Dark matter searches at Belle II
with results from KLOE, BESIII, BaBar and Belle

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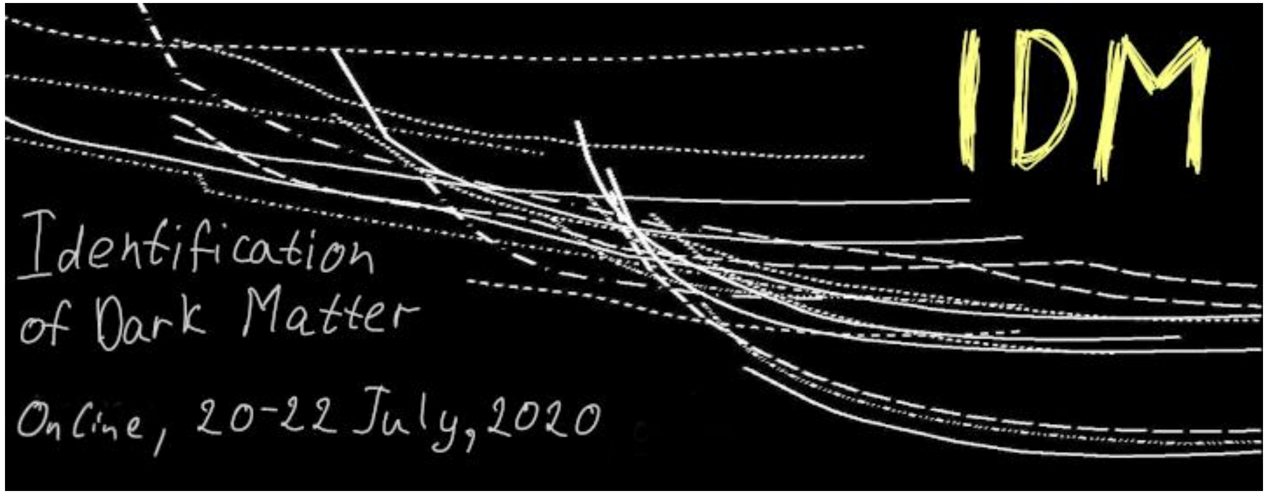
on behalf of the Belle II Collaboration

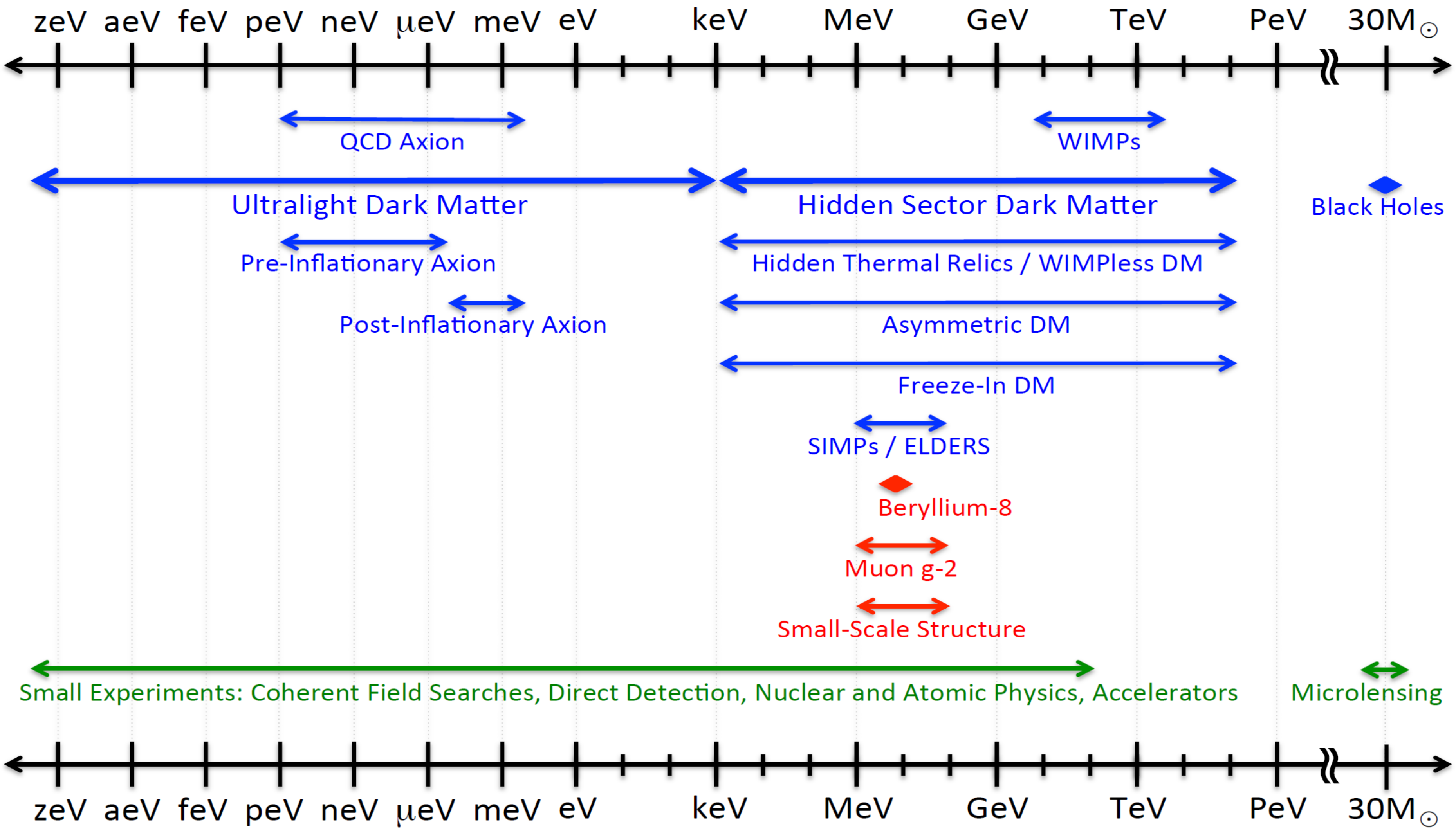


Dark matter search at the intensity frontier

- Introduction: light dark matter
- Highlights of KLOE, BESIII, BaBar, Belle dark searches
- Belle II and SuperKEKB
- Belle II dark searches
- Perspectives & Summary

Searching for dark matter

Dark Sector Candidates, Anomalies, and Search Techniques



Light DM scenario: light WIMPs ⇔ light mediators

Light dark matter not ruled out if light dark mediator(s) exist

WIMP paradigm: $\sigma_{ann}(v/c) \approx 1$ pb $\Rightarrow \Omega_{DM} \approx 0.25$

Electroweak mediators ⇒ Lee – Weinberg window

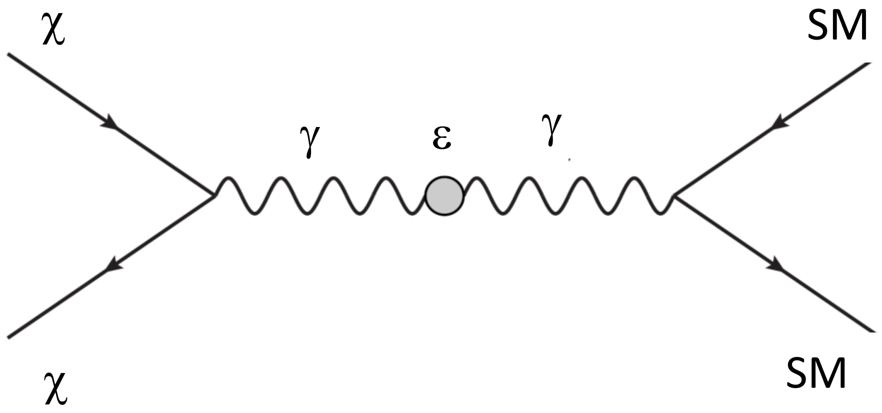
$$\sigma(v/c) \propto \begin{cases} G_F^2\, m_\chi^2 & \text{for } m_\chi \ll m_W \\ 1/\, m_\chi^2 & \text{for } m_\chi \gg m_W \end{cases} \Rightarrow \text{few GeV} < m_\chi < \text{few TeV}$$

It modeled decades of direct search experiment designs

WIMP miracle

If annihilation via a light force carrier, χ can be as light as few MeV

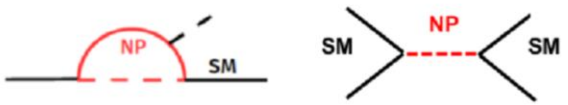
Possibility of Light New Physics, mostly with tiny couplings. Some models are minimal (but UV safe) and show diverse DM phenomenology



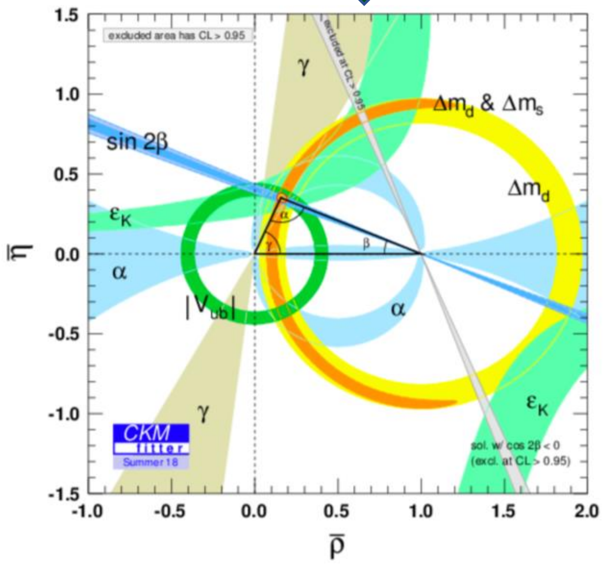
Dark matter hunt: «classical» approach

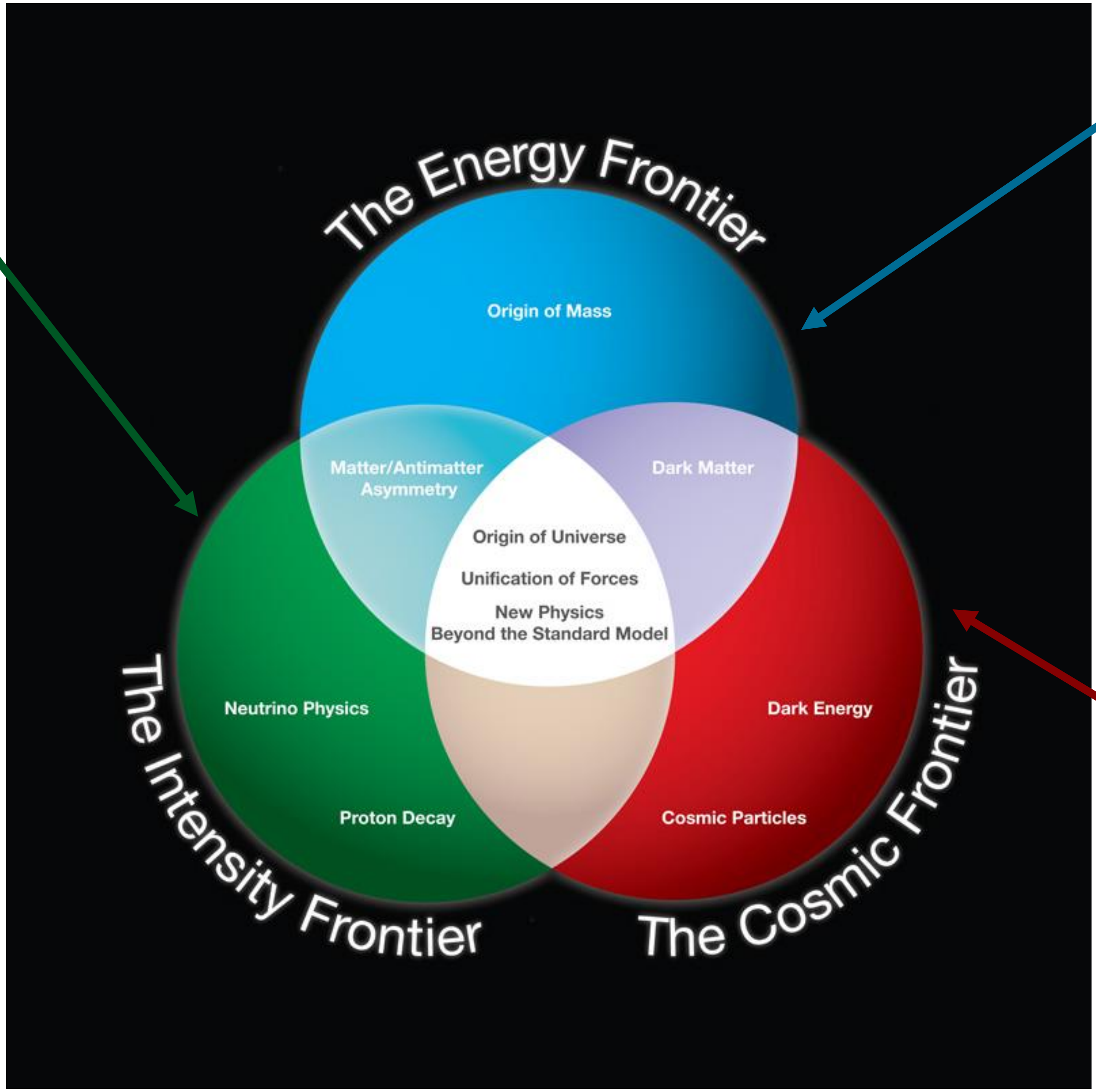
Intensity / precision frontier

New virtual particles in loops/trees transitions, deviation from SM expectations (B factories, LHCb)



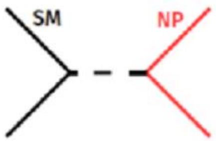
If NP found in direct searches, it is reasonable to expect NP effects in *B, D, tau* decays





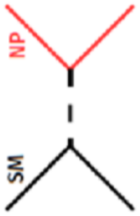
Energy frontier

Direct production of new particles - limited by beam energy (LHC – ATLAS, CMS)

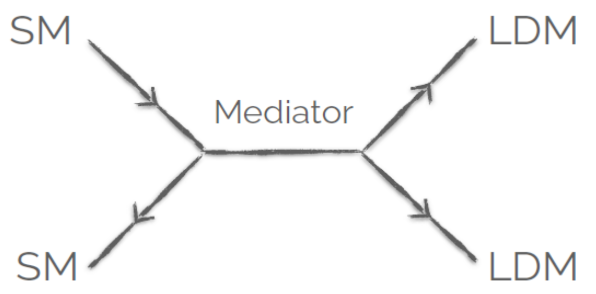


Cosmic frontier

Direct effect search in (mostly) underground experiments



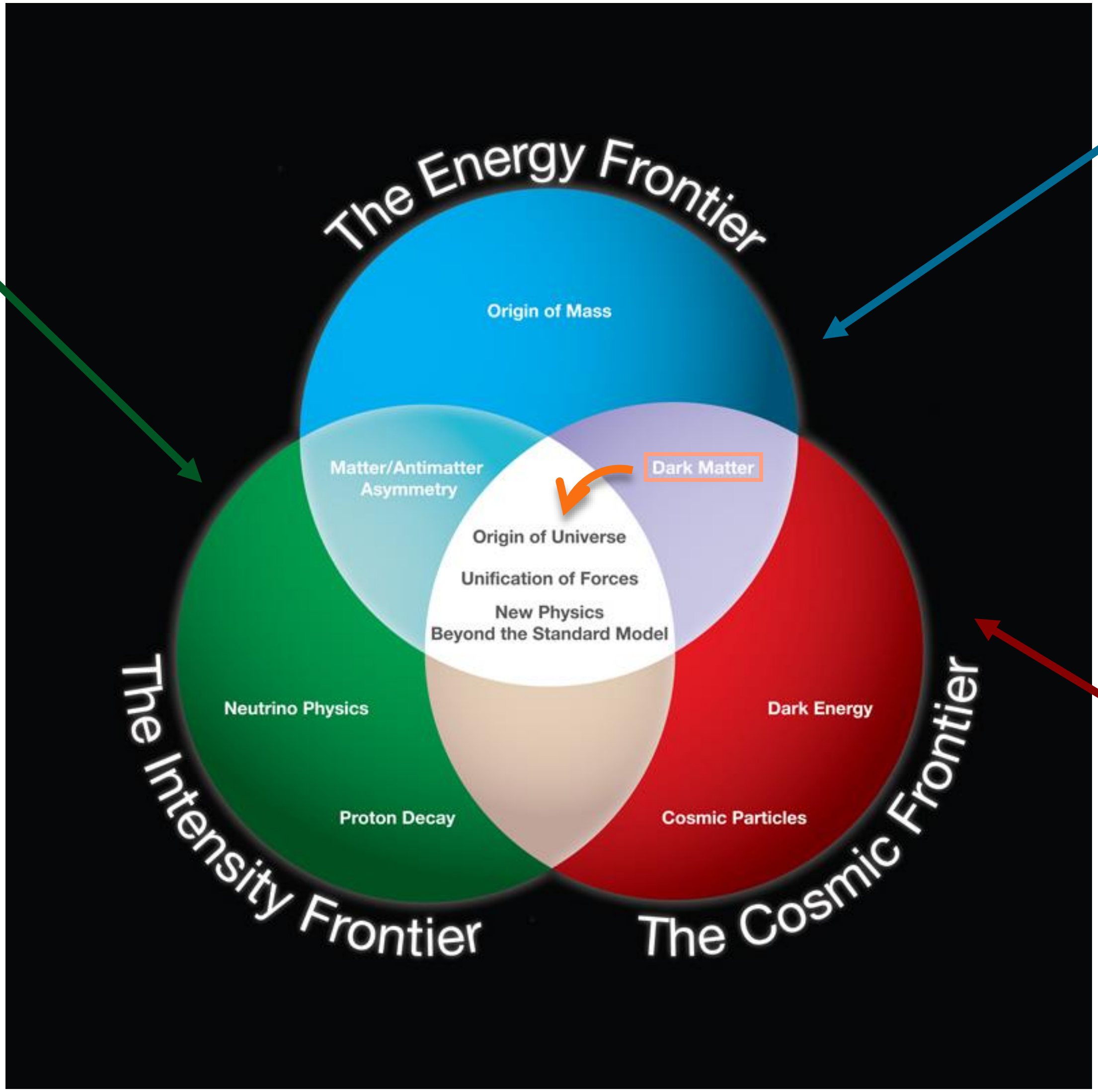
Dark matter hunt with a light sector



LDM → Light Dark Matter
Mediators → portals

⇓

Light Dark Sector with interactions ~ unsuppressed by a (possibly large) NP scale Λ



Energy frontier

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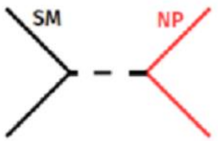

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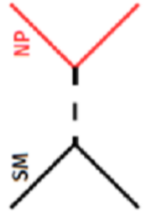
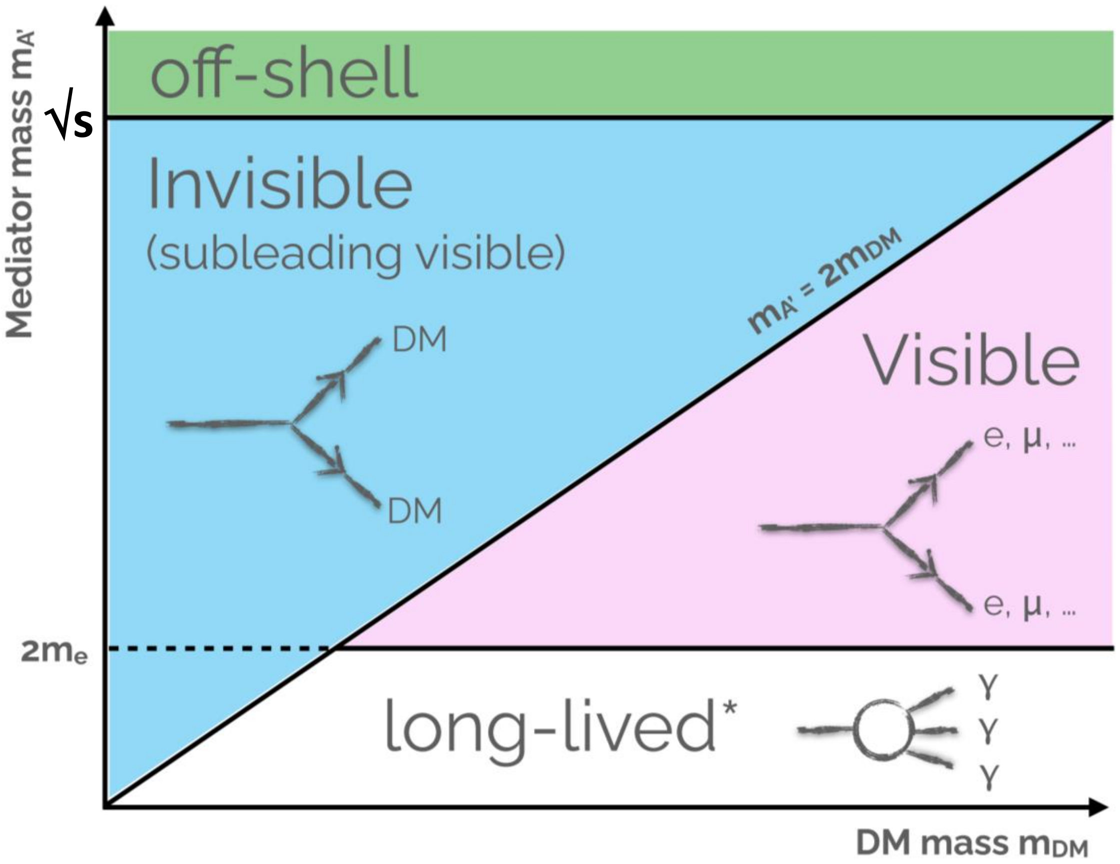


Light Dark matter hunt

Different signatures depending on the DM ↔ mediator mass relation

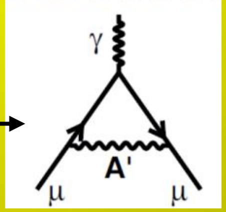


Probability of interaction of LDM detectors is negligible

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

Additional benefits:

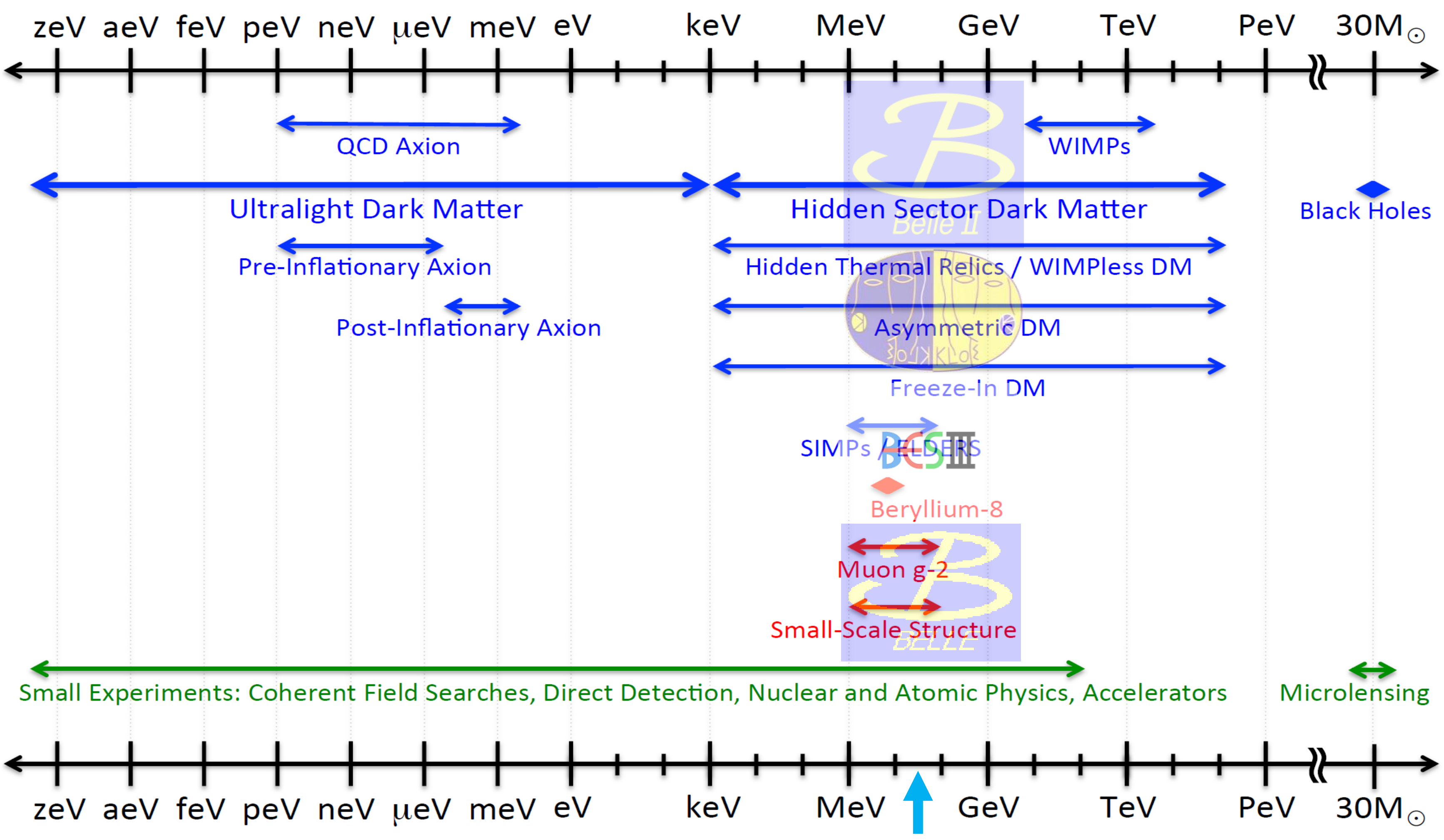
- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, …)
- Explanation of the $(g\text{-}2)_\mu$ effect →



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

Searching for dark matter

Dark Sector Candidates, Anomalies, and Search Techniques



Dark matter/mediators

Vector portal

Dark photon, Z’, …

Pseudoscalar portal

Axions, **ALPs**, …

Scalar portal

Dark Higgs, scalars

Neutrino portal

Sterile neutrino

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}

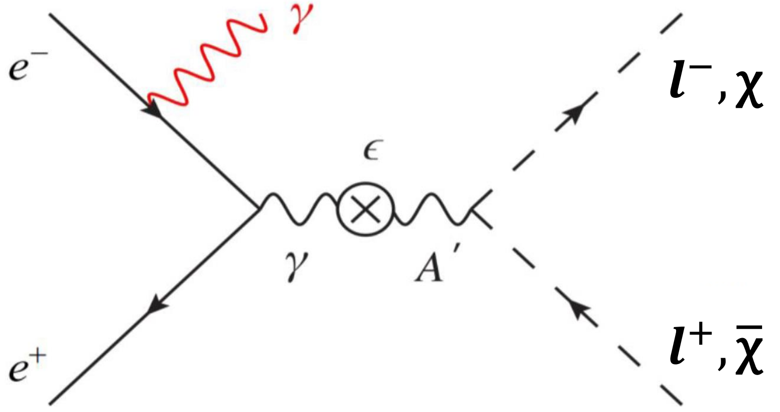
Belle II ≈ 74 fb^{-1} in progress

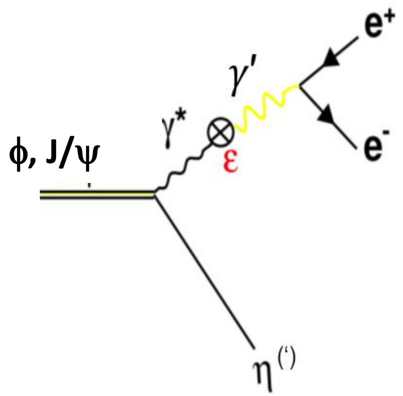
Dark photon: introduction

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

A', U, γ'

- 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

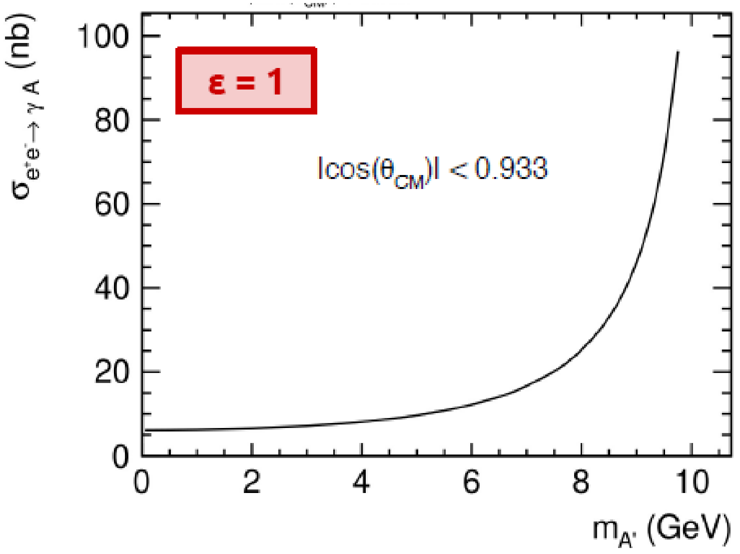




ISR

Rare meson decays

Production cross section



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

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

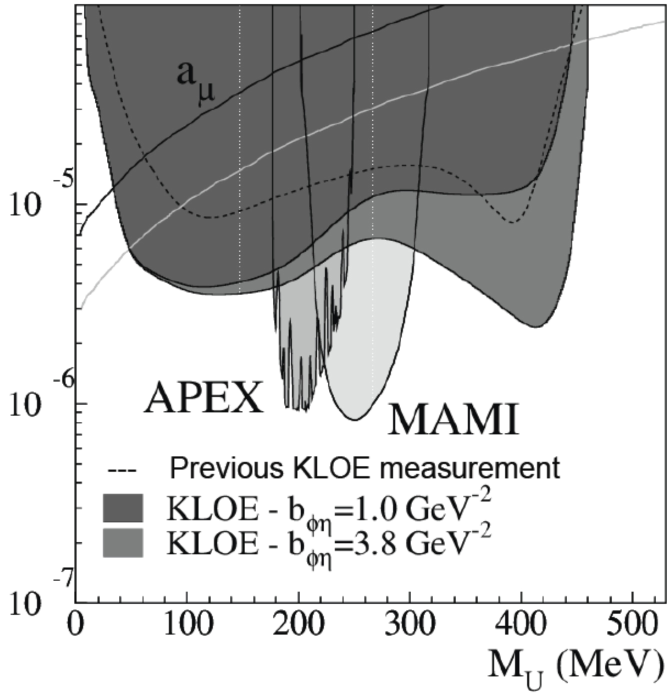
$m_{A'} > 2m_\chi \Rightarrow$ A' decays ≈100% invisibly to DM particles

Visible dark photon in rare meson decays

KLOE

$\phi \to \eta e^+e^-$ $\eta \to \pi^0\pi^0\pi^0$ $\eta \to \pi^+\pi^-\pi^0$

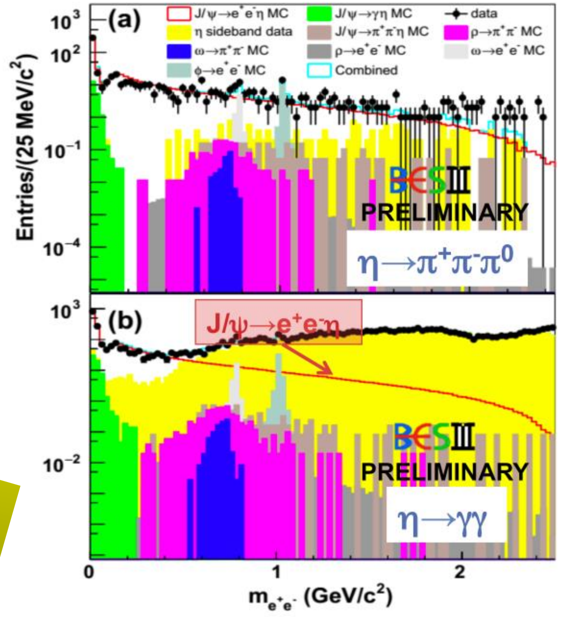
Phys.Lett. B720 (2013) 111

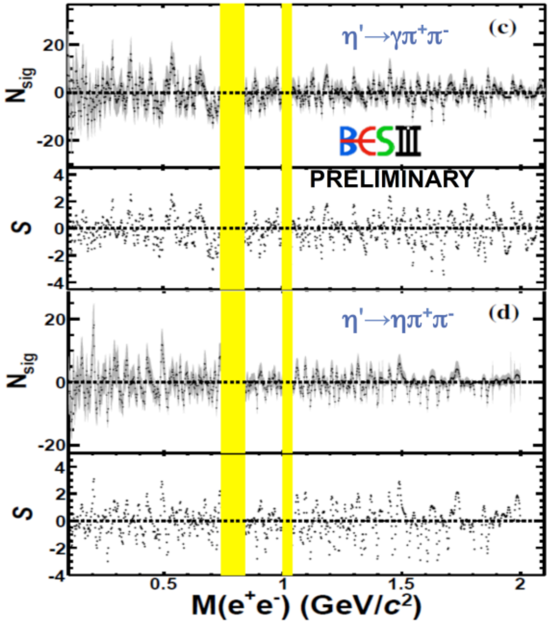


BESIII

$J/\psi \to \eta e^+e^-$ $\eta \to \pi^+\pi^-\pi^0$
$J/\psi \to \eta' e^+e^-$ $\eta \to \gamma\gamma$

Phys. Rev D99 012006 (2019)
Phys. Rev D99 012013 (2019)





Visible dark photon with ISR

Phys.Lett. B757 (2016) 356

KLOE

L=1.93 fb^{-1}

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

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

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

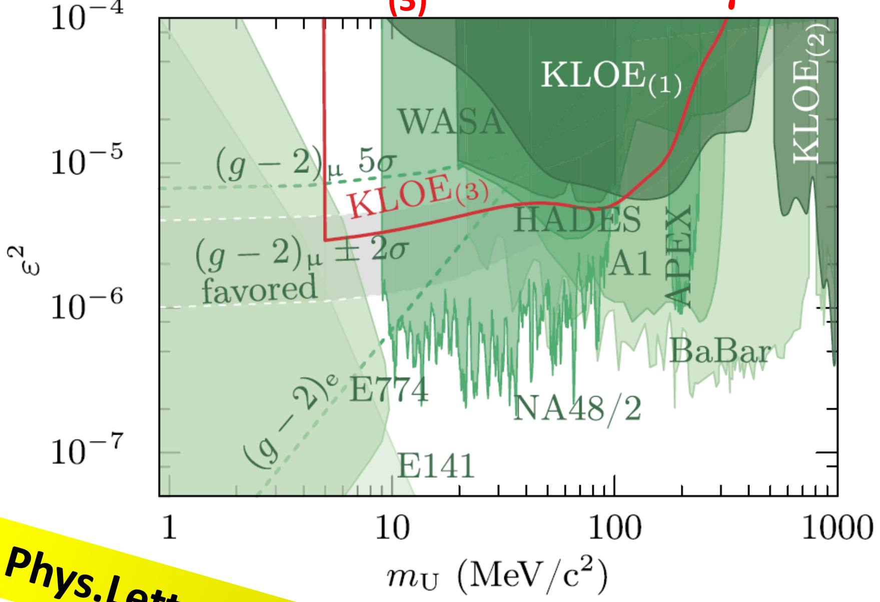
BESIII

L=2.93 fb^{-1}

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

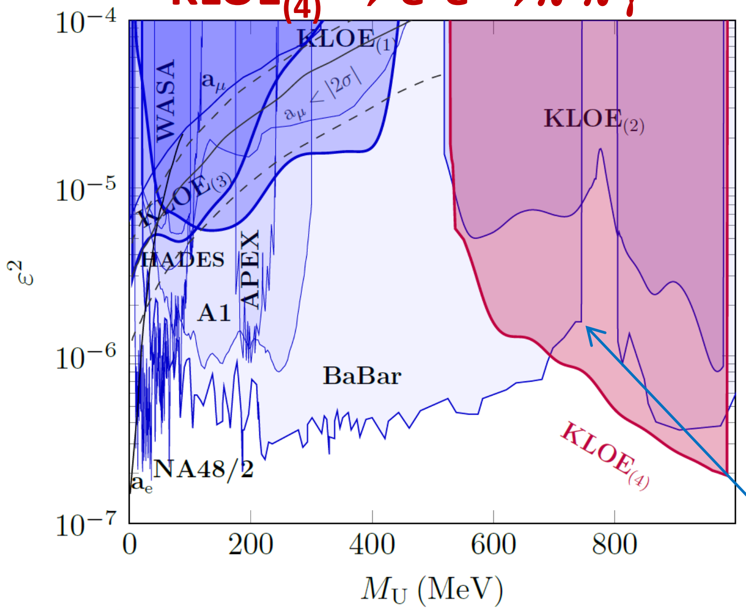
$e^+e^- \to \mu^+\mu^-\gamma$

KLOE$_{(3)}$ $\to$ $e^+e^- \to e^+e^-\gamma$

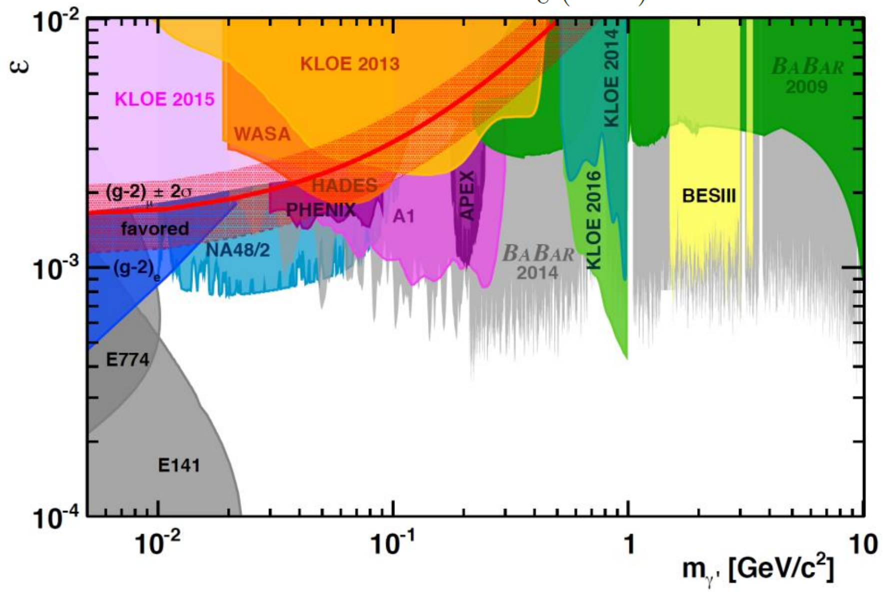


Phys.Lett. B750 (2015) 633

KLOE$_{(4)}$ $\to$ $e^+e^- \to \pi^+\pi^-\gamma$

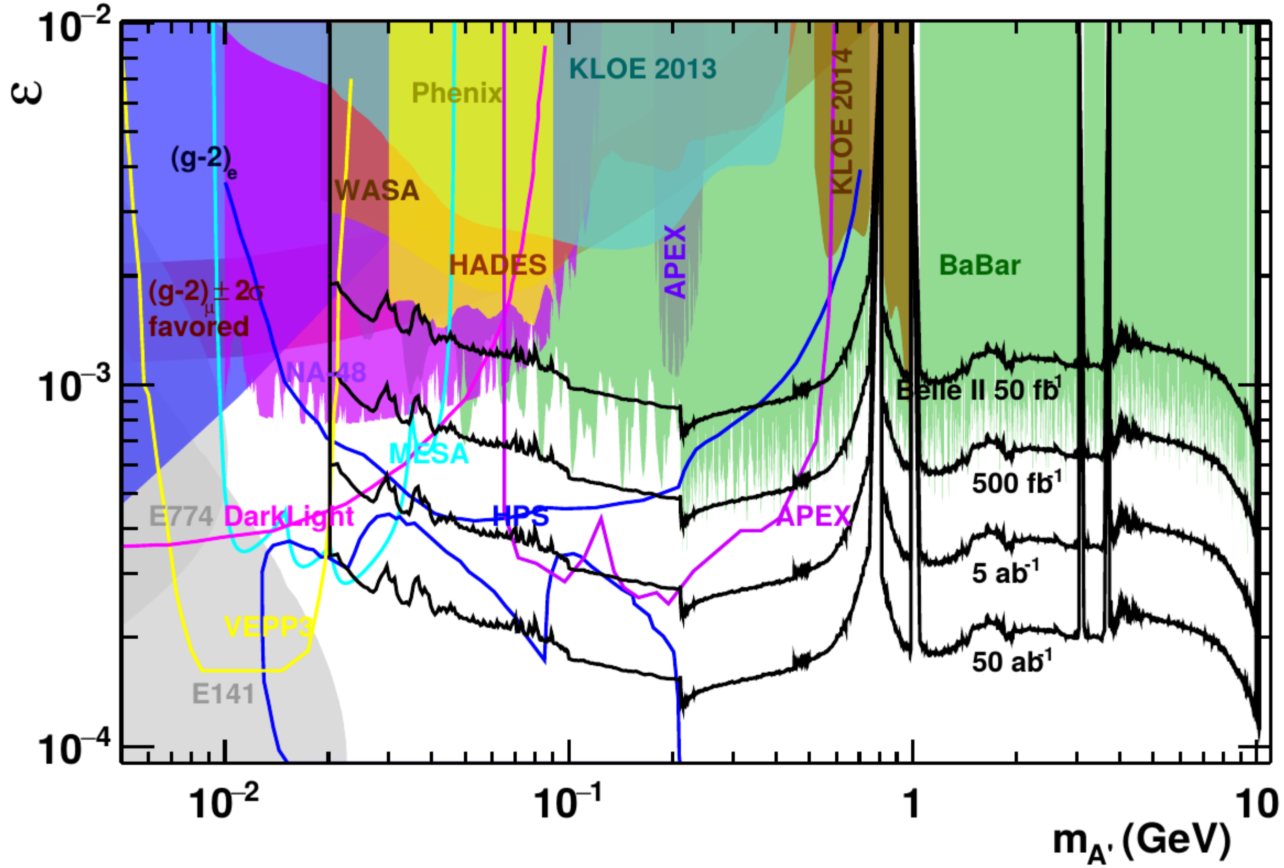


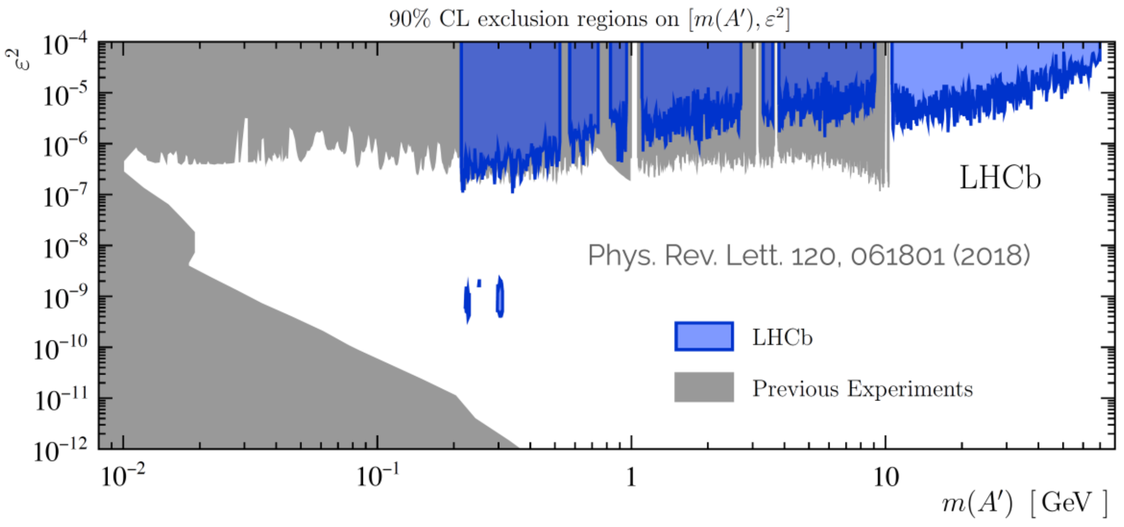
ρ region covered for the first time



Phys.Lett. B774 (2017) 252

Visible dark photon: sensitivity





Competition with LHCb:

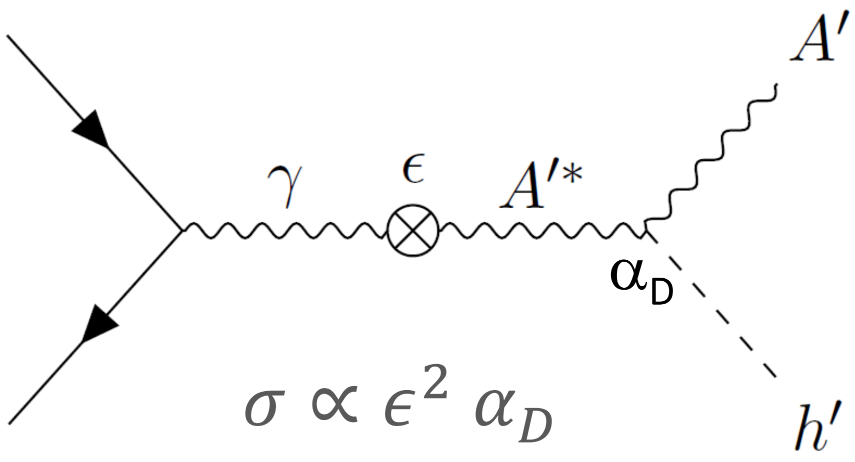
Drell-Yan processes
Displaced vertices
$D^* \to D A'$, $A' \to ee$

PRL 113, 201801 (2014)

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

Dark Higgsstrahlung: A′h′



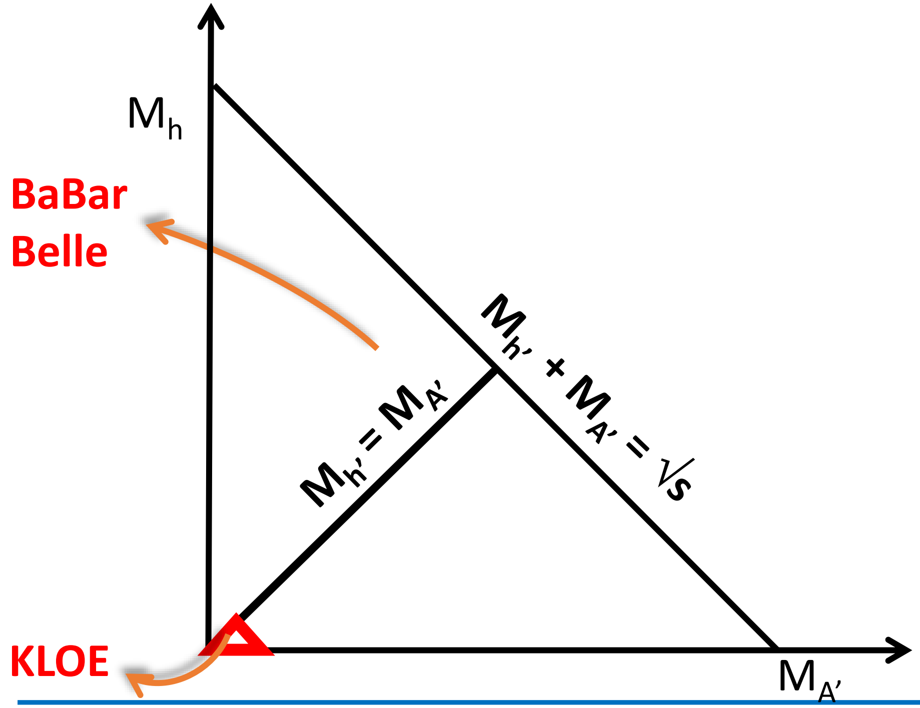
$$\sigma \propto \epsilon^2 \alpha_D$$

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



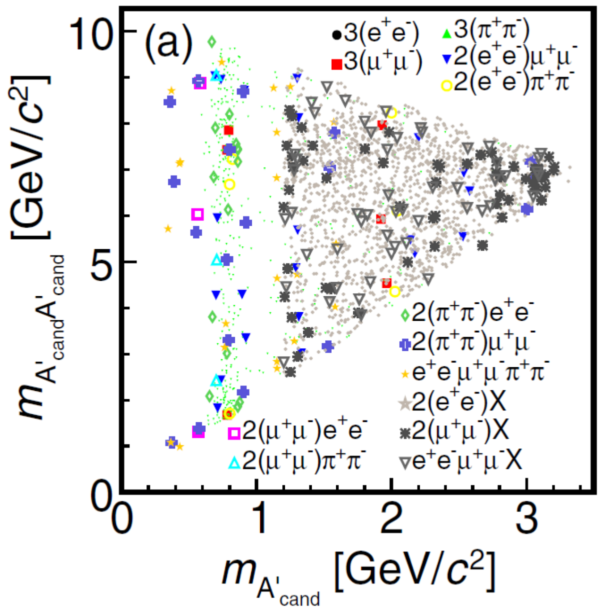
Dark Higgsstrahlung: A′h′, h’→ A’A’

BaBar, Belle

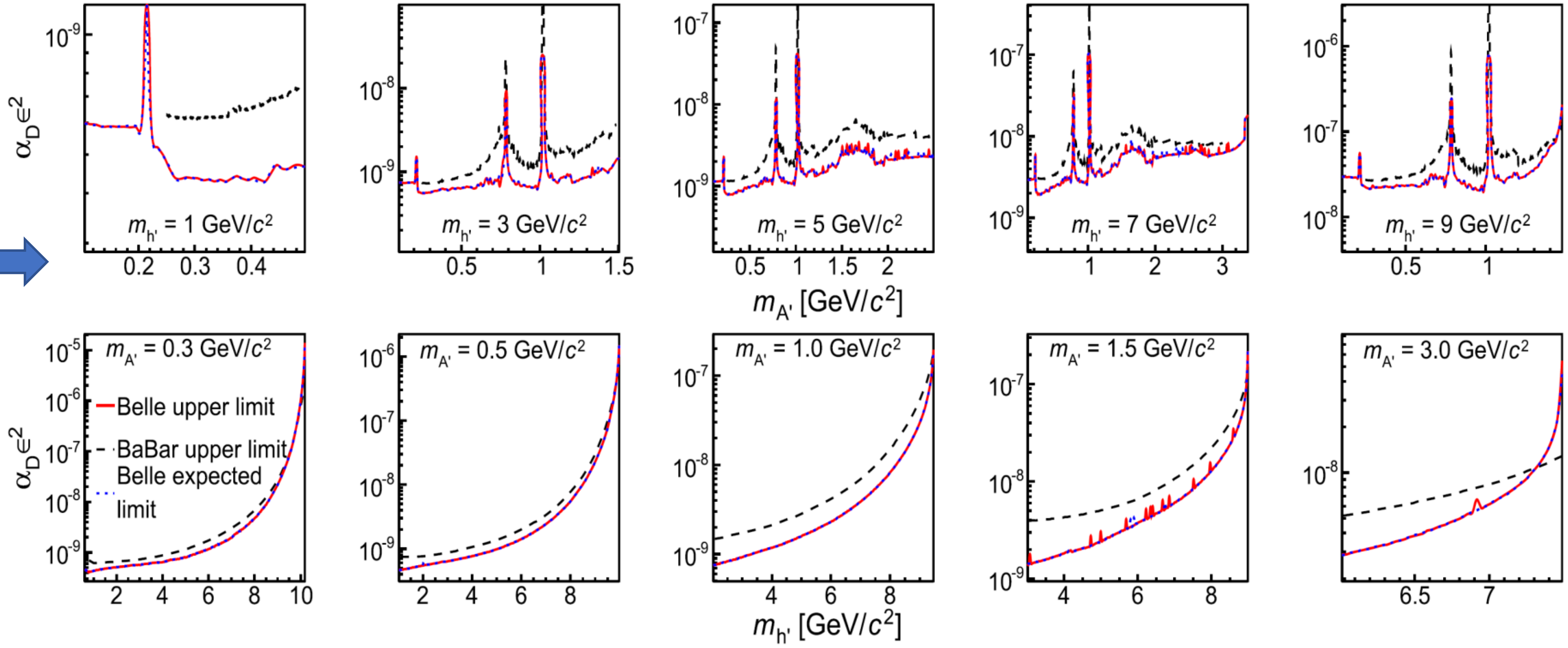
Three pairs of tracks (ee, μμ, ππ) at the same mass
No missing energy
~ background free (but in the ρ region)

BaBar
PRL 108, 211801 (2012)
Belle
PRL 114, 211801 (2015)

Observed events



Upper limts 90% CL



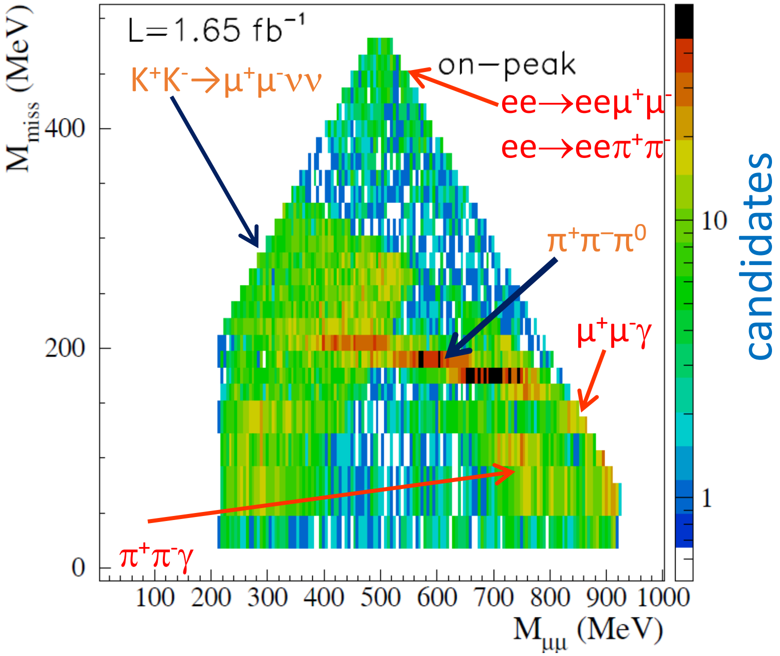
Dark Higgsstrahlung: A′h′, h’ invisible

KLOE

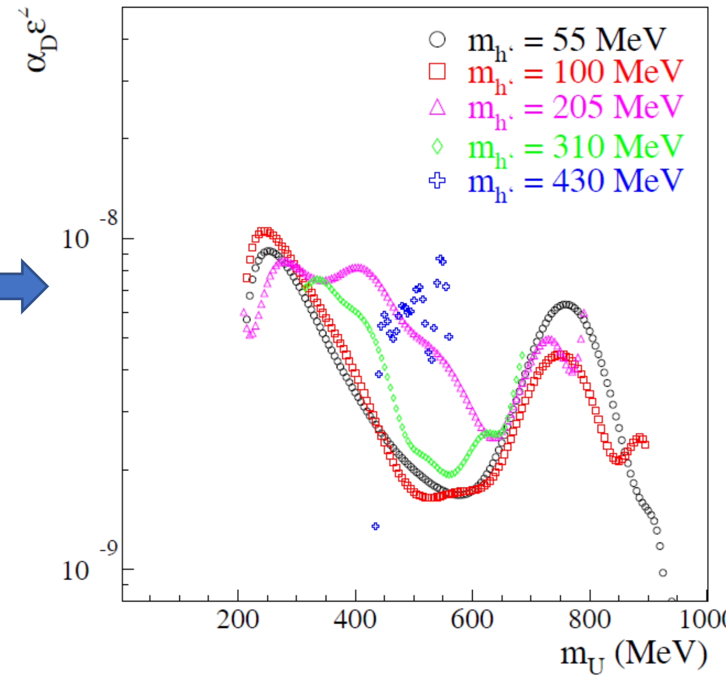
Two muons + missing energy
Background from K^+K^-, $\pi^+\pi^-\pi^0$, $\mu^+\mu^-(\gamma)$, $\pi^+\pi^-(\gamma)$, two-photon

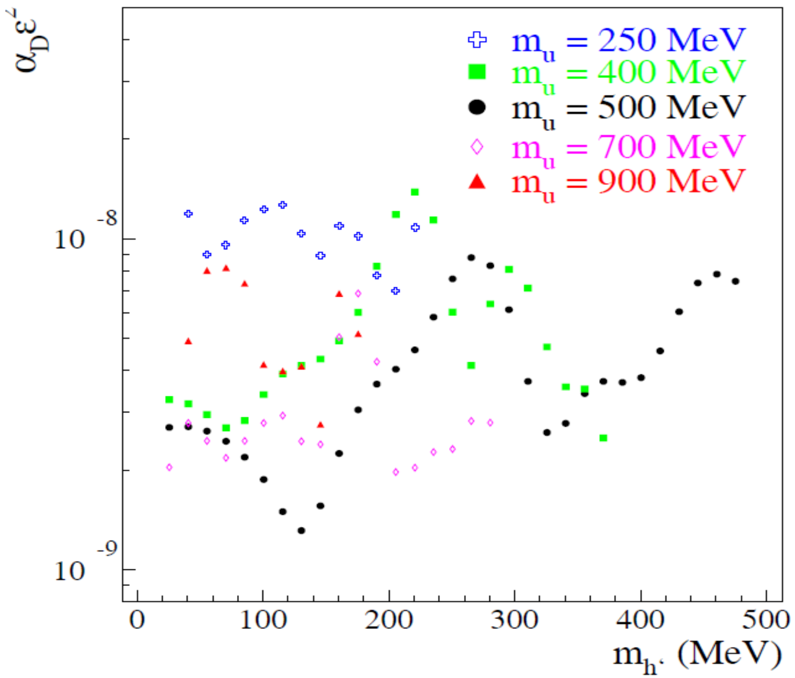
Phys.Lett. B747 (2015) 365

Observed events



Upper limts 90% CL





CP-odd Higgs boson A^0

BaBar, Belle

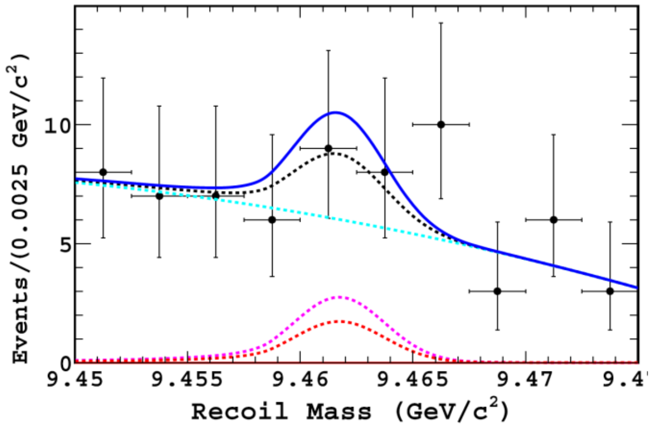
BaBar
PRL 107 021804 (2011)

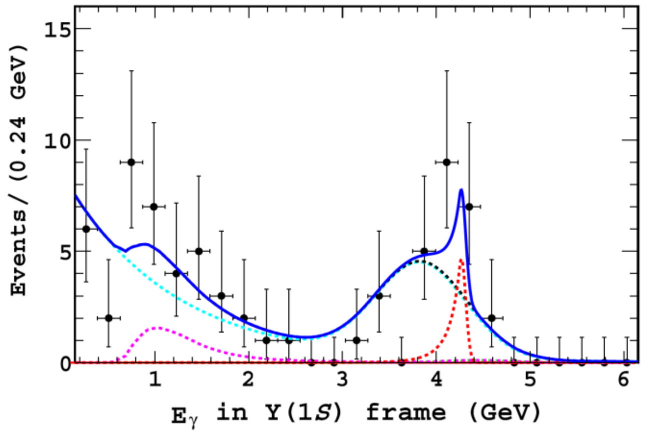
Belle
PRL 122 011801 (2019)

NMSSM

$\Upsilon(1S)$ tag

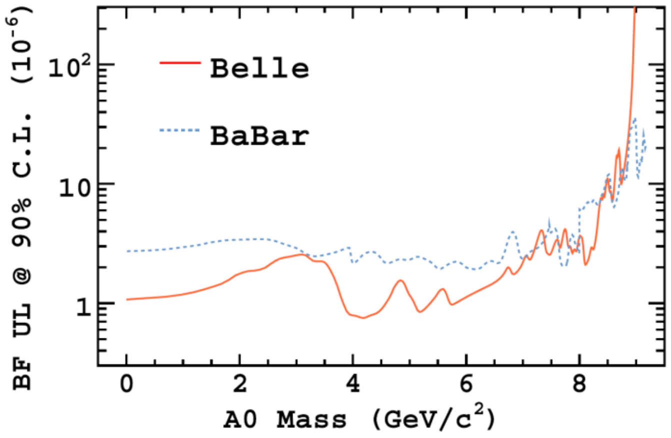
$$\Upsilon(2S) \rightarrow \Upsilon(1S)\,\pi^+\pi^-$$
$$\Upsilon(1S) \rightarrow \gamma A^0$$
$$A^0 \rightarrow \chi\chi$$

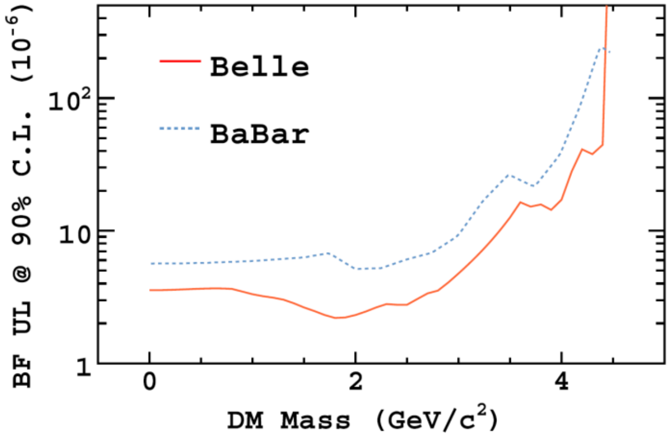




- - - - Continuum background
- - - - $\Upsilon(1S)$ background
- - - - Total background
- - - - A^0 signal
—— Total

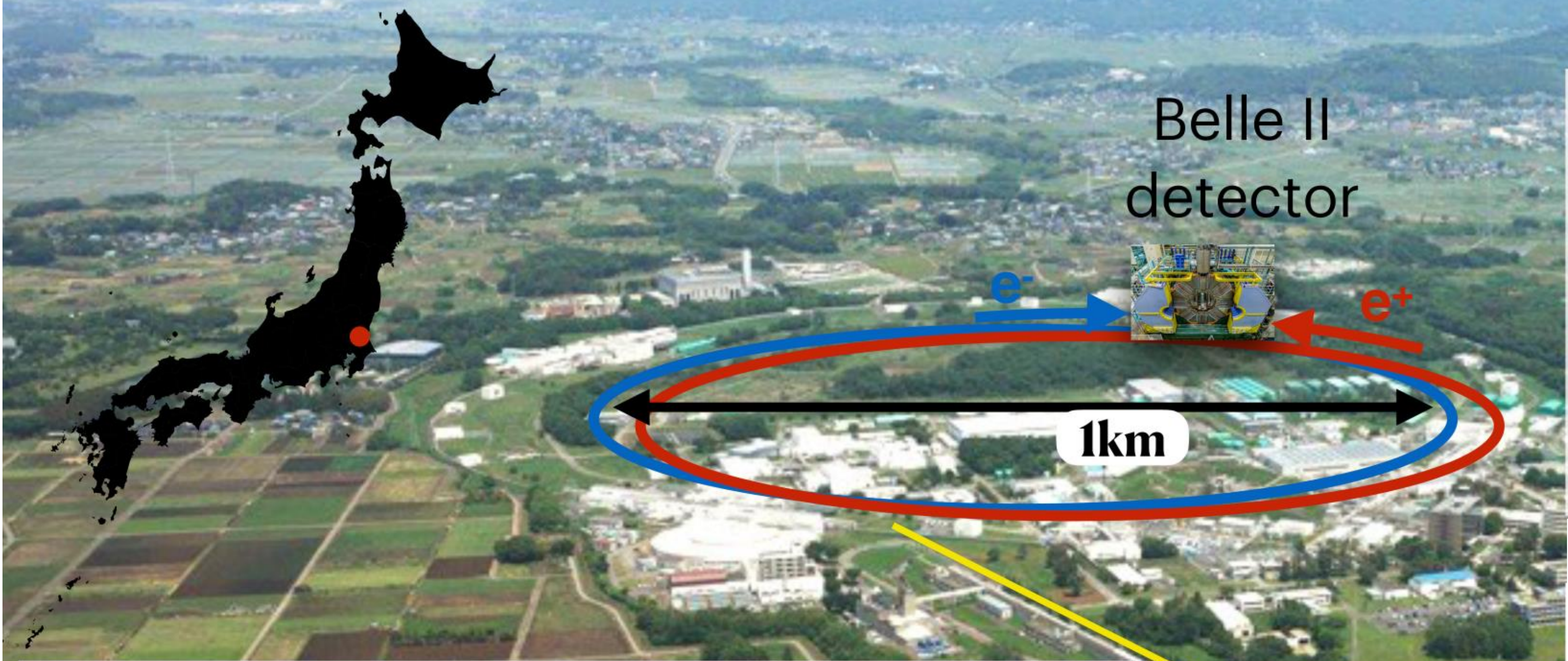
M_{A0} =2.946 GeV/c^2
Significance 2.1 σ





Belle II @ Super-KEKB

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



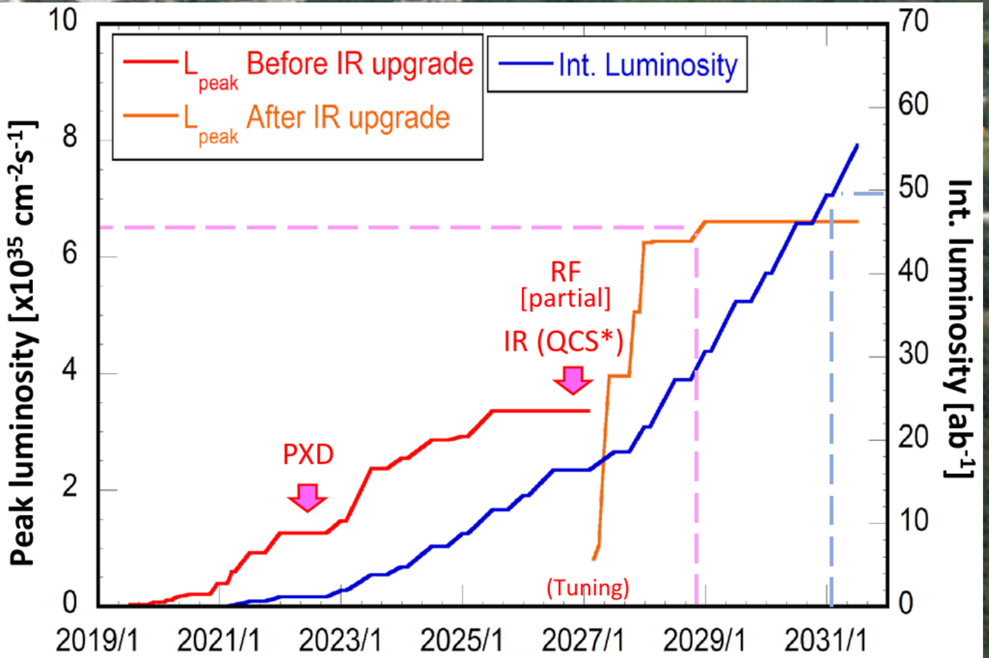
7 GeV e^-, 4 GeV e^+

E_{CM} Υ(4S) = 10.58 GeV + scans

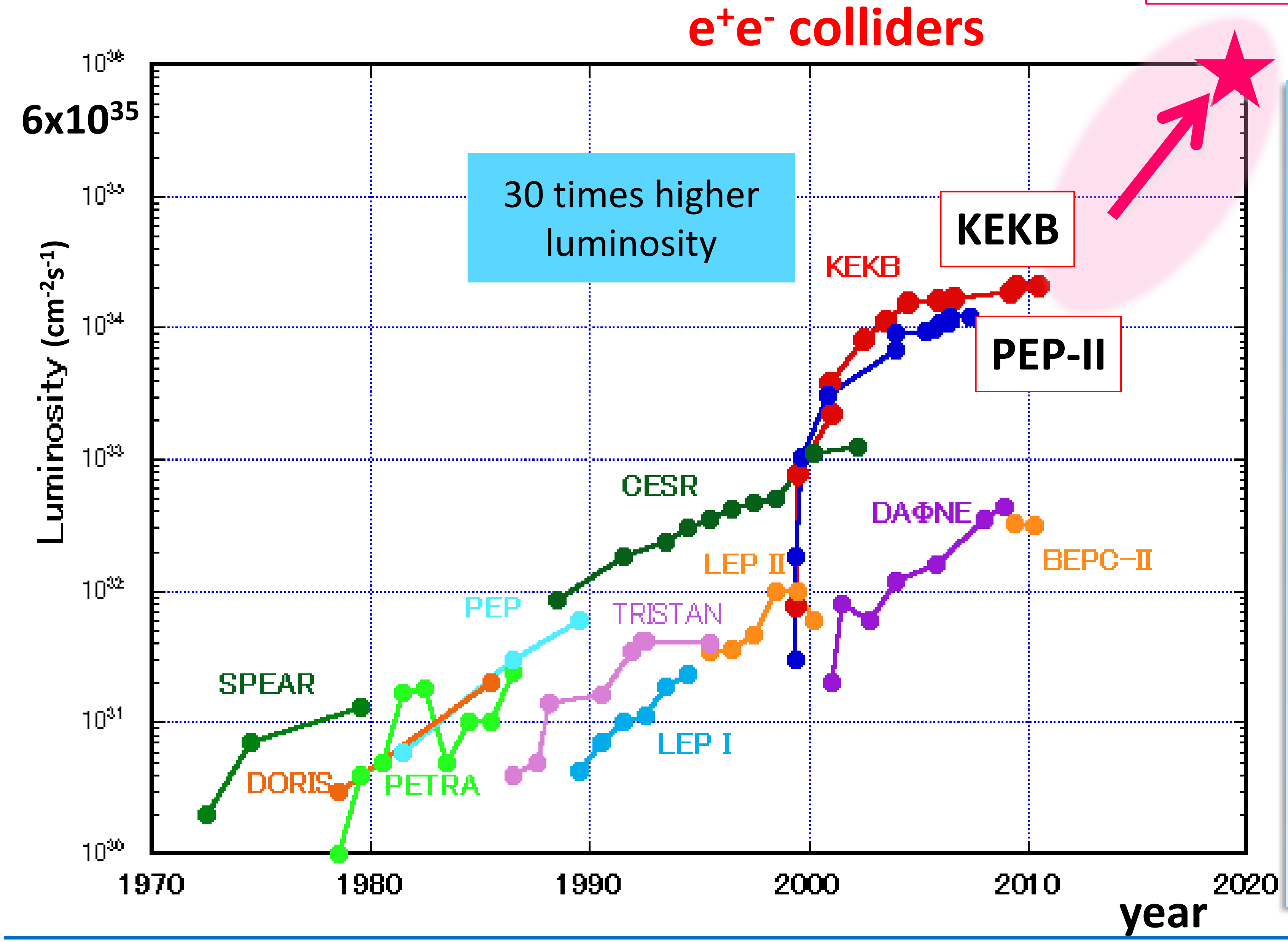
Υ(4S) → B anti-B

B + Charm + τ + Υ factory + ?

~1050 researchers
(355 grad students)
from 23 countries.



Peak luminosity trend



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

- 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

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

Classical electron radius

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

Vertical beta function@IP

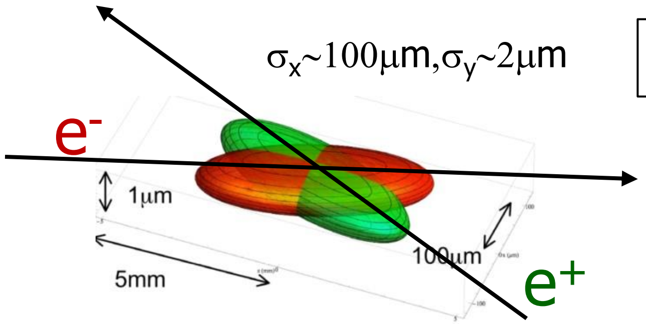
Lumi. reduction factor (crossing angle)&
Tune shift reduction factor (hour glass effect)
0.8 ~ 1 (short bunch)

x30

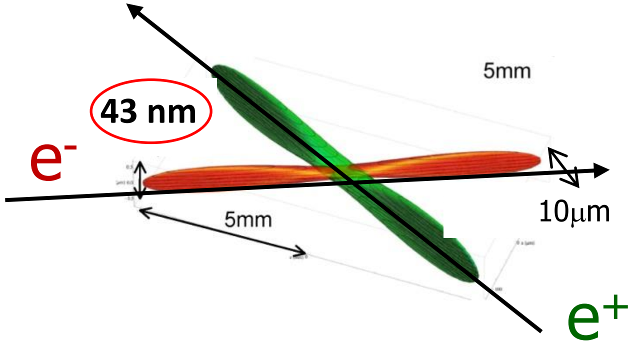
β^*_y=0.30/0.30 mm

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

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

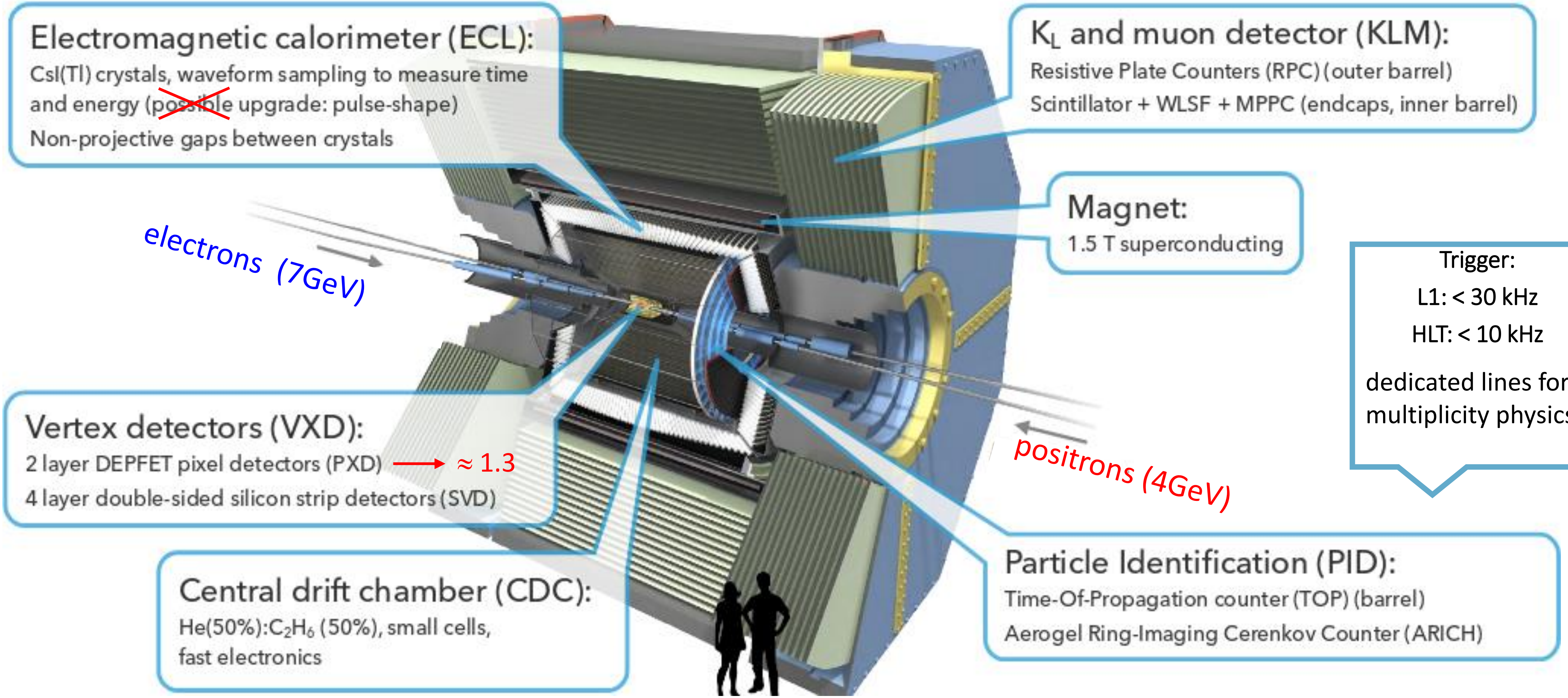


Nano-Beam scheme



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

Belle II detector



Trigger:

L1: < 30 kHz

HLT: < 10 kHz

dedicated lines for low multiplicity physics

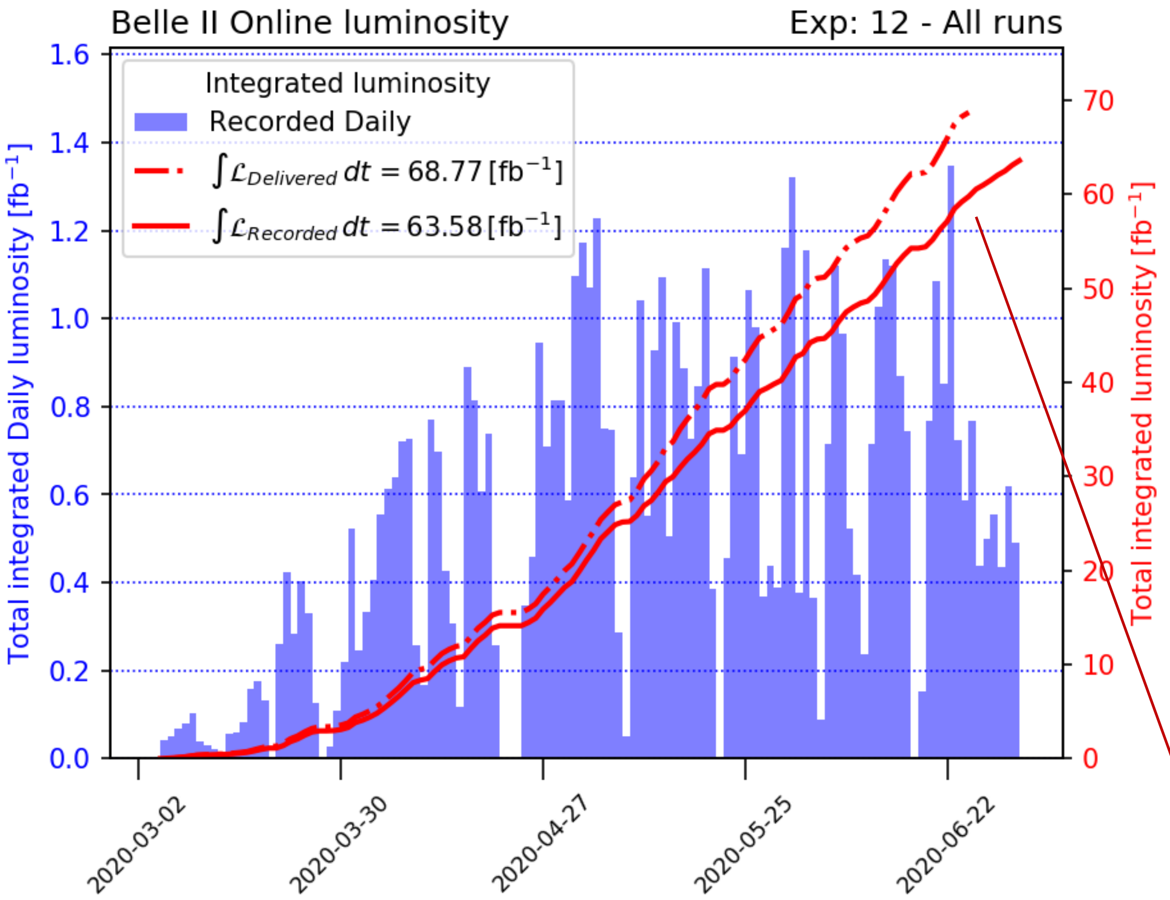
Belle II vs Belle

better detector, much better trigger, but higher backgrounds

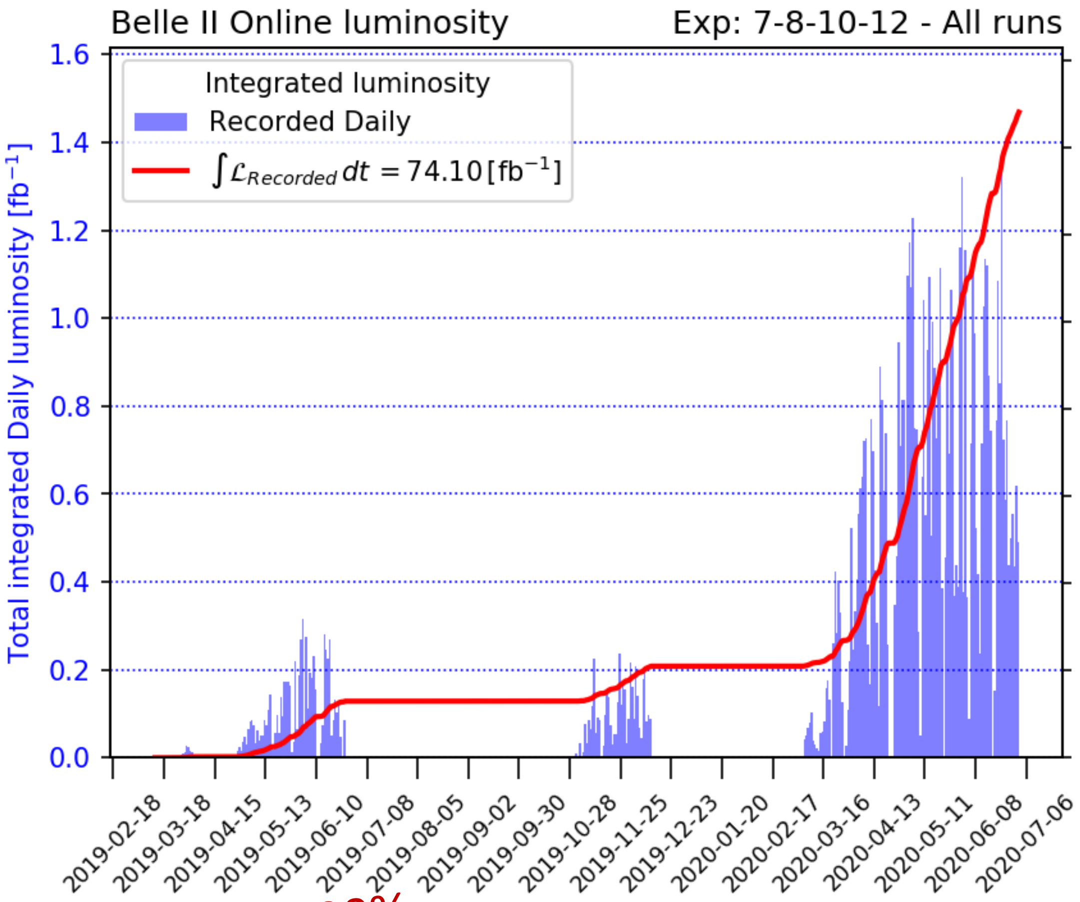
Final goal: L= 50 ab^{-1}

Belle II luminosity record

Collected luminosity during spring run



Collected luminosity up to now: 2019+2020



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

Fall run to start in ~September/October

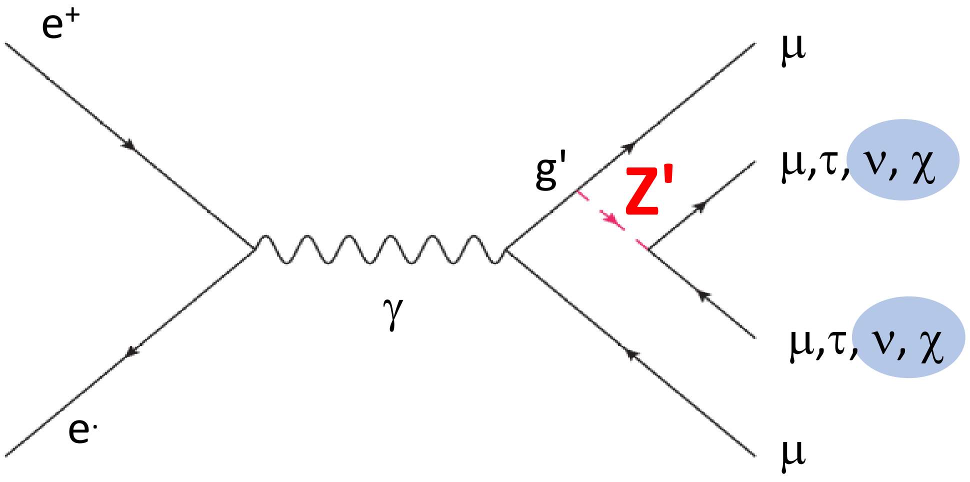
Data taking efficiency ≈ 90%

Pilot run 2018: L ≈ 0.5 fb^{-1}

Z': L_μ - L_τ model

- Gauging L_μ - L_τ , 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

Explored for the first time

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

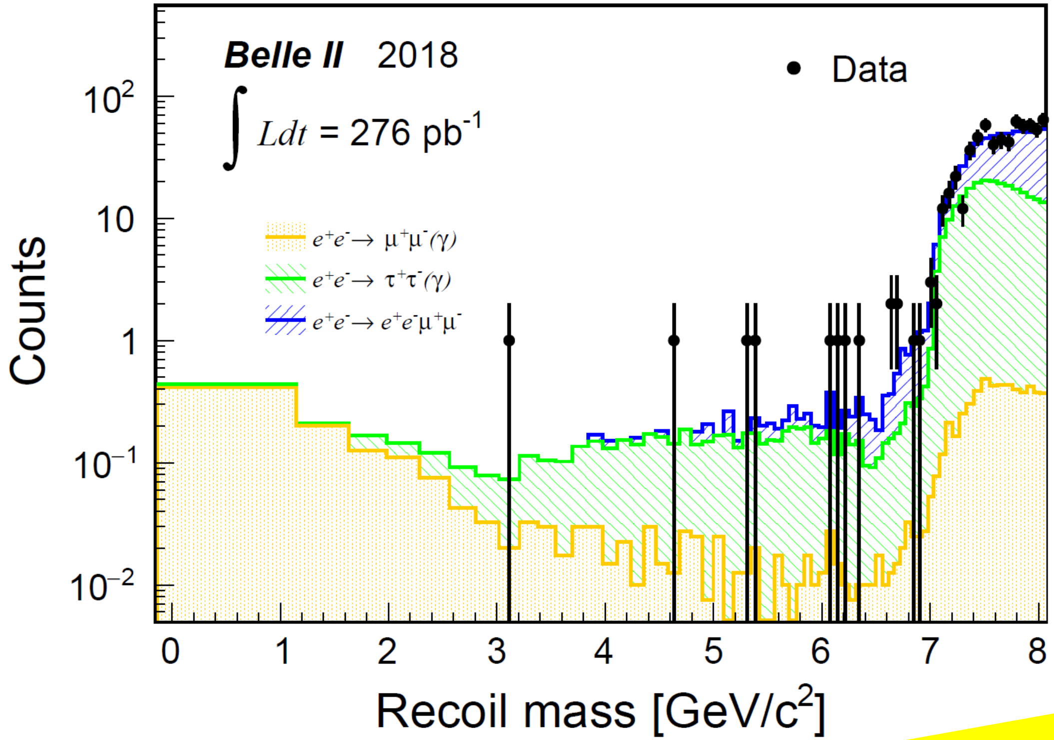
Look for bumps in recoil mass against a $\mu^+\mu^-$ pair

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

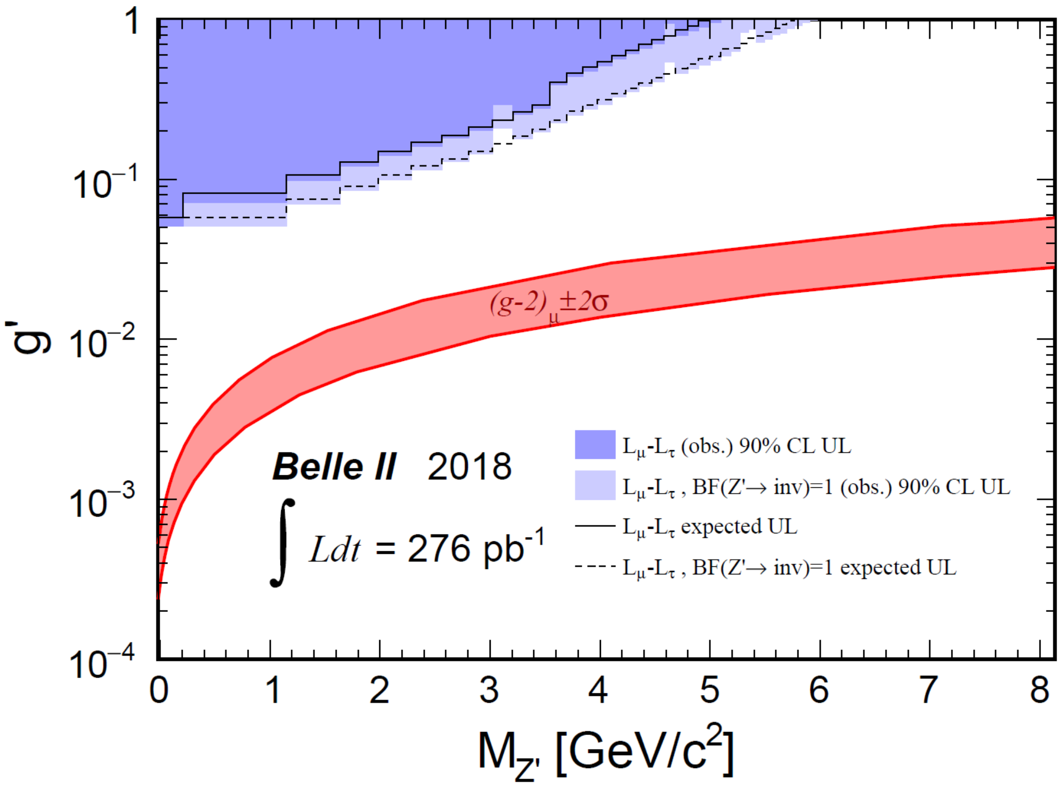
Pilot run physics results



Systematics

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

will decrease with new data

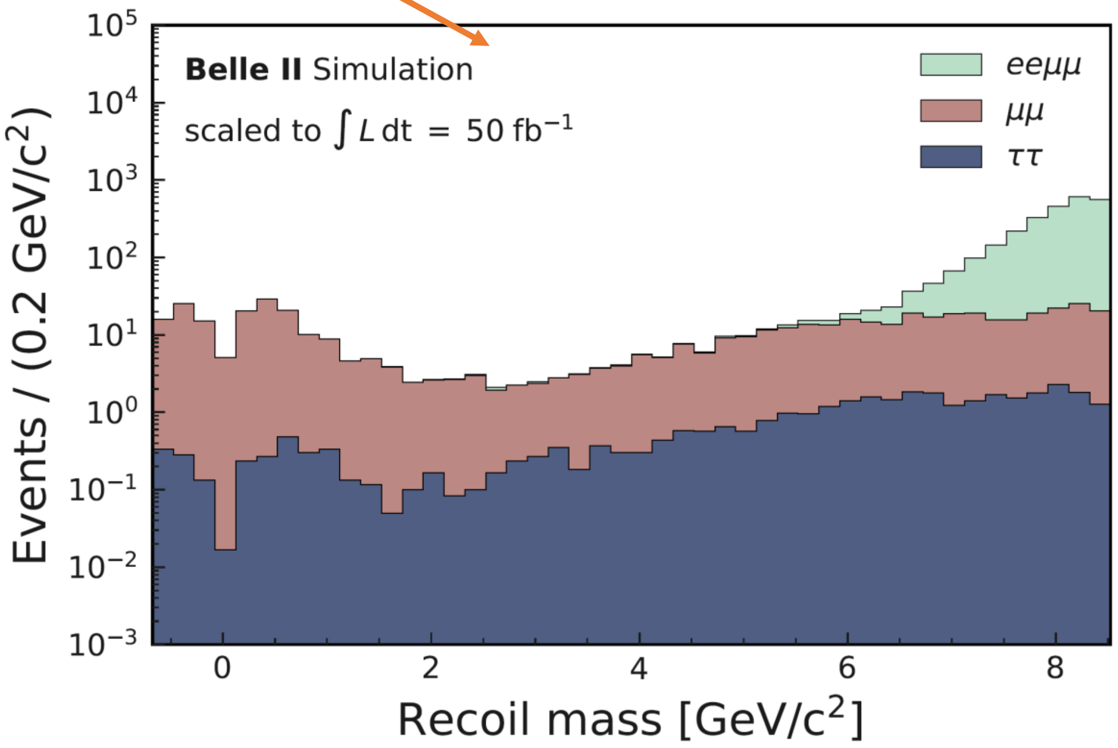


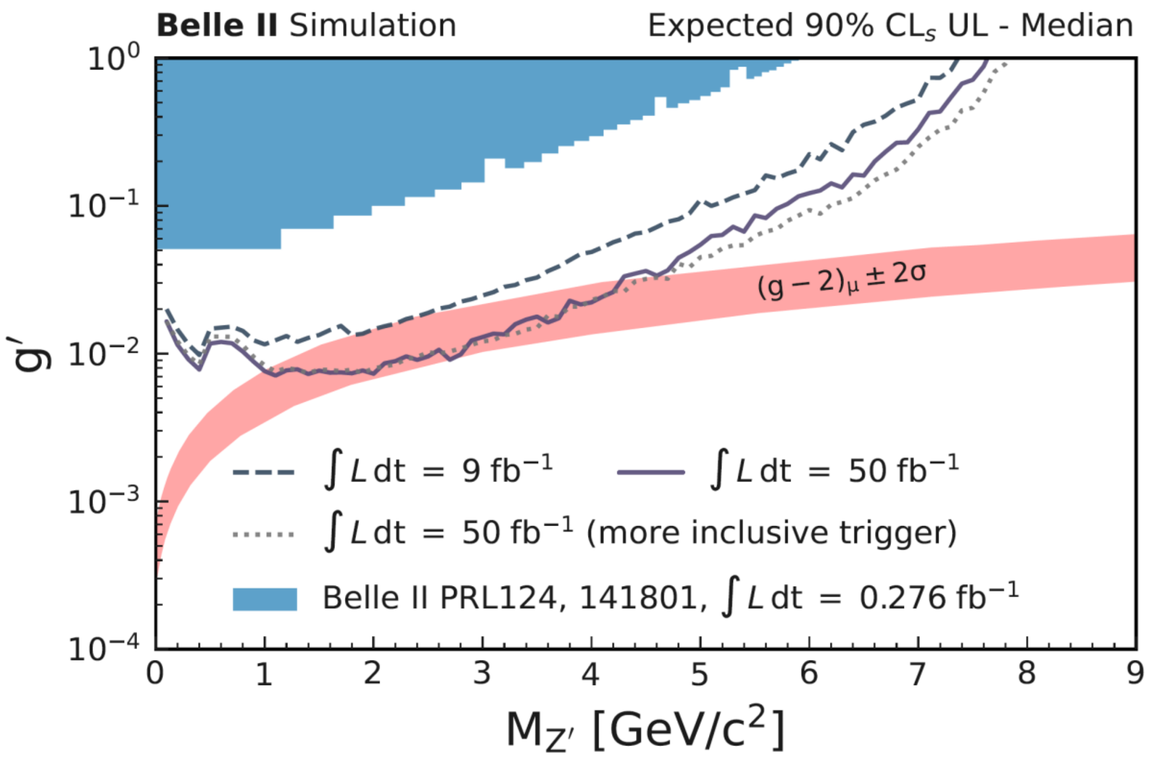
First physics paper by Belle II
PRL 124 (2020), 141801

Z' to invisible: early phase 3 projections

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

Very low expected background → UL scale~1/L



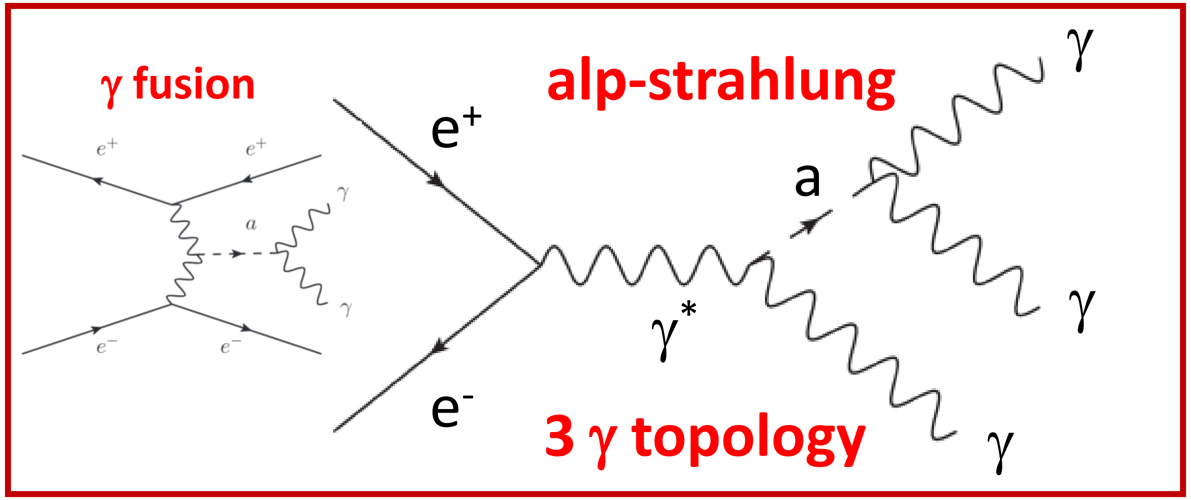


Axion Like Particles (ALPs)

- 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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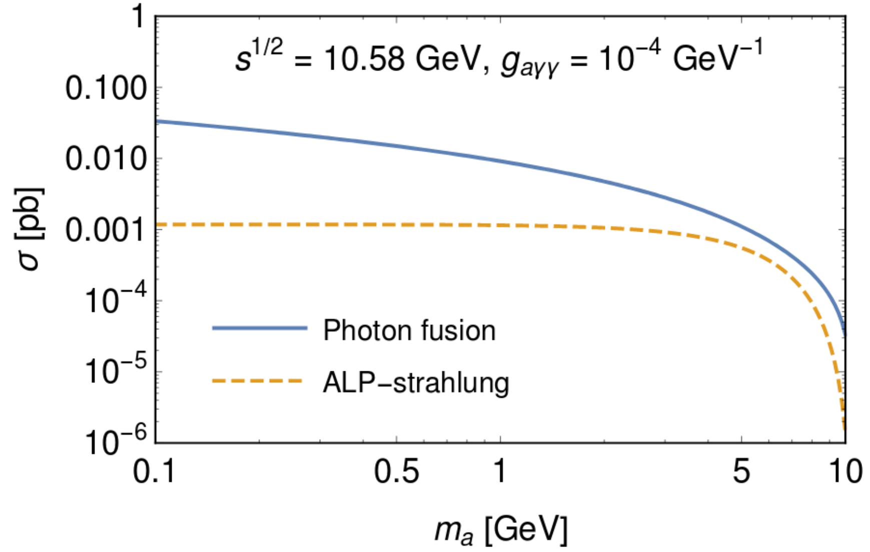
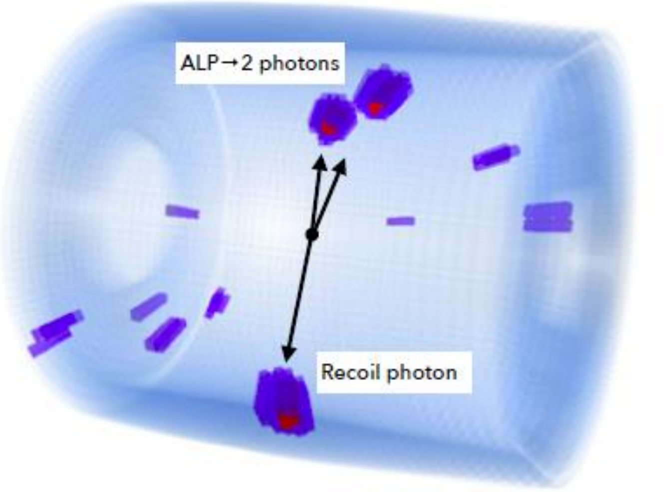


photon fusion sensitivity under study

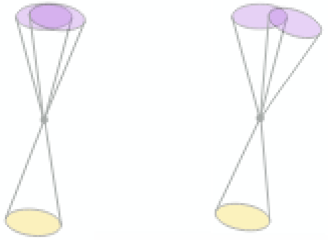
Axion Like Particles (ALPs): signal

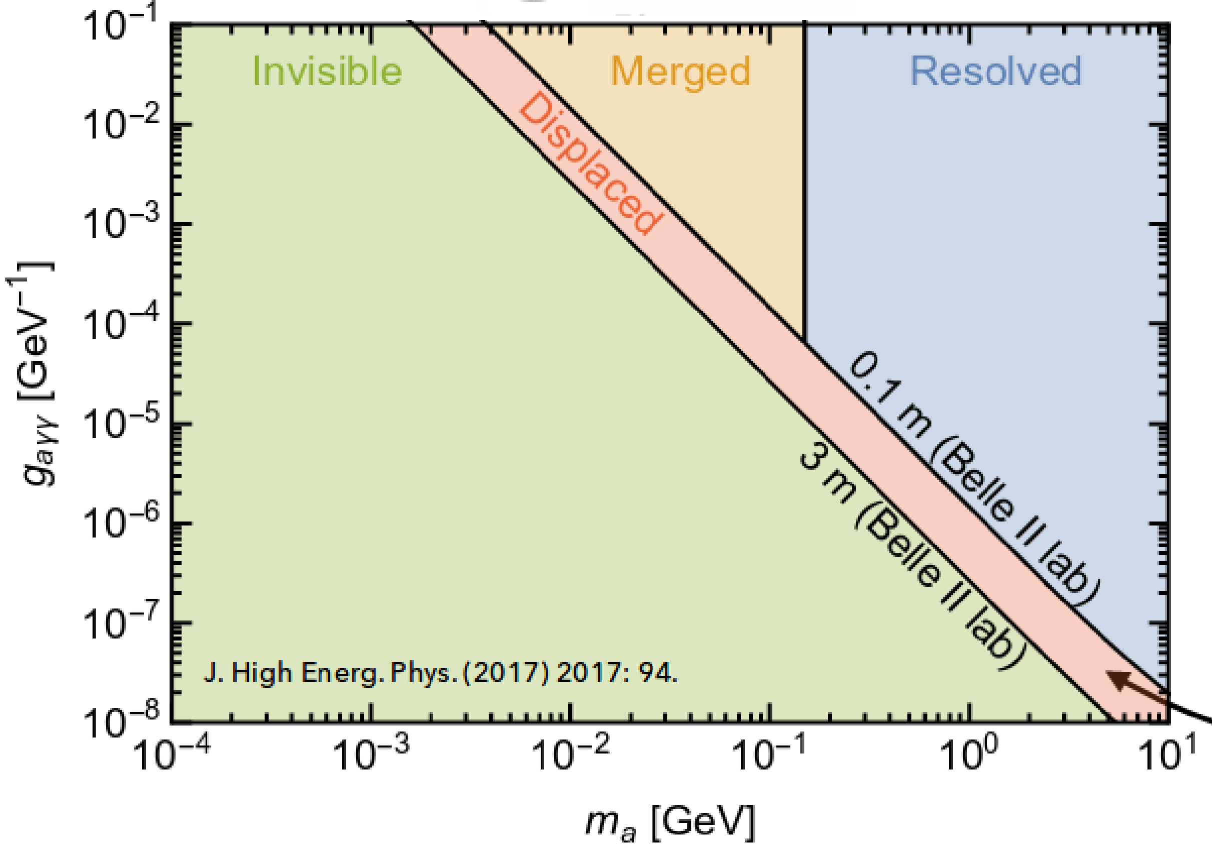
3 γ topology, but…



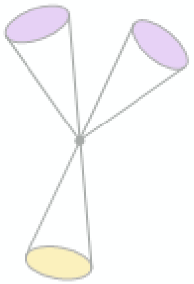
ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

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





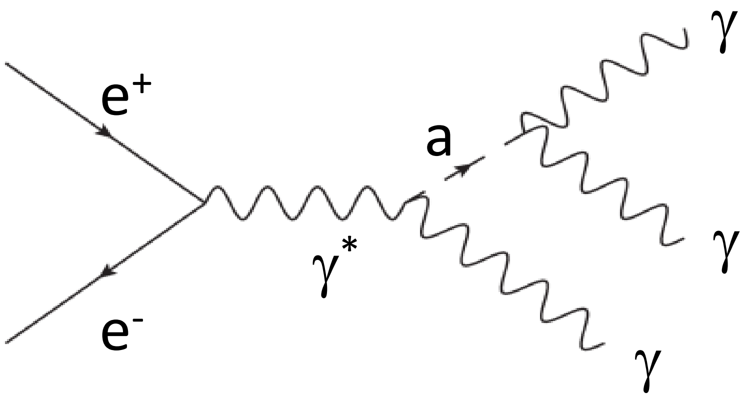
Three **resolved**, high energetic photons.

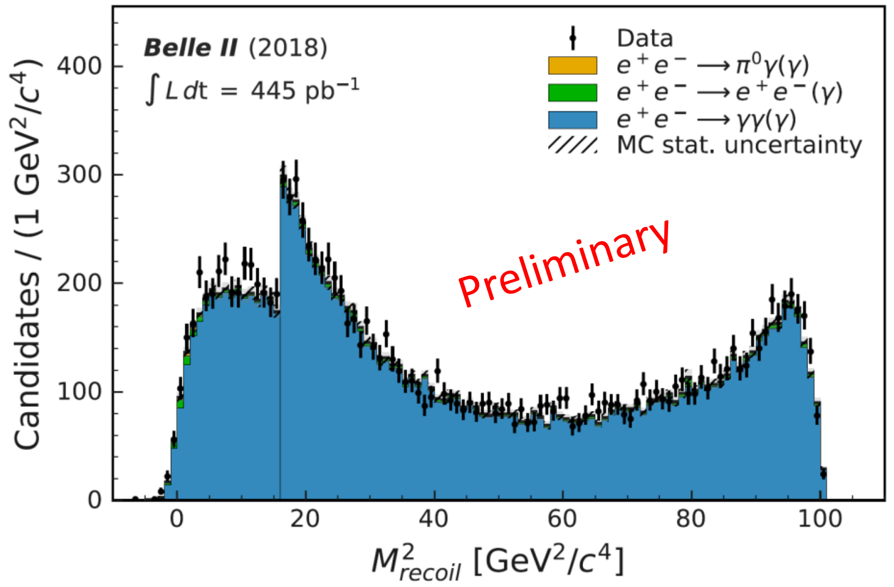


The searches for invisible and visible ALP decays veto this region.

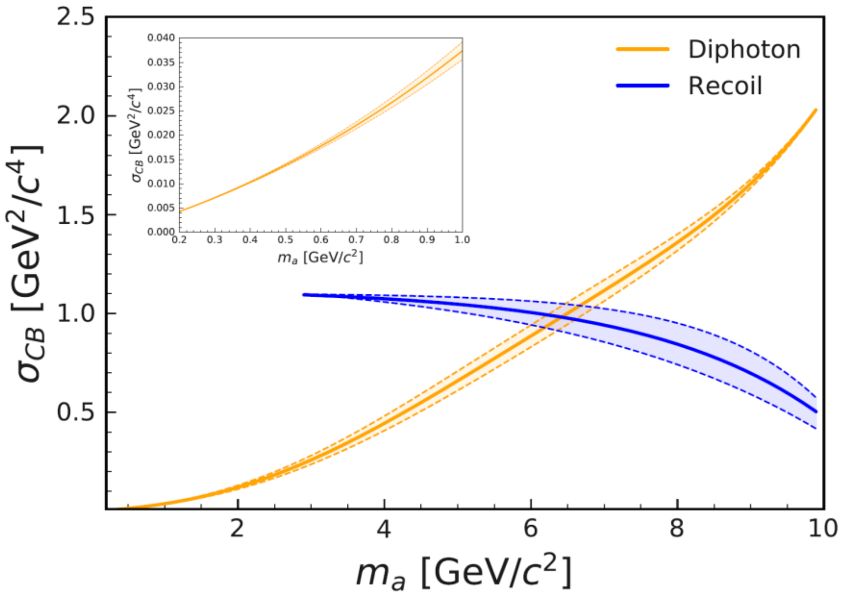
ALPs can also decay to DM → single photon topology

Axion Like Particles (ALPs)





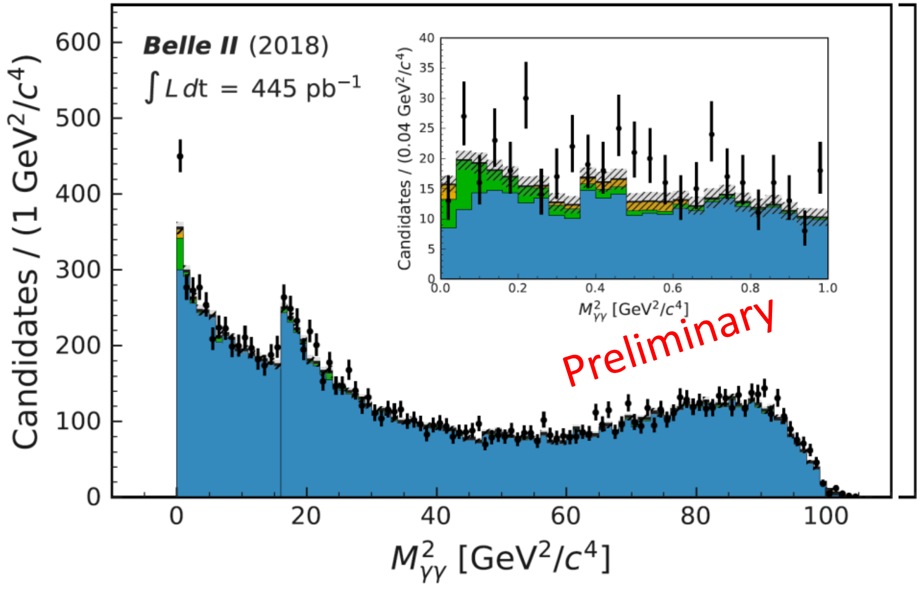
Search for peaks either in the recoil invariant mass (high m_a) or in diphoton mass (low m_a)



Main backgrounds:

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

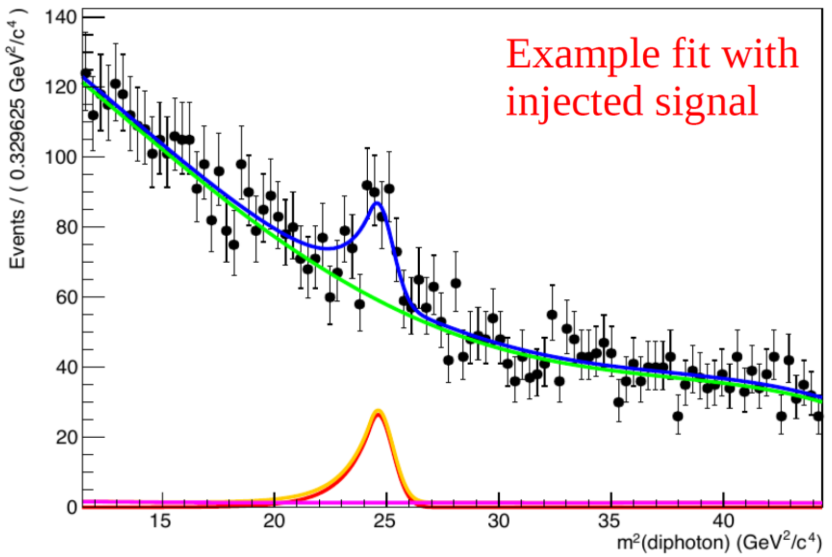
$e^+e^- \rightarrow e^+e^-\gamma$

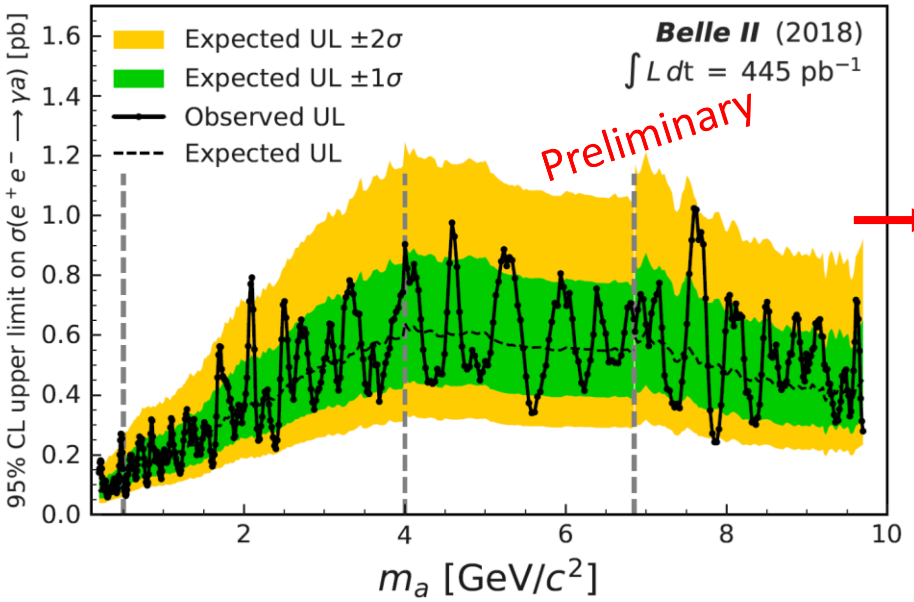


Axion Like Particles (ALPs)

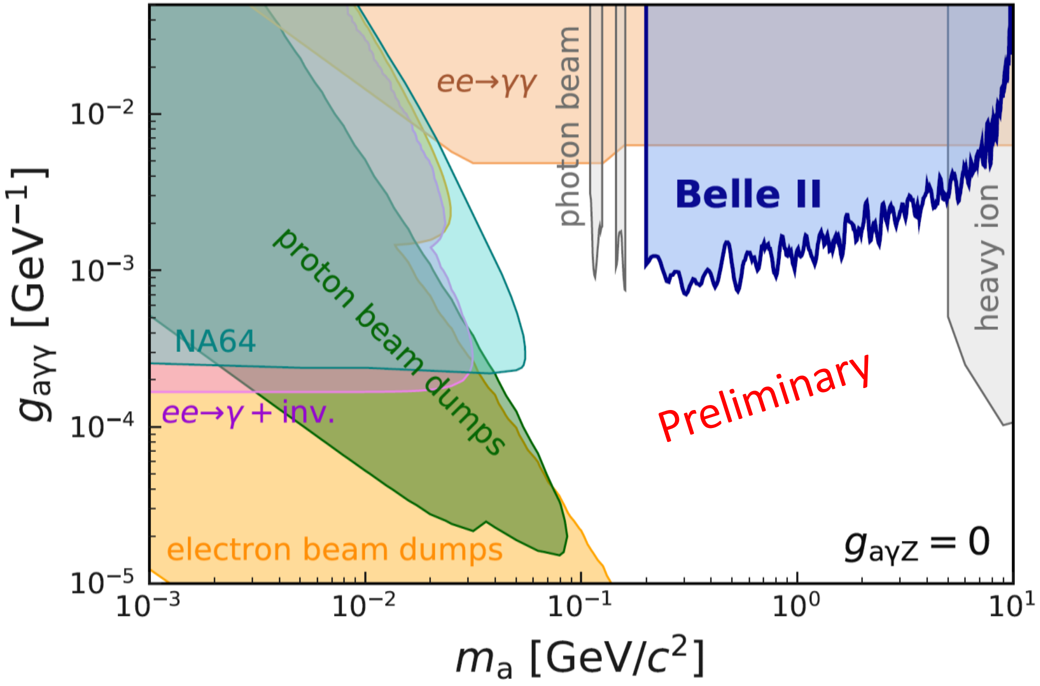
- ~500 fits in sliding ranges with steps of half resolution
- No peaking backgrounds expected
- $0.2 < m_a < 9.7\ \mathrm{GeV}/c^2$

Second physics paper by Belle II being submitted to PRL

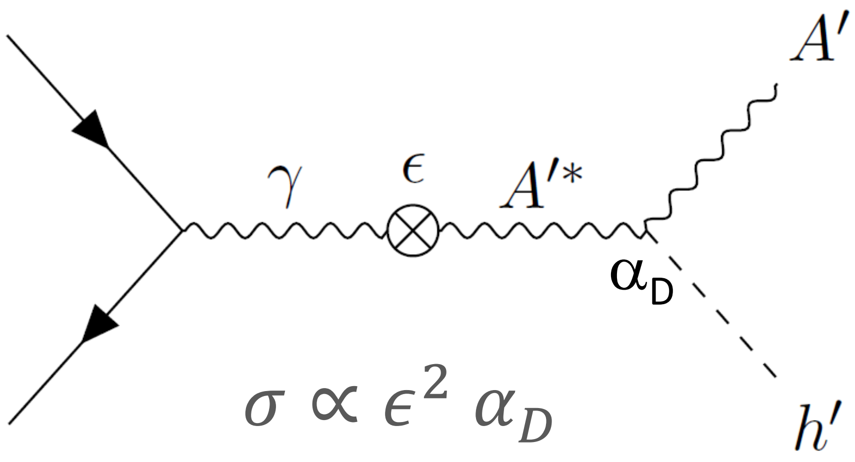




$$\sigma_a = \frac{g^2_{a\gamma\gamma}\alpha_{\mathrm{QED}}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$



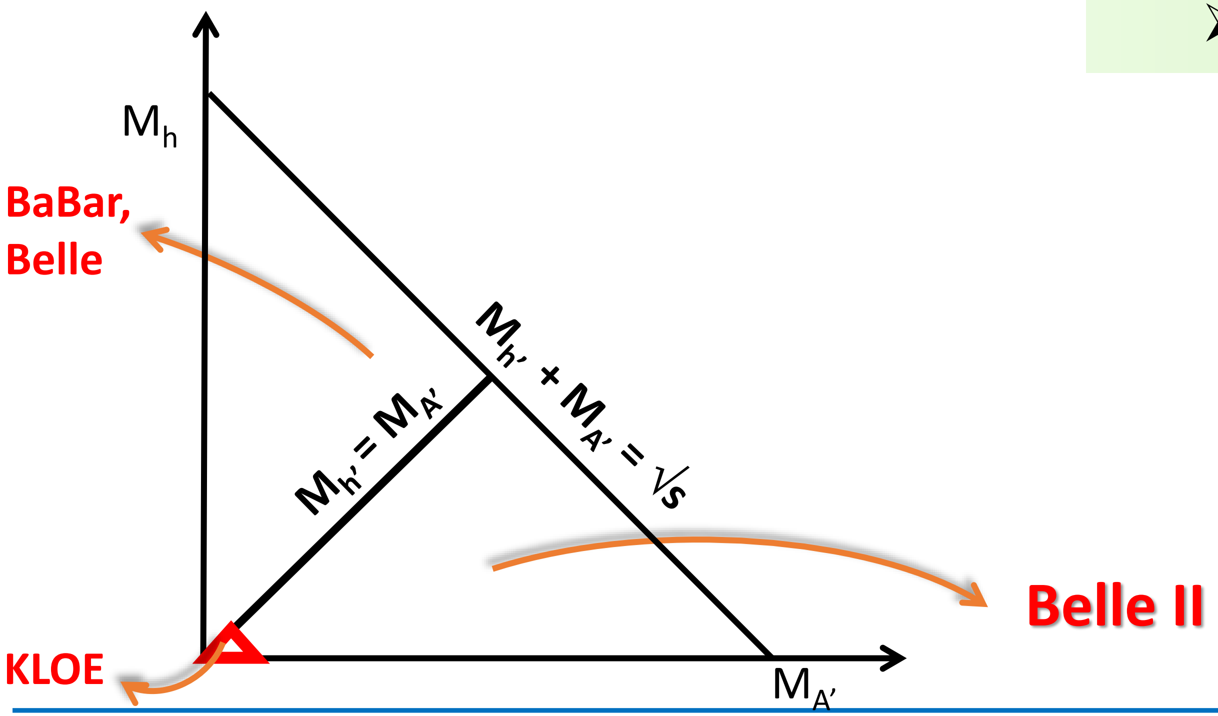
Dark Higgsstrahlung: A′h′



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

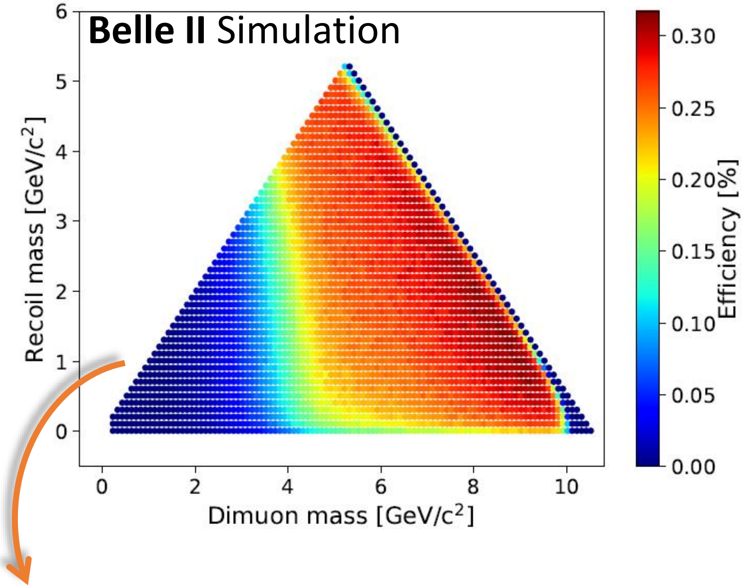
- Dark photon A′ + dark higgs h′
- h′ → spontaneous symmetry breaking to give mass to A′
- Less suppressed in ε wrt standard A′ search
- Very different scenarios depending on:
  - $M_{h'} > M_{A'} \Rightarrow h' \to A'A' \to 4l$, 4 *had*, $2l$ + 2 *had*
  - $M_{h'} < M_{A'} \Rightarrow h'$ "invisible"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

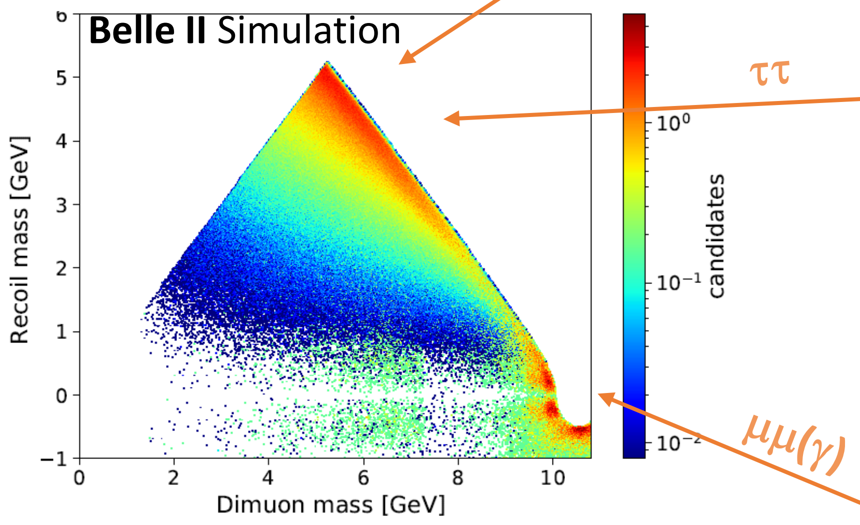
Long lived

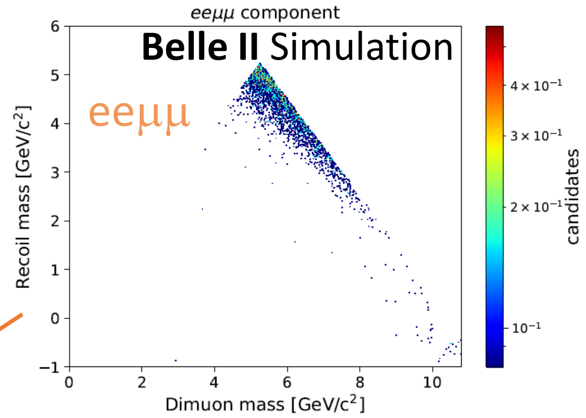


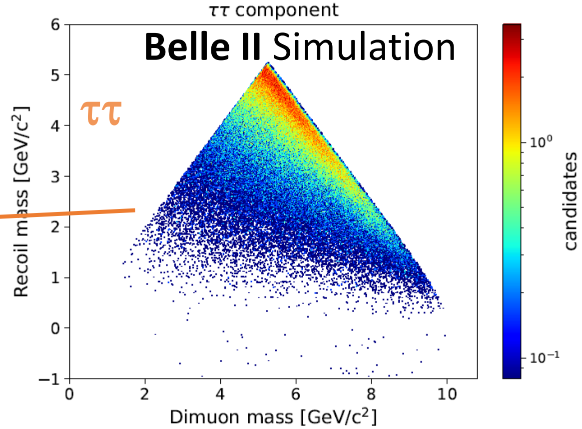
Dark Higgsstrahlung: A′h′

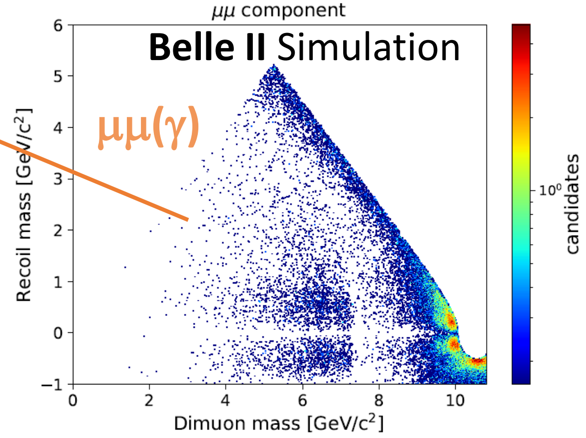
- **$\mu^+ \mu^-$ + missing energy** → same final state as in invisible Z′
- 2d peak in recoil vs dimuon mass
- Background naturally low due to 2d phase space
- **2019 data being used: L ≈ 9 fb^{-1} → next paper**











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

Dark Higgsstrahlung: A′h′

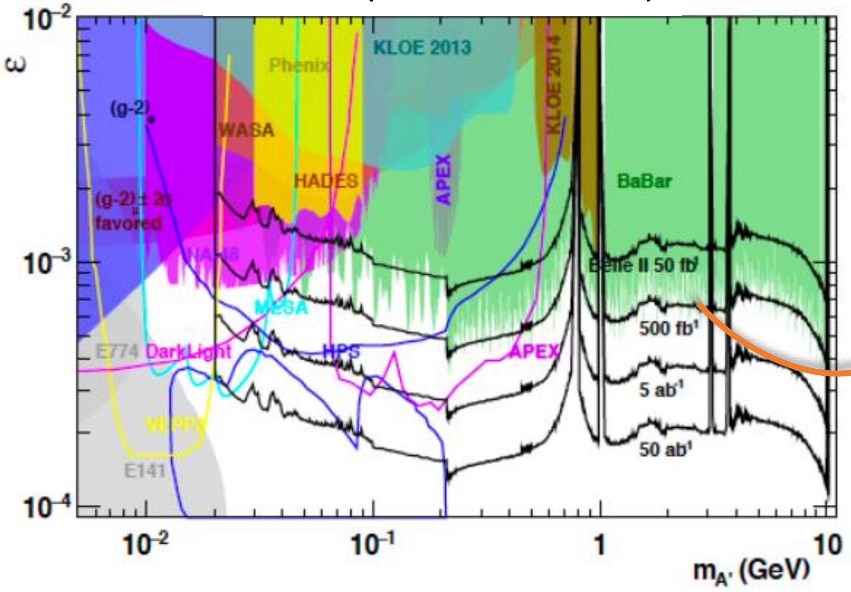
Very promising results even with the 2019 only dataset (9 fb^{-1})

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

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

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

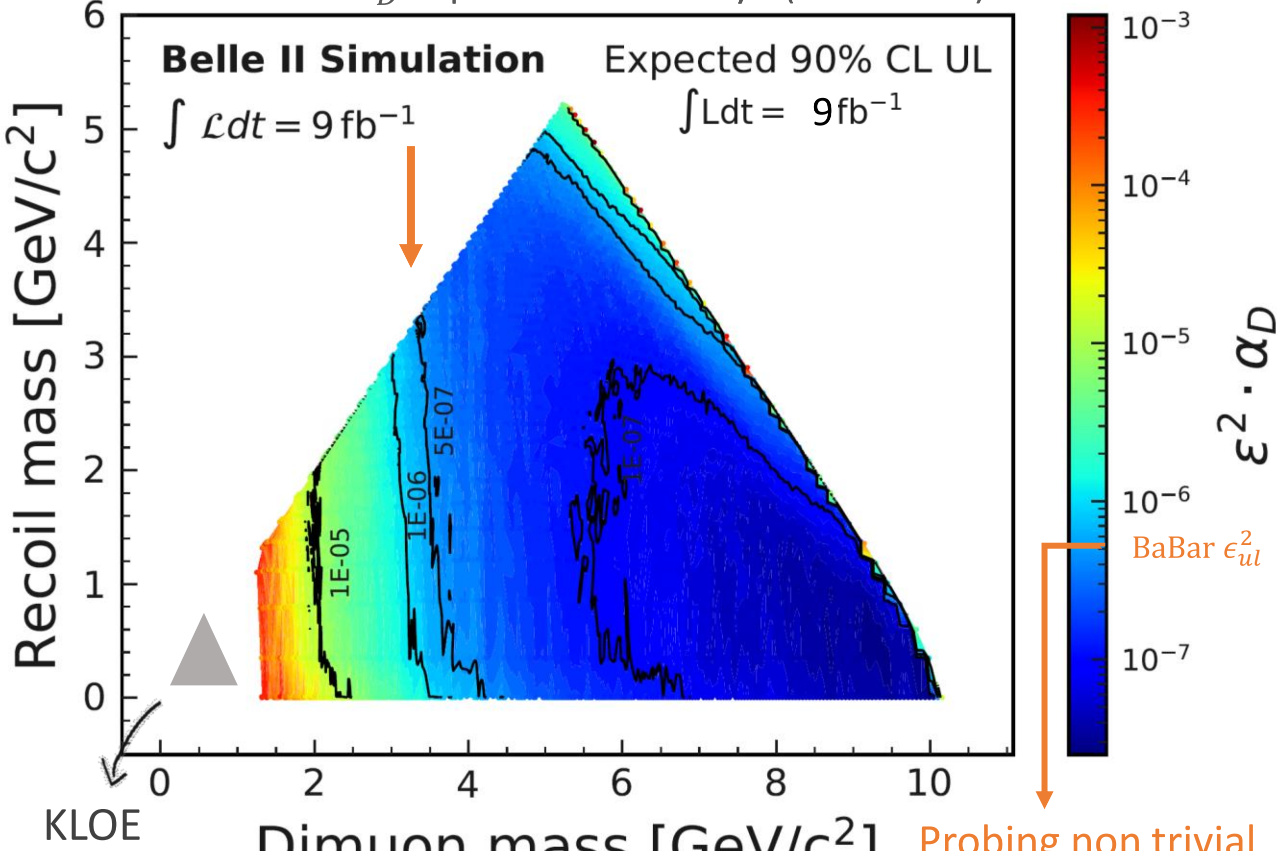
UL on ϵ (visible searches)



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

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

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

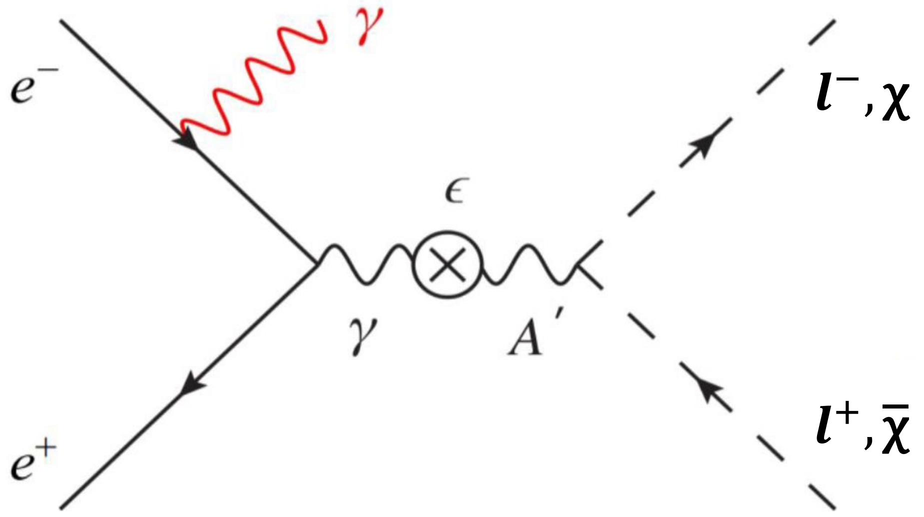


Probing non trivial regions

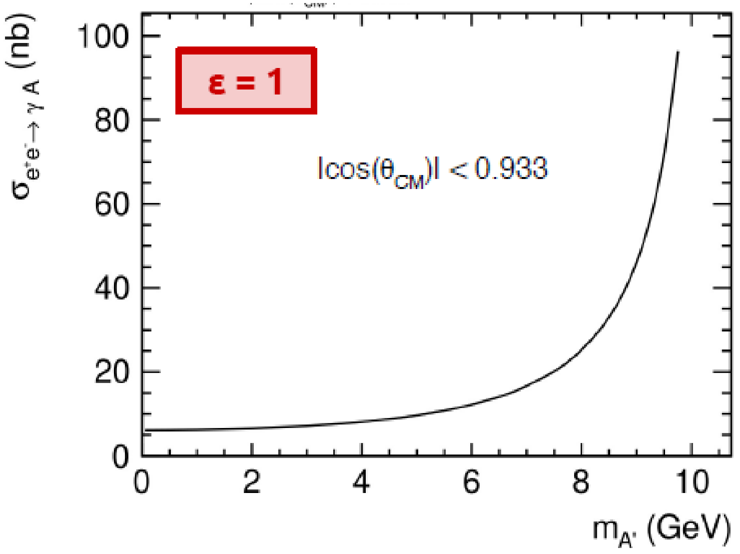
Invisible dark photon

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



Production cross section

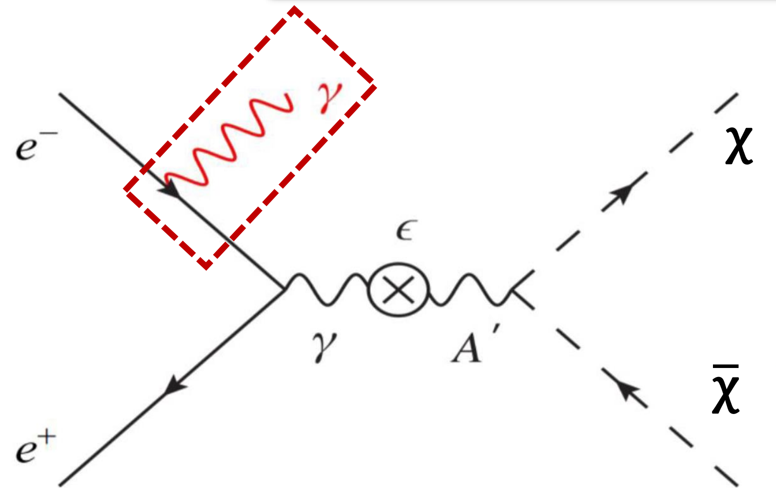


two basic scenarios depending on A′ vs χ DM mass relationship

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

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

Invisible dark photon: experimental signature



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

→ Bump in recoil mass or photon energy

Only **one photon** in the detector

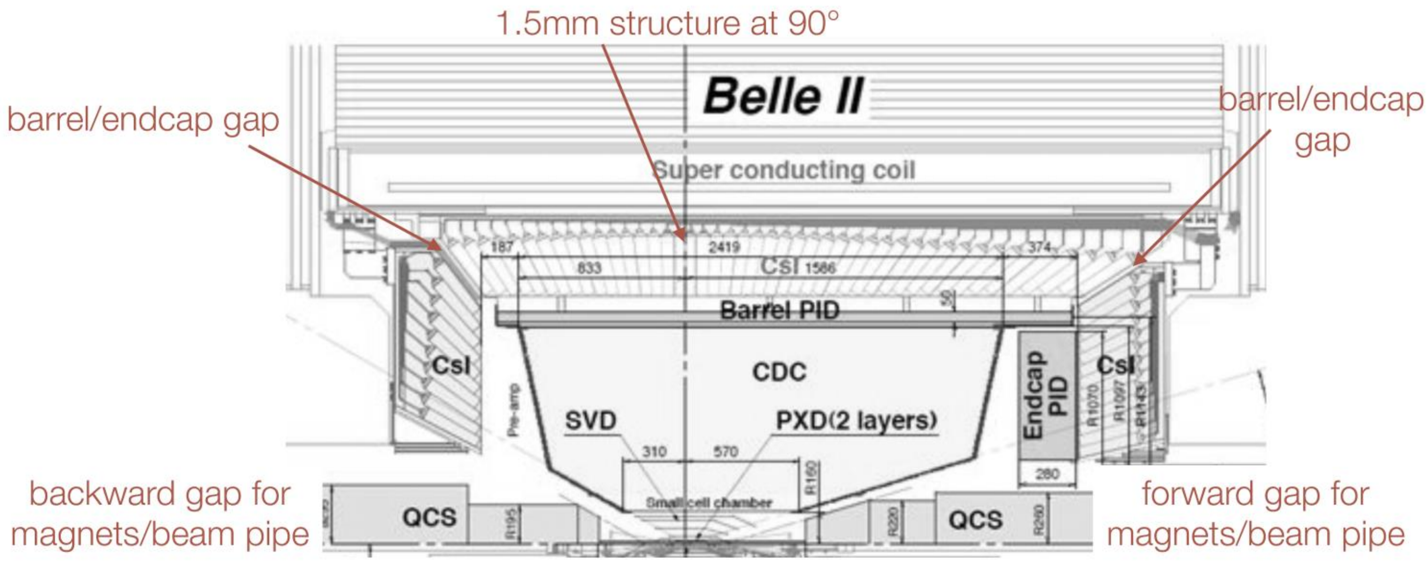
Needs a **single photon trigger**
(*not available in Belle, ≈ 10% of data in BaBar*)

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

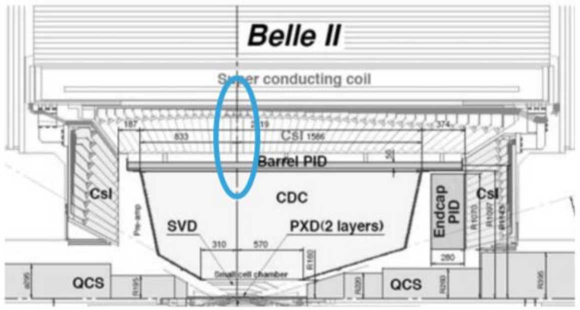
Backgrounds

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

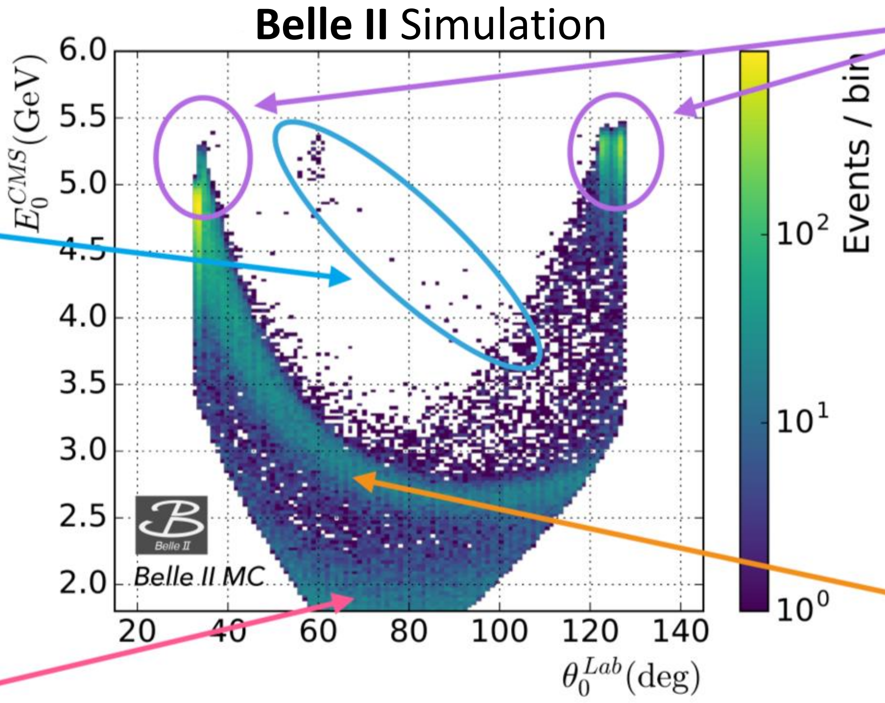
Cosmics
$e^+e^- \to \gamma\nu\nu$

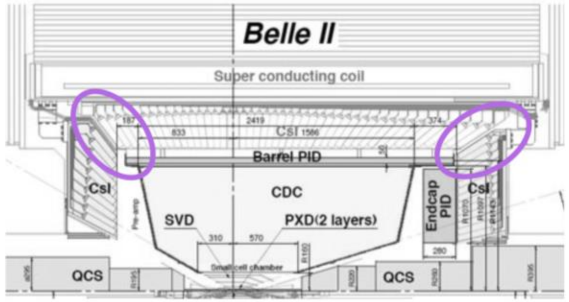


Invisible dark photon: background

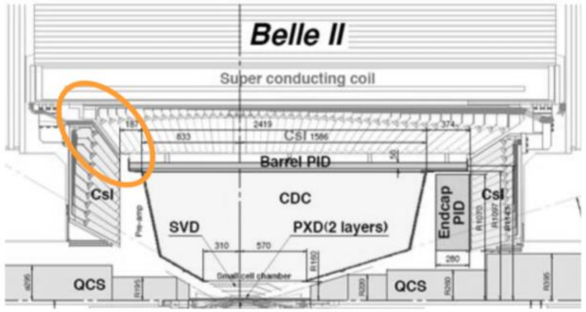


ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance





ee→2γ
1γ in ECL BWD or FWD gap



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

ee→eeγ
both electrons
out of tracking acceptance

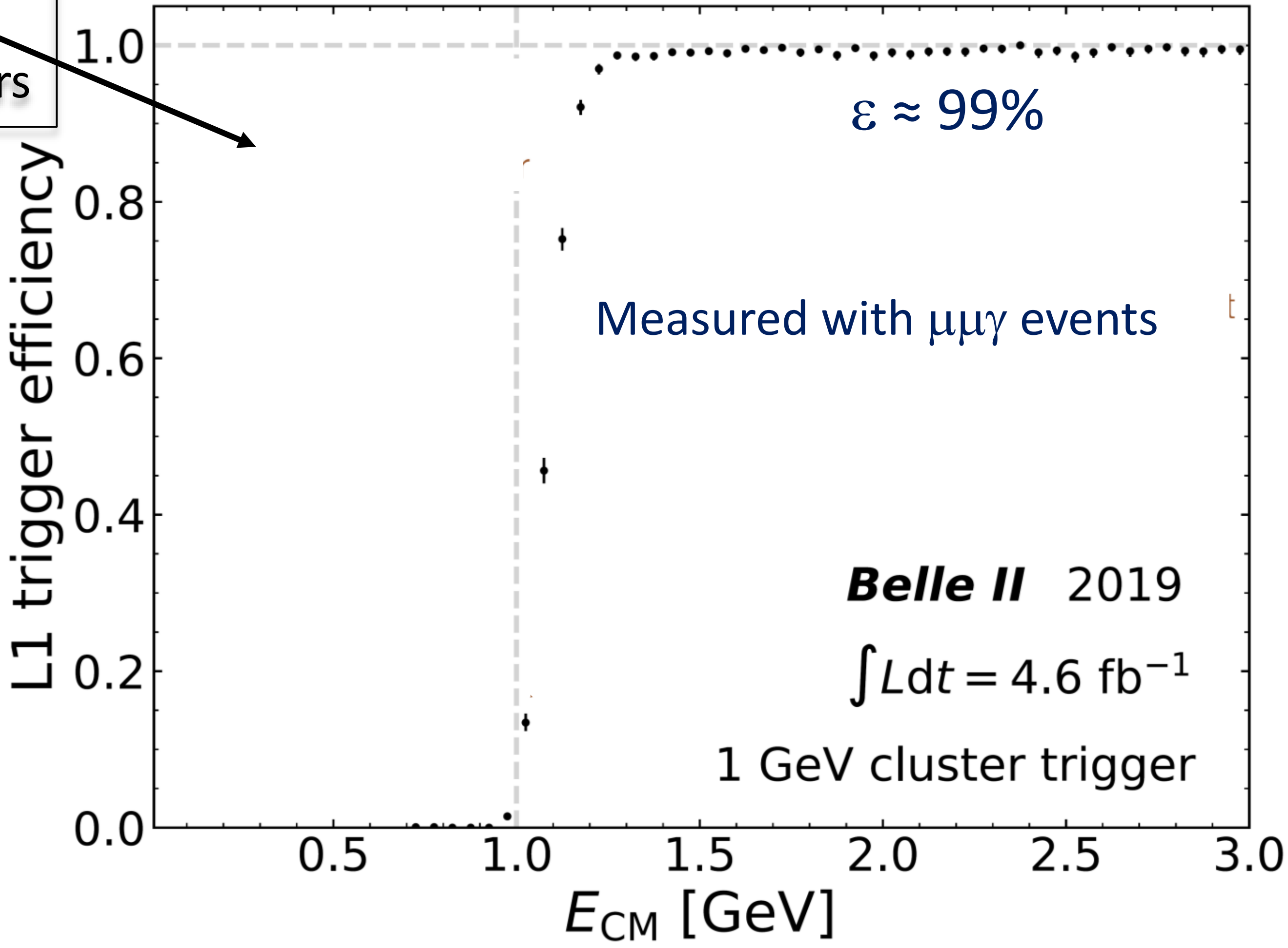
Crucial usage of KLM to veto photons in ECL gaps

Invisible dark photon: single photon trigger

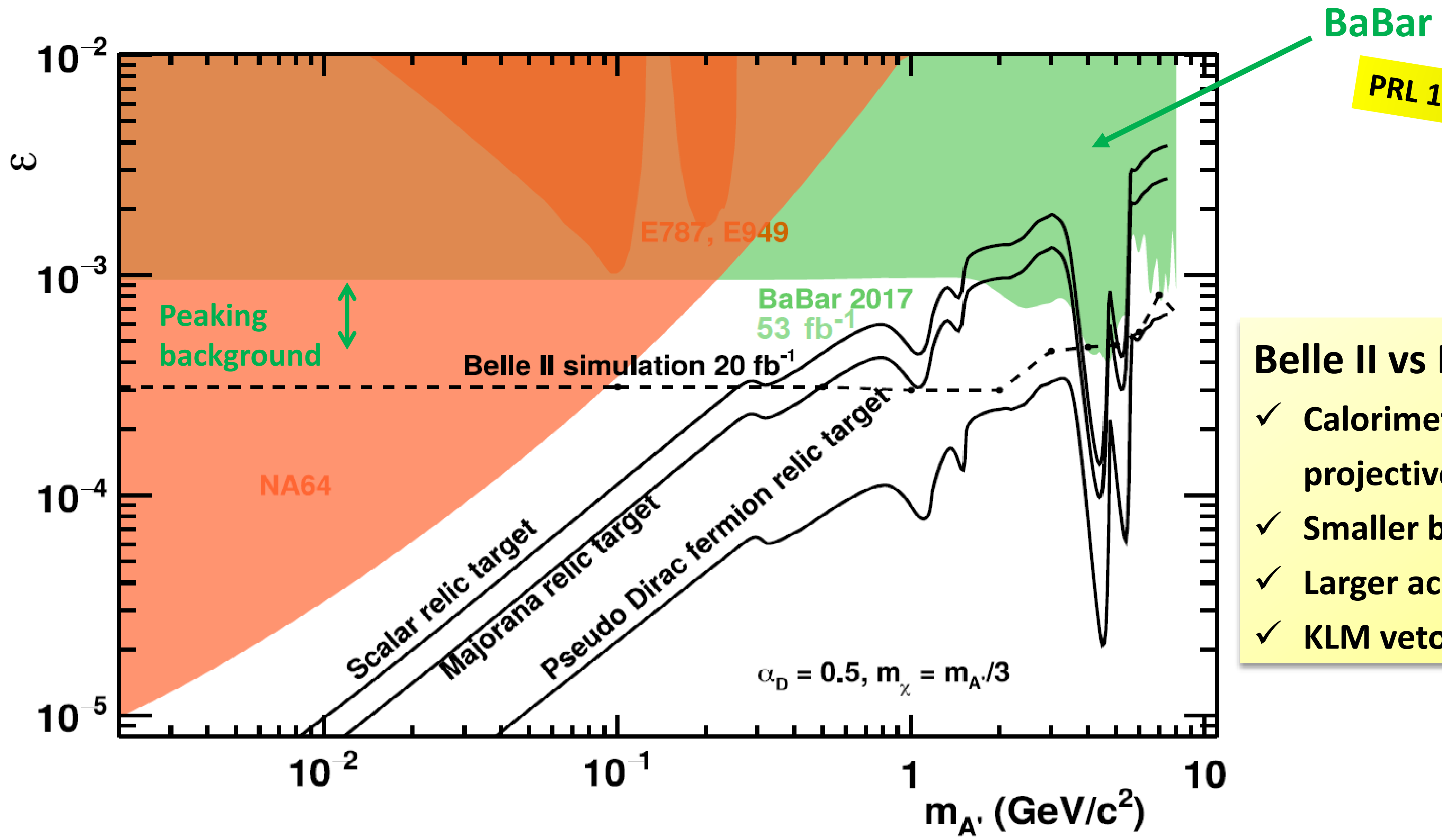
- E_{CM} > 2 GeV
- E_{CM} > 1 GeV in barrel + no other clusters
- E_{CM} > 0.5 GeV in central barrel + no other clusters

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

Much more aggressive than in the Physics Book. Good conditions to perform the measurement as soon as possible.



Invisible dark photon: sensitivity



PRL 119 131804 (2017)

Belle II vs BaBar

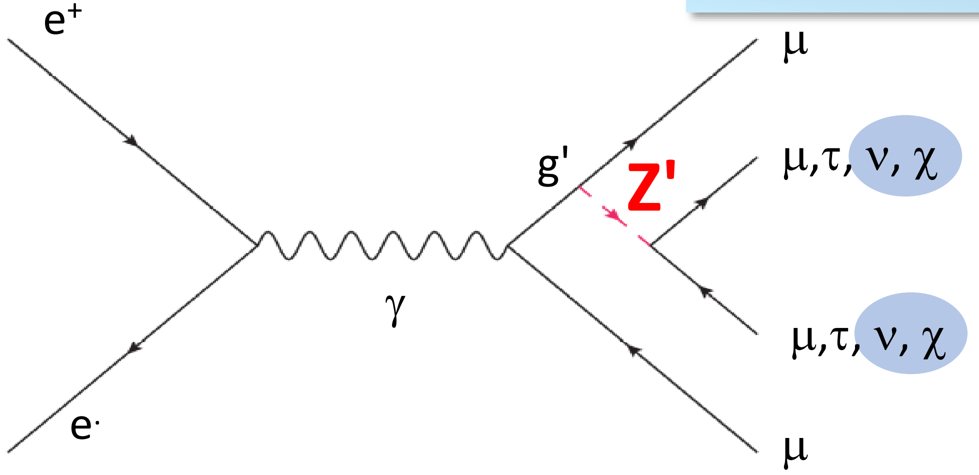
- ✓ Calorimeter with no projective cracks in ϕ
- ✓ Smaller boost
- ✓ Larger acceptance
- ✓ KLM veto

Summary

- The persisting null results from new physics at LHC searches and in direct underground searches (not definitive in both cases) make the light dark sector senario more and more attractive.
- Experiments at the intensity frontier are in the best position to probe such a sector
- KLOE/KLOE-2, BESIII, BaBar, Belle already excluded many models or relevant part of their parameter space
- **Belle II** started operation in 2018: 74 fb^{-1} collected up to now
- Broad program of dark searches: Z', dark photons, dark scalars, light Higgs, LLPs, iDM, monopoles, …
- First physics results and publications are out: **invisible Z' and ALP→$\gamma\gamma$**
- Next papers: dark Higgsstrahlung (first half 2021), invisible dark photon (~ end 2021)

SPARE SLIDES

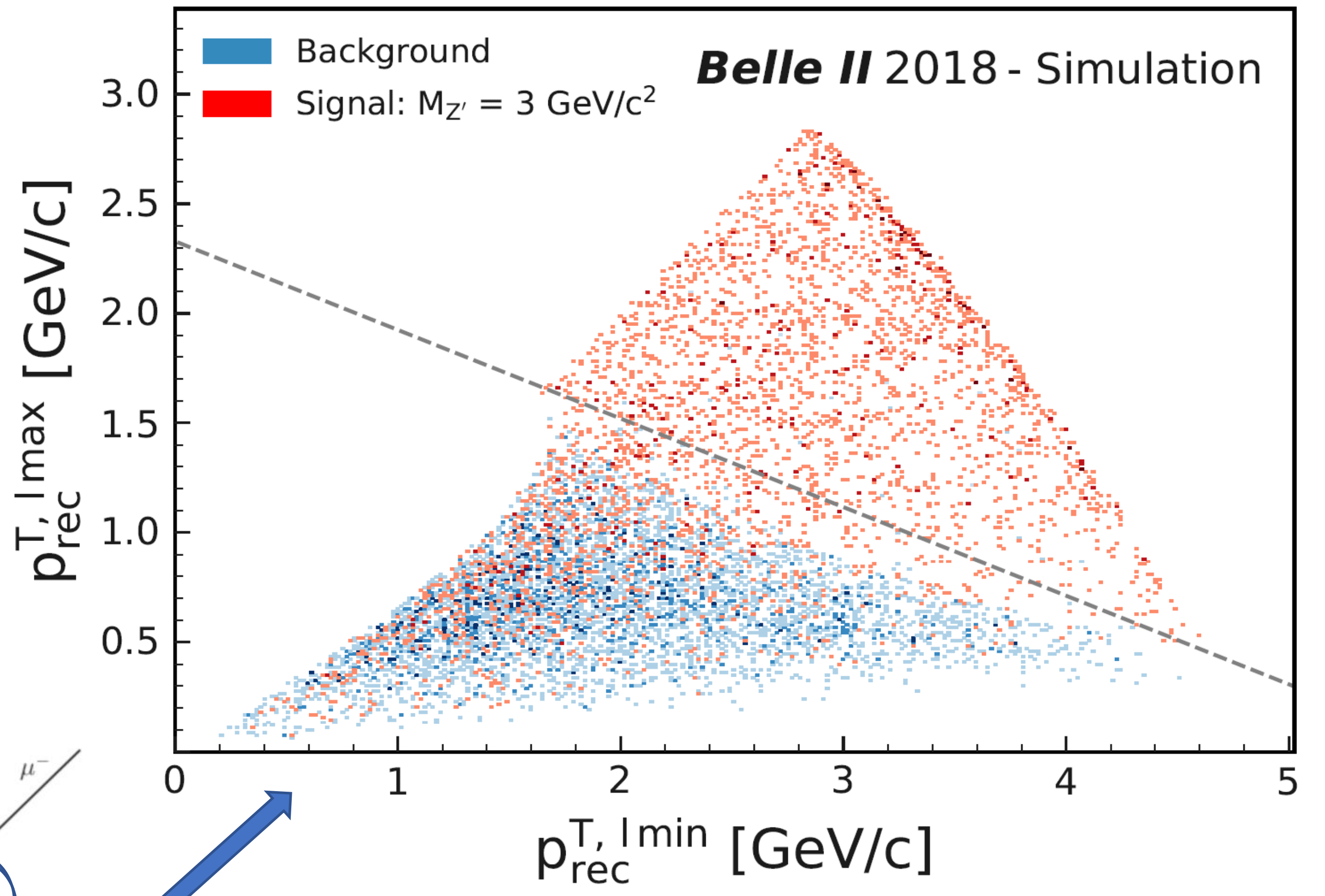
Z' to invisible: $L_\mu - L_\tau$ model



Explored for the first time

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

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

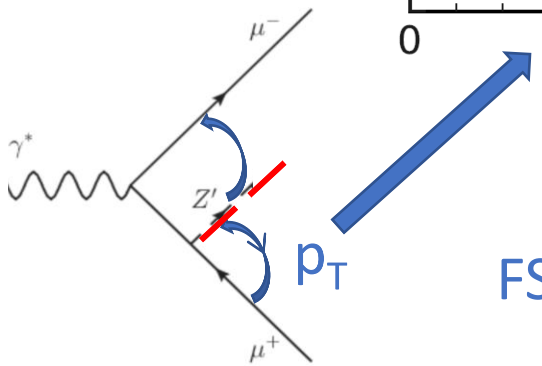


Main backgrounds:

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

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

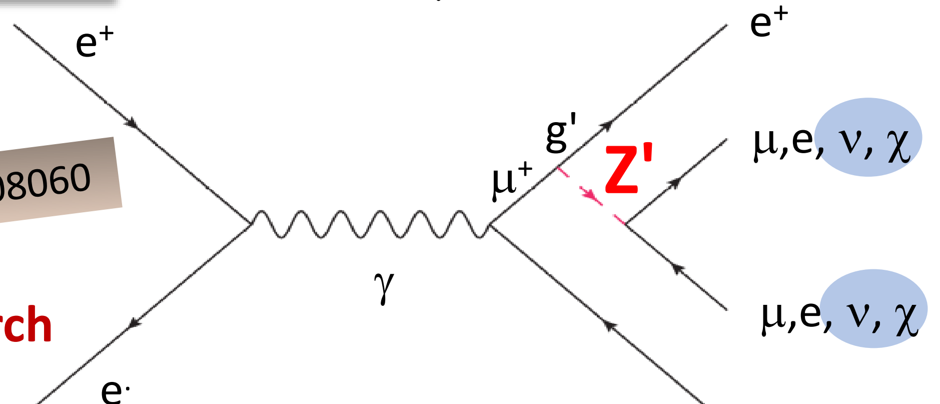
$e^+e^- \rightarrow e^+e^- \mu^+\mu^-$



FSR vs ISR + τ decay

LFV Z' to invisible

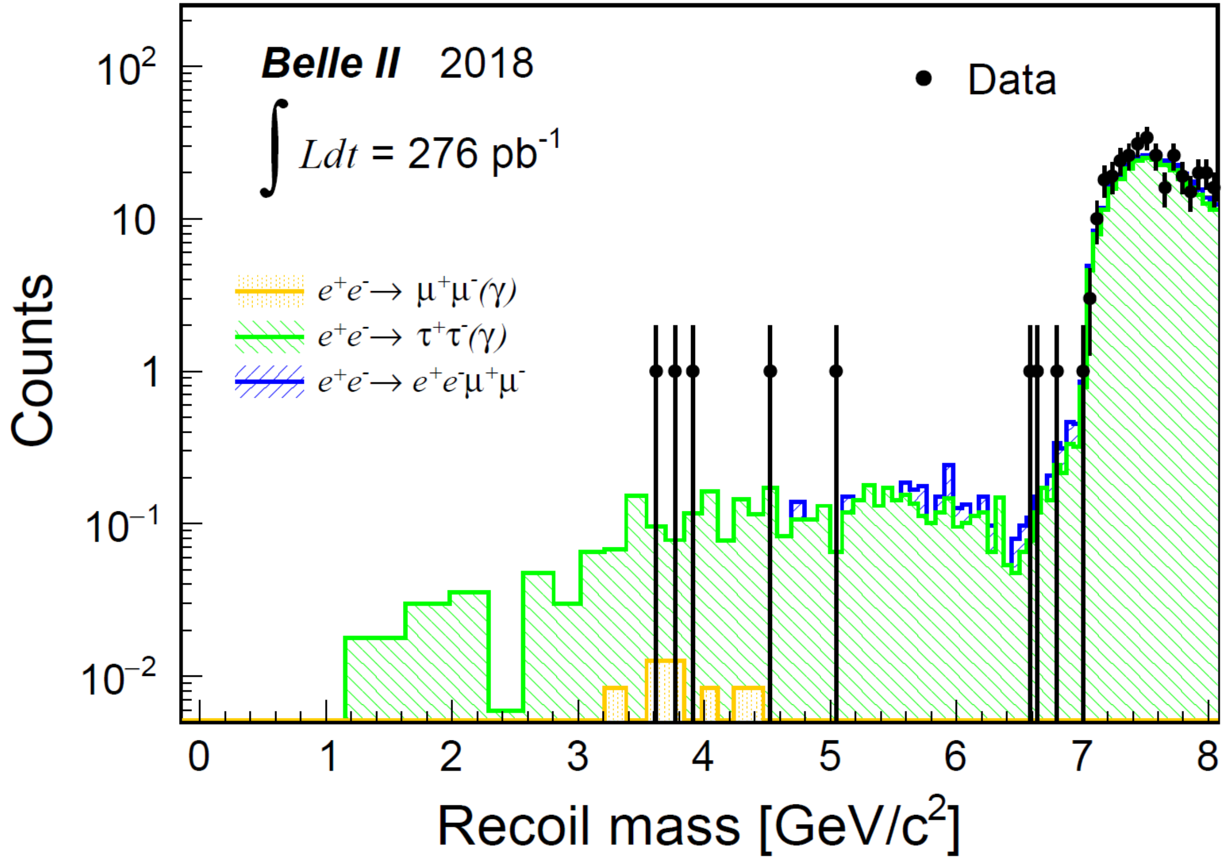
$e^+e^- \rightarrow e^+\mu^-$ + *missing energy*



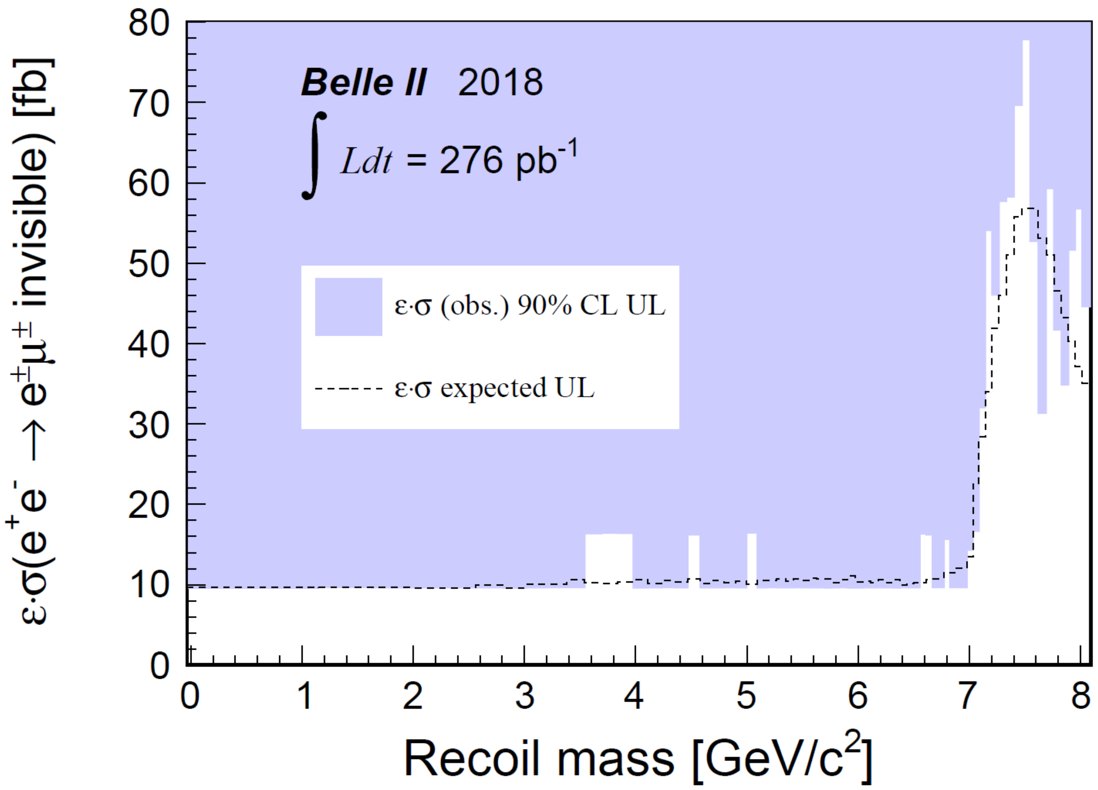
What about a Lepton Flavour Violating Z'?

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

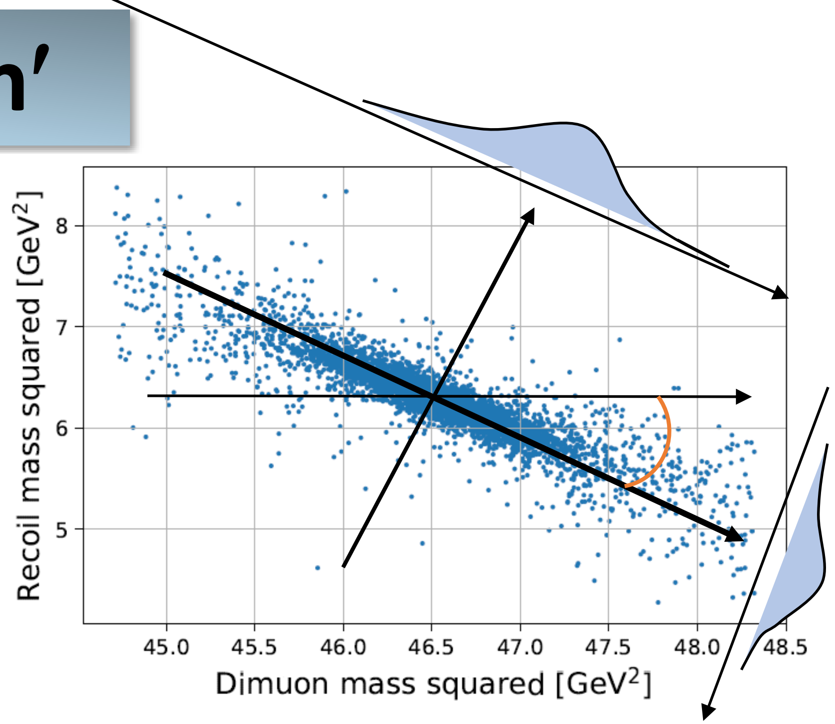


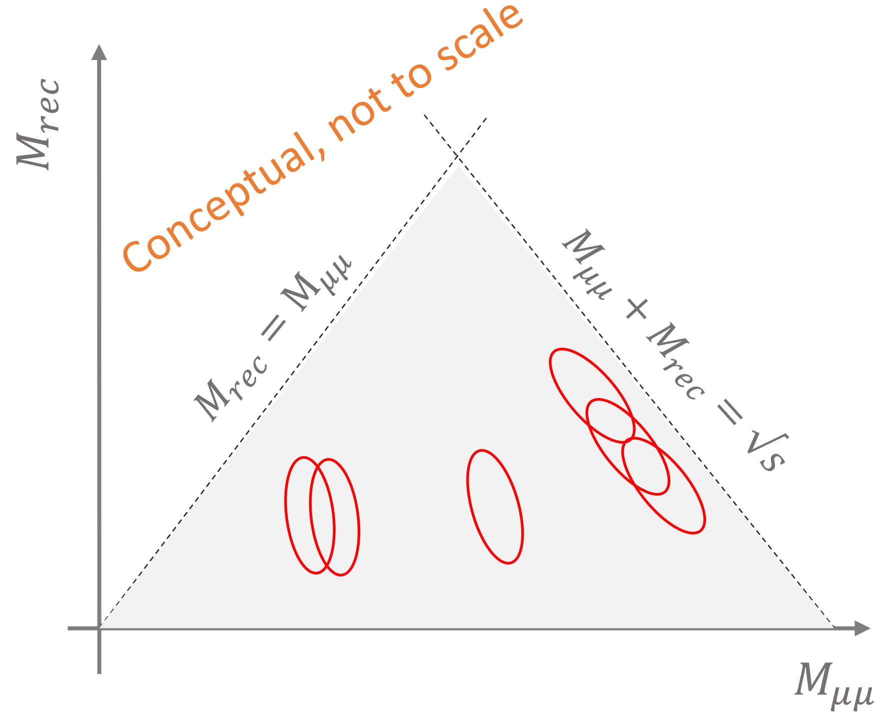
Dark Higgsstrahlung: A′h′

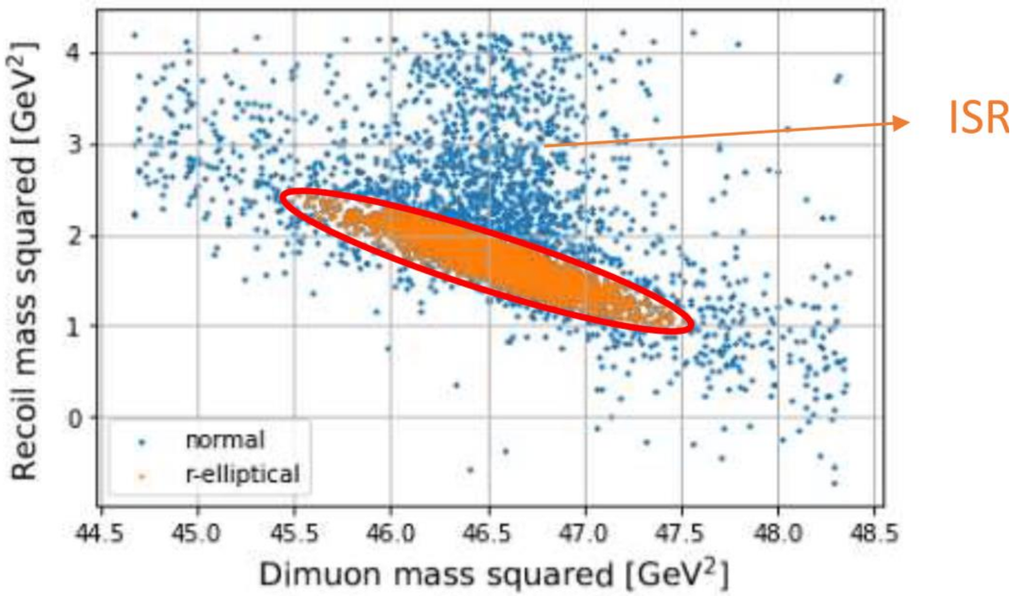
- Negative correlation between μμ and recoil mass
- Variable across the plane: evalutaed in the no ISR case

- Mass windows: overlapping tilted ellipses of variable angles with semiaxes ≈2 widths

- In total: 9011 mass hypotheses (windows) across the plane







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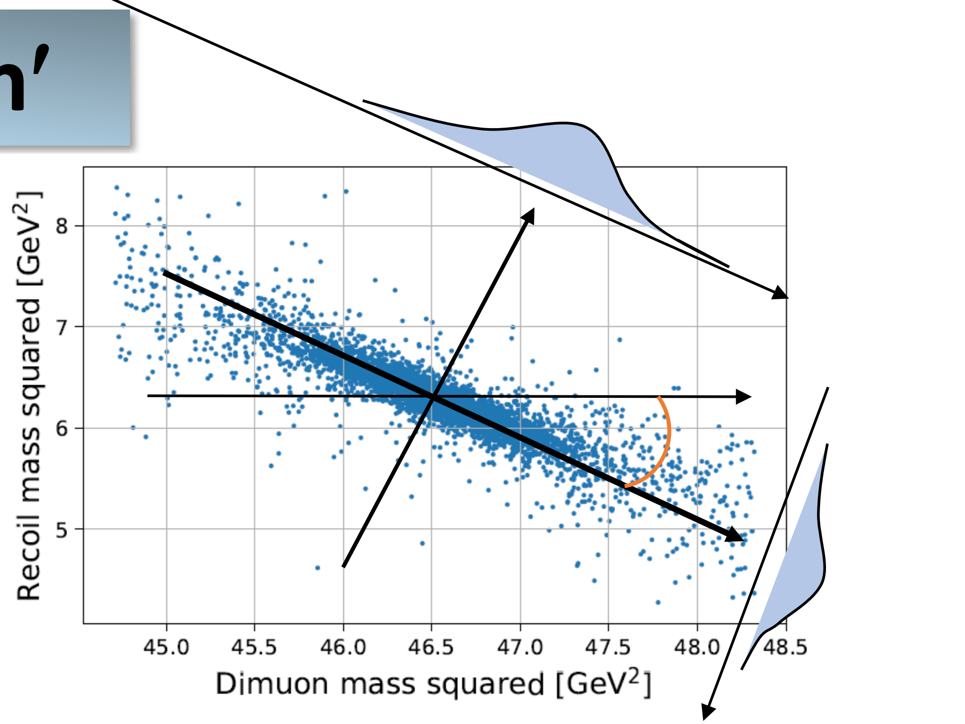
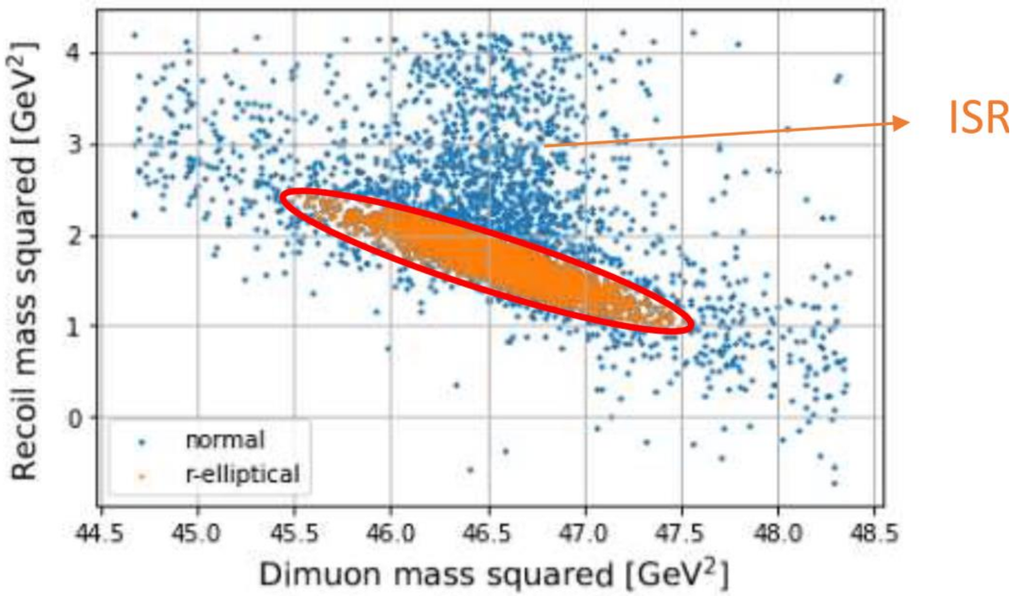
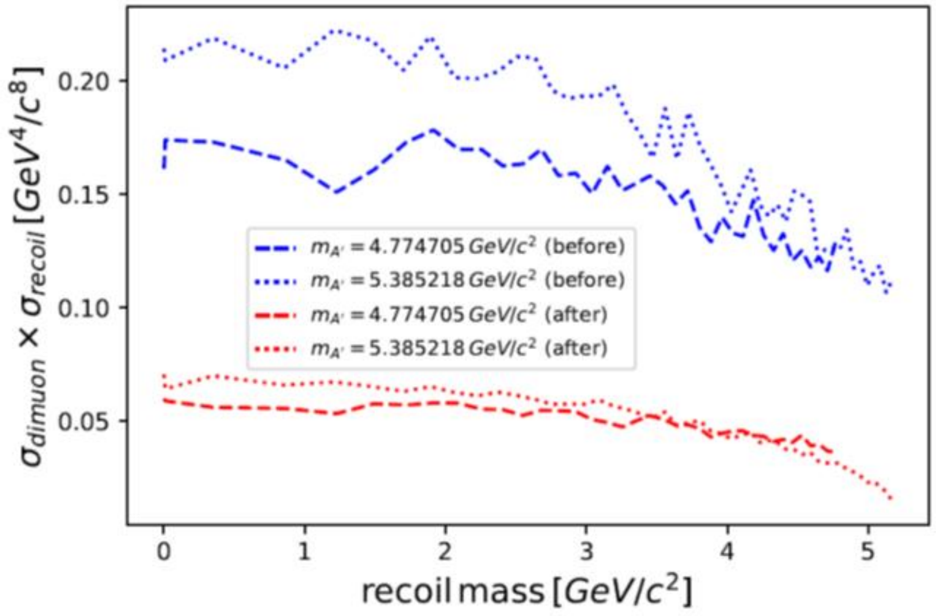




Background reduction 3-4



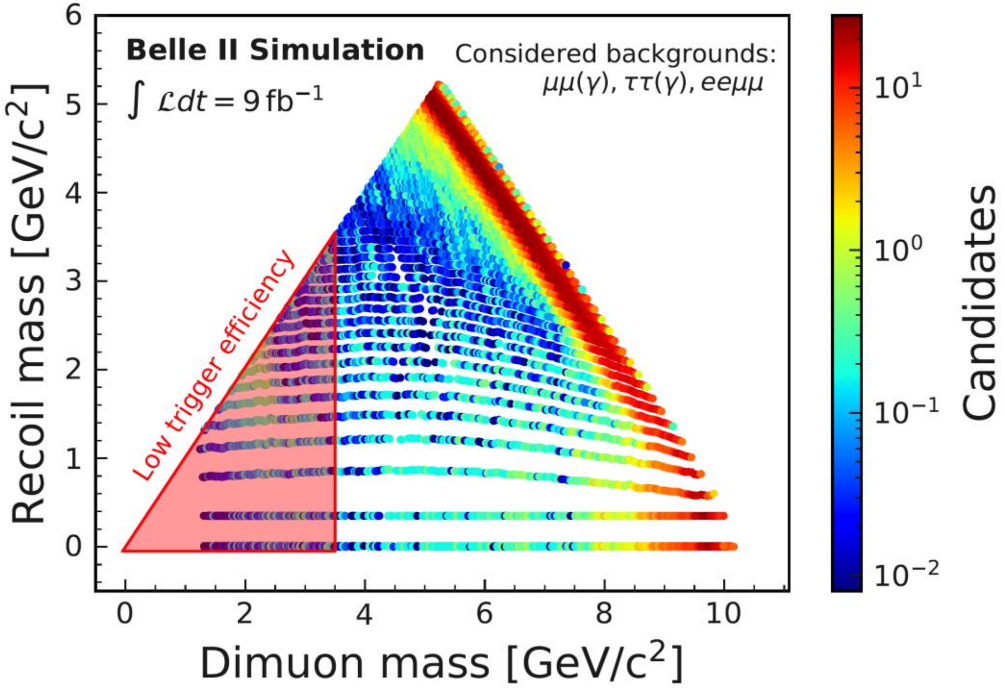
Dark Higgsstrahlung: A′h′

Final background suppression based on kinematic features.

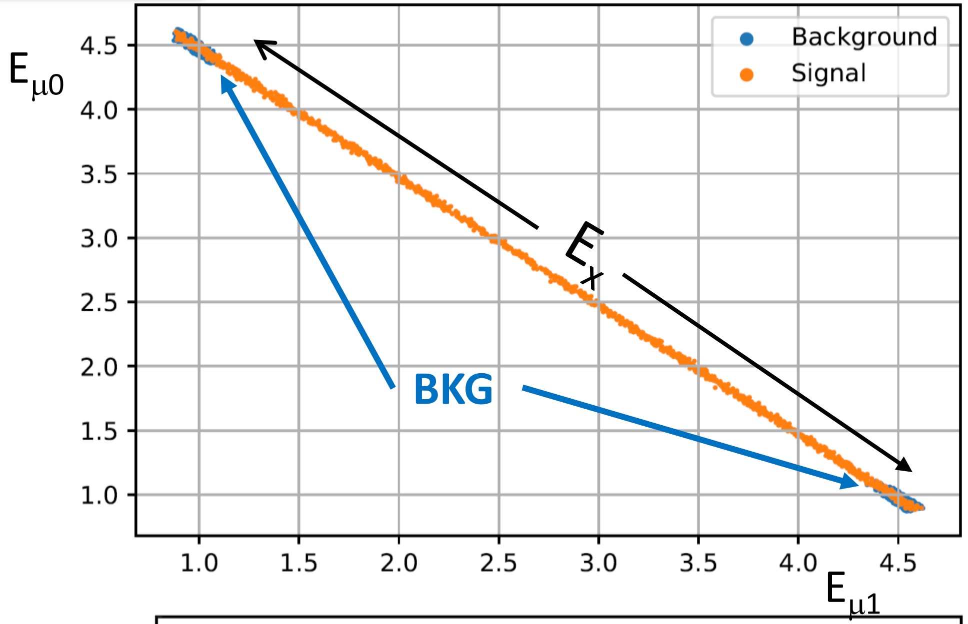
$E_{\mu 0} + E_{\mu 1}$ approximately constant within mass windows.

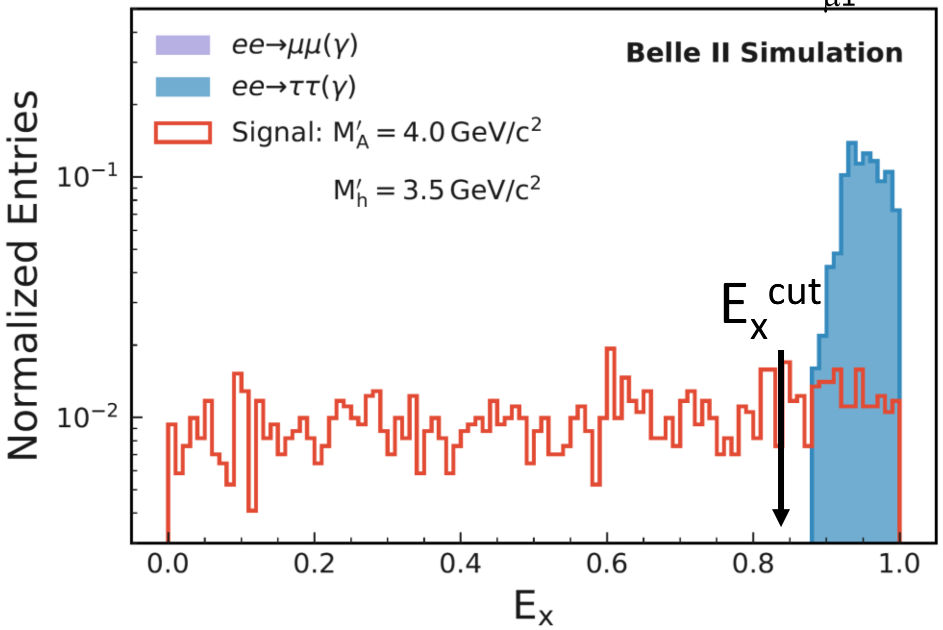
$$E_{\mu 0} + E_{\mu 1} = \frac{s + M_{\mu\mu}^2 - M_{rec}^2}{2\sqrt{s}} = E_0$$

E_x^{cut} optimized across the plane



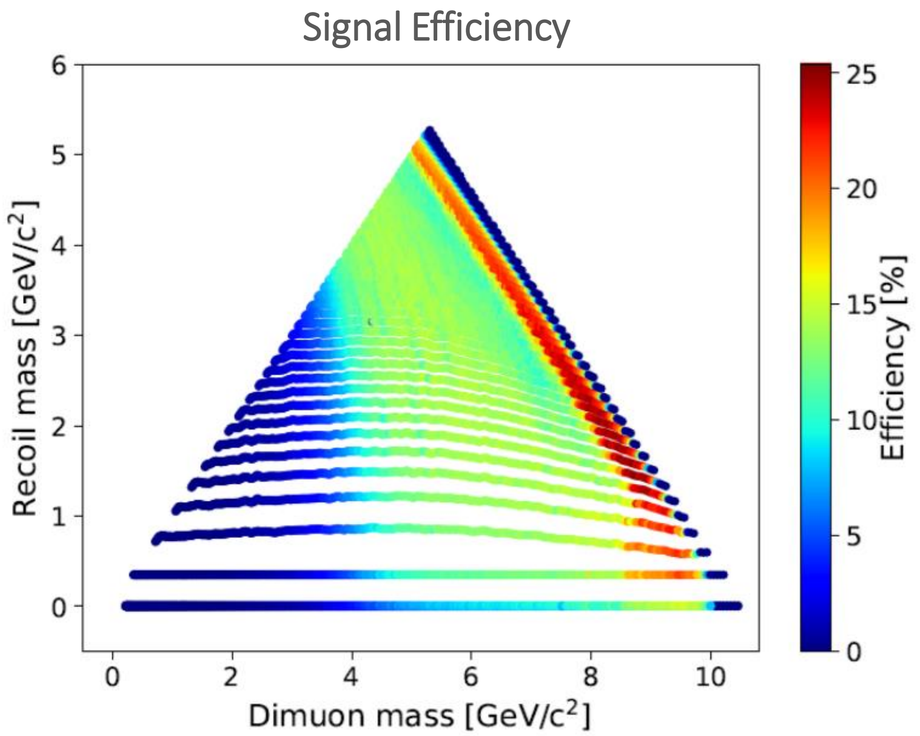
Rejection factor 10-1000

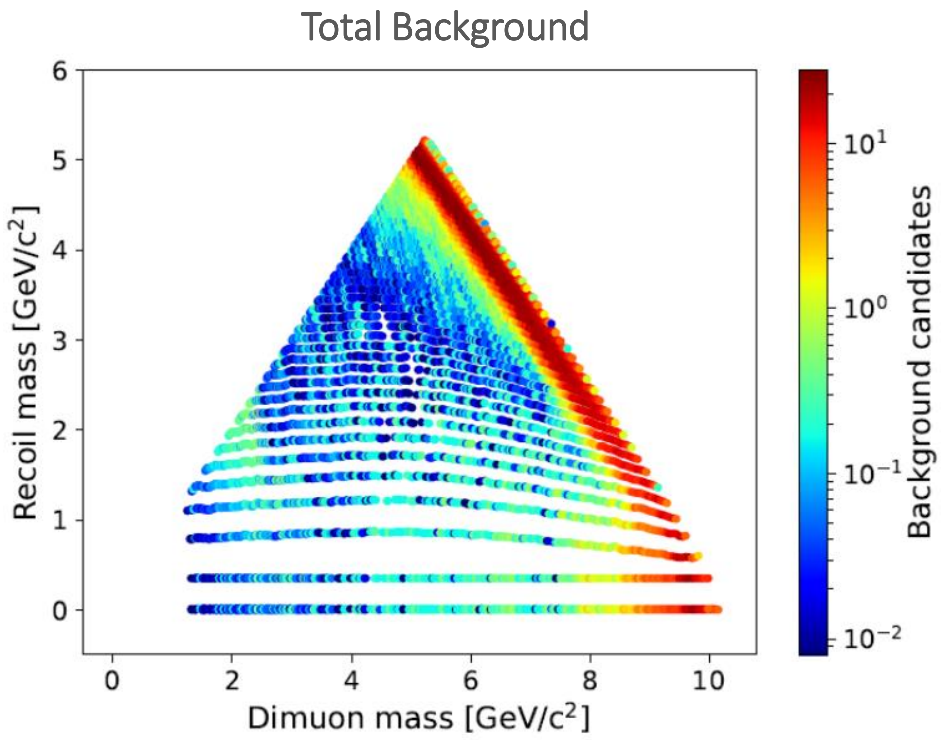




Dark Higgsstrahlung: A′h′

- Signal efficiency > 10% for $M_{\mu\mu} > 4$ GeV;
- <1 candidate per mass window in most of the space;



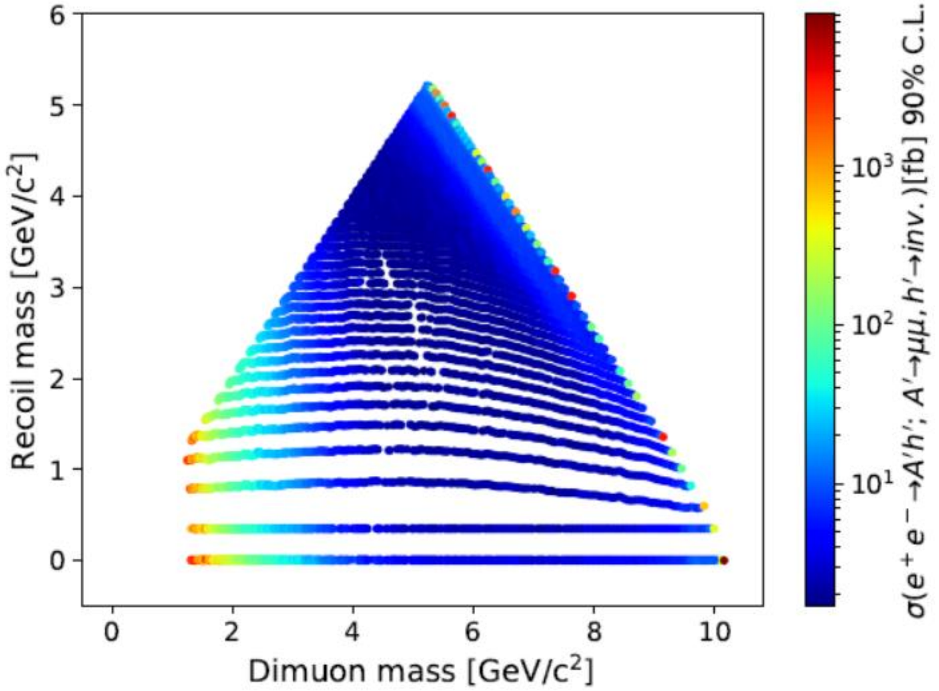


Dark Higgsstrahlung: A′h′

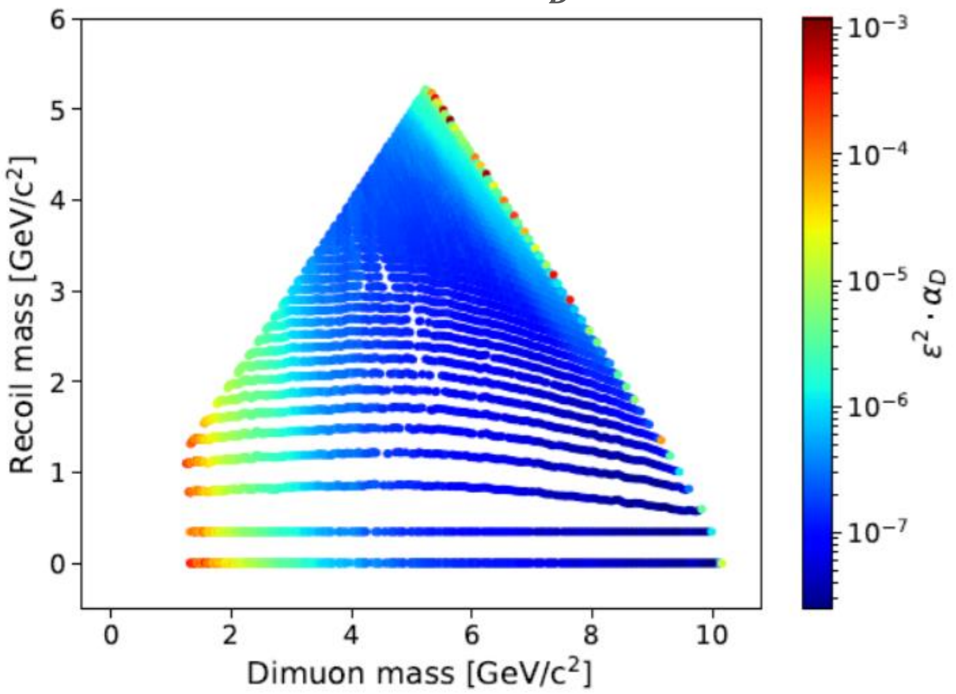
Sensitivity estimate

- Systematics: rough (conservative) estimate based on invisible Z’ experience.
  - 10% fully correlated on efficiency and BKG, plus additional 20% on BKG only.

90% UL on cross section



90% UL on $\epsilon^2 \alpha_D$



Invisible dark photon: sensitivity