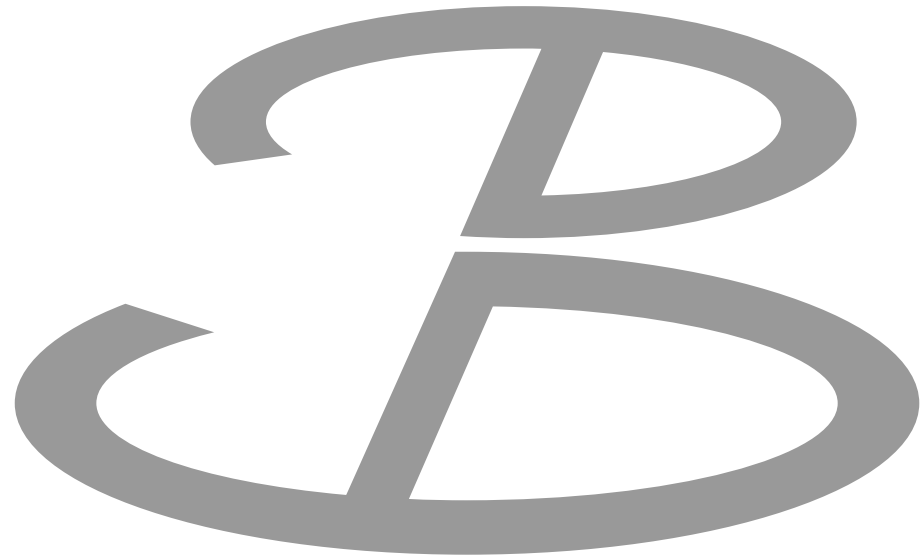


# Dark sector physics with Belle II.

Sam Cunliffe

EPS HEP, Ghent, 11.07.2019

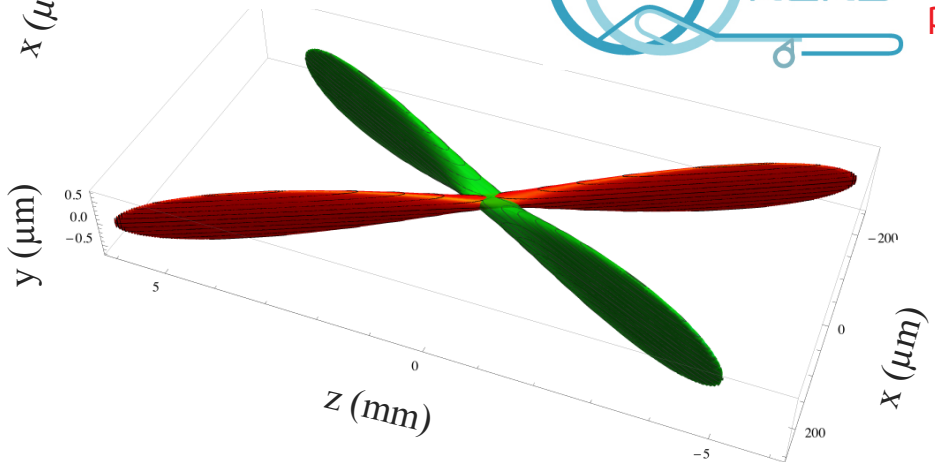
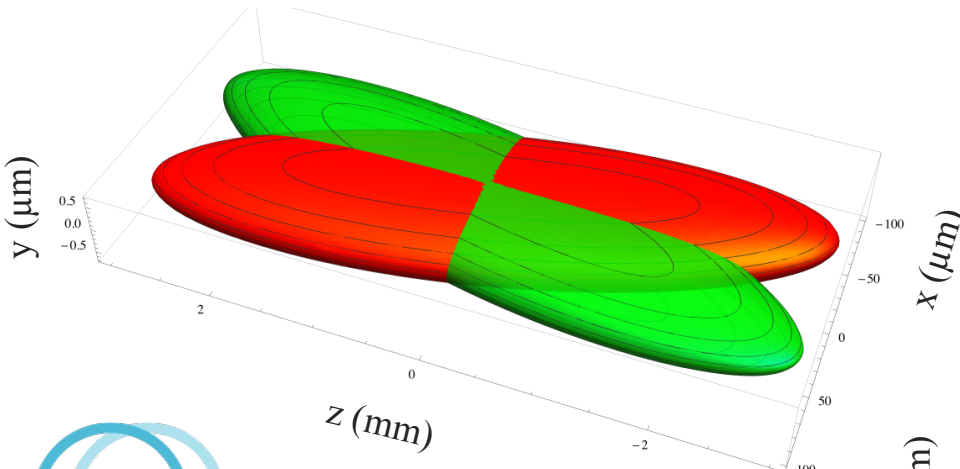
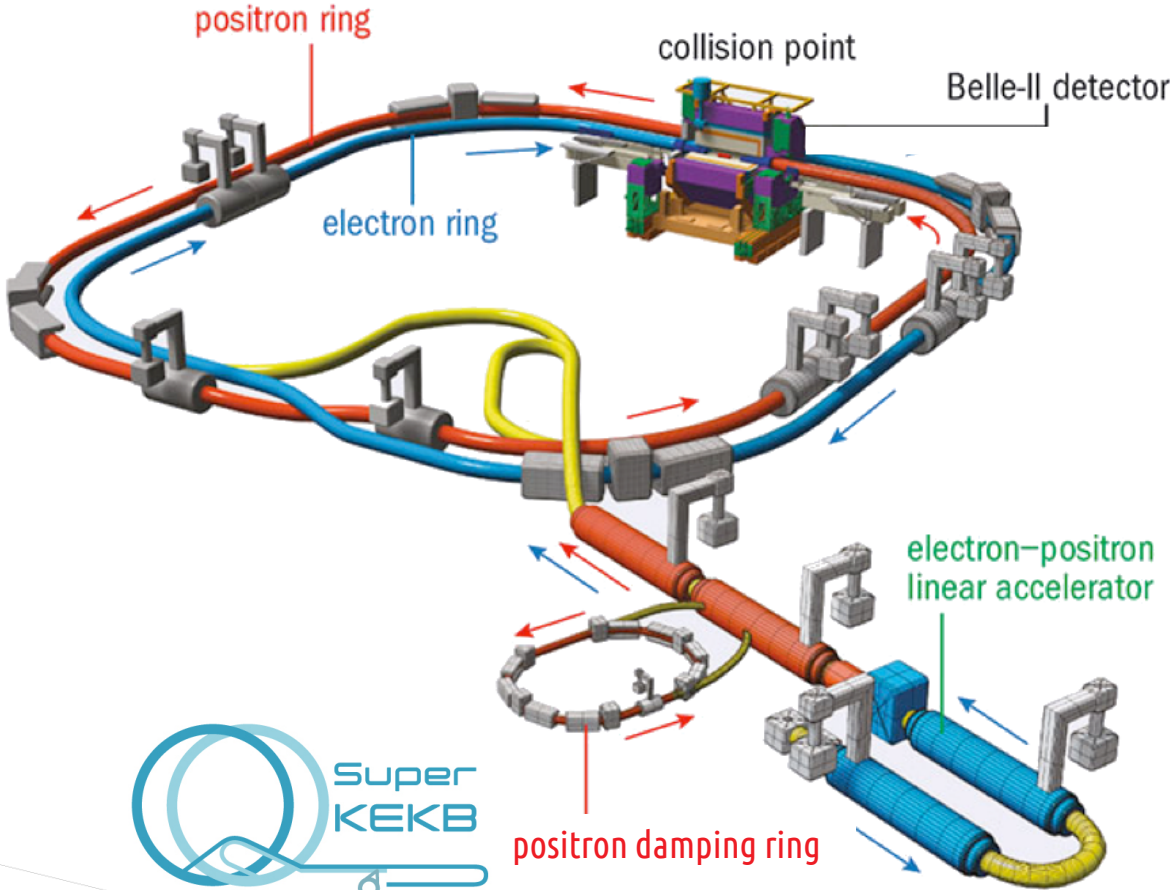


*Belle II*



# SuperKEKB

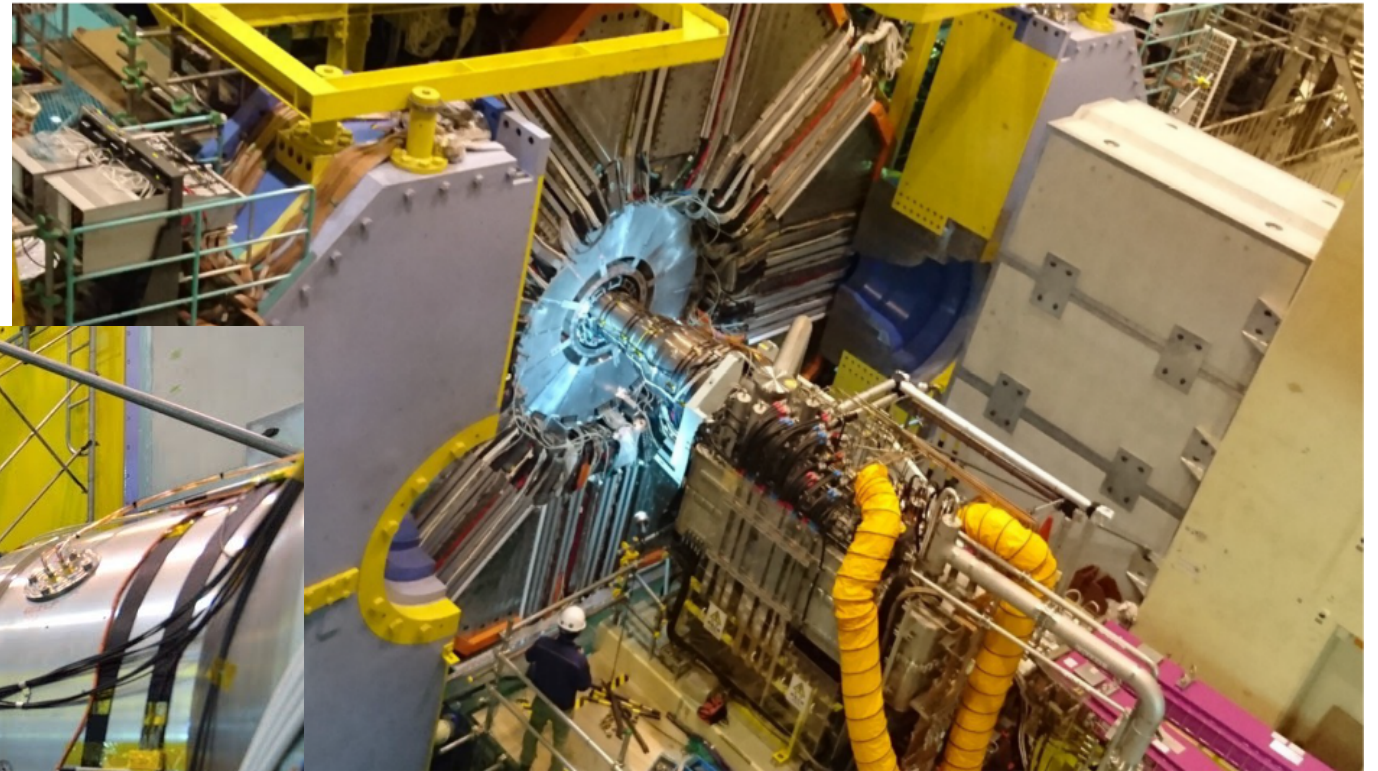
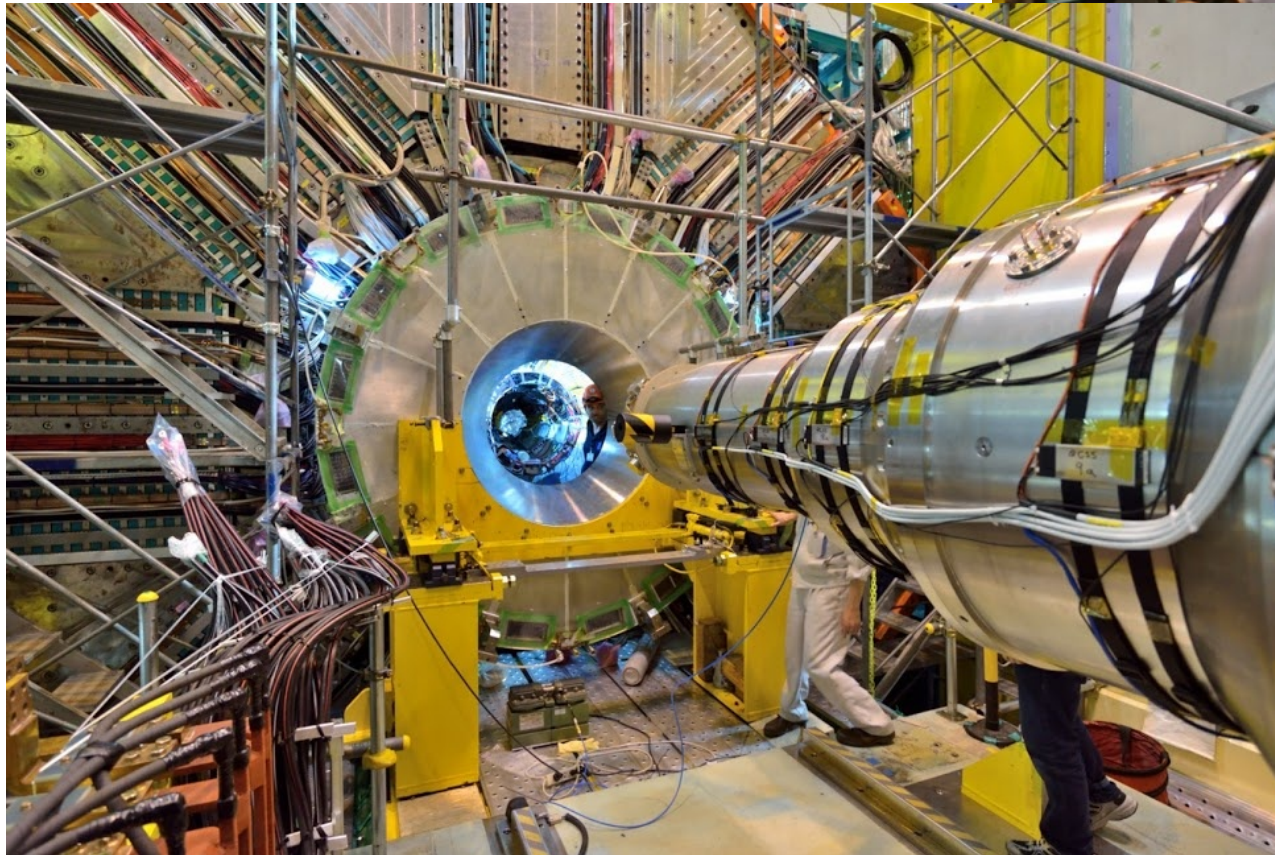
- Reason for the second iteration of the project: **upgraded accelerator.**
- A factor **40** increase in instantaneous luminosity
  - ▶  $\times 2$  from upgraded ring (higher beam current)
  - ▶  $\times 20$   $\beta^*$  from final focus magnets.





# Final focus magnets

February 2018



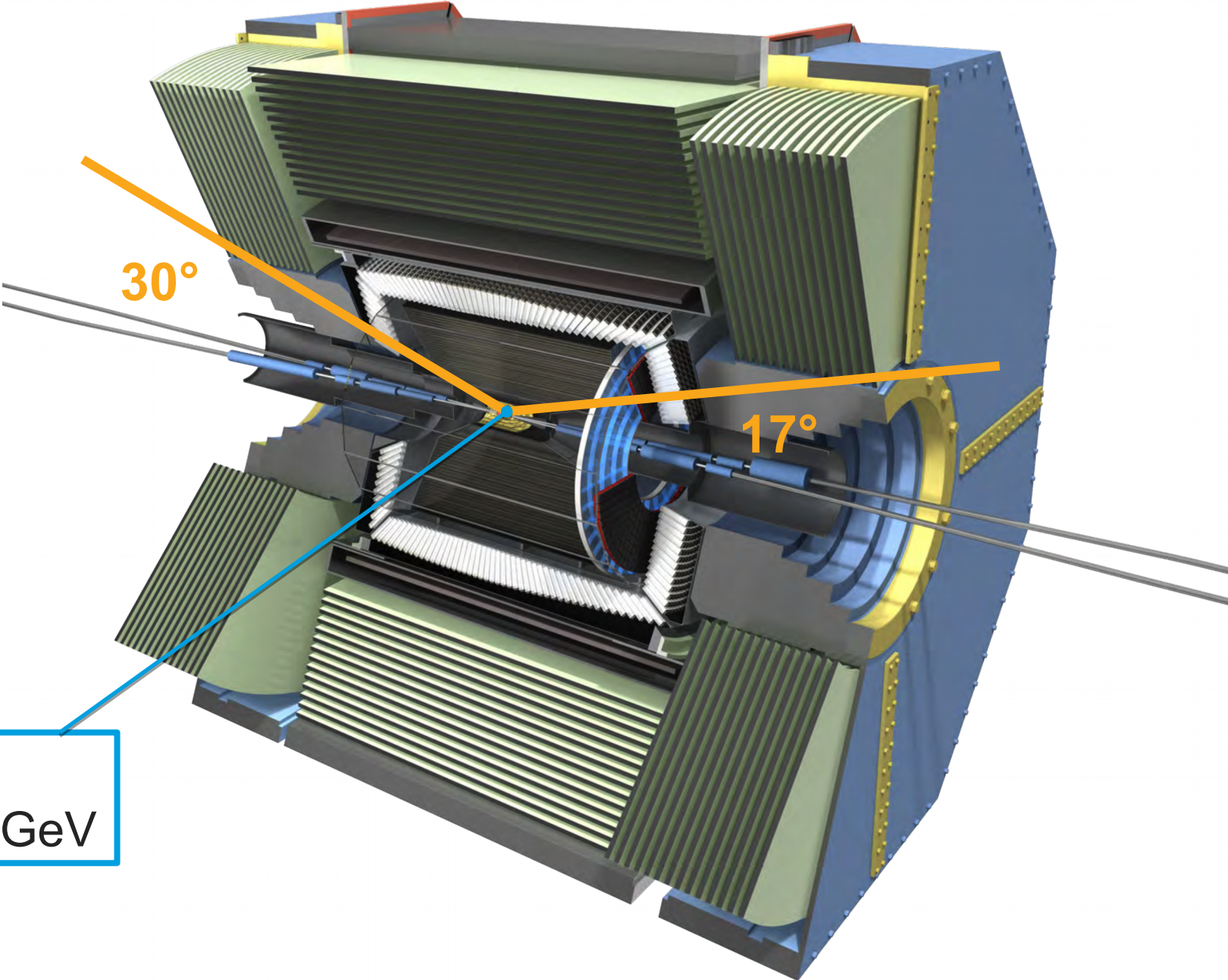


# Belle II

## The detector

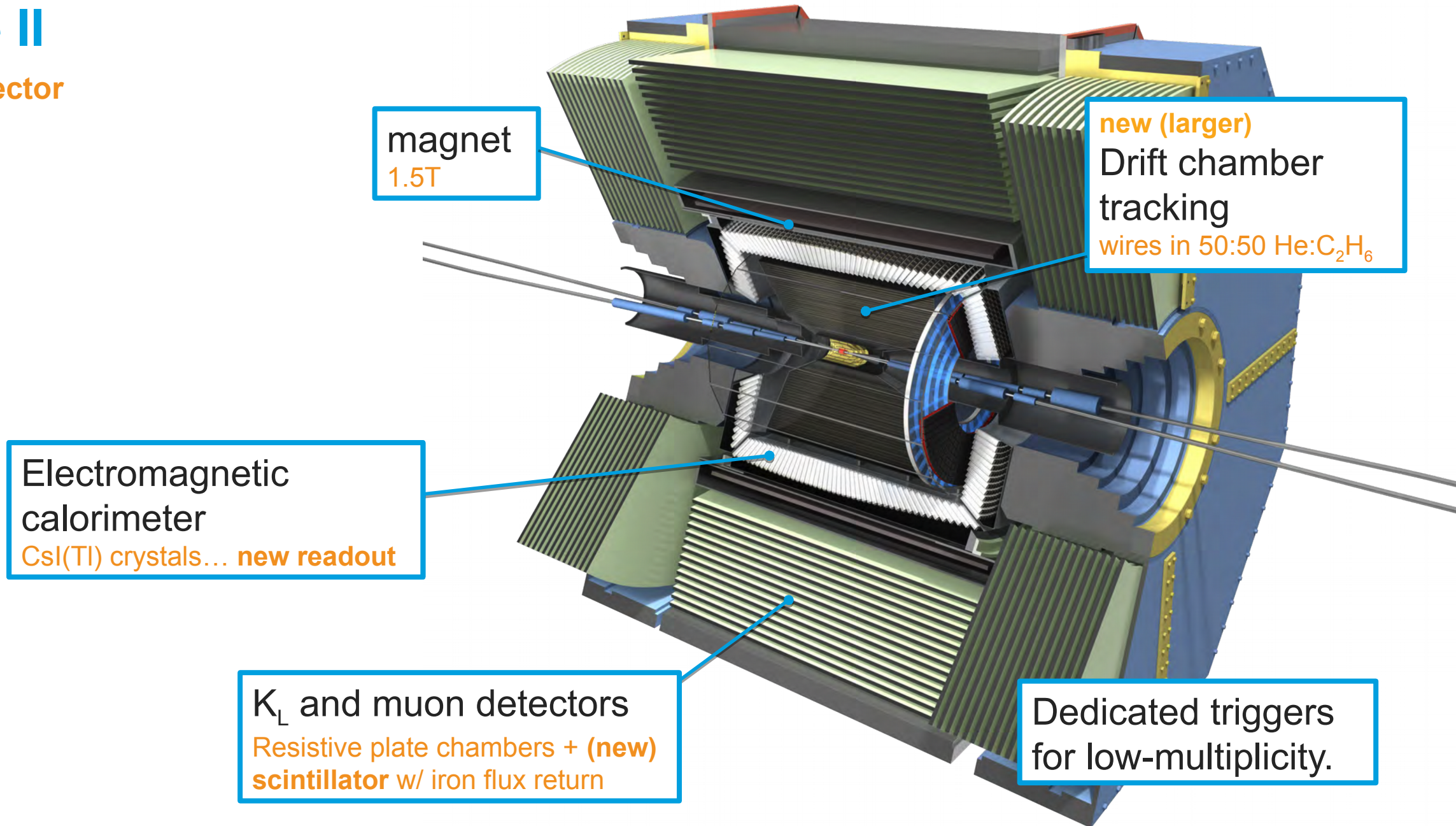
Direction of boost  
Direction of electron beam  
"Forward"

$e^+e^-$  collision  
@  $\sqrt{s} = 10.58$  GeV



# Belle II

## The detector



magnet  
1.5T

new (larger)  
Drift chamber  
tracking  
wires in 50:50 He:C<sub>2</sub>H<sub>6</sub>

Electromagnetic  
calorimeter  
CsI(Tl) crystals... new readout

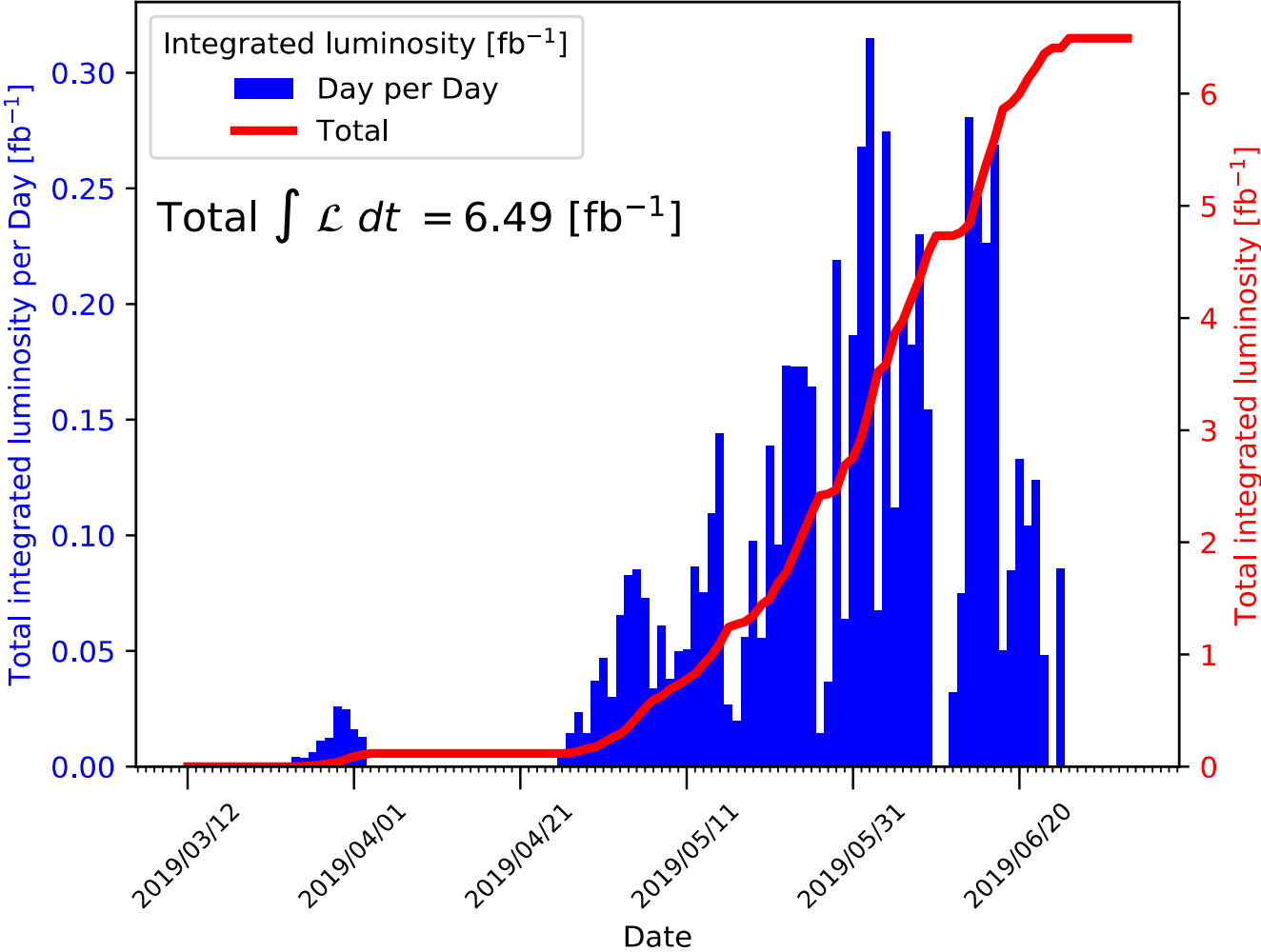
K<sub>L</sub> and muon detectors  
Resistive plate chambers + (new)  
scintillator w/ iron flux return

Dedicated triggers  
for low-multiplicity.



# Data taking this year

Belle II online luminosity      Exp: 7-8 - All runs

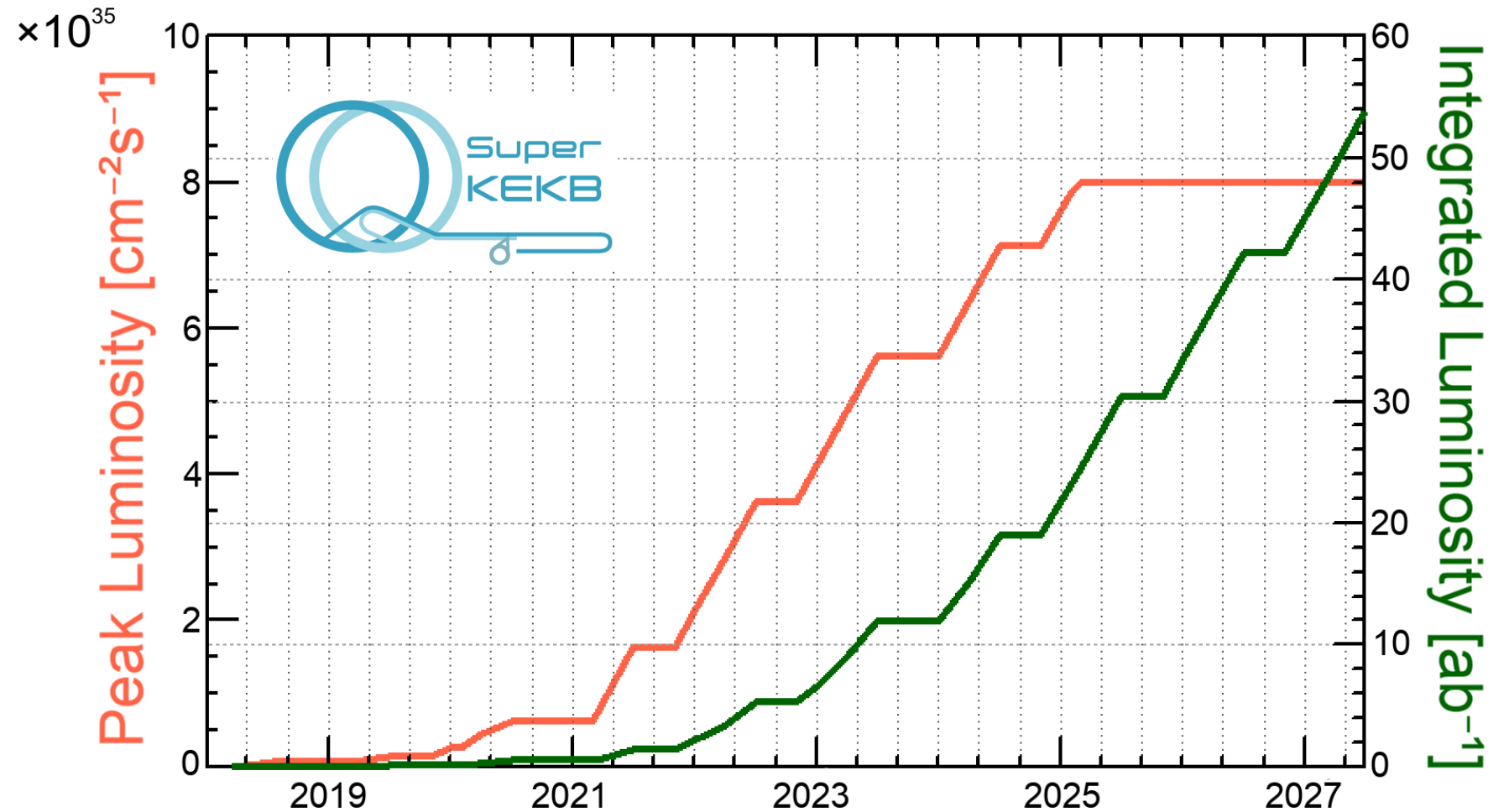


Spokesperson, run coordinators after the first fb<sup>-1</sup>



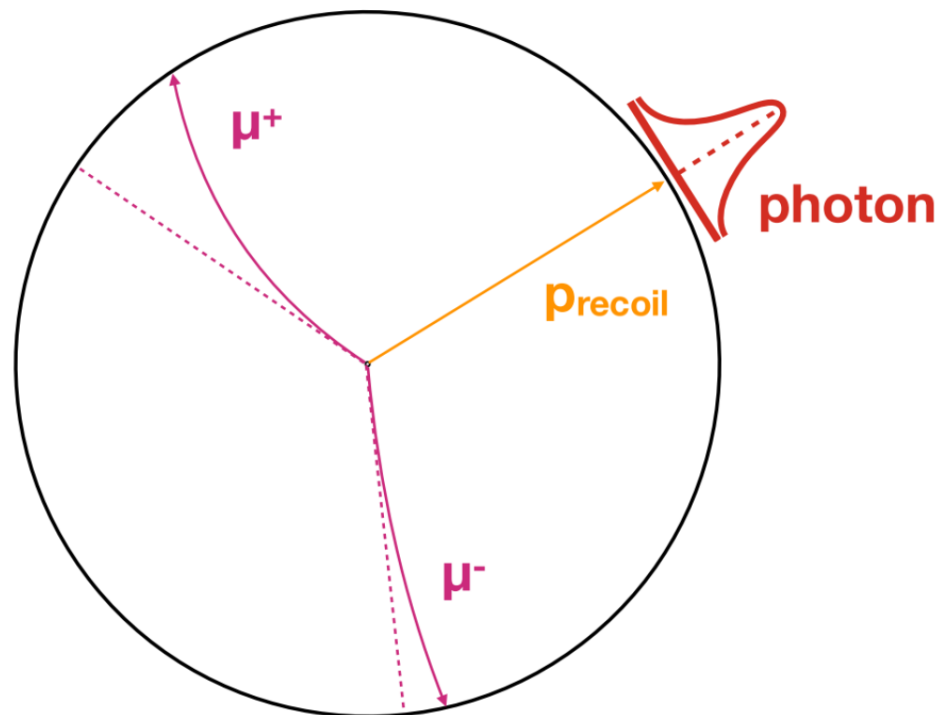
# Data schedule

- Last year: 500 pb<sup>-1</sup>.
  - ▶ *Commissioning* data.
- This year: ~6.5 fb<sup>-1</sup> **delivered**.
- Lifetime data set: 50 ab<sup>-1</sup>.

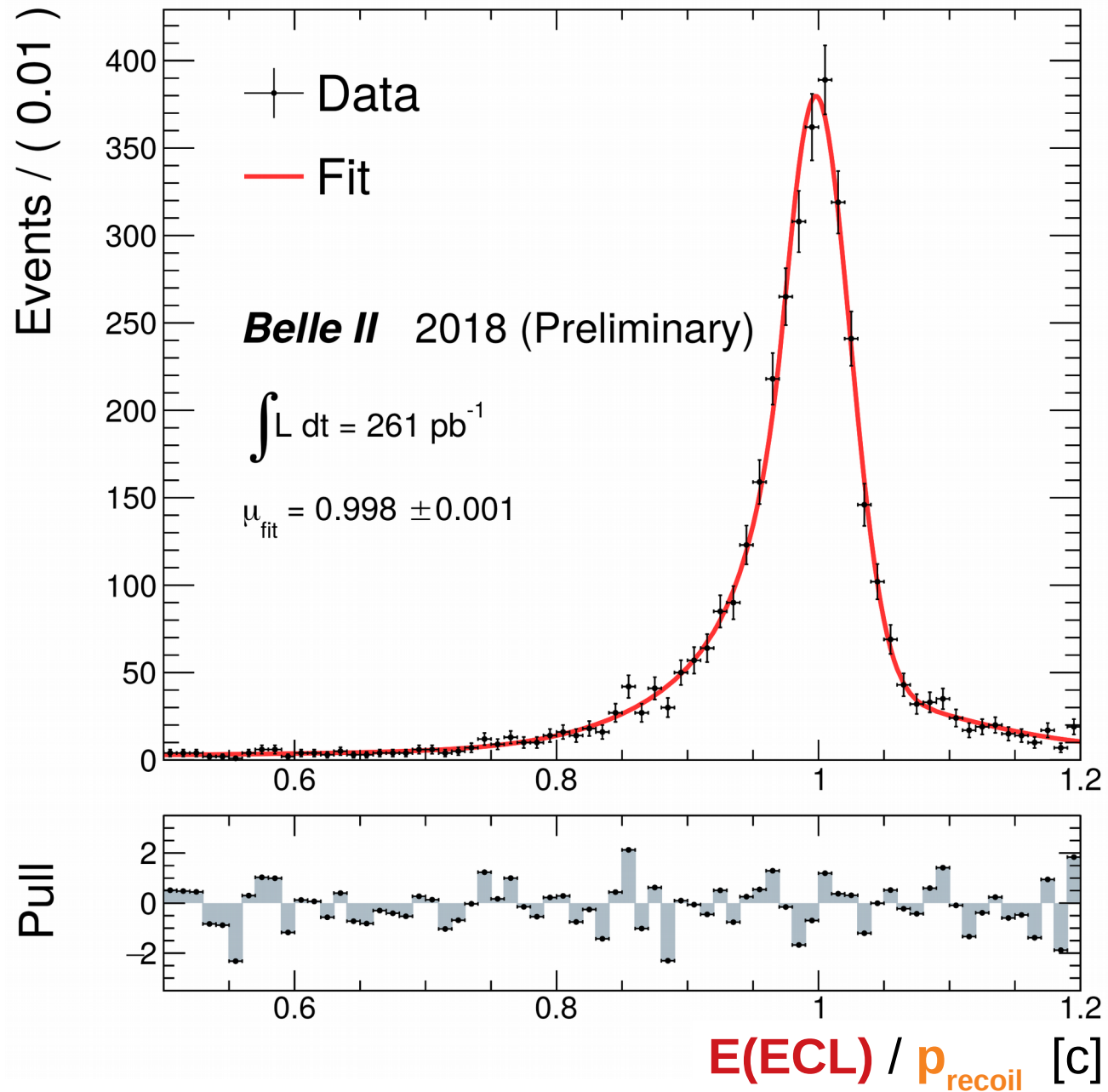


# Tracking and clustering

## Radiative dimuon events in first data



$$ee \rightarrow \mu\mu\gamma$$



# Dark matter

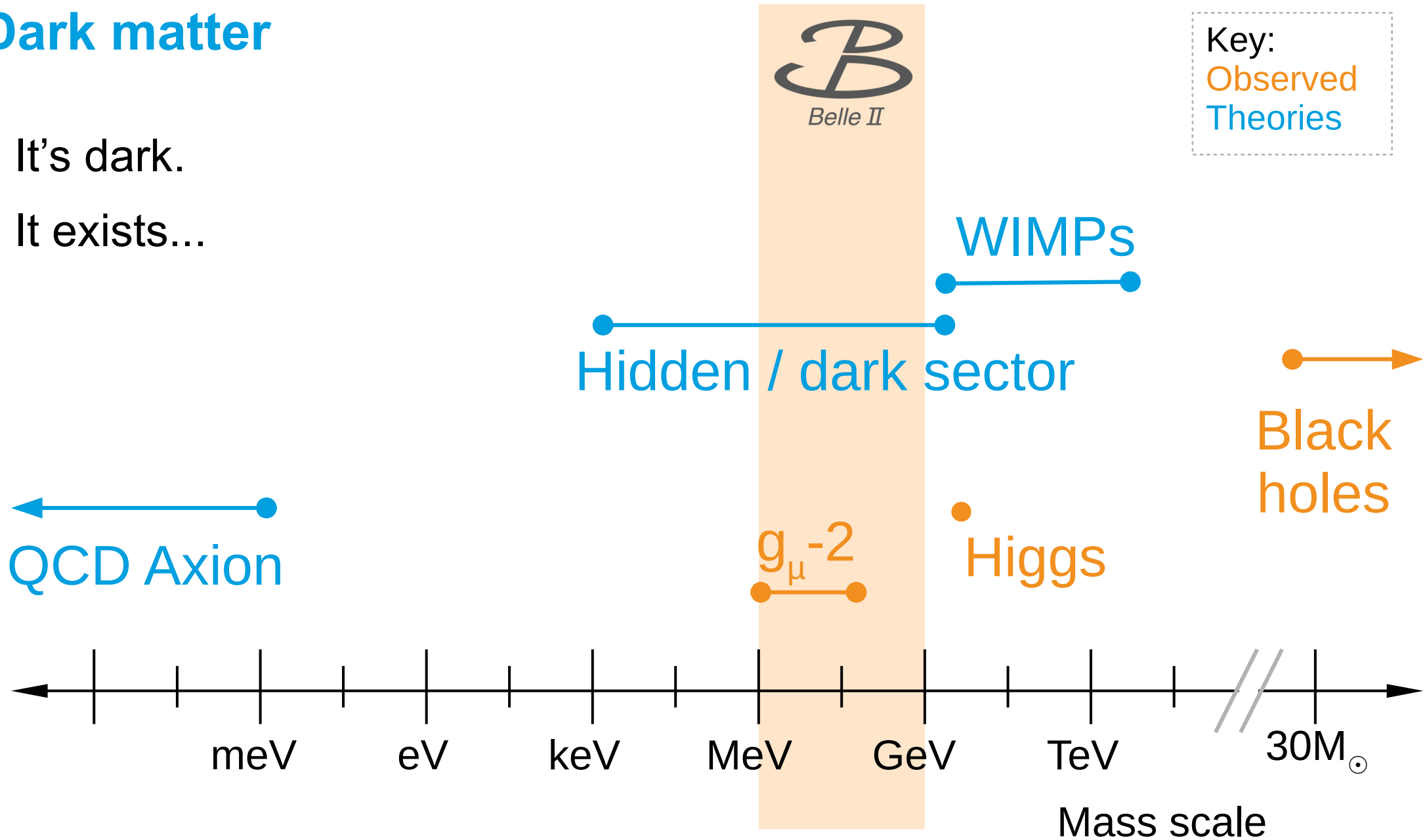


# Dark matter

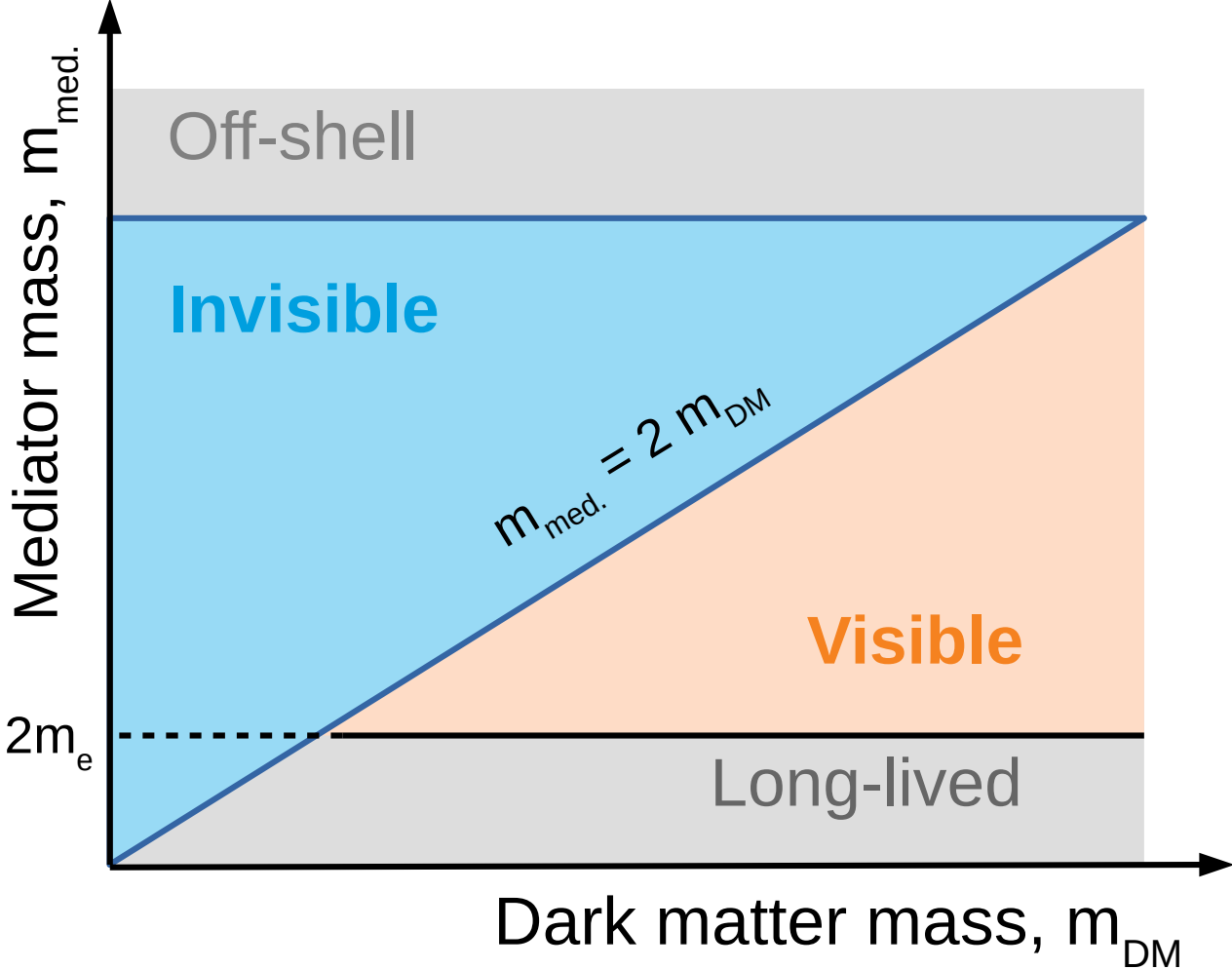
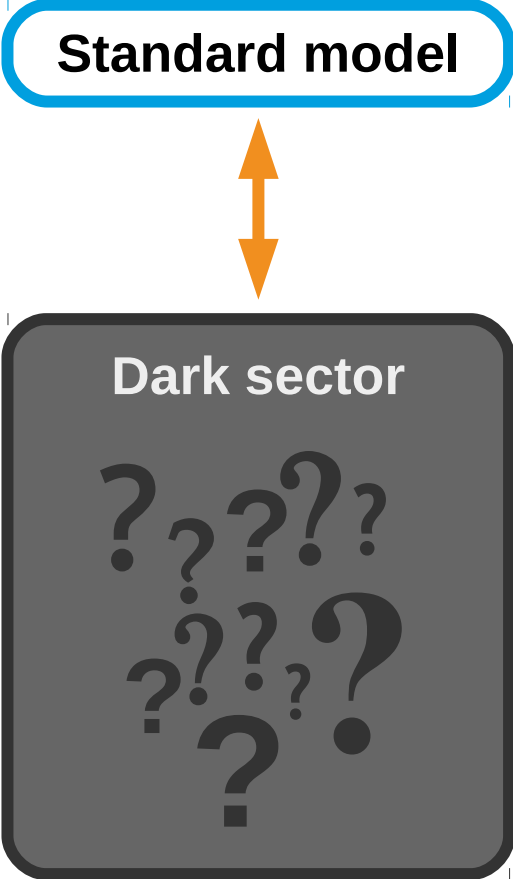
- It's dark.
- It exists...

# Dark matter

- It's dark.
- It exists...



# Dark sector





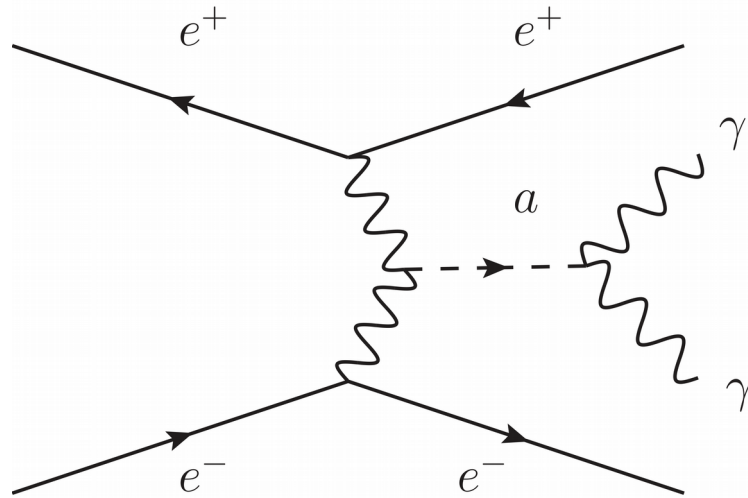
# Axion-like particle

## Theory

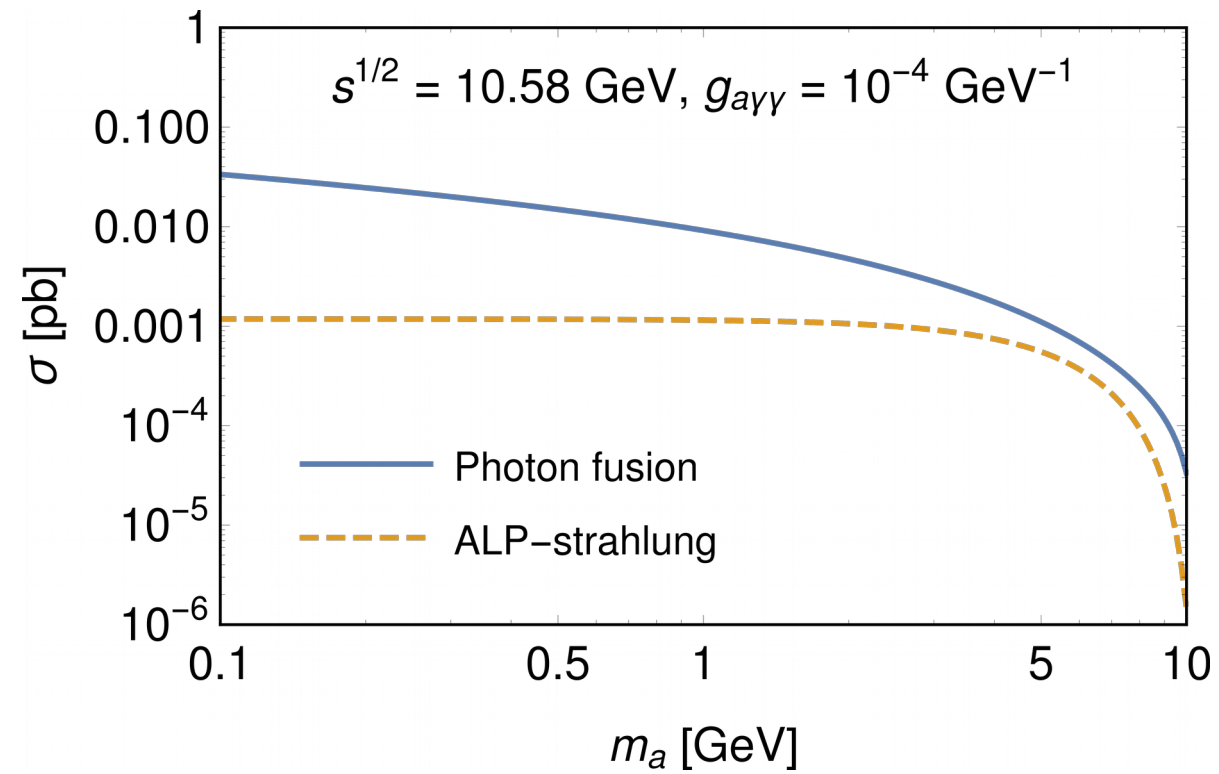
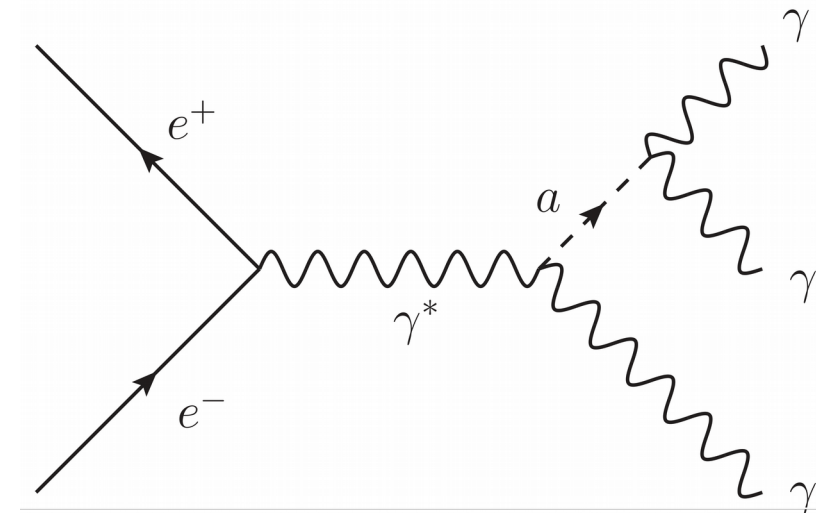
- After EWSB, four terms:

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4} a F_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} a W_{\mu\nu} \tilde{W}^{\mu\nu}$$

Photon fusion



ALP-strahlung



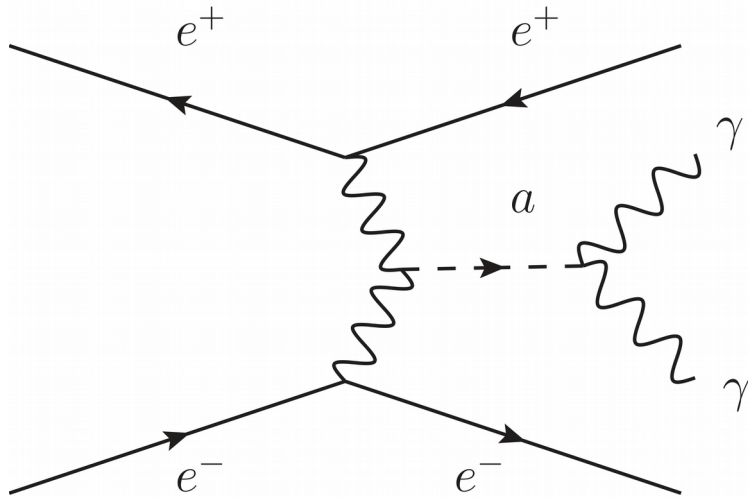
# Axion-like particle

## Theory

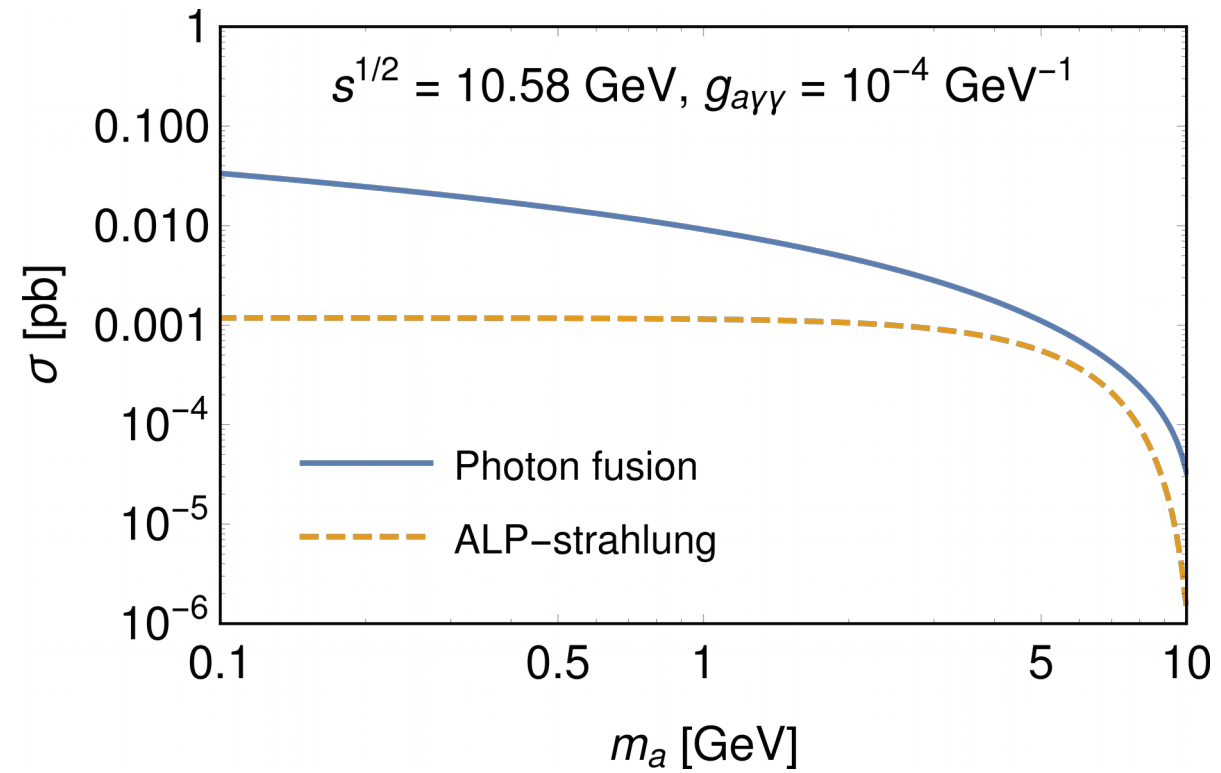
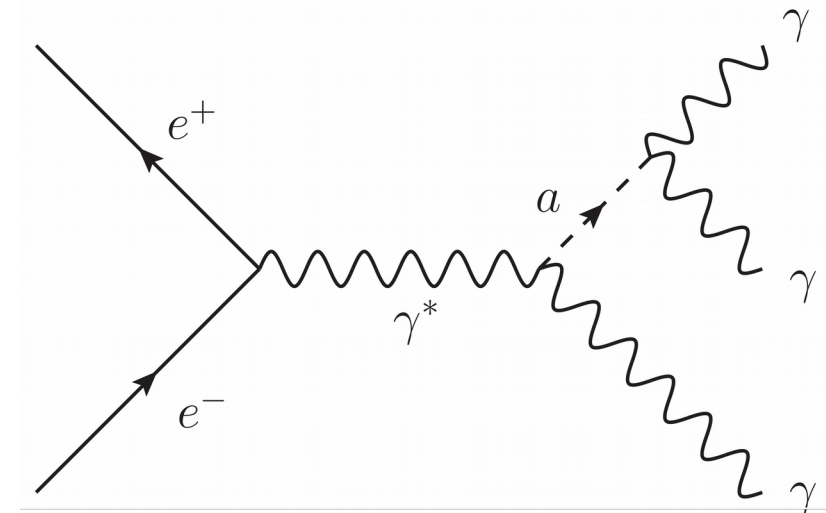
- After EWSB, four terms:

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4} a F_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} a W_{\mu\nu} \tilde{W}^{\mu\nu}$$

Photon fusion



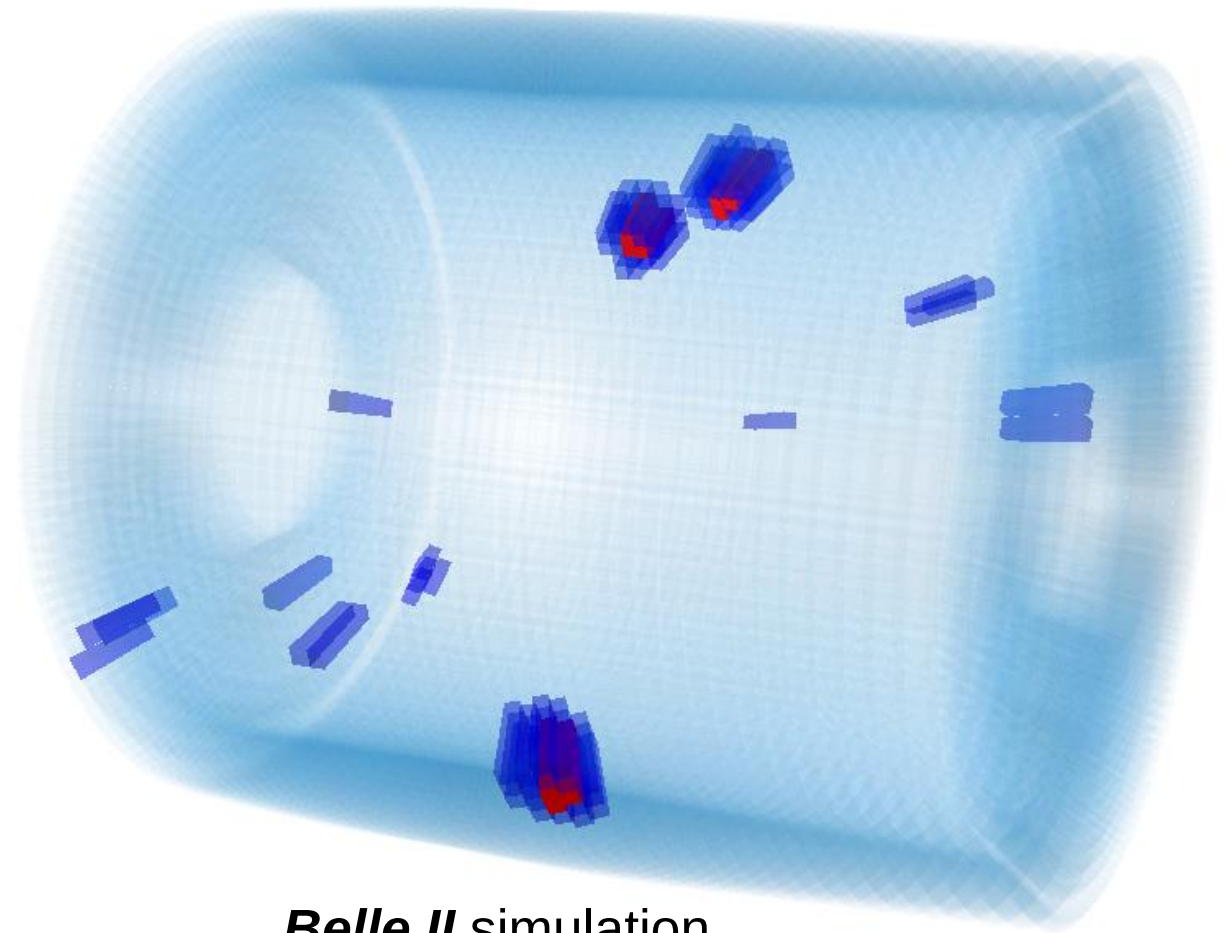
ALP-strahlung



# ALPs @ Belle II

## 3 $\gamma$ analysis

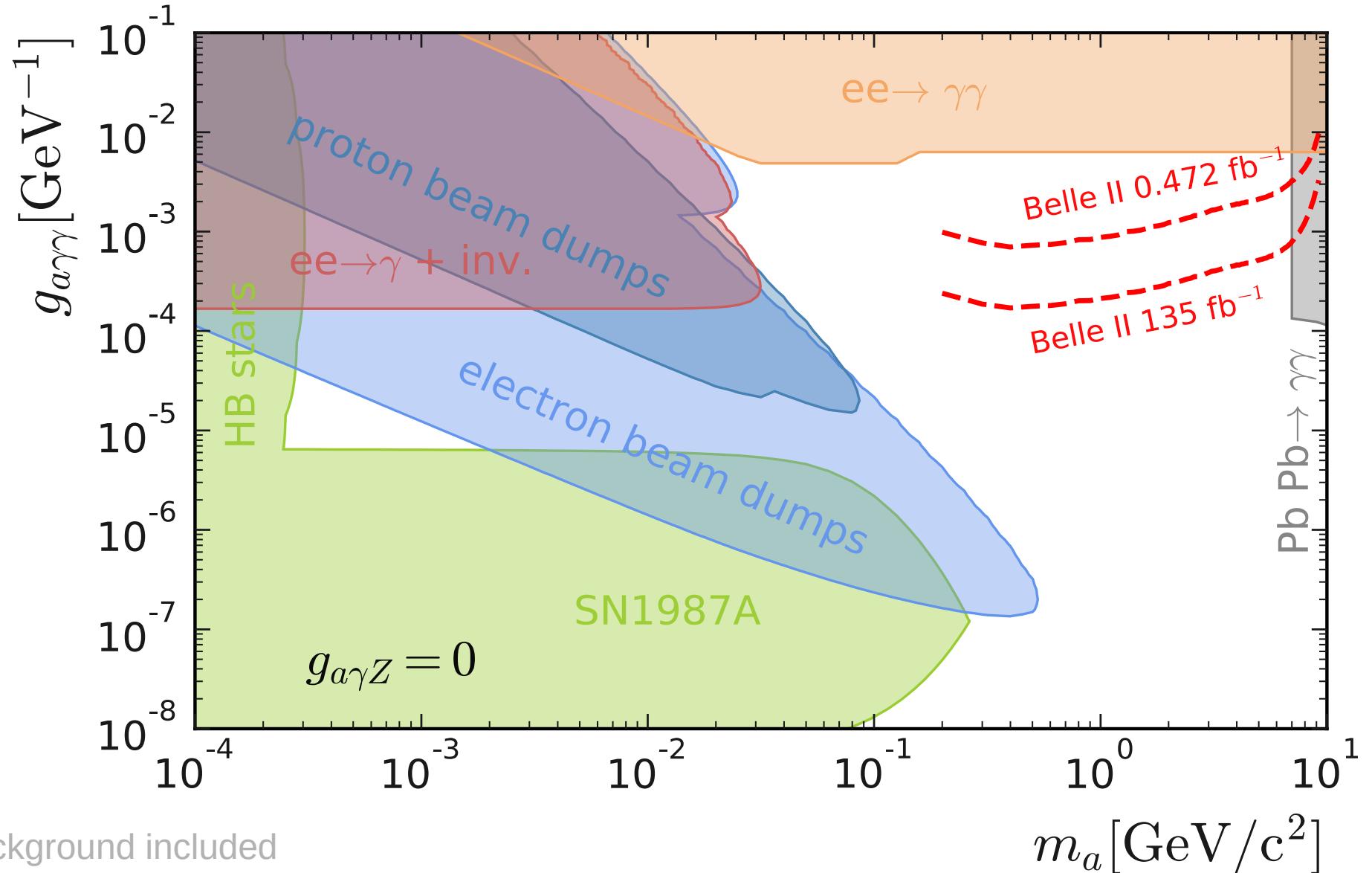
- ALP-strahlung is much easier experimentally.
  - ▶ Do this first.
- Three photons within tracking acceptance: add up to beam energy.
  - ▶ Zero tracks.
  - ▶ Bump on di-photon mass.
- The SM background:  $ee \rightarrow \gamma\gamma(\gamma)$ 
  - ▶ Does not peak in  $\gamma\gamma$ .
  - ▶ Not a 2-body system: use angles & kinematics to suppress.



*Belle II* simulation  
signal only

# ALPs @ Belle II

## Physics reach



No systematics.

Only (dominant)  $ee \rightarrow \gamma\gamma\gamma$  background included

135fb<sup>-1</sup> assumes no  $\gamma\gamma$  trigger veto in the barrel

# Dark photon

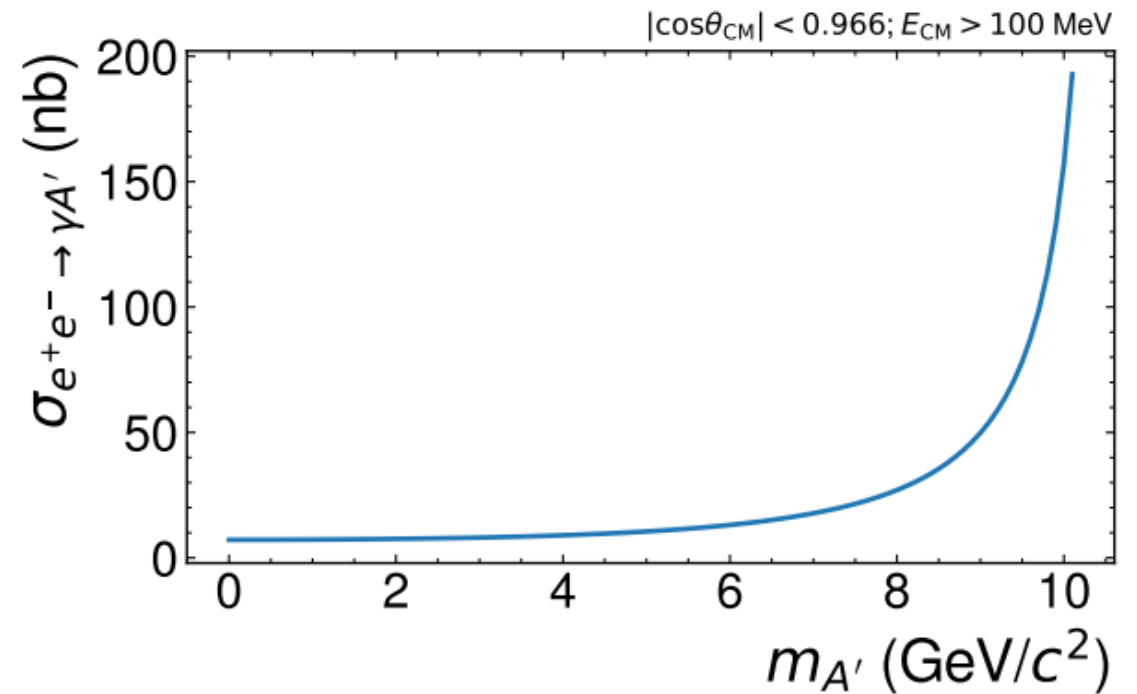
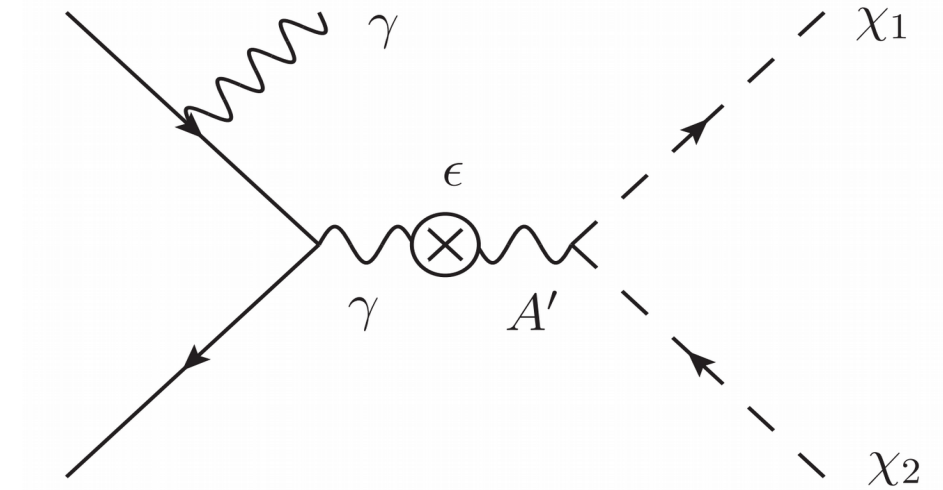
## Theory

- Massive vector particle  $A'$ , mixes with the SM photon:

$$\mathcal{L} \supset \epsilon g_D A'_\mu J_{\text{EM}}^\mu$$

- Can decay directly to dark matter final state. Experimentally invisible  $A' \rightarrow \chi_1 \chi_2$
- Can decay to two leptons  $A' \rightarrow l^+ l^-$
- Experimentalist's trick: require ISR photon.

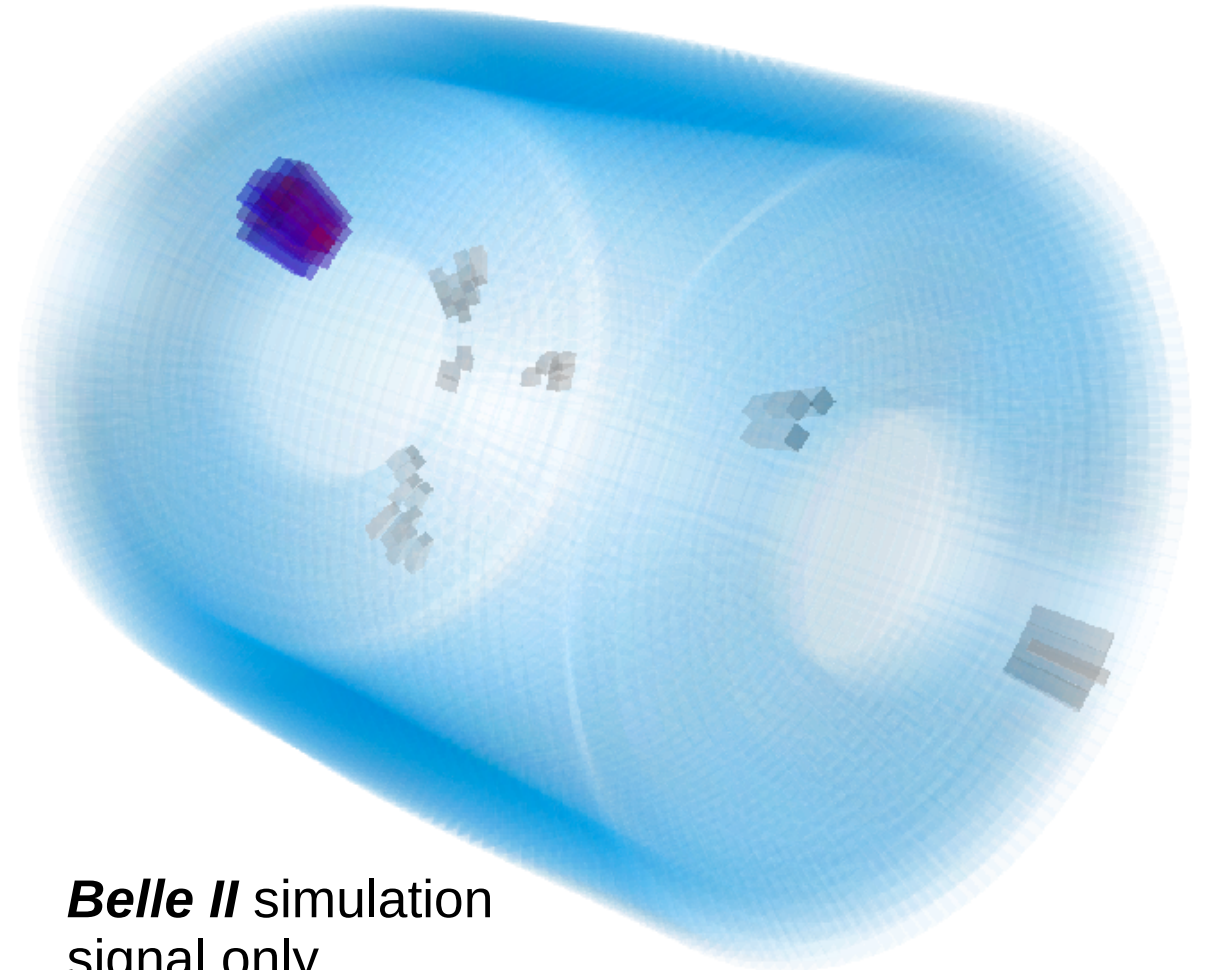
$$E_{\gamma_{\text{ISR}}} = \frac{s - m_{A'}^2}{2\sqrt{s}}$$



# Dark photon

## Analysis

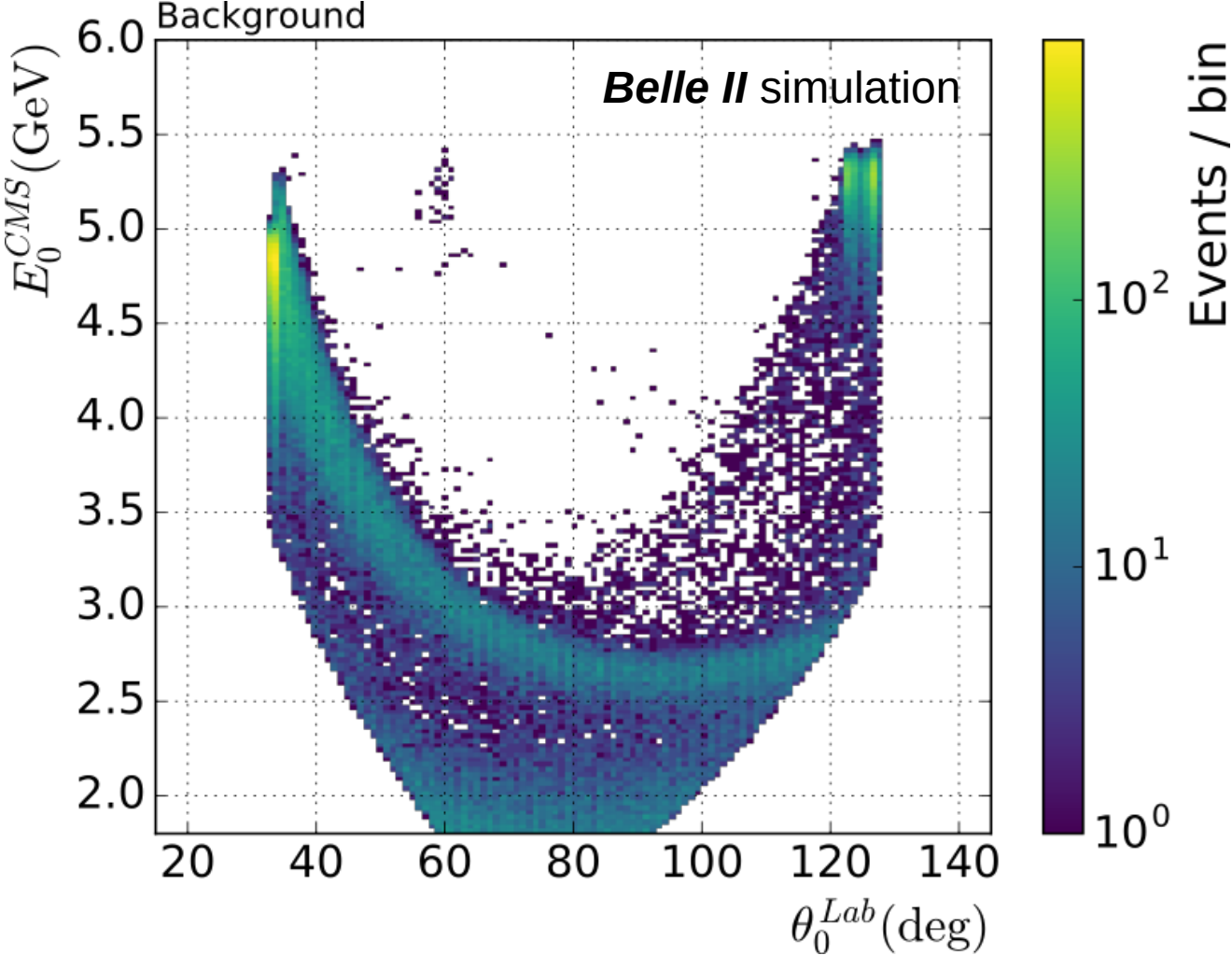
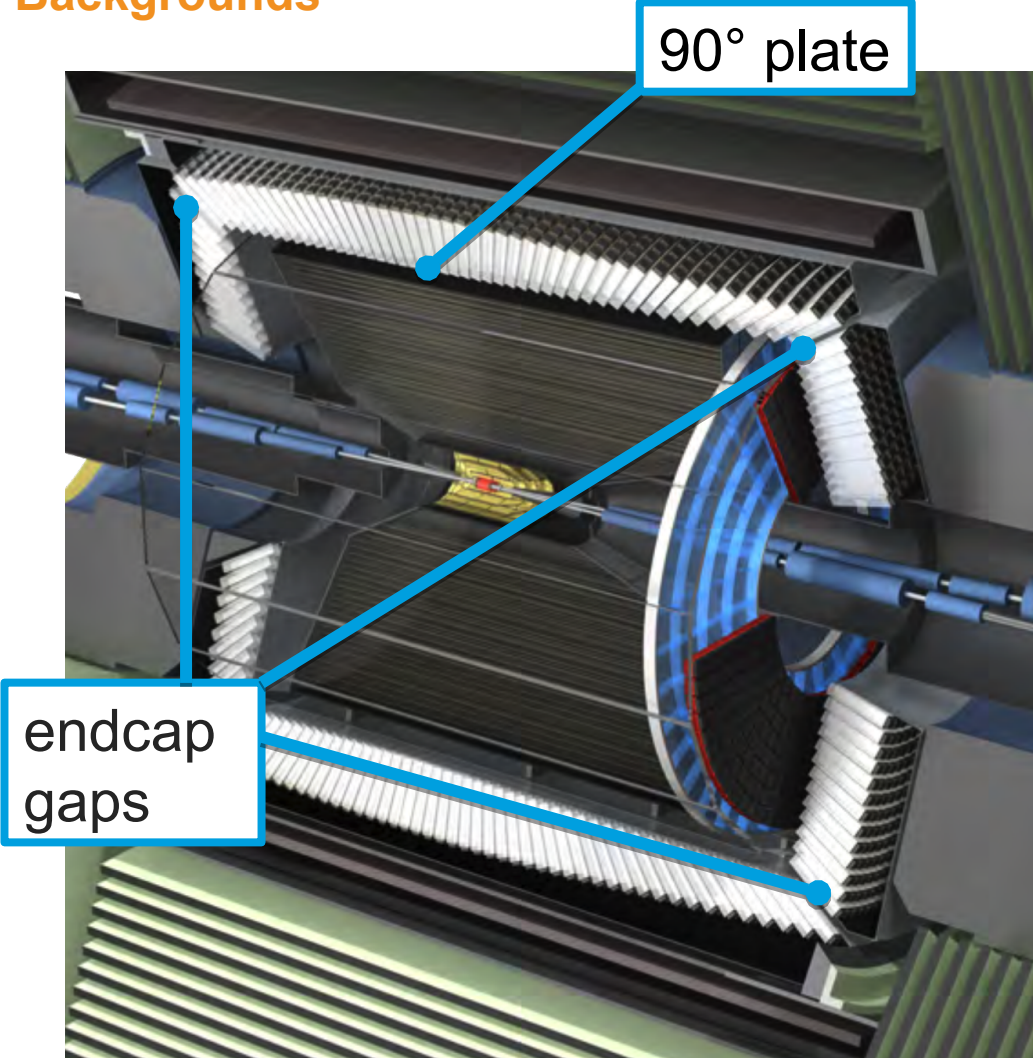
- First analysis:  $ee \rightarrow \gamma A' \rightarrow \gamma(\chi_1 \chi_2)$
- One photon. (no tracks, other good photon clusters).
  - ▶ Bump search in recoil mass spectrum.
- **Backgrounds**
  - ▶ Cosmics
  - ▶ Beam interactions
  - ▶  $ee \rightarrow ee\gamma(\gamma)$
  - ▶  $ee \rightarrow \gamma\gamma(\gamma)$





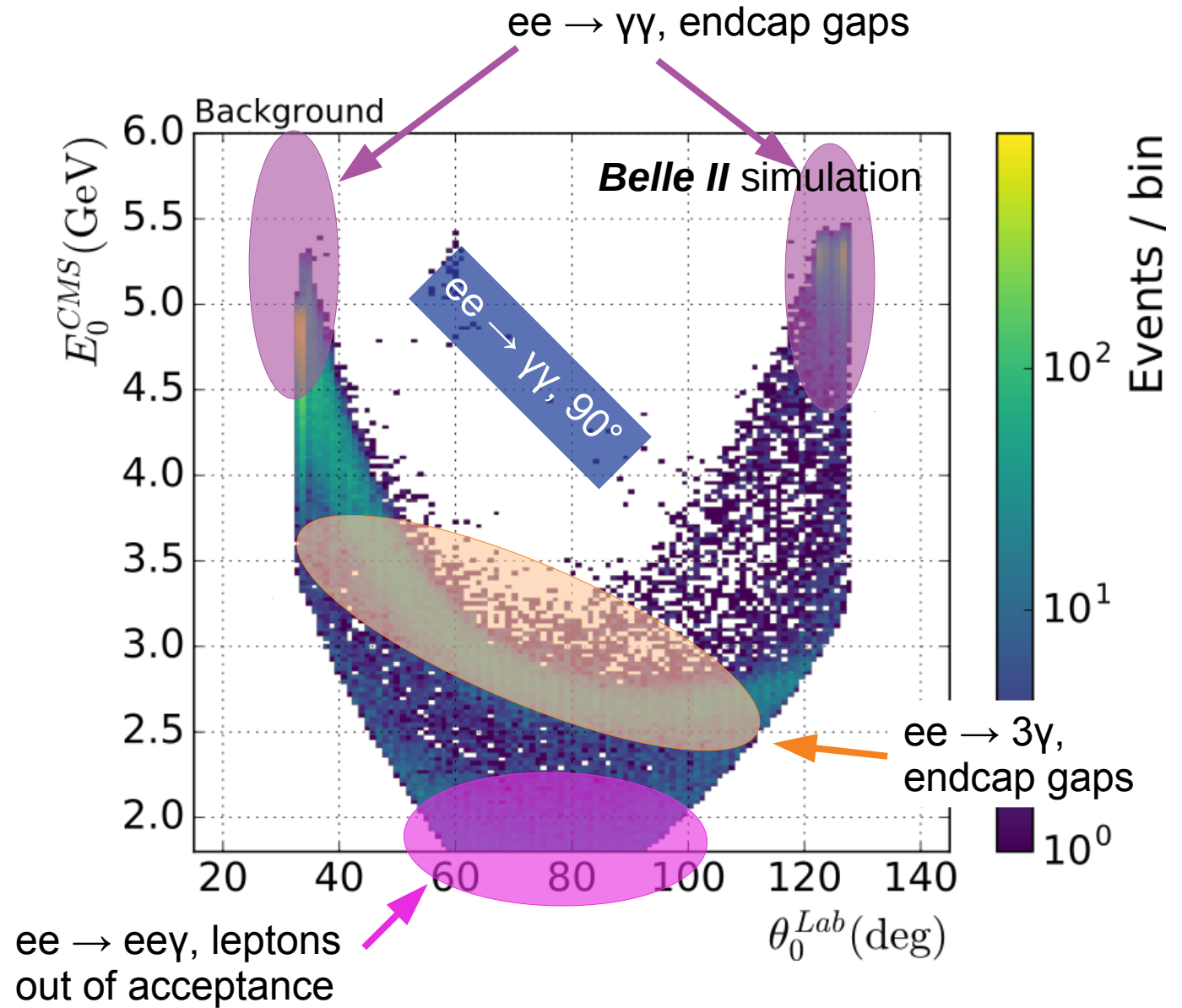
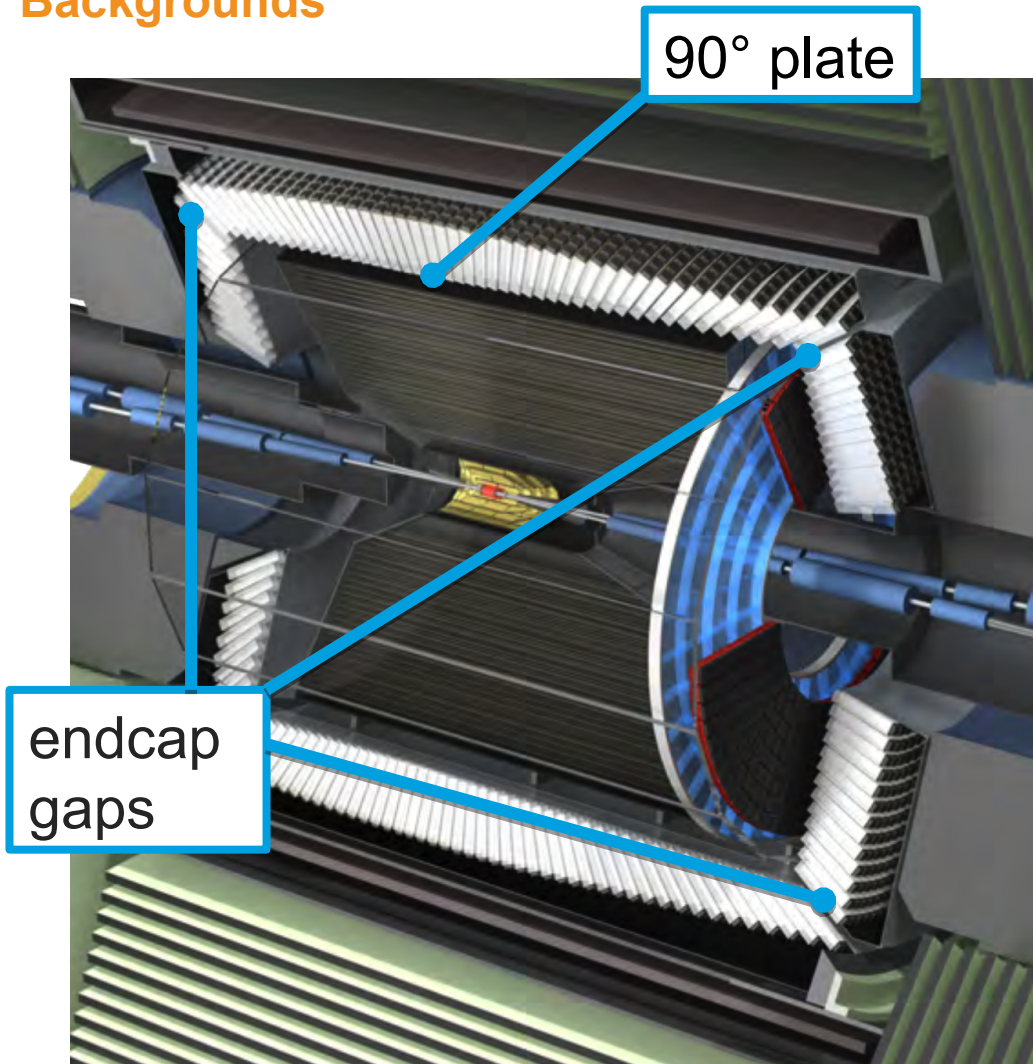
# Dark photon

## Backgrounds



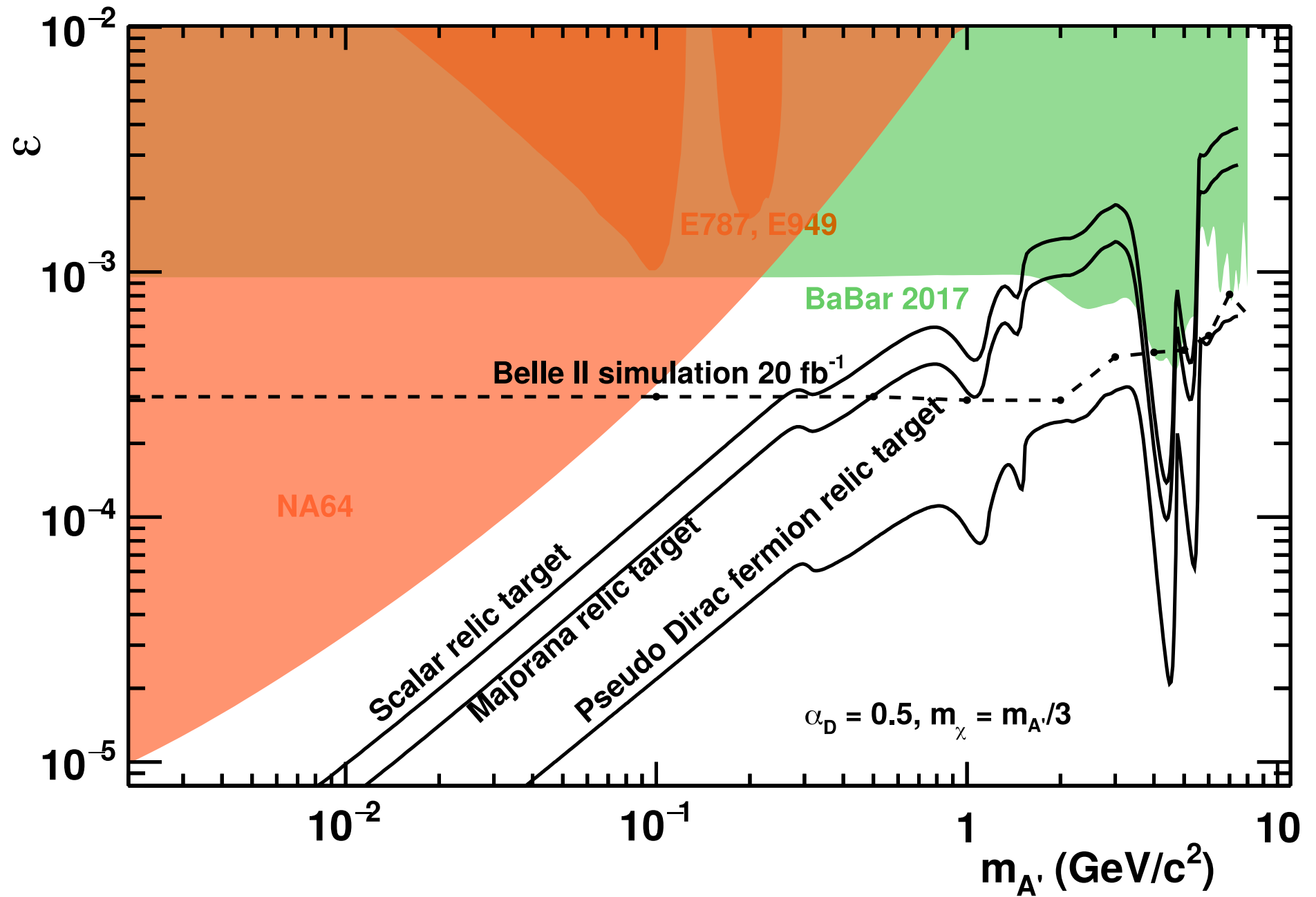
# Dark photon

## Backgrounds



# Dark photon

## Physics reach



The Belle II Physics book:

[arXiv:1808.10567](https://arxiv.org/abs/1808.10567)

BaBar 2017 analysis:

[PRL.119.131804](https://arxiv.org/abs/1711.13180)

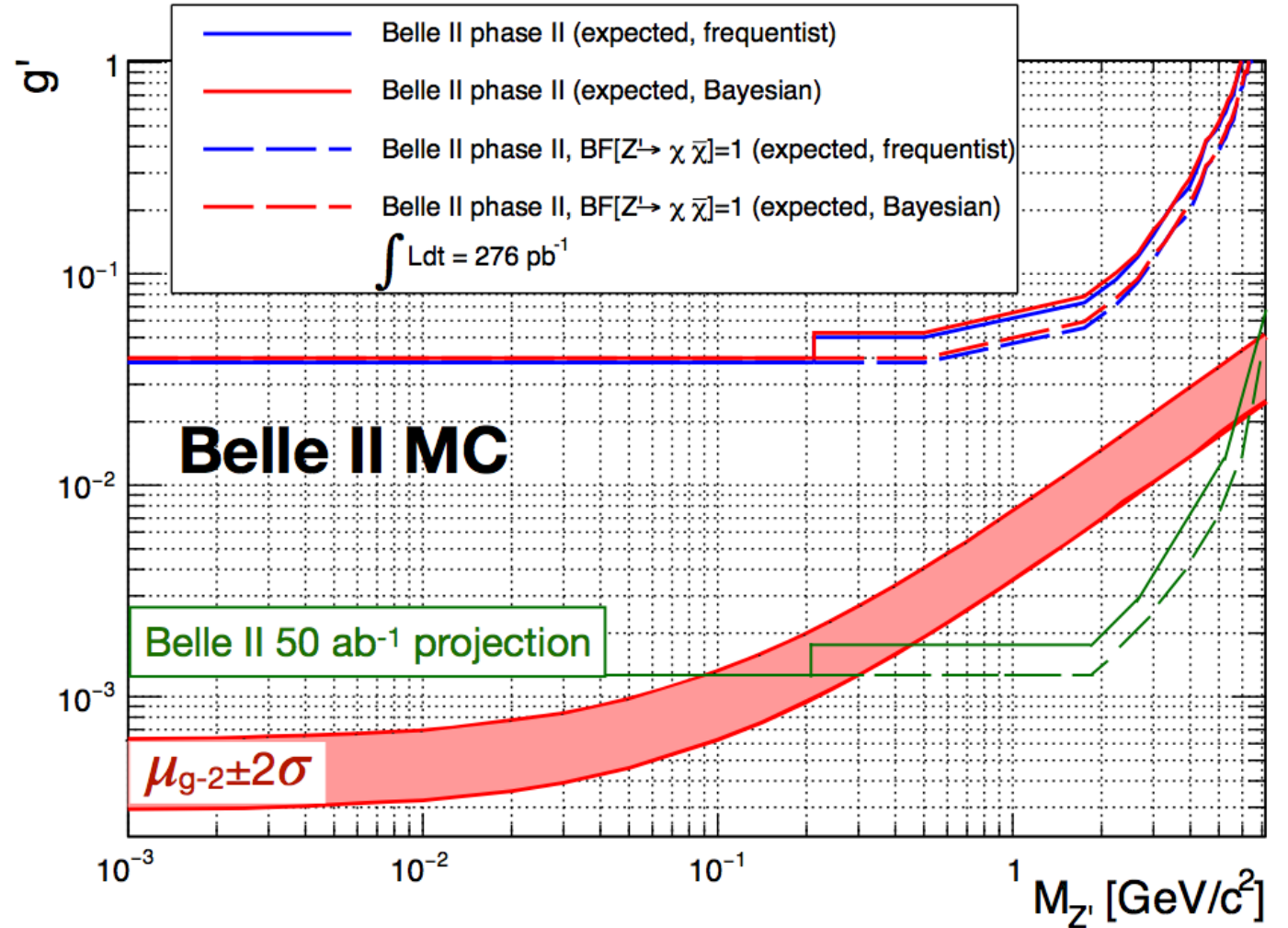
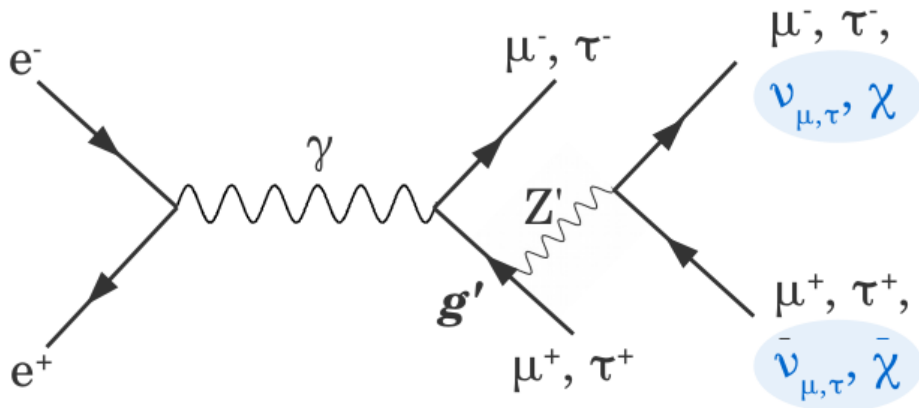
NA64 2019 analysis:

[arXiv:1906.00176](https://arxiv.org/abs/1906.00176)



# Z'

- “Dark photon”  $\rightarrow$  Z' if non minimal.
- Mediator coupling to muons and taus, not electrons ( $L_\mu - L_\tau$ )
- $ee \rightarrow \mu\mu Z'$  ( $Z' \rightarrow$  invisible)
- Bump hunt in recoil mass against  $\mu\mu$ . Nothing in the rest of the event.

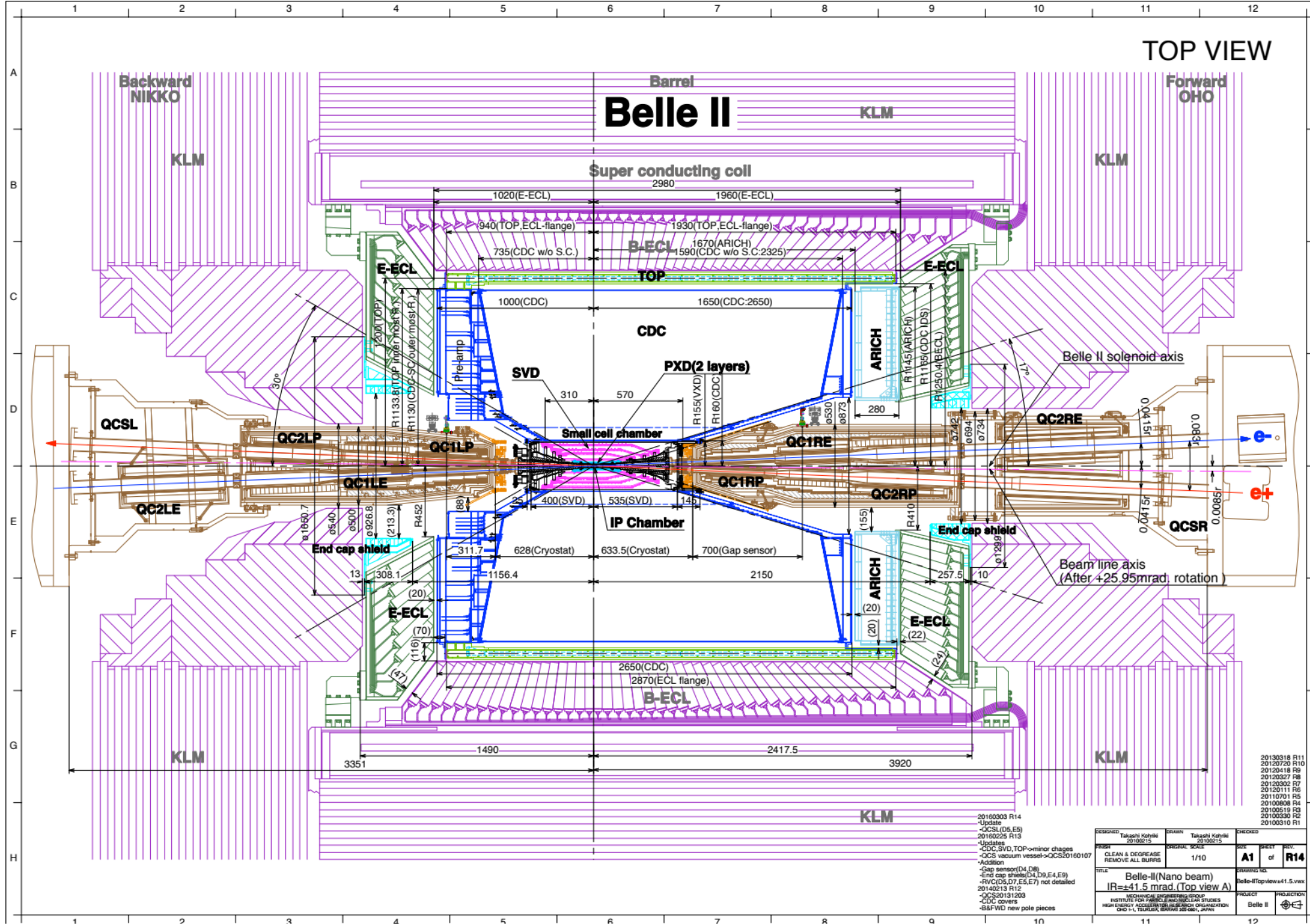


# Summary

- Next generation  $e^+e^-$  collider. Belle II taking data now.
- Dark sector physics  $\rightarrow$  good prospects even with very early data.
- **$3\gamma$** : ALP-strahlung and decaying to two photons.
  - ▶ Experimentally clean.
  - ▶ Can perform analysis with *calibration* collisions data ( $\sim 500 \text{ pb}^{-1}$  2018).
- **Single  $\gamma$** : dark photon decaying to stable dark matter.
  - ▶ Can improve limits from BaBar with  $20 \text{ fb}^{-1}$ .
- **$\mu\mu Z'$** :  $L_\mu - L_\tau$  dark vector decaying to stable dark matter.
  - ▶ First analysis with early data.

# Appendix





TOP VIEW

20130318	R11
20120720	R10
20120418	R9
20120327	R8
20120302	R7
20120111	R6
20110701	R5
20100808	R4
20100519	R3
20100330	R2
20100310	R1

- 20160303 R14
- Update
- QCSD5,E5
- 20160225 R13
- Update
- CDC,SVD,TOP<minor changes
- CCS vacuum vessel->CCS20160107
- Justification
- Gap sensor(D4,D8)
- End cap shield(D4,D5,E4,E9)
- RVCI(D5,D7,E5,E7) not detailed
- 20140213 R12
- QC20131203
- CDC covers
- B&FWD new pole pieces

DESIGNED	Takashi Kohno	DRAWN	Takashi Kohno	CHECKED	
DATE	20160215	DATE	20160215	DATE	
REV.		ORIGINAL SCALE	1/10	SHEET	A1 of R14
TITLE <b>Belle-II(Nano beam)</b> <b>IR=±41.5 mrad (Top view A)</b>			PROJECT Belle-II		
DRAWING NO. Belle-II/TopviewA1.5.v16x			PROJECTION 		

## Contact

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Elektronen-Synchrotron

[www.desy.de](http://www.desy.de)

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