Dark Sector Physics with Belle II

Andrea Fodor, McGill University

SUSY 2017

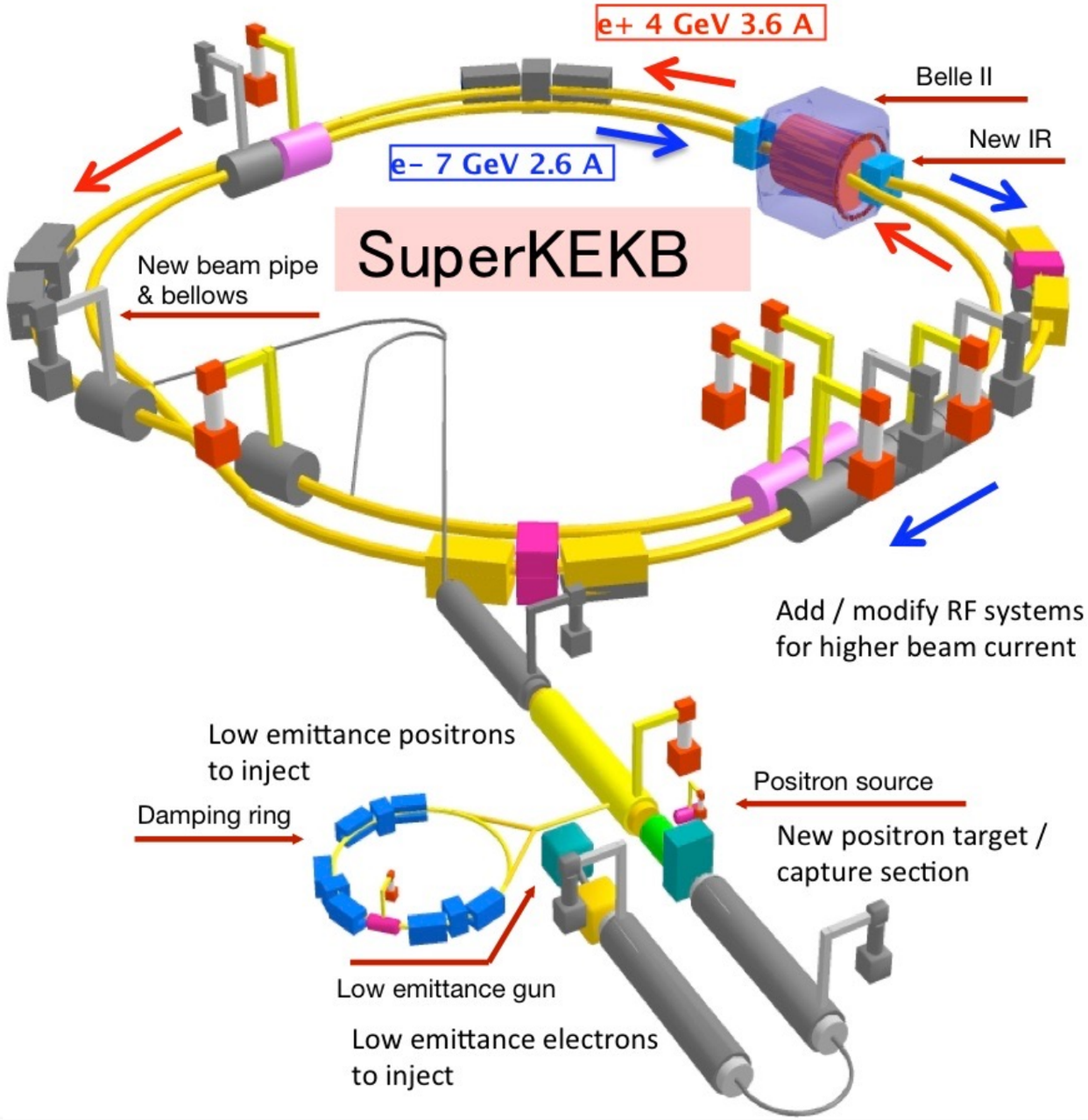
McGill UNIVERSITY

Outline

- Belle II and SuperKEKB
- Searches for the dark photon
- Searches for Axion-Like Particles
- Other DM Searches with Belle II
- Summary

Belle II experiment and SuperKEKB

- Electron - positron collider located at KEK Laboratory in Tsukuba, Japan
- High Energy electron ring (HER) - **7 GeV**
- Low Energy positron ring (LER) - **4 GeV**
- Collisions at the center of mass energy 10.58 GeV ⇒ **Y(4S)** resonance



- Successor to the KEKB collider
- "Nano-beam" and continuous injection scheme
- Design instantaneous luminosity $8 \cdot 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Design integrated luminosity $50\ \mathrm{ab}^{-1}$

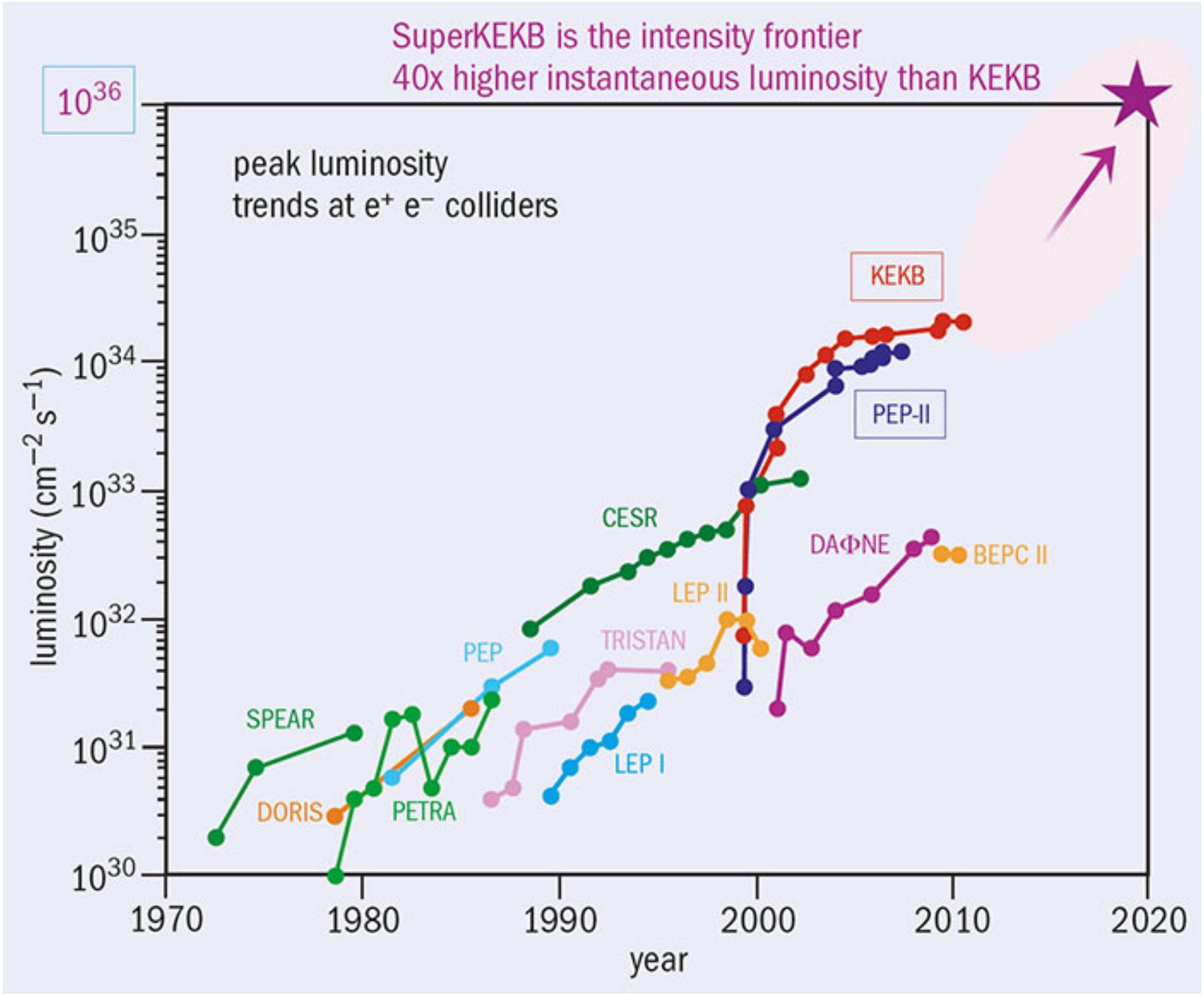
2 times larger

$$L = \frac{\gamma_\pm}{2er_e}\left(\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

20 times smaller

40-fold increase in instantaneous luminosity compared to KEKB

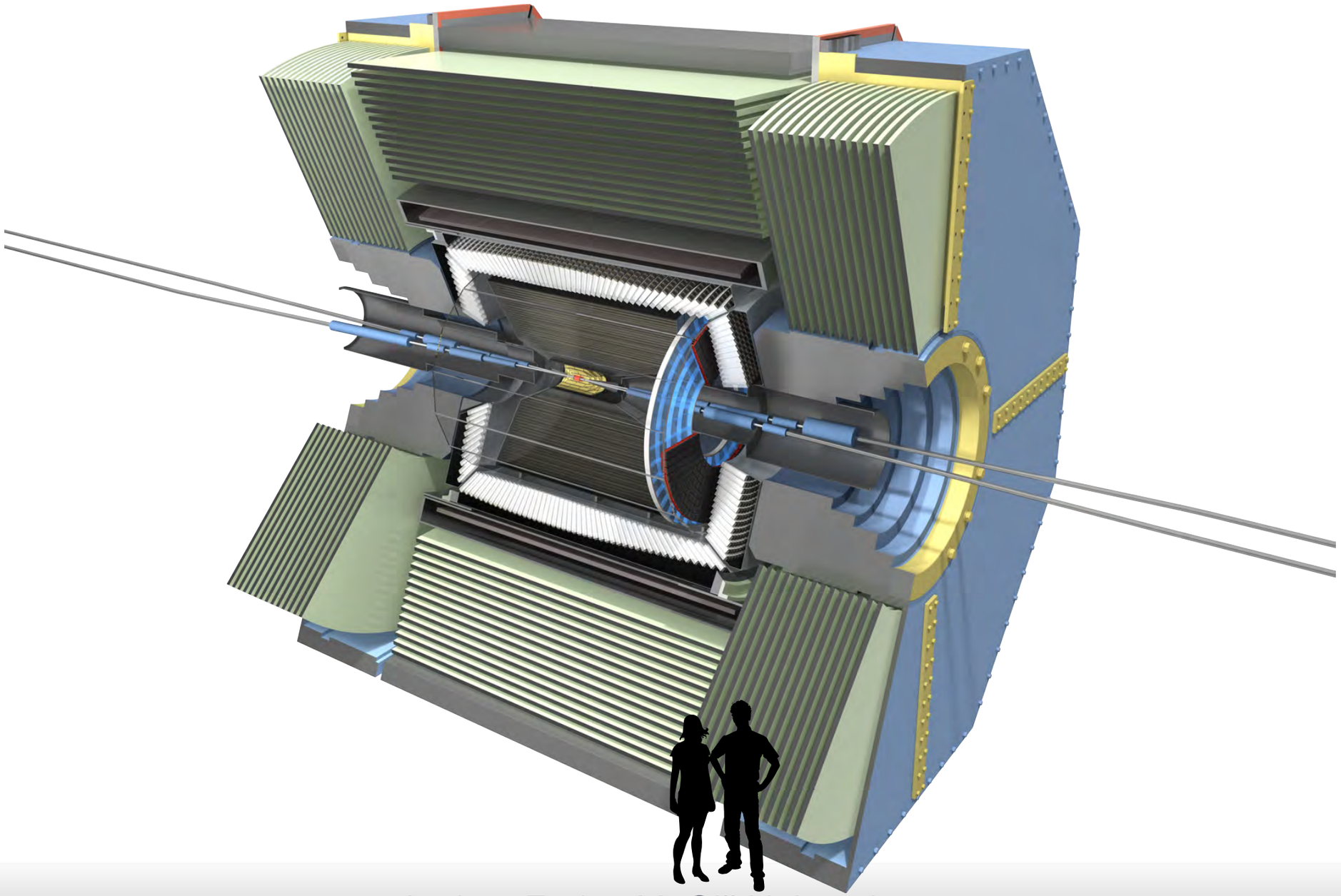
Belle II experiment and SuperKEKB



CERN Courier, Aug 2016

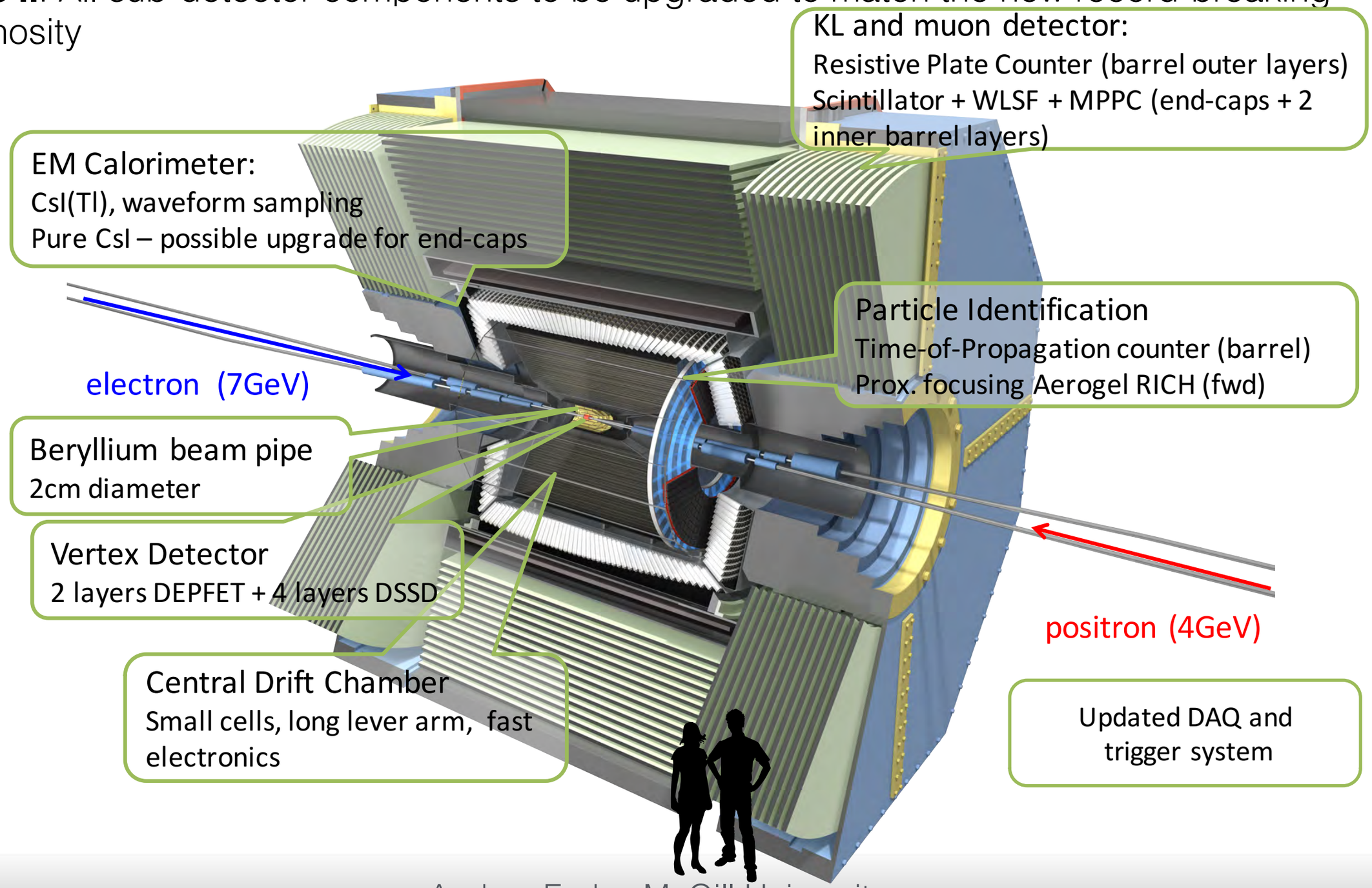
Belle II experiment and SuperKEKB

- **Belle**: ran from 1999 to 2010
  - Important discoveries including first observation of CP violation in the neutral B meson system
- **Belle II**: All sub-detector components to be upgraded to match the new record-breaking luminosity

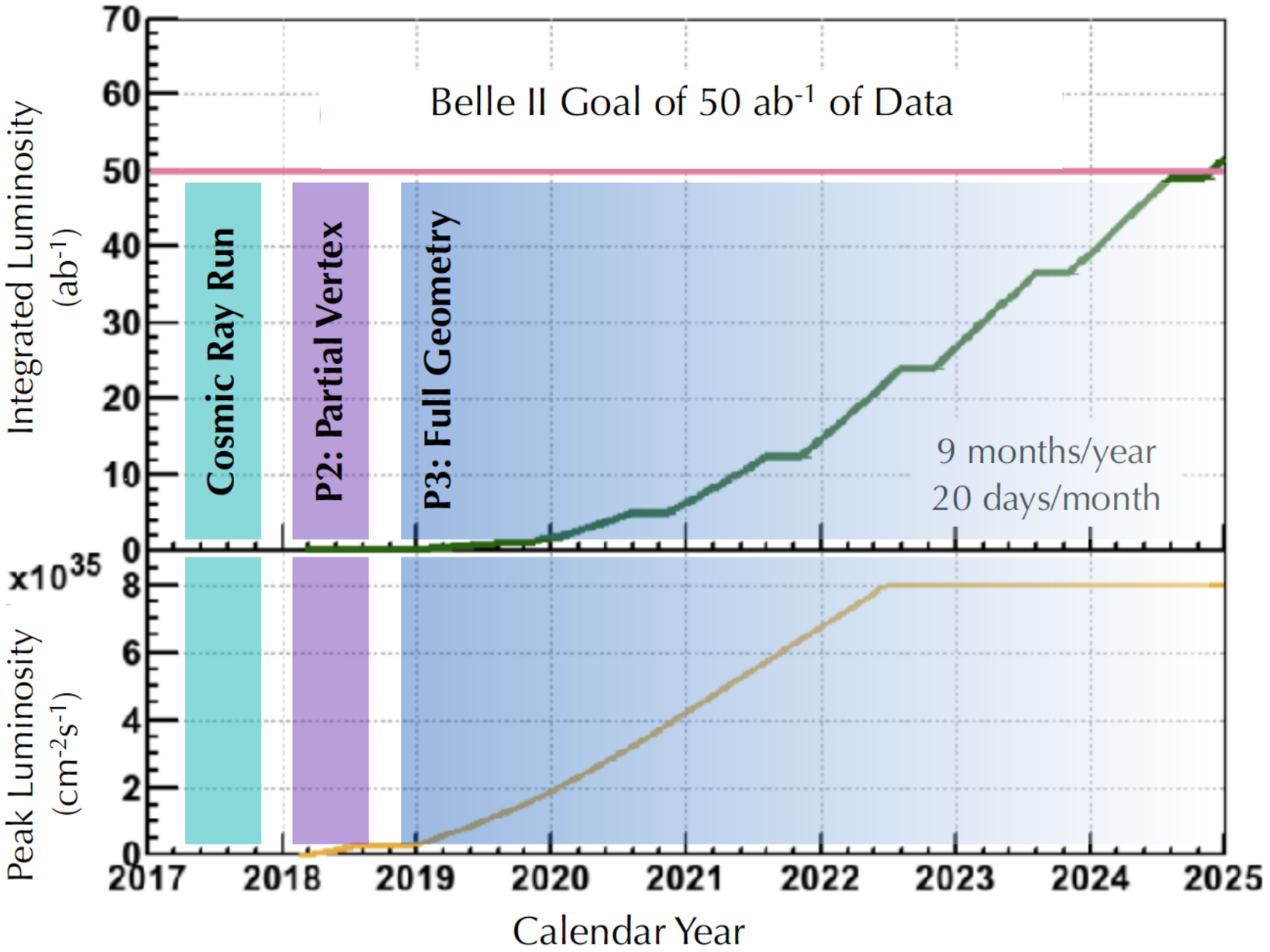


Belle II experiment and SuperKEKB

- **Belle**: ran from 1999 to 2010
  - Important discoveries including first observation of CP violation in the neutral B meson system
- **Belle II**: All sub-detector components to be upgraded to match the new record-breaking luminosity



Data-collection schedule

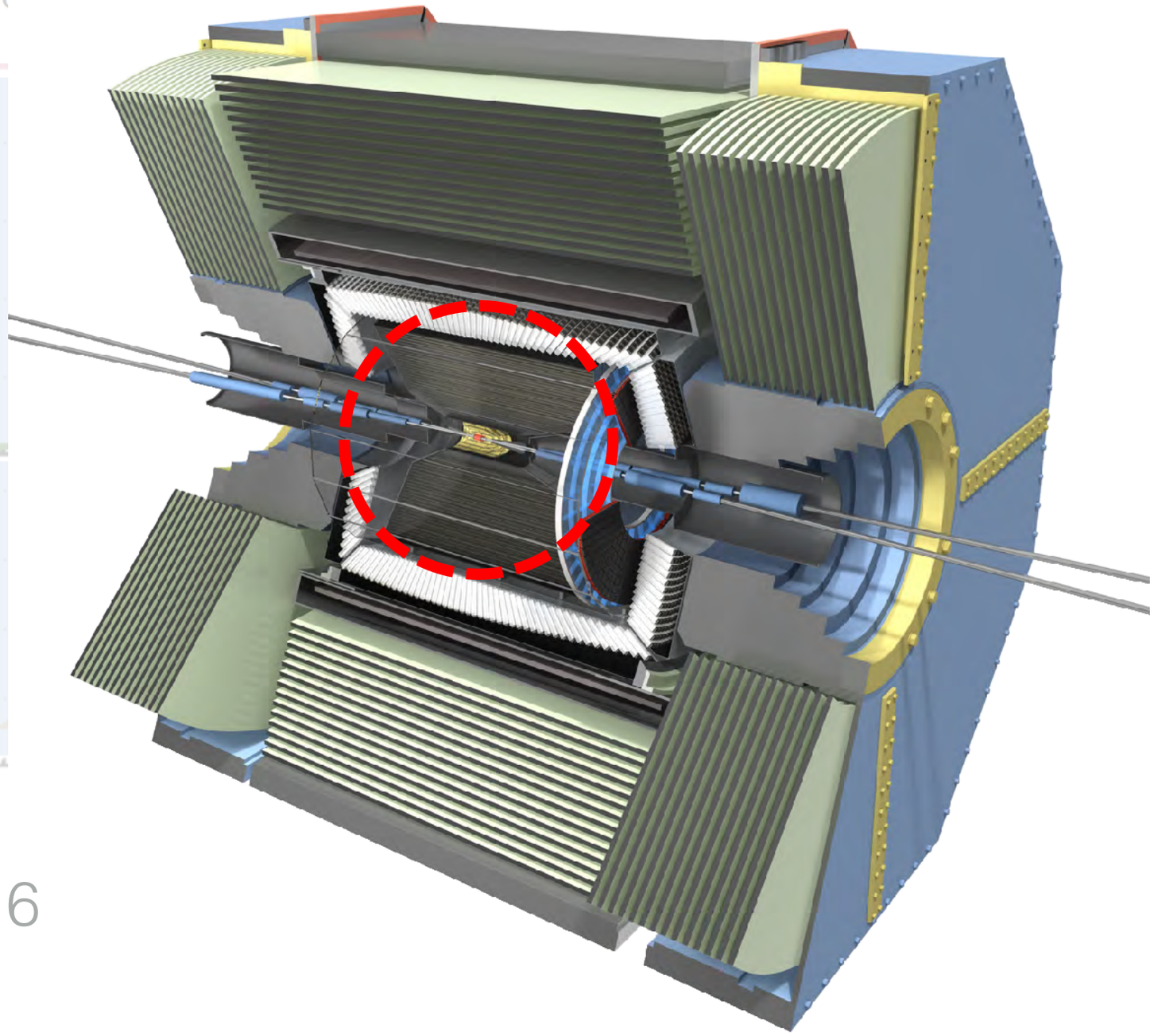


Phase 1: February - June 2016 - NIM-A paper coming soon

Phase 2: March - July 2018

Phase 3: December 2018

Data-collection schedule

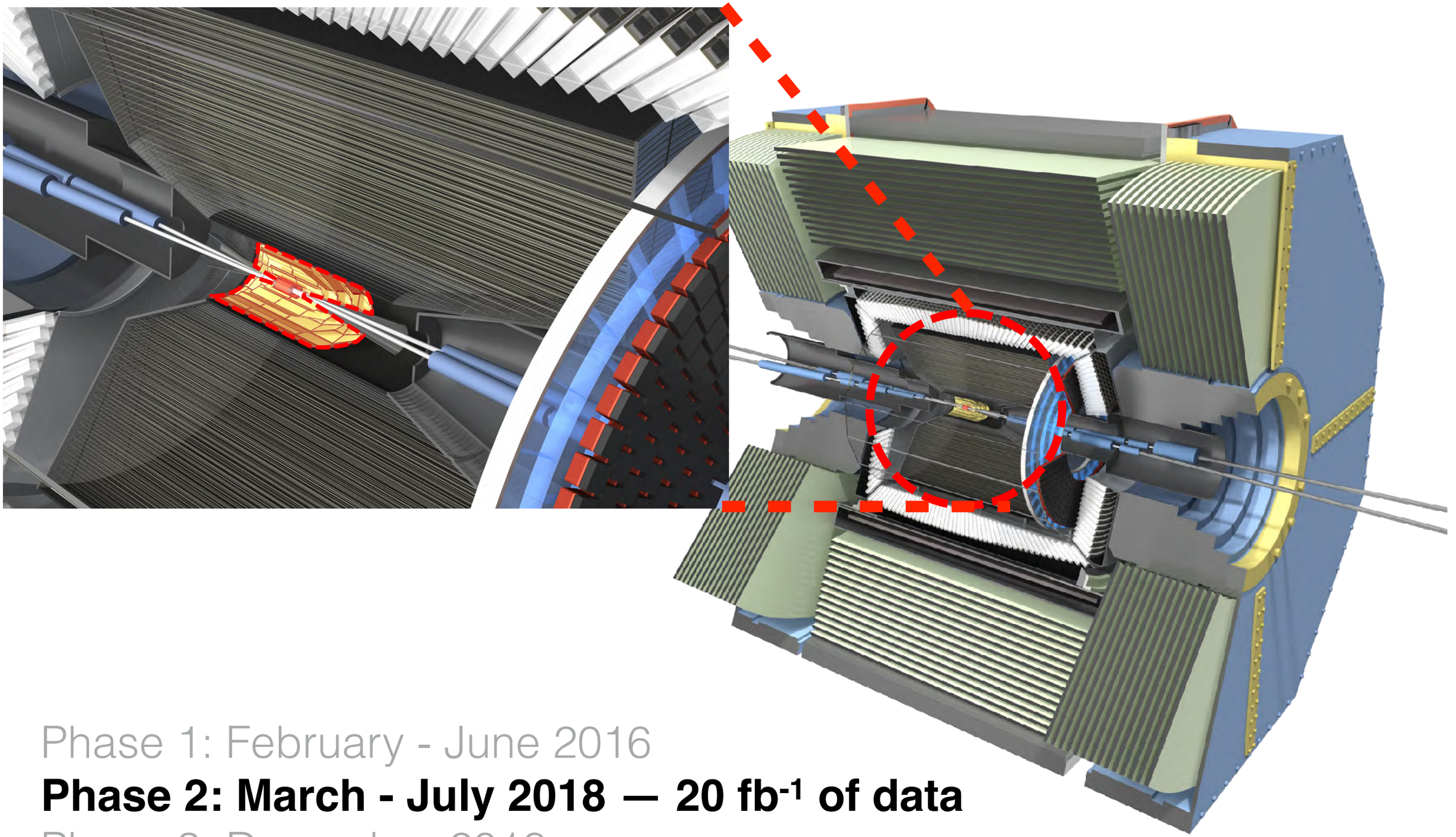


Phase 1: February - June 2016

Phase 2: March - July 2018

Phase 3: December 2018

Data-collection schedule

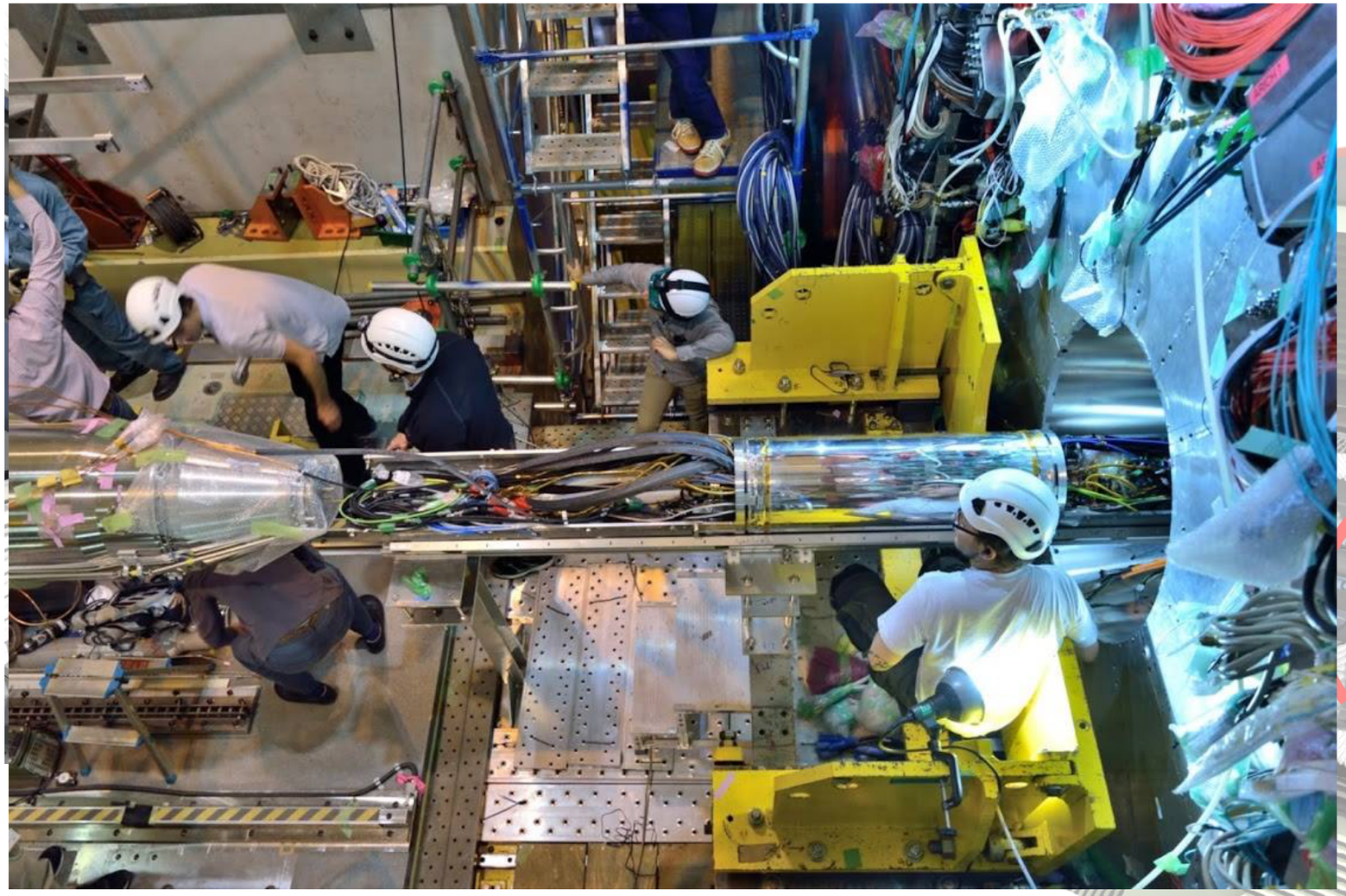


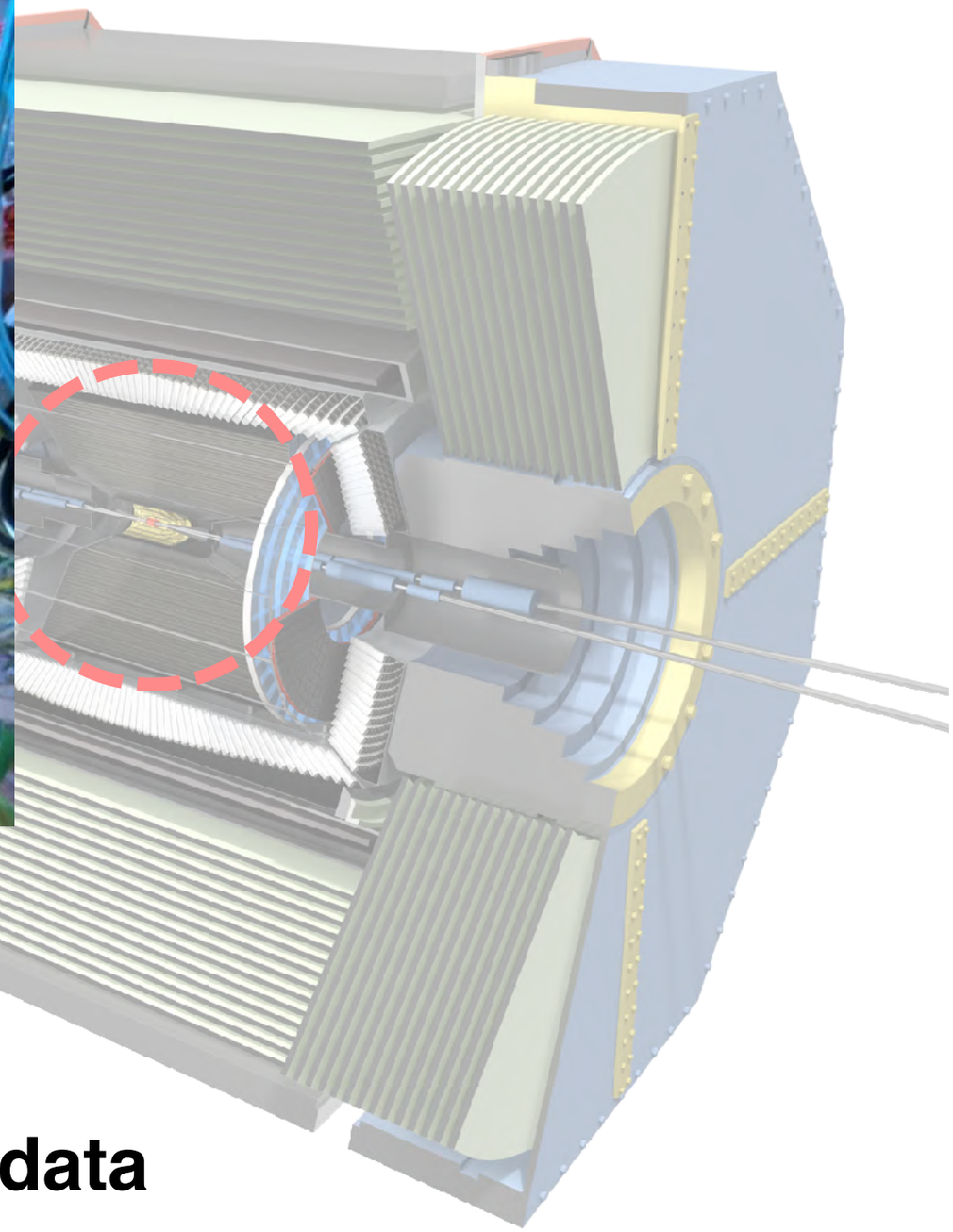
Phase 1: February - June 2016

Phase 2: March - July 2018 — 20 fb^{-1} of data

Phase 3: December 2018

Data-collection schedule





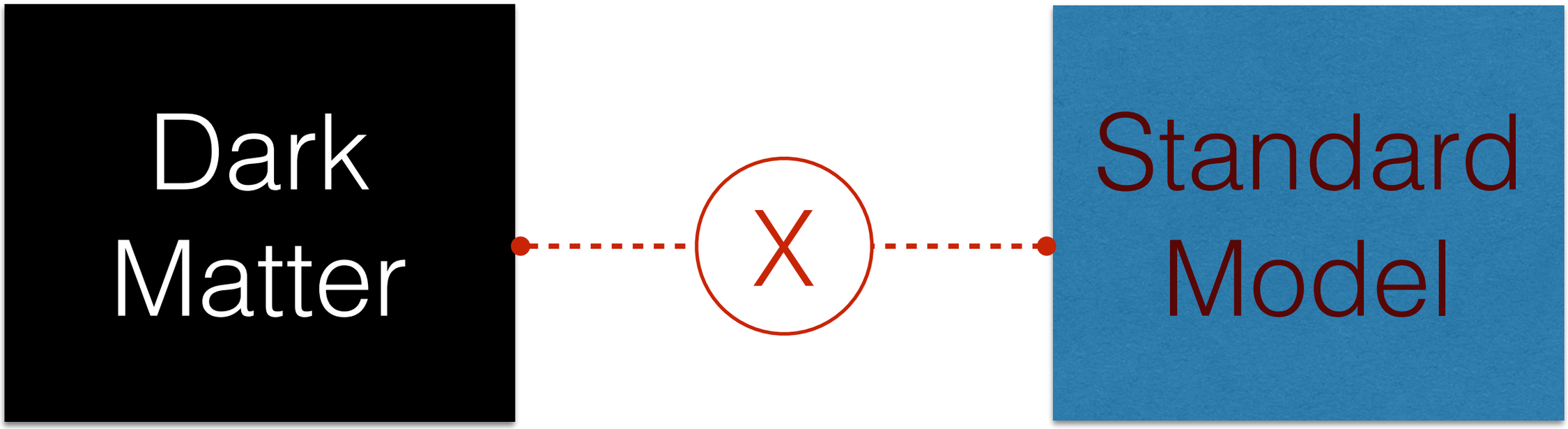
Phase 1: February - June 2016

Phase 2: March - July 2018 — 20 fb^{-1} of data

Phase 3: December 2018

Dark Matter Searches with Belle II

Dark Matter Coupling to Standard Model



Different possible portals between Standard Model and Dark Matter:

Vector Portal → *Dark Photon*

Scalar Portal → *Higgs/Dark Scalars*

Pseudoscalar Portal → *Axion-like Particles*

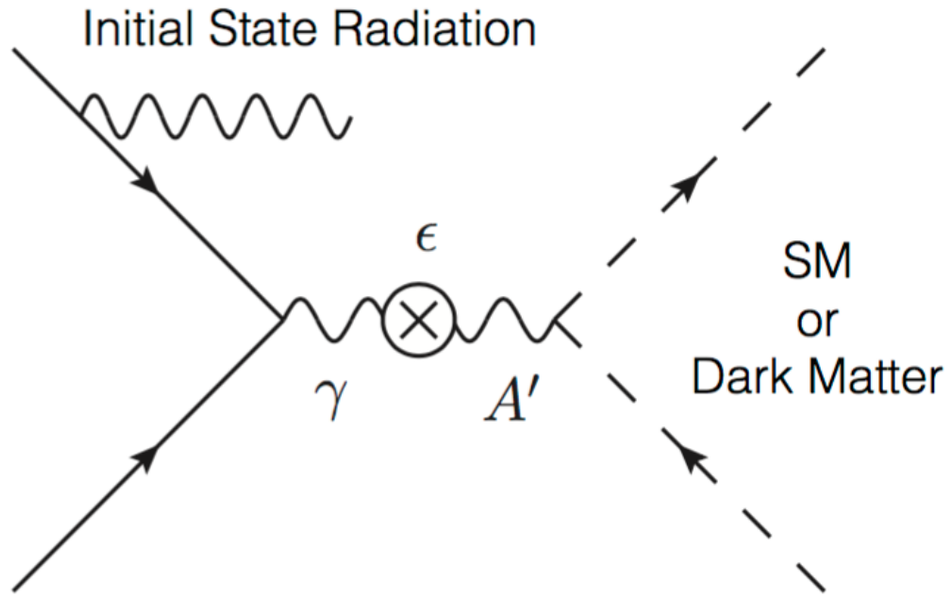
Neutrino Portal → *Sterile Neutrinos*

DM search: vector portal

- massive ‘dark photon’ A′ mixes with SM with coupling strength ε

$$\mathcal{L} \supset \epsilon V_\mu J^\mu_{\mathrm{SM}}$$

- depending on the DM mass, dark photon decays to:
  - DM (invisible)
  - SM fermions (visible)

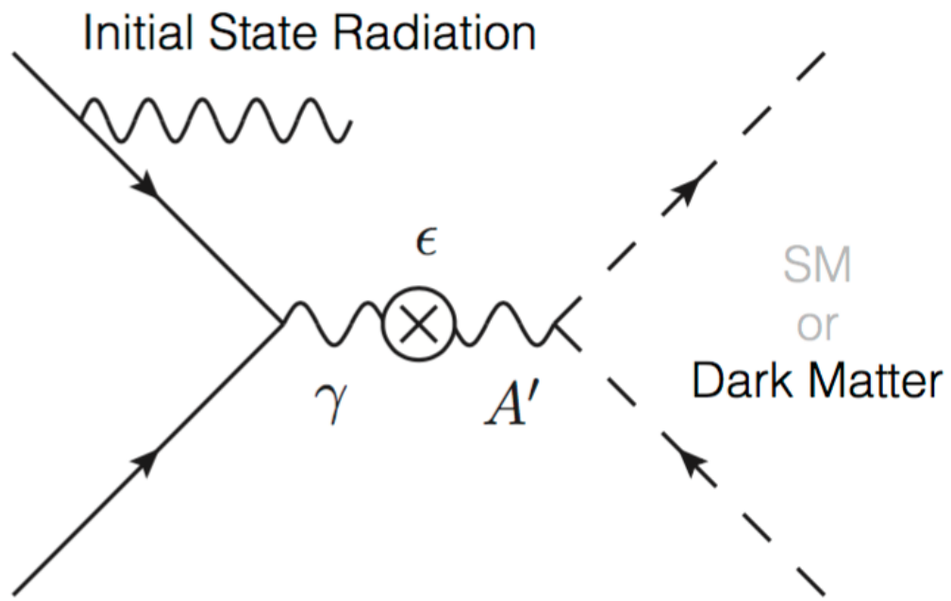


DM search: vector portal

- massive ‘dark photon’ A′ mixes with SM with coupling strength ε

$$\mathcal{L} \supset \epsilon V_\mu J^\mu_{\mathrm{SM}}$$

- depending on the DM mass, dark photon decays to:
  - **DM (invisible)**
  - SM fermions (visible)

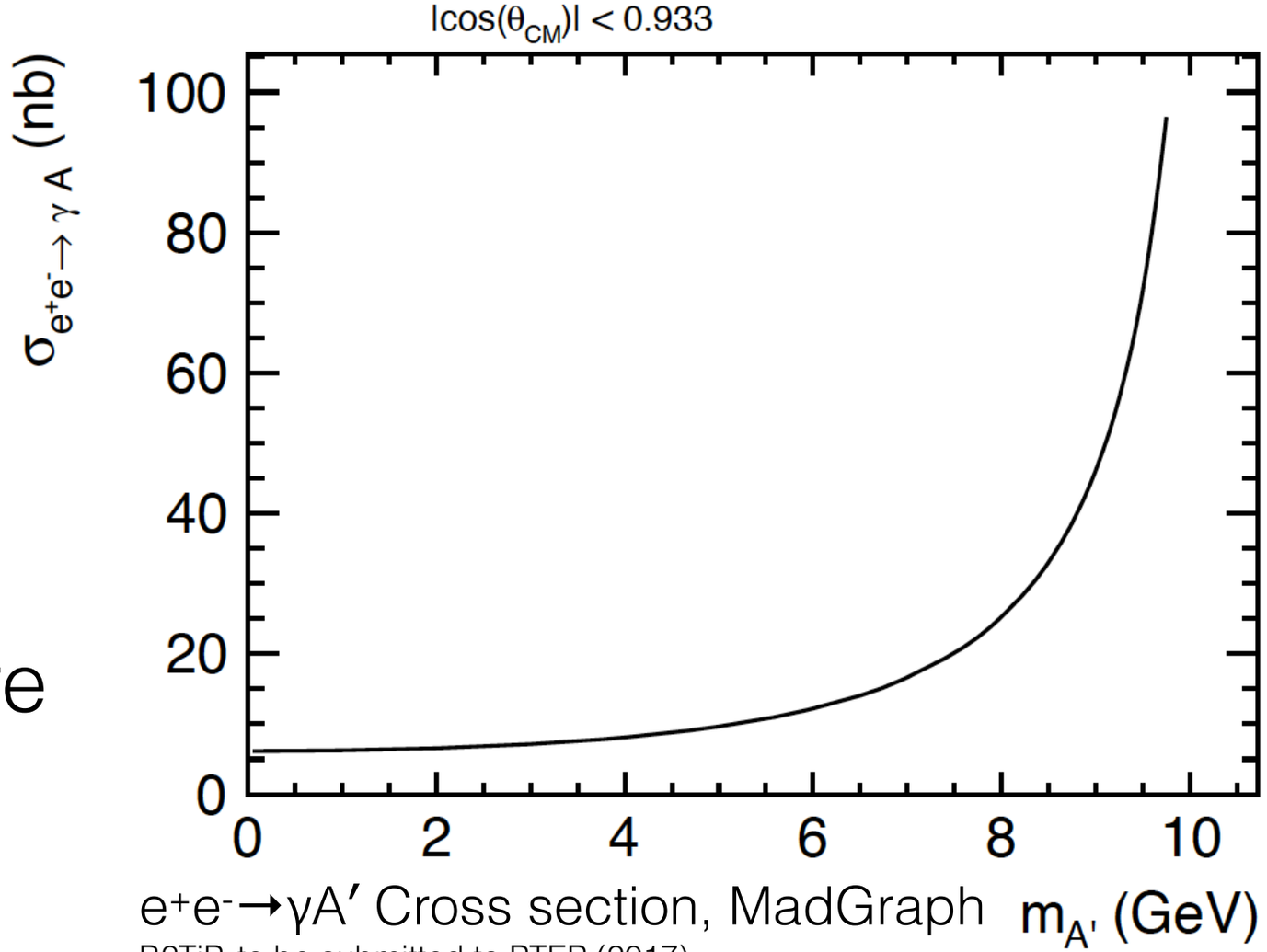


→ Single-Photon Searches

$m_{A'} \geq 2m_\chi$

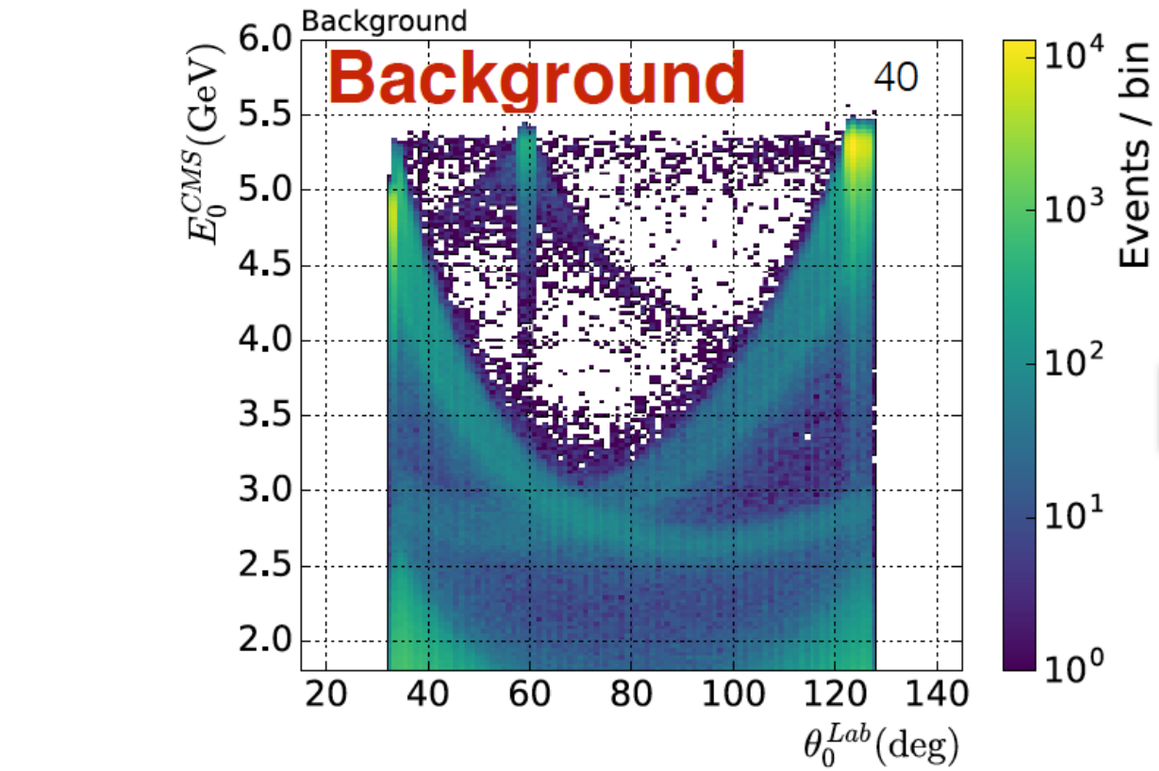
Single-photon searches

- **Signature**: single mono-energetic photon, $E_\gamma = \frac{(E_{CM}^2 - M_{A'}^2)}{2E_{CM}}$
- **Background**: mainly Bhabha and $e^-e^+ \to \gamma\gamma(\gamma)$
- **Dedicated triggers** with 2 GeV and 1 GeV (CMS Energy) threshold
- Belle didn't have a suitable trigger for this search
- BaBar took a fraction of data with single-photon trigger
- Belle II calorimeter is more hermetic compared to BaBar



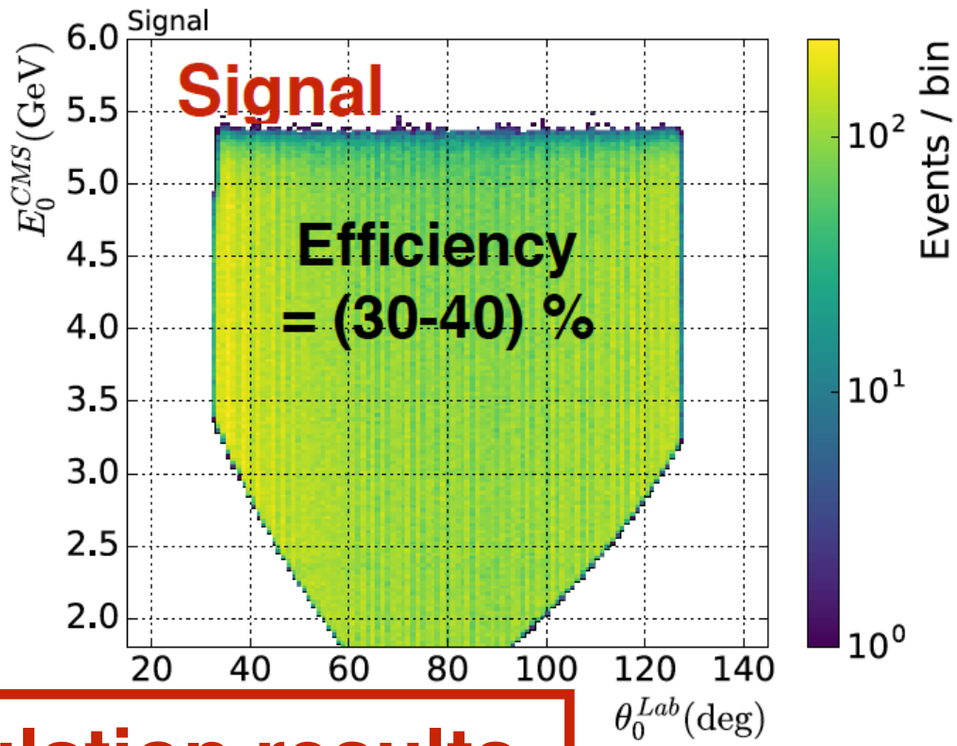
B2TiP, to be submitted to PTEP (2017)

Single-photon searches: Event Selection



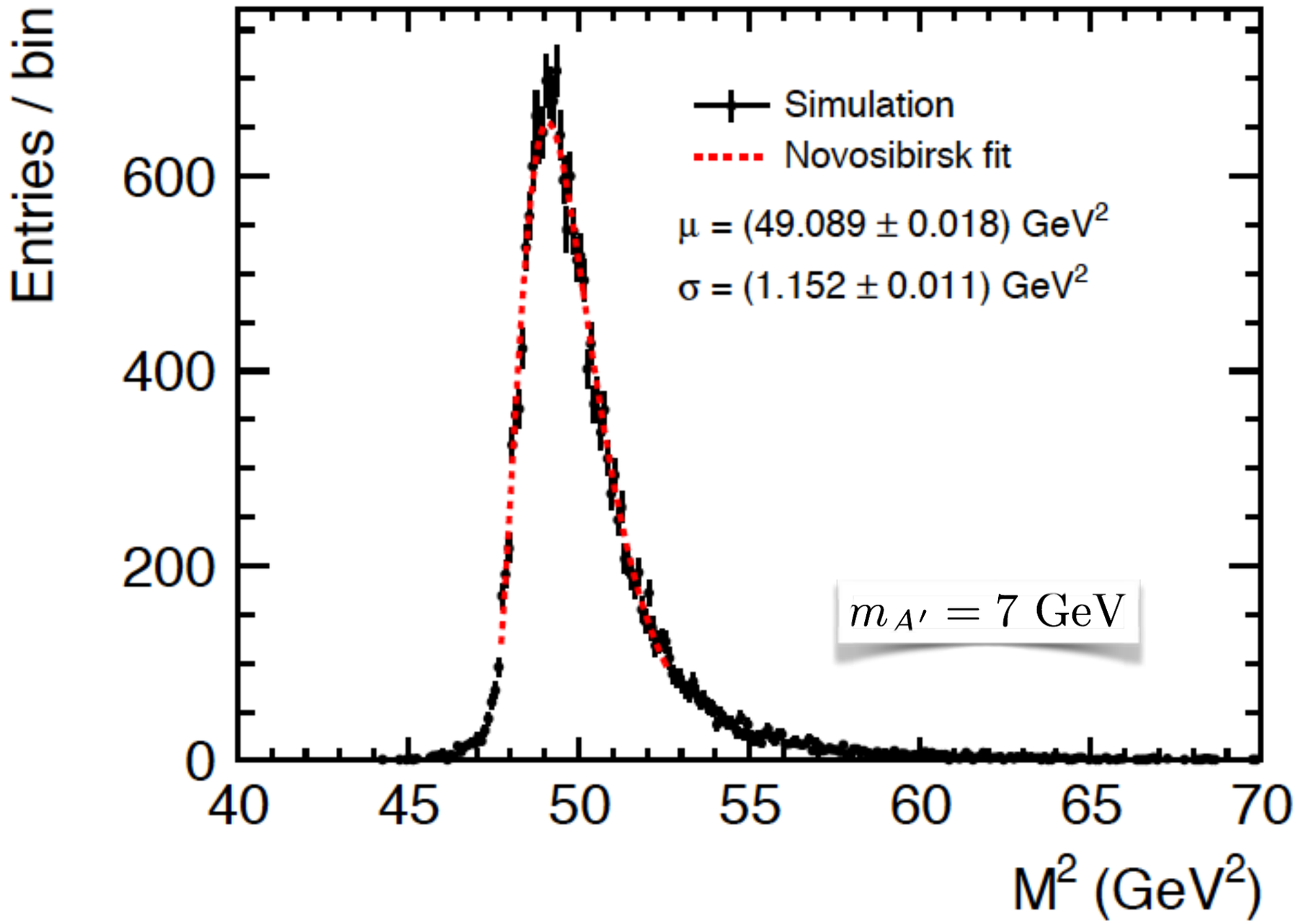
selection

- Electromagnetic calorimeter (ECL) cluster with energy E* > 1.8 GeV
- ECL and KLong and muon detector (KLM) both used for photon detection
- Additional angular dependent selection on Eγ*



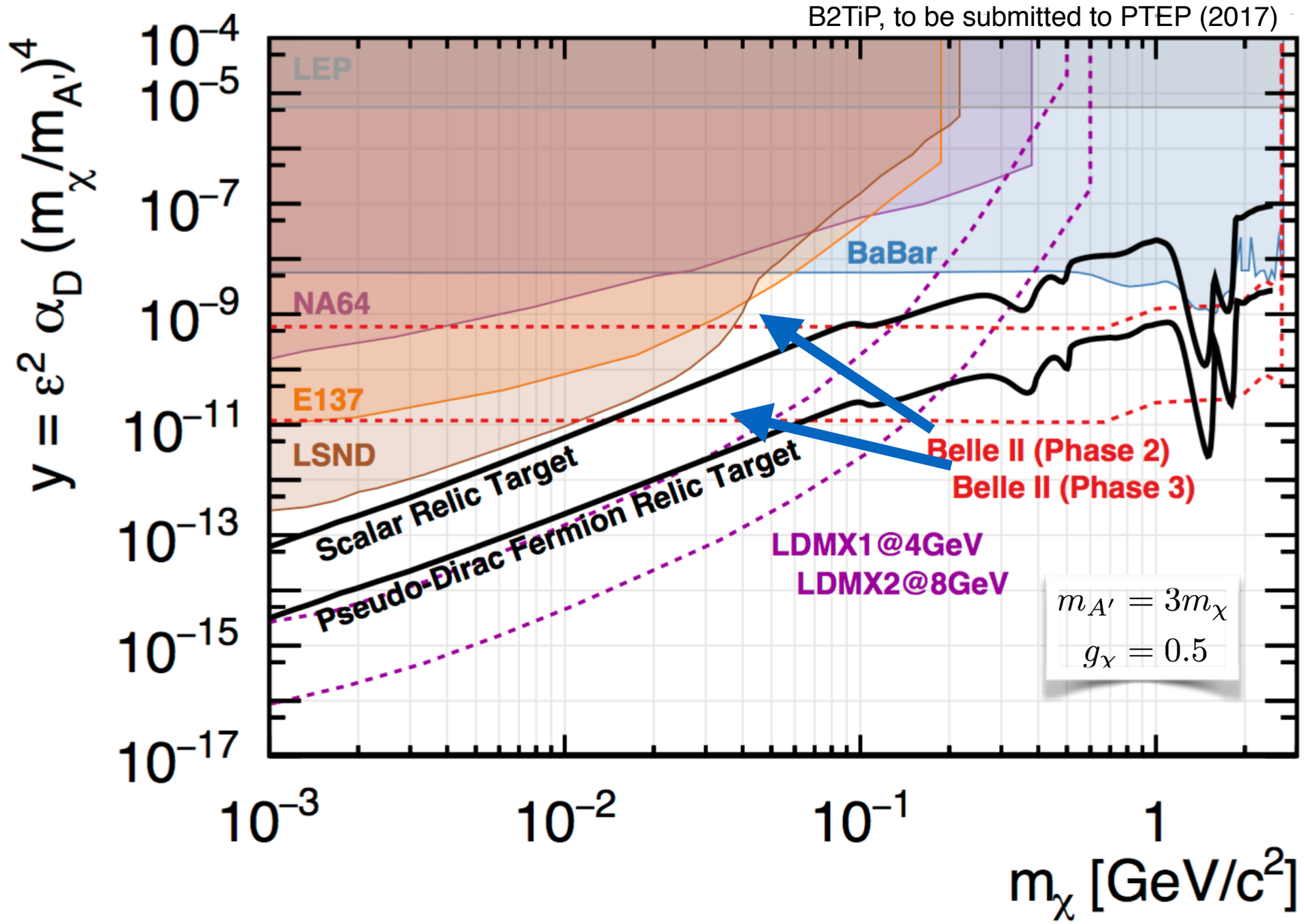
Preliminary Monte Carlo Simulation results

Single-photon searches: Sample Signal



- fit of the recoil mass squared distribution

Belle II Projections



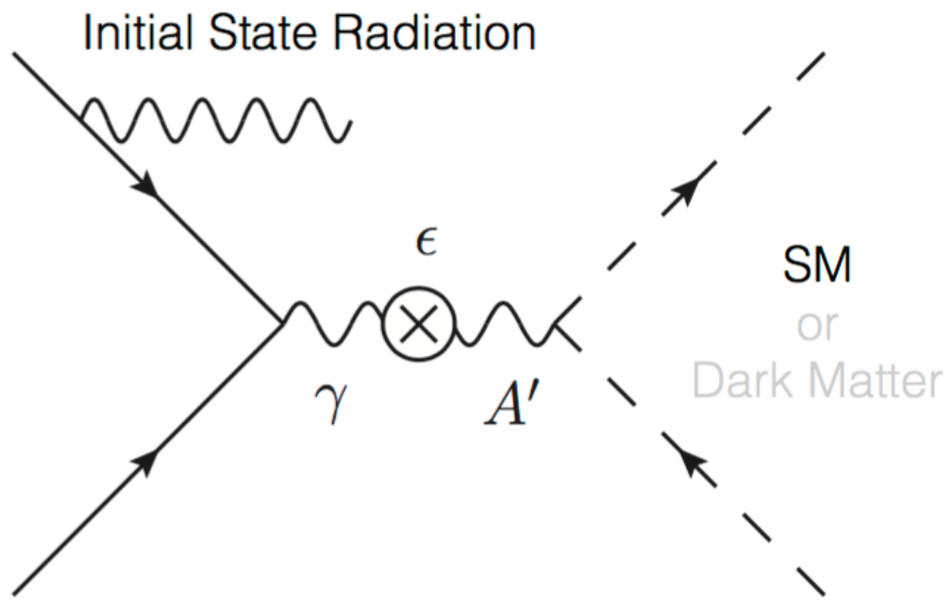
Direct production LDM constraints in the context of
a kinetically mixed Dark Photon coupled to a LDM state that scatters elastically

DM search: vector portal

- massive ‘dark photon’ A′ mixes with SM with coupling strength ε

$$\mathcal{L} \supset \epsilon V_\mu J^\mu_{\mathrm{SM}}$$

- depending on the DM mass, dark photon decays to:
  - DM (invisible)
  - **SM fermions (visible)**

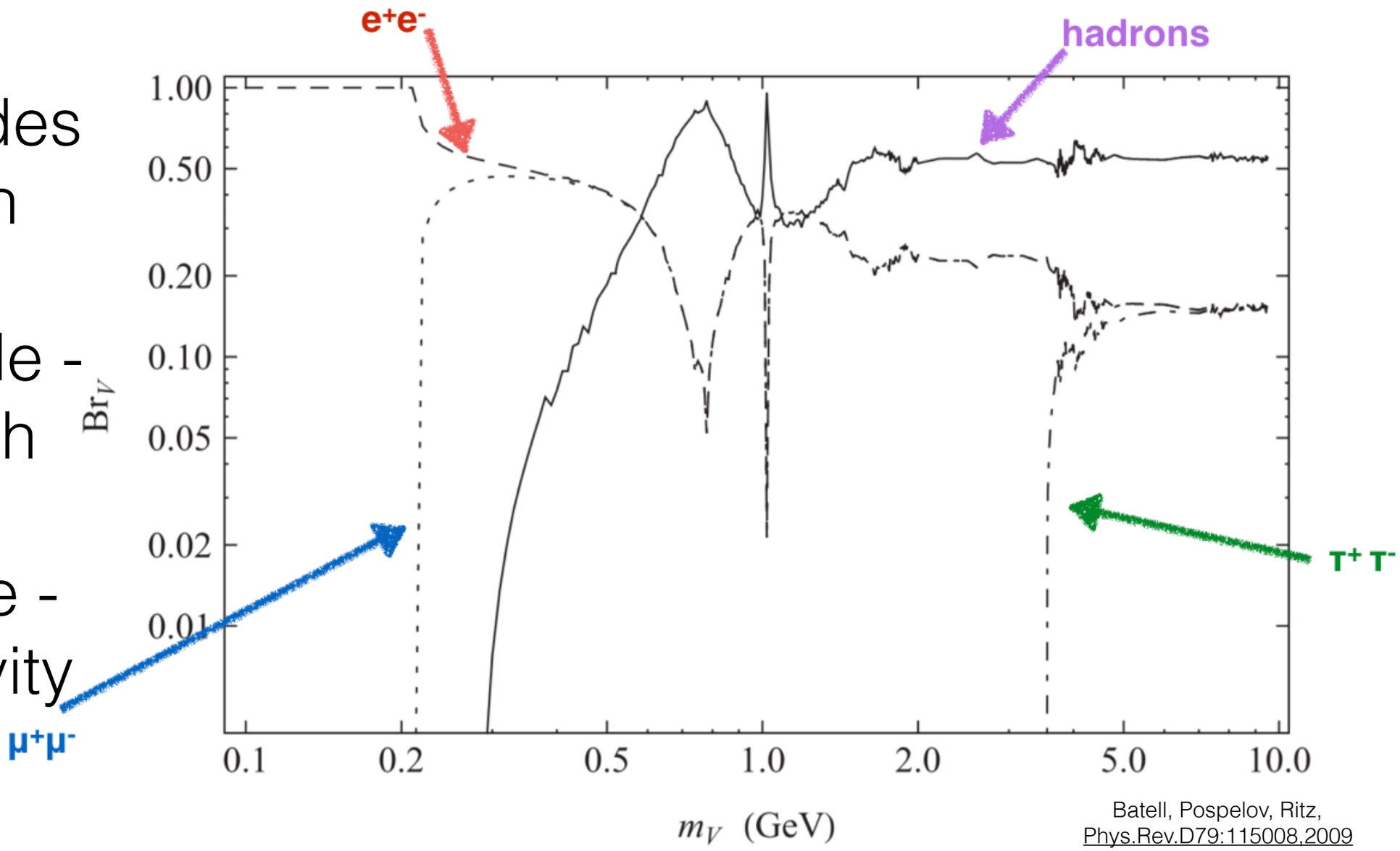


→Dilepton Mode

$m_{A'} \leq 2m_\chi$

Dark Photon: Visible Decays

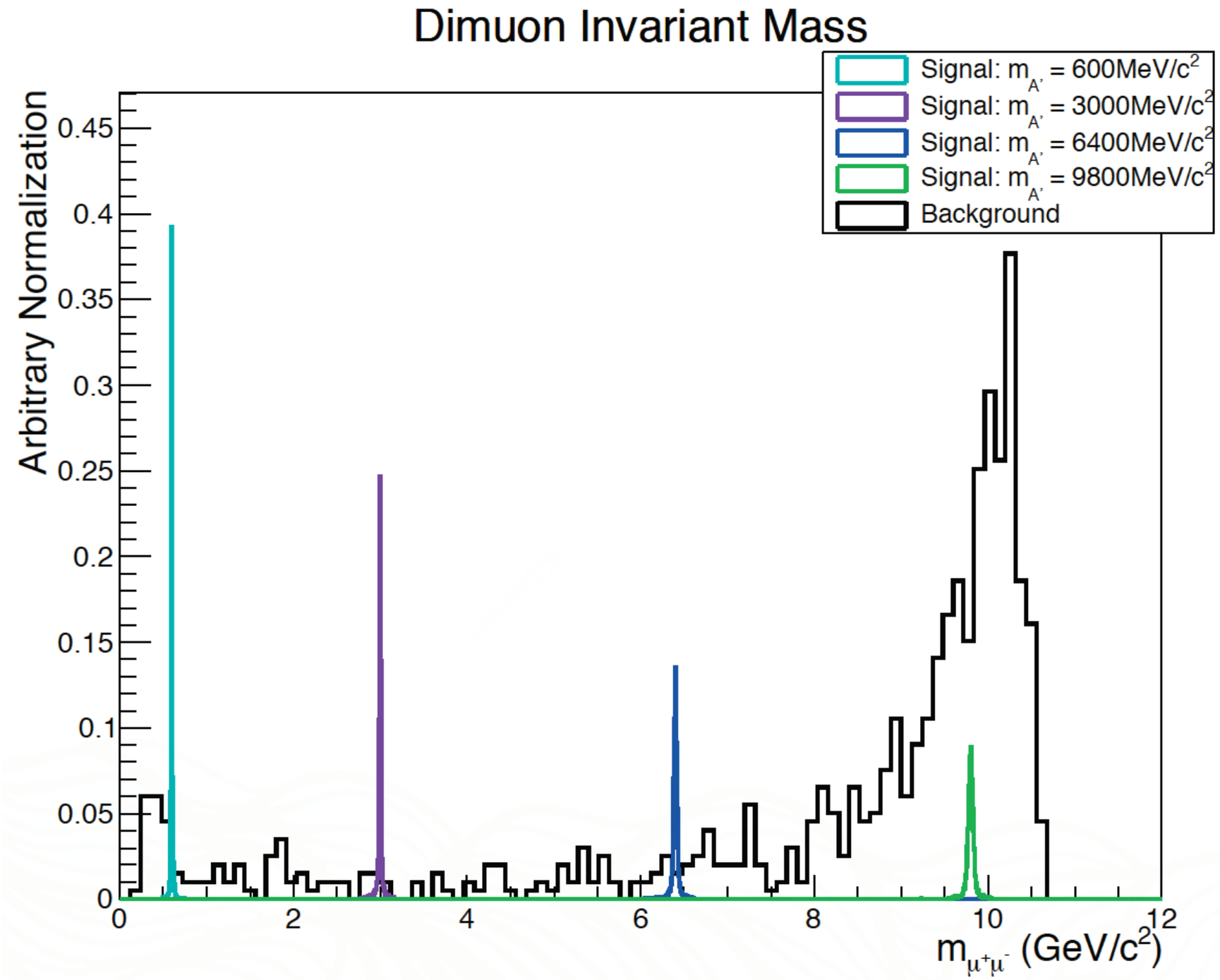
- Different modes analyzed with Belle II
- Electron mode - large BR, high background
- Muonic mode - good sensitivity



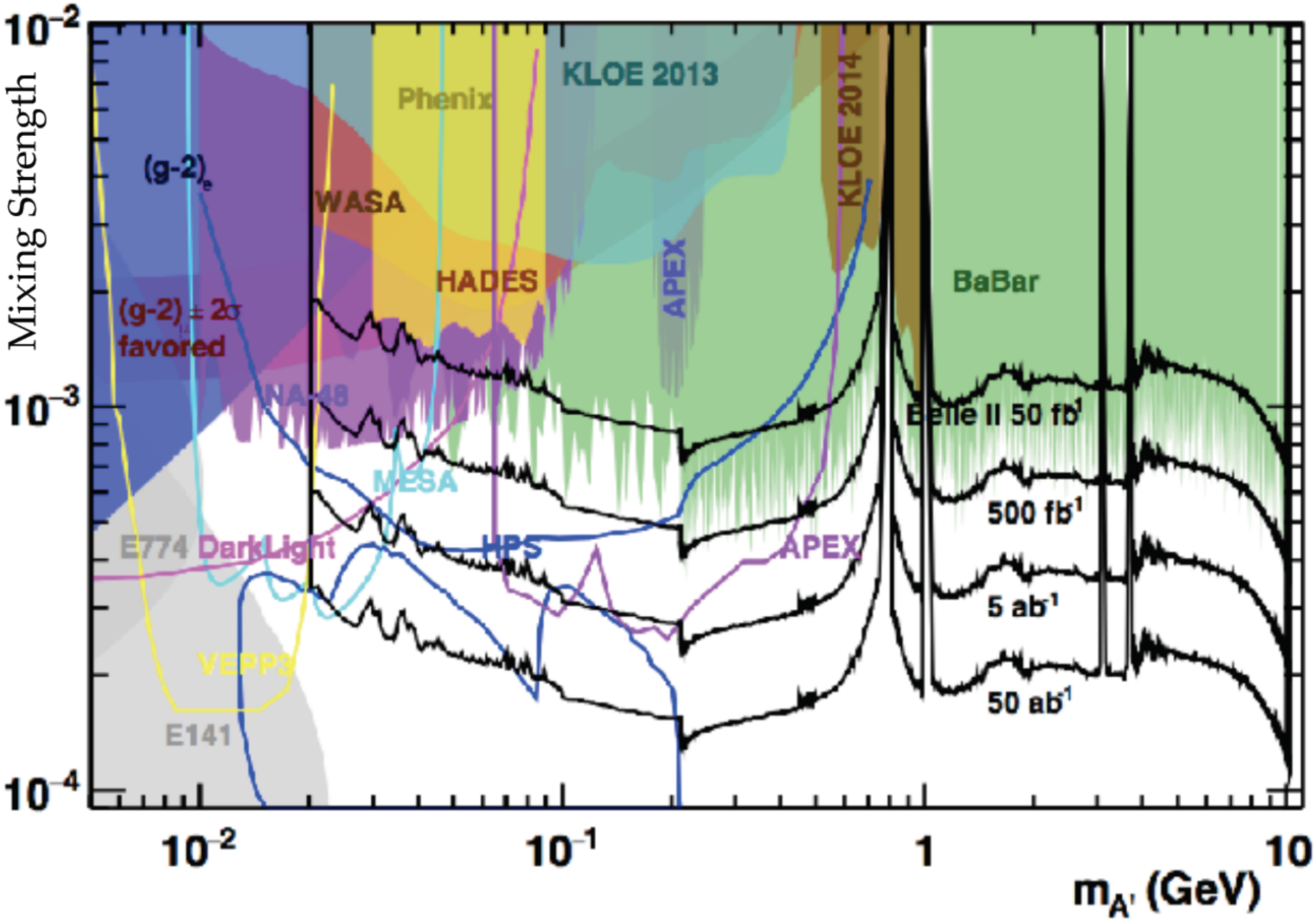
Batell, Pospelov, Ritz, Phys.Rev.D79:115008,2009

Dark Photon: Muonic Decay- Sample Signal

- Double-Gaussian fit of invariant dimuon mass
- Higher A' mass signal has higher background



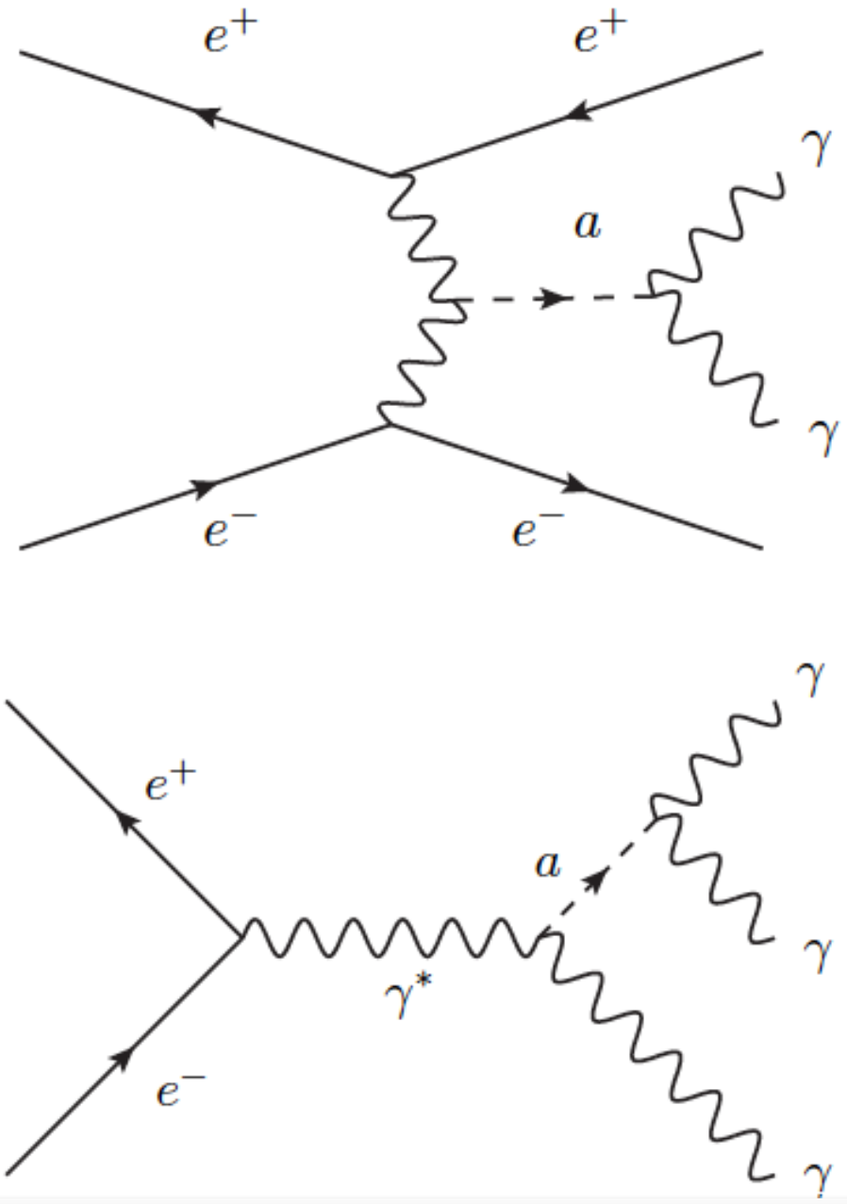
Belle II Projections for A′→ *visible*



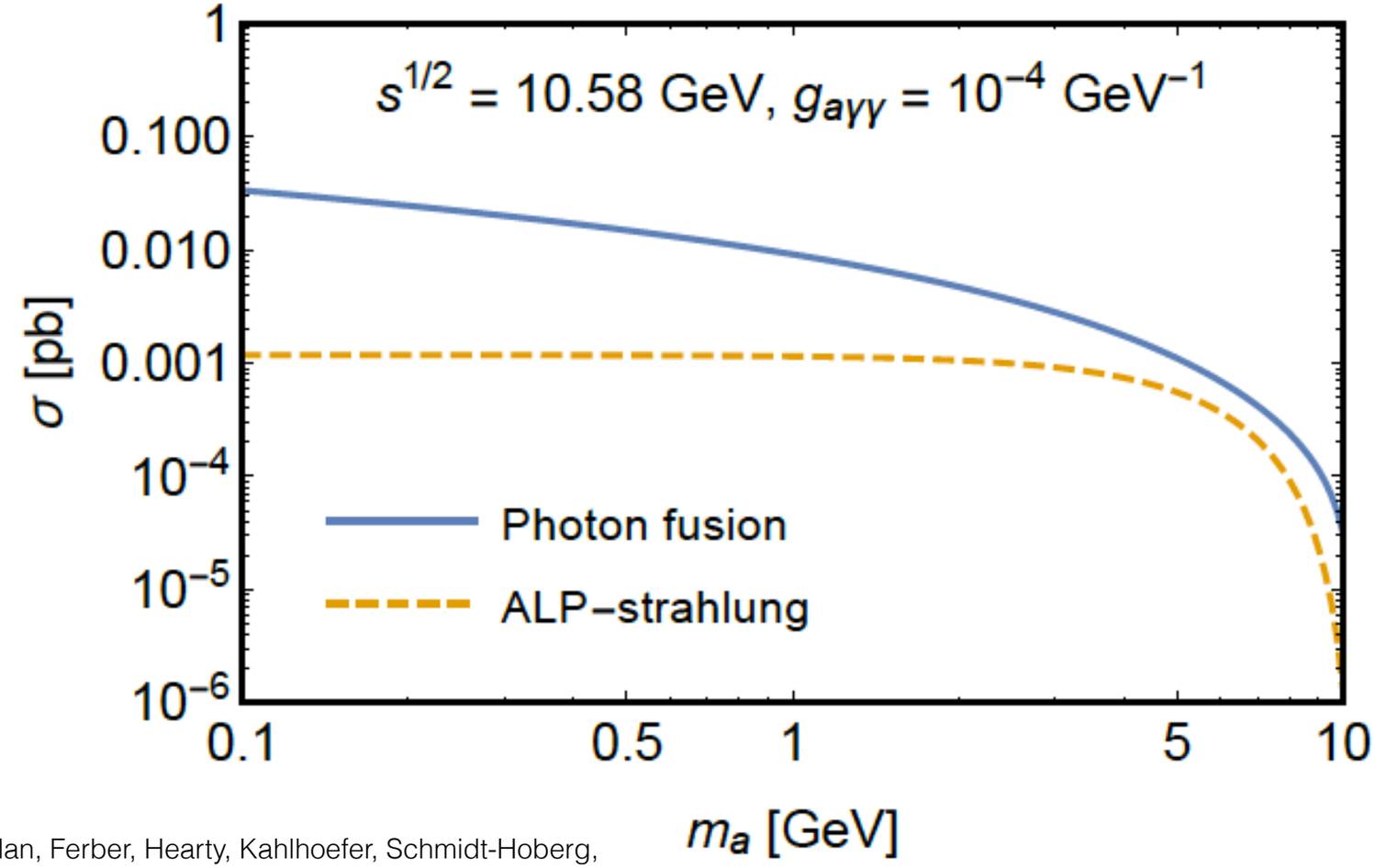
90% CL upper limits on the mixing strength —
projections made from results of BaBar's 2014 search (arXiv:1406.2980)

Search for Axion-like particles

- Pseudo-scalar particles, coupling to bosons, no mass and coupling relation
- Belle II focuses on ALP coupling to photons

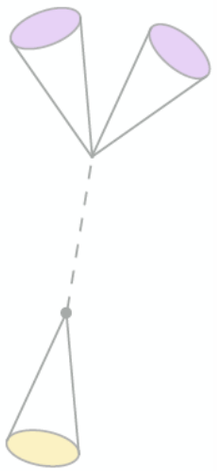


$$\mathcal{L} \supset -\frac{g_{\gamma\gamma}}{4} F^{\mu\nu} \tilde{F}^{\mu\nu} P$$

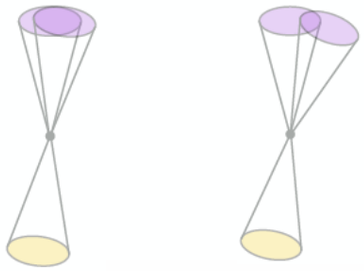


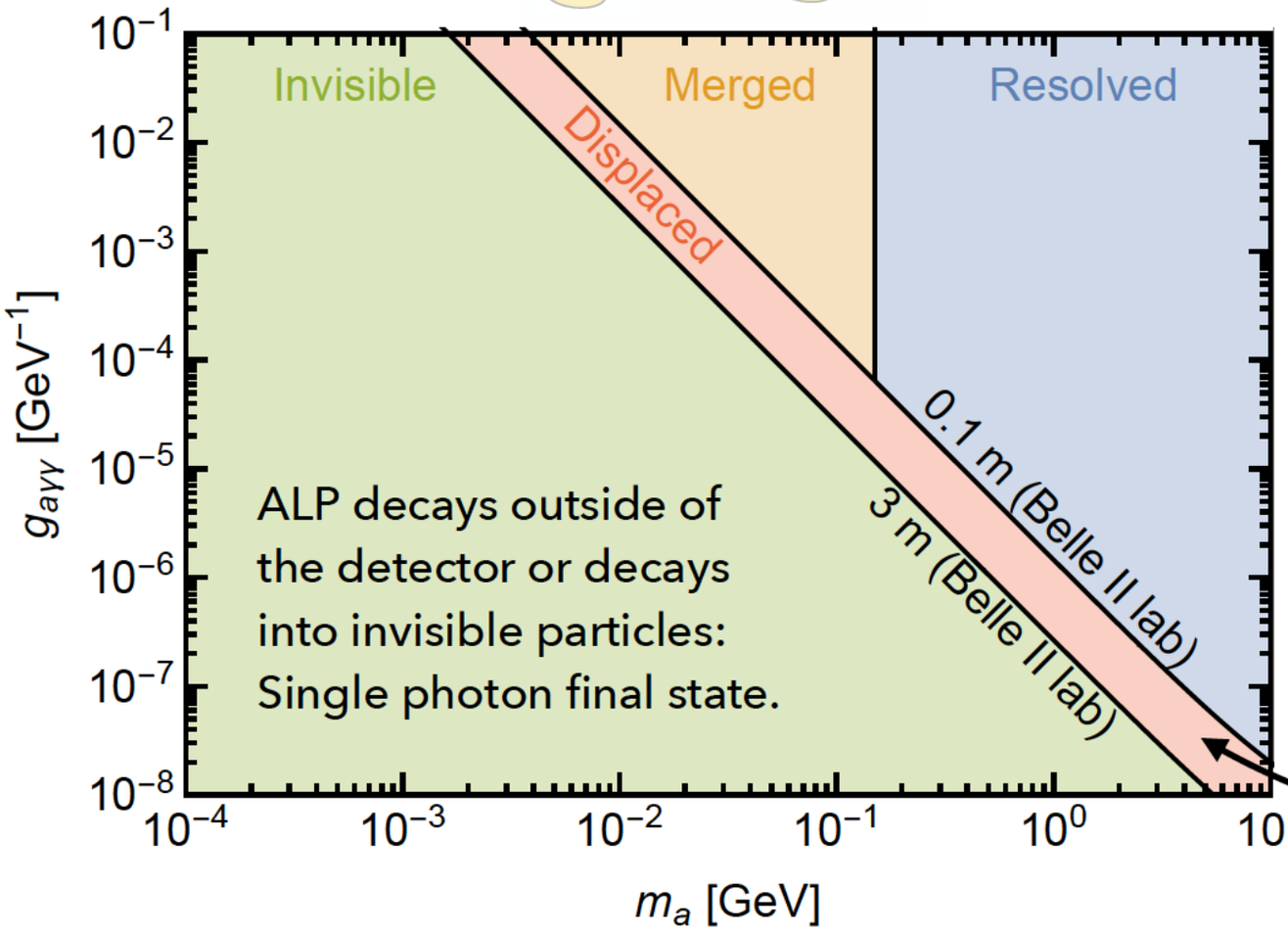
Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, submitted to JHEP(2017), arXiv:1709.00009

Search for Axion-like particles

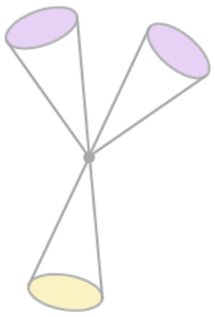


Two of the photons overlap or merge.





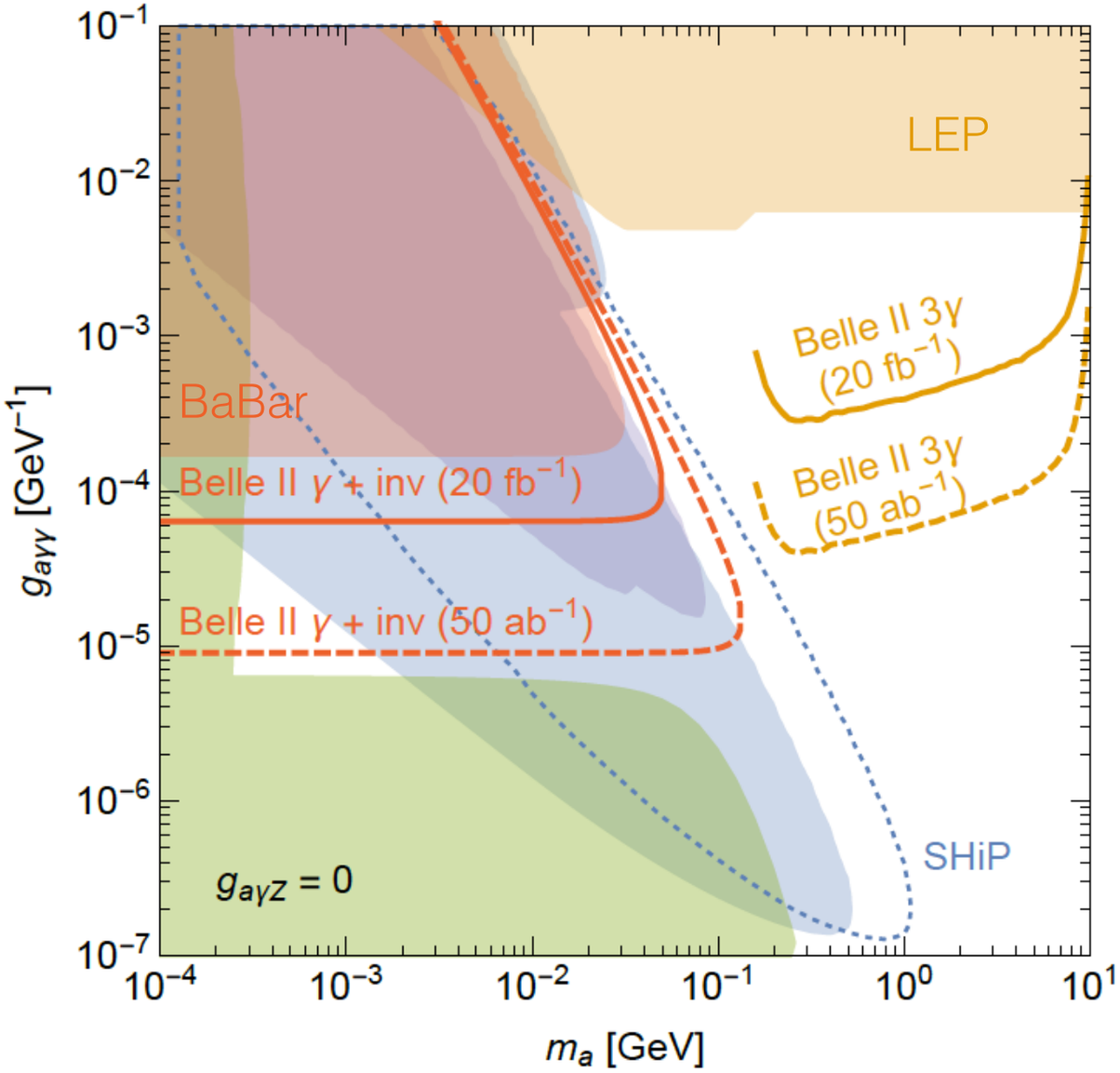
Three resolved, high energetic photons.

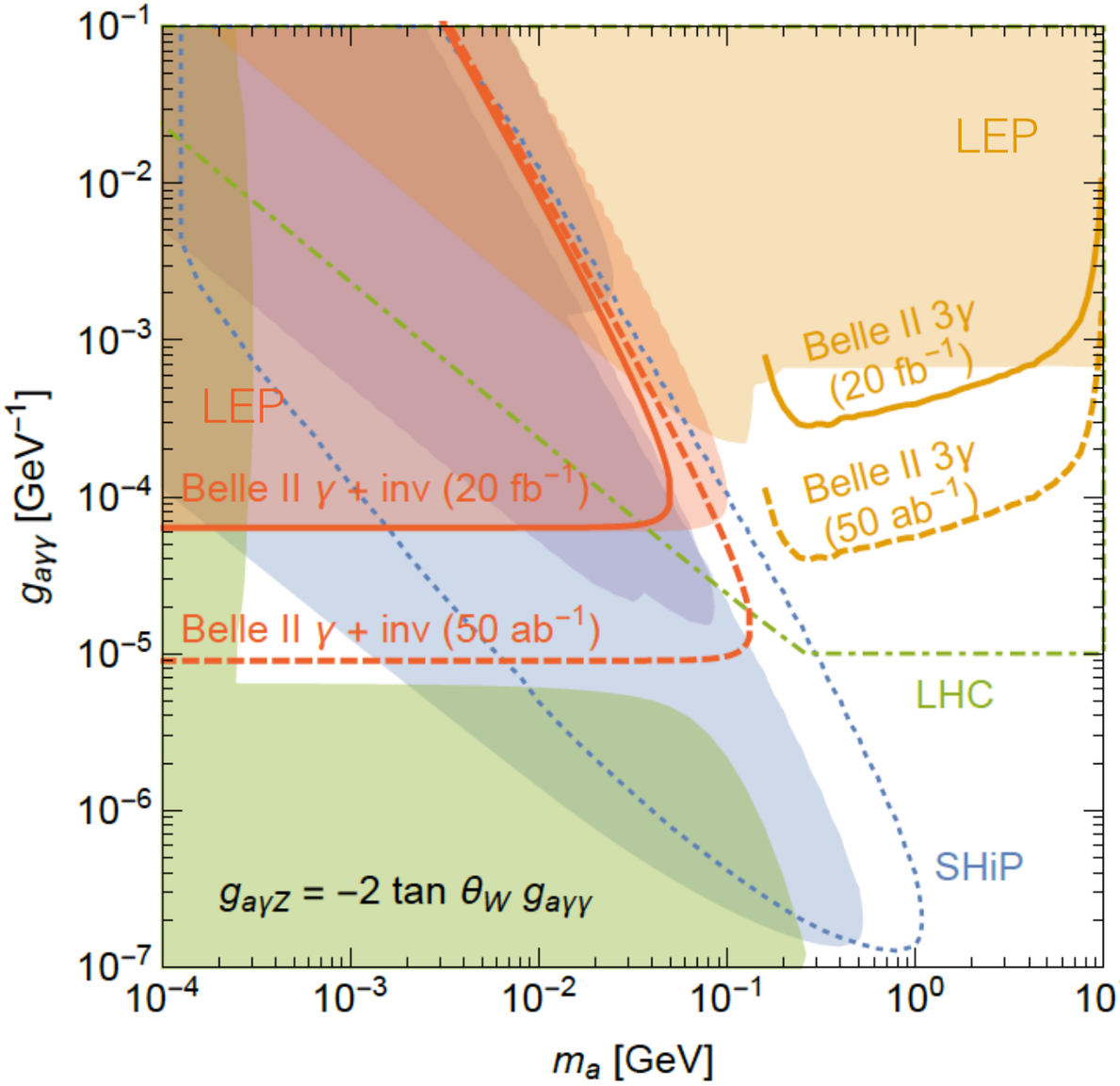


Nominal analyses veto long-lived topologies.

Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, submitted to JHEP(2017), arXiv:1709.00009

Search for Axion-like particles





Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, submitted to JHEP(2017), arXiv:1709.00009

Other DM Belle II searches

- Off-shell A′ decays
- Dark Photons decaying into pseudo-Dirac DM
- Muonic Dark Force: $e^+e^- \rightarrow \mu^+\mu^- A'$
  - $A' \rightarrow \mu^+\mu^-$
  - $A' \rightarrow$ invisible
- Dark Higgs
- Invisible Y(1S) decays via Y(3S) → Y(1S) $\pi^+\pi^-$
- Dark Scalar e+e- → $\tau^+ \tau^- S$, S → l^+l^-
- …

Other searches

- **Off-shell A′ decays**
- **Dark Photons decaying into pseudo-Dirac DM**
- Muonic Dark Force: $e^+e^- \rightarrow \mu^+\mu^- A'$
  - $A' \rightarrow \mu^+\mu^-$
  - **$A' \rightarrow$ invisible**
- Dark Higgs
- Invisible Y(1S) decays via $Y(3S) \rightarrow Y(1S)\, \pi^+\pi^-$
- Dark Scalar $e+e- \rightarrow \tau^+\tau^- S$, $S \rightarrow l^+l^-$
- **...**

*** possible during Phase 2**

Summary

- Different DM searches available with Belle II:
  - Dark photon searches
  - Axion-like particle searches
  - …

- Phase 2 data available in June 2018

- Belle II Physics Book* to be submitted for publication in the following months

*https://confluence.desy.de/display/BI/B2TiP+ReportStatus

Summary

- Different DM searches available with Belle II:
  - Dark photon searches
  - Axion-like particle searches
  - …

- Phase 2 data available in June 2018

- Belle II Physics Book to be submitted for publication in the following months

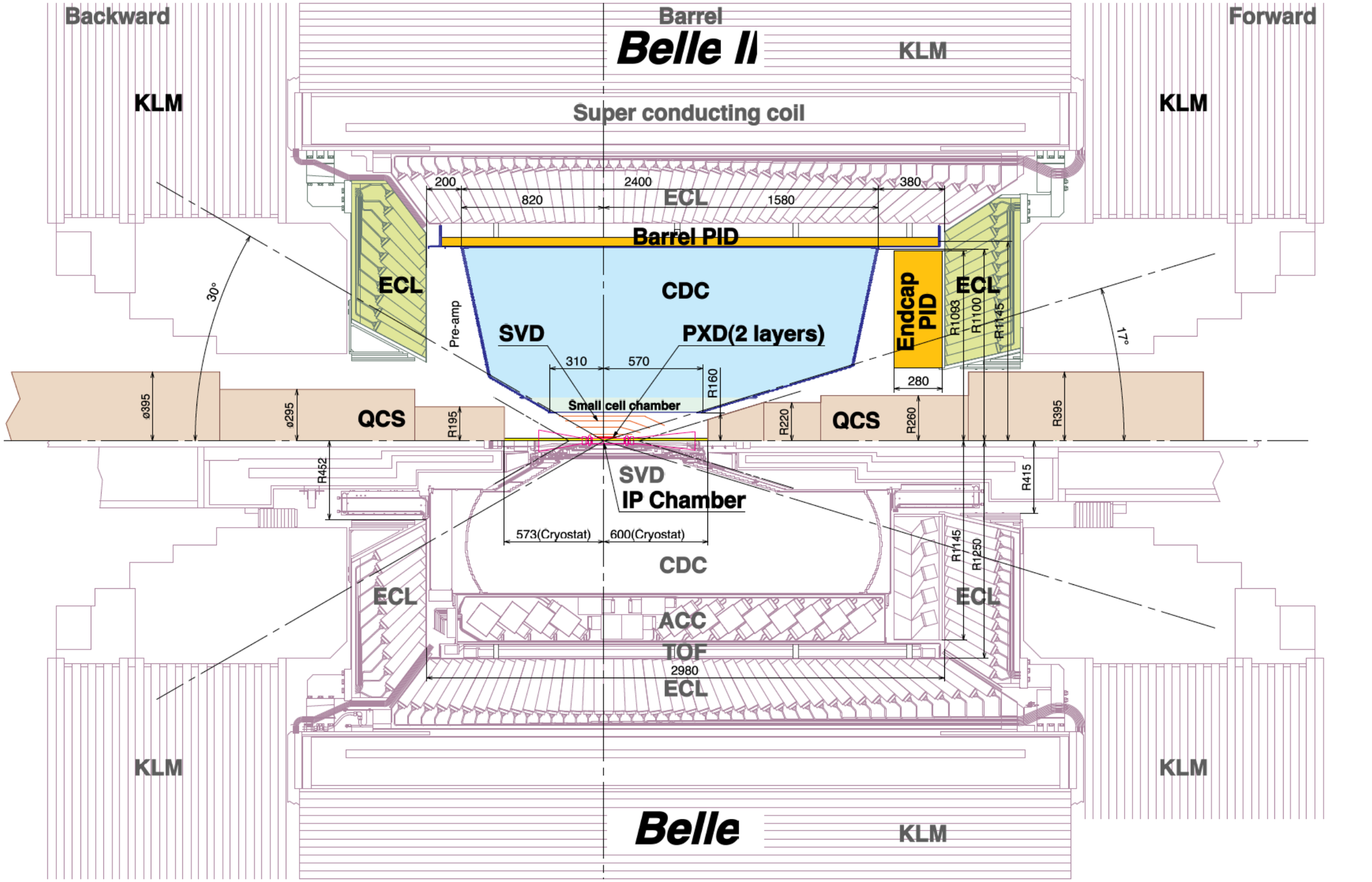
Thank you!

*https://confluence.desy.de/display/BI/B2TiP+ReportStatus

Backup

Belle II vs. Belle detector

SIDE VIEW



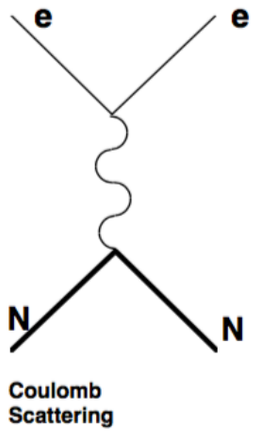
Belle II TDR, arXiv:1011.0352

Beam backgrounds at SuperKEKB

- Deterioration of detector resolution, damage to detector components
- Expected ~40-fold increase in beam backgrounds compared to KEKB
- Scattered e^-/e^+ hit the beam-pipe and create electromagnetic showers and neutrons
- Simulations used to get an estimate of background rates in each sub-detector

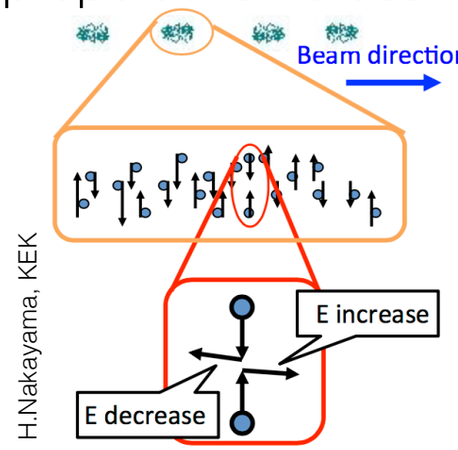
Beam-gas interactions

- Coulomb scattering of beam particles off of residual gas
- Bremsstrahlung
- Proportional to beam current



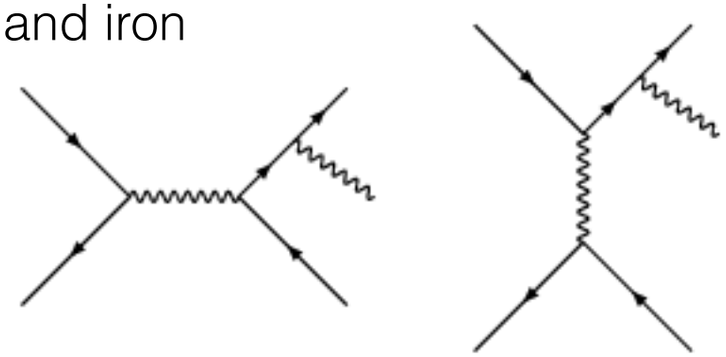
Touschek scattering

- Intra-beam scattering
- Scattering rate inversely proportional to beam size, proportional to beam current



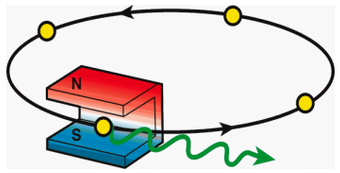
Luminosity backgrounds

- e^-e^+ Bhabha scattering
- Followed by photon emission
- Rate proportional to luminosity
- Neutrons copiously produced in a photo-nuclear reaction of photons and iron



Synchrotron radiation

- Collimators and shielding prevent scattered particles from reaching the detector



H.Nakayama, KEK

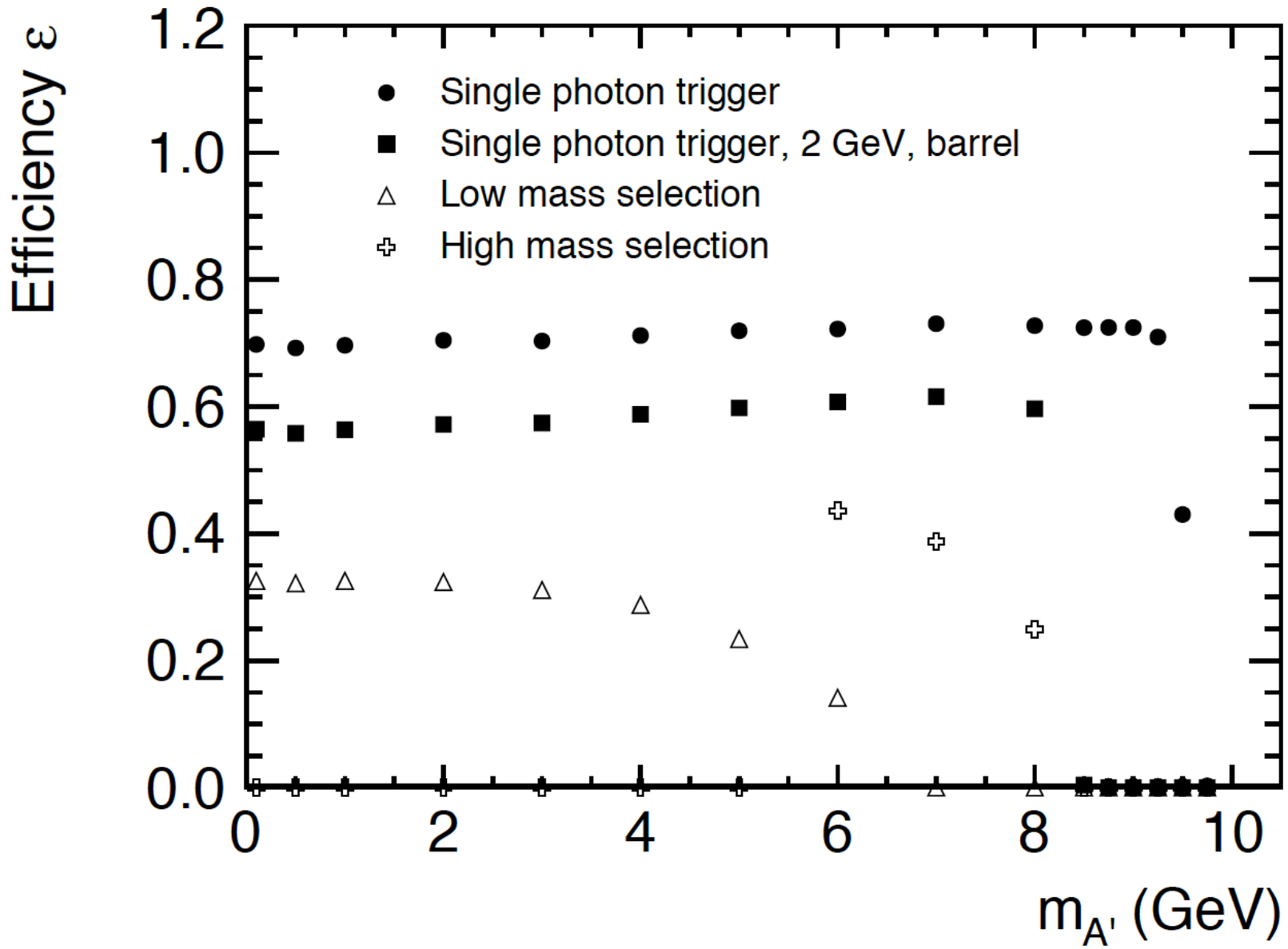
Injection background

- New particles injected every 100 ns
- Newly injected particles interact with existing beam particles
- Hard to simulate

Single-photon triggers

Trigger	γγ	Bhabha		Total
		both e have θ* > 1°	one e has θ* < 1°	
1 GeV* E*>1 GeV and second cluster E* < 0.2 GeV	0.2 nb	0.4 nb	1.6 nb	2.2 nb rate@1/40 lumi: 0.05 kHz rate@final lumi.: 1.76 kHz
2 GeV* E*>2 GeV and eclbhabhaveto and bhabhveto	0.5 nb	2.9 nb	0.1 nb	3.5 nb rate@1/40 lumi: 0.08 kHz rate@final lumi.: 2.80 kHz

Single-photon triggers



Axion-like particle triggers

Trigger	Total (γγ)
2 GeV* Barrel E*>2 GeV and polar angle in ECL barrel	1.7 nb rate@1/40 lumi: 0.03 kHz rate@final lumi.: 1.36 kHz
2 GeV* ECL E*>2 GeV and polar angle in ECL trigger acceptance excluding extreme endcaps	2.8 nb rate@1/40 lumi: 0.06 kHz rate@final lumi.: 2.24 kHz