
INTENSITY frontier GDR-InF

GDR-InF annual workshop

Nov 15 – 17, 2021
LPNHE

Dark sector searches at flavor experiments

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GDR-InF – Paris, 2021/11/15

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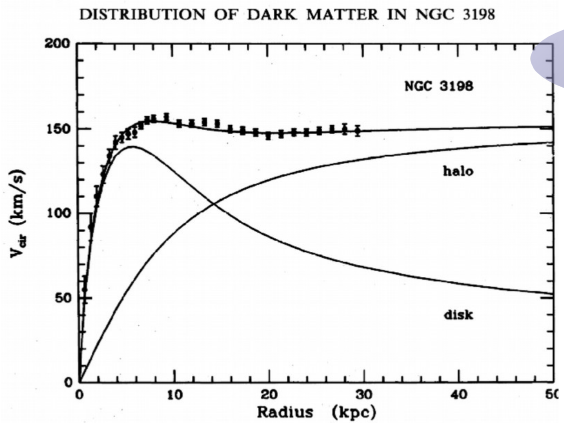
Dark matter puzzle

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

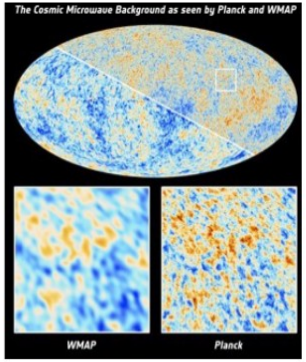


It exists...

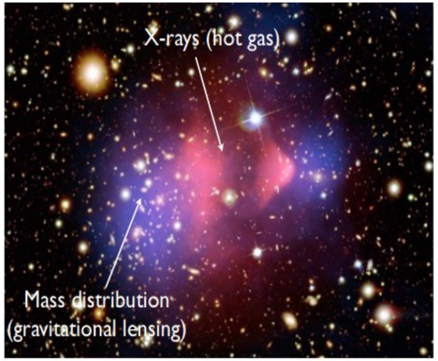
Flat rotational curves

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

CMB fluctuations

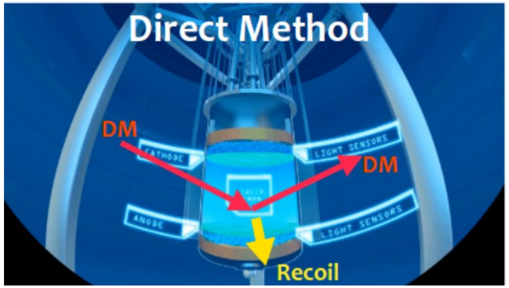


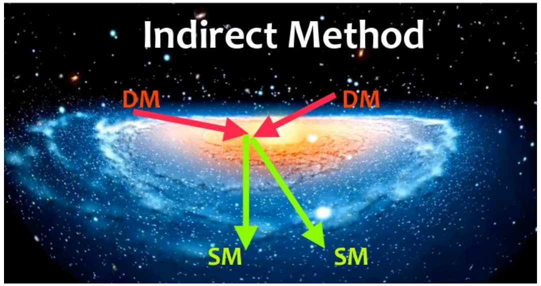
Gravitational lensing



...how to search for it?

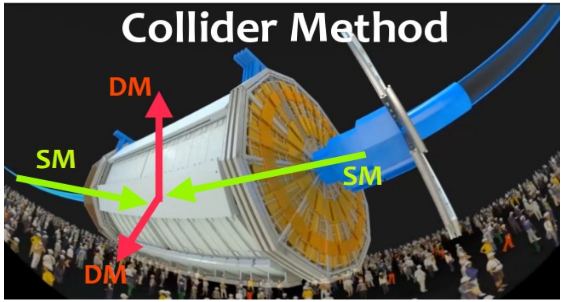
1) Detect the energy of *nuclear/electron recoil* (WIMP direct searches)





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

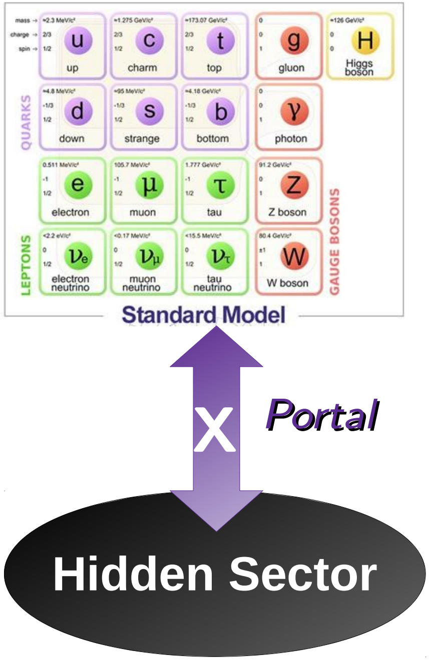
3) DM weakly couples to SM particles and it can be produced in *SM-particles annihilation* at ***accelerators***



→ ***focus on dark sector searches at colliders***

Light dark sectors

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



Light dark sectors

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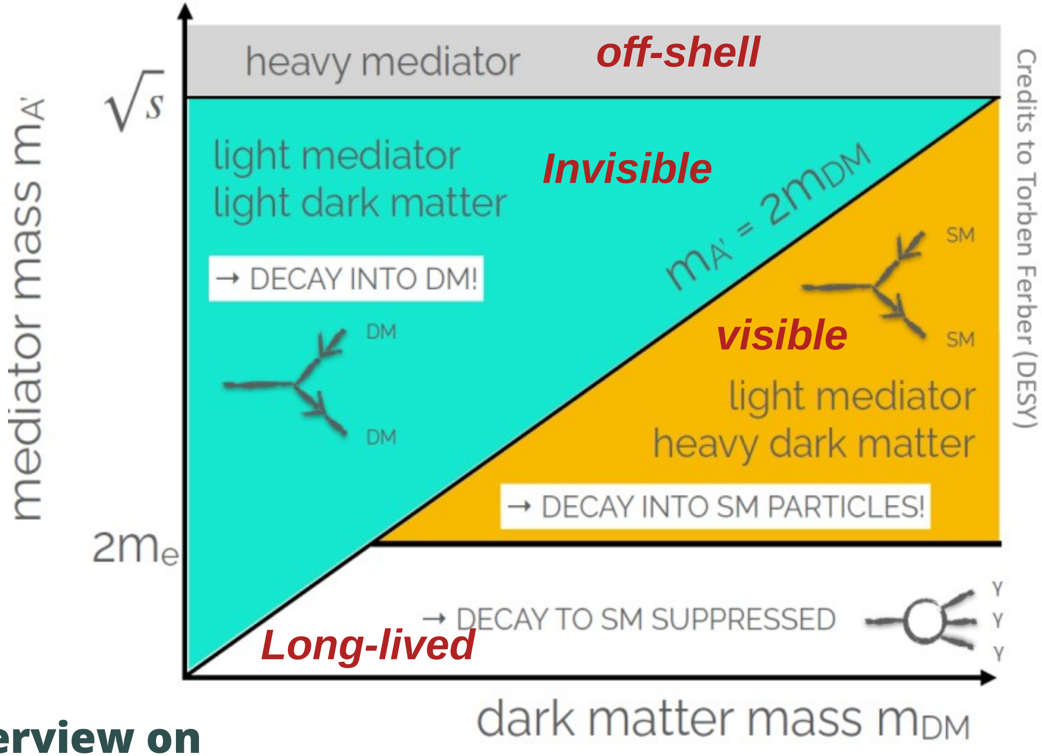


Credits to Torben Ferber (DESY)

→ different topologies leading to different kinds of DM searches

Disclaimer: non exhaustive talk, <u>biased</u> overview on some recent results and promising searches…

Experiments at B-factories

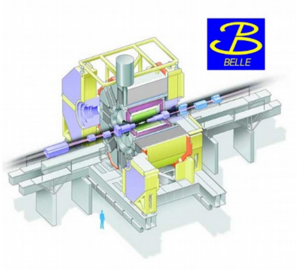
- **Clean environment and hermetic detectors** → efficient reconstruction of **neutrals** (π^0, η), recoiling system and ***missing energy*** final states

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

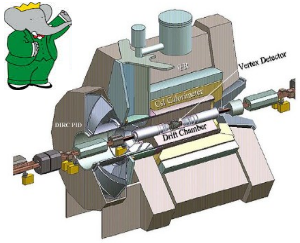
B & τ factory ($\sigma_{bb} \sim \sigma_{\tau\tau} \sim 1$ nb) +

light dark sectors

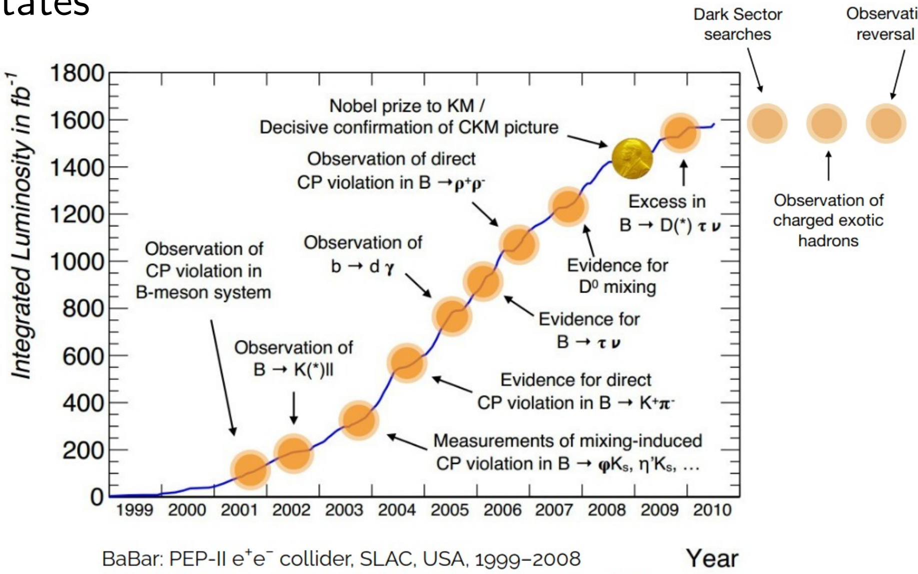
First generation of B-factories



at the KEKB collider (KEK, Japan)



at the PEP II collider (SLAC, California)



BaBar: PEP-II e^+e^- collider, SLAC, USA, 1999–2008
Belle: KEKB e+e– collider, KEK, Tsukuba, Japan, 1999–2010

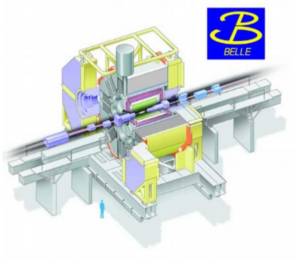
Experiments at B-factories: second generation

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

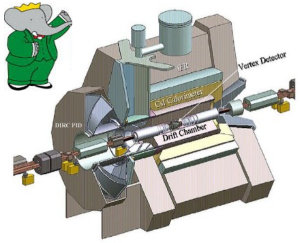
$e^+e^- \rightarrow \Upsilon(4S)$ [10.58 GeV] $\rightarrow B\bar{B}$

B & τ factory ($\sigma_{bb} \sim \sigma_{\tau\tau} \sim 1$ nb) +
light dark sectors

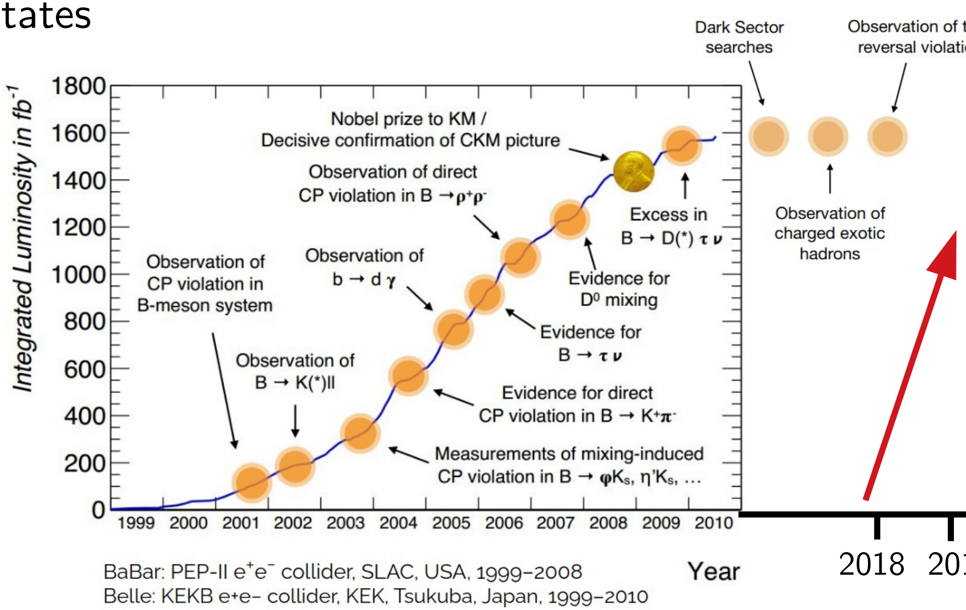
First generation of B-factories



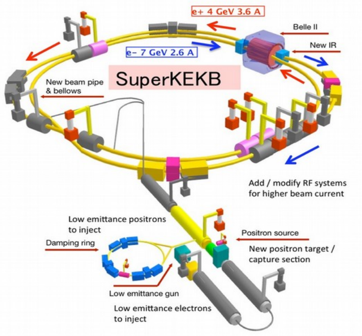
at the KEKB collider (KEK, Japan)

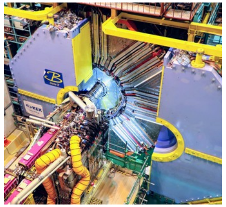


at the PEP II collider (SLAC, California)



SuperKEKB





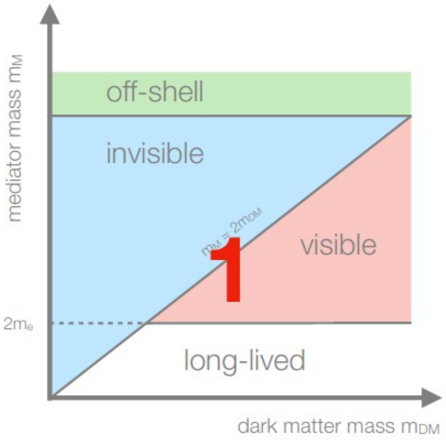
Belle II

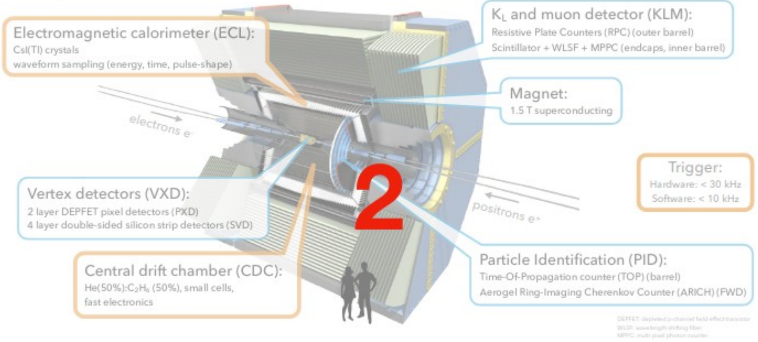
- 30 x KEKB peak luminosity (*nano-beam* scheme*, *1.5 x beam currents*): ***$L = 6 \cdot 10^{35}$ cm^{-2} s^{-1}***
- Final target: ***50 ab^{-1}***

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

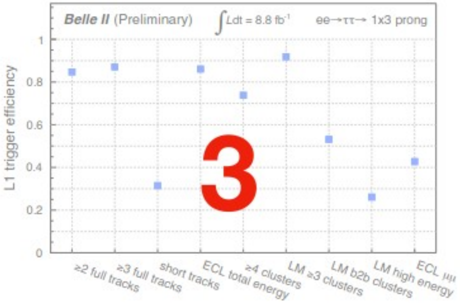
Main ingredients for dark searching

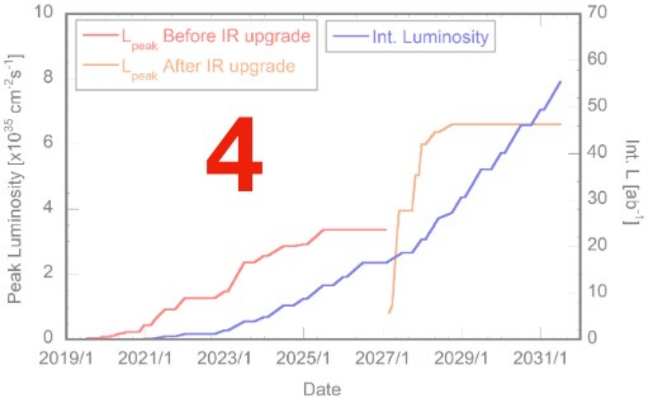
- No leading model, possibly very small couplings:
  1) Be model independent and enlarge the spectrum of detectable final states
  2) Profit of B-factories clean and closed kinematics
  3) Devise specific triggers
  4) Collect largest luminosity





Signature first!

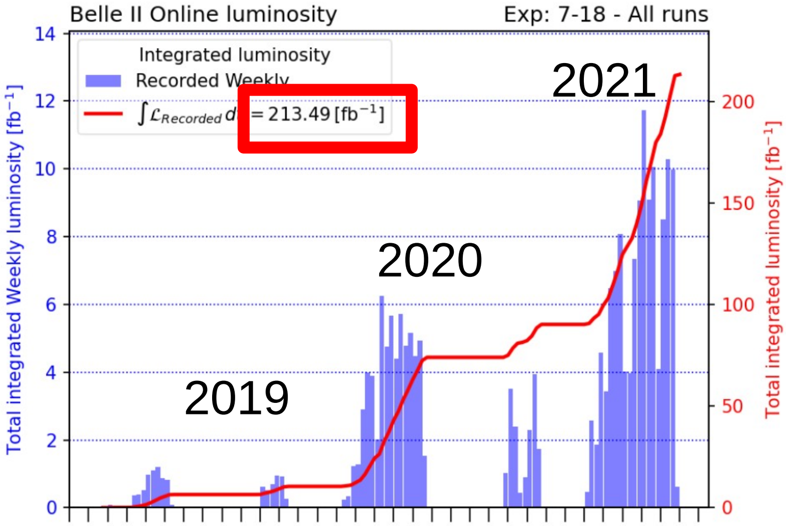




Dark sectors at Belle II

First collisions on 2018 April 26th

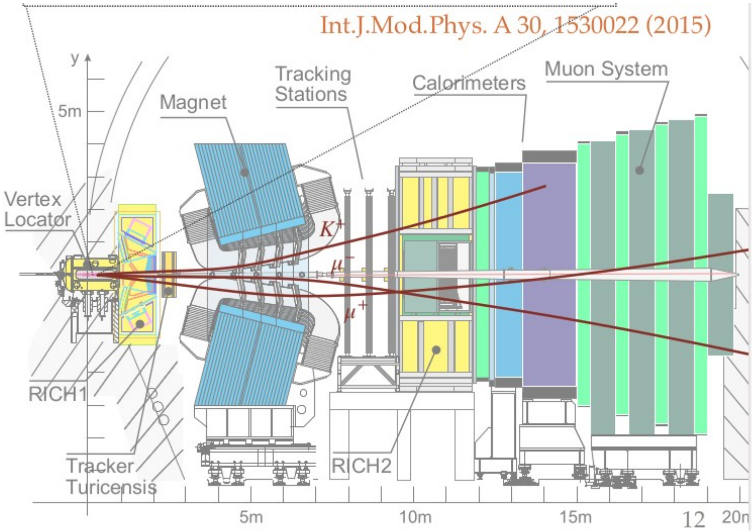
- B-factories can access the GeV range naturally favored by light dark sectors:
  - **Special low multiplicity triggers** *(single photon trigger, single muon trigger, 3D track reconstruction at hardware trigger using Neural Network)*
- collected **0.5 fb^{-1}** during the **pilot run April-July 2018** → **published two searches on this data set**
  - *Z' → invisible* ***PRL 124 (2020) 141801***
  - *ALPs →* $\gamma\gamma$ ***PRL 125 (2020) 161806***
- Since March 2019 collected > **213 fb^{-1}** and hit the **3.1×10^{34} cm^{-2}s^{-1}** instantaneous luminosity → *many analyses in the pipeline*

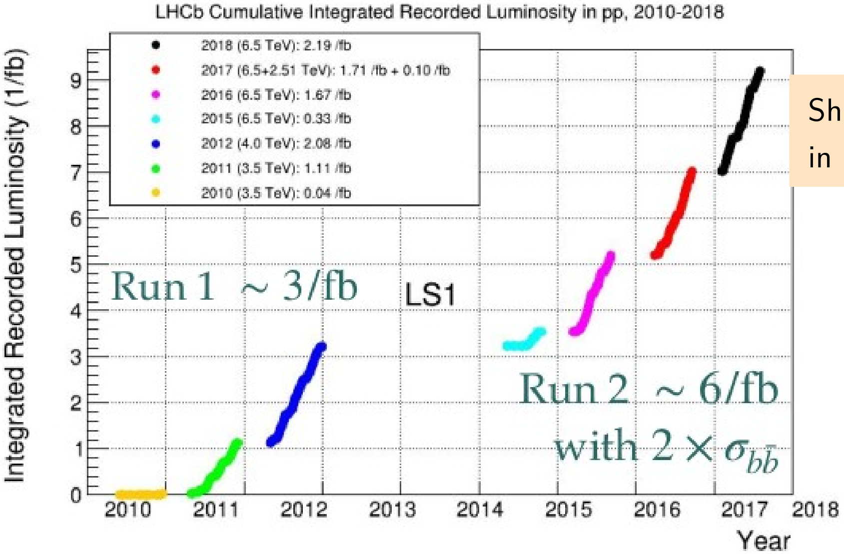


→ Data taking restarted Oct 29

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



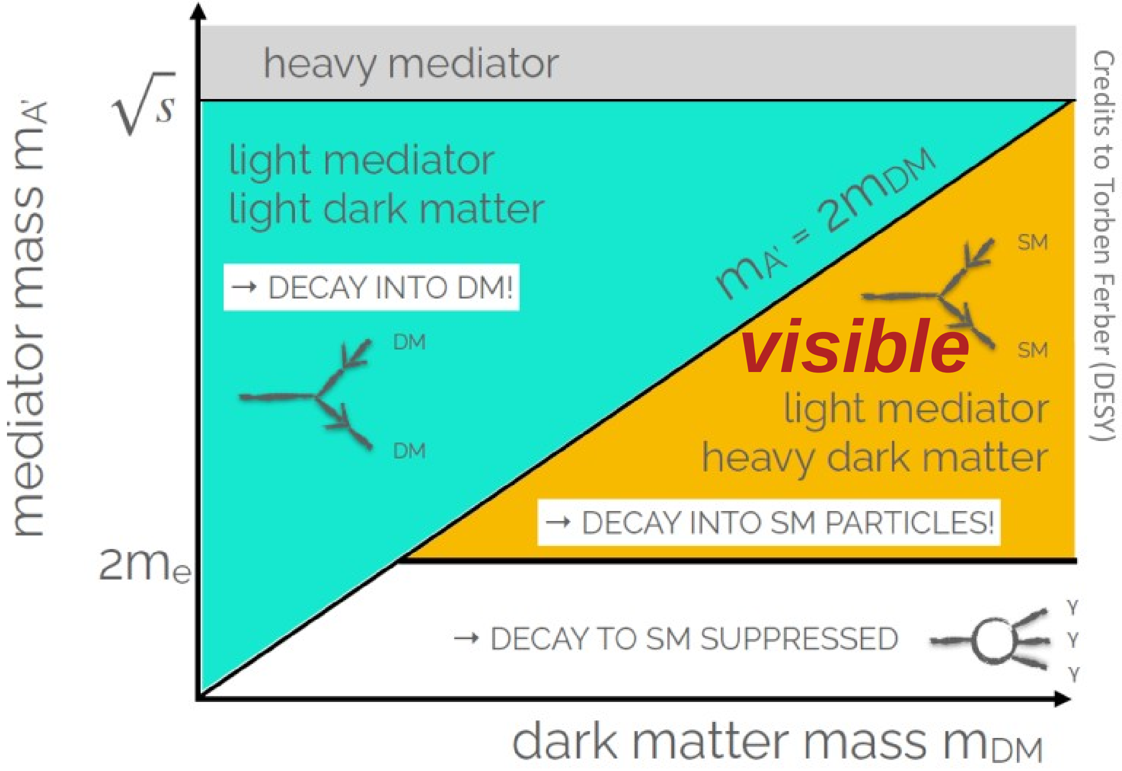


Shutdown2 in progress

B-Factories Vs LHCb in a nutshell:

- LHCb has larger background (pp collision), no hermetic detector
- Cross-section σ_{bb} ($\sqrt{s}$ = 13 TeV)~0.5 μb (forward region) > σ_{bb} ($\sqrt{s}$ = 10.58 GeV) ~ 1 nb
- All b-hadron species produced, excellent performance on *di-muon final states* and heavy b-hadrons
- Very displaced b-vertex due to large boost $\beta\gamma \sim 20$ (>> 0.28 @Belle II)

Visible searches



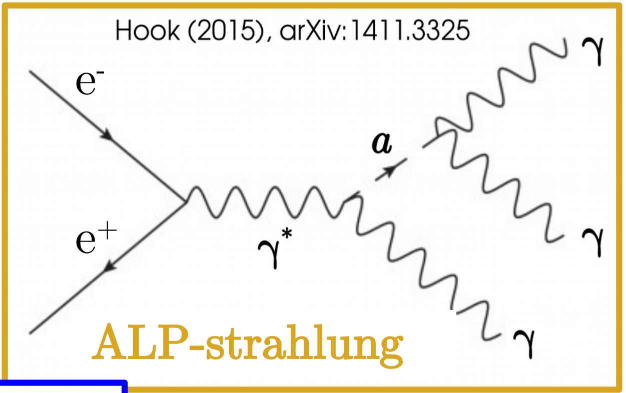
- ALPs to photons
- Dark photons (A' → ll)
- Z' bosons to leptons

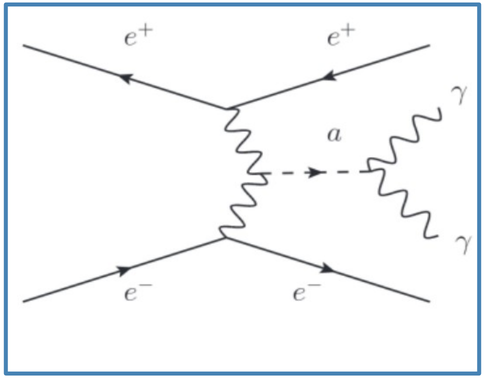
Axion Like Particles (ALPs)

- Axion Like Particles are pseudo-scalars coupling mainly to bosons, with non-renormalizable coupling constants [g_{aV}] ~ 1/M
- Explored photon coupling $g_{a\gamma\gamma}$ in *ALP-strahlung* processes → **second Belle II physics paper**

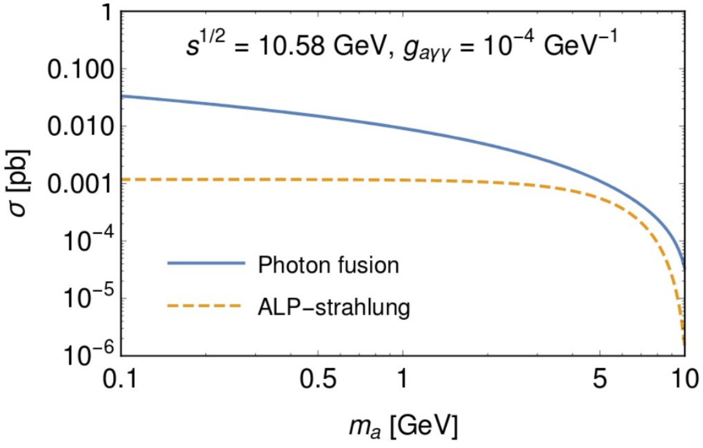
  (*photon fusion:* sensitivity under study)
- Exploit *Flavor Changing Neutral Current* (FCNC) and rare meson decays to investigate g_{aW} coupling

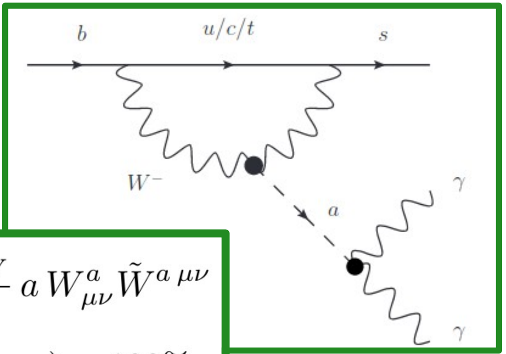
  ongoing studies for B→Ka





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





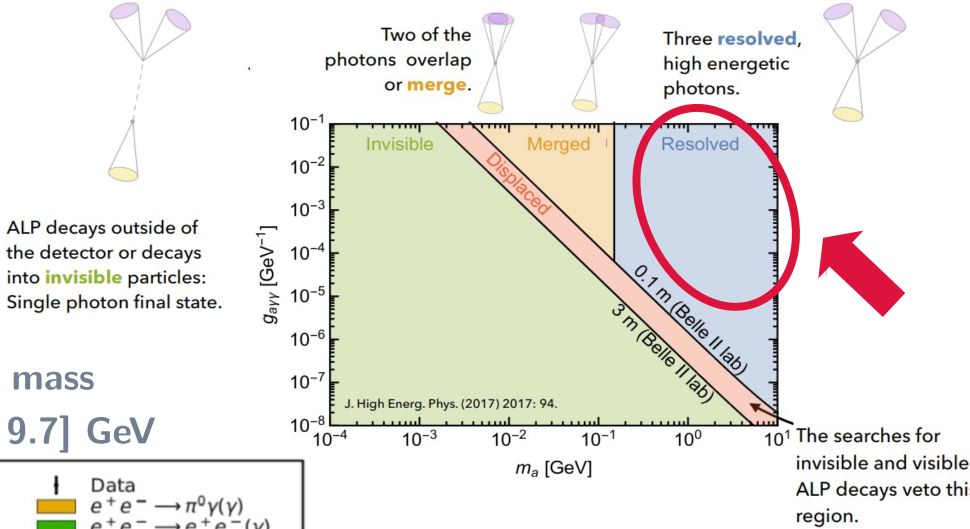
$$\mathcal{L} = -\frac{g_{aV}}{4}\, a\, W^{a}_{\mu\nu} \tilde{W}^{a\,\mu\nu}$$

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

ALPs: a → γγ 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 → optimize to maximize ALP sensitivity
- Signal yield extracted with binned extended max likelihood fits in sliding ranges (half mass resolutions step) to:


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

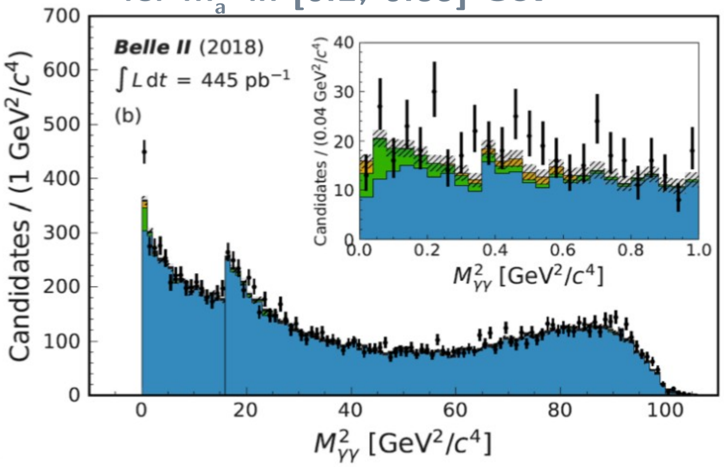
Two of the photons overlap or **merge**.

Three **resolved**, high energetic photons.

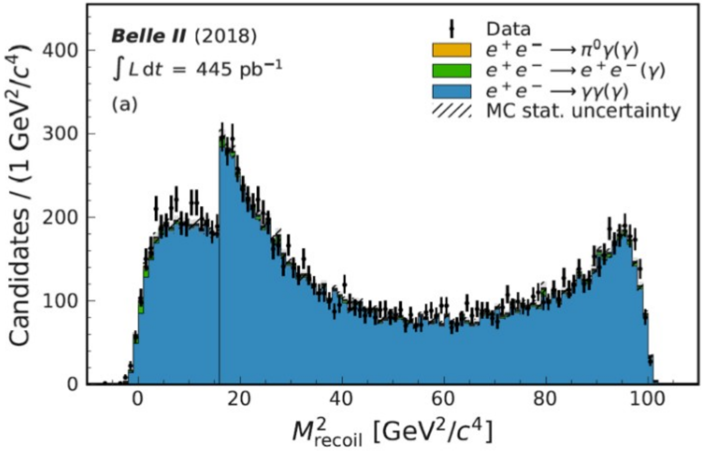
The searches for invisible and visible ALP decays veto thi

J. High Energ. Phys. (2017) 2017: 94.

Diphoton invariant mass for m_a in [0.2, 6.85] GeV



Recoil invariant mass for m_a in [6.85, 9.7] GeV



no excess found (highest local significance of 2.8σ)

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

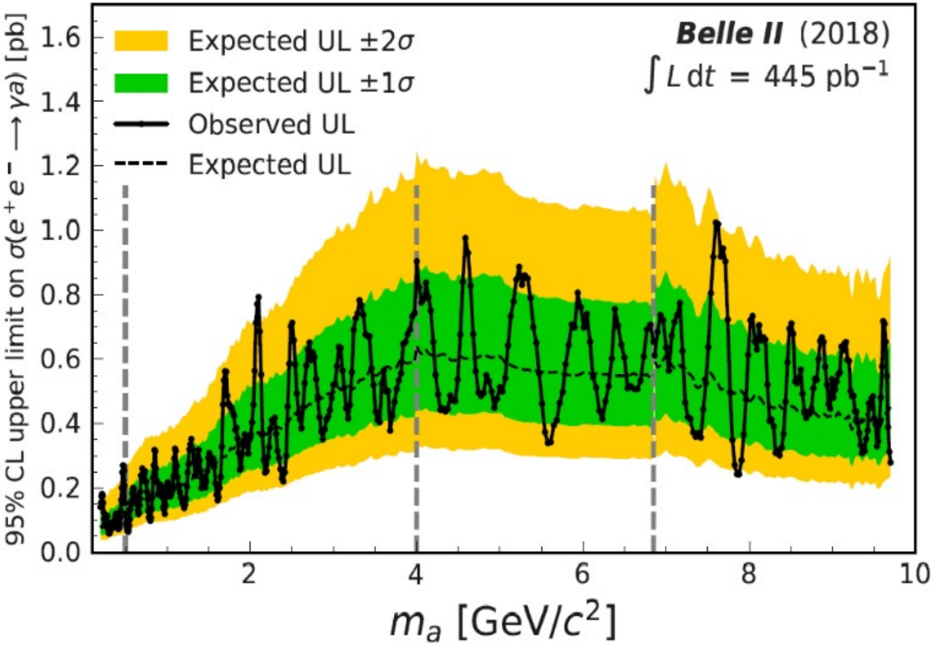
ALPs: a → γγ results

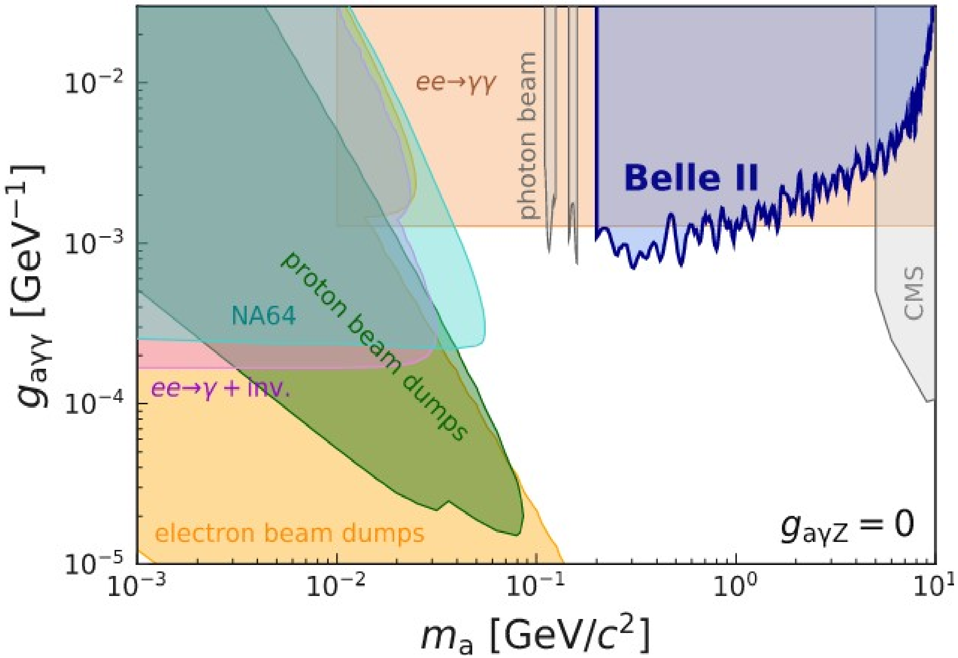
PRL 125 (2020) 161806

- Set 95% CL upper limits on the signal cross section and translated in $g_{a\gamma\gamma}$ limits

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

→ With only 1/100 000th of final target data set



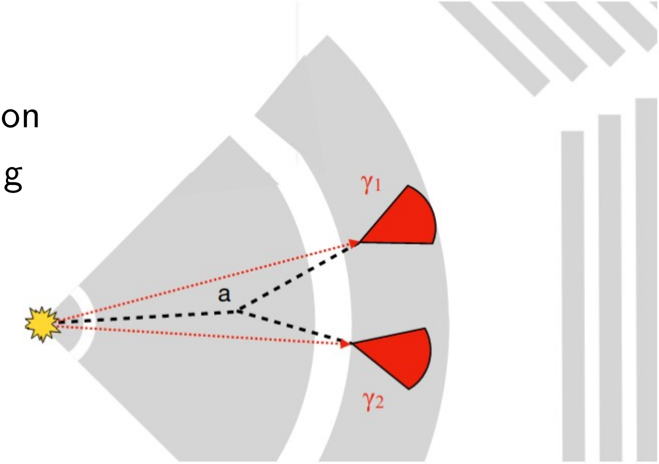


ALPs in meson decays

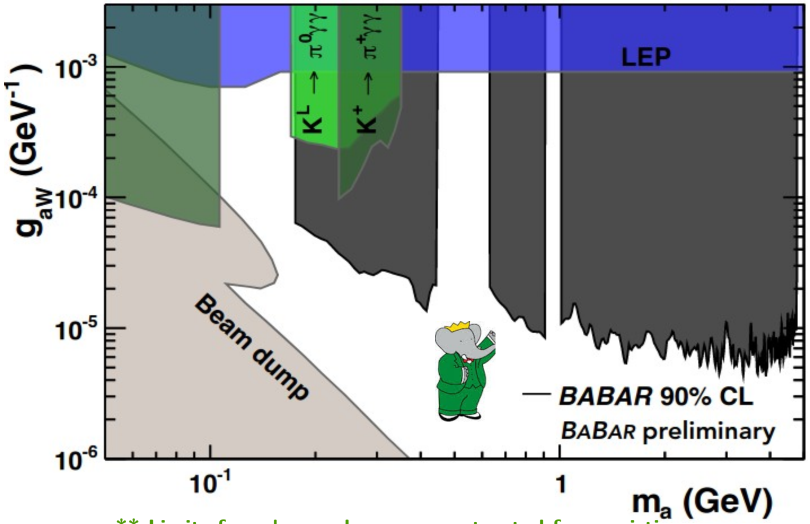
**E. Izaguirre, T. Lin, B. Shuve, PRL 118 (2017)*

b→ sγγ is extremely rare in the SM and uniquely sensitive to very small **ALP-W coupling* g_{aW}**

- For $m_a << m_W$ naturally *long-lived* ALPs mainly decay into photons
- Preliminary results for the searched process **$B^\pm \rightarrow K^\pm a$, $a \rightarrow \gamma\gamma$** from BaBar (on **424/fb at Υ(4S)**): look at narrow peaks in the **diphoton invariant mass** vetoing peaking background regions, both *prompt* and *displaced* vertex signatures.

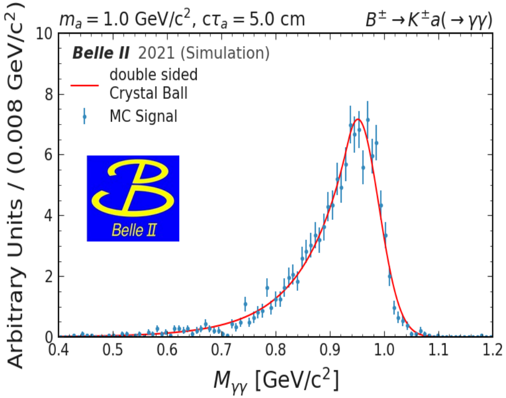


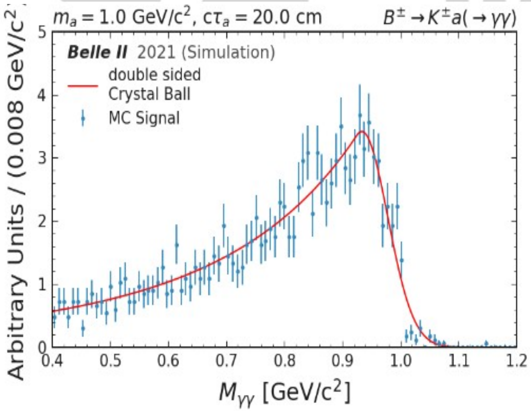
From B.Shuve's talk at ICHEP2020



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

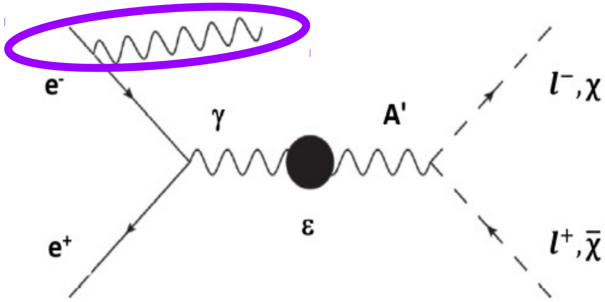
Belle II ongoing studies





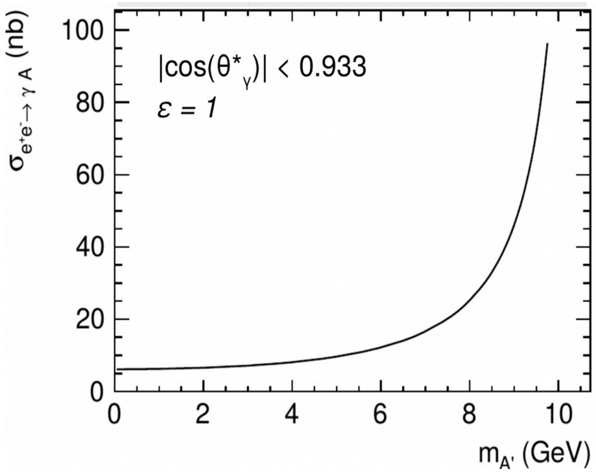
Dark photons

- A possible U(1) extension of the SM includes 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 $\boldsymbol{e^+e^- \to \gamma\, A'}$.



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

Batell et al. (2009), arXiv:0903.0363



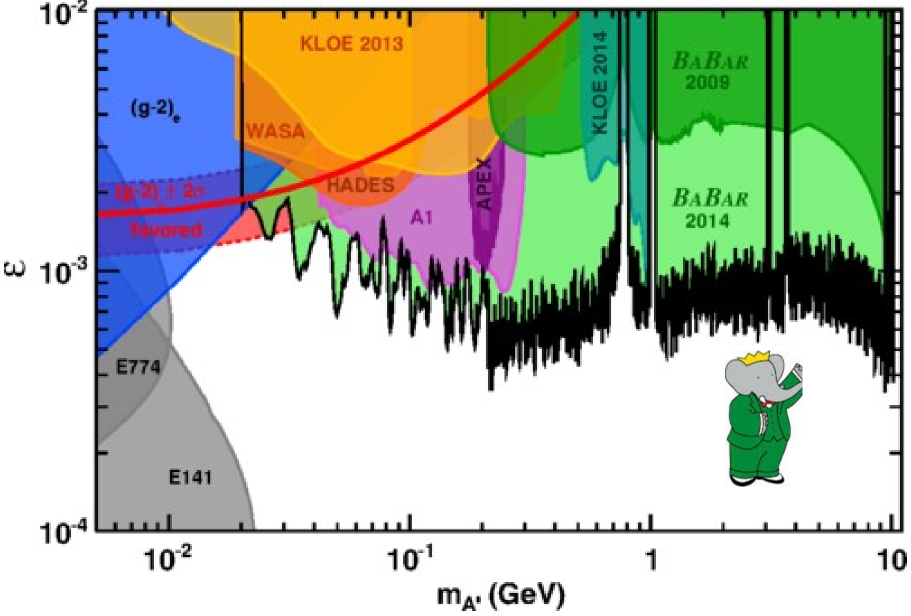
MadGraph simulation based on arXiv:1008.0636

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

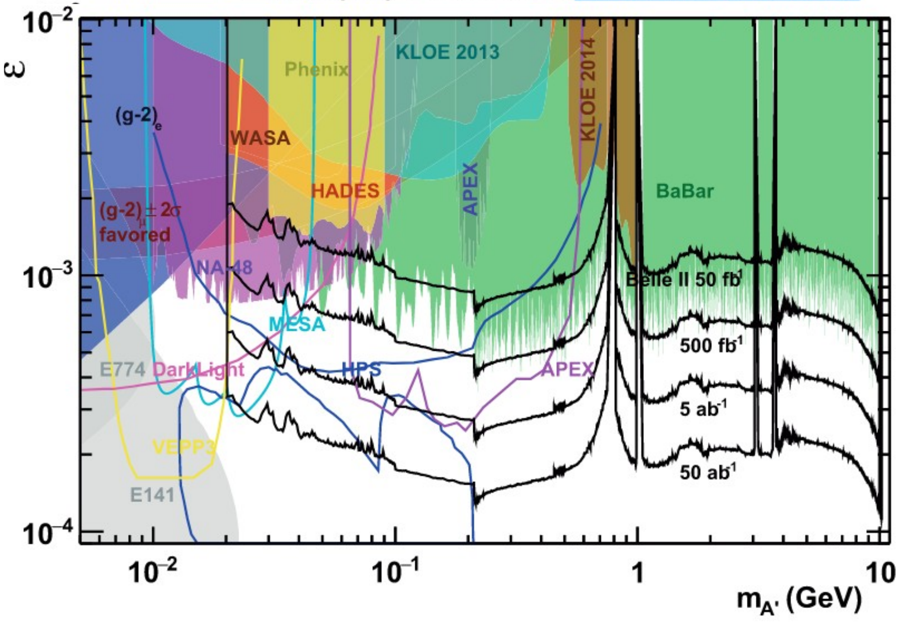
Visible dark photon

- Existing results by BaBar, currently the best limits in all the GeV range:
  - bump search in the reconstructed di-lepton spectrum from the full data set (514 fb^{-1})
- Belle II will lead the sensitivity with the final data set of 50 ab $^{-1}$

Phys. Rev. Lett. 113 (2014)



Belle II projections from *PTEP* **2019** 12 (2019)

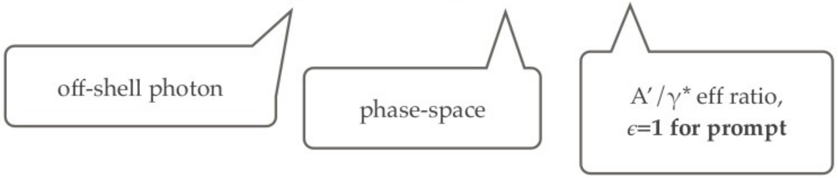


Visible dark photons at LHCb

PRL 124 (2020) 041801

- Search for $A' \rightarrow \mu^+\mu^-$ 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 $\sigma[m(\mu^+\mu^-)]/2$
    - → **Data driven approach:** normalize to off-shell $\gamma^* \rightarrow \mu\mu$ production, no need for efficiencies from simulation

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

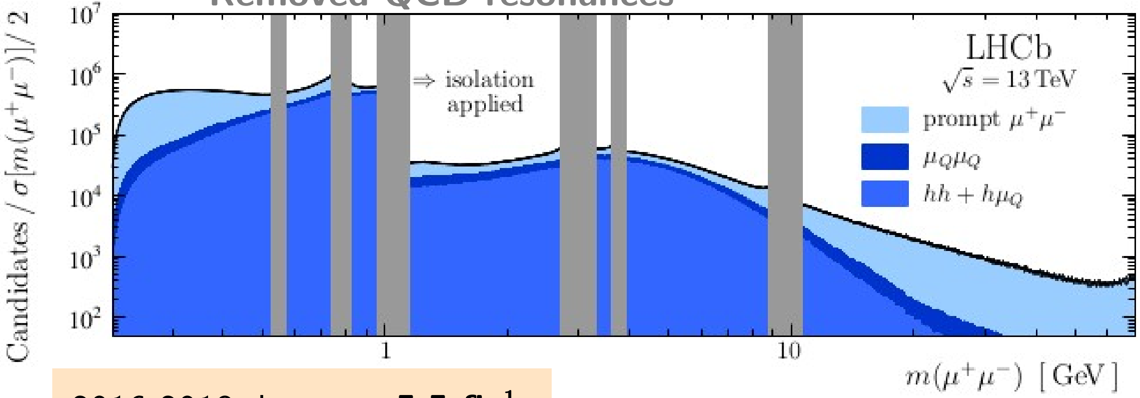


off-shell photon

phase-space

A'/γ^* eff ratio, **ϵ=1 for prompt**

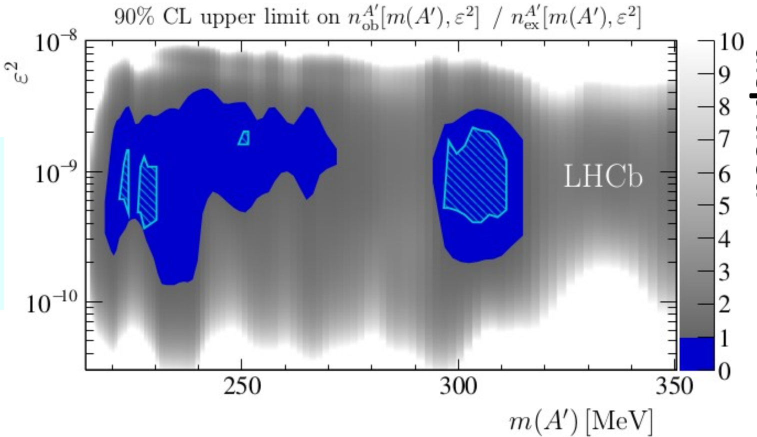
Removed QCD resonances



prompt-like

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

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

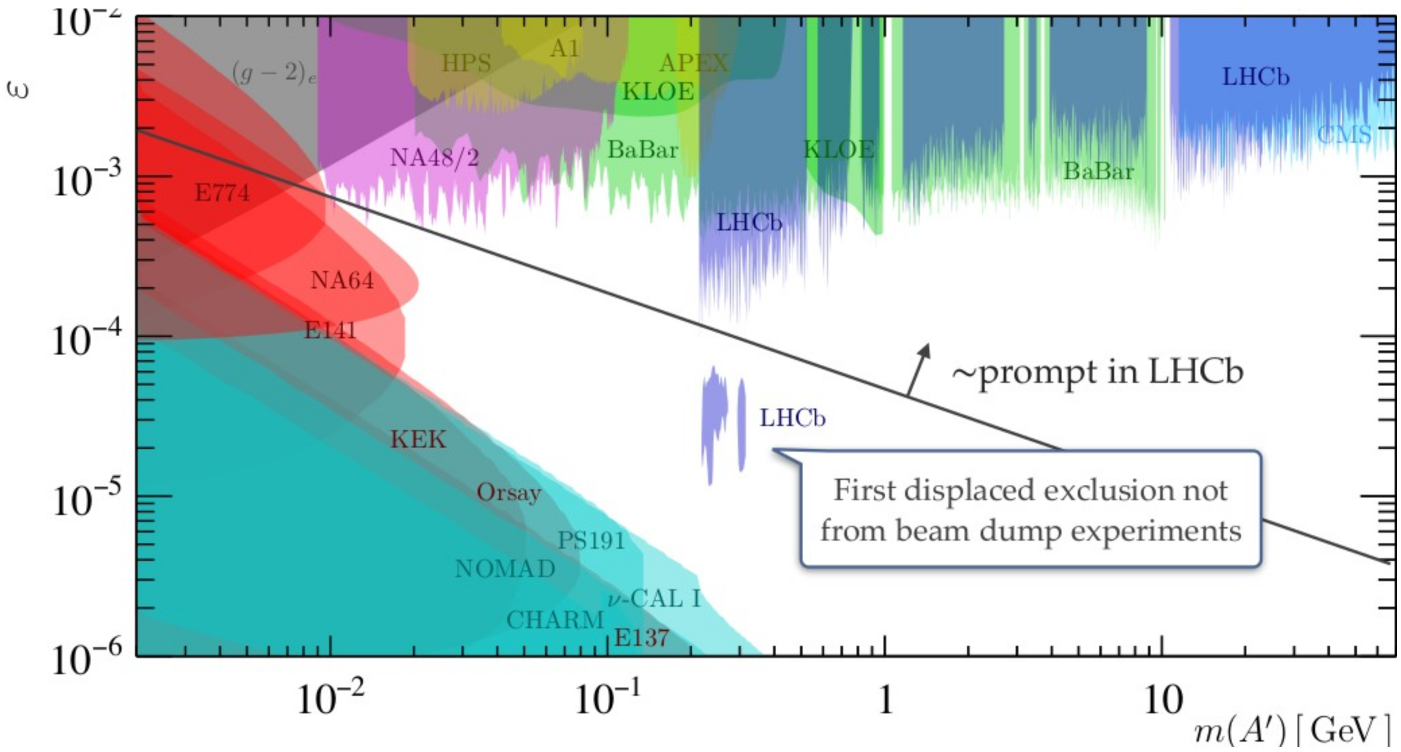


displaced

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 MeV for long-lived A'



~prompt in LHCb

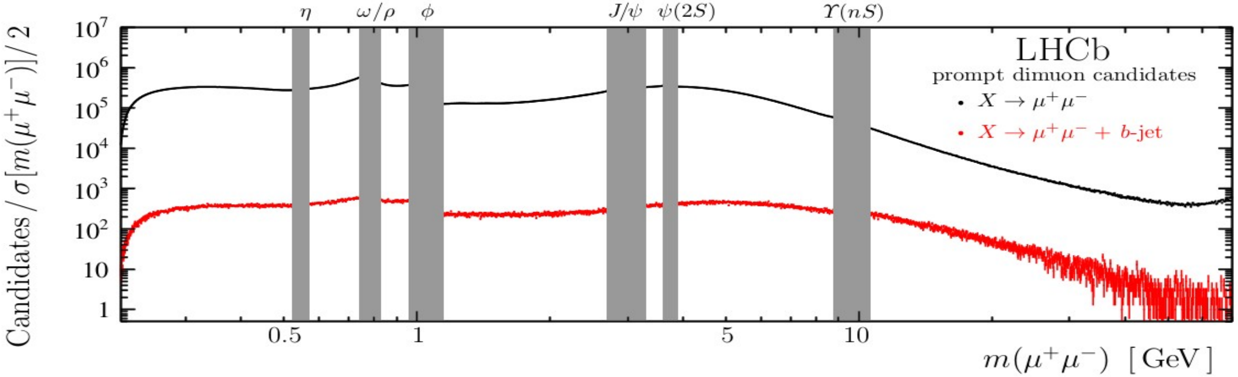
First displaced exclusion not from beam dump experiments

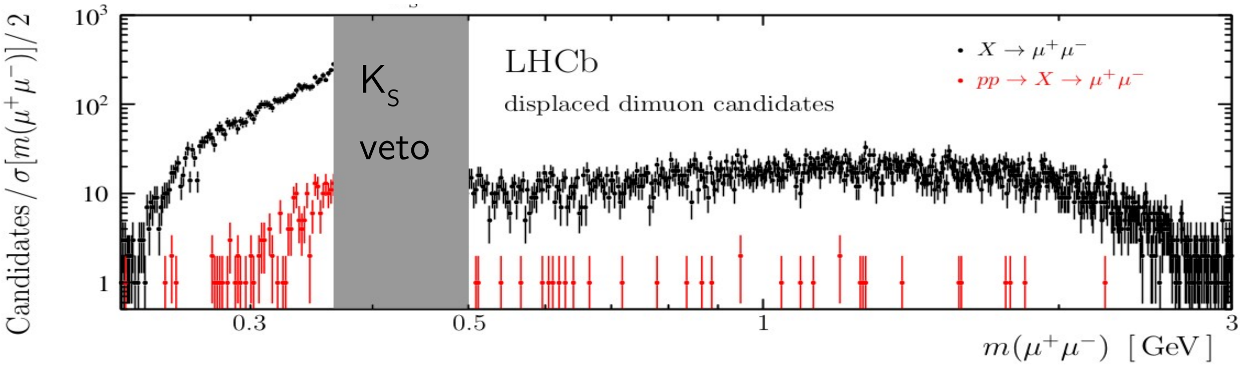
Inclusive X→ μμ search at LHCb

JHEP 10 (2020) 156

- Inherits dark photons triggers, drop kinetic mixing assumption with γ* and probe more dark sectors in di-muon resonances

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



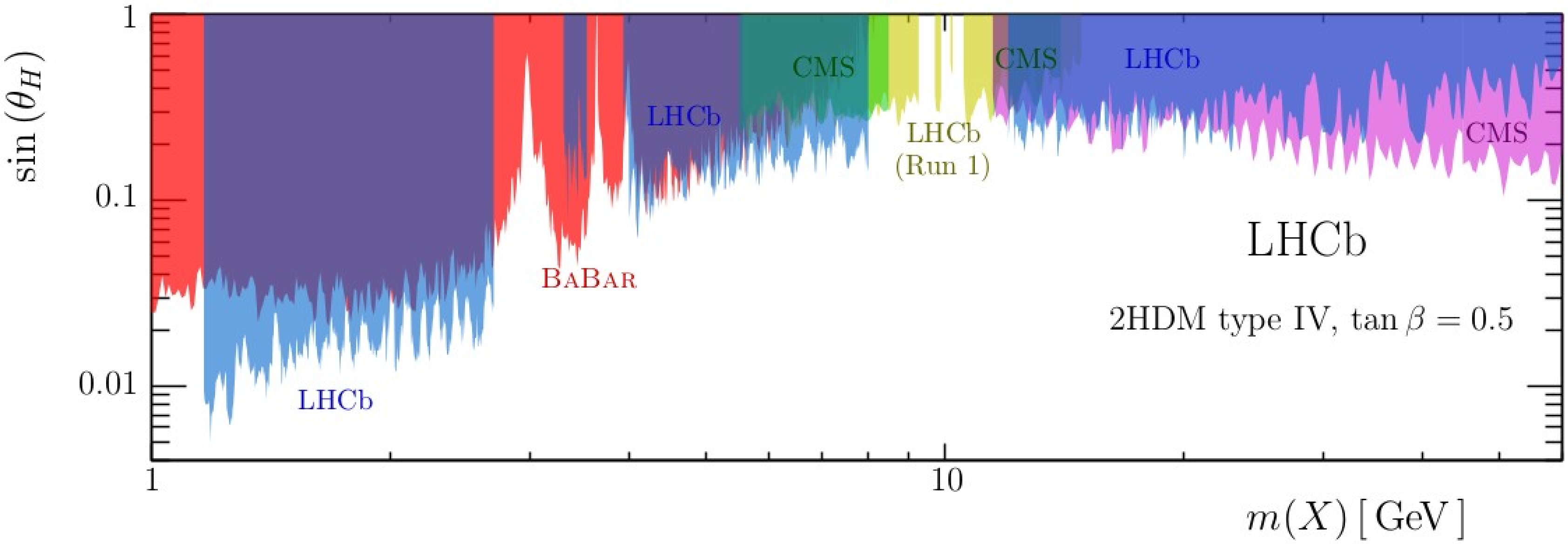


- Minimize assumptions on production mechanism
- Explore $2m_\mu < m(X) < 60$ GeV with non negligible width (up to 20 GeV)

Inclusive X→ μμ search at LHCb

JHEP 10 (2020) 156

- Interpret results as 90% CL upper limits on X-Higgs mixing angle θ_H



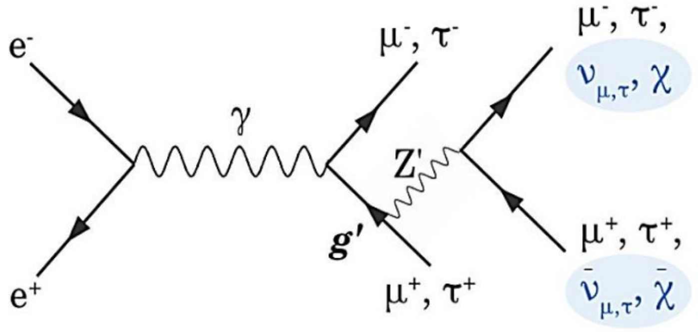
Muonic dark forces: L_μ-L_τ model

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

- DM puzzle
- $(g\text{-}2)_\mu$ anomaly
- Anomalies observed in rare B decays, B→ K*μμ, $R_{K(*)}$

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

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



- Search for the process:

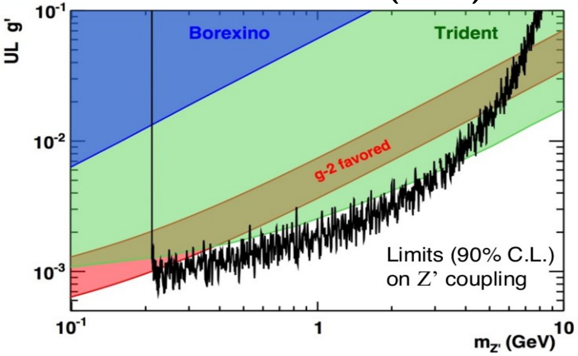
$$e^+e^- \rightarrow \mu^+\mu^- Z' \text{ , } Z' \rightarrow l, \nu, X$$

- Existing limits on the Z' coupling (g'):
  - searches for **visible decays** $Z' \rightarrow \mu^+\mu^-$ (BaBar **PRD 94, 011102 (2016)**, CMS **arXiv:1808.03684**) and neutrino-nucleus scattering processes (*neutrino trident production*, CCFR experiment at Fermilab)
  - search for **Z' → invisible:** Belle II first physics result, **PRL 124 (2020) 141801**

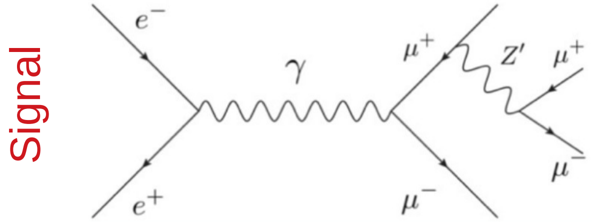
Z’ $\rightarrow$ $\mu^+\mu^-$

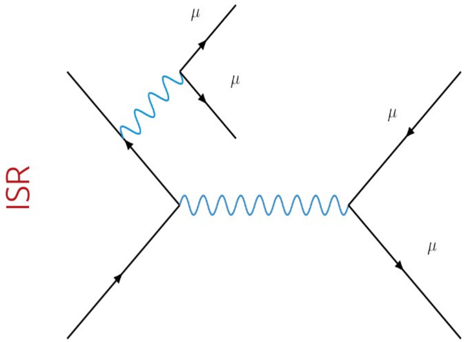
- Search for a di-muon invariant mass peak in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ events

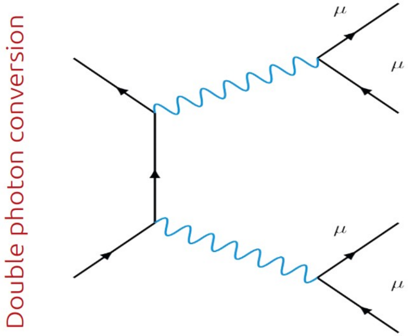
PRD 94, 011102 (2016)



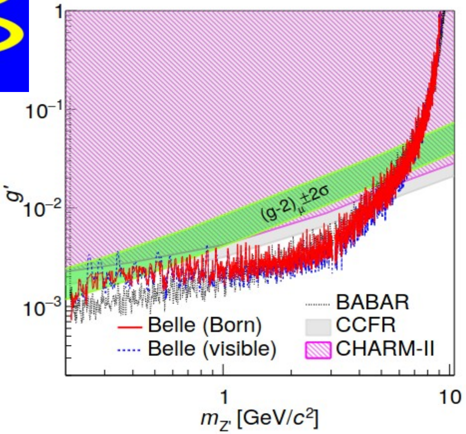
Searched final data set of 514 fb^{-1}







arXiv:2109.08596v2



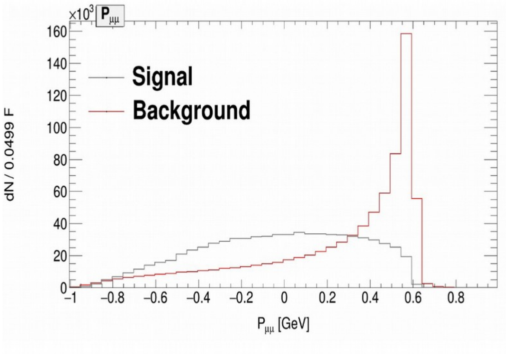
Searched on 643 fb^{-1}

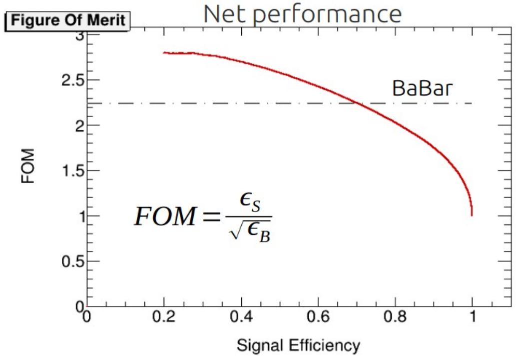
Main backgrounds from SM QED processes: $\mu^+\mu^-\mu^+\mu^-$, *ISR, double photon conversion, combinatorial*

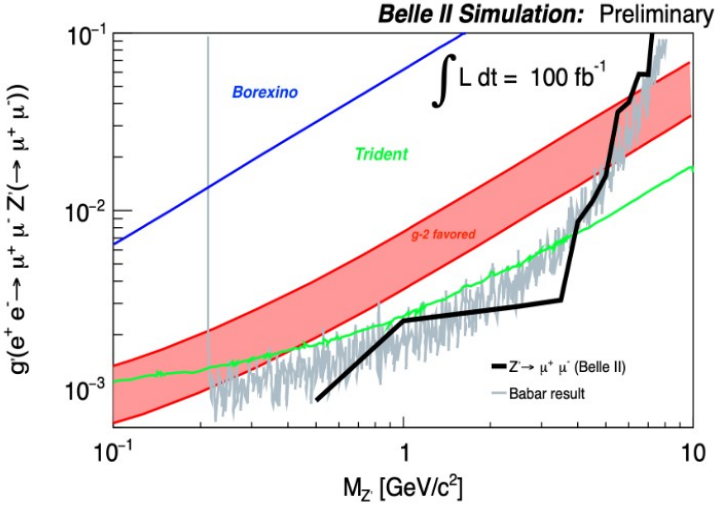
Competitive with early data set (~ 100 fb^{-1}) **due to aggressive background suppression!**

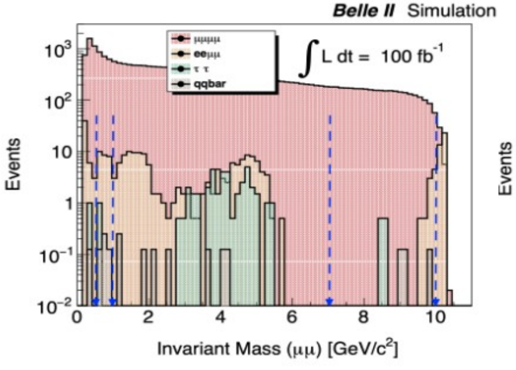
Z’ $\rightarrow \mu^+\mu^-$: background rejection

- Neural Network (*MLP, MultiLayer Perceptron*) exploiting dimuon momentum ($P_{\mu\mu}$) and other 14 discriminating variables in 4 different mass ranges to reject background

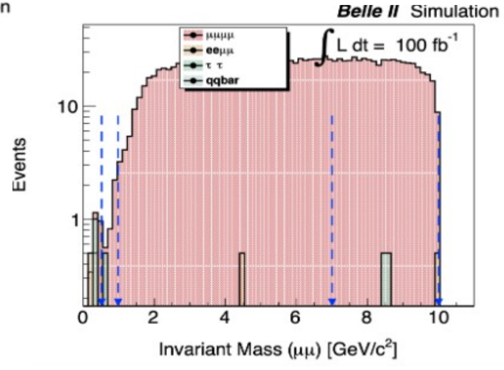








Before MLP



After MLP

→ Background suppressed by 2 orders of magnitude over the whole sensitive range

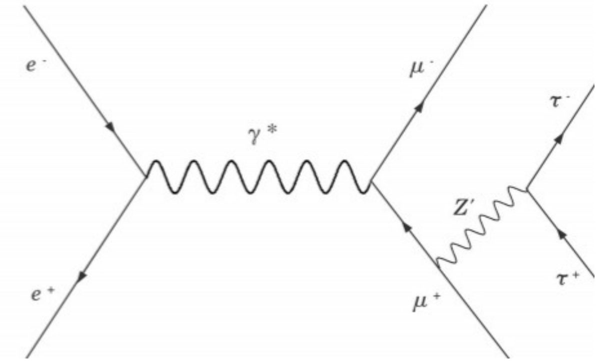
- Sensitivity computation ongoing: preliminary results from fitting technique (90% CL upper limits), no systematic effects included

$Z' \to \tau\tau$

- Also ongoing studies on:

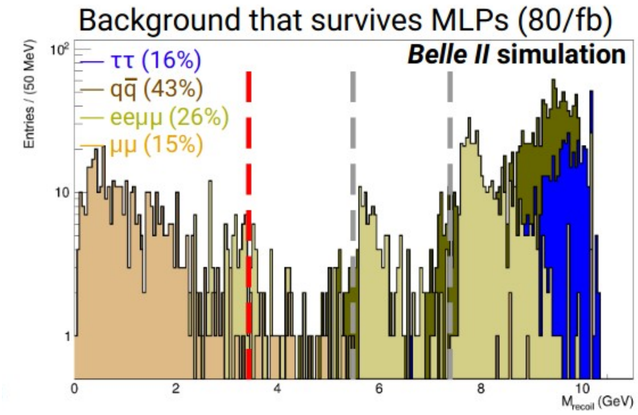
$e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \tau\tau$

First time search!



  - Almost model independent analysis
  - Selection optimized for the final state μμττ (τ → l/h , 1-prong decays)

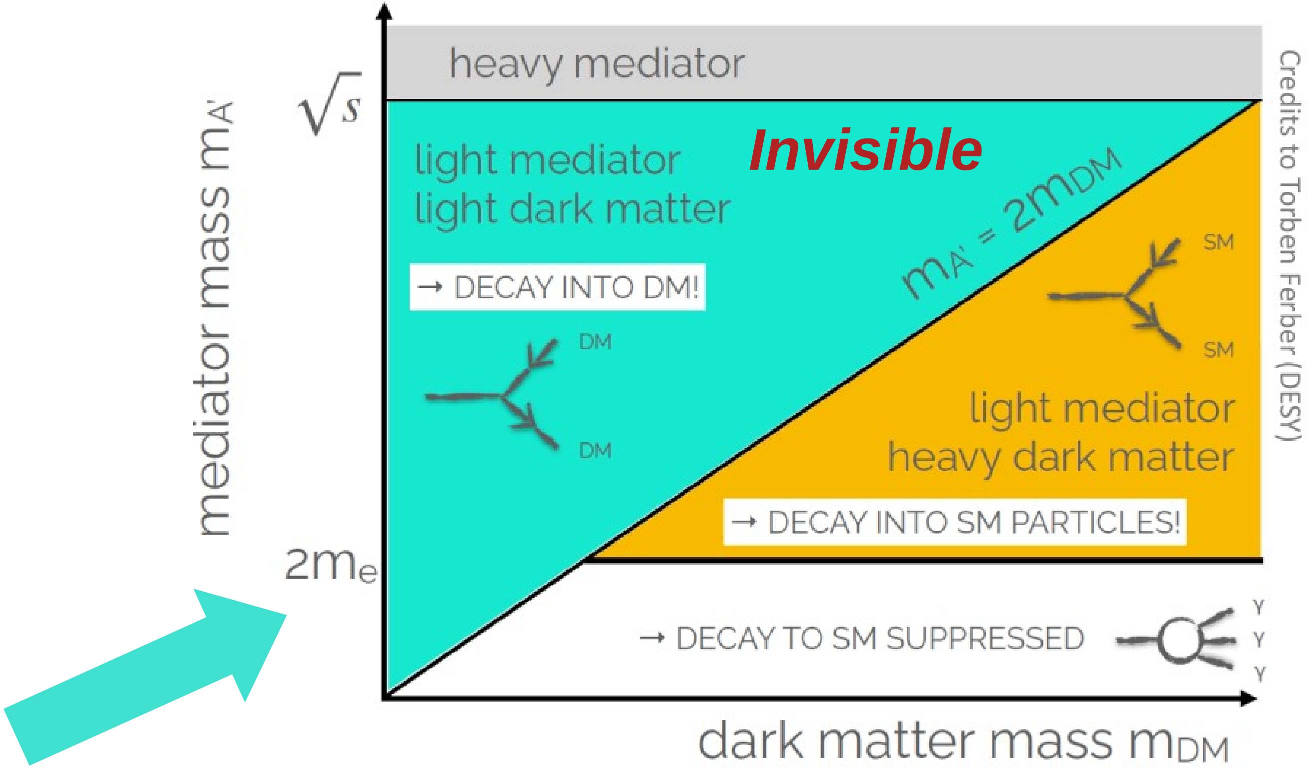
Compute upper limits on the product $\sigma \cdot B(X \to \tau\tau)$ → could be re-interpreted by any models



Challenging due to high background and neutrinos

→ profit of B-factory clean environment and MVA techniques

Invisible searches



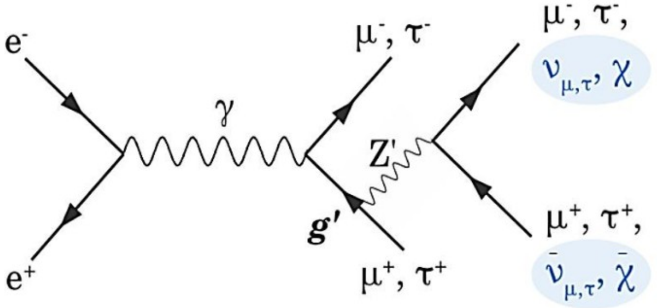
- Z' → invisible
- Dark higgs
- Single photon search

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 $\mu^+\mu^-$ pair in events where **nothing** else is detected.
- **Only 276 pb^{-1}** of 2018 pilot run data usable due to trigger conditions.



$e^+e^- \rightarrow \mu^+\mu^- + missing\ energy$

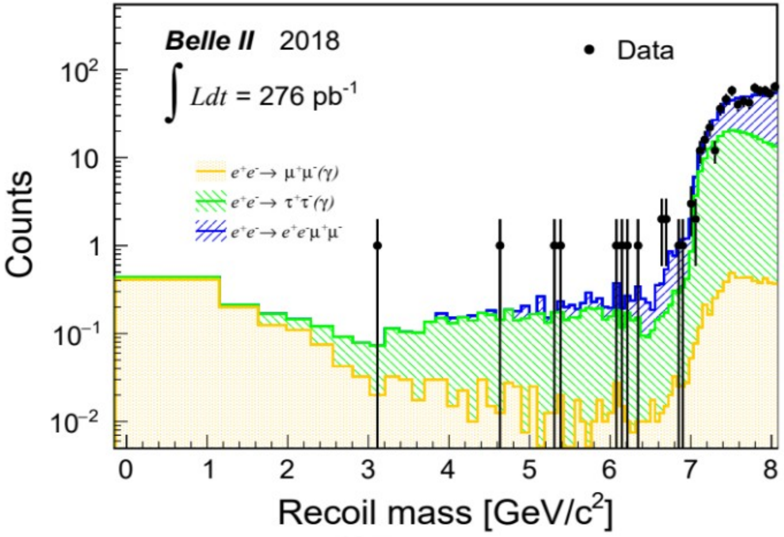
Branching ratios:

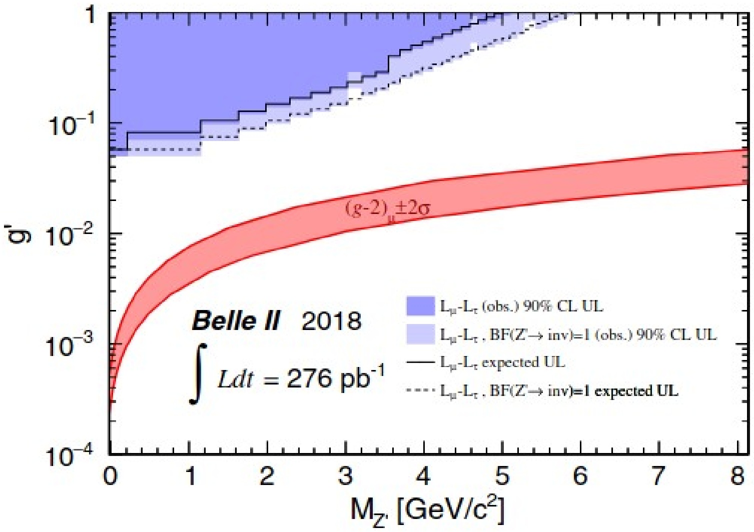
$M_{Z'} < 2M_\mu \rightarrow \Gamma(Z' \rightarrow inv.) = 1$

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

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

If light DM is accessible, BR(Z’→ DM)~1





Invisible signature investigated for the first time!

First Belle II physics paper

Search for Z’ to invisible

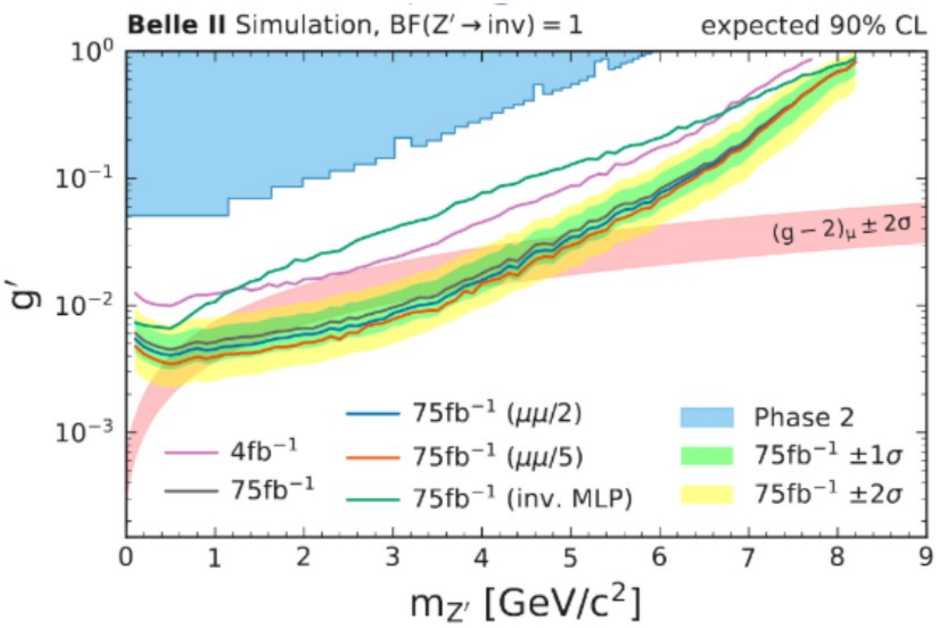
PRL 124 (2020) 141801

- Search for a peak in the mass spectrum of the recoil against

Branching ratios:

Z’ → inv UPDATE

- Improve sensitivity and probe higher value of Z’ mass using **2019+2020 data**:
  - Much higher luminosity (~ x 300)
  - Analysis improvements
    - Better particle identification (muon ID)
    - Better background suppression algorithm (MVA)
    - Frequentist approach for UL extraction based on fitting
  - New trigger lines (devised after the pilot run)

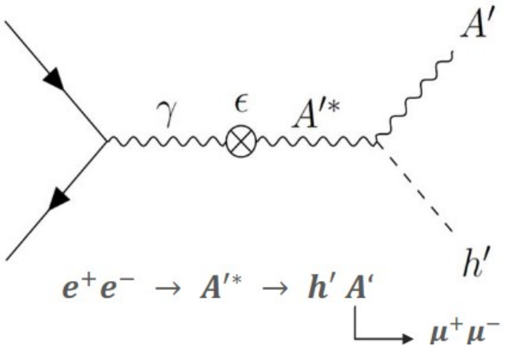


Recoil mass [GeV/c^2]

$M_{Z'}$ [GeV/c^2]

Dark Higgsstrahlung

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

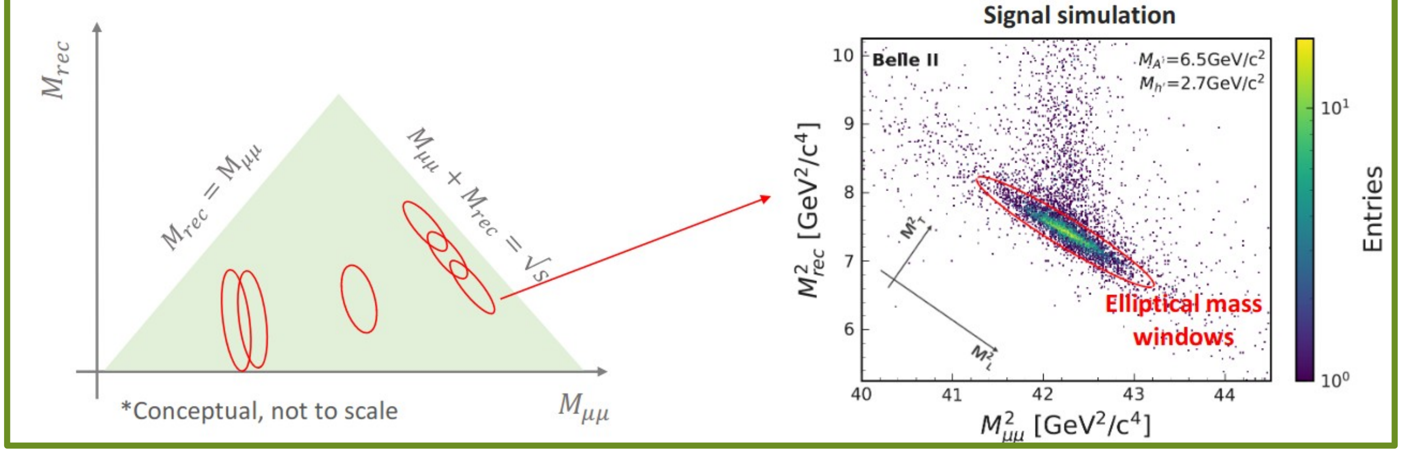


- Belle II has unique capability to probe the invisible h' decay ($m_{h'} < m_{A'}$) with A' decaying to a muon pair

Analysis Strategy:

→ *Scan dimuon and recoil mass searching for peaks in sliding windows*

→ *Apply Bayesian counting technique (challenging Look-elsewhere effect)*



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* Batell, Pospelov, Ritz, Phys. Rev. D 79, 115008 (2009)

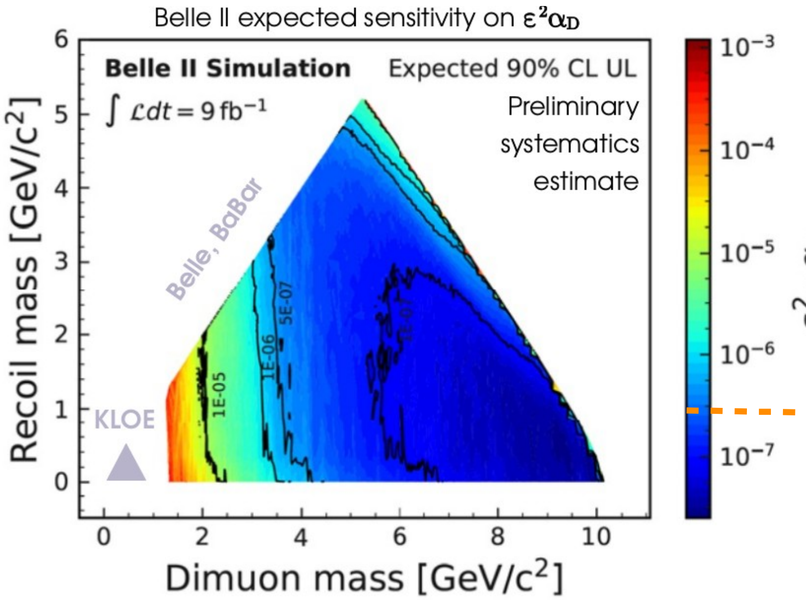
Dark Higgsstrahlung: expected sensitivity

- Belle II has complementary sensitivity to BaBar and KLOE (*)

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

- Promising results unblinding already a small portion of data

- Full unblinding and internal review almost finalized, preparing ***PRL submission***



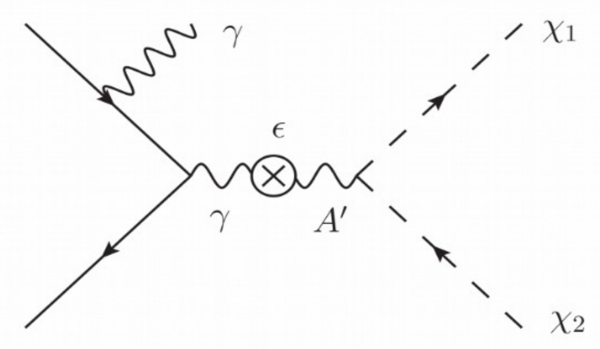
Babar UL on A' → ll ~ 5 x 10^{-7}

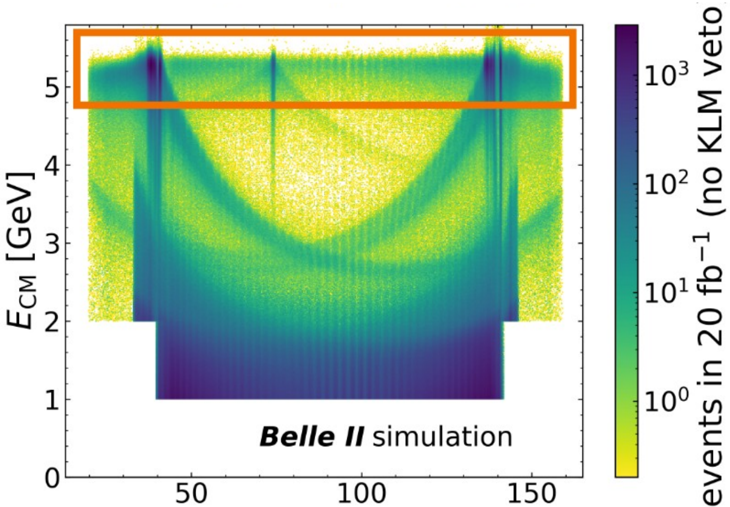
These results can be interpreted in a wider class of theoretical models, e.g., models with a higgs mixing with h_{SM} with enough lifetime to escape the detector.

* Babusci et al. (2015), Phys.Lett. B 747 pg. 365-372, 0370-2693

Dark photon to invisible at B-factories

- 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

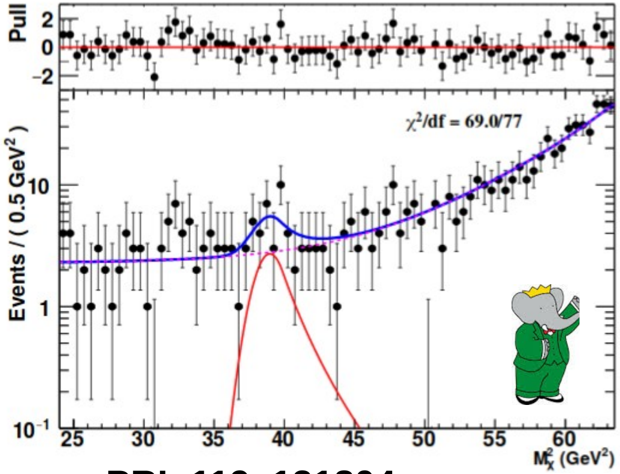




Belle II Simulation Preliminary

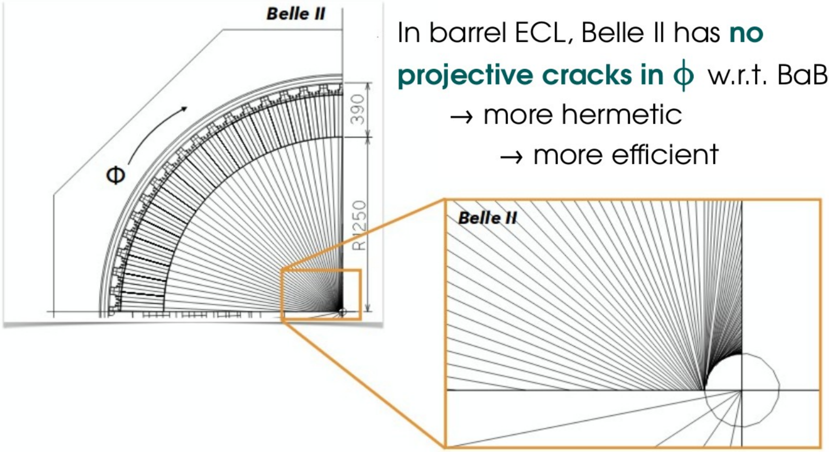
→ only one photon in the detector requires a dedicated **single photon trigger**

→ *at Belle was not available, at BaBar was available only on ~10% data (53 fb^{-1})*



PRL 119, 131804 (2017)

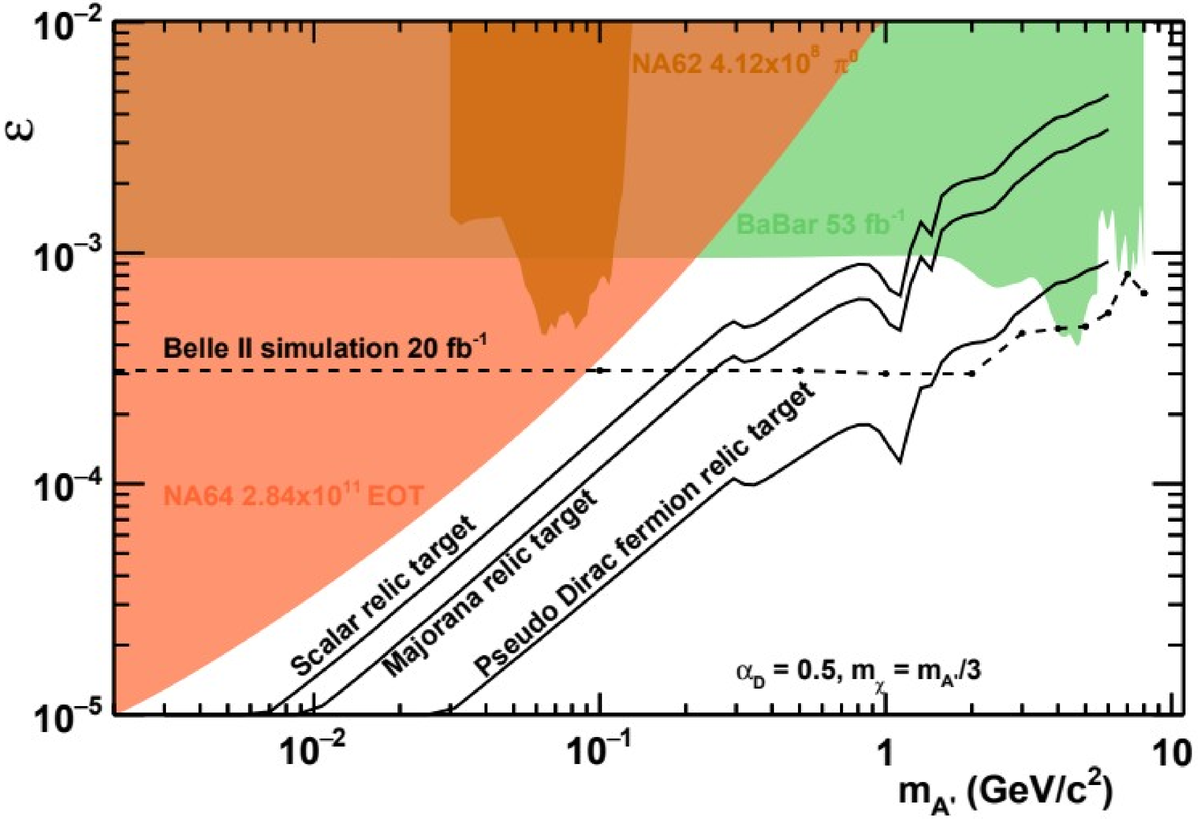
Invisible dark photon sensitivity at Belle II



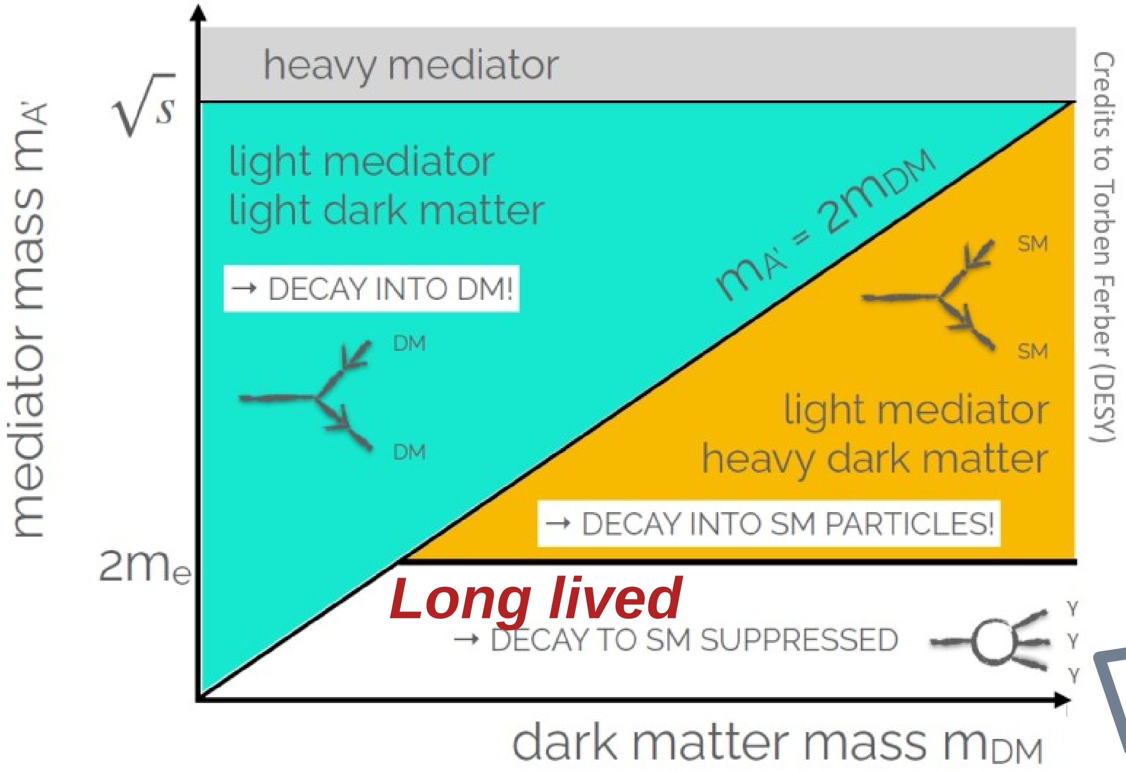
In barrel ECL, Belle II has **no projective cracks in ϕ** w.r.t. BaBar:
→ more hermetic
→ more efficient

- No calorimeter cracks pointing to the interaction region and possibility to compensate for photon detection gap with KLM veto
- Better hermeticity (smaller boost βγ=0.28, larger acceptance)
- Improved hardware trigger lines

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



Escaping detection, displaced vertices



Credits to Torben Ferber (DESY)

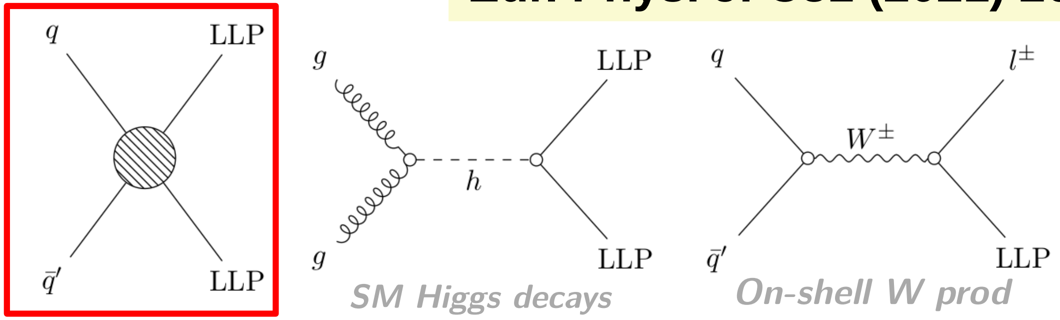
- LLP → ll'ν
- Long-lived scalars
- Inelastic Dark Matter

Search for LLP → eμν at LHCb

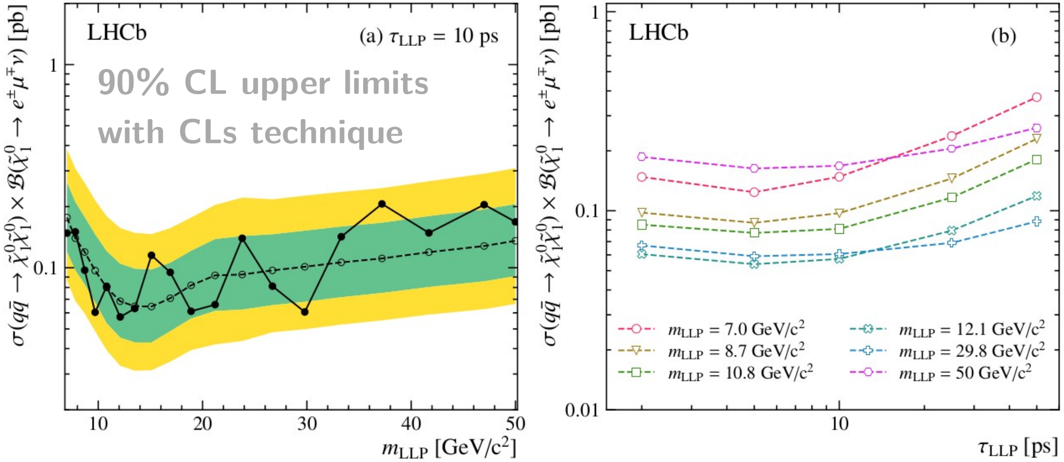
Eur. Phys. J. C81 (2021) 261

- 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 > $15 \cdot \sigma_{PV}$)
- Compute the LLP mass (m_{LLP}) as the corrected mass:

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



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

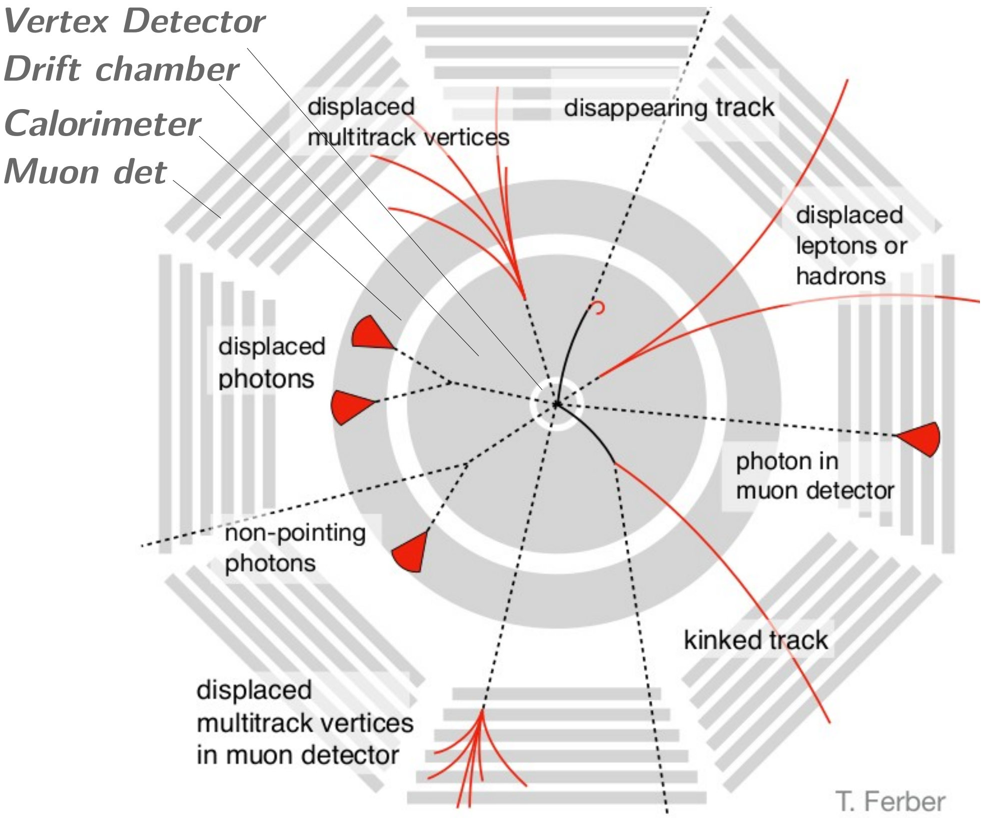


90% CL upper limits with CLs technique

- 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, $2 < \tau_{LLP} < 50$ ps}

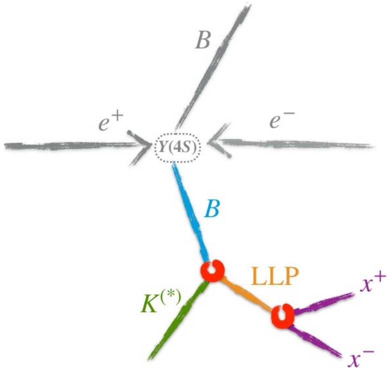
Long-lived particles at Belle II

Different experimental signatures allow to search for several long-lived (LL) mediator scenarios:

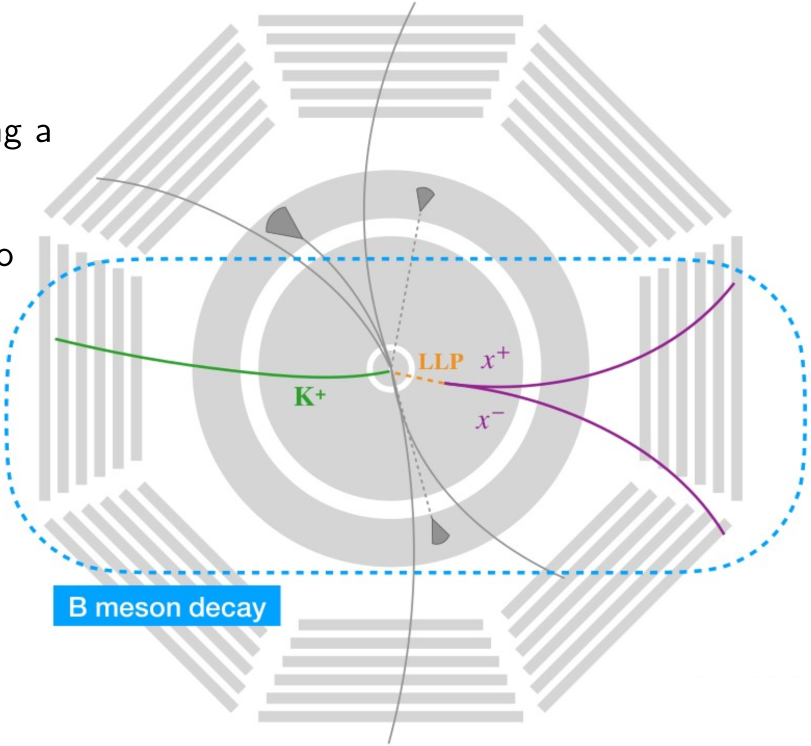


- Long-lived particles in b → s transitions:
  - displaced vertex (*scalar*, Dark Higgs)
  - displaced photons (*pseudo-scalar*, ALPs)
- Inelastic Dark Matter (iDM)

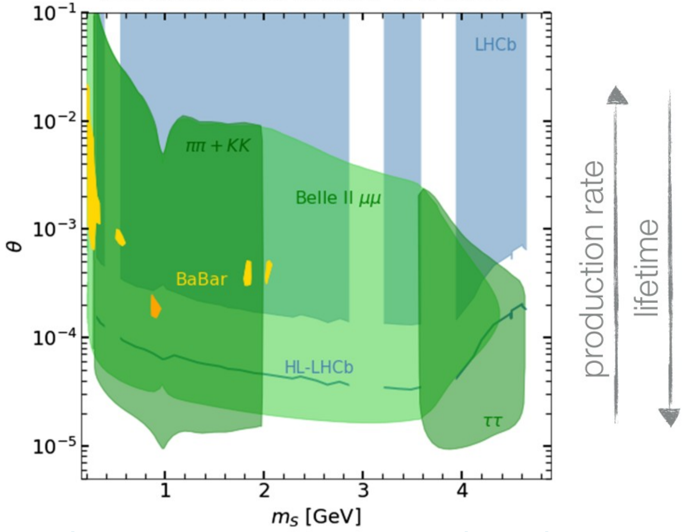
Long-lived (scalar) particles at Belle II



- Reconstruct B meson decay
  - prompt Kaon + two opposite-sign tracks forming a displaced vertex (LLP)
  - Exploit B-factory closed kinematics constraint to suppress continuum ($q\bar{q}$ hadronization)
  - Main background: SM long-lived, K_S and Λ



A. Filimonova, R. Schäfer, S. Westhoff



Phys. Rev. D 101, 095006 (2020)

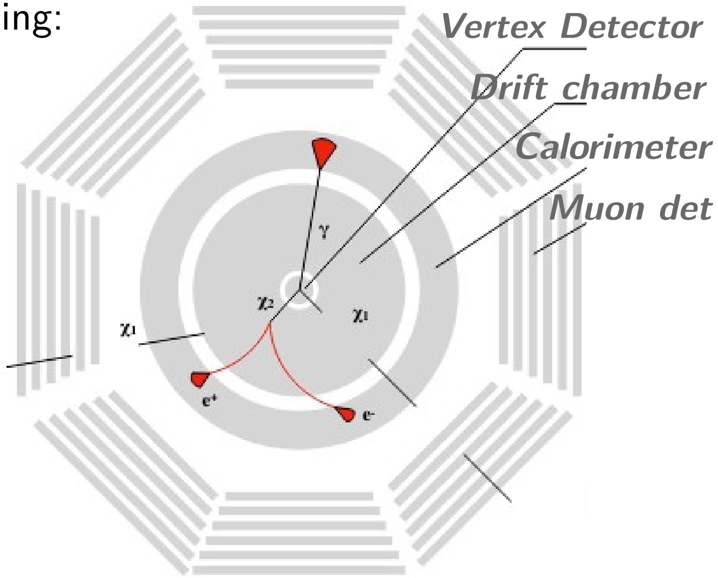
- Compute limits on cross-sections $\sigma(e^+ e^- \to \Upsilon(4S) \to [B \to K\ LLP\ ]\ \bar{B})$ at each scanned mass for different lifetimes
- Translate into model dependent limits on m_S & θ_S where $c\tau_S = f\ (m_S\ ,\ \theta_S\ )$

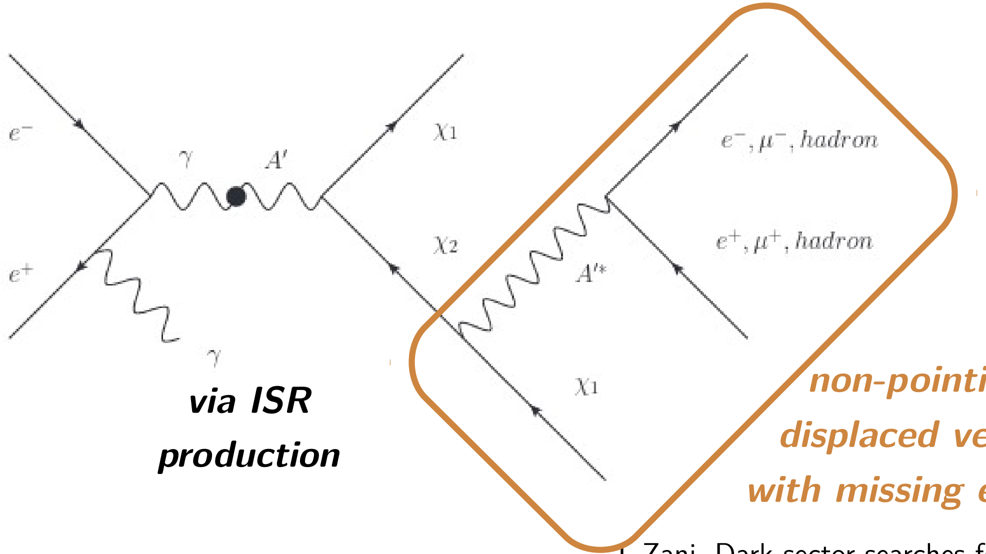
Inelastic Dark Matter (iDM)

Dark photon A' and two dark matter states χ1 and χ2 with a small mass splitting:

  - χ1 is stable (relic)
  - χ2 is long-lived at small values of kinetic-mixing coupling (ε)

- unconstrained by direct detection experiments, both inelastic and elastic scattering suppressed
- focus on $m_{A'} > m_{\chi 1} + m_{\chi 2}$, such that A'→ χ1 χ2 is dominant decay channel





via ISR production

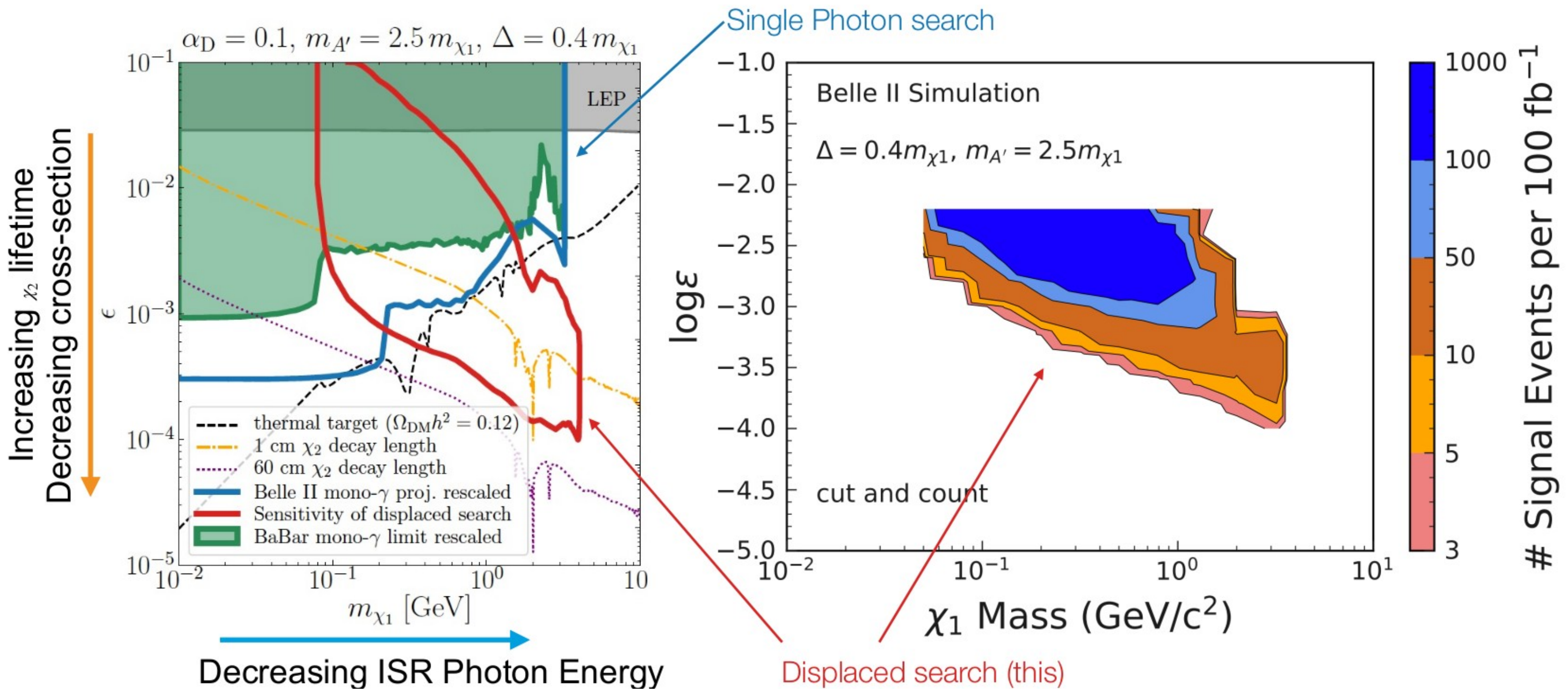
non-pointing displaced vertex with missing energy

5 parameter model:
$m_{A'}$ (fixed relative to $m_{\chi 1}$)
$m_{\chi 1}$ (scan)
mass difference $\Delta = m_{\chi 2} - m_{\chi 1}$ (categorical)
dark coupling α_D (fixed to benchmarks)
kinetic mixing parameter ε (limit)

Journal of High Energy Physics volume 2020, Article number: 39 (2020)

IDM sensitivity at Belle II

- Belle II can explore a large region of new iDM parameter space, constraining with early data set (100/fb) the kinetic mixing parameter down to 10^{-4}



Increasing χ_2 lifetime

Decreasing cross-section

Decreasing ISR Photon Energy

Single Photon search

Displaced search (this)

Journal of High Energy Physics volume 2020, Article number: 39 (2020)

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* interesting to probe not only the DM puzzle, but also many anomalies in flavor.

- Belle II proved already its capability to produce ***world leading results*** even on a minimal data set (1/100 000th of the final target one)

  → *Increased luminosity, upgraded detector and better analysis strategies will improve existing limits and provide soon new results.*

Z' → inv PRL 124 (2020) 141801
a → γγ PRL 125 (2020) 161806

A'→ μμ PRL 124 (2020) 041801
X→ μμ JHEP 10 (2020) 156
LLP → eμν, EPJ C81 (2021) 261

... more to come: *dark-Higgsstrahlung, (in)visible dark photon, LLPs, Heavy Neutral Lepton searches ...*

The Belle II Physics book   *LHCb prospects on ALPs searches*

Thanks for your attention.

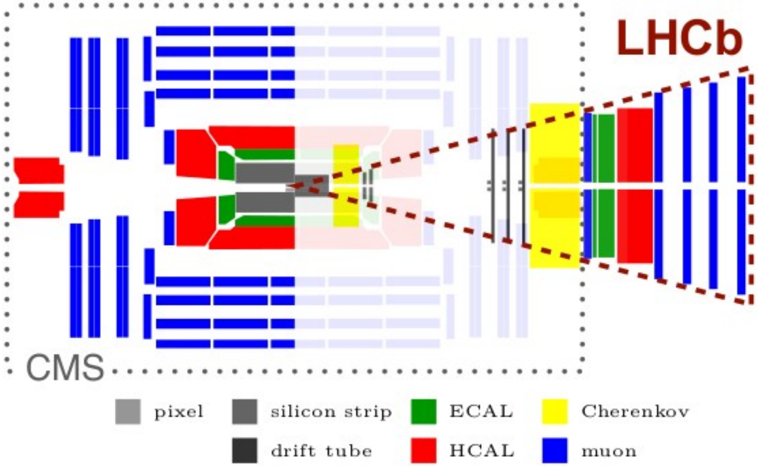
Backup

The LHCb detector

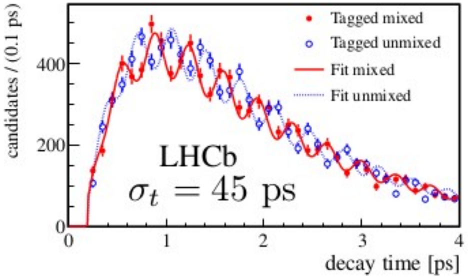
- Only LHC detector fully instrumented in **forward** region
- Excellent vertex and momentum resolution
- Lower luminosity (@ low pile-up) 3/fb in Run 1, 5.9/fb in Run 2
- **Capable of soft triggers!**
  - In hardware $p_T(\mu^\pm) > 1.8$ GeV while $p_T(e^\pm, h^\pm) > 3$ - 4 GeV
  - Very flexible software 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

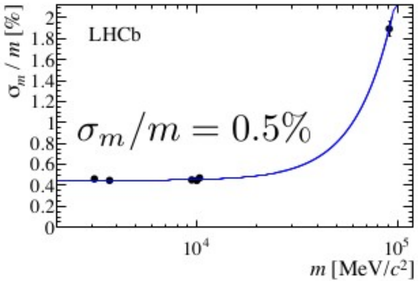
Int.J.Mod.Phys. A 30, 1530022 (2015)



vertex reconstruction



mass resolution



X→ μμ: signal searches

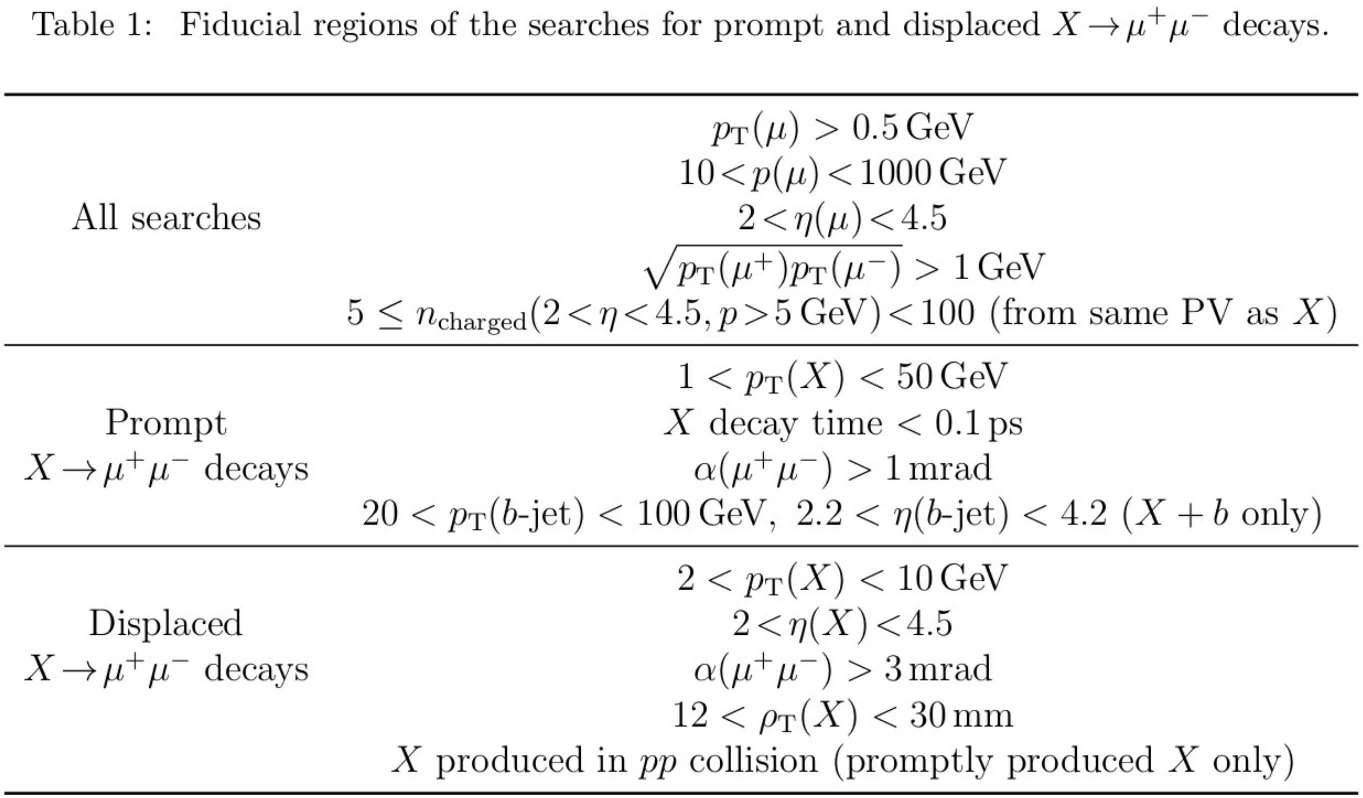


Table 1: Fiducial regions of the searches for prompt and displaced $X \to \mu^+\mu^-$ decays.

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 → eμ: efficiencies

- Selection efficiencies rely on simulations

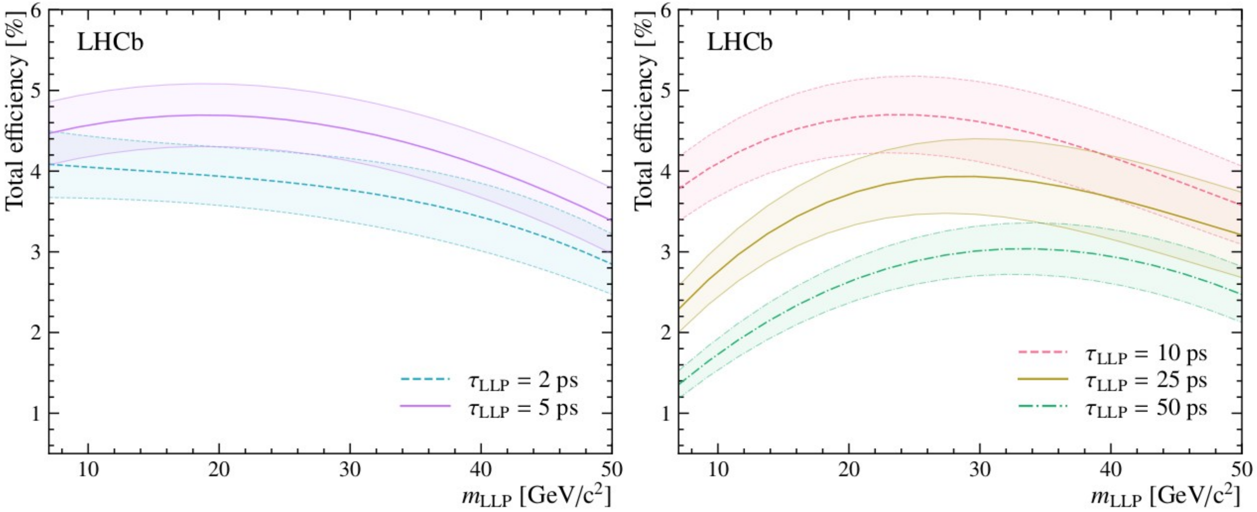


Figure 5: Total detection efficiency for LLP produced through the DPP mechanism as a function of m_{LLP} (central line) and its uncertainty (coloured band), obtained for different values of τ_{LLP}.

Search for LLP → eμ: systematics

- Main systematic uncertainty comes from differences between simulation and data

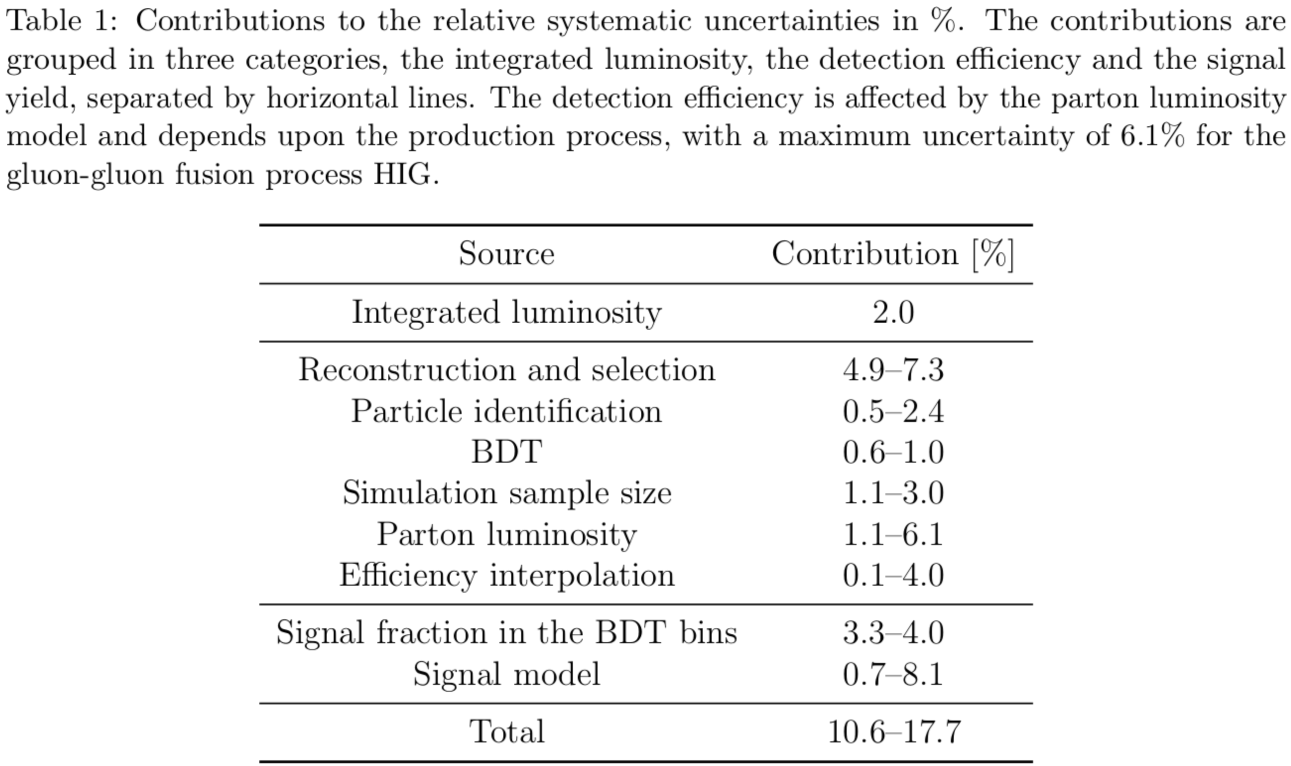
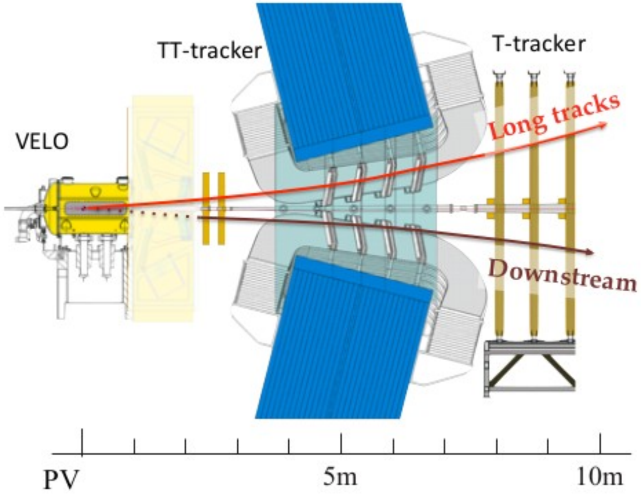


Table 1: Contributions to the relative systematic uncertainties in %. The contributions are grouped in three categories, the integrated luminosity, the detection efficiency and the signal yield, separated by horizontal lines. The detection efficiency is affected by the parton luminosity model and depends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

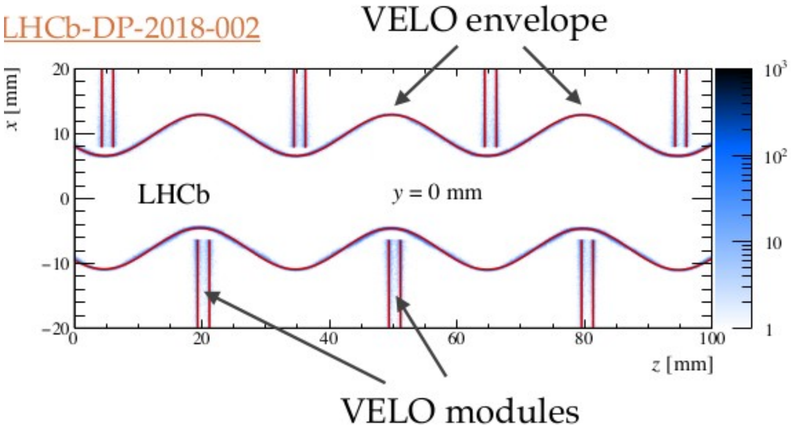
Source	Contribution [%]
Integrated luminosity	2.0
Reconstruction and selection	4.9–7.3
Particle identification	0.5–2.4
BDT	0.6–1.0
Simulation sample size	1.1–3.0
Parton luminosity	1.1–6.1
Efficiency interpolation	0.1–4.0
Signal fraction in the BDT bins	3.3–4.0
Signal model	0.7–8.1
Total	10.6–17.7

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]

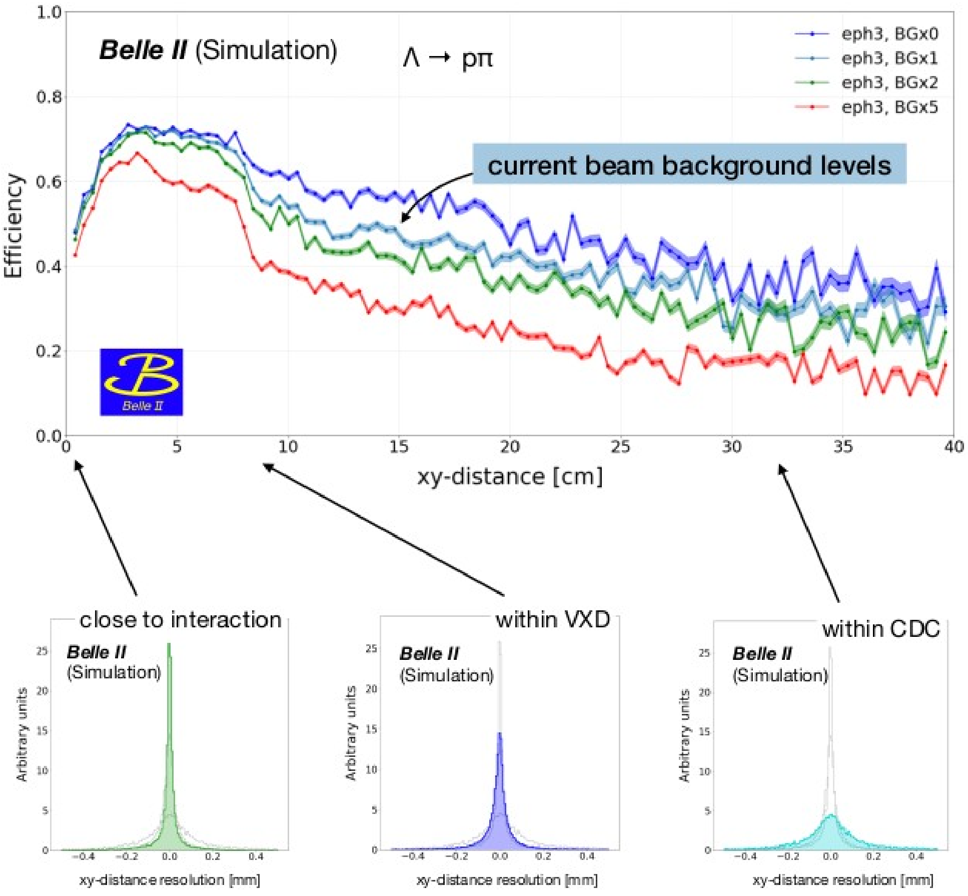
Backgrounds in VELO

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

Displaced vertex at Belle II

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

- Vertex efficiency larger than 30% out to ~60 cm
  - But expect boost roughly 10 × smaller than LHCb
- Mass resolution worsens for more displaced vertices
- Efficiency depends on background level

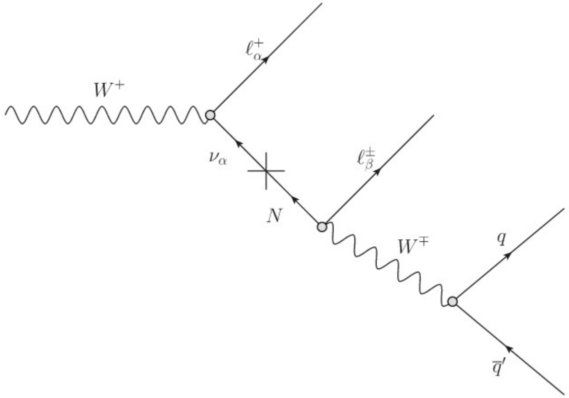


Search for Heavy Neutral Lepton at LHCb

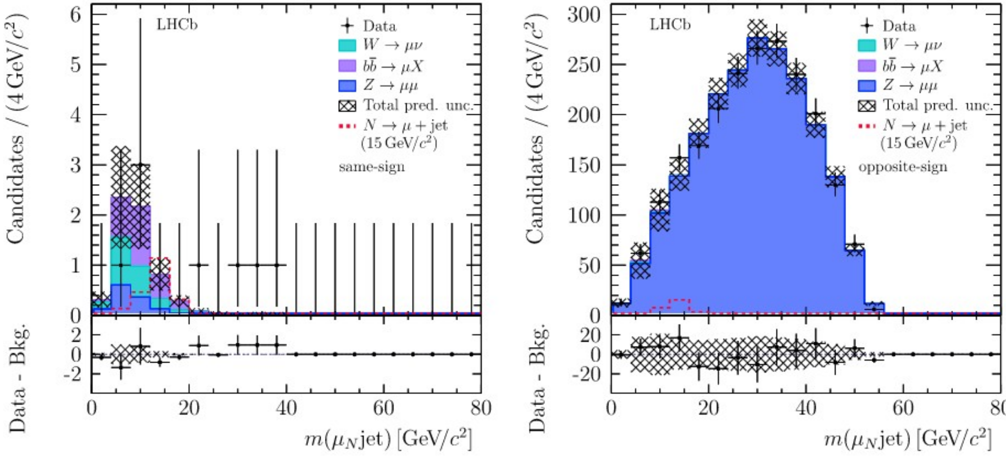
https://arxiv.org/pdf/2011.05263.pdf

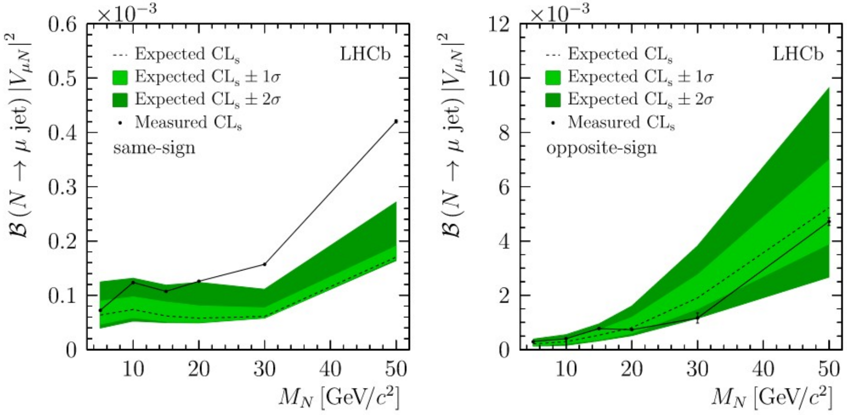
- **Data set**: 3/fb at 7-8 TeV center of mass energy
- Search for di-muon + jet in W decays, normalize to control channel W→μν

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



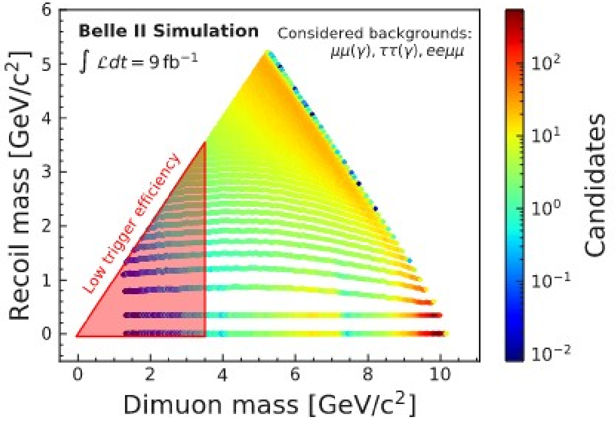
- No excess found in the range 5 < m_{HNL} < 50 GeV → set 95% CL upper limits

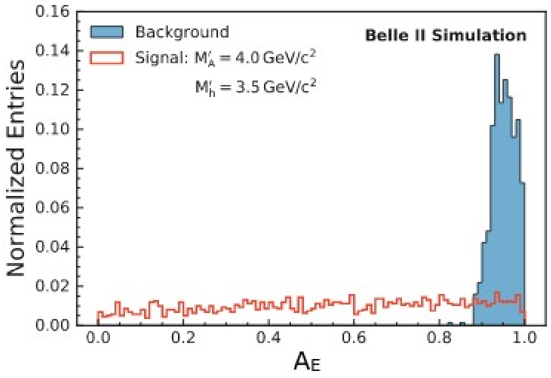


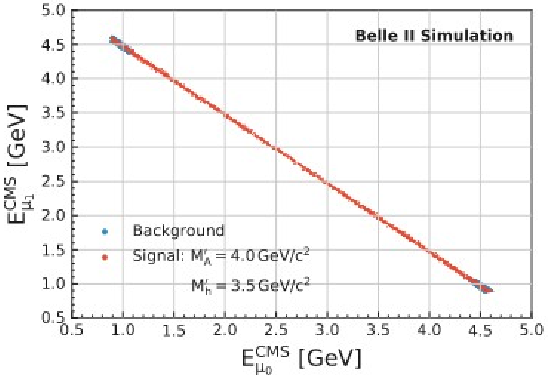


Dark Higgsstrahlung: analysis strategy

- look for two oppositely charged muons plus missing energy
- find a peak in two dimensional distribution of recoiling mass vs dimuon mass
- main SM background contributions arise from
  - $\mu^+\mu^-(\gamma)$
  - $\tau^+\tau^-(\gamma)$
  - $e^+e^-\mu^+\mu^-$
- **main challenge:** measurement strategy
  - scan+count in elliptical mass windows
  - continuous grid of 9k (overlapping) ellipses
- background suppression based on helicity angle, energy asymmetry between muons



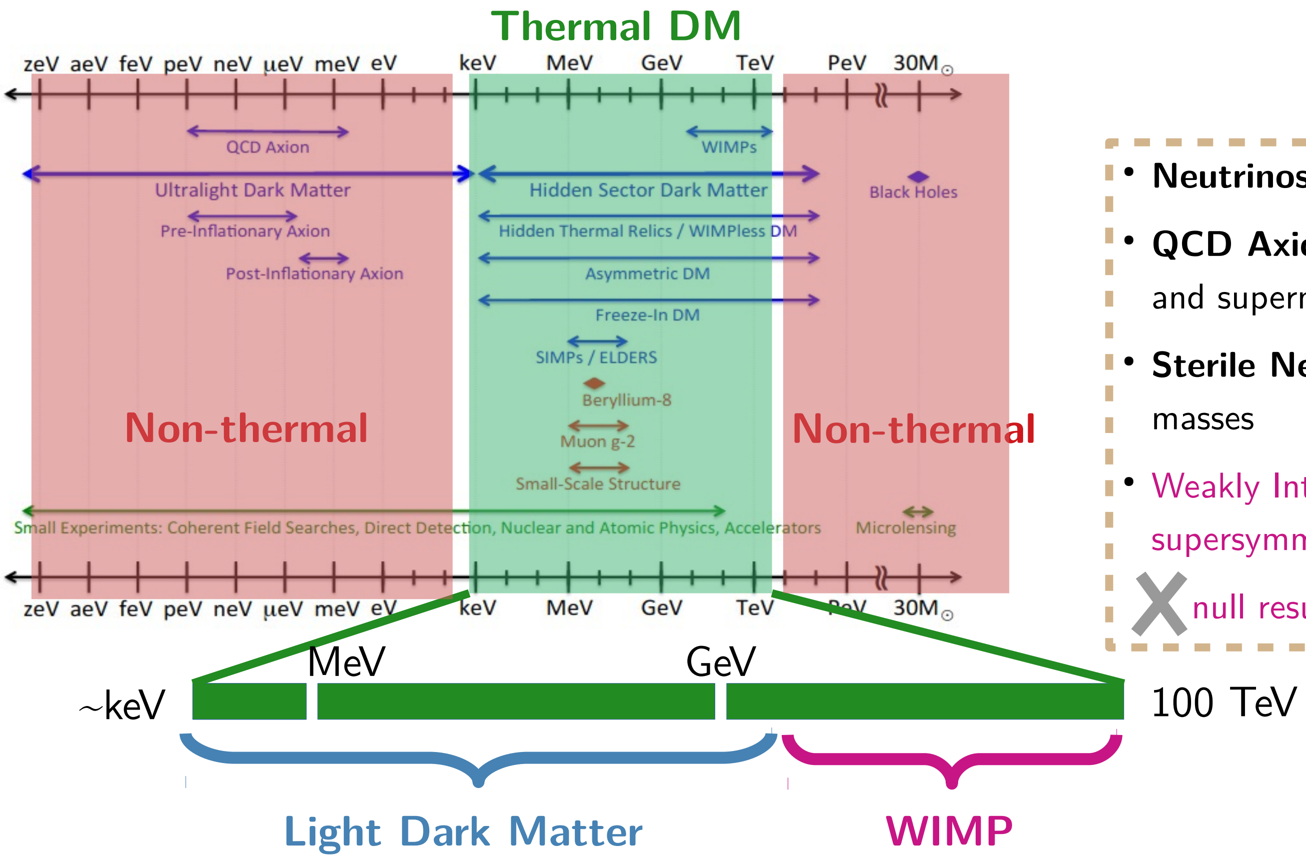




Dark matter candidates

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

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



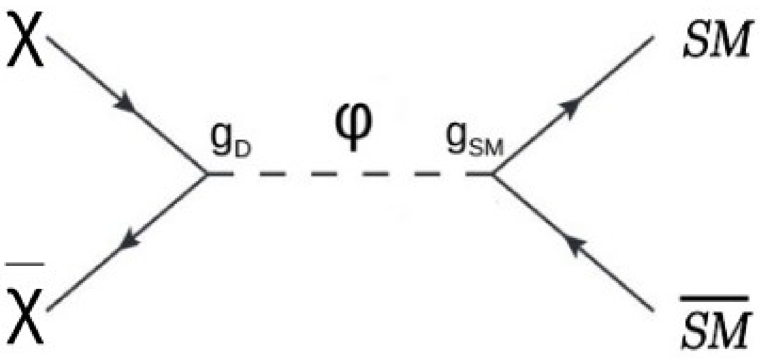
→ Particle candidates

- **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

$$\langle\sigma v\rangle_{relic} \sim \frac{\overset{<1}{\boxed{g_D g_{SM}}}\, m_\chi^2}{m_\phi^4}$$

→ **Experimentally constrained by current searches**

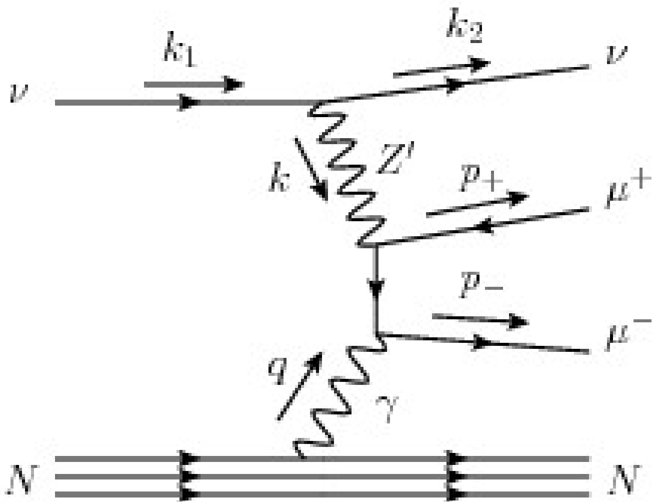
$$m_\phi^4 \leq \frac{m_\chi^2}{<\sigma v>} \text{ since g} < O(1)$$

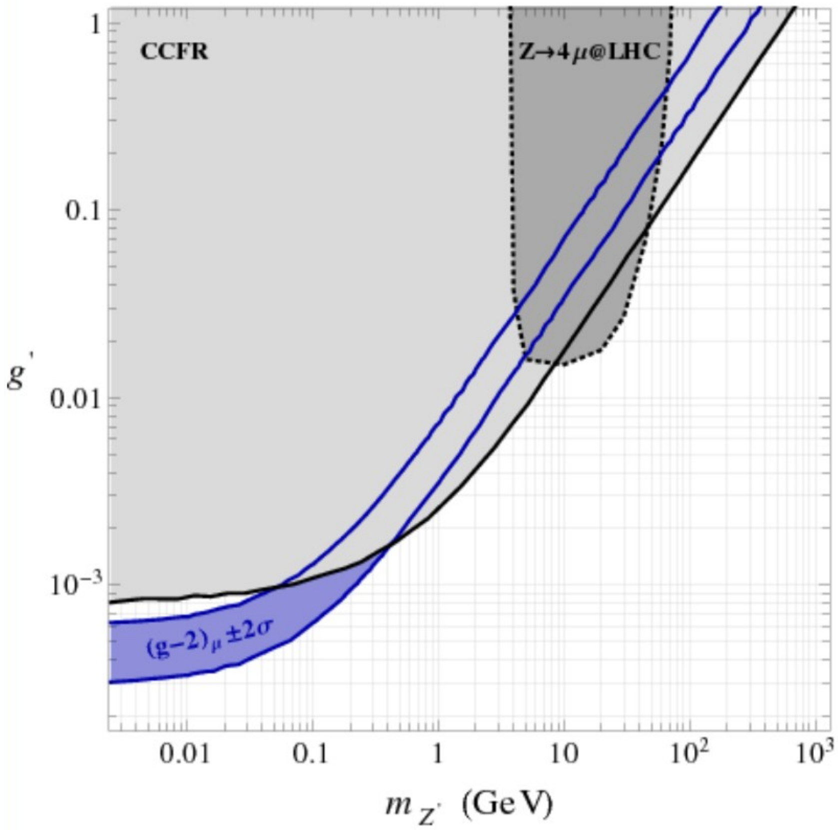
May be too small to be consistent with the mass of any known SM mediator

→ NEW PORTALS

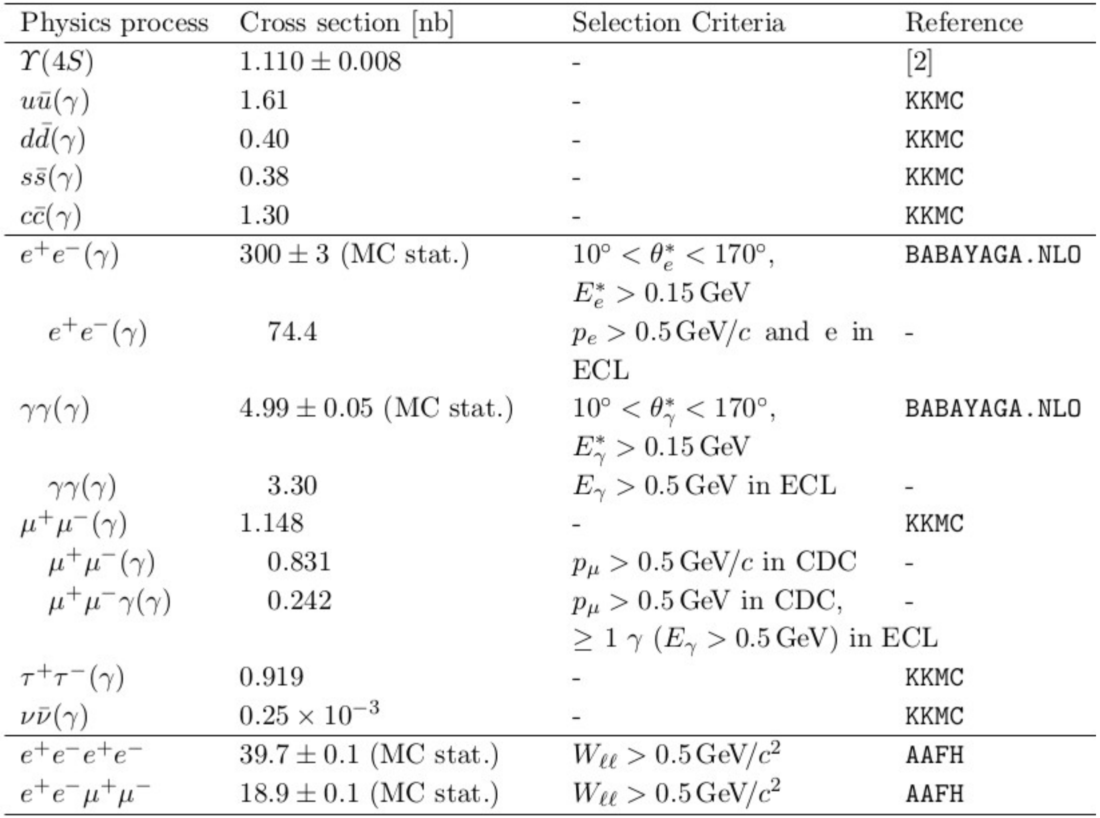
Neutrino trident production

- 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

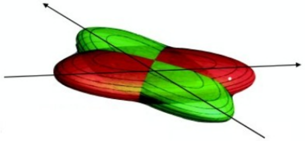
The Belle II Physics Book [arXiv:1808.10567]

- 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].

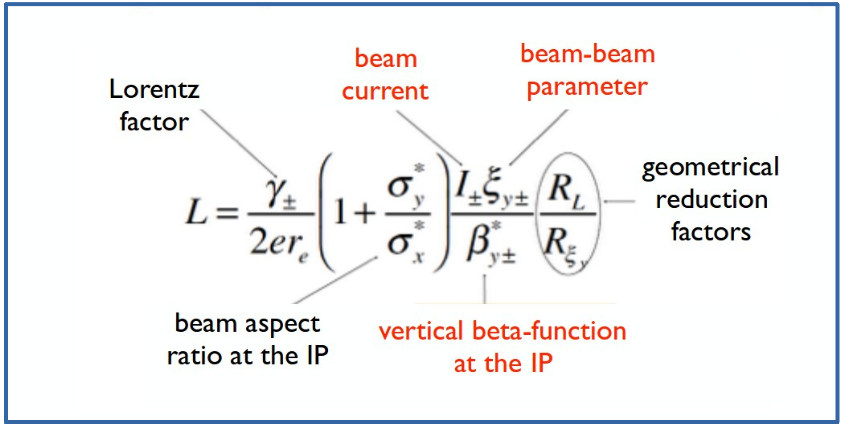
KEKB



SuperKEKB

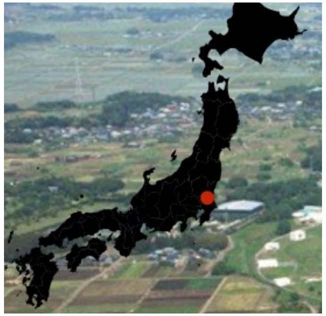
I (A): ~ 1.6/1.2 → **X 1,5** → I (A): ~ 3.6/2.6

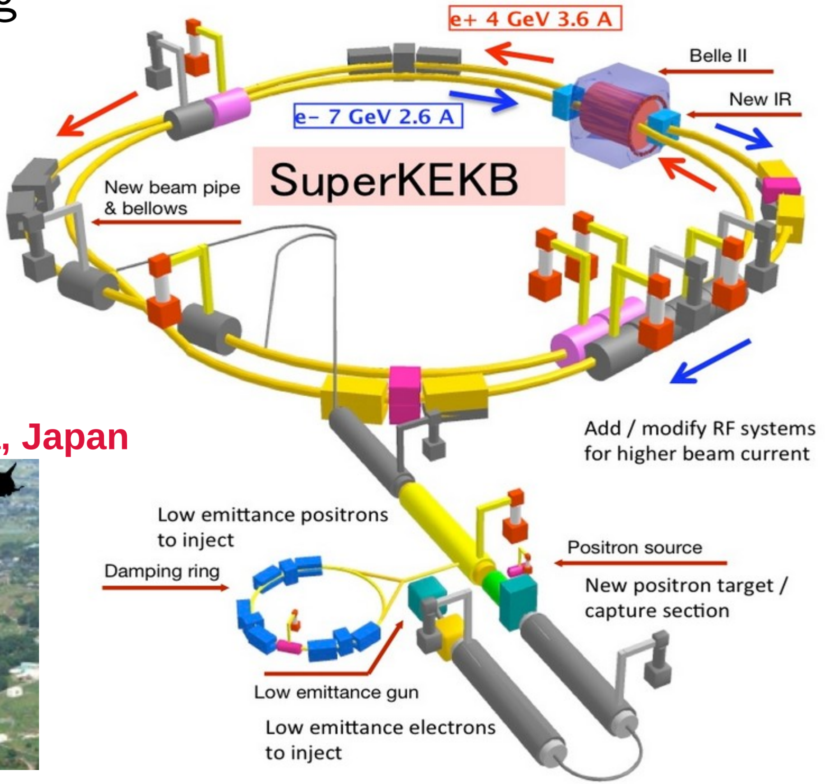
β^*_y (mm): ~ 5.9/5.9 → **x 1/20** → β^*_y (mm): ~ 0.27/0.3



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

KEK
Tsukuba, Japan

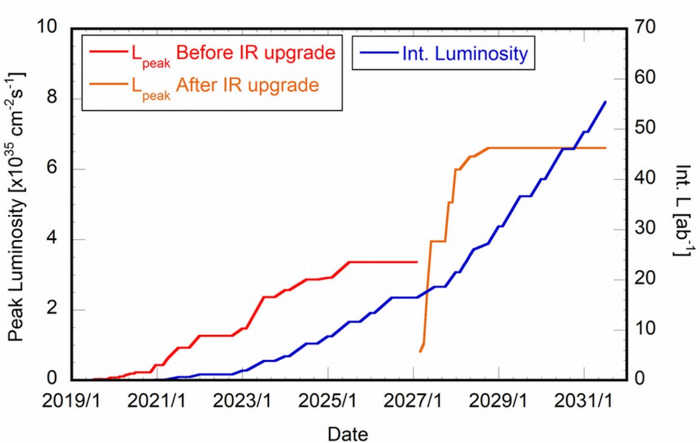


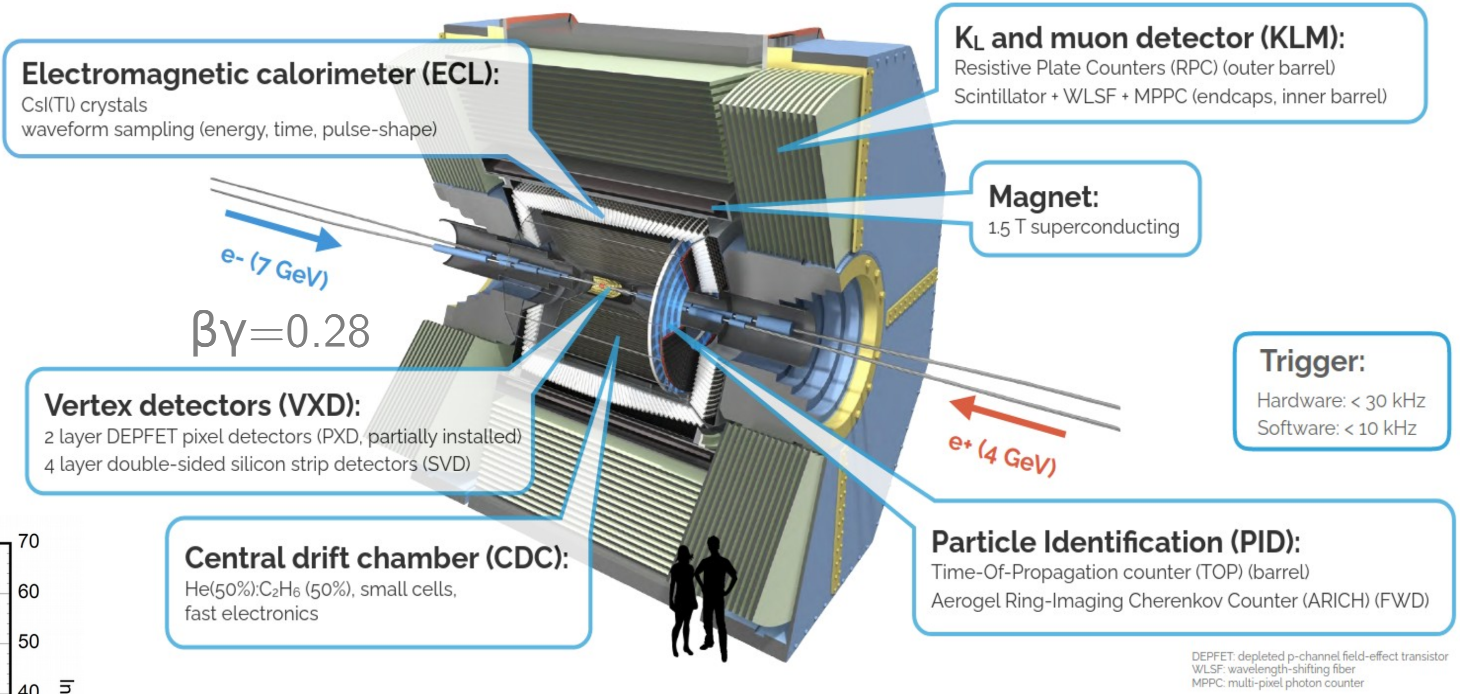


30x KEKB peak luminosity: $\mathcal{L} = 6 \cdot 10^{35}$ cm^{-2} s^{-1}

Belle II at SuperKEKB

- Updated detector:
  - provide comparable/better efficiencies and resolutions in a higher background
  - Improved dedicated triggers for low multiplicity and missing energy final states → *see more in previous session talks*





Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
waveform sampling (energy, time, pulse-shape)

K$_L$ and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting

Trigger:
Hardware: < 30 kHz
Software: < 10 kHz

Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD, partially installed)
4 layer double-sided silicon strip detectors (SVD)

Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells,
fast electronics

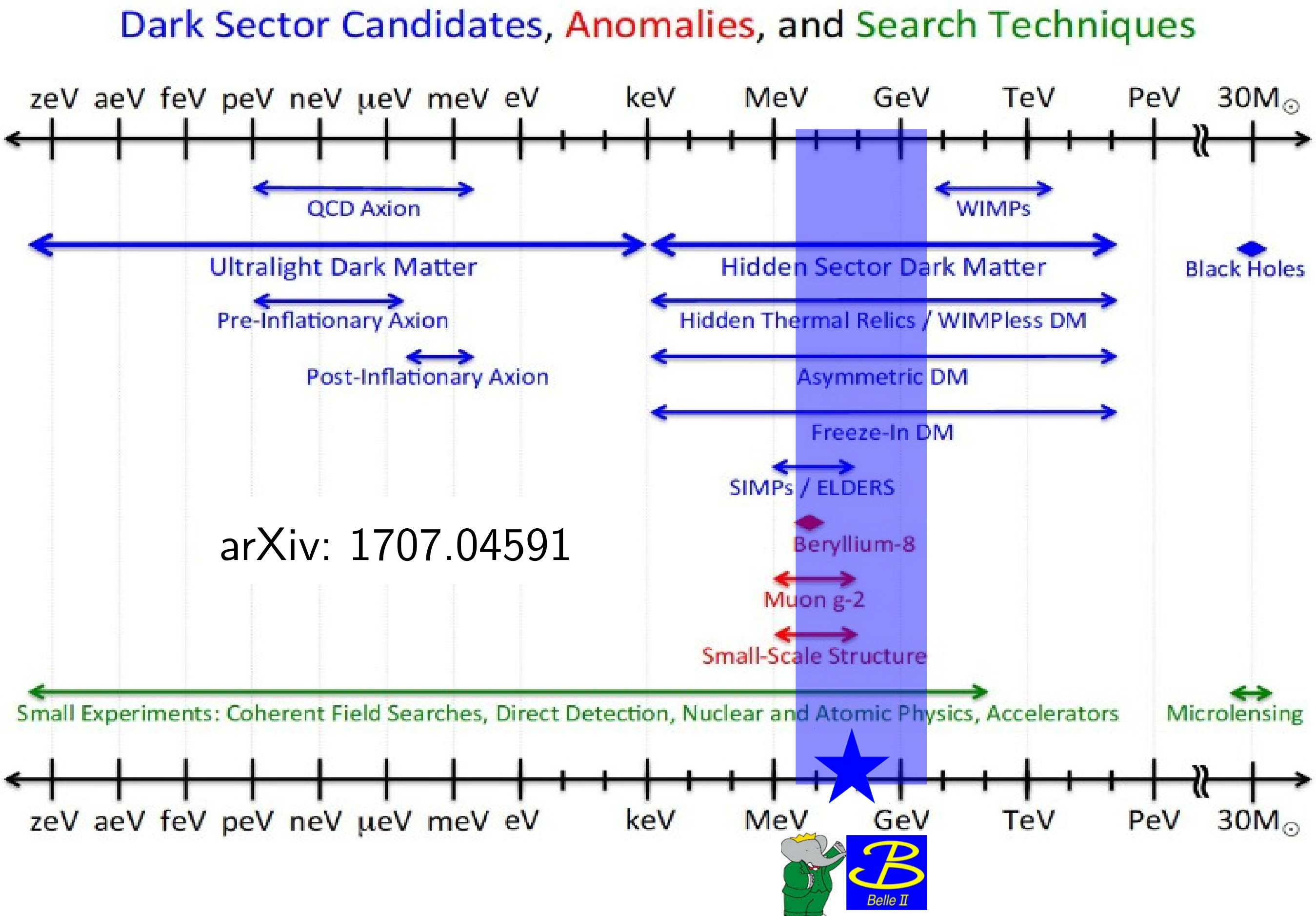
Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

GOAL: 50 ab^{-1}

The Belle II Physics Book, PTEP 2019 12 (2019)

Overview of dark sector searches

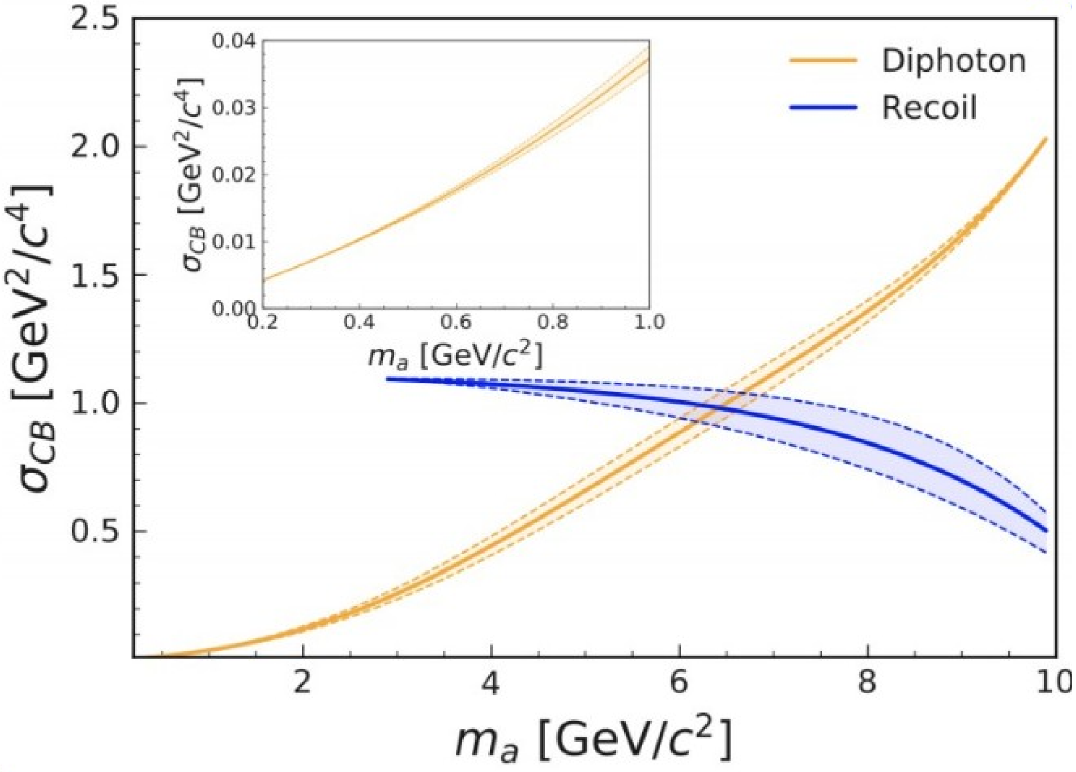


arXiv: 1707.04591

★ B-factories can access the mass range naturally favored by ***light dark sectors***

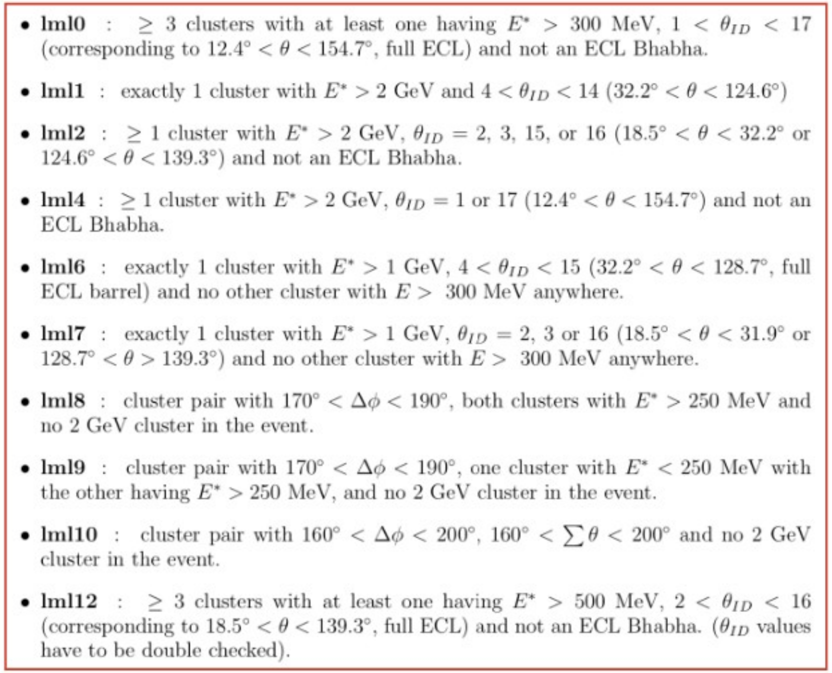
ALPs at Belle II: resolutions

- Signal resolutions for di-photon and recoil masses



Low multiplicity triggers

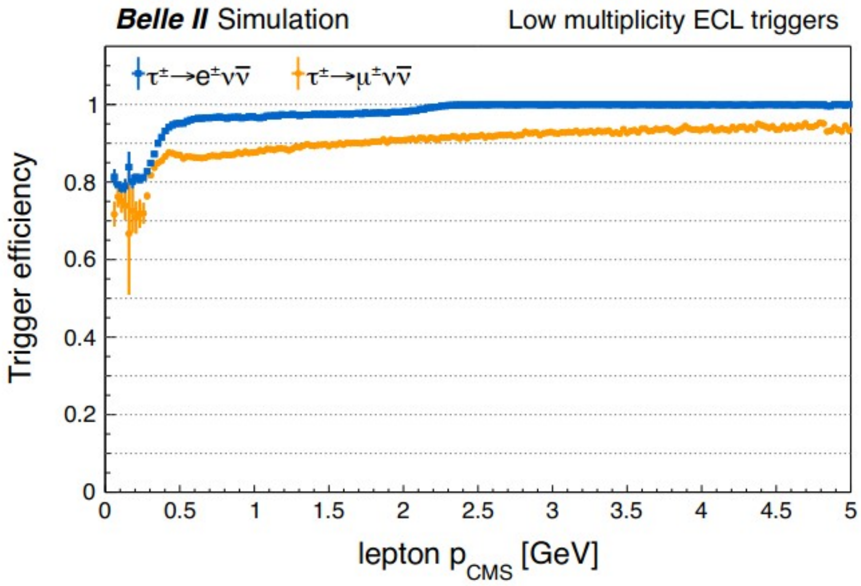
- Events are required to fire the logical OR of several unprescaled low-multiplicity (**lml**) ECL triggers



- **lml0** : ≥ 3 clusters with at least one having $E^* > 300$ MeV, $1 < \theta_{ID} < 17$ (corresponding to $12.4° < \theta < 154.7°$, full ECL) and not an ECL Bhabha.
- **lml1** : exactly 1 cluster with $E^* > 2$ GeV and $4 < \theta_{ID} < 14$ ($32.2° < \theta < 124.6°$)
- **lml2** : ≥ 1 cluster with $E^* > 2$ GeV, $\theta_{ID} = 2$, 3, 15, or 16 ($18.5° < \theta < 32.2°$ or $124.6° < \theta < 139.3°$) and not an ECL Bhabha.
- **lml4** : ≥ 1 cluster with $E^* > 2$ GeV, $\theta_{ID} = 1$ or 17 ($12.4° < \theta < 154.7°$) and not an ECL Bhabha.
- **lml6** : exactly 1 cluster with $E^* > 1$ GeV, $4 < \theta_{ID} < 15$ ($32.2° < \theta < 128.7°$, full ECL barrel) and no other cluster with $E >$ 300 MeV anywhere.
- **lml7** : exactly 1 cluster with $E^* > 1$ GeV, $\theta_{ID} = 2$, 3 or 16 ($18.5° < \theta < 31.9°$ or $128.7° < \theta > 139.3°$) and no other cluster with $E >$ 300 MeV anywhere.
- **lml8** : cluster pair with $170° < \Delta\phi < 190°$, both clusters with $E^* > 250$ MeV and no 2 GeV cluster in the event.
- **lml9** : cluster pair with $170° < \Delta\phi < 190°$, one cluster with $E^* < 250$ MeV with the other having $E^* > 250$ MeV, and no 2 GeV cluster in the event.
- **lml10** : cluster pair with $160° < \Delta\phi < 200°$, $160° < \sum\theta < 200°$ and no 2 GeV cluster in the event.
- **lml12** : ≥ 3 clusters with at least one having $E^* > 500$ MeV, $2 < \theta_{ID} < 16$ (corresponding to $18.5° < \theta < 139.3°$, full ECL) and not an ECL Bhabha. (θ_{ID} values have to be double checked).

- Absolute trigger efficiency in MC (TSIM, release-05-02-00):

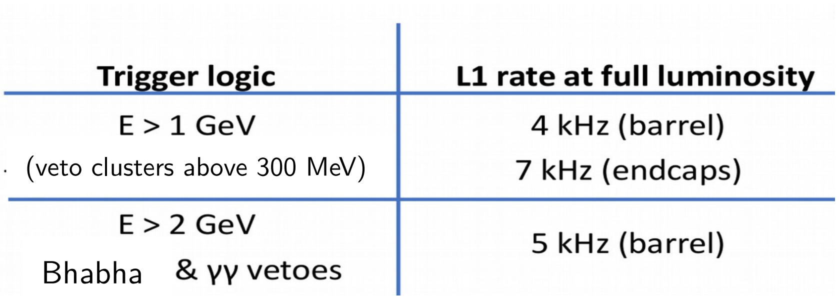
$$\epsilon_{L1} = \frac{\textbf{lml0}\ or\ \textbf{lml1}\ or\ \textbf{lml2}\ or\ \textbf{lml4}\ or\ \textbf{lml6}\ or\ \textbf{lml7}\ or\ \textbf{lml8}\ or\ \textbf{lml9}\ or\ \textbf{lml10}\ or\ \textbf{lml12}}{\text{all events}}$$



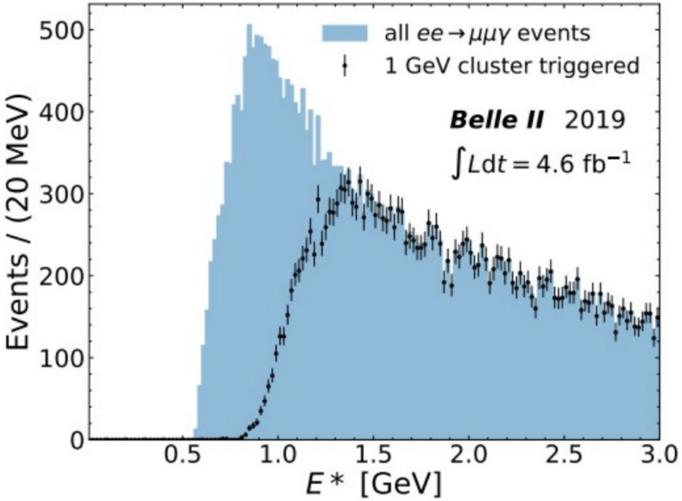
- For this trigger configuration, TSIM has been shown to reproduce data efficiency within ~1%.

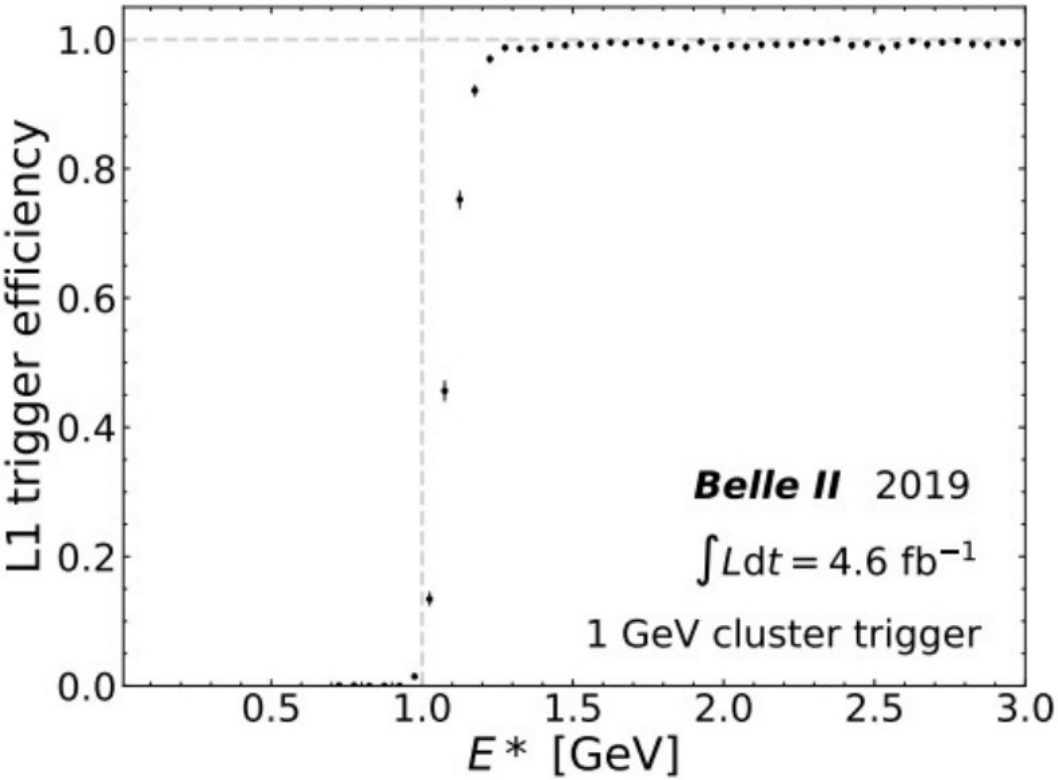
Dark photon to invisible: single photon trigger

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 & $\gamma\gamma$ vetoes	5 kHz (barrel)

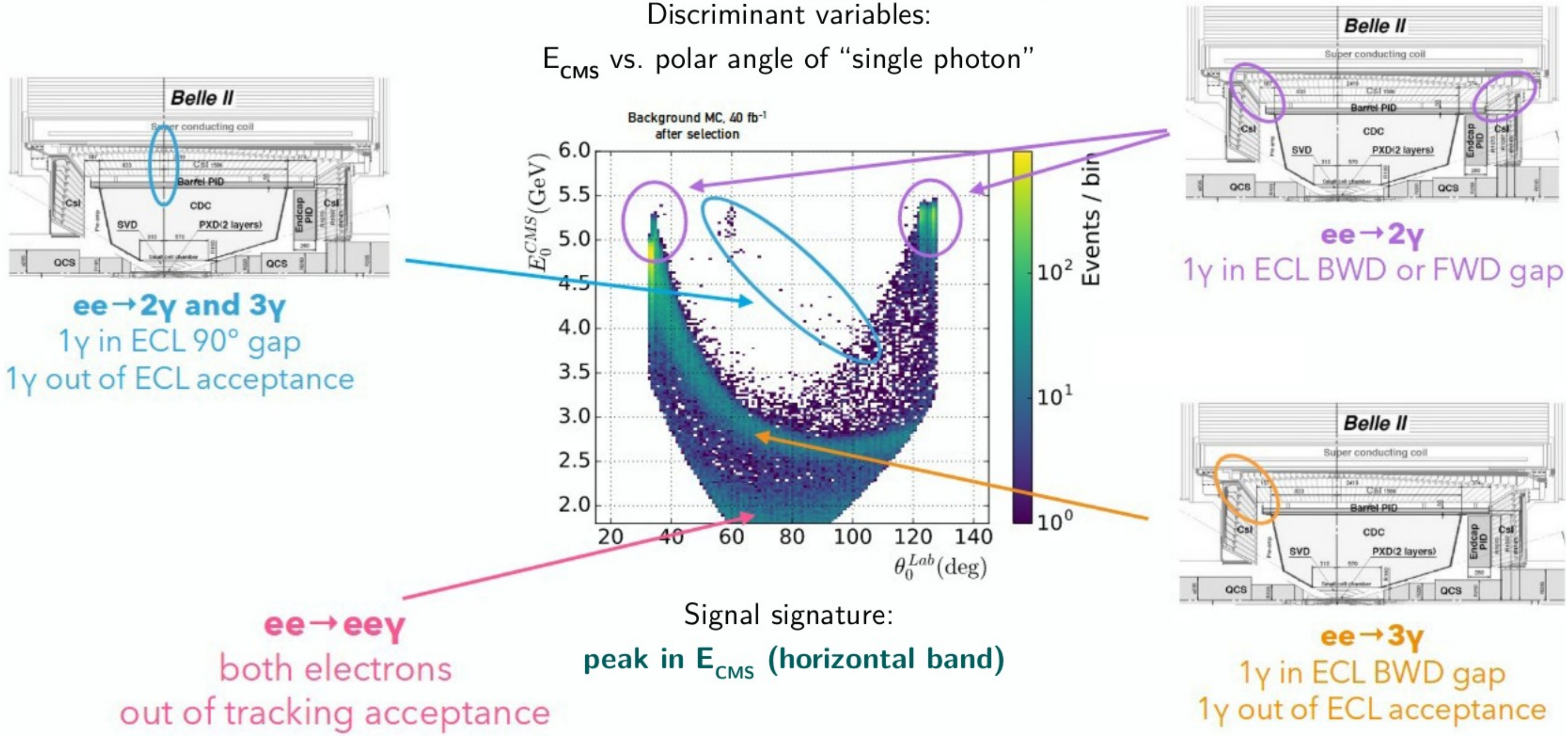




Dark photon to invisible: backgrounds

Discriminant variables:

E_{CMS} vs. polar angle of “single photon”



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

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)