Dark sector searches at *Belle II*: recent results and future prospects

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Online Conference

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on behalf of the *Belle II* collaboration
Outline

- Introduction to SuperKEKB and the *Belle II* experiment
- Overview on dark sector analysis @ *Belle II*
- Conclusions
**B-factories**

- Asymmetric $e^+e^-$ colliders optimized for the production of $B$ meson pairs, but also $D$ mesons, $\tau$ leptons, ...
- Collisions occur at $Y(nS)$ resonances
  - Mainly at $Y(4S)$: $\sqrt{s} = 10.58$ GeV just above the production threshold of $B\bar{B}$
    - $BR(Y(4S) \rightarrow B\bar{B}) > 96%$
- Beam asymmetric energies: boosted $B\bar{B}$ pairs, for CP-violation time-dependent measurements
- High peak luminosity $L > 10^{34}$ cm$^{-2}$s$^{-1}$

**First generation of B-factories**

Belle@KEKB, KEK, Tsukuba (JP)
1999–2010, $\int L \, dt = 1$ ab$^{-1}$

BaBar@PEP-II, SLAC (USA)
1999–2008, $\int L \, dt = 0.5$ ab$^{-1}$

Tot: 1.5 ab$^{-1}$
The SuperKEKB collider

- SuperKEKB: new generation of $B$-factory that provides luminosity to the Belle II experiment

  ➔ Asymmetric beam energies: $e^-$ (7 GeV)/$e^+$ (4 GeV)
  Operating mainly at $\Upsilon(4S)$, but foreseen runs from $\Upsilon(2S)$ to $\Upsilon(6S)$

  ➔ Highest world peak luminosity with the nano-beam scheme

KEKB
- $I(A) \sim 1.6/1.2$
- $\beta_y^*(\text{mm}) \sim 5.9/5.9$

SuperKEKB
- $I(A) \sim 2.8/2.0$
- $\beta_y^*(\text{mm}) \sim 0.27/0.3$

30x peak luminosity: $6.5 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
SuperKEKB: a new intensity frontier machine

- Set a new luminosity world record on June 22\textsuperscript{nd}, 2021:
  \[3.12 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\]

- SuperKEKB peak performance:
  \[I(e^-/e^+) = 830/690 \text{ mA (target: } \sim 2.9/2.0 \text{ A)}\]
  \[\beta_y^* = 1 \text{ mm (target: } \sim 0.3 \text{ mm)}\]

- Target peak luminosity: \[6.5 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}\]
**Belle II detector @ SuperKEKB**

- Major upgrade of Belle@KEKB
- Covers more than 90% of the total solid angle

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

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

**Central drift chamber (CDC):**
He(50%):C_{2}H_{6} (50%), small cells, fast electronics

**Magnet:**
1.5 T superconducting

**K_{L} and muon detector (KLM):**
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

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

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

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Belle II operations

- First collisions during commissioning run on April 26\textsuperscript{th} 2018
  
  \(\Rightarrow\) 0.5 fb\(^{-1}\) collected in 2018

- First collisions with full detector on March 2019
  
  \(\Rightarrow\) > 240/fb collected in almost 3 years of data taking

- Target integrated luminosity of the Belle II experiment: 50/ab (x30 Belle + BaBar)

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Thanks to the high luminosity and the detector performance, Belle II will be competitive in many physics researches:

- Flavor physics
- Standard Model tests
- Search for rare or suppressed processes in Standard Model
- Dark Sector physics
Thanks to the high luminosity and the detector performance, Belle II will be competitive in many physics researches:

- **Flavor physics**
- **Standard Model tests**
- **Search for rare or suppressed processes in Standard Model**
- **Dark Sector physics**

**Belle II physics program**

**First Belle II physics publications**

**Invisibly Decaying $Z'$** Bo$\text{s}$on at Belle II in $e^+e^- \rightarrow \mu^+\mu^- (e^\pm\mu^\pm)$ Plus Missing Energy Final States

**Axionlike Particles** Produced in $e^+e^-$ Collisions at Belle II
General introduction to dark sector @ Belle II
Main motivation: the absence of dark matter discoveries at the electroweak scale by the LHC or direct detection experiments motivates the interest for models with low-mass dark matter candidates.

Theoretical scenarios introducing light dark matter with $M \sim 0$ (MeV-GeV) need light mediators too.

- Dark matter not charged directly under the Standard Model.
- Dark matter may interact to Standard Model through several "portal" interactions $[1,2]$:
  - vector portal (dark photon, $Z'$,...)
  - scalar portal (dark Higgs,...)
  - pseudo-scalar portal (axions, axion-like particles),
  - neutrino portal (heavy neutrinos)

- Not just solving the dark matter puzzle. Could explain:
  - some astrophysics anomalies: positron excess, ..., (PAMELA, Fermi, ...)
  - some anomalies in $B$ meson decays: $R_K$, $R_{K^*}$,... (Belle, LHCb, ...)
  - the $(g - 2)_\mu$ anomaly, recently confirmed at Fermilab $[3]$

References:

Dark sector searches @ $B$-factories

- Negligible interaction probability of dark matter with the detector
  - Search for mediators (visibles or invisibles)
  - Search for final states with missing mass
  - Search for both

- Advantages of $B$-factories
  - High luminosity
  - Well known initial state
  - Clean environment with low background
  - Hermetic detector with good PID performance

- Excellent capabilities for low multiplicities and missing energy signatures at $B$-factories

The relationship between mass of the mediators and DM candidates leads to different topologies.
Dark sector searches @ Belle II

- High luminosity provided by SuperKEKB
- All advantages of the $B$-factories
- High performance detector with dedicated triggers

Belle II will provide an important contribution in the search for dark sector physics with $M \sim 0$ (MeV – GeV)

- Dark matter candidates
- Observed anomalies

Belle II

Dark Sector

Berillium-8

$\mu^30M\mu$

QCD-axions

WIMPS

Black Holes

$\mu eV$

meV

eV

keV

MeV

GeV

TeV

$30M_0$

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**Belle II dark sector trigger**

- **2-level trigger:**
  - Hardware-based Level1 Trigger (L1): < 30 kHz
  - Software-based High Level Trigger (HLT): < 10 kHz
- New “dark sector” triggers make the dataset collected up to now world-unique
  - Single photon trigger operational for entire dataset
    - not present in Belle
    - 53/fb in BaBar recorded with single photon trigger
  - Single muon trigger using KLM recently introduced, efficiency ~ 90%
  - 3D track reconstruction at L1 level using neural networks

*Actually, newly designed trigger allows sensitivity down to 0.5 GeV of single photon*
Overview on dark sector searches @ Belle II
Search for a $Z'$ boson

- Vector boson $Z'$ with a coupling $g'$ only to the 2\textsuperscript{nd} and 3\textsuperscript{rd} generations of leptons, introduced by the $L_\mu - L_\tau$ model [1,2,3]:

$$\mathcal{L} = \sum_\ell \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell \quad \theta =+1 \text{ se } l = \mu \
\theta =-1 \text{ se } l = \tau$$

- Possible final states:

  - Invisible decays:
    - $Z' \rightarrow \nu \nu$ ($\mu$ or $\tau$ neutrinos)
    - primarily $Z' \rightarrow \chi \bar{\chi}$ (light dark matter) if kinematically accessible

  - Visible decays:
    - $Z' \rightarrow \mu \mu$
    - $Z' \rightarrow \tau \tau$

**Z' → Invisible**

- Searching for an invisible Z' for the first time, with 0.276/fb collected by Belle II in 2018
  - If dark matter particles kinematically accessible exist, then $BR(Z' \rightarrow \text{invisible}) = 1$
  - $BR(Z' \rightarrow \text{invisible}) = 1$ for $M_{Z'} < 2m_\mu$ whatever the dark matter is

- Hermetic Belle II detector and clean $e^+e^-$ collisions allow precision determination of missing energy

- Two cases:
  - $e^+e^- \rightarrow \mu^+\mu^- + \text{Missing Energy}$
  - $e^+e^- \rightarrow \mu^\pm e^\mp + \text{Missing Energy}$ (Lepton-Flavor Violation)

- Search for a narrow peak in the recoil mass distribution against $\mu^+\mu^-$ (LFV: $\mu^\pm e^\mp$)

$$M_{\text{recoil}}^2 = s + M_{\mu\mu}^2 - 2\sqrt{s}(E_{\mu^+}^{CMS} + E_{\mu^-}^{CMS})$$

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Z' → Invisible ($\mu^+\mu^-$)

- $e^+e^- \to \mu^+\mu^- + \text{Missing Energy}$

- Main background components:
  - $e^+e^- \to \tau^+\tau^- (\gamma)$: missing energy due to neutrinos
  - $e^+e^- \to \mu^+\mu^- (\gamma)$: missing energy due to undetected photons
  - $e^+e^- \to e^+e^-\mu^+\mu^-$: missing energy due to undetected electrons
**Z’ → Invisible (μ⁺μ⁻)**

- **e⁺e⁻ → μ⁺μ⁻ + Missing Energy**

- Main background components:
  - $e⁺e⁻ → \tau^+\tau^−(γ)$: missing energy due to neutrinos
  - $e⁺e⁻ → μ⁺μ^−(γ)$: missing energy due to undetected photons
  - $e⁺e⁻ → e⁺e^+μ^−μ^−$: missing energy due to undetected electrons

- Dedicated background suppression based on the different origin of missing momentum in background (neutrinos for $\tau\tau$ and ISR for $μμ(γ)$) and signal (FSR)

  ➔ Exploits lepton kinematics
**Z’ → Invisible (μ⁺μ⁻)**

- **e⁺e⁻ → μ⁺μ⁻ + Missing Energy**

- Main background components:
  - e⁺e⁻ → τ⁺τ⁻(γ): missing energy due to neutrinos
  - e⁺e⁻ → μ⁺μ⁻(γ): missing energy due to undetected photons
  - e⁺e⁻ → e⁺e⁺μ⁺μ⁻: missing energy due to undetected electrons

- Dedicated background suppression based on the different origin of missing momentum in background (neutrinos for ττ and ISR for μμ(γ)) and signal (FSR)
  
  - Exploits lepton kinematics

- **No significant excess observed in data**
- 90% CL upper limits on the coupling constant $g'$ as a function of the $Z'$ mass $- g' < 5 \cdot 10^{-2}$

Z’ → Invisible (LFV)

- No excess observed in data
- First model independent limits on $\epsilon \cdot \sigma(e^+e^- \rightarrow e^\pm\mu^\mp + \text{invisible})$ down to 10 fb
- First Belle II physics publication: 
  

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**Belle II 2018**

\[ \int Ldt = 276 \text{ pb}^{-1} \]

**LFV: $\mu^\pm e^{\mp}$**

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**Belle II 2018**

\[ \int Ldt = 276 \text{ pb}^{-1} \]

$\epsilon \cdot \sigma(e^+e^- \rightarrow e^\pm\mu^\mp + \text{invisible})$
Z’ → Invisibile, future prospects

- **Short-term program**
  - Much more integrated luminosity (already available)
  - Analysis improvements (MVA based background suppression)
  - New trigger lines

- **Preliminary sensitivity**
  - Starting to investigate the model parameters that can explain the \((g - 2)_\mu\)

- Analysis will be finalized by Moriond 2022 (Spring 2022)
Highlights on $Z' \rightarrow \mu\mu$ @ Belle II

- $e^+e^- \rightarrow \mu^+\mu^-'Z', Z' \rightarrow \mu^+\mu^-'$

- Existing results by BaBar with 514/fb and Belle with 643/fb

- Competitive with early dataset (100/fb) due to aggressive background suppression

- MLP (Multi-Layer Perceptron (NN)) based background suppression

- Main background: QED $\mu\mu\mu\mu$ processes
  - ISR
  - Double-photon conversion

- Analysis will be finalized by Summer 2022

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Highlights on $Z' \to \mu\mu$ @ Belle II

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

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- Main background: QED $\mu\mu\mu\mu$ processes
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- Preliminary sensitivity at 90% CL w/o systematics included, using fit scan strategy on dimuon invariant mass

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Highlights on $Z' \to \tau\tau$ @ Belle II

- $e^+e^- \to \mu^+\mu^-Z', Z' \to \tau^+\tau^-$: First time search!
- Benchmark model: possibility to reinterpret the results found for the $Z'$ boson of the $L_\mu - L_\tau$ in other models, and in particular those with $\tau\tau$ resonance in a $\mu\mu\tau\tau$ final state
- The analysis is challenging:
  - The presence of neutrinos in the final state makes it impossible to exploit the $\Upsilon(4S)$ kinematic constraint
- Main background components expected: $q\bar{q}, \tau\tau, \mu\mu, e\bar{e}\mu\mu$
- Background suppression:
  - MLP (Multi-Layer Perceptron (NN)) based
- Profit of $B$-factory clean environment
- Analysis will be finalized by Summer 2022
Highlights on $Z' \rightarrow \tau \tau$ @ Belle II

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- Background suppression:
  - MLP (Multi-Layer Perceptron (NN)) based
- Profit of $B$-factory clean environment
- Analysis will be finalized by Summer 2022
- Preliminary 90% CL sensitivity w/o systematics on MC, using cut and count strategy (final strategy: fit scan on recoil mass against $\mu\mu$)
Axion-like particle (ALP)

- GeV-scale ALPs: pseudo-scalar portal mediator between dark sector and Standard Model
- If ALP-photon coupling \( g_{\alpha\gamma\gamma} \) dominates, than \( BR(\alpha \rightarrow \gamma\gamma) \sim 100\% \)
- Different topologies depending on model parameters \( (m_{\alpha}, g_{\alpha\gamma\gamma}) \): focus on mass region where ALP decay is prompt and photons can be well resolved by Belle II

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Search for an ALP

- Select events with three photon invariant mass compatible with collision $\sqrt{s}$
- Search for a narrow peak in $M_{\gamma\gamma}^2$ or $M_{\text{recoil}}^2$ depending on best resolution of signal peak
- Largest background from $e^+e^- \rightarrow \gamma\gamma(\gamma)$

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Search for an ALP: results

- Search ranges from $0.2 < m_a < 9.7 \text{ GeV/c}^2$, with the 0.445/fb collected in 2018 with Belle II
  - 500 fits with steps of half mass resolution
- No excess in data observed
  - Highest local significance $2.8\sigma$, observed at $m_a = 0.477 \text{ GeV/c}^2$

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Exclusion on $g_{\alpha\gamma\gamma}$

- 95% CL upper limits on the coupling constant $g_{\alpha\gamma\gamma}$
  - $g_{\alpha\gamma\gamma}$ below $10^{-3}$

- Limits improve over recast from $e^+e^- \rightarrow \gamma\gamma$ analysis by LEP-II

- First result for ALP at B-factories and second physics publication of Belle II
Search for a dark photon $A'$

- New massive vector gauge boson, $A'$, with a coupling to the Standard Model photon through the kinetic mixing mechanism, with strength $\epsilon$ [1,2]

$$\mathcal{L}_{int} = e \epsilon A'_\mu J_{em}^\mu$$

- This gauge boson can be produced at $e^+e^-$ colliders through different processes:
  - direct production: $e^+e^- \rightarrow \gamma_{ISR} A'$
  - meson decays: $\pi^0 \rightarrow A'\gamma$
  - dark higgsstrahlung: $e^+e^- \rightarrow A'^* A'^h$

- **Direct production with ISR particularly interesting:** $e^+e^- \rightarrow \gamma_{ISR} A'$

- Two basic scenarios depending on dark photon mass:
  - $M_{A'} > 2m_\chi$: invisible decay $A' \rightarrow \chi\bar{\chi}$
  - $M_{A'} < 2m_\chi$: visible decay in Standard Model particles

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A' → invisible

- Single photon in the final state needs a single photon trigger, present in the full Belle II dataset

- For signal events: peak in the energy of the photon depending on the $M_{A'}$

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

- Main background components:
  - $e^+e^- \rightarrow e^+e^- (\gamma)$: electrons out of acceptance
  - $e^+e^- \rightarrow \gamma\gamma (\gamma)$: photons lost in e.m. calorimeter (ECL) inefficient regions (gaps)
  - cosmic rays

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A’ → invisible, background

- Event selection criteria based on $E_γ$ vs $θ_γ$ distribution

\[ γγγ, \text{ with two undetected photons} \]

\[ e^+e^-γ, \text{ with both } e^+e^- \text{ out of detector acceptance} \]

Background simulation, assuming 20/fb

$γγ$, with an undetected photon

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90% CL Exclusion on $\varepsilon$

- $\mathrm{e}^+\mathrm{e}^- \to \gamma_{\mathrm{ISR}} \bar{A}' (A' \to \text{inv.})$: very promising @ Belle II, even with low statistics [1]

- Expected to perform better than BaBar [2]:
  - smaller boost and bigger calorimeter: larger acceptance
  - KLM veto: reject events with a photon undetected in the calorimeter
  - no ECL cracks in pointing to the interaction region: better calorimeter hermeticity

- Analysis timescale ~ end of 2022

Search for a dark Higgs

- Dark photon mass produced by the Higgs mechanism involving a dark Higgs boson [1]

- Both $A'$ and $h'$ can be produced at $e^+e^-$ colliders through the dark higgsstrahlung process

- Different signatures depending on $h'$ mass

  - $M_{h'} > M_{A'}$: prompt decay $h' \rightarrow A'A'$, up to 6 tracks in the final state. Investigated by BaBar(2012) and Belle(2015)

  - $M_{h'} < M_{A'}$: $h'$ is long-lived, thus invisible. Investigated by KLOE(2015)

- **Belle II focuses on the invisible $h'$**

Dark higgstrahlung @ Belle II

- $e^+e^- \rightarrow A'h', A' \rightarrow \mu\mu, h' \rightarrow \text{invisible}$

  → Signature: 2D peak in recoil vs dimuon mass

- Analysis strategy:
  
  → scan+count in elliptical mass windows (9k overlapping ellipses)

- Background from QED:
  - $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$
  - $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$
  - $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$

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**Dark higgstrahlung @ Belle II**

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  - $e^+e^- \to \mu^+\mu^-(\gamma)$
  - $e^+e^- \to \tau^+\tau^-(\gamma)$
  - $e^+e^- \to e^+e^-\mu^+\mu^-$
- Background suppression based on helicity angle
  (muon energy asymmetry)

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Very promising expectations even with the 2019-only dataset (less than 9/fb)

- Complementary to BaBar and Belle
- Probing the region left unexplored by KLOE
- Probing non-trivial $\varepsilon^2\alpha_D$ couplings (below $5 \cdot 10^{-7}$)

- Analysis is going to be published soon!
Highlights on $B \rightarrow Kh'$

- Long-lived $h'$ produced in $b \rightarrow s$ transition
- $h'$ mixes with the Standard Model Higgs boson with angle $\theta$
- Search for a bump in the invariant mass of tracks coming from a displaced vertex
- LHCb and Belle II complementary

- Exclusion regions expected with 50/ab at Belle II in green
- Analysis timescale ~ end of 2022
Inelastic Dark Matter (iDM) @ Belle II

- Expanded dark sector with two dark matter states with a small mass splitting and a dark photon
  - $\chi_1$ is stable (relic candidate)
  - $\chi_2$ is long-lived
- Focus on $M_{A'} > m_{\chi_1} + m_{\chi_2}$: the decay $A' \rightarrow \chi_1\chi_2$ is favored

[1] Duerr et al., JHEP04 (2021) 39
[2] Duerr et al., JHEP04 (2021) 146
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Search for iDM

- Search for a peak in the center-of-mass frame energy of the ISR photon plus a displaced vertex $V^0$
- Background:
  - photon conversion, $e^+e^- \rightarrow \gamma\gamma(y), \gamma \rightarrow e^+e^-$
  - meson decays, $e^+e^- \rightarrow K_S^0K_L^0(y), K_S^0$ decays
- Background suppression:
  - $V^0$ momentum
  - Pointing angle $\alpha_{PA}$

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iDM prospects

- Estimate signal yield by counting events in ISR photon energy window (final analysis will use a template fit)
- With early Belle II dataset expect to probe dark sector-Standard Model couplings down to $10^{-3} - 10^{-4}$
- New displaced vertex trigger under consideration
- Analysis timescale ~ end of 2022

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Conclusions

- The Belle II experiment is exploring Dark Sectors at the luminosity frontier
  - Will lead in the MeV-GeV mass range in the coming years
- > 240/fb collected up to now
- World-leading results with early data:
  - $Z' \rightarrow$ invisible: *Phys. Rev. Lett.* **124** (2020) 141801
  - $a \rightarrow \gamma \gamma$: *Phys. Rev. Lett.* **125**, 161806 (2020)
- Many new searches ongoing: dark Higgs, dark photon, visible $Z'$, Long-lived dark particles ...
Thank you for the attention!

Luigi Corona - INFN and University of Pisa
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on behalf of the Belle II collaboration
Backup Slides
Taking data during the pandemic

- Non-stop operations with COVID-19 pandemic
  - Social distancing requirements
  - Strong developments for close to or fully remote sub-system operations
  - Huge commitments from Japanese colleagues and residents in Japan

Data-taking efficiency: 89.5%
Luminosity

\[ L = \frac{\gamma^\pm}{2e r_e} \left( 1 + \frac{\sigma^*_y}{\sigma^*_x} \right) \frac{I_\pm \xi_y^\pm}{\beta^*_y} \frac{R_L}{R_{\xi_y}} \]

**Beam currents**

**Beam-beam parameter**

**Geometrical reduction parameter** (~0.8 – 1)

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

Vertical beta function at IP
UL on visible $A'$ searches

BaBar limit on $\epsilon \sim 7 \cdot 10^{-4}$
Weak direct detection bounds

- Large detectors search for DM scattering against nuclei/electrons

Access to mass below few GeV

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