Heidelberg University

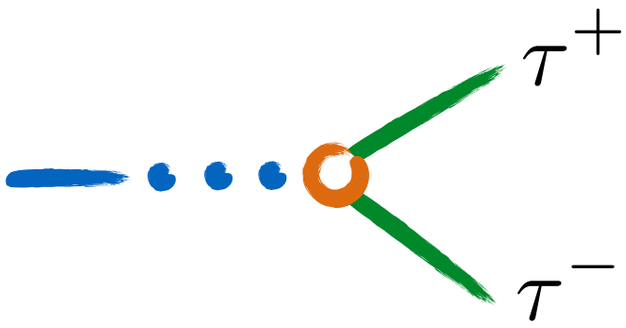
Carl Zeiss Foundation

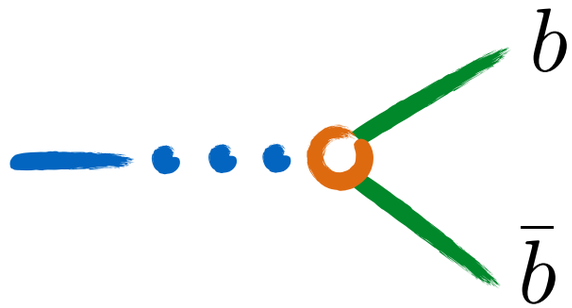
DISPLACED AND SOFT taus and bottoms

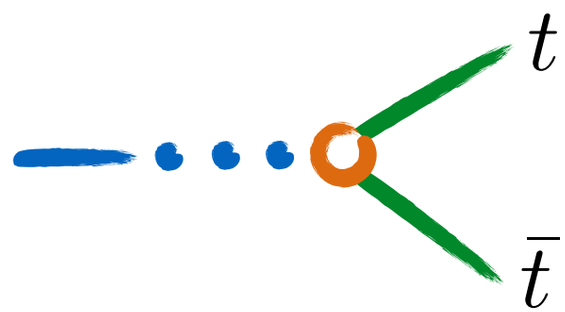
Susanne Westhoff
Heidelberg University

Workshop on *Long-lived particles and the third generation* | Nov 20-22, 2019 | Higgs Centre Edinburgh

Why the third generation?



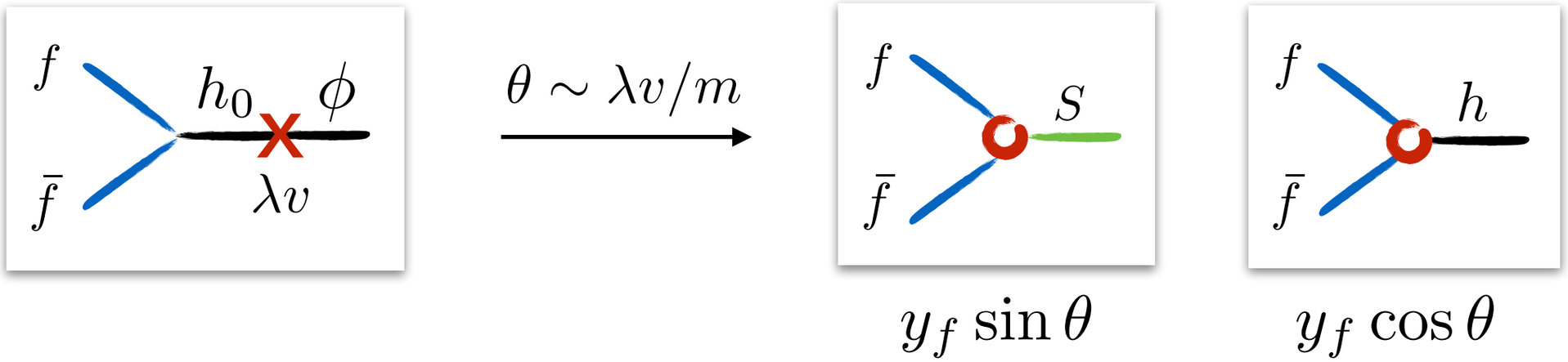




Dark scalars

$$\mathcal{L} \supset -\lambda |H|^2 \phi - y_\chi \bar{\chi} \chi \phi$$

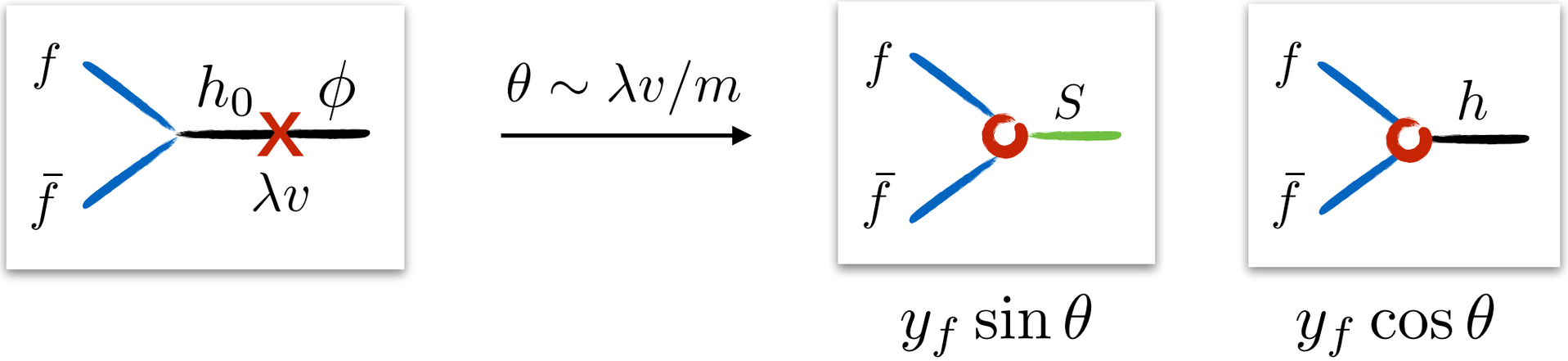
Scalar inherits Higgs couplings through mixing:



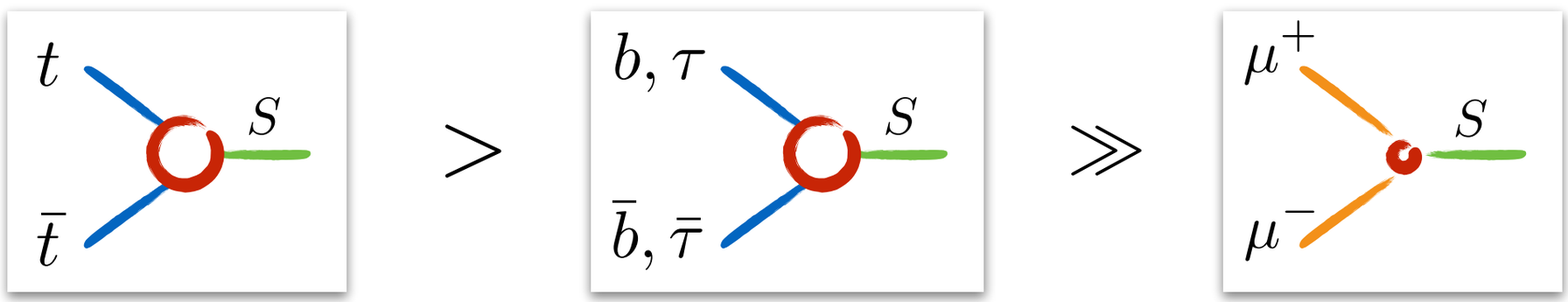
Dark scalars

$$\mathcal{L} \supset -\lambda |H|^2 \phi - y_\chi \bar{\chi} \chi \phi$$

Scalar inherits Higgs couplings through mixing:



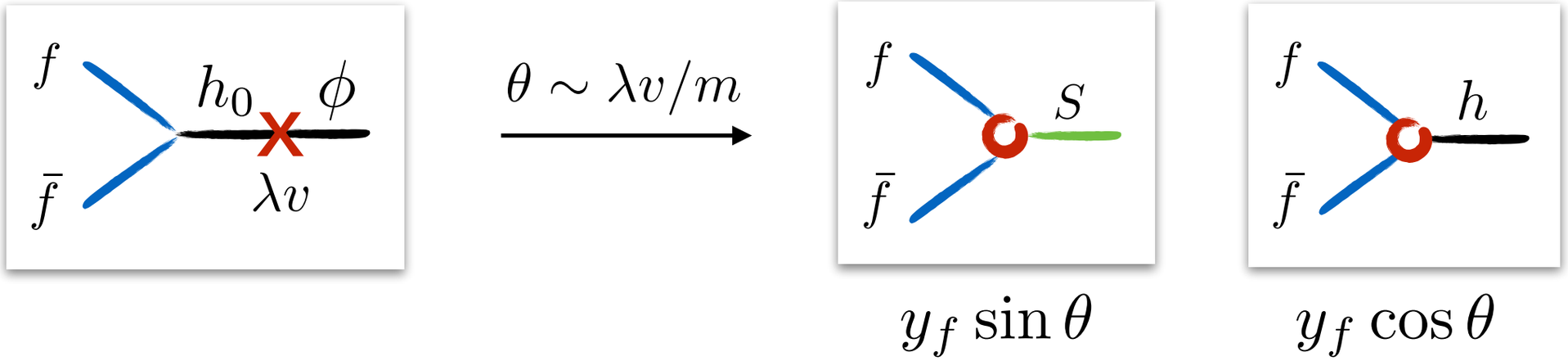
Fermion couplings are flavor-hierarchical:



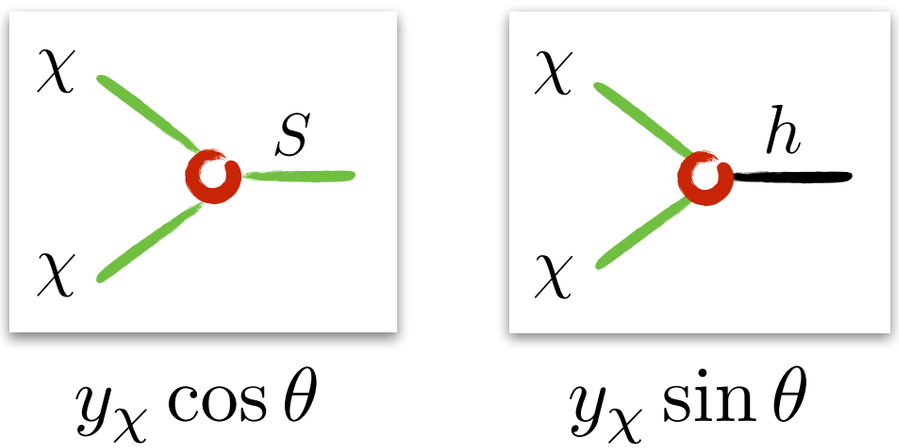
Dark scalars

$$\mathcal{L} \supset -\lambda |H|^2 \phi - y_\chi \bar{\chi} \chi \phi$$

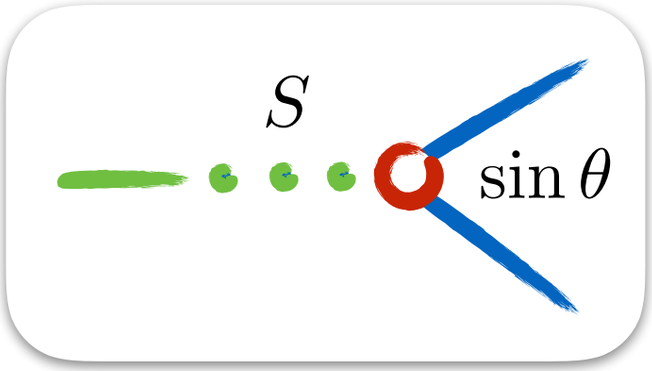
Scalar inherits Higgs couplings through mixing:



Higgs inherits dark couplings:



Why long-lived?

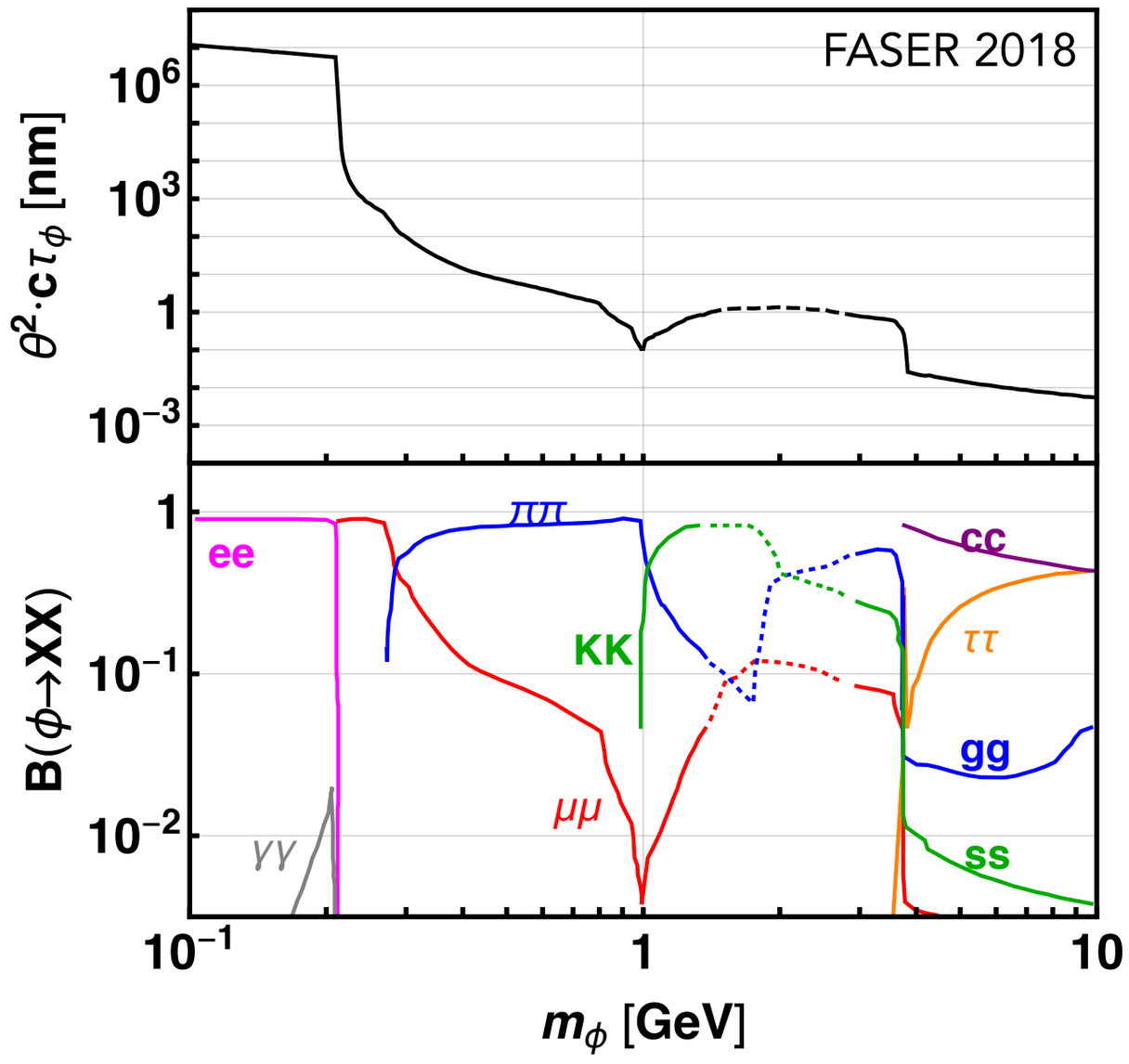


Scalar width $\Gamma_S = s_\theta^2\,\Gamma_{\rm SM} + c_\theta^2\,\Gamma_{\chi\bar{\chi}}$

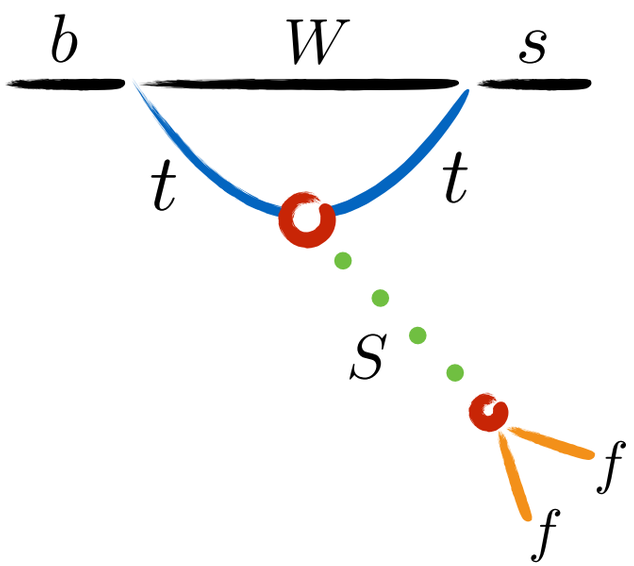
Nominal decay length $c\tau_S = \Gamma_S^{-1}$

Long scalar lifetime

- for small Higgs mixing
- suppr. invisible decay
- decay near threshold



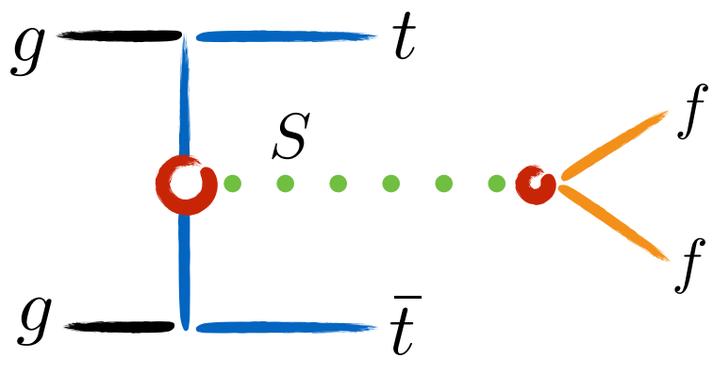
Signatures of long-lived dark scalars



Rare meson decays:

$$\mathcal{B}(B \to KS)\mathcal{B}(S \to ff) \propto s_\theta^2 \frac{s_\theta^2 \Gamma_{ff}}{\Gamma_S}$$

Sizeable rate for light resonant scalars.



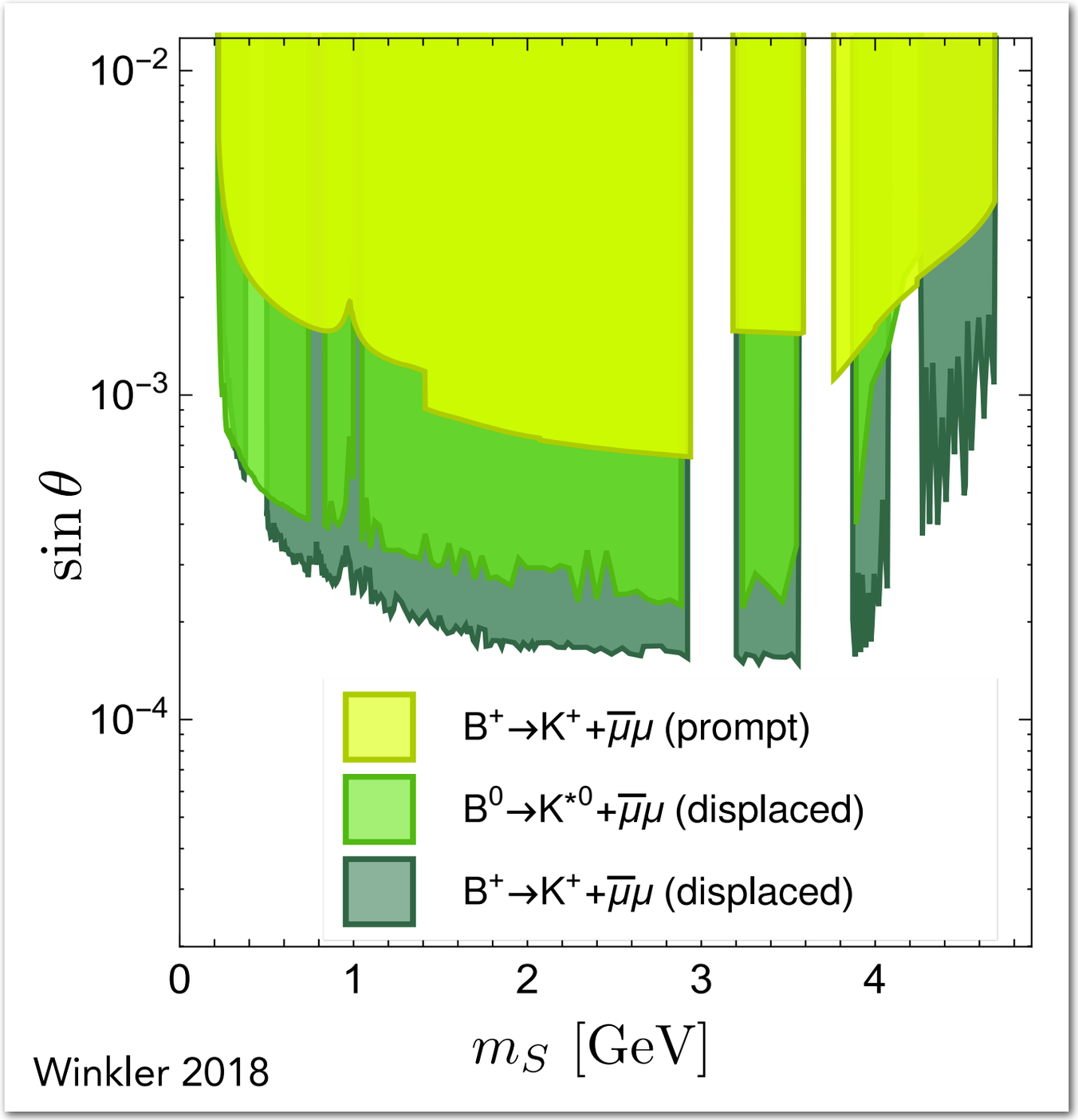
Tops and displaced particles?

Smaller rate for decay to heavy fermions.

Batell, Pospelov, Ritz 2010; Clarke et al. 2014

Evans et al. 2017; Winkler 2018; Boiarska et al. 2019; Filimonova, Schaefer, Westhoff 2019

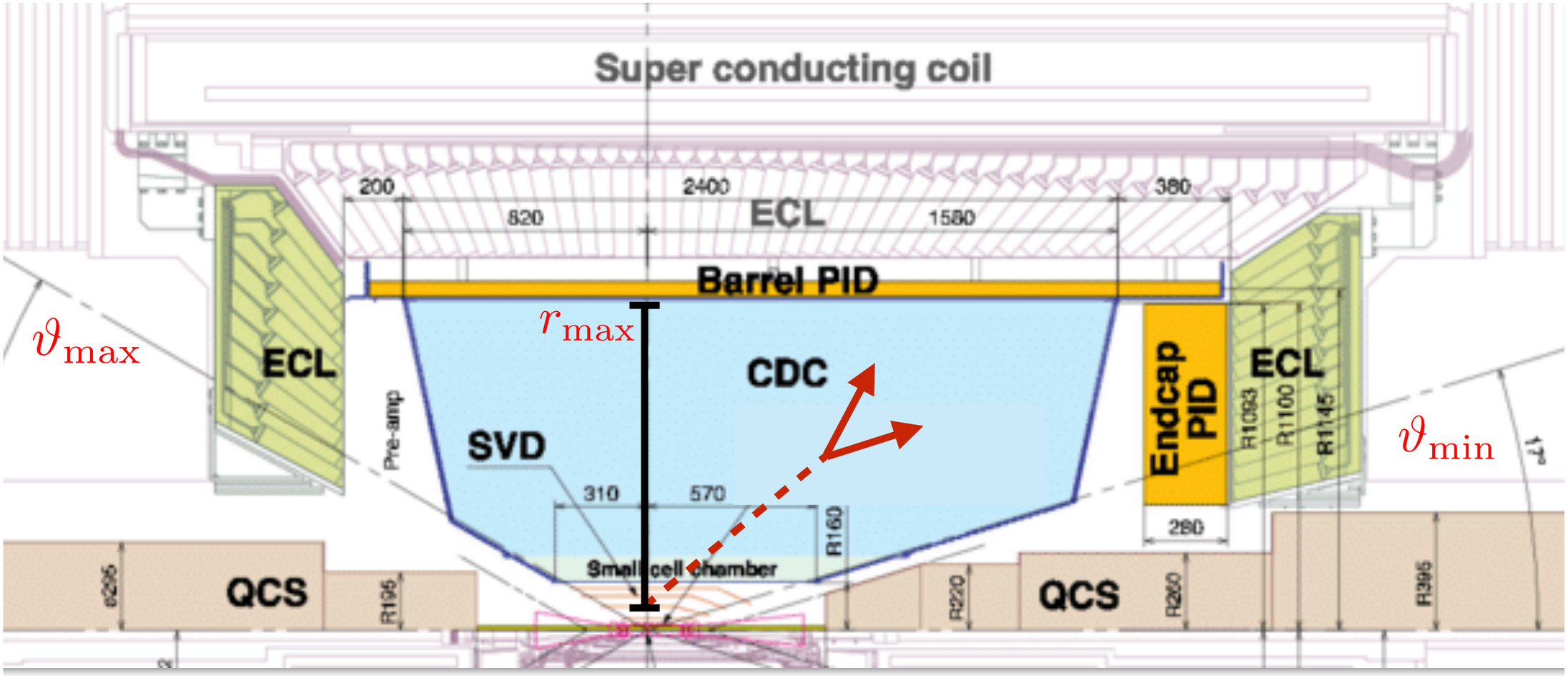
Displaced muon pairs at LHCb



Winkler 2018

based on
LHCb 2015 & 2016

Displaced muon pairs at Belle II

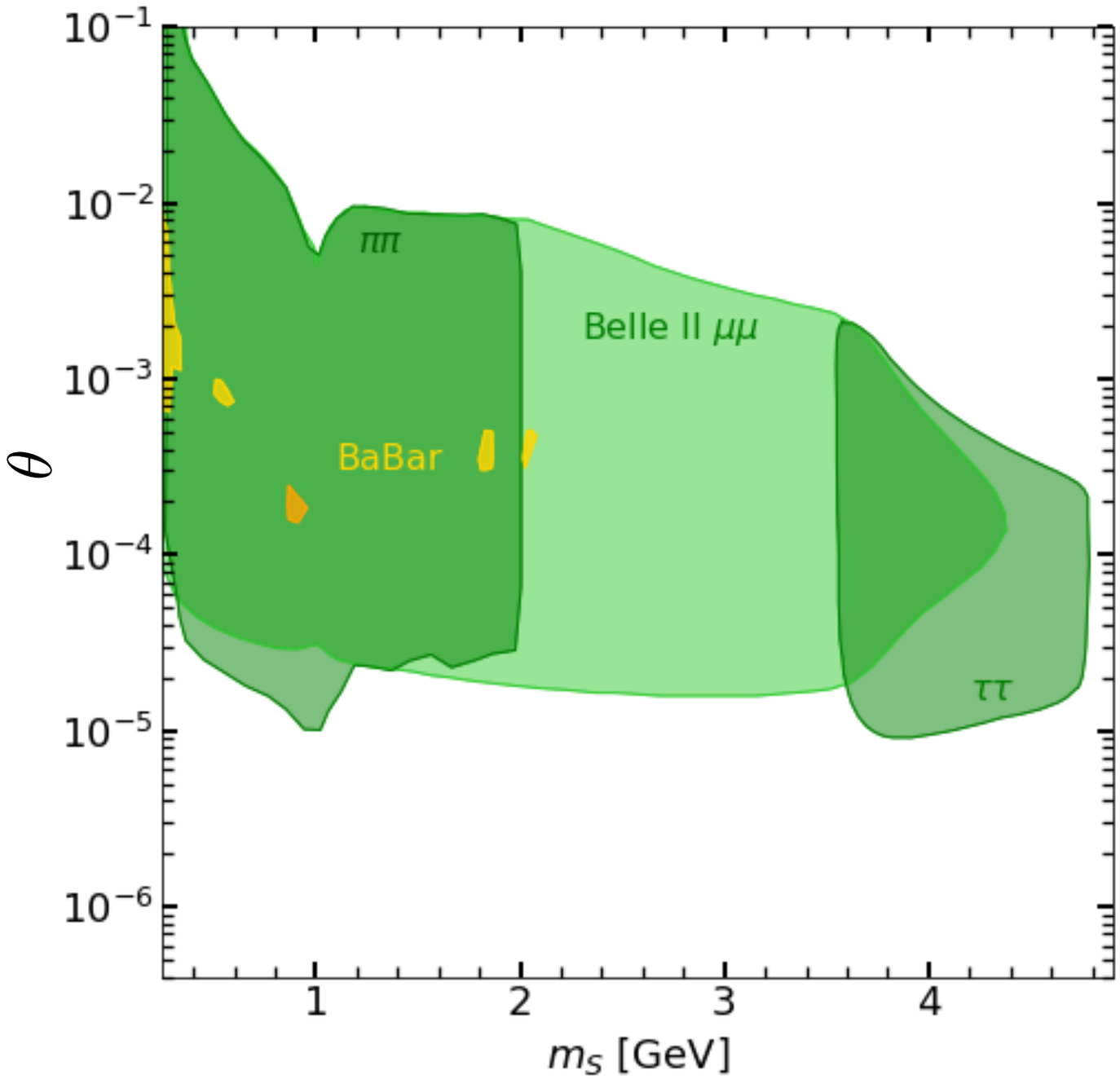


Number of muon pairs decaying inside drift chamber:

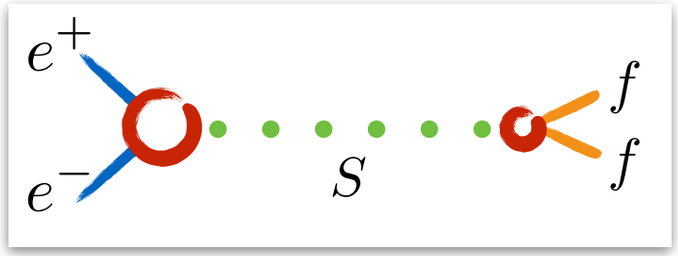
$$N_{\mu\bar{\mu}} = N_{B\bar{B}} \times 2\mathcal{B}(B \to KS)\mathcal{B}(S \to \mu\bar{\mu})$$

$$\times \int_{\vartheta_{\min}}^{\vartheta_{\max}} d\vartheta \, \frac{\sin\vartheta}{2} \left[e^{-\frac{r_{\min}/\sin\vartheta}{\langle\beta\gamma_S\rangle c\tau_S}} - e^{-\frac{r_{\max}/\sin\vartheta}{\langle\beta\gamma_S\rangle c\tau_S}} \right]$$

Displaced vertices at Belle II and BaBar

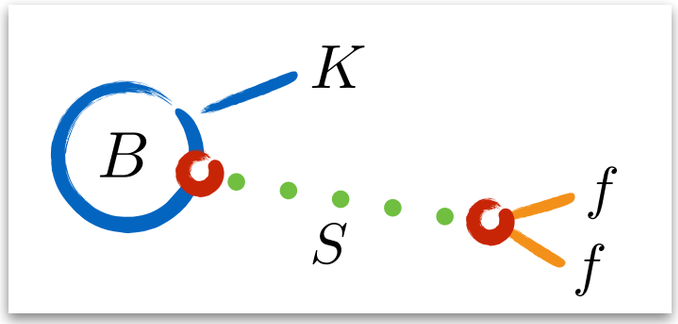


inclusive



BaBar 2015: 90% CL excl; 1/ab

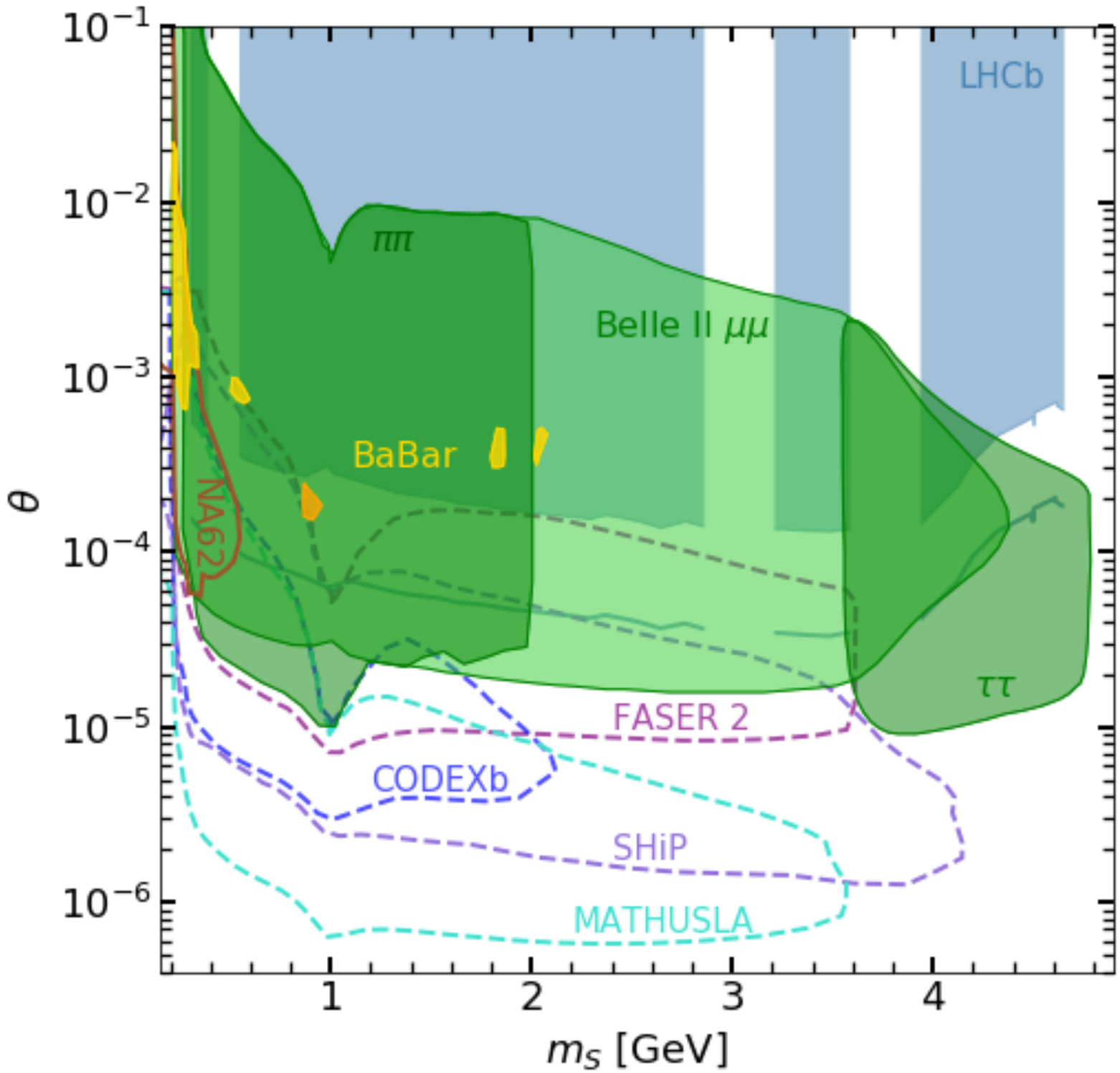
exclusive



Belle II prediction: N=3; 3/ab

Filimonova, Schaefer, Westhoff 2019

Compare with long-baseline experiments

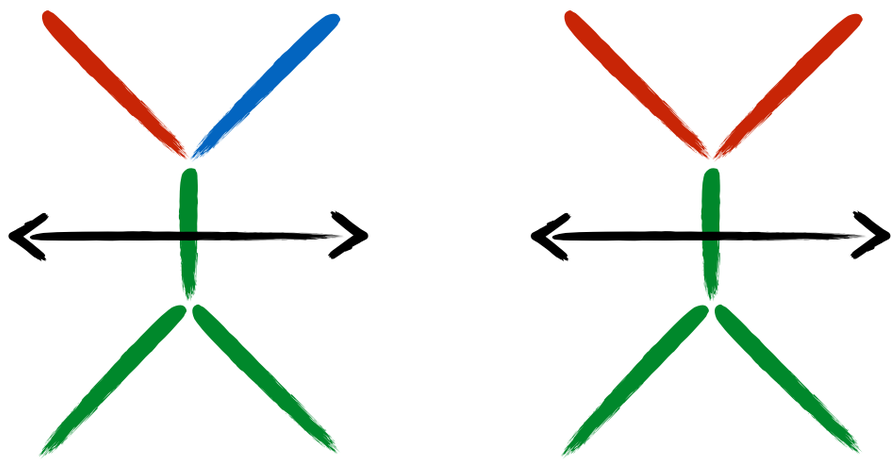


Filimonova, Schaefer, Westhoff 2019

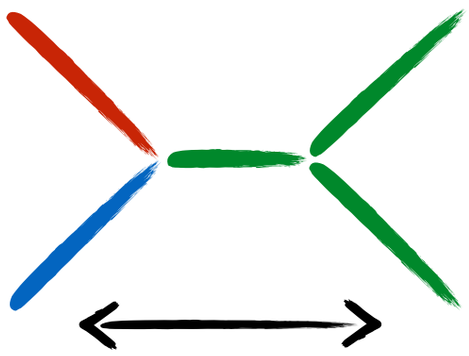
Why soft?

Dark matter freeze-out in the early universe.

in equilibrium:



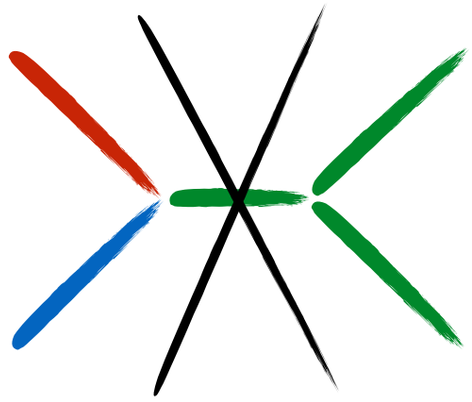
(co)-annihilation



universe

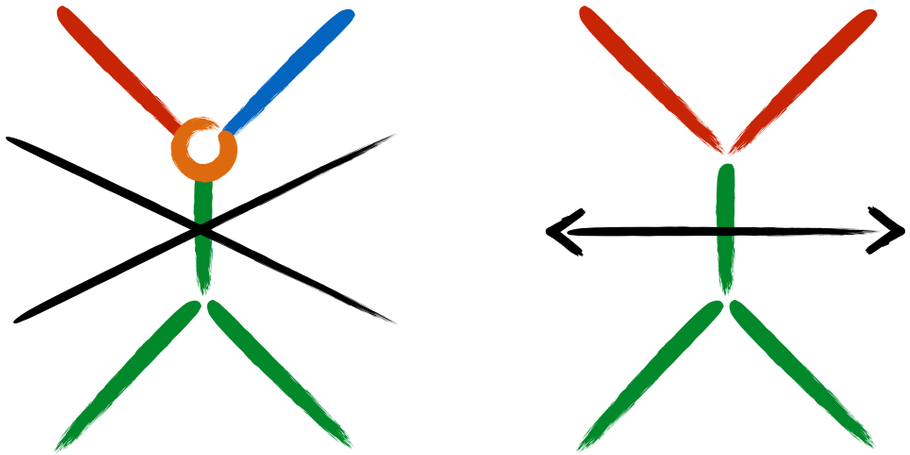
expands

freeze-out

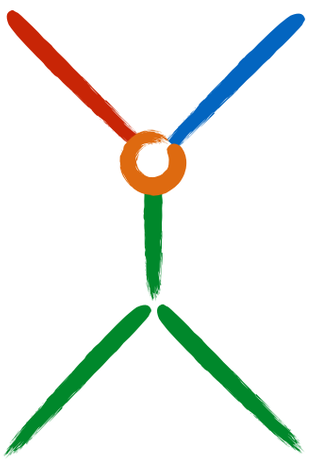


Co-scattering

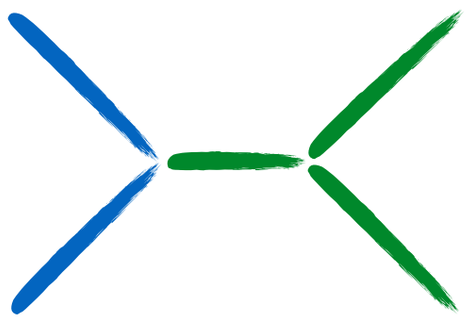
small coupling: leaving chemical equilibrium



co-scattering

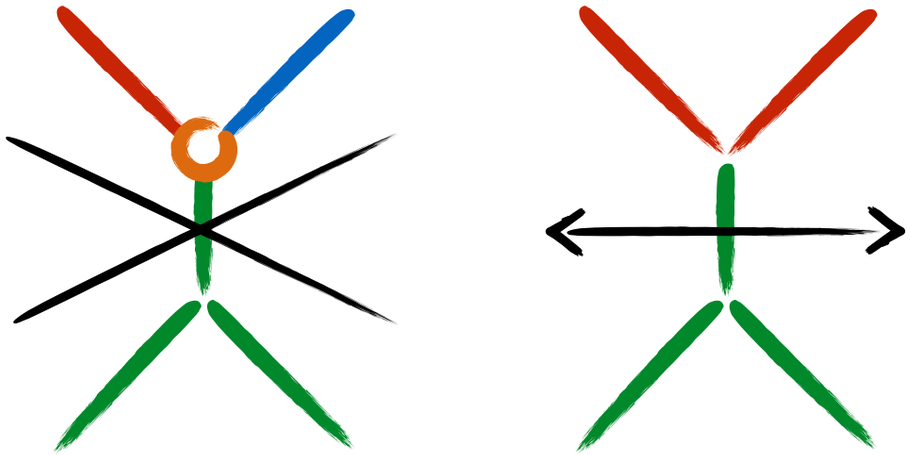


mediator annihilation

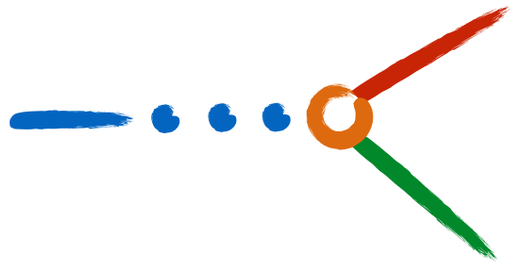


Co-scattering

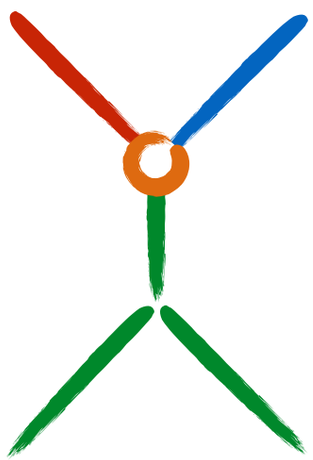
leaving chemical equilibrium:



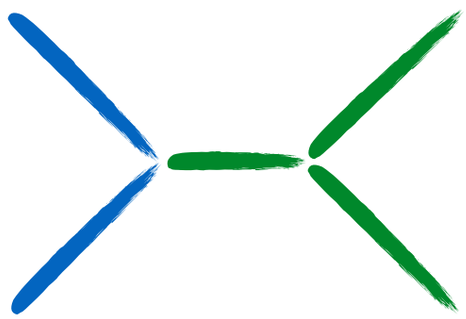
long-lived mediators



co-scattering

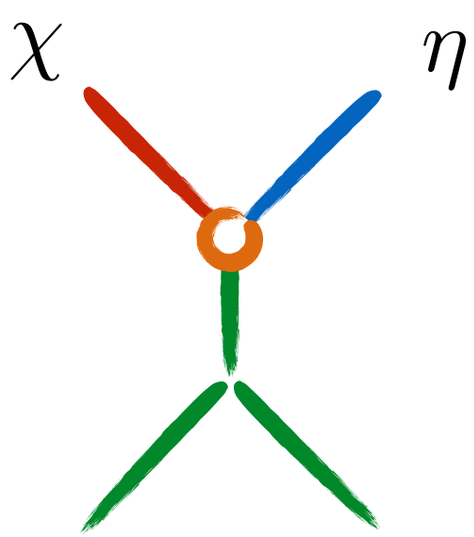


mediator annihilation



Characteristics of co-scattering

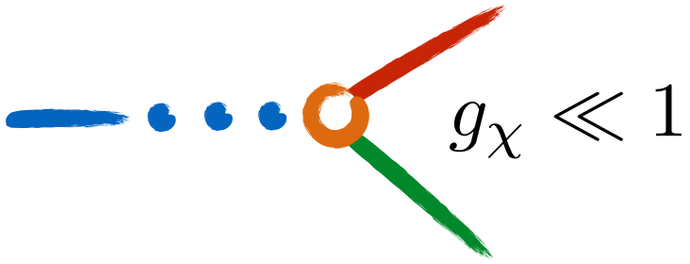
co-scattering



number densities related:

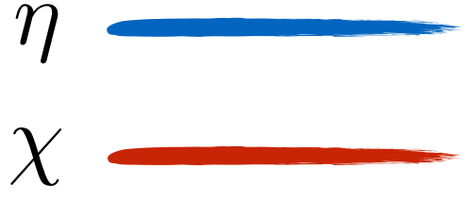
$$\frac{n_\eta}{n_\chi} \sim \left(\frac{m_\eta}{m_\chi}\right)^{\frac{3}{2}} e^{-\frac{\Delta m}{T}}$$

long-lived mediators:



soft

compressed spectrum:

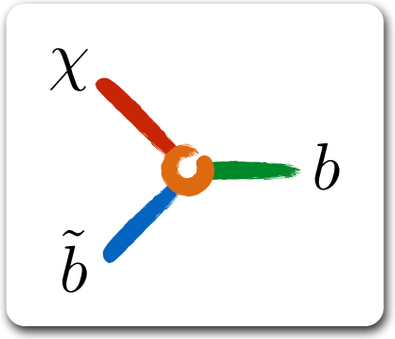


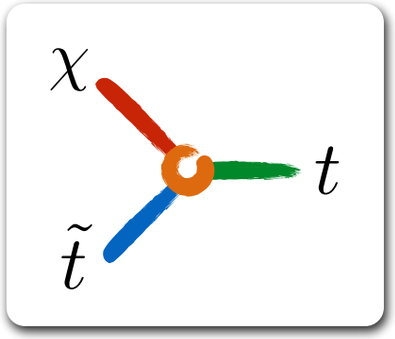
$$\frac{\Delta m}{m} \approx 10\,\%$$

Models with co-scattering

Fermion portal cf. SUSY sbottom, stop

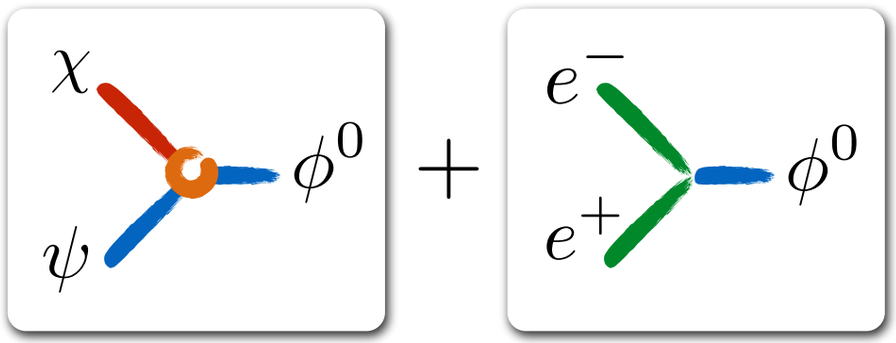
Garny et al., 1705.09292 & 1802.00814



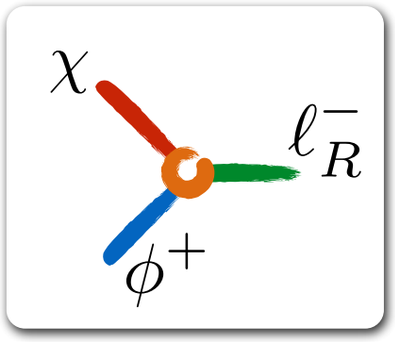


Leptophilic dark matter

D'Agnolo et al.
1705.08450
1906.09269



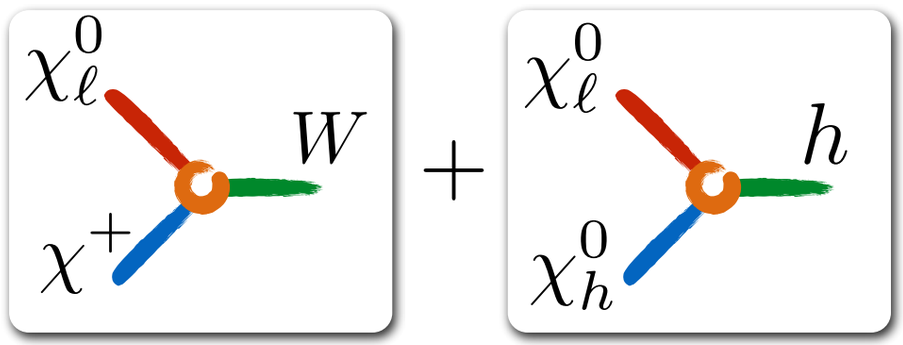
Junius et al.
1904.07513



Higgs portal cf. SUSY wino-bino

Bharucha et al., 1804.02357

Filimonova, Westhoff, 1812.04628



see also: Cheng, Zheng 1805.12139; Kim, Kuflik 1906.00981

Higgs portal with weak interactions

Naturally small portal coupling

$$\mathcal{L}_{\text{eff}} = -\frac{m_S}{2}\overline{\chi}_S\chi S - \frac{m_T}{2}\overline{\chi}_T\chi_T + \frac{\kappa}{\Lambda}\left[(H^\dagger\overline{\chi}_T H)\chi_S + \overline{\chi}_S(H^\dagger\chi_T H)\right]$$

Dark fermion mixing

$$\theta \sim \frac{\mu}{m_T - m_S} \quad \text{with} \quad \mu = \frac{\kappa v^2}{\sqrt{2}\Lambda}$$

Mass eigenstates

$$\chi^0_\ell = \cos\theta\,\chi^0_S - \sin\theta\,\chi^0_T$$

$$\chi^0_h = \sin\theta\,\chi^0_S + \cos\theta\,\chi^0_T$$

$$\chi^+,\ \chi^-$$

Filimonova, Westhoff 2018

Higgs portal with weak interactions

Naturally small portal coupling

$$\mathcal{L}_{\text{eff}} = -\frac{m_S}{2}\overline{\chi}_S\chi S - \frac{m_T}{2}\overline{\chi}_T\chi_T + \frac{\kappa}{\Lambda}\left[(H^\dagger\overline{\chi}_T H)\chi_S + \overline{\chi}_S(H^\dagger\chi_T H)\right]$$

Dark fermion mixing

$$\theta \sim \frac{\mu}{m_T - m_S}$$

$$\mu = \frac{\kappa v^2}{\sqrt{2}\Lambda}$$

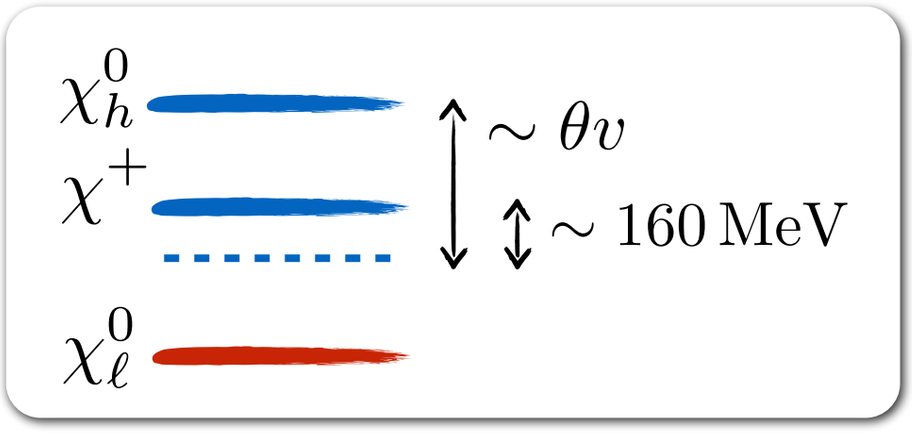
Mass eigenstates

$\chi_\ell^0 = \cos\theta\,\chi_S^0 - \sin\theta\,\chi_T^0$

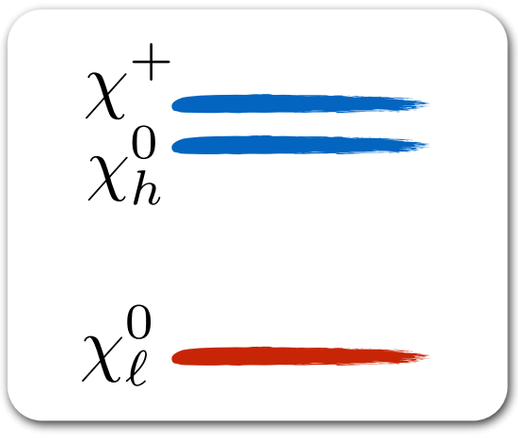
$\chi_h^0 = \sin\theta\,\chi_S^0 + \cos\theta\,\chi_T^0$

$\chi^+,\ \chi^-$

$\theta v > 160\,\text{MeV}$



$\theta v \lesssim 160\,\text{MeV}$



Filimonova, Westhoff 2018

Higgs portal with weak interactions

Naturally small portal coupling

$$\mathcal{L}_{\text{eff}} = -\frac{m_S}{2}\overline{\chi}_S\chi S - \frac{m_T}{2}\overline{\chi}_T\chi_T + \frac{\kappa}{\Lambda}\left[(H^\dagger\overline{\chi}_T H)\chi_S + \overline{\chi}_S(H^\dagger\chi_T H)\right]$$

Dark fermion mixing

$$\theta \sim \frac{\mu}{m_T - m_S}$$

$$\mu = \frac{\kappa v^2}{\sqrt{2}\Lambda}$$

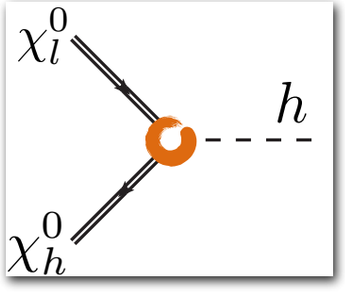
Mass eigenstates

$$\chi^0_\ell = \cos\theta\,\chi^0_S - \sin\theta\,\chi^0_T$$

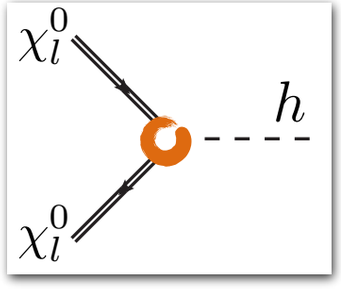
$$\chi^0_h = \sin\theta\,\chi^0_S + \cos\theta\,\chi^0_T$$

$$\chi^+,\ \chi^-$$

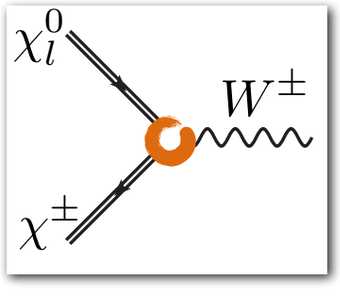
Weak interactions



$$\frac{\mu}{v}\cos(2\theta)$$

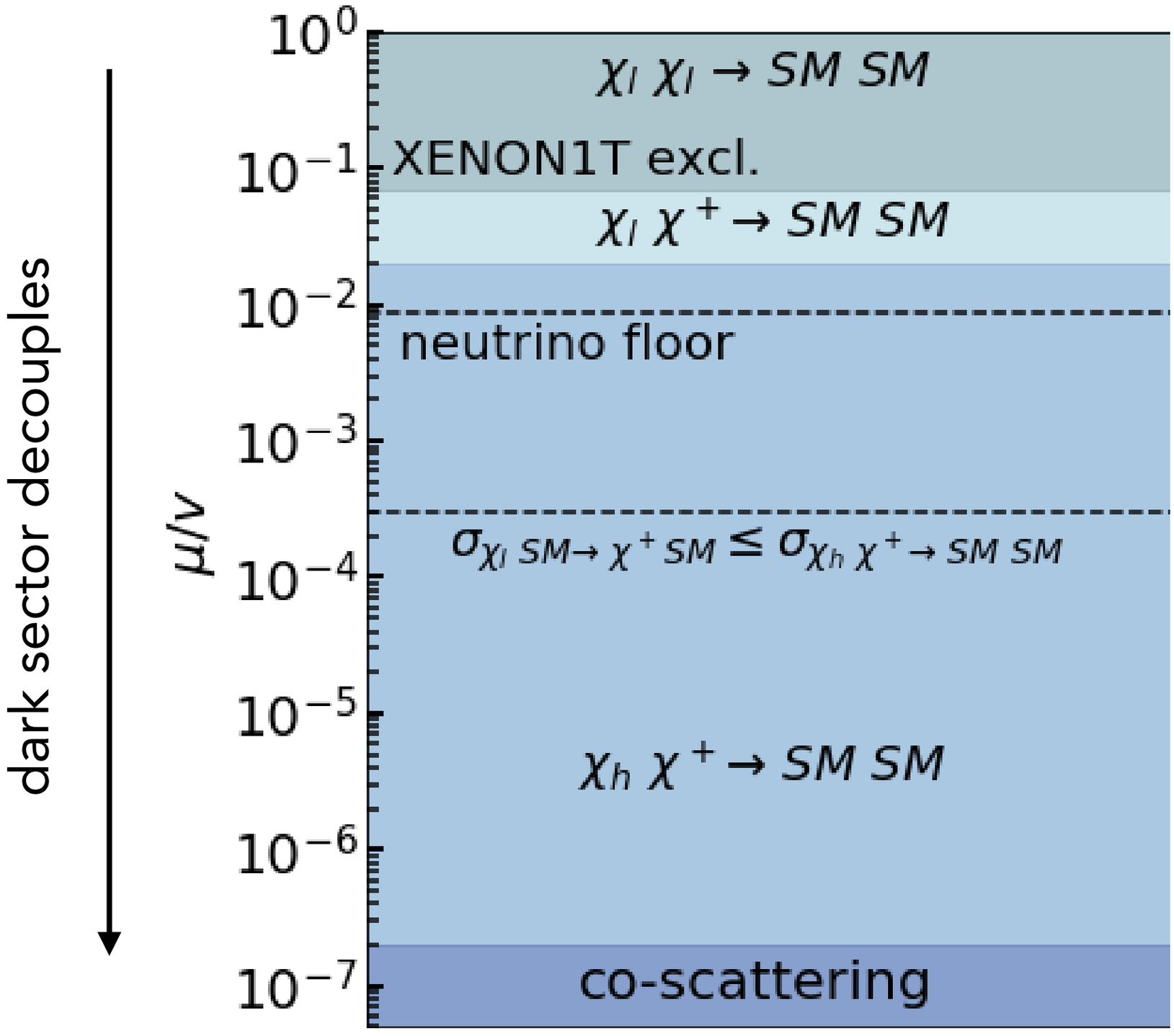


$$\frac{\mu}{v}\sin(2\theta)$$

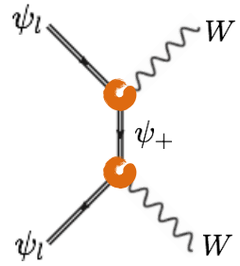


$$g\sin\theta\,\gamma_\mu$$

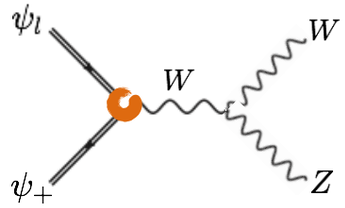
Phases of freeze-out



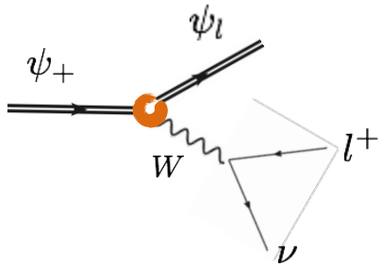
pair annihilation



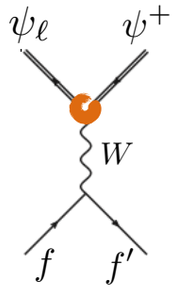
co-annihilation



inverse decay

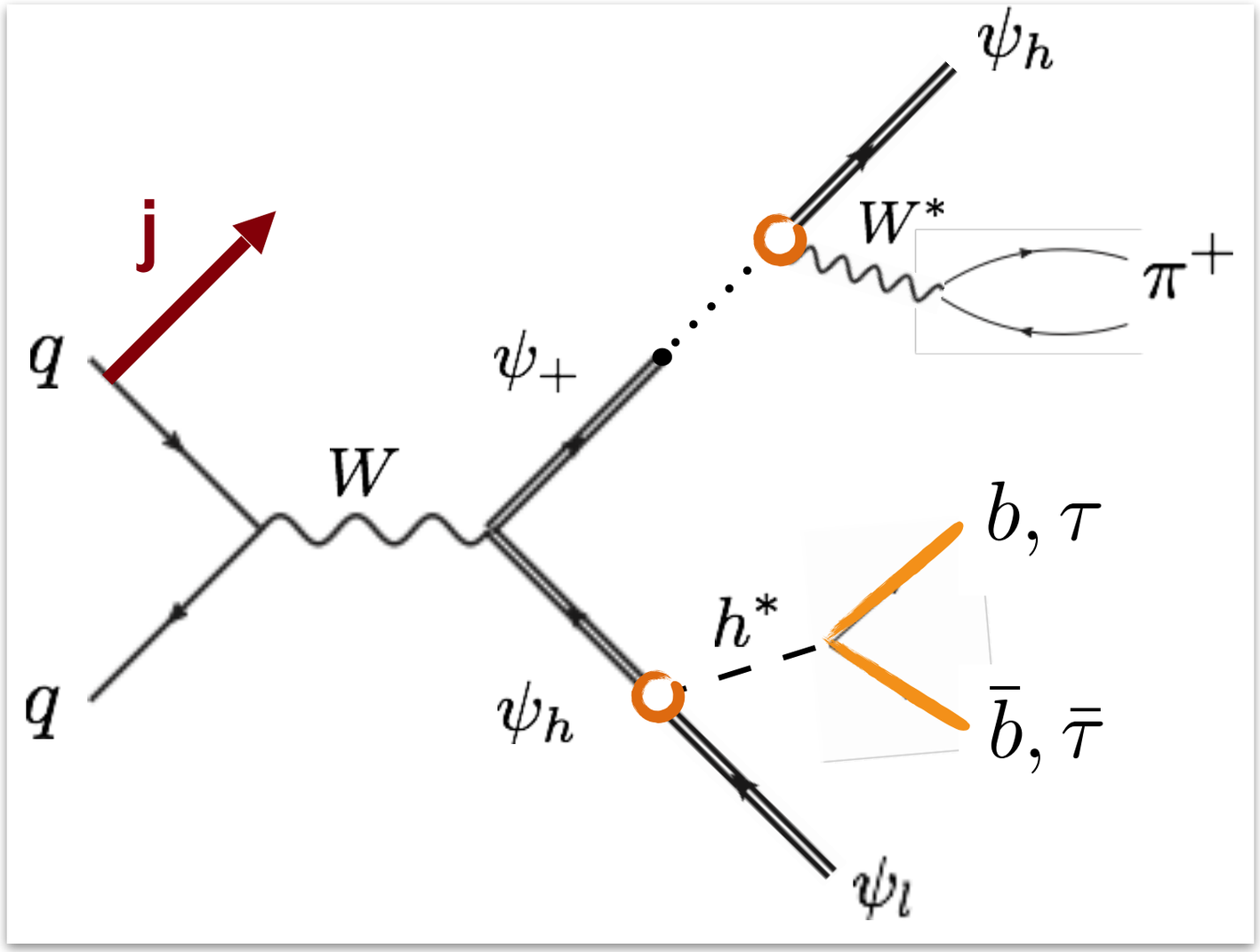


co-scattering



Soft displaced vertices at the LHC

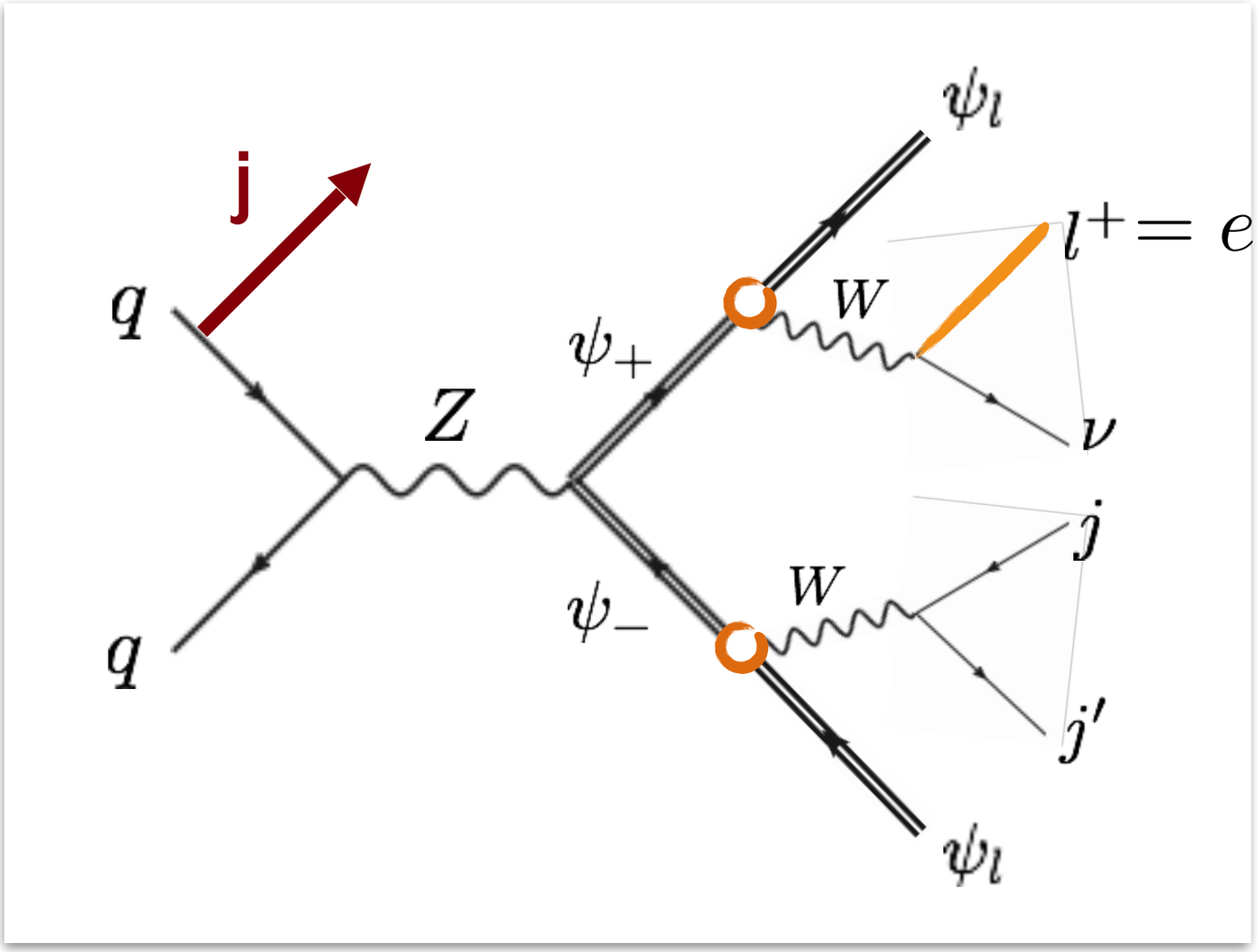
Mediator decays are suppressed as $\Gamma_\chi \sim \theta^2 (\Delta m)^x$.



Signal: soft displaced bottom/tau pairs and missing energy.

Nagata, Otono, Shirai 2015; Garny et al. 2017; Filimonova, Westhoff 2018

Soft displaced leptons at the LHC

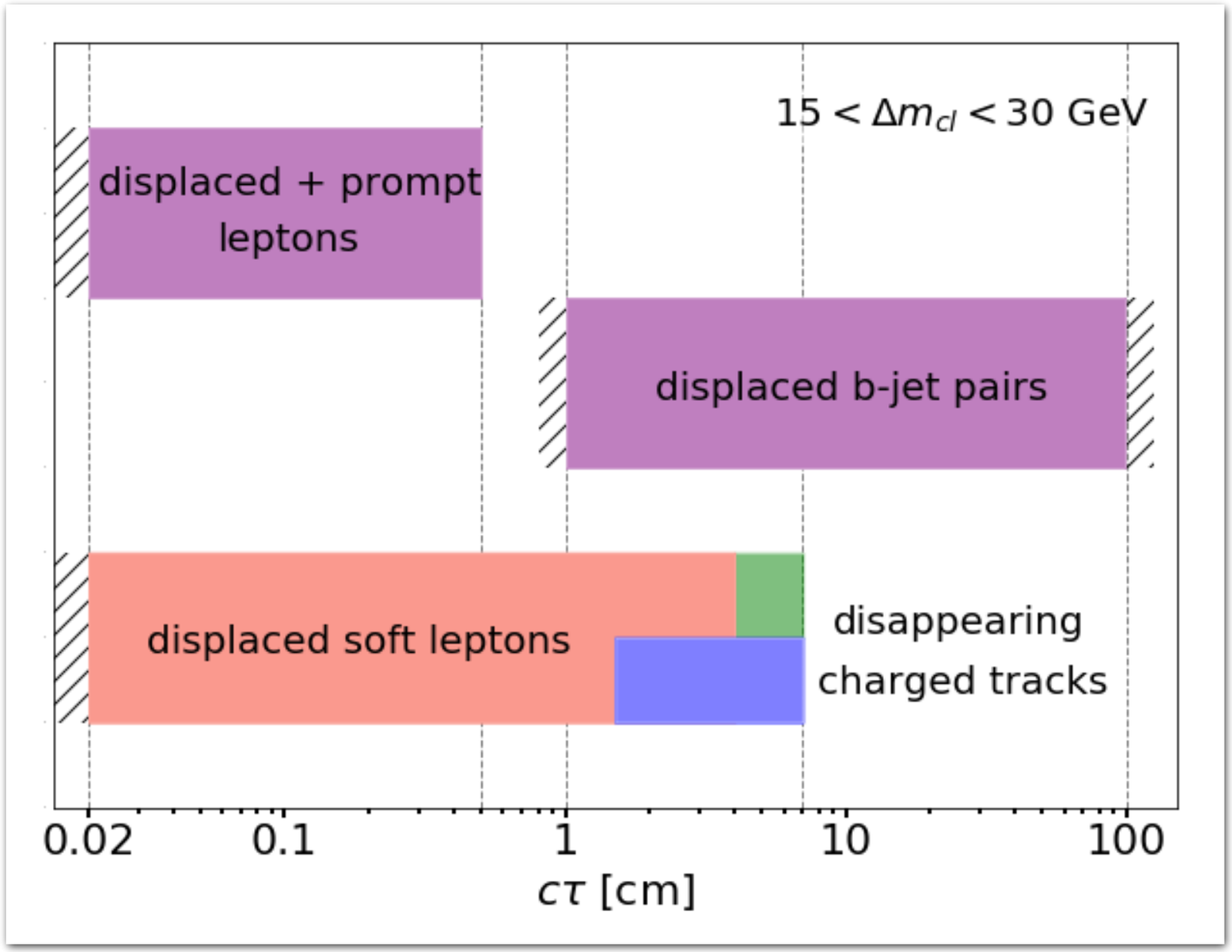


Signal: one/two soft displaced lepton(s) and missing energy.

Background: seemingly isolated leptons from meson decays.

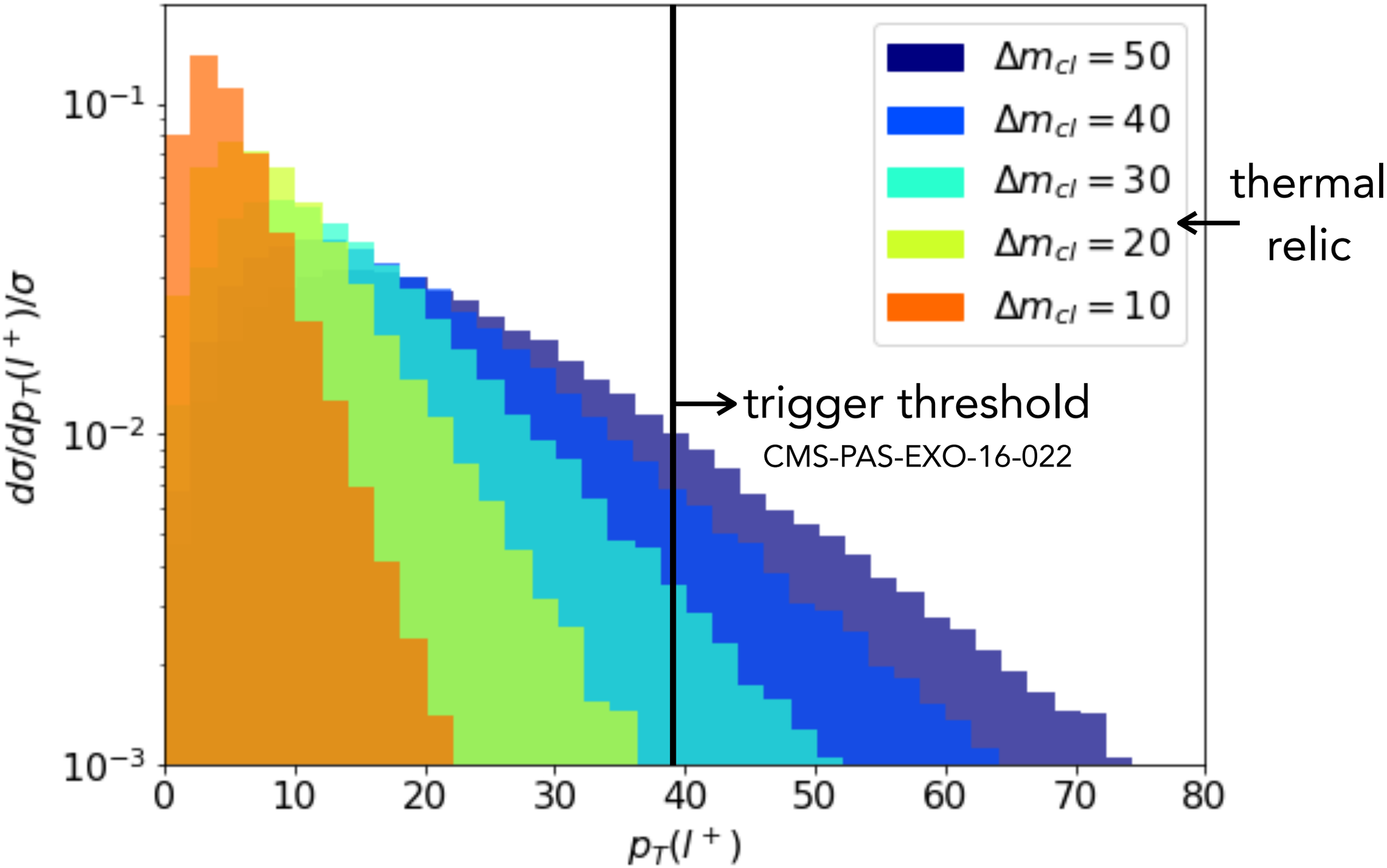
Bharucha et al., 2018; Filimonova, Westhoff 2018; Junius et al. 2019

How displaced?



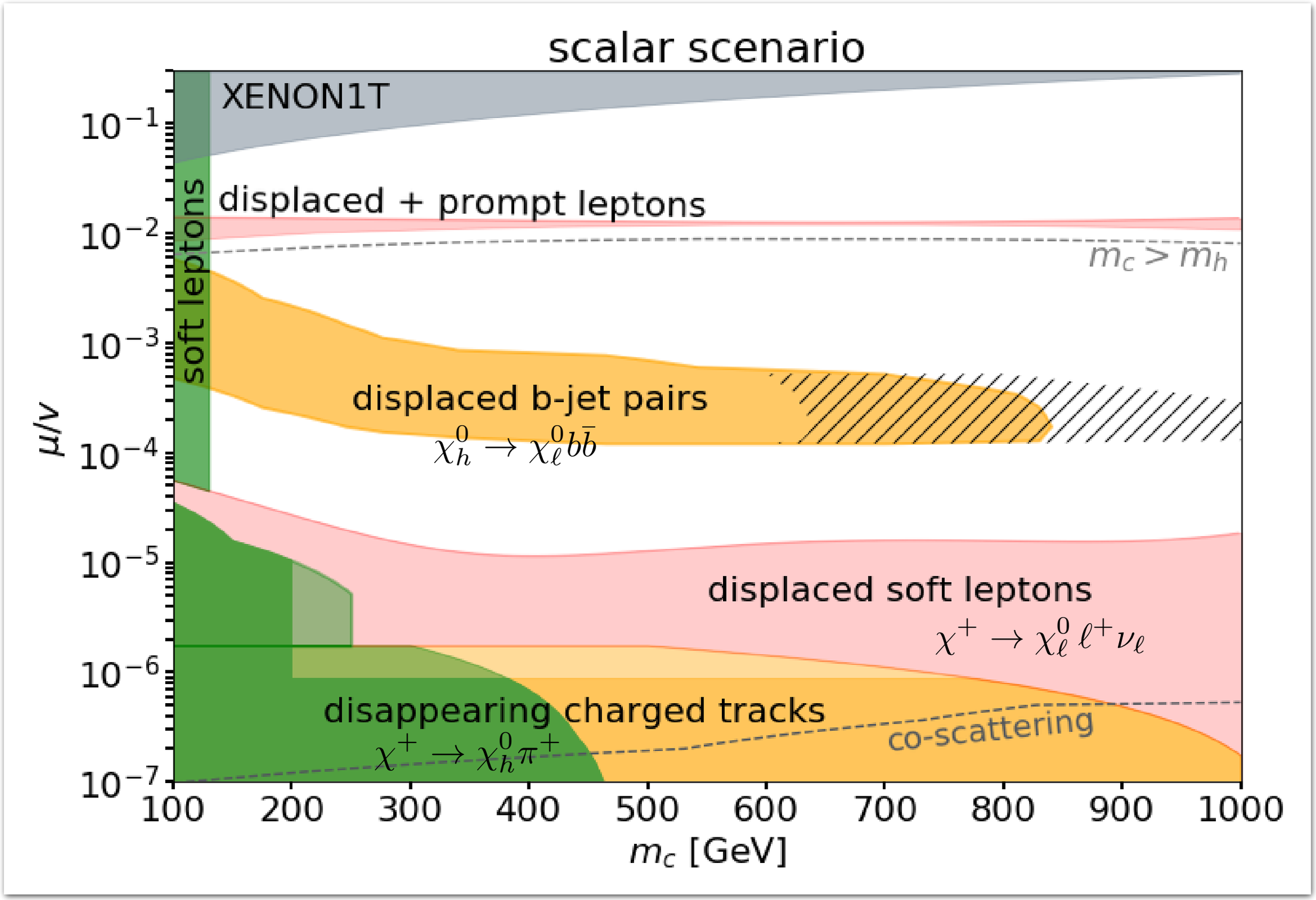
Transverse impact parameter typically O(mm) - O(cm).

How soft?



A. Filimonova, work in progress

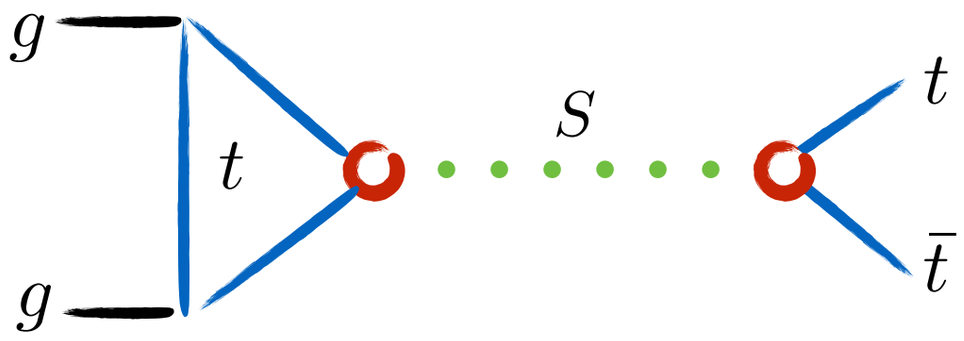
LHC searches for co-scattering mediators



Filimonova, Westhoff 2018

How about displaced tops?

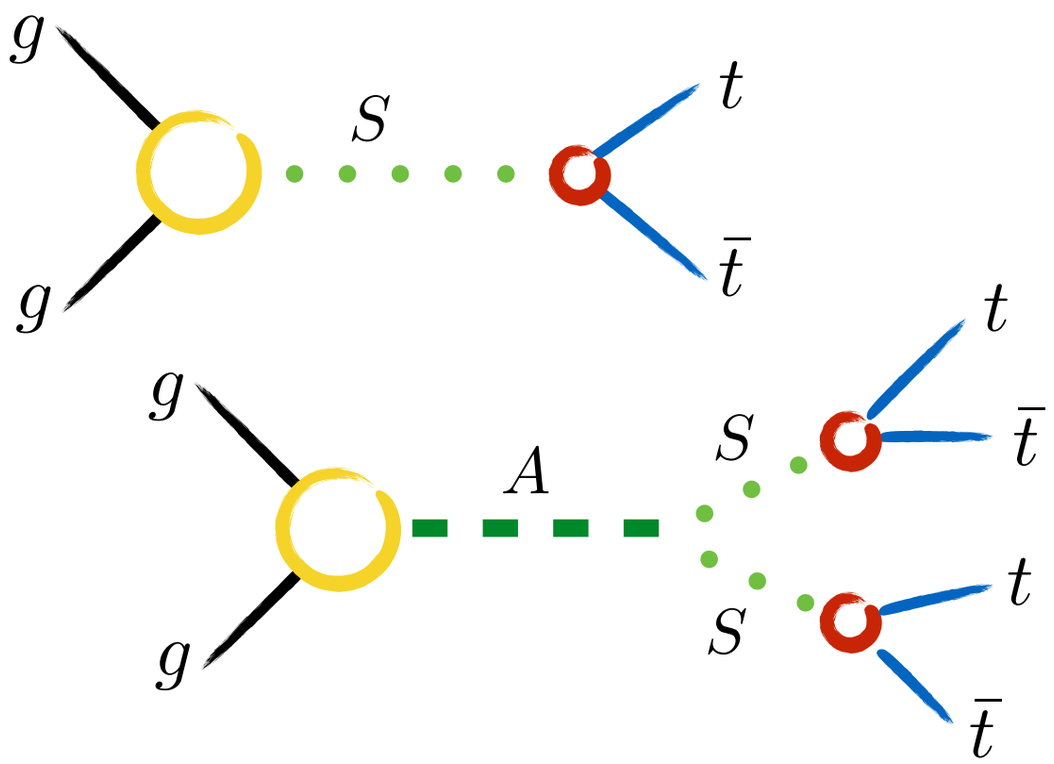
S production through tops:



Rate drops with top coupling.

- at kinematic threshold: soft displaced tops

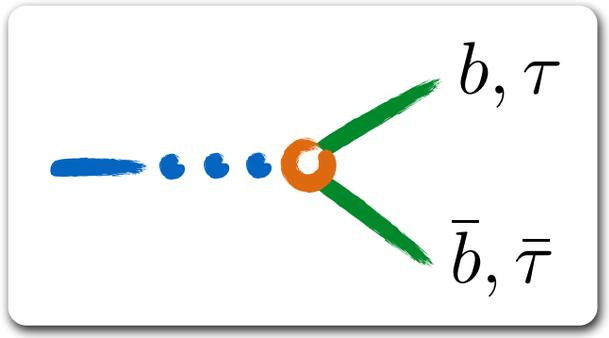
S production unrelated to decay:



- decay of a heavy resonance: (pairs of) displaced tops

Take home

- long-lived dark scalars

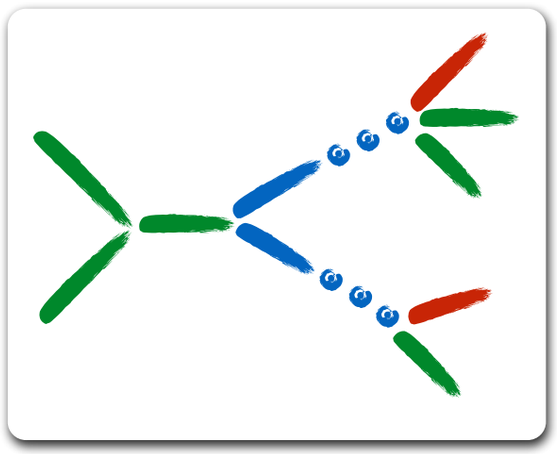


- At Belle (II), NA62, FASER … :

  displaced taus in meson decays

flavor-hierarchical couplings (unlike dark vectors)

- long-lived dark fermions with weak interactions



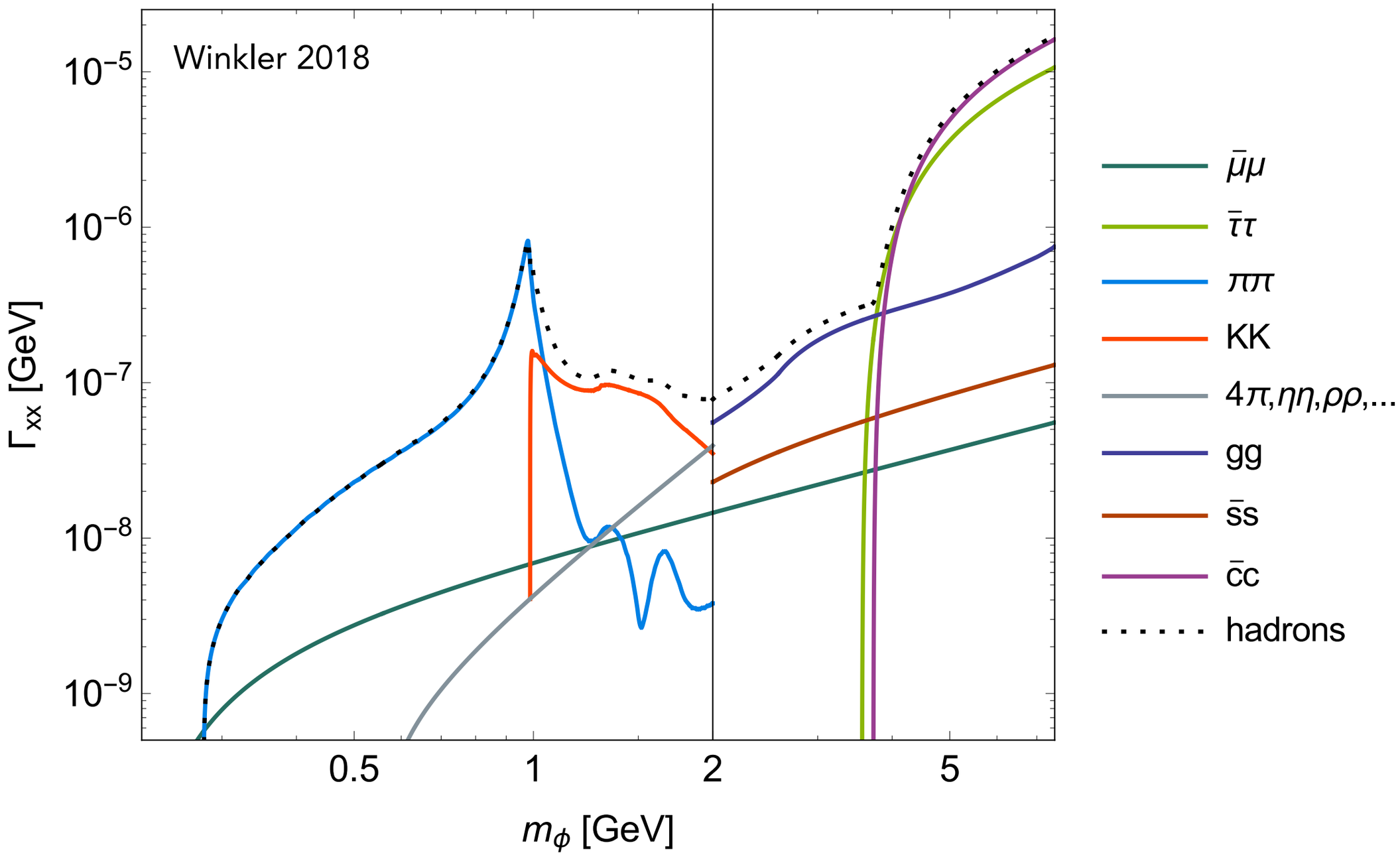
- At the LHC:

  displaced soft bottoms or taus from mediator decays

small couplings and compressed spectrum from co-scattering

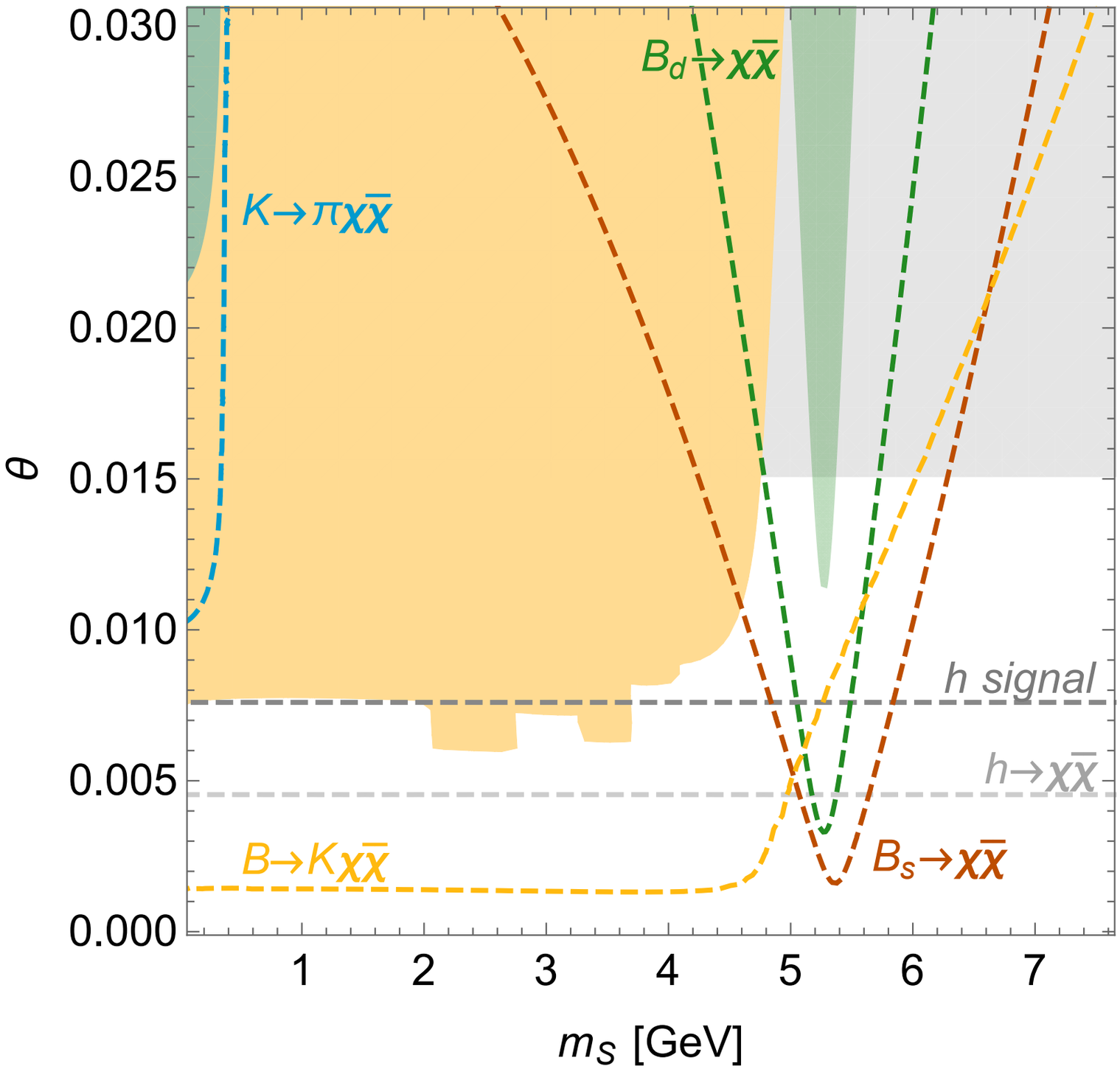
Backup

Visible scalar decays



Predictions for 1 GeV < mS < 2 GeV subject to large uncertainties.

Invisibly decaying dark scalars



Excluded at 95% CL:

- $B_d \to \text{inv}$
- $B^+ \to K^+ + \text{inv}$ diff.
- $K^+ \to \pi^+ + \text{inv}$ (E949)

Projected sensitivity

- Belle II $5\,\text{ab}^{-1}$
- Belle II $50\,\text{ab}^{-1}$
- NA62

Filimonova, Schaefer, Westhoff 2019