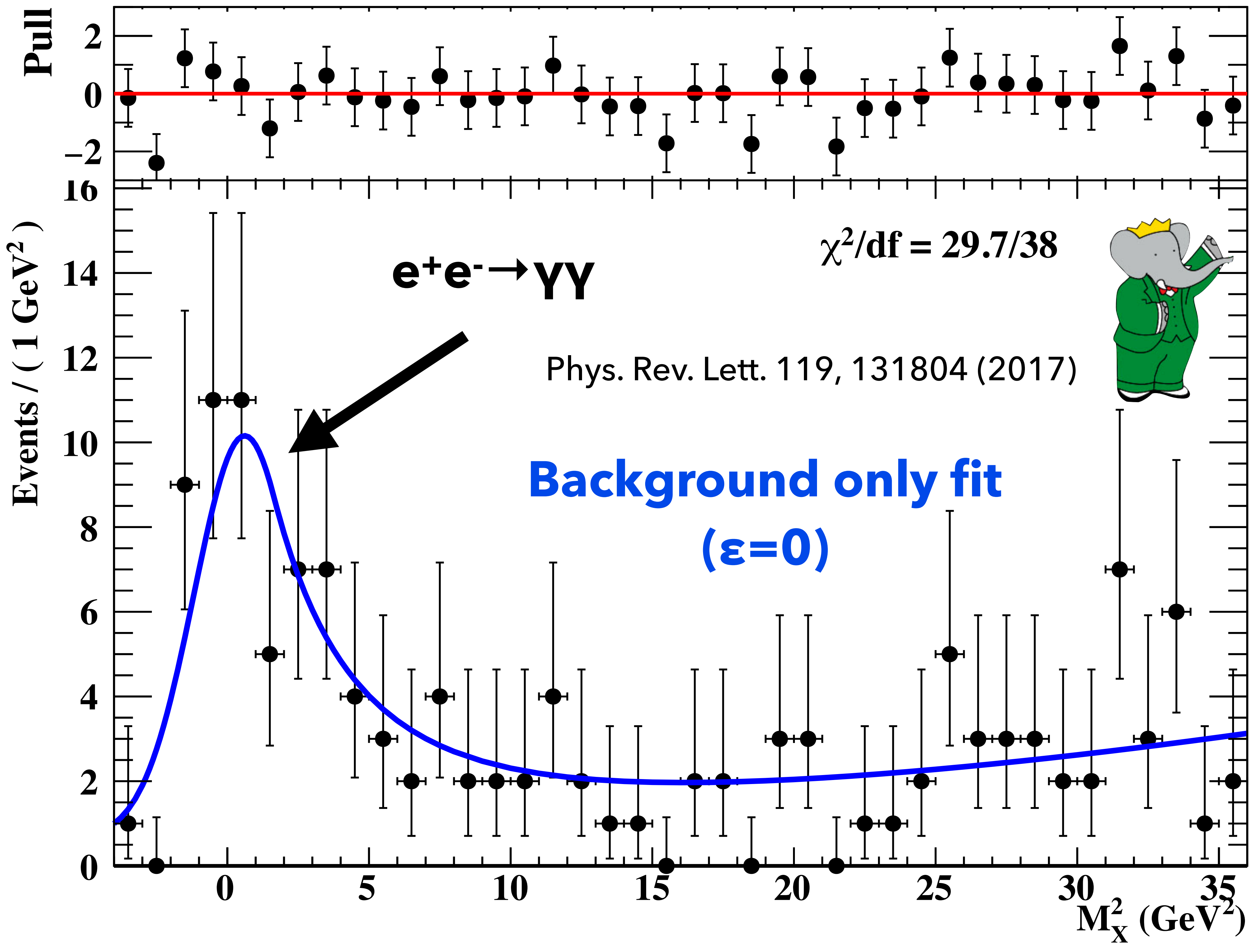
BaBar: Invisible Dark Photon decays, backgrounds

- Backgrounds:
  - $e^+e^- \to \gamma\gamma$, 1γ undetected: Peaking, identical to the signal for $m_{A'} < 1.6$ GeV/c^2. Photons can escape undetected through azimuthal gaps between calorimeter crystals and other inefficient detector regions.
  - $e^+e^- \to \gamma\gamma\gamma$, 1$\gamma$ undetected, 2nd out of the detector acceptance.
  - $e^+e^- \to e^+e^-\gamma$, both electrons out of the detector acceptance (γ energy limited by kinematics).
  - Beam background photons do not fake signal γ, but can be the 2nd γ in a signal event.
  - Irreducible SM background $e^+e^- \to \nu\nu\gamma$ is negligible.

BaBar: Invisible Dark Photon decays, results

- **High A′ mass region** (low γ energy) $m_{A'}$ >5.5 GeV/c² is dominated by radiative Bhabha background smooth in recoil mass.
- **Low A′ mass region** has both peaking and smooth backgrounds. Select data using two statistically independent cuts on BDT and θ.



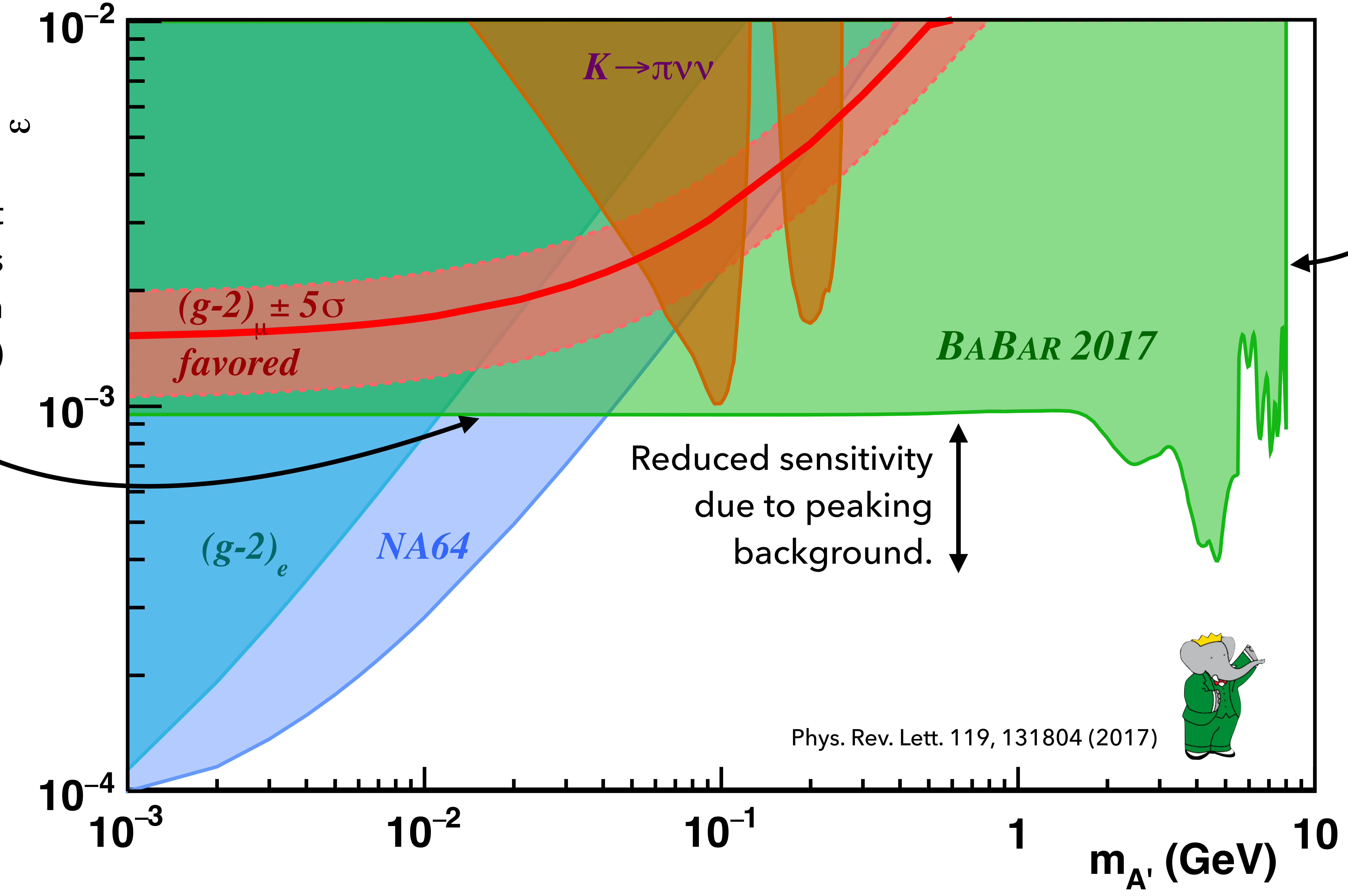


BaBar: Invisible Dark Photon decays, results

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

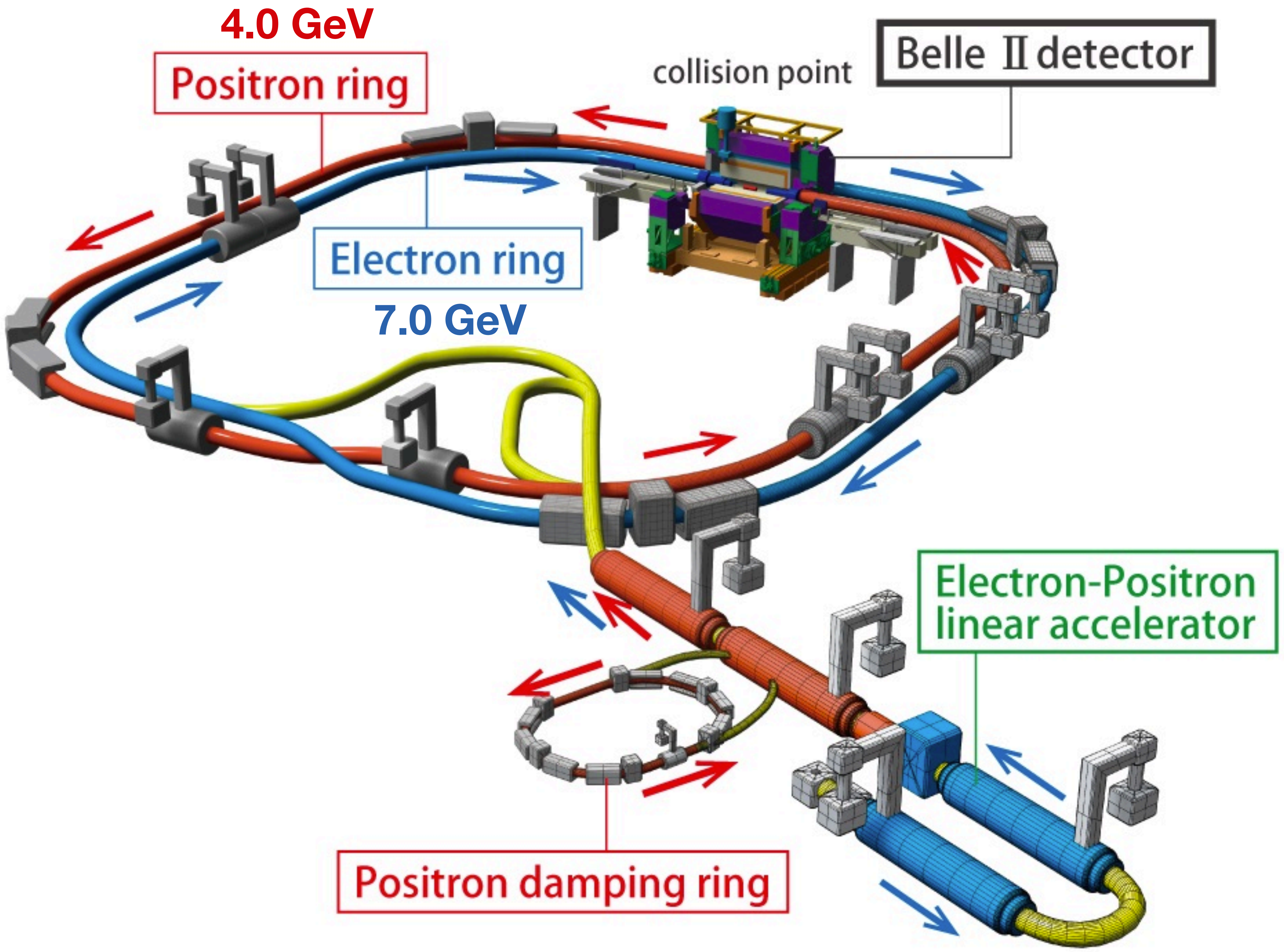
Flat because one cannot resolve different masses here (single photon with ~beam energy)

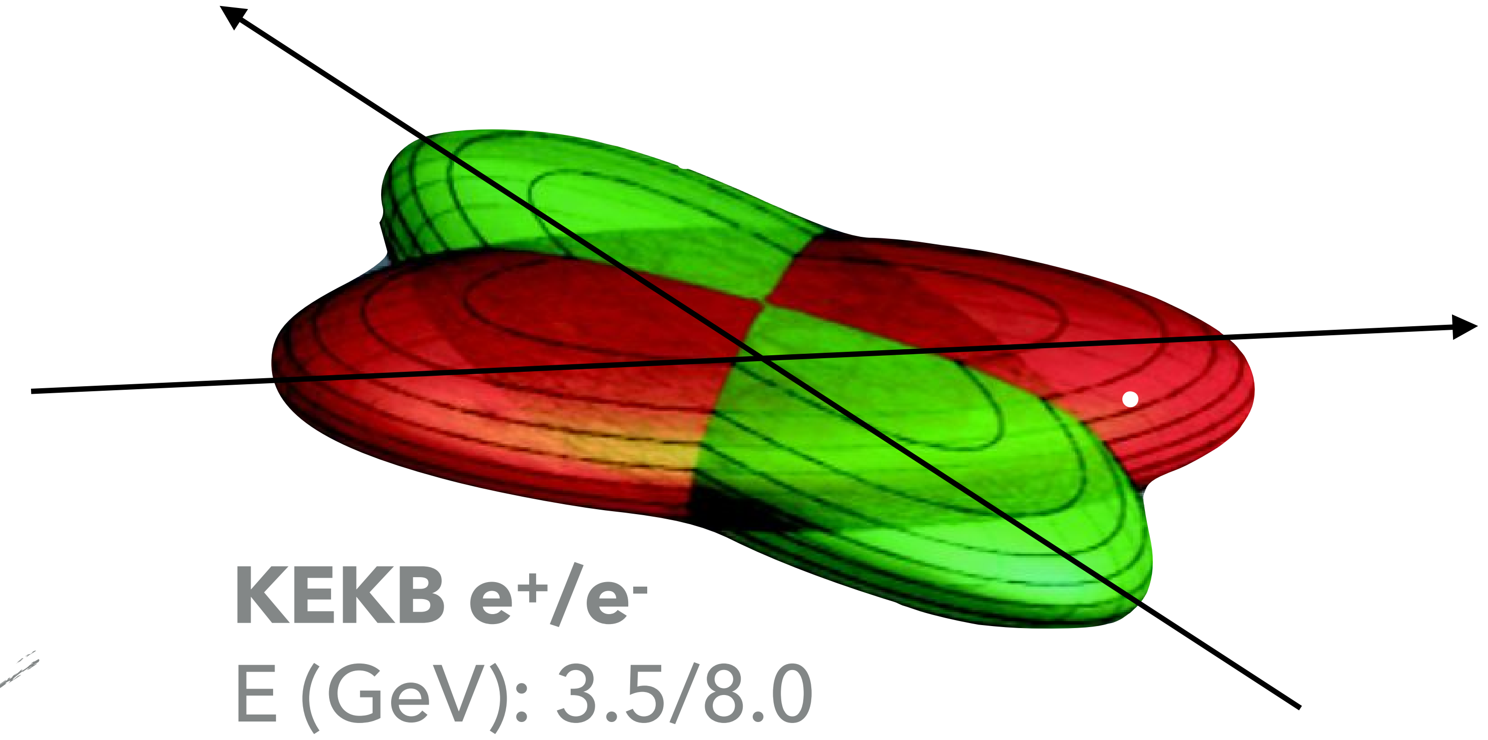
Limited by beam energy and trigger threshold for high $m_{A'}$



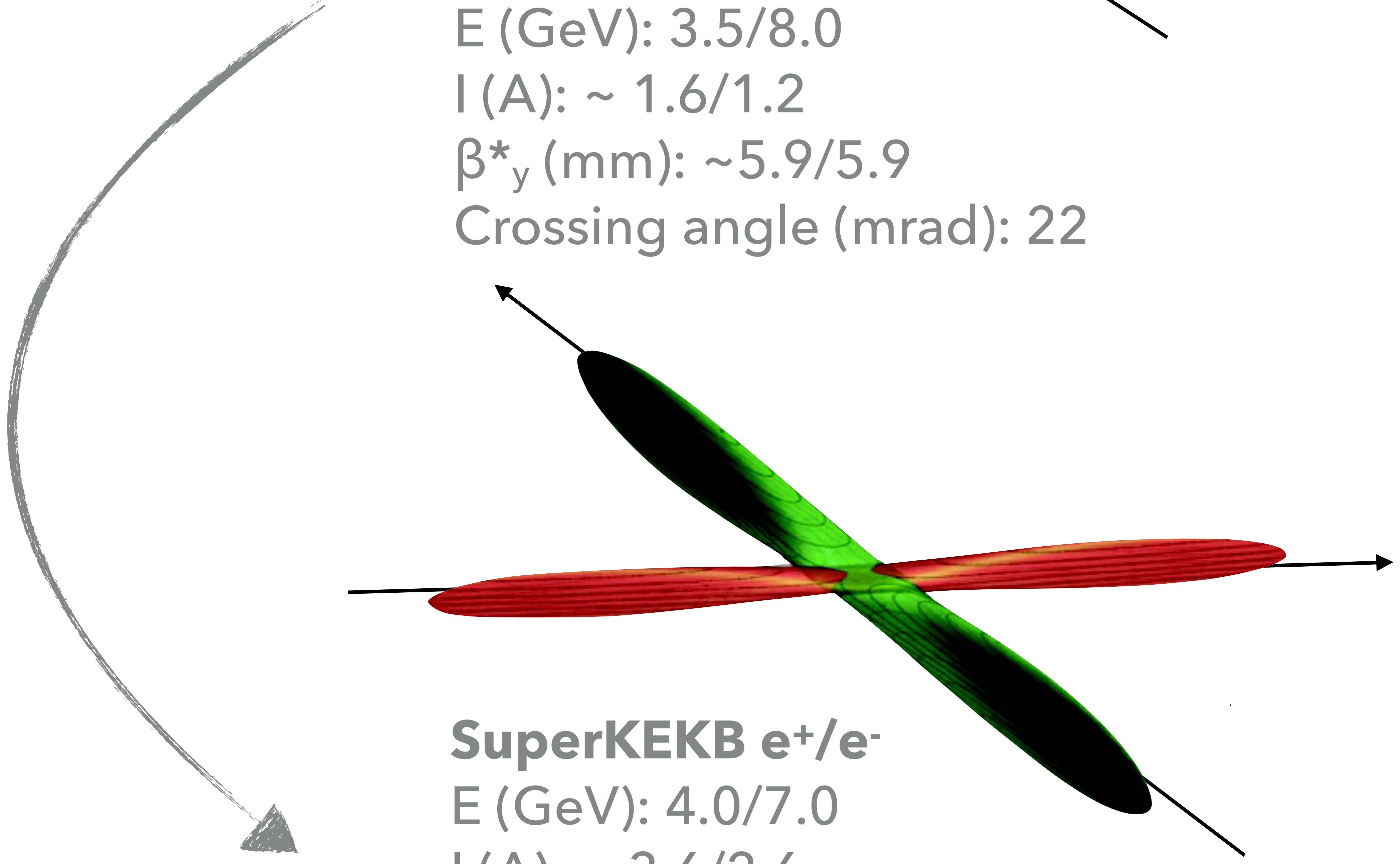
Reduced sensitivity due to peaking background.

SuperKEKB asymmetric e^+e^- collider at 10.57 GeV



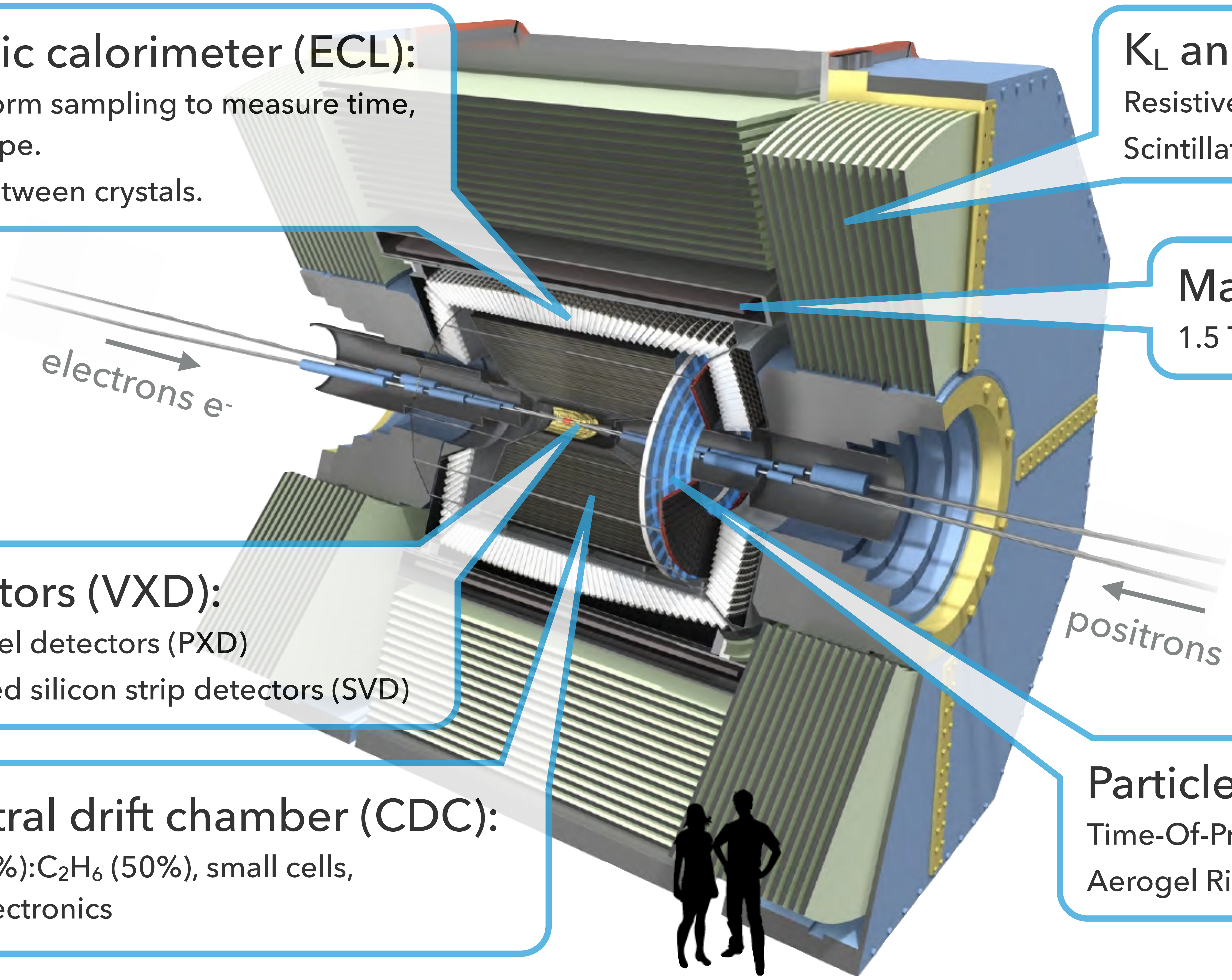


KEKB e^+/e^-
E (GeV): 3.5/8.0
I (A): ~ 1.6/1.2
β^*_y (mm): ~5.9/5.9
Crossing angle (mrad): 22



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
→ **Luminosity increase x40**

Belle II detector



Electromagnetic calorimeter (ECL):

CsI(Tl) crystals, waveform sampling to measure time, energy, and pulse-shape.

No projective gaps between crystals.

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):

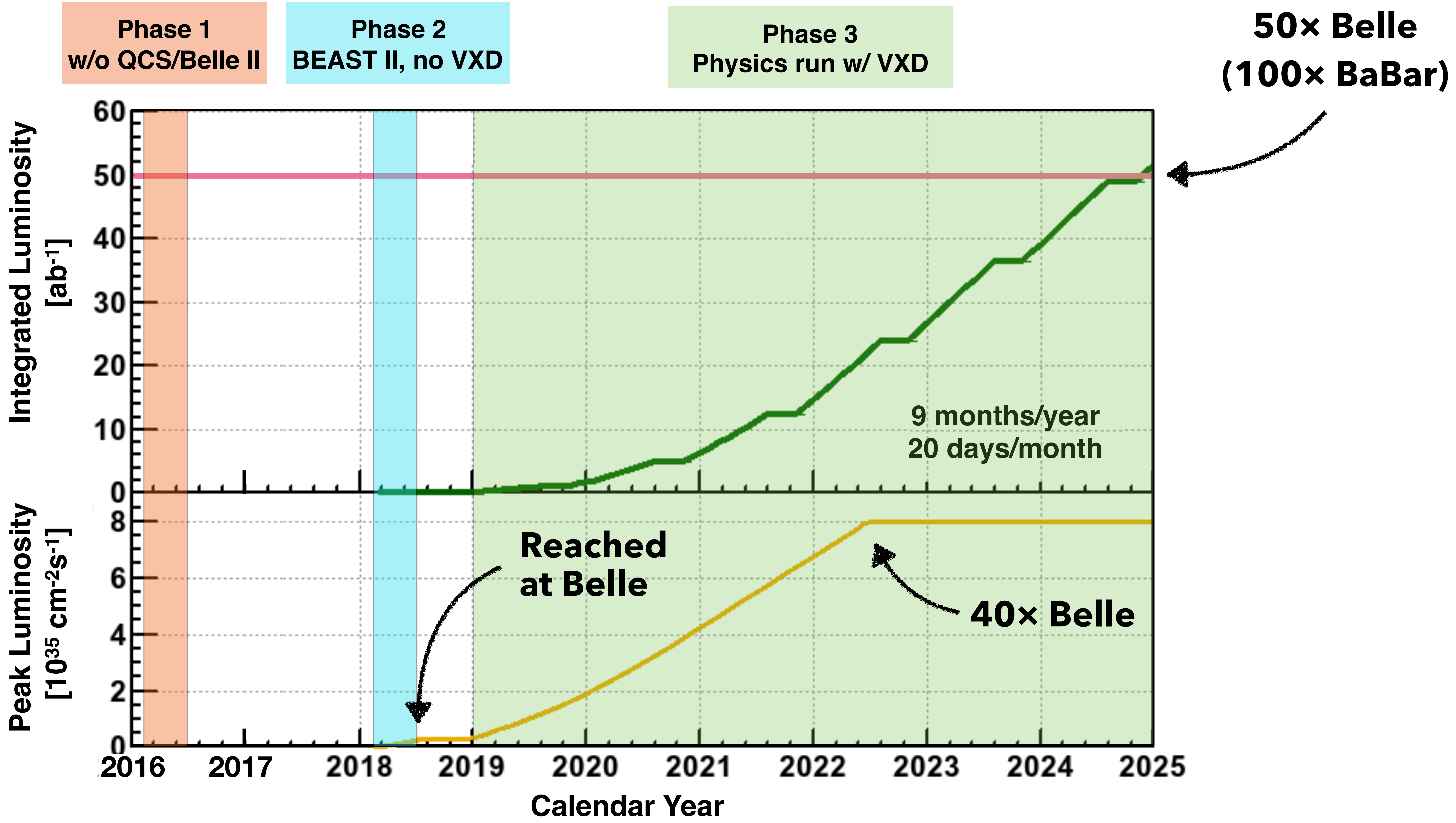
He(50%):C_2H_6 (50%), small cells,
fast electronics

Particle Identification (PID):

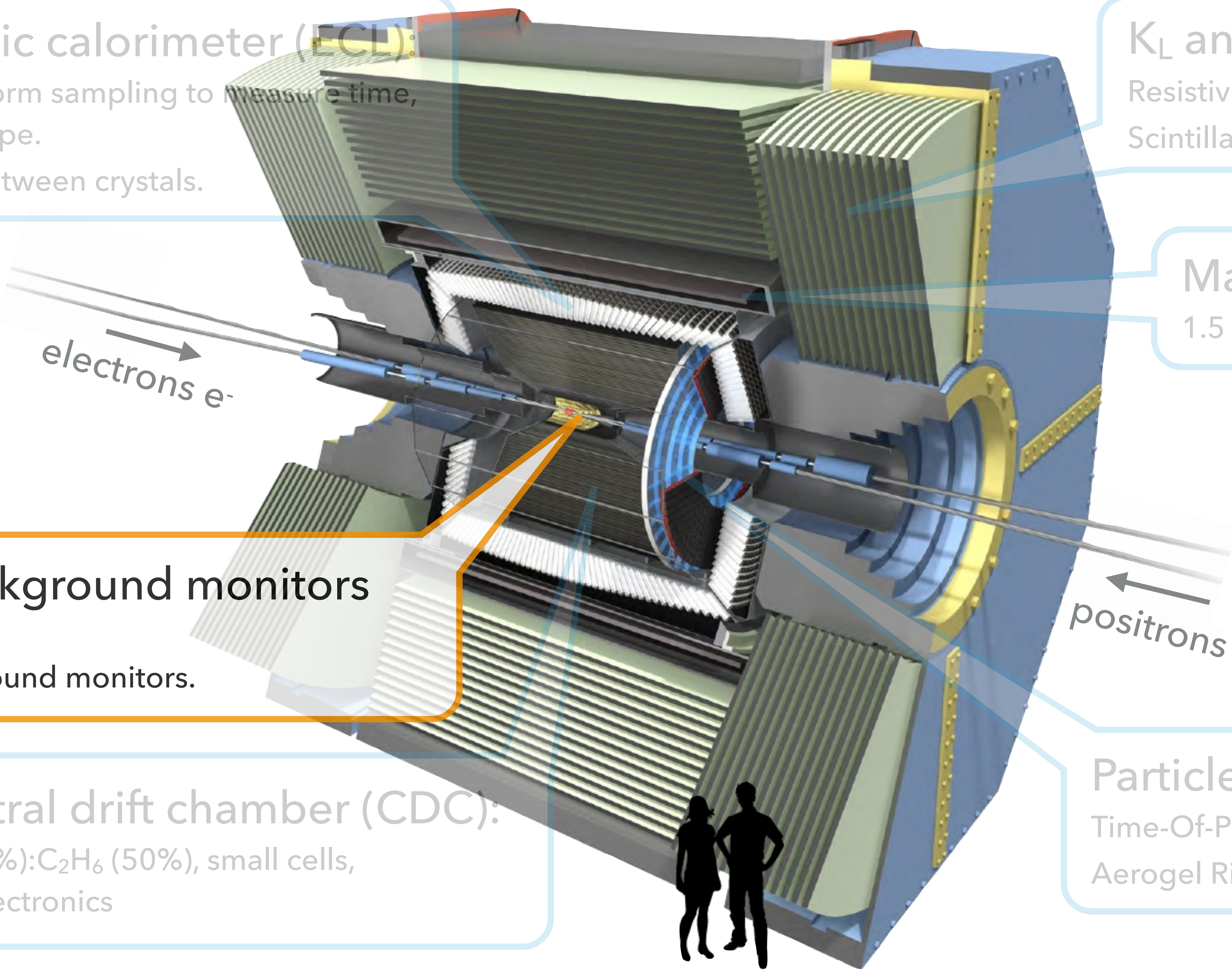
Time-Of-Propagation counter (TOP) (barrel)

Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

Belle II projected luminosity



Belle II detector during Phase 2 (2018)



Electromagnetic calorimeter (ECL):
CsI(Tl) crystals, waveform sampling to measure time, energy, and pulse-shape.
No projective gaps between crystals.

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

Magnet:
1.5 T superconducting

BEAST II background monitors
1/8 PXD, 1/16 SVD
Additional background monitors.

Trigger:
Hardware: < 8 kHz
no software trigger

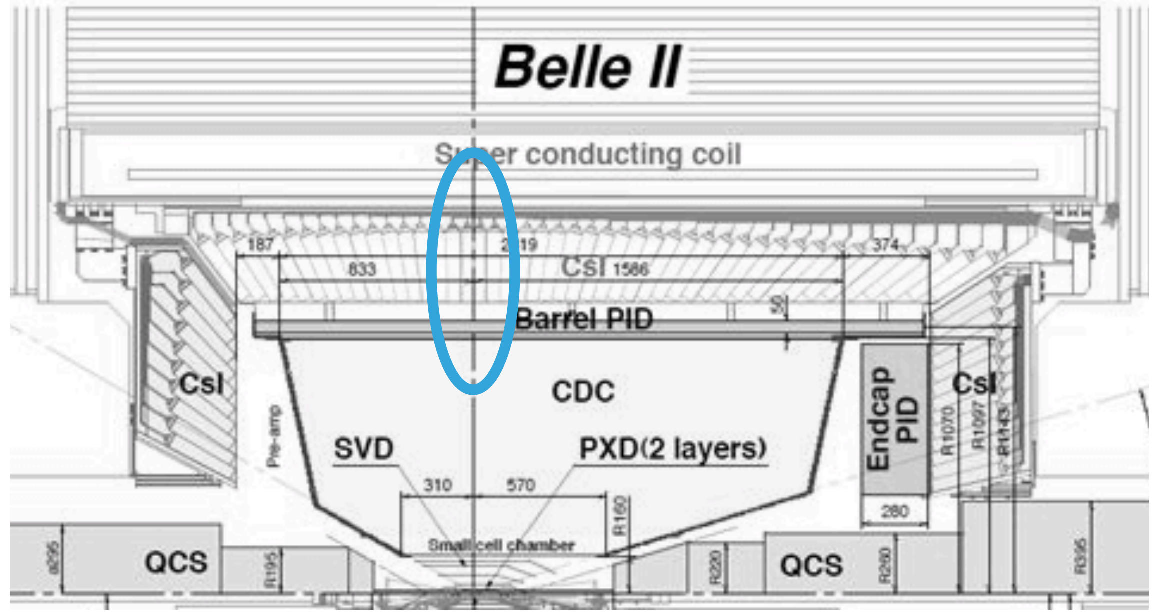
Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells,
fast electronics

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

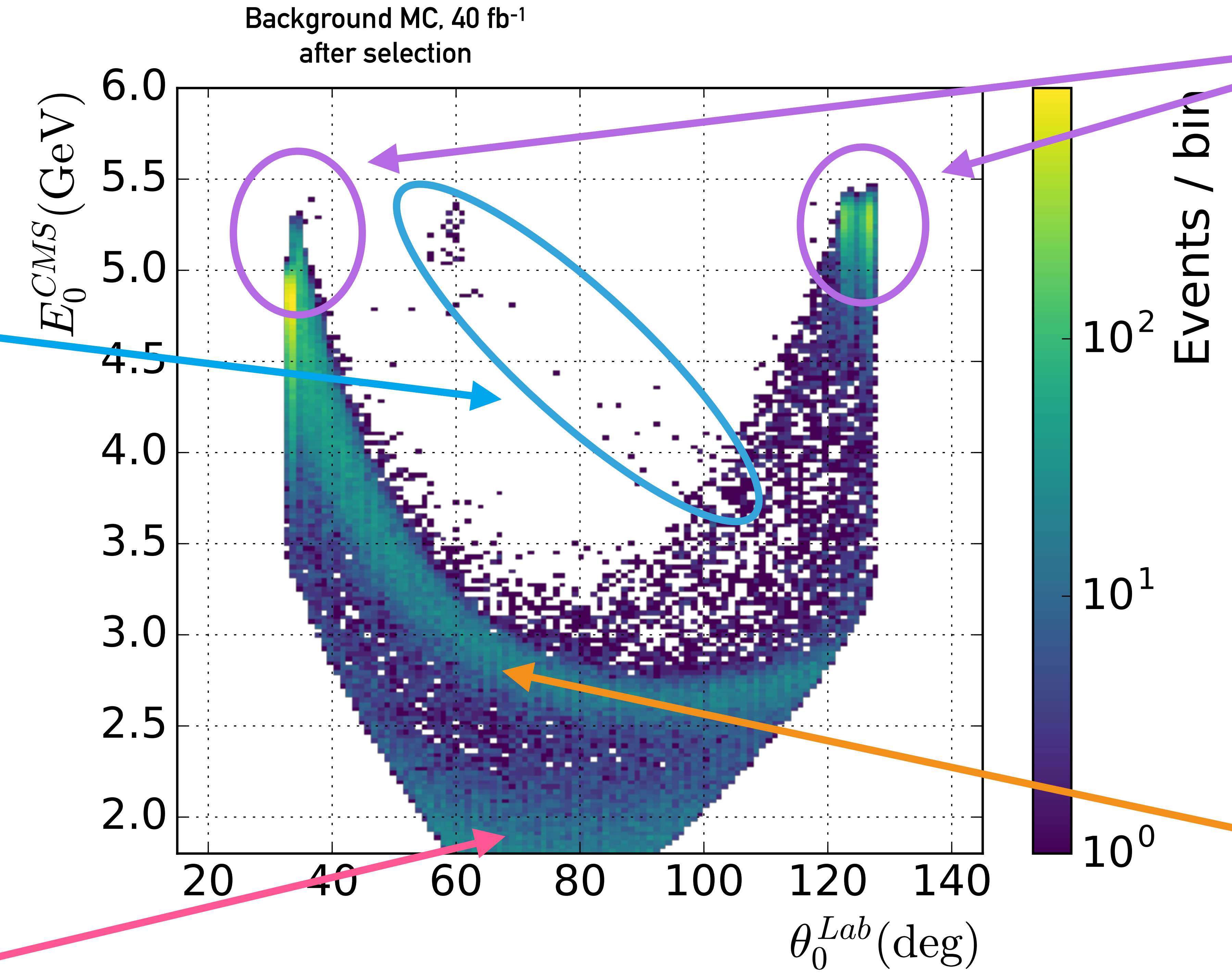
Belle II during Phase 2

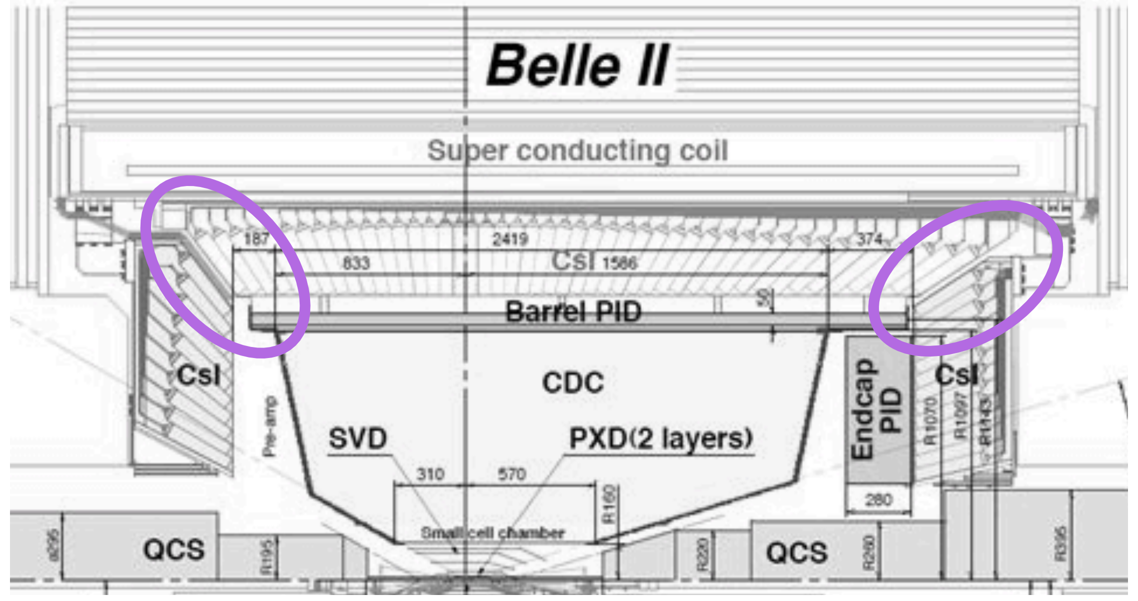
- **No vertex detectors**: Rather bad vertex resolution. Momentum resolution for high pt tracks almost unaffected.
- Very **high relative trigger bandwidth** (rate/luminosity): Loose triggers at L1.
- **Low(er) beam backgrounds**, but from experience we expect the initial backgrounds to be rather high until everything is optimized.
- **No high-level trigger** (HLT).
- **Less material in front of calorimeter** but also less formal approach setting up the cables and other service materials…
- New accelerator, new detector, new reconstruction software: **Learning phase**.
- **Small dataset** compared to BaBar and Belle → Better sensitivity must come from better triggers or detector.

Belle II: Invisible Dark Photon decays, backgrounds

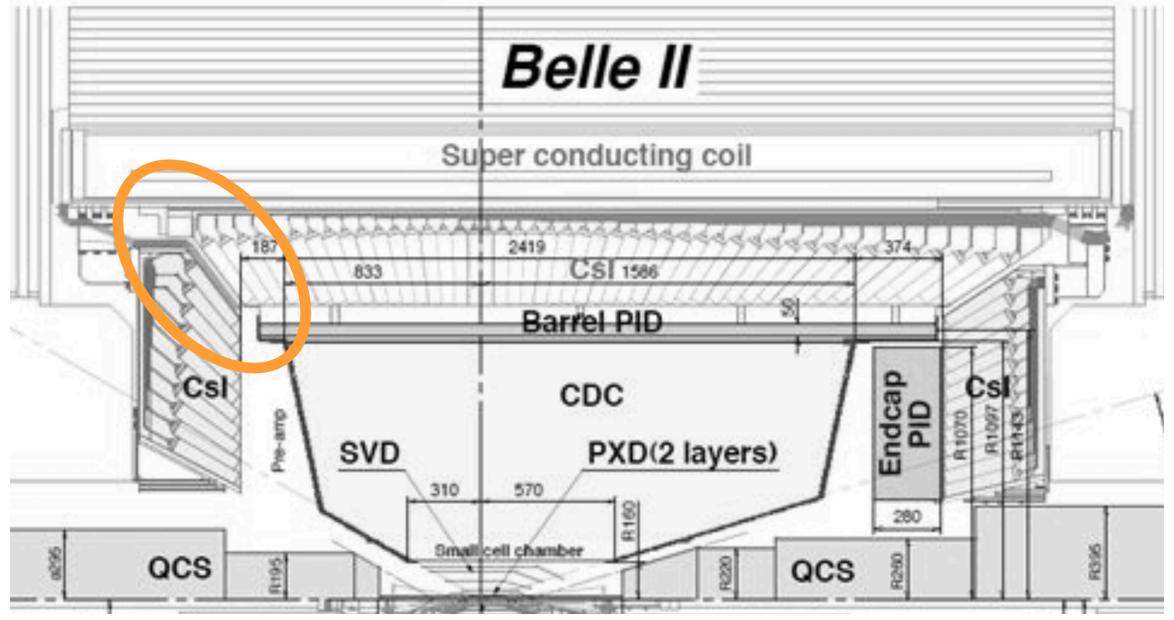


ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance





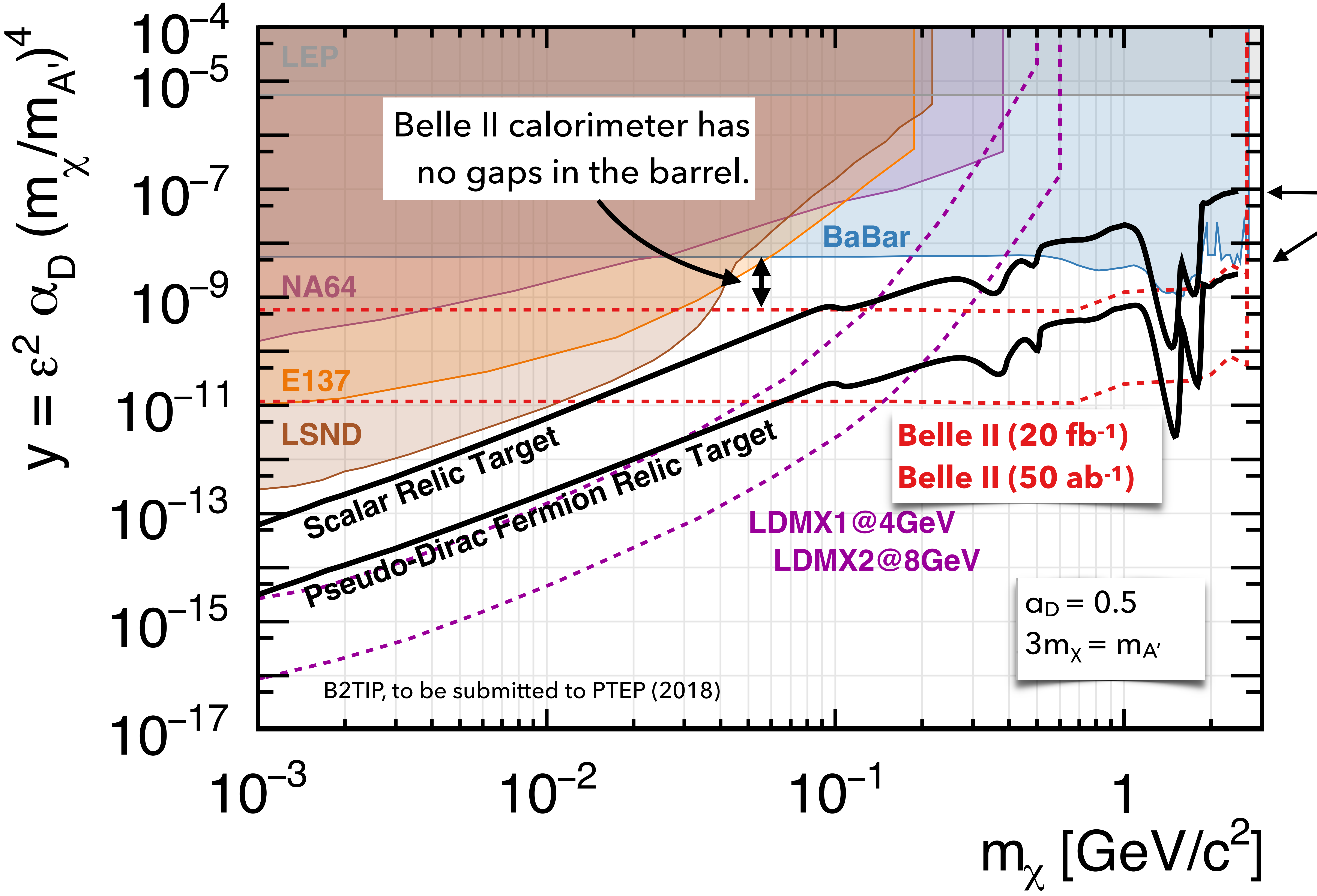
ee→2γ
1γ in ECL BWD or FWD gap



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

ee→eeγ
both electrons
out of tracking acceptance

Belle II: Invisible Dark Photon decays, exp. sensitivity

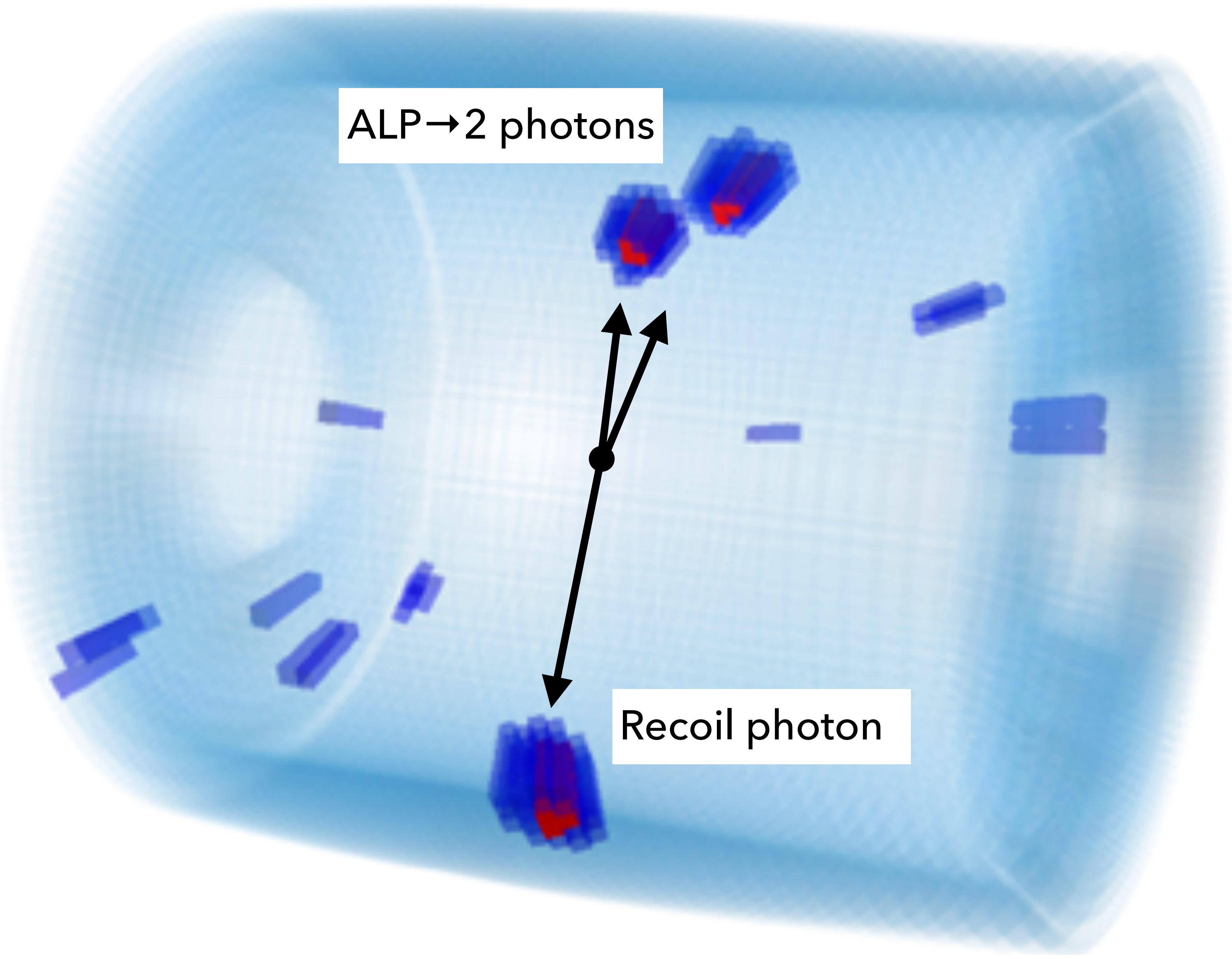


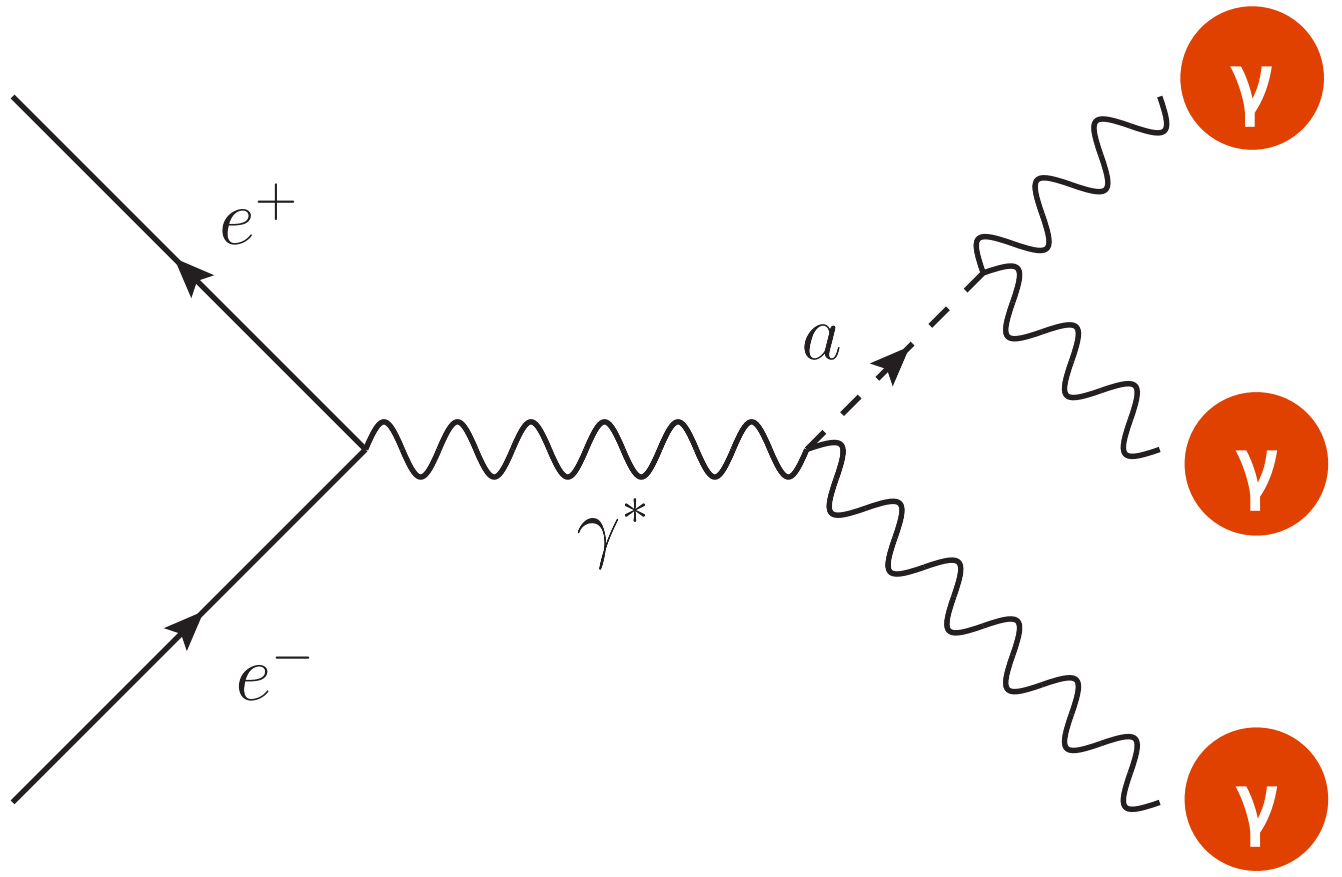
References:
J. Alexander et al. (2016), arXiv:1608.08632
Natalia Toro, private communication (20170
J. P. Lees et al., BaBar (2017), arXiv:1702.0332
B2TIP, to be submitted in PTEP (2018)

*Relic density lines assume a standard cosmological history and that there is only a single component of dark matter, which only interacts via Dark Photon exchange.

Belle II: Axion-Like Particles decaying to photons

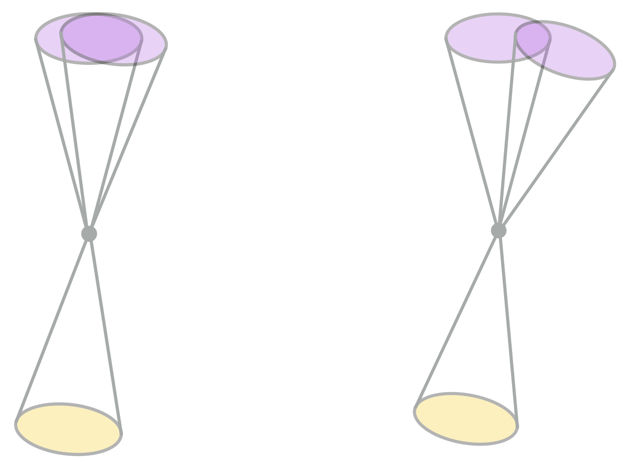
- Axion-like particles (ALPs) are pseudo-scalars and couple to bosons. Unlike QCD Axions, ALPs have no relation between mass and coupling.
- Focus on coupling to photons ($g_{a\gamma\gamma}$).
- B-decays give access to coupling to charged bosons (need rather large datasets »1ab^{-1} to improve).
- No Belle or BaBar analysis yet.

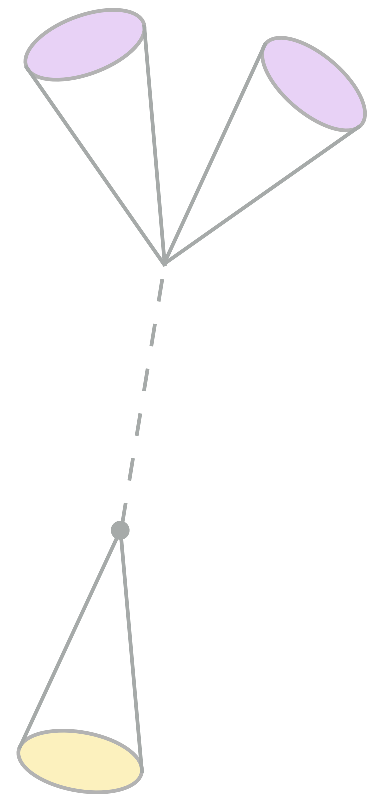




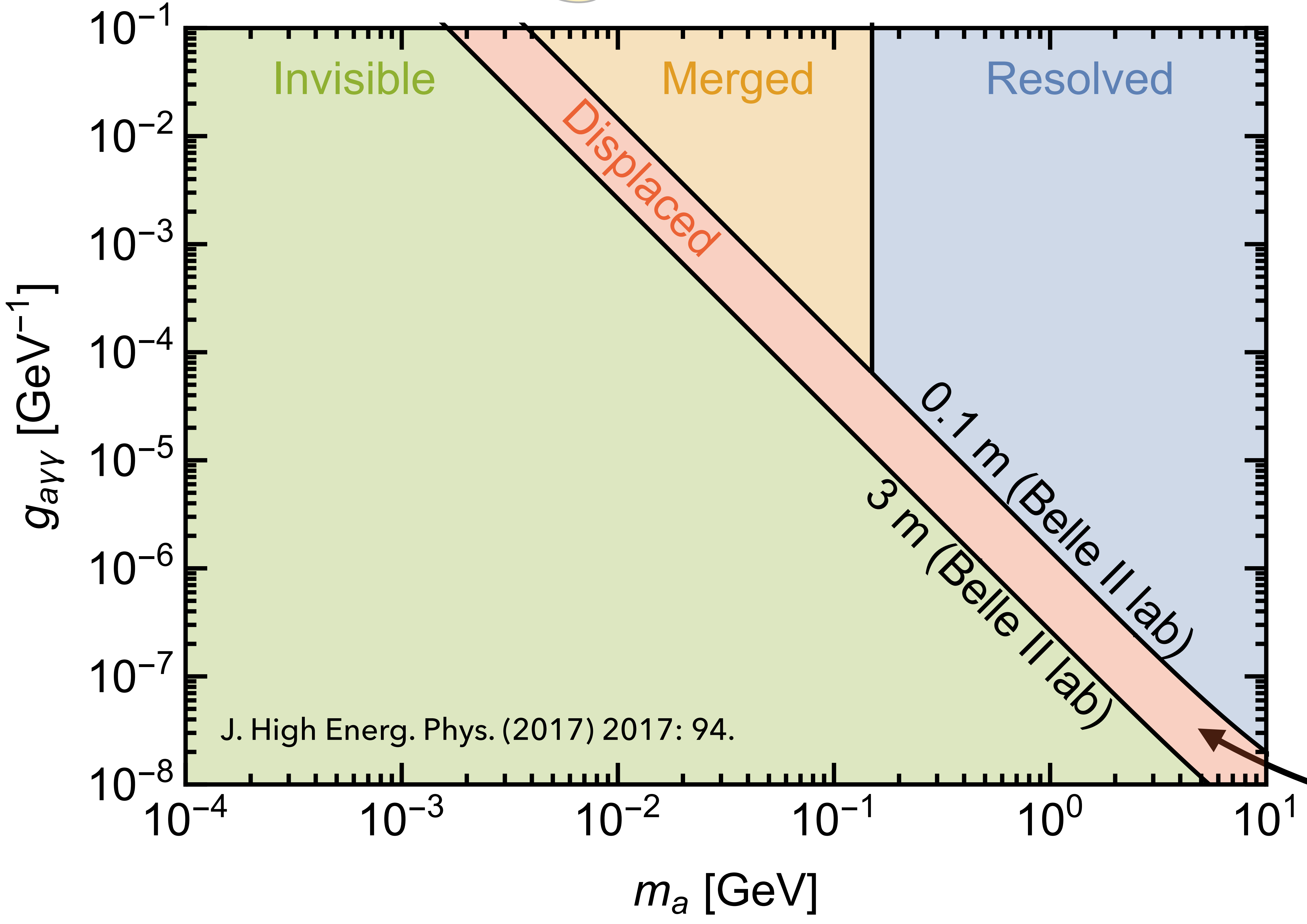
Belle II: Axion-Like Particles decaying to photons

Two of the photons overlap or **merge**.

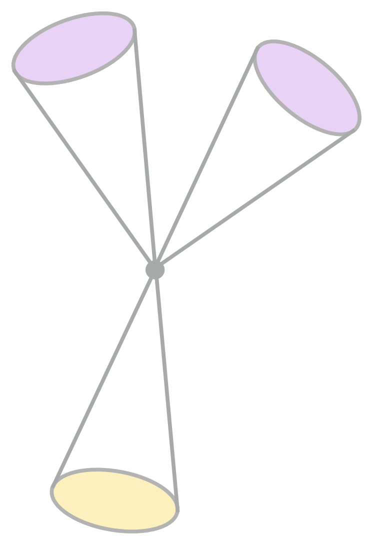




ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.



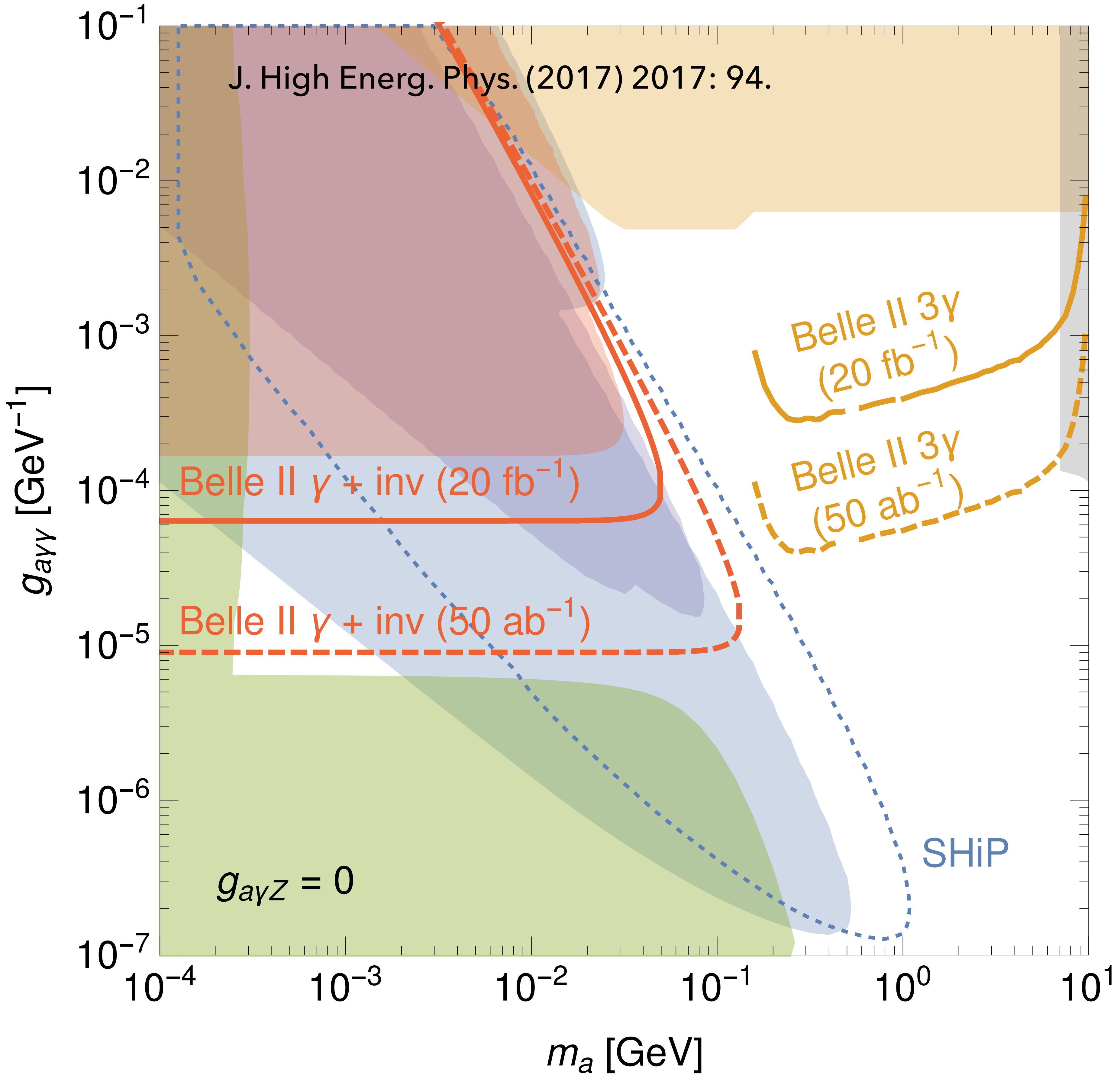
Three **resolved**, high energetic photons.



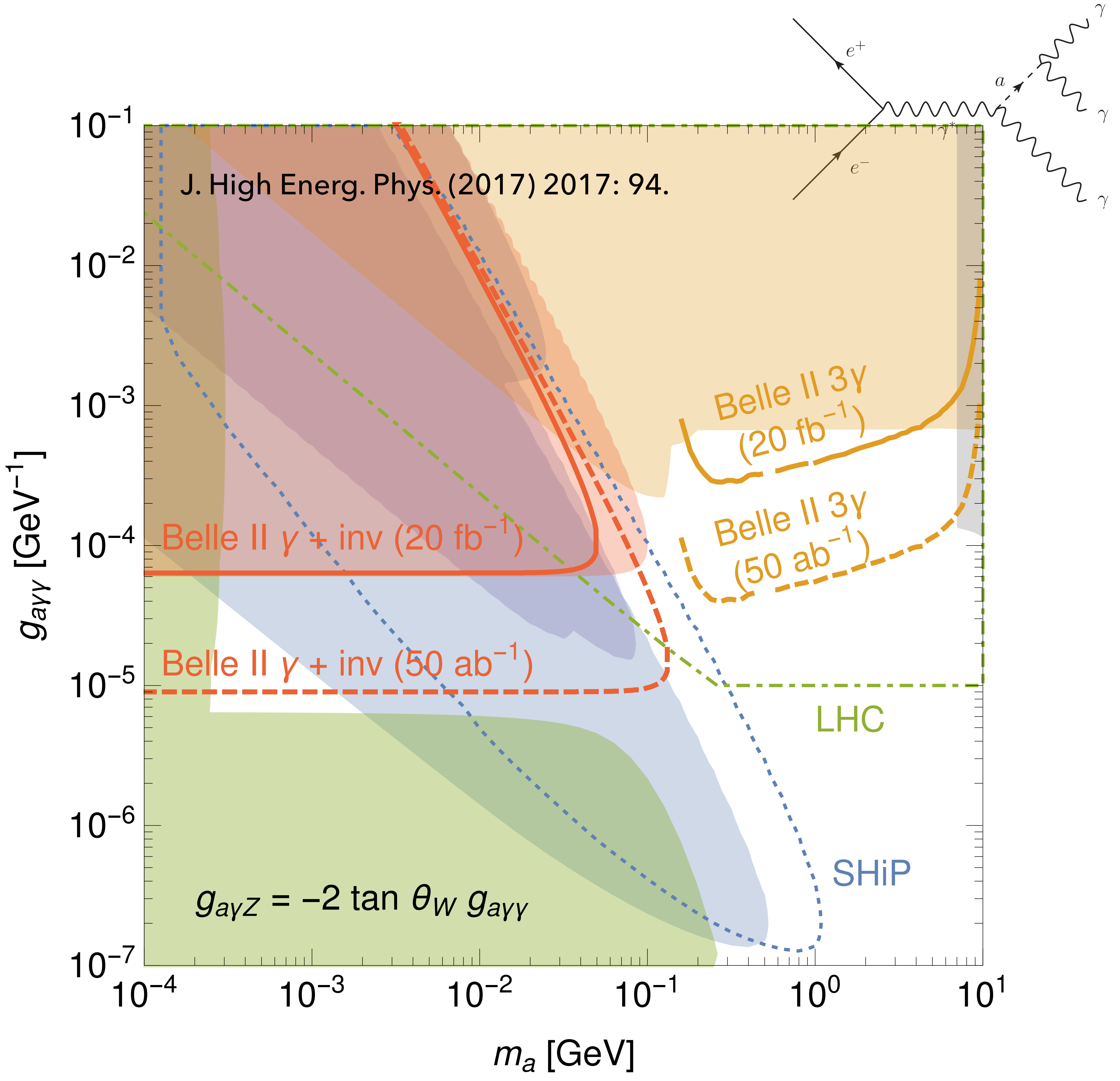
The searches for invisible and visible ALP decays veto this region.

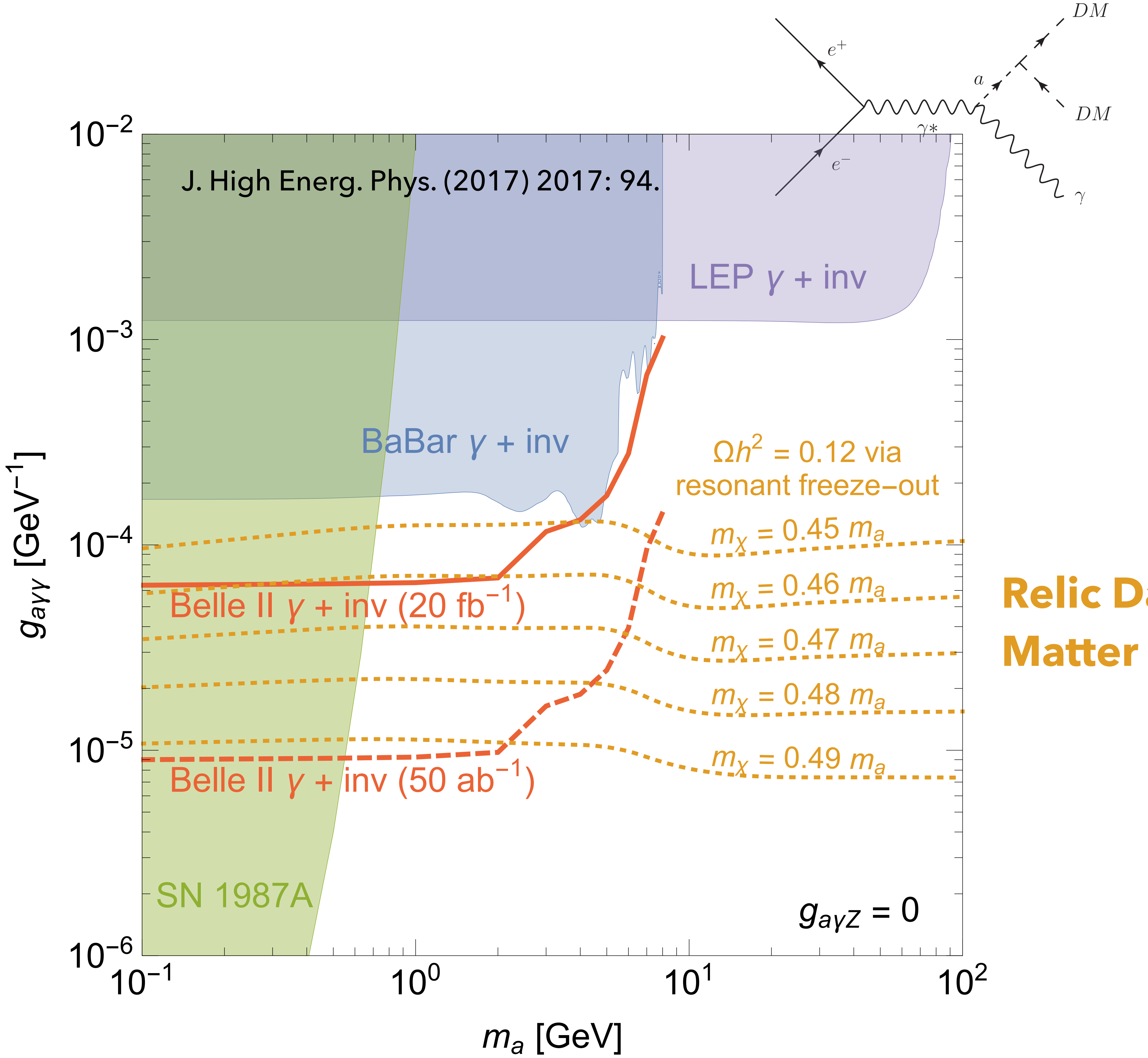
Belle II: Axion-Like Particles decaying to photons

- Select events with three ECL clusters with E ≥ 0.25 GeV and search for a bump in the invariant 2γ mass spectrum.
- Backgrounds are ee→γγγ and ee→γγ followed by γ→ee (pair conversion) outside of the tracking volumes.
- Requires a single photon trigger for long-lived ALPs and a good cluster separation for low mass ALPs at trigger level.



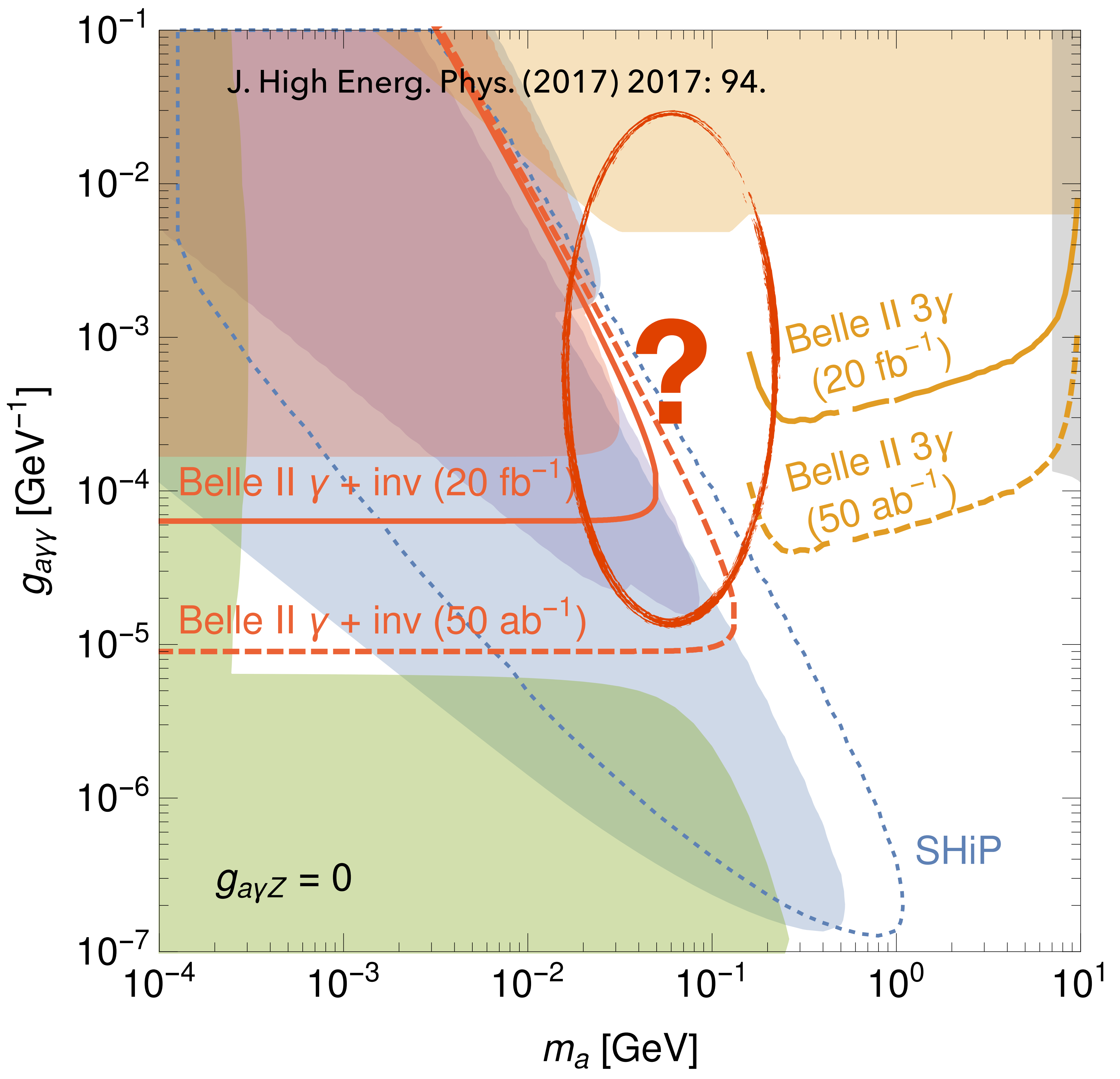
Belle II: γZ couplings and ALPs as mediators for Dark Matter





Relic Dark Matter Density

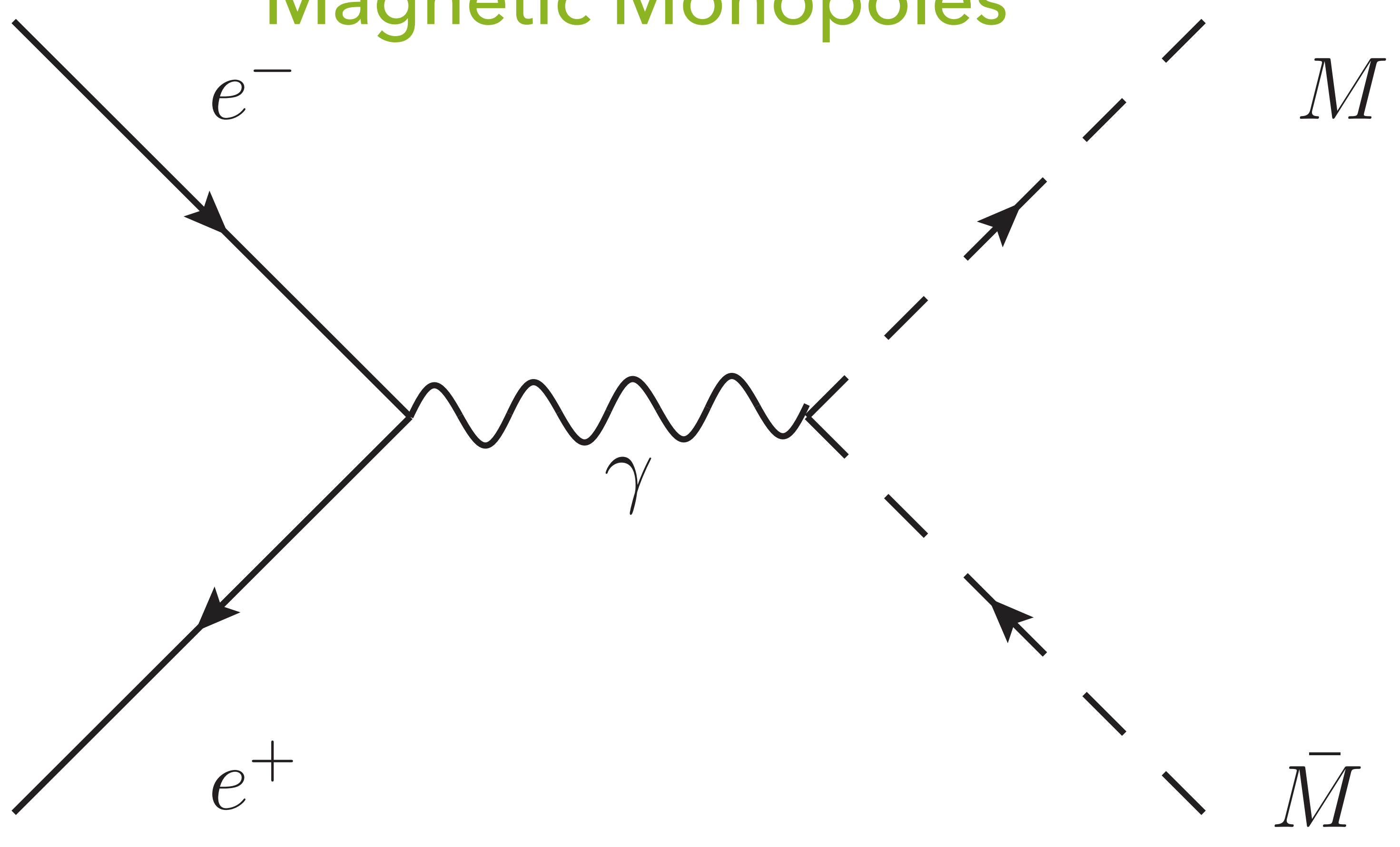
Belle II: ALPs with intermediate masses are difficult



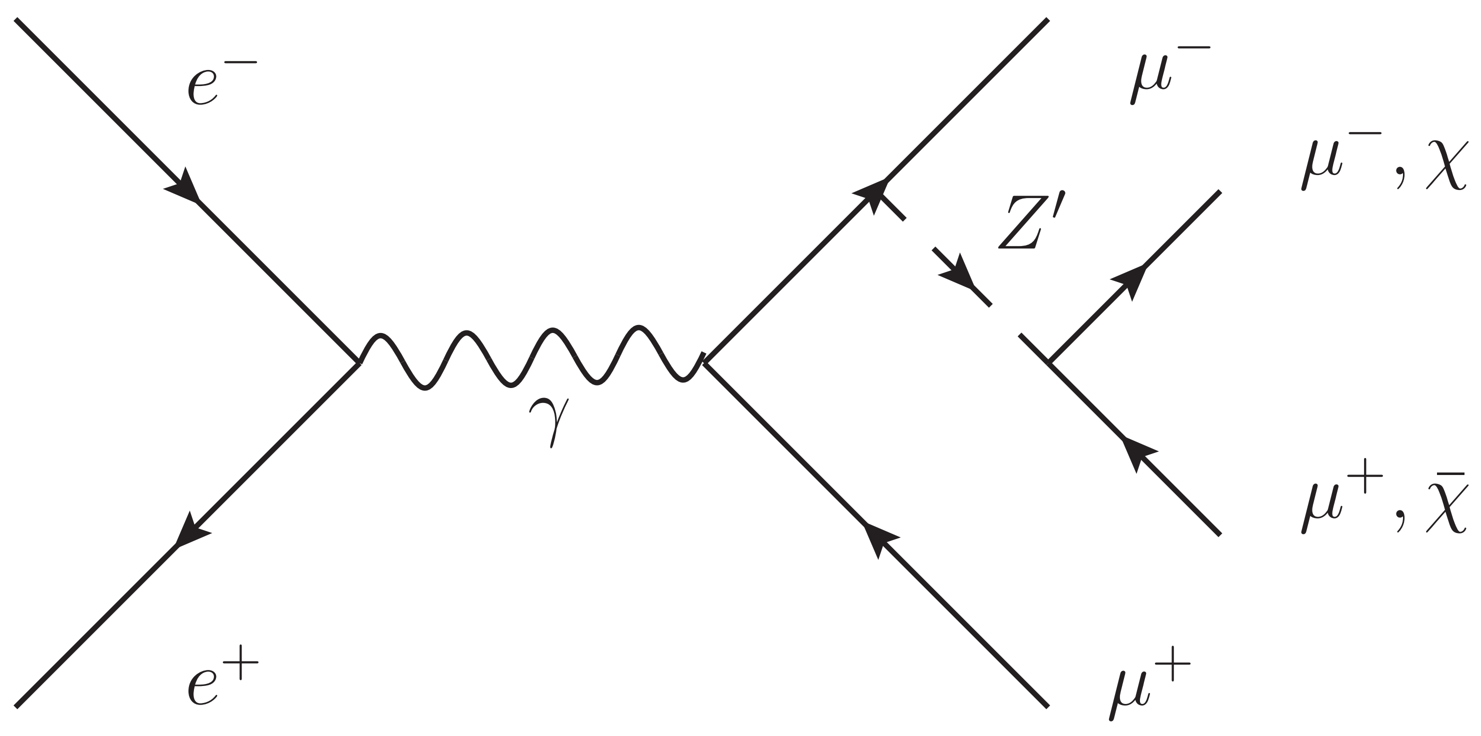
- For small m_a the two decay photons overlap at Belle II, reconstruction limits:
  - > 0.2 GeV (HLT and offline)
  - > 0.5 GeV (L1 trigger)
    - Do not prescale ee→γγ events at L1?
- Additional challenge: SM background ee→γπ^0
- Possible solutions:
  - Improve L1 trigger clustering (detect overlaps)
  - Pair conversion (γ→ee) of one decay photon.
  - Photon fusion production of ALPs.

Belle II: Other exotics searches

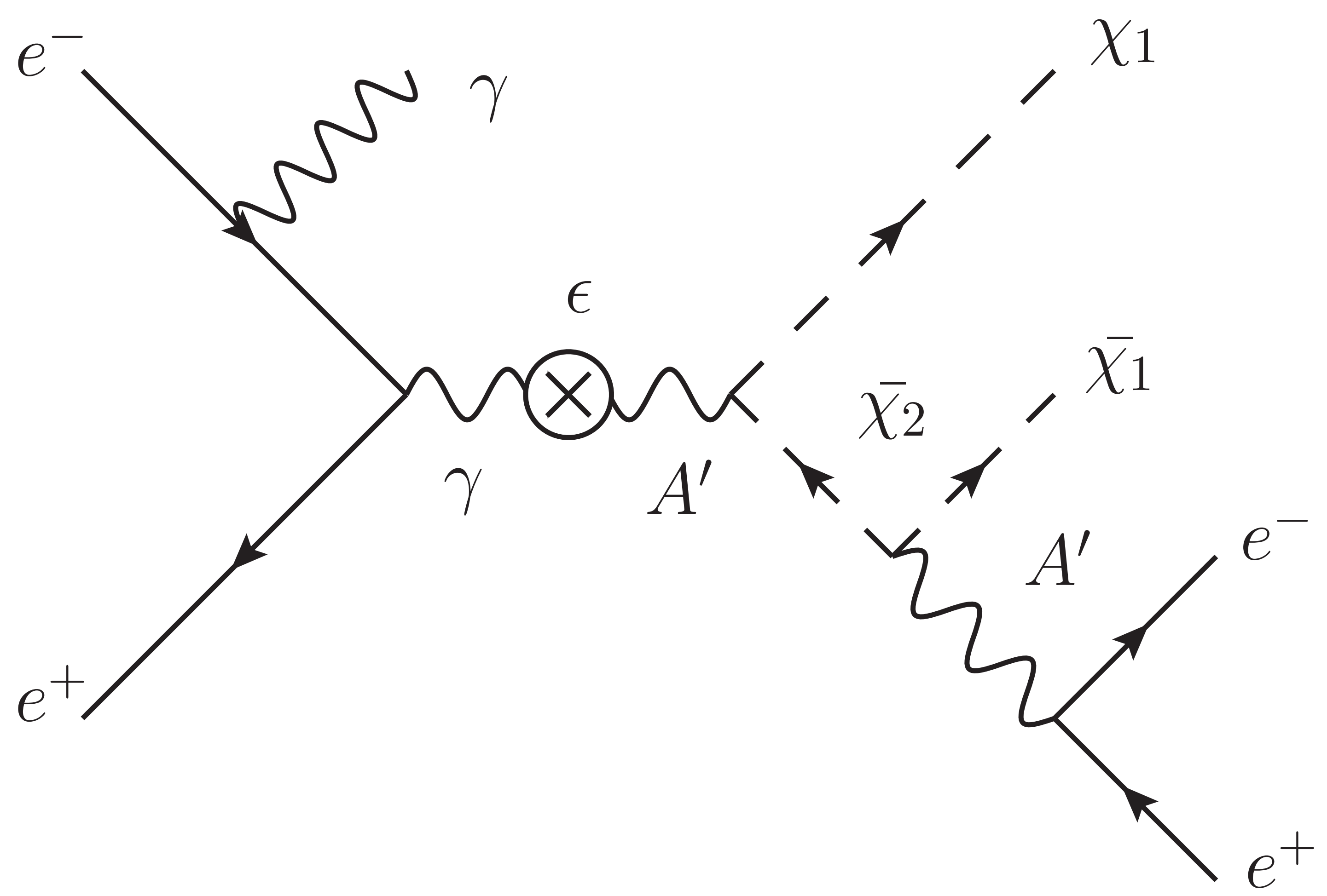
Magnetic Monopoles



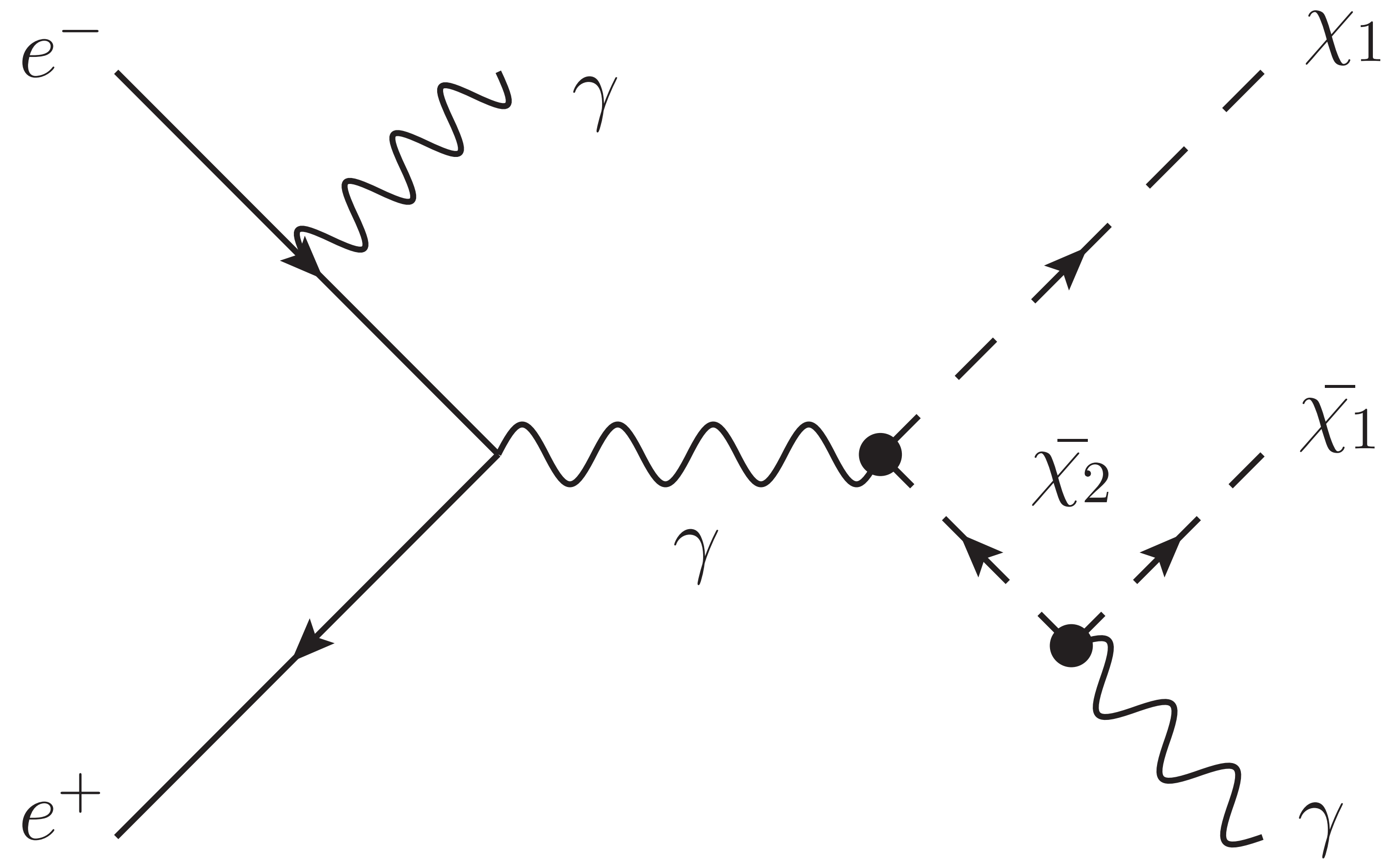
Invisible Z′ decays



Inelastic Dark Matter

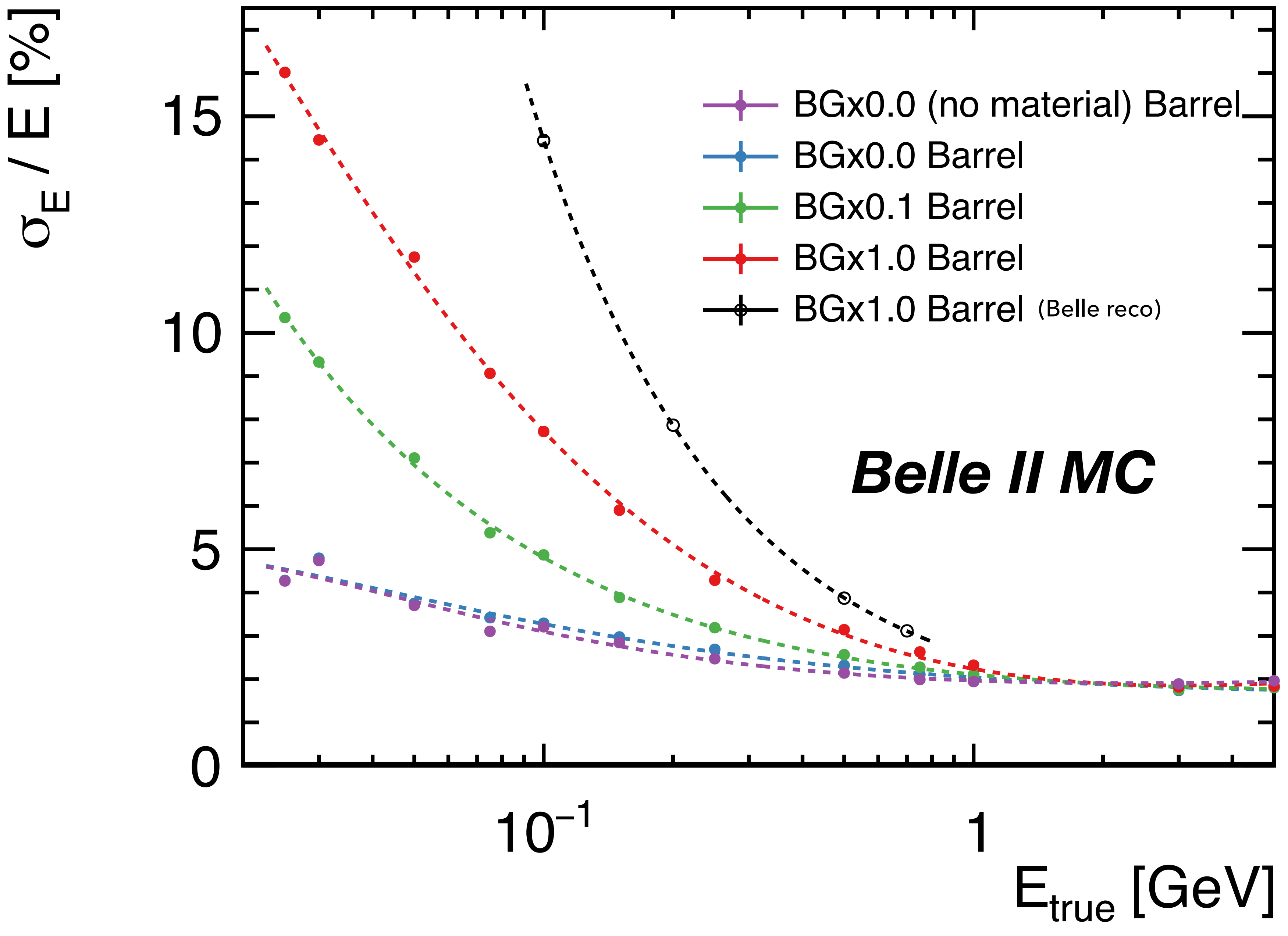


Magnetic Inelastic Dark Matter



Belle II: From 20 fb^{-1} (2018, Phase 2) to 50 ab^{-1} (2025, Phase 3)
→ Higher event rate, higher beam backgrounds

- Trigger
  - From 8 kHz (L1)/8 kHz (HLT) (@4×10^{34} $cm^{-2}s^{-1}$) to 30 kHz (L1)/10 kHz HLT (@8×10^{35} $cm^{-2}s^{-1}$). Trigger rate is almost only Bhabha debris (cannot be easily identified). Single photon triggers probably ok. $\gamma\gamma$ prescale may be challenging for low mass ALPs.
- Physics background:
  - Mostly relevant for "extra energy" analyses and analyses that use photons ≲100 MeV. Single photon ok, ALPs slightly affected (efficiency loss due to higher energy selections).
- Resolution:
  - Most detectors suffer, largest impact on calorimeter. Energy resolution at low energies degrades significantly.

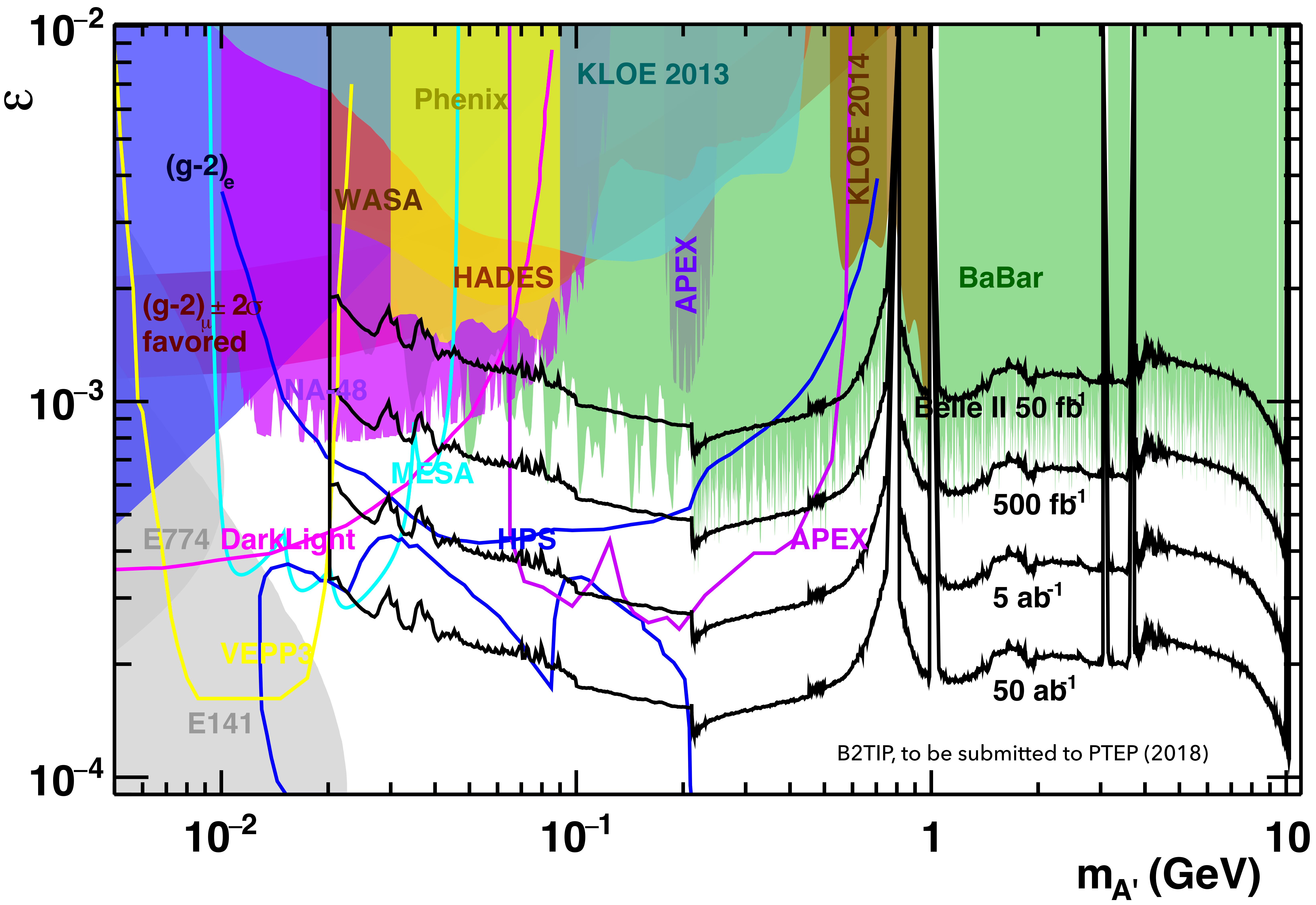


Summary

- BaBar single photon search excludes g-2 favoured region of parameter space.
- Belle II at the SuperKEKB collider in Japan starts data taking this year. The planned integrated luminosity is 50 times larger than Belle.
- Belle II is an ideal place to search for invisible and fully neutral final states
- Dedicated triggers for Dark Sector searches at Belle II: Ready for 2018 run, we aim to have them for the full Belle II running.
- Already a small dataset ($\sim 20 fb^{-1}$) will give world leading sensitivity for invisible Dark Photon decays at Belle II

Additional information

Dark Photon: Visible decays



L1 trigger menu: Basic items

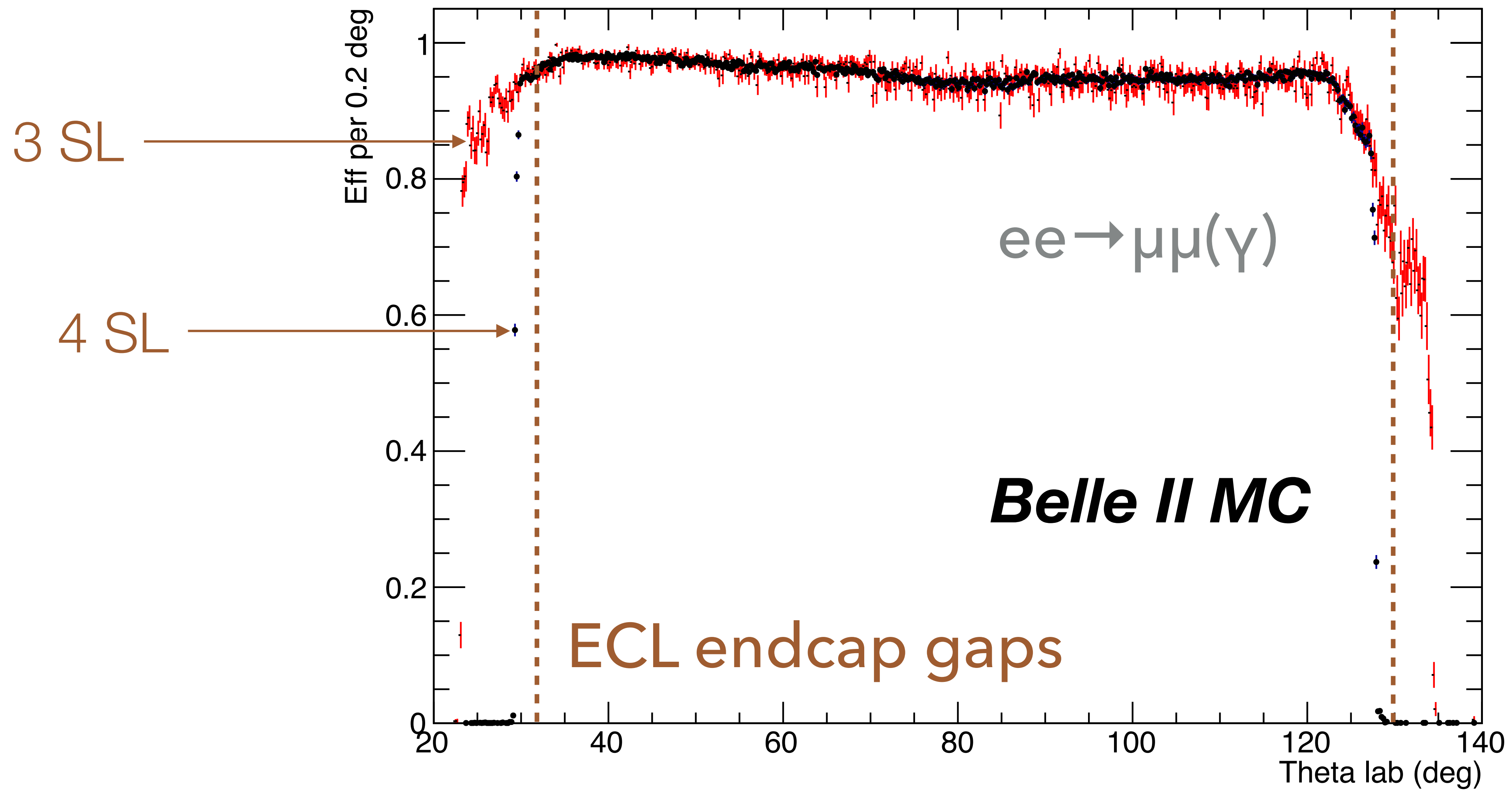
ECL trigger objects

nClust	ECL clusters
n300MeV	Clusters with E > 300 MeV
n2GeV	Clusters with E*>2 GeV
n2GeV414	Clusters with E*>2 GeV and ThetaID in [4,14]
n2GeV231516	Clusters with E*>2 GeV and ThetaID = 2, 3, 15 or 16
n2GeV117	Clusters with E*>2 GeV and ThetaID = 1 or 17
n1GeV415	Clusters with E*>1 GeV and ThetaID in [4,15]
n1GeV2316	Clusters with E*>1 GeV and ThetaID = 2, 3, or 16
n1GeV117	Clusters with E*>1 GeV and ThetaID = 1 or 17
nPhiPairHigh	Pairs of clusters back-to-back in ϕ*, both clusters >250 MeV
nPhiPairLow	Pairs of clusters back-to-back in ϕ*, at least 1 cluster <250 MeV
n3DPair	Pairs of clusters back-to-back in ϕ* and θ*
nECLBhabha	Bhabhas or γγ selected using ECL only
iBhabha1	Index of 1st cluster in ELCBhabha
iBhabha2	Index of 2nd cluster in ELCBhabha

Number of clusters with different energy thresholds.

Back-to-back clusters

CDC trigger objects



nTrk2D	Tracks (2D)
nTrk3D	Tracks (3D)
nTrkZ25	Tracks with |Z0| < 25 cm
nTrkZ10	Tracks with |Z0| < 10 cm

Number of tracks

ECL+CDC trigger objects

nTrkBhabha	Bhabhas selected using ECL and CDC
nSameHem1Trk	Clusters in the same hemisphere as the track, 1 track event
nOppHem1Trk	Clusters in the opposite hemisphere as the track, 1 track event

Tracks matched to clusters.

L1 trigger menu

	Bit	Phase 2 and 2019	Prescale Phase 2	Changes for 2020	Prescale 2020
	0	3 or more 3D tracks			
$\Upsilon(3S)\to\pi\pi\Upsilon(1S)$, $Z'\to$Invisible	1	2 3D tracks, ≥1 within 25 cm, not a trkBhabha		2 3D tracks, ≥1 within 10 cm, not a trkBhabha	
	2	2 3D tracks, not a trkBhabha	20		20
	3	2 3D tracks, trkBhabha			2
	4	1 track, <25cm, clust same hemi, no 2 GeV clust		1 track, <10cm, clust same hemi, no 2 GeV clust	
$\tau\tau$	5	1 track, <25cm, clust opp hemi, no 2 GeV clust		1 track, <10cm, clust opp hemi, no 2 GeV clust	
	6	≥3 clusters inc. ≥1 300 MeV, not an eclBhabha		≥3 clusters inc. ≥2 300 MeV, not an eclBhabha	
ISR, ALPs	7	2 GeV E* in [4,14], not a trkBhabha			
	8	2 GeV E* in [4,14], trkBhabha			2
	9	2 GeV E* in 2,3,15,16, not eclBhabha			
low mass ALPs	10	2 GeV E* in 2,3,15 or 16, eclBhabha			
	11	2 GeV E* in 1 or 17, not eclBhabha	10		20
	12	2 GeV E* in 1 or 17, eclBhabha	10		20
$A\to$Invisible	13	exactly 1 E*>1 GeV and 1 E>300 MeV, in [4,15]			
	14	exactly 1 E*>1 GeV and 1 E>300 MeV, in 2,3 or 16			5
	15	clusters back-to-back in phi, both >250 MeV, no 2 GeV			
ALPs from $\gamma\gamma$ fusion	16	clusters back-to-back in phi, 1 <250 MeV, no 2 GeV		clust back-to-back in phi, <250 MeV, no 2 GeV, no trk>25cm	3
Endcap muons	17	clusters back-to-back in 3D, no 2 GeV			5

Tracks only

Tracks and clusters

Clusters

L1 Phase 2 & 2019 Summary: L=4×10^{34} cm^{-2}/s = 40 nb^{-1}/s = 5% nominal

Sample	Note	Generated sigma nb	Percentage selected	Accepted sigma nb	Rate Hz 40 nb-1/sec	Fiducial efficiency %	Barrel efficiency %
Bhabha	0.5 & 5 deg	122760	0.150	184	7358	92.2	100
gamma gamma		25.2	12.4	3.1	125	96.9	100
e e e e		1693	0.28	4.7	188		
e e mu mu		67.8	3.1	2.1	84		
tau tau		0.919	91.9	0.8	34	94.6	97.6
mu mu		1.115	70.8	0.8	32	92.5	100
BB		1.05	100.0	1.1	42		
u u-bar		1.61	90.7	1.5	58		
d d-bar		0.4	90.4	0.4	14		
s s-bar		0.38	95.9	0.4	15		
c c-bar		1.3	100.0	1.3	52		
2gamma production of ALP	0.2 GeV					12.1	
	0.5 GeV					85.9	
	2 GeV					97.6	
	10 GeV					99.0	100
2gamma production of pi0	no tag					2.1	0.2
	1 tag						
ALP--> invisible	9.3 GeV					82.7	93.1
ALP --> gamma gamma	0.2 GeV					99.1	100
	0.5 GeV					99.3	
	3 GeV					99.6	
	9.3 GeV					99.7	
a' --> e e	0.5 GeV					97.8	100
a' --> invisible	0.5 GeV					83.6	100.0
	9.3 GeV					74.4	94.0
gamma pi+pi-	0.5 GeV					96.3	99.9
tau --> e gamma						99.4	100.0
tau --> mu gamma						98.8	99.8
Y3S --> pi pi Y1S						44.0	49.8
TOTAL				200	8003		

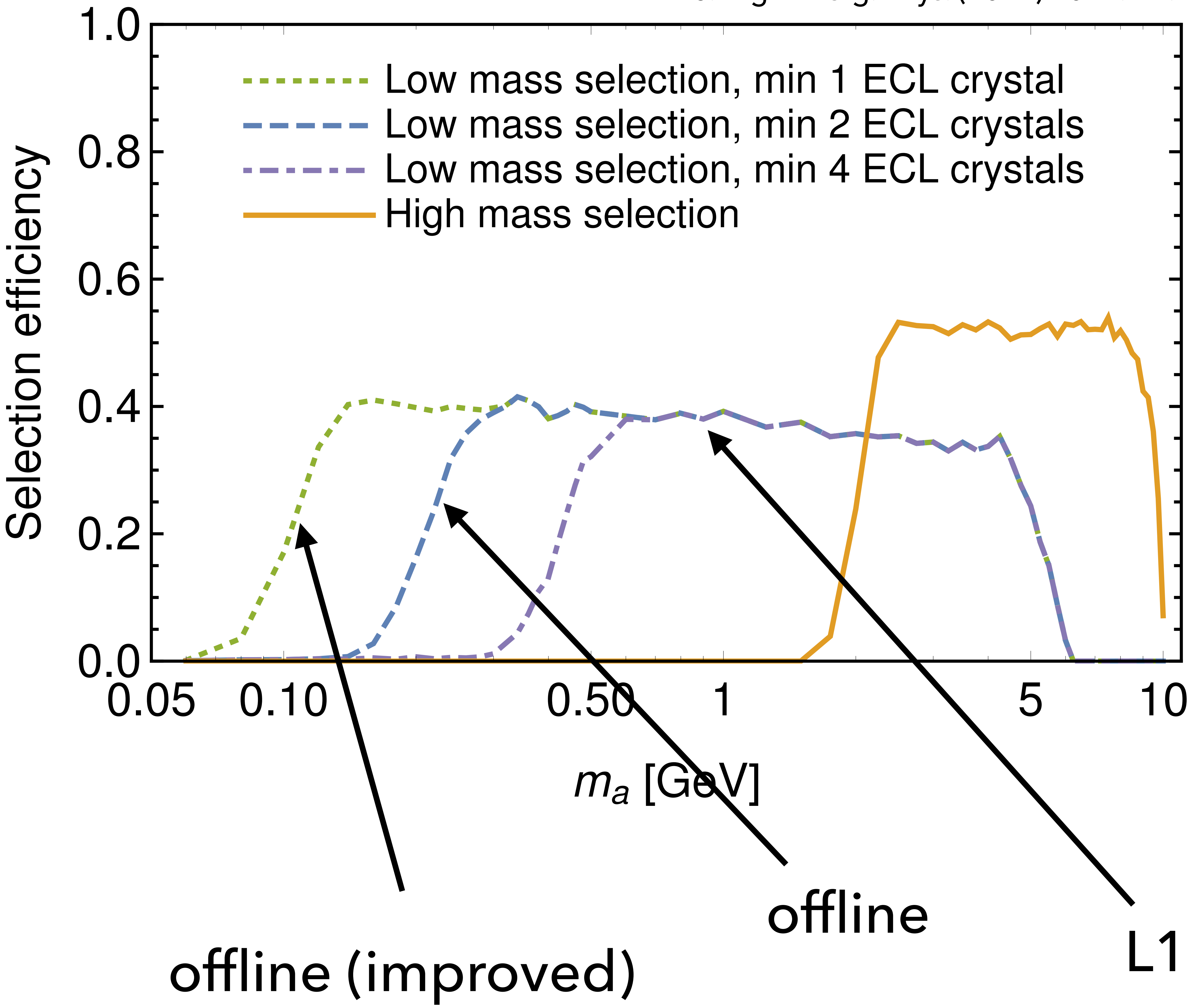
Bhabha (0.5°): 7.4 kHz rate

B and D physics: 100% efficiency

Phase 2 physics: 75-100% efficiency

ALPs: Cluster overlaps

J. High Energ. Phys. (2017) 2017: 94.



SuperKEKB machine parameters

2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.20×10^{-4}	4.55×10^{-4}		
σ_δ	$7.92(7.53)\times10^{-4}$	$6.37(6.30)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

http://www-superkekb.kek.jp/documents/MachineParameters_170901.pdf