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

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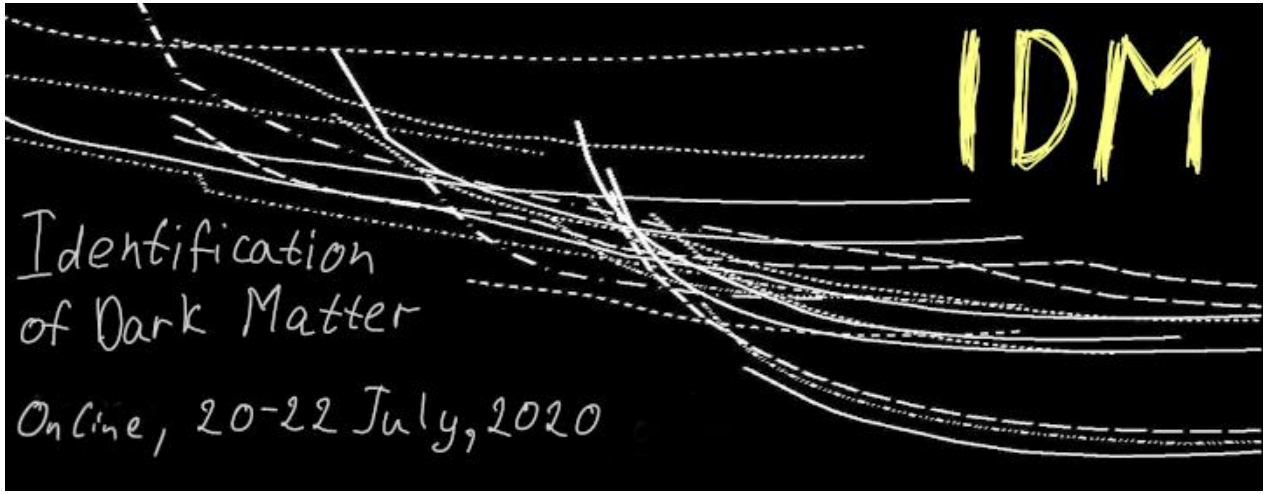
INFN – Roma 3

on behalf of the Belle II Collaboration

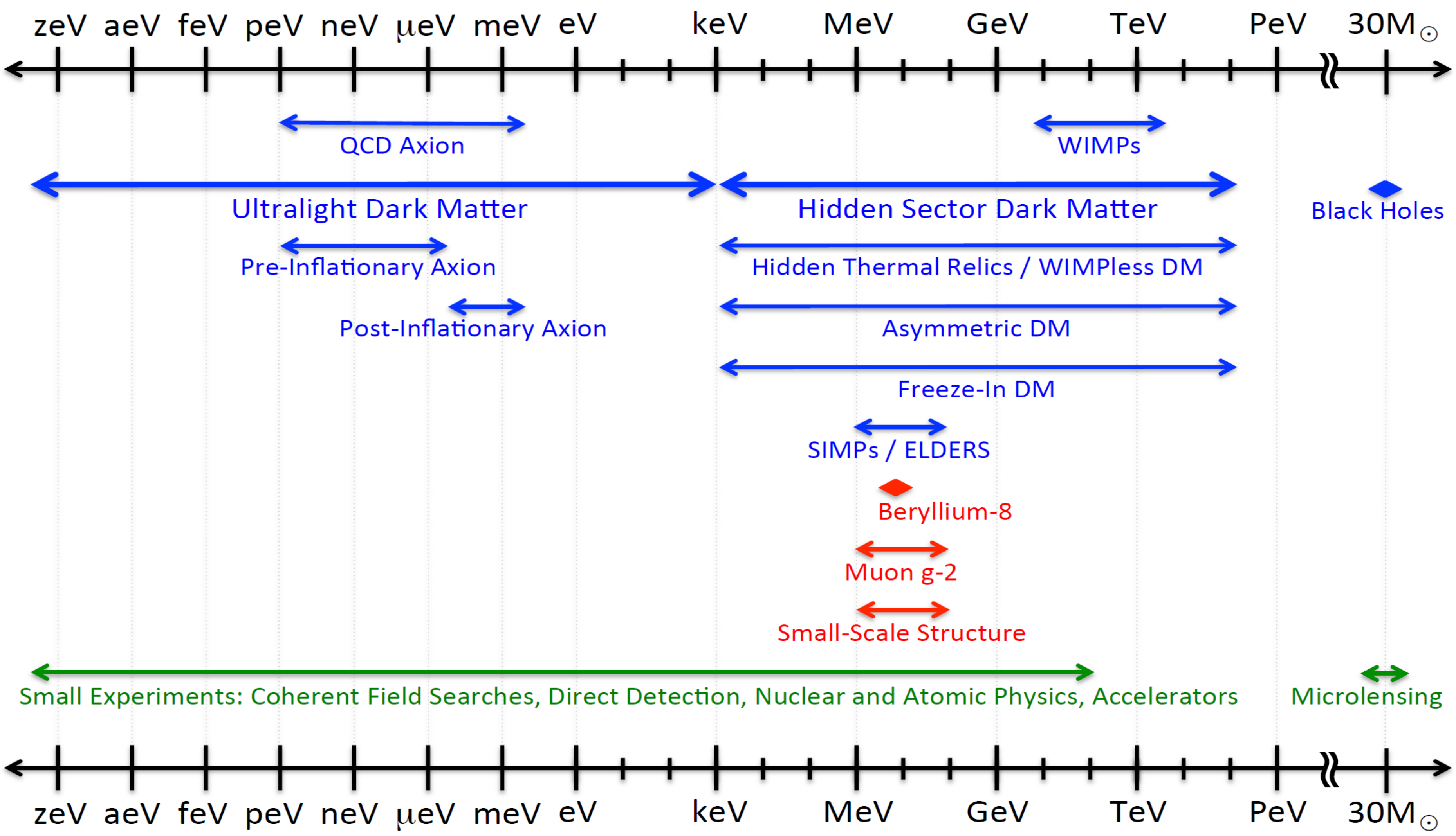


Dark matter search at the intensity frontier

- Introduction: light dark matter
- Highlights of KLOE, BESIII, 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 – Weimberg window

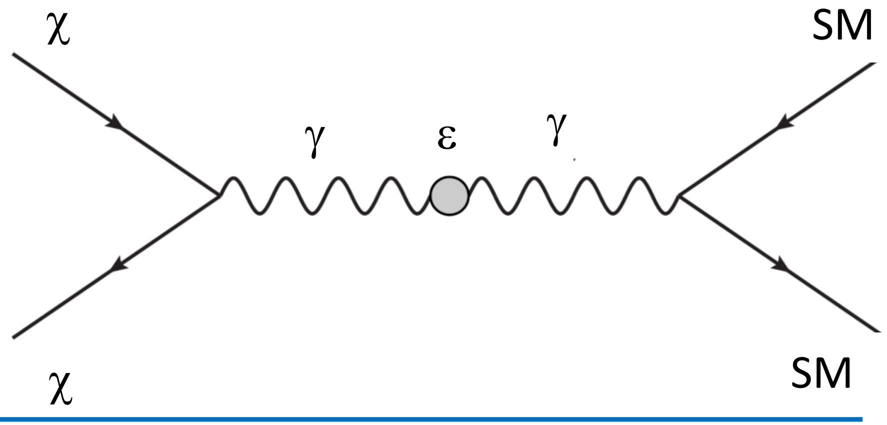
It modeled decades of direct search experiment designs

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

WIMP miracle

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

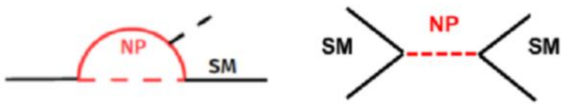
Possibility of Light New Physics, mostly with tiny couplings. Some models are minimal (but UV safe) and show diverse DM fenomenology



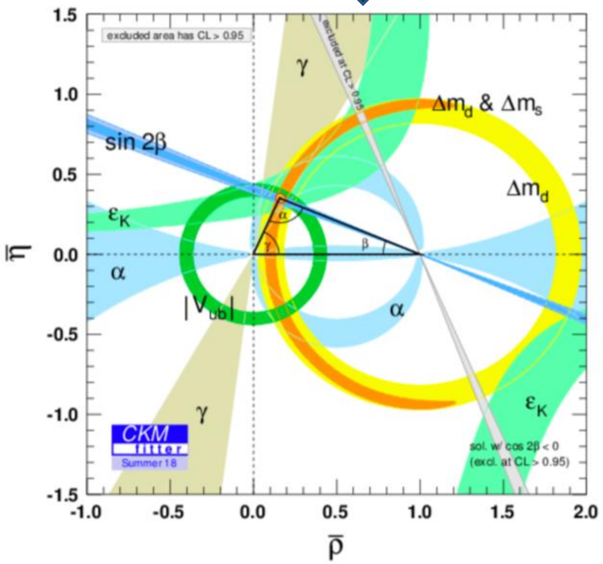
Dark matter hunt: «classical» approach

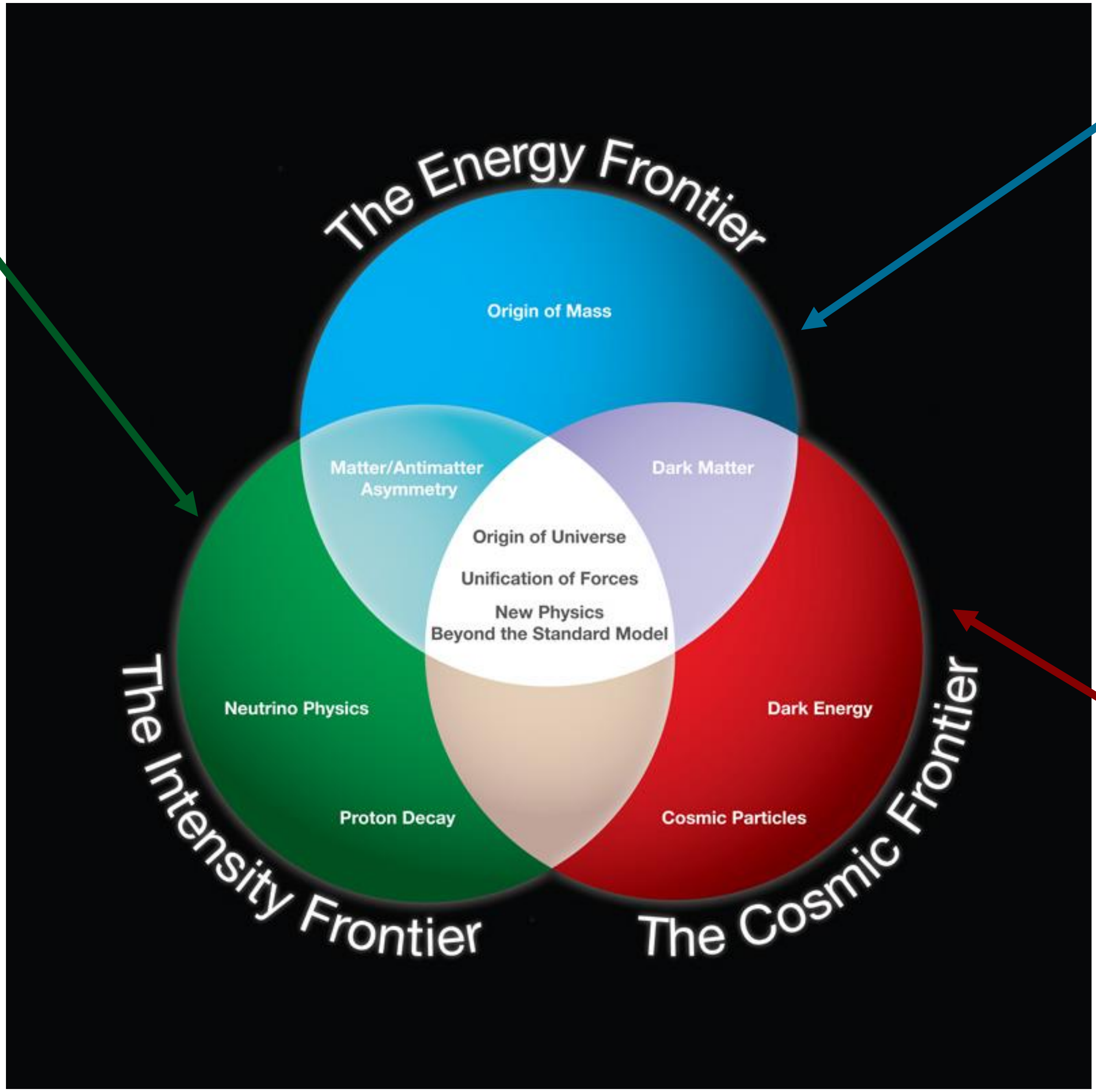
Intensity / precision frontier

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



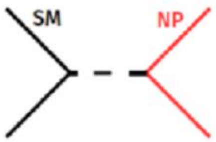
If NP found in direct searches, it is reasonable to expect NP effects in *B, D, tau* decays





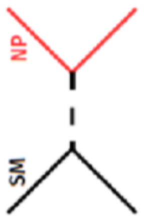
Energy frontier

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

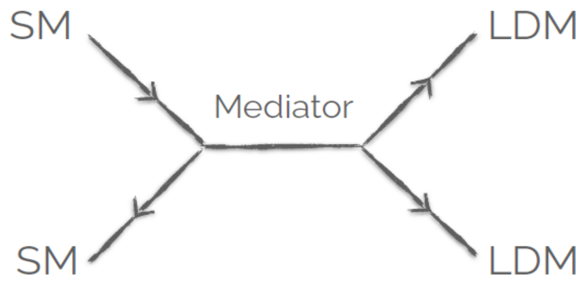


Cosmic frontier

Direct effect search in (mostly) underground experiments



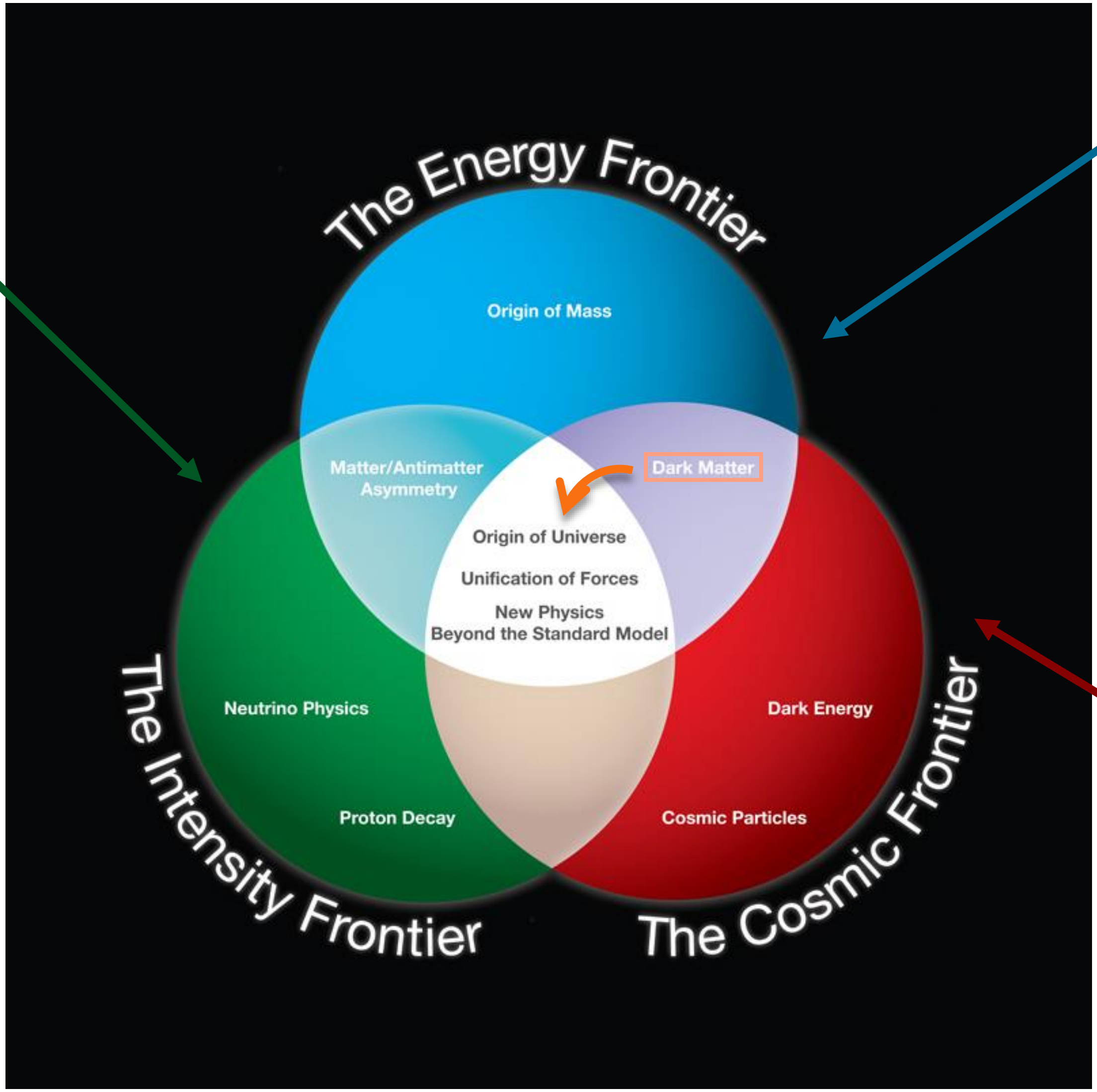
Dark matter hunt with a light sector



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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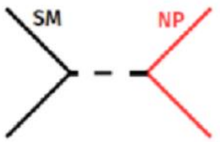

Cosmic frontier

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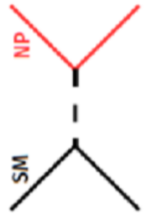
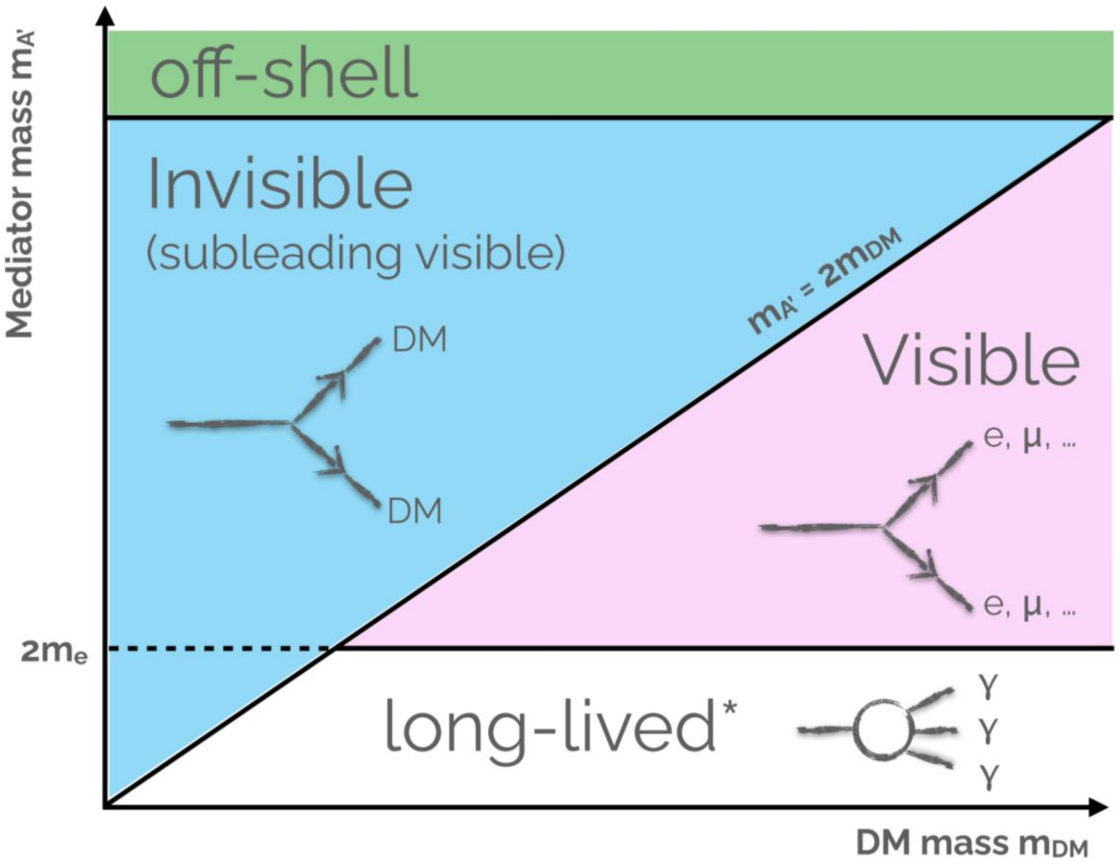


Light Dark matter hunt

Different signatures depending on the DM $\leftrightarrow$ mediator mass relation

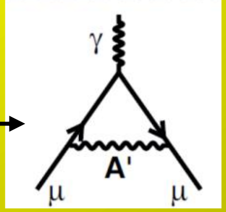


Probability of interaction of LDM detectors is negligible

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

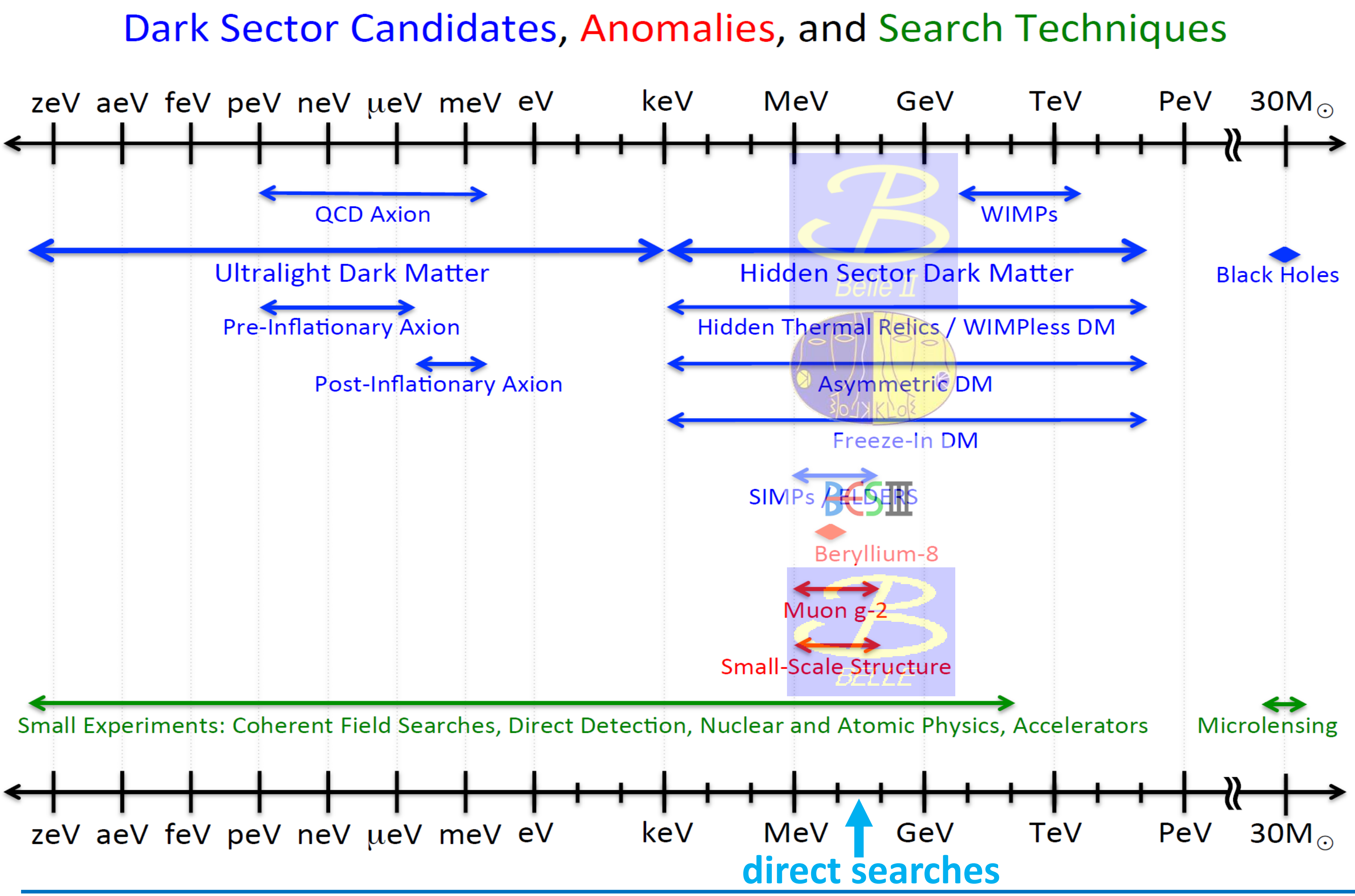
Additional benefits:

- 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 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, 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 ≈ 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

Belle ≈ 1 ab^{-1}

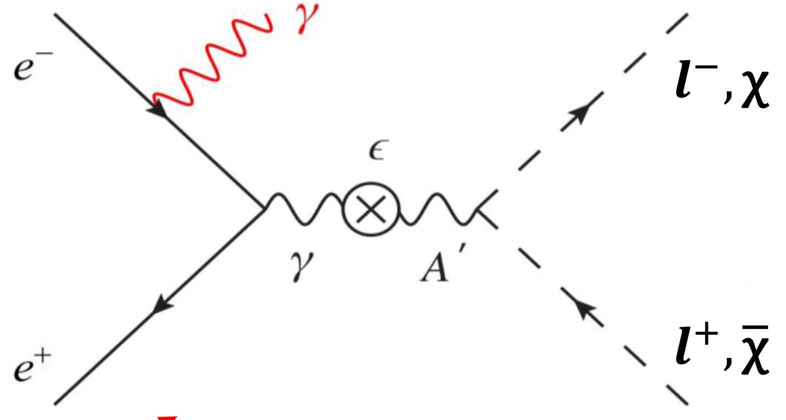
Belle II ≈ 74 fb^{-1} in progress

Dark photon: introduction

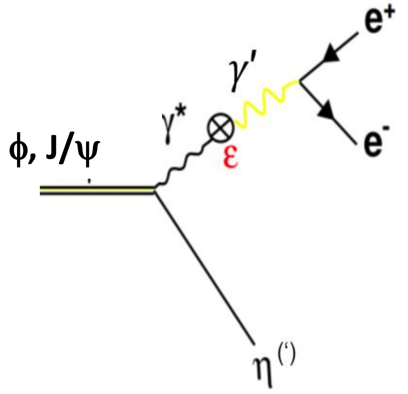
P. Fayet, Phys. Lett. B **95**, 285 (1980),
P.Fayet, Nucl. Phys. B **187**, 184 (1981)

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
- may acquire mass through Higgs or Stuckelberg mechanism

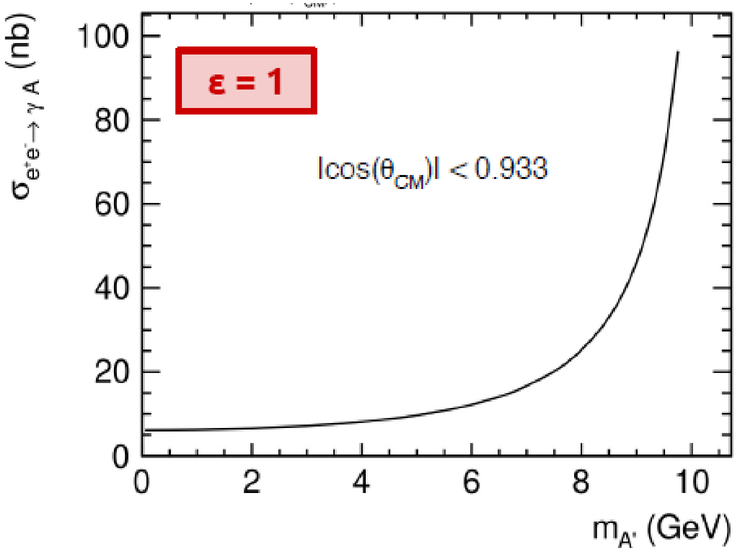


ISR



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*)

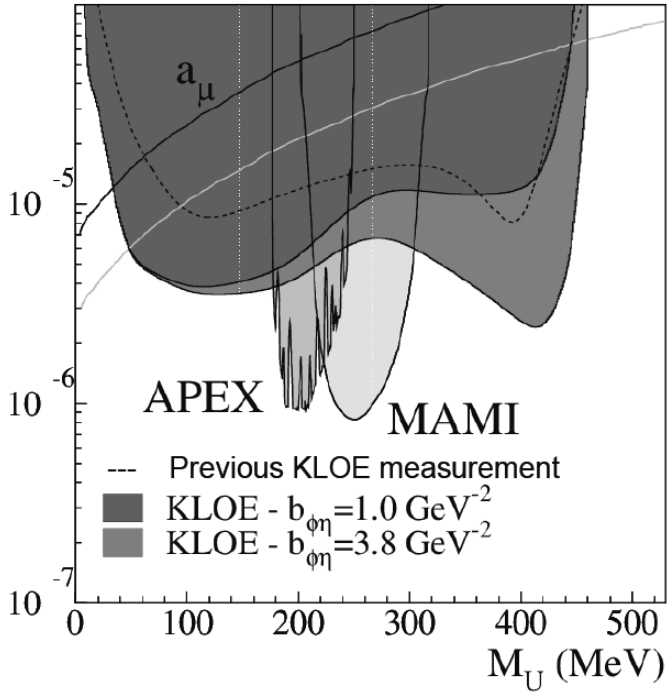
$m_{A'} > 2m_\chi \Rightarrow$ A' decays ≈100% invisibly to DM particles

Visible dark photon in rare meson decays

KLOE

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

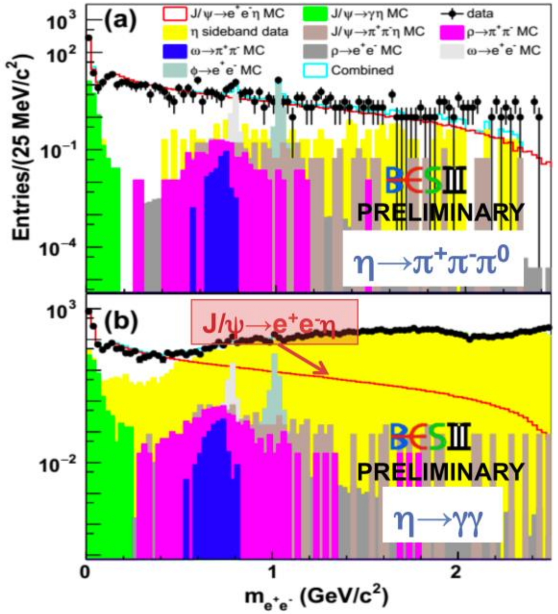
Phys.Lett. B720 (2013) 111

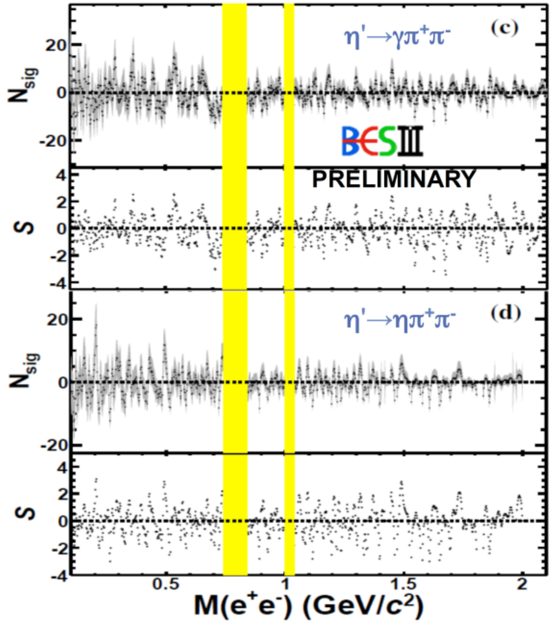


BESIII

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

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





Visible dark photon with ISR

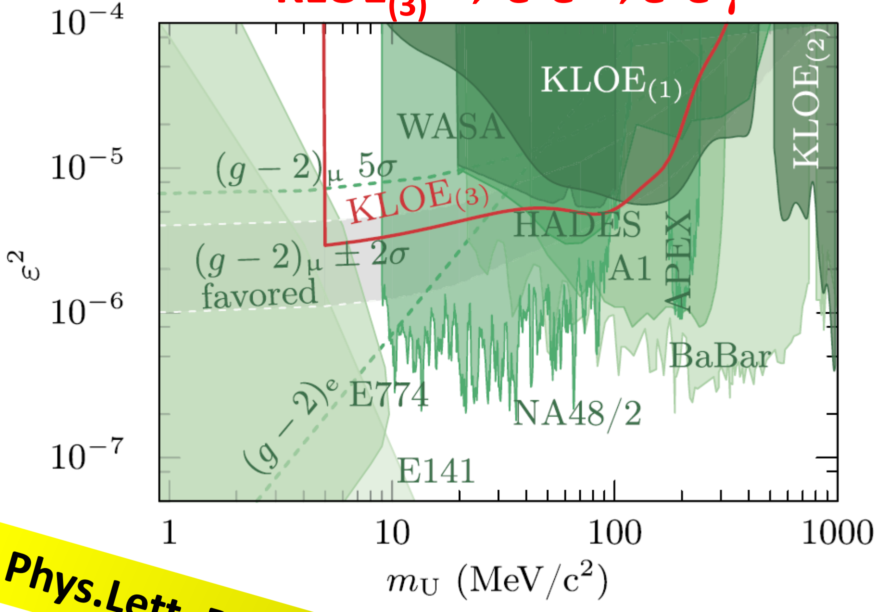
Phys.Lett. B757 (2016) 356

KLOE

L=1.93 fb^{-1}

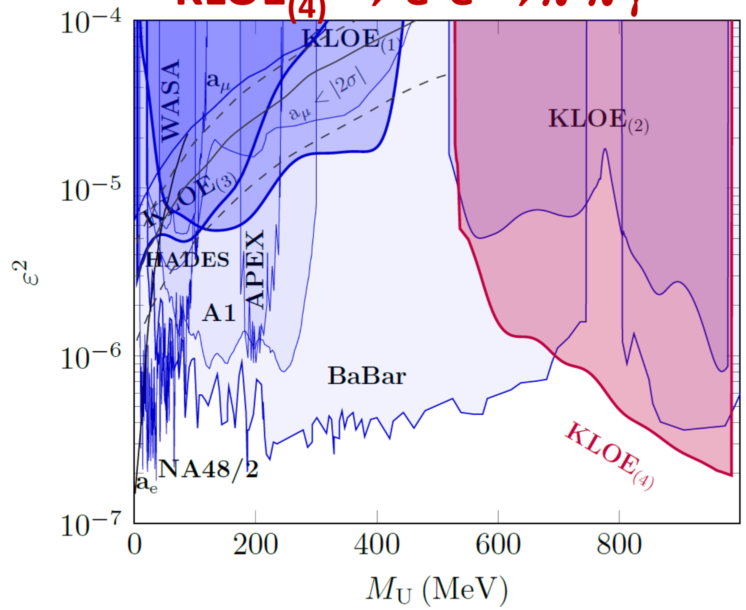
$e^+e^- \to e^+e^-\gamma$
$e^+e^- \to \mu^+\mu^-\gamma$
$e^+e^- \to \pi^+\pi^-\gamma$

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



Phys.Lett. B750 (2015) 633

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

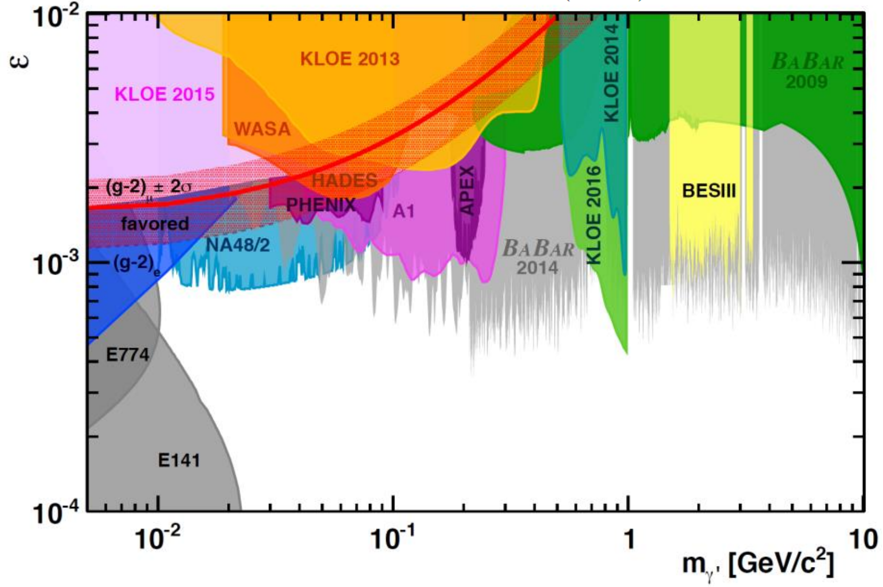


BESIII

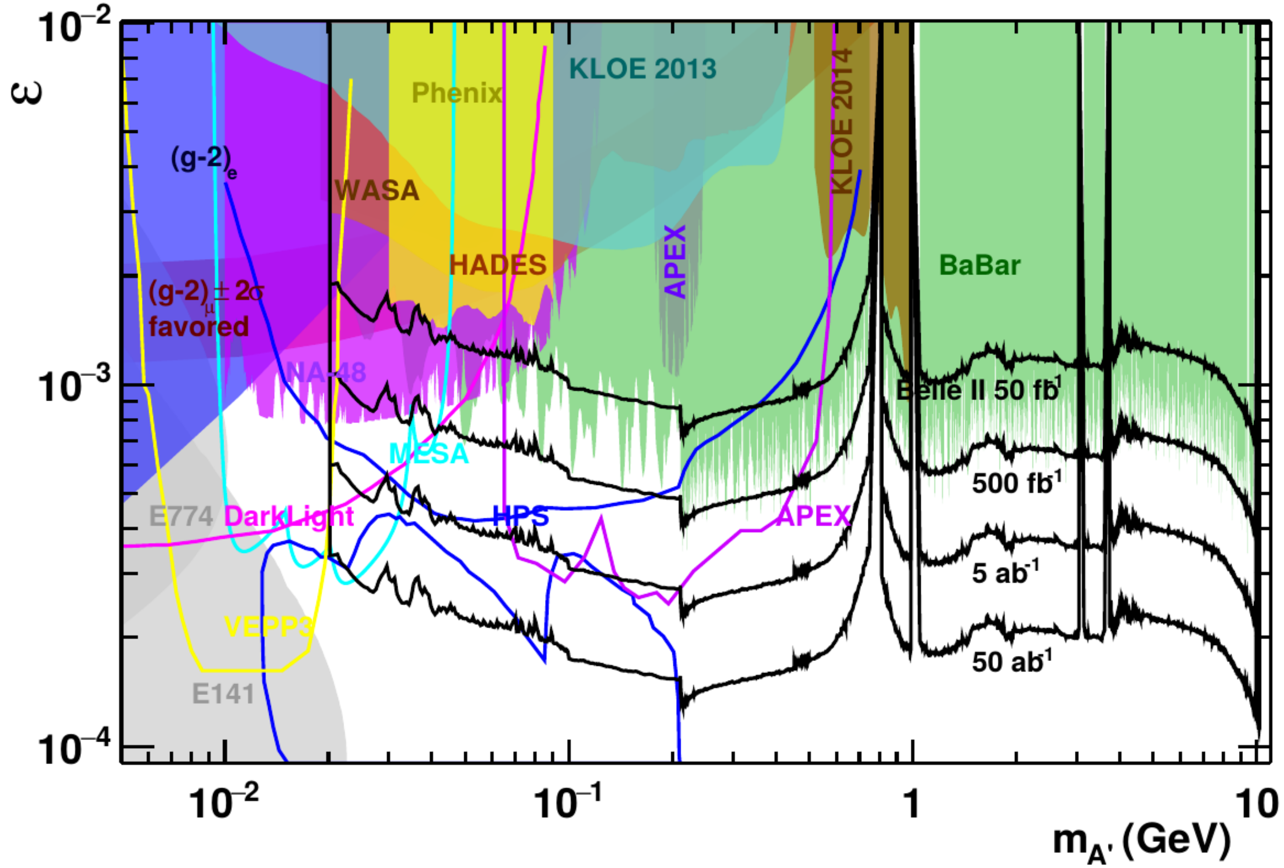
L=2.93 fb^{-1}

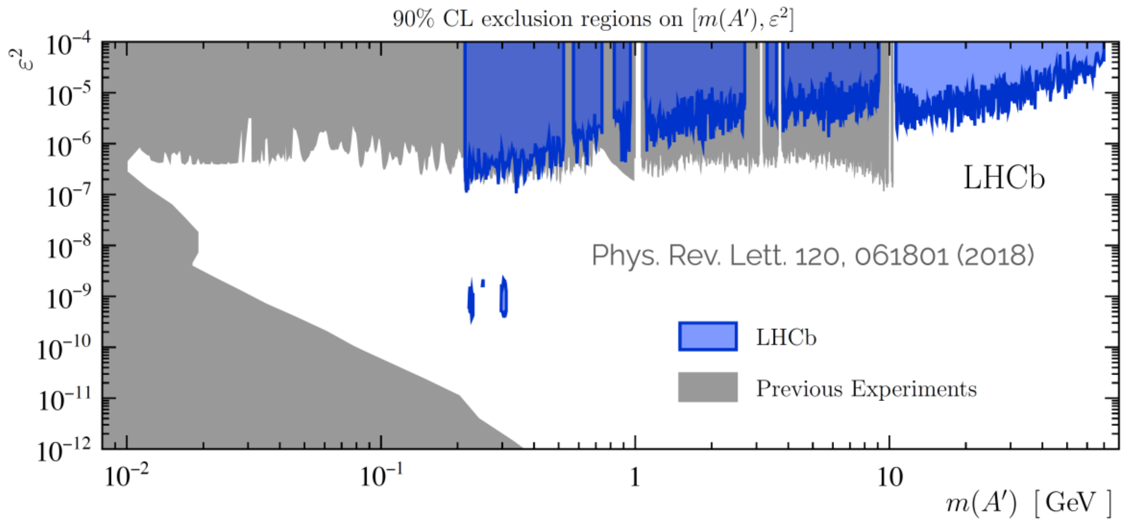
$e^+e^- \to e^+e^-\gamma$
$e^+e^- \to \mu^+\mu^-\gamma$

Phys.Lett. B774 (2017) 252



Visible dark photon: sensitivity





Competition with LHCB:

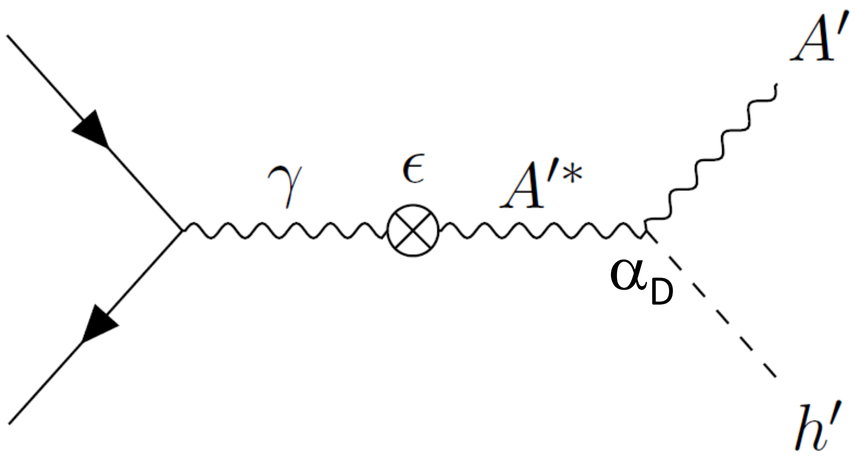
Drell-Yan processes
Displaced vertices
$D^* \rightarrow D A'$, $A' \rightarrow ee$

Belle had no suitable low mutiplicity triggers for this search

Hadronic and ττ final states much harder

Belle II needs some years of data for leading sensitivity: search currently on hold

Dark Higgsstrahlung: A′h′

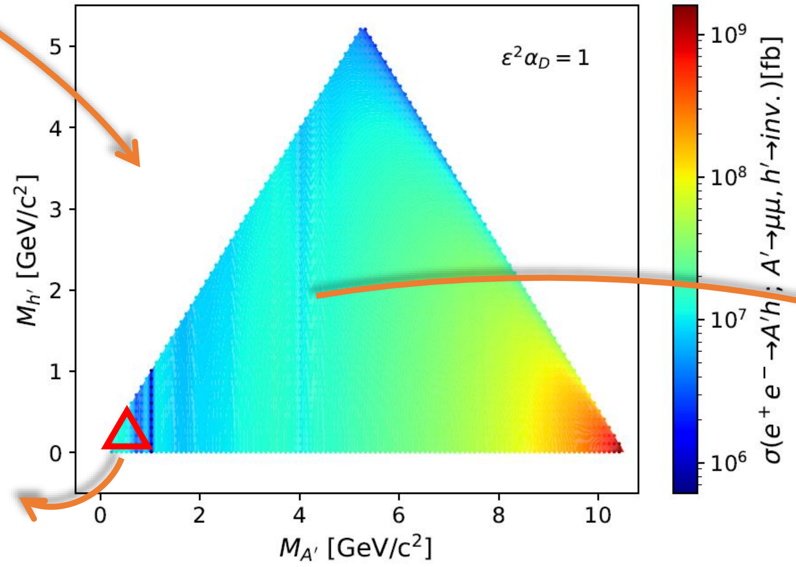


Batell, Pospelov, Ritz, Phys. Rev. D 79, 115008 (2009)

- 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* **BELLE, BABAR**
  - $M_{h'} < M_{A'} \Rightarrow$ h′ "invisible" ← **KLOE**

BELLE, BABAR

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



KLOE

BELLE II

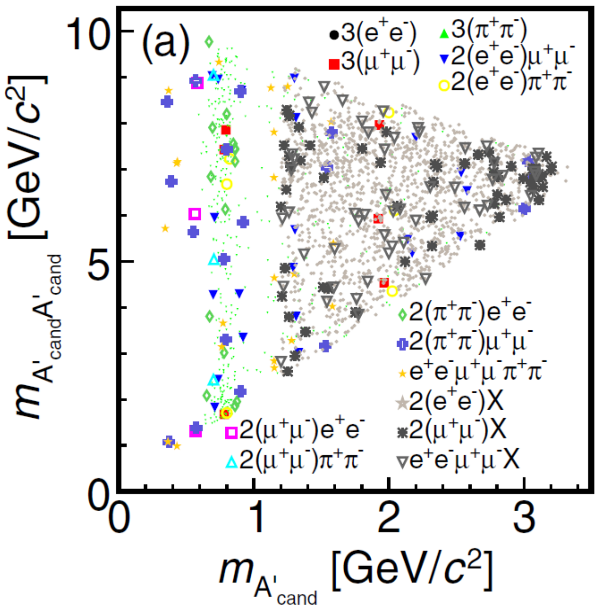
h′ → l^+l^- via loop process $\Rightarrow$ $\tau_{h'} \to \beta\gamma c\tau_{h'} \approx$ 100 m – 10 km

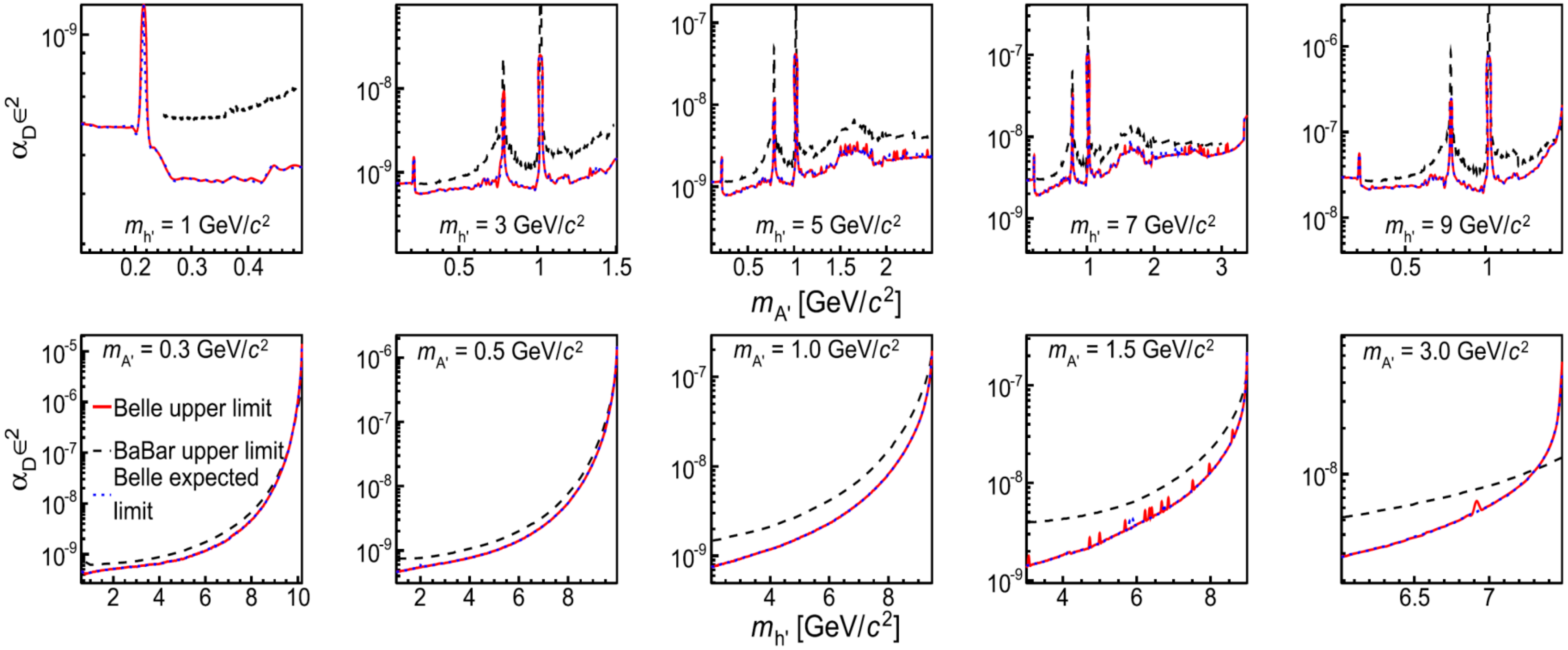
Dark Higgsstrahlung: A′h′, h′→ A′A′

Belle

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

PRL 114, 211801 (2015)



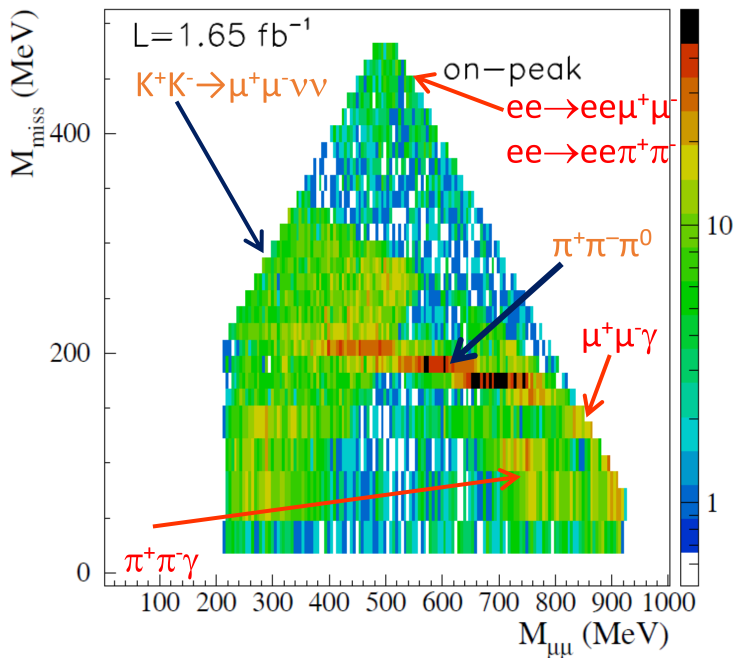


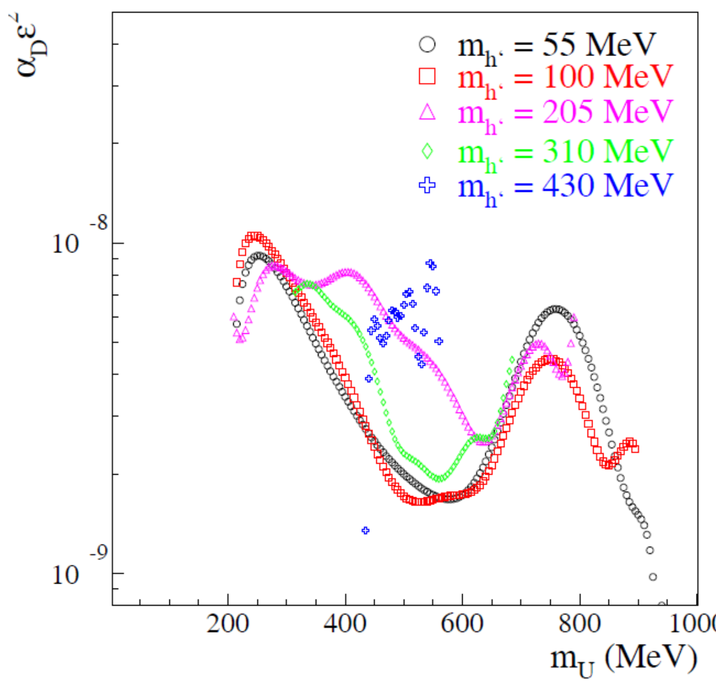
Dark Higgsstrahlung: A′h′, h′ invisible

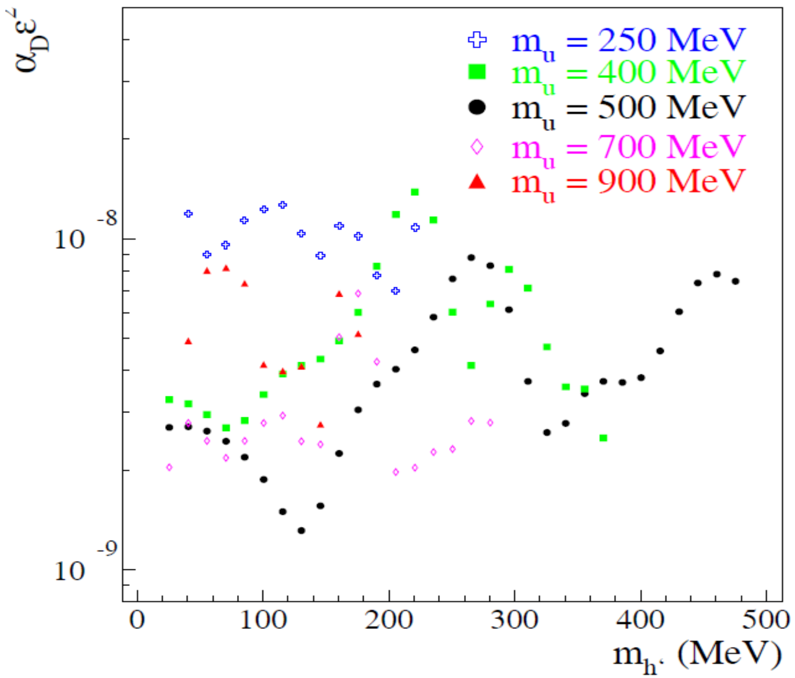
KLOE

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







CP-odd Higgs boson A^0

Υ(1S) tag

NMSSM

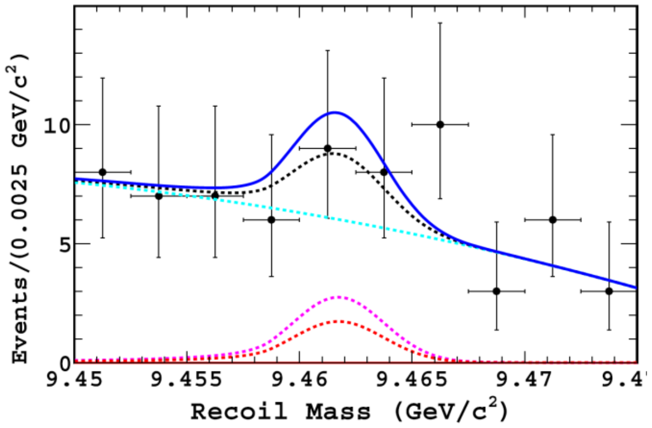
Belle

$\Upsilon(2S) \rightarrow \Upsilon(1S)\, \pi^+\pi^-$

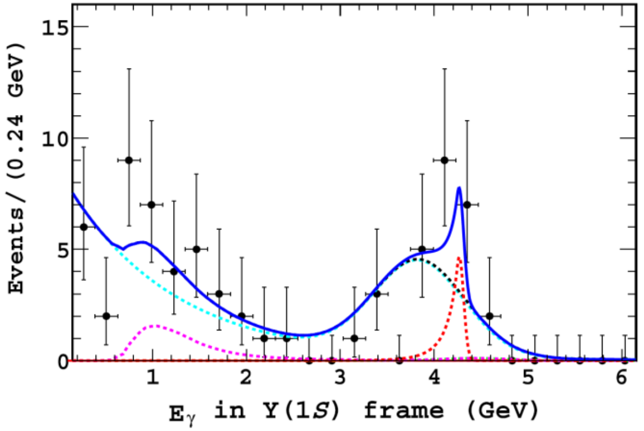
$\Upsilon(1S) \rightarrow \gamma A^0$

$A^0 \rightarrow \chi\chi$

PRL 122 011801 (2019)

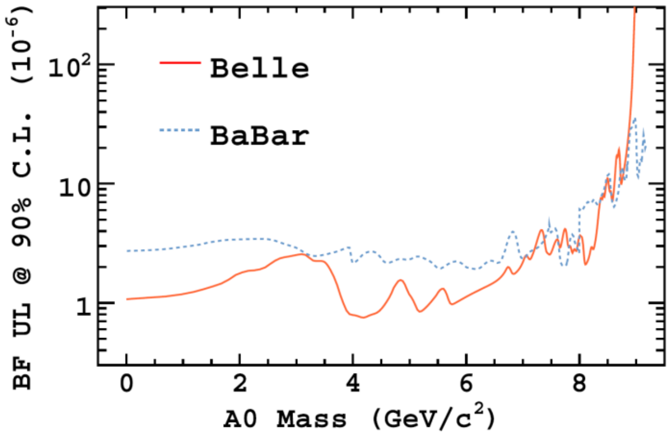


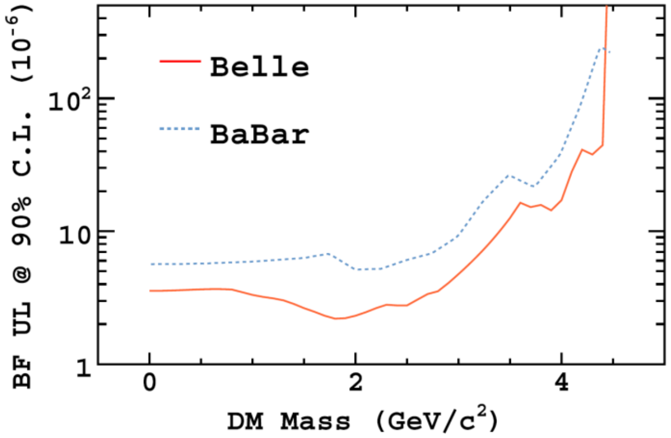
- - - - Continuum background
- - - - Υ(1S) background
- - - - Total background
- - - - A^0 signal
—— total



M_{A0} =2.946 GeV/c^2

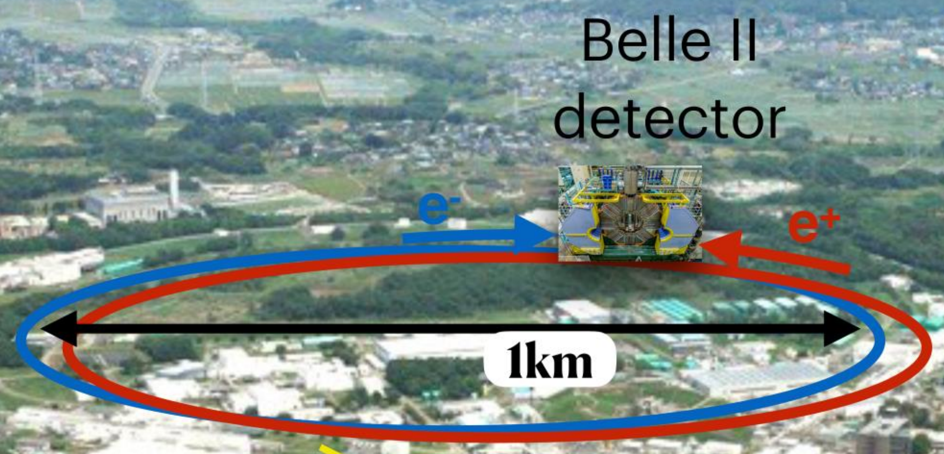
Significance 2.1 σ





Belle II @ Super-KEKB

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



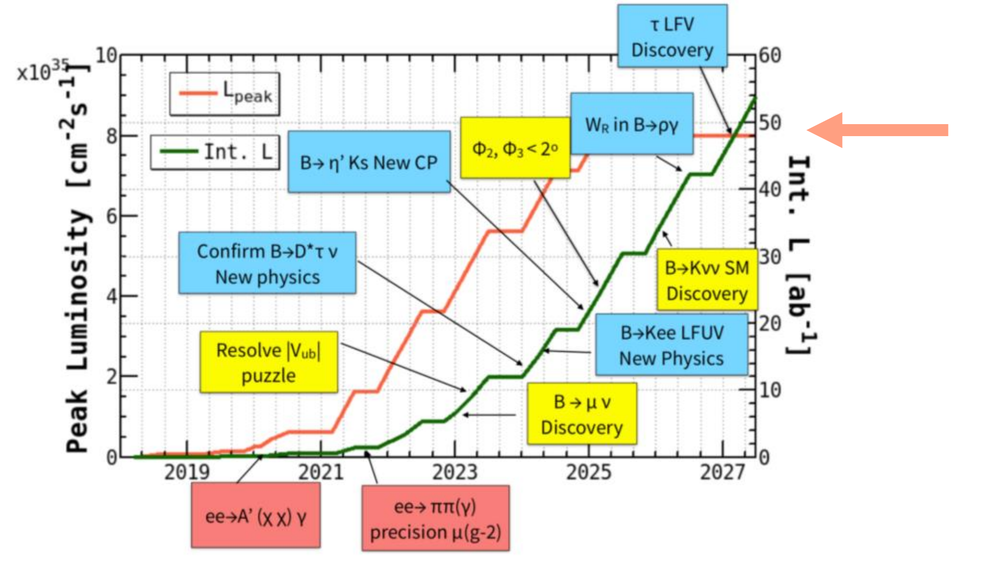
7 GeV e^-, 4 GeV e^+

E_{CM} Υ(4S) = 10.58 GeV + scans

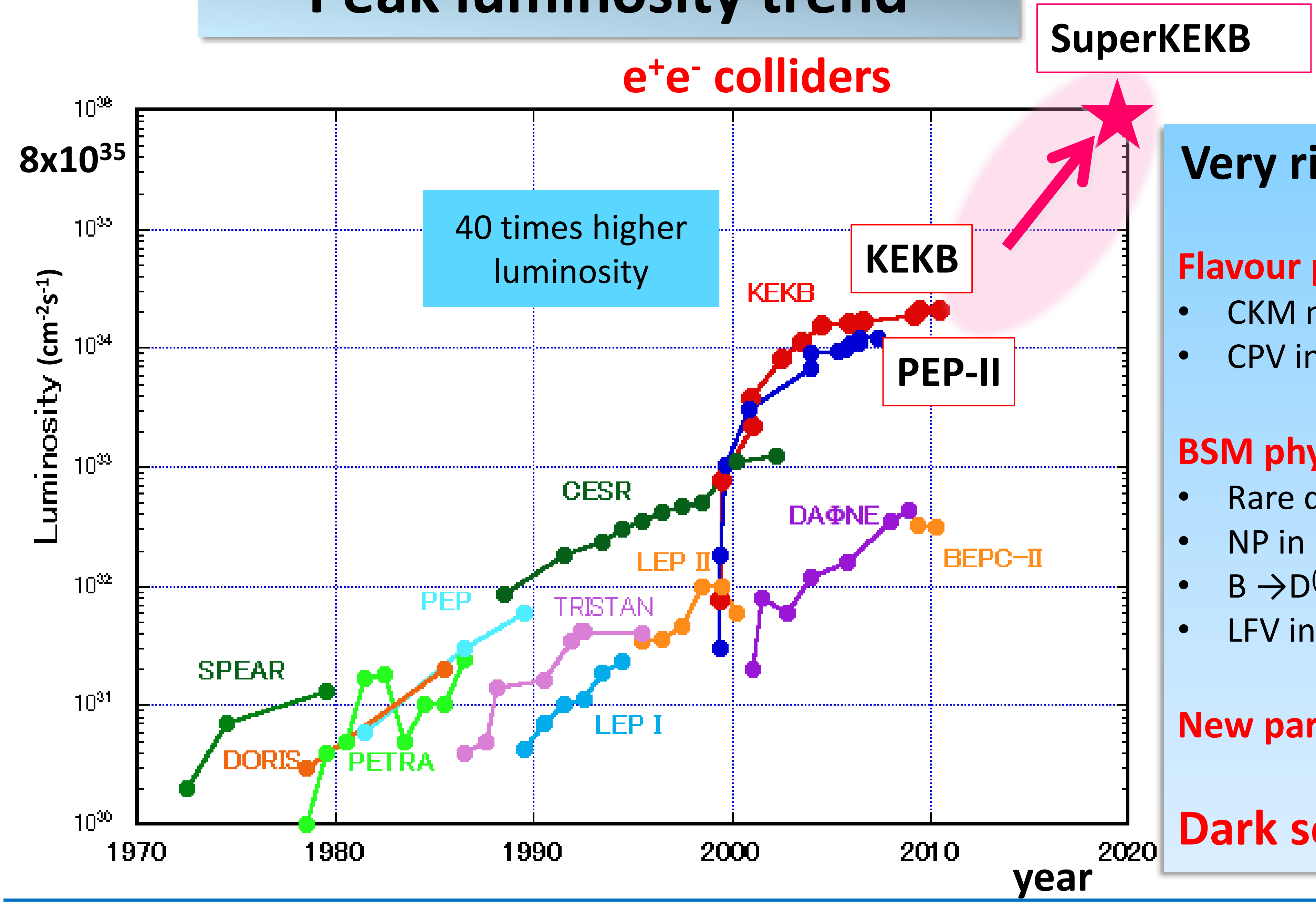
Υ(4S) → B anti-B

B + Charm + τ + Υ factory + ?

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



Peak luminosity trend



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

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

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

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

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)

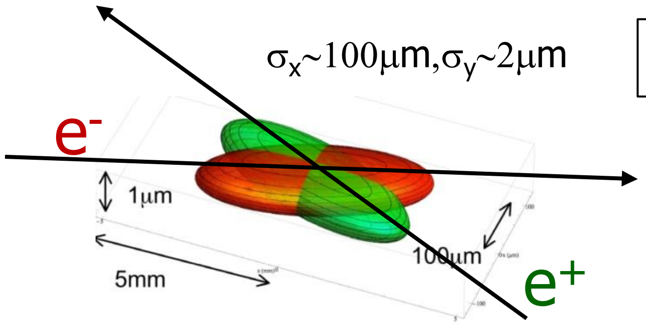
Vertical beta function@IP

x20 x2

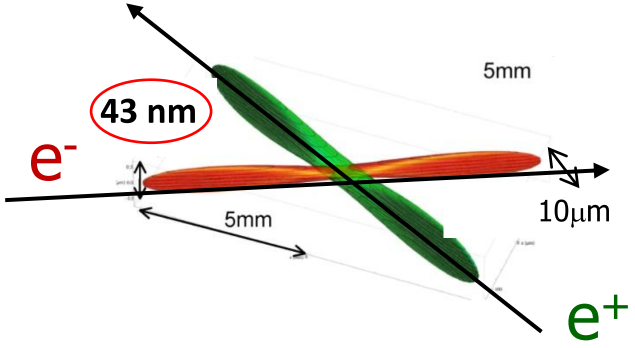
β^*_y=0.27/0.30 mm

$I_{+/-}$=3.6/2.6 A

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

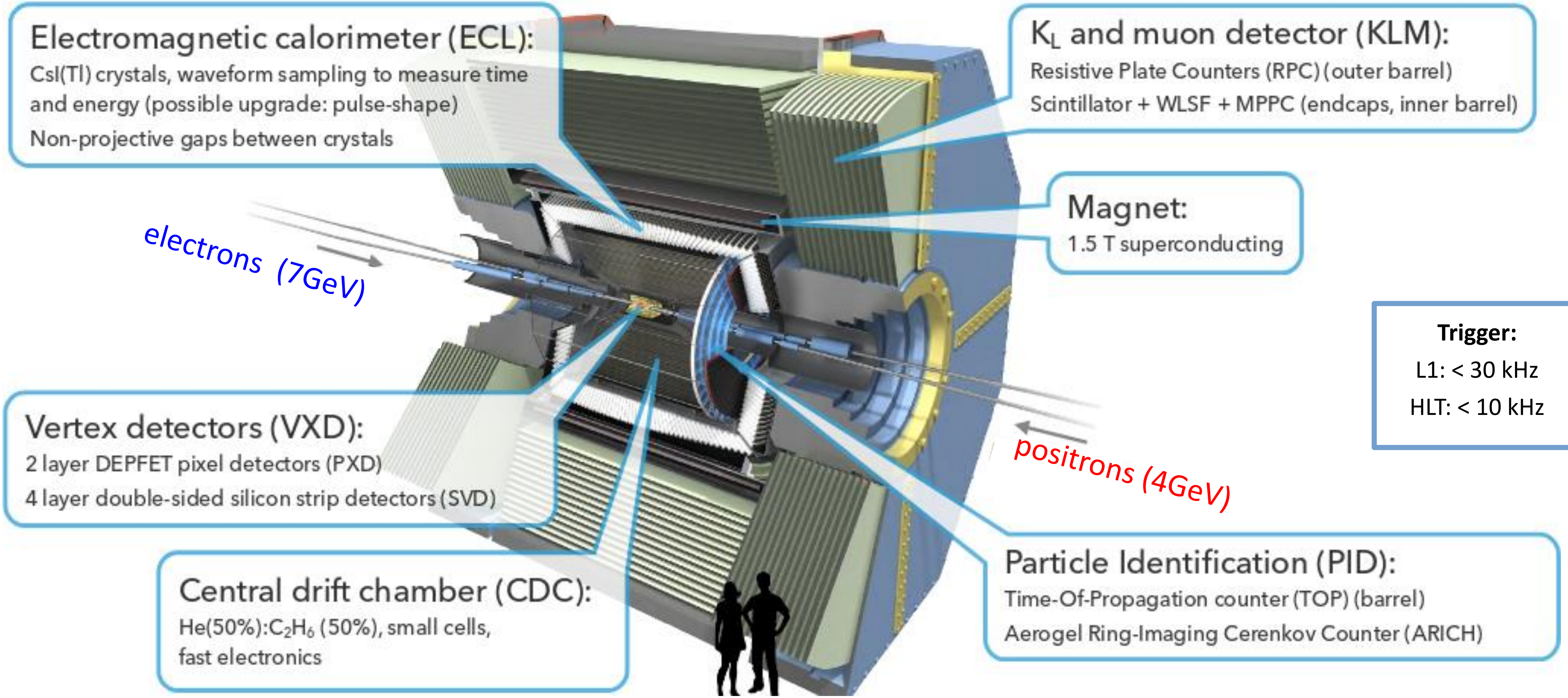


Nano-Beam scheme



... For a 40x increase in intensity you have to make the beam as thin as a few x100 atomic layers

Belle II detector



Trigger:

L1: < 30 kHz

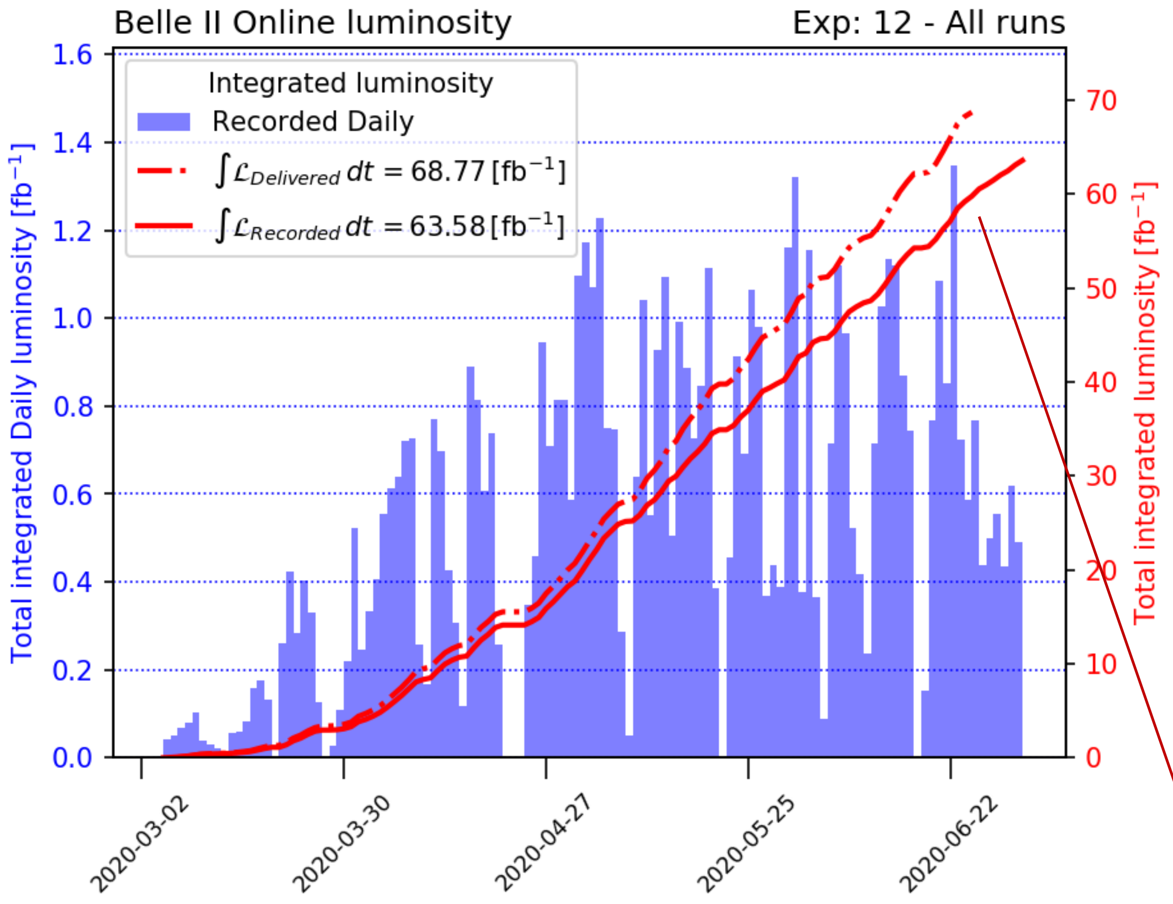
HLT: < 10 kHz

Belle II vs Belle

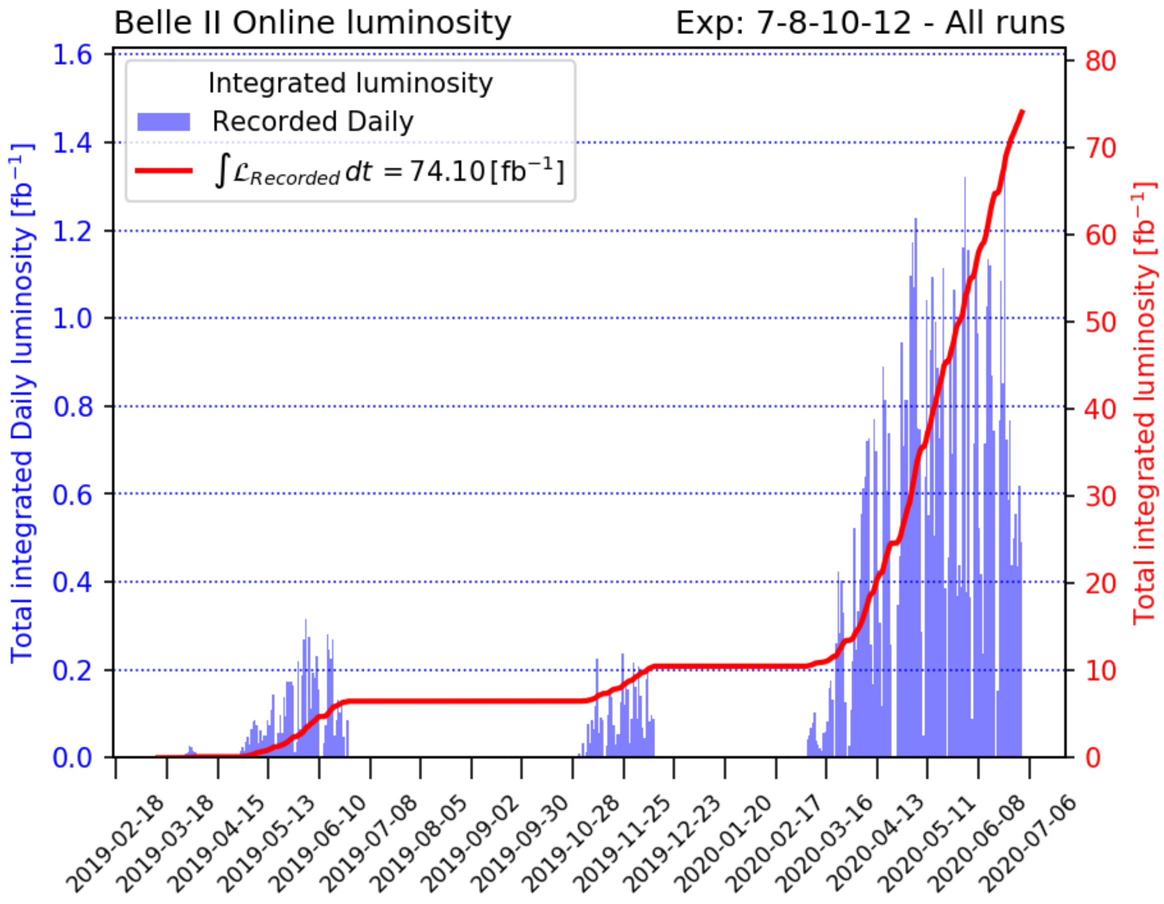
better resolution, PID and capability to cope with higher background

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

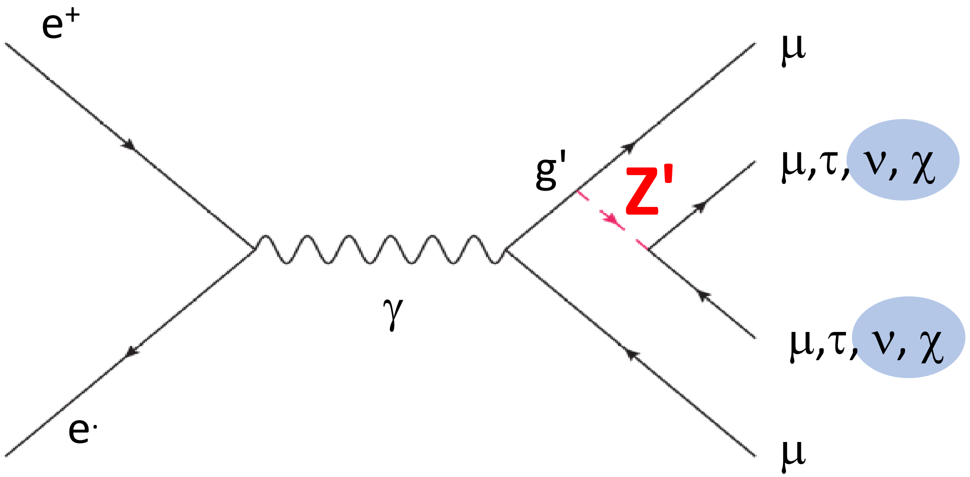
Fall run to start in ~September/October

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

Z': L_μ - L_τ model

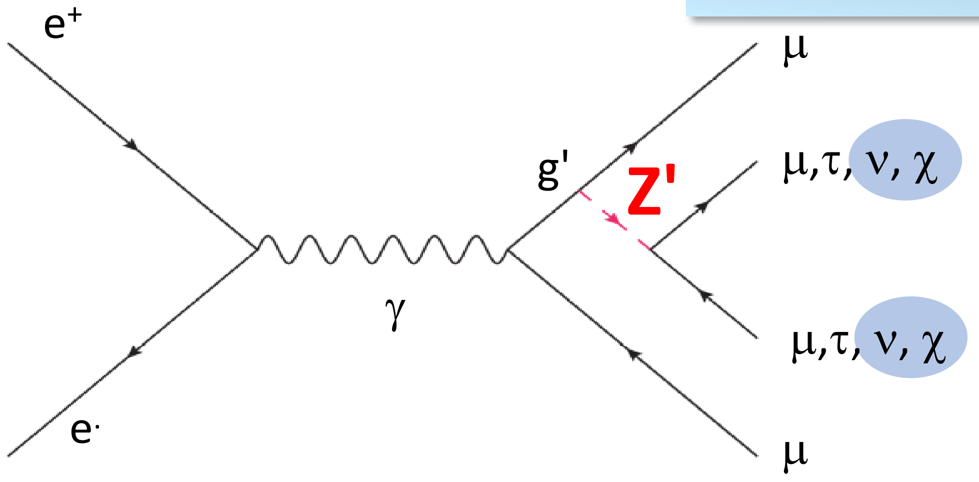
- Gauging L_μ - L_τ , the difference of leptonic μ and τ number
- A new gauge boson which couples only to the 2° and 3° lepton family
- Anomaly free (by construction)
- It may solve
  - **dark matter puzzle** → Sterile ν's / Light Dirac fermions
  - **$(g\text{-}2)_\mu$**
  - **$B \to K^{(*)}\mu\mu$,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

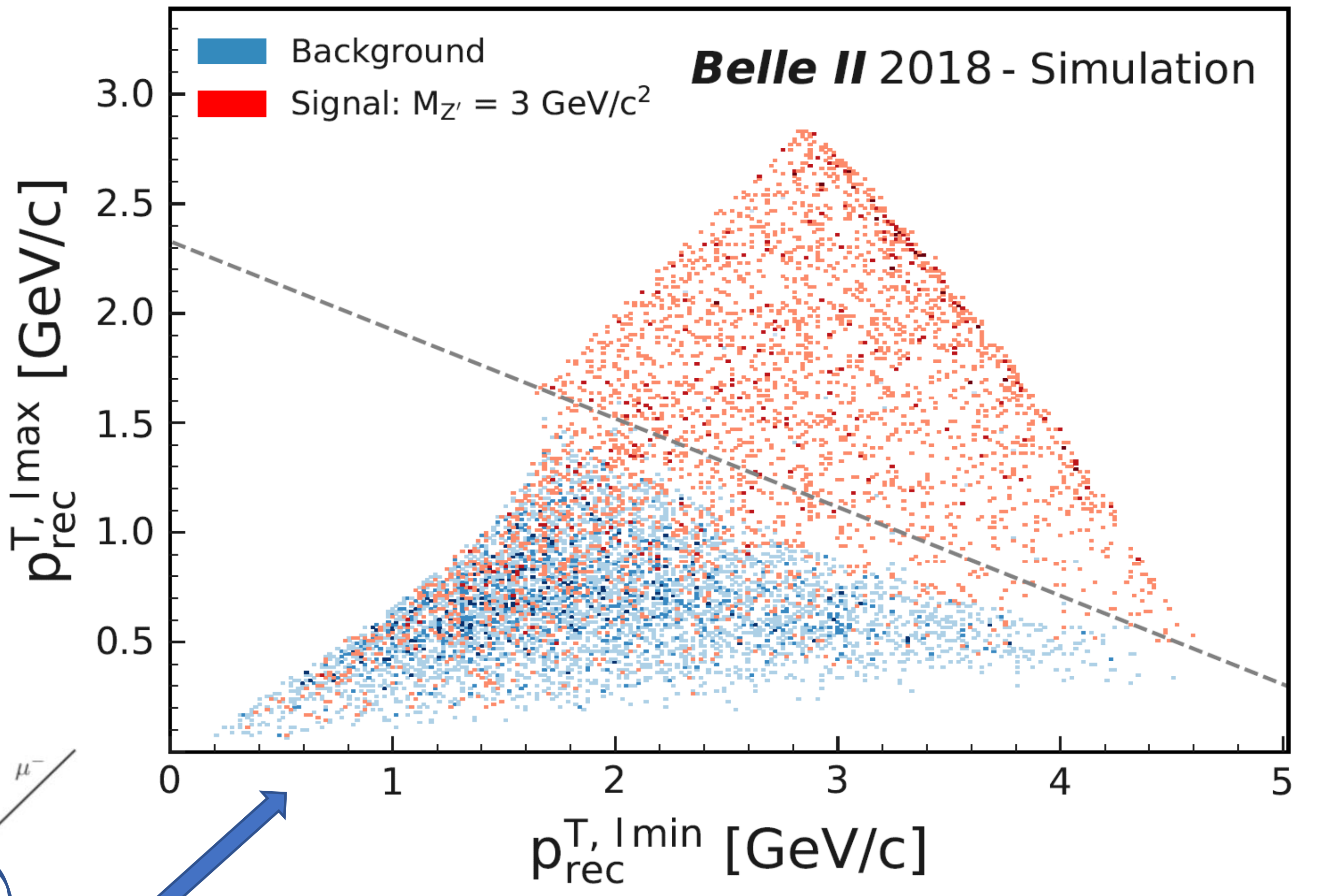
Shuve et al. (2014), arXiv 1408.2727
Altmannshofer et al. (2016) arXiv 1609.04026



Non-minimal dark photon

Z’ to invisible: L_μ - L_τ model





Explored for the first time

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

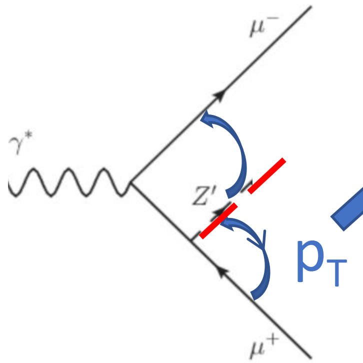
Look for bumps in recoil mass against a $\mu^+\mu^-$ pair

Main backgrounds:

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

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

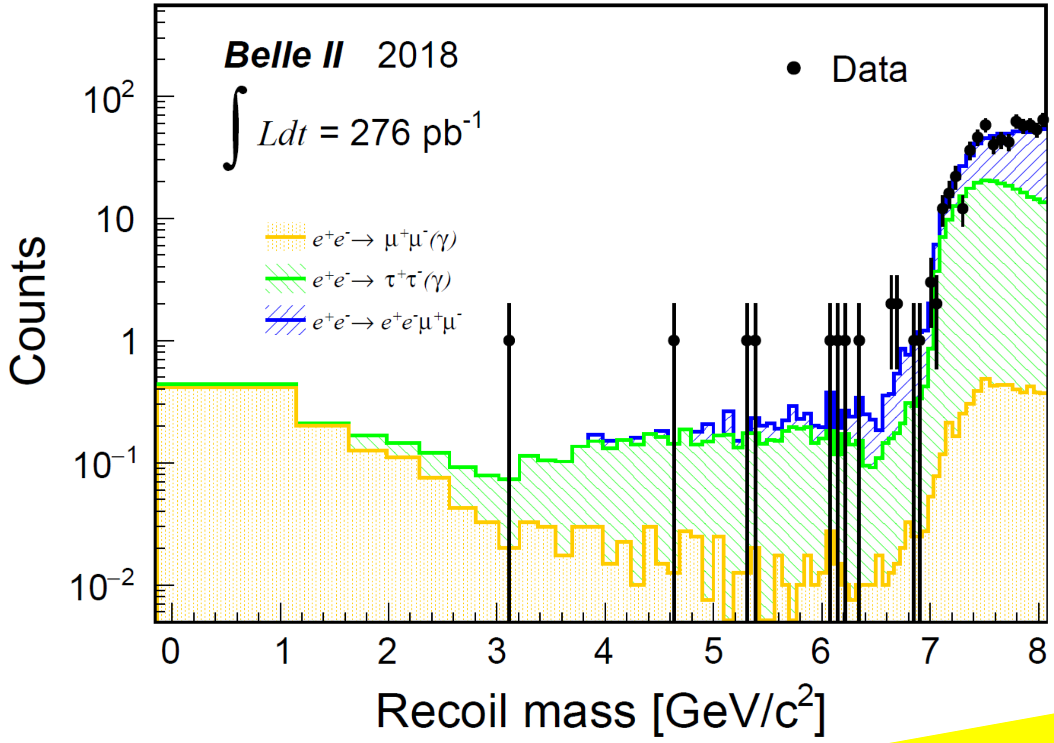
$e^+e^- \rightarrow e^+e^- \mu^+\mu^-$



FSR vs ISR + τ decay

Z' to invisible: results

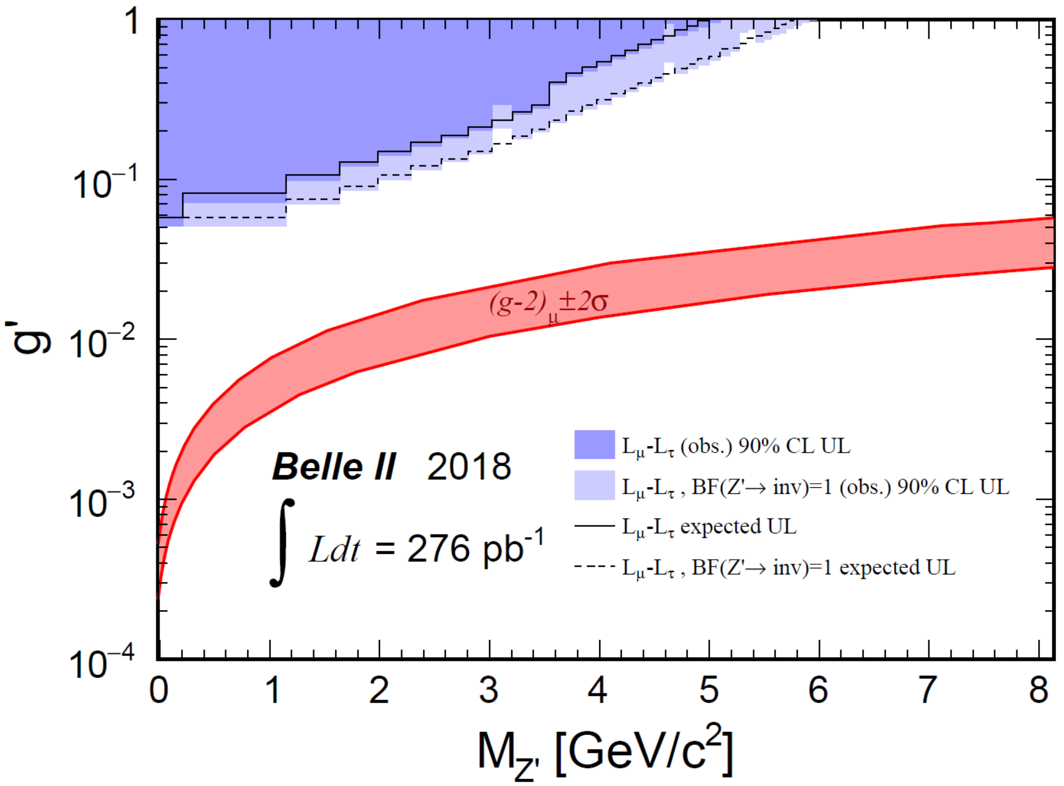
Phase 2 results



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

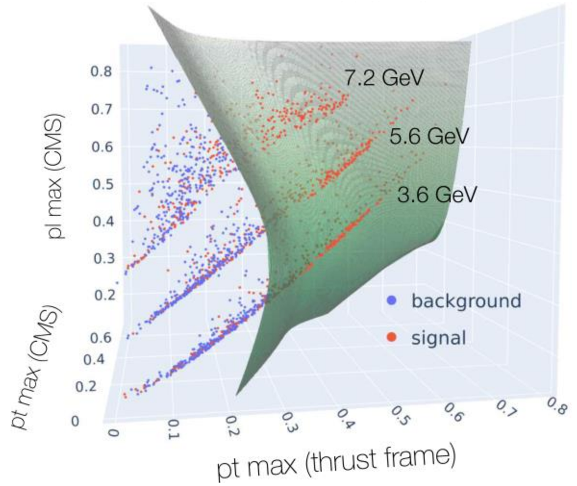


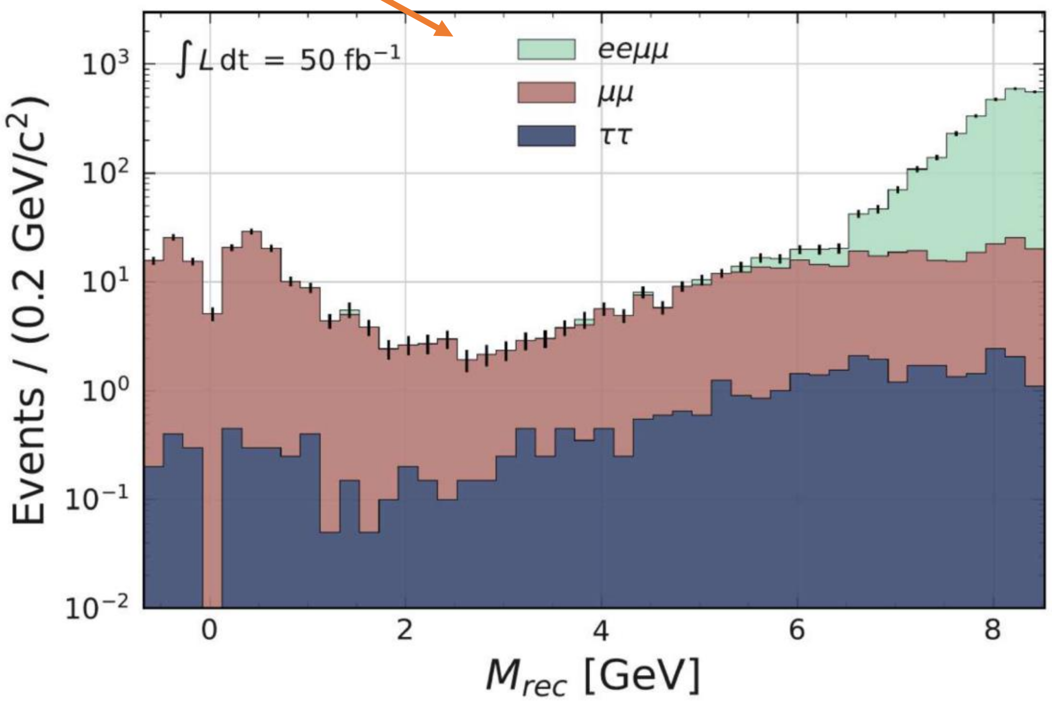
First physics paper by Belle II
PRL 124 (2020), 141801

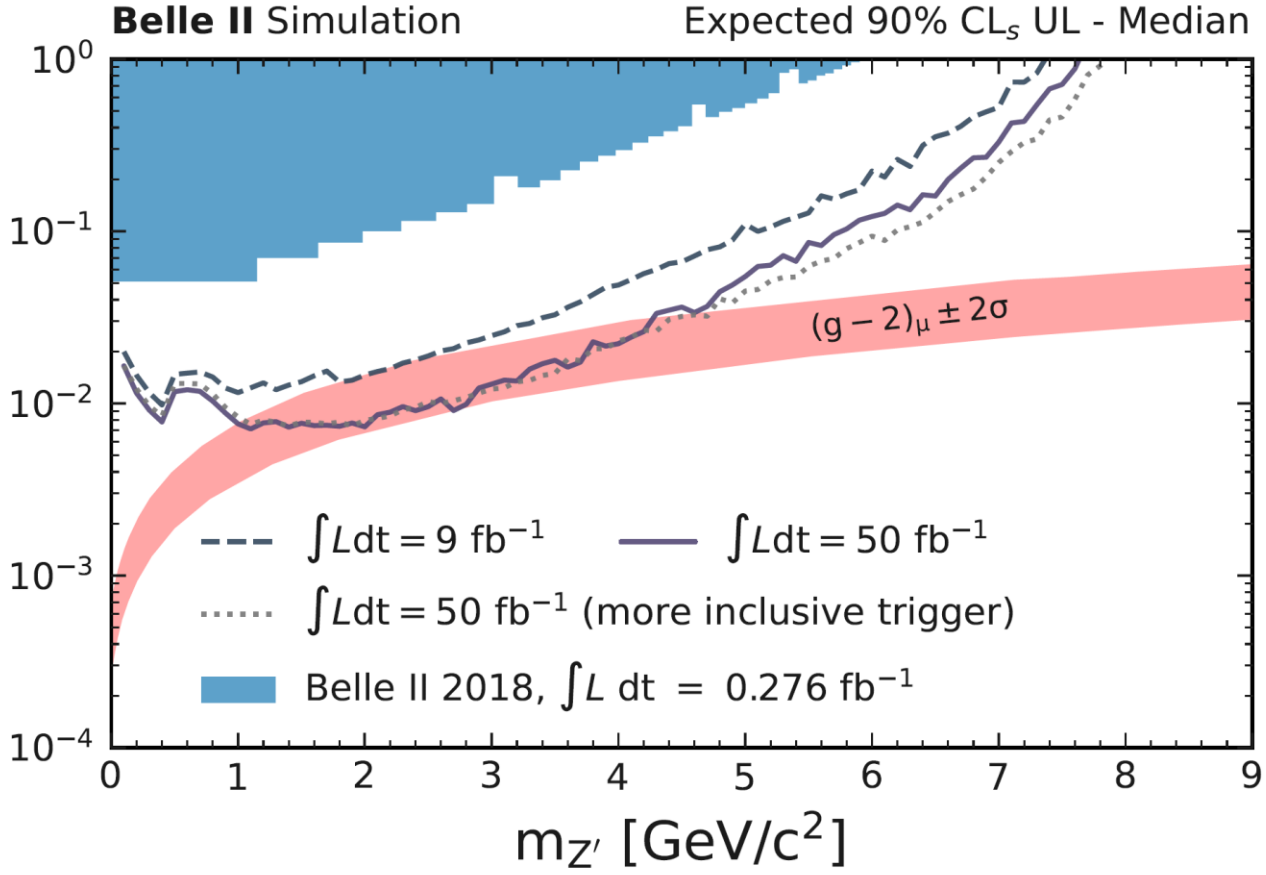
Z' to invisible: early phase 3 projections

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

Very low expected background → UL scale~1/L





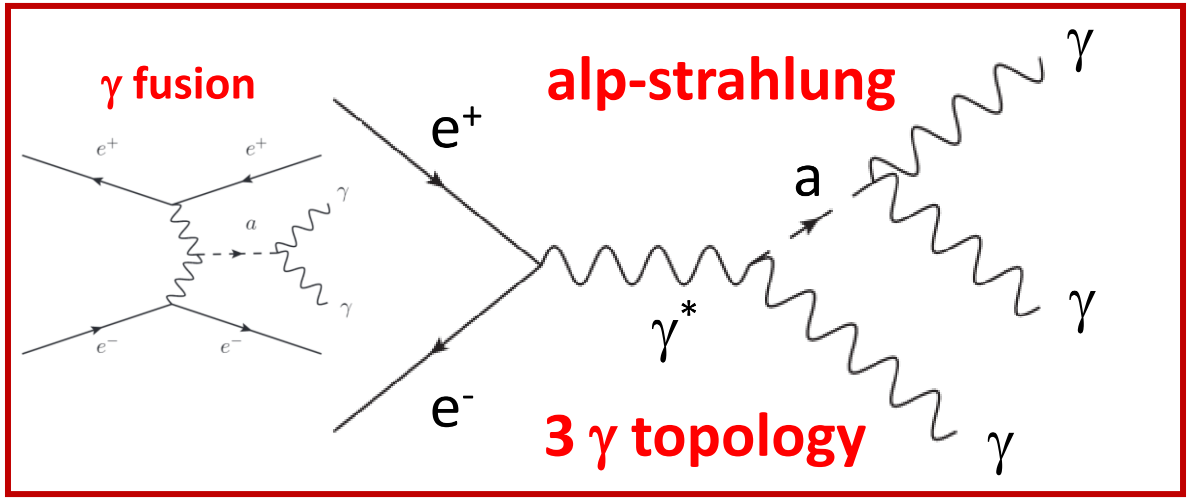


Axion Like Particles (ALPs)

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

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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Belle II

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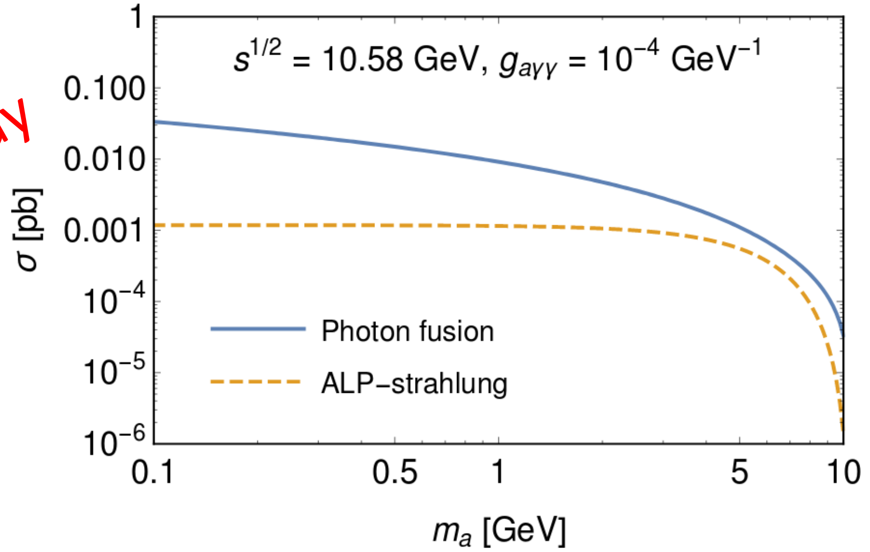
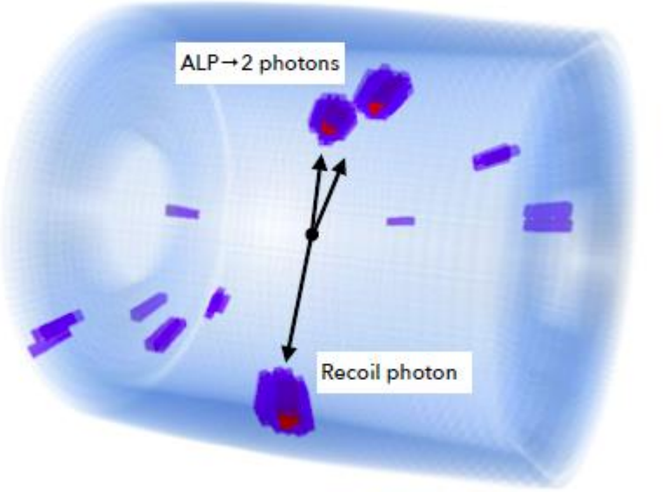
photon fusion sensitivity under study



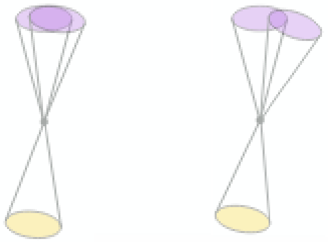
Axion Like Particles (ALPs): signal

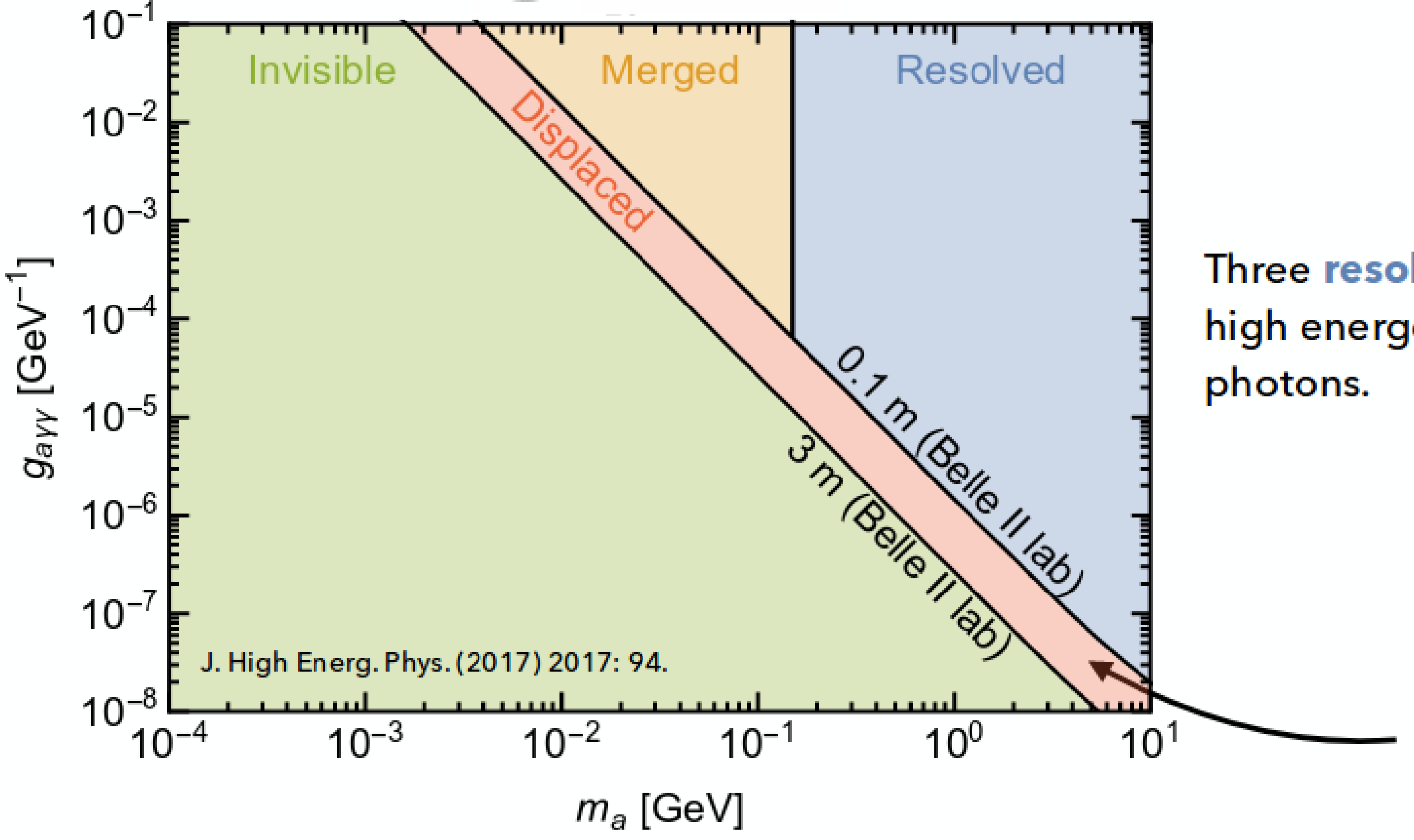
3 γ topology, but…



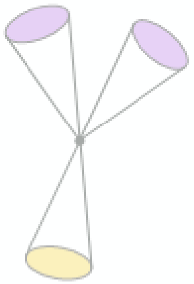
ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

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





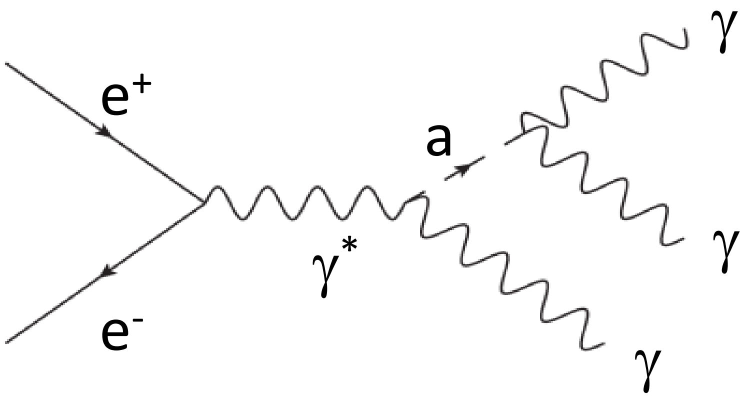
Three **resolved**, high energetic photons.

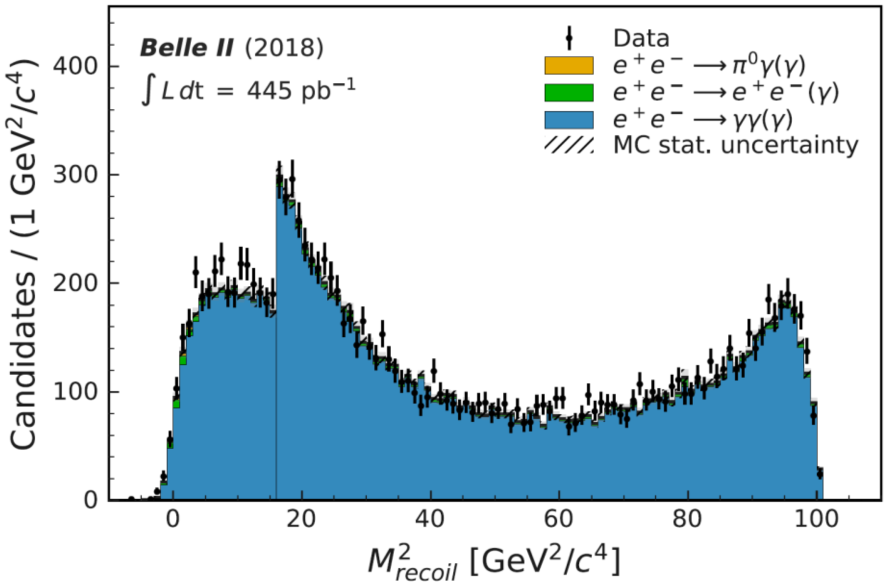


The searches for invisible and visible ALP decays veto this region.

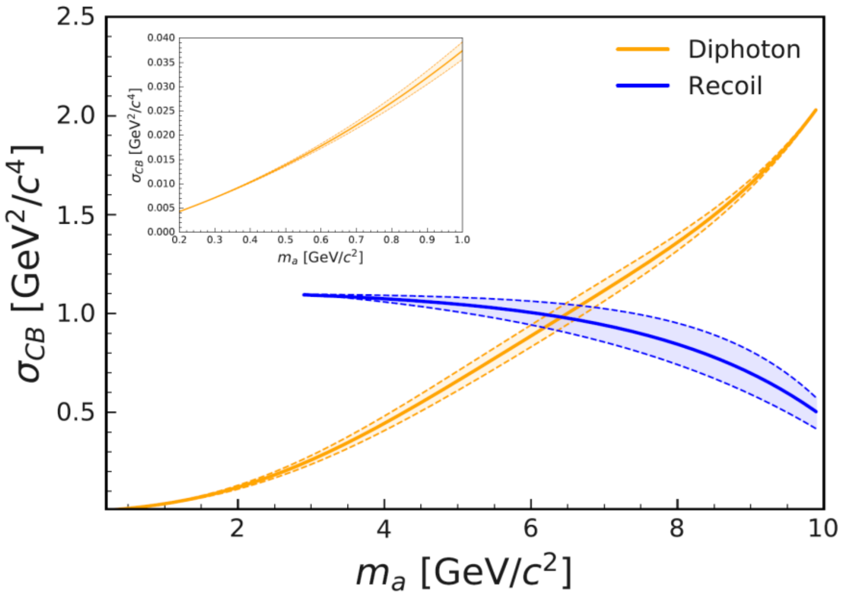
ALPs can also decay to DM → single photon topology

Axion Like Particles (ALPs)





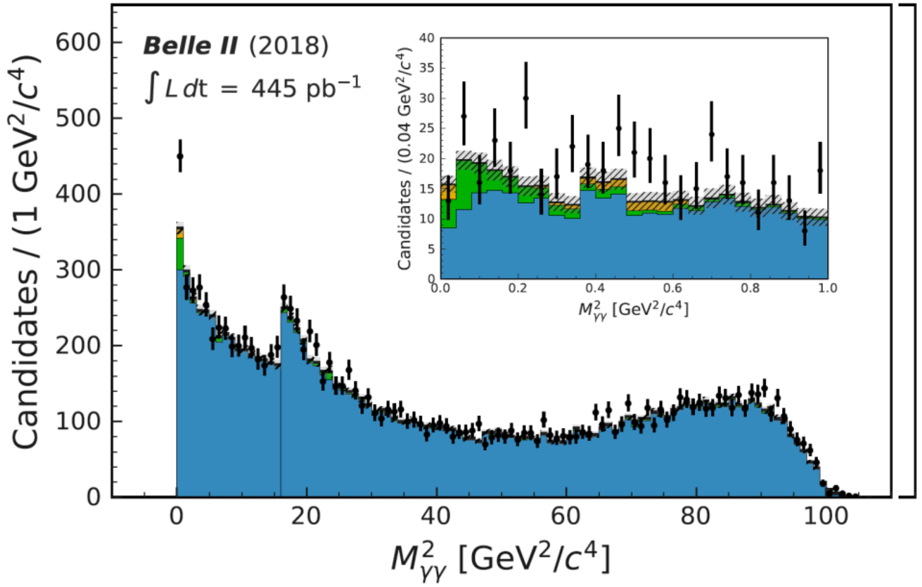
Search for peaks either in the recoil invariant mass (high m_a) or in diphoton mass (low m_a)



Main backgrounds:

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

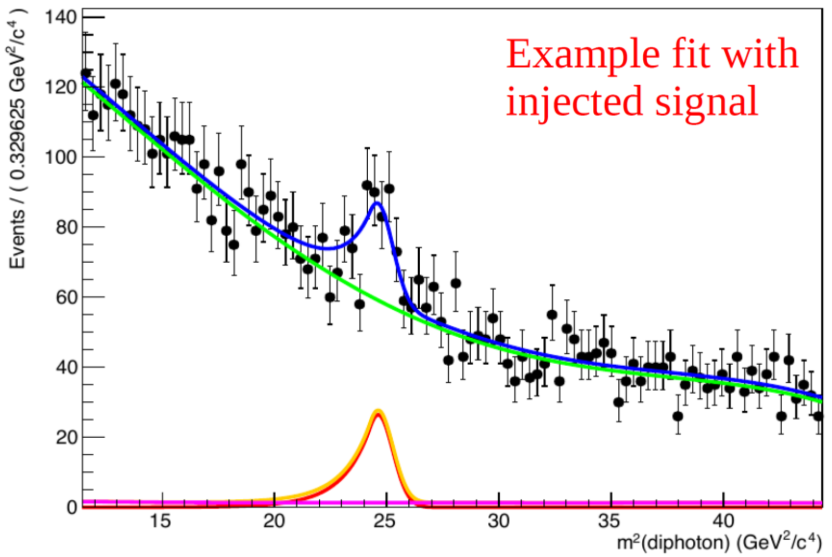
$e^+e^- \to e^+e^-\gamma$



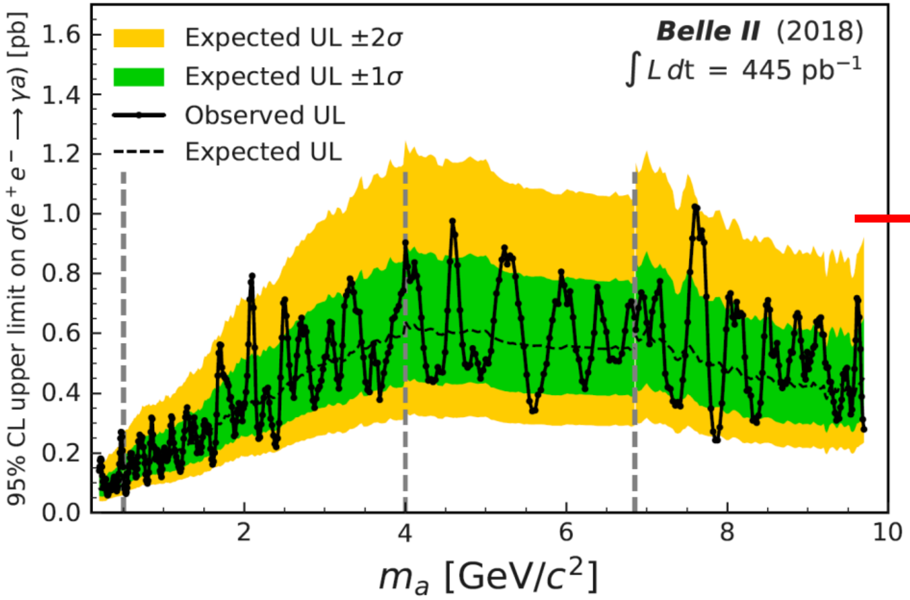
Axion Like Particles (ALPs)

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

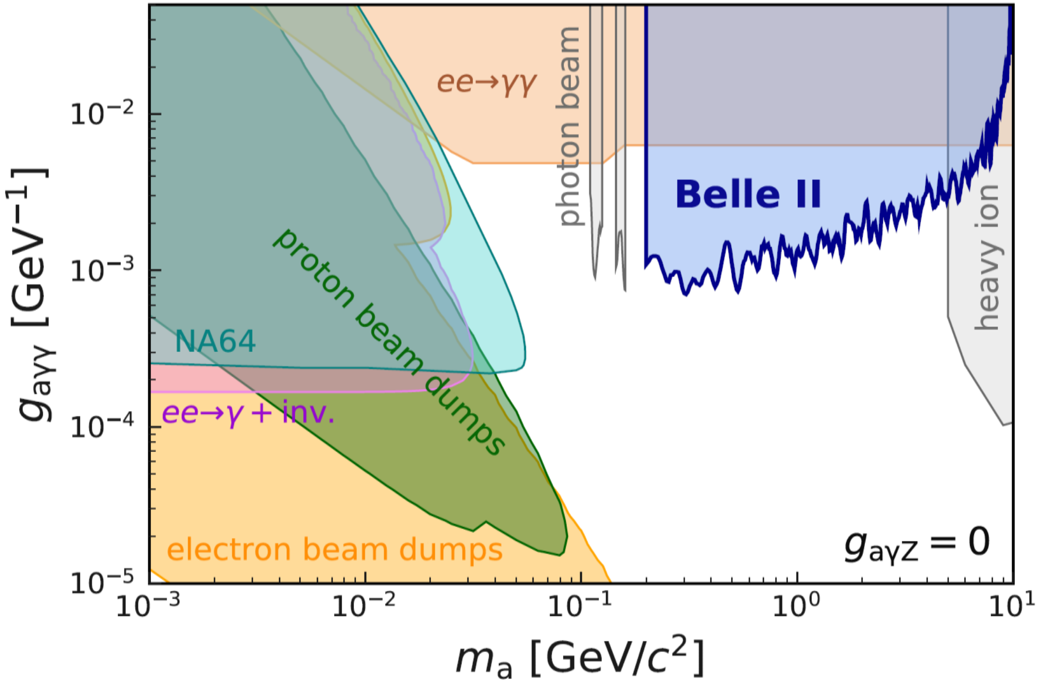
Second physics paper by Belle II being submitted to PRL



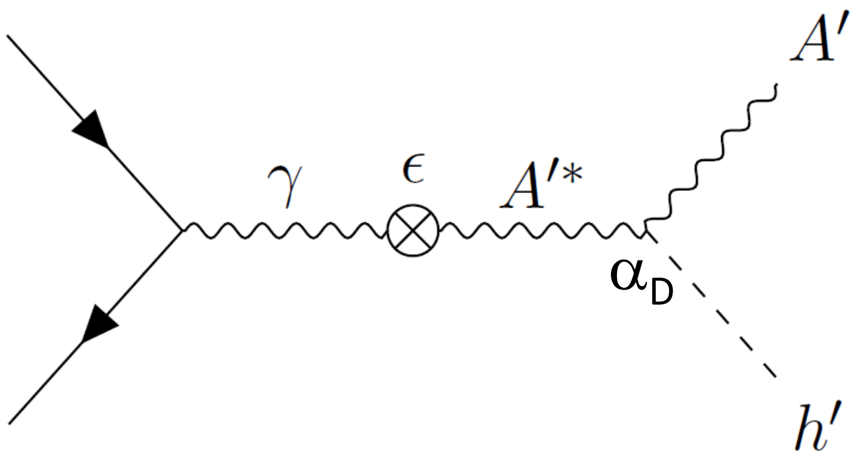
Biggest local significance 2.8 σ



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



Dark Higgsstrahlung: A′h′

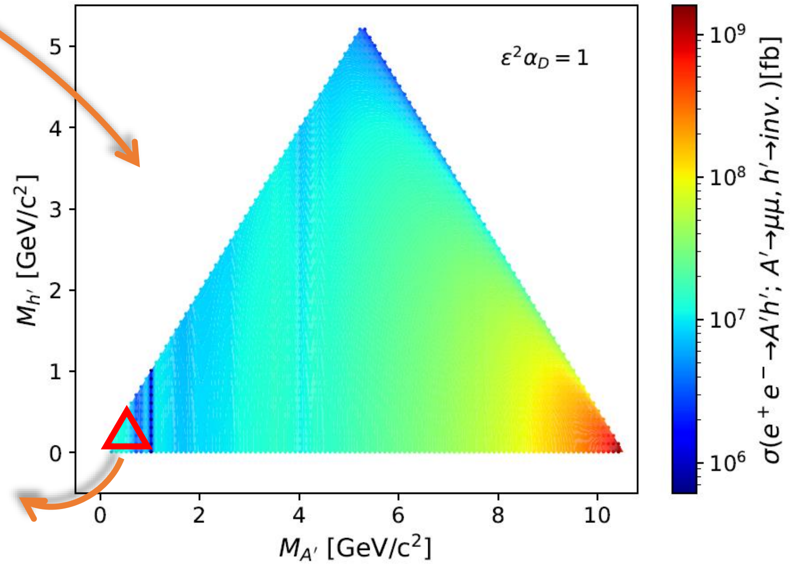


Batell, Pospelov, Ritz, Phys. Rev. D 79, 115008 (2009)

- 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′ → A′A′ → 4*l*, 4 *had*, 2*l* + 2 *had* **BELLE, BABAR**
  - $M_{h'} < M_{A'} \Rightarrow$ h′ "invisible" ← **KLOE, BELLE II**

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

BELLE, BABAR



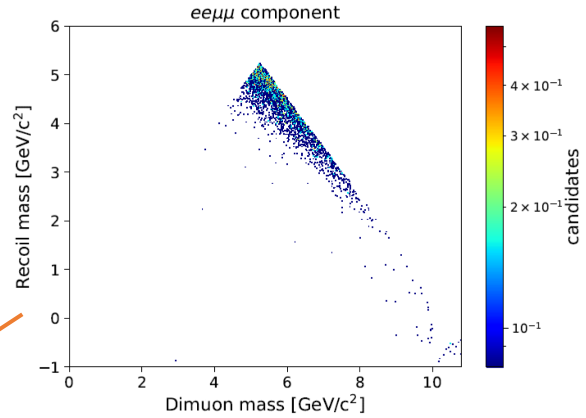
KLOE

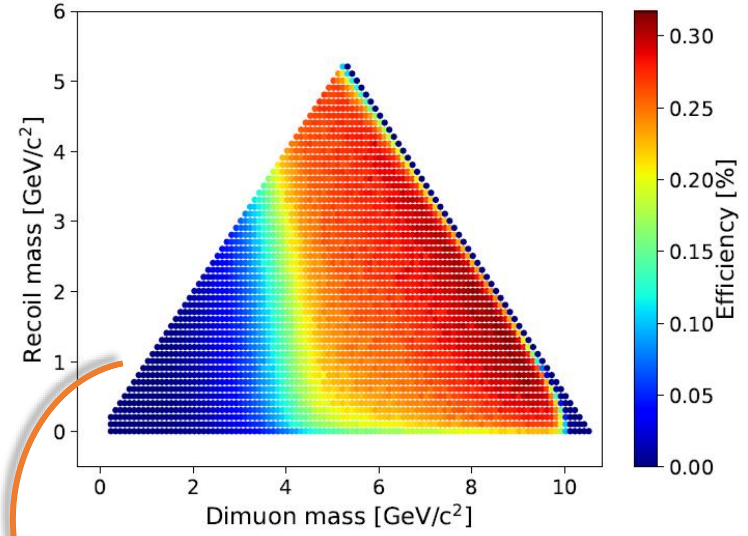
BELLE II

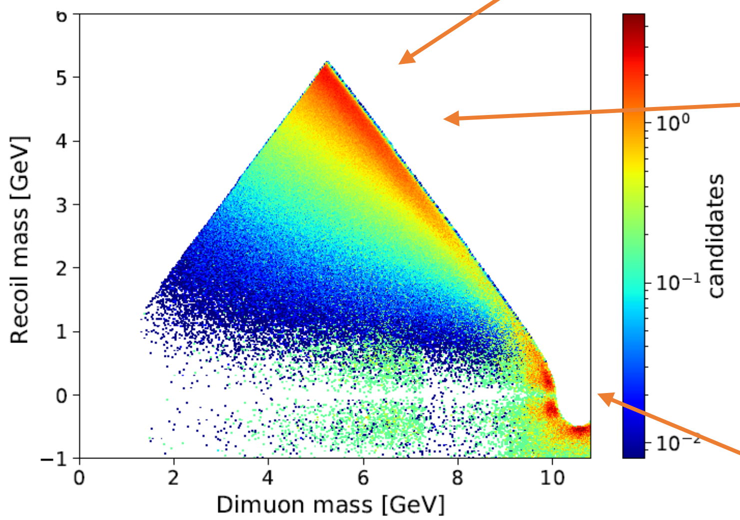
$h' \to l^+l^-$ via loop process $\Rightarrow \tau_{h'} \to \beta\gamma c\tau_{h'} \approx$ 100 m – 10 km

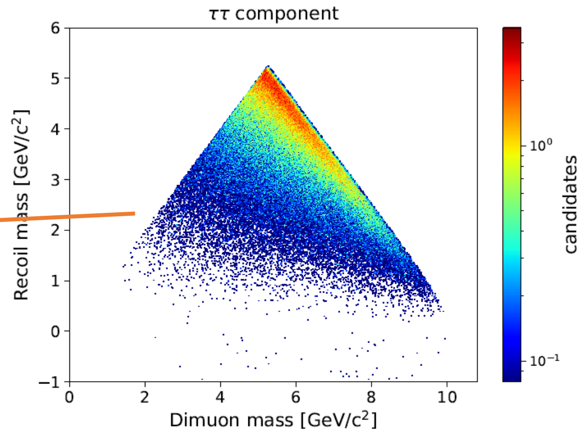
Dark Higgsstrahlung: A′h′

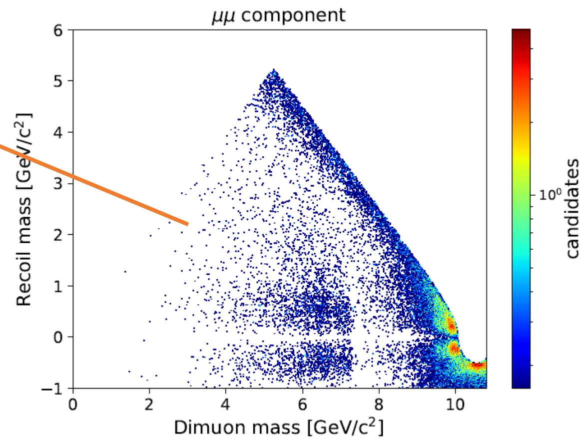
- **$\mu^+ \mu^-$ + missing energy** → same final state as in invisible Z′
- 2d peak in recoil vs dimuon mass
- Background naturally low due to 2d phase space
- **2019 data being used: L ≈ 9 fb^{-1} → next paper**











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

Dark Higgsstrahlung: A′h′

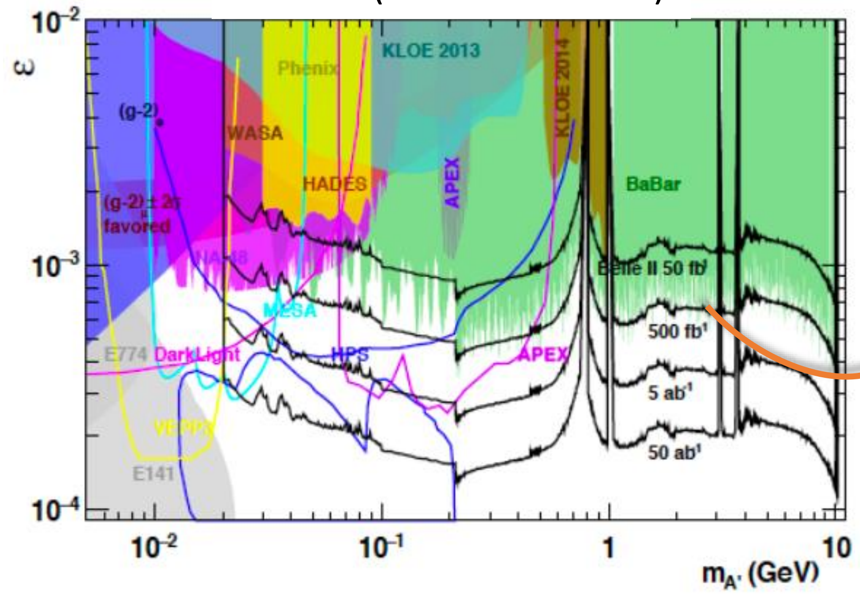
- Systematics: rough & conservative estimate
  - 10% fully correlated on efficiency and BKG, plus additional 20% on BKG only.

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* $\alpha_D=1$

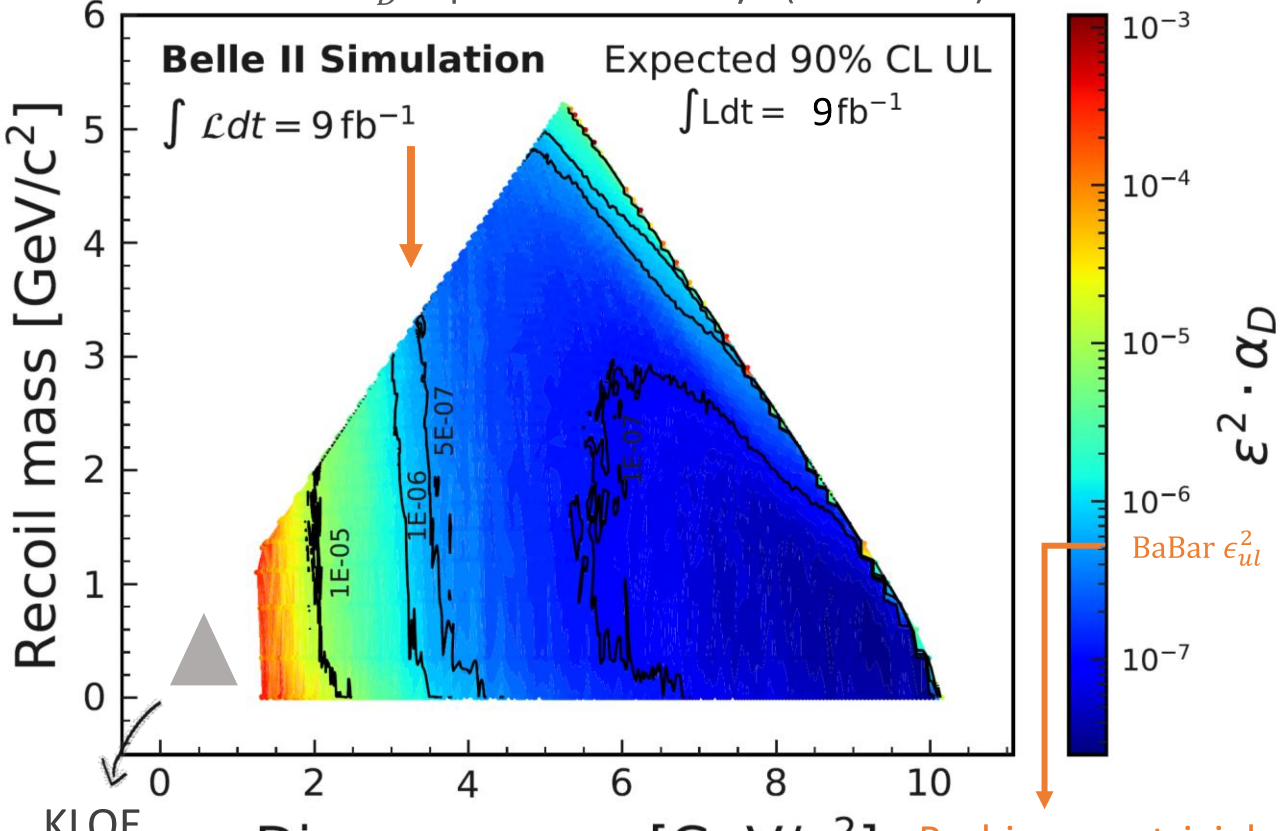
UL on ϵ (visible searches)



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

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

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



KLOE

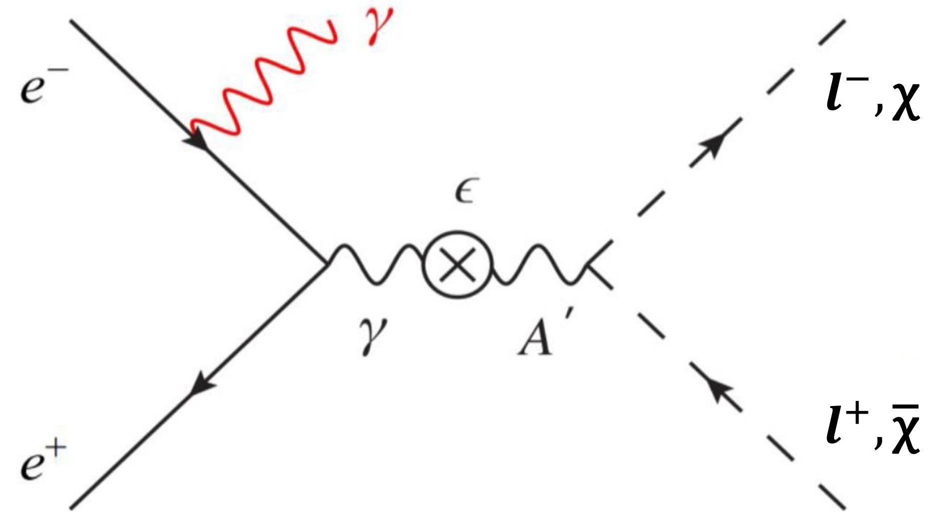
BaBar ϵ^2_{ul}

Probing non trivial regions

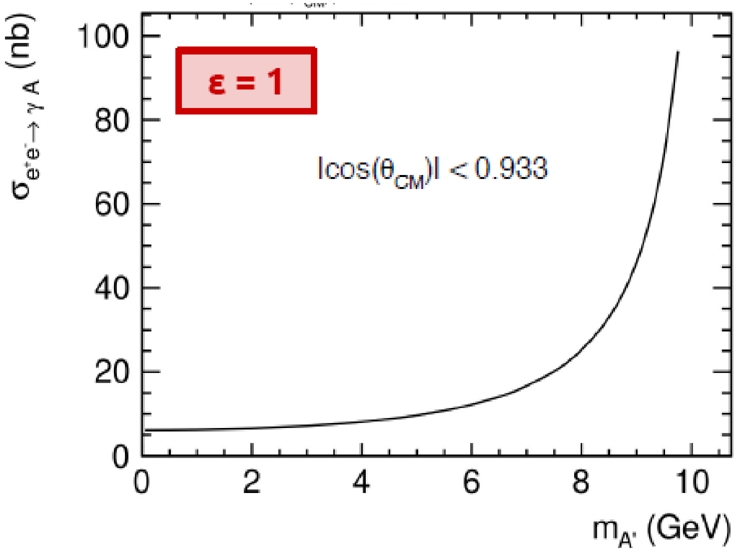
Invisible dark photon

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
- may acquire mass through Higgs or Stuckelberg mechanism



Production cross section

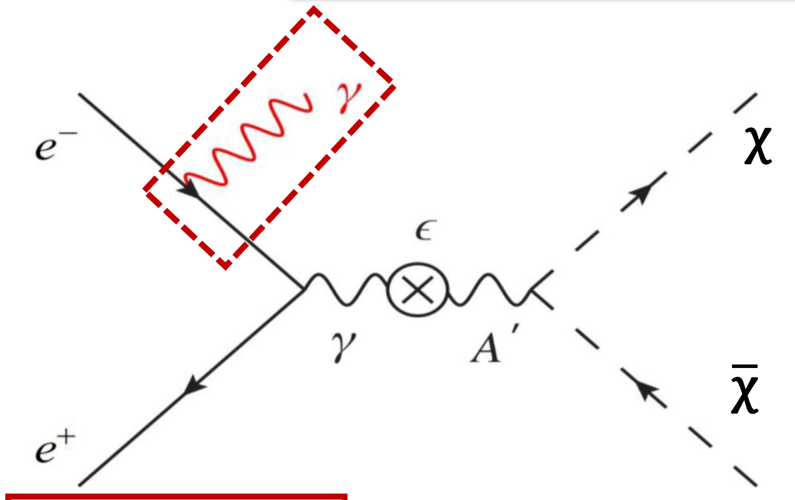


two basic scenarios depending on A′ vs χ DM mass relationship

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

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

Invisible dark photon: experimental signature



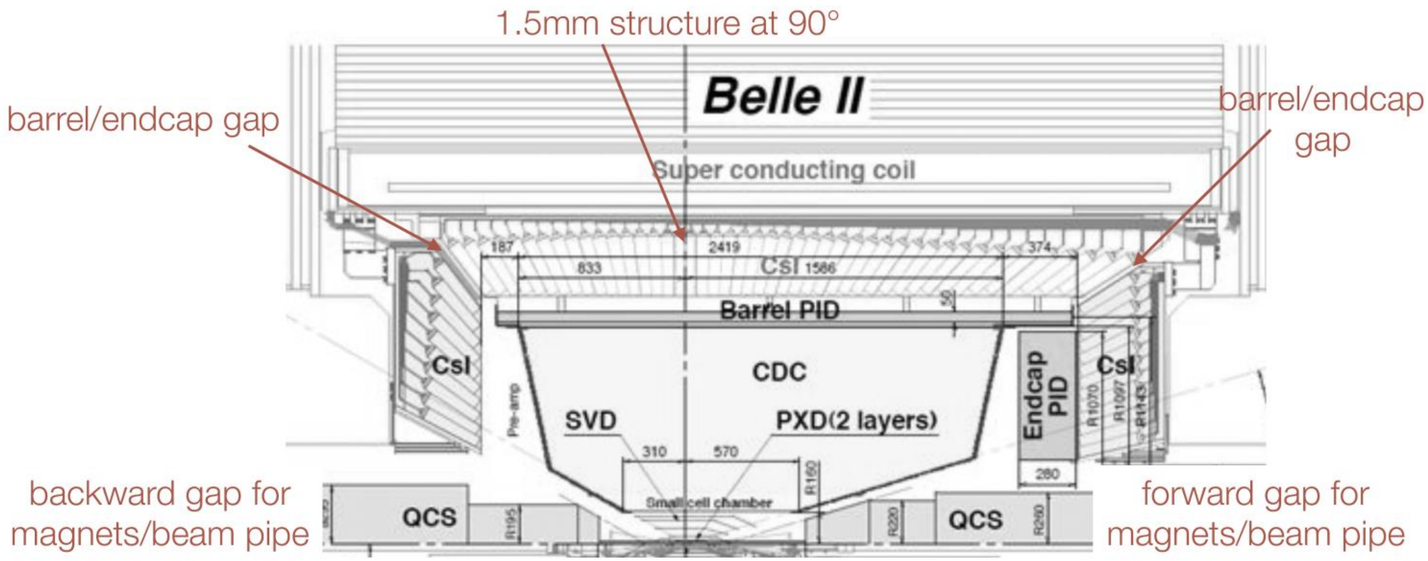
Only **one photon** in the detector.

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

Needs a ~ perfect knowledge of the **detector acceptance**

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

→ Bump in recoil mass or photon energy

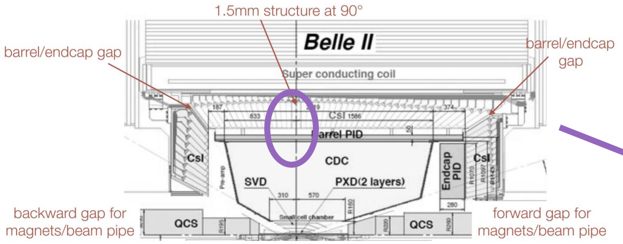


Backgrounds

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

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

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

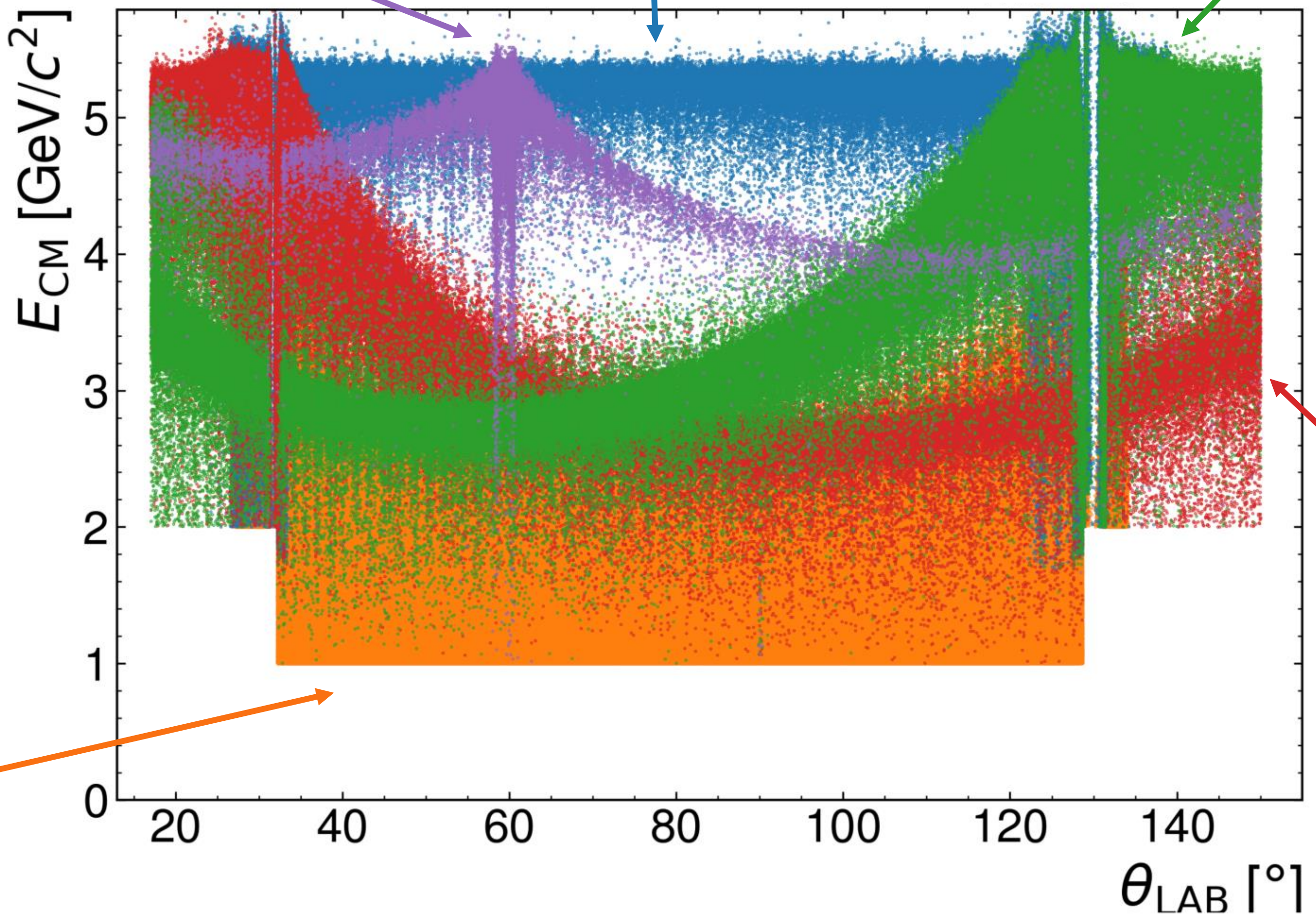


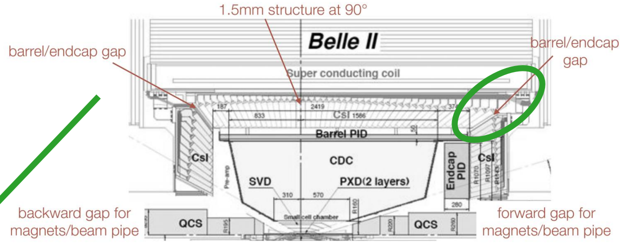
$e^+e^- \to \gamma\gamma\gamma$

1 γ in 90^0 gap

1 γ out of ECL acceptance

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

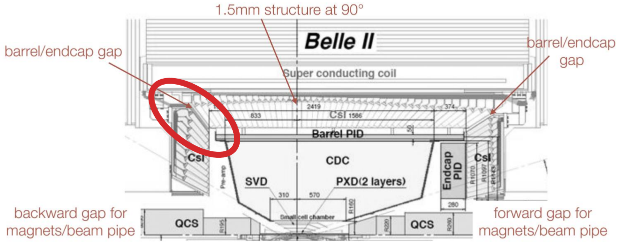




$e^+e^- \to \gamma\gamma\gamma$

1 γ in FWD gap

1 γ out of ECL acceptance



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

1 γ in BWD gap

1 γ out of ECL acceptance

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

2 γ out of ECL acceptance

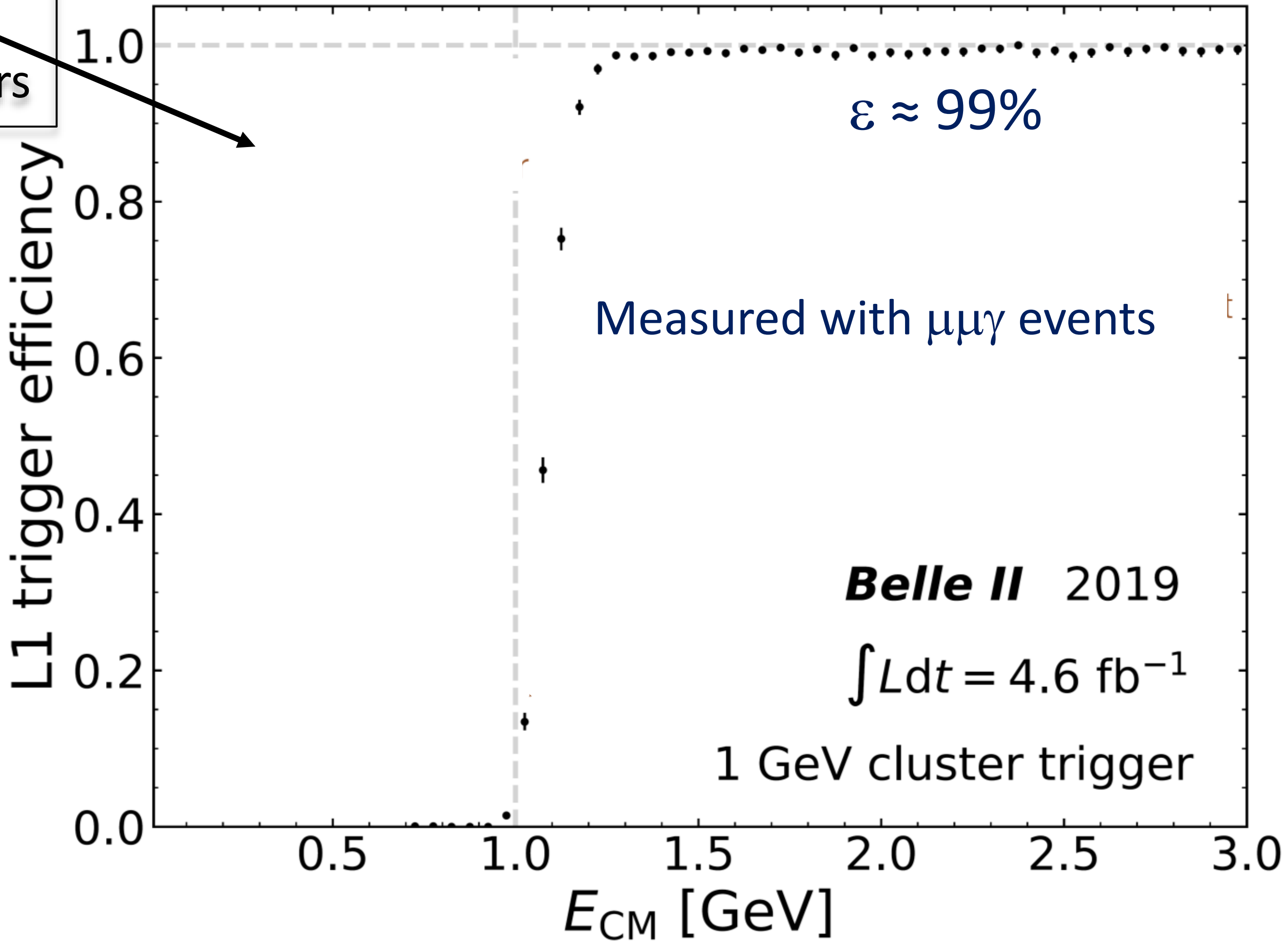
Crucial usage of KLM to veto photons in ECL gaps

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

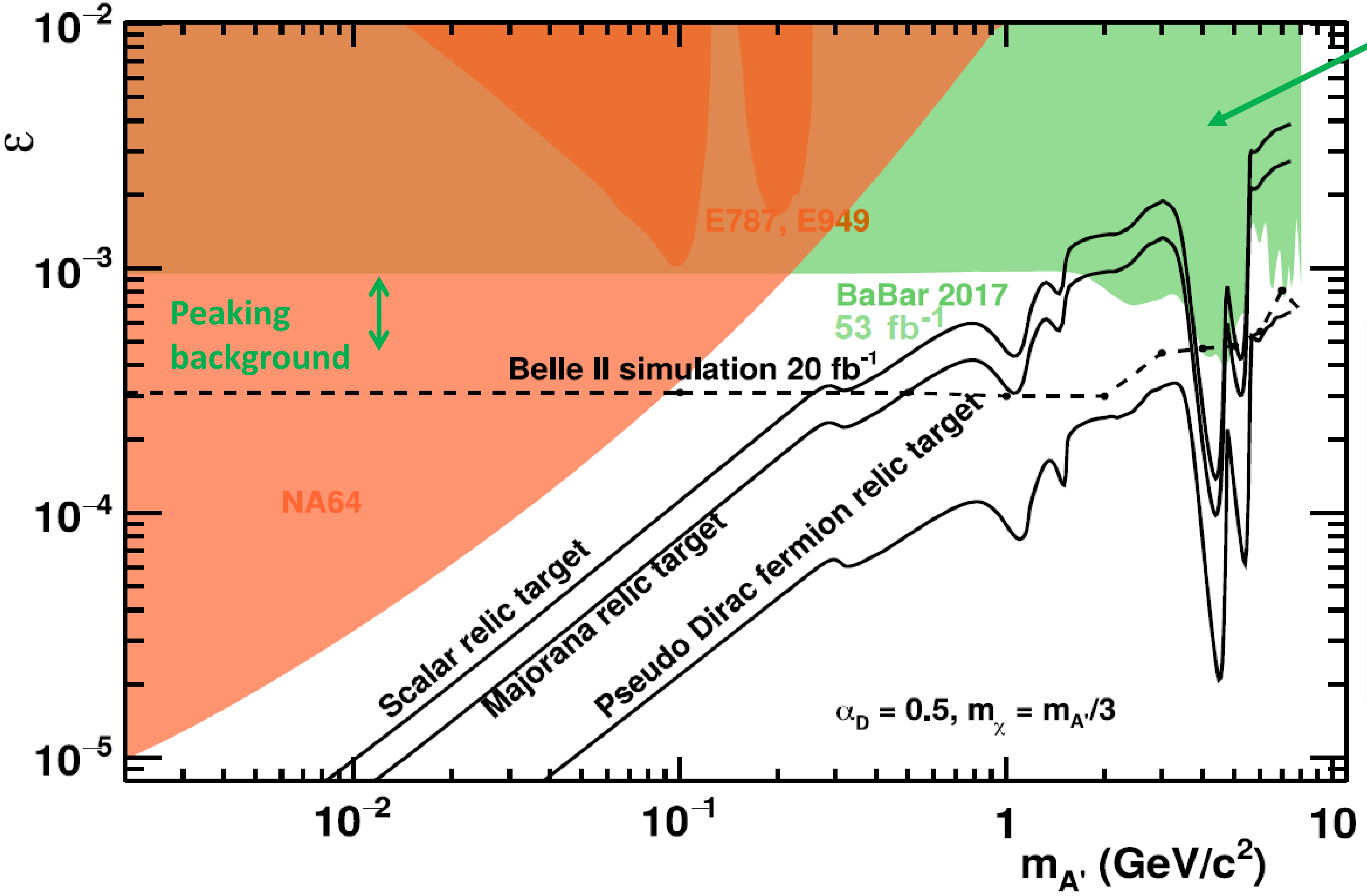
Would extend the search range up to $M_{A'}$<≈10 GeV (psycological threshold)

Not guaranteed to sustain the trigger rates with high luminosity. Some prescaling or threshold adjustment might be needed.
⇒ difficult to make luminosity projections



Invisible dark photon: sensitivity

BaBar, Phys. Rev. Lett 119, 131804 (2017)



Belle II vs BaBar

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

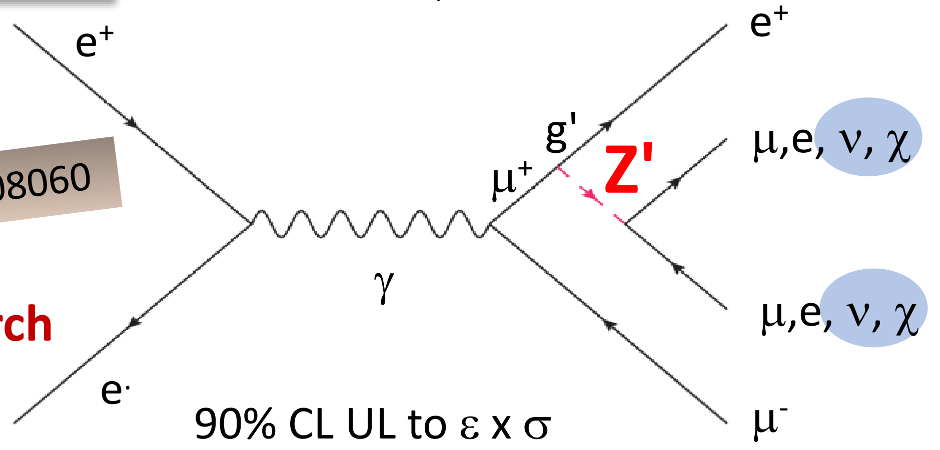
Summary

- The persisting null results from heavy new physics LHC searches and 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, BELLE (+ BABAR) already excluded many models
- 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$\rightarrow\gamma\gamma$
- Next papers: dark Higgsstrahlung (first half 2021), invisible dark photon ($\sim$ end 2021)

SPARE SLIDES

LFV Z' to invisible

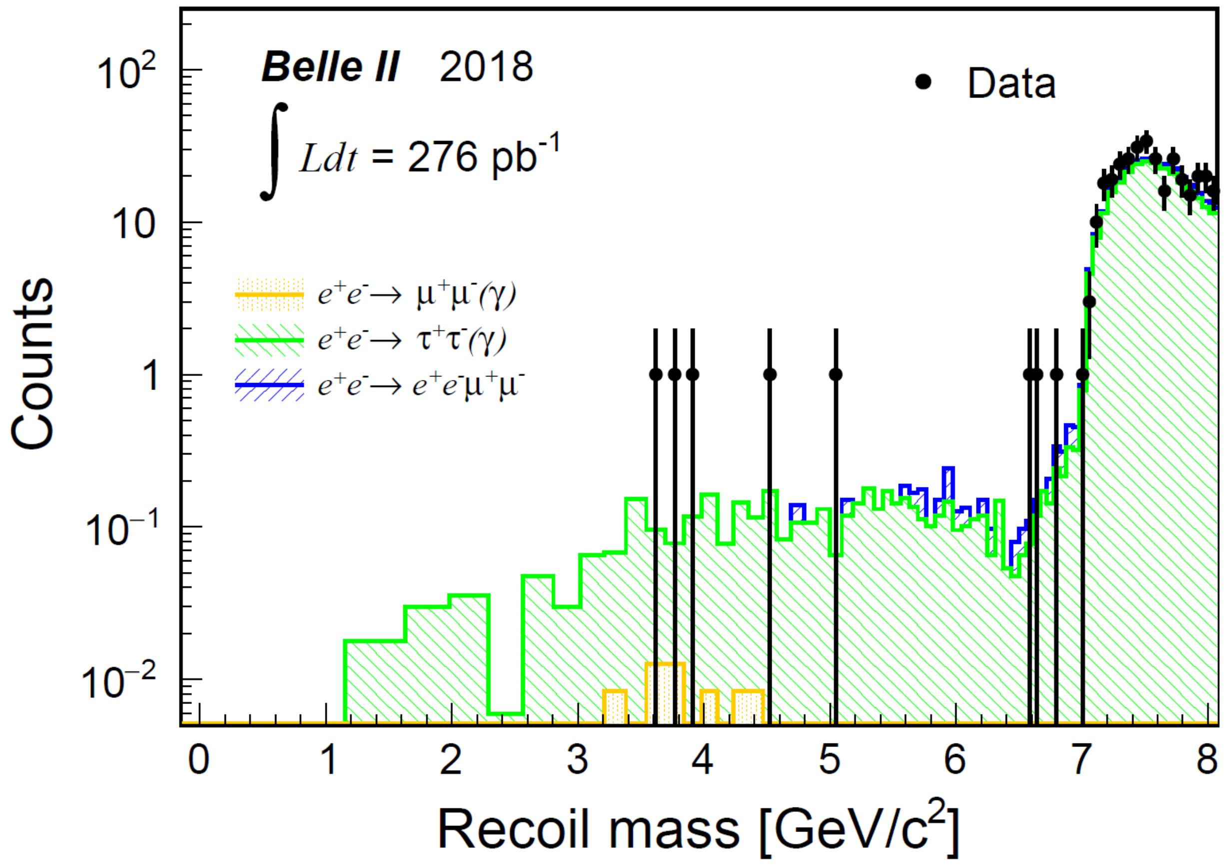
$e^+e^- \rightarrow e^+\mu^- +$ *missing energy*



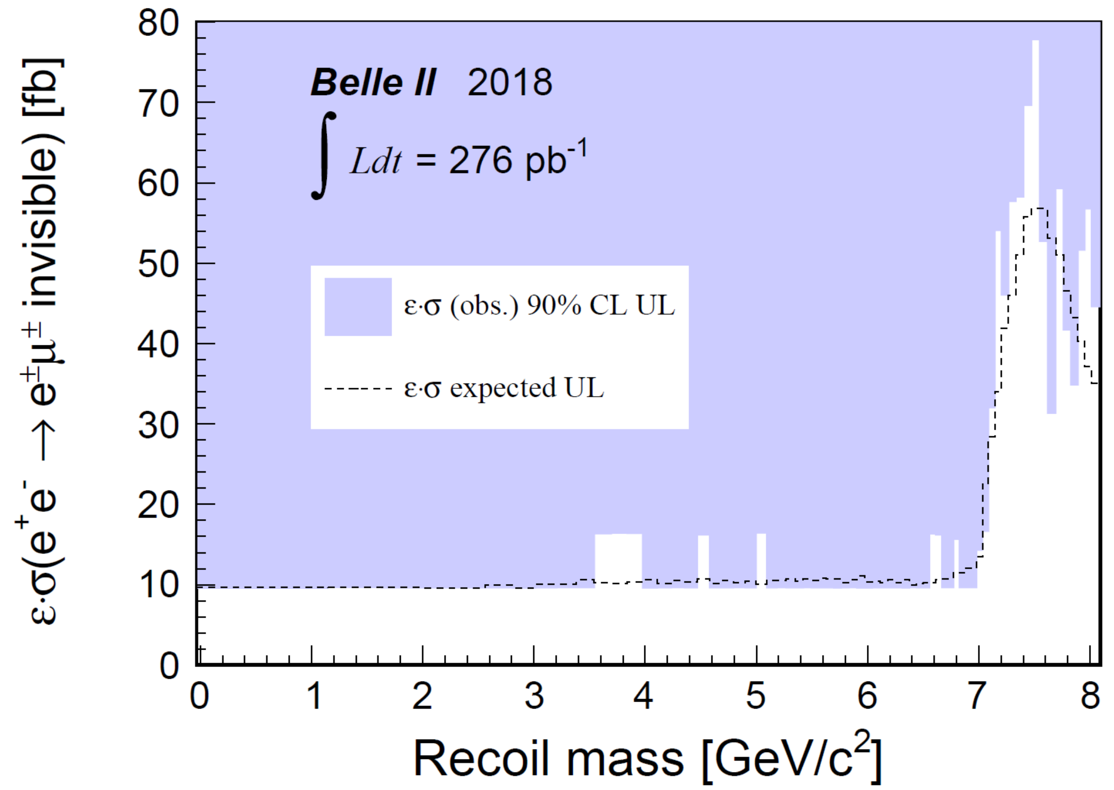
What about a Lepton Flavour Violating Z'?

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

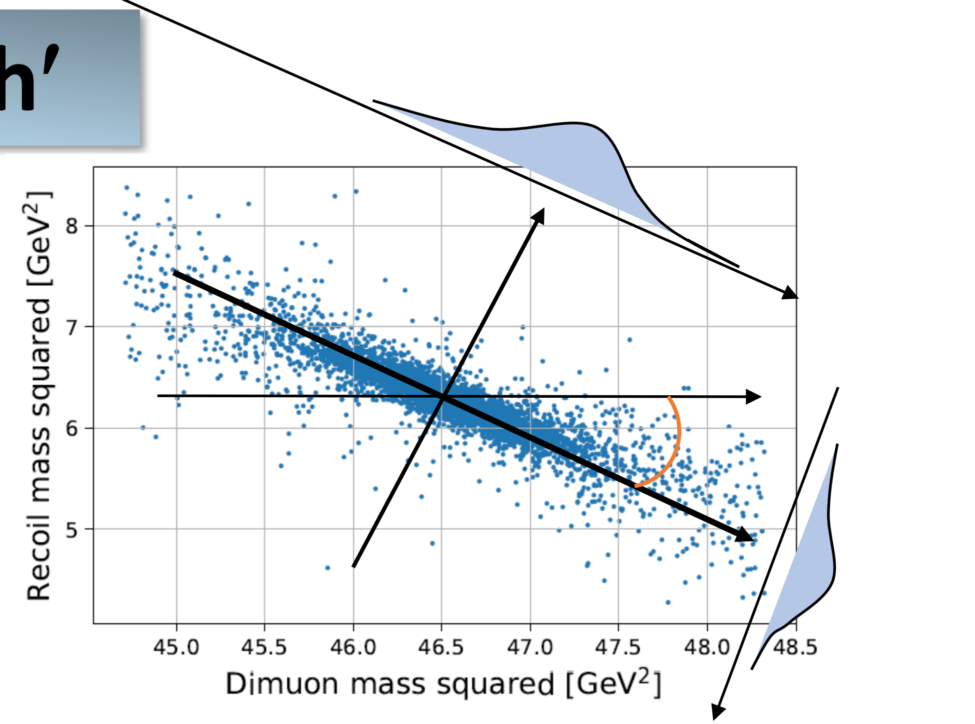


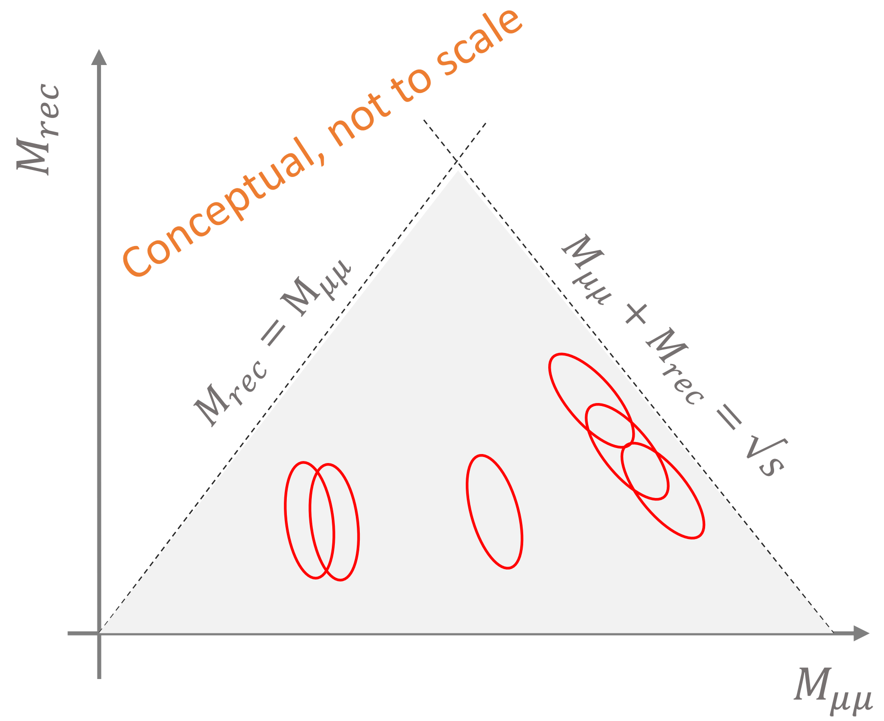
Dark Higgsstrahlung: A′h′

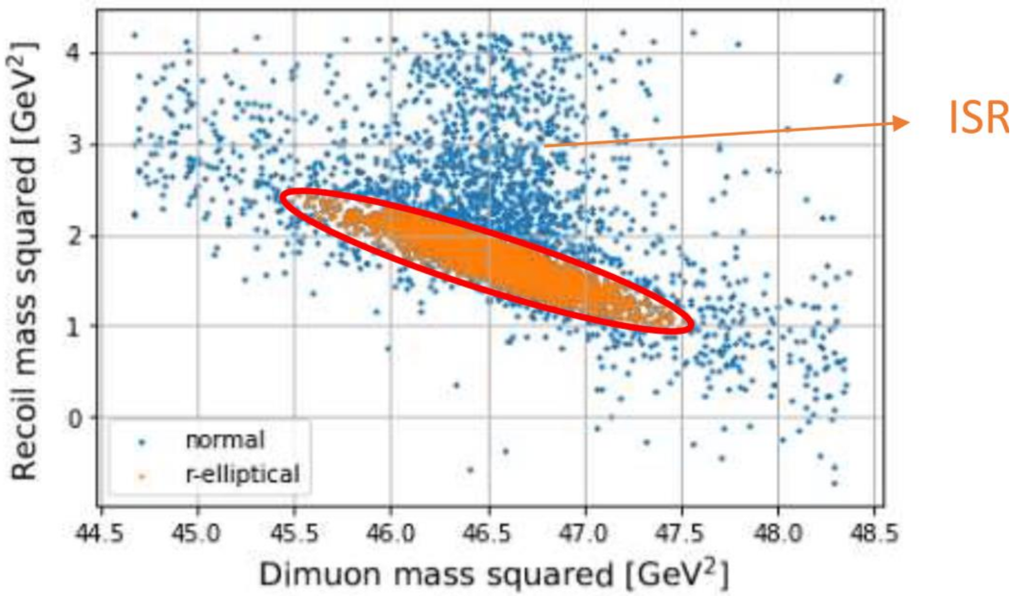
- Negative correlation between μμ and recoil mass
- Variable across the plane: evalutaed in the no ISR case

- 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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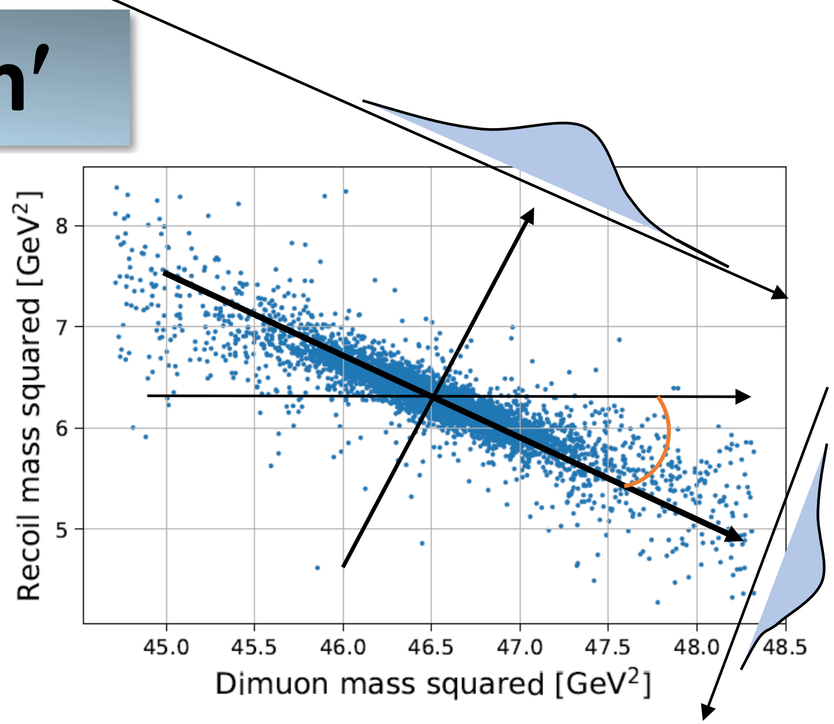
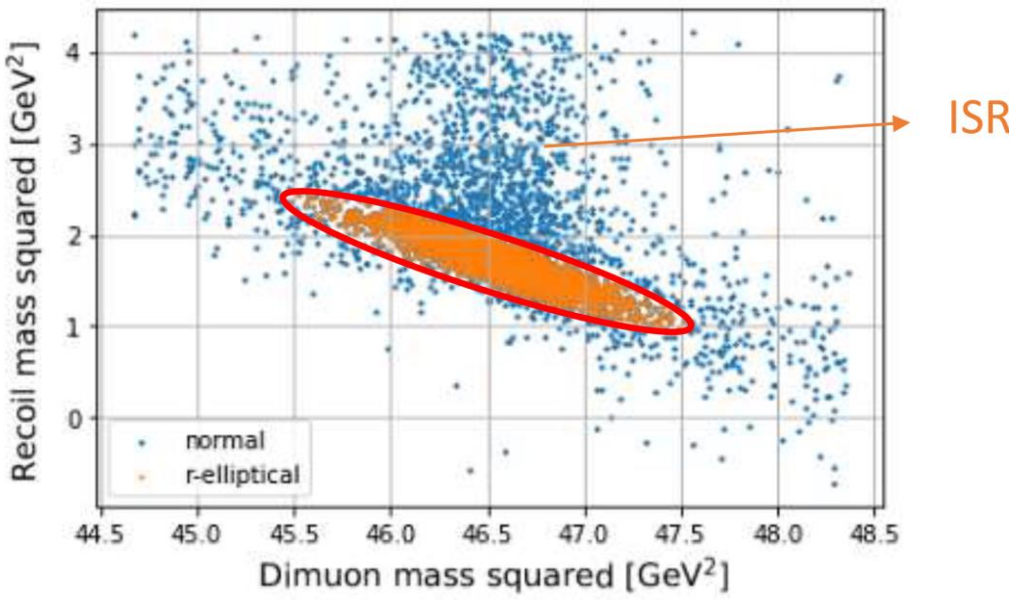
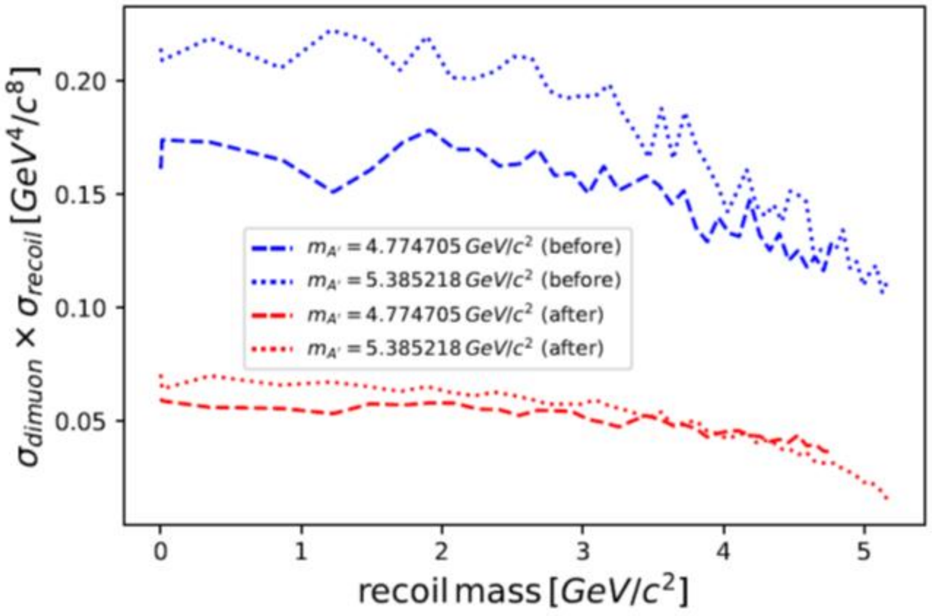




Background reduction 3-4



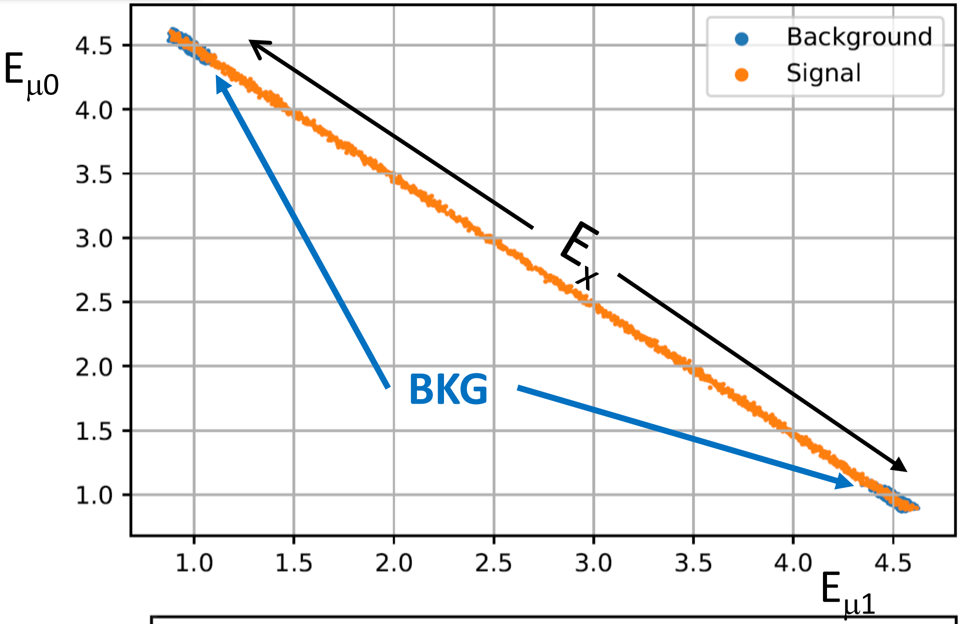
Dark Higgsstrahlung: A′h′

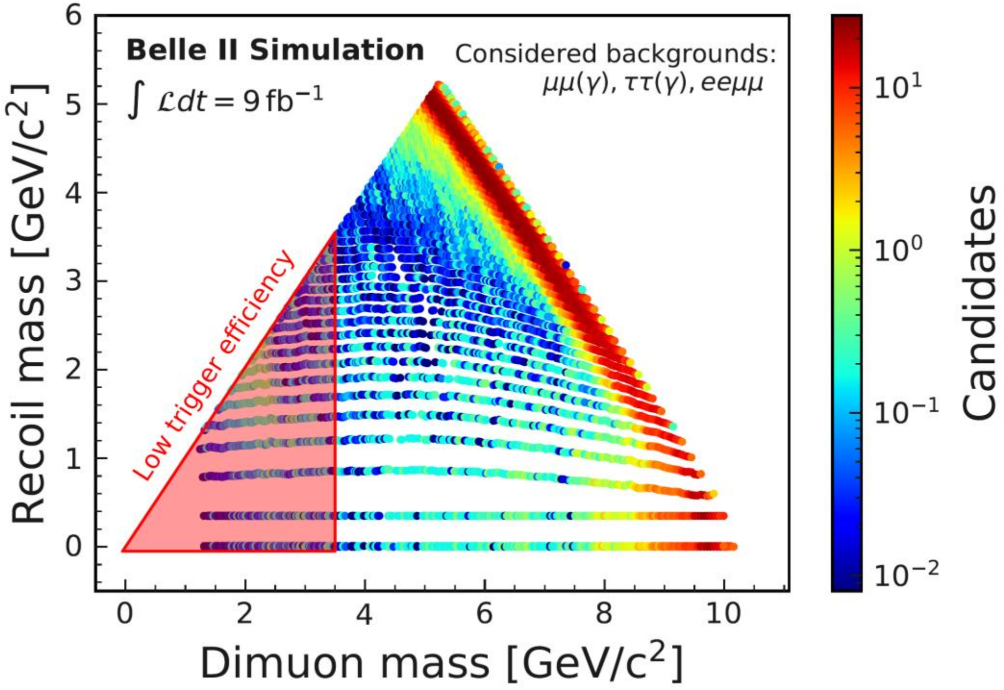
Final background suppression based on kinematic features.

$E_{\mu0} + E_{\mu1}$ approximately constant within mass windows.

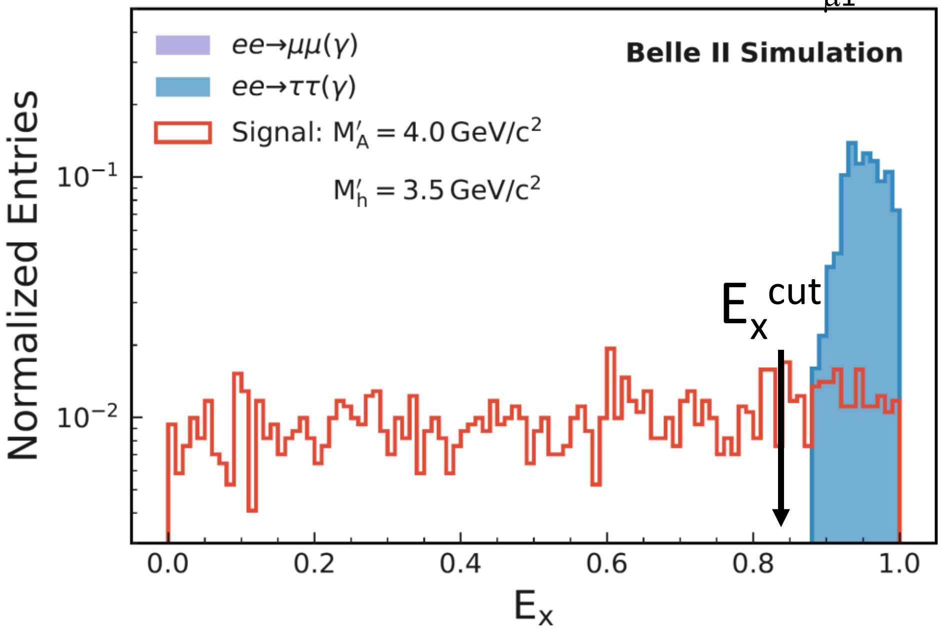
$$E_{\mu0} + E_{\mu1} = \frac{s + M^2_{\mu\mu} - M^2_{rec}}{2\sqrt{s}} = E_0$$

E_x^{cut} optimized across the plane



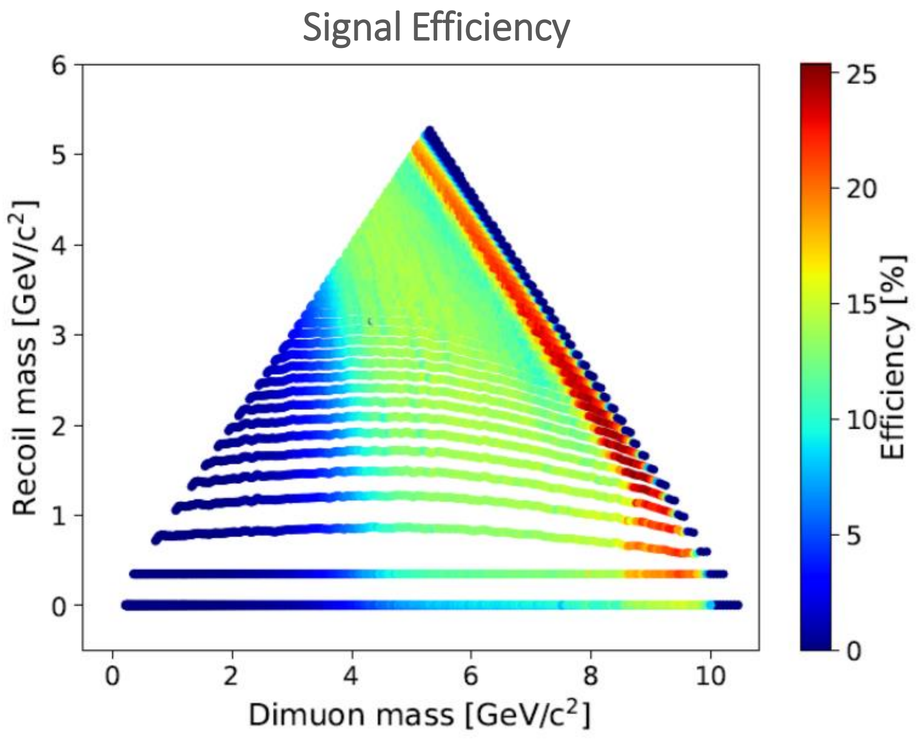


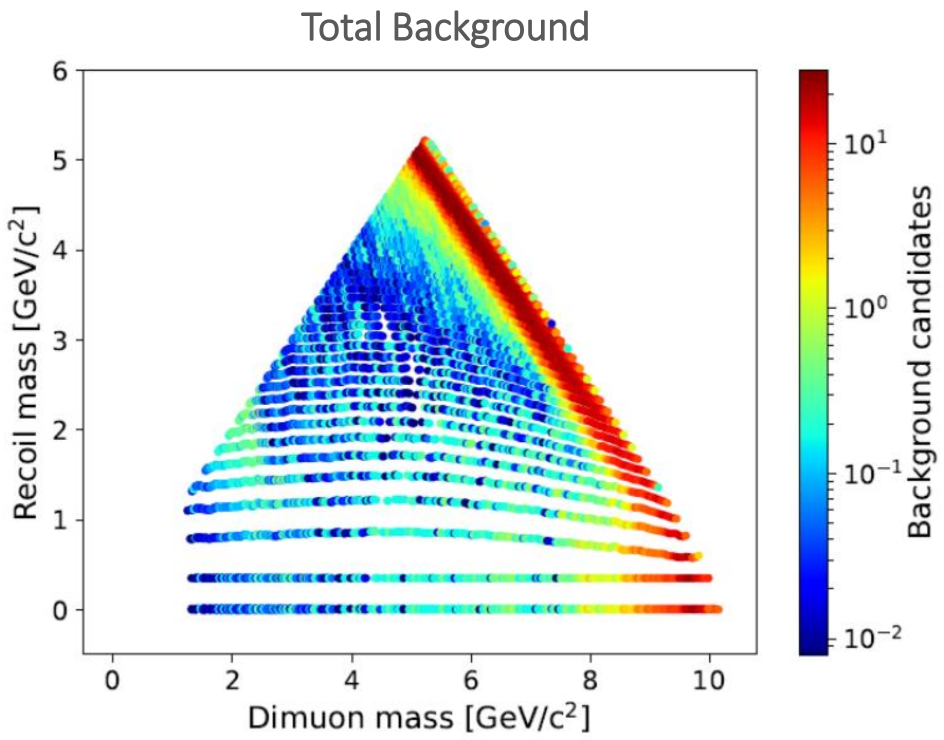
Rejection factor 10-1000



Dark Higgsstrahlung: A′h′

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



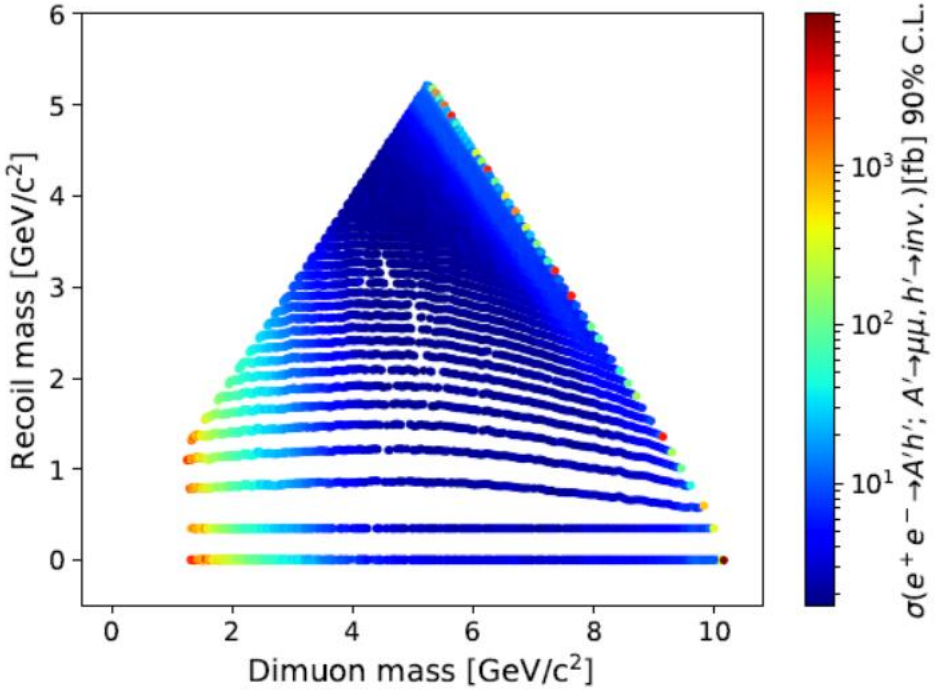


Dark Higgsstrahlung: A′h′

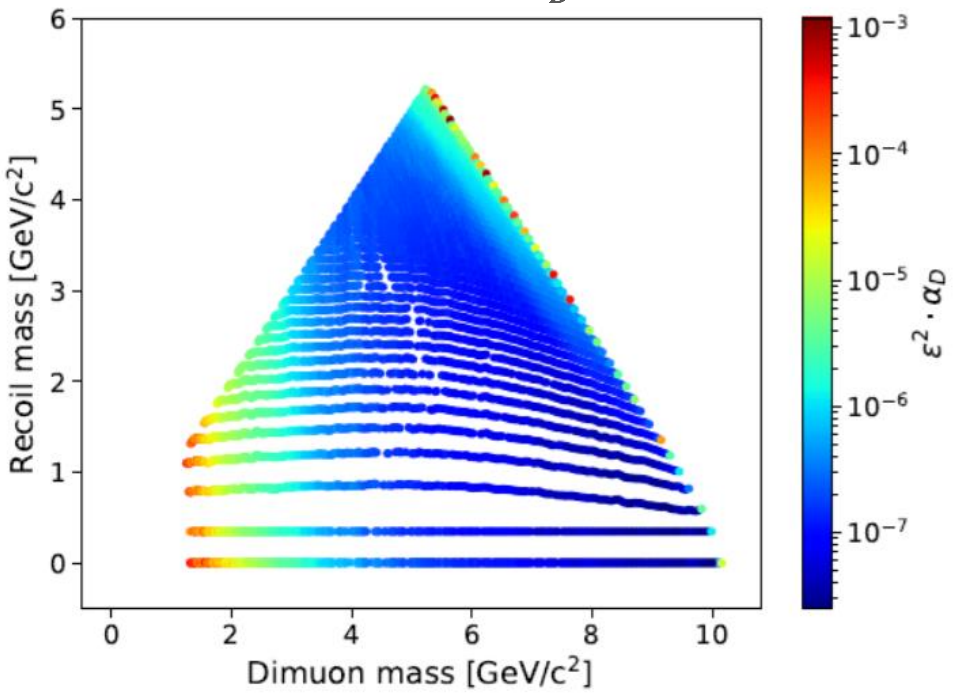
Sensitivity estimate

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

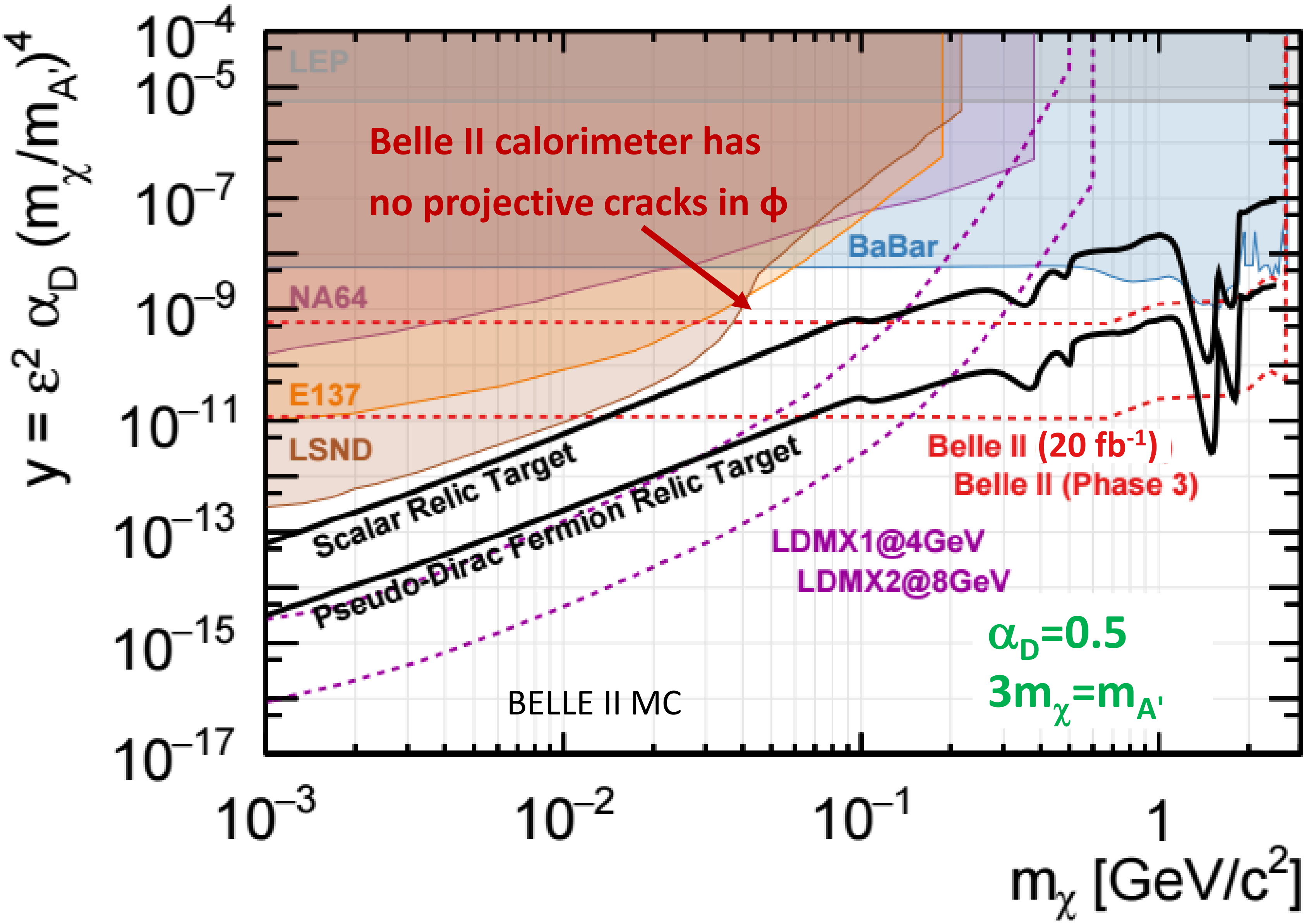
90% UL on cross section



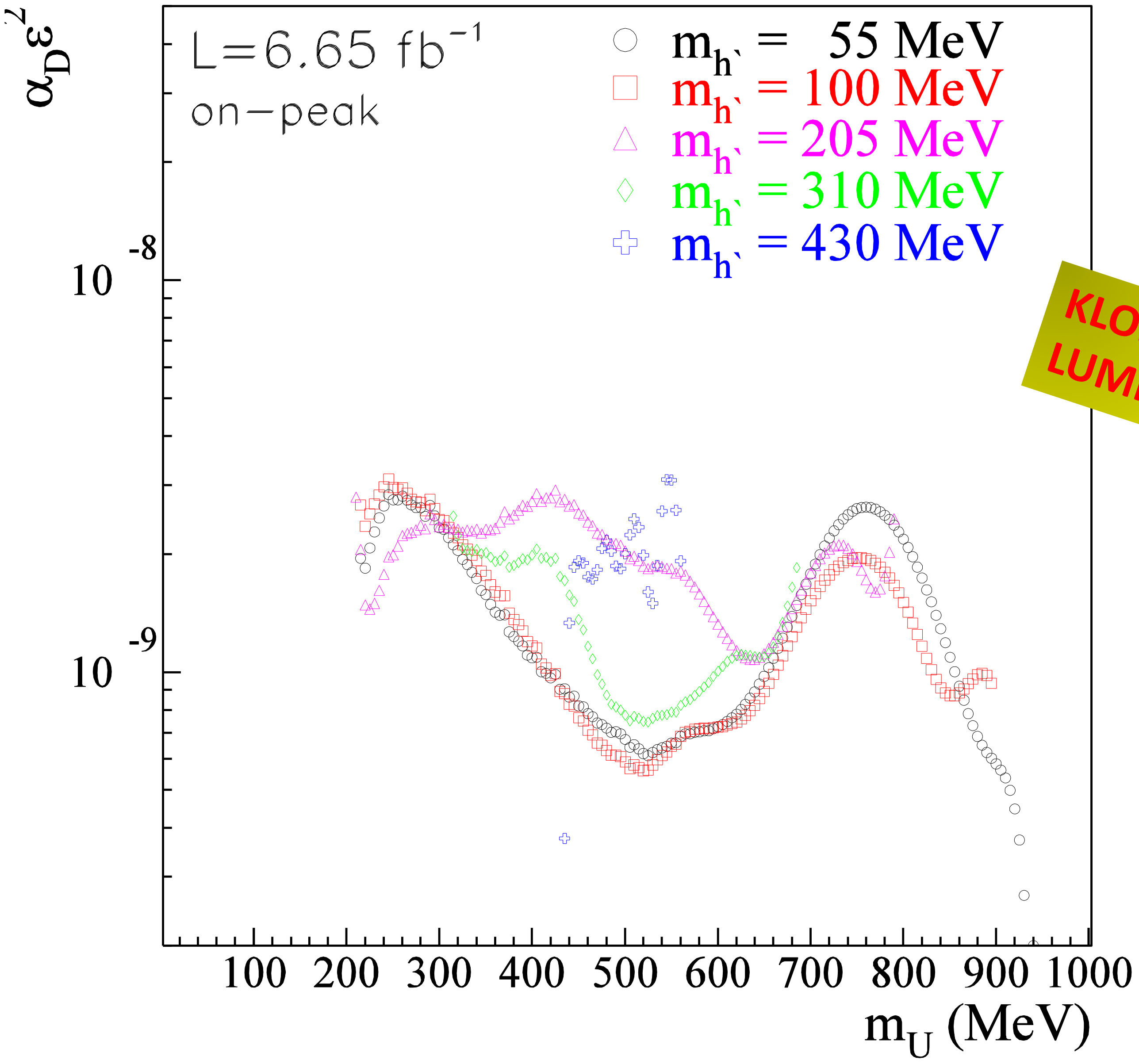
90% UL on $\epsilon^2 \alpha_D$



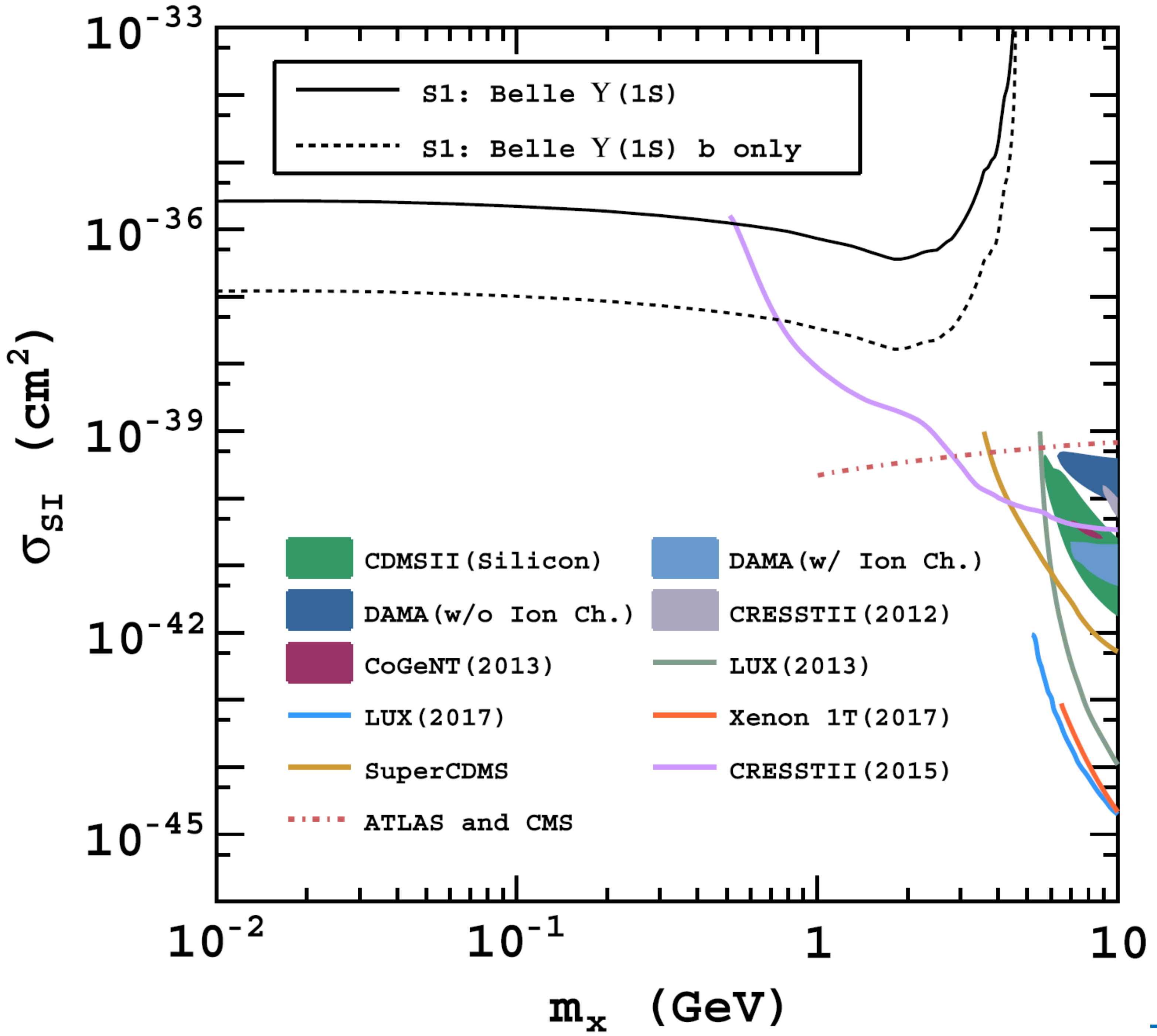
Invisible dark photon: sensitivity

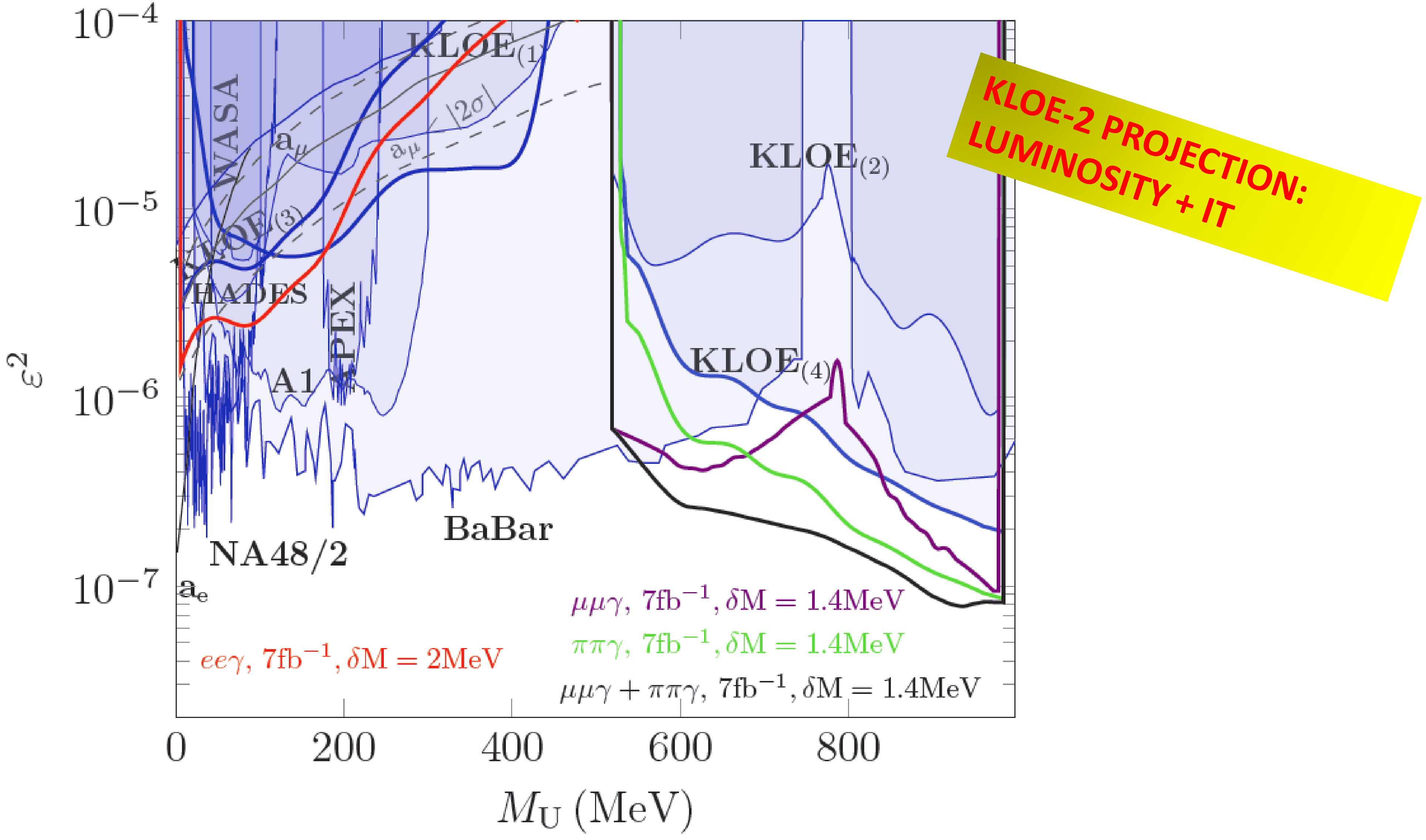


The $e^+e^- \to h'U$ process at KLOE-2



KLOE-2 PROJECTION:
LUMINOSITY + IT


S1: Belle Υ(1S)
S1: Belle Υ(1S) b only
CDMSII(Silicon)
DAMA(w/ Ion Ch.)
DAMA(w/o Ion Ch.)
CRESSTII(2012)
CoGeNT(2013)
LUX(2013)
LUX(2017)
Xenon 1T(2017)
SuperCDMS
CRESSTII(2015)
ATLAS and CMS
10^{-33}
10^{-36}
10^{-39}
10^{-42}
10^{-45}
σ_{SI} (cm^2)
10^{-2}
10^{-1}
1
10
m_x (GeV)



10^{-4}
10^{-5}
10^{-6}
10^{-7}
ε^2
KLOE(1)
KLOE(2)
KLOE(3)
KLOE(4)
WASA
HADES
APEX
A1
a_μ
a_e
2σ
NA48/2
BaBar
$\mu\mu\gamma$, 7fb^{-1}, δM = 1.4MeV
$\pi\pi\gamma$, 7fb^{-1}, δM = 1.4MeV
$\mu\mu\gamma + \pi\pi\gamma$, 7fb^{-1}, δM = 1.4MeV
$ee\gamma$, 7fb^{-1}, δM = 2MeV
0
200
400
600
800
M_U (MeV)
KLOE-2 PROJECTION:
LUMINOSITY + IT