

Studies of Dark Sector particles at Belle

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Outline

- Searches for dark-sector
 - ✓ motivations & opportunities at e^+e^- B -factories
- Recent results from Belle
 - ✓ Dark-photon search via Higgsstrahlung
 - ✓ Search for dark-boson in η decays
 - ✓ Search for D^0 decays to invisible final states
- Prospects with Belle II \Rightarrow *talk by T. Ferber*

PRL 114, 211801 (2015)

PRD 94, 092006 (2016)

PRD 95, 011102(R) (2017)



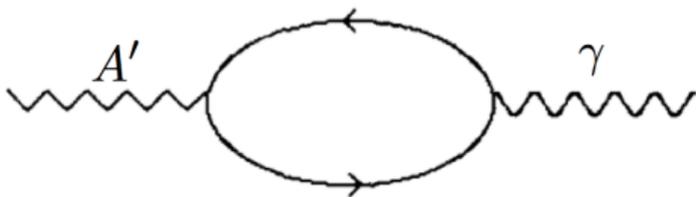
Linking SM and the Dark Sector

- Astrophysical observation by, e.g. PAMELA, AMS, etc. have triggered light dark matter and dark sector scenarios.
- The dark sector can be connected to SM via the so-called “**portals**”.

$H^\dagger H(AS + \lambda S^2)$	Higgs portal	(dim= 3, 4),
$\kappa F_{\mu\nu}^Y F'_{\mu\nu}$	Vector portal	(dim= 4),
$Y_N \bar{L} H N$	Neutrino portal	(dim= 4),
$f_a^{-1} \bar{\psi} \gamma_\mu \gamma_5 \psi \partial_\mu a$	Axion portal	(dim= 5).

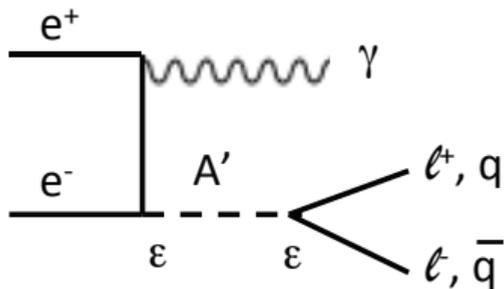
Dark photon & kinetic mixing – as a portal

- Dark photon, first proposed in P. Fayet, PL B95, 285 (1980)
- (Holdom, 1986) A boson A' belonging to an additional $U(1)'$ would mix kinetically with γ

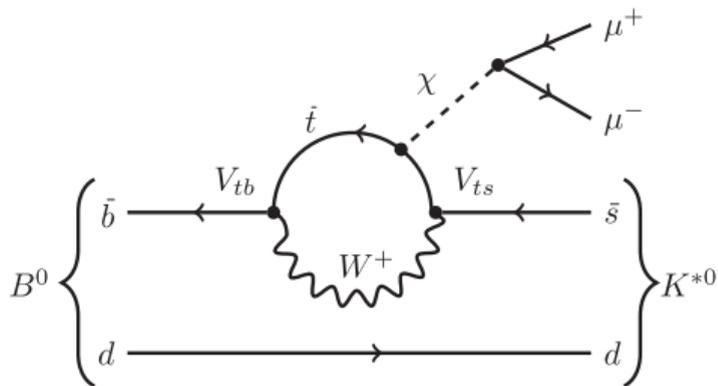


- in general, one can express kinetic mixing as $(1/2)\epsilon F_{\mu\nu}F'^{\mu\nu}$
- ϵ , the strength of the kinetic mixing, is supposed to be small, ($10^{-5} \sim 10^{-2}$).
- For A' to acquire mass, an extended Higgs sector is required to break this $U(1)'$

What to look for with B -factories



ISR



B decays

What to look for with B -factories

$$e^+e^- \rightarrow \gamma A' (\rightarrow \chi\bar{\chi}) \quad e^+e^- \rightarrow \gamma A' (\rightarrow \ell^+\ell^-)$$

$$e^+e^- \rightarrow \Upsilon(nS) \rightarrow \gamma A^0$$

$$e^+e^- \rightarrow h' (\rightarrow A'A') A' \text{ with } A' \rightarrow \ell^+\ell^-$$

$$B \rightarrow SS \rightarrow 2(\ell^+\ell^-)$$

$$B \rightarrow K^{(*)}S \rightarrow K^{(*)}\ell^+\ell^-$$

$$B \rightarrow K^{(*)}A' (\rightarrow \ell^+\ell^-)$$

$$B \rightarrow K^{(*)}h' \text{ with } h' \rightarrow A'A' \rightarrow 2(\ell^+\ell^-)$$

$$B \rightarrow 2h' \rightarrow 4A' \rightarrow 4(\ell^+\ell^-)$$

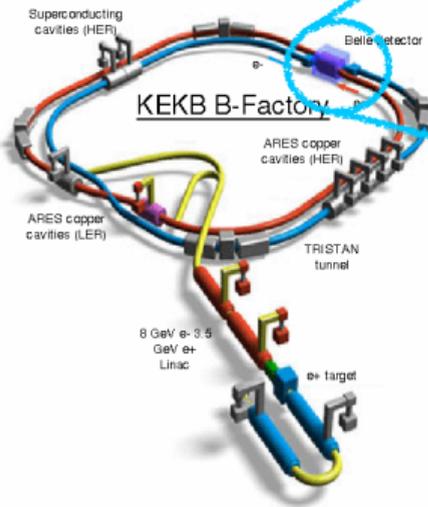
$$B \rightarrow A'A' \rightarrow 2(\ell^+\ell^-) \text{ through off-shell } h - h' \text{ mixing}$$

B decay modes from Batell, Pospelov, Ritz, PRD 83, 054005 (2011)



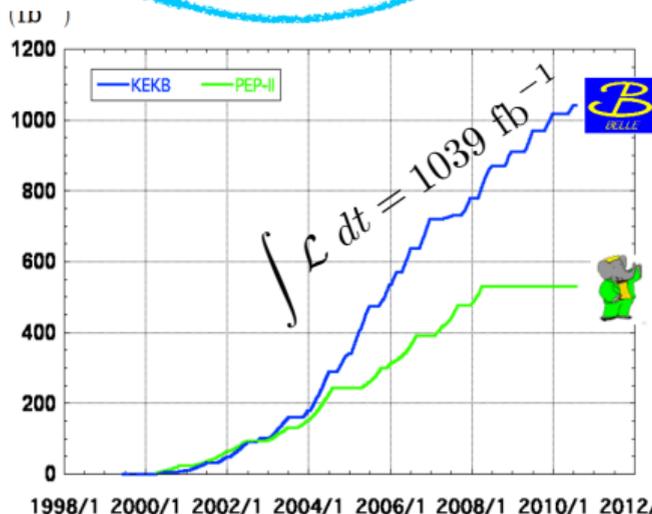
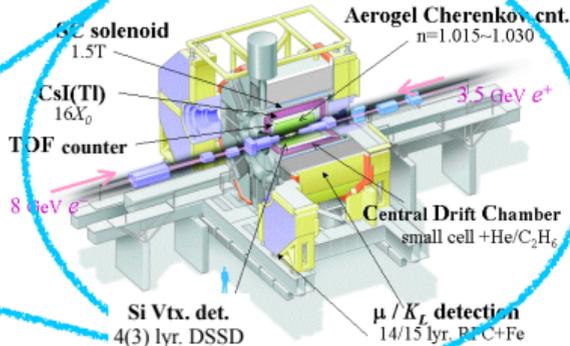
20 countries
90 institutions
~450 members

$$\mathcal{L}_{\text{peak}} = 21.1 \text{ nb}^{-1} \text{ s}^{-1}$$



$$e^- \xrightarrow{8 \text{ GeV}} (\star) \xleftarrow{3.5 \text{ GeV}} e^+$$

Belle Detector

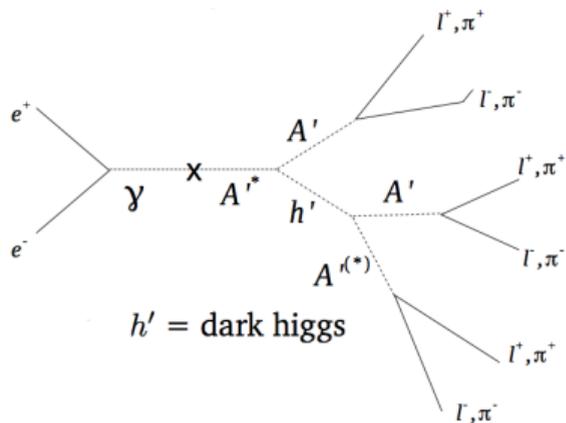


> 1 ab⁻¹
On resonance:
 Y(5S): 121 fb⁻¹
 Y(4S): 711 fb⁻¹
 Y(3S): 3 fb⁻¹
 Y(2S): 25 fb⁻¹
 Y(1S): 6 fb⁻¹
Off reson./scan:
 ~ 100 fb⁻¹

~ 550 fb⁻¹
On resonance:
 Y(4S): 433 fb⁻¹
 Y(3S): 30 fb⁻¹
 Y(2S): 14 fb⁻¹
Off resonance:
 ~ 54 fb⁻¹

Dark photon search via Higgsstrahlung

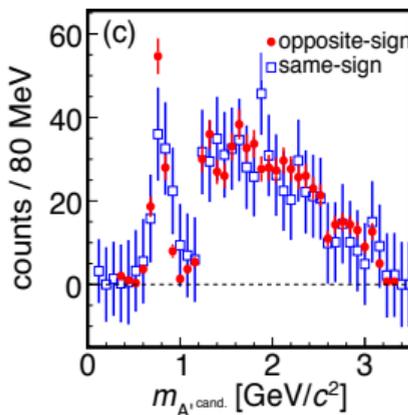
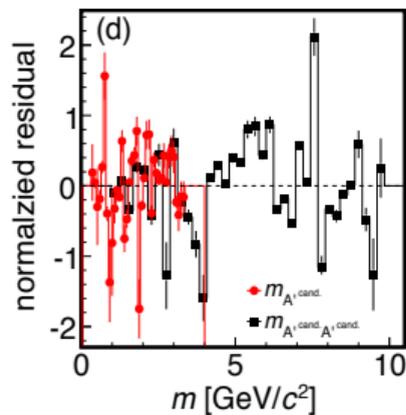
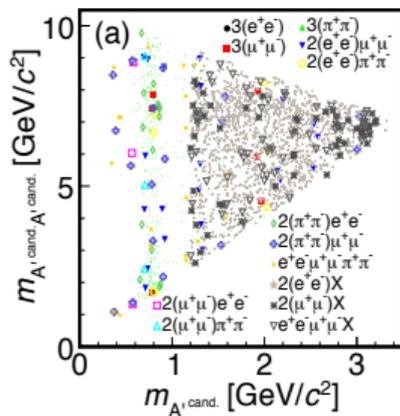
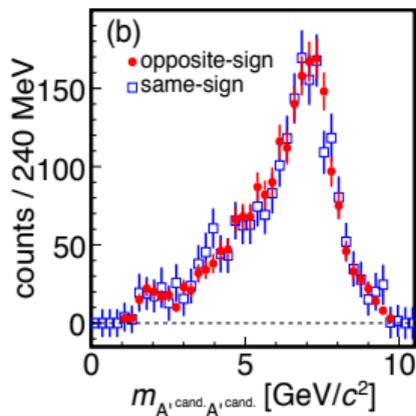
Belle, PRL 114, 211801 (2015)



- Search mode depends on $M_{h'}$ and $M_{A'}$
- In this study, only $M_{h'} > 2M_{A'}$ is considered
 $\Rightarrow h' \rightarrow A'A'$ is used
- $\int \mathcal{L} dt = 977 \text{ fb}^{-1}$

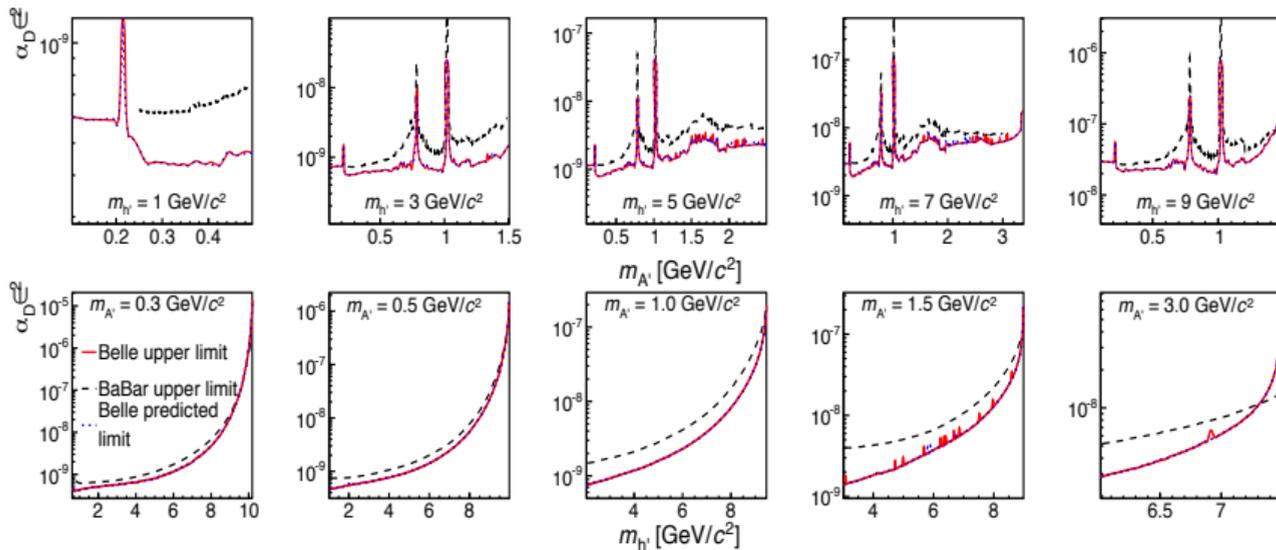
Look for 3 (or 2, for inclusive channels) lepton/hadron pairs (e^+e^- , $\mu^+\mu^-$, or $\pi^+\pi^-$)

- 10 exclusive channels: $3e^+3e^-$, $3\mu^+3\mu^-$, $2e^+2e^-\mu^+\mu^-$, $2\mu^+2\mu^-e^+e^-$, $3\pi^+3\pi^-$, $2\pi^+2\pi^-e^+e^-$, $2\pi^+2\pi^-\mu^+\mu^-$, $2e^+2e^-\pi^+\pi^-$, $2\mu^+2\mu^-\pi^+\pi^-$, $e^+e^-\mu^+\mu^-\pi^+\pi^-$
- 3 inclusive channels for $m_{A'} > 1.1 \text{ GeV}/c^2$: $2e^+2e^-X$, $2\mu^+2\mu^-X$, $e^+e^-\mu^+\mu^-X$



- 19% of events due to $3(\pi^+\pi^-)$
- 74% due to $2(\pi^+\pi^-)X$
- no excess of signals in any channel

Limits on kinetic mixing parameters



- $\epsilon \lesssim 8 \times 10^{-4}$ for $\alpha_D = 1/137$, $M_{h'} < 8 \text{ GeV}/c^2$, $M_{A'} < 1 \text{ GeV}/c^2$
 - ✓ Compare with BaBar limits with 516 fb^{-1} PRL 108, 211801 (2012)
- first limits (by any experiment) on $3(\pi^+\pi^-)$ and $2(e^+e^-)X$
- expect linear improvement with more data (almost background-free for many modes)

Search for $\eta \rightarrow U'(\rightarrow \pi^+\pi^-)\gamma$ at Belle

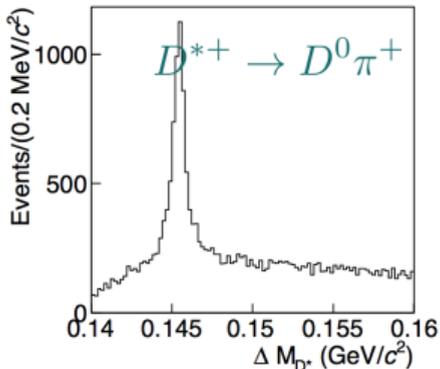
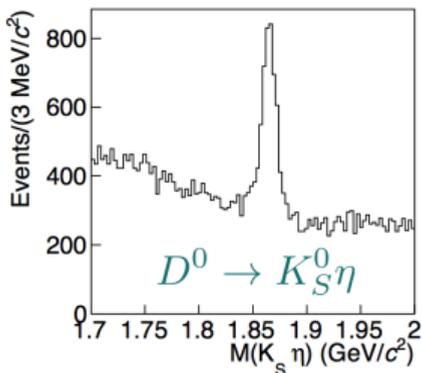
Belle, PRD 94, 092006 (2016)

- Search for a dark vector boson U' that couples to quarks ($U' \rightarrow \pi^+\pi^-$)
 - ✓ to constrain the baryonic fine structure constant $\alpha_{U'} \equiv g_{U'}^2/4\pi$, where the interaction is given by $\mathcal{L} = (1/3)g_{U'}\bar{q}\gamma^\mu qU'_\mu$

à la S. Tulin, PRD 89, 114008 (2014)

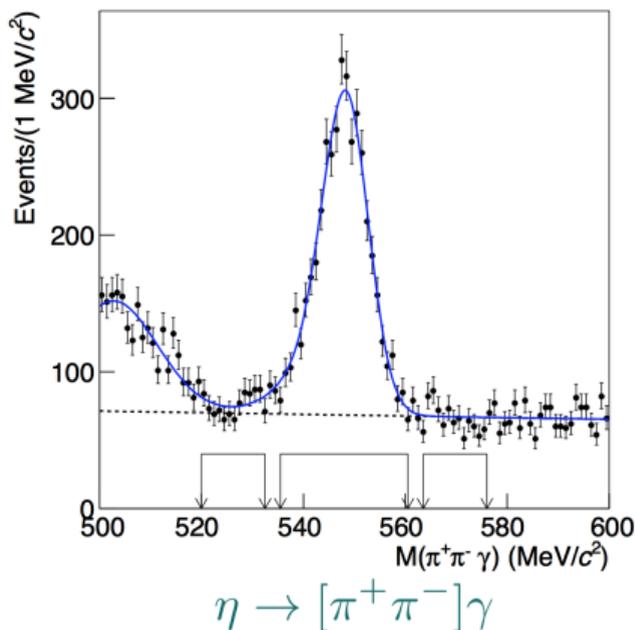
- Use Belle data sample of 976 fb^{-1}
- To suppress combinatorial background, demand:
 - ✓ η to come from $D^0 \rightarrow K_S^0\eta$
 - ✓ D^0 to come from $D^{*+} \rightarrow D^0\pi^+$

Search for $\eta \rightarrow U'(\rightarrow \pi^+\pi^-)\gamma$ at Belle



- γ selection
 - ✓ $E_\gamma > 60$ (100) MeV for barrel (endcap)
 - ✓ “E9/E25” > 0.85
- K_S^0 selection by neural net
- vertex χ^2 cut for η and mass-constraint
- $p_{D^*}^{\text{cm}} > 2.5, 2.6, 3.0$ GeV for \sqrt{s} below, at, or above $\Upsilon(4S)$ resonance

Search for $\eta \rightarrow U'(\rightarrow \pi^+\pi^-)\gamma$ at Belle



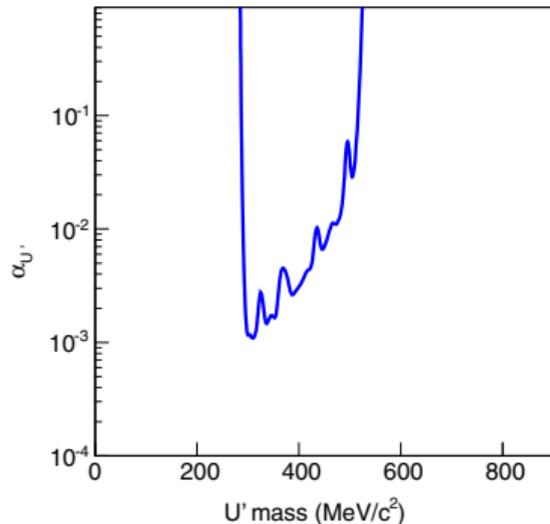
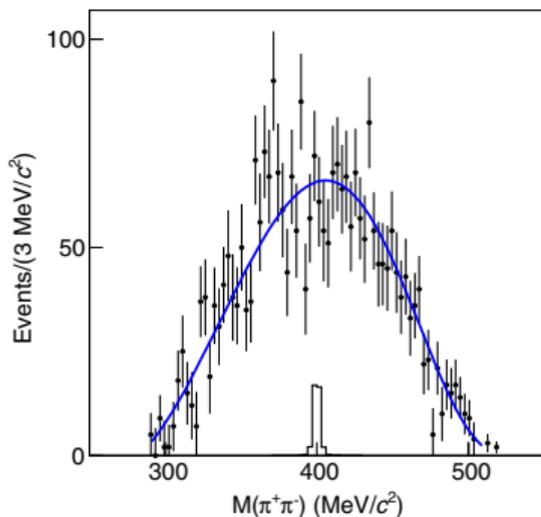
- $N_\eta = 2974 \pm 90$ events by binned max. likelihood fit to $M(\pi^+\pi^-\gamma)$
- Cross-check by measuring the ratio

$$\frac{\mathcal{B}(\eta \rightarrow \pi^+\pi^-\gamma)}{\mathcal{B}(\eta \rightarrow \pi^+\pi^-\pi^0)} = 0.185 \pm 0.007$$

c.f. 0.184 ± 0.004 for W.A.

- Fit to $M(\pi^+\pi^-)$ after η sideband subtraction
 - ✓ global shape: QCD-based $d\Gamma/ds$
 - ✓ add U' part with $\sigma_M \sim (1 \sim 2)$ MeV

Results for $\eta \rightarrow U'(\rightarrow \pi^+\pi^-)\gamma$

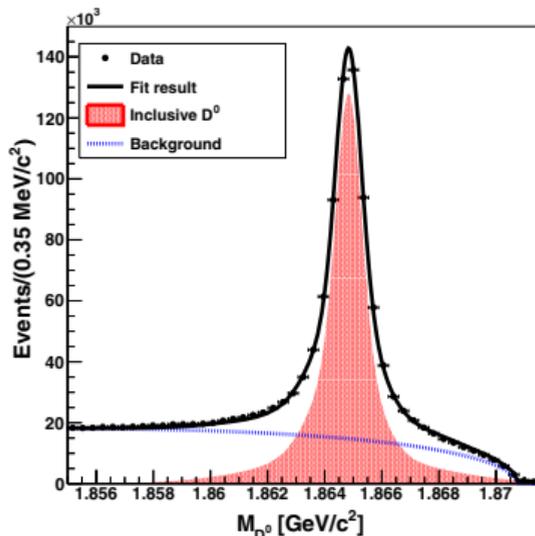
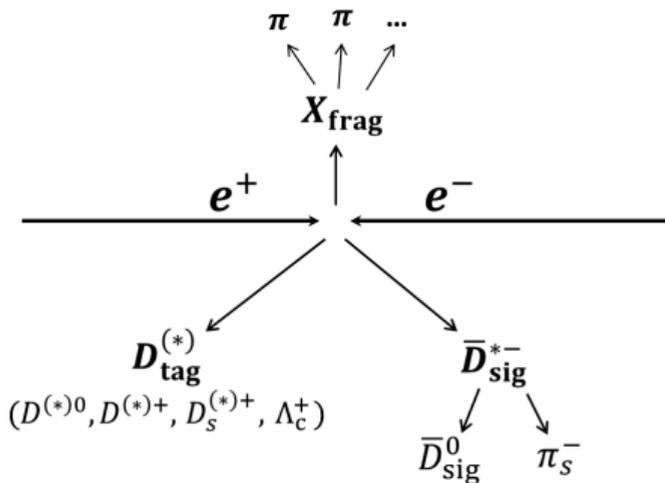


$$\alpha_{U'} = \left[\frac{\alpha}{2} \left(1 - \frac{m_{U'}^2}{m_\eta^2} \right)^{-3} \left| \mathcal{F}(m_{U'}^2) \right|^{-2} \frac{1}{\mathcal{B}(U' \rightarrow \pi^+\pi^-)} \right] \\ \times \left[\frac{\Gamma(\eta \rightarrow \pi^+\pi^-\gamma)}{\Gamma(\eta \rightarrow \gamma\gamma)} \right] \left[\frac{\Gamma(\eta \rightarrow U'\gamma \rightarrow \pi^+\pi^-\gamma)}{\Gamma(\eta \rightarrow \pi^+\pi^-\gamma)} \right],$$

- First search for U' in the $\pi^+\pi^-$ mode
- $\alpha_{U'} \lesssim (10^{-3} \sim 10^{-2})$ @ 95% CL.
for $290 < m(U') < 520 \text{ MeV}/c^2$

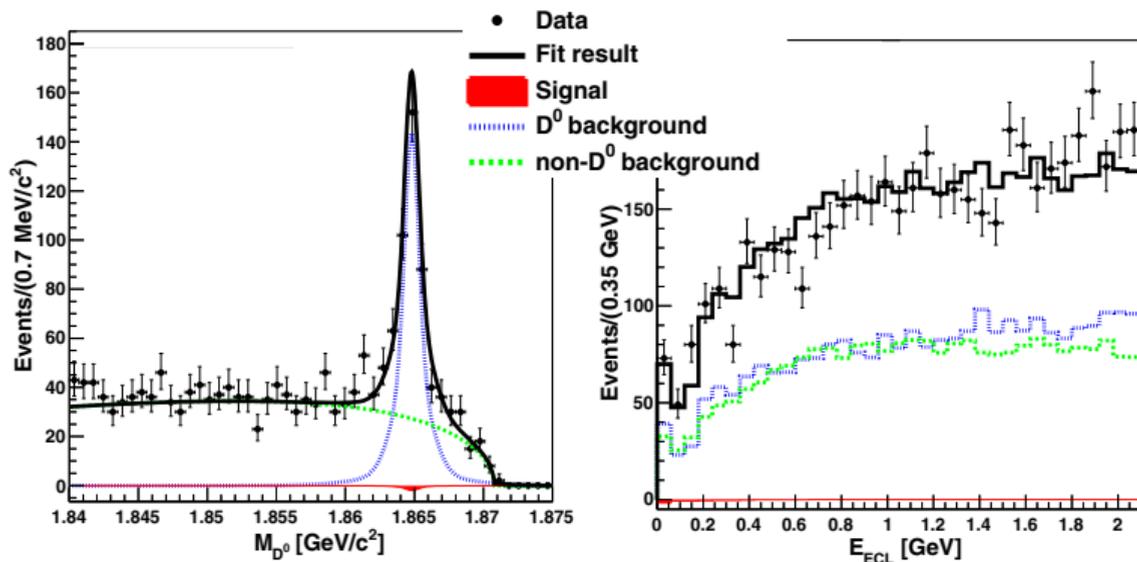
D^0 decays to invisible final states

- In SM, $D^0 \rightarrow \nu\bar{\nu}$ is helicity suppressed with $\mathcal{B} \sim \mathcal{O}(10^{-30})$, but the rate could be enhanced via DM final states
- Belle uses ‘charm tagger’ method to collect inclusive D^0 samples for the search using $\int \mathcal{L} dt = 924 \text{ fb}^{-1}$



$$M_{D^0} \equiv M_{\text{miss}}(D_{\text{tag}}^{(*)} X_{\text{frag}} \pi_s^-) \quad N(D^0) = 0.7 \text{ M, inclusive}$$

D^0 decays to invisible final states



- Result of the first-ever search

- ✓ $N_{\text{sig}} = -6.3_{-21.0}^{+22.5}$ from 2D fit to (M_{D^0}, E_{ECL})
- ✓ $\mathcal{B}(D^0 \rightarrow \text{invisible}) < 9.4 \times 10^{-5}$ @ 90% CL.

Belle, PRD 95, 011102(R) (2017)

Closing words

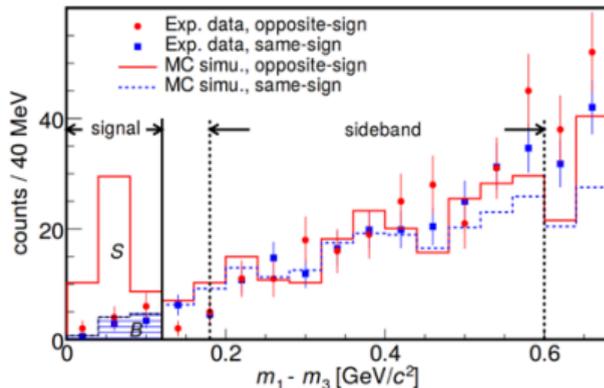
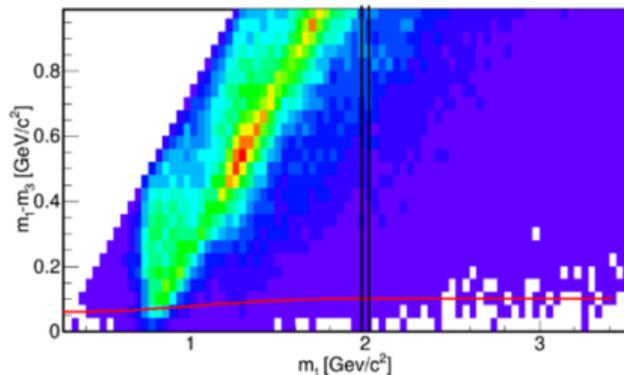
- B -factory experiments are not merely good old CPV/CKM machines, but they probe much wider regions of physics.
 - * e.g. exotic particles, heavy invisible particles, dark sector, etc.
- Dark photon searches at e^+e^- B -factories become available one by one.
 - * Depending on the mass parameters of the dark sector, significant limits have been obtained in $\mathcal{O}(\text{GeV})$ region.
 - * But there are many other modes which have yet to be explored.
 - * *Please stay tuned for Belle II*

Back-up slides

Background

- estimated using “same-sign” pairs from $e^+e^- \rightarrow (\ell^+\ell^+)(\ell^+\ell^-)(\ell^-\ell^-)$
- Sort the pairs by invariant mass, $m_1 > m_2 > m_3$ then plot $m_1 - m_3$ vs. m_1
- For each $M_{\ell^+\ell^-}$ region, scale same-sign yield to $\ell^+\ell^-$ in the side-band, then extrapolate into the $M_{\ell^+\ell^-}$ signal region.

for 6π mode, with $m_1 = 2 \text{ GeV}/c^2$



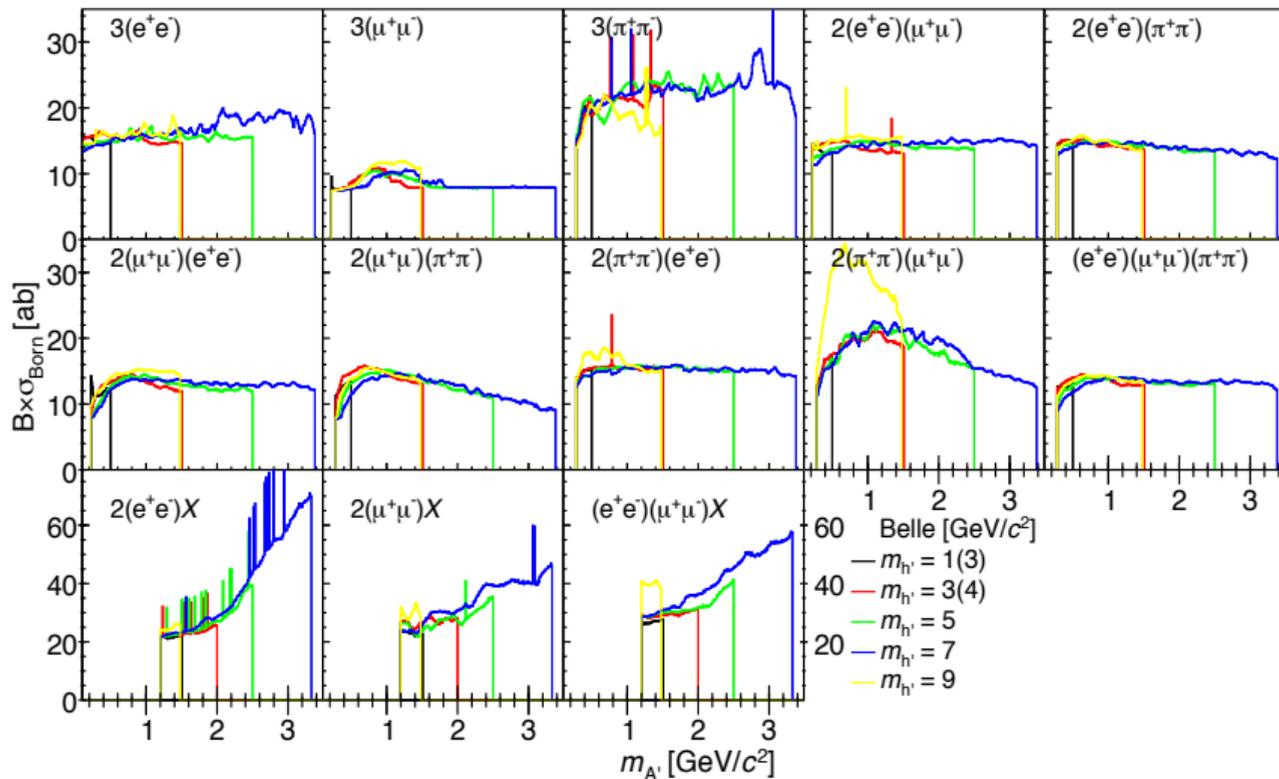
Results – Limits on $\mathcal{B} \times \sigma_{\text{Born}}$

$$N_{\text{obs}} = \sigma_{\text{Born}} (1 + \delta) |1 - \Pi(s)|^2 \mathcal{L} \mathcal{B} \epsilon + N_{\text{bkg}}$$

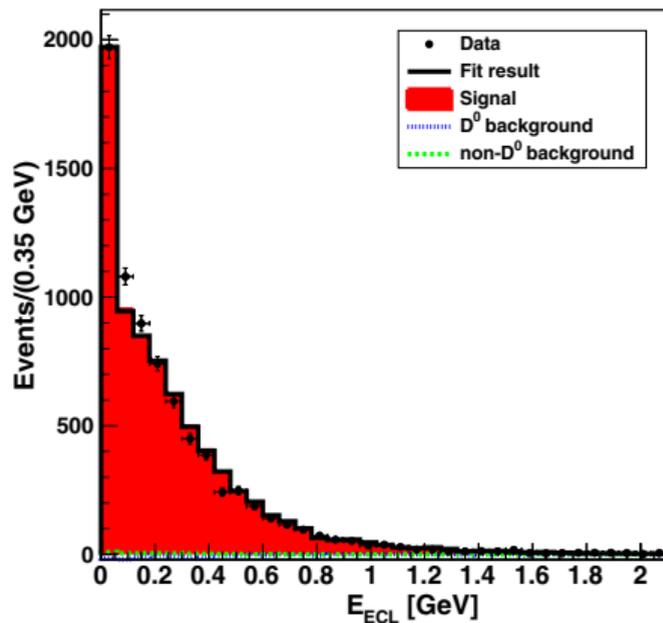
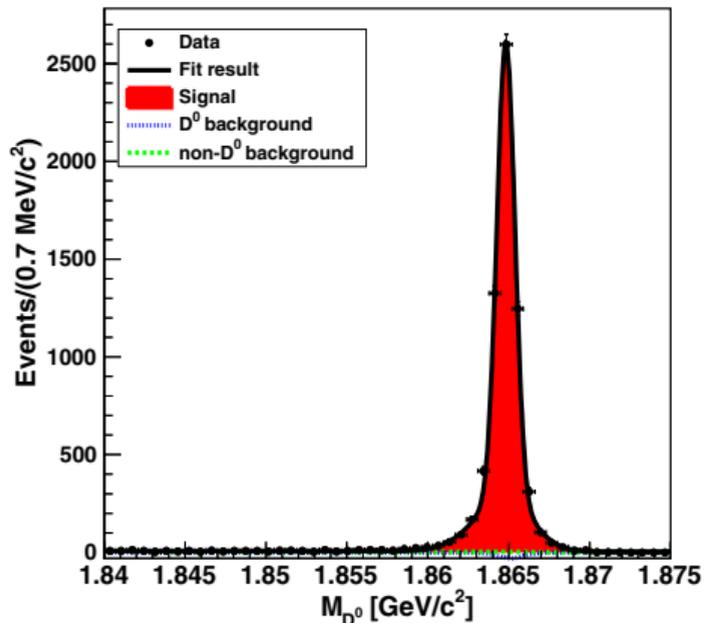
- $(1 + \delta)$ from E.A. Kuraev and V.S. Fadin, Sov. J. Nucl. Phys. 41, 466 (1985)
- $|1 - \Pi(s)|^2$ from S. Actis *et al.*, Eur. Phys. J. C 66, 585 (2010) and F. Ignatov, <http://cmd.inp.nsk.su/~ignatov/vpl/>.
- Limits are obtained from Bayesian method, using Markov Chain Monte Carlo¹
 - * logarithmic prior for σ_{Born}
 - * gaussian prior for other parameters

¹A. Caldwell, D. Kollar, K. Kröninger, BAT -The Bayesian Analysis Toolkit, Comp. Phys. Comm. 180, 2197 (2009).

Results – Limits on $\mathcal{B} \times \sigma_{\text{Born}}$



Control sample study



2D fit results for the control channel $D^0 \rightarrow K^- \pi^+$