SUSY2019

Search for Dark Matter at Belle II

Texas A&M University
Corpus Christi, May 20-24.

Luigi Corona
~
INFN and University of Pisa
~
on behalf of the Belle II collaboration

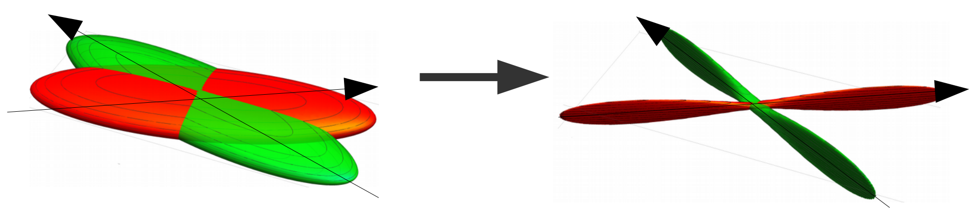
luigi.corona@pi.infn.it

Outline

- SuperKEKB and the Belle II experiment
- Dark Matter at Belle II
- Conclusions

SuperKEKB collider

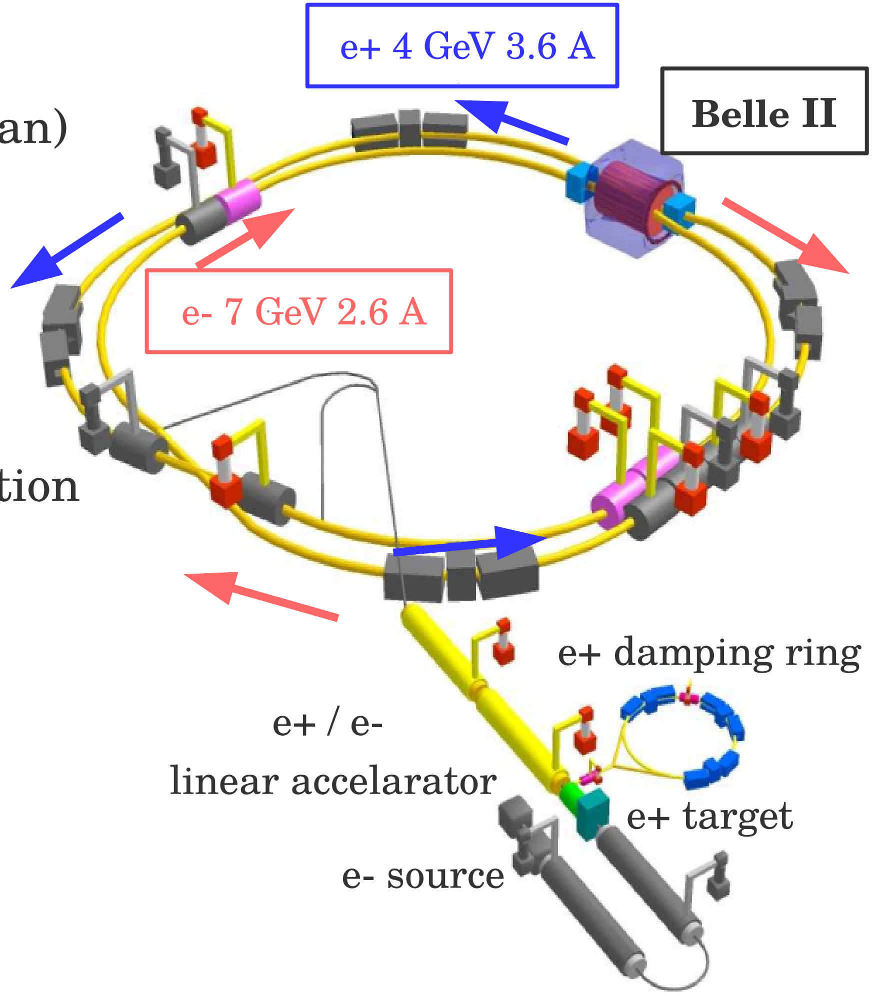
- Super-B factory, successor of KEKB (Tsukuba, Japan)
- e^+/e^- asymmetric collider, E* ~10.58 GeV (ϒ(4S))
- It will provide the **highest world luminosity** applying the **Nano-beam scheme**
  - Squeeze beams → increase probability of interaction



  - Higher currents and smaller beams than KEKB

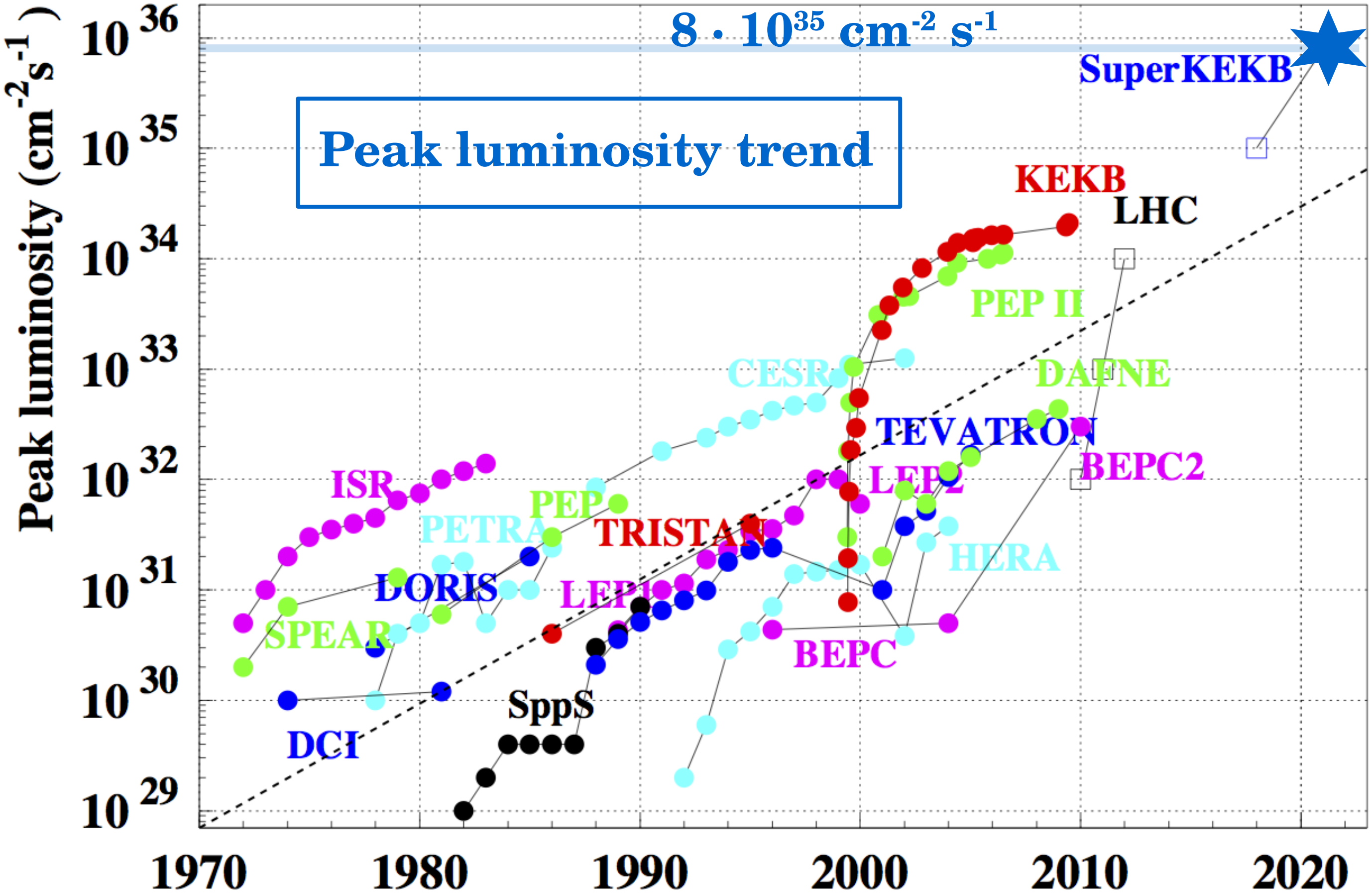
KEKB: I(A): ~ 1.6/1.2; β^*_y(mm)~ 5.9/5.9

SuperKEKB: I(A): ~ 3.6/2.6 (↑ x 2); β^*_y(mm)~ 0.27/0.3 (↓ x 1/20)



x40 higher luminosity than KEKB

Physics program



★ **x40 higher luminosity than KEKB**

Flavor physics and SM Test:

- CKM parameters
- CPV in B decays
- $B/D/\tau$ physics

BSM physics:

- rare or suppressed or forbidden processes in the SM

Search for:

- new light particles
- **Light Dark Sector**

Belle II detector

Belle II covering > 90% of 4π

K_L and μ detector (KLM):

Resistive Plate Chambers (RPC) (outer barrel)

Scintillators + SiPM (endcaps, inner barrel)

Magnet:

1.5 T, superconducting

E.M. calorimeter (ECL):

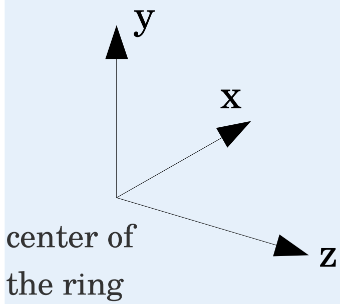
CsI(Tl) crystals

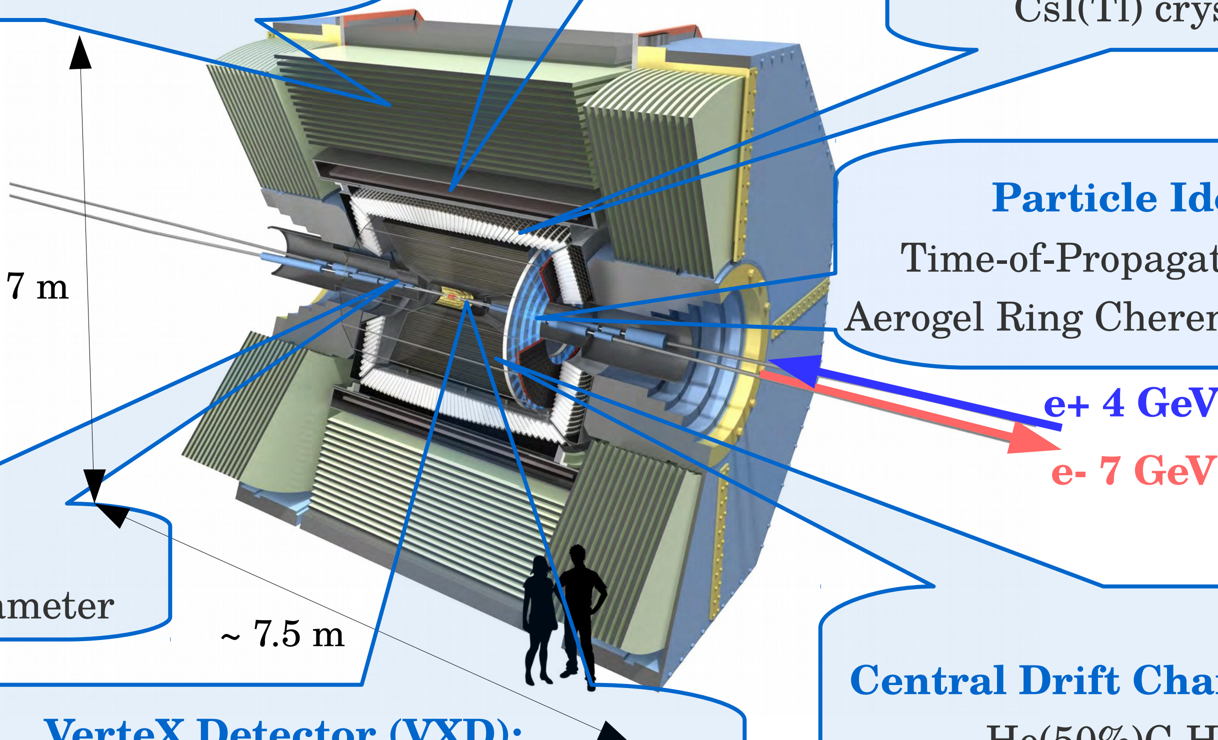
Particle Identification:

Time-of-Propagation (TOP) (barrel)

Aerogel Ring Cherenkov (ARICH) (FWD)

Coordinate system





Beam pipes:

beryllium, 2 cm of diameter

VerteX Detector (VXD):

2 layer DEPFET pixel detectors (PXD)***

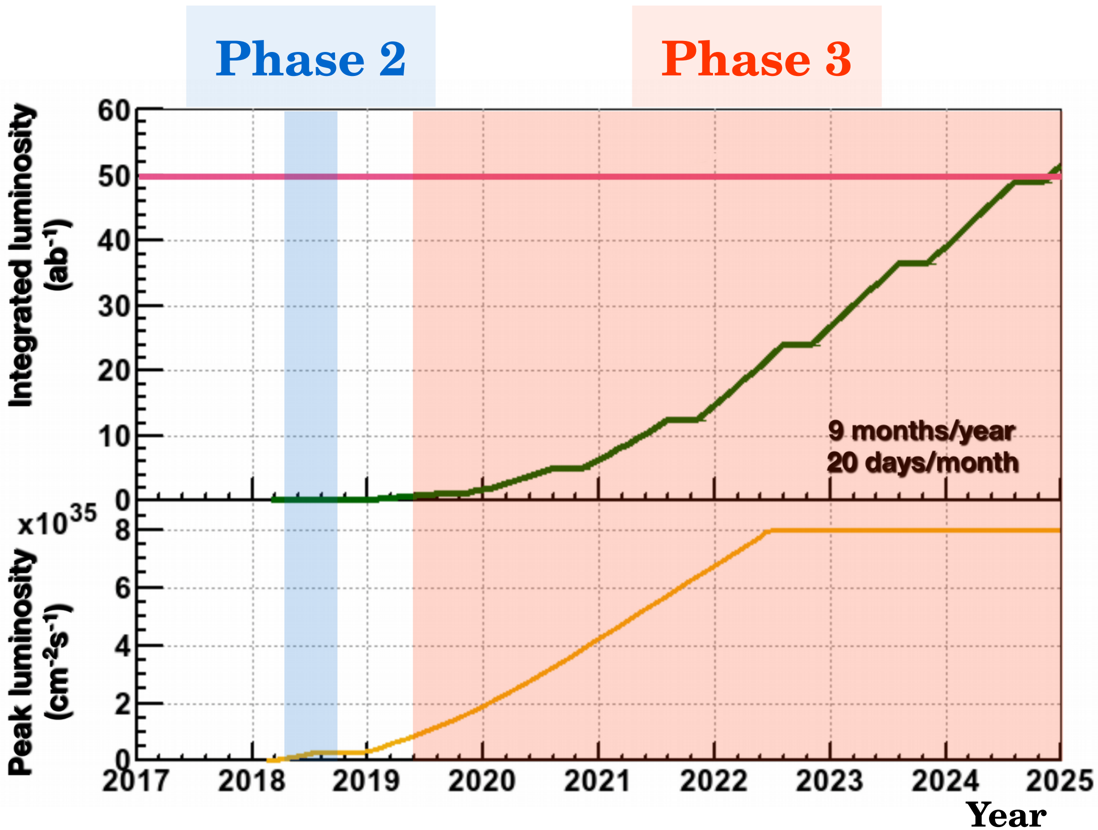
4 layer DSSD silicon vertex detectors (SVD)

Central Drift Chamber (CDC):

$He(50\%)C_2H_6(50\%)$

***second layer not complete

SuperKEKB plans



Phase 2:

- commissioning of the machine, detector and software
- collected data: ~ 0.5 fb^{-1}
- ~1/8 of VXD in φ
- flexible hardware trigger ★
- pass-through software trigger (HLT)

Phase 3:

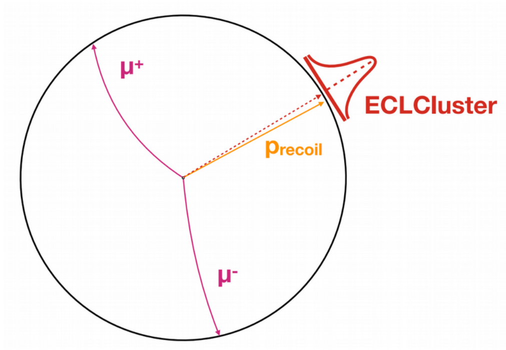
- Goal → 50 ab^{-1} with the full detector

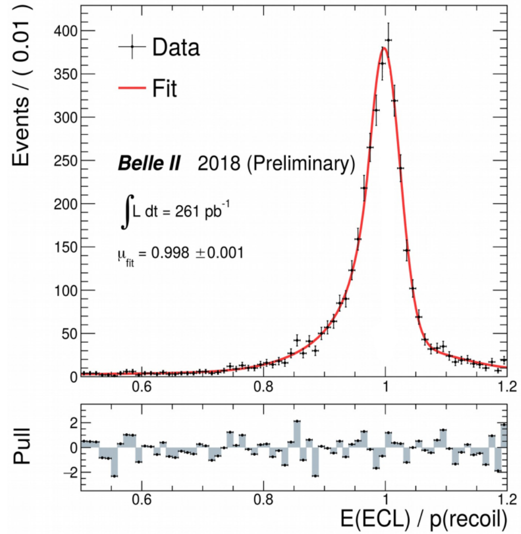
★ **Phase 2 → rediscoveries, Dark Sector physics**

★ **x50 data set of its predecessor**

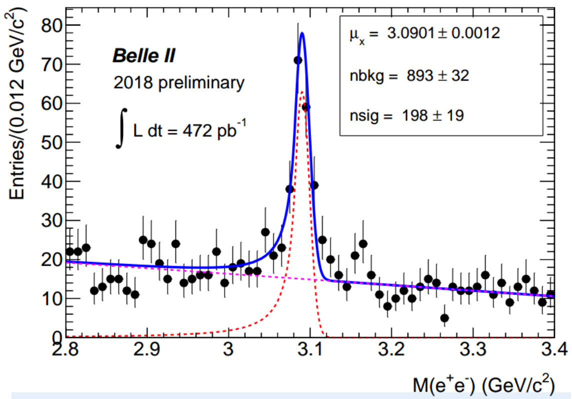
Highlights from Phase 2

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

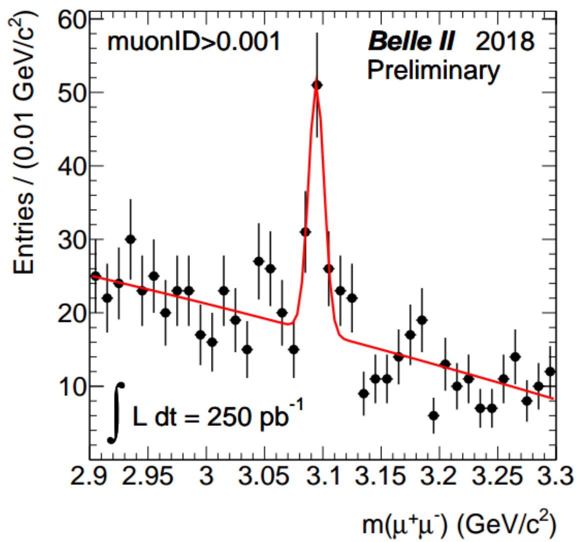




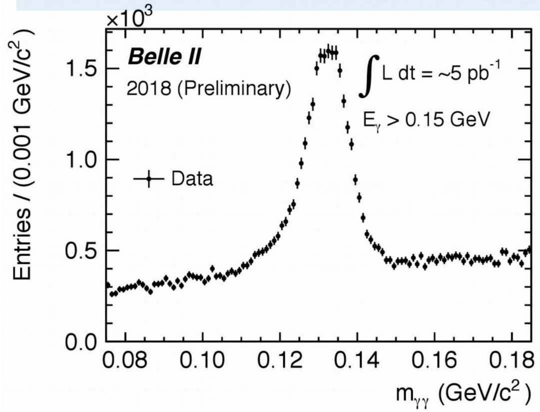
$J/\psi \to e^+e^-$



$J/\psi \to \mu^+\mu^-$



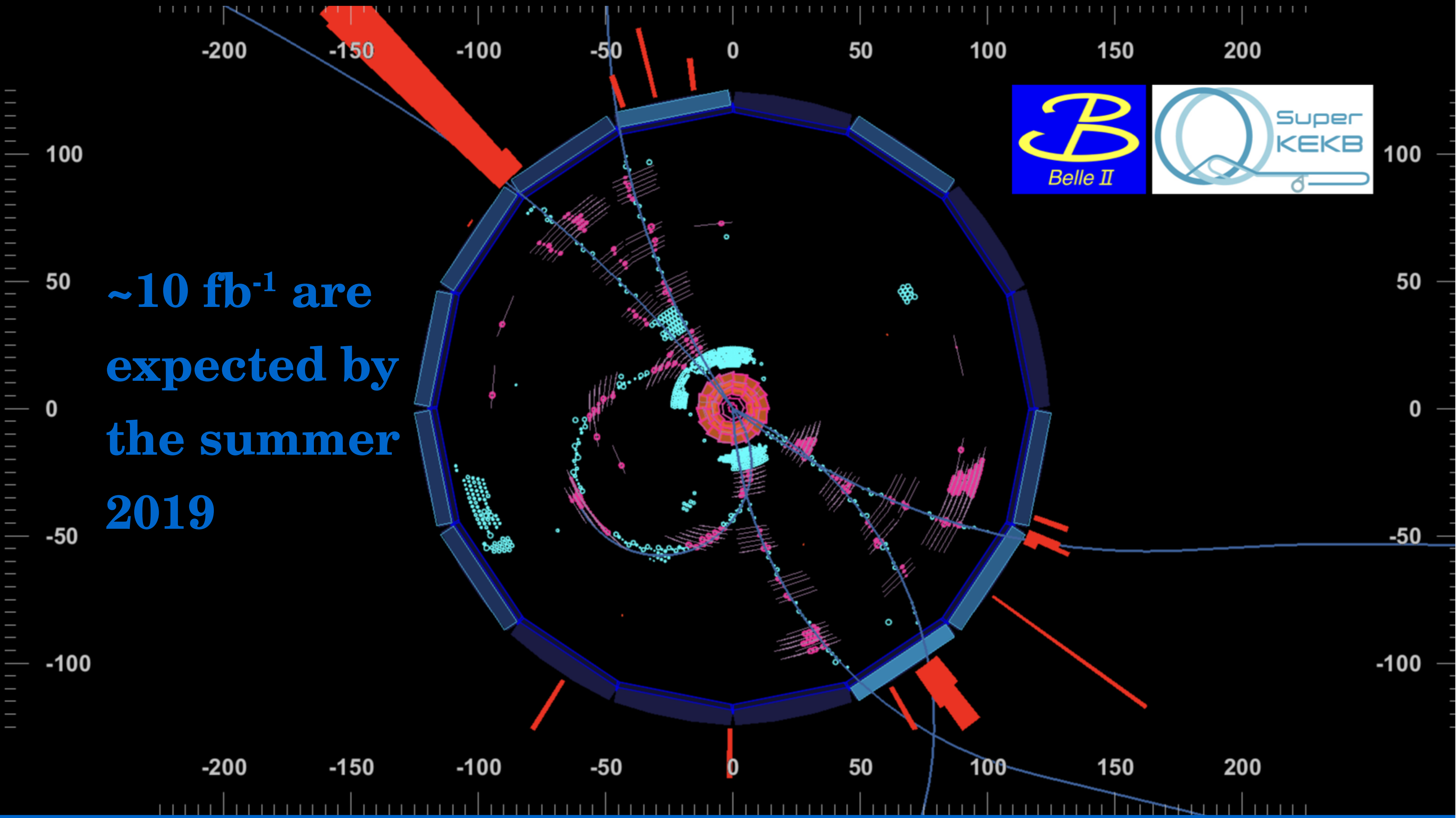
$\pi^0 \to \gamma\gamma$



Good condition for dark searches:

- $e^+e^- \to \gamma X$
- $e^+e^- \to ALP\gamma \to \gamma(\gamma\gamma)$
- …

Phase 3: Started on March 25th



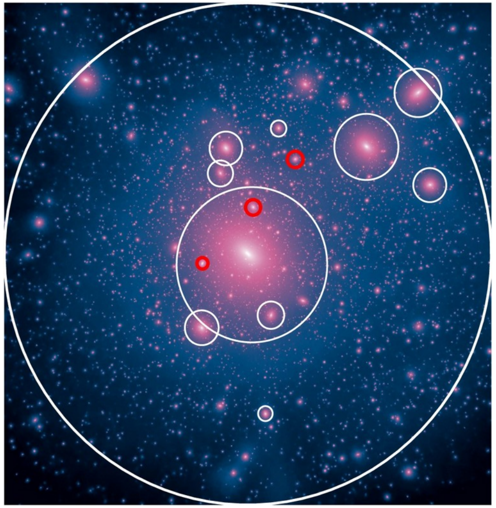
~10 fb^{-1} are expected by the summer 2019

Dark Matter at Belle II

Dark Matter (DM)-SM Interactions

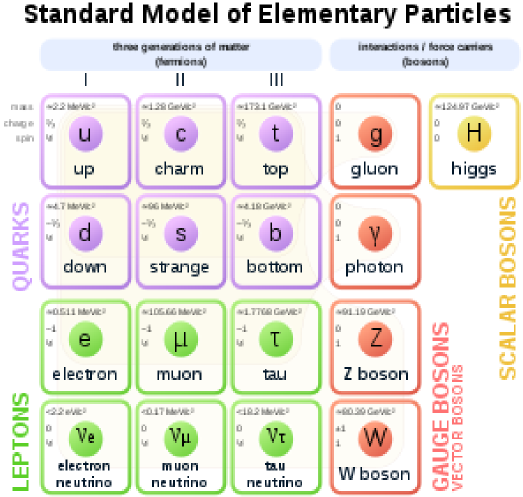
- DM-SM: Only gravitational interaction
- Possible sub-GeV theoretical scenarios: Light-DM weakly coupled with SM through a light dark sector mediator X

Dark Matter



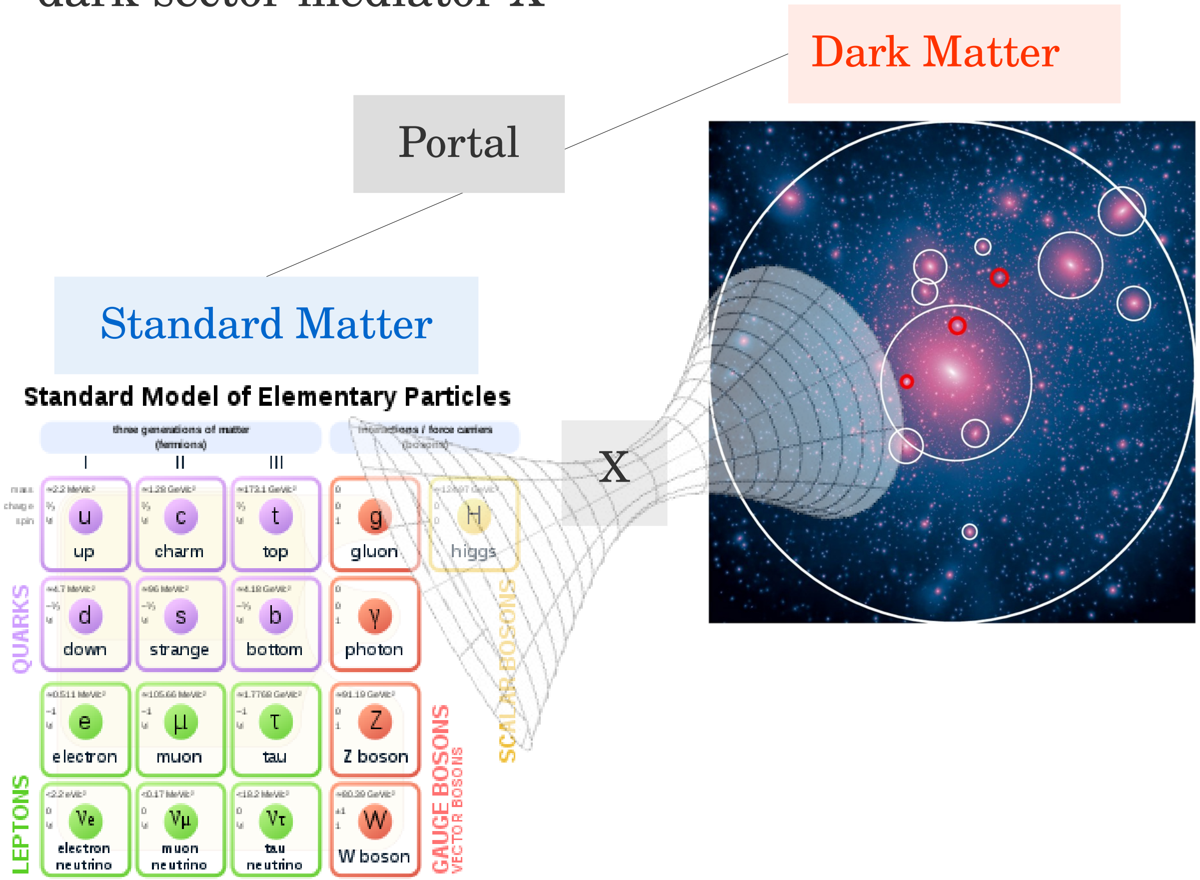
1. Vector Portal → Dark Photon A', Dark Z'
2. Pseudo-scalar Portal → Axion Like Particles (ALPs, axion)
3. Scalar Portal → Dark Higgs / Dark Scalar
4. Neutrino Portal → Sterile Neutrinos

Standard Matter



DM-SM Interaction

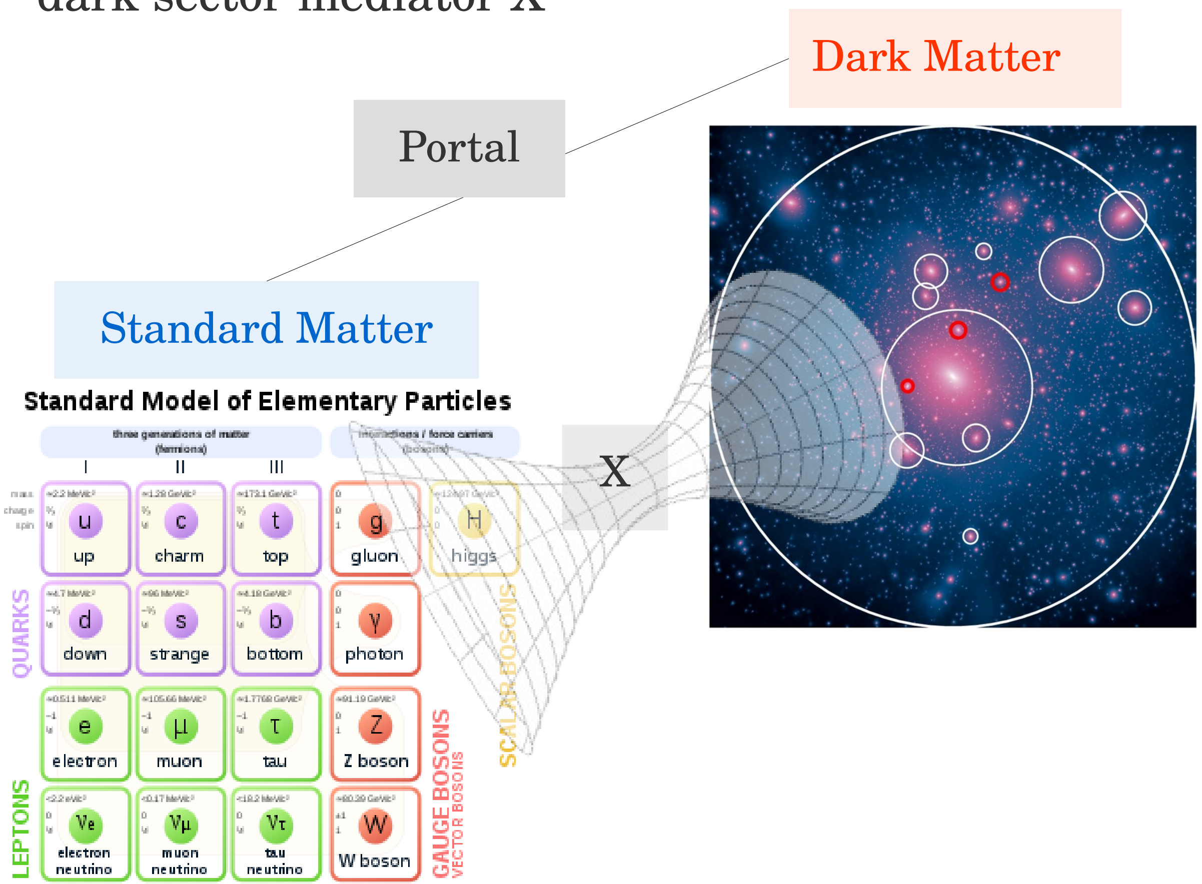
- DM-SM: Only gravitational interaction
- Possible sub-GeV theoretical scenarios: Light-DM weakly coupled with SM through a light dark sector mediator X



1. Vector Portal → Dark Photon A', Dark Z'
2. Pseudo-scalar Portal → Axion Like Particles (ALPs, axion)
3. Scalar Portal → Dark Higgs / Dark Scalar
4. Neutrino Portal → Sterile Neutrinos

DM-SM Interaction

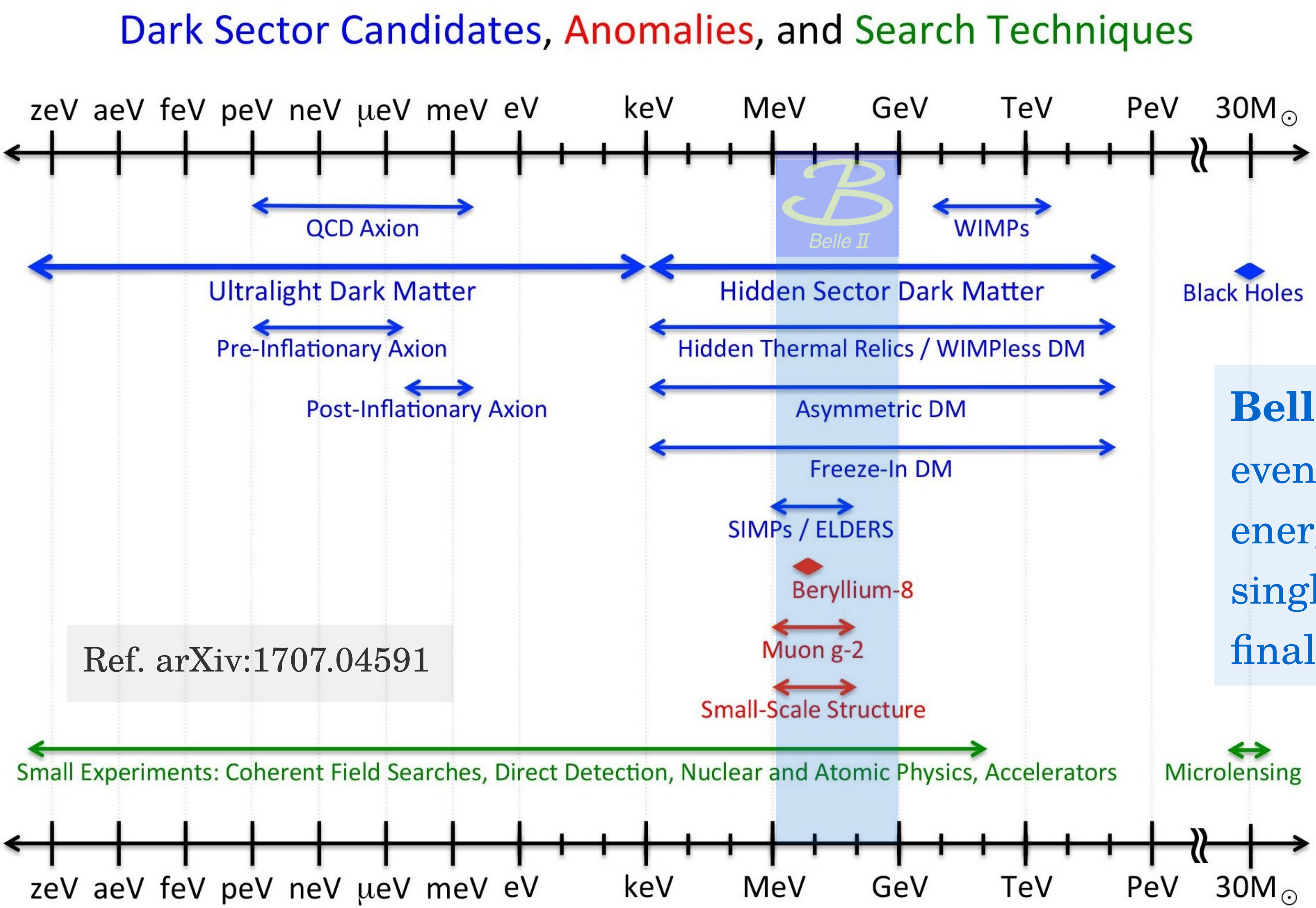
- DM-SM: Only gravitational interaction
- Possible sub-GeV theoretical scenarios: Light-DM weakly coupled with SM through a light dark sector mediator X



1. Vector Portal → Dark Photon A', Dark Z'
2. Pseudo-scalar Portal → Axion Like Particles (ALPs, axion)
3. Scalar Portal → Dark Higgs / Dark Scalar
4. Neutrino Portal → Sterile Neutrinos

Phase 2

Search for Dark Matter



Ref. arXiv:1707.04591

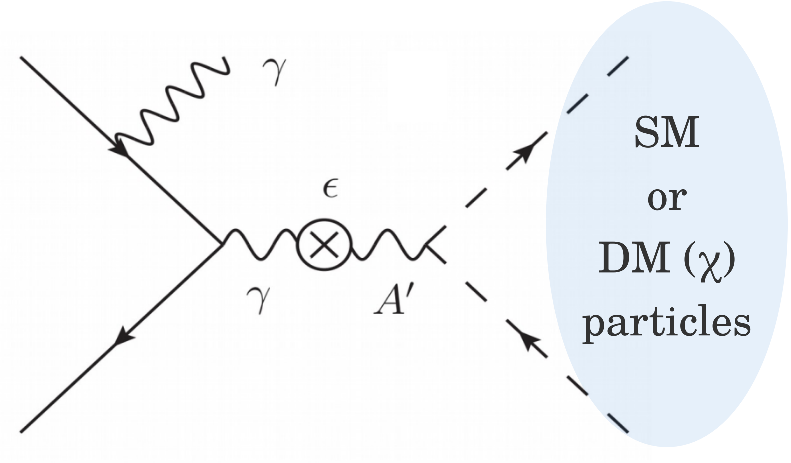
Belle II: search for events with missing energy, dark forces, single/multi photons final state...

Dark Photons

Dark photons A'

- Extension of the SM: → additional U(1)' symmetry
- Massive dark photon that mixes with the photon with strenght ε

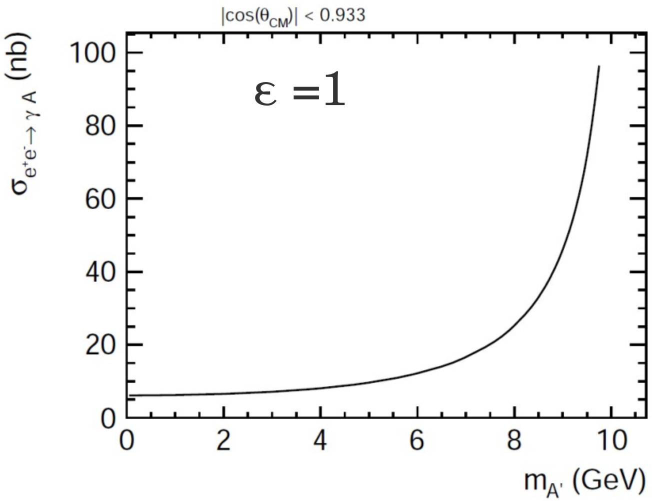
$$e\varepsilon J^{\mu}_{SM} A'_{\mu}$$



- $m_\chi > 0.5\ m_{A'}$ → A' visible decays to SM particles
- $m_\chi < 0.5\ m_{A'}$ → A' invisible decays to Light-DM particles

References:
P. Fayet, Phys. Lett. B 95, 285 (1980),
P. Fayet Nucl. Phys. B 187, 184 (1981)
B. Holdom, Phys. Lett. B 166, 196 (1986)

Production cross section



Madgraph simulation based on arXiv: 1008.0636

Invisible dark photon searching strategy

Signal signature:

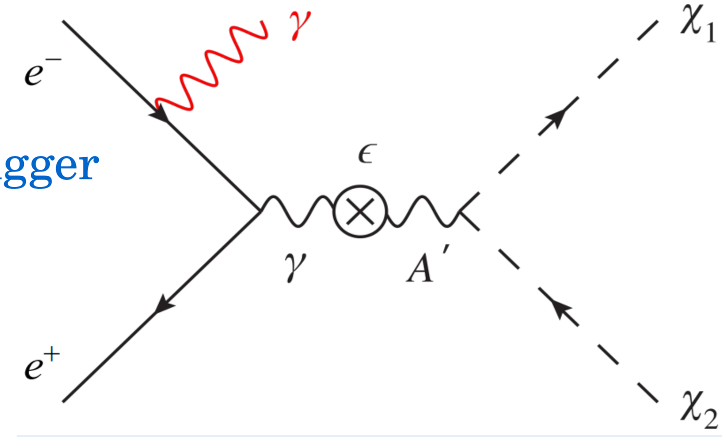
- Single photon final state → Needs a single photon trigger
- Look for a bump in the variable:

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

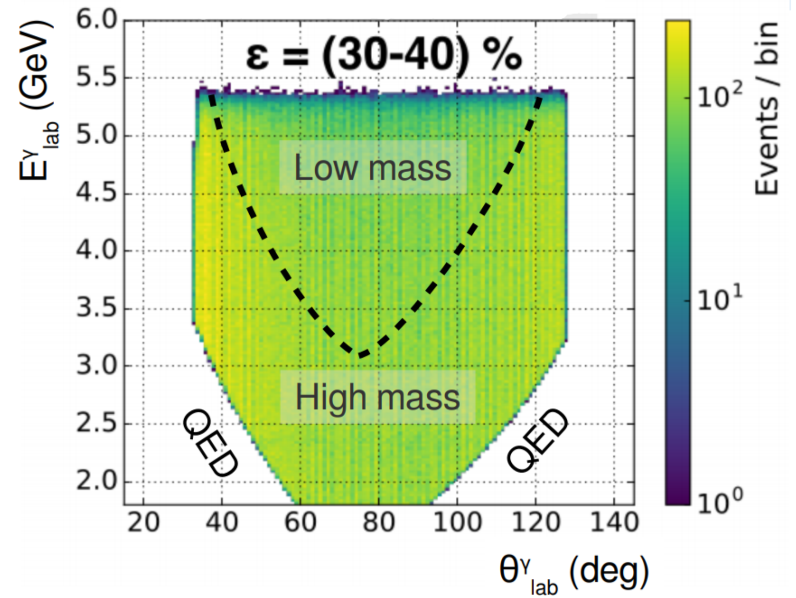
- Selection criteria: E_γ^* vs θ_γ^{LAB}

Belle II single photon trigger logic:

- E > 1 GeV and 2nd cluster E < 300 MeV
- E > 2 GeV and Bhabha veto and $e^+e^- \to \gamma\gamma$ veto

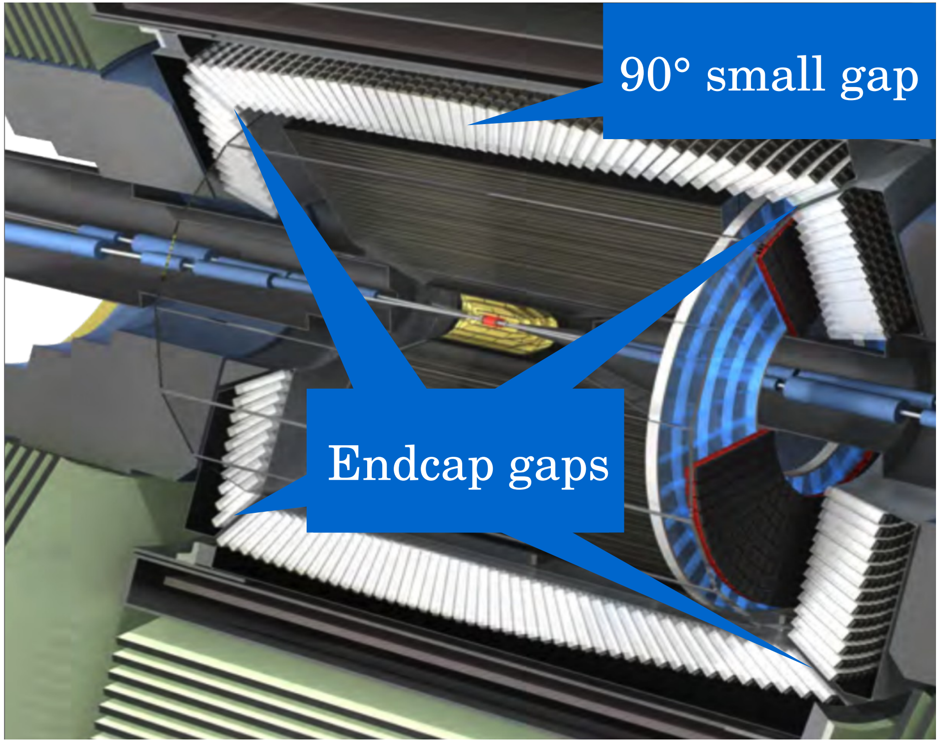


Simulated signal efficiency

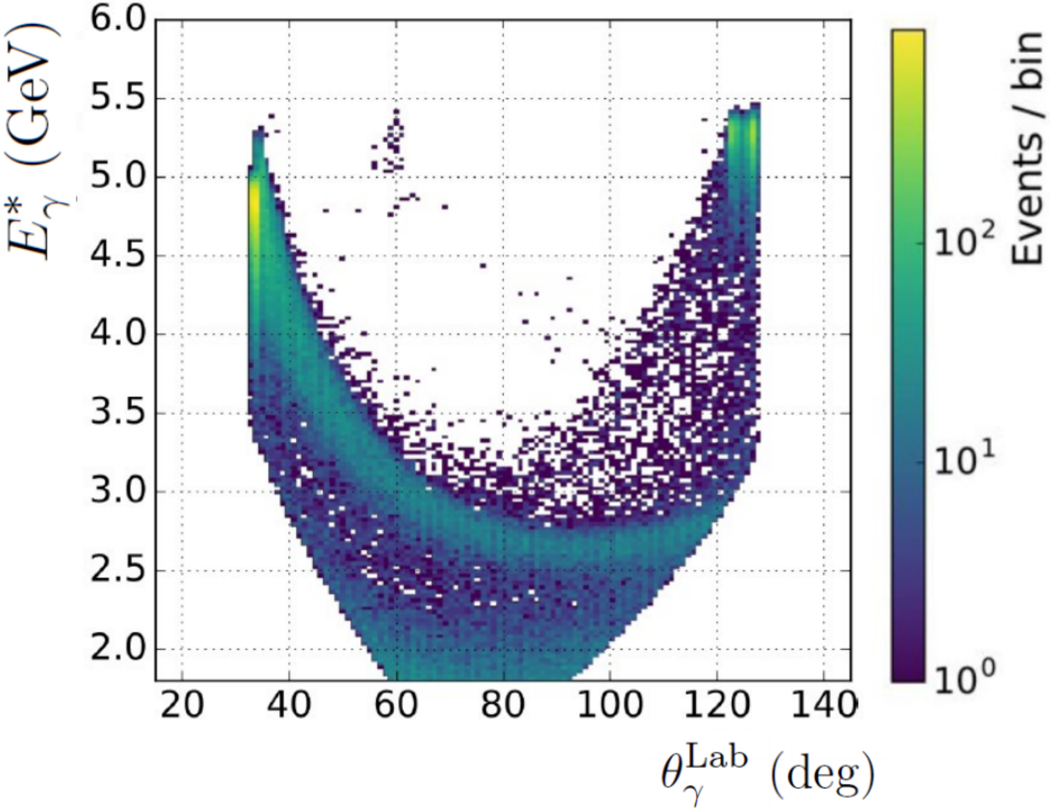


Invisible dark photon backgrounds

Sources of ECL inefficiency



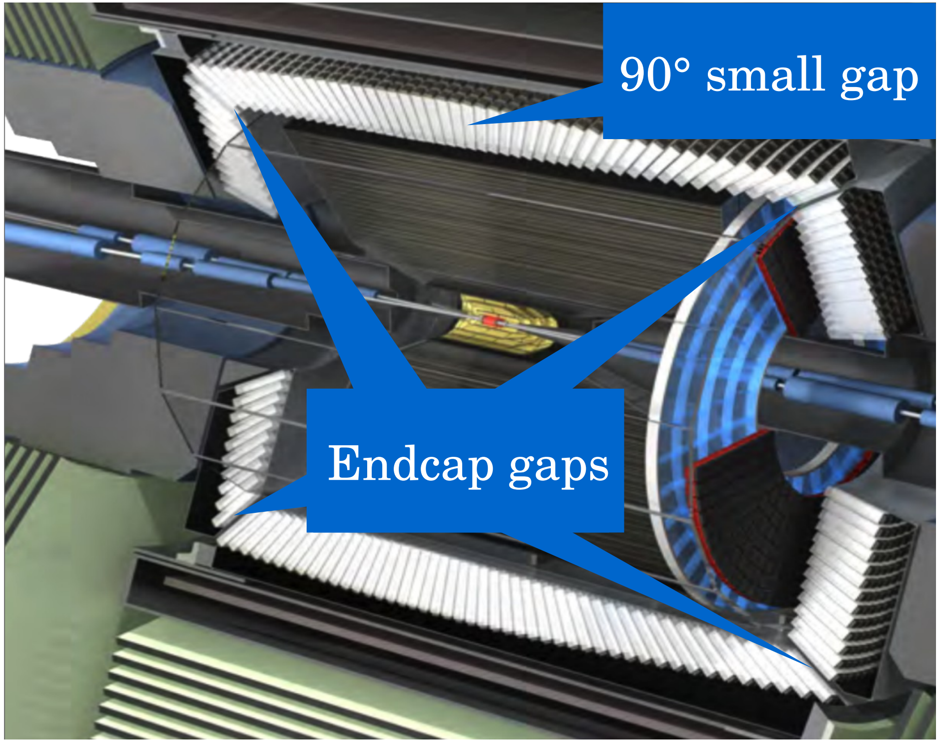
Simulated background rates



- Backgrounds:
  $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to \gamma\gamma(\gamma)$

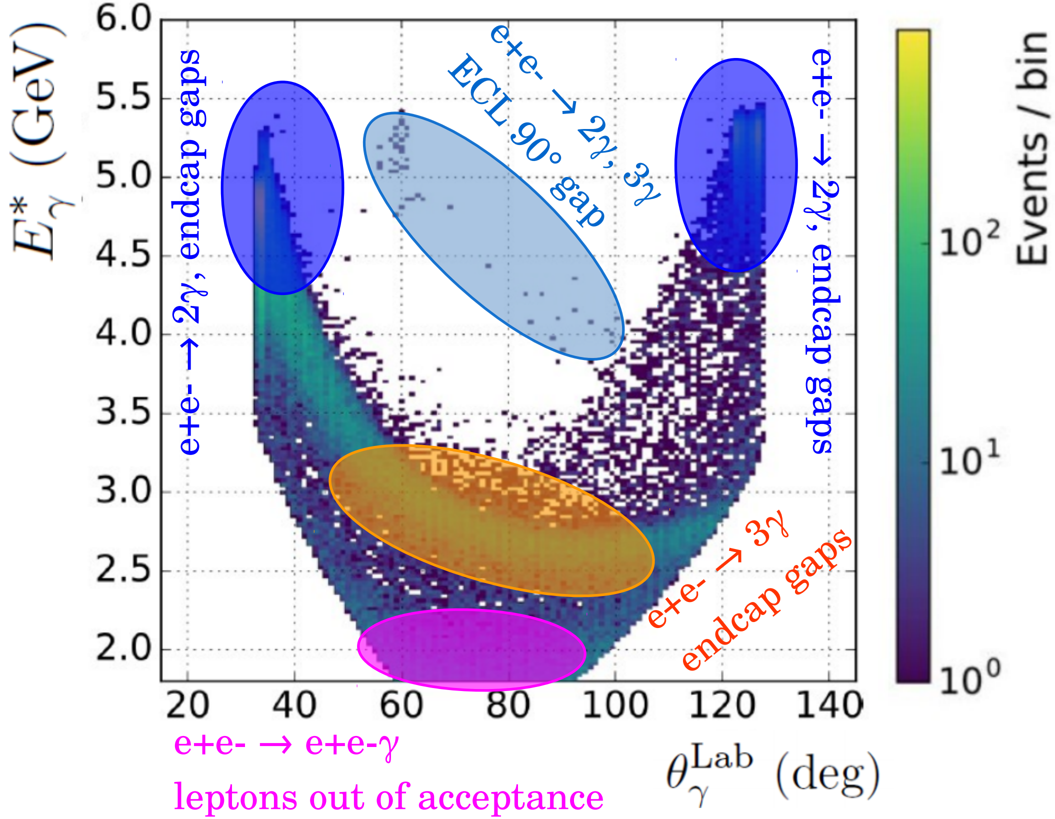
Invisible dark photon backgrounds

Sources of ECL inefficiency



- Backgrounds:
  $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to \gamma\gamma(\gamma)$

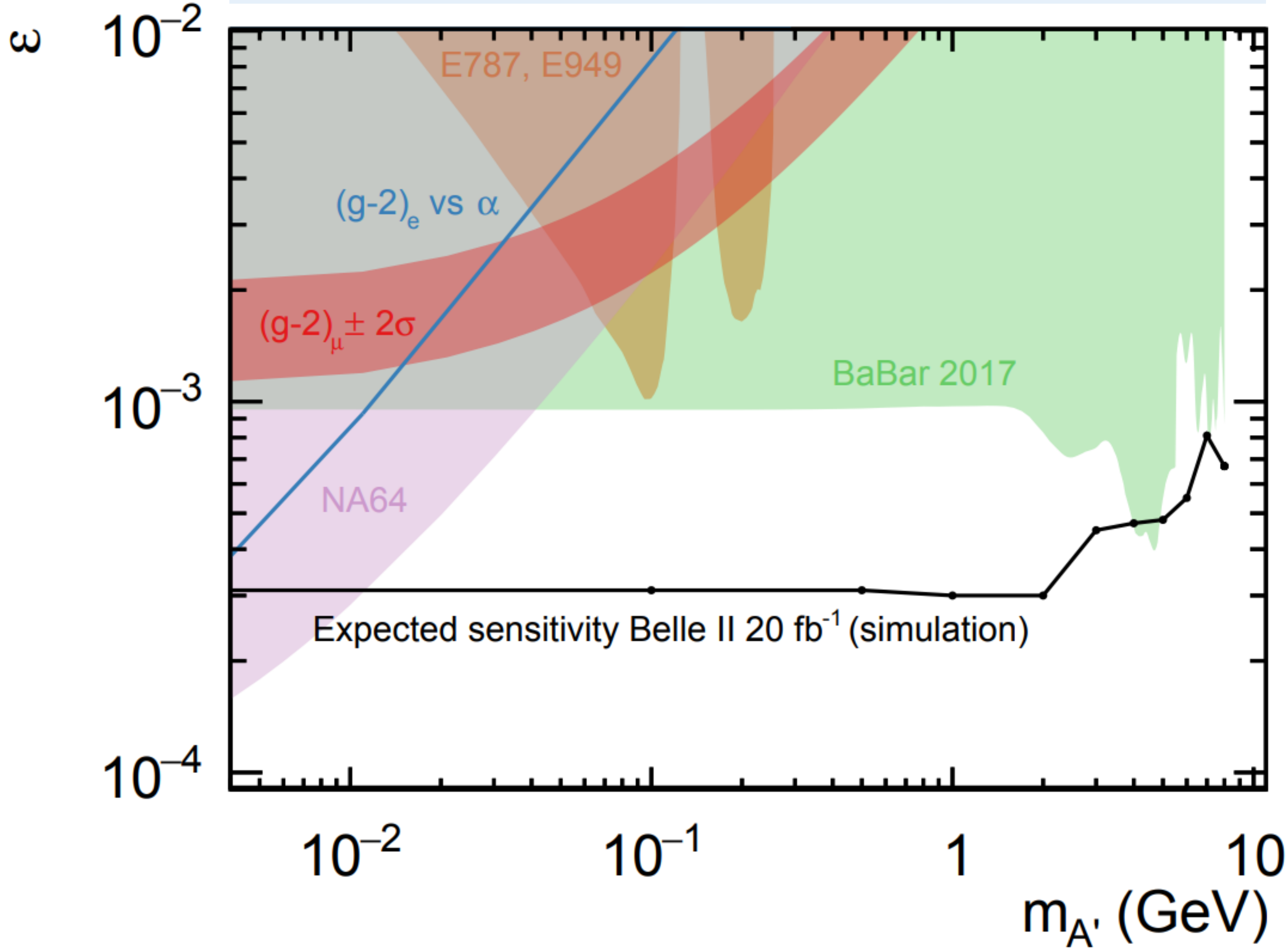
Simulated background rates



Peaking $e^+e^- \to \gamma\gamma(\gamma)$ dominates the analysis

Projected upper limits on ε, invisible dark photon

$e^+e^- \rightarrow \gamma A', A' \rightarrow invis.$



- Significantly better than BaBar (53 fb^{-1}) due to better hermeticity of the ECL and the efficiency of the KLM

BaBar: arXiv:1702.03327

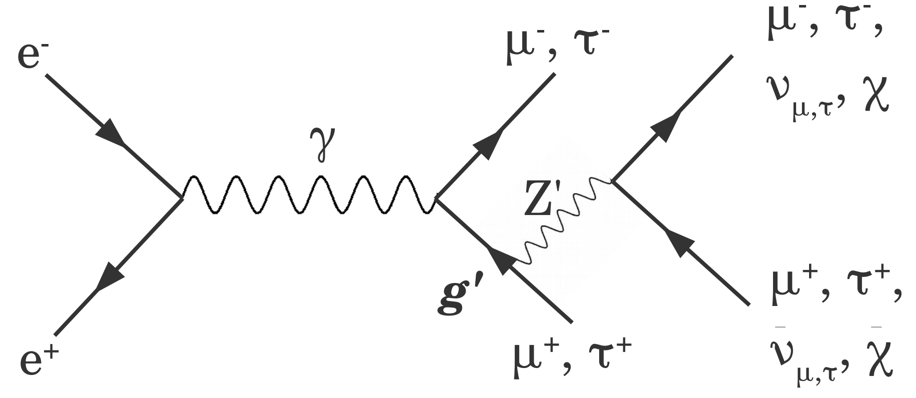
Belle II Physics book: arXiv:1808.10567

Search for Z'

$L_\mu - L_\tau$ model

Shuve et al. (2014), arXiv:1403.2727

- Extension of the SM: → additional $U(1)_{L\mu - L\tau}$ symmetry
- Introduces a light vector boson $\boldsymbol{Z'}$ with coupling $\boldsymbol{g'}$ only with the 2nd and 3rd generation of leptons . It is mediator through the Dark Sector
- May explain: $(g\text{-}2)_\mu$, Abundance of DM in the Universe, nature of the neutrino mass...
- Invisible decay channel to be explored for the first time



Invisible Branching Ratios

to SM ν's:

$M_{Z'} < 2M_\mu \rightarrow Br(Z' \rightarrow inv.) = 1$

$2M_\mu < M_{Z'} < 2M_\tau \rightarrow Br(Z' \rightarrow inv.) \sim 0.5$

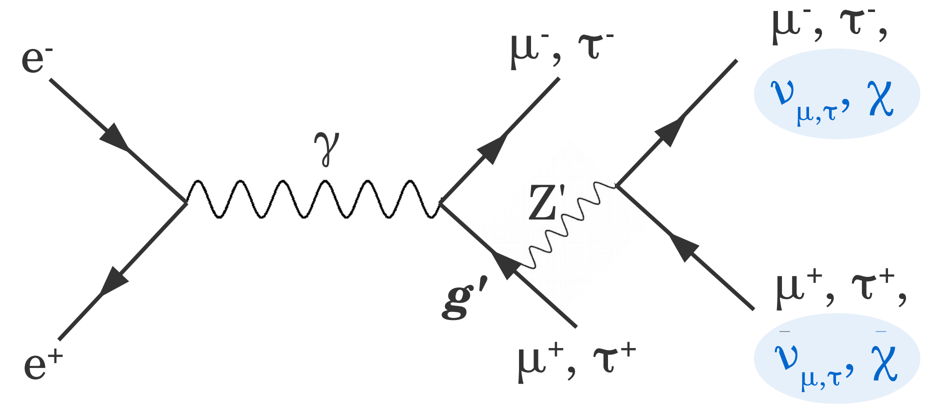
$M_{Z'} > 2\,M_\tau \rightarrow Br(Z' \rightarrow \text{inv.}) \sim 1/3$

enhanced by the presence of LDM χ

$Br(Z' \rightarrow inv.) = 1$

$L_\mu - L_\tau$ model

Shuve et al. (2014), arXiv:1403.2727



- Extension of the SM: → additional $U(1)_{L\mu - L\tau}$ symmetry
- Introduces a light vector boson ***Z'*** with coupling ***g'*** only with the 2nd and 3rd generation of leptons . It is mediator through the Dark Sector
- May explain: $(g\text{-}2)_\mu$, Abundance of DM in the Universe, nature of the neutrino mass...
- Invisible decay channel to be explored for the first time

Invisible Branching Ratios to SM ν's:

$M_{Z'} < 2M_\mu \rightarrow Br(Z' \rightarrow inv.) = 1$

$2M_\mu < M_{Z'} < 2M_\tau \rightarrow Br(Z' \rightarrow inv.) \sim 0.5$

$M_{Z'} > 2\,M_\tau \rightarrow Br(Z' \rightarrow \text{inv.}) \sim 1/3$

enhanced by the presence of LDM χ

$Br(Z' \rightarrow inv.) = 1$

Z' to invisible search

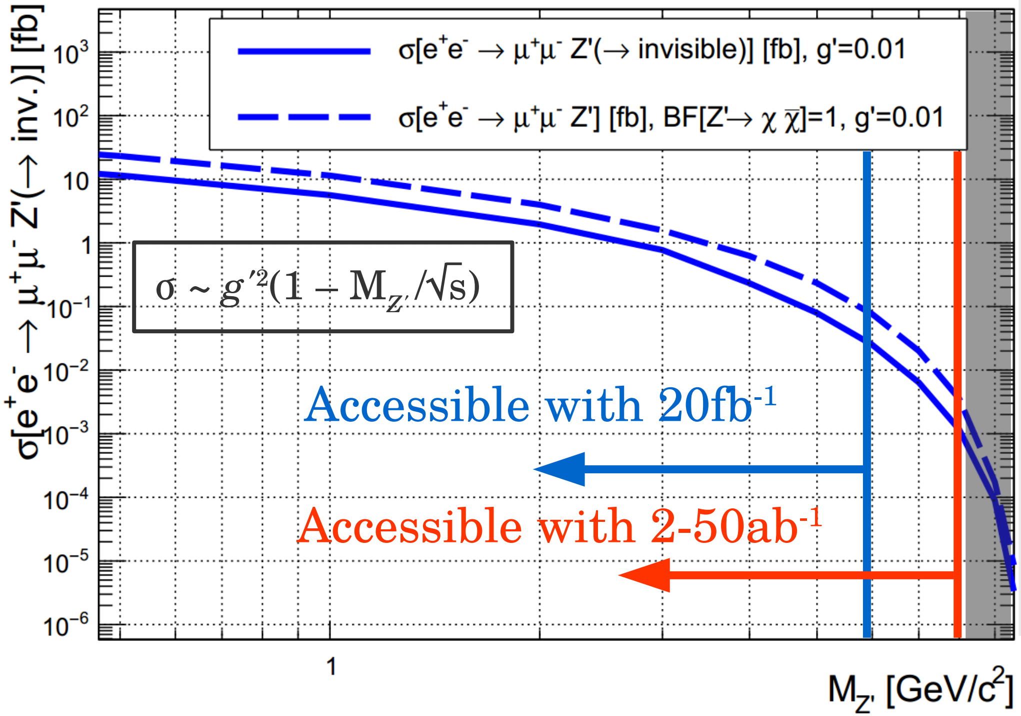
Signal events:

- look for bumps in recoil mass against a $\mu^+\mu^-$ pair (+ nothing in the rest of event)
- simulated and reconstructed several Z' masses from 0.1 to 10 GeV/c²

Main background events:

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

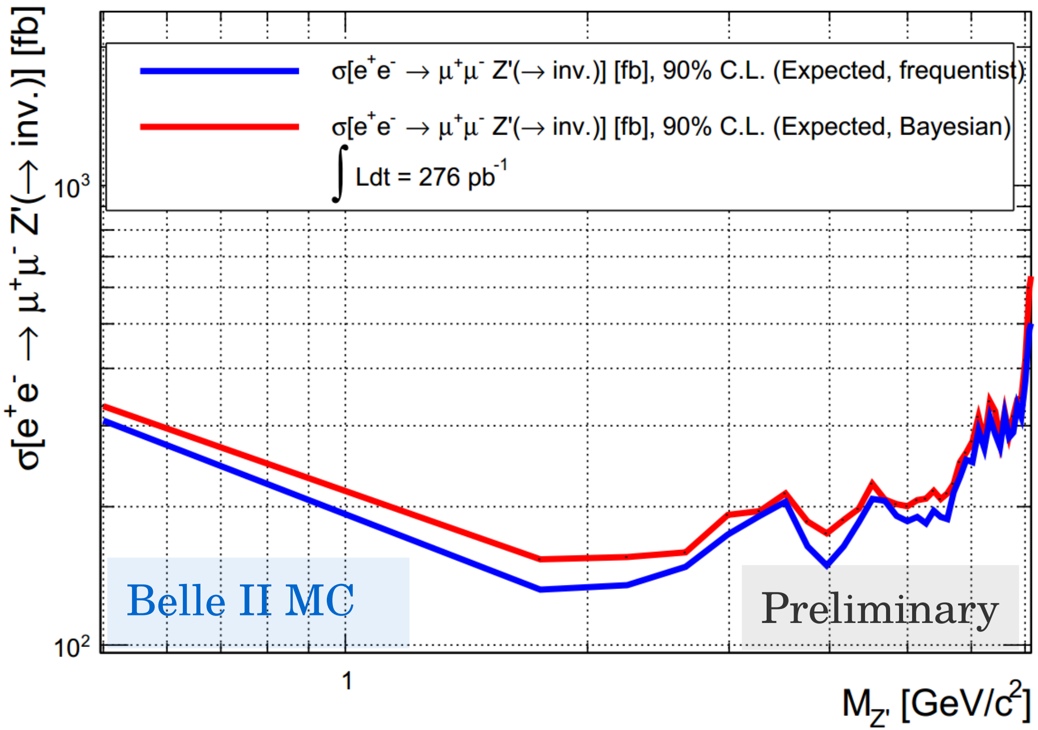
Production cross section

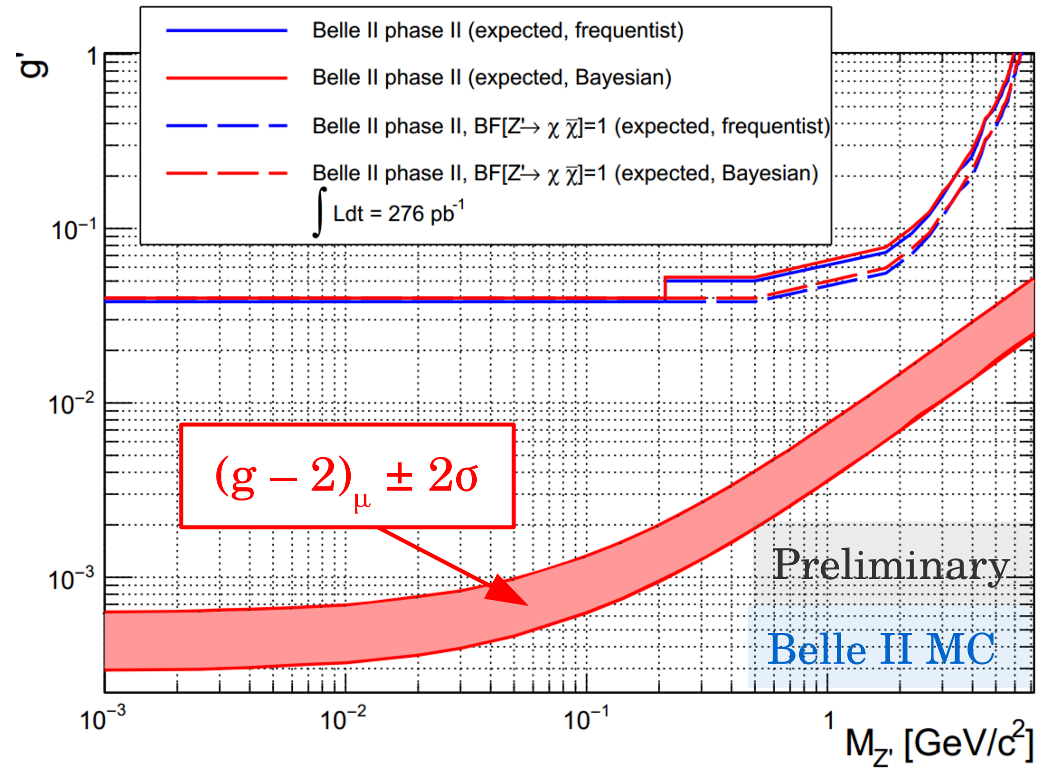


Computed with MadGraph5

No sensitivity to the parameter space region for $M_{Z'}$ > 8 GeV/c²

Expected upper limits on Phase 2 data





Systematics effects:

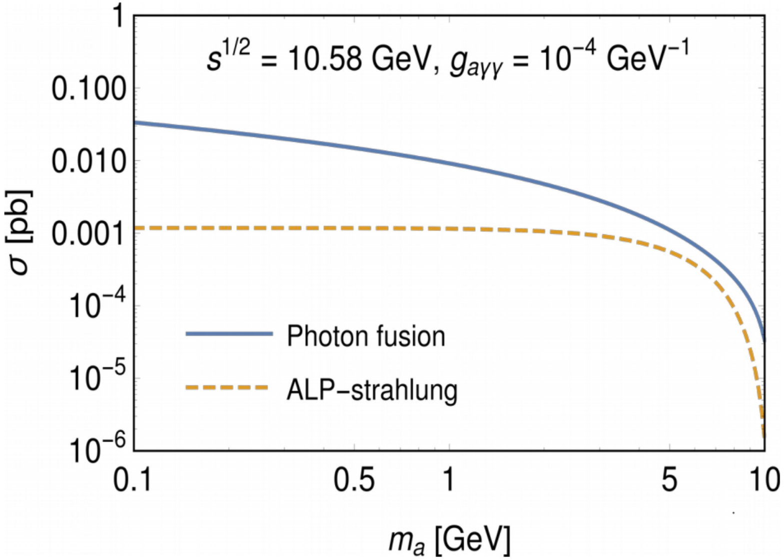
- some systematics included, trigger + tracking + PID + mass resolution (~10%)
- possible additional systematics on background estimate not included (0-30%)
- analysis optimisation still ongoing

Axion-Like Particles

Axion-like particles (ALPs)

- Pseudo-scalar particles which couple to SM bosons
- No relation between mass and coupling → different from QCD axions
- m_a < MeV → excellent DM candidates
- m_a ~ GeV → mediator of interaction between SM and yet undiscovered DM particle
- Focus on coupling to photons → $-\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$
- Two production processes possible:
  - Focus on ALP-strahlung
    - $e^+e^- \to \gamma + inv.$
    - $e^+e^- \to 3\gamma$

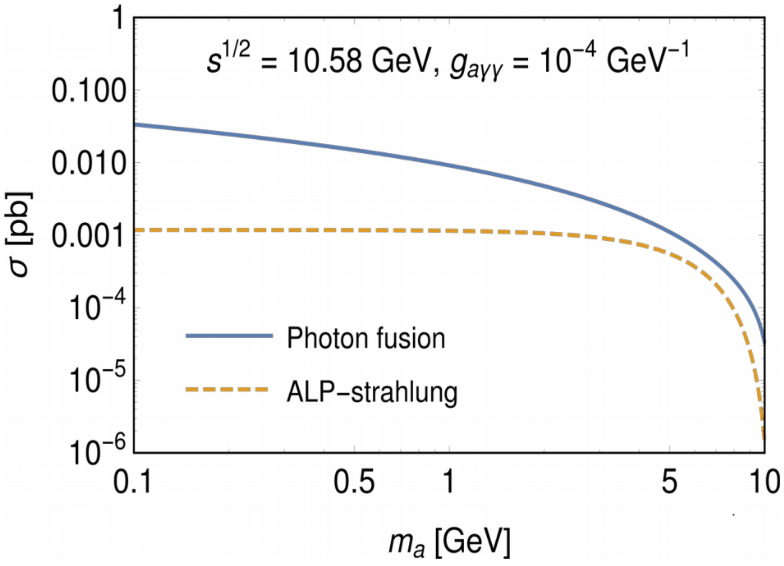
JHEP 1712 (2017) 094 arXiv:1709.00009



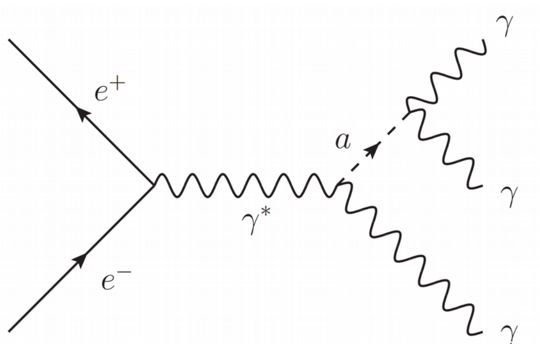
Axion-like particles (ALPs)

- Pseudo-scalar particles which couple to SM bosons
- No relation between mass and coupling → different from QCD axions
- m_a < MeV → excellent DM candidates
- m_a ~ GeV → mediator of interaction between SM and yet undiscovered DM particle
- Focus on coupling to photons → $-\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$
- Two production processes possible:
  - Focus on ALP-strahlung
    - $e^+e^- \to \gamma + inv.$
    - $e^+e^- \to 3\gamma$

JHEP 1712 (2017) 094 arXiv:1709.00009

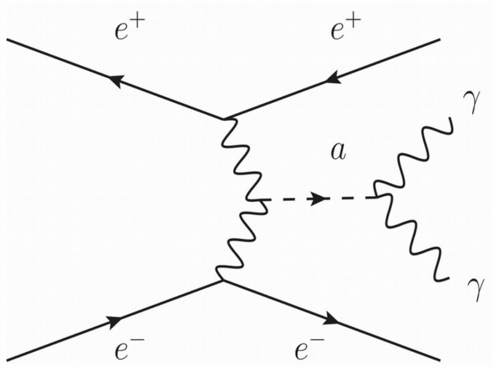


ALP-strahlung

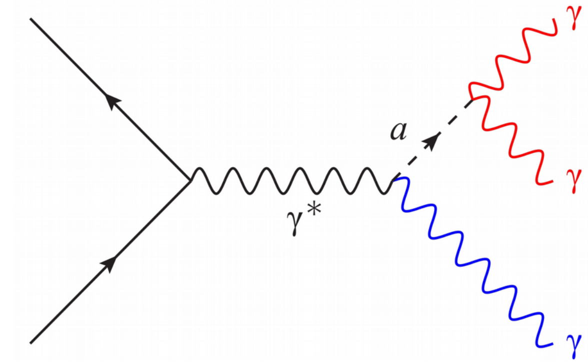


Sensitivity under study

Photon-fusion



Axion-like particles: signal

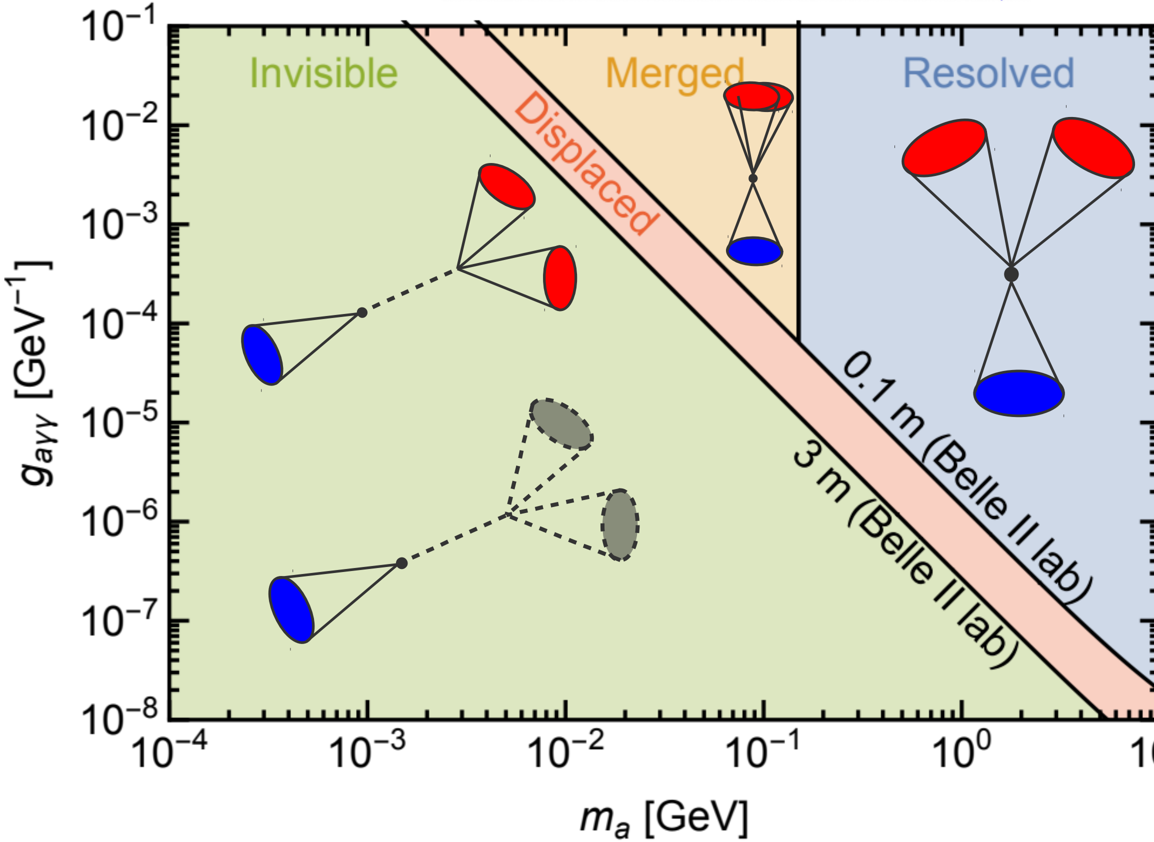


Parameters (m_a, $g_{a\gamma\gamma}$) determine the displacement and the θ angle between the 2γ

- $\tau = 1/m_a^2 g_{a\gamma\gamma}^2$

Four Signatures:

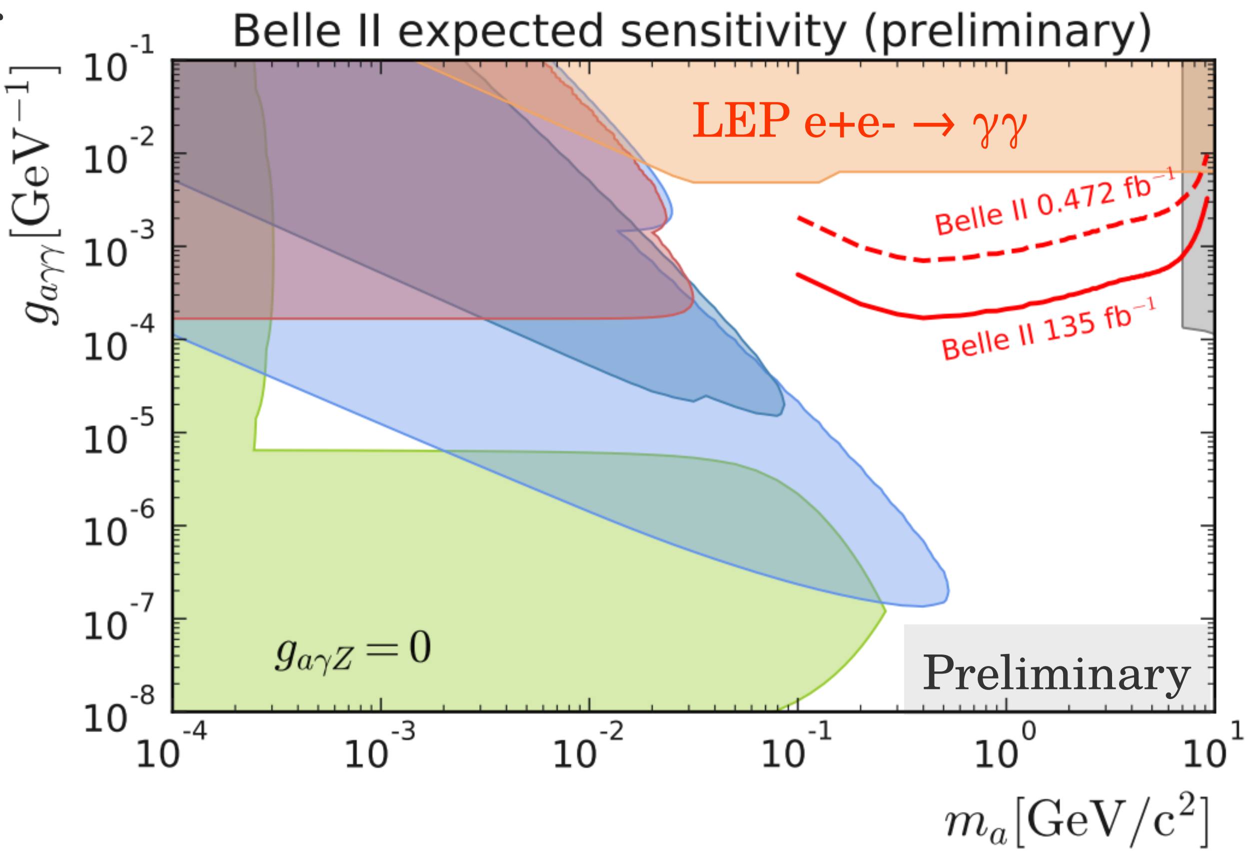
- Resolved: prompt decay, large θ
- Merged: prompt decay, small θ
- Invisible: a decays outside the detector or a decays to invisible particles, as DM particles
- Displaced: veto this region (indistinguishible from $e^+e^- \to \gamma\gamma$)



JHEP 1712 (2017) 094 arXiv:1709.00009

Axion-like particles: sensitivity

- Focus on: $e^+e^- \to \gamma a$, $a \to \gamma\gamma$
- Observable: Invariant mass of the two photons
- Main SM background:
  - $e^+e^- \to \gamma\gamma(\gamma)$
  - $e^+e^- \to e^+e^-(\gamma)$
  - $e^+e^- \to P\gamma(\gamma)$, $P = (\pi^0, \eta, \eta')$
- Belle II expected limits
  - No systematics included
  - beam background negligible



Conclusions

Conclusions

- Belle II Phase 2 finished in 2018 → Successful SuperKEKB commissioning and collected 0.472 fb^{-1} of data → b and charm physics rediscoveries, but also search for DM

- Many searches are ongoing, A', Z', ALPs, and there is possibility to explore many more Dark Sector models
  - ***A′ → inv.***, expected sensitivity: $\varepsilon \sim 8 \cdot 10^{-3}$ with L_{int} = 20 fb^{-1}, better than the current limits set by BaBar
  - ***Z′ → inv.***, expected sensitivity: $g' \sim 10^{-1}$ with Phase 2 data → with Phase 3: possibility to exclude the parameter region that explain $(g-2)_\mu$
  - **ALPs**, $\boldsymbol{a \rightarrow \gamma\gamma}$, expected sensitivity: $g_{a\gamma\gamma} \sim 10^{-3}$ with Phase 2 data, better than current limits

- Phase 3 is starting with full detector and ~10 fb^{-1} are expected by the end of July

Thank you!

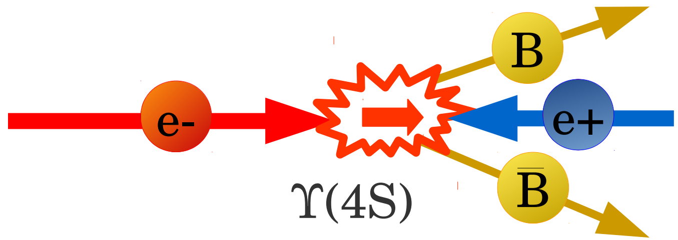
luigi.corona@pi.infn.it

BFactories

B-factory: asymmetric e+/e- collider (SuperKEKB: E(e-) = 7 GeV, E(e+) = 4 GeV) optimized for the production of B mesons (but also charm physics, tau physics…)

$e^+e^- \to \Upsilon(4S)[b\bar{b}]$ (10.58 GeV/c^2)

B.R.($\Upsilon(4S) \to B\bar{B}$) > 96%,



Process	Cross Section [nb]
$e^+e^- \to \mu^+\mu^-$	1.148 ± 0.005 (full angle)
$e^+e^- \to \tau^+\tau^-$	0.919 ± 0.003 (full angle)
$e^+e^- \to e^+e^-(\gamma)$	294 ± 2 (10-170 deg)
$e^+e^- \to \gamma\gamma(\gamma)$	4.96 ± 0.02 (10-170 deg)
$e^+e^- \to e^+e^-e^+e^-$	39.74 ± 0.03 (full angle)
$e^+e^- \to e^+e^-\mu^+\mu^-$	18.87 ± 0.02 (full angle)
$e^+e^- \to u\bar{u}(\gamma)$	1.605 (full angle)
$e^+e^- \to d\bar{d}(\gamma)$	0.401 (full angle)
$e^+e^- \to s\bar{s}(\gamma)$	0.383 (full angle)
$e^+e^- \to c\bar{c}(\gamma)$	1.329 (full angle)
$e^+e^- \to \Upsilon(4S) \to B^+B^-$	0.5346 (full angle)
$e^+e^- \to \Upsilon(4S) \to B\bar{B}^0$	0.5654 (full angle)

First generation of B-factories:

- BaBar at the PEP II collider (SLAC California)
- Belle at the KEKB collider (KEK, Japan)

Some features: well known initial state, high signal / noise ration, detector with high angular acceptance and composed of several subdetectors

Nano-beam scheme and luminosity

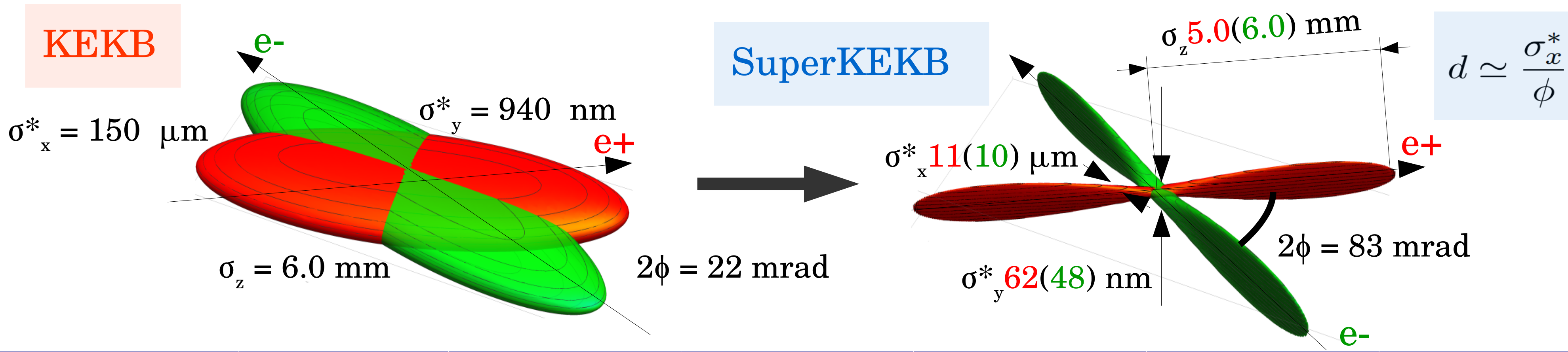
currents — beam-beam parameter

$$\mathcal{L} = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\frac{R_L}{R_{\xi_y}}$$

geometrical reduction parameter ~0.8-1

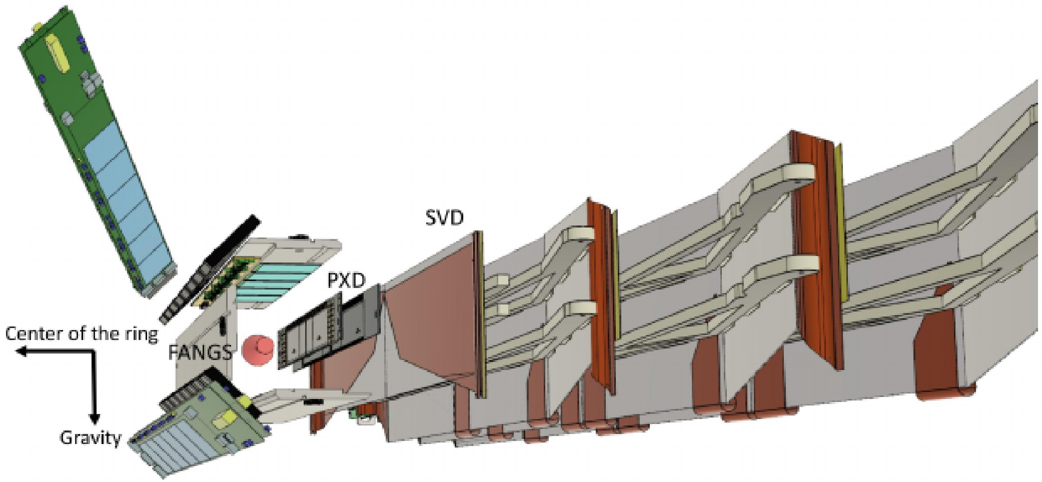
Ratio between the y and x dimension of the beam 0.01 – 0.02

vertical beta function at IP

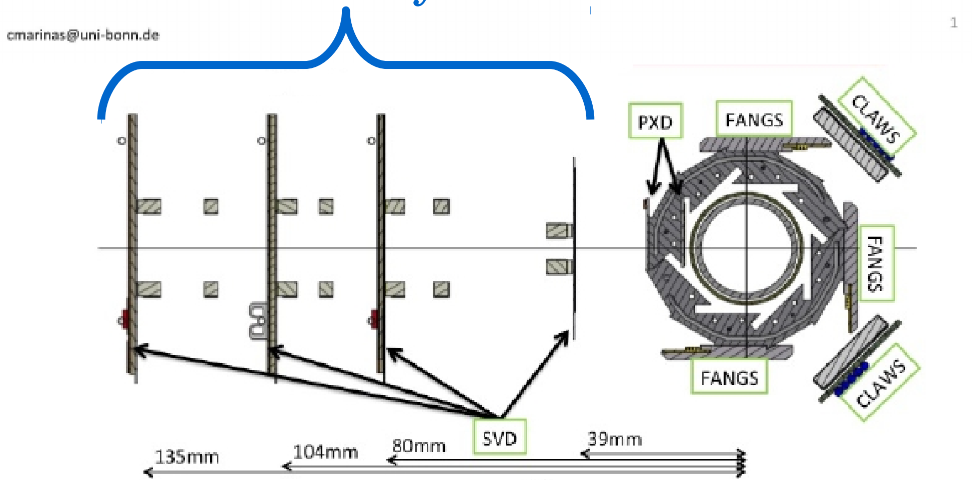


	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	ϕ (mrad)	I(A) LER/HER	L($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	$2.1 \cdot 10^{34}$
SuperKEKB	4.0/7.0	0.27/0.30 x1/20	3.2/2.5	41.5	3.6/2.6 x2	$80 \cdot 10^{34}$ x40

Phase 2 and Phase 3 VXD geometry (1/2)



4 SVD layers



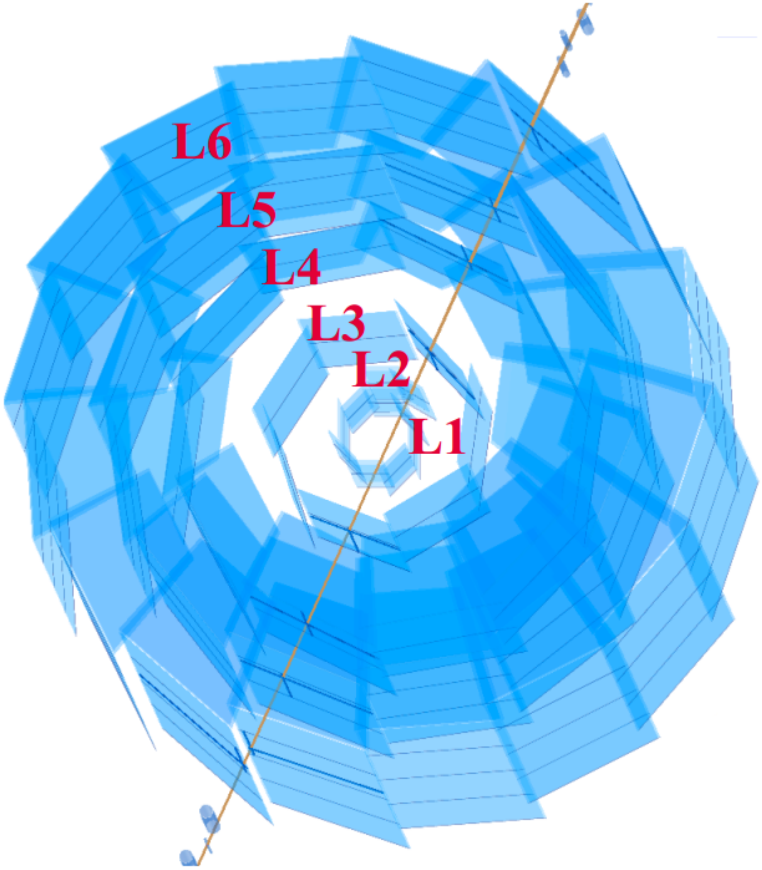
Phase 2

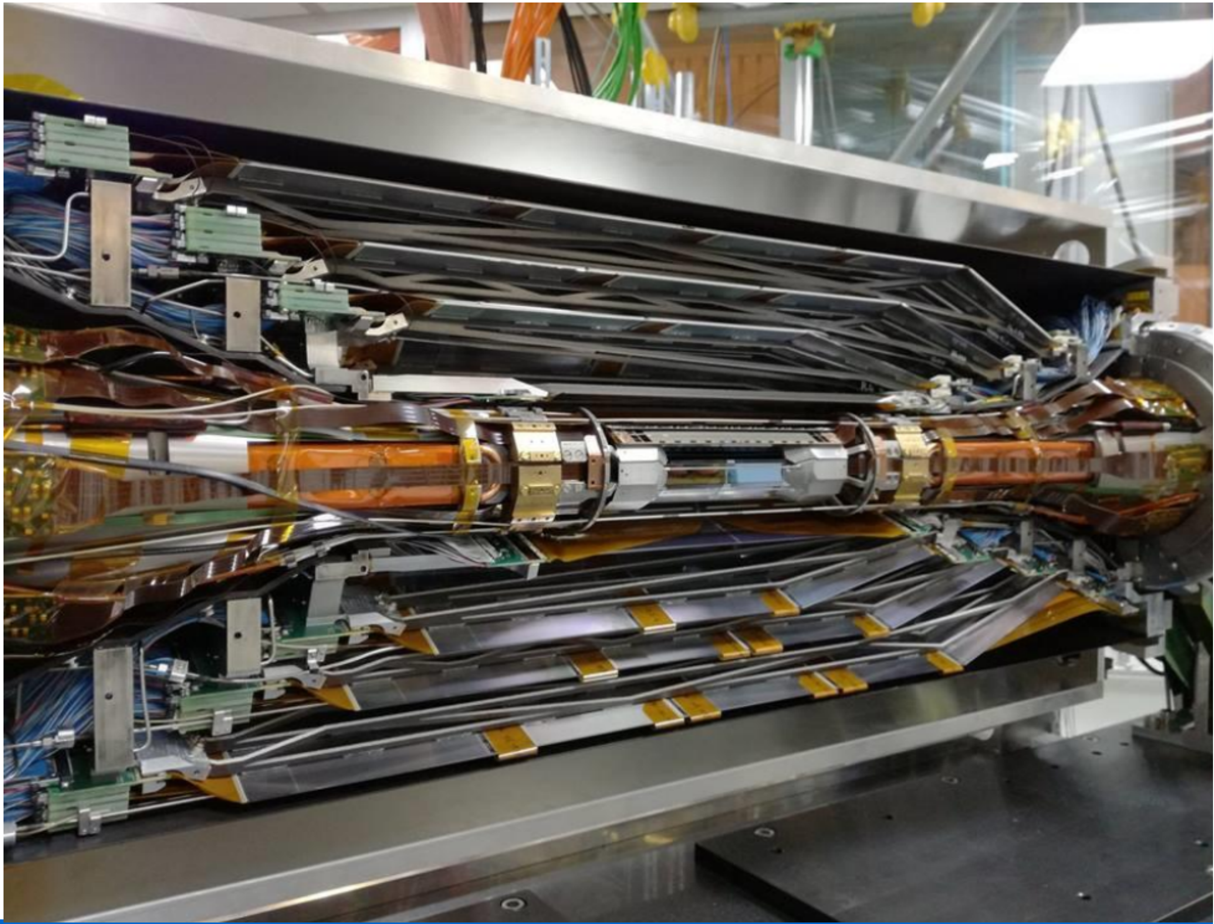
CLAWS, FANGS, PLUME and diamond sensors → study and monitor the beam background levels

Phase 2 and Phase 3 VXD geometry (2/2)

Phase 3

- SVD L3,4,5,6 → Low material budget, precise hit time resolution (σ ~ 3 ns)
- PXD L1,2 → Low material budget, innermost layer at 1.4 cm





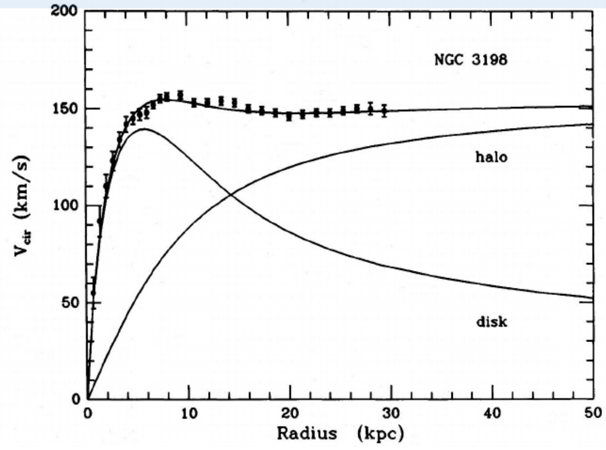
Belle II single photon trigger

Trigger logic	L1 rate at full lominosity
E > 1 GeV 2^{nd} cluster E < 300 MeV	4 kHz (barrel) 7 kHz (endcaps)
E > 2 GeV Bhabha and $\gamma\gamma$ veto	5 kHz (barrel)

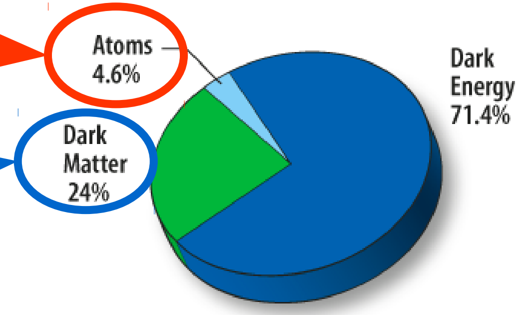
Dark Matter (DM): Introduction

- **Massive** → gravitational interation with Standard Model (SM) matter
- **Dark** → does not interact with SM matter thorugh any other interaction
- Many astrophysical observations in agreement with DM existance: flat galaxy rotation curves, gravitational lensing, galaxy velocity dispersion…

Flat galaxy rotation curves (first experimental evidence)

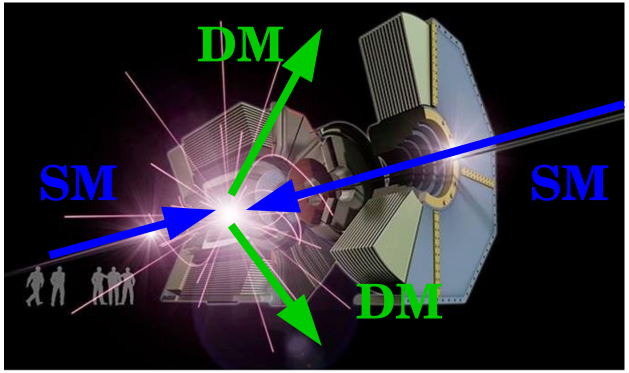


Abundance of standard matter in the Universe



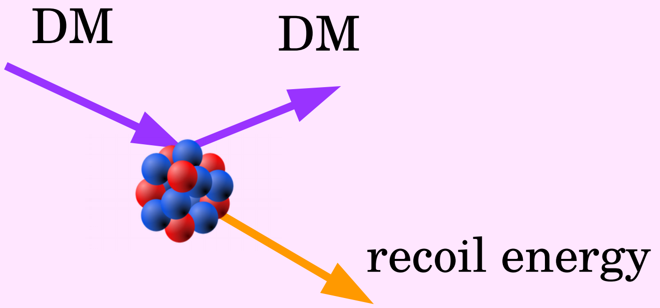
Abundance of DM in the Universe

If DM exists as particles and interact with SM, although very weakly, it is possible to produce it in colliders

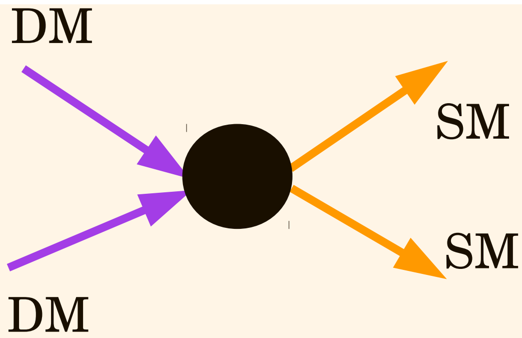


Detection of DM as particles

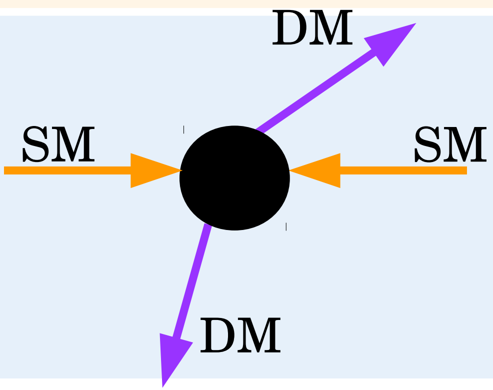
Direct detection: interaction of DM particles with atomic nuclei → detection of the recoil of the nucleus



Indirect detection: DM particles annihilate or decay in SM particles → detection of the product of the annihilation or decay

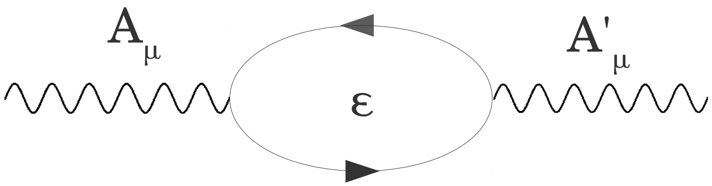


Detection at colliders: DM production in SM particles interactions → the interation could involve dark sector mediators



Kinetic mixing

- Extension of the SM: → additional U(1)' symmetry that mix with the photon



$$-\frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

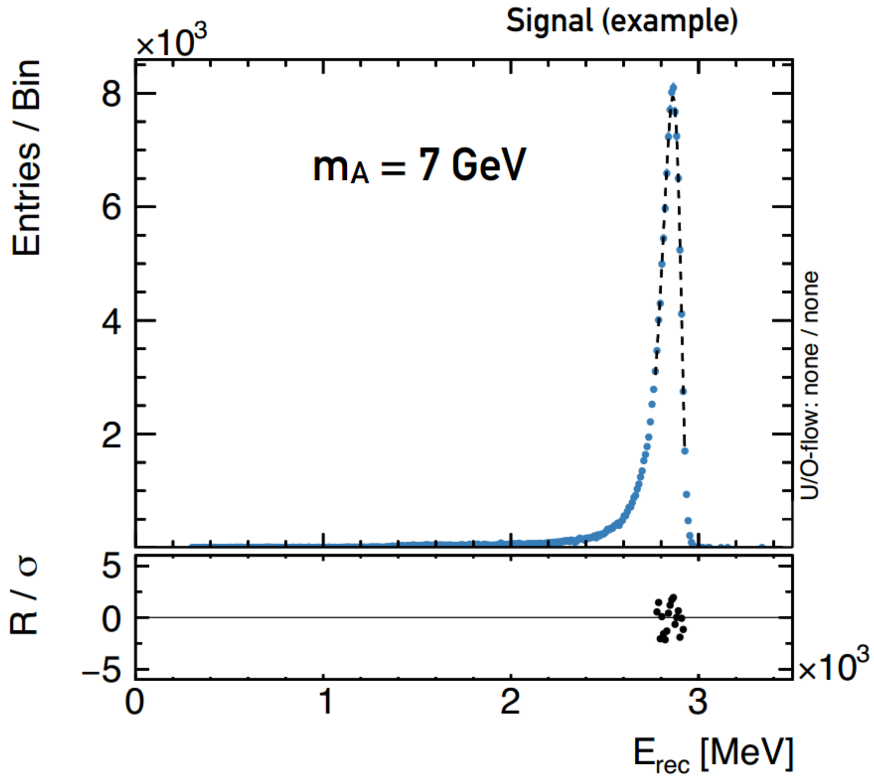
- Off diagonal kinetic term
- ε is the strengh of the kinetic mixing ($\varepsilon \lesssim 10^{-2}$)

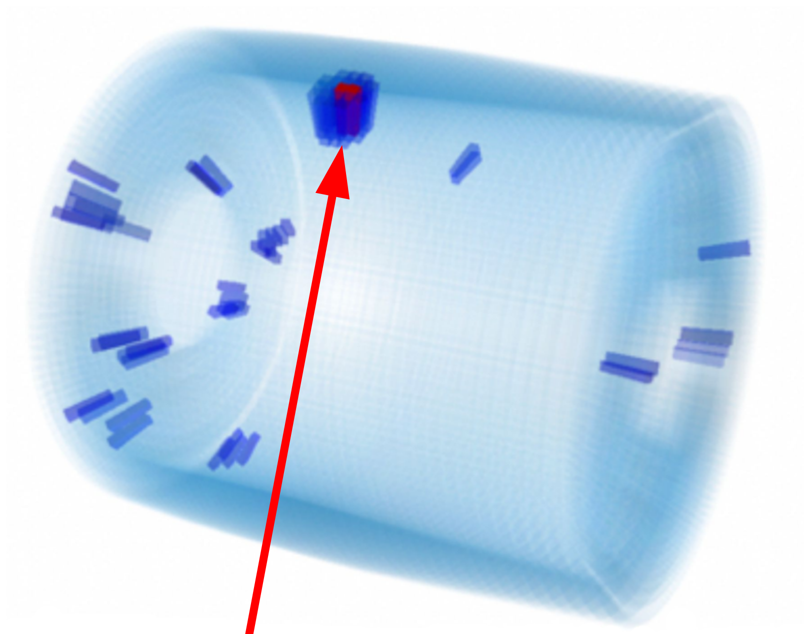
- After the ridefinition of fields ($A_\mu \rightarrow A_\mu - \varepsilon A'_\mu$) the diagonal kinetic term is restored and the interaction term $e\varepsilon J^\mu_{SM} A'_\mu$ arises in the theory
- The symmetry U(1)' can be broken spontaneously by a dark Higgs mechanism that gives mass to the dark photon

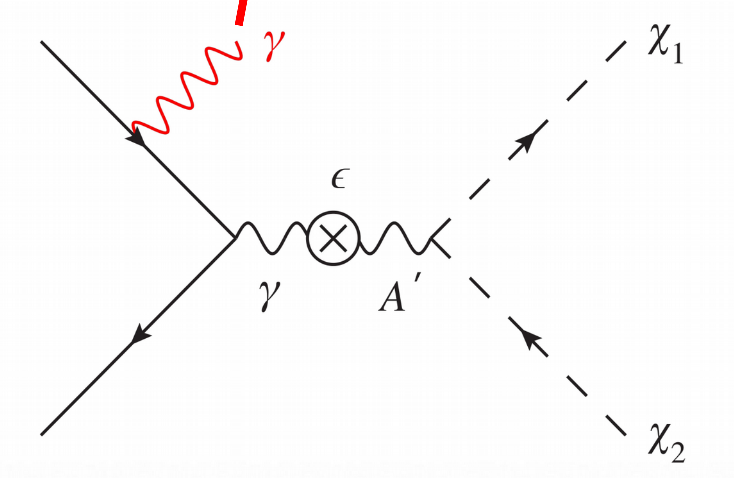
References:
P. Fayet, Phys. Lett. B 95, 285 (1980),
P. Fayet Nucl. Phys. B 187, 184 (1981)
B. Holdom, Phys. Lett. B 166, 196 (1986)

Dark photon to invisible

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

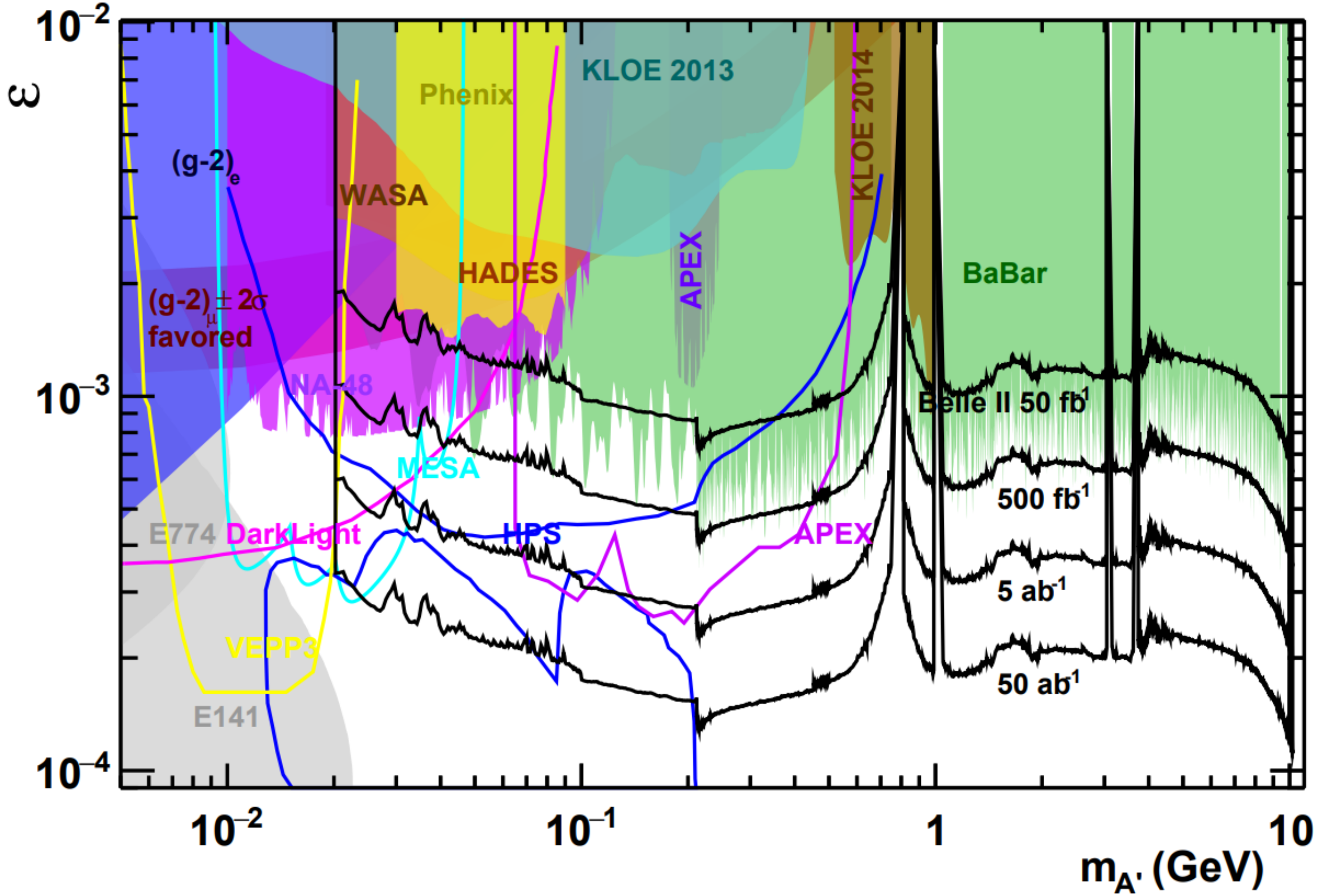


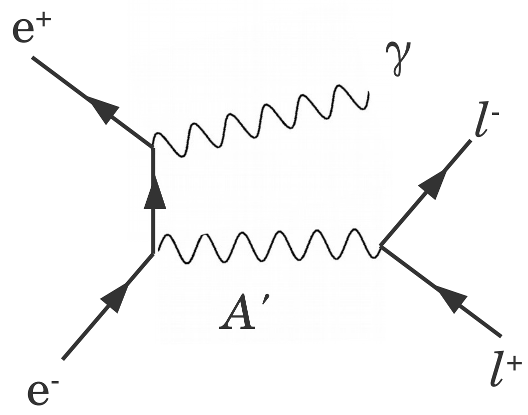




Projected upper limits on ε, visible dark photon

$e^+e^- \to \gamma A', A' \to l^+l^-$

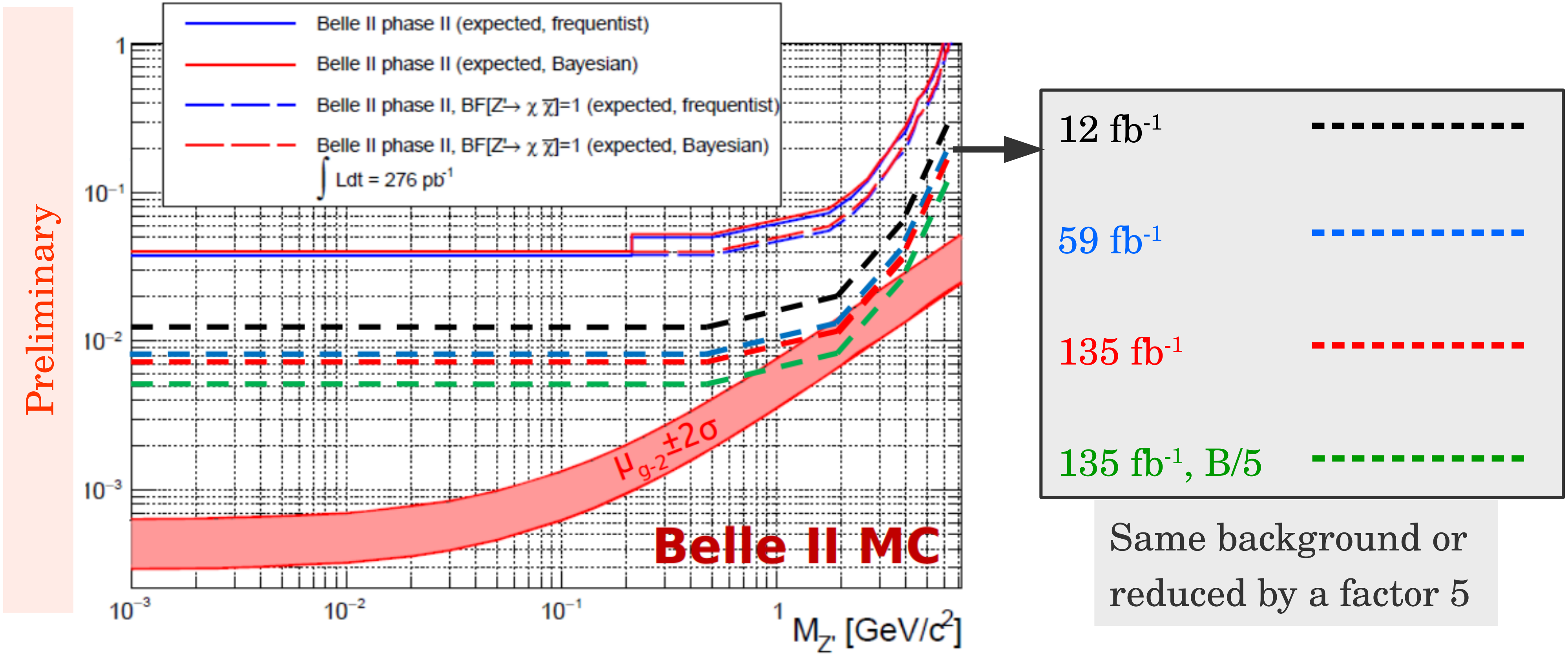




Belle II is competitive only in Phase 3

Belle 2 physics book
arXiv:1808.10567

Projected upper limits on Phase 3 data



Same background or reduced by a factor 5

Some possible factors of improvement: PID, vertex fit (full VXD), Multivariate Analysis

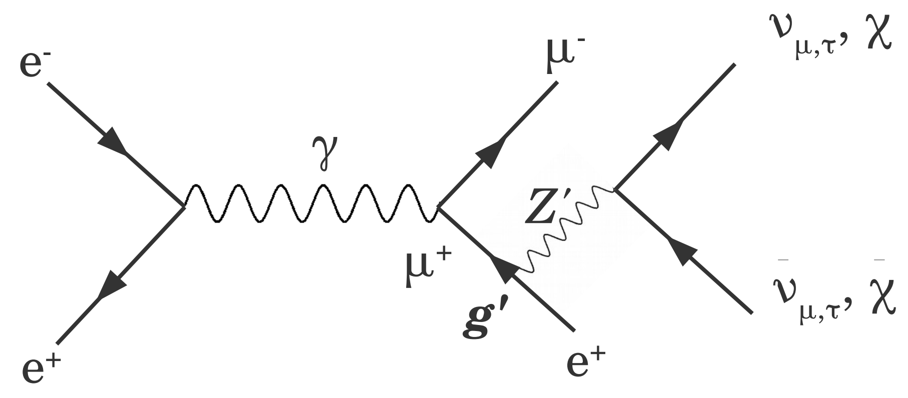
LFV Z': invisible and visible channel

What if symmetries of SM are not kept in the dark sector, or if DM violates Lepton Flavour symmetry?

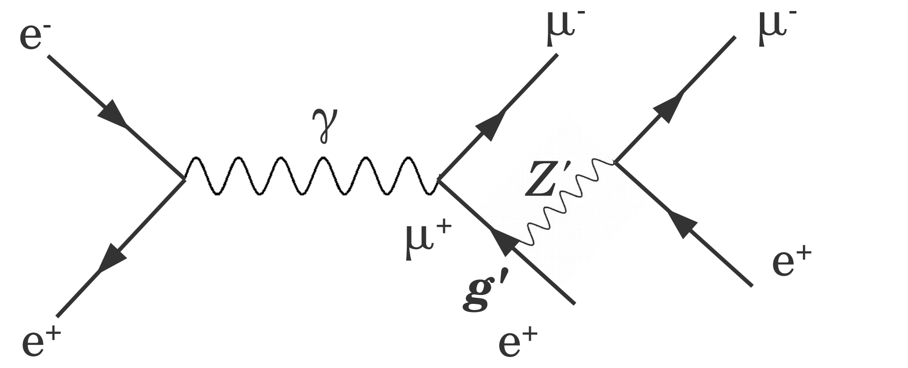
- For example: eμ coupling
- $e^+e^- \rightarrow e^+\mu^- Z'$, $Z' \rightarrow inv.$
- $e^+e^- \rightarrow e^+\mu^- Z'$, $Z' \rightarrow e^+\mu^-$ + c.c
- Low background from SM processes

See arXiv:1610.08060, arXiv:1701.08767

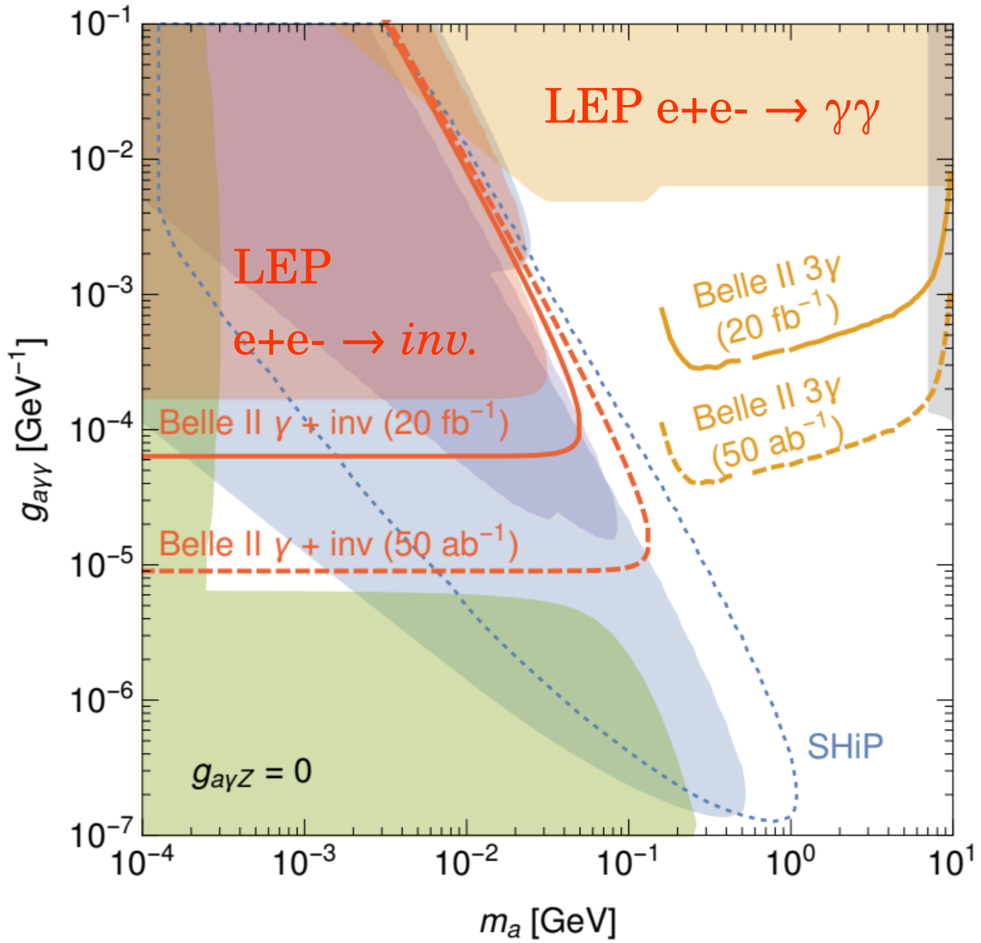
Final state: $e^+\mu^-$ + c.c + missing energy

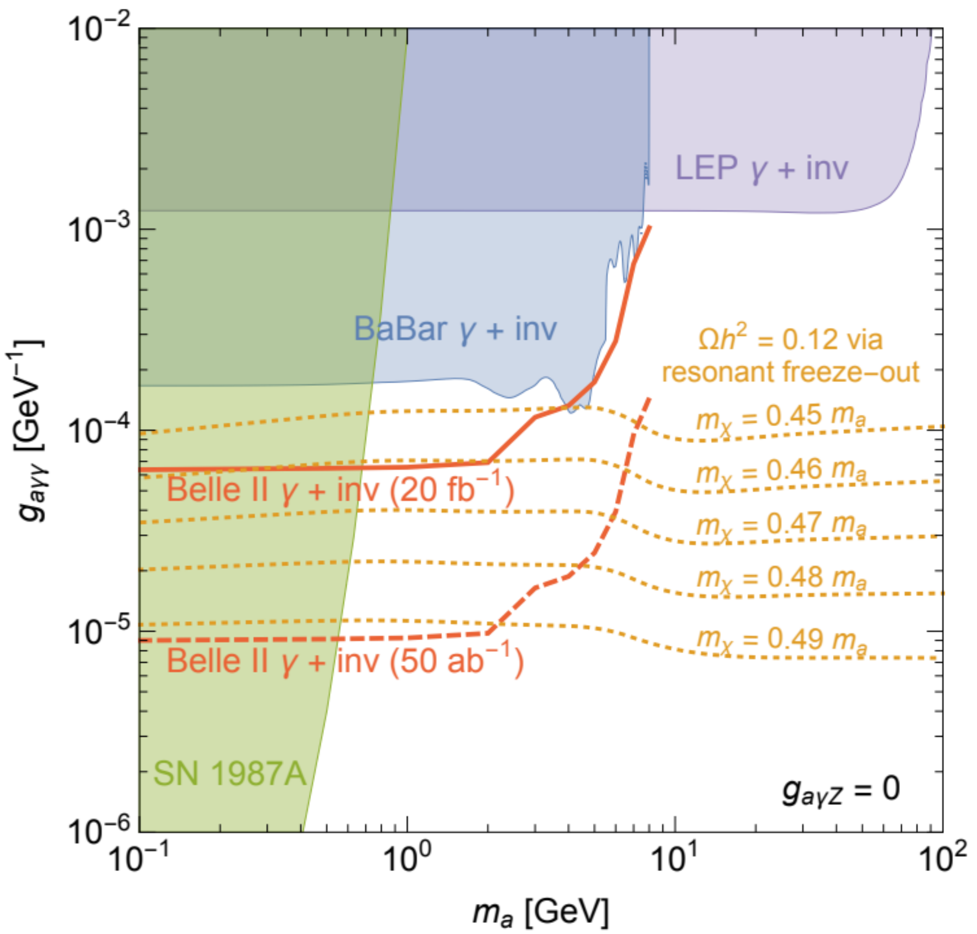


Final states: $e^+e^+\mu^-\mu^-$, $e^+e^-\mu^+\mu^-$



ALPs expected limits





Other planned dark sector and exotic searches

- Visible dark photon decays
- Off-shell dark photon decays***
- Muonic dark force: $e^+e^- \rightarrow \mu^+\mu^- Z'$, $Z' \rightarrow \mu^+\mu^-$

BaBar: arXiv:1606.03501 (514 fb^{-1})

- Dark sector with Lepton Flavor Violation: Z'
- Dark scalar: $e^+e^- \rightarrow \tau^+\tau^- S$, $S \rightarrow l^+l^-$
- Magnetic monopoles with small magnetic charges***
- Invisible $\Upsilon(1S)$ decays via $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^-$
(Requires beam energies at $\Upsilon(3S)$)

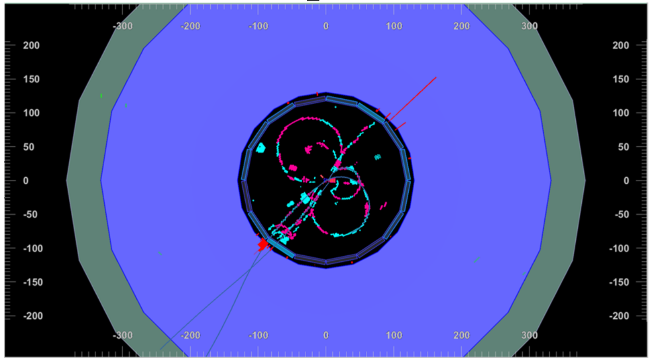
For further details:
arXiv:1808.10567

- Dark Higgs/Higgstrahlung
- ...

***Possible with Phase 2 data

Highlights from Phase 2

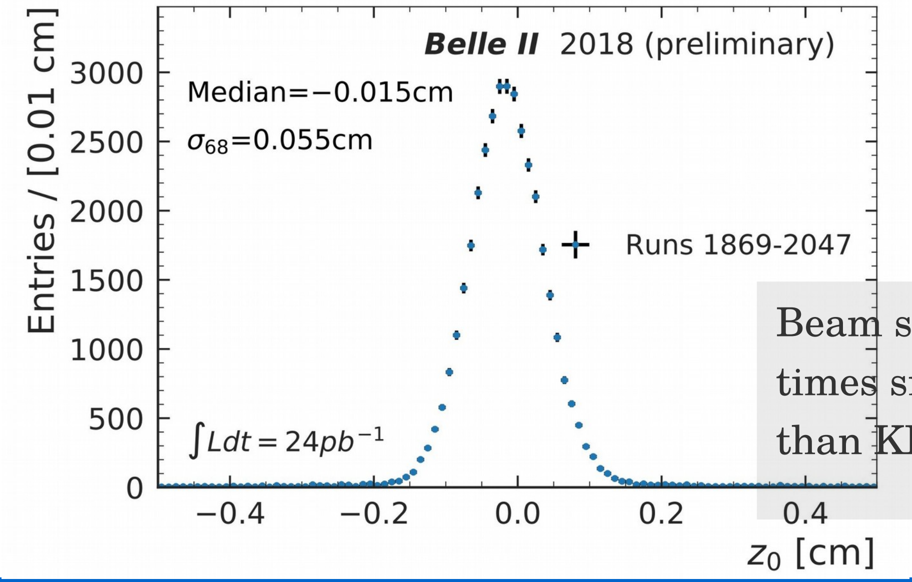
Started on April 26th, 2018



Ended on July 7th, 2018

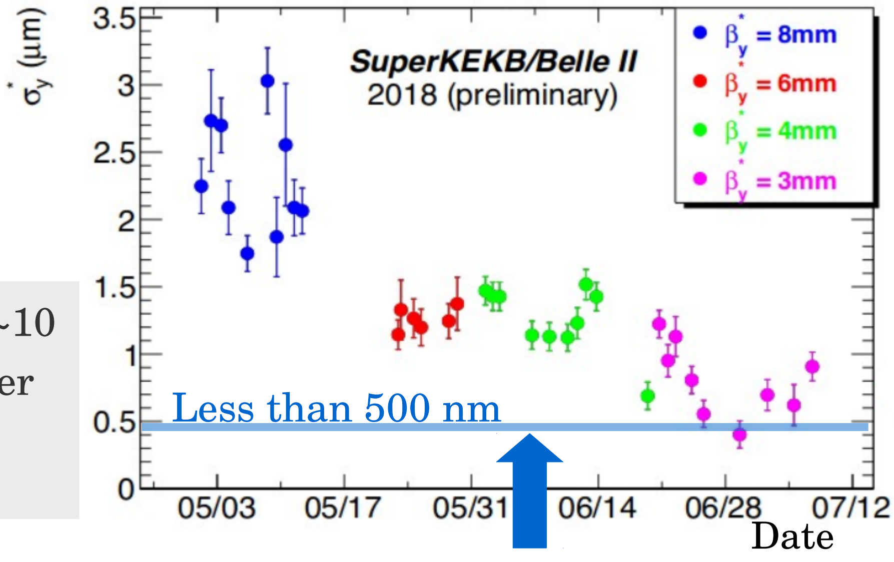
- L ~ 5.5 · 10^{33} cm^{-2} s^{-1}
- 0.472 fb^{-1} collected
- Nano-beam scheme works
- β_y* = 3 mm, σ_y ~ 400 nm (target: β_y* = 0.3 mm, σ_y ~ 50 nm)

Measured longitudinal IP position



Beam spot ~10 times smaller than KEKB

Measured vertical beam size

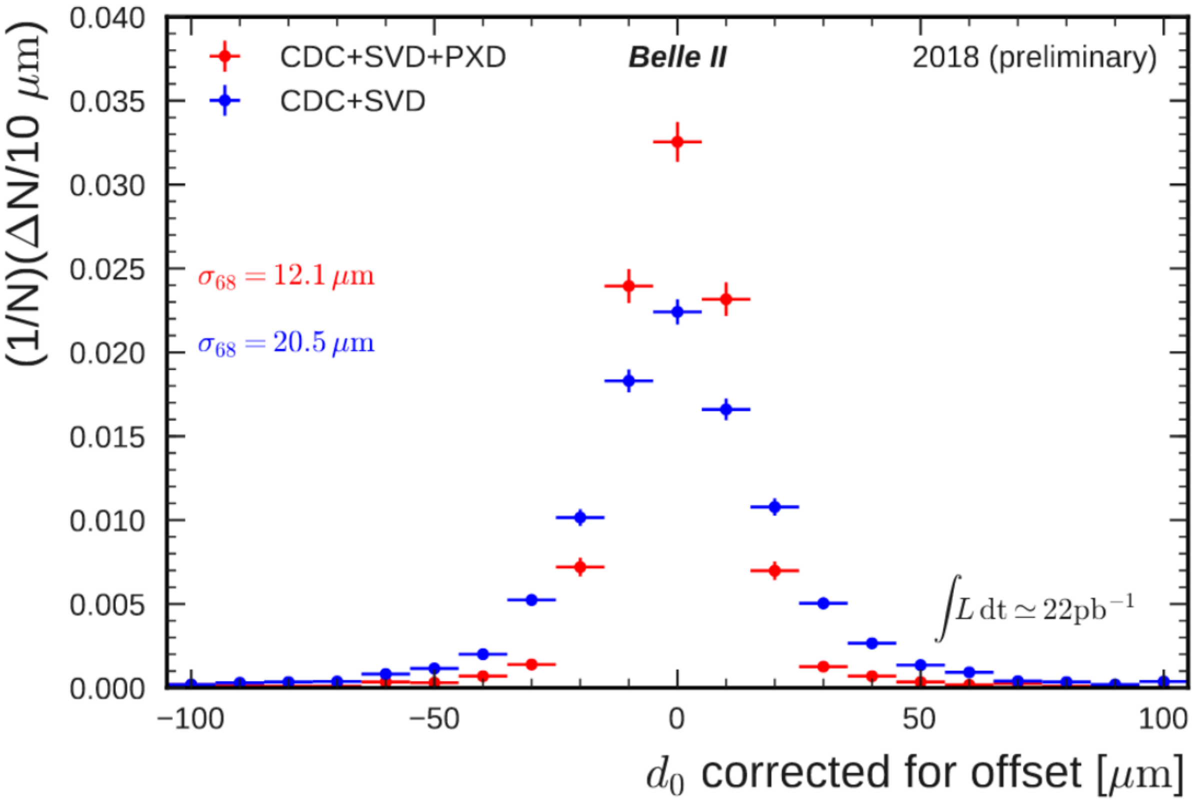


Vertexing: impact parameter resolution

Measured: 12.1 μm,
Expected: ~ 10 μm

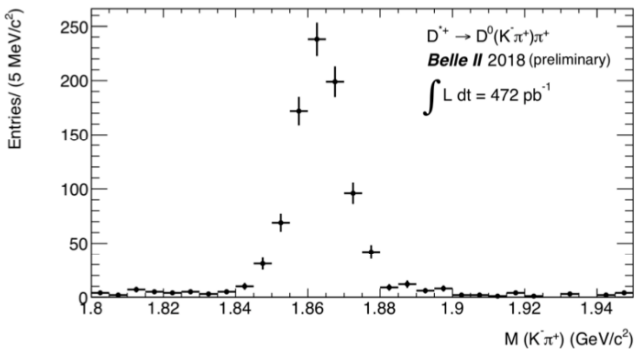
PXD contribution is crucial

Belle II **data**: bhabha events

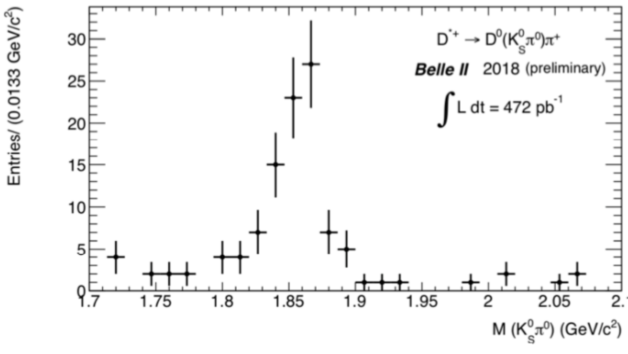


Phase 2: hadronic D and B reconstruction

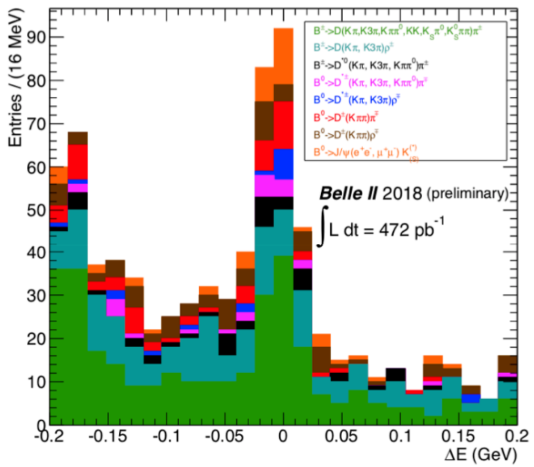
$D^0 \rightarrow K^- \pi^+$

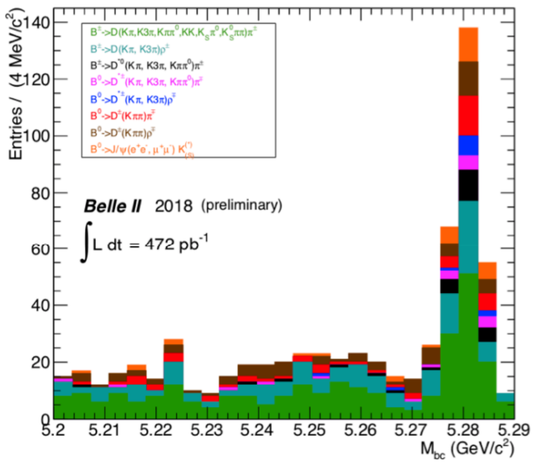


$D^0 \rightarrow K_S\, \pi^0$



$B \rightarrow D^{(*)}\, h$, $B \rightarrow J/\psi\, K^{(*)}$





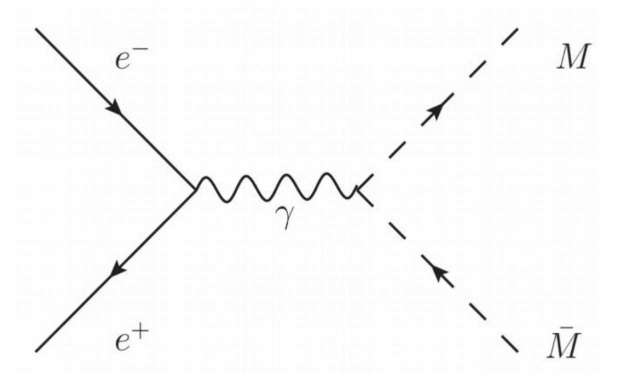
$$\Delta E = E_{cm}/2 - E_{recon}$$

$$M_{bc} = \sqrt{(E_{cm}/2)^2 - p_{recon}^2}$$

Magnetic monopoles

M. K. Sullivan, D. Fryberger arXiv:1707.05295

Particle carrying magnetic charge



Distinct signature in drift chamber:

- Tracks are strainght in (x,y) plane
- Tracks are curved in (r,z)

They need a dedicated tracking system

Detection efficiency is high: 40-97%, depending on magneton mass