IBS CTPU Seminar
IBS, Daejeon, Korea

Dark matter with e+e- collider

2015. 7. 29.

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Contents

Introduction

May 22, 2014

- Particle Physics Project Prioritization Panel (P5)

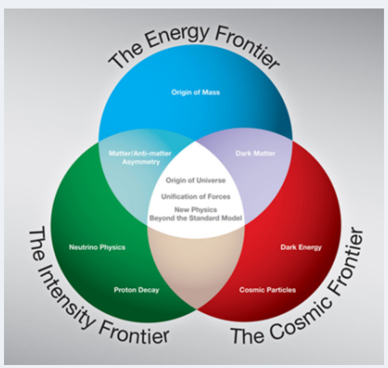
P5 report

Executive Summary

Particle physics explores the fundamental constituents of matter and energy. It reveals the profound connections underlying everything we see, including the smallest and the largest structures in the Universe. The field is highly successful. Investments have been rewarded recently with discoveries of the heaviest elementary particle (the top quark), the tiny masses of neutrinos, the accelerated expansion of the Universe, and the Higgs boson. Current opportunities will exploit these and other discoveries to push the frontiers of science into new territory at the highest energies and earliest times imaginable. For all these reasons, research in particle physics inspires young people to engage with science.

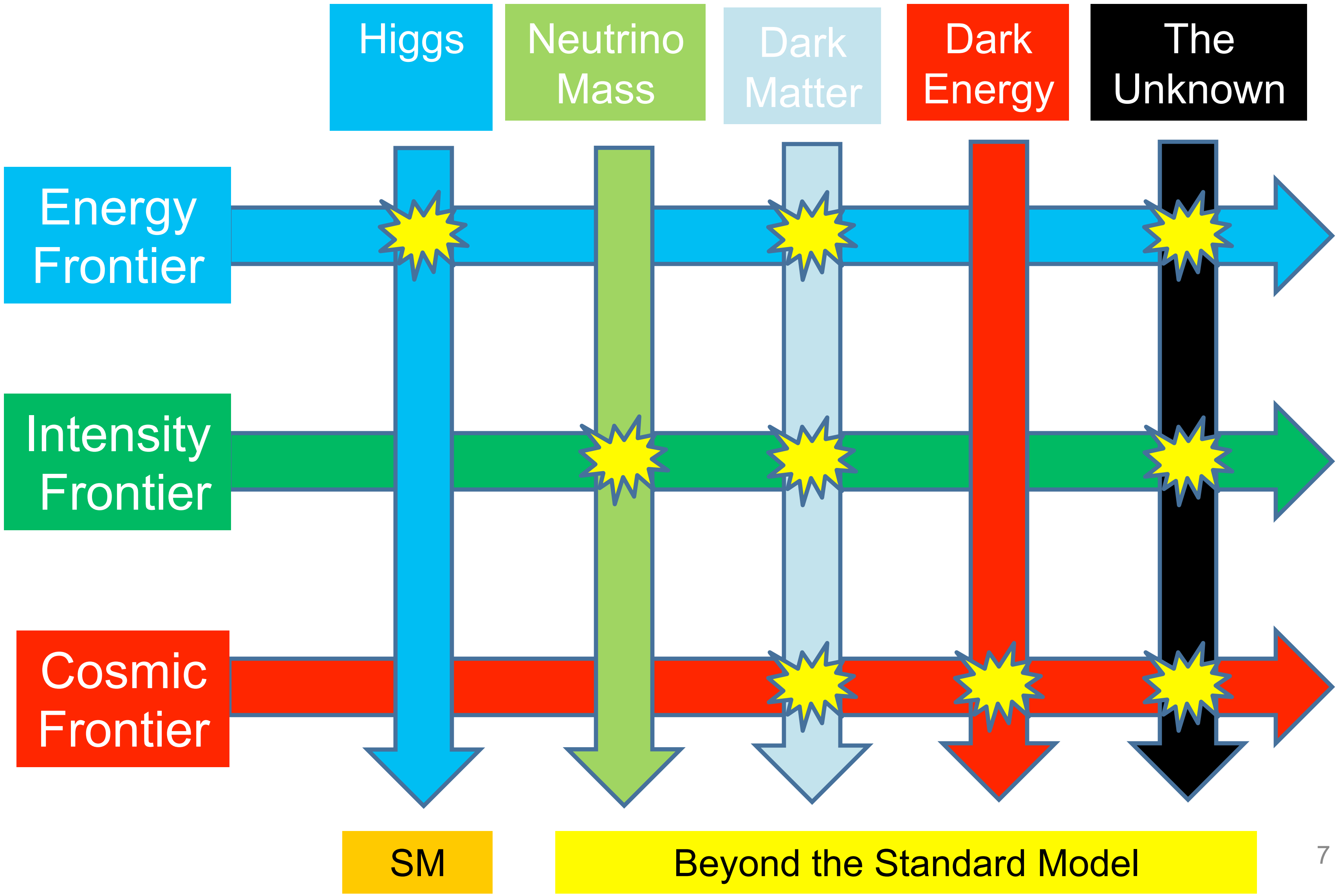
What is Future Plan?

Before May 22, 2014	After May 22, 2014 (~20 years from now)
○ Energy Frontier ○ Intensity Frontier ○ Cosmic Frontier	○ Higgs Boson ○ Neutrino Mass ○ Dark Matter ○ Dark Energy ○ Explore the unknown



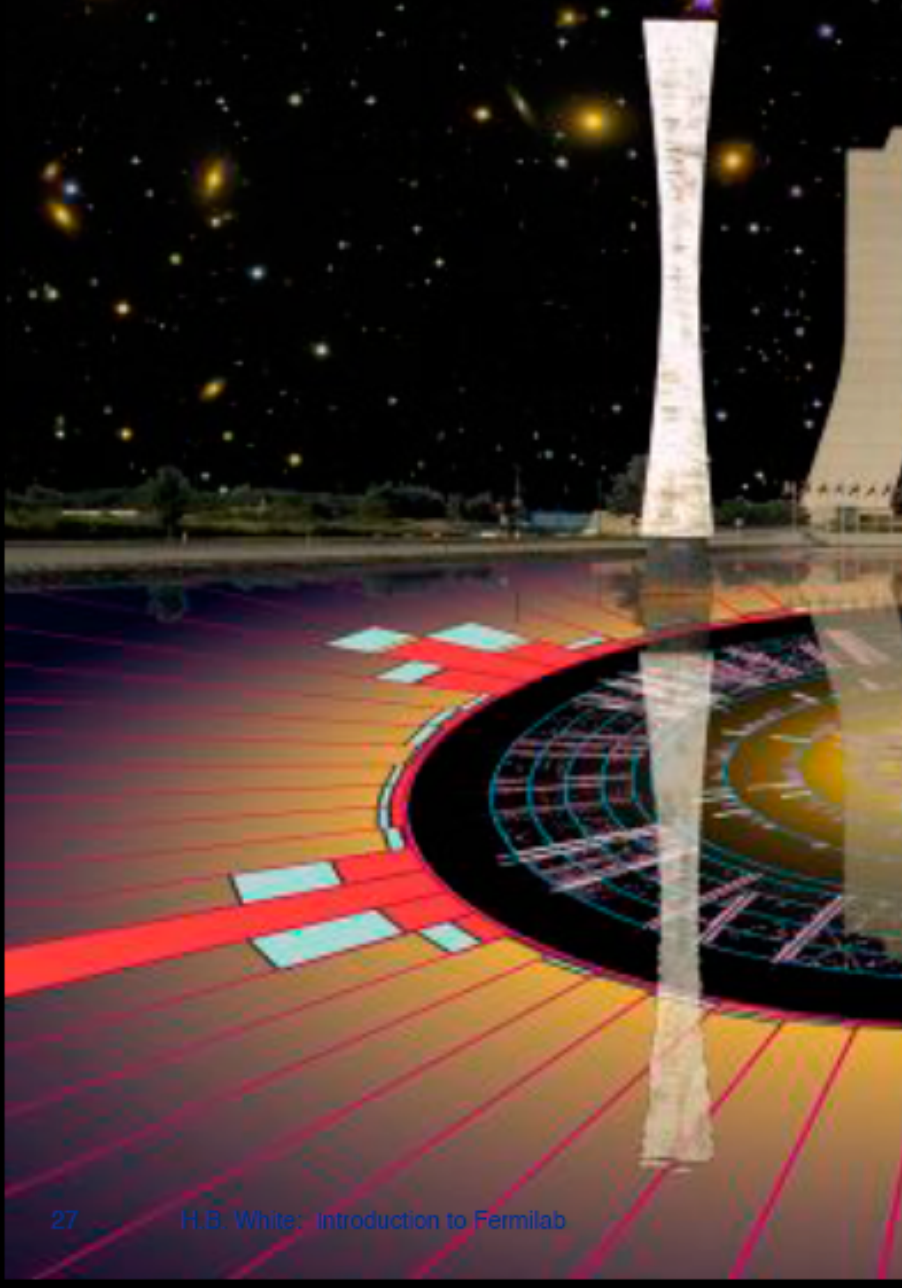
The Particle Physics Project Prioritization Panel's report, released today, recommends a strategic path forward for US particle physics, reports Kathryn Jepsen in symmetry magazine.

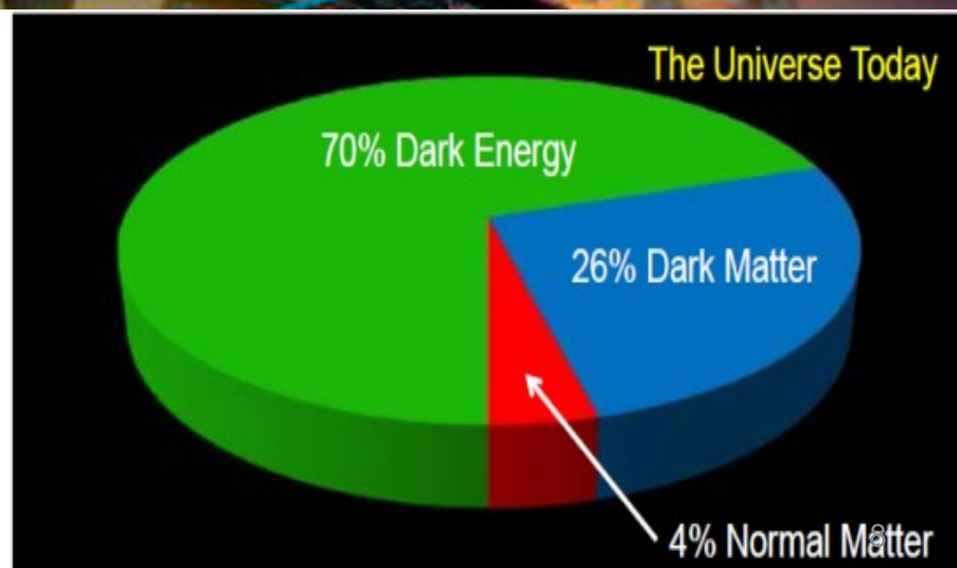
Frontiers vs. Sciences



The Cosmic Frontier: Quarks to Cosmos

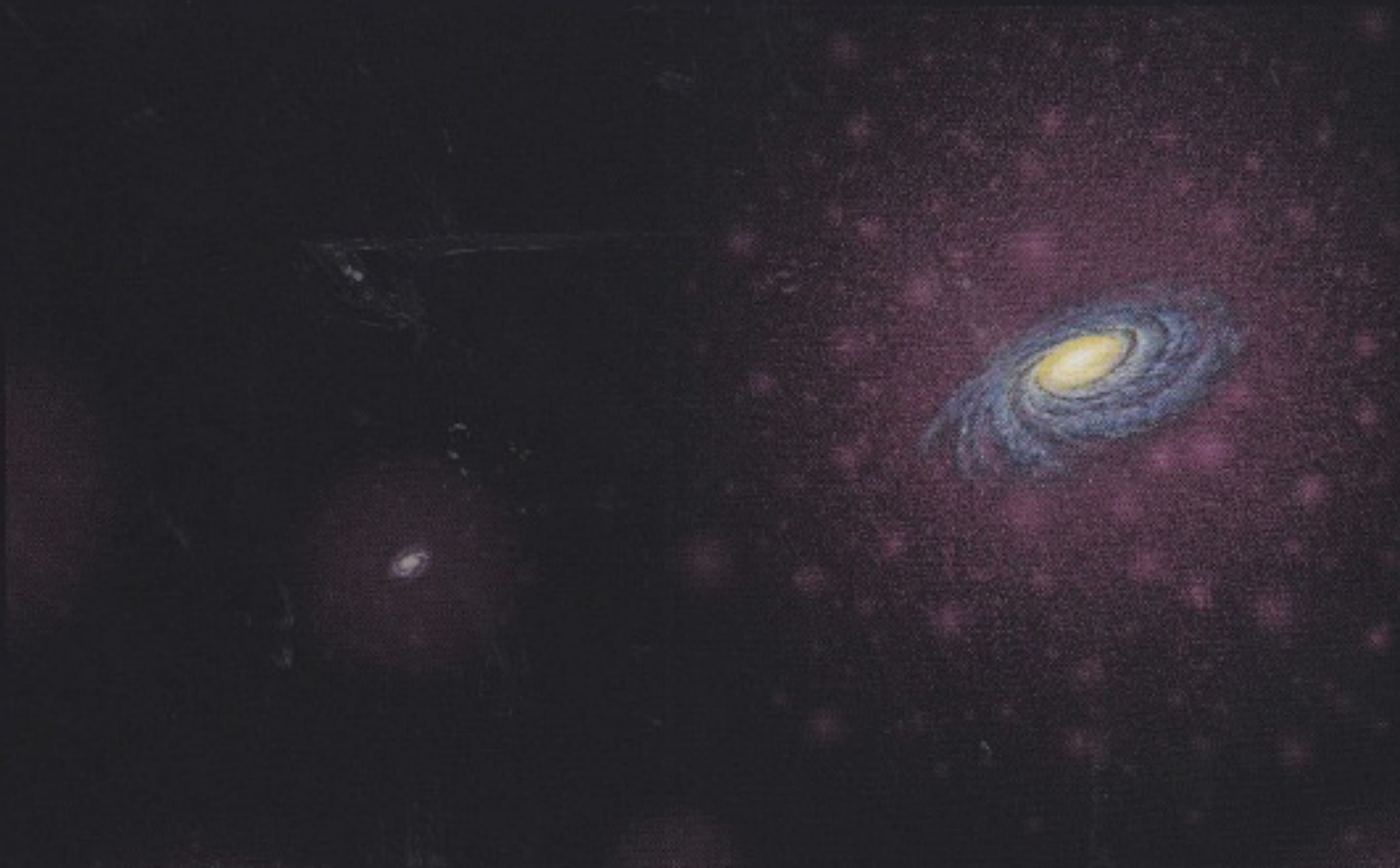
Dark Matter
Dark Energy
Ultra High Energy Cosmic Rays



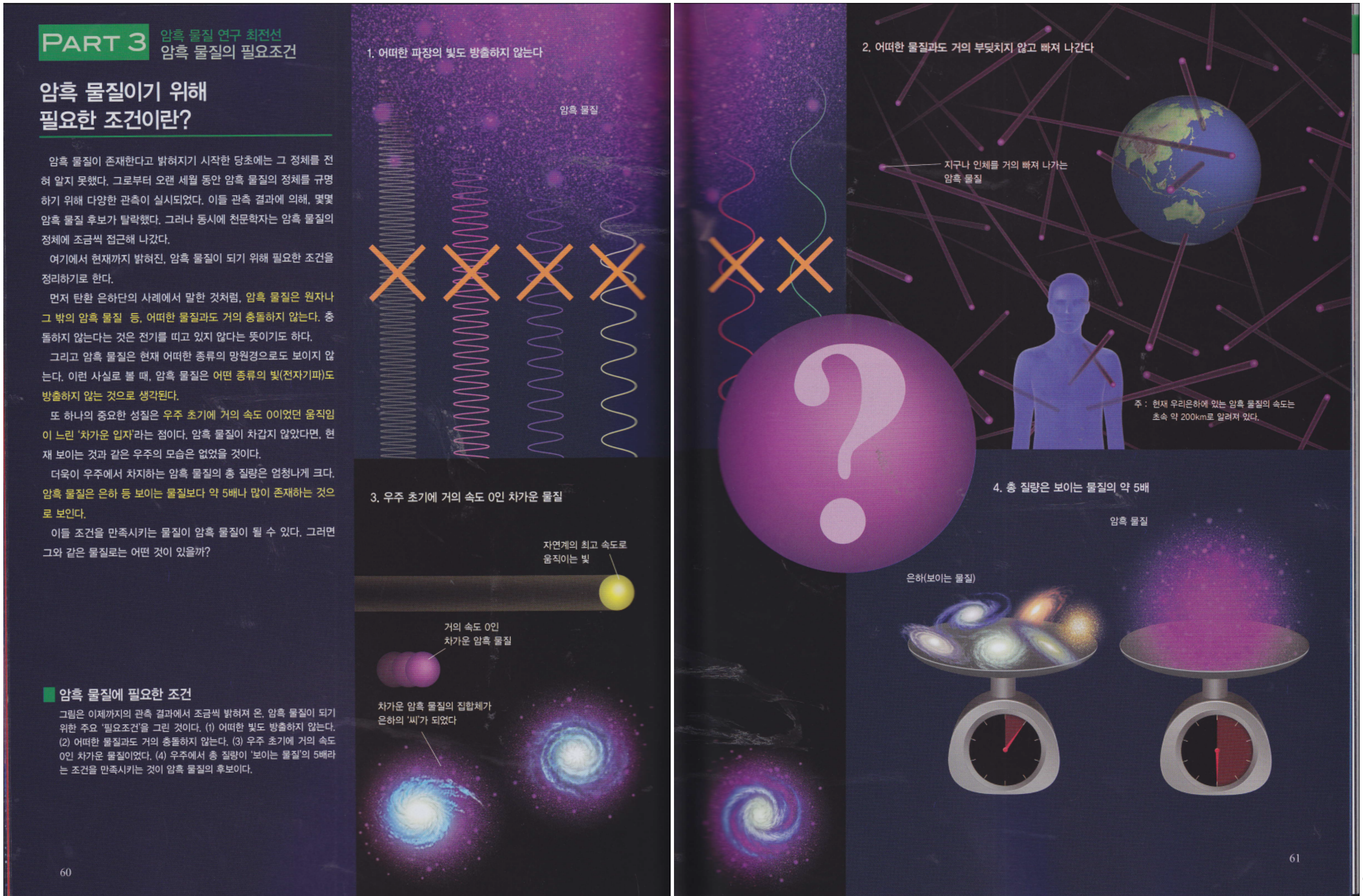


우주의 보이지 않는 지배자

암흑 물질



Dark Matter



PART 3 암흑 물질 연구 최전선
암흑 물질의 필요조건

암흑 물질이기 위해 필요한 조건이란?

암흑 물질이 존재한다고 밝혀지기 시작한 당초에는 그 정체를 전혀 알지 못했다. 그로부터 오랜 세월 동안 암흑 물질의 정체를 규명하기 위해 다양한 관측이 실시되었다. 이들 관측 결과에 의해, 몇몇 암흑 물질 후보가 탈락했다. 그러나 동시에 천문학자는 암흑 물질의 정체에 조금씩 접근해 나갔다.

여기에서 현재까지 밝혀진, 암흑 물질이 되기 위해 필요한 조건을 정리하기로 한다.

먼저 탄환 은하단의 사례에서 말한 것처럼, 암흑 물질은 원자나 그 밖의 암흑 물질 등, 어떠한 물질과도 거의 충돌하지 않는다. 충돌하지 않는다는 것은 전기를 띠고 있지 않다는 뜻이기도 하다.

그리고 암흑 물질은 현재 어떠한 종류의 망원경으로도 보이지 않는다. 이런 사실로 볼 때, 암흑 물질은 어떤 종류의 빛(전자기파)도 방출하지 않는 것으로 생각된다.

또 하나의 중요한 성질은 우주 초기에 거의 속도 0이었던 움직임이 느린 '차가운 입자'라는 점이다. 암흑 물질이 차갑지 않았다면, 현재 보이는 것과 같은 우주의 모습은 없었을 것이다.

더욱이 우주에서 차지하는 암흑 물질의 총 질량은 엄청나게 크다. 암흑 물질은 은하 등 보이는 물질보다 약 5배나 많이 존재하는 것으로 보인다.

이들 조건을 만족시키는 물질이 암흑 물질이 될 수 있다. 그러면 그와 같은 물질로는 어떤 것이 있을까?

암흑 물질에 필요한 조건

그림은 이제까지의 관측 결과에서 조금씩 밝혀져 온, 암흑 물질이 되기 위한 주요 '필요조건'을 그린 것이다. (1) 어떠한 빛도 방출하지 않는다. (2) 어떠한 물질과도 거의 충돌하지 않는다. (3) 우주 초기에 거의 속도 0인 차가운 물질이었다. (4) 우주에서 총 질량이 '보이는 물질'의 5배라는 조건을 만족시키는 것이 암흑 물질의 후보이다.

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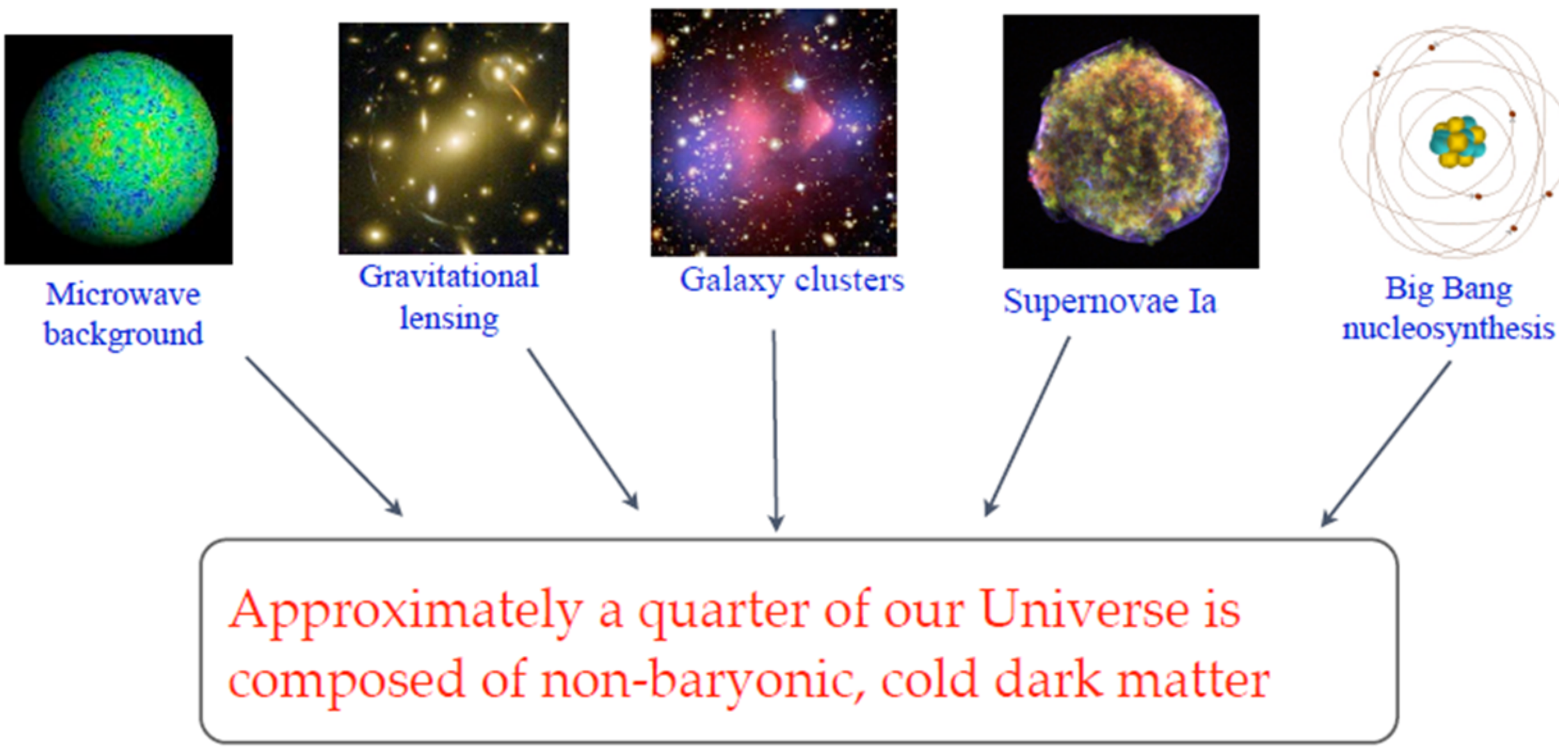
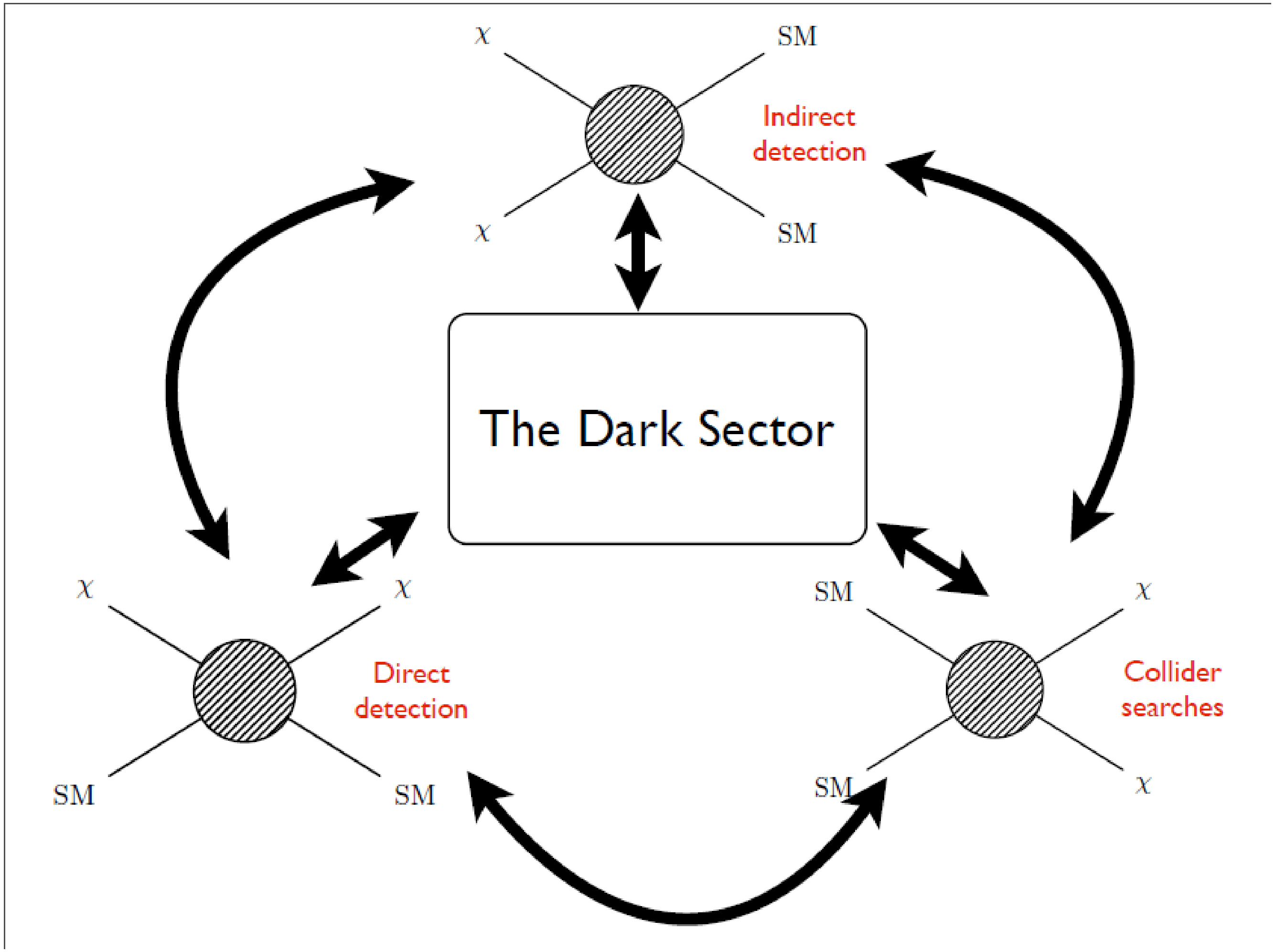
Newton.

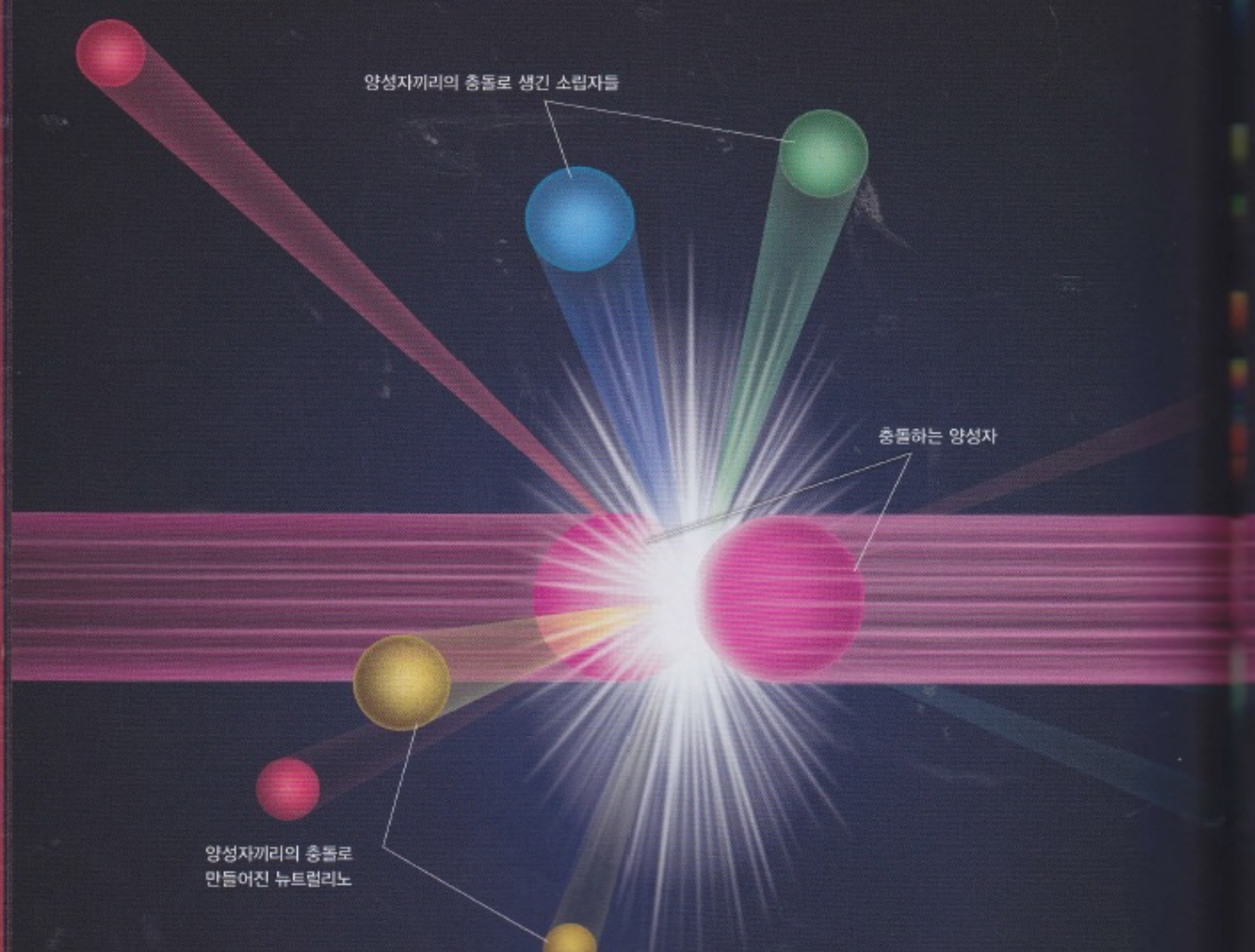
Properties of Dark Matter

- No EM wave
- Weakly interaction
- Cold
- Non-Baryon (5 times of Baryon)



Dark Matter Search

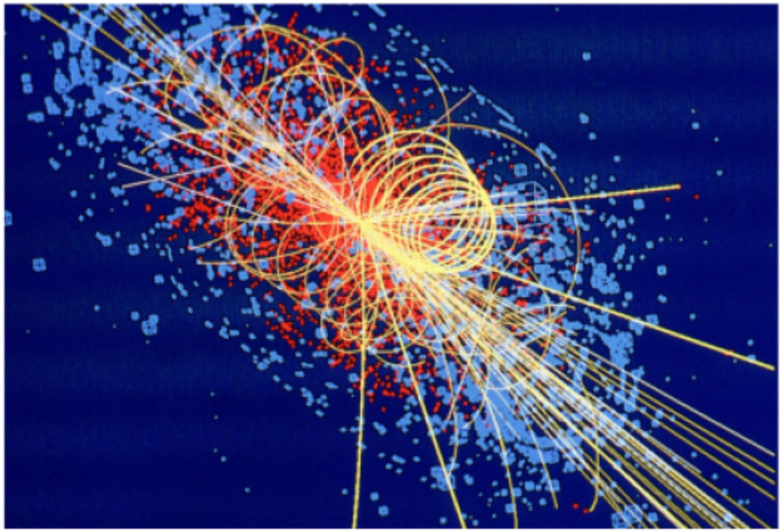



양성자끼리의 충돌로 생긴 소립자들
충돌하는 양성자
양성자끼리의 충돌로
만들어진 뉴트럴리노

Simulation

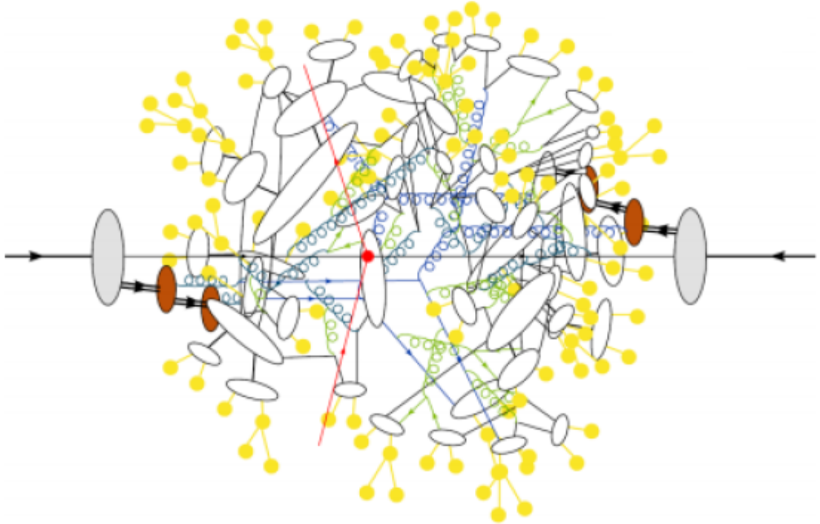
Large-scale MC simulation is crucial for relating experimentally measured variables to the parameters of the underlying theory

$\sim$ 600 million/second events rate at **LHC** (15PB data/year)



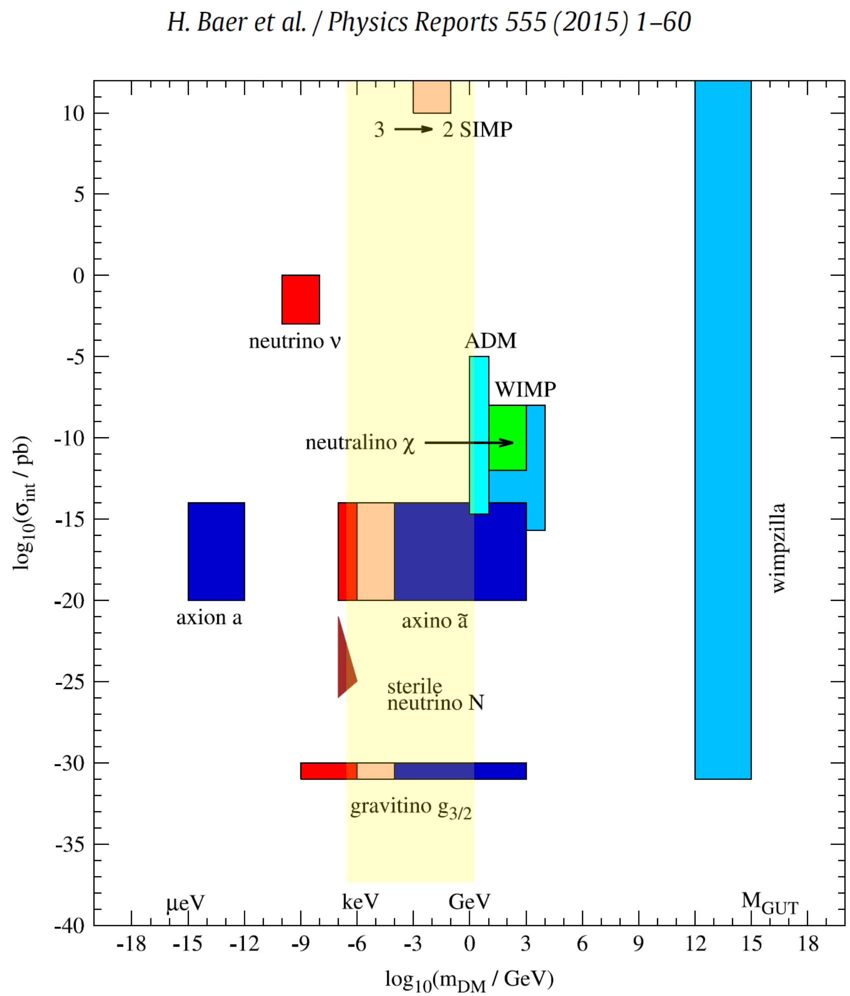
what we might see at the LHC

Higgs event



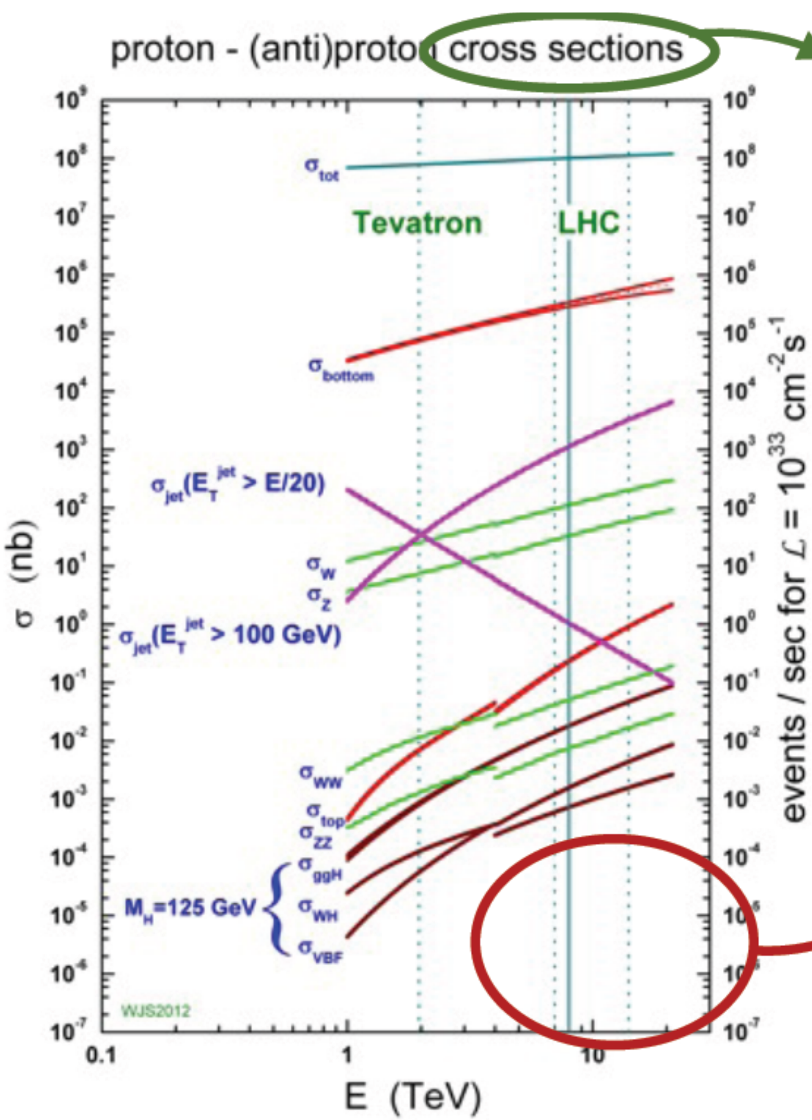
how we understand it

Cross-section for Dark Matter



H. Baer, K.Y. Choi, et al, Physics Reports 555, 1 (2015)

Dark Matter Search

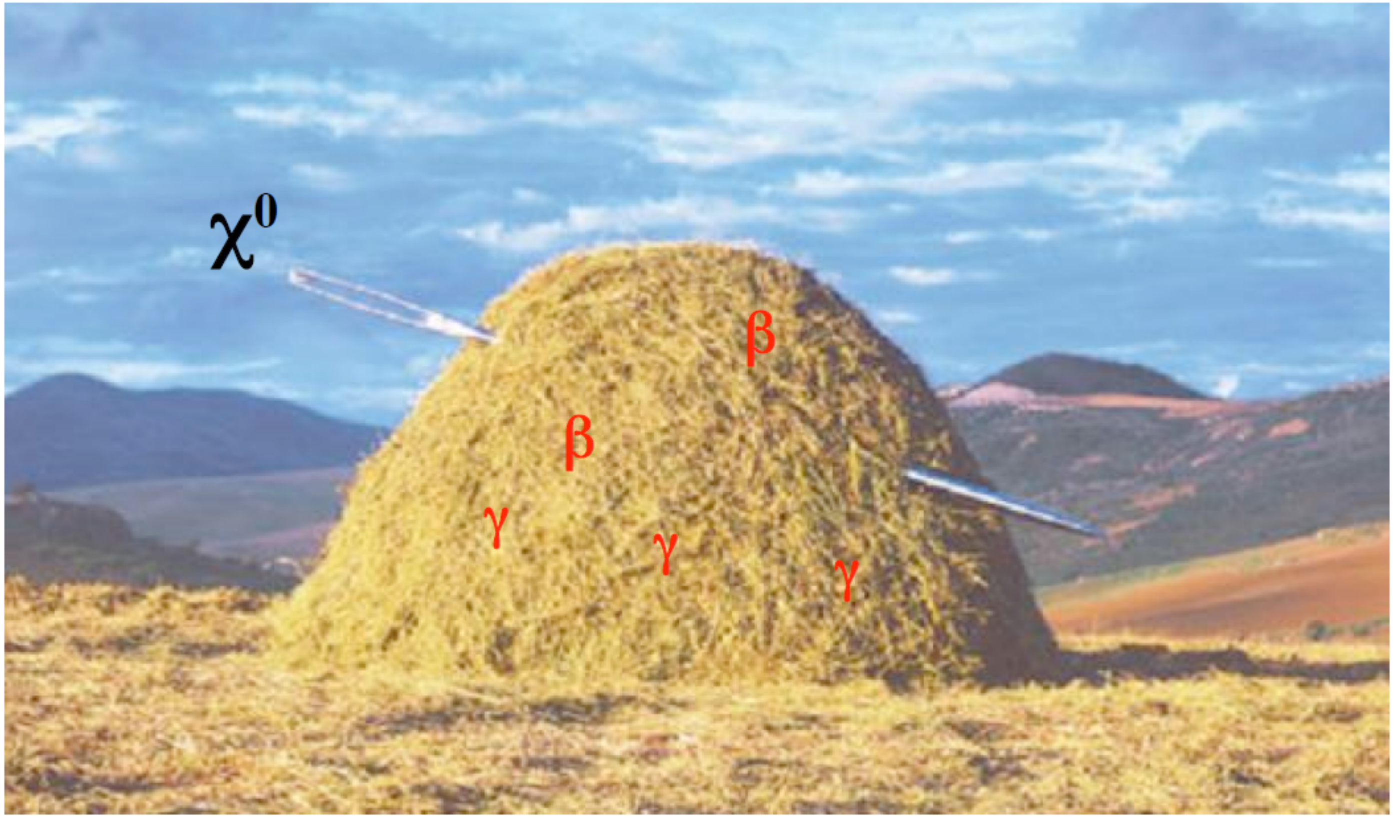


= production rate: to be calculated

- ✦ This is where any new phenomenon would hide
  - ✤ Supersymmetry
  - ✤ Extra-dimensions
  - ✤ Grand-Unified Theories
  - ✤ *etc.*
- ✦ Cross sections = production rate
  - ✤ 1 possible new physics event (if any)
  - ✤ 1.000 Higgs events
  - ✤ 1.000.000.000.000 Standard Model events

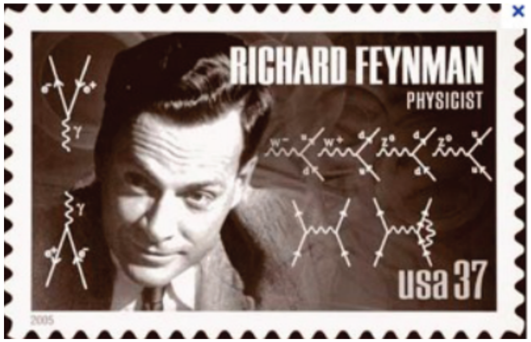
To find signal

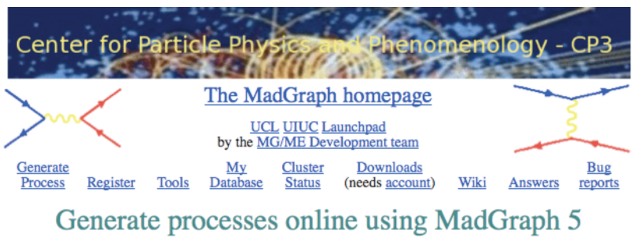
- To find a needle in the hay
- All hope is not a loss if our needle is VERY BIG!

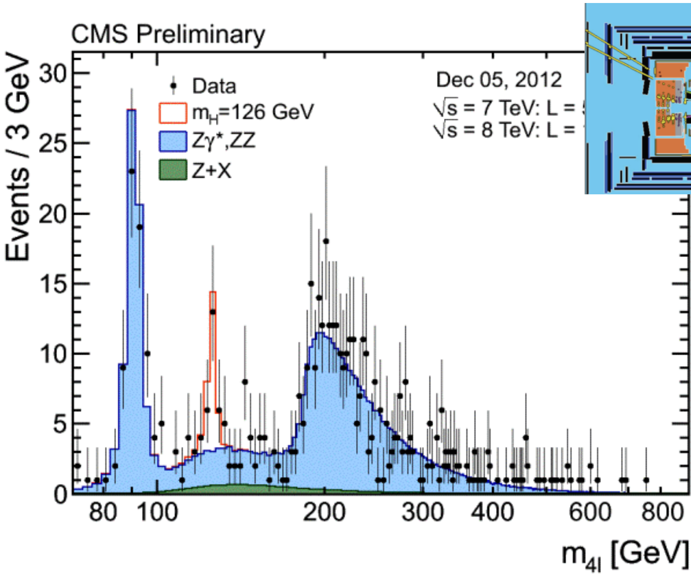


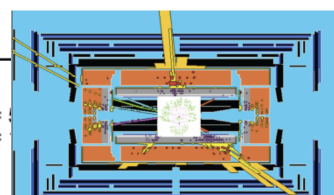
In real world …

MC Simulation Study









New Physics Model

⇓ ⇒ Feynman rules calculation

FeynRules

⇓ ⇒ Model implementation

MadGraph/CalcHEP

⇓ ⇒ Process creation

PYTHIA

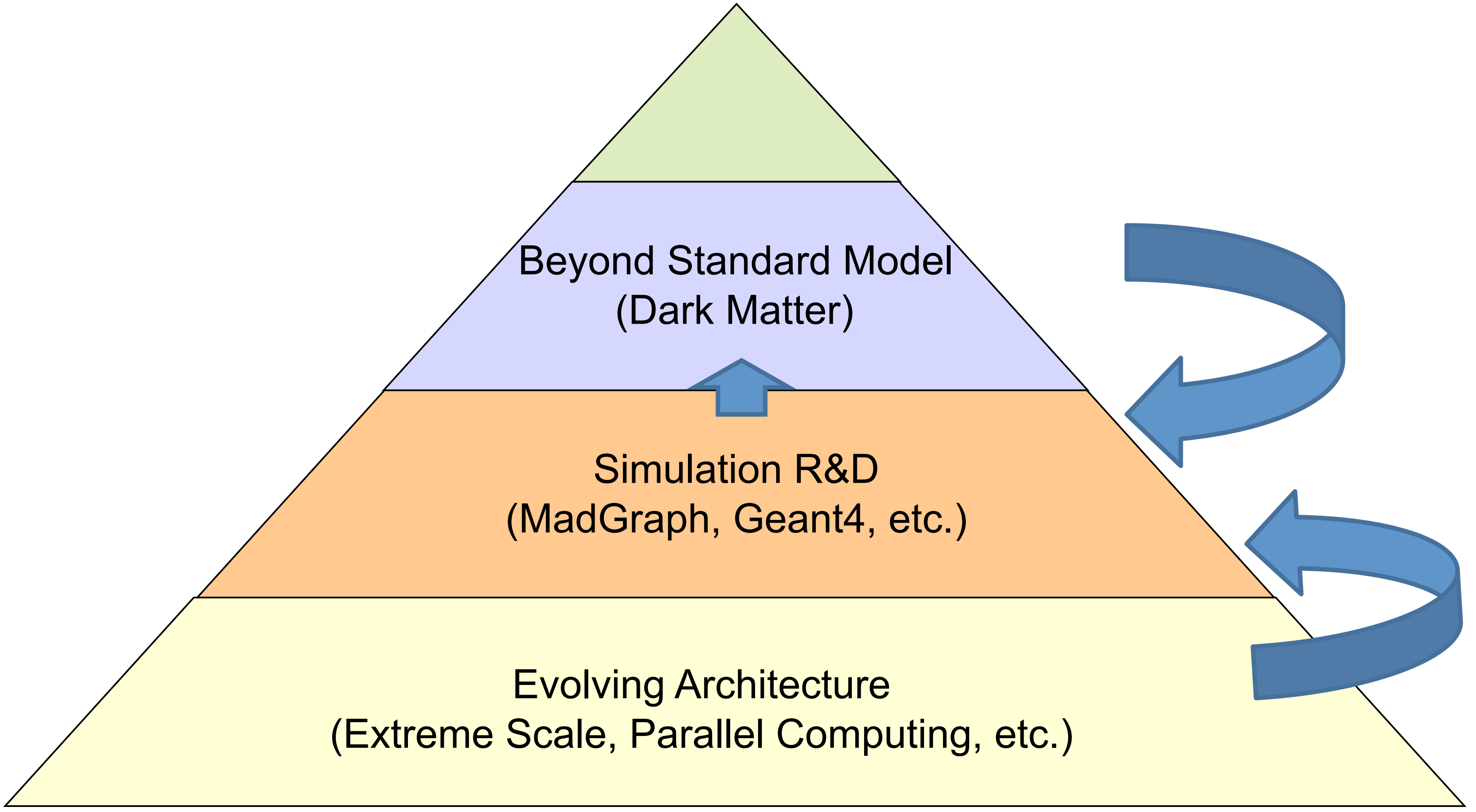
⇓ ⇒ Event generation (physics)

PGS/Delphes/Geant4

⇓ ⇒ Detector simulation

MadAnalysis/ROOT/Mathematica

Evolving Architecture for Beyond Standard Model



Dark Matter
at e+e- Collider

Why Dark Matter?

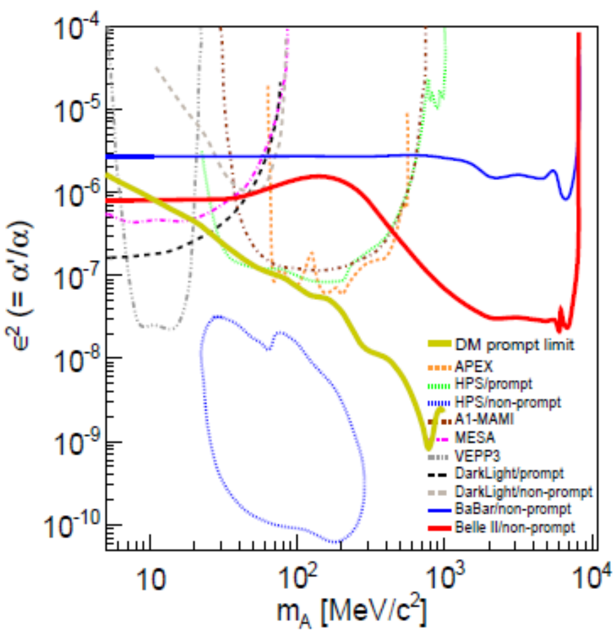
- Dark Matter is an evidence of BSM Physics.
- Its mass is not well constrained.
- Weak-scale DM has lots of attention:
  - Weak-scale, masses, couplings ⇒ correct abundance
  - Good candidates in models designed to understand the weak sc ale
  - Huge experimental efforts (direct detection, LHC, ...)
- Up to now, not too much new physics at the LHC
- Maybe dark matter is not connected to the weak scale, o r 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 at fixed target experiments

- Recently 6 fixed target experiments have been approved.
- Will cover region between 1MeV/c^2~1GeV/c^2.

- Predicted sensitivity



- VEPP3/Russia (new setup), $e^+ + p \to \gamma A$
- APEX/USA-JLAB (new setup), $e^- +$ nucleus $\to \gamma A$
- HPS/USA-JLAB, $e^- +$ nucleus $\to \gamma A$
- DarkLight/USA-JLAB (new setup), $e^- + \mathrm{H} \to \gamma A$
- A1-MAMI/Germany, $e^- +$ nucleus $\to \gamma A$
- MESA/Germany (new accelerator and setup),

  $e^- +$ nucleus $\to \gamma A$

A not necessarily prompt

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

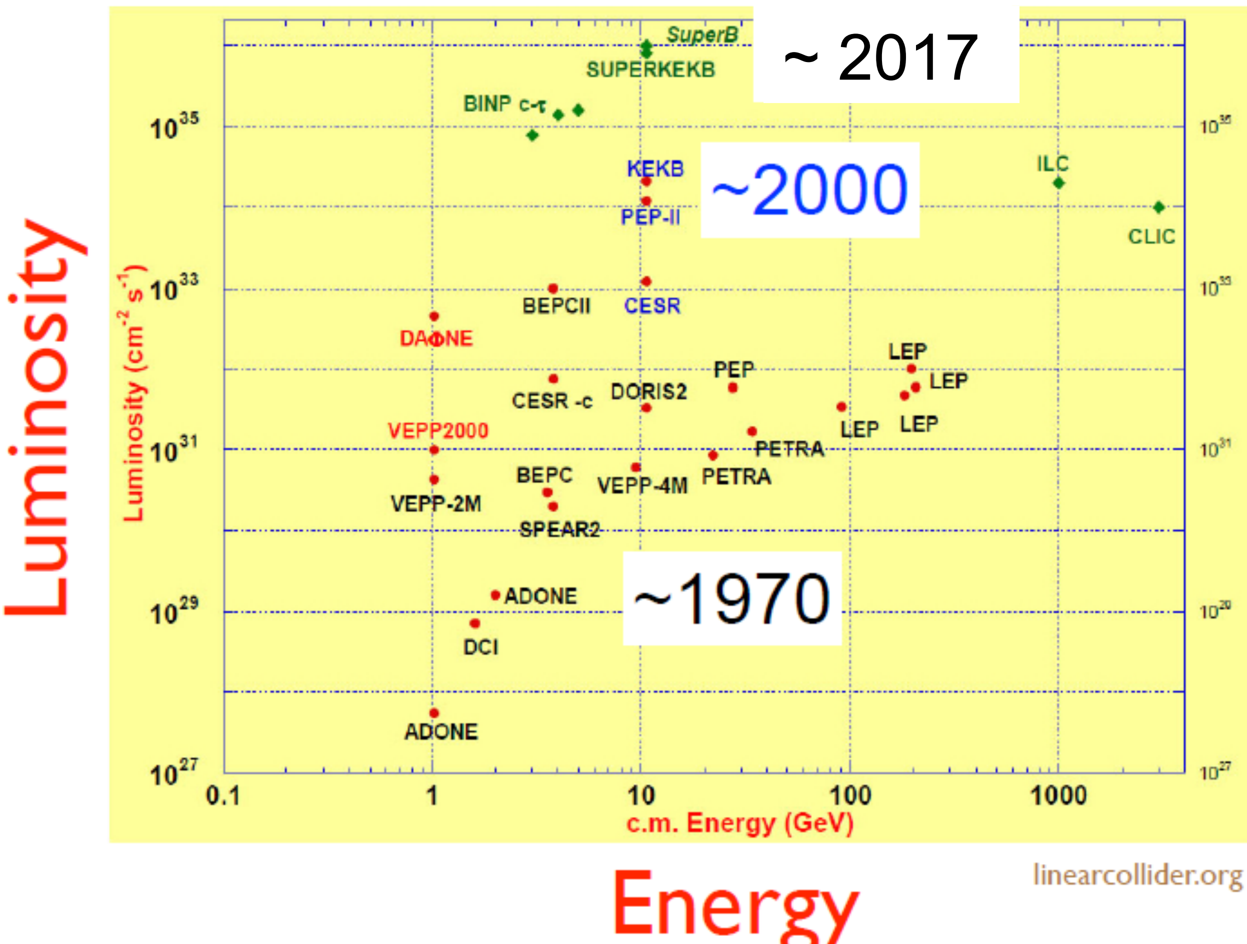
- All experiments use prompt decays & $A \to l^+ l^-$
- HPS & DarkLight use displacement decays, too.

Dark Matter at e+e- collider

- 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

e+e- collider

- Enormous increases in luminosity over last few decays.



e+e- collider experiments

Experiments	CM Energy(GeV)	Date	Place
KLOE	1	2001~	INFN, Italy
BaBar	10.58	1999~2008	SLAC, USA
Belle	10.58	1999~2010	KEK, Japan
Belle II	10.58	2017~	KEK, Japan
ILC	~500	2025~	Japan??

Nomenclature

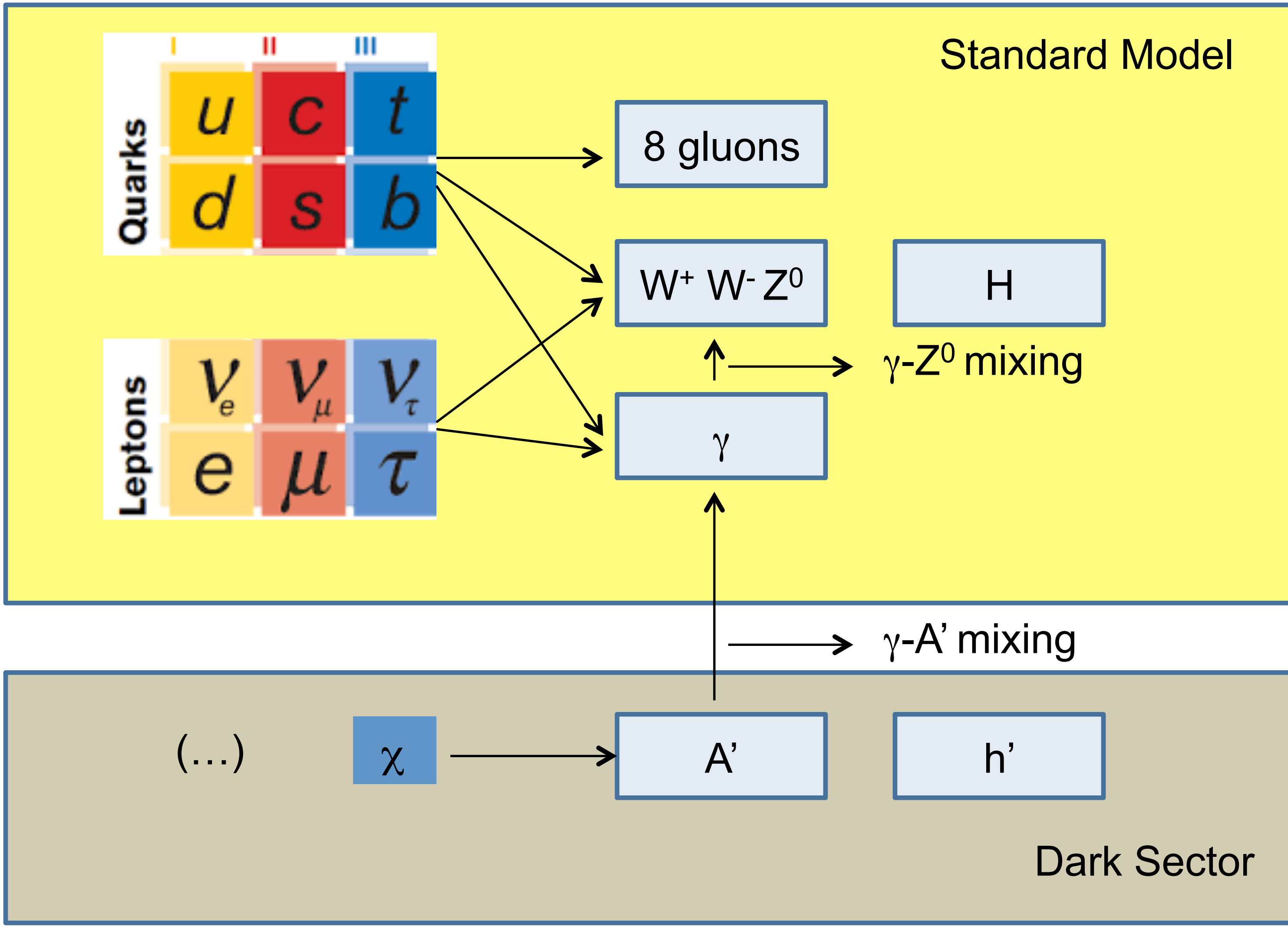
- Dark photon
  - Heavy photon
  - Dark force
  - Light dark gauge boson

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

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

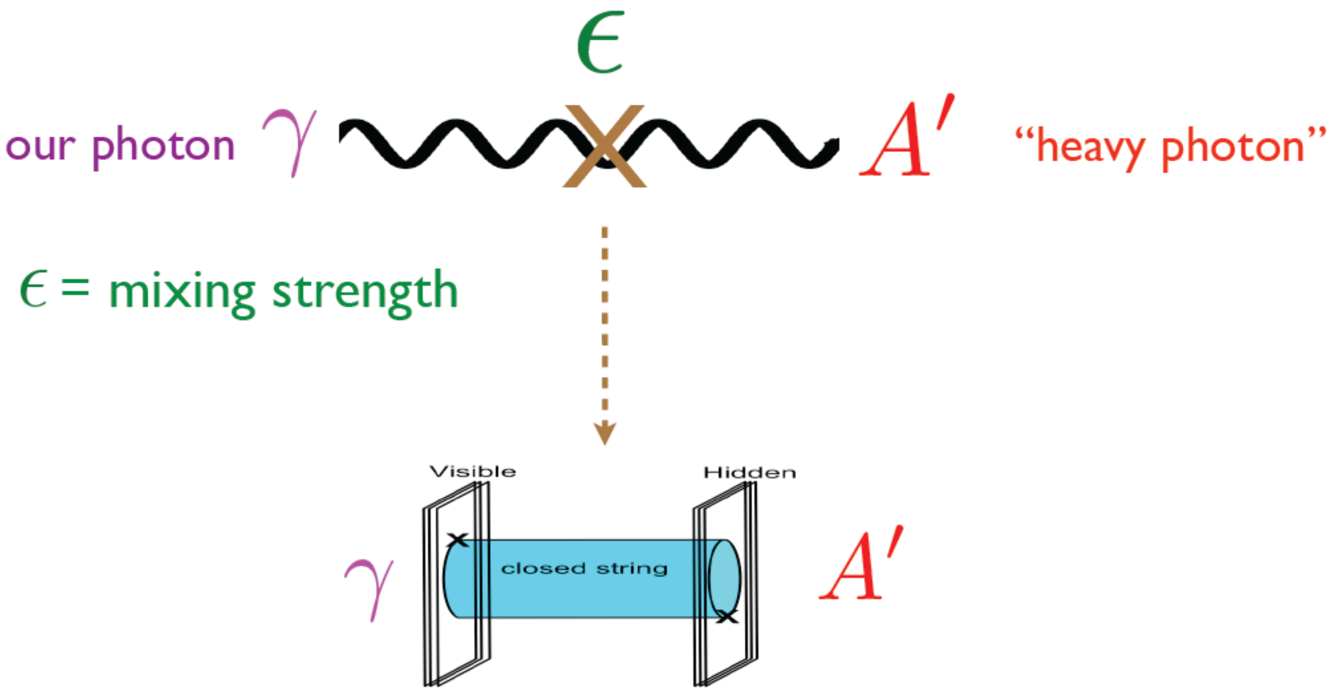
- Dark sector constant
  - $\alpha_D = \alpha' = g_D^2 / 4\pi$
- Dark sector
  - Hidden sector
  - Secluded sector
  - …

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
$W^+ W^- Z^0$
H
γ
γ-Z^0 mixing
γ-A' mixing
(…)
χ
A'
h'
Dark Sector

Dark Sector (γ-A' mixing)



Eassig (2012)

Dark Sector

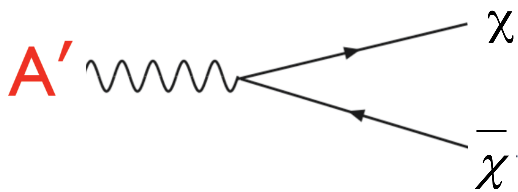
1. Dark Matter
2. Dark photon
3. Higgs-strahlung

1. Dark Matter (1/3)

- A' decay to DM

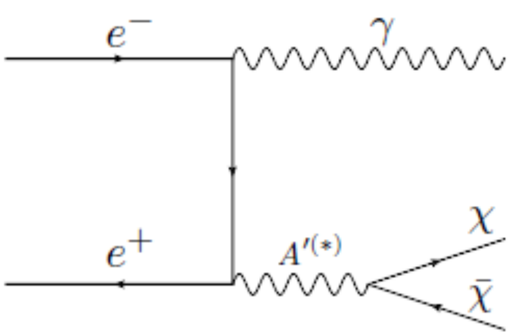
Eassig, et al, JHEP 11, 167 (2013).

Eassig, ArXiv: 1309.5084 [hep-ph]

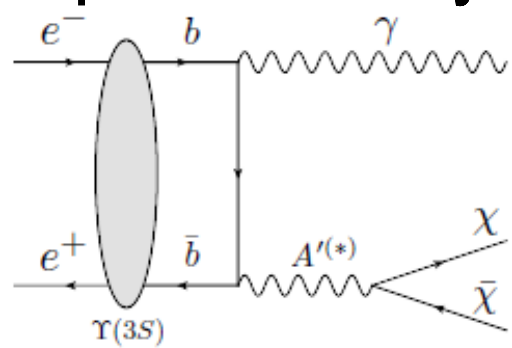


Neutral under SU(3)XSU(2)XU(1)

- Two body decay

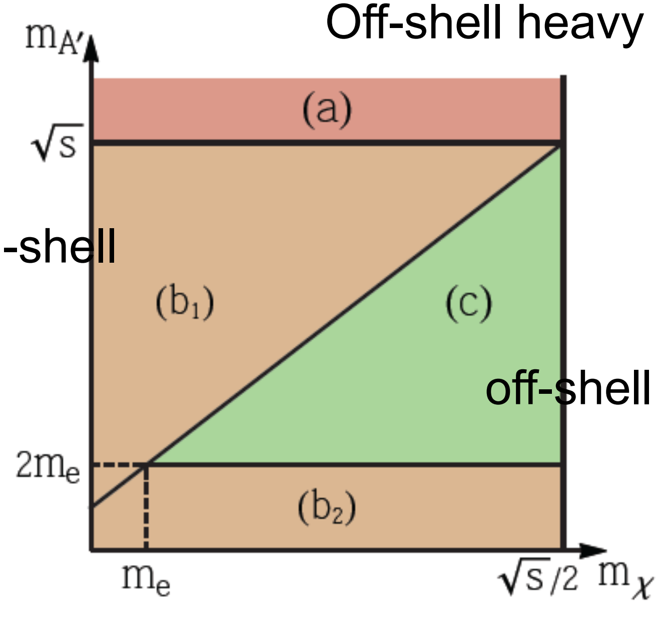


- Upsilon decay



1. Dark Matter (2/3)

- 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).

1. Dark Matter (3/3)

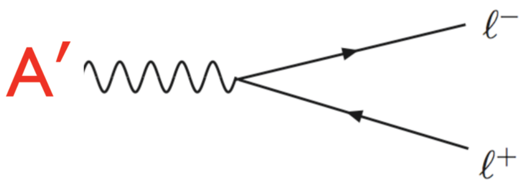
- A' decays to dark matter on-shell or off-shell with different gamma spectrum
  - Radiative production in e+e- collision
  - Only one photon in the final state with

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

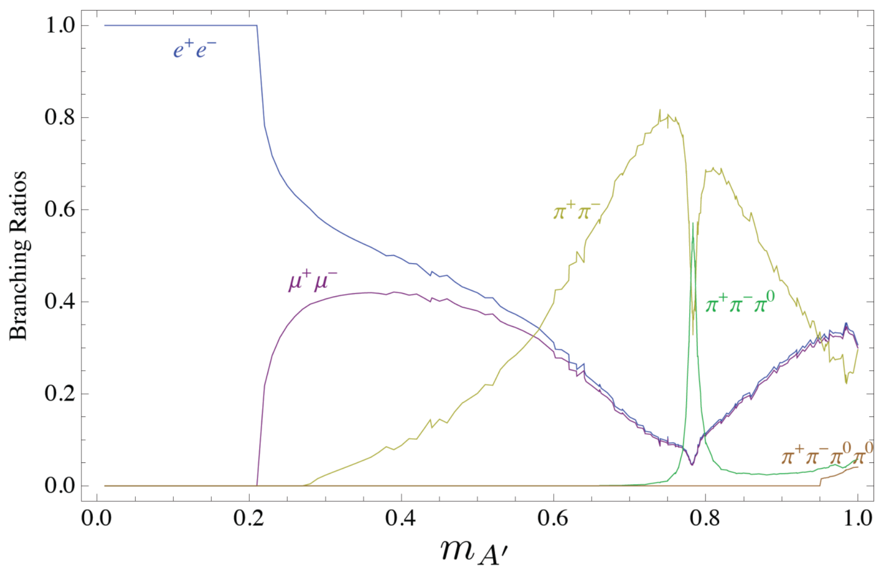
- Requires high single photon trigger
  - Not available in Belle,
  - The BaBar implemented a single photon trigger (arXiv e: 0808.0017[hep-ex])
  - On-going discussions for Belle II

2. Dark Photon (1/2)

A′ can decay directly to Standard Model



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



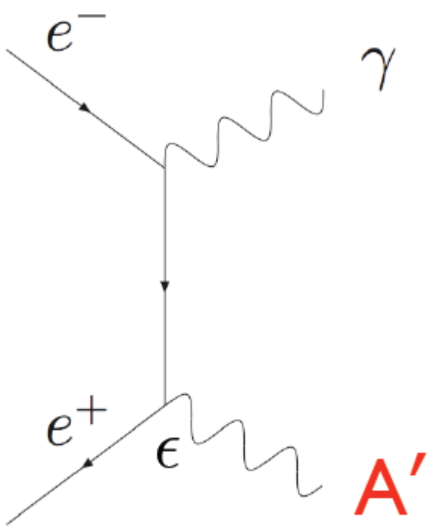
ArXiv: 0903.0363 [hep-ph]

Broad array of searches needed and underway

2. Dark Photon (2/2)

Produce A′ in e^+e^- collisions

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



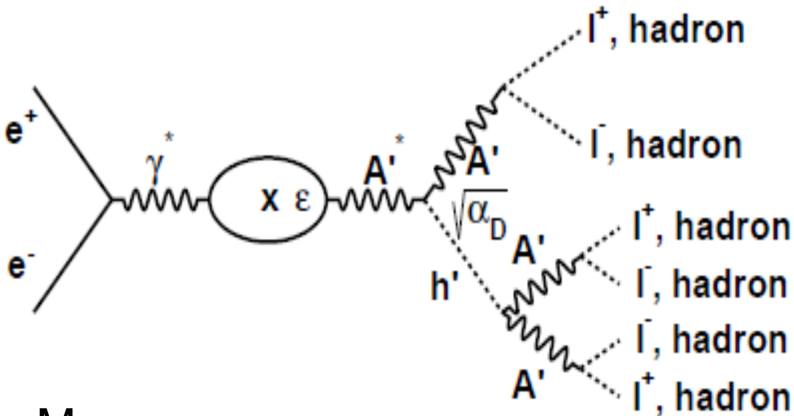
$$\sigma \propto \frac{\epsilon^2}{E_{cm}^2}$$

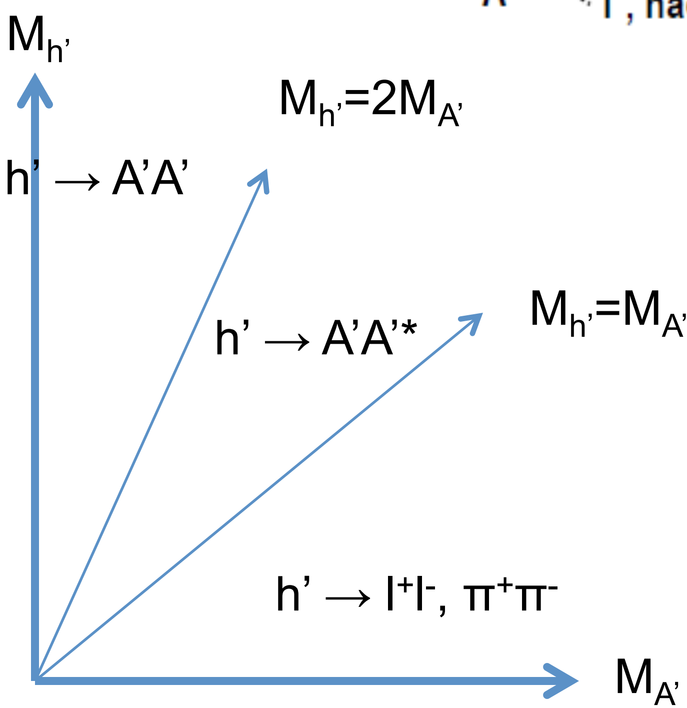
$\Longrightarrow$ want low-energy (1-10 GeV), high intensity colliders (BaBar, BELLE, KLOE, ...)

Eassig (2012)

ArXiv: 0903.0363 [hep-ph]

3. Higgs-Strahlung





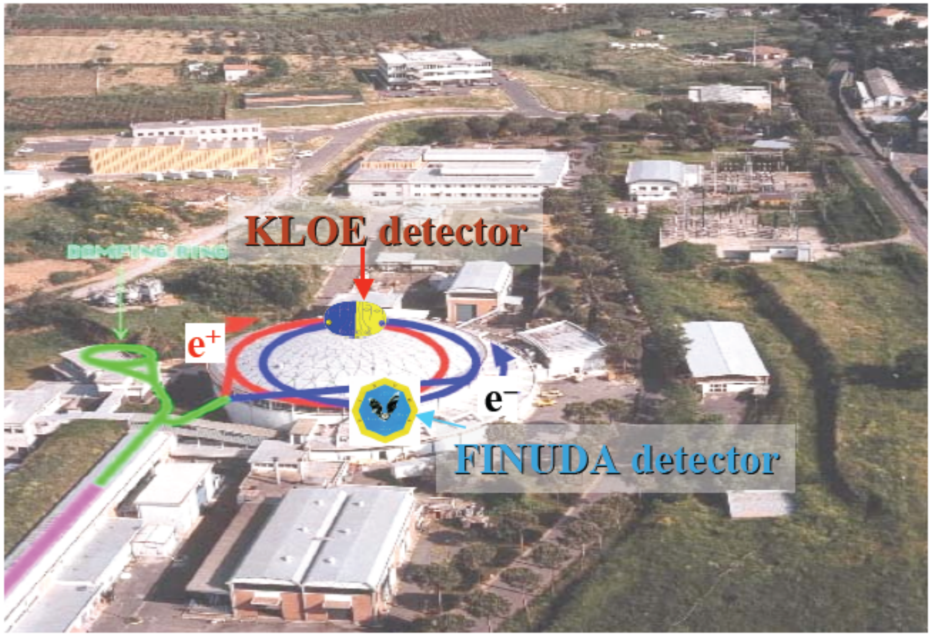
- h' decays depending on $M_{h'}$ and $M_{A'}$.
- To measure the coupling consta nt of the dark photon to the dark higgs, α_D
  1) $M_{h'} > 2M_{A'}$: h' → A'A', very low backgro und
     - Exclusive: 3 charged track pairs with same in variant mass and total energy of event
     - Inclusive: 2 charged track pairs, same invaria nt mass, third A from 4 mom. of e+e- system
  2) $M_{A'} < M_{h'} < 2M_{A'}$: h' → A'A'*
  3) $M_{h'} < M_{A'}$: h' long-lived and h' → l^+l^-, $\pi^+\pi^-$

Search for Dark Matter at e+e- collider

e+e- Collider Experiments

Experiment	Dark Matter	Dark photon	Higg-Strahulung	Heavy flavor lepton
1. KLOE		• 2 charged lepton+one photon • 2 charged lepton + η	$\mu\mu$+ missing E_T(h')	
2. BaBar	one photon + missing E_T	2 charge tracks + one photon	• 3 charged track pairs • 4 or more charged tracks	
3. Belle		2 charge track + one photon	3 charged track pairs	• Two lepton pairs • A lepton pairs + missing E_T
4. 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

- $e^+e^- \to \phi \quad \sqrt{s} \sim m_\phi = 1019.4$ 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

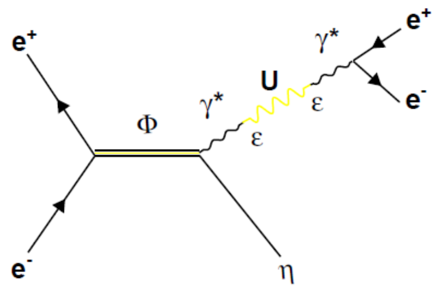
- Physics Program

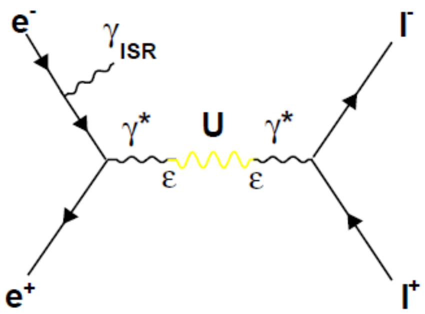
  - Kaon physics, Spectroscopy, hadron cross-section, $\gamma\gamma$ physics, Dark sector

Dark Photon (1/2)

- Dark Photon (ηe^+e^-)

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

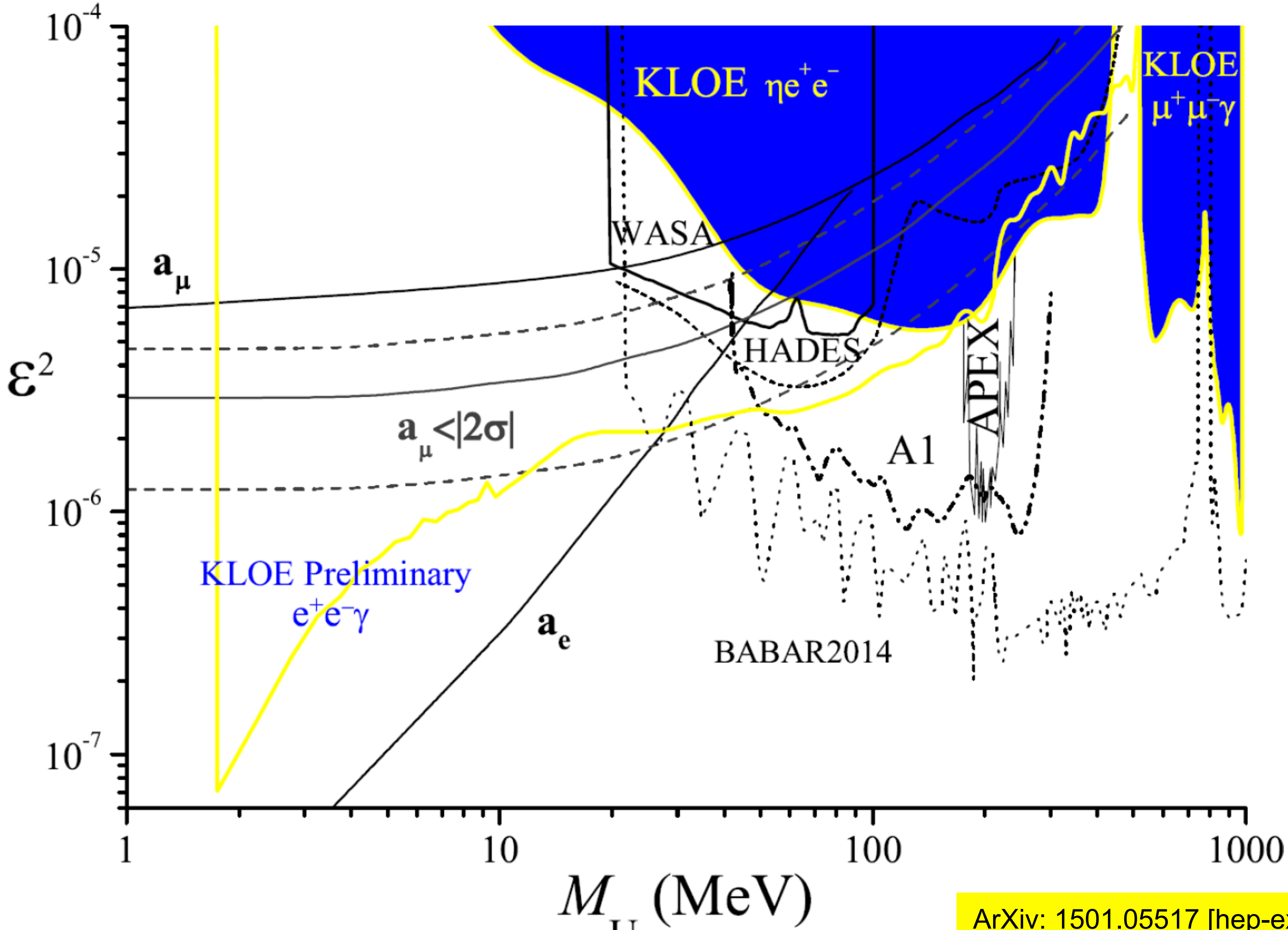




- Dark photon ($e^+e^-\gamma$ & $\mu^+\mu^-\gamma$)

ArXiv: 1501.05517 [hep-ex]

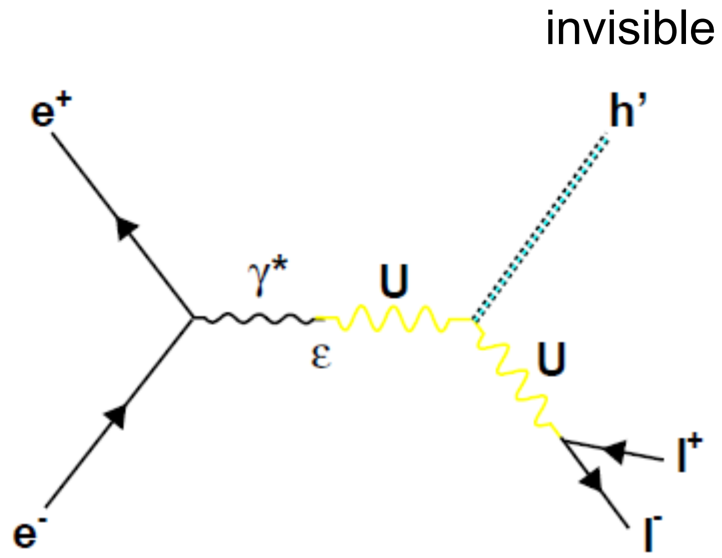
Dark Photon (2/2)

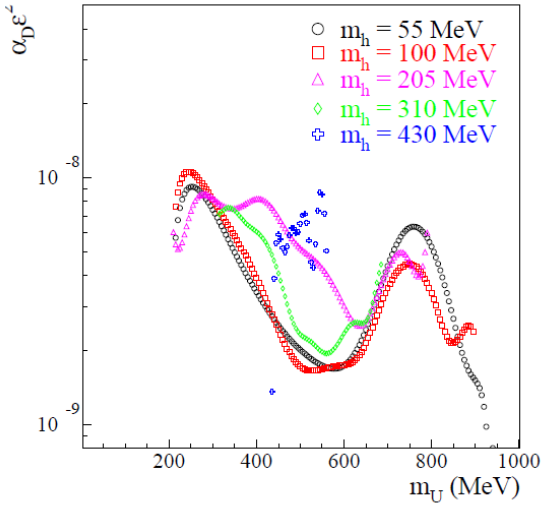


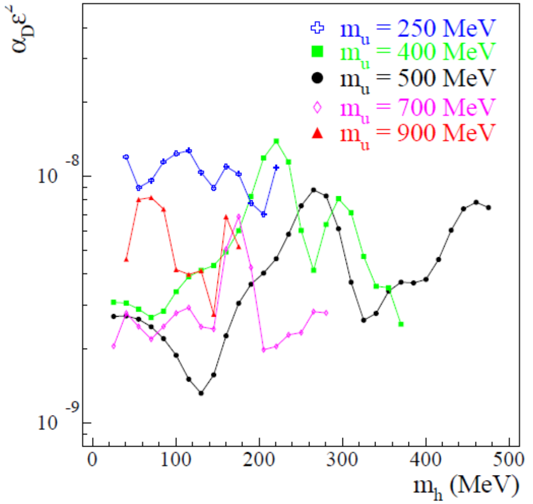
ArXiv: 1501.05517 [hep-ex]

Higgs-Strahlung

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



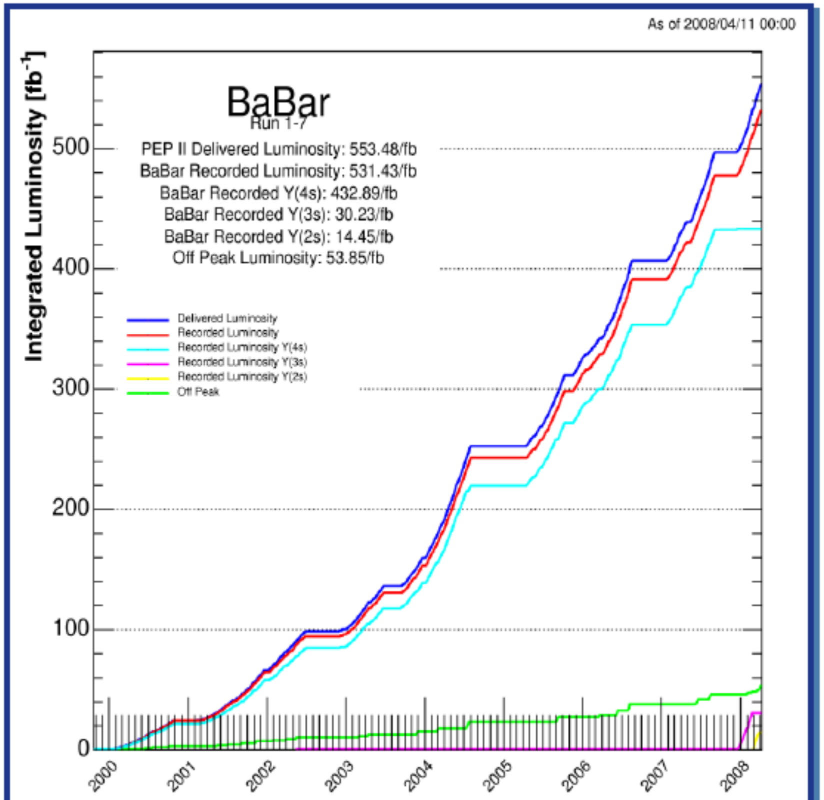


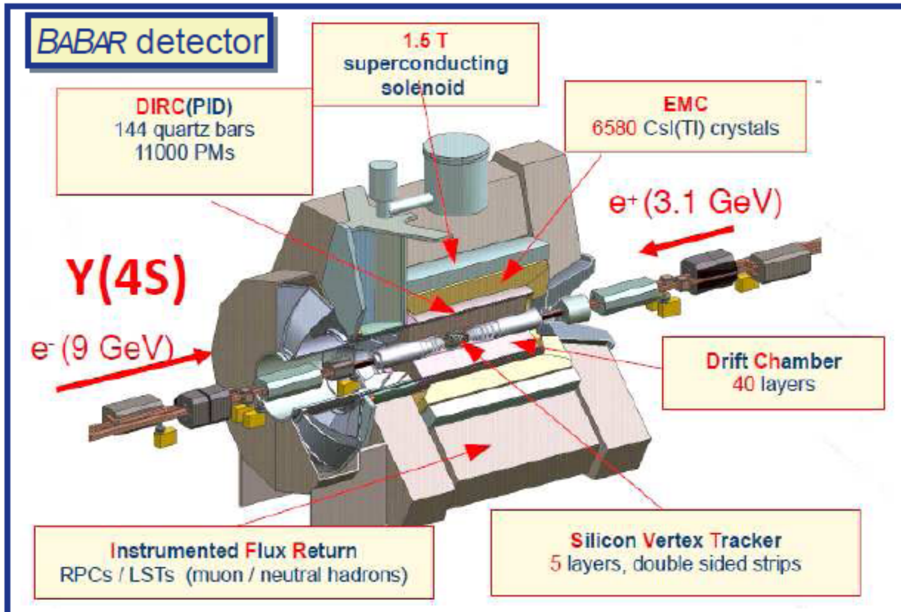


ArXiv: 1501.05517 [hep-ex]

2. BaBar Experiment

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





data samples

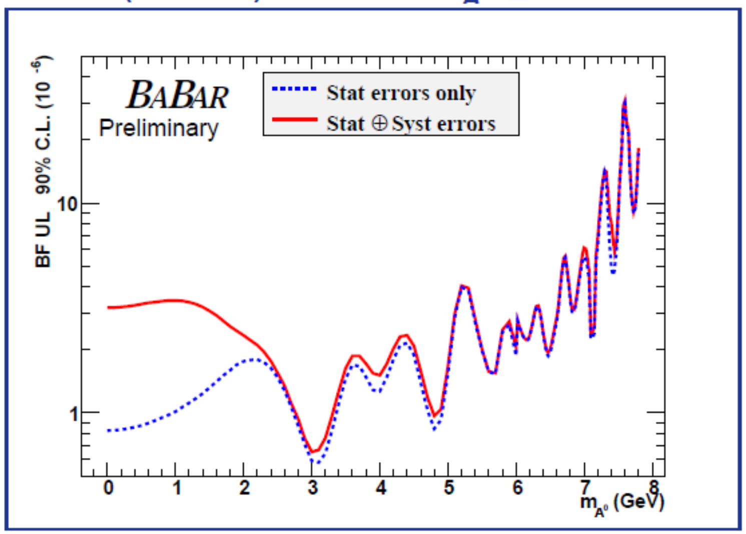
$\sim 470 \cdot 10^6$	$\Upsilon(4S)$
$\sim 120 \cdot 10^6$	$\Upsilon(3S)$
$\sim 100 \cdot 10^6$	$\Upsilon(2S)$

A. Lusiani (2014)

Dark Matter (1/2)

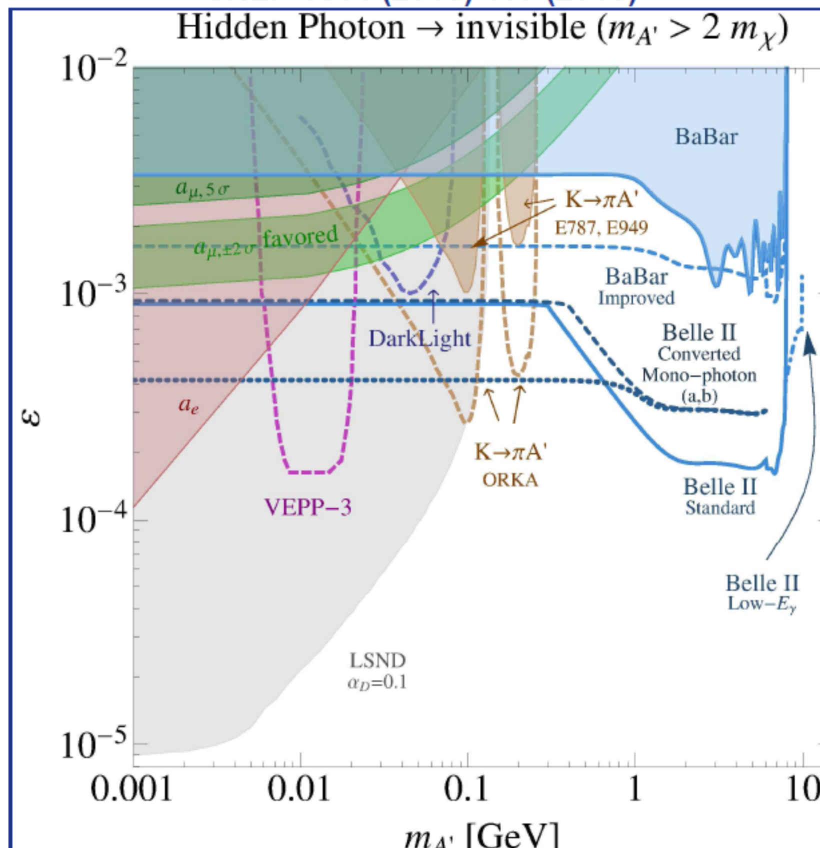
$\Upsilon(3S) \to \gamma A^0$, $A^0 \to$ invisible arXiv:0808.0017 [hep-ex]

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



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

Dark Photon constraints by R.Essig et *al.*
JHEP 1311 (2013) 167 (2013)

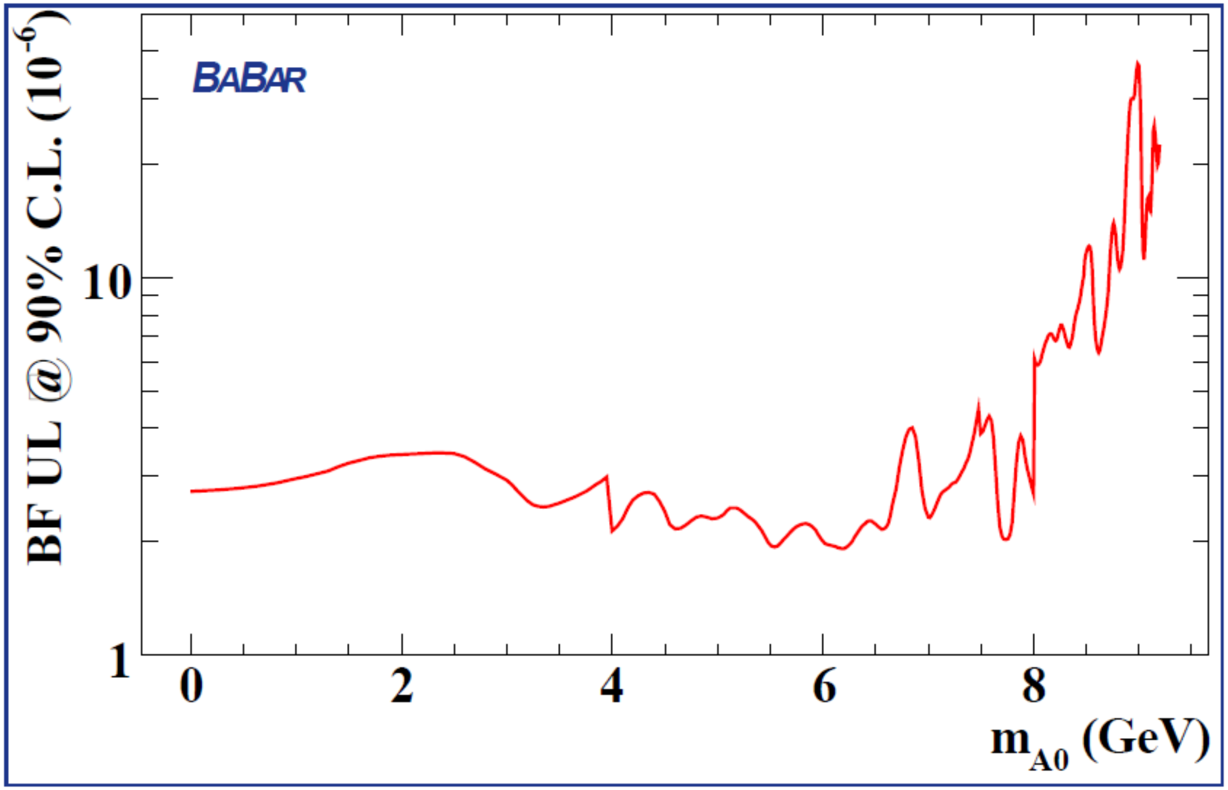


A. Lusiani (2014)

Dark Matter (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 $B(\Upsilon(1S) \to \gamma A^0) \times B(A^0 \to \text{invisible})$
$< (1.9\text{–}4.5) \times 10^{-6}$ for $m_{A^0} \leq 8.0$ GeV
$< (2.7\text{–}37) \times 10^{-6}$ for $m_{A^0} \leq 9.2$ GeV



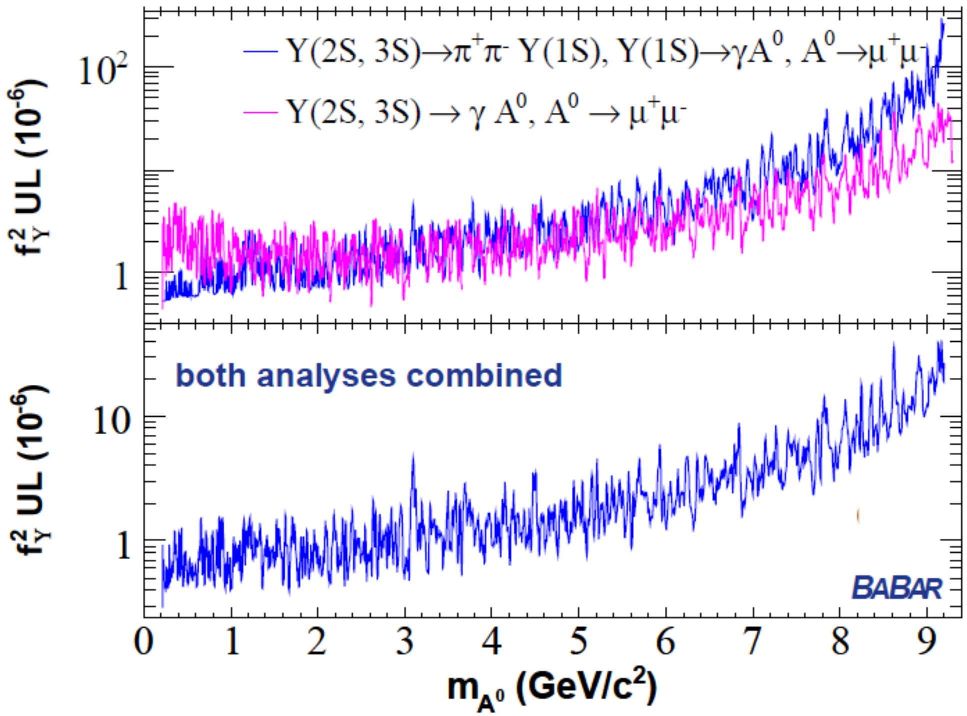
A. Lusiani (2014)

Dark Photon

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 $m_{A^0} \leq 1.2\ \mathrm{GeV}/c^2$

90% CL upper limits on $f_\Upsilon^2 \cdot B(A^0 \to \mu^+\mu^-)$



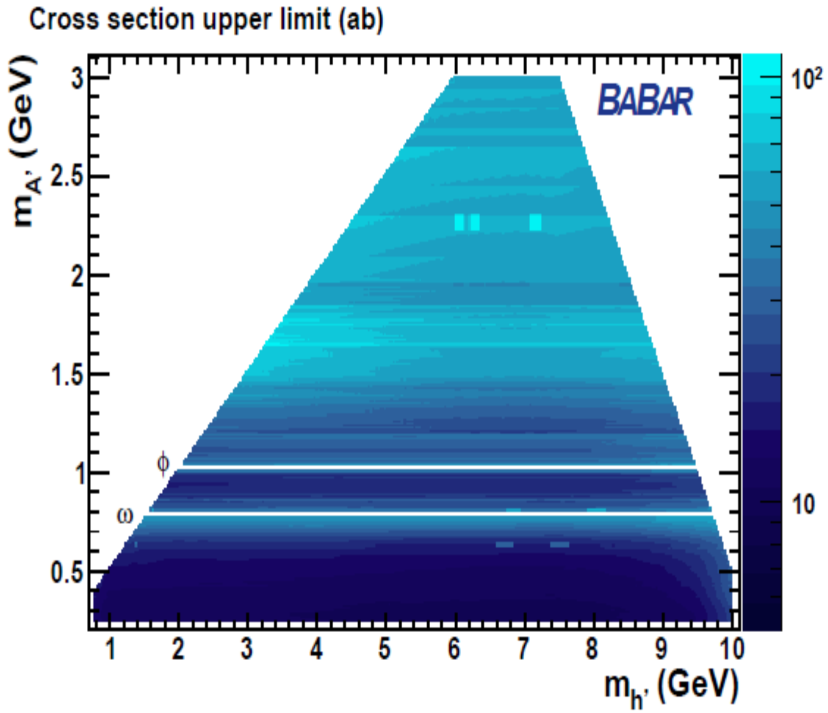
PRD 87, 031102(R) (2013), arXiv:1210.0287

A. Lusiani (2014)

Higgs-Strahlung

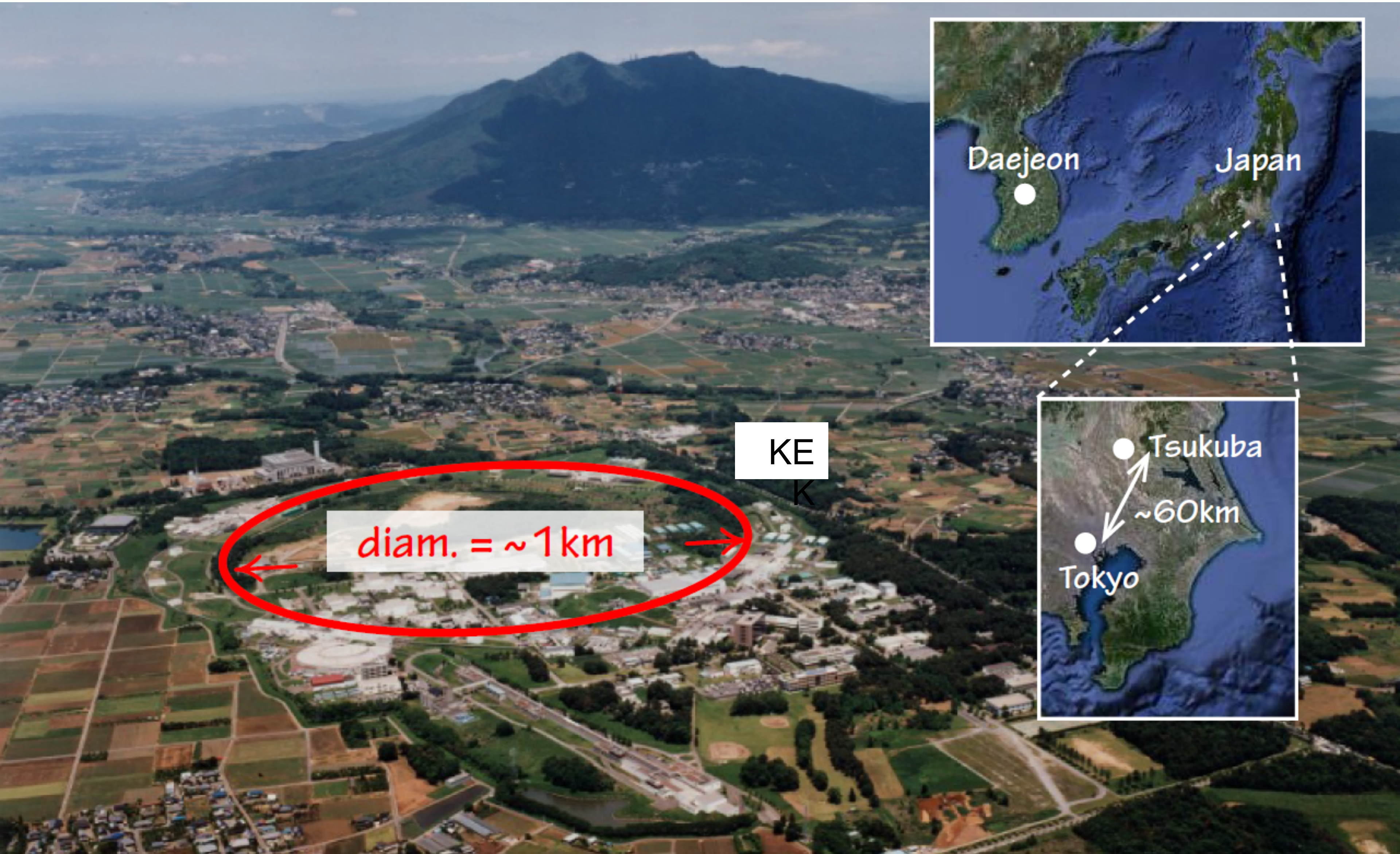
Search for Dark Higgs Boson in BABAR, upper limits PRL 108 (2012) 2118

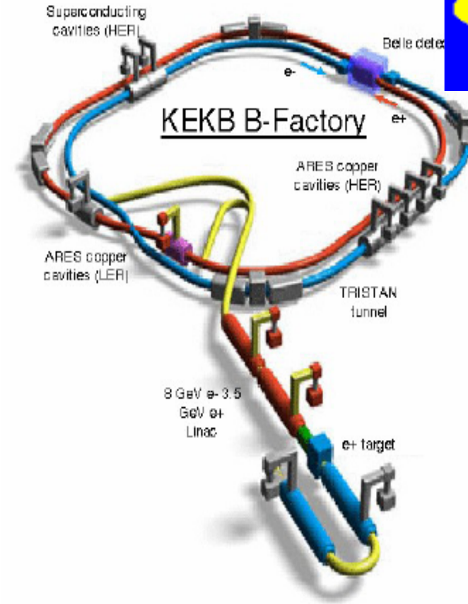
- 90% CL limits on $\sigma(e^+e^- \to h'A', \quad h' \to A'A')$ as function of h' and A' masses
  - conservative approach, no BKG subtraction
- convert into limits on $\alpha_D \epsilon^2$ ($\alpha_D = g_D^2/4\pi$, g_D = the dark sector gauge coupling)



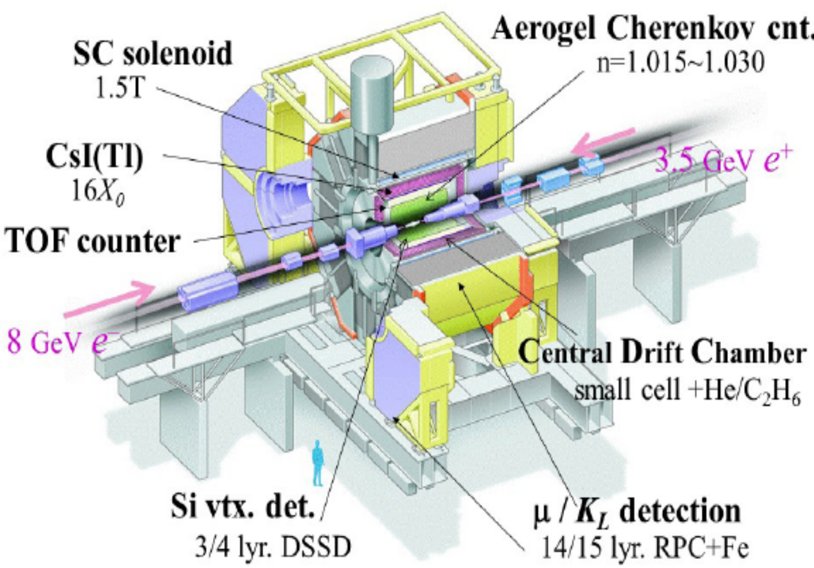
A. Lusiani (2014)

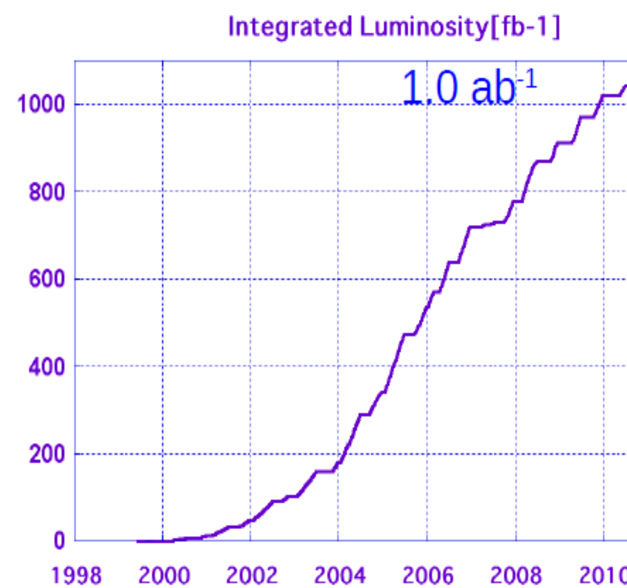
3. Belle Experiment





Belle Detector





Search for the Dark Photon and the Dark Higgs Boson at Belle

I. Jaegle,[13] I. Adachi,[14,10] H. Aihara,[55] S. Al Said,[50,25] D. M. Asner,[44] T. Aushev,[35,22] R. Ayad,[50] A. M. Bakich,[49] V. Bansal,[44] M. Barrett,[13] B. Bhuyan,[16] A. Bozek,[41] M. Bračko,[31,23] T. E. Browder,[13] D. Červenkov,[4] M.-C. Chang,[7] B. G. Cheon,[12] K. Chilikin,[22] K. Cho,[26] V. Chobanova,[32] S.-K. Choi,[11] Y. Choi,[48] D. Cinabro,[59] J. Dalseno,[32,52] Z. Doležal,[4] Z. Drásal,[4] A. Drutskoy,[22,34] D. Dutta,[16] S. Eidelman,[3] D. Epifanov,[55] H. Farhat,[59] J. E. Fast,[44] T. Ferber,[6] O. Frost,[6] V. Gaur,[51] N. Gabyshev,[3] S. Ganguly,[59] A. Garmash,[3] D. Getzkow,[8] R. Gillard,[59] Y. M. Goh,[12] B. Golob,[30,23] O. Grzymkowska,[41] K. Hayasaka,[37] H. Hayashii,[38] X. H. He,[45] M. Hedges,[13] W.-S. Hou,[40] T. Iijima,[37,36] K. Inami,[36] A. Ishikawa,[54] Y. Iwasaki,[14] T. Julius,[33] K. H. Kang,[28] E. Kato,[54] T. Kawasaki,[42] D. Y. Kim,[47] J. B. Kim,[27] J. H. Kim,[26] S. H. Kim,[12] K. Kinoshita,[5] B. R. Ko,[27] P. Kodyš,[4] S. Korpar,[31,23] P. Križan,[30,23] P. Krokovny,[3] A. Kuzmin,[3] Y.-J. Kwon,[61] J. S. Lange,[8] I. S. Lee,[12] P. Lewis,[13] L. Li Gioi,[32] J. Libby,[17] D. Liventsev,[14] D. Matvienko,[3] H. Miyata,[42] R. Mizuk,[22,34] G. B. Mohanty,[51] A. Moll,[32,52] R. Mussa,[21] E. Nakano,[43] M. Nakao,[14,10] N. K. Nisar,[51] S. Nishida,[14,10] S. Ogawa,[53] P. Pakhlov,[22,34] G. Pakhlova,[22] H. Park,[28] T. K. Pedlar,[62] L. Pesántez,[2] M. Petrič,[23] L. E. Piilonen,[58] M. Ritter,[32] A. Rostomyan,[6] Y. Sakai,[14,10] S. Sandilya,[51] L. Santelj,[14] T. Sanuki,[54] Y. Sato,[36] V. Savinov,[46] O. Schneider,[29] G. Schnell,[1,15] C. Schwanda,[19] D. Semmler,[8] K. Senyo,[60] O. Seon,[36] I. Seong,[13] M. E. Sevior,[33] V. Shebalin,[3] T.-A. Shibata,[56] J.-G. Shiu,[40] B. Shwartz,[3] F. Simon,[32,52] R. Sinha,[20] Y.-S. Sohn,[61] M. Starič,[23] M. Sumihama,[9] K. Sumisawa,[14,10] U. Tamponi,[21,57] G. Tatishvili,[44] Y. Teramoto,[43] F. Thorne,[19] M. Uchida,[56] S. Uehara,[14,10] Y. Unno,[12] S. Uno,[14,10] S. E. Vahsen,[13] C. Van Hulse,[1] P. Vanhoefer,[32] G. Varner,[13] A. Vinokurova,[3] M. N. Wagner,[8] C. H. Wang,[39] M.-Z. Wang,[40] P. Wang,[18] X. L. Wang,[58] M. Watanabe,[42] Y. Watanabe,[24] K. M. Williams,[58] E. Won,[27] J. Yamaoka,[44] S. Yashchenko,[6] Y. Yook,[61] Y. Yusa,[42] V. Zhilich,[3] V. Zhulanov,[3] and A. Zupanc[23]

(Belle Collaboration)

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[7]*Department of Physics, Fu Jen Catholic University, Taipei 24205*
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[10]*The Graduate University for Advanced Studies, Hayama 240-0193*
[11]*Gyeongsang National University, Chinju 660-701*
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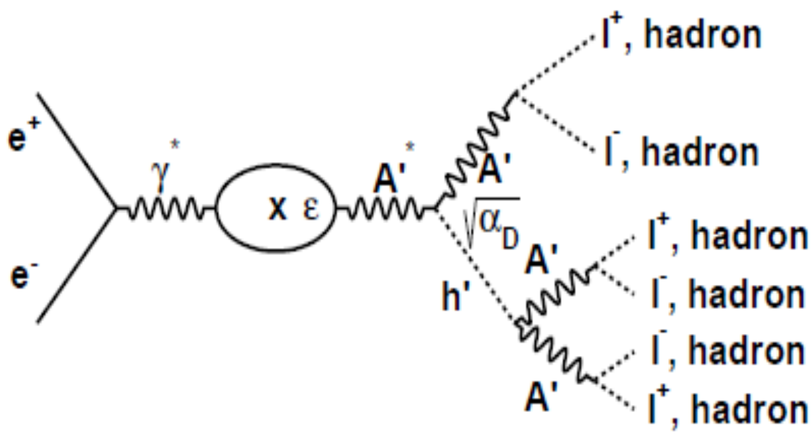
Higgs-Strahlung (1/3)

- Dark Matter
  - Invisible final state $e^+e^- \rightarrow \gamma A', A' \rightarrow \chi\bar{\chi}$
  - No Trigger at Belle (cf. BaBar has the trigger)
  - ⇒ Search for Dark photon and Dark higgs at Belle
- Higgs-Strahlung
  - Case 1) $M_{h'} > 2M_{A'}$: $h' \rightarrow A'A'$,
  - Prompt of h' and A'
  - 10 exclusive channels: $3(l^+l^-)$, $2(l^+l^-)(\pi^+\pi^-)$, $2(\pi^+\pi^-)(l^+l^-)$ with $l=e,\mu$
  - 3 inclusive channels: $2(l^+l^-)X$ with X dark photon (Missing mass)



Higgs-Starahlung (2/3)

Dark photon

Dark higgs

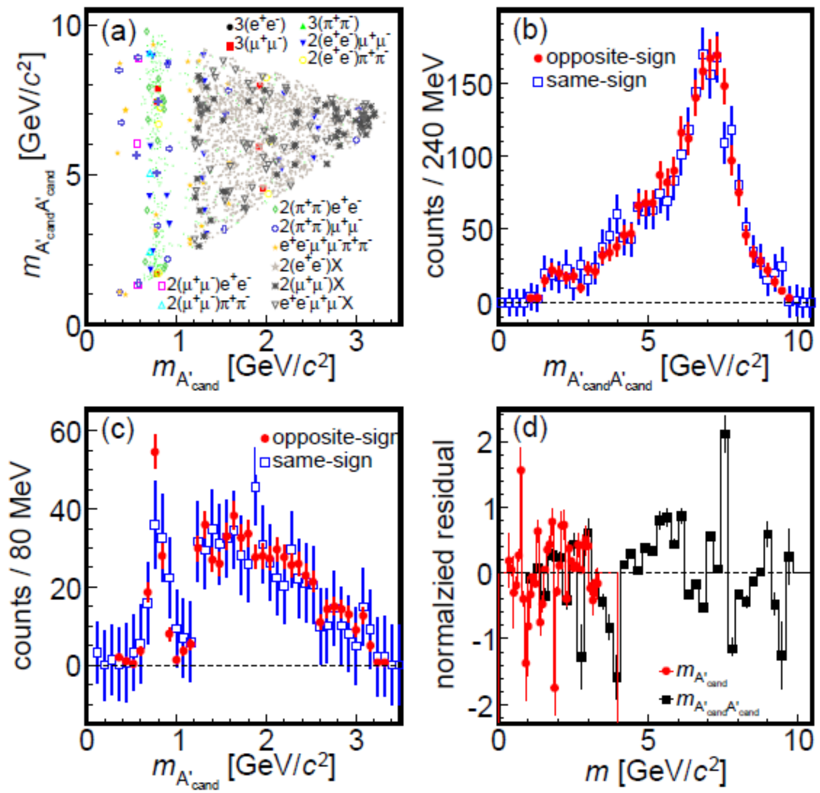


TABLE I. Number of events observed after all selection criteria are applied.

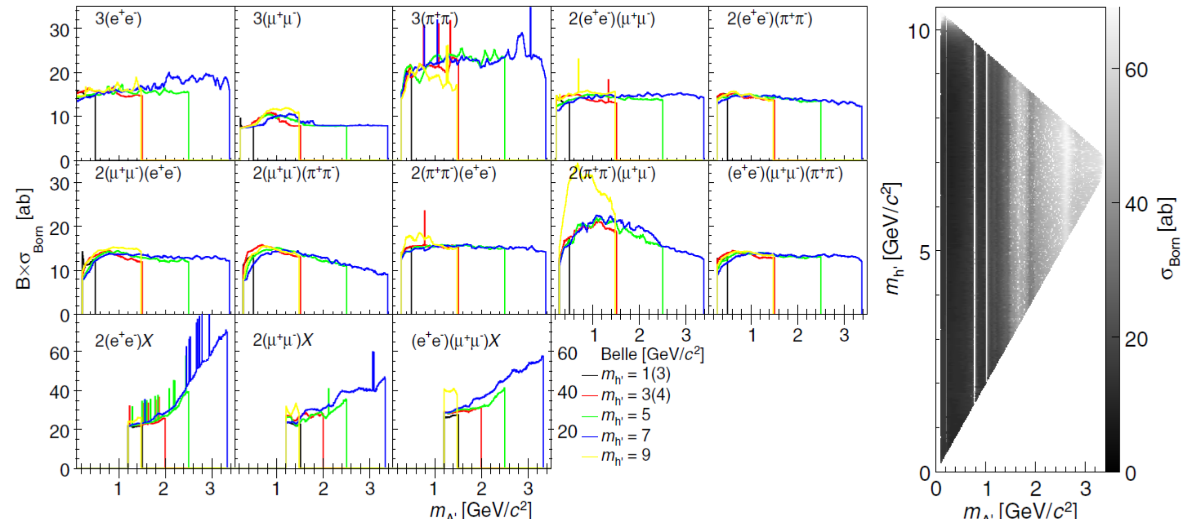
Final state	Events	Final state	Events
$3(e^-e^+)$	1	$2(\mu^+\mu^-)(e^+e^-)$	1
$3(\mu^+\mu^-)$	2	$2(\mu^+\mu^-)(\pi^+\pi^-)$	1
$3(\pi^+\pi^-)$	147	$2(\pi^+\pi^-)(e^+e^-)$	5
$2(e^+e^-)(\mu^+\mu^-)$	7	$2(\pi^+\pi^-)(\mu^+\mu^-)$	6
$2(e^+e^-)(\pi^+\pi^-)$	2	$(e^+e^-)(\mu^+\mu^-)(\pi^+\pi^-)$	7
$2(e^+e^-)X$	572	$(e^+e^-)(\mu^+\mu^-)X$	30
$2(\mu^+\mu^-)X$	20		

- Background vs. number of events observed
  - BG: SM 2γ processes with ρ or ω final state
  - Discontinuity at 1.1GeV du e to selection criteria

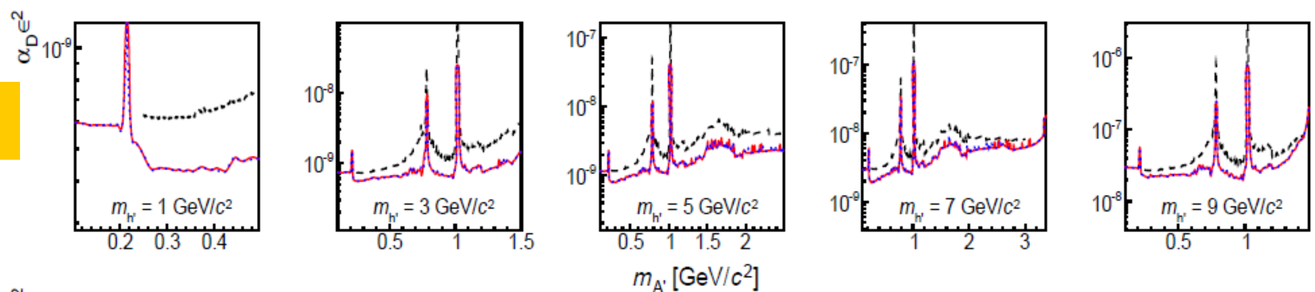
Higgs-Strahlung (3/3)

- Dark photon and Dark higgs distributions

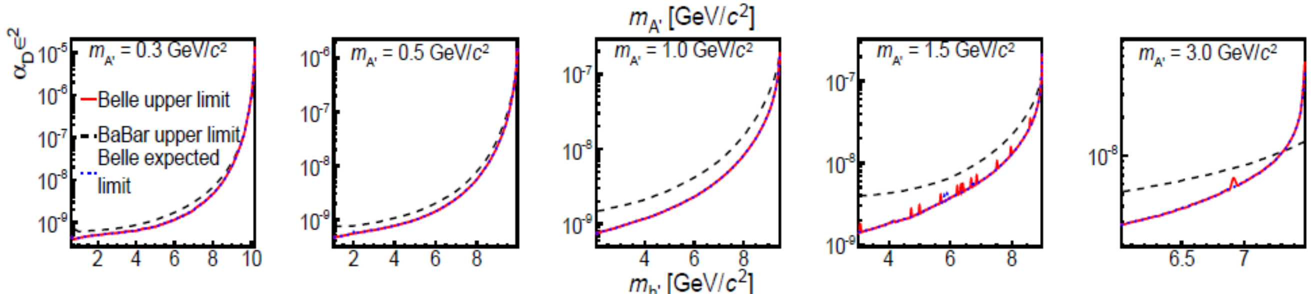
Dark photon



Dark photon



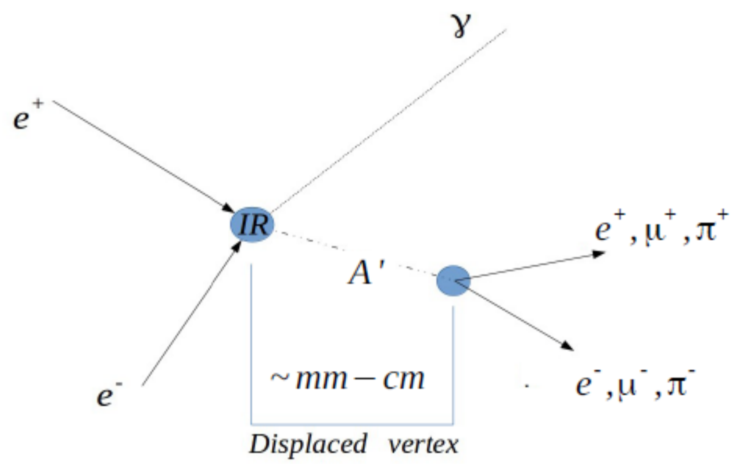
Dark higgs



Dark Photon

- Dark photon decays SM particles.

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



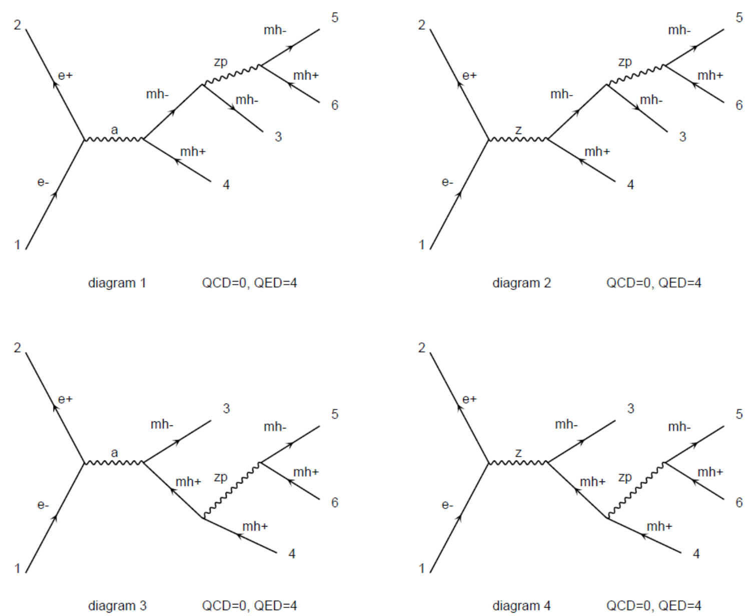
- To call a "long-lived gauge boson" instead of dark photon
- Same analysis for Higgs-Strahlung

⇒ work on progress

Gianluca Inguglia (2015)

A' couples only to heavy-flavor leptons

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



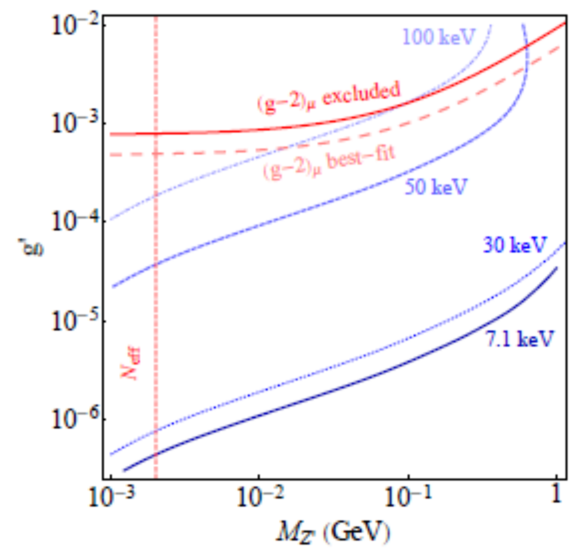
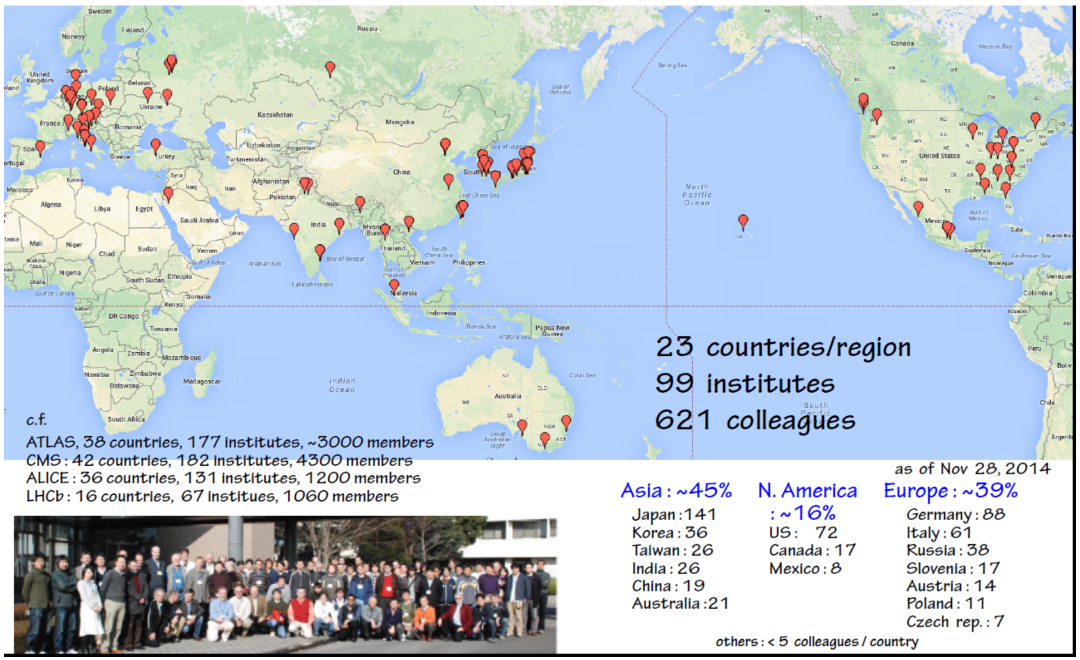
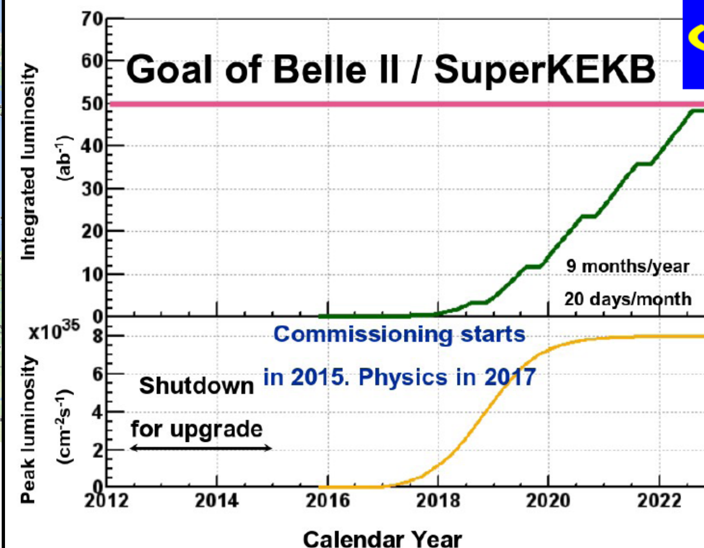


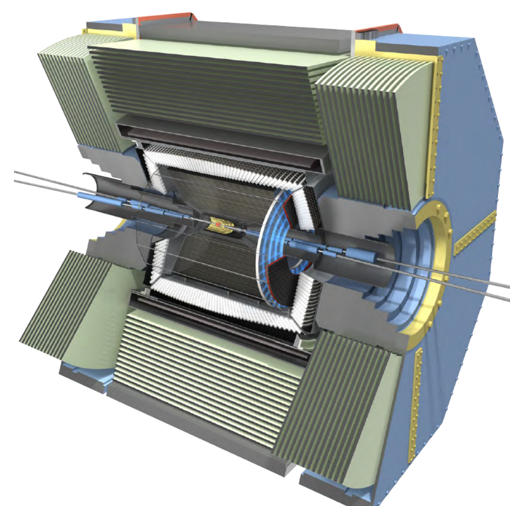
FIG. 3. A contour plot of the sterile neutrino abundance in the $M_{Z'} - g'$ plane. Shown are the contours corresponding to the observed DM relic abundance, $Y_{DM} = 4.7 \times 10^{-4}(\mathrm{keV}/m_s)$, for different values of the sterile neutrino mass m_s. The mixing angle for each m_s is at the 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 on progress at Belle

4. Belle II Experiment



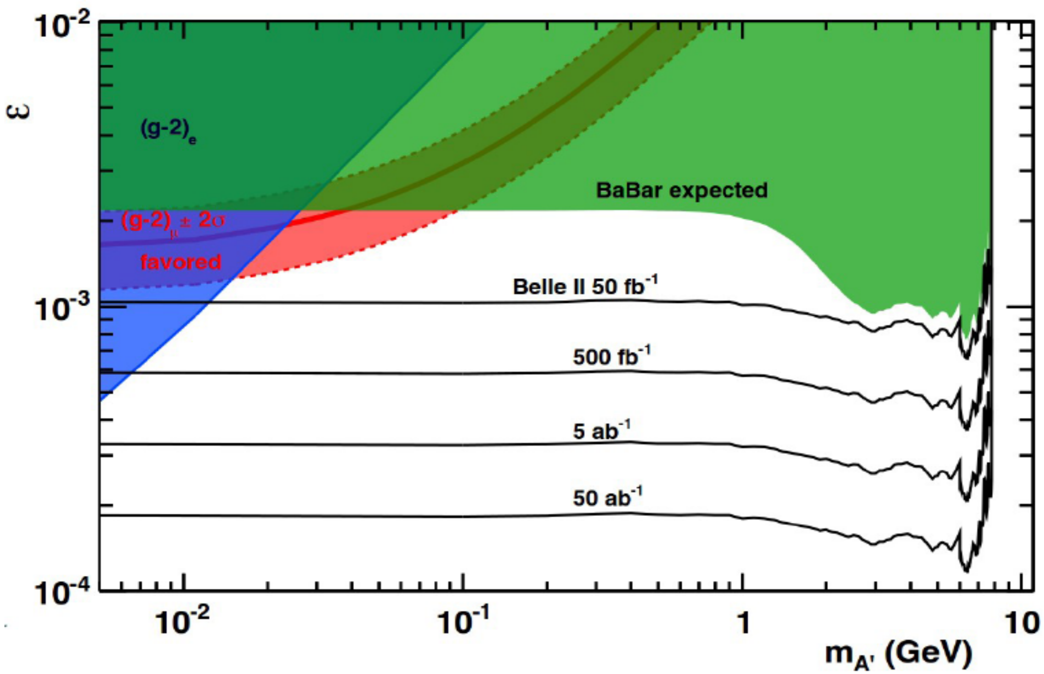




Dark Matter

- Dark photon decays DM. $e^+e^- \rightarrow \gamma A', A' \rightarrow \chi\bar{\chi}$
- Mono-energetic photon signature
- Full luminosity 50 ab^{-1} and 1% trigger fraction
- Need a single photon trigger at Belle II

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

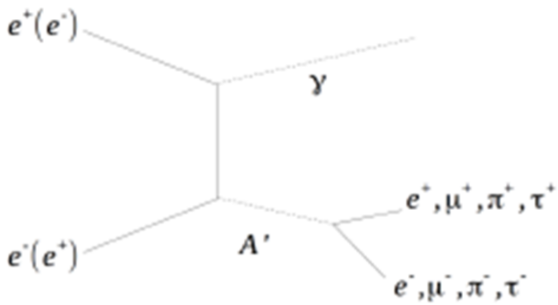


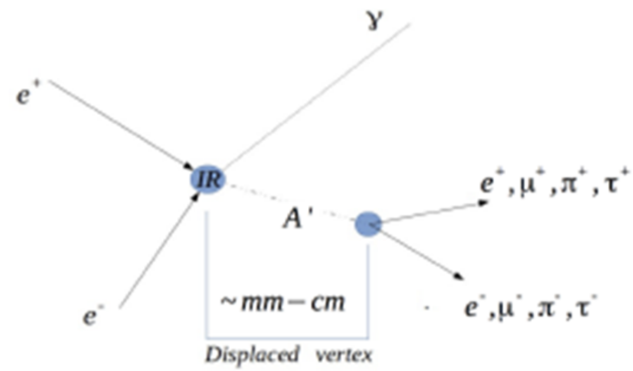
Eassig, et al, JHEP 11, 167 (2013).

Dark photon (1/3)

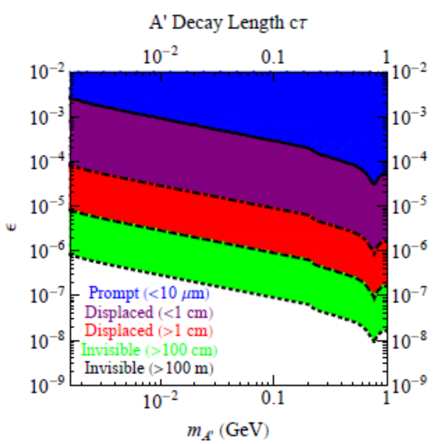
- Dark photon decays SM particles:

$$e^+e^- \to \gamma A', A' \to l^+ l^- \text{ hadrons} \quad (1)$$





- Plot shows lifetime of A as a function of its mass, m_A, and ϵ
  R. Essig et al, PRD 80 (2009) 015003



- To set A' limit a few MeV/c^2 ~ 7G eV/c^2

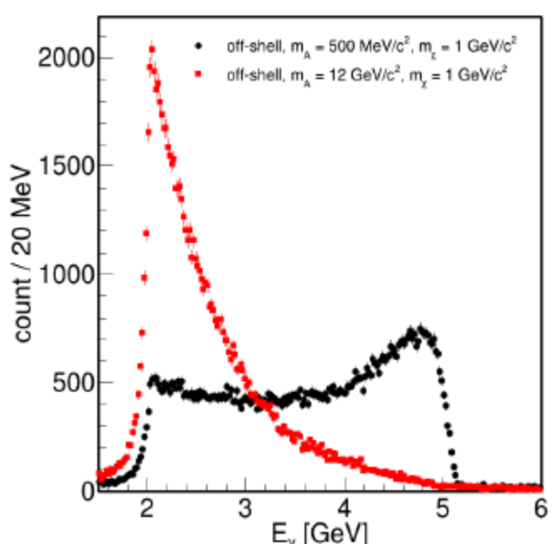
Igal Jaegle (2014)

Dark photon (2/3)

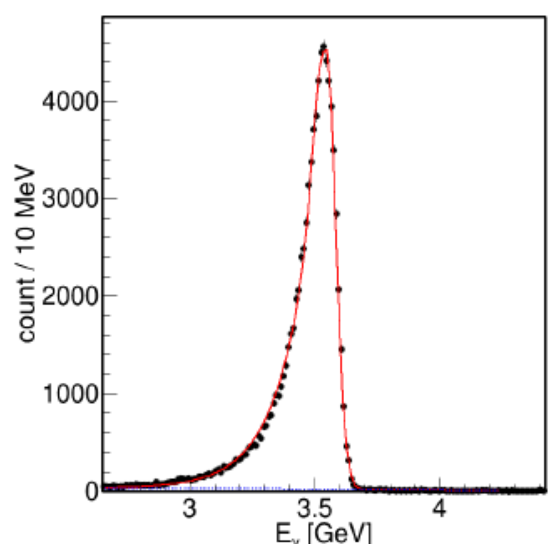
- MC simulation of signal signature
  - Off-shell $e^+e^- \to \gamma\chi\bar{\chi}$
  - On-shell $e^+e^- \to \gamma A', A' \to \chi\bar{\chi}$

    $e^+e^- \to \gamma A', A' \to l\bar{l}$ or hadrons

▸ Off-shell case



▸ On-shell case, $m_A = 1$ GeV/c²



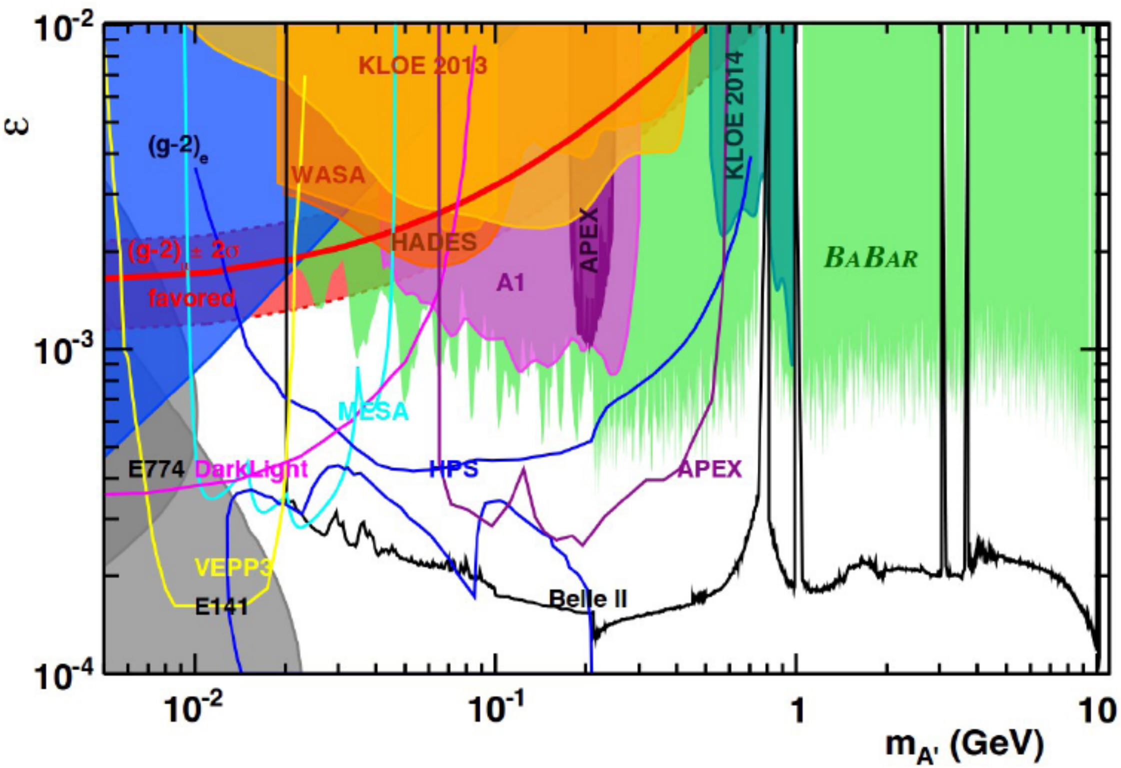
Igal Jaegle (2014)

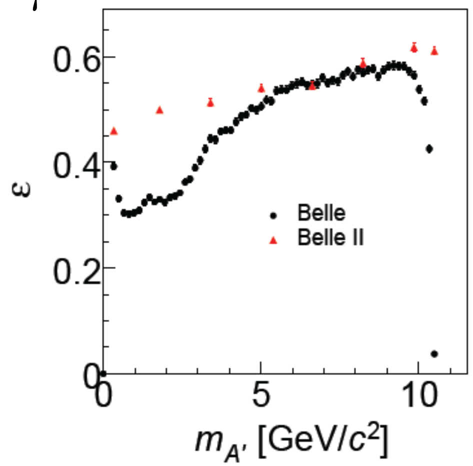
- Off-shell signature => broad energy distribution
- On-shell signature => mono-photon, => dark photon with displaced vertex decaying into leptons not detected by Belle II will have the same signature

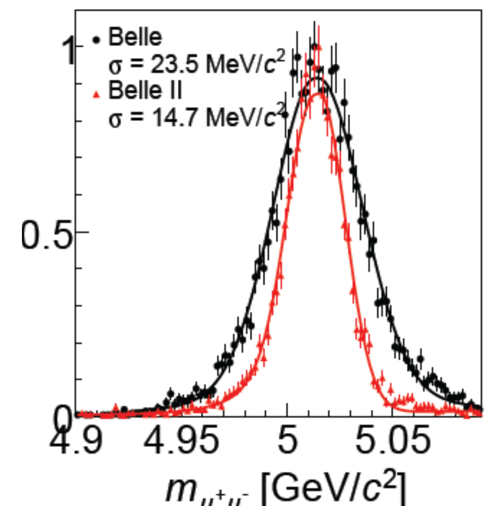
Dark photon (3/3)

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

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

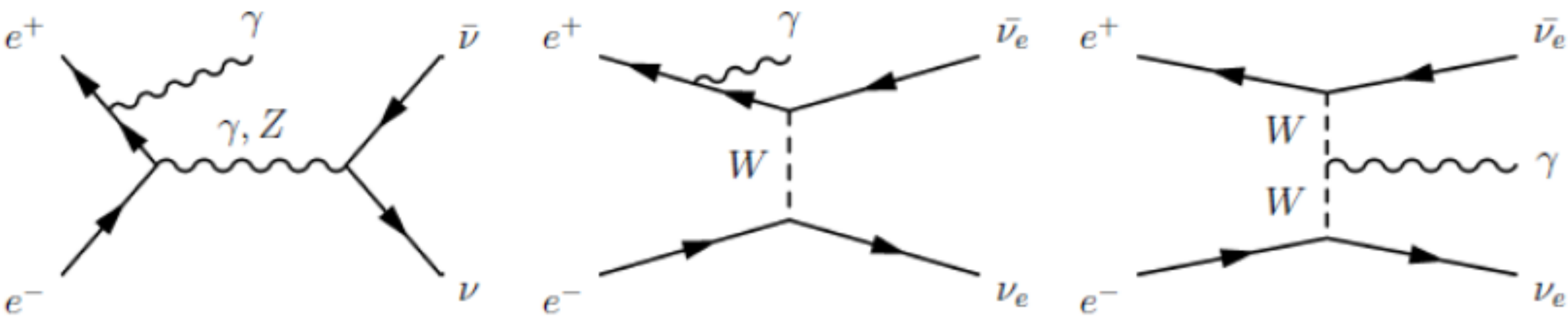






Eassig, et al, JHEP 11, 167 (2013).

Background Study

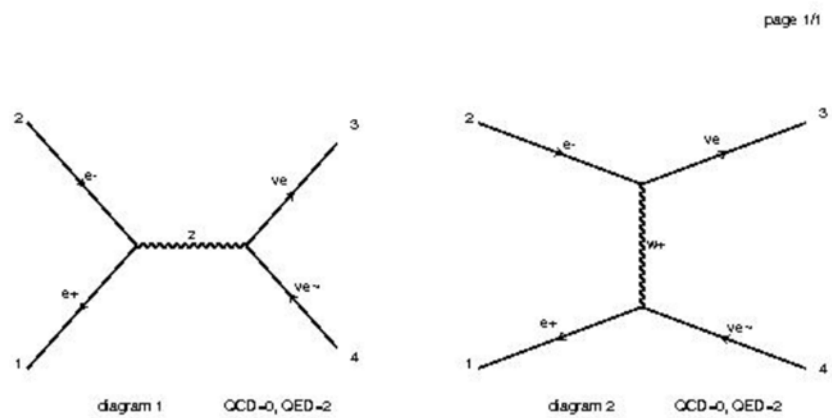


$e^{+} e^{-} \rightarrow \nu \nu$

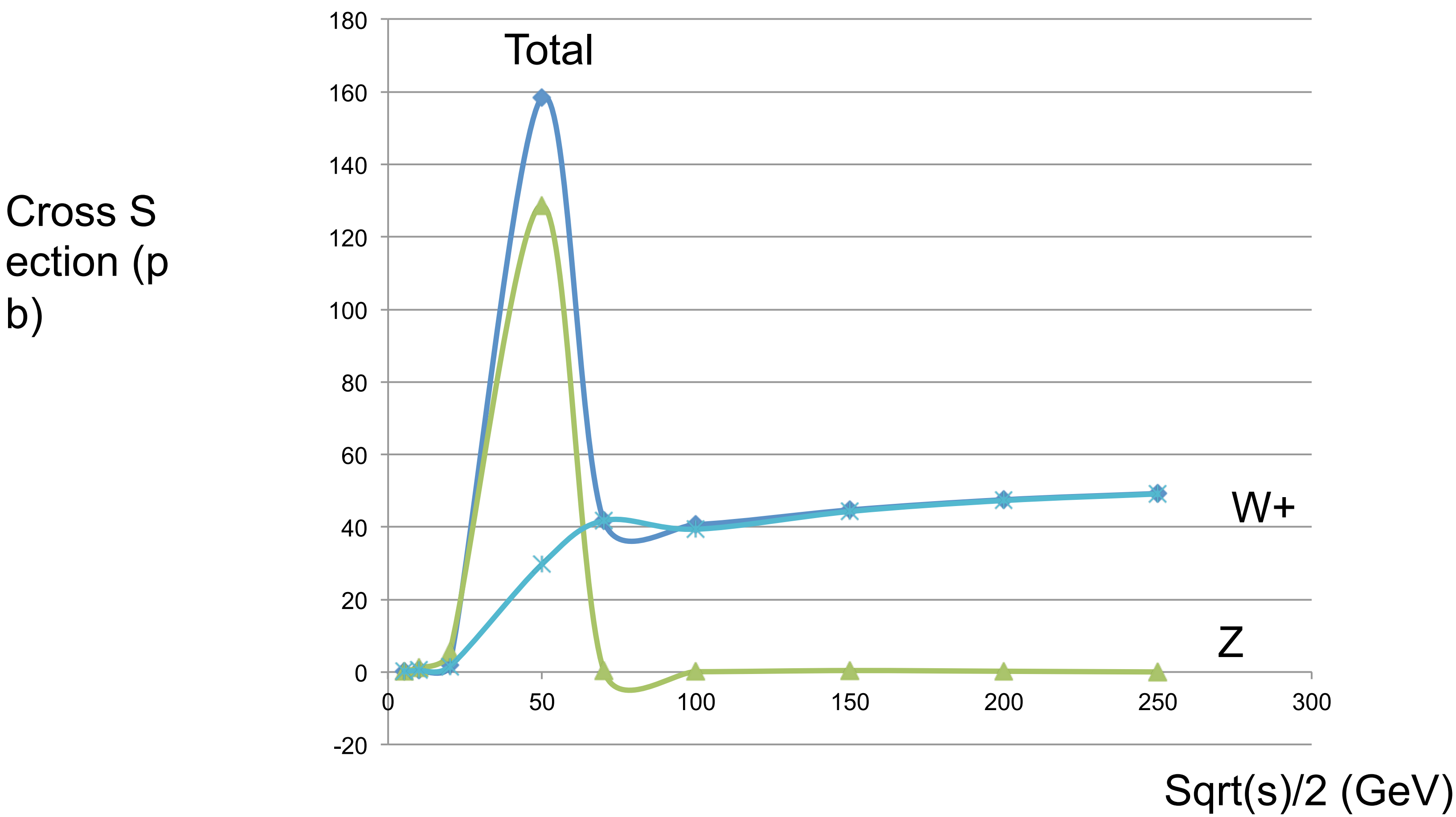
- Background Mode
- MC @ Belle/BaBar
  - Does not included
- Cross Section check using MadGraph

Feynman Diagrams file:///home/cho/products/MG5_aMC_v2_2_3/bin/e...

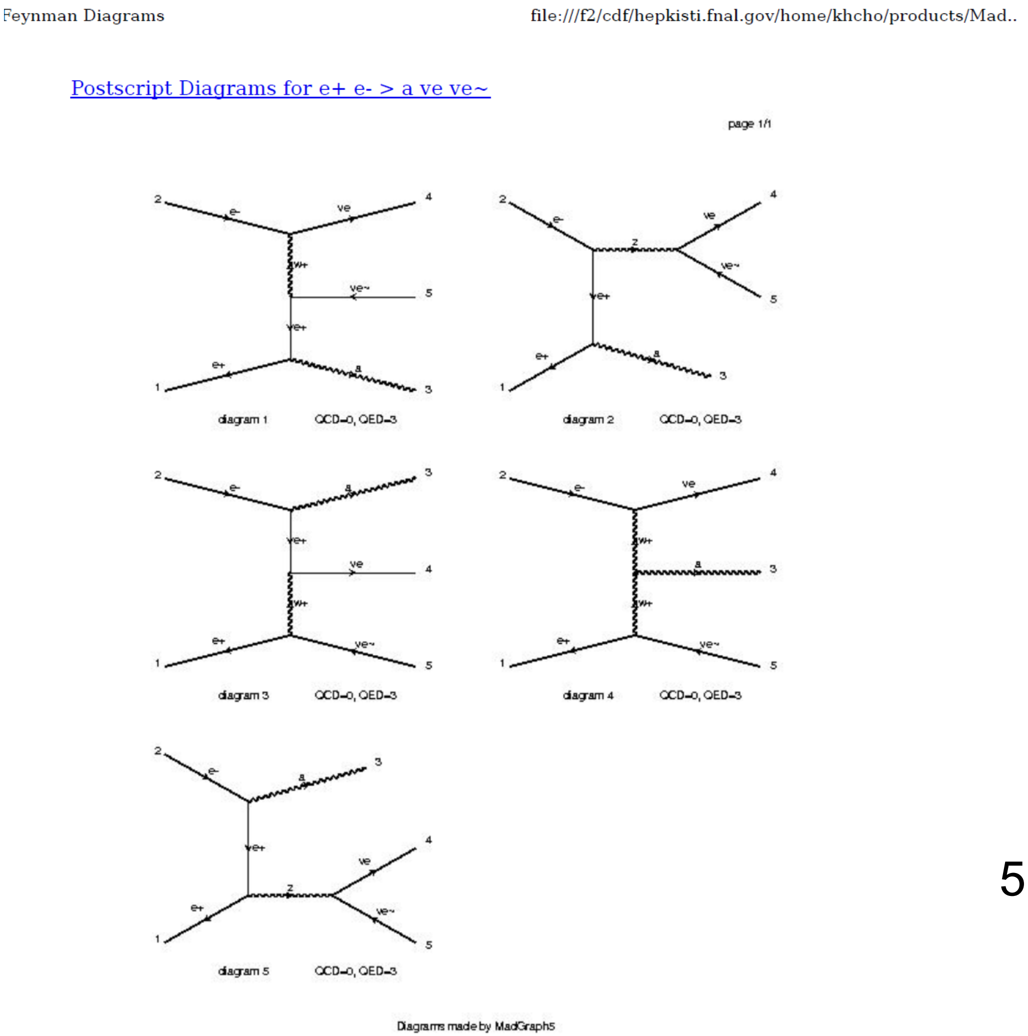
Postscript Diagrams for e+ e- > ve ve~



Total Cross Section

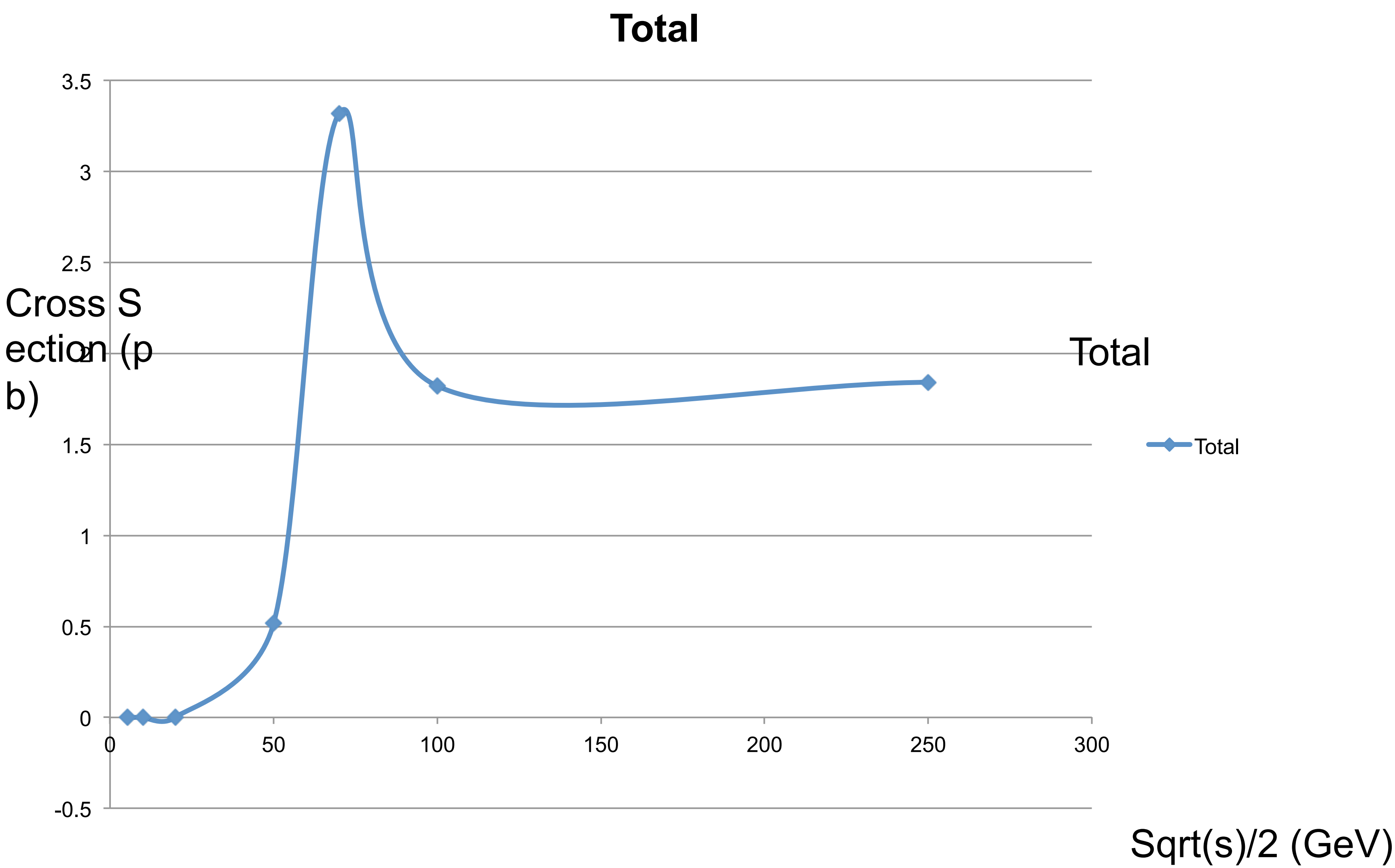


$e^{+} e^{-} \to \nu\, \nu\, \gamma$



5 diagrams

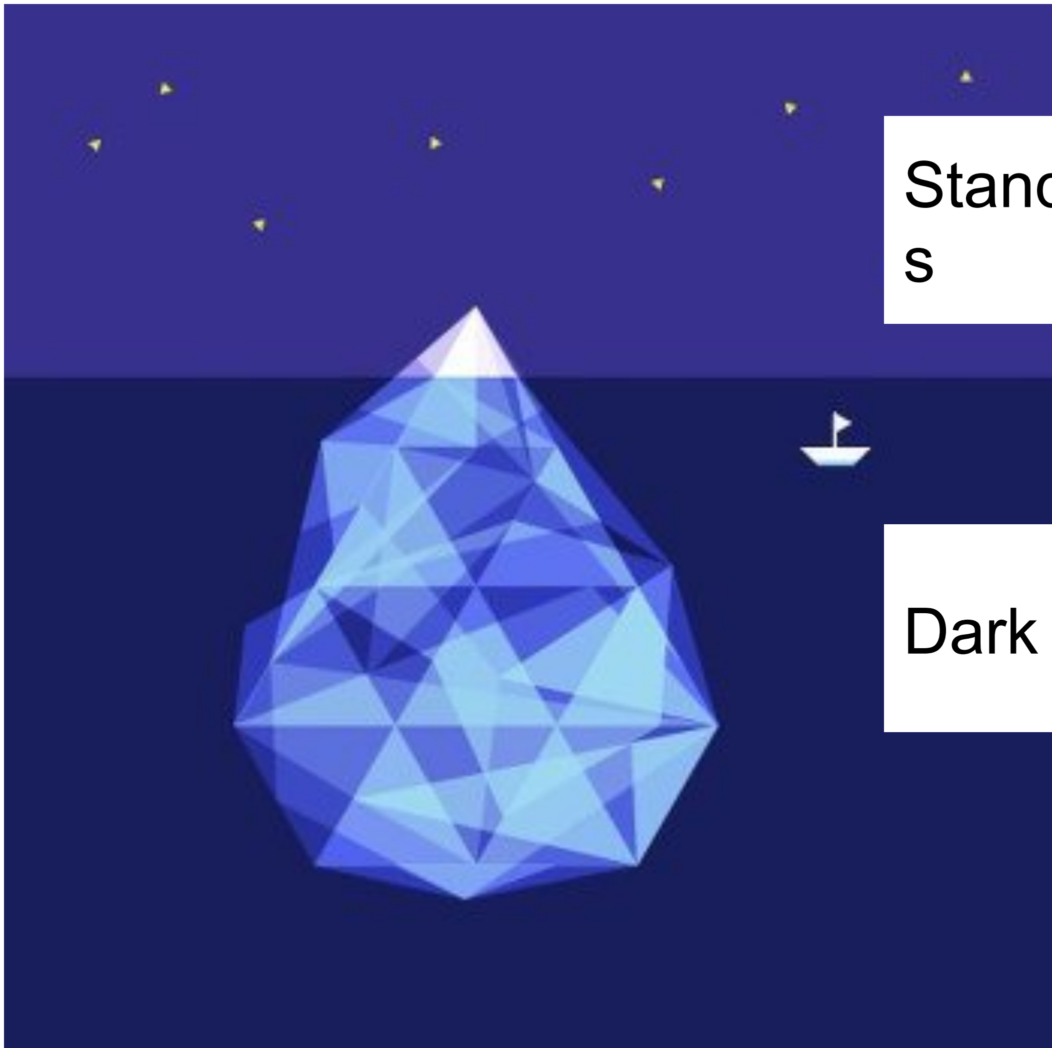
$$e^+ e^- \to \nu \nu \gamma$$



Summary

- The e+e- collider experiments (KLOE, BaBar, Belle) contribute to search for light Dark Matter particles.
- Belle II will search for Dark Matter in radiative decays with the trigger.
- With 50 ab^{-1}, Belle II may also cross-check any signals discovered by fixed target experiments.

Beyond the Standard Model



Standard Model Particle
s

⇒ Still going

Dark Matter

Acknowledgement

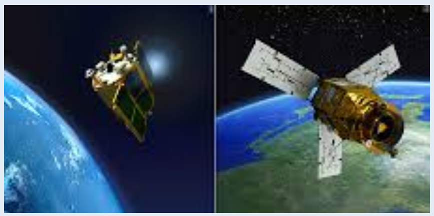
- Youngjoon Kwon
- Patrick Fox
- Chaehyun Yu
- Soo-hyeon Nam
- Jangho Kim
- J. Cooley
- Rouven Essig
- K.Y. Choi

Thank you.

Appendix:
Dark Matter Research Cluster

- Title: Dark matter research cluster based on computational science
- Object: To meet researchers between government institutes (KISTI+KASI)
  + anyone (Universities, Industries, IBS, …)
- Source: NST (국가과학기술연구회, National research council of Science & Technology)
- Fund: 50,000,0000 won/year * 2years
- Usage: Just for seminar/workshop and meeting
- Date: 2015.9.1~2017.8.31
- Status: proposal

계산과학 기반 암흑물질 클러스터

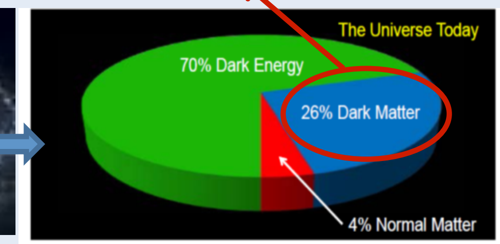


한국천문연구원

KISTI

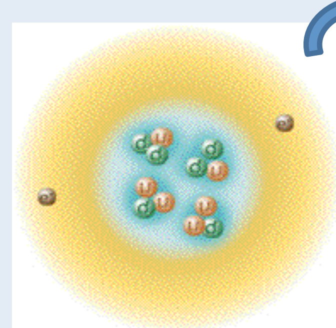
우주의 비밀

암흑물질

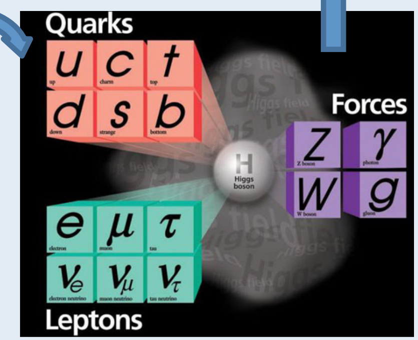


우주의 구성

표준모형



물질의 근원



표준모형

대학 (인력 양성)

궁극적 목표 | 계산과학 기반 국가 R&D 융합 연구의 선도

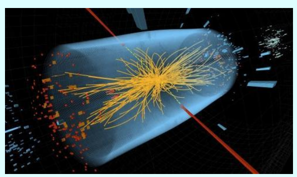
과제목표 | 암흑 물질 탐색 연구 클러스터 구축

연구내용

가속기

- 고에너지 가속기 실험/시뮬레이션 데이터 활용 암흑물질 탐색 연구
- 슈퍼컴 활용 현상론적 모델 제시

(가속기 충돌 실험)



KISTI/천문연/대학

우주론

- 우주론에서 암흑물질 탐색 계산 연구
- 관측데이터 활용 연구

천문연/KISTI/대학

계산과학 기반

빅 데이터 | 일본 KEK의 Belle/Belle II 가속기 실험 데이터, MC 시뮬레이션 데이터, 천체 관측 데이터 등

인프라 (KISTI) | 슈퍼컴퓨터, GSDC(대용량데이터센터), 첨단연구망

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