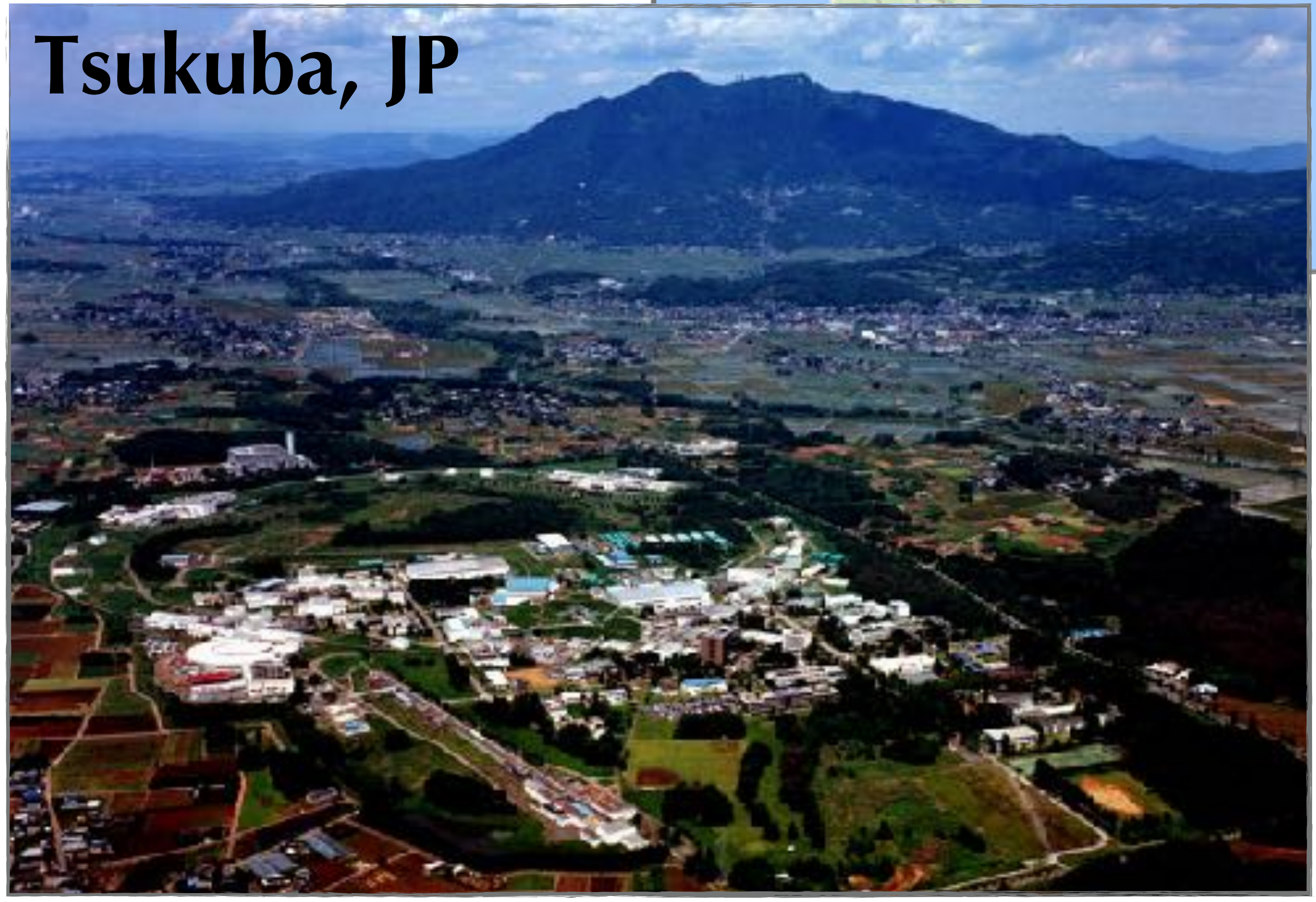
DARK SECTOR PROSPECTS AT BELLE II

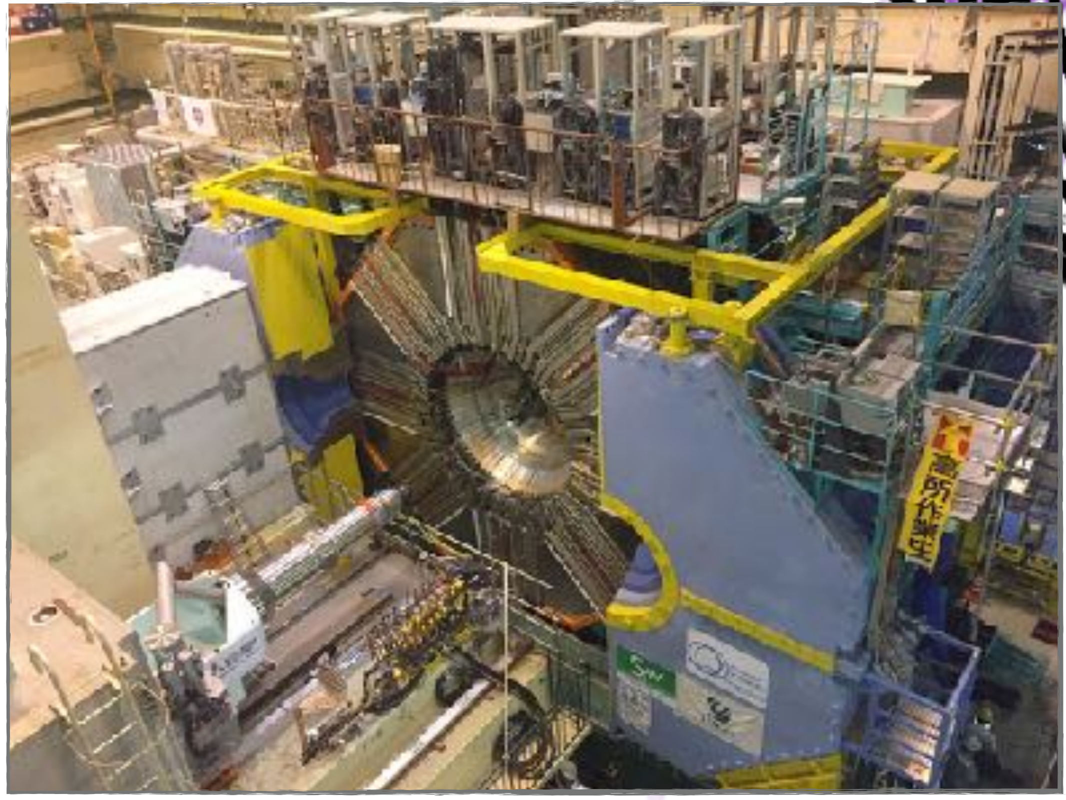
Caitlin MacQueen on behalf of The Belle II Collaboration

Dark Side of the Universe — Daejeon, South Korea — July 10th, 2017

SUPERKEKB AND BELLE II

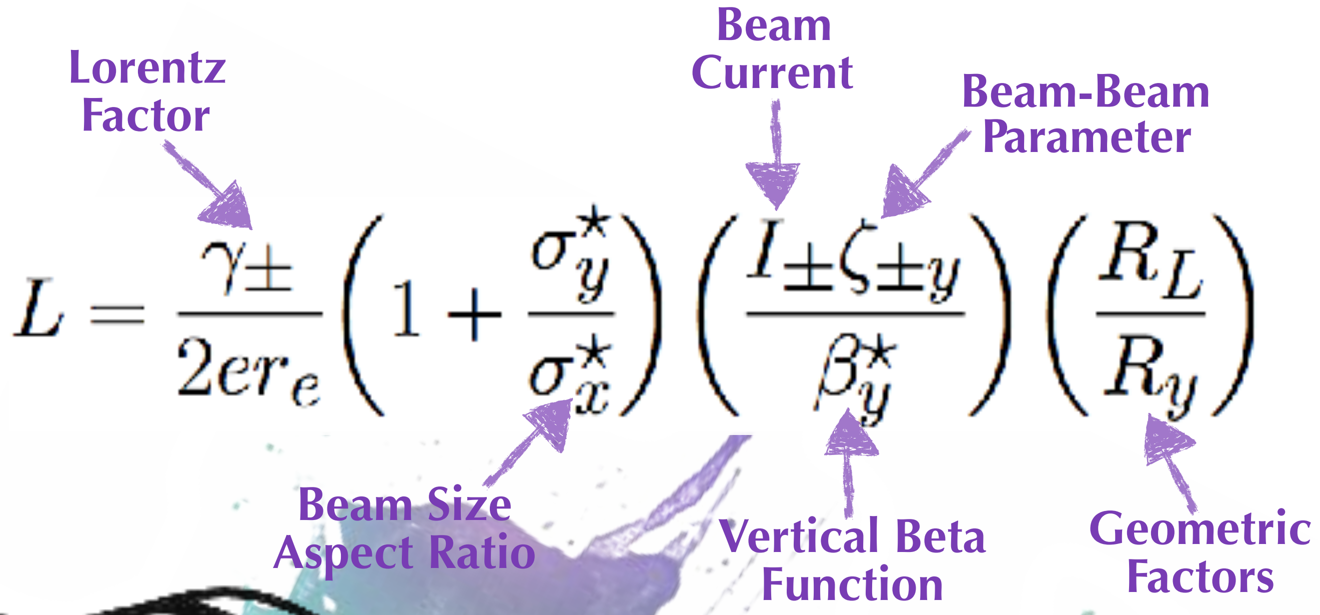
- 700+ scientists
- 100+ institutions
- 24 countries


Tsukuba, JP

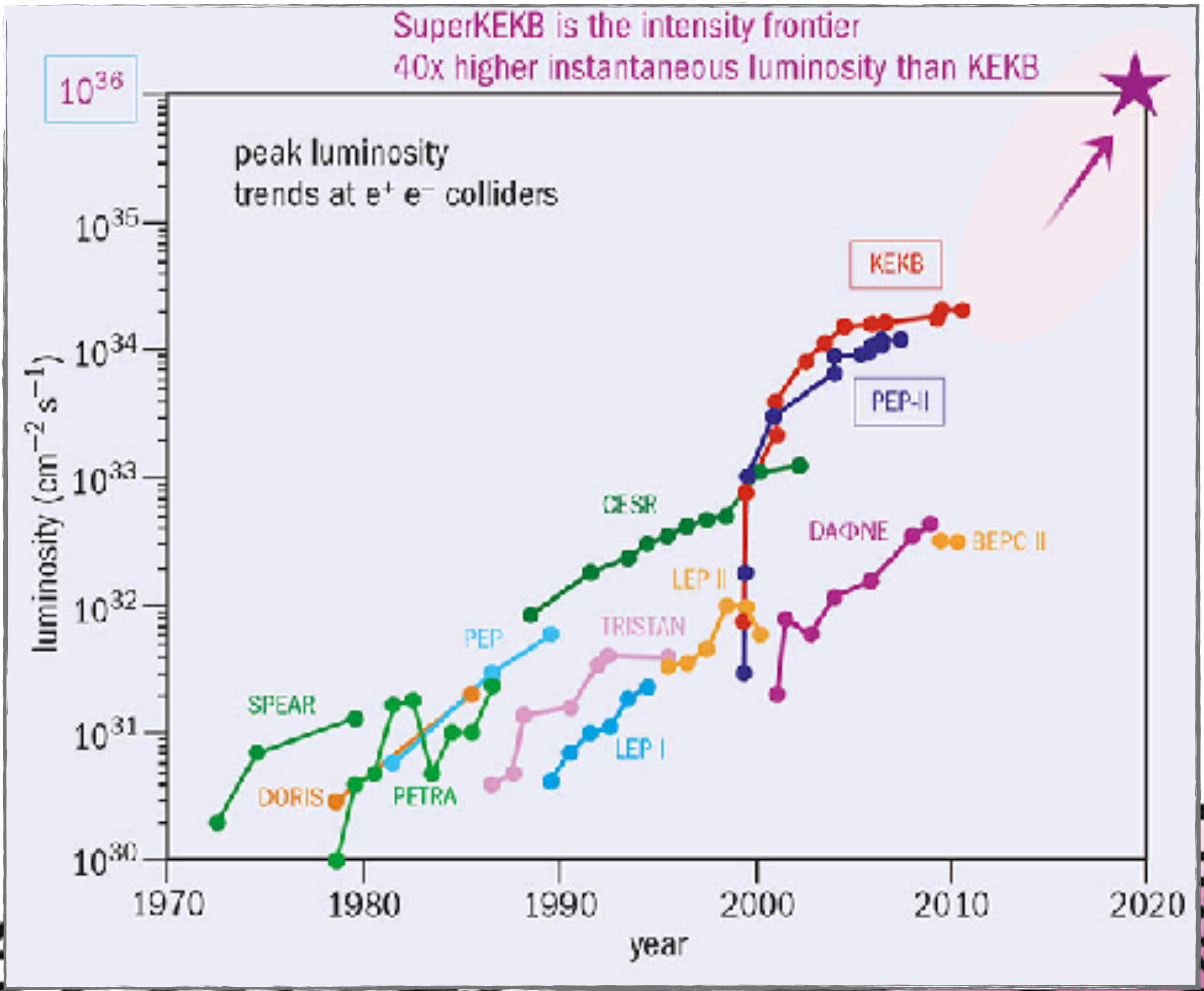


SUPERKEKB: ON THE INTENSITY FRONTIER

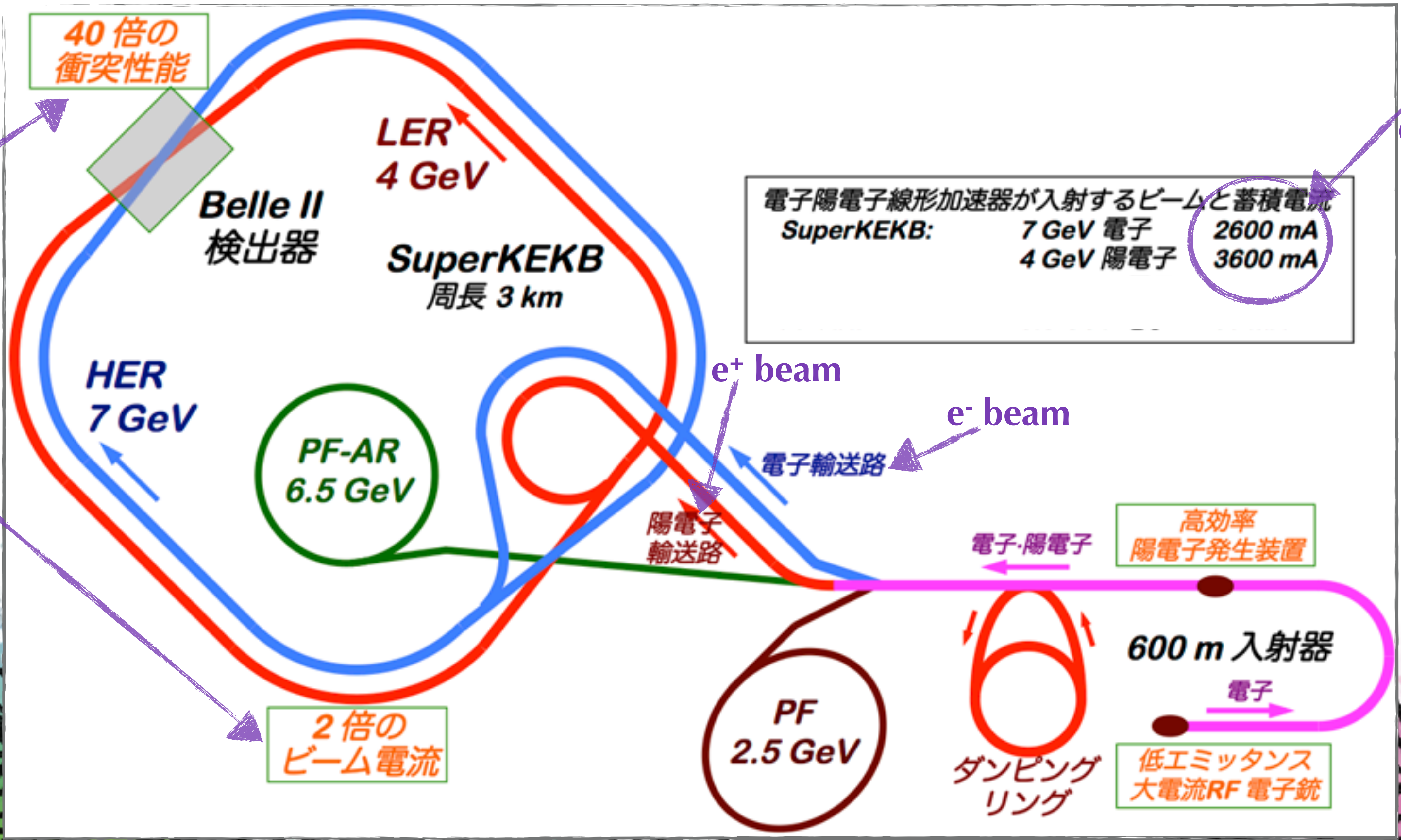
- **40 times** the peak luminosity of KEKB
- 2 times as much current
- 20 times smaller vertical beam size



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



SUPERKEKB: ON THE INTENSITY FRONTIER



電子陽電子線形加速器が入射するビームと蓄積電流

SuperKEKB:	7 GeV 電子	2600 mA
	4 GeV 陽電子	3600 mA

40x Peak Luminosity

2x Beam Current

Final Target Currents

e$^+$ beam

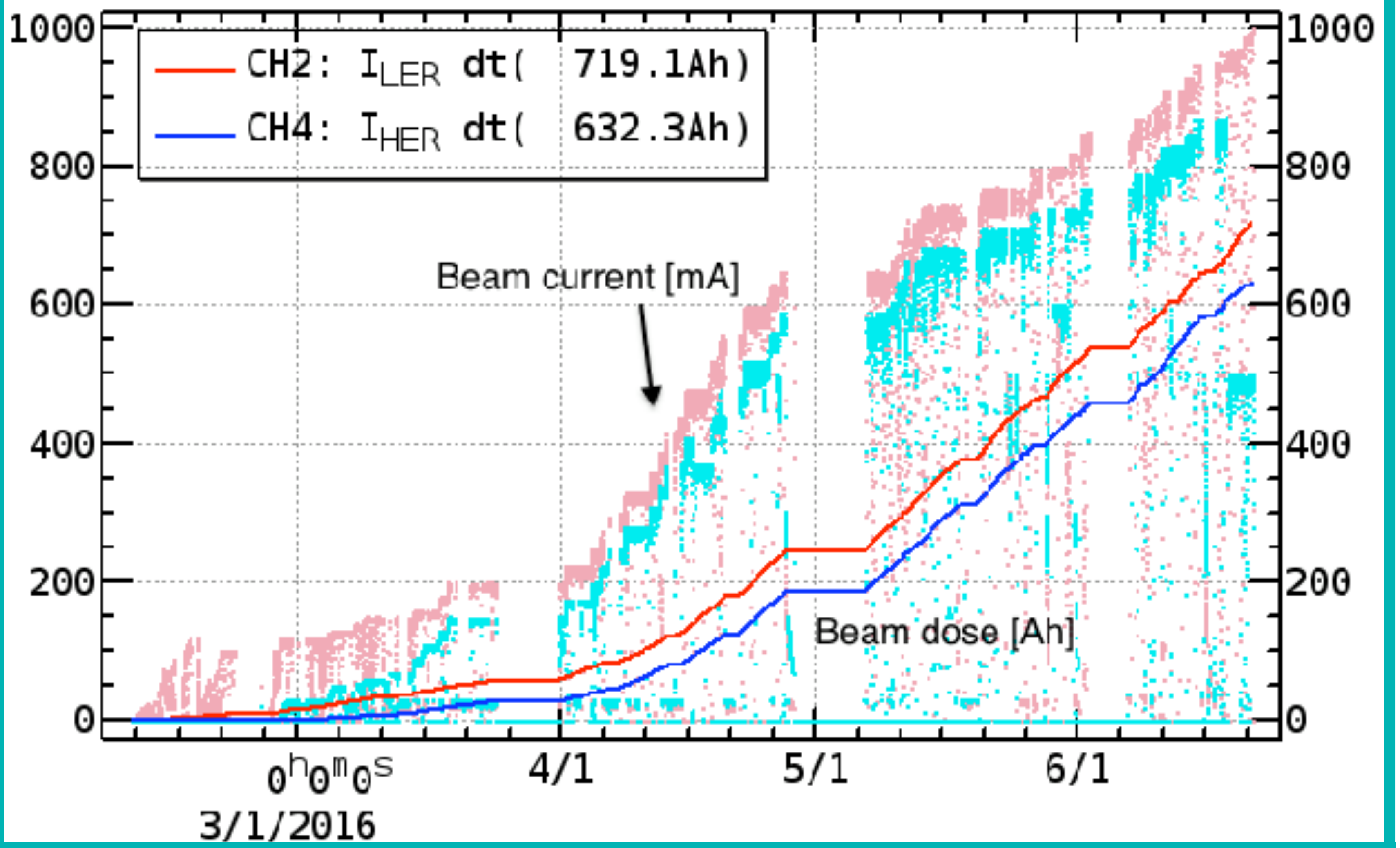
e$^-$ beam

DETECTOR COMMISSIONING

IP - August 2016

- Phase 1: non-collision run
    - February - June, 2016
- Phase 2: **first collisions**
    - Beginning in **February, 2018**
    - Partial detector (1 vertex detector segment), resulting in lower efficiencies
    - **20 +/- 20 $\mathbf{fb^{-1}}$** of data collection
- Phase 3: full data-taking period
    - Beginning in late 2018
    - Full detector

PHASE 1: STATUS OF THE ACCELERATOR

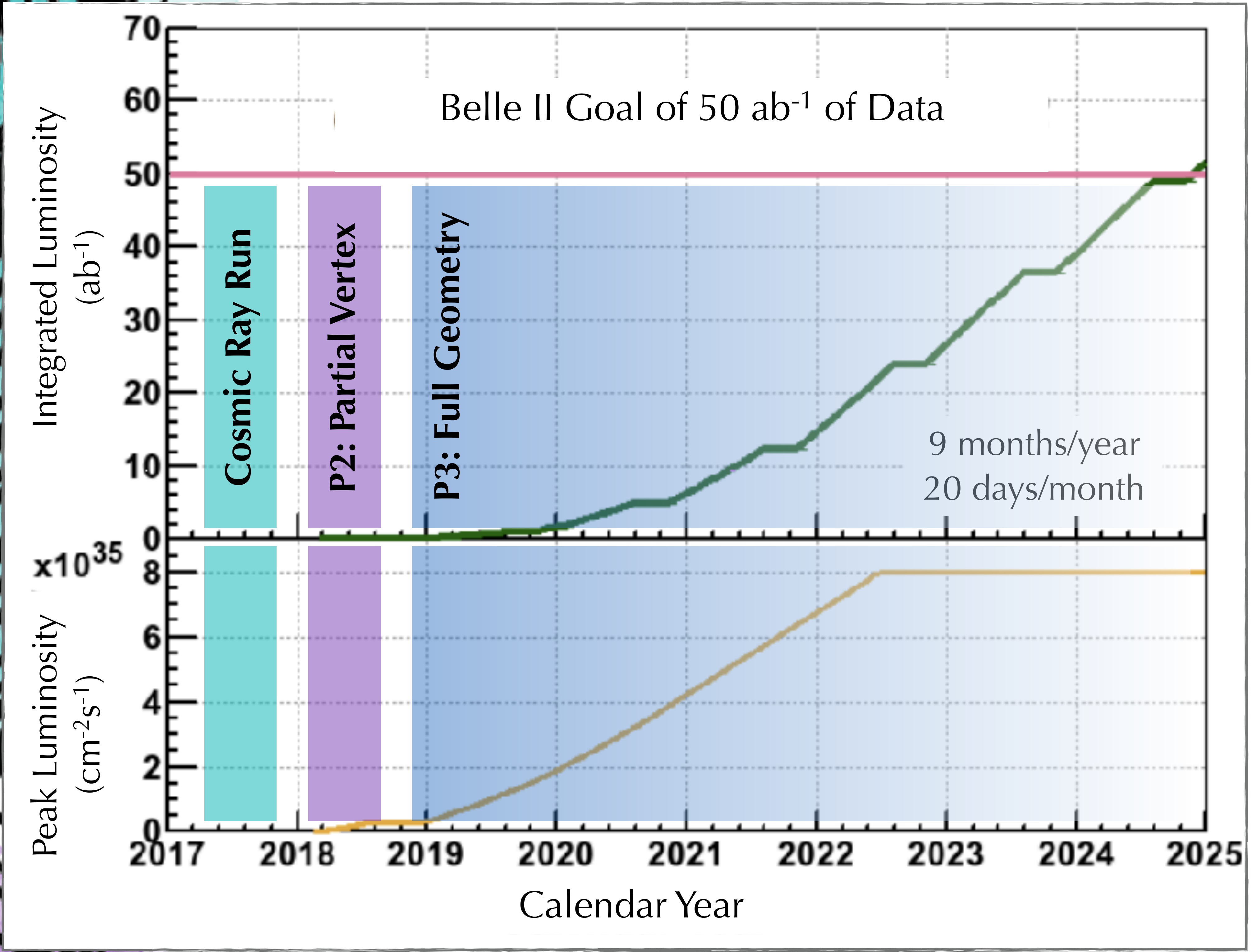


5 Months of Operation (2/1 - 6/30)

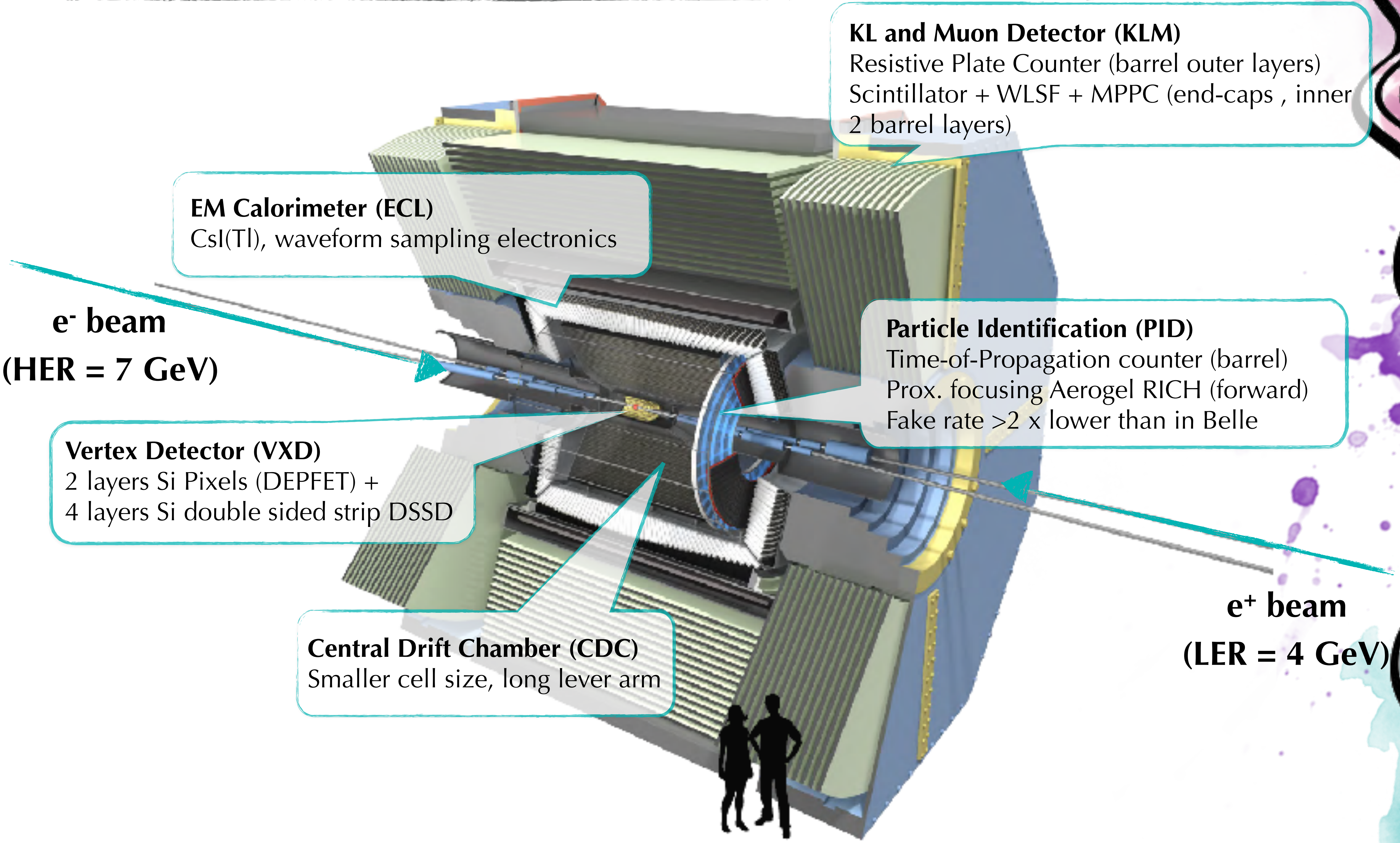
- Last year, Phase 1 ran — this was the first operation of SuperKEKB.

	e^- beam (HER = 7 GeV)	**e^+ beam (LER = 4 GeV)**
Final Target Currents	**2600 mA**	**3600 mA**

DATA COLLECTION SCHEDULE



THE BELLE II DETECTOR



KL and Muon Detector (KLM)
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)

EM Calorimeter (ECL)
CsI(Tl), waveform sampling electronics

e$^-$ beam
(HER = 7 GeV)

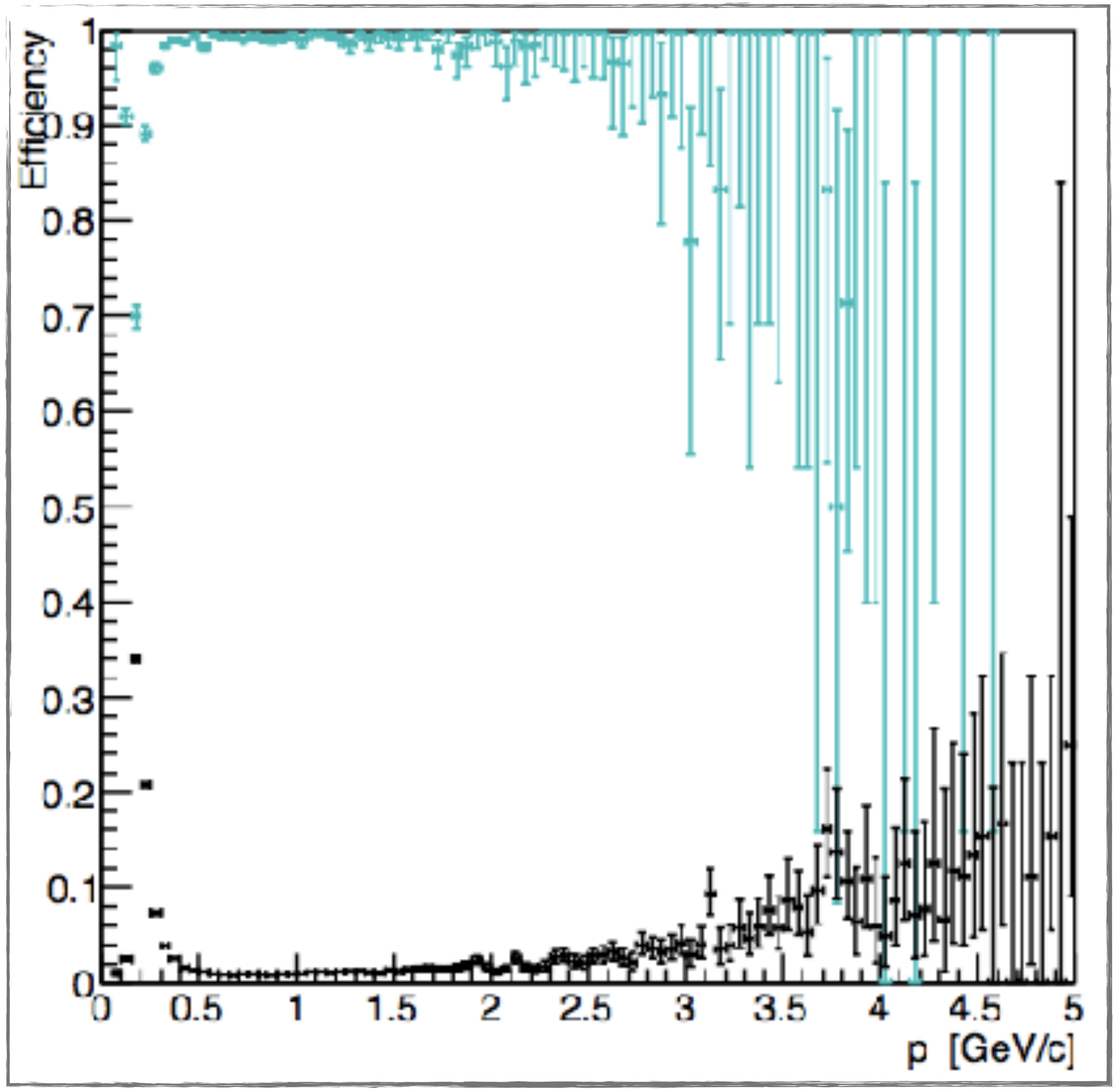
Particle Identification (PID)
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)
Fake rate >2 x lower than in Belle

Vertex Detector (VXD)
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD

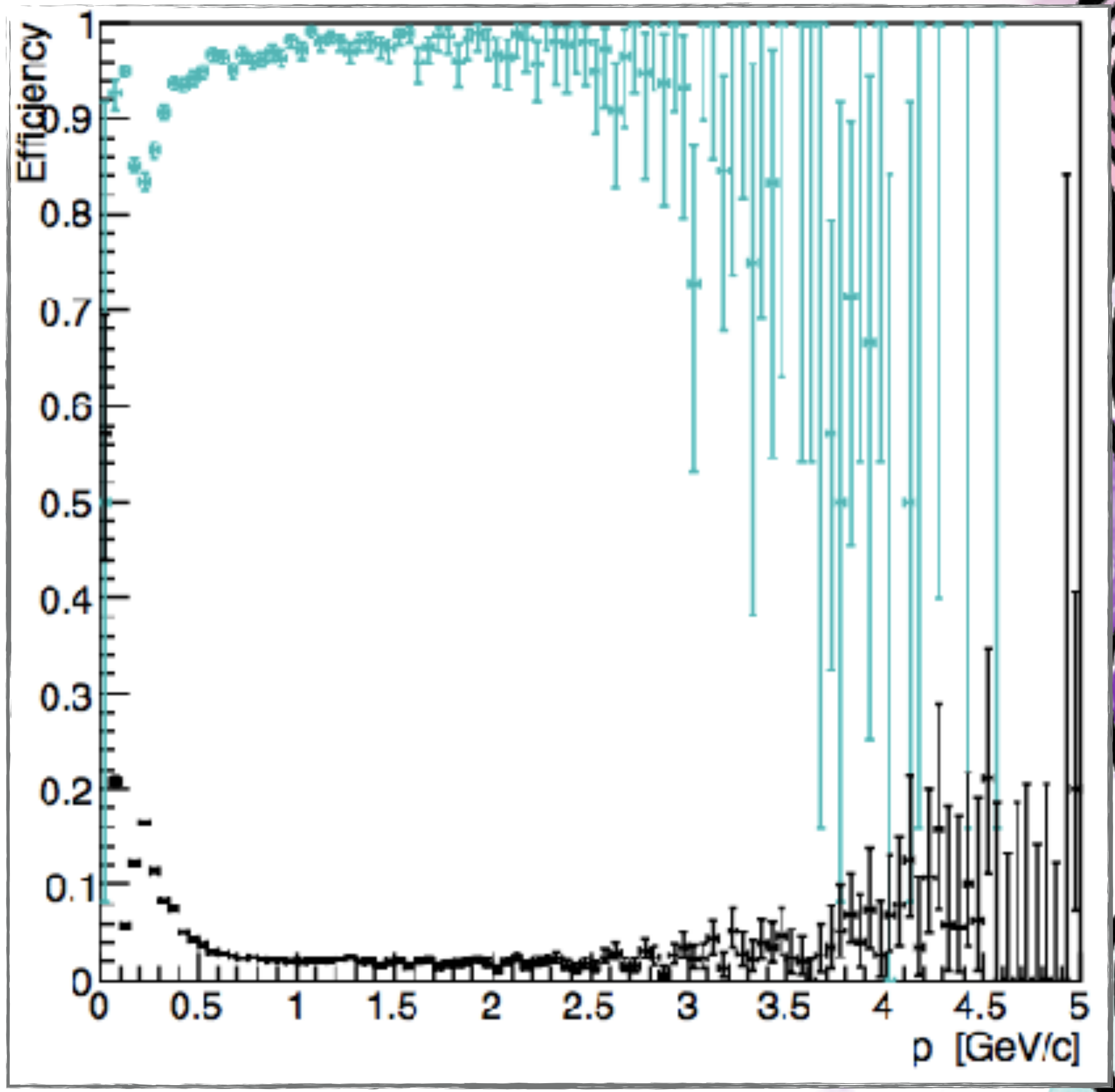
e$^+$ beam
(LER = 4 GeV)

Central Drift Chamber (CDC)
Smaller cell size, long lever arm

DETECTOR PERFORMANCE: ELECTRON ID AND PION FAKE RATE



CDC Likelihood



dE/dx and ECL Likelihood

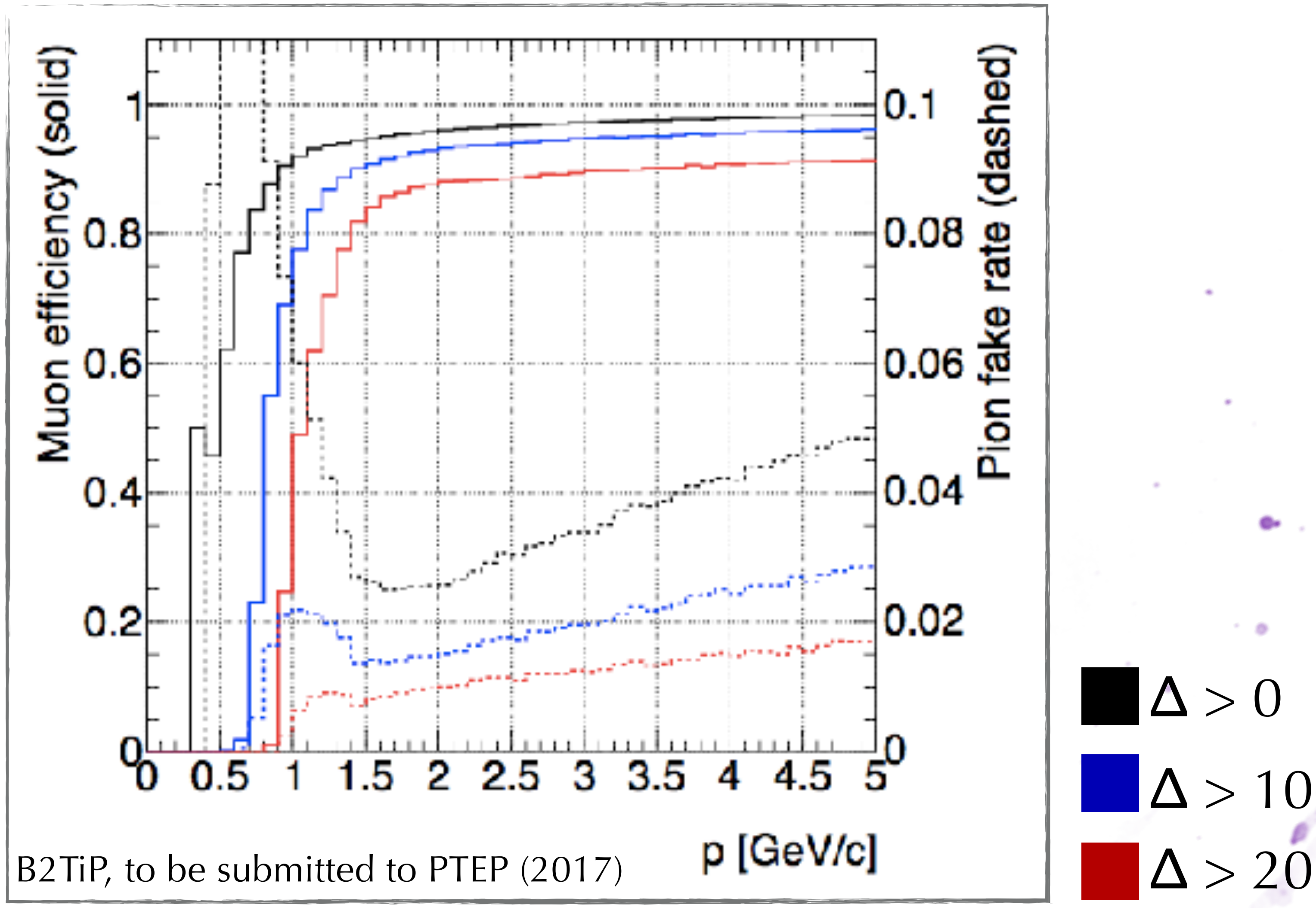
🟦 Electrons

⬛ Pions

Global Electron PID

DETECTOR PERFORMANCE: MUON ID AND PION FAKE RATE

$$\Delta \equiv \ln(\mathcal{L}(\mu^+; O,\ \ell,\ D,\ \vec{x},\ \chi^2,\ n)) - \ln(\mathcal{L}(\pi^+; O,\ \ell,\ D,\ \vec{x},\ \chi^2,\ n))$$



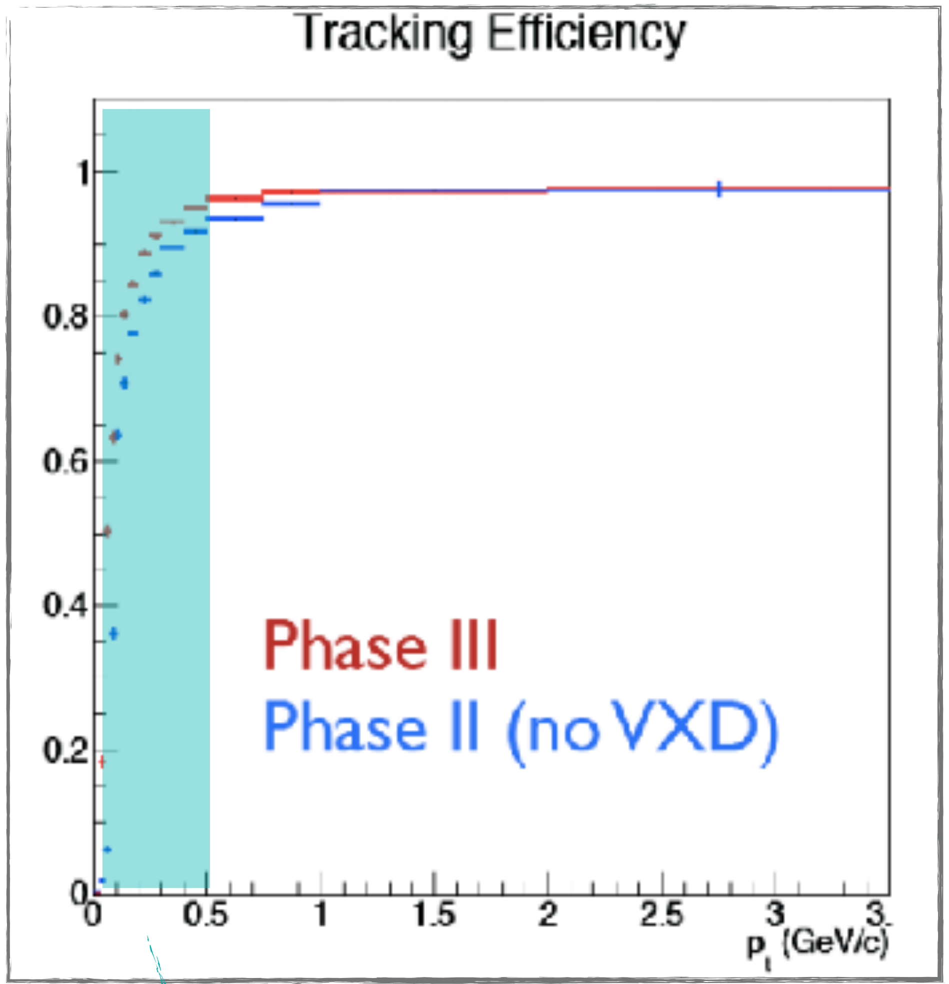
B2TiP, to be submitted to PTEP (2017)

KLM Likelihood

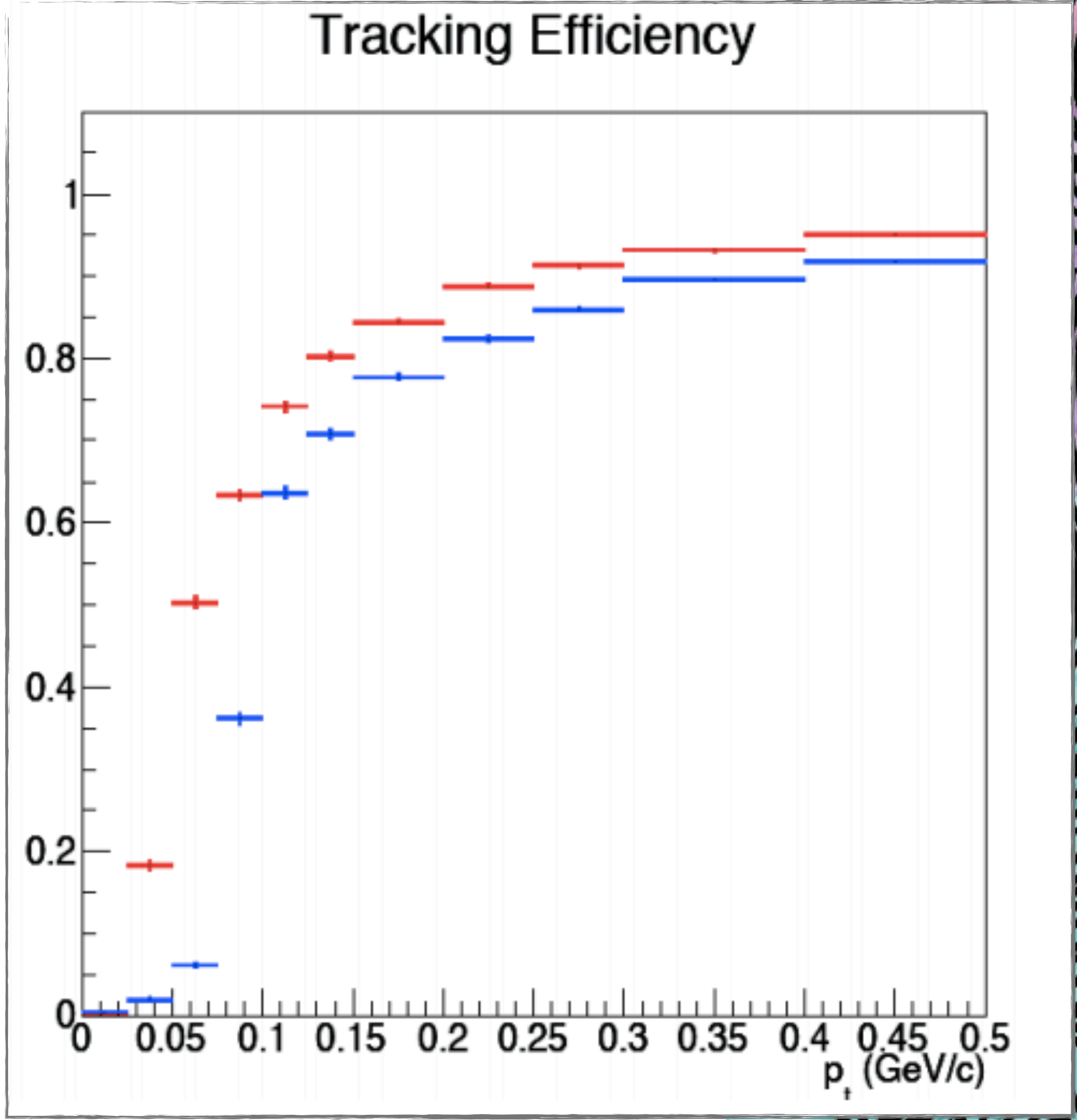
↓

Global Muon PID

DETECTOR PERFORMANCE: TRACKING EFFICIENCIES



Tracking Efficiencies are >90% for p_T>0.3GeV/c



BEAM BACKGROUND

Phase 1

Touschek Scattering

- Intra-bunch scattering process
- Dominant with highly compressed beams

Beam-Gas Scattering

- Bremsstrahlung (negligible) and Coulomb interactions with residual gas atoms and molecules

Synchrotron Scattering

- Emission of photons by charged particles when deflected by B-field

Phase 2

Radiative Bhabha

- Photon emission prior to or after Bhabha scattering
- Interaction with iron in the magnets

Two-Photon

- Production of very low momentum electron-positron pairs
- Increased hit occupancy in inner detectors

BELLE II TRIGGER SYSTEM

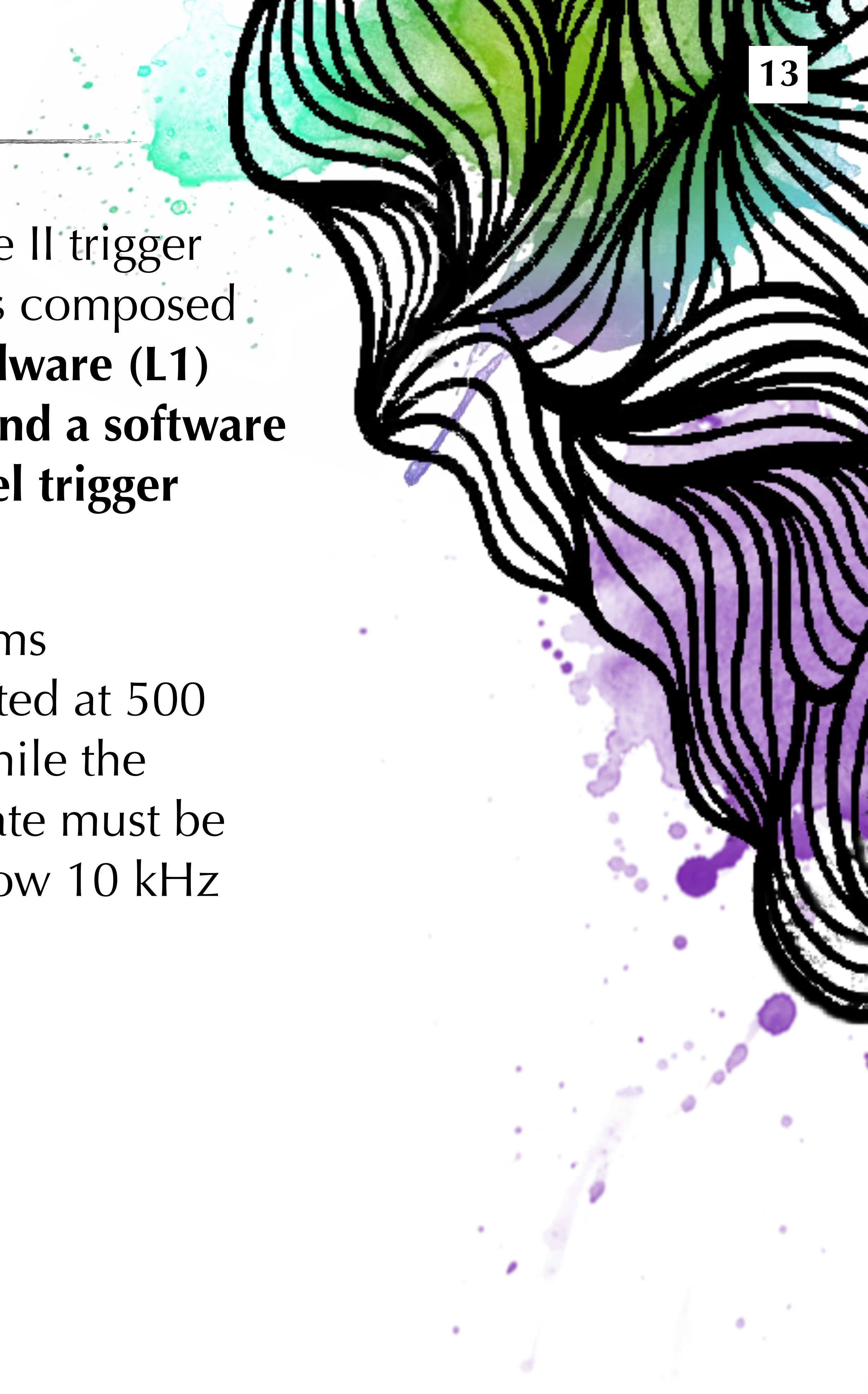
	Cross Section (acceptance) [nb]
BB	1.1
c	1.3
uds	2.4
ττ	0.9
μμ*	0.9
γγ*	3.1
ee*	74
eeee/eeμμ	60
Total	143.7

total cross section: ~140nb

- The Belle II trigger system is composed of **a hardware (L1) trigger and a software high level trigger (HLT)**
- e^+e^- beams accelerated at 500 MHz, while the output rate must be kept below 10 kHz

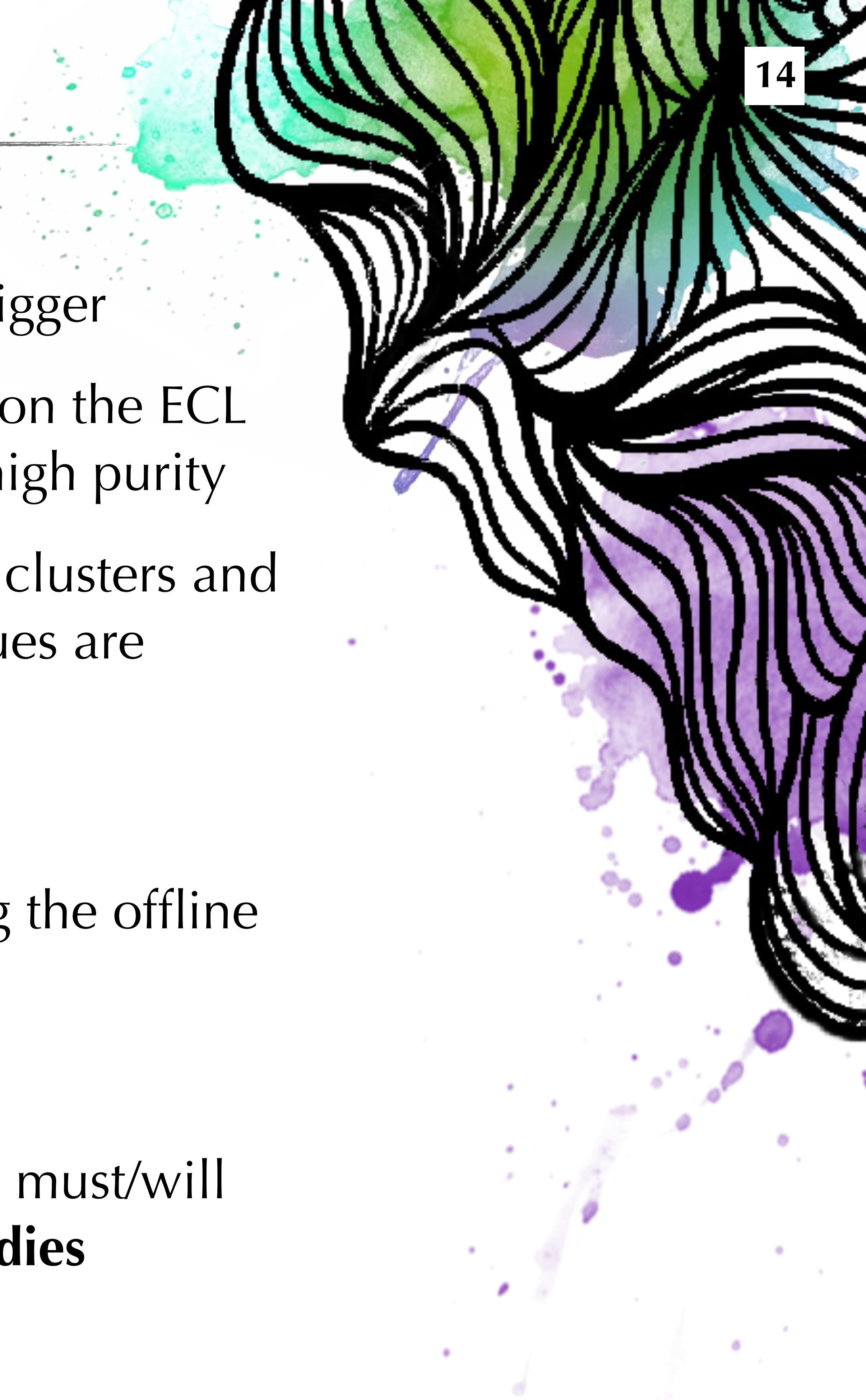
Subdetector Acceptances
CDC: $17^o < \theta < 150^o$
ECL: $12.4^o < \theta < 155.1^o$

*two particles in ECL coverage

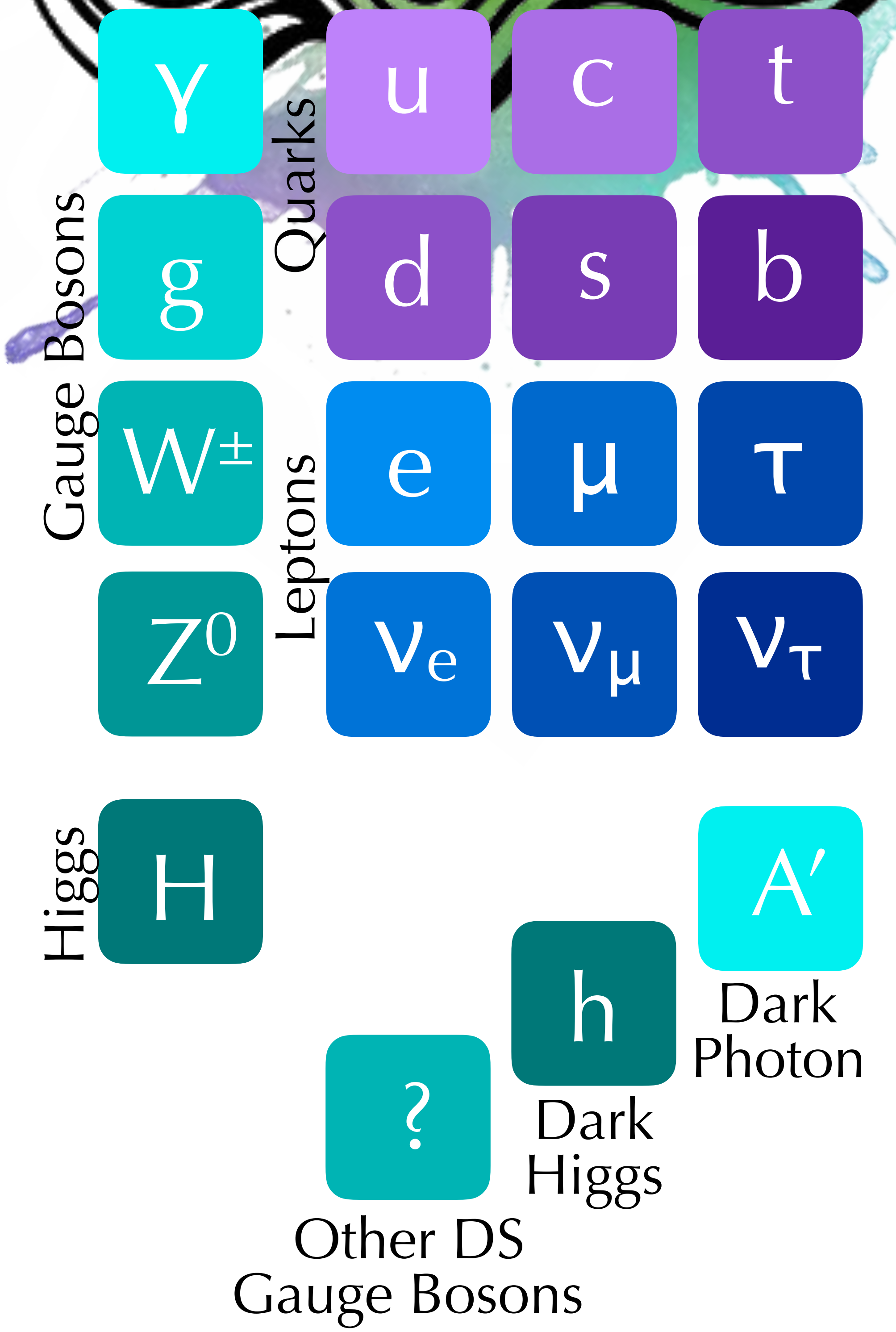


BELLE II TRIGGER SYSTEM

- L1 trigger
  - 3D tracking is implemented on CDC trigger
  - 3D **ECL bhabha veto logic** is available on the ECL trigger to identify bhabha events with high purity
  - Matches between CDC tracks and ECL clusters and other low level reconstruction techniques are implemented on the L1 trigger
- HLT trigger
  - Reconstructs the events online by using the offline reconstruction algorithm
  - 6000 cpu cores at target luminosity
- As we will see, the Belle II trigger system must/will implement **dedicated triggers for DS studies**

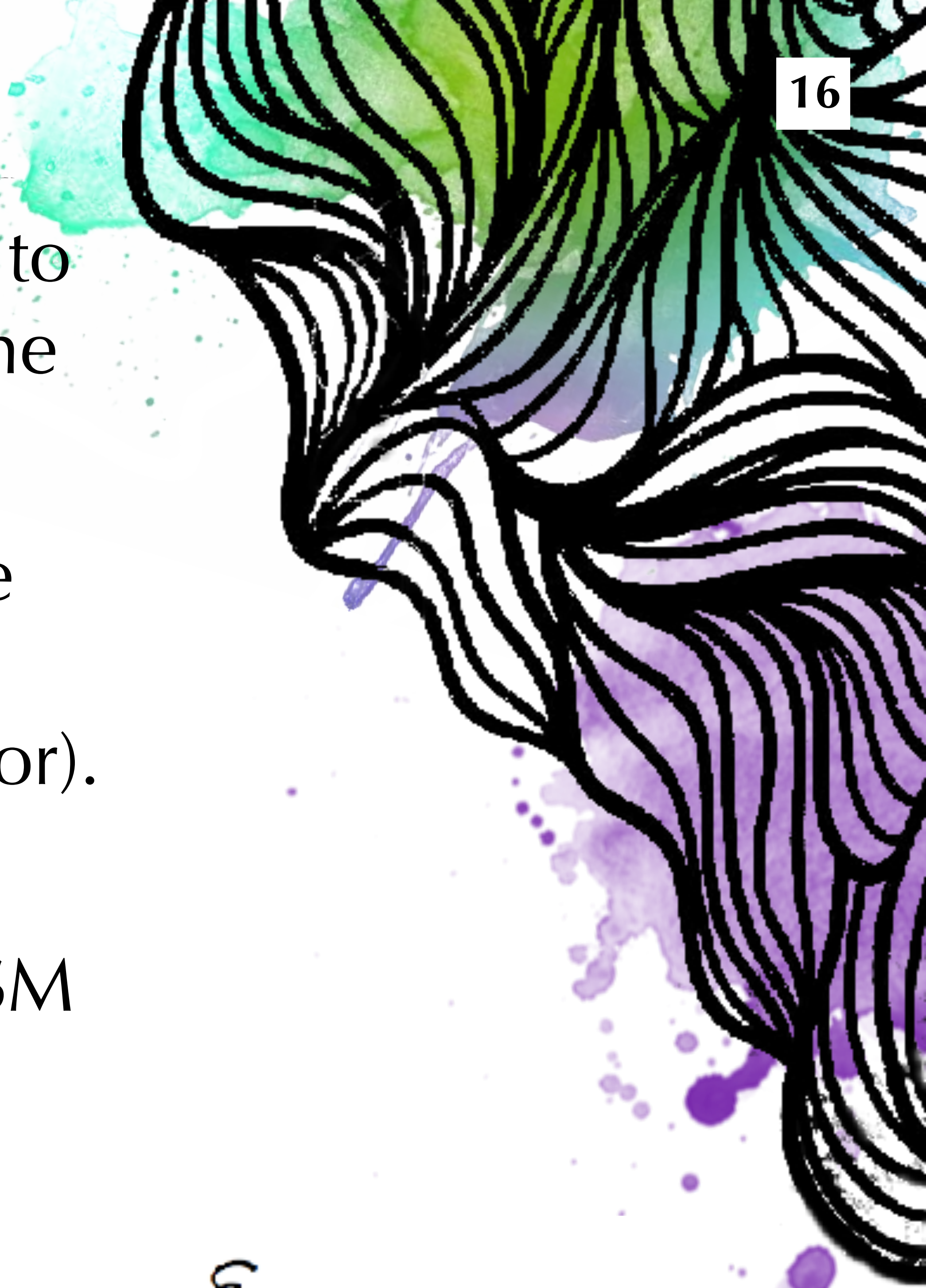


SHORTCOMINGS OF THE SM



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

INTRODUCING THE DARK PHOTON



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

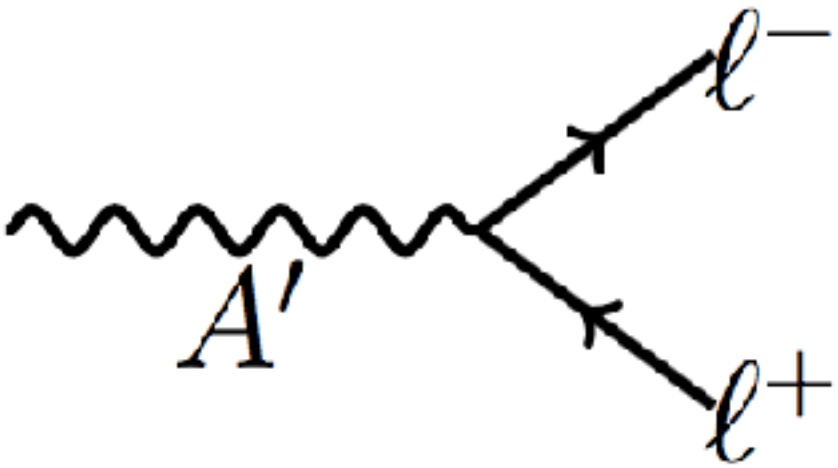
$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\varepsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

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

FERMIONIC INTERACTIONS

- $U(1)_X \otimes U(1)_Z$ 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**.

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



THE DARK PHOTON PRODUCTION CROSS SECTION

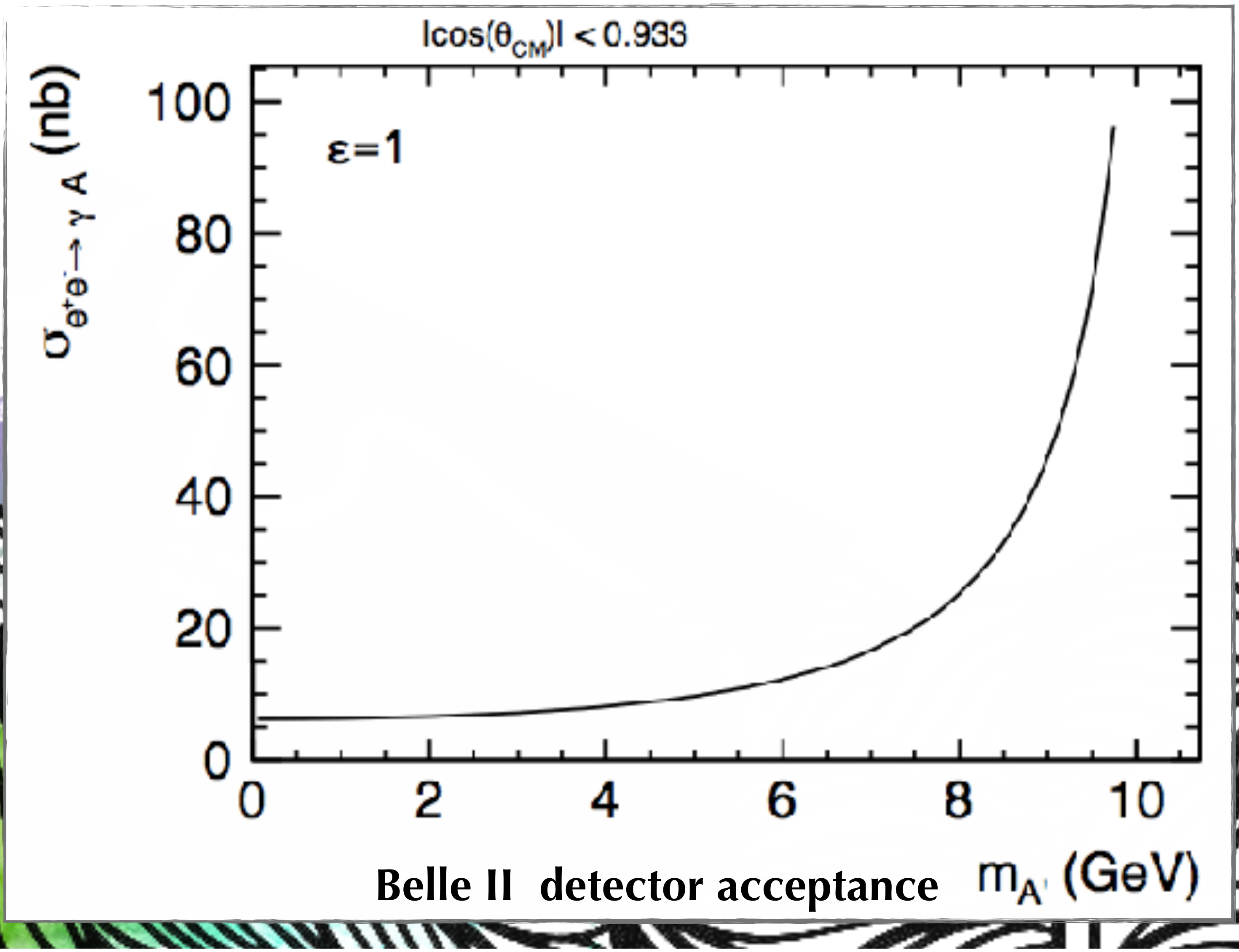
- The mixing strength between the photon and the dark photon is constrained through the cross section as…

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

Mixing Strength Parameter

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

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

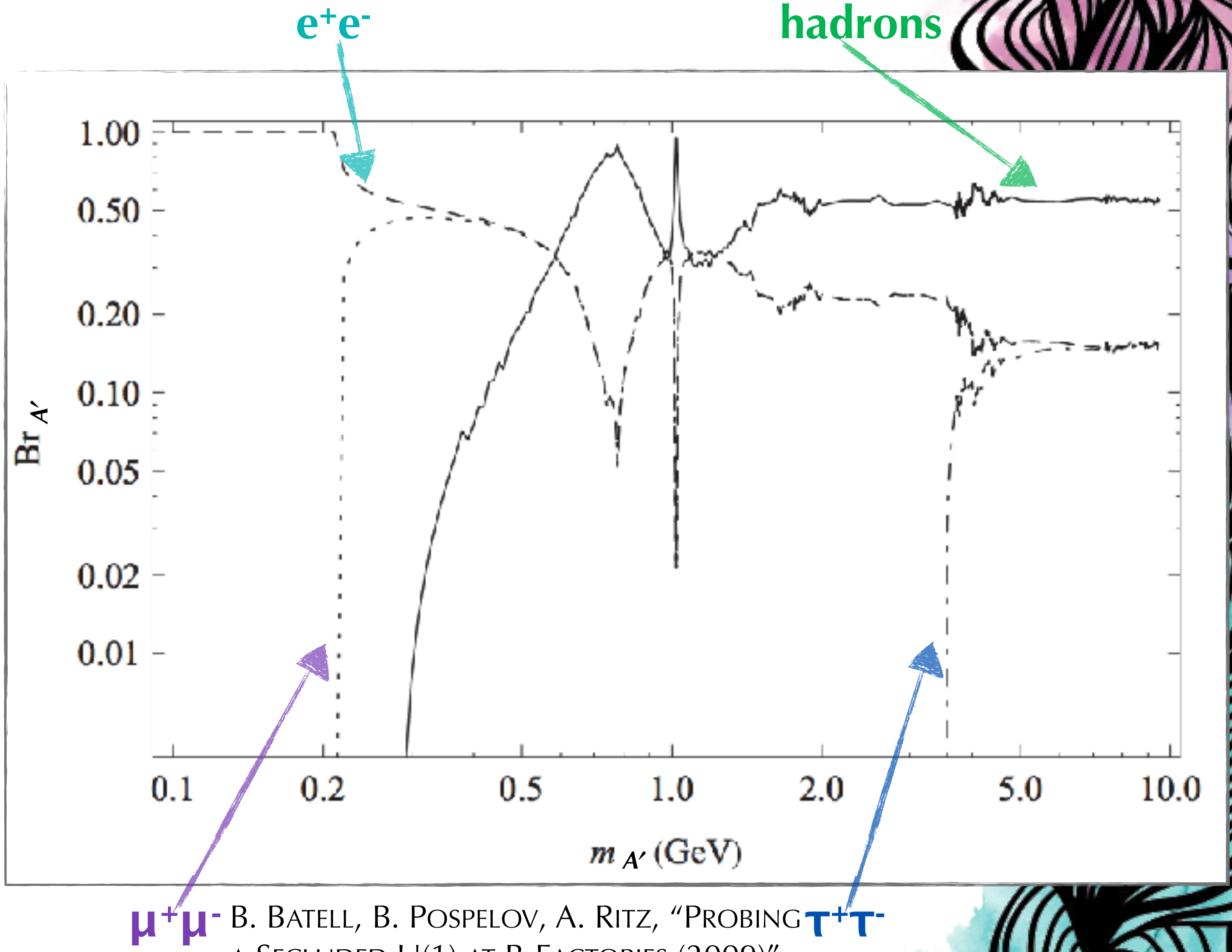


Belle II detector acceptance

DARK PHOTON BRANCHING RATIOS

Strictly for Decays to Visible Matter

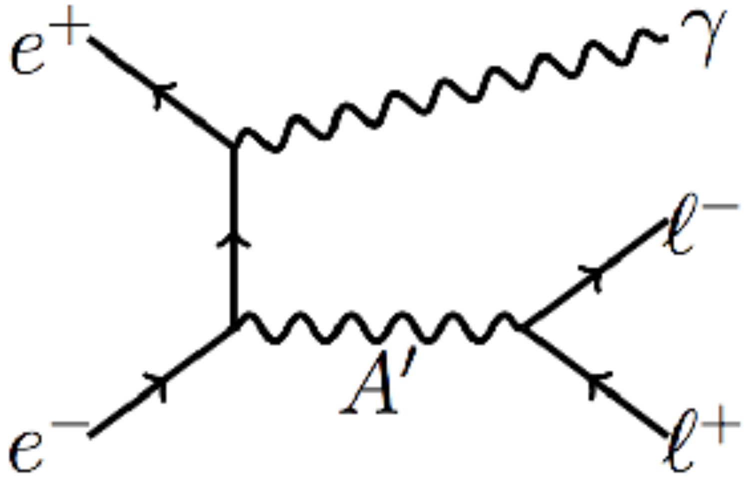
- Dielectron mode has the largest branching fraction.
- Dimuon mode will have higher sensitivity above threshold as there exist far fewer backgrounds.



B. BATELL, B. POSPELOV, A. RITZ, "PROBING A SECLUDED U(1) AT B-FACTORIES (2009)"

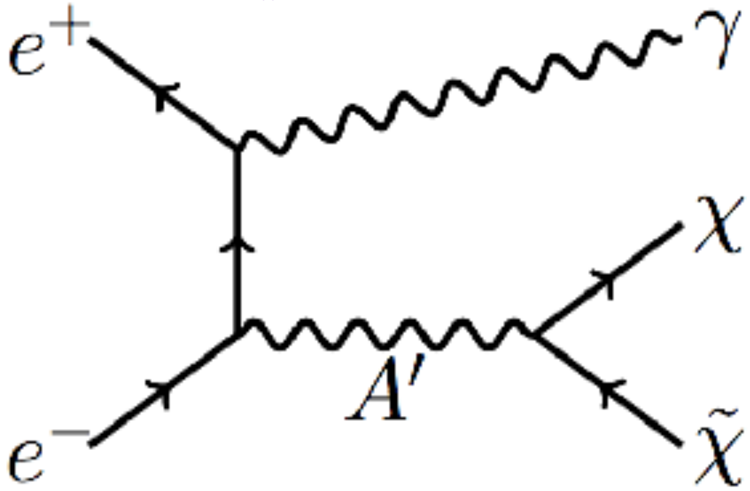
DARK PHOTON SIGNAL MODES AT BELLE II

Dilepton Mode



- 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"**.

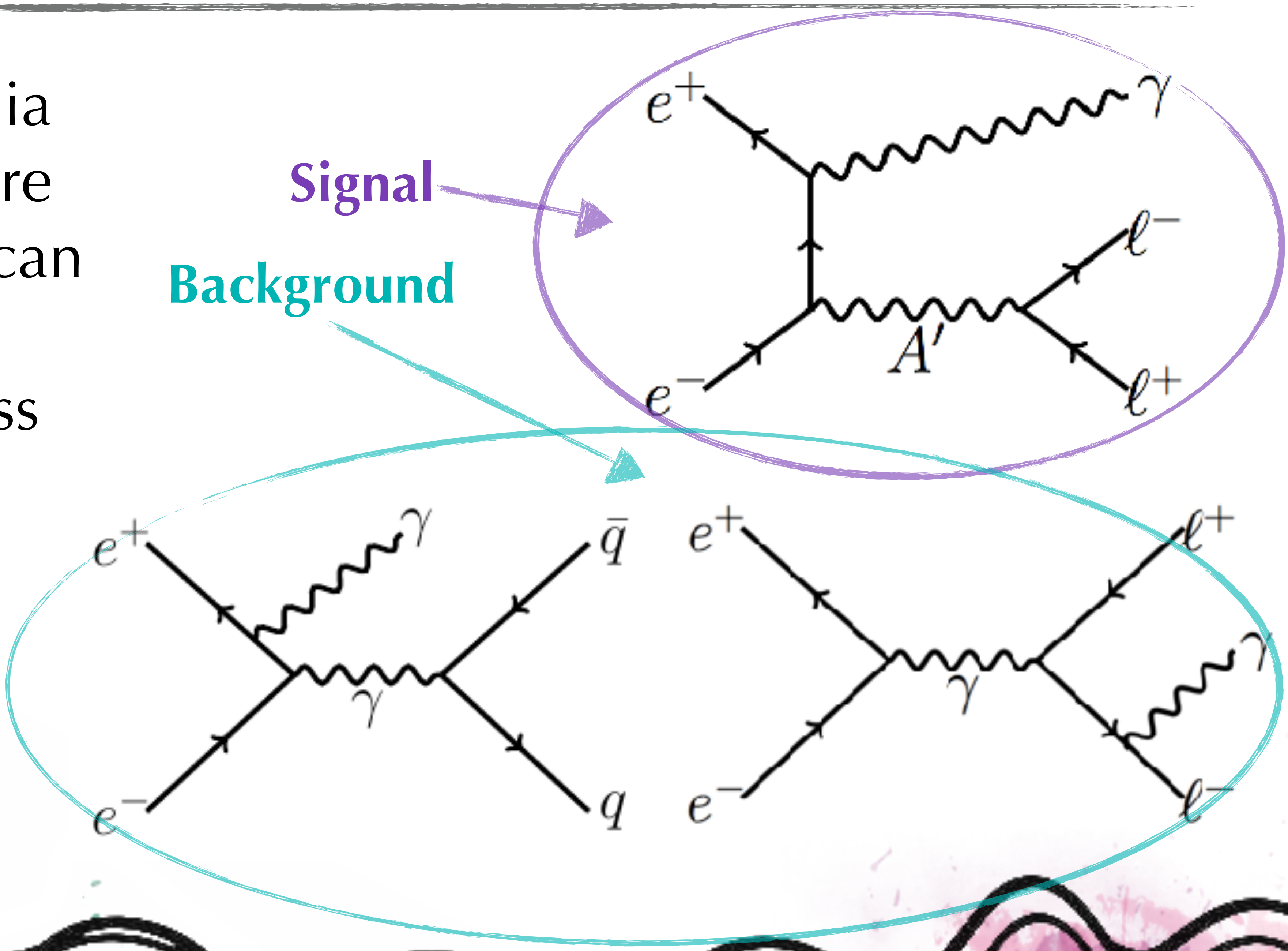
Monophoton Mode



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

BACKGROUND PROCESSES FOR THE DILEPTON MODE

- **ISR** results in quarkonia resonances — these are well understood and can be included in our dilepton invariant mass fits
- **FSR** is also a large background to be concerned with



Signal

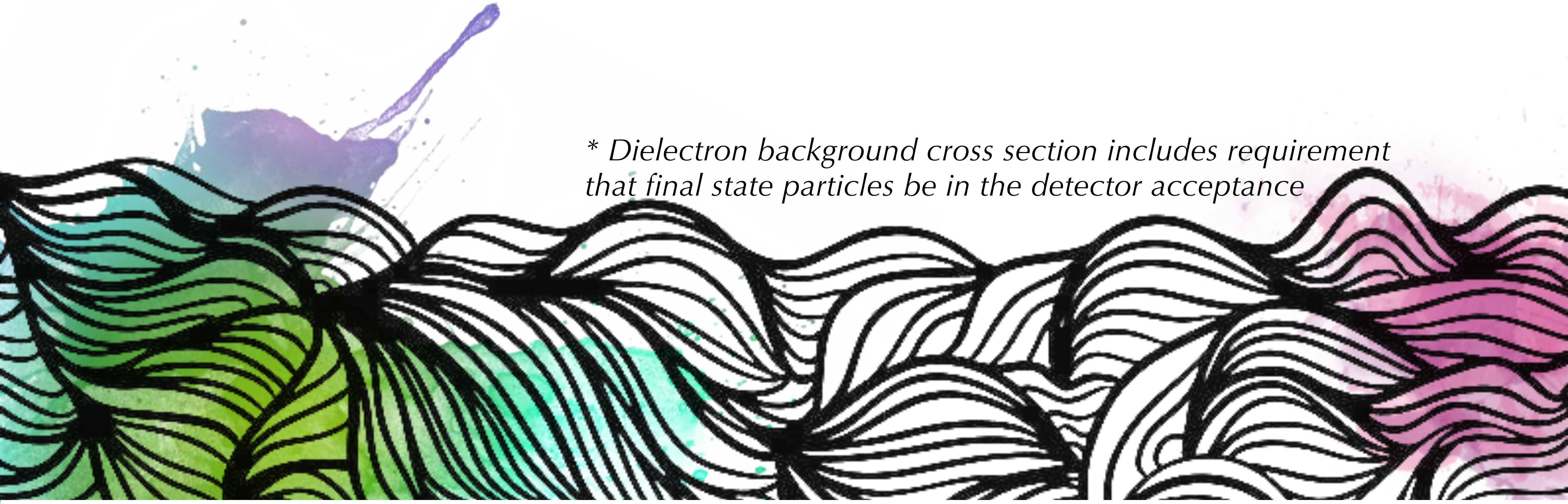
Background

HOW DOES BACKGROUND COMPARE TO SIGNAL?

		Belle	**Belle 2 Phase II**	**Belle 2 Phase III**
		1ab^{-1}	20fb^{-1}	50ab^{-1}
Signal	$\sigma_{A'\gamma} \approx 1\text{fb}$	1×10^3	2×10	5×10^4
	$\sigma_{A'\gamma} \approx 10\text{fb}$	1×10^4	2×10^2	5×10^5
Bkg	$\sigma_{e^+e^-\gamma} = 300\text{nb}$	3×10^{11}	6×10^9	1.15×10^{13}
	$\sigma_{\mu^+\mu^-\gamma} = 1.148\text{nb}$	1.148×10^9	2.296×10^7	5.74×10^{10}

$$\sigma = \frac{N_{\mathbf{sig}}}{\epsilon L}$$

Assuming Perfect Efficiency



** Dielectron background cross section includes requirement that final state particles be in the detector acceptance*

HOW DOES BACKGROUND COMPARE TO SIGNAL?

		Belle 1ab^{-1}	**Belle 2 Phase II** 20fb^{-1}	**Belle 2 Phase III** 50ab^{-1}
Signal	$\sigma_{A'\gamma} \approx 1\text{fb}$	1×10^3	2×10	5×10^4
	$\sigma_{A'\gamma} \approx 10\text{fb}$	1×10^4	2×10^2	5×10^5
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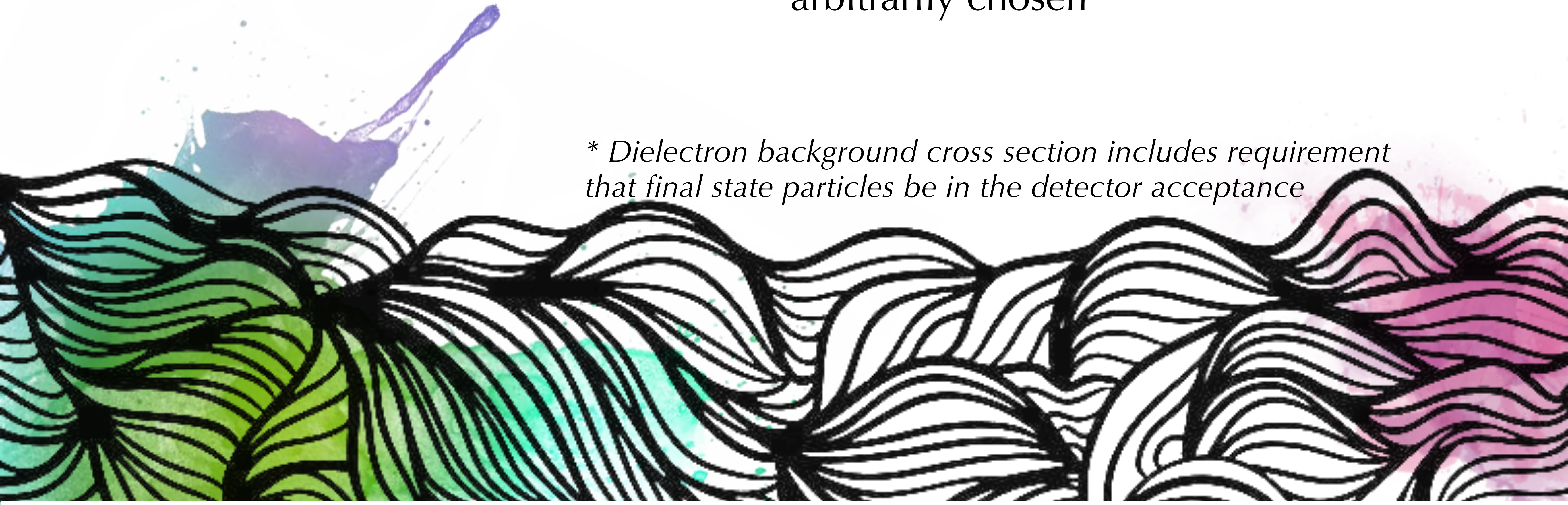
Assuming Perfect Efficiency

Example cross-sections arbitrarily chosen

** Dielectron background cross section includes requirement that final state particles be in the detector acceptance*



How Does Background Compare to Signal?

		Belle	**Belle 2 Phase II**	**Belle 2 Phase III**
		1ab^{-1}	20fb^{-1}	50ab^{-1}
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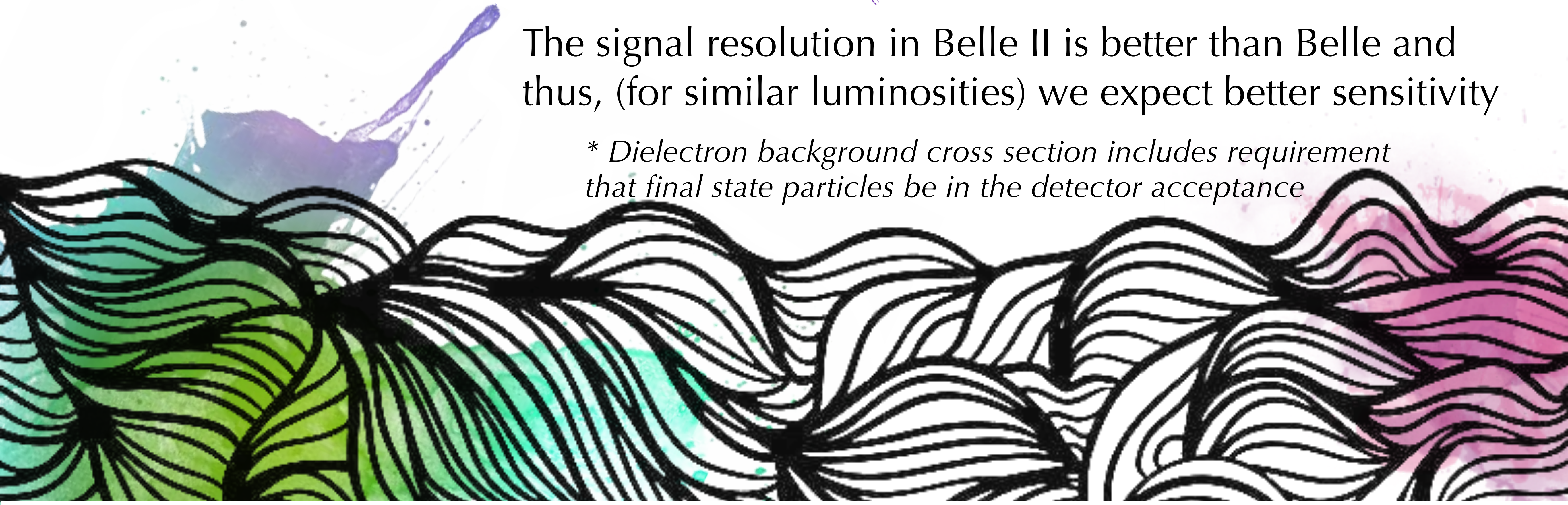
$$\sigma = \frac{N_{\text{sig}}}{\epsilon L}$$

Assuming Perfect Efficiency

The signal resolution in Belle II is better than Belle and thus, (for similar luminosities) we expect better sensitivity

** Dielectron background cross section includes requirement that final state particles be in the detector acceptance*



HOW DOES BACKGROUND COMPARE TO SIGNAL?

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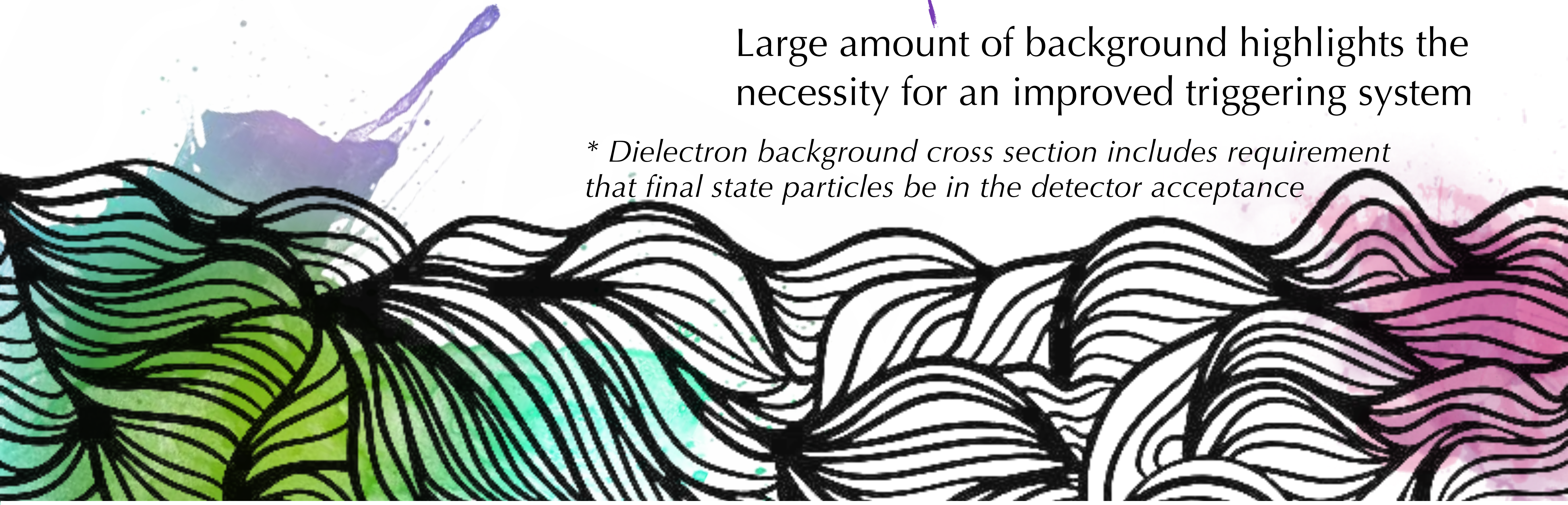
$$\sigma = \frac{N_{\text{sig}}}{\epsilon L}$$

Assuming Perfect Efficiency

Large amount of background highlights the necessity for an improved triggering system

** Dielectron background cross section includes requirement that final state particles be in the detector acceptance*



DS-FRIENDLY TRIGGER LOGIC: A′ —> VISIBLE

- Our main background ee->$\gamma\gamma(\gamma)$, ee(γ) which is proportional to the instantaneous luminosity
- Optimize the trigger efficiency with **dedicated trigger schemes** for different luminosity periods
- In Belle, our **Bhabha veto trigger** was highly efficient but also threw out many low-multiplicity events with the same signature as our DS searches.

DILEPTON MODE SELECTION CRITERIA

1. Two oppositely charged, “well-identified” (eid or muid > 0.1) lepton tracks
2. Total invariant mass (two tracks AND photon) near the ϒ(4S) resonance ($9.5 \leq m_{(\mu^+\mu^- \text{ or } e^+e^-)\gamma} \leq 10.8$ GeV/c^2)
3. One photon with $E_\gamma \geq 0.2$ GeV (reduced background from bremsstrahlung)

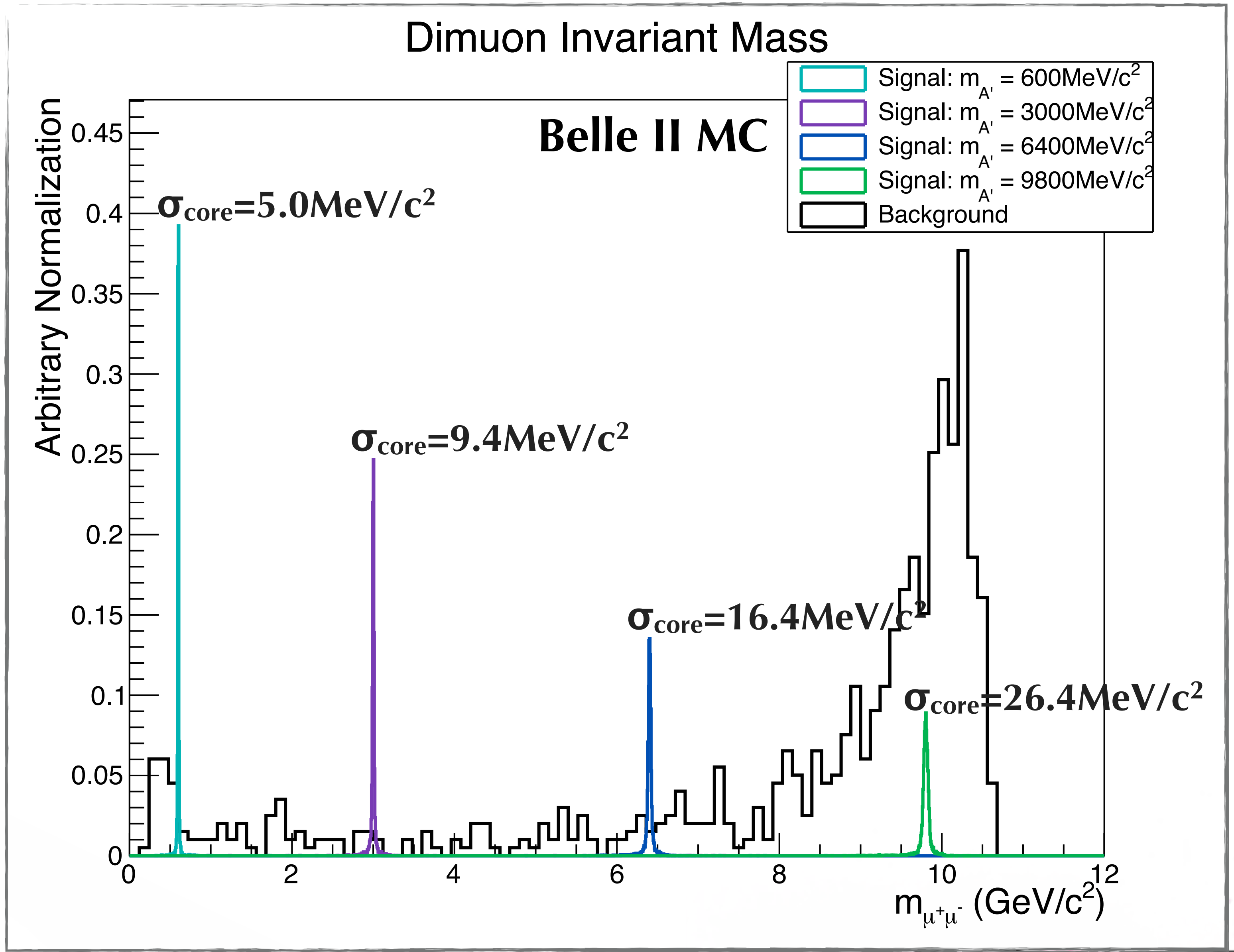
Dimuon mode Belle II MC

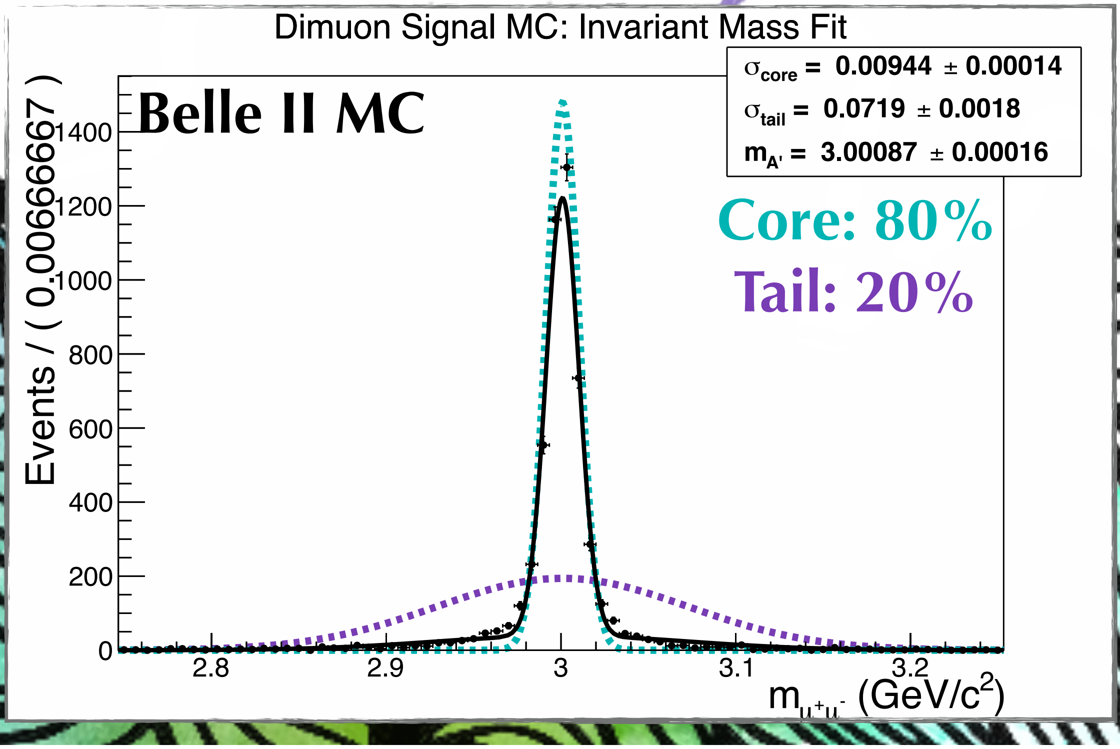
A′ Mass Hypothesis*	Cut 1 (%)	Cut 2 (%)	Cut 3 (%)
0.6 GeV	67.81	56.64	56.63
3.0 GeV	61.41	52.86	52.86
6.4 GeV	74.60	65.57	65.57
9.8 GeV	80.56	75.07	73.00
Background	20.57	14.23	7.96

** 52 Mass Hypotheses from 0.2 to 10.4 GeV were examined. 4 have been arbitrarily chosen to show here.*

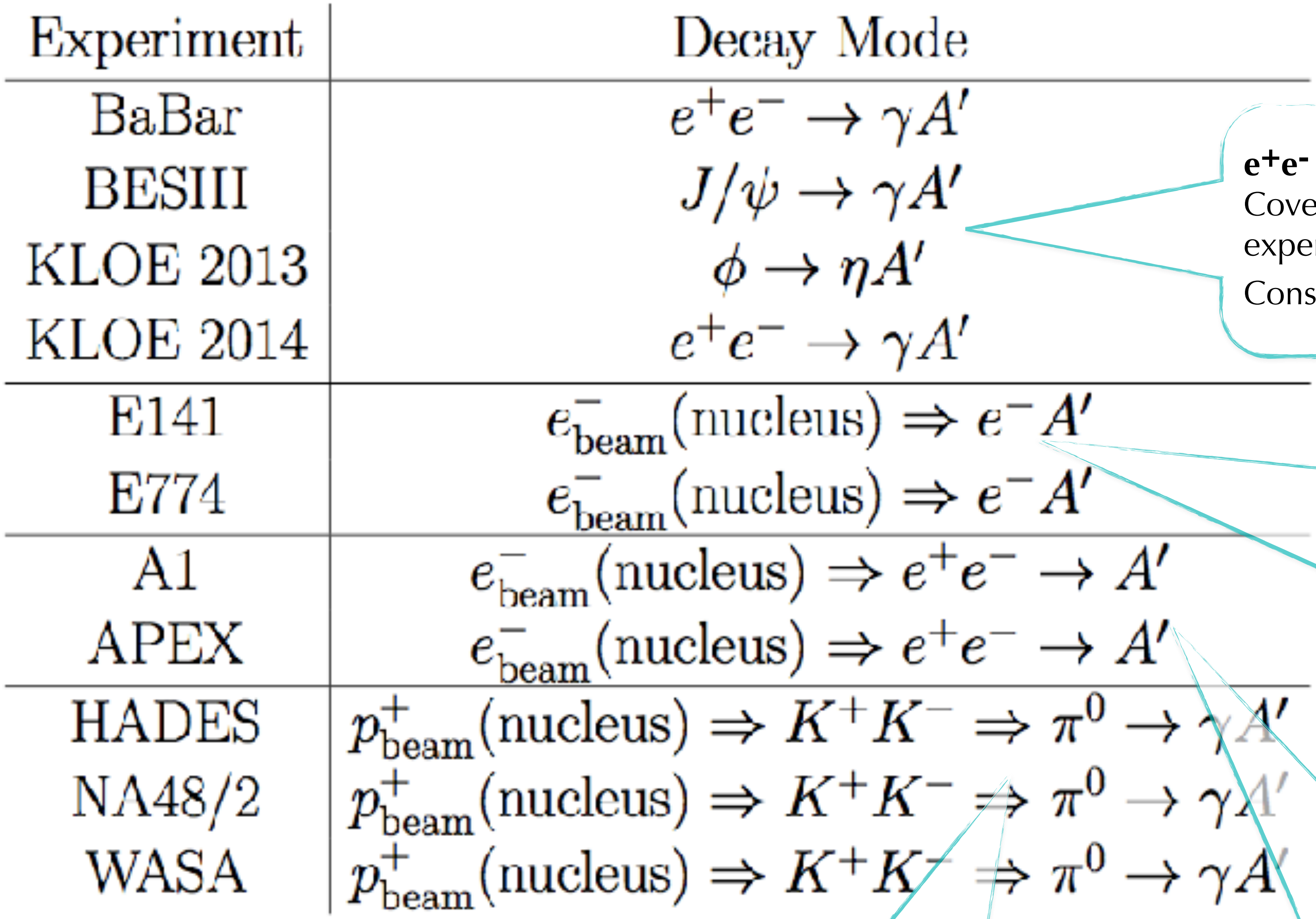
AN EXAMPLE: DIMUON INVARIANT MASS PEAKS

- Mass resolutions are determined by a double Gaussian fit
- Increased A′ mass degrades the signal resolution
- Overall, Belle II signal resolutions are **improved over Belle by ~30%**





GLOBAL EXPERIMENTAL EFFORTS: A′ —> VISIBLE



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 $e^+e^- \to \gamma\gamma$ cross-sections

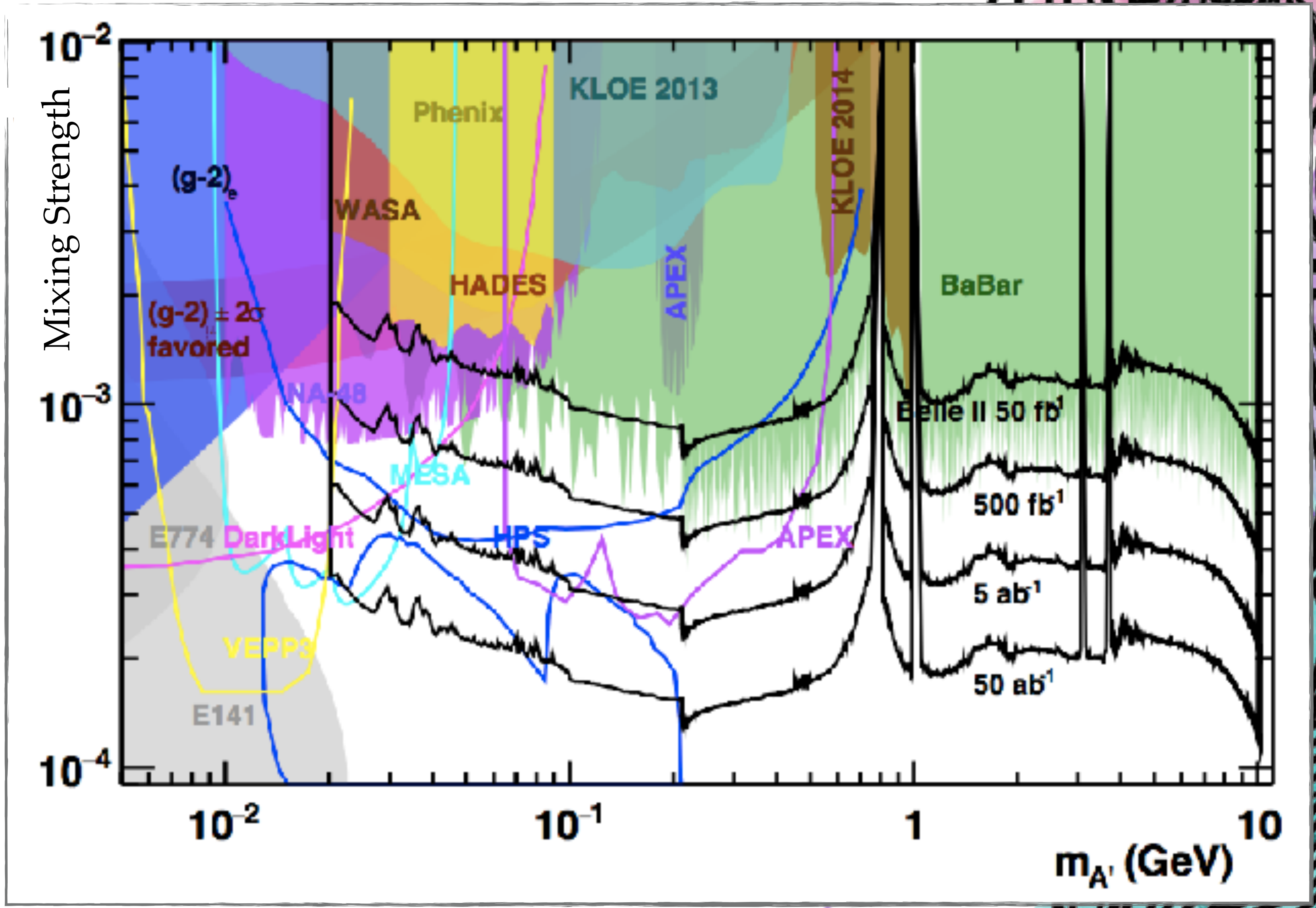
Electron Beam-Dump Experiments
Dark Photons are emitted via Bremsstrahlung
Secondary to original processes being explored

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

Proposed Reach of Belle II: A′ —> Visible

90% CL upper limits on the mixing strength — projections made from the results of BaBar's 2014 search*



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

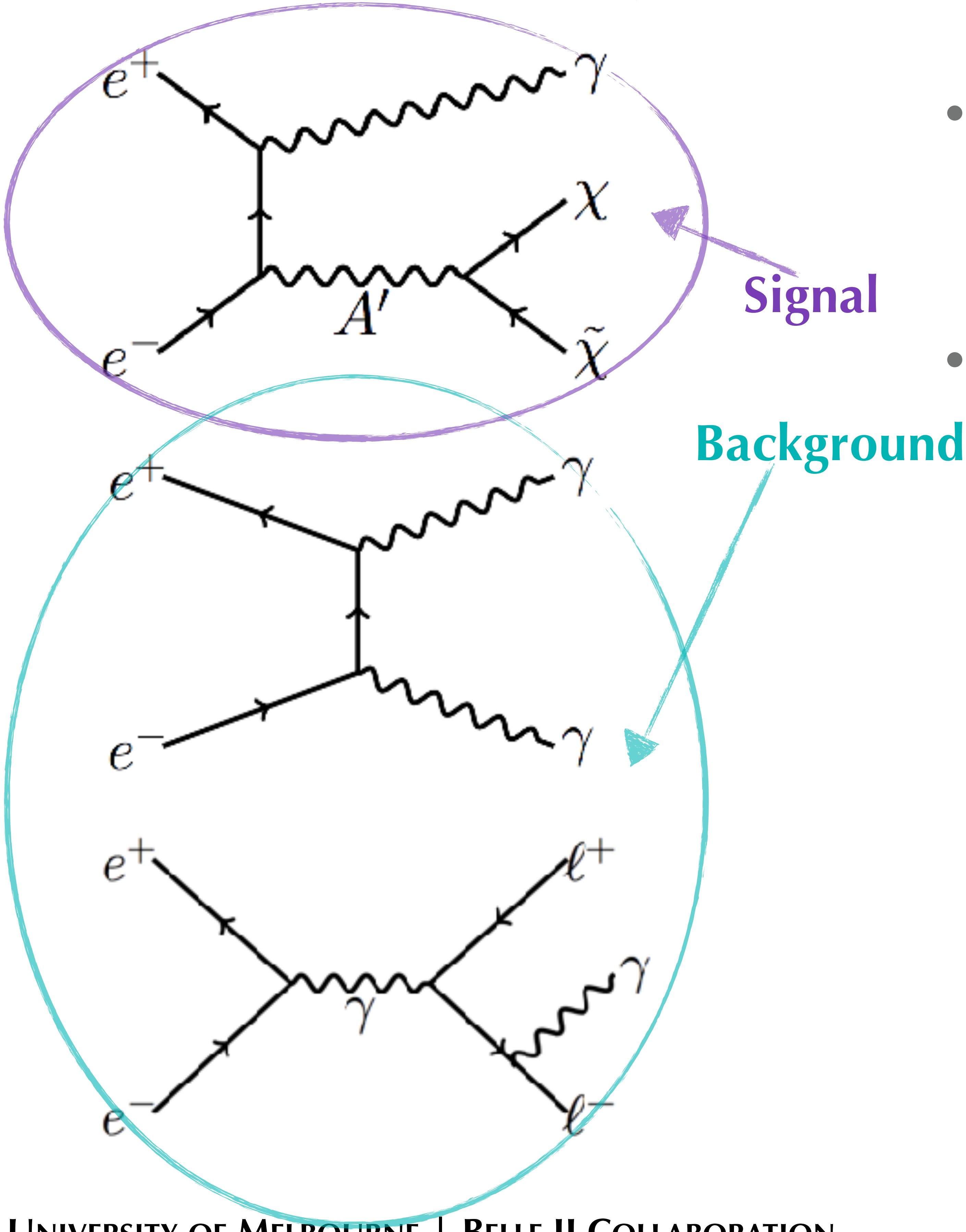
Total Belle Data Set: 1000 fb^{-1}

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

(BaBar): J.P. Lees et al., Phys Rev Lett 113(20):201801 (2014)
(BESIII): V. Prasad et al., Charm Phys Workshop (2015)

**Better mass resolution and trigger efficiencies were assumed in making extrapolations*

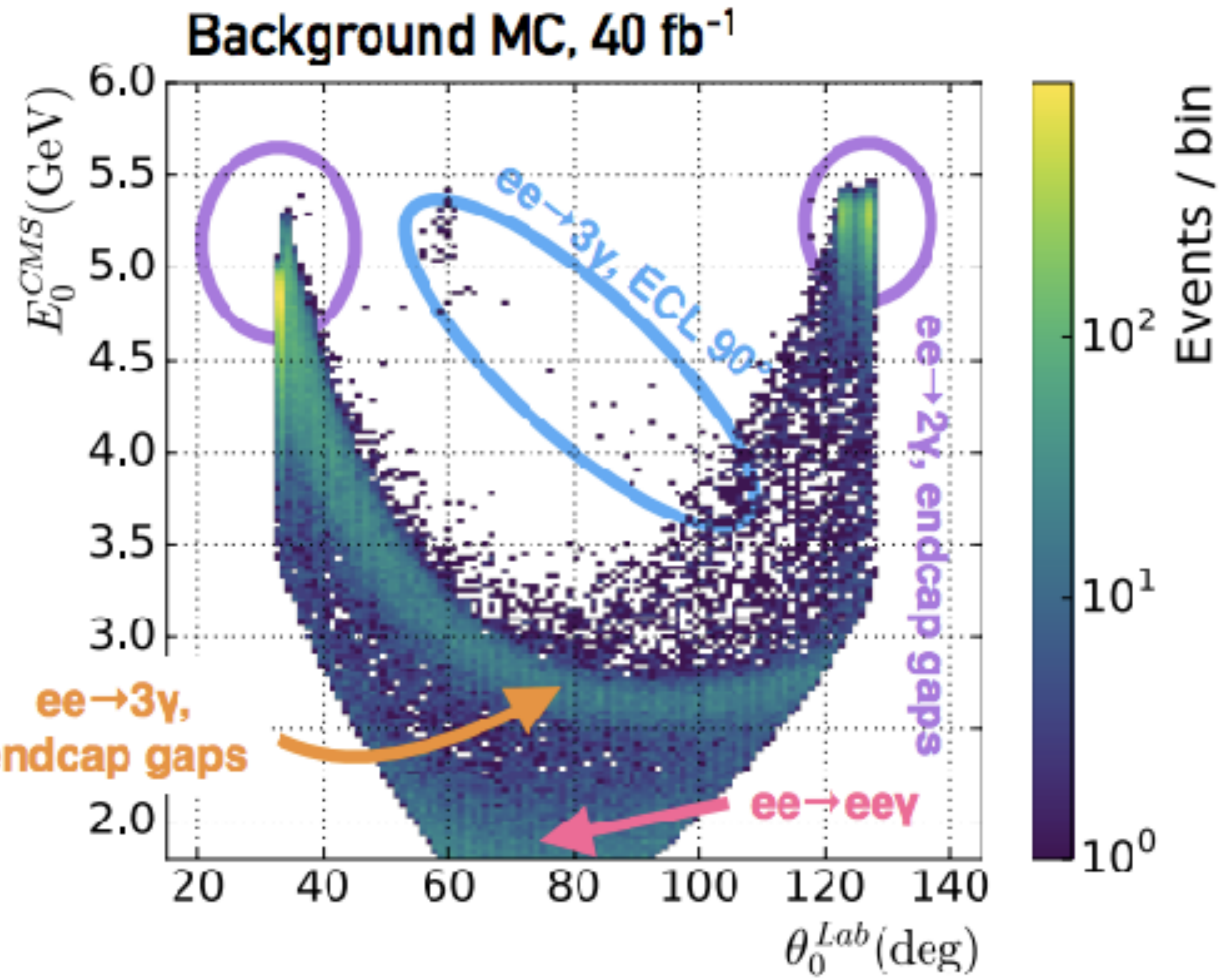
BACKGROUND PROCESSES FOR THE MONOPHOTON MODE

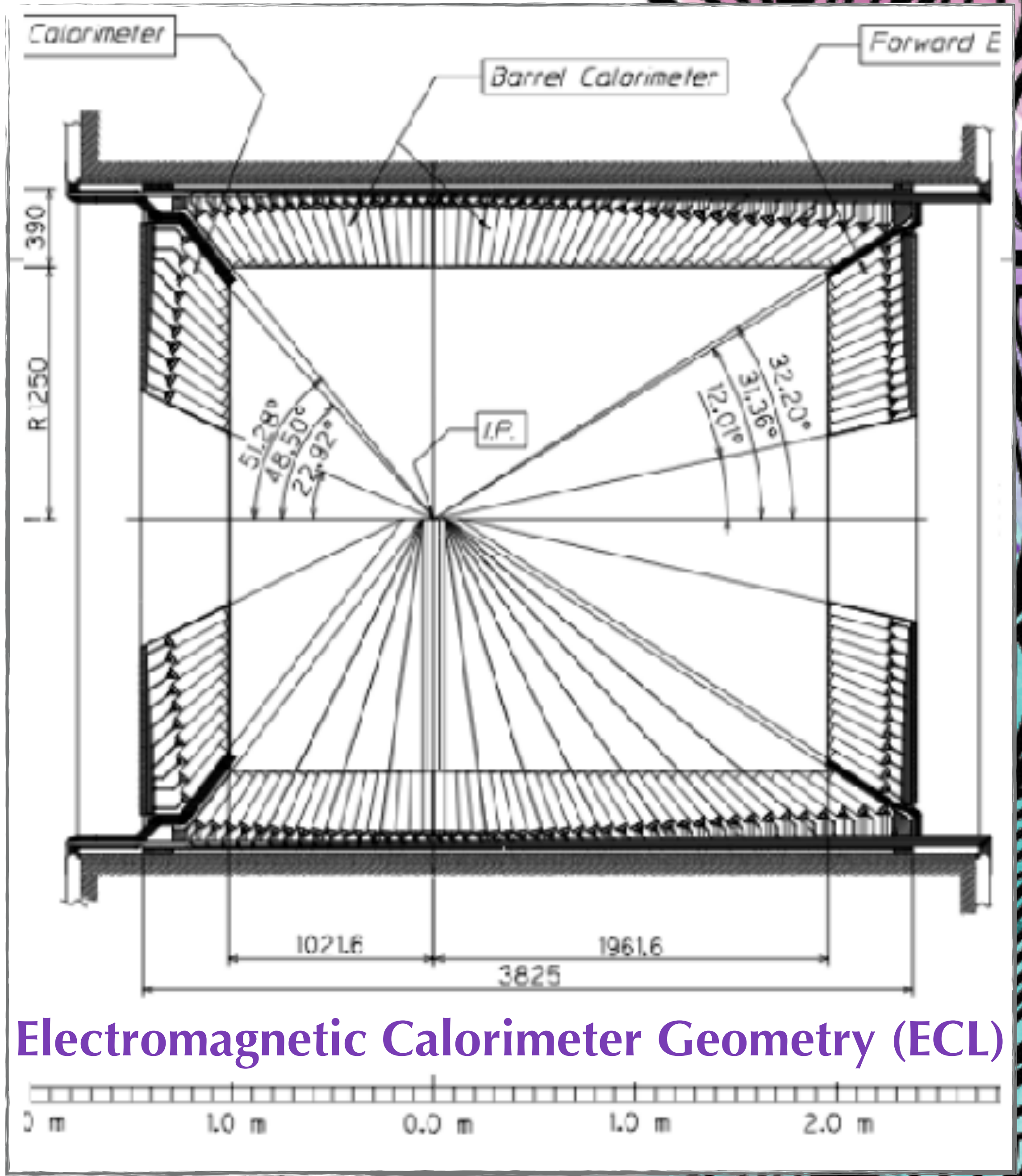


- Search performed by fitting the **recoil mass distribution**
- Background arises from events in which all final state particles except one photon are outside the detector acceptance

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 $\theta=0^o$.
- Irreducible backgrounds — events at low energy and wide angles.



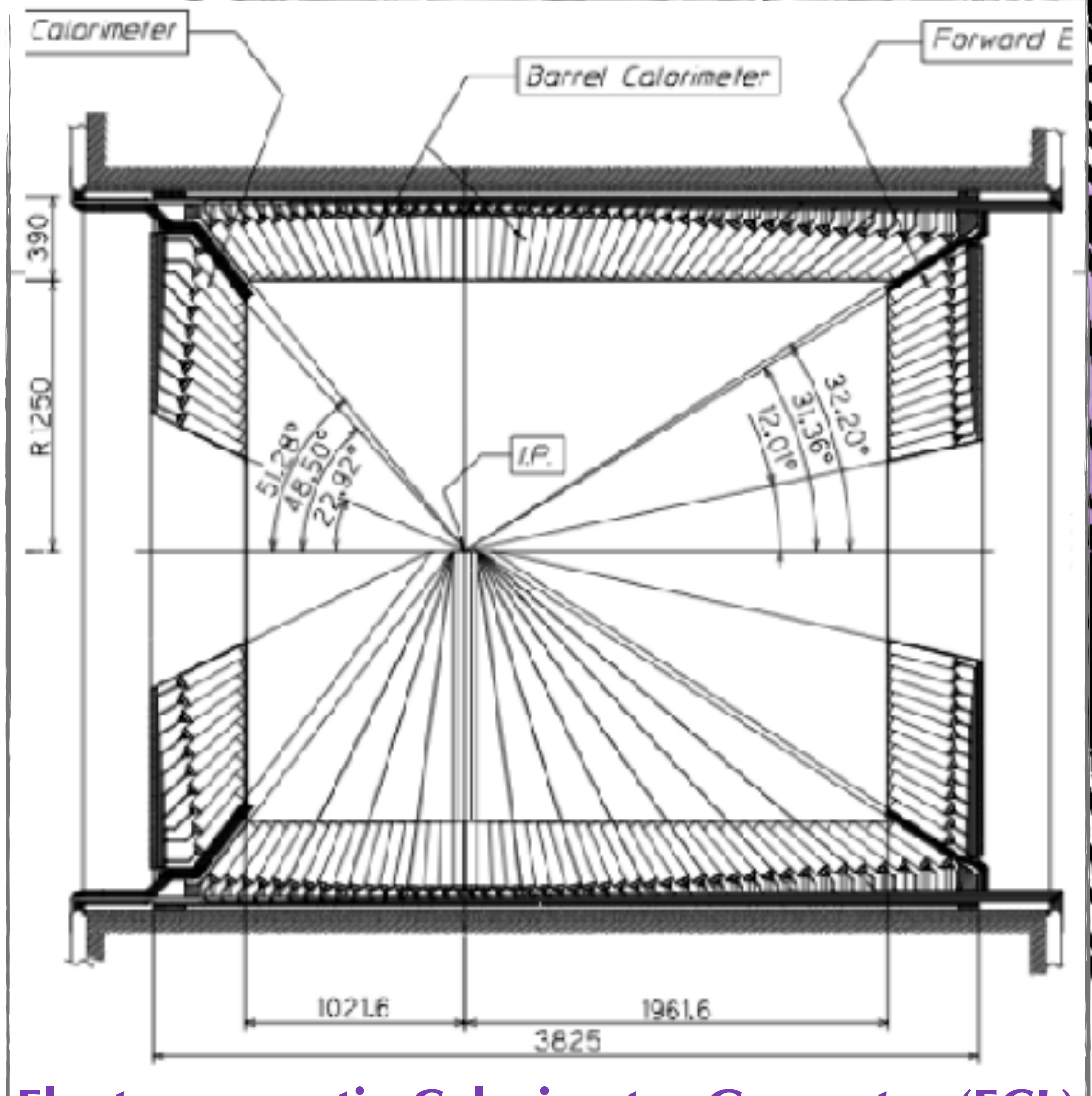


Electromagnetic Calorimeter Geometry (ECL)

T. FERBER, "EPS CONFERENCE: DS AT BELLE II" (JULY 2017)

DS-FRIENDLY TRIGGER LOGIC: A′ —> INVISIBLE

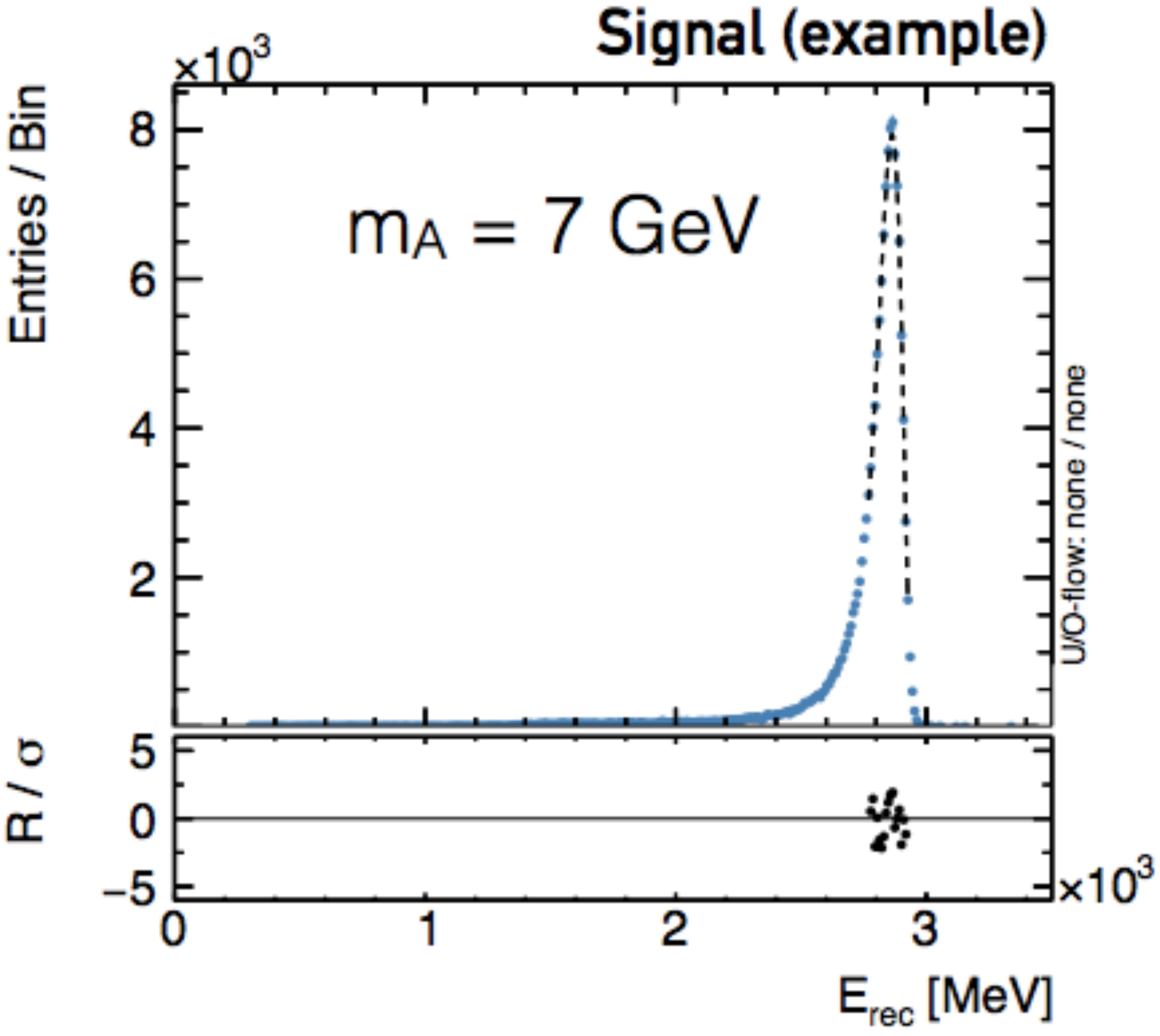
- Dedicated **2 GeV and 1 GeV (CMS Energy) threshold triggers** are developed
- The clusters in the ECL are **divided into barrel and end cap clusters** with different trigger logics applied to each
- Tighter trigger logic is applied in the end cap to suppress high background in the region



Electromagnetic Calorimeter Geometry (ECL)

MONOPHOTON SELECTION CRITERIA

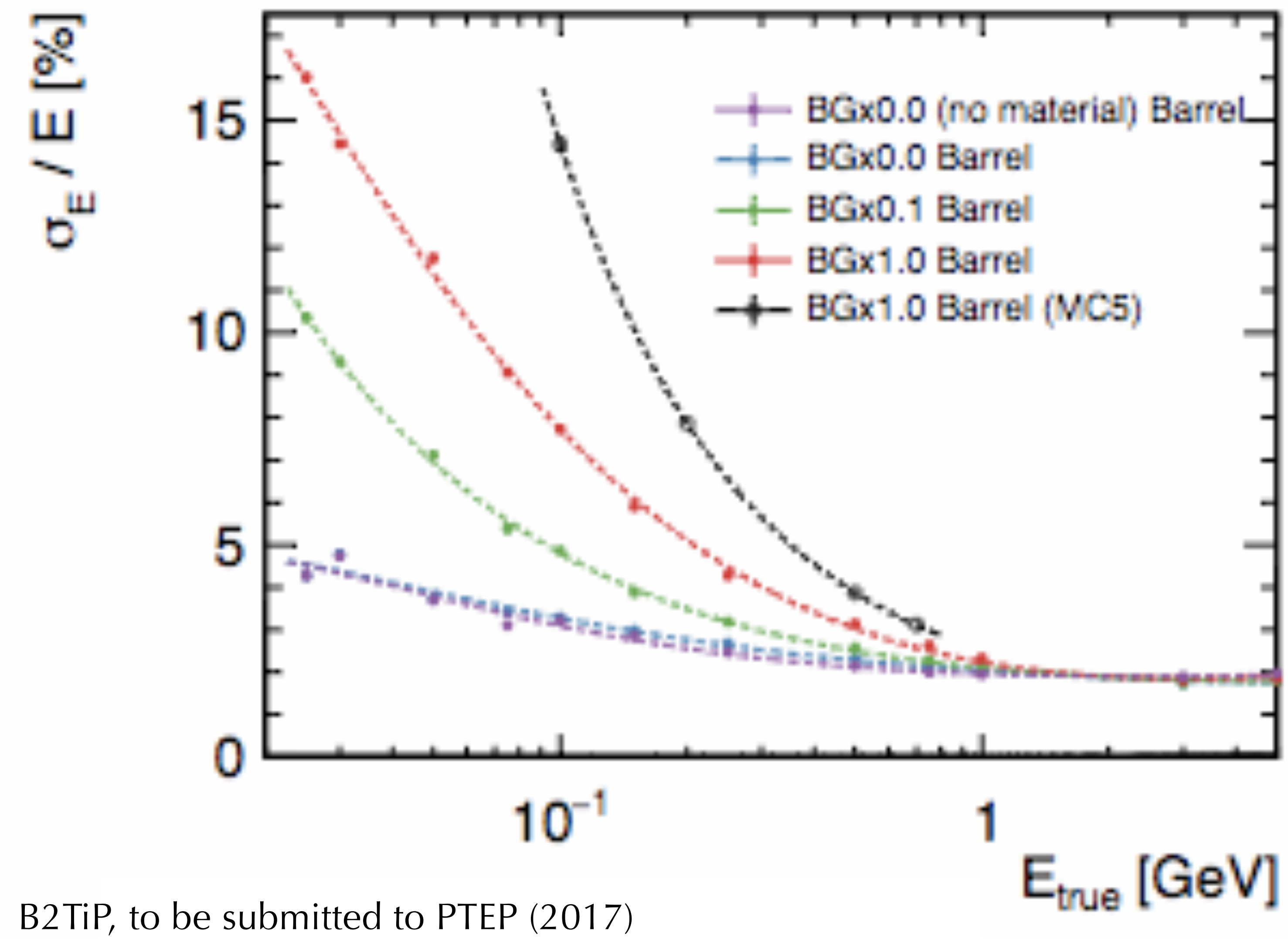
- One photon with $E_\gamma \geq 1.8$ GeV (selection not yet optimized)
  - Additional ECL clusters are permitted so long as $E \leq 0.1$ GeV
- Charged particle tracks are permitted so long as $p_T \leq 0.2$ GeV/c
- The analysis method fits the recoil mass squared distribution



T. Ferber, “EPS Conference: DS at Belle II” (July 2017)

PHOTON EFFICIENCY

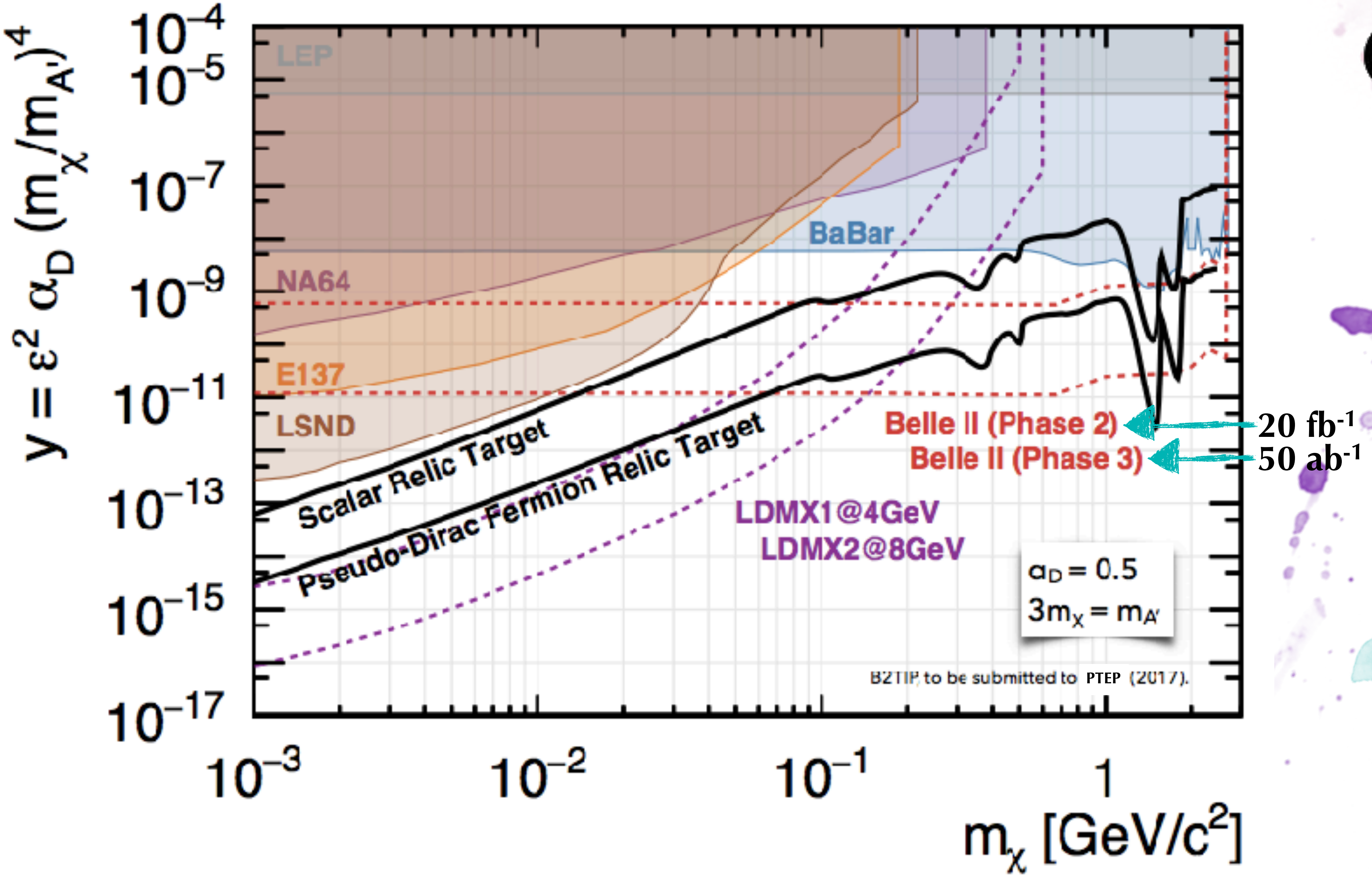
Barrel Region Efficiency



B2TiP, to be submitted to PTEP (2017)

- Good photon efficiency is crucial for the monophoton signal

Proposed Reach of Belle II: A′ —> invisible

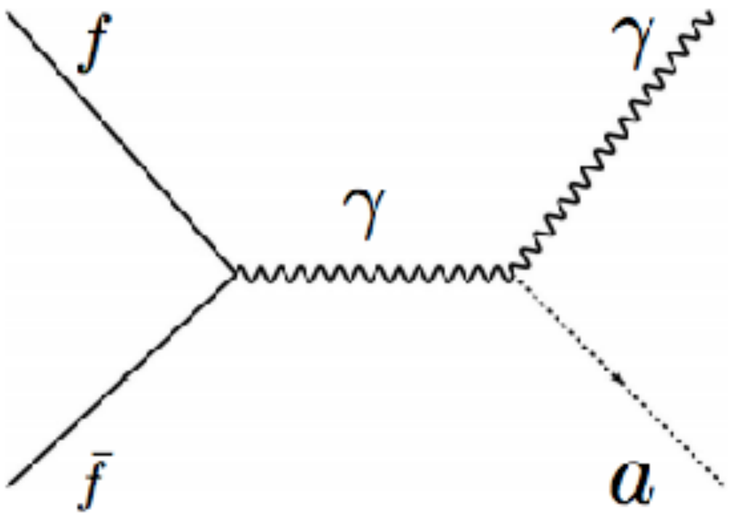


B2TIP to be submitted to PTEP (2017).

Results indicate we can perform dark photon searches for the monophoton mode in Phase 2 (starting in February 2018)

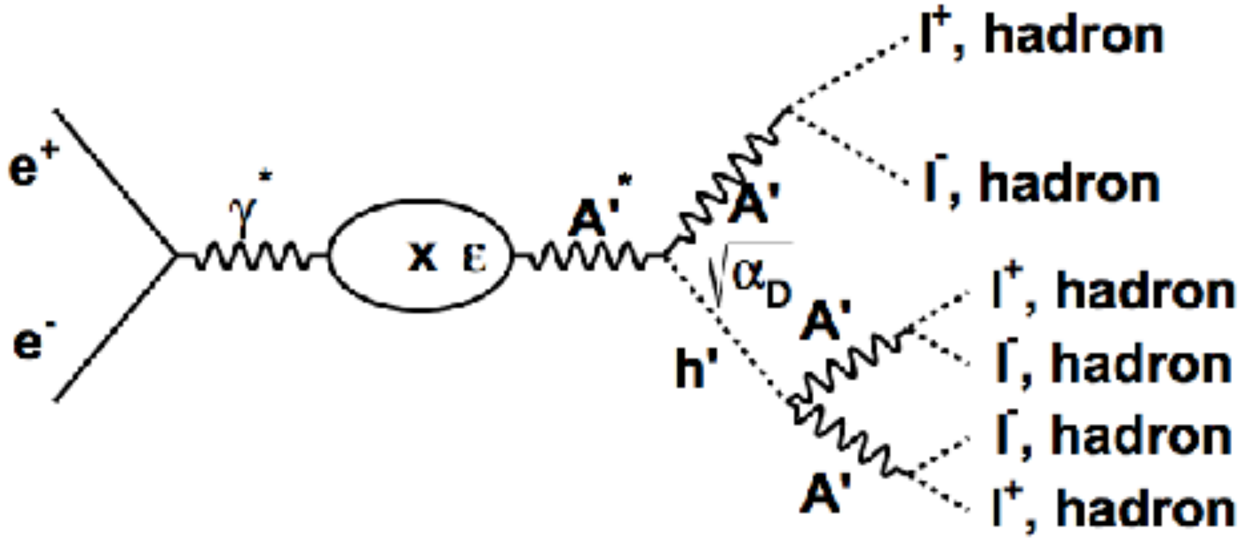
T. Ferber, "EPS Conference: DS at Belle II" (July 2017)

Other DS Work



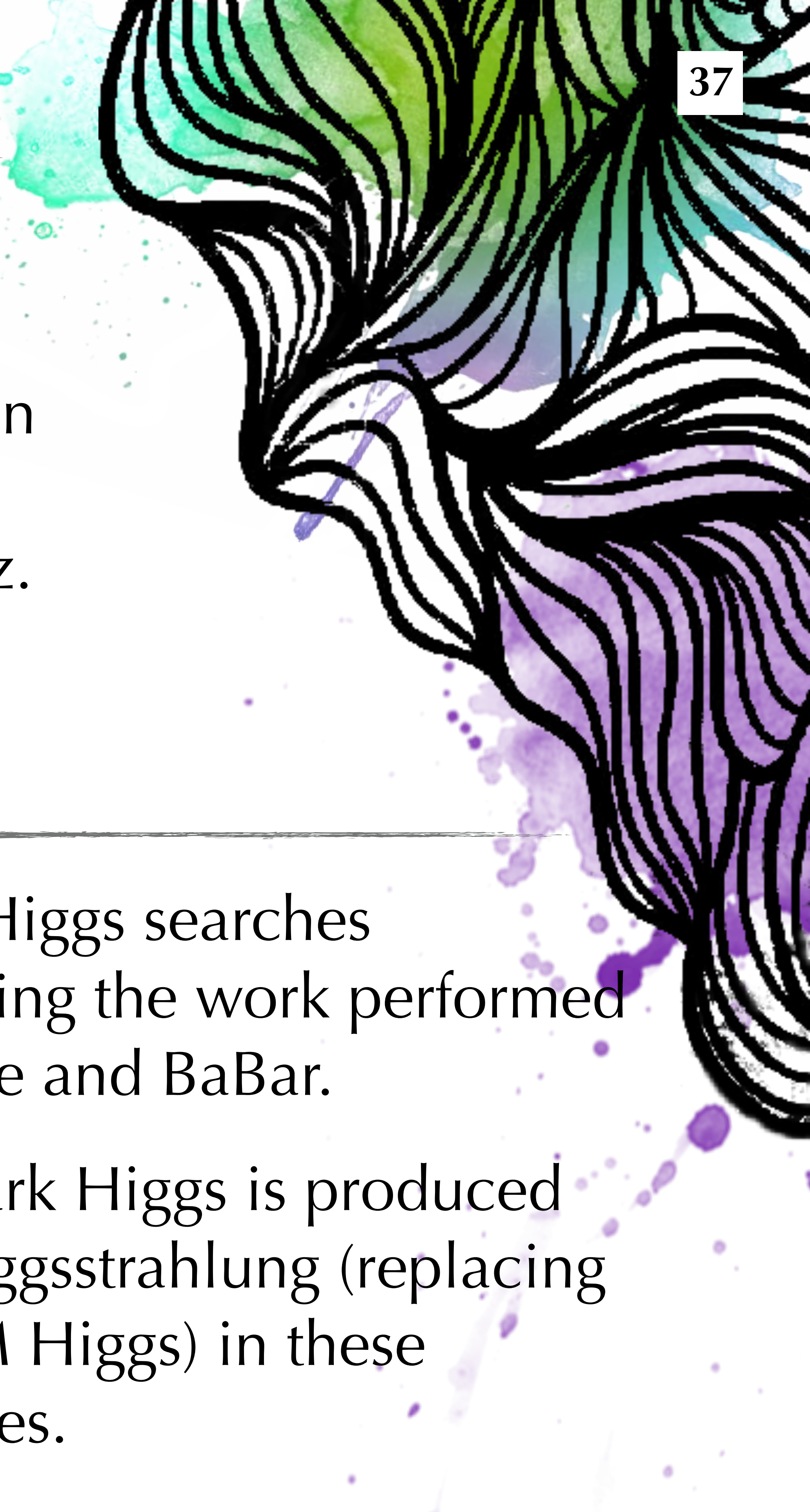
- Axion-like particle searches following the theory laid out in the paper by K. Mimasu and V. Sanz.

K. Mimasu, V. Sanz, ALPs at Colliders, JHEP 1506 (2015)
C. Hearty, T. Ferber, B2Tip Report: Submitted to PTEP (2017)



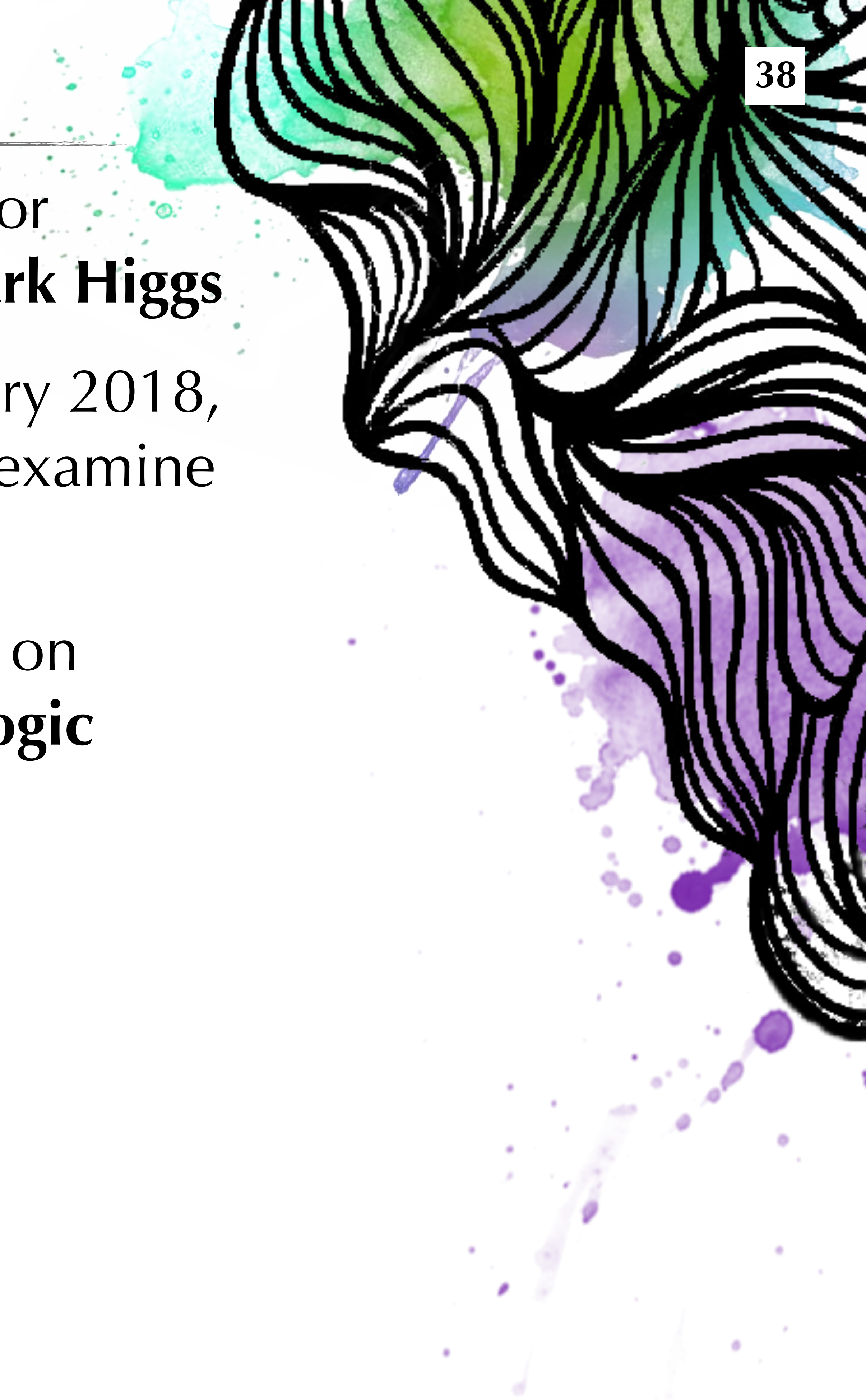
- Dark Higgs searches following the work performed at Belle and BaBar.
- The dark Higgs is produced via Higgsstrahlung (replacing the SM Higgs) in these searches.

J.P. Lees et al., BaBar Collaboration, arXiv:1202:1313 (2012)
I. Jaegle et al., Belle Collaboration, arXiv:1502:00084 (2015)



FINAL REMARKS

- Belle II is preparing many dark sector searches — **Dark Photon, ALPs, Dark Higgs**
- **Phase 2 physics** data taking (February 2018, 20 fb^{-1}) provides an opportunity to examine dark sector searches
- Dark sector searches at Belle II rely on implementation of **unique trigger logic**



CONTACT INFORMATION

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BACKUP SLIDES

SSB AND MASS MECHANISM

Standard Model

$SU(2)_L \otimes U(1)_Y$

EW Breaking

$U(1)_{EM}$

- $U(1)_X \otimes U(1)_Z$ 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 $m_{A'} > 0$.

My Model

$SU(2)_L \otimes U(1)_Y$

EW Breaking

$U(1)_Z$

then

$U(1)_X \otimes U(1)_Z$

$U(1)_{EM}$

Alternative Model

$SU(2)_L \otimes U(1)_Z$

$U(1)_Y$

then

$U(1)_X \otimes U(1)_Y$

EW Breaking

$U(1)_{EM}$

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