Search for Dark Particles at Belle and Belle II

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for the Belle and Belle II Collaborations

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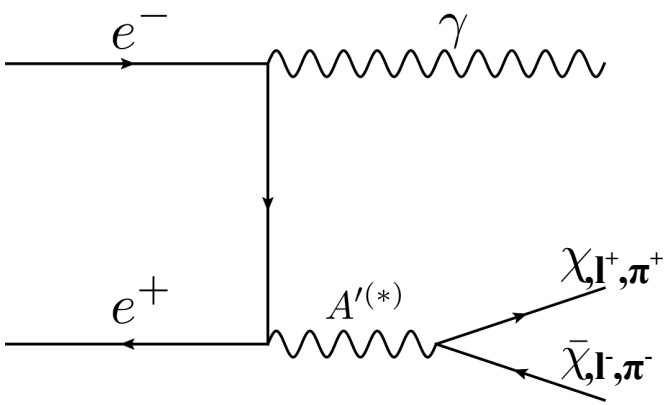
Dark matter represents about 80% of all matters

- Dark matter naturally explained by Supersymmetry, but
- Absence of Supersymmetry in LHC gives new light to Dark Sector Models
- Search for new hidden forces accessible to Belle

PRD 75 115017 (2007)

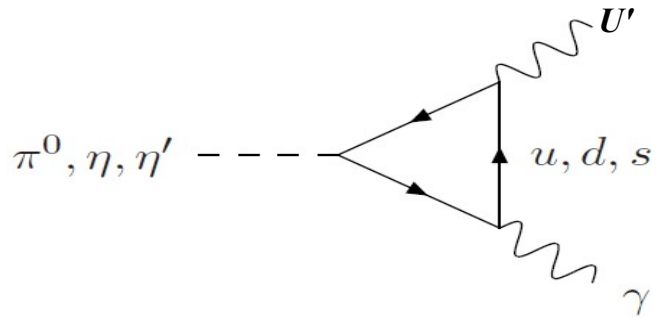
- Coupling of charged matter to new, dark photon, A', $q = \varepsilon e$
- $\mathcal{L} = -\frac{1}{2}\varepsilon F^{\mu\nu}_{dark} F_{\mu\nu}$



- Feynman diagram
- A' short or long lived or invisible

PRD 89 114008 (2014)

- Coupling of all quarks to new, baryonic boson, U', $g_{U'} = \sqrt{4\pi\alpha_{U'}}$
- $\mathcal{L} = \frac{1}{3} g_{U'} \bar{q} \gamma^\mu q U'_\mu$



- Feynman diagrams for hadronic U' decay
- Above π threshold U' short lived

All models point to new particles with mass of the order of MeV – GeV

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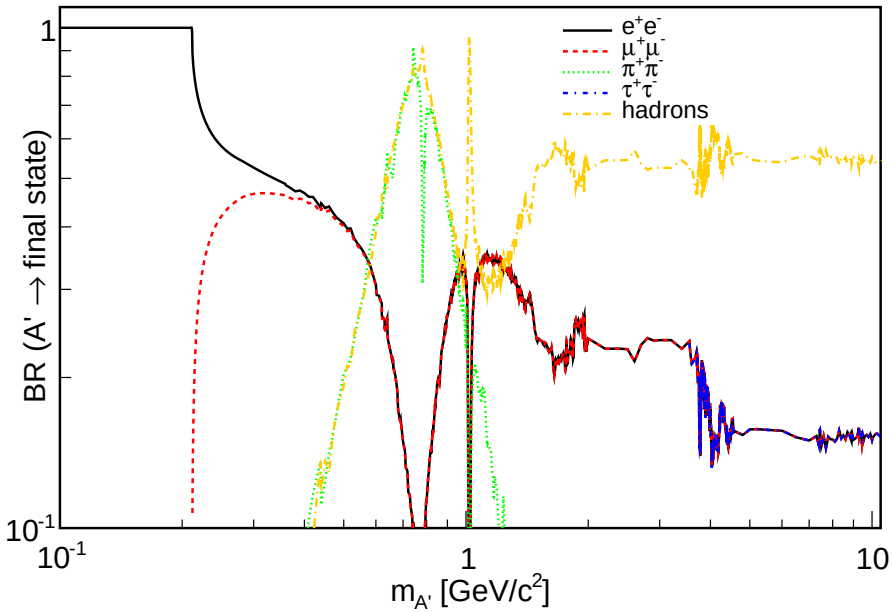
- Search for new hidden forces accessible to Belle

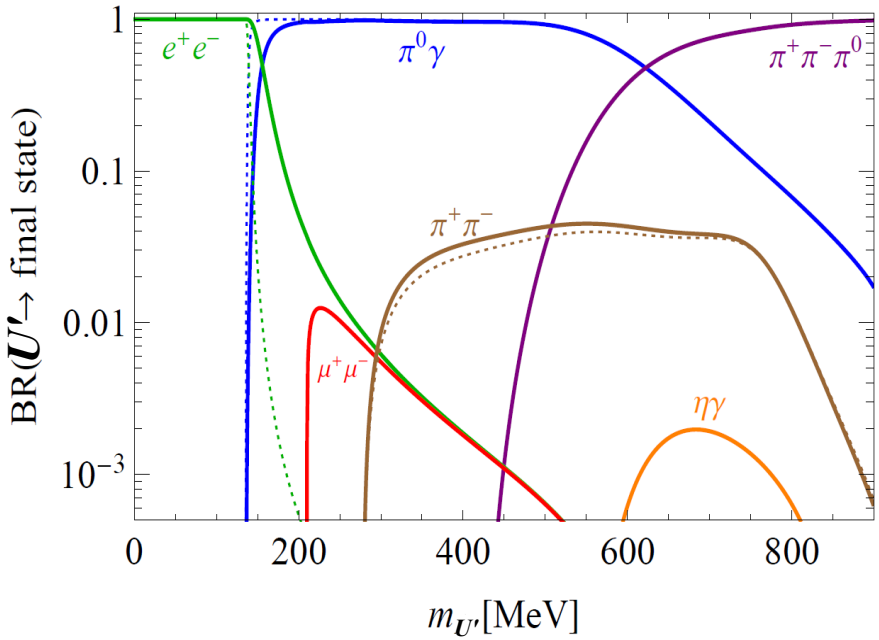
- Branching ratio for A' decay

  PRD 79 115008 (2008)



- Branching ratio for U' decay

  PRD 89 114008 (2014)

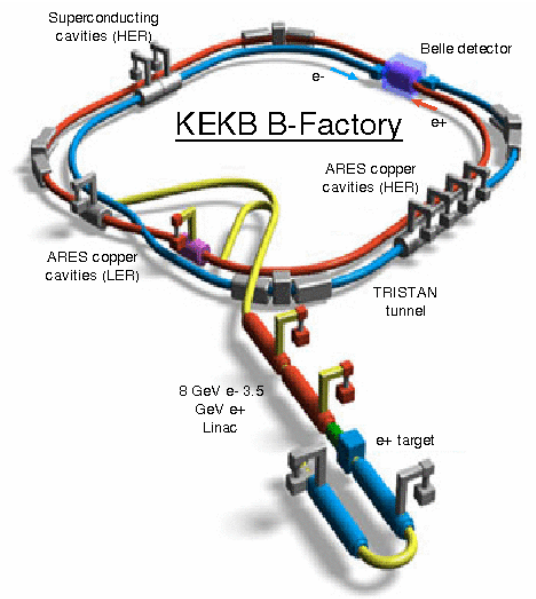


All models point to new particles with mass of the order of MeV – GeV

KEKB and SuperKEKB

KEKB/SuperKEKB collider, located in Japan, Tsukuba, is the world's highest-luminosity electron-position collider

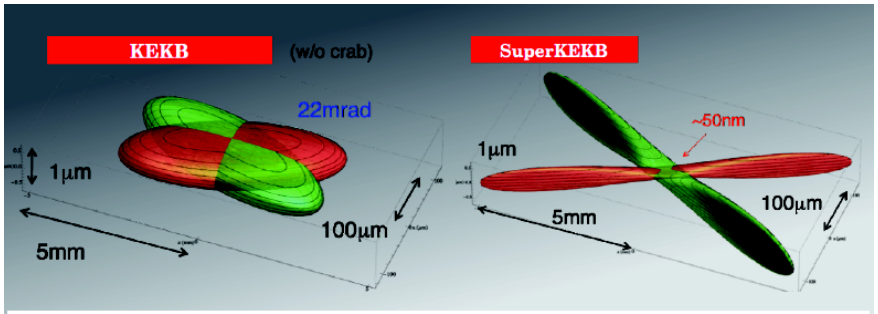
- 1999-2010: Belle collected $\mathcal{L}_{int} = 1050$ fb^{-1} at $\Upsilon(1S, 2S, 3S, 4S, 5S)$ and continuum
- 2016-2026: Belle II (upgrade version of Belle) expects to collect $\mathcal{L}_{int} = 50\ ab^{-1}$



Schematic view of KEKB

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor | Beam current | Beam-Beam parameter | Geometrical reduction factors (crossing angle, hourglass effect) | Beam aspect ratio at IP | Vertical beta function at IP | Minimum value is limited by hourglass effect



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

KEKB beam vs. SuperKEKB nano-beam

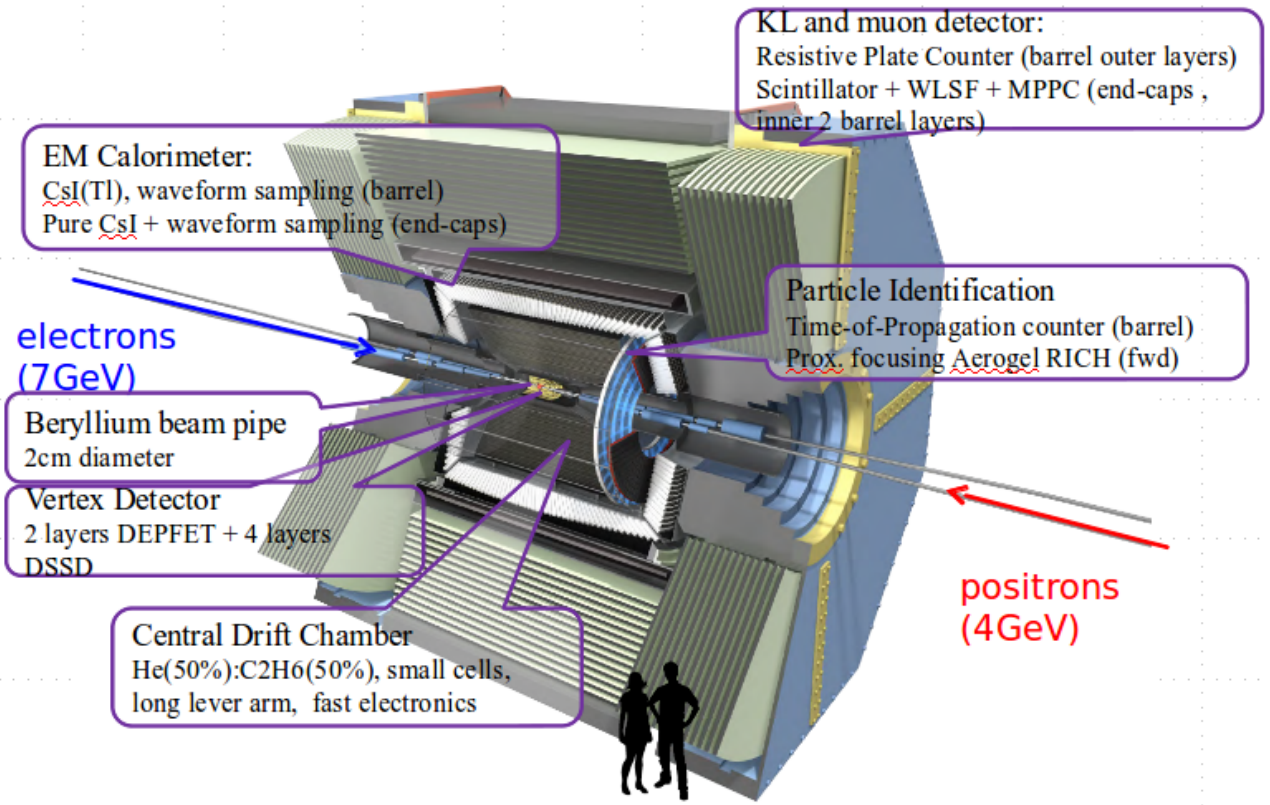
S. Kurokawa and E. Kikutani, NIM A 499, 1 (2003)

Belle II $\mathcal{L}_{peak} = 8 \times 10^{35} cm^{-2} s^{-1}$

Belle and Belle II experiments

CP violation measurement in the B-meson system with Belle and *BABAR*, established the Kobayashi Maskawa mechanism as a valid description of CP violation in the Standard Model.

- Main motivations
  - Study of CP violation (i.e. matter-antimatter asymmetry)
  - Study of heavy flavor
  - Search for physics beyond the Standard Model
- Complementary to efforts at energy frontier



Add PID in endcaps

Add μ ID in endcaps

Increase K_S efficiency

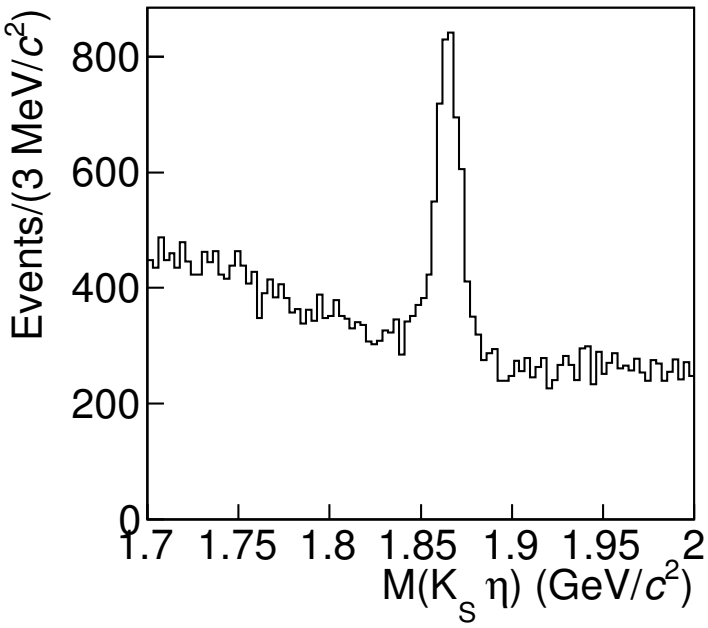
Improve IP and secondary vertex resolution

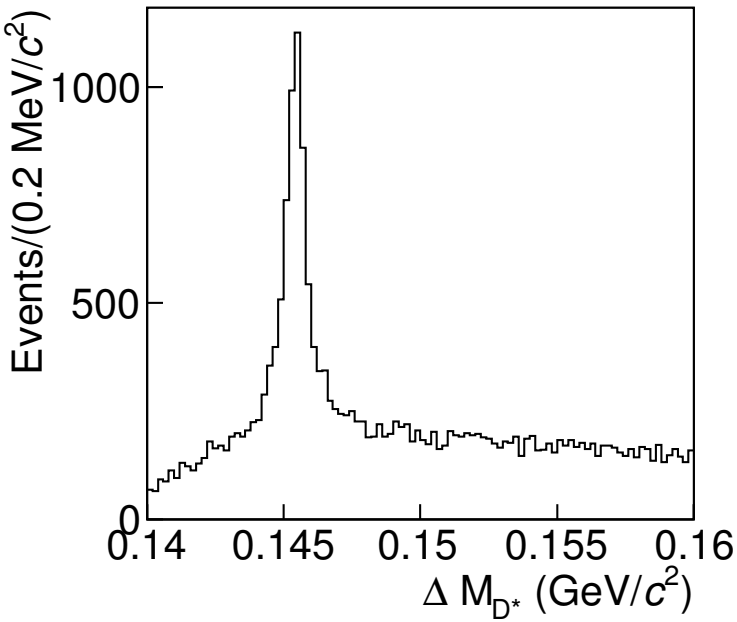
Improve π/K separation

Improve π^0 efficiency

Belle II is an upgrade of Belle

- Search for $U' \to \pi^+\pi^-$ in $D^0 \to K^0_S\eta$, $\eta \to U'\gamma$ using $977 fb^{-1}$ of Belle data
- Exclusive charm meson decays to reduce background



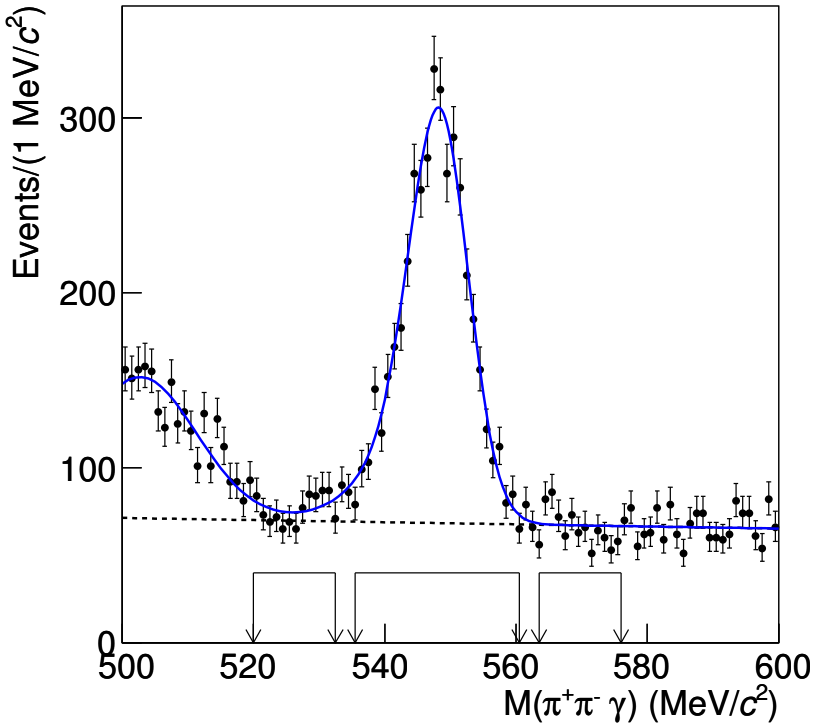


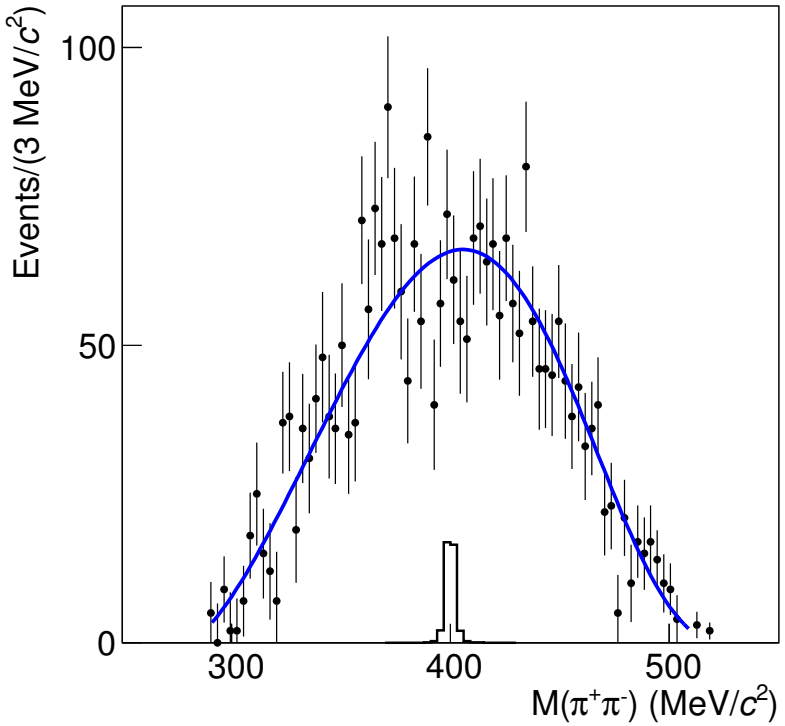
- $K^0_S\eta$ invariant mass
- D^*–D^0 mass difference

- Cut on D^0 and mass difference and look at $\pi^+\pi^-\gamma$ invariant mass

Search for a light vector gauge boson

- Background estimated and subtracted using the side bands



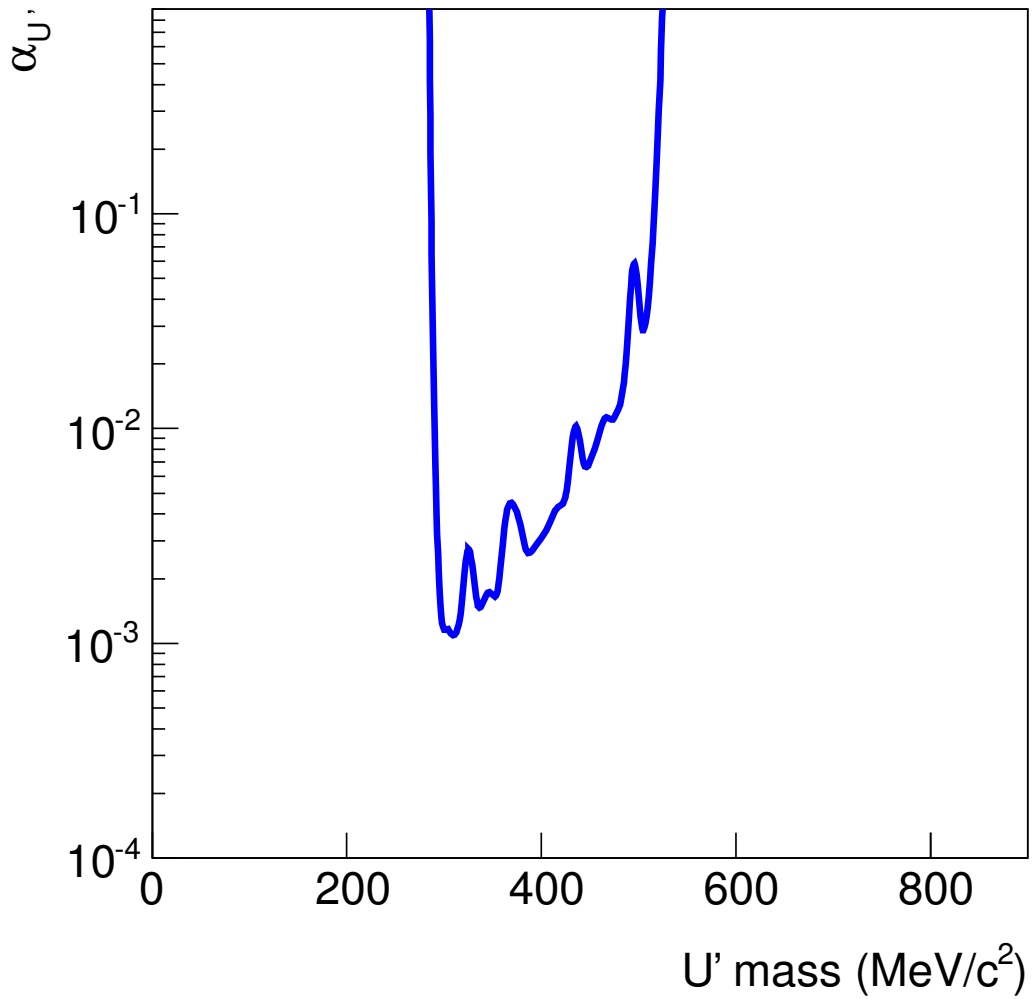


- $\pi^+\pi^-\gamma$ invariant mass
- $\pi^+\pi^-$ invariant mass after background substraction

- $\pi^+\pi^-$-line shape fitted by $\frac{d\Gamma}{ds} \propto |P(s)F_V(s)|^2(m_\eta^2 - s)^3 s(1 - 4m_\pi^2/s)^{3/2}$
  [PLB 707, 243 (2012) and PLB 707, 184 (2012)]
  - $P(s)$ reaction-specific perturbative part
  - $F_V(s)$ pion vector form factor
- No signal found, example of U' MC sim. signal of 400 MeV/c^2 mass is shown

New Belle limit

PRD, Phys. Rev. D 94, 092006 (2016) (Eunil Won et al.)

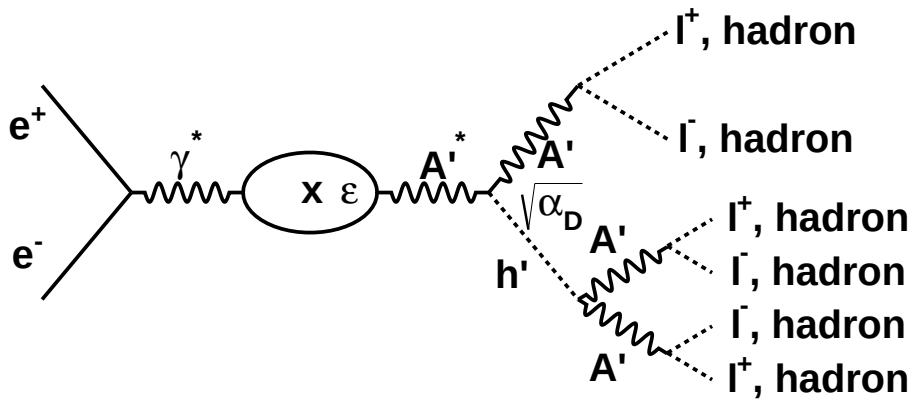


- 95% CL limit on the baryonic fine structure constant
- Better limit for $m_{U'} > 450\text{MeV}/c^2$ and $\phi \to e^+e^-\gamma$

Search for the dark photon and the dark Higgs boson

Belle limits, PRL 114 211801 (2015). Production in the so-called Higgs-strahlung channels, $e^+e^- \to A'h'$, with $h' \to A'A'$.

- A' and h' assuming prompt decays
- $m_{h'} > 2m_{A'}$
- $0.1 < m_{A'} < 3.5$ GeV$/c^2$ and $0.2 < m_{h'} < 10.5$ GeV$/c^2$



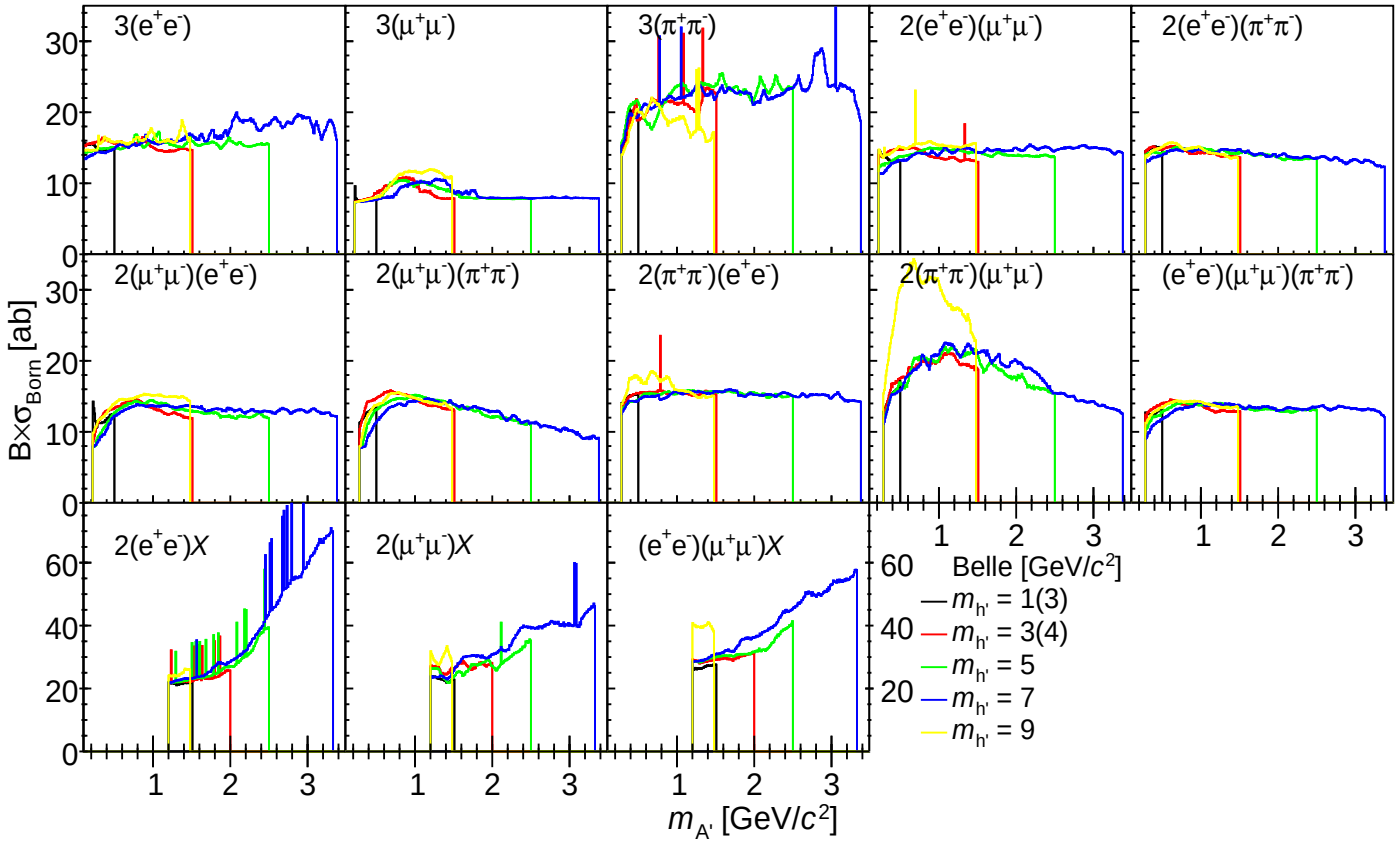
α_D: dark sector constant
ε: kinetic mixing

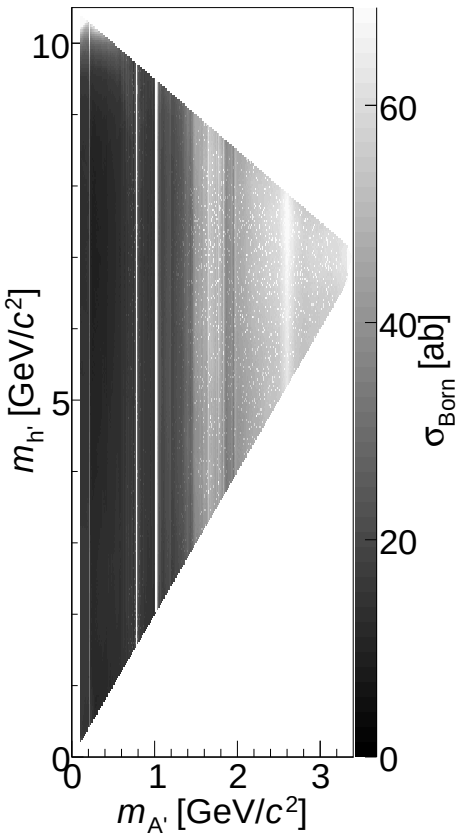
- 10 exclusive channels: $3(l^+l^-)$, $2(l^+l^-)(\pi^+\pi^-)$, $2(\pi^+\pi^-)(l^+l^-)$, and $3(\pi^+\pi^-)$, where l^+l^- is an electron or muon pair
- 3 inclusive channels for $m_{A'} > 1.1$ GeV$/c^2$: $2(l^+l^-)X$, where X is a dark photon candidate detected via missing mass

If $\alpha_D = 1$, Higgs-strahlung channels most sensitive to A'

Belle limits / results

- Belle limits for $\mathcal{L} = 977$ fb^{-1} on $\mathcal{B} \times \sigma_{\rm Born}$ and $\sigma_{\rm Born}$
  - 90% CL upper limit for each of the 13 final states
  - 90% CL upper limit on the combined Born cross section





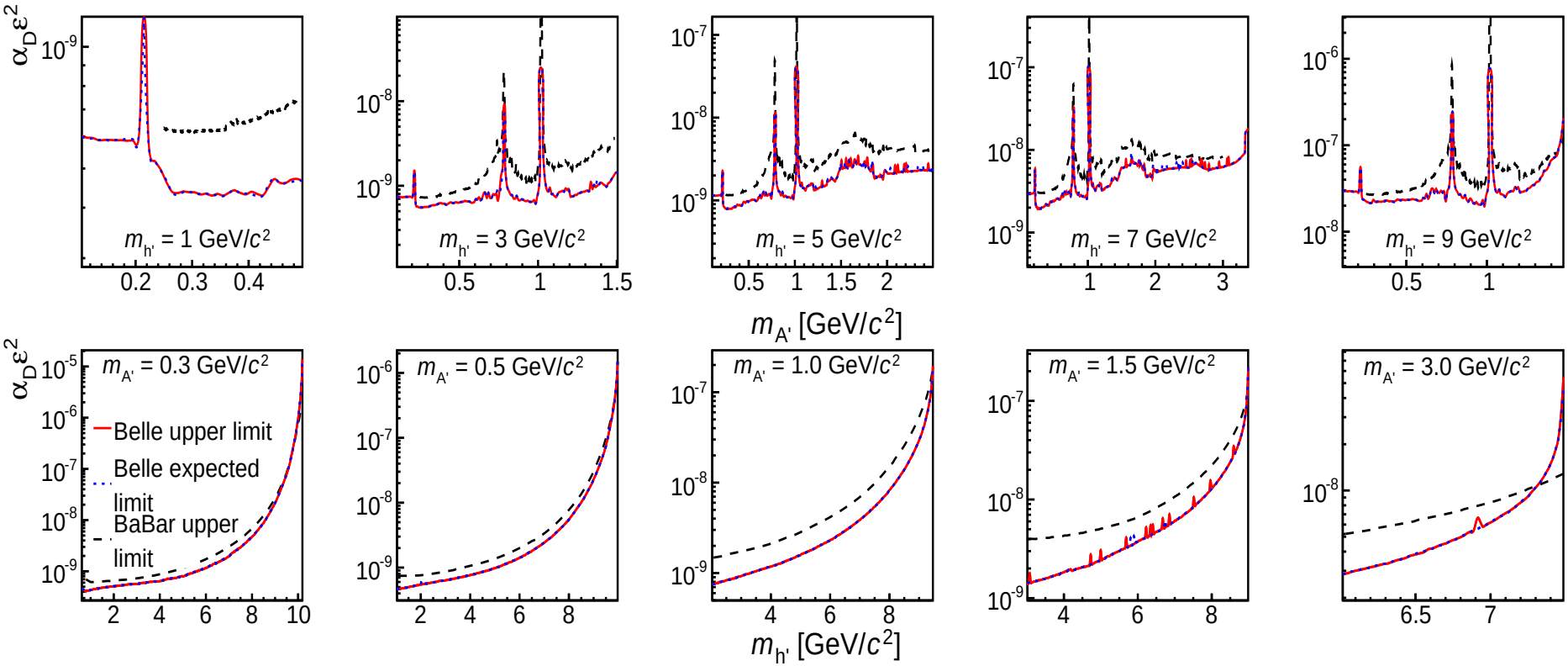
- 90 % Credibility Level (CL) upper limit determined by Bayesian inference method with the use of Markov Chain Monte Carlo A'. Caldwell et al., CPC 180 (2009) 2197-2209

Limits from $3(\pi^+\pi^-)$ and $2(e^+e^-)X$ are the first placed by any experiment

Limits on the product of $\alpha_D \varepsilon^2$ / results

Belle combined limits compared to *BABAR* combined limits

- Belle limits for $\mathcal{L} = 977$ fb^{-1} based on the Born cross section, ISR effect non negligible
- *BABAR* limits for $\mathcal{L} = 520$ fb^{-1} based on the visible cross section PRL 108 211801 (2012)



90% CL upper limit on the product $\alpha_D \times \varepsilon^2$ versus dark photon mass (top row) and dark Higgs boson mass (bottom row)

- Assuming branching fractions and couplings versus cross section from B. Batell et al. PRD 79 (2009) 115008

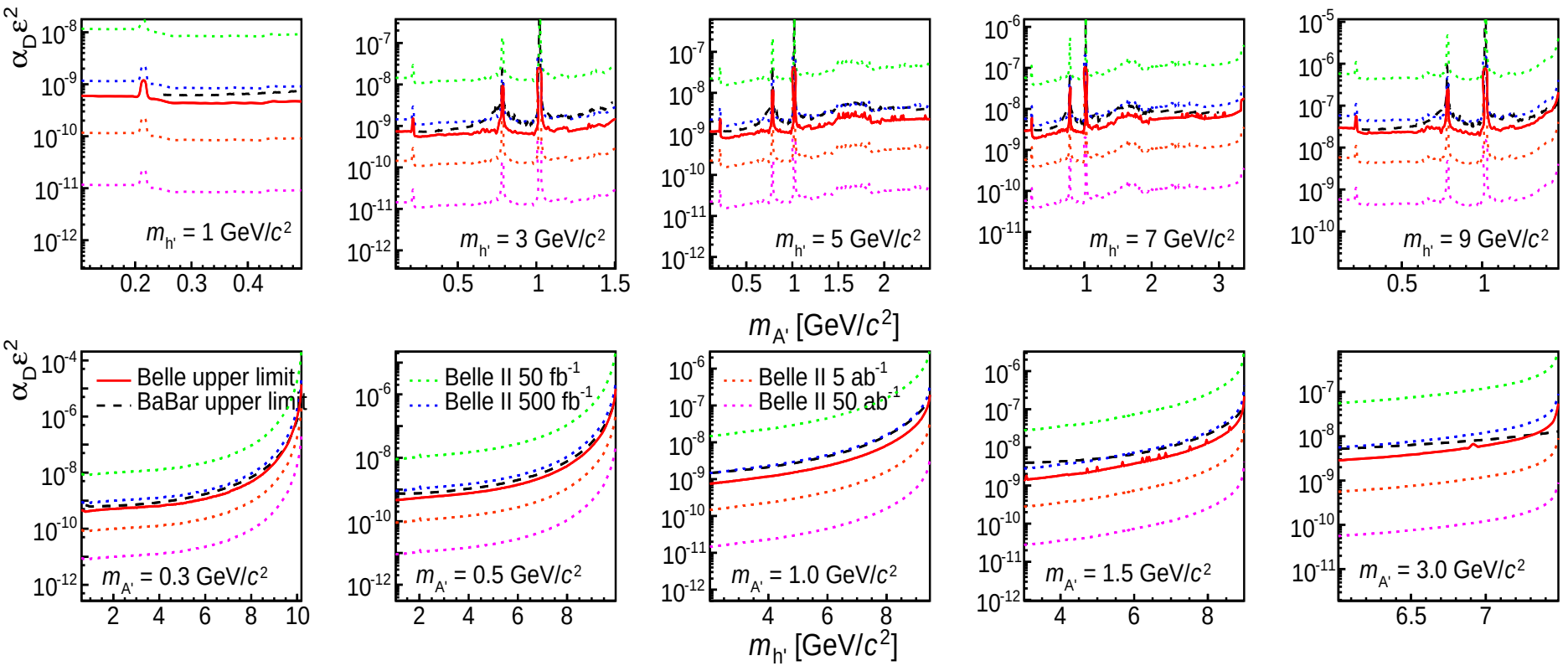
Results scale nearly linearly with integrated luminosity.This bodes well for future searches with Belle II.

Belle II prospects for the Higgs-strahlung channels

Predicted Belle II upper limits $U_{\alpha_D \varepsilon^2}$ in the $\alpha_D \varepsilon^2$ vs $m_{A'}$ vs $m_{h'}$ plane by scaling the Belle limits linearly with the integrated luminosity:

$$\frac{U_{\alpha_D \varepsilon^2}}{U^0_{\alpha_D \varepsilon^2}} = \frac{\mathcal{L}^0}{\mathcal{L}},$$

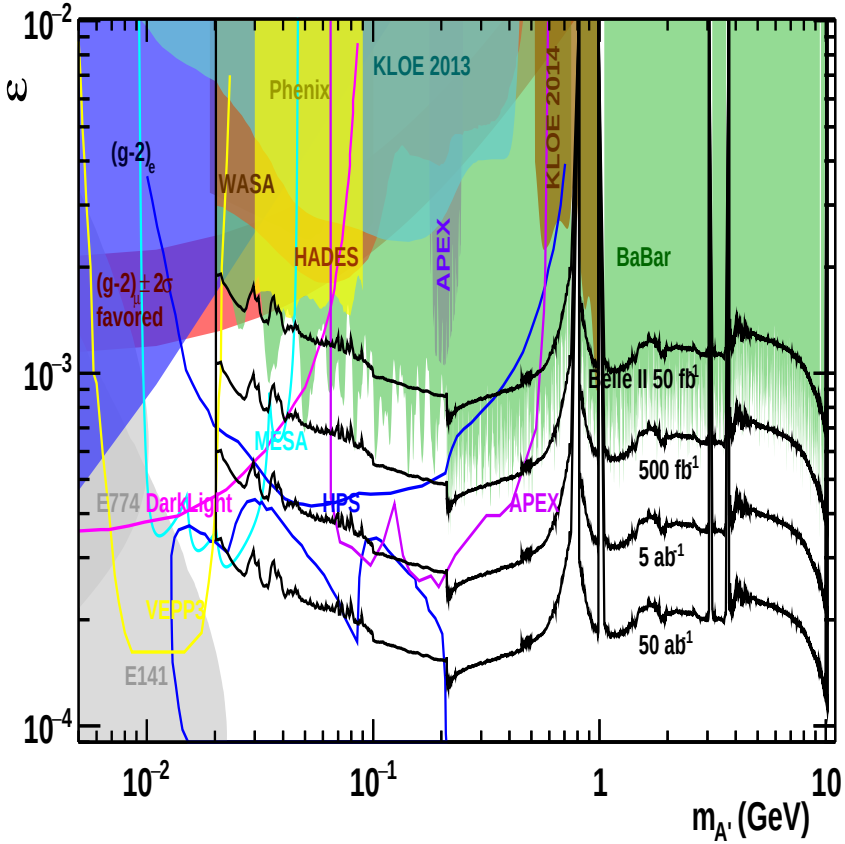
where the superscript 0 corresponds to Belle values. $\mathcal{L}$ is integrated luminosity. The scaling uses both statistical and systematic uncertainties.

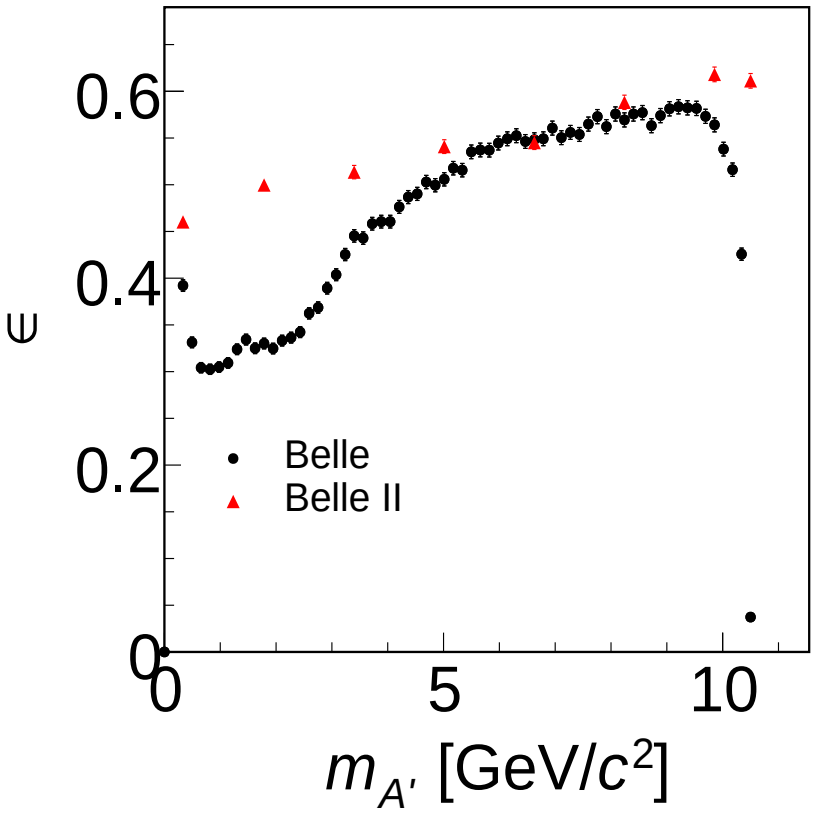


Belle (II) prospect for the radiative decays

Predicted Belle II upper limits extrapolated from *BABAR* PRL 113, 201801 (2014) (C. Hearty, B2TIP2014)

- $e^+e^- \to \gamma A'$, $A' \to l^+l^-$, with $l = e$ or μ
- Belle II will have an improve low multiplicity trigger compared to Belle





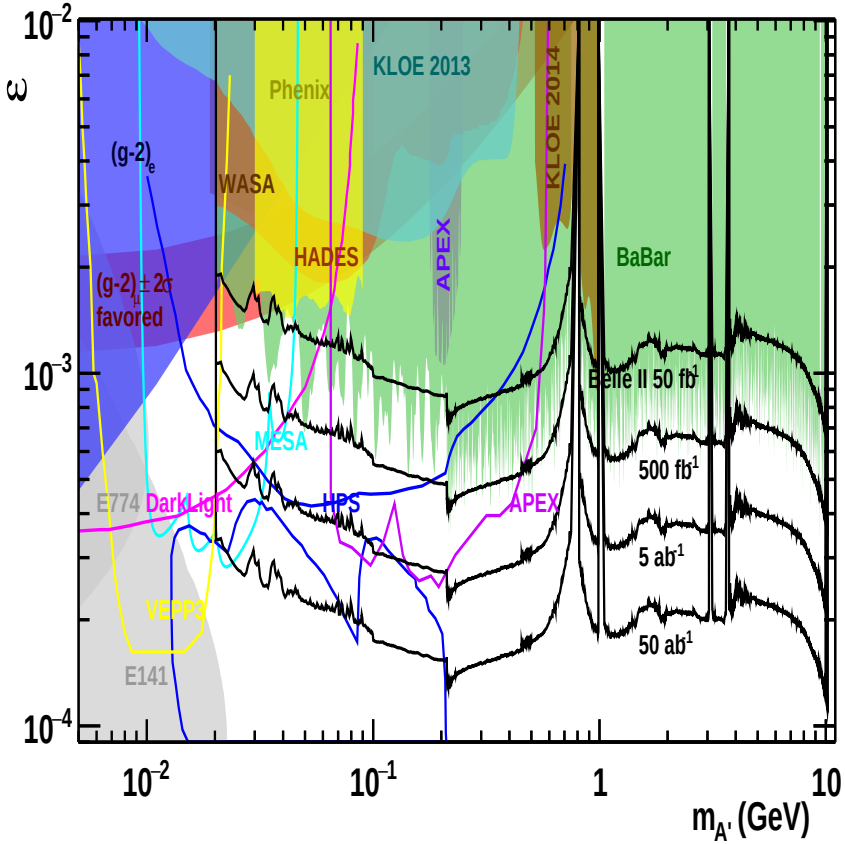
Left: Belle II prediction. Right: preliminary Belle and Belle II preliminary fiducial detection efficiency for $A' \to \mu^+\mu^-$

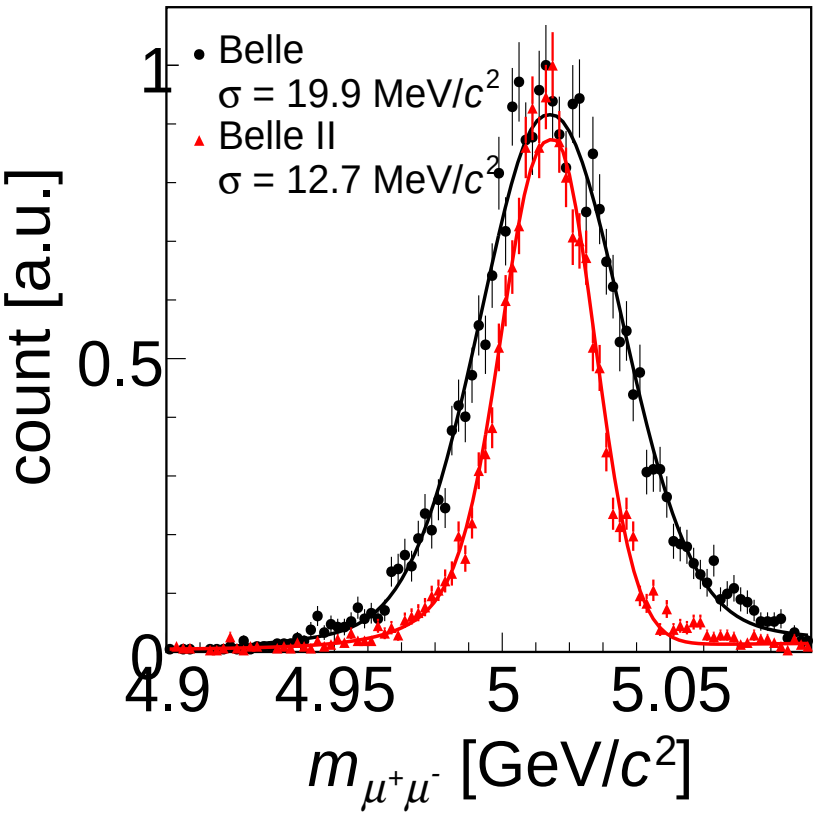
Belle II will have a better efficiency for low momentum muon compared to Belle

Belle (II) prospect for the radiative decays

Predicted Belle II upper limits extrapolated from *BABAR* PRL 113, 201801 (2014) (C. Hearty, B2TIP2014)

- $e^+e^- \to \gamma A'$, $A' \to l^+l^-$, with $l = e$ or μ
- Belle II dimuon invariant mass resolution improved by $\sim 35\%$ compared to Belle





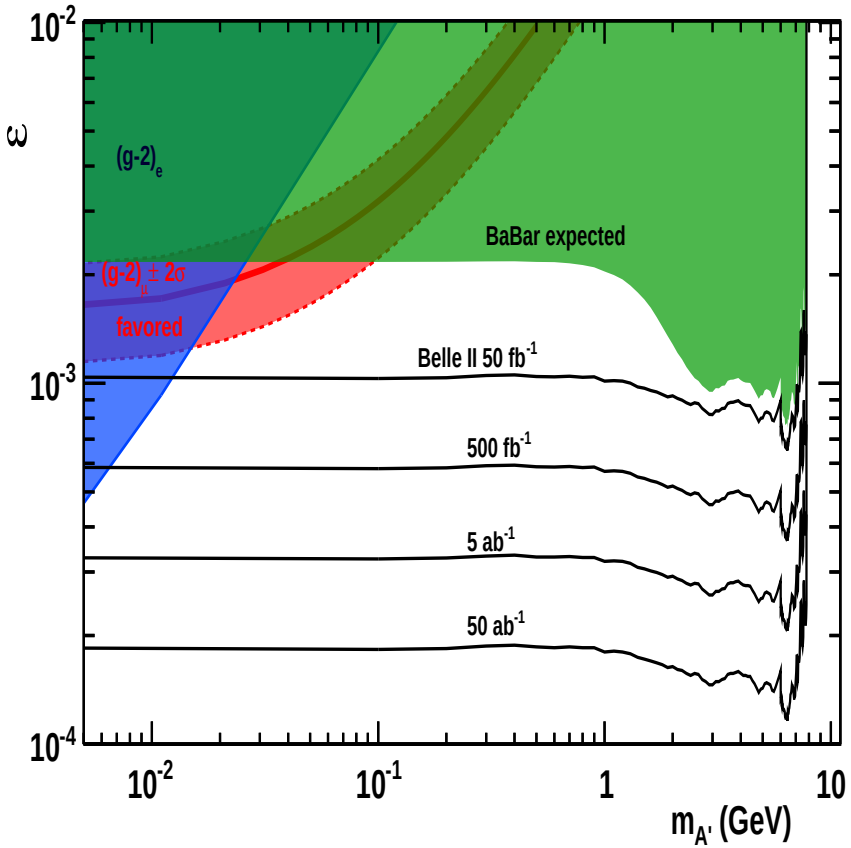
Left: Belle II prediction. Right: simulation for $m_{A'} = 5.015$ GeV/c^2

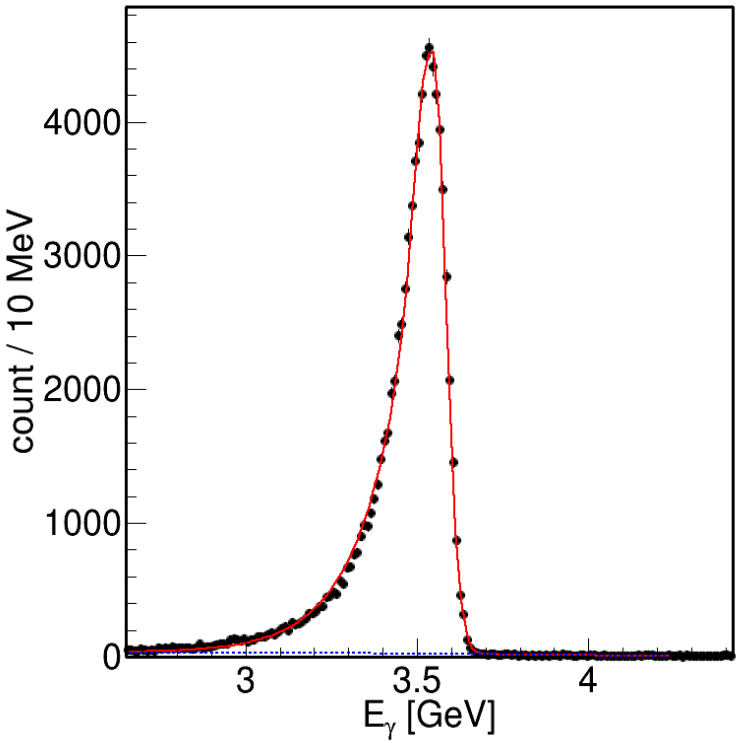
Complementary to fixed target experiments

Belle (II) prospect for the radiative decays

Predicted Belle II upper limits extrapolated from *BABAR* arxiv:0808.0017 (C. Hearty, B2TIP2014)

- $e^+e^- \to \gamma A'$, $A' \to \chi\chi$, χ light dark matter R. Essig et al. arXiv:1309.5084
- Require implementation of a single photon trigger in Belle II





Left: Belle II prediction. Right: Simulated mono-energetic photon signature for $m_{A'} = 6$ GeV/c^2

Belle II is expected to have a better single photon trigger with a lower energy sum than *BABAR*

Conclusion

- New Belle limit has been presented on the baryonic fine constant, $\alpha_{U'}$, in a exclusive charm decays
  - $280 < m_{U'} < 550$ MeV/c^2
  - We found that:
    - ★ No signal found
    - ★ Better limit for $m_{U'} > 450$MeV/c^2 and $\phi \to e^+e^-\gamma$
- Belle limits for prompt decays of the dark photon and the dark Higgs boson:
  - $0.1 < m_{A'} < 3.5$ GeV/c^2
  - $0.2 < m_{h'} < 10.5$ GeV/c^2
  - We found that:
    - ★ No significant excess over the background estimation
    - ★ Belle limit improvement scales nearly linearly with integrated luminosity
- Ongoing Belle analysis on $e^+e^- \to A'\gamma$ (prompt and displaced vertex), $e^+e^- \to \chi\chi\gamma$, $e^+e^- \to \mu^+\mu^- Z'$, and $e^+e^- \to \tau^+\tau^- h''$

- Belle II will also search for dark particles
- With 50 ab^{-1}, Belle II might potentially also cross-check any signals discovered by fixed target experiments
- First collisions in 2018 with partial vertex detector

Thank you for your attention