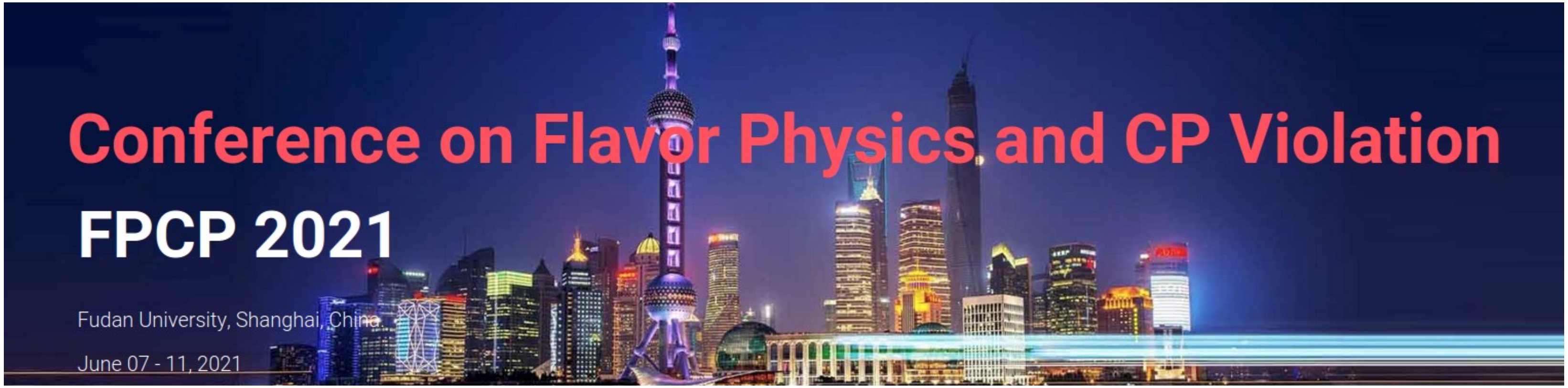


19th FPCP

Dark sector searches at flavor experiments (BaBar, Belle II, LHCb)

Laura Zani*

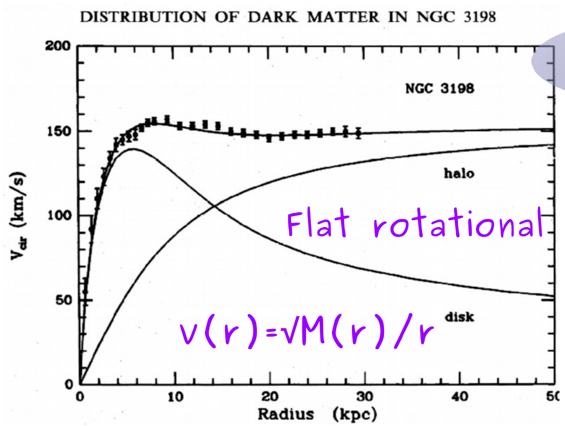
On behalf of the Belle II collaboration

*zani@cppm.in2p3.fr - Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

Dark matter puzzle

- ***Dark Matter (DM)*** is one of the most compelling reason for New Physics (NP) searches

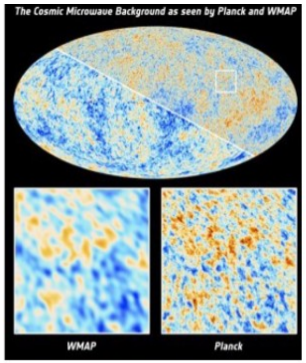
It exists...



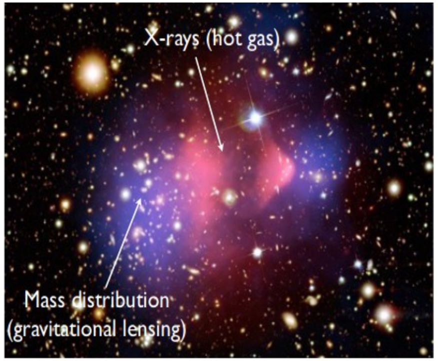
Flat rotational curves

$v(r)=\sqrt{M(r)/r}$

CMB fluctuations

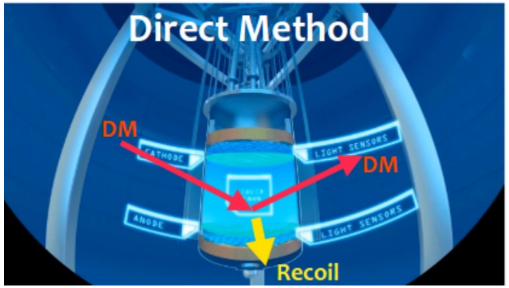


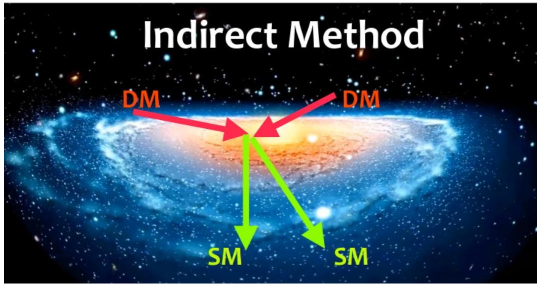
Gravitational lensing



...how to search for it?

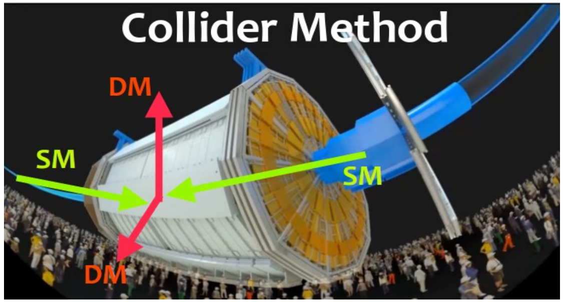
1) Detect the energy of *nuclear(electron) recoil*





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

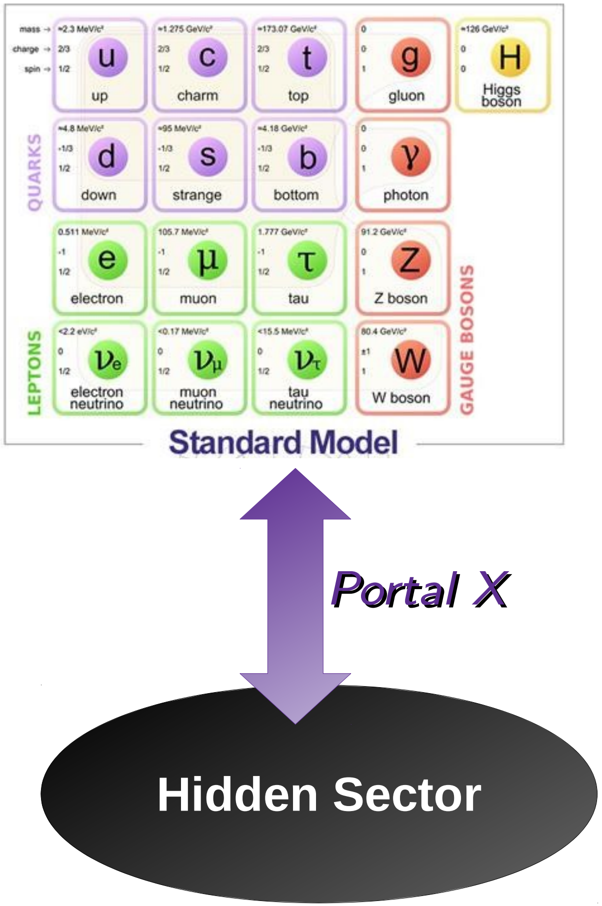
3) DM weakly couples to SM particles and it can be produced in *SM-particles annihilation* at ***accelerators***



→ This presentation will focus on DM searches at colliders

Light dark sectors

- Possible *non-WIMP* scenario: light dark sector weakly coupled to SM through a light ***mediator X***
  - Vector portal $\rightarrow$ Dark Photons (A'), Z' bosons
  - Pseudo-scalar portal $\rightarrow$ Axion Like Particles (ALPs)
  - Scalar portal $\rightarrow$ Dark Higgsstrahlung/Scalars
  - Neutrino portal $\rightarrow$ Sterile Neutrinos

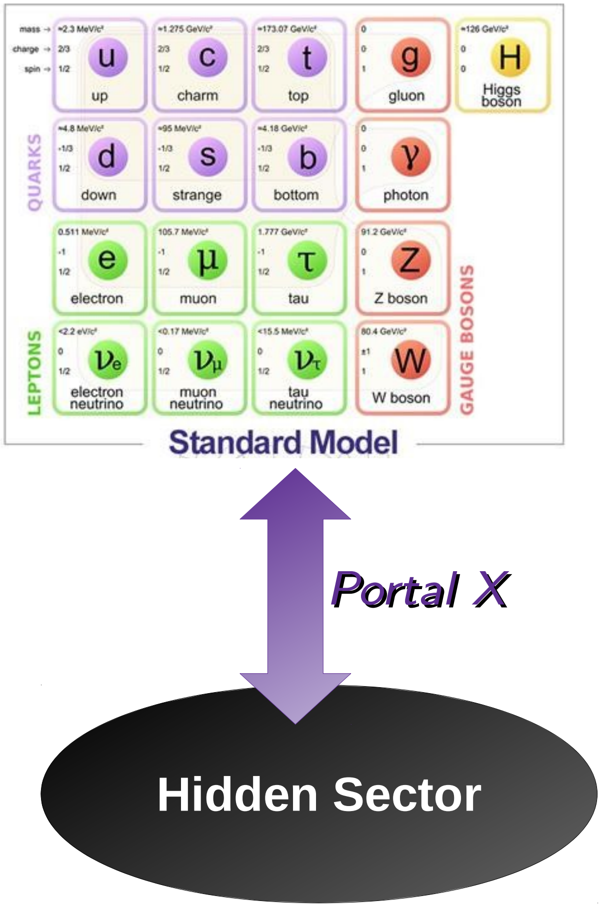


Light dark sectors (II)

- Possible *non-WIMP* scenario: light dark sector weakly coupled to SM through a light ***mediator X***
  - Vector portal $\rightarrow$ **Dark Photons (A'), Z' bosons**
  - Pseudo-scalar portal $\rightarrow$ **Axion Like Particles** (ALPs)
  - Scalar portal $\rightarrow$ **Dark Higgsstrahlung/Scalars**
  - Neutrino portal $\rightarrow$ Sterile Neutrinos

> ➢ Self-interacting dark matter (*darkonium*)
>
> ➢ Displaced vertex searches (*long lived particles*)

Disclaimer: non exhaustive talk, biased overview on some recent results...

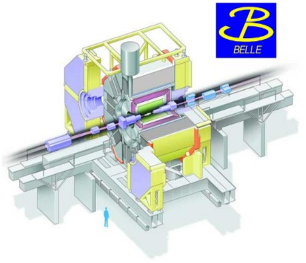


Experiments at B-factories

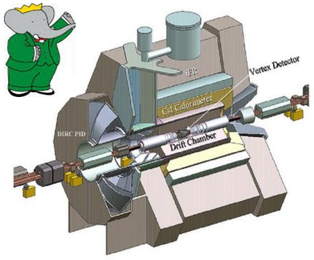
- **Clean environment and hermetic detectors** → efficient reconstruction of **neutrals** (π^0, η), recoiling system and ***missing energy*** final states

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

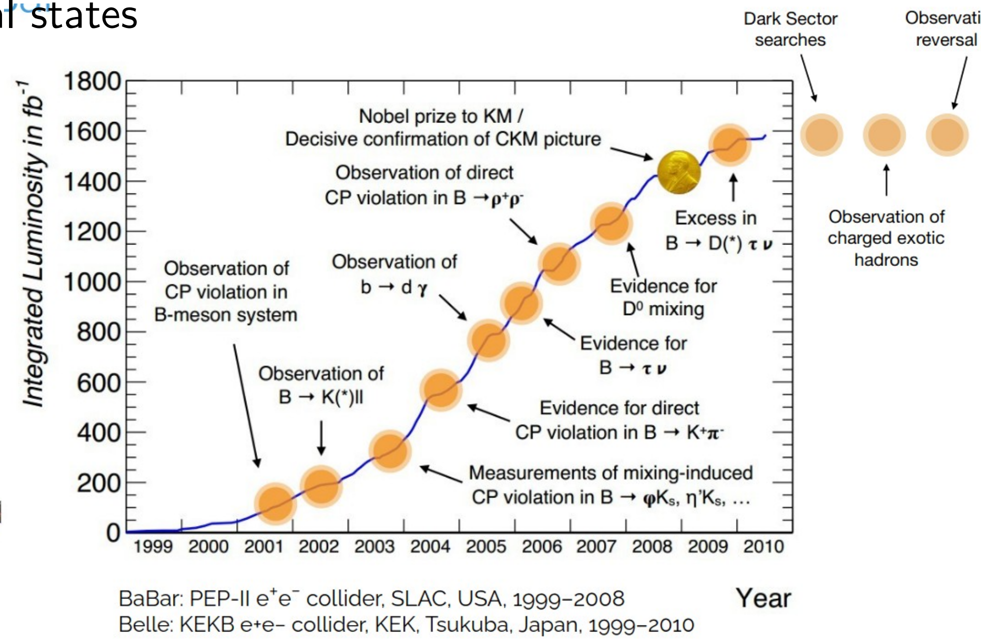
First generation of B-factories



at the KEKB collider (KEK, Japan)



at the PEP II collider (SLAC, California)



Experiments at B-factories

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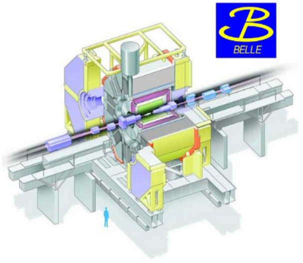
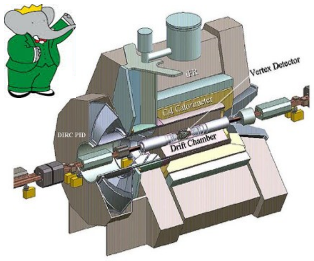
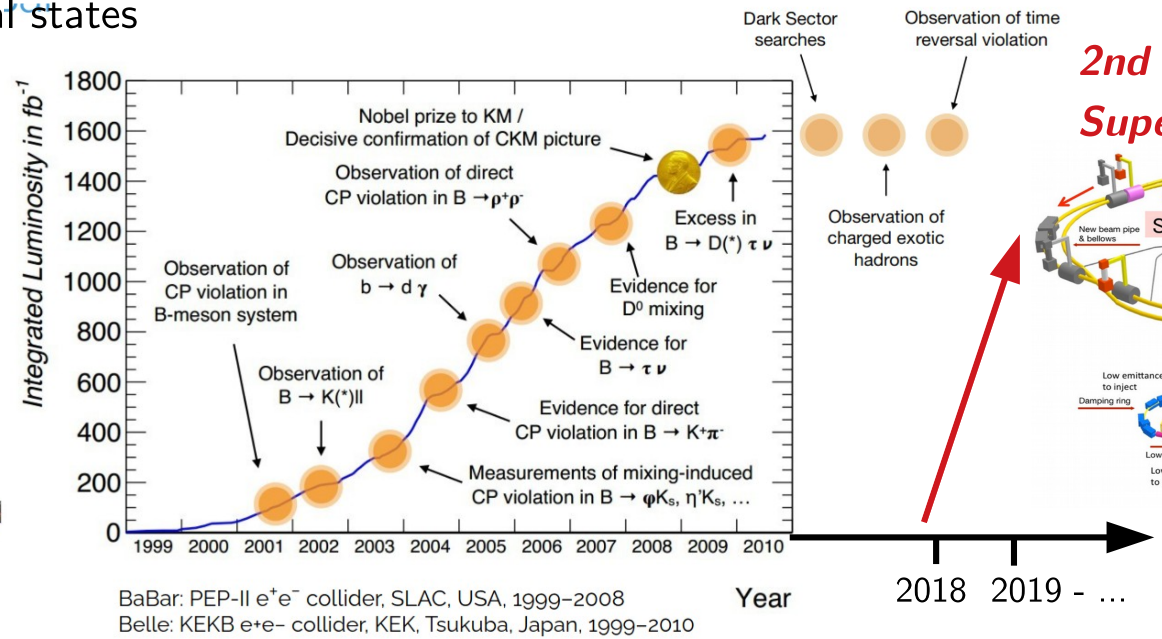


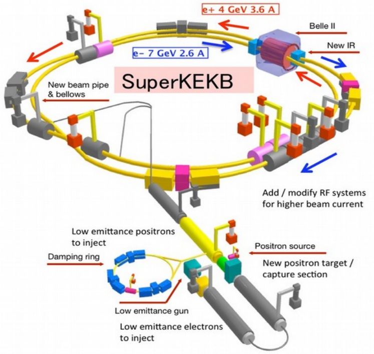
at the KEKB collider (KEK, Japan)



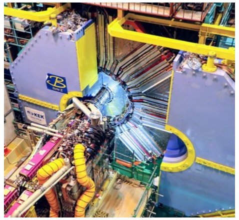
at the PEP II collider (SLAC, California)



2nd generation: SuperKEKB



- *nano-beam* scheme* (vertical beam size 50nm at IP)
- 30 x KEKB peak luminosity: $\mathbf{L = 6 \cdot 10^{35}\ cm^{-2}\ s^{-1}}$

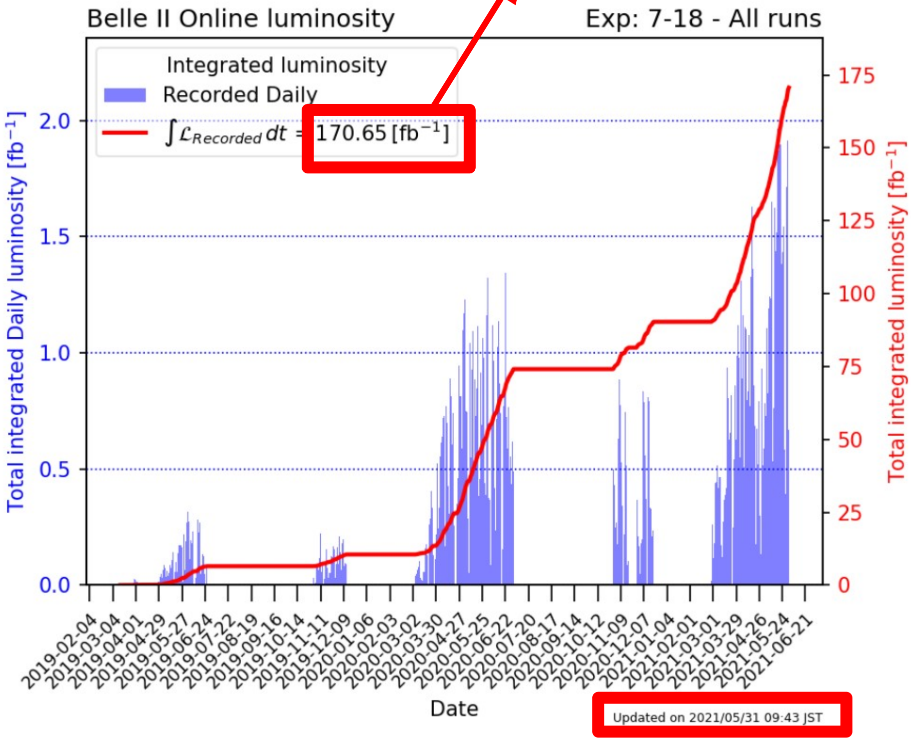


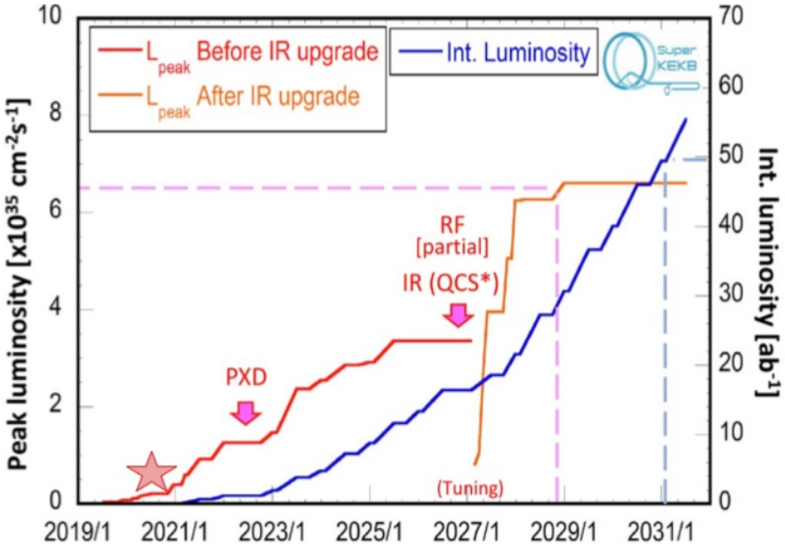
Belle II

*https://arxiv.org/abs/0709.0451

Belle II data taking

- collected **0.5 fb^{-1}** during the **pilot run April-July 2018** (*first collisions on April 26th*)
- Since March 2019 collected > **170 fb^{-1}** and hit the **2.9x10^{34} cm^{-2}s^{-1}** instantaneous luminosity!



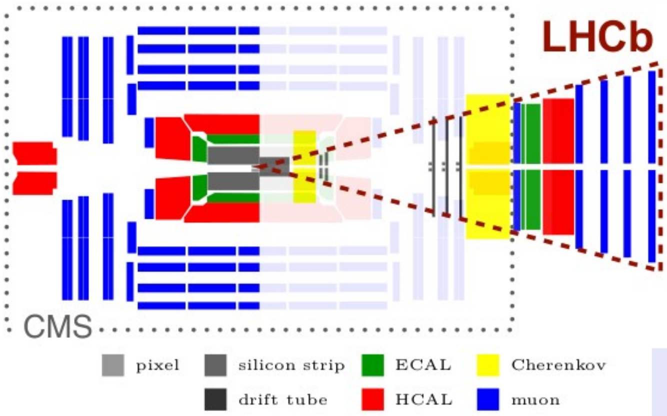


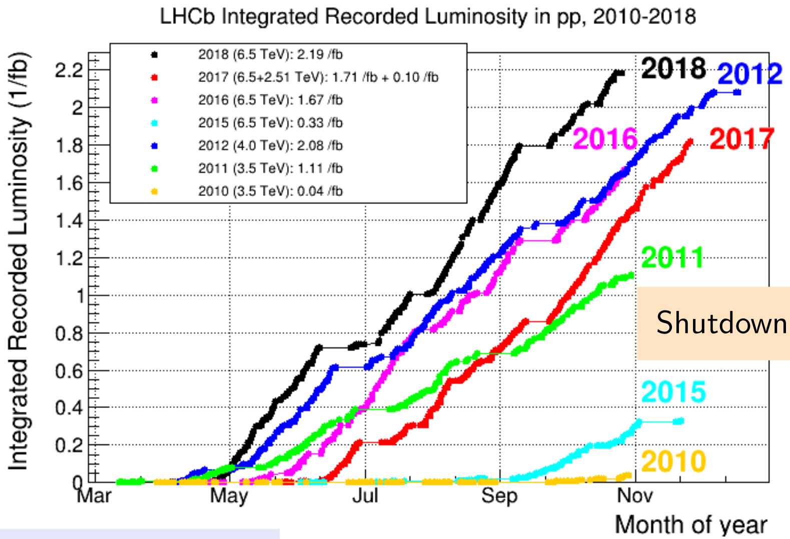
GOAL: 50 ab^{-1}

Interplay with flavor experiments at LHC

- LHCb is a single-arm forward spectrometer at LHC collider covering the region $2 < \eta < 5$:
  - excellent vertex and momentum resolutions
  - soft triggers and online-analysis capability

Int.J.Mod.Phys. A 30, 1530022 (2015)



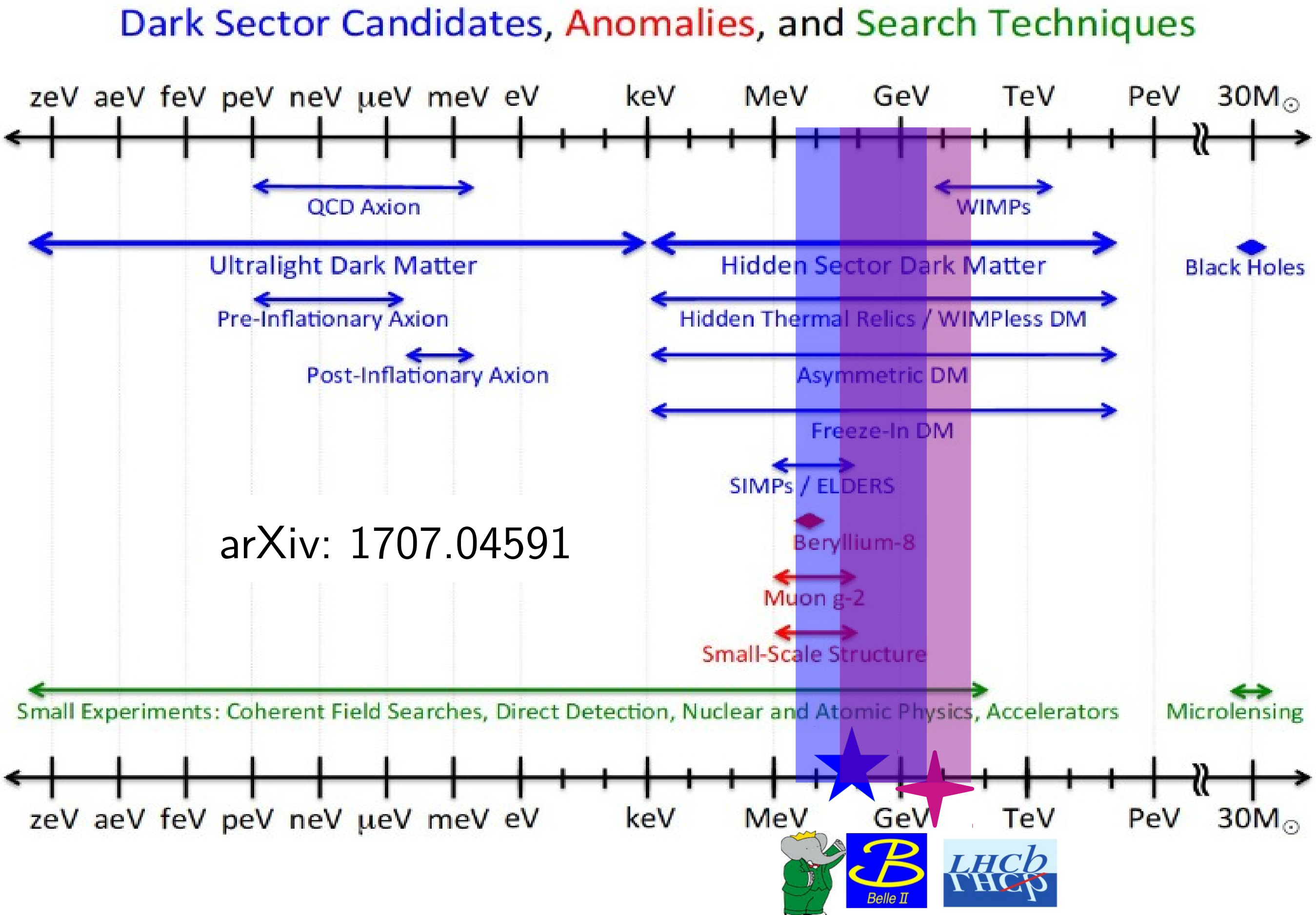


Shutdown2 in progress

B-Factories Vs LHCb in a nutshell:

- LHCb has larger background (pp collision), no hermetic detector
- Cross-section $\sigma_{bb}\,(\sqrt{s} = 13$ TeV$)= 284\ \mu b > \sigma_{bb}\,(\sqrt{s} = 10.58$ GeV$) = 1.11$ nb
- All b-hadron species produced, excellent performance on *di-muon final states* and heavy b-hadrons

Overview of dark sector searches



arXiv: 1707.04591

- B-factories can access the mass range naturally favored by ***light dark sectors***
- LHCb can probe higher mass regions and wider phase space for Long Lived Particles, Heavy Neutral Leptons (more in **backup**)

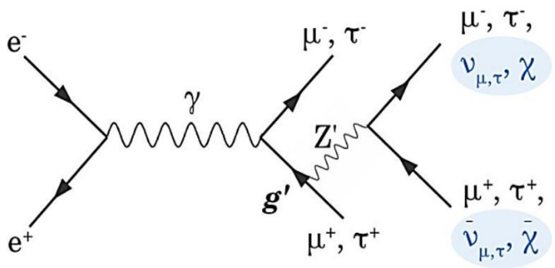
Muonic dark forces: L_μ-L_τ model

→ New gauge boson Z' coupling only to the **2^{nd} and 3^{rd}** generation of leptons (L_μ-L_τ):

- May explain the $(g-2)_\mu$ anomaly and anomalies observed in rare B decays, $B \to K^*\mu\mu$, $R_{K(*)}$
- May solve the light DM puzzle (sterile neutrinos, Dirac light fermions)

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

B.Shuve and I.Yavin (2014) Phys. Rev. D 89, 113004.
Altmannshofer et al JHEP 1612 (2016) 106.



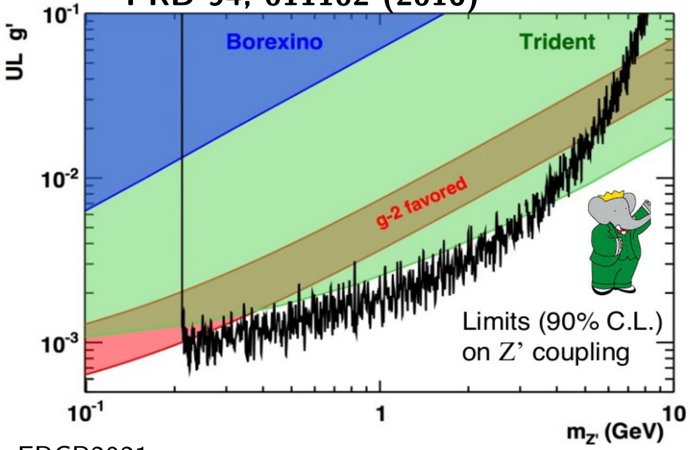
- Search for the process:

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

- Existing limits on the Z' coupling (g') came from searches for **visible decays** $Z' \to \mu^+\mu^-$ (BaBar **PRD 94, 011102 (2016)**, CMS **arXiv:1808.03684**) and neutrino-nucleus scattering processes (*neutrino trident production*, CCFR experiment at Fermilab)

- **NEW:** search for **Z' → invisible,** Belle II first physics result, **PRL 124 (2020) 141801**

PRD 94, 011102 (2016)



Search for Z' to invisible

PRL 124 (2020) 141801

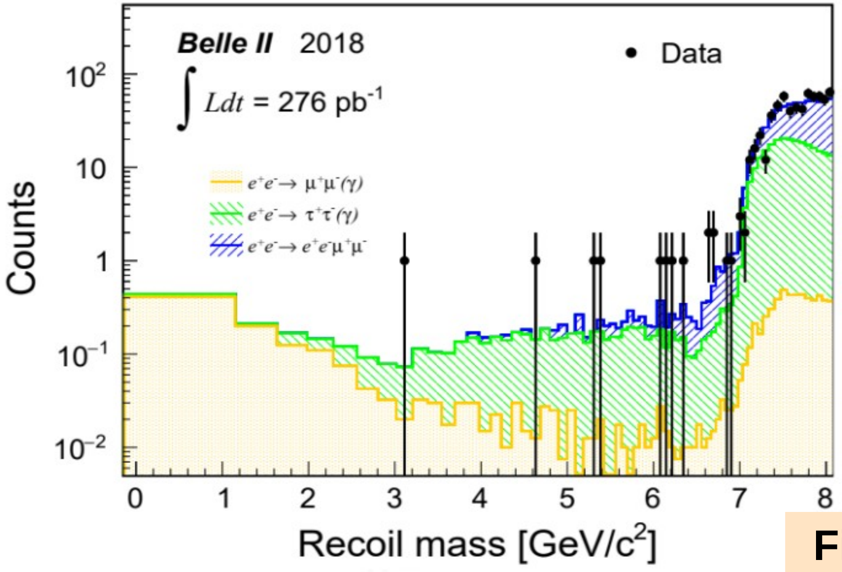
- Search for a peak in the mass spectrum of the recoil against a $\mu^+\mu^-$ pair in events where **nothing** else is detected.
- **Only 276 pb^{-1}** of 2018 pilot run data usable due to trigger conditions.

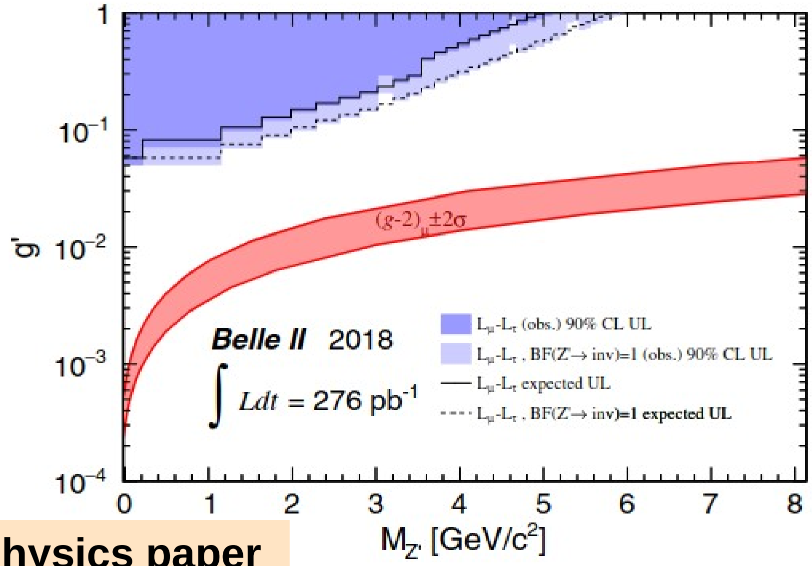
Branching ratios:

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

If light DM is accessible, BR(Z'$\rightarrow$ DM)~1

Invisible signature investigated for the first time!





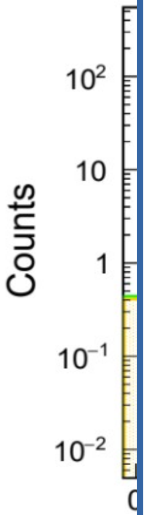
First Belle II physics paper

Search for Z’ to invisible

PRL 124 (2020) 141801

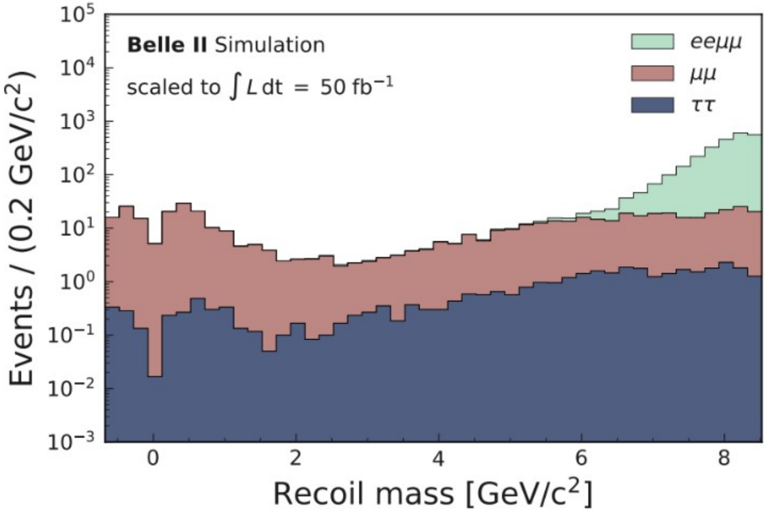
- Search for a peak in the mass spectrum of the recoil against a $\mu^+\mu$…
- **Only** … condi…

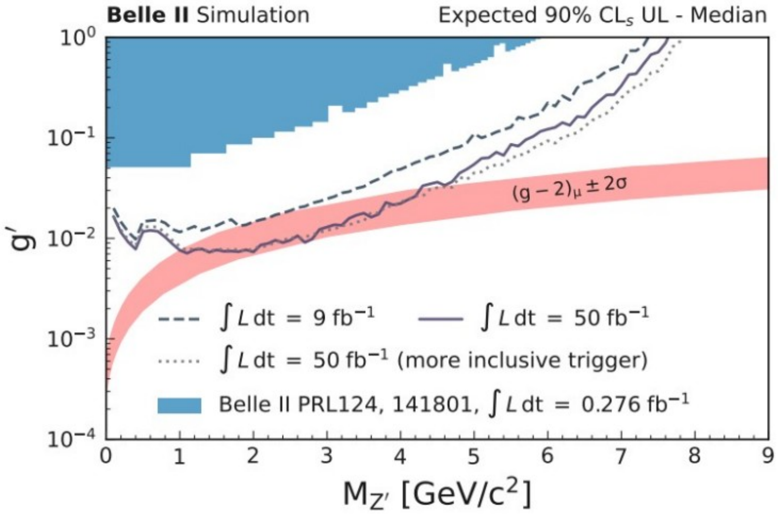
Branching ratios:



Short term projections including several improvements:

- much higher integrated luminosity (already on tape);
- analysis improvements (better muonID, MVA selection);
- new triggers w.r.t. 2018 pilot run.





Starting to probe the $(g-2)_\mu$ band already with 50 fb^{-1}

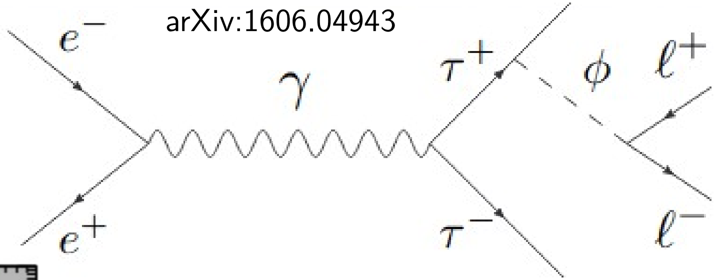
Dark tauonic force

PRL 125, 181801 (2020)

$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\phi_L \ell$$

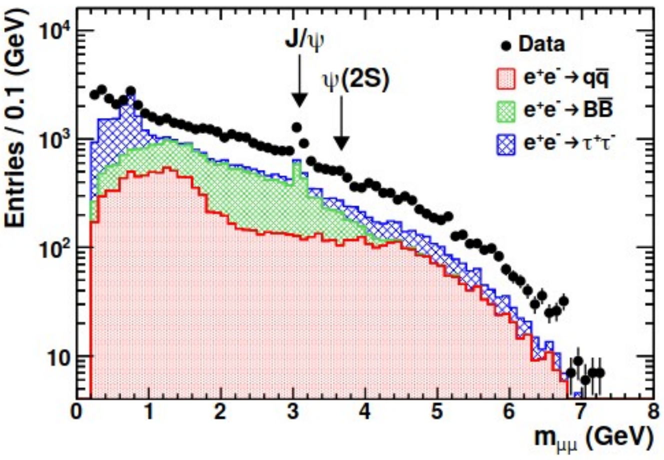
arXiv:1606.04943

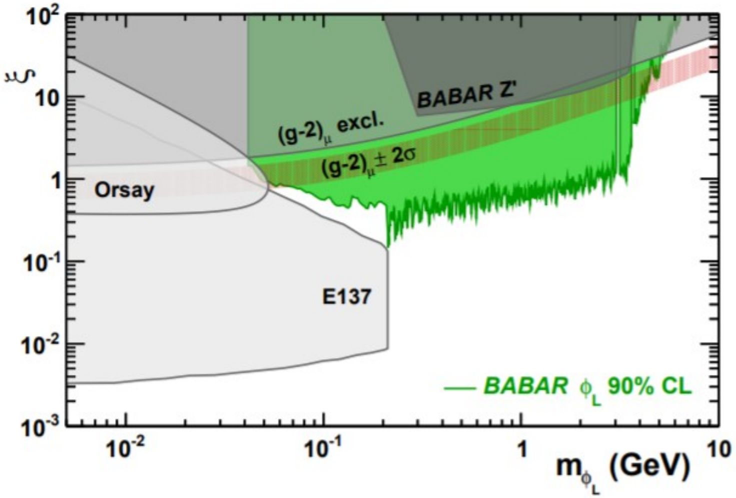
- New **light dark scalar** with mass-proportional coupling to leptons, could explain the g-2 muon anomaly (only weakly constrained by previous searches*)
- Look for a narrow resonance in **dilepton spectrum** in $\mathbf{e^+e^- \to \tau^+\tau^-\, l^+l^-}$ events
  - reconstruct 4 tracks + missing energy due to neutrinos
  - $m_{\varphi L} < 2m_\mu$ search separately for lifetimes $c\tau_{\varphi L} = 0, 1, 10, 100$ mm → *ee* possibly displaced (above dimuon threshold, only prompt decays)



→ Radiative emission may be enhanced due to larger tau masses

Total BaBar data set at ϒ(2S), ϒ(3S), ϒ(4S) and their vicinities: **514 fb^{-1}**





→ No significant excess, set 90% CL upper limits on leptophilic scalar coupling ξ

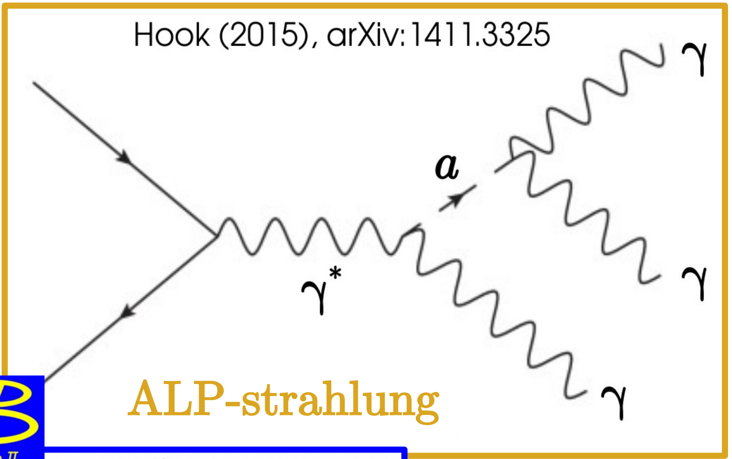
* Phys. Rev. D 94,011102 (2016)

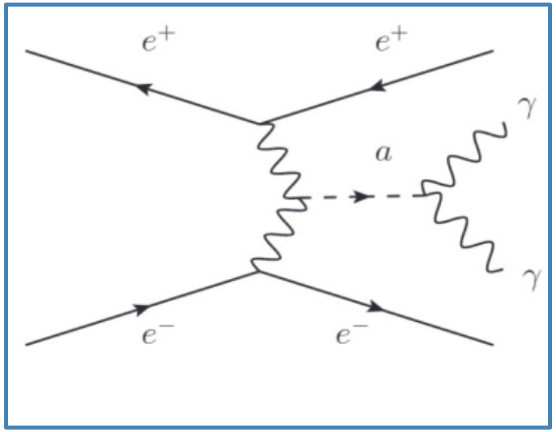
Axion Like Particles (ALPs)

- Axion Like Particles are pseudo-scalars coupling mainly to bosons, with non-renormalizable coupling constants [g_{aV}] $\sim 1/M$
- Explored photon coupling $g_{a\gamma\gamma}$ in *ALP-strahlung* processes → **Belle II** (*photon fusion:* sensitivity under study)

  → more on ALPs prospects at LHCb in the **backup**

- Exploit *Flavor Changing Neutral Current* (FCNC) and rare meson decays to investigate g_{aW} coupling → **BABAR preliminary**

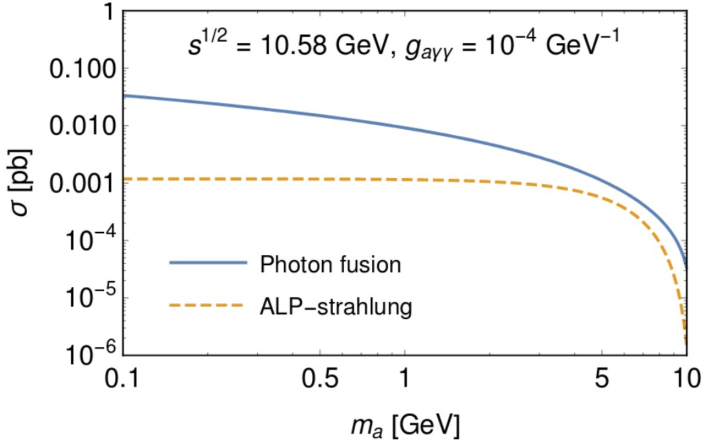




$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\mathcal{L} = -\frac{g_{aV}}{4}\, a\, W^{a}_{\mu\nu}\tilde{W}^{a\,\mu\nu}$$

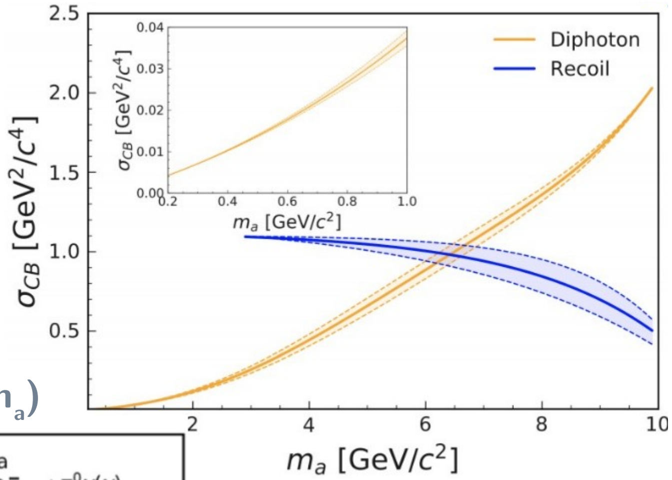
$$BF(a \to \gamma\gamma) = 100\%$$



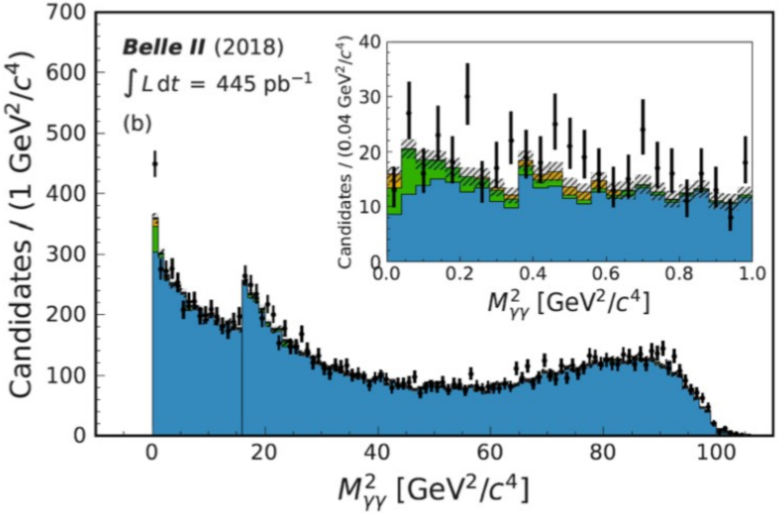
ALPs: a $\rightarrow \gamma\gamma$ at Belle II

PRL 125 (2020) 161806

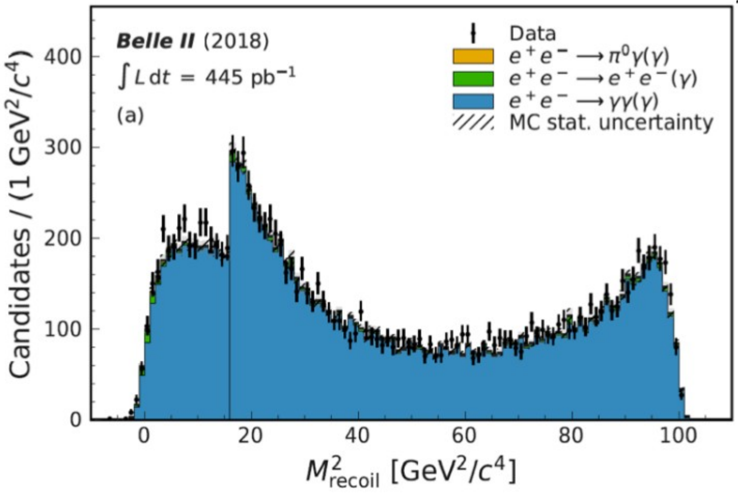
- Select fully neutral events consisting of 3 isolated photons with a total invariant mass consistent with center of mass energy
- Search strategy optimized to maximize ALP sensitivity
- Transition point for signal yield extraction at equal sensitivity, for $m_a = 6.85$ GeV



Diphoton invariant mass (low m_a)



Recoil invariant mass (high m_a)



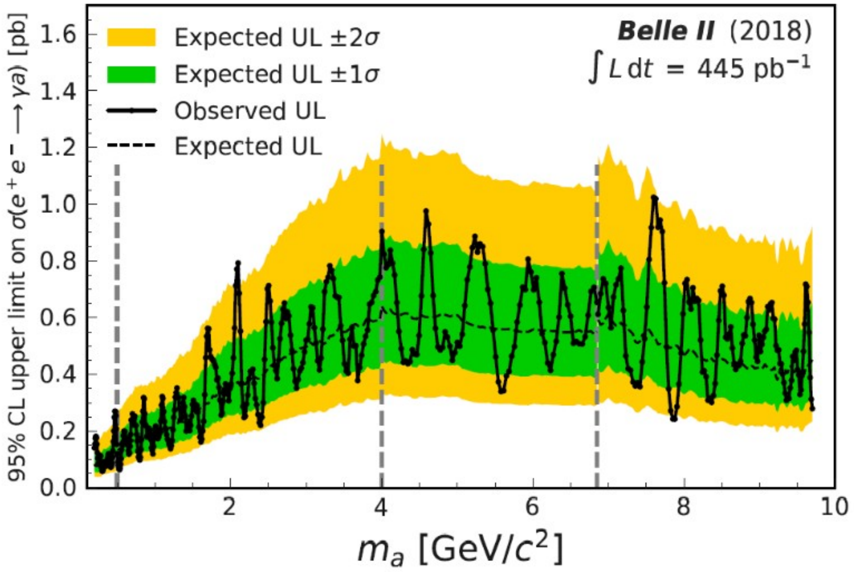
Data set: **445 pb^{-1}** from 2018 pilot run

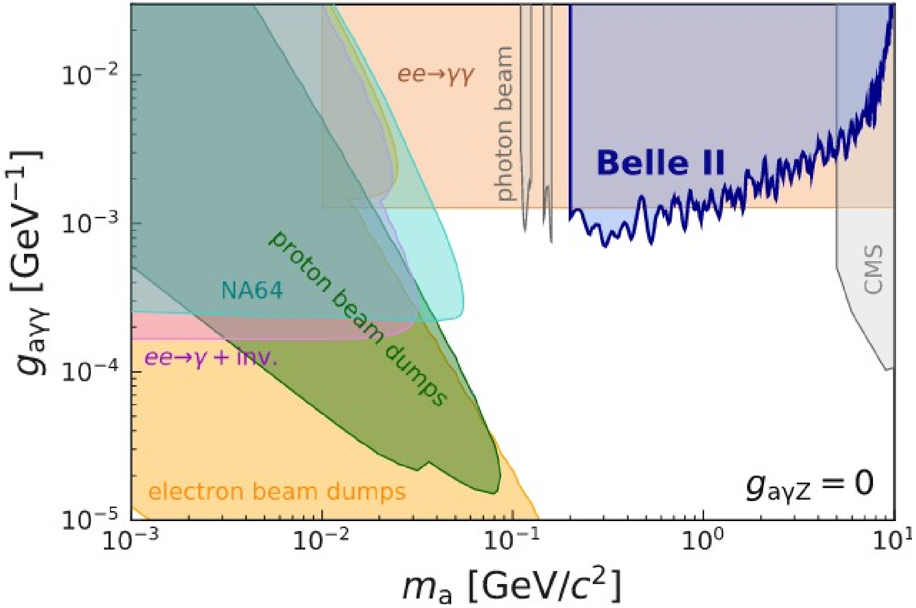
ALPs: a → γγ results

PRL 125 (2020) 161806

- Binned extended max likelihood fits in sliding ranges, with half mass resolution as step, between 0.2 and 9.7 GeV → no excess found (highest local significance of 2.8σ)
- Set 90% CL upper limits on the signal cross section, translated in $g_{a\gamma\gamma}$ limits

$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{QED}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$





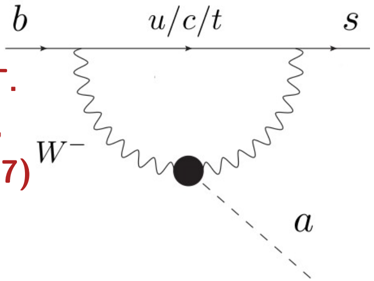
→ With only 1/10000th of target final data set

ALPs in meson decays

PRELIMINARY

→ *signature searched for the **first time**!*

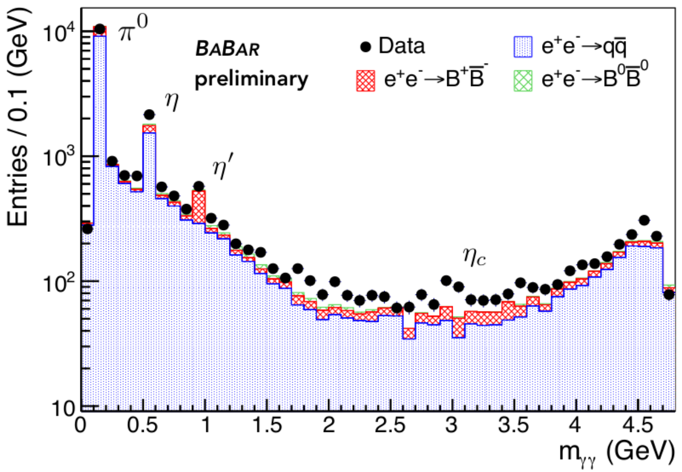
- *FCNC* processes perfect testbed to search for low mass ALP emitted by a W boson
- B → Kγγ is extremely rare in the SM and hence uniquely sensitive to very small **ALP-W coupling g_{aW}**
- Search for the process **$B^{\pm} \to K^{\pm}a$, $a \to \gamma\gamma$** by looking at narrow peaks in the **diphoton invariant mass**



E. Izaguirre, T. Lin, B. Shuve, PRL 118 (2017)

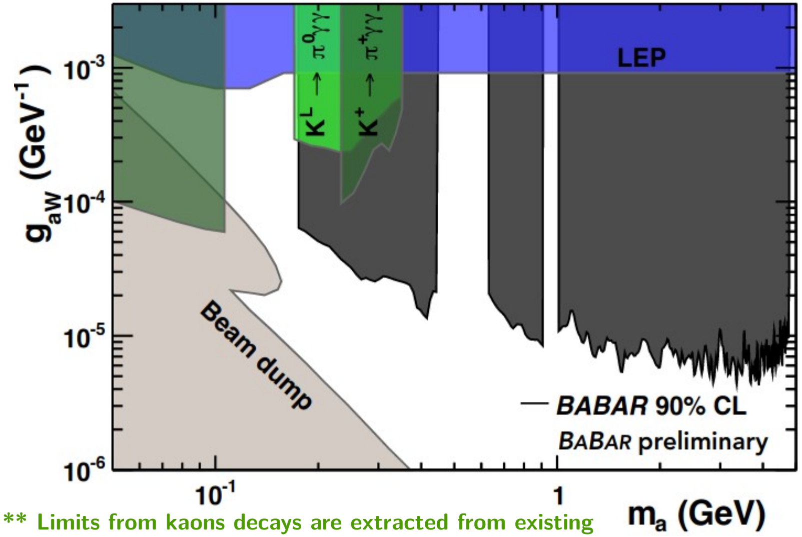
➔ *Select events with a good kaon candidate + two photons kinematically constrained to come from the beam spot and use B-meson kinematic variables (m_{ES}, ΔE) to reject continuum*

➔ $\tau \sim 1/m_a^3 g^2_{a\gamma\gamma}$: allow displaced vertex signature, set long-lived particle constraints



Data set: 424/fb at ϒ(4S), ~240M B^+B^- pairs

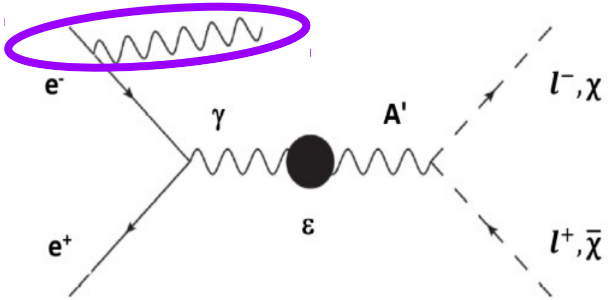
→Improve limits on g_{aW} coupling by two orders of magnitude for $m_a < 5$ GeV



** Limits from kaons decays are extracted from existing measurements presented in: Phys.Rev.Lett. 118 (2017) 11, 111802

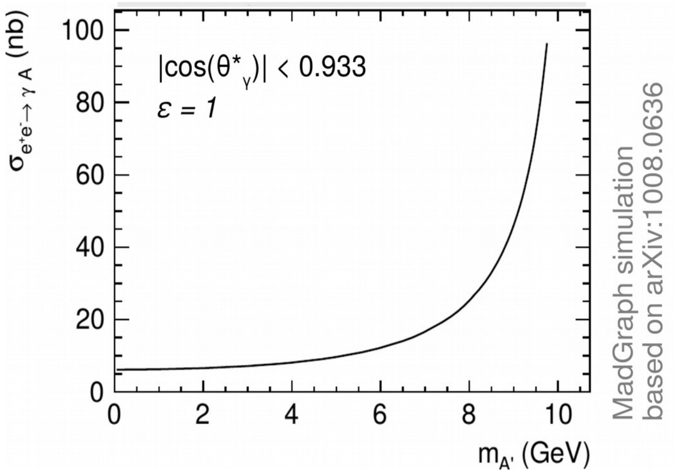
Dark photons

- A possible U(1) extension of the SM include a new massive vector gauge boson A' coupling to the SM photon through the kinetic mixing with strength ε → the ***dark photon***
- At e^+e^- colliders investigate the ISR production $e^+e^- \to \gamma\, A'$.



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

Batell et al. (2009), arXiv:0903.0363

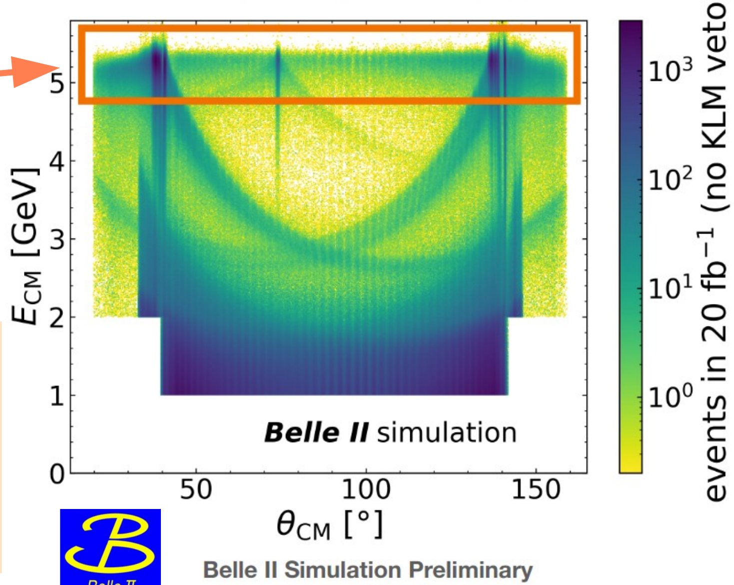


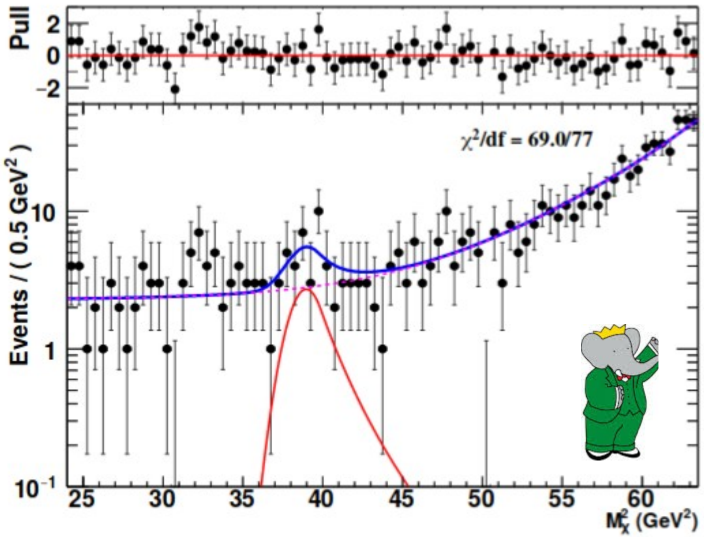
- $m_{A'} > 2m_\chi$ A' decays 100% invisibly into DM particle (***single photon search***)
- $m_{A'} < 2m_\chi$ → A' decays visibly to SM particle (leptons)

→ Data-driven search for prompt and displaced A' decays to muon pairs at LHCb, normalized to off-shell production $\gamma^* \to \mu\mu$

Dark photon to invisible

- Select events with **nothing** but a single high energetic *ISR photon.* Look for a bump in the reconstructed photon energy $E_\gamma = (s - m^2_{A'})/2\sqrt{s}$
- **Background:** QED processes $e^+e^- \to \gamma\gamma(\gamma)$ (*low mass* region) and radiative Bhabha $e^+e^- \to e^+e^- \gamma(\gamma)$ (*high mass* region) + cosmics





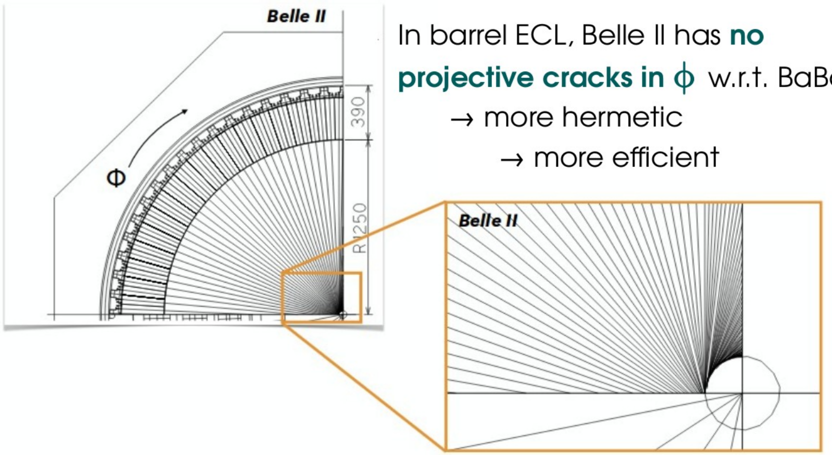
→ only one photon in the detector requires a dedicated **single photon trigger**
→ *at Belle was not available, at BaBar was available only on ~10% data*

PRL 119, 131804 (2017)

Optimize analysis separately in the Low Mass region, $M_X^2 < 36$ GeV^2, and High Mass region, $24 < M_X^2 < 69$ GeV^2, with two different BDT→ results based on 53 fb^{-1} data

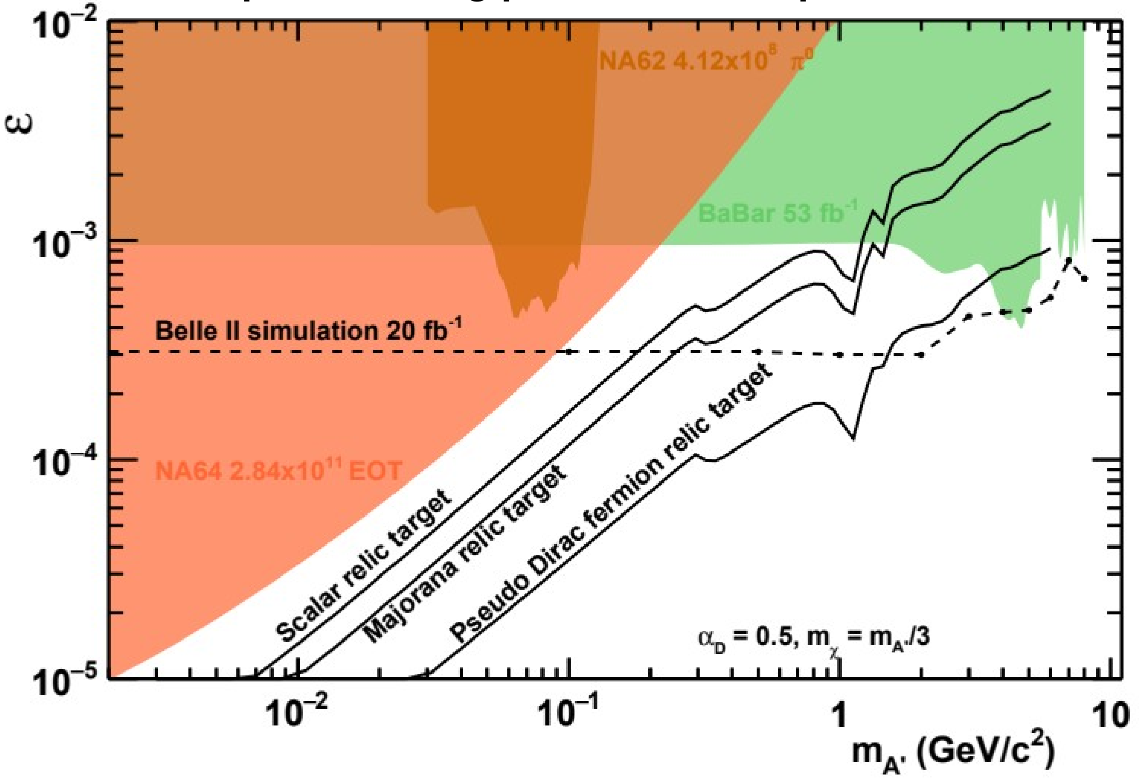
Invisible dark photon sensitivity at Belle II

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 and possibility to compensate for ECL photon detection gap with KLM
- Better hermeticity (smaller boost $\beta\gamma = 0.28$, larger acceptance)
- Improved hardware trigger lines

https://arxiv.org/pdf/2104.10280.pdf

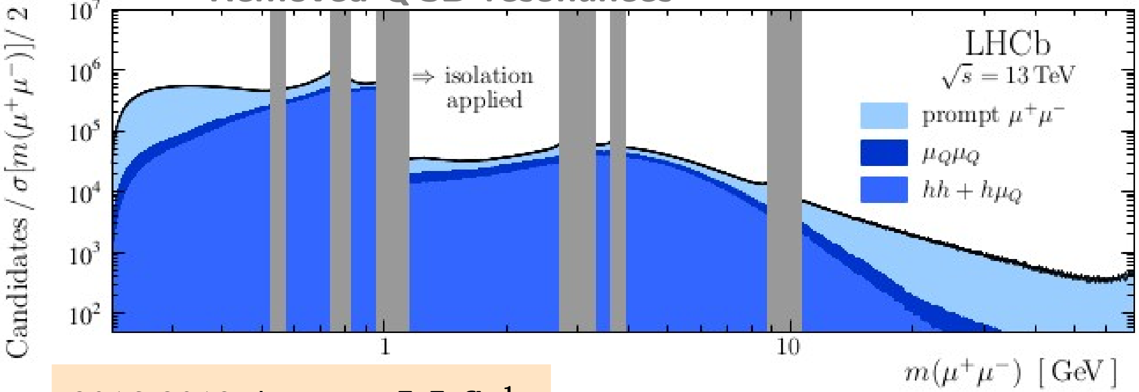


Visible dark photons at LHCb

PRL 124 (2020) 041801

- Search for $A' \to \mu^+\mu^-$ by looking for peaks in di-muon invariant mass up to $m_{A'}=70$ GeV
- Extract $n_{ob}[m(A')]$ with binned extended max likelihood fits in step of $\sigma[m(\mu^+\mu^-)]/2$

Removed QCD resonances



2016-2018 data set: **5.5 fb^{-1}**

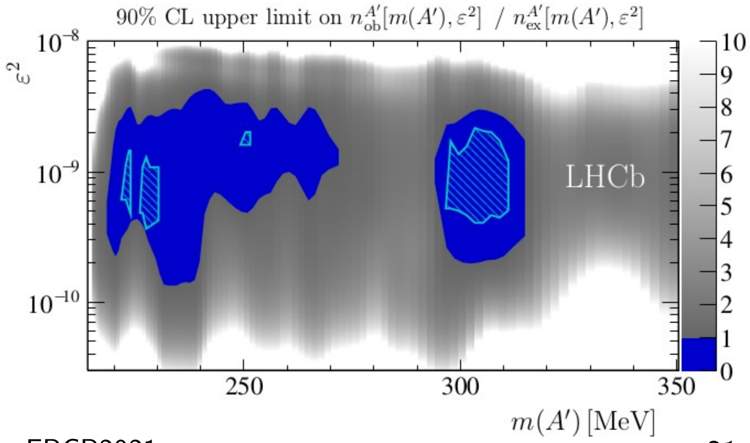
$$n_{\rm ex}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\rm ob}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\, \epsilon_{\gamma^*}^{A'}[m(A'),\tau(A')]$$

off-shell photon

phase-space

A'/γ^* eff ratio, ϵ=1 for prompt

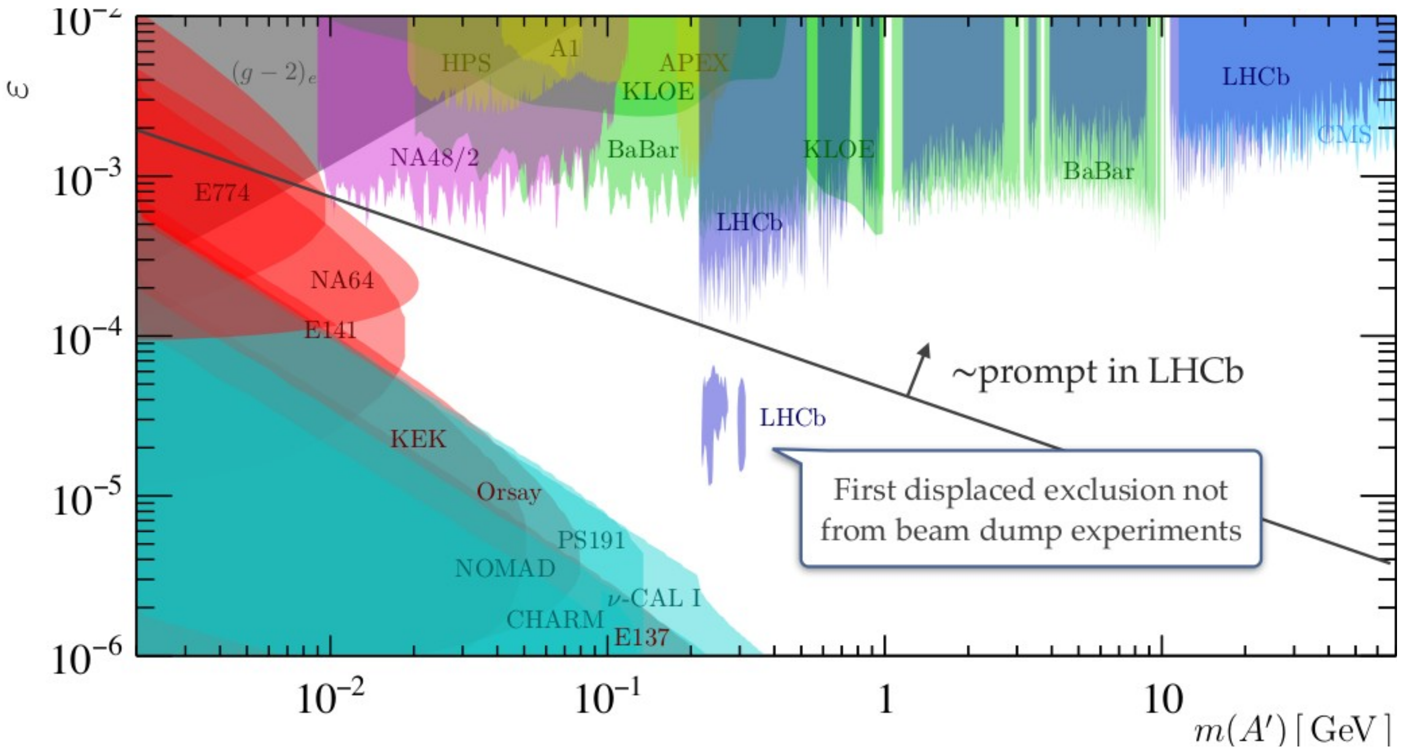
Exclude at 90% CL regions where $n_{ob}[m(A')] < n_{ex}[m(A')]$



A'→ μ μ: results

PRL 124 (2020) 041801

- Most stringent limits on ε for 214 < $m_{A'}$< 740 MeV and 10.6 < $m_{A'}$ < 30 GeV for prompt decays and 214 < $m_{A'}$< 350 for long-lived A'

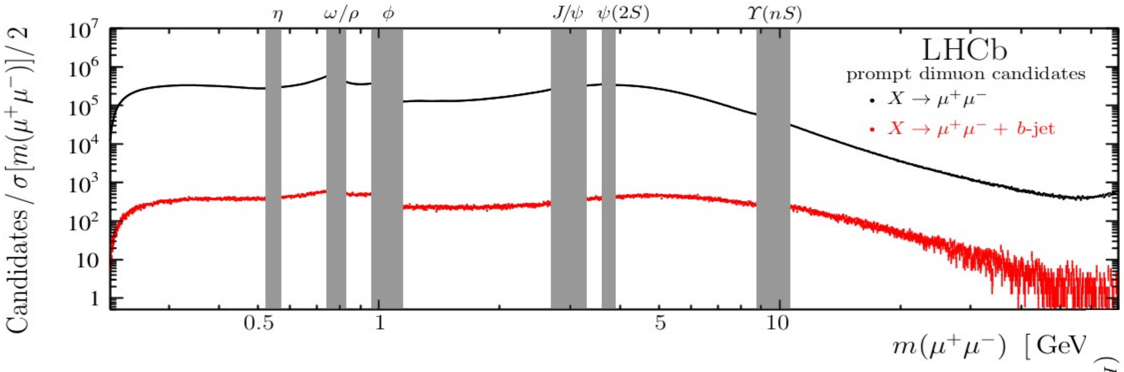


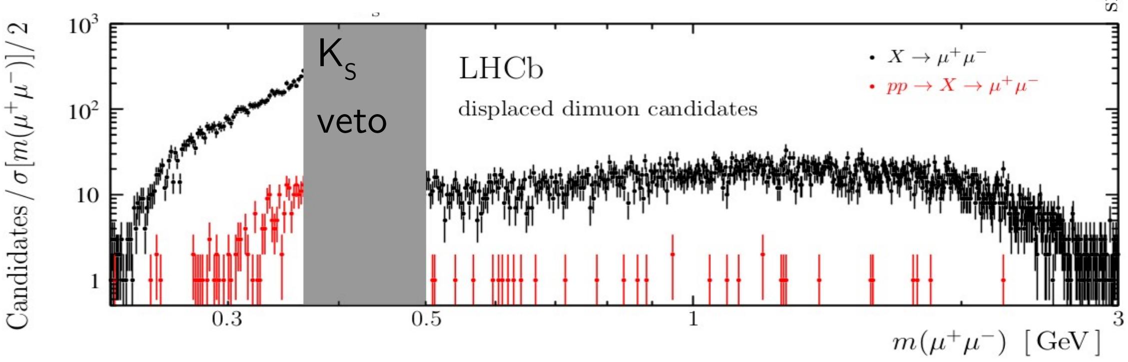
X→ μμ search at LHCb

JHEP 10 (2020) 156

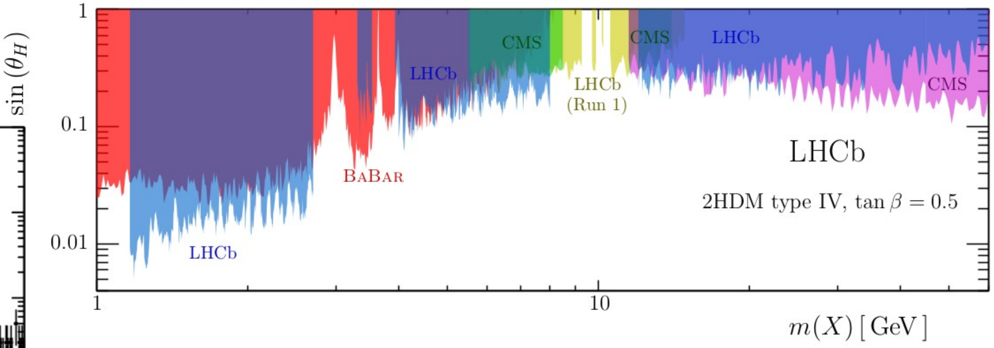
- Drop kinetic mixing assumption with γ* and probe more dark sectors in di-muon resonances

2016-2018 data set: **5.1 fb^{-1}**





- Explore $2m_\mu < m(X) < 60$ GeV with non negligible width (up to 20 GeV)
- Interpret results as 90% CL upper limits on X-Higgs mixing angle θ_H

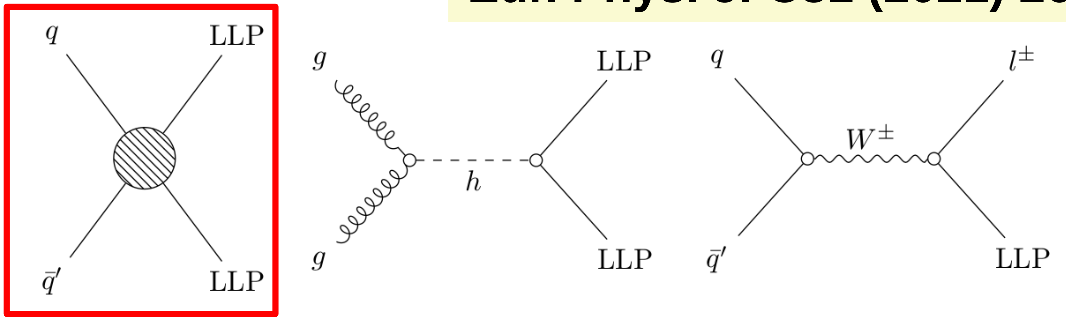


Search for LLP → $e\mu\nu$

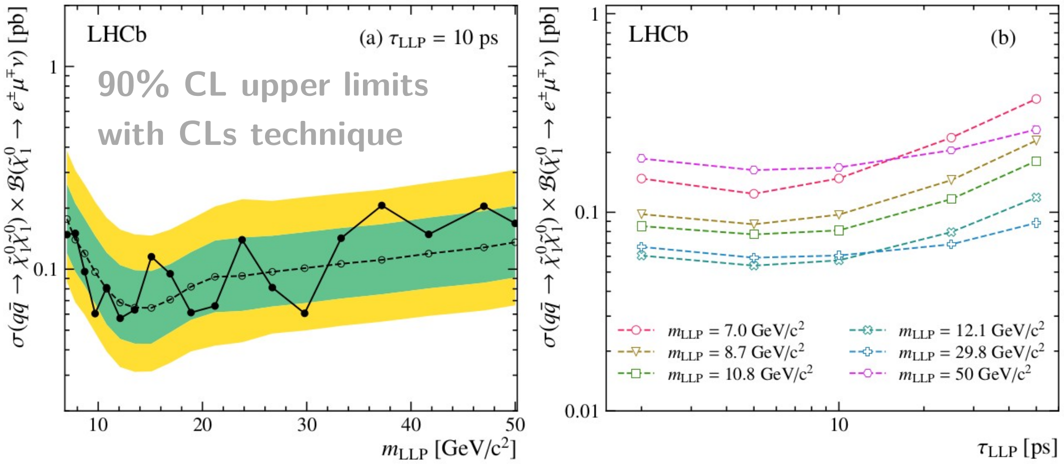
Eur. Phys. J. C81 (2021) 261

- Many SM extension includes new massive particles with lifetimes >> τ_{SM} : long-lived particles (LLP)
- **Signal signature**: muon and electron oppositely charged with good-quality displaced vertex within the VELO tracker (d > 15·σ_{PV})
- Compute the LLP mass (m_{LLP}) as the corrected mass:

$$m_{\rm corr} = \sqrt{m(e\mu)^2 + p(e\mu)^2 \sin^2\theta} + p(e\mu)\sin\theta$$



Investigated 3 production mechanisms, direct pair production $q\bar{q}$→ LLPs has the highest efficiency



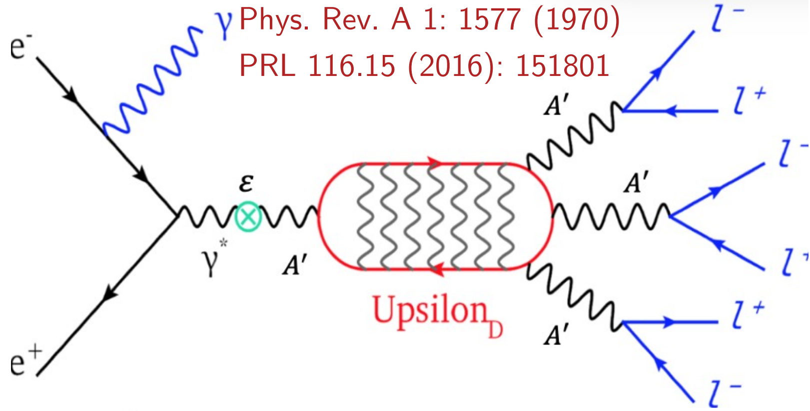
- Main background due to $b\bar{b}$ candidates, rejected by applying a BDT selection
- No significant signal found in the searched range { 7<m_{LLP}< 50 GeV, 2 <τ_{LLP}<50 ps}

Self-interacting dark matter

PRELIMINARY

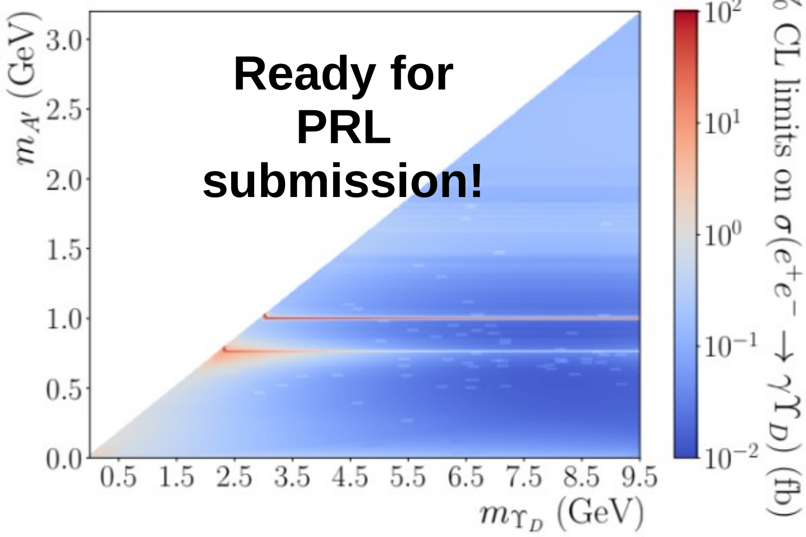
- Sufficiently light dark photons A' could result in an attractive force between dark fermions (χ) and the formation of bound states $\chi\bar{\chi}$ (*darkonium*, Υ_D)
- Search 514 fb^{-1} for the reaction: $e^+e^- \to \gamma\Upsilon_D$, $\Upsilon_D \to A'A'A'$, A' subsequently decays to leptons or pions pairs

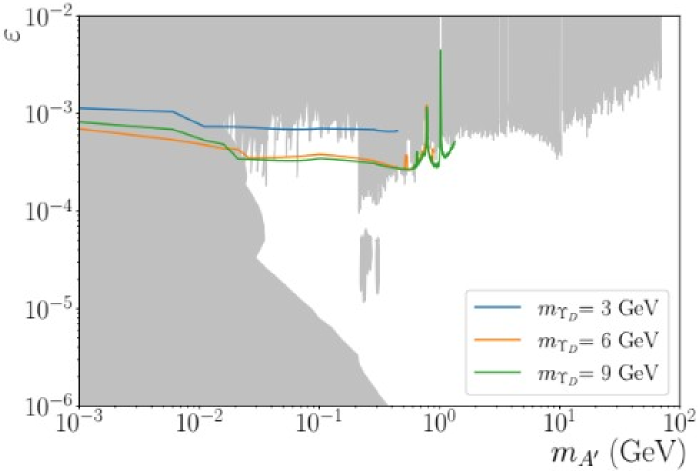
Phys. Rev. A 1: 1577 (1970)
PRL 116.15 (2016): 151801



- Select six track events, apply PID and combine in similar A' masses to form Υ_D
- Look also for displaced vertex signature (for $m_{A'} < 0.2$ GeV, $c\tau_{A'} = 0.1, 1, 10$ mm)

Ready for PRL submission!

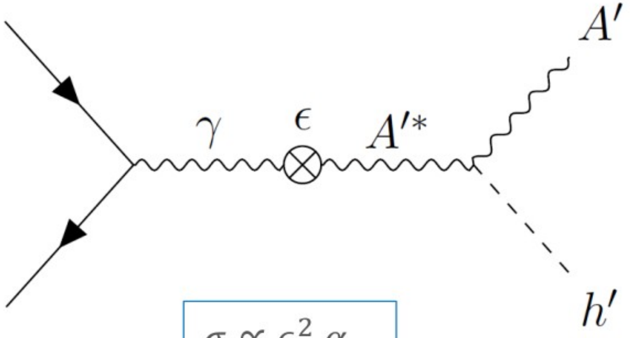




Dark Higgsstrahlung

PRELIMINARY

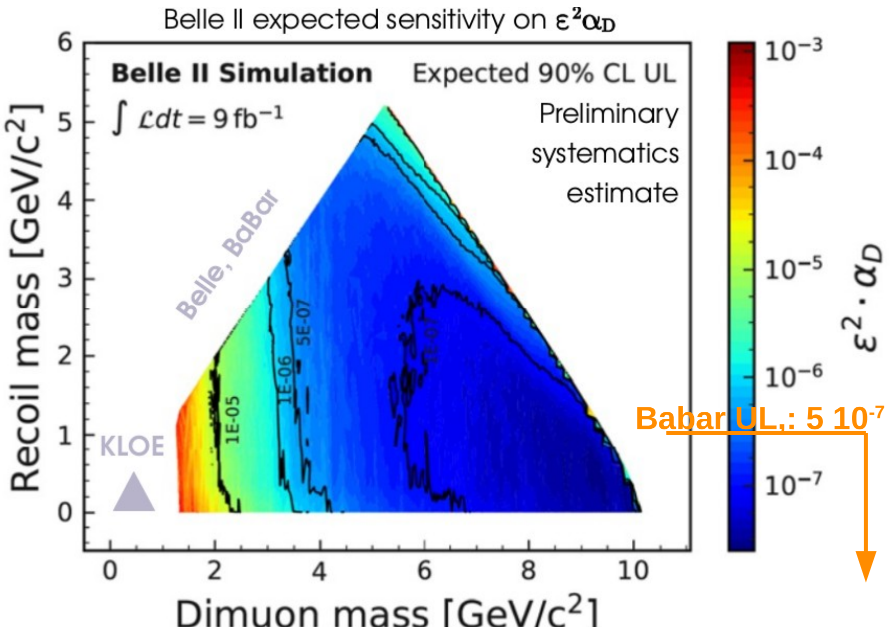
- Dark photon (A') mass can be generated via a spontaneous symmetry breaking(*) mechanism, by adding a dark Higgs boson (h') : *dark Higgsstrahlung* process, $e^+e^- \rightarrow A'^* \rightarrow h' A'$



$\sigma \propto \epsilon^2 \alpha_D$

- Belle II can probe the invisible h' decay ($m_{h'} < m_{A'}$) with A' decaying to a muon pair currently constrained only by **KLOE(**)**:

  → Constrain virgin phase space region and probe non-trivial $\varepsilon^2\alpha_D$ couplings



* Batell, Pospelov, Ritz, Phys. Rev. D 79, 115008 (2009), ** Babusci et al. (2015), Phys.Lett. B 747 pg. 365-372, 0370-2693

Conclusions

- Very active and wide-ranging program of searches for dark sectors at flavor experiments
- B-factories and LHCb can provide ***complementary competitive limits on several models***
- Increased luminosity, upgraded detectors and better analysis strategies will improve existing limits and provide soon new results

LHCb:
$A' \to \mu\mu$ PRL 124 (2020) 041801
$X \to \mu\mu$ JHEP 10 (2020) 156
LLP $\to e\mu\nu$, EPJ C81 (2021) 261

BaBar:
$Z' \to \mu\mu$ PRD 94, 011102 (2016)
$\varphi_L \to \ell\ell$ PRL 125, 181801 (2020)
$A' \to$ inv. PRL 119, 131804 (2017)

Belle II:
$Z' \to$ inv PRL 124 (2020) 141801
$a \to \gamma\gamma$ PRL 125 (2020) 161806

… more to come: *invisible dark photon, darkonium, dark-Higgsstrahlung, LLPs, Heavy Neutral Lepton searches …*

The Belle II Physics book

LHCb prospects on ALPs searches

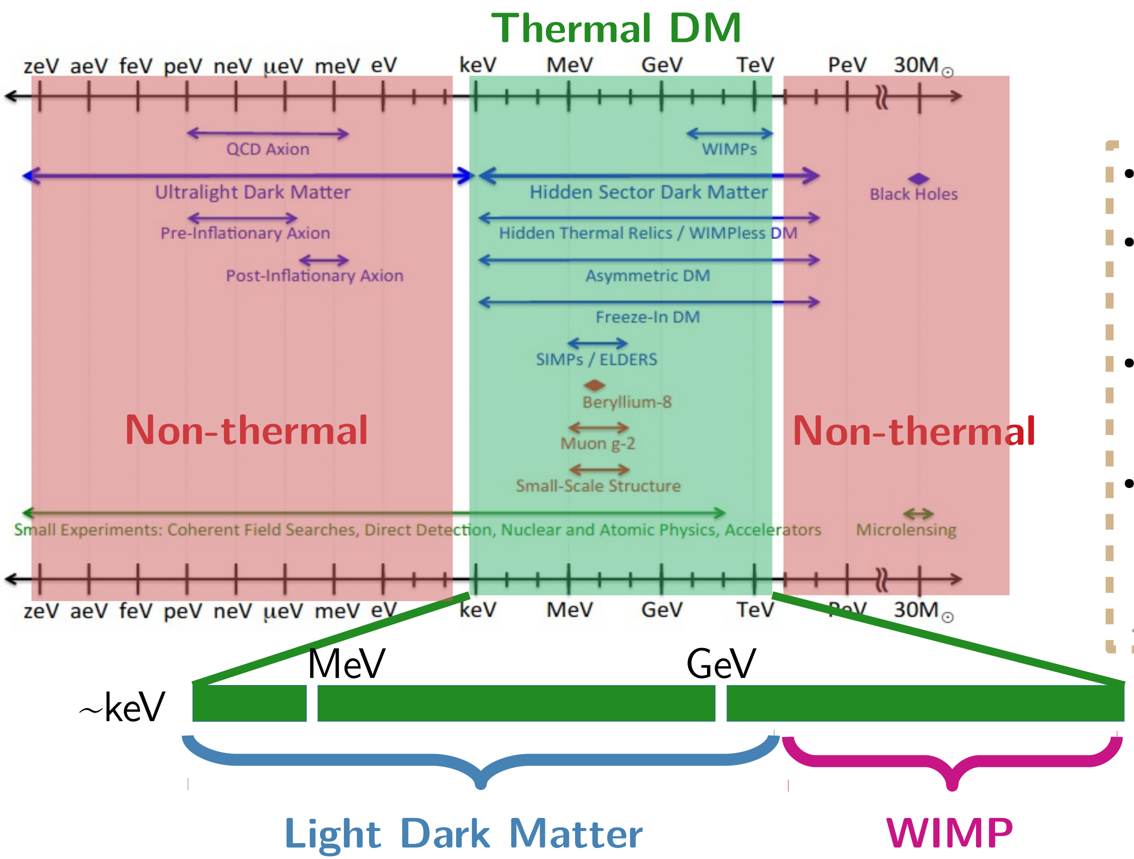
Thanks for your attention.

Backup

Dark matter candidates

- DM is an unsolved puzzle → Unknown origin and nature!

→ Modified Newtonian Gravity...
→ Non-particle candidates: MACHOs



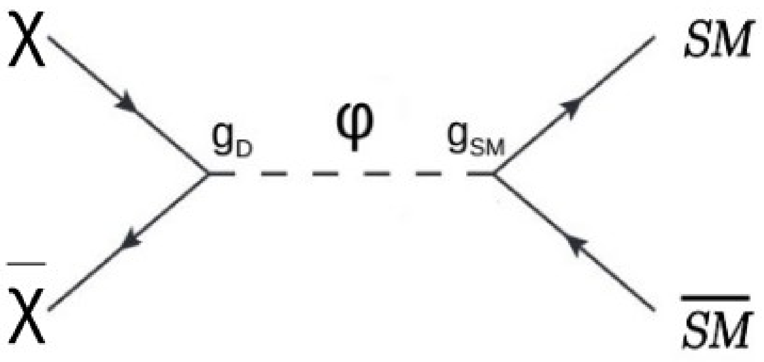
→ Particle candidates

- **Neutrinos** ✗ hot, relativistic candidates
- **QCD Axions** ✗ constrained by stellar cooling processes and supernovae dynamics, disfavoring thermal production
- **Sterile Neutrinos** ✓ observed DM abundance ✓ neutrino masses
- Weakly Interacting Massive Particles (**WIMPs**) ✓ match supersymmetric candidates (neutralino, *WIMP miracle*)

✗ null results from direct searches

Light dark matter scenarios

- No evidences for WIMP favor light DM hypotheses
- Possibility of *light dark sectors* motivates the search for a ***DM mediator (φ):***



Measured from cosmological observations

$$\langle \sigma v \rangle_{relic} \sim \frac{g_D g_{SM} m_\chi^2}{m_\phi^4}$$

<1

Experimentally constrained by current searches

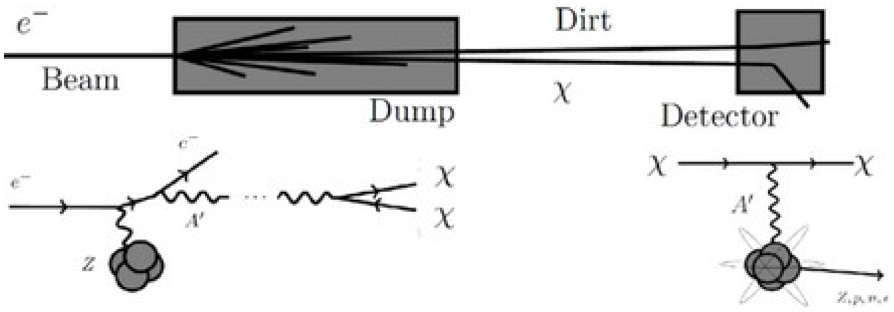
$$m_\phi^4 \leq \frac{m_\chi^2}{< \sigma v >} \text{ since g} < O(1)$$

May be too small to be consistent with the mass of any known SM mediator

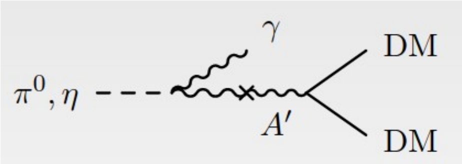
→ NEW PORTALS

Dark matter production at accelerators

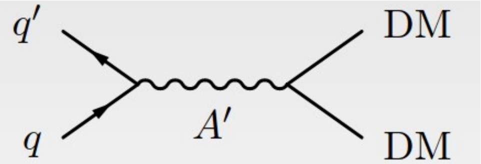
- Fixed-target experiment
  - ➔ Electron beam dump



  - ➔ Proton beam dump (DM at neutrino facilities)



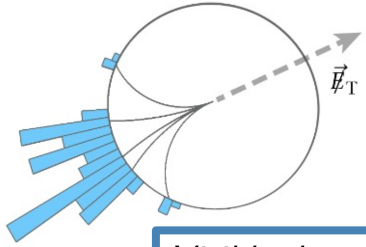
Via meson production

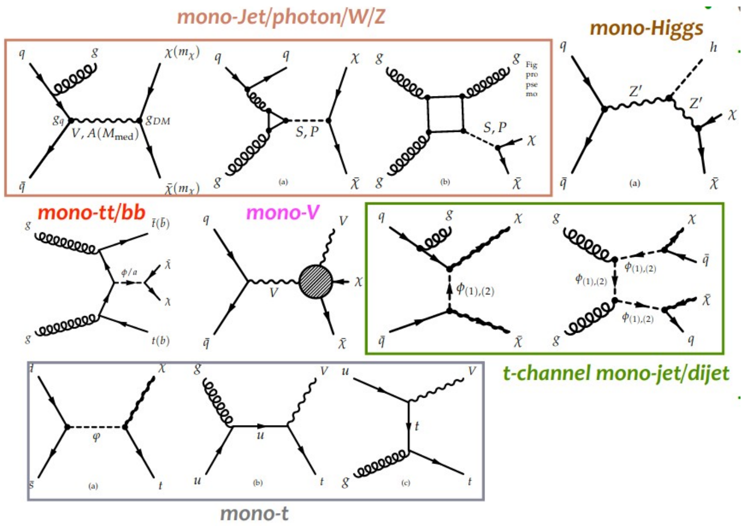


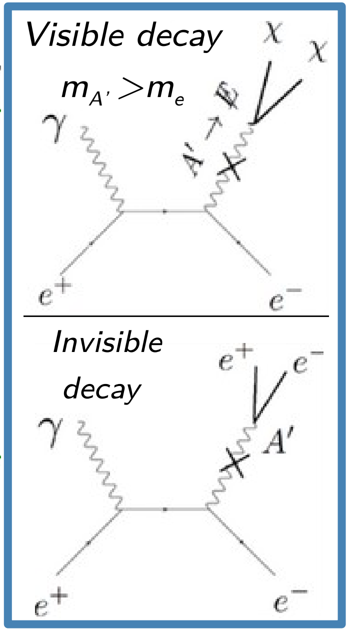
Direct production

- Colliders

Mono-X searches: detect a well-reconstructed SM object (ISR photon, jets..) + missing energy

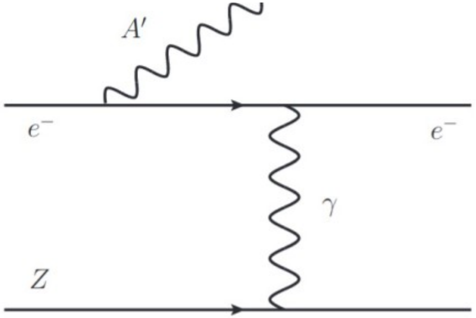






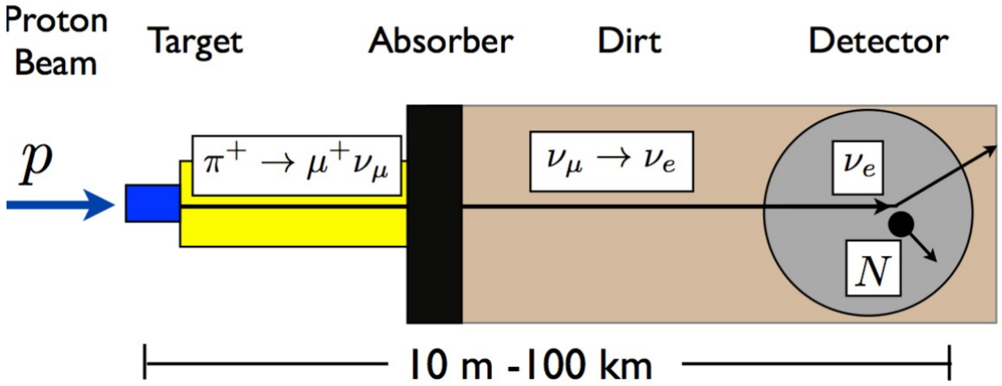
Dark matter searches at fixed-target

- Electron beam dump



- Suitable to investigate *vector* portals for mediator masses $2m_e < m_{A'} < GeV$
- Larger luminosity
- Scattering cross section enhanced by nuclear charge coherence
- Compact special-purpose detectors (dual-arms spectrometer @JLAB, MAMI, forward vertexing spectrometer @HPS)

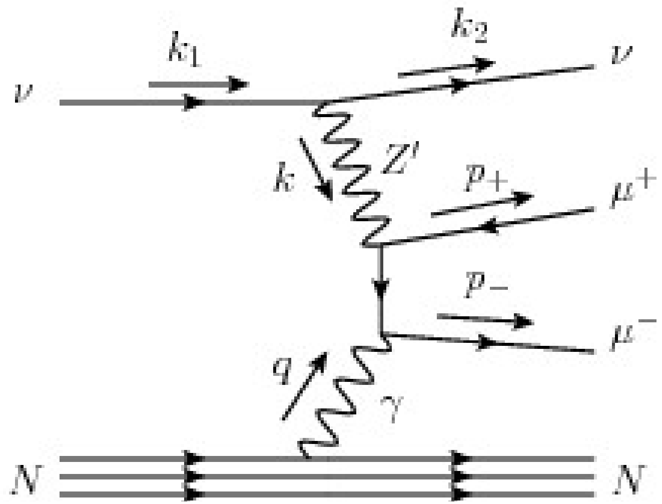
- Proton beam dump: exploiting neutrino facilities

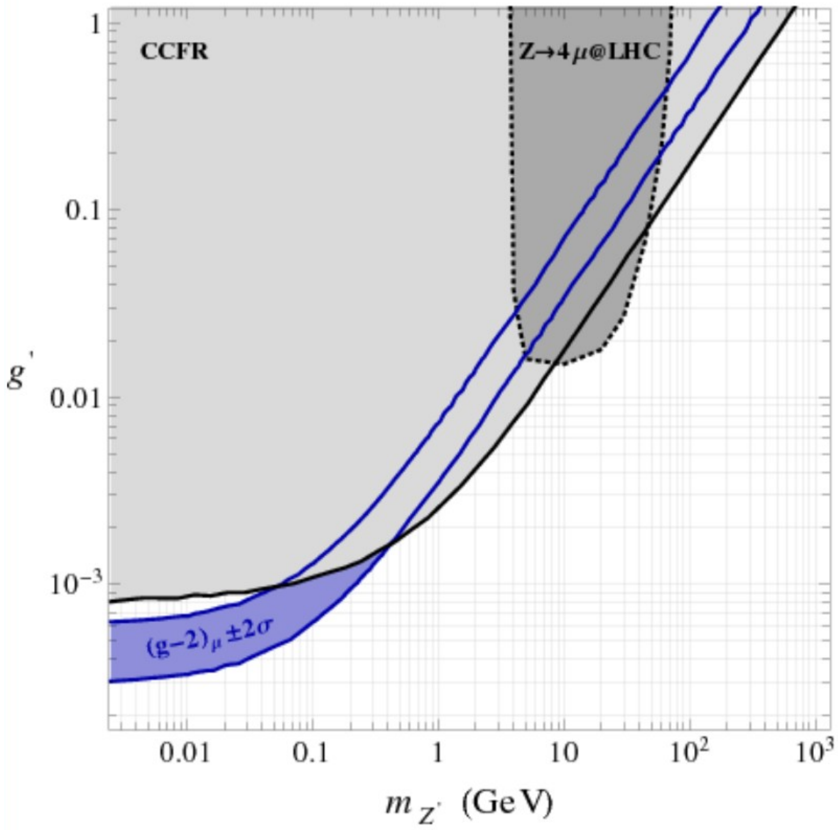


- Exploit existing neutrino facilities
- Look for neutral pion conversions to photons that may kinetically mix with the dark photon
- Signal signature: dilepton resonances, long-lived particle, missing energy

Neutrino trident production

- Neutrino trident production with a Z' boson





Cross section in e^+e^- collision at 10.58 GeV

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.)	$10° < \theta_e^* < 170°$, $E_e^* > 0.15\,\mathrm{GeV}$	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	$p_e > 0.5\,\mathrm{GeV}/c$ and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta_\gamma^* < 170°$, $E_\gamma^* > 0.15\,\mathrm{GeV}$	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5\,\mathrm{GeV}$ in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5\,\mathrm{GeV}/c$ in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5\,\mathrm{GeV}$ in CDC, $\geq 1\ \gamma\ (E_\gamma > 0.5\,\mathrm{GeV})$ 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.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	AAFH
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	AAFH

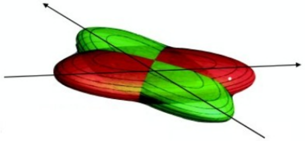
The Belle II Physics Book [arXiv:1808.10567]

- Low multiplicity event cross sections rapidly diverge compared to hadronic ones
- Selections applied at MC generator level to reduce the effective cross section (acceptance, particle momentum selections)
- W_{ll} is the minimum invariant secondary fermion pair mass

SuperKEKB accelerator

- **World highest luminosity,** applying the large crossing angle (83 mrad) *nano-beam scheme* [arXiv:0709.0451].

KEKB



SuperKEKB

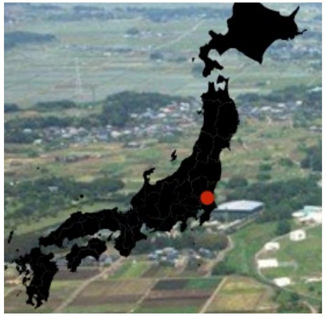
I (A): ~ 1.6/1.2 → **x 2** → I (A): ~ 3.6/2.6

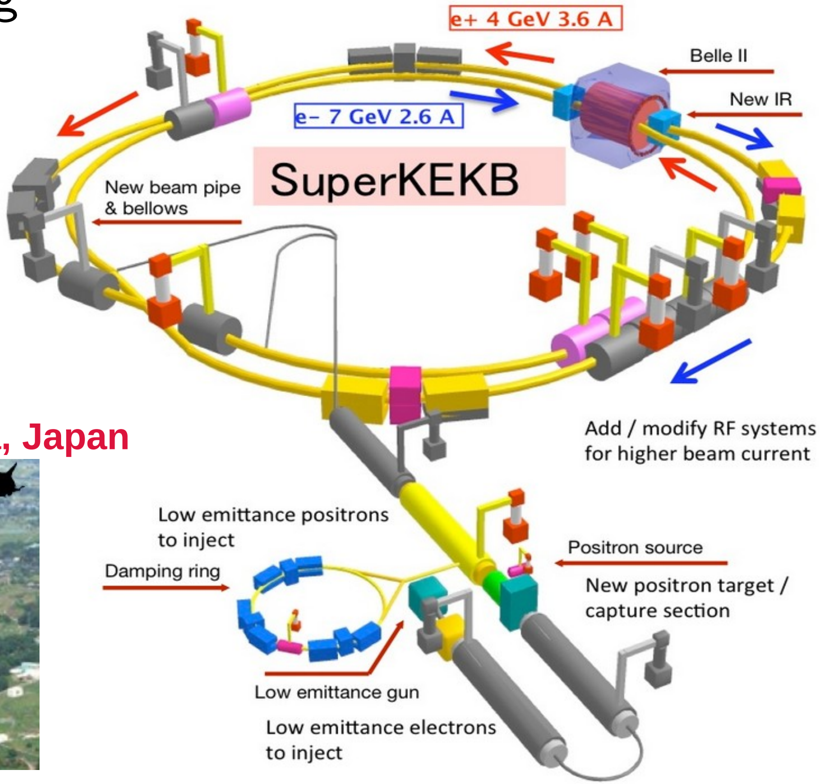
β^*_y (mm): ~ 5.9/5.9 → **x 1/20** → β^*_y (mm): ~ 0.27/0.3

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

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

KEK
Tsukuba, Japan

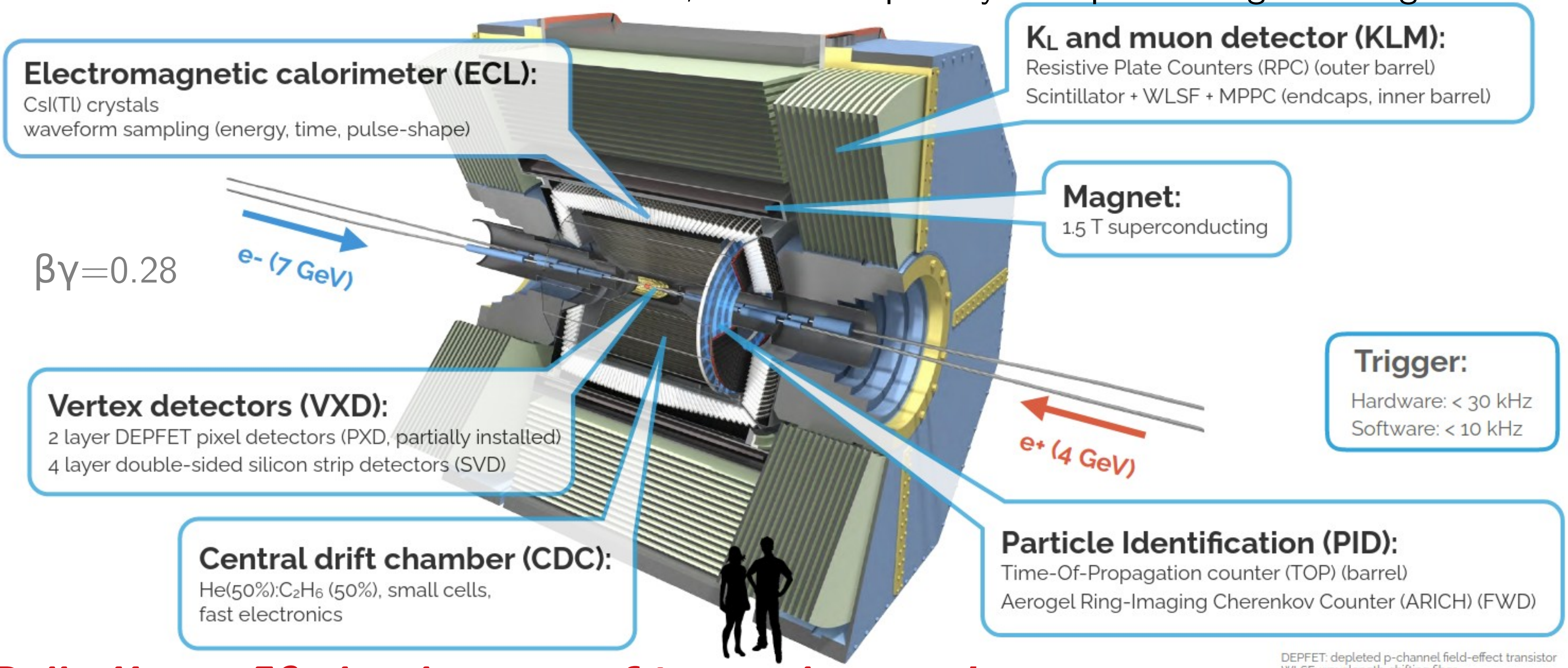




30x KEKB peak luminosity: $\mathcal{L} = 6 \cdot 10^{35}$ cm^{-2} s^{-1}

Belle II detector

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



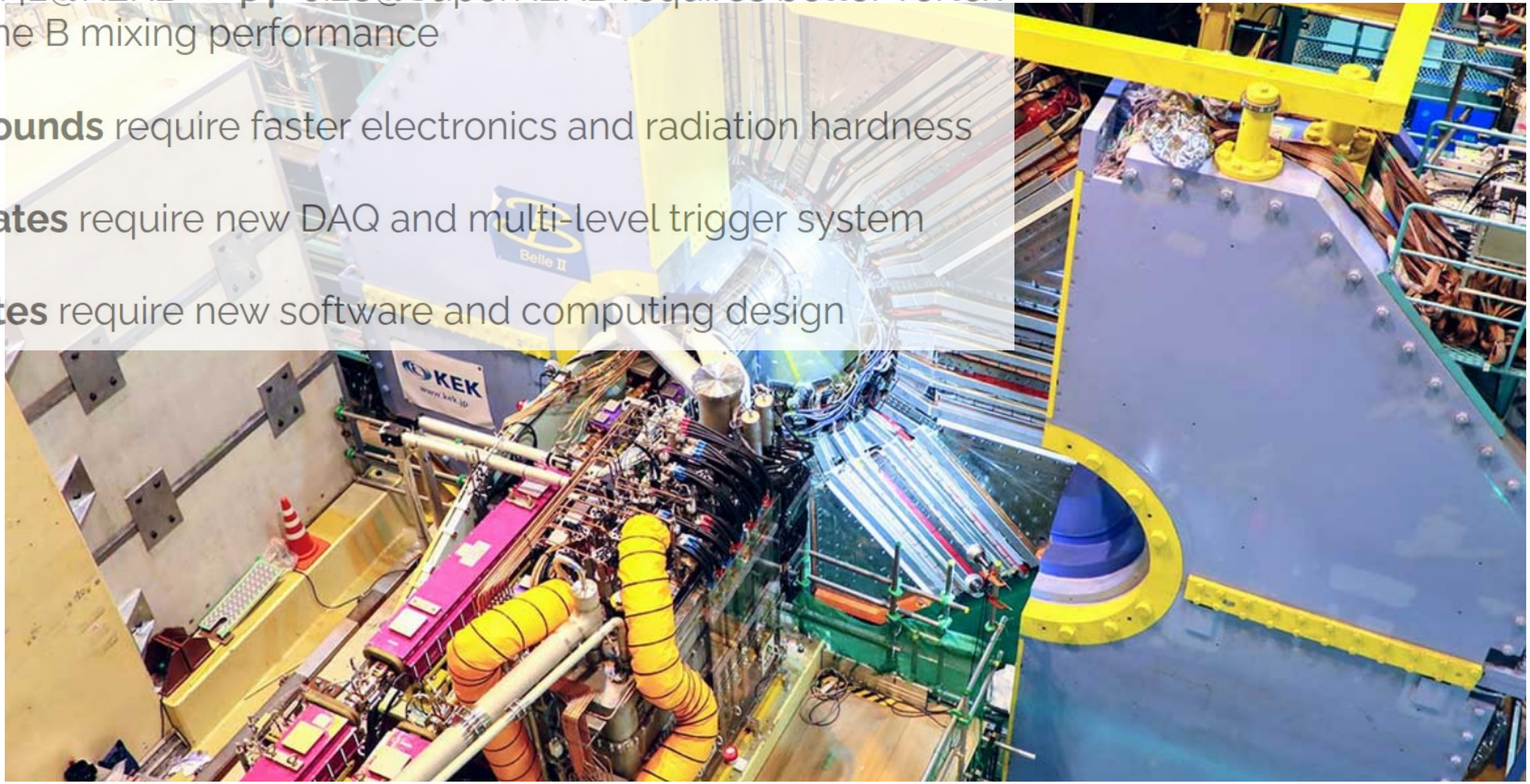
Belle II $\rightarrow$ x50 the data set of its predecessor!

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}		$cm^{-2}s^{-1}$	

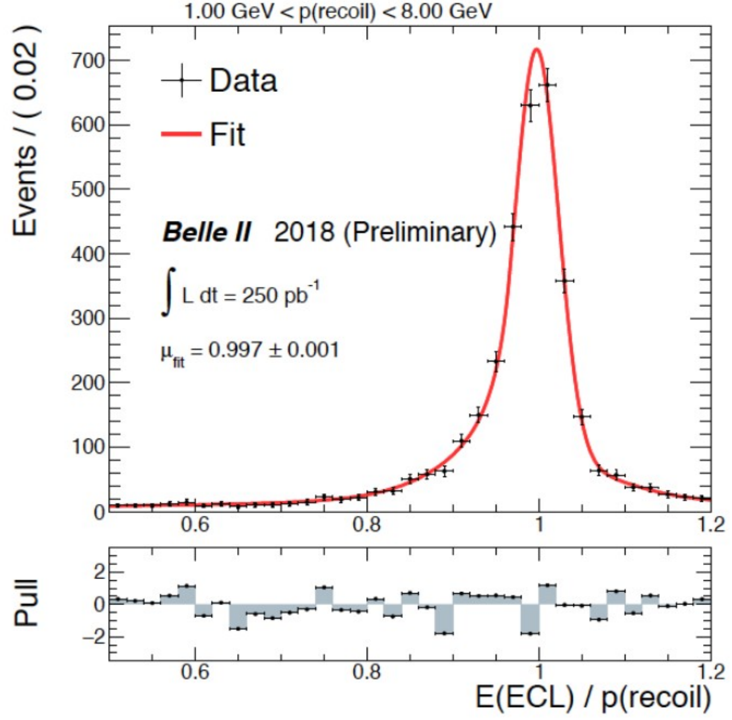
Belle II Challenges

- **Reduced boost** βγ=0.42@KEKB → βγ=0.28@SuperKEKB requires better vertex resolution for the same B mixing performance
- Much **higher backgrounds** require faster electronics and radiation hardness
- Much **higher event rates** require new DAQ and multi-level trigger system
- Much **higher data rates** require new software and computing design

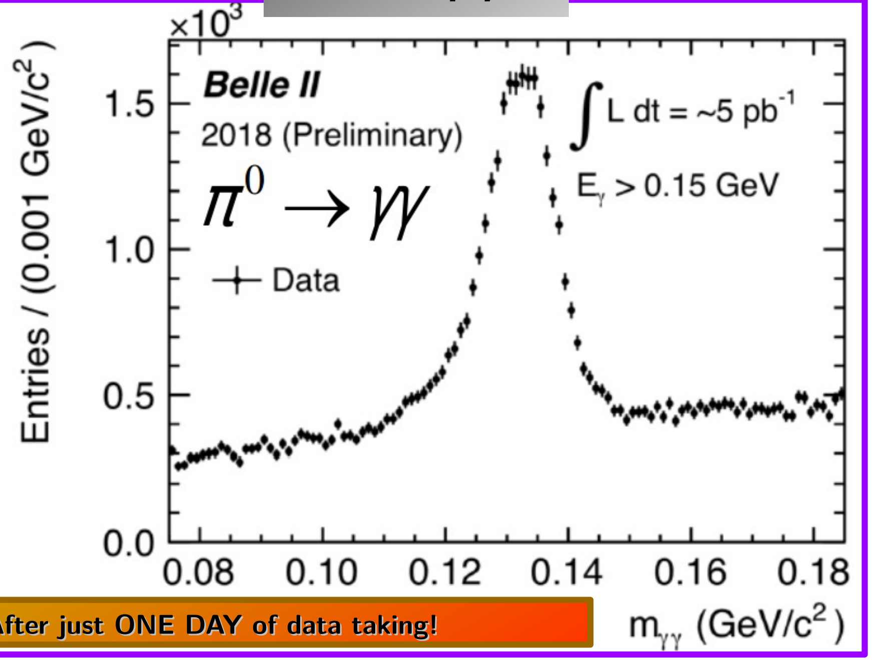


Belle II Performances in Phase 2: photon reconstruction

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



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

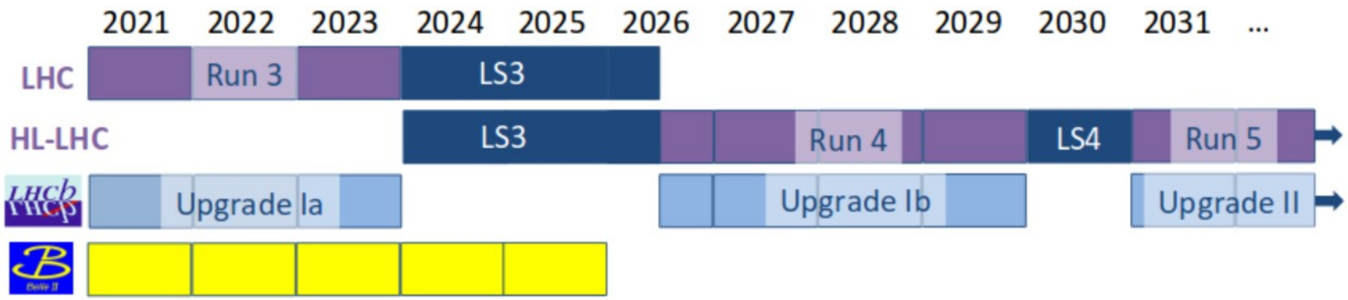


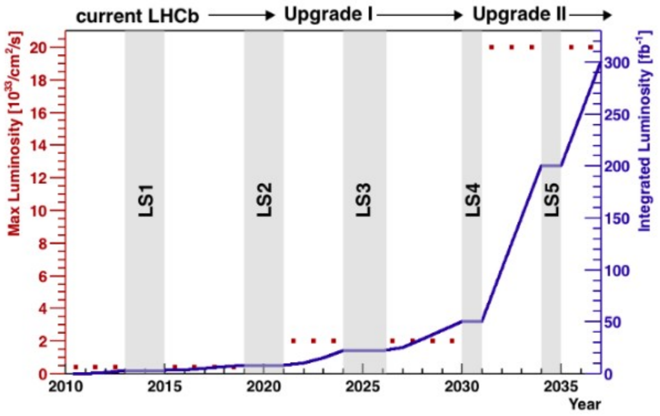
After just ONE DAY of data taking!

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

Future of LHCb

Physics case for an LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era [CERN-LHCC-2018-027]





- **Challenging conditions** – higher rate, pile-up, occupancy and fluence.
- Expect to collect 300 fb^{-1} by the end of Upgrade II.
- Detector sub-systems have to be able to cope with such conditions.
- In particular – **trigger** and **tracking systems** are crucial for exotic searches.

Muonic dark forces: visible Z'

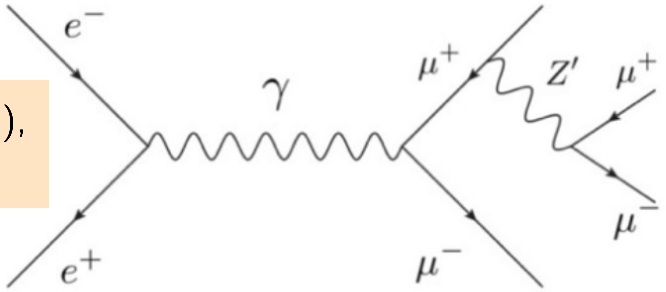
PRD 94, 011102 (2016)

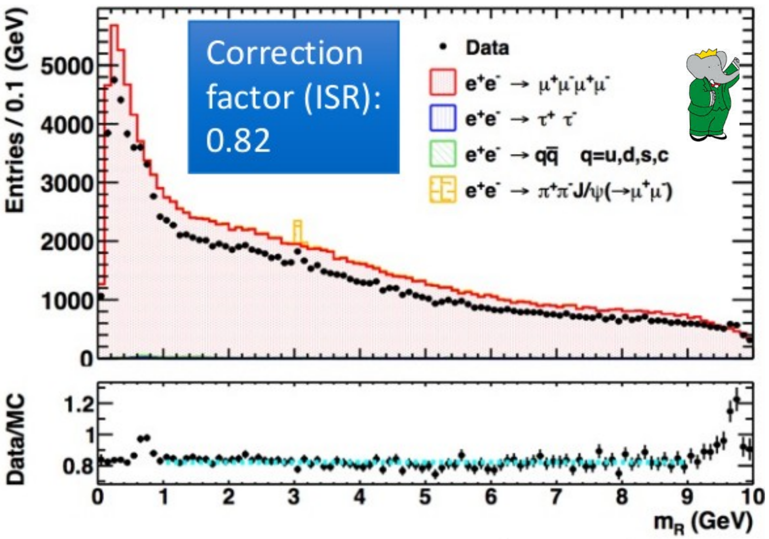
Search for a di-muon invariant mass peak in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ events

Main sources of background:

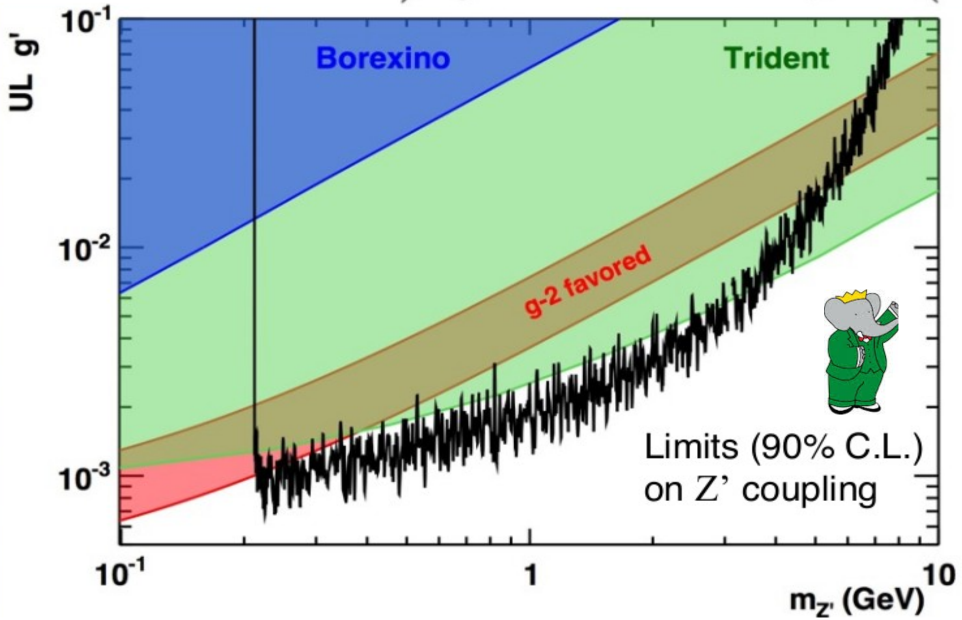
- QED combinatorial
- Resonant $e^+e^- \to \pi^+\pi^- J/\psi\ (\to \mu^+\mu^-)$

Total BaBar data set at $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$ and their vicinities: **514 fb^{-1}**





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



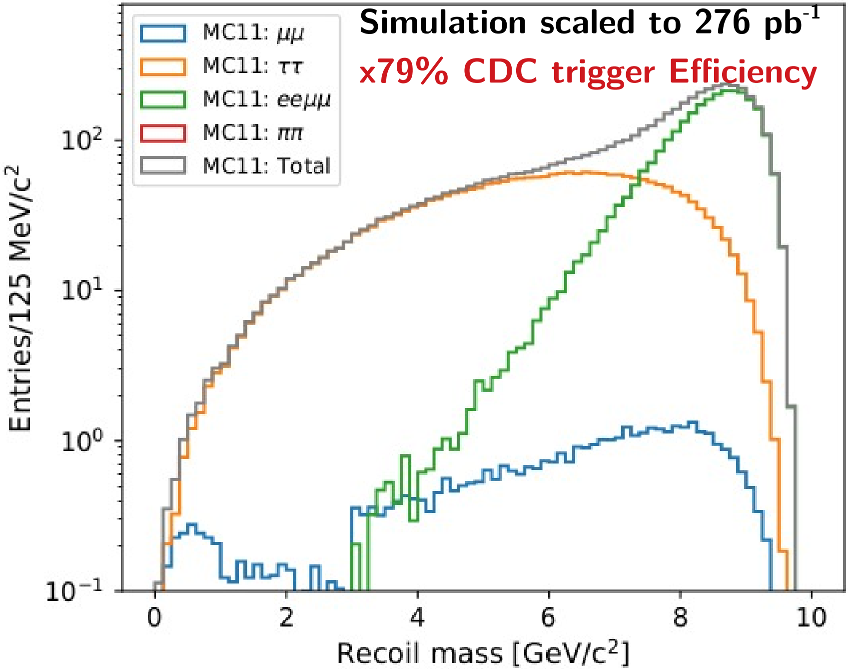
Limits (90% C.L.) on Z' coupling

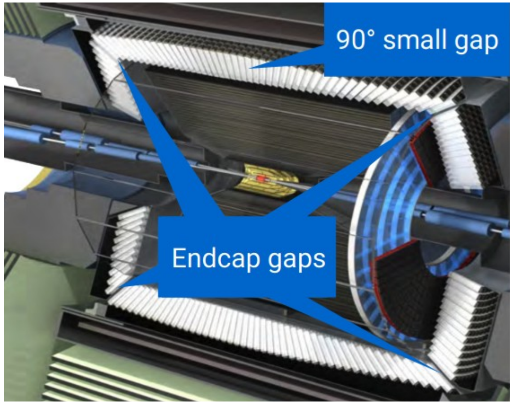
Z' to invisible: event selection

- Two good tracks coming from the interaction point and satisfying an ECL-based muon identification → *dimuon candidate*

Muon ID:
0.15< clusterE < 0.4 GeV
clusterE/p < 0.4

- Tracks pointing to a fiducial ECL barrel region, 37° < θ_μ < 120°, and similarly the recoil momentum
- **For $\mu\mu$ events CDC trigger fired in data and mimic the trigger effect in the selection: 2-track opening angle in the range [90°, 172°]**



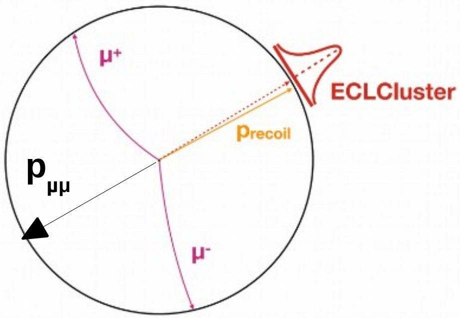


- Clean the ***Rest Of Event*** (**ROE**):

  → no ECL cluster (clusterE > 100 MeV) within 15° cone with respect to the reconstructed recoil momentum *(closest photon veto)*

  → no reconstructed π^0 candidate *(π^0 veto)*

  → no energy deposited in the ROE > 400 MeV *(extra energy veto)*



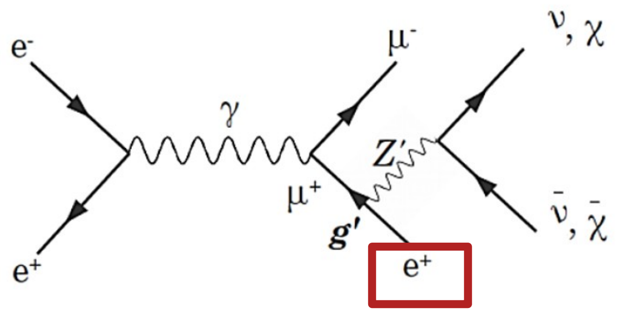
Z' to invisible: event selection (LFV Z')

- LFV Z' inherits the same selections, replacing a muon with an electron
- **For eμ events ECL trigger fired in data and mimic the trigger effect in the selection: ECL cluster energy for electron track >1.5 GeV**
- Same vetos (*closest photon, π^0 , extra energy veto*) applied to clean the ***Rest Of Event*** (**ROE**)

Muon ID:
clusterE/p $<$ 0.4

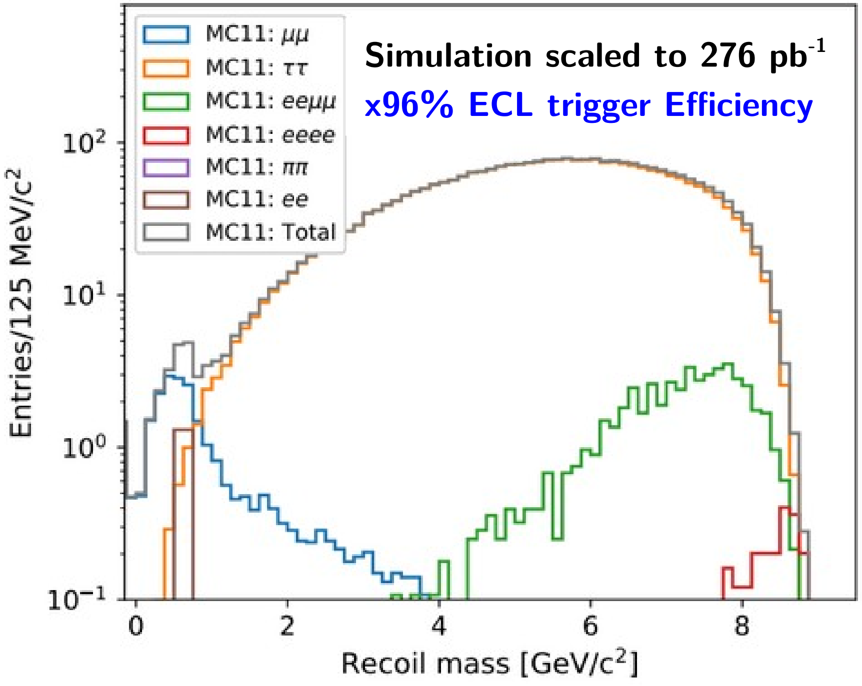
→

Electron ID:
0.8 $<$ clusterE/p $<$ 1.2



$e^+e^- \to e^\pm \mu^\mp +$ *missing energy*

Galon et al. (2016), arXiv:1610.08060



LFV Z' results

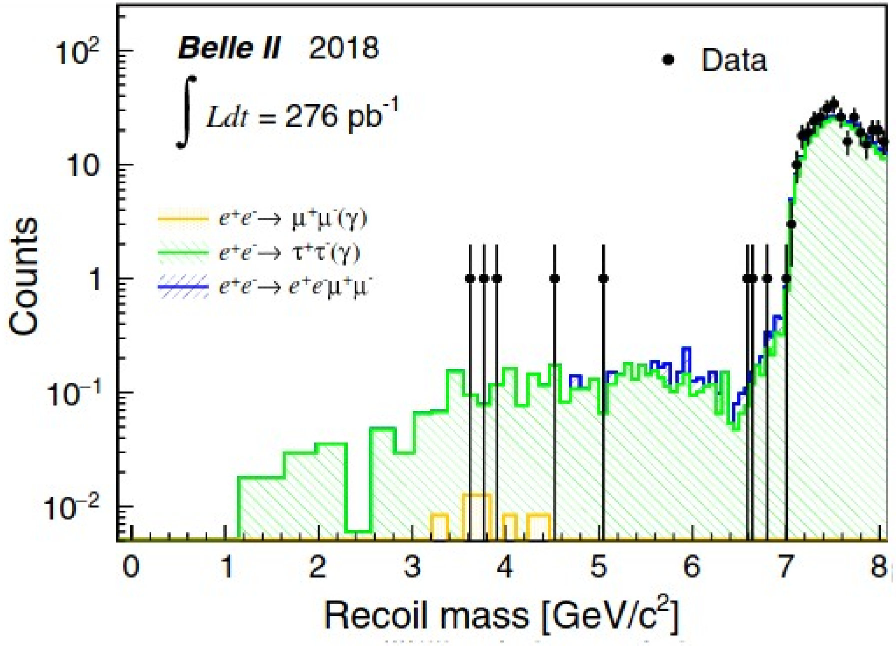


FIG. 4. Recoil mass spectrum of the $e^{\pm}\mu^{\mp}$ sample. Simulated samples (histograms) are rescaled for luminosity, trigger (0.79), and tracking (0.90) efficiencies. Histogram bin widths indicate the recoil mass windows.

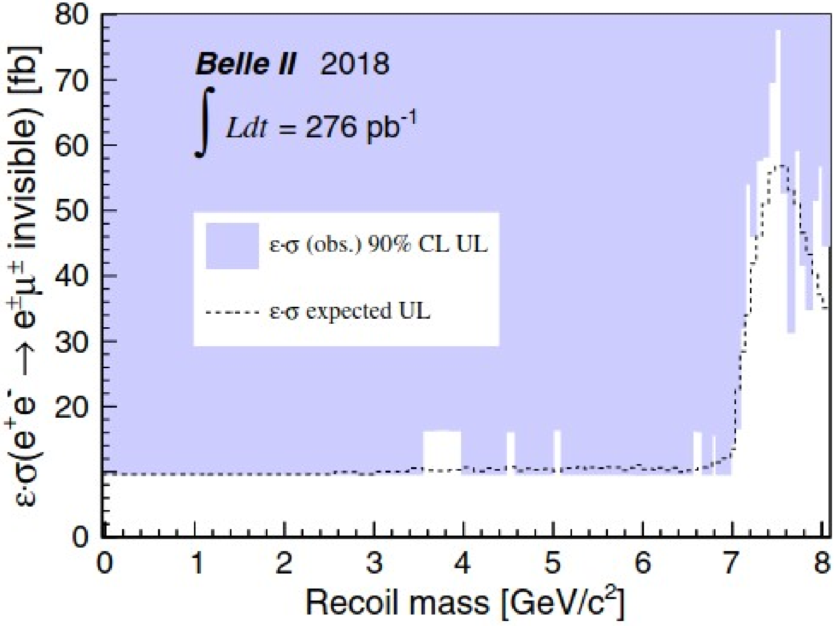


FIG. 5. 90% C.L. upper limits on efficiency times cross section $\epsilon \times \sigma[e^+e^- \to e^{\pm}\mu^{\mp}\text{invisible}]$. The dashed line is the expected sensitivity.

Z' to invisible: background rejection

Background from QED processes that can mimic the final state of 2 muons + missing mass because of acceptance or undetected particles:

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

> - affects the low mass range $M_{rec} < 3$ GeV, rejected by general selections
> - **Dominant contribution in the recoil mass range ~ 3-7 GeV → needs dedicated suppression**
> - Affects high mass spectrum $M_{rec} > 7$ GeV where sensitivity is also limited by the decreasing production cross section

- Selections optimization by maximizing the *Punzi figure of merit* in each recoil mass bin.

$$FOM_{Punzi} = \varepsilon/(a/2 + \sqrt{B}),\ a=1.64\ (90\%\ CL)$$

- Number of surviving events and signal efficiencies computed for each recoil mass bin →

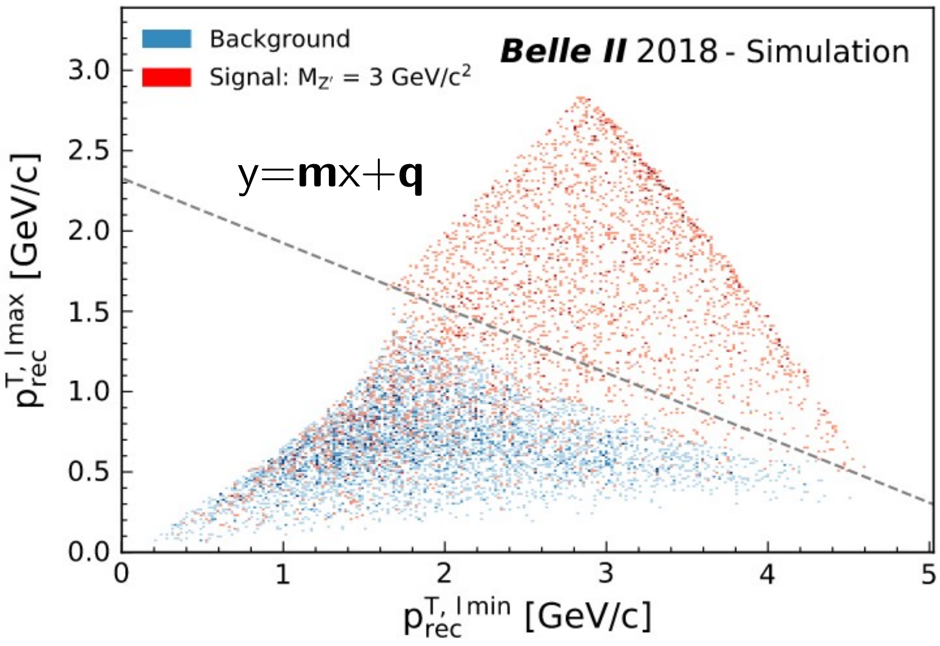
Binning scheme:

I. Contiguous bins have been defined interpolating the fitted σ_w to cover all the recoil mass spectrum
II. Punzi-optimized bin-widths = $\pm 2\sigma_w$

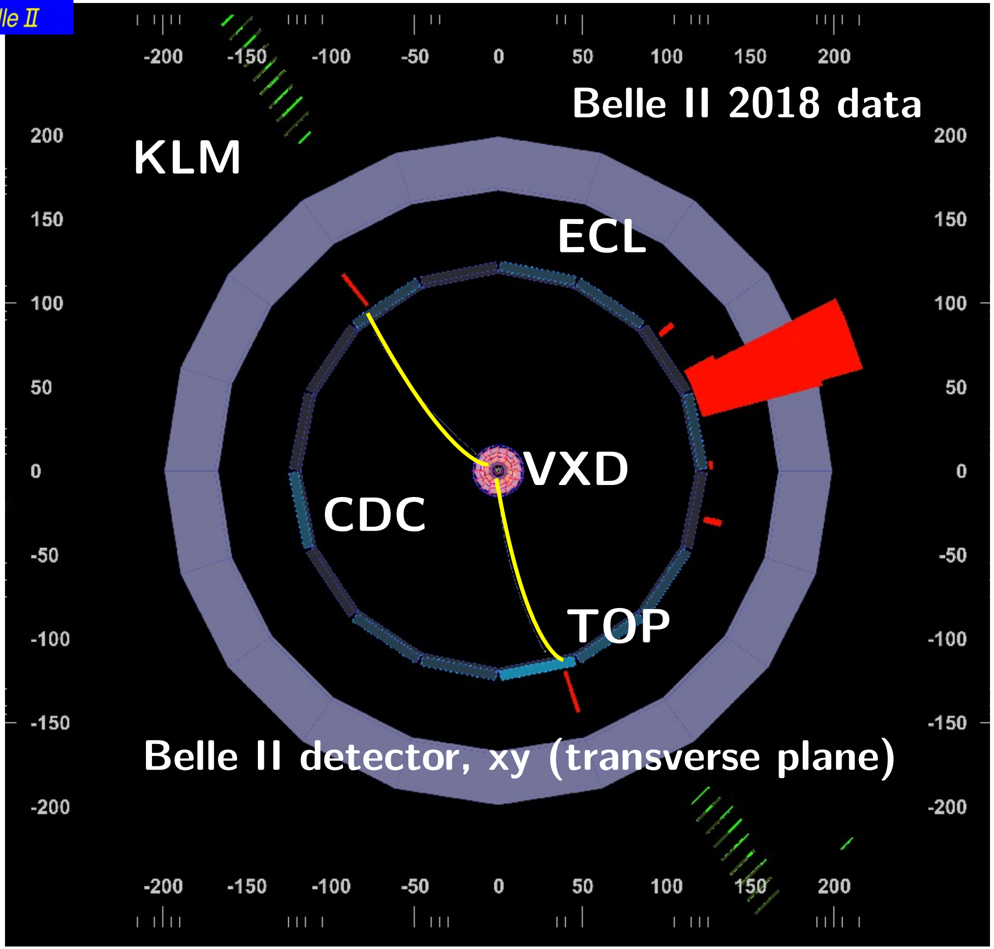
Z' to invisible: τ-suppression procedure

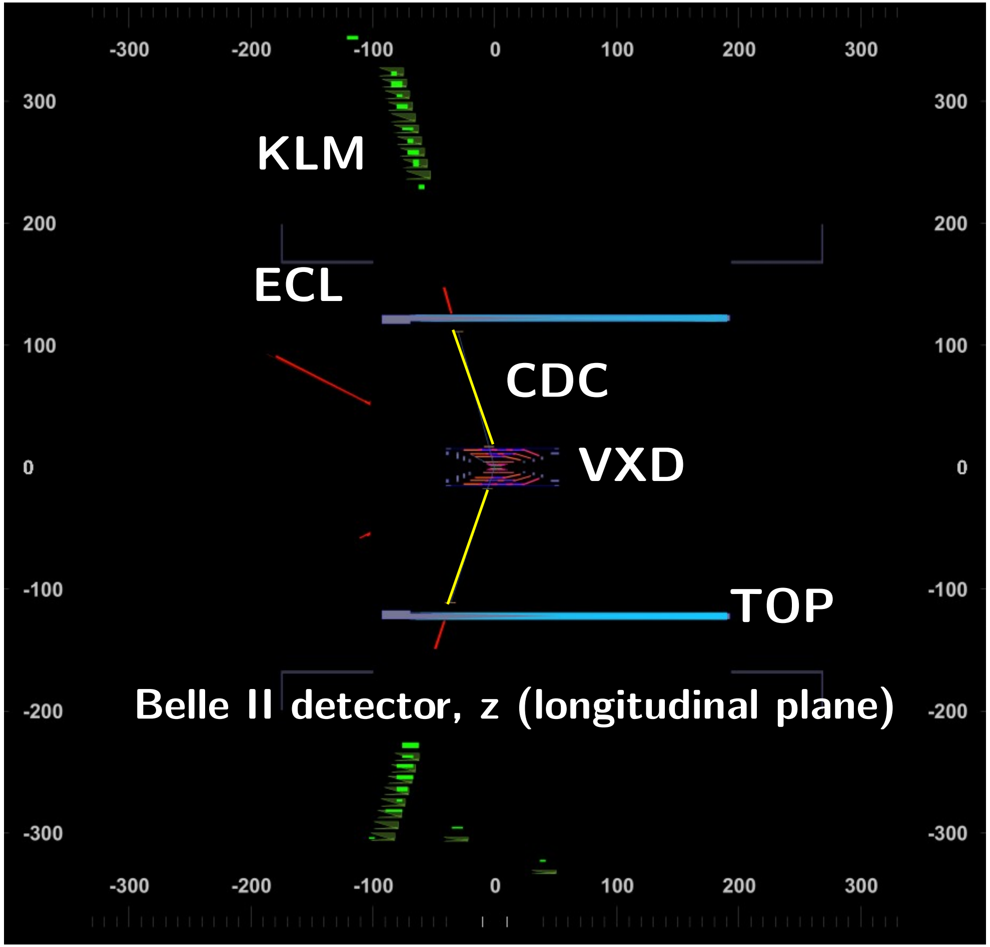
- **Discriminant variables:**
  - $\mathbf{p^{T,max}_{rec}}$, $\mathbf{p^{T,min}_{rec}}$, transverse component of recoil momentum along the direction of the maximum/minimum lepton momentum
  - $\mathbf{p^{T}_{\mu\mu}}$, dimuon candidate transverse momentum

➔ Z' is *final state radiation* from one muon leg, missing momentum in ττ events is due to neutrinos from both muons



- Optimal selections found by simultaneously maximizing the Punzi FOM
- Interpolated as a function of M_{rec}
- Achieved rejection factor ($N_{bkg}^{before}/N_{bkg}^{after}$) up to 400; relative efficiencies ~40-70%

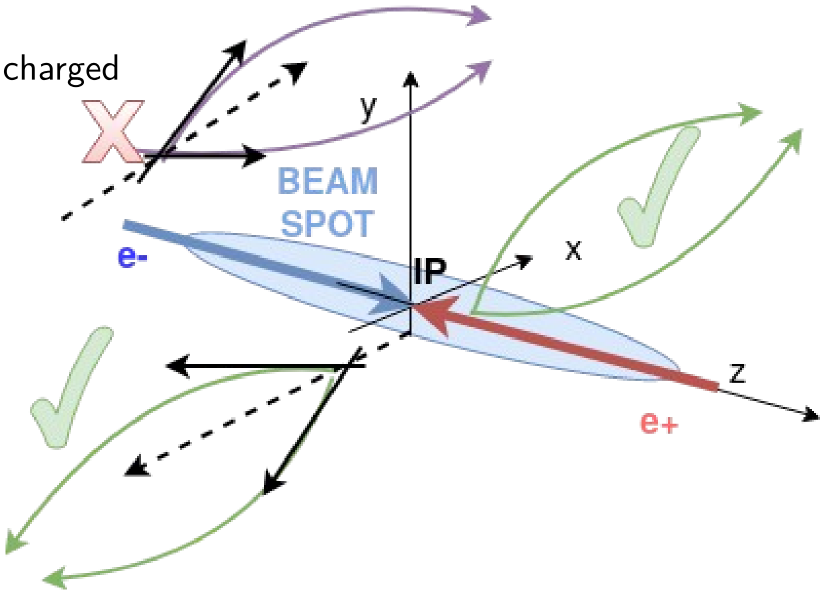

Belle II 2018 data
KLM
ECL
VXD
CDC
TOP
Belle II detector, xy (transverse plane)


KLM
ECL
CDC
VXD
TOP
Belle II detector, z (longitudinal plane)

Dark leptophilic scalar: event selection

- Only 4 tracks + missing energy/momentum due to τ neutrinos
- Apply Lepton Identification and reconstruct φ_L candidates as two oppositely charged leptons, kinematically fitted to the **same vertex**:
  - Constrain to beam spot region for dimuon resonance (prompt only)
  - Resulting momentum points back to Interaction Point for e^+e^-

    $\rightarrow$ ***allow for displaced vertex signatures***
- Reject radiative dilepton + pair conversions contamination:
  - Visible mass lower than 9 GeV
  - Angular isolation from nearby tracks for reconstructed φ_L candidate
  - Missing momentum of the event > 300 MeV



- **Boosted Decision Tree** optimized for best signal sensitivity as function of the φ_L mass
- Remaining **peaking background** from J/ψ and $\Upsilon(2S)$ contamination $\rightarrow$ corresponding mass not scanned in the signal search
- ***$\pi^0 \rightarrow \gamma\gamma$, with $\gamma \rightarrow e^+e^-$ conversions*** observed for $c\tau_{\varphi L} = 1$mm $\rightarrow$ broader feature than signal resonances, included in the scan and model as background component

Dark leptophilic scalar: results

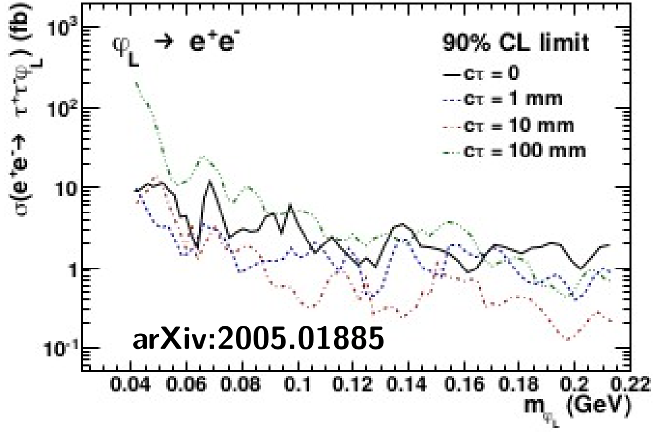
- From the fitted signal yields compute the cross section for $e^+e^- \to \tau^+\tau^-\varphi_L$, $\varphi_L \to \ell^+\ell^-$ (ℓ=e,μ) for different {lifetime, final state} as a function of the beam energy

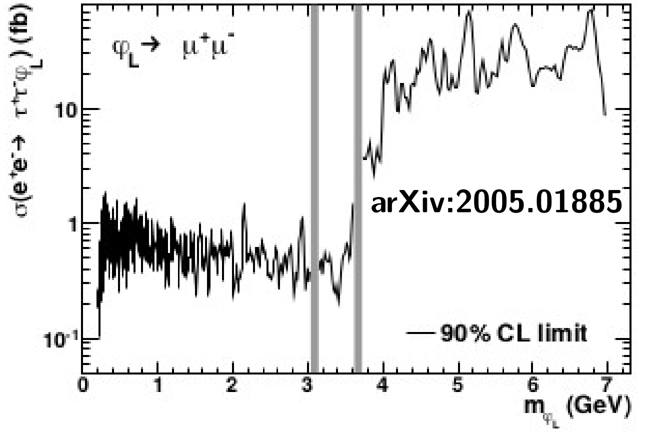
$$\sigma_{4S} = \frac{N_{sig}}{\sum_{i=2S,3S,4S} \left(\frac{\sigma_{th,i}}{\sigma_{th,4S}}\epsilon_i \mathcal{L}_i\right) BF(\phi_L \to \ell^+\ell^-)}$$

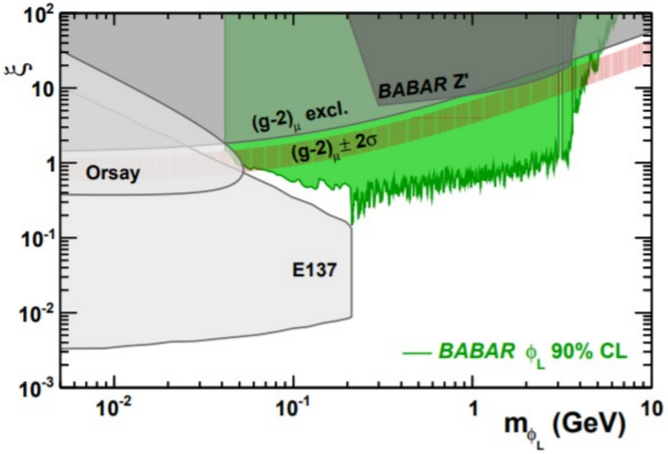
- Extract 90% CL Bayesian upper limits

  → flat positive priors and Gaussian-distributed systematic uncertainty ***included by marginalizing***

  – dominant systematic effect coming from data/MC comparison → assign 3.8% (4%) systematic uncertainty in the dielectron (dimuon) signal efficiency



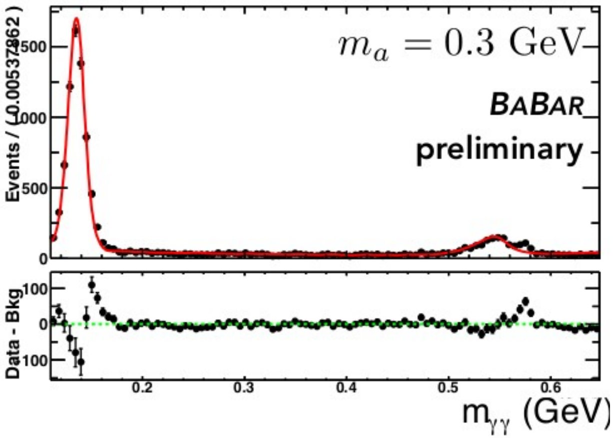




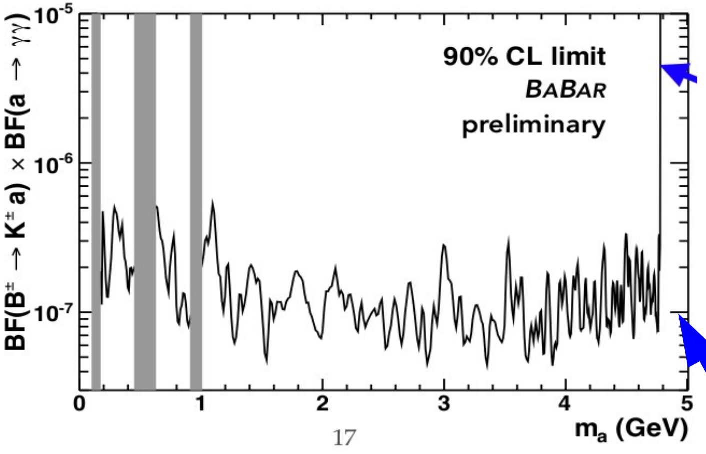
Limits on the *leptophilic scalar coupling* as a function of the searched mass are derived within MadGraph5 (iterative procedure)

$B^{\pm} \rightarrow K^{\pm}a$: fit strategy and signal extraction

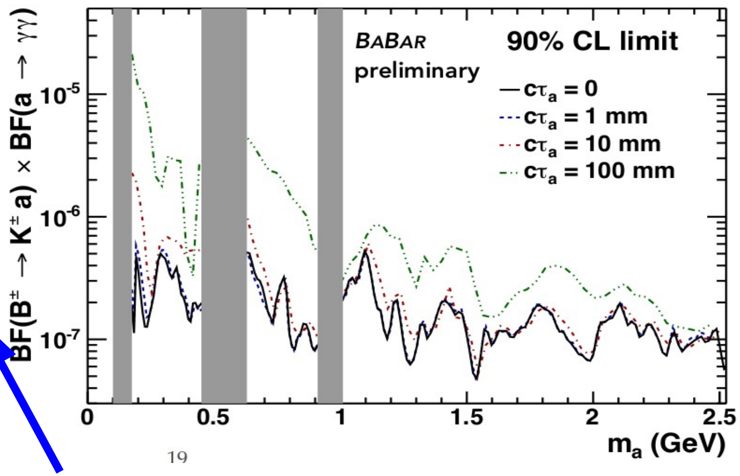
- Scan diphoton spectrum: **476 unbinned maximum likelihood fits** for each mass hypothesis (excluding scan in the vicinity of peaking background contamination from π^0, η, η')
- Fit windows vary from 30-70σ, with **σ the signal resolution** (8-14 MeV) → extracted from fits to signal simulations by using double-side Crystal Ball function and interpolated for intermediate values
- Same selection and fit procedures as optimized for **prompt ALPs** applied to *long-lived ALPs*, for $m_a < 2.5$ GeV



Prompt decaying ALPs



Long-lived ALPs



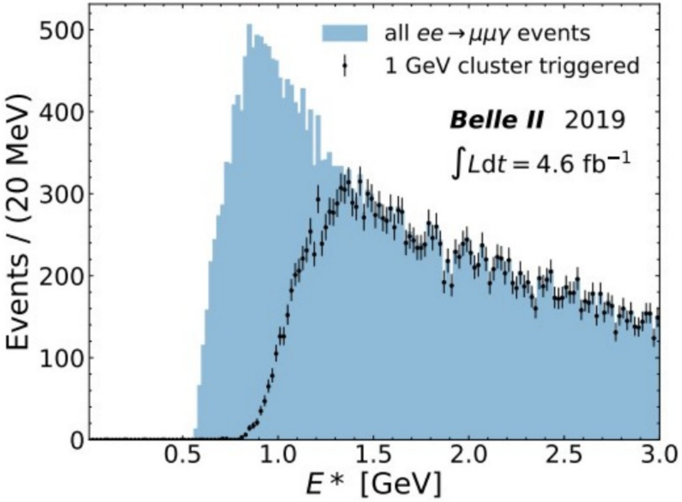
kinematic limit $m_a > m_B - m_K$

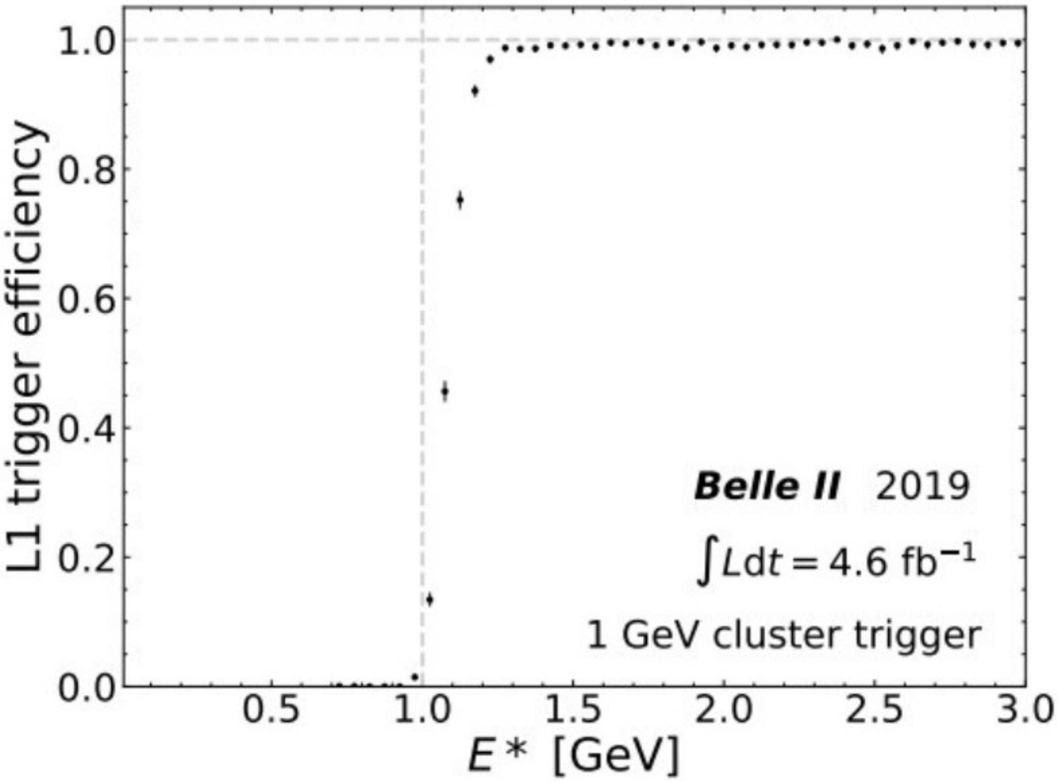
Highest global significance <1σ after including trial factors

Dark photon to invisible: single photon trigger

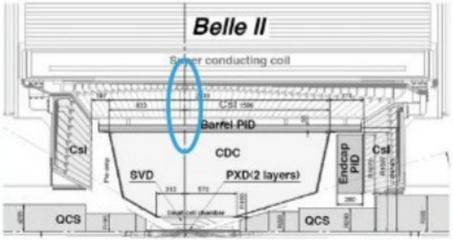
Belle II Phase 3 (Design)

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)





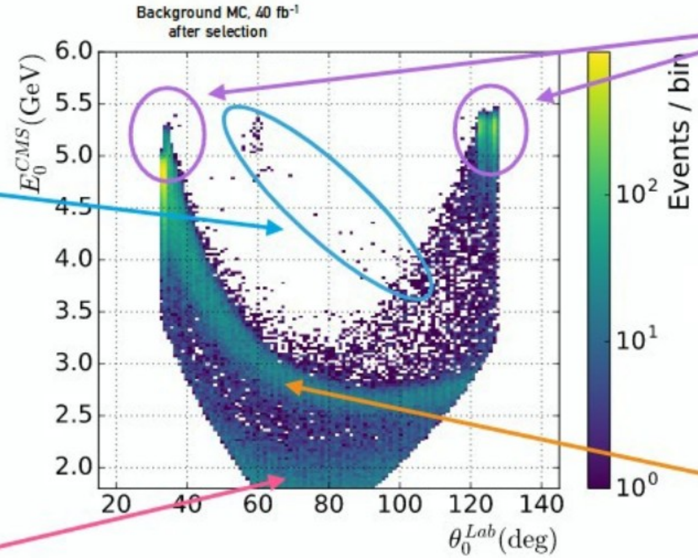
Dark photon to invisible: backgrounds

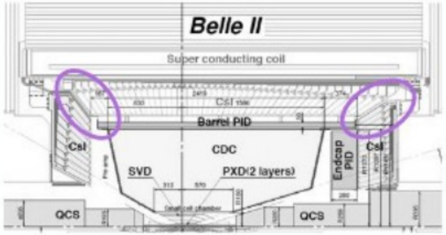


ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance

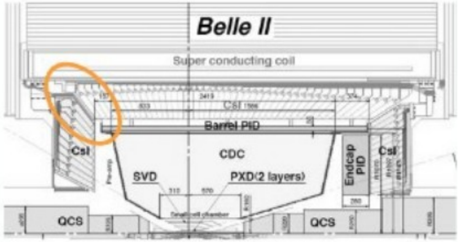
Discriminant variables:

E_{CMS} vs. polar angle of "single photon"





ee→2γ
1γ in ECL BWD or FWD gap



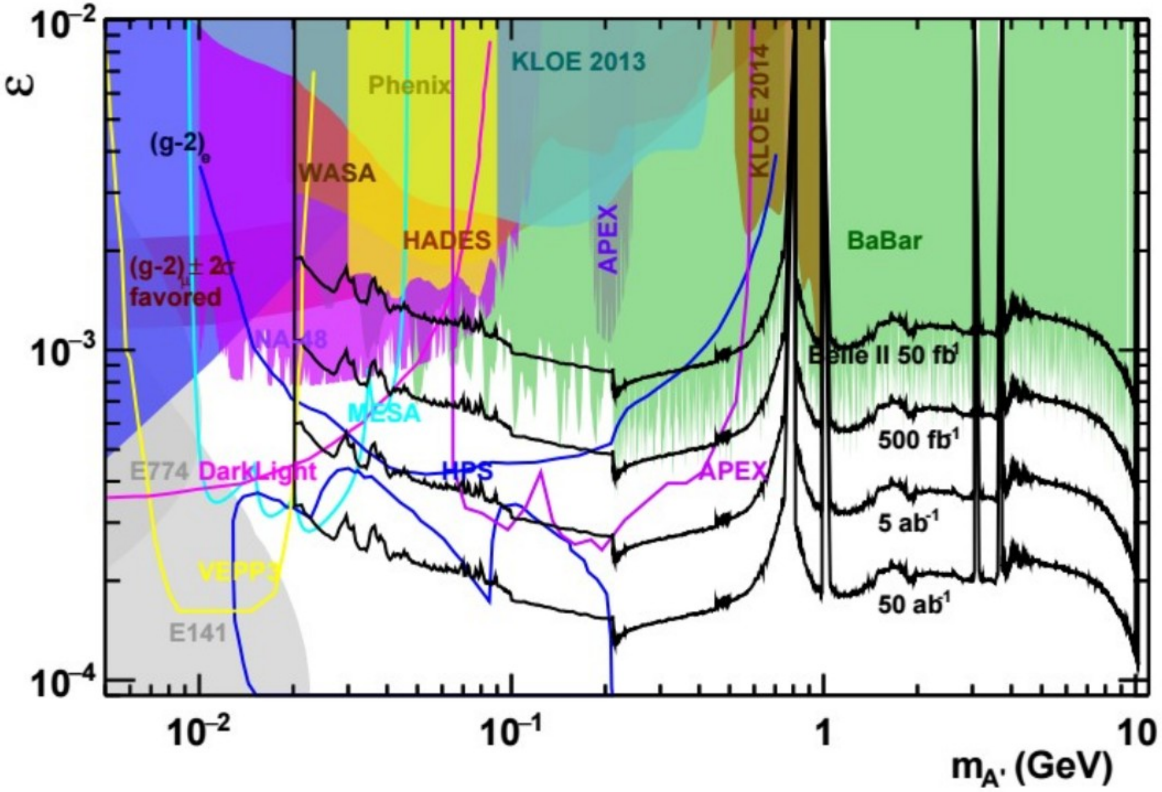
ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

ee→eeγ
both electrons
out of tracking acceptance

Signal signature:

peak in E_{CMS} (horizontal band)

Visible dark photons: leptonic decays



Look for a bump in the e^+e^- or $\mu^+\mu^-$ invariant mass over a (large) QED background

Belle II sensitivity is obtained by scaling the BaBar measurement:

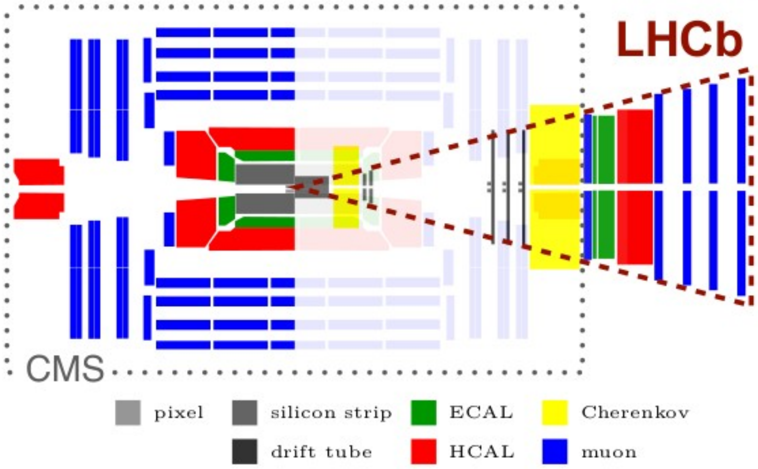
- **expected better invariant mass resolution**
- **expected better triggers**

The LHCb detector

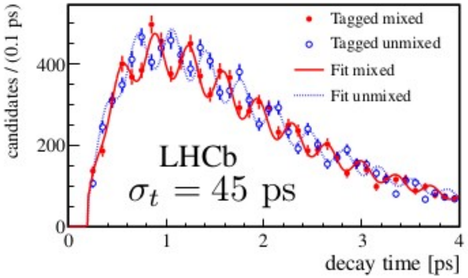
- Only LHC detector fully instrumented in **forward** region
- Excellent vertex and momentum resolution
- Lower luminosity (@ low pile-up) 3/fb in Run 1, 5.9/fb in Run 2
- **Capable of soft triggers!**
  - In hardware $p_T(\mu^\pm) > 1.8$ GeV while $p_T(e^\pm, h^\pm) > 3$ - 4 GeV
  - Very flexible software trigger
- **In LHC Run 2:**
  - Real-time analysis with offline-quality alignment
  - Keeping only interesting part of event (Turbo stream)

LHCb, JINST 10 (2015) P06013

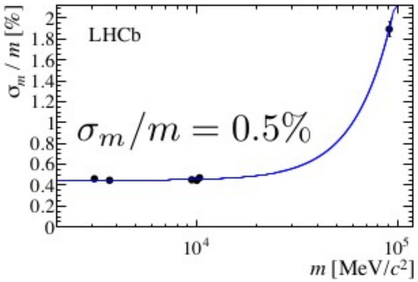
Int.J.Mod.Phys. A 30, 1530022 (2015)



vertex reconstruction



mass resolution



X→ μμ: signal searches

Table 1: Fiducial regions of the searches for prompt and displaced $X \to \mu^+\mu^-$ decays.

All searches	$p_{\mathrm{T}}(\mu) > 0.5\,\mathrm{GeV}$ $10 < p(\mu) < 1000\,\mathrm{GeV}$ $2 < \eta(\mu) < 4.5$ $\sqrt{p_{\mathrm{T}}(\mu^+)p_{\mathrm{T}}(\mu^-)} > 1\,\mathrm{GeV}$ $5 \leq n_{\mathrm{charged}}(2 < \eta < 4.5, p > 5\,\mathrm{GeV}) < 100$ (from same PV as X)
Prompt $X \to \mu^+\mu^-$ decays	$1 < p_{\mathrm{T}}(X) < 50\,\mathrm{GeV}$ X decay time $< 0.1\,\mathrm{ps}$ $\alpha(\mu^+\mu^-) > 1\,\mathrm{mrad}$ $20 < p_{\mathrm{T}}(b\text{-jet}) < 100\,\mathrm{GeV},\ 2.2 < \eta(b\text{-jet}) < 4.2$ ($X + b$ only)
Displaced $X \to \mu^+\mu^-$ decays	$2 < p_{\mathrm{T}}(X) < 10\,\mathrm{GeV}$ $2 < \eta(X) < 4.5$ $\alpha(\mu^+\mu^-) > 3\,\mathrm{mrad}$ $12 < \rho_{\mathrm{T}}(X) < 30\,\mathrm{mm}$ X produced in pp collision (promptly produced X only)

Search for LLP $\rightarrow$ eμ: efficiencies

- Selection efficiencies rely on simulations

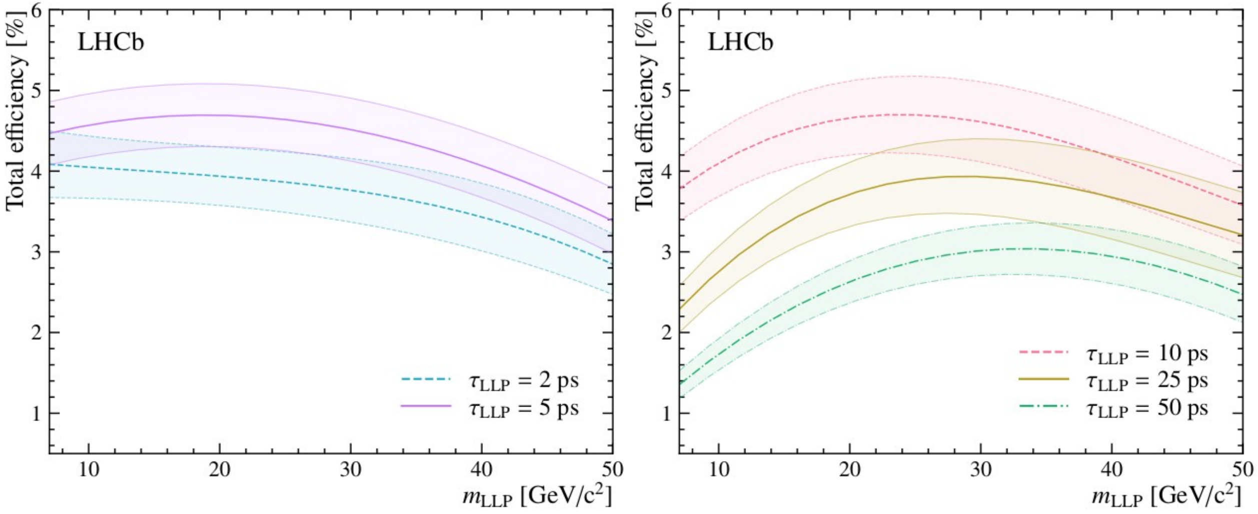


Figure 5: Total detection efficiency for LLP produced through the DPP mechanism as a function of m_{LLP} (central line) and its uncertainty (coloured band), obtained for different values of τ_{LLP}.

Search for LLP → eμ: systematics

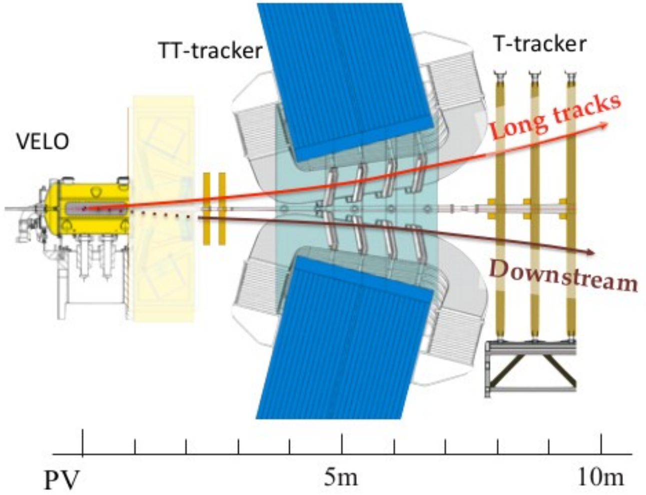
- Main systematic uncertainty comes from differences between simulation and data

Table 1: Contributions to the relative systematic uncertainties in %. The contributions are grouped in three categories, the integrated luminosity, the detection efficiency and the signal yield, separated by horizontal lines. The detection efficiency is affected by the parton luminosity model and depends upon the production process, with a maximum uncertainty of 6.1% for the gluon-gluon fusion process HIG.

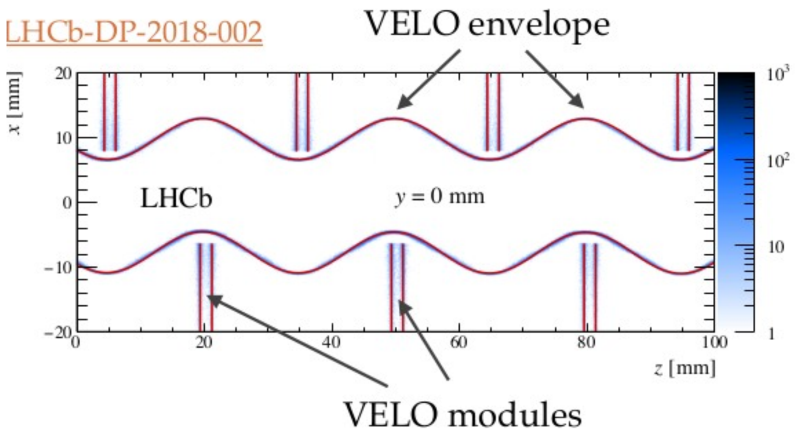
Source	Contribution [%]
Integrated luminosity	2.0
Reconstruction and selection	4.9–7.3
Particle identification	0.5–2.4
BDT	0.6–1.0
Simulation sample size	1.1–3.0
Parton luminosity	1.1–6.1
Efficiency interpolation	0.1–4.0
Signal fraction in the BDT bins	3.3–4.0
Signal model	0.7–8.1
Total	10.6–17.7

Displaced vertex at LHCb

@credit to M.Borsato (Univ. of Heildeberg)



LHCb-DP-2018-002



- Currently only **within VELO**
  - Displacement < 20 cm (but with boost)
- Could extend to ***downstream tracks***
  - Displacement < 200 cm
  - Worse vertex and p resolution ($m(\pi\pi)$ resolution 2× larger)
  - Being optimised in the trigger

[LHCb-PUB-2017-005]

Backgrounds in VELO

- Heavy Flavour displaced decays
  - $\tau(B)$~1.5 ps, $\beta\gamma$~10 ⇒ few mm
- Thin VELO envelope (RF foil)
  - **< 5 mm**: background mainly from heavy-flavour background
  - **> 5 mm**: background mainly from material interaction

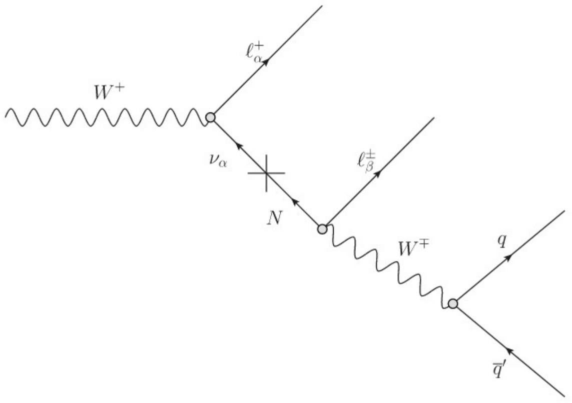
Search for Heavy Neutral Lepton at LHCb

- **Data set**: 3/fb at 7-8 TeV center of mass energy

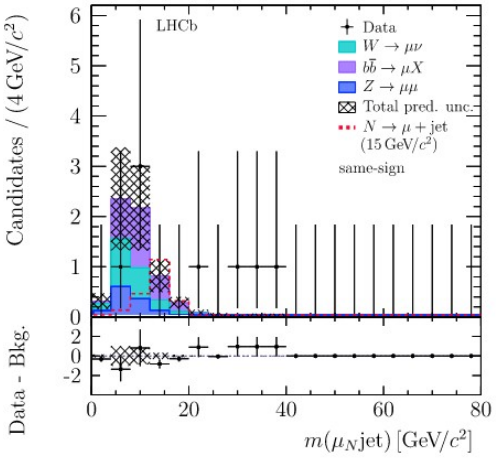
https://arxiv.org/pdf/2011.05263.pdf

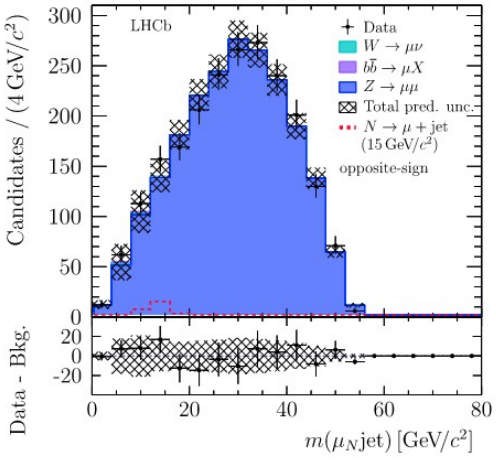
- Search for di-muon + jet in W decays, normalize to control channel $W \to \mu\nu$

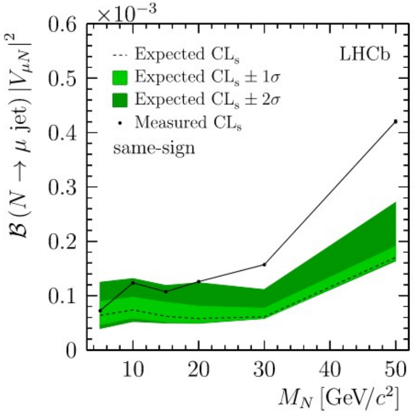
$$\mathcal{B}(N \to \mu\,\text{jet})\,|V_{\mu N}|^2 = \frac{N_{\text{sig}}}{N_{\text{norm}}}\frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}\left(1-\frac{m_N^2}{m_W^2}\right)^{-2}\left(1+\frac{m_N^2}{2m_W^2}\right)^{-1}$$

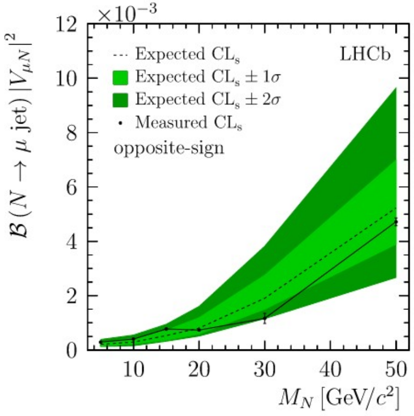


- No excess found in the range $5 < m_{HNL} < 50$ GeV → set 95% CL upper limits



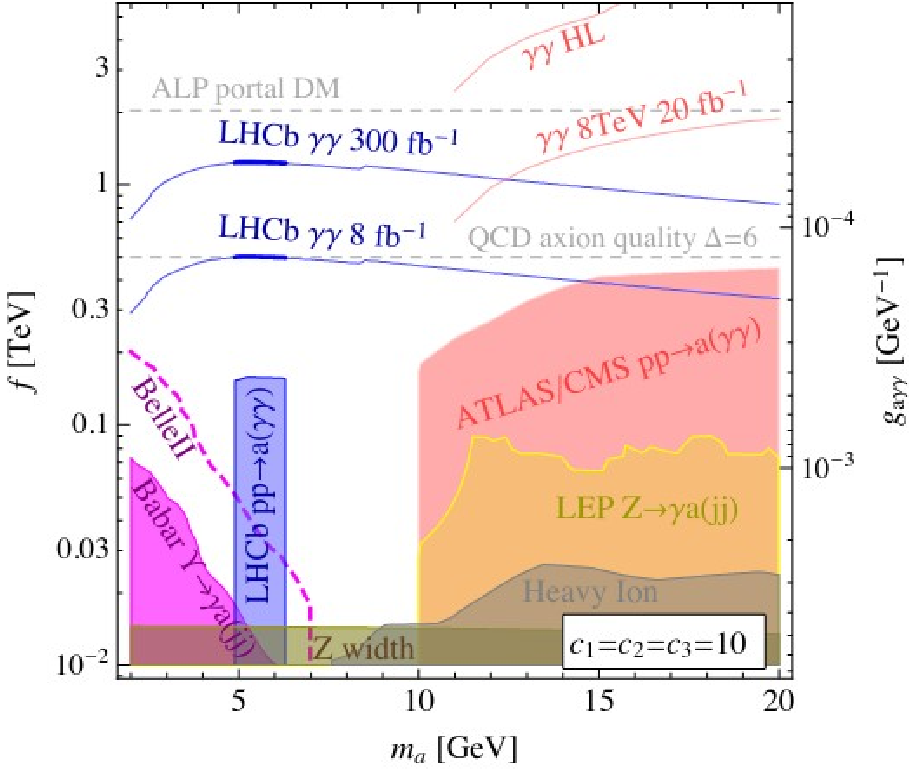






ALPs prospects at LHCb

- Search for ALPs with masses within 2 - 20 GeV as pseudo-Nambu-Goldstone-Boson counterpart of new massive particles (M_{NP} above LHC reach)
- Explore couplings to gluons and photons (dedicated 80/pb diphoton data collected with the low mass $B_s \to \gamma\gamma$ trigger, ref. here)
- Gluon coupling dominates on the photon coupling, but much more difficult to separate from SM background



arXiv:1810.09452v2