KAON2019 - XI International Conference on Kaon Physics

Dark Sector studies at Belle II: First results and prospects

University of Perugia, Perugia, September 10-13th, 2019

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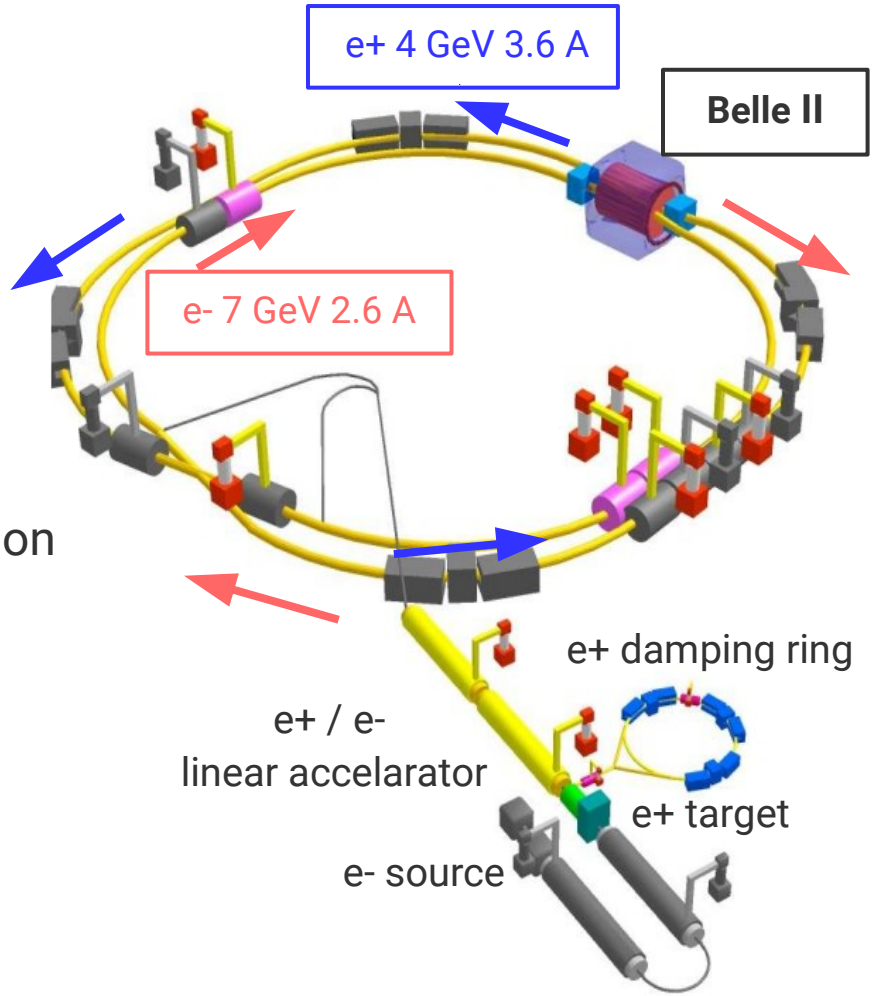
- on behalf of the Belle II collaboration

Outline

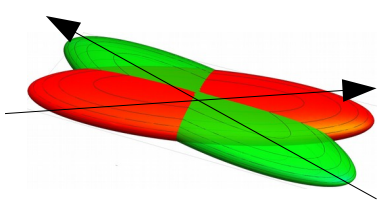
- SuperKEKB and the Belle II experiment
- Dark Sector with Belle II
- Conclusions

SuperKEKB collider

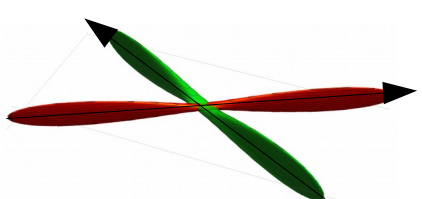
- Second generation of B-factory, successor of KEKB (Tsukuba, Japan)
- e^+/e^- asymmetric collider - E* ~10.58 GeV (= $M_{\Upsilon(4S)}$)
- highest world luminosity → Nano-beam scheme
  - Squeeze beams → increase probability of interaction
  - Higher currents and smaller beams than KEKB



KEKB



SuperKEKB

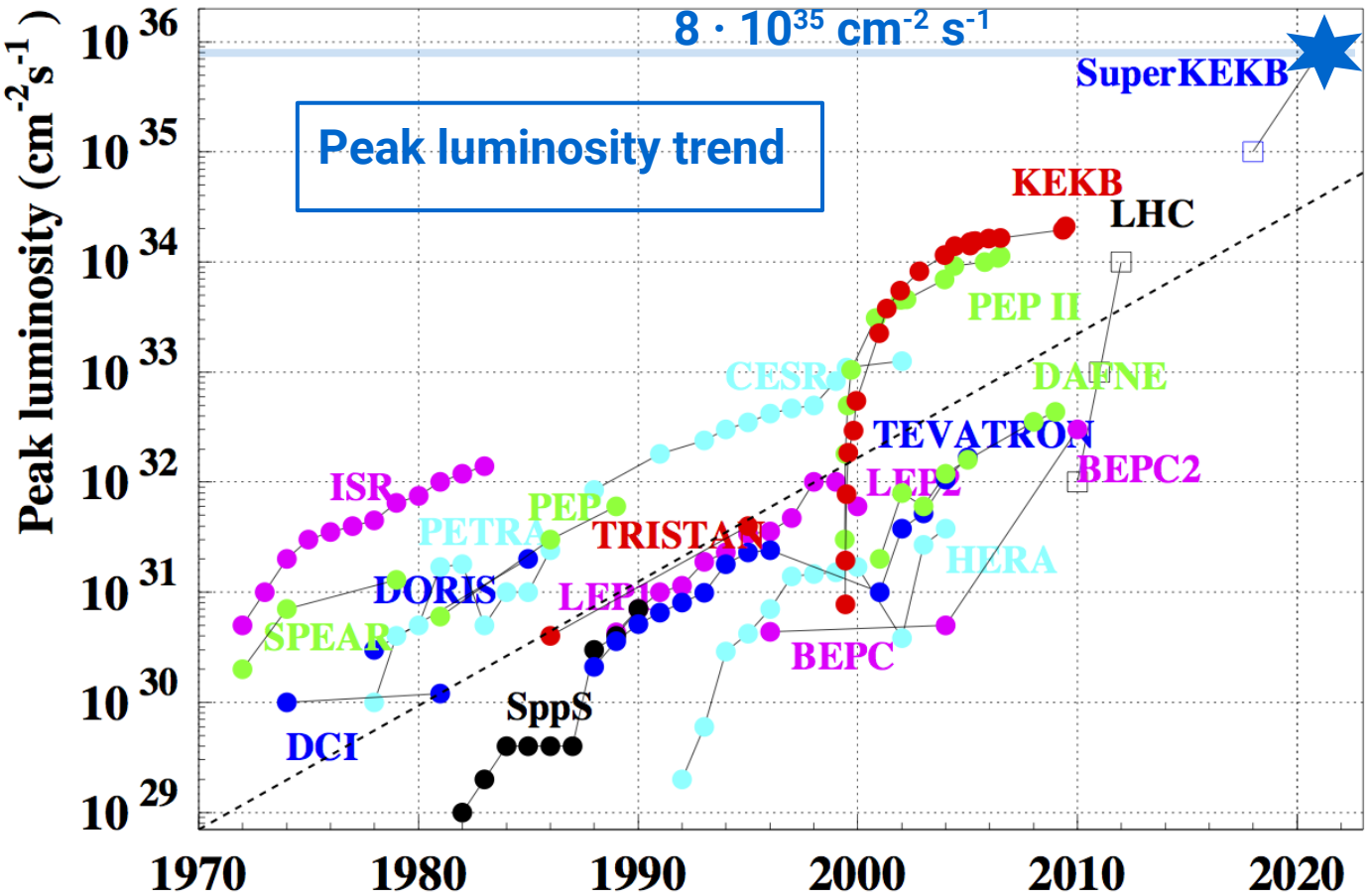


I(A): ~ 1.6/1.2
β^*_y(mm)~ 5.9/5.9

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



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

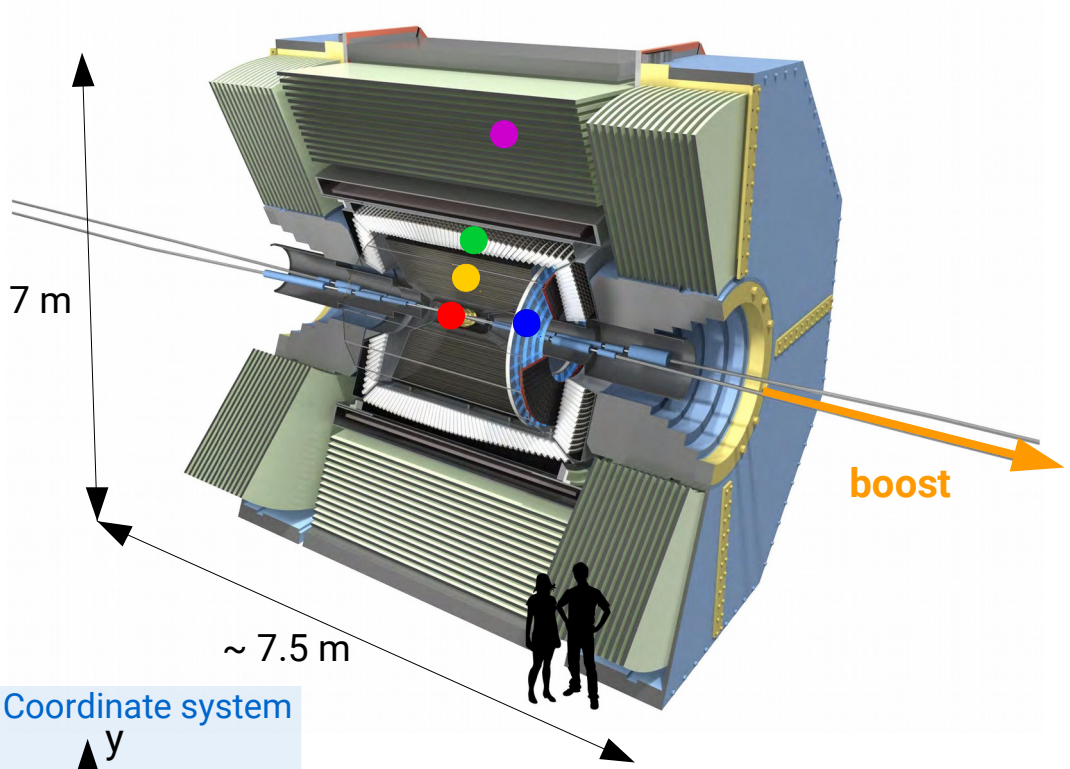
Search for:

- **light Dark Sector**

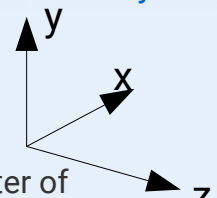
x40 higher luminosity than KEKB

Belle II detector

▸ See Pavel Krokovny talk: 13/09, 9:00!



Coordinate system



Belle II covering > 90% of 4π

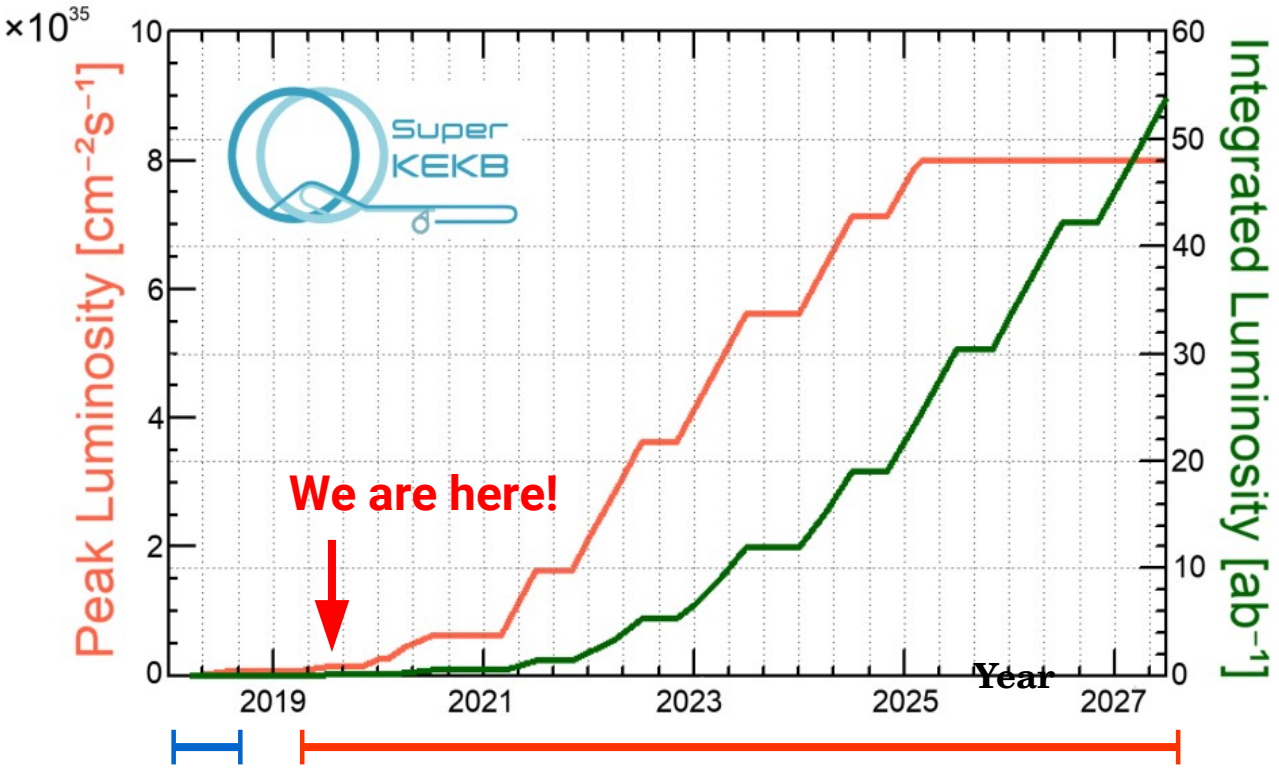
- **VerteX Detector (VXD):**
  2 layer DEPFET pixel detectors (PXD)***
  4 layer DSSD silicon vertex detectors (SVD)
- **Central Drift Chamber (CDC):**
  $He(50\%)C_2H_6(50\%)$
- **Particle Identification:**
  Time-of-Propagation (TOP) (barrel)
  Aerogel Ring Cherenkov (ARICH) (FWD)
- **E.M. calorimeter (ECL):**
  CsI(Tl) crystals
- **K_L and μ detector (KLM):**
  Resistive Plate Chambers (RPC) (outer barrel)
  Scintillators + SiPM (endcaps, inner barrel)

***second layer not complete

SuperKEKB schedule

Phase 1 (2016):

- dedicated to machine commissioning, w/o detector



Phase 2 (Last year):

- commissioning data
- 500 pb^{-1} collected
- incomplete detector: ~1/8 of VXD in φ
- rediscoveries, Dark Sector physics

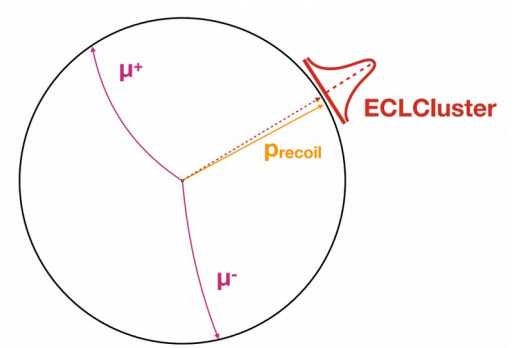
Phase 3:

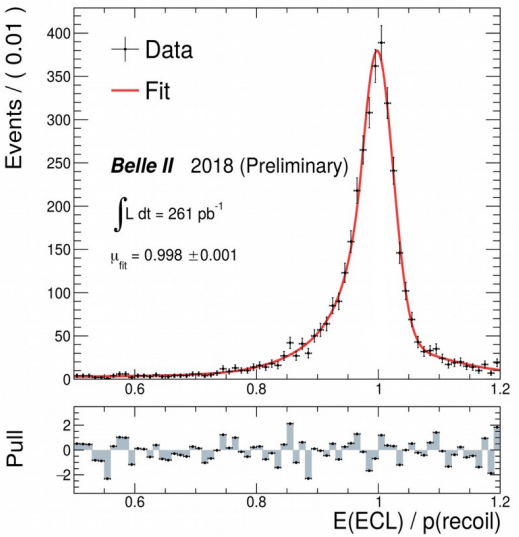
- began on March 25th, 2019
- 6.5 fb^{-1} collected
- goal: 50 ab^{-1} with the full detector (x50 data set than its predecessor)

Highlights from Phase 2

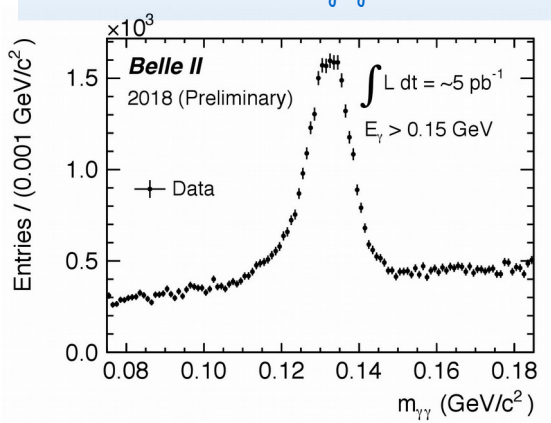
▲ Photon reconstruction performance

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





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

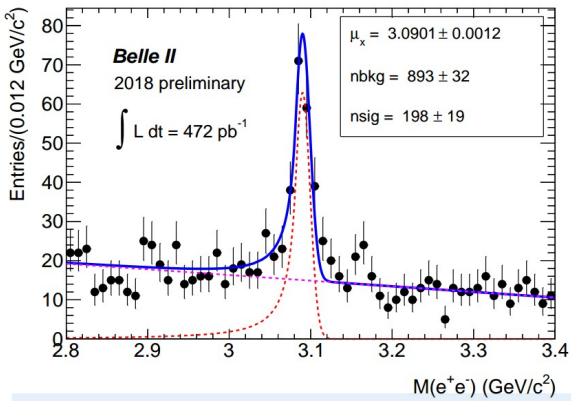


Good condition for dark searches:

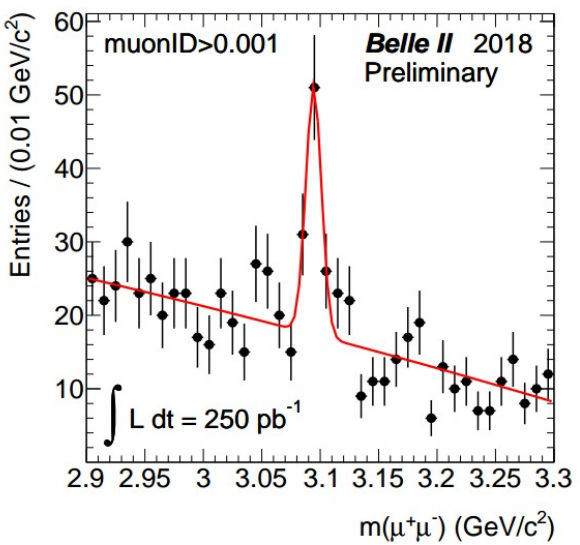
- $e^+e^- \to \gamma X$
- $e^+e^- \to ALP\gamma \to \gamma(\gamma\gamma)$
- ...

▲ Tracking performance

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



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



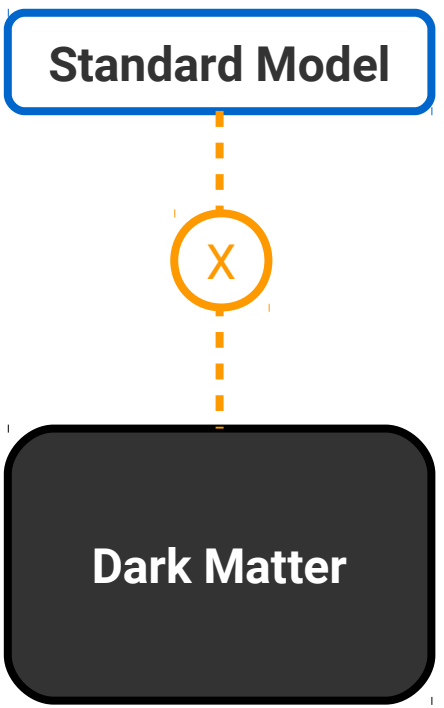
Dark Sector Physics

- Many astrophysical observations provide evidence for the existence of some kind of matter that interacts mostly gravitationally with the Standard Model (SM) particles: **Dark Matter.**

- Possible GeV and sub-GeV theoretical scenarios: Light-DM weakly coupled with SM through a light Dark Sector mediator X

- Different possible portals between Dark Matter and SM depending on the mediator X:

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



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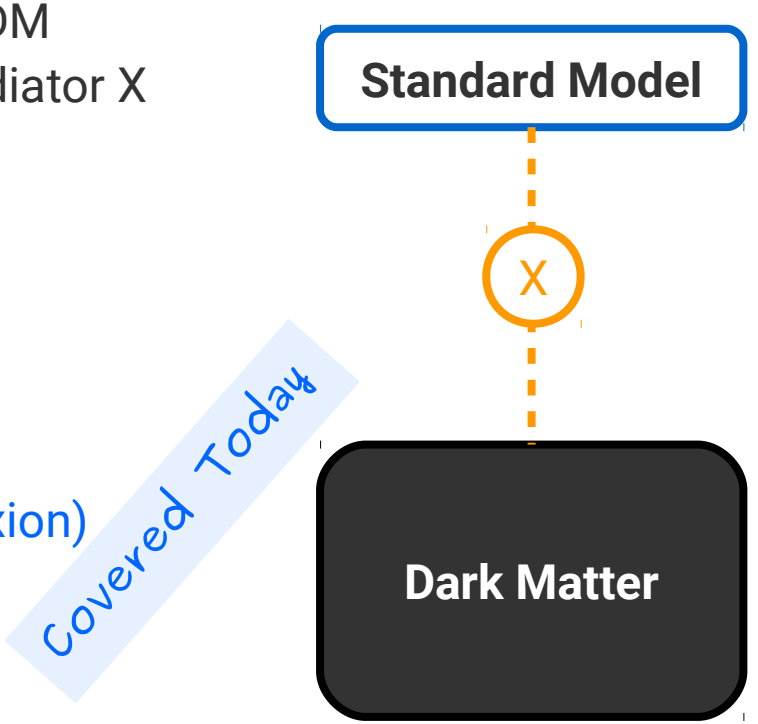


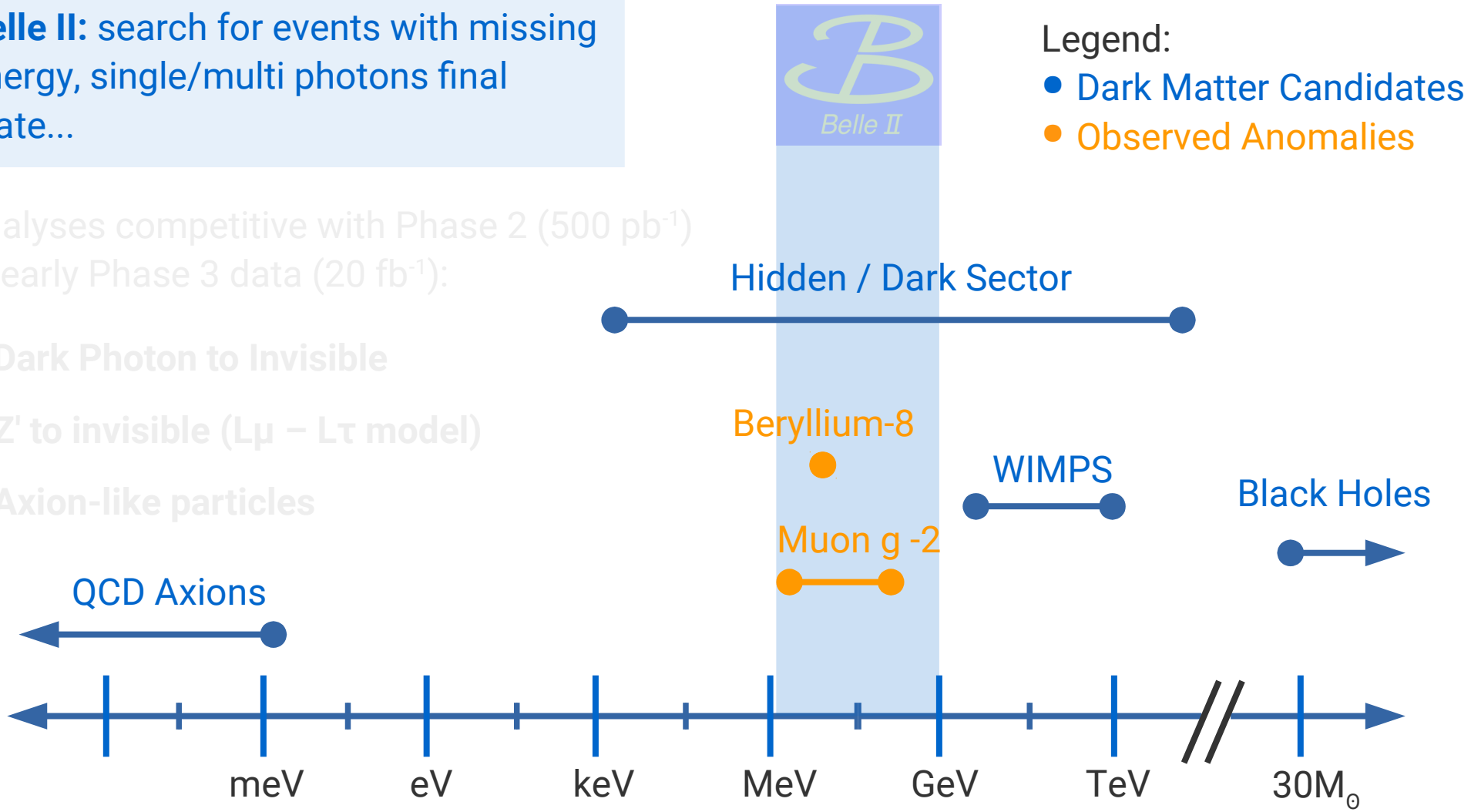
Search for Dark Matter

Ref. arXiv:1707.04591

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

Analyses competitive with Phase 2 (500 pb^{-1}) or early Phase 3 data (20 fb^{-1}):

- Dark Photon to Invisible
- Z' to invisible (Lμ – Lτ model)
- Axion-like particles



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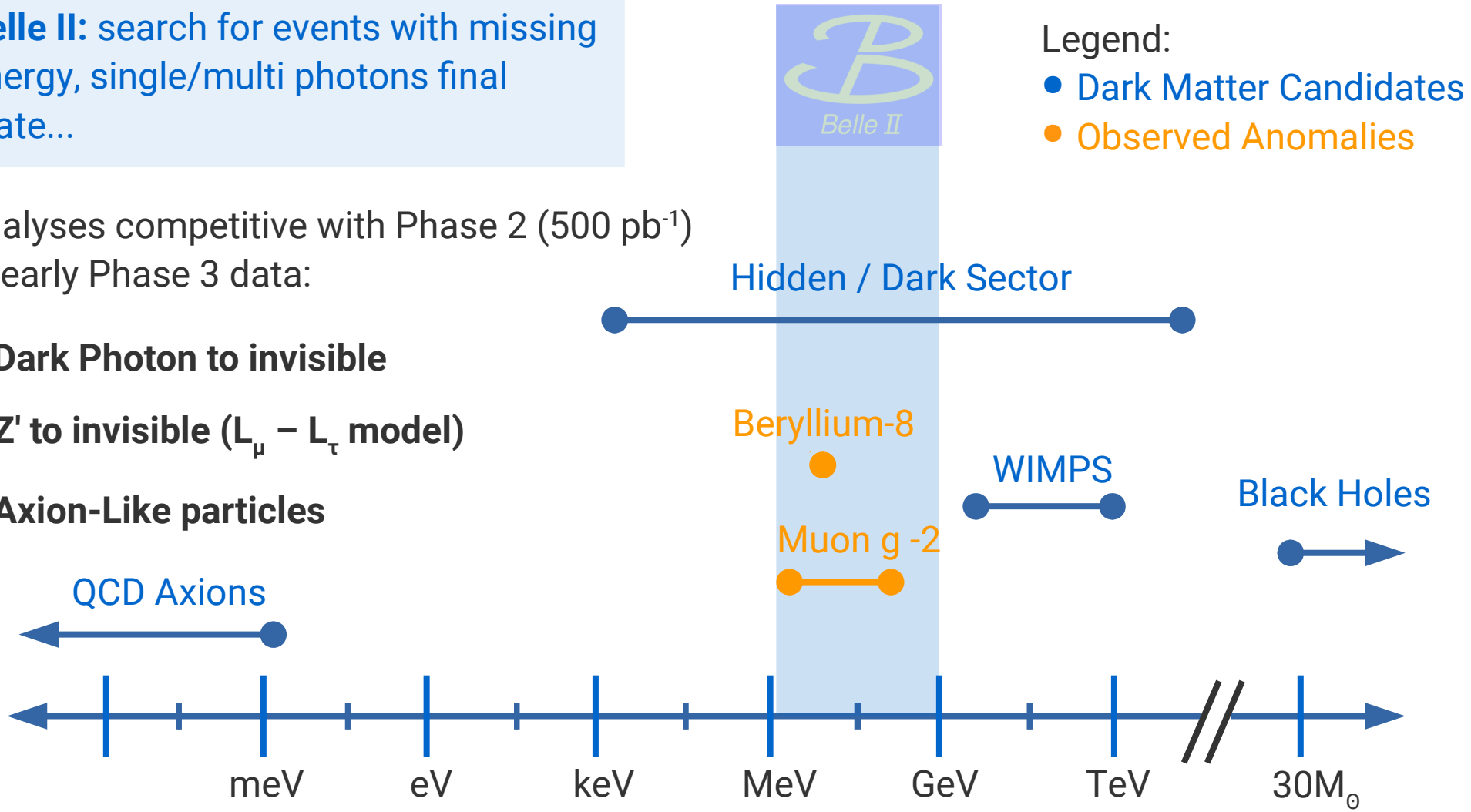
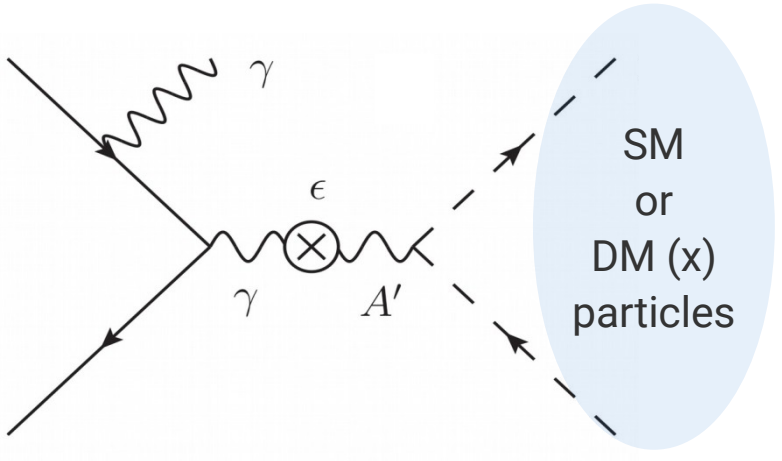


Dark photons *A′*

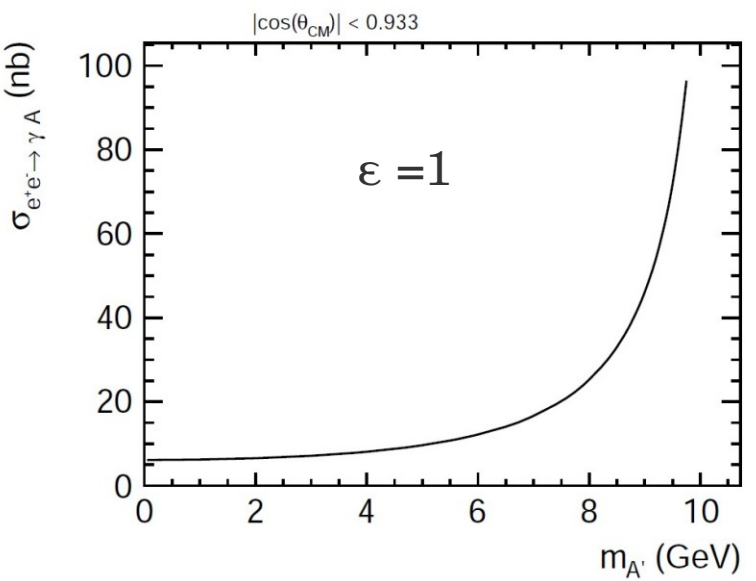
- Extension of the SM: → additional U(1)' symmetry
- Massive dark photon that mixes with the photon with strenght ε

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

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



Production cross section



Madgraph simulation based on arXiv: 1008.0636

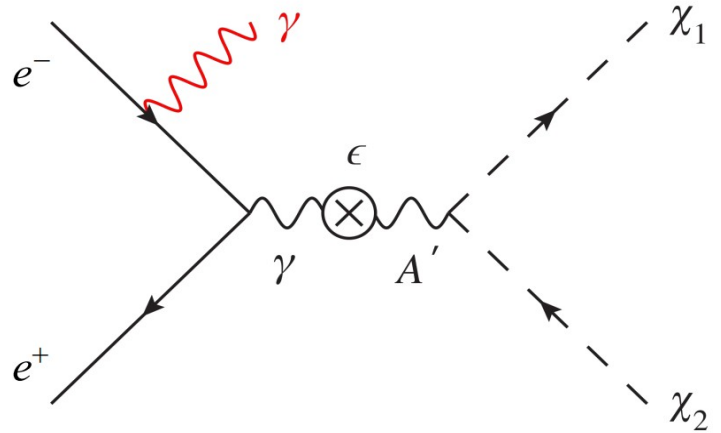
References:
P. Fayet, Phys. Lett. B 95, 285 (1980),
P. Fayet Nucl. Phys. B 187, 184 (1981)
B. Holdom, Phys. Lett. B 166, 196 (1986)

Invisible dark photon searching strategy

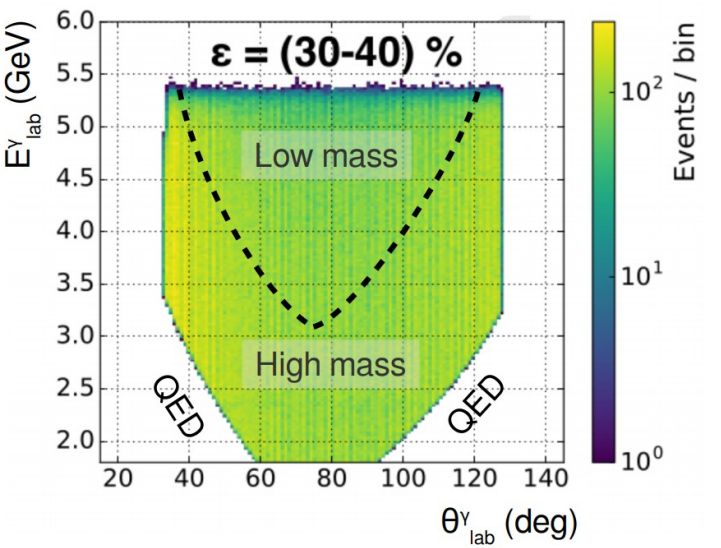
- Signal signature:
  - Single high-energetic ISR photon final state
  - Needs a single photon trigger (not available in Belle, ≈ 10% of data in BaBar)
  - Look for a bump in the variable:

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

- Selection criteria → E_γ^{LAB} vs θ_γ^{LAB}

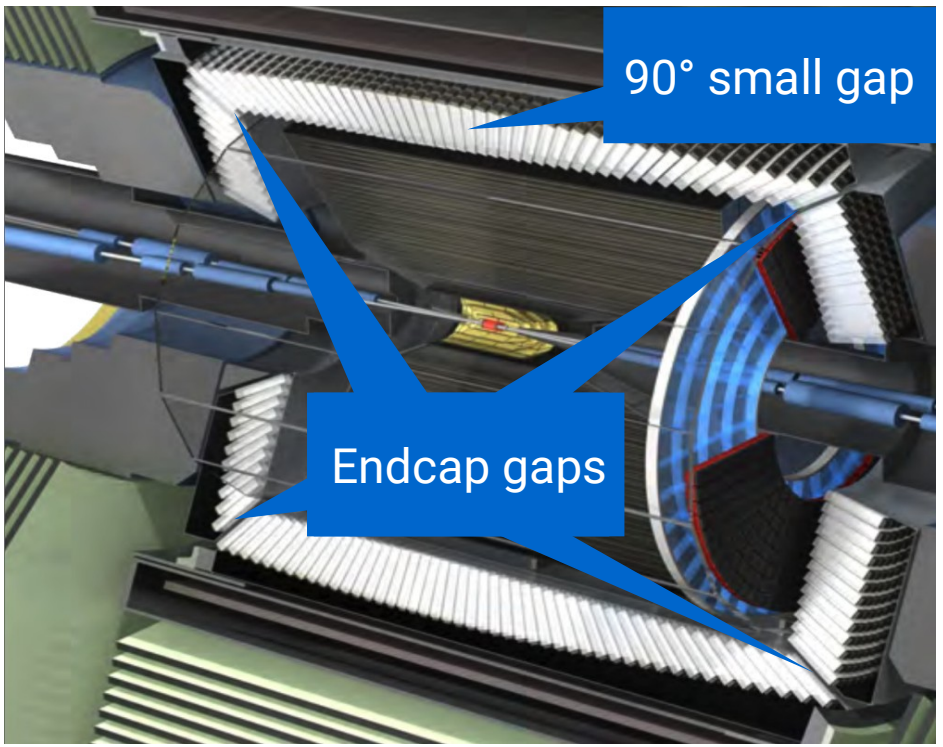


Simulated signal efficiency

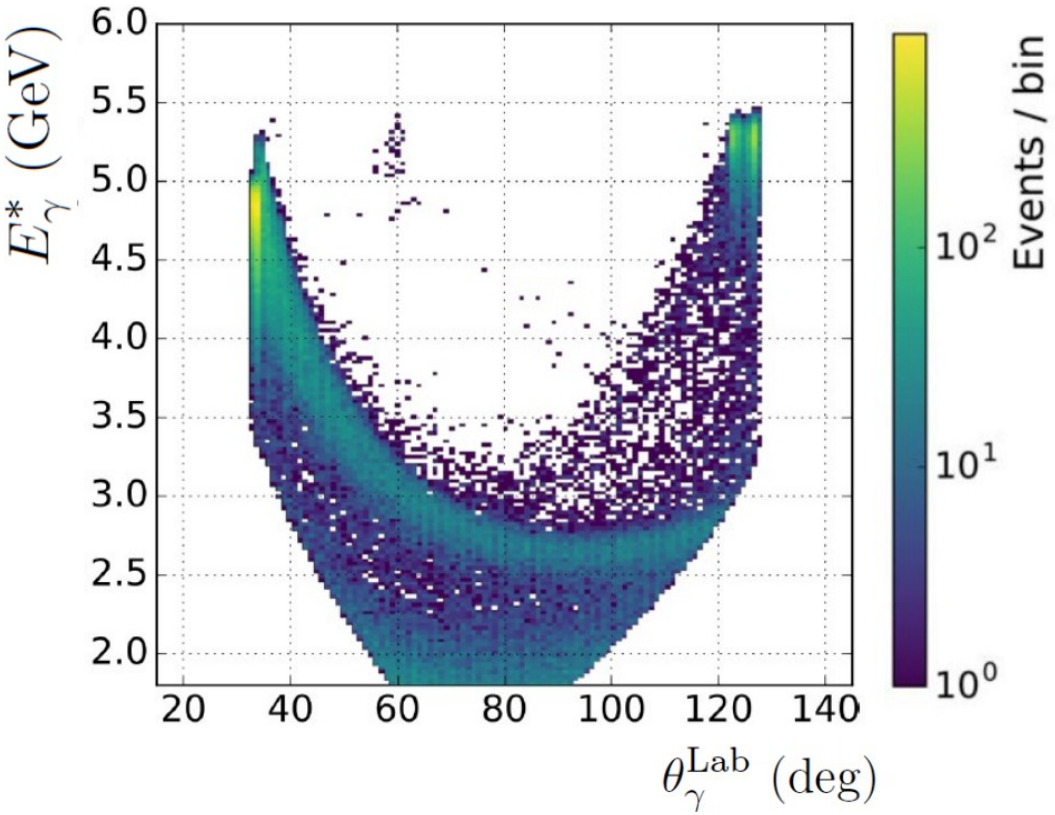


Invisible dark photon backgrounds

Sources of ECL inefficiency



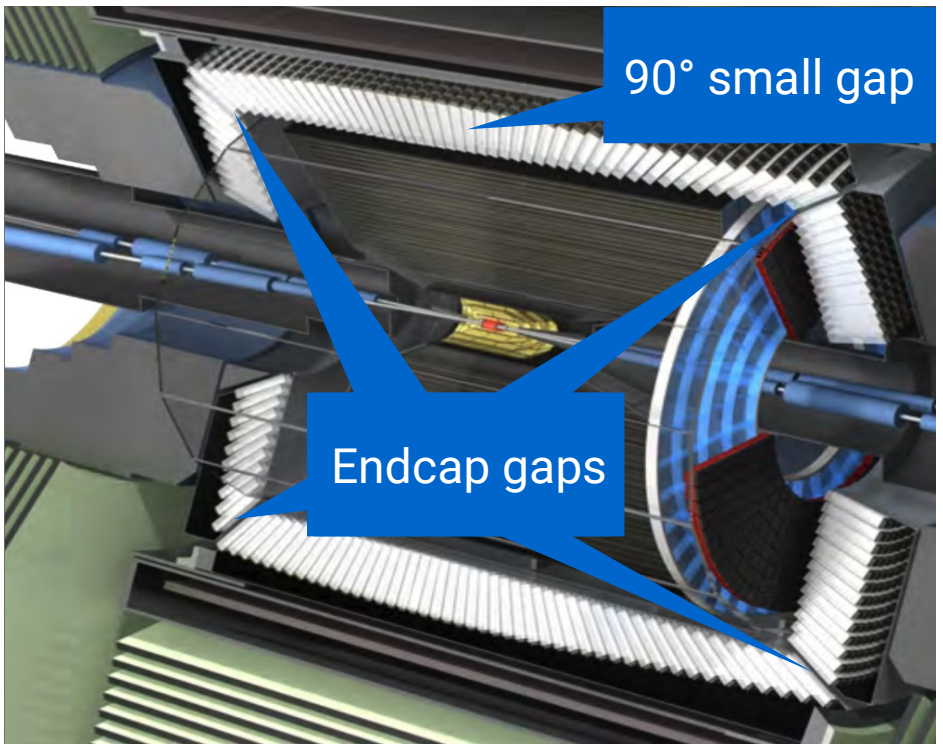
Simulated background rates



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

Invisible dark photon backgrounds

Sources of ECL inefficiency



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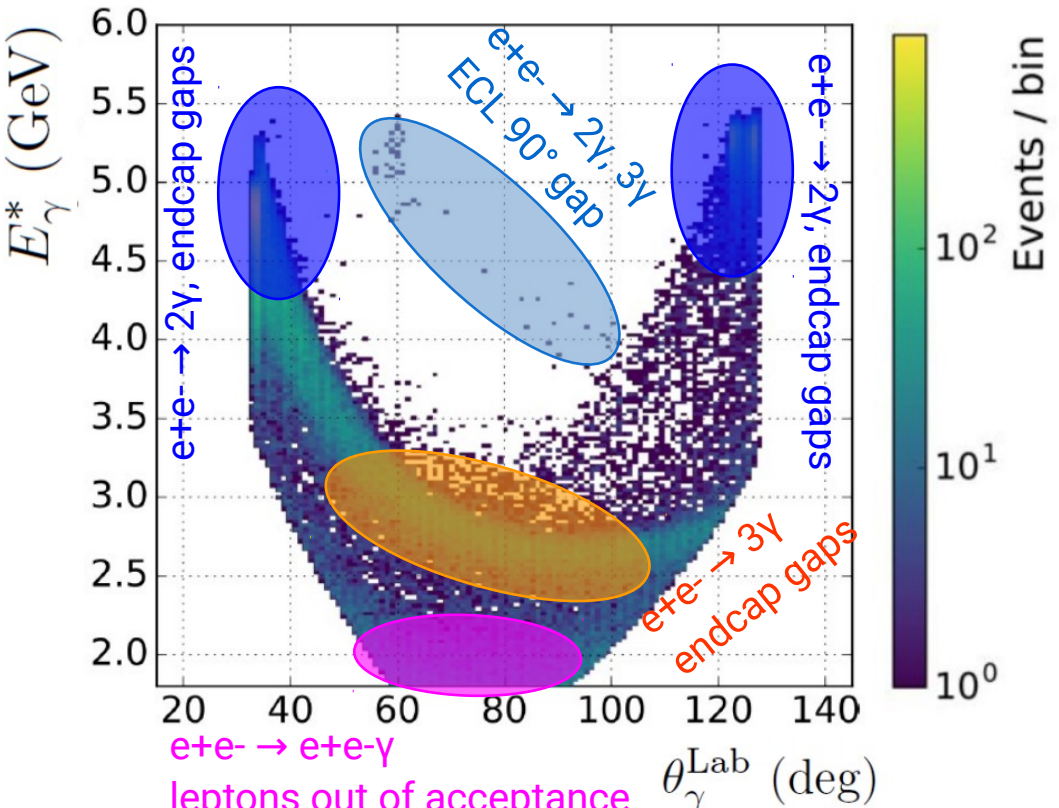
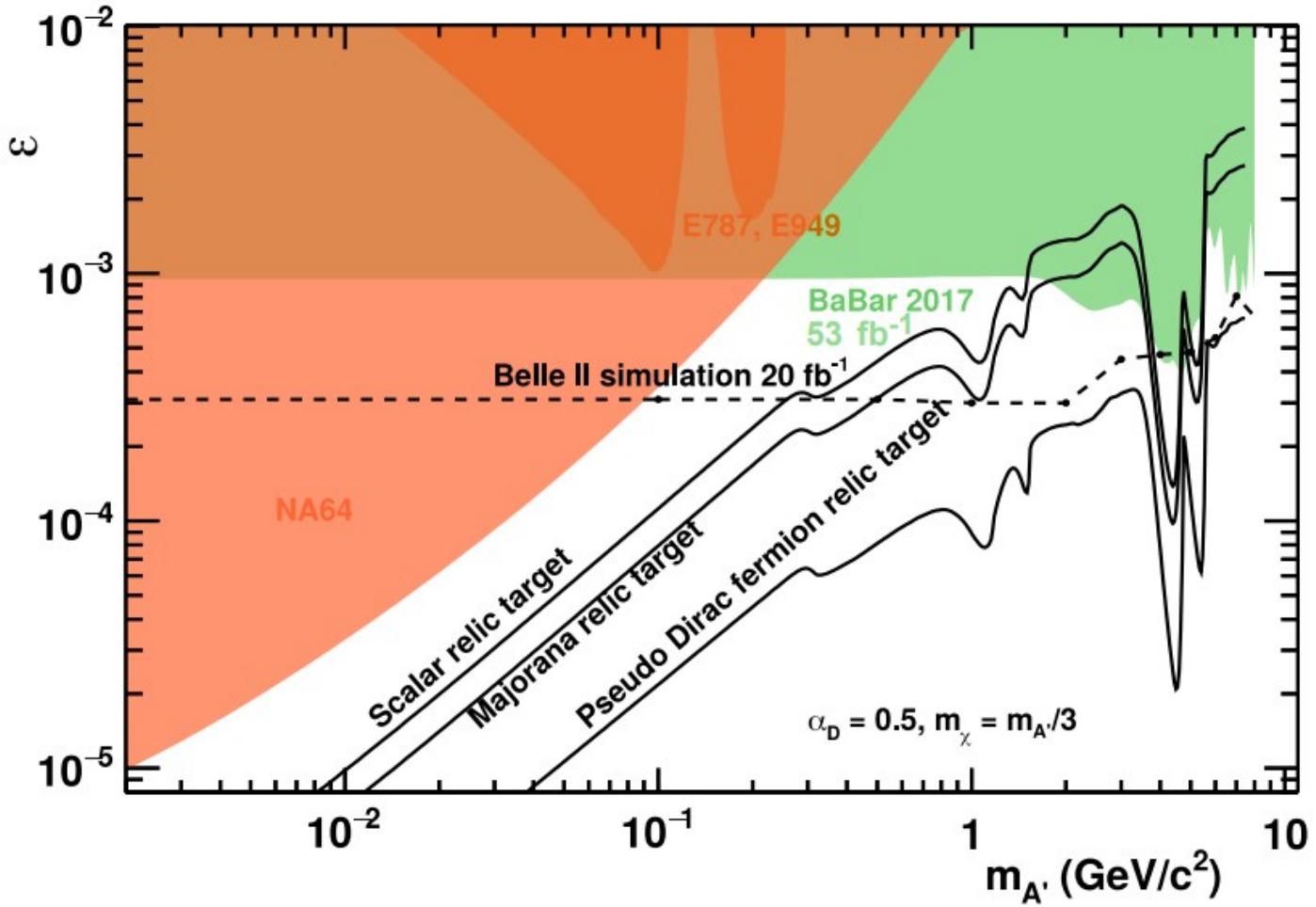


- Main Backgrounds events:
  - $e^+e^- \to e^+e^-\gamma$
  - $e^+e^- \to \gamma\gamma(\gamma)$

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

Projected upper limits on ε, invisible dark photon

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



BaBar 2017, 53 fb^{-1}
arXiv:1702.03327

Belle II projection at 20 fb^{-1}
arXiv:1808.10567

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

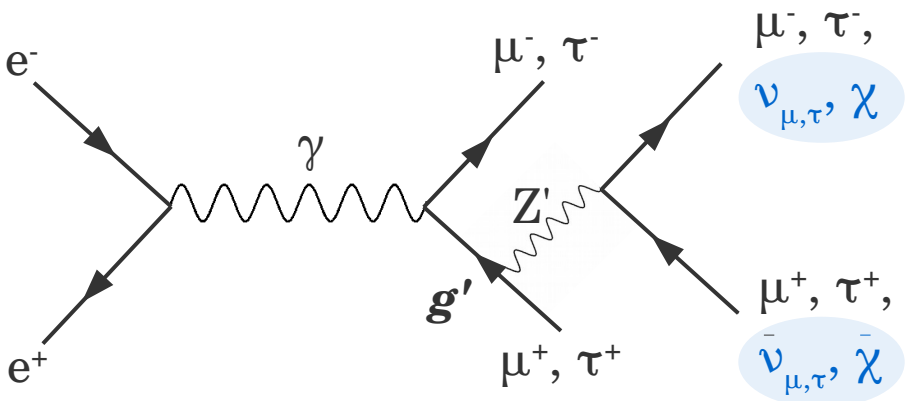
Z' to invisible: theory

Shuve et al. (2014), arXiv:1403.2727
Altmannshofer et al. (2017) arXiv:1609.04026

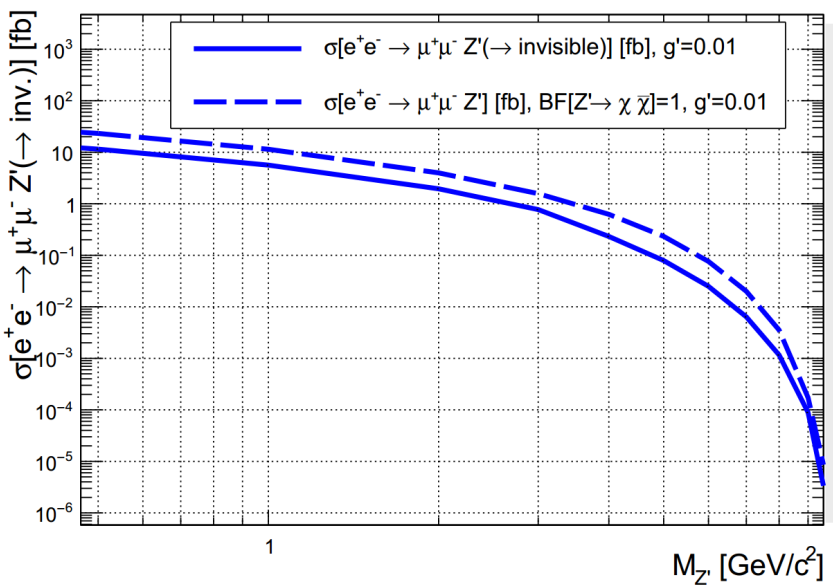
- Extension of the SM: additional $U(1)_{L\mu - L\tau}$ symmetry

$$\mathcal{L} = \sum_{\ell} \theta g' \bar{\ell} \gamma^{\mu} Z'_{\mu} \ell$$

- Introduces a light vector boson *Z'* with coupling *g'* only with the 2nd and 3rd generation of leptons
- If kinematically accessible, Z' could decay to DM
- May explain: $(g-2)_{\mu}$, abundance of DM in the Universe
- Invisible decay channel to be explored for the first time: $e^+e^- \rightarrow \mu^+\mu^-$ + *missing energy*



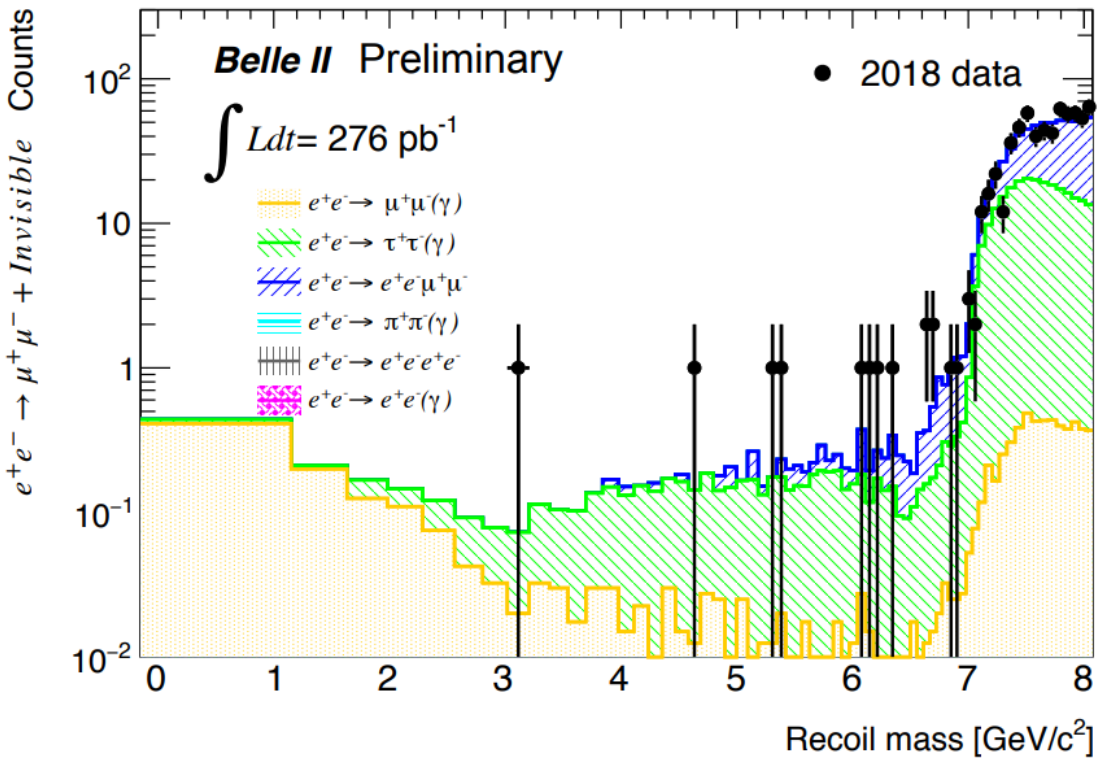
Production cross section



Z' to invisible search

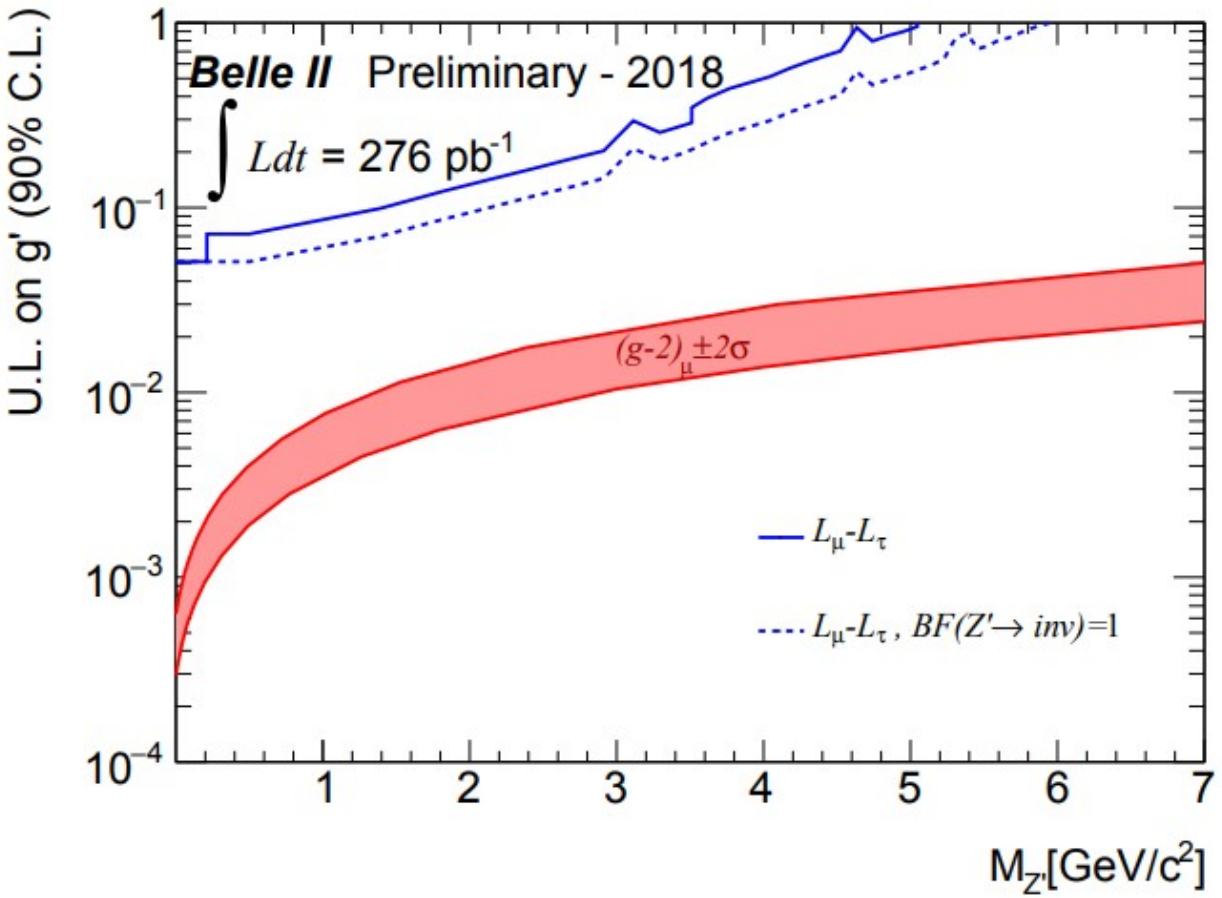
- Signal signature:
  - look for bumps in the recoil mass against a $\mu^+\mu^-$ pair
  - nothing in the rest of event
- Main background events from QED processes:
  - $e^+e^- \to \mu^+\mu^- (\gamma)$
  - $e^+e^- \to \tau^+\tau^- (\gamma)$, $(\tau \to \mu\nu\nu)$
  - $e^+e^- \to e^+e^-\mu^+\mu^-$
- Only 276 pb^{-1} used due to trigger conditions for two tracks events

Recoil Mass distribution



*No sensitivity to the parameter space region for $M_{Z'} > 8$ GeV/c^2

g' upper limits



- First result ever for the *Z'* to invisible decay

List of systematic uncertainties:

Tracking 4%

Trigger 5%

LeptonID 4%

Luminosity 1.5%

Analysis selections (background) 22%

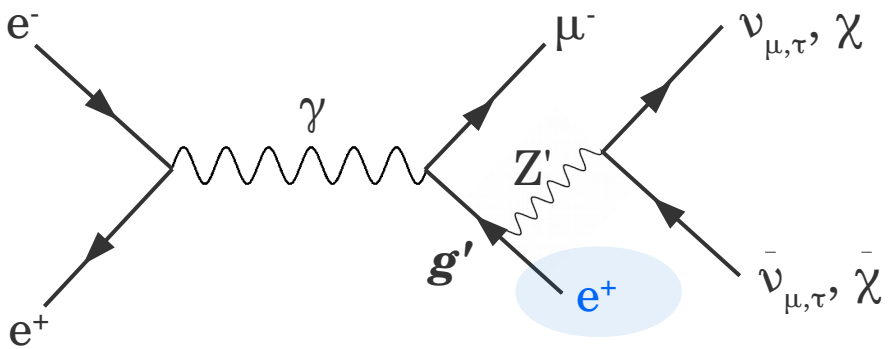
muon yields (signal) 12.5%

muon yields (background) 2%

- Contribution will decrease with the new data

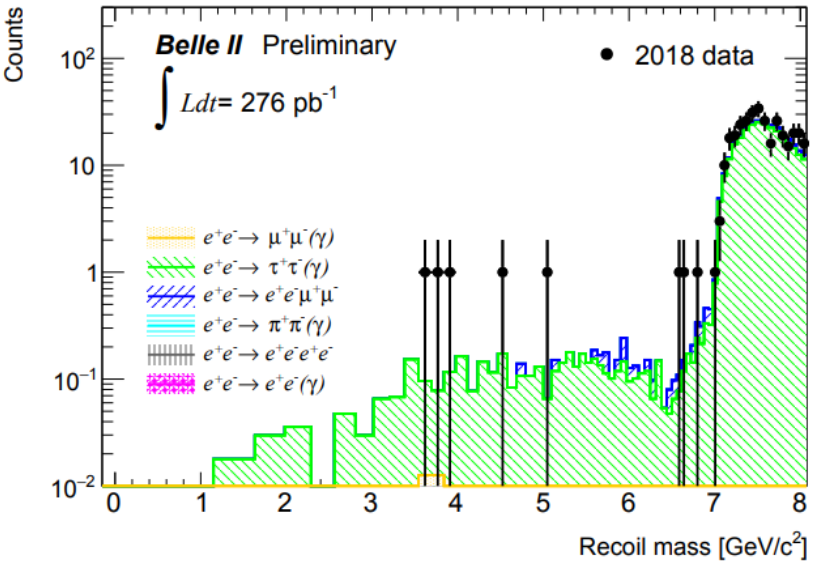
*If Dark Matter is kinematically accessible, it can be assumed BR(*Z'* → *inv.*) = 1

Lepton Flavor Violating Z'

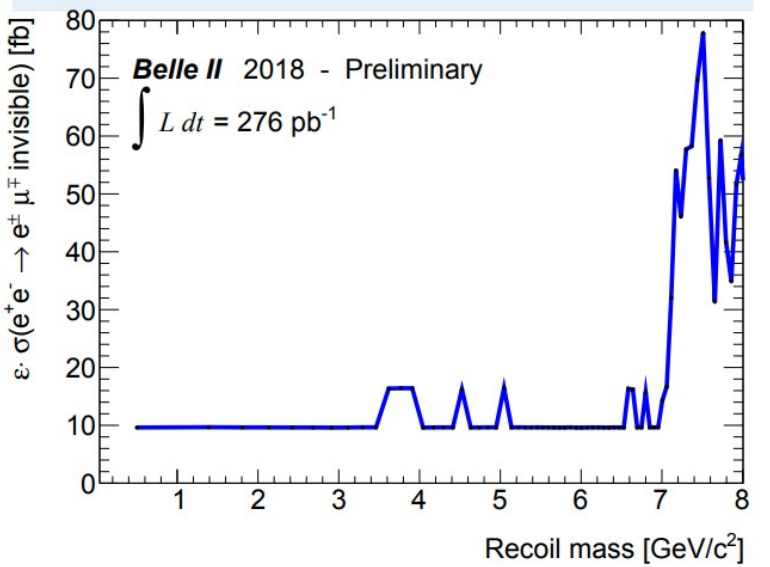


I. Galon et al.: arXiv:1610.08060, arXiv:1701.08767

- Searching for a lepton flavor violating Z' that couples to eμ: $e^+e^- \to e^+\mu^- Z'$ ($Z' \to$ *inv.*)
- Expected low background from SM processes
- No working model to test → Model independent approach
- Same selection criteria from flavor-conserving Z' to invisible search used



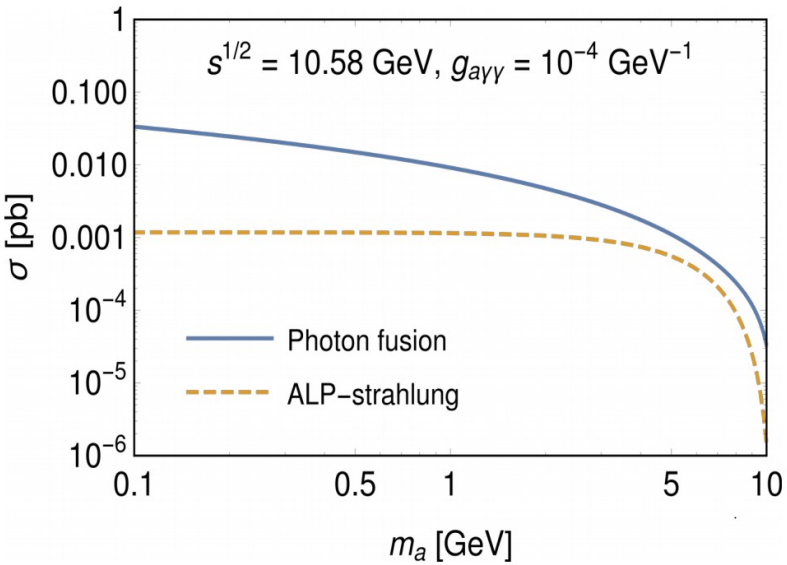
ε·σ upper limits



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



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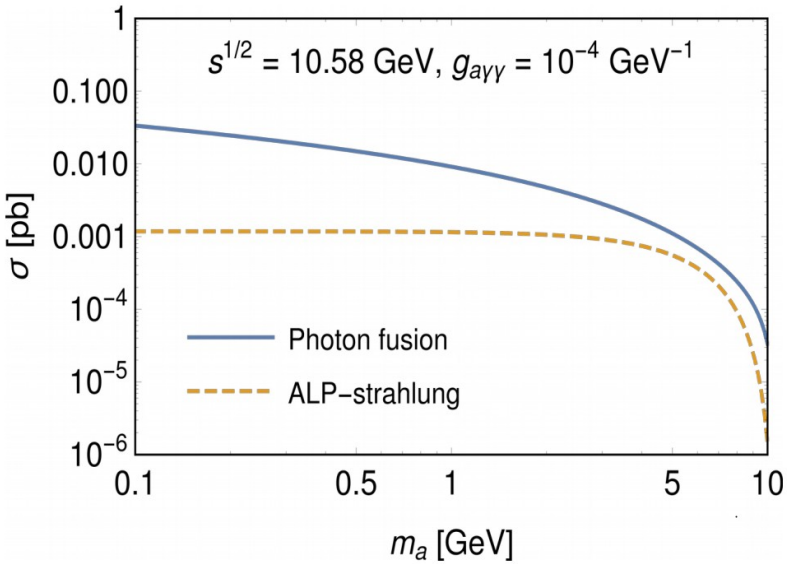
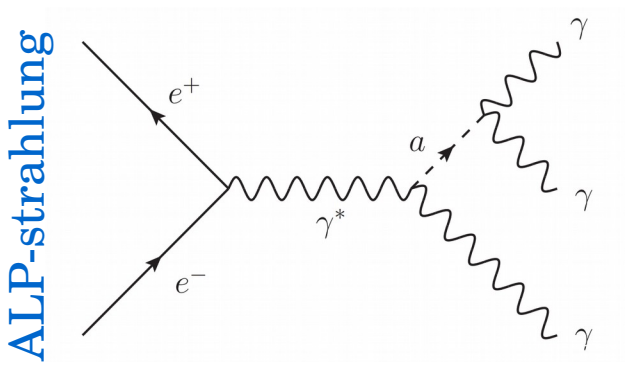
JHEP 1712 (2017) 094 arXiv:1709.00009

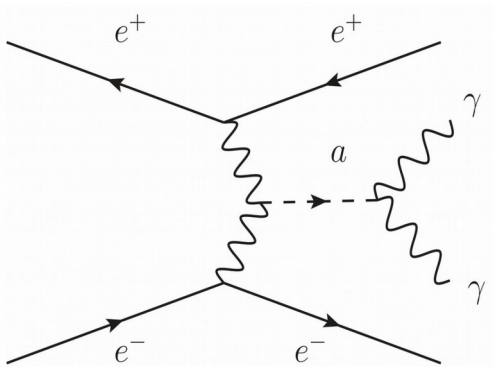


Sensitivity under study

ALP-strahlung



Photon-fusion



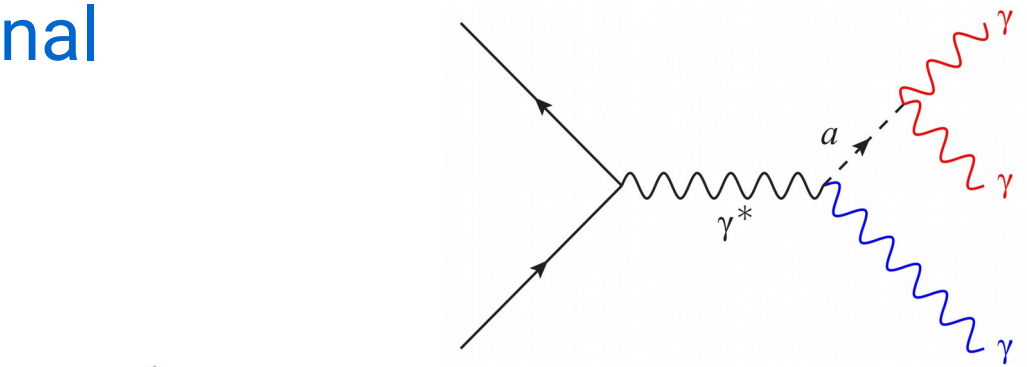
Axion-like particles: signal

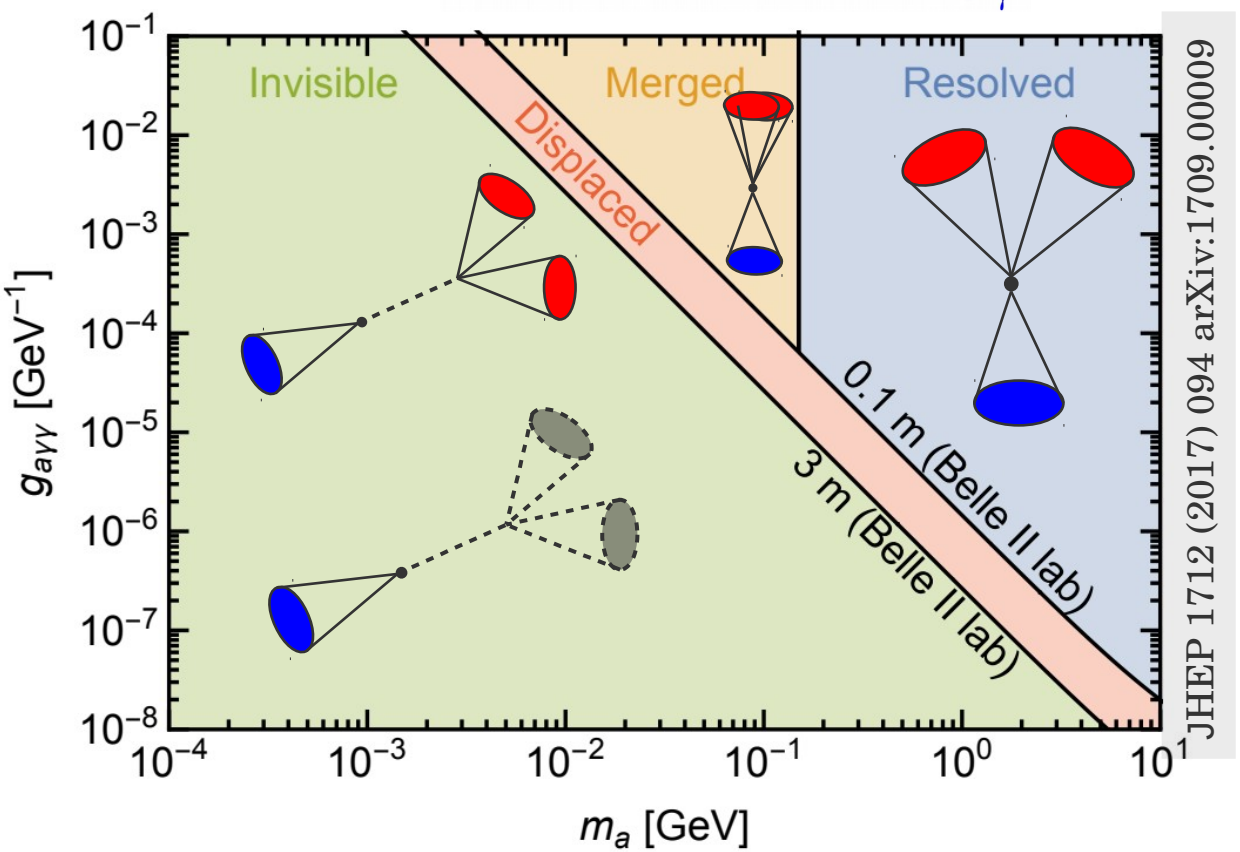
Parameters (m_a, $g_{a\gamma\gamma}$) determine the displacement and the θ angle between the 2γ

- ALP lifetime: $\tau \sim 1/m_a^2 g_{a\gamma\gamma}^2$

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 (indistinguishable from $e^+e^- \to \gamma\gamma$)

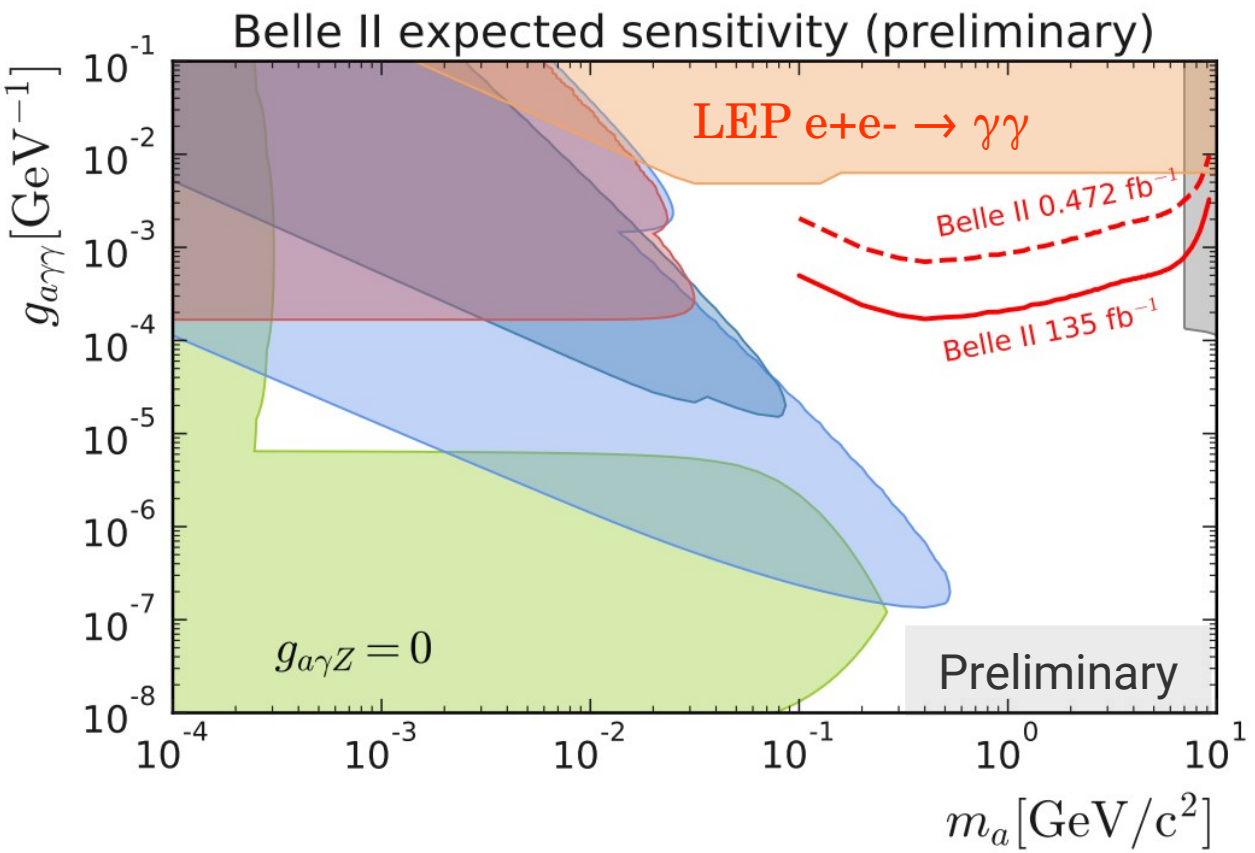




JHEP 1712 (2017) 094 arXiv:1709.00009

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 assumed to be negligible



Conclusions

- The Belle II experiment, designed mainly for B-physics, has a broad and active program to explore the Dark Sector physics
- 2018: successful SuperKEKB commissioning and collected ~0.5 fb^{-1} of data → b and charm physics rediscoveries, but also search for Dark Sector
- 2019: phase 3 started this year on March 25th → up to now 6.5 fb^{-1} collected
- Many searches are ongoing, A', Z', ALPs, and there will be the possibility to explore many more Dark Sector models
  - ***A'* → *inv.***, expected sensitivity: $\varepsilon \sim 2 \cdot 10^{-4}$ with L_{int} = 20 fb^{-1}, better than the current limits set by BaBar
  - ***Z'* → *inv.***, expected sensitivity: $g' \sim 10^{-2} - 10^{-1}$ with Phase 2 data; with Phase 3: possibility to exclude the parameter region that explain $(g-2)_\mu$
  - **ALPs, *a* → $\gamma\gamma$**, expected sensitivity: $g_{a\gamma\gamma} \sim 10^{-3} - 10^{-2}$ with Phase 2 data, better than current limits

Thank you

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~
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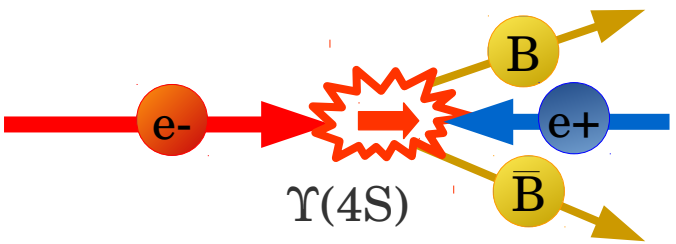
B-Factories

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...)

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

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



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

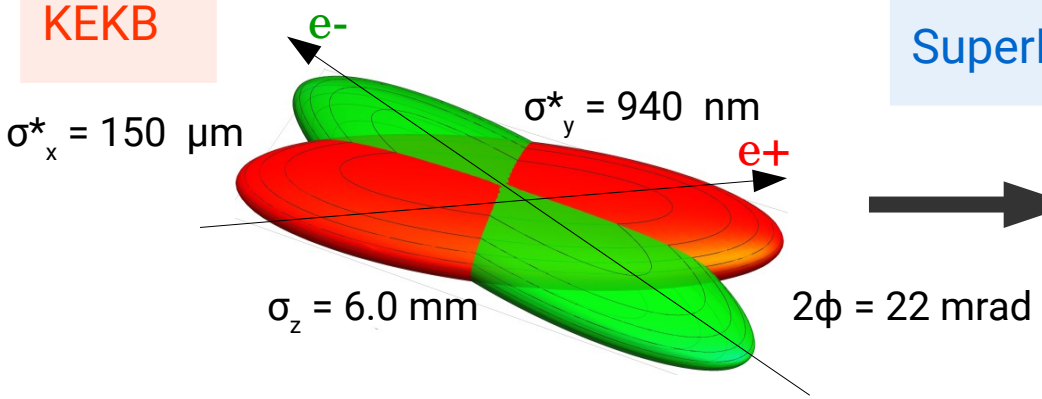
$$\mathcal{L} = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\frac{R_L}{R_{\xi_y}}$$

geometrical reduction parameter ~0.8-1

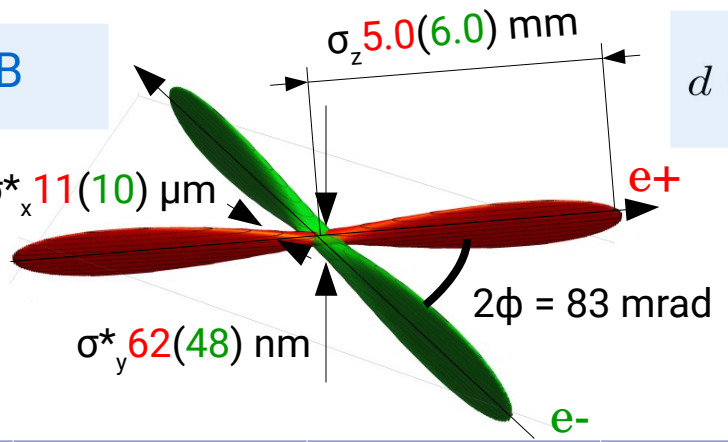
Ratio between the y and x dimension of the beam 0.01 – 0.02

vertical beta function at IP

KEKB



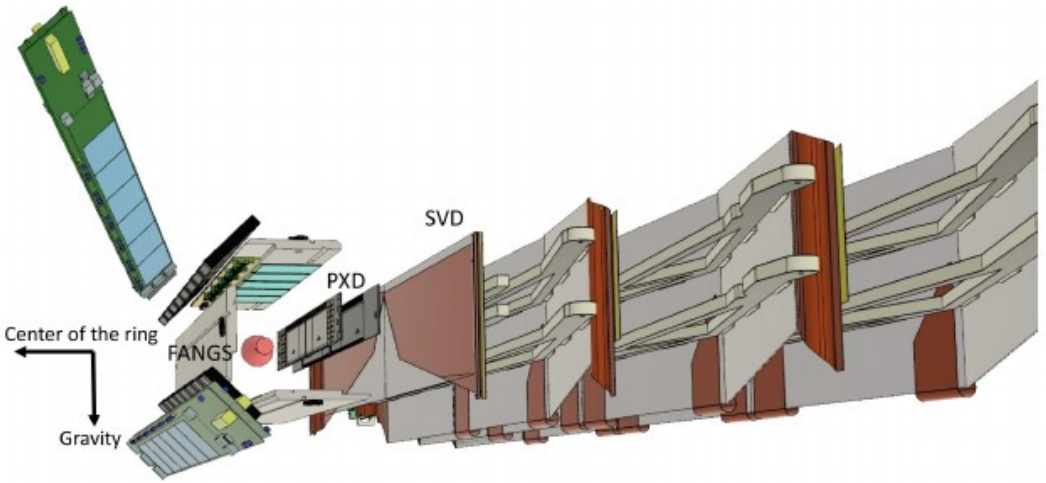
SuperKEKB

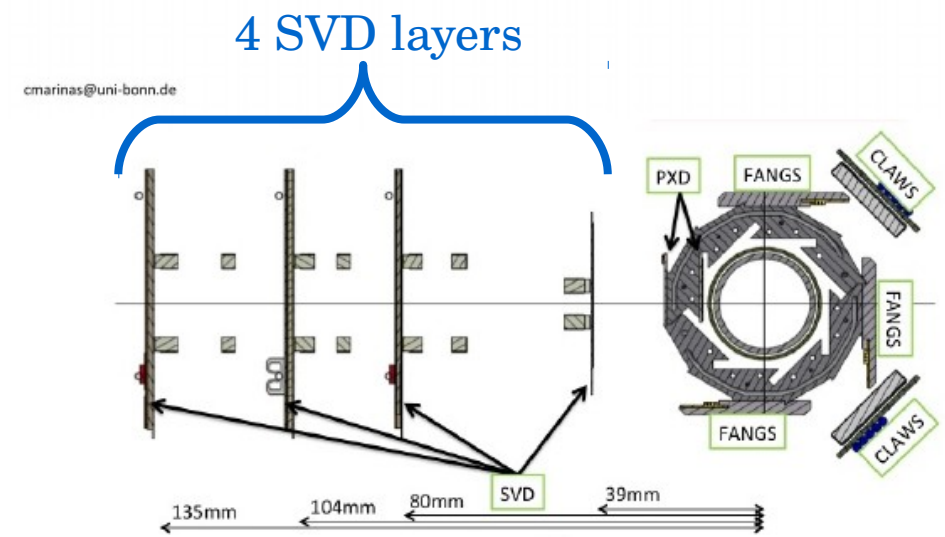


$$d \simeq \frac{\sigma_x^*}{\phi}$$

	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)





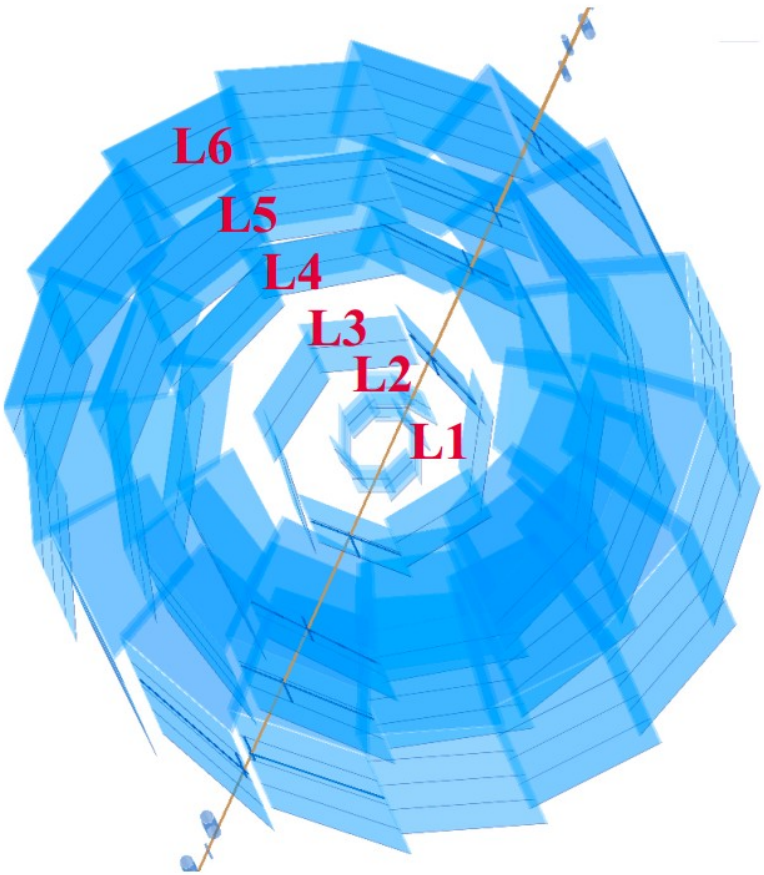
Phase 2

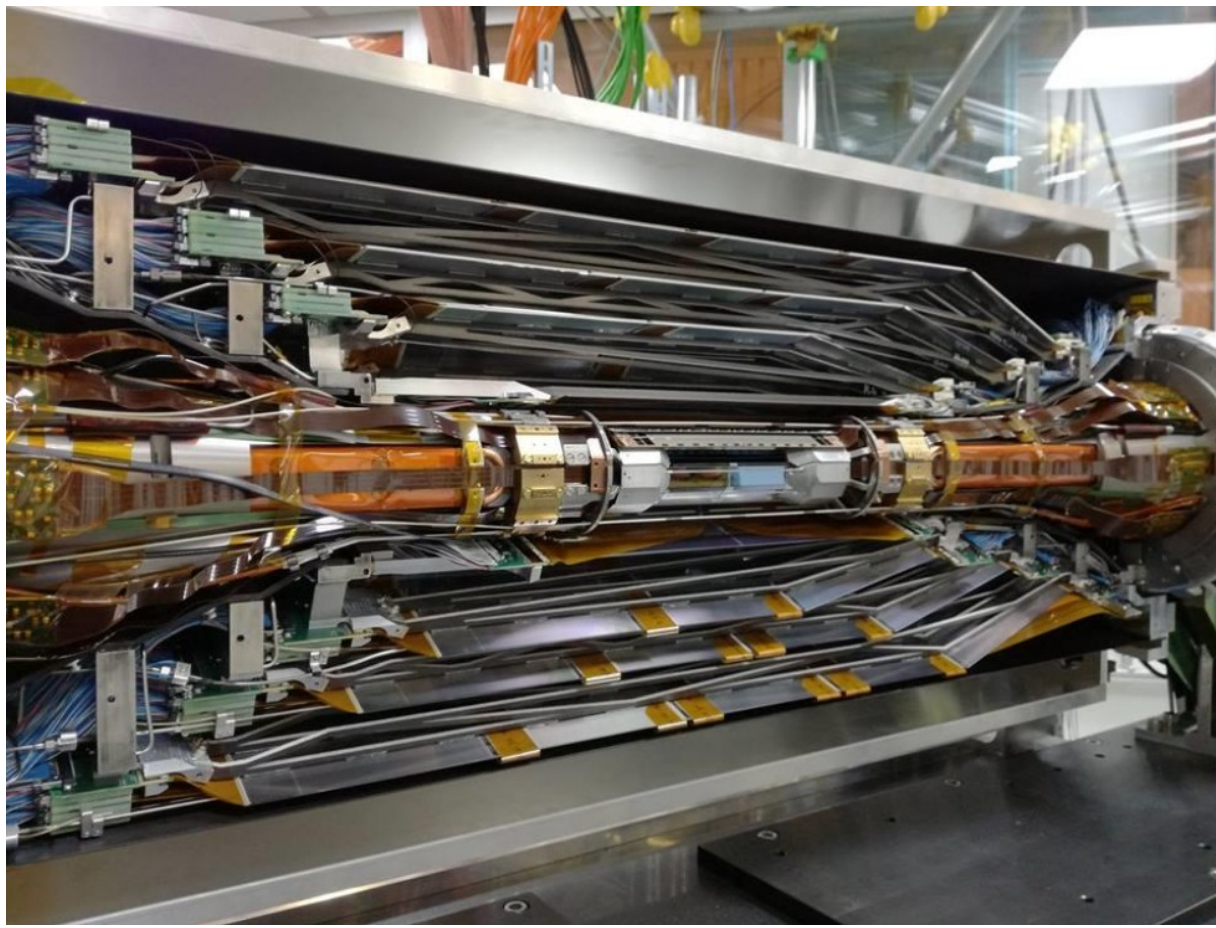
- CLAWS
- FANGS
- PLUME
- diamond sensors
  - study and monitor the beam background levels

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

- 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

Phase 3



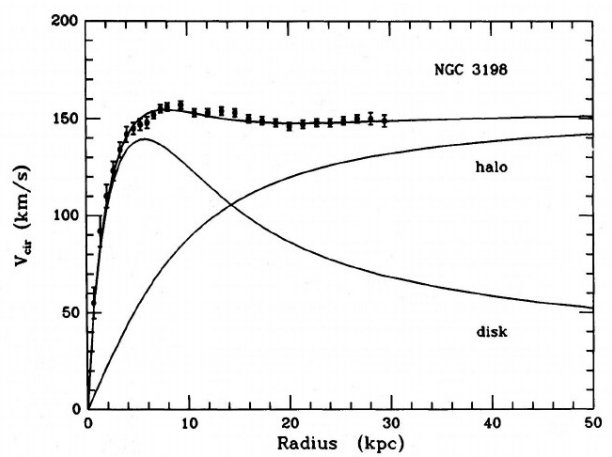


Dark Matter (DM): Introduction

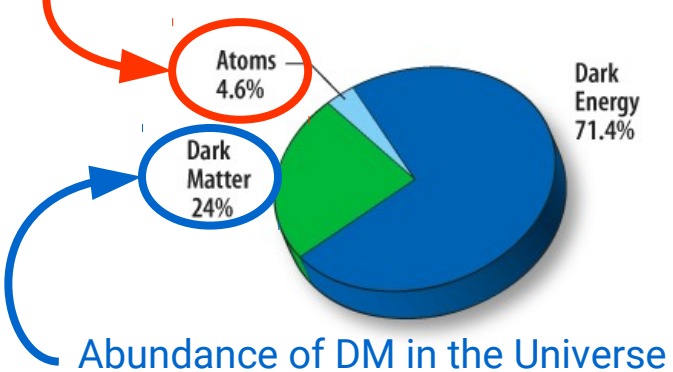
- **Massive** → gravitational interation with Standard Model (SM) matter
- **Dark** → does not interact with SM matter thorugh any other interaction
- Many astrophysical observations in agreement with DM existance: flat galaxy rotation curves, gravitational lensing, galaxy velocity dispersion…

Flat galaxy rotation curves

(first experimental evidence)

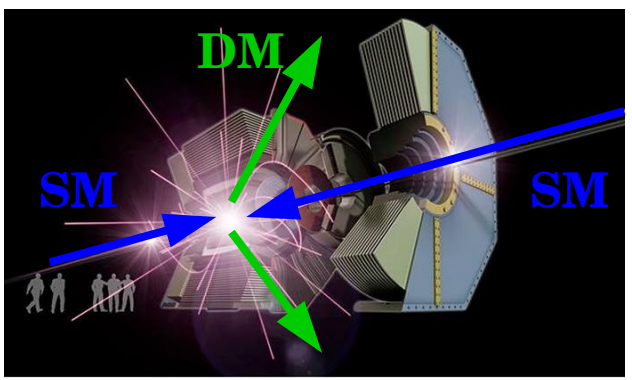


Abundance of standard matter in the Universe



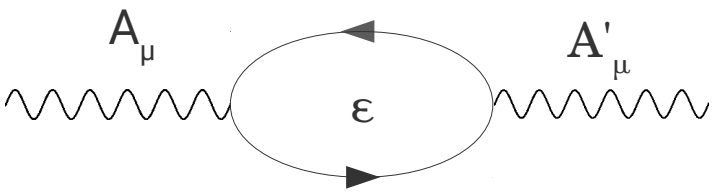
Abundance of DM in the Universe

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



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 ($\varepsilon \leq 10^{-2}$)

- 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)

Other planned dark sector and exotic searches

- Visible dark photon decays
- Off-shell dark photon decays***
- Muonic dark force: $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$ BaBar: arXiv:1606.03501 (514 fb^{-1})
- Dark sector with Lepton Flavor Violation: Z'
- Dark scalar: $e^+e^- \to \tau^+\tau^- S$, $S \to l^+l^-$
- Magnetic monopoles with small magnetic charges***
- Invisible Y(1S) decays via Y(3S) → Y(1S)$\pi^+\pi^-$ (Requires beam energies at Y(3S))
- Dark Higgs/Higgstrahlung
- ...

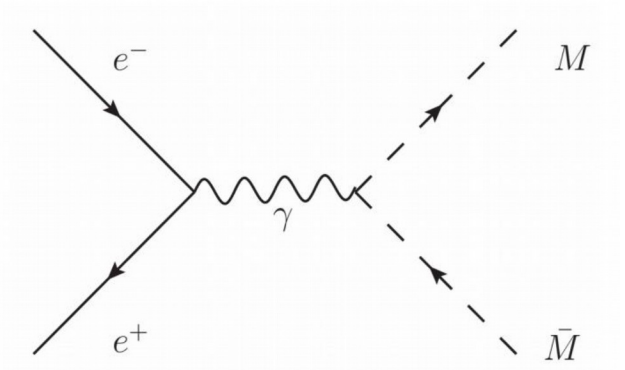
For further details:

- The Belle II Physics Book arXiv:1808.10567

***Possible with Phase 2 data

Magnetic monopoles

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



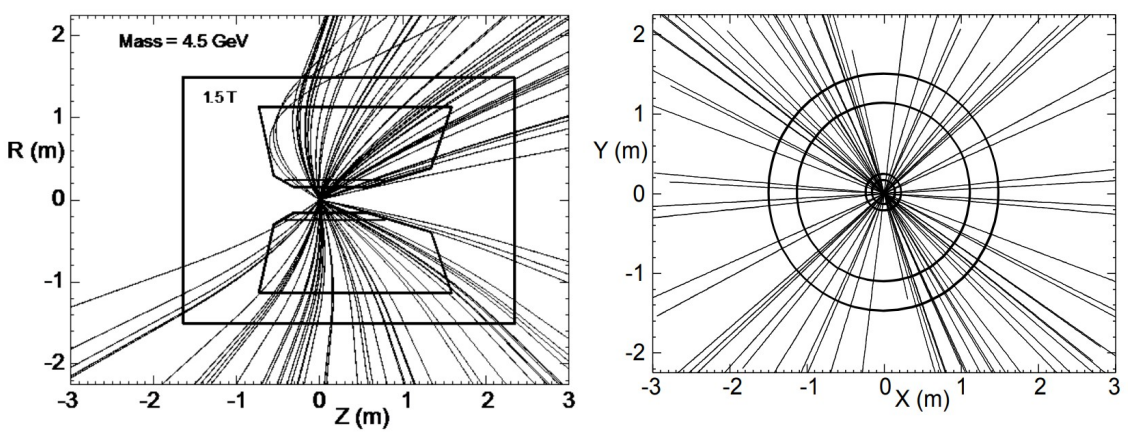
Particle carrying magnetic charge

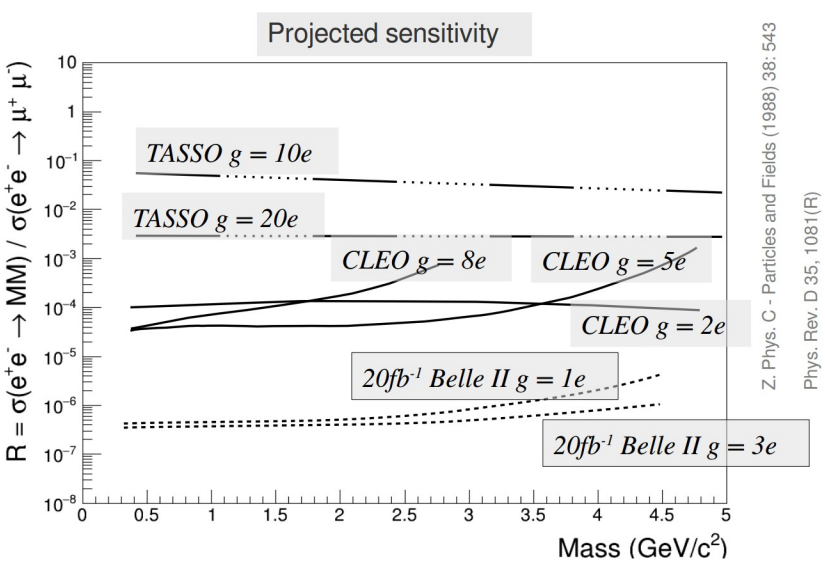
Distinct signature in drift chamber:

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

They need a dedicated tracking system

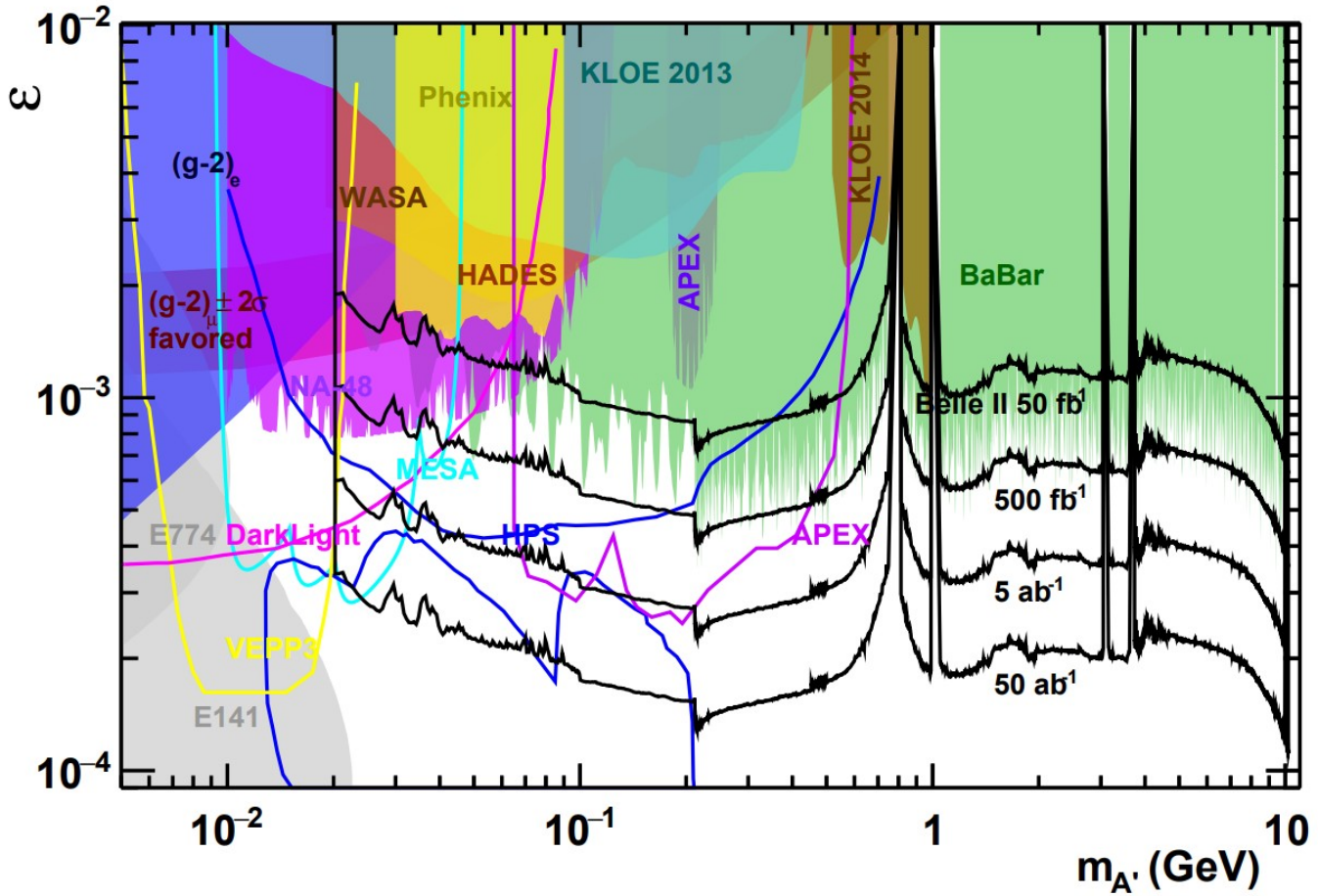
Detection efficiency is high: 40-97%, depending on magneton mass

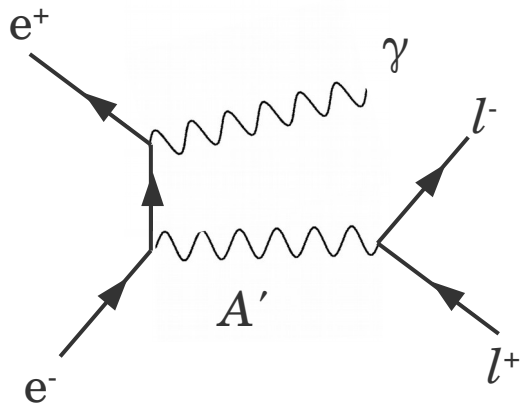




Projected upper limits on ε, visible dark photon

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

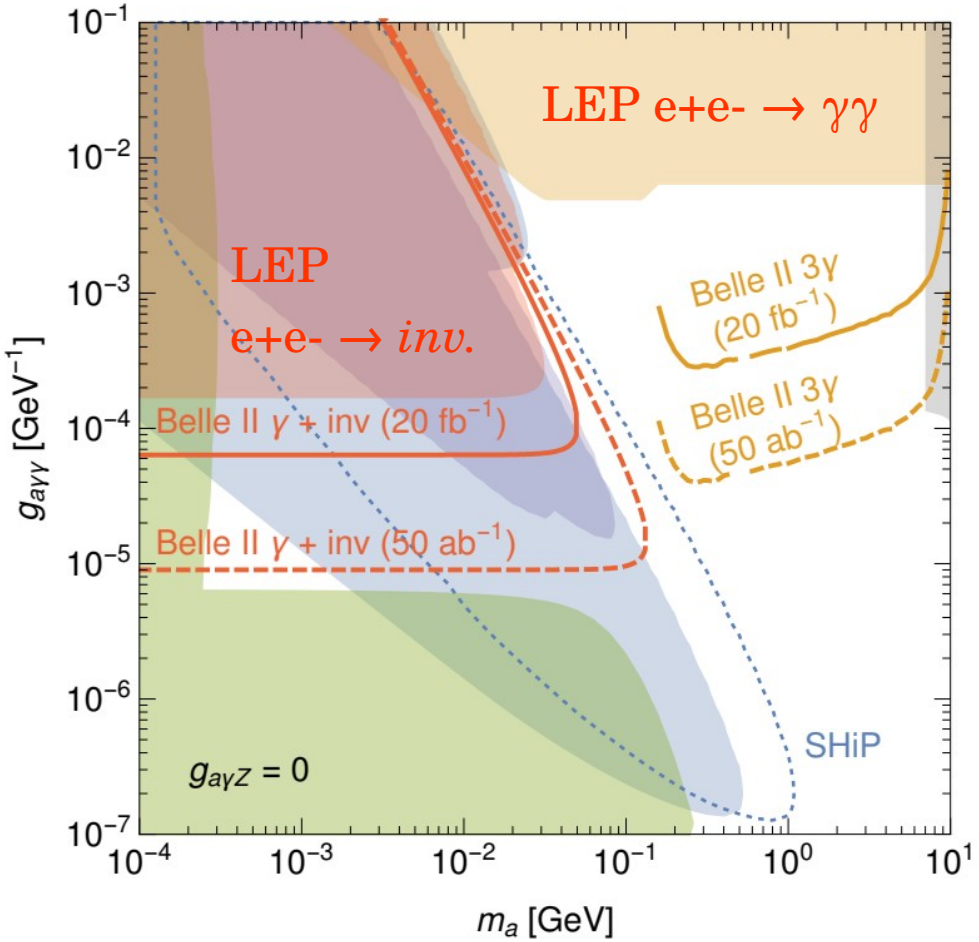




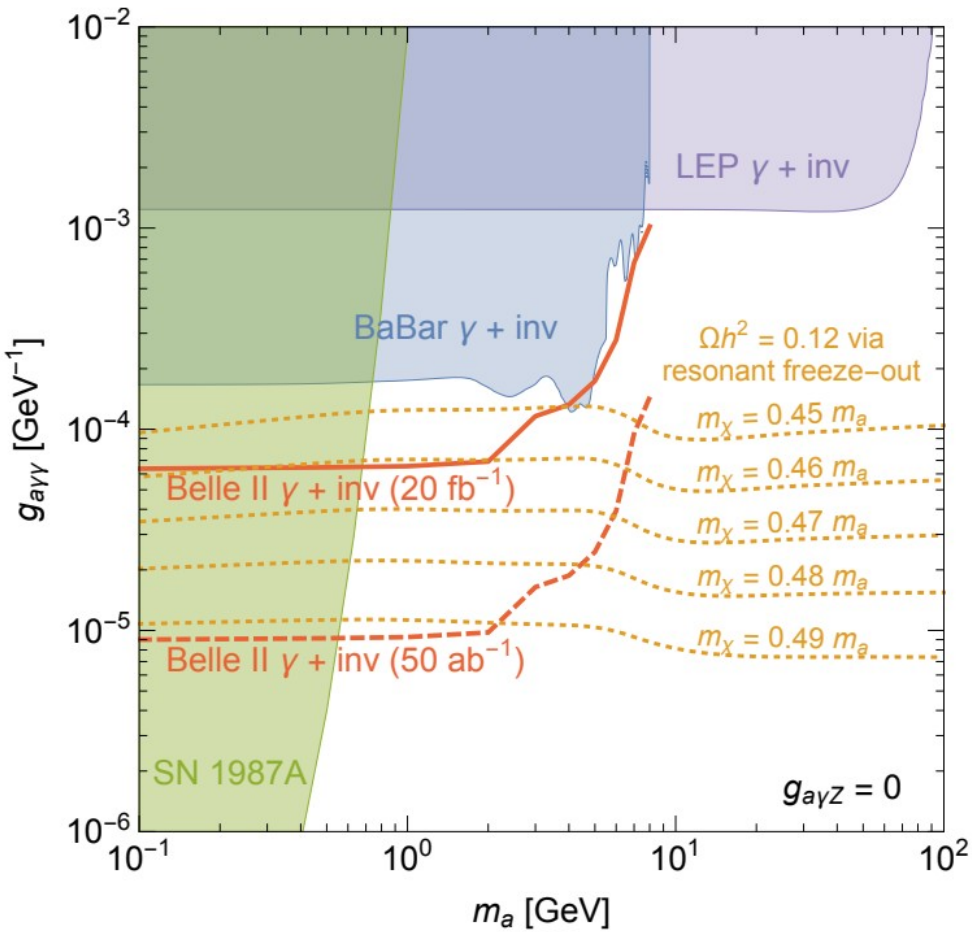
- Belle II is competitive only in Phase 3
- The Belle II Physics Book arXiv:1808.10567

ALPs expected limits

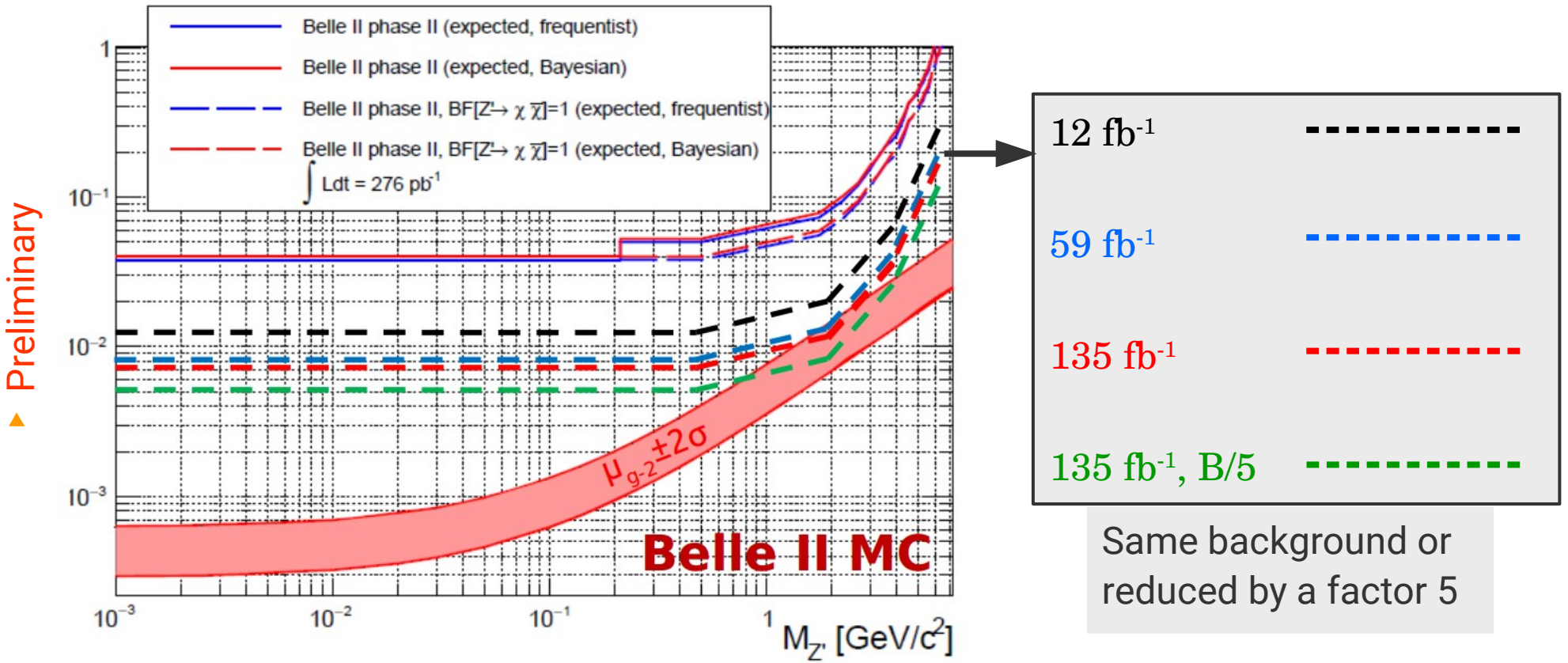
$a \to \gamma\gamma$



$a \to inv$



Projected upper limits on g' with Phase 3 data

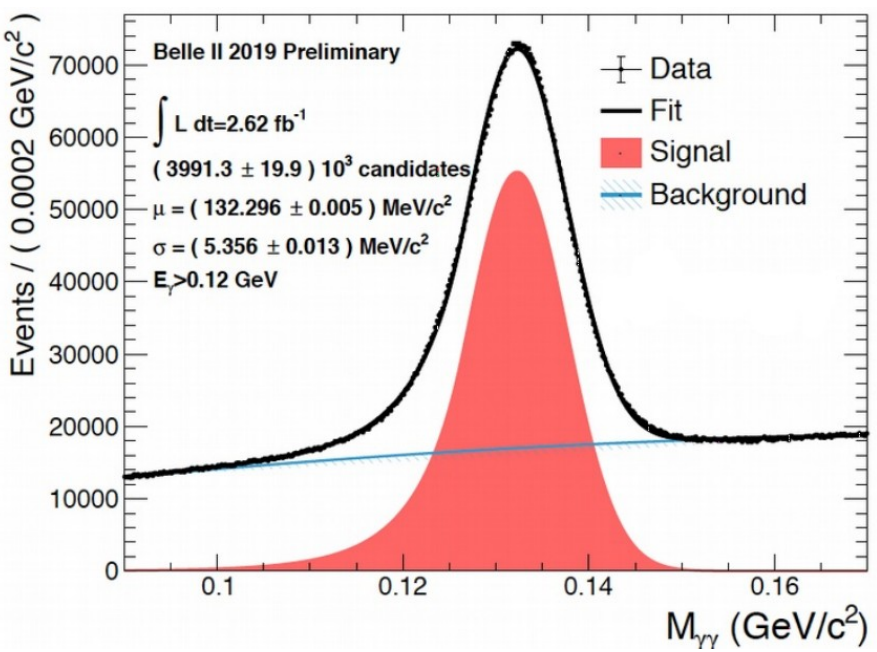


- Some possible factors of improvement: PID, vertex fit (full VXD), Multivariate Analysis

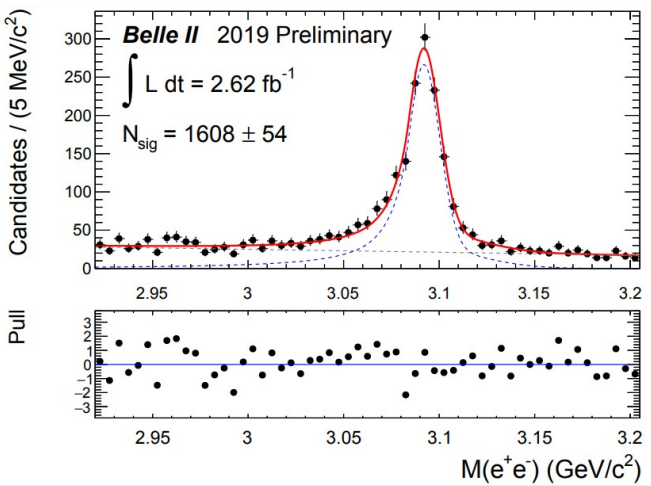
Highlights from Phase 3

- Results for early Phase 3 data:
  - based on 2.62 fb-1

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



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



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