Dark Sector Searches at B-Factories

QWG 2019 – The 13th international Workshop on Heavy Quarkonium

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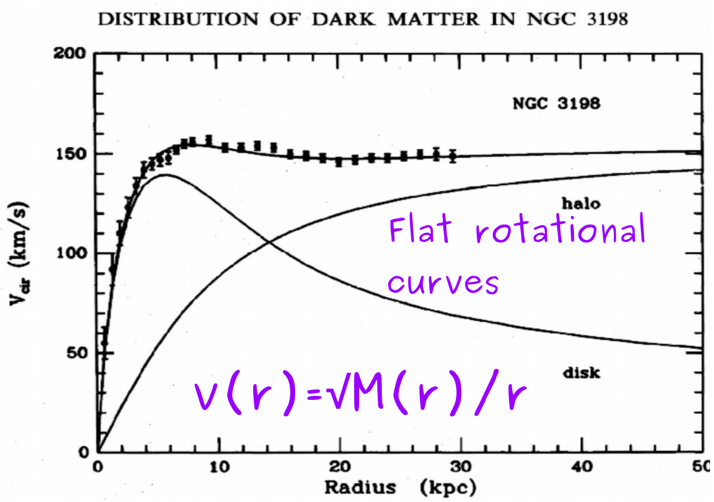
on behalf of the BaBar and Belle II Collaborations

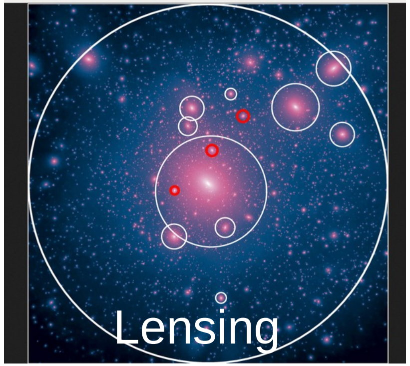
Outline

- Motivation
- B-Factories, first and second generation
- Bottomonium and dark matter:
  - $\Upsilon(1S)$ invisible decays
  - $X_{b0} \rightarrow \tau\tau$
- Summary

Dark Sector: Introduction

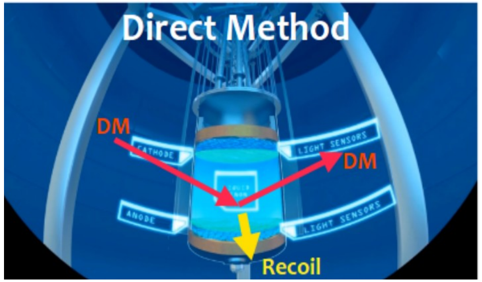
- Many astrophysical observations provide evidence for the existence of a kind of matter that almost does not interact with the Standard Model (SM) particles (*mostly* gravitational interaction) → ***Dark Matter (DM)***

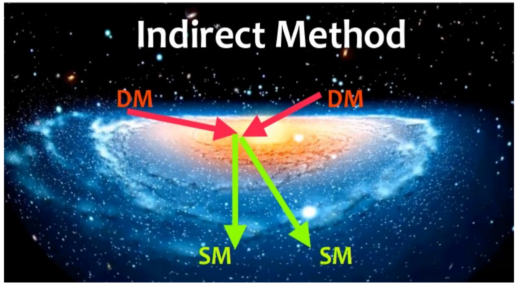




How to search it?

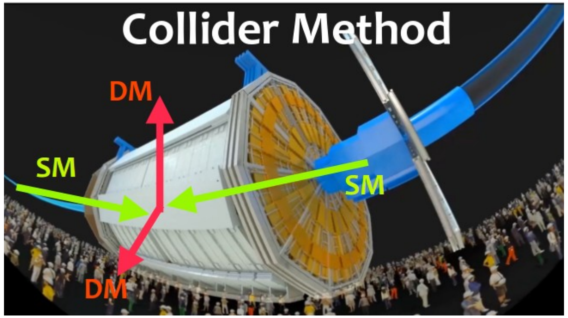
1) Detect the energy of *nuclear recoil*





2) Detect the *flux of visible particles* produced by *DM annihilation* and decay

3) DM weakly couples to SM particles and it can be produced in *SM-particles annihilation* at ***colliders***



→ ***In this presentation I will focus on the search at electron-positron colliders***

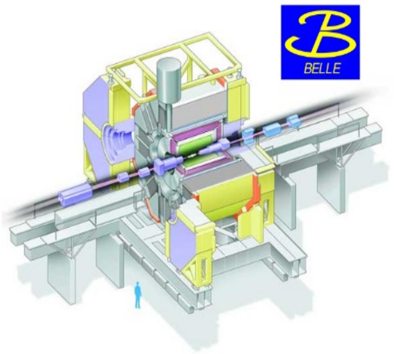
B-Factories: the high intensity frontier

B-factories: dedicated experiments at *e^+e^- asymmetric-energy colliders* for the production of quantum coherent $B\bar{B}$ pairs → **CPV studies**.

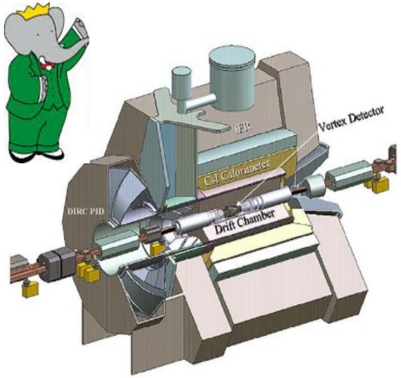
$$e^+e^- \rightarrow \Upsilon(4S)\ [10.58\ \text{GeV}] \rightarrow B\bar{B}$$

$\Upsilon(nS)$ = bound state of b quark and b anti-quark

First generation of B-factories



at the KEKB collider (KEK, Japan)



at the PEP II collider (SLAC, California)

- **Clean environment** → lower background, high resolution
- **Hermetic detector** with excellent PID capability → efficient reconstruction of ***neutrals*** (π^0, η, …), recoiling system and ***missing energy*** final states

B-Factories: the high intensity frontier

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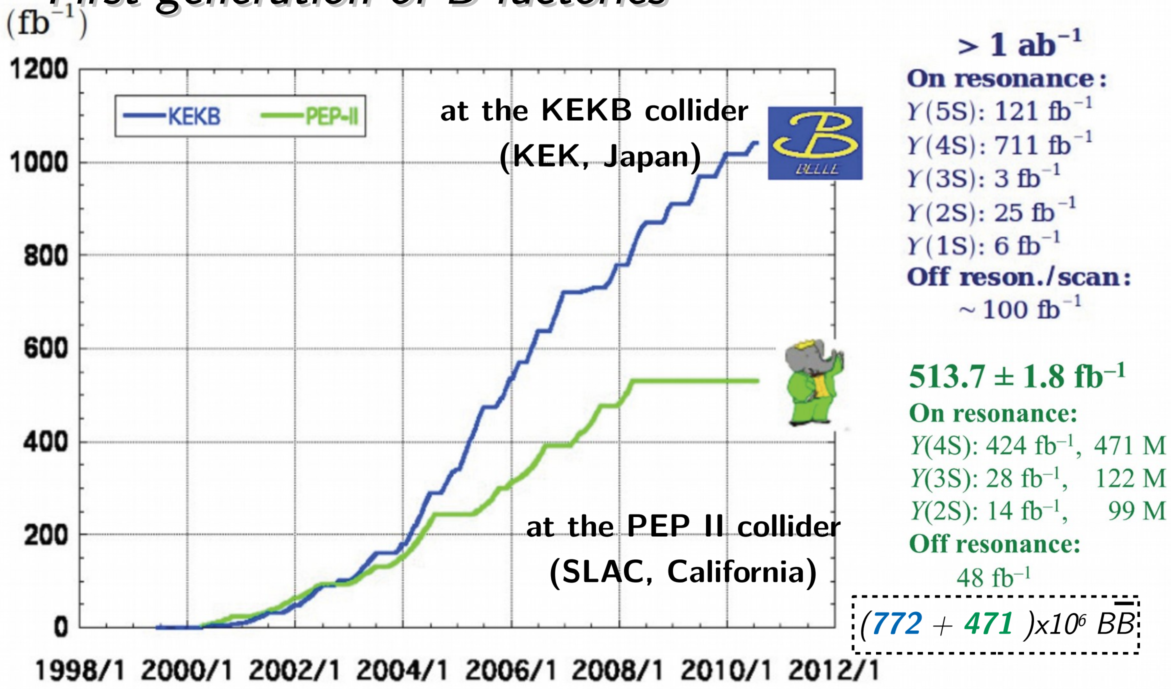


(772 + 471)x10^6 $B\overline{B}$

- Clean environment → lower background,

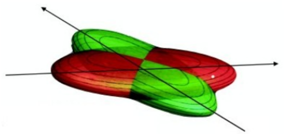
Rich physics program:

- ✔ Discovery of CPV in B mesons
- ✔ SM test, precision flavor physics
- ✔ Rare/suppressed/forbidden processes
- ✔ *Search for new particles (quarkonium)*
- ✔ *Search for light Dark Sector and mediators*

Second Generation: SuperKEKB

- **World highest luminosity,** applying the *large crossing angle nano-beam scheme. (P.Raimondi for SuperB, M. Bona et al., arXiv:0709.0451)*

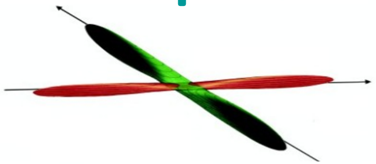
KEKB



I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

SuperKEKB



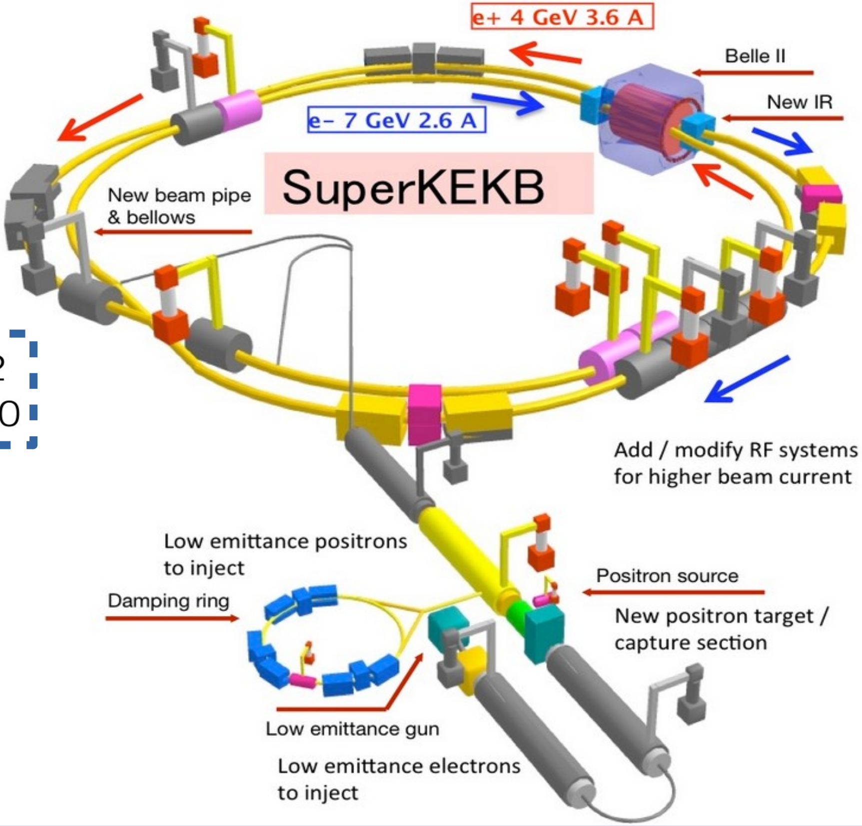
I (A): ~ 3.6/2.6

β^*_y (mm): ~ 0.27/0.3

I ↑ x 2
β^*_y ↓ x 1/20

$$L = \frac{\gamma_\pm}{2 e r_e}\left(1 + \frac{\sigma^*_y}{\sigma^*_x}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

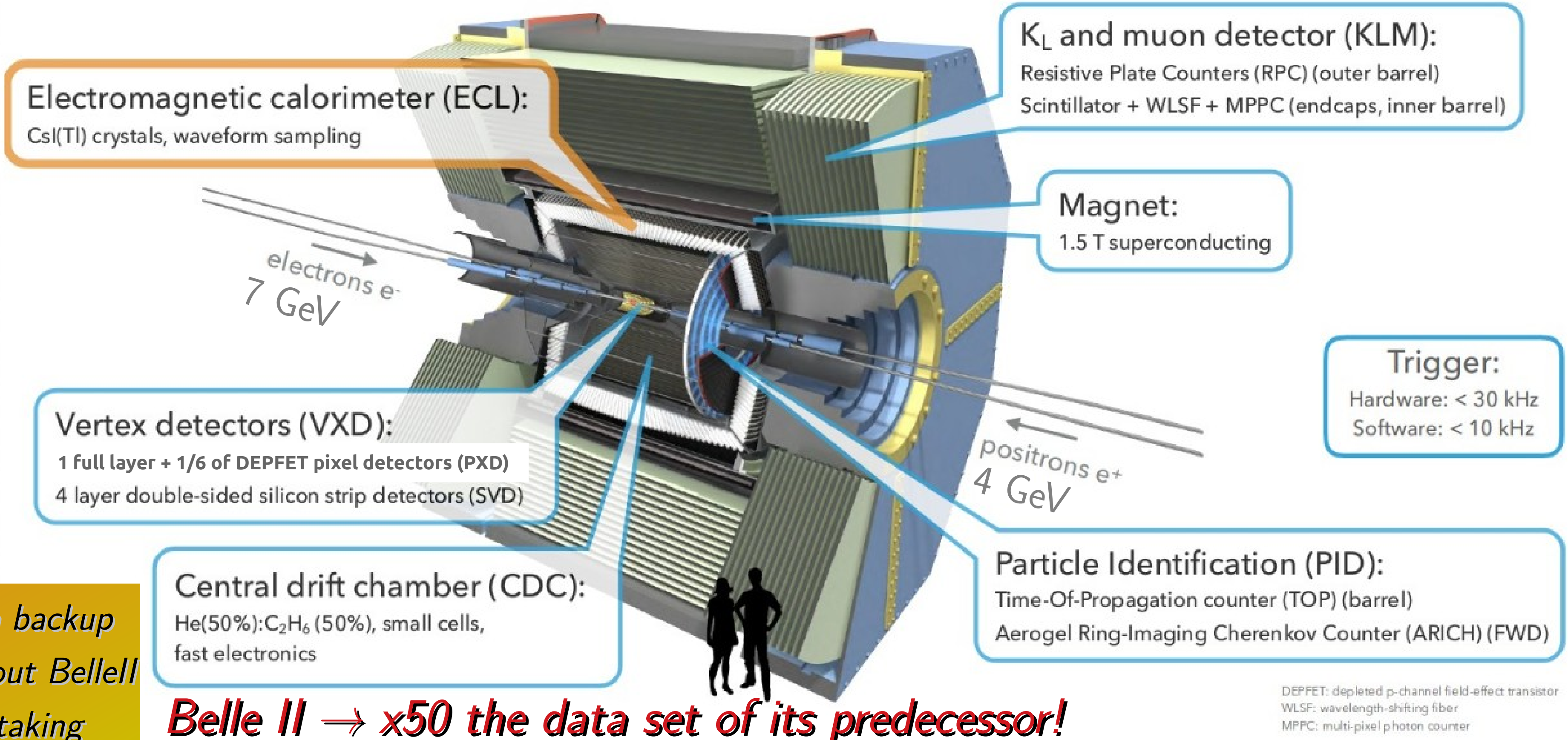
Lorentz factor; beam current; beam-beam parameter; geometrical reduction factors; beam aspect ratio at the IP; vertical beta-function at the IP



40x KEKB peak luminosity: $\mathcal{L} = 8 \cdot 10^{35}$ cm^{-2} s^{-1}

Belle II Detector

- The Belle II detector has better resolution, PID and capability to cope with higher background

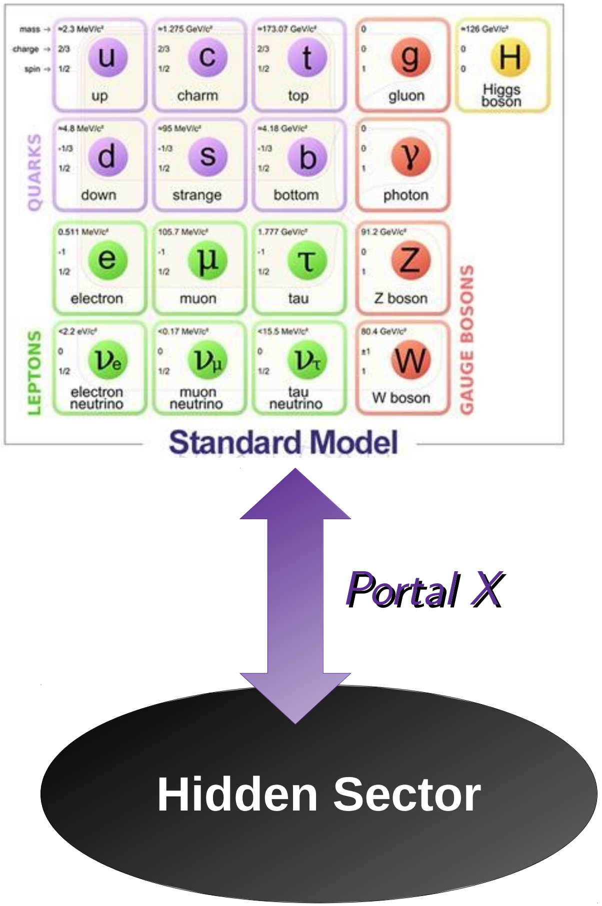


More in backup slides about BelleII data taking

Belle II $\rightarrow$ x50 the data set of its predecessor!

Dark Sector at B-Factories

- Possible sub-GeV scale scenario: light dark sector weakly coupled to SM through a light ***mediator X***
  - Scalar portal $\rightarrow$ Dark Higgs/Scalars
  - Vector portal $\rightarrow$ Dark Photon A'
  - Pseudo-scalar portal $\rightarrow$ Axion Like Particles (ALPs)
  - Neutrino portal $\rightarrow$ Sterile Neutrinos



Dark Sector @B-Factories (II)

- Possible sub-GeV scale scenario: light dark sector weakly coupled to SM through a light ***mediator X***
  - ***Scalar portal → Dark Higgs/Scalars***
  - ***Vector portal → Dark Photon A'***
  - Pseudo-s ... (ALPs)
  - N

Invisible final state + single photon

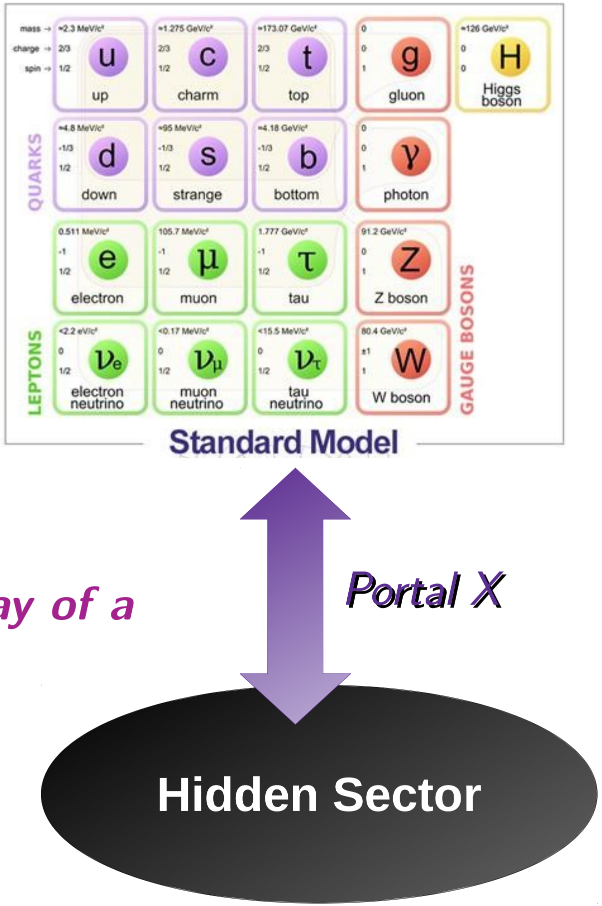
→ Search for CP-odd light Higgs at dipion transition $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$

- BaBar 2011 (PRL107,021804)
- Belle 2019 (PRL122, 011801)
- *Belle II prospects*

See K.Chilikin's talk on Friday

→ Search for invisible decay of a Dark Photon

- BaBar 2017 (PRL119, 131804)
- *Belle II prospects*

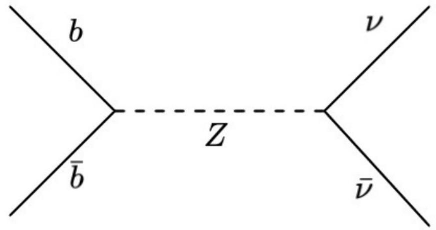


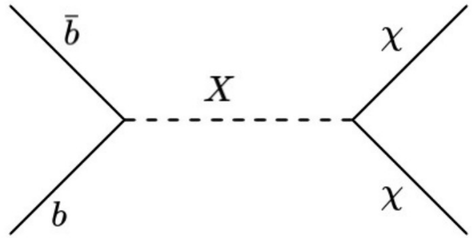
$\Upsilon(1S)$ invisible decays

- BR($\Upsilon(1S)\to$ inv) is well calculable in SM
- DM candidates could enhance the branching ratio, if $\Upsilon(1S)\to\chi\chi$ kinematics allows
- New mediators (Z', A^0) may also contribute
- In absence of NP observation, ***Belle II*** can measure the BR ($\Upsilon(1S)\to\nu\nu$)!

$$\frac{BR(Y(1S)\to\nu\bar{\nu})}{BR(Y(1S)\to e^+e^-)}=\frac{27G^2M^4_{Y(1S)}}{64\pi^2\alpha^2}\left(-1+\frac{4}{3}\sin^2\theta_W\right)^2=4.14\times10^{-4}$$

$$BR(Y(1S)\to\nu\bar{\nu})\sim9.9\times10^{-6}$$





$\Upsilon(1S) \to \gamma$ DM DM

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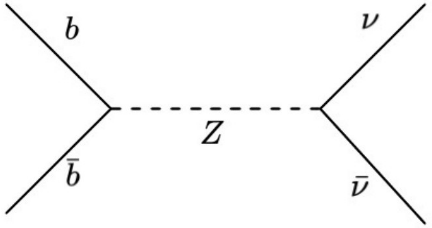
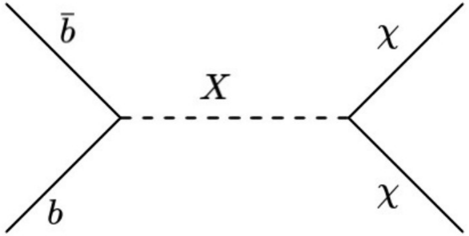




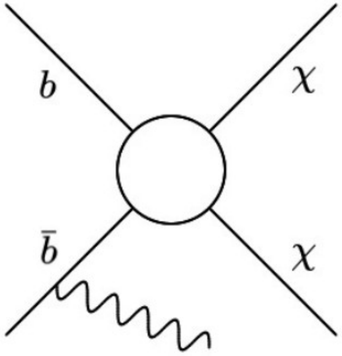
$$\frac{BR(Y(1S) \to \nu\bar{\nu})}{BR(Y(1S) \to e^+ e^-)} = \frac{27 G^2 M^4_{Y(1S)}}{64 \pi^2 \alpha^2} \left(-1 + \frac{4}{3} \sin^2 \theta_W\right)^2 = 4.14 \times 10^{-4}$$

$$BR(Y(1S) \to \nu\bar{\nu}) \sim 9.9 \times 10^{-6}$$

Adding one photon

- **BR($\Upsilon(1S) \to \gamma$ inv)^{SM} ~ 10^{-9}** out of current experimental sensitivity
- Searches for processes ***$\Upsilon(1S) \to$ γχχ*** (expected BR ~ 10^{-5}-10^{-4})

  → investigate also ***Wilzcek production for on-shell scalar*** BR($\Upsilon(1S) \to \gamma A^0$) x BR($A^0 \to \chi\chi$)
- Limit NP models involving light Higgs bosons and light DM states *



* *Fernandez, Seong, Stengel, PRD93, 054023, (2016)*

$\Upsilon(1S) \to \gamma$ DM DM: Analysis Strategy

- Tag a clean sample of $\Upsilon(1S)$ exploiting *bottomonium* transitions with 2 soft pions
- Select events with ***2 tracks*** + ***one single photon + missing energy (nothing else in the detector)***

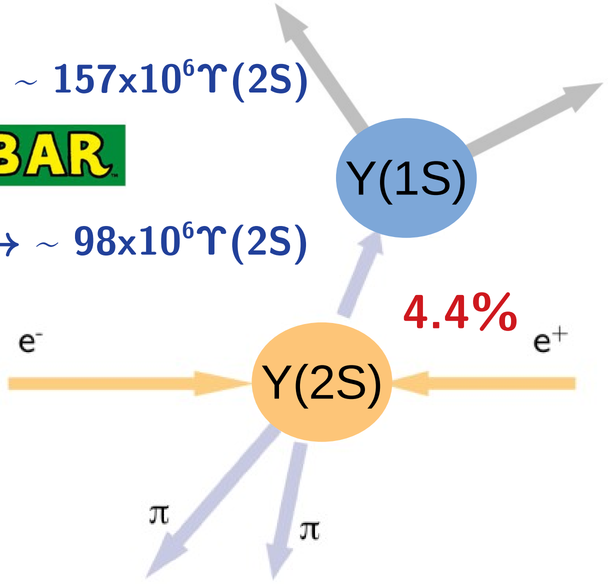
  → ***Experimental challenges:***

  1) low-momentum pions (CDC information only, ~10% contamination)

  2) dedicated hardware trigger lines for low-multiplicity events (efficiency depends on the mass region)

25 fb^{-1} → ~ 157x10^{6}Υ(2S)

14.4 fb^{-1} → ~ 98x10^{6}Υ(2S)



- Define the squared recoil mass of the dipion system as:

$$M_r^2 = s + M_{\pi^+\pi^-}^2 - 2\sqrt{s}E_{\pi^+\pi^-}^{CMS}$$

- Extract the signal from an *extended unbinned maximum likelihood scan* in m_χ , m_{A0} of the 2D distributions :

M^2_r Vs M^2_{miss} , with M^2_{miss} the square missing mass of the system $M^2_{miss} = (P_{e+e-} - P_{\pi+\pi-} - P_\gamma)^2$

M_r Vs E^*_γ

Signal: excess of events peaking in the M_r distribution at $\Upsilon(1S)$ mass, 9.460 GeV

$\Upsilon(1S) \to \gamma$ DM DM: Background

Continuum

- Bremsstrahlung contamination
- QED background with charged escaping detection: $e^+e^- \to \gamma\, \pi^+\pi^-$
- Neutral hadron radiative decays (not detected in EM calorimeter): $\Upsilon(1S) \to \gamma K_L K_L$

Suppression

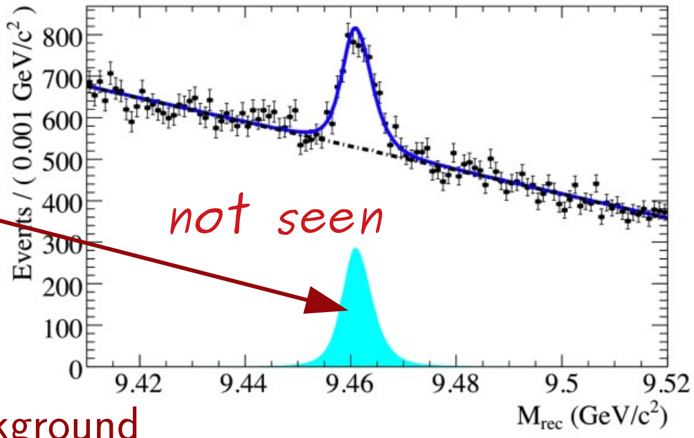
- Multivariate method to reject ***continuum*** using dipion system kinematics variables
- Angular isolation: minimum angle between photon direction and the charged tracks/dipion system
- Require clean 20° cone in the direction opposite to the primary photon

Peaking

- 2-photon events, $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\eta', \eta' \to \gamma\pi^+\pi^-$
- $\Upsilon(2S) \to \tau\tau\ (\to \pi\nu_\tau)$
- $\Upsilon(1S) \to l^+l^-$
- $\Upsilon(1S) \to \gamma hh$

→ Estimated from MC simulation, irreducible background

BaBar Phys.Rev.Lett.103:251801 (2009)



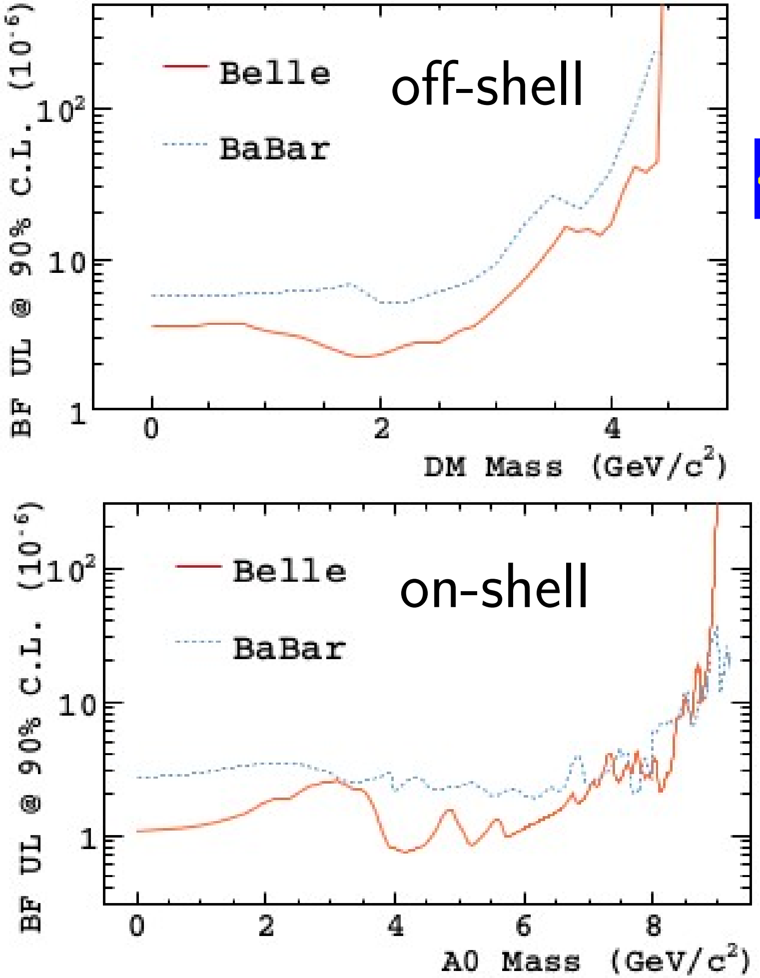
not seen

Selection optimization

	Maximized figure of merit:	Signal efficiency:
BaBar	$\varepsilon/1.5 + \sqrt{B}$	2-11% (MVA method)
Belle	$S/\sqrt{B}$	0.001-14% (linear cuts)

Lower trigger efficiency at high masses due to low energy photons

$\Upsilon(1S) \to \gamma$ DM DM: Results



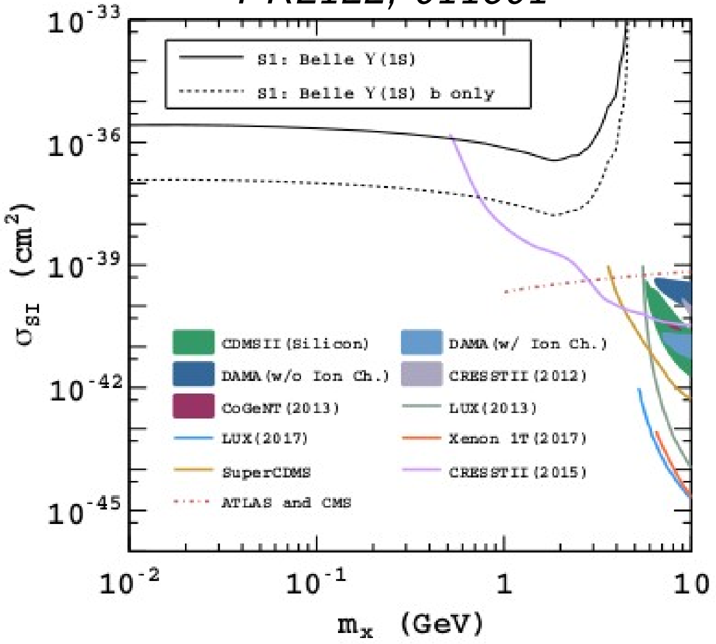
Searched range:

$0 \leq m_\chi \leq 4.5$ GeV, $0 \leq m_{A0} \leq 9.2$ GeV

$0 \leq m_\chi \leq 4.44$ GeV, $0 \leq m_{A0} \leq 8.97$ GeV

Statistically limited!

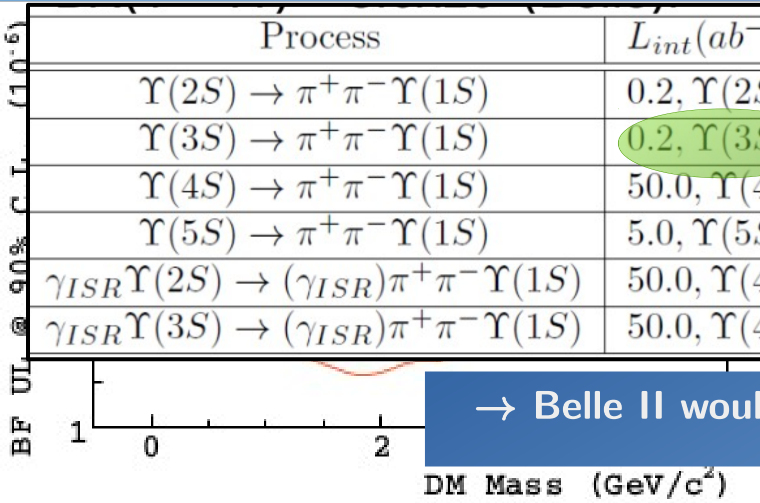
PRL122, 011801



$\Upsilon(1S) \to \gamma$ DM DM: Belle II prospects

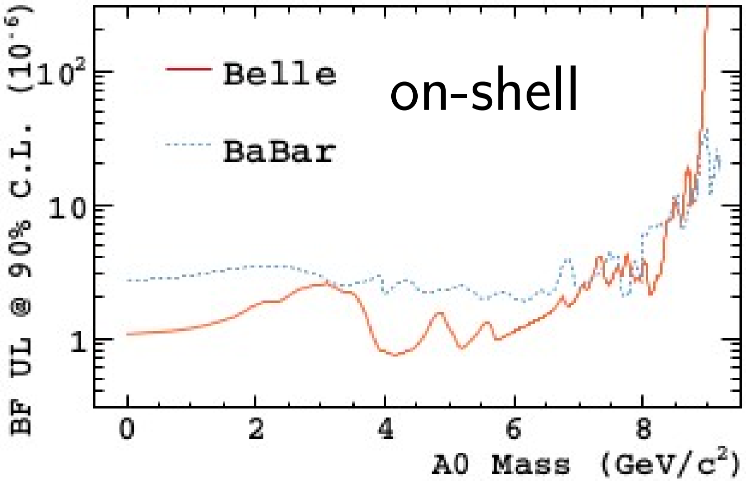
Process	$L_{int}(ab^{-1})$	ϵ	$N(\Upsilon(1S))$	$N_{\Upsilon(1S)\to\nu\bar{\nu}}$	N_{NP}
$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$	0.2, $\Upsilon(2S)$	0.1-0.2	2.3×10^8	230-460	6900-13800
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$	0.2, $\Upsilon(3S)$	0.1-0.2	3.2×10^7	32-64	945-1890
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1-0.2	5.5×10^6	5.5-11	165-310
$\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1S)$	5.0, $\Upsilon(5S)$	0.1-0.2	7.6×10^6	7.6-15.2	228-456
$\gamma_{ISR}\Upsilon(2S) \to (\gamma_{ISR})\pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1-0.2	1.5×10^8	150-300	4500-9000
$\gamma_{ISR}\Upsilon(3S) \to (\gamma_{ISR})\pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1-0.2	3.5×10^7	35-70	1050-2100

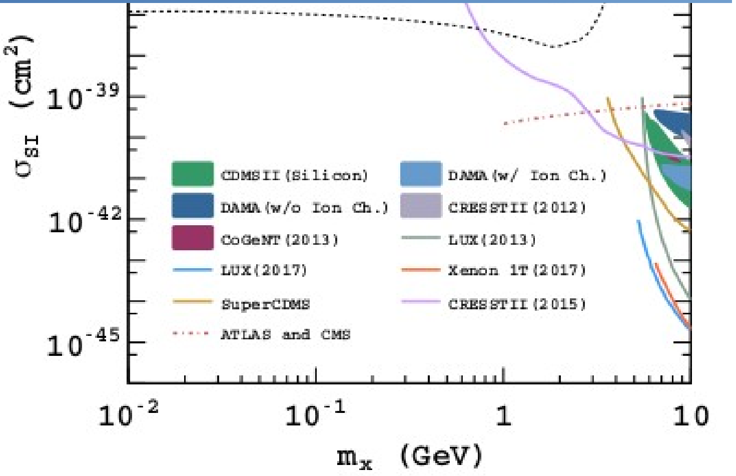
Statistically limited!



→ **Belle II would expect to collect >200 fb^{-1} @$\Upsilon(3S)$**

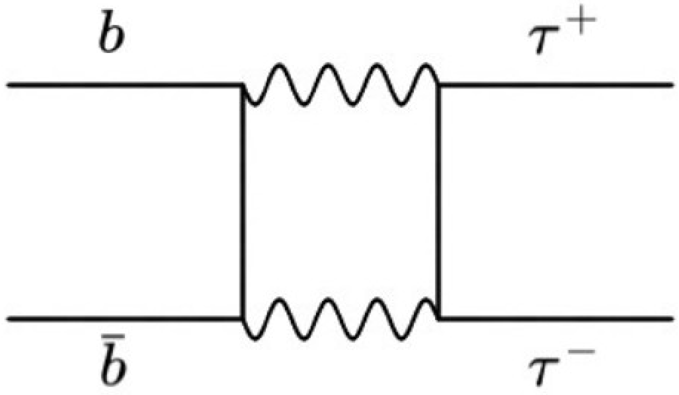
- Statistics
- Better background rejection by exploiting ***MVA method for peaking background-signal separation***



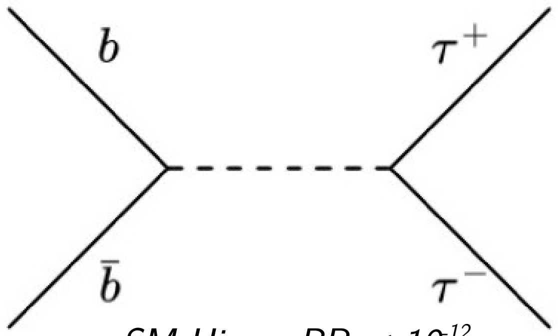


Other possibilities at $\Upsilon(3S)$...

- The decay to third generation leptons of the scalar bottomonium $X_{b0} \to \tau\tau$ is highly suppressed in the SM
- Sensitive to *s*-channel exchange of CP-even neutral Higgs bosons via $\Upsilon(3S) \to \gamma X_{b0} \to \gamma\tau\tau$



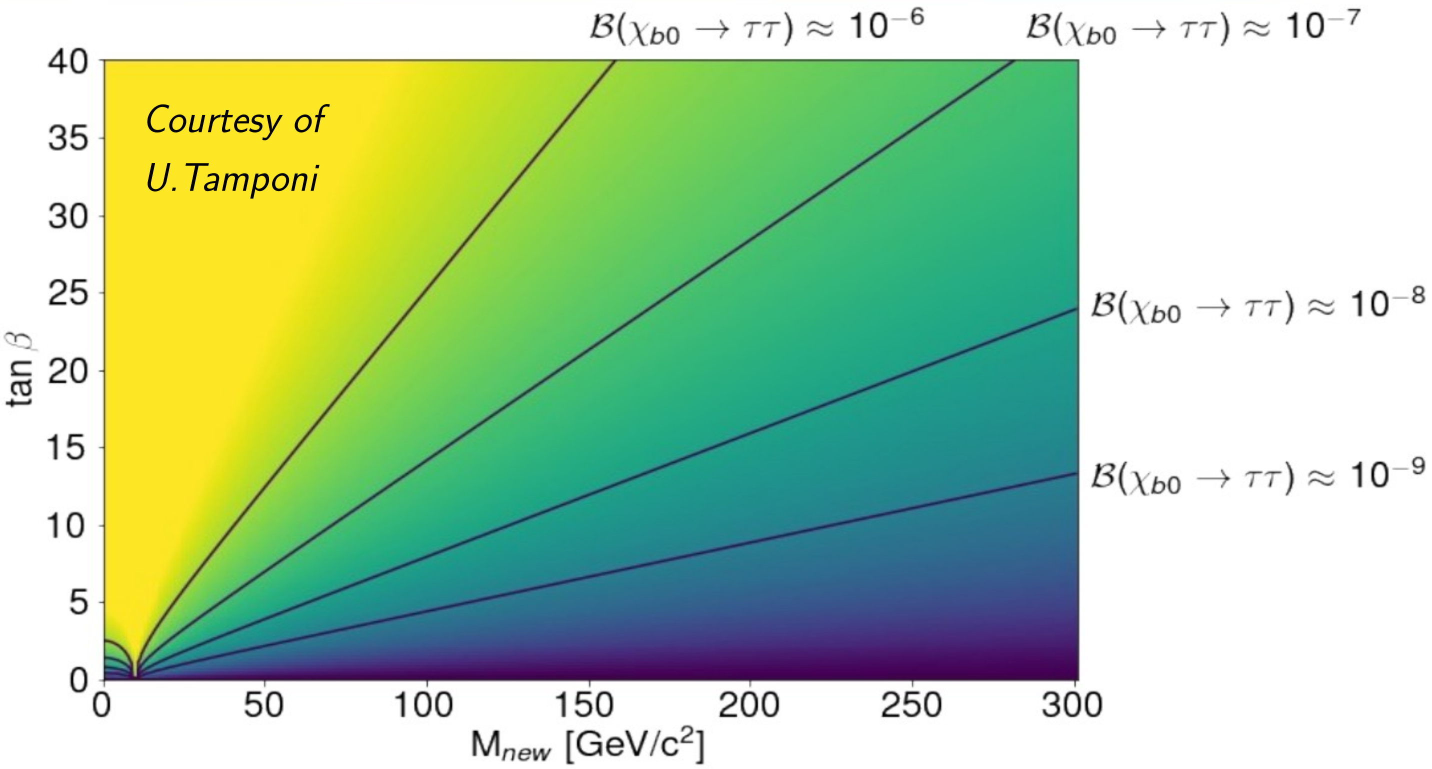
QED, BR < 6 x 10^{-9}



SM Higgs, BR < 10^{-12}

Rare leptonic decays

- BR depends on M_{NEW} and tanβ
- Its measurement can constrain type-II 2-Higgs-Doublet-Model*



$$\Gamma^H(\chi_0 \to \ell^+\ell^-) = \frac{M_{\chi_0}}{8\pi}\left[1 - \frac{4m_\ell^2}{M_{\chi_0}^2}\right]^{3/2}\left(\frac{m_q m_\ell}{v^2 M_H^2}\right)^2 f_{\chi_0}^2 \cdot \times \left[1 + \frac{M_H^2}{M_{\text{new}}^2 - M_{\chi_{b0}}^2}\tan^2\beta\right]^2$$

** Phys. Rev. D 93, 055014*

Rare leptonic decays (II)

- The decay to third generation leptons of the scalar bottomonium $X_{b0} \to \tau\tau$ can constrain type-II 2HDM models*
- Sensitive to *s*-channel exchange of CP-even neutral Higgs bosons via $\Upsilon(3S) \to \gamma X_{b0} \to \gamma\tau\tau$
- BR depends on M_{NEW} and $\tan\beta$
- ***95%CL sensitivity curve, assuming to reject all reducible background***

$BF[Y3S \to \gamma\chi_{b0}\,(nP)] \sim 5.9\ \%$

$\sigma[e^+e^- \to \gamma\chi_{b0}\,(nP)] \sim 0.2\ nb$

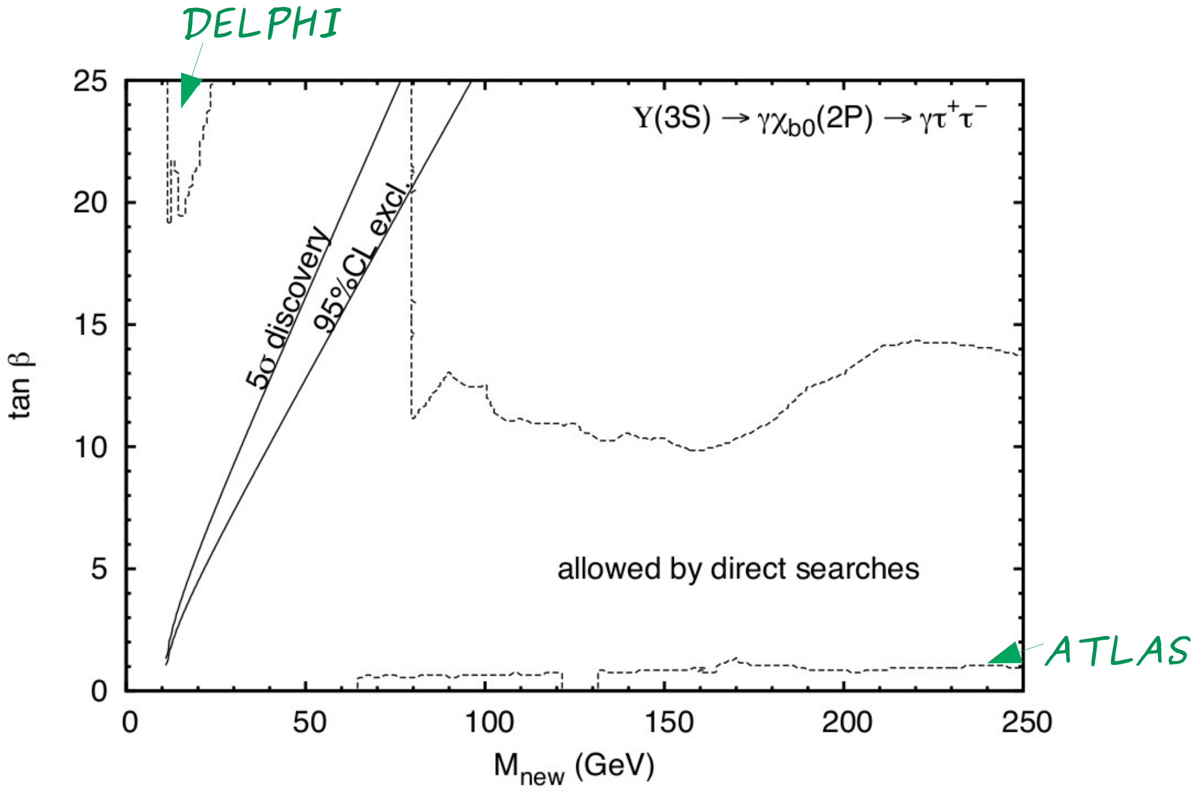
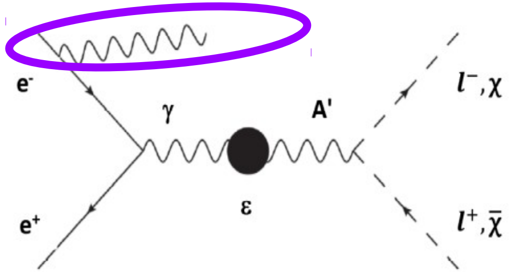


Fig. 212: 5σ discovery and 95% confidence level (CL) exclusion reach in the Type-II 2HDM from 250 fb^{-1} of data on the $\Upsilon(3S)$. The sensitivity is to the regions to the left of the solid

* *Phys. Rev. D 93, 055014*

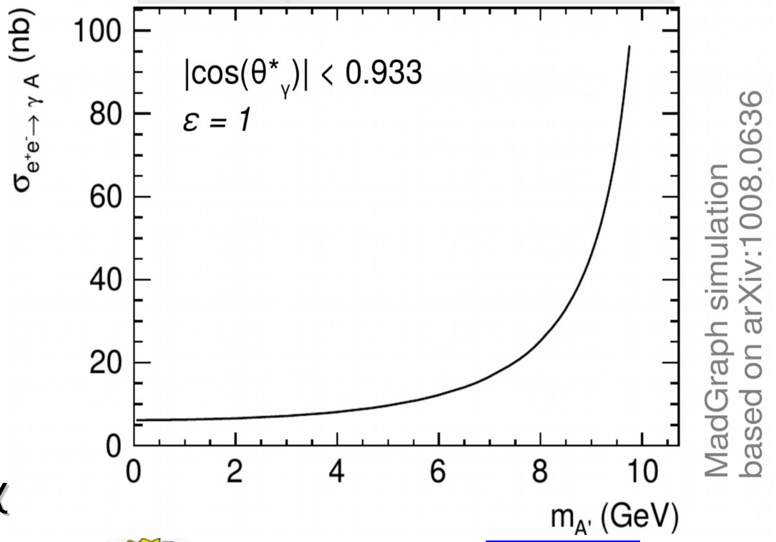
...and in the continuum: Dark Photon

- A possible extension of the SM include a new massive ($m_{A'}$) gauge boson A' of spin = 1 coupling to the SM through the kinetic mixing with strength ε → the ***dark photon***
- At e^+e^- colliders we investigate the ISR production $e^+e^- \rightarrow \gamma\, A'$.



$$\mathcal{L} \supset \varepsilon A'_\mu J^\mu_{\mathrm{SM}}$$

Batell et al. (2009), arXiv:0903.0363

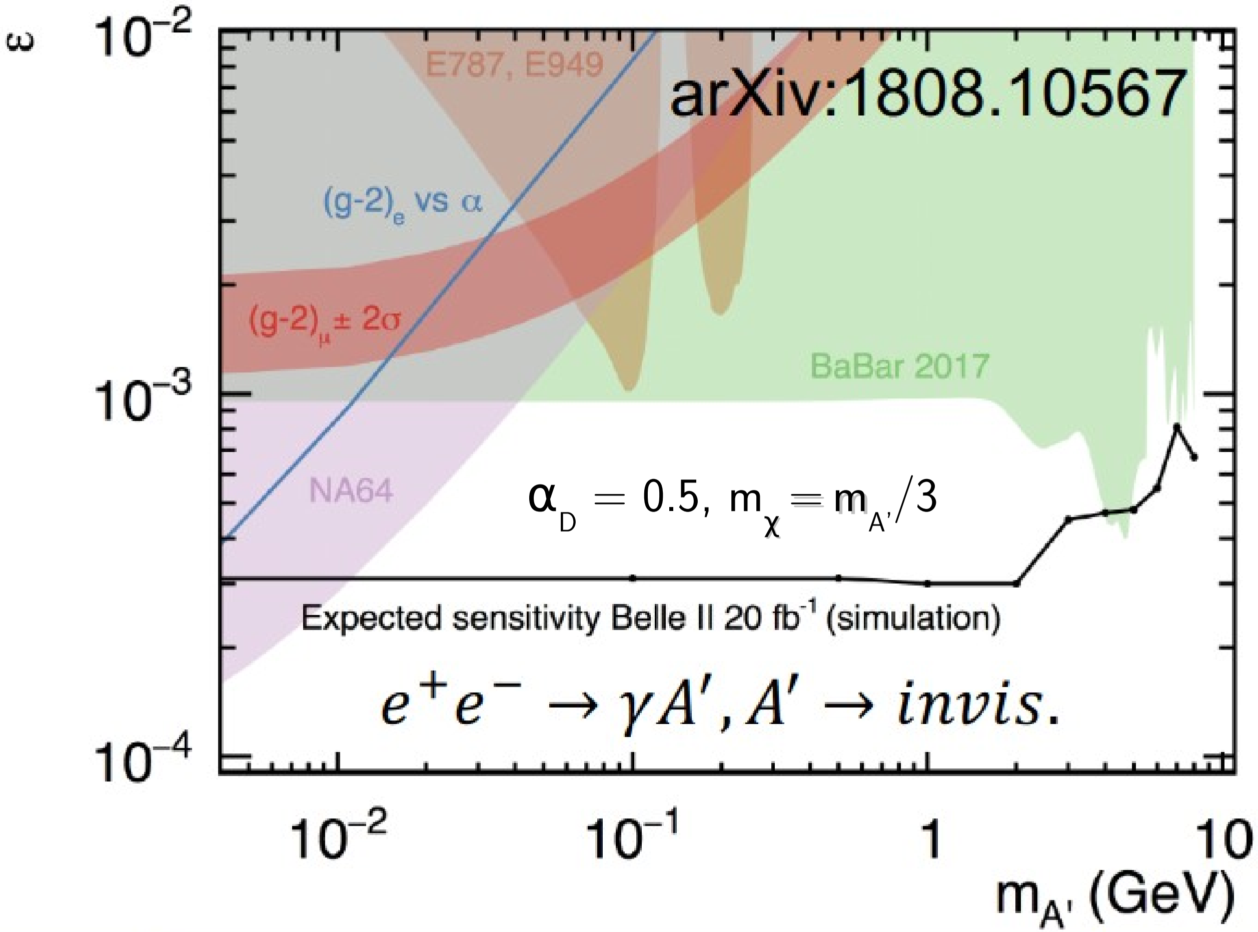


- If $m_\chi < 1/2\, m_{A'}$ → A' decays into DM particle, $e^+e^- \rightarrow \gamma + A'$, $A' \rightarrow \chi\chi$
- ***ANALYSIS STRATEGY:***
  - Nothing in the event but a single high energetic **ISR photon**
  - Look for a bump in the recoil mass spectrum $M^2_x = s - 2E^*_\gamma\sqrt{s}$
  - Background contribution from $e^+e^- \rightarrow e^+e^-\gamma(\gamma)$, $e^+e^- \rightarrow \gamma\gamma(\gamma)$

53 fb^{-1} ~**10 fb^{-1} good quality data**

Dark photon: Results

- Belle II advantages:
  - ✔ No ECL cracks pointing to the Interaction region
  - ✔ KLM can compensate ECL photon detection gap
  - ✔ Better hermeticity
  - ✔ Improved L1 trigger lines
- Complementary to dark searches in *bottomonium*:
  - Different mediator type (spin)
  - Different contaminating backgrounds
  - Different experimental challenges



Summary

First generation B-factories still can provide competitive results constraining light dark matter models, involving dark sector Higgs mediators, through the search for ***invisible decays of bottomonium***

Main limit is ***statistics*** $\rightarrow$currently upper limits only

$>$200 fb^{-1} collected at $\Upsilon(3S)$ ***@Belle II*** may lead to observation of 30-300 events of ***Υ(1S)→invisible***
(assuming 10^{-5} (SM) $<$ BR(Υ(1S)→*invisible*) $<$ 10^{-4} (NP) + Belle efficiencies)

→ Interplay with theory needed to connect direct and indirect searches and effectively constrain dark sector models!

A rich dark sector program is under investigation @Belle II, both at bottomonium resonances and in continuum (Invisible Dark Photon, Invisible Z', ALPs and much more…The Belle II Physics Book, arXiv:1808.10567)

- Magnetic monopole
- Muonic dark forces
- Dark Higgs/Higgsstrahlung
- Dark scalars
- Inelastic Dark Matter
- Long-lived particles
- …

Summary

First generation B-factories still can provide competitive results constraining light dark matter models, involving dark sector Higgs mediators, through the search for ***invisible decays of bottomonium***

Main limit is ***sta***

$>$200 fb^{-1} collec ... v ... g

10^{-5} (SM)$<$ BR

→ ***Interplay w*** ... ***ea***

constrain dark

Now collecting data @Belle II. Data analysis is starting!

A rich dark sector program is under investigation @Belle II, both at bottomonium resonances and in continuum (Invisible Dark Photon. Invisible Z', ALPs and much more…The Belle II Physics Book, arXiv:1808.10567)

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- Muonic dark forces
- Dark Higgs/Higgsstrahlung
- Dark scalars
- Inelastic Dark Matter
- Long-lived particles
- …

Backup

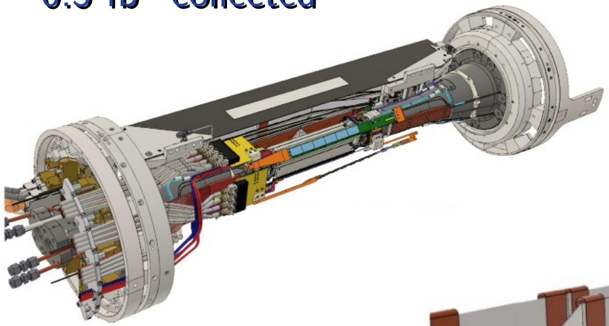
SuperKEKB Numbers

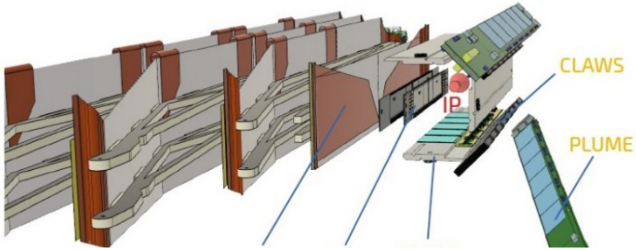
2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.20×10^{-4}	4.55×10^{-4}		
σ_δ	$7.92(7.53) \times 10^{-4}$	$6.37(6.30) \times 10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

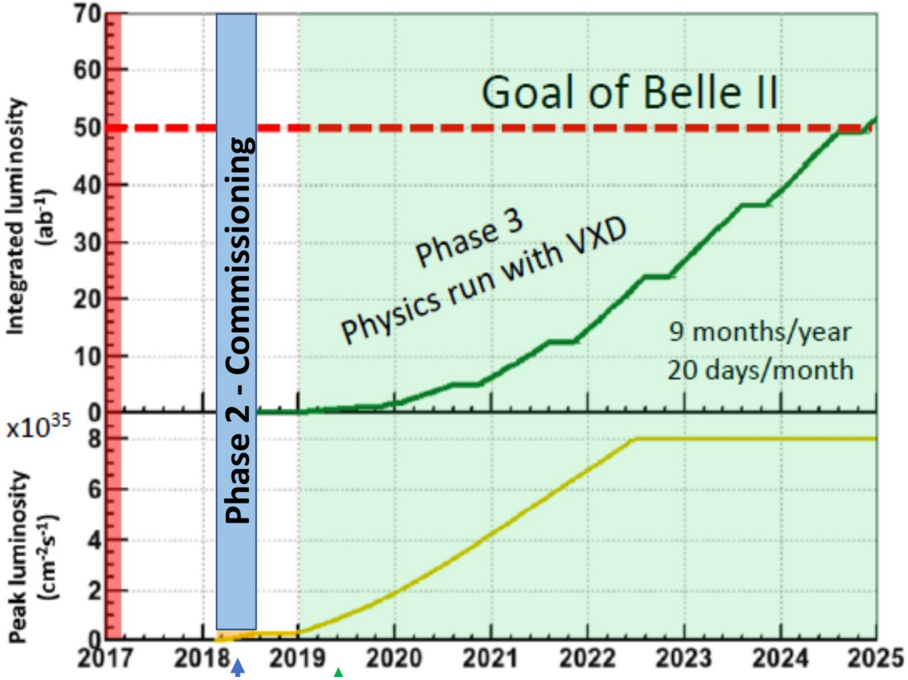
Belle II Data Taking: Phase 2

Phase 2 (April 26th– July17th 2018)

- Pilot run with only 1/8th VXD
- Verify nano-beam scheme, commission the detector and measure the background level
- **Max peak luminosity 0.5 x 10^{34} cm^{-2} s^{-1}**
- **0.5 fb^{-1} collected**







- Lower backgrounds
- Flexible hardware triggers
- Pass-through software trigger

Good conditions for Dark Sector Searches

Belle II Data Taking: Phase 3

Phase 3 (March 2019 –)

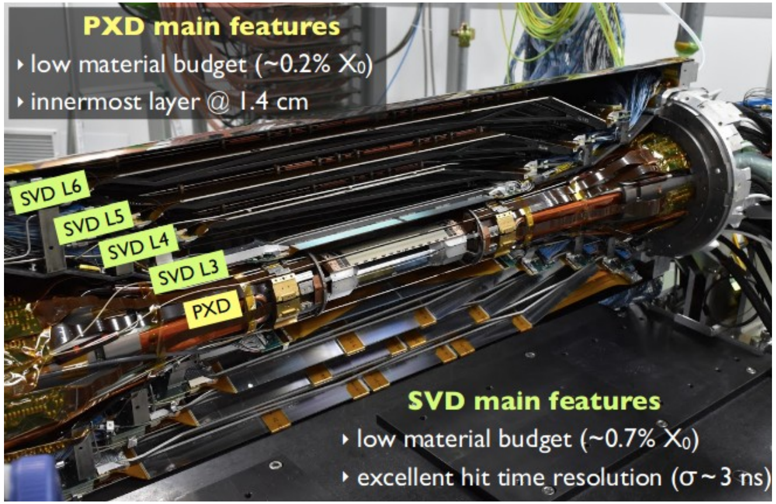
- VXD detector installed

  → 4 full layers of silicon strips

  → 1 + 1/6 full layers of pixels

  (complete installation ~2020)

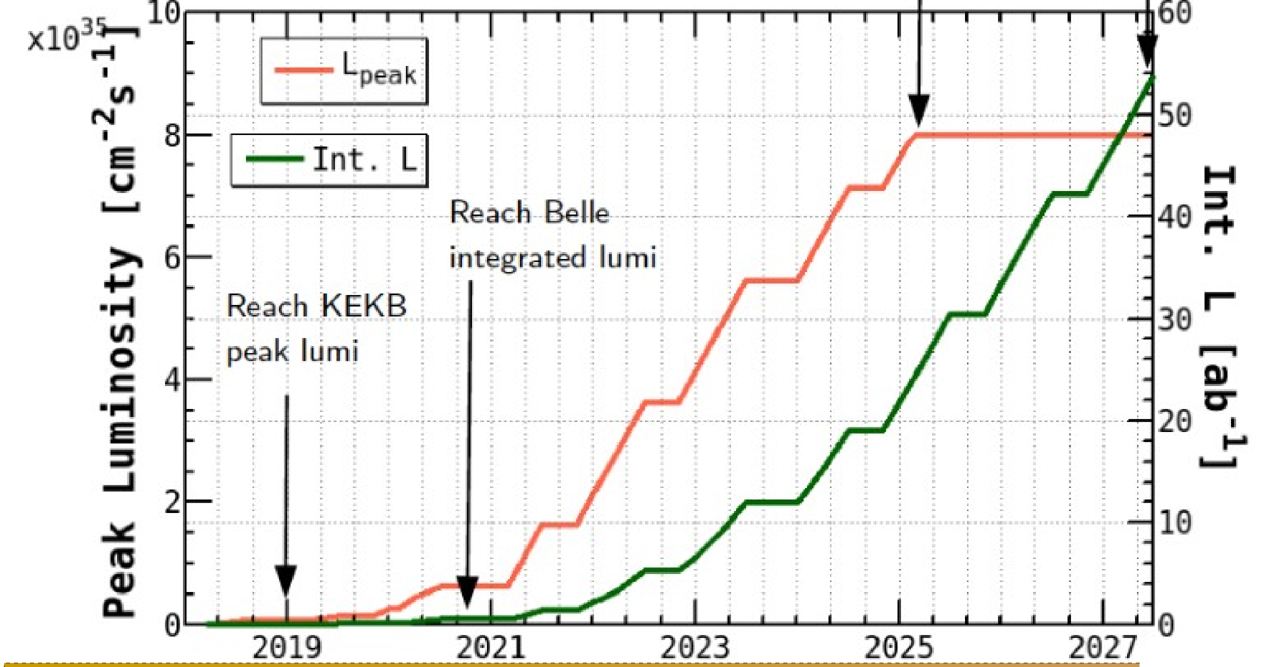
- 20 fb^{-1} by summer 2019



Final goal: 40x KEKB luminosity

Int. lumi = 50 ab^{-1}

Peak lumi = 8×10^{35} Hz/cm^{-2}

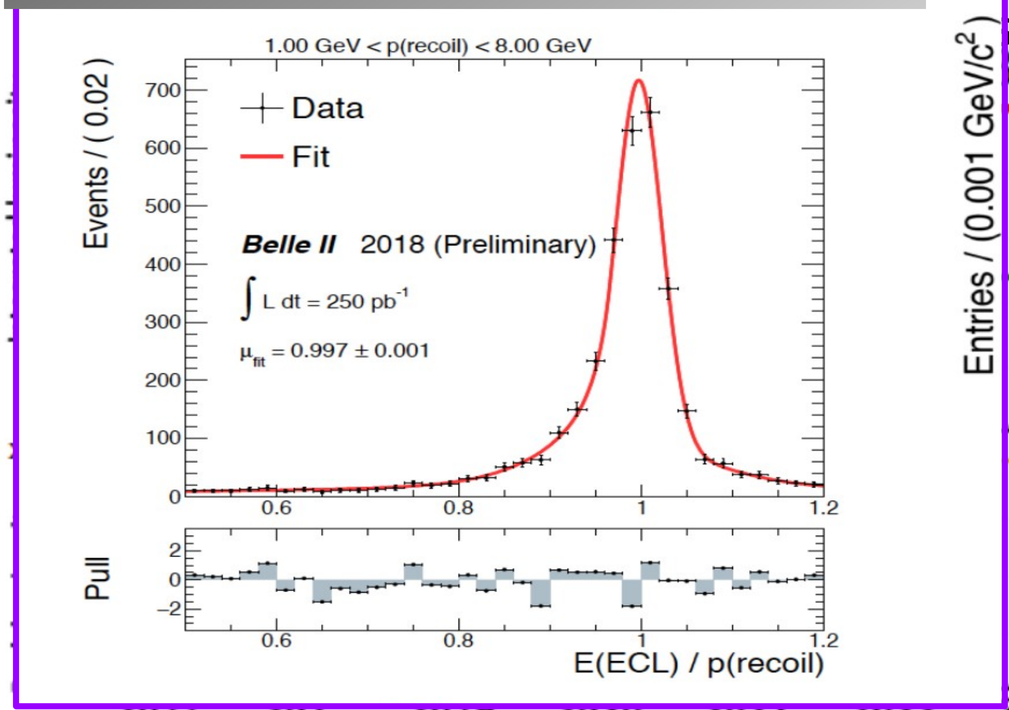


Phase 3: Run with full detector at peak luminosity, $L = 8 \cdot 10^{35}$ cm^{-2} s^{-1}

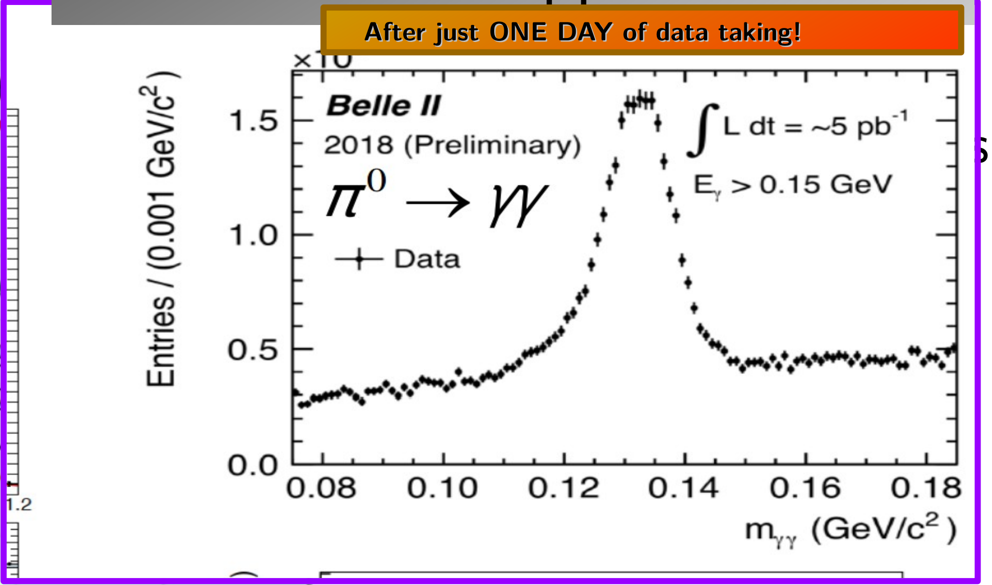
GOAL: collect 50 ab^{-1}

Belle II Performances: photon reconstruction

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



$\pi^0 \to \gamma\gamma$



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

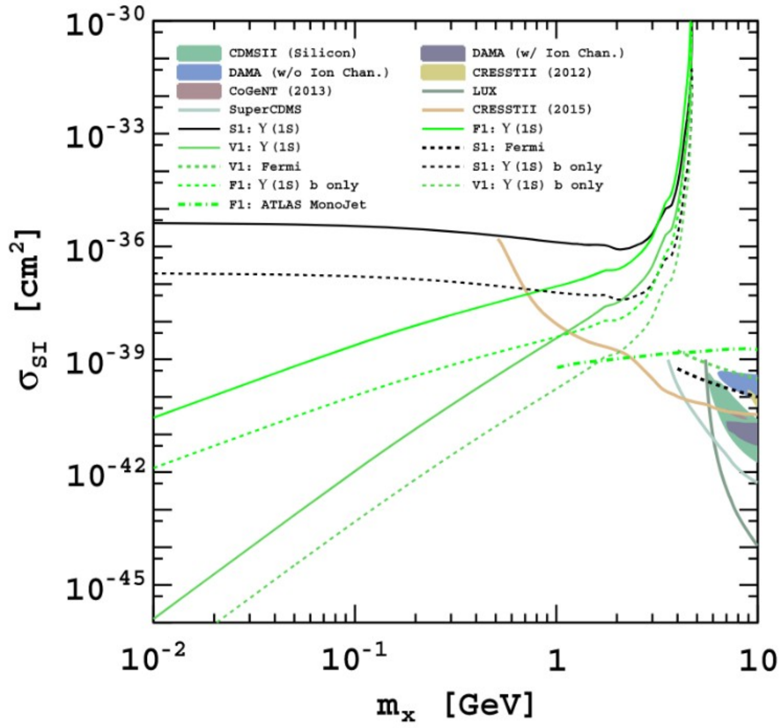
$e^+e^- \to \gamma\ ALPS \to \gamma(\gamma\gamma)$

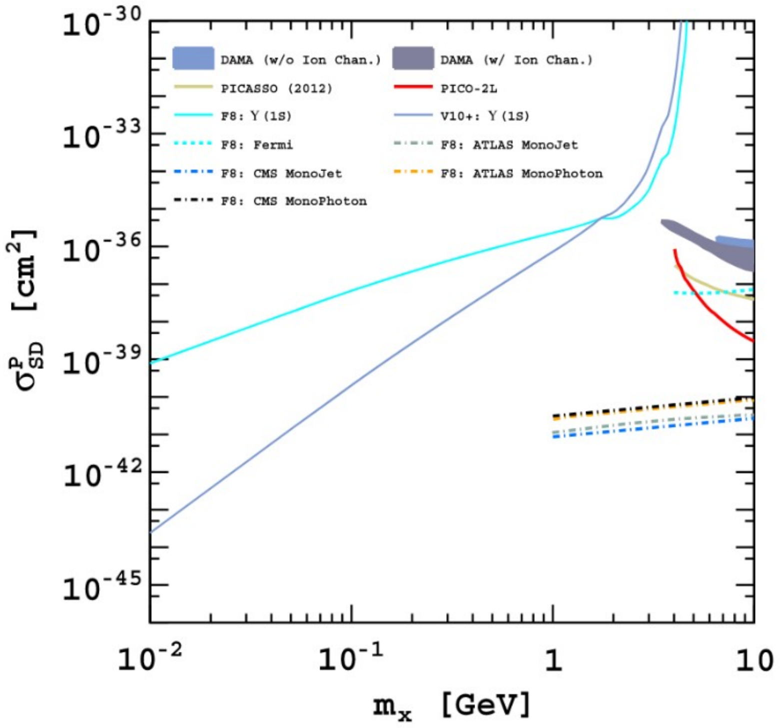
GOOD CONDITIONS for DARK SEARCHES

- ✔ Tracking and cluster L1 trigger
- ✔ Bhabha veto L1
- ✔ Single Photon L1 trigger

$\Upsilon(1S) \to \gamma$ DM DM

ArXiv: 1511.03728, 1404.6599





$\Upsilon(1S) \to \gamma$ DM DM: BaBar Constraint

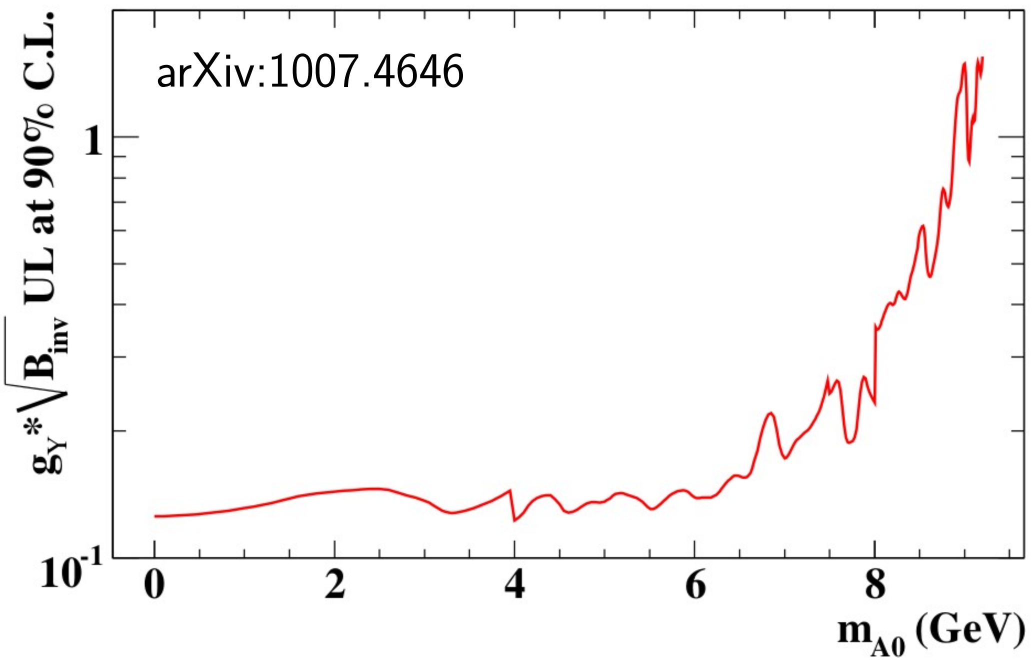
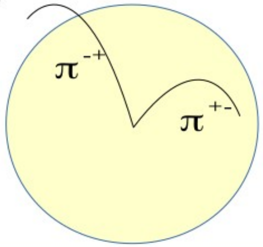


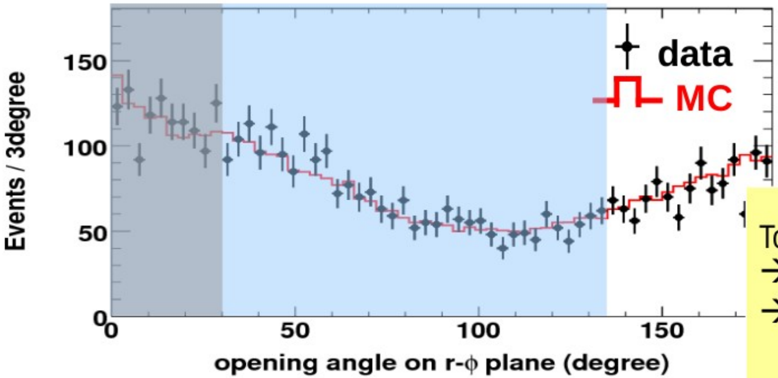
FIG. 5: Upper limits on the product $g_\Upsilon \times \sqrt{\mathcal{B}(A^0 \to \text{invisible})}$ at 90% C.L. as a function of m_{A^0}. The parameter g_Υ is an effective coupling of the CP-odd Higgs A^0 to bound state $\Upsilon(1S)$; in NMSSM, $g_\Upsilon = \tan\beta \cos\theta F_\Upsilon$, where $\cos\theta$ is the fraction of non-singlet component in A^0, $\tan\beta$ is the ratio of Higgs vacuum expectation values, and F_Υ is the effective form-factor (including the QCD and QED corrections). The theoretically preferred region in NMSSM [13] is $g_\Upsilon > 1$.

Trigger Considerations

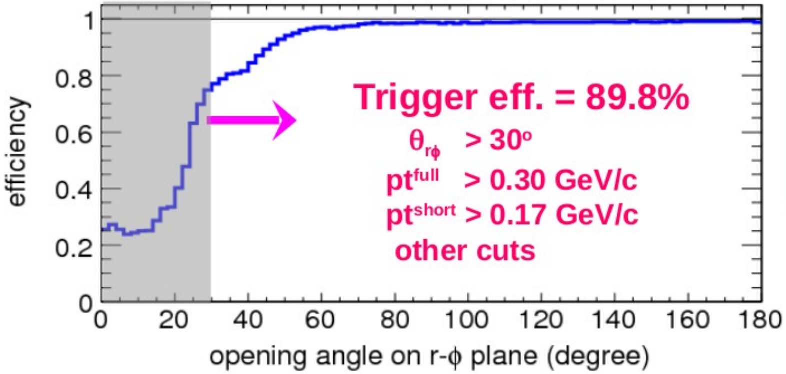
$\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$

$\Upsilon(1S) \rightarrow \mu^+\mu^-$





Too low efficiency with usual condition (>135°)
→ Higher efficiency with looser condition
→ Special trigger condition was implemented
(~850 Hz, twice as usual condition)



Single track trigger was implemented, too with 1/500 pre-scale rate (pt>250 MeV/c)

$$\frac{\text{2-track trigger \& 1-track trigger}}{\text{1-track trigger}}$$

for efficiency monitoring

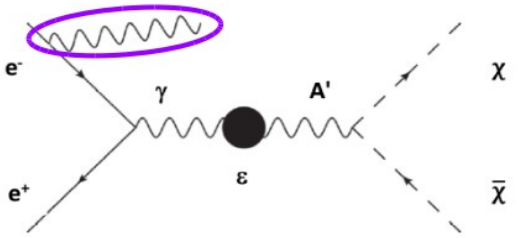
BELLE

Dark Photon to Invisible

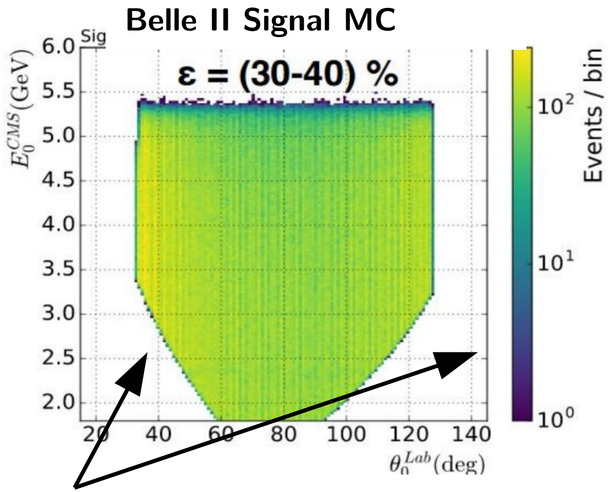
- Signal Signature:
  - select events with a single, monochromatic, high energetic *ISR photon*
  - Look for a bump in the reconstructed photon energy $E_\gamma = (s - m^2_{A'})/2\sqrt{s}$

    $\rightarrow$ only one photon in the detector requires a dedicated ***single photon trigger.***

(@Belle was not available, ~10% BaBar data)



Discriminant variables: E^*_γ, θ_γ



Effect of selection on $E^*(\theta)$ for background rejection

BaBar

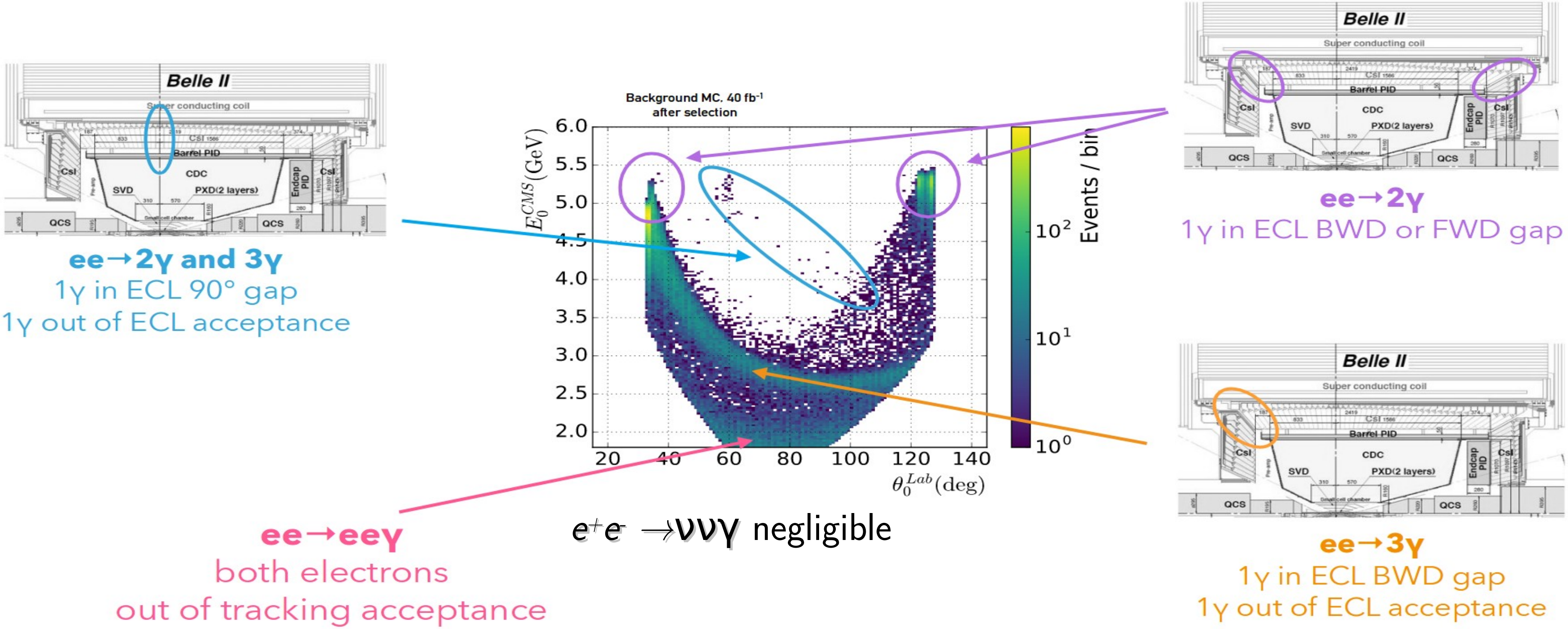
	L1 trigger	L3 trigger
LowM	$E_\gamma^{LAB} > 0.8$ GeV	$E^*_\gamma > 2$ GeV && no tracks from IP
HighM	$E_\gamma^{LAB} > 0.8$ GeV	$E^*_\gamma > 1$ GeV && no tracks from IP

Belle II Phase 3 (Designed)

Trigger logic	L1 rate at full luminosity
E > 1 GeV + 2nd cluster E < 300 MeV	4 kHz (barrel) 7 kHz (endcaps)
E > 2 GeV +Bhabha & γγ vetoes	5 kHz (barrel)

Dark Photon to Invisible: Backgrounds

- Background dominated by QED processes:
  - $e^+e^- \rightarrow \gamma\gamma(\gamma)$ where one photon is not detected (ECL gaps) and the second out of acceptance
  - radiative Bhabha $e^+e^- \rightarrow e^+e^- \gamma(\gamma)$ with the electron-positron pair out of acceptance.



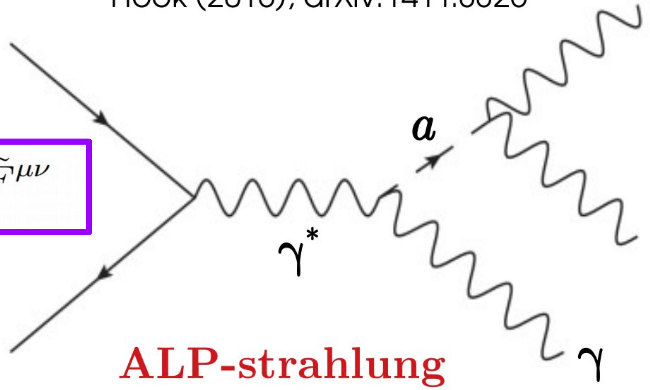
Axion Like Particles (ALPs)

- Axion Like Particles are pseudo-scalars coupling to bosons
- Unlike for QCD Axions, there is no relation between the coupling and the mass
- Explored photon coupling $g_{a\gamma\gamma}$ in *ALP-strahlung* processes

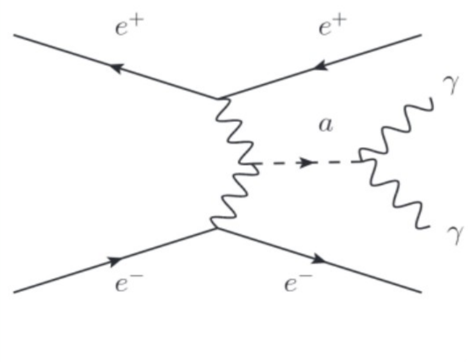
  (*photon fusion:* sensitivity under study)

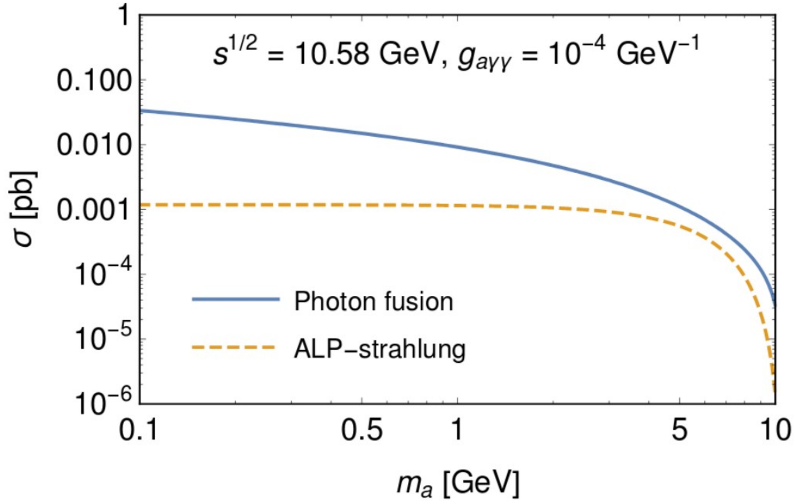
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Hook (2015), arXiv:1411.3325



- $\tau = 1/m_a^2 g^2_{a\gamma\gamma}$
  - Displaced vertex
  - Long-lived particle



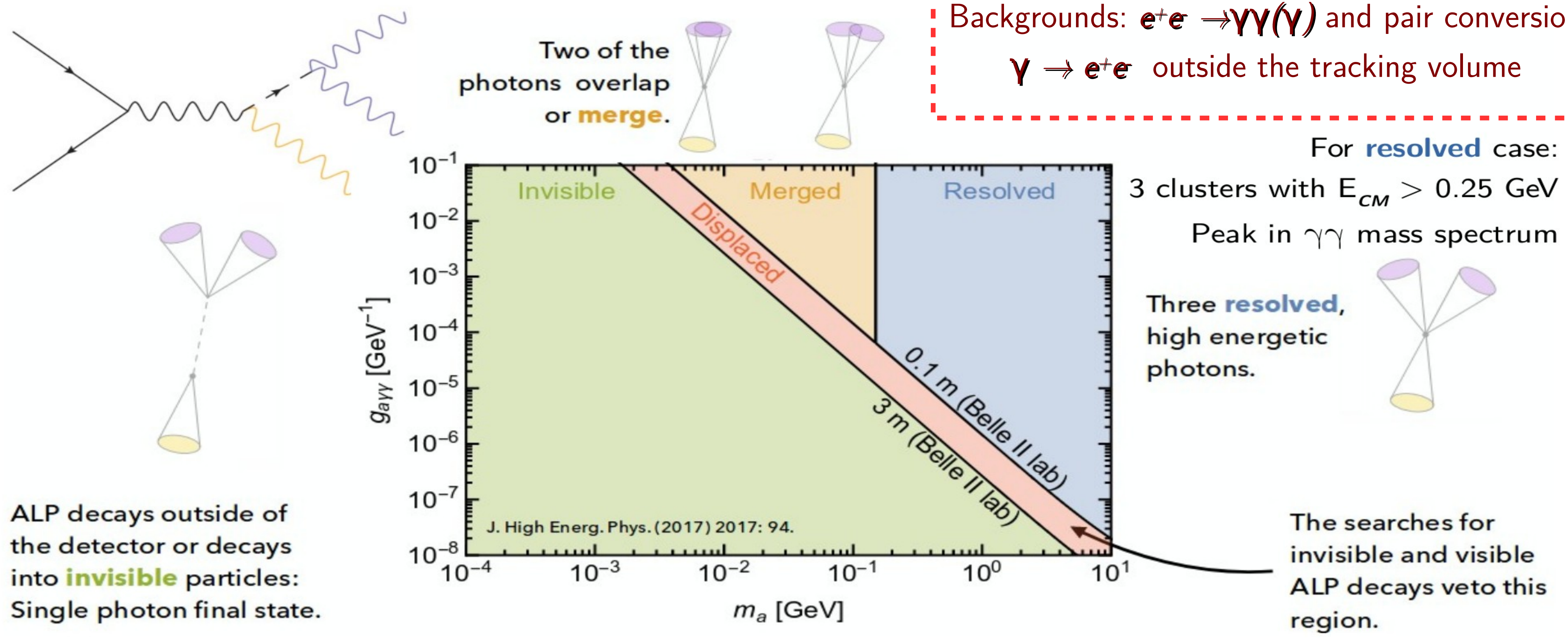


ALPs: Experimental Signature

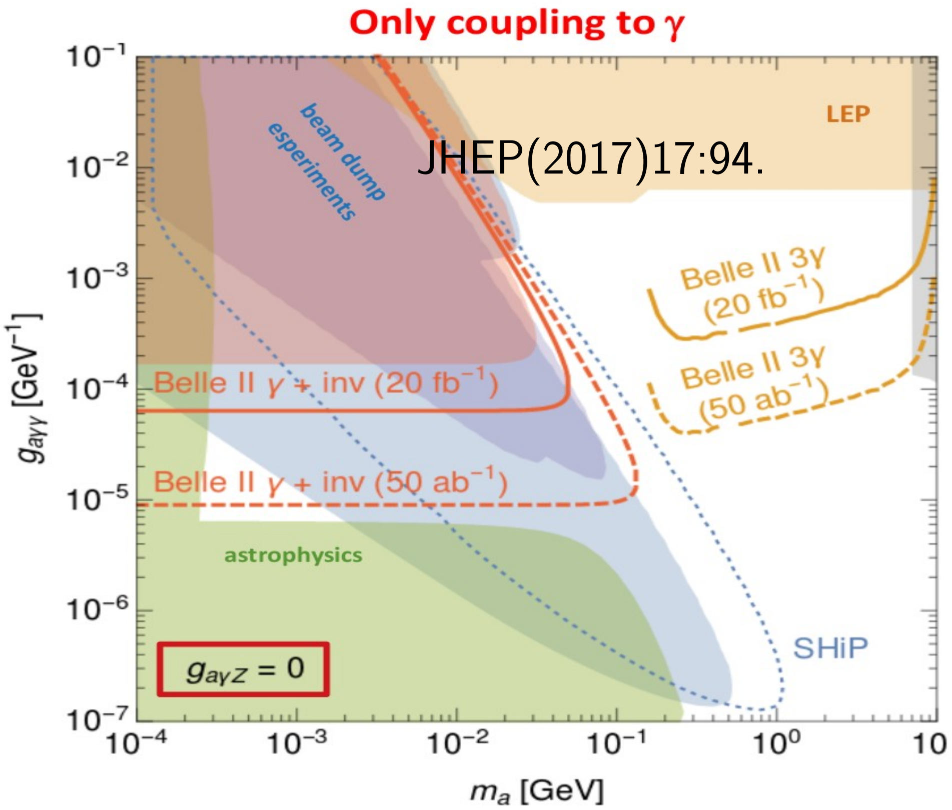
- Signal signatures: 3γ final state, several topologies $\rightarrow$ 4 categories
- ALPS may also decay to invisible (DM) $\rightarrow$ single photon topology

Backgrounds: $e^+e^- \rightarrow \gamma\gamma(\gamma)$ and pair conversion
$\gamma \rightarrow e^+e^-$ outside the tracking volume

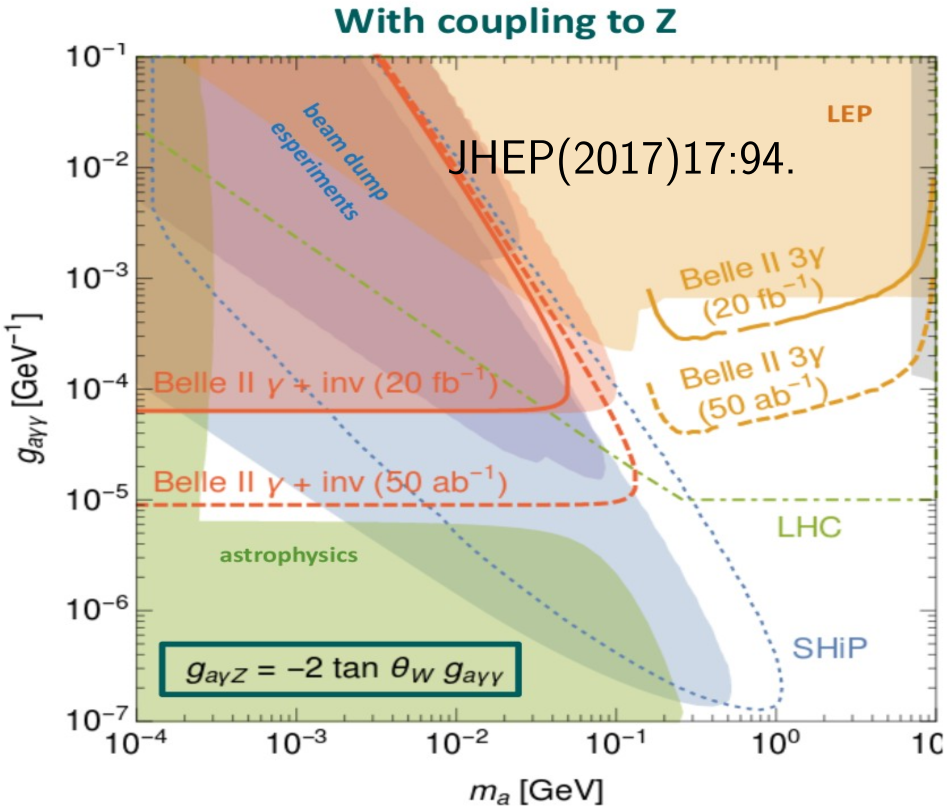
For **resolved** case:
3 clusters with $E_{CM} > 0.25$ GeV
Peak in $\gamma\gamma$ mass spectrum



ALPs: Sensitivity

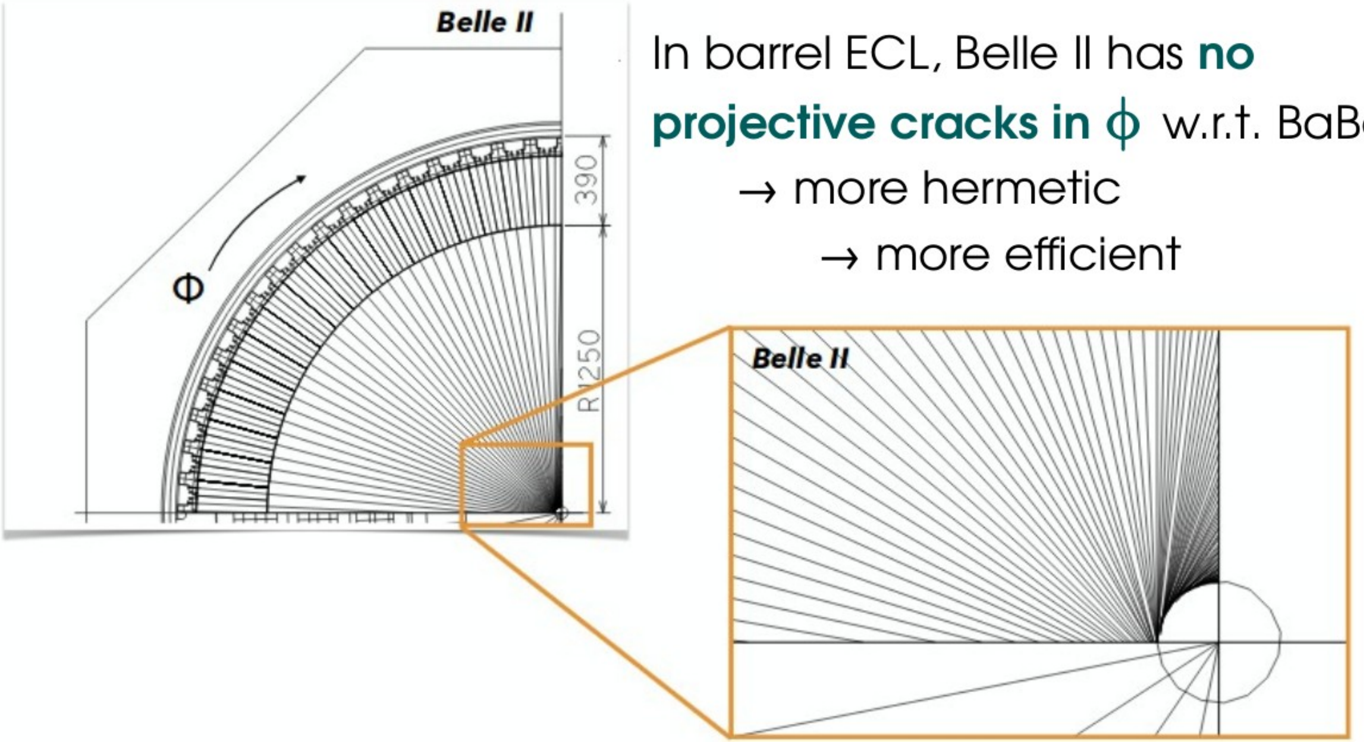


JHEP(2017)17:94.



JHEP(2017)17:94.

Belle II Electromagnetic Calorimeter (ECL)

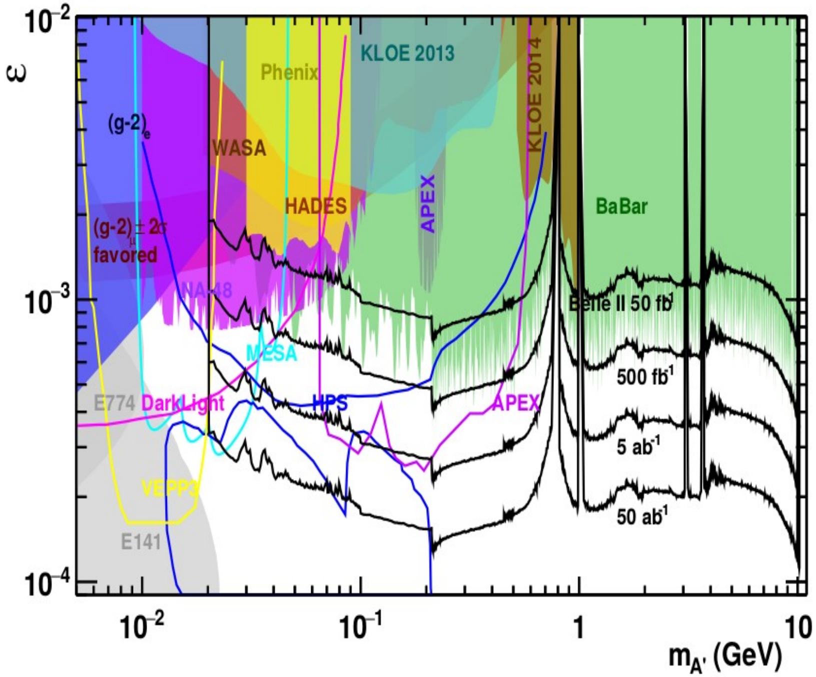


In barrel ECL, Belle II has **no projective cracks in ϕ** w.r.t. BaBar:

→ more hermetic

→ more efficient

Dark Photon to leptons: Sensitivity



From Belle II Physics Book, arXiv:1808.10567

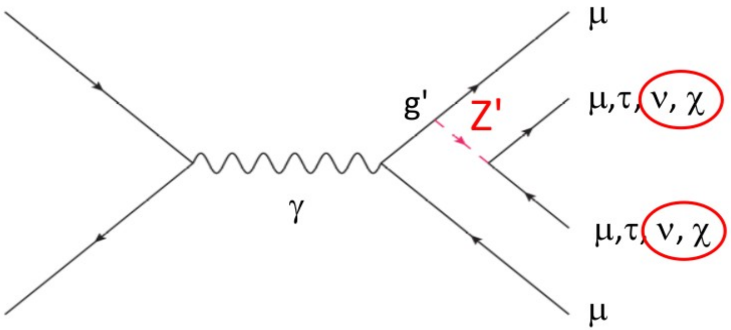
Fig. 211: Existing exclusion regions (90% CL) on the dark photon mixing parameter ε and mass $M_{A'}$ (solid regions) for $A' \to \ell\ell$, with projected limits for Belle II and other future experiments (lines) (Figure reproduced from [1820]).

Z' to Invisible: L_μ-L_τ model

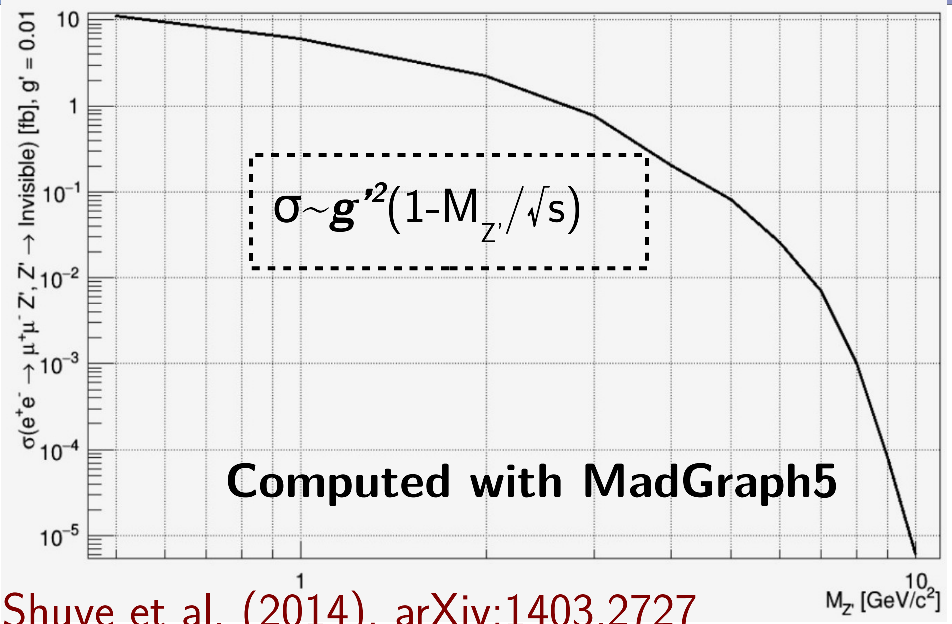
- New gauge boson Z' coupling only to the **2nd and 3rd** generation of leptons (L_μ-L_τ)

  Detecting the L_μ-L_τ gauge boson at Belle II, arXiv:1702.01497

- Invisible signature investigated for the first time in the process $e^+e^- \to \mu^+\mu^- Z'$ + *missing energy*
- May explain the $(g-2)_\mu$ anomaly
- BR(Z'→ inv) may be enhanced by the presence of kinematically accessible DM (e.g. sterile neutrinos)



* If LDMA is accessible, BR(Z'→ DM)~1



Shuve et al. (2014), arXiv:1403.2727

Branching ratios:

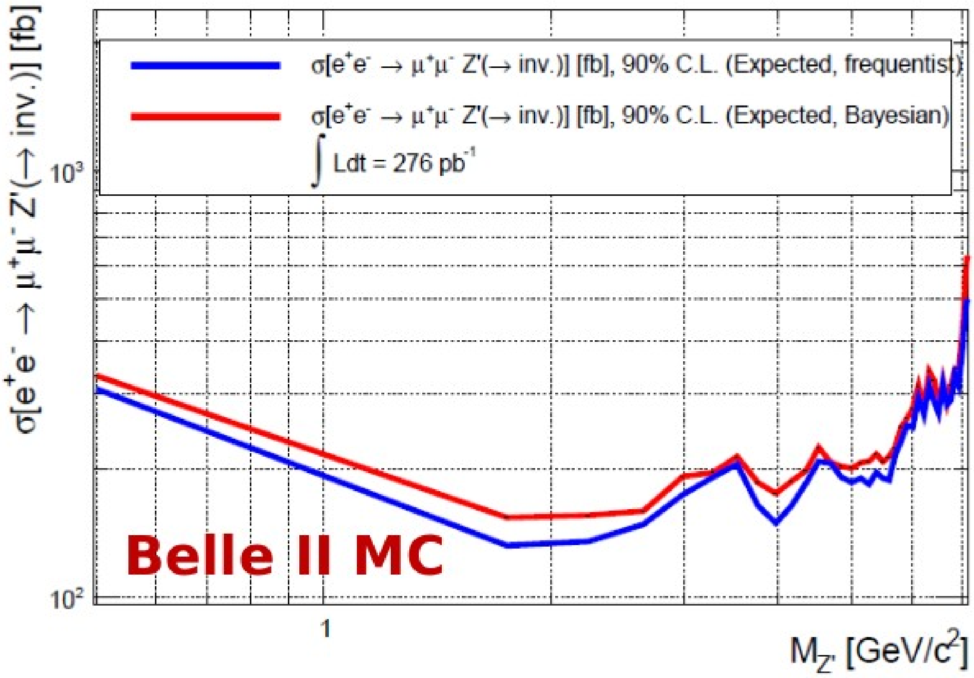
$$M_{Z'} < 2M_\mu \to \Gamma(Z' \to \text{inv.}) = 1$$

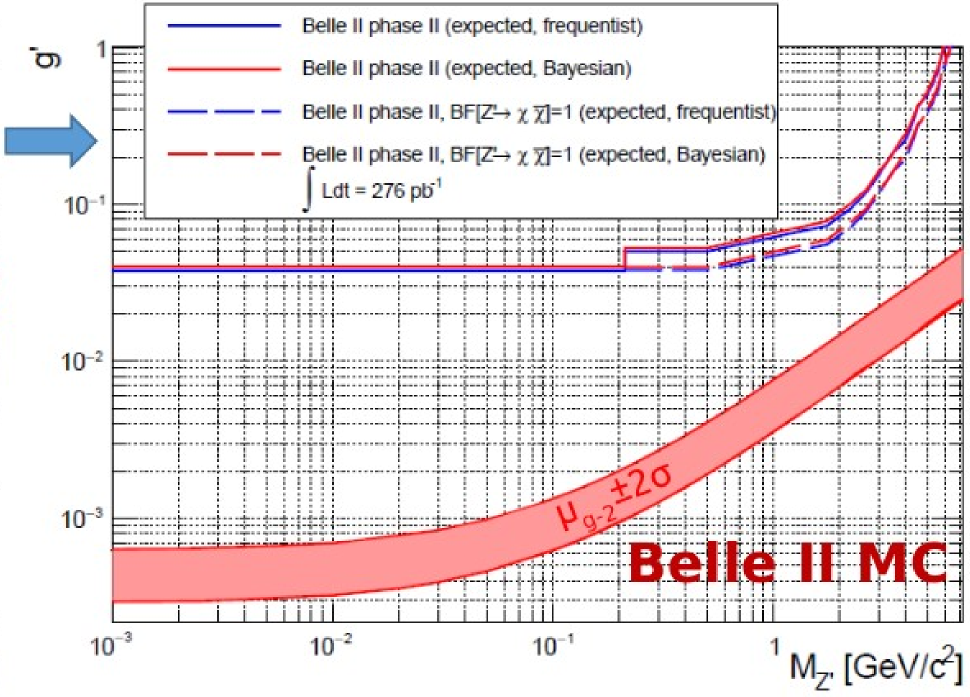
$$2M_\mu < M_{Z'} < 2M_\tau \to \Gamma(Z' \to \text{inv.}) \sim 1/2$$

$$M_{Z'} > 2M_\tau \to \Gamma(Z' \to \text{inv.}) \sim 1/3$$

Z' to Invisible @Belle II

- Data validation and analysis optimization under finalization on Phase 2 samples, L=276/pb
- Results from simulation studies



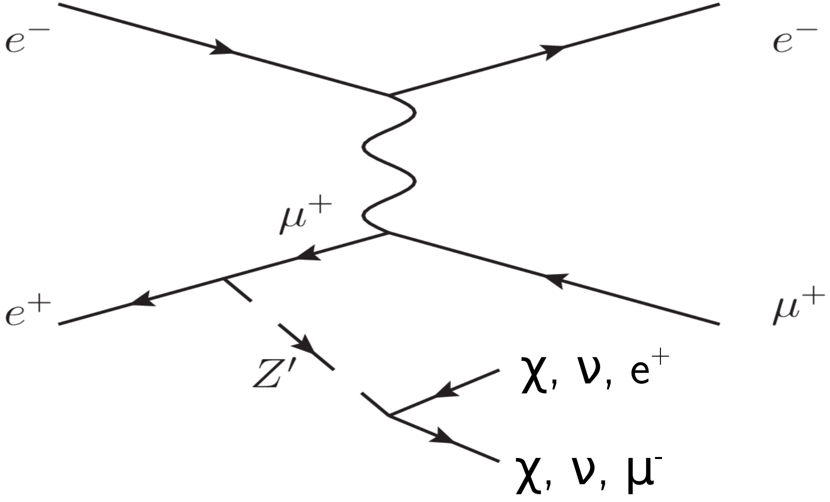


LFV Z': invisible and visible channel

What if symmetries of SM are not kept in the Dark Sector?

What if DM violates Lepton Flavour?

One can imagine, for example, $e\mu$ coupling



$e^+e^- \rightarrow e^+\mu^- Z'$; $Z' \rightarrow$ invisible

Dominant background: $e^+e^- \rightarrow \tau^+\tau^- (\gamma)$, $\tau^\pm \rightarrow \mu^\pm, e^\pm \nu\nu$

$e^+e^- \rightarrow e^+\mu^- Z'$; $Z' \rightarrow e^+\mu^-$ **+ c.c.**

no SM background