Dark sector first results at Belle II

Enrico Graziani

INFN – Roma 3

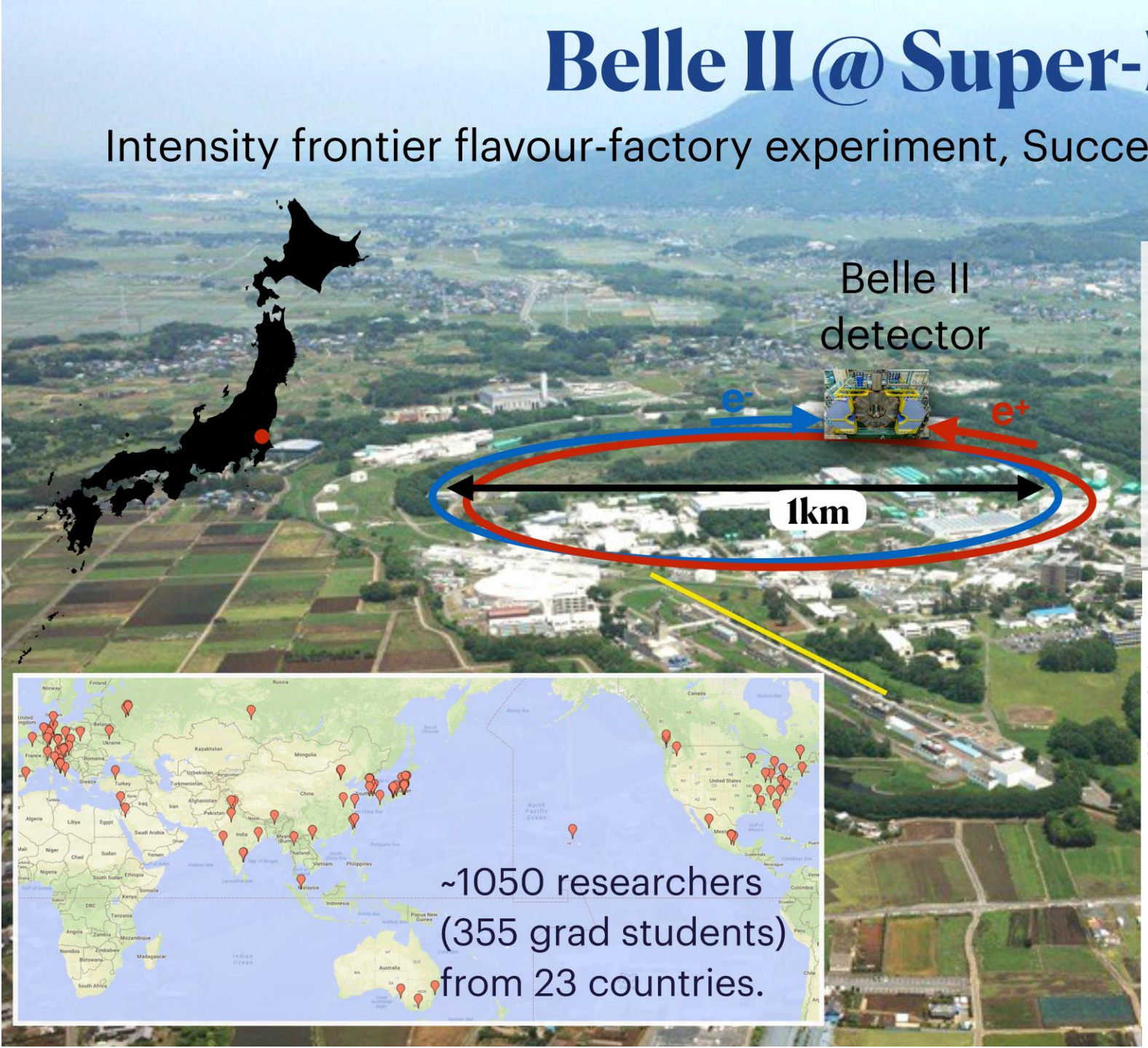
on behalf of the Belle II Collaboration

OUTLINE OF THE TALK

- ✓ Belle II and SuperKEKB
- ✓ Search of
  - ➢ Z' to invisible
  - ➢ ALP →γγ **new**
  - ➢ Dark Higgsstrahlung
  - ➢ Invisible dark photon
- ✓ Perspectives & Summary

Belle II @ Super-KEKB

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

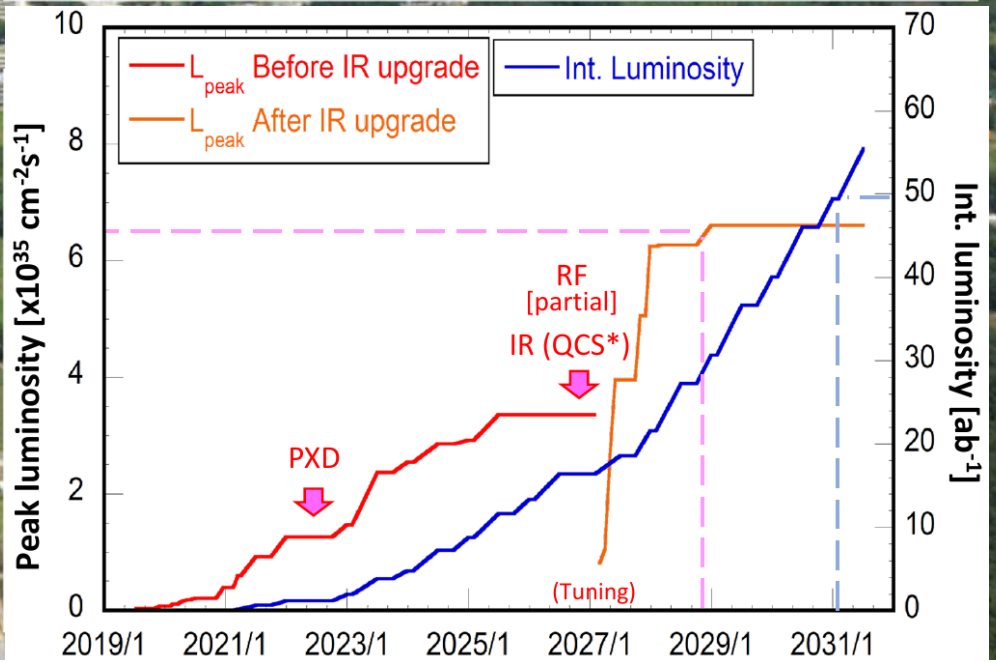


7 GeV e^-, 4 GeV e^+

E_{CM} Υ(4S) = 10.58 GeV + scans

Υ(4S) → B anti-B

B + Charm + τ + Υ factory + ?

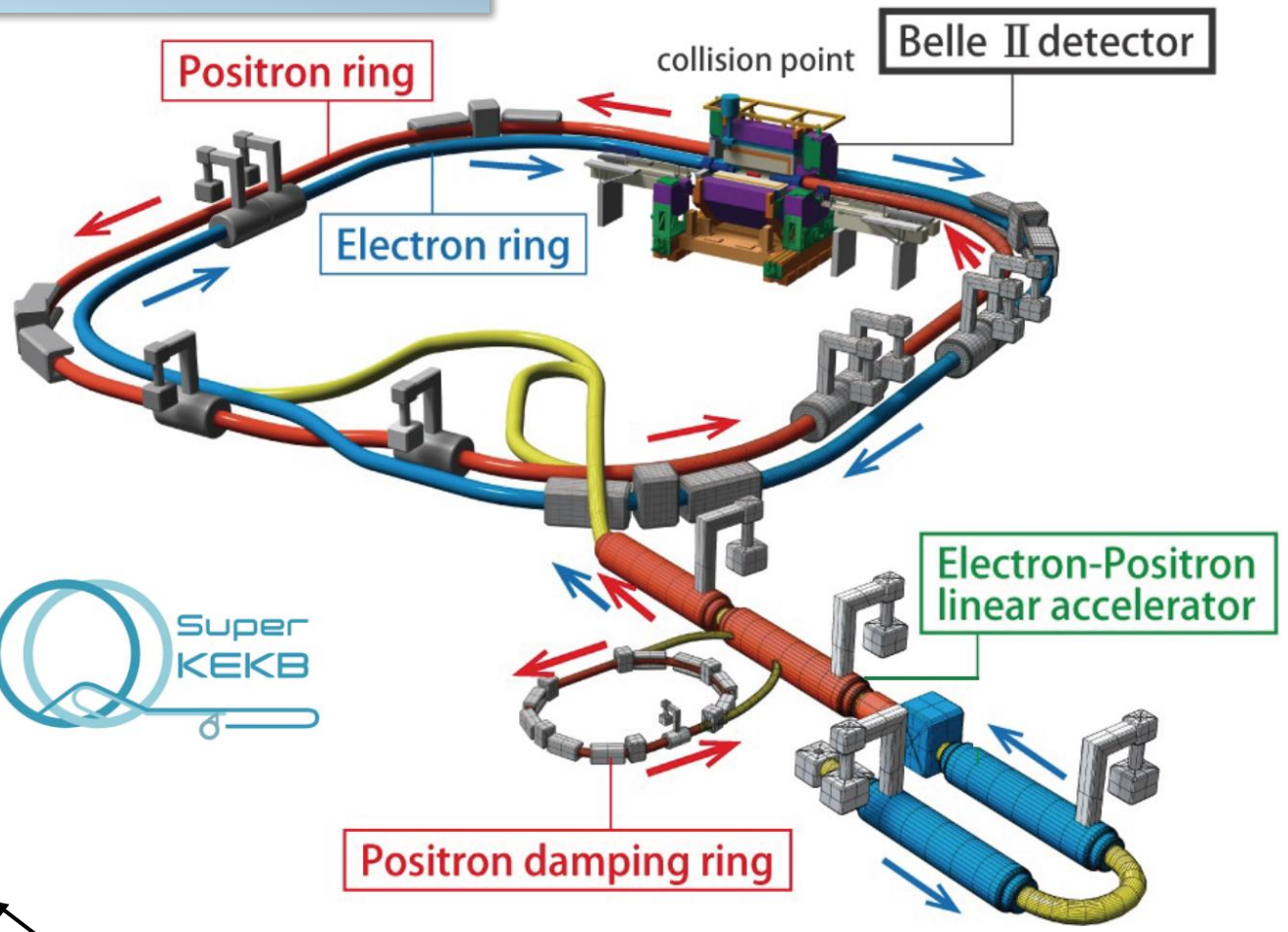


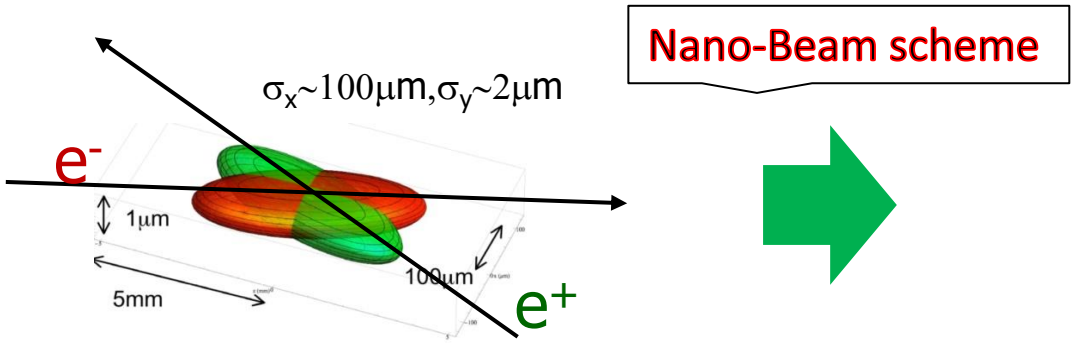
From KEKB to SuperKEKB

- **Upgraded rings**
  - New e^+ Damping Ring
  - Increased currents
- **Nano-beam scheme**
  - New Final Focus magnets (QCS)
  - Large crossing angle

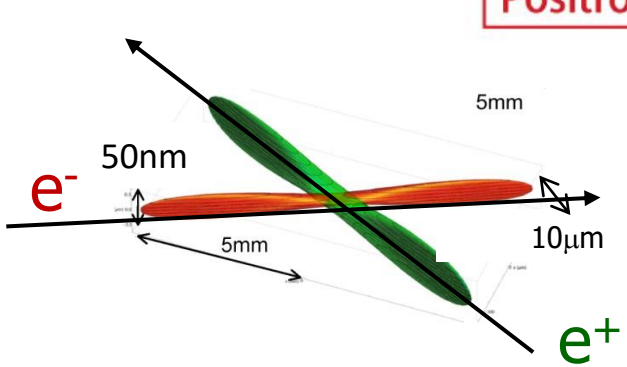
x20 → x30

Final goal : 50 ab^{-1}

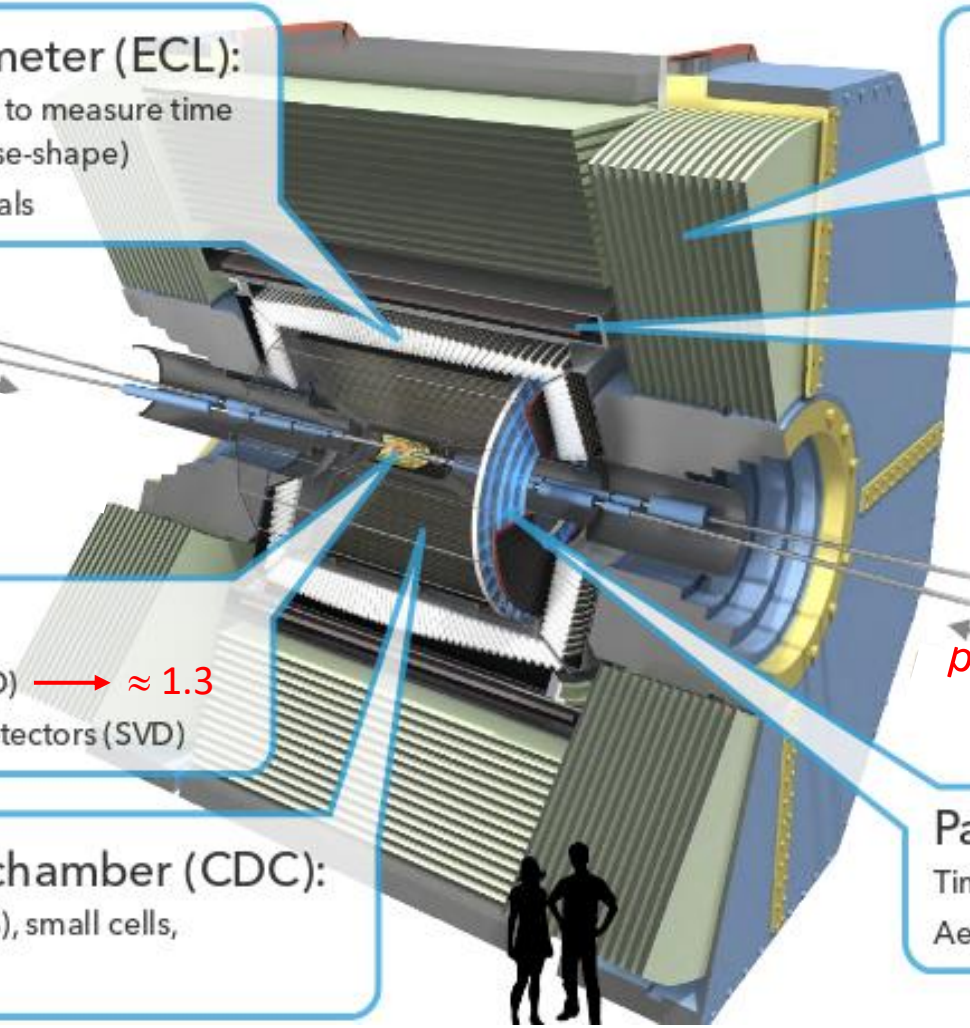




Nano-Beam scheme



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) → ≈ 1.3
4 layer double-sided silicon strip detectors (SVD)

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

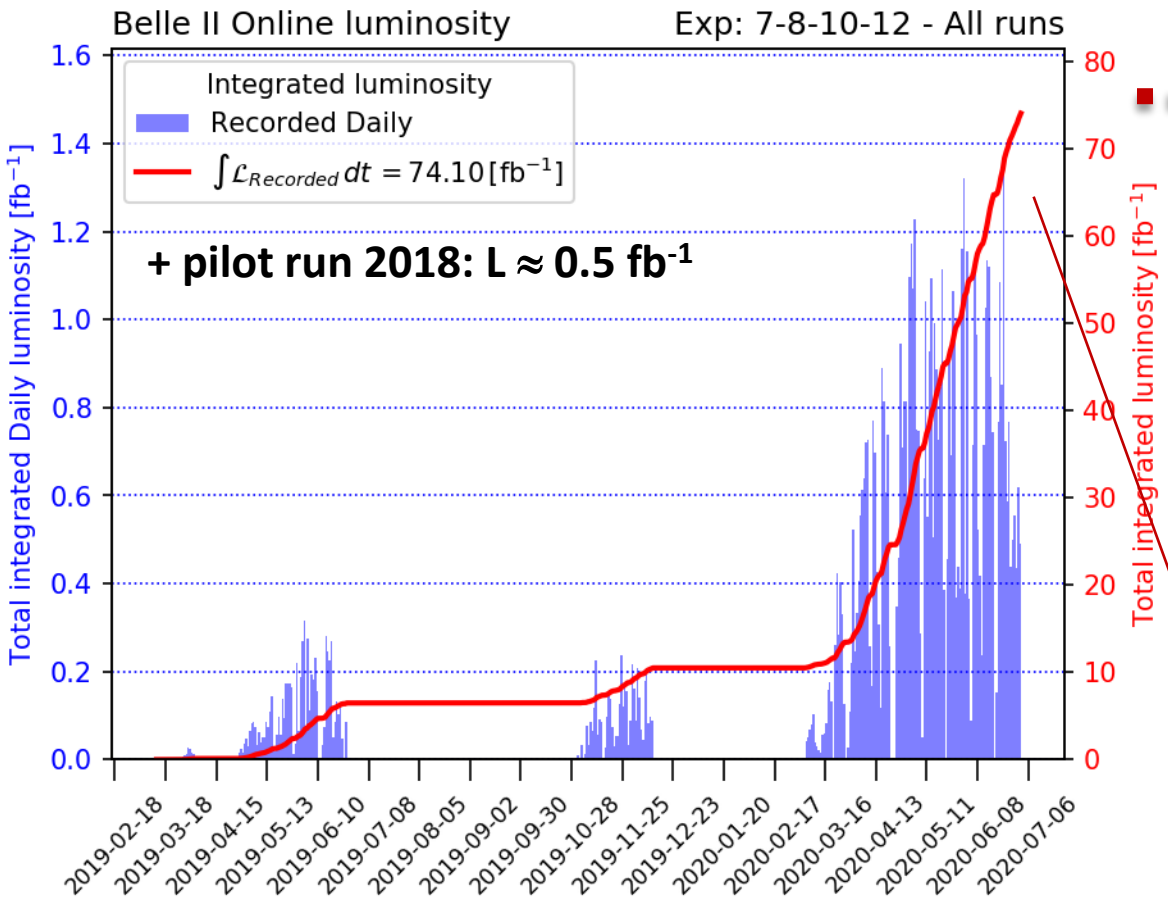
Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cerenkov Counter (ARICH)

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

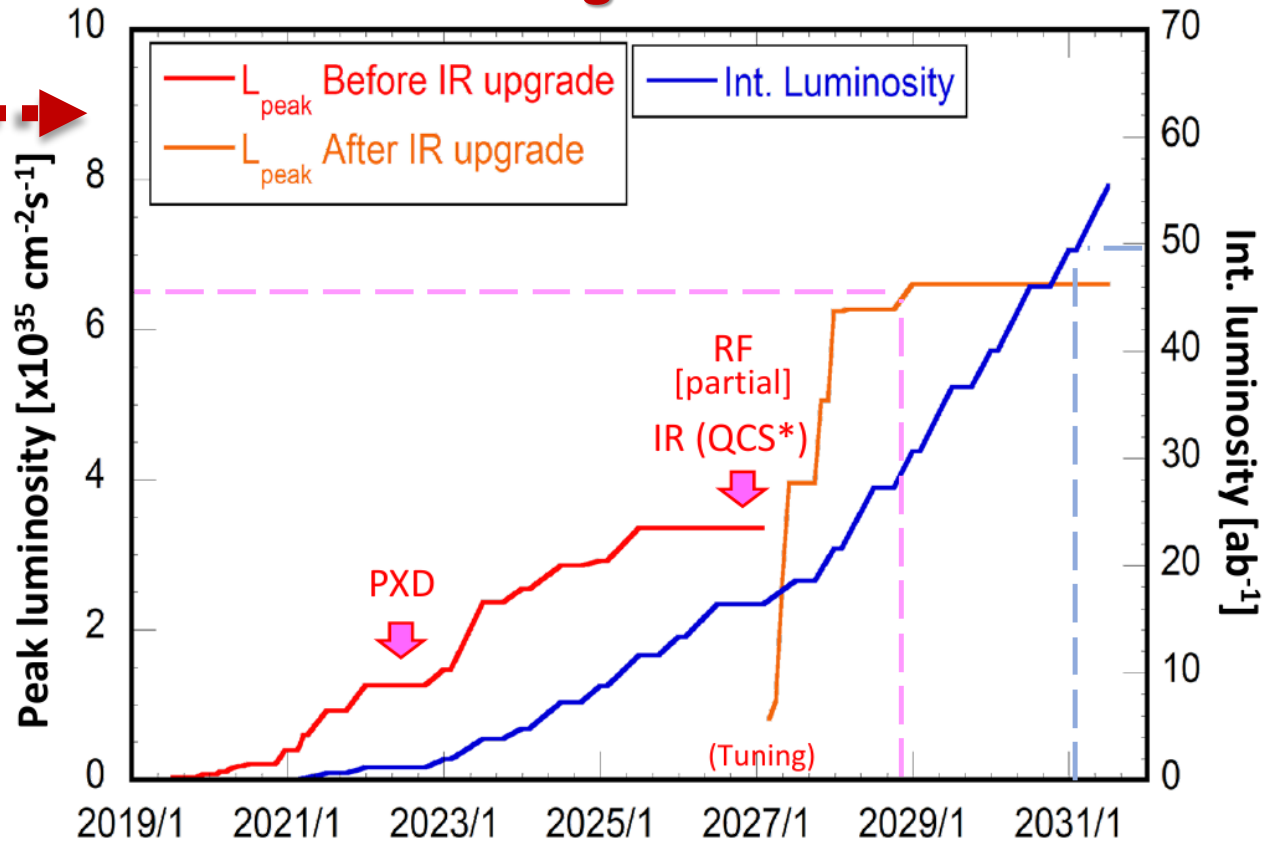
Belle II luminosity record and plan

see K. Matsuoka's talk

Collected luminosity up to now: 2019+2020



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



Data taking efficiency ≈ 90%

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

Fall run to start in ~September/October

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

$$\sigma(v/c) \propto \begin{cases} G^2_F \, m^2_\chi & \text{for } m_\chi << m_W \\ 1/\, m^2_\chi & \text{for } m_\chi >> m_W \end{cases}$$

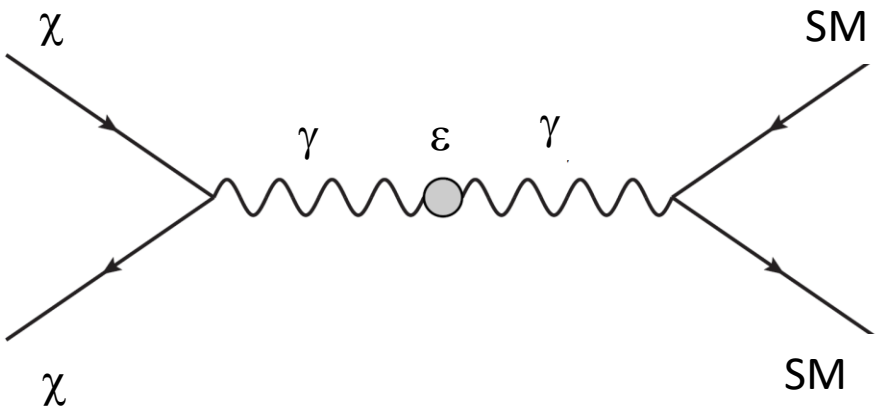
$\Rightarrow$ few GeV < m_χ < few TeV

It modeled decades of direct search experiment designs

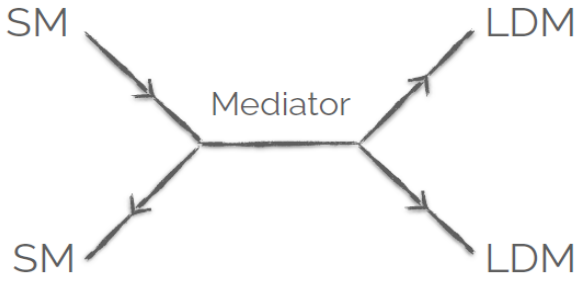
WIMP miracle

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



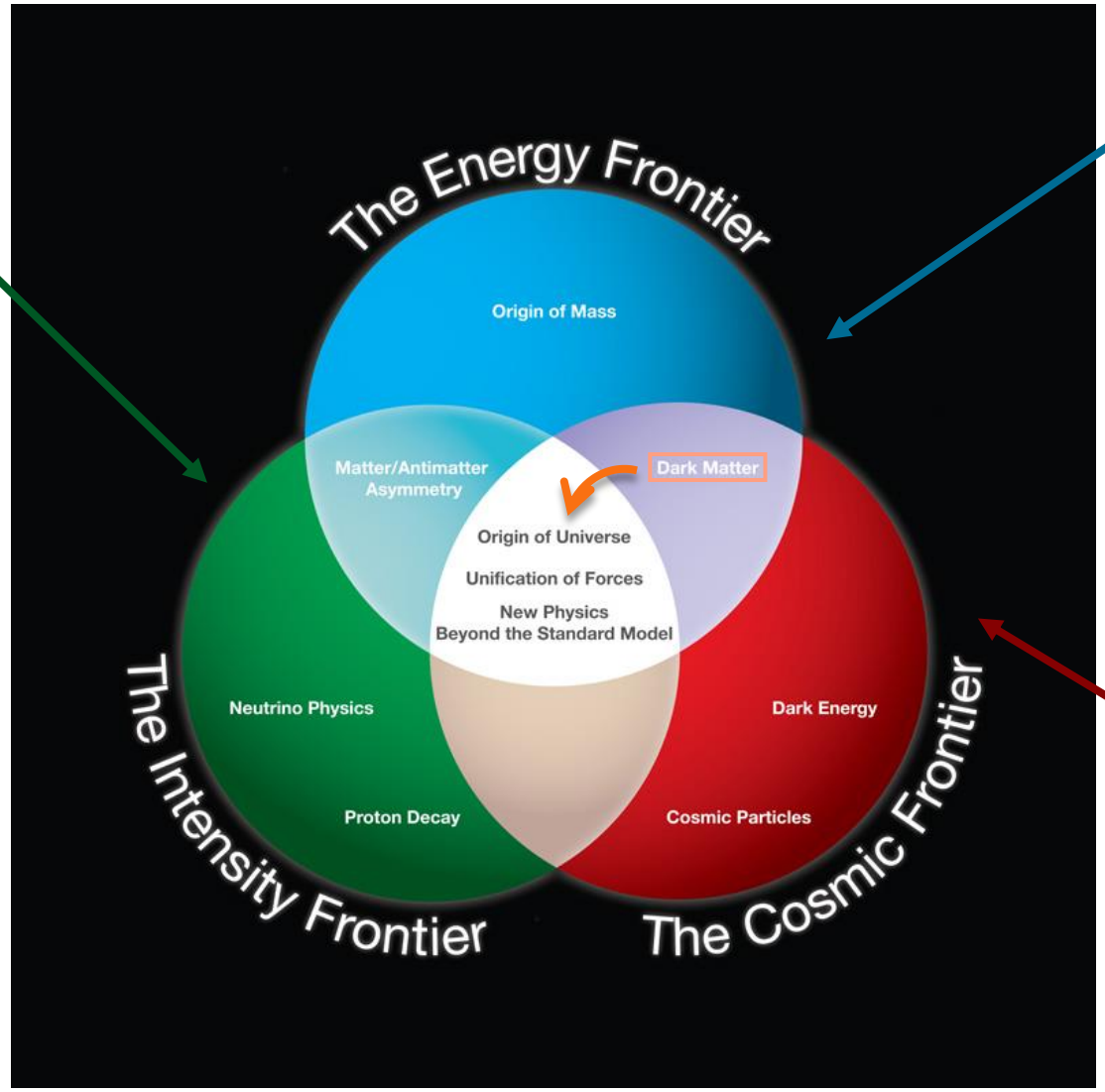
Dark matter hunt with a light sector



LDM → Light Dark Matter
Mediators → portals

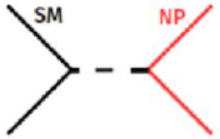
⇓

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



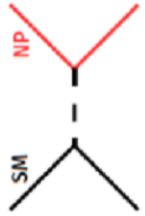
Energy frontier

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



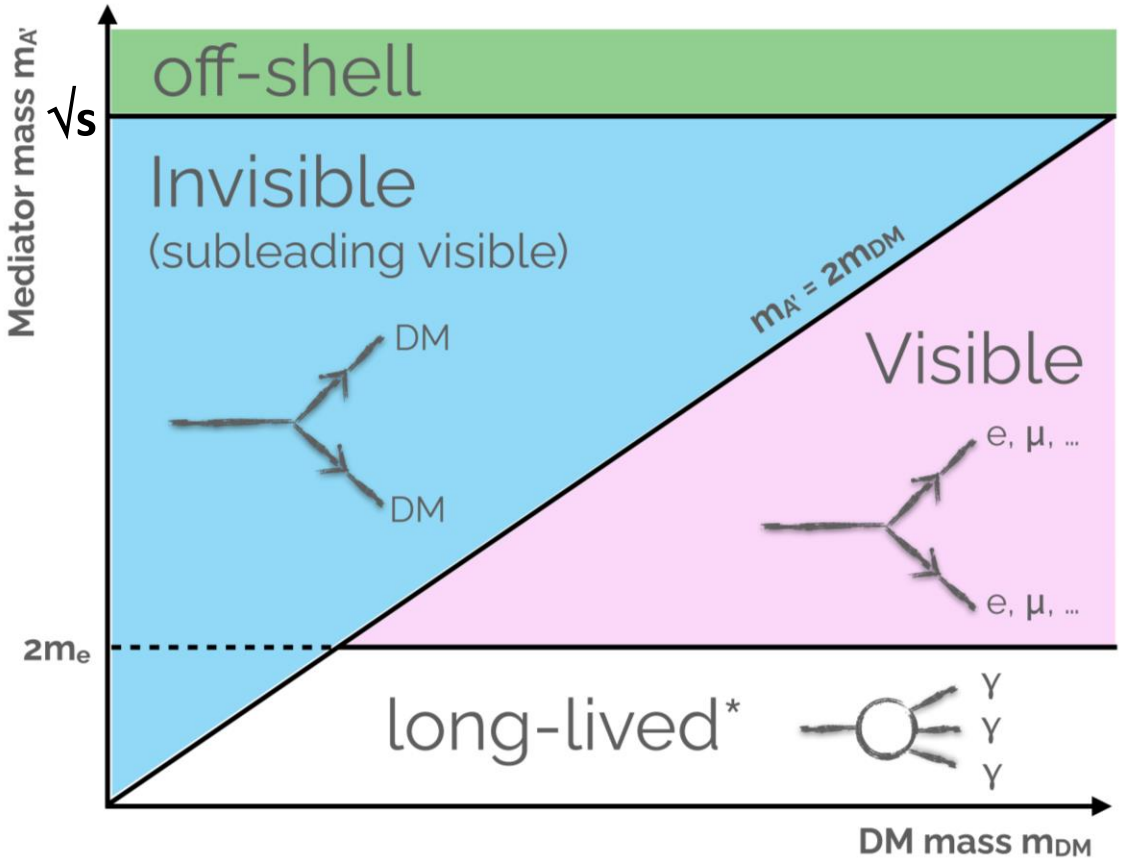
Cosmic frontier

Direct effect search in (mostly) underground experiments



Light Dark matter hunt

Different signatures depending on the DM ↔ mediator mass relation

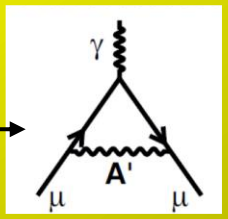


Probability of interaction of LDM detectors is negligible

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

Additional benefits:

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

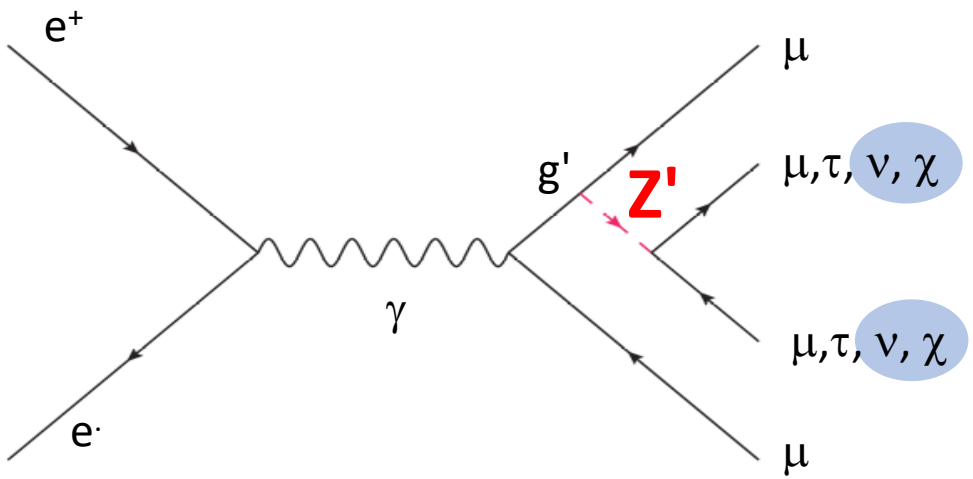


- Explanation (with additional hypotheses) of some flavour anomalies (LHCB, Belle, …)
- Some light mediators (not interacting with quarks) could escape direct search exclusion limits

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

Explored for the first time

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

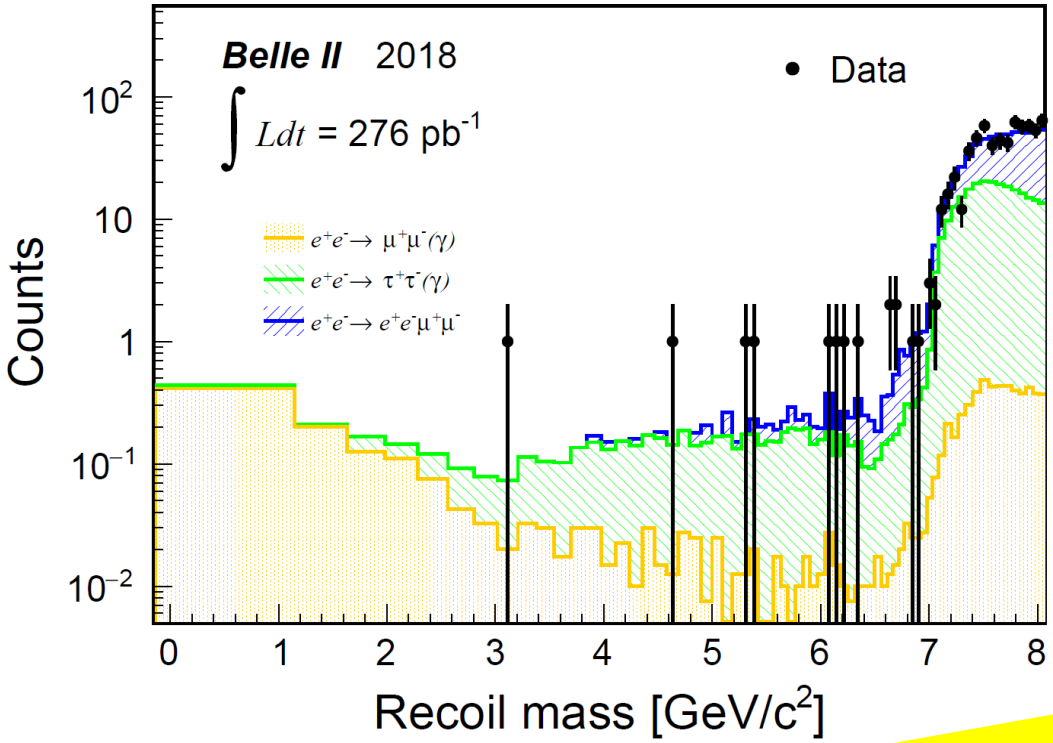
Look for bumps in recoil mass against a $\mu^+\mu^-$ pair

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

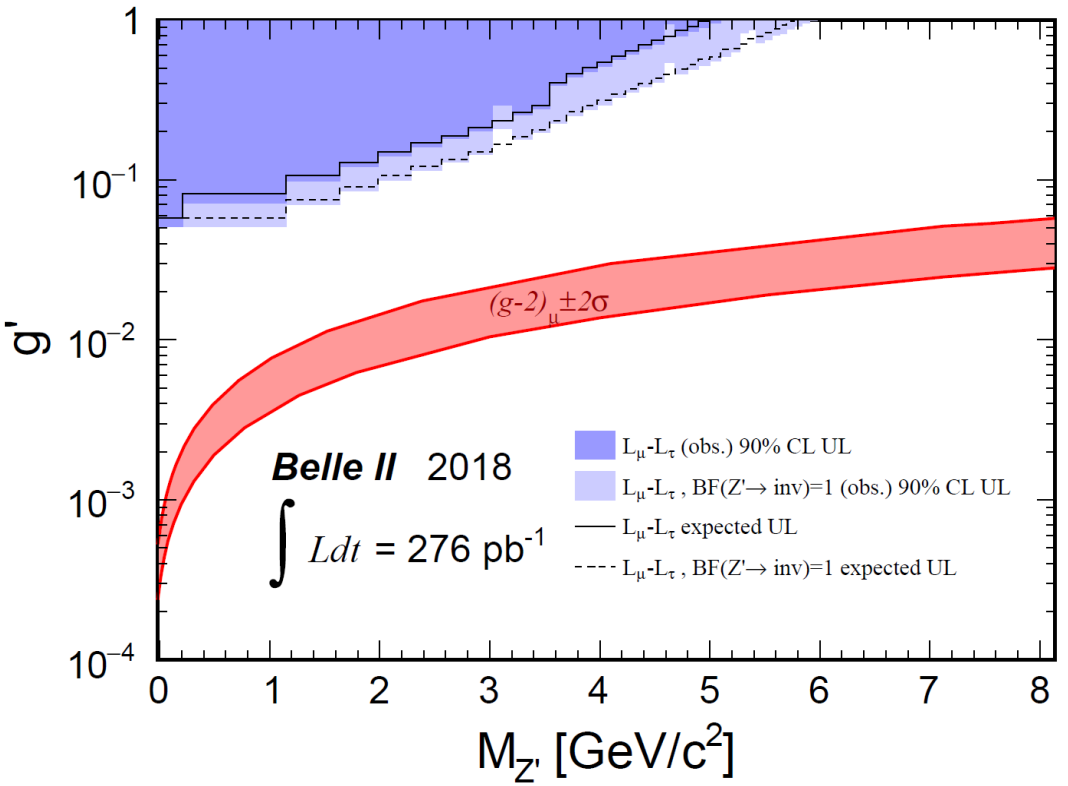


First physics paper by Belle II
PRL 124 (2020), 141801

Systematics

Source	Error
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%

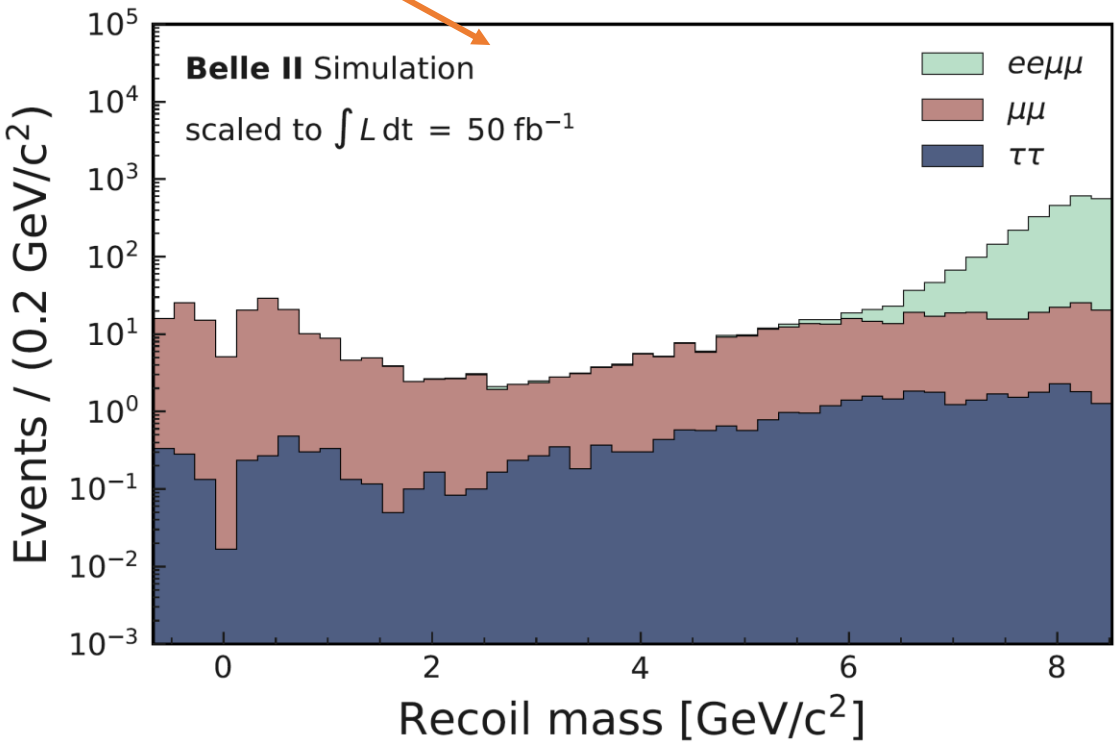
will decrease with new data

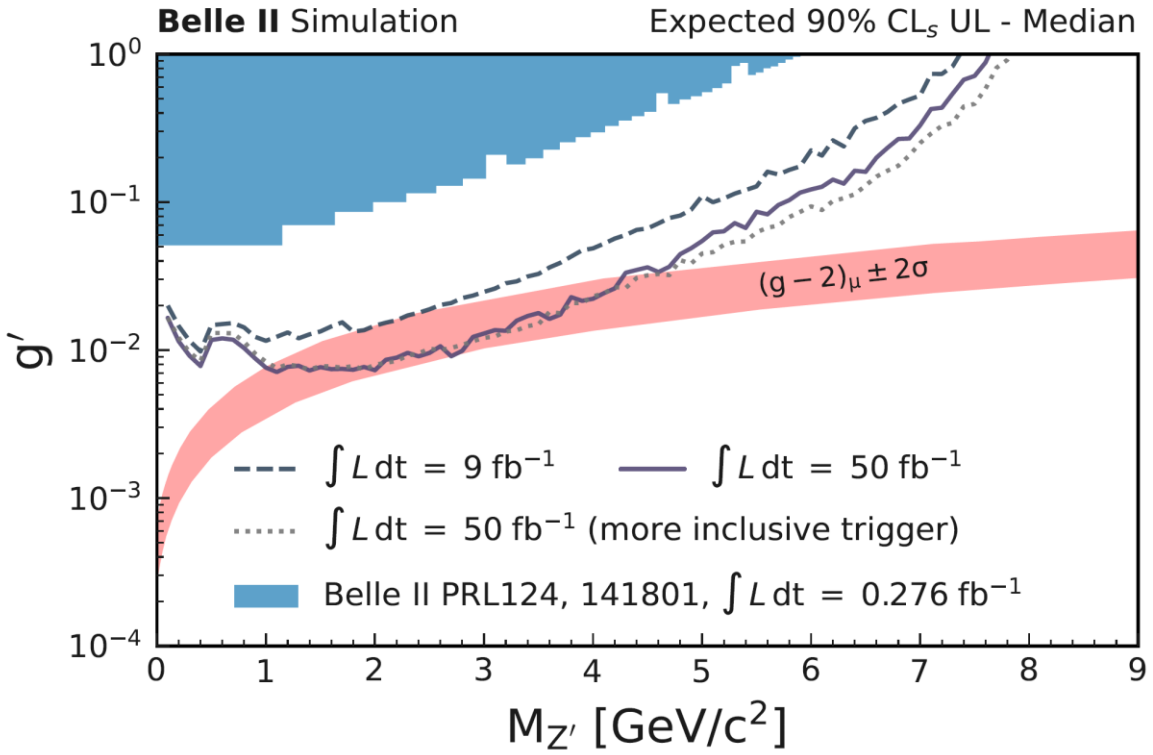


Z’ to invisible: short term luminosity projections

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

Very low expected background → UL scale~1/L





LFV Z' to invisible

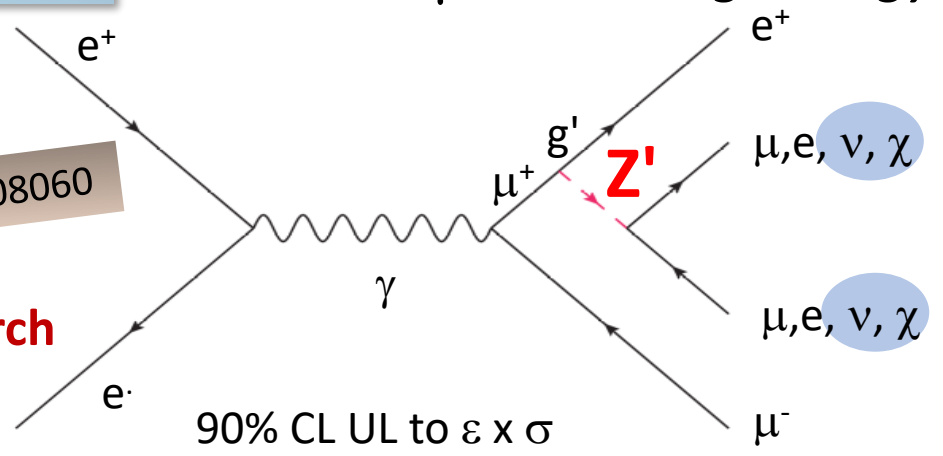
$e^+e^- \rightarrow e^+\mu^- +$ *missing energy*

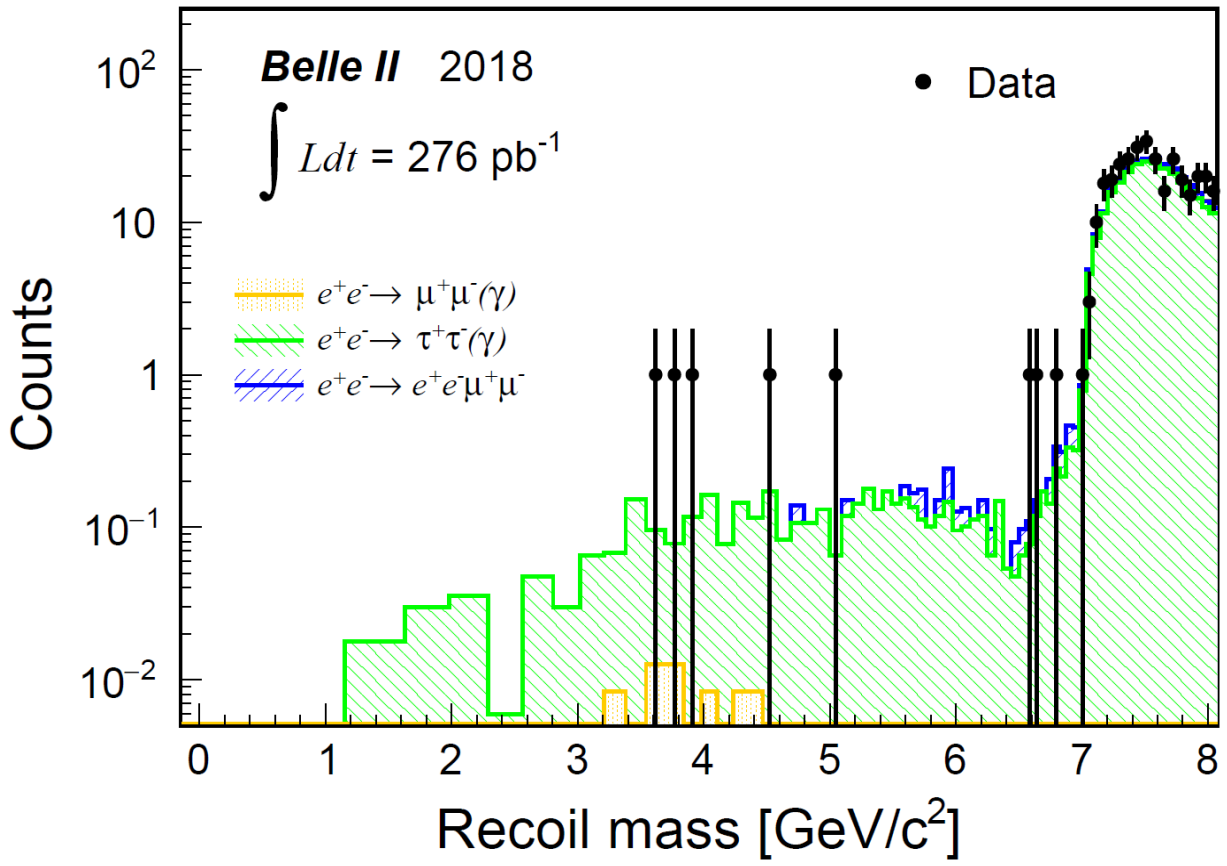
What about a Lepton Flavour Violating Z'?

Only e-μ coupling taken into account

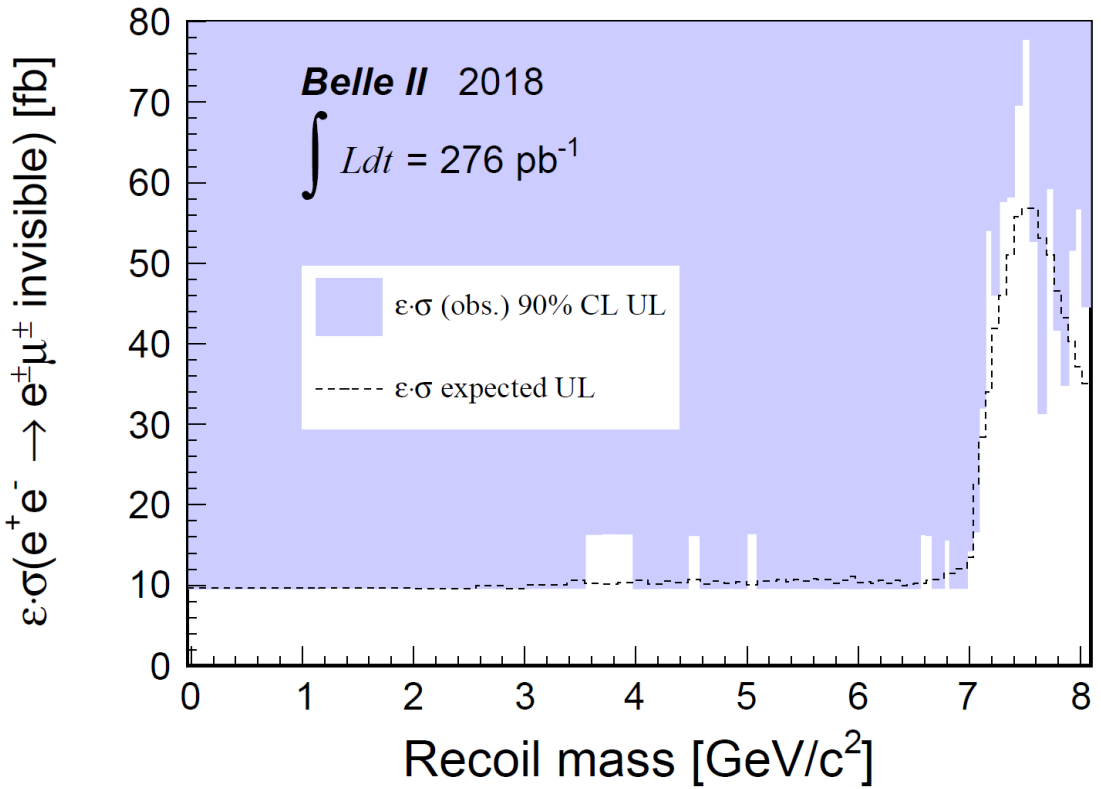
For example I.Galon et al. (2016), arXiv 1610.08060

Model independent search





90% CL UL to ε x σ

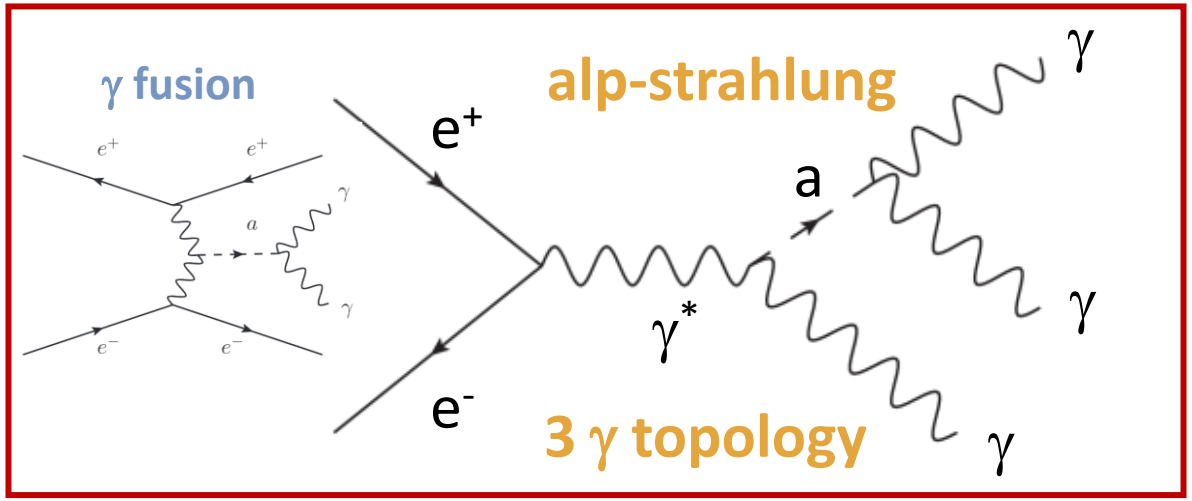


Axion Like Particles (ALPs)

- 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
- $\tau \sim 1 / g_{a\gamma\gamma}^2 \, m_a^3$

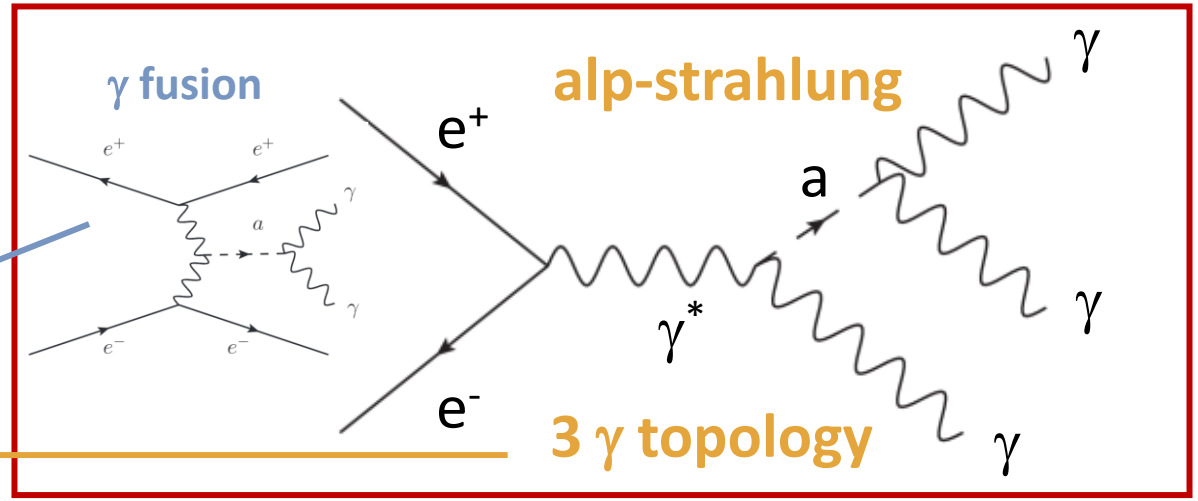


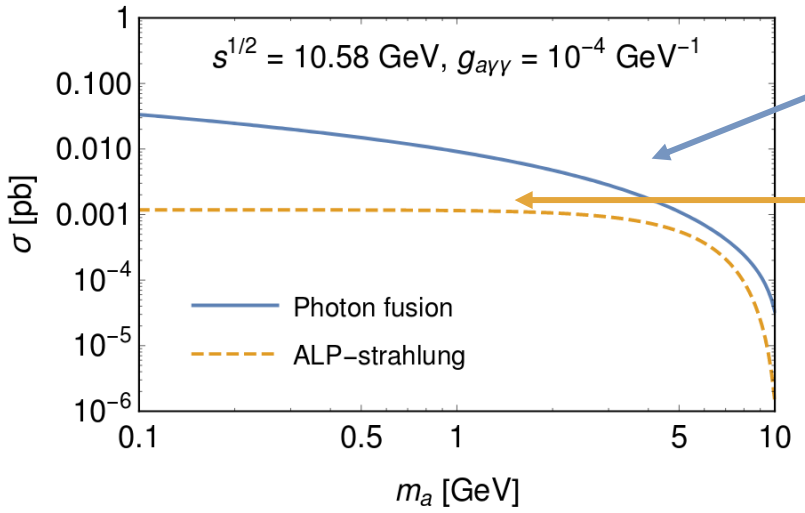
Axion Like Particles (ALPs)

- 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
- $\tau \sim 1 / g_{a\gamma\gamma}^2 \, m_a^3$



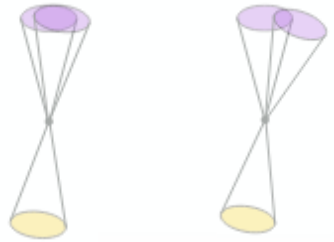


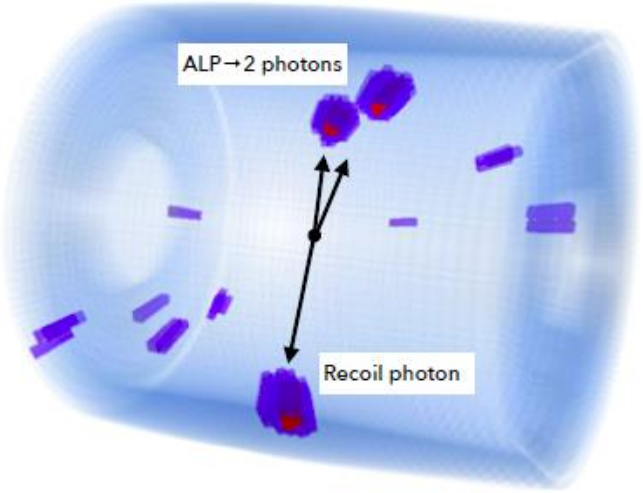
photon fusion sensitivity under study

Axion Like Particles (ALPs): signal

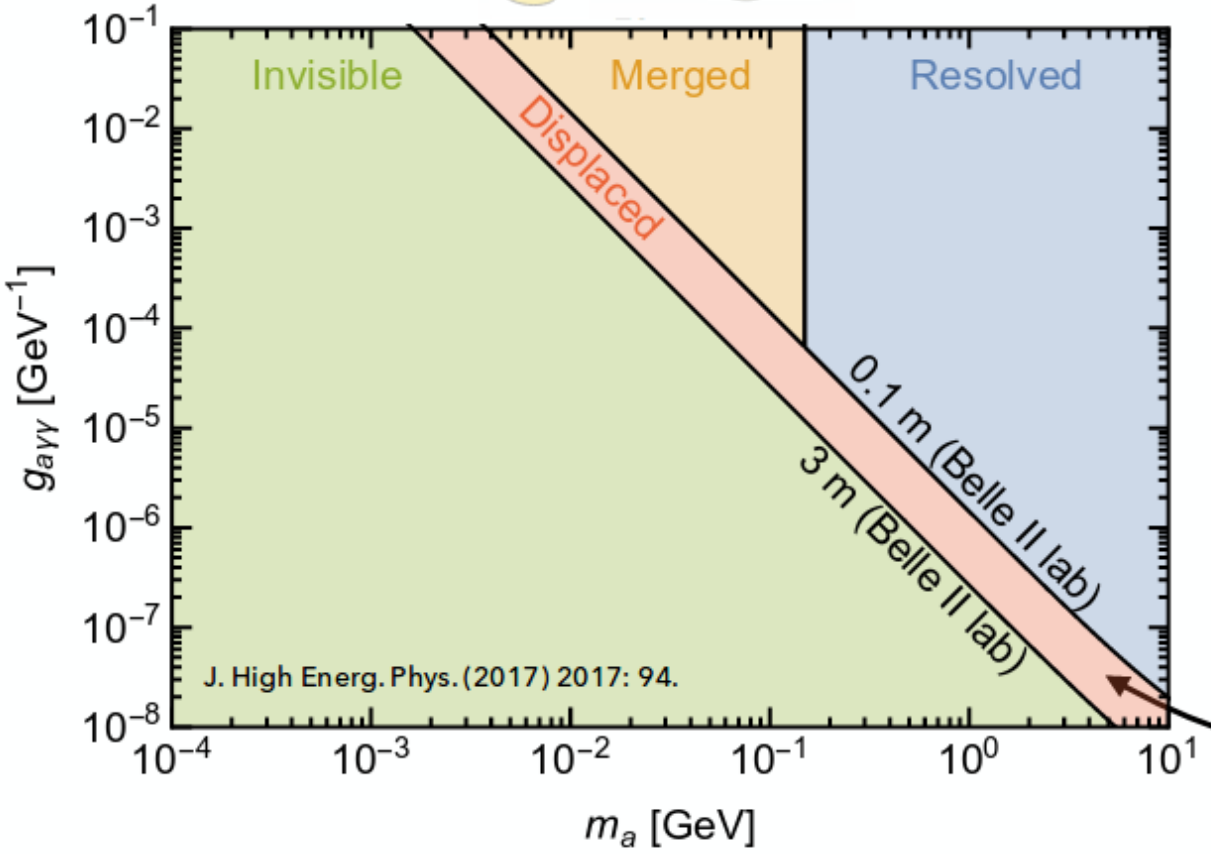
3 γ topology, but…

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

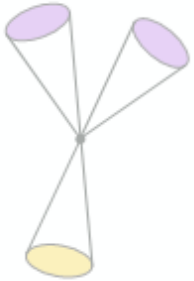




ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.



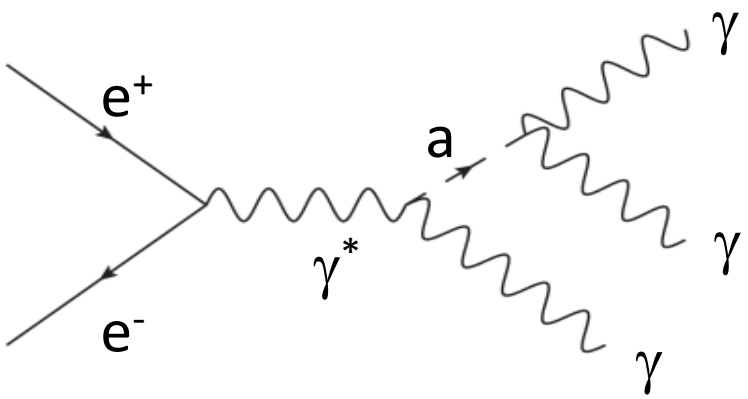
Three **resolved**, high energetic photons.



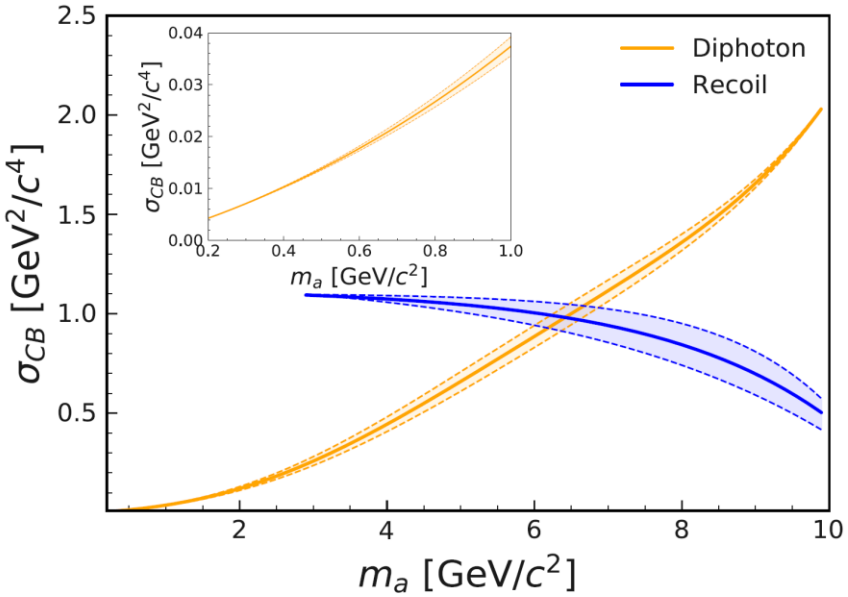
The searches for invisible and visible ALP decays veto this region.

ALPs can also decay to DM → single photon topology

Axion Like Particles (ALPs)



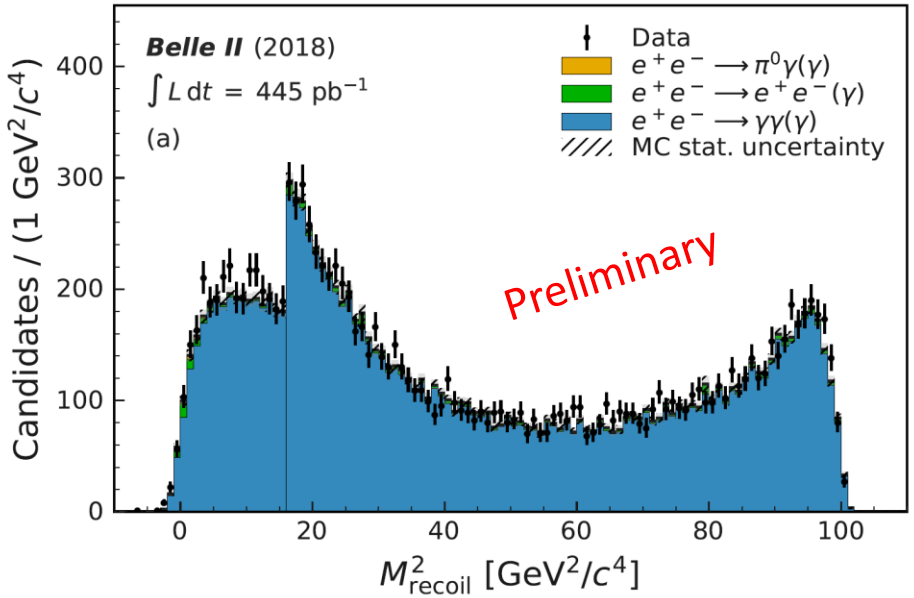
Search for peaks either in the recoil invariant mass (high m_a) or in diphoton mass (low m_a)

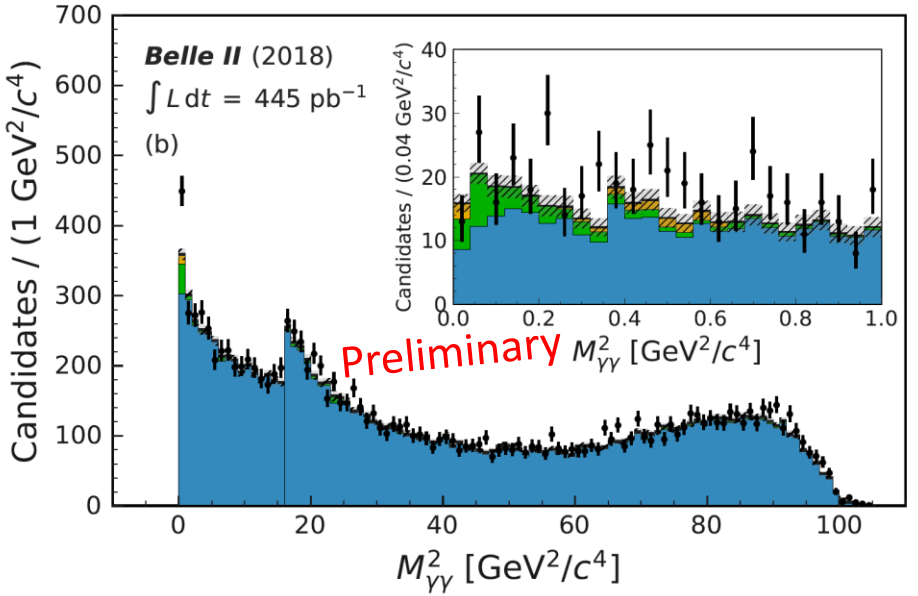


Main backgrounds:

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

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

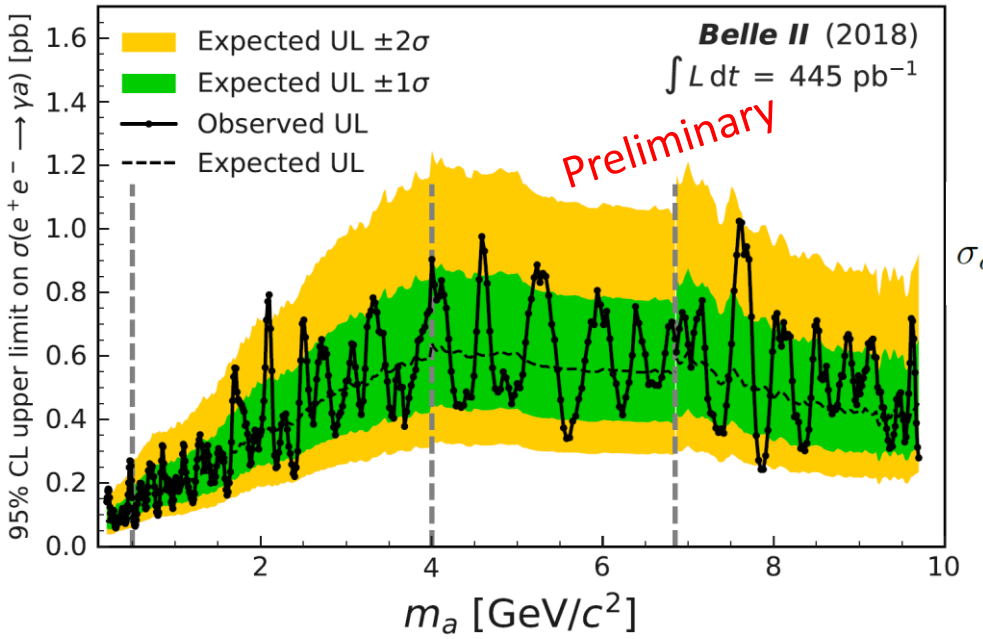




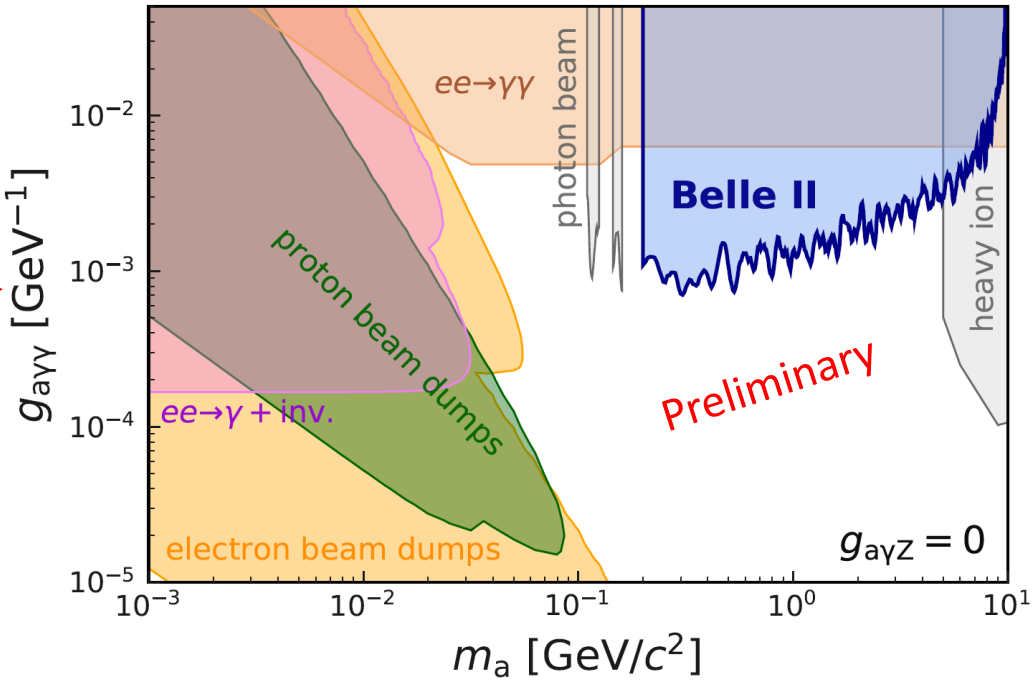
Axion Like Particles (ALPs)

- ~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



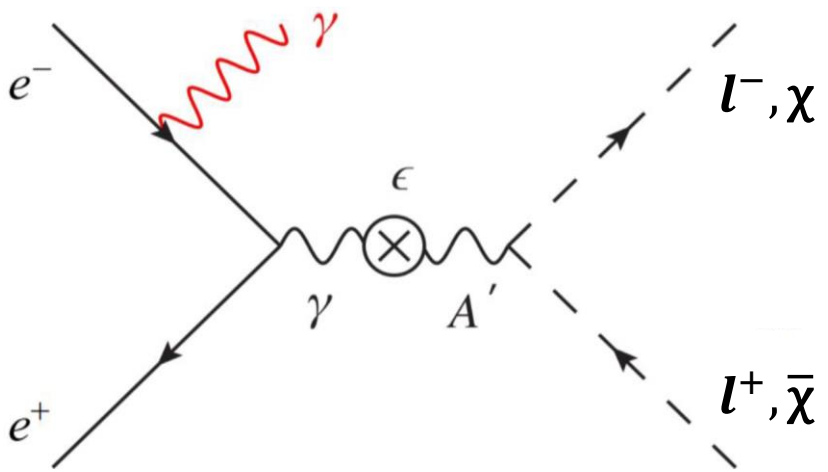
$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\mathrm{QED}}}{24}\left(1-\frac{m_a^2}{s}\right)^3$$



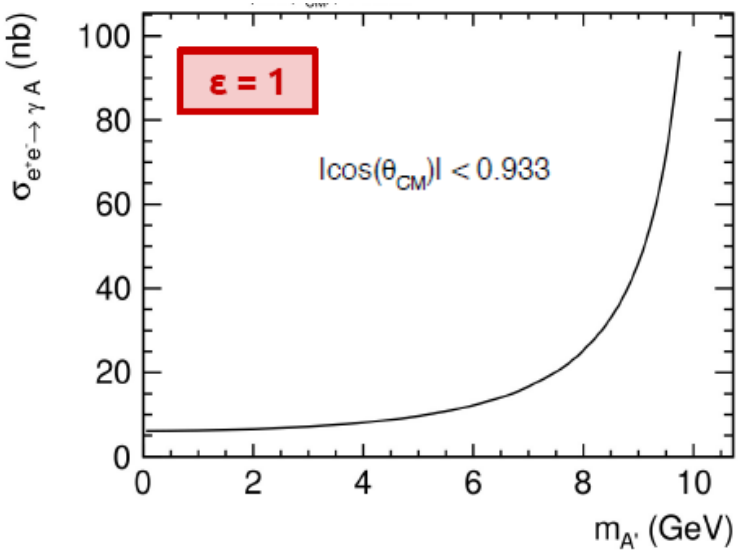
Dark photon: introduction

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



Production cross section

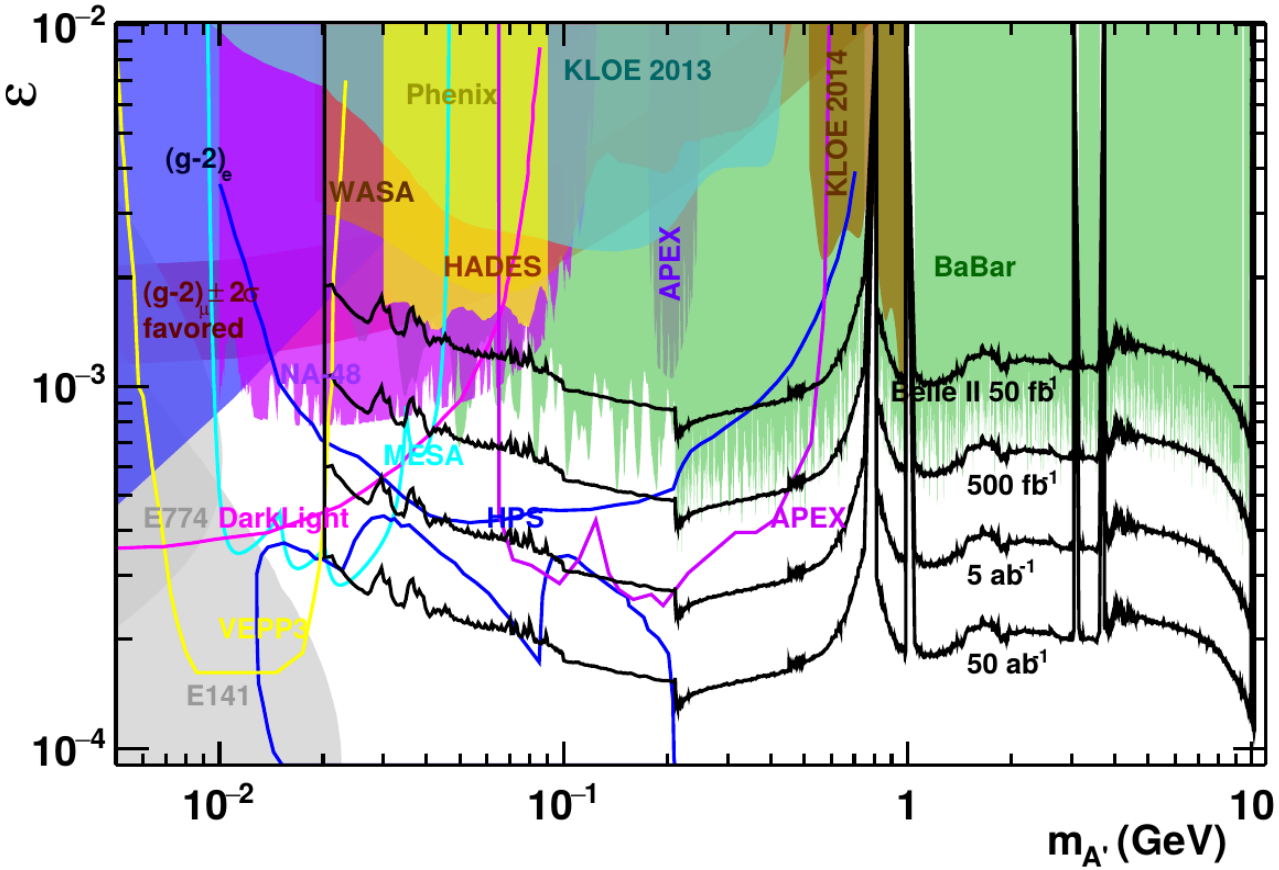


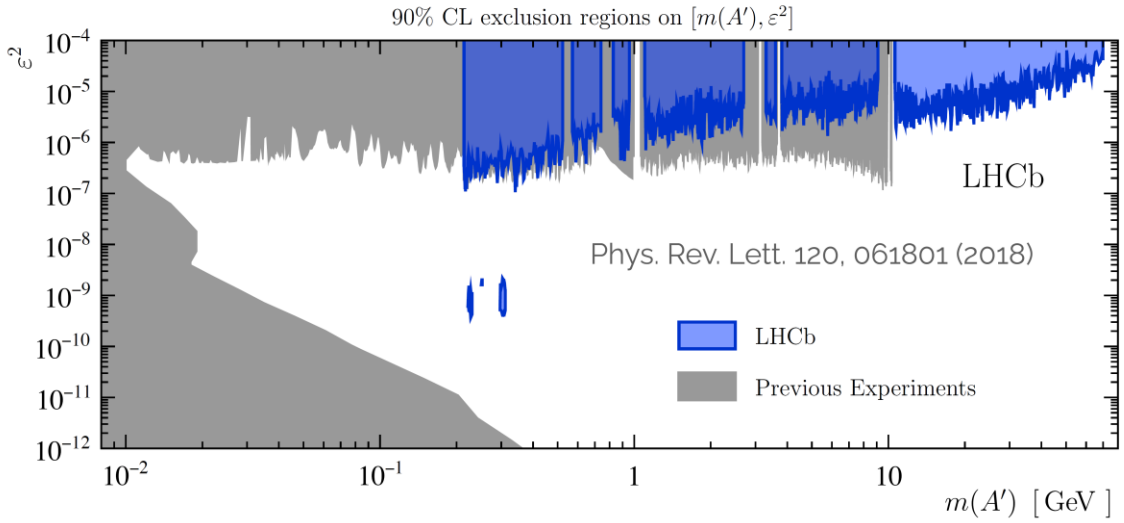
two basic scenarios depending on A′ vs χ DM mass relationship

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

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

Visible dark photon: sensitivity





Competition with LHCb:

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

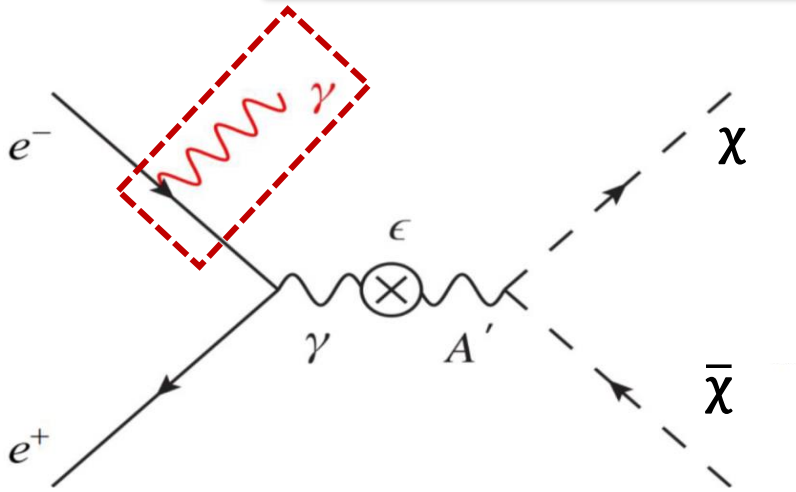
Best limits in the GeV region from **BaBar**

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

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

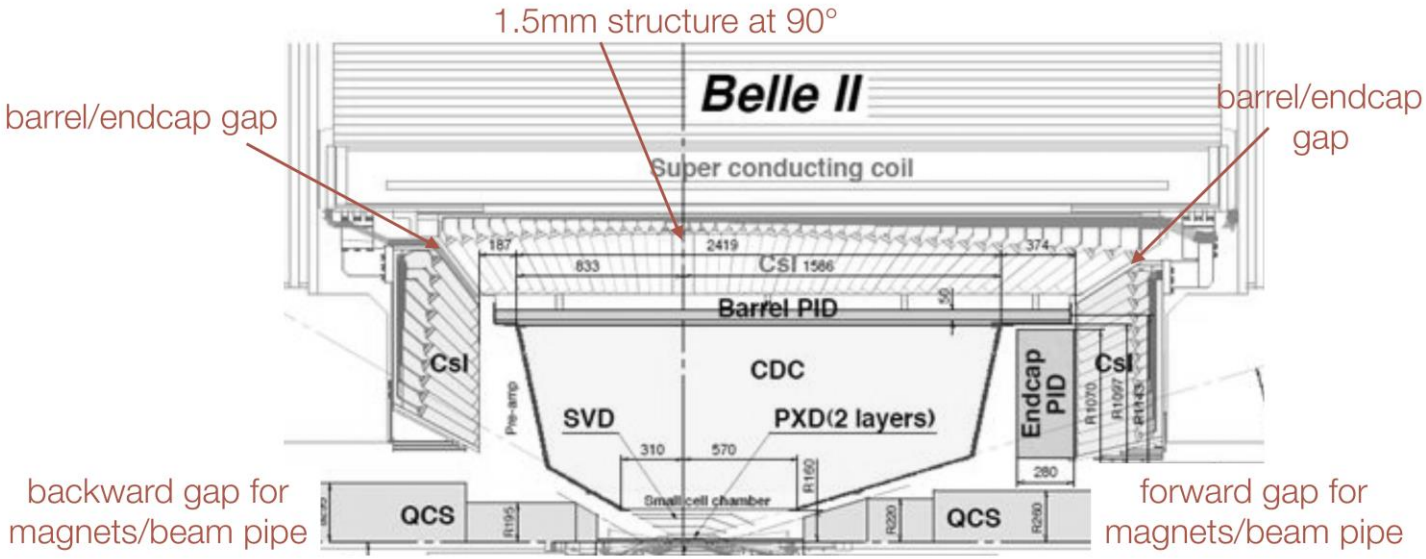
Backgrounds

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

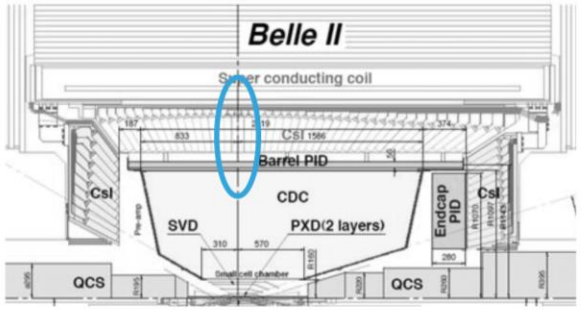
$e^+e^- \to \gamma\gamma(\gamma)$ → low $M_{A'}$ region

Cosmics

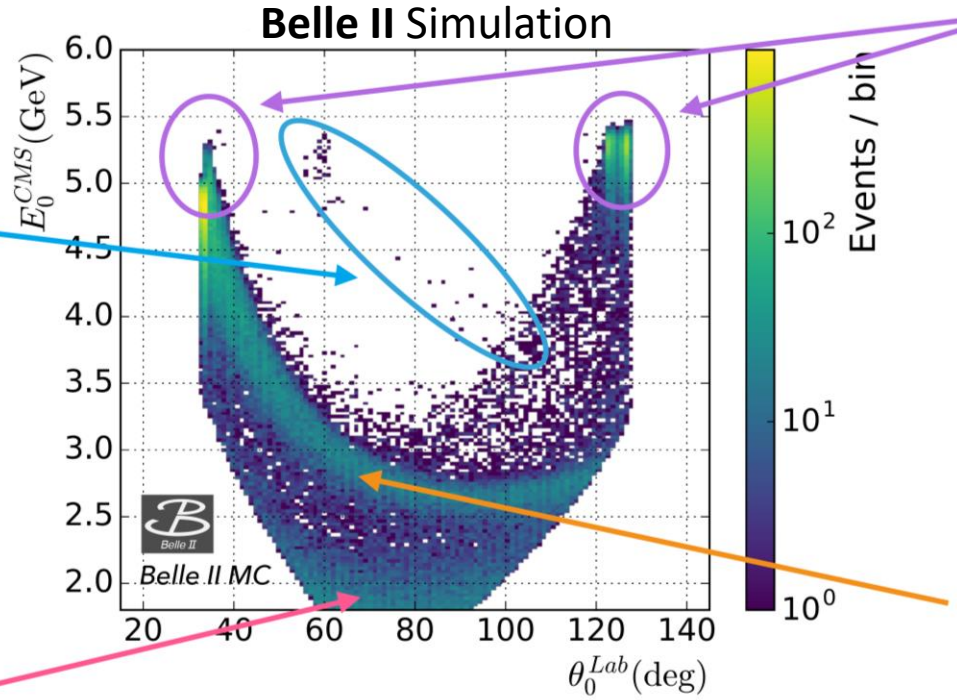
$e^+e^- \to \gamma\nu\nu$

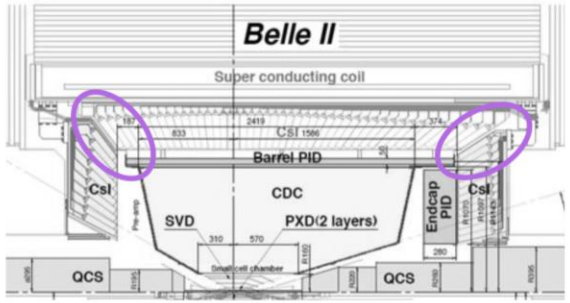


Invisible dark photon: background



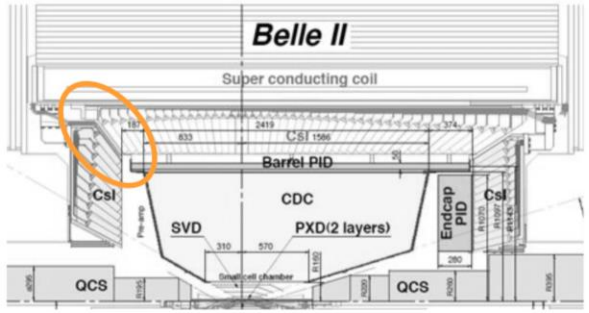
ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance





ee→2γ
1γ in ECL BWD or FWD gap

ee→eeγ
both electrons
out of tracking acceptance



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

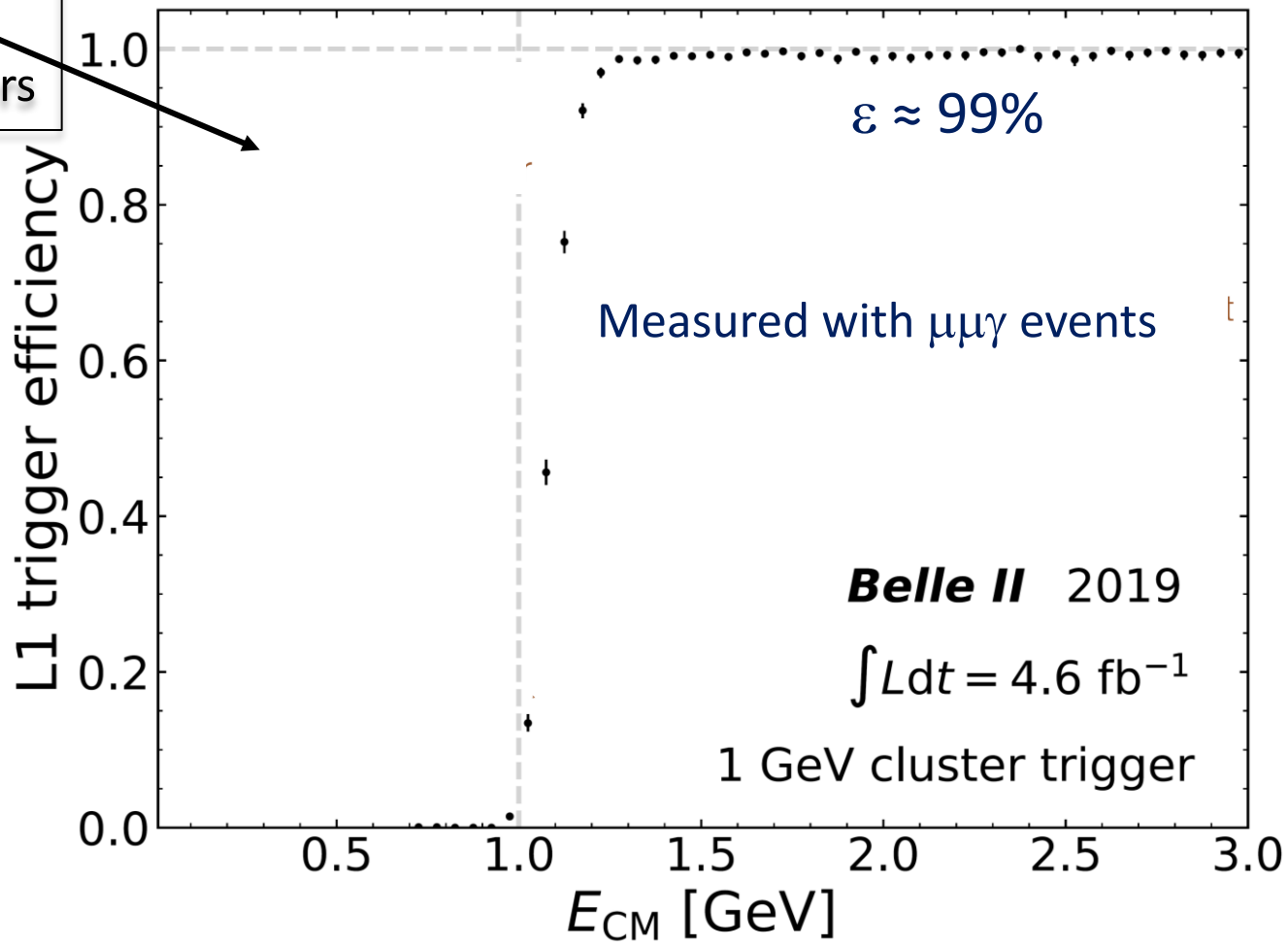
Crucial usage of KLM to veto photons in ECL gaps

Invisible dark photon: single photon trigger

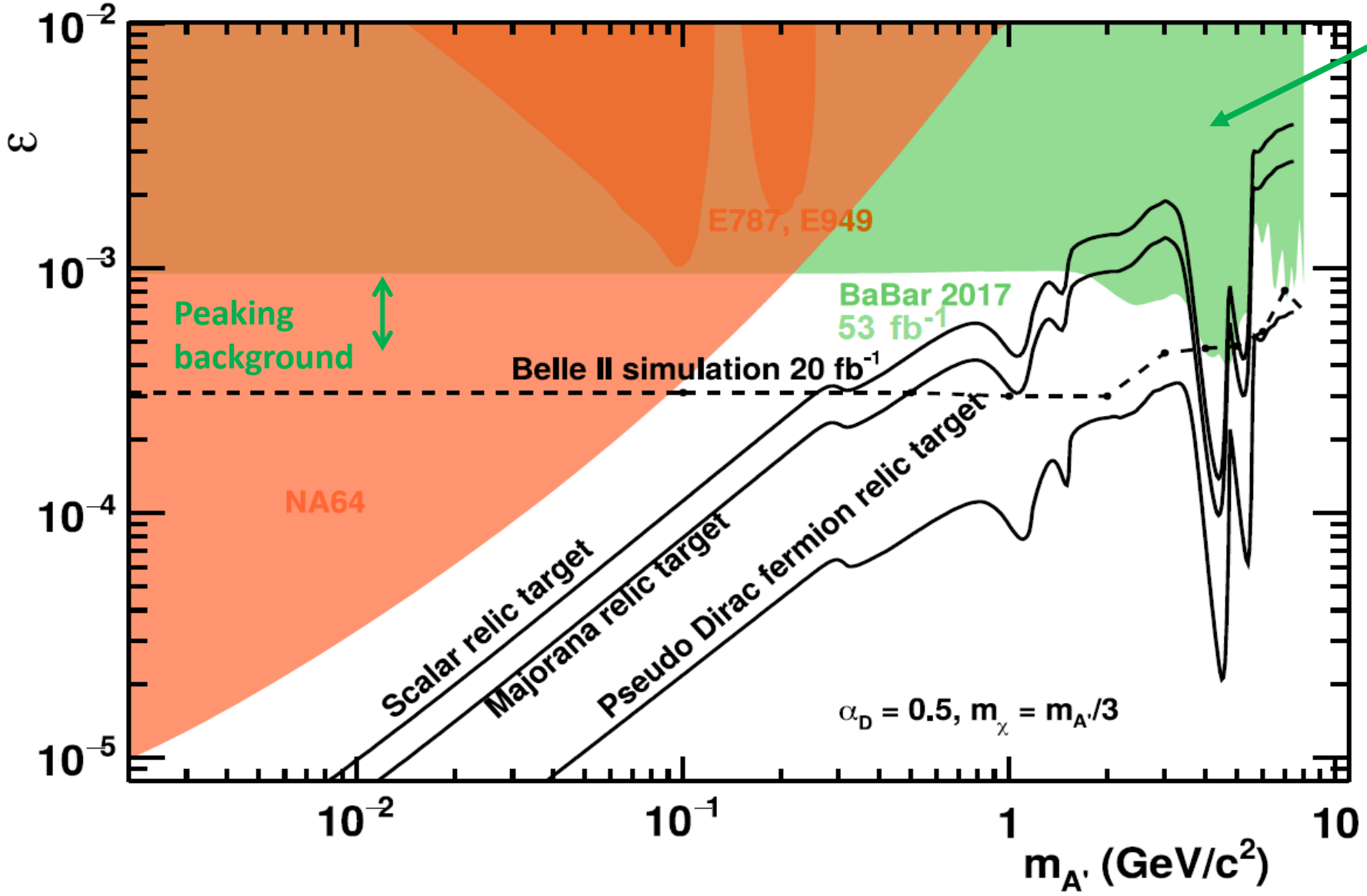
- **E_{CM} > 2 GeV**
- **E_{CM} > 1 GeV** in barrel + no other clusters
- **E_{CM} > 0.5 GeV** in central barrel + no other clusters

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

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



Invisible dark photon: sensitivity



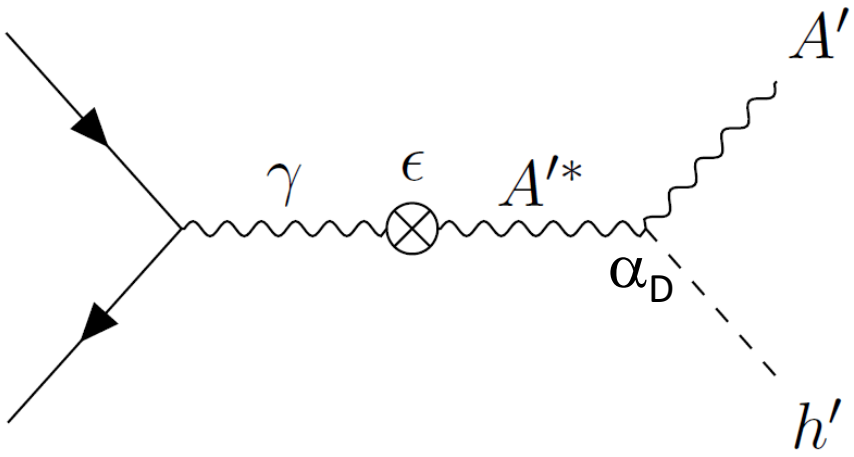
Belle II vs BaBar

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

↓

- ✓ Larger acceptance
- ✓ KLM veto

Dark Higgsstrahlung: A'h'



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

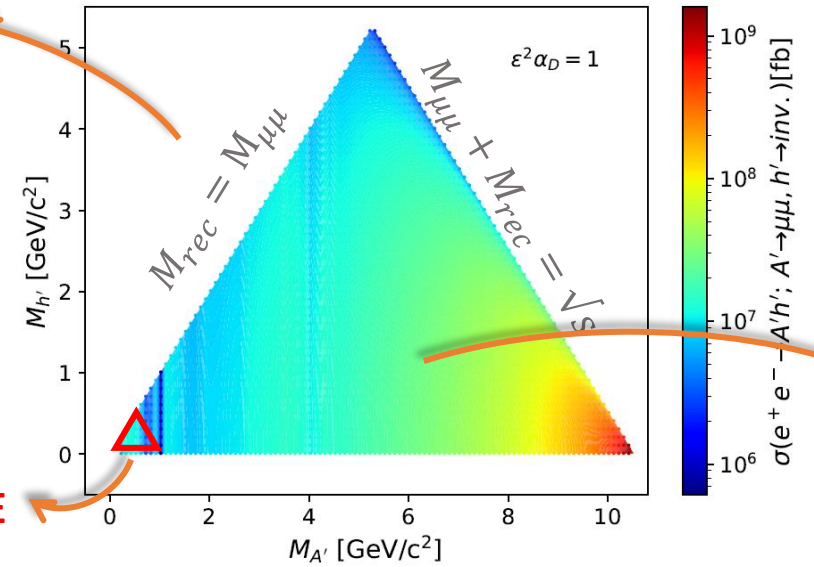
- Dark photon A′ + dark higgs h′
- h′ → spontaneous symmetry breaking to give mass to A′
- Less suppressed in ε wrt standard A′ search
- Very different scenarios depending on:
  - $M_{h'} > M_{A'} \Rightarrow$ h′→ A′A′ → 4*l*, 4 *had*, 2*l* + 2 *had* — **BaBar, Belle**
  - $M_{h'} < M_{A'} \Rightarrow$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

Long lived

Available results

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

BaBar
Belle



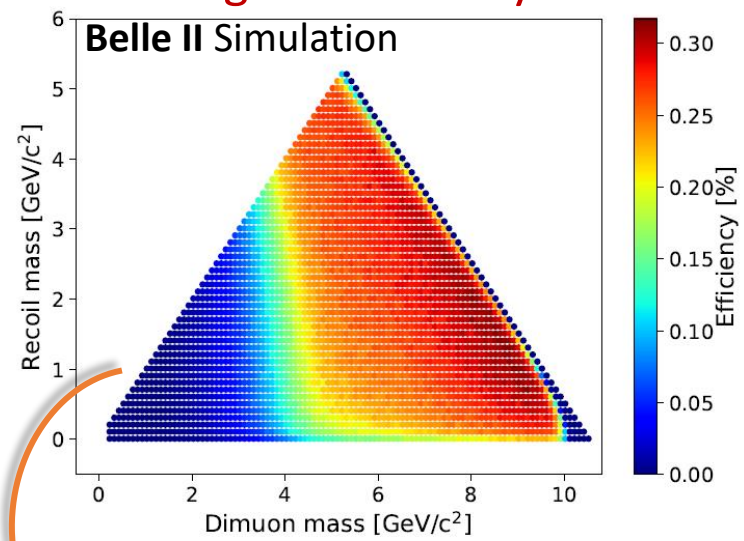
KLOE

Belle II

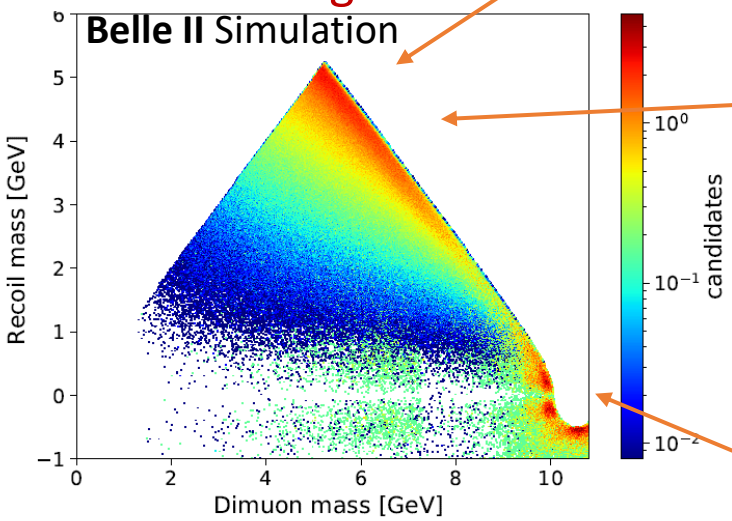
Dark Higgsstrahlung: A'h'

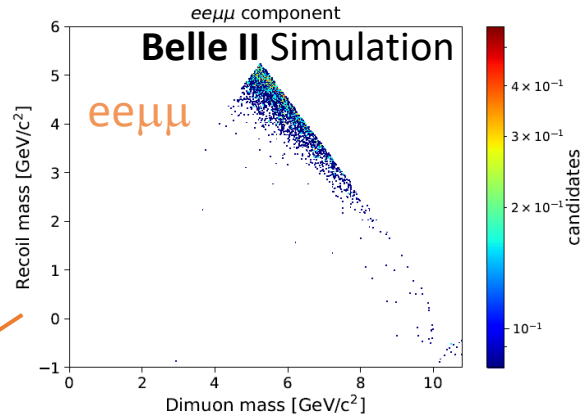
- **$\mu^+ \mu^-$ + missing energy** → same final state as in invisible Z'
- 2d peak in recoil vs dimuon mass
- Background naturally low due to 2d phase space
- **2019 data being used: L ≈ 9 fb^{-1} → next paper**

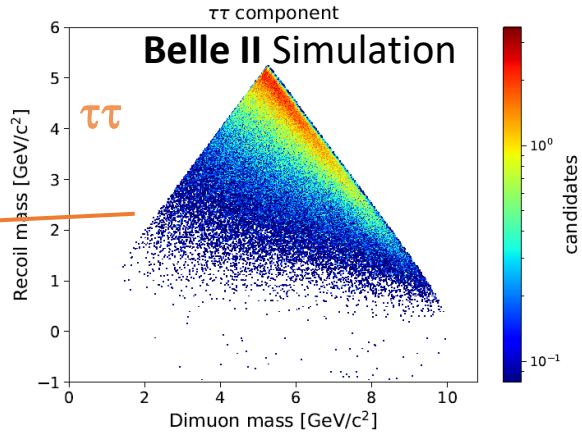
Signal efficiency

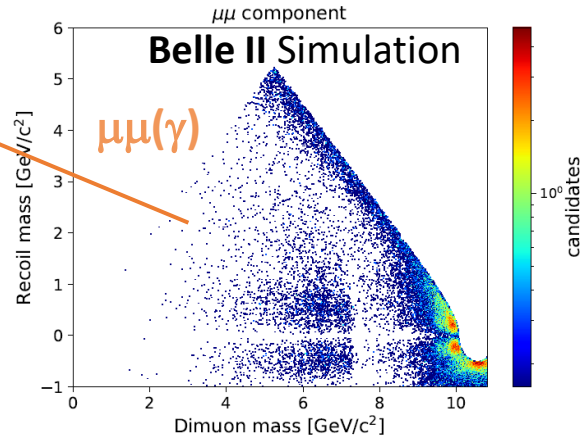


Total background









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′

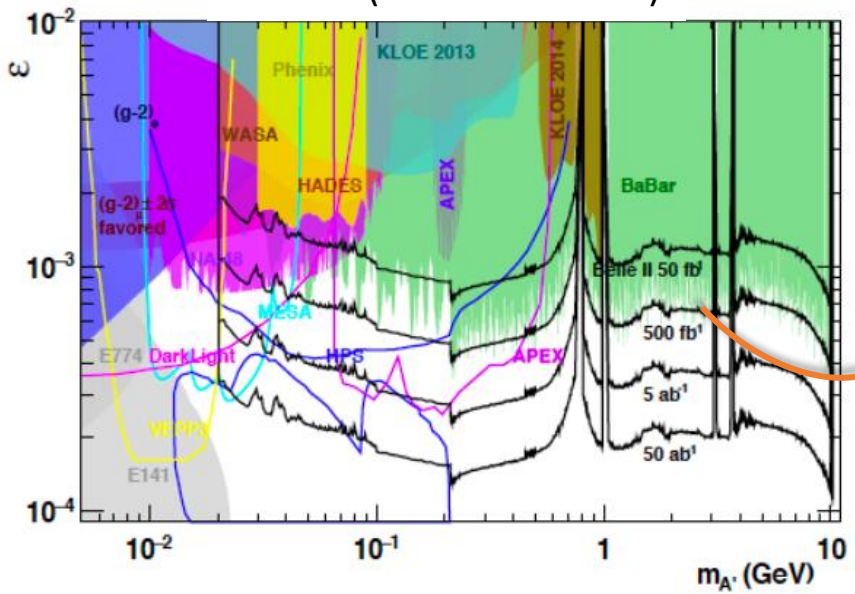
Very promising results even with the 2019 only dataset (9 fb^{-1})

- 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.

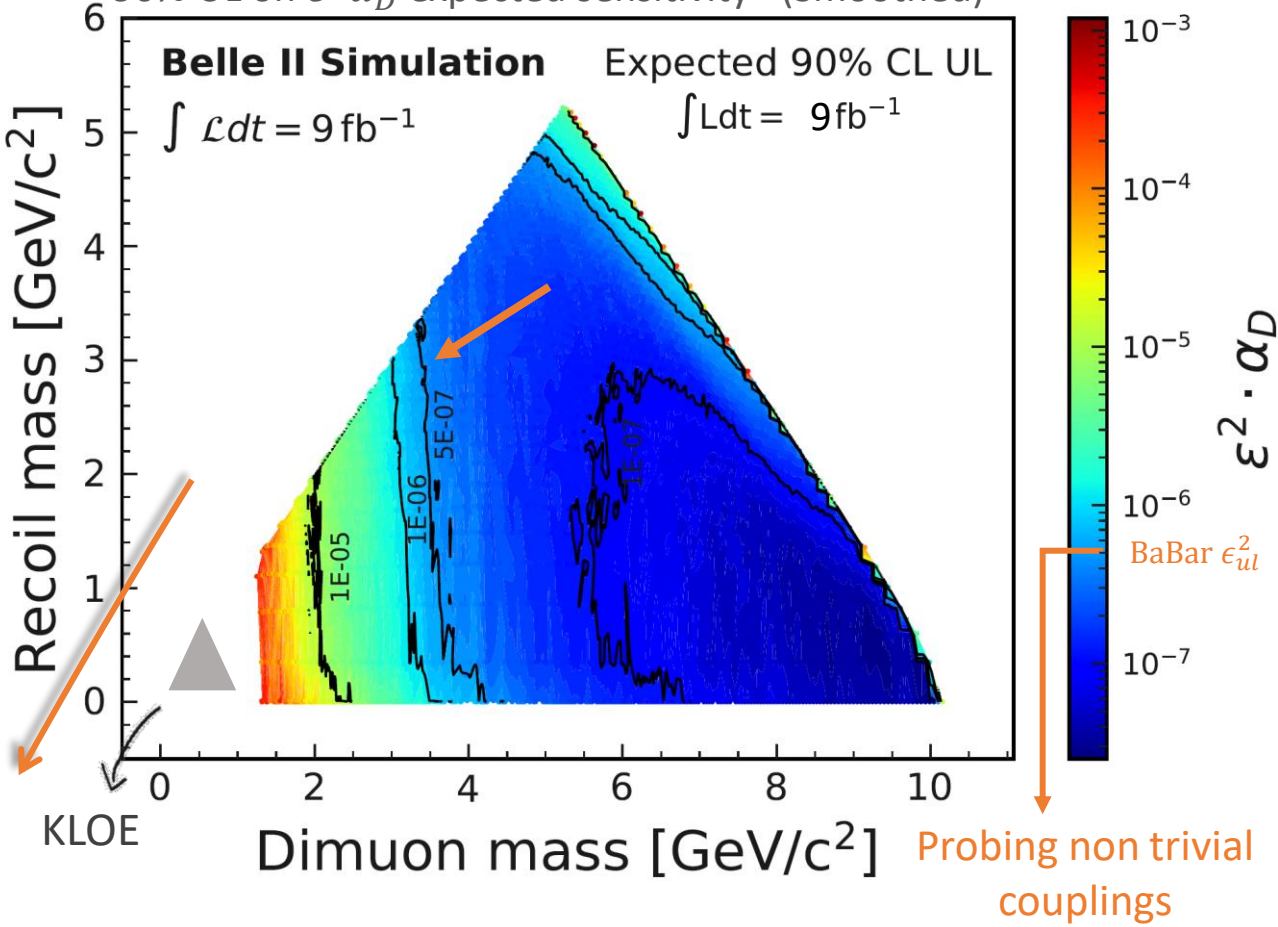
UL on ϵ (visible searches)



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

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′

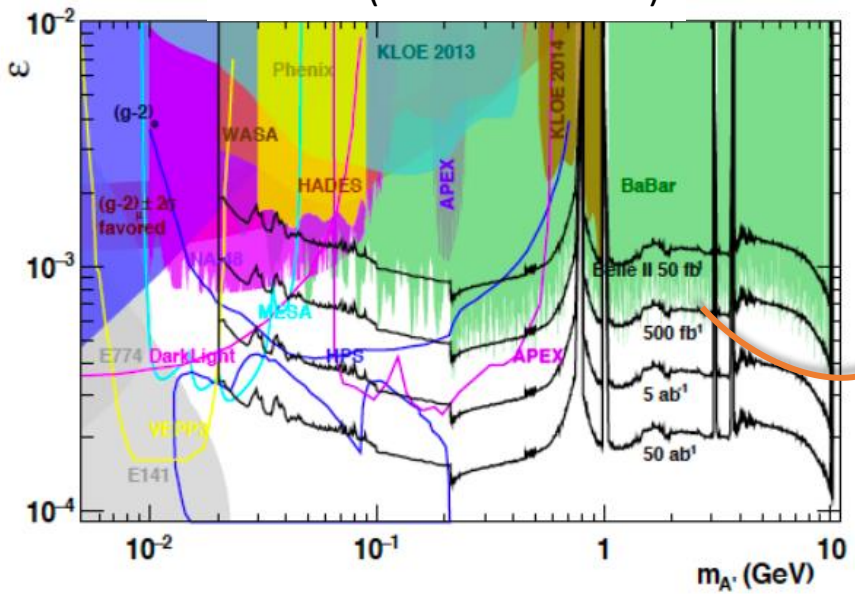
Very promising results even with the 2019 only dataset (9 fb^{-1})

- 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.

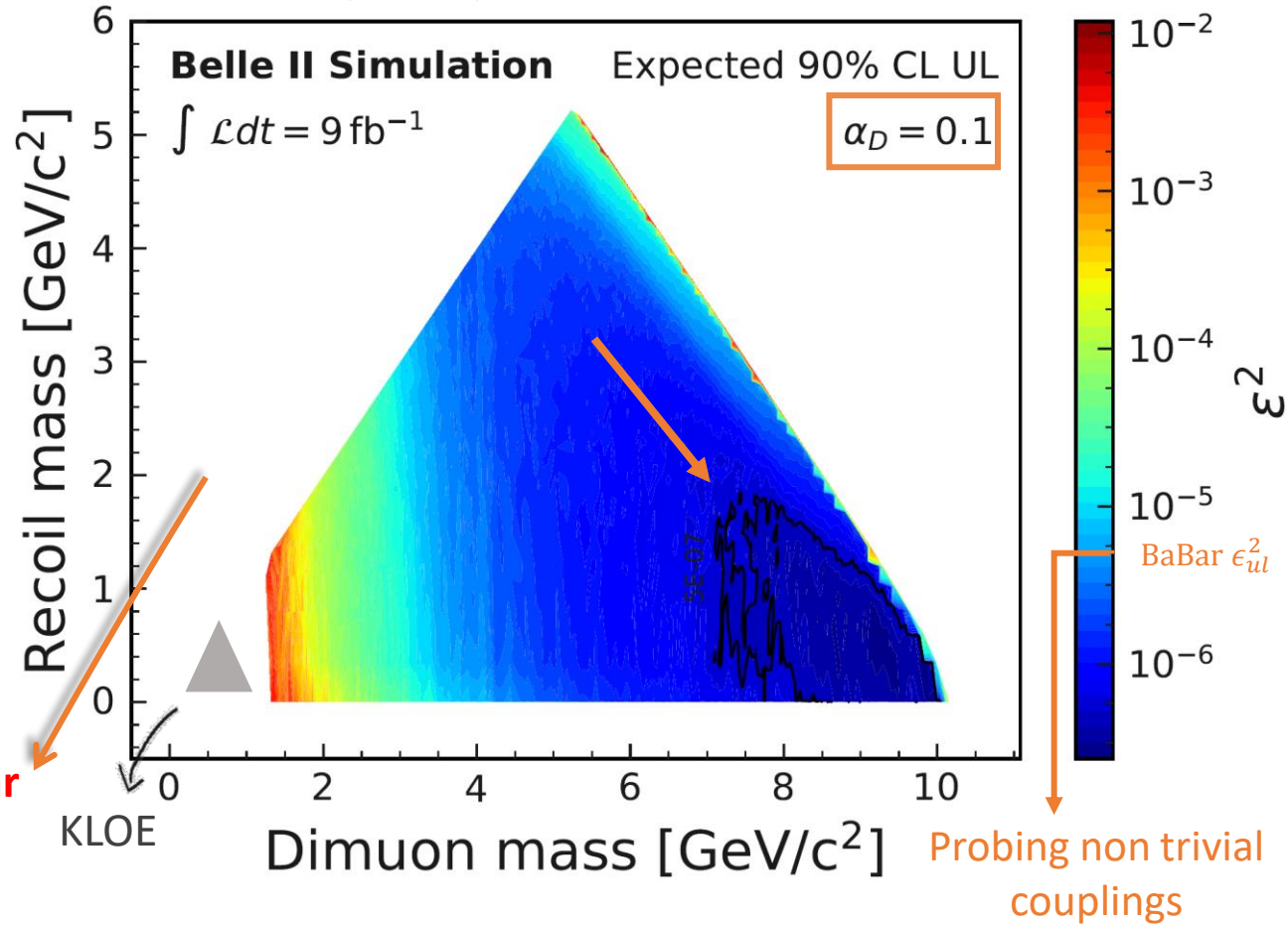
UL on ϵ (visible searches)



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

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

90% UL on ϵ^2 $(\alpha_D = 1)$ expected sensitivity* (Smoothed)



Probing non trivial couplings

Summary

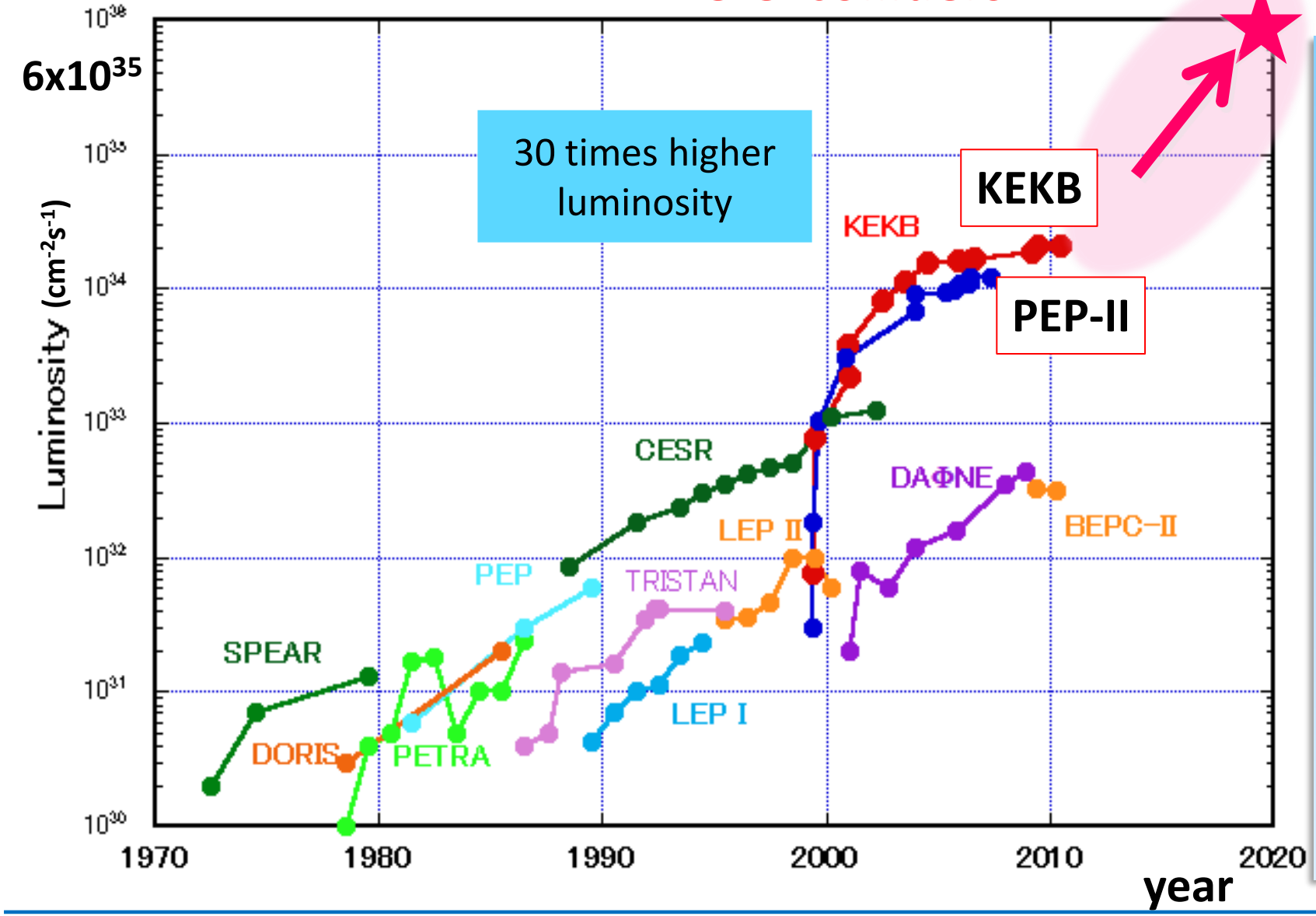
- **Belle II** started operation in 2018: 74 fb^{-1} collected up to now
- The persisting null results from new physics at LHC searches and in direct underground searches (not definitive in both cases) make the light dark sector senario more and more attractive
- Belle II has a broad program of dark searches: Z', dark photons, dark scalars, light Higgs, LLPs, iDM, monopoles, …
- First physics results and publications are out: **invisible Z'** and **ALP→γγ**
- Next results/papers: dark Higgsstrahlung (first half 2021), invisible dark photon (~ end 2021)

SPARE SLIDES

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

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

Lorentz factor

Beam current

Beam-beam parameter

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

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

Classical electron radius

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

Vertical beta function@IP

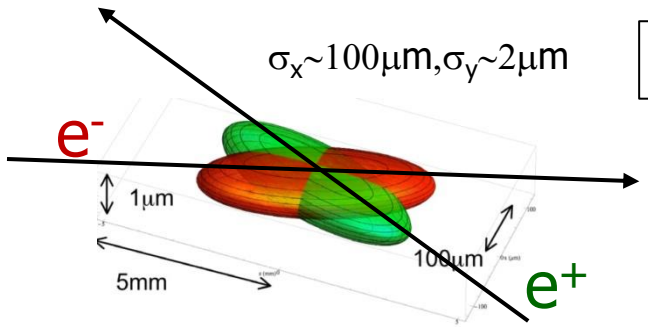
Lumi. reduction factor
(crossing angle)&
Tune shift reduction factor
(hour glass effect)
0.8 ~ 1
(short bunch)

x30

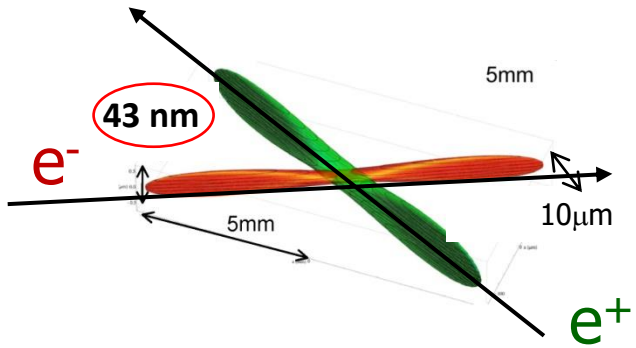
(1) Smaller β_y^*
(2) Increase beam currents
(3) Increase ξ_y

β^*_y=0.30/0.30 mm

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

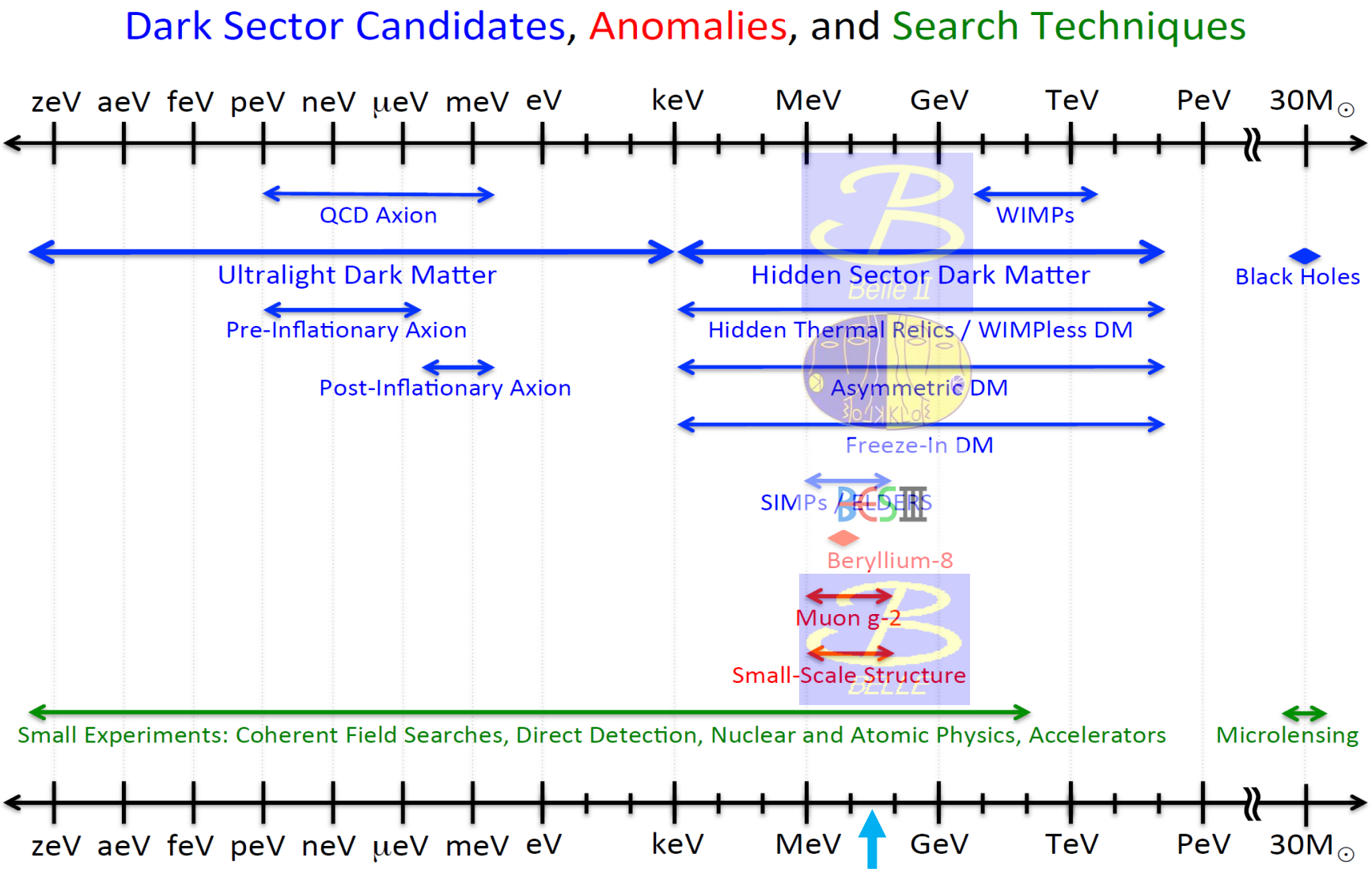


Nano-Beam scheme



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

Searching for dark matter



Dark matter/mediators

Vector portal

Dark photon, Z', …

Pseudoscalar portal

Axions, **ALPs**, …

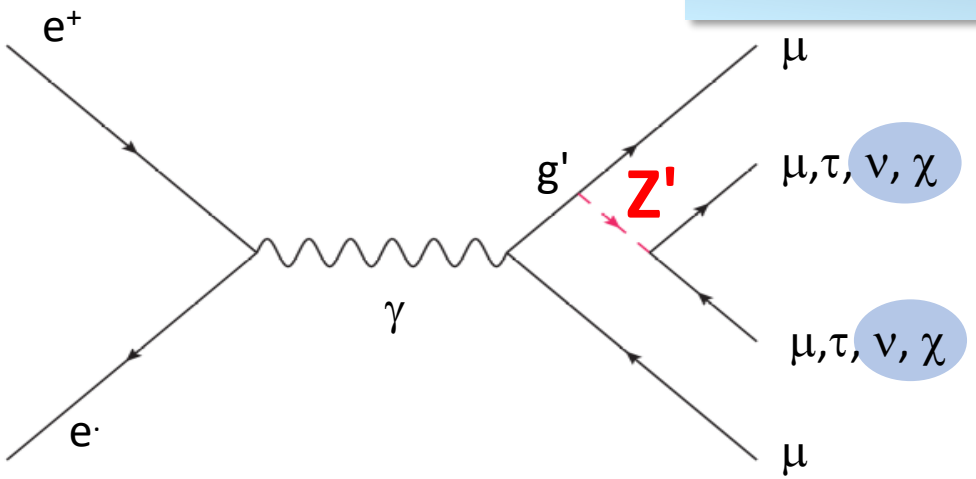
Scalar portal

Dark Higgs, scalars

Neutrino portal

Sterile neutrino

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



Explored for the first time

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

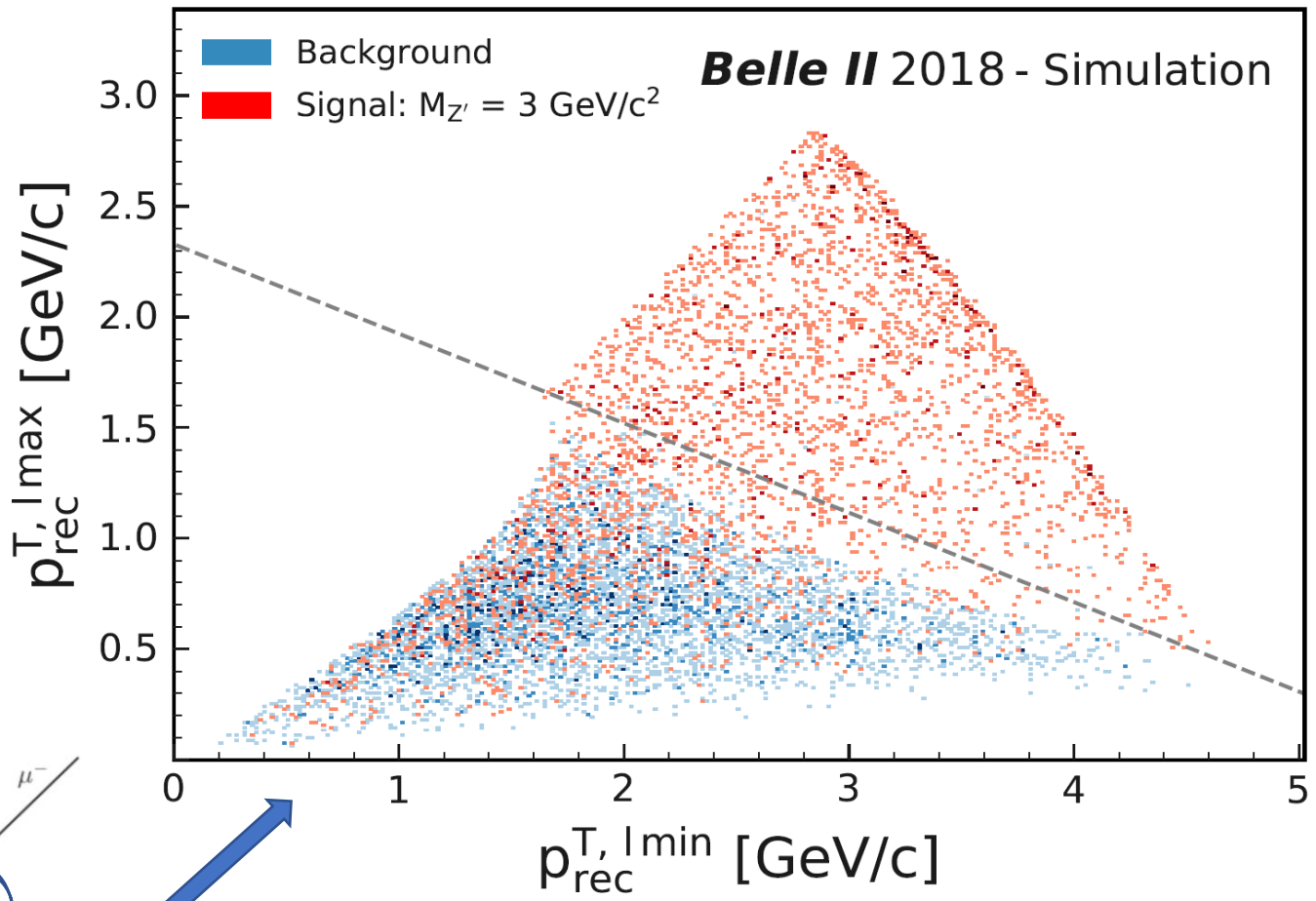
Look for bumps in recoil mass against a $\mu^+\mu^-$ pair

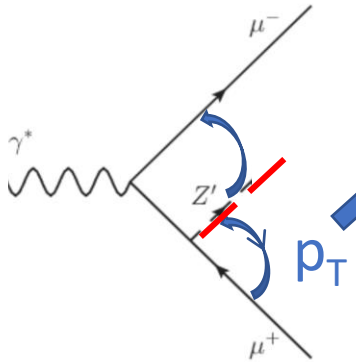
Main backgrounds:

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

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

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





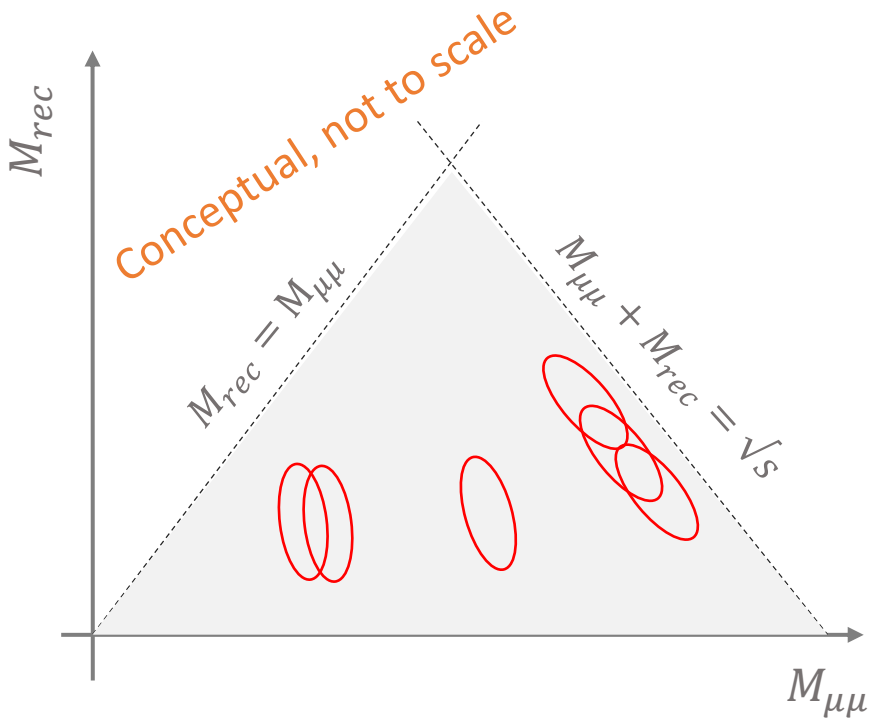
FSR vs ISR + τ decay

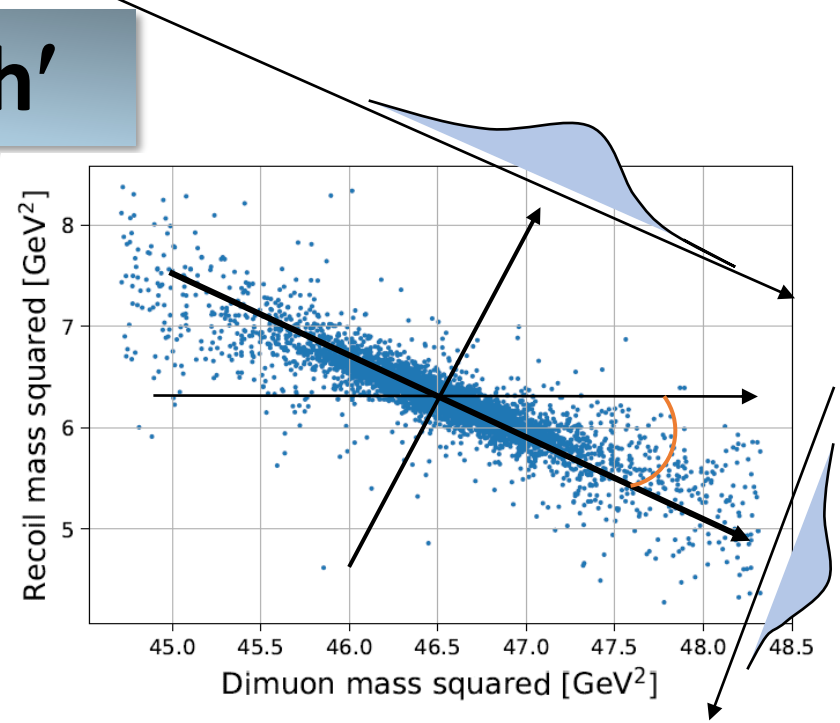
Dark Higgsstrahlung: A′h′

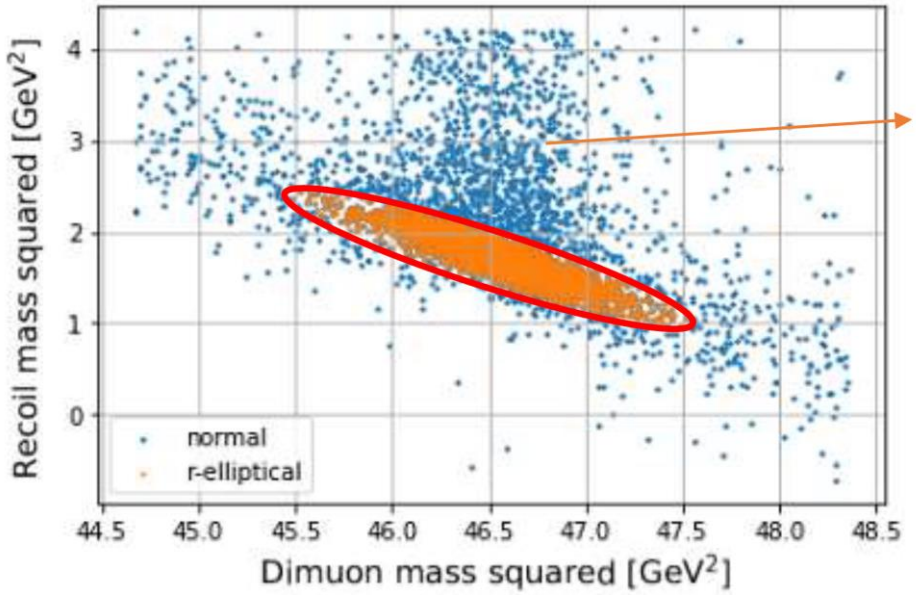
- Negative correlation between μμ and recoil mass
- Variable across the plane: evalutaed in the no ISR case

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

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

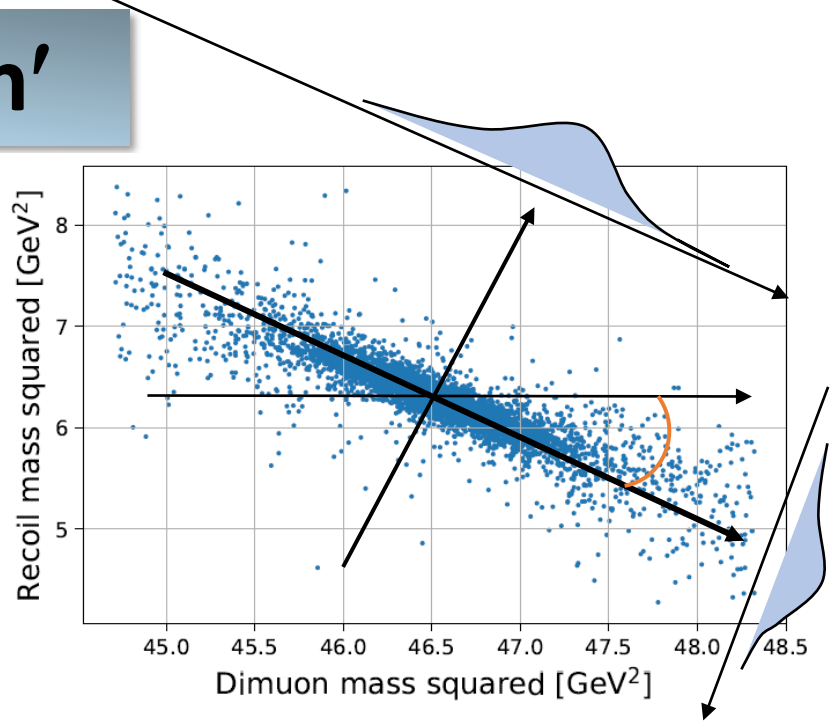


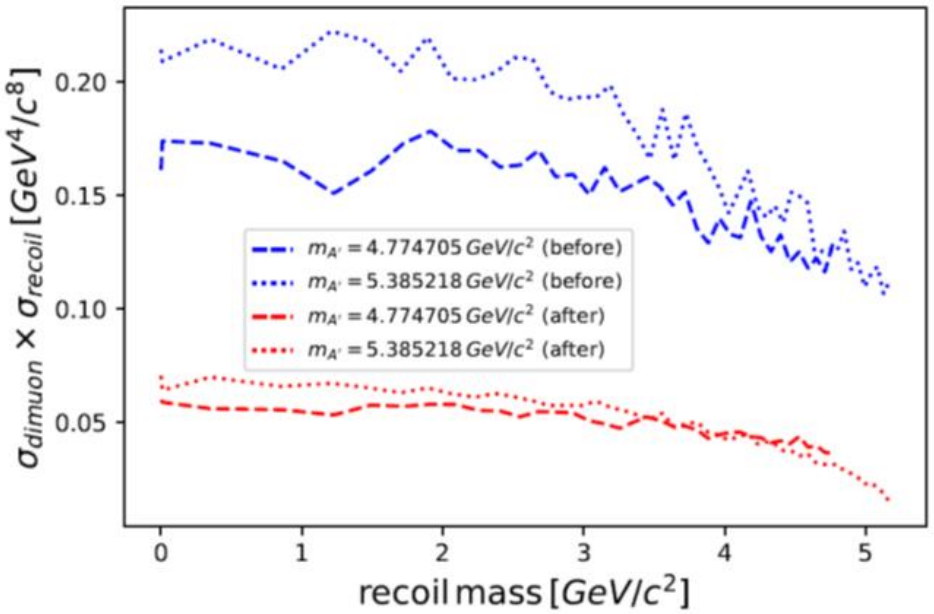




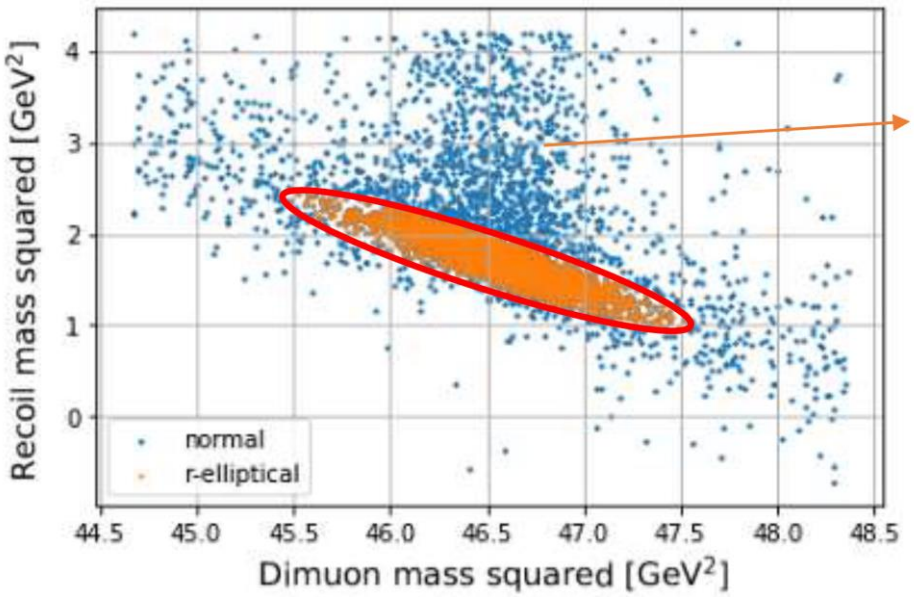
Dark Higgsstrahlung: A′h′

- 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





Background reduction 3-4



ISR

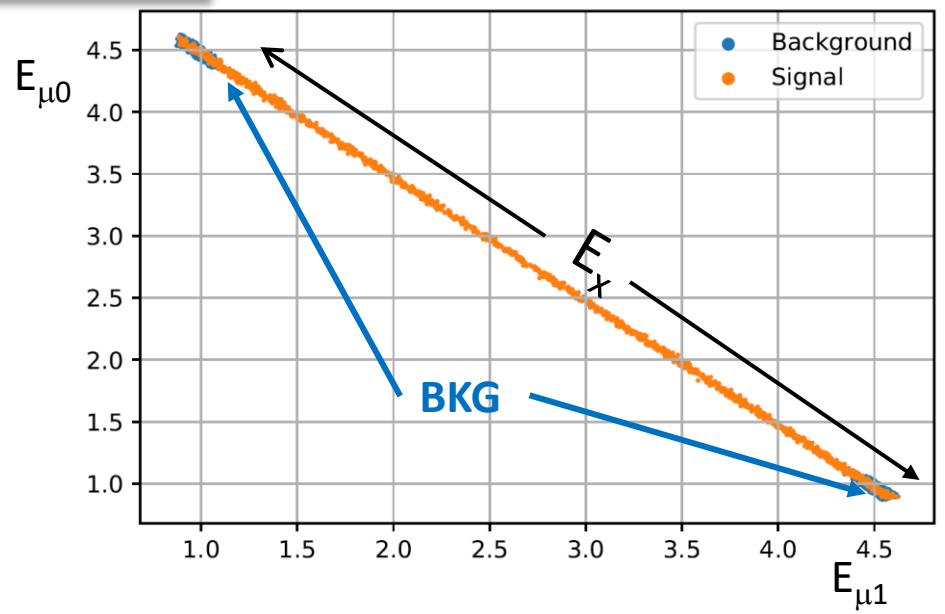
Dark Higgsstrahlung: A′h′

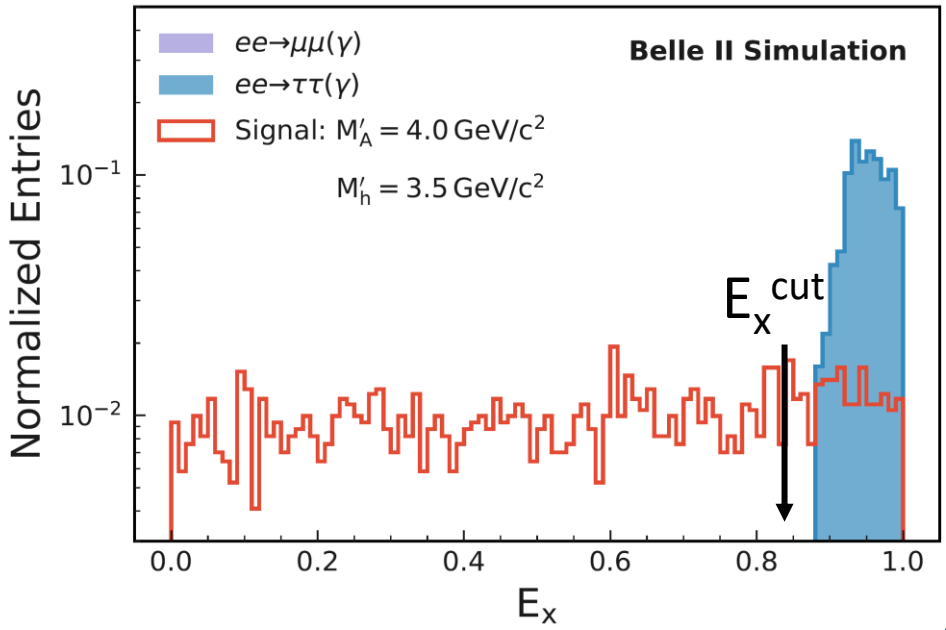
Final background suppression based on kinematic features.

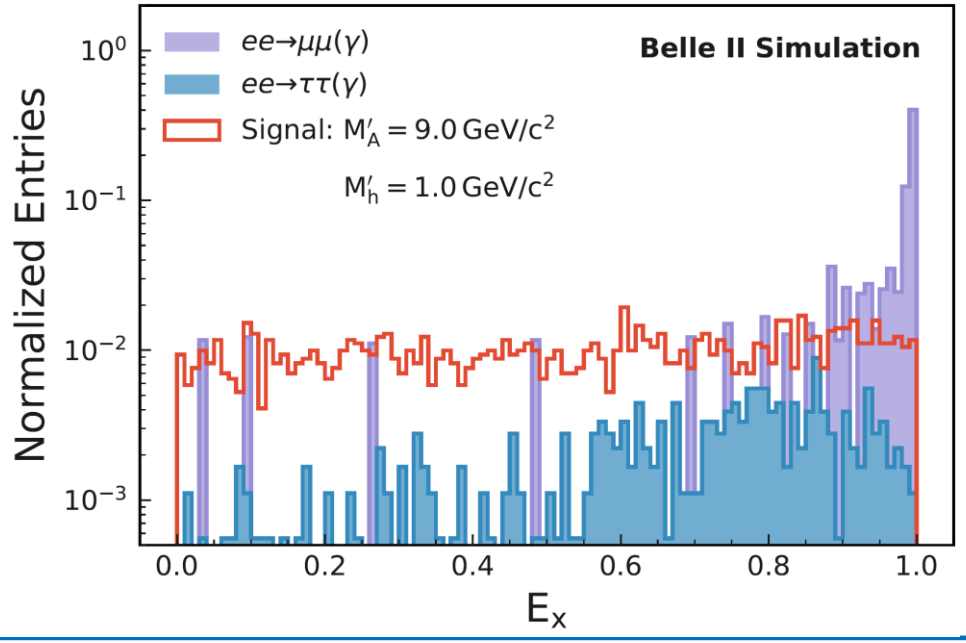
$E_{\mu 0} + E_{\mu 1}$ approximately constant within mass windows.

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

E_x^{cut} optimized across the plane





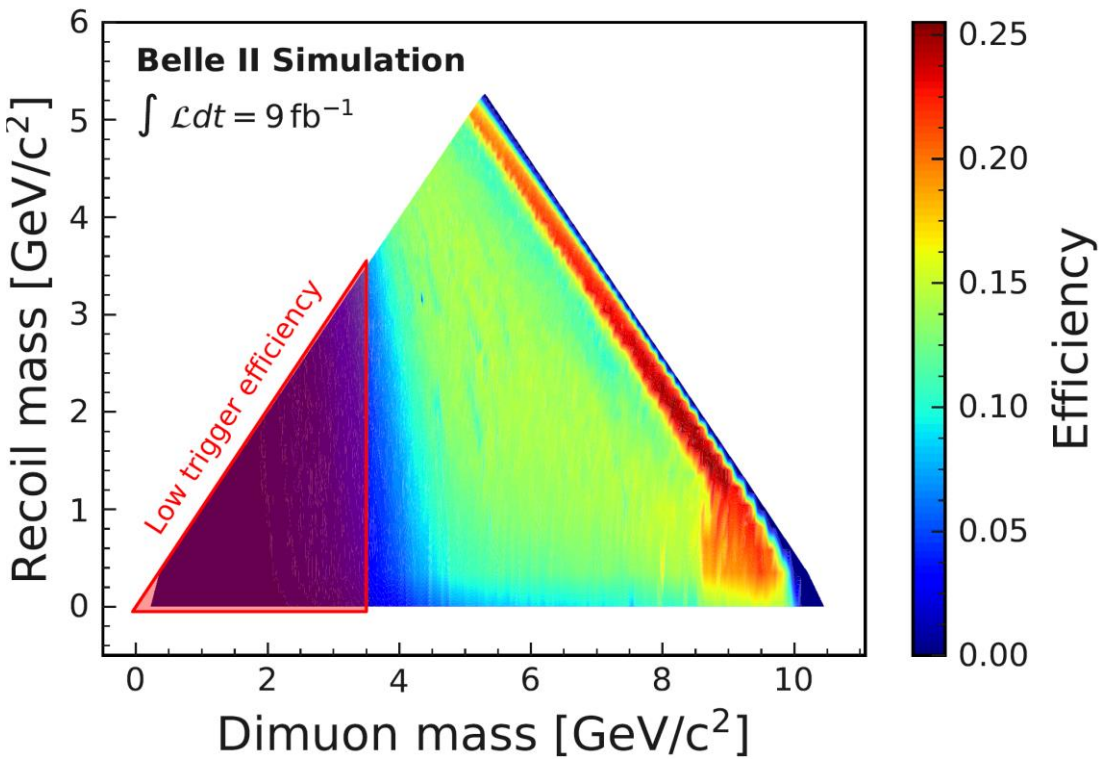


Rejection factor 10-1000

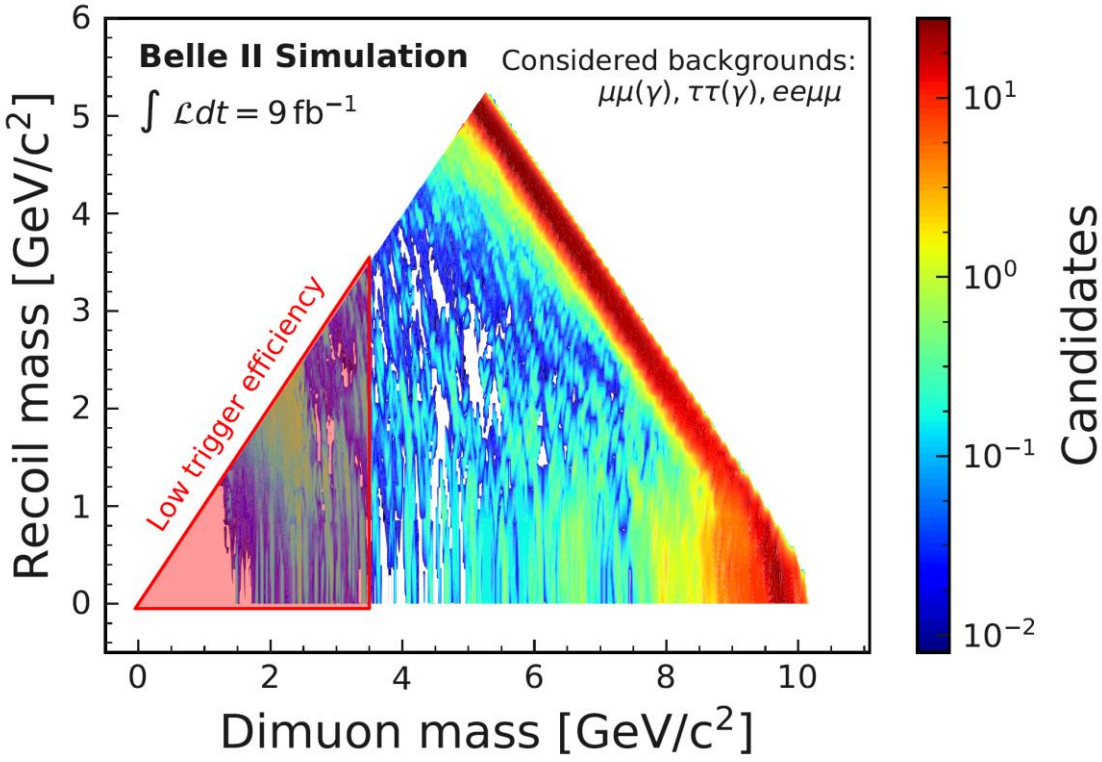
Dark Higgsstrahlung: A′h′

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

Signal Efficiency



Total Background



Invisible dark photon: sensitivity