Dark Sector Physics with Belle II

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On behalf of the Belle II collaboration

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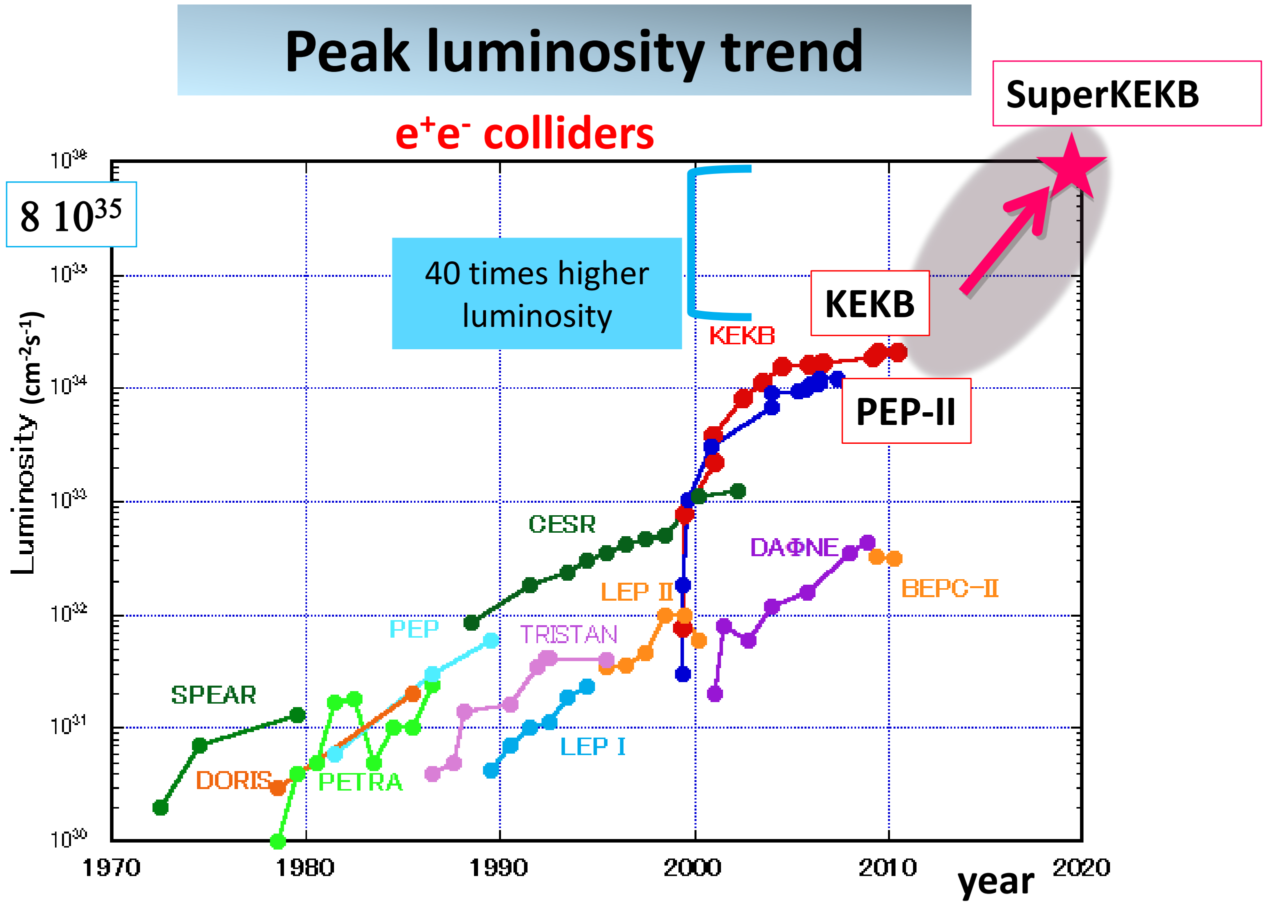
Outline

- SuperKEKB and Belle II
- The dark sector
- Searches for dark sector particles at Belle II

On the Intensity Frontier: SuperKEKB

- Peak luminosity of 8×10^{35} cm^{-2}s^{-1}
  - 40 times the peak luminosity of KEKB
- "Nano-beams" are the key:
  - Vertical beam size is 50 nm at IP
  - Beam current "only" a factor 2 higher then KEKB



From KEKB to SuperKEKB

Beam-beam parameter

Lorentz factor

Beam current

$$L = \frac{\gamma_{e\pm}}{2e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lumi. reduction factor (crossing angle)&
Tune shift reduction factor (hour glass effect)
0.8 ~ 1
(short bunch)

Classical electron radius

Beam size ratio@IP
1 ~ 2 % (flat beam)

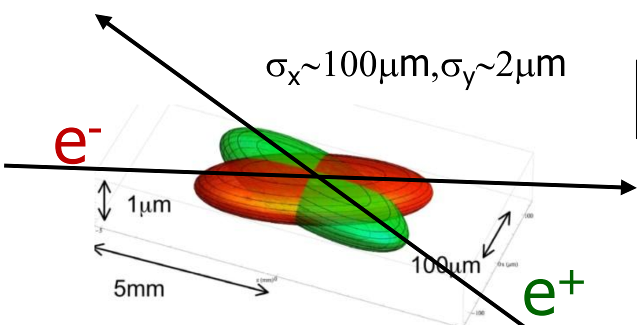
Vertical beta function@IP

x20 x2

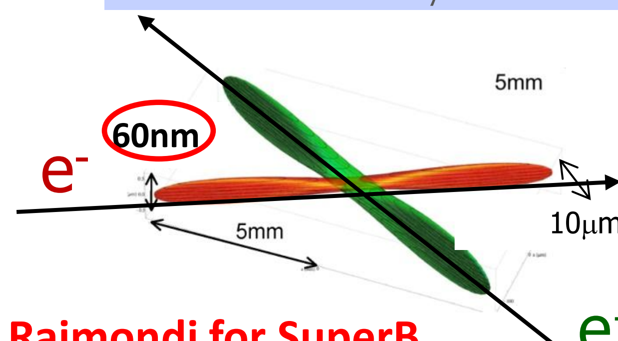
(1) Smaller β_y^*

(2) Increase beam currents

(3) Increase ξ_y

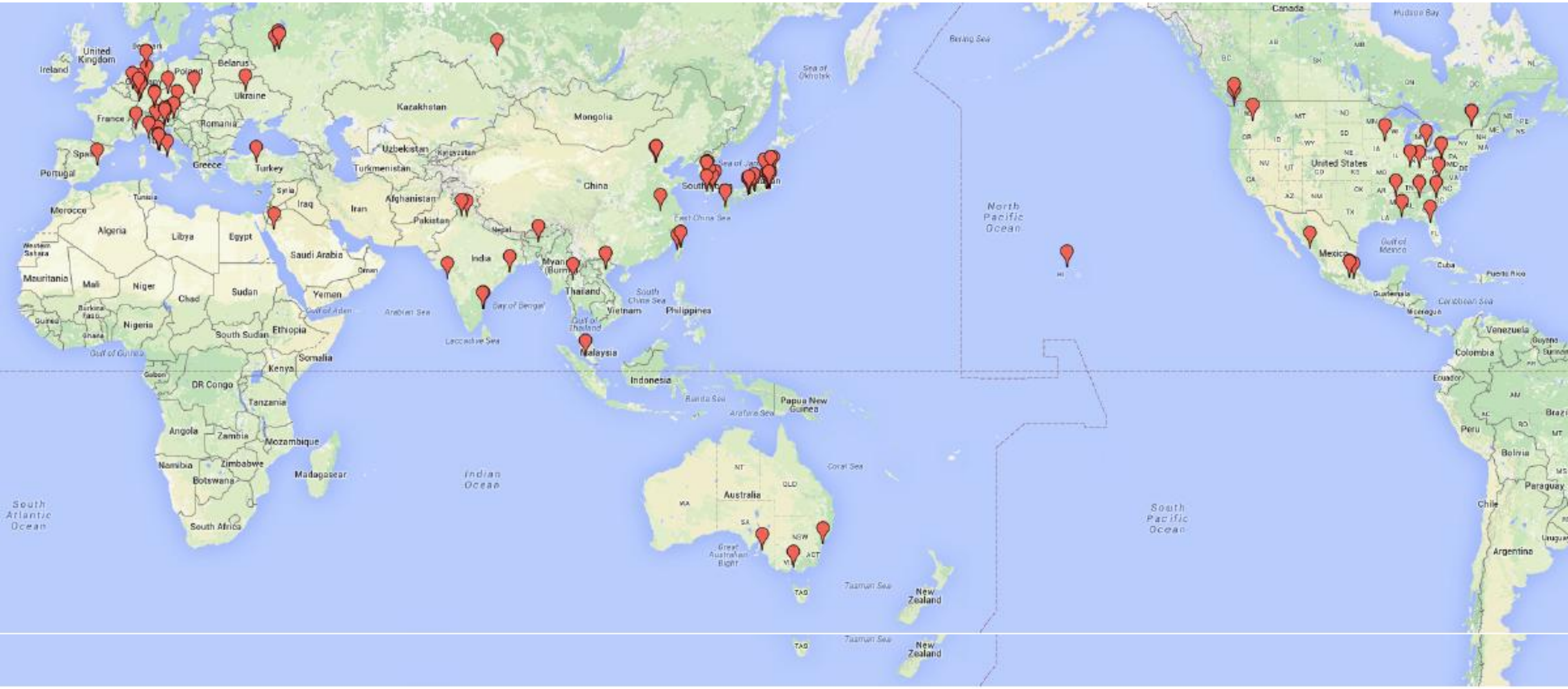


Nano-Beam scheme



originally proposed by P.Raimondi for SuperB

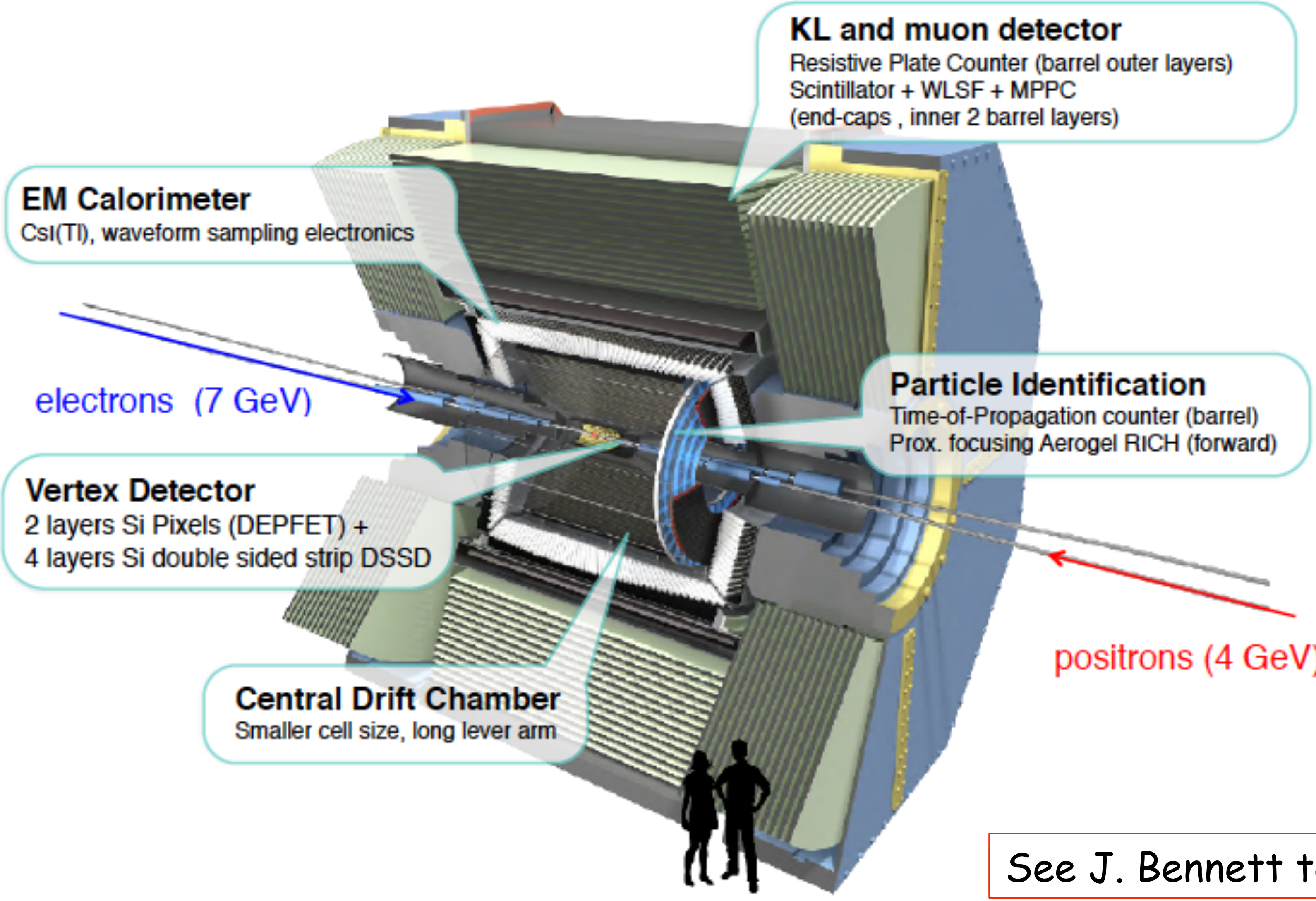
The Belle II Collaboration



700+ scientists
100+ institutions
24 countries

The Belle II Detector

Belle II TDR, arXiv:1011.0352

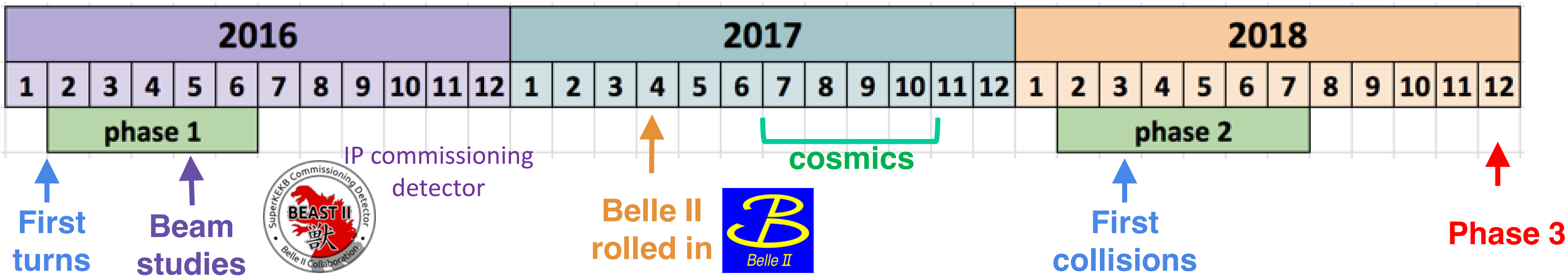


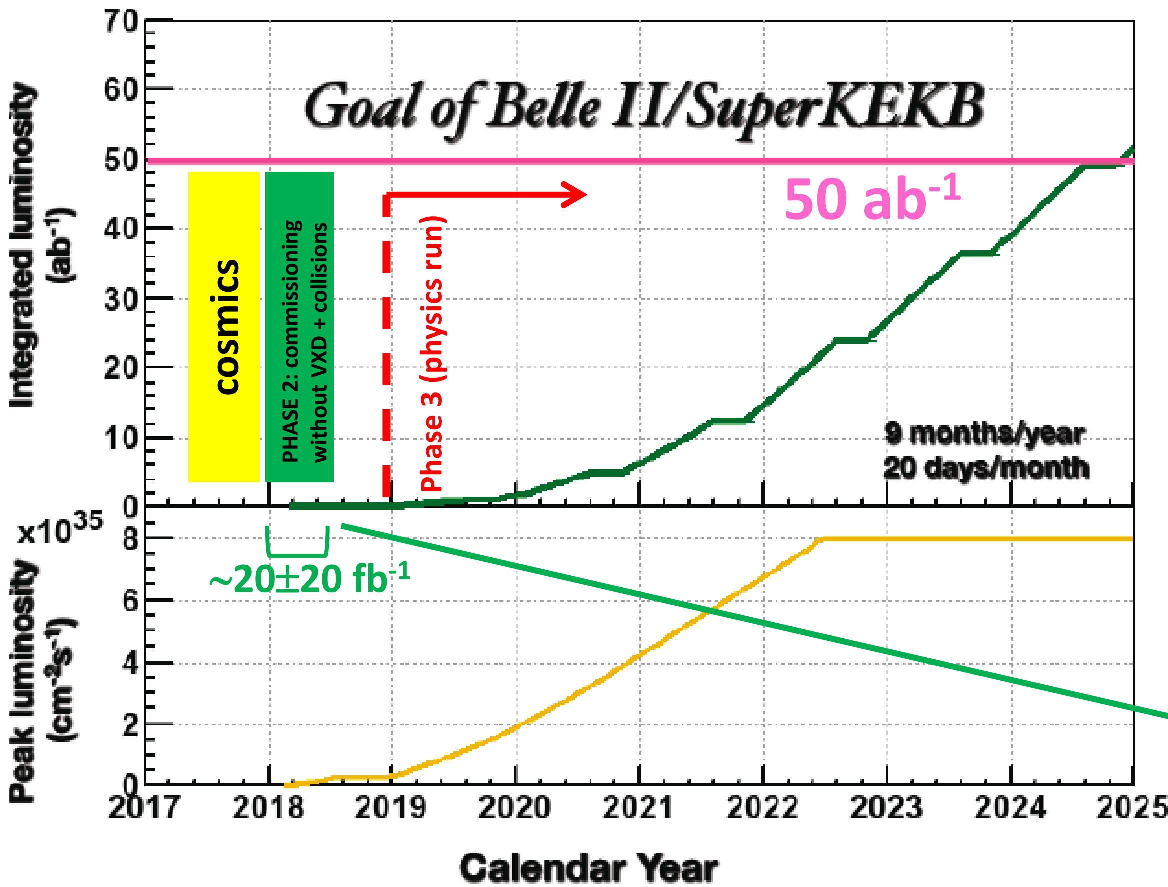
See J. Bennett talk

Belle II Trigger

- Hardware trigger + Software trigger
  - Level 1 (L1): hardware based, readout rate: 30 kHz
  - High Level Trigger (HLT): software based, readout rate: 10 kHz
- L1 Trigger:
  - L1 CDC Trigger with 3D tracking
  - L1 ECL Trigger with 3D Bhabha-veto logic using cluster position information and cluster energy requirements
  - L1 Track-Cluster Match
- High Level Trigger:
  - Operating offline reconstruction algorithms as a component of DAQ
  - Suppress event rate to 10 kHz for the offline storage
  - Strong computing power to cope with high event rate
    - From 1500 cores at beginning of data taking to 6000 cores with target luminosity

The Schedule



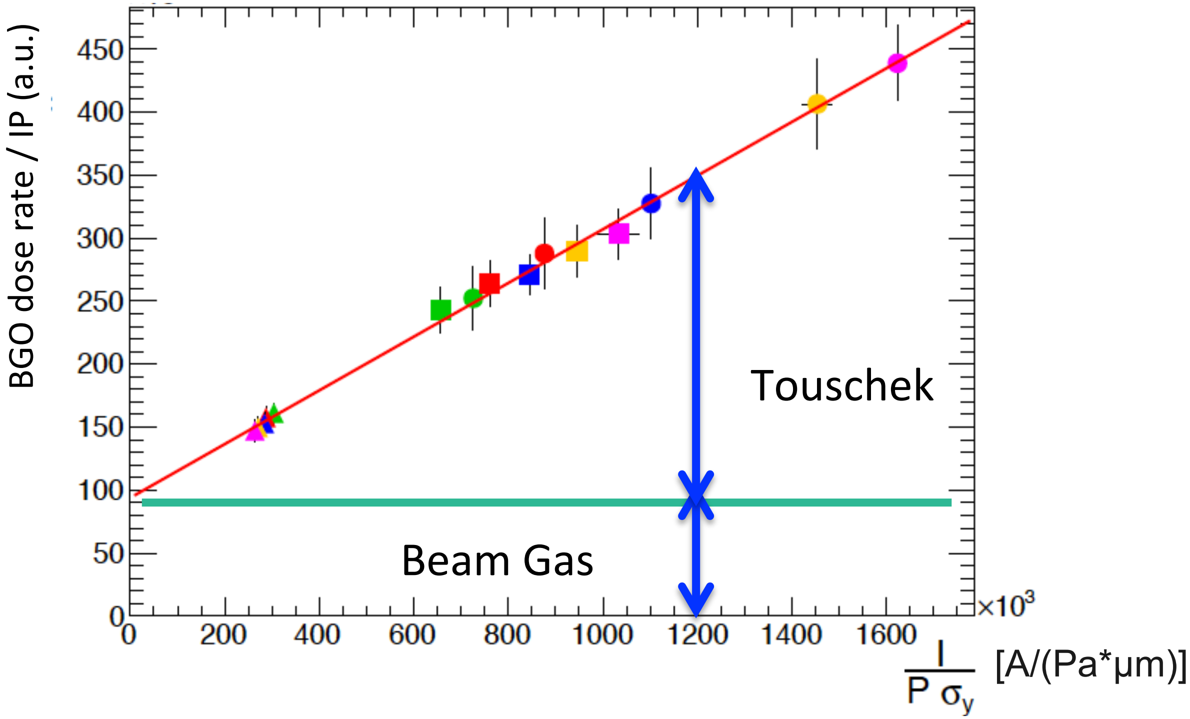


- Phase 1: done
  - Beam commissioning
- Phase 2: Start of 2018
  - Peak Lumi O(10^{34})
  - Beam BG measurement
  - Belle II detector with partial vertex sensors
- Phase 3: End of 2018
  - Data taking with full Belle II detector

20±20 fb^{-1} for physics analysis without VXD

Beam Background Studies at Phase 1

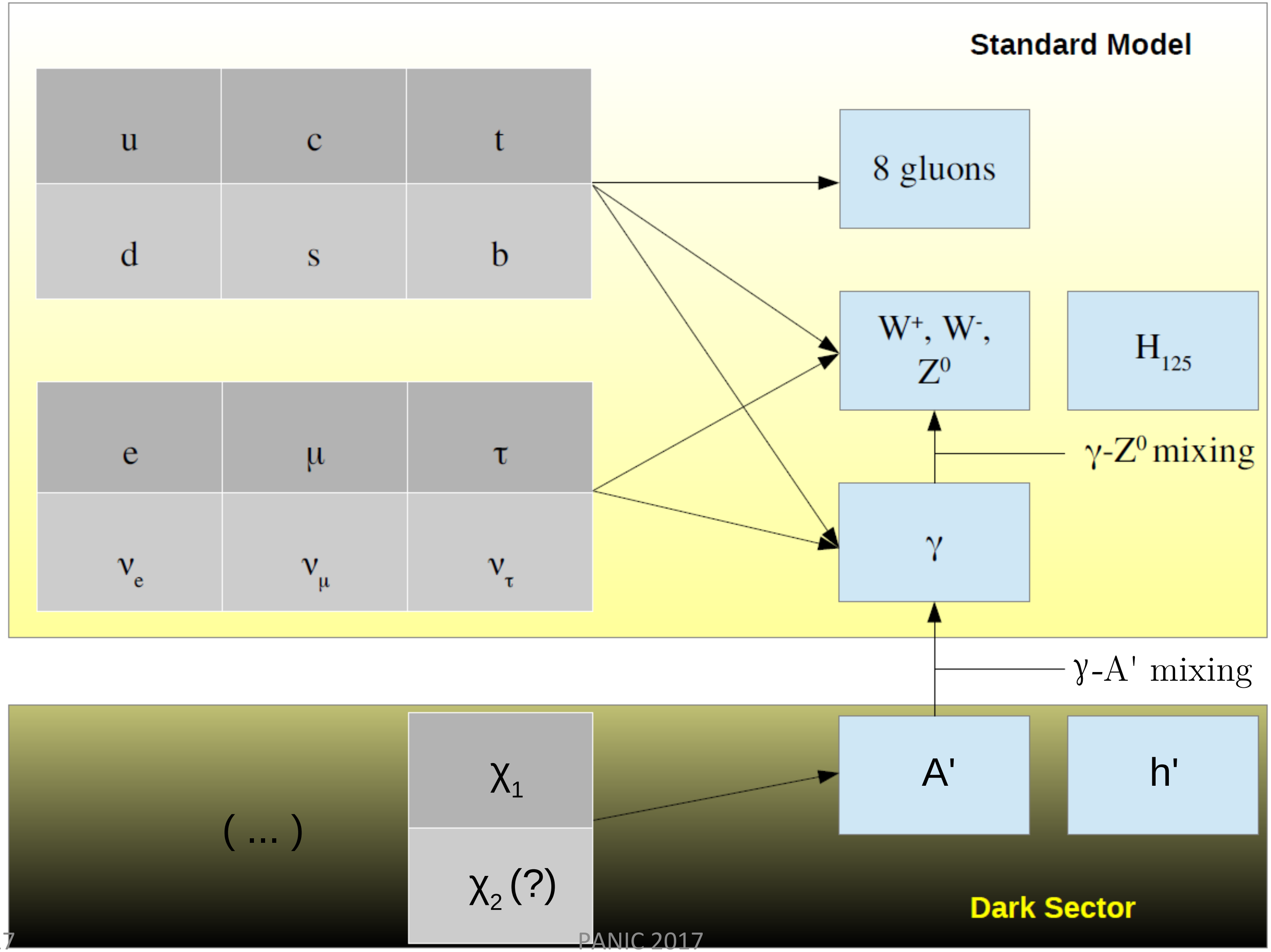
- BEAST Phase 1 analyses now near completion
  - Documented in a O(100) pages note that will become a NIM paper
- A number of new techniques developed
- Current focus: ensure internal consistency, consult with SuperKEKB group, extrapolate to Phase 3



Improved model and re-calibrated beam size measurements. BGs for a wide range of beam currents and beam sizes now described consistently by a single set of parameters.

Beam background control is a key point in searches for NP in events with missing energy

The Dark Sector



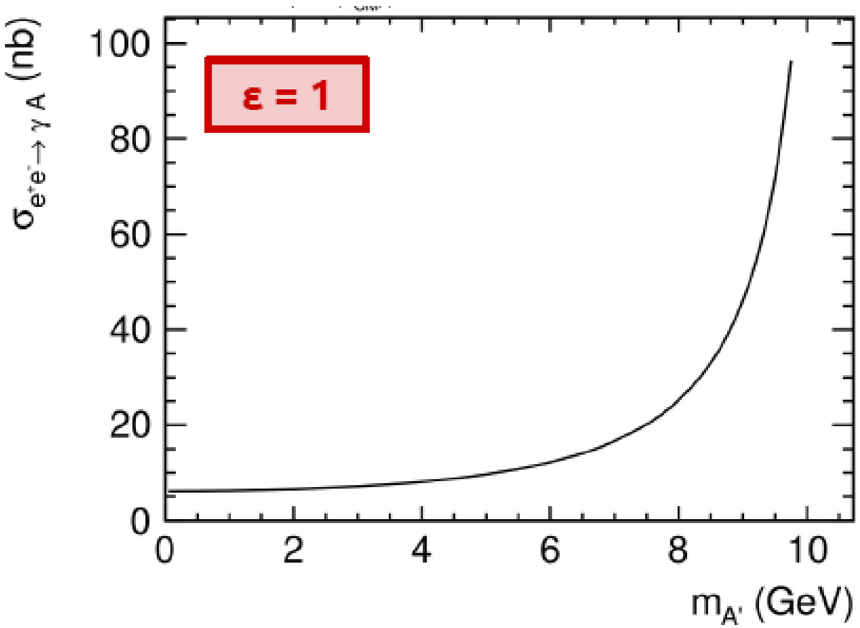
The Dark Photon Cross Section

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

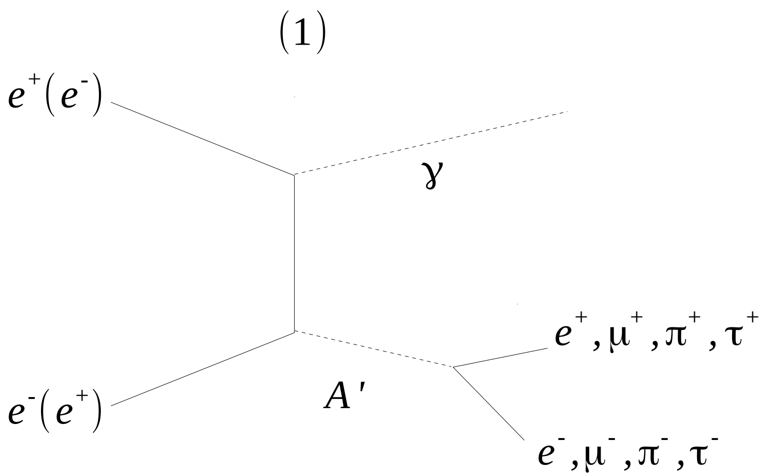
where $$\Theta \equiv \log\left(\frac{(1+\cos\theta_{\rm max})(1-\cos\theta_{\rm min})}{(1+\cos\theta_{\rm min})(1-\cos\theta_{\rm max})}\right)$$

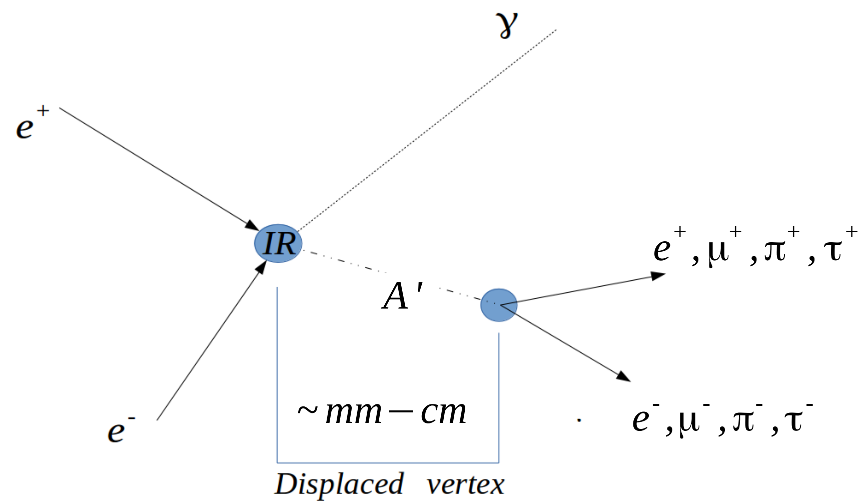
R. Essig, P. Schuster, and N. Toro; Phys. Rev. D80:015003(2009)

The cross section depends on the mixing strength ε between the photon and the dark photon and on the dark photon mass



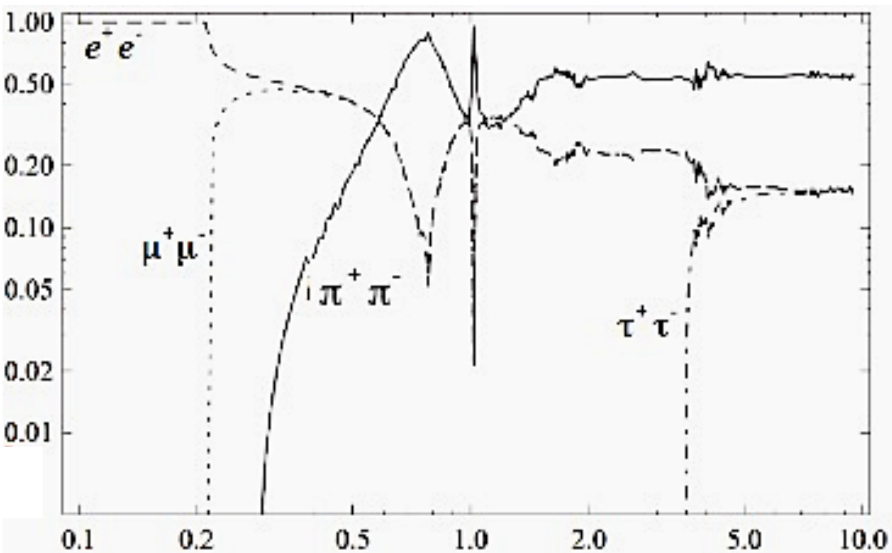
Dark Photon Decays (1)





A' will decay to light DM if allowed by kinematics or to SM final states through kinetic mixing

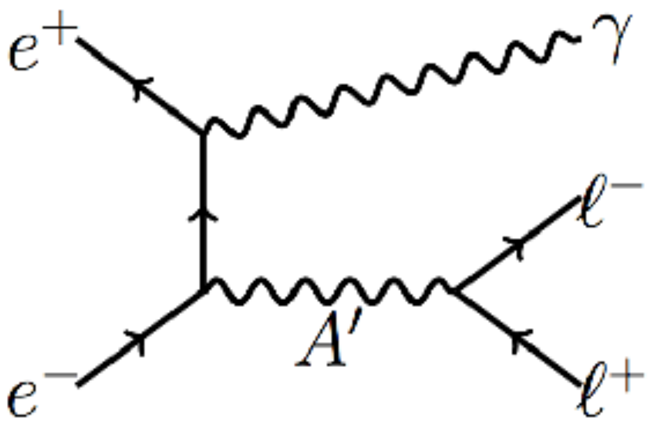
Low multiplicity final states: 1 photon and eventually 2 charged tracks (prompt or displaced vertex).



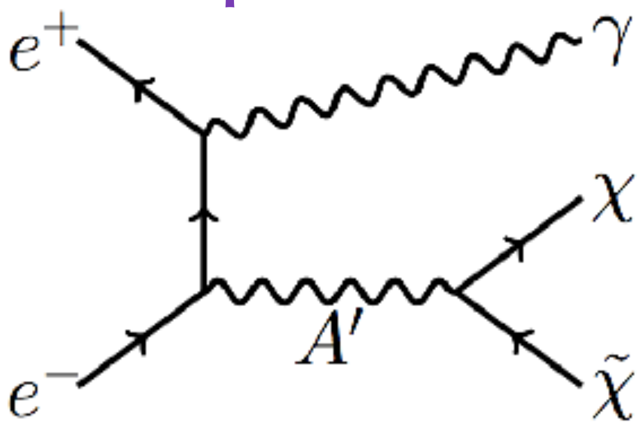
B. Batell, M Pospelov, A. Ritz ; Phys. Rev. D79:115008(2009)

Dark Photon Decays (2)

Dilepton Mode



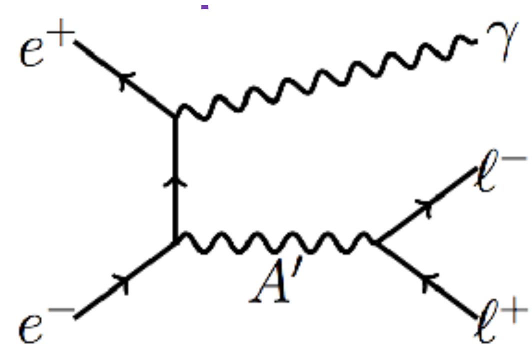
Monophoton Mode



- If dark photon is the lightest DM particle, we expect to mostly observe decays to SM leptons (e or μ).
- Search for a "bump" in the di-lepton invariant mass distribution.

- Otherwise, the dark photon will decay to light DM. The signal will be a mono-energetic photon.
- More difficult to detect (larger irreducible backgrounds).
- Search relies heavily on special triggers.

Dilepton Mode



- Background is mostly from events with ISR or FSR
- ISR effects in quarkonia resonances are well known and can be included into invariant mass fits

		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
Signal	$\sigma_{A'\gamma} \approx 10\text{fb}$	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}
Bkg	$\sigma_{\mu^+\mu^-\gamma} = 1.148\text{nb}$	1.148×10^9	2.296×10^7	5.74×10^{10}

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

Assuming Perfect Efficiency

Background cross section includes requirement that final state particles are in the detector acceptance

Need to optimize the trigger efficiency with dedicated trigger schemes for different luminosity periods

Dilepton Mode: Selection Criteria

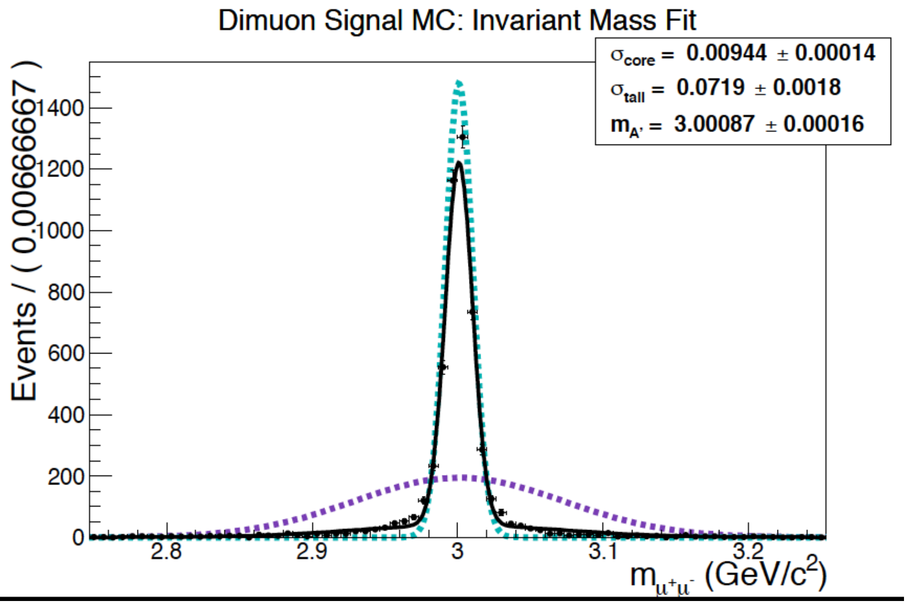
1. Two oppositely charged, "well- identified" lepton tracks
2. Total invariant mass (two tracks AND photon) near the $\Upsilon(4S)$ resonance ($9.5 \leq m(\mu+\mu-$ or $e+e-)\gamma \leq 10.8$ GeV/c^2)
3. One photon with $E_\gamma \geq 0.2$ GeV (reduced background from bremsstrahlung)

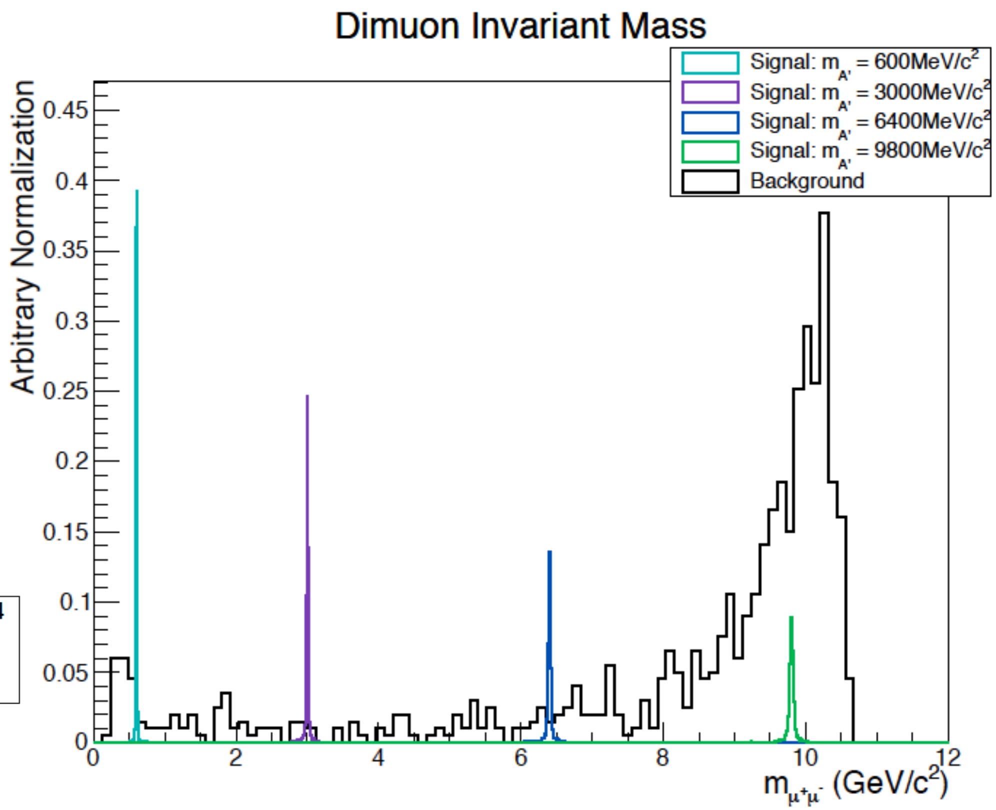
Dimuon mode Belle II MC

A' Mass Hypothesis (GeV)	Cut 1 (%)	Cut 2 (%)	Cut 3 (%)
0.6	67.8	56.6	56.6
3.0	61.4	52.9	52.9
6.4	74.6	65.6	65.6
9.8	80.6	75.1	73.0
Background	20.6	14.2	8.0

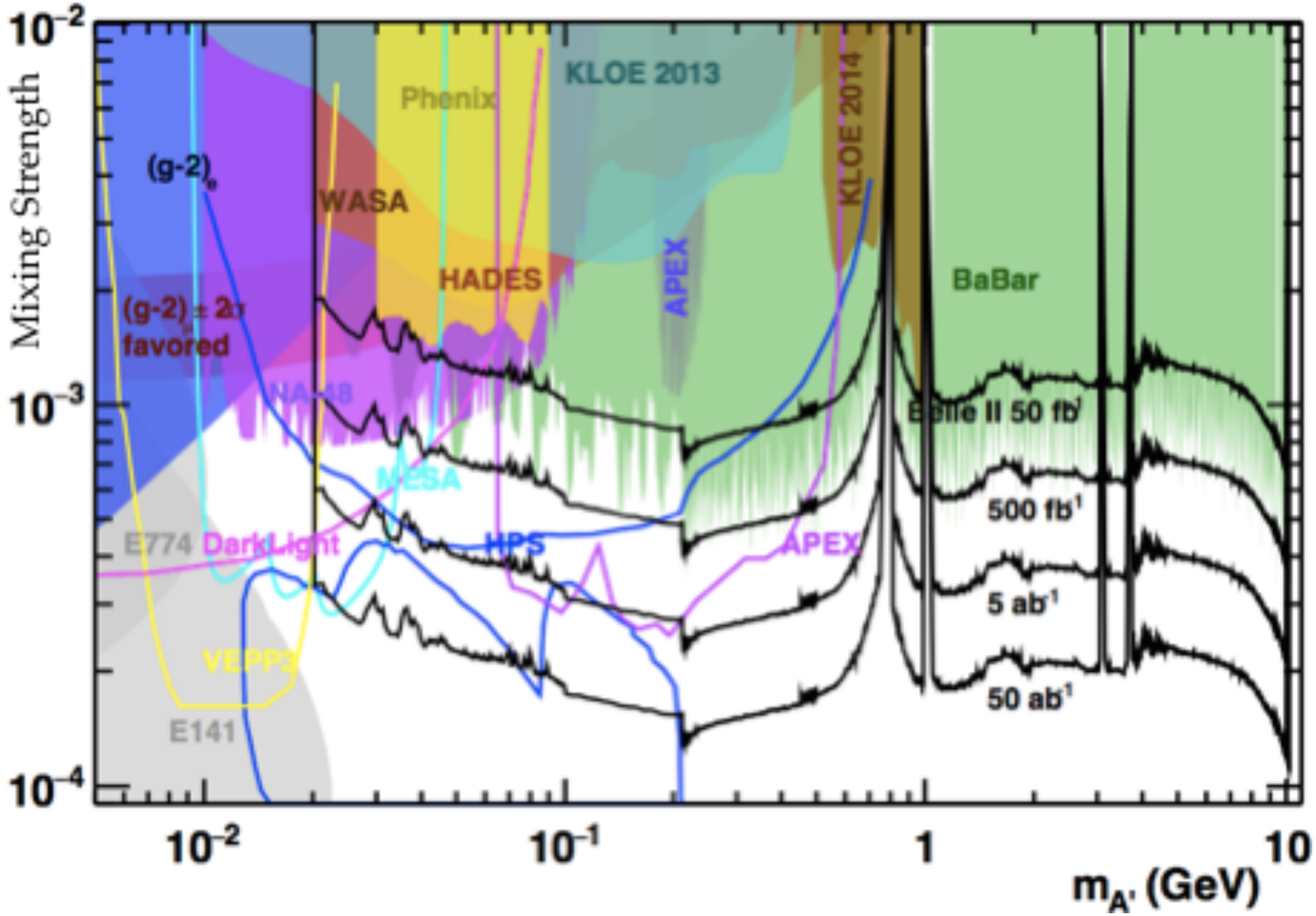
Dimuon Mode: Example Mass Peaks

- Mass resolutions are determined by a double Gaussian fit
- Increased A′ mass degrades the signal resolution





Expected Reach of Belle II in Dilepton Mode

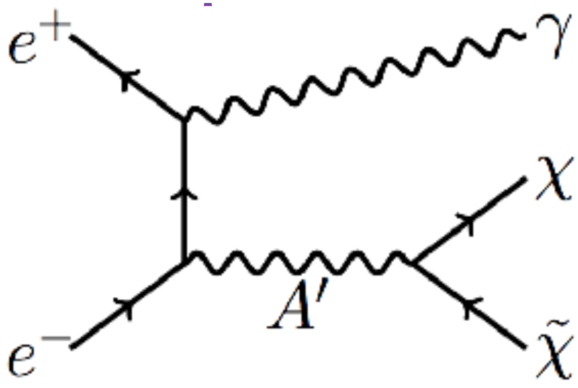


90% CL upper limits on the mixing strength parameter

Monophoton Mode

- Need a dedicated trigger
- Search performed by fitting the recoil mass distribution

$$E_\gamma^* = (s - M_{A'}^2)/2\sqrt{s}$$



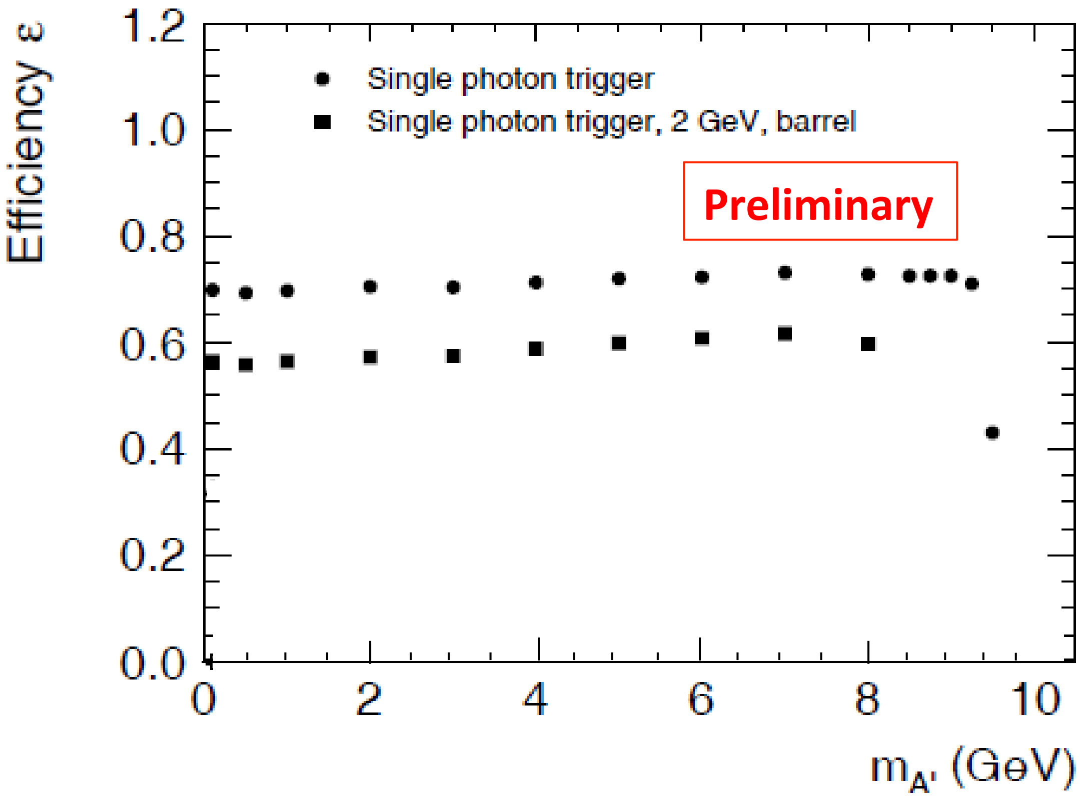
- Background arises from events in which all final state particles except one photon are outside the detector acceptance
- Mostly from high cross section QED processes:
  - e+e- —> e+e-(γ)
  - e+e- —> γγ(γ)

Monophoton Mode:Single Photon Trigger

Two level 1 single photon triggers, both excluding the innermost ECL crystal towers

- $E_{\gamma 1}* > 1$ GeV, with the second cluster energy $E_{\gamma 2}* < 0.2$ GeV (4 nb)
- $E_{\gamma 1}* > 2$ GeV + Bhabha veto + e+e- —> $\gamma\gamma$ veto (2.5 nb)

For comparison hadronic $+ \tau\tau + \mu\mu$ cross section is 6.8 nb at Υ(4S)

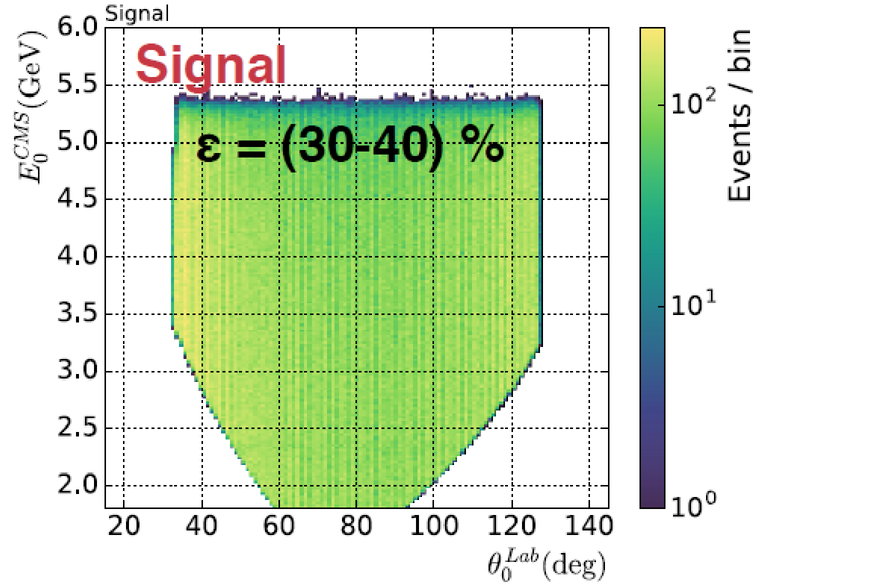


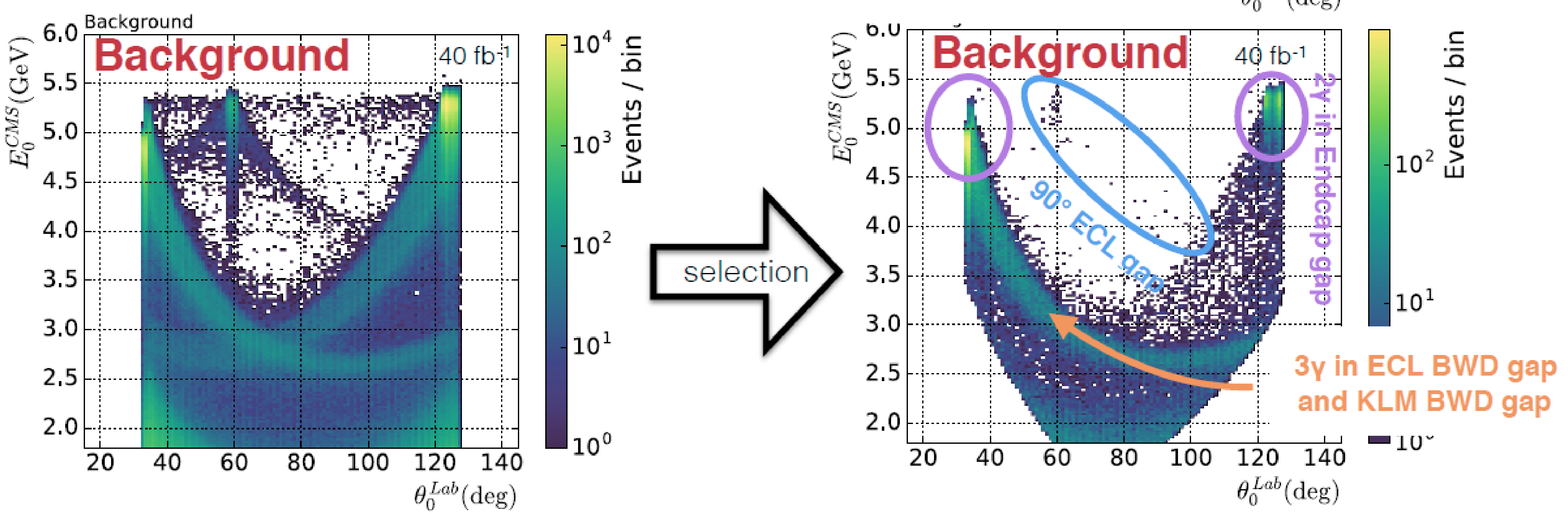
Trigger efficiency is expected to be high and mostly limited by acceptance (up to 95% within angular acceptance)

Main issue is sustainability of SPT with Luminosity increase in Phase 3

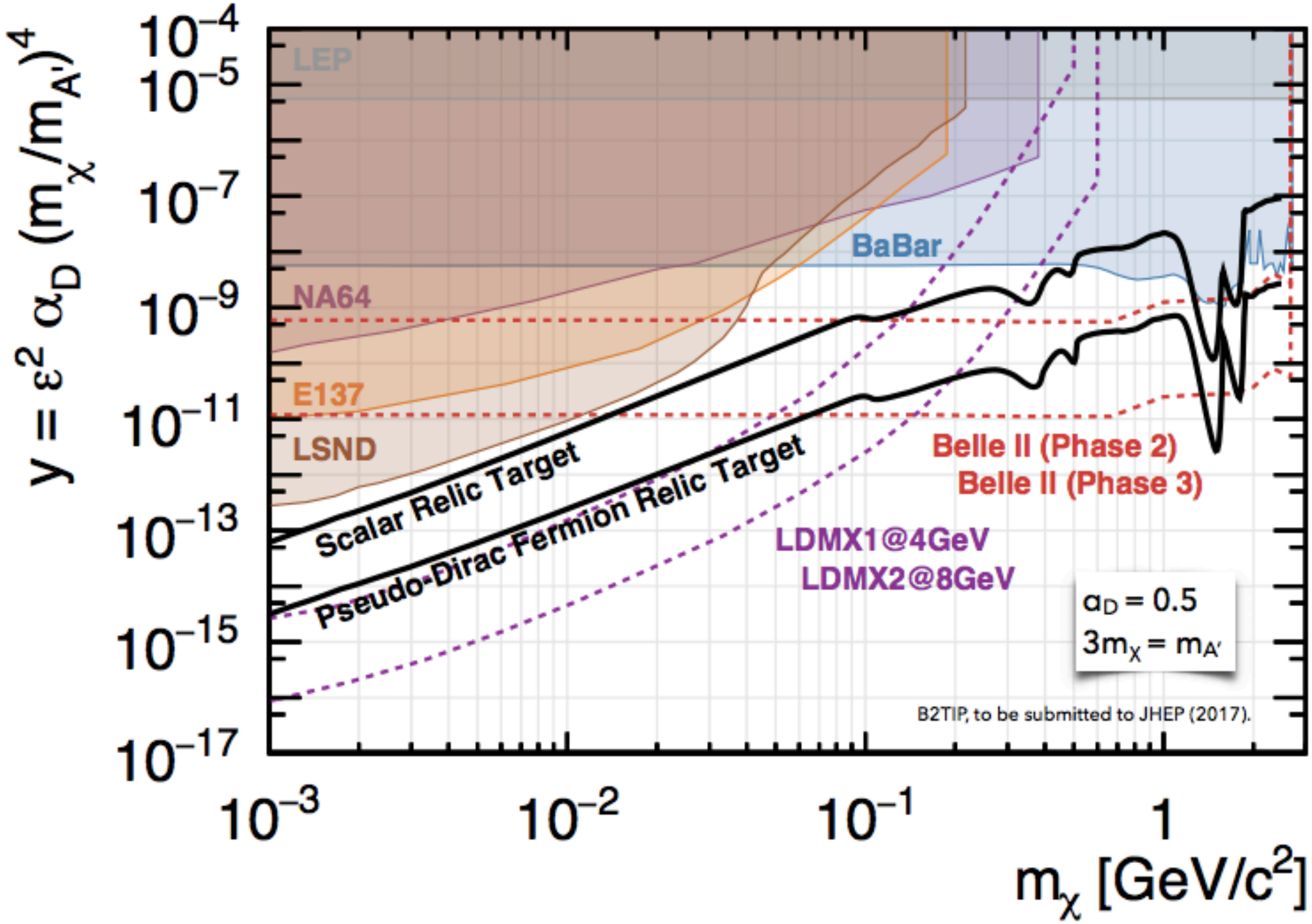
Monophoton Mode: Event Selection

- E_γ^* > 1.8 GeV
- No KLM clusters back to back
- No KLM clusters in veto regions (various ECL gaps)
- Additional angular dependent selection on E_γ^*





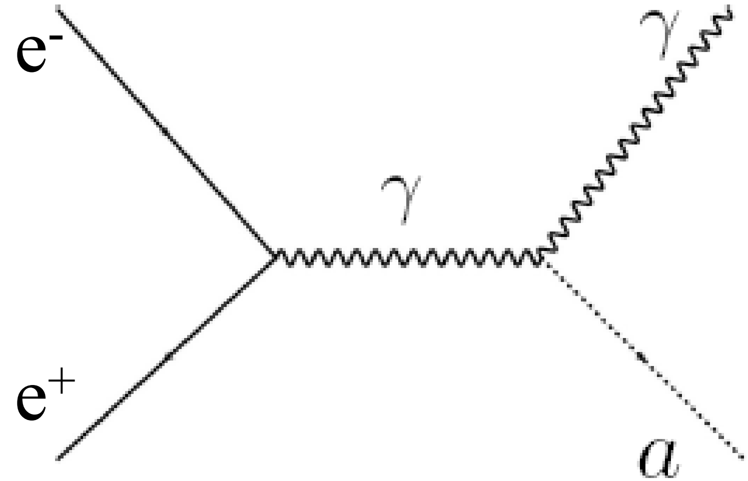
Monophoton Mode: Expected Reach of Belle II



Belle II can perform competitive dark photon searches even in Phase 2

Higher sensitivity than BaBar, mainly due to the non projective geometry of the calorimeter cracks

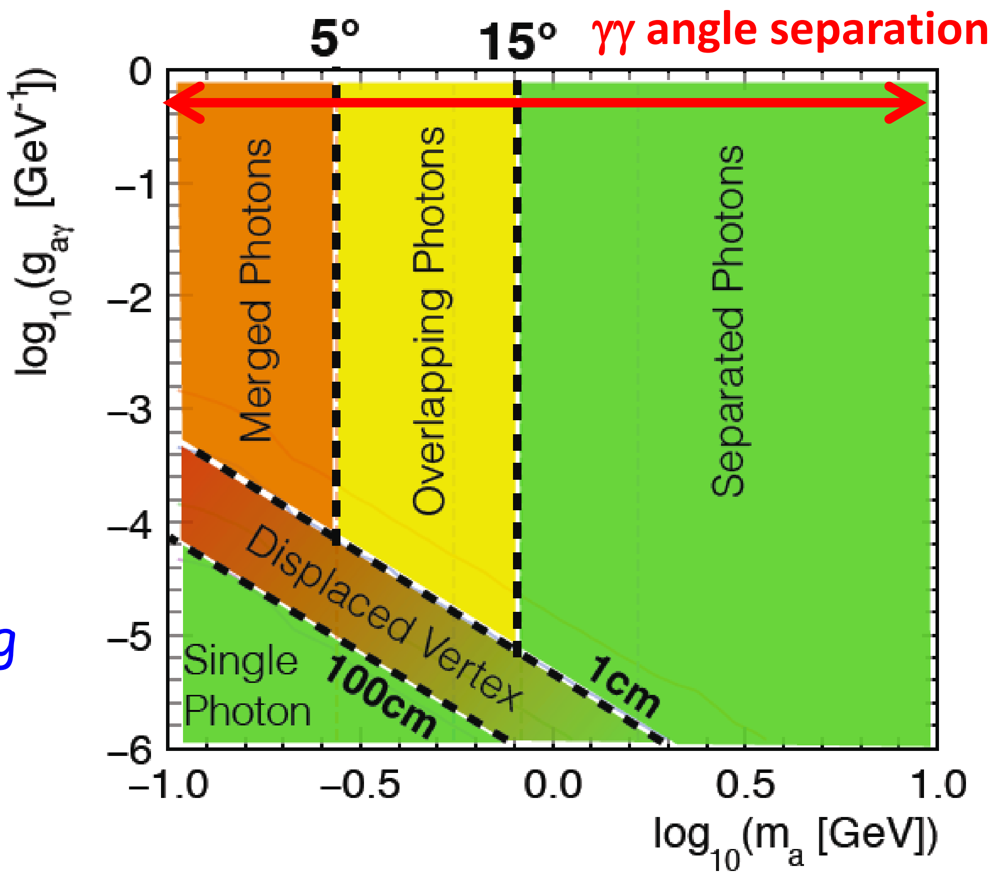
Axion Like Particles



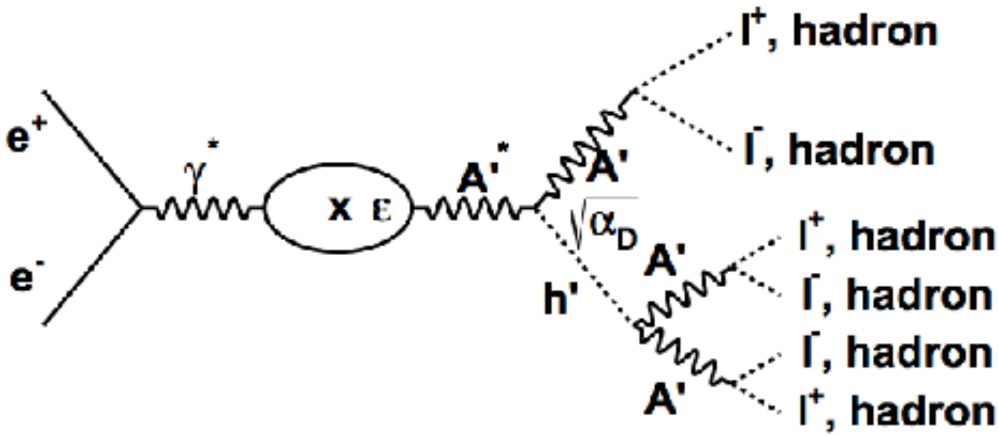
Assume $a \rightarrow \gamma\gamma$

$g_{a\gamma}$ is the relevant coupling

- Three photon final state, but …
  - γ's from axion decay can overlap or be merged for low a masses
  - for very low couplings, a can fly away undetected
- Three, two and one photon final states
- Sensitivities at Belle II are being investigated



Dark Higgs



The dark Higgs is produced via Higgsstrahlung (replacing the SM Higgs)

h' decays depend on $M_{h'}$ and $M_{A'}$. Measures the coupling constant of the dark photon to the dark Higgs, α_D.

$M_{h'} > 2M_{A'}$: h' →A'A', Very low background.

Exclusive: 3 charged tracks pairs with same invariant mass and total energy of the event.

Inclusive: 2 charged tracks pairs, same invariant mass, third *A* from 4-mom. of e^+e^- system

$M_{A'} < M_{h'} < 2M_{A'}$: h' →A'A'*

$M_{h'} < M_{A'}$: h' long lived and h'→l^+l^-,$\pi^+\pi^-$.

Summary

- Belle II successfully rolled in to its final position in SuperKEKB
- 20±20 fb^{-1} expected for physics in Phase 2 starting at the beginning of 2018
- Data taking with the full detector (Phase 3) will start at the end of 2018
- Belle II will have a strong impact on the search for New Physics in the coming years.
  - The search for the invisible decay of the dark photon to light dark matter looks very promising, even in Phase 2