Probing dark sectors with long-lived particles at Belle II

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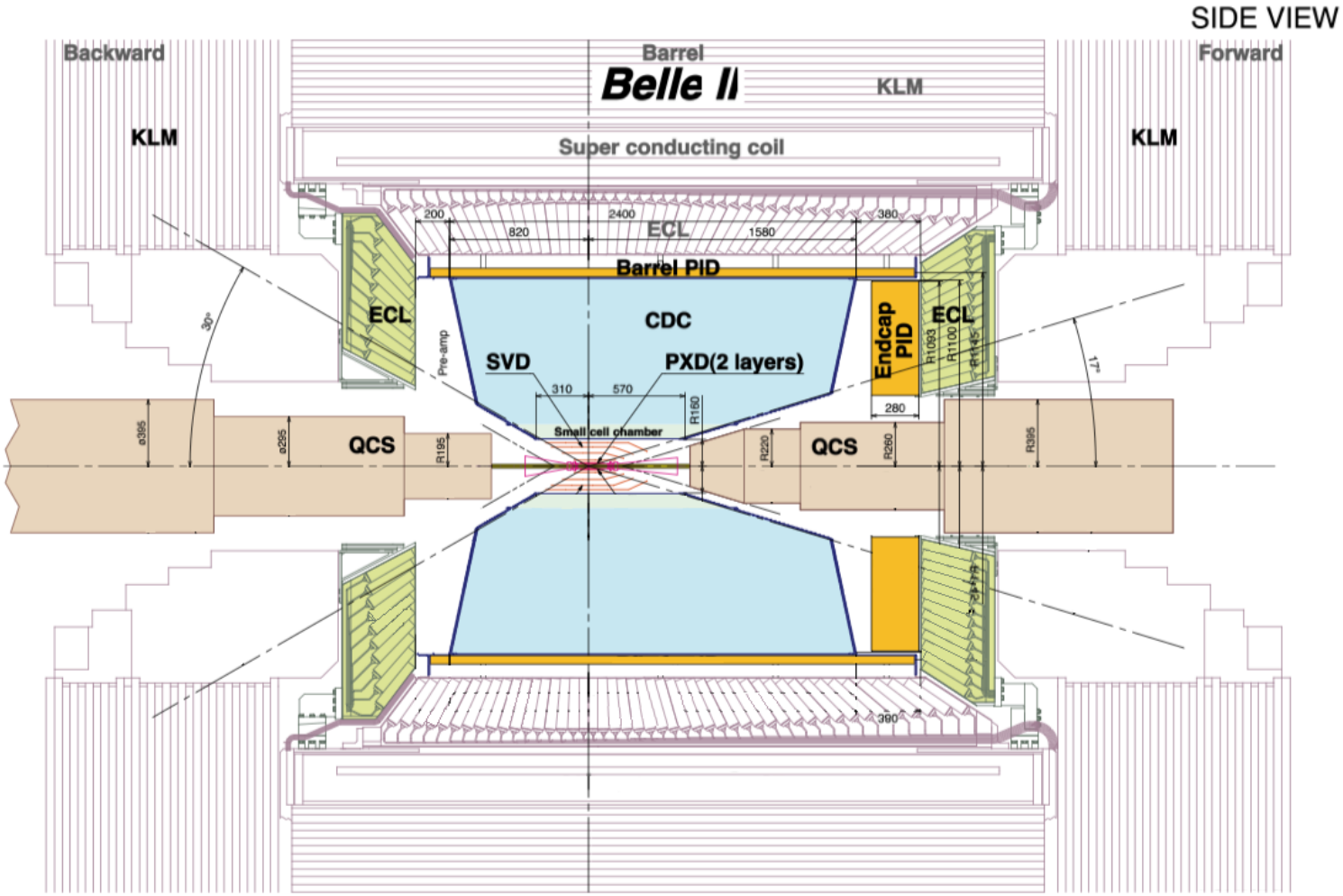
STEALTH at LHCb
Santiago de Compostela

Based on [1911.03490] with Susanne Westhoff and Anastasiia Filimonova

Belle II detector



Belle II: [1011.0352]

Belle II and LHCb

	Belle II	LHCb
detector	e^+e^- at $\Upsilon(4S)$	pp
detector direction	transverse	forward
boost $\langle\gamma_B\rangle$	1.03	15.2
detector length [cm]	160	60

Belle II: [1808.10567], LHCb: [1612.07818]

Overview

- Higgs Portal
  - Simple renormalisable extension
  - Preserves Flavour Hierarchy
- Light Scalar
  - Thermal dark matter candidates
  - Mediator of dark force

Higgs Portal to Dark Sector

- SM singlet scalar ϕ, dark fermion χ
- $\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{m_\phi^2}{2}\phi^2 - \mu|H|^2\phi - y_\chi \overline{\chi}\chi\phi - \frac{m_\chi}{2}\overline{\chi}\chi$

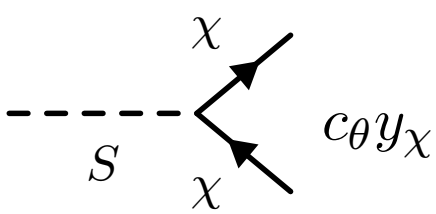
BC4 of [1901.09966] (Beacham, et al.)

Scalar mixing

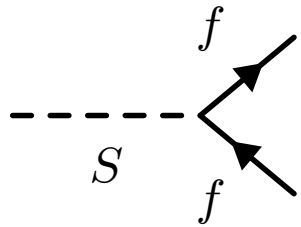
- $\mathcal{L}_{\text{mass}} = -\frac{m_\phi^2}{2}\phi^2 - \frac{m_{H_{\text{SM}}}^2}{2}H_{\text{SM}}^2 - \mu v H_{\text{SM}}\phi$
  $= -\frac{m_h^2}{2}h^2 - \frac{m_S^2}{2}S^2$
- Mass eigenstates h, S
- $S = c_\theta \phi + s_\theta H_{\text{SM}}$
- Mixing angle $s_\theta^2 = \frac{1}{2}\left(1 + \frac{m_\phi^2 - m_{H_{\text{SM}}}^2}{\Delta m^2}\right)$

Decays of the scalar S

- $\Gamma_S = c_\theta^2 \Gamma^\phi_{\chi\bar{\chi}} + s_\theta^2 \Gamma^h_{\mathrm{SM}}$



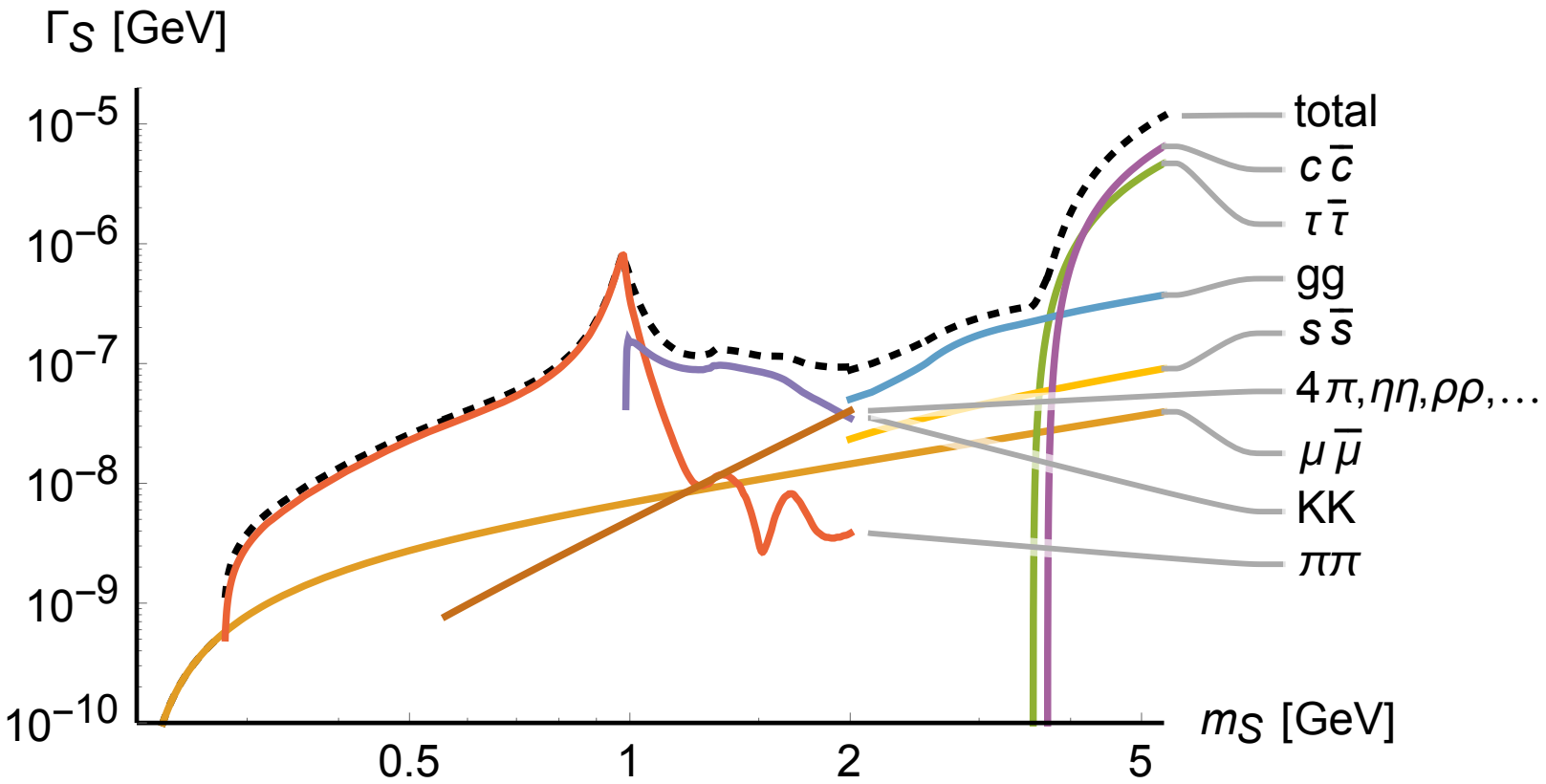
$c_\theta y_\chi$



$s_\theta \frac{m_f}{v}$

$$\Gamma^S_{\chi\bar{\chi}} = c_\theta^2 y_\chi^2 \frac{m_S}{8\pi} \left(1 - 4\frac{m_\chi^2}{m_S^2}\right)^{3/2} \qquad \Gamma^S_{f\bar{f}} = s_\theta^2 \frac{m_f^2}{v^2} \frac{m_S}{8\pi} \left(1 - 4\frac{m_f^2}{m_S^2}\right)^{3/2}$$

Decays of the scalar S



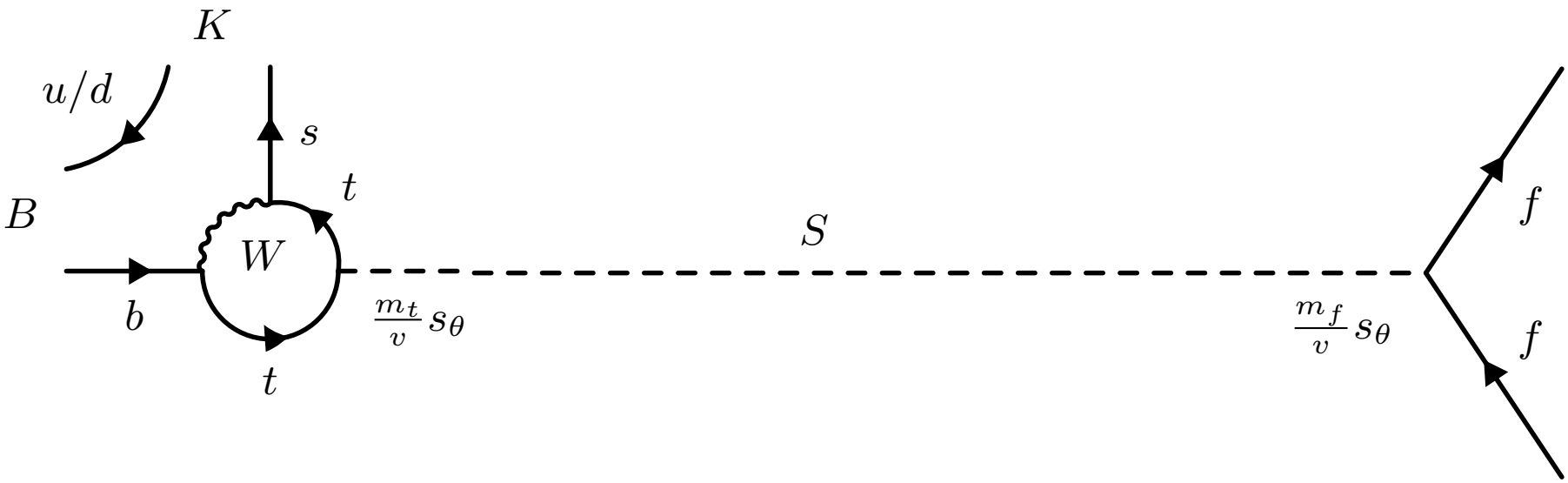
Winkler: [1809.01876], for maximal mixing $\theta = \frac{\pi}{2}$

Search regions

- $2m_\chi > m_S$
- No dark decay
- Displaced searches

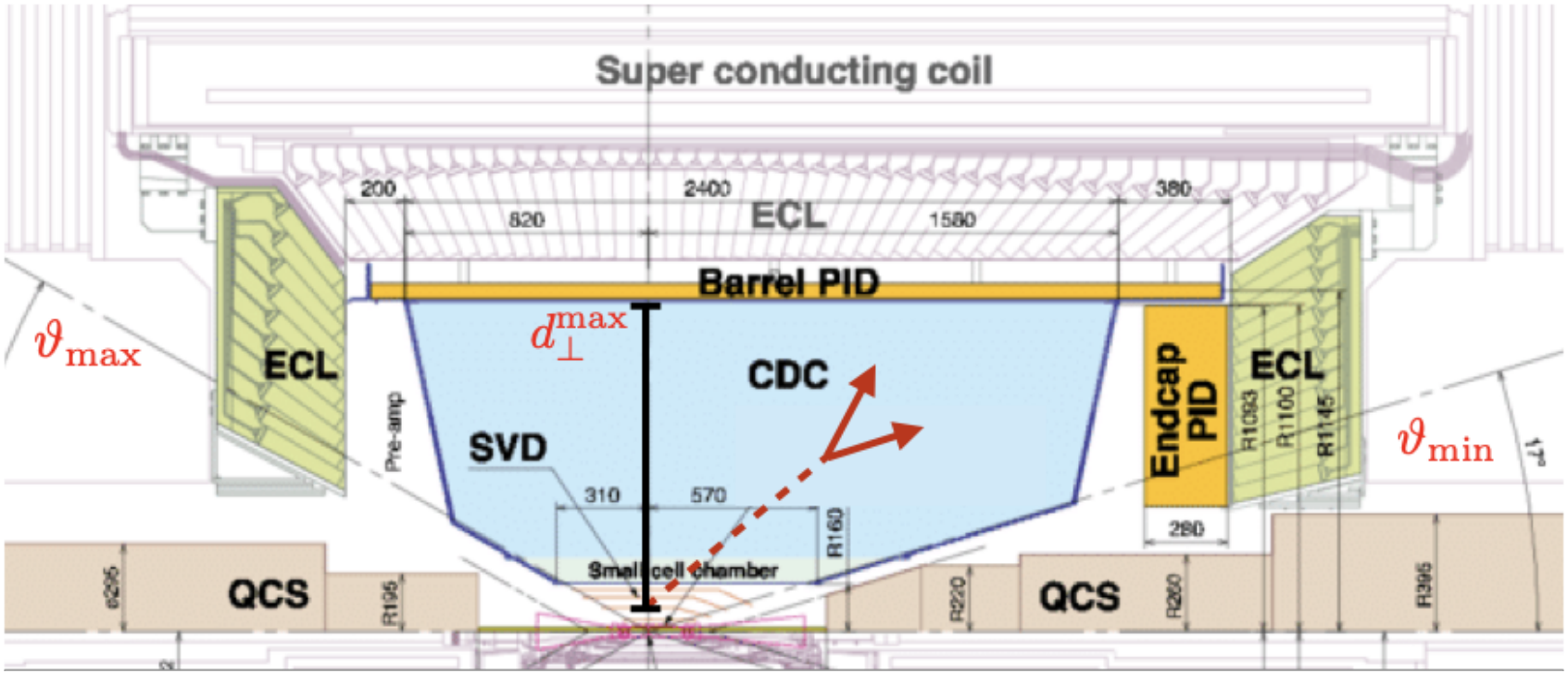
- $2m_\chi < m_S$
- Dark decay dominant
- Search for missing energy

Displaced Signatures

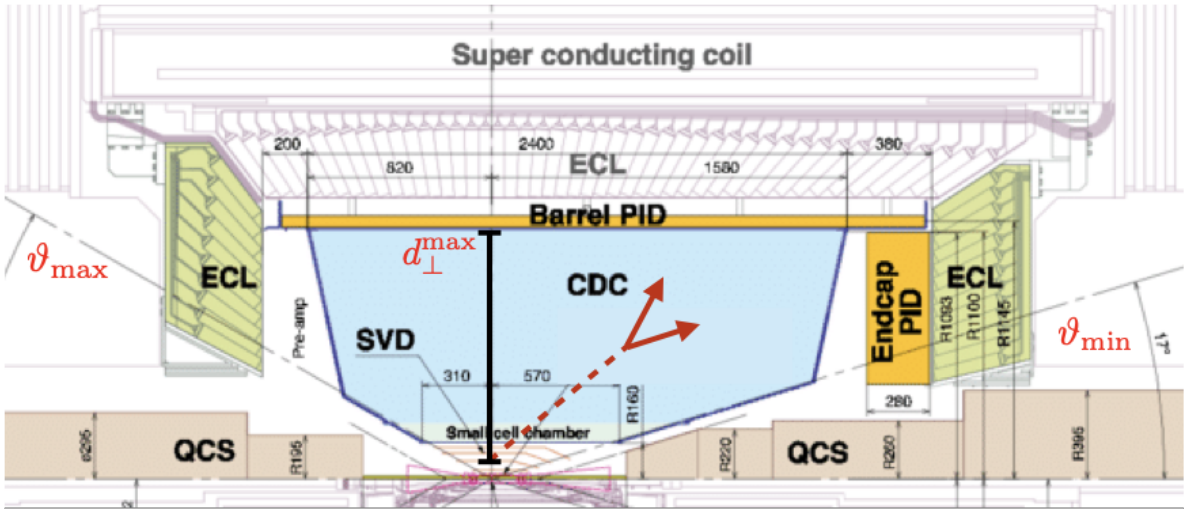


- For $m_S = m_K$, $\tau_S = \tau_{K_S}$ at a mixing angle of $\theta \approx 5 \cdot 10^{-4}$

Displaced Signatures at Belle II



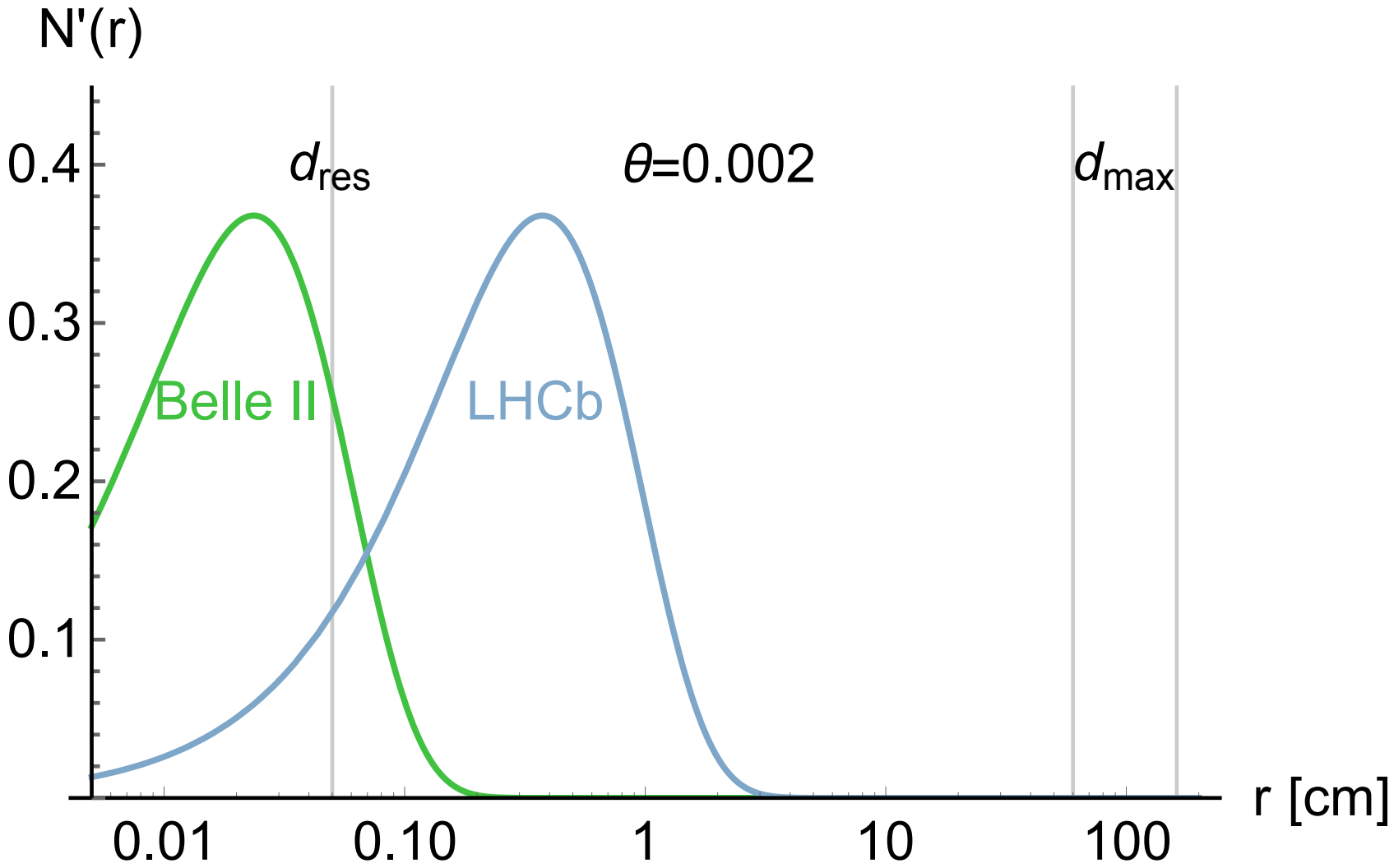
Displaced Signatures at Belle II



- Number of displaced $\mu\bar{\mu}$ pairs produced

$$N_{\mu\bar{\mu}} = N_{B\bar{B}} \times 1.93 \times Br(B^+ \to K^{+(*)} S) \times Br(S \to \mu\bar{\mu})$$
$$\times \frac{1}{4(\langle\beta\gamma_S\rangle c\tau_S)^3} \int_{d_{\text{res}}}^{d_\perp^{\max}} r^2 \mathrm{d}r \int_{\vartheta_{\min}}^{\vartheta_{\max}} \frac{\mathrm{d}\vartheta}{\sin^2\vartheta} e^{-\frac{r/\sin\vartheta}{\langle\beta\gamma_S\rangle c\tau_S}}$$

Where do the particles mostly decay?



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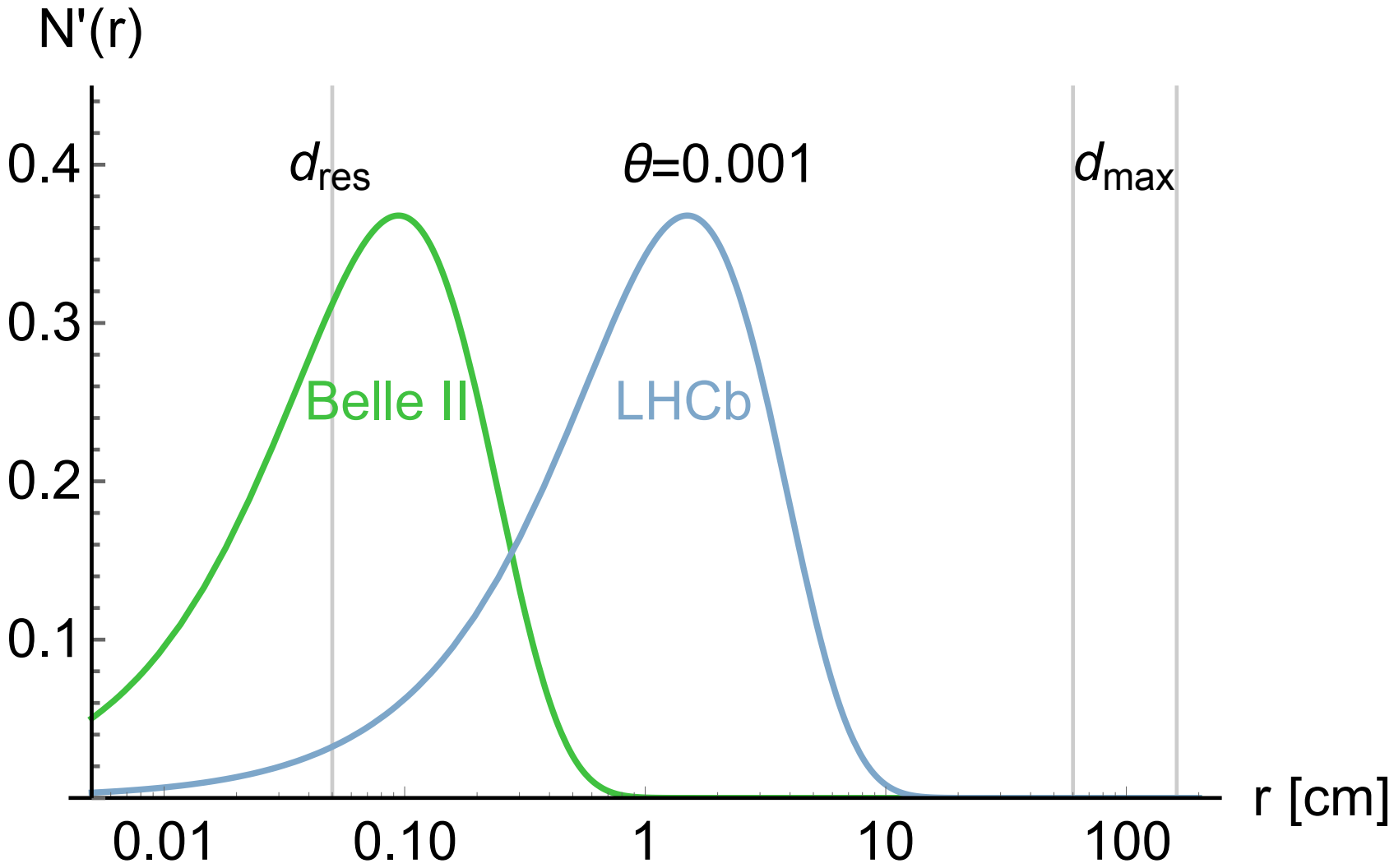

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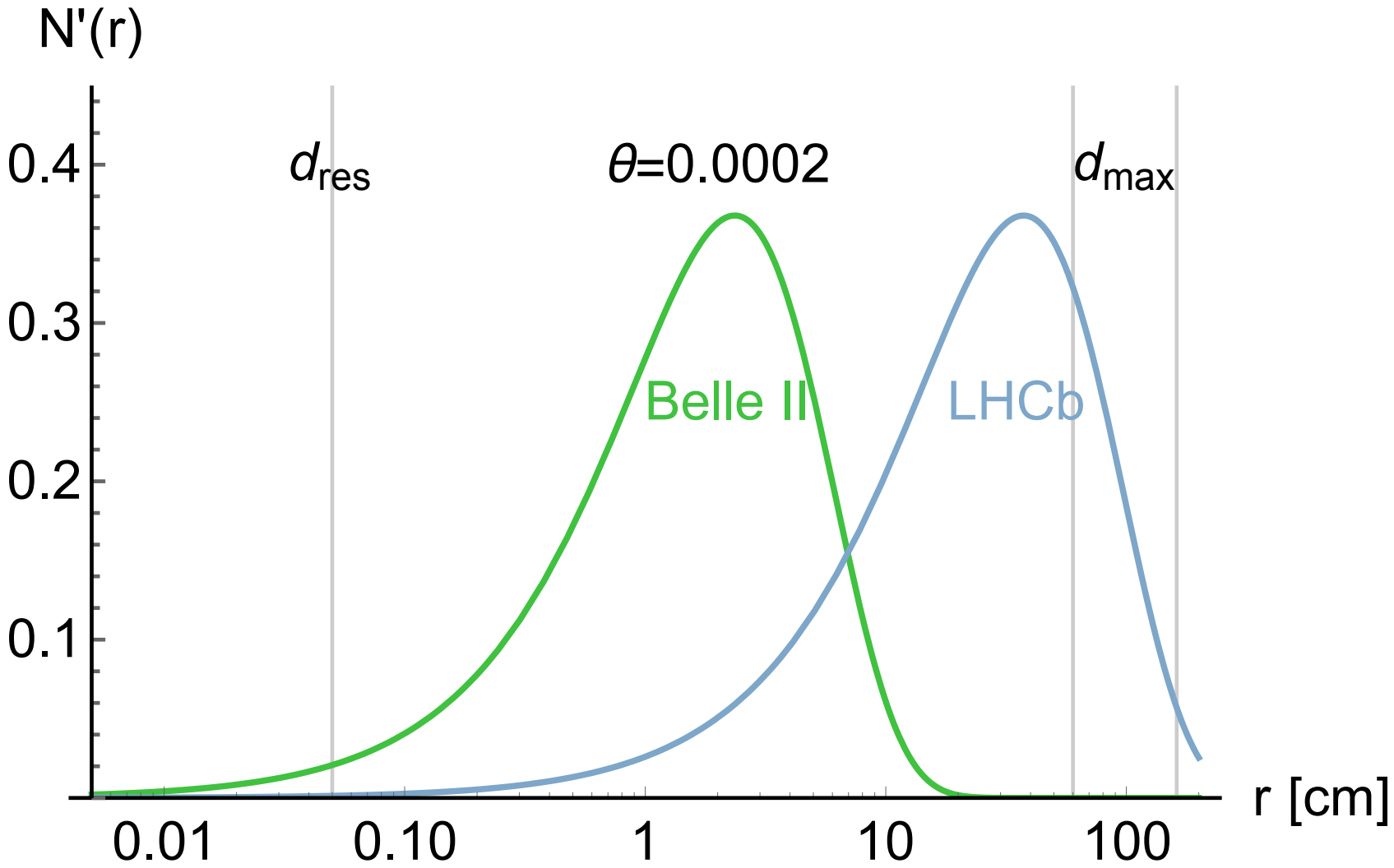

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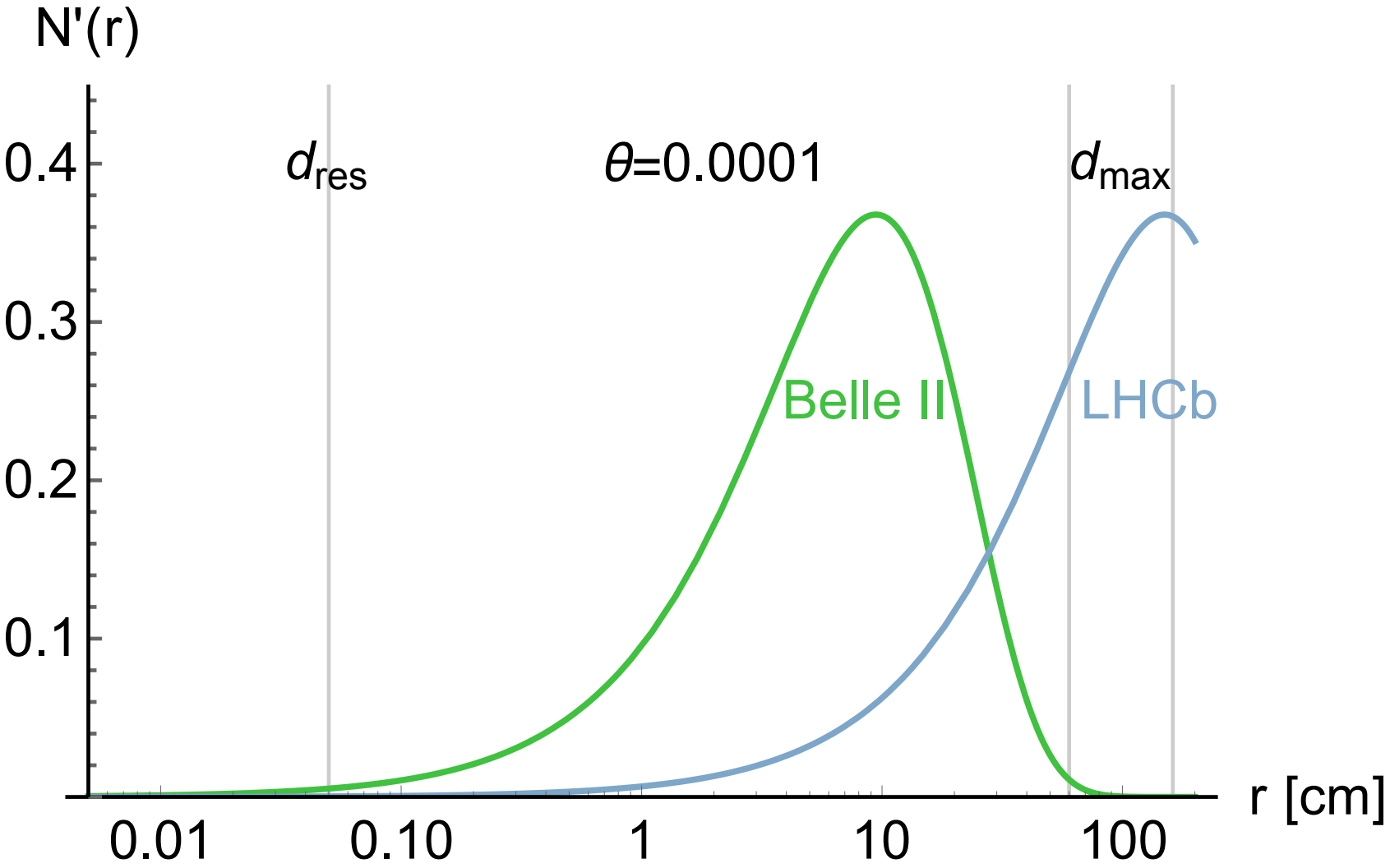
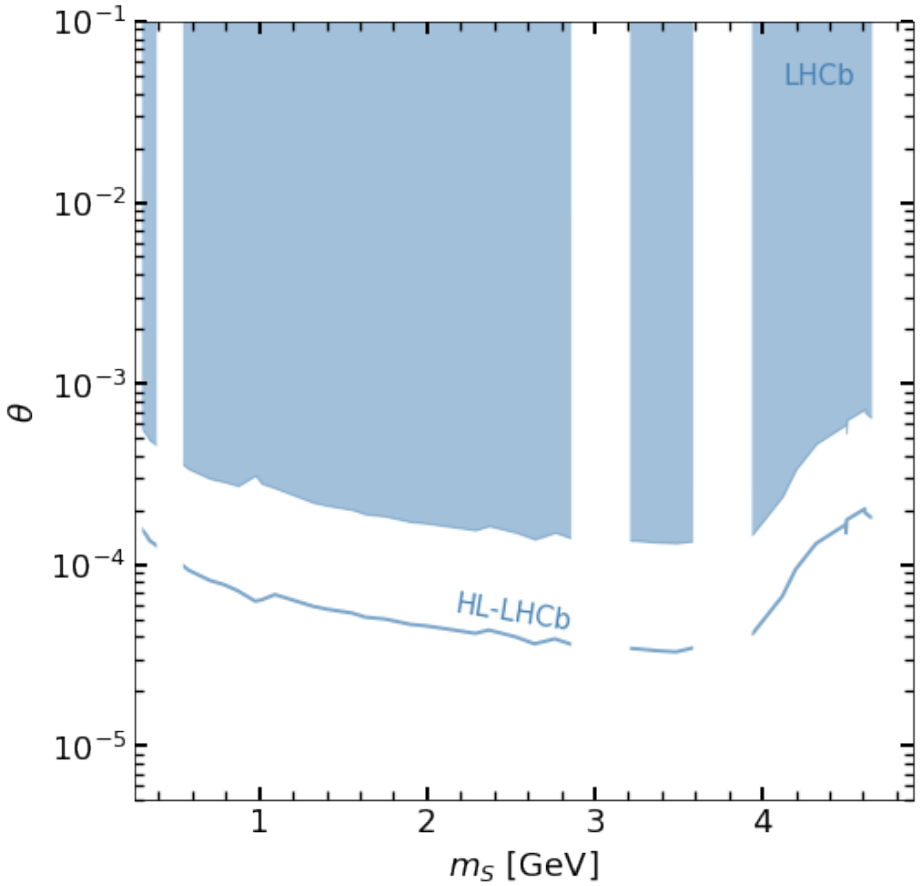


Searching for Displaced Signatures at Belle II



- LHCb muons

LHCb: [1612.07818], Bodarenko et al.: [1909.08632]

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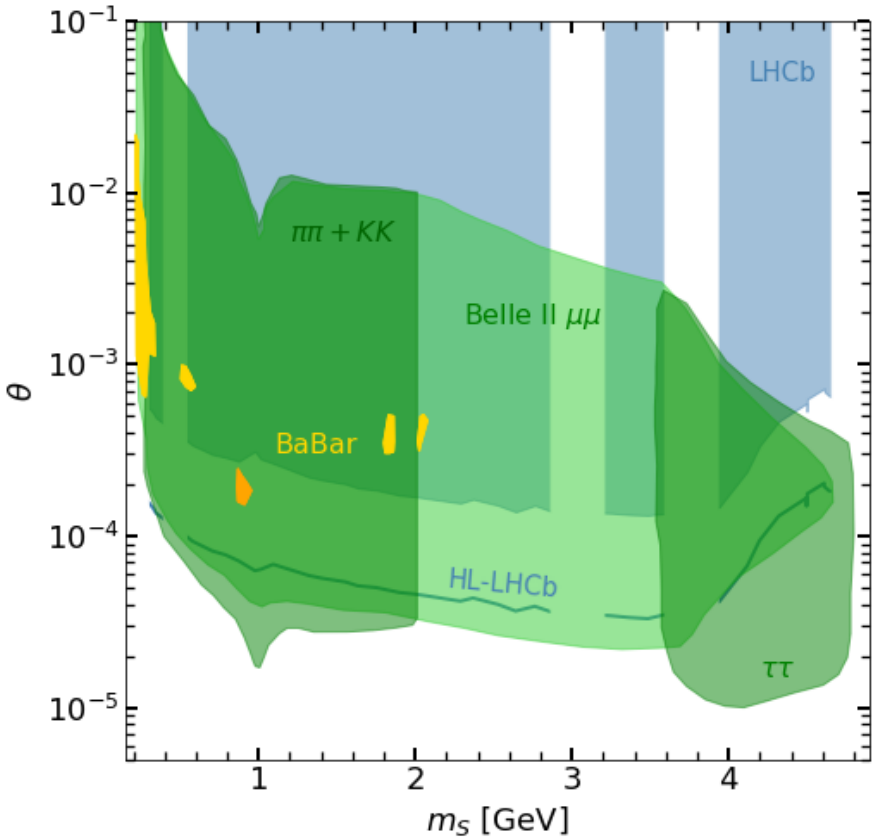
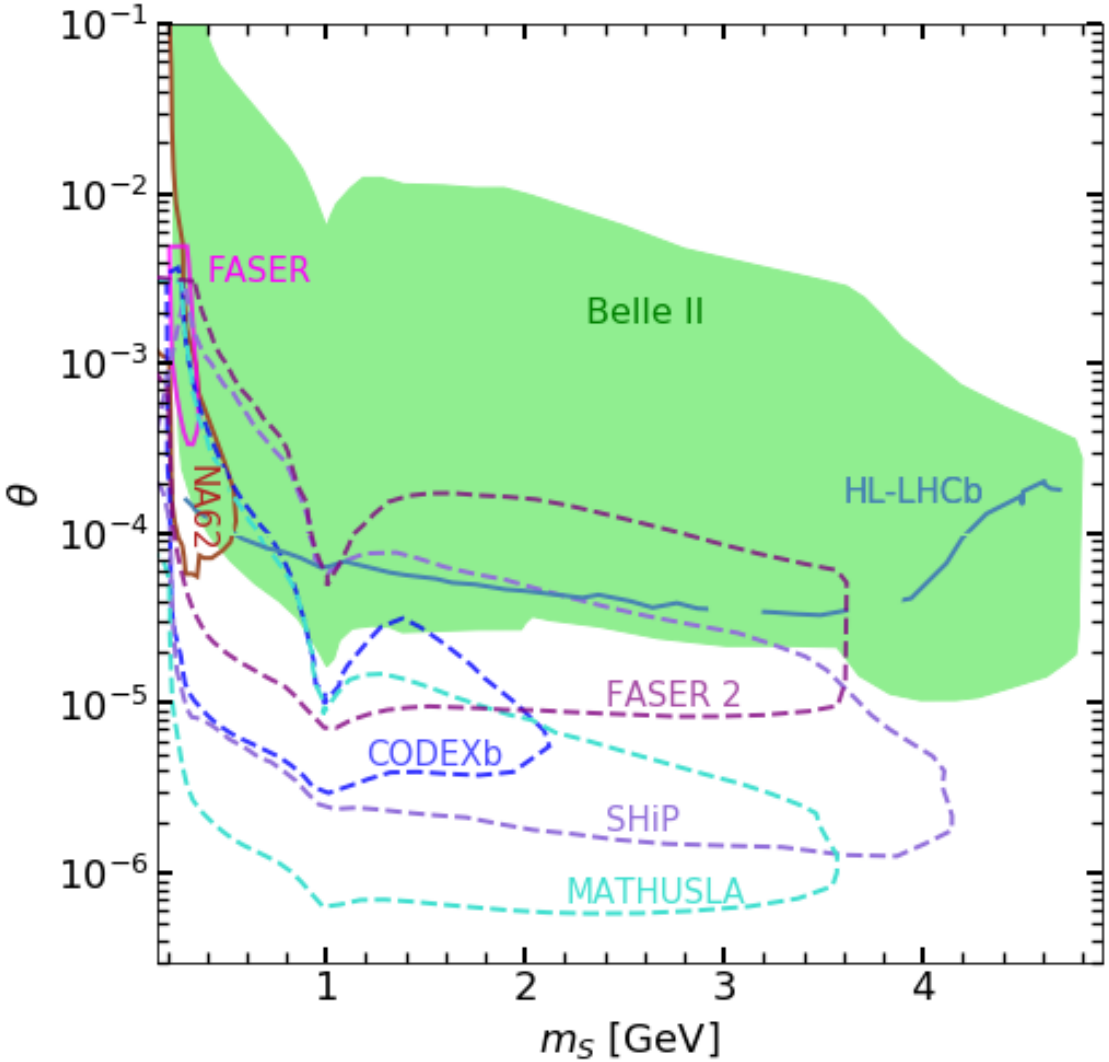


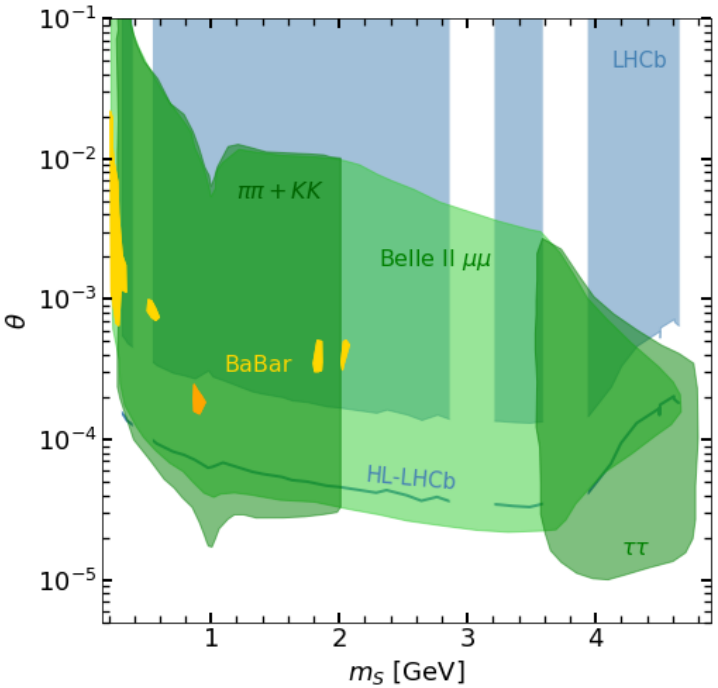
- LHCb muons
- BaBar muons
- BaBar pions
- Belle II muons
- Belle II pions + kaons, taus

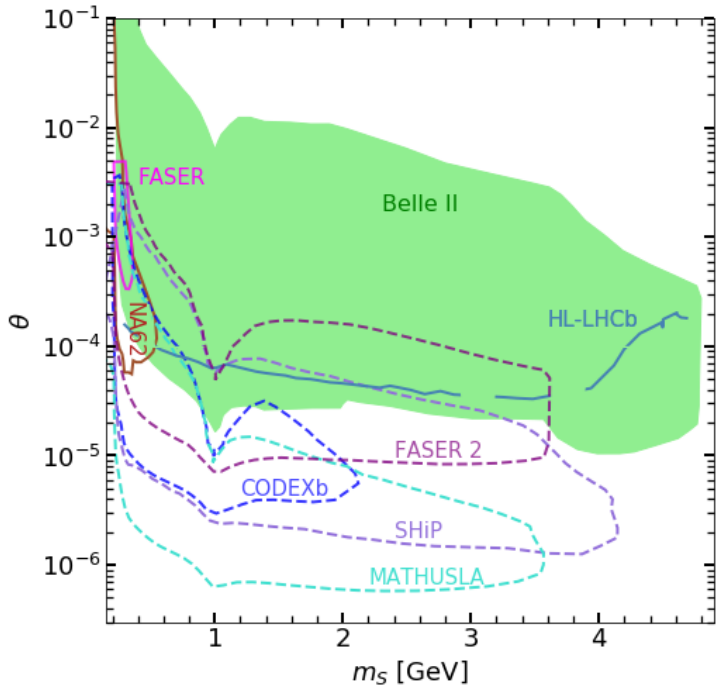
BaBar: [1502.02580], Filimonova, RS, Westhoff: [1911.03490]

Displaced Signatures at Belle II and future experiments



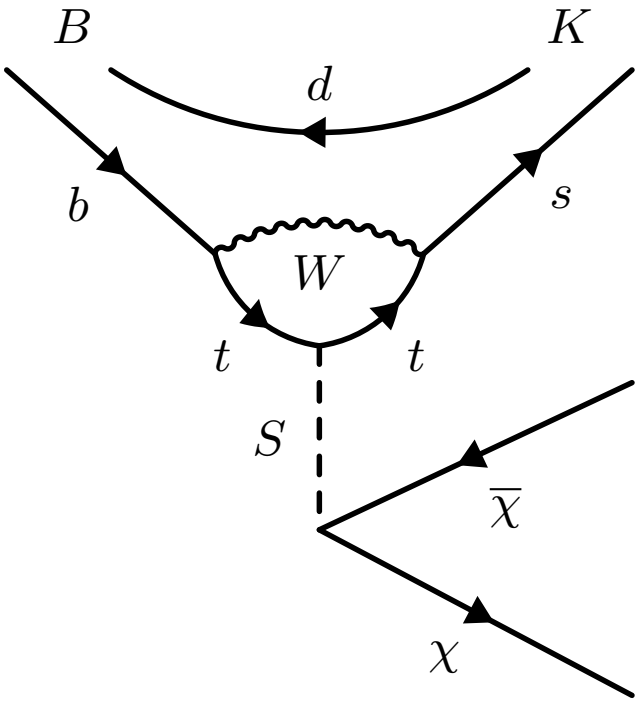
Summary

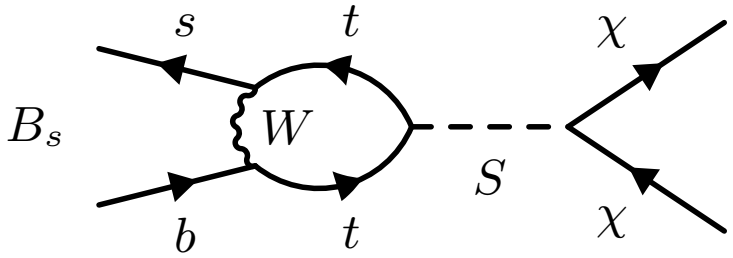




- New proposed Belle II search
- Complementary to colliders and dedicated experiments

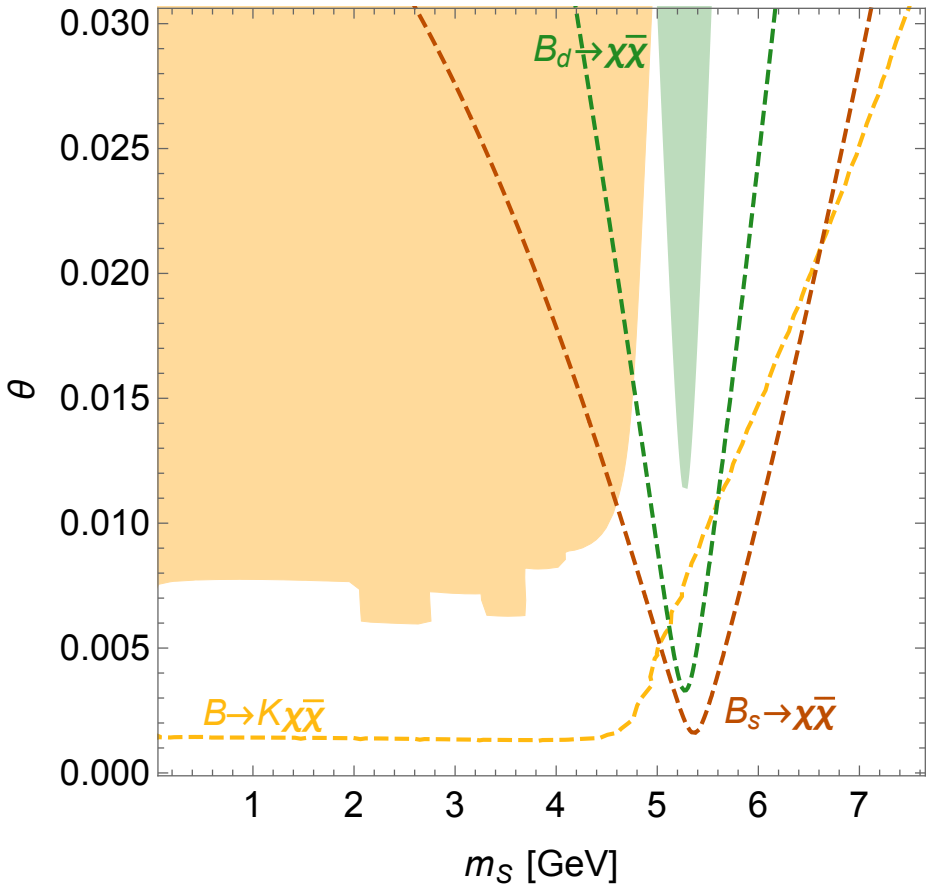
Missing Energy Signatures





- For dominant decay to invisible: $Br \propto s_\theta^2, \propto y_\chi$
- Missing energy final state, like neutrino searches $B \to K\nu\bar{\nu}$

Searching for Missing Energy Signatures at Belle II

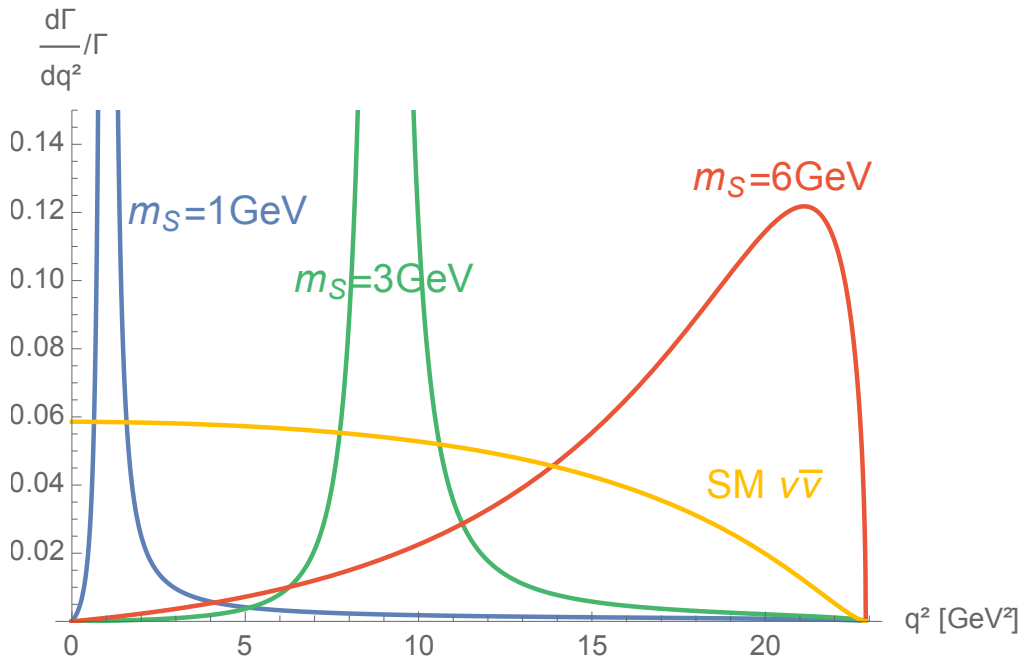


- $\frac{\mathrm{d}Br(B \to K + \text{inv.})}{\mathrm{d}q^2}$
- $Br(B \to K + \text{inv.})$
- $Br(B_d \to \text{inv.})$
- $Br(B_s \to \text{inv.})$

[1303.7465], [1206.5948], [1808.10567]

Differential Branching Ratio

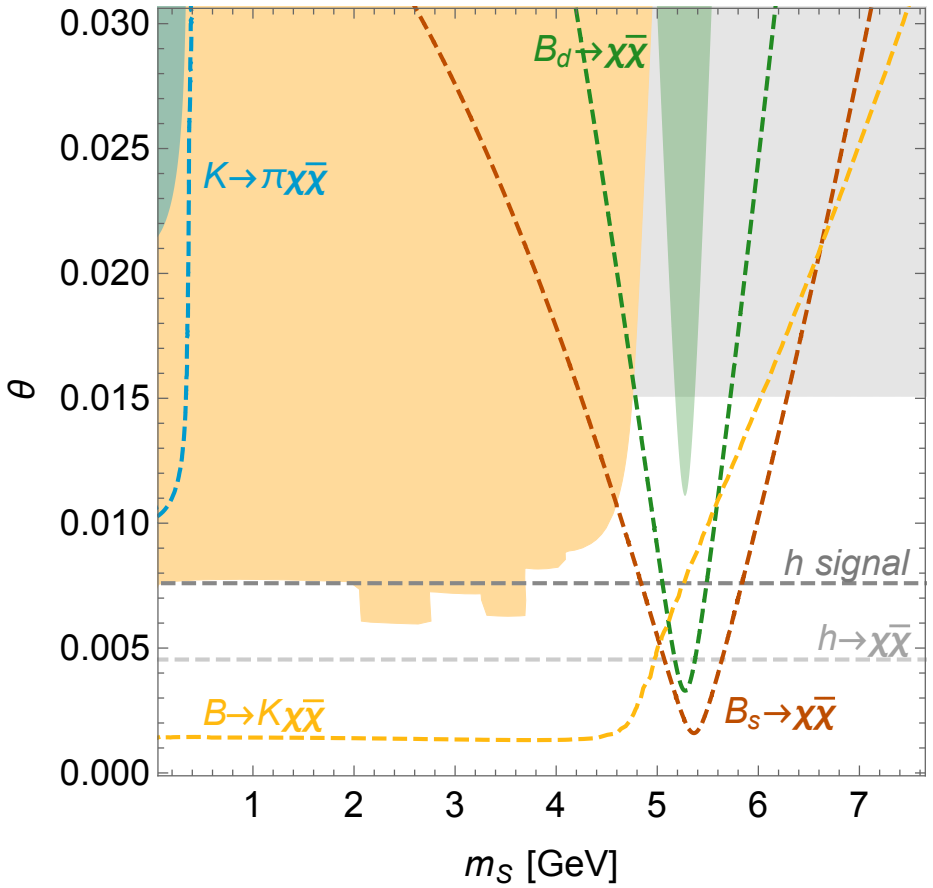
- $$\frac{\mathrm{d}Br(B\to K+\mathrm{inv.})}{\mathrm{d}q^2} = \frac{\mathrm{d}Br(B\to K\nu\bar{\nu})}{\mathrm{d}q^2} + \frac{\mathrm{d}Br(B\to K\chi\bar{\chi})}{\mathrm{d}q^2}$$



Constraints from Higgs measurements

- $Br(h \to \text{inv}) = \frac{\mathrm{s}_\theta^2 \Gamma^\phi_{\chi\bar{\chi}}}{\mathrm{c}_\theta^2 \Gamma^{\mathrm{h}}_{\mathrm{SM}} + \mathrm{s}_\theta^2 \Gamma^\phi_{\chi\bar{\chi}}}$
- Signal strength $\mu = \frac{\sigma^h}{\sigma^h_{\mathrm{SM}}} \times \frac{Br(h \to \mathrm{vis})}{Br(h \to \mathrm{vis})_{\mathrm{SM}}} = c_\theta^2 \frac{c_\theta^2 \Gamma^h_{\mathrm{SM}}}{c_\theta^2 \Gamma^h_{\mathrm{SM}} + s_\theta^2 \Gamma^\phi_{\chi\bar{\chi}}}$

Searching for Missing Energy Signatures at Belle II



- $\frac{\mathrm{d}Br(B \to K + \mathrm{inv.})}{\mathrm{d}q^2}$
- $Br(B \to K + \mathrm{inv.})$
- $Br(B_d \to \mathrm{inv.})$
- $Br(B_s \to \mathrm{inv.})$
- $K \to \pi + \mathrm{inv.}$
- $Br(h \to \mathrm{inv.})$
- Higgs signal strength μ

[1303.7465], [1206.5948], [1808.10567], [0808.2459], [1809.10733]