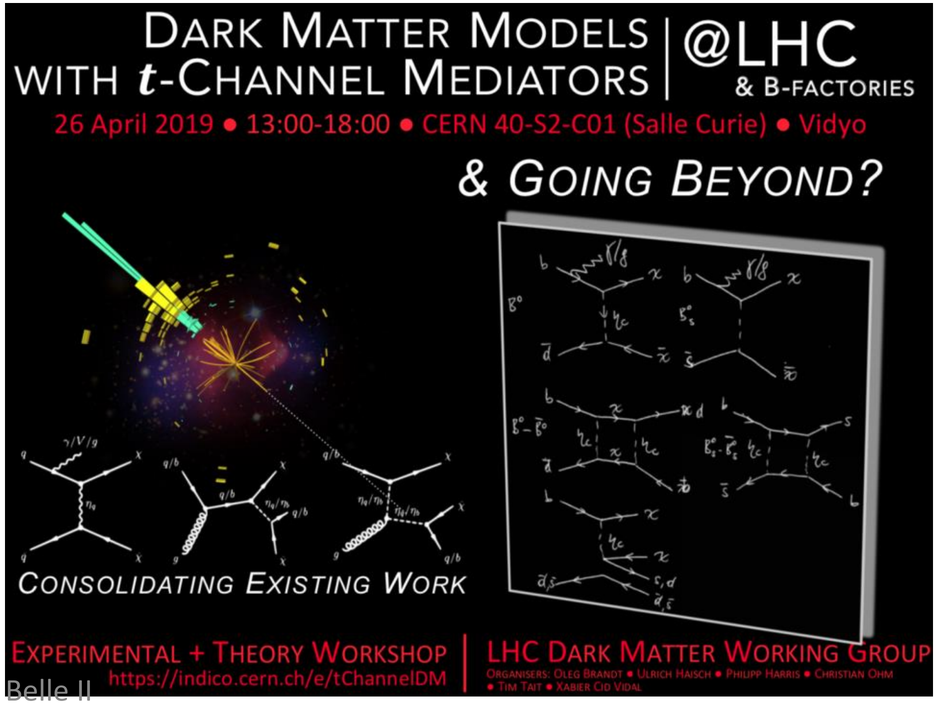
# Dark Matter Search with Belle II


## Enrico Graziani

INFN – Roma 3

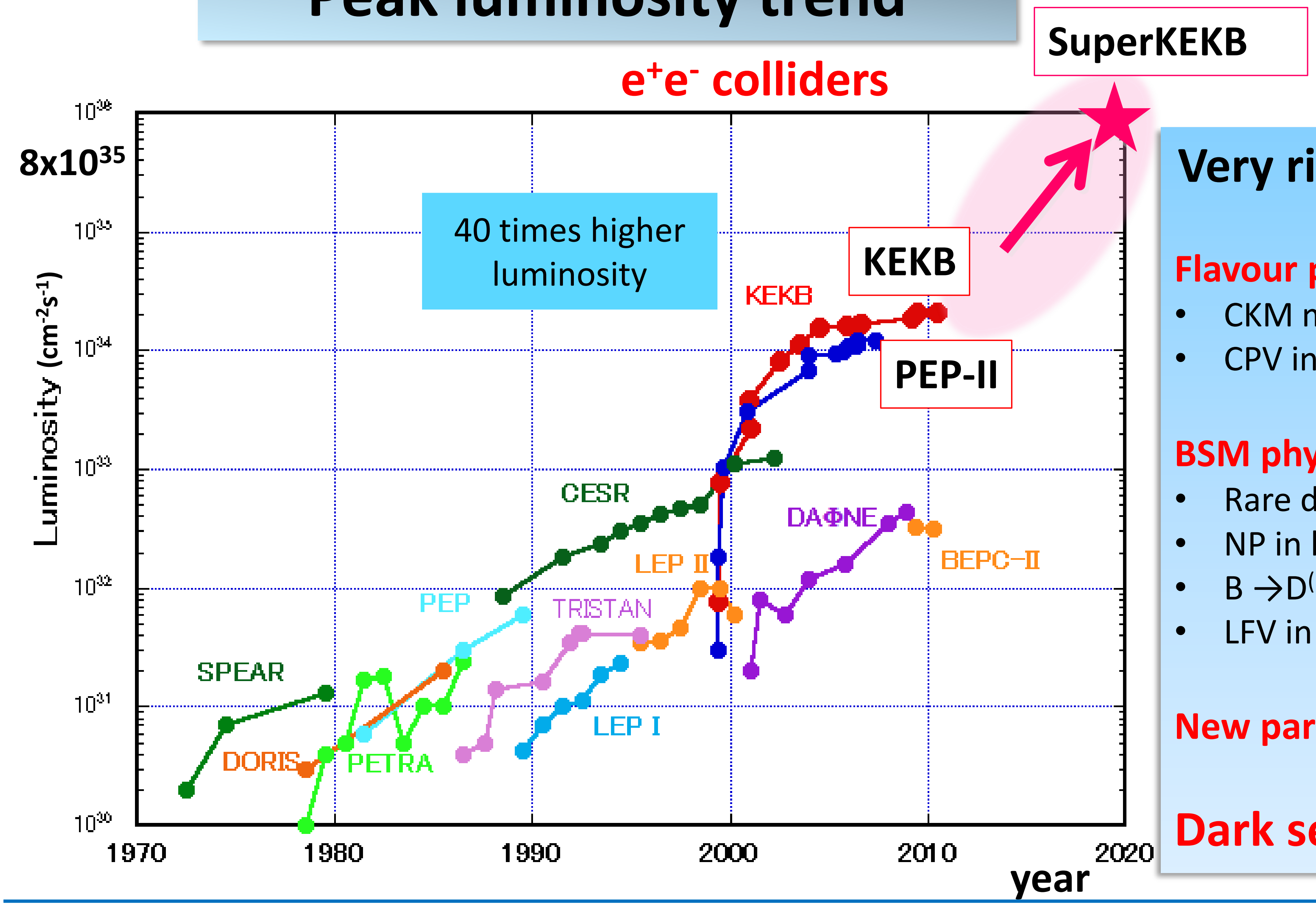
**on behalf of the Belle II Collaboration**


## OUTLINE OF THE TALK

- **Belle II and SuperKEKB**
- **Highlights of Belle II dark searches**
  **No t channel, sorry …**
- **Perspectives & Summary**

# Peak luminosity trend




## Very rich physics program

**Flavour physics**

- CKM matrix
- CPV in B deacys

**BSM physics**

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

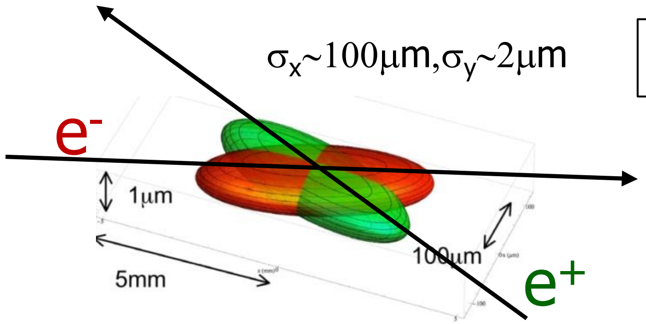
x20

x2

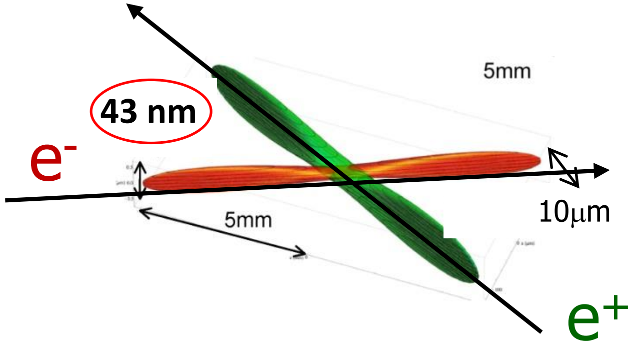
**$\beta^*_y$=0.27/0.30 mm**

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

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

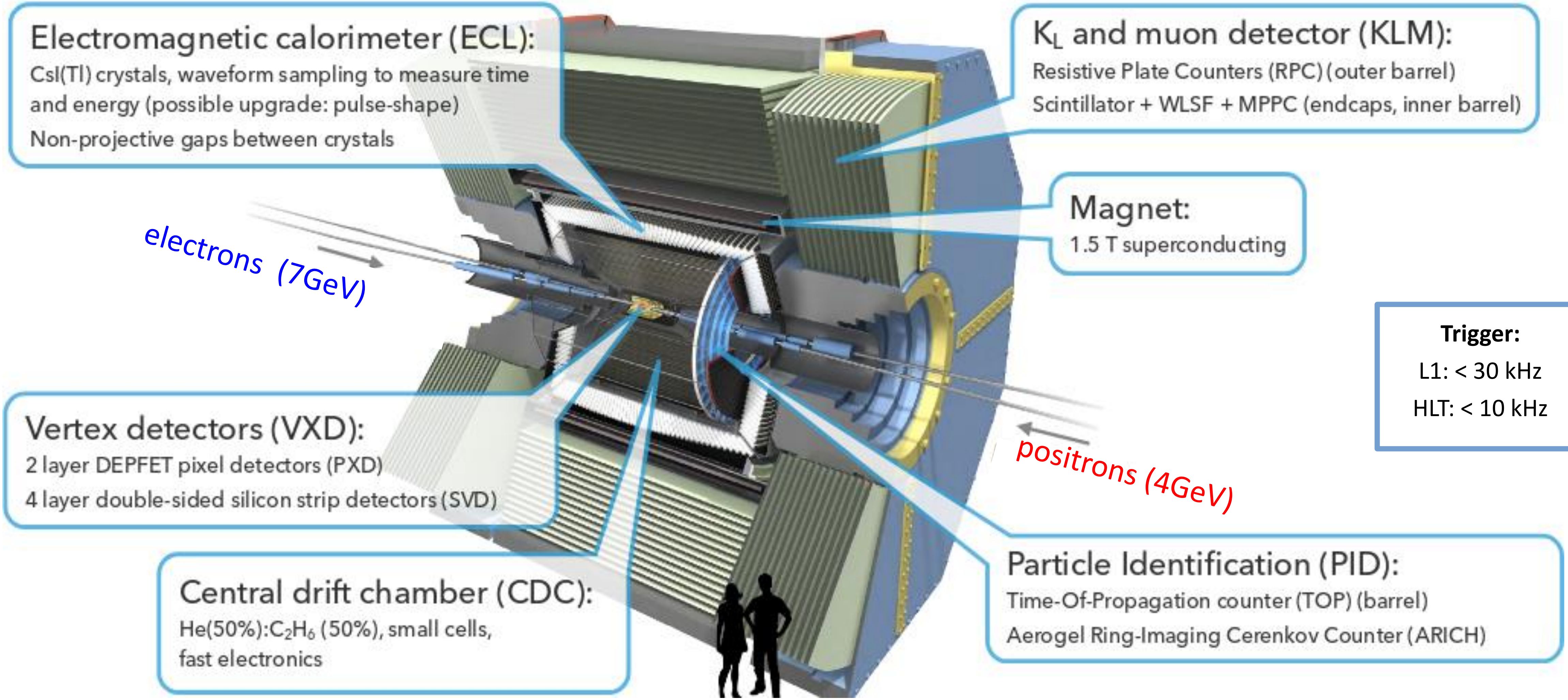



Nano-Beam scheme




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

# Belle II detector

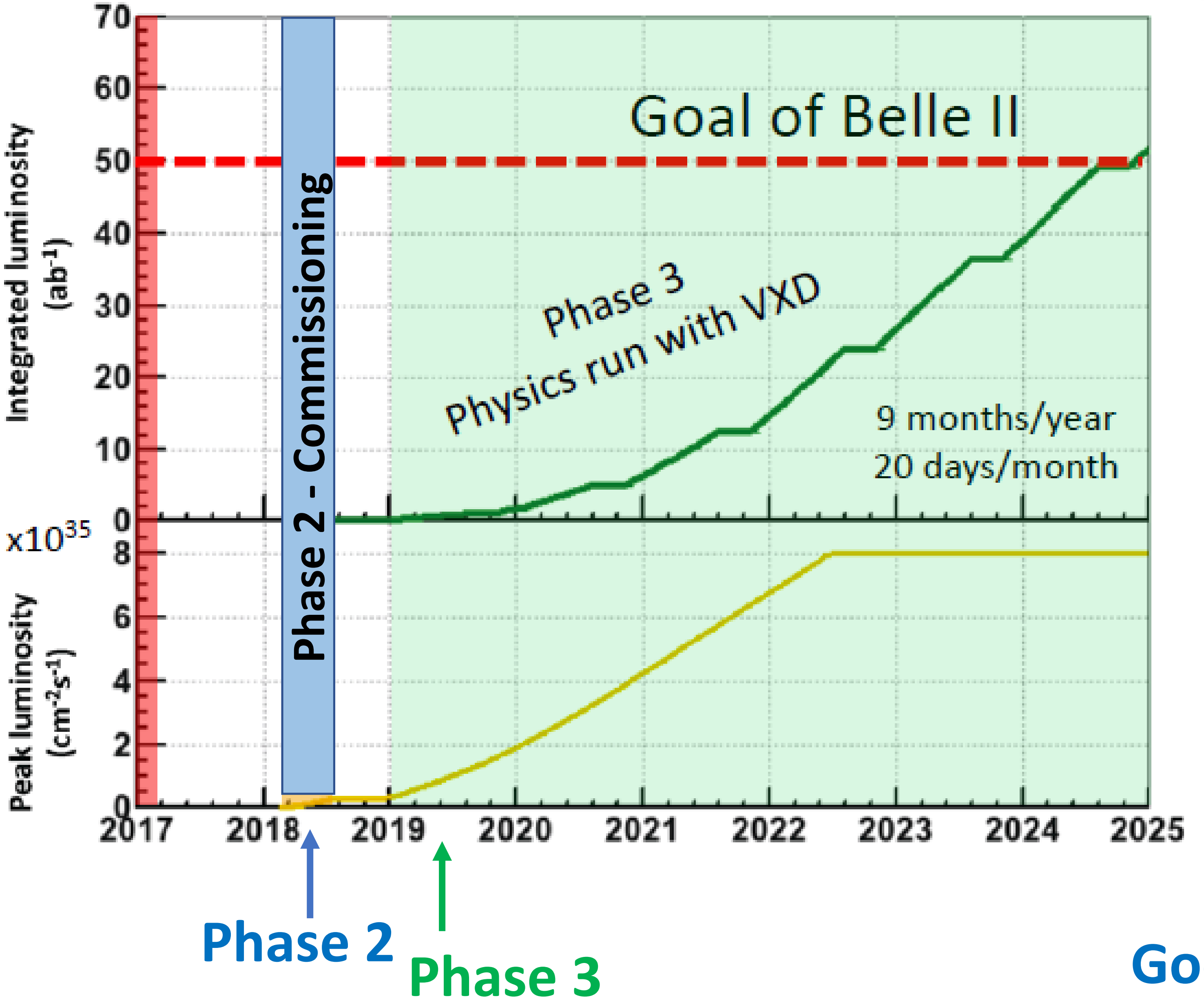



**Trigger:**
L1: < 30 kHz
HLT: < 10 kHz

**Belle II vs Belle**

better resolution, PID and capability to cope with higher background

# Belle II data taking plan: the past (2018)




## Phase 2

**Phase 2 finished July 2018**

- **Nano-beam scheme works!**
- **$L=5.5\times10^{33}\ cm^{-2}s^{-1}$ achieved**
- **$L_{int}\approx0.5\ fb^{-1}$ collected**

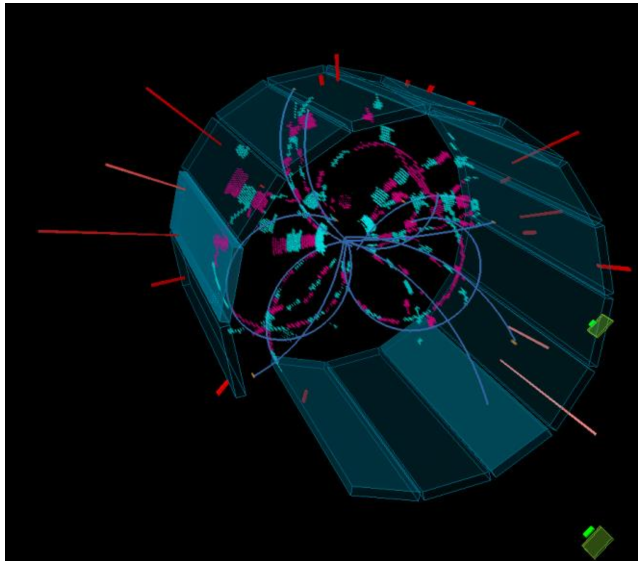
- 1/8 of vertex detector
- Low backgrounds
- Pass-through HLT (software) trigger

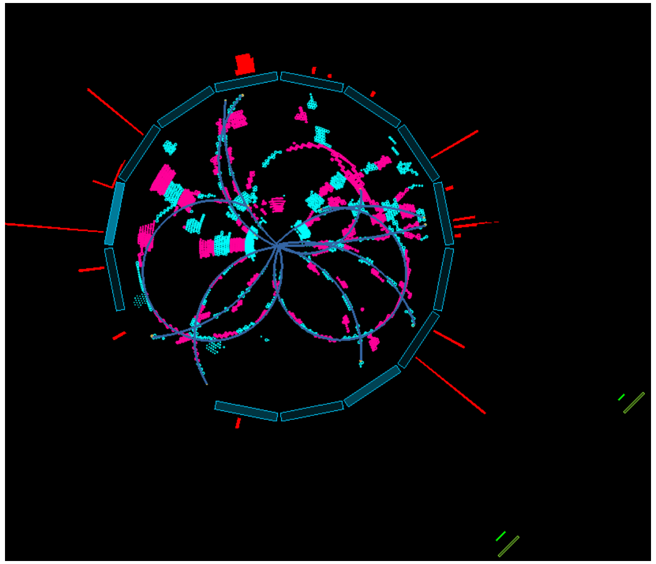
- ❑ Tracking and clustering L1 trigger
- ❑ Bhabha veto L1 trigger
- ❑ Some single photon L1 trigger

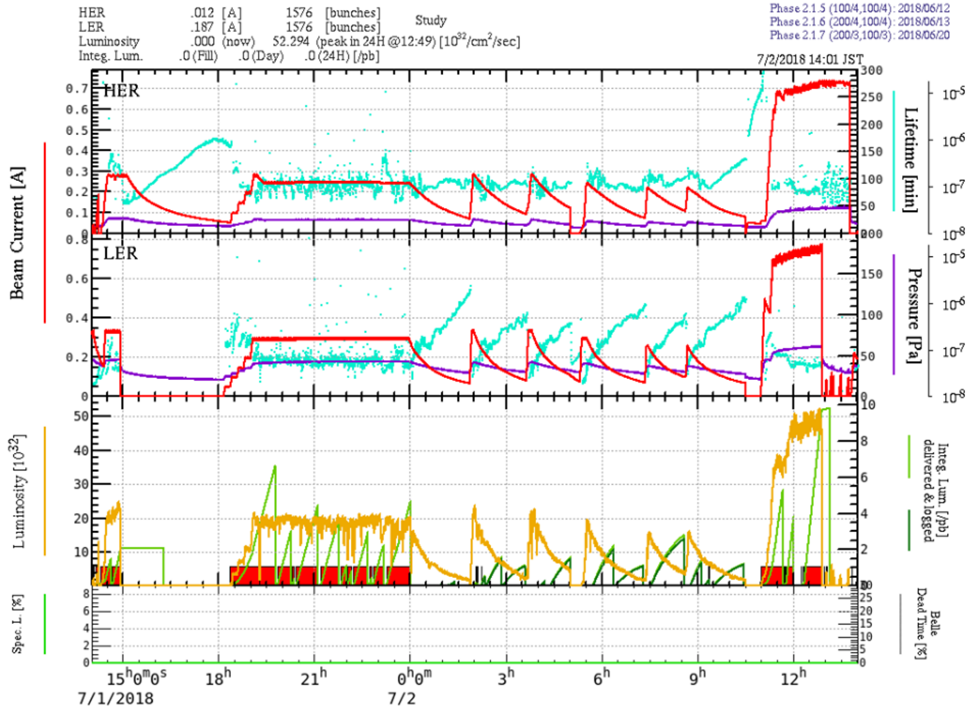
**Good conditions for dark searches**

# Belle II & SuperKEKB Phase 2

## Start of collisions: April 25th 2018







# Belle II & SuperKEKB Phase 2

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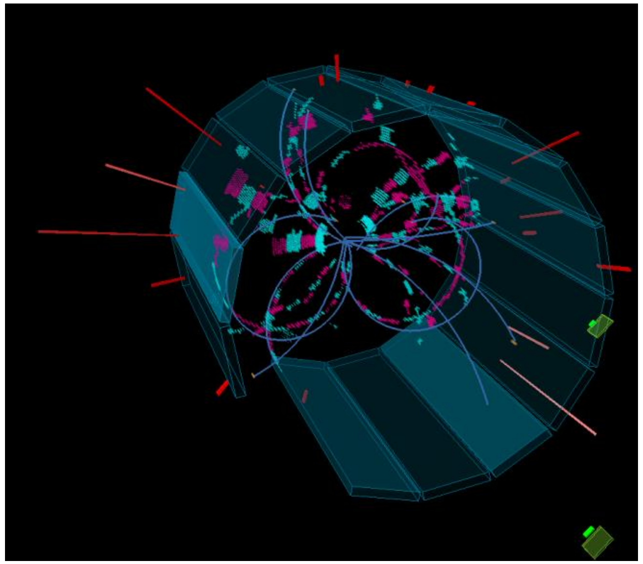
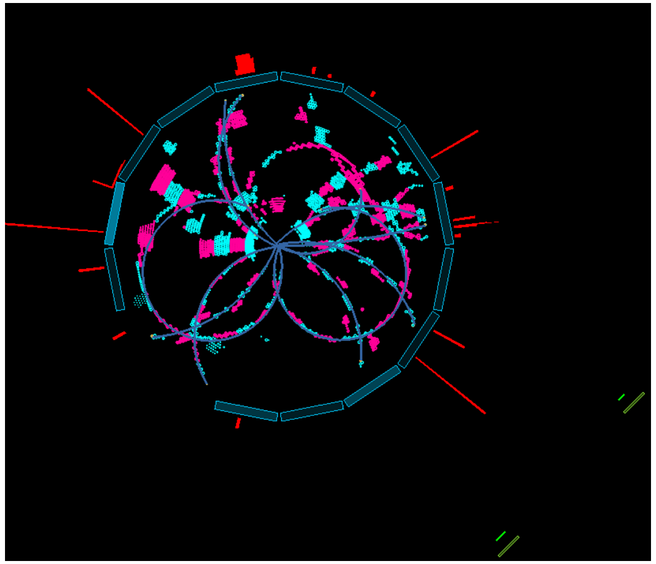
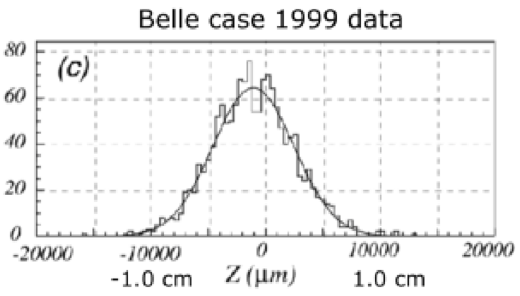




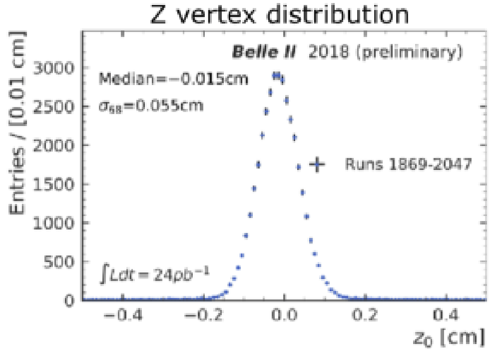
### Effective bunch length: from KEKB to SuperKEKB Phase 2

**Ordinary collision (KEKB)**




**σ = 4.5 mm**

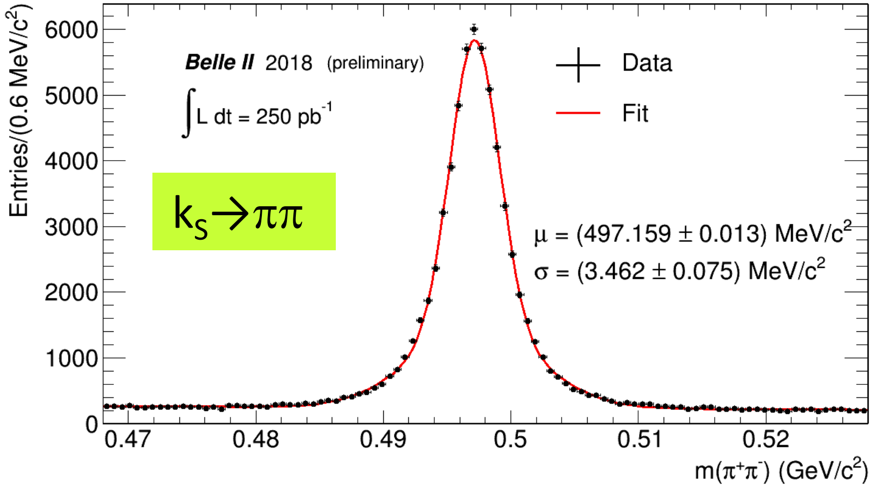
**Nano-Beam (SuperKEKB Phase2)**

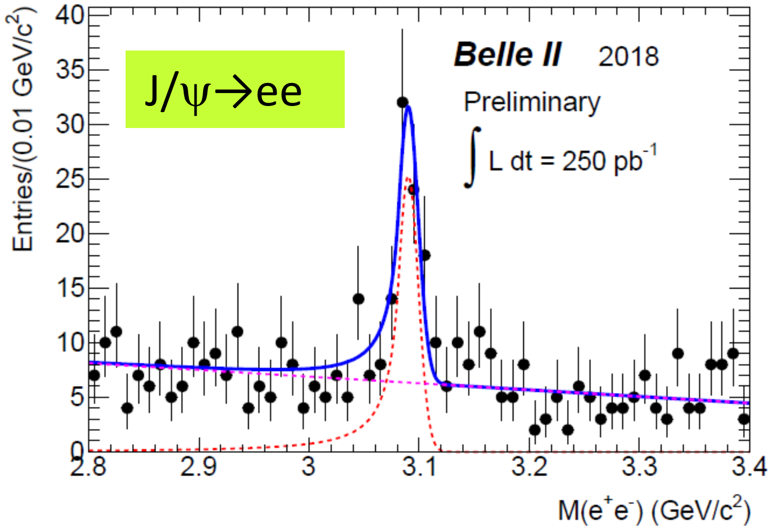


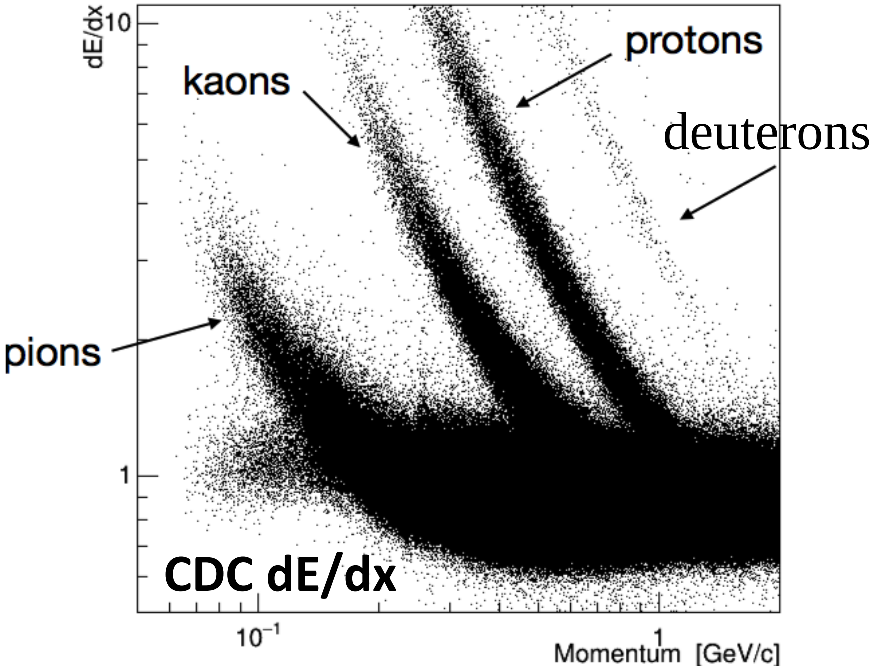

**σ = 550 μm**

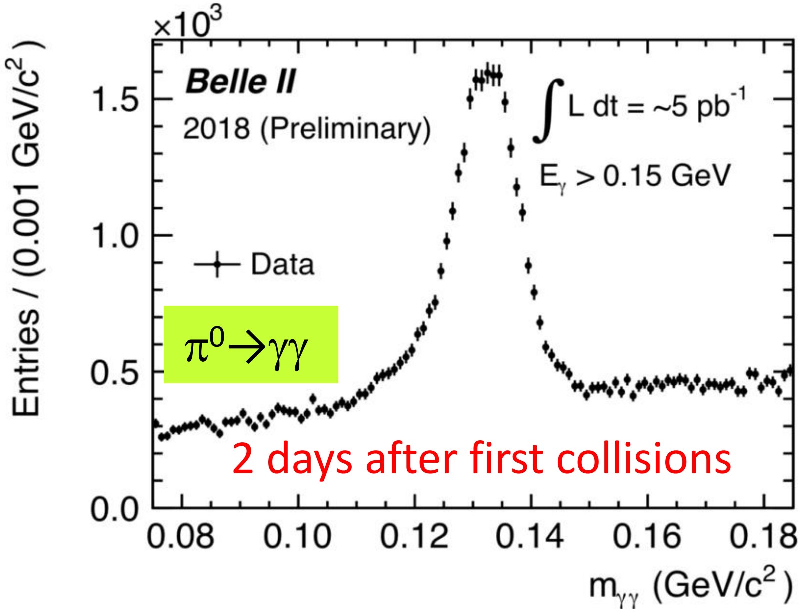
**Nano-beam scheme works!**

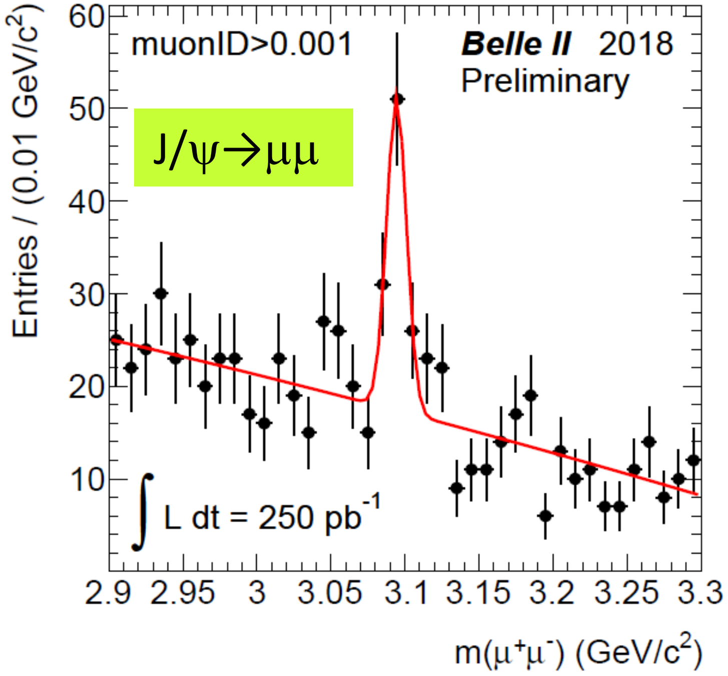
# Belle II performance snapshots

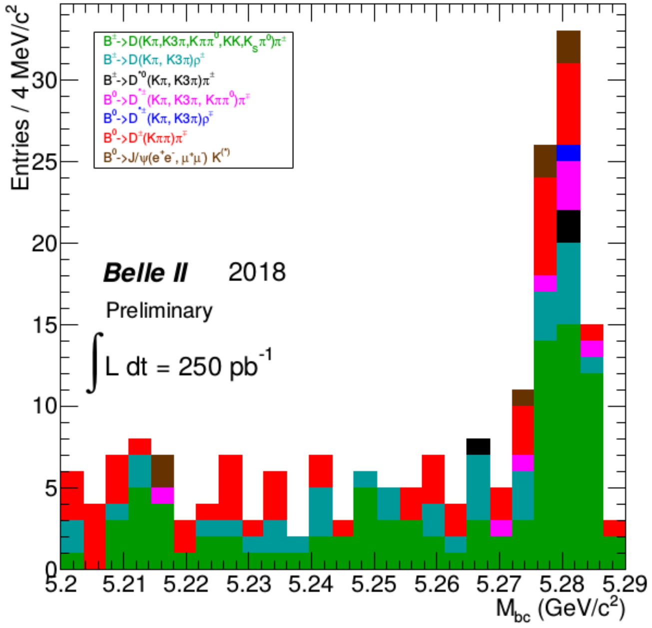


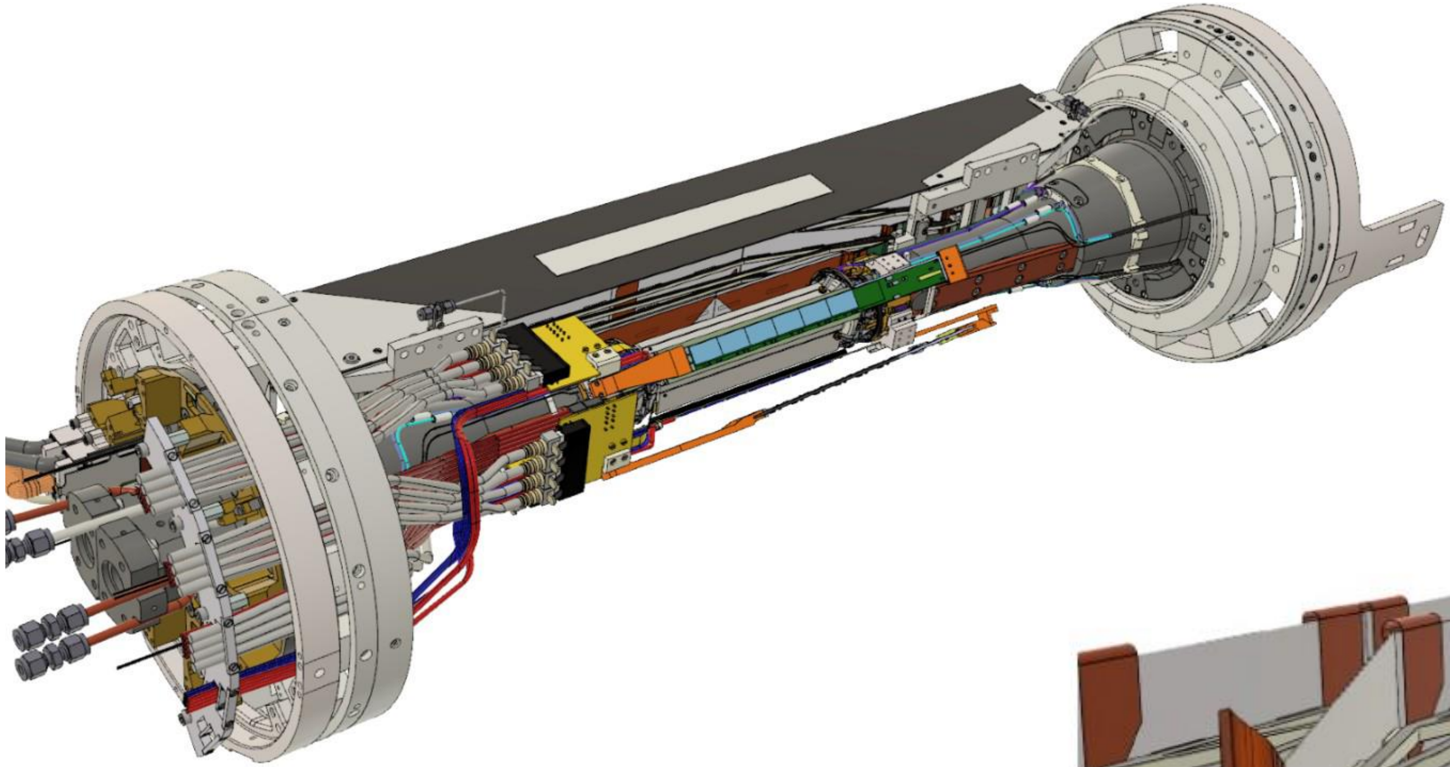



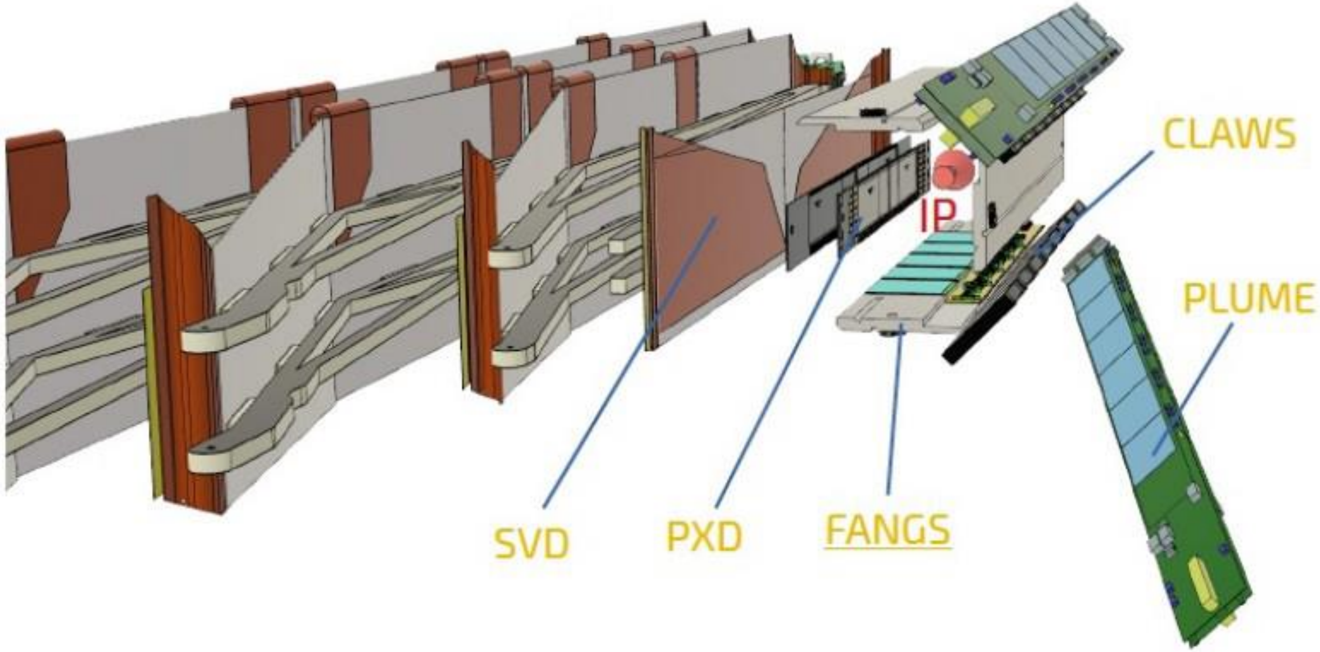



# From Phase 2 to Phase 3





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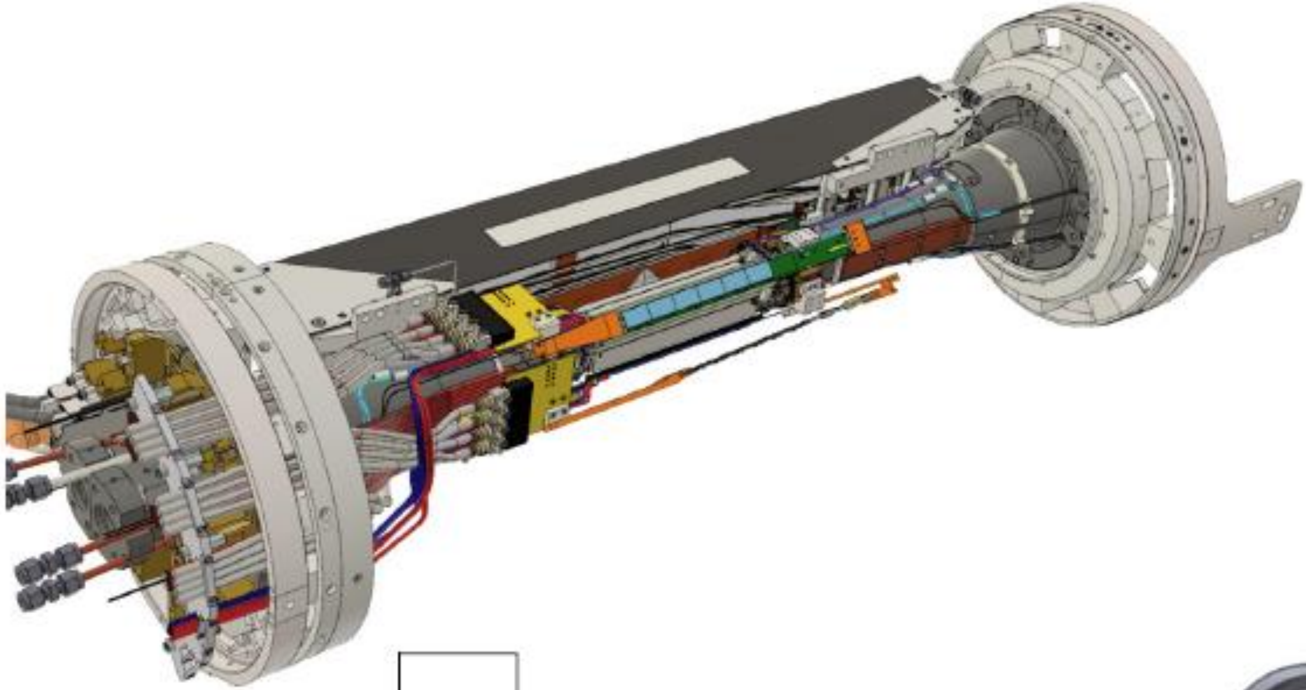
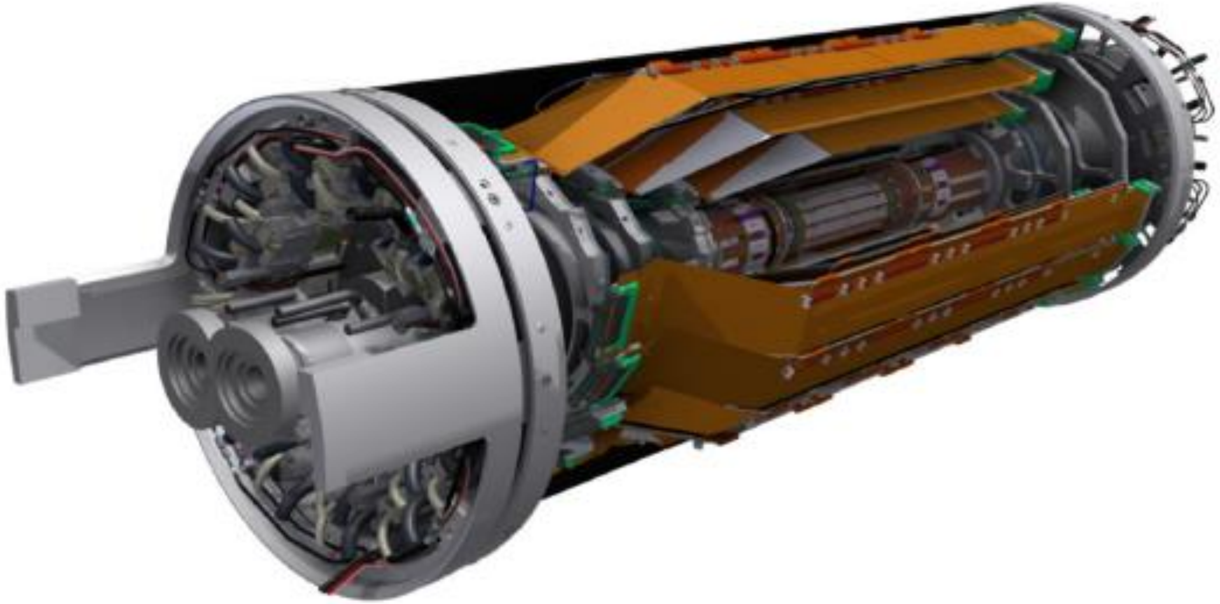


Phase 3 = (almost) final setup for physics

→ 4 full layers of silicon strips

→ 1 + 1/6 full layers of pixel

→ full installation approx in 2020



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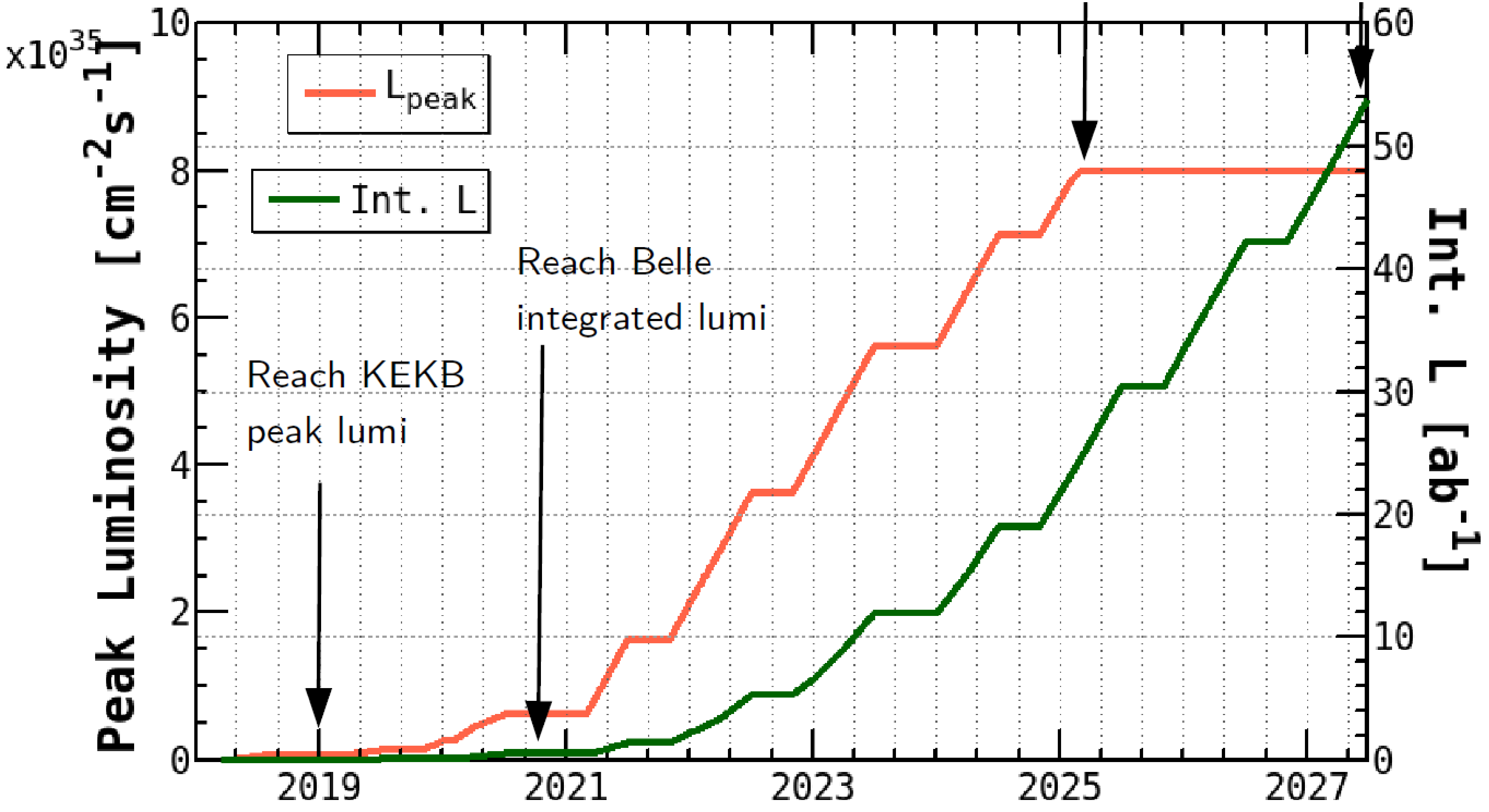

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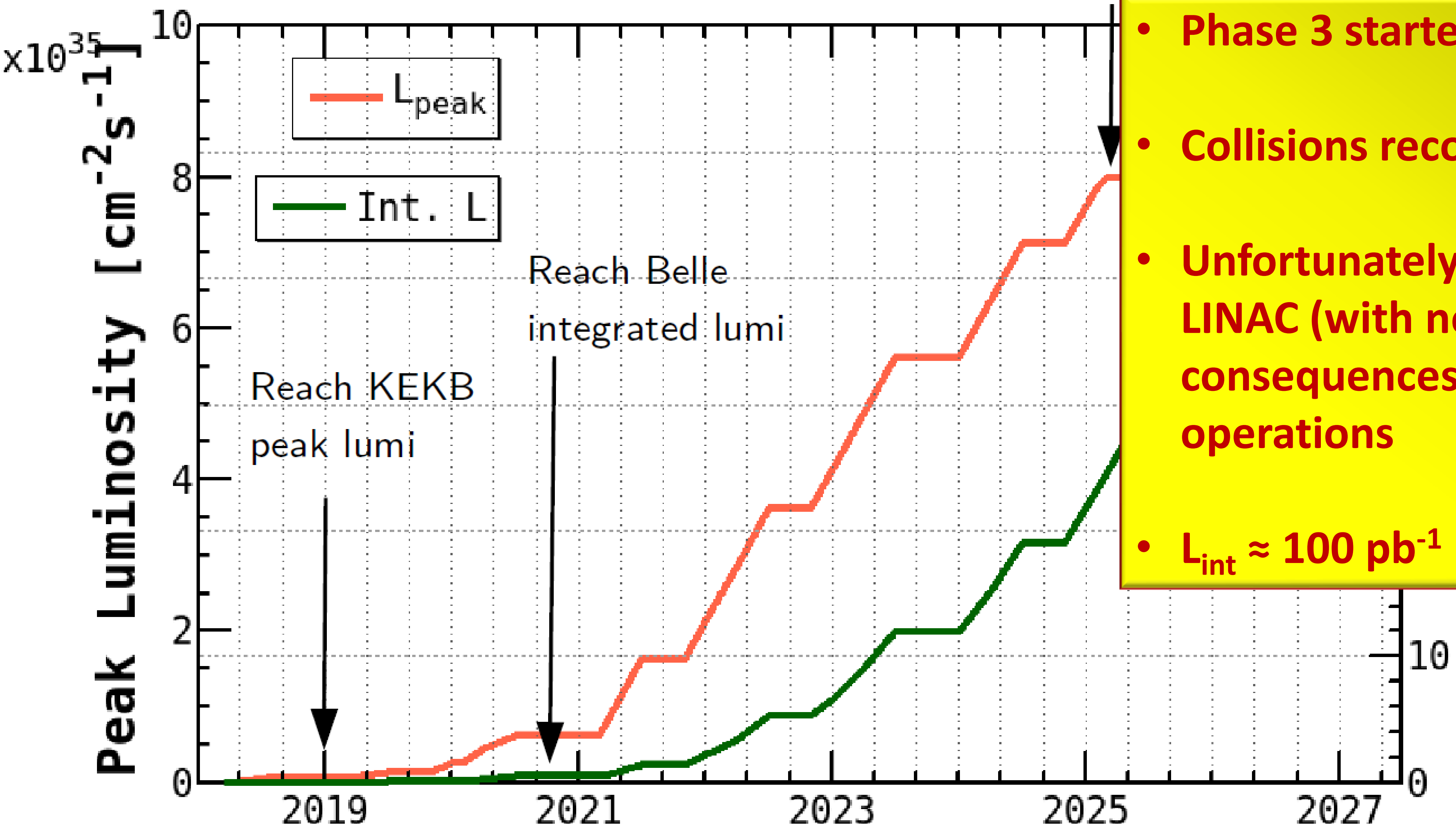



- **Phase 3 started on March 11**
- **Collisions recorded since March 25**
- **Unfortunately a fire accident at LINAC (with no serious consequences) slowed down operations**
- **$L_{int} \approx 100\ pb^{-1}$**

# What can we do at B-factories that we can't at the LHC in terms of DM searches?

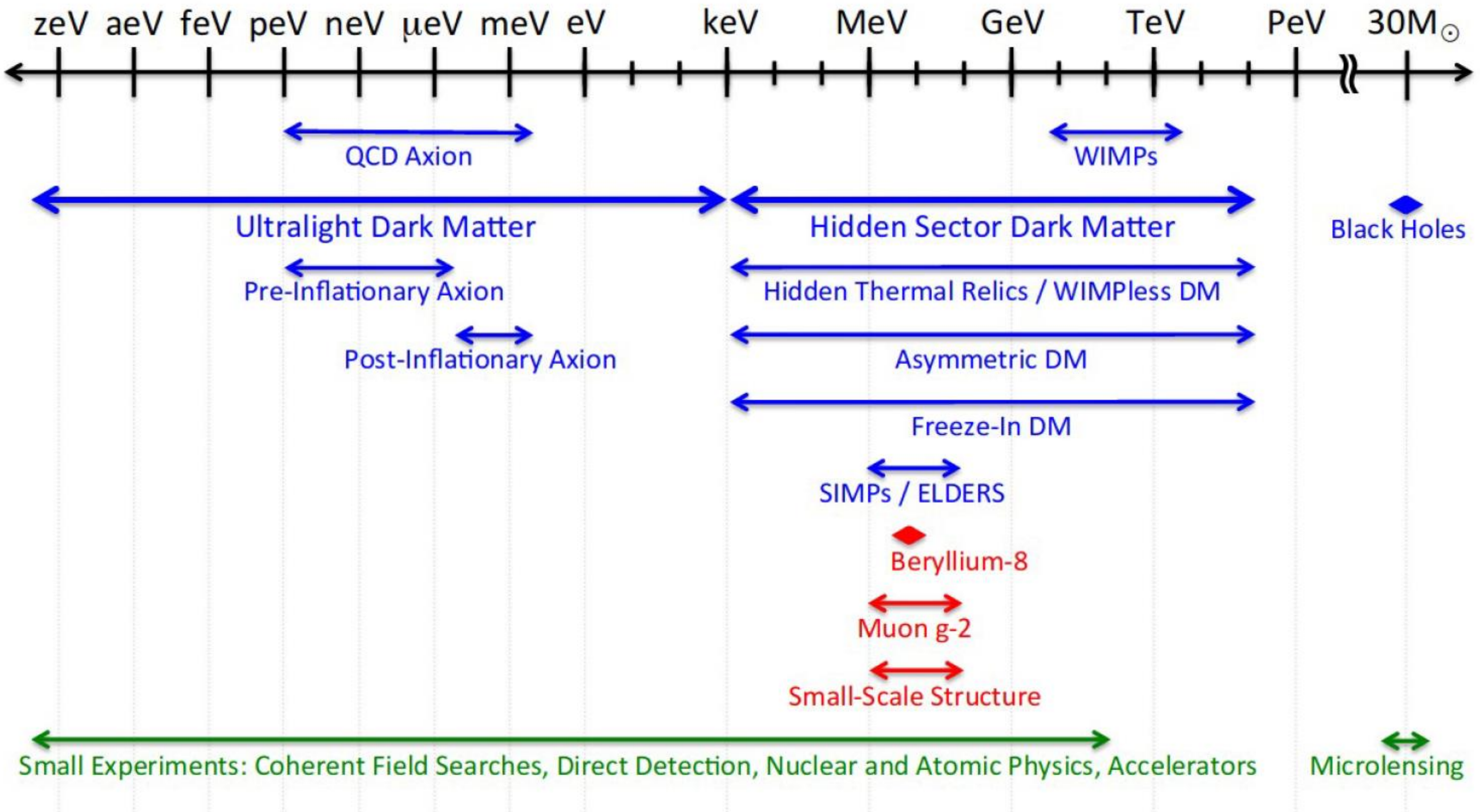
- Clean, «energy conserving» environment
- 3d momentum conservation
- Easiness of tag & probe techniques
- Full Event Interpretation
- Less model dependency

↓

- Low multiplicity signatures
- Missing energy channels
- Invisible particles
- Some fully neutral final states accessibility

- Cleanliness and luminosity sometimes compensate for cross section → competition

# Dark Sector Candidates, Anomalies, and Search Techniques



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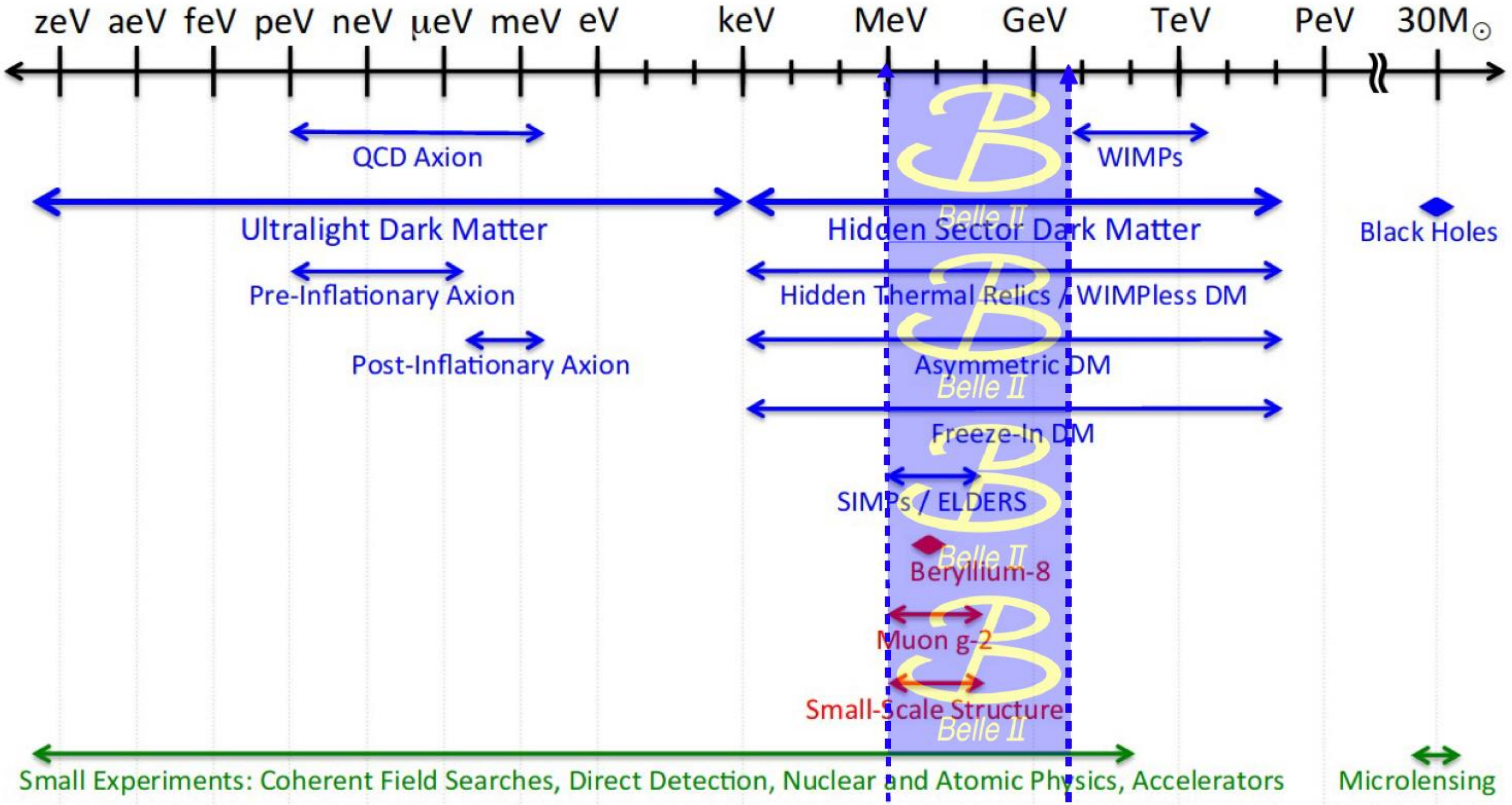
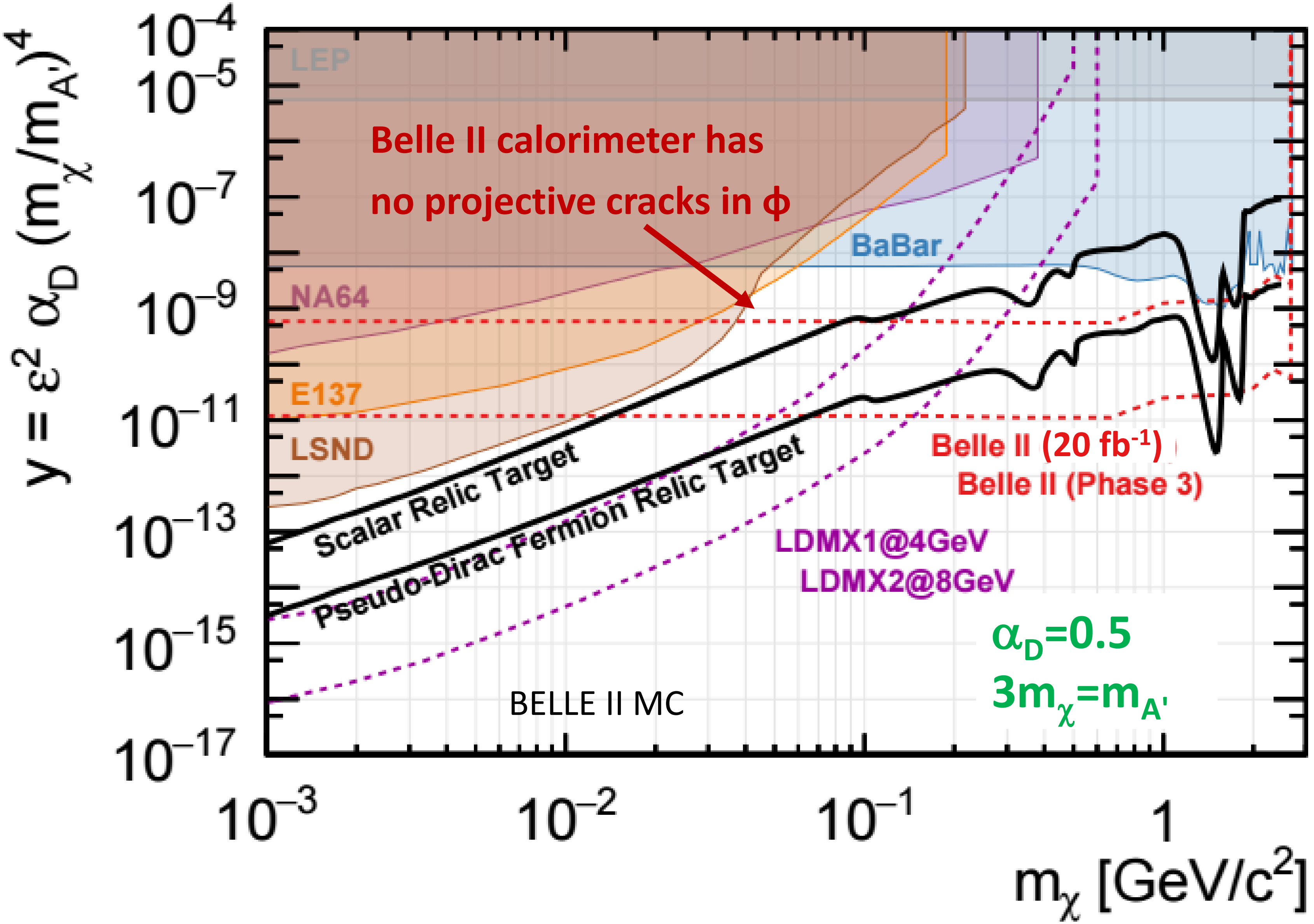
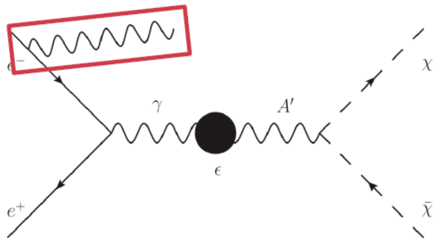


# Invisible dark photon: sensitivity



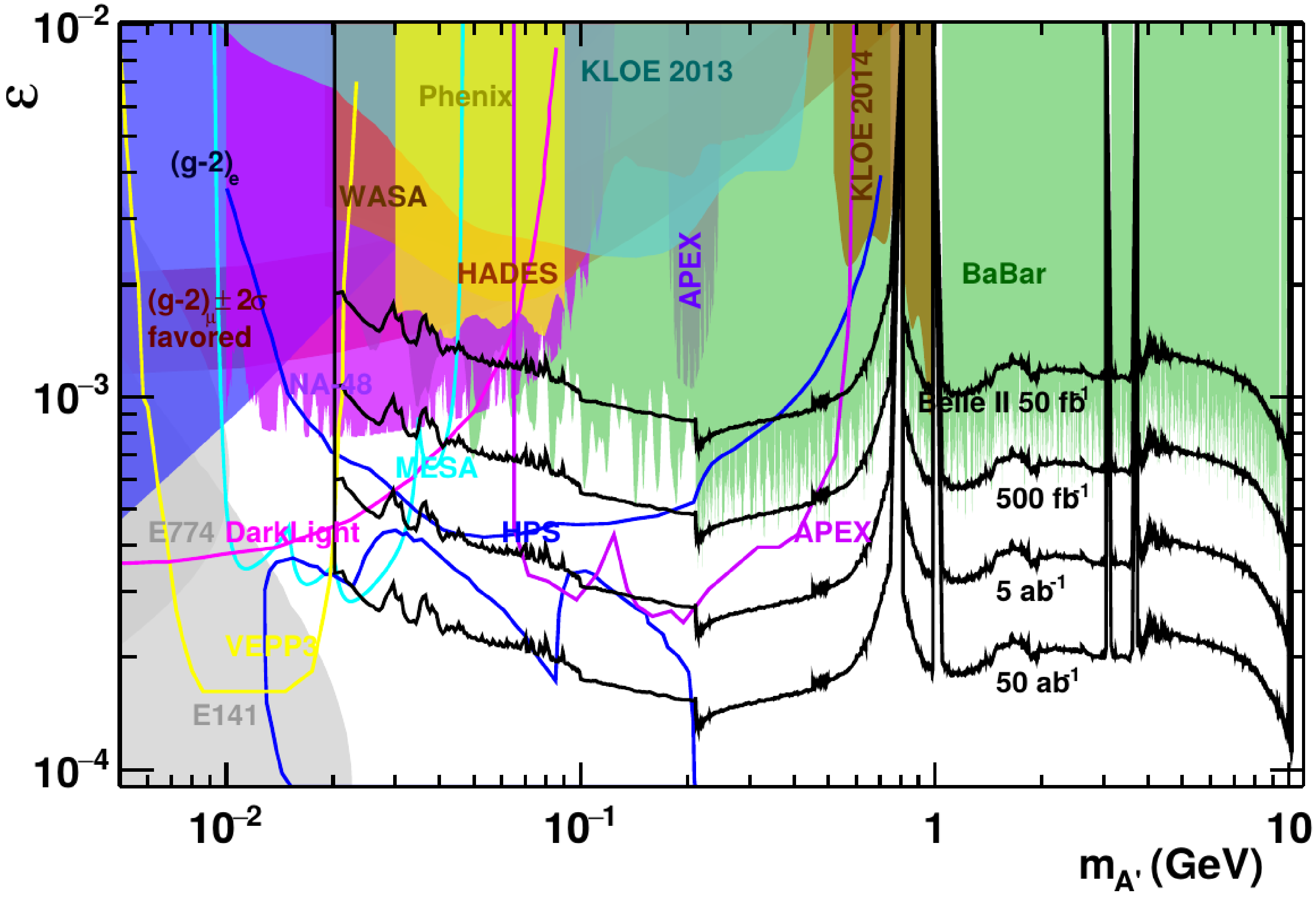



Lower trigger threshold wrt BaBar

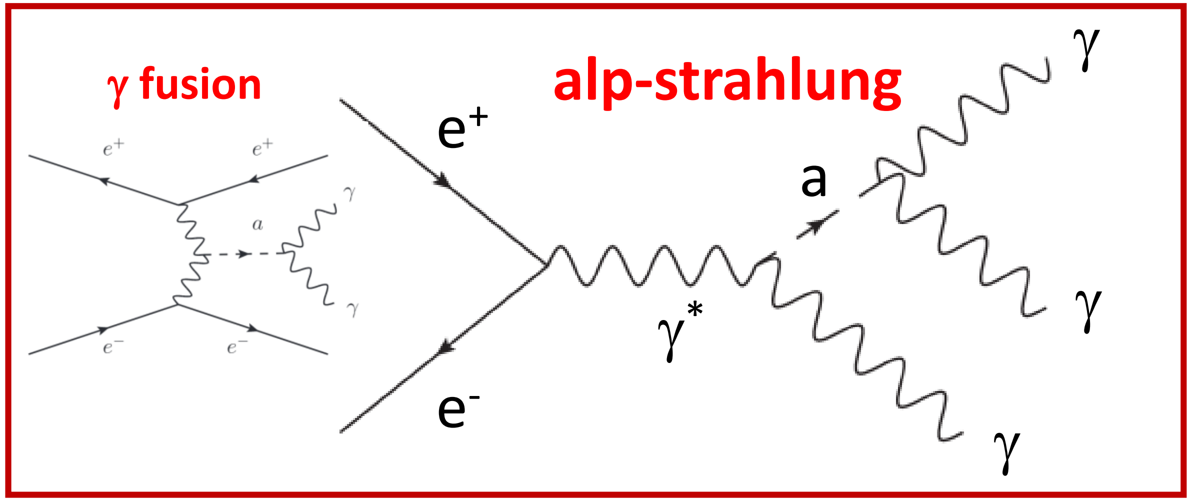
$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$

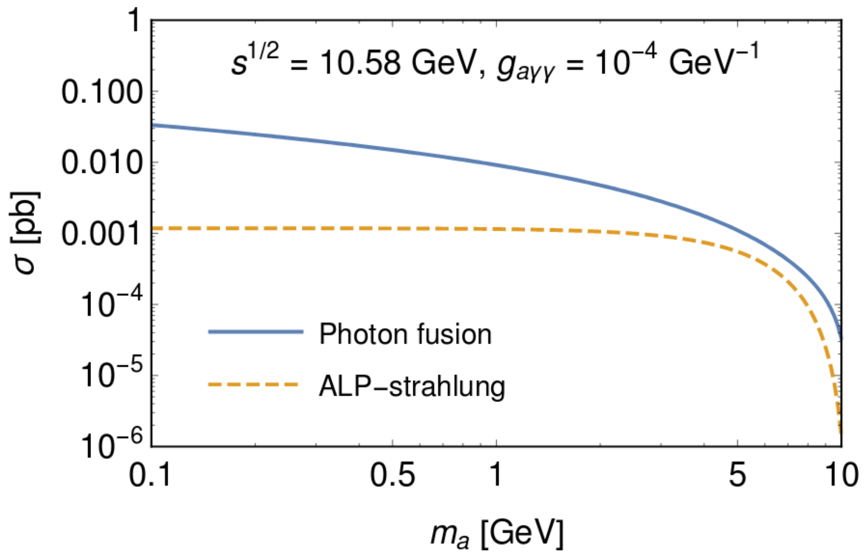
Needs a single photon trigger

# Visible dark photon: sensitivity

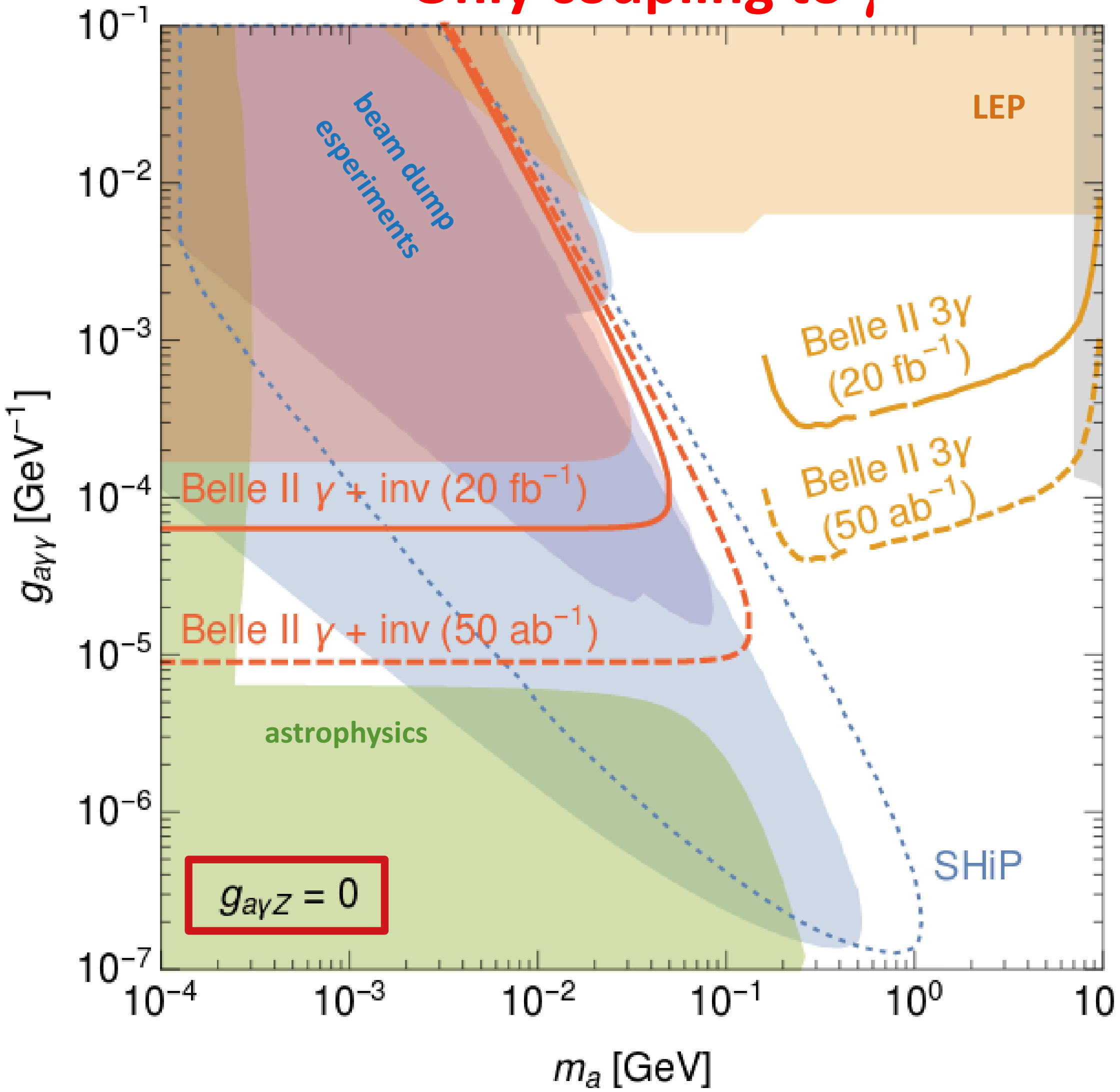


# Axion Like Particles (ALPs): sensitivity




Only coupling to γ



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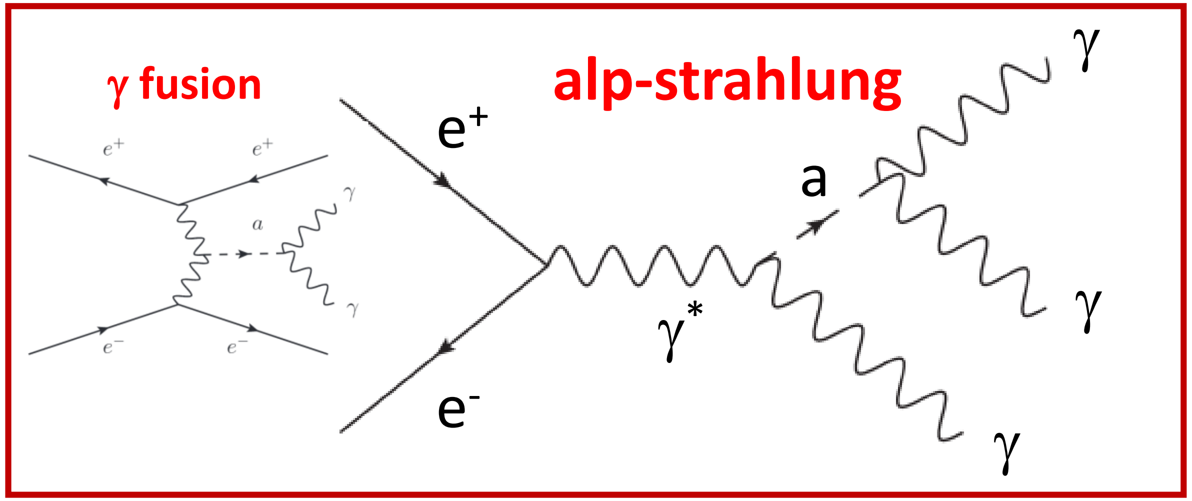
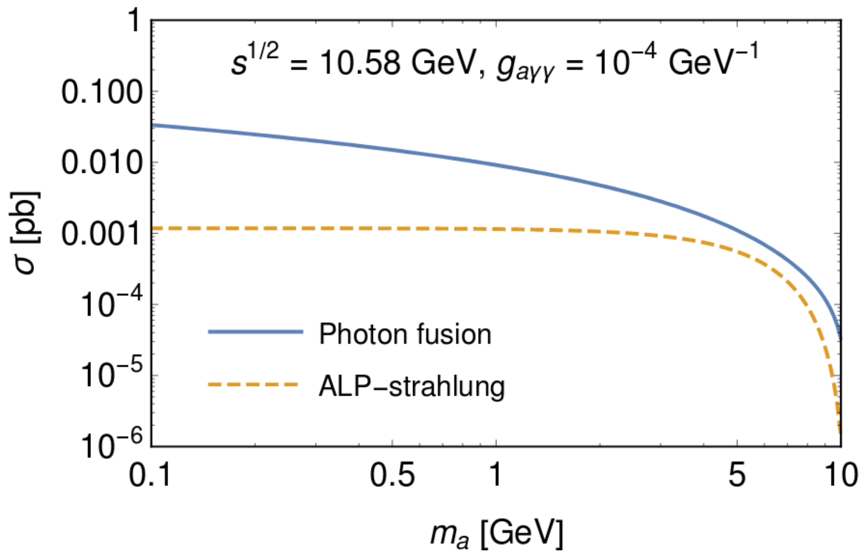
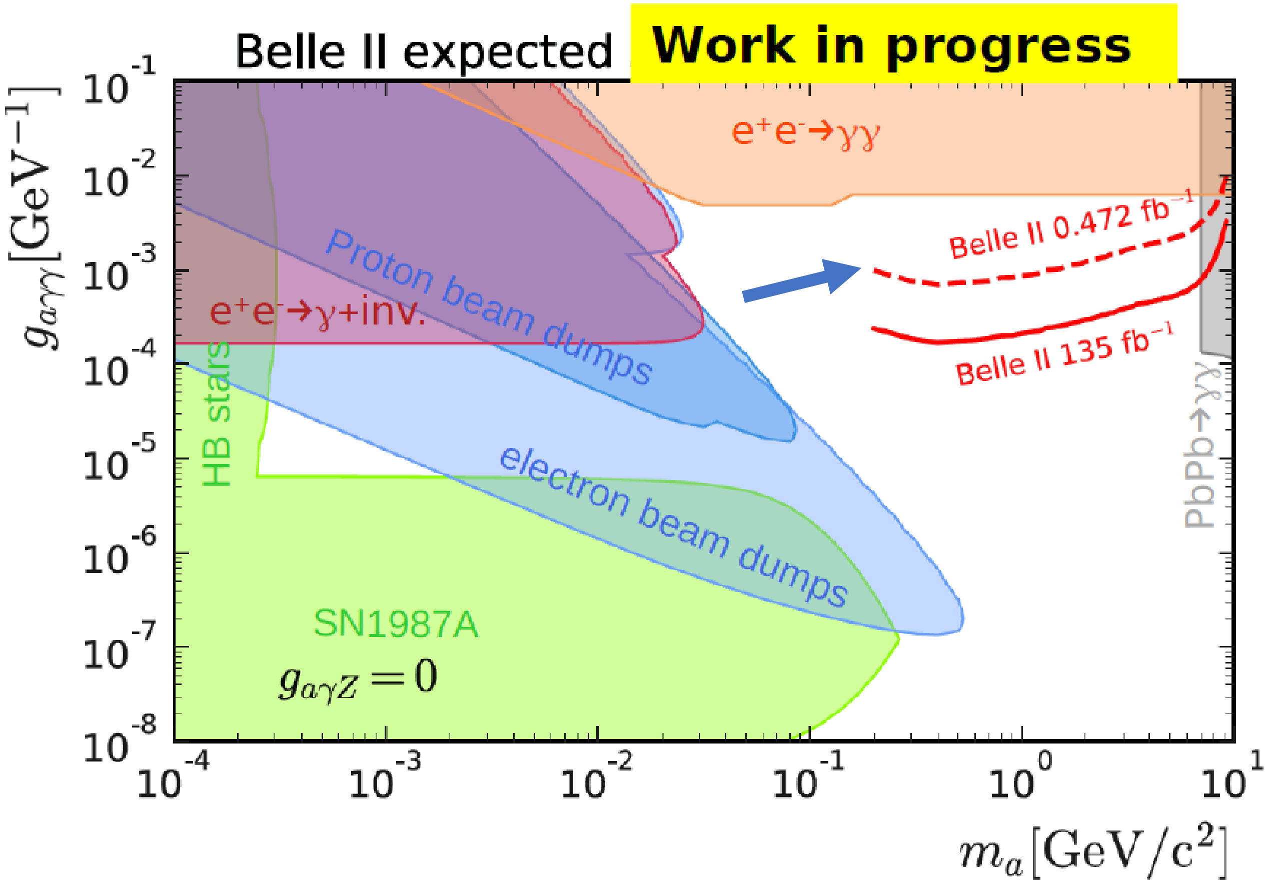


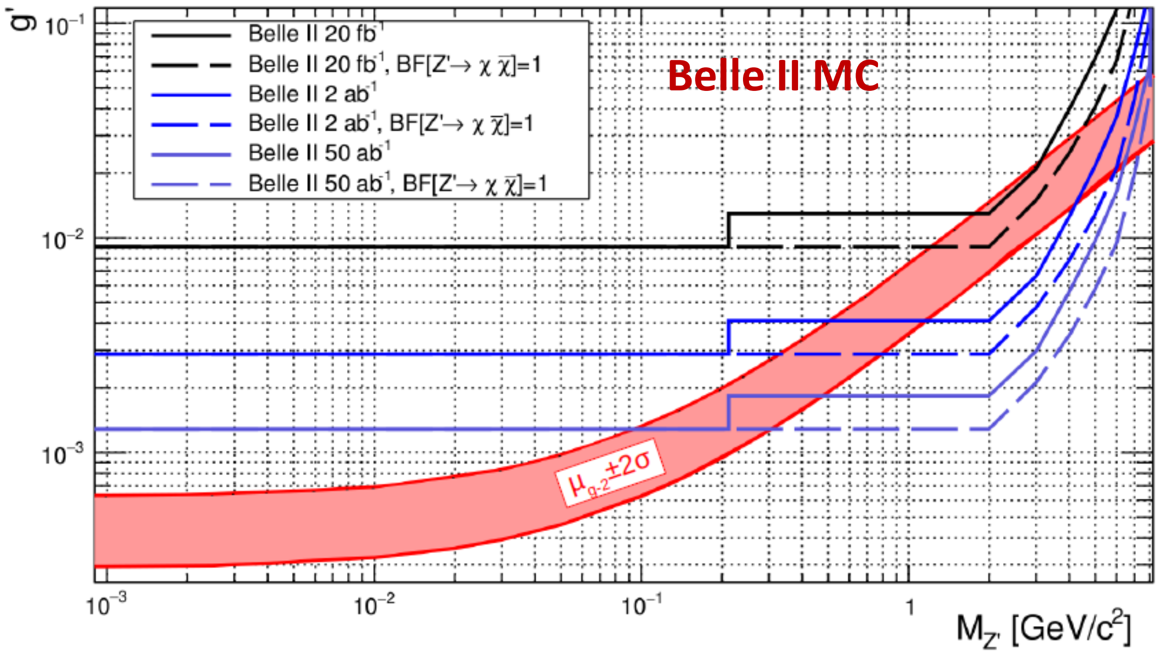




**With some assumptions on the trigger (no γγ veto in barrel)**

**Results expected with Phase 2 data**

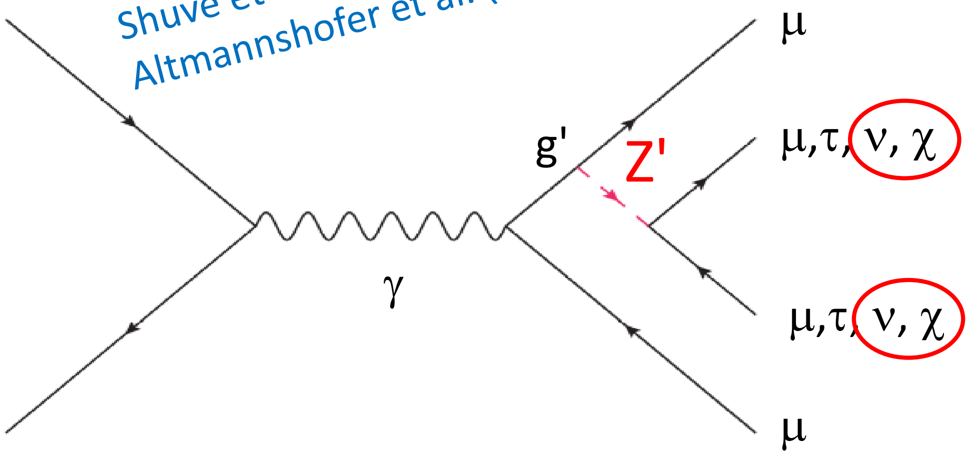
# $L_\mu$ - $L_\tau$: Z' invisible decay

- couples only to the 2° and 3° lepton family
- calls for LFU violation
- May explain $(g-2)_\mu$
- Invisible BR possibly enhanced by LDMA (sterile neutrinos, light Dirac fermions)
- Might solve $B \to K^{(*)}\mu\mu$, $R_K$, $R_{K^*}$ anomalies




**Very preliminary systematics, very conservative limits**

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



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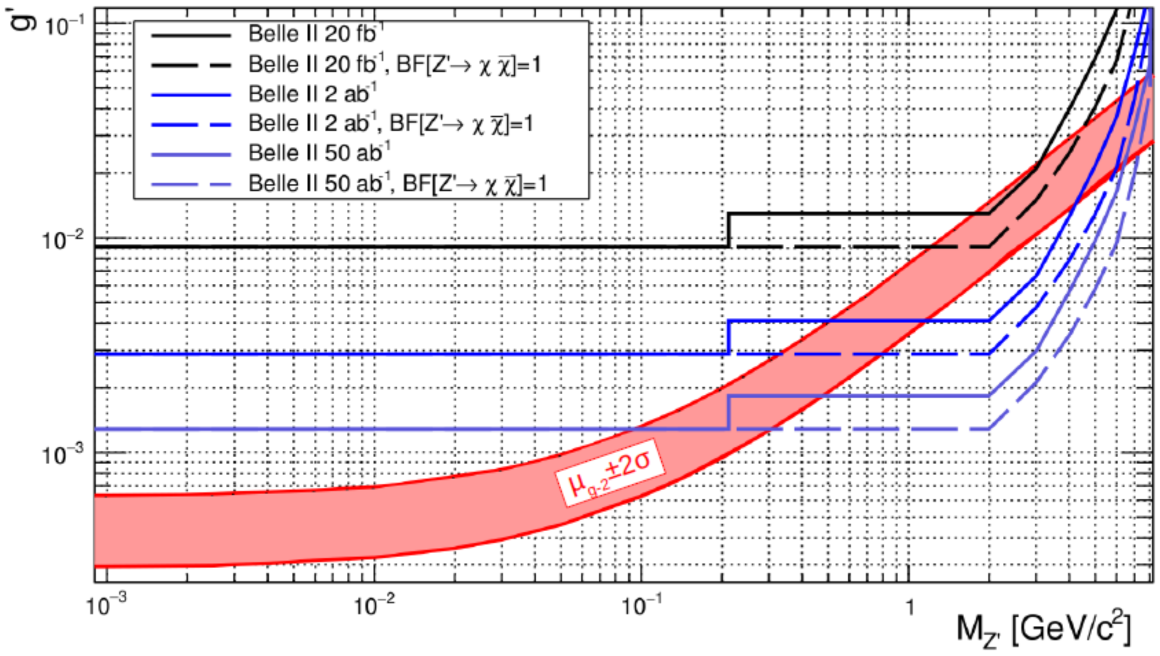


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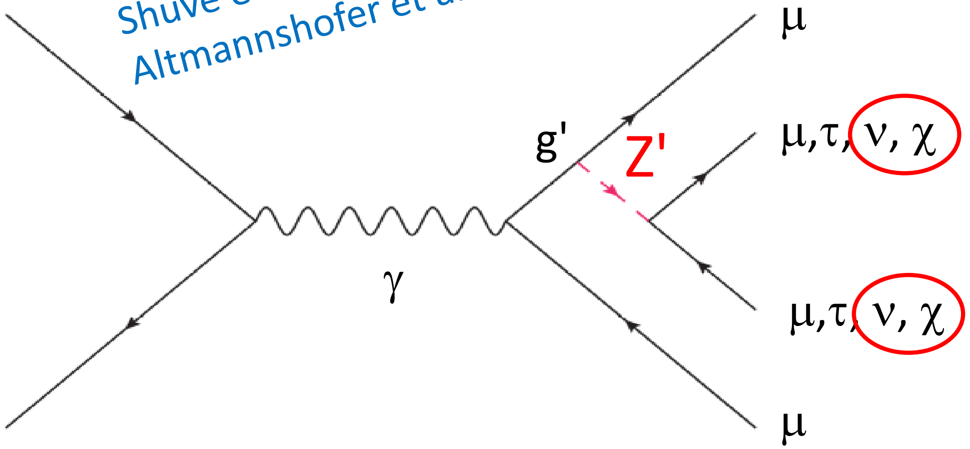



Z′ LFV
$Z' \to e\mu$ ← t-channel
$Z' \to \mu\tau$
Visible + invisible

# Invisible Υ(1S) decay searches in e+e- collisions

## BABAR vs. Belle vs. Belle II

$$\frac{BR(\Upsilon(1S)\to\nu\bar{\nu})}{BR(\Upsilon(1S)\to e^+e^-)}=\frac{27G^2M^4_{\Upsilon(1S)}}{64\pi^2\alpha^2}\left(-1+\frac{4}{3}\sin^2\theta_W\right)^2=4.14\times10^{-4}$$

$$BR(\Upsilon(1S)\to\nu\bar{\nu})\sim9.9\times10^{-6}$$

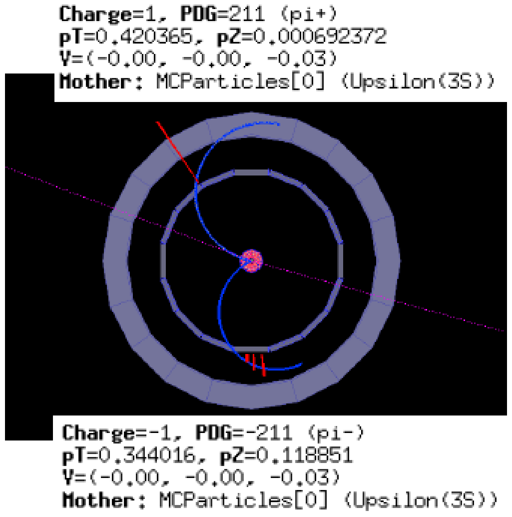
G. Inguglia

- Low mass dark matter particles however might might play a role in the decays of Υ(1S), having Υ(1S)→χχ if kinematic allowed. [Phys. Rev. D **80,** 115019, 2009]
- Also, new mediators (Z', $A^0$, $h^0$) or SUSY particles might enhance Υ(1S)→νν(γ). [Phys. Rev. D **81**, 054025, 2010]
- In absence of new physics enhancement, Belle2 should be able to observe the SM Υ(1S)→νν

$$e^+e^-\to\Upsilon(3S)$$
$$\downarrow(4.4\%)$$
$$\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$$
$$\downarrow$$
$$\Upsilon(1S)\to invisible$$

$$e^+e^-\to\Upsilon(2S)$$
$$\downarrow(18.1\%)$$
$$\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$$
$$\downarrow$$
$$\Upsilon(1S)\to invisible$$

*Belle2 Simulation*
Υ(3S)→$\pi^+\pi^-$Υ(1S),
Υ(1S)→ νν




A signal of Υ(1S)→*invisible* is an excess of events over the background in the $M_r$ distribution at a mass equivalent to that of the Υ(1S) (9.460 GeV/c²)

$$M_r^2=s+M_{\pi^+\pi^-}-2\sqrt{s}E^{CMS}_{\pi^+\pi^-}$$

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Requires running at Υ(3S) ≈ 200 $fb^{-1}$ with special low $p_T$ trigger

# Translating Υ(1S)→ invisible search to dark matter limits

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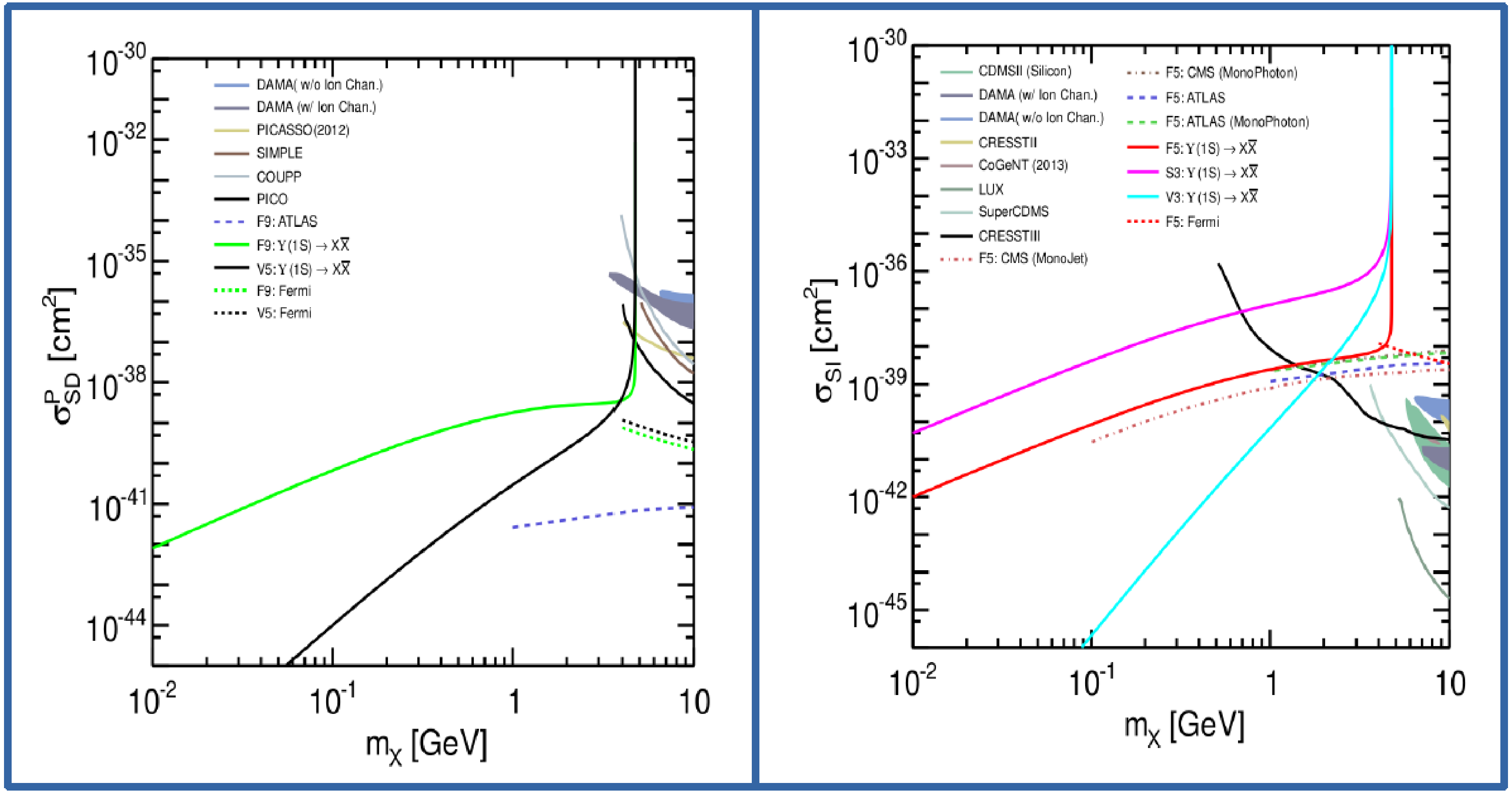
Extrapolation based on ArXiv: 1511.03728, 1404.6599

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# Summary

- Belle II Phase2 finished in July 2018
- Early data taking mostly devoted to commissioning
- $L_{int} \approx 0.5\ fb^{-1}$, with $L_{MAX} = 5.5x10^{33}cm^{-2}s^{-1}$
- Resonances, b-physics and charm physics «rediscovered»
- Belle II Phase III (complete detector) just started
- $L_{int} \approx 100\ pb^{-1}$ before the fire incident
- Hopefully $\approx 10 \div 20\ fb^{-1}$ by summer conferences

- **Invisible dark photon search**
- **ALP search**
- **Z' to invisible search**
- **Z' LFV search**
- **Y(1S) to invisible**

**Still to be started: dark searches in flavour physics**

**$B \rightarrow K^+ A$, $A \rightarrow \gamma\gamma$**

**$Y(1S) \rightarrow \gamma A$, $A \rightarrow gg$**

**$B \rightarrow X_c \mu \nu Z'$**

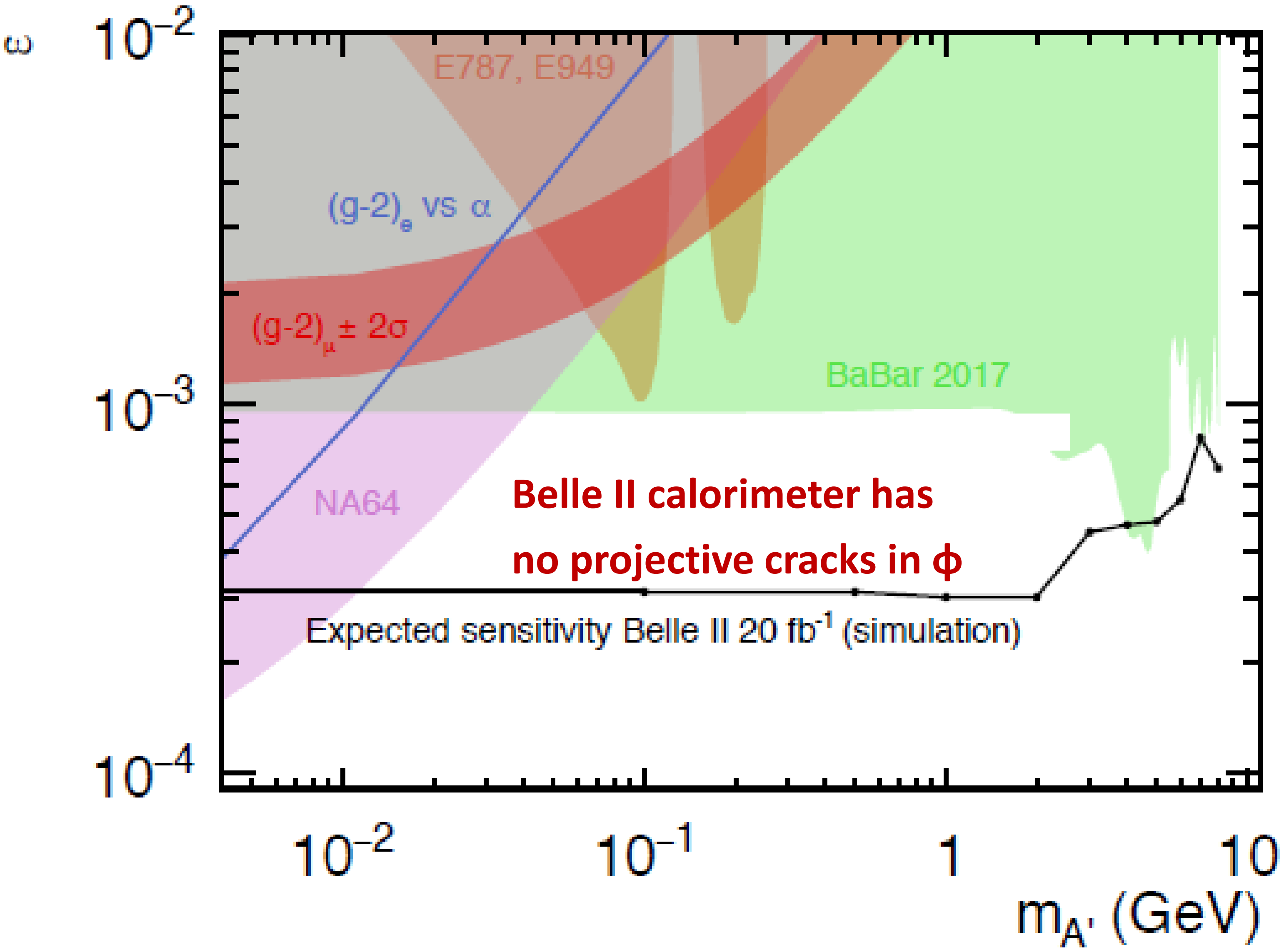
**....**

<u>Not even mentioned</u>

- Magnetic monopoles
- muonic dark force
- dark Higgs
- dark Higgsstrahlung
- dark scalars
- inelastic dark matter
- dark search in $\tau$ decays
- long-lived particles
- ...

# SPARE SLIDES

# Invisible dark photon: sensitivity



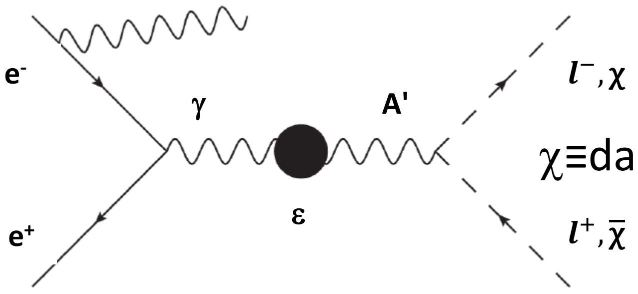

**Belle II calorimeter has no projective cracks in ϕ**

**Lower trigger threshold wrt BaBar**

# Dark photon: introduction

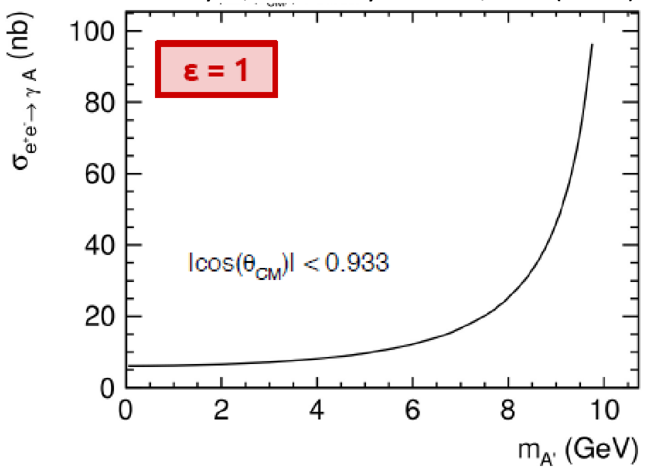
Some astrophysical observations suggest the possibility of the existence of a new light (GeV scale) hidden dark sector with a mediator A′ (dark photon), weakly coupled to the Standard Model via kinetic mixing, and light dark matter.

At $e^+e^-$ colliders




$\chi \equiv$dark matter particle

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




two basic scenarios depending on **A′** vs matter mass relationship

**$m_\chi > 1/2\ m_{A'} \Rightarrow$ A′ visible decays (SM particles)** → 

$A' \to l^+l^-$

$A' \to \pi^+\pi^-$, $h^+h^-$

h′ A′ dark higgstrahlung

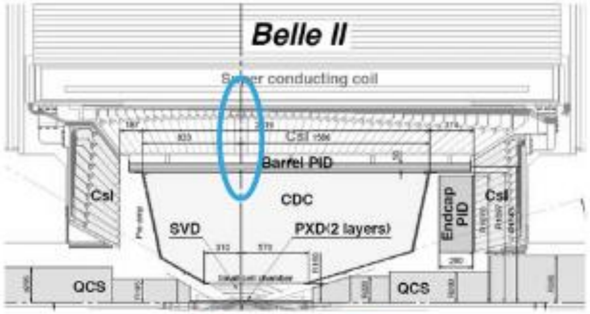
→ $h' \to A'A'$, $A'A'A' \to 6\ l^\pm + \pi^\pm$

→ A′+missing

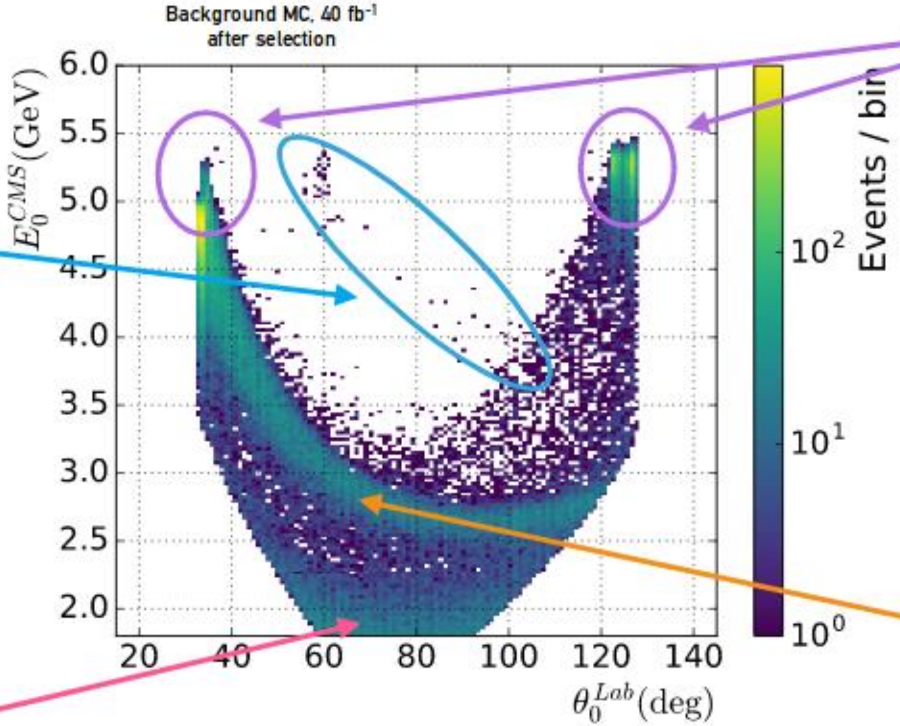
**$m_\chi < 1/2\ m_{A'} \Rightarrow$ A′ invisible decays to LDMA** → $A' \to \chi\bar{\chi}$

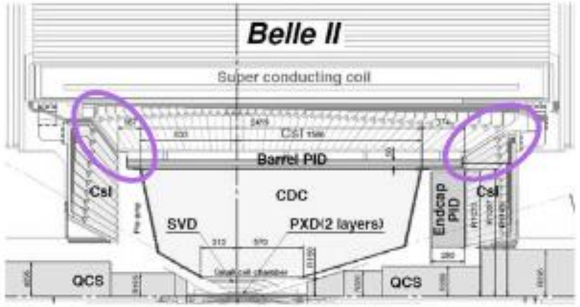
**access to light dark matter particles**

# Invisible dark photon: backgrounds

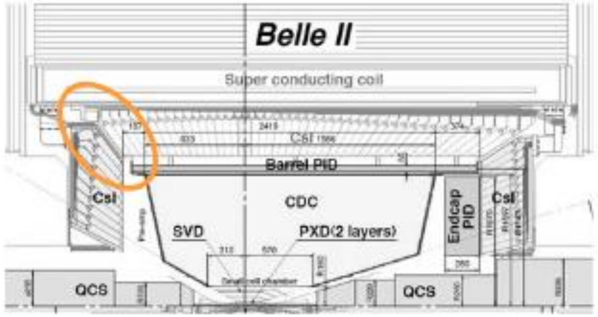



**ee→2γ and 3γ**
1γ in ECL 90° gap
1γ out of ECL acceptance




**ee→2γ**
1γ in ECL BWD or FWD gap




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

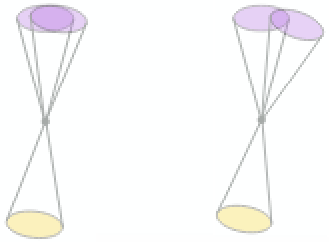
**ee→eeγ**
both electrons
out of tracking acceptance

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

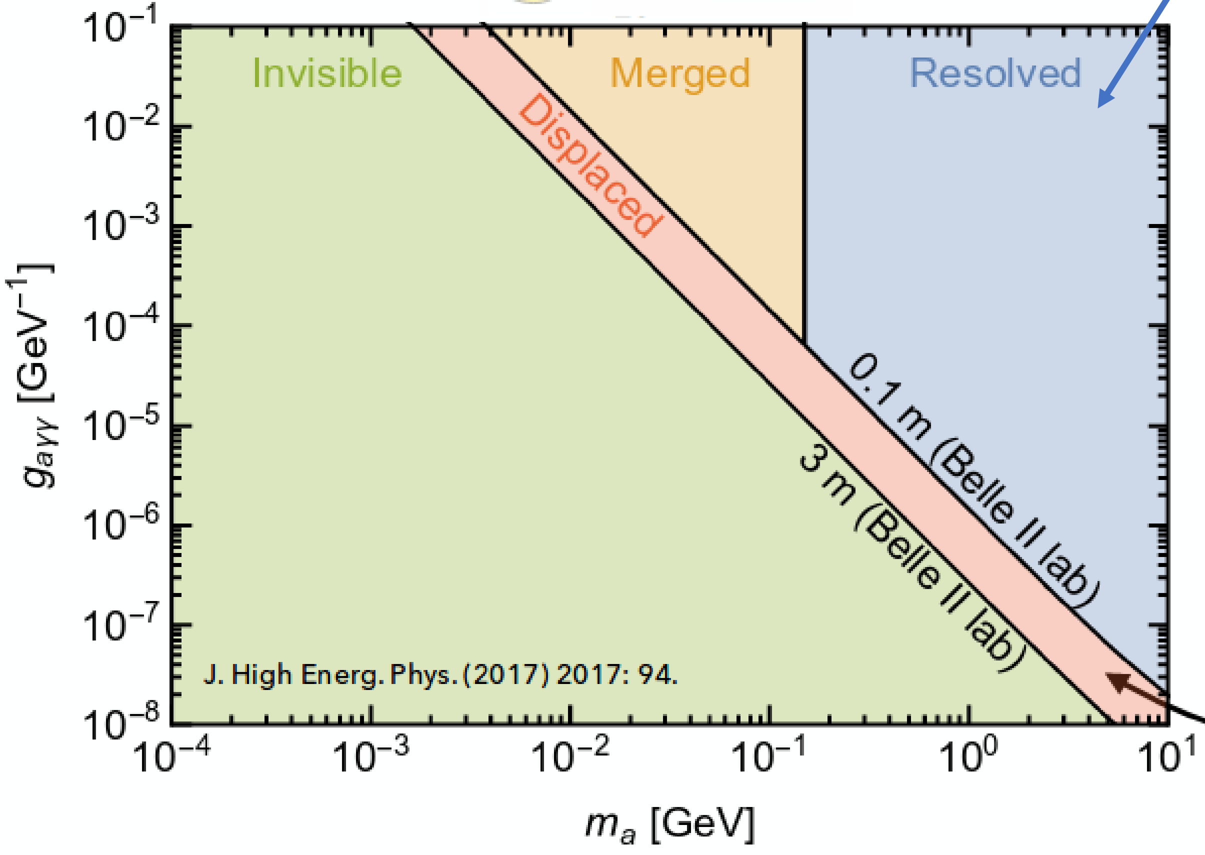
# Axion Like Particles (ALPs): signal

**3 $\gamma$ topology, but…**

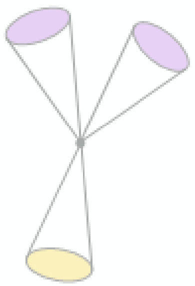
Two of the photons overlap or **merge**.

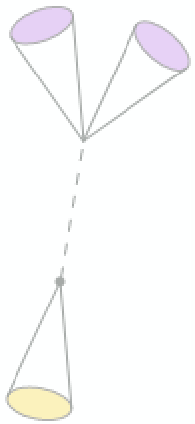


$\varepsilon \approx 20 \div 40\%$




Three **resolved**, high energetic photons.





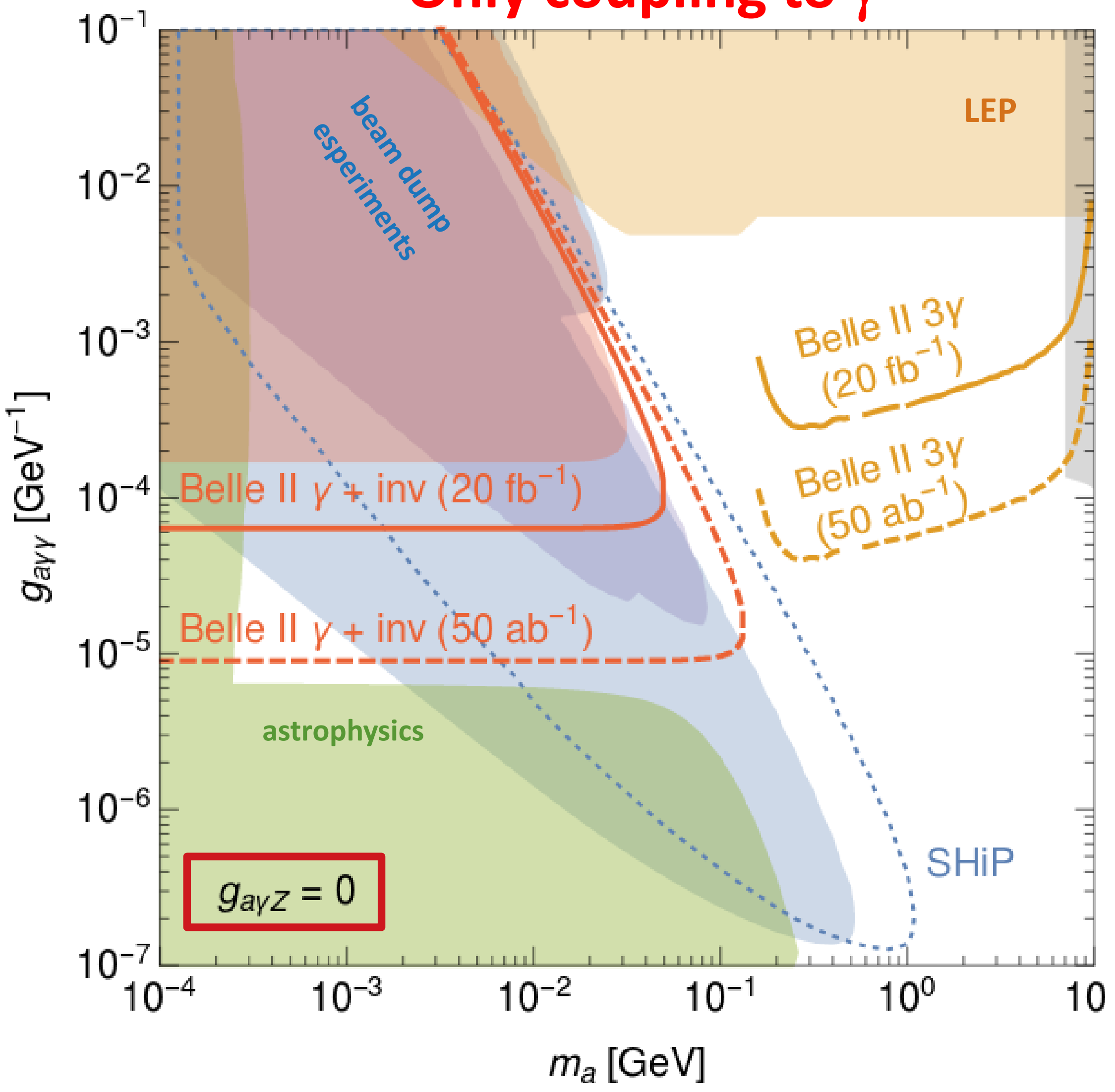
ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

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

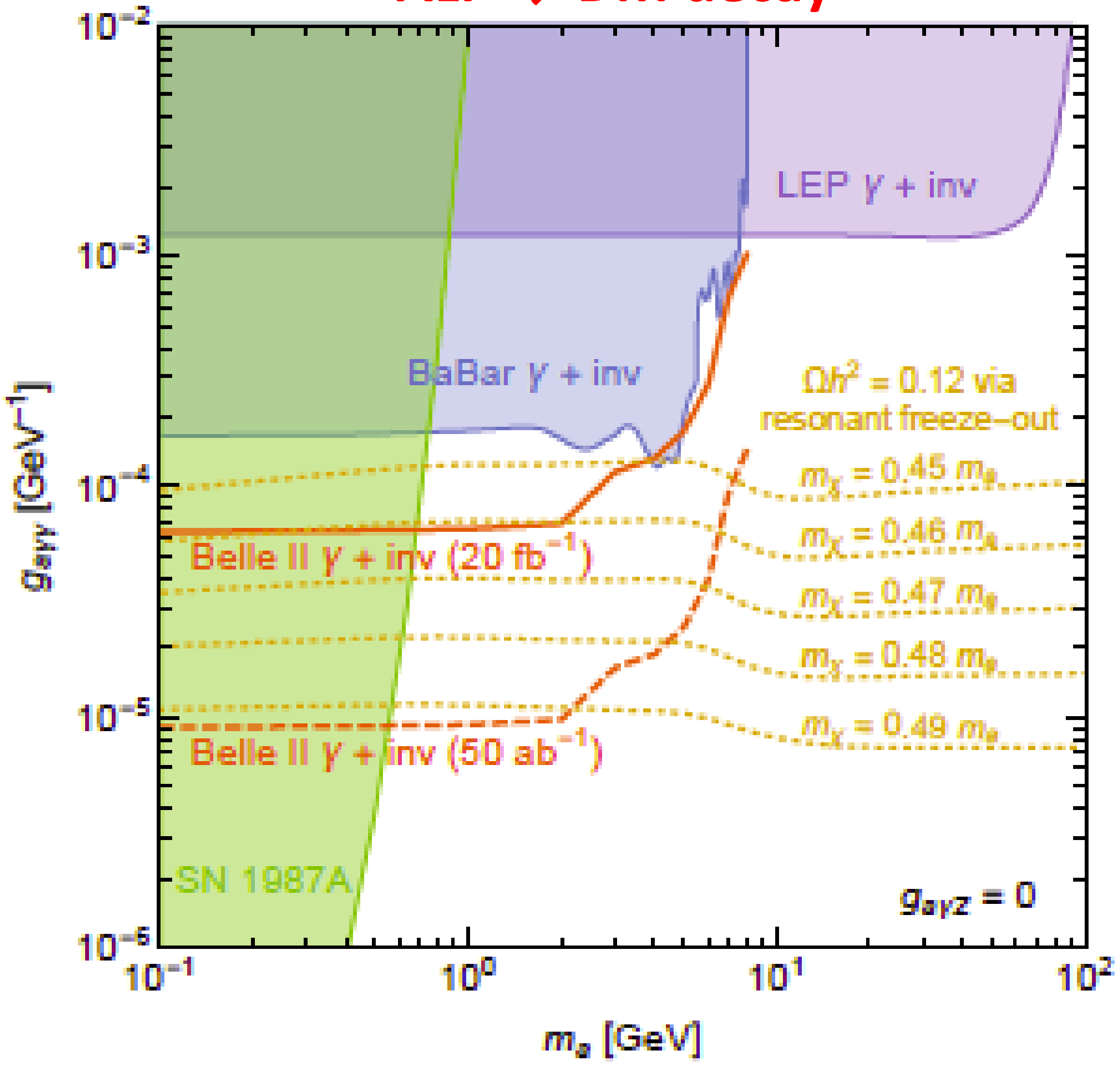
**ALPs can also decay to DM → single photon topology**

# Axion Like Particles (ALPs): sensitivity

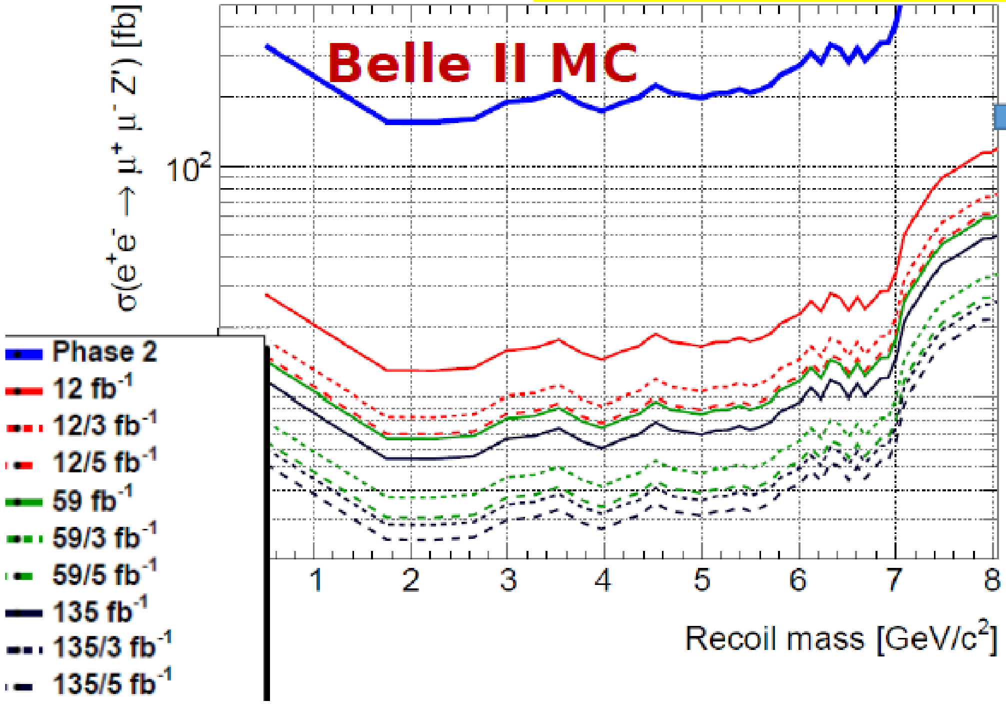
**Only coupling to γ**

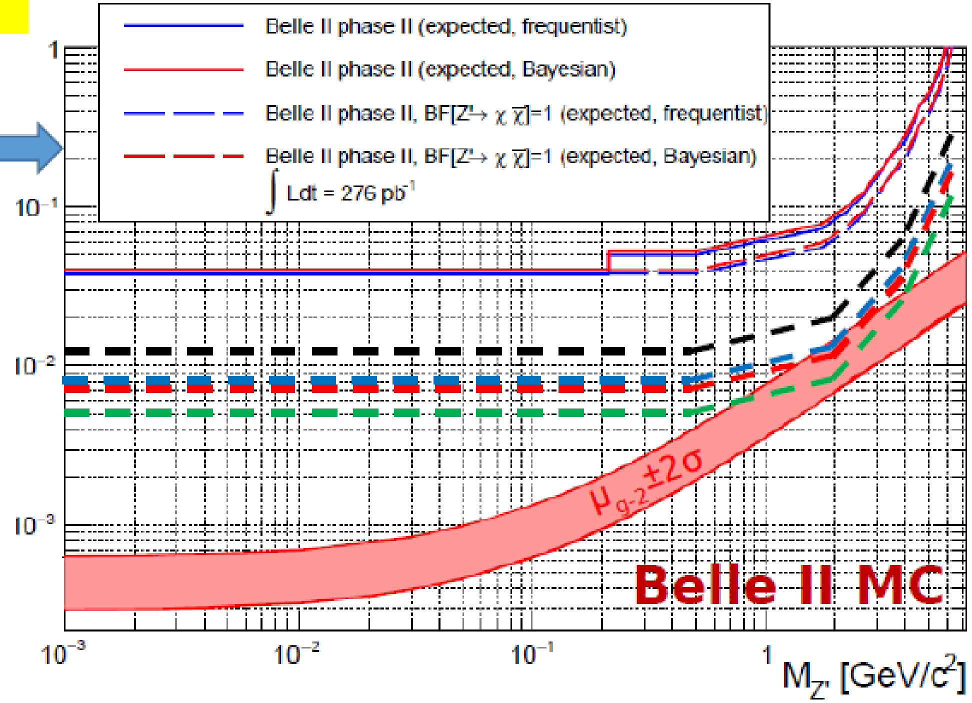



**ALP → DM decay**



**Work in progress**




Possible (big) factors of improvement beyond luminosity:

- PID (up to 7 on τ bkg)
- Resolution (VXD)
- Vertex fit →τ rejection
- MVA vs linear cut analysis
- See also previous slide for assumptions on systematics

→ same background or background reduced by factors 3 and 5

- - - - 12 $fb^{-1}$
- - - - 59 $fb^{-1}$
- - - - 135 $fb^{-1}$
- - - - 135 $fb^{-1}$, B/5

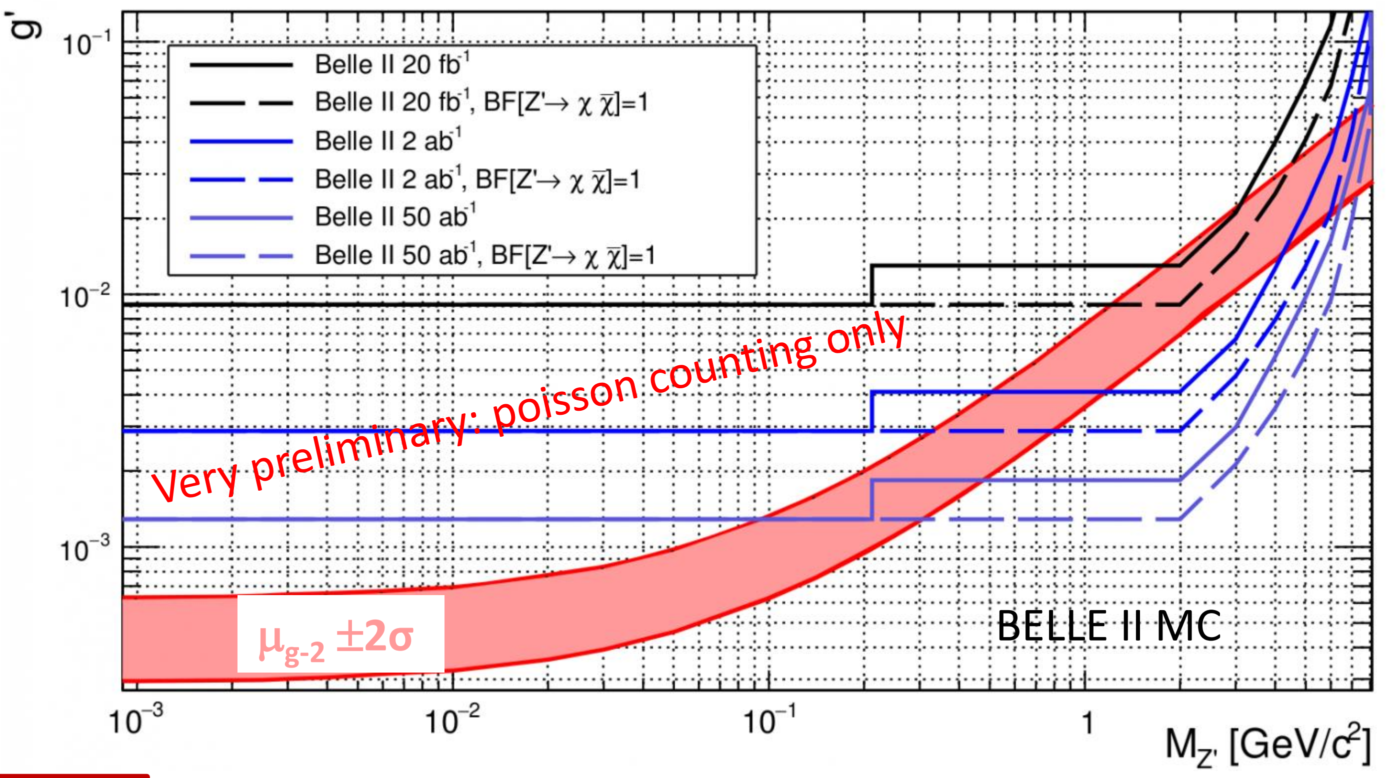
# $L_\mu - L_\tau$, Z' invisible decay sensitivity

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

Main backgrounds:

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

Belle II expected sensitivity for Z'→ invisible




**Alternative model under search**

**LFV Z' (eμ coupling)**

$e^+ e^- \to e^+ \mu^- Z'$ ; $Z' \to$ invisible
$e^+ e^- \to e^+ \mu^- Z'$ ; $Z' \to e^+ \mu^-$ (no SM background expected)

Z'→ visible decay (muonic dark force)

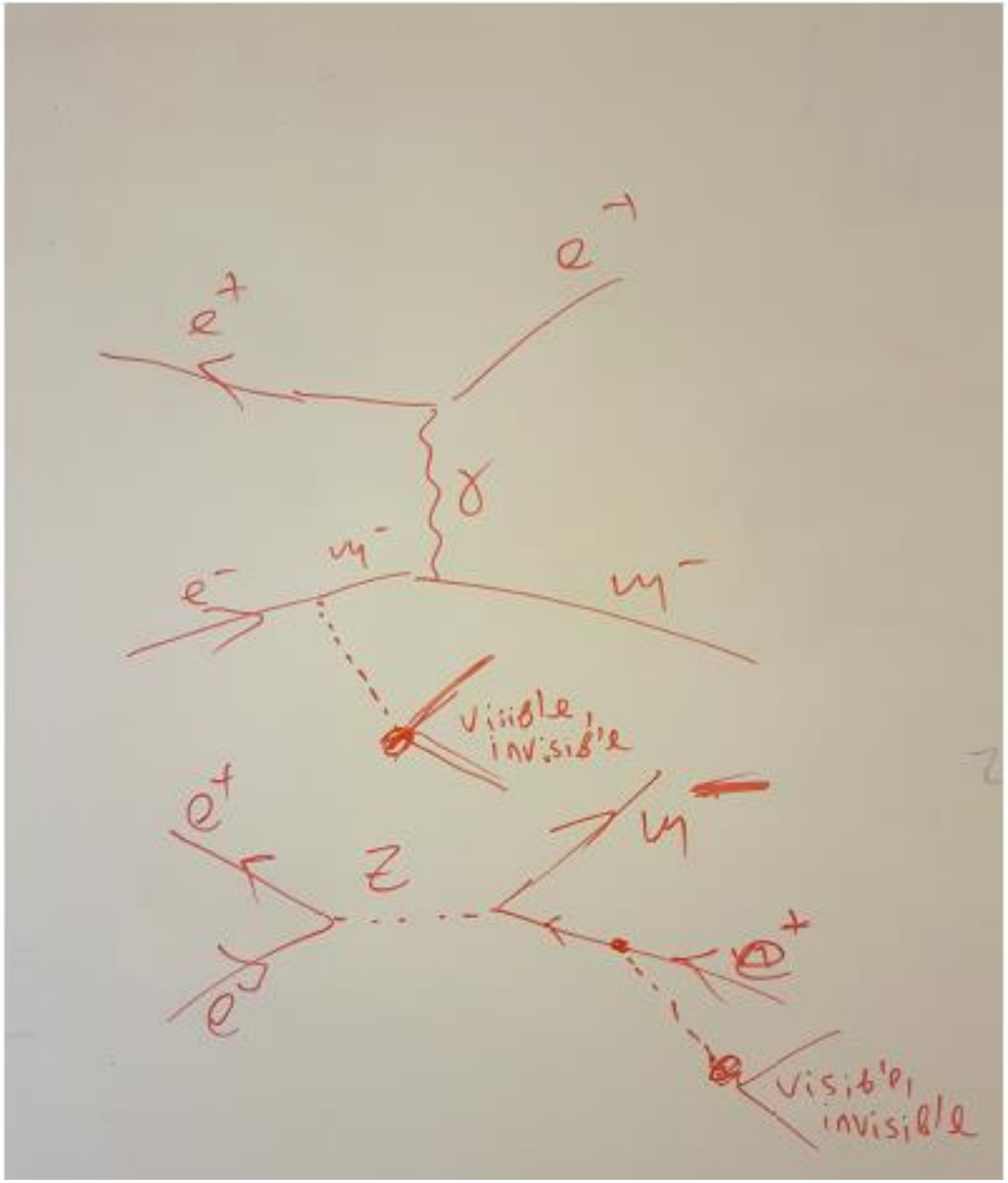
$e^+ e^- \to \mu^+ \mu^- Z'$ ; $Z' \to \mu^+ \mu^-$ will be competitive in Phase 3 (due to BaBar result)

# Z' LFV: invisible + visible

What if symmetries of SM are not kept in the Dark Sector?

What if DM violates Lepton Flavour?

One can imagine, for example, $e\mu$ coupling




$e^+ e^- \rightarrow e^+ \mu^- Z'$ ; $Z' \rightarrow$ invisible

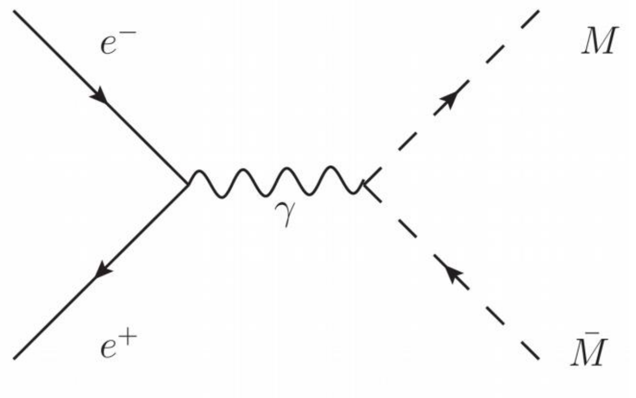
Dominant background: $e^+e^- \rightarrow \tau^+\tau^- (\gamma)$, $\tau^\pm \rightarrow \mu^\pm, e^\pm \nu\nu$

$e^+ e^- \rightarrow e^+ \mu^{--} Z'$ ; $Z' \rightarrow e^+ \mu^-$ **+ c.c.**

no SM background

# Magnetic monopoles

- Particle carrying magnetic charge
- Recent searches for magnetic charges $g$ > 68.5e
- Small charges $g$ < 10e are not excluded
- Weaker ionisation due to absence of $1/\beta^2$ factor for magnetic charges
- Tracks are straight in XY and curved in RZ
- They need a dedicated tracking (parabolas rather than helices)




$$z(s) = z_0 + \frac{p_z}{p_T}s + \frac{gBm}{2p_T^2}s^2$$