LDM and mediator searches at B-factories

Belle II + BaBar/Belle

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INFN – Roma 3

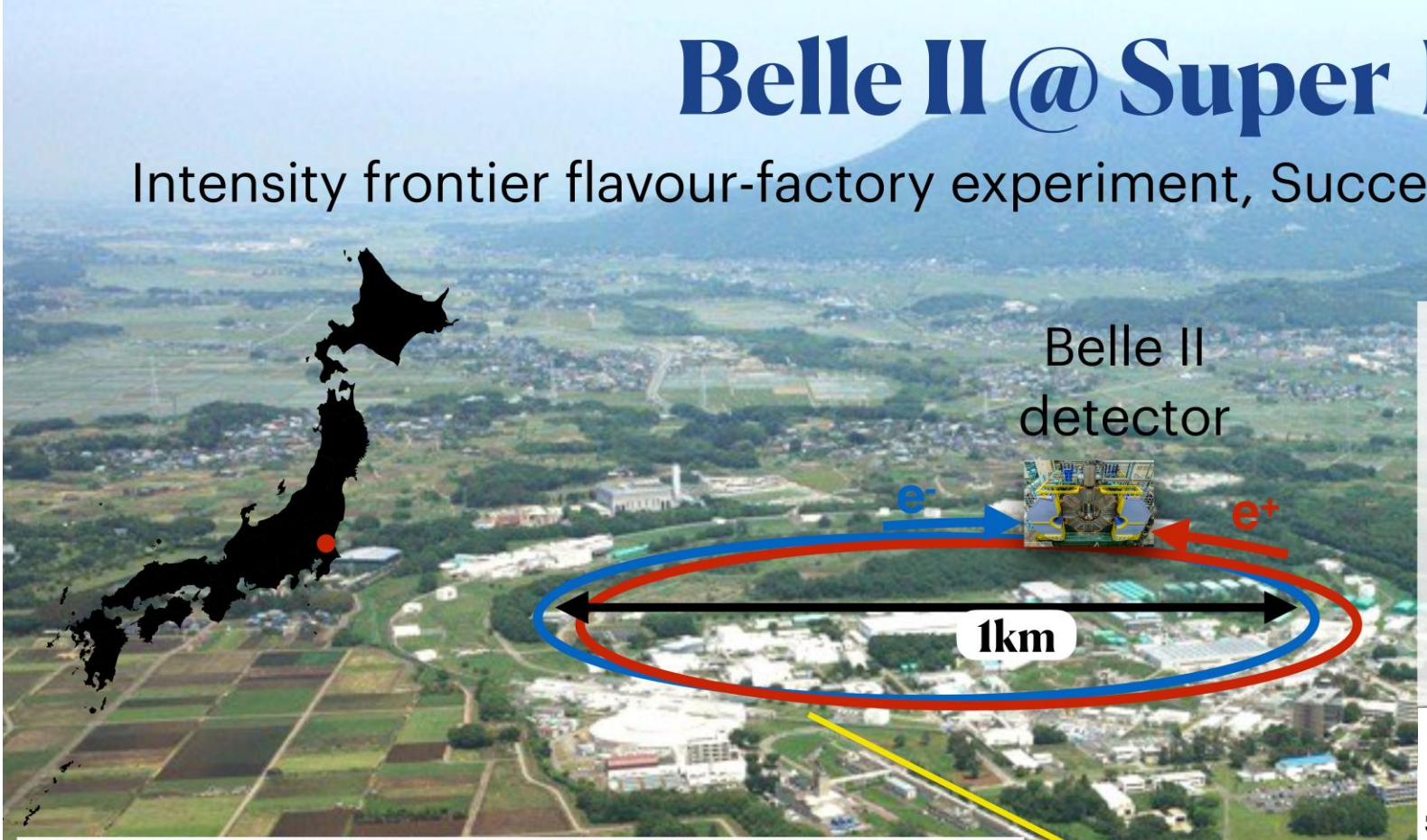
on behalf of the Belle II Collaboration

OUTLINE OF THE TALK

- ✓ Belle II and SuperKEKB
- ✓ Minimal dark photons
  - ➢ Visible A'
  - ➢ Invisible A'
- ✓ Non minimal dark photons
  - ➢ Z' → μμ
  - ➢ Z' → invisible
  - ➢ Dark Higgsstrahlung
- ✓ ALP → γγ
- ✓ Perspective & Summary

Belle II @ Super KEKB

Intensity frontier flavour-factory experiment, Successor to Belle @KEKB (1999-2010)

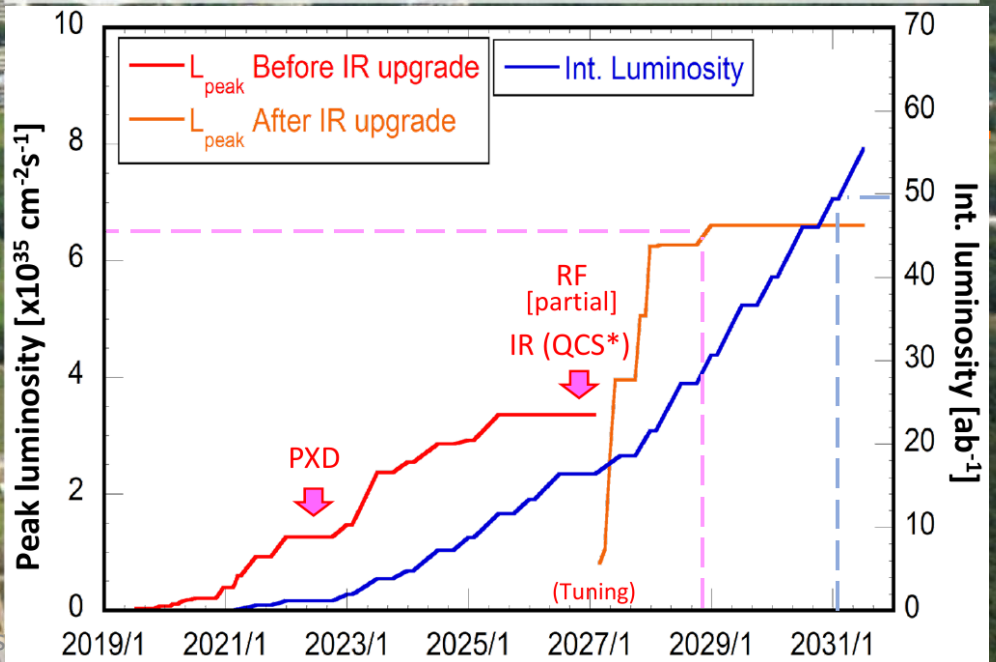


7 GeV e^-, 4 GeV e^+

E_{CM} Υ(4S) = 10.58 GeV + scans

Υ(4S) → B anti-B

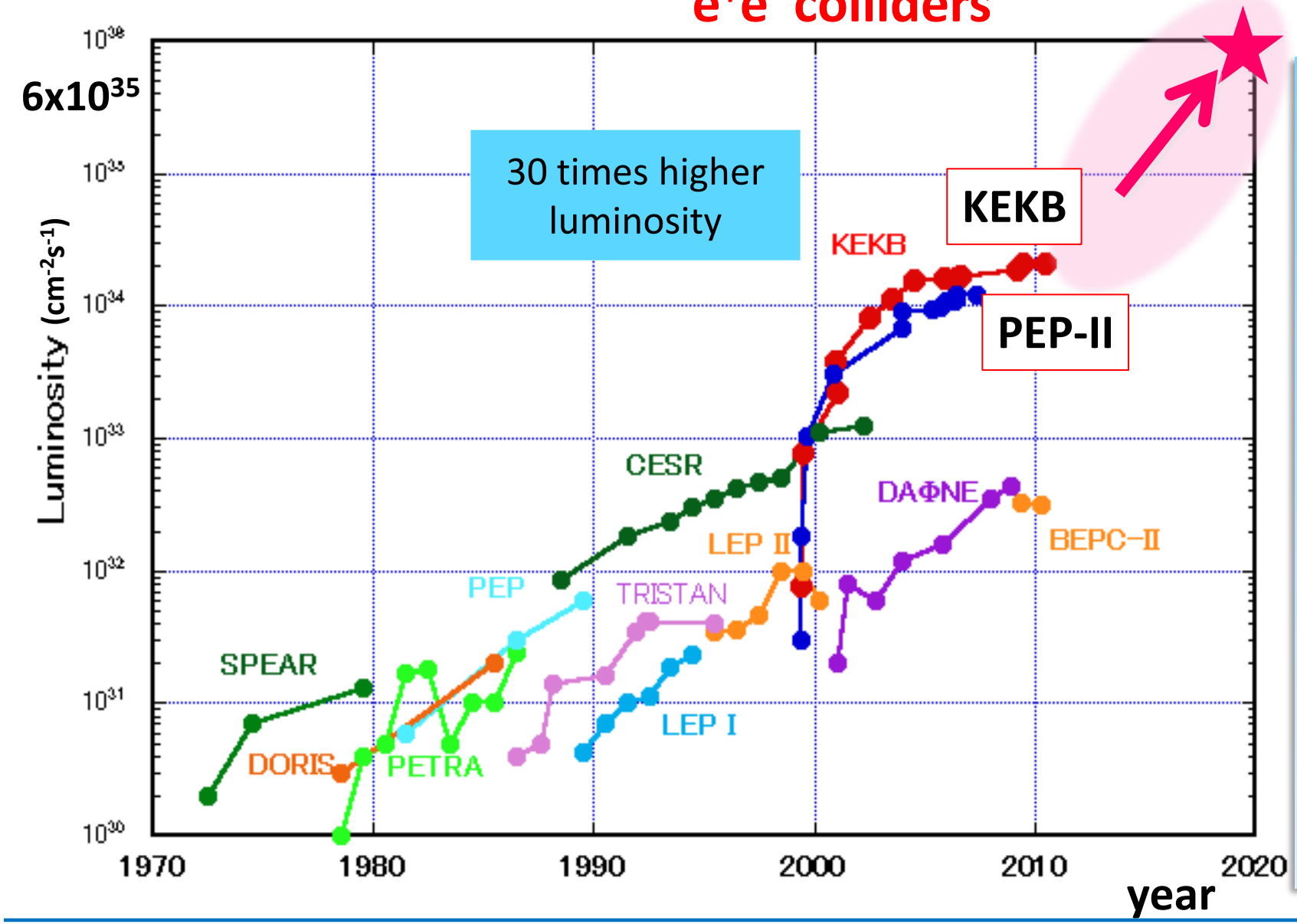
B + Charm + τ + Υ factory + ?



Peak luminosity trend

SuperKEKB

e^+e^- colliders



Final goal: L= 50 ab^{-1} (~ 2030)

Very rich physics program

Flavour physics

- CKM matrix
- CPV in B deacys

BSM physics

- Rare decays
- NP in loops in $b\to s\gamma$, $b\to sll$
- $B\to D^{(*)}\tau\nu$
- LFV in τ decays

New particles (quarkonium)

Dark sector

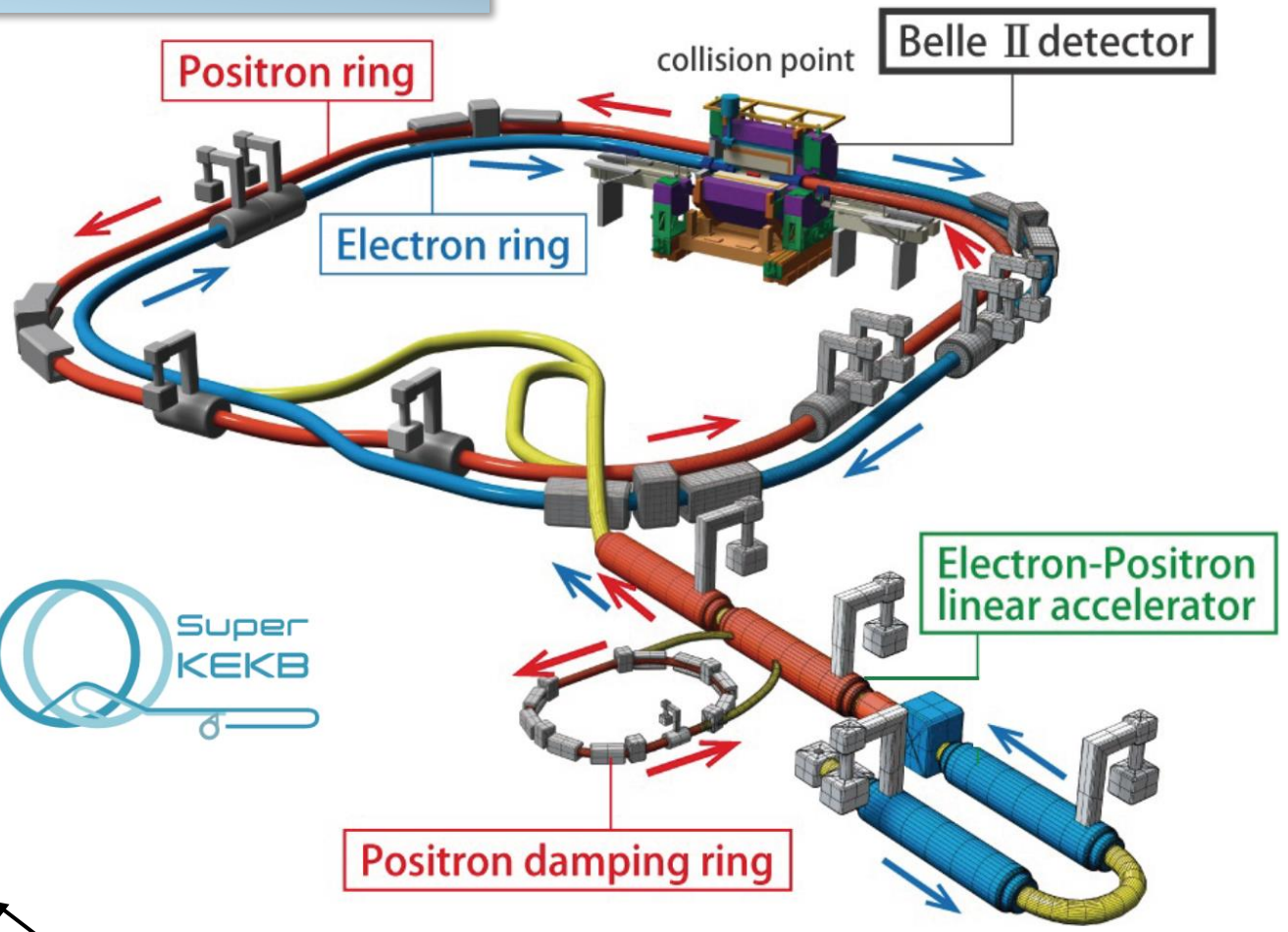
From KEKB to SuperKEKB

- **Upgraded rings**
  - New e^+ Damping Ring
  - Increased currents

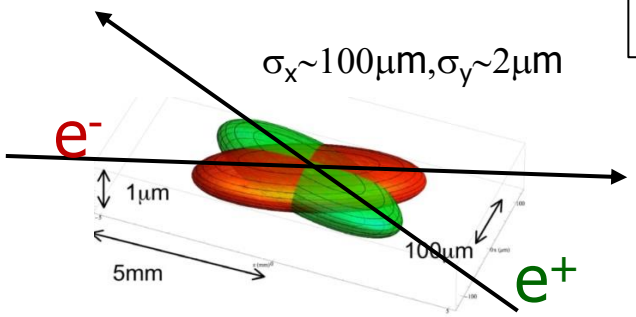
x30

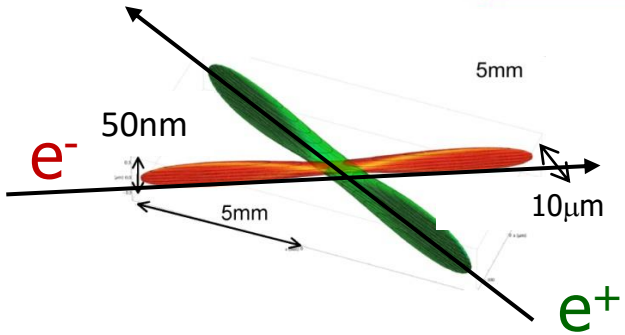
- **Nano-beam scheme** (x20)
  - New Final Focus magnets (QCS)
  - Large crossing angle

Final goal : 50 ab^{-1}

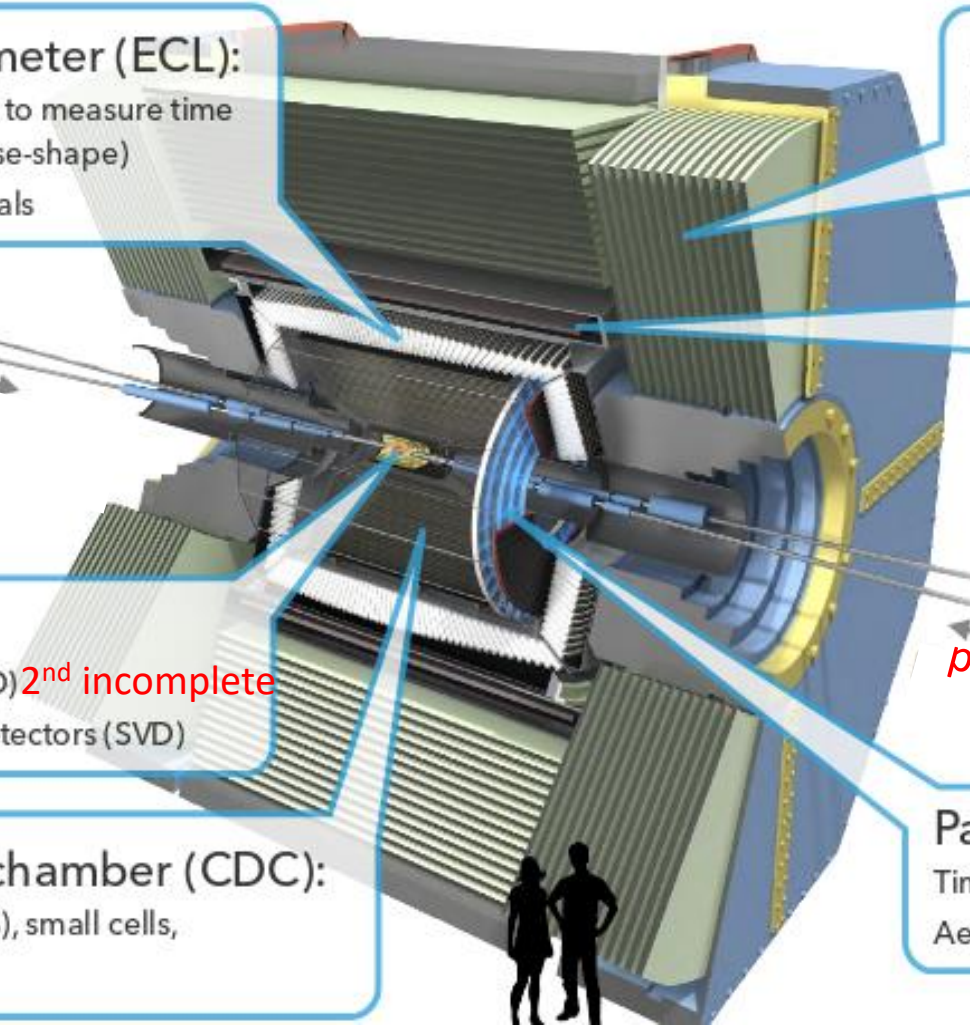


Nano-Beam scheme





Belle II detector



Electromagnetic calorimeter (ECL):
CsI(Tl) crystals, waveform sampling to measure time and energy (~~possible~~ upgrade: pulse-shape)
Non-projective gaps between crystals

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

Magnet:
1.5 T superconducting

electrons (7GeV)

positrons (4GeV)

Trigger:
L1: < 30 kHz
HLT: < 10 kHz
dedicated lines for low multiplicity physics

Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD) 2nd incomplete
4 layer double-sided silicon strip detectors (SVD)

Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells, fast electronics

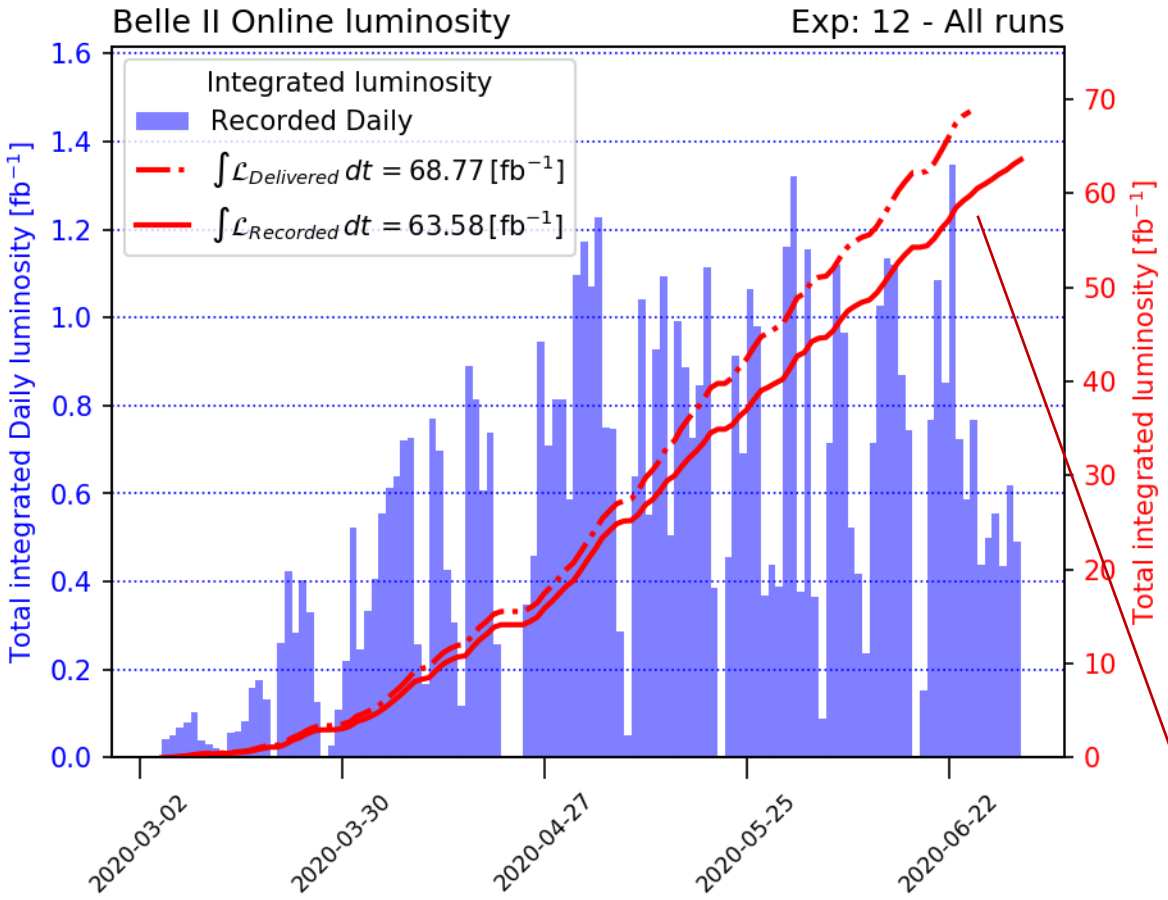
Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cerenkov Counter (ARICH)

Belle II vs Belle better detector, much better triggers, but higher backgrounds

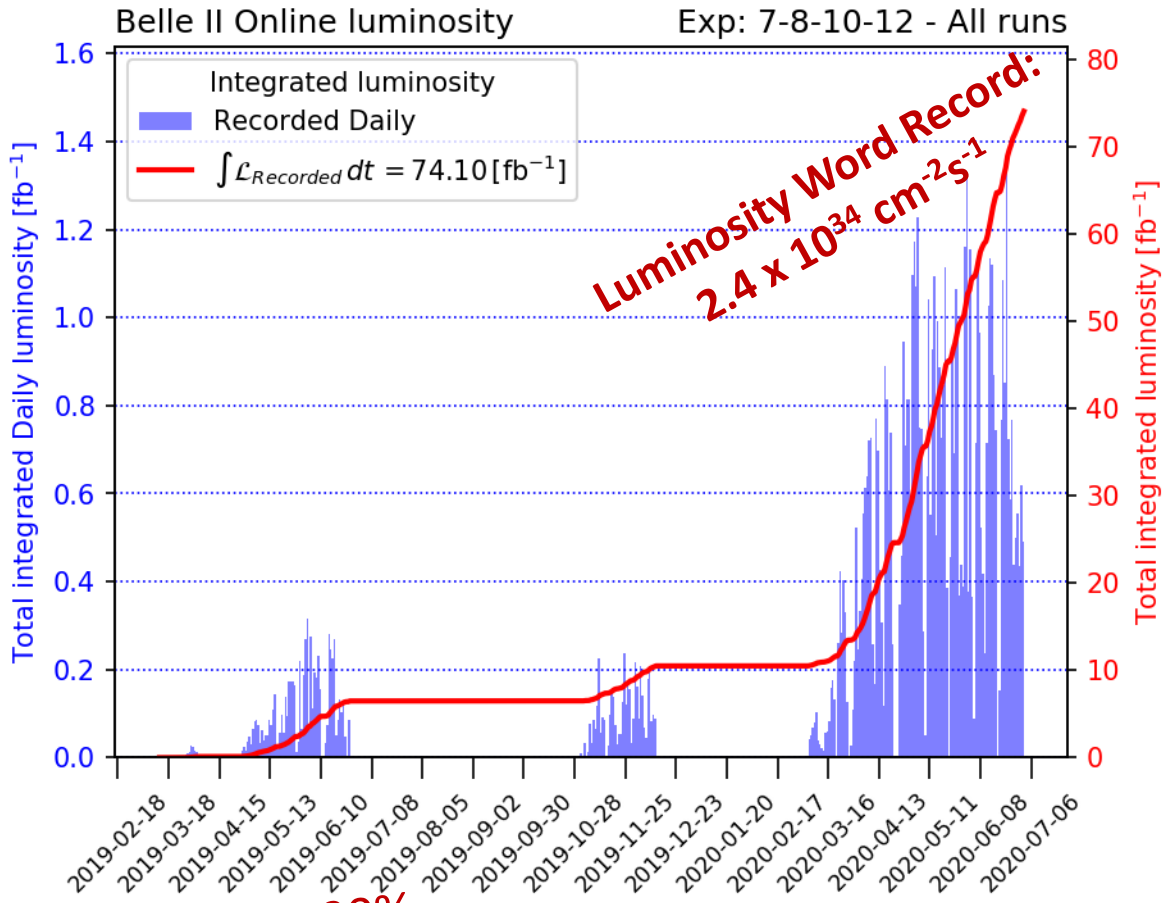
Final goal: L= 50 ab^{-1}

Belle II luminosity record

Collected luminosity during spring run



Collected luminosity up to now: 2019+2020



Data taking efficiency ≈ 90%

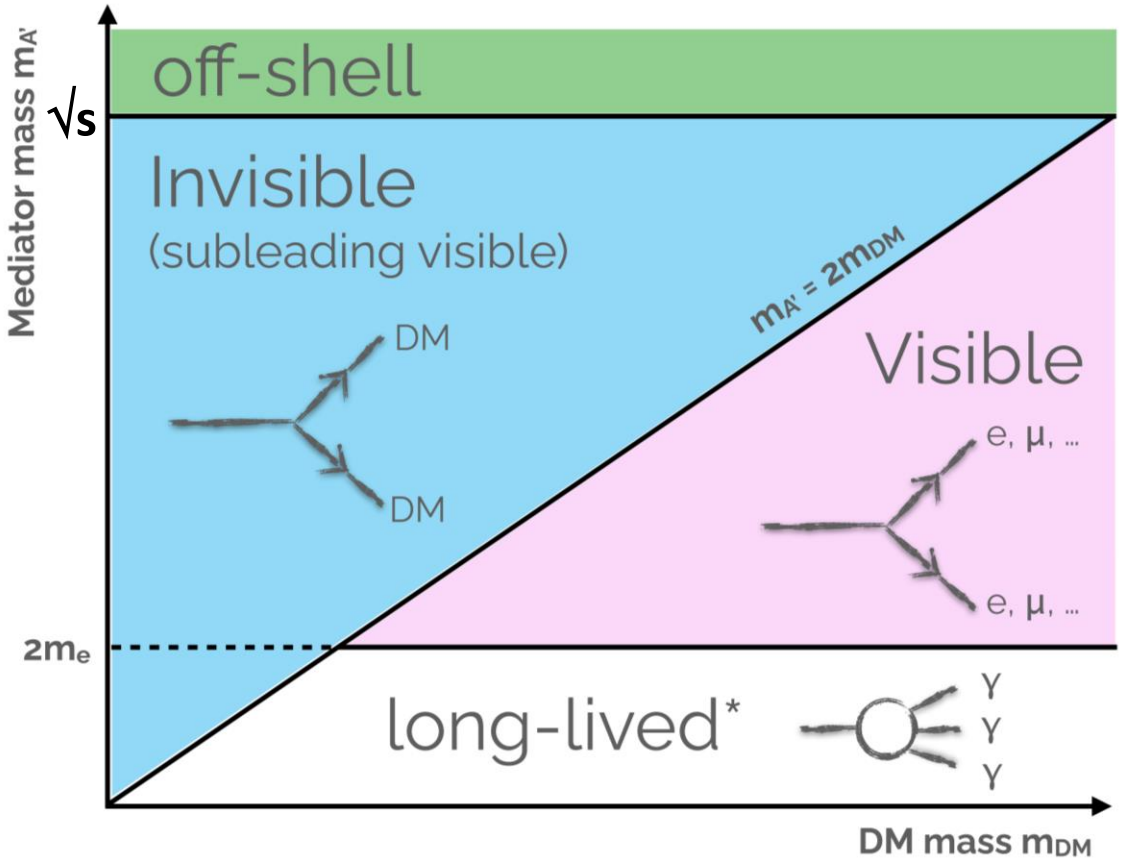
Spring run (2020 a+b) ended on July 1st

Fall run to start in ~September/October

Pilot run 2018: L ≈ 0.5 fb^{-1}

Light Dark matter hunt

Different signatures depending on the DM ↔ mediator mass relation

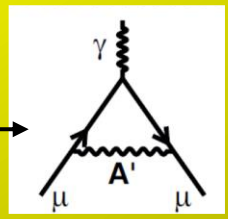


Probability of interaction of LDM detectors is negligible

- Search for mediators
- Search for missing energy signature
- Search for both

Additional benefits:

- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, …)
- Explanation of the $(g\text{-}2)_\mu$ effect →



- Explanation (with additional hypotheses) of some flavour anomalies (LHCb, Belle, …)
- Some light mediators (not interacting with quarks) could escape direct search exclusion limits

What can we do at B-factories that we can't at the LHC?

- Closeness to the light region
- Clean, low background, «energy conserving» environment, closed kinematics
- 3d momentum conservation, as opposed to p_T
- Easiness of tag & probe techniques
- Full Event Interpretation

- Low multiplicity signatures
- Missing energy channels
- Invisible particles, often in closed kinematics regime
- Some fully neutral final states accessibility

- Cleanliness and luminosity sometimes compensate for cross section → competition

Searching for dark matter at the intensity frontier

KLOE/KLOE-2, BESIII, BaBar, Belle, Belle II: optimal position to probe a dark sector at the GeV scale:

- They operate **exactly** at that scale: $\sqrt{s}$= **DAϕNE ≈ 1 GeV**, **BEPC ≈ 3-4 GeV**, **(SUPER)KEKB, PEPII ≈ 10-11 GeV**
- Most of the interesting cross sections scale with 1/s
- Unique places to study some rare light meson decays (ϕ, J/ψ, Υ factories!)

Collected luminosities

KLOE ≈ 2 fb^{-1}
KLOE-2 ≈ 5 fb^{-1} not used for these results

BESIII ≈ 15 fb^{-1} at different $\sqrt{s}$ in progress

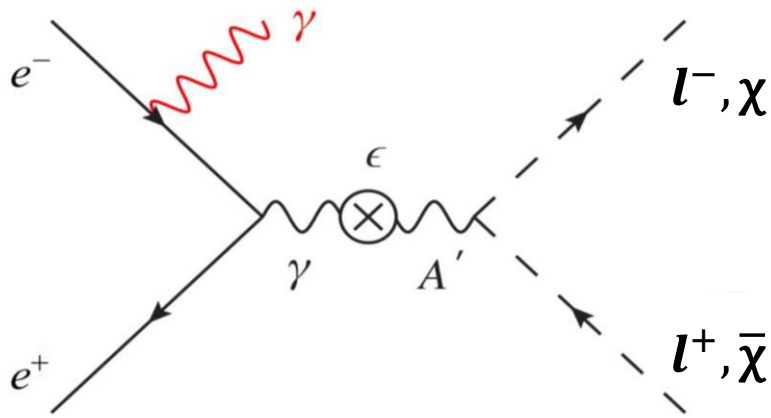
BaBar ≈ 0.5 ab^{-1}
Belle ≈ 1 ab^{-1}

Belle II ≈ 74 fb^{-1} in progress

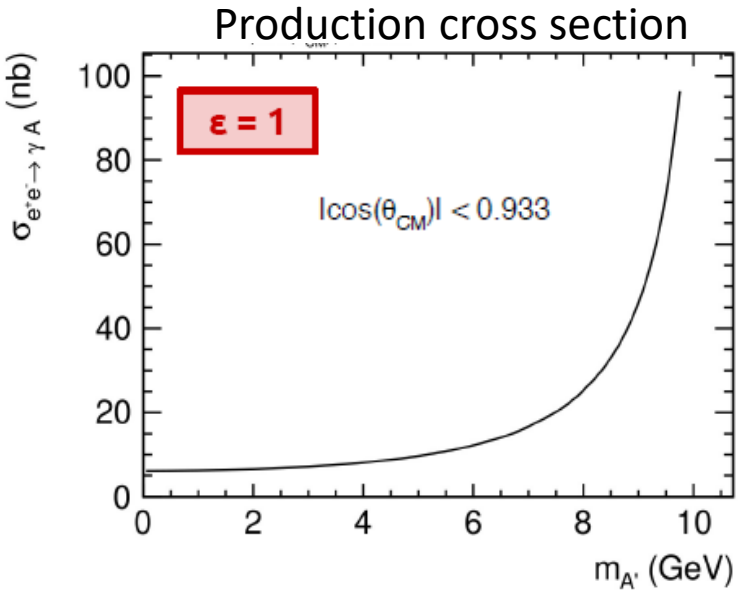
Dark photon: introduction

P. Fayet, Phys. Lett. B **95**, 285 (1980),
P.Fayet, Nucl. Phys. B **187**, 184 (1981)

- Paradigm of the vector portal extension of the SM
- QED inspired: U(1)' → new spin 1 gauge boson A'
- Couples to SM hypercharge Y through kinetic mixing ε
- Couples to dark matter with strength α_D
- Mass through Higgs or Stuckelberg mechanism



Minimal dark photon

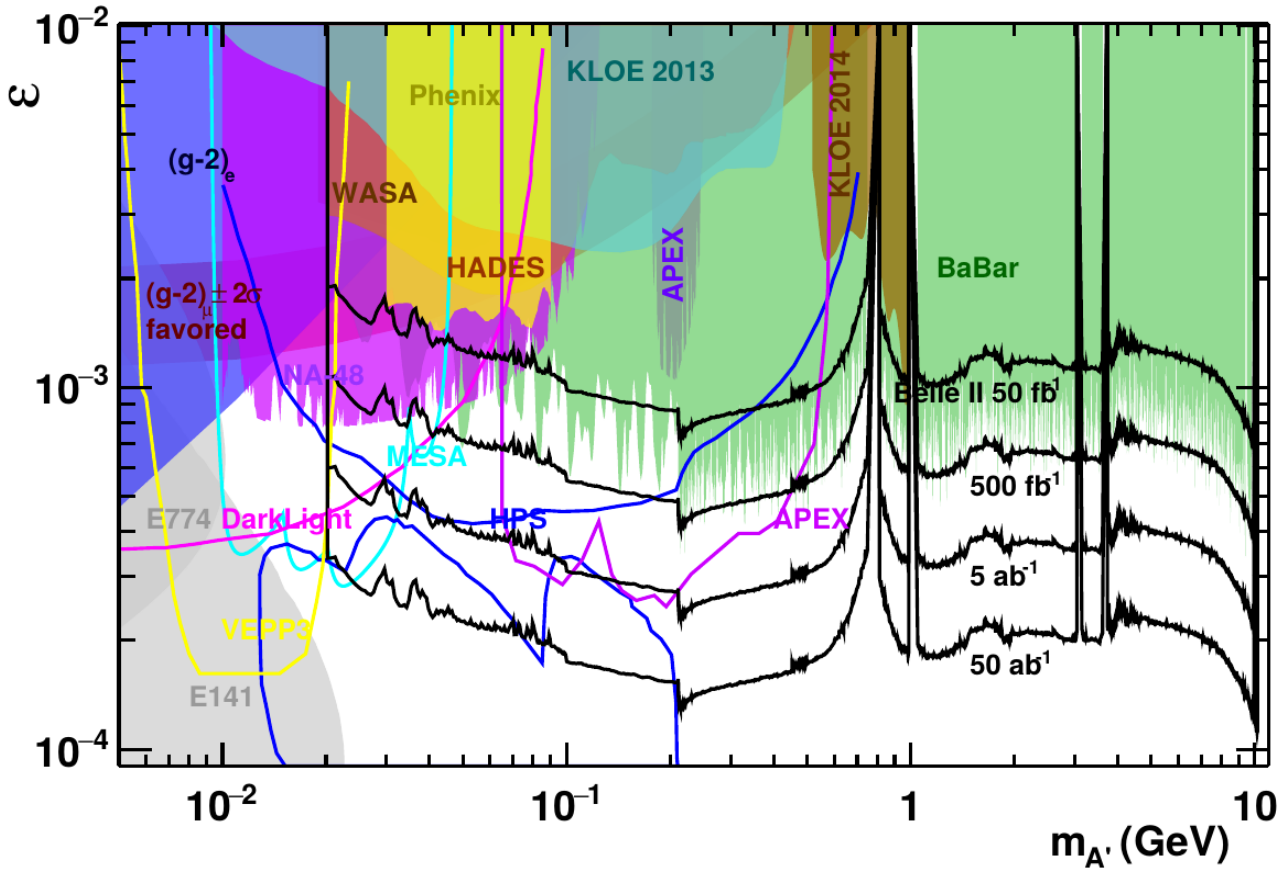


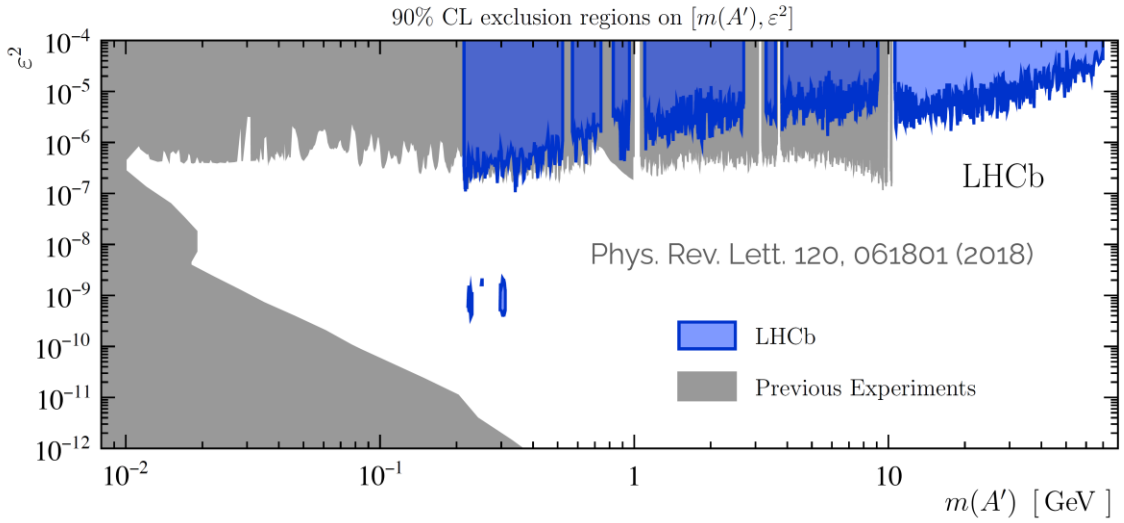
two basic scenarios depending on A′ vs χ DM mass relationship

$m_{A'} < 2m_\chi \Rightarrow$ A' decays visibly to SM particles (*l*, *h*)

$m_{A'} > 2m_\chi \Rightarrow$ A' decays ≈100% invisibly to DM particles

Visible dark photon: sensitivity





Competition with LHCb:

Drell-Yan processes
Displaced vertices
$D^* \rightarrow D\ A', A' \rightarrow ee$

Best limits in the GeV region from **BaBar**

PRL 113, 201801 (2014)

Belle had no suitable low mutiplicity triggers for this search

Hadronic and $\tau\tau$ final states much harder

Belle II needs some years of data for leading sensitivity: search currently in preparation

Invisible dark photon

P. Fayet, Phys. Lett. B **95**, 285 (1980),
P.Fayet, Nucl. Phys. B **187**, 184 (1981)

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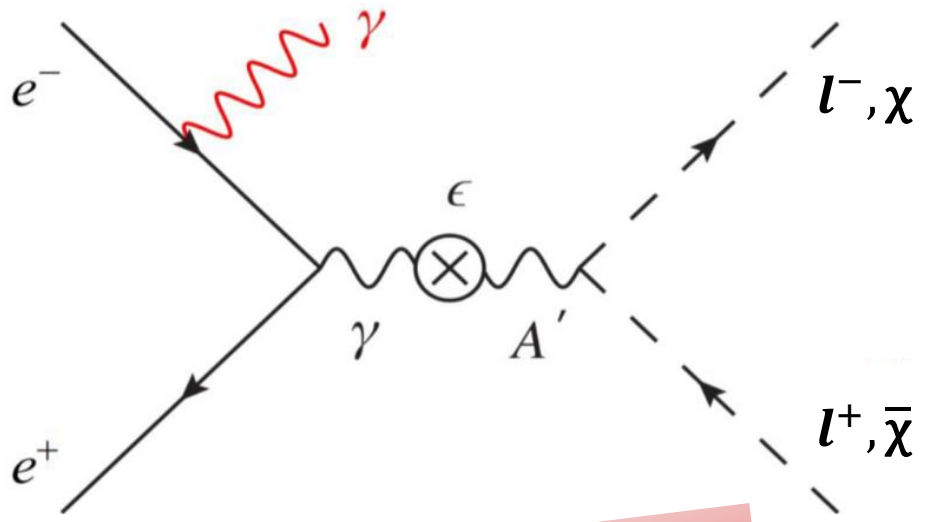
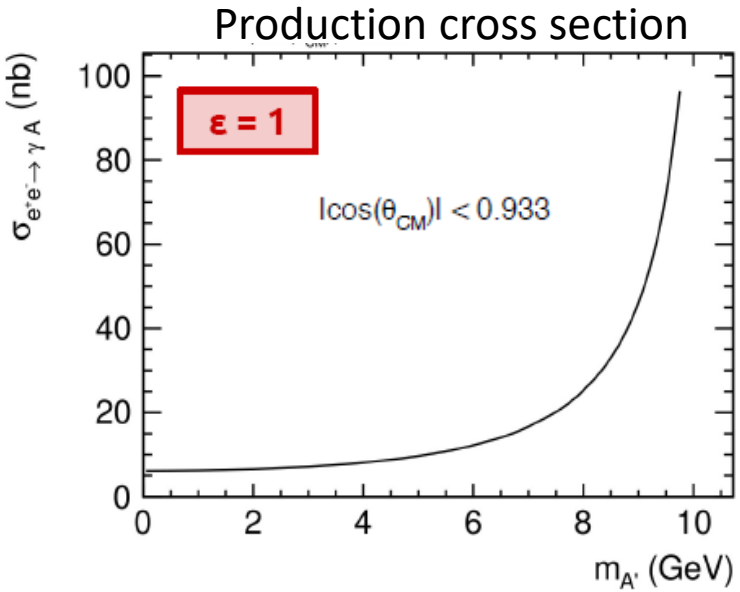


Minimal dark photon



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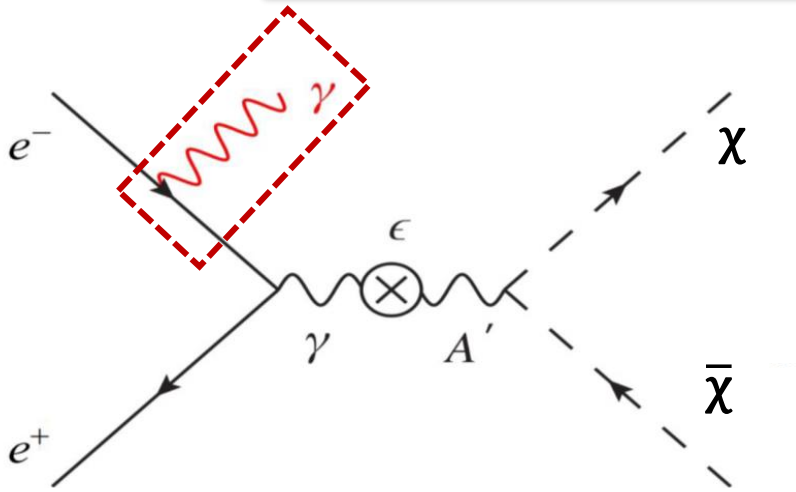
Invisible dark photon: experimental signature



Only **one photon** in the detector

Needs a **single photon trigger**
(*not available in Belle, ≈ 10% of data in BaBar*)

Needs an excellent knowledge of the **detector acceptance**

$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$

→ Bump in recoil mass or photon energy

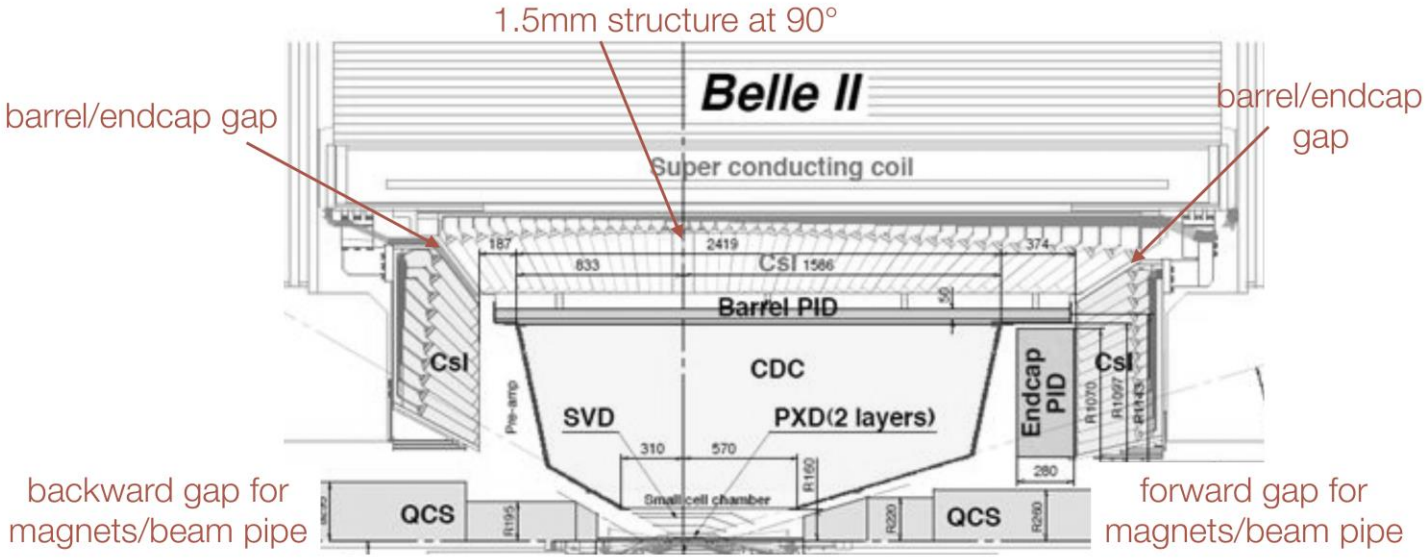
Backgrounds

$e^+e^- \rightarrow e^+e^-\gamma(\gamma)$ → high $M_{A'}$ region

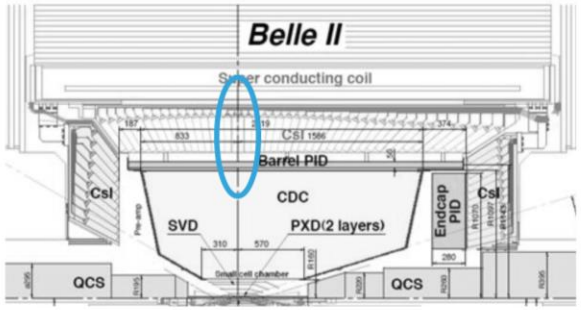
$e^+e^- \rightarrow \gamma\gamma(\gamma)$ → low $M_{A'}$ region

Cosmics

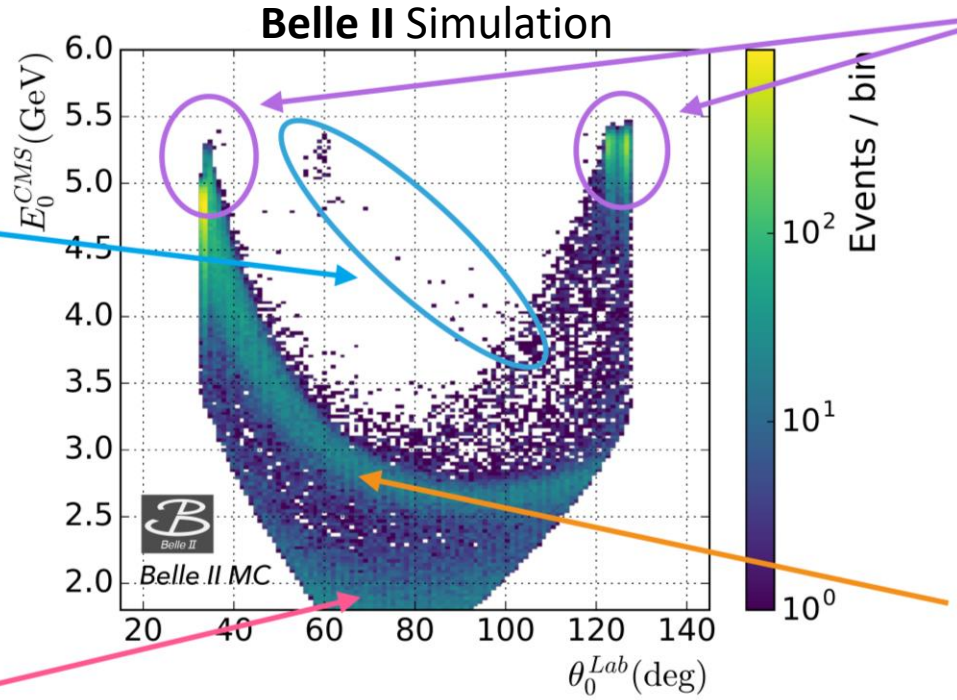
$e^+e^- \rightarrow \gamma\nu\nu$

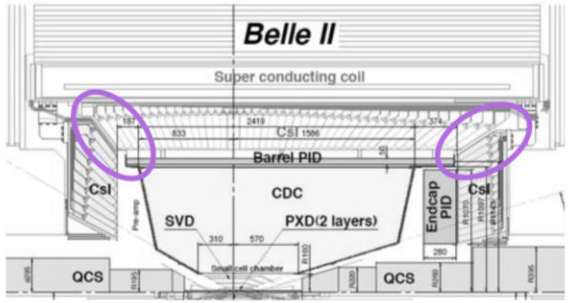


Invisible dark photon: background



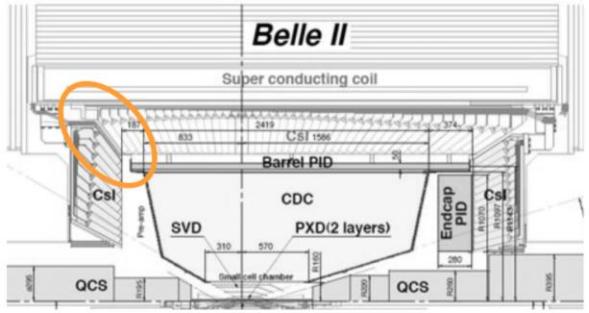
ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance





ee→2γ
1γ in ECL BWD or FWD gap

ee→eeγ
both electrons
out of tracking acceptance



ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

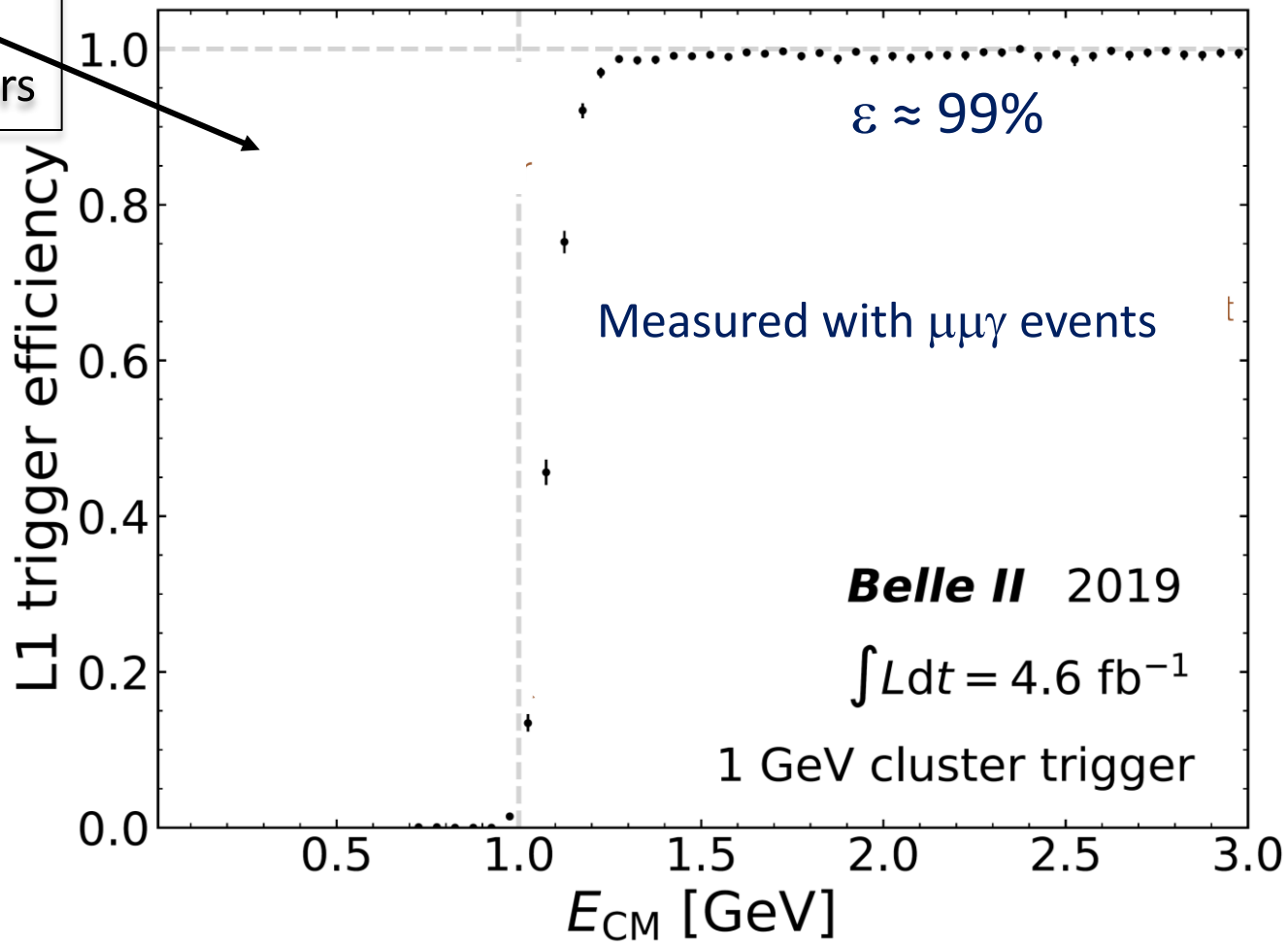
Crucial usage of KLM to veto photons in ECL gaps

Invisible dark photon: single photon trigger

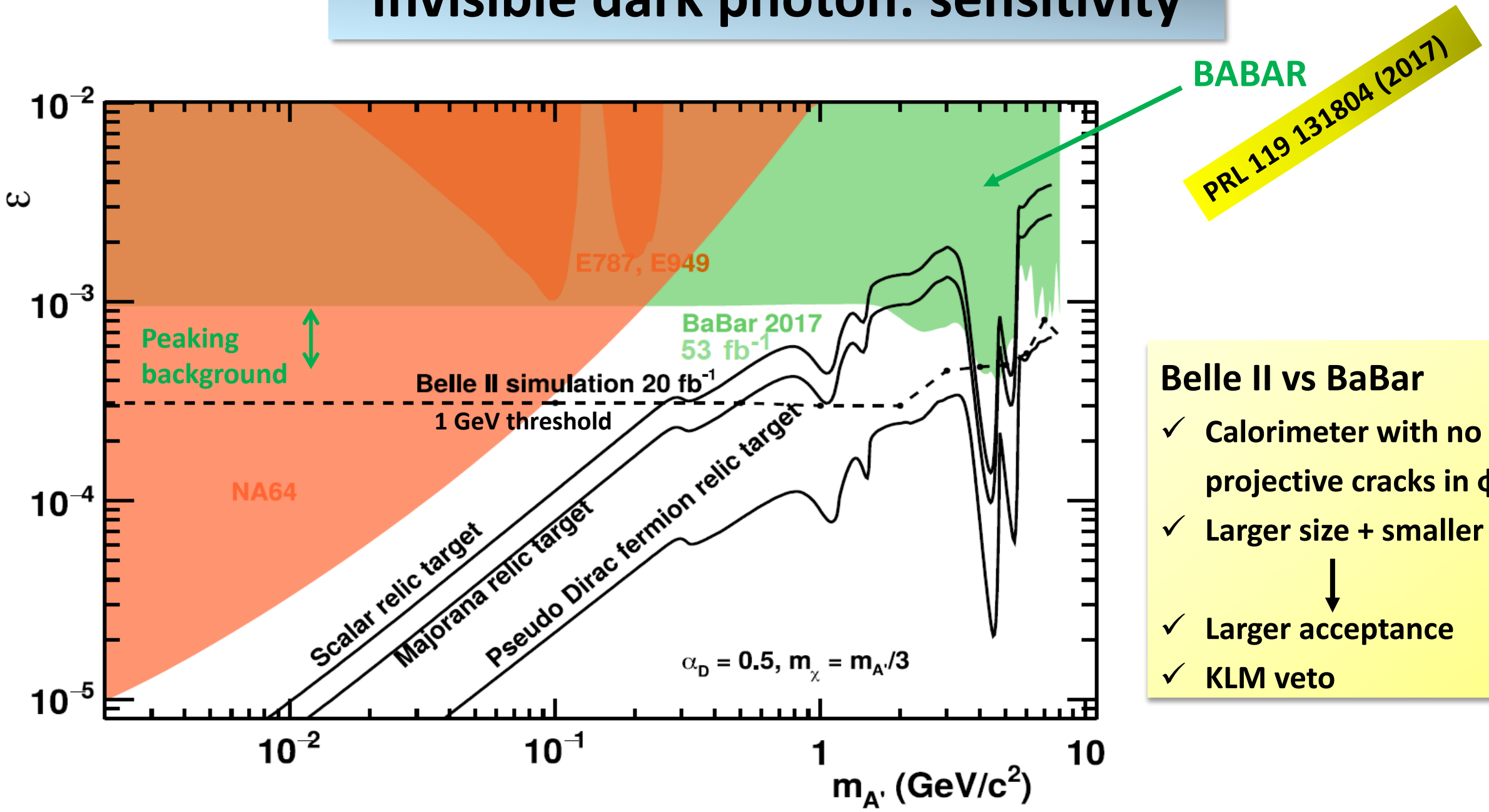
- **E_{CM} > 2 GeV**
- **E_{CM} > 1 GeV** in barrel + no other clusters
- **E_{CM} > 0.5 GeV** in central barrel + no other clusters

Would extend the search range up to
$M_{A'}$<≈10 GeV (psycological threshold)

Much more aggressive than originally expected.
Good conditions to perform the measurement as soon as possible.



Invisible dark photon: sensitivity



Belle II vs BaBar

- ✓ Calorimeter with no projective cracks in ϕ
- ✓ Larger size + smaller boost

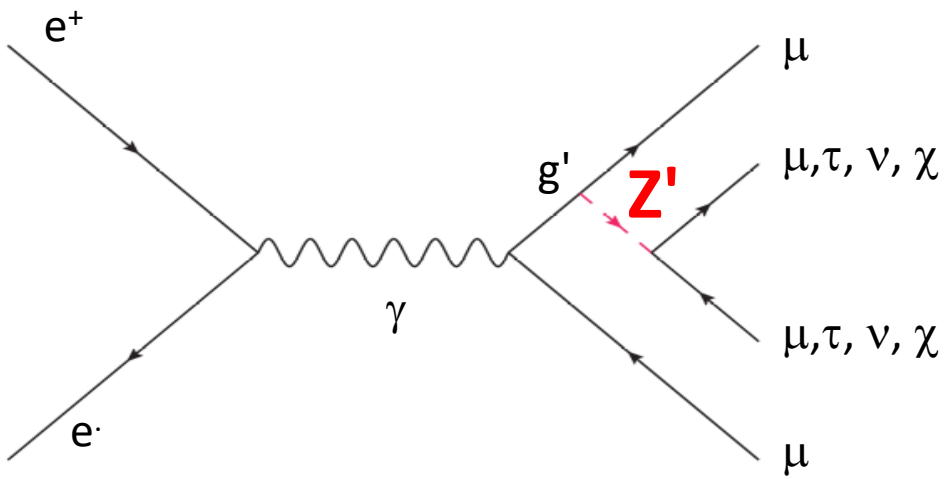
↓

- ✓ Larger acceptance
- ✓ KLM veto

Z': $L_\mu - L_\tau$ model

- Gauging $L_\mu - L_\tau$, the difference of leptonic μ and τ number
- A new gauge boson which couples only to the 2° and 3° lepton family
- Anomaly free (by construction)
- It may solve
  - **dark matter puzzle** → Sterile ν's / Light Dirac fermions
  - **$(g-2)_\mu$**
  - **$B \to K^{(*)}\mu\mu$, R_K, R_{K^*} anomalies**

Shuve et al. (2014), arXiv 1408.2727
Altmannshofer et al. (2016) arXiv 1609.04026



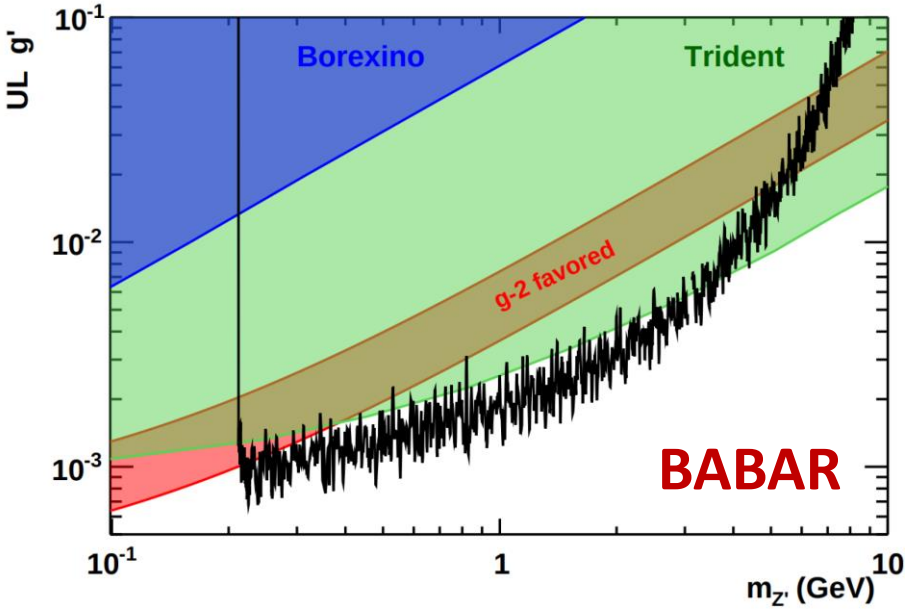
Non-minimal dark photon

Z'→μμ
- **BABAR**
- **CMS** → $Z^0 \to Z'\mu\mu$
- Belle (in preparation)
- Belle II

Z'→invisible → **Belle II**

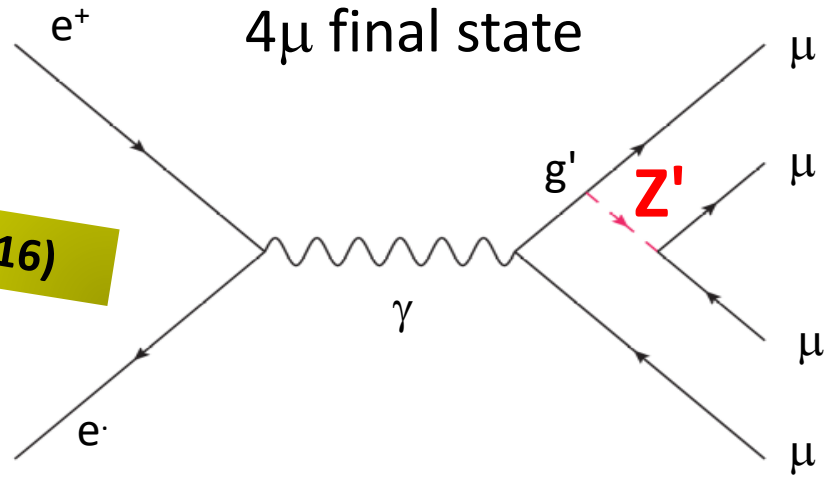
Z' →μμ: muonic dark force

L=514 fb^{-1}



Phys Rev D 94, 011102 (2016)

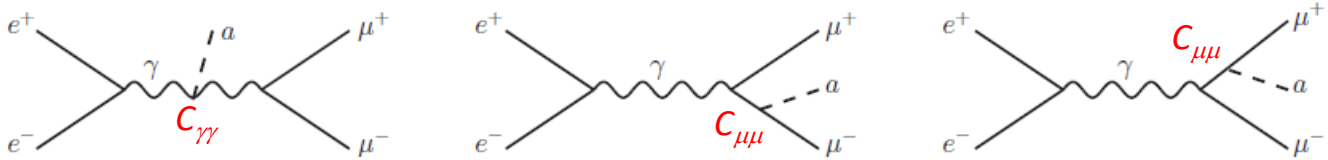
4μ final state



Same final state as in ALP→μμ

M.Bauer, M.Neubert, A.Thamm arXiv:1708.00443v2

$C_{\gamma\gamma}$, $C_{\mu\mu} \neq 0$



Belle: in preparation, based on full luminosity

Belle II: ≈ 100 fb^{-1} to compete (with aggressive background suppression)

Belle II: Z' to invisible

- Gauging $L_\mu - L_\tau$, the difference of leptonic μ and τ number
- A new gauge boson which couples only to the 2° and 3° lepton family
- Anomaly free (by construction)
- It may solve
  - **dark matter puzzle** → Sterile ν's / Light Dirac fermions
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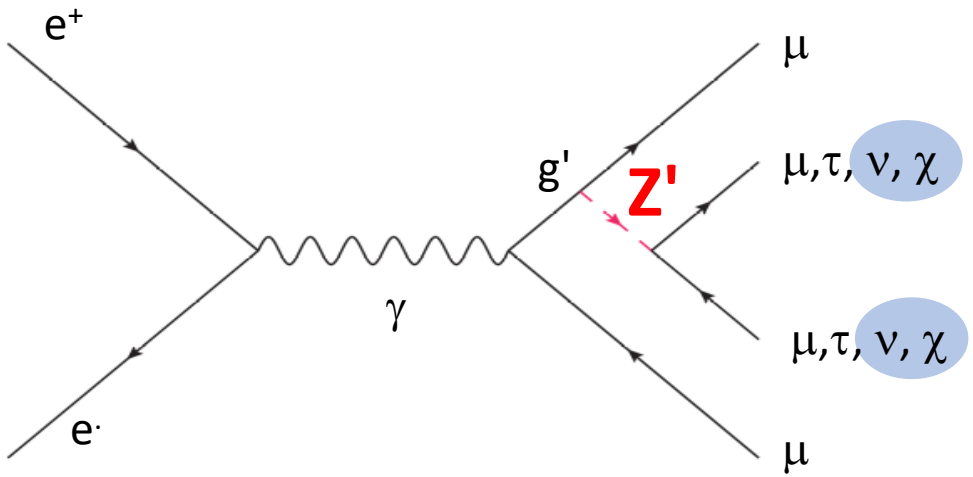


Non-minimal dark photon

Explored for the first time

$e^+e^- \to \mu^+\mu^-$ + *missing energy*

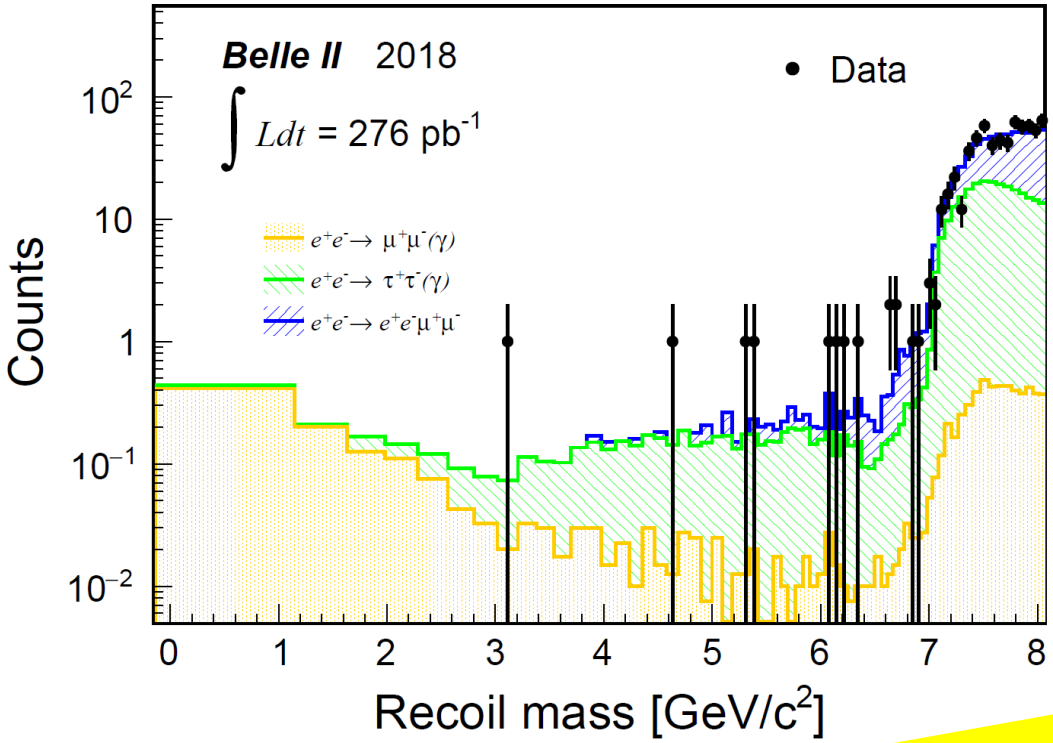
Look for bumps in recoil mass against a $\mu^+\mu^-$ pair

Main backgrounds:

$e^+e^- \to \mu^+\mu^- (\gamma)$
$e^+e^- \to \tau^+\tau^- (\gamma)$, $\tau^\pm \to \mu^\pm\nu\nu$
$e^+e^- \to e^+e^- \mu^+\mu^-$

Z' to invisible: results

Pilot run physics results

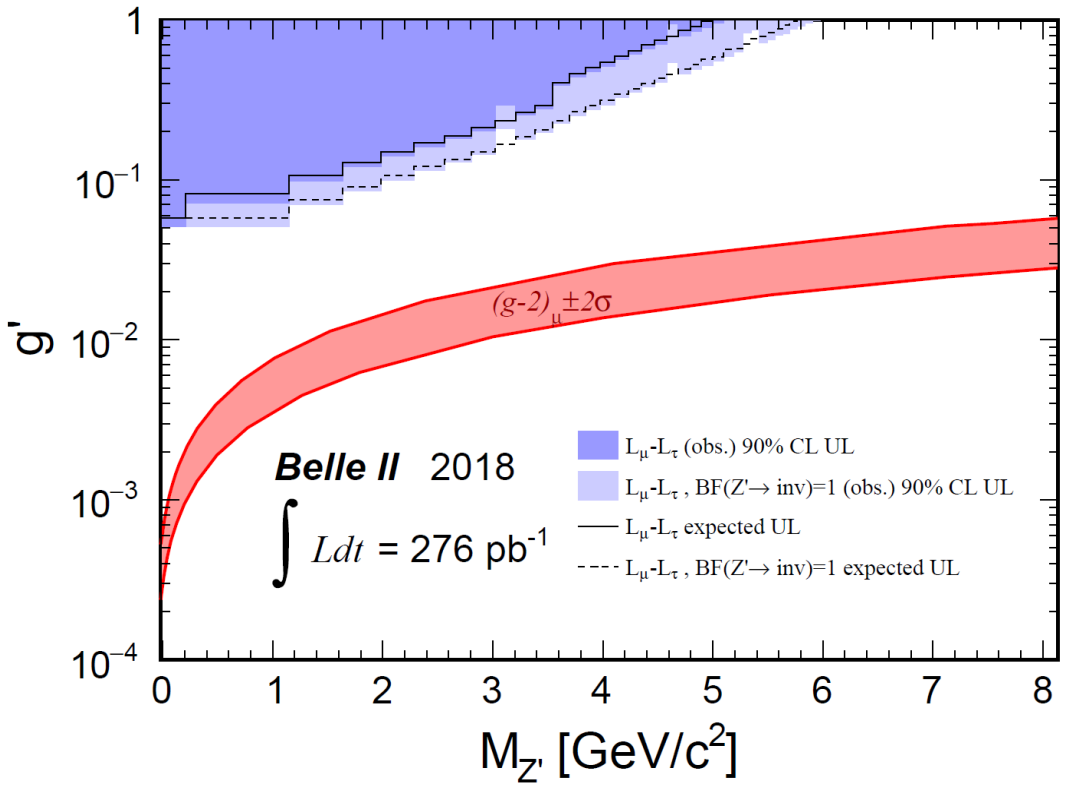


First physics paper by Belle II
PRL 124 (2020), 141801

Systematics

Source	Uncertainty
Trigger efficiency	6%
Tracking efficiency	4%
PID	4%
Luminosity	1.5%
Background before τ suppression	2%
τ suppression (background)	22%
Discrepancy in μμ yield (signal)	12.5%

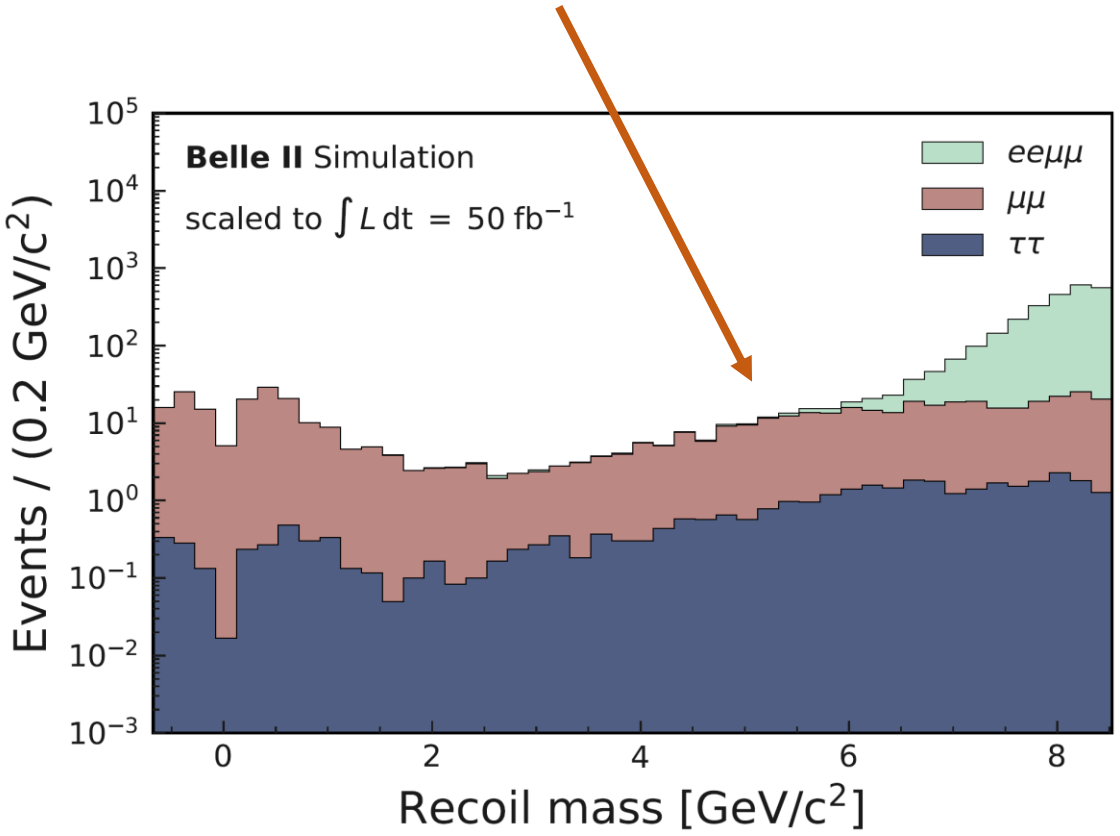
will decrease with new data

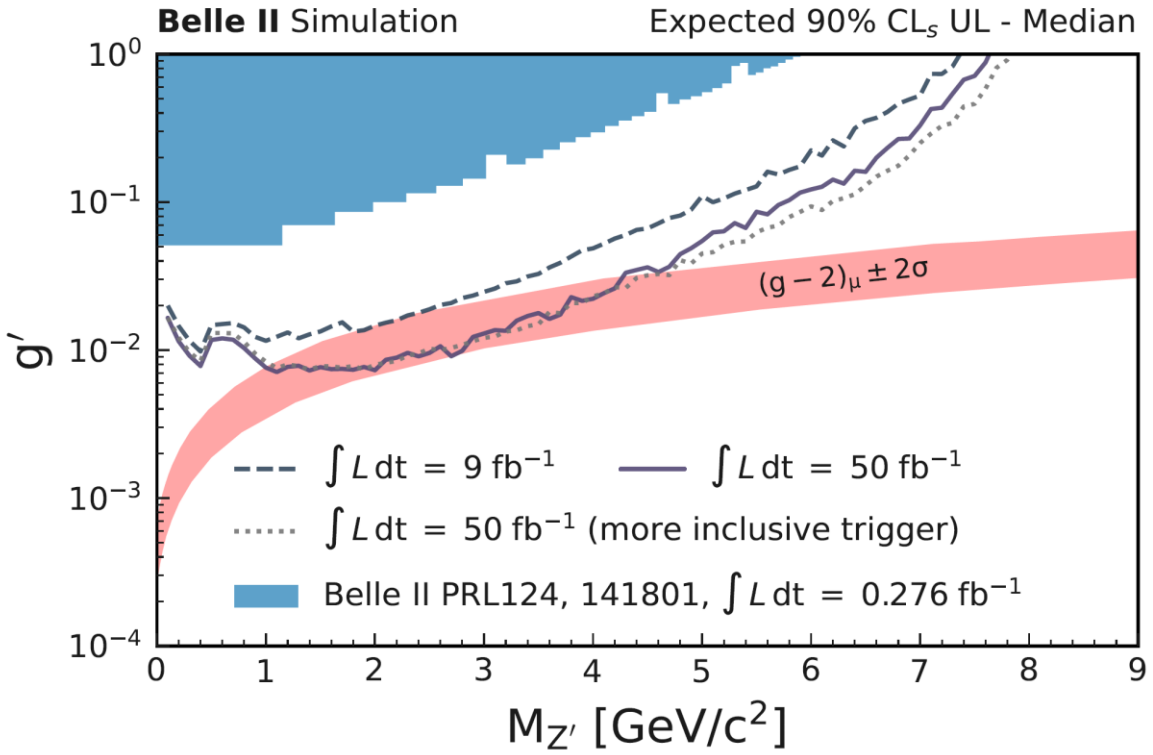


Z’ to invisible: short term projections

- KLM μID
- New triggers
- MVA selection
- Preliminary (conservative) systematics

Very low expected background → UL scale~1/L





LFV Z' to invisible

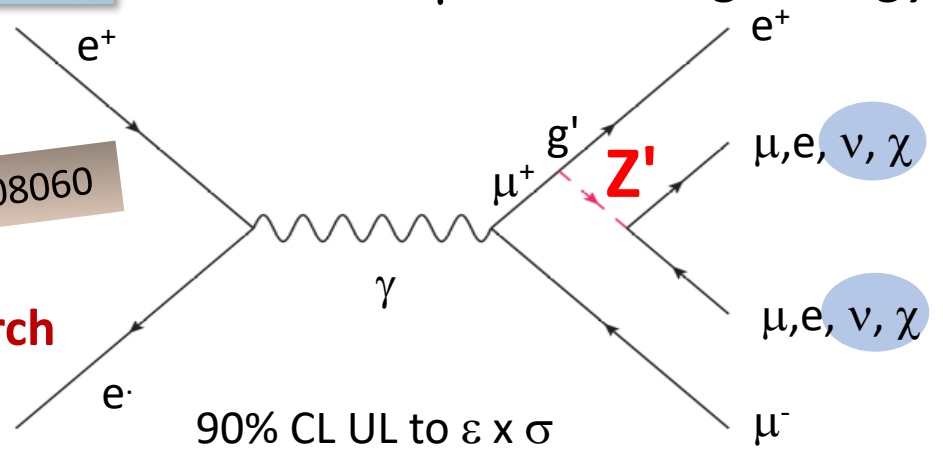
$e^+e^- \rightarrow e^+\mu^- +$ *missing energy*

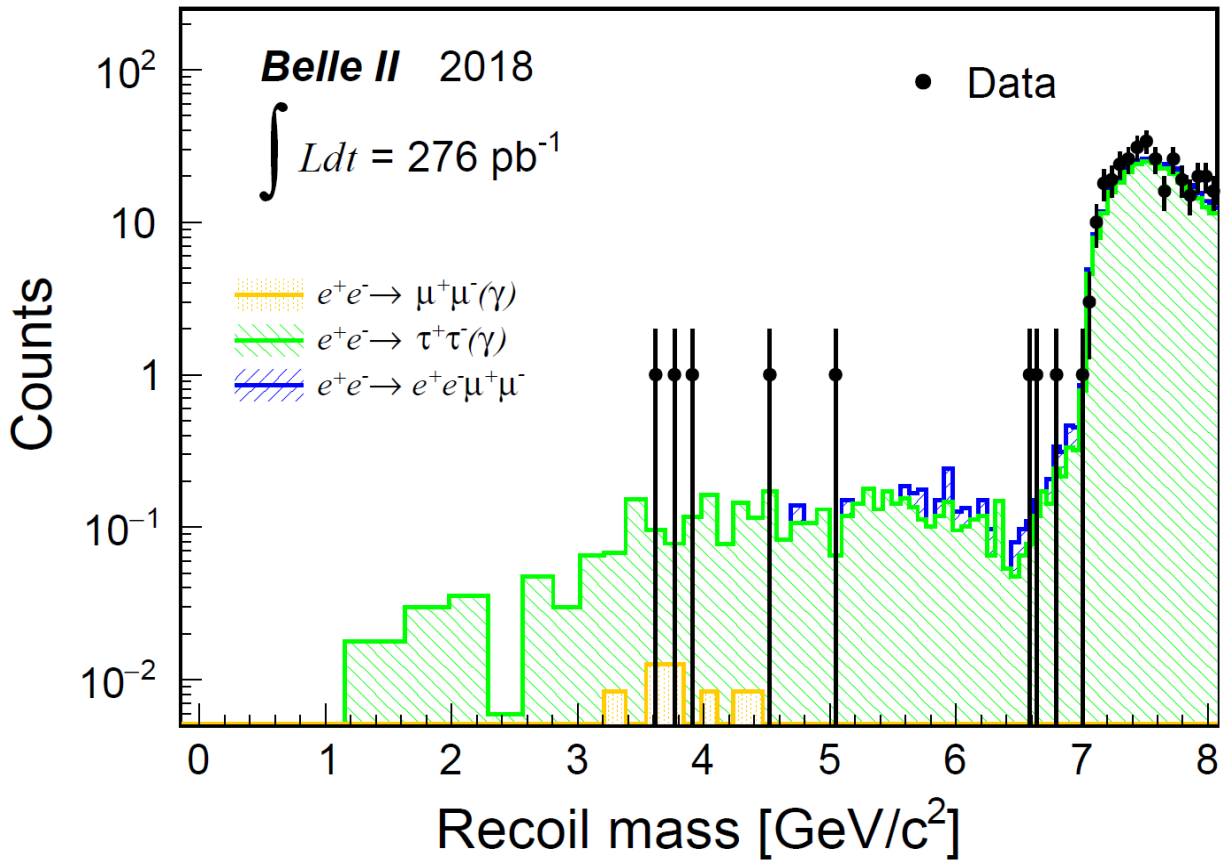
What about a Lepton Flavour Violating Z'?

Only e-μ coupling taken into account

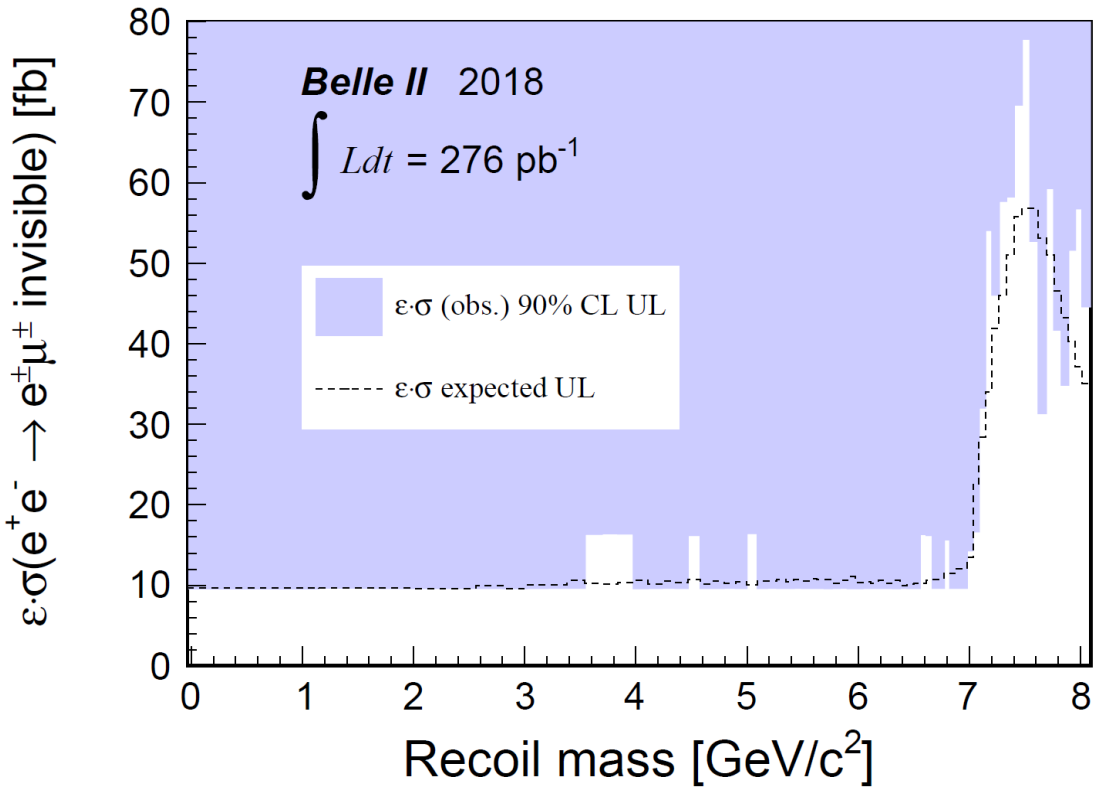
For example I.Galon et al. (2016), arXiv 1610.08060

Model independent search

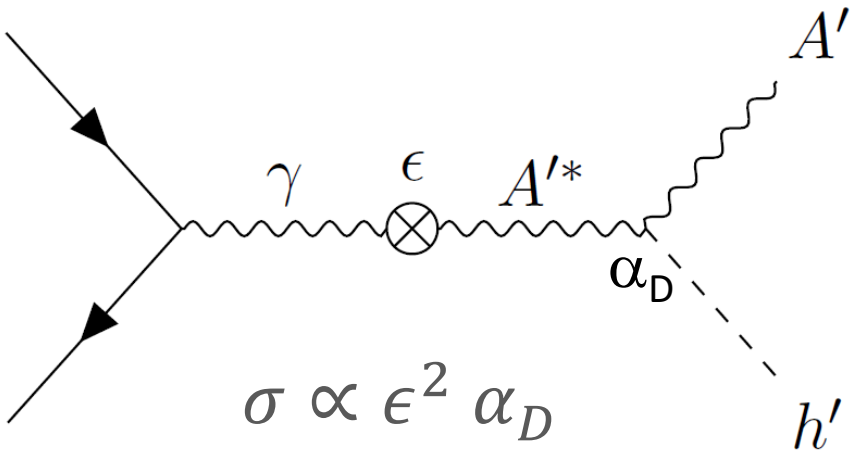


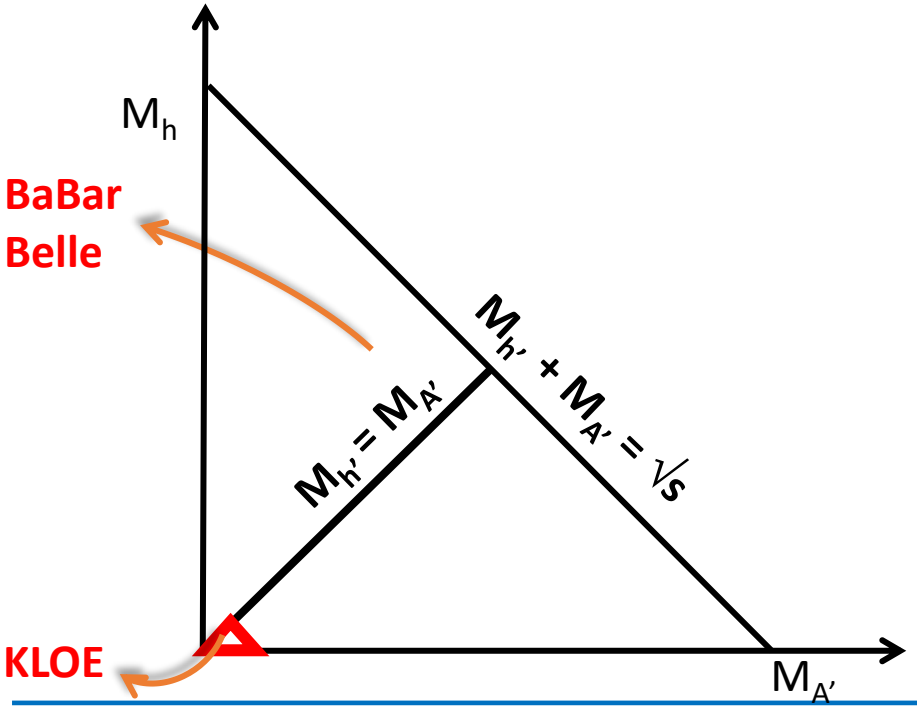


90% CL UL to ε x σ



Dark Higgsstrahlung: A'h'





Batell, Pospelov, Ritz, Phys. Rev. D 79, 115008 (2009)

- Dark photon A' + dark higgs h'
- h' → spontaneous symmetry breaking to give mass to A'
- Less suppressed in ε wrt standard A' search
- Very different scenarios depending on:
  - $M_{h'} > M_{A'} \Rightarrow$ h' → A'A' → 4*l*, 4 *had*, 2*l* + 2 *had* — **BaBar, Belle**
  - $M_{h'} < M_{A'} \Rightarrow$ h' "invisible" — **KLOE**

Long lived

Available results

minimal dark photon
non minimal model

Dark Higgsstrahlung: A'h', h'→ A'A'

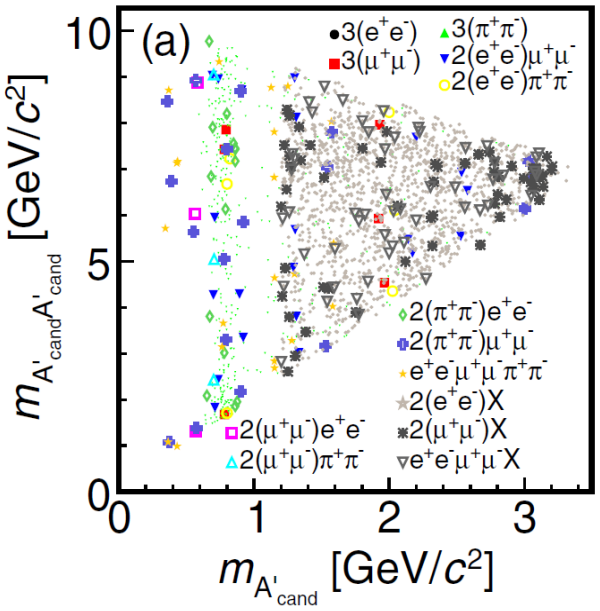
BaBar, Belle

- Three pairs of tracks (ee, μμ, ππ) at the same mass
- No missing energy
- ~ background free (but in the ρ region)

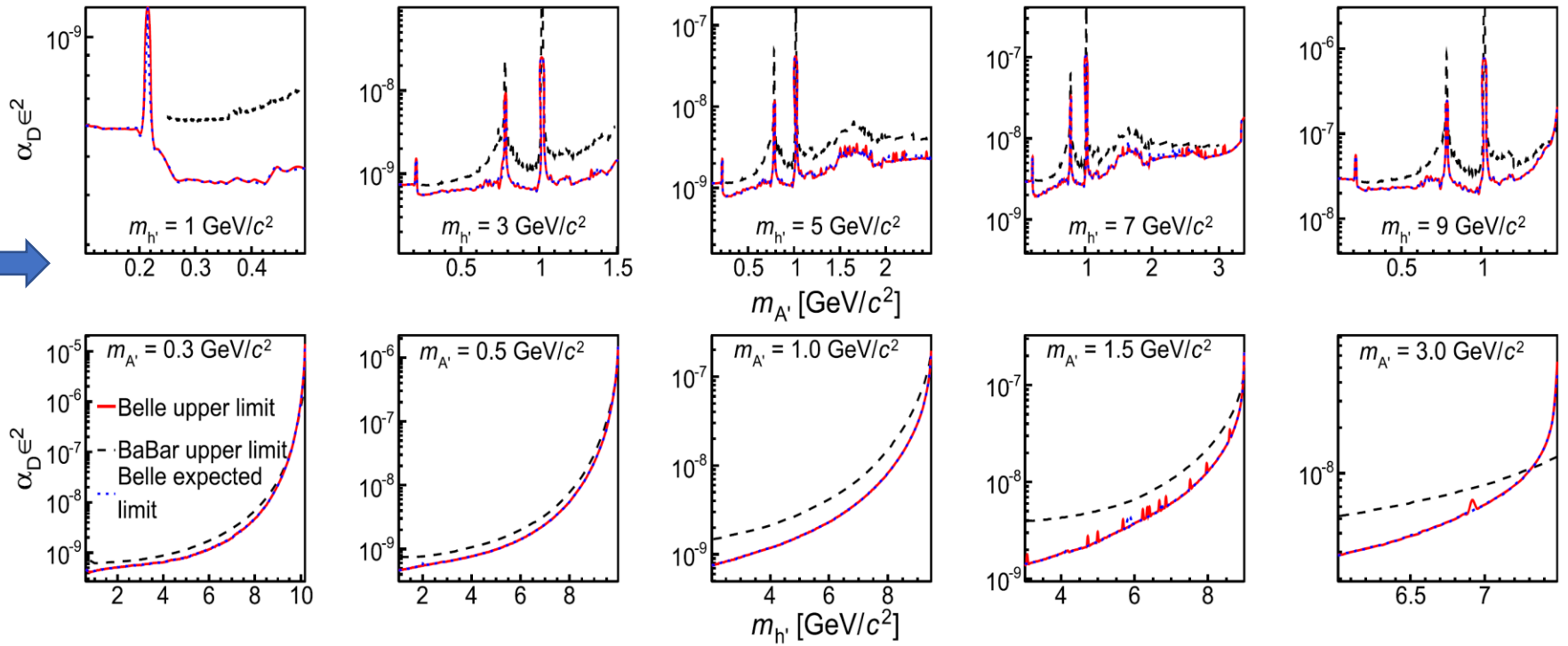
BaBar
PRL 108, 211801 (2012)

Belle
PRL 114, 211801 (2015)

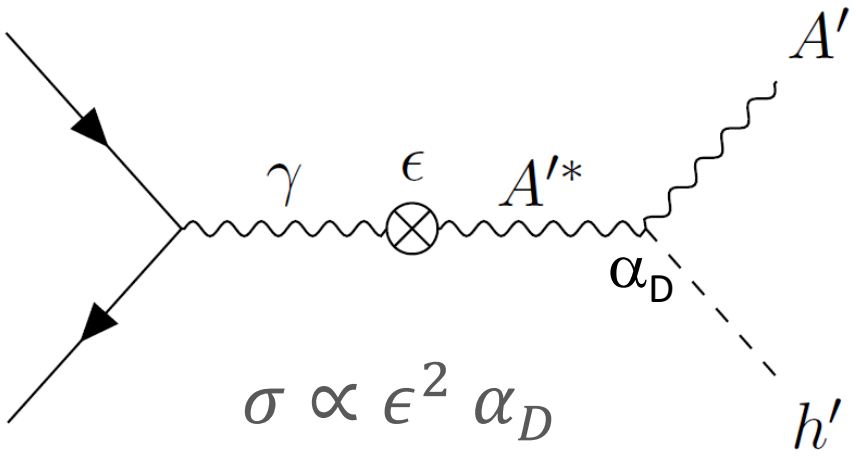
Belle observed events



Belle and BABAR Upper limts 90% CL



Dark Higgsstrahlung: A'h'



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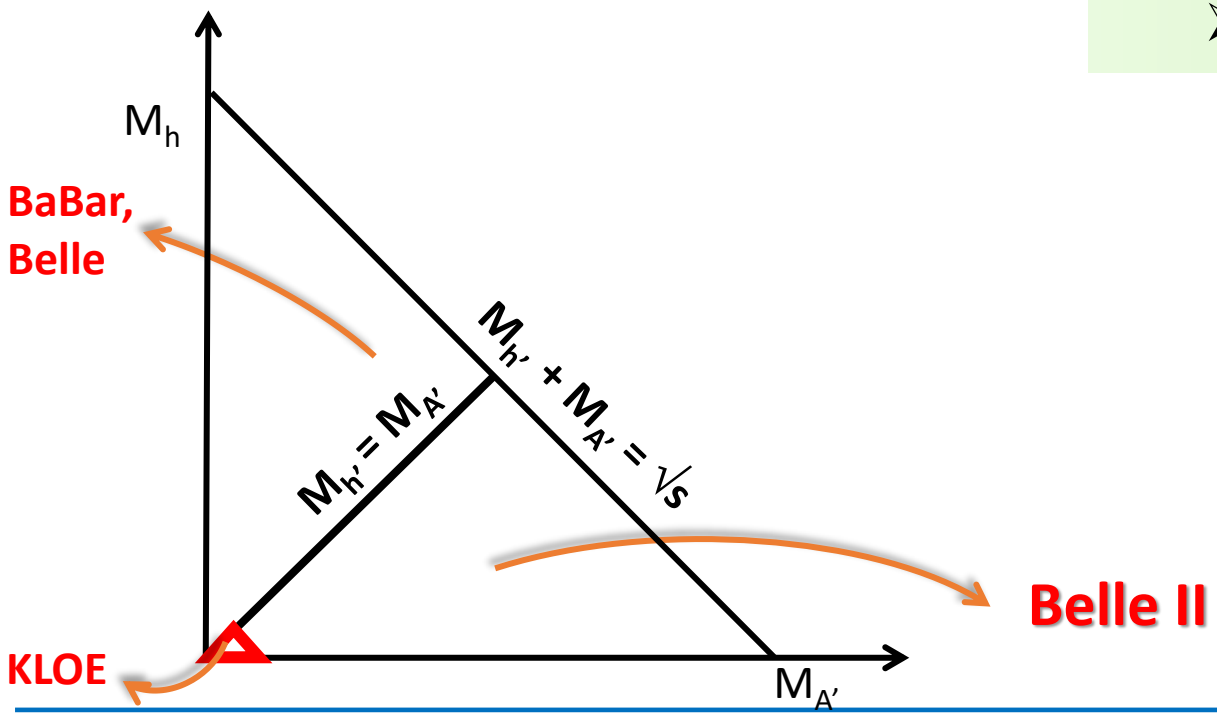
Long lived



minimal dark photon
non minimal model

Dark Higgsstrahlung: A′h′, h′ invisible

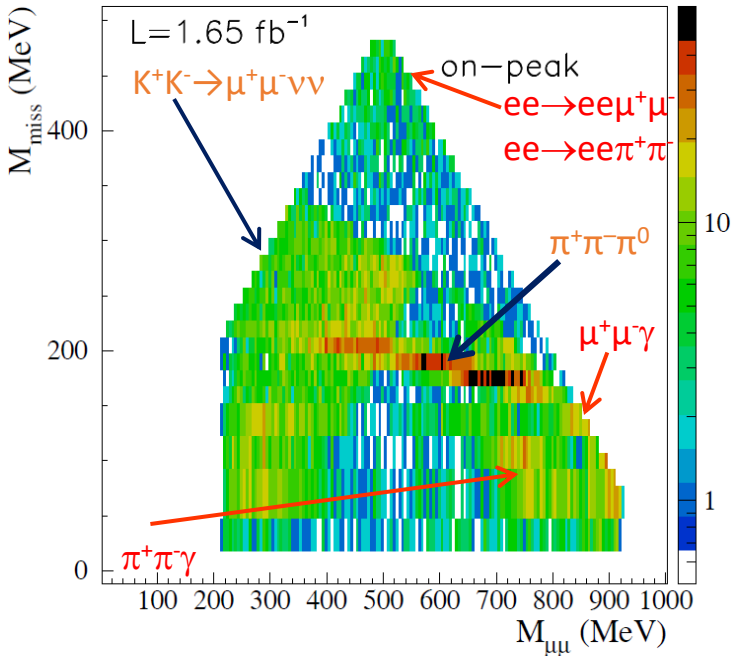
KLOE

Two muons + missing energy

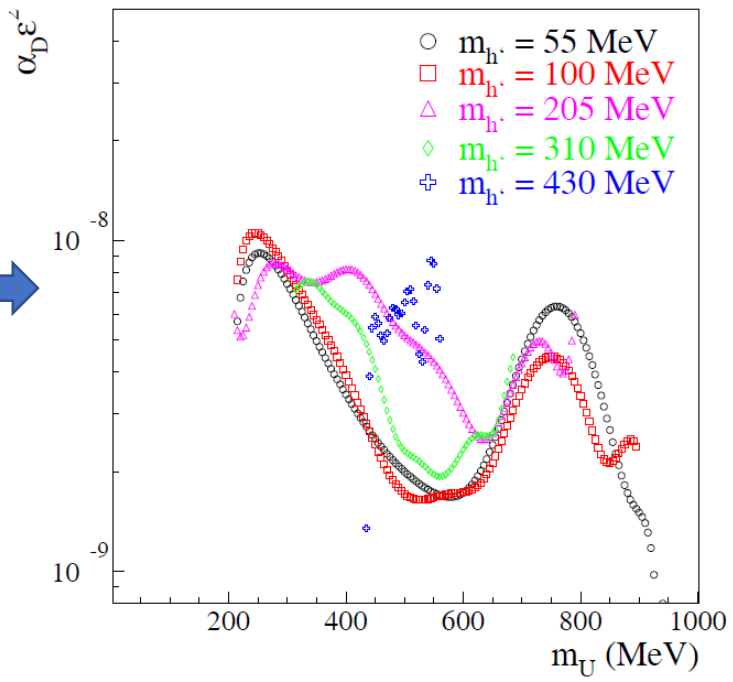
Background from K^+K^-, $\pi^+\pi^-\pi^0$, $\mu^+\mu^-(\gamma)$, $\pi^+\pi^-(\gamma)$, two-photon

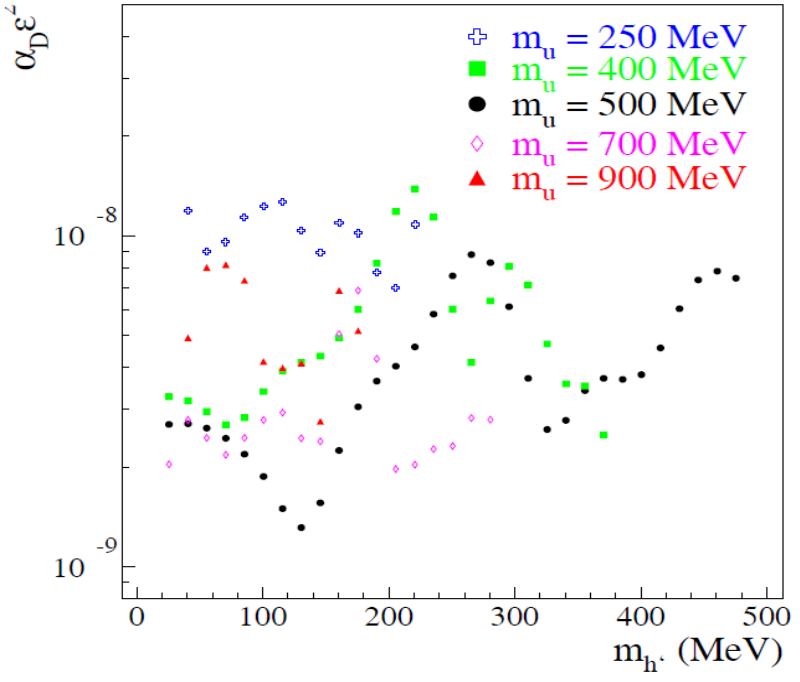
Phys.Lett. B747 (2015) 365

Observed events



Upper limts 90% CL

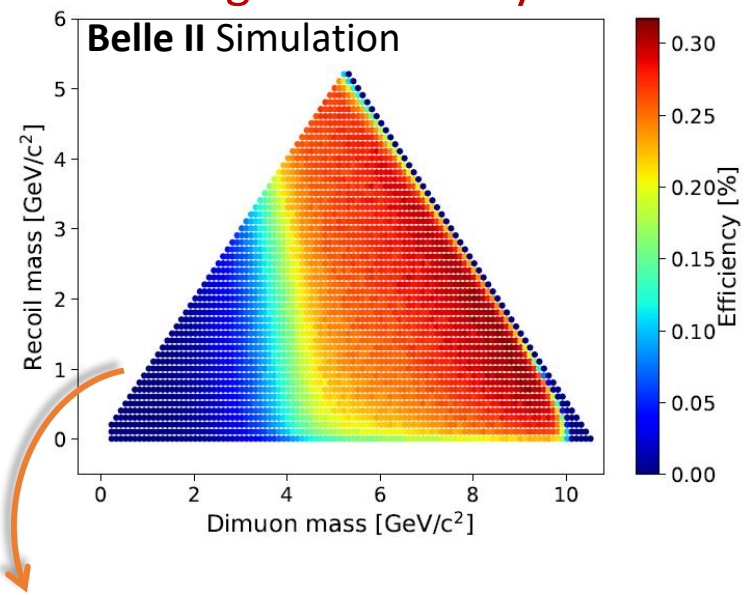




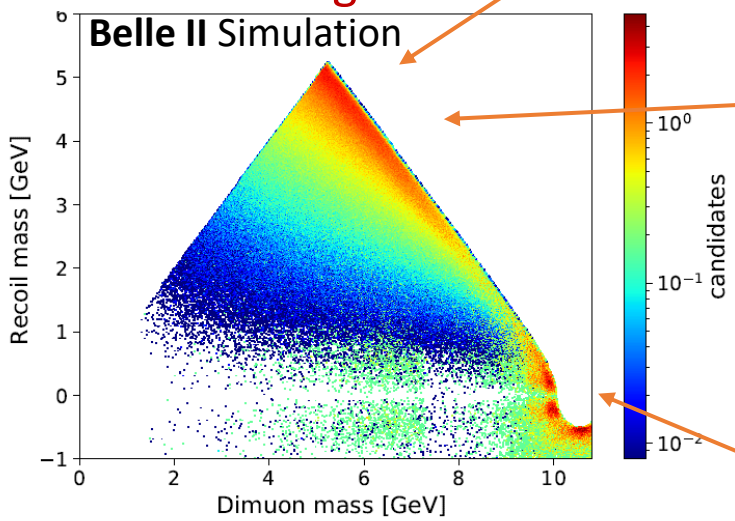
Dark Higgsstrahlung: A'h'

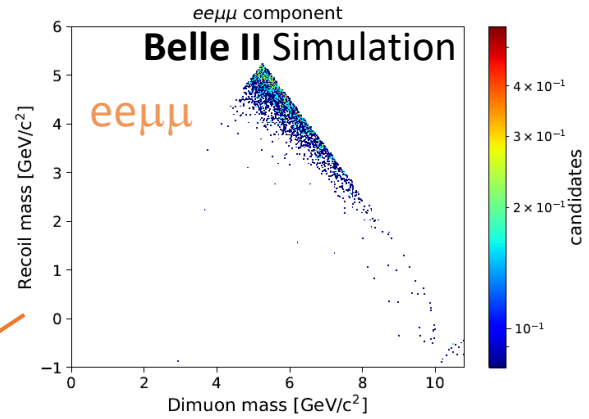
- **$\mu^+ \mu^-$ + missing energy** → same final state as in invisible Z'
- 2d peak in recoil vs dimuon mass
- Background naturally low due to 2d phase space
- **2019 data being used: L ≈ 9 fb^{-1} → next paper**

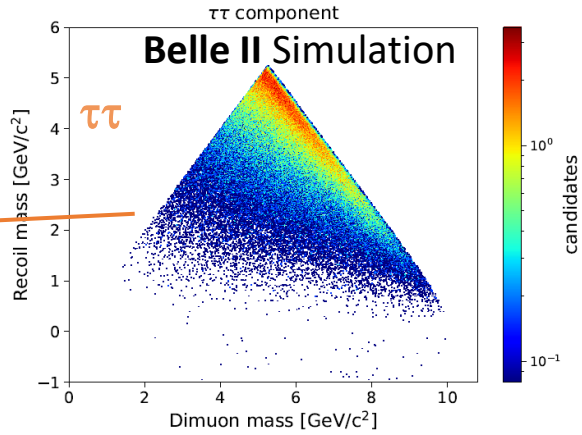
Signal efficiency

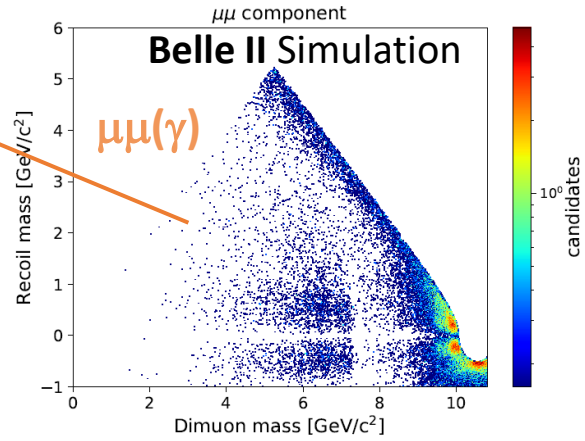


Total background









eeμμ

ττ

μμ(γ)

- Large trigger inefficiency for $M_{A'}$<4 GeV;
- recoverable in 2020 with new CDC and KLM single-muon trigger.

Dark Higgsstrahlung: A'h'

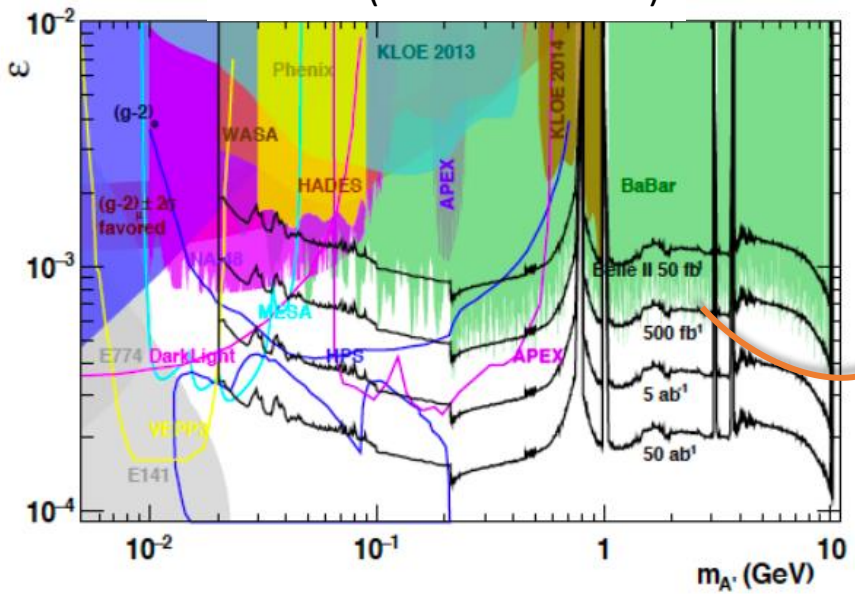
Very promising results even with the 2019 only dataset (9 fb^{-1})

- Accessing unconstrained regions, well beyond KLOE coverage.
- Probing *non-trivial* $\epsilon^2\alpha_D$ couplings.

$\varepsilon^2 < \varepsilon^2_{BABAR}$ *for* $\alpha_D = 1$

- Systematics: rough & conservative estimate
  - 10% fully correlated on efficiency and BKG, plus additional 20% on BKG only.

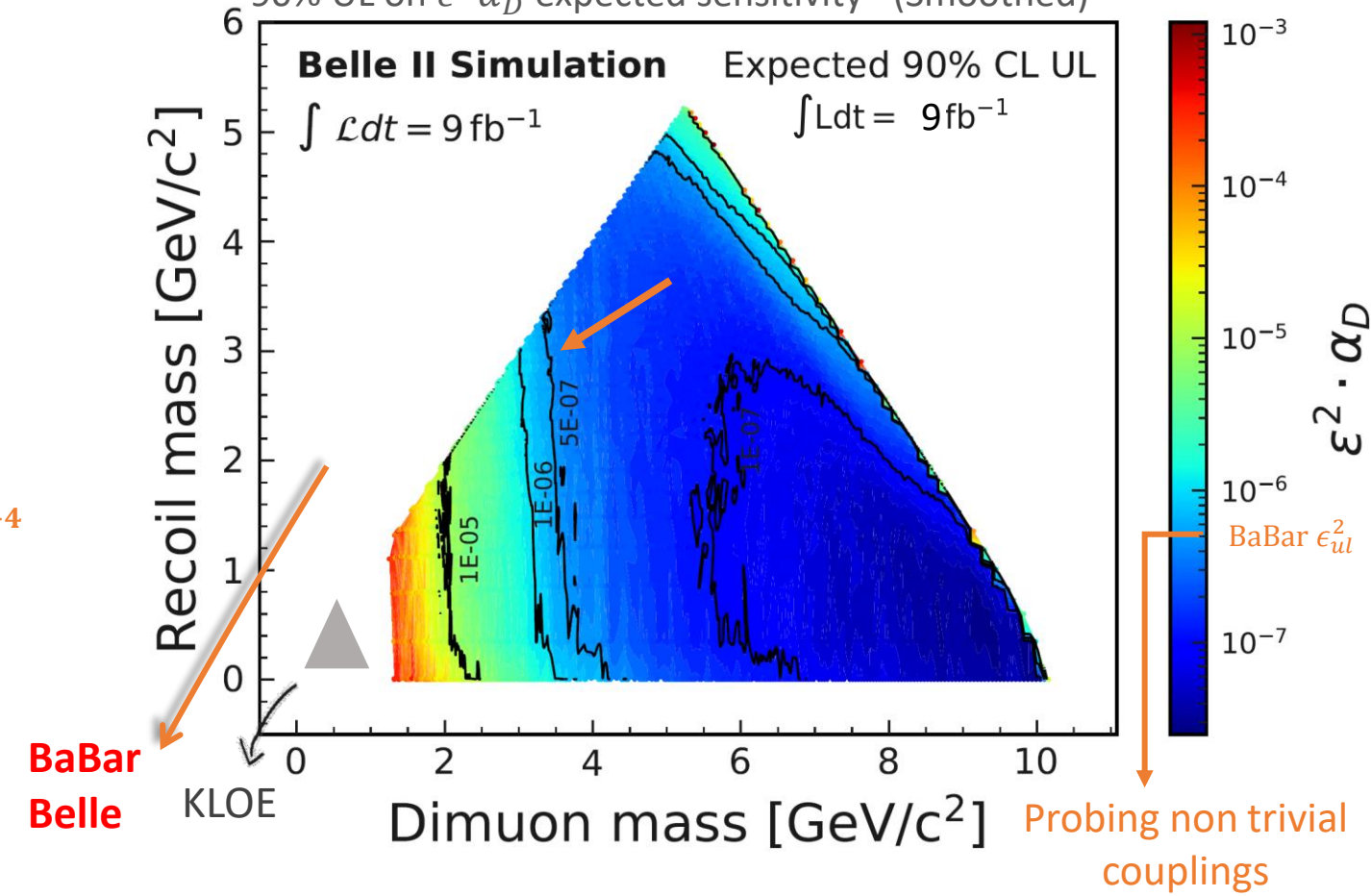
UL on ϵ (visible searches)



$\approx 7 \cdot 10^{-4}$

90% C.L. UL on $\epsilon^2 \sim 5 \cdot 10^{-7}$

90% UL on $\epsilon^2\alpha_D$ expected sensitivity* (Smoothed)



Probing non trivial couplings

Dark Higgsstrahlung: A'h'

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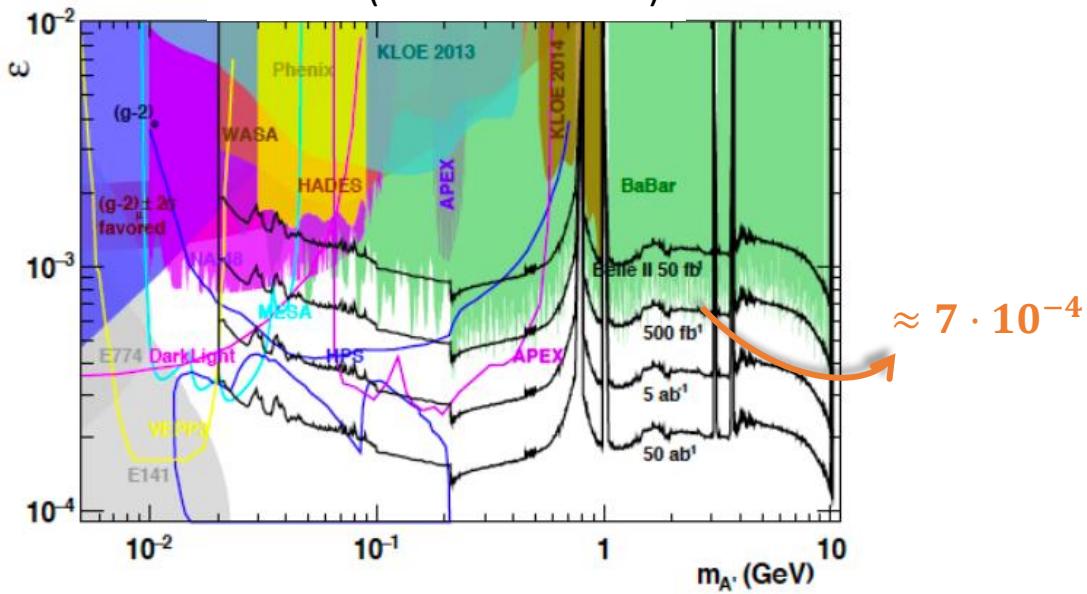

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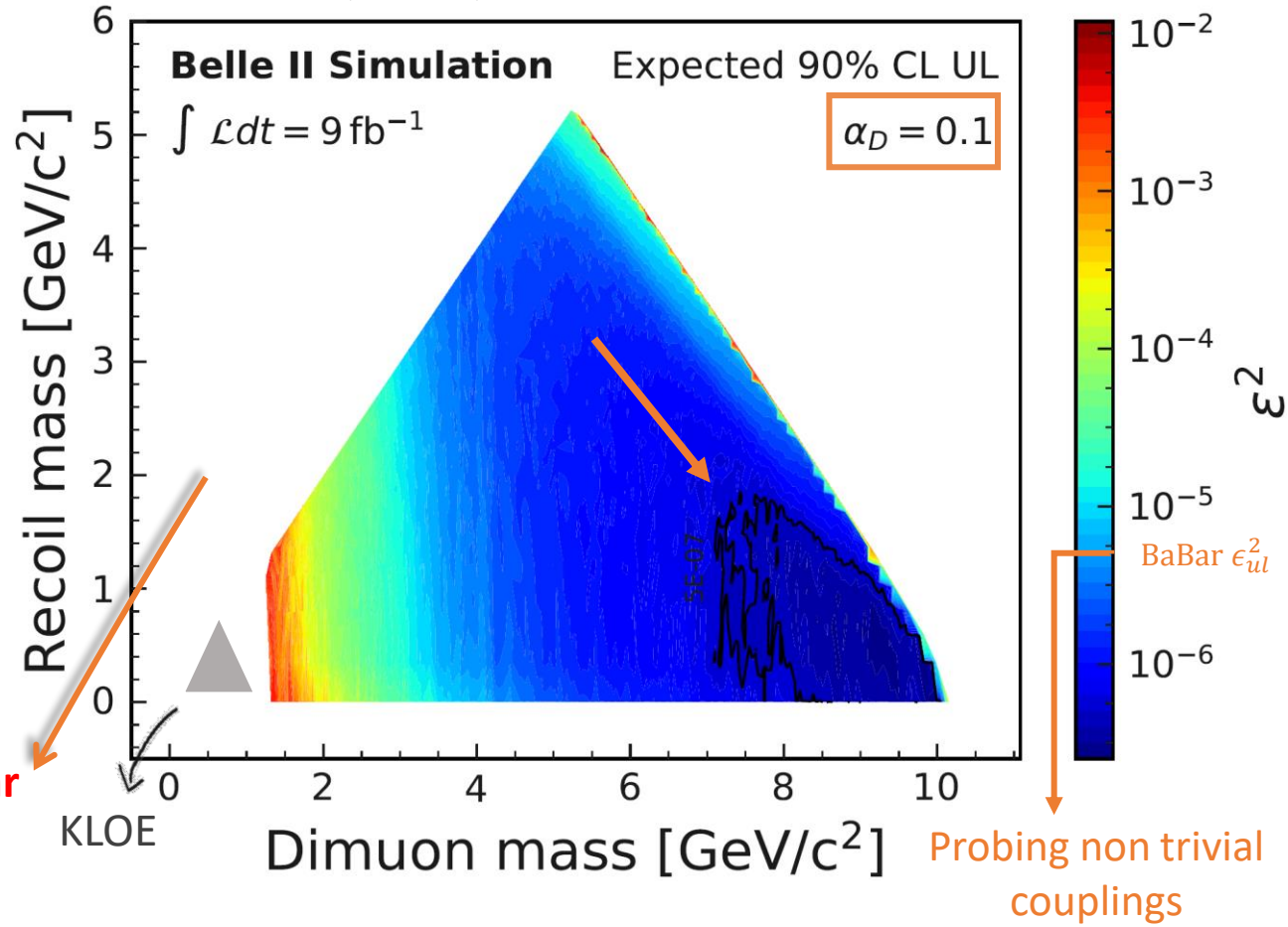
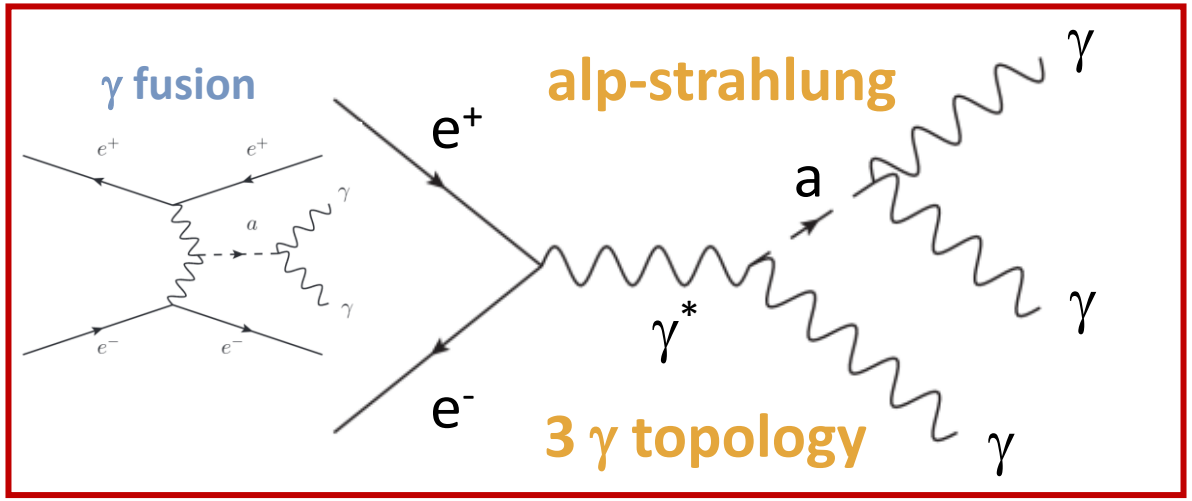


Axion Like Particles (ALPs)

- Appear in SM extensions after some global (i.e. family) symmetry breaking
- Pseudo-Goldstone bosons → Naturally light
- Cold dark matter candidates if m_a is sub MeV
- Couple naturally to photons
- Can couple LFV to fermions
- No mass↔coupling relationship (as for QCD)

Belle II

- Focus on coupling to photons: $g_{a\gamma\gamma}$
- **Alp-strahlung** + photon fusion production mechanisms
- $\tau \sim 1 / g_{a\gamma\gamma}^2 \, m_a^3$



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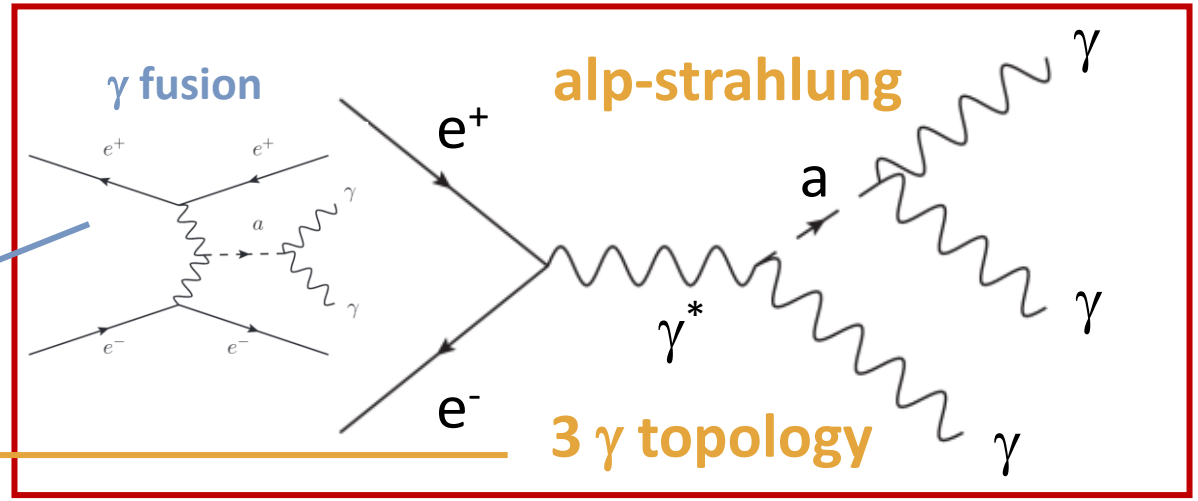
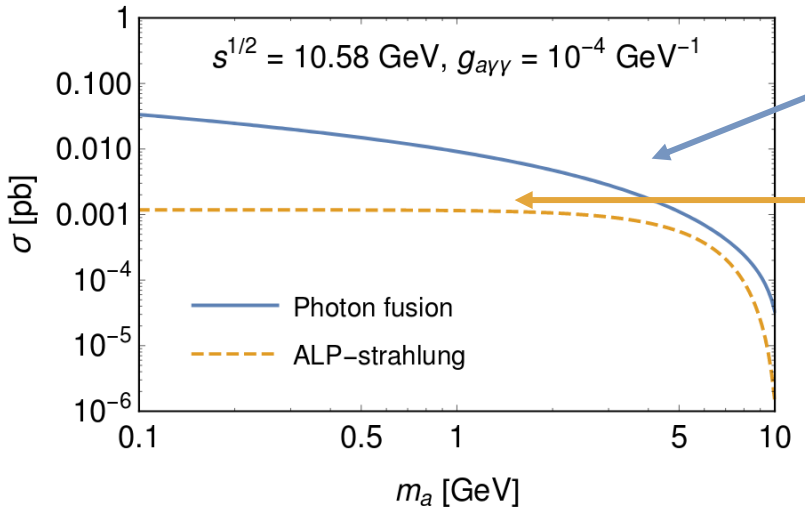
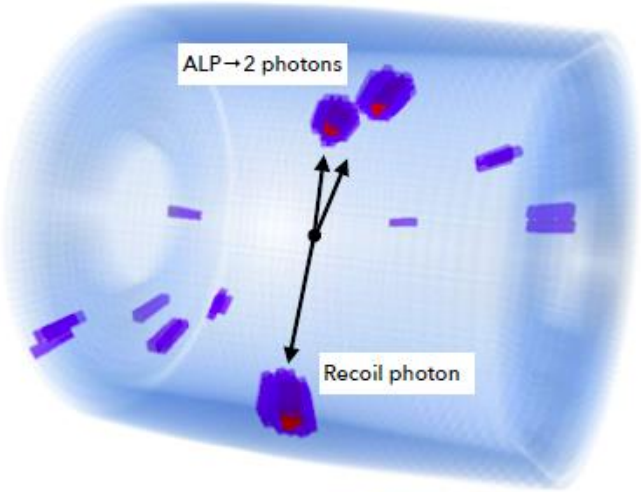




photon fusion sensitivity under study

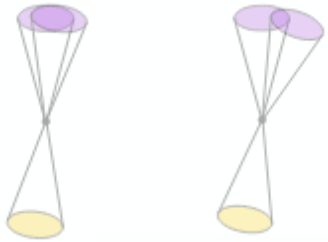
Axion Like Particles (ALPs): signal

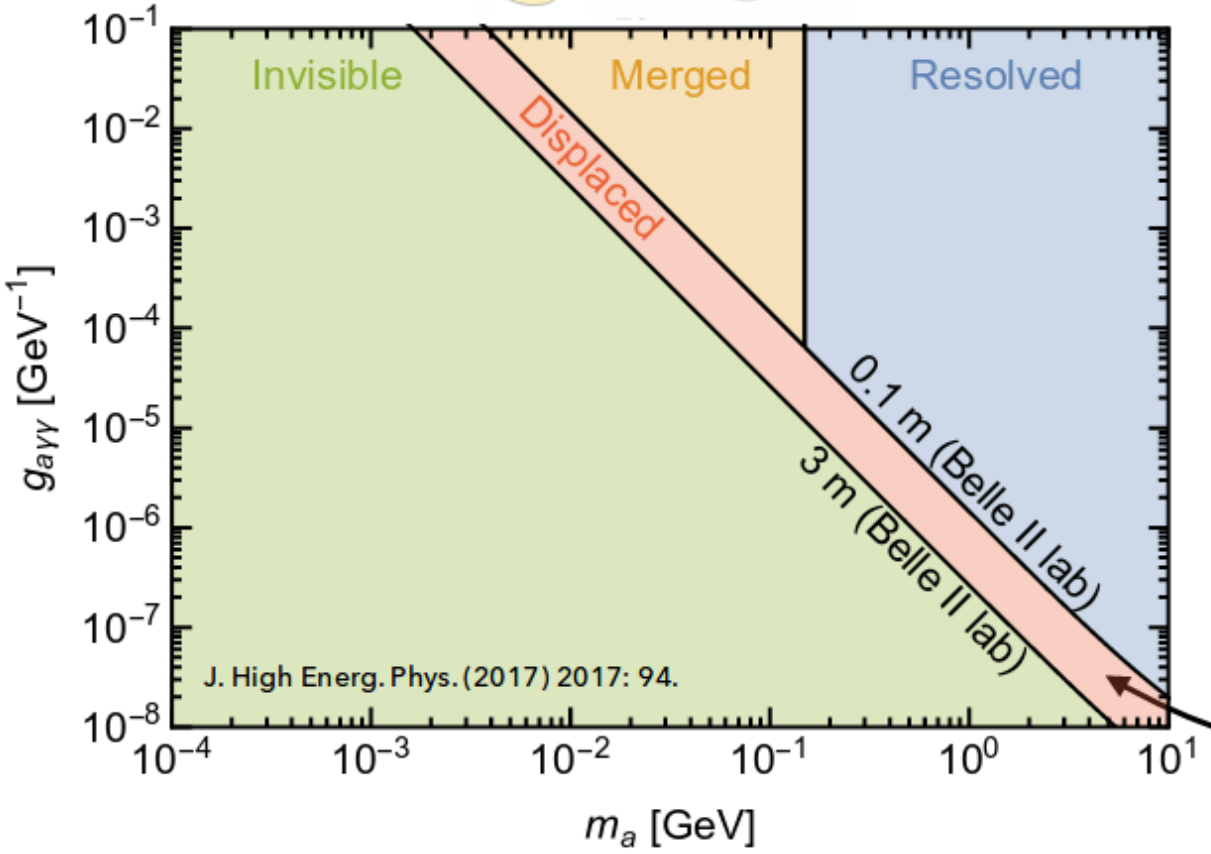
3 γ topology, but…



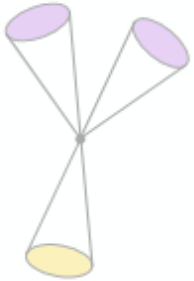
ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

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





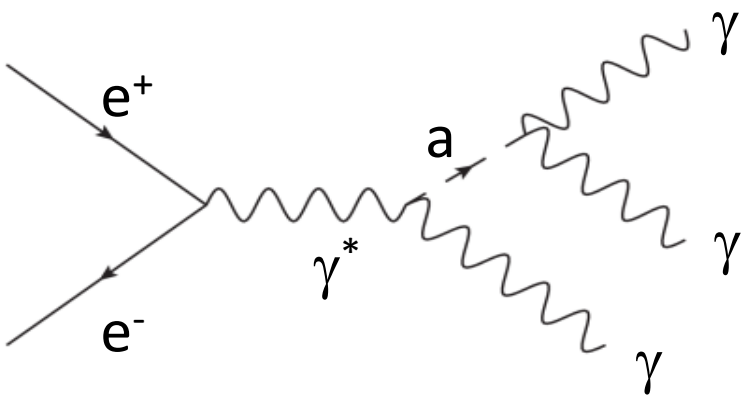
Three **resolved**, high energetic photons.



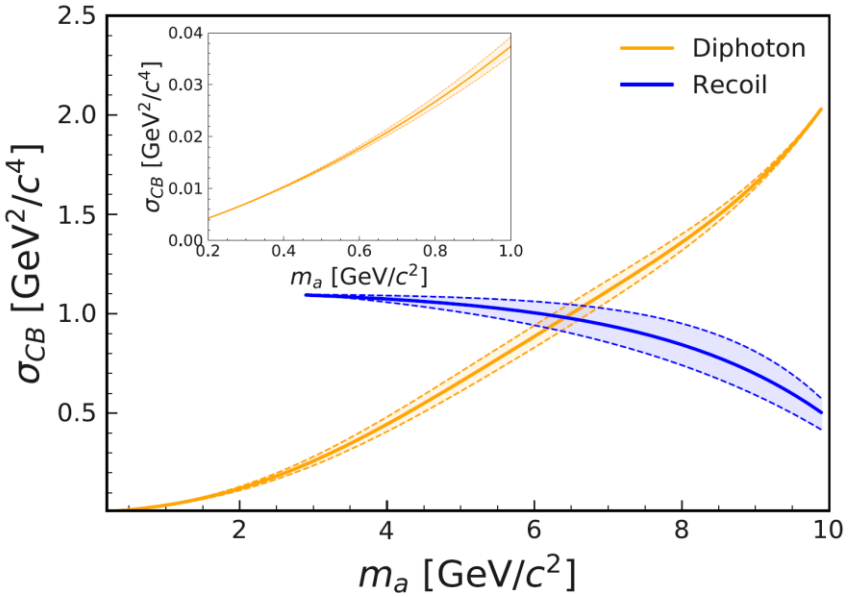
The searches for invisible and visible ALP decays veto this region.

ALPs can also decay to DM → single photon topology

Axion Like Particles (ALPs)



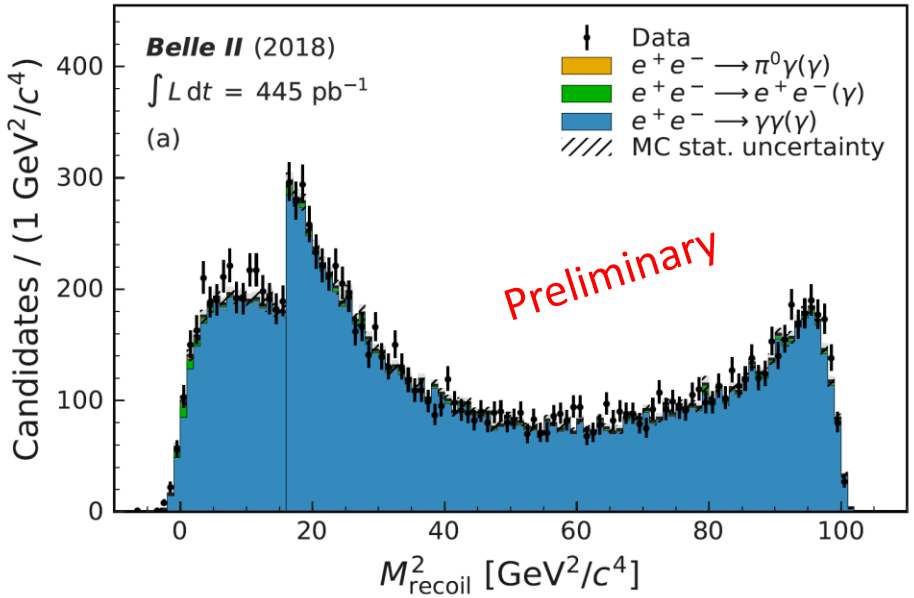
Search for peaks either in the recoil invariant mass (high m_a) or in diphoton mass (low m_a)

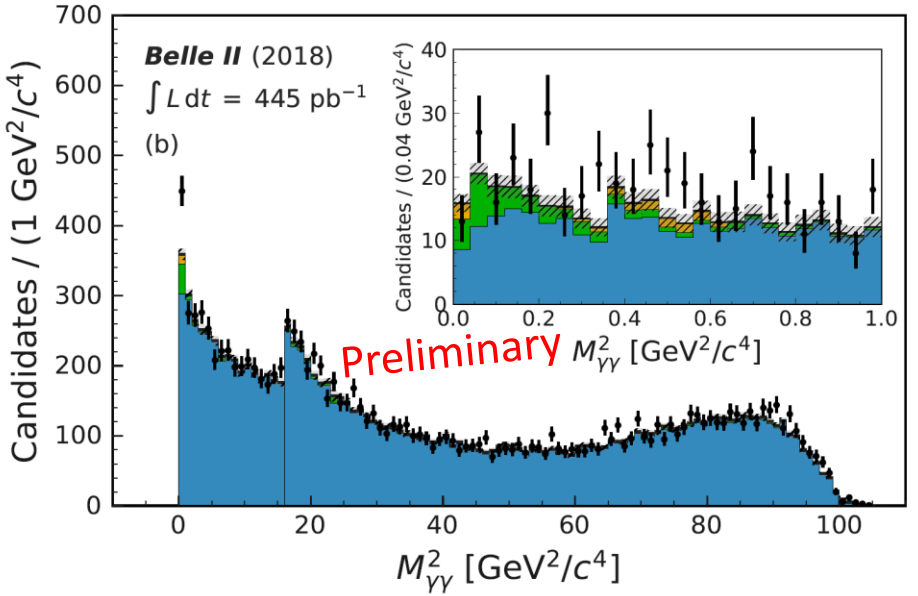


Main backgrounds:

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

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



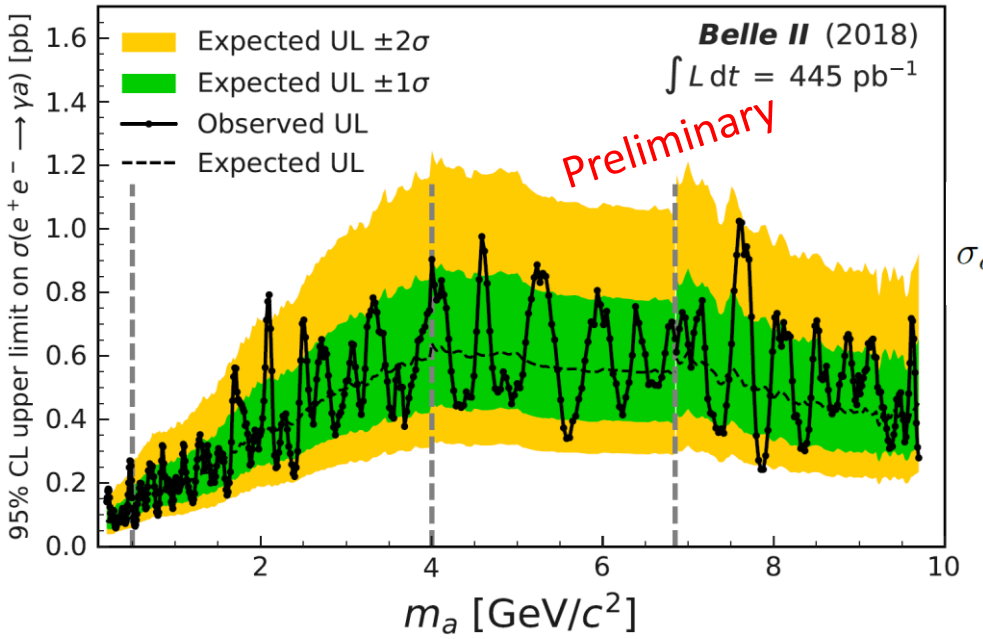


Axion Like Particles (ALPs)

- ~500 fits in sliding ranges with steps of half resolution
- No peaking backgrounds expected
- $0.2 < m_a < 9.7$ GeV/c^2

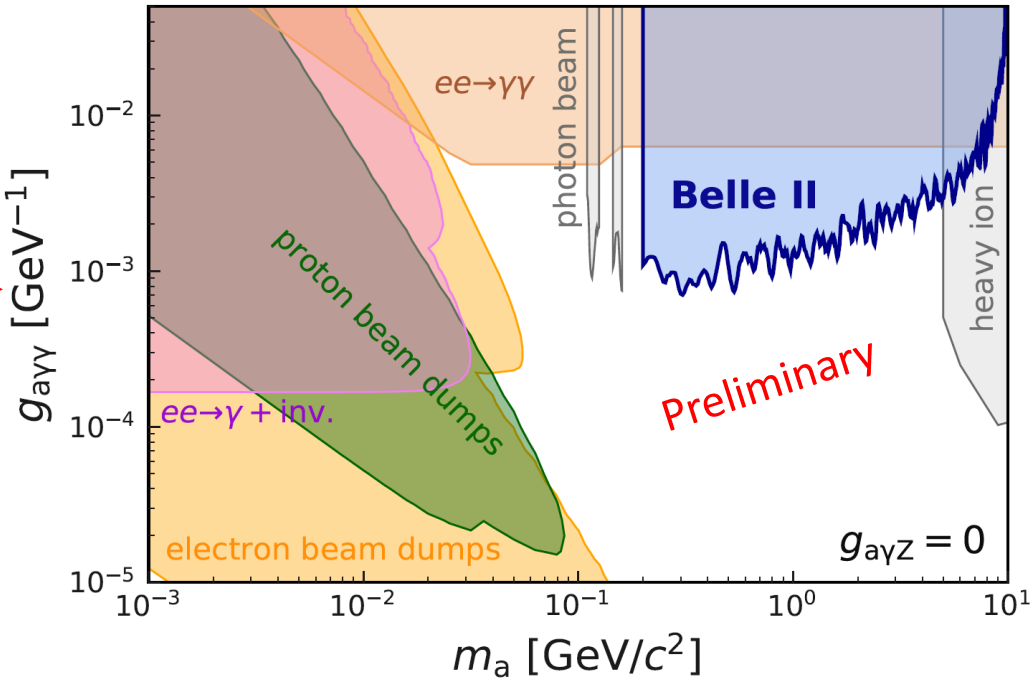
Second physics paper by Belle II
arXiv:2007.13071, submitted to PRL

See also F. Kahlhoefer's talk



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

new



Summary

- The persisting null results from new physics at LHC searches and in direct underground searches make the light dark sector senario more and more attractive.
- KLOE/KLOE-2, BESIII, BaBar, Belle already excluded many models or relevant part of their parameter space
- **Belle II** started a broad program of searches orthogonal/complementary to LHC
- Will lead sensitivity in most of them

- **Z' to invisible** — Published on PRL
- **Z' LFV to invisible** — Published on PRL
- **ALP →γγ** — Submitted to PRL
- **Dark Higgstrahlung A'h'** — Next paper (2021)
- **Invisible dark photon** — Next-to-next paper (end 2021)
- **Visible dark photon**
- **Visible Z' →μμ, ττ**
- **iDM**
- **Dark scalar S**
- **…**

Not even mentioned

- Leptophilic dark scalar
- Hadronic final states (A', a)
- dark search in τ decays
- $\Upsilon(1S)$ to invisible
- ALP search in $B \to K^* a$
- Z' search in B decays
- Magnetic monopoles
- …

SPARE SLIDES

From KEKB to SuperKEKB

- New e^+ Damping Ring
- New Superconducting Final Focus (QCS)

Beam-beam parameter

$$\xi_{y\pm} = \frac{r_e}{2\pi\gamma_\pm}\frac{N_\mp \beta_y^*}{\sigma_y^*(\sigma_x^*+\sigma_y^*)} R_{\xi_{y\pm}} \propto \frac{N_\mp}{\sigma_x^*}\sqrt{\frac{\beta_y^*}{\varepsilon_y}},$$

Lorentz factor

Beam current

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lumi. reduction factor (crossing angle)& Tune shift reduction factor (hour glass effect) 0.8 ~ 1 (short bunch)

Classical electron radius

Beam size ratio@IP 1 ~ 2 % (flat beam)

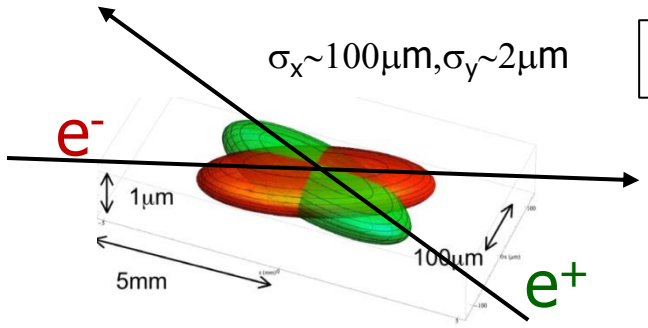
Vertical beta function@IP

x30

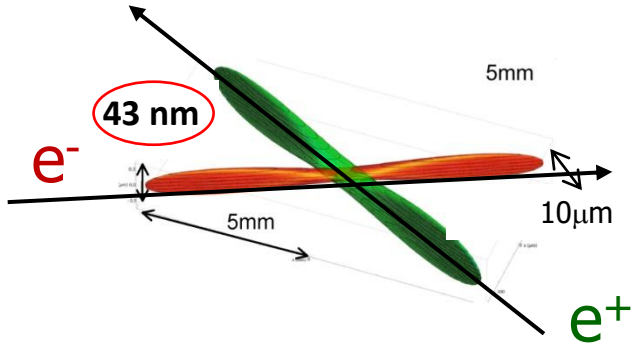
(1) Smaller β_y^*
(2) Increase beam currents
(3) Increase ξ_y

β^*_y=0.30/0.30 mm

$I_{+/-}$=2.8/2.0 A



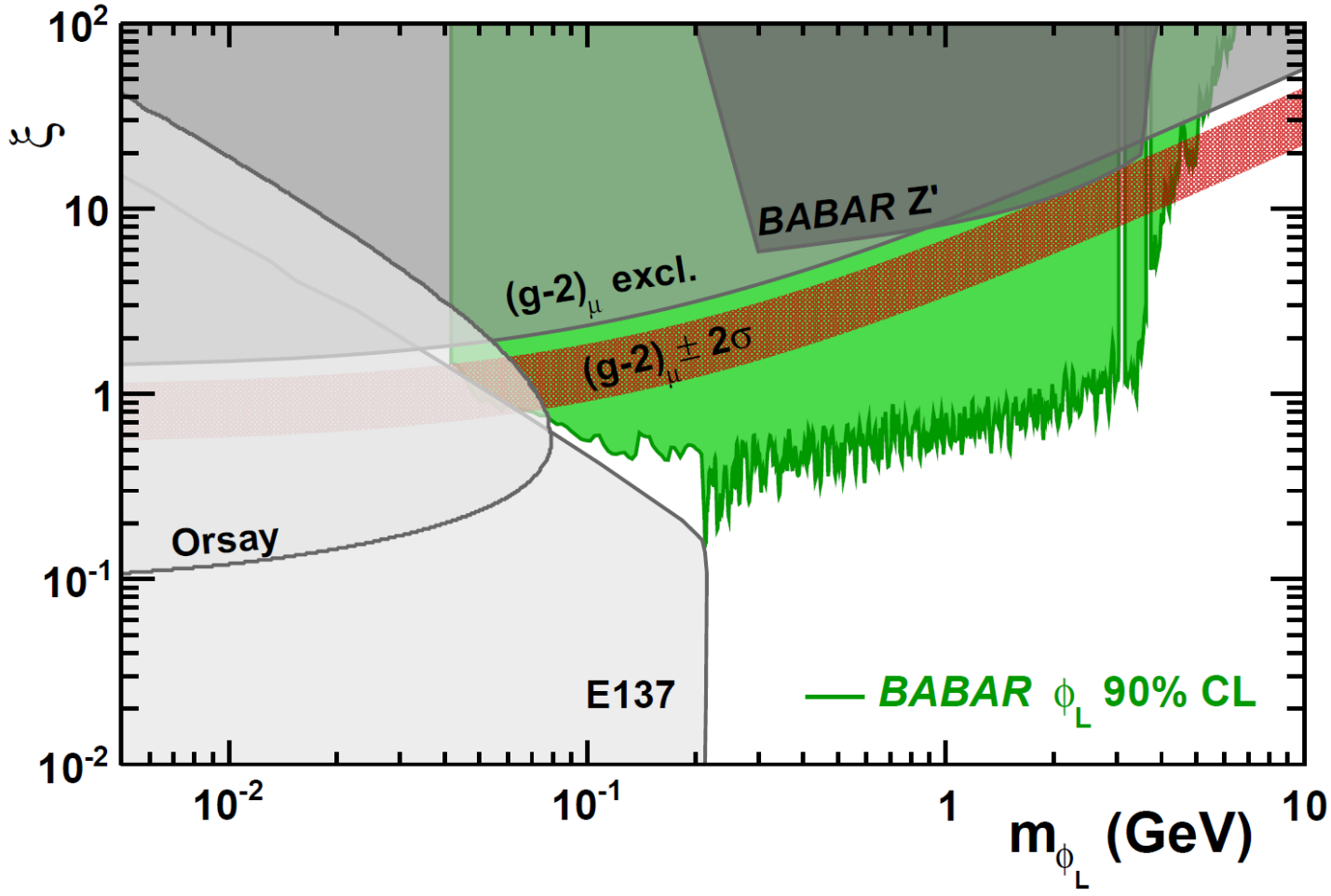
Nano-Beam scheme



... For a 30x increase in intensity you have to make the beam as thin as a few x100 atomic layers

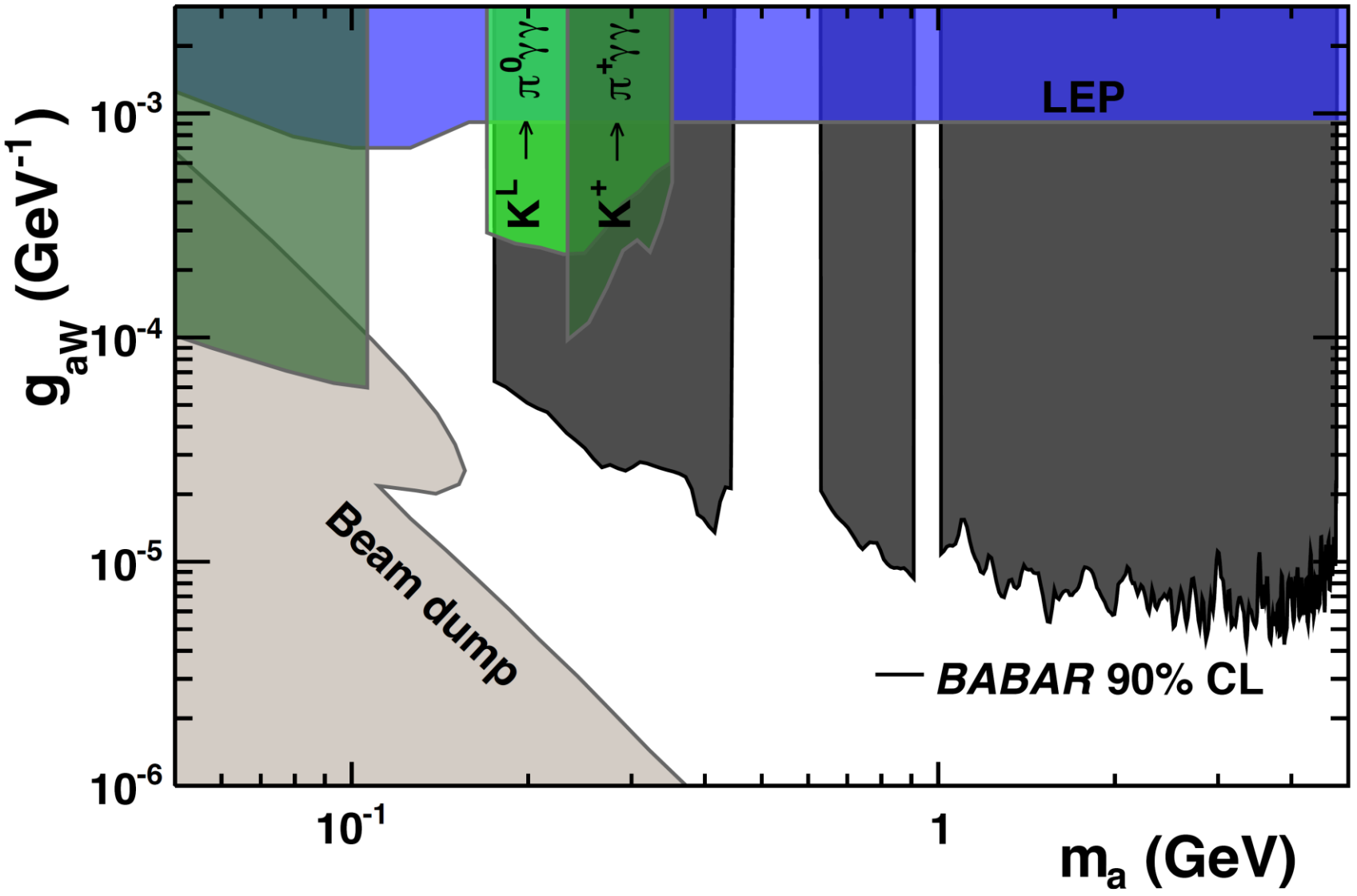
Leptophilic dark scalar (BABAR)

$e^+e^- \to \tau^+\tau^-\phi_L$, $\phi_L \to l^+l^-$ (l= e,μ)



ALPs in B→ka (BABAR)

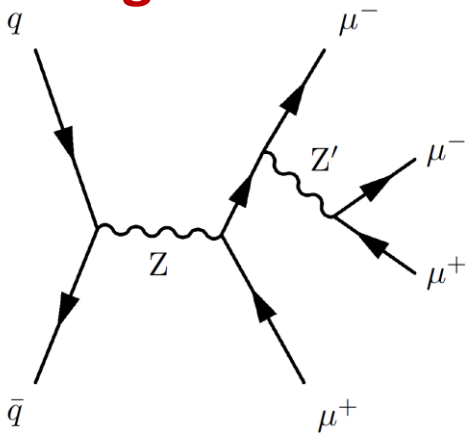
$B^{\pm} \rightarrow K^{\pm}$ a, a → γγ



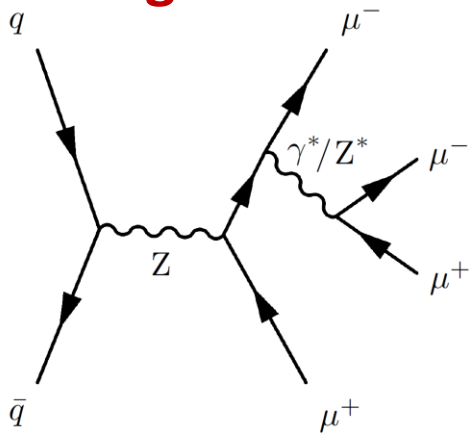
Z’ →μμ: muonic dark force

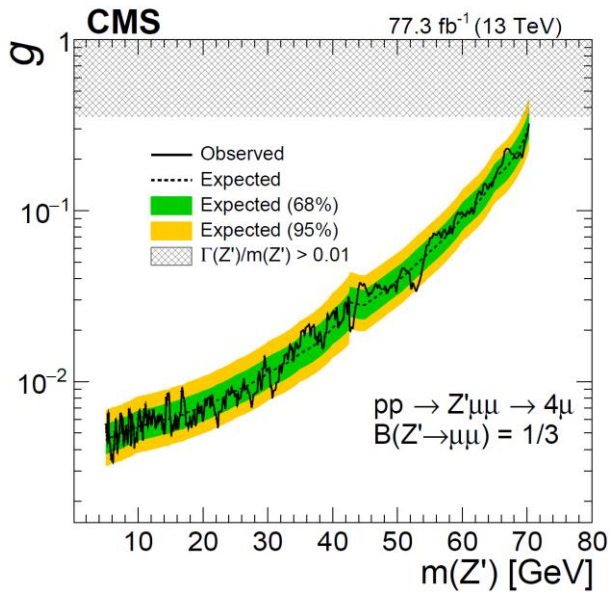
Example of high energy ↔ high luminosity interplay

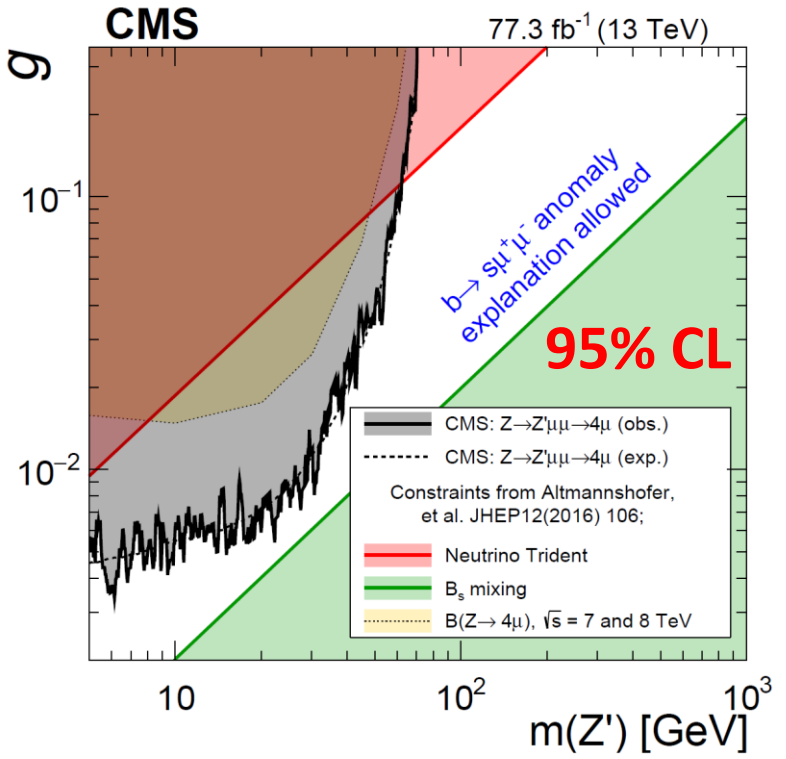
signal



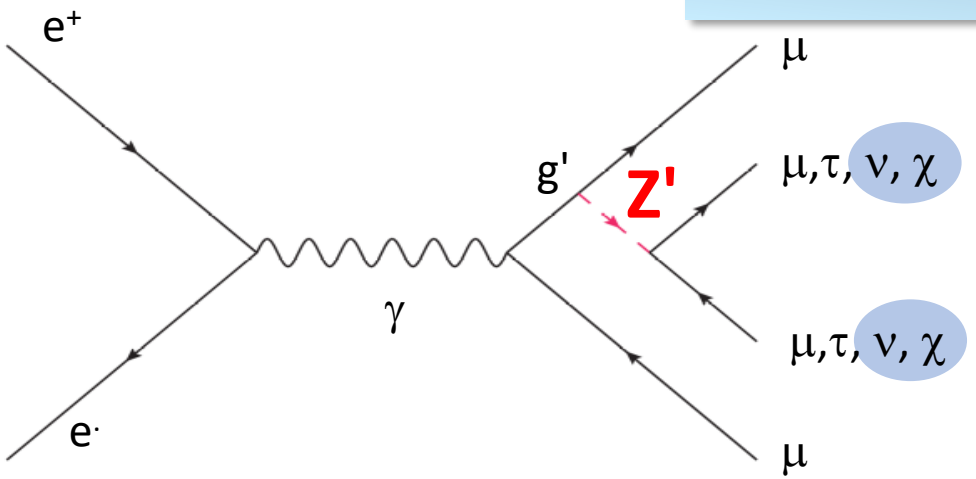
background







Z' to invisible: $L_\mu - L_\tau$ model



Explored for the first time

$e^+e^- \rightarrow \mu^+\mu^-$ + *missing energy*

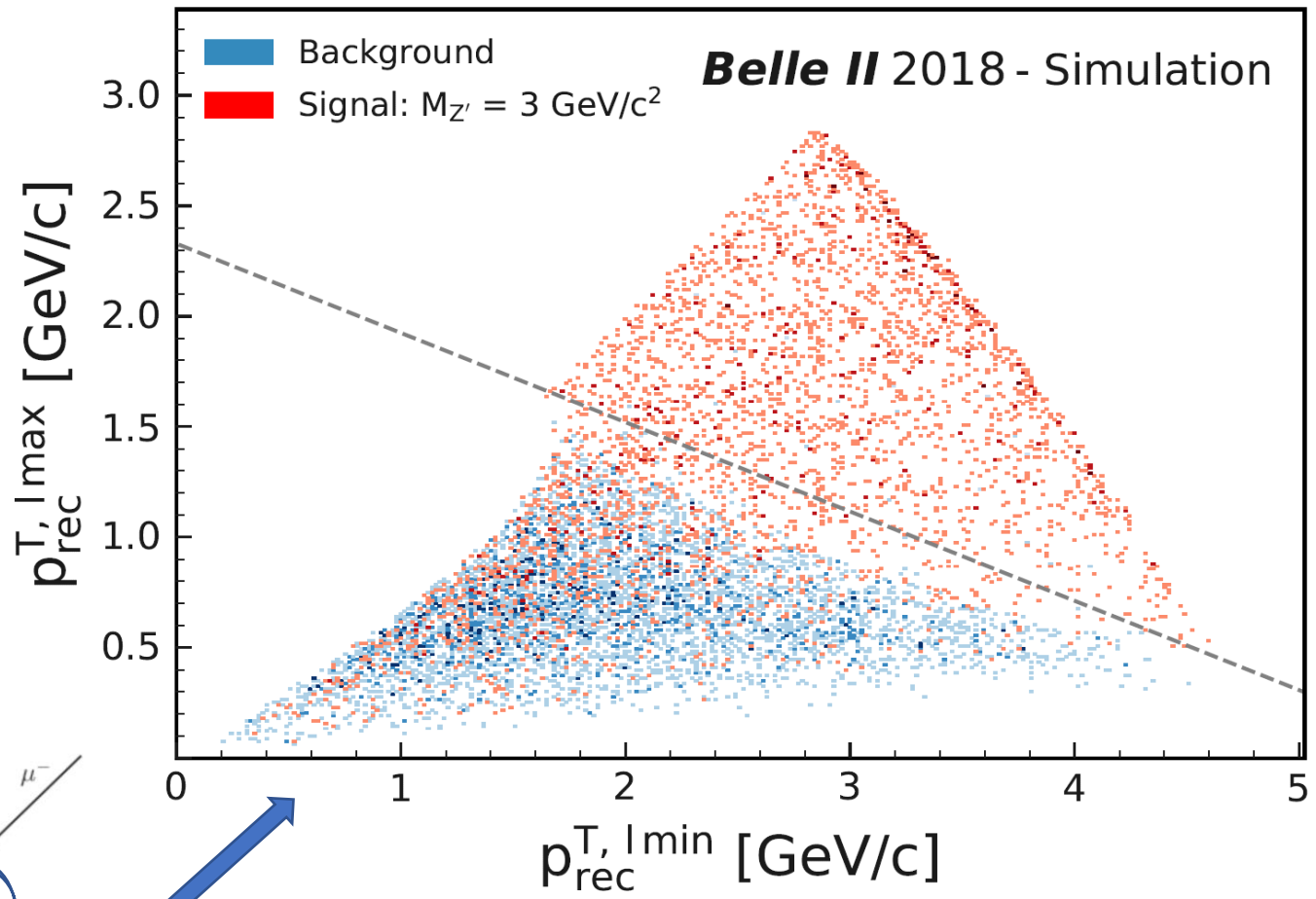
Look for bumps in recoil mass against a $\mu^+\mu^-$ pair

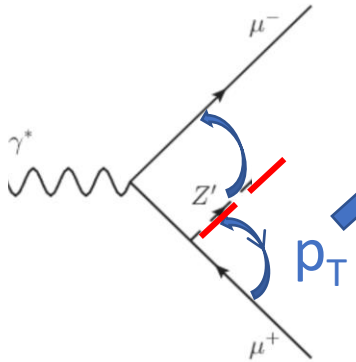
Main backgrounds:

$e^+e^- \rightarrow \mu^+\mu^- (\gamma)$

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

$e^+e^- \rightarrow e^+e^- \mu^+\mu^-$

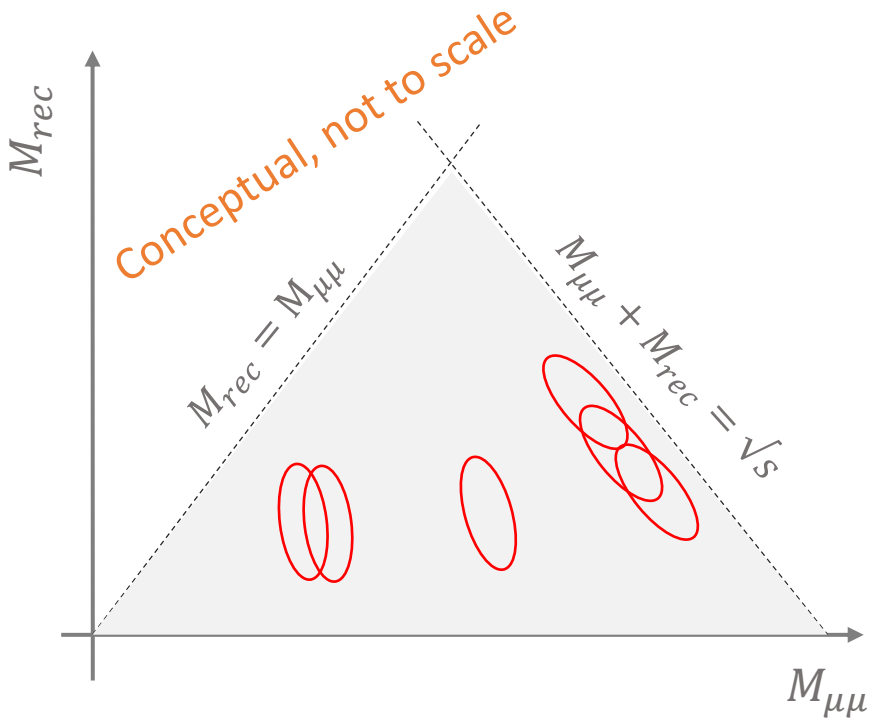


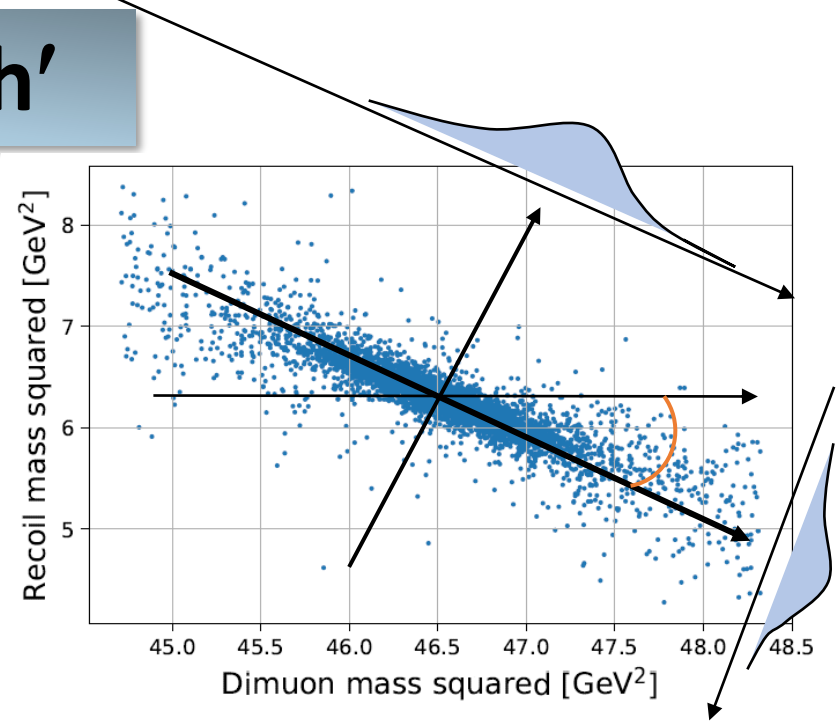


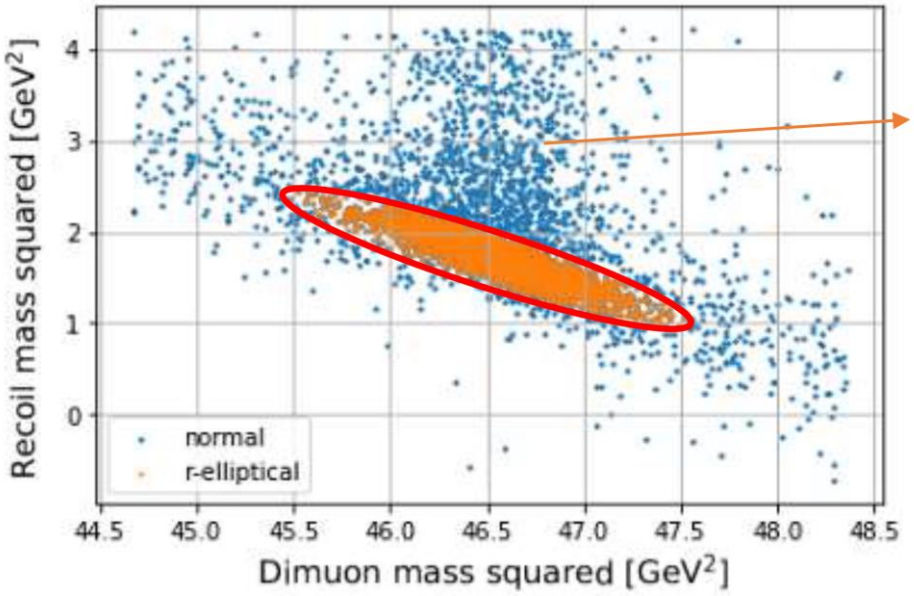
FSR vs ISR + τ decay

Dark Higgsstrahlung: A’h’

- Negative correlation between μμ and recoil mass
- Variable across the plane: evalutaed in the no ISR case
- Mass windows: overlapping tilted ellipses of variable angles with semiaxes ≈2 widths
- In total: 9011 mass hypotheses (windows) across the plane







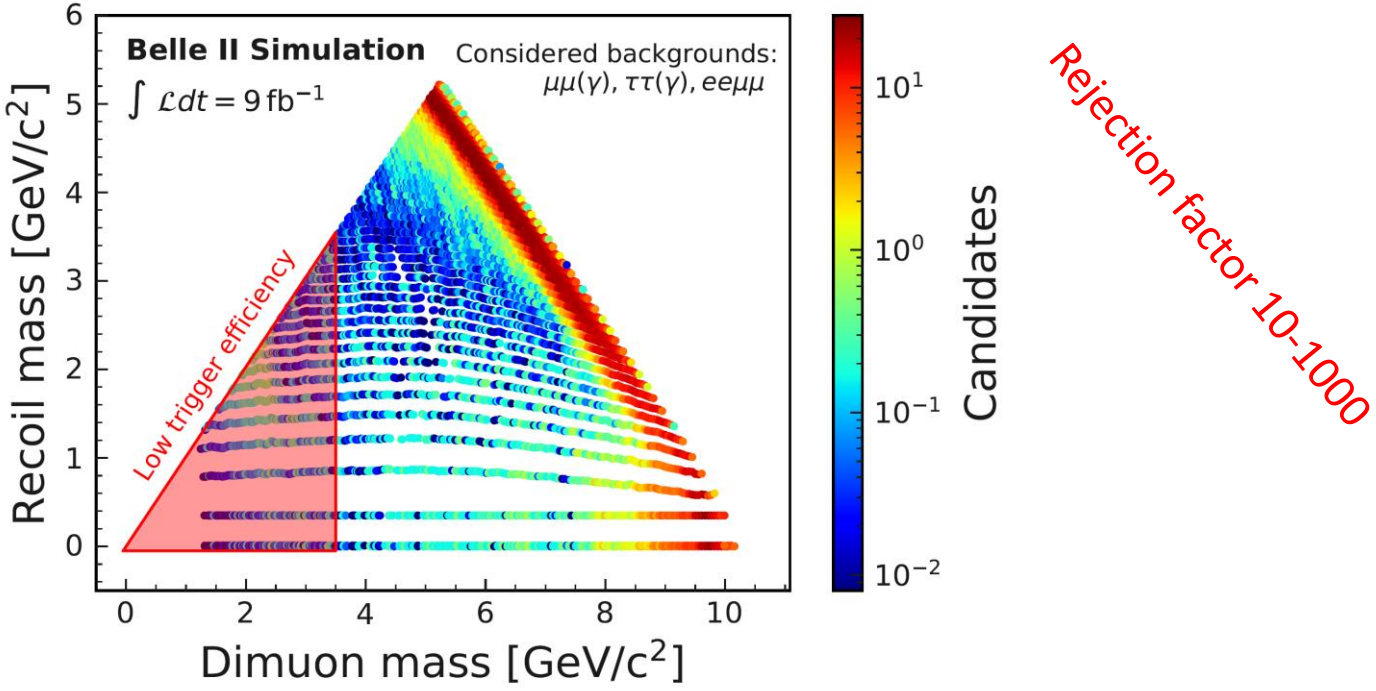
Dark Higgsstrahlung: A’h’

Final background suppression based on kinematic features.

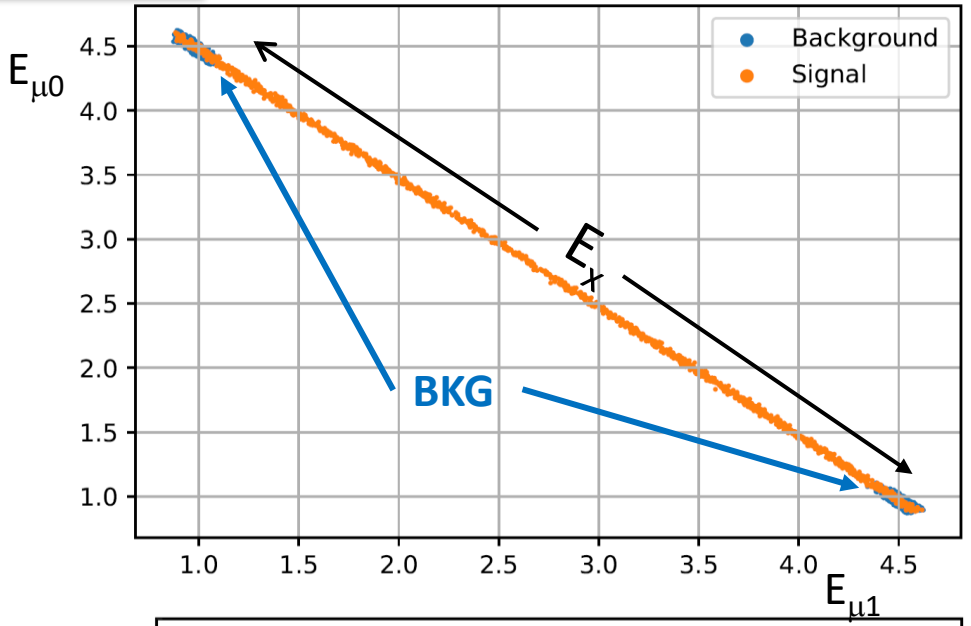
$E_{\mu 0} + E_{\mu 1}$ approximately constant within mass windows.

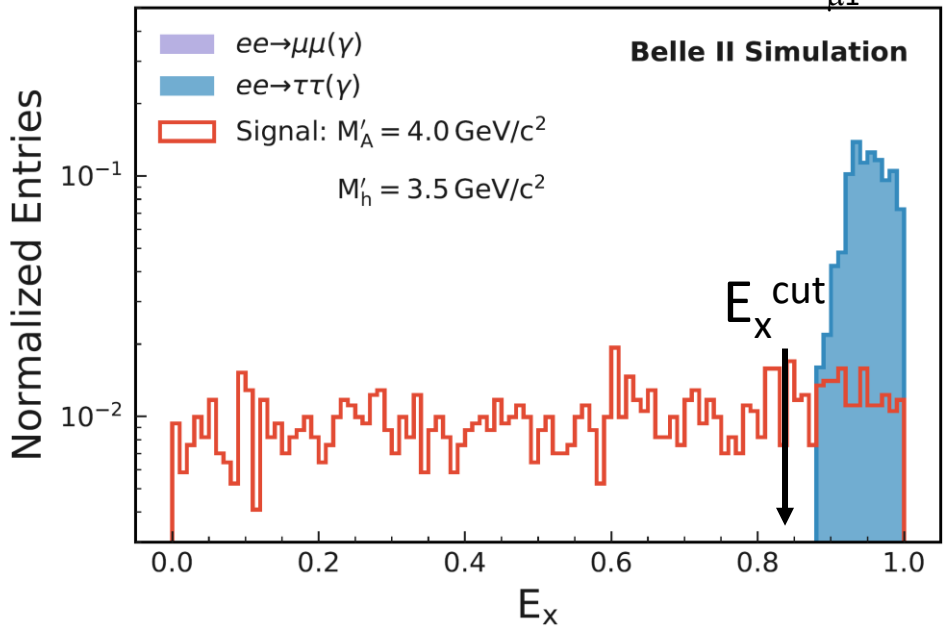
$$E_{\mu 0} + E_{\mu 1} = \frac{s + M_{\mu\mu}^2 - M_{rec}^2}{2\sqrt{s}} = E_0$$

E_x^{cut} optimized across the plane

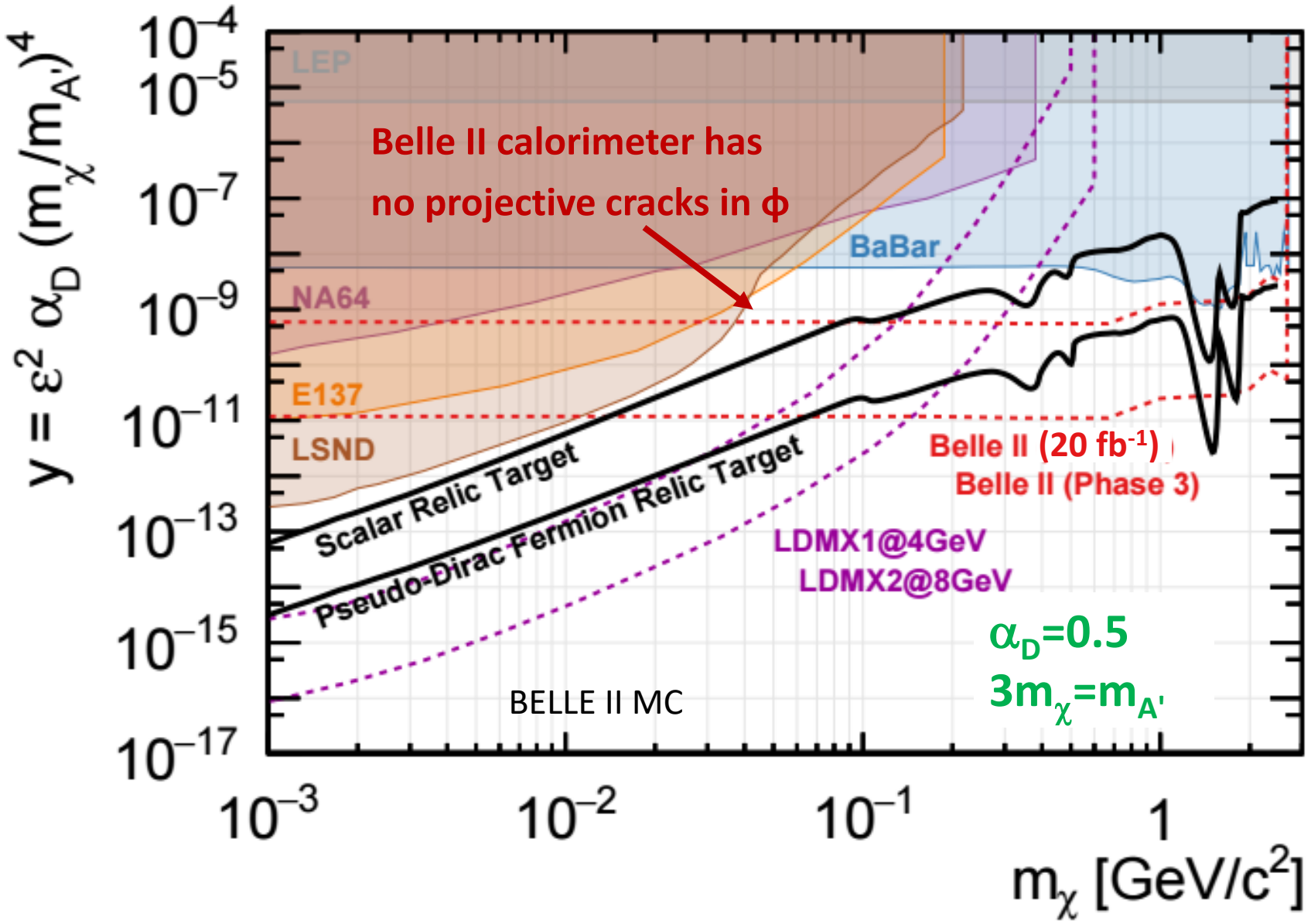


Rejection factor 10-1000





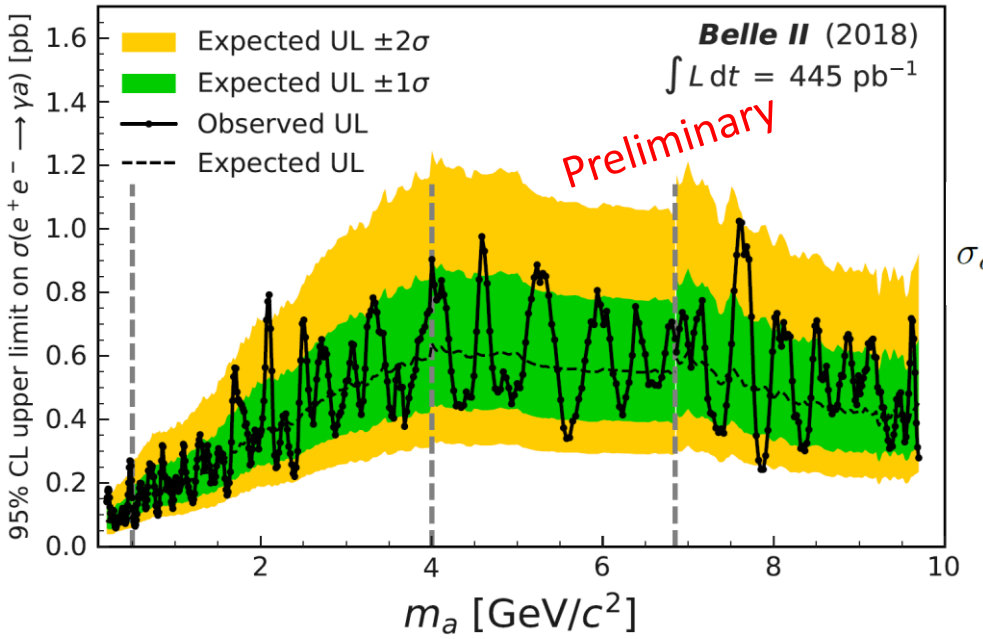
Invisible dark photon: sensitivity



Axion Like Particles (ALPs)

- ~500 fits in sliding ranges with steps of half resolution
- No peaking backgrounds expected
- $0.2 < m_a < 9.7$ GeV/c^2

Second physics paper by Belle II
arXiv:2007.13071, submitted to PRL



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

new