LDMA'19 Light Dark Matter 2019

20-22 November 2019
Fondazione Querini Stampalia - Venezia

Belle II

BABAR

Dark sector searches at B-Factories: BaBar and Belle II first results and prospects

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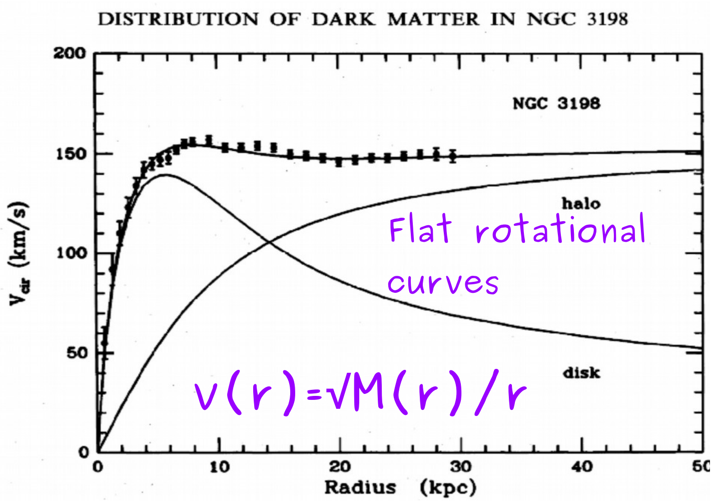
IN SUPREMÆ DIGNITATIS 1343

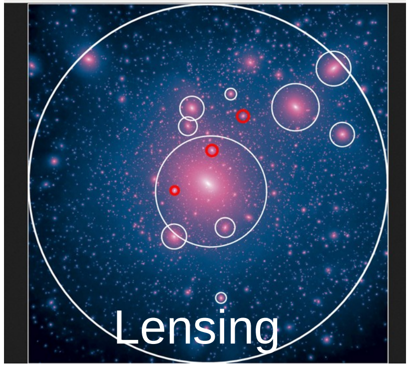
Outline

- Motivations
- B-Factories, first and second generation
- Search for dark matter portals:
  - Dark photon
  - Muonic forces
  - Axion Like Particles
- Summary & Outlook

Dark sector: introduction

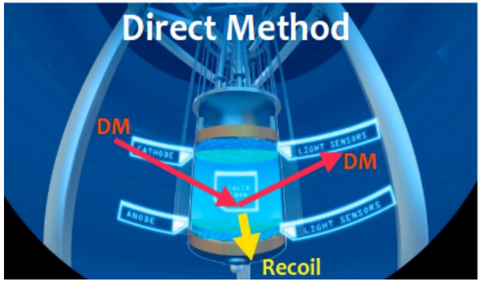
- Many astrophysical observations provide evidence for the existence of a kind of matter that almost does not interact with the Standard Model (SM) particles (*mostly* gravitational interaction) → ***Dark Matter (DM)***

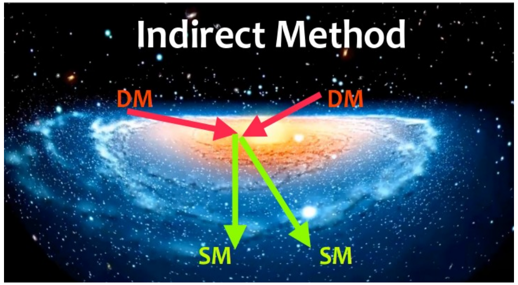




How to search?

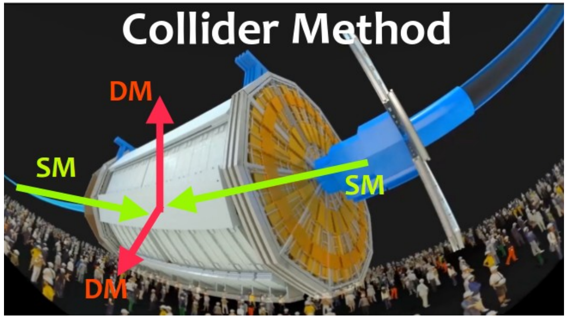
1) Detect the energy of *nuclear recoil*





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***

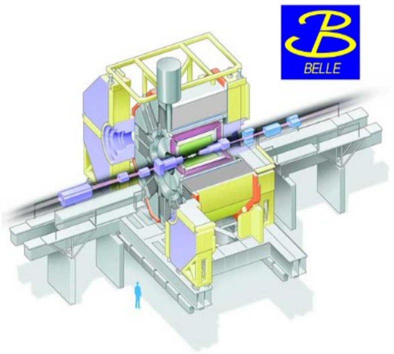
B-Factories: the high intensity frontier

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

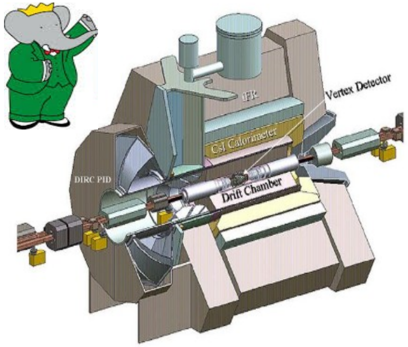
$$e^+e^- \rightarrow \Upsilon(4S)\ [10.58\ \text{GeV}] \rightarrow B\bar{B}$$

$\Upsilon(nS)$ = 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 (II)

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

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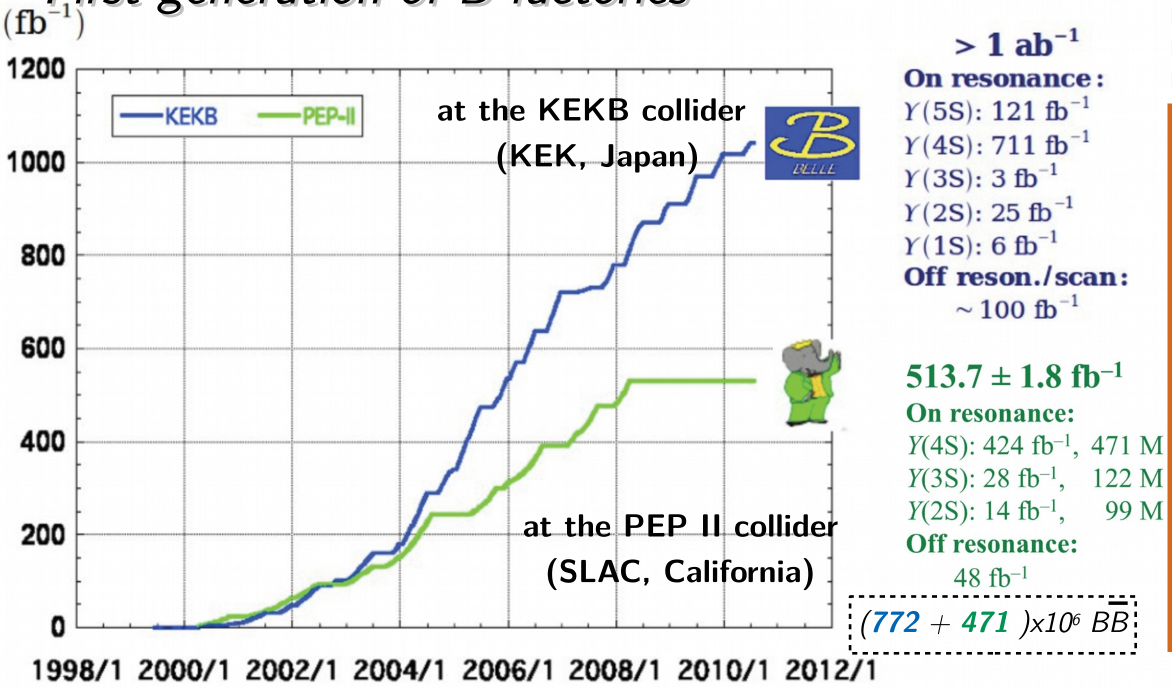
First generation of B-factories



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

- Clean environment → lower background,

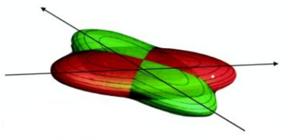
Rich physics program:

- ✔ 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 of B-Factories: SuperKEKB

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

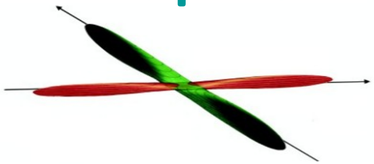
KEKB



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

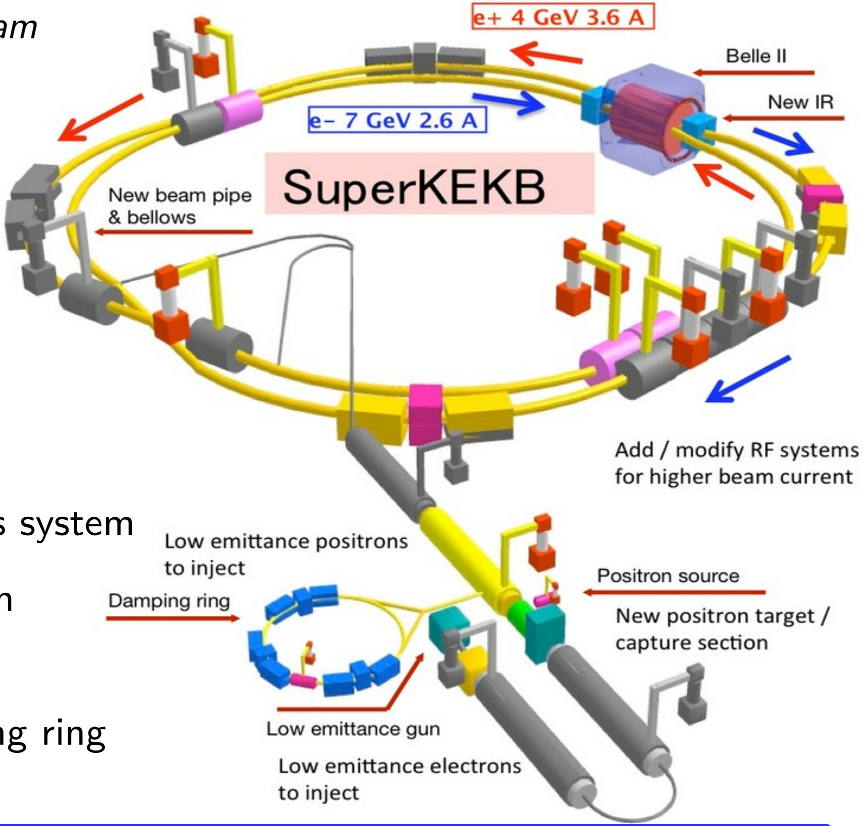
I ↑ x 2

β^*_y ↓ x 1/20

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

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

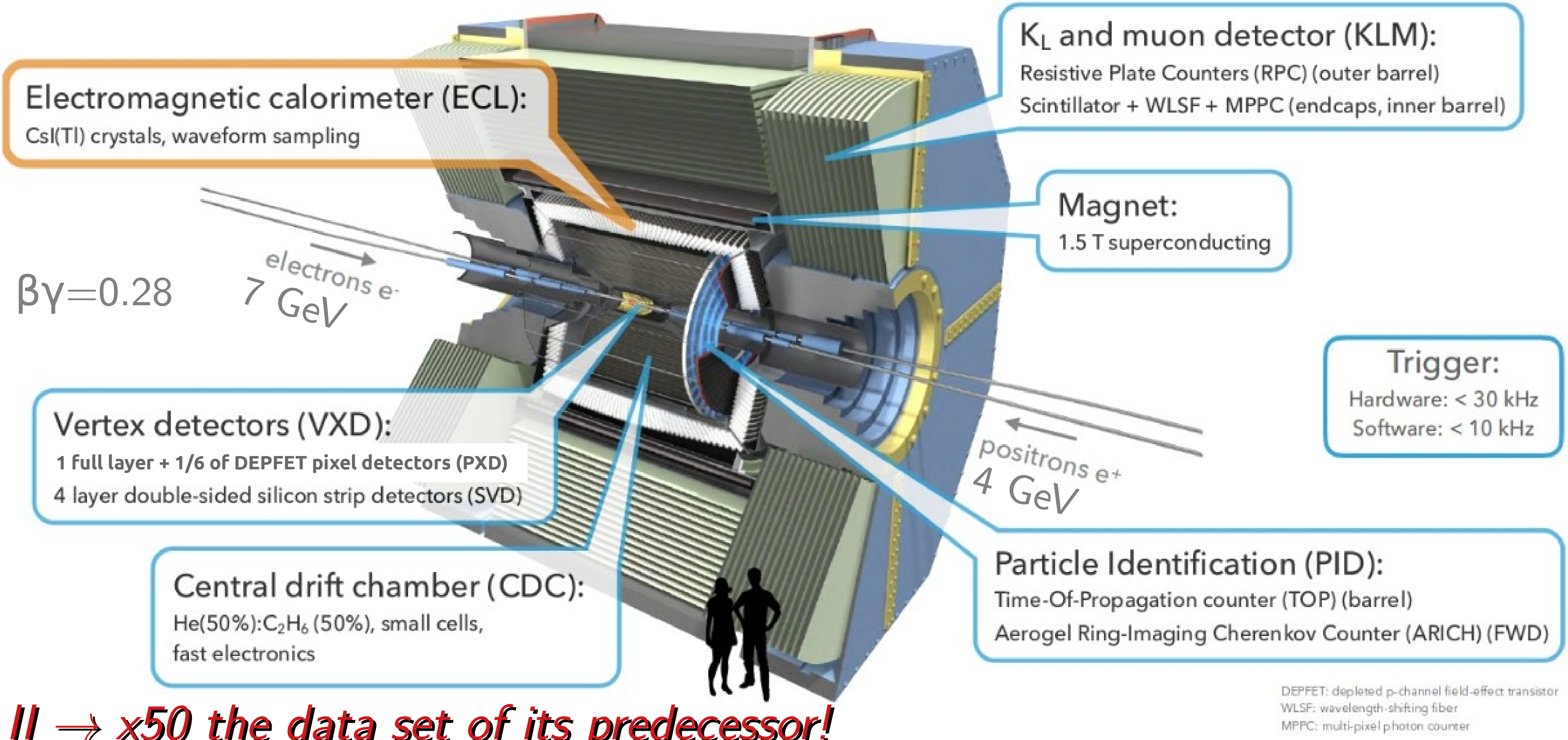
- ✓ New final focus system
- ✓ New Interaction Region
- ✓ New e+ damping ring



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

- Partial VXD installed (one ladder per each layer)
- 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 → suitable for Dark Searches

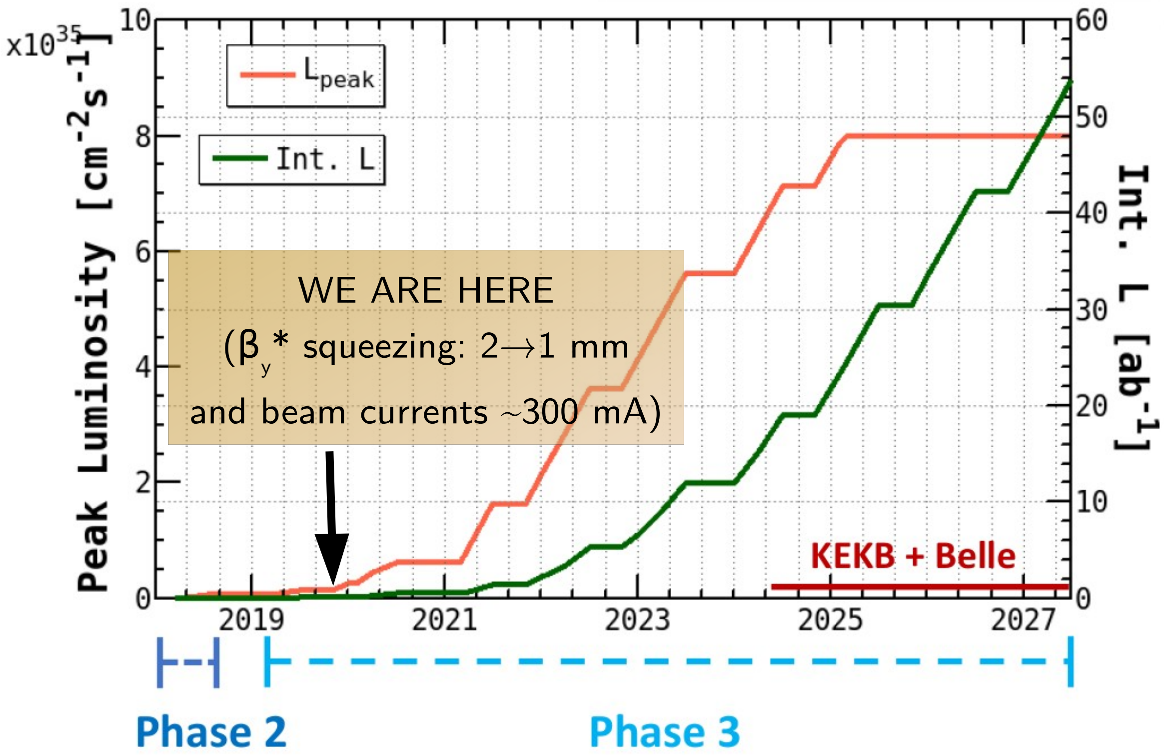
Phase 3: March 2019 – …

- VXD detector installed

  → 4 full layers of silicon strips

  → 1 full of pixels +1/6

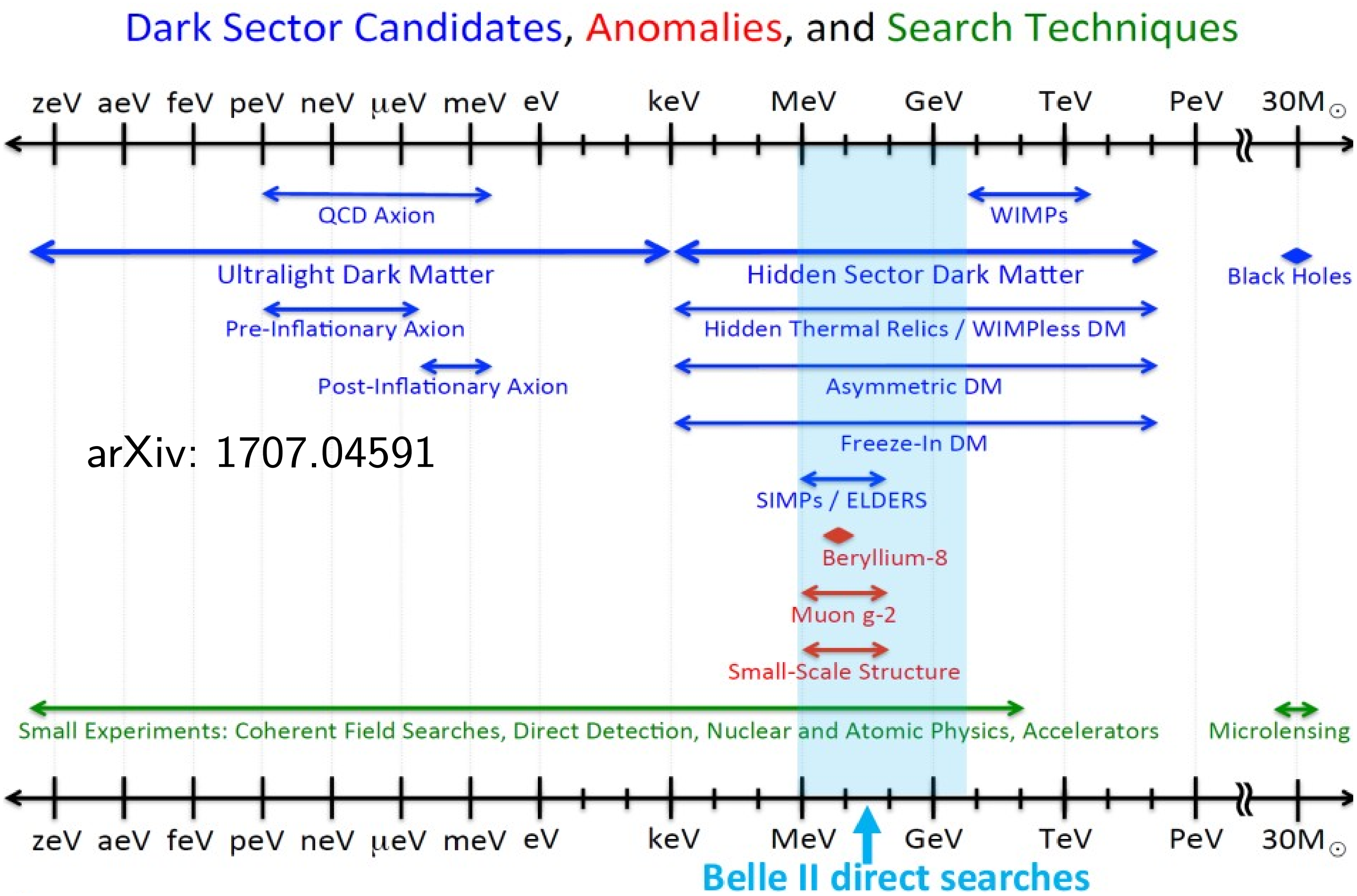
  (installation finalized ~2021)
- ~6.5 fb^{-1} collected during spring runs



Expected ≤20 fb^{-1} by end of the year, ≤200 fb^{-1} by summer 2020

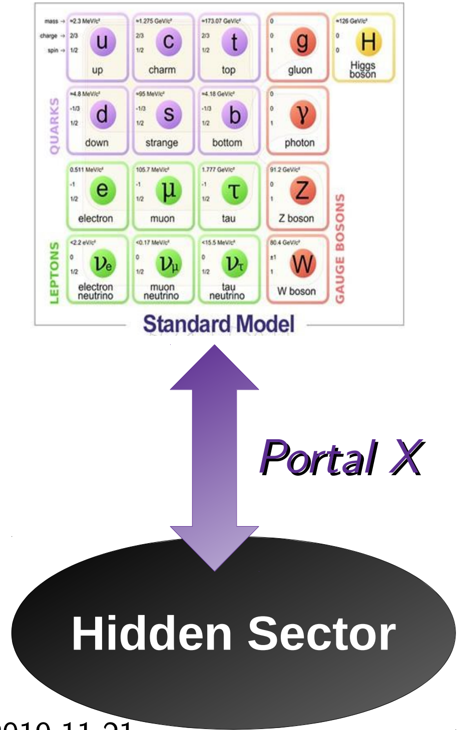
→ FINAL GOAL : 50 ab^{-1}

Panoramic view on dark searches

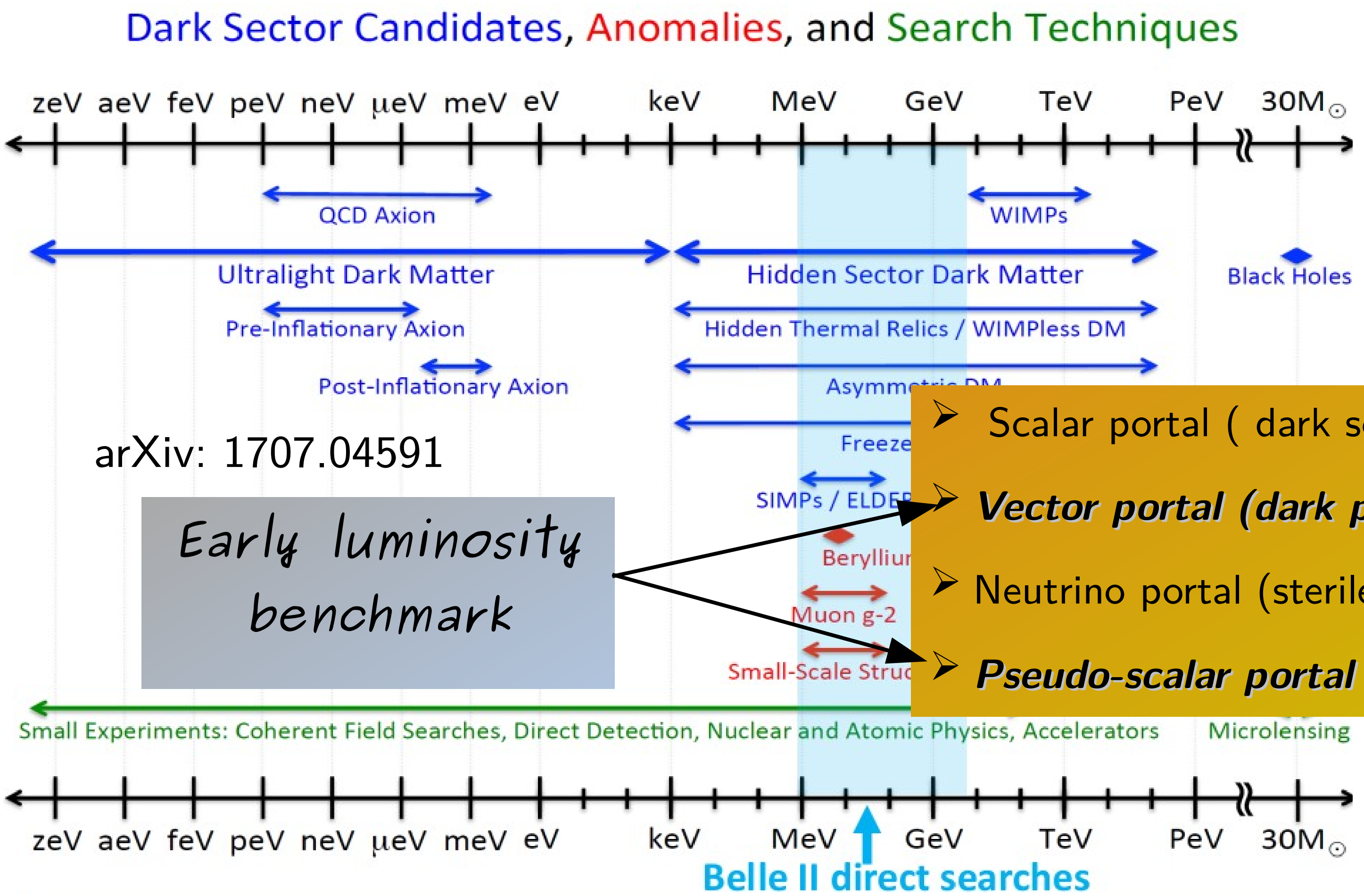


arXiv: 1707.04591

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



Panoramic view on dark searches: dark portals

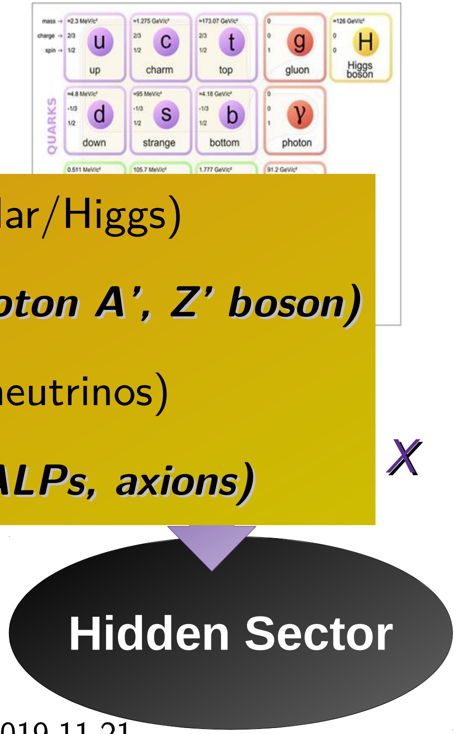


arXiv: 1707.04591

Early luminosity benchmark

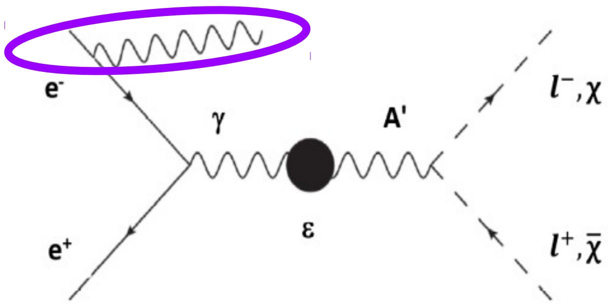
- Scalar portal (dark scalar/Higgs)
- ***Vector portal (dark photon A', Z' boson)***
- Neutrino portal (sterile neutrinos)
- ***Pseudo-scalar portal (ALPs, axions)***

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



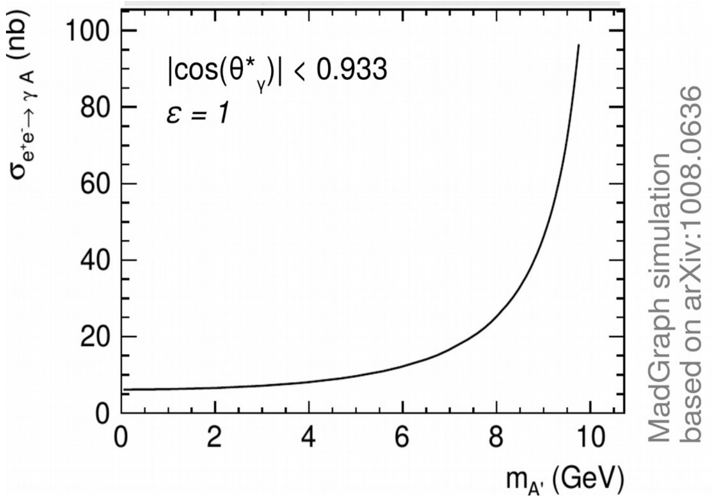
The dark photon

- 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 ε → the ***dark photon***
- At e^+e^- colliders we investigate the ISR production $e^+e^- \to \gamma A'$.



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

Batell et al. (2009), arXiv:0903.0363



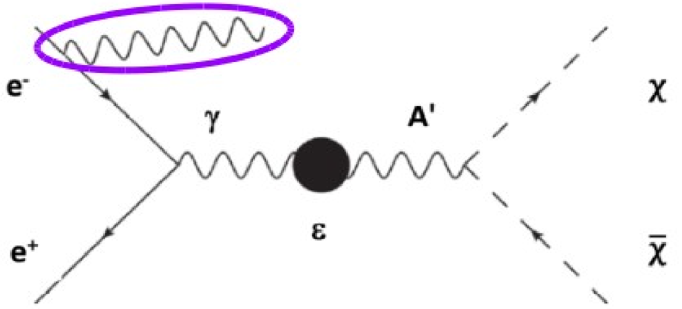
- If $m_{A'} < 2m_\chi$ → A' decays visibly to SM particle (leptons) → **514 fb^{-1}** — **sensitivity studies**
- If $m_{A'} > 2m_\chi$ → A' decays 100 % invisibly into DM particle, $e^+e^- \to \gamma A'$, $A' \to \chi\chi$ → **53 fb^{-1}** — **early Phase 3 benchmark (~ 20 fb^{-1} good quality data)**

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 $E_\gamma = (s - m^2_{A'})/2\sqrt{s}$

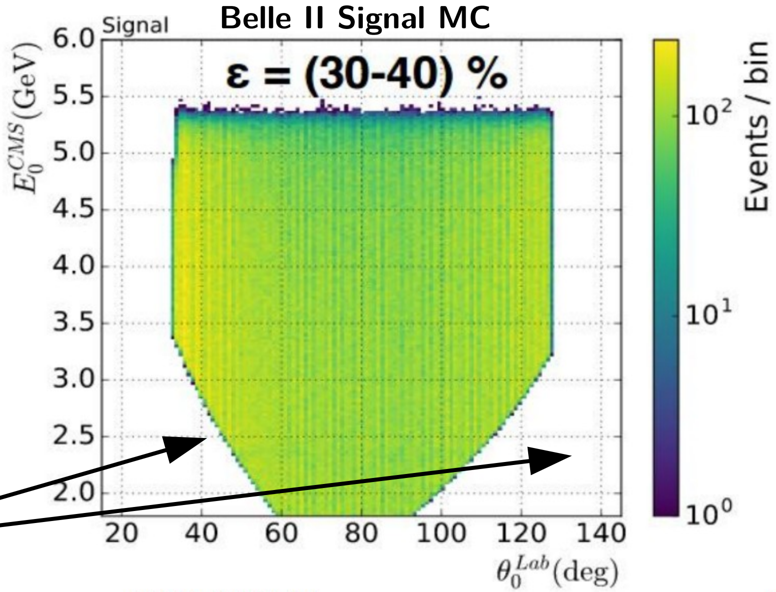
    $\rightarrow$ only one photon in the detector requires a dedicated ***single photon trigger***

    (at Belle was not available, at BaBar was available only on ~10% data)



Belle II Phase 3 (Design)

Trigger logic	L1 rate at full luminosity
E > 1 GeV (veto clusters above 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

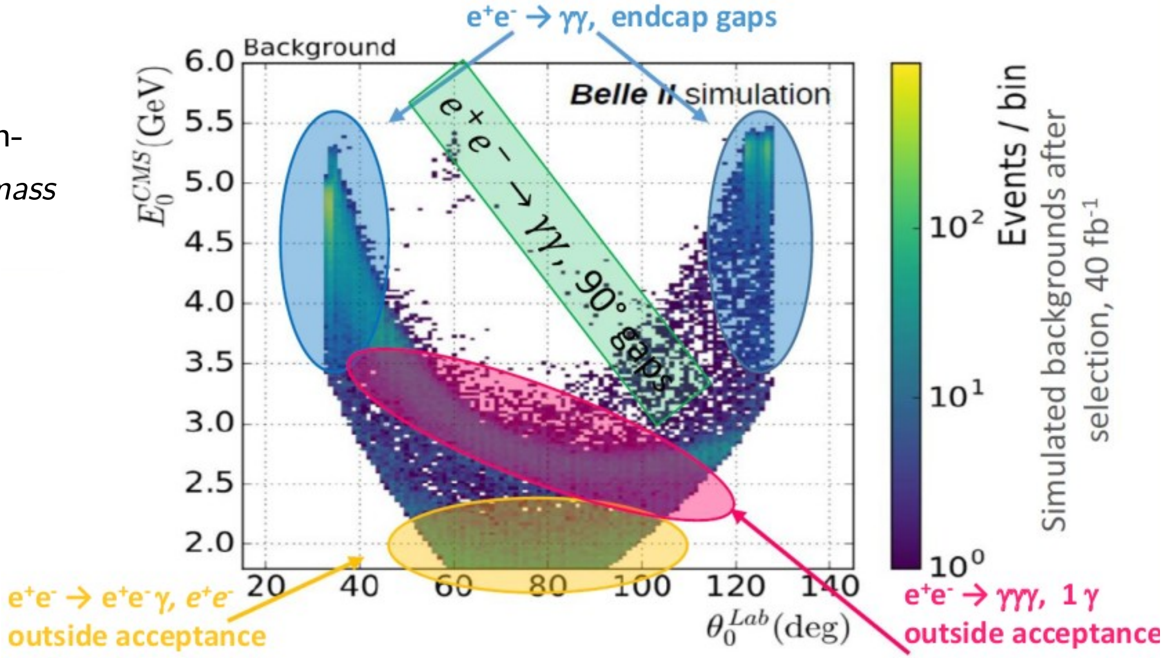
Dark photon to invisible: backgrounds

- Background dominated by QED processes:
  - $e^+e^- \to \gamma\gamma(\gamma)$ where one photon is not detected (ECL gaps) or out of acceptance (dominating *low mass* region)
  - radiative Bhabha $e^+e^- \to e^+e^-\gamma(\gamma)$ with the electron-positron pair out of acceptance (dominating *high mass* region).

Optimize the analysis separately in the Low Mass region, $M_x^2 < 36$ GeV^2, and High Mass region, $24 < M_x^2 < 69$ GeV^2.

- ***BDT discriminant*** **trained on 12 variables (signal cluster shape, cluster properties, additional energy deposited in the calorimeter, etc)**
- **Optimize analysis in model independent approach**
- **Interpret results for dark photon decay (ε, $M_{A'}$)**

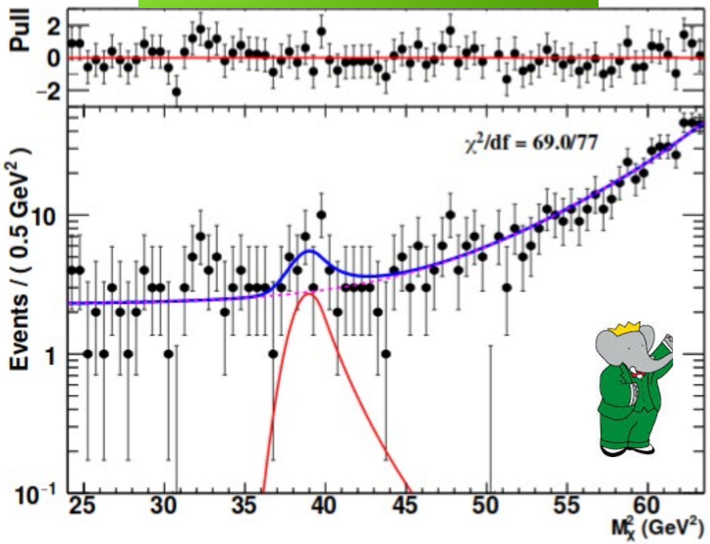
Simulation studies at Belle II

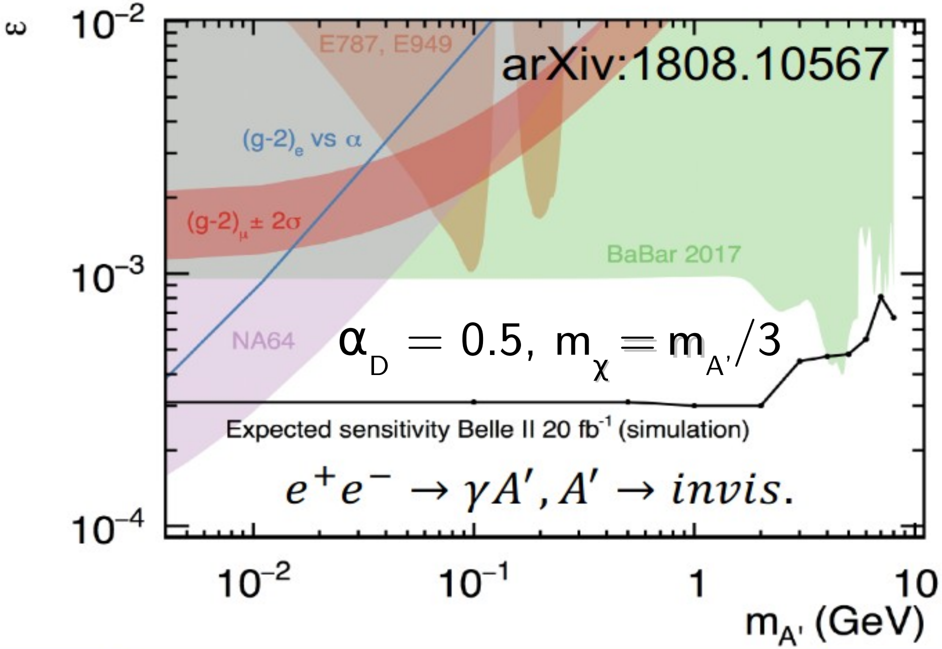


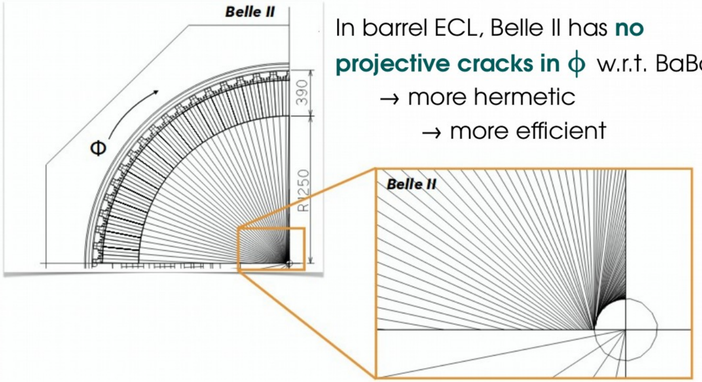
$e^+e^- \to \nu\nu\gamma$ negligible

Invisible dark photon sensitivity

Phys. Rev. Lett. 119, 131804 (2017)







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

→ more hermetic

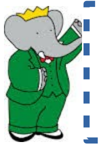
→ more efficient

- No ECL cracks pointing to the Interaction region
- KLM can compensate ECL photon detection gap
- Better hermeticity (smaller boost $\beta\gamma = 0.28$, larger acceptance)
- Improved L1 trigger lines

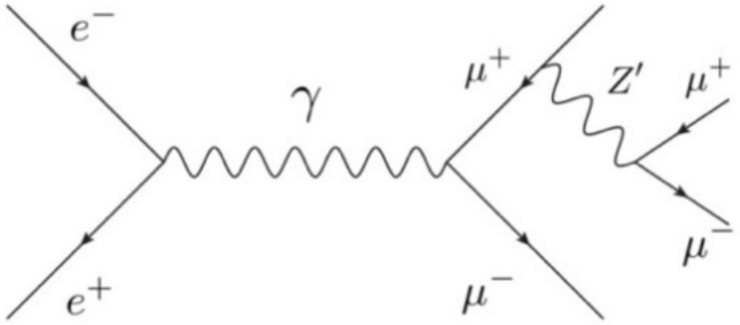
Muonic dark forces: L_μ-L_τ model

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

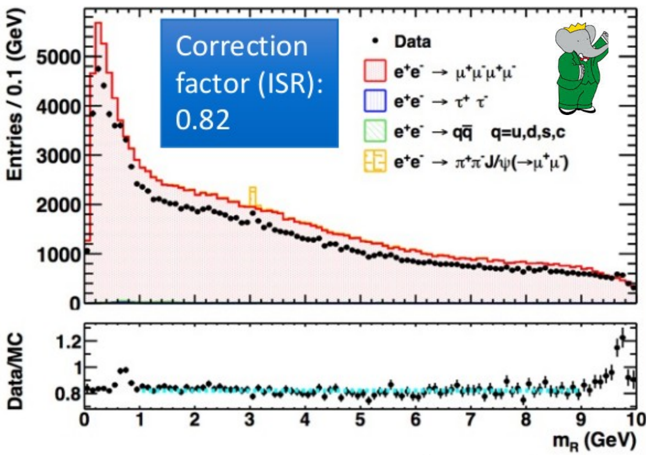
  $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to l, \nu, X$



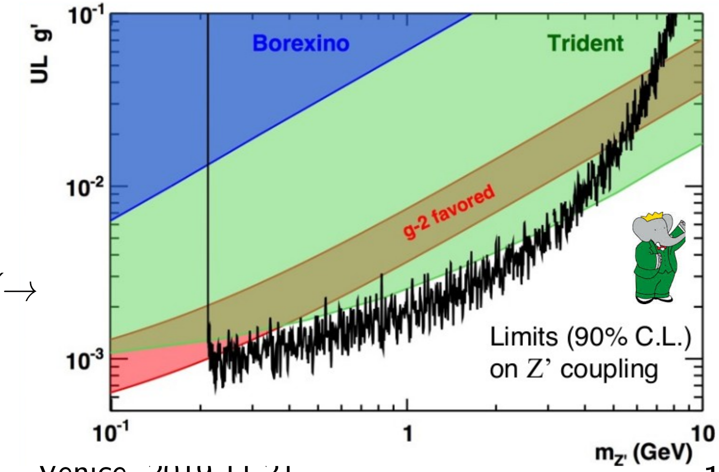
- Muonic dark force at BaBar: visible final state to two muons
- Search for a di-muon invariant mass peak in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$



Backgrounds:
- *QED combinatorial*
- *Resonant $e^+e^- \to \pi^+\pi^- J/\psi$ ($\to \mu^+\mu^-$)*



Di-muon reduced mass: $m_R = (m_{\mu\mu}^2 - 4m_\mu^2)^{1/2}$



Limits (90% C.L.) on Z' coupling

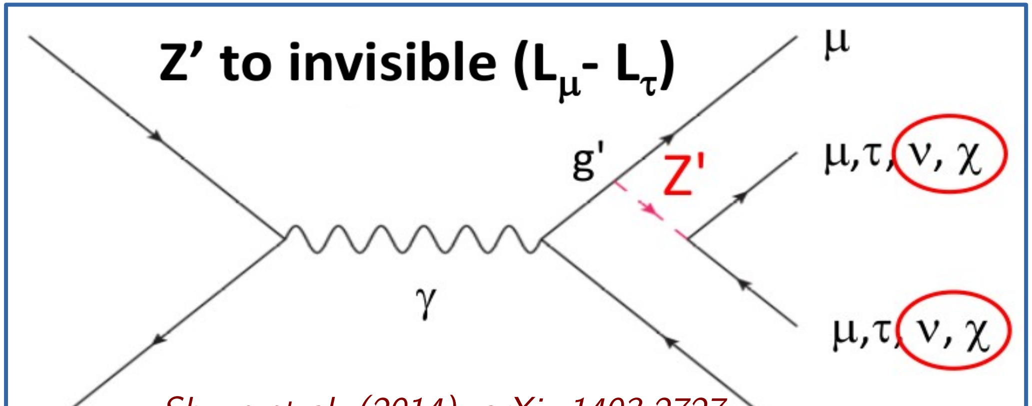
Z' to invisible

Invisible signature investigated for the first time in the process

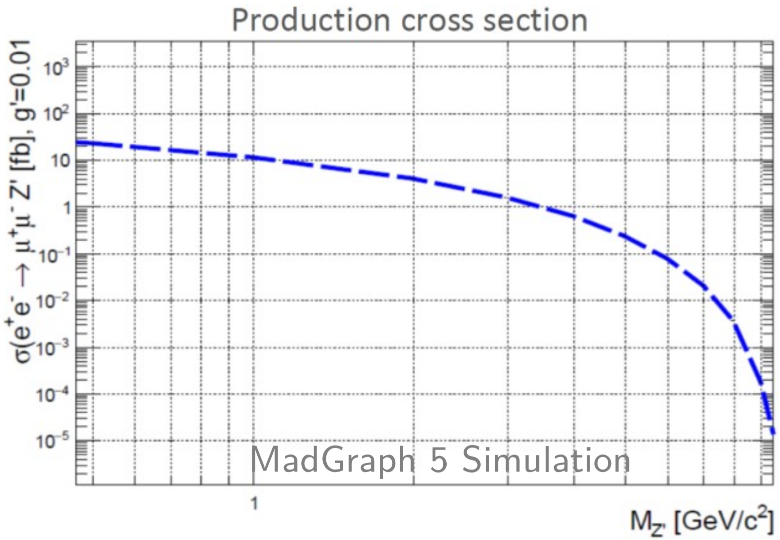
$$e^+e^- \to \mu^+\mu^- + \textit{missing mass}$$

- Search for a peak in the recoil mass spectrum against a $\mu^+\mu^-$ pair in event where *NOTHING* else is detected.
- Background from QED processes that can mimic the final state of 2 muons + missing mass because of acceptance or undetected particles:

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



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



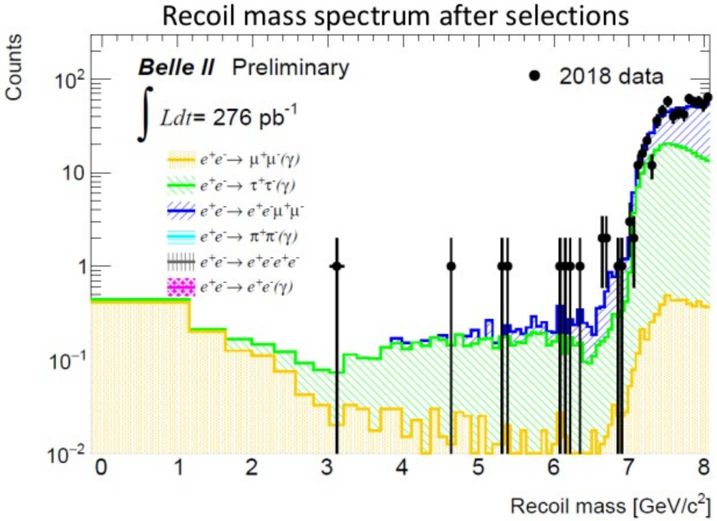
Branching ratios:

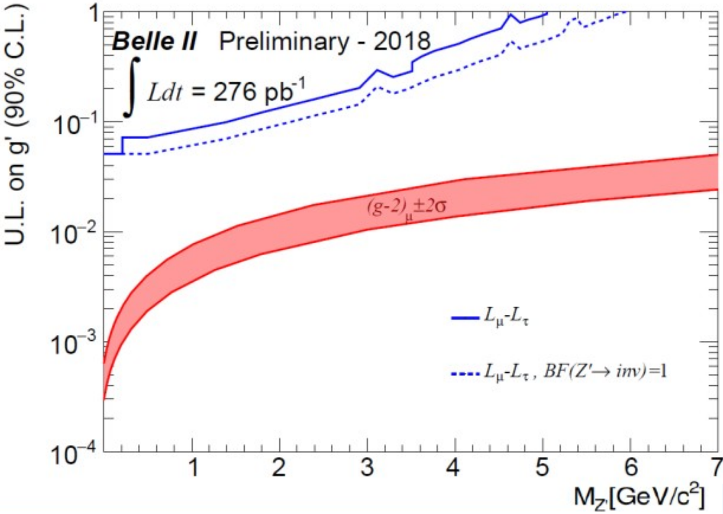
$$M_{Z'} < 2M_\mu \to \Gamma(Z' \to \text{inv.}) = 1$$
$$2M_\mu < M_{Z'} < 2M_\tau \to \Gamma(Z' \to \text{inv.}) \sim 1/2$$
$$M_{Z'} > 2M_\tau \to \Gamma(Z' \to \text{inv.}) \sim 1/3$$

If LDMA is accessible, BR(Z'$\to$ DM)~1

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

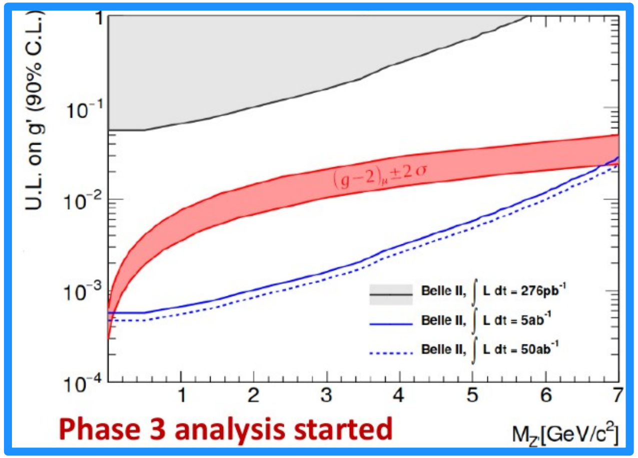
To be submitted to PRL

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}

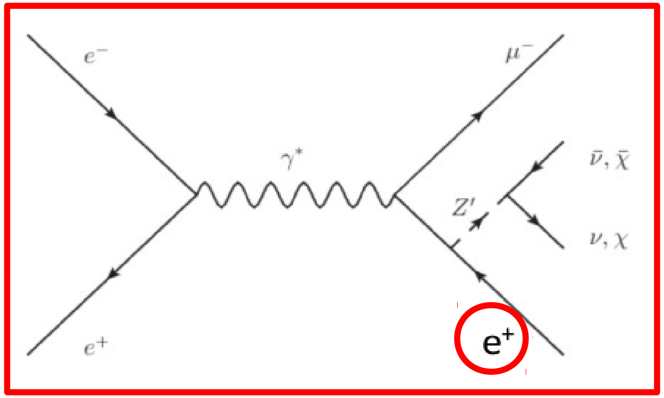


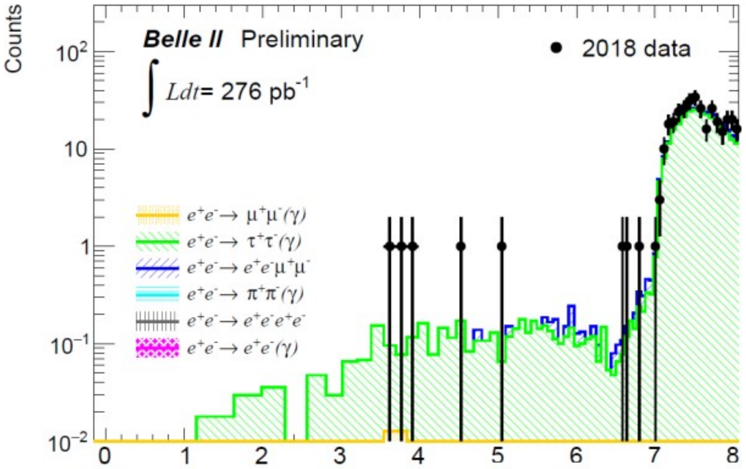
Phase 3 analysis started

LFV Z' to invisible

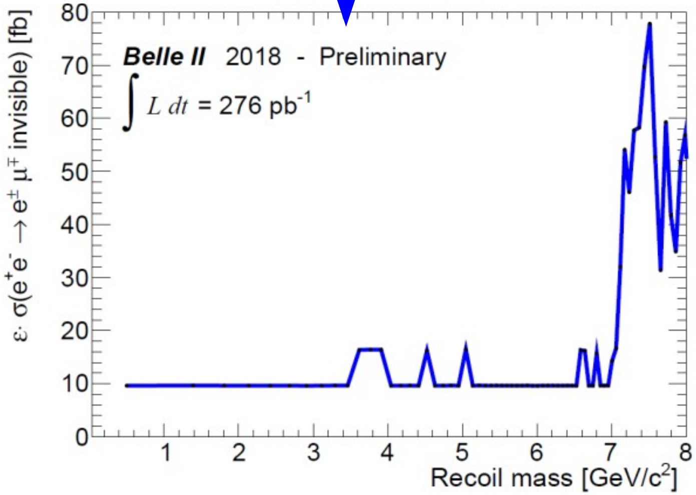
Galon et al. https://doi.org/10.1007/JHEP05(2017)083
Galon et al, https://doi.org/10.1007/JHEP03(2017)064

- 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 *(Ɛxσ) product with 90% CL upper limit*





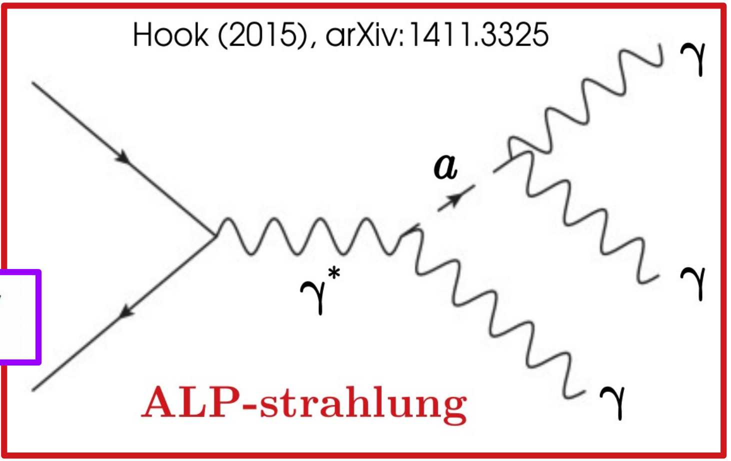
No excess



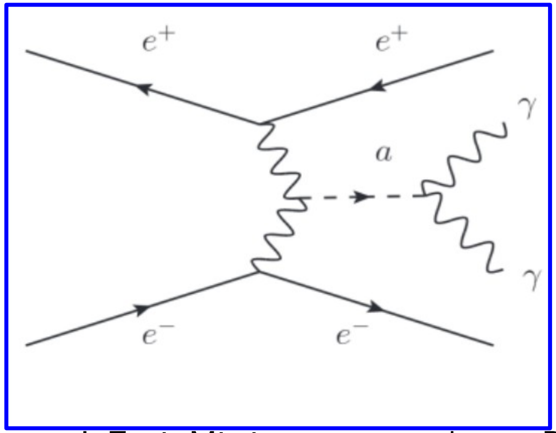
Axion Like Particles (ALPs)

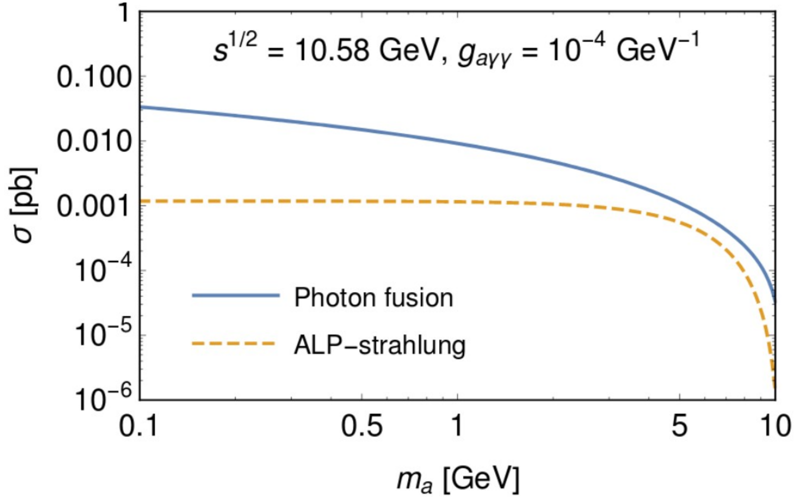
- Axion Like Particles are pseudo-scalars coupling mainly to bosons
- Unlike for QCD Axions, there is no relation between the coupling and the mass

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$



- 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

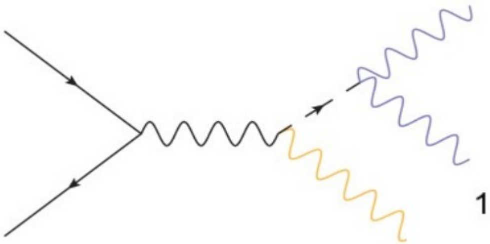


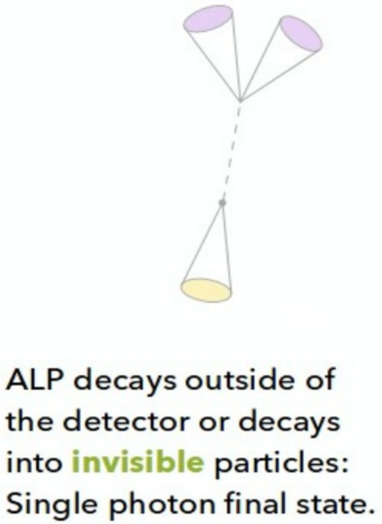


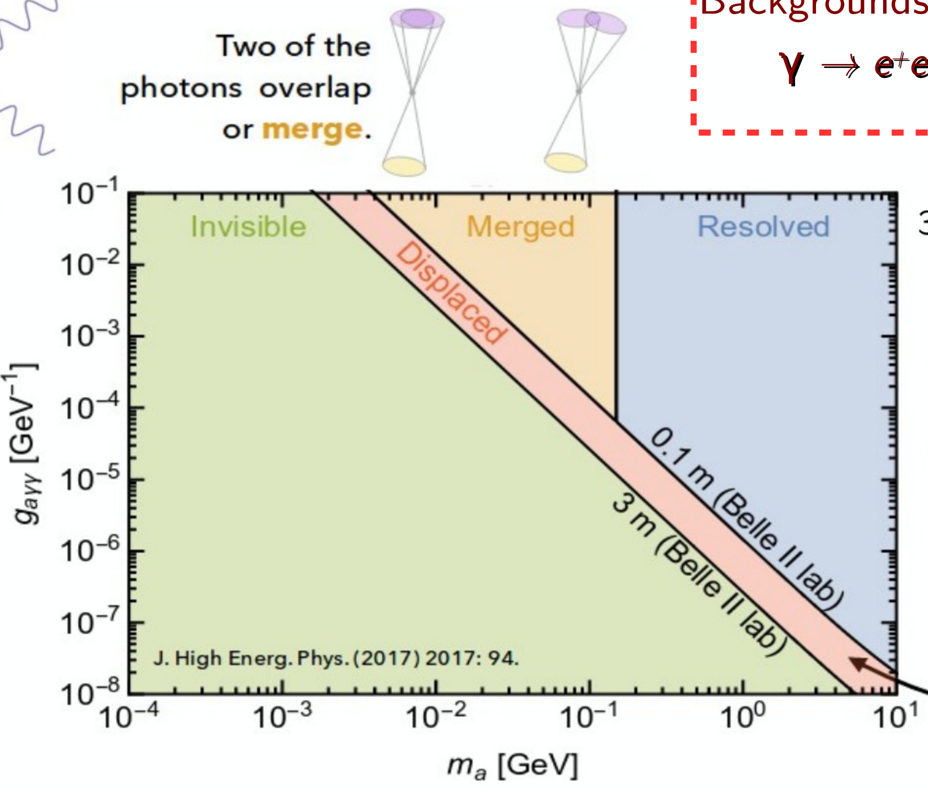
ALPs: experimental signature

- 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







For **resolved** case:

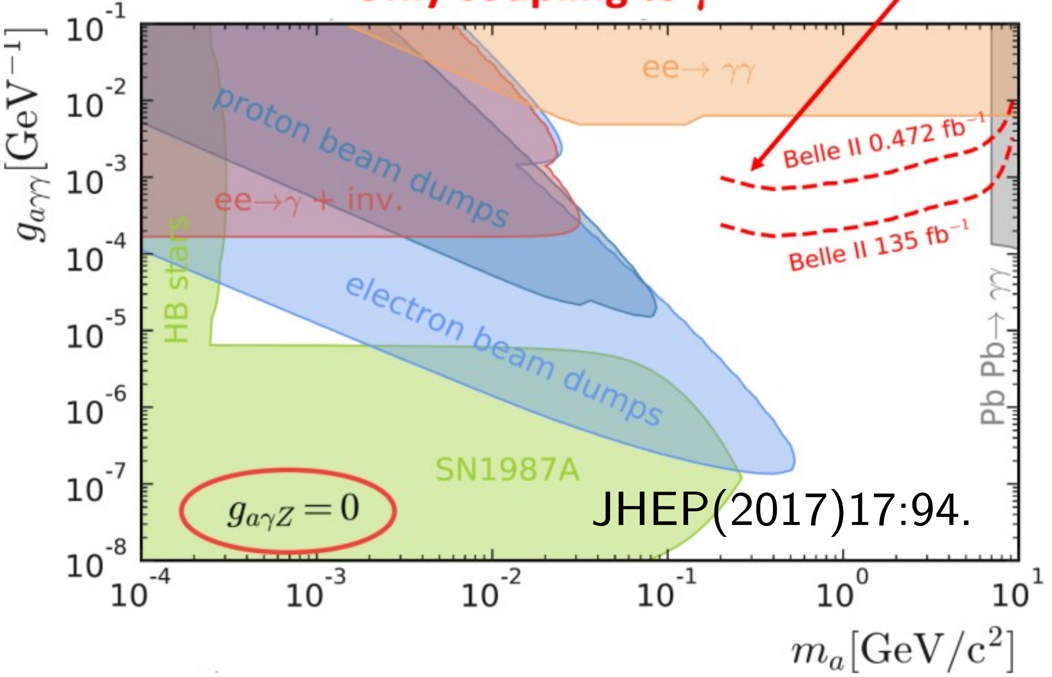
3 clusters with $E_{CM} > 0.25$ GeV

Peak in $\gamma\gamma$ mass spectrum

ALPs: sensitivity

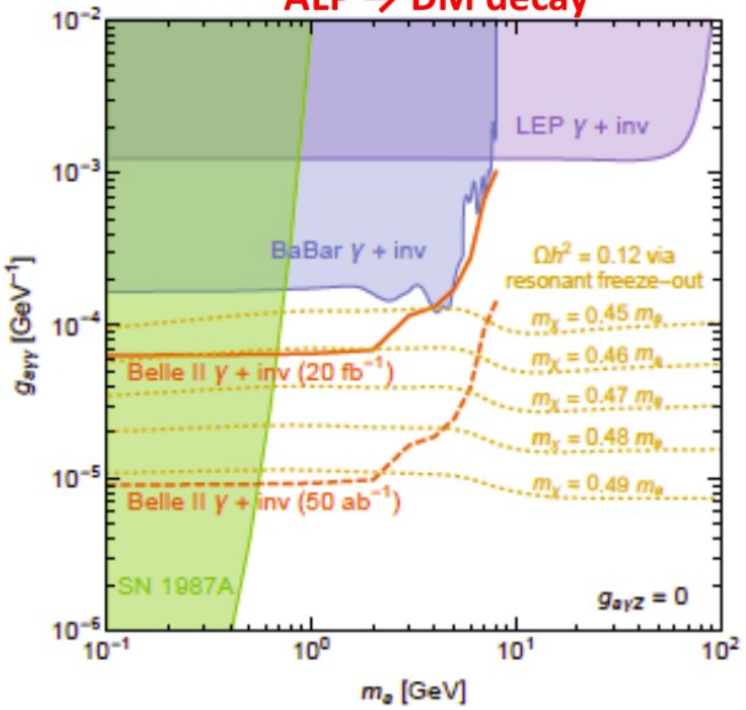
Result expected very soon

Only coupling to γ



JHEP(2017)17:94.

ALP → DM decay



- 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*

Summary

- BaBar pioneered missing mass searches at B-Factories (dark photon to invisible), constraining the kinetic mixing strength down to 10^{-4}-10^{-3} for the mass range < 8 GeV

$\rightarrow$ ***First Belle II physics results are coming soon!***

- Phase 2 (2018) pilot run showed good results for the machine and detector commissioning. The **0.5 fb^{-1} collected data have been used for Dark Searches**
- Phase 3 started in March 2019, **6.5 fb^{-1}** available: rediscover resonances, B and charm physics.

  $\rightarrow$ *New analyses* started!

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
- …

A rich dark sector program is under investigation at Belle II which has a unique potential for ***searches never done before.***

$\rightarrow$ ***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

Backup

First generation B-Factory: BaBar experiment

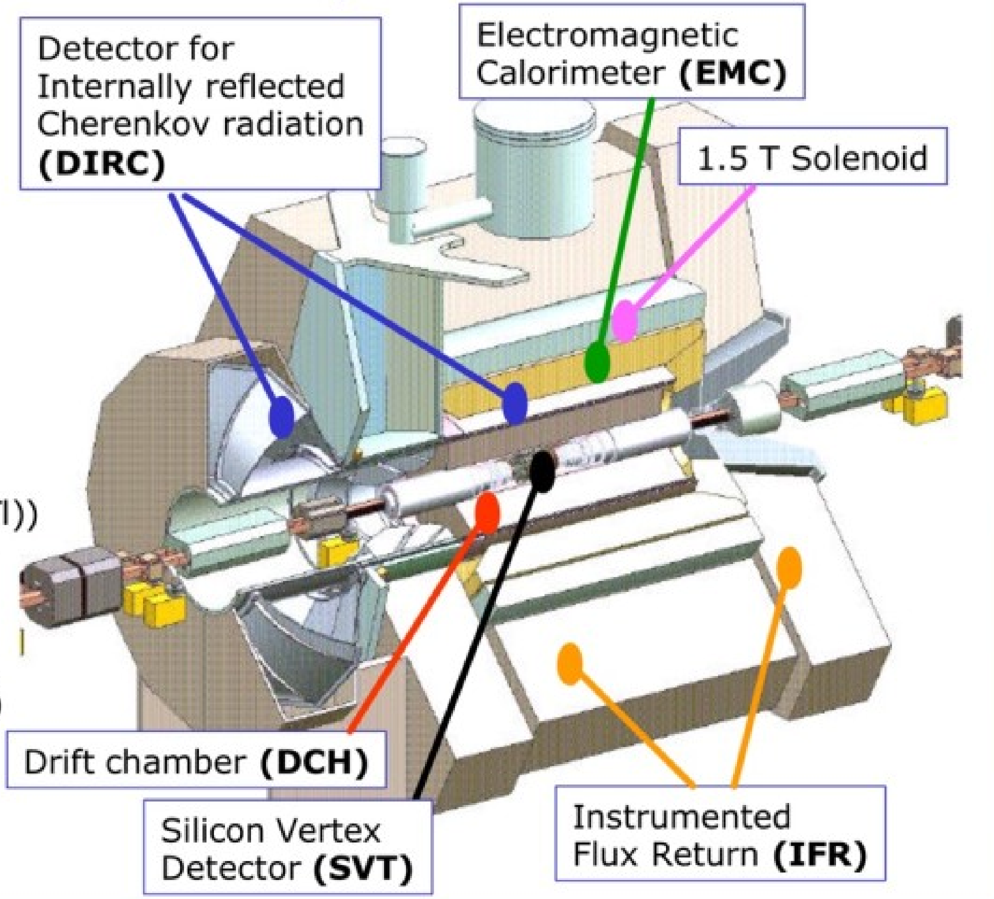
SVT: 5 layers double-sided Si.
Crucial for measuring Δt.

DCH: 40 layers in 10 super-layers, axial and stereo.

DIRC: Array of precisely machined quartz bars.
Excellent Kaon identification.

EMC: Crystal calorimeter (CsI(Tl))
Very good energy resolution.
Electron ID, π^0 and γ reco.

IFR: Layers of RPCs within iron.
Muon and neutral hadron (K_L)



Production cross section at $\Upsilon(4S)$

The Belle II Physics Book, arXiv:1808.10567

Table 18: Total production cross section from various physics processes from collisions at $\sqrt{s} = 10.58$ GeV. $W_{\ell\ell}$ is the minimum invariant secondary fermion pair mass.

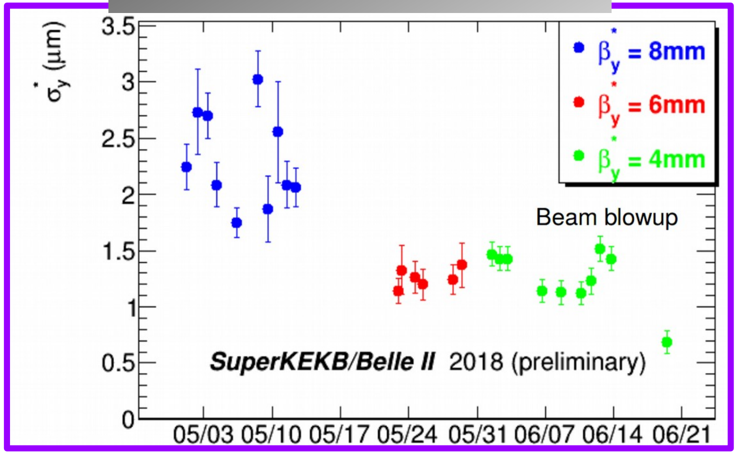
Physics process	Cross section [nb]	Selection Criteria	Reference
$\Upsilon(4S)$	1.110 ± 0.008	-	[2]
$u\bar{u}(\gamma)$	1.61	-	KKMC
$d\bar{d}(\gamma)$	0.40	-	KKMC
$s\bar{s}(\gamma)$	0.38	-	KKMC
$c\bar{c}(\gamma)$	1.30	-	KKMC
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10° < \theta_e^* < 170°$, $E_e^* > 0.15$ GeV	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	$p_e > 0.5$ GeV/c and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta_\gamma^* < 170°$, $E_\gamma^* > 0.15$ GeV	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5$ GeV in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5$ GeV/c in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5$ GeV in CDC, $\geq 1\ \gamma$ ($E_\gamma > 0.5$ GeV) in ECL	-
$\tau^+\tau^-(\gamma)$	0.919	-	KKMC
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	KKMC
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$ GeV/c^2	AAFH
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$ GeV/c^2	AAFH

SuperKEKB Numbers

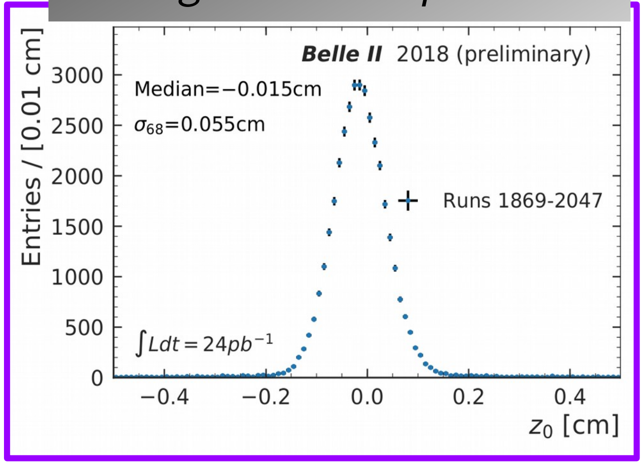
2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	$3.20\text{x}10^{-4}$	$4.55\text{x}10^{-4}$		
σ_δ	$7.92(7.53)\text{x}10^{-4}$	$6.37(6.30)\text{x}10^{-4}$		():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	$8\text{x}10^{35}$		$cm^{-2}s^{-1}$	

Belle II Performances in Phase 2

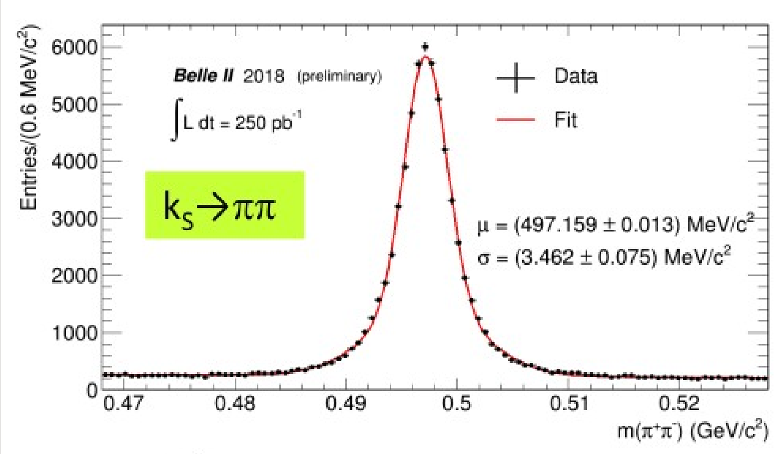
Vertical beam size

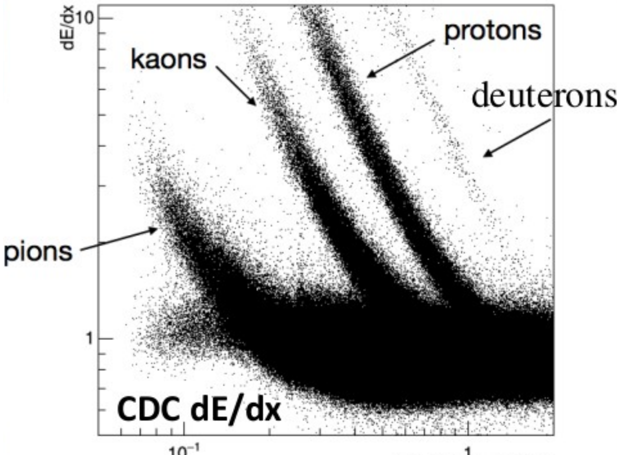


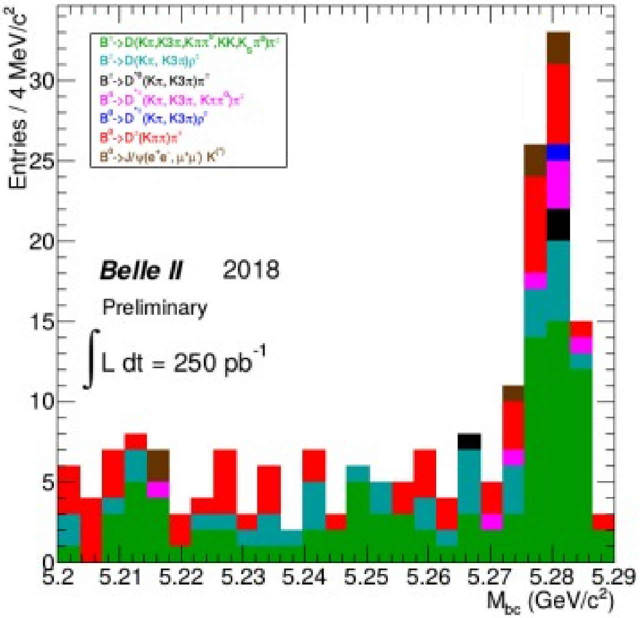
Longitudinal IP position



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

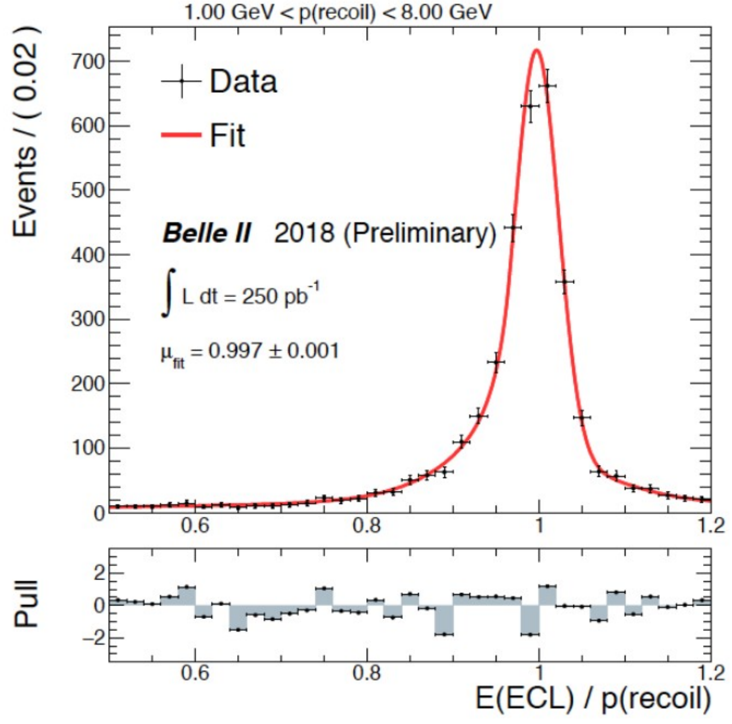




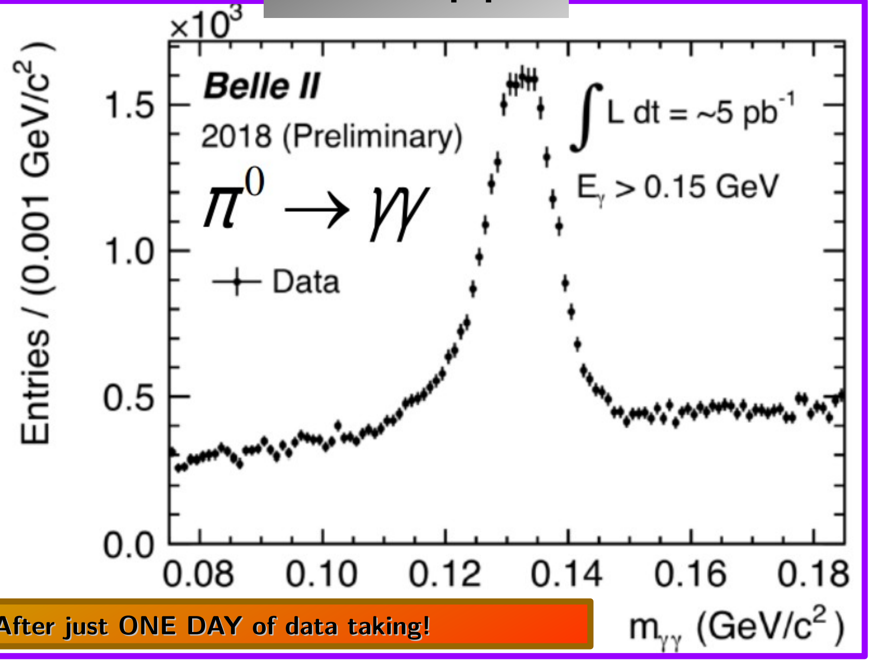


Belle II Performances in Phase 2: photon reconstruction

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



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



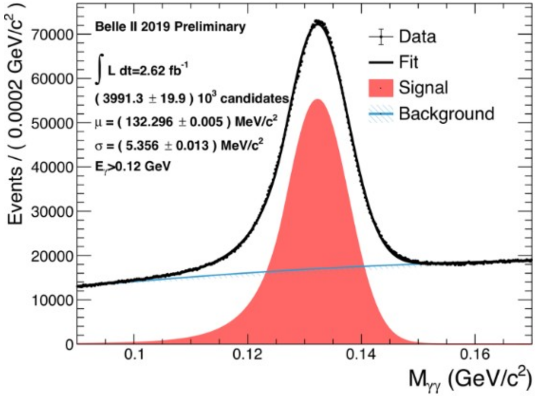
After just ONE DAY of data taking!

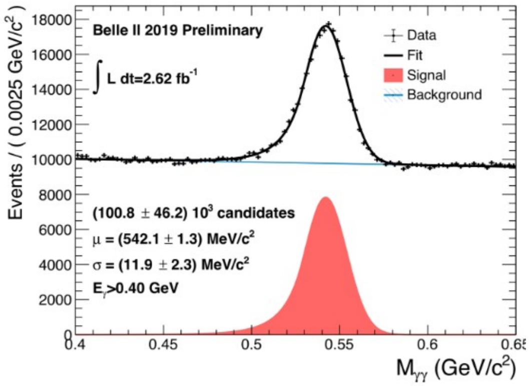
$e^+e^- \to \gamma\ X$

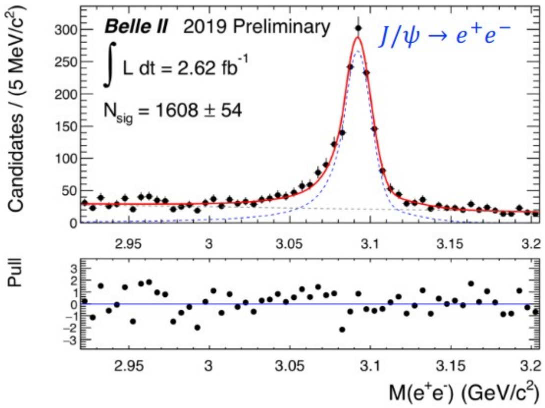
$e^+e^- \to \gamma\ ALPS \to \gamma(\gamma\gamma)$

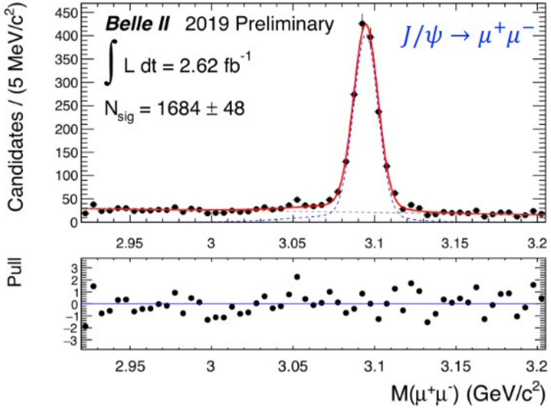
Belle II Phase 3 snapshot

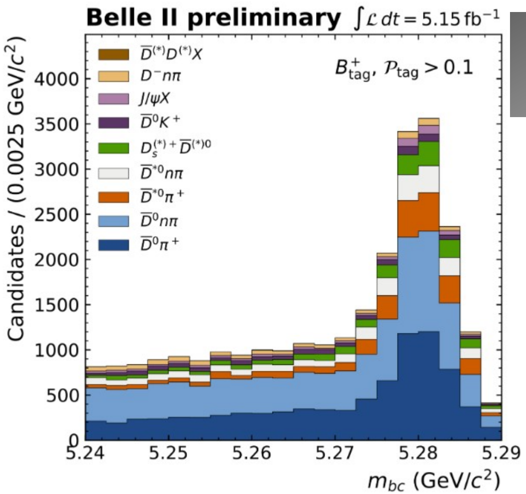
π^0, $\eta \to \gamma\gamma$





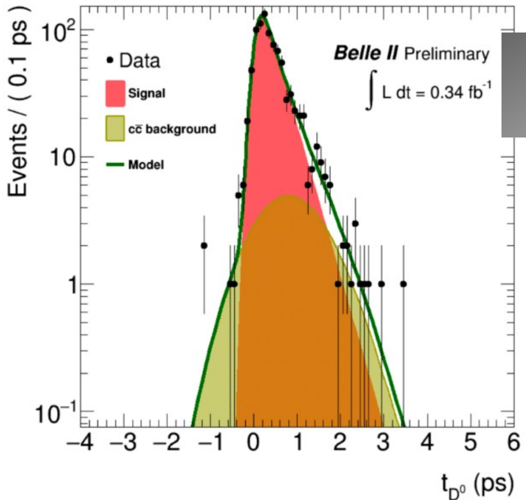






FEI, B tagging

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

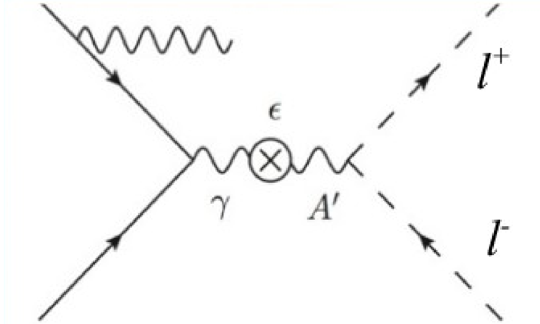


D^0 lifetime

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

PDG average: (410.1 ± 1.5) fs

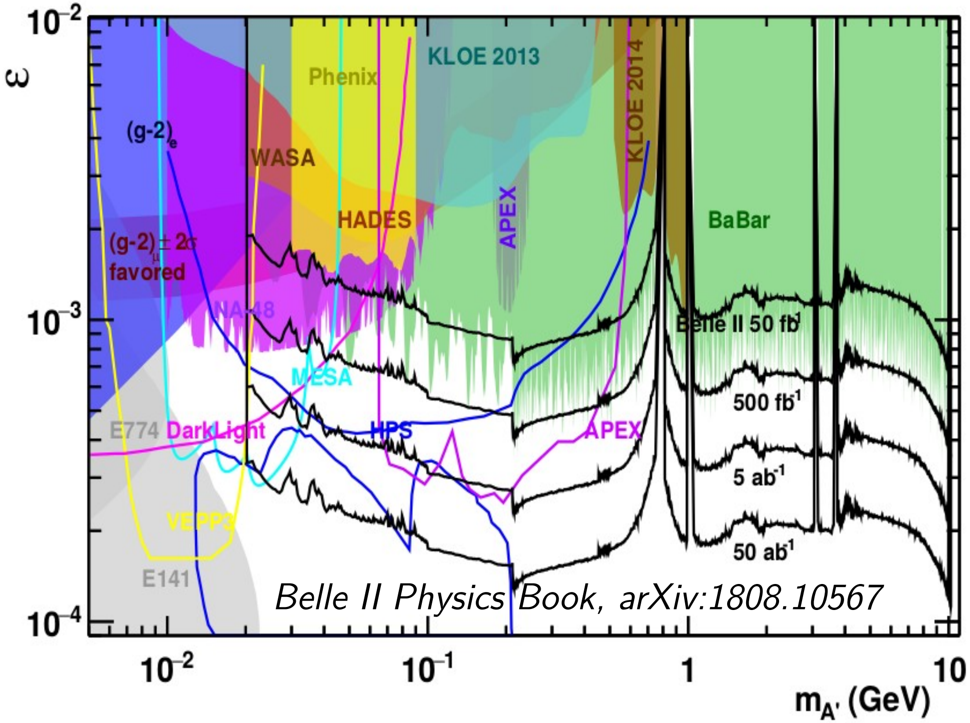
Dark Photon to visible



- Search for a peak in the dilepton (l= e, μ) invariant mass, in the range $0.02 < M_{A'} < 10.2\ \mathrm{GeV}/c^2$ (all available CM energies used)
- Select two oppositely charge tracks and a photon with energy $E_\gamma > 200$ MeV

- *QED backgrounds:* $e^+e^- \to e^+e^- (\mu^+\mu^-)\gamma$, $e^+e^- \to \gamma\gamma(\gamma \to e^+e^-)$

  → *neural network* optimized selection (angular variables, electron flight length)
- Use simulated templates to model the signal shape
- Extract the signal yield by fitting the dielectron (muon reduced mass, $m_R = \sqrt{(m^2_{\mu\mu} - 4m^2_\mu)}$, easier to model at threshold) → obtain 90% CL exclusion limits



Belle II Physics Book, arXiv:1808.10567

Expected improvement of BaBar limits (~10^{-4} mixing strength) due to better mass resolution (factor 2) and L1 trigger performances on two-track events (factor 1.1-2.2).

Invisible Dark Photon at BaBar

Phys. Rev. Lett. 119, 131804 (2017)

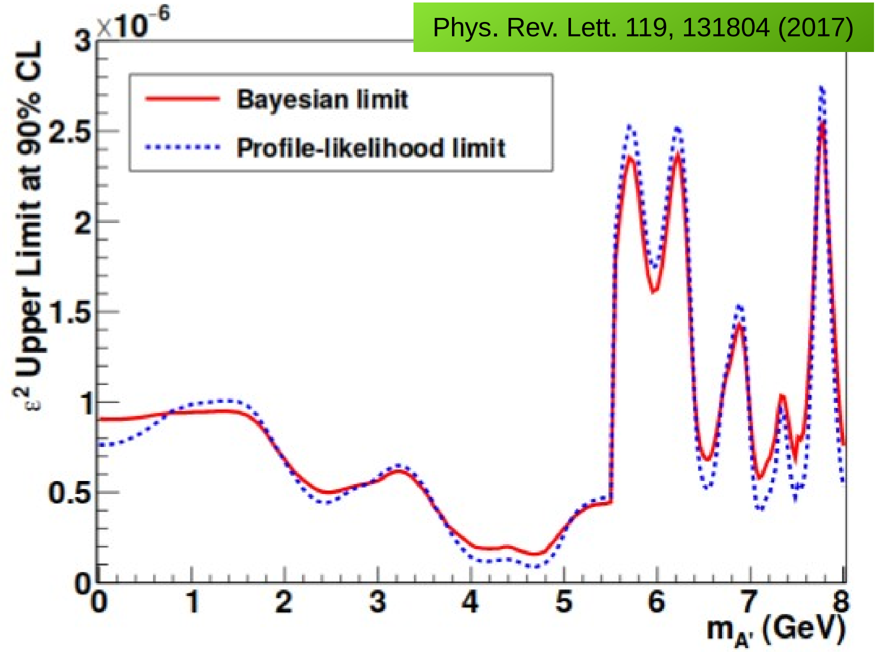


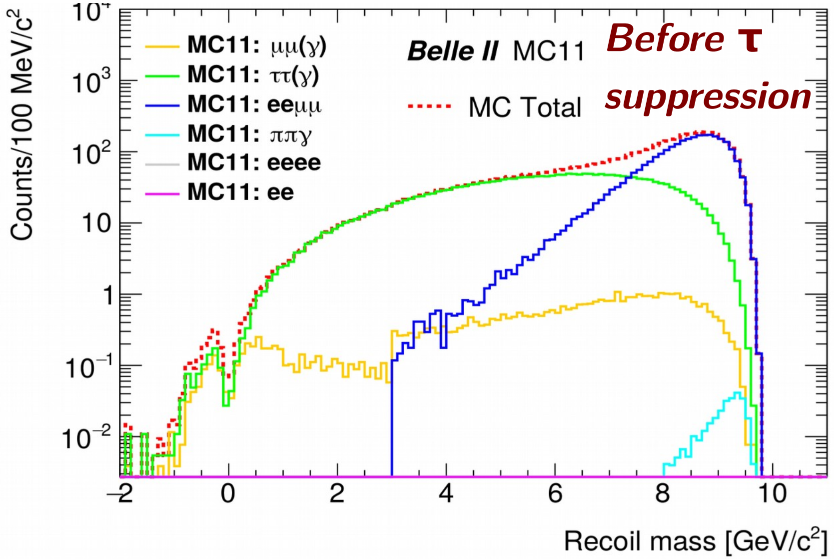
FIG. 4: Upper limits at 90% CL on A' mixing strength squared ε^2 as a function of $m_{A'}$. Shown are the Bayesian limit computed with a uniform prior for $\varepsilon^2 > 0$ (solid red line) and the profile-likelihood limit (blue dashed line).

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: 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