a place of mind

UBC

INSTITUTE OF PARTICLE PHYSICS

Dark sector/dark matter searches at BaBar and outlook for Belle II

Christopher Hearty
U. British Columbia / IPP
October 5, 2018

Third biennial workshop on dark interactions, BNL

On behalf of the BaBar and Belle II collaborations

Outline

- Search for doubly strange stable six-quark states at BaBar
- Dark photon and Z' searches at BaBar
- Belle II status
- Belle II projections for single photon analysis and Axion-like particle search

Search for a stable doubly-strange six-quark state at BaBar

Six-quark states

- G. Farrar has noted that the 6-quark state uuddss [Q=0, B=2, S=-2] is allowed by QCD, and could be the astronomical dark matter.
  - Not everyone agrees that it could be dark matter.

G. R. Farrar, arXiv:1708.08951 [hep-ph]; arXiv:1805.03723 [hep-ph]

EW Kolb & MS Turner, arXiv:1809.06003

- This is not Jaffe's H-dibaryon, which had mass ~2150 MeV and a typical weak lifetime.
  - many unsuccessful searches.

R. L. Jaffe, PRL 38, 195 & PRL 38, 617 (1977)

- The six-quark state (S) is absolutely stable if
  $m_S < 2(m_p + m_e) = 1878$ MeV.

- Cosmologically stable if
  $1878 < m_S < (m_\Lambda + m_p + m_e) = 2055$ MeV.

- Production in Υ decay is expected to be enhanced.
  Our search: $\Upsilon \rightarrow S\bar{\Lambda}\bar{\Lambda}$.
  - reconstruct only the two Λ's.
  - look for $m_S < 2050$ MeV in recoil.
  - 90×10^6 $\Upsilon(2S)$ and 110×10^6 $\Upsilon(3S)$.

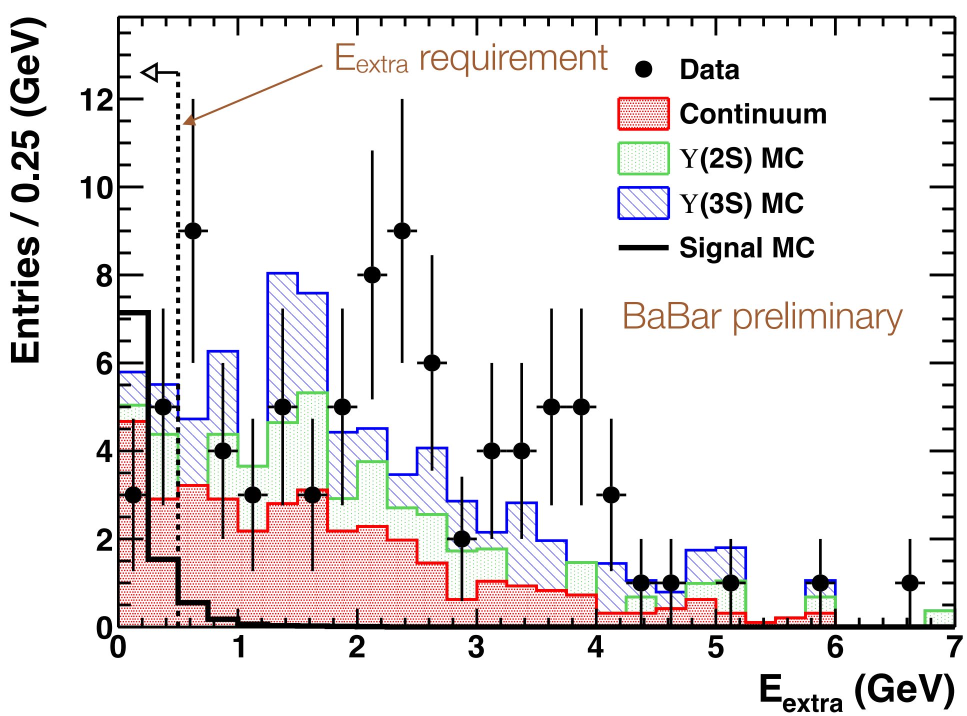
Event selection

- Select two $\Lambda \rightarrow p\pi^-$ (same strangeness) + up to 1 extra track (material interactions).

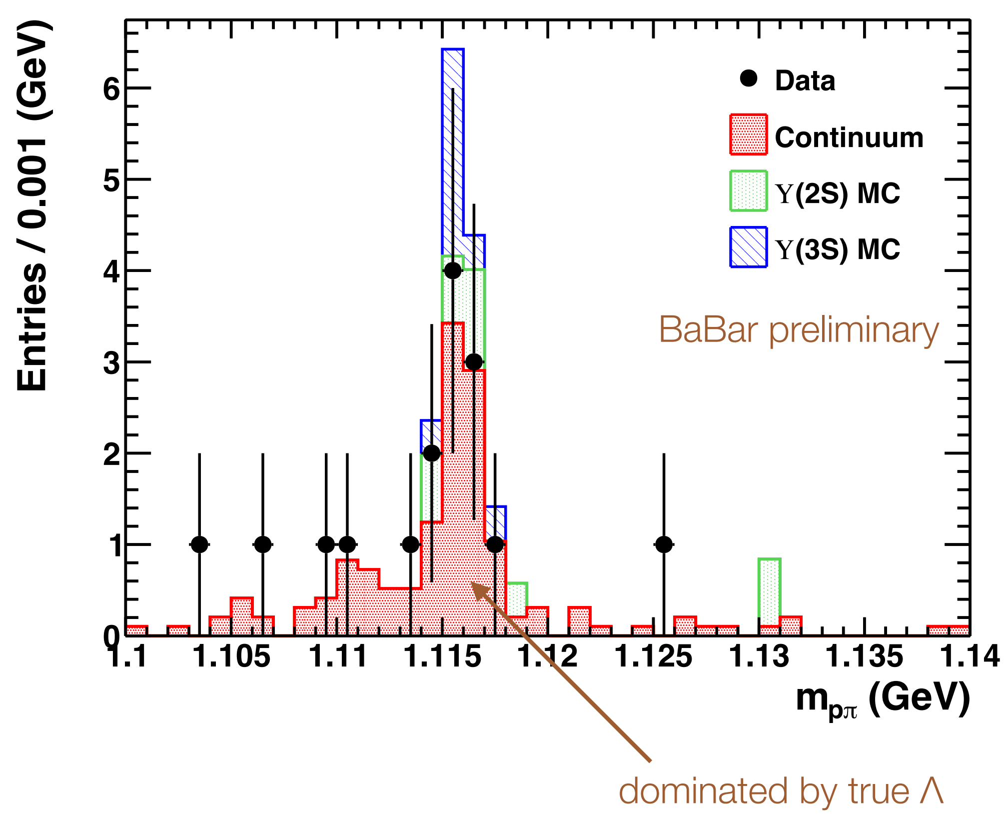
- Λ satisfy proton ID, mass cut, flight significance, flight angle.

- Extra energy in calorimeter < 0.5 GeV, excluding splitoffs from protons and clusters from possible S interactions.
  - S interaction cross section < neutron cross section.

Eextra distribution



Λ candidate mass after Eextra requirement



- Finally, fit both Λ's to pdg mass and to a common production point in the beam spot (leaves 4 events).

- Signal = excess in mass² recoiling against the two Λ.
  - ~2.5 GeV² window centered on the m_S^2 hypothesis.

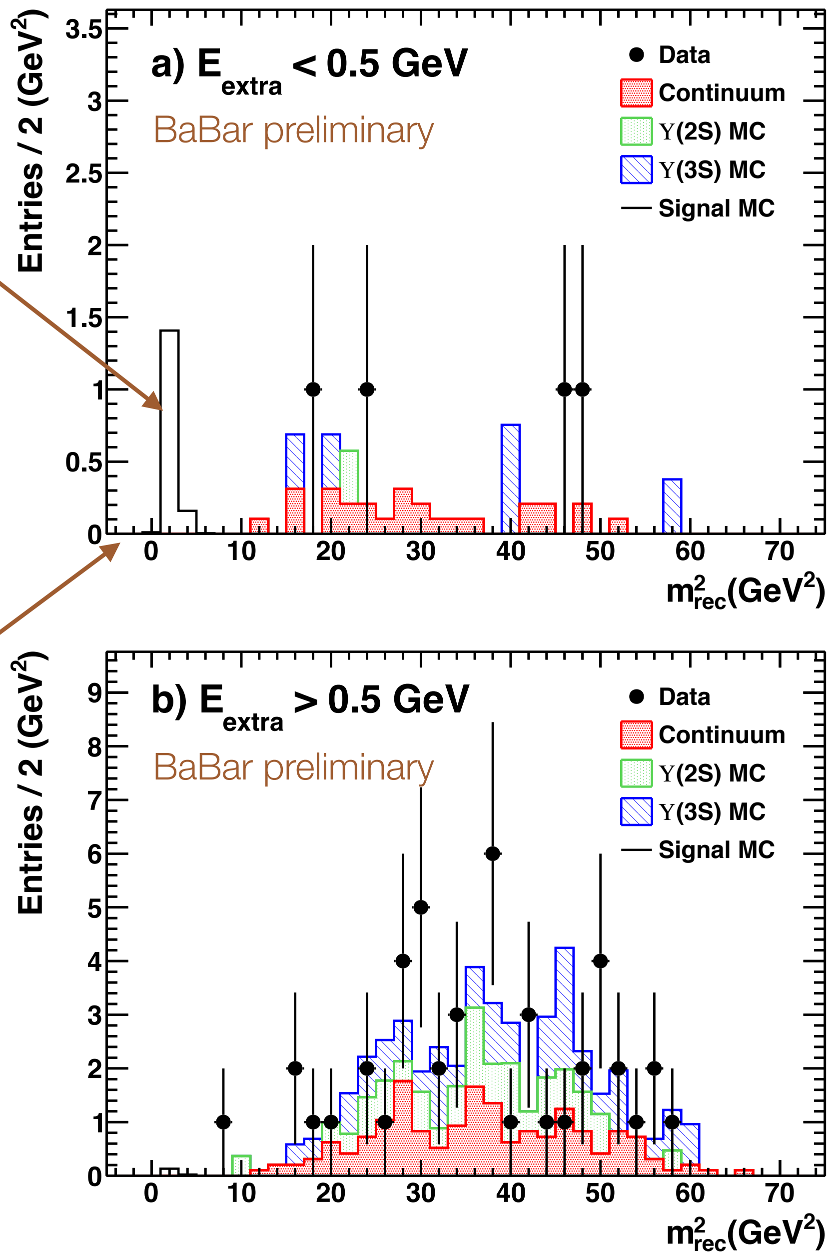
Backgrounds

- Background sources: continuum or Υ decay.
- Continuum: signal branching fraction of Υ(4S) is negligible; no background from B decay ⇒ data recorded at 10.58 GeV can be treated as pure continuum.
- Υ decay: scale Υ(2S, 3S) MC so that MC + continuum (10.58 GeV) matches E_{extra}>0.5 GeV sideband.
- Remaining background ~$\Lambda\Lambda\bar{\Lambda}\bar{\Lambda}(X)$

$$\Lambda \to n\pi^0, \quad \Lambda \to n\pi^0$$

} passes or fails E_{extra} cut

Recoil mass² distribution



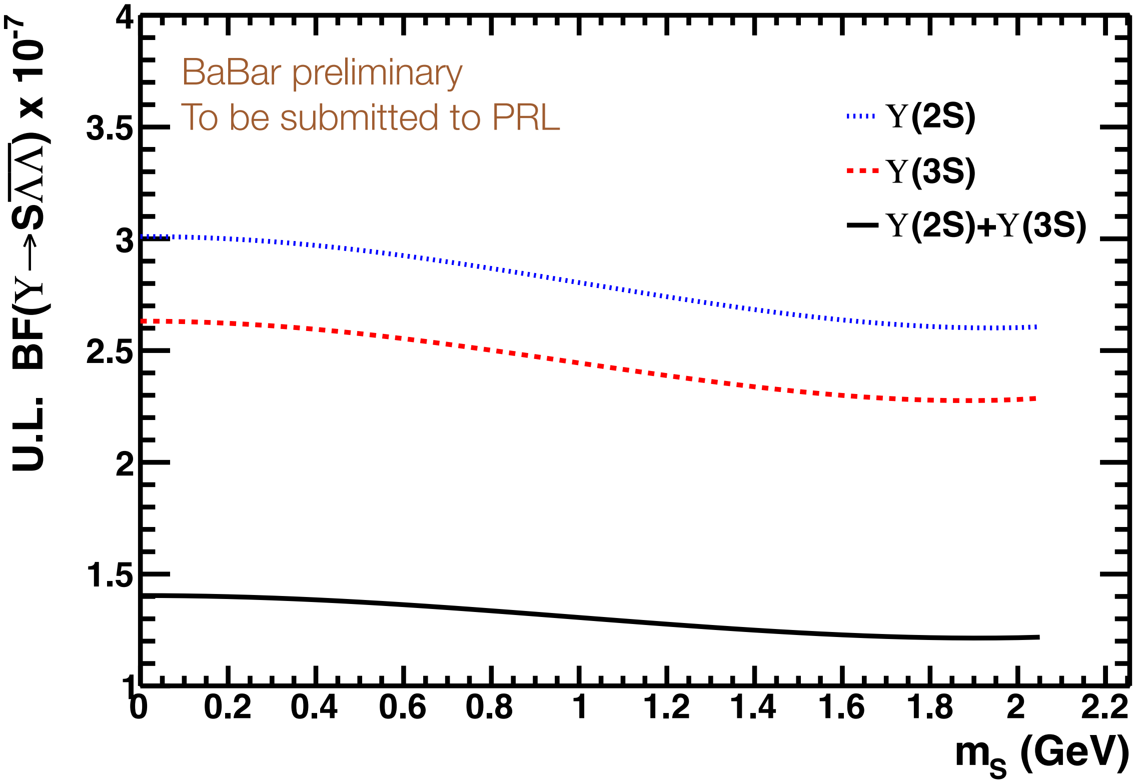
Final event sample

Fails E_{extra} cut (sideband)

signal for m_s = 1.6 GeV, BF = 1 × 10^{-7}

Negligible background in signal region, estimated from E_{extra}>0.5 events

- Efficiency 7.2% — 8.2%. Systematics:
  - angular distribution (4% — 15%),
  - interaction cross section (8% — 10%).



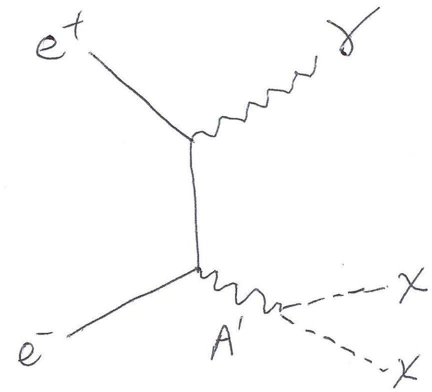
combined upper limit assuming same partial width

- No evidence for a six-quark state in $\Upsilon \rightarrow S\bar{\Lambda}\bar{\Lambda}$.
  Upper limit on branching fraction is (1.2 — 1.4) × 10^{-7}.

BaBar single photon analysis

- Analysis optimized for and interpreted in terms of a dark photon A′ decaying invisibly.

$$E^*_\gamma = \frac{\sqrt{s}}{2} - \frac{m^2_{A'}}{2\sqrt{s}}$$

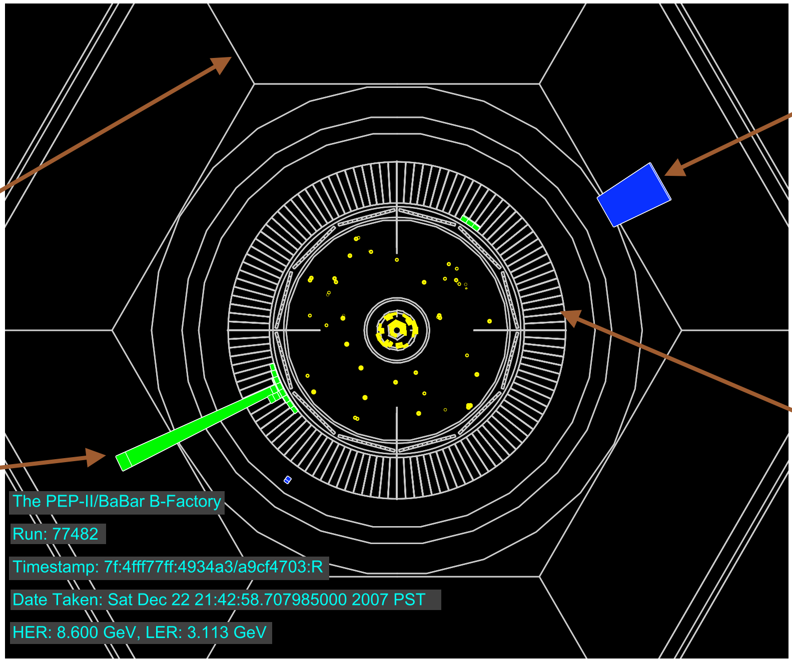


- On-shell A′ ($m_\chi < m_{A'}/2$) ⇒ monoenergetic photon.
  - Analysis not sensitive to m_χ or the χ / A′ coupling.

- Uses ~50 fb^{-1} recorded with single γ trigger in final BaBar running period.

Backgrounds

- $e^+e^- \rightarrow \gamma\,\gamma$ event



photon shower detected in muon system. Inefficiency produces single photon events.

no efficiency in muon system near sector boundaries

beam-energy photon shower

azimuthal gaps between crystals align with collision point

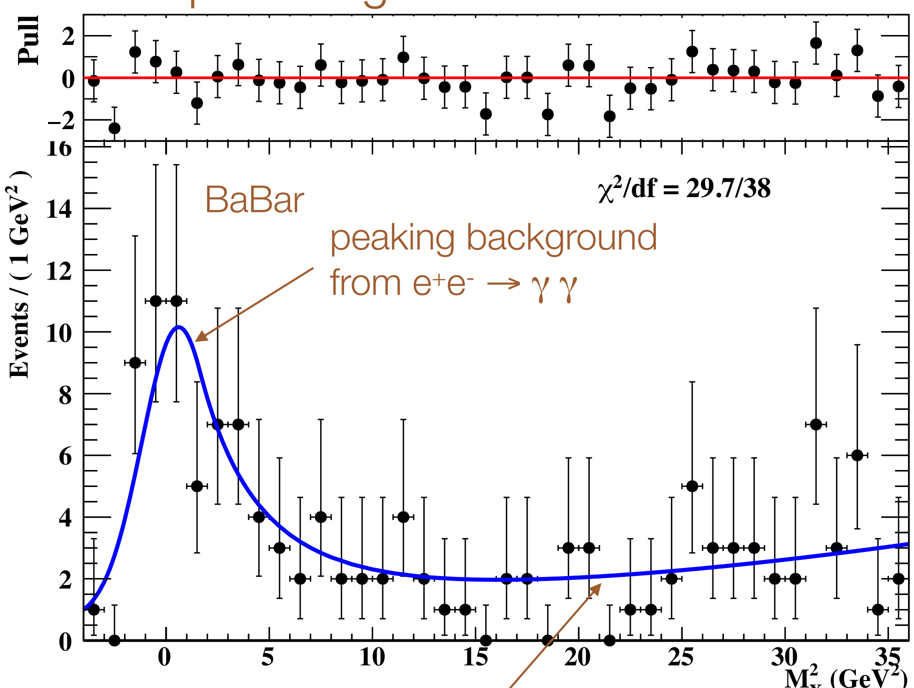
- Could include additional ISR γ down beam pipe.

- Also $e^+e^- \rightarrow e^+e^-\gamma$, neither $e^\pm$ in detector.

- Select events with a boosted decision tree. Exploits correlation in direction of observed and missed photons in $\gamma\gamma(\gamma)$ final state.

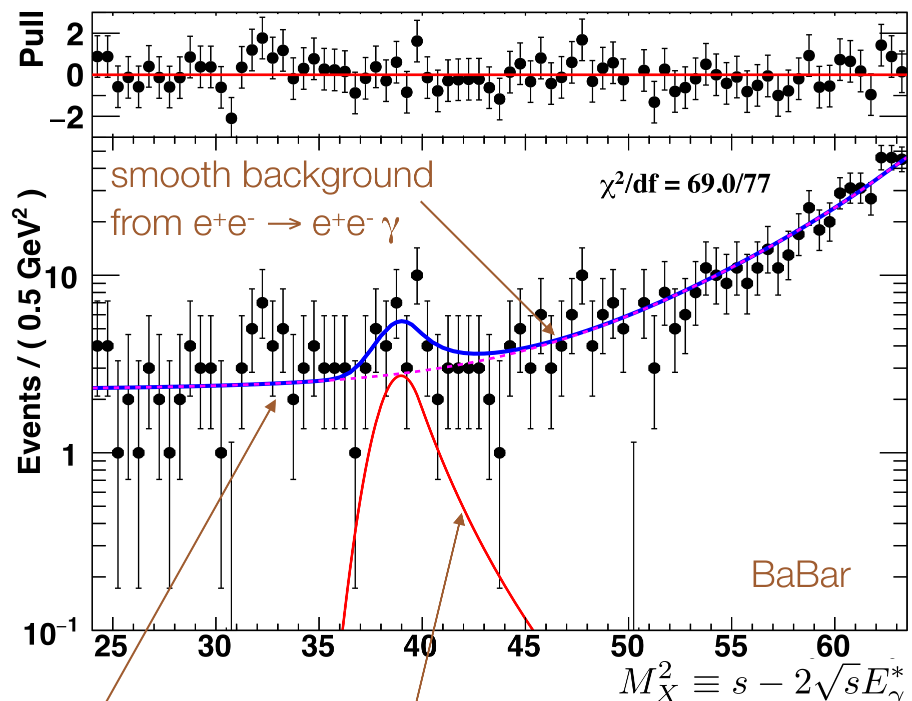
- Fit $M_X^2 \equiv s - 2\sqrt{s}E_\gamma^*$ distribution; float signal, peaking background, and smooth background yields.

Low-mass, Υ(3S) data, loose selection
- separate tight selection not shown



background-only fit

High-mass region, Υ(2S)+Υ(3S)

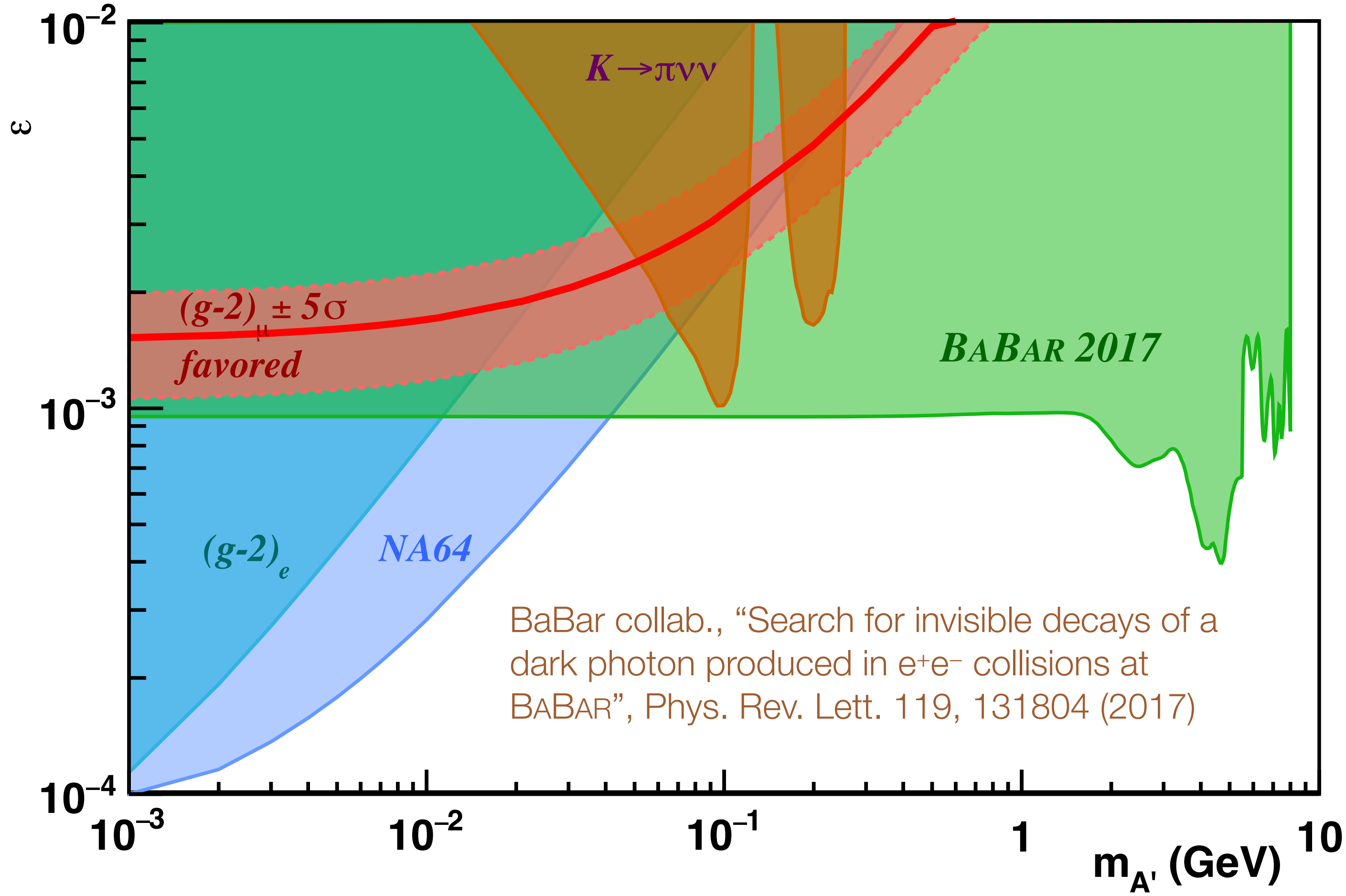


background + signal fit;
most-significant peak

signal component

BaBar exclusion region for invisible decays of a dark photon

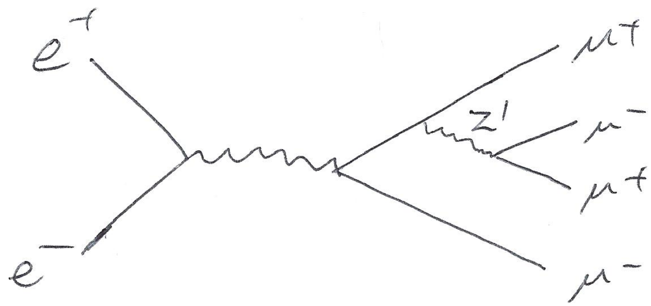
- Excludes region that explains $(g\text{-}2)_\mu$.



BABAR collab., "Search for a muonic dark force at BABAR", Phys. Rev. D94, 011102(R) (2016)

Search for muonic dark forces at BaBar

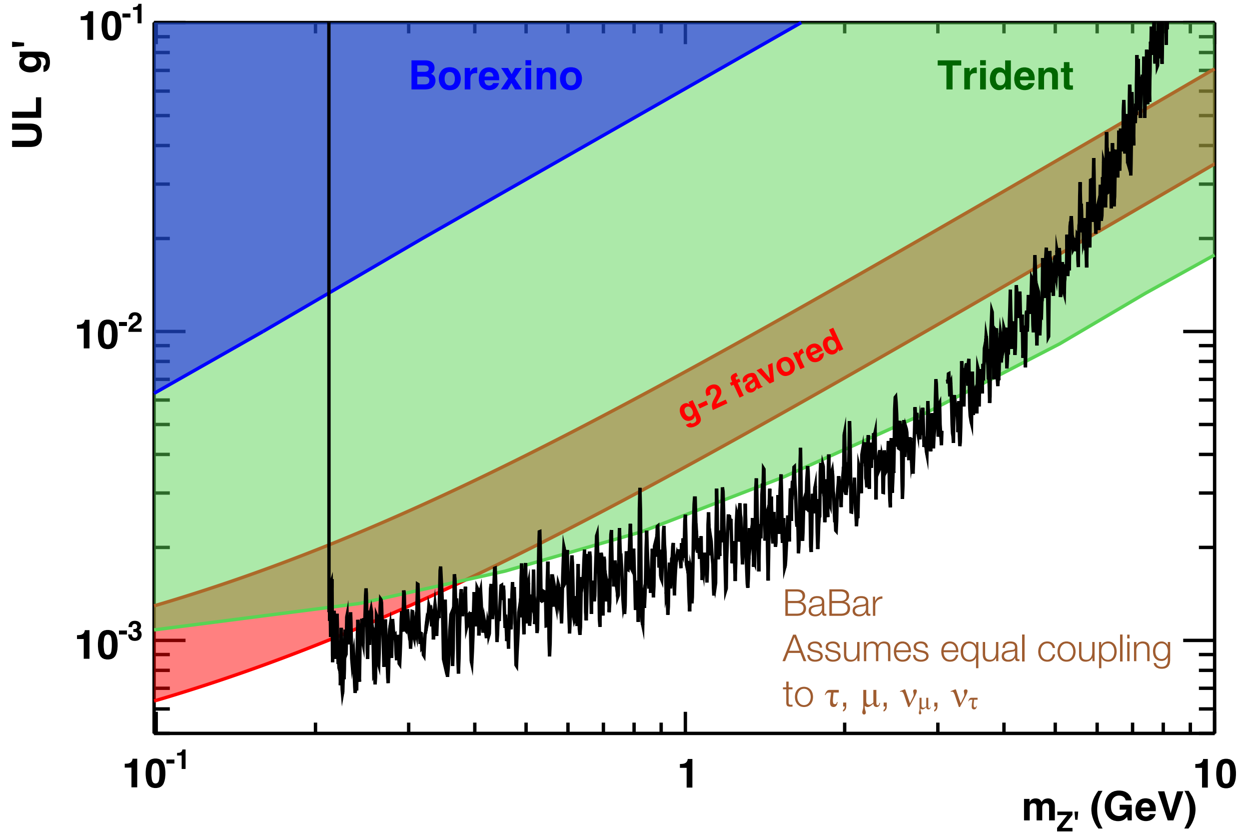
- Dark gauge boson Z′ couples only to 2nd and 3rd generations. Few experimental constraints.



He, Joshi, Lew, Volkas, Phys. Rev. D 43, R22 (1991)

final state = 4 muons

- No evidence for a signal (narrow peak in $\mu^+\mu^-$ spectrum).



- Can also interpret result in a leptonic Higgs model.
  - tau pair final state is then preferred.

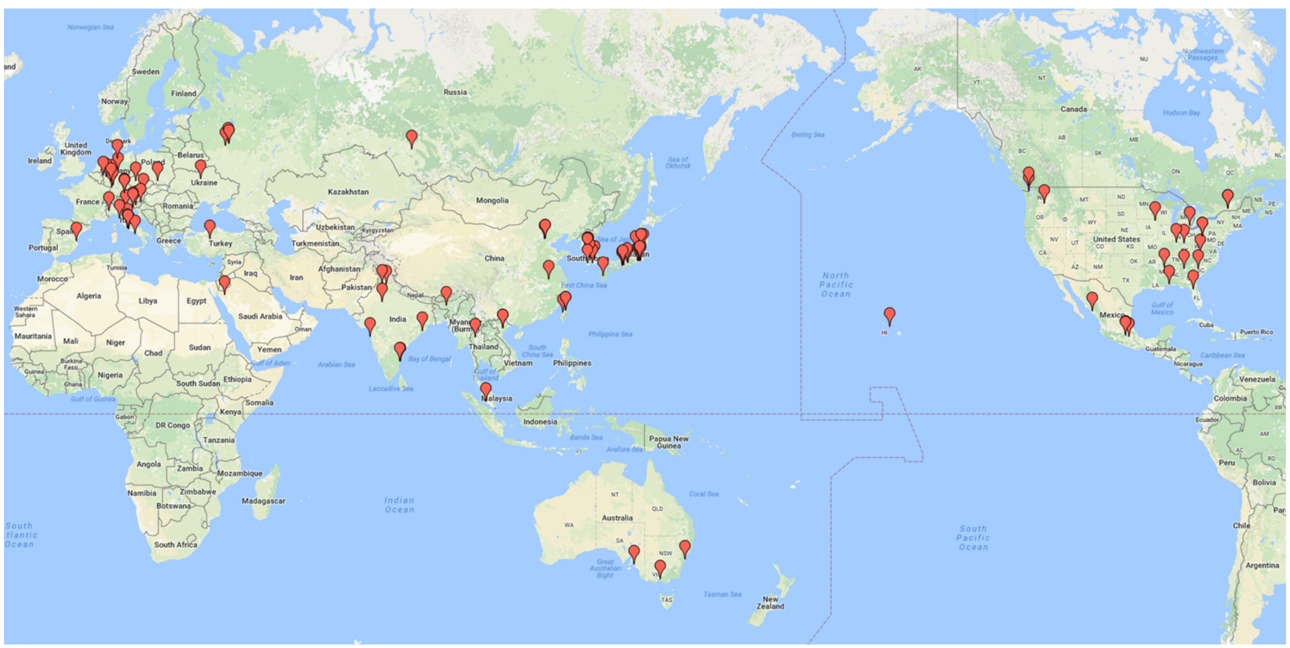
Batell, Lange, McKeen, Pospelov & Ritz,
Phys. Rev. D95, 075003 (2017)

Belle II status

Belle II experiment

- Located at SuperKEKB e^+e^- collider. Goal is 100× data set collected by BaBar, 30× combined BaBar+Belle.

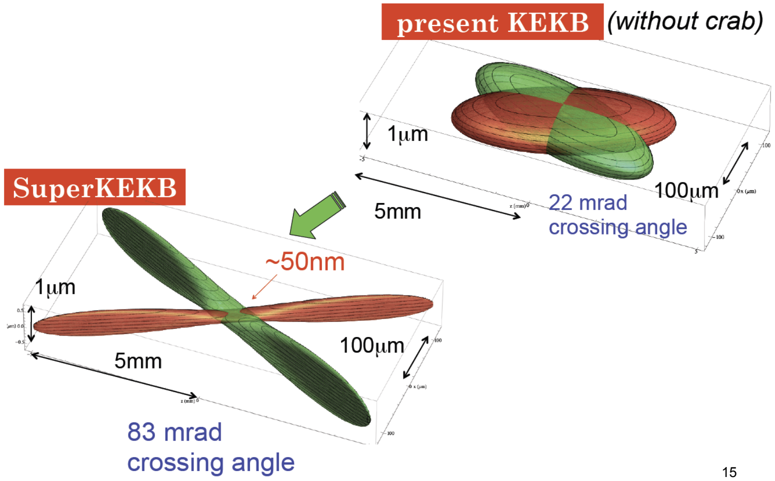
- 23 countries, 100 institutions, 395 PhD physicists, 280 graduate students.



Phase 2 commissioning

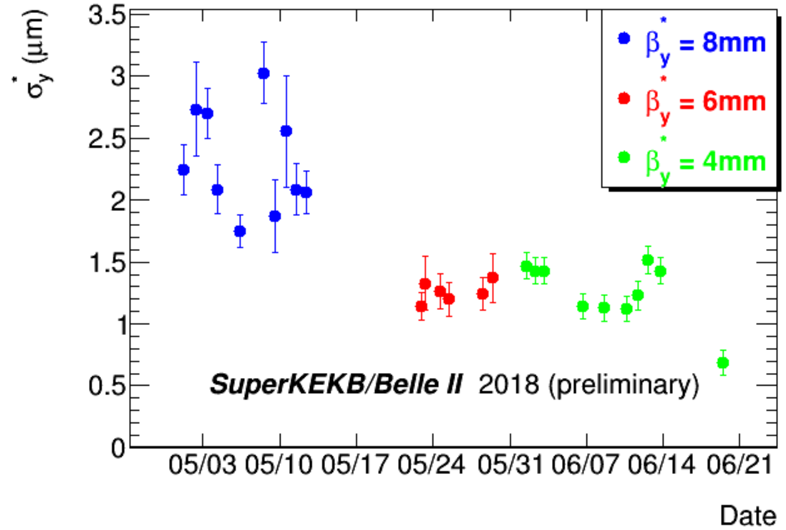
- SuperKEKB commissioning run with colliding beams. April – July 2018. Full Belle II outer detector, but only samples of vertex detectors.

- Goals:
  - peak luminosity $>10^{34}$ $cm^{-2}s^{-1}$ (KEKB design) to verify nanobeams
  - check that background levels are safe to install vertex detectors.

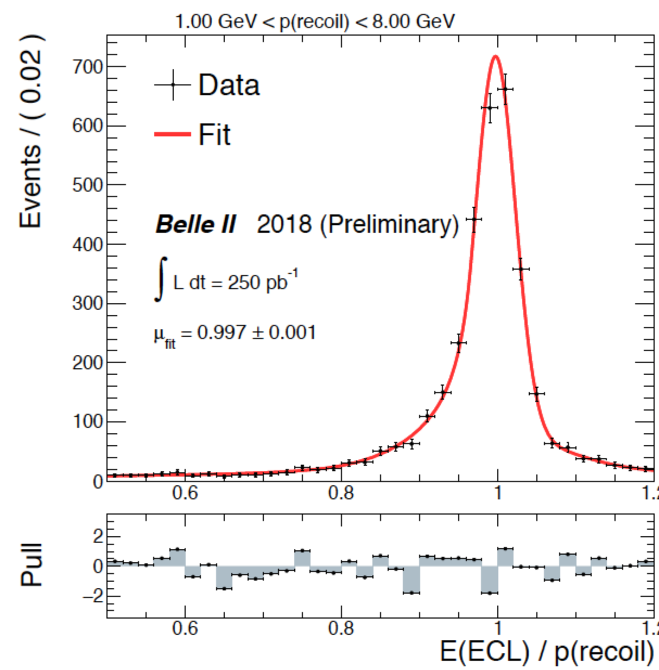


- Per-bunch luminosity goal achieved with vertical size < 1μm.
- Backgrounds are still under study, but are low enough to install vertex detectors.
  - only 1 layer of pixels available.
- Integrated luminosity = 0.5 fb^{-1}, enough to start detector commissioning / calibration.
- Phase 3 commissioning starts March 2019.

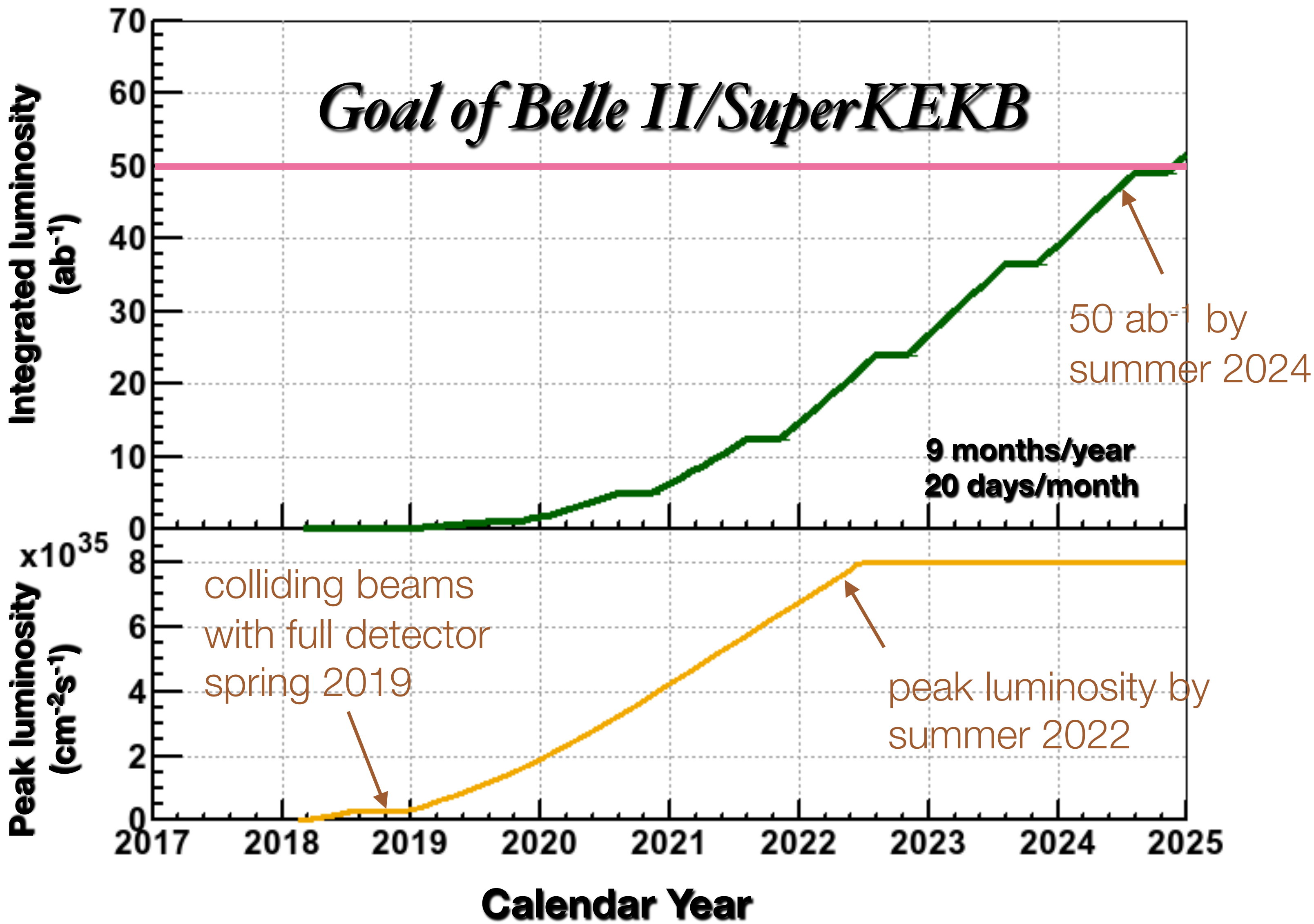
Beam size from beam-beam scans



photons from $e^+e^- \to \mu^+\mu^-\gamma$



SuperKEKB luminosity projection



Belle II single photon analysis

- Key to improving BaBar limits at low mass is reducing and constraining the peaking background from $e^+e^- \rightarrow \gamma\gamma$. Should be lower than BaBar; gaps between calorimeter crystals are not projective.
- Reasonable progress in using Phase 2 data to calibrate MC modelling of γ inefficiency in the calorimeter. Less work in understanding efficiency of the muon system in detecting γ that punch through the calorimeter.

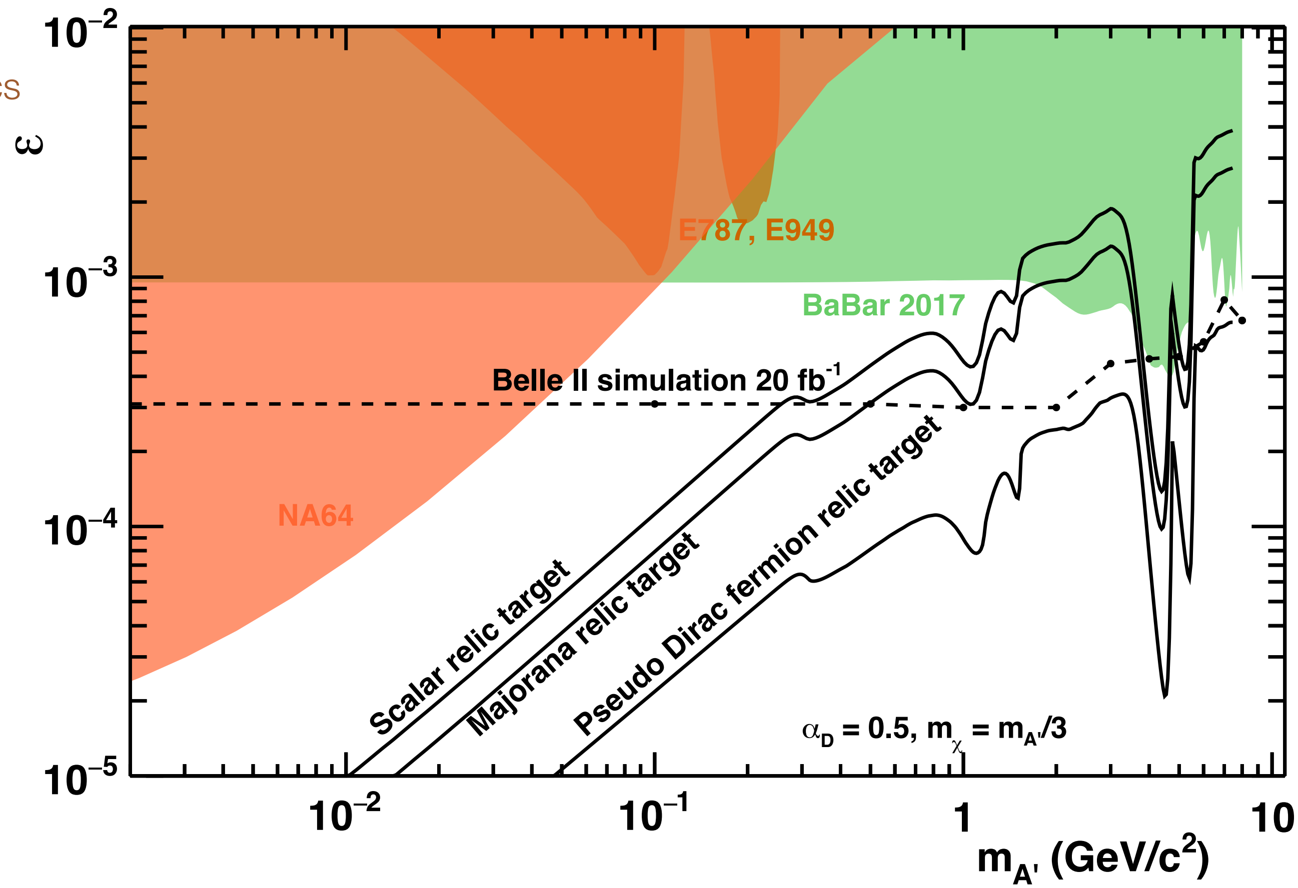
- At higher A′ masses, larger calorimeter coverage suppresses radiative Bhabhas compared to BaBar:
  $-0.94 < \cos\theta^* < 0.96$ Belle II
  $-0.92 < \cos\theta^* < 0.89$ BaBar

- Good trigger efficiency in Phase 2 for $E_\gamma > 1.2$ GeV. Will retain this low threshold for 2019.

Projected Belle II exclusion region, 20 fb^{-1}

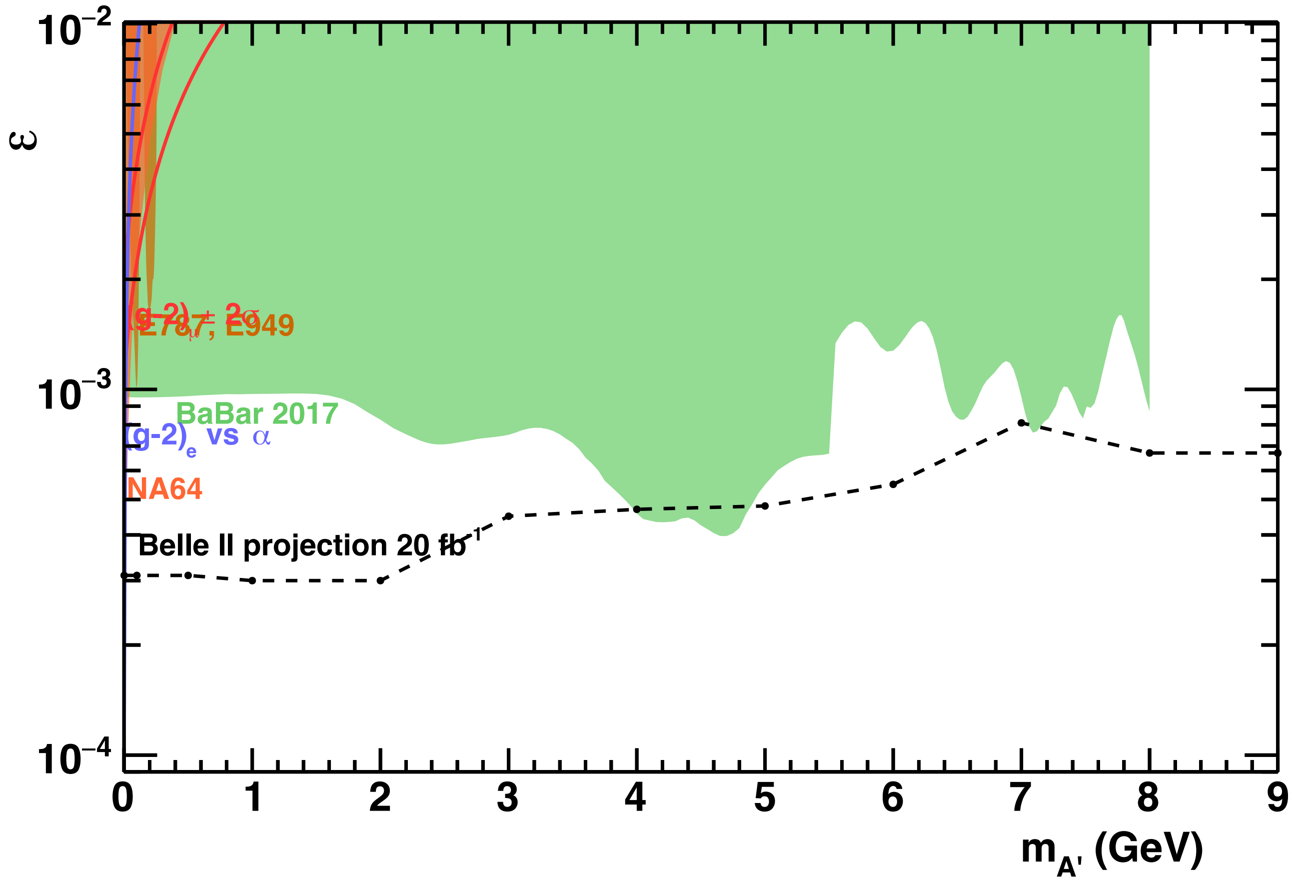
Belle II Collaboration, “The Belle II Physics Book,” arXiv:1808.10567 [hep-ex]

Relic curves derived from E. Izaguirre, G. Krnjaic, P. Schuster, N. Toro, Phys. Rev. Lett. 115, 251301 (2015)



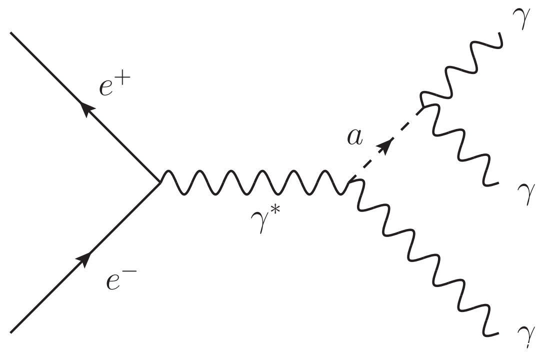
- Extrapolation to higher luminosity is not clear. Need to control systematic error on photon efficiency.

Projected Belle II exclusion region, 20 fb^{-1}



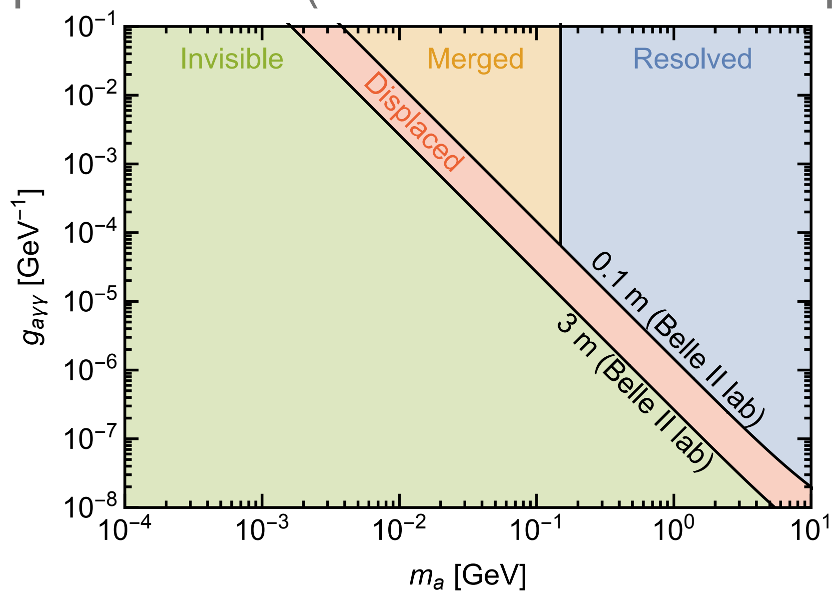
Belle II search for Axion-like particles (ALP)

- Search for ALP decaying to $\gamma\gamma$. 3γ final state, but at low mass, photons may overlap in the calorimeter.

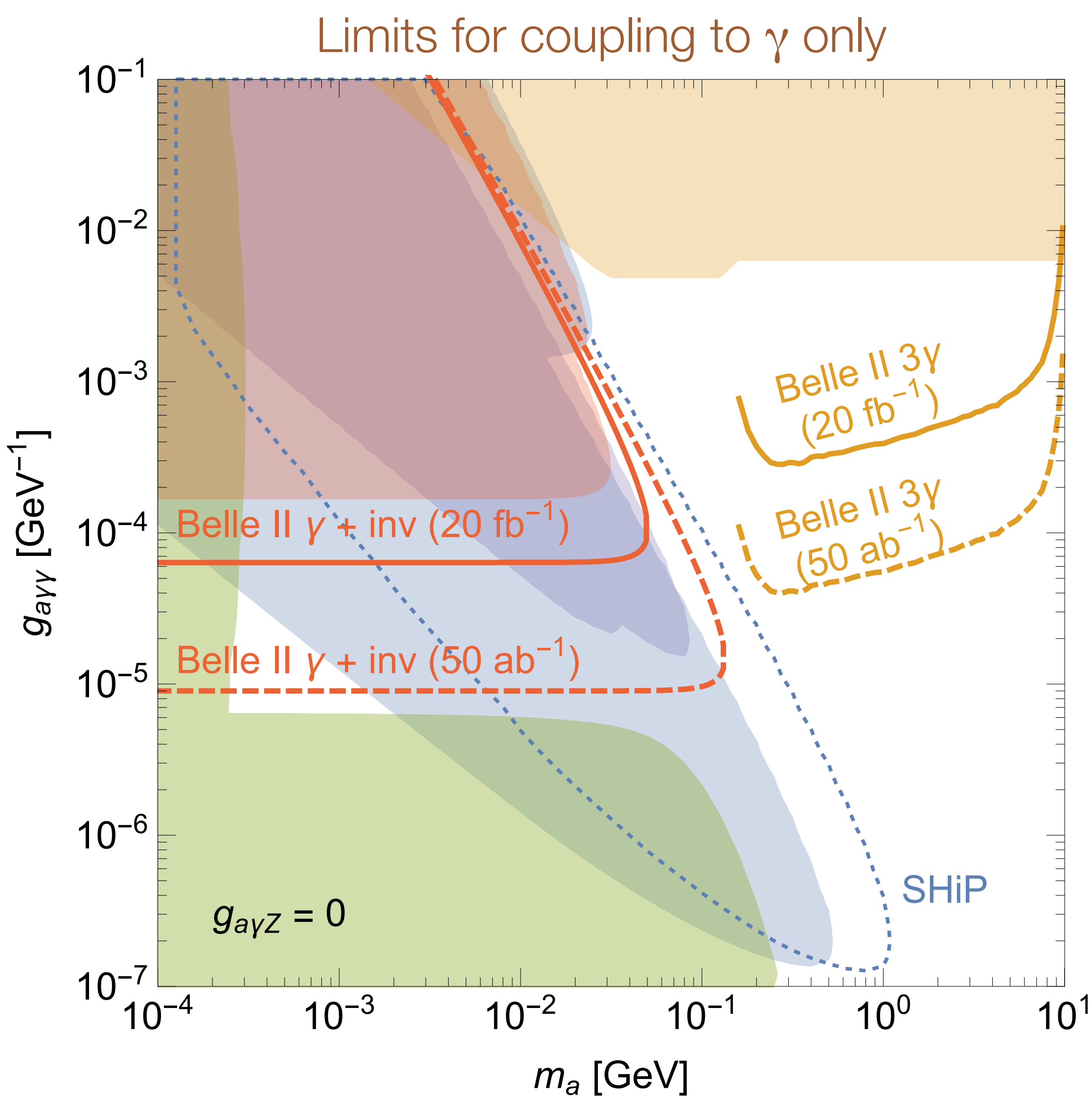


- Can appear to be $e^+e^- \to \gamma\gamma$ in the level 1 trigger. So far, we have not had to prescale (Belle had 100× prescale).

Different experimental signatures for $e^+e^- \to a\gamma$ search



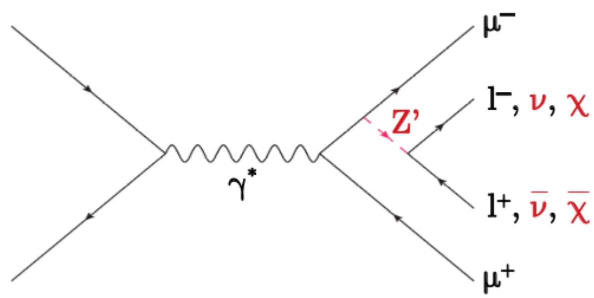
- Interesting limits are possible with a small dataset.



Dolan, Ferber, Hearty, Kahlhoefer & Schmidt-Hoberg, "Revised constraints and Belle II sensitivity for visible and invisible axion-like particles," JHEP 1712, 094 (2017)

Belle II search for $Z' \rightarrow$ invisible

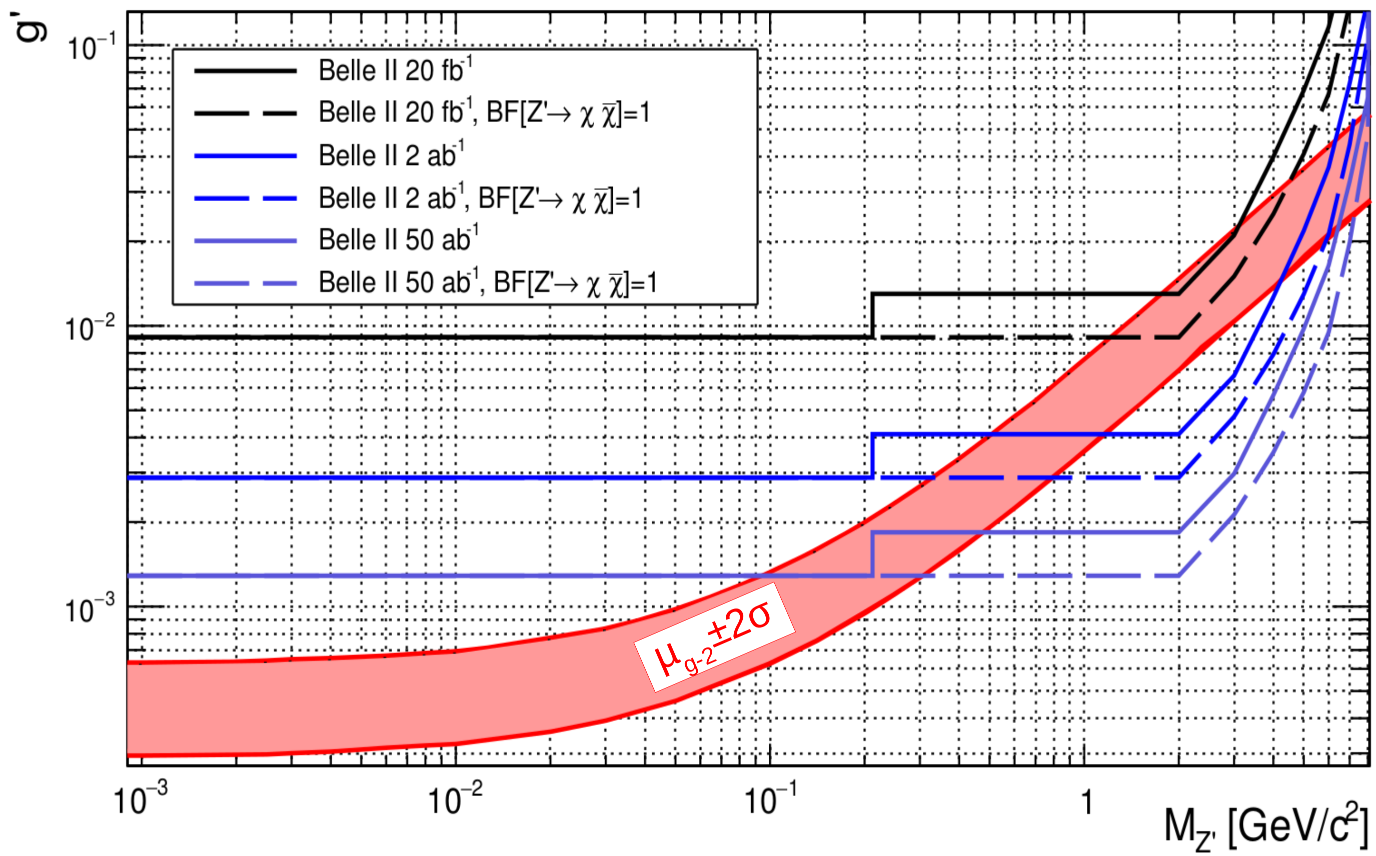
- Low mass Z' decays 100% to neutrinos.
  - alternatively, assume 100% to $\chi\bar{\chi}$ for all masses.



- Select muon pair events with missing momentum vector pointing at barrel calorimeter, and look for a bump in the recoil mass.

- Significant background from $e^+e^- \rightarrow \tau^+\tau^-$.

- Difficult to exclude $(g\text{-}2)_\mu$ band, even with full luminosity. But even a small dataset will allow us to set new limits.



Summary

- BaBar has found no evidence for a stable six-quark bound state in Upsilon decay.
- Belle II has started commissioning of outer detectors with first colliding beam data. First data with full detector will be March 2019.
- Even a relatively small data set will enable interesting dark sector searches by Belle II.

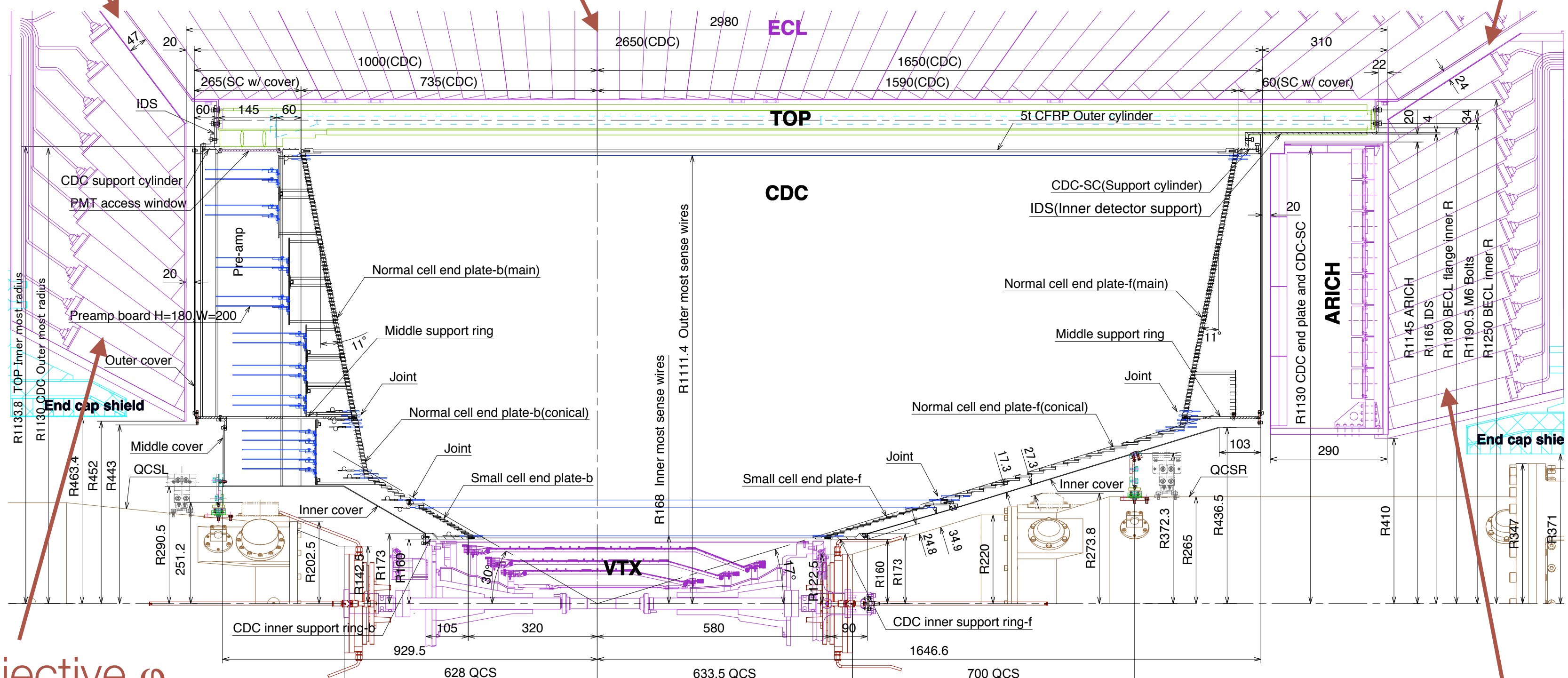
Backup

Sources of calorimeter inefficiency (in order of importance)

1. barrel/endcap gap

4. 1.5mm structure at 90°

2. barrel/endcap gap

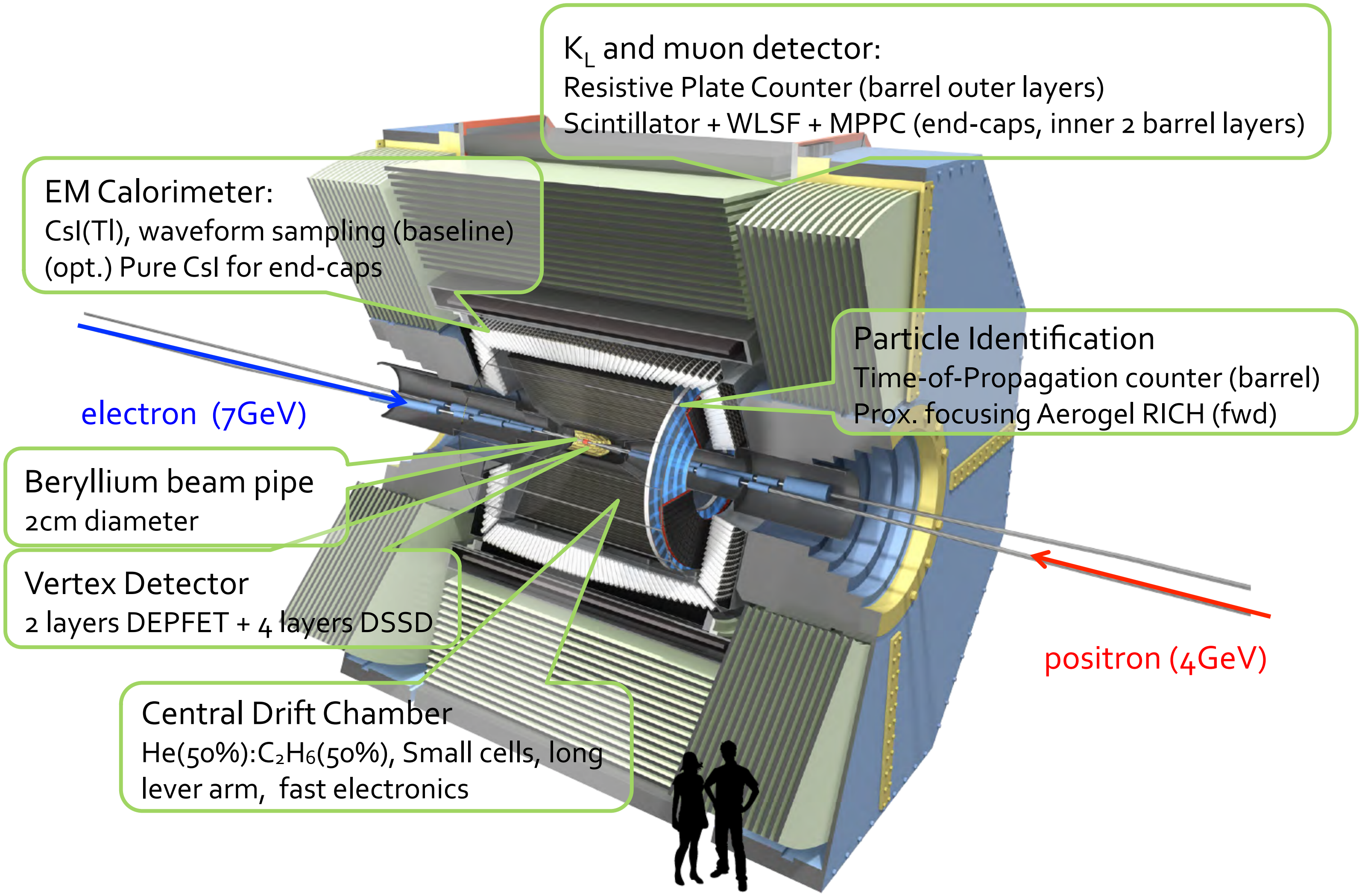


3. projective φ cracks in endcaps

3. projective φ cracks in endcaps

5. γ non-conversion 3 × 10^{-6}

The Belle II detector

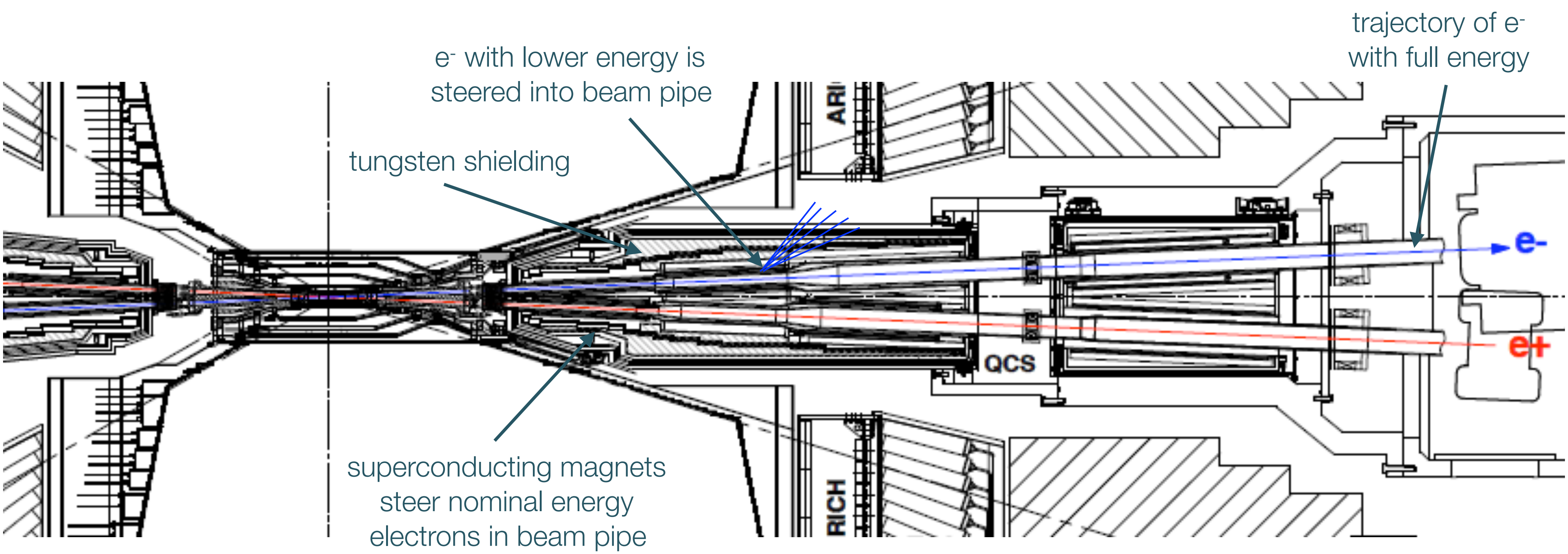


- Reusing solenoid, iron, part of muon system, calorimeter crystals. Remainder optimized for rates and high backgrounds

Beam backgrounds — the major experimental challenge

- Beam backgrounds are particles in the detector (typically low-energy γ and n) not due to the event of interest.

  Biggest source is radiative Bhabhas, $e^+e^- \rightarrow e^+e^-\gamma$.



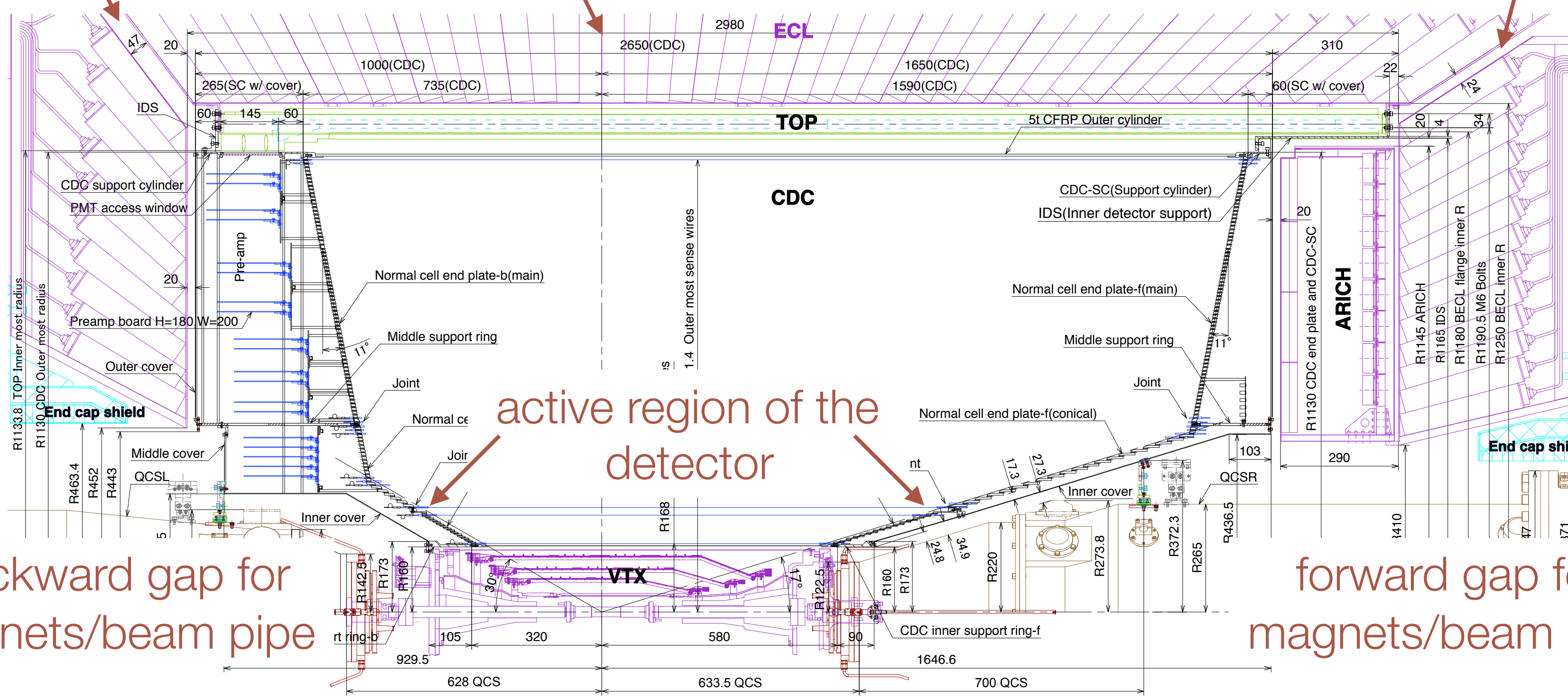
- Despite shielding, many 1—2 MeV photons reach the detector.

Sources of detector inefficiency

barrel/endcap gap

1.5mm structure at 90°

barrel/endcap gap

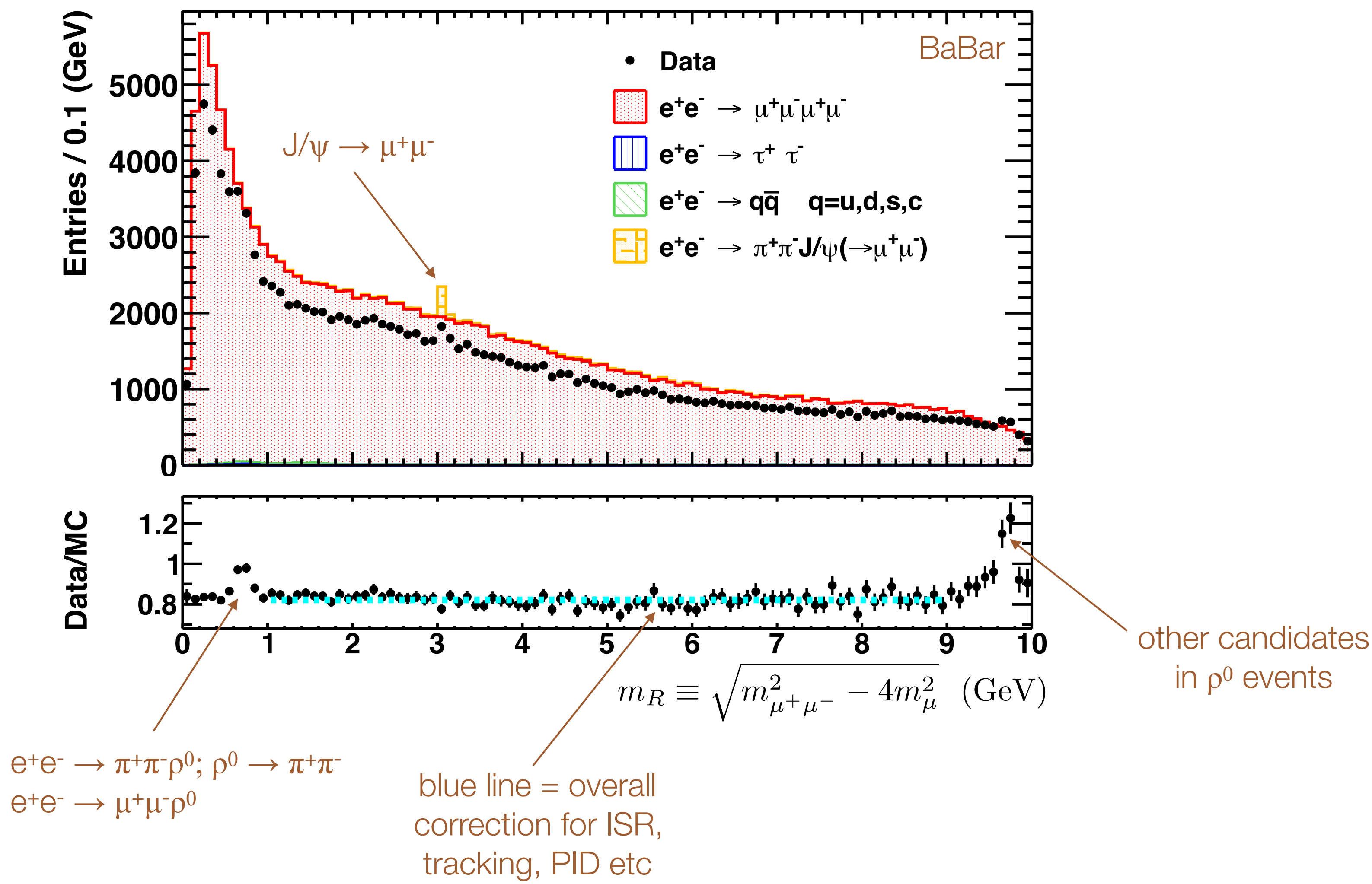


active region of the detector

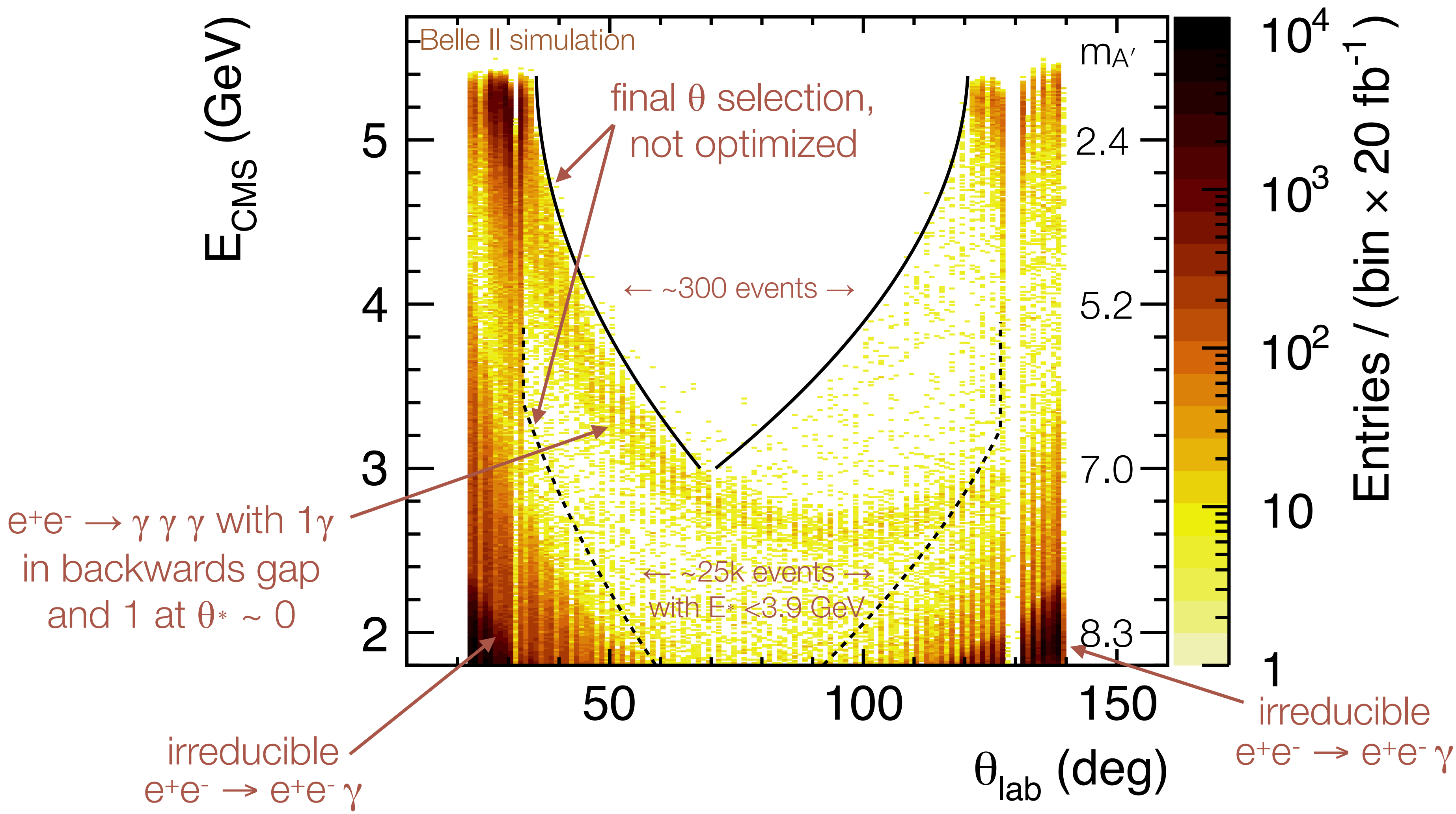
backward gap for magnets/beam pipe

forward gap for magnets/beam pipe

- Plot all four $\mu^+\mu^-$ mass combinations per event, and look for a narrow peak on a smooth background.



- Simulated backgrounds, 20 fb^{-1}. Final sample is almost entirely $e^+e^- \to \gamma\,\gamma\,(\gamma)$ with $\geq 3\gamma$.



- Low mass region has both peaking and smooth backgrounds. Select data using two statistically independent cuts on BDT and θ.