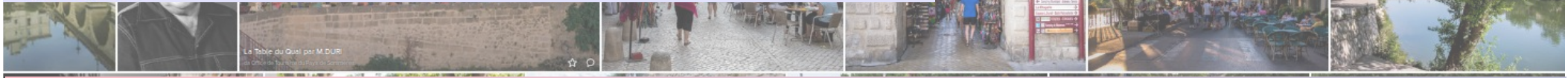
INTENSITY frontier GDR-InF

GDR-InF annual workshop

4-6 November 2019
Sommières



Dark Sector at Belle II: First results and prospects

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IN SUPREMÆ DIGNITATIS 1343

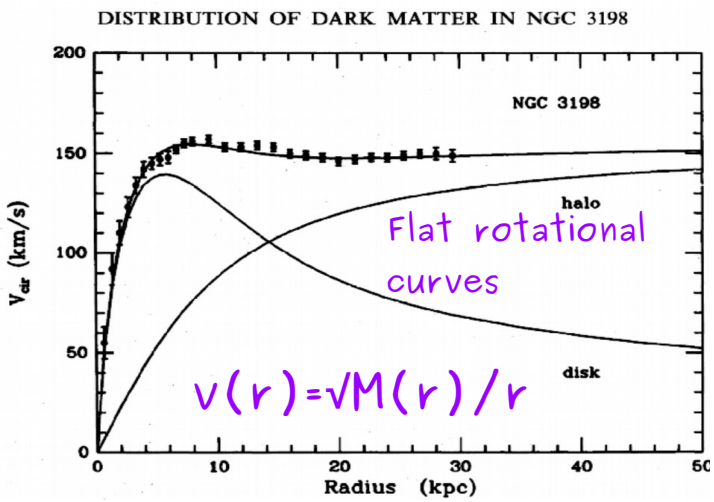
Belle II

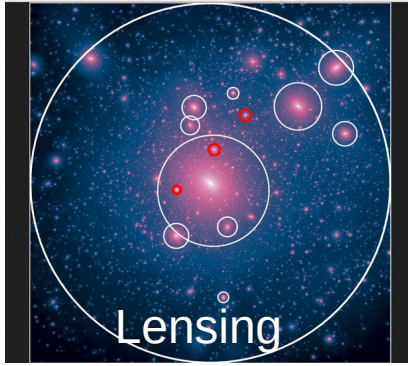
Outline

- The Belle II experiment at SuperKEKB collider
- Data taking phases
- Dark Matter at Belle II:
  - Z' to invisible → ***To be submitted to PRL soon***
  - Axion Like Particles → ***Box opening soon***
  - Dark Photon → ***High priority with upcoming data***
- Summary & Outlook

Dark Sector: Introduction

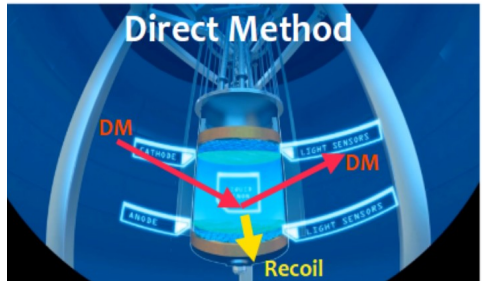
- Many astrophysical observations provide evidence for the existence of a kind of matter that almost does not interact with the Standard Model (SM) particles (*mostly* gravitational interaction) → ***Dark Matter (DM)***

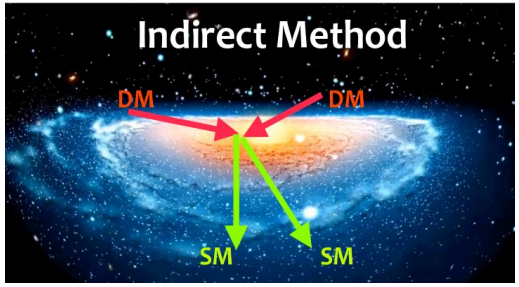




How to search it?

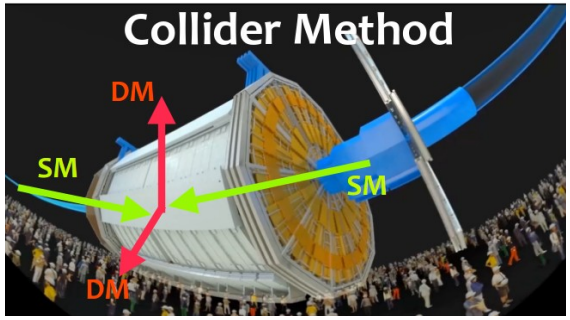
1) Detect the energy of *nuclear recoil*





2) Detect the *flux of visible particles* produced by *DM annihilation* and decay

3) DM weakly couples to SM particles and it can be produced in *SM-particles annihilation* at ***colliders***



→ In this presentation I will focus on the search at electron-positron colliders

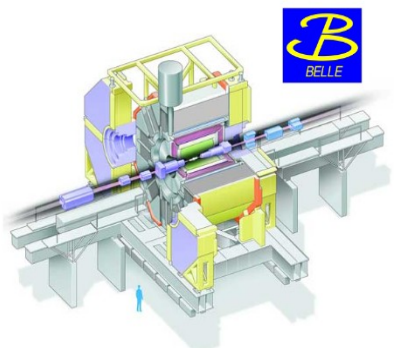
B-Factories: the high intensity frontier

B-factories: dedicated experiments at e^+e^- *asymmetric-energy colliders* for the production of quantum coherent $B\overline{B}$ pairs → **CPV studies**.

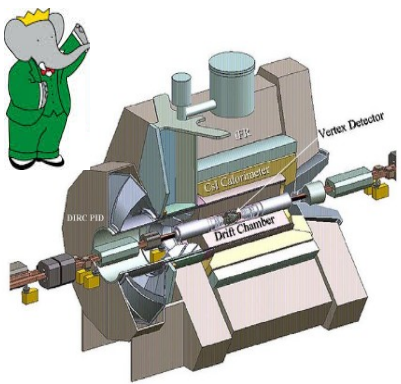
$$e^+e^- \rightarrow \Upsilon(4S)\ [10.58\ \text{GeV}] \rightarrow B\overline{B}$$

$\Upsilon(nS)$ = bound state of b quark and b anti-quark

First generation of B-factories



at the KEKB collider (KEK, Japan)



at the PEP II collider (SLAC, California)

- **Clean environment** → lower background, high resolution
- **Hermetic detector** with excellent PID capability → efficient reconstruction of ***neutrals*** (π^0, η, ...), recoiling system and ***missing energy*** final states

B-Factories: the high intensity frontier

B-factories: dedicated experiments at e^+e^- *asymmetric-energy colliders* for the production of quantum coherent $B\overline{B}$ pairs → **CPV studies**.

$$e^+e^- \rightarrow \Upsilon(4S)\ [10.58\ \text{GeV}] \rightarrow B\overline{B}$$

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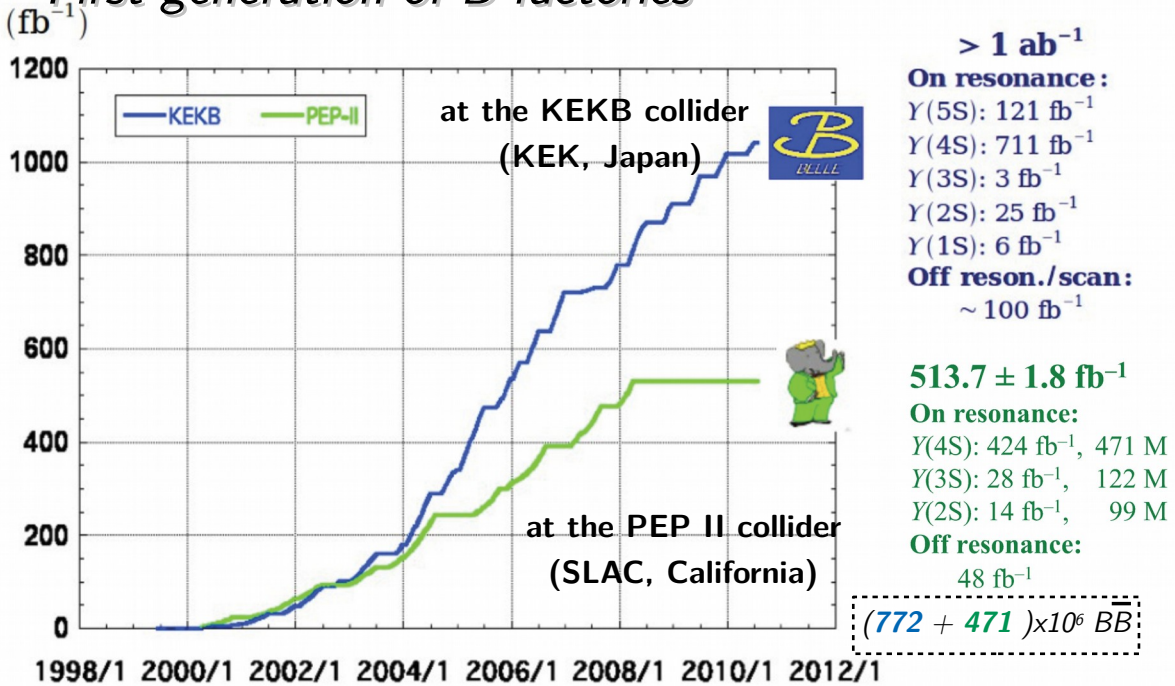
First generation of B-factories



> 1 ab^{-1}
On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

513.7 ± 1.8 fb^{-1}
On resonance:
Υ(4S): 424 fb^{-1}, 471 M
Υ(3S): 28 fb^{-1}, 122 M
Υ(2S): 14 fb^{-1}, 99 M
Off resonance:
48 fb^{-1}

(772 + 471)x10^6 $B\overline{B}$

- Clean environment → lower background, high resolution

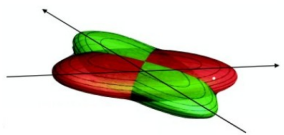
Rich physics program:

- ✔ Discovery of CPV in B mesons
- ✔ SM test, precision flavor physics
- ✔ Rare/suppressed/forbidden processes
- ✔ Search for new particles (quarkonium)
- ✔ *Search for light Dark Sector and mediators*

Second Generation: SuperKEKB

- **World highest luminosity,** applying the *large crossing angle nano-beam scheme (P.Raimondi for SuperB, M. Bona et al., arXiv:0709.0451).*

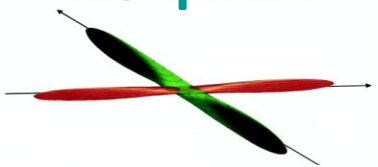
KEKB



I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

SuperKEKB



I (A): ~ 3.6/2.6

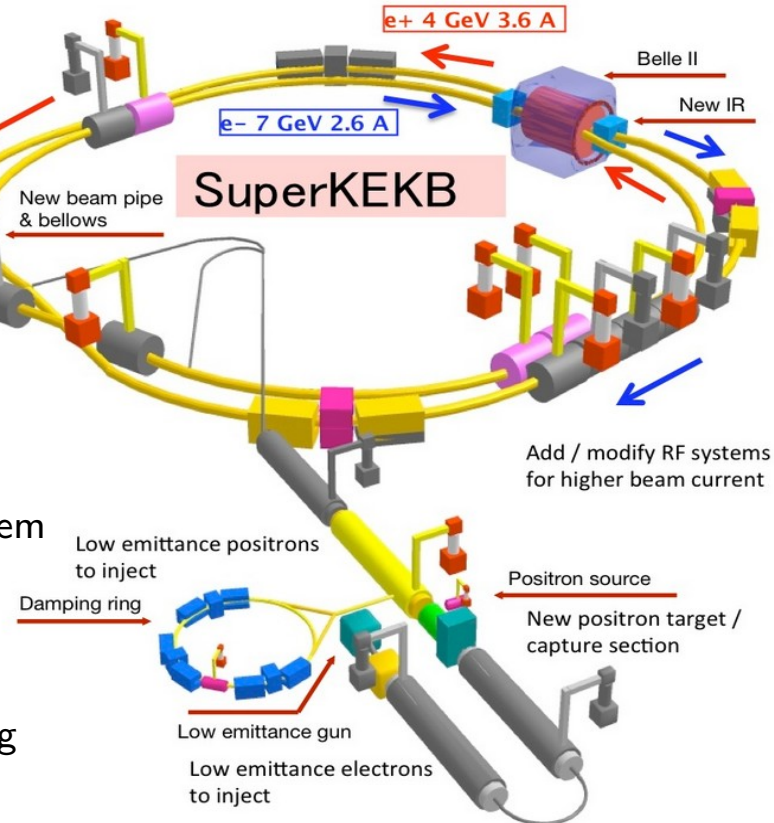
β^*_y (mm): ~ 0.27/0.3

I ↑ x 2

β^*_y ↓ x 1/20

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

Lorentz factor; beam current; beam-beam parameter; geometrical reduction factors; beam aspect ratio at the IP; vertical beta-function at the IP

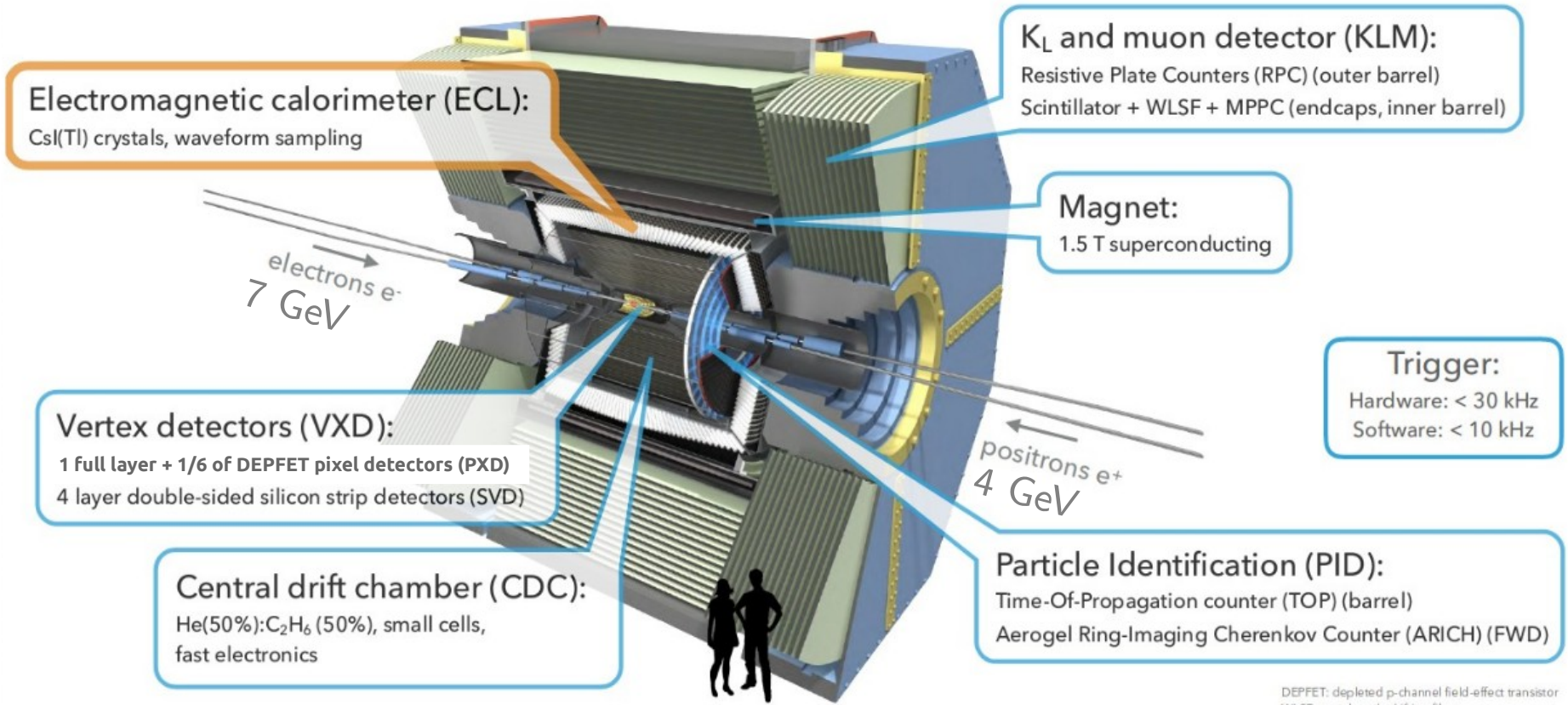


- ✓ New final focus system
- ✓ New Interaction Region
- ✓ New e^+ damping ring

40x KEKB peak luminosity: $\mathcal{L} = 8 \cdot 10^{35}$ cm^{-2} s^{-1}

Belle II Detector

- The Belle II detector has better resolution, PID and capability to cope with higher background



Belle II → x50 the data set of its predecessor!

Belle II Data Taking plan

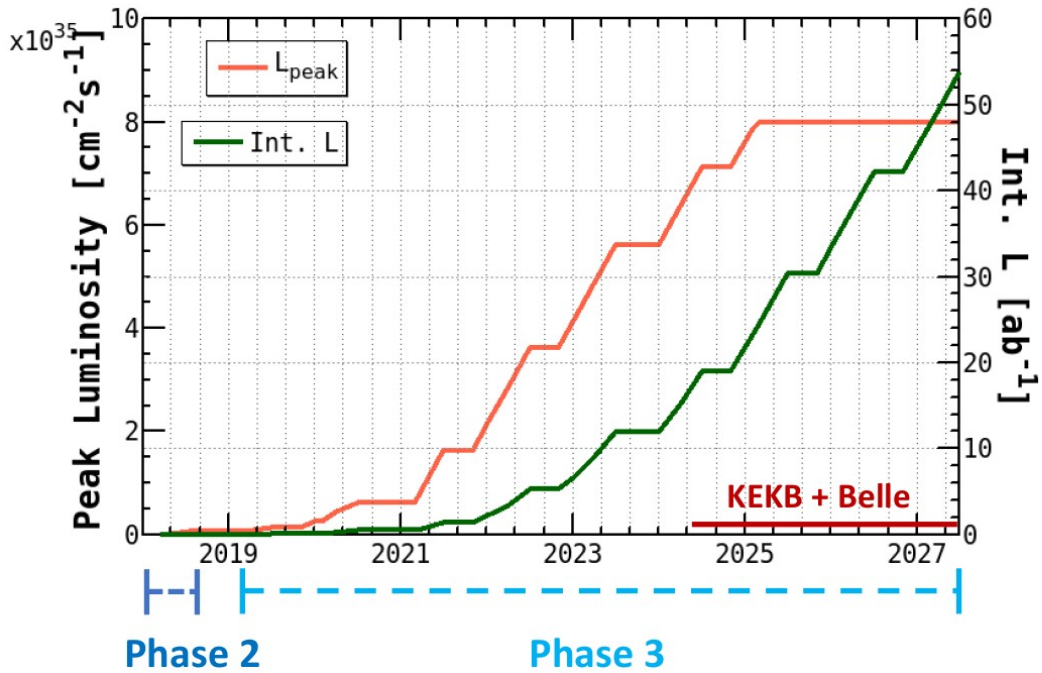
Phase 2: April 26th– July 17th 2018

- 1/8th VXD
- Verify nano-beam scheme, commission the detector and the machine
- Lower backgrounds, flexible hardware triggers and passthrough software trigger
- Max peak luminosity 0.5 x 10^{34} $cm^{-2}\,s^{-1}$
- **0.5 fb^{-1} collected → Dark Searches**

Phase 3: March 2019 – ...

- VXD detector installed
- → 4 full layers of silicon strips
- → 1 full of pixels +1/6

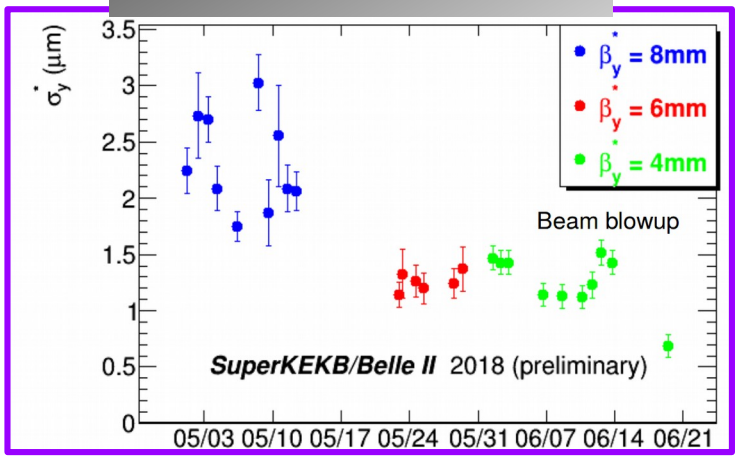
  (installation finalized ~2021)
- **~6.5 fb^{-1} collected** during spring runs



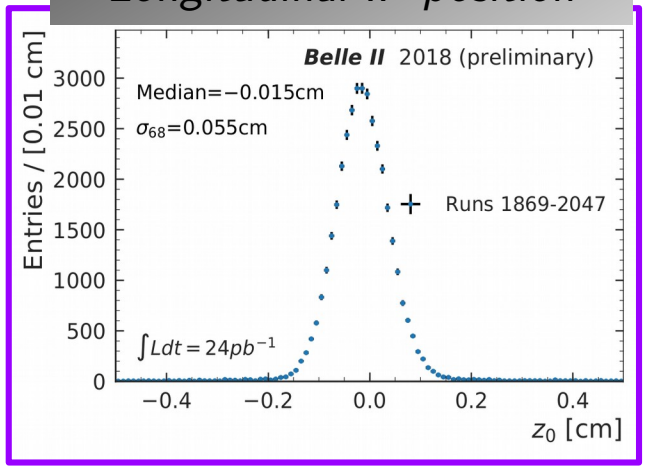
- autumn run restarted October 15, plan to go up with luminosity by squeezing βy* (2→1 mm) and beam currents ~300 mA
- expected 20 fb^{-1} by end of the year, 200 fb^{-1} → FINAL GOAL : 50 ab^{-1}

Belle II Performances in Phase 2

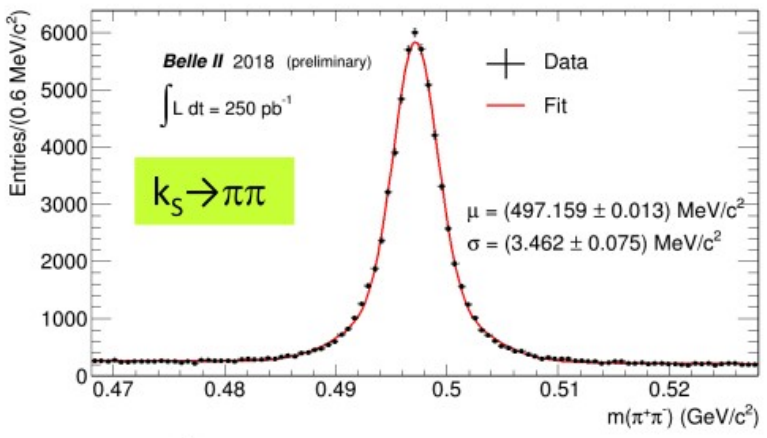
Vertical beam size

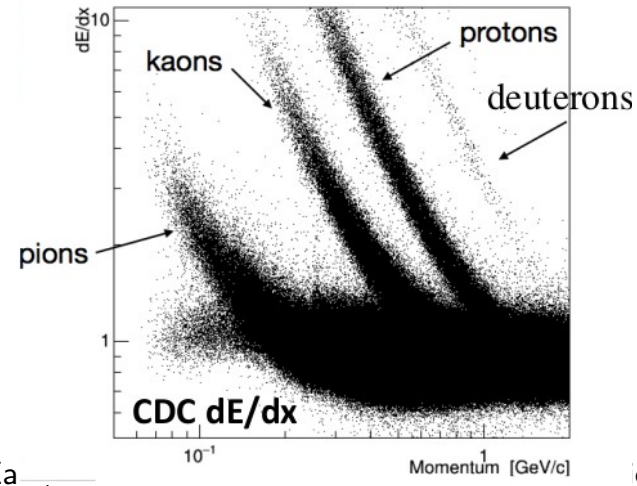


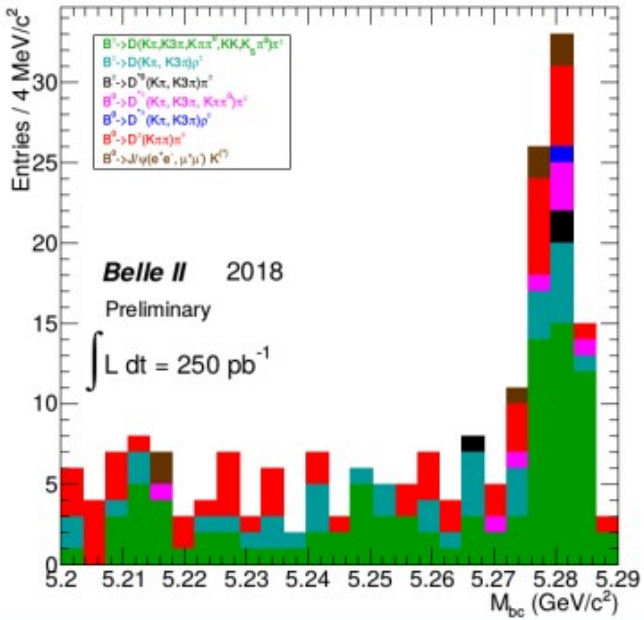
Longitudinal IP position



- ✔ **Nano-beam scheme works**
- ✔ **L = 5.5 · 10^{33} cm^{-2} s^{-1}**
- ✔ **Collected 0.472 fb^{-1}**

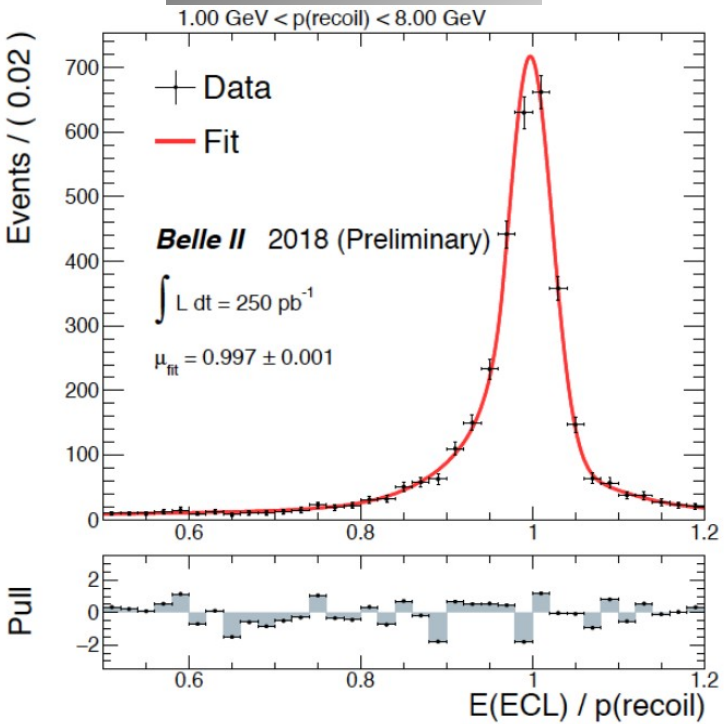




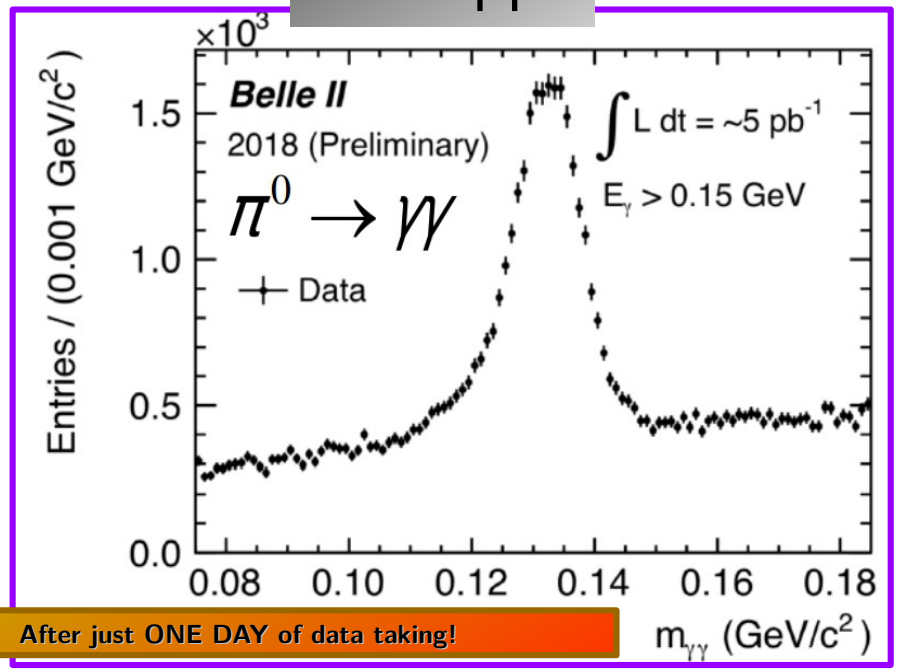


Belle II Performances in Phase 2: photon reconstruction

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



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

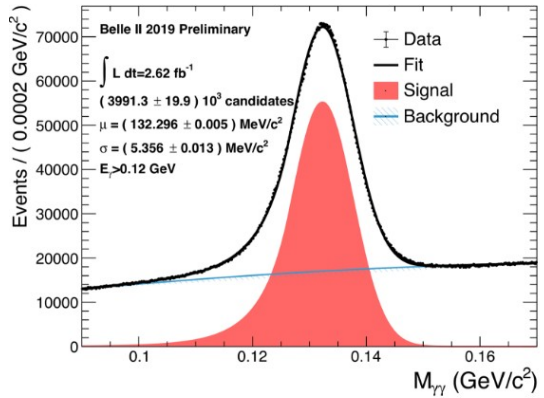


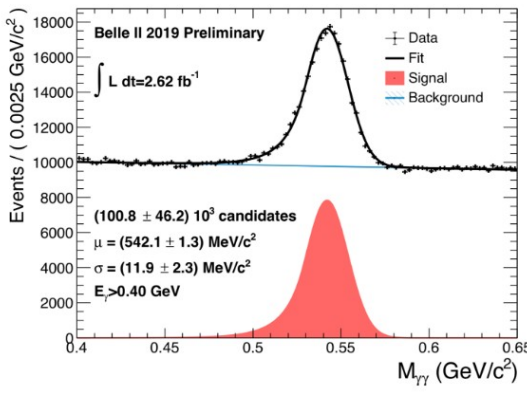
$e^+e^- \to \gamma\ X$

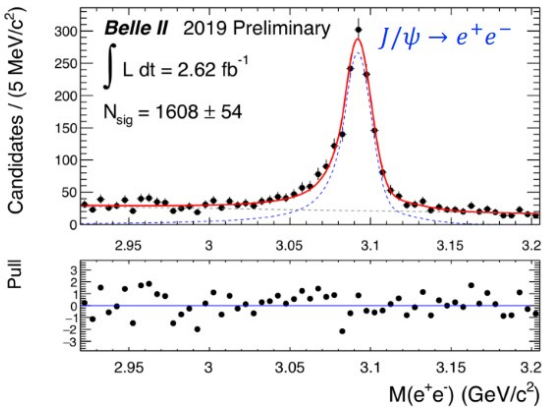
$e^+e^- \to \gamma\ ALPS \to \gamma(\gamma\gamma)$

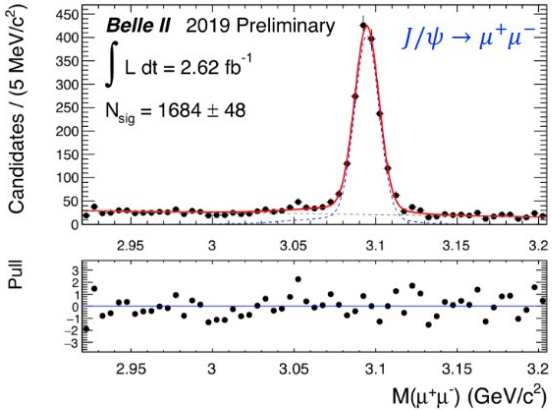
Belle II Phase 3 snapshot

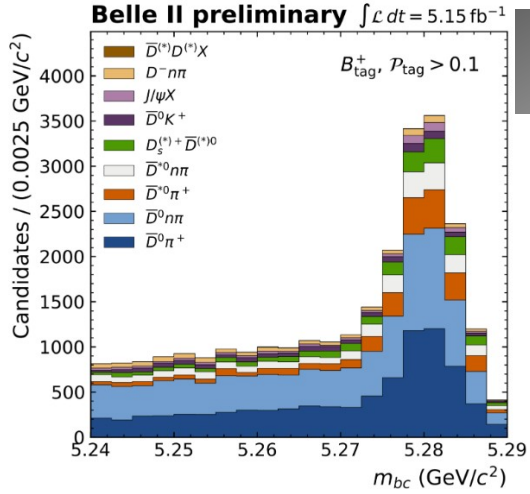
$\pi^0, \eta \to \gamma\gamma$





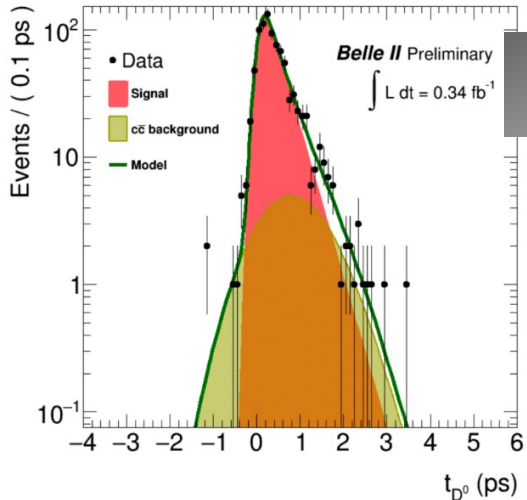






FEI, B tagging

- *Important B factory techniques to reconstruct decay with neutrinos and do inclusive searches*



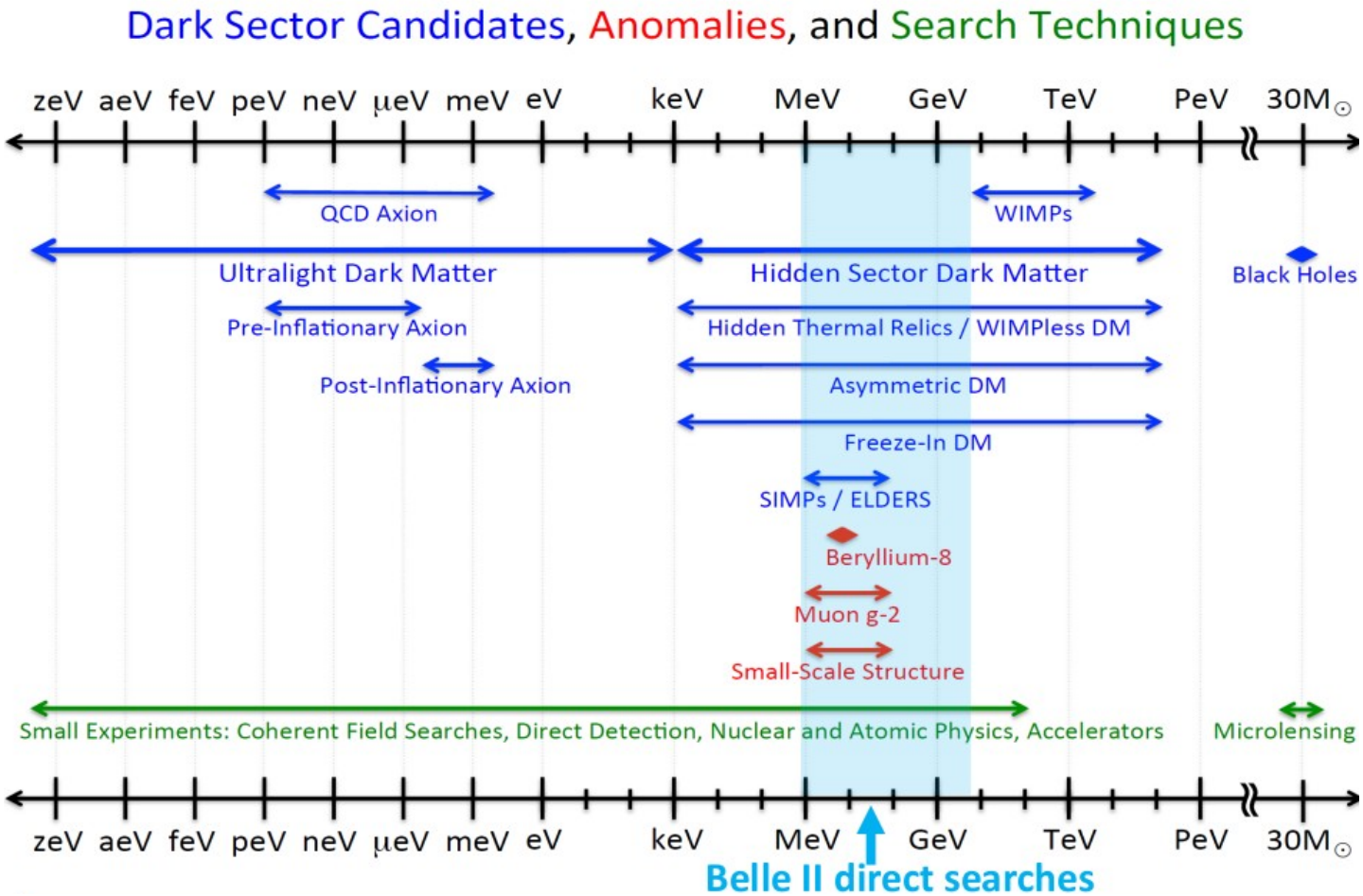
D^0 lifetime

$\tau = (370 \pm 40)$ fs

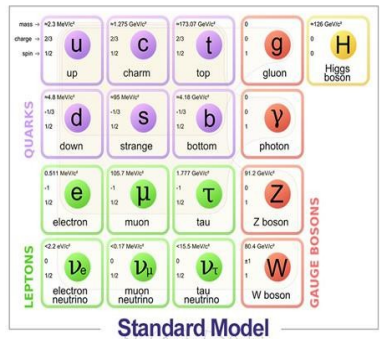
PDG average:

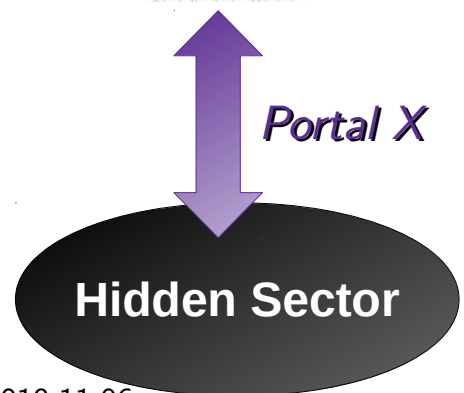
(410.1 ± 1.5) fs

Panoramic view on dark searches

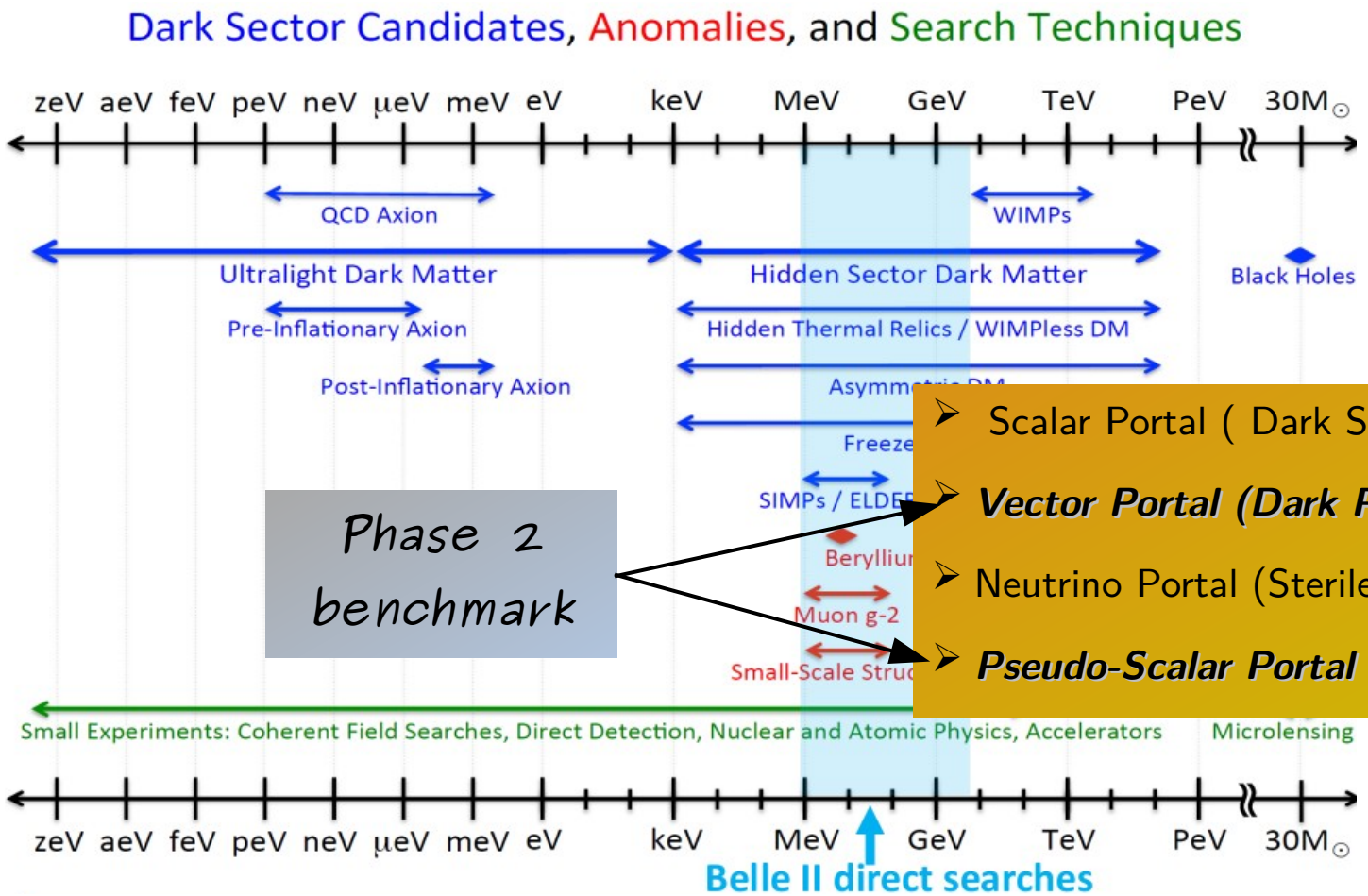


Possibility of *light dark sector* motivates the search for ***DM mediator X:***





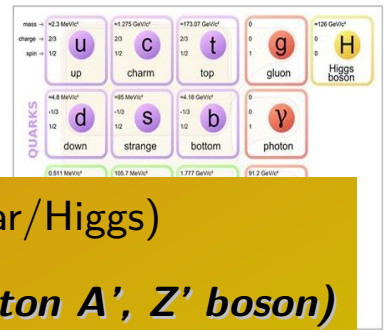
Panoramic view on dark searches: dark portals



Phase 2 benchmark

- Scalar Portal (Dark Scalar/Higgs)
- ***Vector Portal (Dark Photon A', Z' boson)***
- Neutrino Portal (Sterile Neutrinos)
- ***Pseudo-Scalar Portal (ALPs, axions)***

Possibility of *light dark sector* motivates the search for ***DM mediator X:***



X

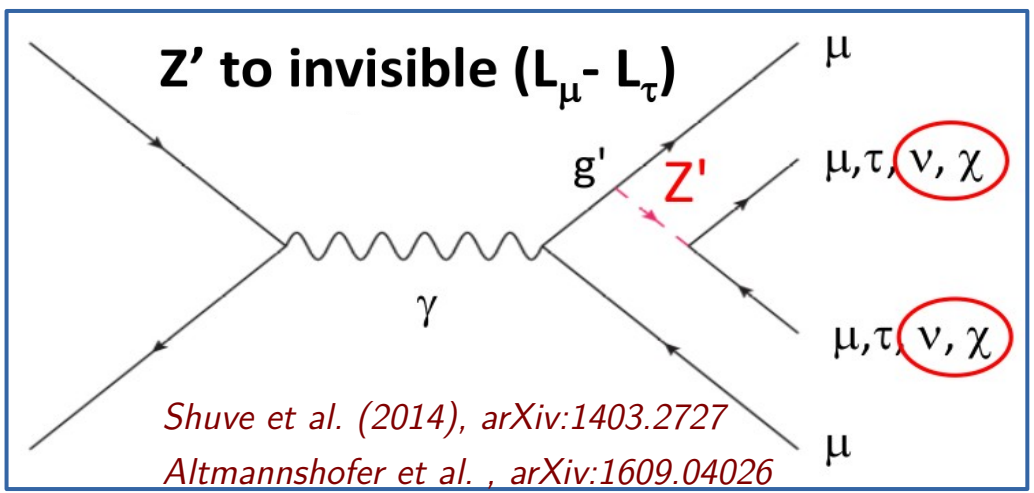
Hidden Sector

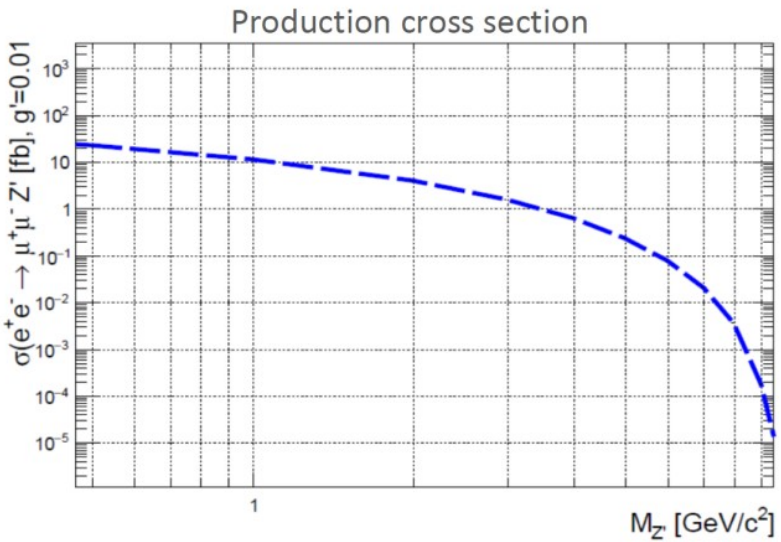
Z' to Invisible: L_μ-L_τ model

- New gauge boson Z' coupling only to the **2nd and 3rd** generation of leptons (L_μ-L_τ)
  - *May explain the (g-2)$_\mu$ anomaly*
  - *May solve the light DM puzzle (e.g. sterile neutrinos, Dirac light fermions)*
  - *May explain anomalies observed in rare B decays, B→ K*μμ, $R_{K(*)}$*
- Invisible signature investigated for the first time in the process

  $^-e^+e^- \rightarrow \mu^+\mu^- +$ *missing mass*

  (Muonic dark force searches at BaBar → only visible final state to two muons)





Branching ratios:

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

$$2M_\mu < M_{Z'} < 2M_\tau \rightarrow \Gamma(Z' \rightarrow \text{inv.}) \sim 1/2$$

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

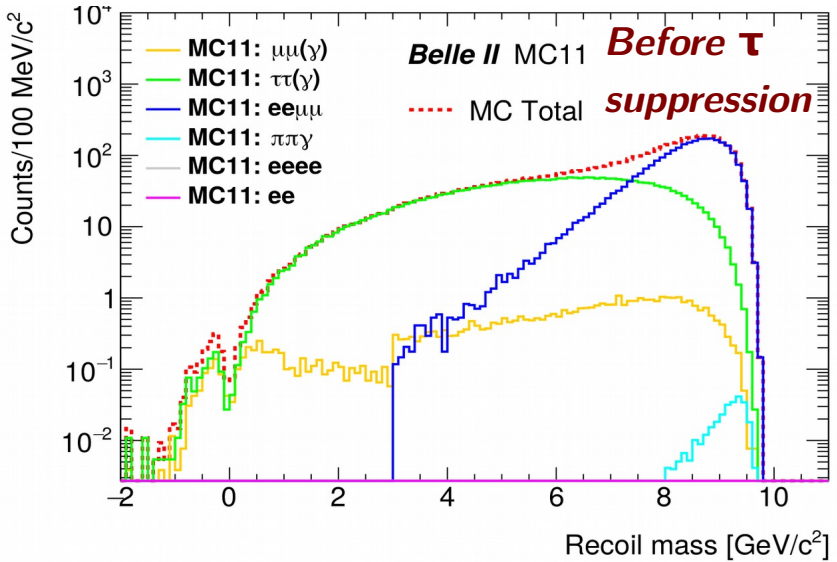
If LDMA is accessible, BR(Z'→ DM)~1

Z' to invisible: analysis overview

- Look for a peak in the recoil mass spectrum against a **$\mu^+\mu^-$ pair** (dimuon candidate) in event where nothing else is detected.
- Reject *QED background* by applying a signal-like selection on the distribution of the transverse momentum of the dimuon candidate $pT_{\mu\mu}$
- $e^+e^- \rightarrow \tau\tau(\gamma)$ is the main source of background contamination:
  - dedicated τ suppression optimized by maximizing *Punzi Figure Of Merit*

$$FOM_{Punzi} = \varepsilon(t)/(a/2 + \sqrt{B(t)})$$

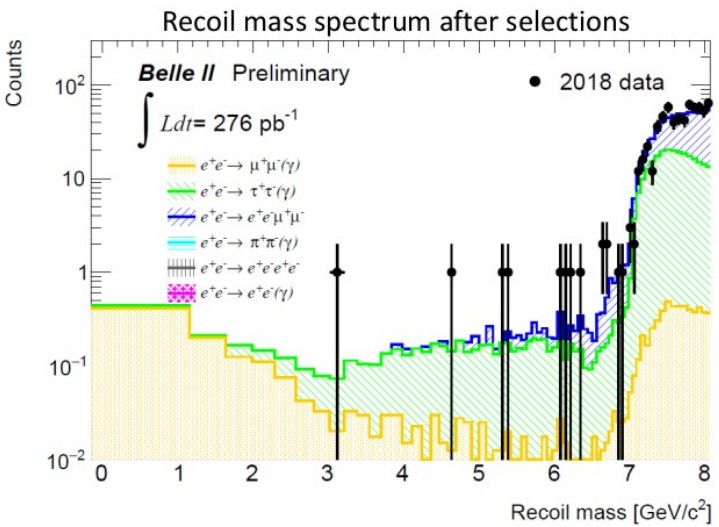
a= 1.64 (90% CL)



- Intense program of **data validation** studies and systematic effects evaluation on 2018 data (Phase 2, 0.5 fb^{-1})+ estimation of sensitivities
- Extract the signal yield by applying a Poisson counting experiment technique for each recoil mass bin
- Compute 90% CL upper limit in each mass bin defined for the simulated Z' masses.

Z' to invisible: results and prospects

Phase 2 results

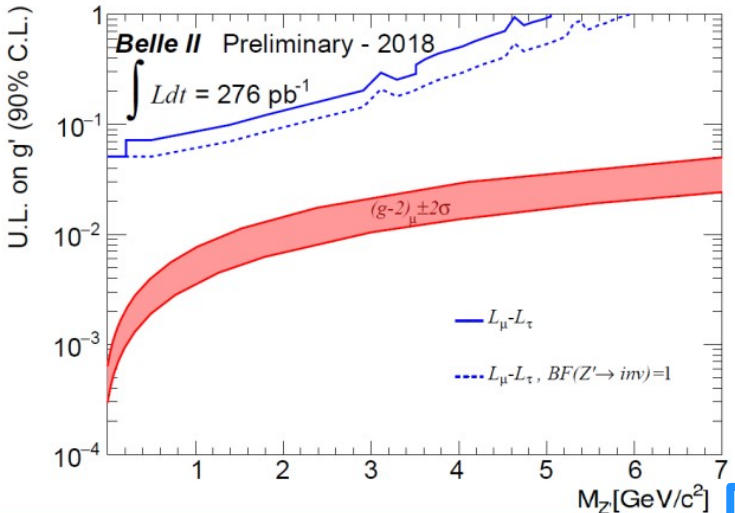


→ only 276 pb^{-1} usable due to trigger conditions

→ No excess observed

Paper under collaboration wide review

To be submitted to PRL

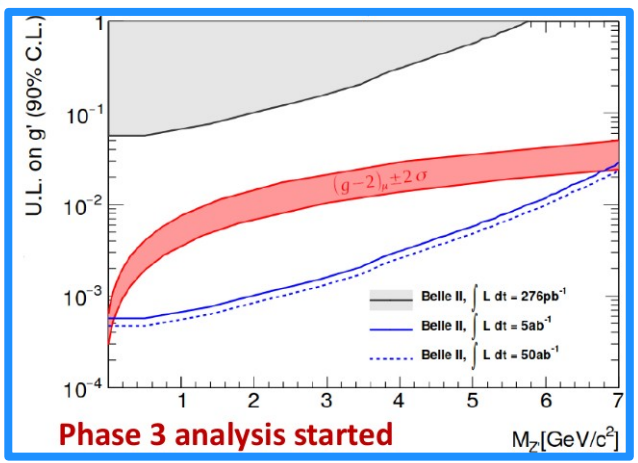


Source	Error
Trigger efficiency	6%
Tracking efficiency	4%
PID	4%
Luminosity	1.5%
Background before τ suppression	2%
τ suppression (background)	22%
Discrepancy in μμ yield (signal)	12.5%

will decrease with new data

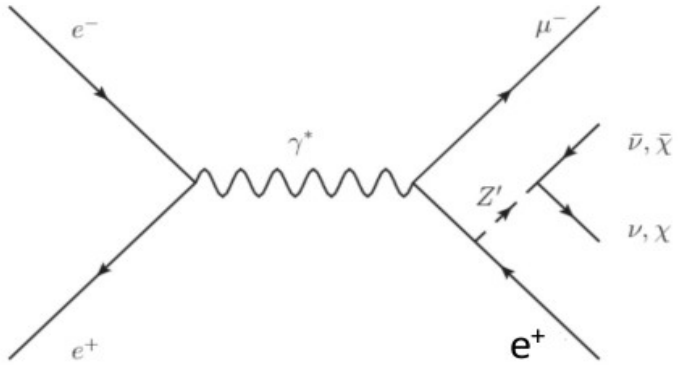
Phase 3 prospects

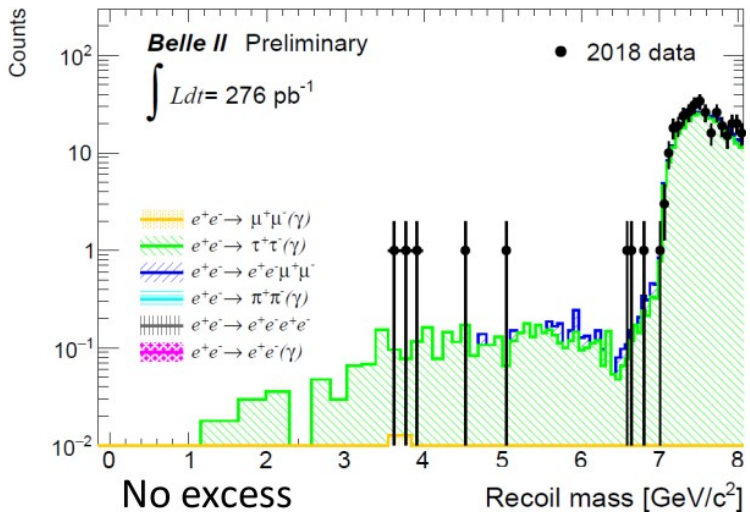
- Reduced systematic uncertainty (3%)
- L_{int}=5, 50 ab^{-1}

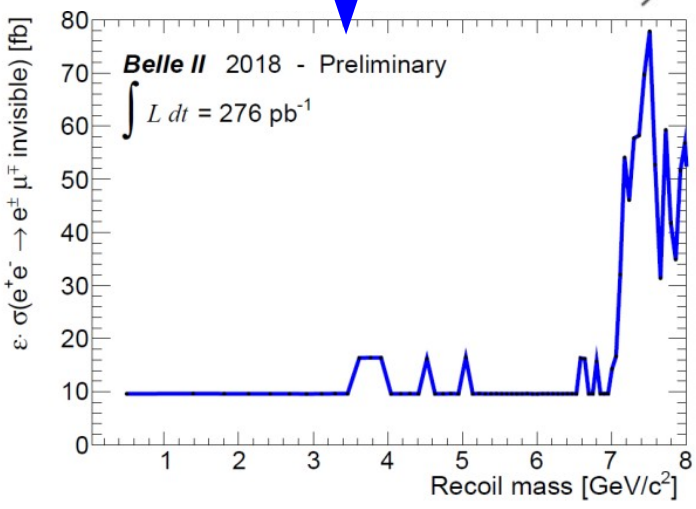


LFV Z' to invisible

- Could couple to different families of lepton (only e-μ coupling investigated)
- Look for a peak in the mass distribution of the recoil against a ***eμ pair***
- Byproduct of the standard Z' search, with minimal adjustment
- Model independent search: constrain *(Εxσ) product with 90% CL upper limit*



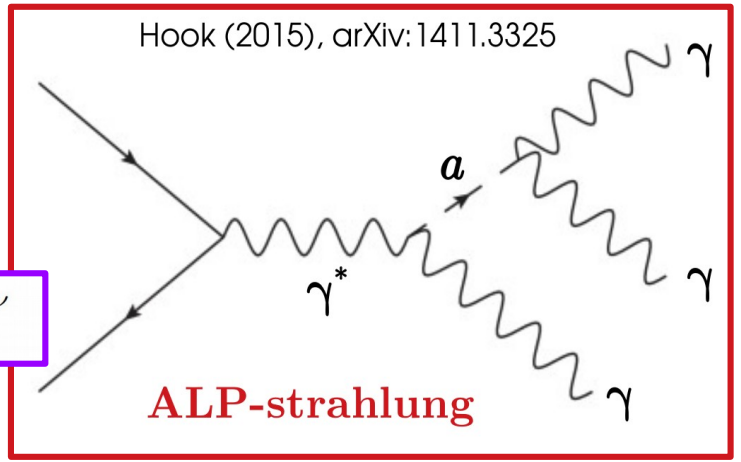


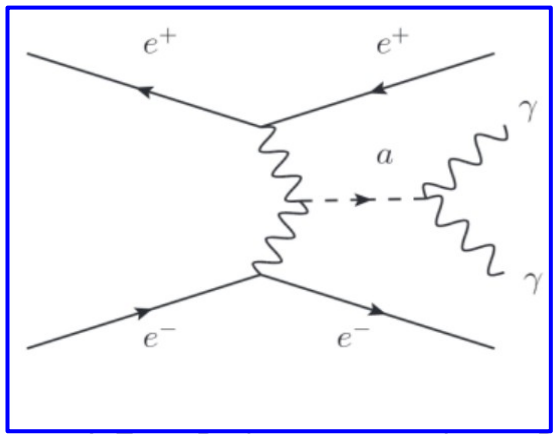


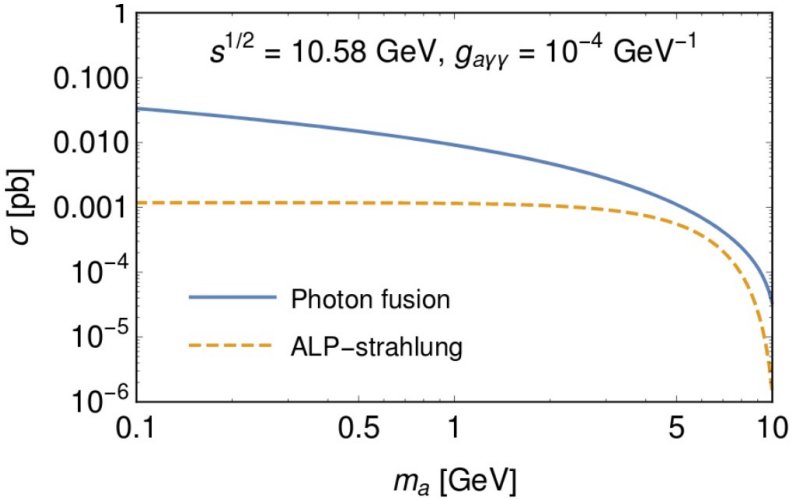
Galon et al. https://doi.org/10.1007/JHEP05(2017)083
Galon et al, https://doi.org/10.1007/JHEP03(2017)064

Axion Like Particles (ALPs)

- Axion Like Particles are pseudo-scalars coupling to bosons
- Unlike for QCD Axions, there is no relation between the coupling and the mass
- Explored photon coupling $g_{a\gamma\gamma}$ in *ALP-strahlung* processes (*photon fusion:* sensitivity under study)
- $\tau \sim 1/m_a^3 g^2_{a\gamma\gamma}$
  - Displaced vertex
  - Long-lived particle



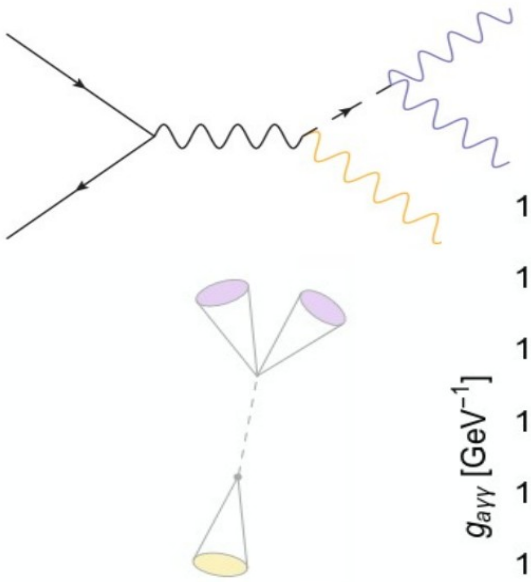




ALPs: Experimental Signature

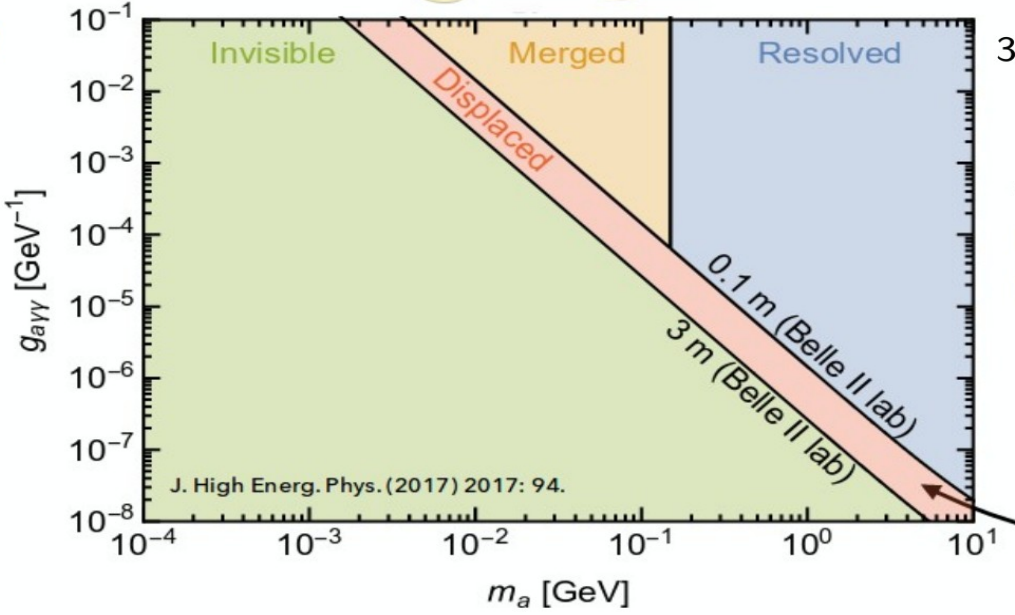
- Signal signatures: 3γ final state, several topologies → 4 categories
- ALPS may also decay to invisible (DM) → single photon topology

Backgrounds: $e^+e^- \to \gamma\gamma(\gamma)$ and pair conversion $\gamma \to e^+e^-$ outside the tracking volume



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

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

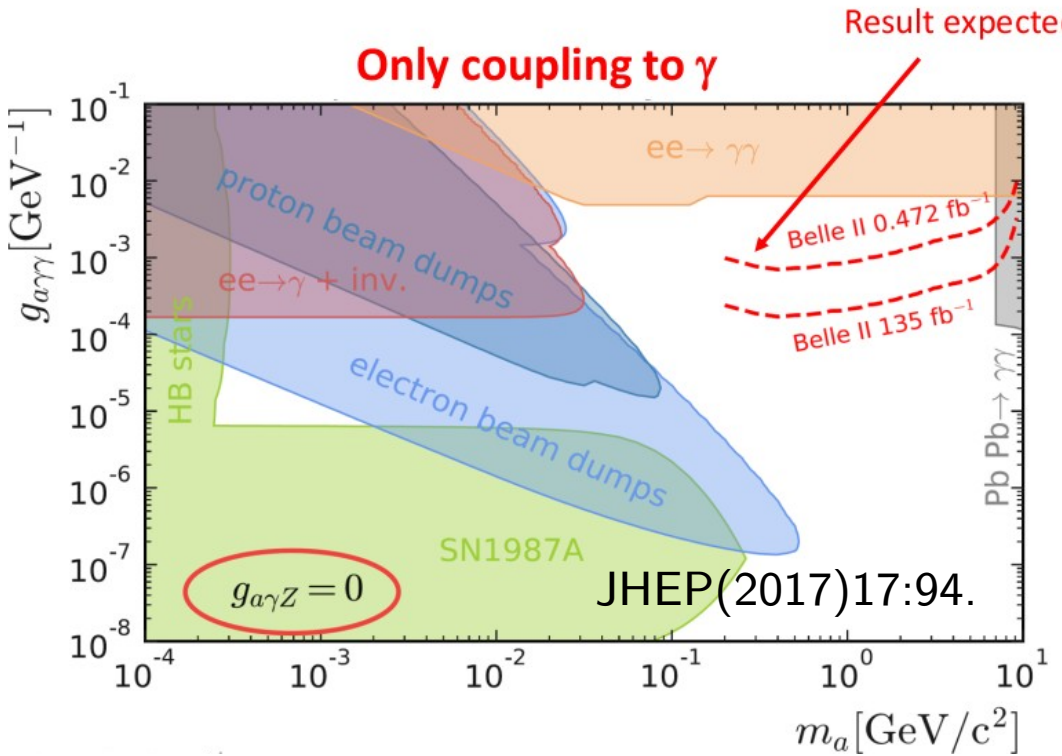


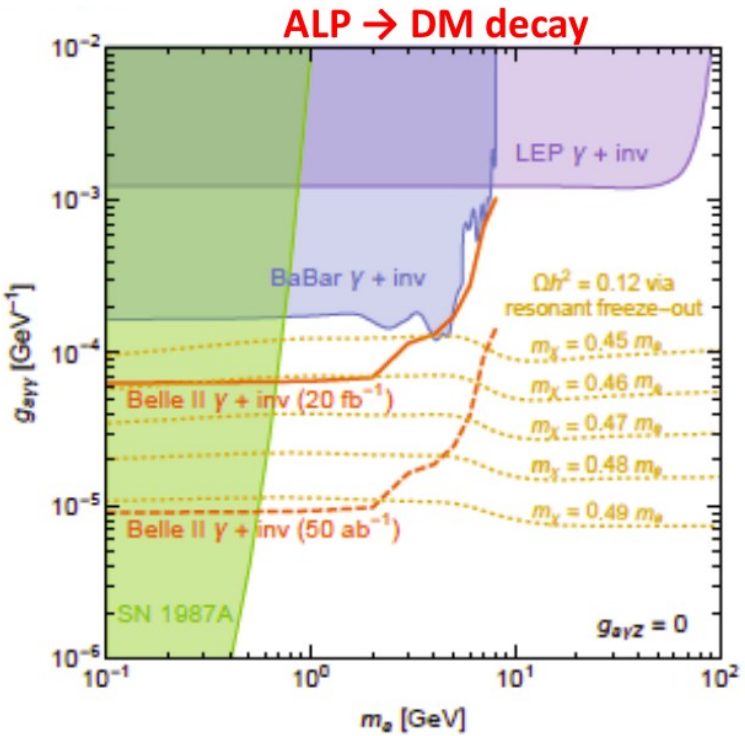
For **resolved** case:
3 clusters with $E_{CM} > 0.25$ GeV
Peak in $\gamma\gamma$ mass spectrum

Three **resolved**, high energetic photons.

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

ALPs: Sensitivity

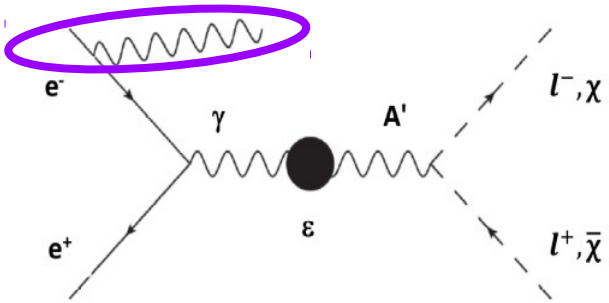




- No systematic contribution yet in the sensitivity
- Only dominant $e^+e^- \to \gamma\gamma(\gamma)$ *background included*
- *135 fb^{-1} assumes no* γγ *veto in the barrel*

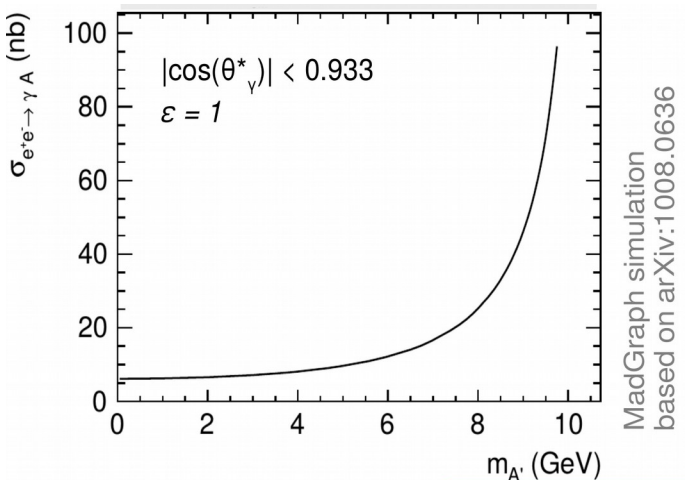
The Dark Photon

- A possible U(1) extension of the SM include a new massive ($m_{A'}$) gauge boson A' of spin = 1 coupling to the SM through the kinetic mixing with strength $\varepsilon \rightarrow$ the ***dark photon***
- At e^+e^- colliders we investigate the ISR production $e^+e^- \rightarrow \gamma A'$.



$$\mathcal{L} \supset \varepsilon A'_\mu J^\mu_{\mathrm{SM}}$$

Batell et al. (2009), arXiv:0903.0363



- If $m_{A'} > 2m_\chi \rightarrow$ A' decays visibly to SM particle
- If $m_{A'} > 2m_\chi \rightarrow$ A' decays 100 % invisibly into DM particle, $e^+e^- \rightarrow \gamma + A'$, $A' \rightarrow \chi\chi$

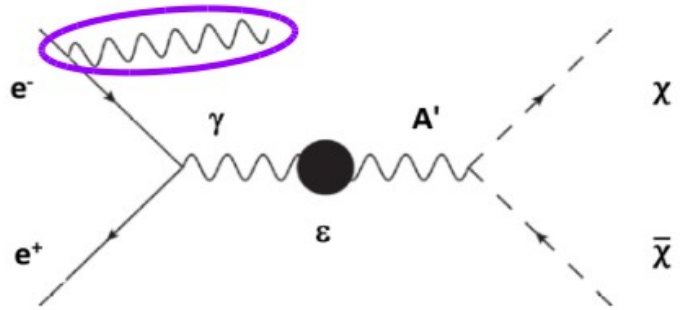
Belle II

53 fb^{-1} **~10 fb^{-1} good quality data**

Dark Photon to Invisible

- Signal Signature:
  - select events with NOTHING but a single high energetic *ISR photon*
  - Look for a bump in the reconstructed photon energy $E_\gamma = (s - m^2_{A'})/2\sqrt{s}$

    → only one photon in the detector requires a dedicated ***single photon trigger*** **(at Belle was not available, ~10% BaBar data)**

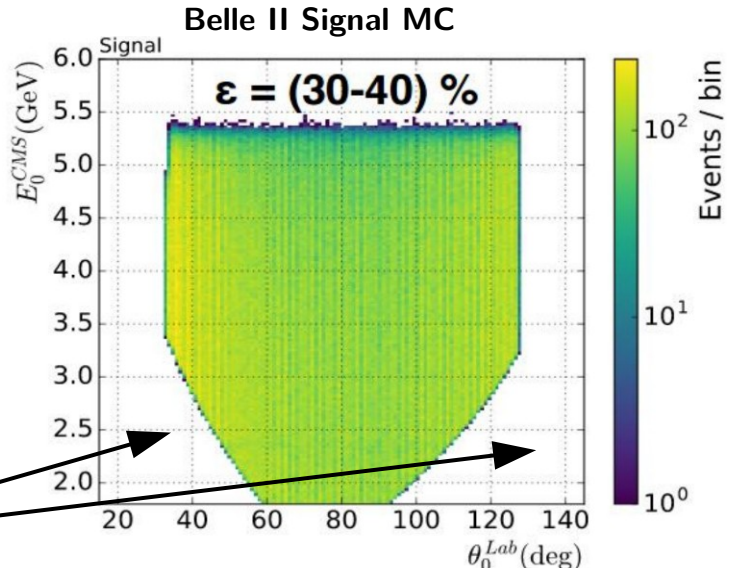


Belle II Phase 3 (Design)

Trigger logic	L1 rate at full luminosity
E > 1 GeV + 2nd cluster E < 300 MeV	4 kHz (barrel) 7 kHz (endcaps)
E > 2 GeV Bhabha & γγ vetoes	5 kHz (barrel)

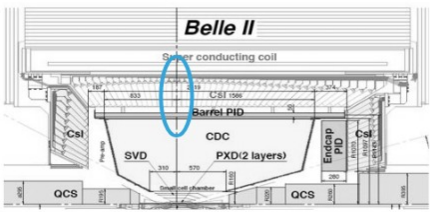
Discriminant variables: E^*_γ, θ_γ

Effect of selection on $E^*(\theta)$ for background rejection

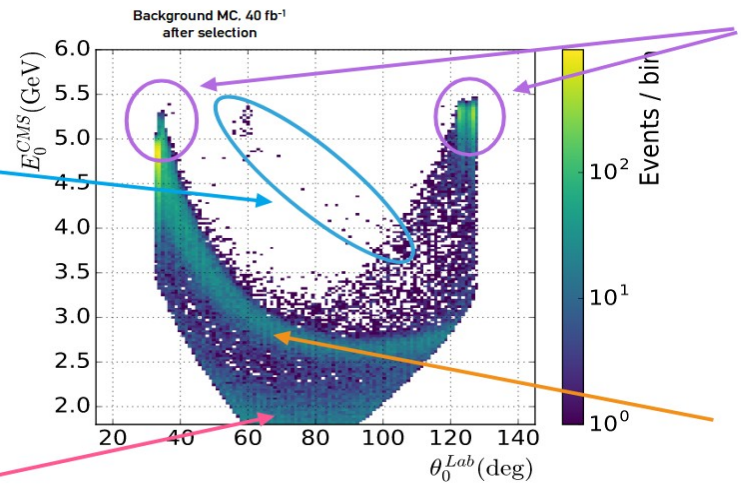


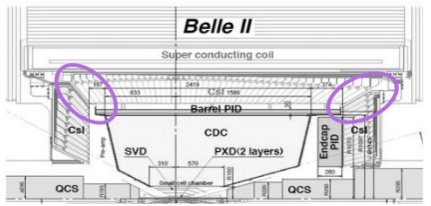
Dark Photon to Invisible: Backgrounds

- Background dominated by QED processes:
  - $e^+e^- \to \gamma\gamma(\gamma)$ where one photon is not detected (ECL gaps) and the second out of acceptance
  - radiative Bhabha $e^+e^- \to e^+e^-\,\gamma(\gamma)$ with the electron-positron pair out of acceptance.



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

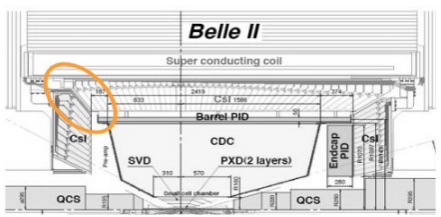




ee→2γ
1γ in ECL BWD or FWD gap

ee→eeγ
both electrons
out of tracking acceptance

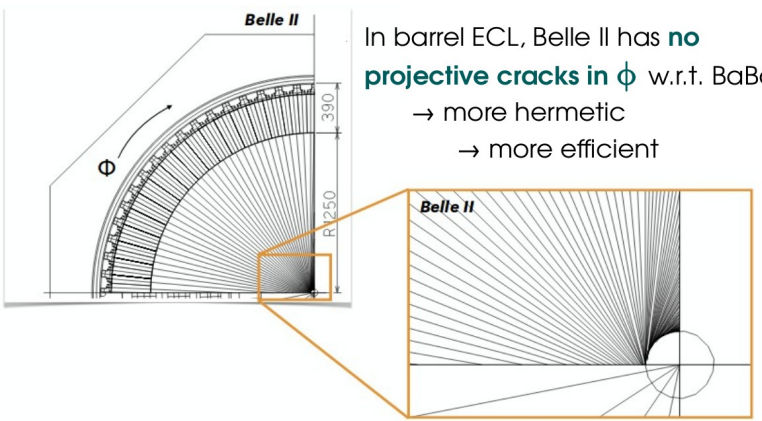
$e^+e^- \to \nu\nu\gamma$ negligible



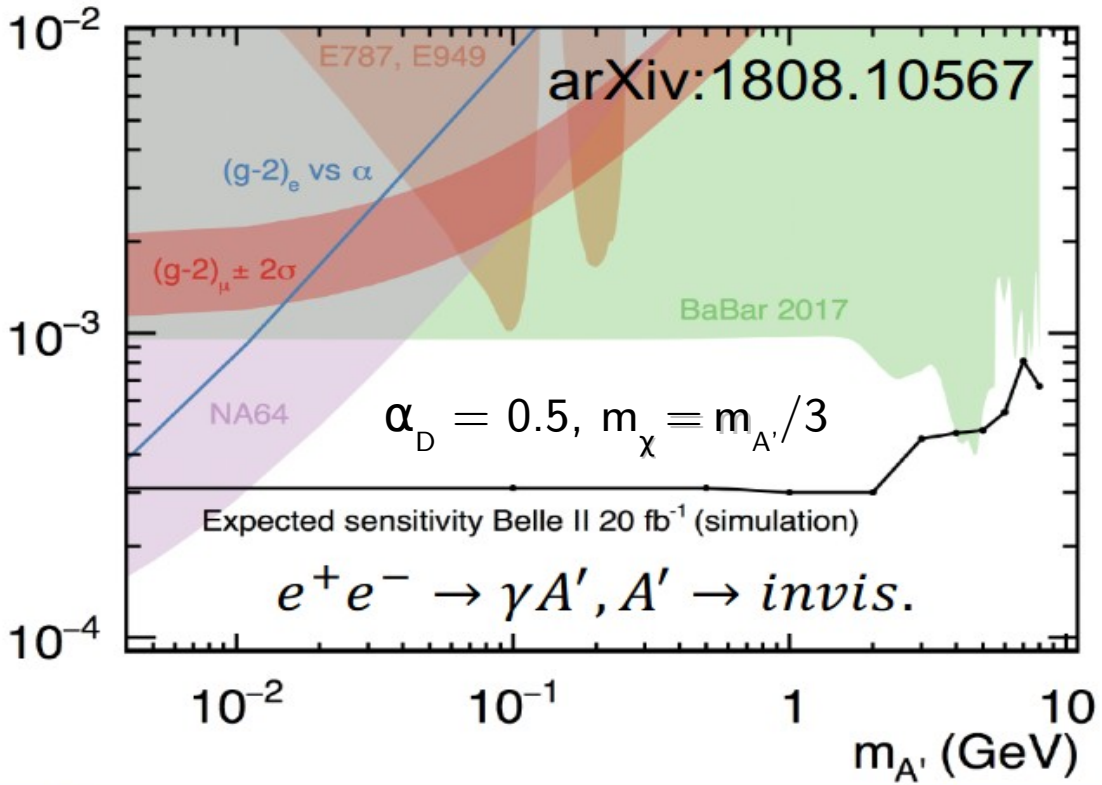
ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

Invisible Dark photon sensitivity

- Belle II advantages:
  - ✔ No ECL cracks pointing to the Interaction region
  - ✔ KLM can compensate ECL photon detection gap
  - ✔ Better hermeticity (smaller boost, larger acceptance)
  - ✔ Improved L1 trigger lines



In barrel ECL, Belle II has **no projective cracks in ϕ** w.r.t. BaBar:
→ more hermetic
→ more efficient



Summary

- Belle II pilot run (2018, Phase 2) showed good results for the machine and detector commissioning:
  - Peak luminosity 0.5 x 10^{34} $cm^{-2}\,s^{-1}$
  - **0.5 fb^{-1} collected ⇒ used for Dark Searches**
- Phase 3 started in March 2019, 6.5 fb^{-1} available:
  - Rediscover resonances, B and charm physics
  - *New analyses* started!
- First Belle II physics results are coming soon!

A rich dark sector program is under investigation at Belle II which has a unique potential for searches never done before.
→ Interplay with theory is crucial to connect with direct searches and effectively constrain dark sector models.

More references in The Belle II Physics Book, arXiv:1808.10567

Phase 2

- (LFV) Z' to invisible search to be submitted soon to PRL
- ALPs search ready for box opening

Phase 3

- Invisible dark photon (high priority with ~20 fb^{-1} good data)
- Expected by 2020

- Visible Dark Photon
- $\Upsilon(1S)$ to invisible
- Muonic dark forces
- Dark scalars / Higgstrahlung
- Magnetic monopoles
- Long-lived particles
- …

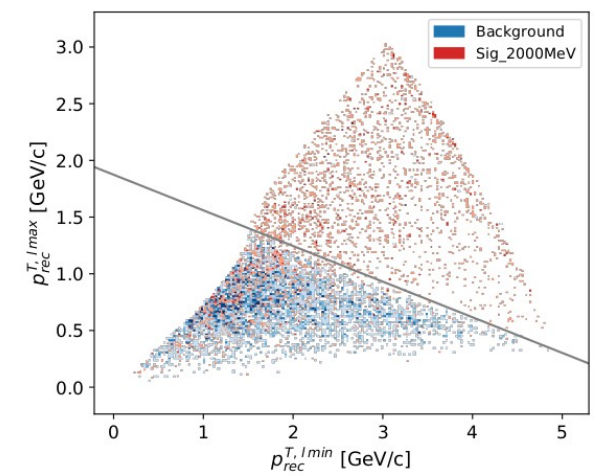
Backup

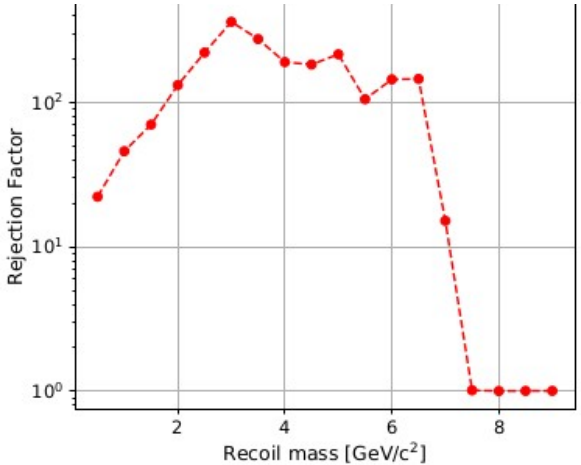
SuperKEKB Numbers

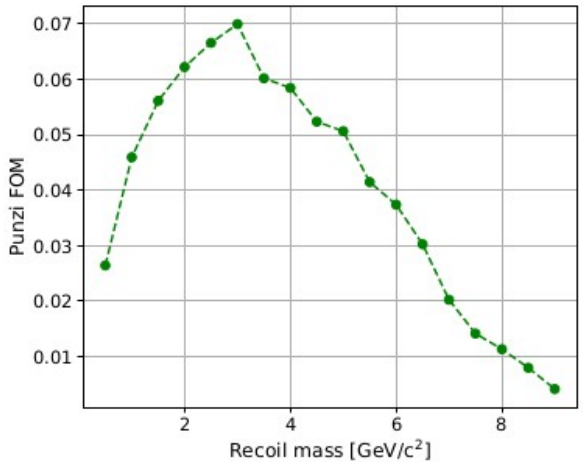
2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.20×10^{-4}	4.55×10^{-4}		
σ_δ	$7.92(7.53)\times10^{-4}$	$6.37(6.30)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

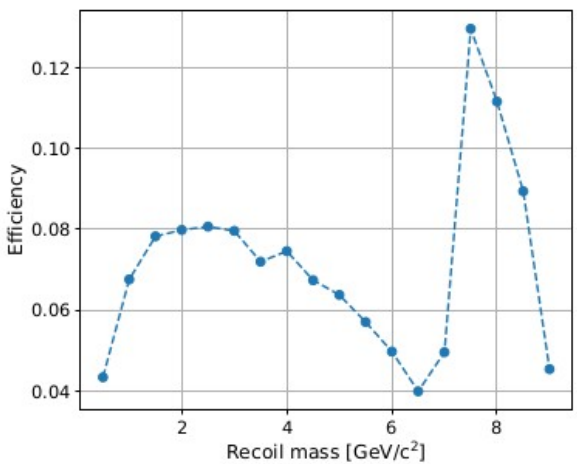
Z' to invisible: τ suppression procedure

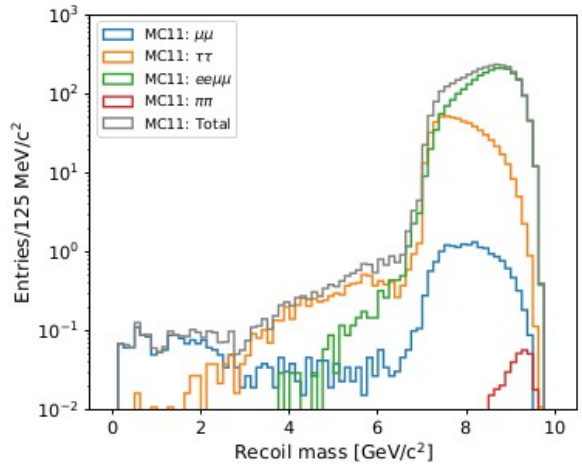
- Z' production is a final state radiation from a μ leg
- τ background is generated from undetected ν's from both legs
- Different asymmetry in the event topologies
- Discriminant variables which can quantify this different level of asymmetry:
  - Projection of the transverse recoil momentum onto the direction of the maximum/minimum lepton momentum











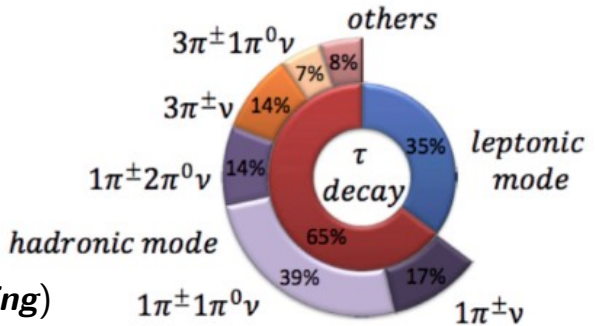
Z' to invisible: Data Validation and Performance studies

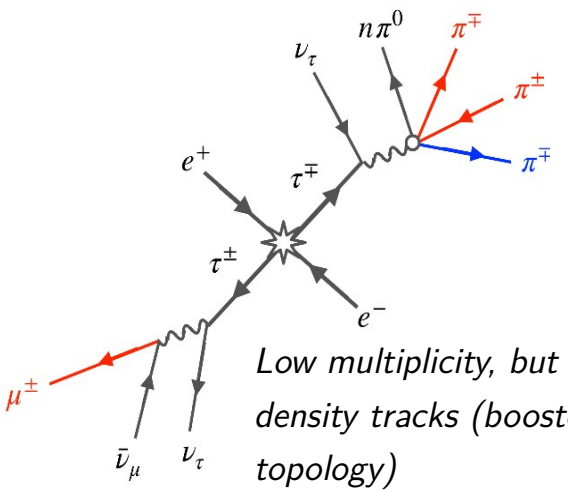
- *Commissioning data* are the first collected with a ***new detector*** at a ***new accelerator***

  → good test for the experiment performance

  → good for some low multiplicity and dark sector physics, but need to be understood!

- To compare data **(Phase 2, ~0.5 fb^{-1})** and MC simulation:
  - Validate shapes and absolute number of events for most relevant kinematics variables
  - Measure detector resolution effects and efficiencies (trigger bias, lepton ID, ***track finding***)





Low multiplicity, but high density tracks (boosted topology)

Tag & probe method

TAG: select events by reconstructing one isolated *good* track consistent with a *electron/muon* hypothesis (*1-prong side*) + two *good* hadronic tracks on the opposite side (*2-prong side*), satisfying $\Sigma q = \pm 1$

PROBE: look for the 4th track in the event, satisfying loose selection requirement and $\Sigma q = 0$.

Count the number of events were the probe track is found (**N4**) and not found (**N3**): $\mathbf{\epsilon^{meas} \times A = N4/(N4 + N3)}$

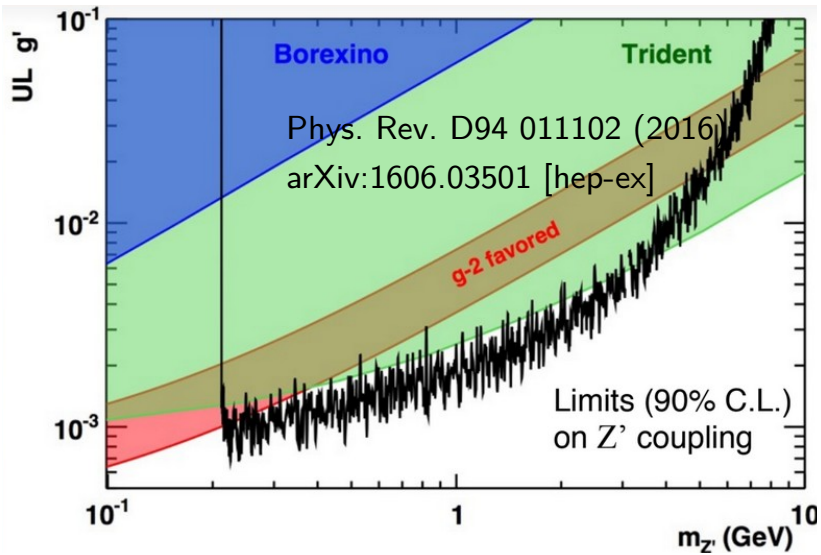
Reference: "*Track finding efficiency in BaBar*" https://arxiv.org/abs/1207.2849

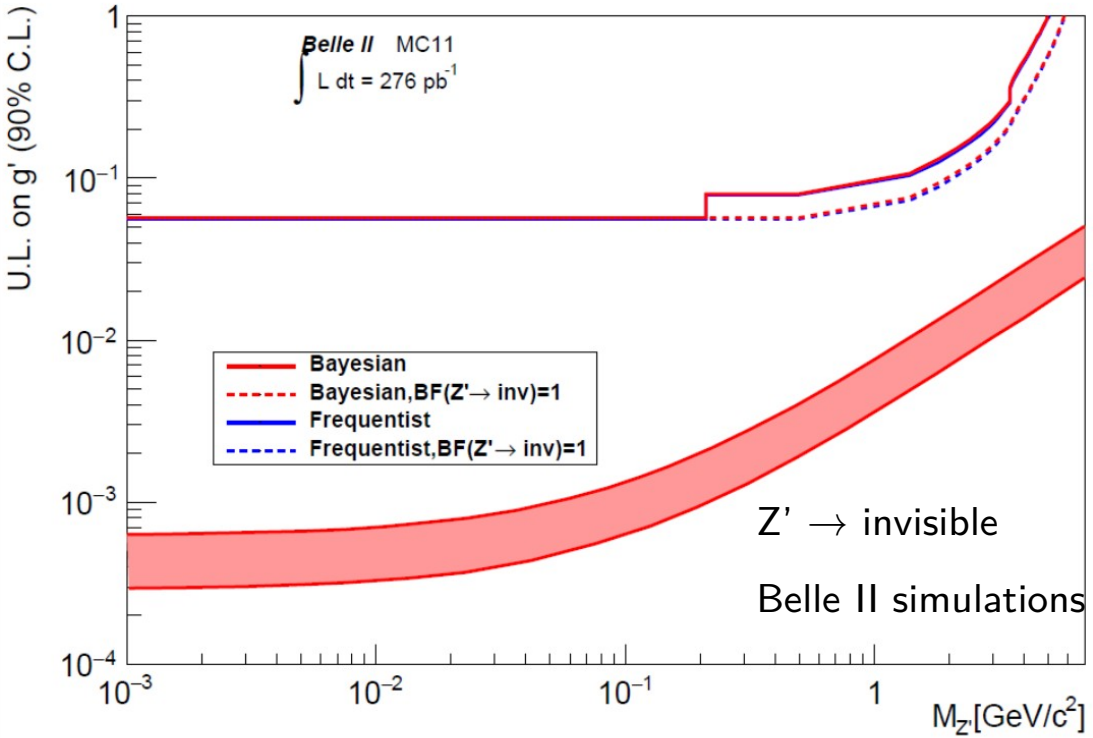
GOAL: estimate the **discrepancy** in tracking efficiency between data and simulation to:

- correct for inefficiencies observed in data
- assign a systematic uncertainty

Z' to invisible: Expected g' Sensitivities

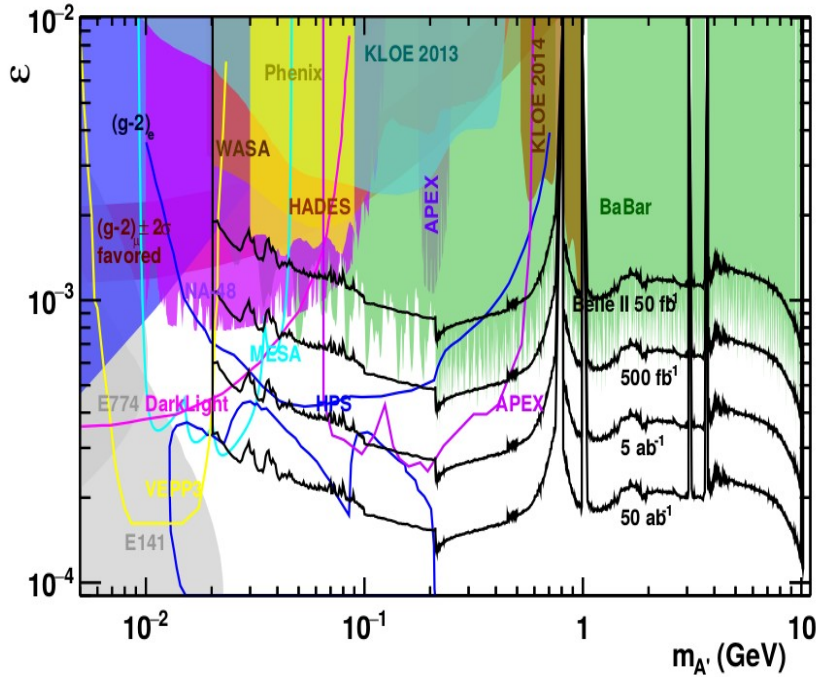
- Muonic dark force, BaBar ($Z' \to \mu\mu$)





- Results still limited by the quality of commissioning Phase 2 data and by **statistics** + inefficiency corrections measured from validation studies

Dark Photon to leptons: Sensitivity



From Belle II Physics Book, arXiv:1808.10567

Fig. 211: Existing exclusion regions (90% CL) on the dark photon mixing parameter ε and mass $M_{A'}$ (solid regions) for $A' \to \ell\ell$, with projected limits for Belle II and other future experiments (lines) (Figure reproduced from [1820]).