Shedding light on dark matter

ongoing searches for the dark photon at Belle and Belle II

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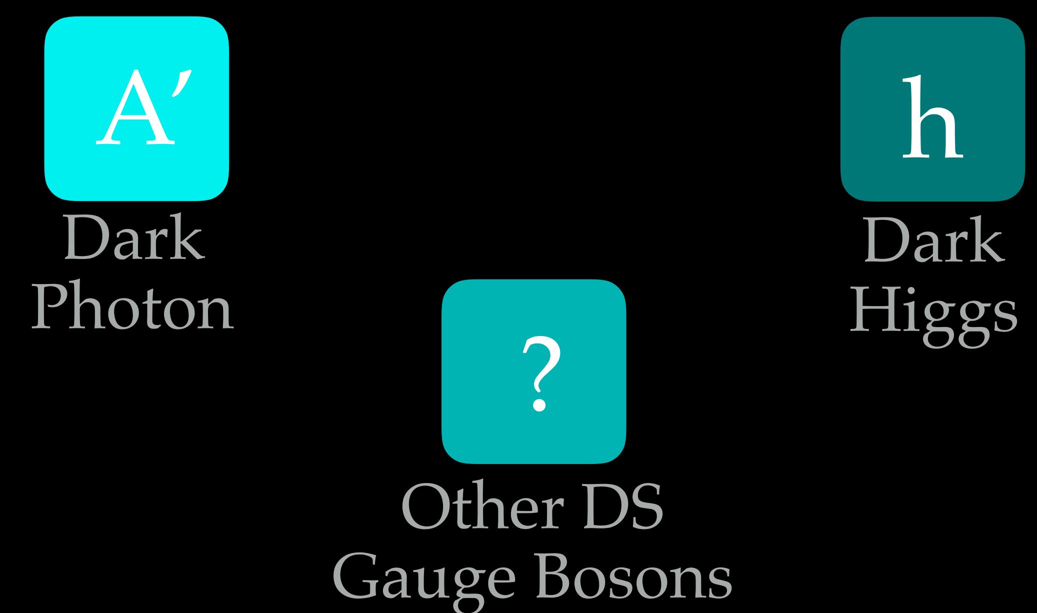
under the supervision of

Dr Phillip Urquijo

University of Melbourne | Belle II Collaboration

- Gauge bosons mediate interactions between visible matter.
- But what mediates interactions between dark matter and itself and dark matter and visible matter?
- If dark matter is not a WIMP, then we must search for a portal between the visible and dark sectors.

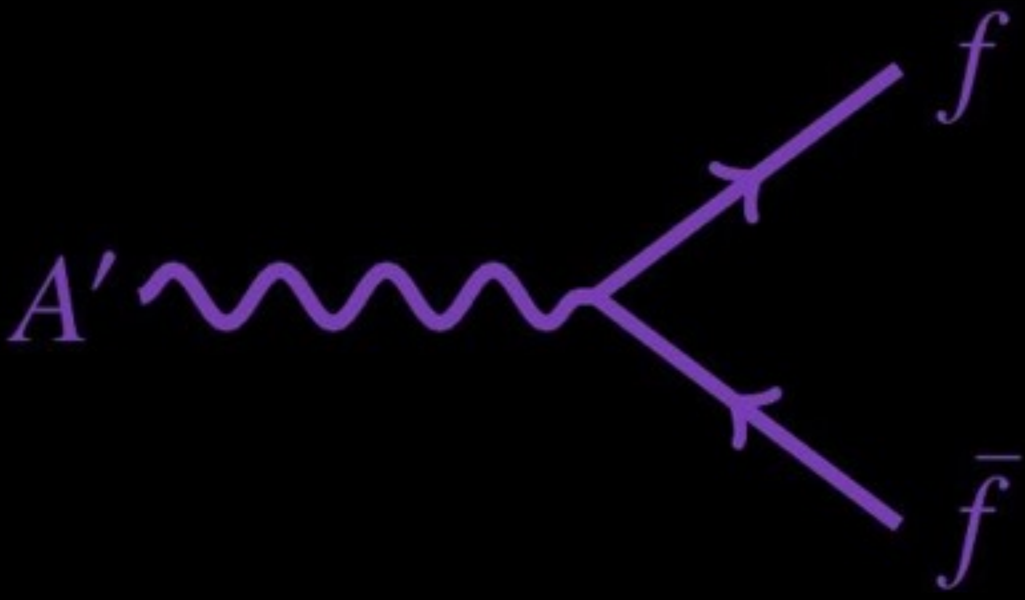


- A dark sector gauge boson couples to the conserved current associated with the dark sector group, $U(1)_X$.
- $U(1)_X$ undergoes kinetic mixing with the SM $U(1)_Z$ gauge group (our portal to the dark sector).
- The inclusion of this dark sector gauge group provides additional terms to the SM Lagrangian.

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

CITATION: B. HOLDOM, PHYS REV LETT B:166:196 (1986)

- $U(1)_X \otimes U(1)_Z$ undergoes SSB similar to that of $SU(2)_L \otimes U(1)_Y$ in the SM.
- This gives rise to mass eigenstates A and A′, where $m_A = 0$ and $m_{A'} > 0$.
- It also follows that the dark photon interacts with BOTH the dark sector and the visible sector.



CITATION: B. BRAHMACHARI, A. RAYCHAUDHURI, NUCL PHYS B:887 (2014)

THE DARK PHOTON PRODUCTION CROSS-SECTION

- The mixing strength between the photon and dark photon is constrained through the cross-section as…

$$\sigma = \frac{2\pi\varepsilon^2\alpha^2}{E_{cm}^2}\left(1-\frac{m_{A'}^2}{E_{cm}^2}\right)\left(\left(1+\frac{2m_{A'}^2/E_{cm}^2}{(1-m_{A'}^2/E_{cm}^2)^2}\right)\Theta - \cos\theta_{max} + \cos\theta_{min}\right)$$

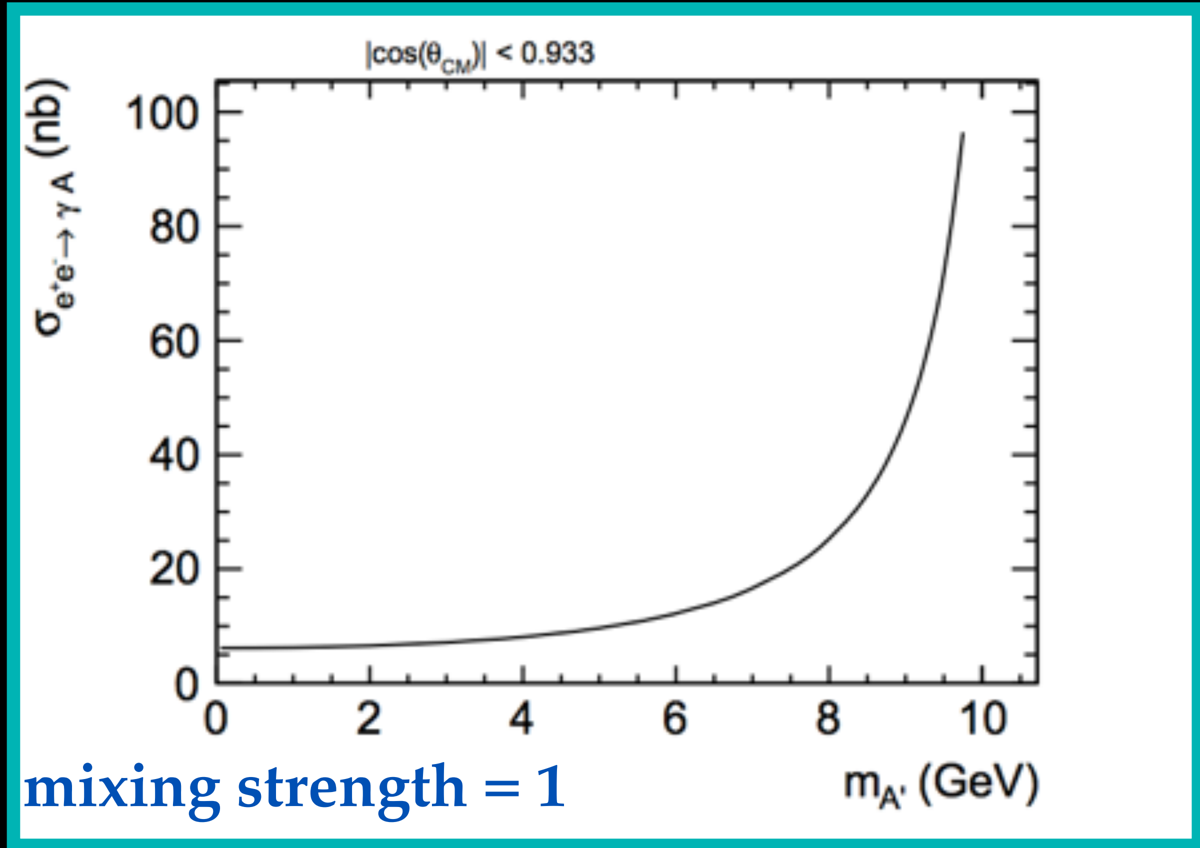
$$\Theta = \log\left(\frac{(1+\cos\theta_{max})(1-\cos\theta_{min})}{(1-\cos\theta_{max})(1+\cos\theta_{min})}\right)$$

Mixing Strength Parameter

CITATION: R. ESSIG, P. SCHUSTER, N. TORO, PHYS REV LETT D:80:015003 (2009)

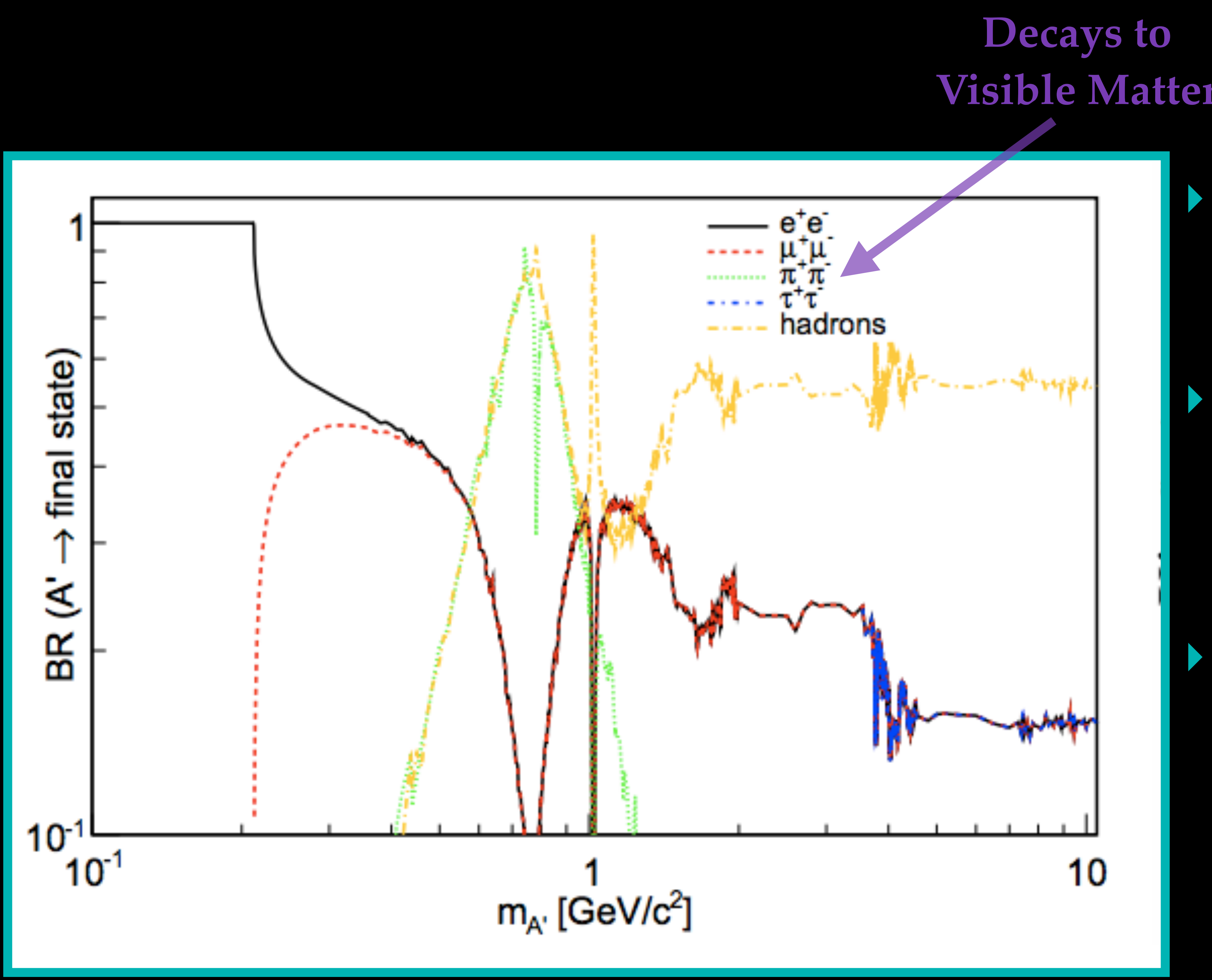
- Belle II projections

- Fixing the mixing strength to 1



CITATION: C. HEARTY, T. FERBER, B2TIP REPORT: TAU/LOW-MULTIPLICITY CHAPTER (2017)

DARK PHOTON BRANCHING RATIOS



- Dielectron mode has the largest branching fraction.
- Dimuon mode will be dominant as there exist far fewer backgrounds.
- We avoid exploring hadronic modes because resonances cause for messy backgrounds.

GLOBAL EXPERIMENTAL EFFORTS

Experiment	Decay Mode
BaBar	$e^+e^- \to \gamma A'$
BESIII	$J/\psi \to \gamma A'$
KLOE 2013	$\phi \to \eta A'$
KLOE 2014	$e^+e^- \to \gamma A'$
E141	$e^-_{\text{beam}}(\text{nucleus}) \Rightarrow e^- A'$
E774	$e^-_{\text{beam}}(\text{nucleus}) \Rightarrow e^- A'$
A1	$e^-_{\text{beam}}(\text{nucleus}) \Rightarrow e^+e^- \to A'$
APEX	$e^-_{\text{beam}}(\text{nucleus}) \Rightarrow e^+e^- \to A'$
HADES	$p^+_{\text{beam}}(\text{nucleus}) \Rightarrow K^+K^- \Rightarrow \pi^0 \to \gamma A'$
NA48/2	$p^+_{\text{beam}}(\text{nucleus}) \Rightarrow K^+K^- \Rightarrow \pi^0 \to \gamma A'$
WASA	$p^+_{\text{beam}}(\text{nucleus}) \Rightarrow K^+K^- \Rightarrow \pi^0 \to \gamma A'$

e^+e^- Collider Experiments
Cover the largest parameter space of experiments searching for Dark Photons
Consequence of high e^+e^- -> $\gamma\gamma$ cross-sections

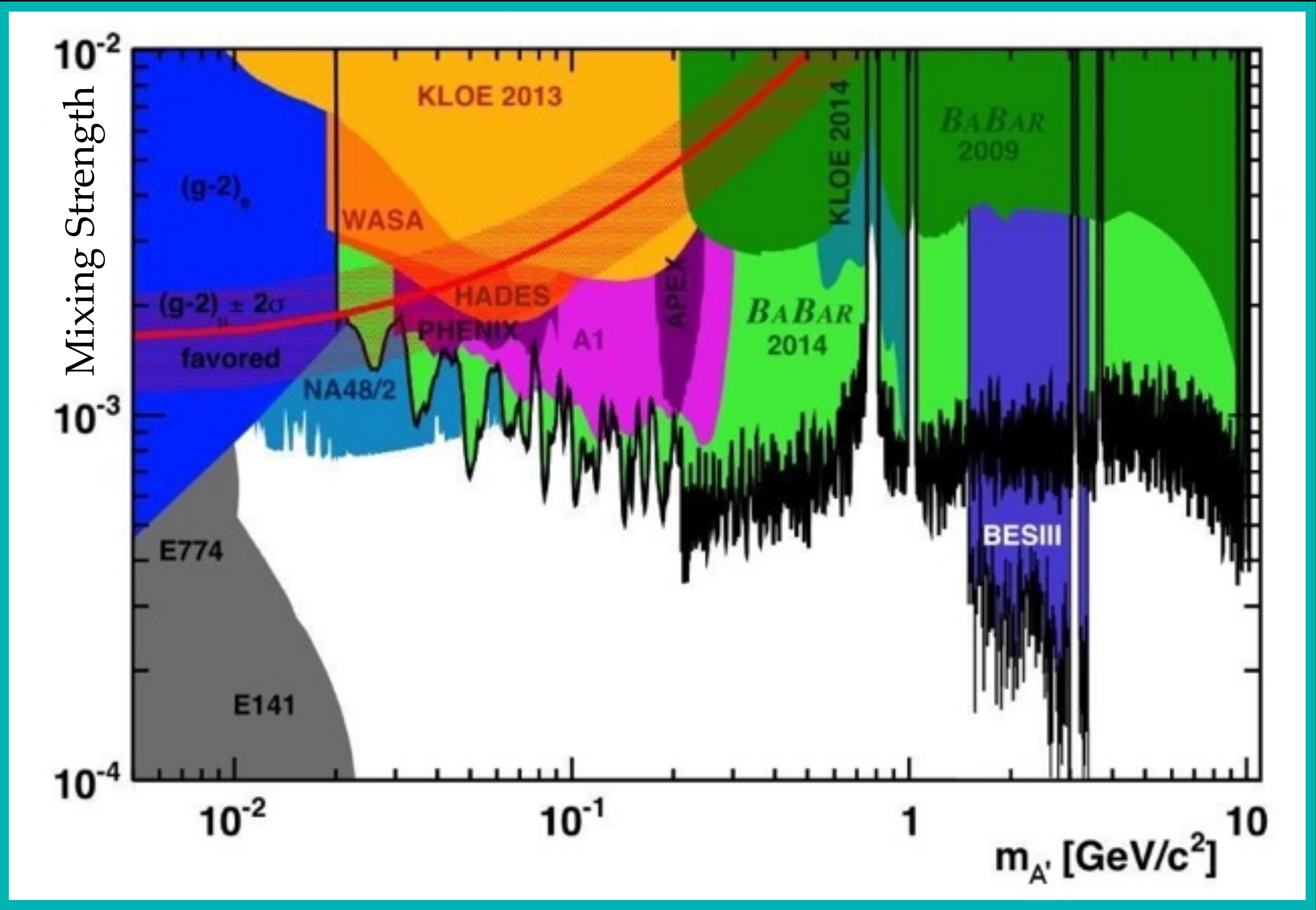
Electron Beam-Dump Experiments
Dark Photons are emitted via Bremsstrahlung
Secondary to original processes being explored

Electron Fixed Target Experiments
Electron beams scatter off heavy nuclei
Dark Photons are produced and decay into e^+e^- pairs

Proton Fixed Target Experiments
Proton beams scatter off of niobium or liquid hydrogen targets
Dark Photons are produced and decay similarly as in electron fixed target experiments

Strictly for Decays to Visible Matter

CURRENT CONSTRAINTS ON THE PARAMETER SPACE



Strictly for Decays to Visible Matter

Total BaBar Data Set: 514 fb^{-1}

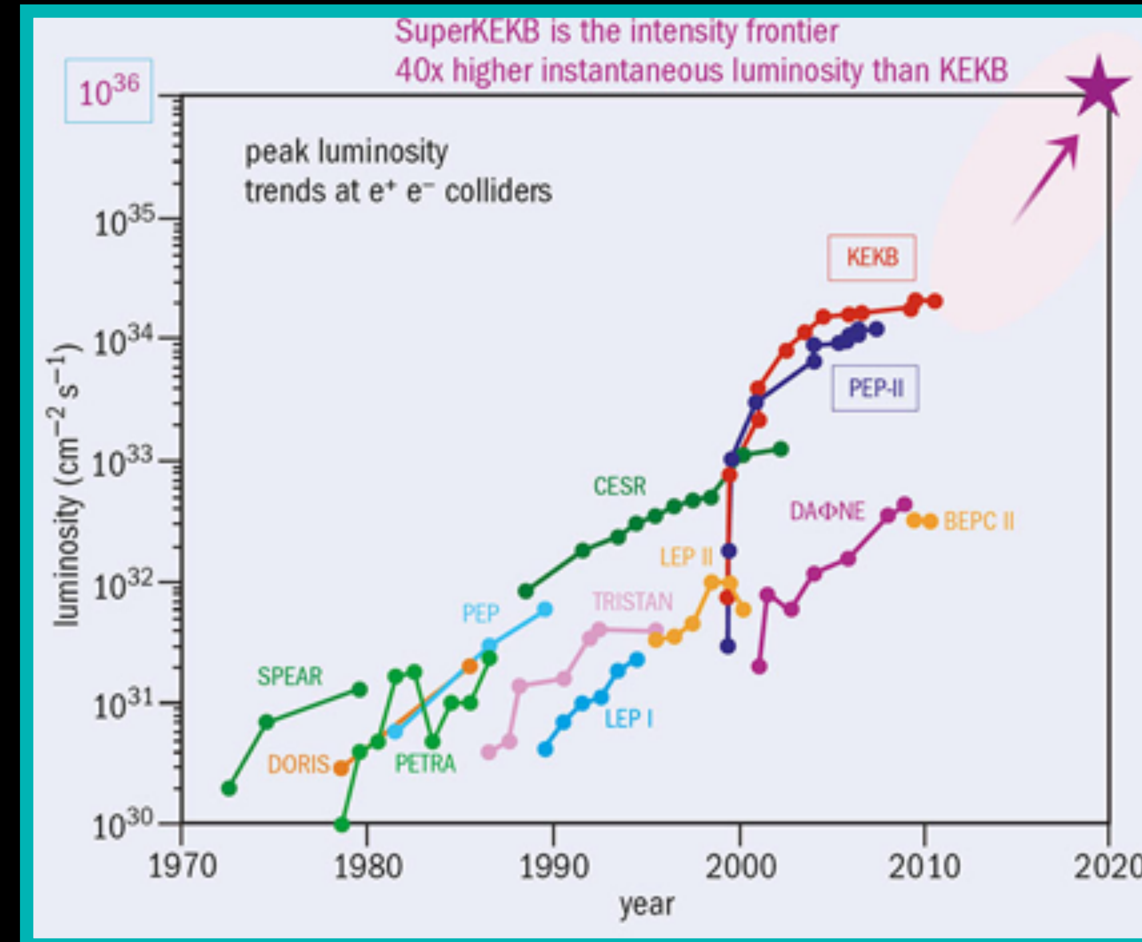
Total Belle Data Set: 1000 fb^{-1}

Expected Belle II Data Set: 50 ab^{-1}

Citation (BaBar): J.P. Lees et al., Phys Rev Lett 113(20):201801 (2014)

Citation (BESIII): V. Prasad Et Al., Charm Phys Workshop (2015)

SUPERKEKB: ON THE INTENSITY FRONTIER

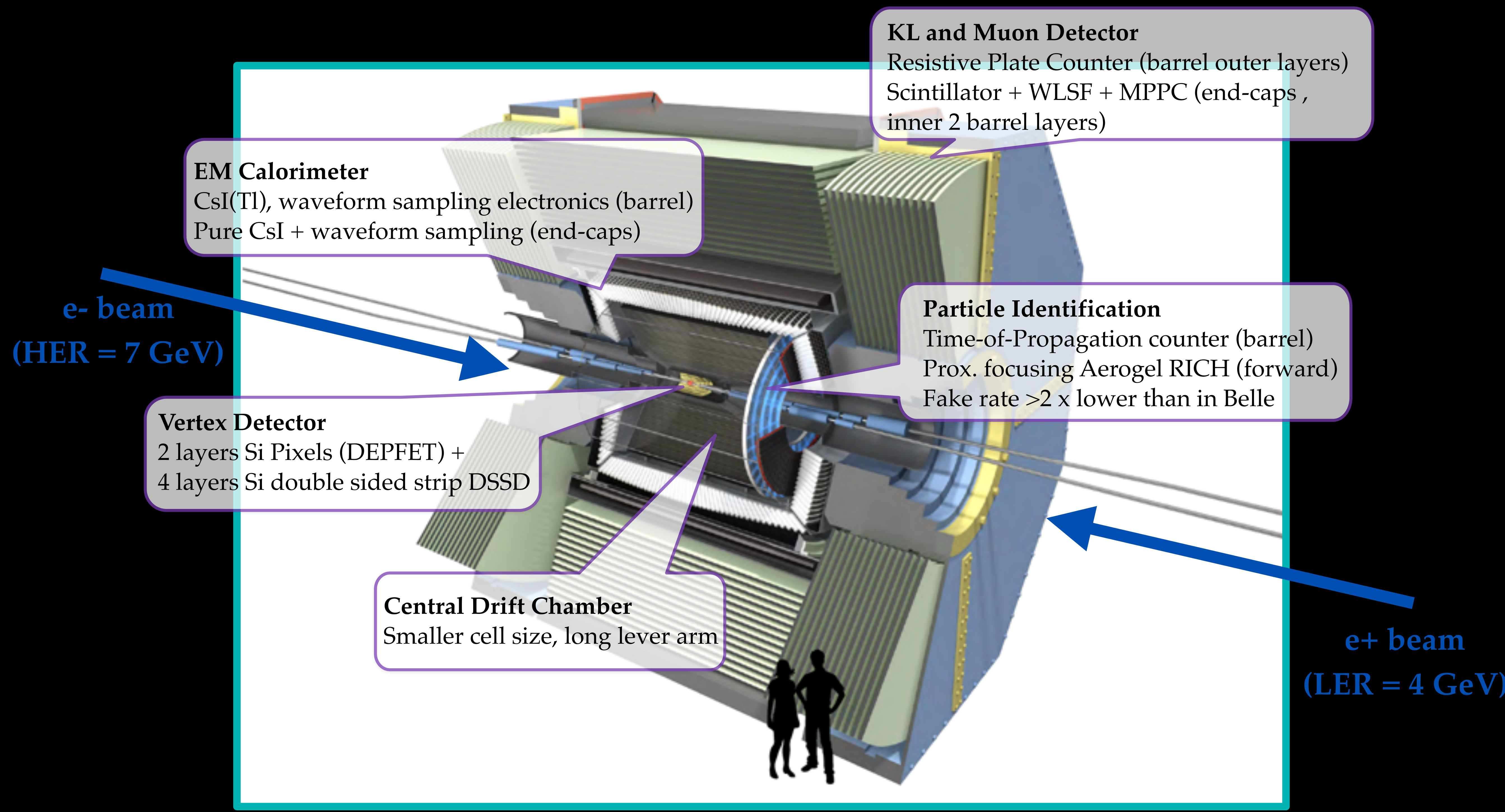


Lorentz factor, beam current, beam-beam parameter

$$L = \frac{\gamma_{\pm}}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{\pm}\,\zeta_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

beam size aspect ratio, vertical β function, geometric factors

- Located in Tsukuba, Japan
- 40 times the peak luminosity of KEKB
- 2 times as much current as KEKB
- 20 times smaller vertical beam size



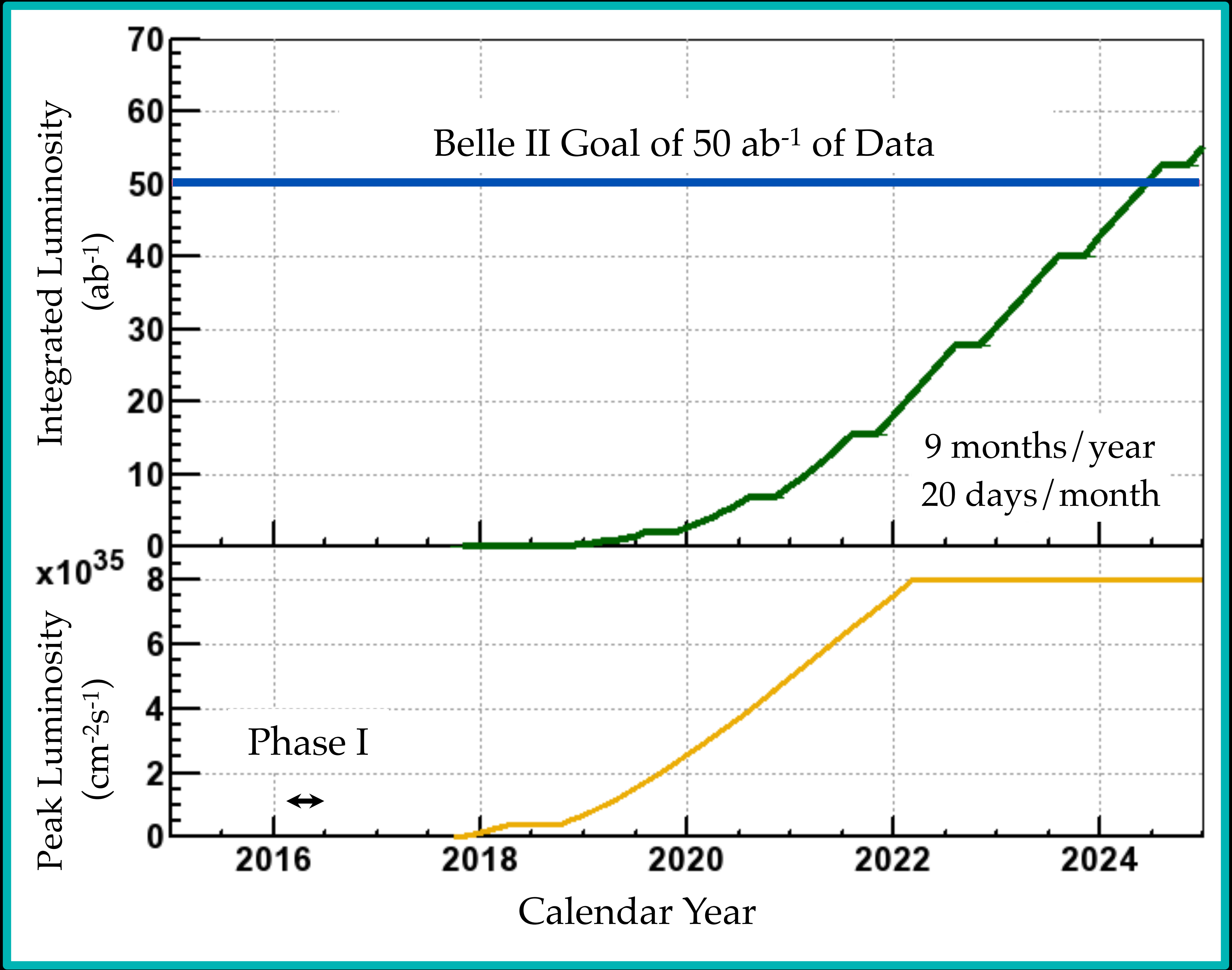
- Asymmetric detector (HER = 7 GeV and LER = 4 GeV) attached to the SuperKEKB.
- Expected to collect 50 ab^{-1} of data throughout its lifetime.

DATA TAKING PHASES AND SCHEDULE

- Phase I: BEAST non-collision run
  - February - June, 2016
- Phase II: first collisions
  - Beginning January, 2018
  - Partial detector (1 vertex detector segment), resulting in lower efficiencies
  - Very exciting
- Phase III: full data-taking period
  - Beginning in late 2018
  - Full detector

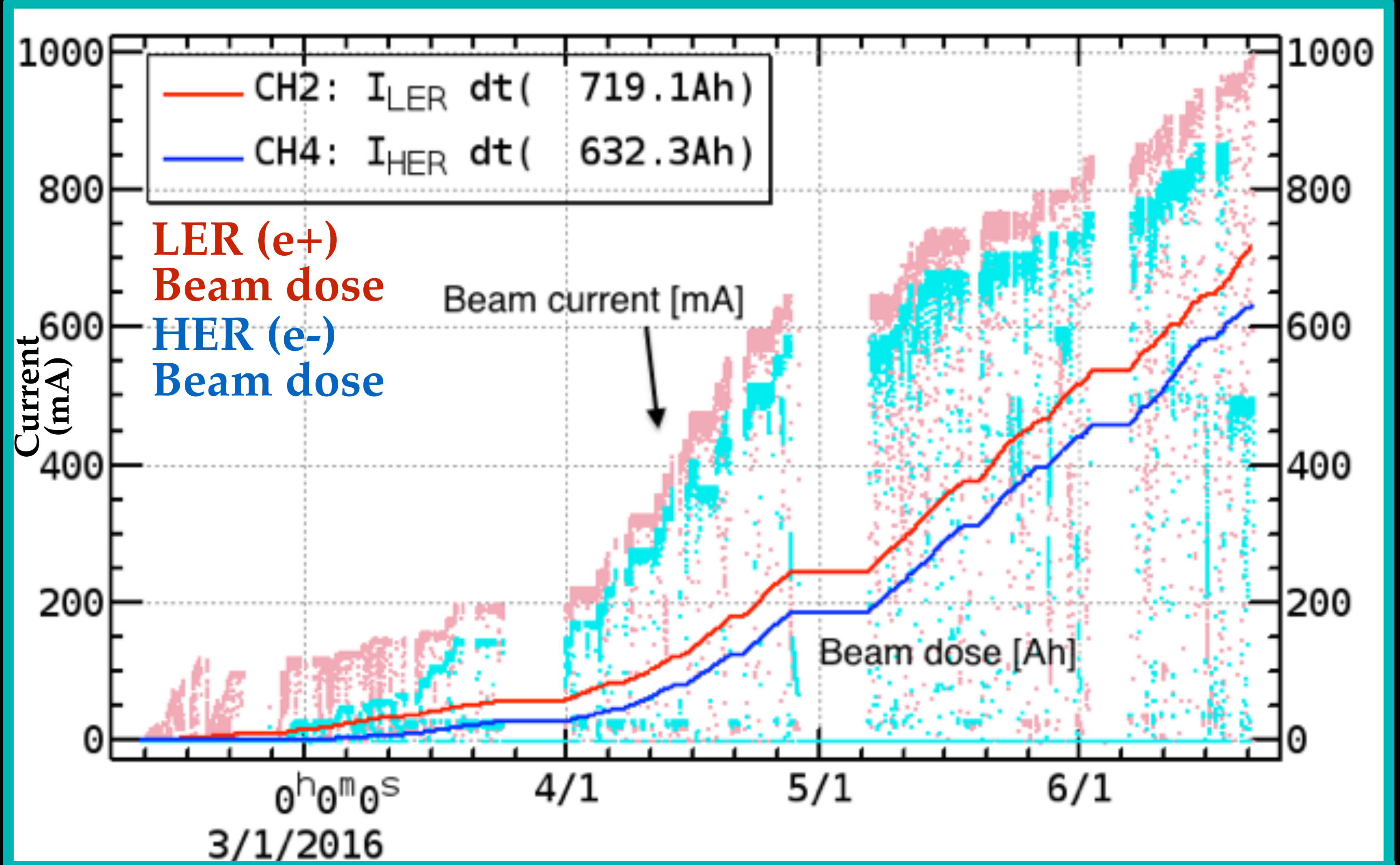
IP as of August 2016

DATA TAKING PHASES AND SCHEDULE



CITATION: P. URQUIJO, "BELLE II: SEARCHING FOR NEW PHENOMENA AT THE INTENSITY FRONTIER" (2016)

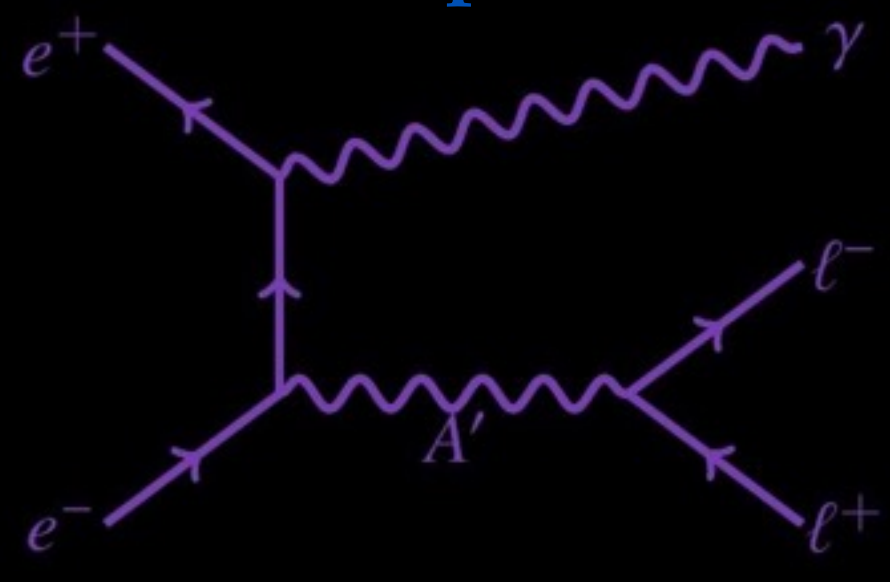
- Last year, BEAST Phase I ran — this was the first operation of SuperKEKB.
- We reached a peak in the instantaneous beam current of 1A (near the required current of each beam for Belle II).



5 Months of Operation (2/1 - 6/30)

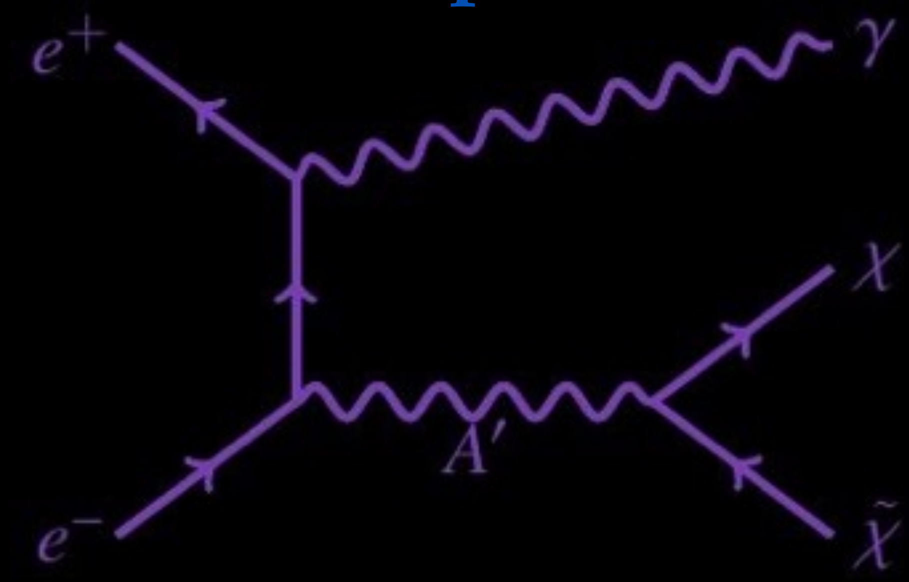
CITATION: P. URQUIJO, "BELLE II: SEARCHING FOR NEW PHENOMENA AT THE INTENSITY FRONTIER" (2016)

Dilepton

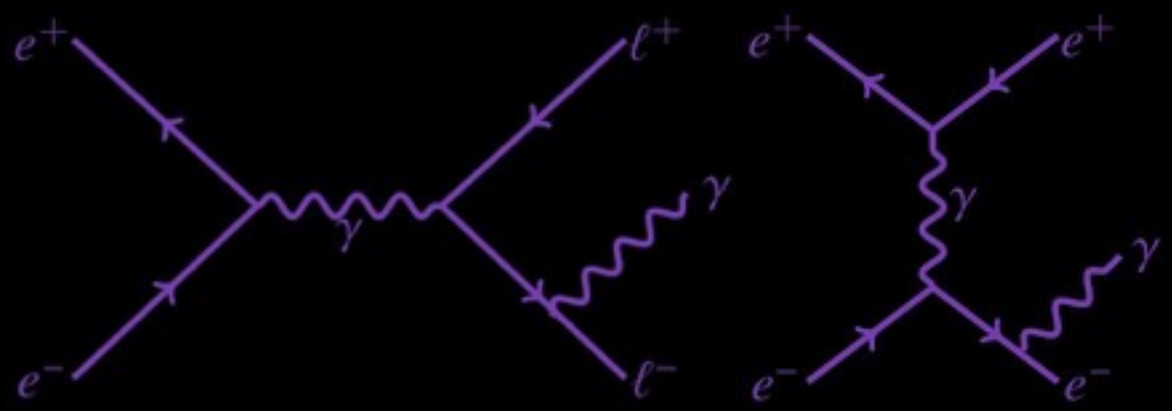


- If dark photon is the lightest DM particle, we expect to mostly observe decays to SM leptons (e or μ).
- Dark photon invariant mass "bump search".

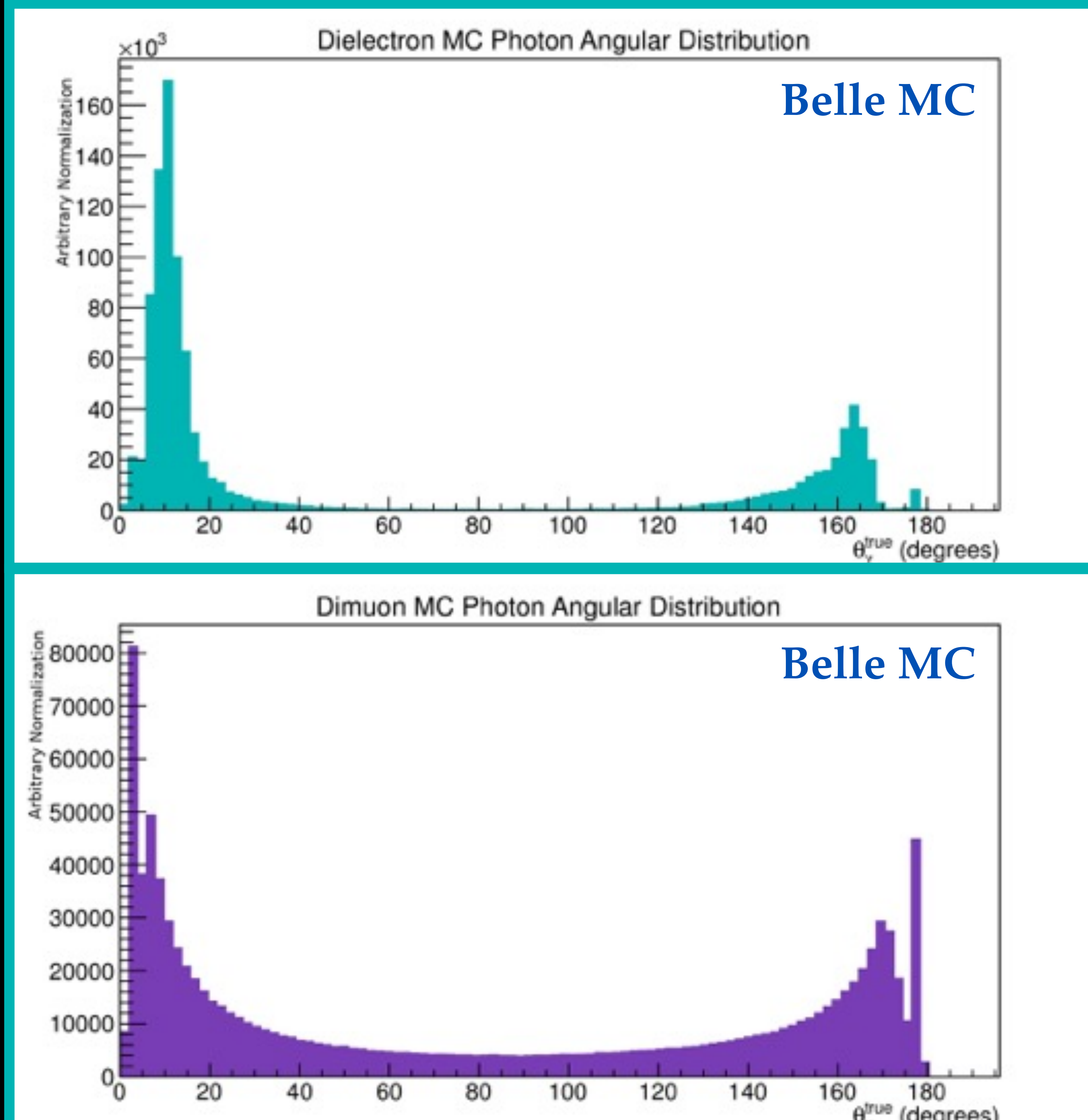
Monophoton



- Otherwise, the dark photon will likely decay to light DM, signal of mono-energetic photon.
- More difficult to detect (larger irreducible backgrounds).
- Search relies heavily on special triggers being employed at Belle II.



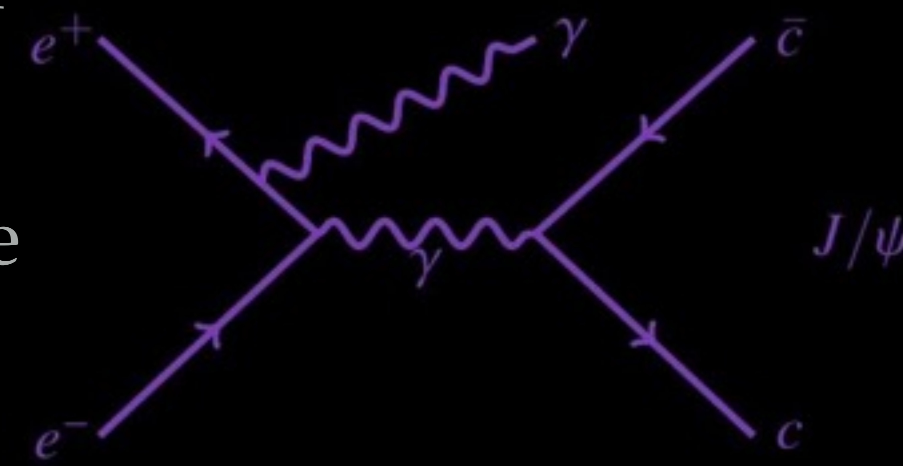
- Background due to FSR (especially in the case of radiative Bhabha events) result in final state photons which lie outside the detector acceptance.

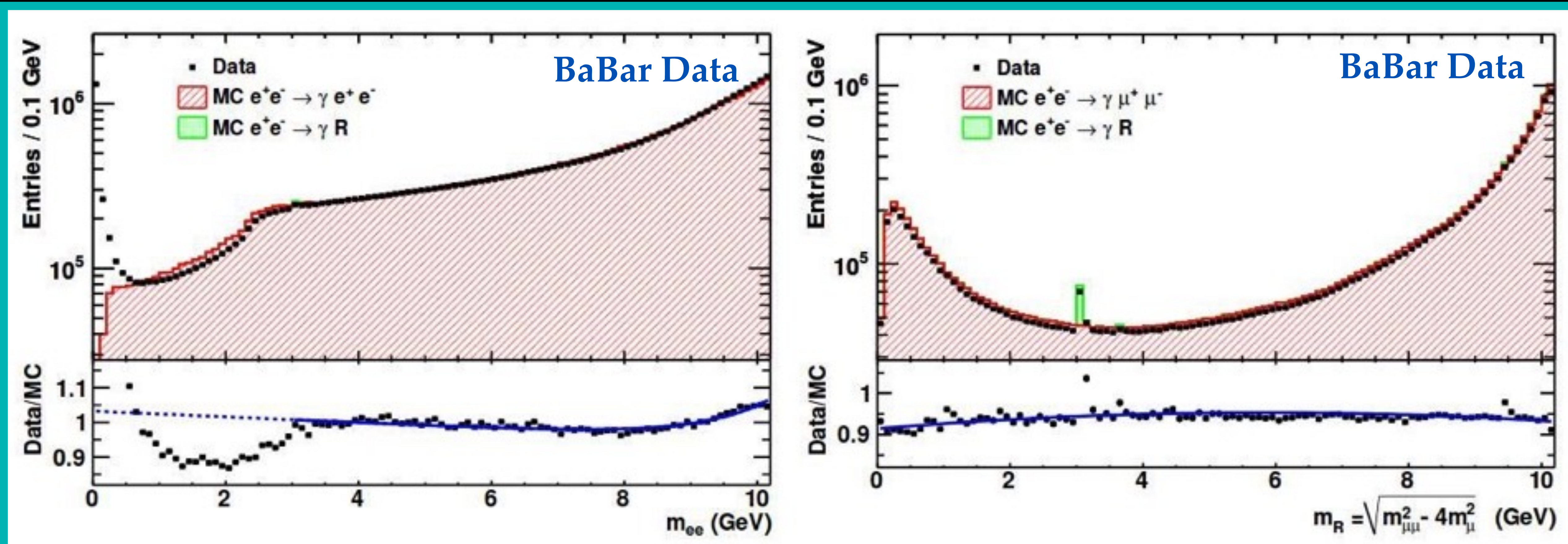


CITATION: CAITLIN MACQUEEN, MSC THESIS (2016)

BACKGROUND PROCESSES FOR THE DILEPTON MODE

- Background due to ISR results in quarkonia resonances.
- Mitigated by creating high quality fits of the shape of known resonances and including these in the modelling of background.





CITATION: J.P. LEES ET AL., BABAR COLLABORATION, PHYS REV LETT 113(20):201801 (2014)

- For the Belle data set ($1000\ fb^{-1}$), we can predict the number of events seen for signal and background:

$$\sigma = \frac{N_{sig}}{\epsilon_{da}\epsilon_{se}\mathscr{L}}$$

Assuming Perfect Efficiency

Signal Processes

$$\sigma_{A'\gamma} \approx 1\ \text{fb} \Rightarrow N_{sig} \approx 10^3\ \text{events}$$

$$\sigma_{A'\gamma} \approx 10\ \text{fb} \Rightarrow N_{sig} \approx 10^4\ \text{events}$$

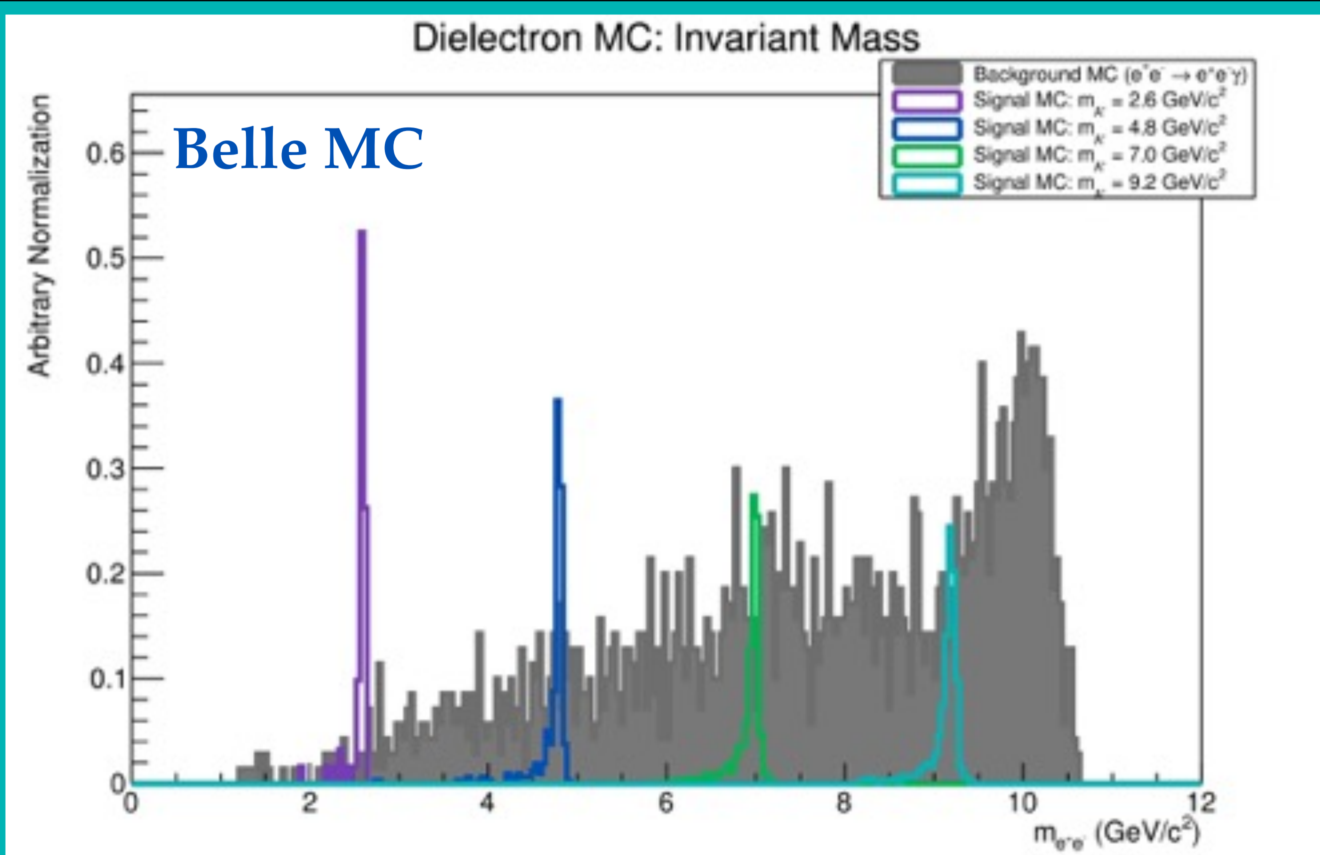
Background Processes

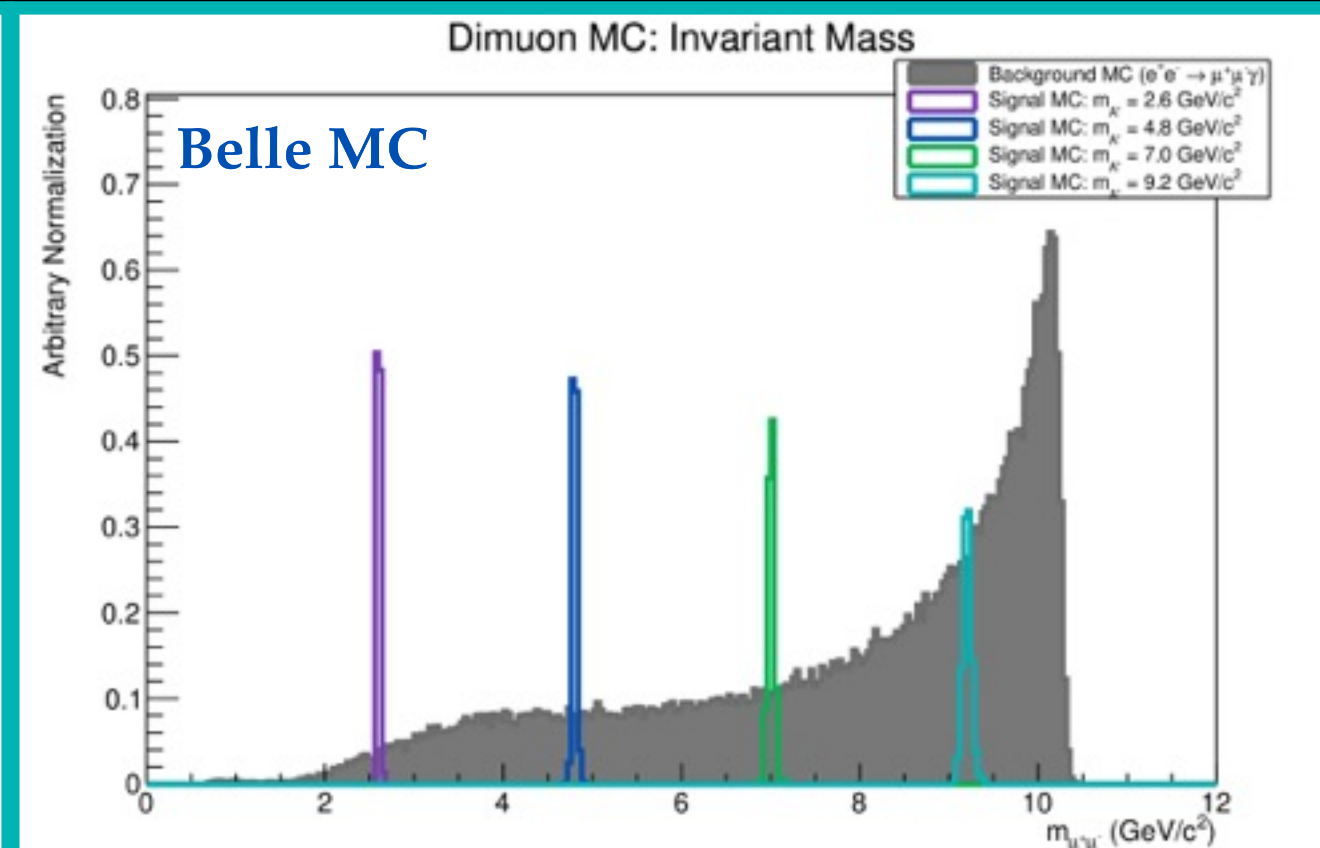
$$\sigma_{e^+e^-\gamma} = 300\ \text{nb} \Rightarrow N_{bkg} \approx 10^{11}\ \text{events}$$

$$\sigma_{\mu^+\mu^-\gamma} = 1.148\ \text{nb} \Rightarrow N_{bkg} \approx 10^{9}\ \text{events}$$

DILEPTON MODE SELECTION CRITERIA

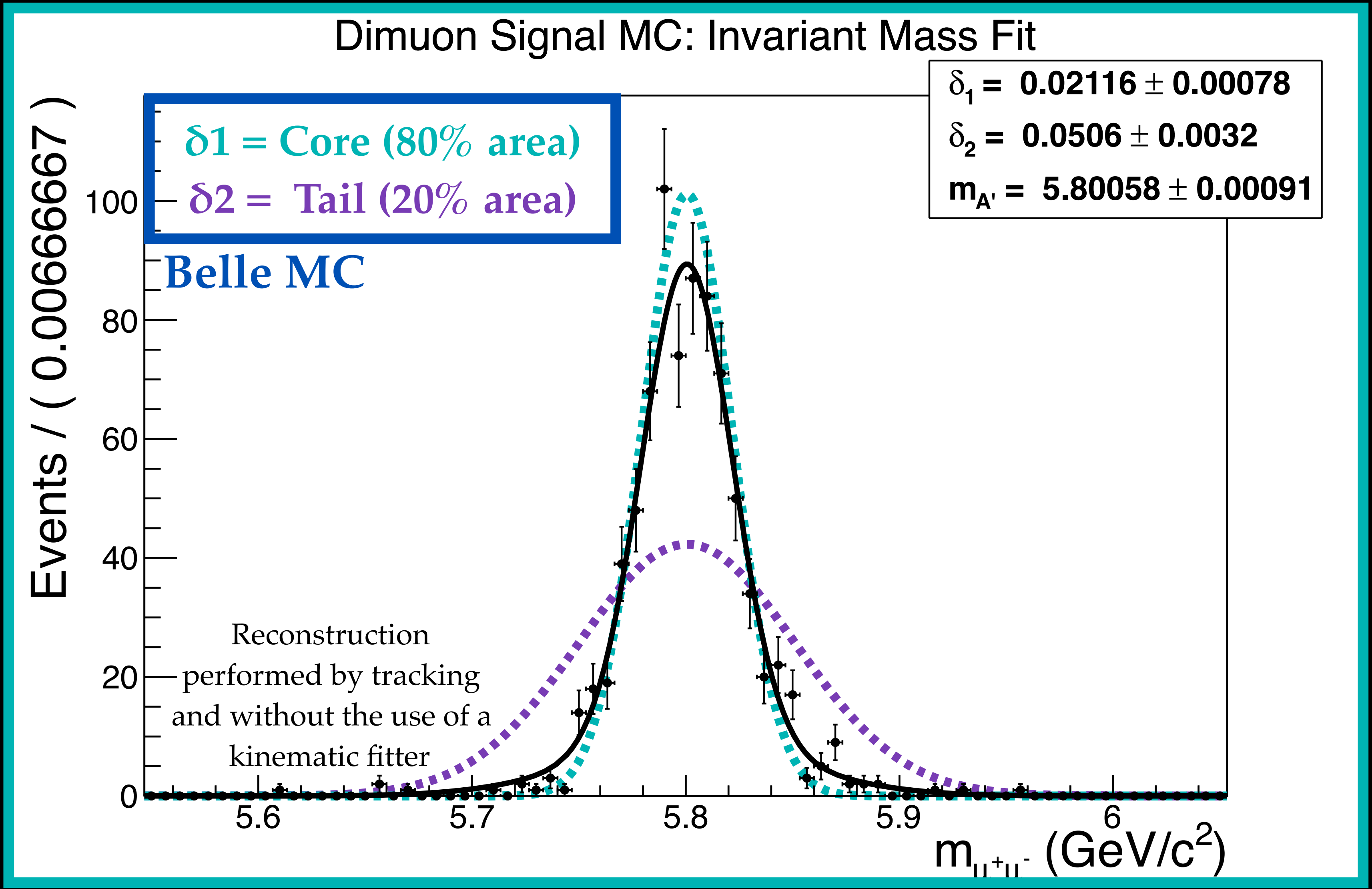
- Exactly two oppositely charged, “well-identified” lepton tracks
- Exactly one photon with $E_\gamma \geq 0.2$ GeV (reduces bremsstrahlung background)
- Total invariant mass (two tracks AND photon) near the $\Upsilon(4S)$ resonance ($9.5 \leq m_{(\mu+\mu- \text{ or } e+e-)\gamma} \leq 10.8$ GeV / c^2)





CITATION: CAITLIN MACQUEEN, MSC THESIS (2016)

AN EXAMPLE: DIMUON SIGNAL MC PDFS



CITATION: CAITLIN MACQUEEN, MSC THESIS (2016)

- PDFs based on fits to dimuon signal MC invariant mass for 52 distinct A′ masses $0.2 \leq m_{A'} \leq 10.4$ GeV / c^2.
- From a simple test with no kinematic fitting, we know the signal resolution improves for Belle II.

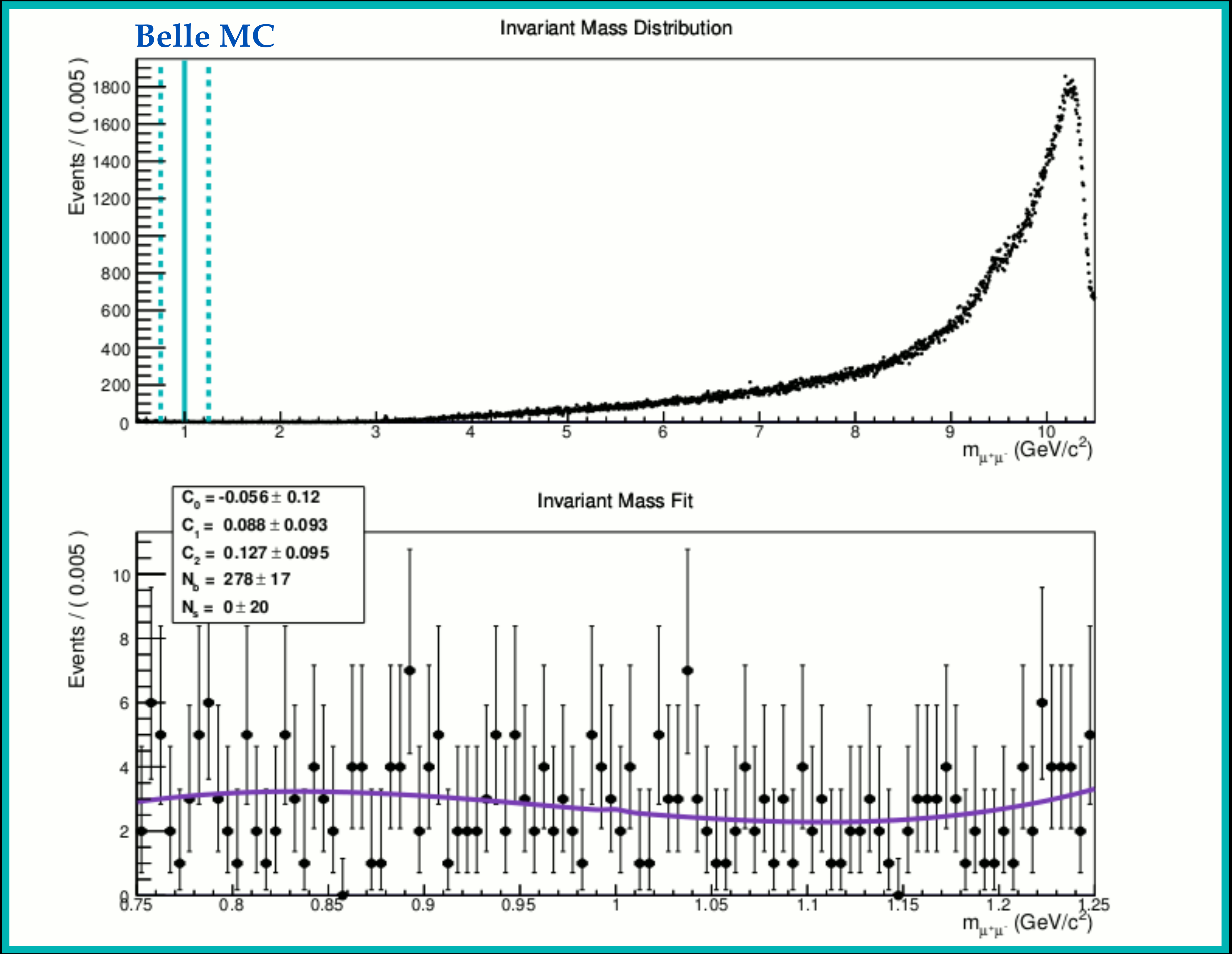
Belle MC

$m_{A'}$ (GeV/c²)	δ_1 (MeV/c²)	δ_2 (MeV/c²)
2	8	24
5	17	46
10	47	78

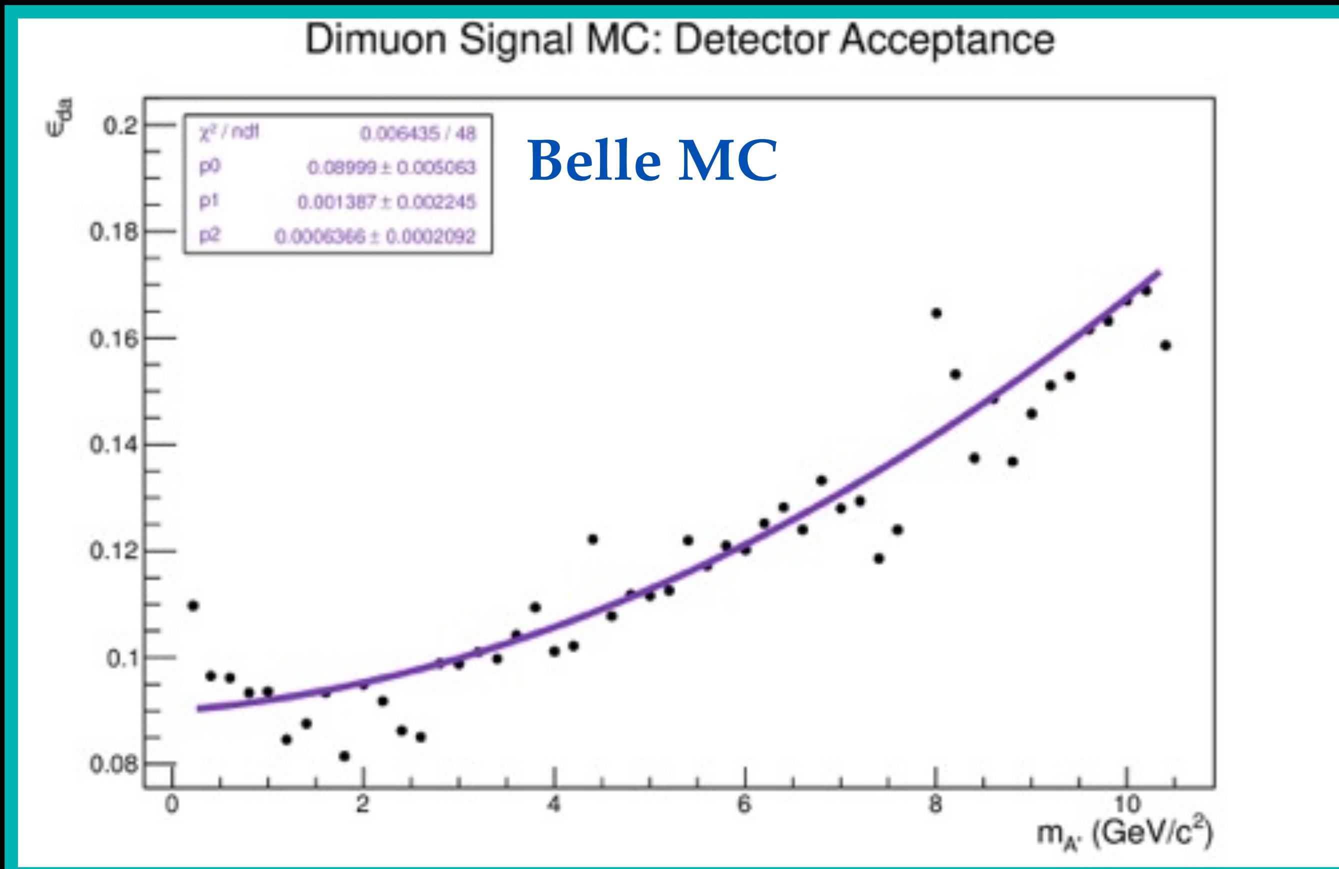
Belle II MC

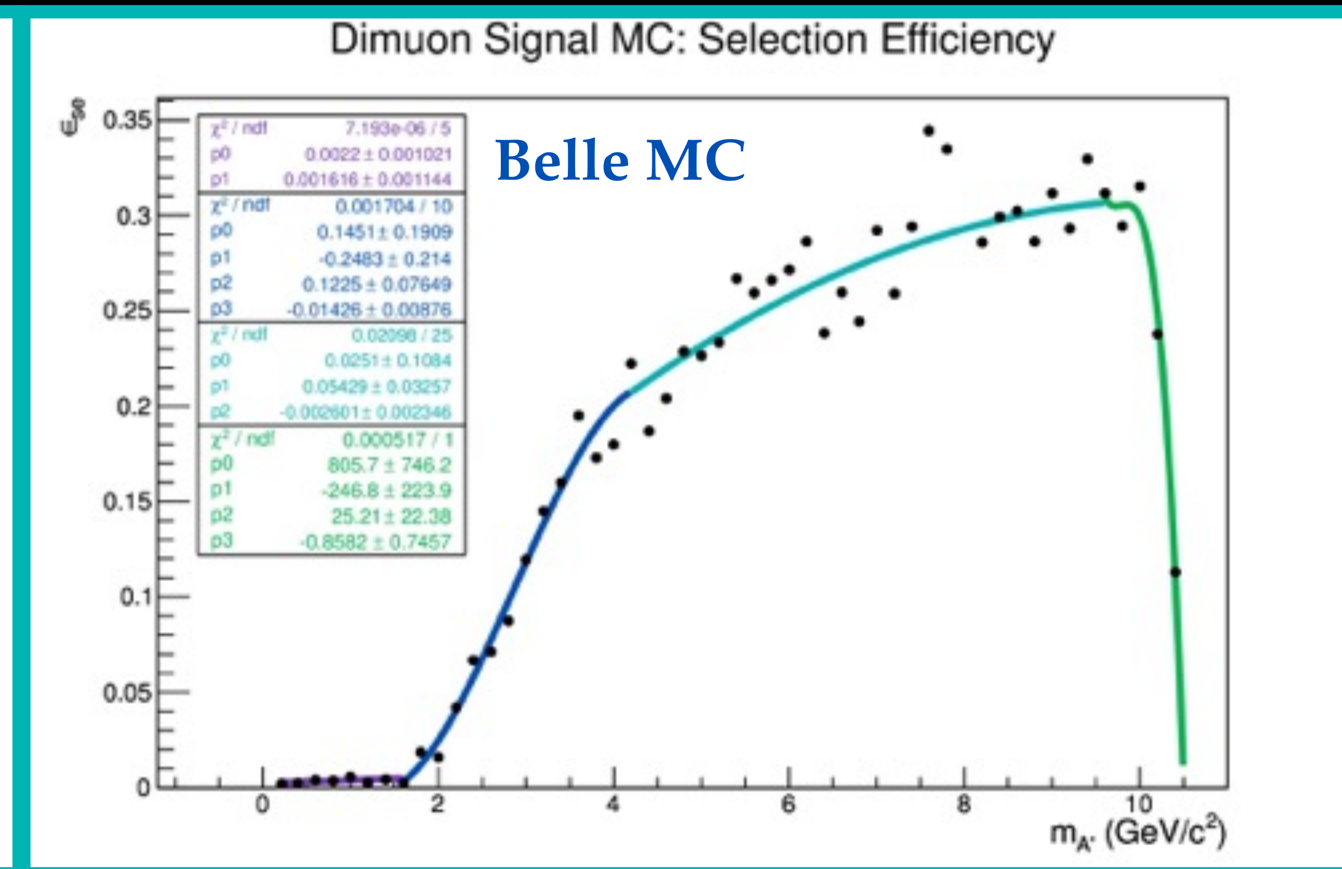
$m_{A'}$ (GeV/c²)	δ_1 (MeV/c²)	δ_2 (MeV/c²)
2	6.5	38
5	16	66
10	37	99

AN EXAMPLE: DIMUON SIGNAL EVENT COUNTING



AN EXAMPLE: DIMUON SELECTION EFFICIENCIES FROM MC





CITATION: CAITLIN MACQUEEN, MSC THESIS (2016)

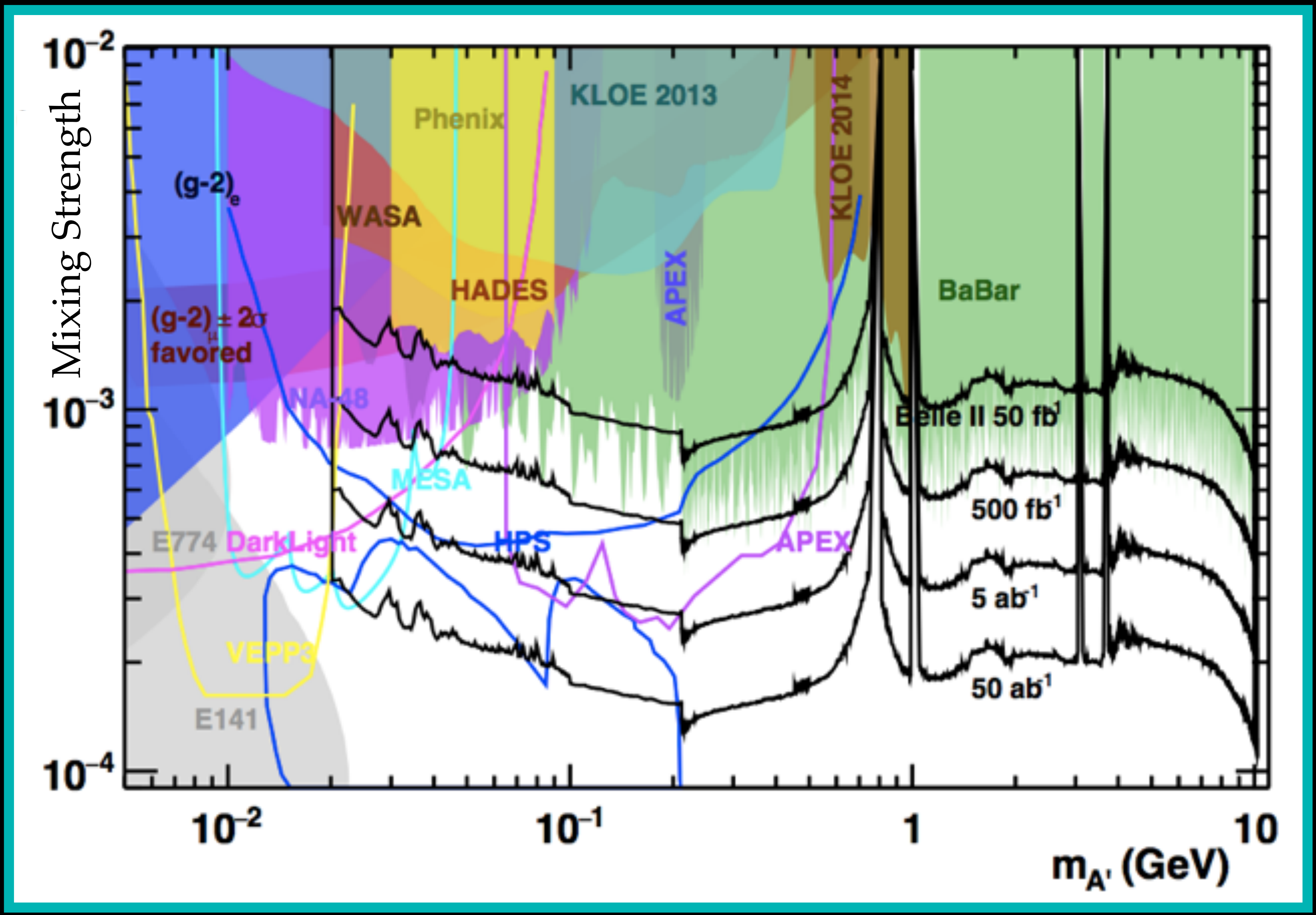
"bump search" output

$$\sigma = \frac{N_{sig}}{\epsilon_{da}\epsilon_{se}\mathcal{L}}$$

~10% ~30%

time-integrated luminosity

THE PROPOSED REACH OF BELLE II

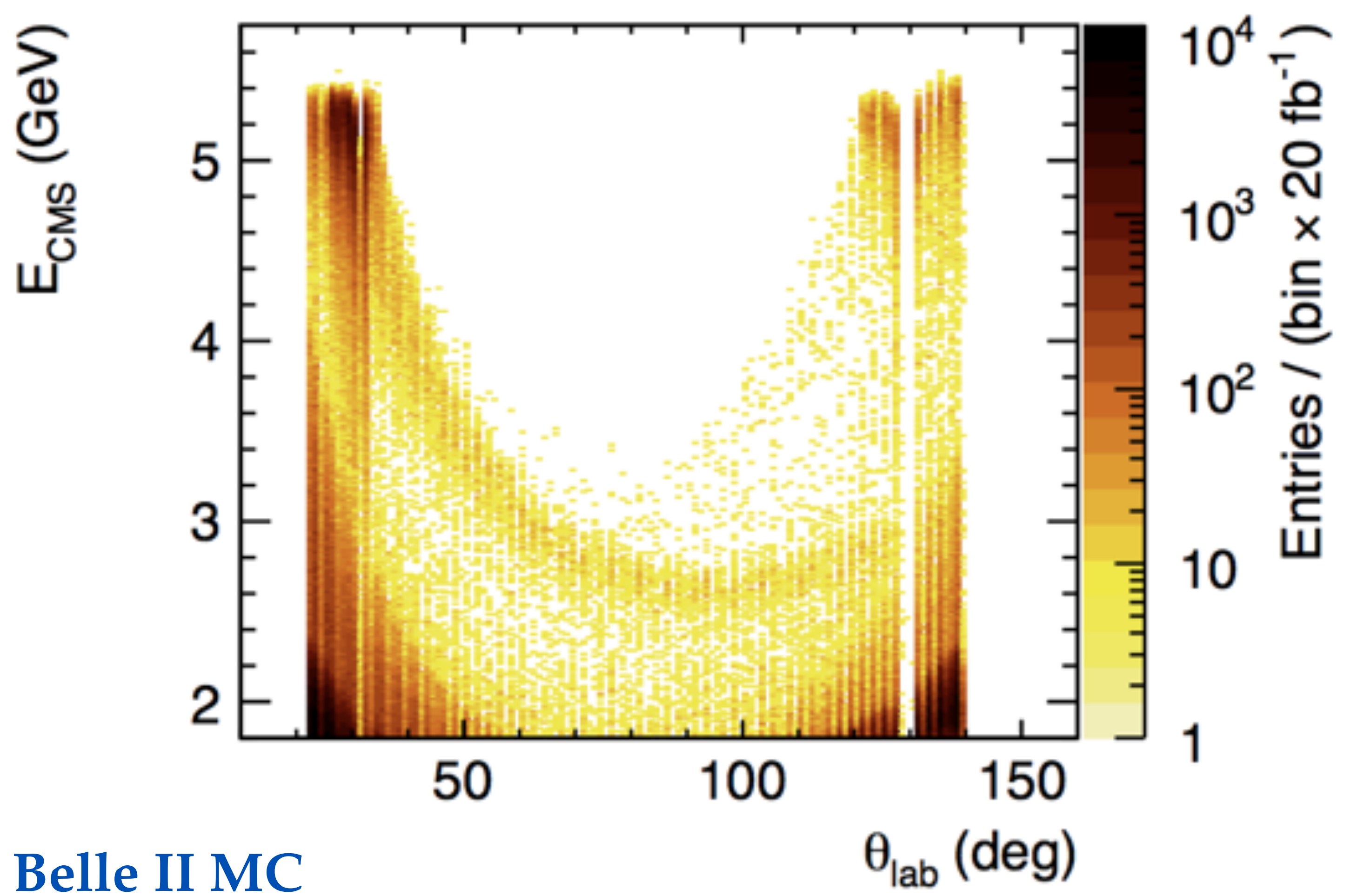


Strictly for Decays to Visible Matter

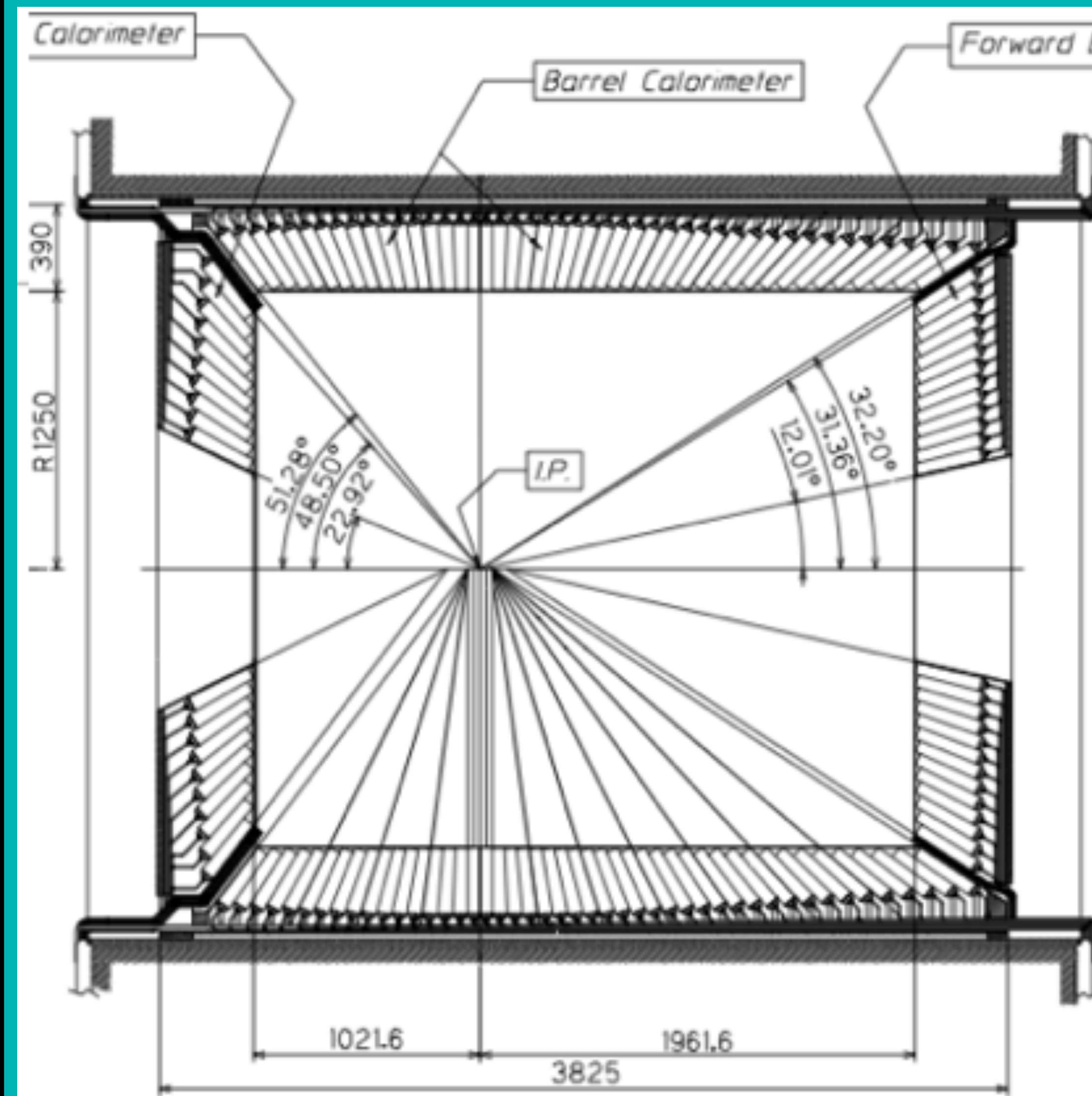
- 90% CL upper limits on the mixing strength, respective to the dark photon mass hypothesis

BACKGROUND PROCESSES FOR THE MONOPHOTON MODE

- e^+e^- —> γγ with one photon going through the ECL gaps.
- e^+e^- —> γγγ with one photon going through the backward ECL gap and one photon near θ=0º.
- Irreducible backgrounds — events at low energy and wide angles.



Belle II MC



Electromagnetic Calorimeter Geometry

CITATION: C. HEARTY, T. FERBER, B2TIP REPORT: TAU/LOW-MULTIPLICITY CHAPTER (2017)

ROLE OF TRIGGER LOGIC IN MONOPHOTON SEARCHES

- The monophoton mode highlights the need for a dedicated dark sector trigger.
- The Belle II trigger is composed of a hardware (L1) trigger and a software high level trigger (HLT).
- e^+e^- collisions occur at 500 MHz, while the output rate must be kept below 10 Hz.

	Cross Section (acceptance) [nb]	Cross Section (output) [nb]
BB	1.1	1.1
c	1.3	1.3
uds	2.4	2.4
ττ	0.9	0.9
μμ*	0.9	0.8
γγ*	3.1	0.5
ee*	74	2.0
eeee/eeμμ	60	1.0
Total	143.7	10

CITATION: P. URQUIJO, C. LI (2016)

total cross section: ~140nb

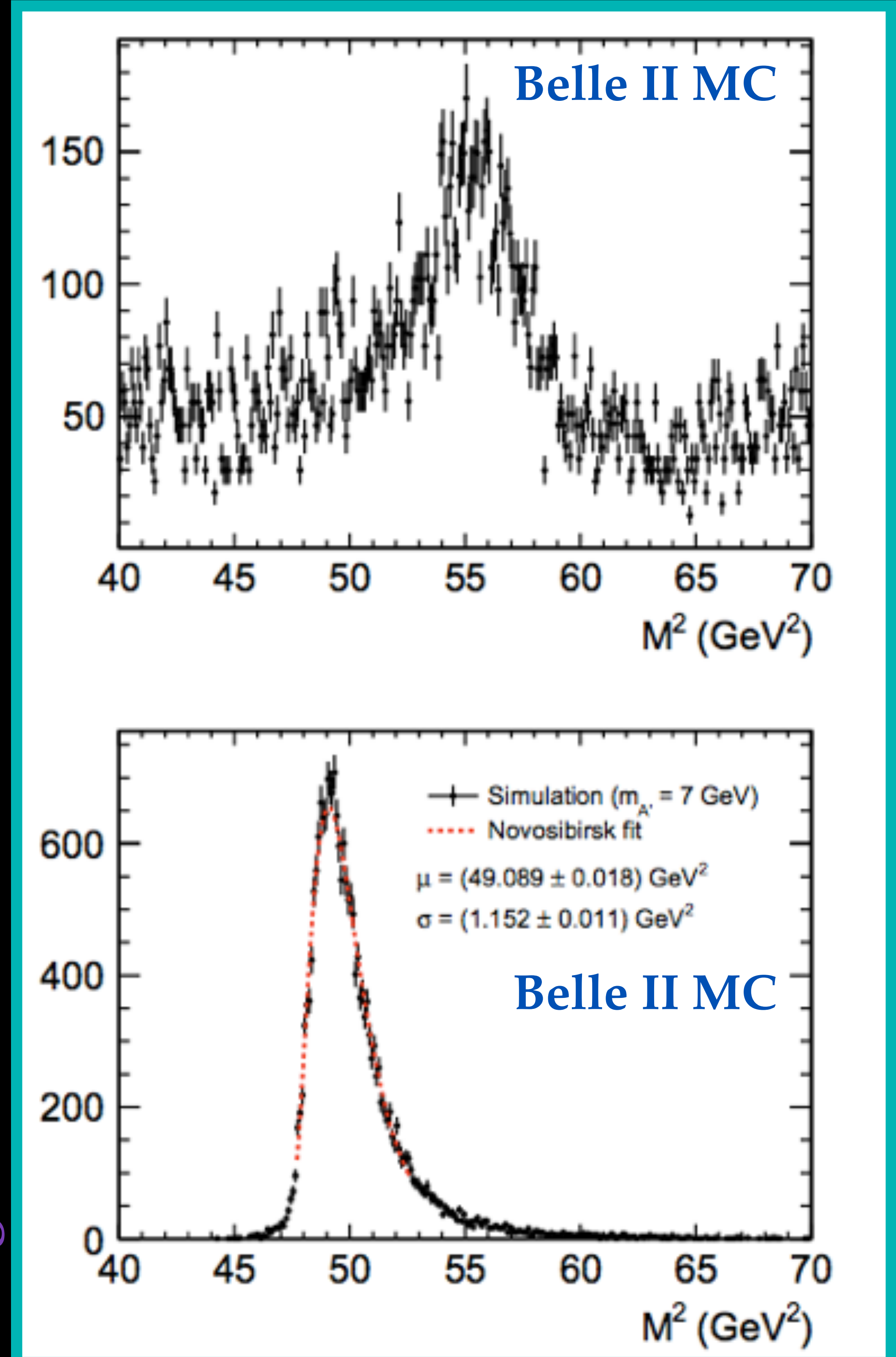
Subdetector Acceptances
CDC: $17^o < \theta < 150^o$
ECL: $12.4^o < \theta < 155.1^o$

*two particles in ECL coverage

- One photon with $E_\gamma \geq 1.8$ GeV (selection not yet optimized)
    - Additional ECL clusters are permitted so long as $E \leq 0.1$ GeV
- Charged particle tracks are permitted so long as $p_T \leq 0.2$ GeV/c
- The analysis method will fit the measured recoil mass squared distribution

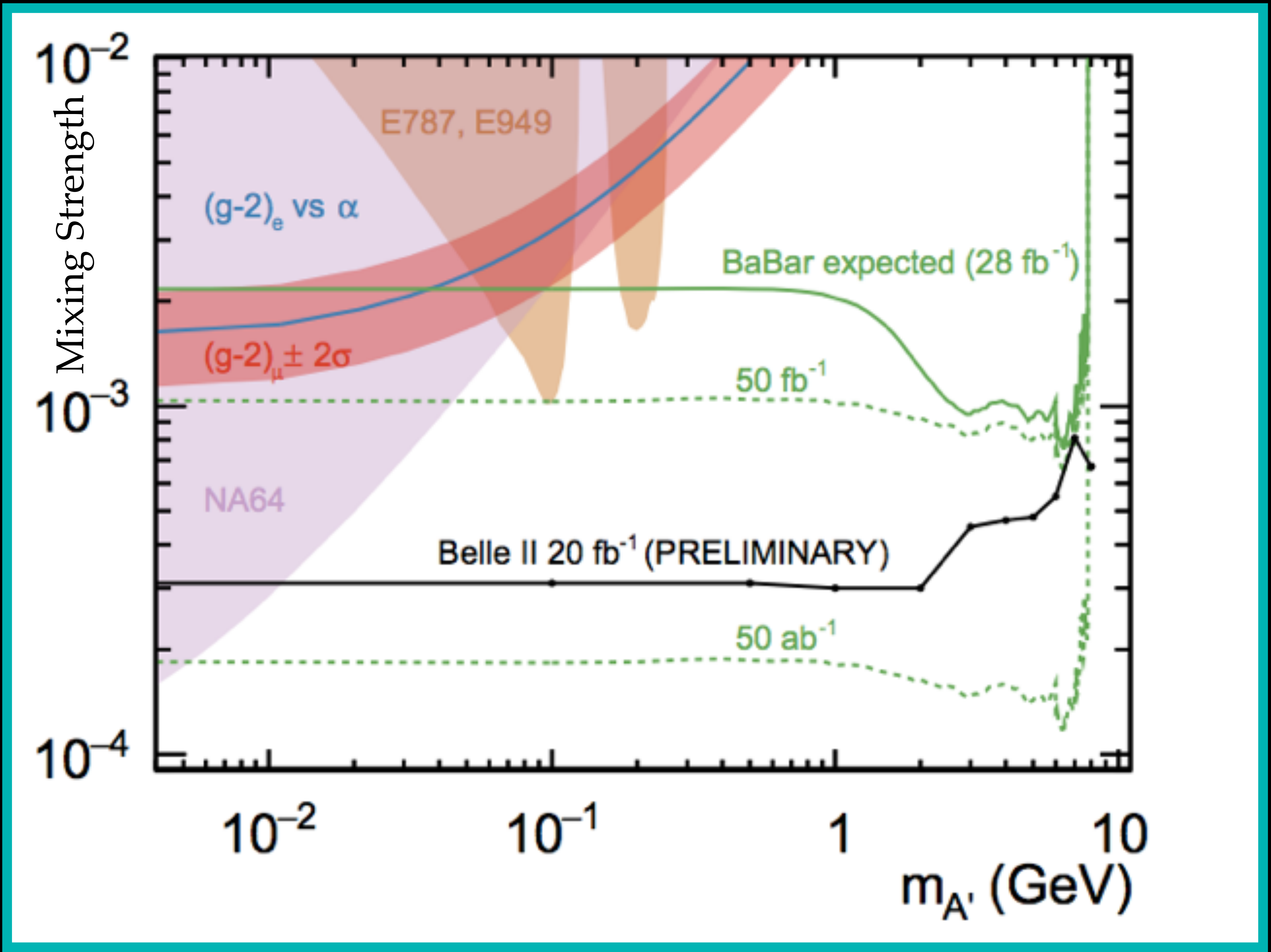
Background

Signal ($m_{A'} = 7$ GeV/c2)



CITATION: C. HEARTY, T. FERBER, B2TIP REPORT: TAU/LOW-MULTIPLICITY CHAPTER (2017)

THE PROPOSED REACH OF BELLE II

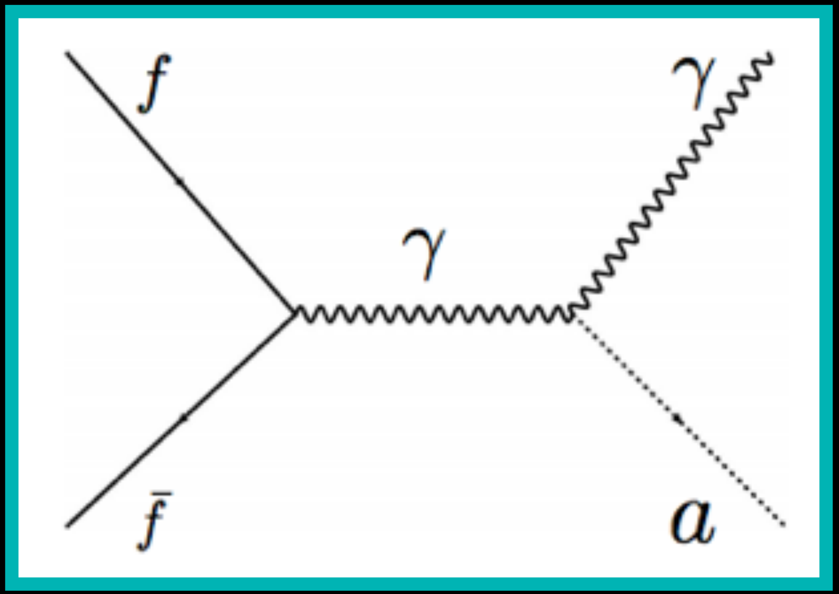


Strictly for Decays to Invisible Matter

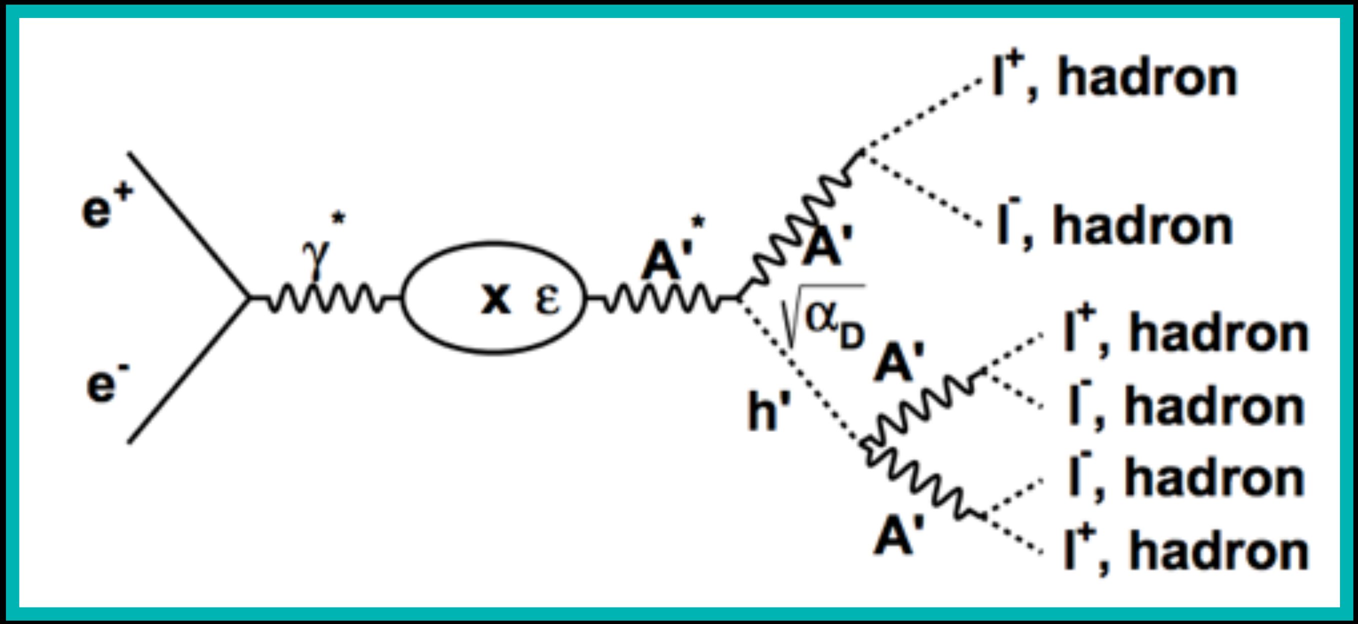
- Results indicate we can perform dark photon searches via the monophoton mode at Phase II (beginning in January 2018).

CITATION: C. HEARTY, T. FERBER, B2TIP REPORT: TAU/LOW-MULTIPLICITY CHAPTER (2017)

- Axion-like particle searches following the theory laid out in the paper by K. Mimasu and V. Sanz.



CITATION: K. MIMASU, V. SANZ, ALPS AT COLLIDERS, JHEP 1506 (2015)
CITATION: C. HEARTY, T. FERBER, B2TIP REPORT: TAU/LOW-MULTIPLICITY CHAPTER (2017)



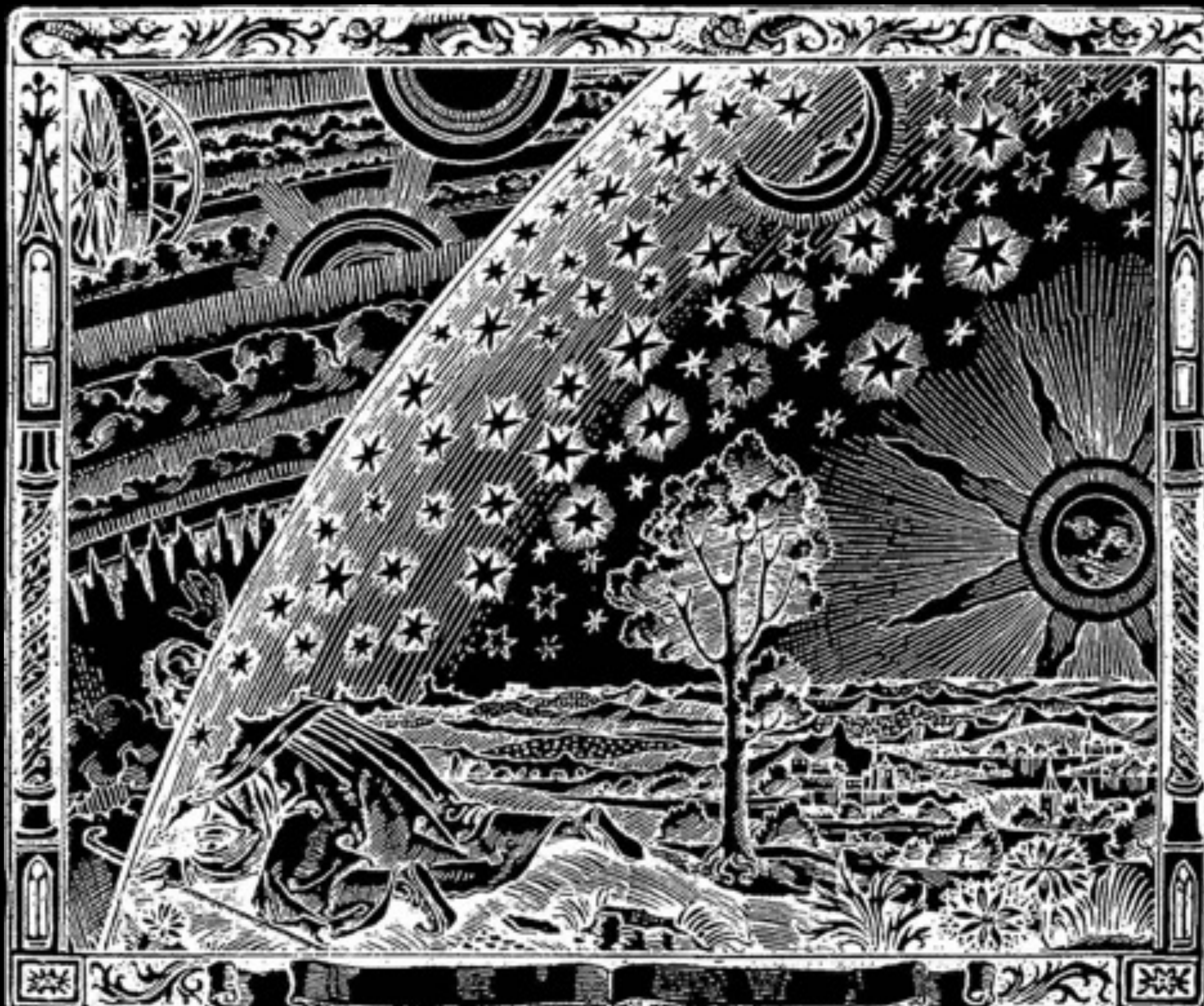
- Dark Higgs searches following the work performed at Belle and BaBar.
- The dark Higgs is produced via Higgsstrahlung (replacing the SM Higgs) in these searches.

CITATION: J.P. LEES ET AL., BABAR COLLABORATION, ARXIV:1202:1313 (2012)
CITATION: I. JAEGLE ET AL., BELLE COLLABORATION, ARXIV:1502:00084 (2015)

FINAL REMARKS

- Dark photons provide a portal to the dark sector.
- Phase II physics data taking (as early as January 2018) provides an excellent opportunity to examine dark photon searches.
  - The dilepton mode will probe mixing strengths ~10^{-3} for 10 MeV/$c^2 \leq m_{A'} \leq$ 10 GeV/c^2.
  - The monophoton mode will probe mixing strengths ~10^{-4} for 10 MeV/$c^2 \leq m_{A'} \leq$ 10 GeV/c^2 (with as little as 20 fb^{-1}).
- Belle II will ultimately probe mixing strengths ~10^{-4} for both, covering unique parameter space.
- Efforts are underway to prepare additional dark sector searches at Belle II.
  - ALPs, dark Higgs, alternative dark photon decay channels, etc

QUESTIONS?



The Flammarion engraving had its first documented appearance in *L'atmosphere: meteorologie populaire* by Camille Flammarion (1888). It is a wood engraving by an unknown artist and is frequently used as a metaphor for scientific and religious questions which drive humanity.

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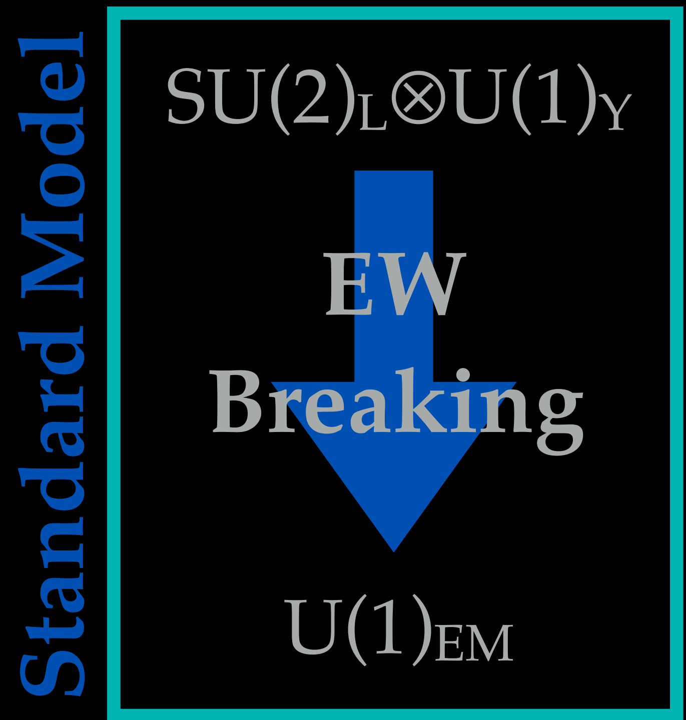
MSc Thesis: Belle Public Page

http://belle.kek.jp/belle/theses/master/macqueen16.pdf

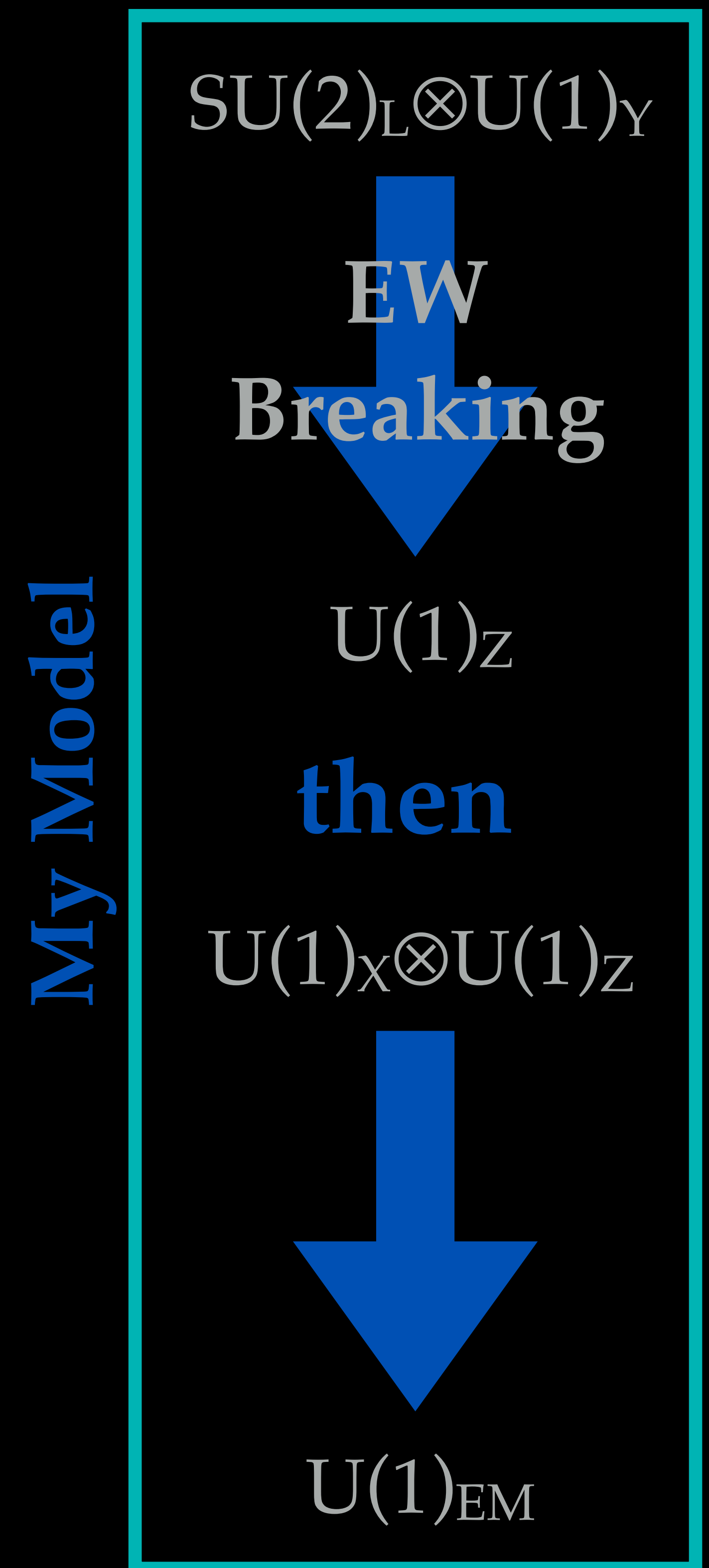
Shedding light on dark matter

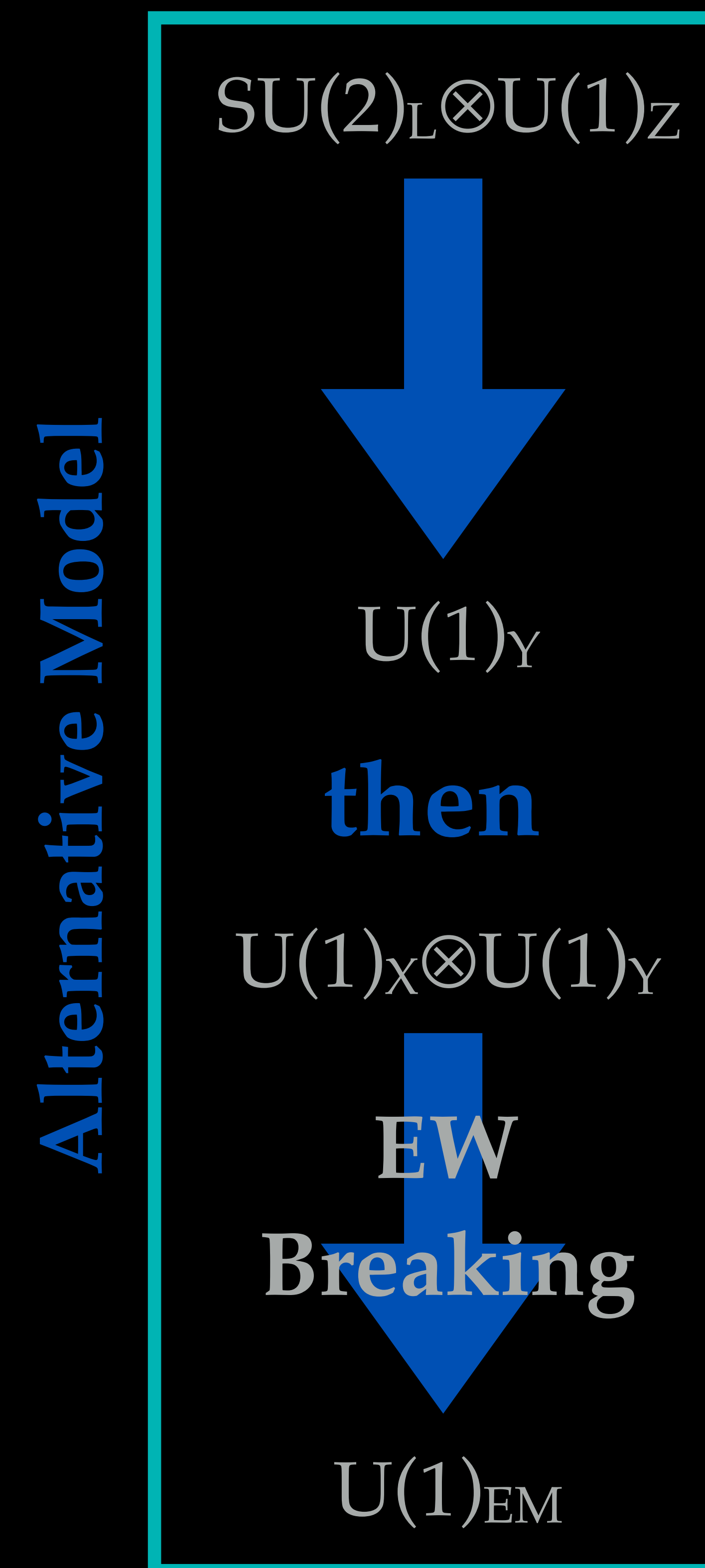
ongoing searches for the dark photon at Belle and Belle II

Backup Slides



- $U(1)_X \otimes U(1)_Z$ undergoes SSB similar to that of $SU(2)_L \otimes U(1)_Y$ in the SM.
- This gives rise to mass eigenstates A and A′, where $m_A = 0$ and $m_{A'} > 0$.





Citation: B. Brahmachari, A. Raychaudhuri, Nucl Phys B:887 (2014)

THE DARK PHOTON AND VISIBLE SECTOR INTERACTIONS

- SSB gives rise to interaction terms in our Lagrangian as…

$$\mathscr{L}_{int} = \frac{1}{\sqrt{\zeta\xi}}\left(\zeta\tilde{g}\tilde{g}'\hat{J}^{\mu}A_{\mu} + (\tilde{g}^2 - \tilde{g}'^2)Q_sQ_s'\hat{J}^{\mu}A_{\mu}' + \xi\hat{J}'^{\mu}A_{\mu}'\right)$$

$$\zeta = Q_s^2 + Q_s'^2 \quad \text{and} \quad \xi = \tilde{g}^2Q_s^2 + \tilde{g}'^2Q_s'^2$$

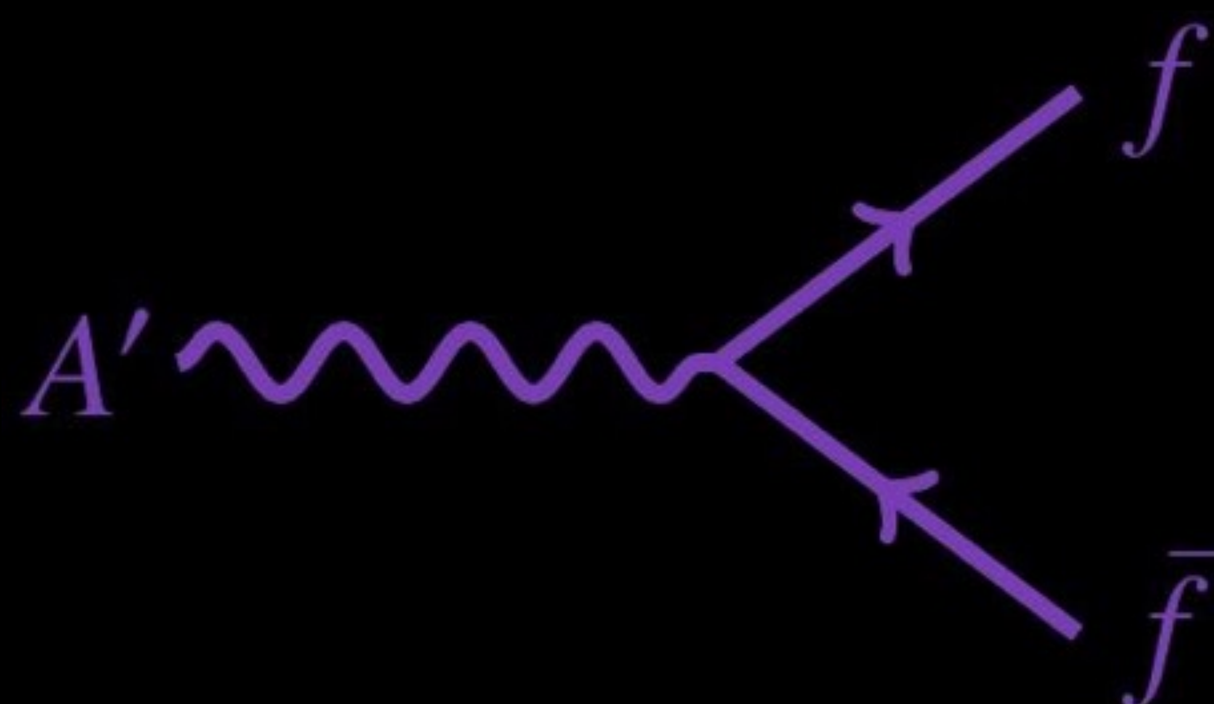
- The SM photon ONLY interacts with the visible sector while the dark photon interacts with BOTH the dark sector and the visible sector.

fermionic currents

$$\hat{J}^{\mu} = Q_f\bar{\psi}\gamma^{\mu}\psi \quad \text{and} \quad \hat{J}'^{\mu} = Q_f'\bar{\psi}\gamma^{\mu}\psi$$

fermionic couplings

$$\tilde{g} = \sqrt{\frac{g^2 + g'^2}{2(1-\varepsilon)}} \quad \text{and} \quad \tilde{g}' = \sqrt{\frac{g^2 + g'^2}{2(1+\varepsilon)}}$$



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