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Searches for dark matter with e+e- collider

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Researches on Dark Matter Using e^+ e^- Collider

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Higgs boson enables the Standard Model (SM) to be established. However, we do not know much about dark matter which occupies approximately six times of the SM particles in universe besides having mass. The interactions of dark matter is much weaker than that of the SM. Further, its mass range is very wide, from the order of eV to PeV. Therefore, many experiments have contributed to search for dark matter by indirect, direct and accelerator research. This paper reviews researches on dark matter using accelerator, especially the e^+ e^- collider, from the viewpoint of experimental high energy physicists.

Keywords: dark matter, e^+ e^- collider, particle physics, astronomical physics

1. INTRODUCTION

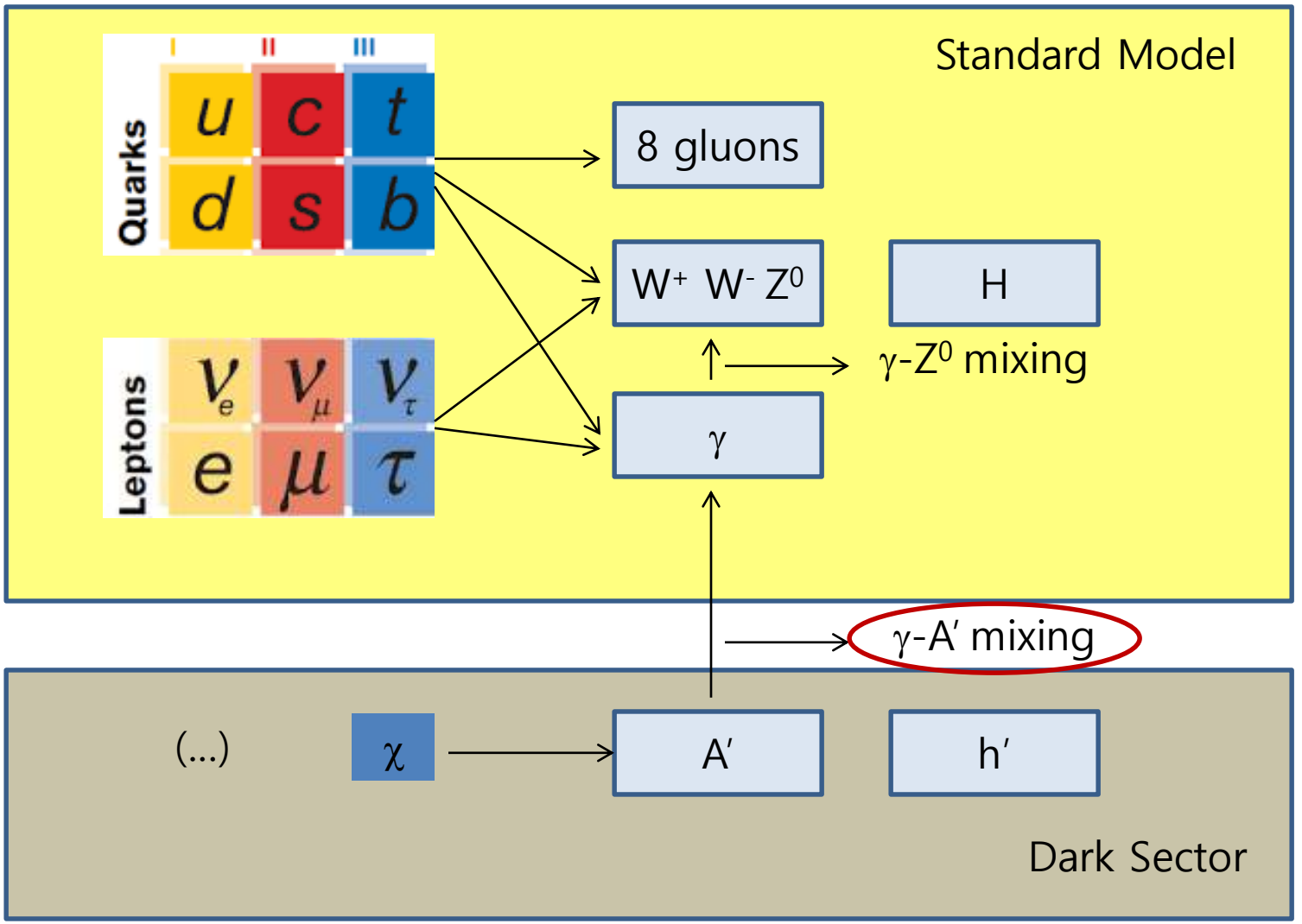
While Higgs boson enables the Standard Model (SM) to be established (ATLAS Collaboration 2012; CMS Collaboration 2012), it has been still noted to be imperfect since the its velocity is almost zero in the early universe (Cho 2016b). There are three experimental methods: direct detection, indirect detection and accelerator detection (Cho 2017). Table 1 shows the experimental types for the accelerator detection (Alexander et al. 2016).

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I. Introduction
II. Dark Matter with e+e- collider
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I. Introduction

Dark Sector


Standard Model
I
II
III
Quarks
u
c
t
d
s
b
Leptons
ν_e
ν_μ
ν_τ
e
μ
τ
8 gluons
W+ W- Z0
H
γ-Z0 mixing
γ
γ-A′ mixing
(…)
χ
A′
h′
Dark Sector

Notation

- Dark photon
  - Heavy photon
  - Dark force
  - Light dark gauge boson

  $=A' = A = A_D$ = U-boson
- Dark higgs

  - $h'=h^0 = H_D$ …
- Kinetic mixing $\varepsilon^2 = \kappa^2 = \chi^2 = \alpha'/\alpha$

- Dark sector constant
  - $\alpha_D = \alpha' = g_D^2 / 4\pi$
- Dark sector
  - Hidden sector
  - Secluded sector
  - …

II. Dark Matter with e+e- Collider

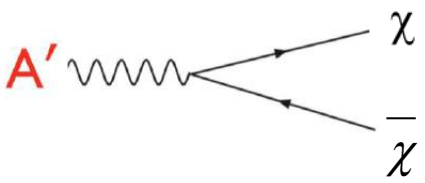
Dark Matter at e+e- collider

- Intensity Frontier
- Fixed CM energy
- Sensitive to light DM: a few MeV/c^2 ~ 5GeV/c^2
- Relatively free from unitarity or validity of EFT
- Clean signal and low background
- Both prompt decay and displacement decay

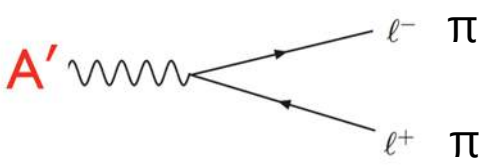
Dark Sector Type

Type:

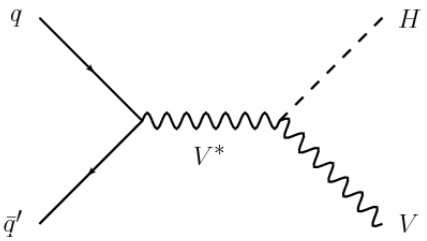
1. Dark Photon to Dark Matter
2. Dark Photon to SM
3. Higgs-strahlung
4. A′ couples only to heavy leptons



Type 1



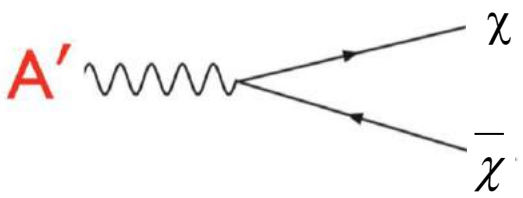
Type2, 4



Type 3

Type1. Dark Photon to DM

- A′ decay to DM

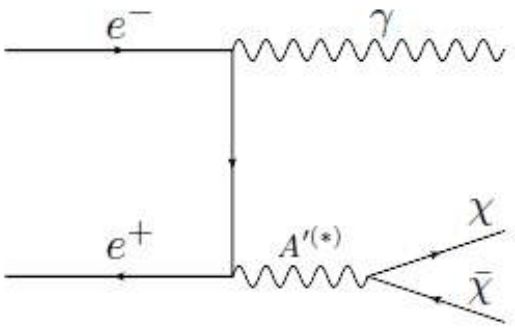


Eassig, et al, JHEP 11, 167 (2013).

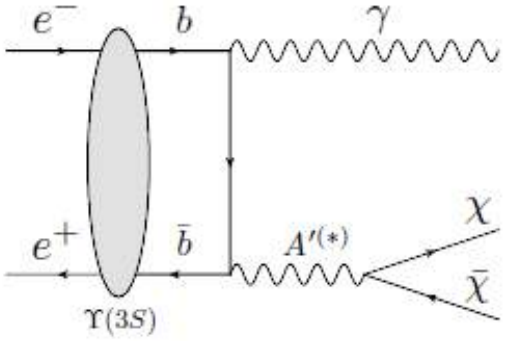
Eassig, ArXiv: 1309.5084 [hep-ph]

Neutral under SU(3)XSU(2)XU(1)

- Two body decay



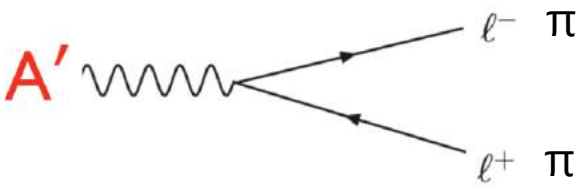
- Upsilon decay



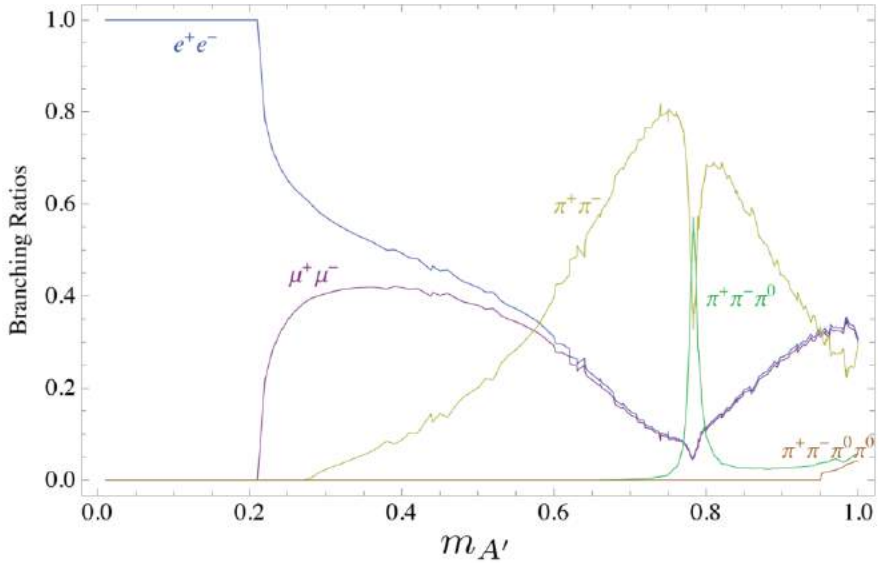
One photon + missing E_T $\quad E^*_\gamma = (s - M^2_{A'})/2\sqrt{s}$

Type2. Dark Photon to SM

A′ can decay directly to Standard Model



($A' \rightarrow$ hidden sector also possible)

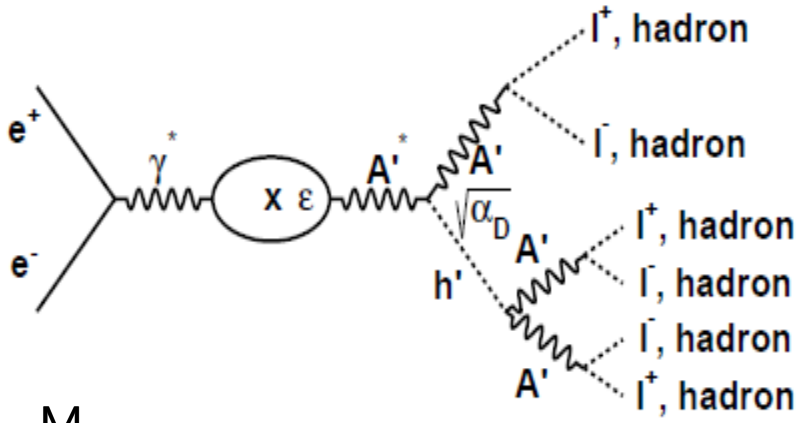


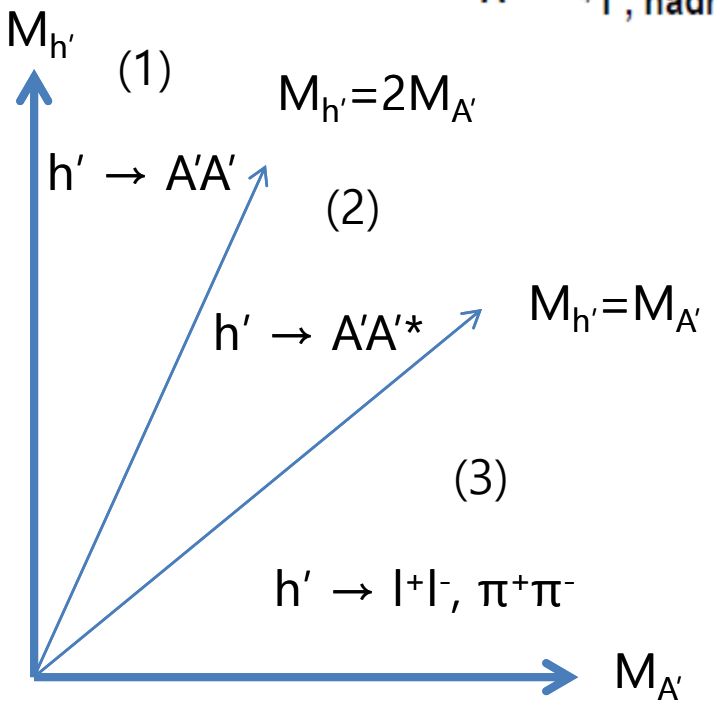
ArXiv: 0903.0363 [hep-ph]

Broad array of searches needed and underway

ArXiv: 0903.0363 [hep-ph]

Type3. Higgs-Strahlung





- h′ decays depending on $M_{h'}$ and $M_{A'}$.
- To measure the coupling constant of the dark photon to the dark higgs, α_D

Case 1) $M_{h'} > 2M_{A'}$: h′ → A′A′, very low background

- Exclusive: 3 charged track pairs with same invariant mass and total energy of event
- Inclusive: 2 charged track pairs, same invariant mass, third A from 4 mom. of e+e- system

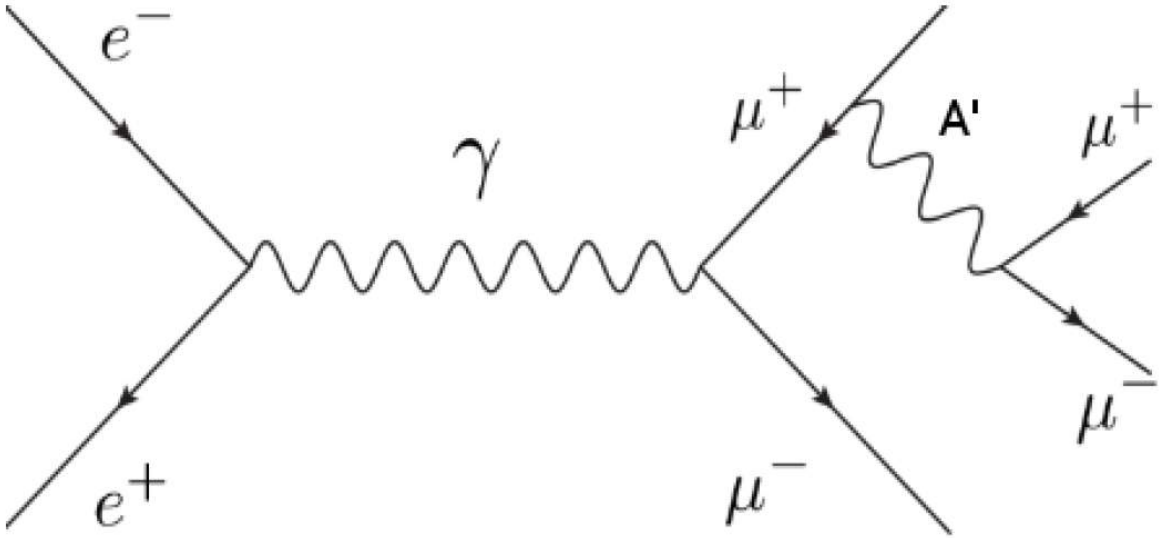
Case 2) $M_{A'} < M_{h'} < 2M_{A'}$: h′ → A′A′*

Case 3) $M_{h'} < M_{A'}$: h′ long-lived and h′ → l^+l^-, $\pi^+\pi^-$

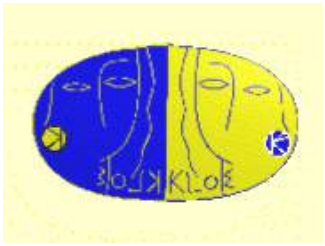
Type4. A′ couples only to heavy leptons

Proposed by Shuve, Pospolov, and al.:

- If SM fields charged under dark force, lepton universality may be broken
  $=>$ A' may decay only to heavy leptons
  - Can explain the muon anomoulus magnetic moment
  - Proton radius extracted by Lamb shift in muonic hydrogen
- $A' \to \nu\nu$ if A' couples directly to left-handed leptons and $m_{A'} < 2m_\mu$
- Focus on: $e^+e^- \to \mu^+\mu^- A'$, $A' \to \mu^+\mu^-$



III. The e+e- collider experiments



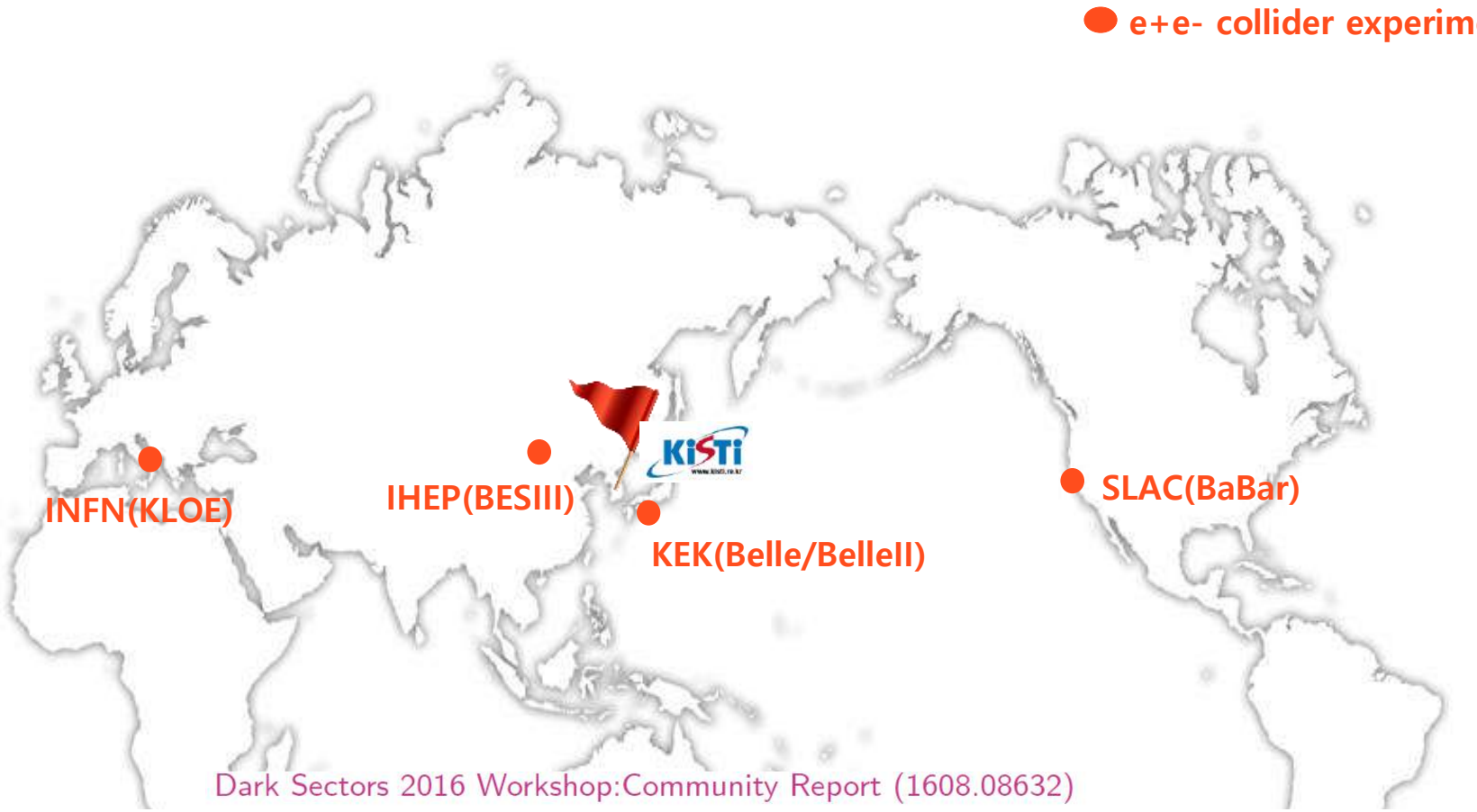








EXPERIMENTS



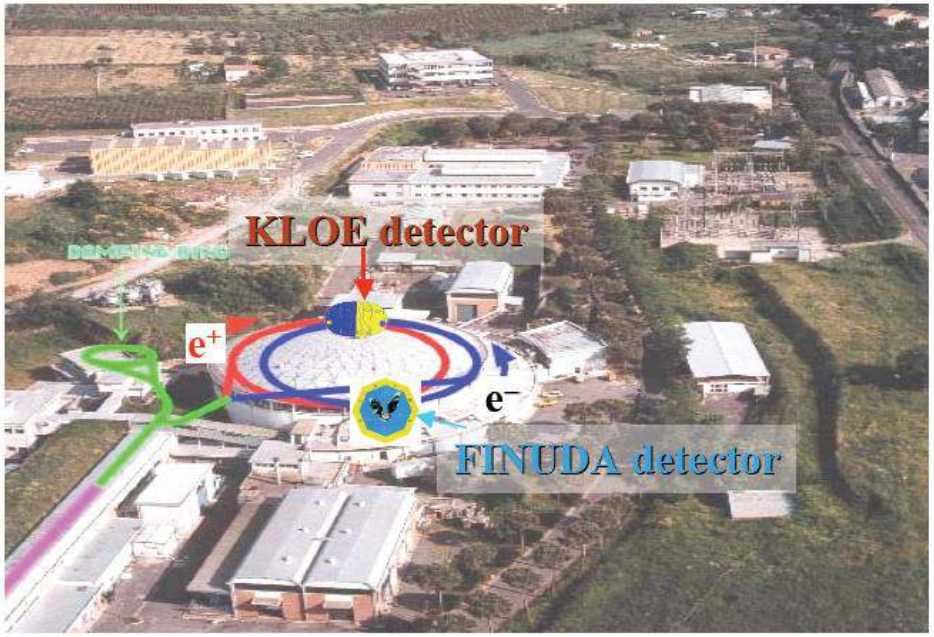
Dark Sectors 2016 Workshop:Community Report (1608.08632)

Exp	Lab	Product	Detect	M(MeV)	Res (MeV)	Beam	EBeam (GeV)	Ibeam/Lim	Run
BES-III	BEPC II	several	vis/in	$\lesssim$ 5GeV	1	e^+e^-	$\leq$4.63	$10^{33} cm^{-2}/s$	2008
BaBar	PEP II	several	vis/in	$\lesssim$ 12GeV	1–5	e^+e^-	9 × 3.1	$3 \times 10^{33} cm^{-2}/s$	2008
KLOE 2	Frascati	several	vis/in	$<$ 1.1GeV	1.5	e^+e^-	0.51	$2 \times 10^{32} cm^{-2}/s$	2014
BELLE	KEKB	several	vis/in	$\lesssim$ 10GeV	1–5	e^+e^-	8 × 3.5	$2 \times 10^{34} cm^{-2}/s$	2008
Belle II	SuperKEK	several	vis/in	$\lesssim$ 10GeV	1–5	e^+e^-	7 × 4	$1 \sim 10 ab^{-1}/y$	2018

Experiment vs. Dark Sector

No.	Exper-iment	Type1. Dark Matter	Type2. Dark photon to SM	Type3. Higg-Strahlung	Type4. Heavy lepton
1)	KLOE		• 2 charged lepton+one photon • 2 charged lepton + η	μμ+ missing $E_T(h')$	
2)	BES III		• 2 charged lepton+one photon		
3)	BaBar	one photon + missing E_T	2 charge tracks + one photon	• 3 charged track pairs • 4 or more charged tracks	
4)	Belle		2 charge track + one photon	3 charged track pairs	• Two lepton pairs • A lepton pairs + missing E_T
5)	Belle II	one photon + missing E_T	2 Charge Track one photon	3 charged track pairs	• Two lepton pairs • A lepton pairs + missing E_T

1) KLOE Experiment



Energy [GeV]	0.51
Trajectory length [m]	97.69
RF frequency [MHz]	368.26
Harmonic number	120
Damping time, τ_E/τ_x [ms]	17.8/36.0
Bunch length at 0 current [cm]	1.0
Bunch length at full current [cm]	2.5
Beam currents e-/e+ [Amps]	1.7/1.3
Number of colliding bunches	107
Beta functions β_x/β_y [m]	1.6/0.017
Emittance, ε_x [mm·mrad] (KLOE)	0.34
Emittance ratio at 0 current [%]	0.25
Emittance ratio at full current [%]	0.60
e- Tunes Qx/Qy	0.091/0.1660
e+ Tunes Qx/Qy	0.1090/0.1910

- $e^+e^- \rightarrow \phi \quad \sqrt{s} \sim m_\phi = 1019.4$ MeV
- beams cross at an angle of 12.5 mrad
- LAB momentum $p_\phi \sim 13$ MeV/c

BR's for selected ϕ decays	
K^+K^-	49.1%
K_SK_L	34.1%
$\rho\pi + \pi^+\pi^-\pi^0$	15.5%

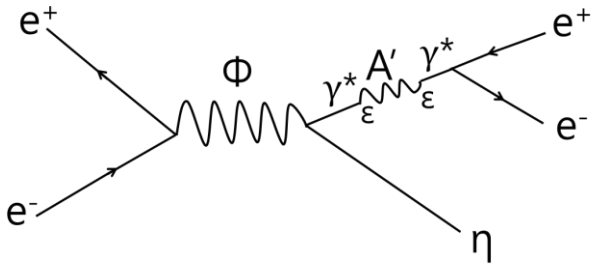
2

- Physics Program
  - Kaon physics, Spectroscopy, hadron cross-section, $\gamma\gamma$ physics, Dark sector

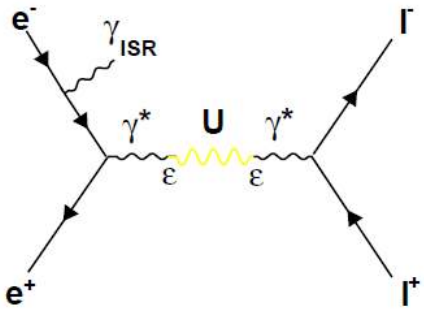
Type2. Dark Photon to SM

- Dark photon (ηe^+e^-)

$$\phi \to \eta A' \qquad A' \to e^+e^- \qquad \eta \to \pi^+\pi^-\pi^0$$



- Dark photon ($e^+e^-\gamma$ & $\mu^+\mu^-\gamma$)

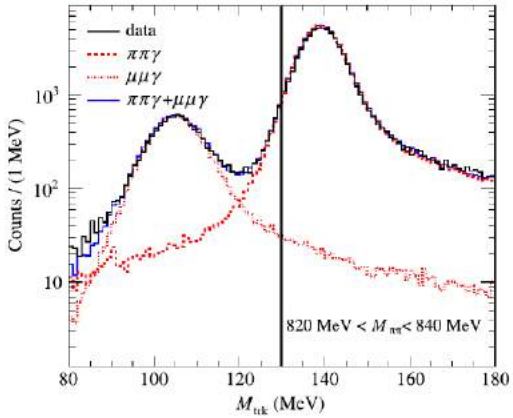


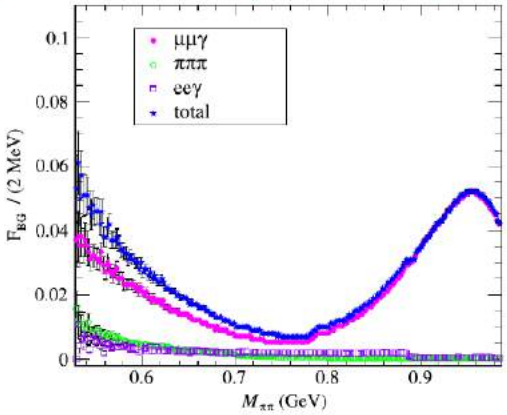
ArXiv: 1501.05517 [hep-ex]

2. Dark Photon to SM(2/2)

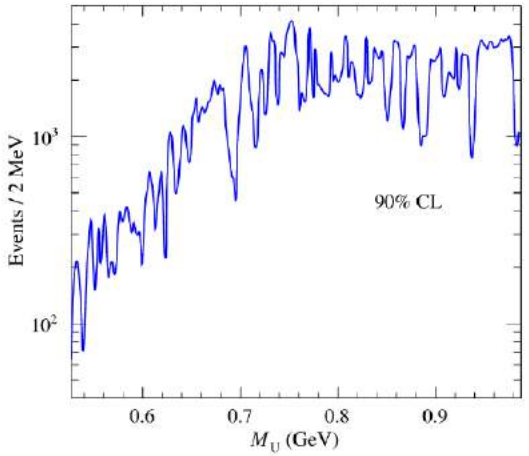
- Dark photon ($\pi^+\pi^-\gamma$ & $\mu^+\mu^-\gamma$)

Limit on the production of a new vector boson in $e^+e^- \to U\gamma$, $U \to \pi^+\pi^-$ Phys.Lett.B 757(2016) p.356



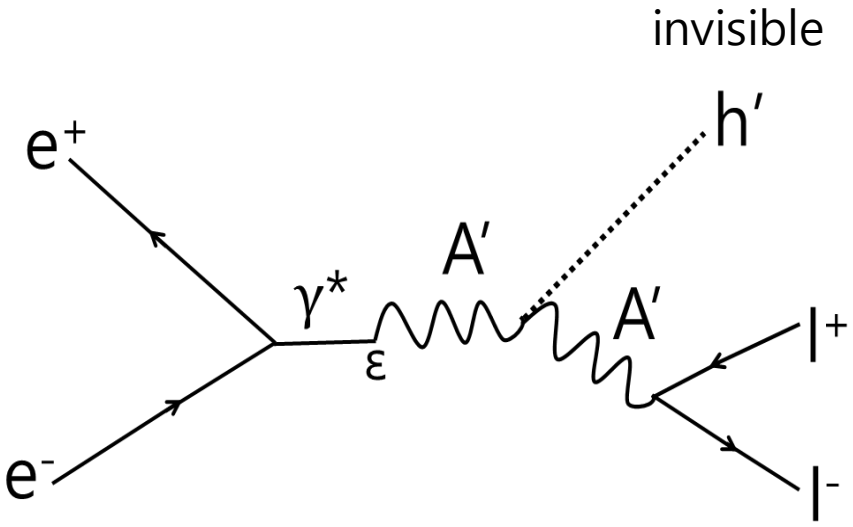


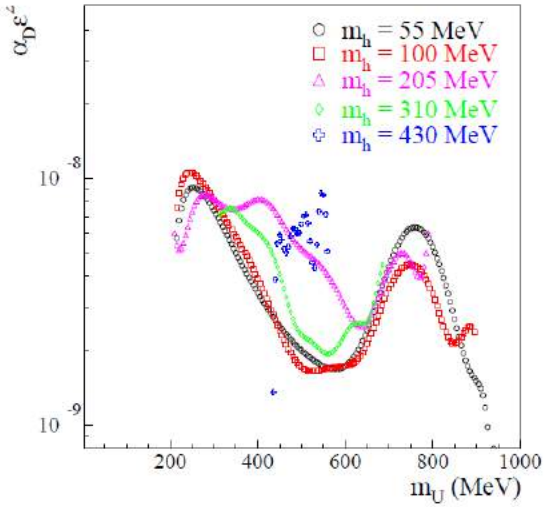
- $e^+e^- \to A'\gamma \to \pi^+\pi^-\gamma$
- no invisible decay assumed due to $m_{A'} < m_\chi$
- **no** signal found
- new constraints on ε^2

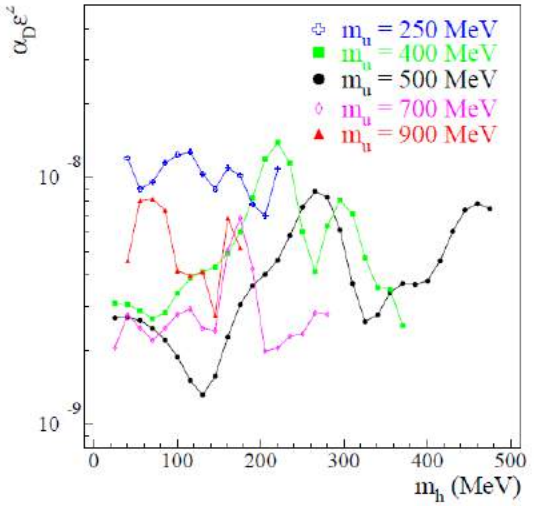


Type3. Higgs-Strahlung

- μμ+ missing $E_T(h')$
- Case 3) If $M_{h'} < M_{A'}$
  - h′ long-lived invisible

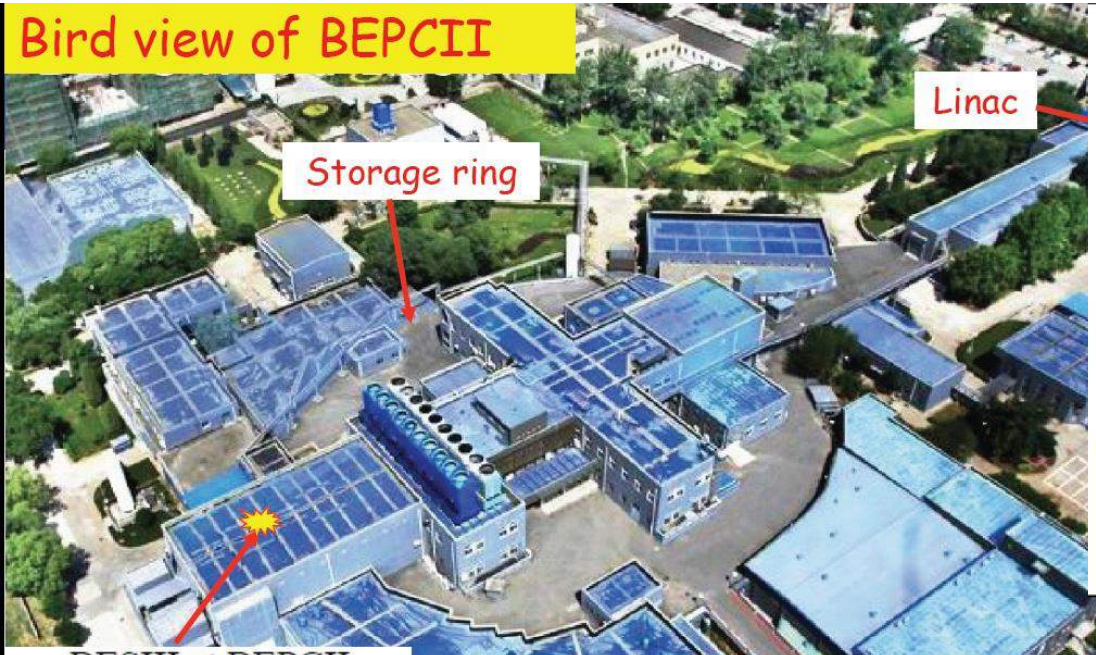






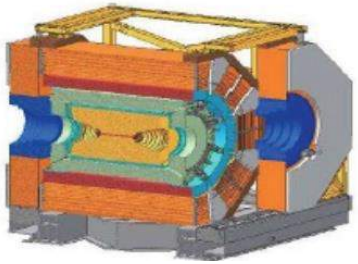
ArXiv: 1501.05517 [hep-ex]

2) BES III Experiment





BESIII at BEPCII





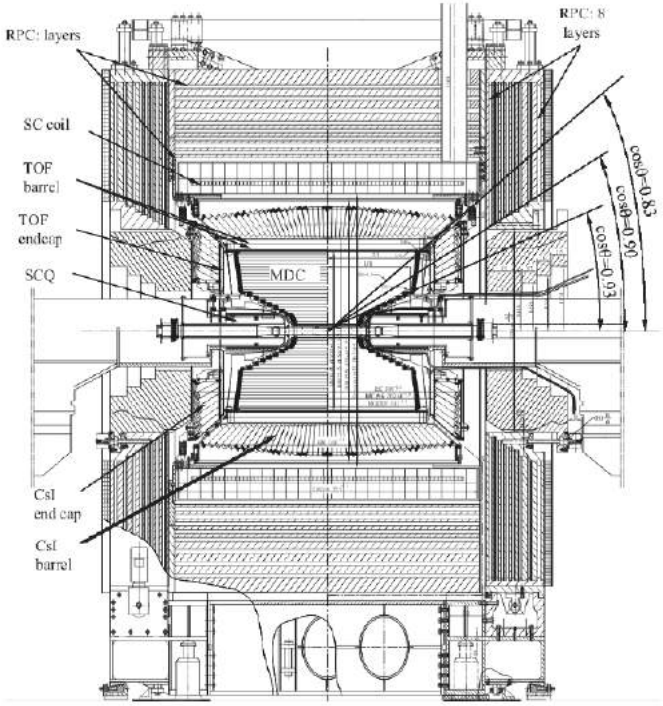
τ –charm physics

- Charmonium(-like) physics
- Light hadron spectroscopy
- Charm physics
- τ physics

Zhiyong Wang (2015)

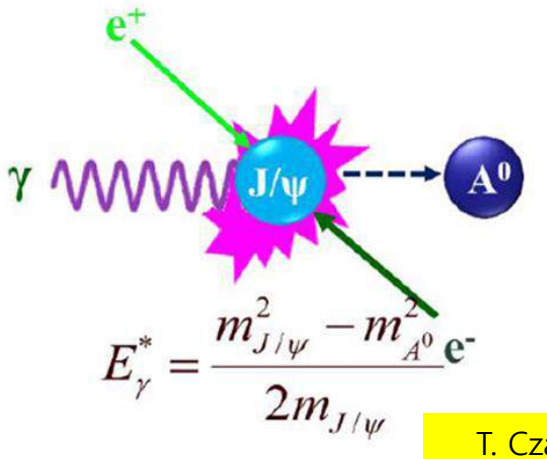
BES III Detector

Design and construction of the BESIII detector Nucl.Instr.and Meth.A, 614(2010), p.345



- Symmetric Collider
- 2×1.89 GeV
- Charm factory
- $\varepsilon < 10^{-2}$

- $2 < \sqrt{s} < 4.63$ GeV collision energy
- $e^+e^- \to A'\gamma_{\mathrm{ISR}} \to \ell^+\ell^-\gamma_{\mathrm{ISR}}$

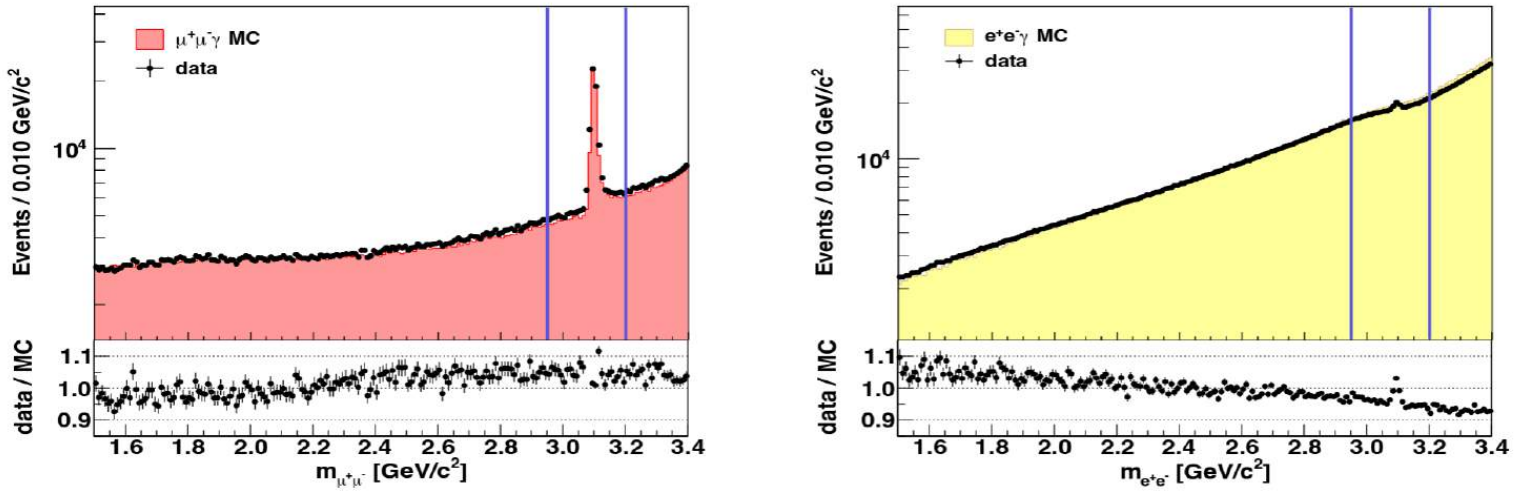


T. Czank

Type2. Dark Photon to SM(1/2)

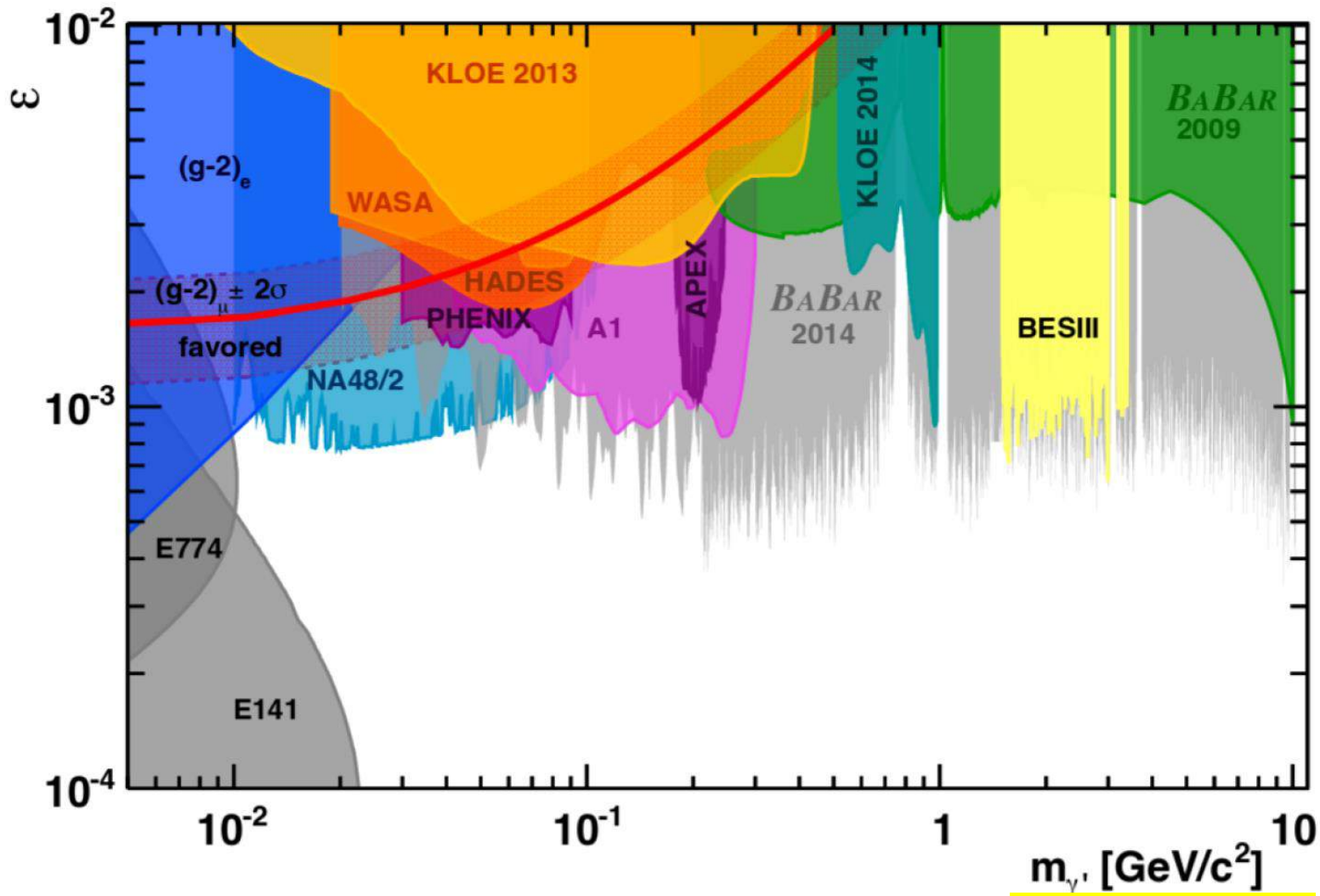
- 2.93 fb^{-1} data taken at $\sqrt{s} = 3.773$ GeV
- $e^+e^- \to e^+e^-(\mu^+\mu^-)\gamma_{\rm ISR}$
- lepton invariant mass **no** obvious increase in $1.5 \sim 3.4$ GeV/c^2

Dark Photon Search in the Mass Range Between 1.5 and 3.4 GeV/c^2 (1705.04265) - 2017



lines for the J/ψ resonance exclusion region

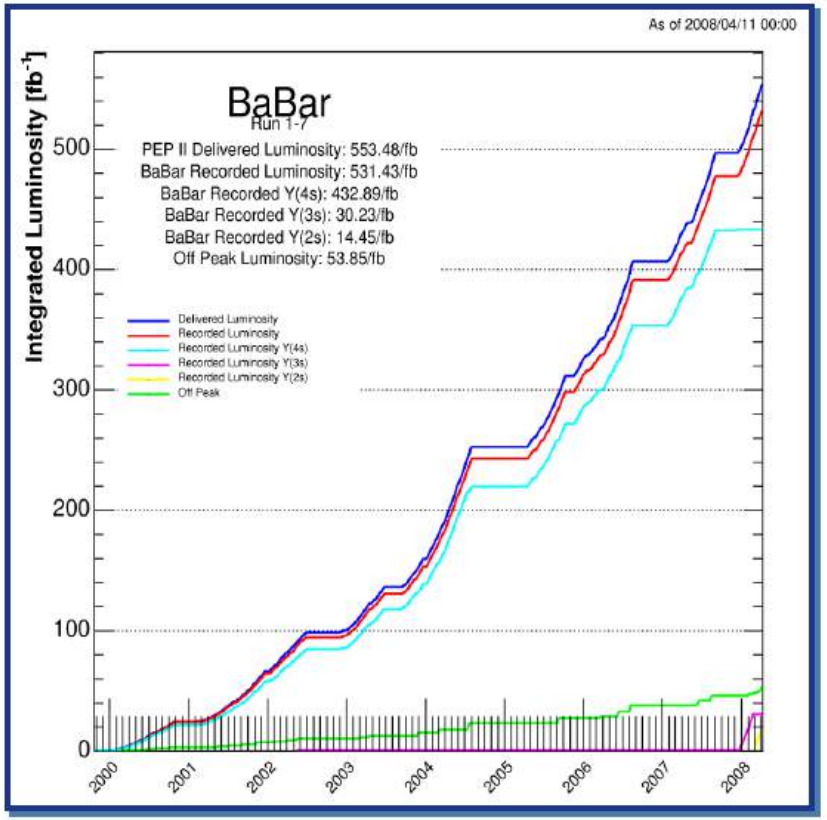
Tyep2. Dark Photon to SM(2/2)

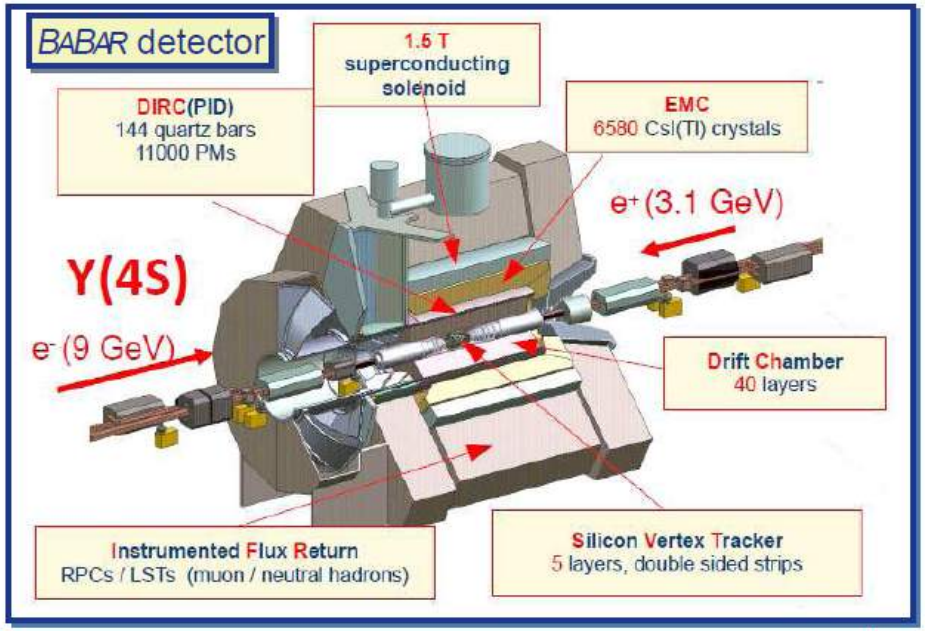


T. Czank

3) BaBar Experiment

BABAR collected ~ 533 fb^{-1} of e^+e^- collisions around the Y(4S) in 1999–2008





data samples

~470·10^6 Y(4S)

~120·10^6 Y(3S)

~100·10^6 Y(2S)

A. Lusiani (2014)

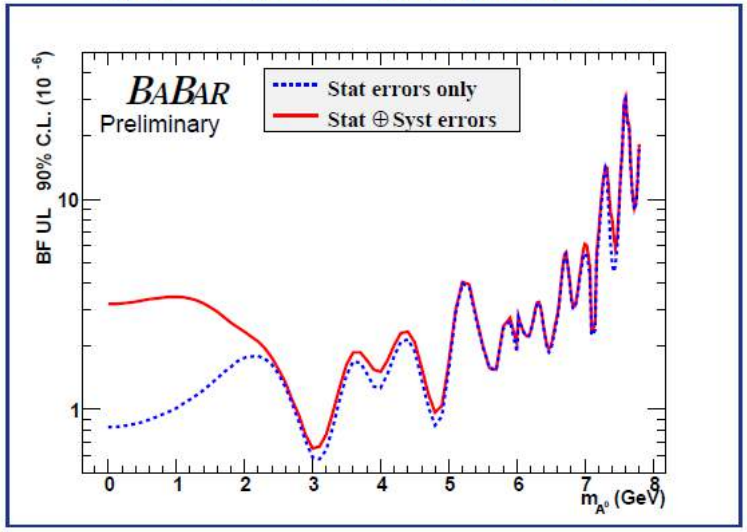
Type1. Dark Photon to DM(1/2)

$\Upsilon(3S) \to \gamma A^0$, $A^0 \to$ invisible arXiv:0808.0017 [hep-ex]

90% CL upper limits on

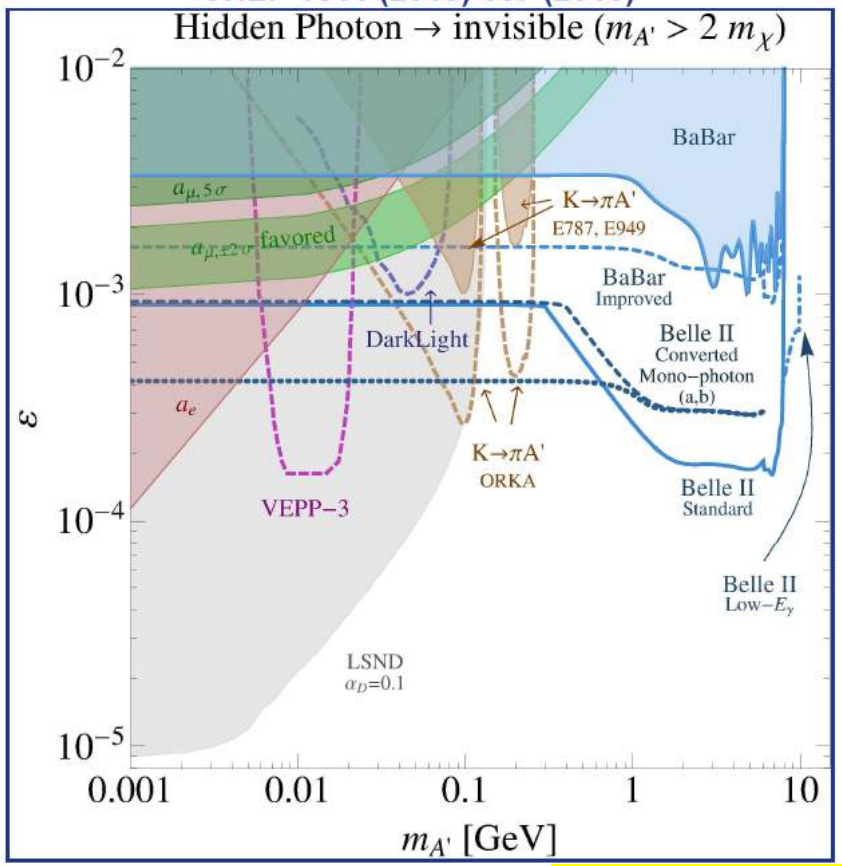
$B(\Upsilon(3S) \to \gamma A^0) \times B(A^0 \to \text{invisible})$

$< (0.7 - 31) \times 10^{-6}$ for $m_{A^0} \leq 7.8$ GeV



Dark Photon constraints by R.Essig et *al.*

JHEP 1311 (2013) 167 (2013)



$$e^+e^- \to \gamma A'(A' \to \chi\bar{\chi})$$

One photon + missing E_T

A. Lusiani (2014)

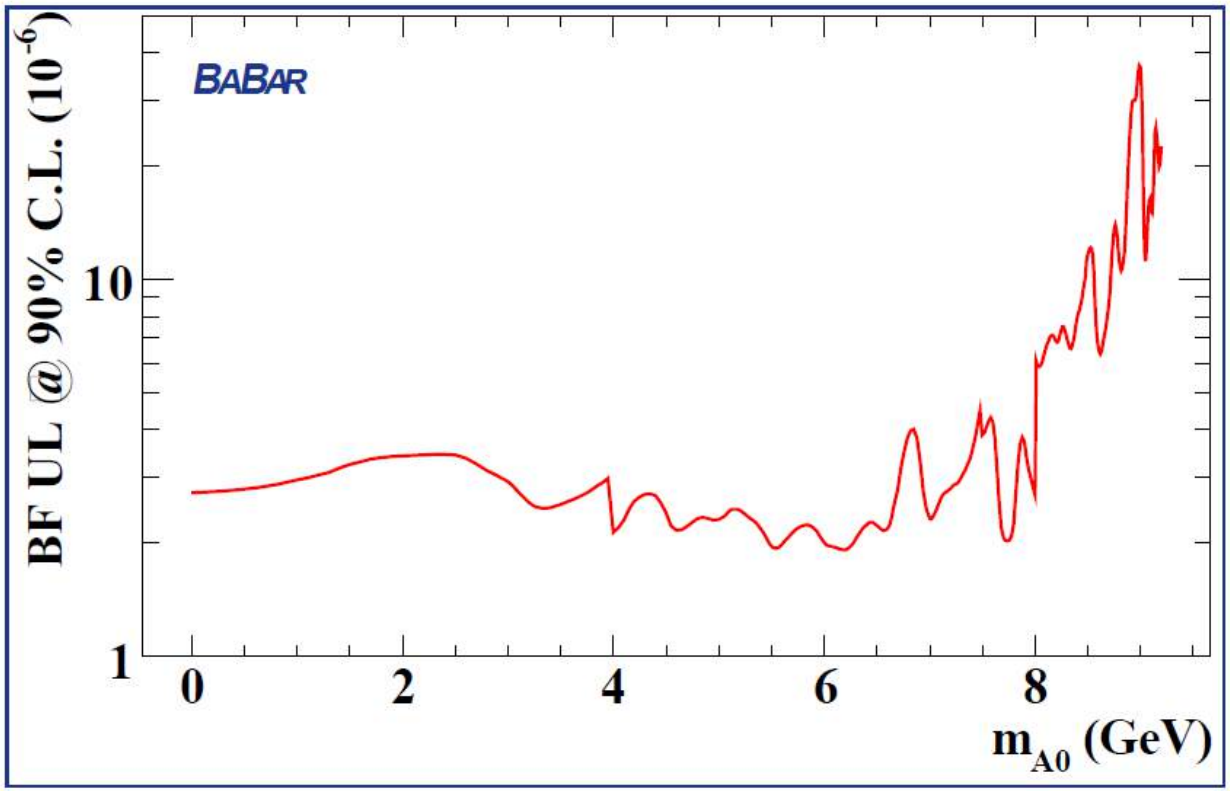
Type1. Dark Photon to DM(2/2)

$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to$ invisible PRL 107 021804 (2011)

90% CL upper limits on $B(\Upsilon(1S) \to \gamma A^0) \times B(A^0 \to \text{invisible})$

$< (1.9–4.5) \times 10^{-6}$ for $m_{A^0} \leq 8.0$ GeV

$< (2.7–37) \times 10^{-6}$ for $m_{A^0} \leq 9.2$ GeV



One photon + missing E_T

A. Lusiani (2014)

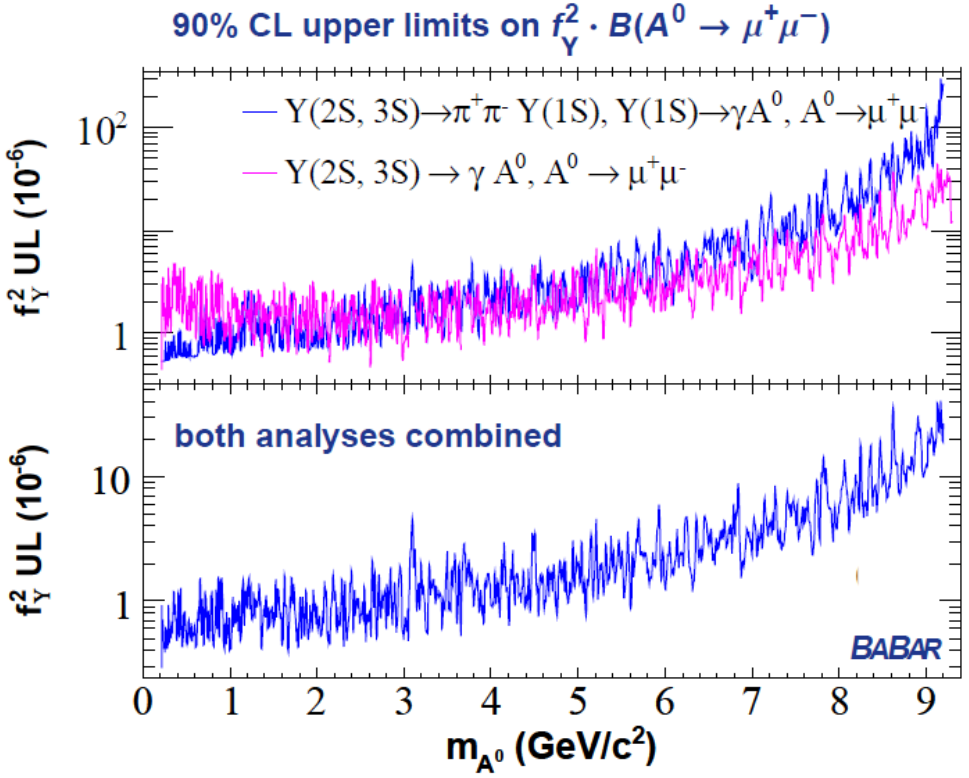
Type2. Dark Photon to SM

Search for $e^+e^- \to \Upsilon(2S, 3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$

2–3 times better than previous 2009 analysis for $m_{A^0} \leq 1.2\,\mathrm{GeV}/c^2$

one photon + μμ

The effective Yukawa coupling (f_Y) of the b quark to the A^0



PRD 87, 031102(R) (2013), arXiv:1210.0287

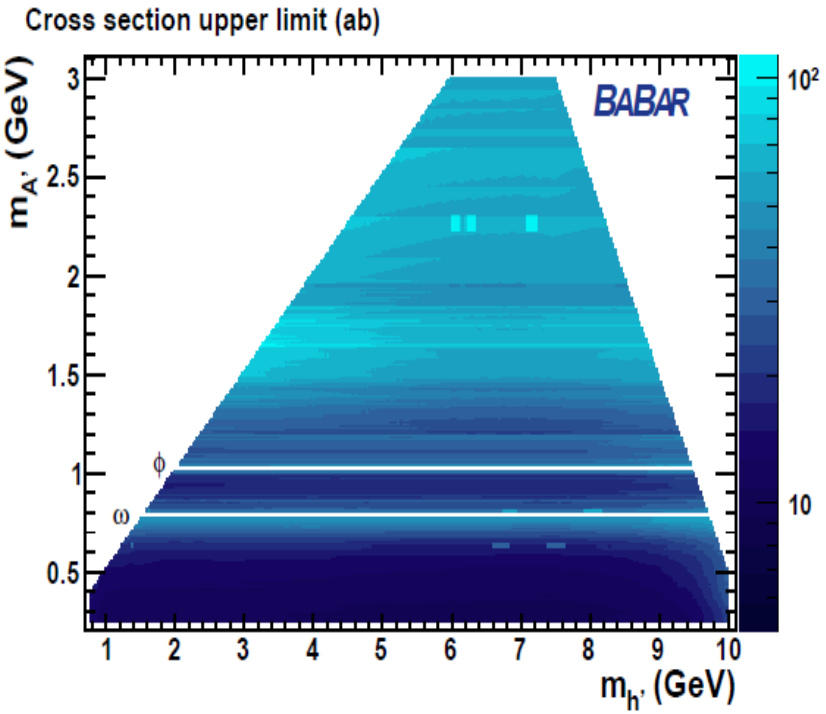
A. Lusiani (2014)

Type3. Higgs-Strahlung

Search for Dark Higgs Boson in *BABAR*, upper limits PRL 108 (2012) 2118

Case 1)

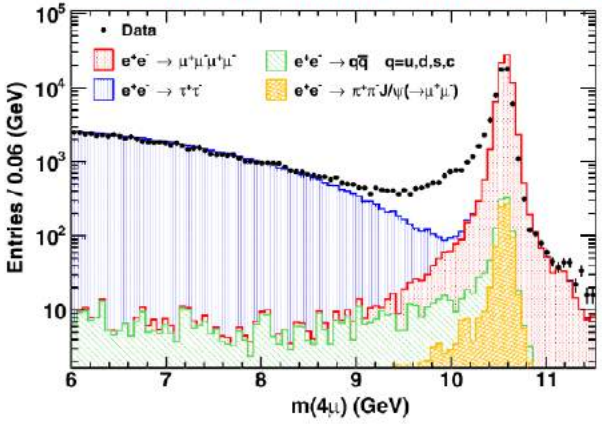
- 90% CL limits on $\sigma(e^+e^- \to h'A', \quad h' \to A'A')$ as function of h' and A' masses
  - ▶ conservative approach, no BKG subtraction
- convert into limits on $\alpha_D \epsilon^2$ ($\alpha_D = g_D^2/4\pi$, g_D = the dark sector gauge coupling)

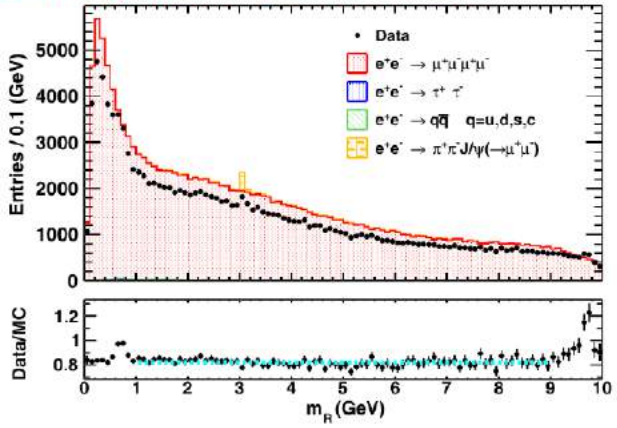


A. Lusiani (2014)

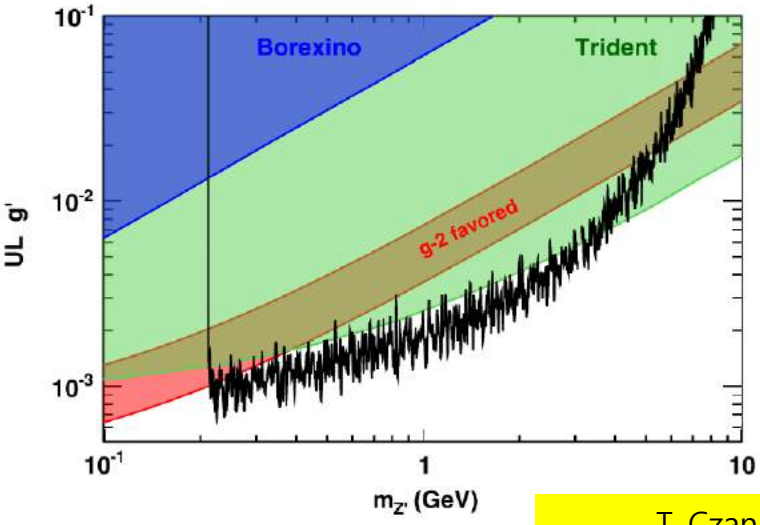
Type4. A′ couples only to heavy leptons

Search for a muonic dark force at BABAR Phys.Rev.D.94.011102 - 2016



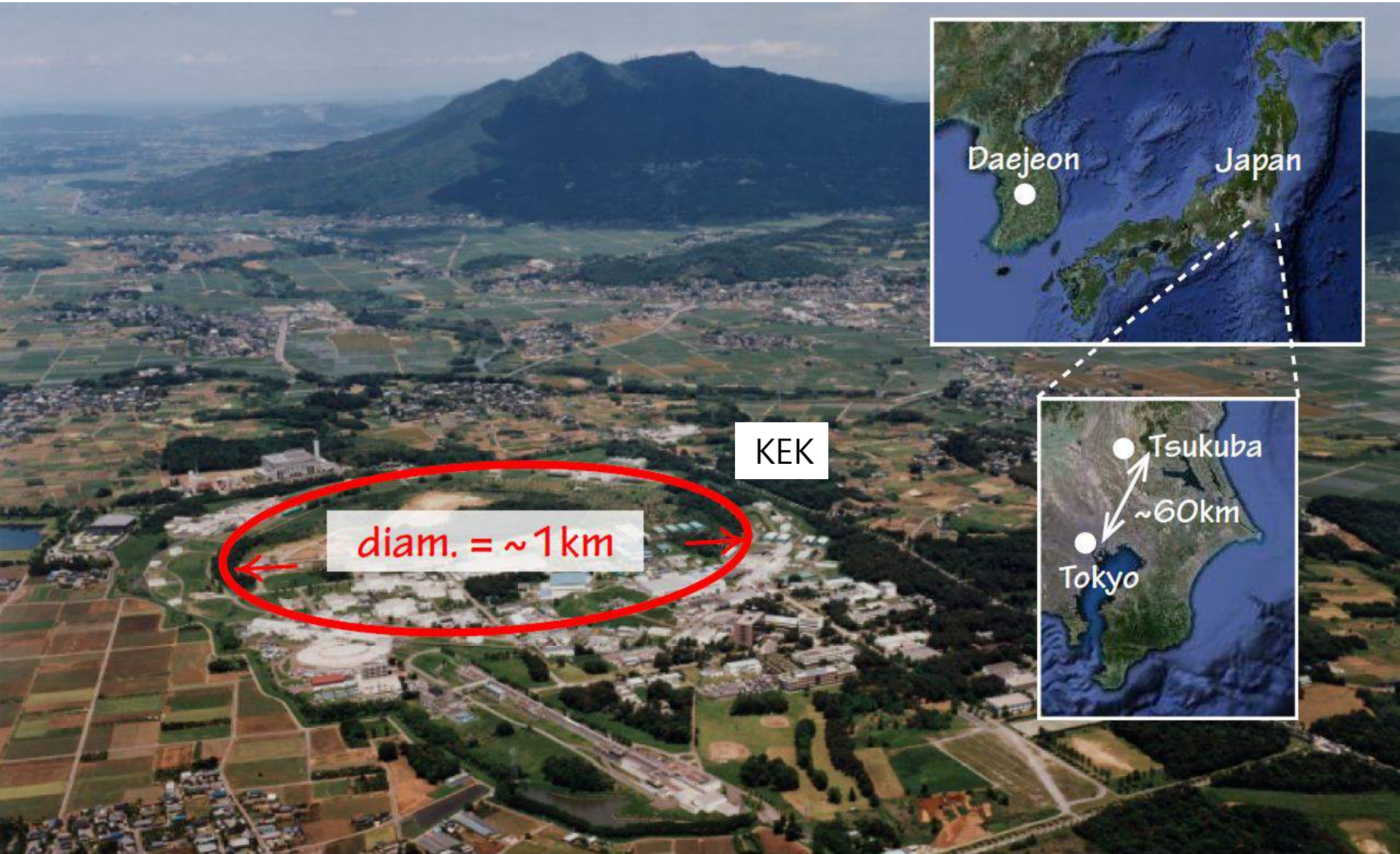


- $e^+e^- \to \mu^+\mu^- Z' \to \mu^+\mu^-\mu^+\mu^-$ search
- Z', lepton coupled dark photon model
- **no** signal found

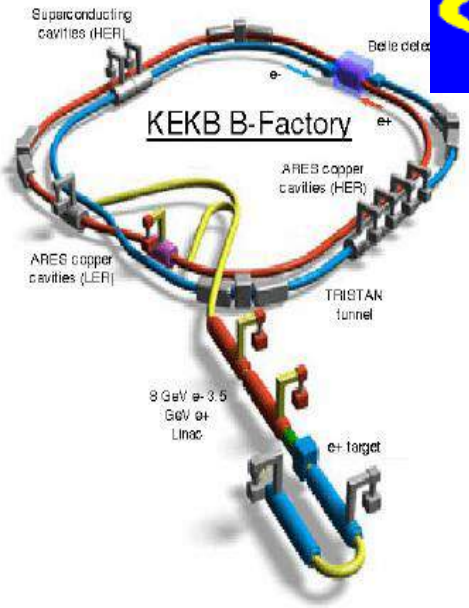


T. Czank

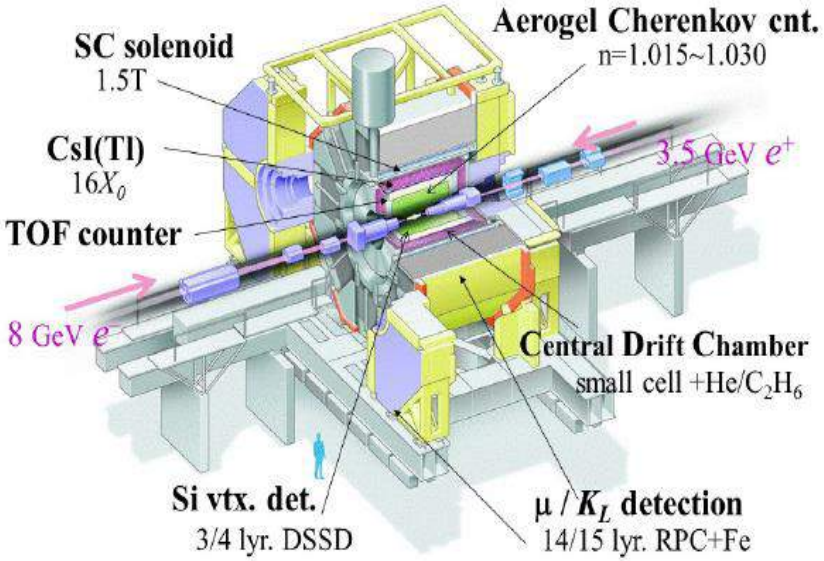
4) Belle Experiment

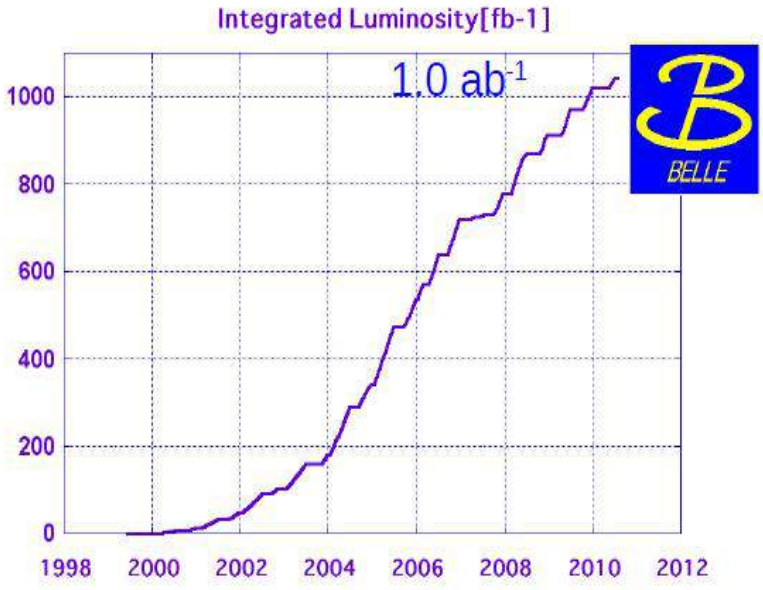






Belle Detector

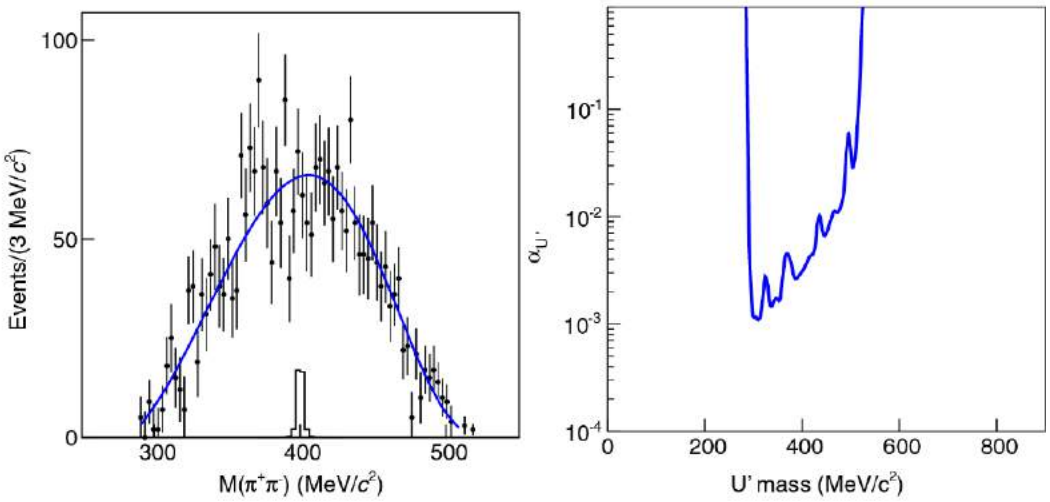




Type2. Dark Photon to SM

Search for a dark vector gauge boson decaying to $\pi^+\pi^-$ using $\eta \to \pi^+\pi^-\gamma$ decays Phys.Rev.D.94.092006

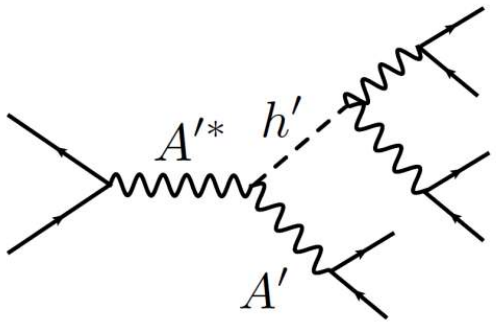
- dark sector gauge boson U'
- $D^{*+} \to D^0\pi^+$, $D^0 \to K^0_S\eta$, $\eta \to U'\gamma$, $U' \to \pi^+\pi^-$
- baryonic fine structure $10^{-3} < \alpha_{U'} < 10^{-2}$
- $290 < U' < 520\mathrm{MeV}/c^2$
- **no** signal found



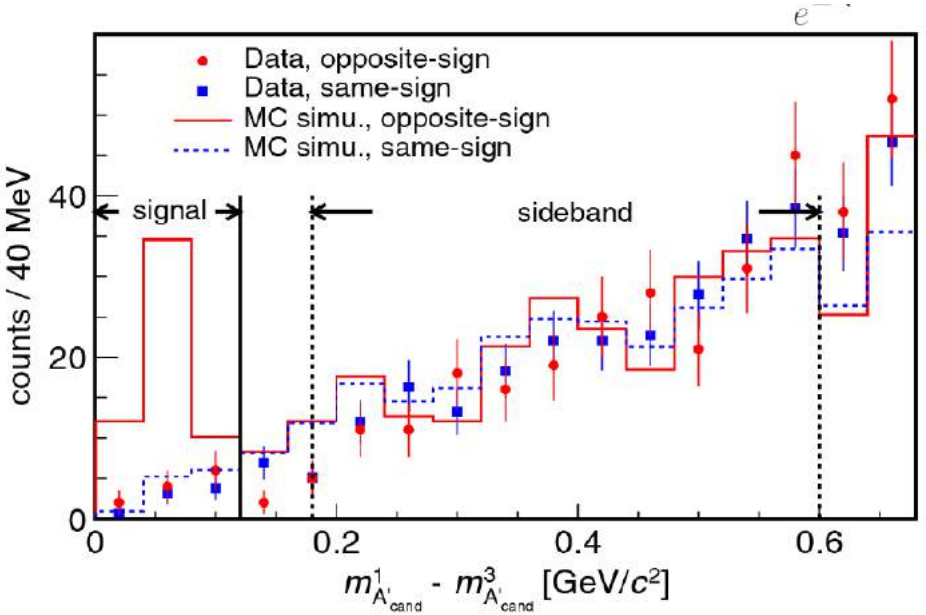
Blue curve is the PDF fitted over the pion pair invariant mass distribution

Type3. Higgs-Strahlung (1/2)

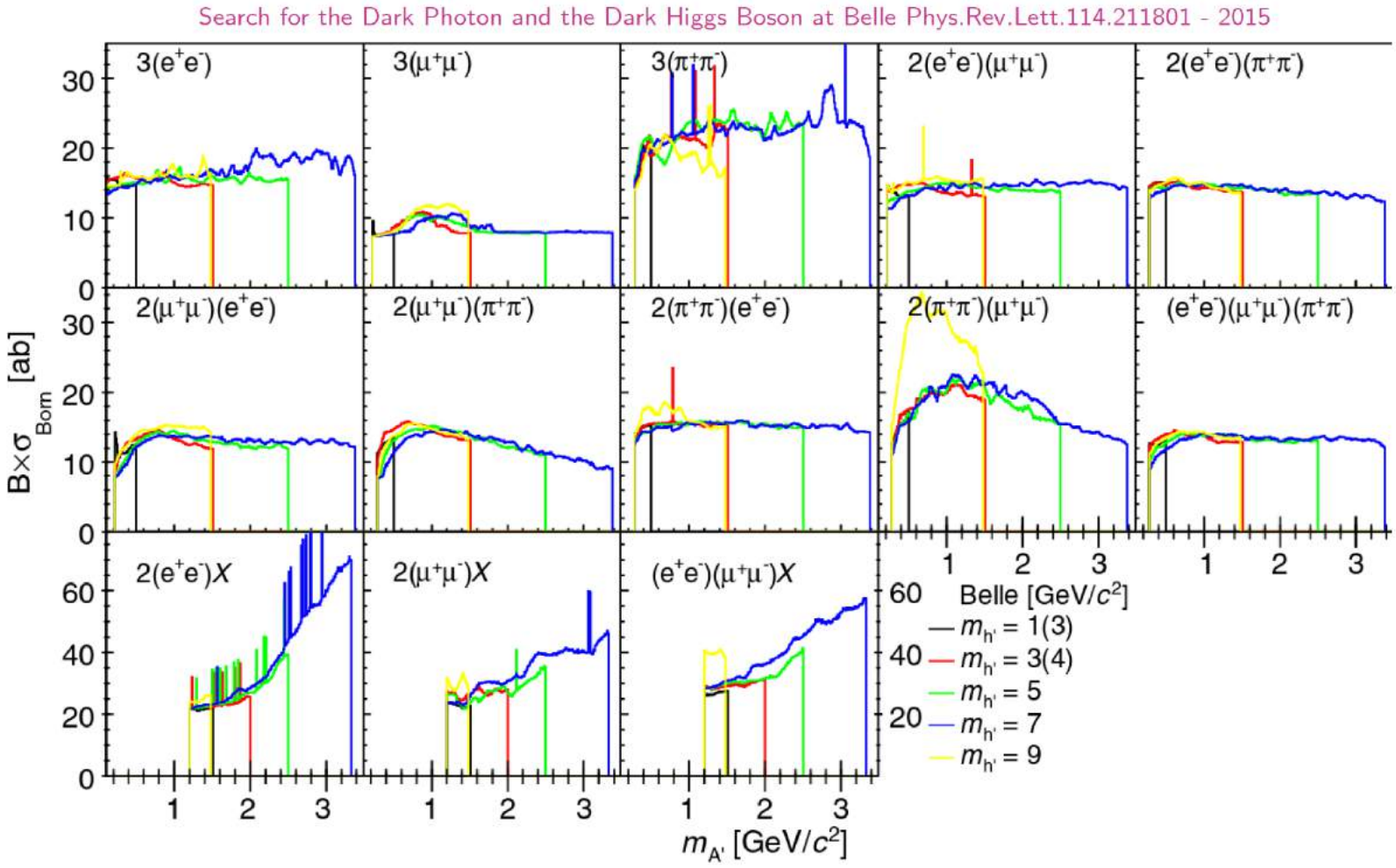
- Case 1) $M_{h'} > 2M_{A'}$: $h' \rightarrow A'A'$,
- Prompt of h' and A'
- 10 exclusive channels: $3(l^+l^-)$, $2(l^+l^-)(\pi^+\pi^-)$, $2(\pi^+\pi^-)$ (l^+l^-), $3(\pi^+\pi^-)$ with $l=e,\mu$
- 3 inclusive channels: $2(l^+l^-)X$ with X dark photon (Missing mass)



light hidden-sector Higgs boson

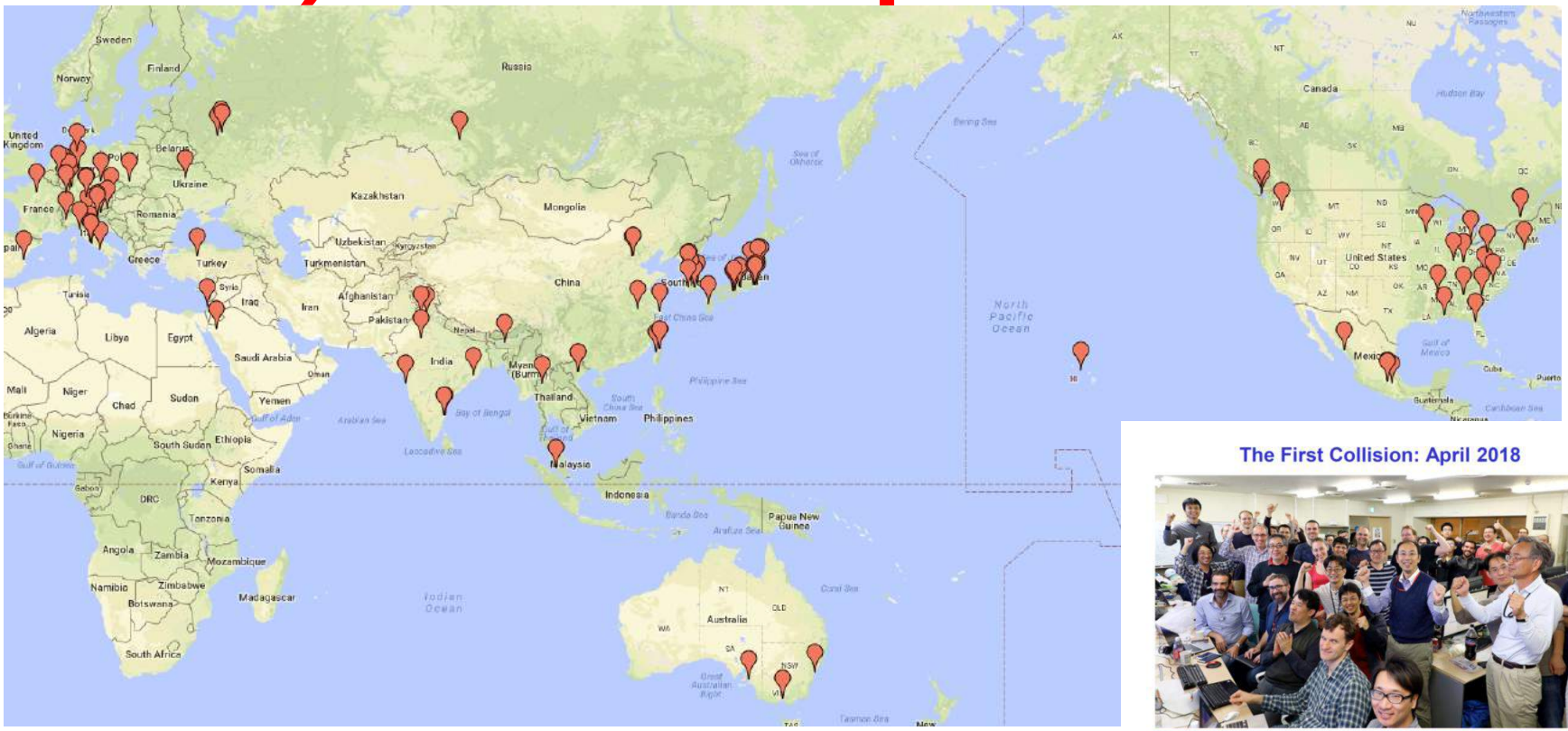


Type3. Higgs-Strahlung (2/2)



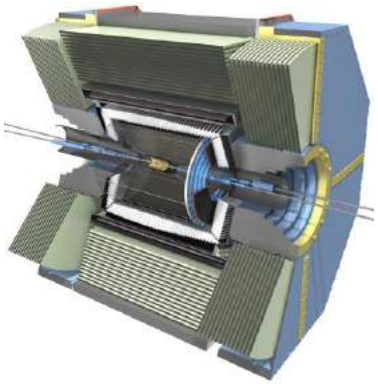
T. Czank

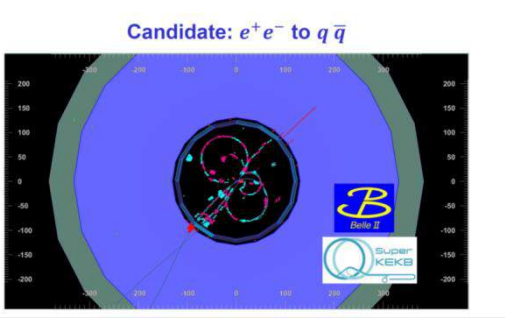
5) Belle II Experiment



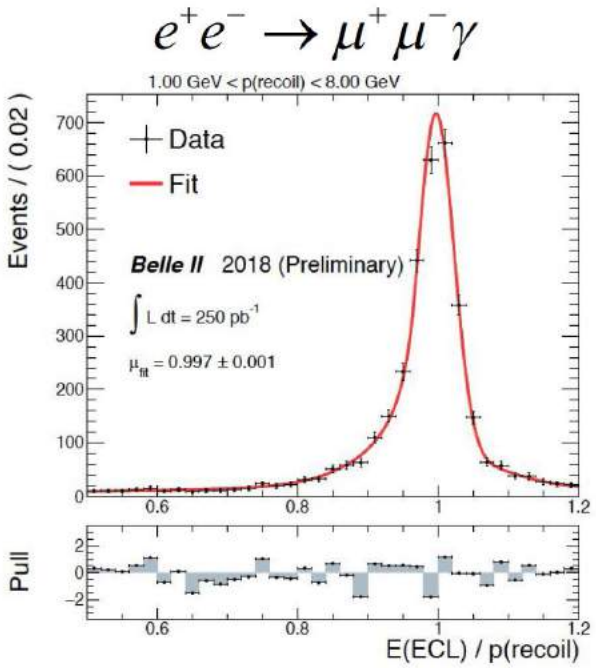
As of January, 2019

910 Collaboration,
113 institutions,
26 countries/regions



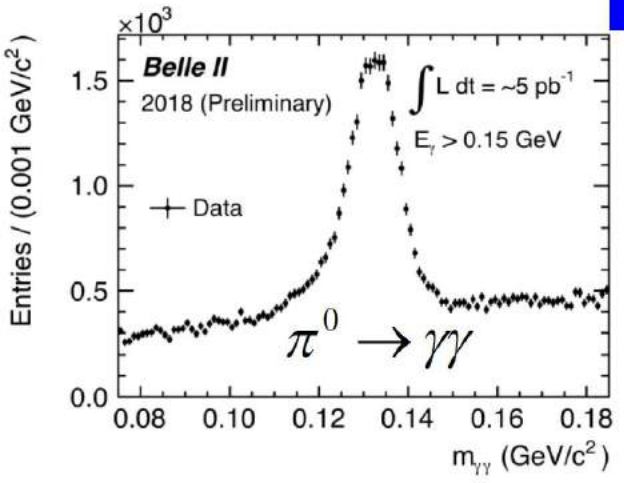


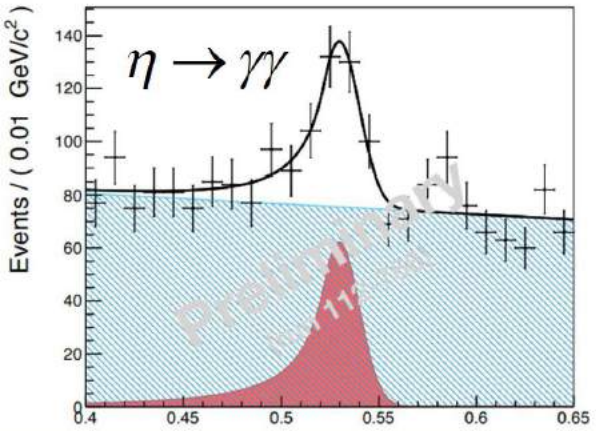
Phase II Events with Photons



Note: Dark sector search

- $e^+e^- \to \gamma A'$
- $e^+e^- \to \gamma ALPS \to \gamma(\gamma\gamma)$
- $e^+e^- \to \ldots$

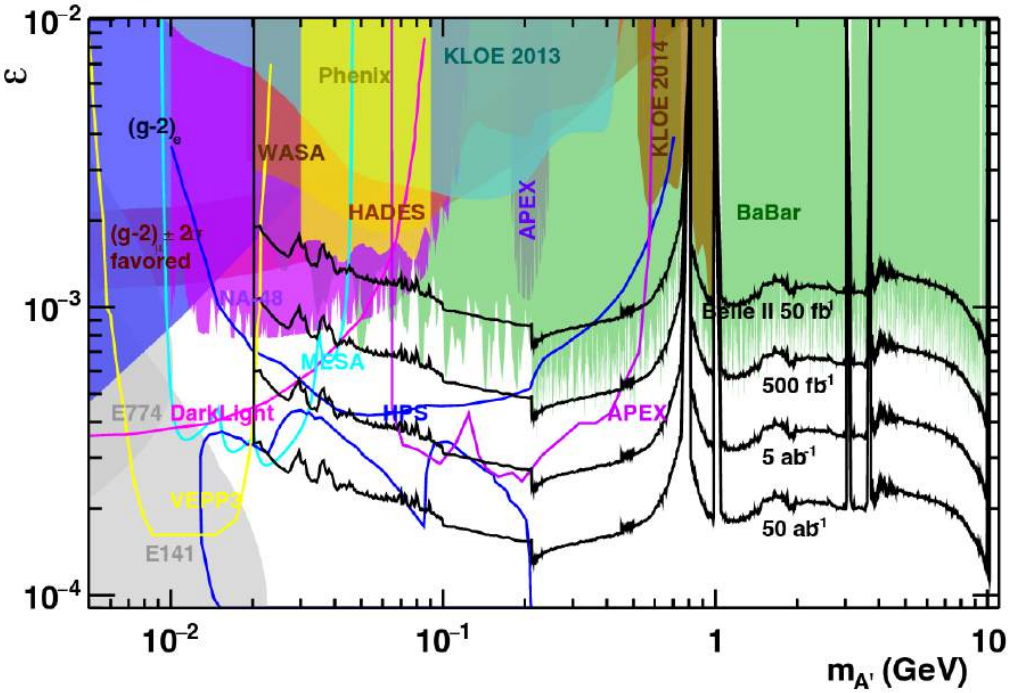




Type1. Dark Photon to DM

- Dark photon decays DM. $e^+e^- \to \gamma A', A' \to \chi\bar{\chi}$
- One photon + missing E_T
- Full luminosity of 50 ab^{-1} and 1% trigger fraction
- Need a single photon trigger at Belle II

C.Hearty (Belle II Collaboration) Dark Sector Workshop 2016



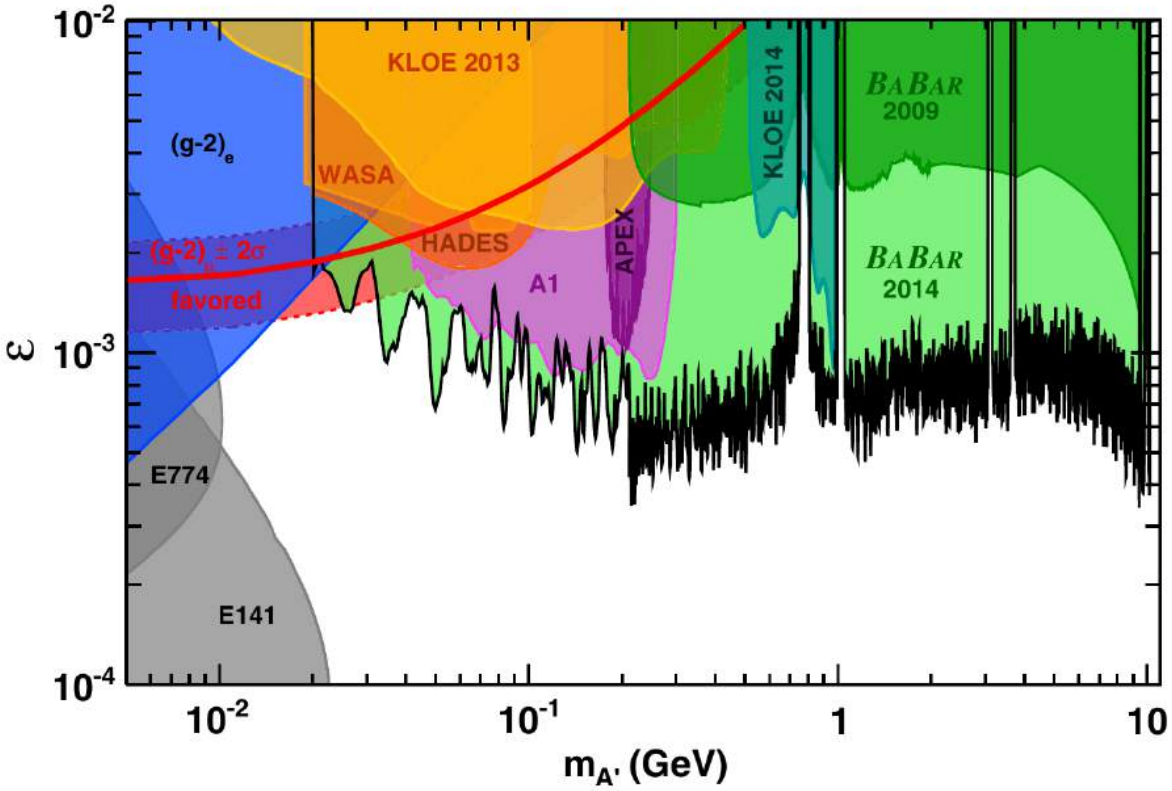
$e^+e^- \to \gamma A' \to \gamma \chi \bar{\chi}$

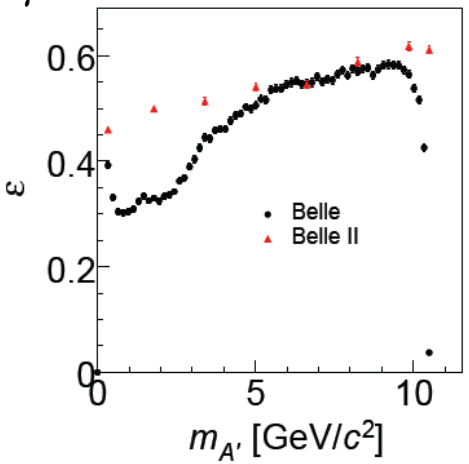
Type2. Dark Photon to SM

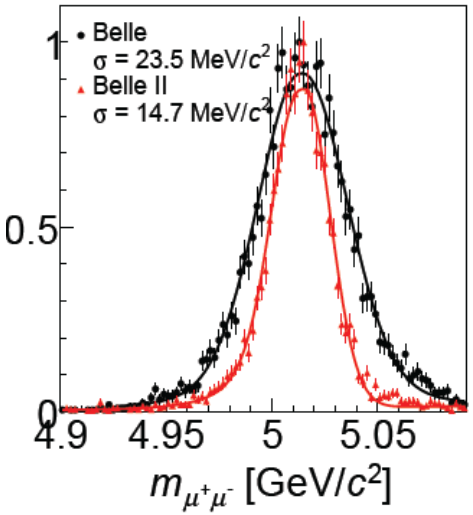
- Belle and Belle II detection efficiency for $A' \to \mu^+\mu^-$

$e^+e^- \to \gamma A' \to \gamma e^+e^-, \gamma\mu^+\mu^-$, *prompt*

J.P.Lees et al.(BaBar Collaboration) Phys.Rev.Lett. 113 201801

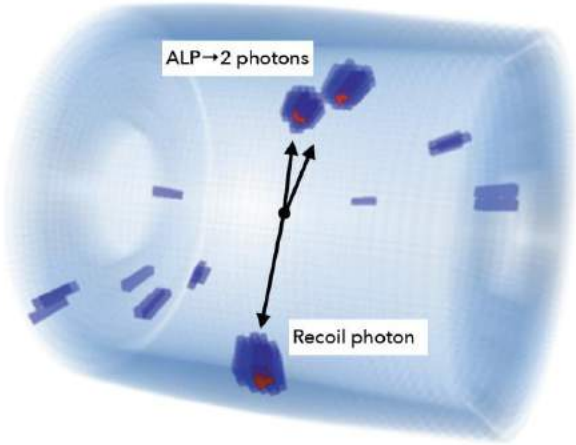


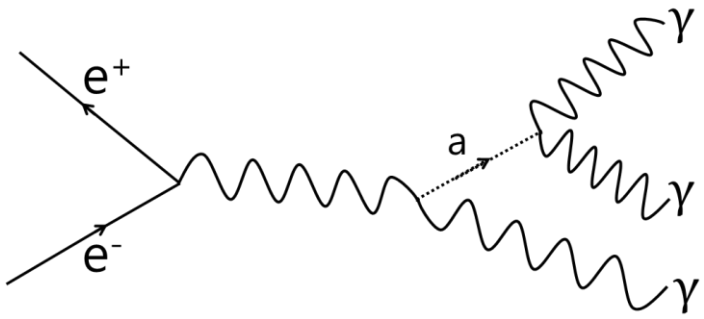




Type5. Axion-Like Particles(1/2)

- Axion-Like Particles(ALP) are pseudo-scalars and couple to bosons.
- Unlike QCD axions, ALPs have no relation between mass and coupling.
- Assuming all axions decay into two photons a → γγ.



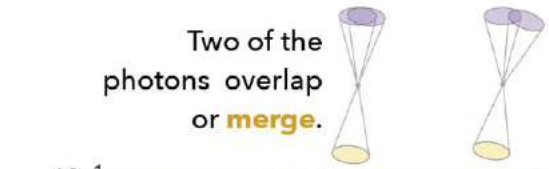


ArXiv: 1409.4792

Type5. Axion-Like Particles(2/2)

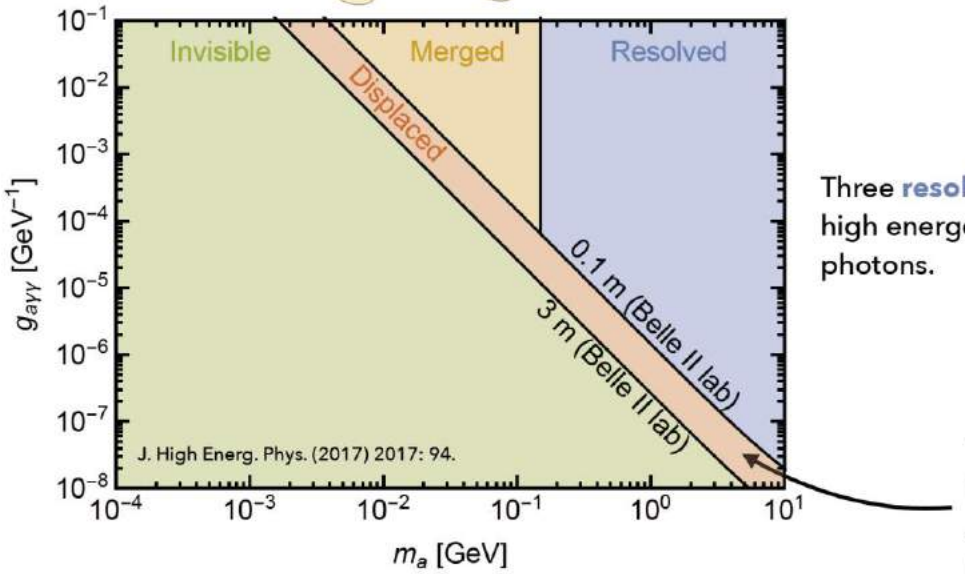
Belle II: Axion-Like Particles decaying to photons

Two of the photons overlap or **merge**.





ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.



Three **resolved**, high energetic photons.



The searches for invisible and visible ALP decays veto this region.

T. Ferber

IV. Summary

- BES III
  - $J/\psi \to A^{'} \ell^{+} \ell^{-}$
  - dark higgstrahlung
- KLOE 2
  - $\phi \to \eta A^{'}$
  - dark higgstrahlung $e^{+}e^{-} \to A^{'} h^{'}$
  - invisible $A^{'}$ decays to light dark matter

⇒ No signal yet

- BABAR
  - dark higgstrahlung $e^{+}e^{-} \to A^{'} h^{'}$
  - invisible decays and displaced vertex decays
- BELLE
  - $e^{+}e^{-} \to A^{'} \gamma_{\mathrm{ISR}}$ channel
  - dark higgstrahlung $e^{+}e^{-} \to A^{'} h^{'}$
  - invisible decays and displaced vertex decays

Belle II will search for Dark Matter in radiative decays with the trigger.

Acknowledgement

- Insung Yeo
- Doris Yangsoo Kim
- Youngjoon Kwon
- Patrick Fox
- Chaehyun Yu
- Soo-hyeon Nam
- Jangho Kim
- J. Cooley
- Rouven Essig
- K.Y. Choi
- Changyoung Kim

Thank you.

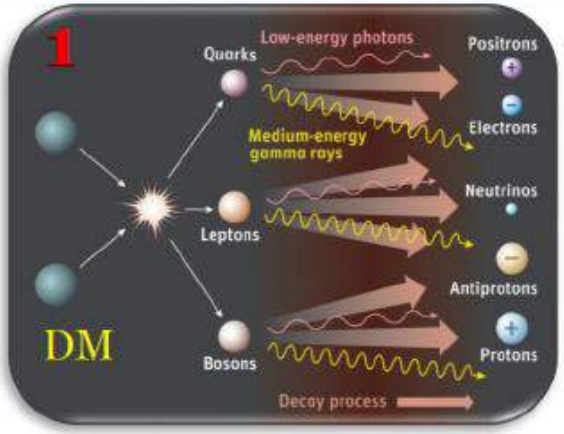
Back-up

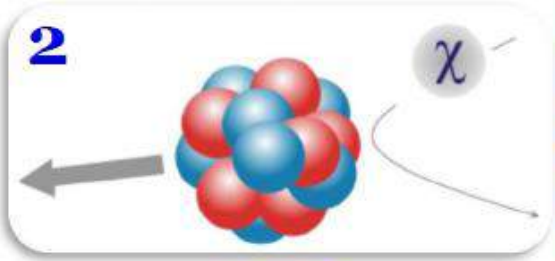
Why Dark Matter?

- Dark Matter is an evidence of BSM Physics.
- Its mass is not well constrained.
- Weak-scale DM has lots of attention:
  - Weak-scale, masses, couplings ⇒ correct abundance
  - Good candidates in models designed to understand the weak scale
  - Huge experimental efforts (direct detection, LHC, ...)
- Up to now, not too much new physics at the LHC
- Maybe dark matter is not connected to the weak scale, or could be part of a complicated sector with a number of scales (as the visible sector is)

⇒ We must look everywhere we can do for DM.

Dark Matter Search







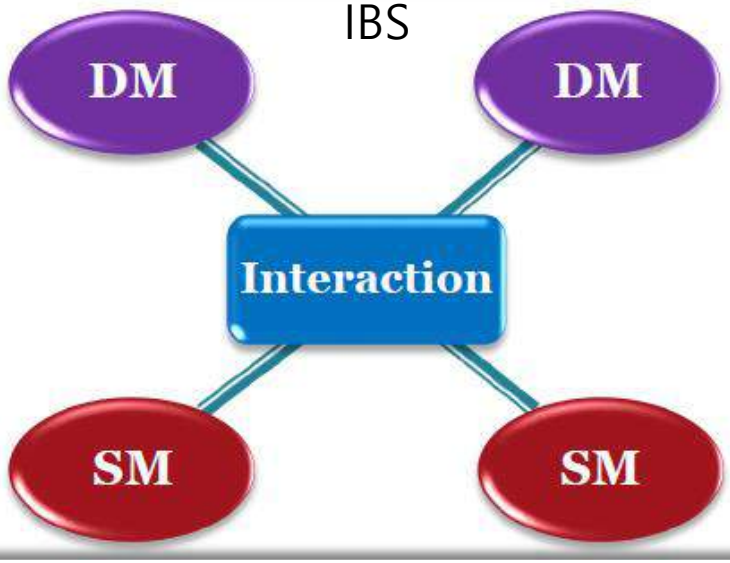
2

IBS



1

Astronomical Data



3



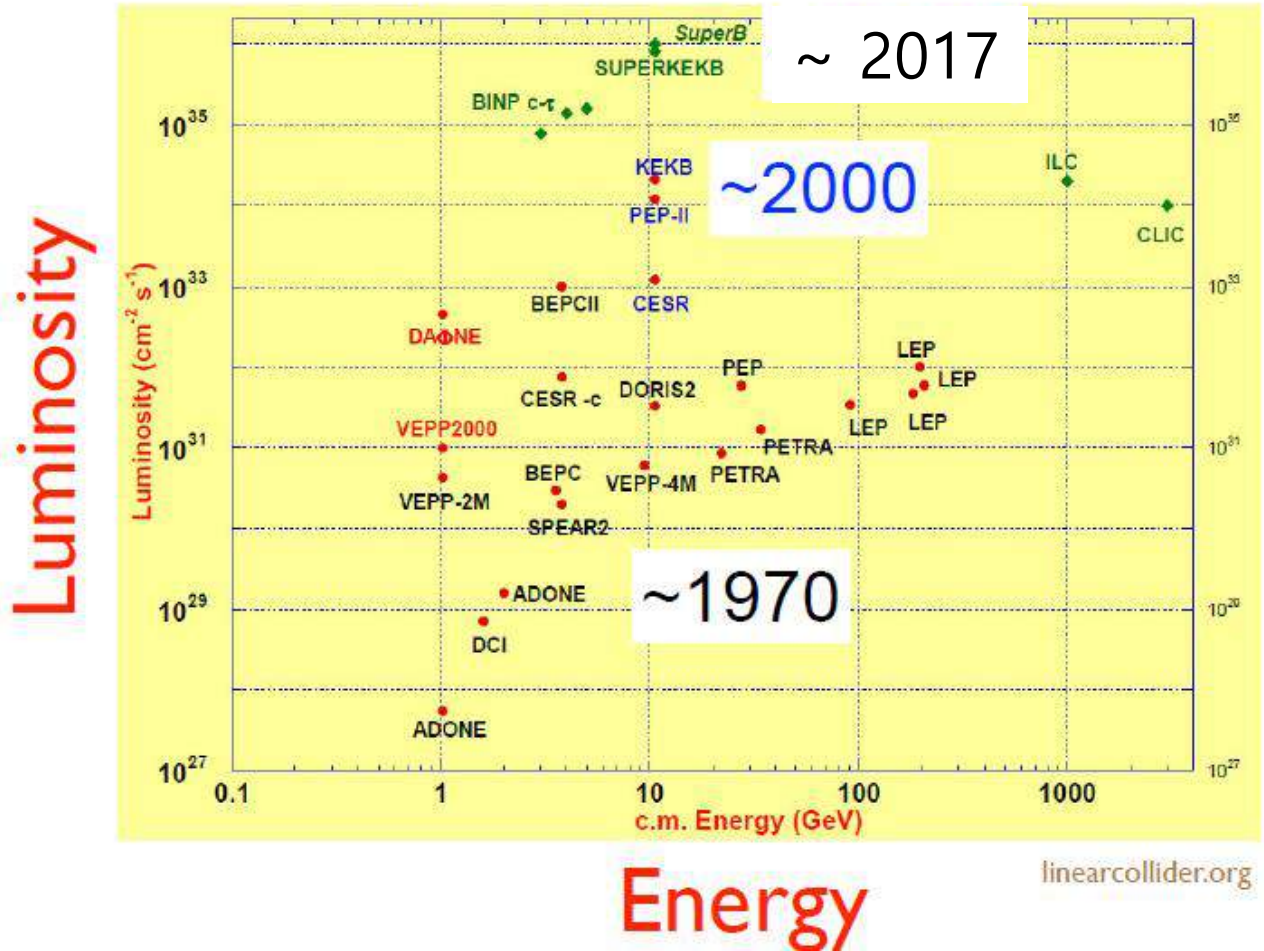
Accelerator Data (Collider)

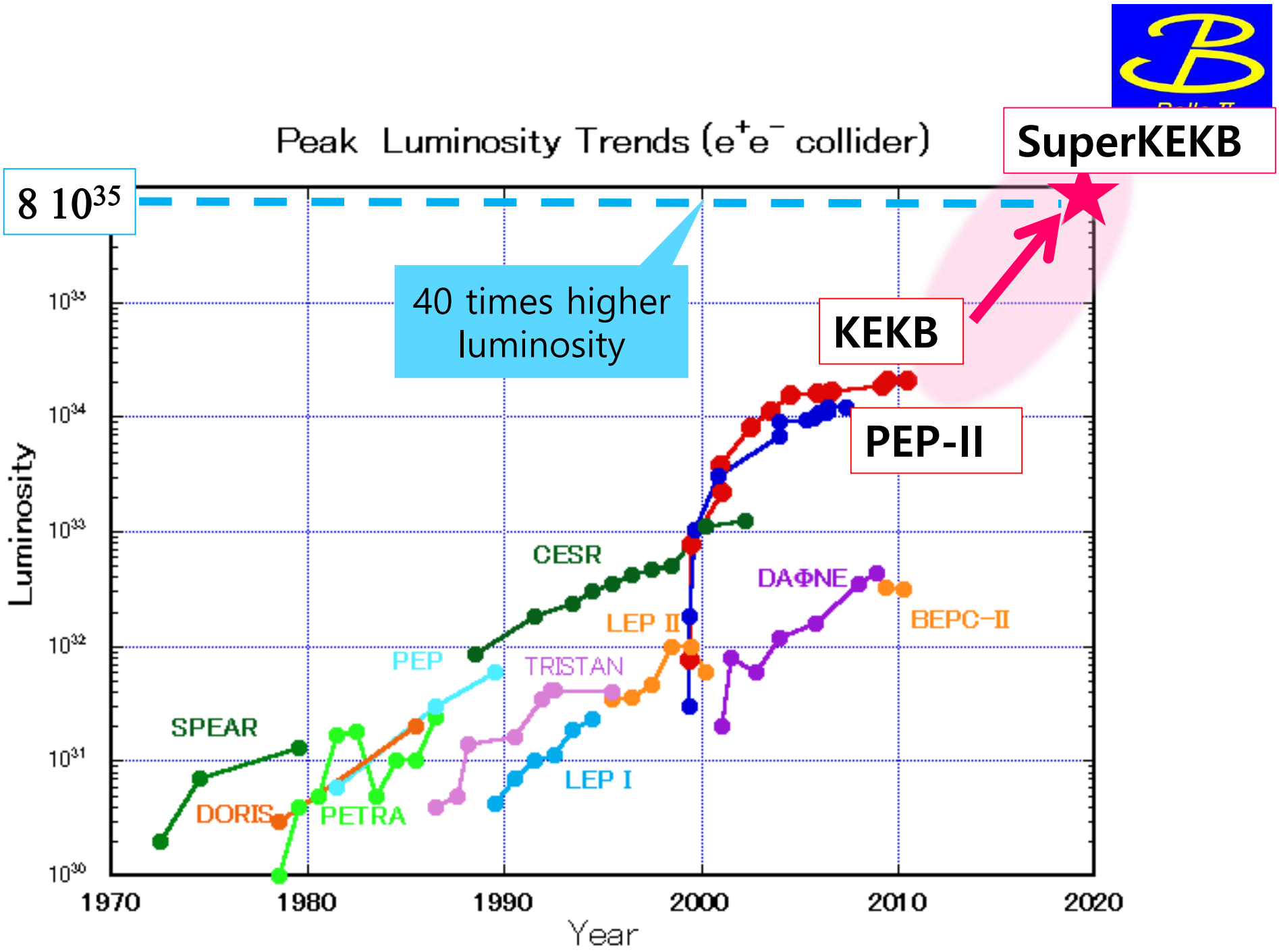
Experiment type

Experiment Class	Typical Production Modes	Detection
e^+e^- collider	$e^+e^- \to \gamma A'$	bump hunt
Electron fixed-target	$e^-Z \to e^-ZA'$	DM scatter or bump hunt
Hadron collider	$pp \to (\mathrm{jet}/\gamma)A'$	bump hunt or Drell-Yan
Positron fixed-target	$e^+e^- \to \gamma A'$	bump hunt
Proton fixed-target	$\pi^0/\eta/\eta' \to \gamma A'$, $q\bar{q} \to A'$, $pZ \to pZA'$	DM scatter or Drell-Yan

e^+e^- collider

- Enormous increases in luminosity over last few decays.




Peak Luminosity Trends (e^+e^- collider)
SuperKEKB
$8\ 10^{35}$
40 times higher luminosity
KEKB
PEP-II
Luminosity
10^{35}
10^{34}
10^{33}
10^{32}
10^{31}
10^{30}
CESR
DAΦNE
LEP II
BEPC-II
PEP
TRISTAN
SPEAR
LEP I
DORIS
PETRA
1970
1980
1990
2000
2010
2020
Year

e^+e^- collider experiments

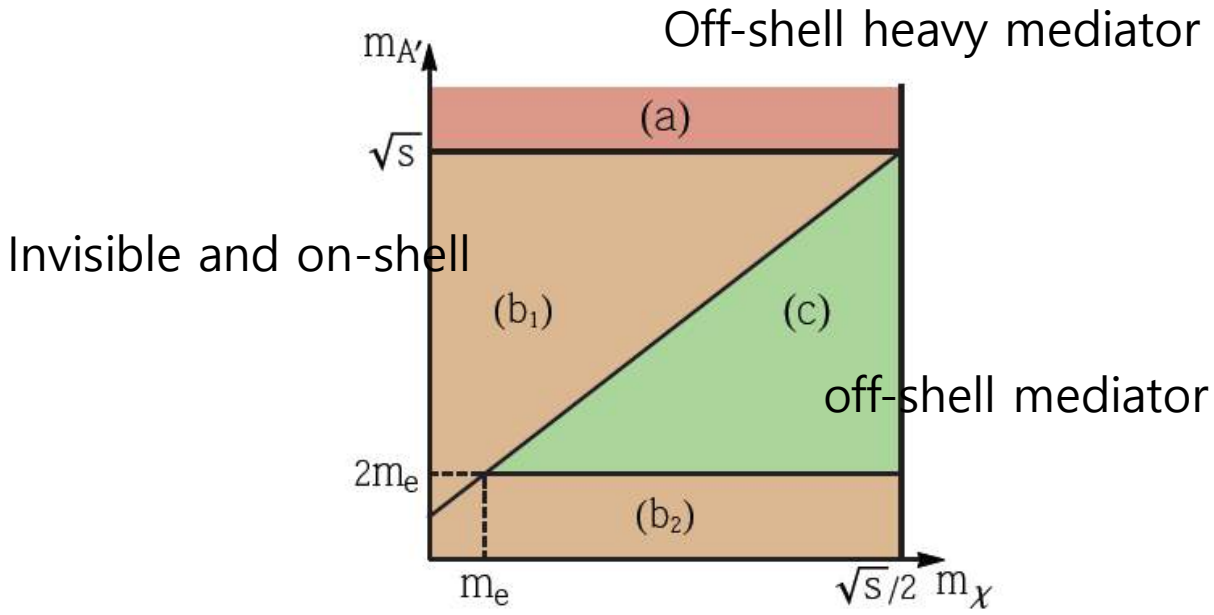
No.	Experiments	CM Energy (Resonance)	Date	Place
1)	KLOE	1.02 GeV (Φ)	2001~	INFN, Italy
2)	BES III	3.78 GeV (J/ψ)	2008~	Beijing, China
3)	BaBar	10.58 GeV (Y(4S))	1999~2008	SLAC, USA
4)	Belle	10.58 GeV (Y(4S))	1999~2010	KEK, Japan
5)	Belle II	10.58 GeV (Y(4S))	2018~	KEK, Japan

Dark Photon to Dark Matter

- Requires high single photon trigger
  - Not available in Belle,
  - The BaBar implemented a single photon trigger (arXive: 0808.0017[hep-ex])
  - On-going discussions for Belle II

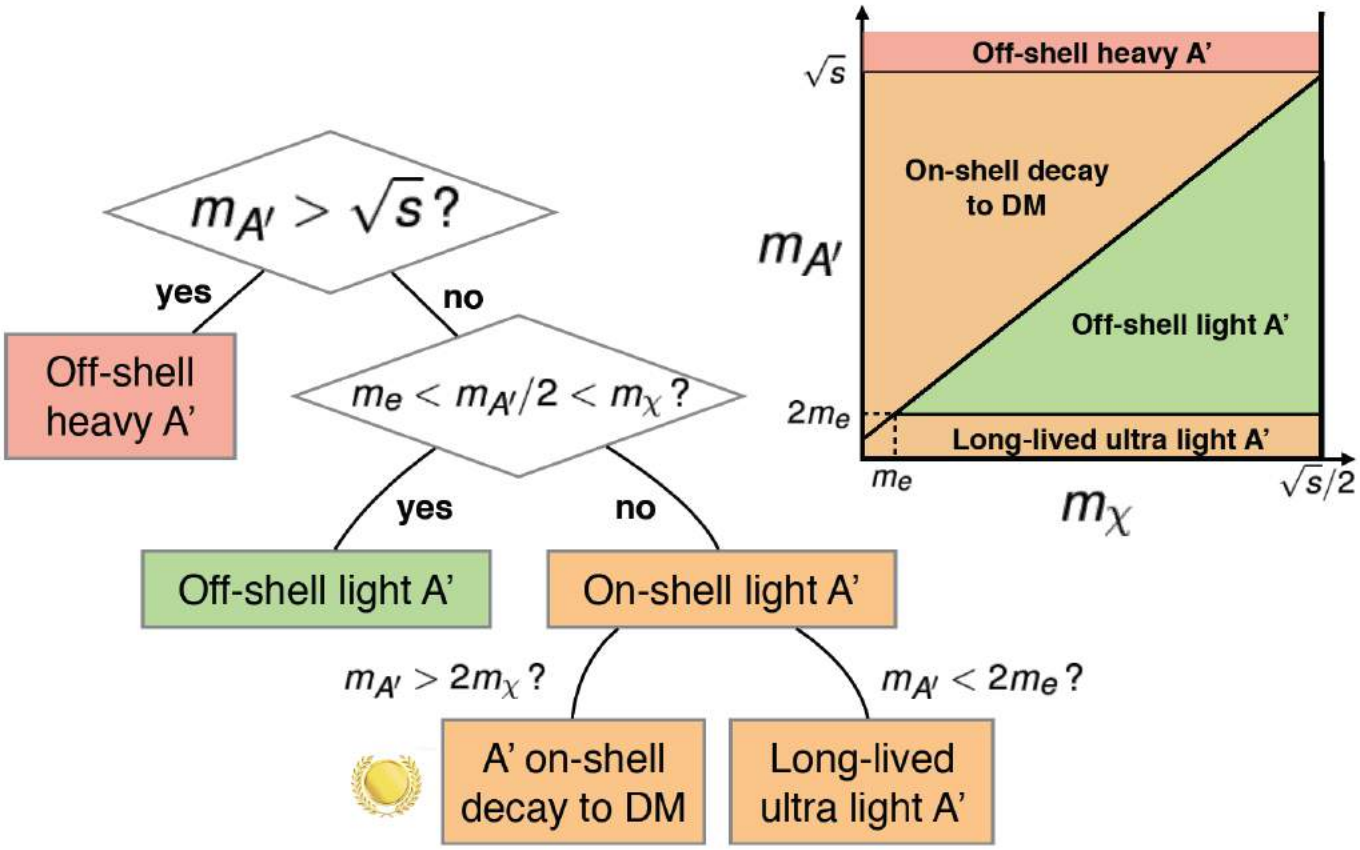
Dark Photon to Dark Matter

- The plane of $m_x - m_{A'}$ with different characteristic single photon and missing E_T signals
- A′ mediator



Eassig, et al, JHEP 11, 167 (2013).

Dark Photon to Dark Matter



T. Ferber

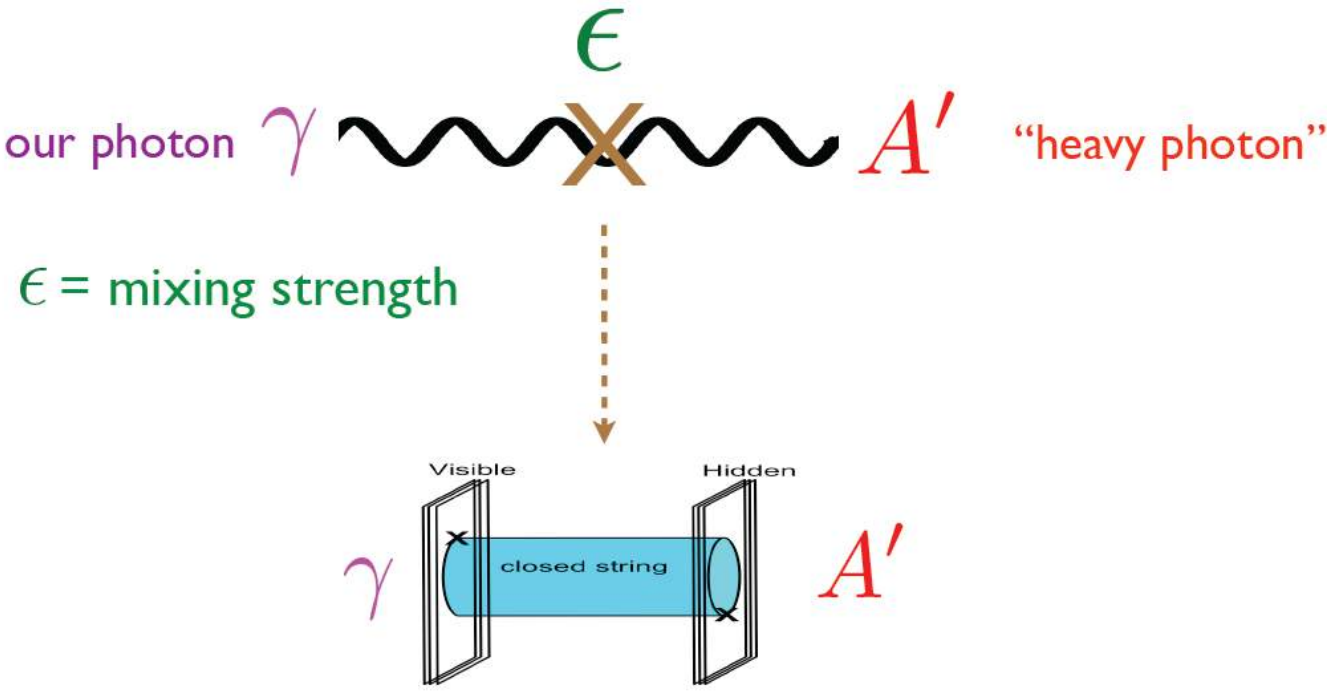
Dark Photon to Dark Matter

- A′ decays to dark matter on-shell or off-shell with different gamma spectrum
  - Radiative production in e+e- collision
  - Only one photon in the final state with

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

- Requires high single photon trigger
  - Not available in Belle,
  - The BaBar implemented a single photon trigger (arXive: 0808.0017[hep-ex])
  - On-going discussions for Belle II

Dark Sector (γ-A′ mixing)

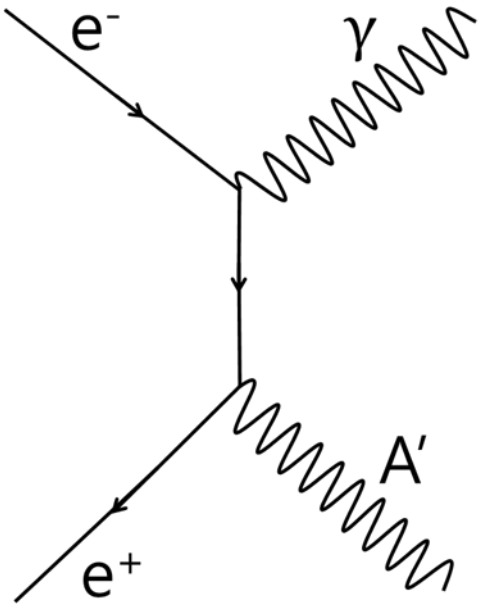


Eassig (2012)

Dark Photon to SM

Produce A′ in e^+e^- collisions

RE, Schuster, Toro
Batell, Pospelov, Ritz
Reece, Wang
Borodatchenkova et.al.
Fayet



$$\sigma \propto \frac{\epsilon^2}{E_{cm}^2}$$

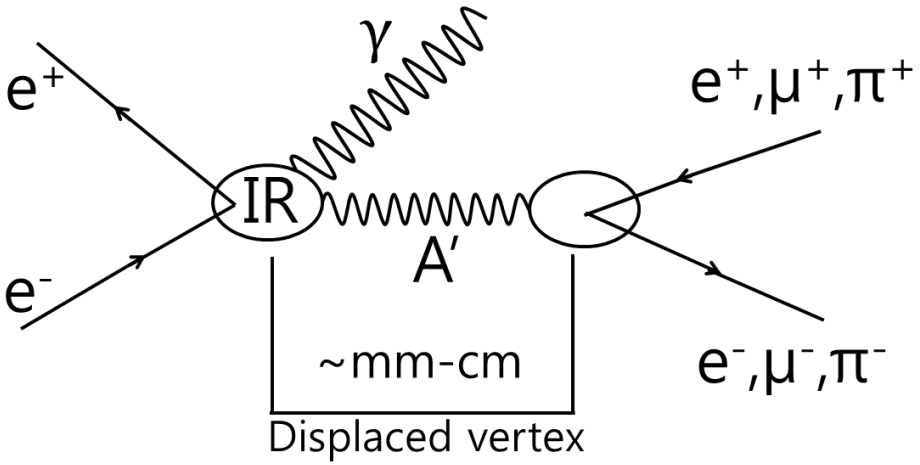
$\Longrightarrow$ want low-energy (1-10 GeV), high intensity colliders (BaBar, BELLE, KLOE, ...)

Eassig (2012)

Dark Photon to SM

- Dark photon decays SM particles.

$$A' \rightarrow e^+ e^-, \mu^+ \mu^-, \pi^+ \pi^-$$
$$M_{A'} = 0.1 - 10\, GeV/c^2$$
$$W_{A'} = 1\, KeV/c^2$$
$$c\tau = 1,\ 5,\ 10\ \ cm$$



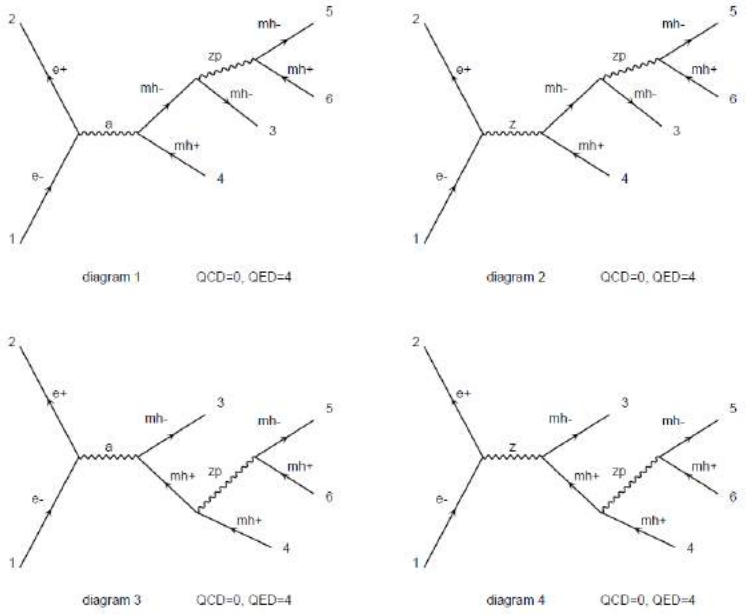
- To call a "long-lived gauge boson" instead of dark photon
- Same analysis for Higgs-Strahlung

⇒ work in progress

Gianluca Inguglia (2015)

Type4. A′ couples only to heavy leptons

- Brian Shuv and Itai Yavin (arXive: 1403.2727[hep-ph])
  - $e^+e^- \rightarrow l^+l^-A'$
    - If $M_{A'} > 2M_\mu$ $A' \rightarrow \mu^+\mu^-$
    - If $M_{A'} < M_\mu$ $A' \rightarrow \nu\bar{\nu}$ or sterile neutrinos



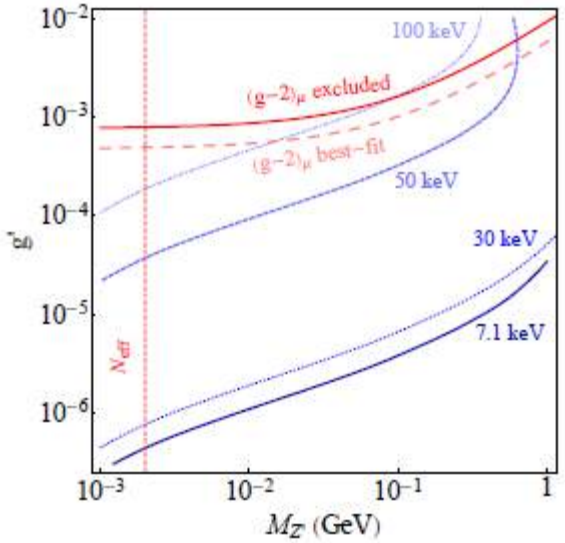
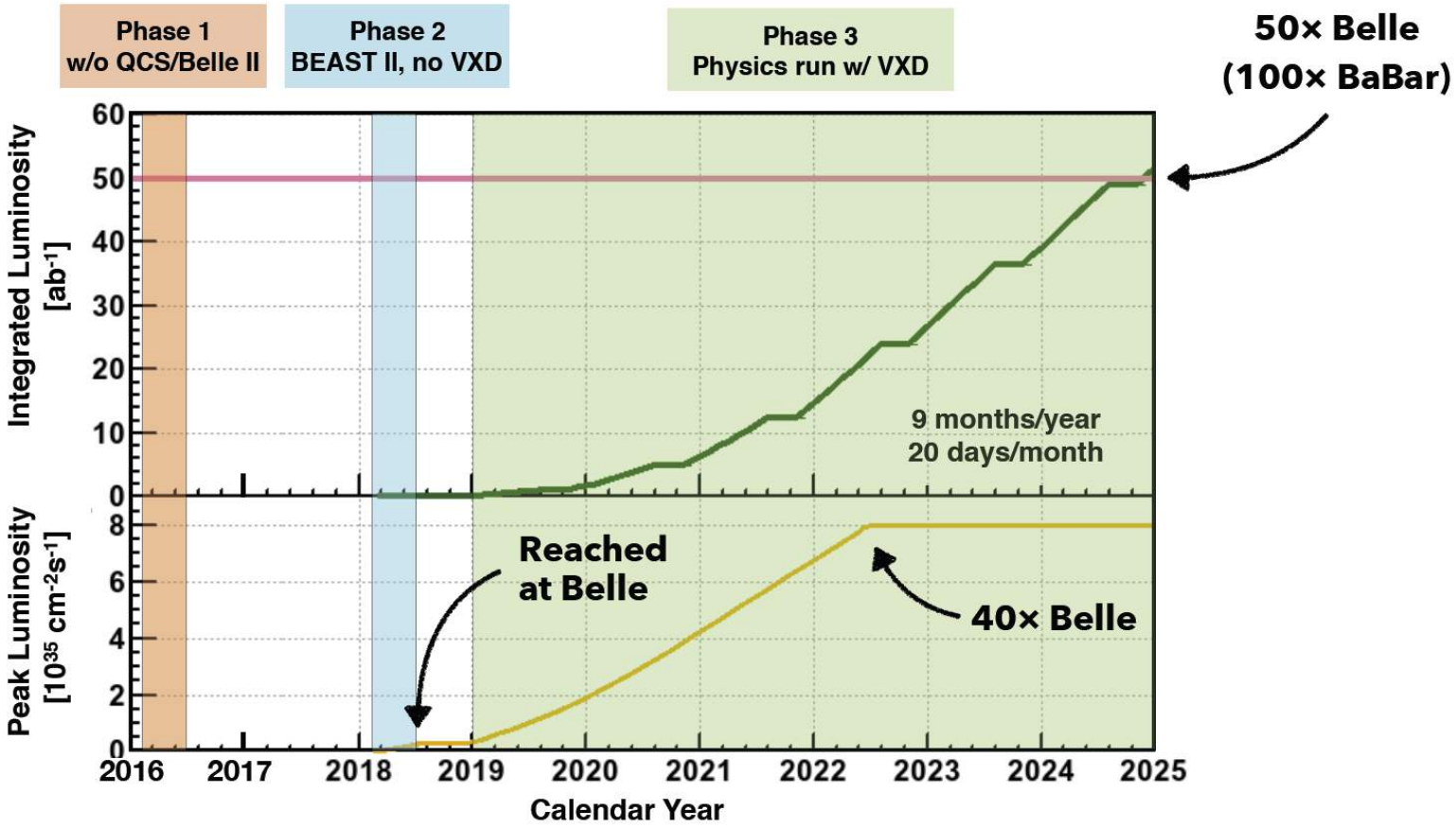


FIG. 3. A contour plot of the sterile neutrino abundance in the $M_{Z'} - g'$ plane. Shown are the contours corresponding to the observed DM relic abundance, $Y_{\rm DM} = 4.7 \times 10^{-4}({\rm keV}/m_s)$, for different values of the sterile neutrino mass m_s. The mixing angle for each m_s is at the upper bound allowed by X-ray constraints [8]: $\sin 2\theta_0 = 8 \times 10^{-6}$ ($m_s = 7.1$ keV), 2.2×10^{-6} ($m_s = 30$ keV), 3.5×10^{-8} ($m_s = 50$ keV), 5×10^{-9} ($m_s = 100$ keV). The solid-red curve depicts the 5σ bound muon $g-2$ [45], and the dashed pink curve shows the coupling that best fits the muon $g-2$ anomaly. The vertical dashed curve corresponds to $M_{Z'} \gtrsim 2.0$ MeV coming from bounds on extra relativistic species in the early universe [17].

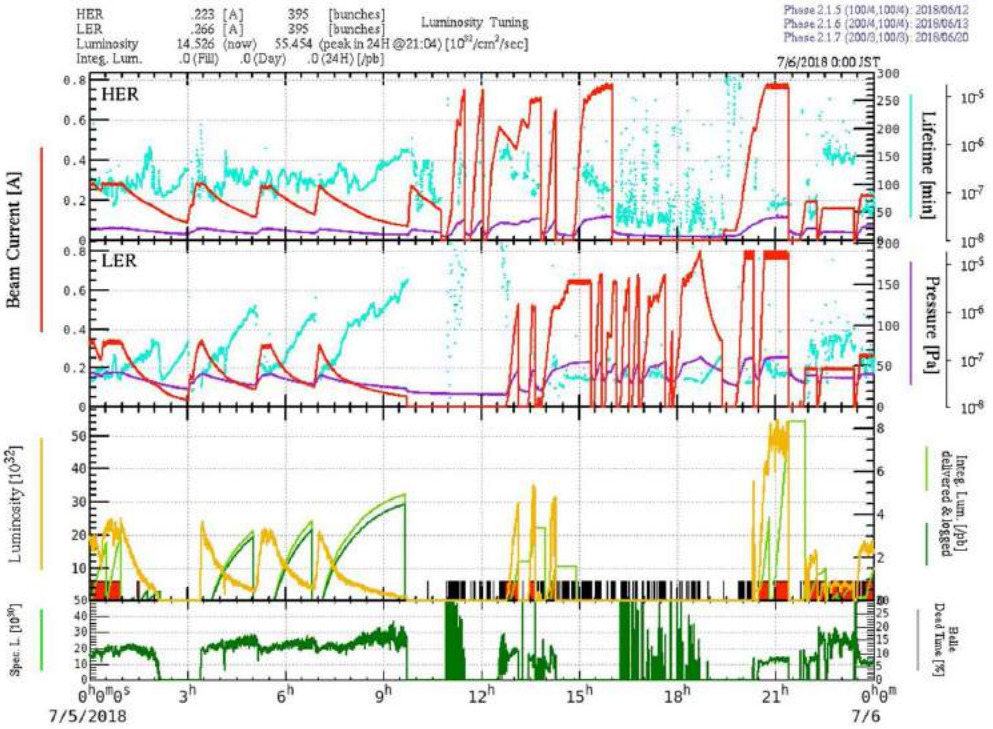
⇒ work in progress at Belle

Belle II projected luminosity



SuperKEKB R&D: July 2018

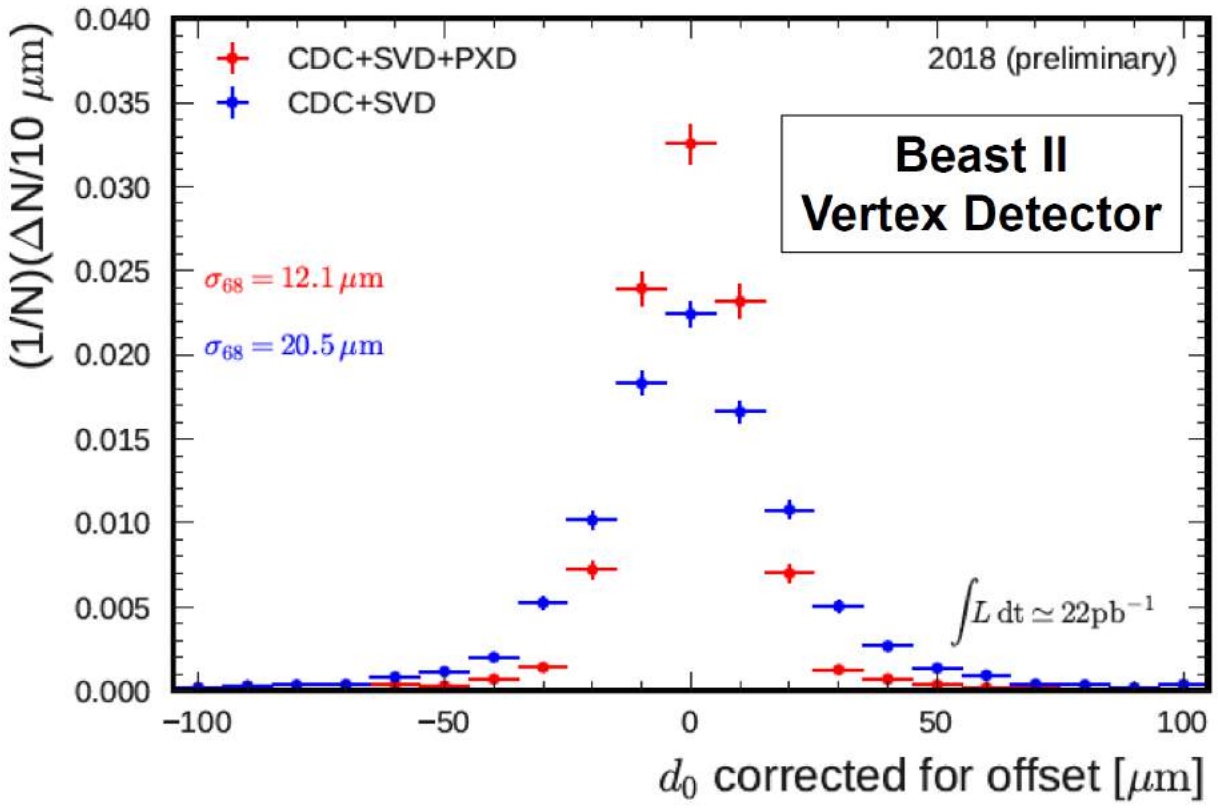
$$L_{peak} = 5.5 \times 10^{33} / cm^2 / \sec$$



- The two beams were squeezed with the superconducting final focus down to β_y^*=3mm.
- However, instantaneous luminosity suffered as β_y^* got squeezed due to beam blowup at high current.
- Expected to reach the design luminosity in 2022.
- The physics data was taken mostly during the night when beam R&D was not done.
- **Collected ~ 0.5/fb.**

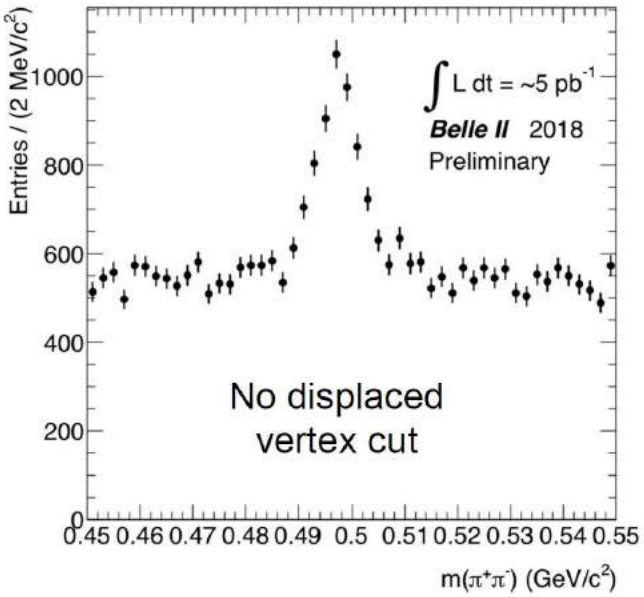
Impact Parameter Resolution

$$\sigma_{68}^{\text{measured}} = 12.1 \pm 0.2\,(\text{stat})^{+0.1}_{-0.3}\,(\text{syst})\,\mu\text{m},$$
$$\sigma^{\text{expected}} = 9.9 \pm 0.2\,(\text{stat})\,\mu\text{m}.$$

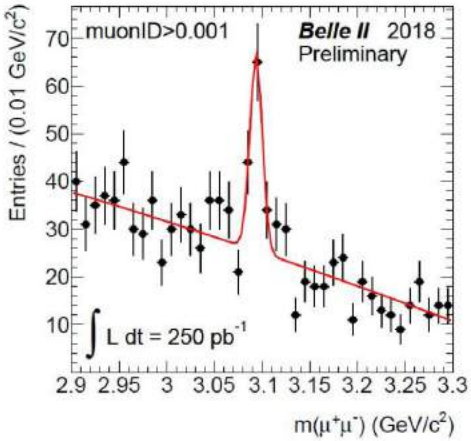


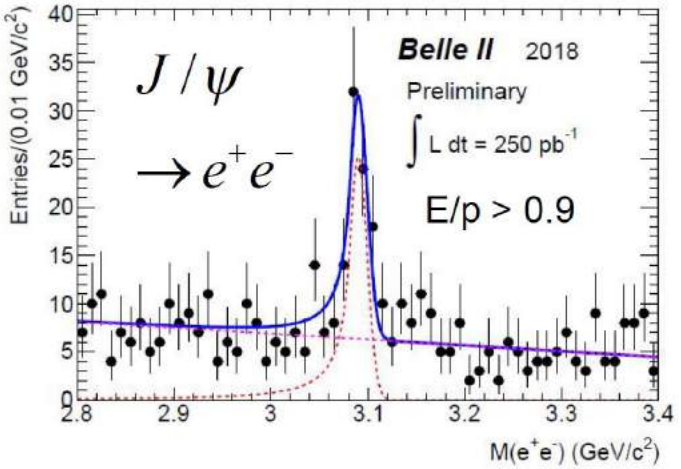
Phase II Particles as Charged Tracks

$K_s \to \pi^+\pi^-$



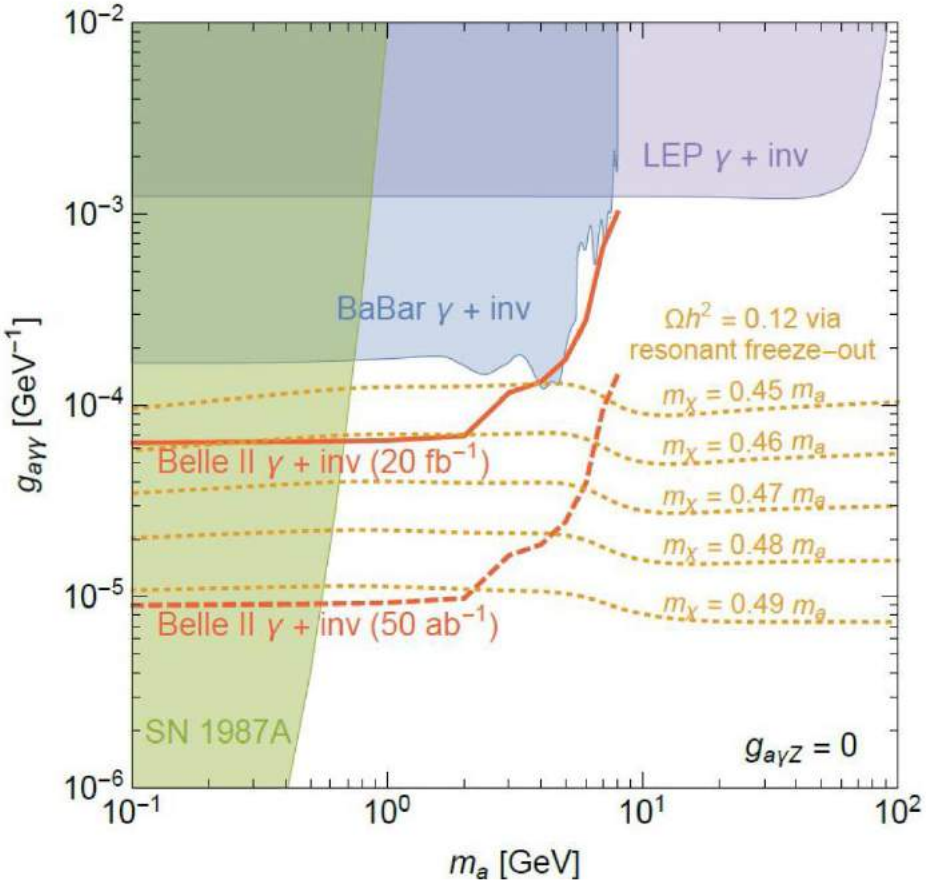
$J/\psi \to \mu^+\mu^-$





Expected Sensitivity for ALP decays to Dark Matter

$\gamma + \text{inv}$: 1 resolved recoil photon + ALP decaying to dark matter



$$e^+e^- \to \gamma a, \quad a \to \chi\chi$$

$$E_\gamma = \frac{s - m_a^2}{2\sqrt{s}}$$

M. J. Dolan et al, JHEP 1712, 094(2017)

Summary for searches











No.	Exper-iment	1.Dark Matter	2.Dark photon	3.Higg-Strahlung	4.Heavy lepton
1)	KLOE		• 2 charged lepton+one photon • 2 charged lepton + η	$\mu\mu$+ missing $E_T(h')$	
2)	BES III		• 2 charged lepton+one photon		
3)	BaBar	one photon + missing E_T	2 charge tracks + one photon	• 3 charged track pairs • 4 or more charged tracks	
4)	Belle		2 charge track + one photon	3 charged track pairs	• Two lepton pairs • A lepton pairs + missing E_T
5)	Belle II	one photon + missing E_T	2 Charge Track one photon	3 charged track pairs	• Two lepton pairs • A lepton pairs + missing E_T