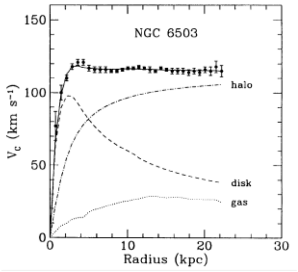
Dark Sector Searches at B-Factories

Dark Matter@LHC 2019 University of Washington Seattle, USA

Seattle – 2019, August 13th – 16th

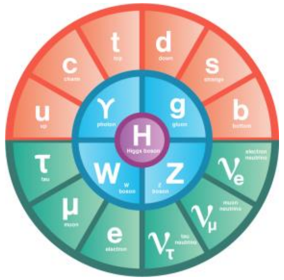
Paolo Branchini
INFN RomaTre
on behalf of the BaBar and Belle II Collaborations

Dark Matter coupling to SM



Dark Matter

X



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Standard Model

Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

Vector portal → Dark Photon

Scalar portal → Dark Higgs/Scalars

Pseudoscalar portal → Axion-Like Particles

Neutrino portal → Sterile Neutrinos

The physics program in this sector is very rich. Many models are present on the market.

In this presentation I'll focus on recent results from BABAR Belle and Belle2

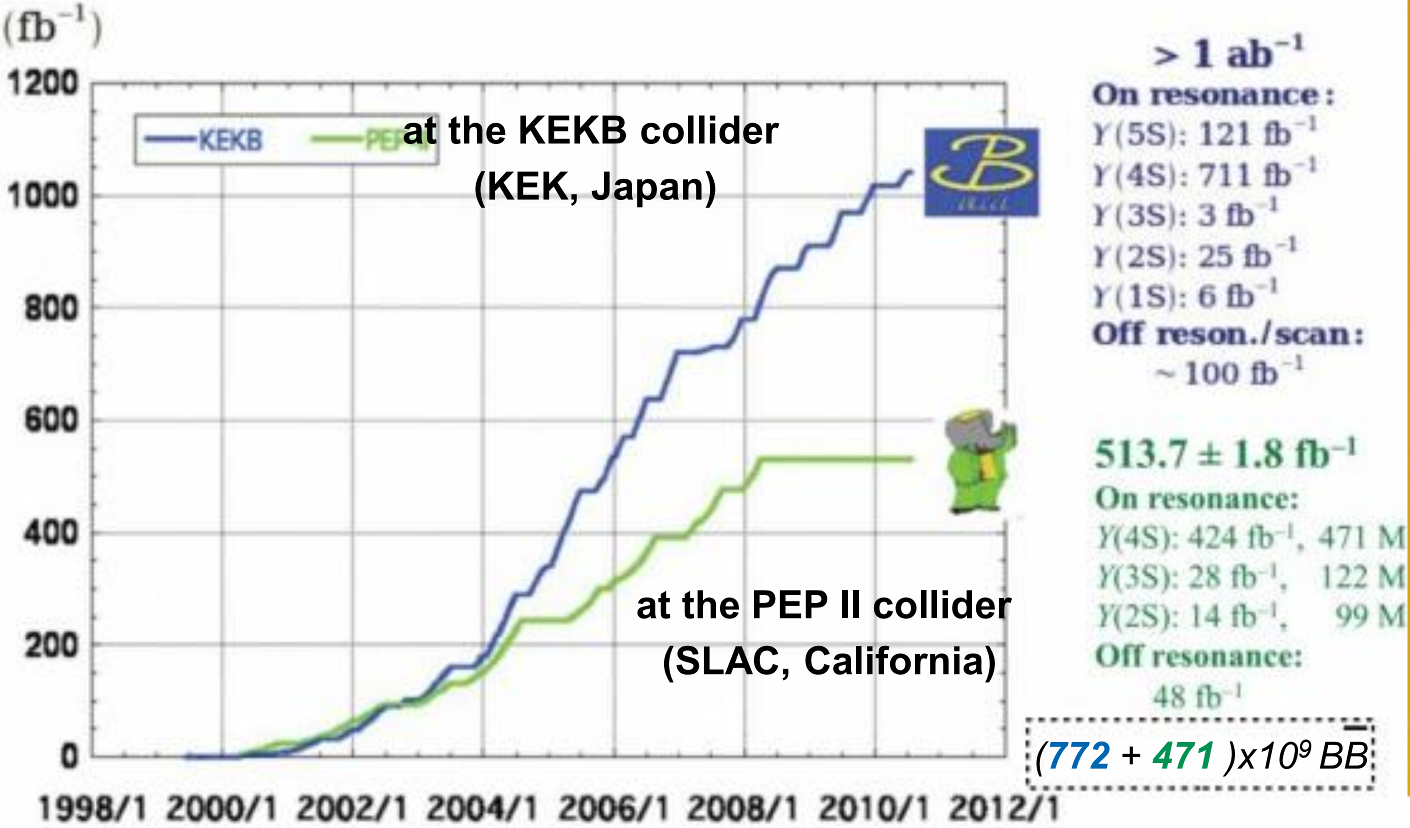
B-Factories:the high intensity frontier

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

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

Y(nS) = bound state of b quark and anti-quark

First generation of B-factories



(772 + 471)x10^9 $B\bar{B}$

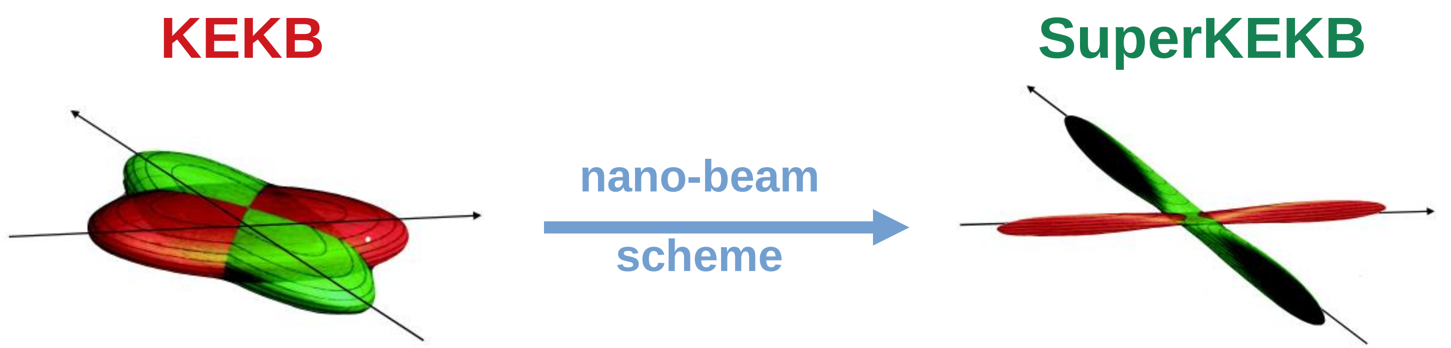
Rich physics program:

- ✔ 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*

SuperKEKB: an Intensity Frontier machine

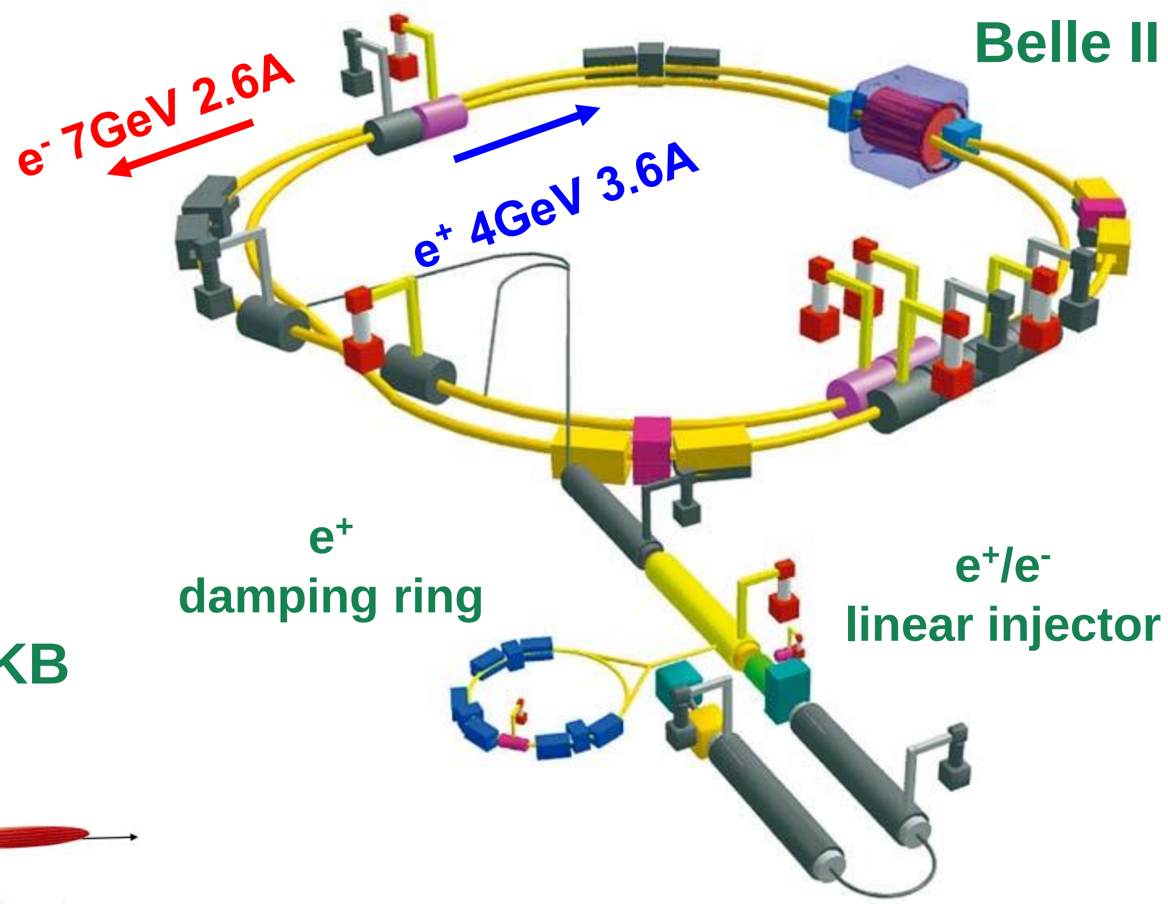
SuperKEKB is a super B-factory located at KEK (Tsukuba, Japan)

It's an asymmetric e^+e^- collider operating mainly at **10.58 GeV**
(**Υ(4S)**, but possible runs from Υ(2S) to Υ(6S))



I (A): ~ 1.6/1.2
β^*_y (mm): ~ 5.9/5.9

I (A): ~ 3.6/2.6
β^*_y (mm): ~ 0.27/0.3

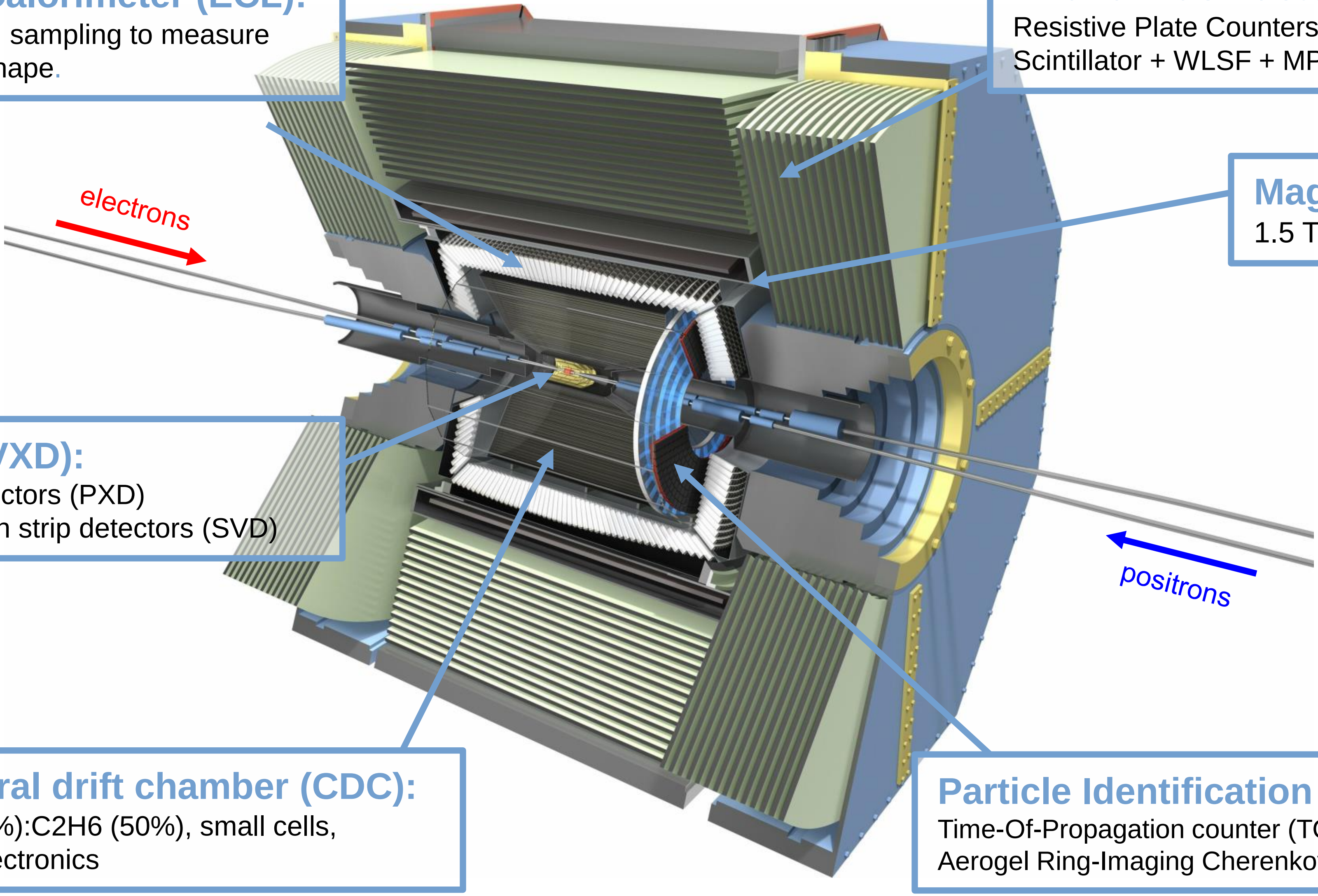


40x peak luminosity:
$8{\cdot}10^{35}$ cm^{-2} s^{-1}

Belle II detector

Electromagnetic Calorimeter (ECL):
CsI(Tl) crystals, waveform sampling to measure time, energy, and pulse-shape.

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)



Magnet:
1.5 T superconducting

Vertex detectors (VXD):
1 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

Trigger:
Hardware: < 30 kHz
Software: < 10 kHz

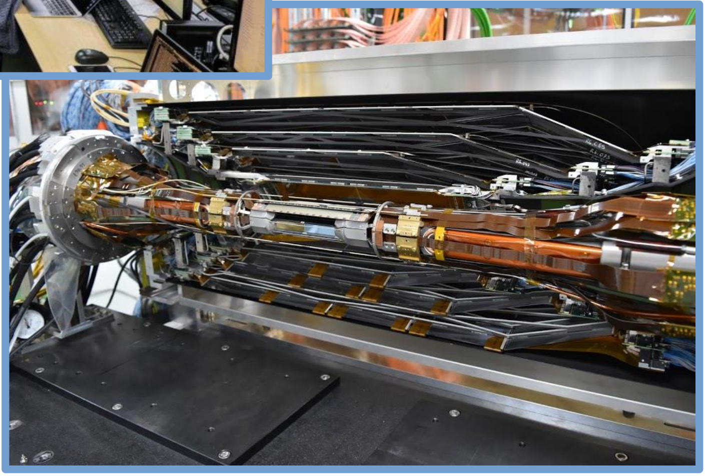
Central drift chamber (CDC):
He(50%):C2H6 (50%), small cells, fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

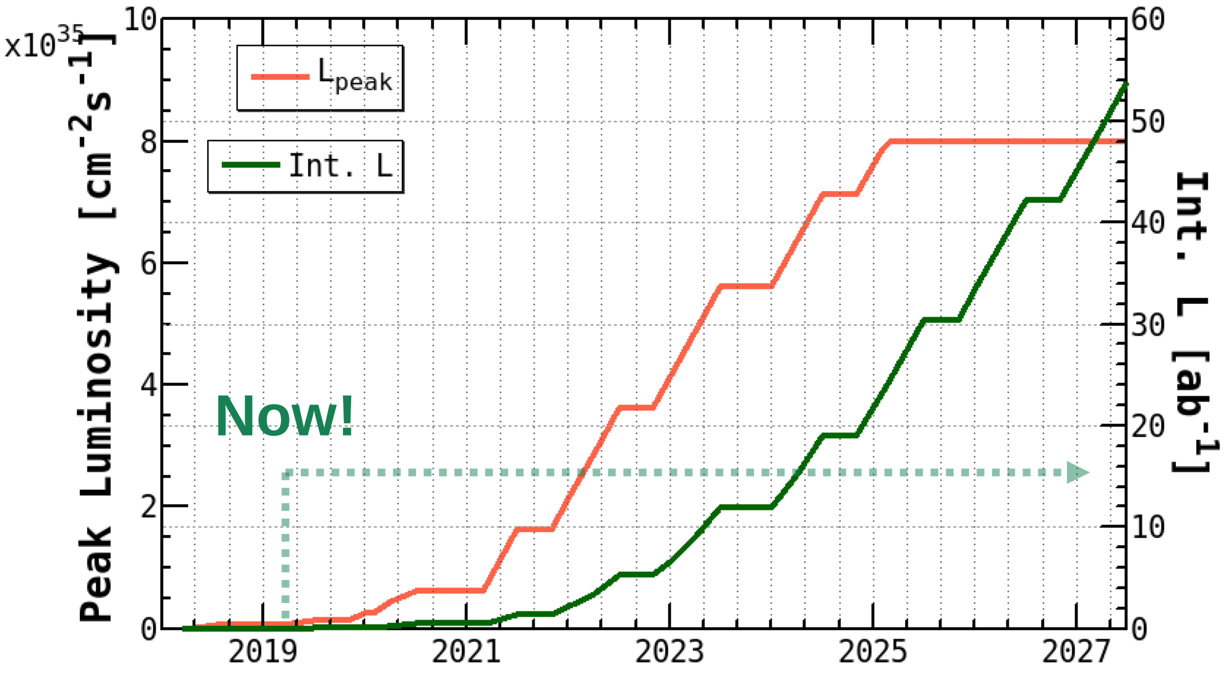
Data collected up to now and final goal

Goal: integrate up to 50 ab^{-1} of data

Phase3 collisions (25th March 2019)



Full angular coverage with PXD and SVD installed



Phase 2: 0.5 fb^{-1}

NOW: 6.5 fb^{-1}

Phase 3: 50 ab^{-1}

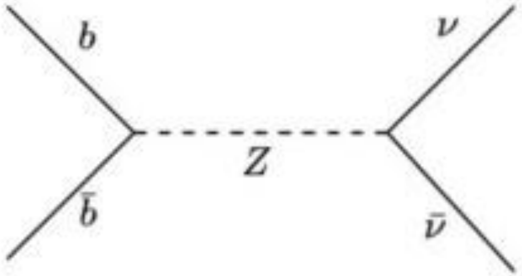
Full detector only in phase 3

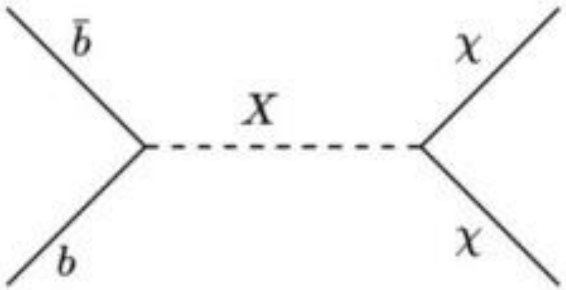
Υ(1S)→ γ DMDM

- BR(Υ(1S)→ inv) is well calculable in SM
- DM candidates could enhance the branching ratio, if Υ(1S)→χχ kinematics allows
- New mediators (Z', A_0) may also contribute
- In absence of NP observation, ***Belle II*** can measure the BR (Υ(1S)→νν)!

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

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

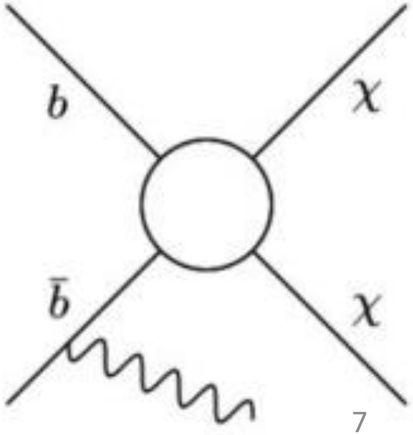




Adding one photon

- **BR(Υ(1S)→ γ inv)$_{SM}$ ~ 10^{-9}** out of current experimental sensitivity
- Searches for processes ***Υ(1S)***→ γχχ (expected BR ~ 10^{-5}-10^{-4})

  → investigate also ***Wilzcek production for on-shell scalar*** BR(Υ(1S)→ γA_0) x BR(A_0 → χχ)
- Limit NP models involving light Higgs bosons and light DM states *



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

Υ(1S) → γ DMDM: Results

Searched range:

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

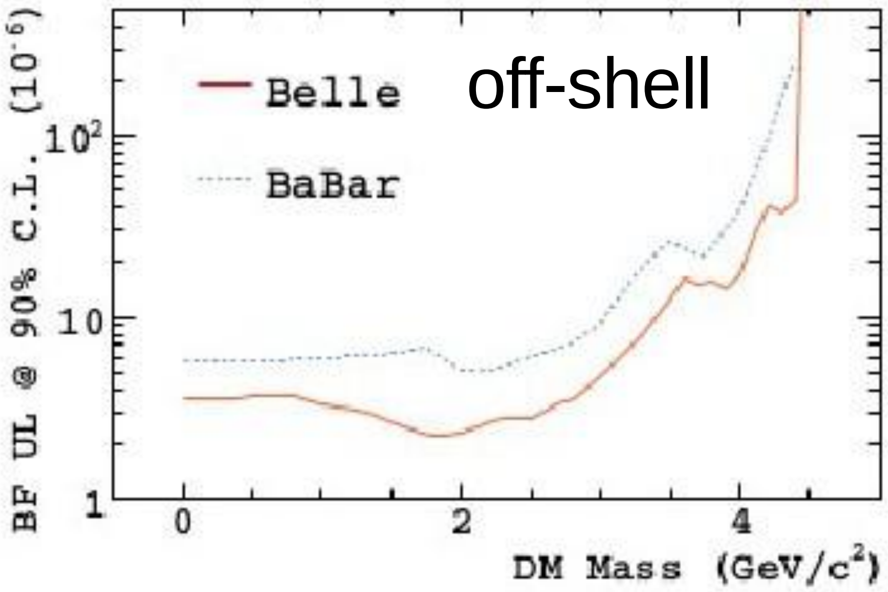
$0 \leq m_\chi \leq 4.44$ GeV, $0 \leq m_{A0} \leq 8.97$ GeV

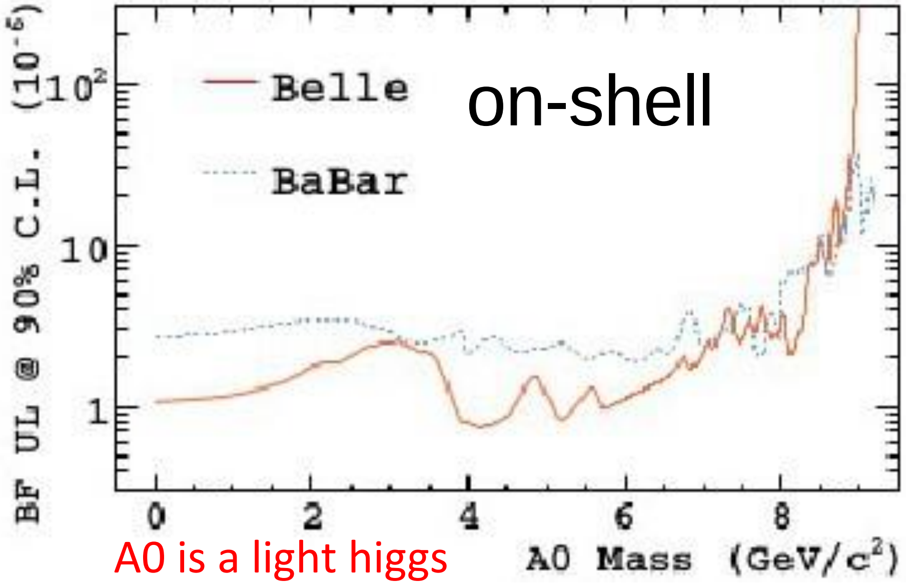
Statistically limited!

- Tag a clean sample of Υ(1S) exploiting *bottomonium* transitions with 2 soft pions
- Select events with ***2 tracks*** + ***one single photon + missing energy***

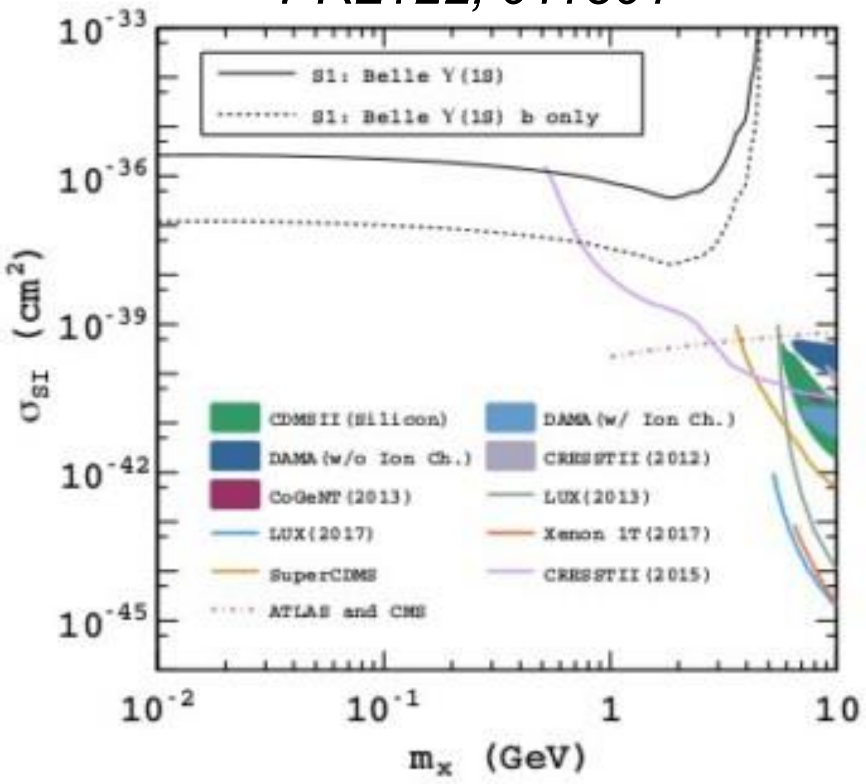
  (nothing else in the detector)

PRL122, 011801





A0 is a light higgs



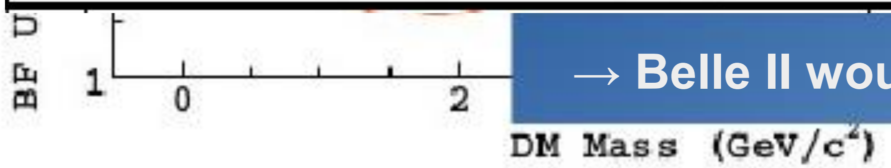
Based on 15 fb^{-1} BaBar @Υ(2S)

25 fb^{-1} Belle@Υ(2S)

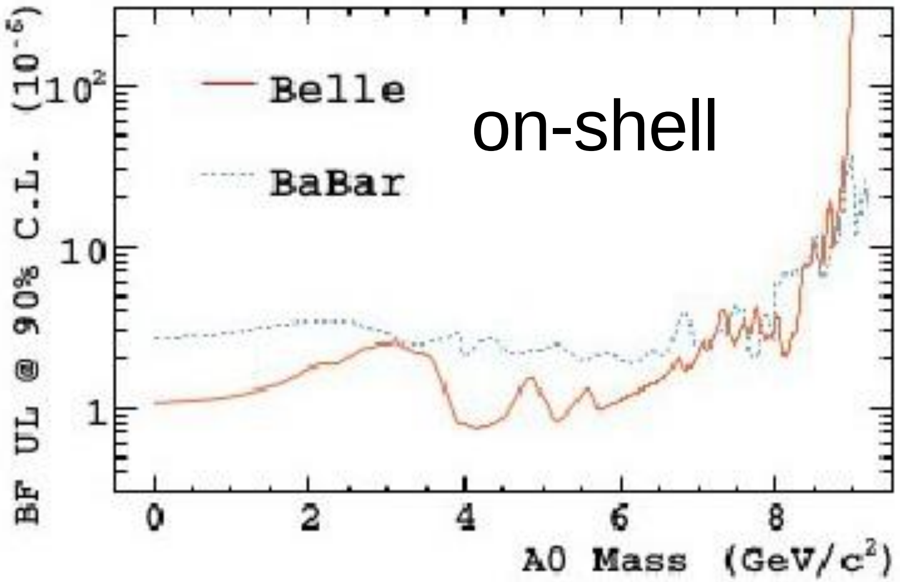
$\Upsilon(1S) \to \gamma$ DMDM: Belle II prospects

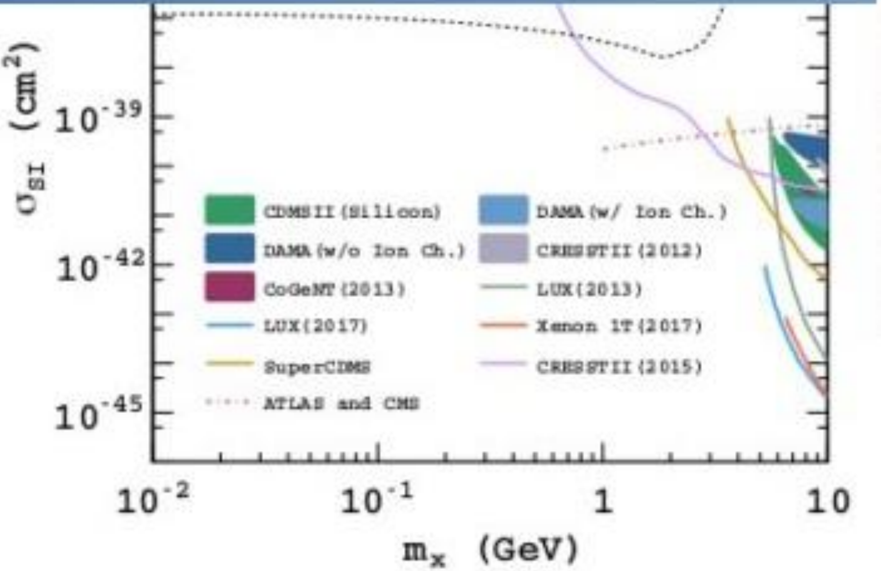
Process	$L_{int}(ab^{-1})$	ϵ	$N(\Upsilon(1S))$	$N_{\Upsilon(1S)\to\nu\bar{\nu}}$	N_{NP}
$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$	0.2, $\Upsilon(2S)$	0.1-0.2	2.3×10^8	230-460	6900-13800
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$	0.2, $\Upsilon(3S)$	0.1-0.2	3.2×10^7	32-64	945-1890
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$	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} @Y(3S)

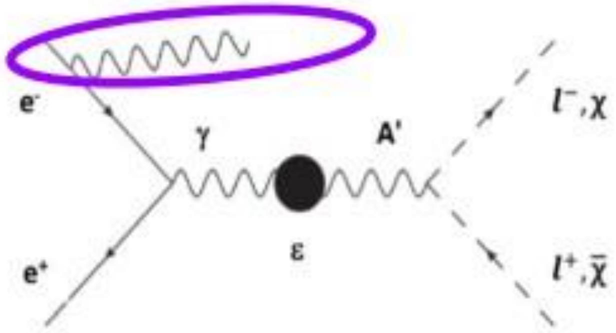




- Statistics
- Better background rejection by exploiting ***MVA method for peaking background-signal separation***

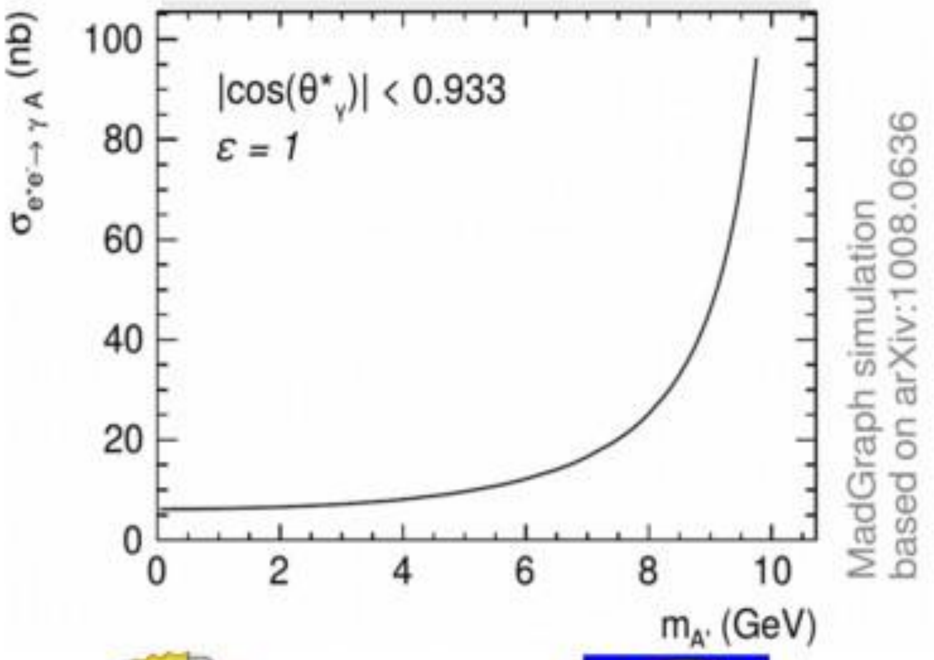
…and in the continuum: invisible dark photon

- 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 $e^+e^- \to \gamma\, A'$.



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

Batell et al. (2009), arXiv:0903.0363

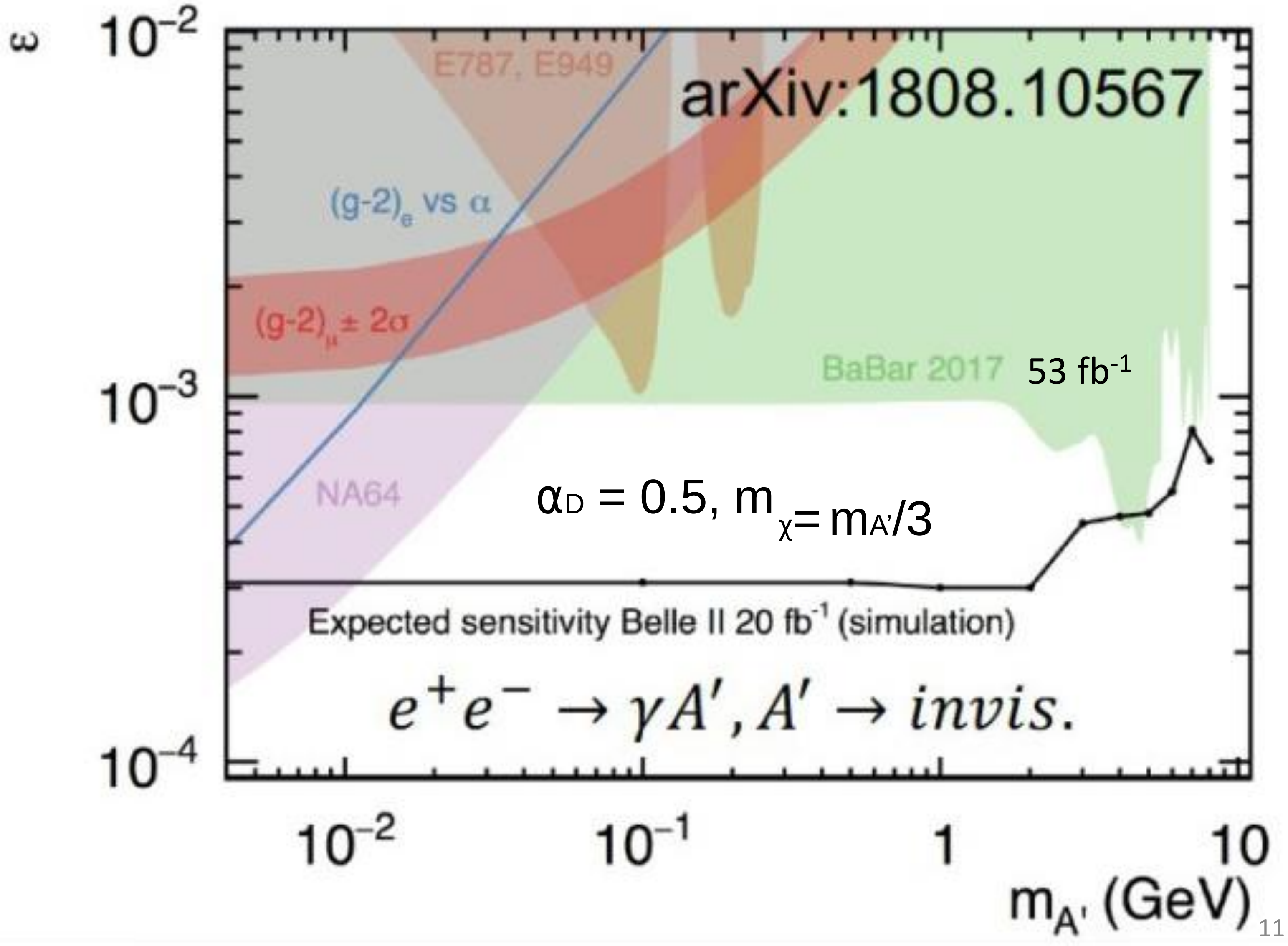


- If $m_\chi < 1/2\, m_{A'}$ → A' decays into DM particle, $e^+e^- \to \gamma + A'$, $A' \to \chi\chi$
- *ANALYSIS STRATEGY:*
  - Nothing in the event but a single high energetic **ISR photon**
  - Look for a bump in the recoil mass spectrum $\mathbf{M^2_{\chi} = s - 2E^*_\gamma\sqrt{s}}$
  - Background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

53 fb^{-1} **~10 fb^{-1} data needed!**

Invisible 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



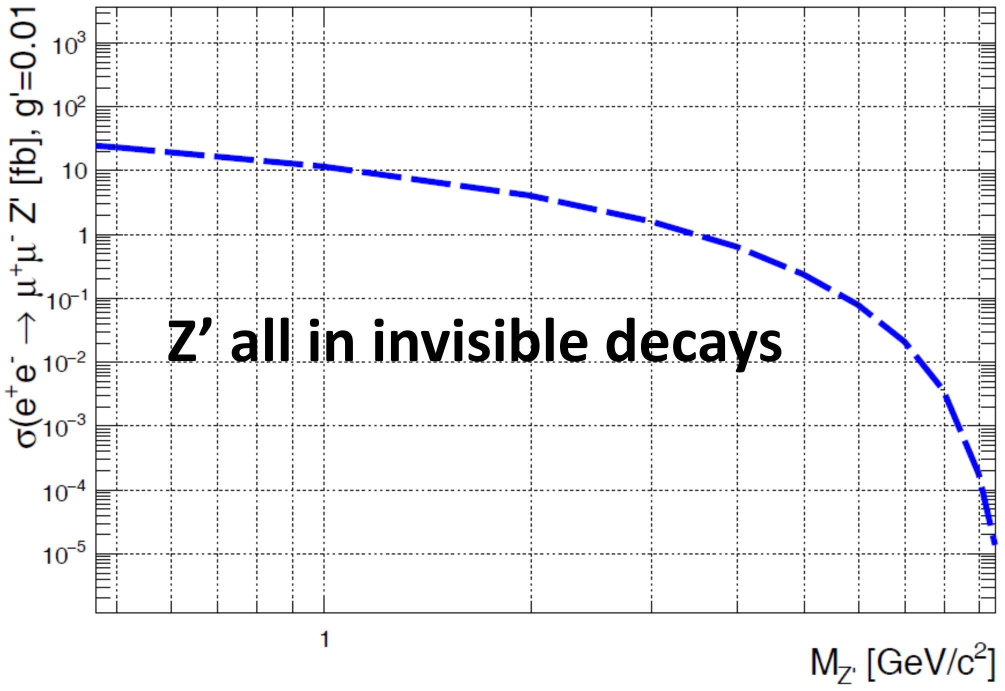
Z': invisible decay 1

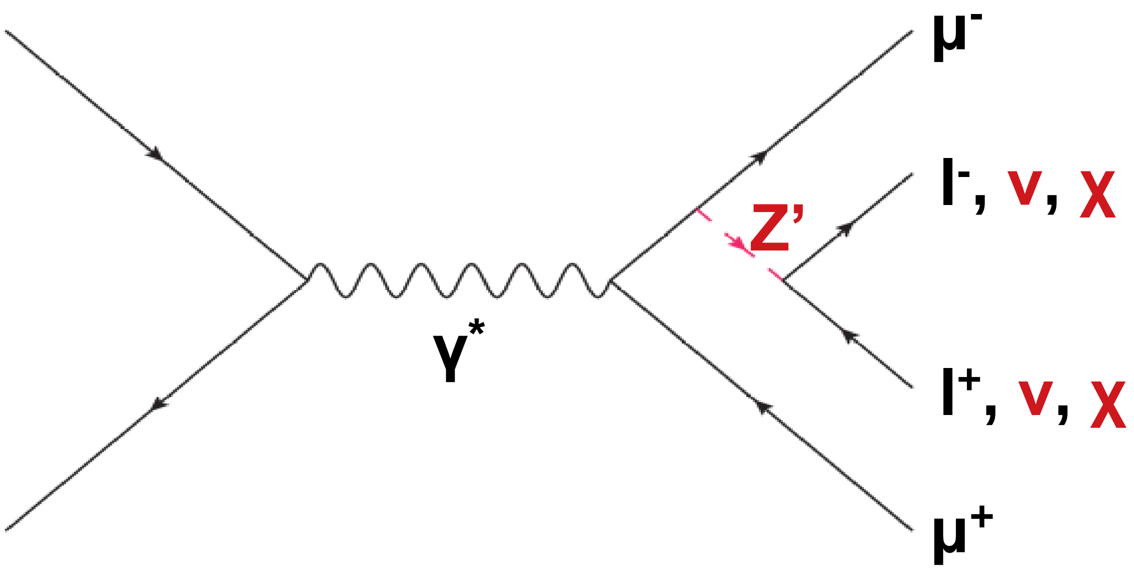
It's possible to consider a gauge boson Z' that couples only to **2nd and 3rd** leptonic generation (**$L_\mu - L_\tau$ model**)

$$\mathcal{L} = -g'\bar{\mu}\gamma^\mu Z'_\mu \mu + g'\bar{\tau}\gamma^\mu Z'_\mu \tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\tau,\mathrm{L}}$$

Shuve et al. (2014), *arXiv:1403.2727*

Altmannshofer et al. (2016) *arXiv* 1609.04026





Branching ratios:

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

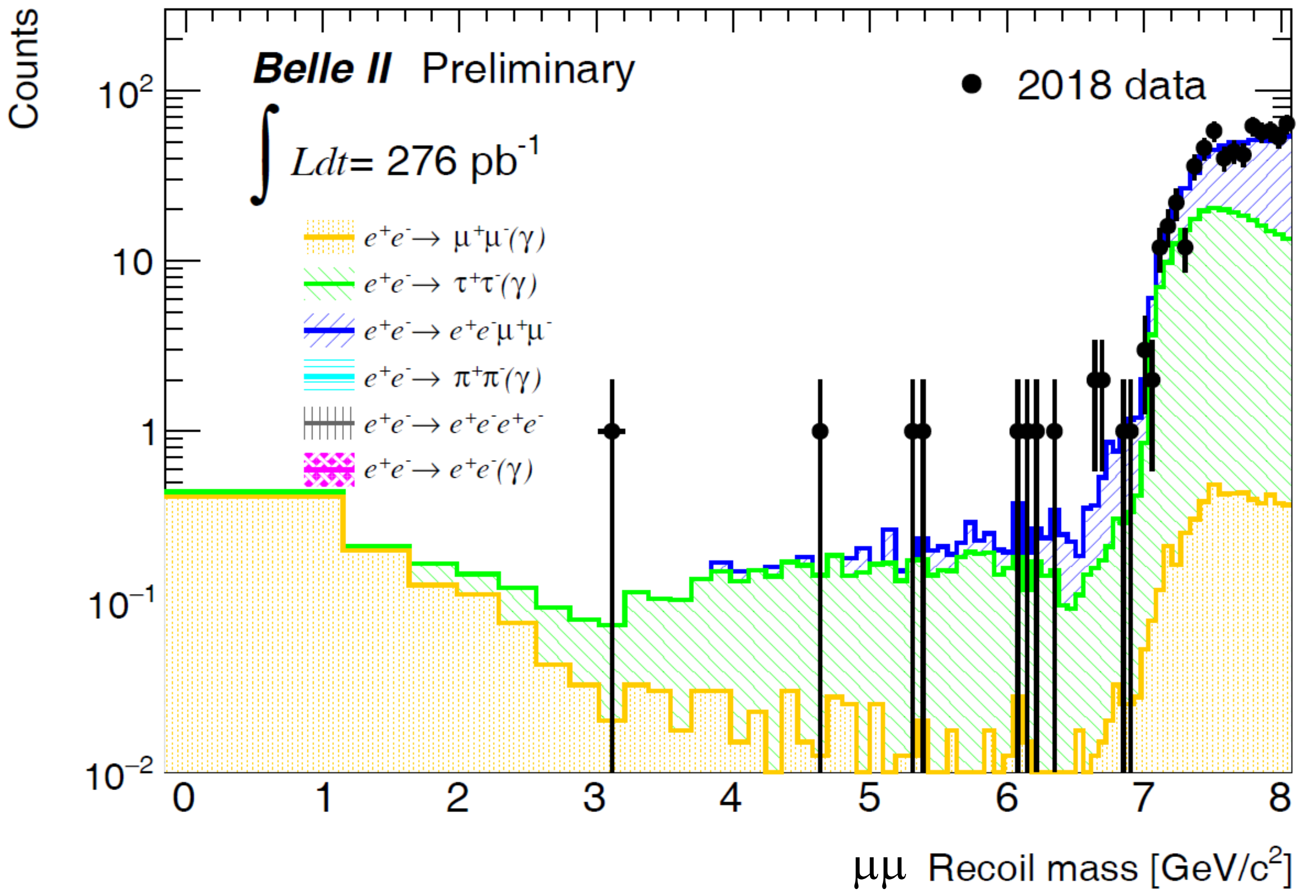
$2M_\mu < M_{Z'} < 2M_\tau \to \Gamma(Z' \to \text{inv.}) \sim 1/2$

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

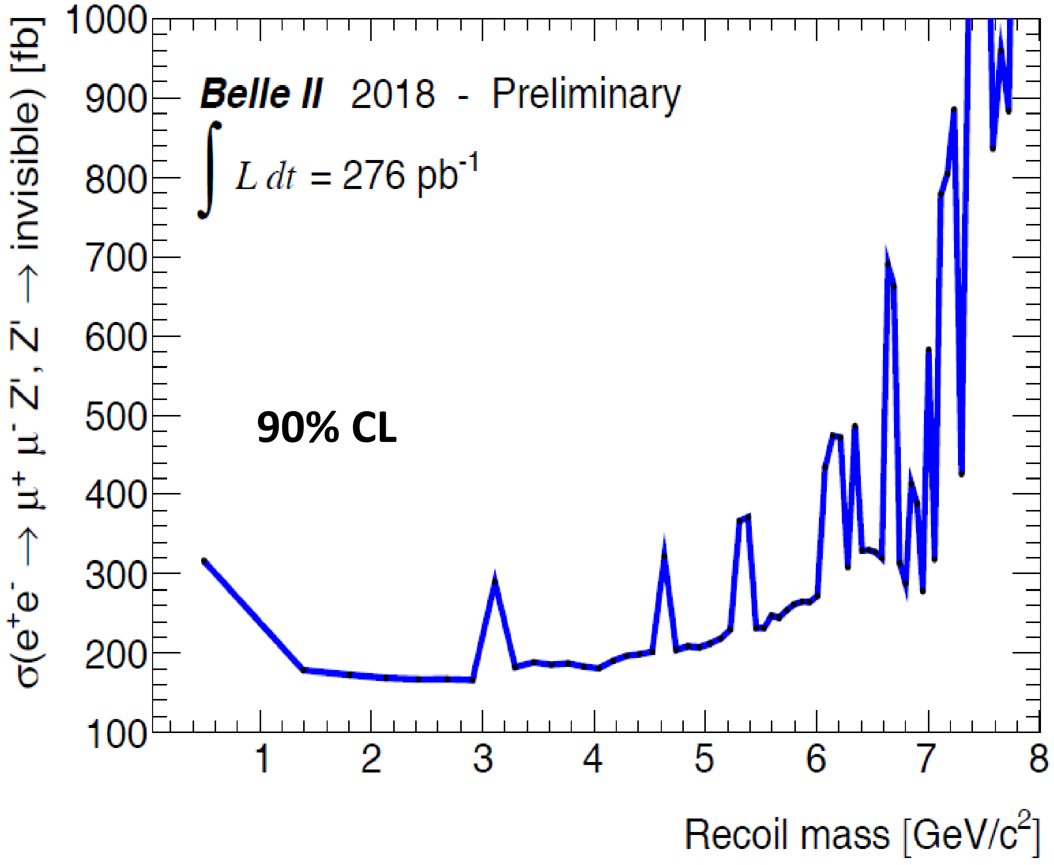
Could help in explaining the b anomaly

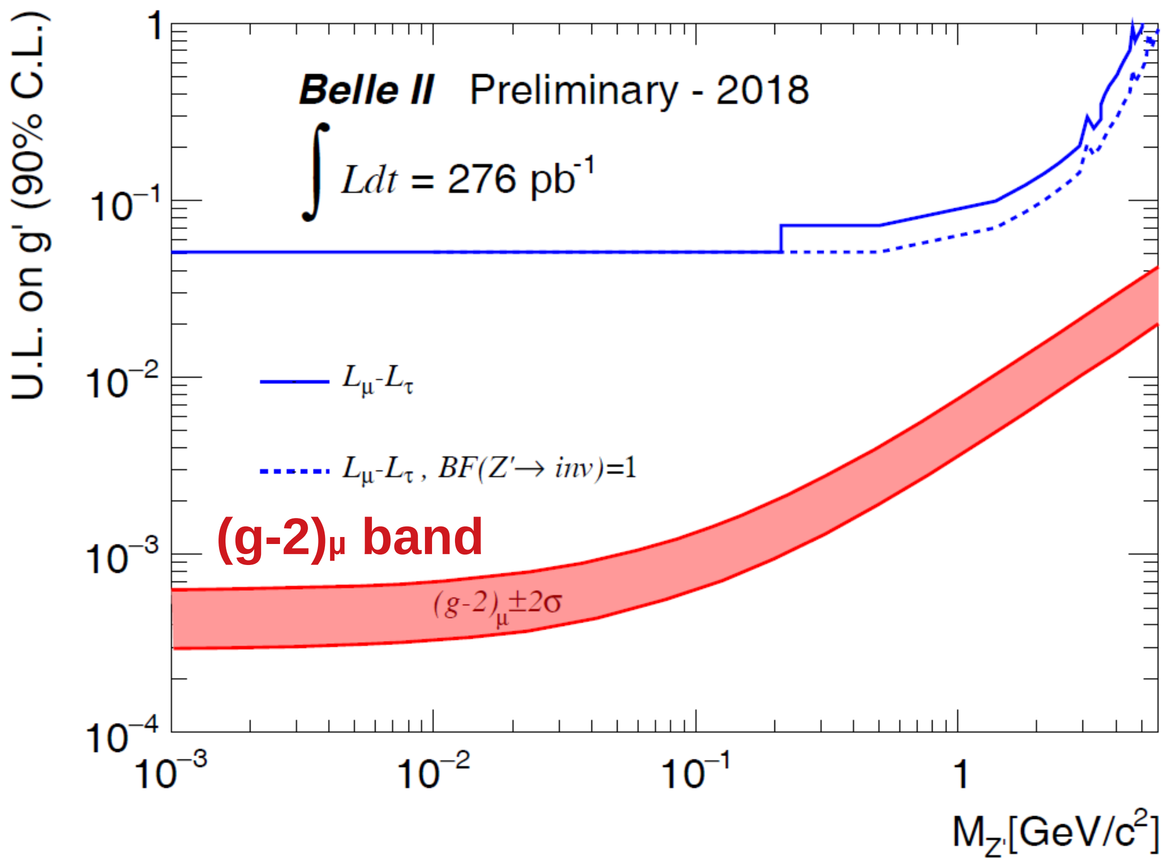
Z' : invisible decay results 1

Invisible decay: reconstruct the recoil mass
w.r.t. the two opposite-charged muons
and look for a peak in the mass spectrum
Additional request:
~ nothing in the rest of the event



Z' : invisible decay results 2





LFV Z’ in invisible 1

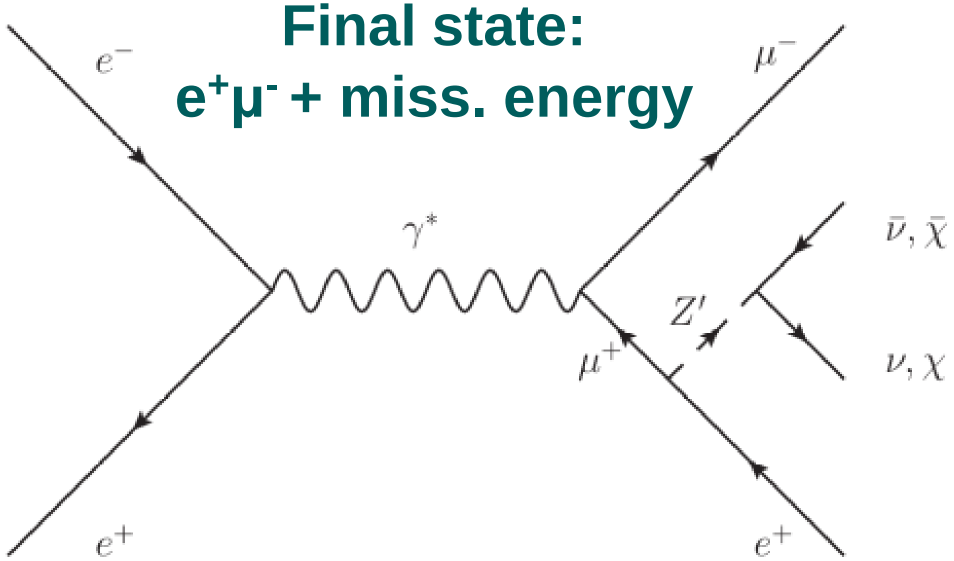
We are also considering a different model, in which a Z’ boson couples to all leptons and we allow for **Lepton Flavour Violation**

See I. Galon et al.: *arXiv:1610.08060*, *arXiv:1701.08767*

Complementarity with searches for:
- low mass Z’
- charged LFV

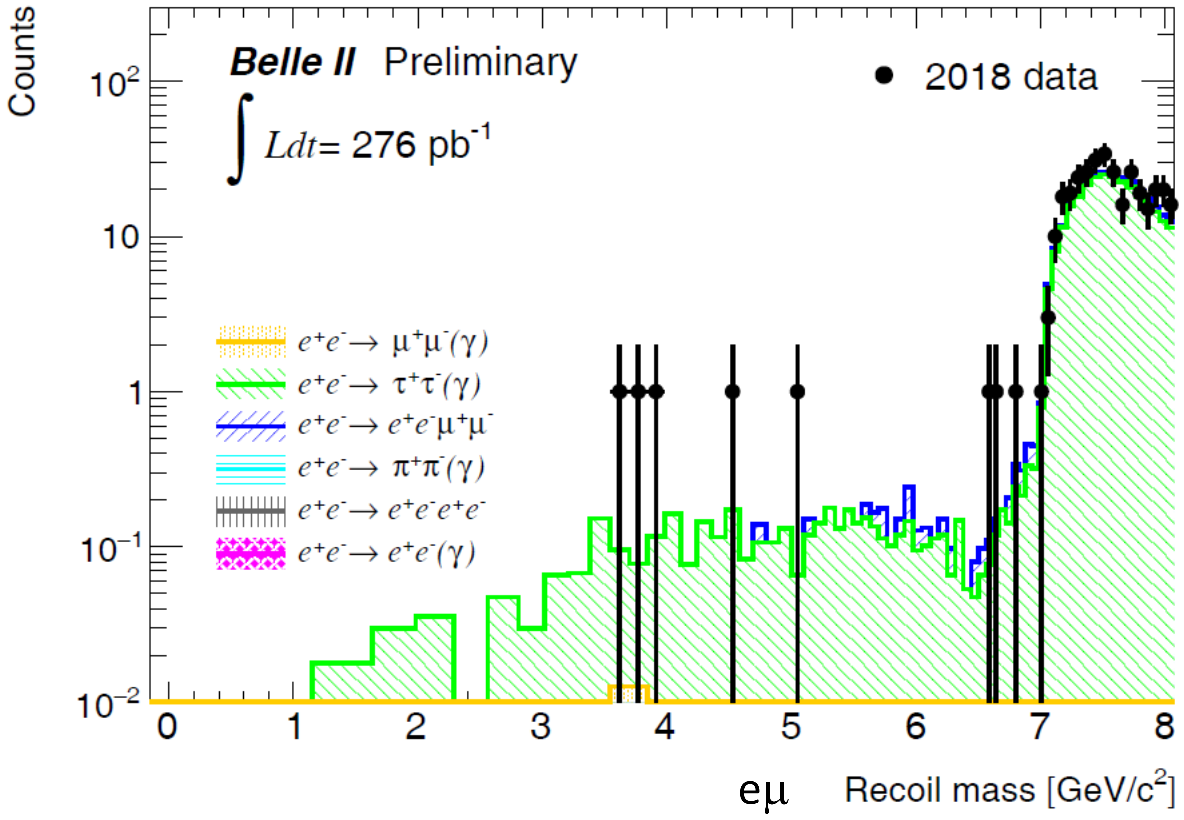
Low background from SM processes!

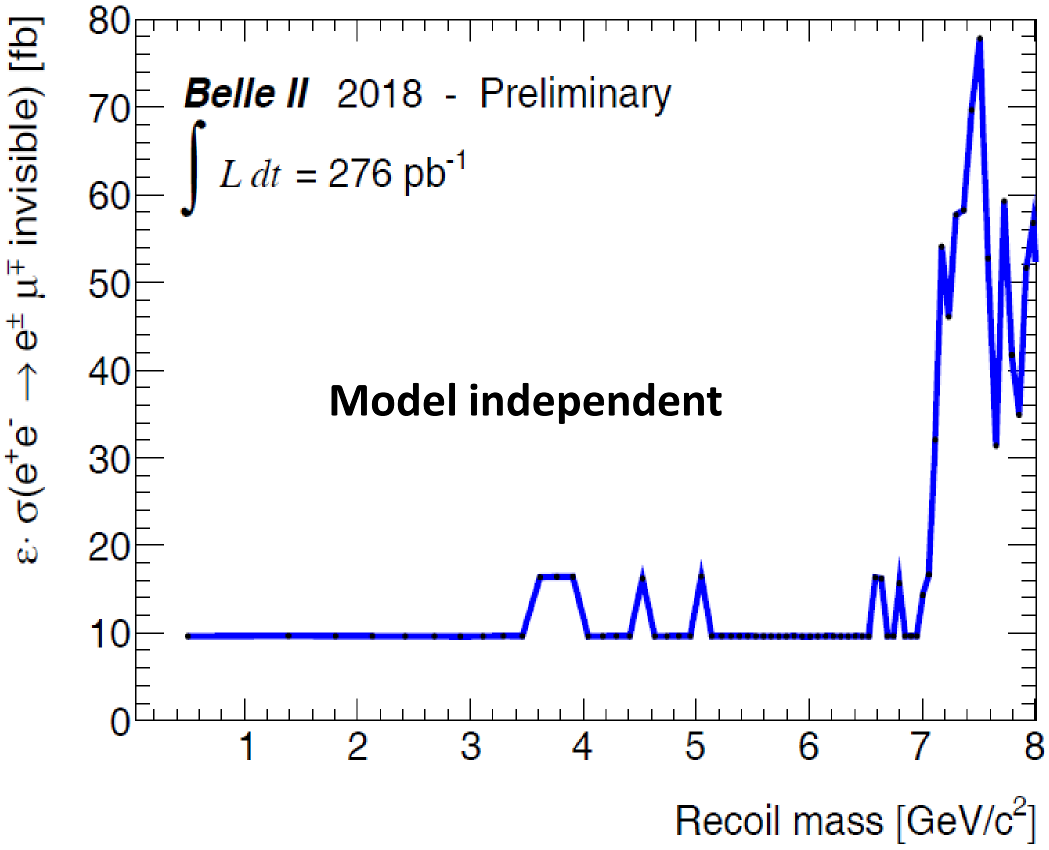
Final state:
$e^+\mu^-$ + miss. energy



Final states:
$e^+e^+\mu^-\mu^-$; $e^+e^-\mu^+\mu^-$

Dark Sector and LFV 2





Axion-Like Particles

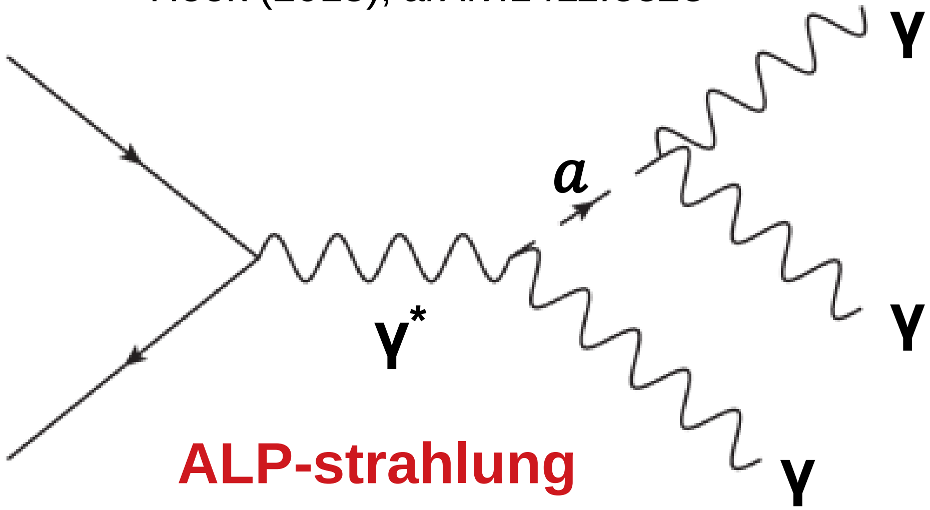
Axion-Like Particles (ALPs) are pseudo-scalars and couple to bosons.
Unlike QCD Axions, ALPs have no relation between mass and coupling.

I will focus on the **coupling to photons**:

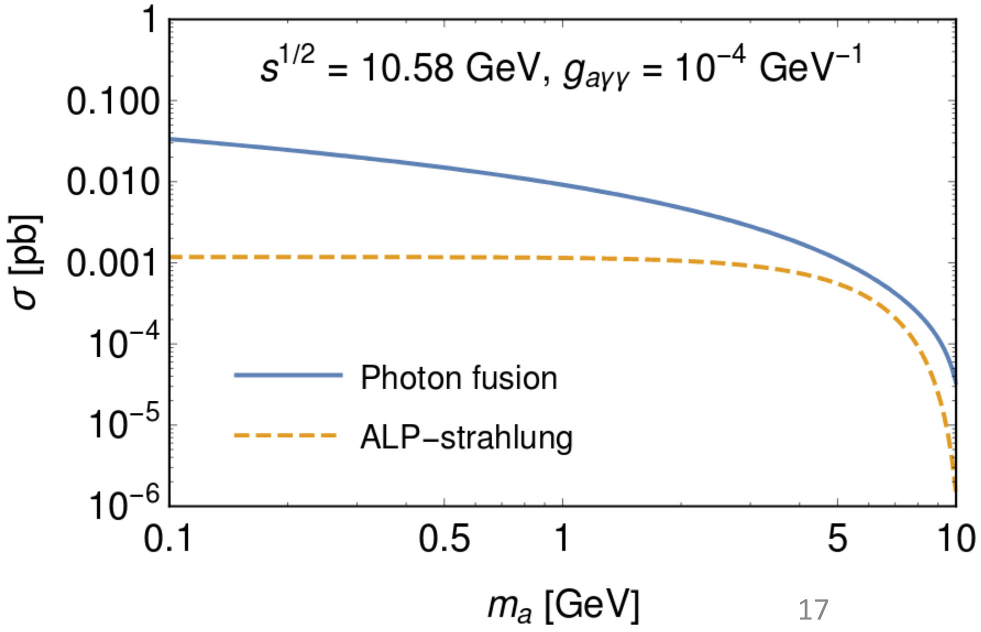
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad \tau_a \sim 1/g_{a\gamma\gamma}^2 m_a^3$$

Belle II will study the **ALP-strahlung** case (low sensitivity to photon fusion production)

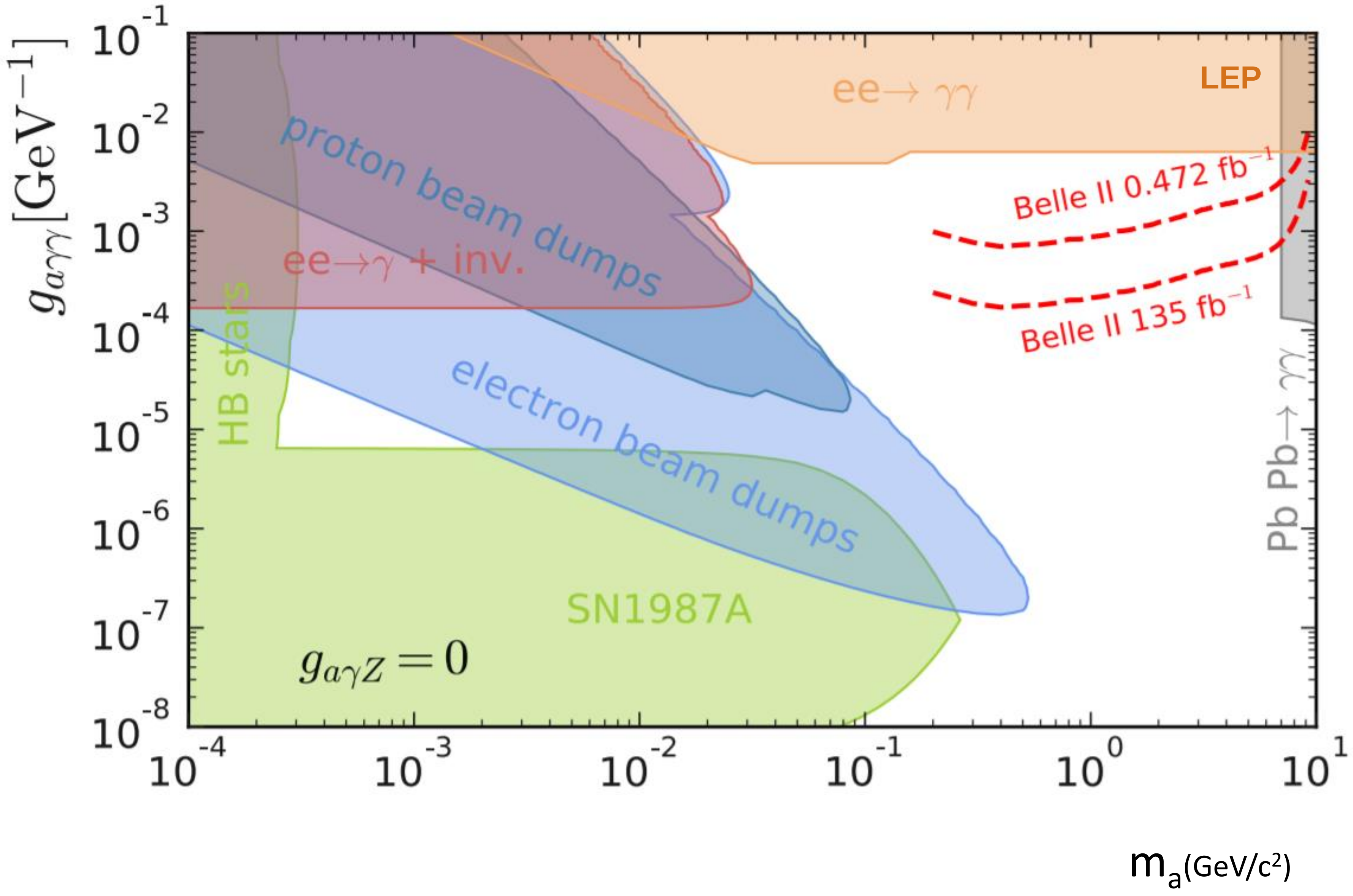
Hook (2015), *arXiv:1411.3325*



ALP-strahlung



Axion-Like Particles (sensitivity)



We expect to improve the current limits for **m_a > 100 MeV**

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*** →currently upper limits only

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

Exploiting the same statistics we could set limits on Z' into invisible and $\mu^+ \mu^-$ or $\mu^+ e^-$ in the final state.

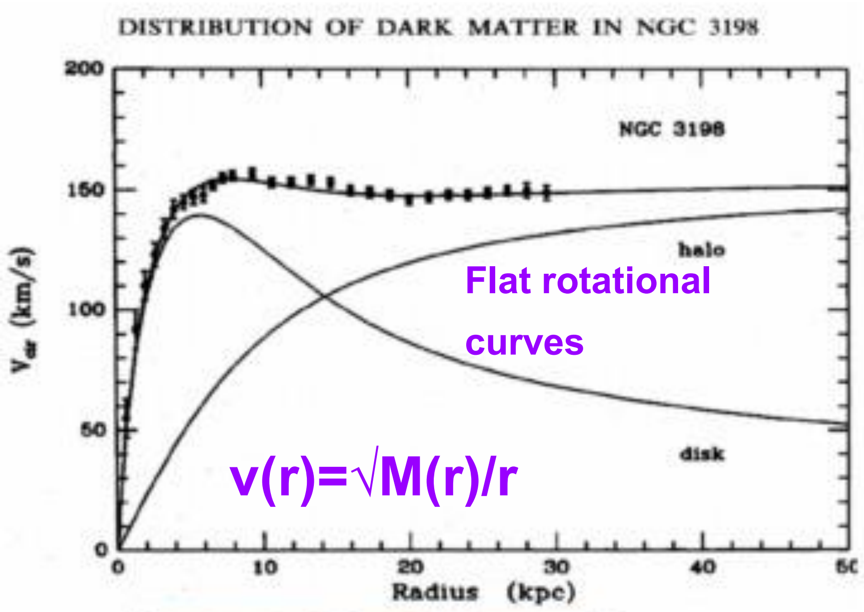
→ ***Interplay with theory needed to connect direct and indirect searches and effectively constrain dark sector models!***

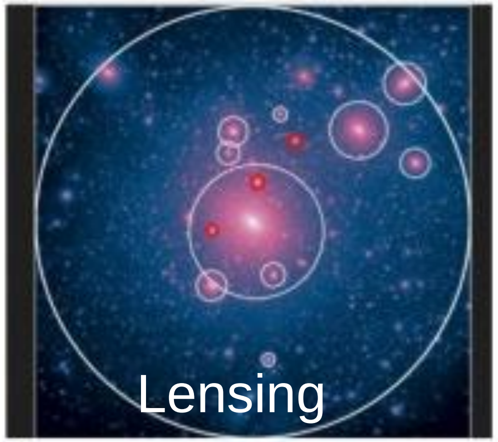
A rich dark sector program is under investigation @Belle II, both at bottomonium resonances and in continuum Dark Photon, Invisible Z', ALPs and much more. (The Belle II Physics Book, arXiv:1808.10567). New results are coming out right now, allowing us to constrain dark sector models.

BACK up slides

Dark Sector: Introduction

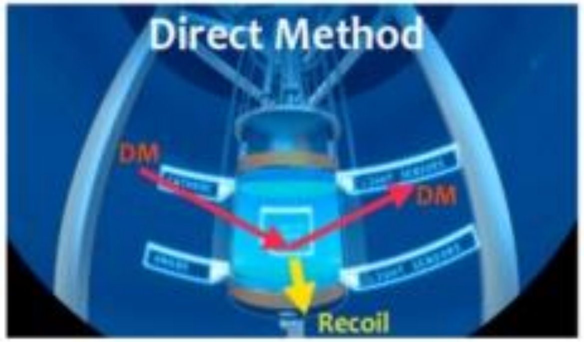
- Many astrophysical observations provide evidence for the existence of a kind of matter that almost does not interact with the Standard Model (SM) particles (*mostly* gravitational interaction) → ***Dark Matter (DM)***

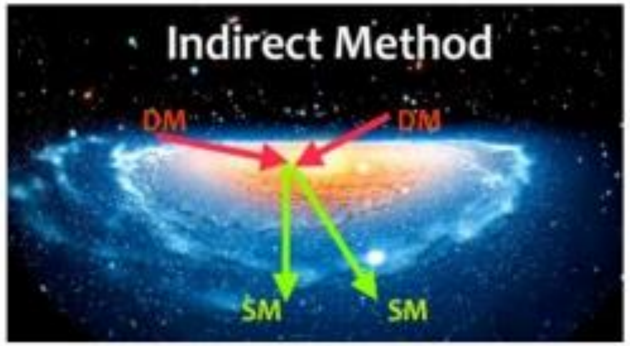




How to search it?

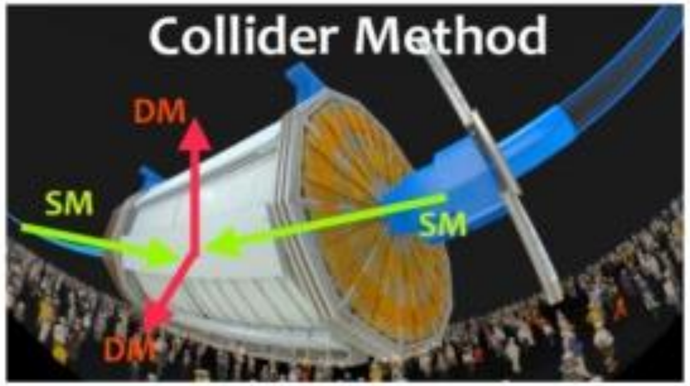
1) Detect the energy of *nuclear recoil*





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***



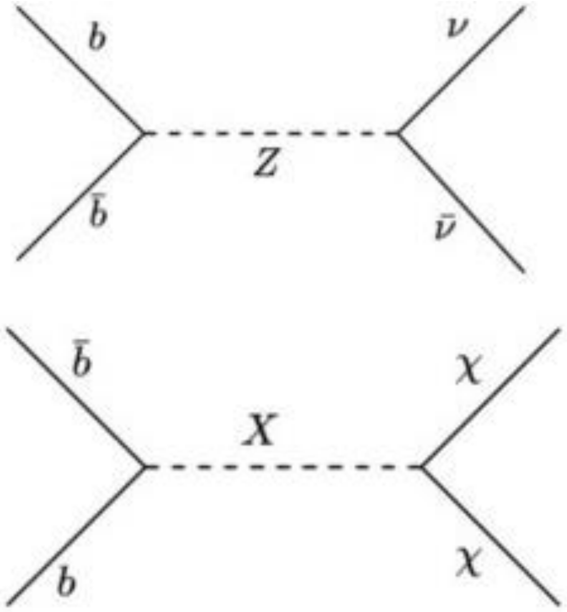
→ In this presentation I will focus on the search at electron-positron colliders

Y(1S) invisible decays

- BR(Y(1S)→ inv) is well calculable in SM
- DM candidates could enhance the branching ratio, if Y(1S)→χχ kinematics allows
- New mediators (Z', A_0) may also contribute
- In absence of NP observation, ***Belle II*** can measure the BR (Y(1S)→νν)!

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

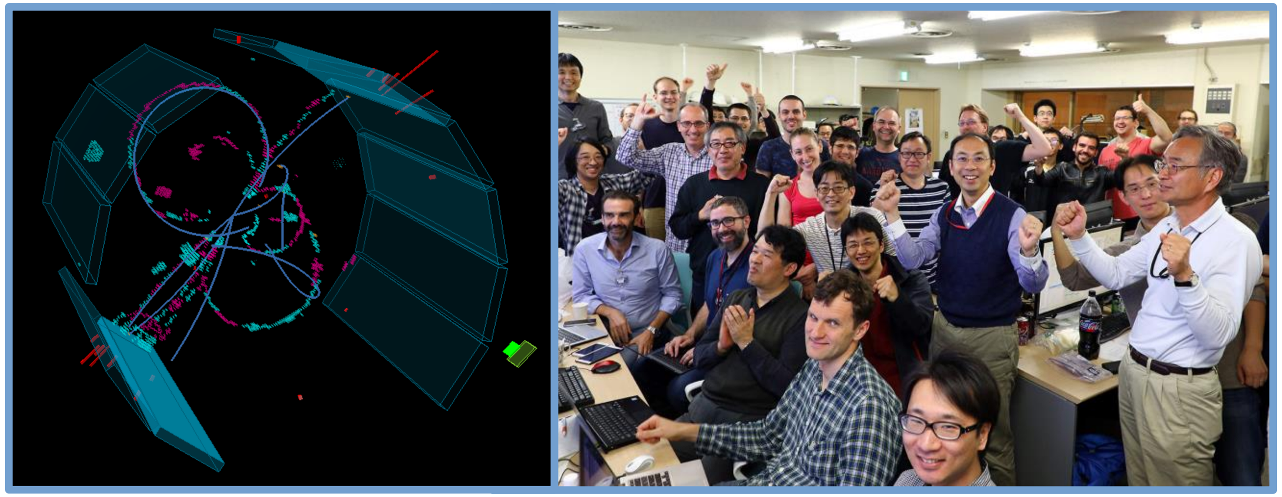
$$BR(Y(1S)\to\nu\bar{\nu})\sim9.9\times10^{-6}$$



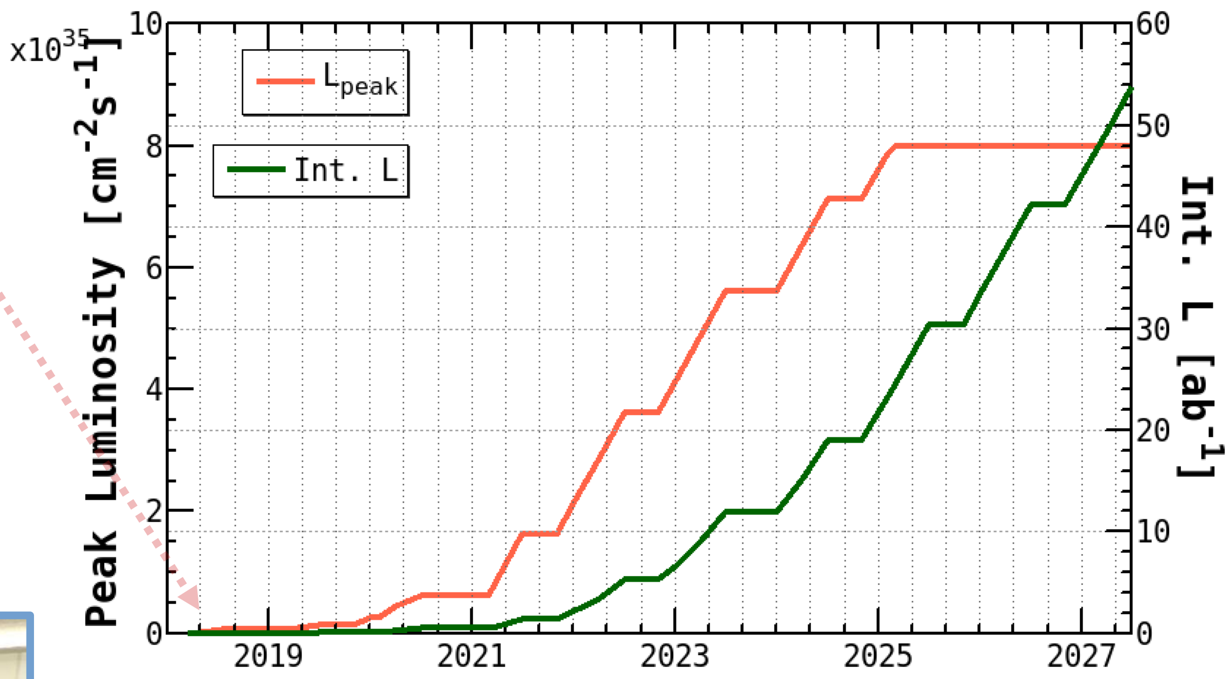
First period of data taking: Phase 2

During the Phase 2 run (**2018**)
Belle II had partial **VXD detector**

Main goals:
- accelerator commissioning
- measure beam background
- detector commissioning
- **dark sector physics**



First collisions: 26th April 2018



Phase 2: **0.5 fb^{-1}**

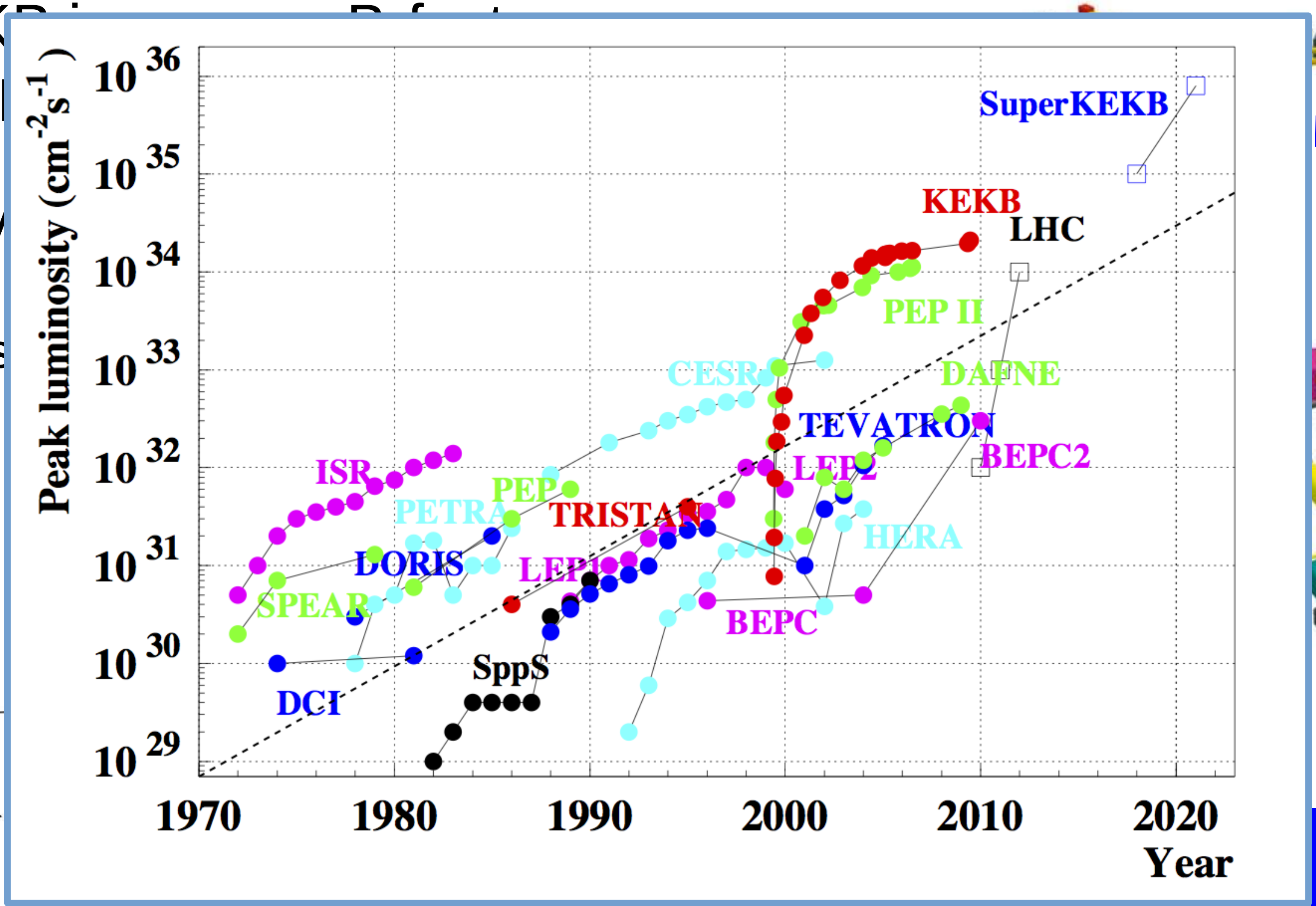
Phase 3: **50 ab^{-1}**

Instant luminosity achieved: 5.5·10^{33} cm^{-2} s^{-1}

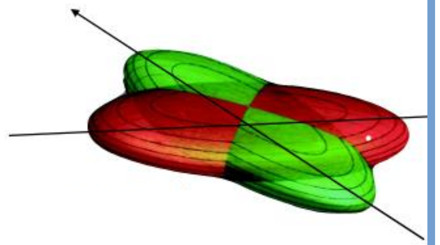
SuperKEKB: an Intensity Frontier machine

SuperKEK... located at ...

It's an asy... operating... (Y(4S), but poss...

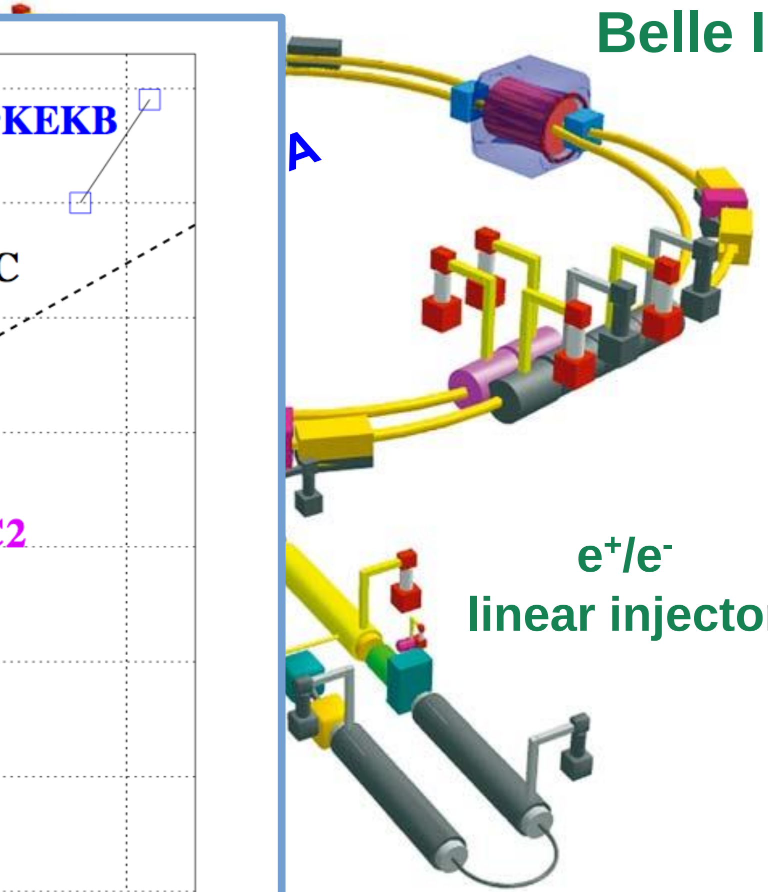


KEKB



I (A): ~ 1.6/1.2

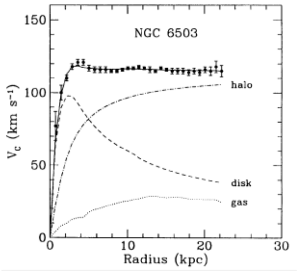
β^*_y (mm): ~ 5.9/5.9



β^*_y (mm): ~ 0.27/0.3

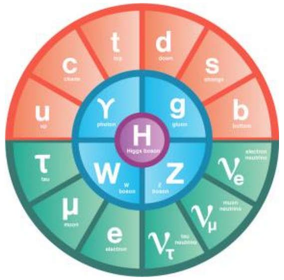
luminosity:
$8 \cdot 10^{35}$ cm^{-2} s^{-1}

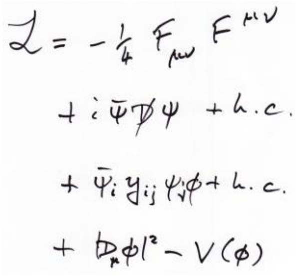
Dark Matter coupling to SM



Dark Matter

X

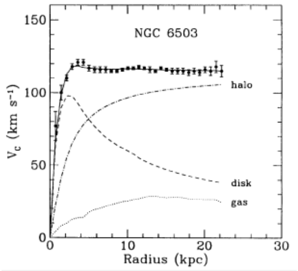




Standard Model

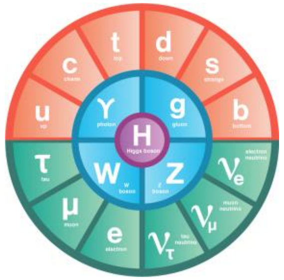
Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

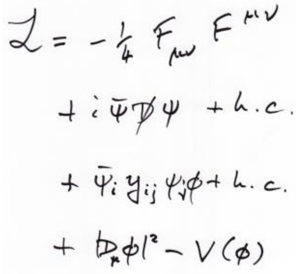
Dark Matter coupling to SM

Dark Matter

X





Standard Model

Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

Vector portal → Dark Photon

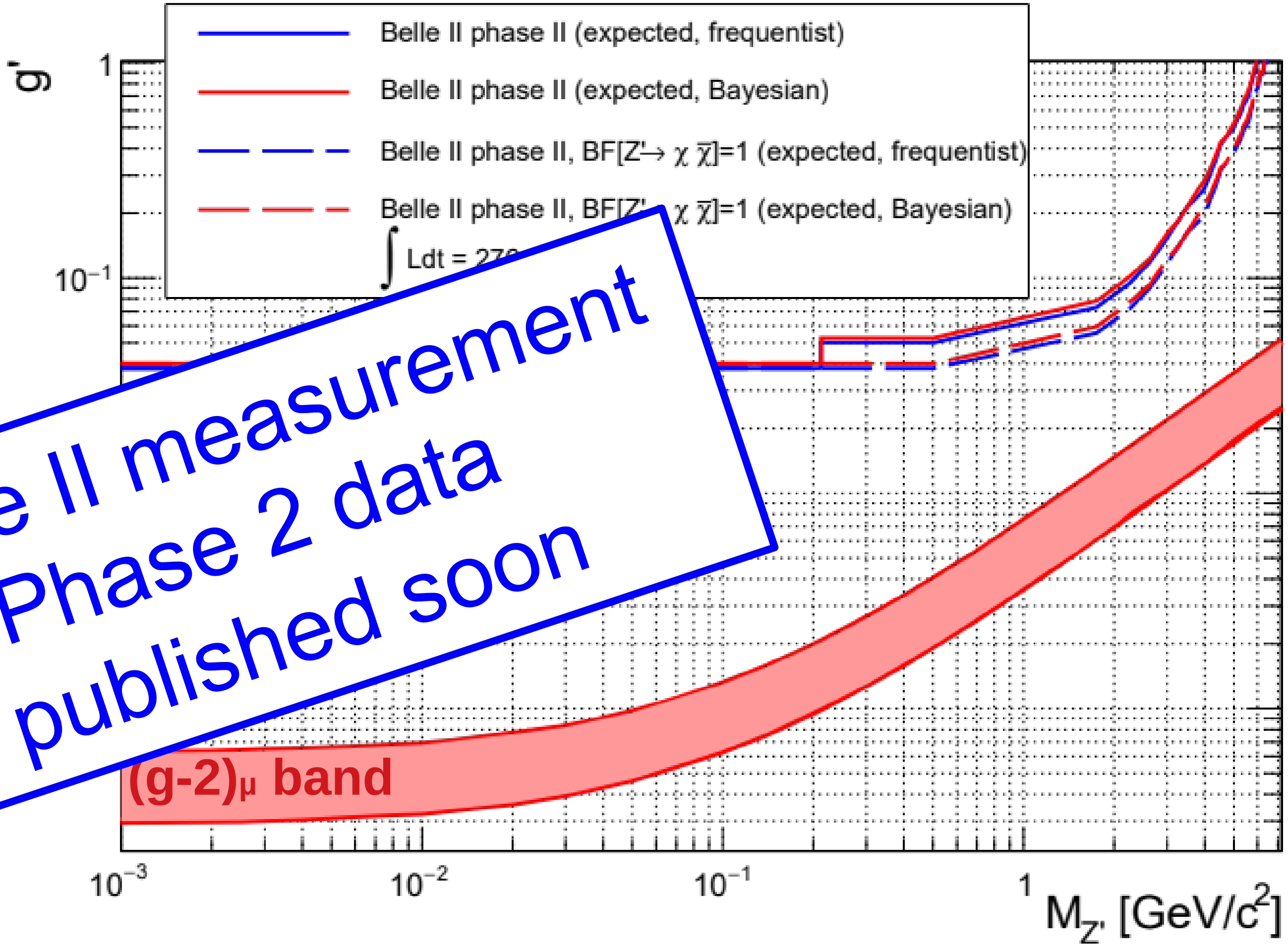
Muonic Dark Force: invisible decay

Invisible decay: reconstruct the recoil mass
w.r.t. the two opposite-charged muons
and look for a peak in the mass spectrum
Additional request:
~ nothing in the rest of the event

Considered several **mass hypothesis for Z'** with full simulation and reconstruction

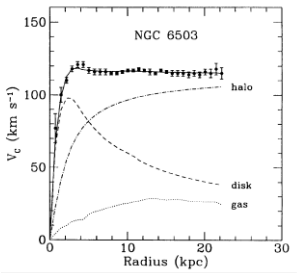
Consid…
mai…
e…
e^+…
$e^+ e^-$ –…

Goal: Belle II measurement with Phase 2 data to be published soon

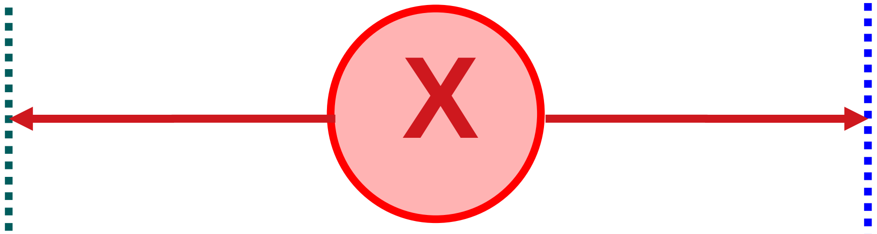


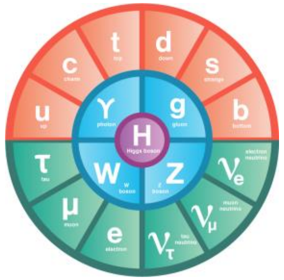
Trigger + tracking + PID + mass resolution systematics already included here (10%)
Possible additional systematics on background estimate not included (0-30%)

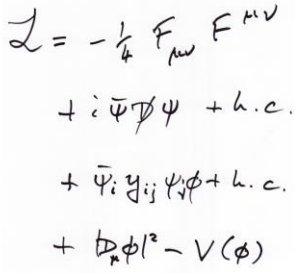
Dark Matter coupling to SM



Dark Matter





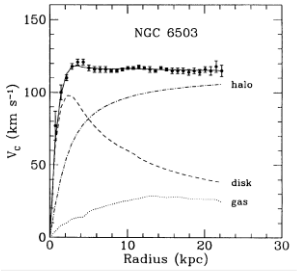


Standard Model

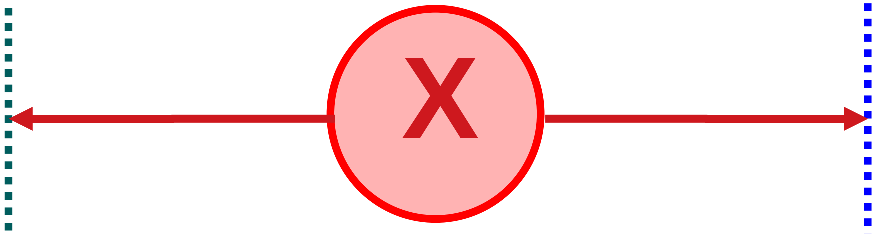
Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

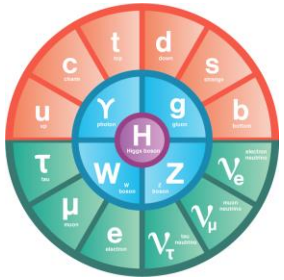
Vector portal → Dark Photon
Scalar portal → Dark Higgs/Scalars

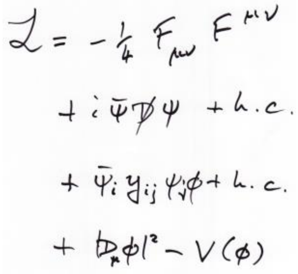
Dark Matter coupling to SM



Dark Matter







Standard Model

Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

Vector portal → Dark Photon
Scalar portal → Dark Higgs/Scalars
Pseudoscalar portal → Axion-Like Particles

B-Factories:the high intensity frontier

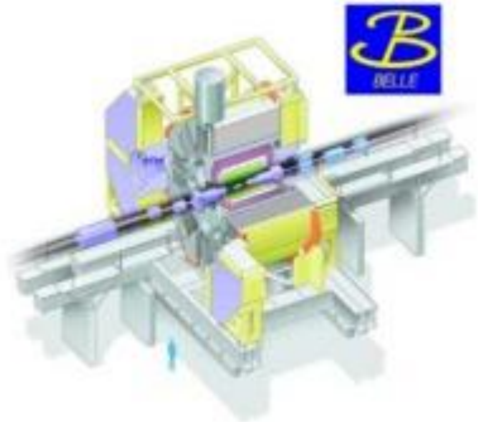
B-factories: dedicated experiments at *e^+e^- asymmetric-energy colliders* for the production of quantum coherent

$B\bar{B}$ pairs → **CPV studies**.

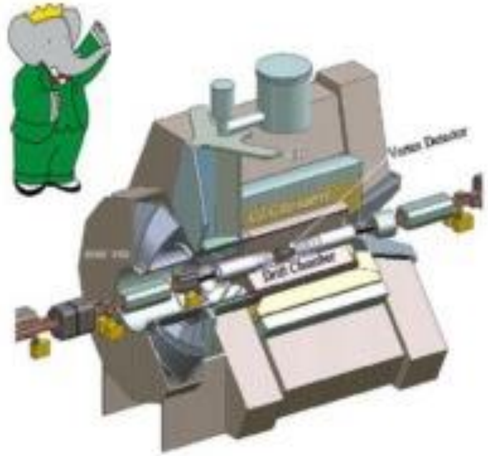
$e^+e^- \to Y(4S)$ [10.58 GeV] $\to B\bar{B}$

Y(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

$\Upsilon(1S) \rightarrow \gamma$ DMDM: Analysis Strategy

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

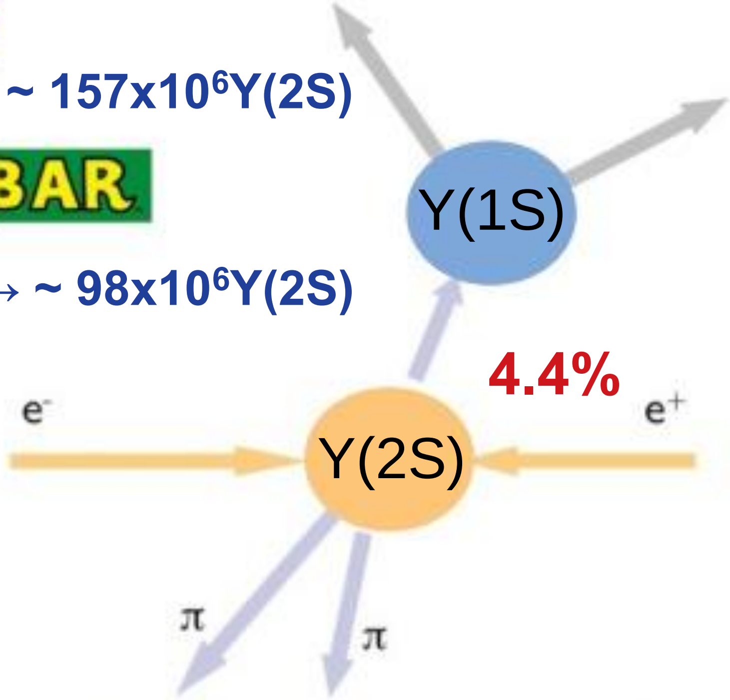
  → ***Experimental challenges:***

  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)



4.4%

- 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_γ)^2

  M_r Vs E^*_γ

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

Υ(1S)→γ DMDM: Background

Continuum

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

Suppression

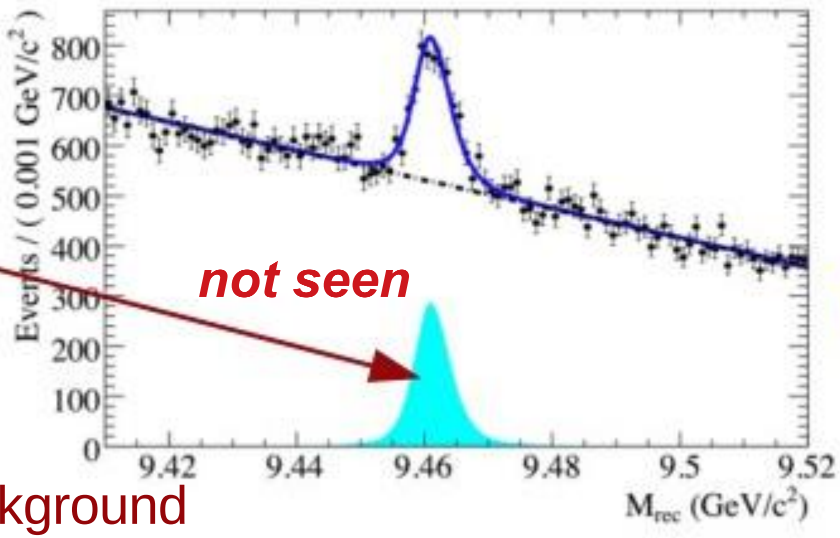
- Multivariate method to reject ***continuum*** using dipion system kinematics variables
- Angular isolation: minimum angle between photon direction and the charged tracks/dipion system
- Require clean 20° cone in the direction opposite to the primary photon

Peaking

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

→ Estimated from MC simulation, irreducible background

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



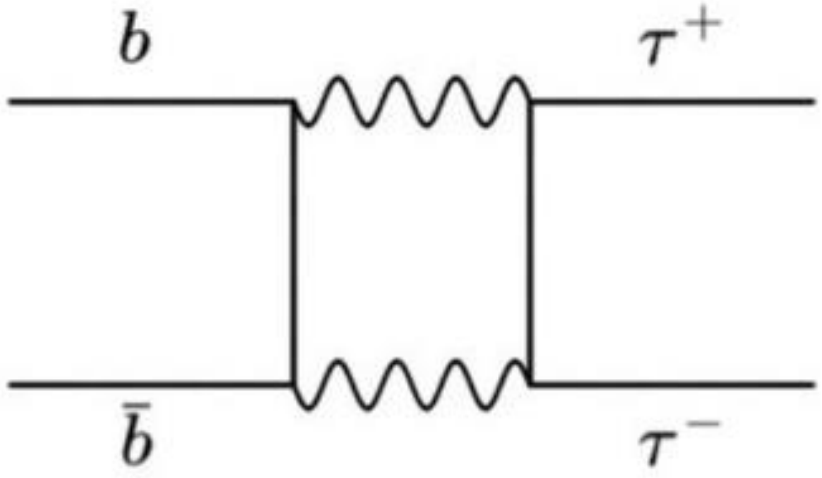
Selection optimization

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

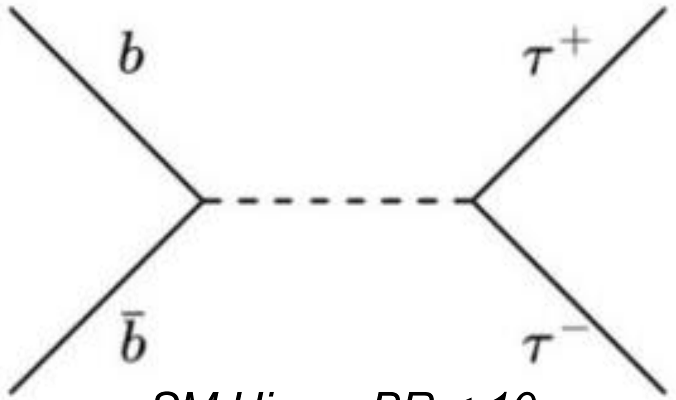
Lower trigger efficiency at high masses due to low energy photons

Other possibilities at Υ(3S)

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



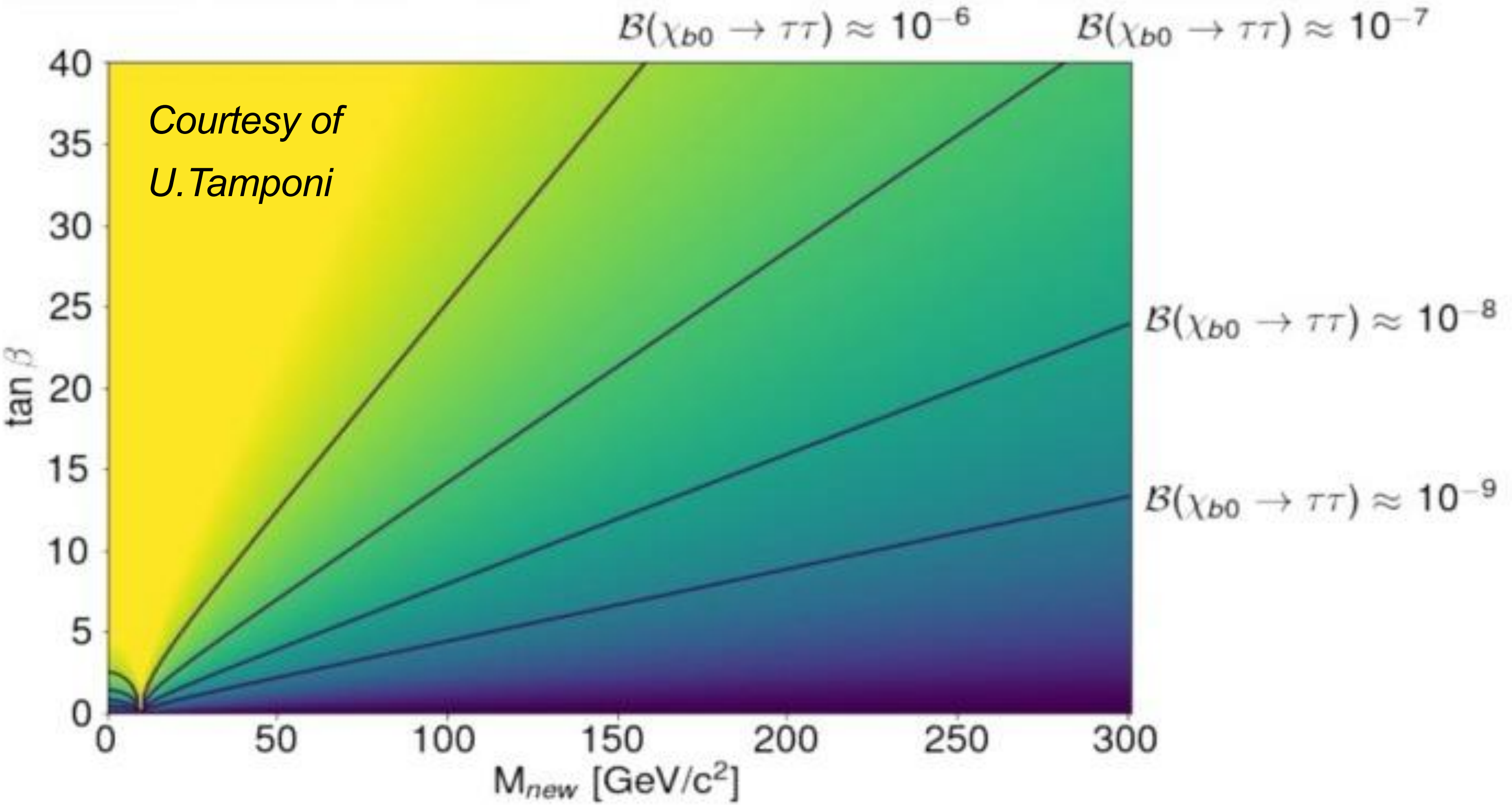
QED, BR < 6 x 10^{-9}



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*



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

* Phys. Rev. D 93, 055014

Belle II prospects(II)

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

$$BF[Y3S \rightarrow \gamma\chi_{b0}(nP)] \sim 5.9\ \%$$
$$\sigma[e^+e^- \rightarrow \gamma\chi_{b0}(nP)] \sim 0.2\ nb$$

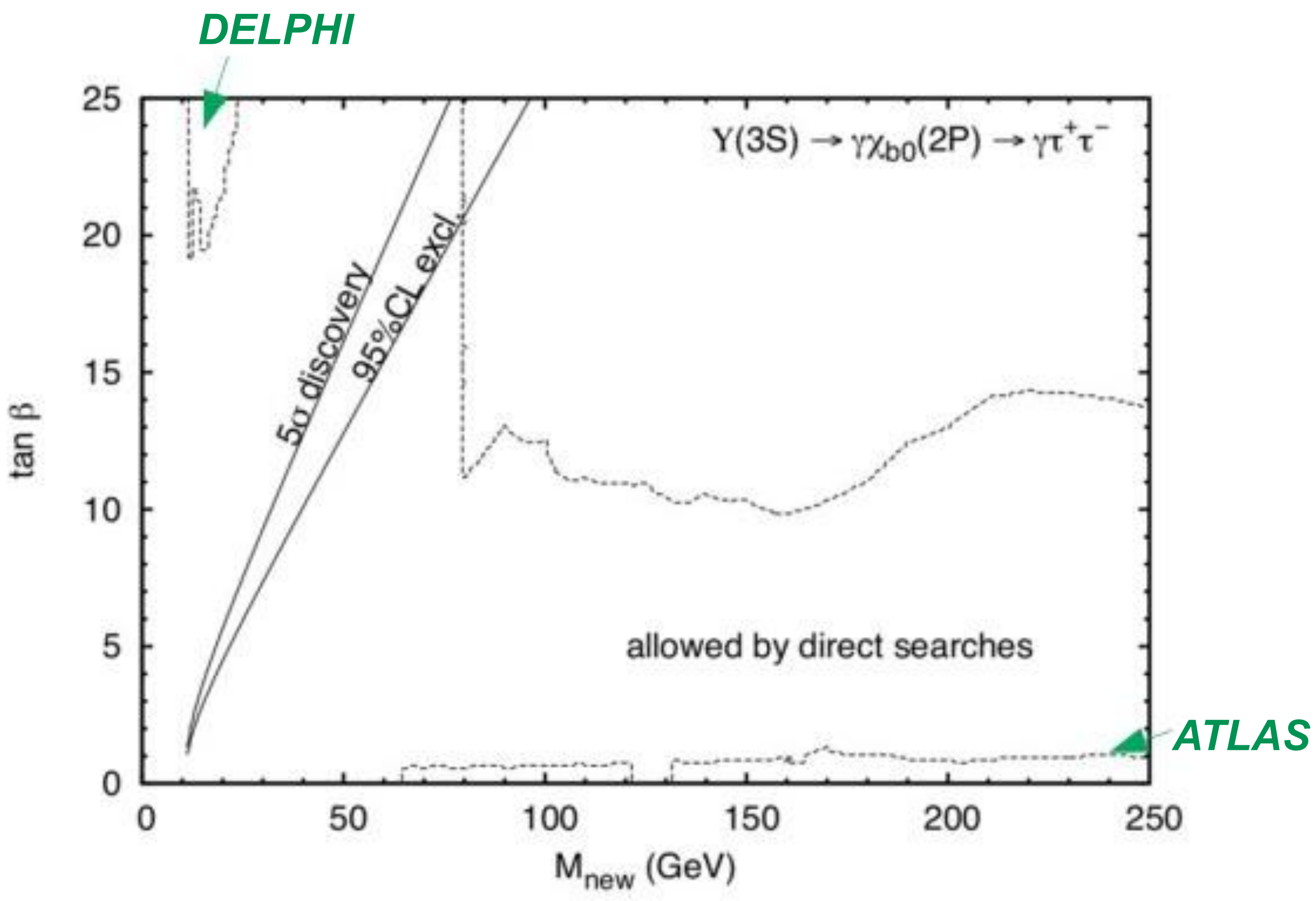


Fig. 212: 5σ discovery and 95% confidence level (CL) exclusion reach in the Type-II 2HDM from 250 fb^{-1} of data on the $\Upsilon(3S)$. The sensitivity is to the regions to the left of the solid

* *Phys. Rev. D 93, 055014*

Dark Sector and LFV

We are also consideri… …odel,
in which a Z' b… …ons
and w… …**ion**

…v.1701.08767

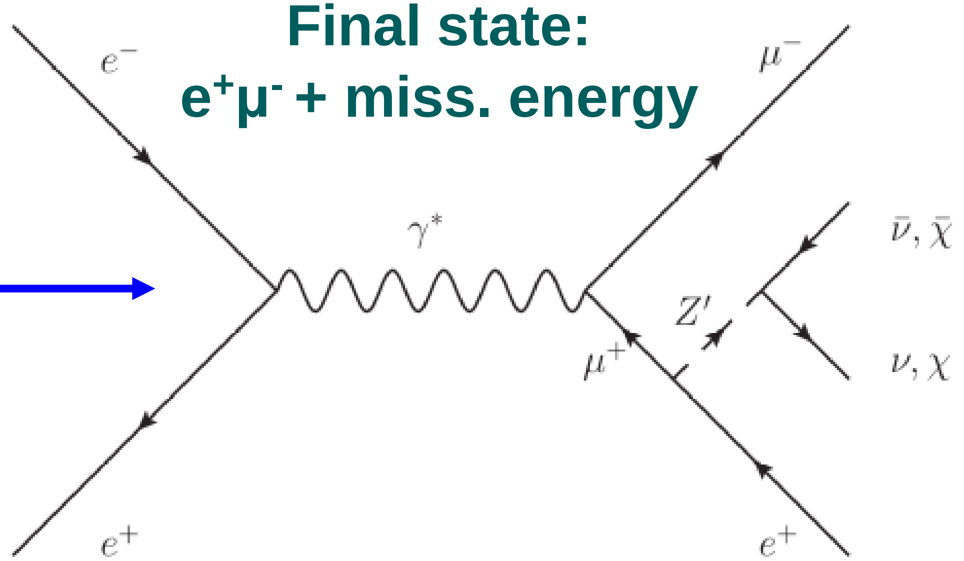
Goal: Belle II measurement with Phase 2 data to be published soon

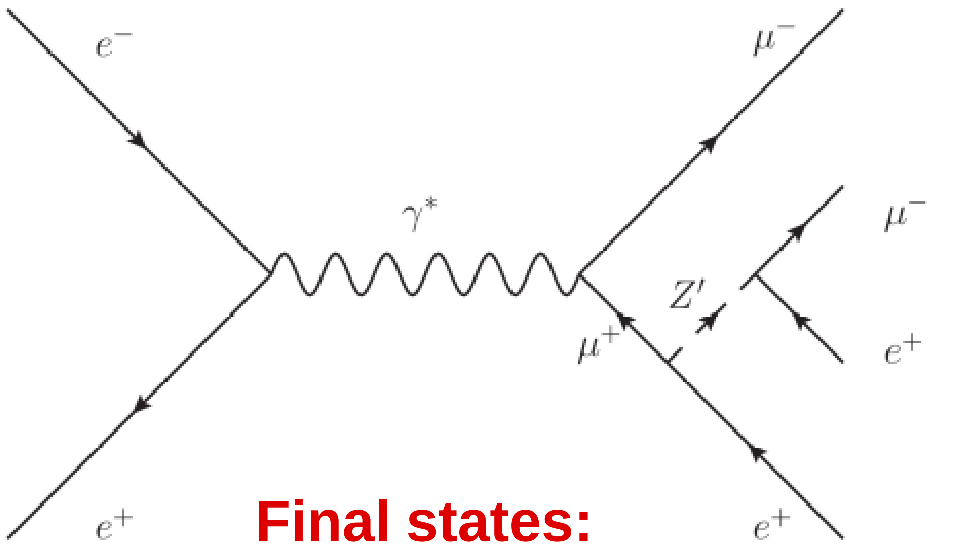
C… …nity with searches for:

- low mass Z'
- charged LFV

Low background from SM processes!

Final state:
$e^+\mu^-$ + miss. energy

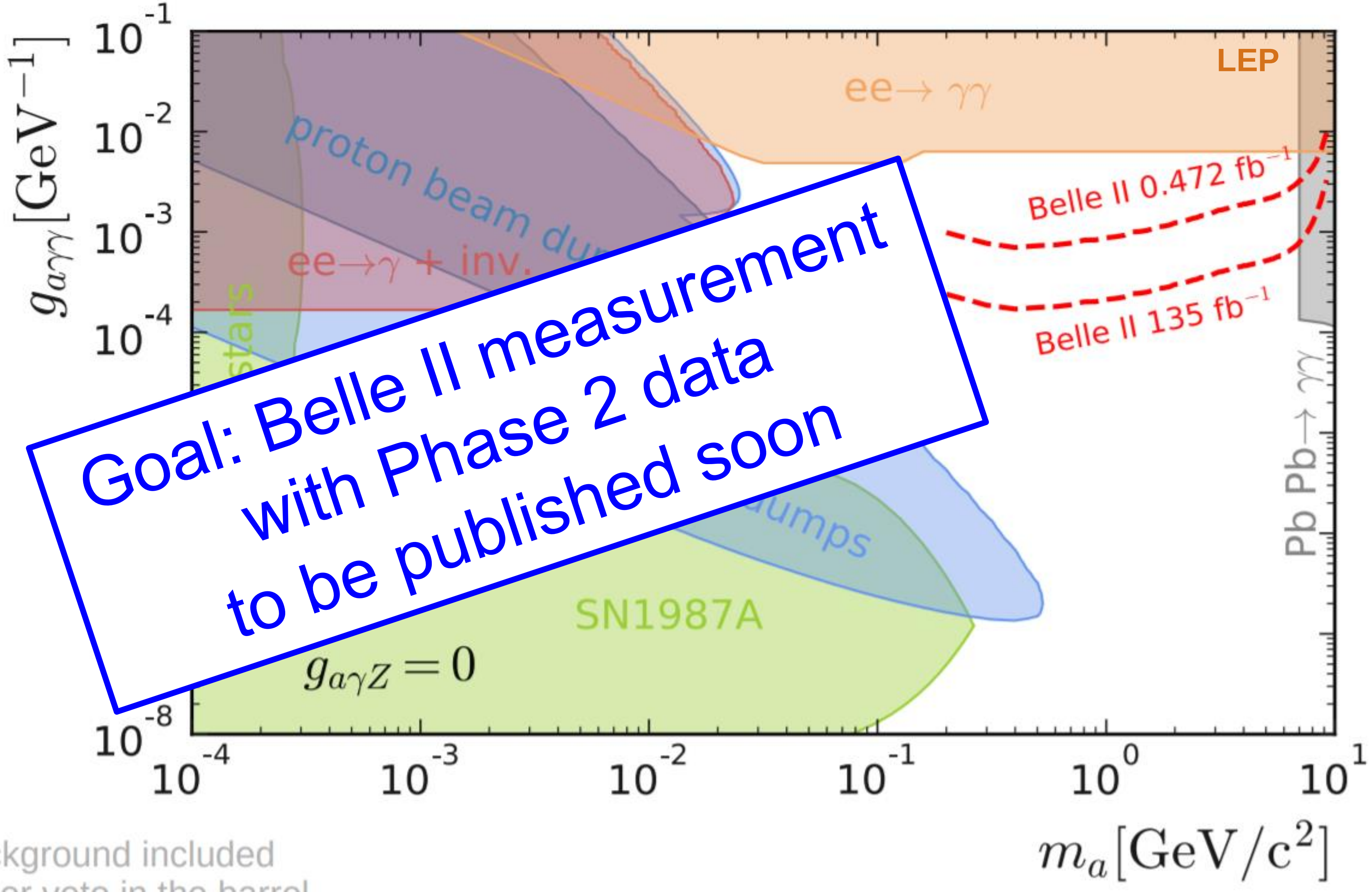




Final states:
$e^+e^+\mu^-\mu^-$; $e^+e^-\mu^+\mu^-$

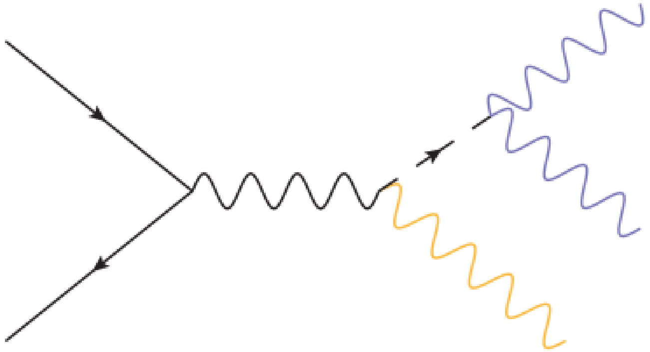
Axion-Like Particles (sensitivity)

We expect to improve the current limits for
m_a > 100 MeV

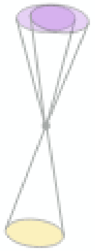


No systematics.
Only (dominant) ee→γγγ background included
135fb -1 assumes no γγ trigger veto in the barrel

Axion-Like Particles (signal)

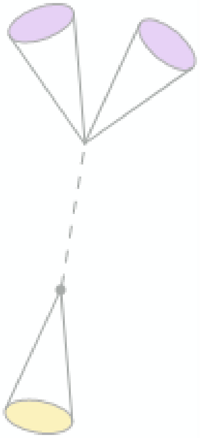


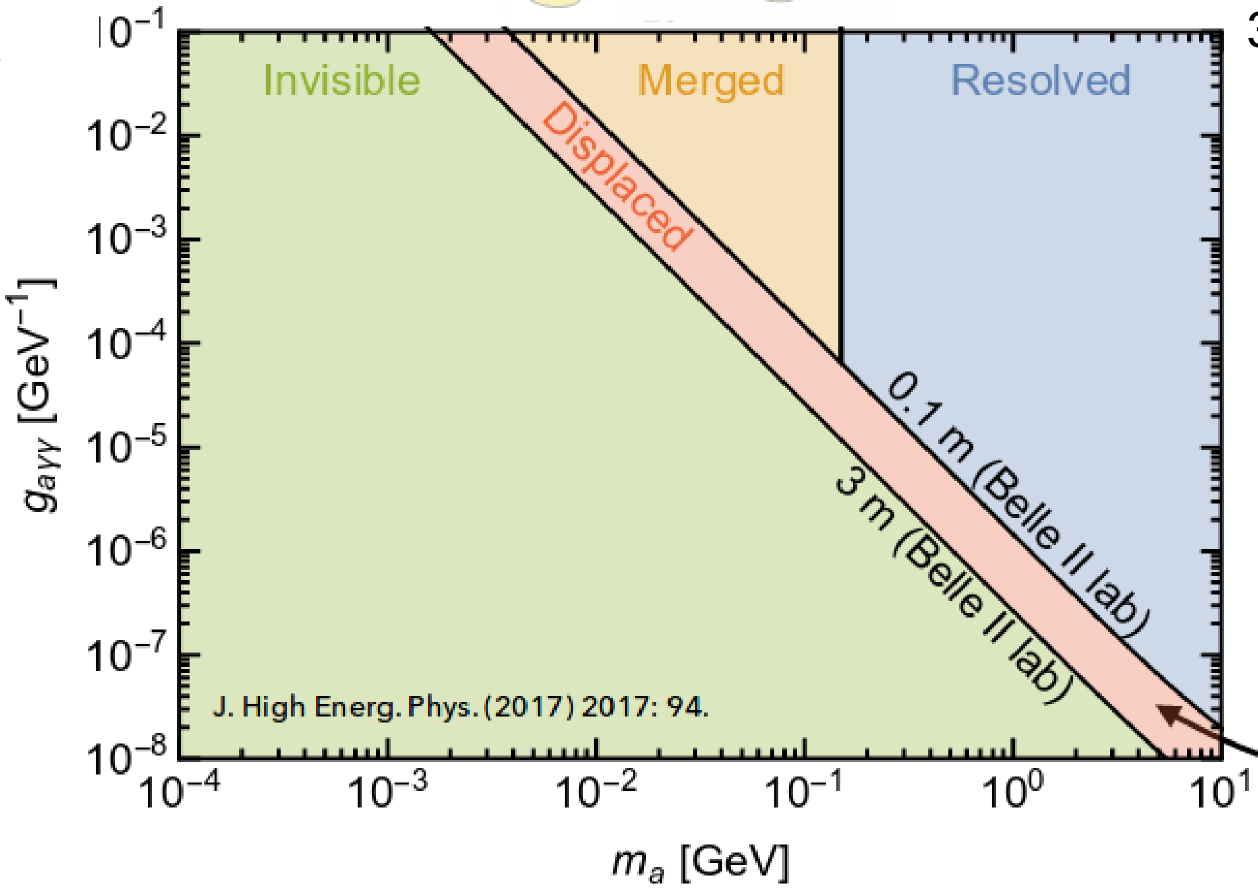
Two of the photons overlap or **merge**.



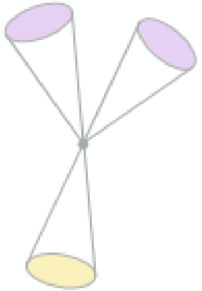
$$\tau_a \sim 1/g_{a\gamma\gamma}^2 m_a^3$$

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





Three **resolved**, high energetic photons.



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

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