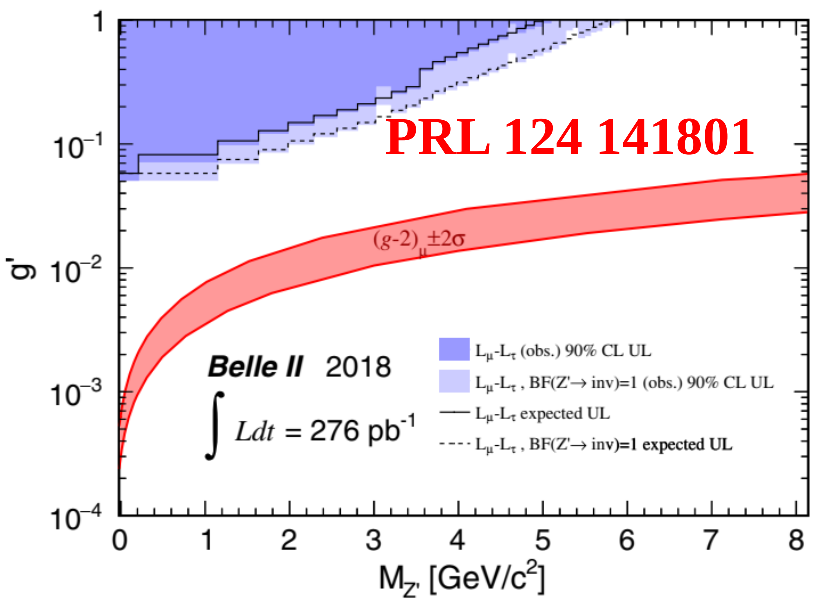
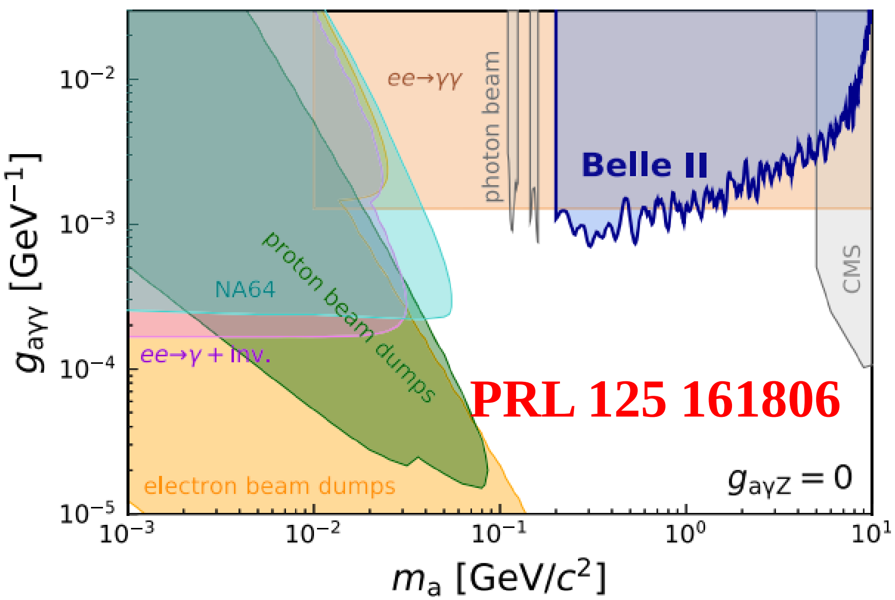
Dark sector searches at Belle II

鄢文标 (中国科学技术大学)

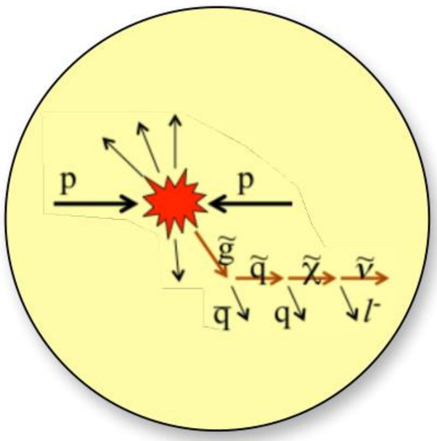




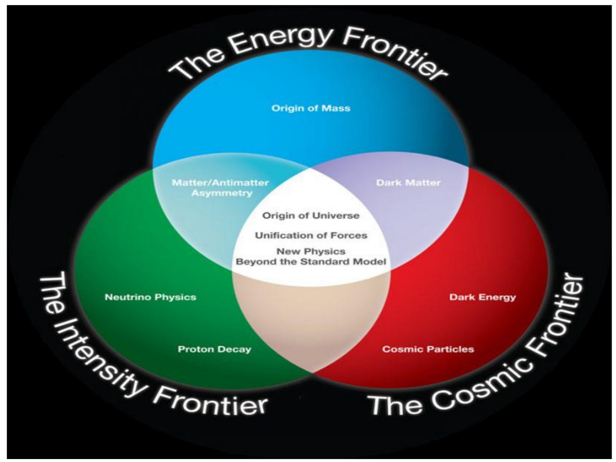
2021年BESIII新物理研讨会，2021.11.7，青岛

Complementary ways to new physics

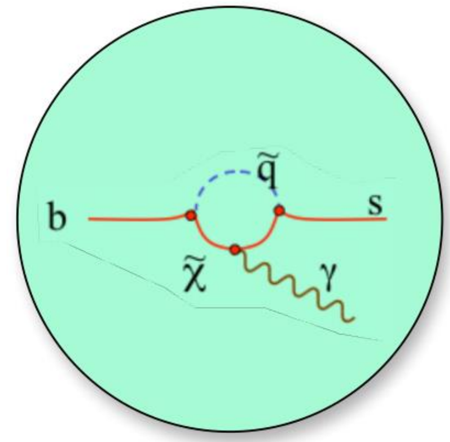
Energy frontier



Direct production of new particles



Intensity frontier

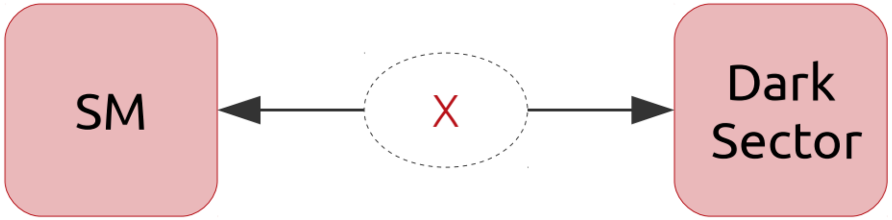


Indirect sensitivity through loops

- **Presently no unambiguous evidence for Beyond Standard Model (SM) physics at the high energy frontier.**
- **The intensity frontier offers indirect sensitivity to very high scales**

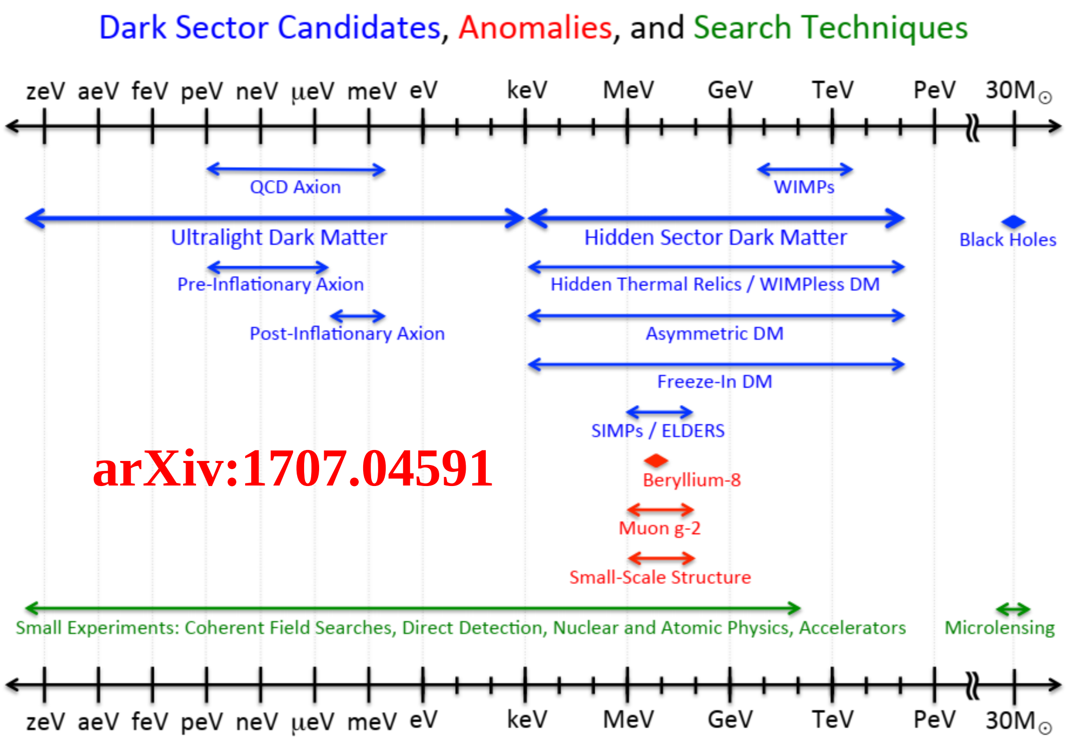
Dark sector

- **In recent years, the possibility that both Dark Matter (DM) and particles mediating its interactions to the SM have a mass at or below the GeV scale has gained much traction.**



- **Light DM weakly interacting to SM though a new light mediator**
  - ✓ **Vector portal: dark photon A’, dark Z’**
  - ✓ **Pseudo-scalar portal: axion-like particles (ALPs)**
  - ✓ **Scalar portal: dark scalars, extended Higgs model**
  - ✓ **Neutrino portal: sterile neutrino**

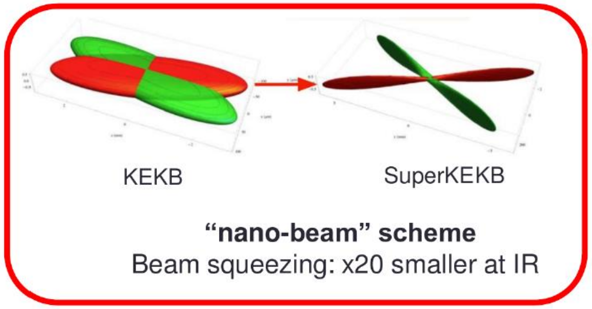
Overview of dark sector searches

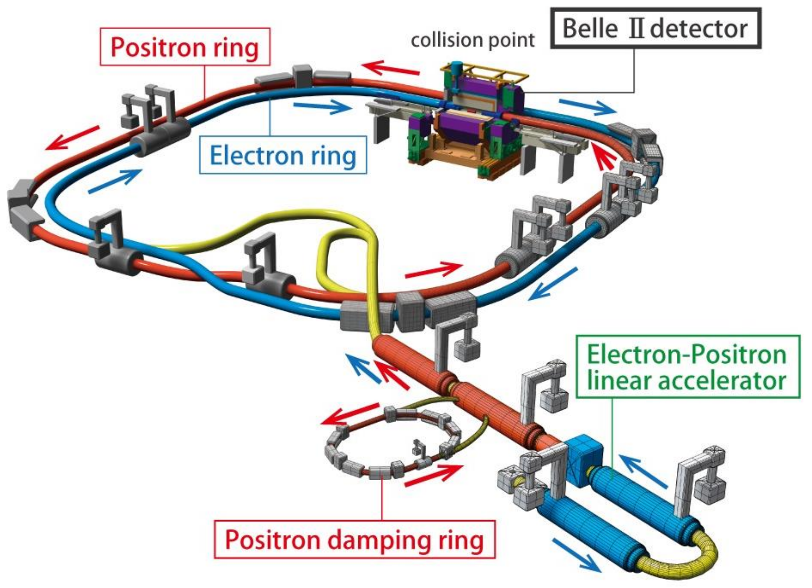


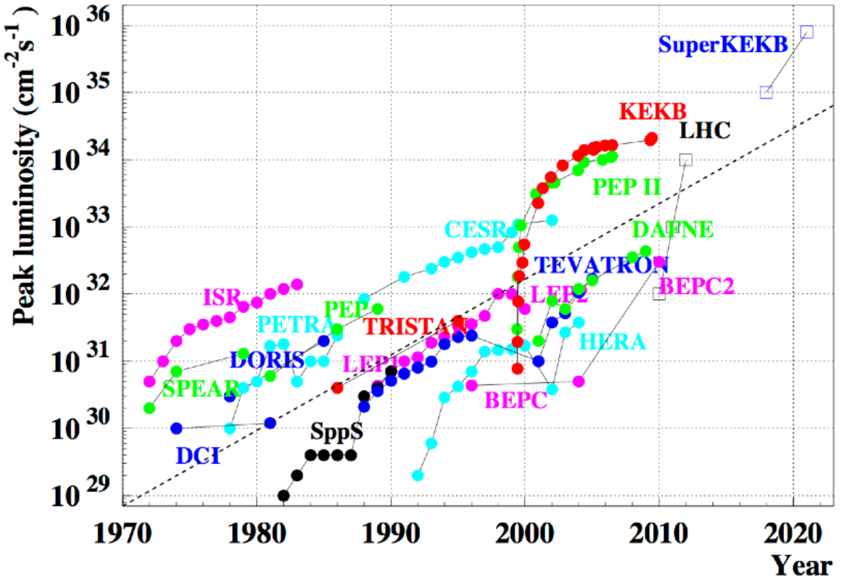
- **B-factories can access the mass range naturally favored by light dark sectors**
- **LHC can probe higher mass regions and wider phase space for long lived particles, heavy neutral leptons.**

The SuperKEKB accelerator

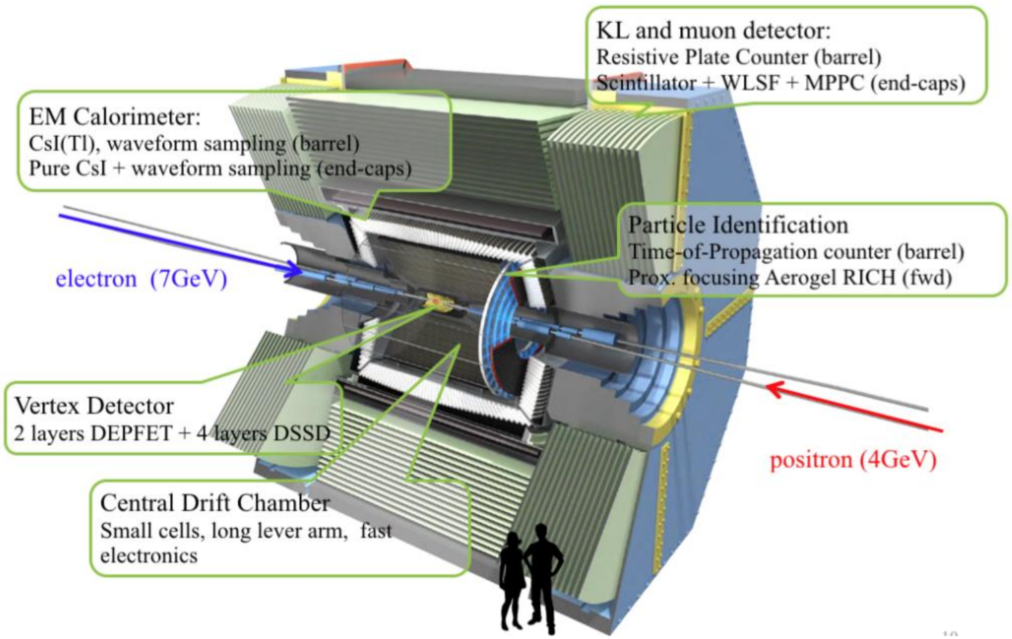
- Super B-factory @ Tsukuba, Japan
- Asymmetric collider, around 10.58 GeV
- Nano-beam scheme: 40×KEKB
  - ✓ Higher background
  - ✓ Higher trigger rate

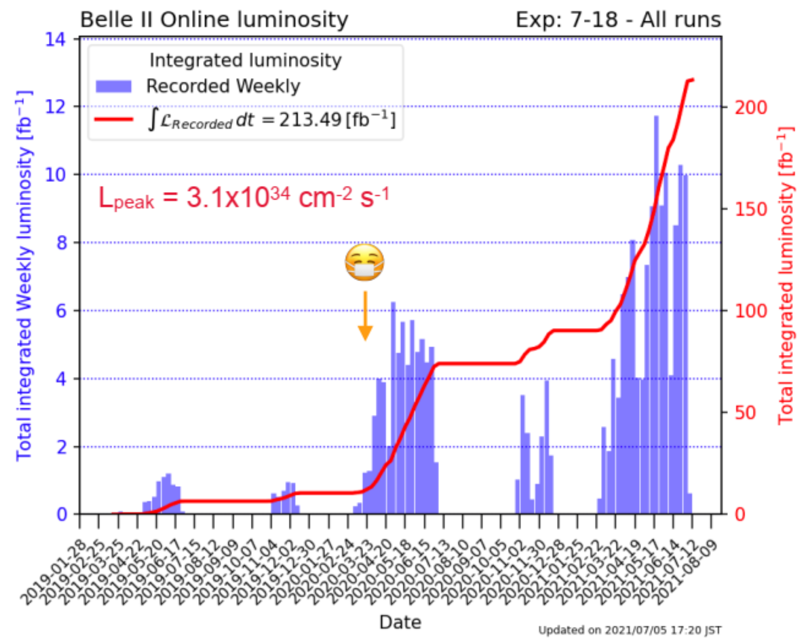






Belle II detector

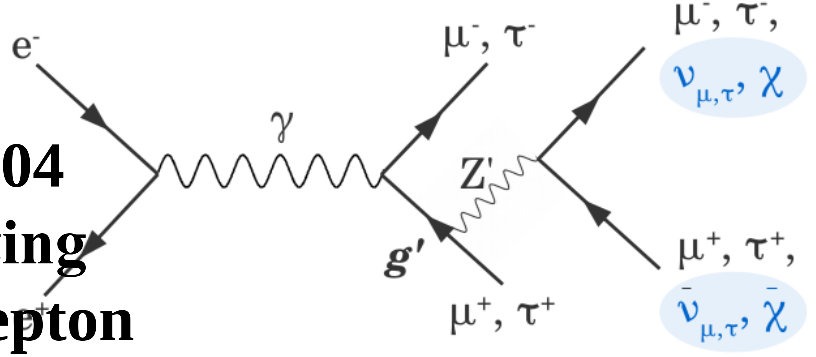




- **On searching for light dark matter or mediators**
  - ✓ **Hermetic detector and well known initial condition**
  - ✓ **Low background and excellent PID**
  - ✓ **Dedicated triggers for low multiplicity events**
- **Physics run @ 2019, Goal 50 ab^{-1} data (50×Belle)**

L_μ-L_τ model

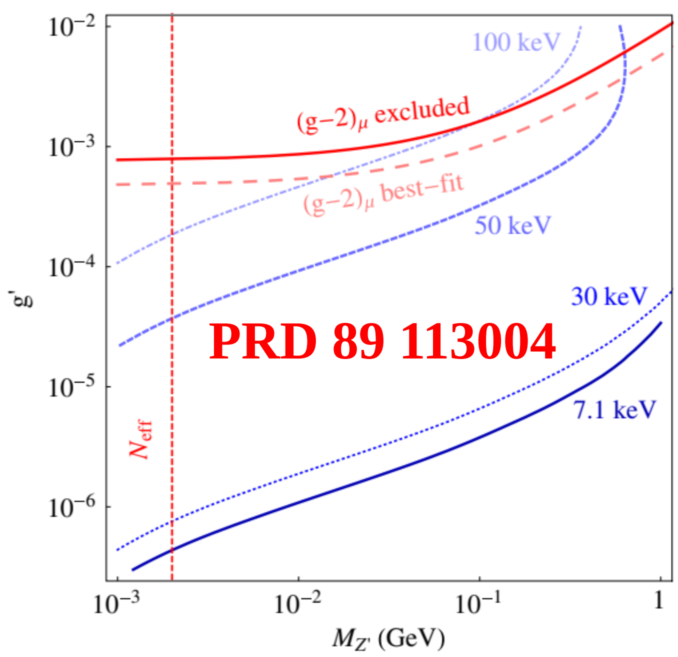
- **Theory L_μ-L_τ model**
  - ✓ **JHEP 1612, 106; PRD89, 113004**
- **New light gauge boson Z' interacting only with 2nd and 3rd generation of lepton**
- **This model could explain**
  - ✓ **Dark matter puzzle**
  - ✓ **Muon g-2 anomaly**
  - ✓ **b -> s $\mu^+ \mu^-$ anomaly**



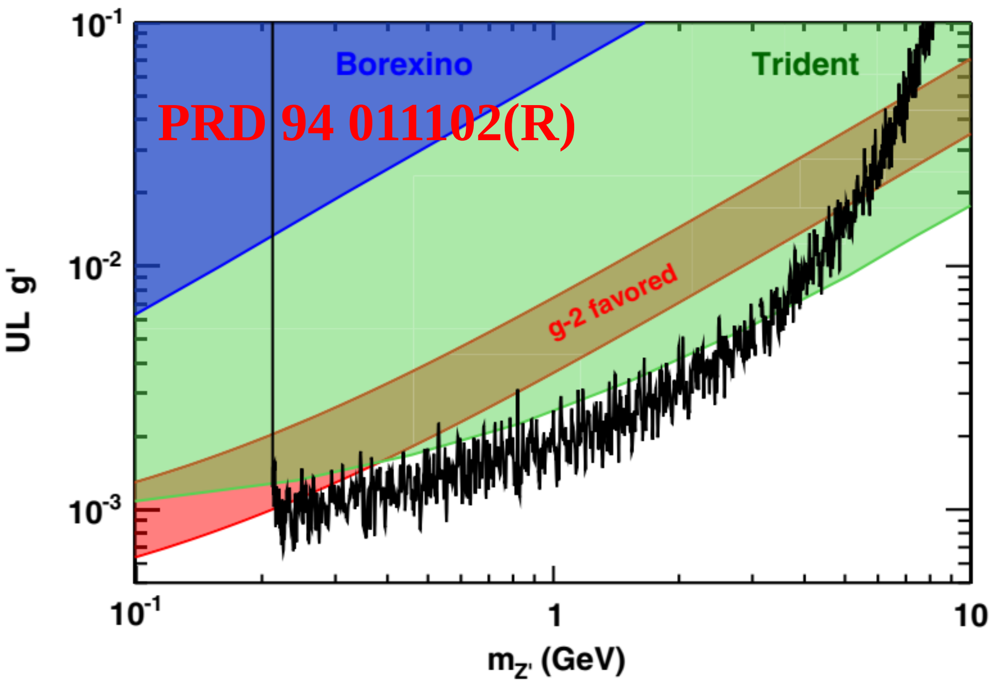
$$
\begin{aligned}
M_{Z'} < 2M_\mu \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] = 1,\\
2M_\mu < M_{Z'} < 2M_\tau \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] \simeq 1/2,\\
M_{Z'} > 2M_\tau \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] \simeq 1/3.
\end{aligned}
$$

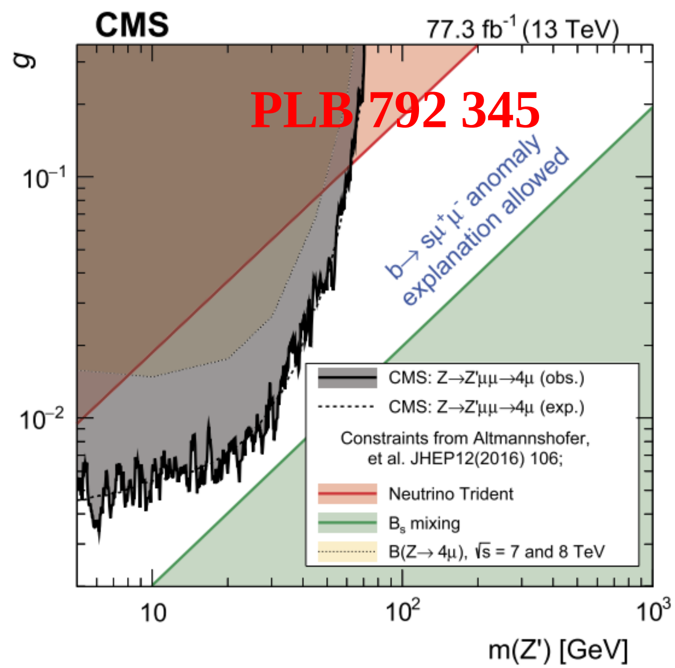
$$\text{if } M_{Z'} > 2M_\chi$$
$$BF(Z' \to \chi\bar{\chi}) = 1$$

$$\mathcal{L} = \sum_\ell \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell$$



Z’ -> $\mu^+ \mu^-$

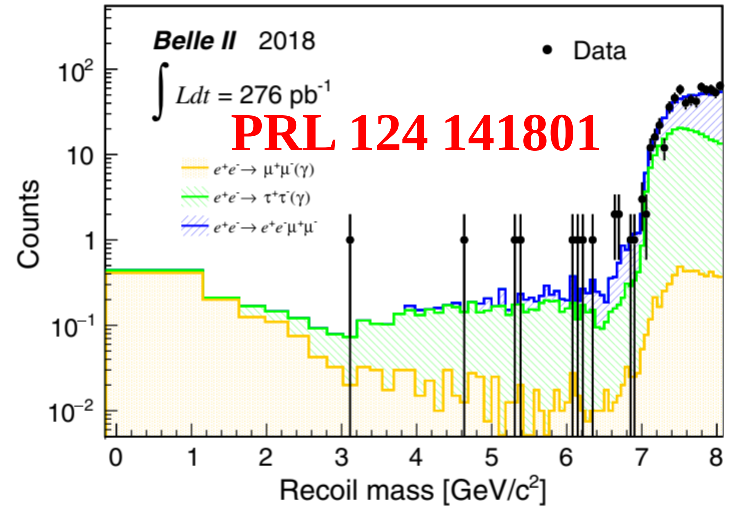


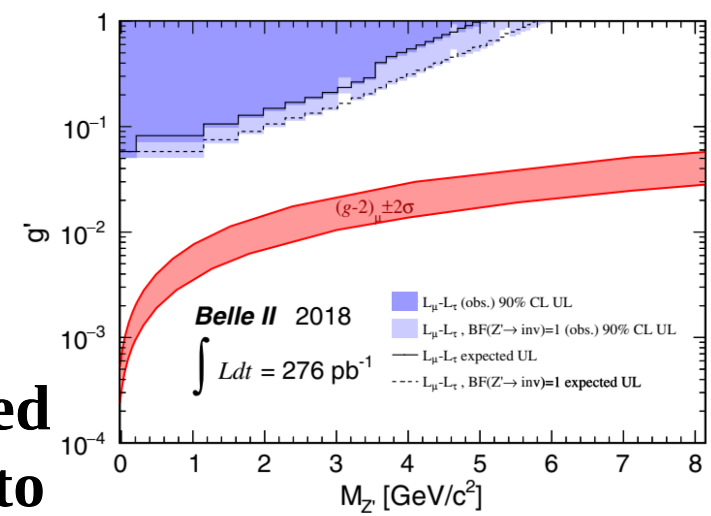


- **Existing limits on Z’ coupling (g’) with visible decay Z’ -> $\mu^+\mu^-$ by BaBar, CMS and neutrino-nucleus scattering processes.**

Z' invisible decay

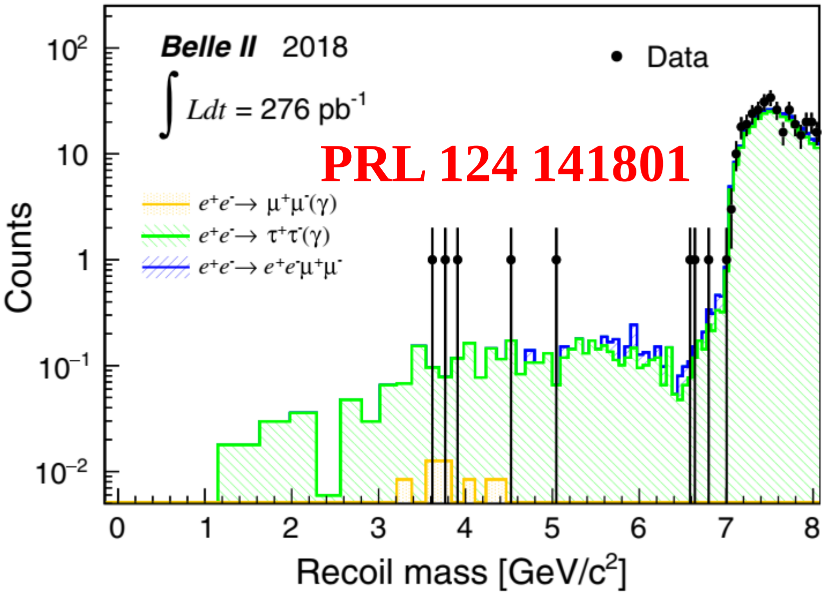
- Search for Z' invisible decay
  - ✓ $e^+ e^- \to \mu^+ \mu^-$ + missing energy
  - ✓ $e^+e^- \to e^{\pm}\mu^{\mp}$ + missing energy
- Belle II data: 276 pb^{-1} data
- Z' signal event
  - ✓ peak in distribution of invariant mass of system reoiling again of lepton pair
  - ✓ Events with exactly two tracks identified as e/μ
- Dominant backgrounds
  - ✓ $e^+ e^- \to (\gamma)\ \mu^+ \mu^-, (\gamma)\ \tau^+ \tau^-, e^+ e^- \mu^+ \mu^-$
- Recoil mass: no anomalies are observed
- Cross section results are translated into 90% C.L. upper limits on the coupling g'

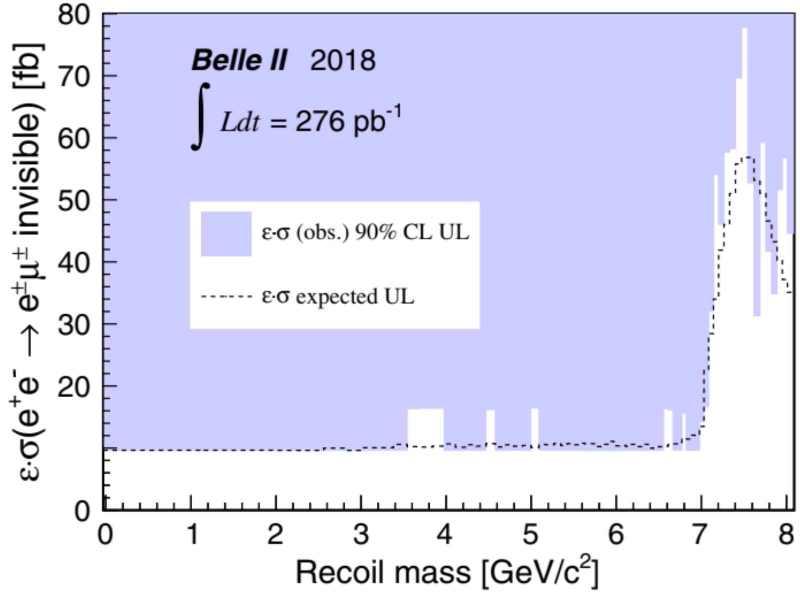




Z’ invisible decay

- **Lepton flavor violation channel:** **e^+e^- -> $e^{\pm}\mu^{\mp}$ + missing energy**



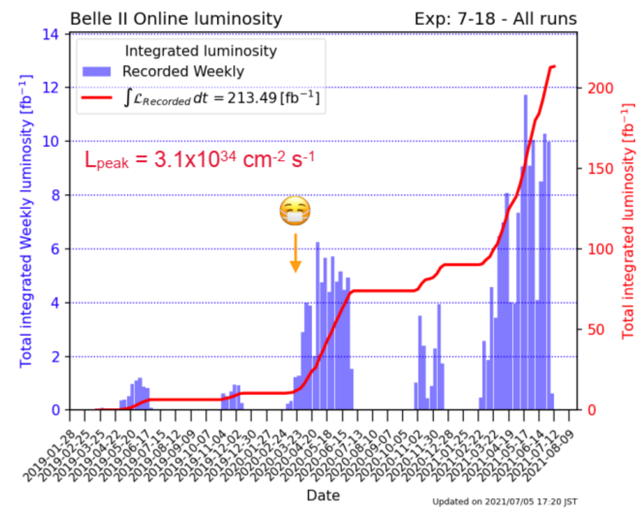


- **No anomalies are observed above 3σ.**
- **90% C.L. upper limits on efficiency times cross section as function of recoil mass**
- **The dashed line is the expected sensitivity**

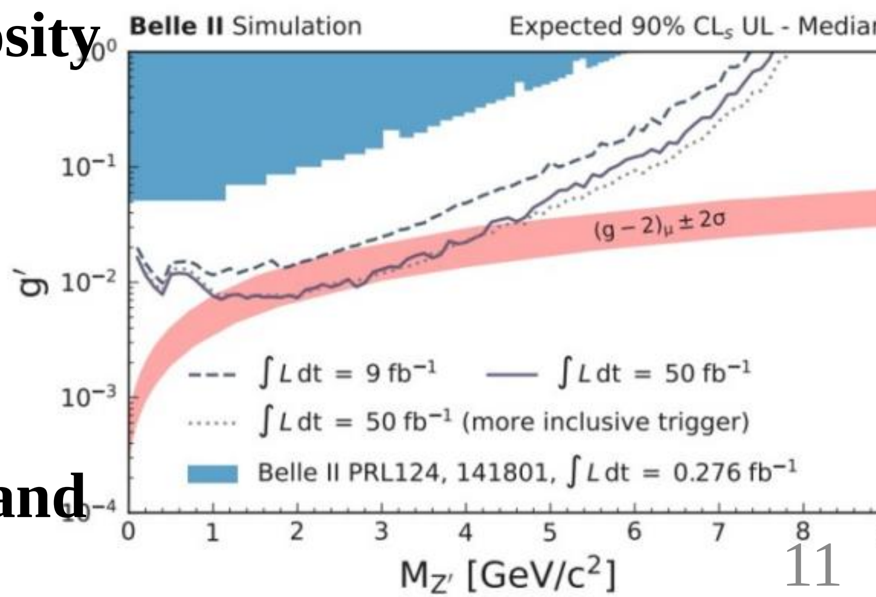
Future about Z' invisible decay

Source	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Trigger efficiency	6%	1%
Tracking efficiency	4%	4%
PID	4%	4%
Luminosity	0.7%	0.7%
τ suppression (background)	22%	22%
Background before τ suppression	2%	2%
Discrepancy in $\mu\mu$ yield (signal)	12.5%	

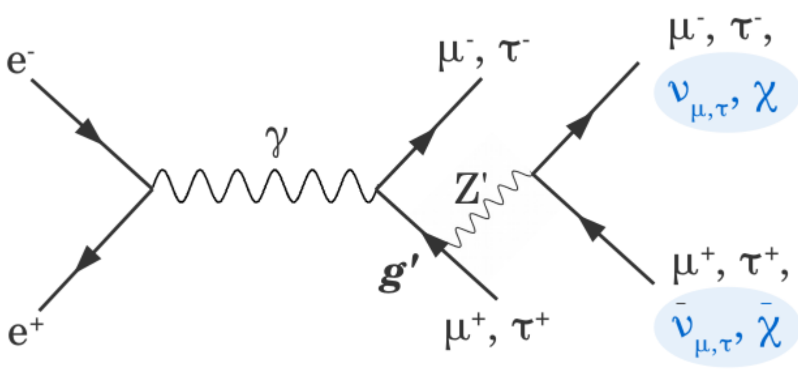
PRL 124 141801

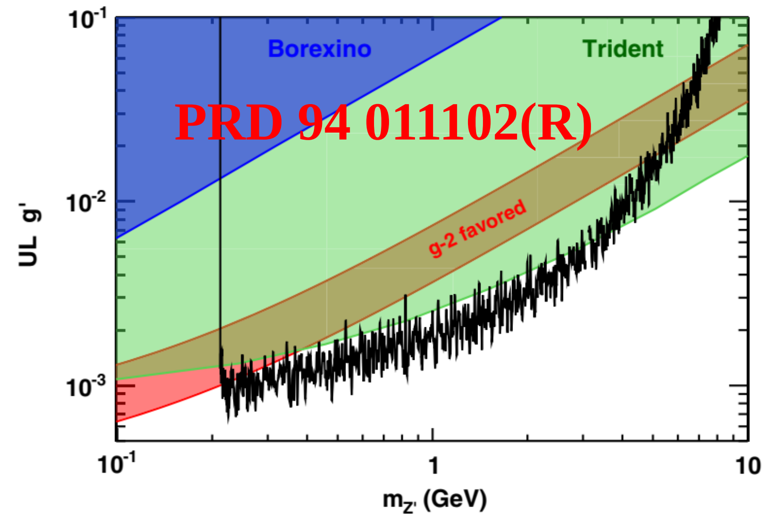


- **Much higher integrated luminosity (already on tape)**
- **Analysis improvements**
  - ✓ **Better muon PID**
  - ✓ **MVA selection**
- **New trigger**
- **Starting to probe muon (g-2) band with 50 fb^{-1} data**



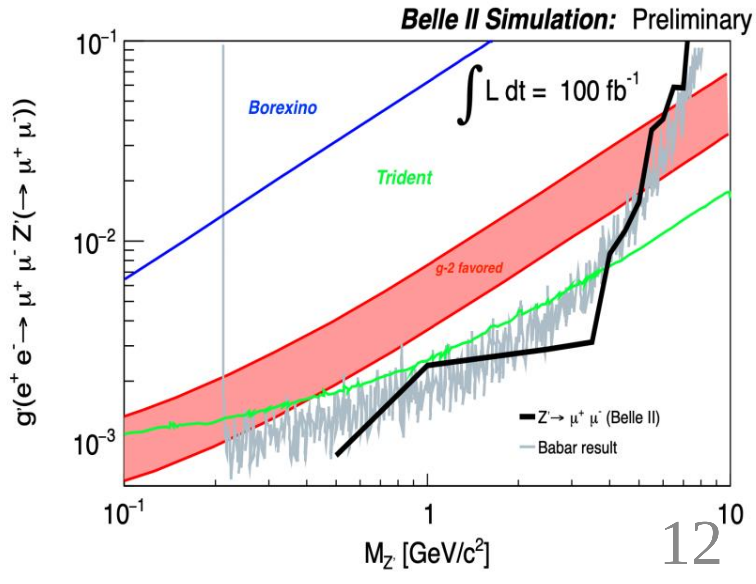
Z' visible decay: Z' -> $\mu^+ \mu^-$



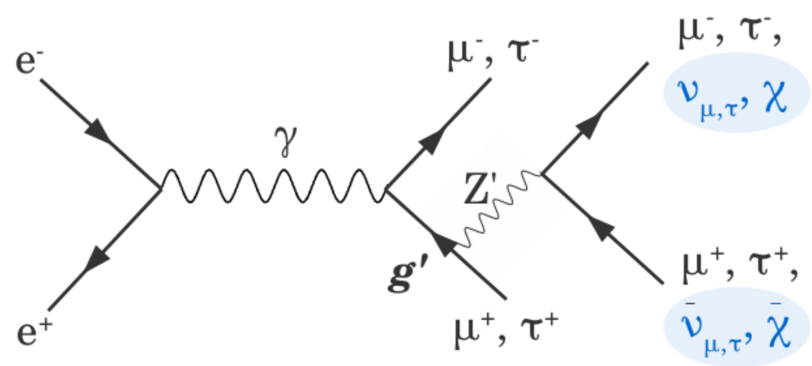


$e^+ e^-$ -> $\mu^+ \mu^-$ + Z'; Z' -> $\mu^+ \mu^-$

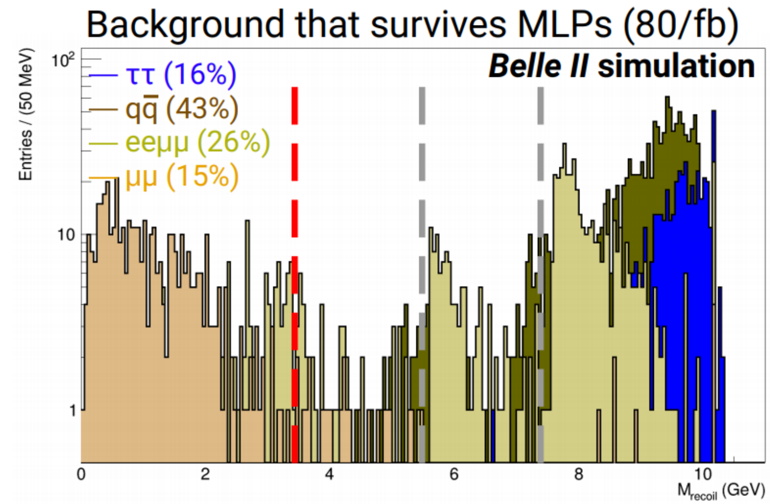
- **BaBar used 514 fb^{-1} data on Z' visible decay $\mu^+ \mu^-$ mode**
- **Belle II wants to obtain same (or better) results than BaBar with less luminosity (100 fb^{-1}) by an aggressive background suppression**



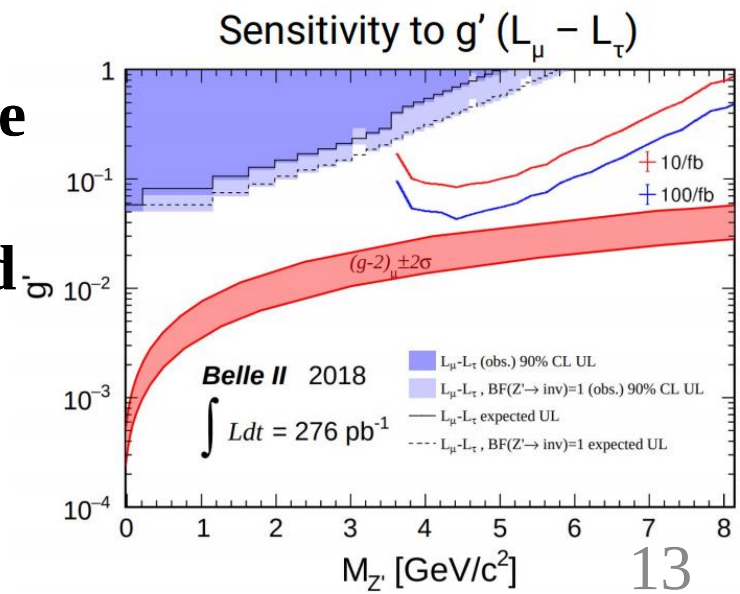
Z’ visible decay: Z’ -> $\tau^+ \tau^-$



e$^+$ e$^-$ -> $\mu^+ \mu^-$ + Z’; Z’ -> $\tau^+ \tau^-$

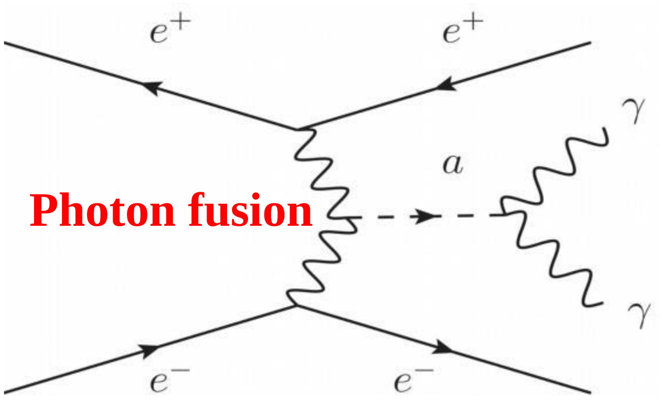


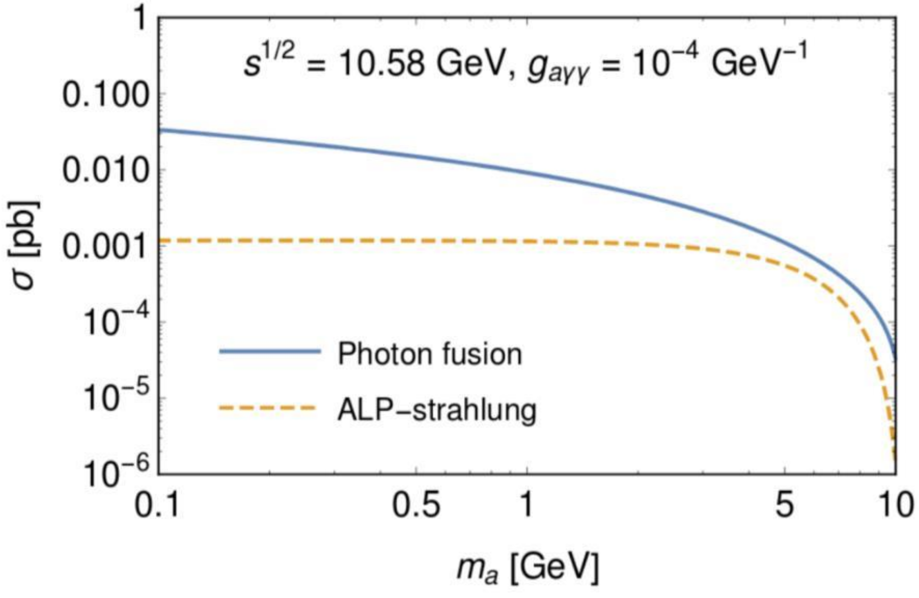
- Same theory motivation for invisible decay and Z’ -> $\mu^+ \mu^-$
- Z’ -> $\mu^+ \mu^-$ have never been searched before
- Challenging because of neutrinos and background

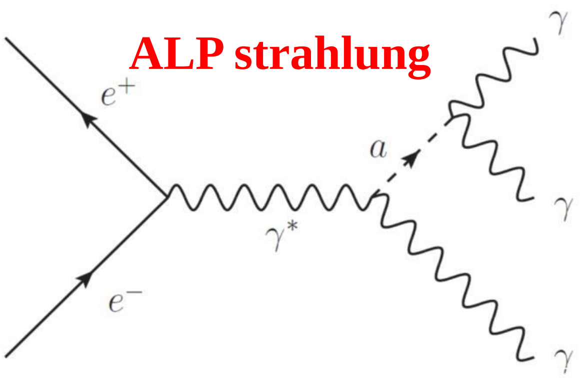


Axion-like particles (ALPs)

- **Axion-like particles are pseudo-scalars coupling mainly to bosons**
- **Two possible scenarios are possible at e^+e^- colliders**
- **Extract photon coupling $g_{a\gamma\gamma}$ @ e^+e^-**

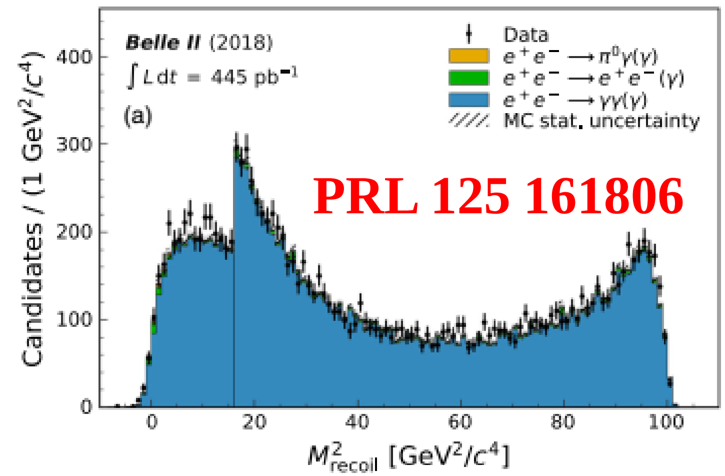






ALPs: a -> γ γ

- a -> γ γ signal event
  - ✓ Three photons summing up to beam energy and no other particles
  - ✓ No tracks
  - ✓ Search for a bump into diphoton and recoil mass
- Dominant backgrounds
  - ✓ $e^+ e^-$ -> (γ)γγ, and $\gamma\pi^0/\eta/\eta'(\gamma\gamma)$
  - ✓ $e^+ e^-$ -> (γ) e^+e^-: tracking inefficiencies
- The data agree well with simulation except for a small excess around one.
- ALP signal with smaller width at this region.



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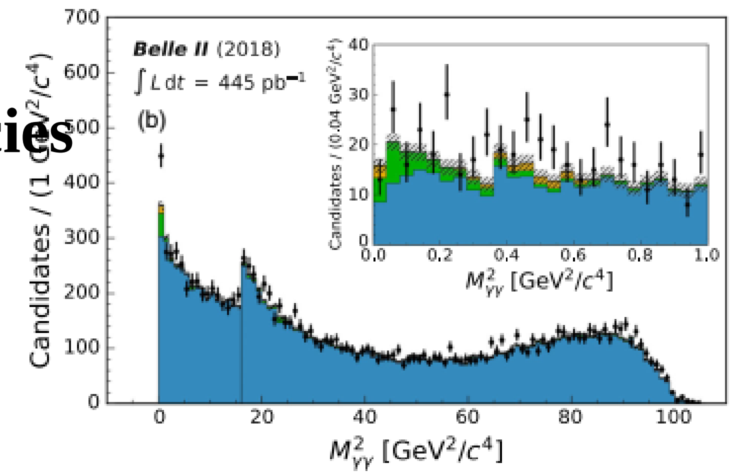
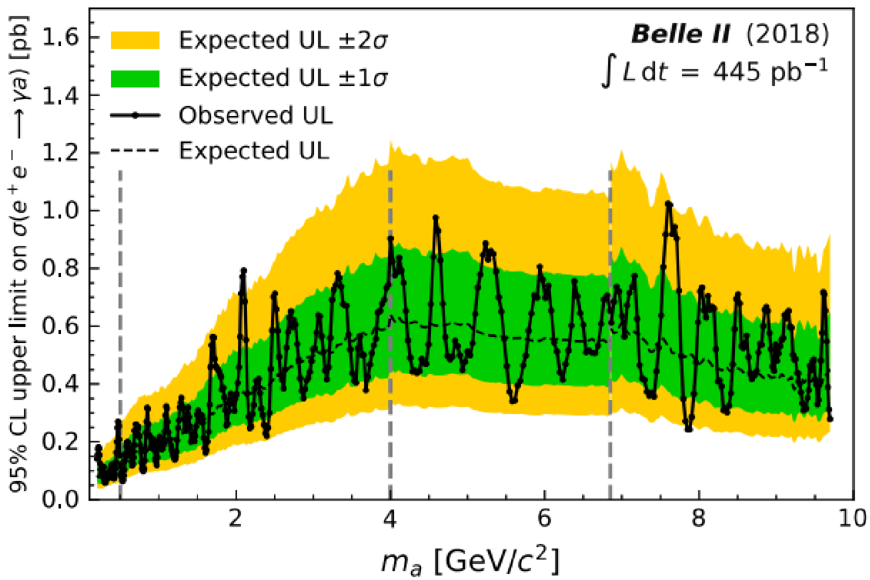
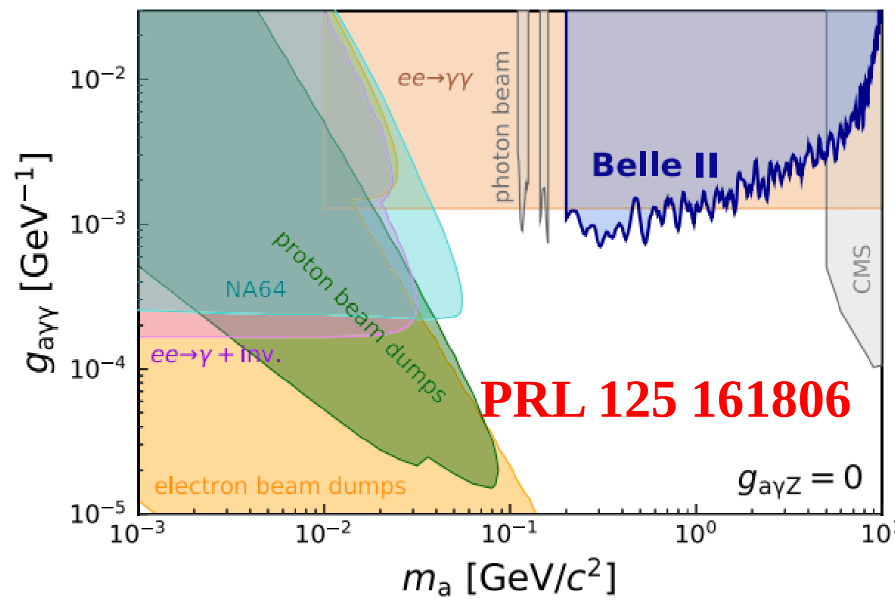


ALPs: a -> γ γ



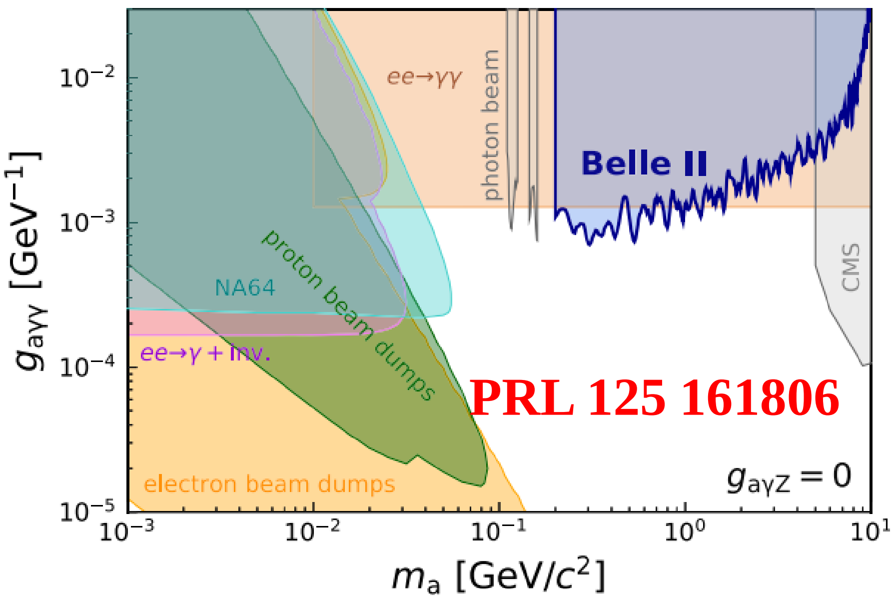


PRL 125 161806

- **95% C.L. upper limit to cross section**
- **These limits are the first obtained for fully reconstructed with three photons**
- **More restrictive than previous limits**

$$\sigma_a = \frac{g^2_{a\gamma\gamma}\alpha_{\mathrm{QED}}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$

ALPs: future a -> γ γ



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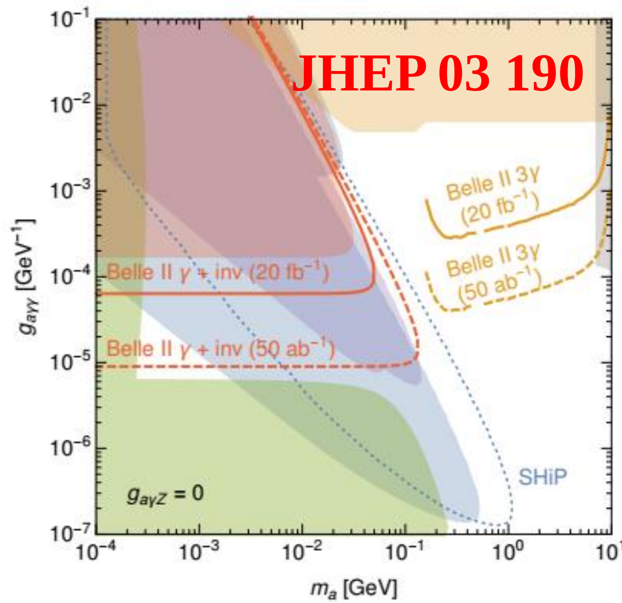
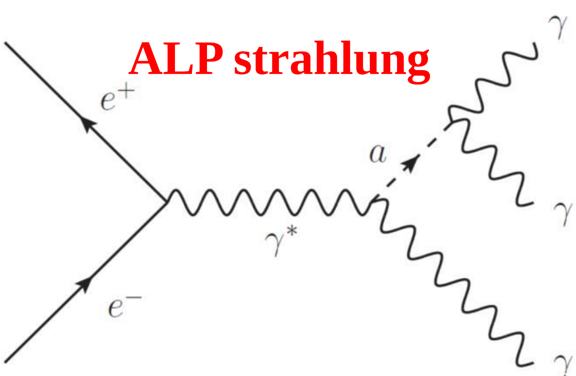


- **Belle II data: 445 pb^{-1} data**
- **Goal 50 ab^{-1} data**
  - ✓ **future prospects**

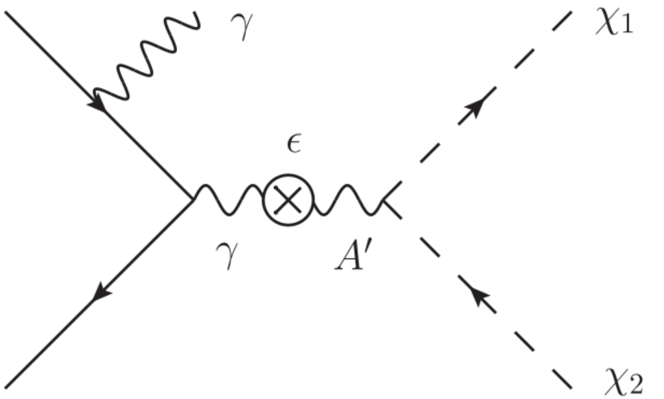
ALP strahlung



Dark photon

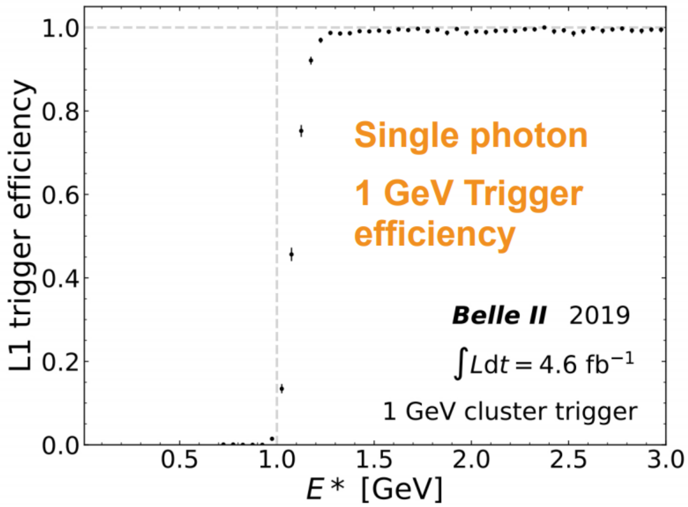
- A possible U(1) extension of the SM include a new massive vector gauge boson A’ coupling to SM photon through **kinematic mixing** with **strength ε** -> the dark photon
- At e^+e^- colliders, investigate the ISR production e^+e^- -> γ A’

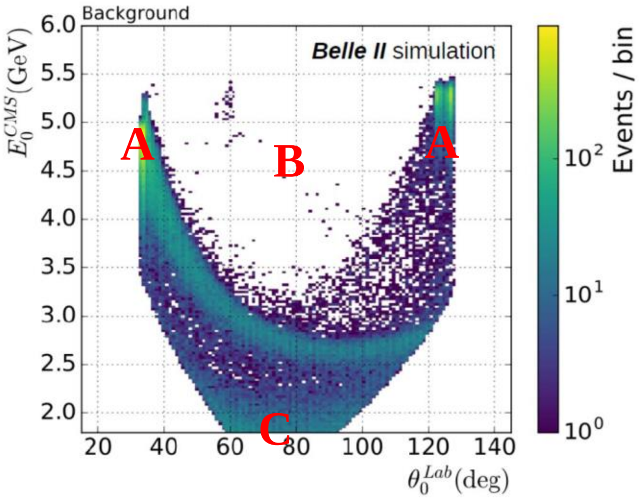
- Two basic scenarios depending on A’ and dark matter mass relationship
  - ✓ $m_{A'} > 2m_\chi$: A’ invisible decays Into DM particle
  - ✓ $m_{A'} < 2m_\chi$: A’ visible decays to SM particle (leptons)



Invisible dark photon

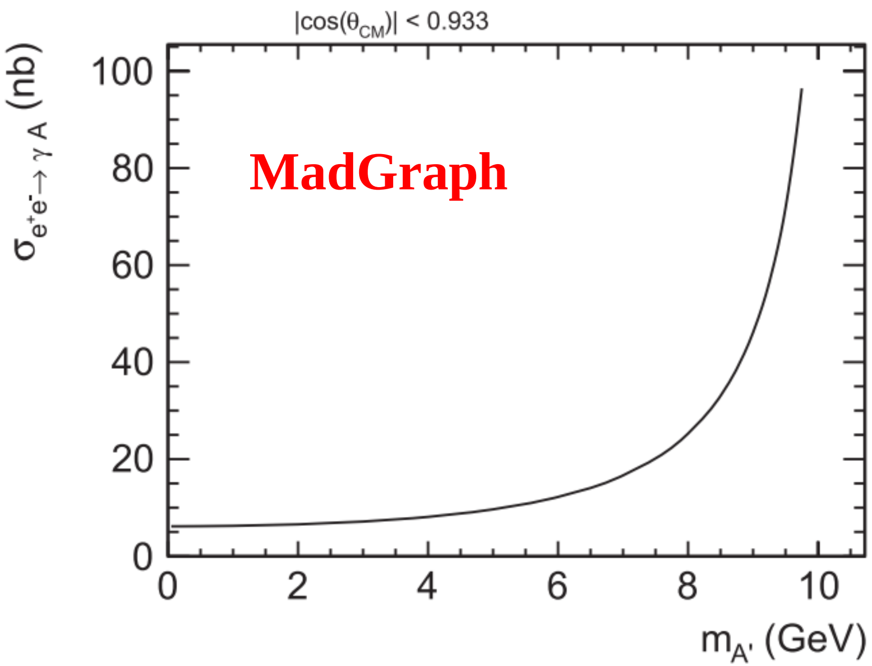
- Select events with nothing but a single high energetic ISR photon. Look for a bump in the photon energy
- Need single photon trigger
- Backgrounds
  - ✓ $e^+ e^- \to (\gamma)\gamma\gamma$ (low mass region)
  - ✓ $e^+ e^- \to (\gamma) e^+e^-$ (high mass region)
  - ✓ Cosmic

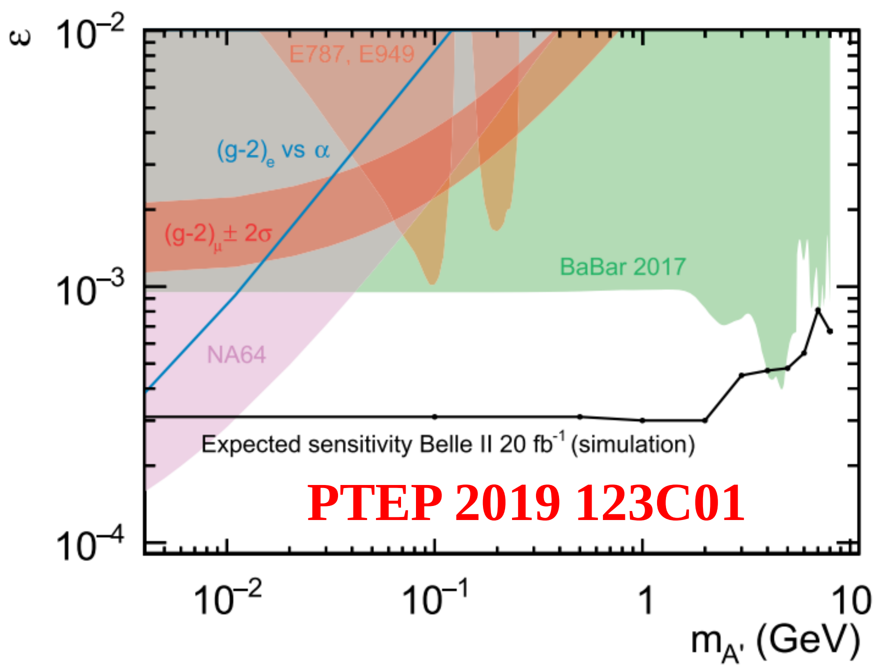




A: $e^+ e^- \to (\gamma)\gamma\gamma$, endcap gaps
B: $e^+ e^- \to (\gamma)\gamma\gamma$, 90^O gaps
C: $e^+ e^- \to (\gamma)e^+e^-$, leptons out of acceptance

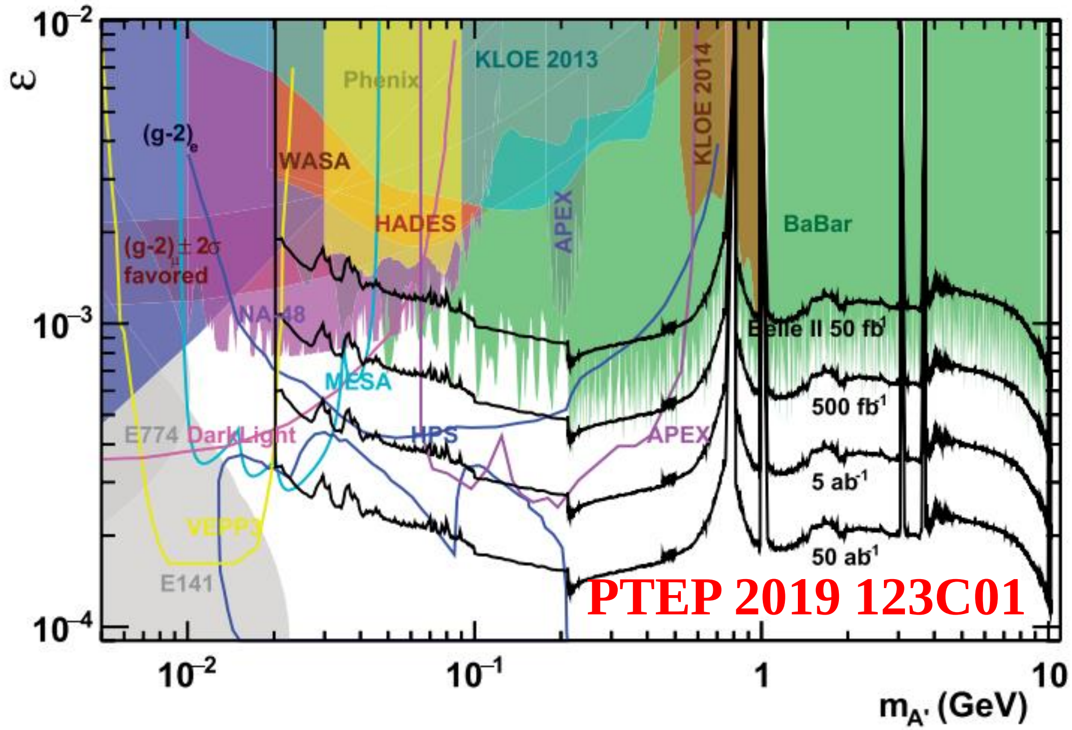
Invisible dark photon





- **Expected sensitivity @ Belle II**
- **Very promising results with 20 fb^{-1} data (1/3 BaBar)**
  - ✓ **No ECL gaps pointing to the interaction region**
  - ✓ **Better hermeticity (smaller boost βγ, larger acceptance)**

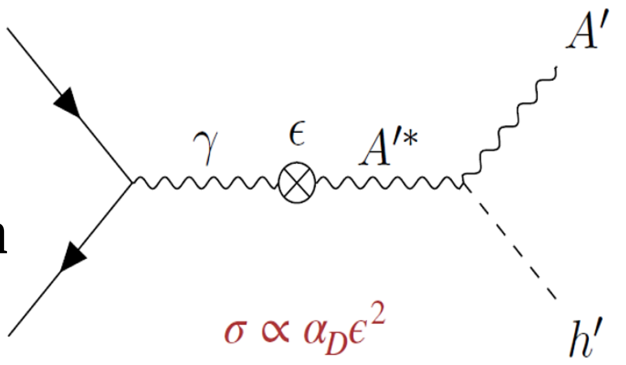
Visible dark photon

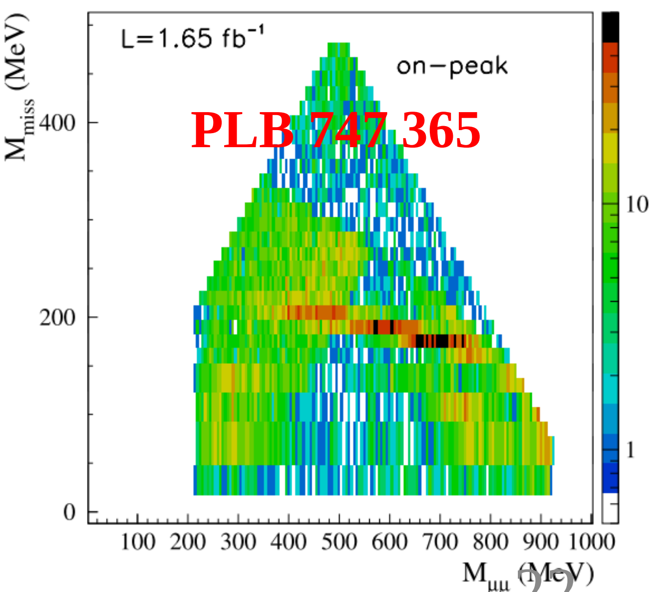


- **Expected sensitivity @ Belle II**
- **Investigate the ISR production e^+e^- -> γ A'**
- **A' visible decays to e^+e^- and $\mu^+ \mu^-$ decays**
- **Belle II has larger radius drift chamber with better invariant mass resolution, and better trigger efficiency of electron and muon**

Dark Higgsstrahlung

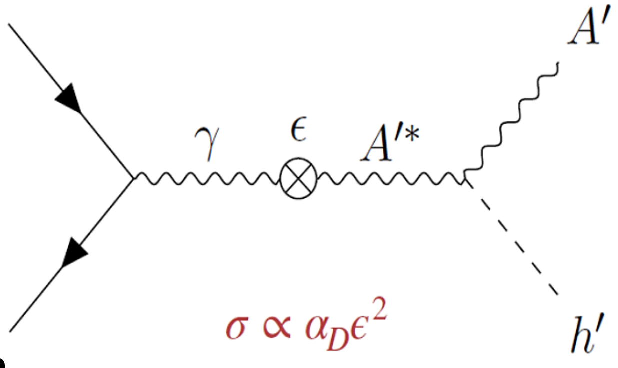
- **Dark photon A' mass can be generated via a spontaneous symmetry breaking mechanism by add a dark Higgs boson h'**
- **A minimal scenario: a single dark photon A' and a single dark Higgs boson h'**
- **The h' could be produced in the Higgsstrahlung process, which is sensitive to dark sector coupling constant α_D**
- **Case: $m_{h'} < m_{A'}$ with invisible h'**
- **Up to know only by KLOE**
  - ✓ **A' -> $\mu^+ \mu^-$**
  - ✓ **invisible h'**

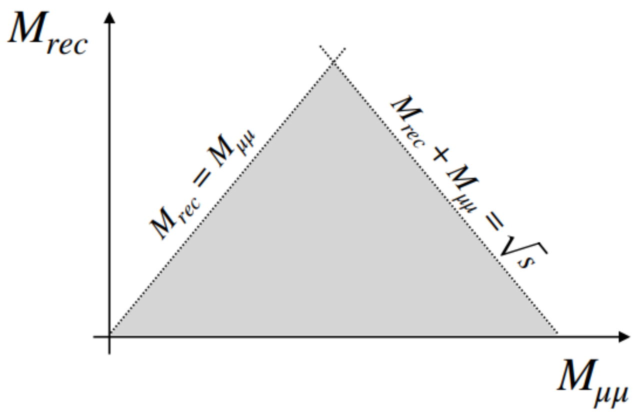




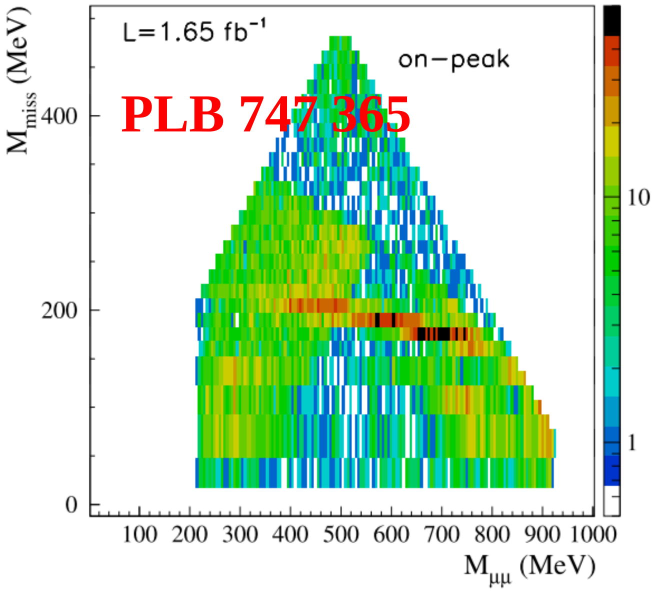
Dark Higgsstrahlung

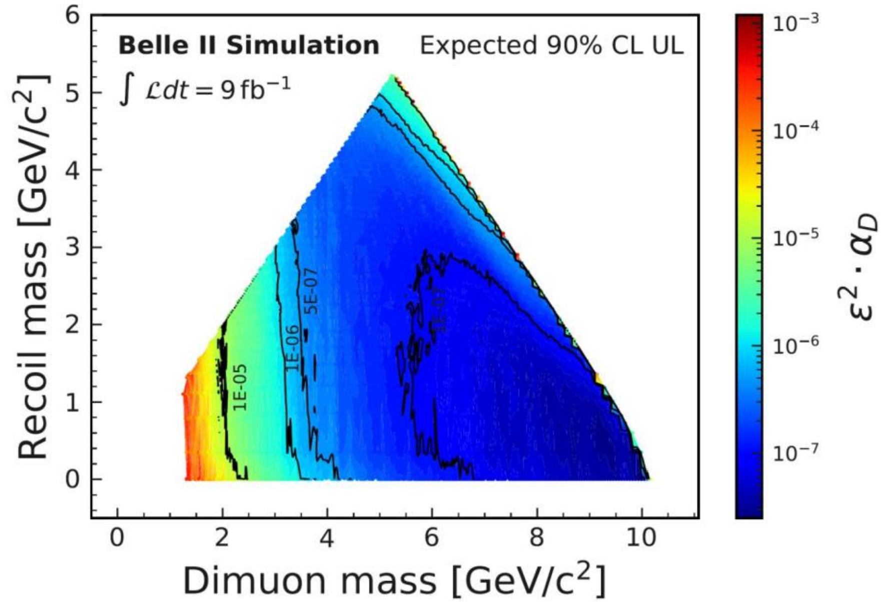
- $e^+ e^- \to A' h'$
  - ✓ $A' \to \mu^+ \mu^-$
  - ✓ invisible h'
- Experimental signature
  - ✓ $\mu^+ \mu^-$ plus missing energy
  - ✓ peak in two dimensional distribution of recoil mass and dimuon mass
- Dominant backgrounds
  - ✓ $e^+ e^- \to (\gamma)\, \mu^+ \mu^-$
  - ✓ $e^+ e^- \to (\gamma)\, \tau^+ \tau^-$
  - ✓ $e^+ e^- \to e^+ e^- \mu^+ \mu^-$
  - ✓ $e^+ e^- \to (\gamma)\, \pi^+ \pi^-$





Dark Higgsstrahlung





- **Expected sensitivity @ Belle II**
- **Very promising results with 9 fb^{-1} data**
  - ✓ **Unconstrained regions, well beyond KLOE coverage**
  - ✓ **Probing non-trivial coupling $\varepsilon^2\alpha_D$**

Invisible Y(1S) decay

- **Within SM, invisible Y(1S) decay @ PL B441 449**

$$\frac{\Gamma\left(\Upsilon \to \nu\bar{\nu}\right)}{\Gamma\left(\Upsilon \to e^+e^-\right)} = \frac{27G^2M_\Upsilon^4}{64\pi^2\alpha^2}(-1+\frac{4}{3}\sin^2\theta_W)^2$$
$$= 4.14 \times 10^{-4} ,$$

with 2-3% uncertainty

- **Br[Y(1S) -> $\nu\bar{\nu}$] ≈ 10^{-5} @ theory; < 3.0 × 10^{-4} @ 90% CL**
- **New physics maybe enhance the Br[Y(1S) -> $\nu\bar{\nu}$], e.g. low mass dark matter (smaller than m_b)**
- **Assume SM (1× 10^{-5}) and NP (3× 10^{-4})**

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	232–464	6960–13920
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$	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
$\gamma\Upsilon(2S) \to (\gamma)\pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1–0.2	1.5×10^8	150–300	4500–9000
$\gamma\Upsilon(3S) \to (\gamma)\pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1–0.2	6.5×10^7	65–130	1950–3900

Light CP even Higgs boson

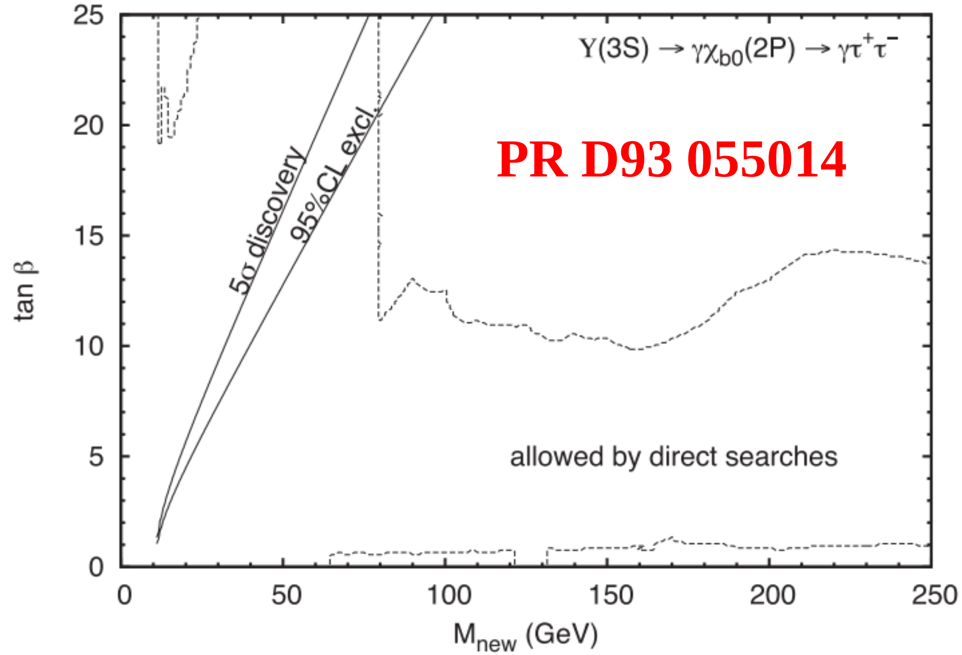
- χ_{b0} -> $\tau^+ \tau^-$ can be sensitive to s channel exchange of CP-even neutral Higgs.
- Event rate for SM Higgs exchange is too small to be observed.

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

- Significant constrains on parameters of type-II two-Higgs-doublet model.
- With second Higgs resonance

$$\mathrm{Br}[\chi_{b0} \to \tau^+ \tau^-] = (1.9 \pm 0.5) \times 10^{-12} \times \left[1 + \frac{M_H^2}{M_{\mathrm{new}}^2 - M_{\chi_{b0}}^2}\tan^2\beta\right]^2$$

Light CP even Higgs boson



- **Expected sensitivity @ Belle II with 250 fb^{-1} Υ(3S) data**
- **Probe large region of tryp-II 2DHM parameter space with H_{new} mass below 80 GeV, and large tanβ region, which is Currently unconstrained by existing searches**

Summary

- The Belle II experiment is exploring light dark matter or mediators at the luminosity frontier.
- New dark sector triggers enable to target unique low multiplicity final states
- Belle II already published results on Z' and ALP
  - ✓ PRL 124, 141801 (2020)
  - ✓ PRL 125, 161806 (2020)
- A lot of dark sector searches are in progress.