

# Search for Dark Matter with early Belle II data

**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
- ✓ Search of ALP
- ✓ Search of the invisible dark photon
- ✓ Perspectives & Summary

**BEAUTY**  
2019

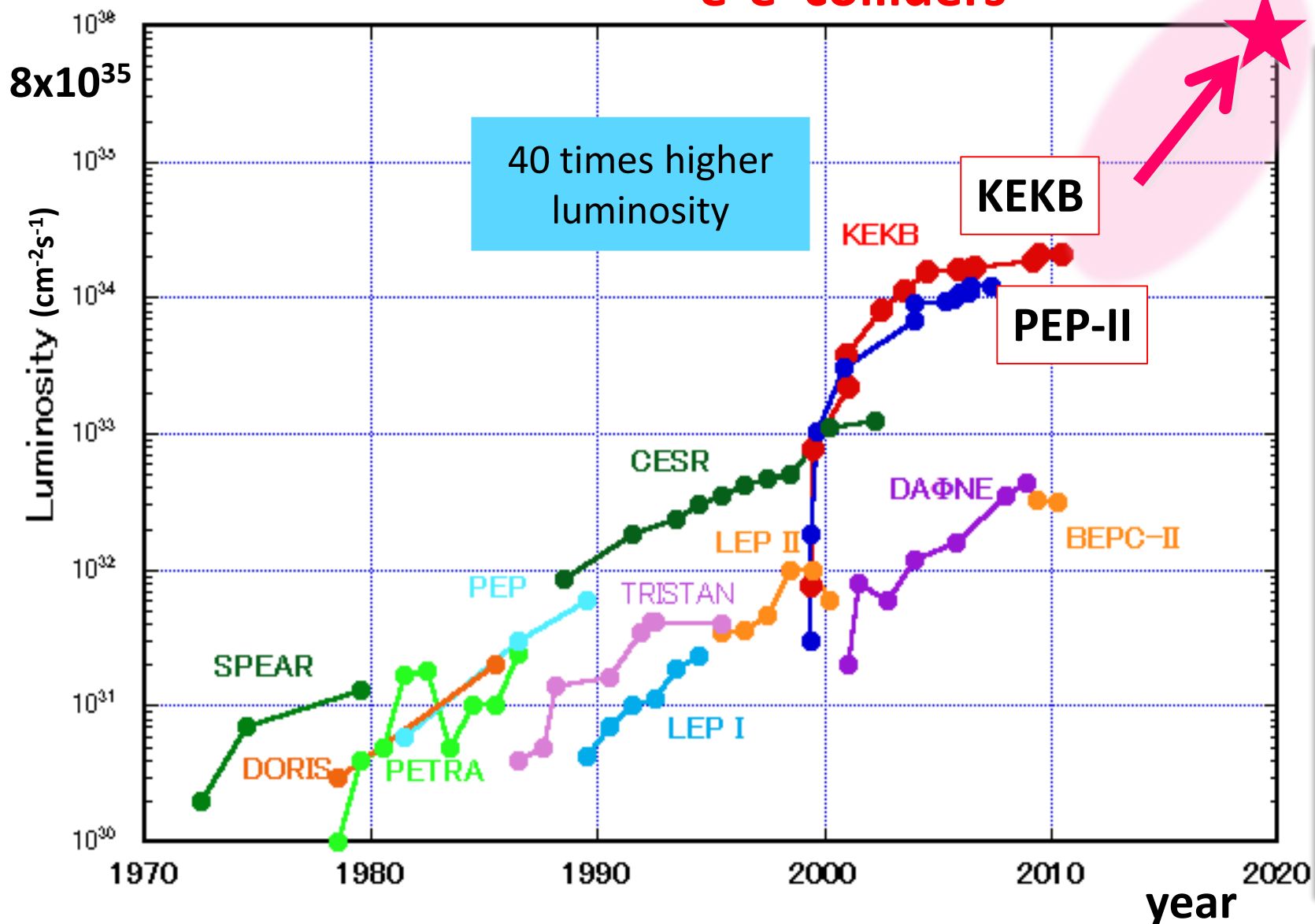
18<sup>th</sup> INTERNATIONAL CONFERENCE  
ON B-PHYSICS AT FRONTIER MACHINES

Ljubljana, Slovenia

September 30 - October 4, 2019

# Peak luminosity trend

$e^+e^-$  colliders



SuperKEKB

## Very rich physics program

### Flavour physics

- CKM matrix
- CPV in B decays

see M. Yonenaga's talk

### BSM physics

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

### New particles (quarkonium)

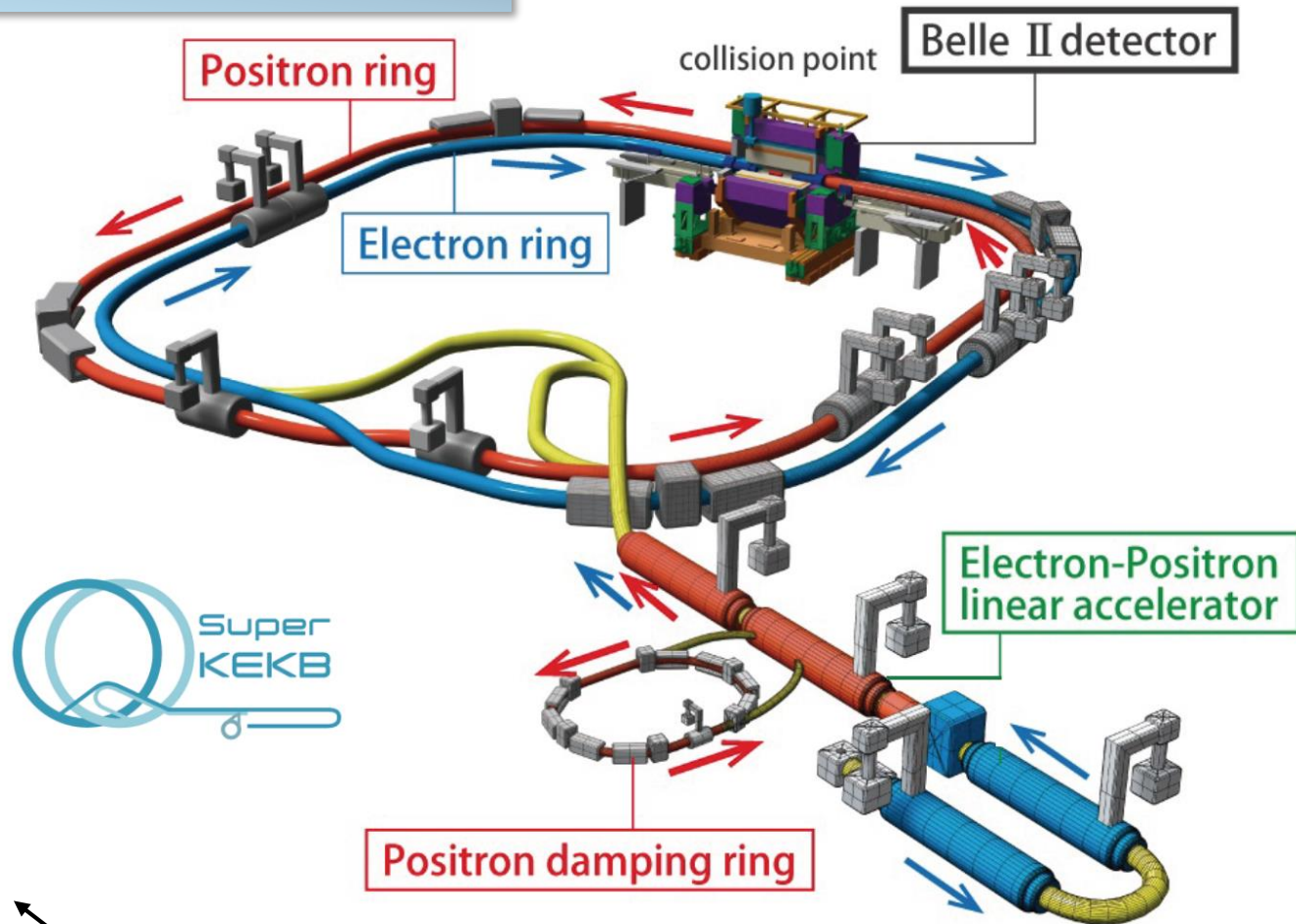
### Dark sector

# From KEKB to SuperKEKB

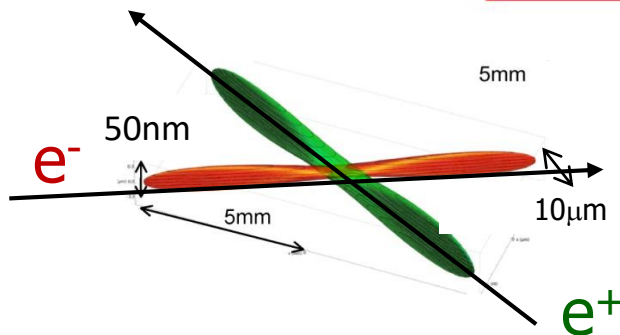
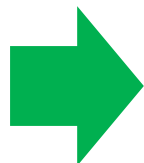
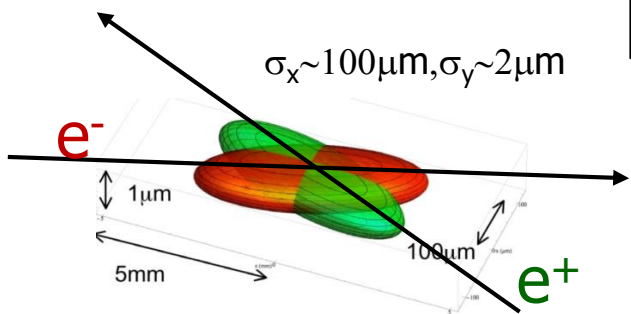
see G. Mohanty's and F. Tenchini's talks

- Upgraded rings → x2
  - New e<sup>+</sup> Damping Ring
  - Increased currents
- Nano-beam scheme → x20
  - New Final Focus magnets (QCS)
  - Large crossing angle

Final goal : 50 ab<sup>-1</sup>



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

## Trigger:

L1: < 30 kHz  
HLT: < 10 kHz

## Vertex detectors (VXD):

2 layer DEPFET pixel detectors (PXD)  
4 layer double-sided silicon strip detectors (SVD)

## Central drift chamber (CDC):

He(50%):C<sub>2</sub>H<sub>6</sub> (50%), small cells,  
fast electronics

## Particle Identification (PID):

Time-Of-Propagation counter (TOP) (barrel)  
Aerogel Ring-Imaging Cerenkov Counter (ARICH)

electrons (7GeV)

$\Upsilon_{4S}$

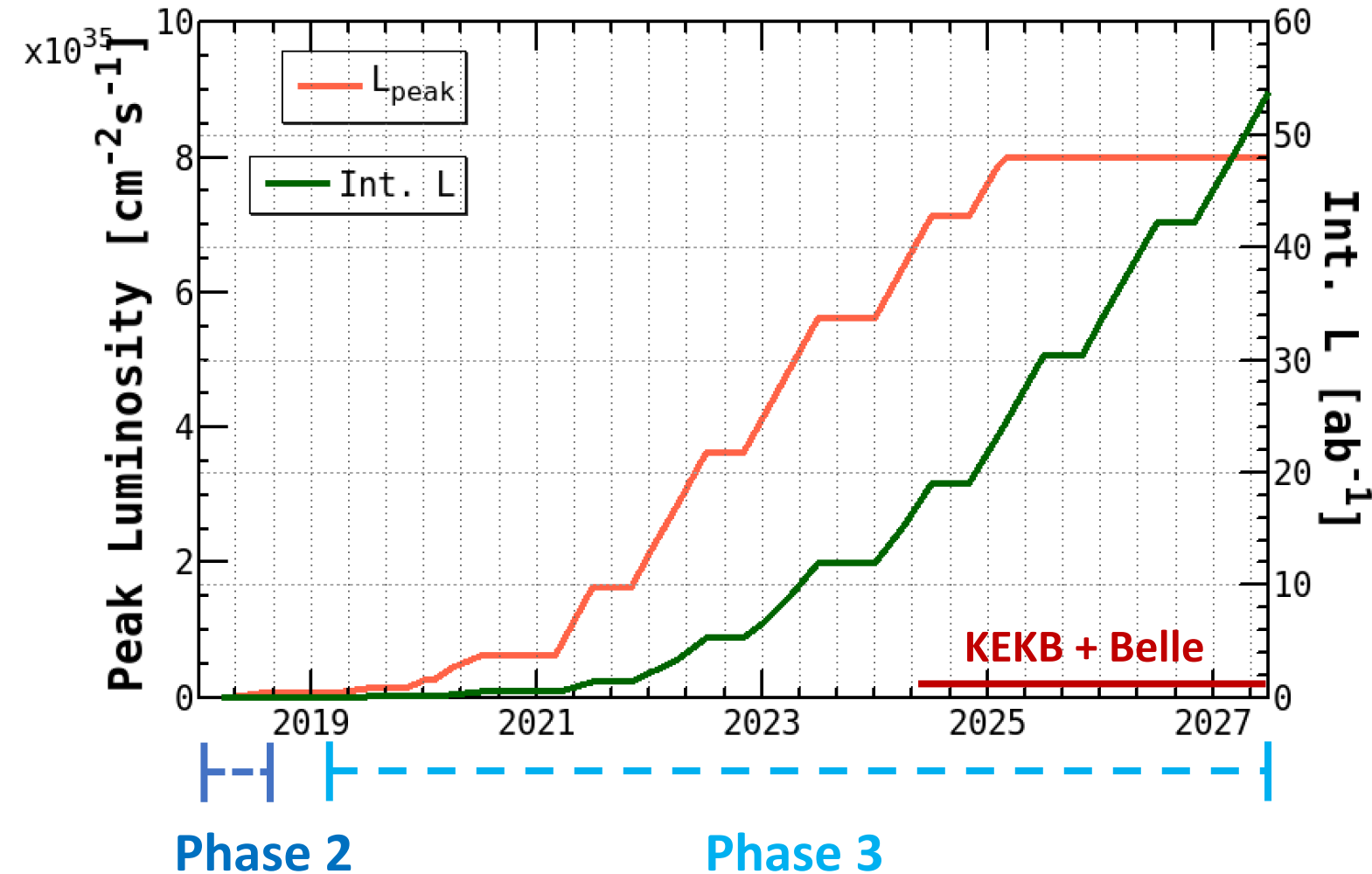
positrons (4GeV)

Belle II vs Belle

better resolution, PID and capability  
to cope with higher background



# Data taking plan



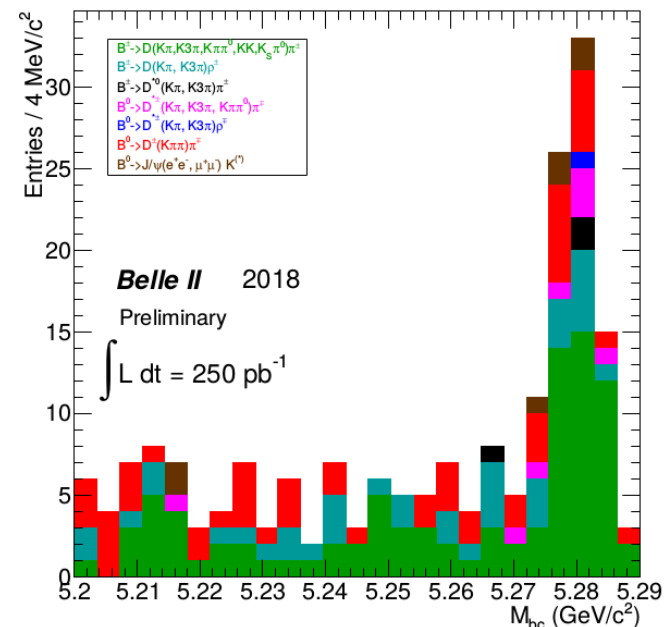
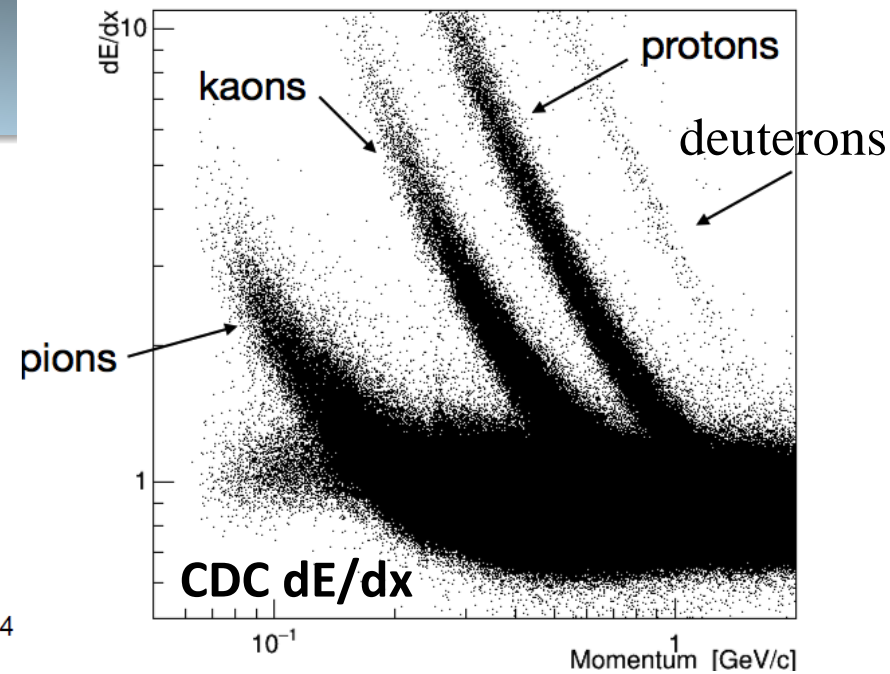
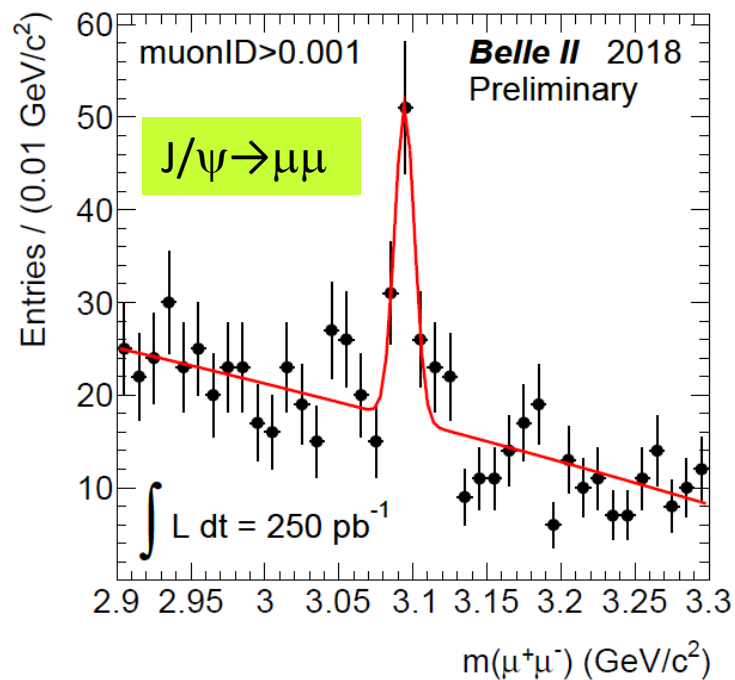
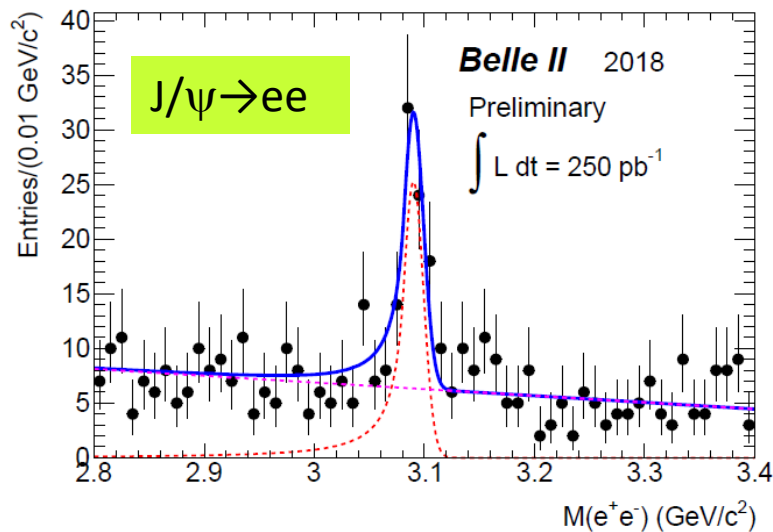
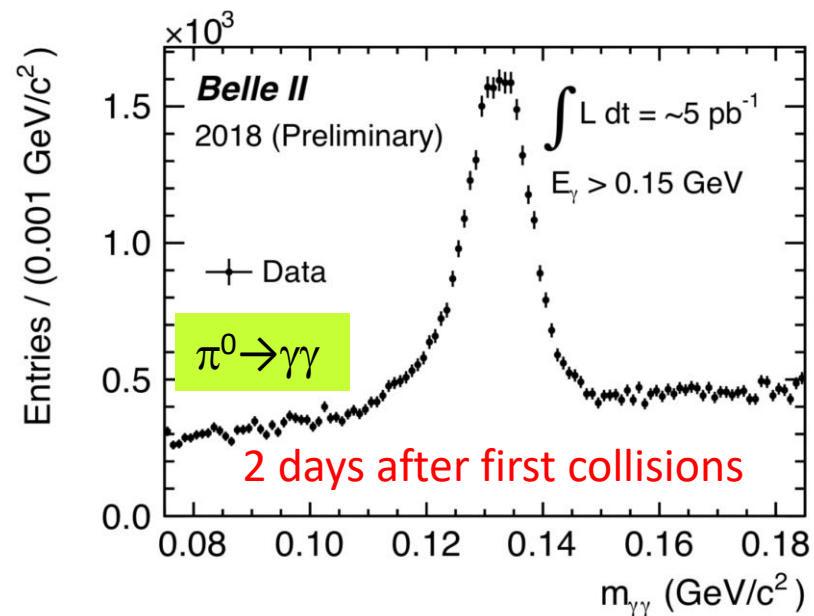
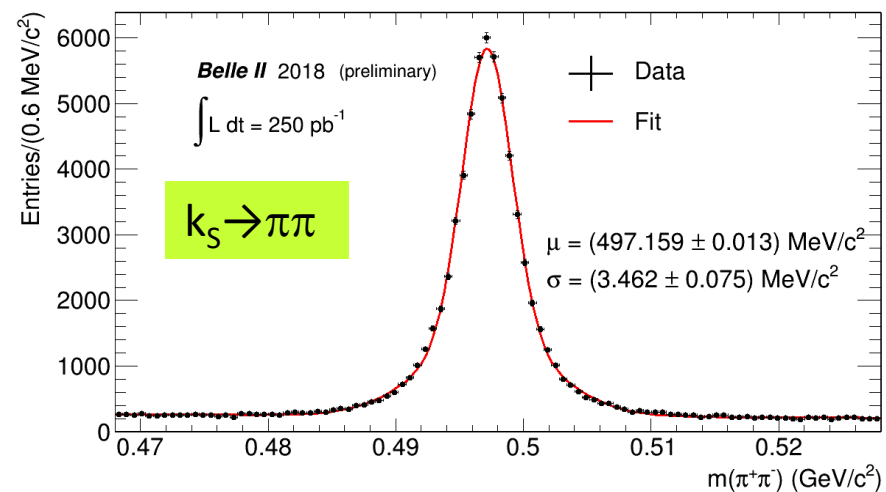
## Phase 2: 2018

- ✓ Incomplete detector (1/8 VXD)
- ✓ Machine + experiment commissioning
- ✓ First physics data:  $\approx 500 \text{ pb}^{-1}$
- ✓ **First dark sector searches**

## Phase 3: 2019 →

- ✓ Physics run started on March 11
- ✓ Complete detector
- ✓  $6.5 \text{ fb}^{-1}$  collected up to now
- ✓ Will continue 7-9 months/year

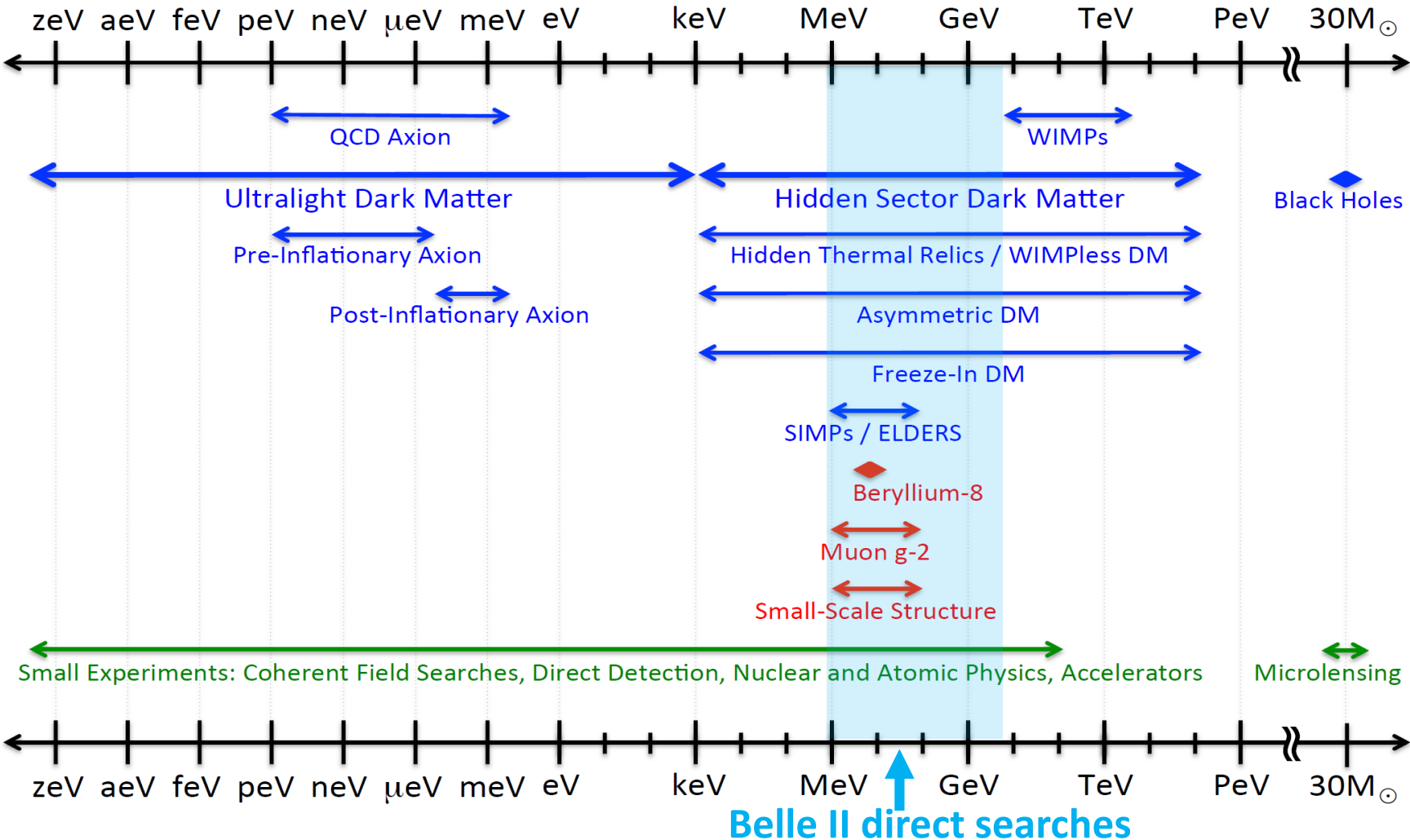
# Belle II performance snapshots: Phase 2



# Searching for dark matter

arXiv: 1707.04591

## Dark Sector Candidates, Anomalies, and Search Techniques



## Dark matter/mediators

**Vector portal** ←

Dark photon,  $Z'$ , ...

**Pseudoscalar portal** ←

Axions, ALPs, ...

**Scalar portal**

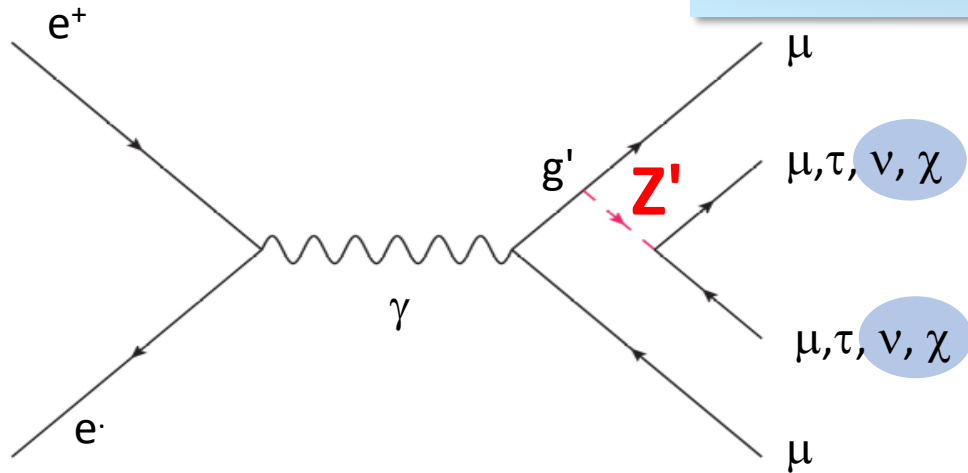
Dark Higgs, scalars

**Neutrino portal**

Sterile neutrino ←

→ Covered here

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



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

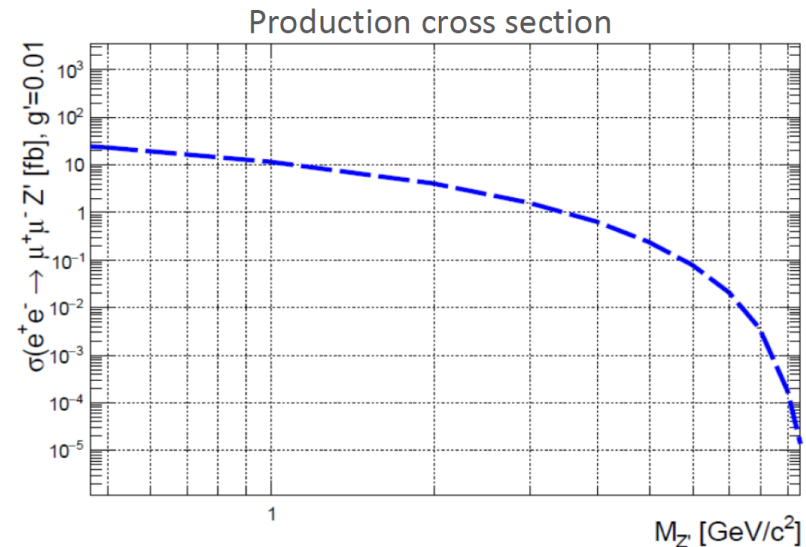
- A new gauge boson which couples only to the 2<sup>o</sup> and 3<sup>o</sup> lepton family
- Invisible decay channel explored for the first time
- It may solve
  - **dark matter puzzle**
    - Sterile  $\nu$ 's
    - Light Dirac fermions
  - $(g-2)_\mu$
  - $B \rightarrow K^{(*)} \mu \mu, R_K, R_{K^*}$  anomalies

$$e^+e^- \rightarrow \mu^+\mu^- + \text{missing energy}$$

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

Main backgrounds:

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





# Z' to invisible: results

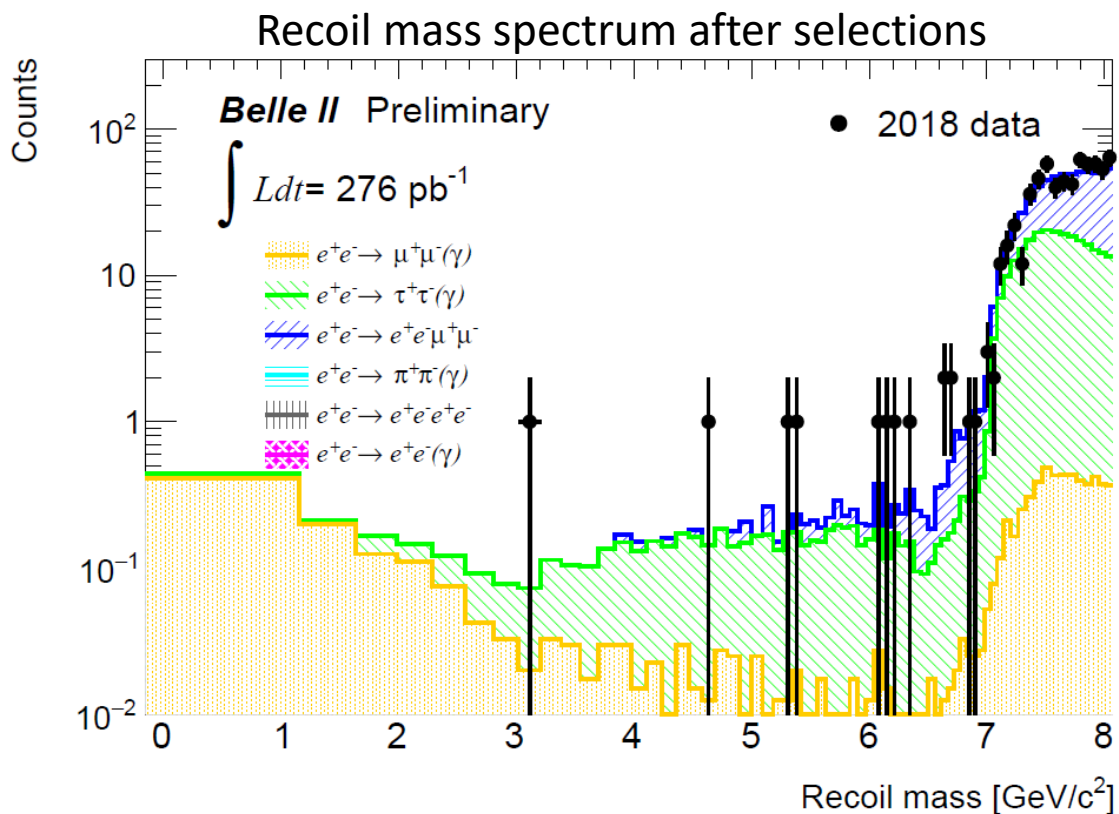
## Phase 2 results

Only 276 pb<sup>-1</sup> usable due to trigger conditions

### Systematics

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

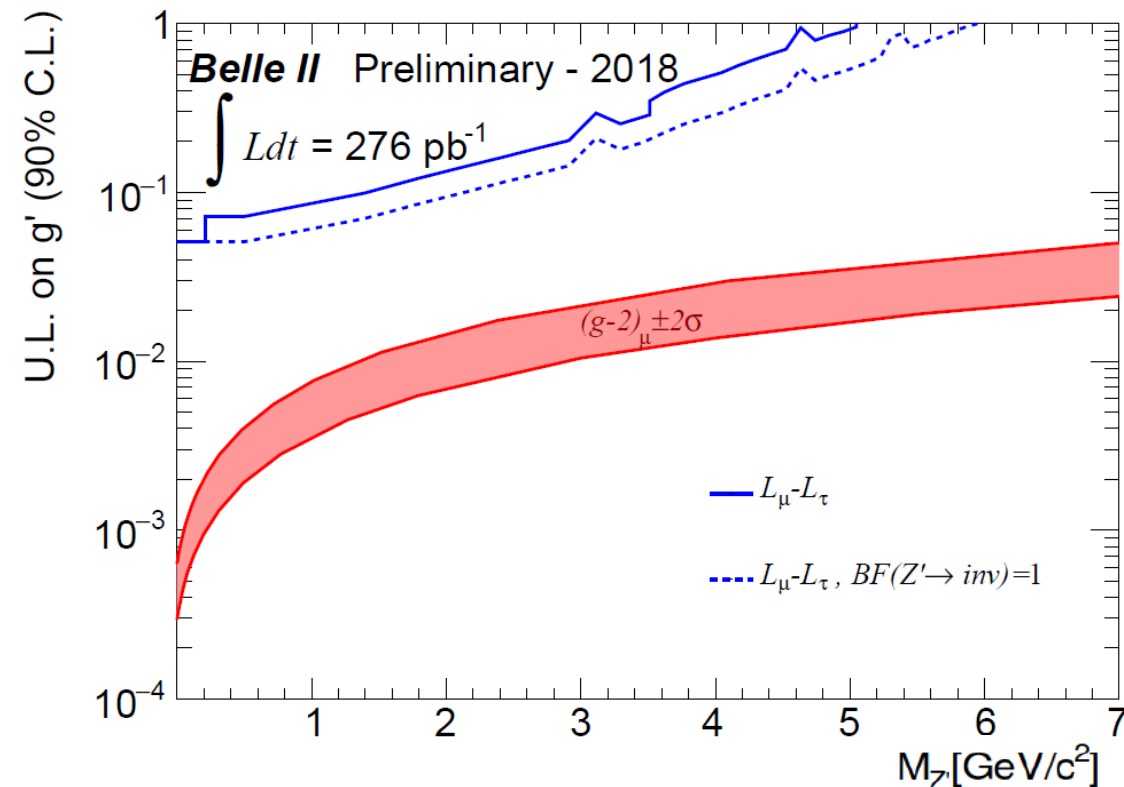
will decrease with new data



No excess

**PRL paper close to submission**

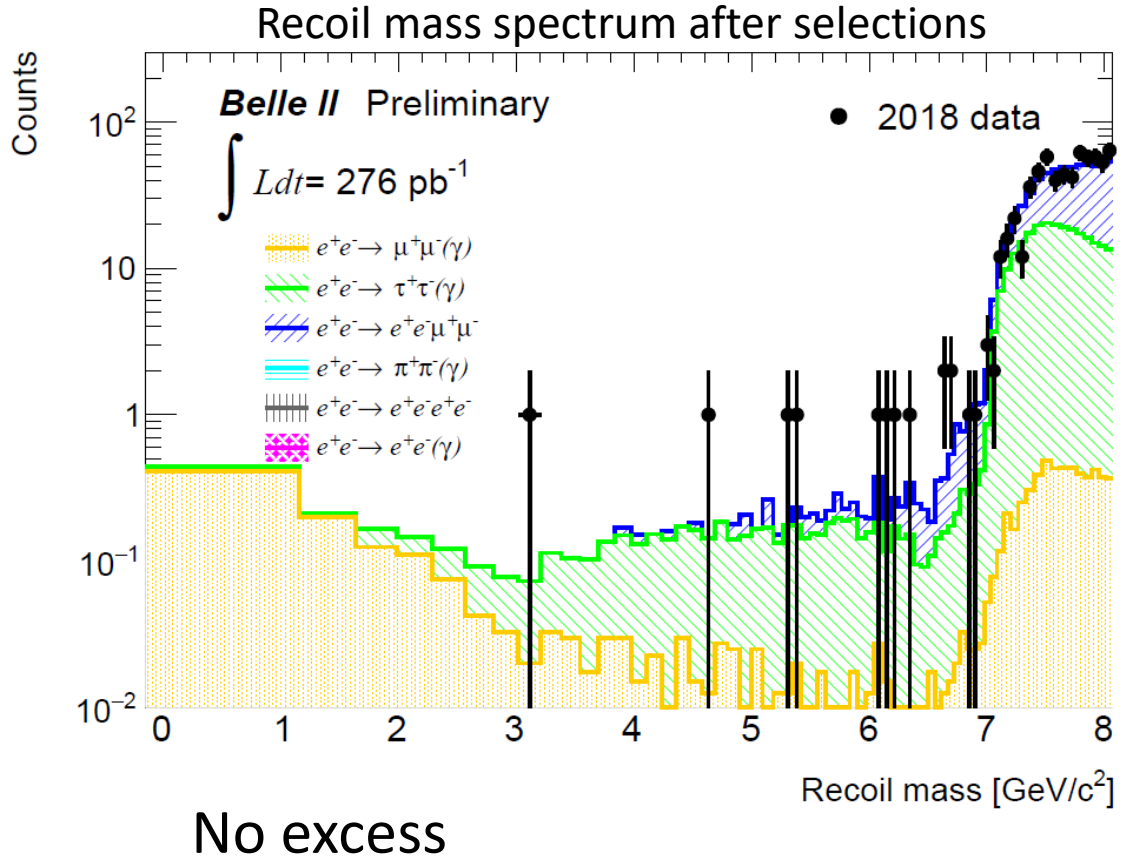
**First physics paper by Belle II**



# Z' to invisible: results

## Phase 2 results

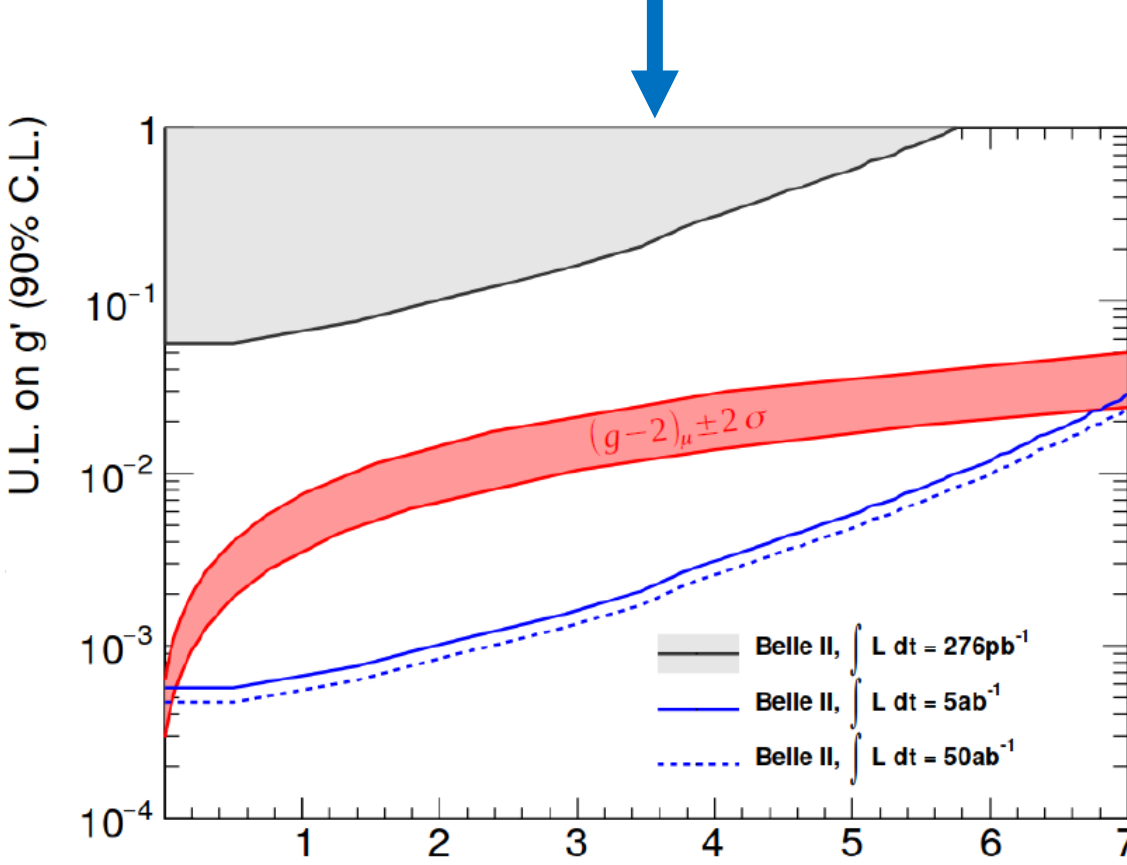
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**PRL paper close to submission**  
**First physics paper by Belle II**

## Projections

- Systematics down to 3%
- $L_{\text{int}} = 5, 50 \text{ ab}^{-1}$



**Phase 3 analysis started**

# LFV $Z'$ to invisible

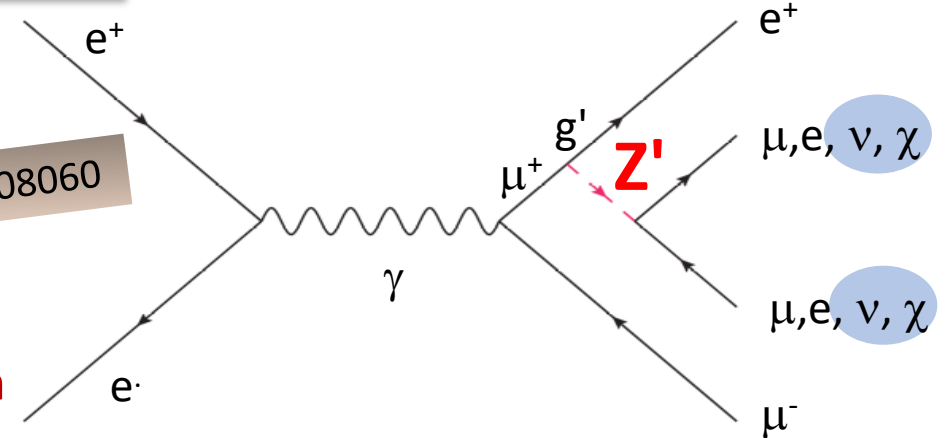
What about a Lepton Flavour Violating  $Z'$ ?

Only e- $\mu$  coupling taken into account

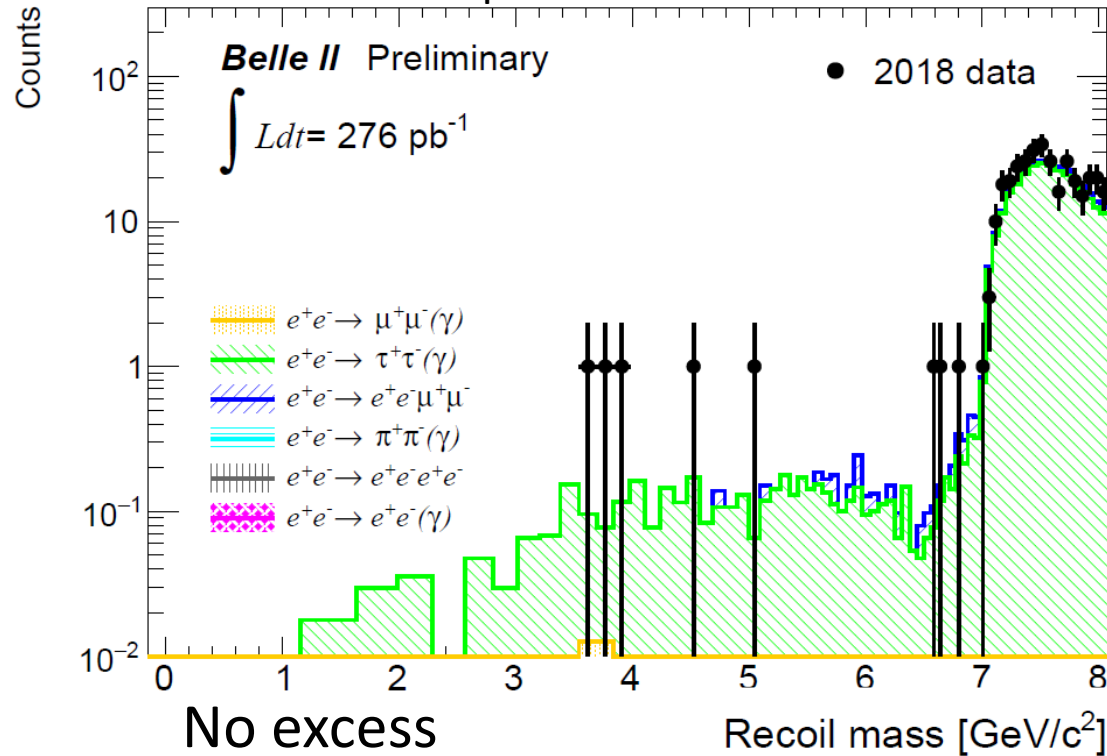
For example I.Galon et al. (2016), arXiv 1610.08060

Model independent search

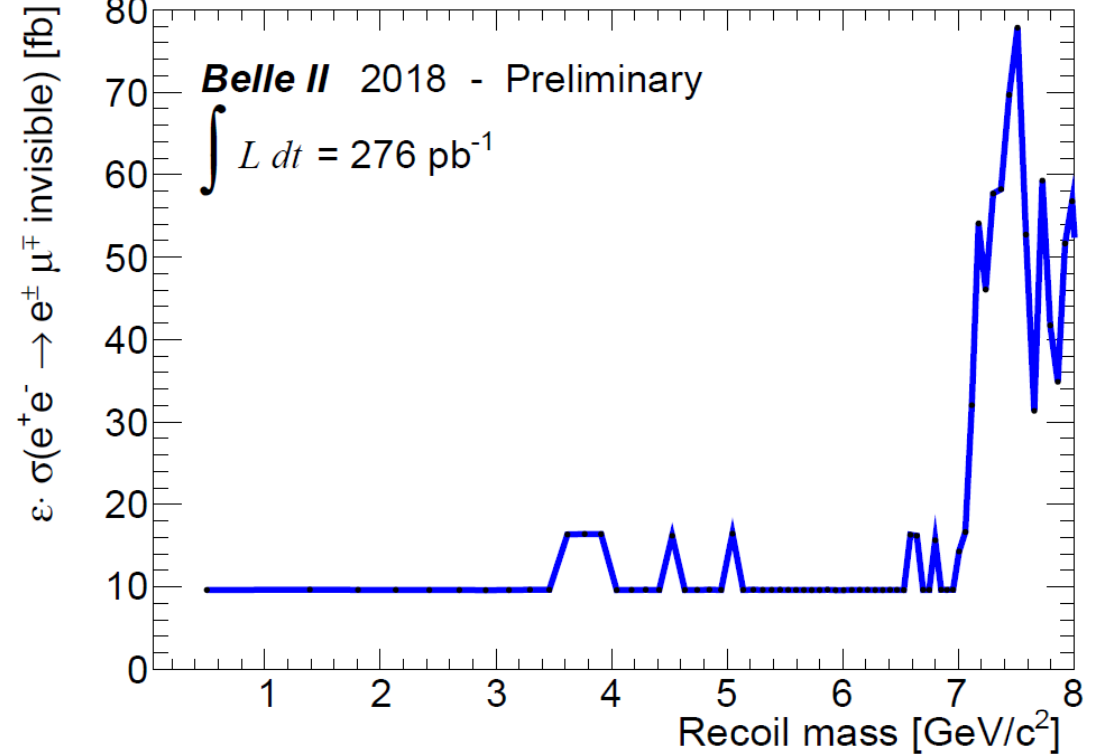
$$e^+e^- \rightarrow e^+\mu^- + \text{missing energy}$$



Recoil mass spectrum after selections



90% CL UL to  $\epsilon \times \sigma$



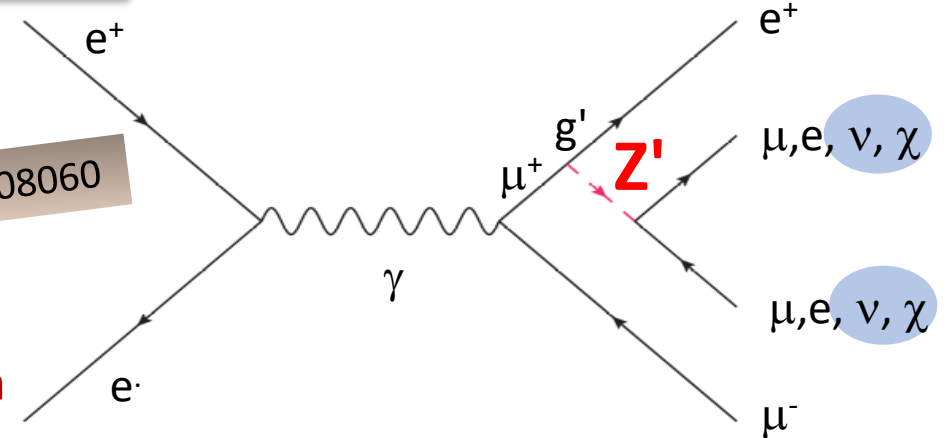
# LFV $Z'$ to invisible

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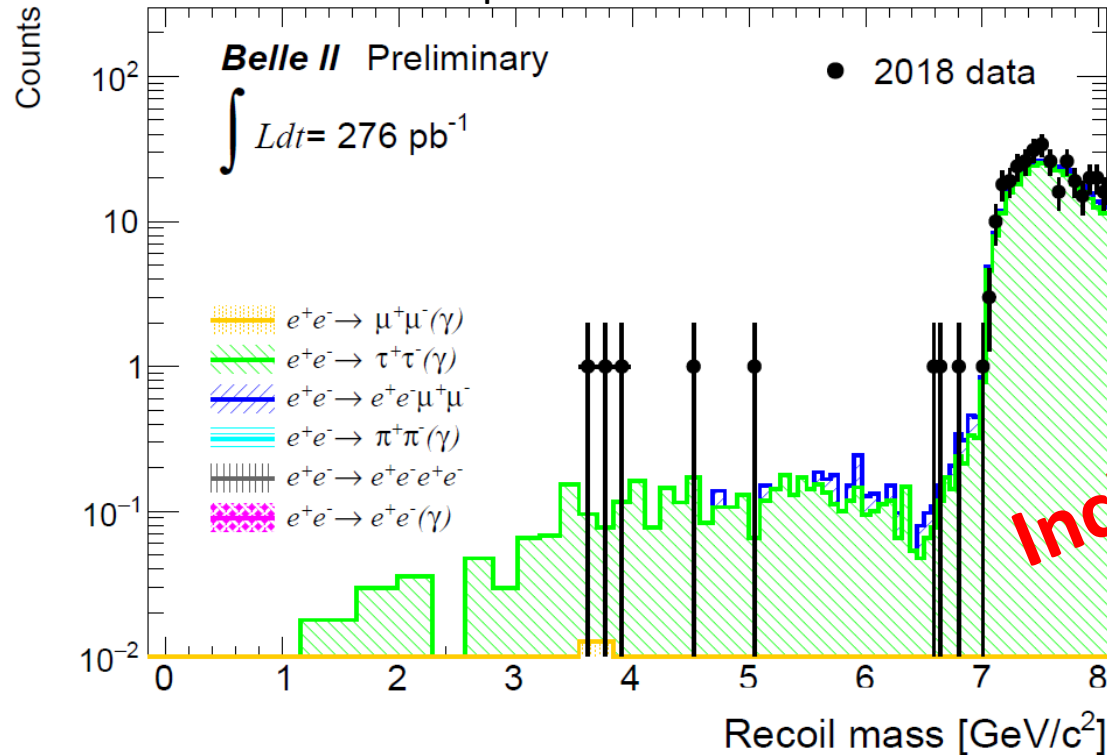
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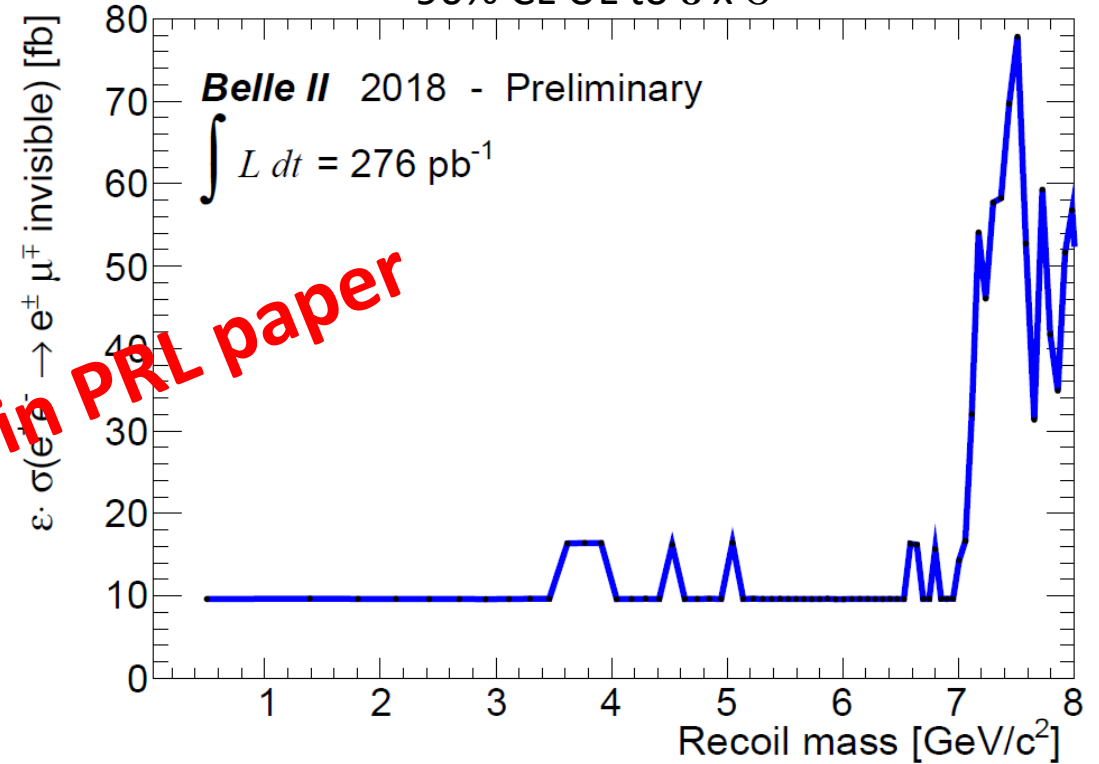


Model independent search

Recoil mass spectrum after selections

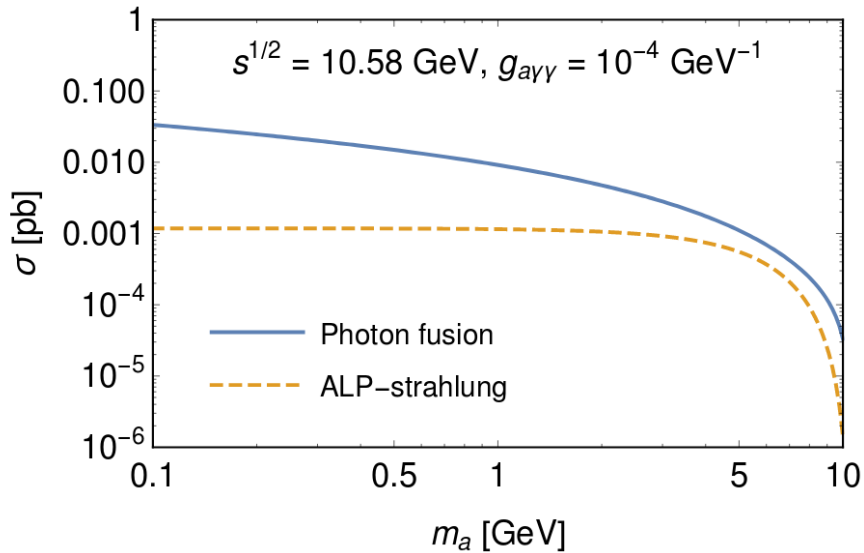
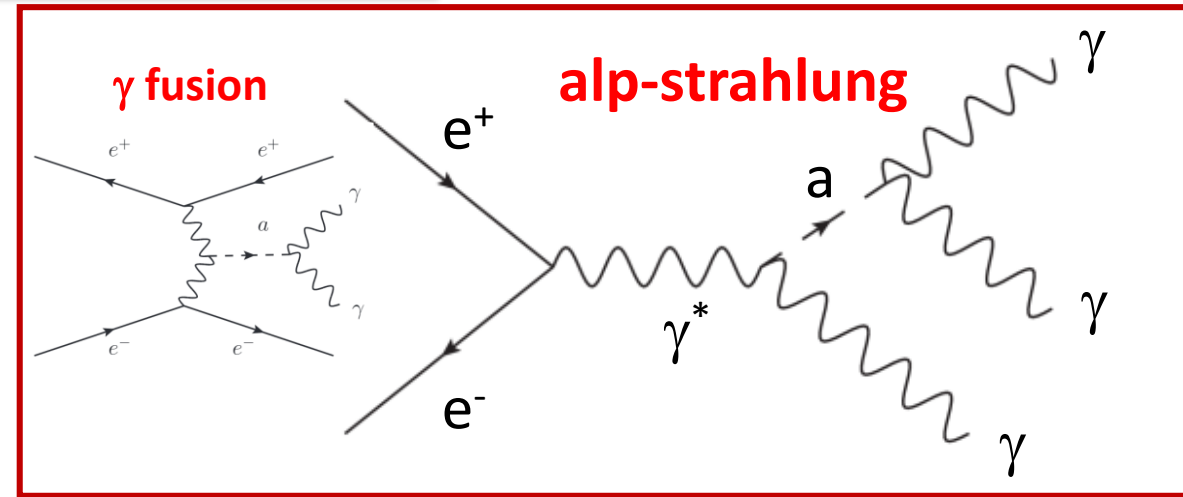


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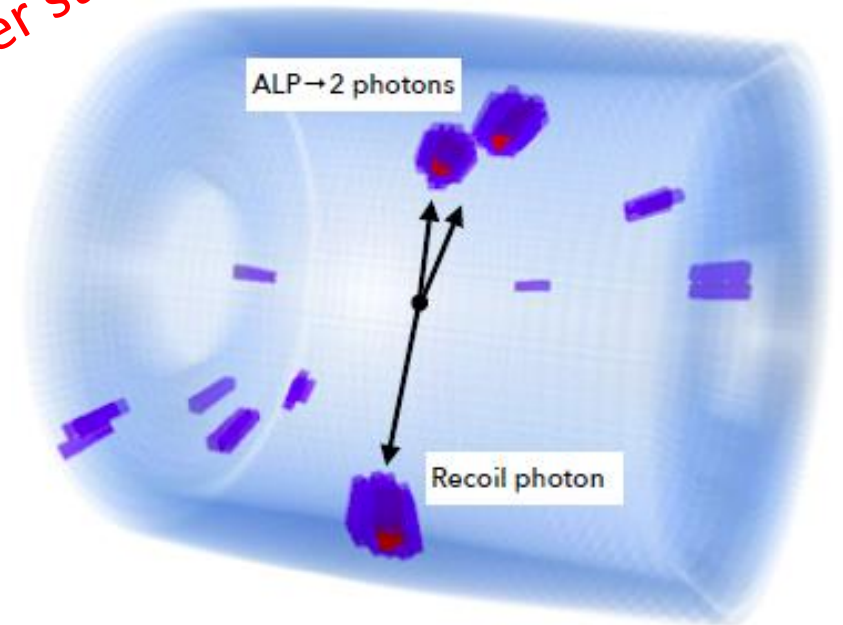
# Axion Like Particles (ALPs)

- Pseudo-scalars particles which couple to bosons
- No mass $\leftrightarrow$ coupling relationship
- Focus on coupling to photons:  $g_{a\gamma\gamma}$
- Alp-strahlung + photon fusion production mechanisms
- $\tau \sim 1 / g_{a\gamma\gamma}^2 m_a^3$
- No results at B factories yet



photon fusion sensitivity under study

3  $\gamma$  topology



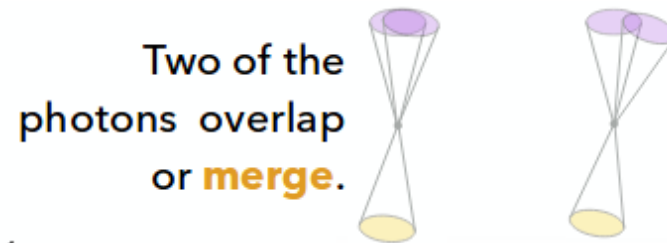


# Axion Like Particles (ALPs): signal

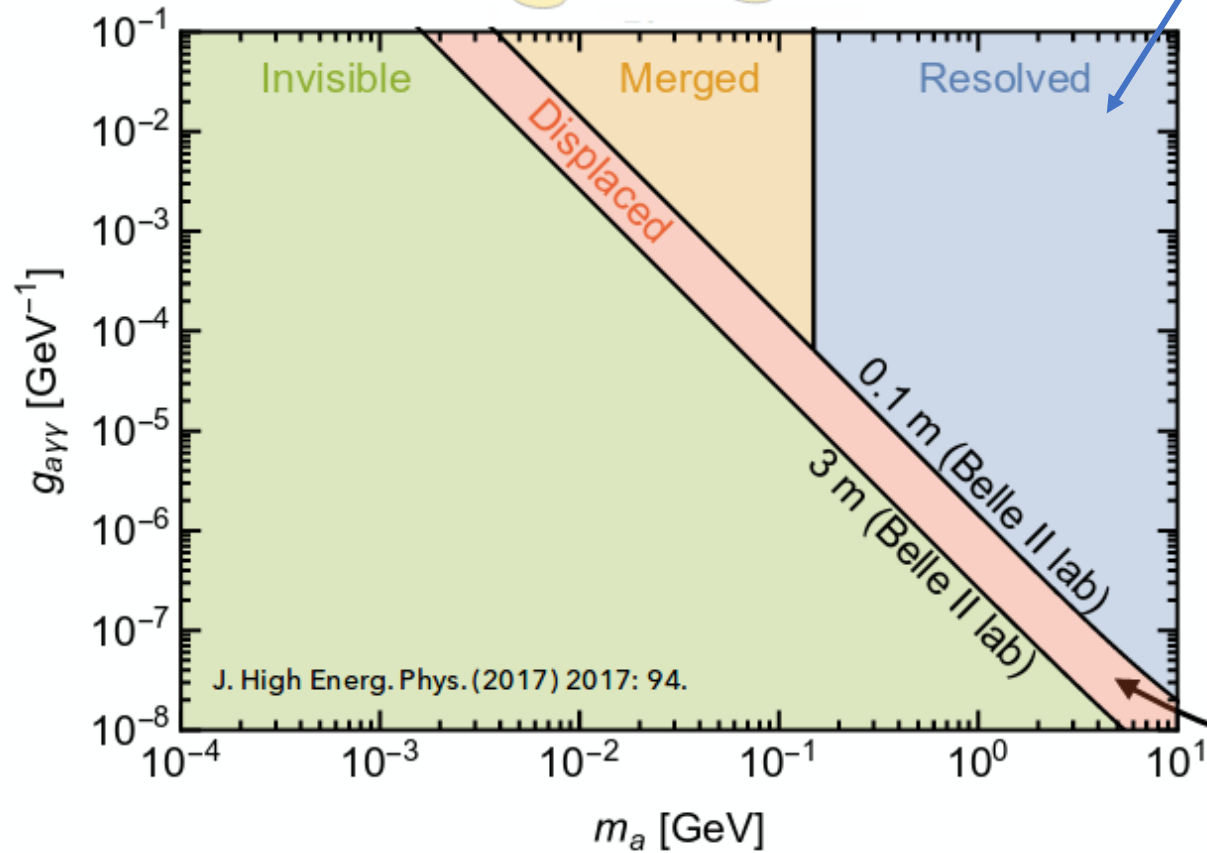
3  $\gamma$  topology, but...



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



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



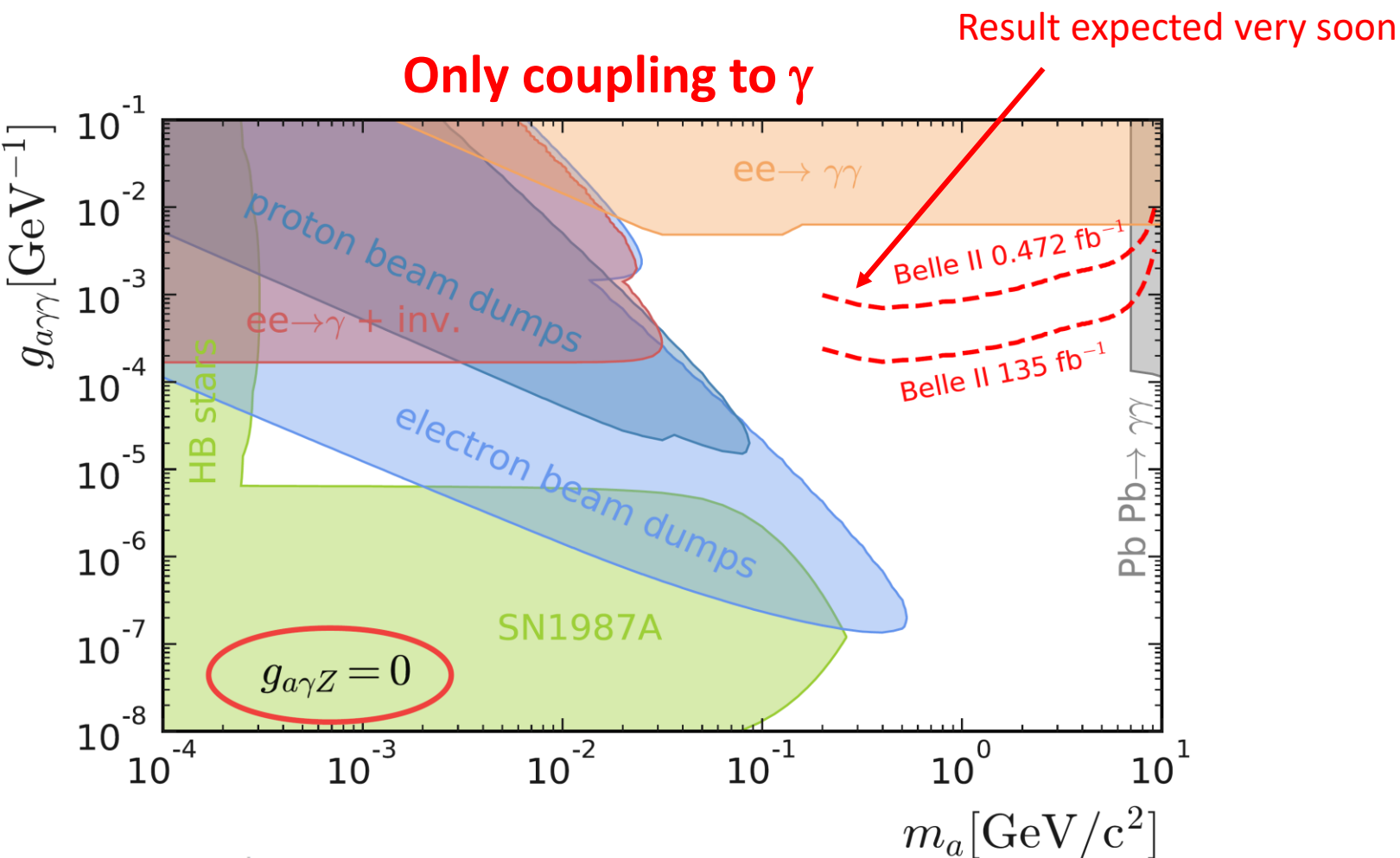
Three **resolved**, high energetic photons.



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

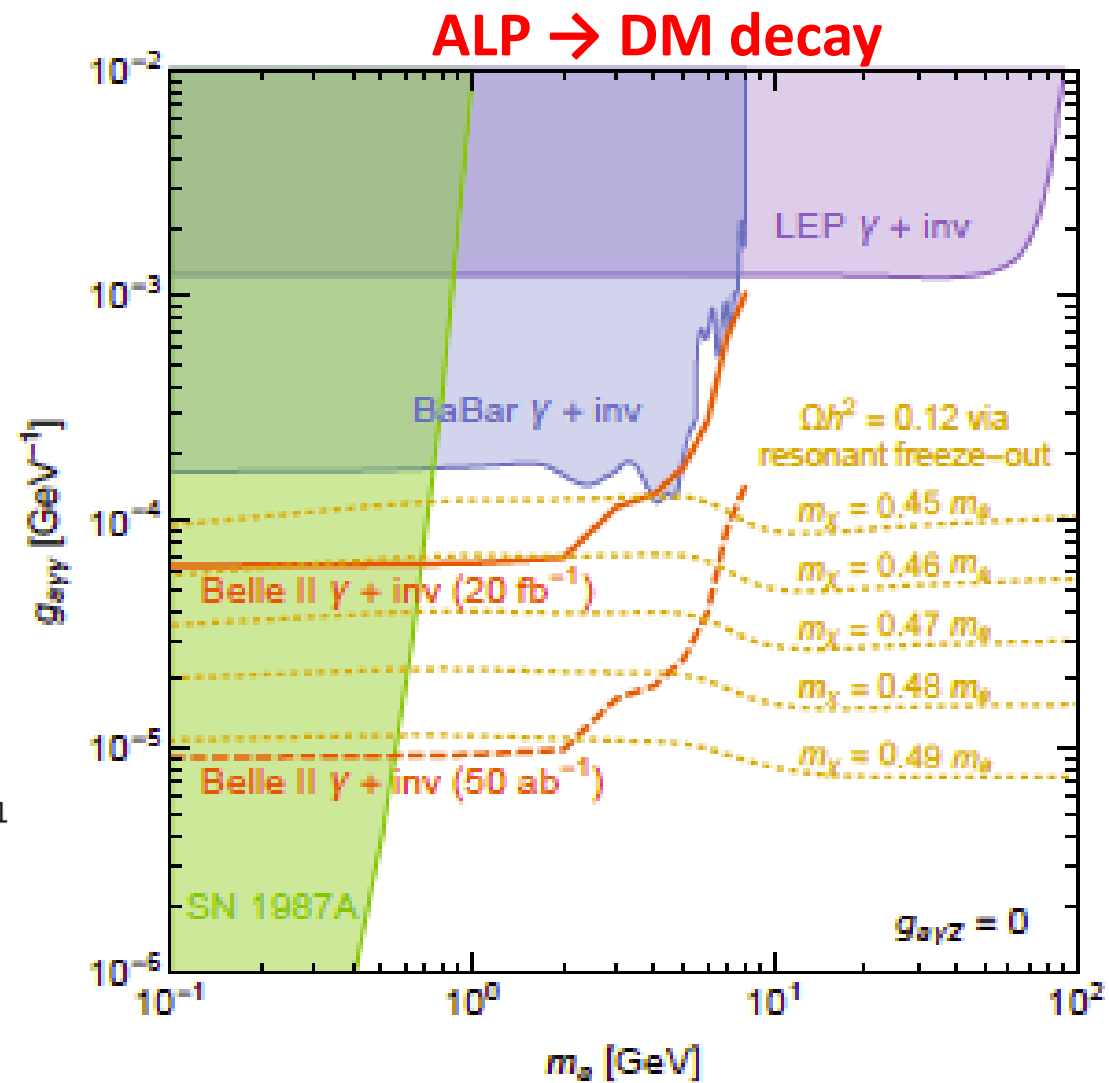
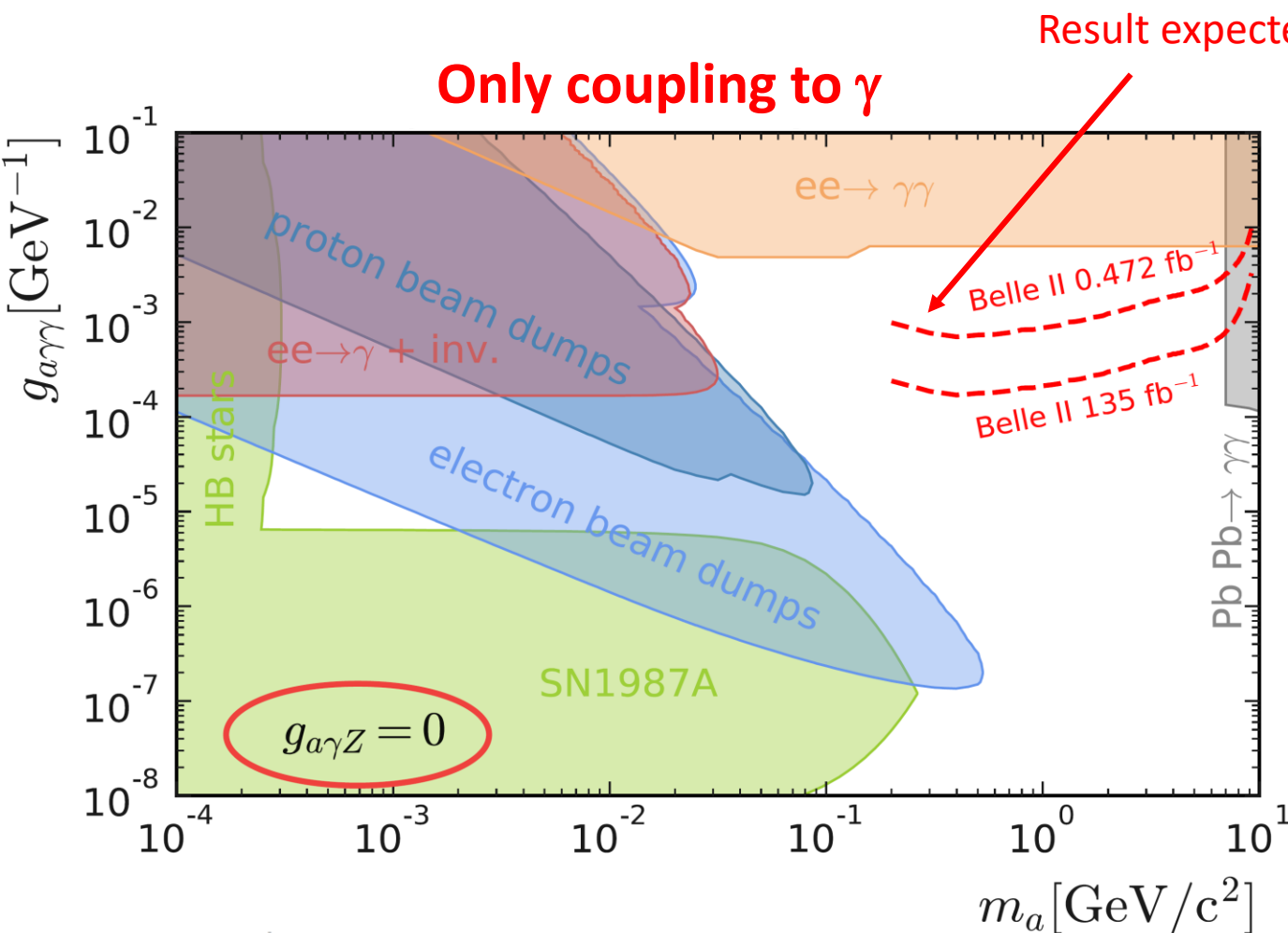
**ALPs can also decay to DM  $\rightarrow$  single photon topology**

# Axion Like Particles (ALPs): sensitivity



- ✓ No systematics yet in sensitivity evaluation
- ✓ Only dominant  $\gamma\gamma\gamma$  background included
- ✓ 135  $\text{fb}^{-1}$  assumes no  $\gamma\gamma$  trigger veto in the barrel

# Axion Like Particles (ALPs): sensitivity

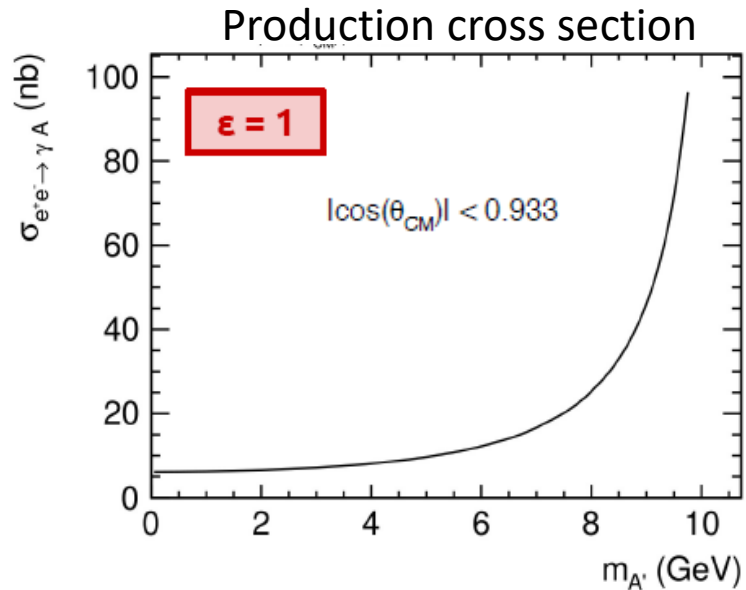
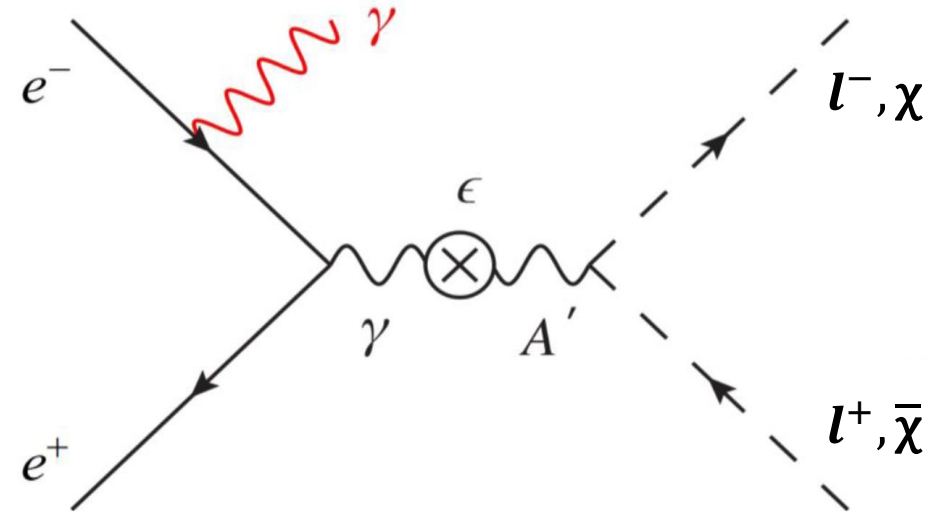


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- ✓ Only dominant  $\gamma\gamma\gamma$  background included
- ✓  $135 \text{ fb}^{-1}$  assumes no  $\gamma\gamma$  trigger veto in the barrel

# 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
- Additional  $U(1)'$   $\rightarrow$  new spin 1 gauge boson  $A'$
- Couples to SM with kinetic mixing  $\epsilon$
- Couples to dark matter with strength  $\alpha_D$
- may acquire mass through Higgs or Stuckelberg mechanism



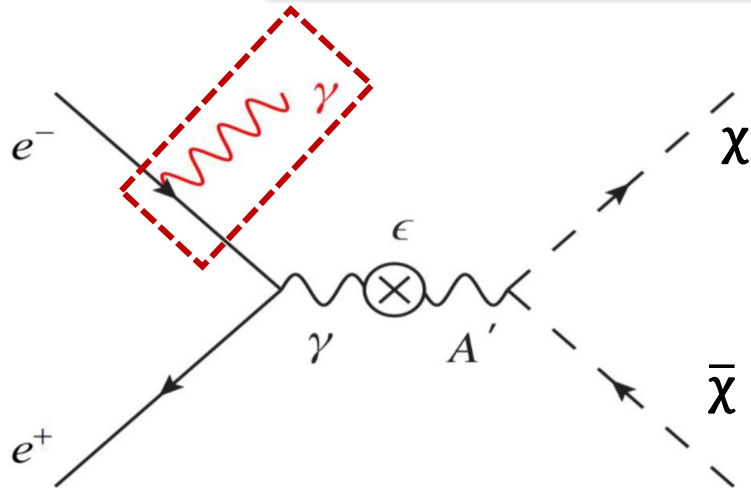
**two basic scenarios depending on  $A'$  vs DM mass relationship**

$m_{A'} < 2m_\chi \Rightarrow A'$  decays visibly to SM particles

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

# Invisible dark photon: experimental signature

Only **one photon** in the detector.  
 Needs a **single photon trigger**  
 (not available in Belle,  $\approx 10\%$  of data in BaBar)

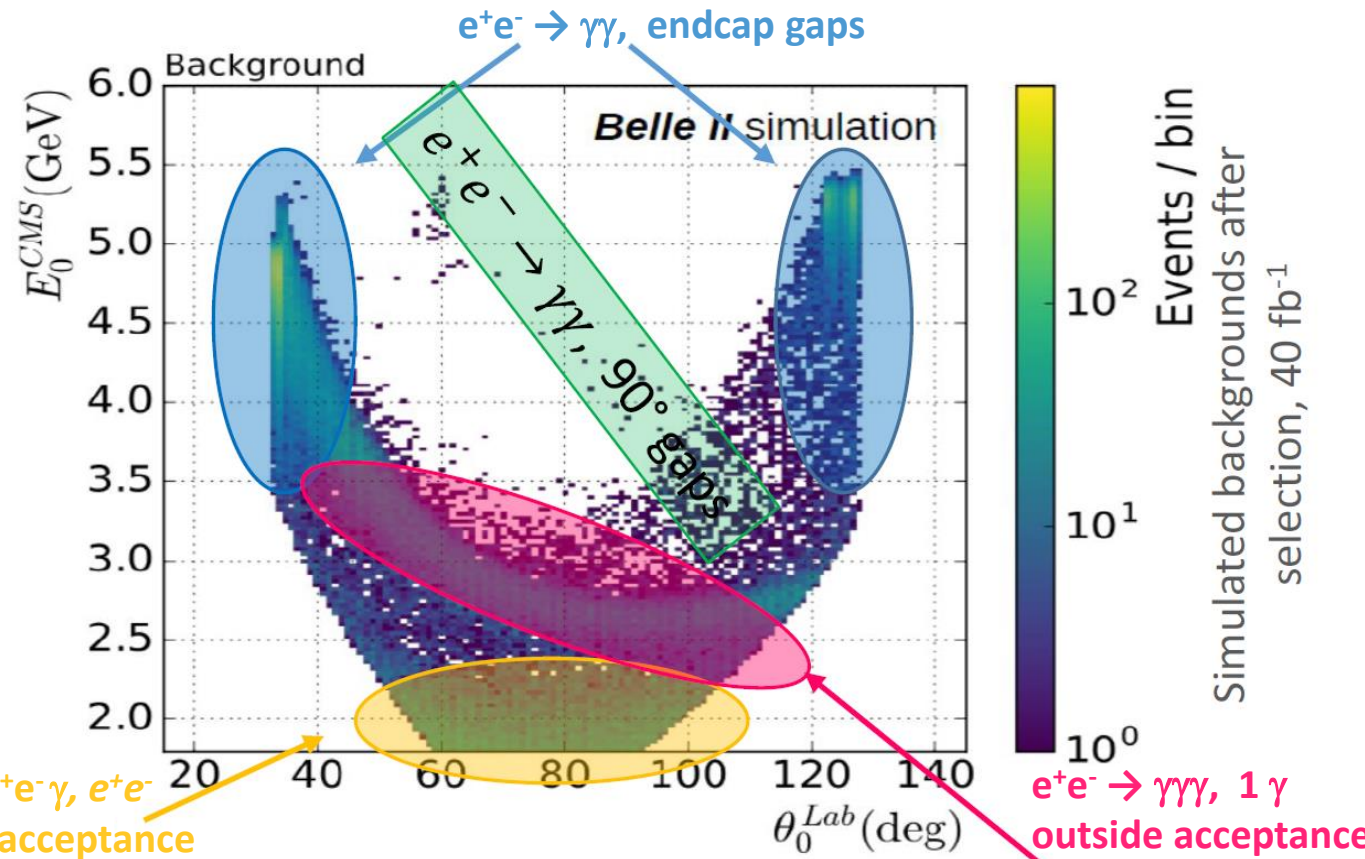


$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$

Bump in recoil mass or photon energy

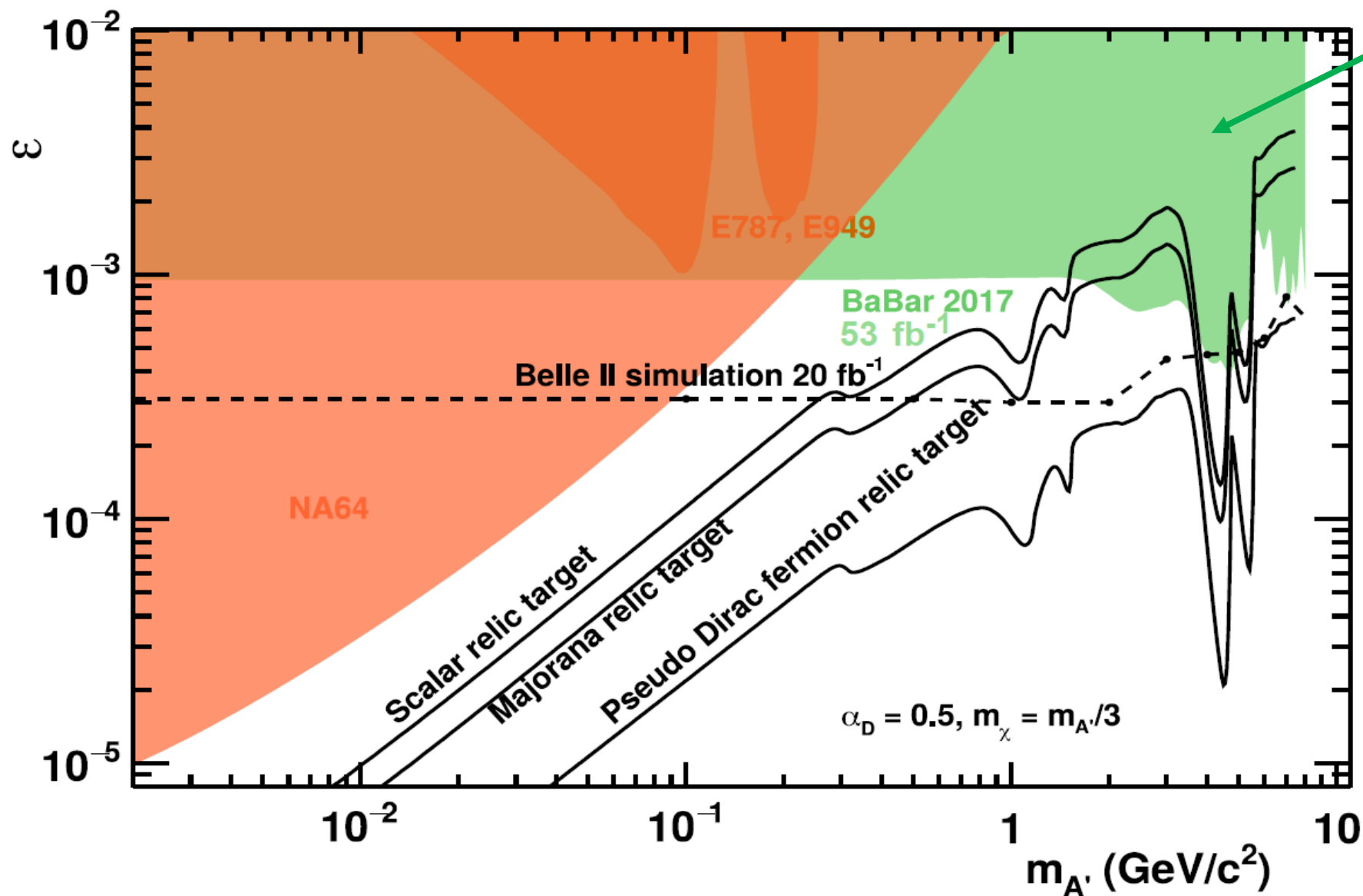
## Backgrounds

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





# Invisible dark photon: sensitivity



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

- Belle II vs BaBar**
- ✓ calorimeter with no projective cracks in  $\phi$
  - ✓ Smaller boost
  - ✓ Larger acceptance

# Summary

- Belle II started operations in 2018 (Phase 2) with  $0.5 \text{ fb}^{-1}$
- Successful detector and machine commissioning
- Physics run (Phase 3) started in March:  $6.5 \text{ fb}^{-1}$  collected up to now.
- Resonances, b-physics and charm physics «rediscovered»
- First physics results with Phase 2 data are coming

*see G. Mohanty's and F. Tenchini's talk*

- **Z' to invisible search** →
- **Z' LFV to invisible search** → **Very close to PRL submission**
- **ALP search** → **Ready for box opening (Phase 2)**
- **Invisible dark photon search** → **High priority in Phase 3  
Results expected by 2020**

## Not even mentioned

- Y(1S) to invisible
- visible dark photon
- muonic dark force
- dark Higgstrahlung
- dark scalars
- Magnetic monopoles
- long-lived particles
- ...

**We have ideas for measurements never done before. Theory/phenomenology inputs are very welcome**

# SPARE SLIDES

# From KEKB to SuperKEKB



Beam-beam parameter

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

Beam current

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

Lorentz factor

Classical electron radius

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

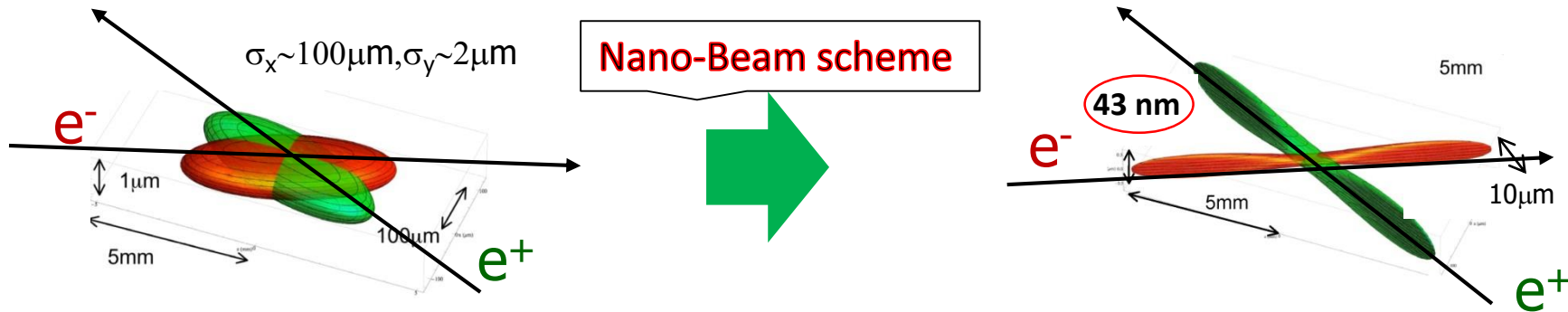
Lumi. reduction factor (crossing angle) & Tune shift reduction factor (hour glass effect)  
0.8 ~ 1 (short bunch)

Vertical beta function@IP

- (1) Smaller  $\beta_y^*$  x20
- (2) Increase beam currents x2
- (3) Increase  $\xi_y$

$\beta_y^* = 0.27/0.30$  mm  
 $I_{+/-} = 3.6/2.6$  A

- New e<sup>+</sup> Damping Ring
- New Superconducting Final Focus (QCS)



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



# Belle II & SuperKEKB

## Phase 2

Start of collisions: April 25<sup>th</sup> 2018



## Phase 3

Start of collisions: March 25<sup>th</sup> 2019

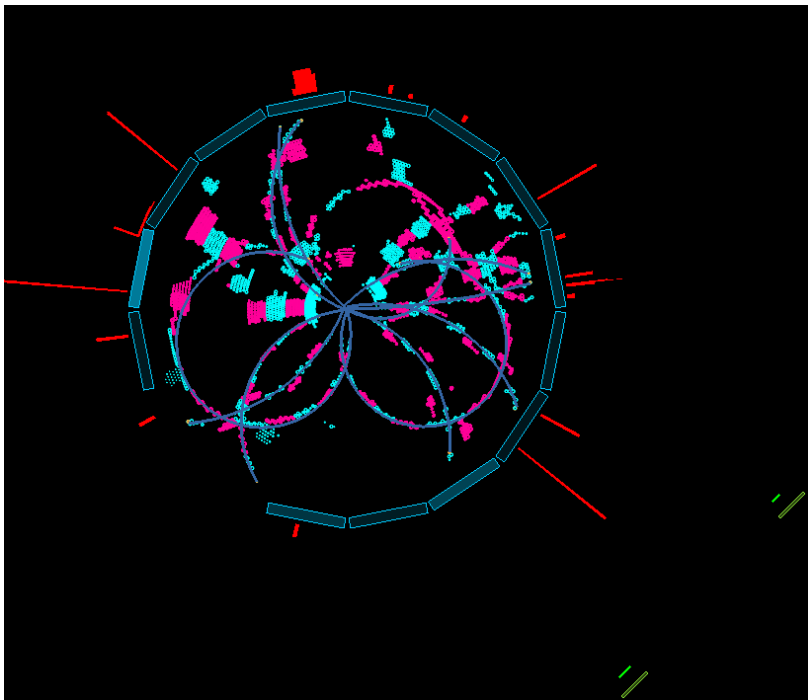




# Belle II & SuperKEKB

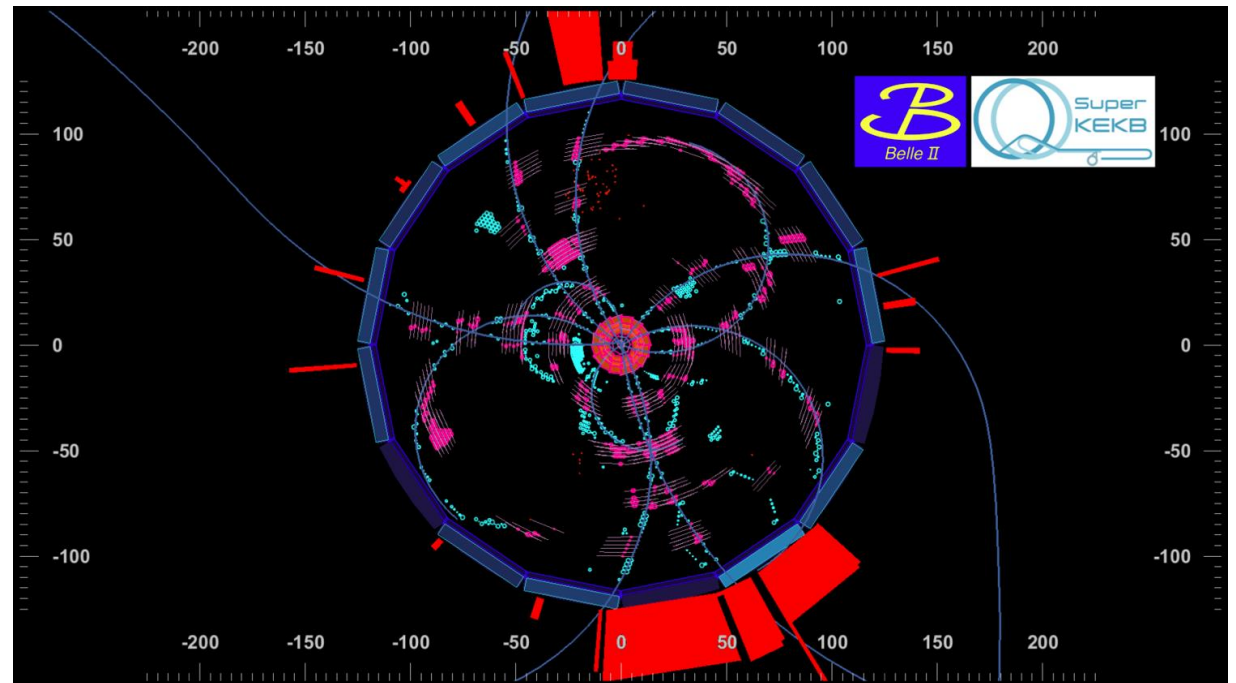
## Phase 2

Start of collisions: April 25<sup>th</sup> 2018

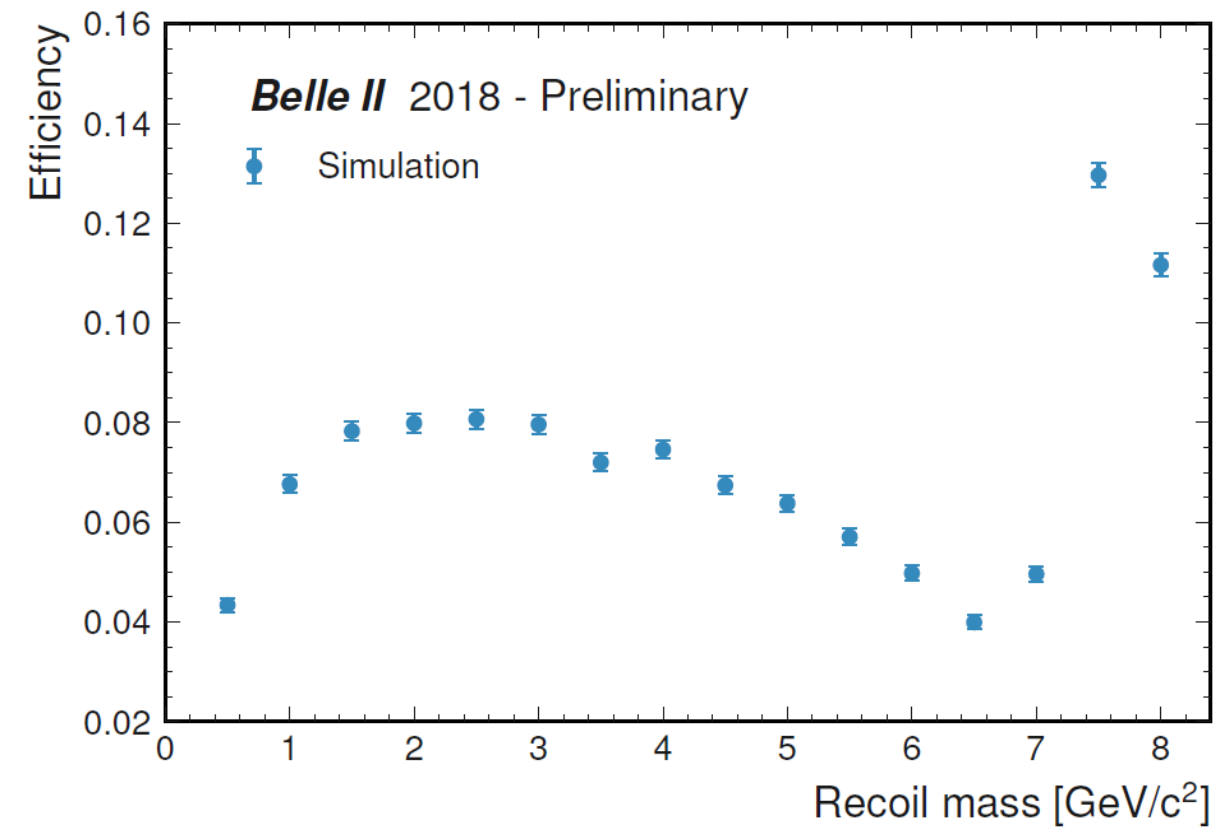
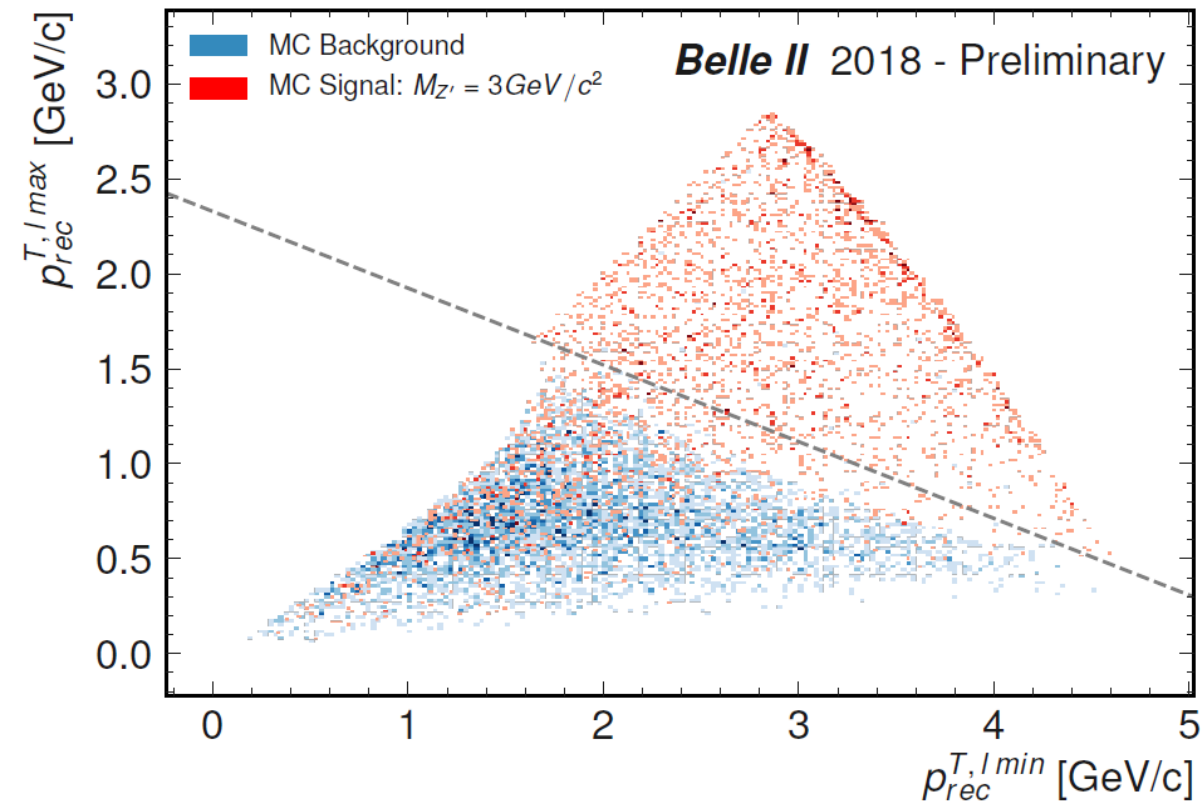


## Phase 3

Start of collisions: March 25<sup>th</sup> 2019

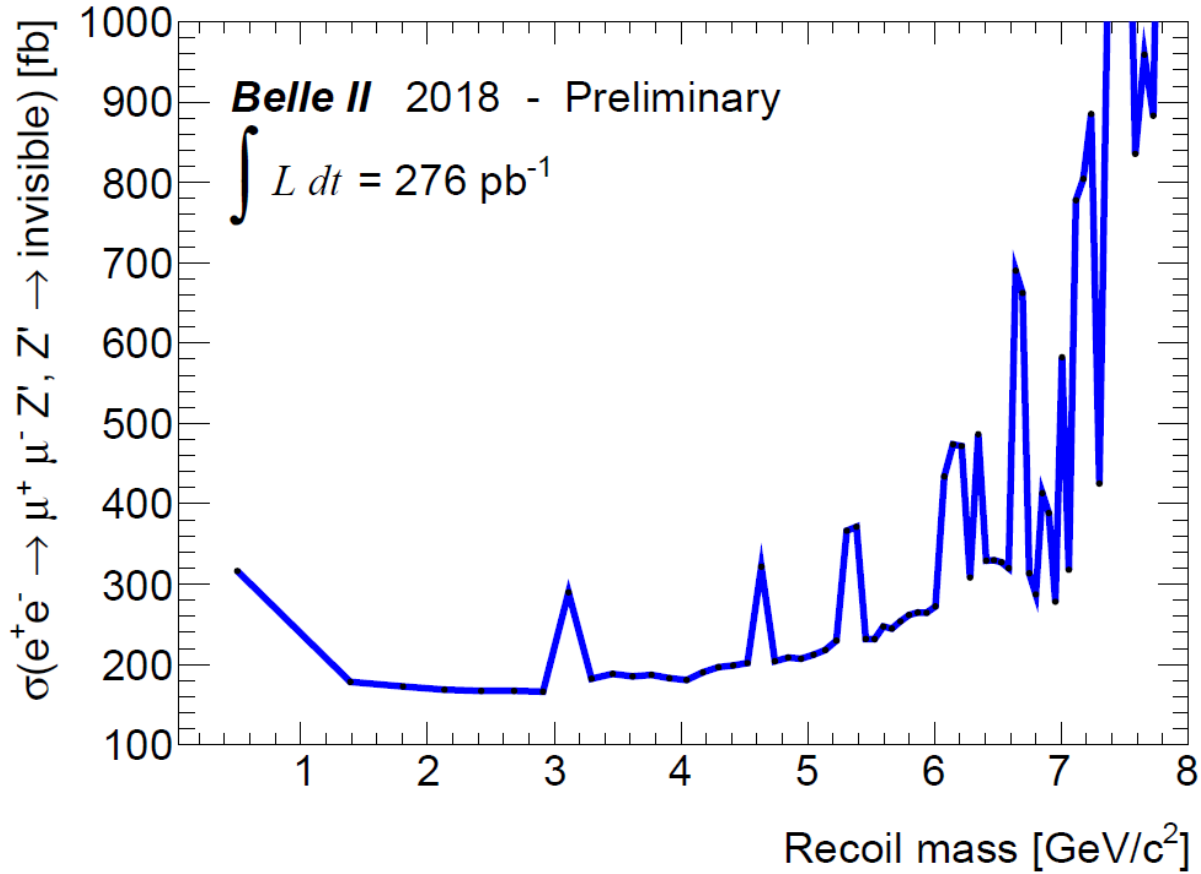


# Z' to invisible: analysis

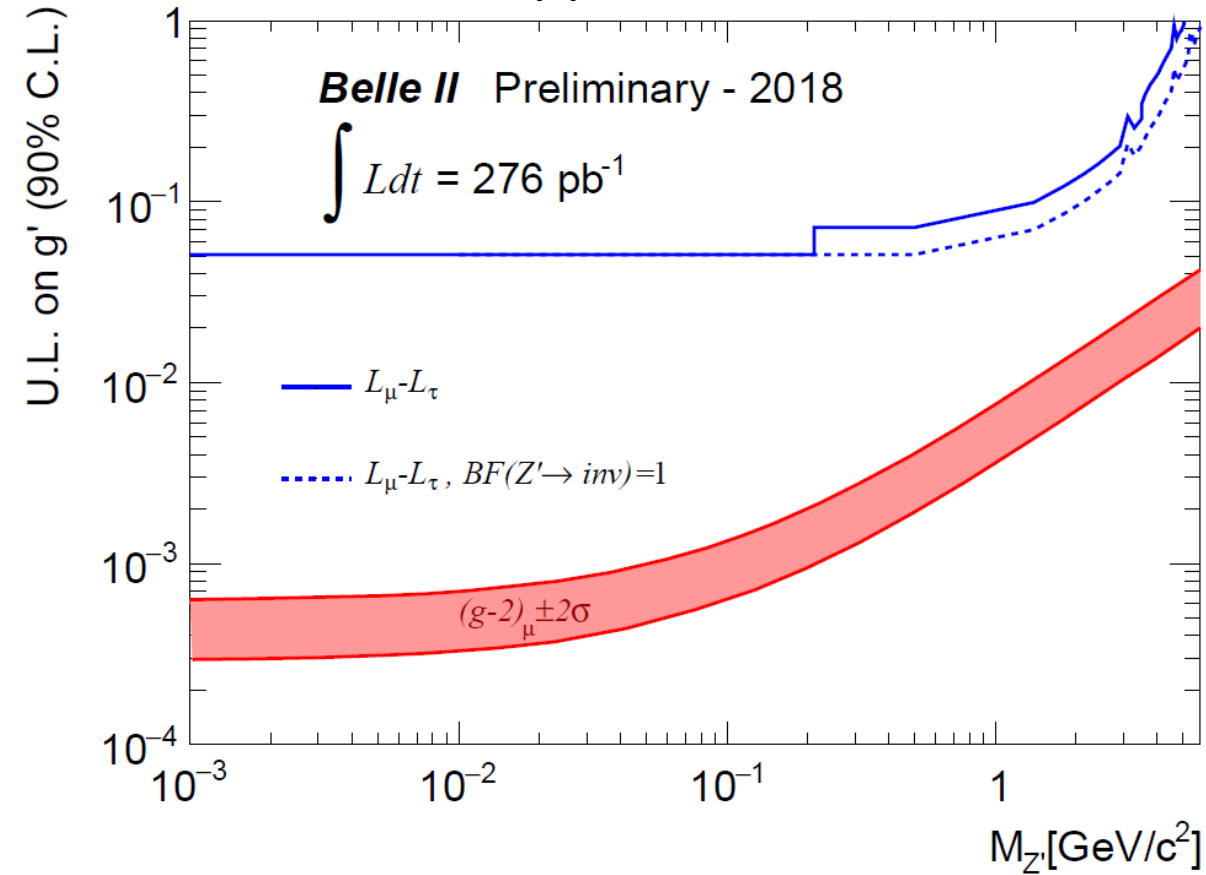


# Z' to invisible: results

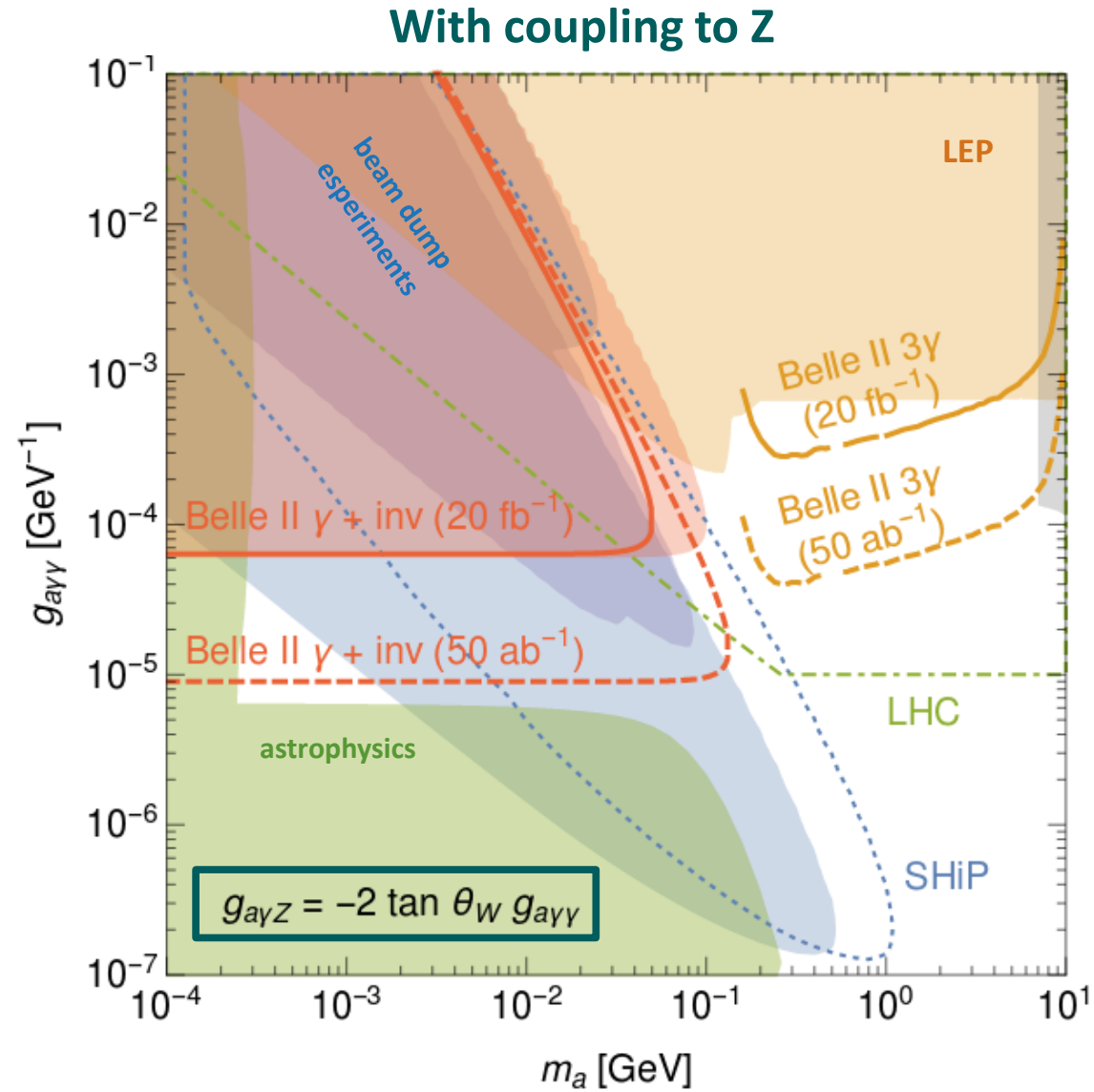
90% CL Upper Limits



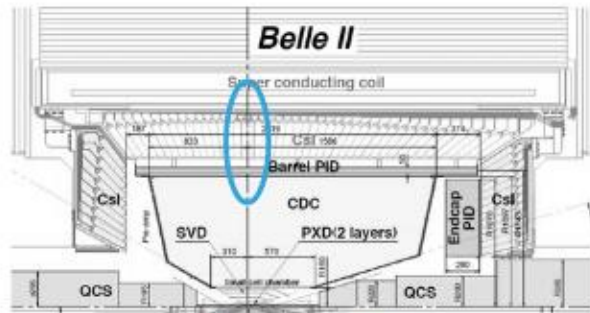
90% CL Upper Limits



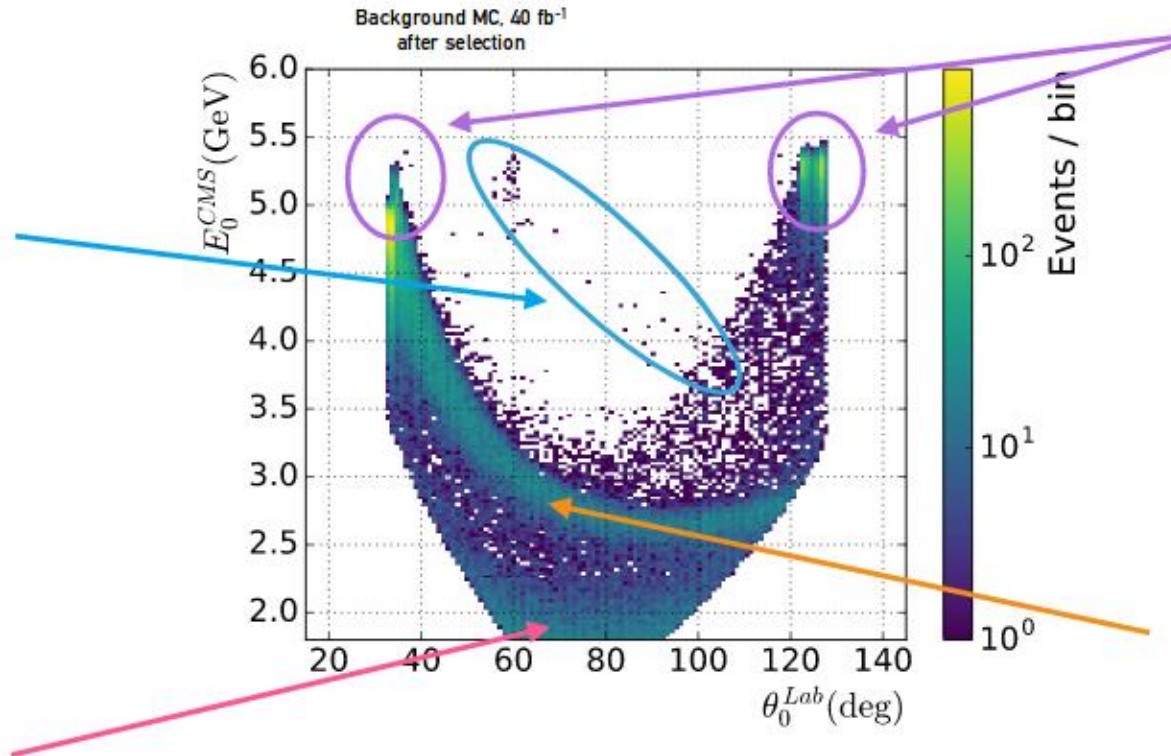
# Axion Like Particles (ALPs): sensitivity



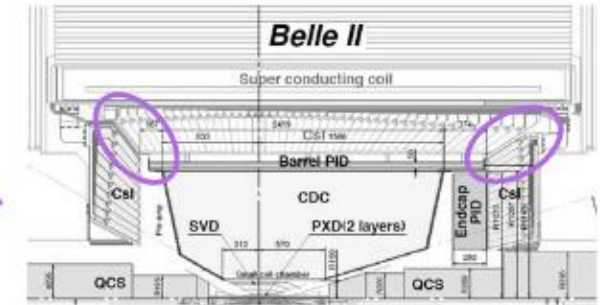
# Invisible dark photon: backgrounds



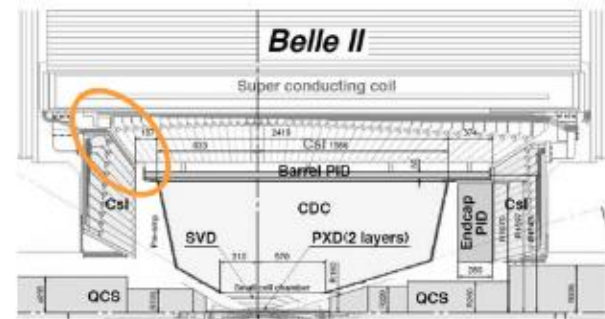
**$ee \rightarrow 2\gamma$  and  $3\gamma$**   
 1 $\gamma$  in ECL 90° gap  
 1 $\gamma$  out of ECL acceptance



**$ee \rightarrow eey$**   
 both electrons  
 out of tracking acceptance



**$ee \rightarrow 2\gamma$**   
 1 $\gamma$  in ECL BWD or FWD gap

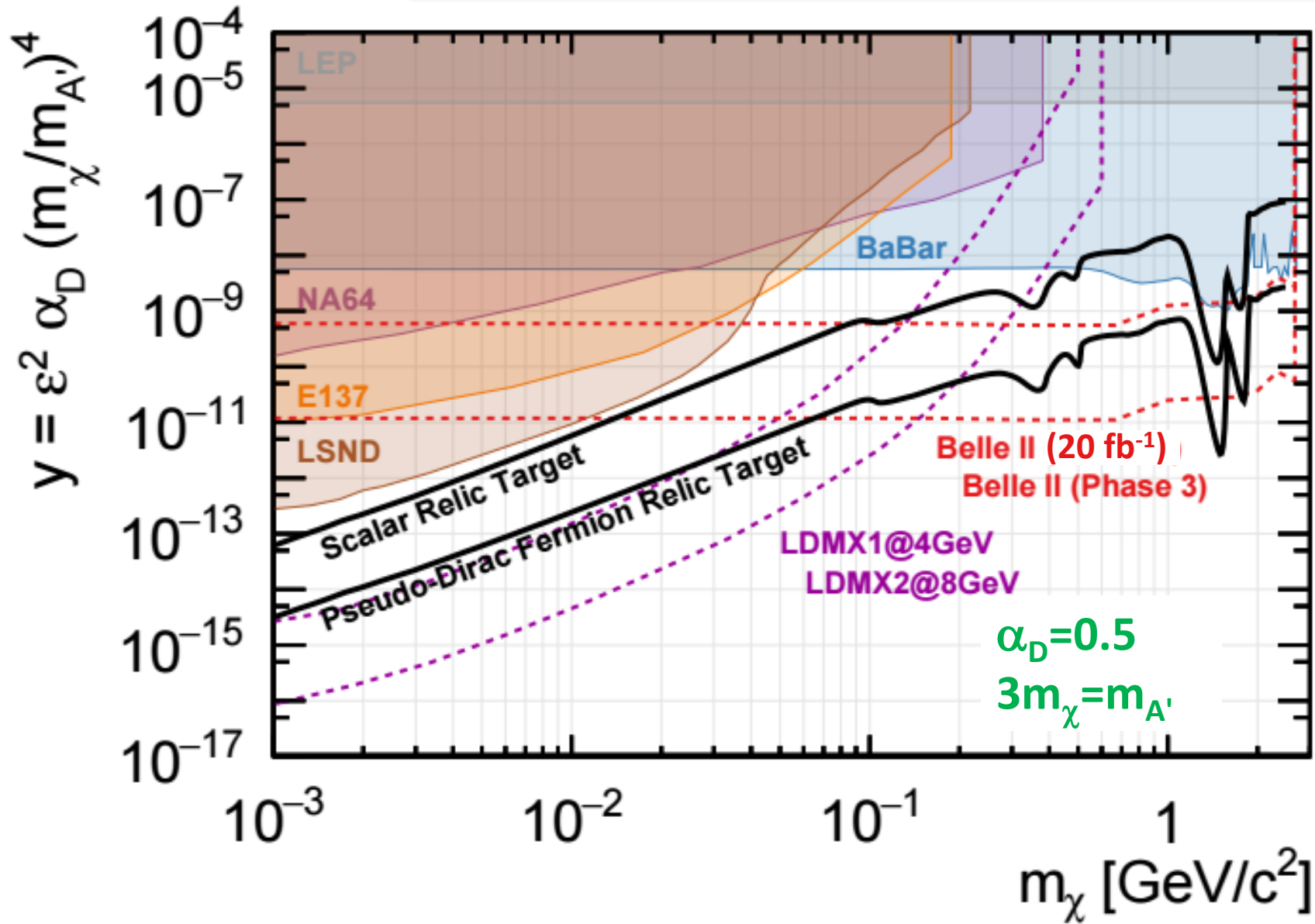


**$ee \rightarrow 3\gamma$**   
 1 $\gamma$  in ECL BWD gap  
 1 $\gamma$  out of ECL acceptance

**Crucial usage of KLM to veto photons in ECL gaps**



# Invisible dark photon: sensitivity



BaBar, 50 fb<sup>-1</sup>  
Phys. Rev. Lett 119,  
131804 (2017)

# Visible dark photon: sensitivity

