Relaxions

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CLICWEEK2019

Compact Linear Collider Workshop

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Some pictures borrowed from E.Fuchs GGI 2018 talk

What is a relaxion?

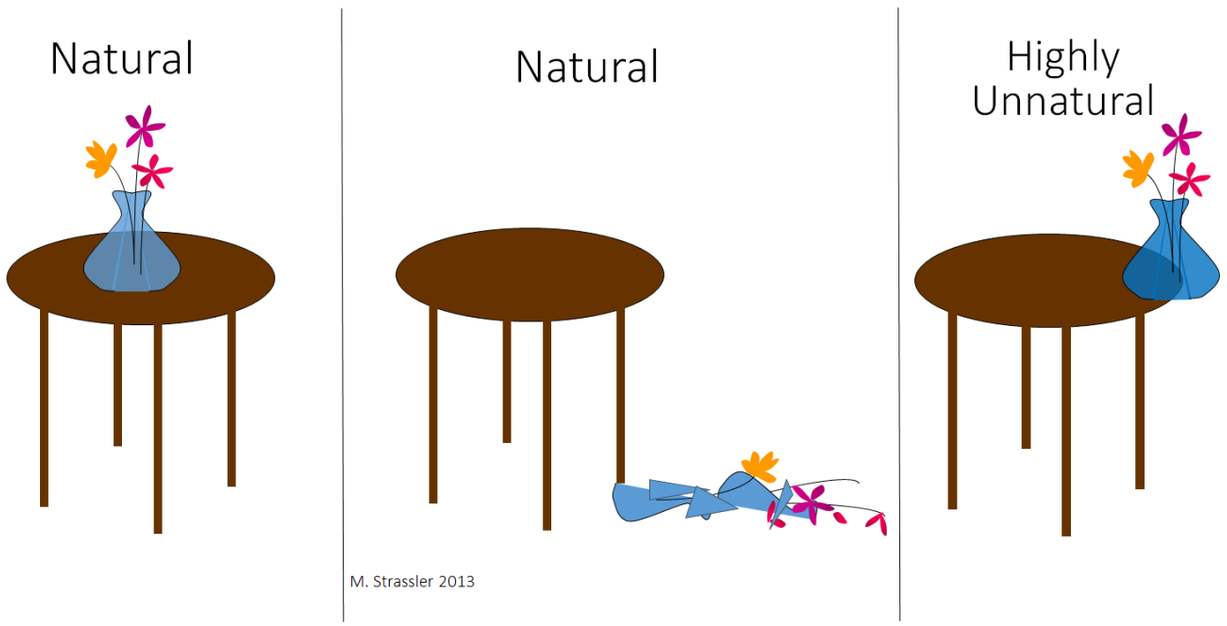
A pseudo-Nambu-Goldstone boson (pNGB) associated to a new solution to the electroweak hierarchy problem where the Higgs mass is stabilised dynamically

Graham, Kaplan & Rajendran 2015

Why is the Higgs light?

Naturalness problem of the electroweak scale

Quantum field theory suggests the mass of the Higgs should be close to the highest scale in nature, that is 17 orders of magnitude heavier.



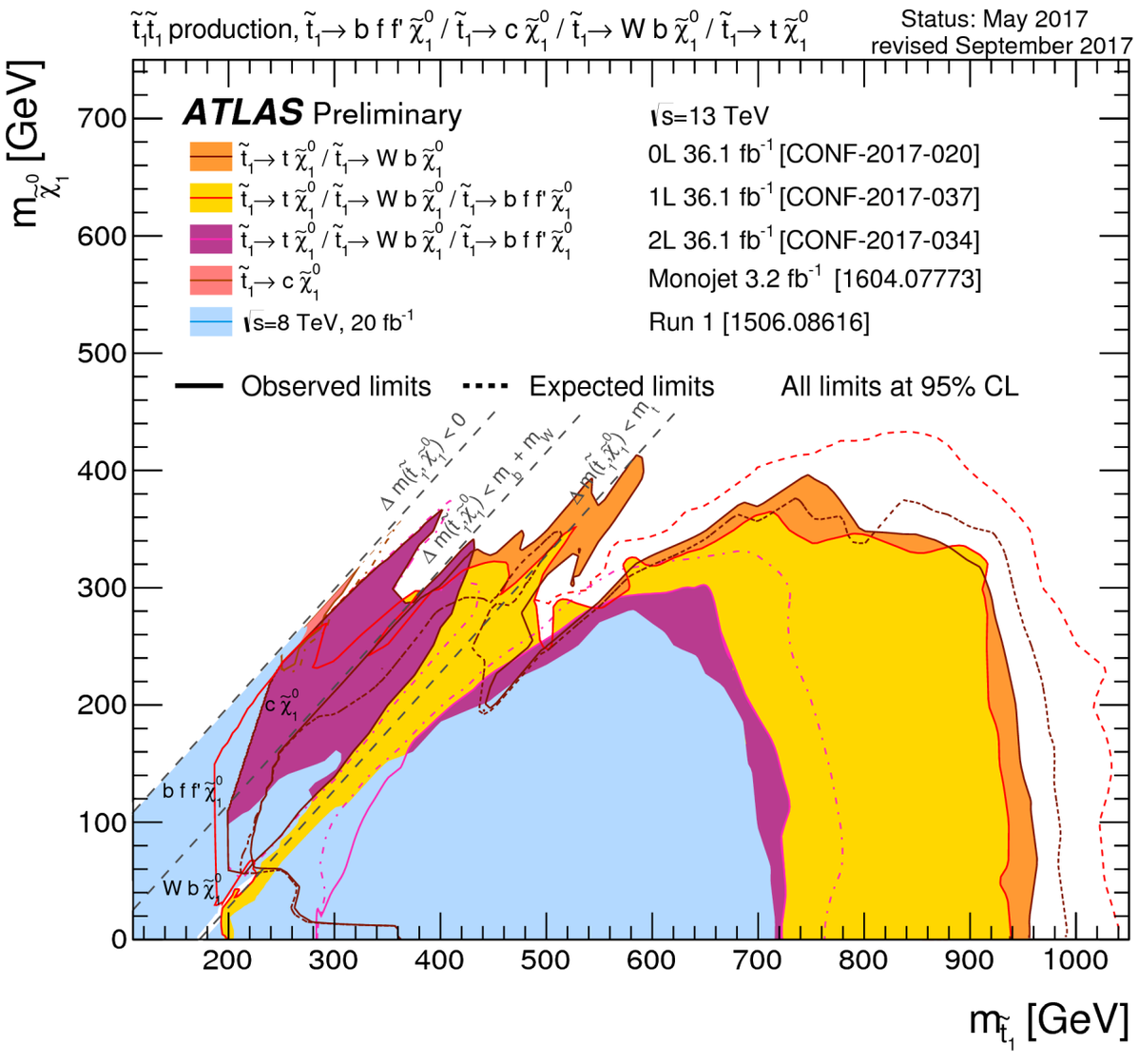
Quantum corrections grow proportionally with Λ

$$\frac{\delta m_h^2}{m_h^2} = \left(\frac{\Lambda}{500\mathrm{GeV}}\right)^2$$

Standard solution: symmetry principle.
Partners for Standard Model particles (strong limits from the LHC)
Example: Supersymmetry

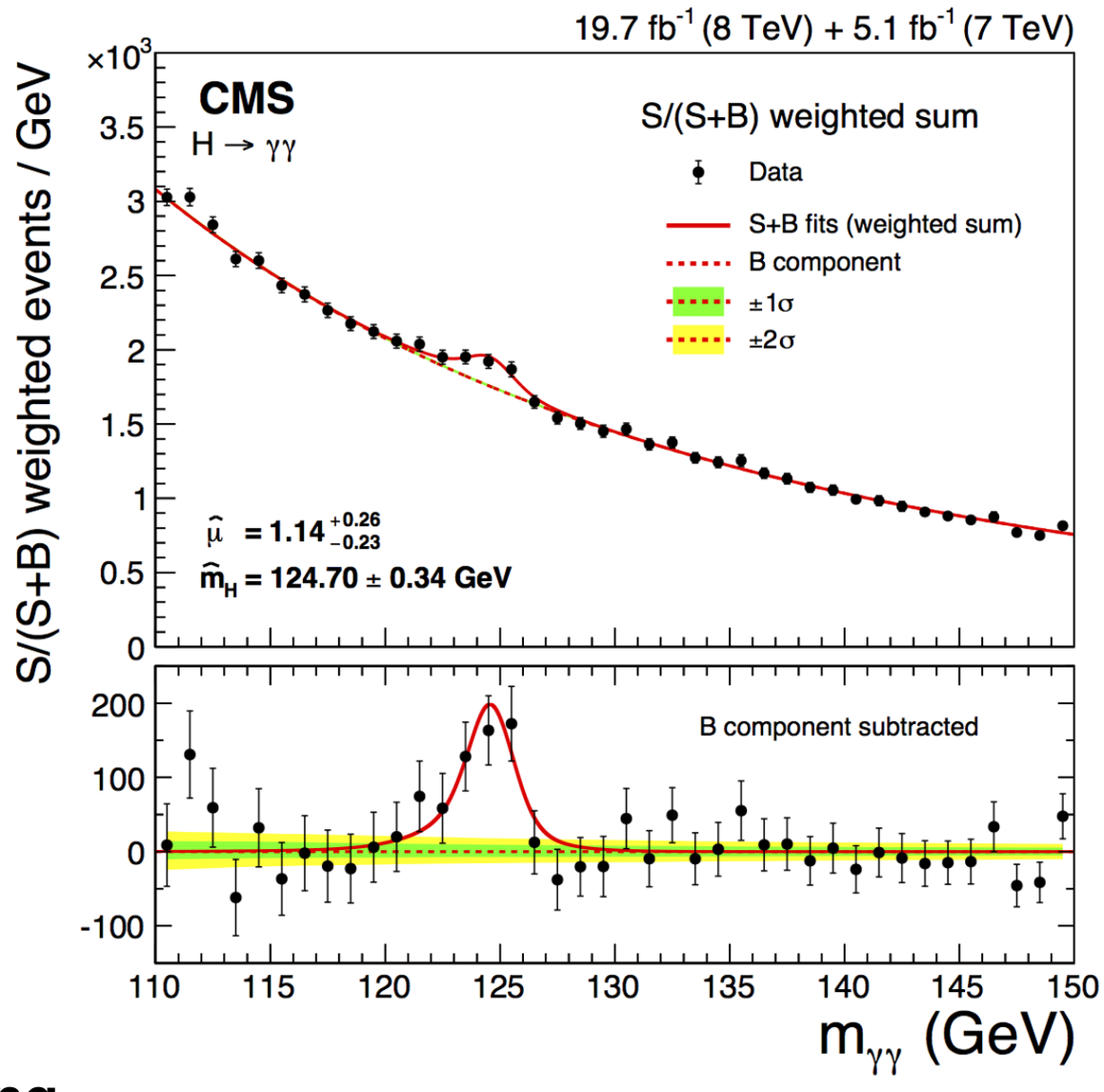
The LHC has deeply changed our perspective on the hierarchy problem

Strong limits on colored particles



Discovery of a 125 GeV Higgs

(too heavy for naive SUSY
too light for naive composite H models)



1 TeV bound on stops —> few percent tuning

A dynamical solution to the hierarchy problem

Graham, Kaplan & Rajendran 2015

Non QCD relaxion

Relaxion dependent Higgs mass

$$V(H) = \mu^2(\phi) H^\dagger H + \lambda (H^\dagger H)^2$$

$$\mu^2(\phi) = -\Lambda^2 + g\Lambda\phi + ...$$

The initial value of the Higgs mass is positive and large

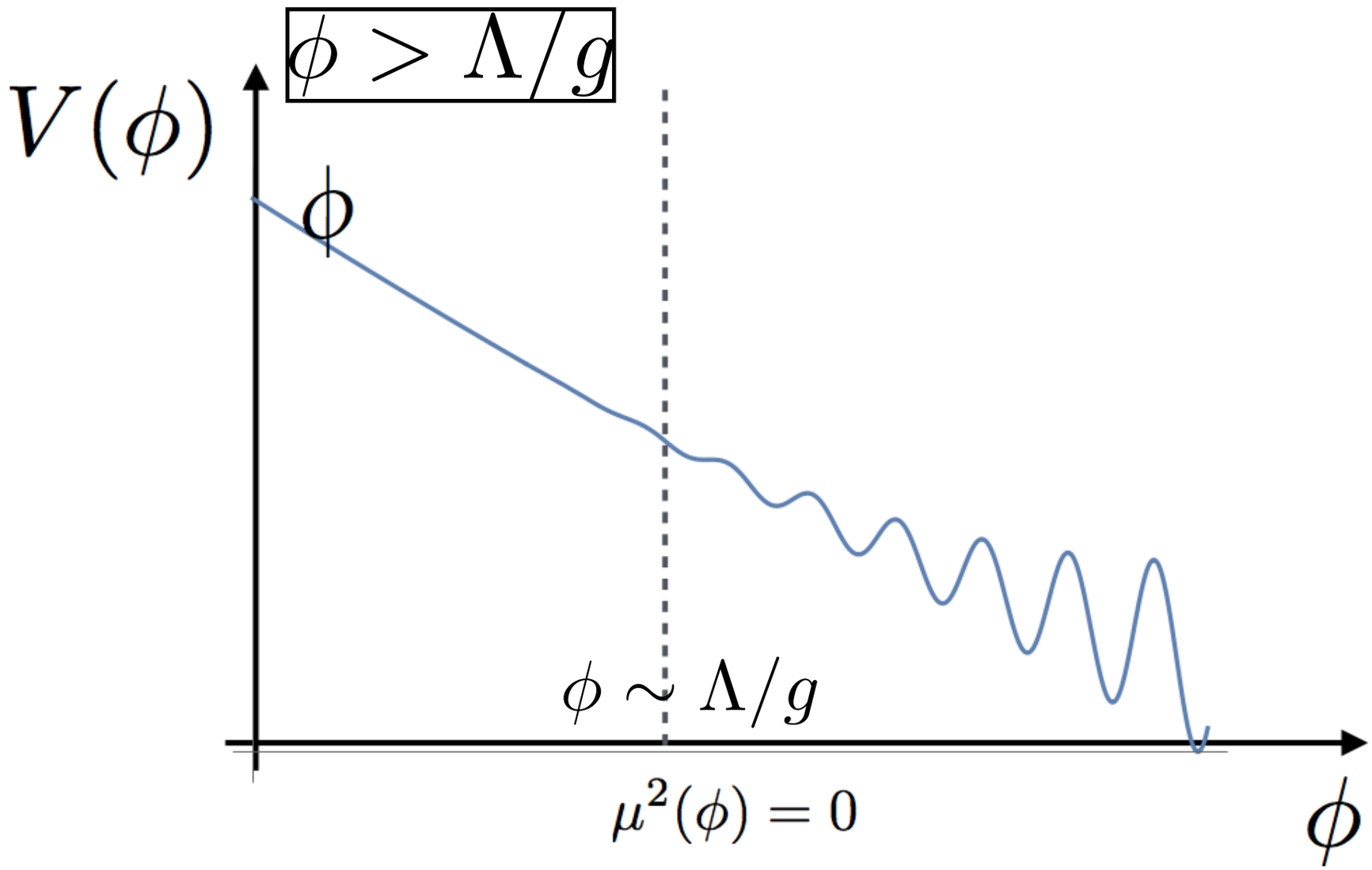
$$\Lambda >> v$$

A dynamical solution to the hierarchy problem

Graham, Kaplan & Rajendran 2015

During inflation the relaxion slow roll and scan the mass of the Higgs

$$V(\phi, H) = g\Lambda^3\phi + ..$$ slow roll potential



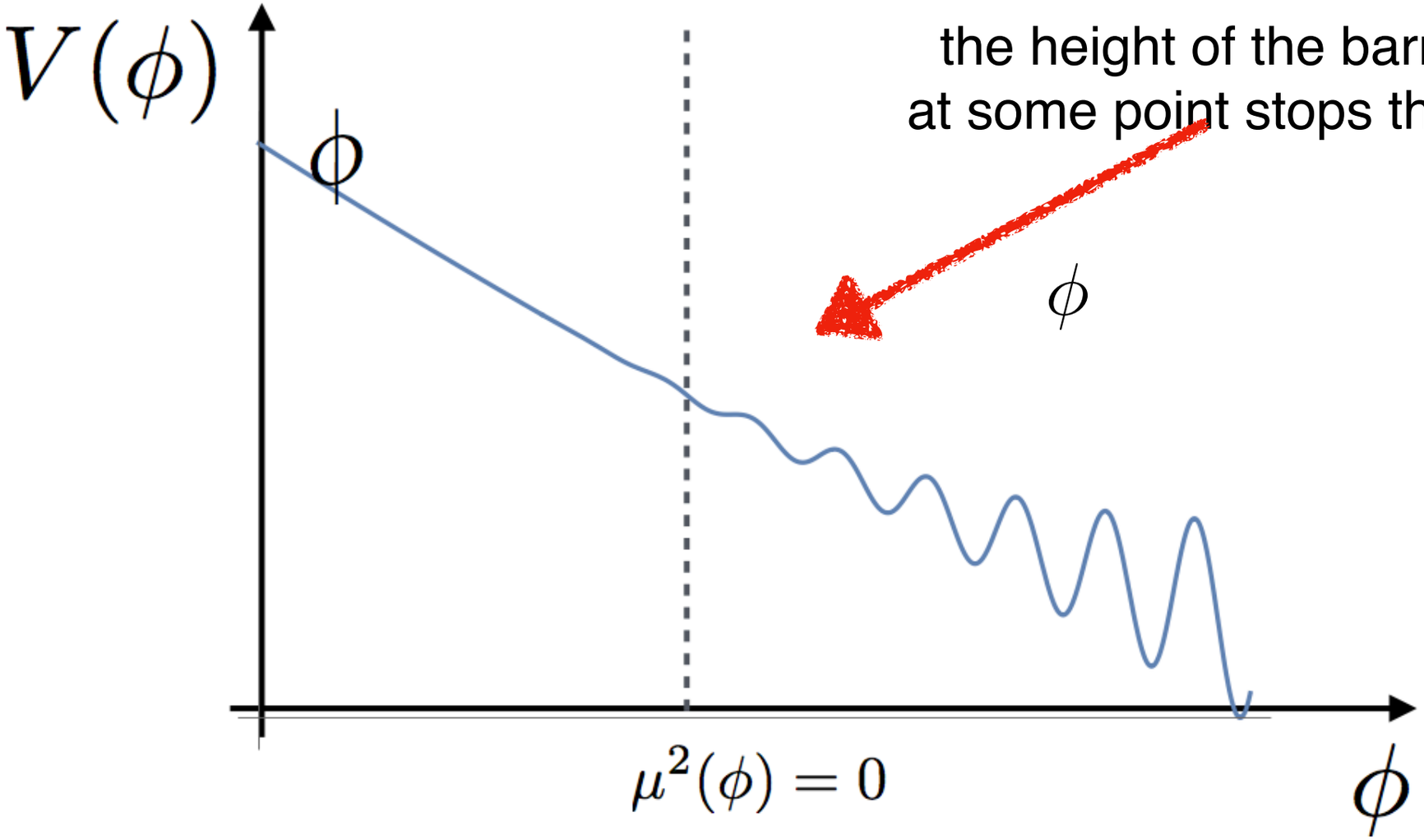
A dynamical solution to the hierarchy problem

Graham, Kaplan & Rajendran 2015

$$\text{When } \mu(\phi) = 0 \implies < h > \neq 0$$

$$V_{\text{br}}(h, \phi) = -\tilde{M}^{4-j} \left(\frac{v(\phi)+h}{\sqrt{2}} \right)^j \cos\left(\frac{\phi}{f} \right)$$

Back reaction sector: model dependent (j=1 axion-models, j=2 ex: familon model)



the height of the barrier starts to grow and
at some point stops the rolling of the relaxion

Many theoretical challenges

see e.g.: Espinosa et al.; Choi, Kim & Sekiguchi; Kobayashi, Seto, Shimomura & Urakawa; Di Chiara et al.; Jaeckel, Mehta & Witkowski; Patil & Schwaller; Hardy ...

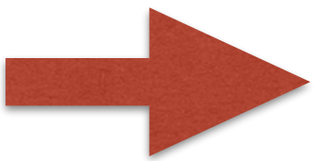
however

It represents a new solution to the hierarchy problem and it leads to radical departure in terms of the naturalness phenomenology

NO TOP PARTNERS!

What is the relaxion scale?

Relaxion mass spans several orders of magnitude from sub eV to tens of GeV



Hierarchy problem at the low energy frontier!

$$m_\phi \sim \frac{\Lambda_{\rm br}^2}{f}$$

$$\Lambda_{\rm br}(v(\phi))^4 \equiv \tilde{M}^{4-j} v(\phi)^j / \sqrt{2}^j$$

Scale of PQ symmetry breaking f

$$\Lambda_{\rm br}(v(\phi_0))^2 \lesssim \mathcal{O}(2\pi v^2)$$

CP is typically spontaneously broken

Mixing between the Higgs boson and the relaxion

$$\sin\theta \sim \frac{8\Lambda_{br}^4}{v^3 f} s_0$$

$$\sin\theta \leq 2\frac{m_\phi}{v}$$ Maximal relaxion mixing

[Flacke,CF, Fuchs,Gupta,Perez 2016] [Choi,Im 2016]

Coupling to SM fermions and gauge bosons

CP even coupling

Relaxion inherits SM Higgs couplings suppressed by mixing ⇔ Higgs portal

$$g_{\phi X} = \sin\theta \, g_{hX}$$

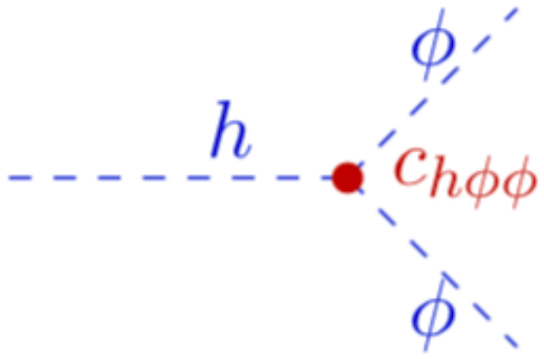
CP odd coupling

CP odd couplings are highly model dependent (back-reaction sector)

$$\mathcal{L} \supset \sum_{i=B,W} \frac{\tilde{g}_{\phi i}}{4\pi f} F_i \tilde{F}_i \phi$$

Relaxion-Higgs coupling

[Flacke,CF, Fuchs,Gupta,Perez 2016]



$$V_{\rm br}(h,\phi) = -\tilde{M}^{4-j}\left(\frac{v(\phi)+h}{\sqrt{2}}\right)^j \cos\left(\frac{\phi}{f}\right)$$

$$\Lambda_{\rm br}^4 \equiv \tilde{M}^{4-j} v(\phi_0)^j/\sqrt{2}^j$$

$$c_{\phi\phi h} = \frac{\Lambda_{\rm br}^4}{vf^2}c_0 c_\theta^3 - \frac{2\Lambda_{\rm br}^4}{v^2 f}s_0 c_\theta^2 s_\theta - \frac{\Lambda_{\rm br}^4}{2f^3}s_0 c_\theta^2 s_\theta - \frac{2\Lambda_{\rm br}^4}{vf^2}c_0 c_\theta s_\theta^2 + 3v\lambda c_\theta s_\theta^2 + \frac{\Lambda_{\rm br}^4}{v^2 f}s_0 s_\theta^3\,,$$

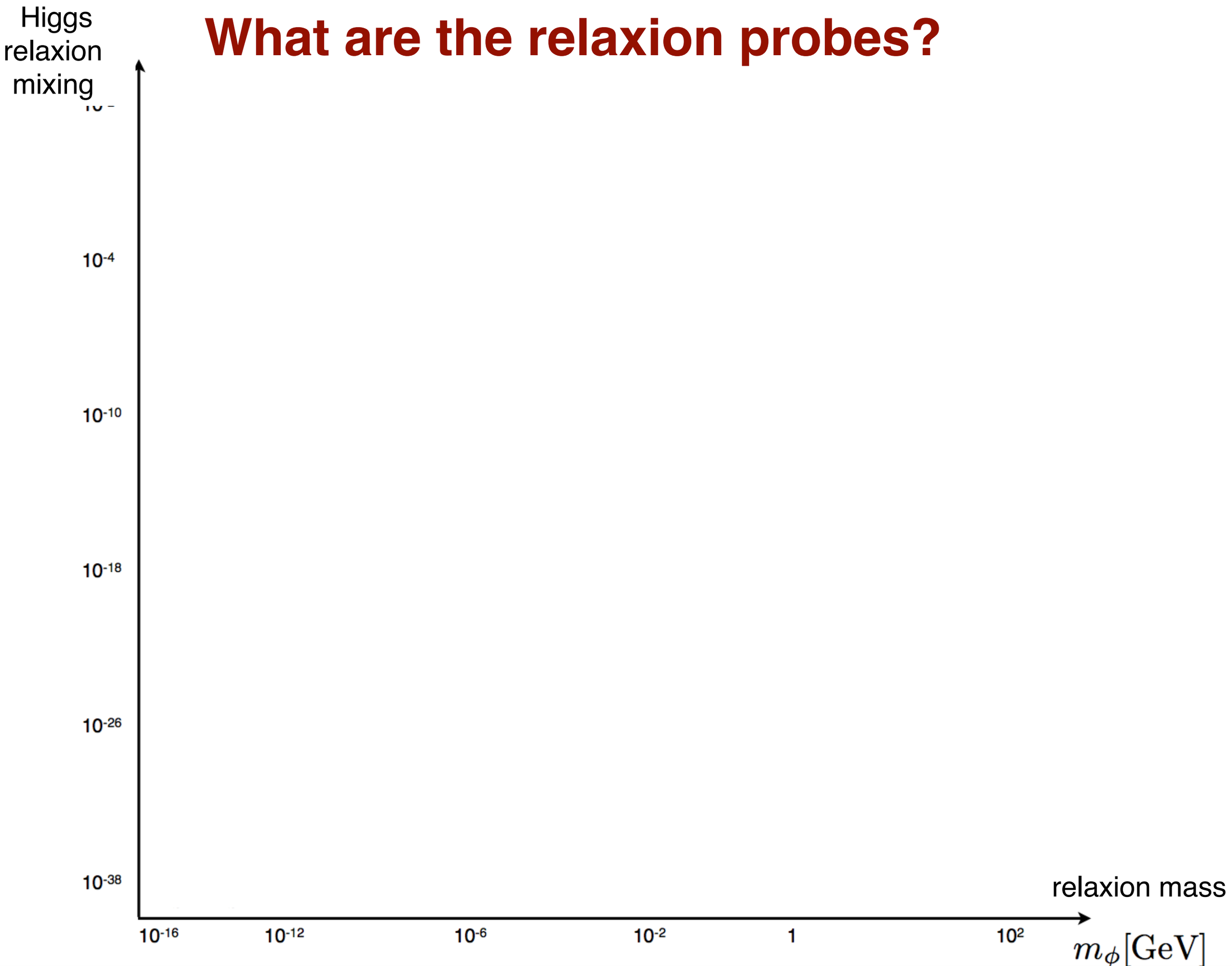
Highly relaxion dependent!! For generic Higgs portal suppressed by the mixing angle

Small mixing limit $$c_{\phi\phi H} \simeq \frac{m_\phi^2}{2v}$$

The coupling with the Higgs is a powerful probe of the relaxion!

Relaxion probes?

What are the relaxion probes?



What are the relaxion probes?

Higgs relaxion mixing

schematic summary of
[Flacke,CF, Fuchs,Gupta,Perez 2016]
slide credit to G.Perez

10^{-2}

MeV-GeV probed by high intensity frontier
(meson decays, electron and proton beam dump..)

few GeV probed by colliders

10^{-10}

10^{-18}

Astrophysics and cosmology for sub MeV relaxions

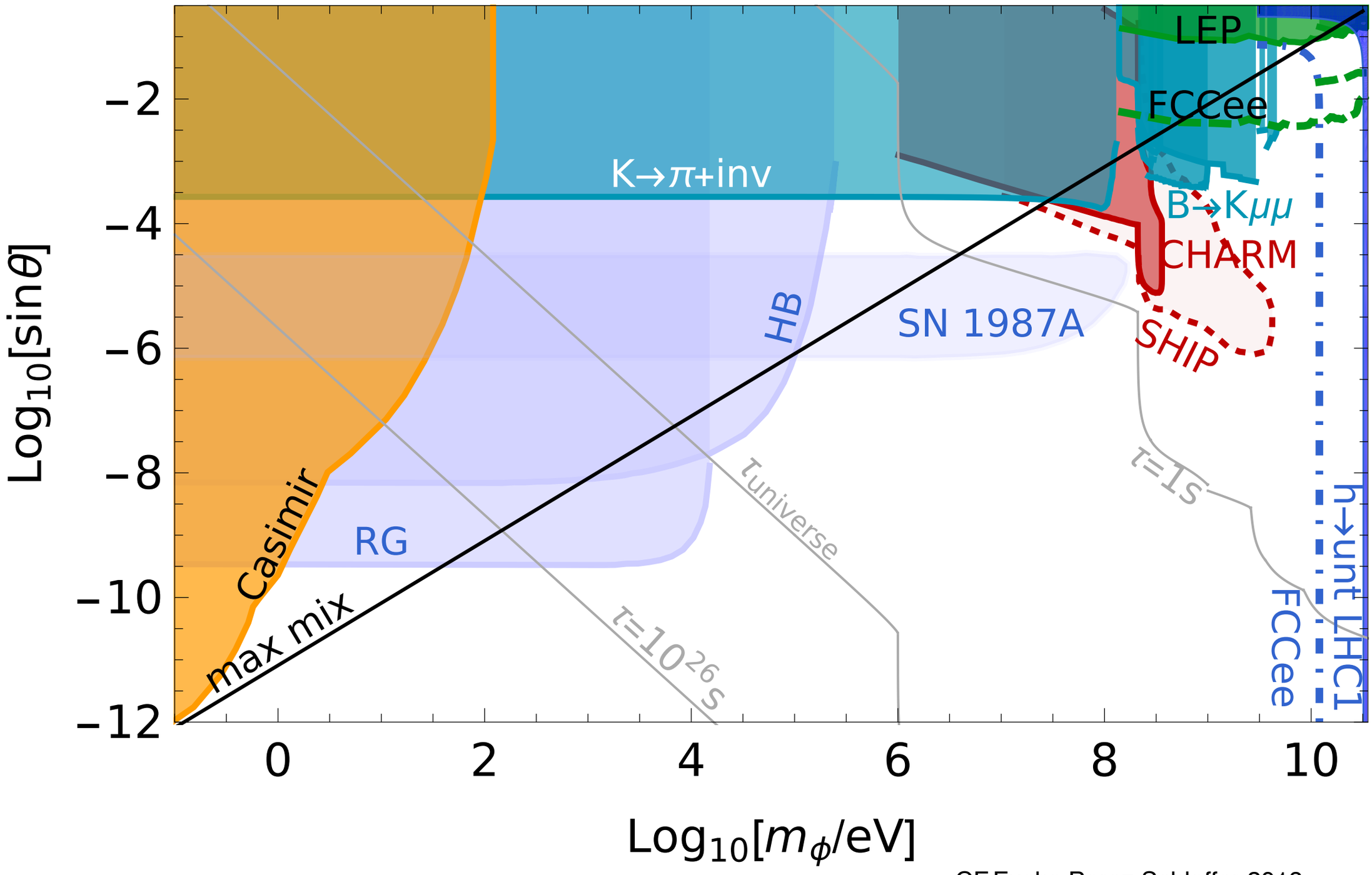
10^{-26}

Fifth force experiments for sub eV particles

10^{-38}

relaxion mass

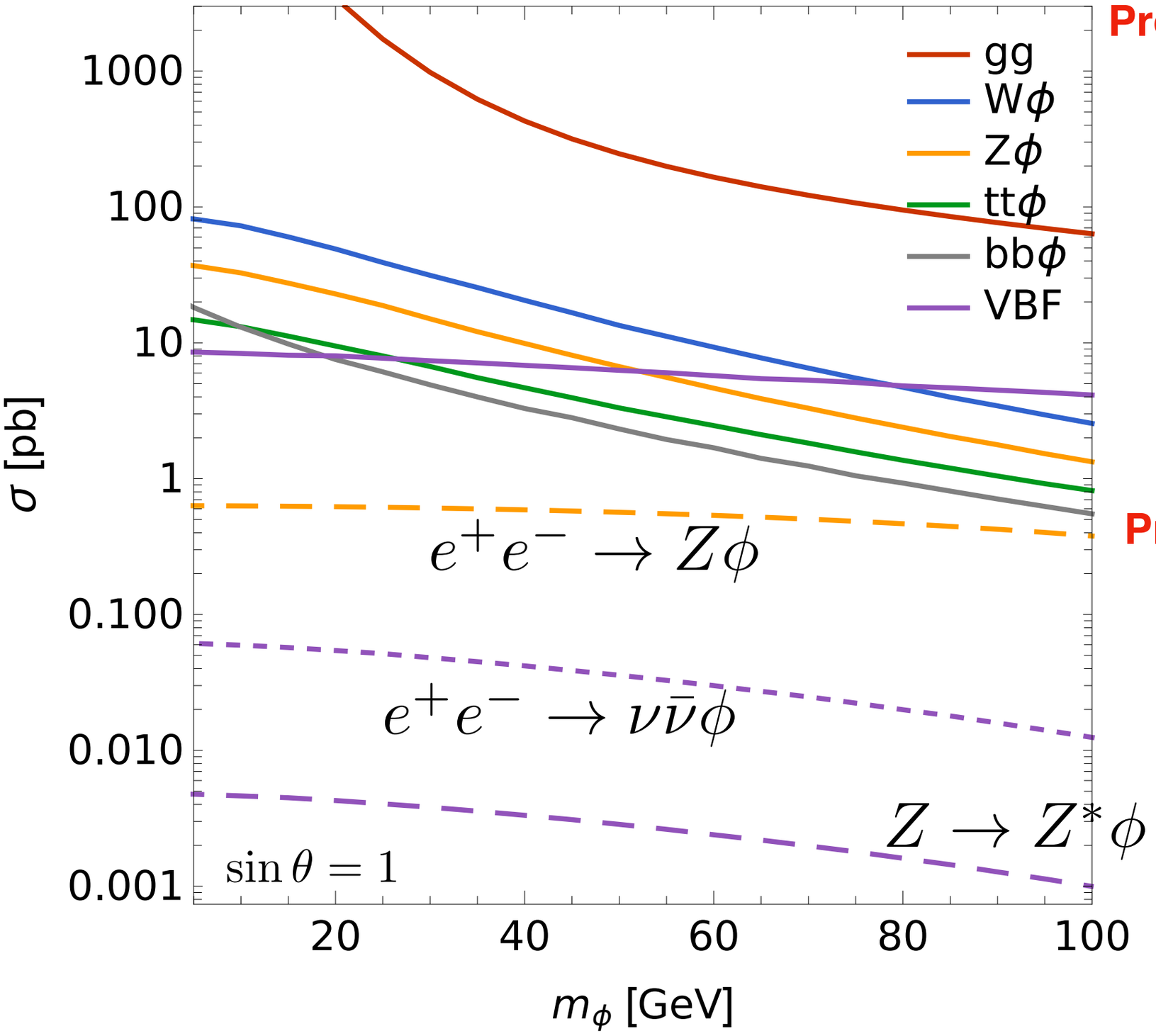
Relaxion probes overview



CF,Fuchs,Perez,Schlaffer 2018

Relaxion @ colliders

Relaxions @ colliders



Production at the LHC13 (solid)

- $pp \to \phi$ (gg)
- $pp \to Z\phi, W\phi$
- $pp \to t\bar{t}\phi, b\bar{b}\phi$
- $pp \to \phi jj$ (VBF)

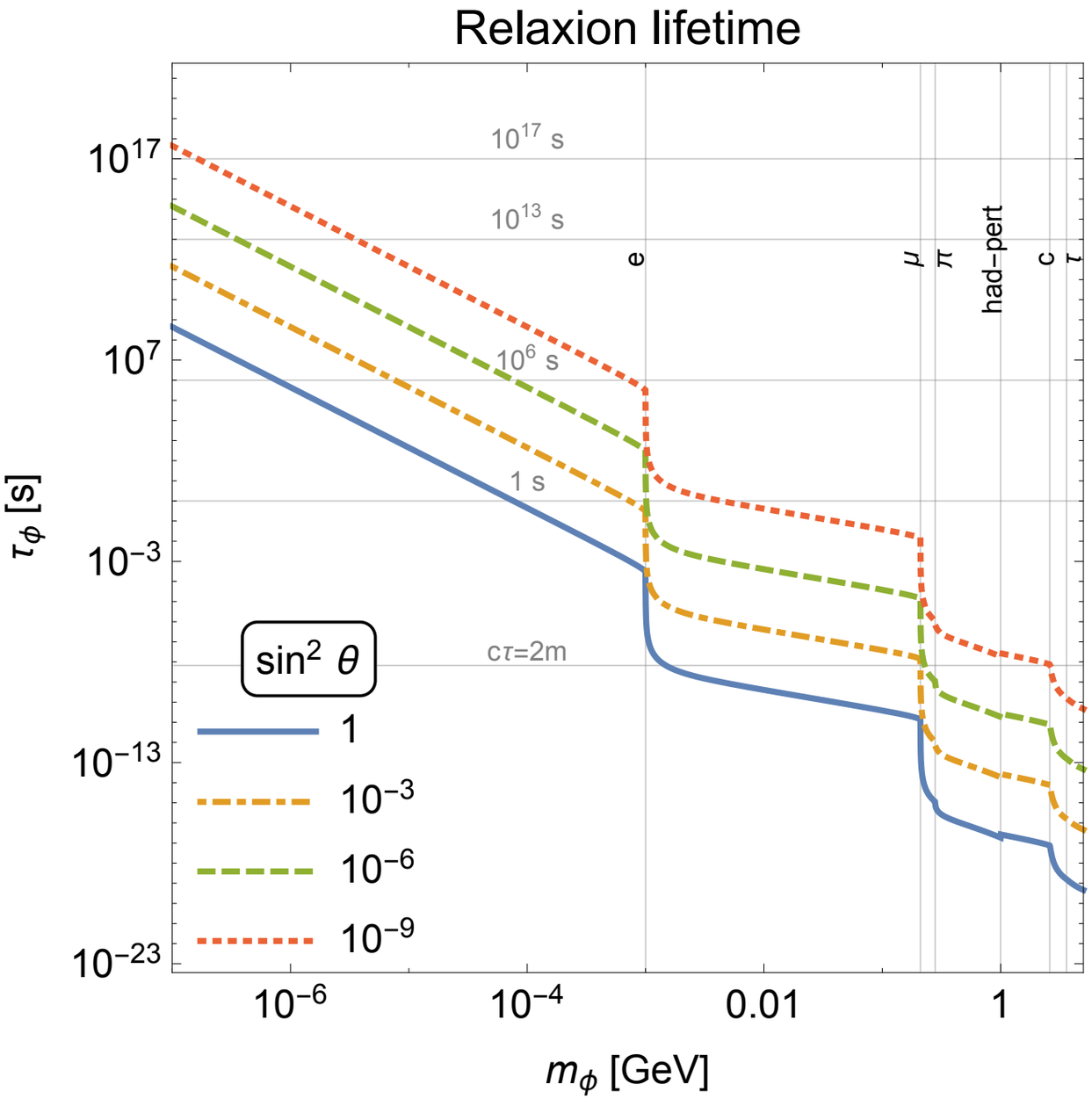
$p_T > 20$ GeV

Production at lepton collider (dashed)

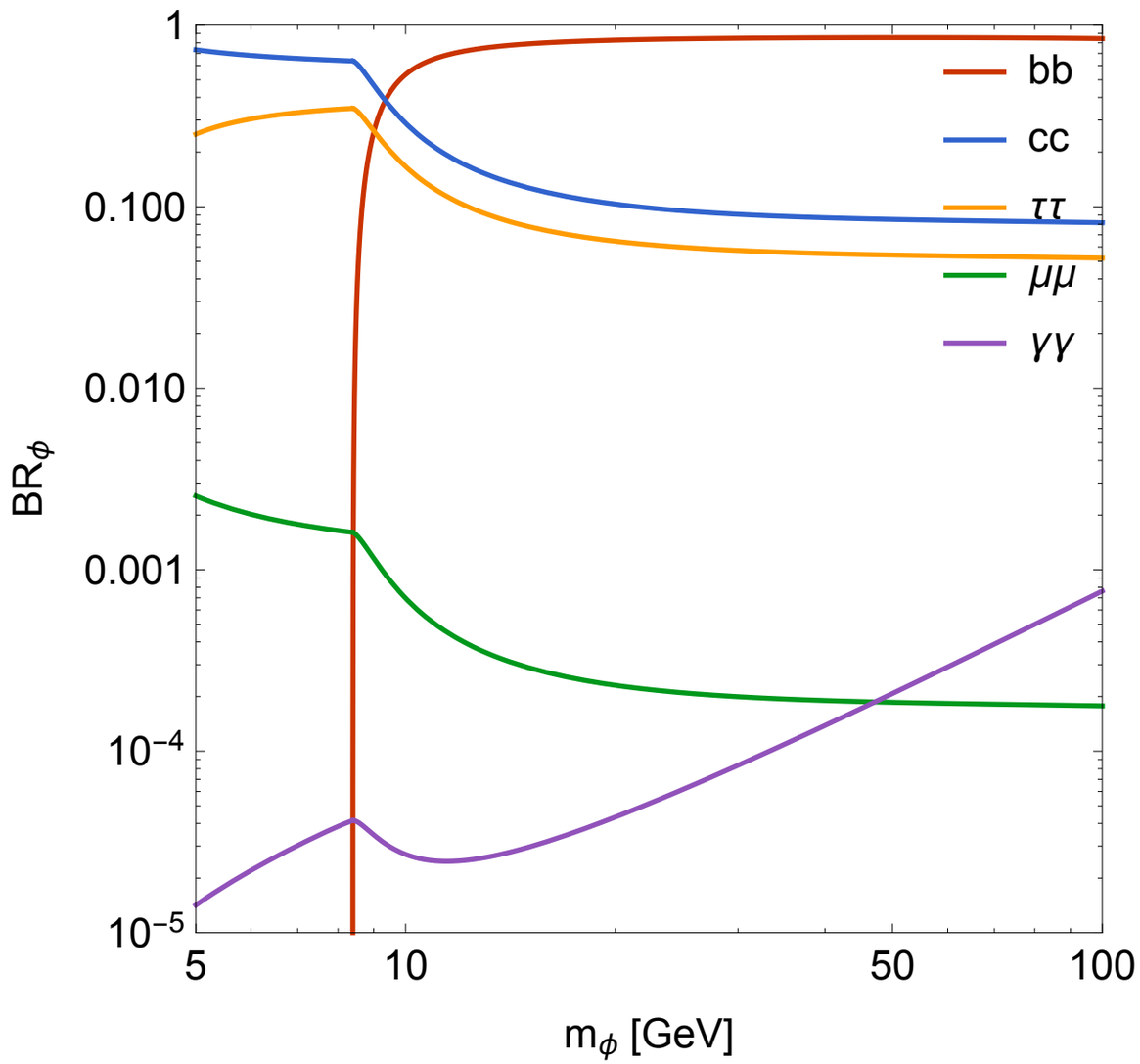
$\sqrt{s} = 240\text{GeV}$

[CF,Fuchs,Perez,Schlaffer 2018]

Relaxions @ colliders

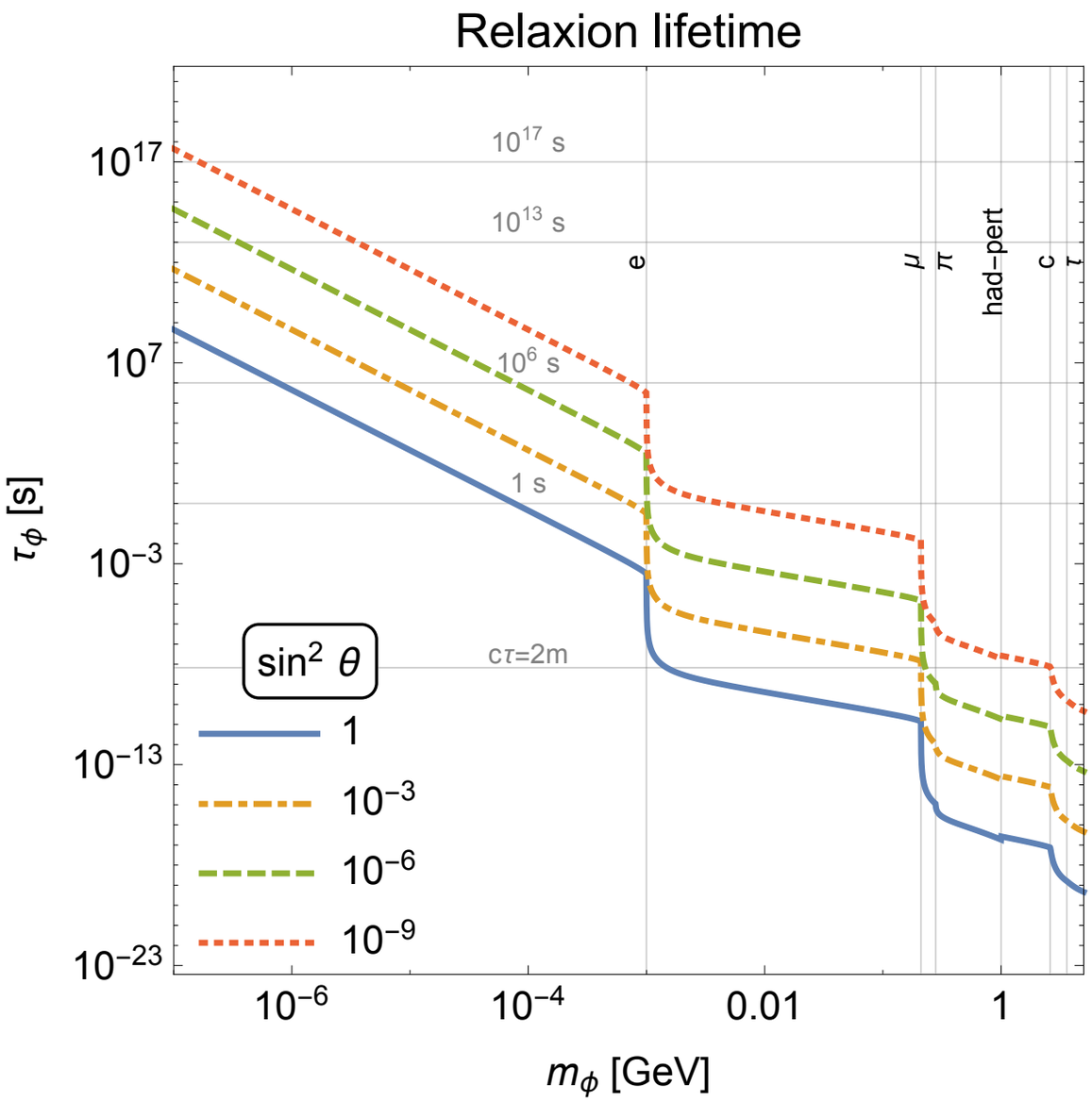


[Flacke,CF, Fuchs,Gupta,Perez 2016]

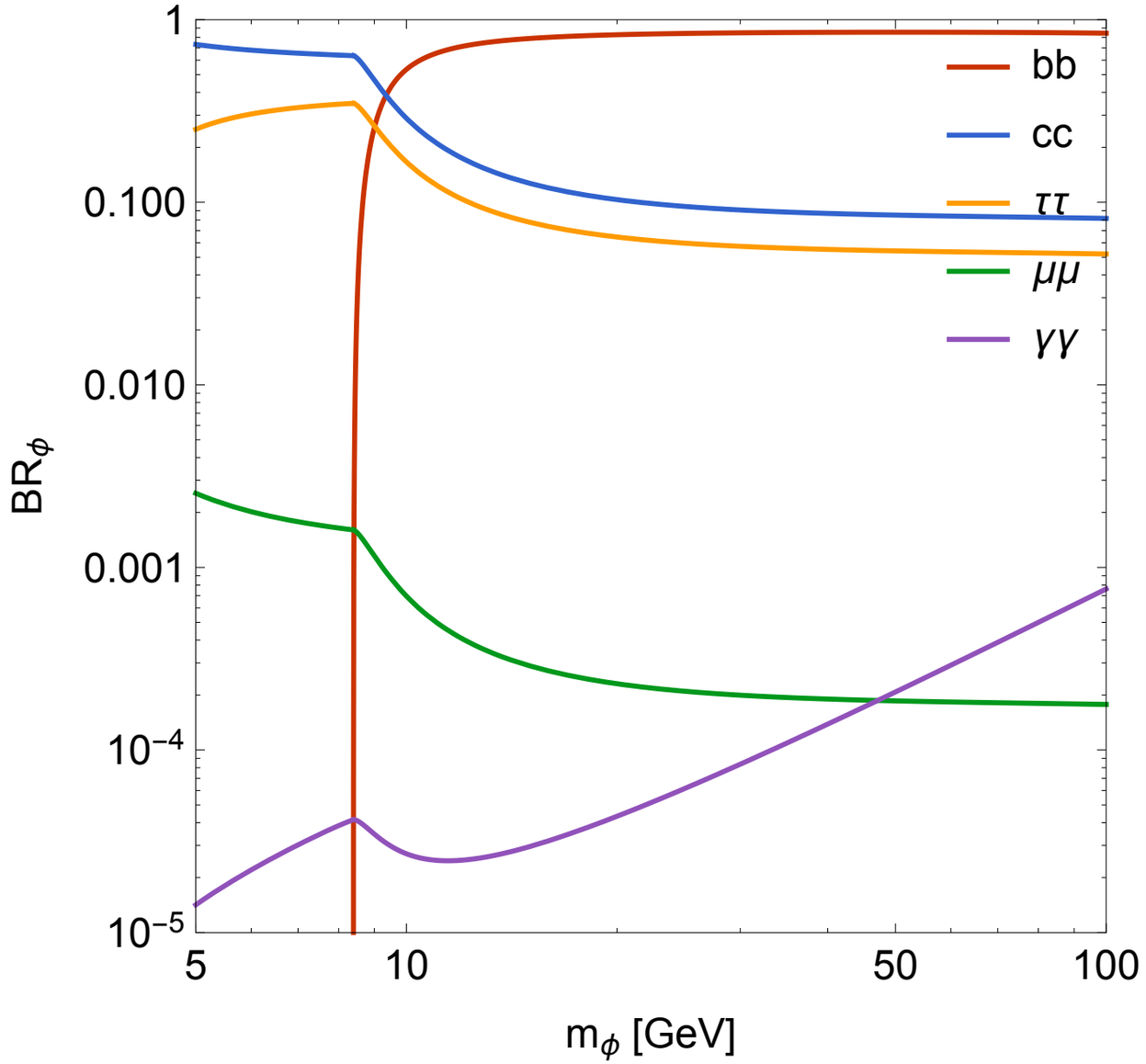


[CF,Fuchs,Perez,Schlaffer 2018]

Relaxions @ colliders

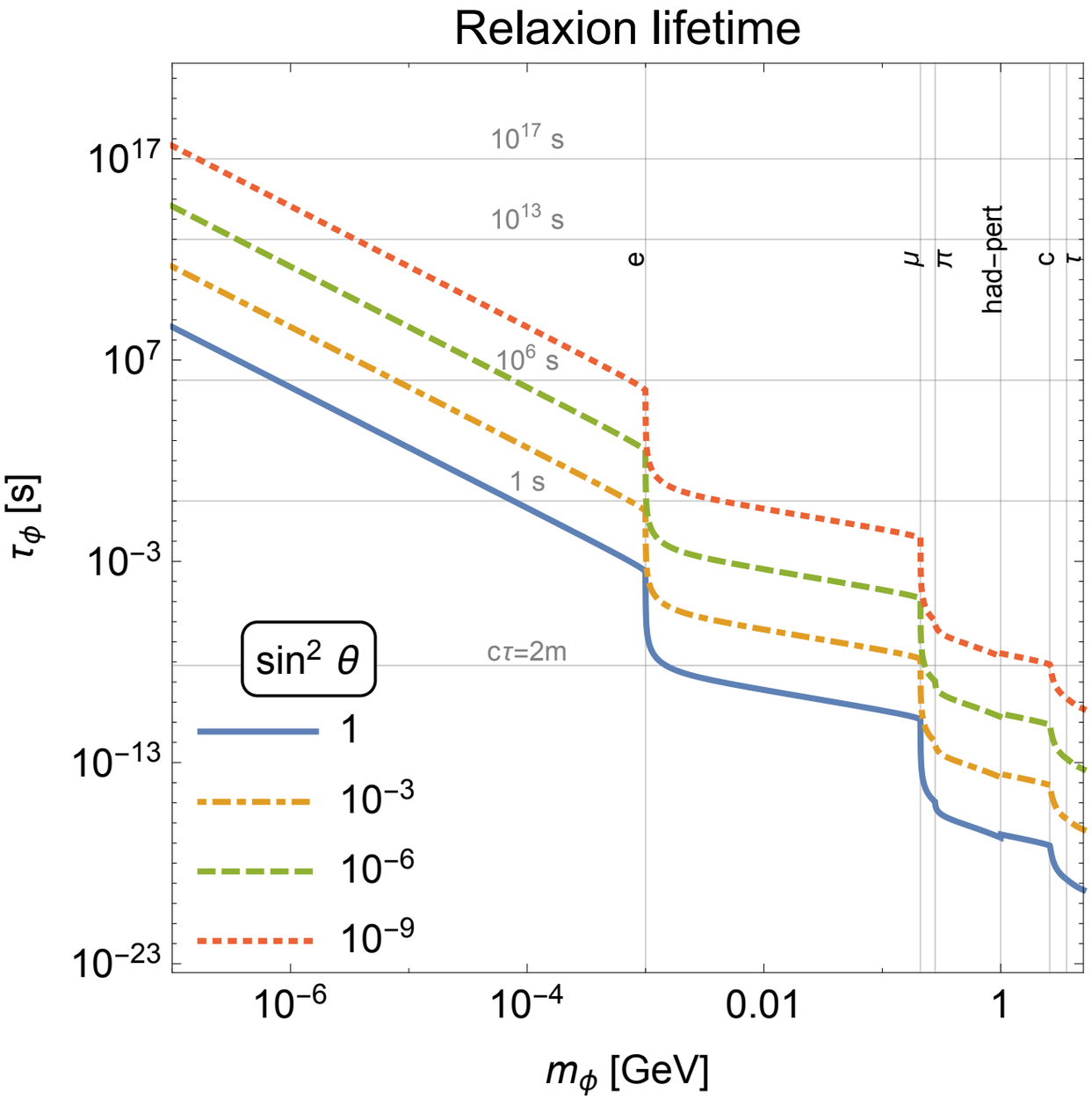


[Flacke,CF, Fuchs,Gupta,Perez 2016]



[CF,Fuchs,Perez,Schlaffer 2018]

Relaxions @ colliders



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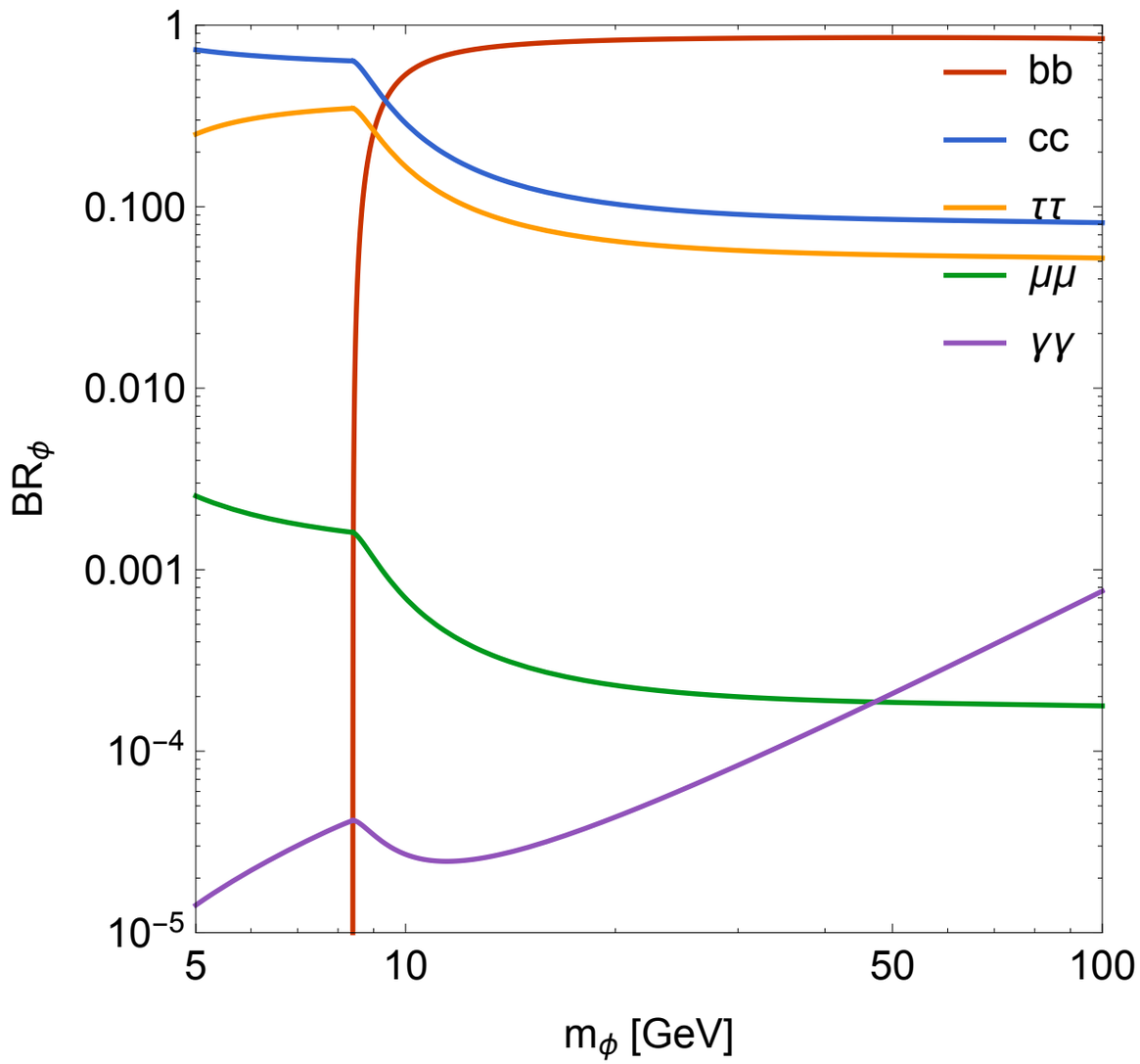
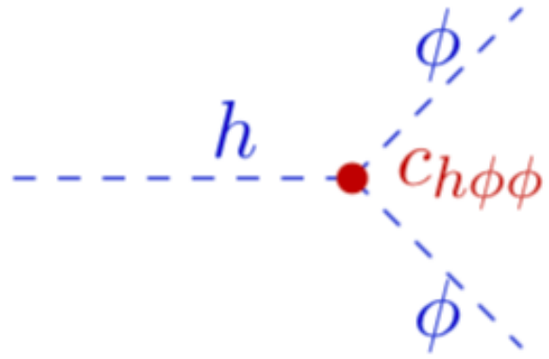


[CF,Fuchs,Perez,Schlaffer 2018]

Relaxions @ colliders



Via Higgs-relaxion coupling

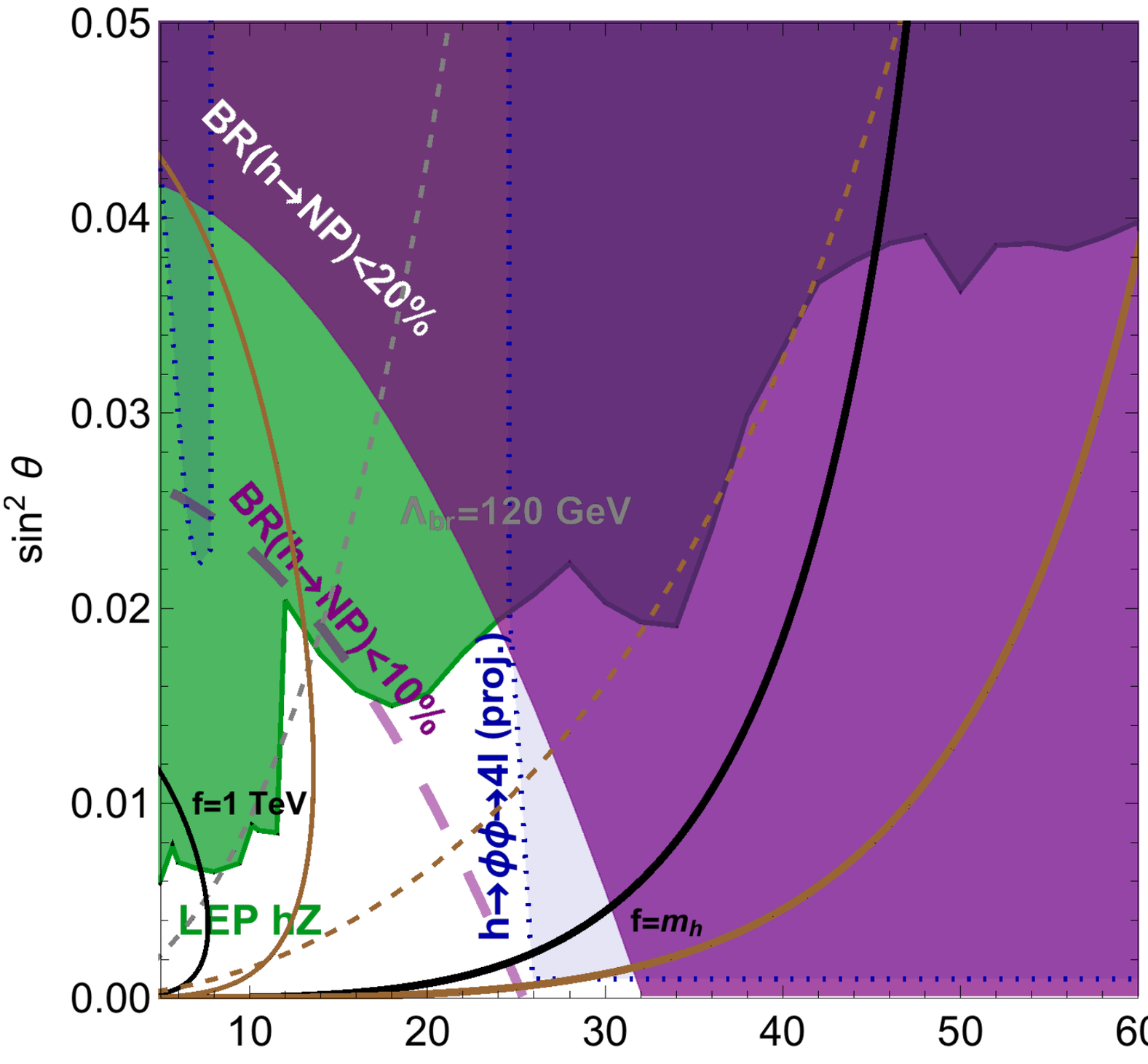
Small mixing: bound on the relaxion mass! $c_{\phi\phi H} \simeq \frac{m_\phi^2}{2v}$

(1) Direct production: relaxion decay products
—> Prompt decay in 4 fermions (2 fermions 2 photons)

(2) Indirectly via 2 parameters fit to Higgs couplings
(bound on Higgs to untagged)

$k = cos\theta(\text{universal coupling modifier})$ and $BR(h \to NP(\phi\phi))$

GeV relaxion window



$$BR(h \to \mathrm{NP}) \leq 20\% \ @ \ 95\%$$

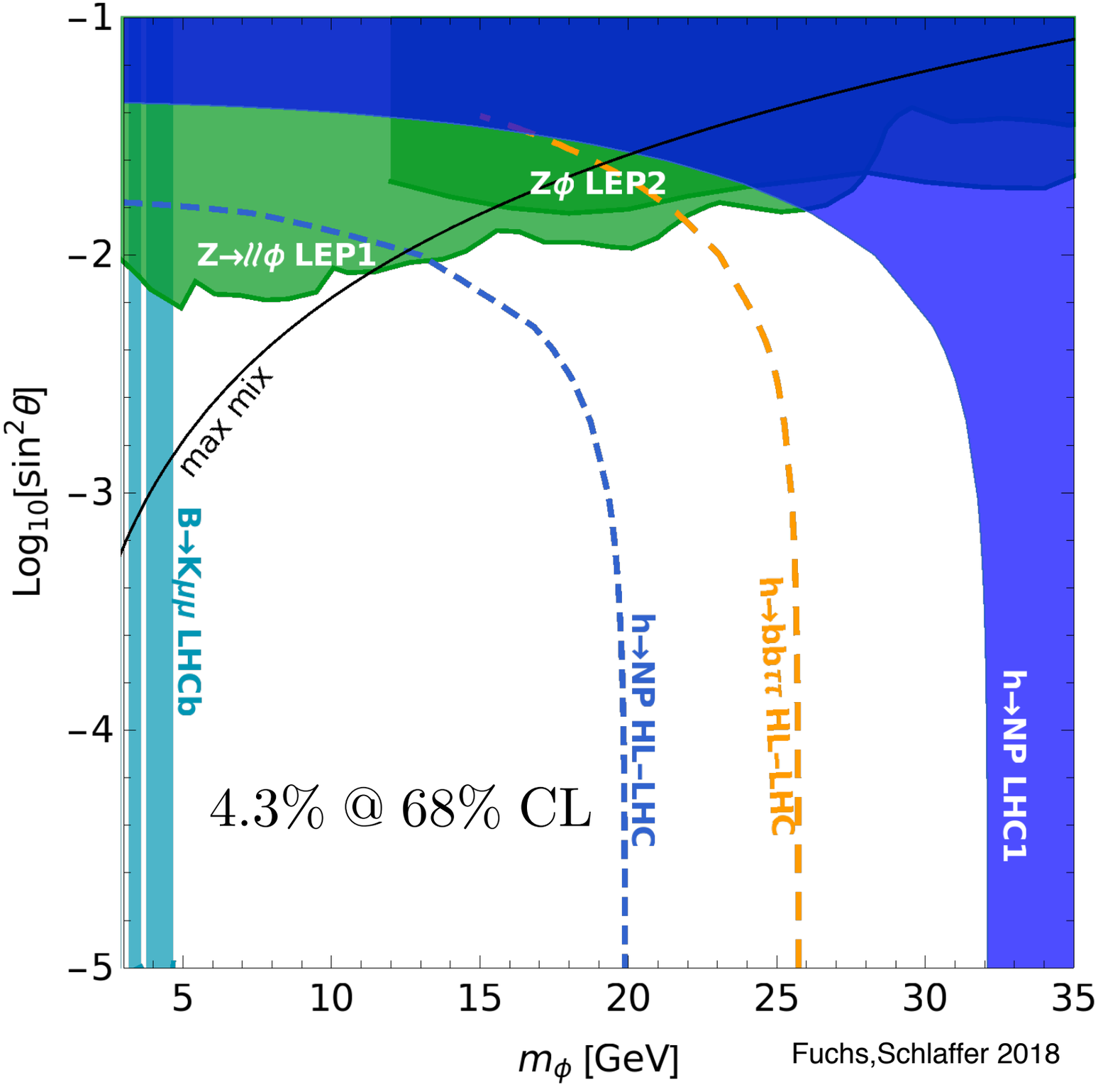
ATLAS and CMS at 8 TeV

P. Bechtle, S. Heinemeyer, O. Stal,
T. Stefaniak and G. Weiglein,2014

[Flacke,CF, Fuchs,Gupta,Perez 2016]

HL-LHC projections

$3\ \mathrm{ab}^{-1}$



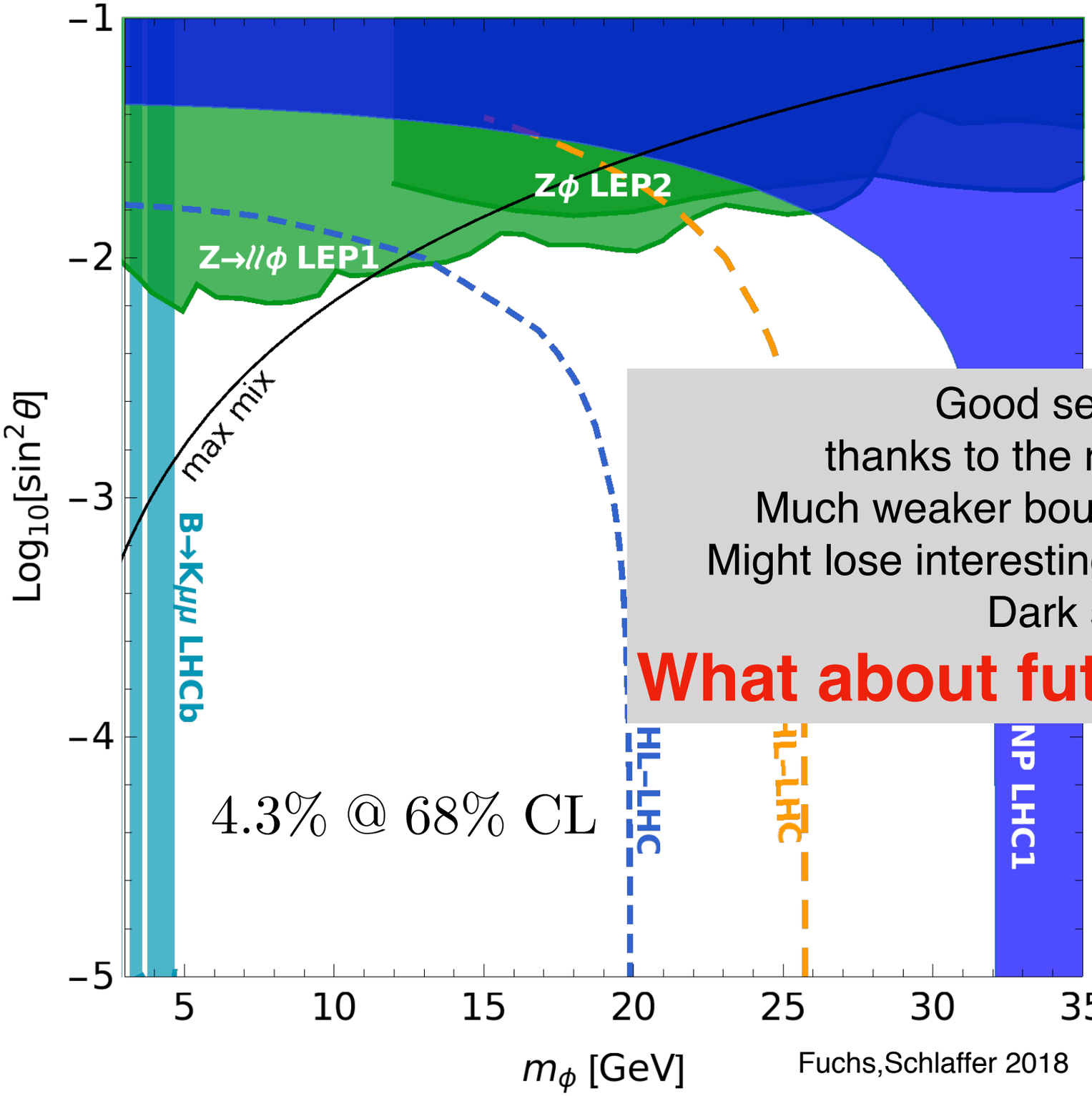
Fuchs,Schlaffer 2018

Extrapolation of CMS-PAS-HIG-17-024 @ 13 TeV

$35.9\ \mathrm{fb}^{-1}$

HL-LHC projections

$3\ \mathrm{ab}^{-1}$



Fuchs,Schlaffer 2018

Extrapolation of CMS-PAS-HIG-17-024 @ 13 TeV

$35.9\ \mathrm{fb}^{-1}$

Good sensitivity of HL-LHC
thanks to the relaxion-Higgs couplings.
Much weaker bounds for generic Higgs portal.
Might lose interesting connections with dark matter,
Dark sectors models..

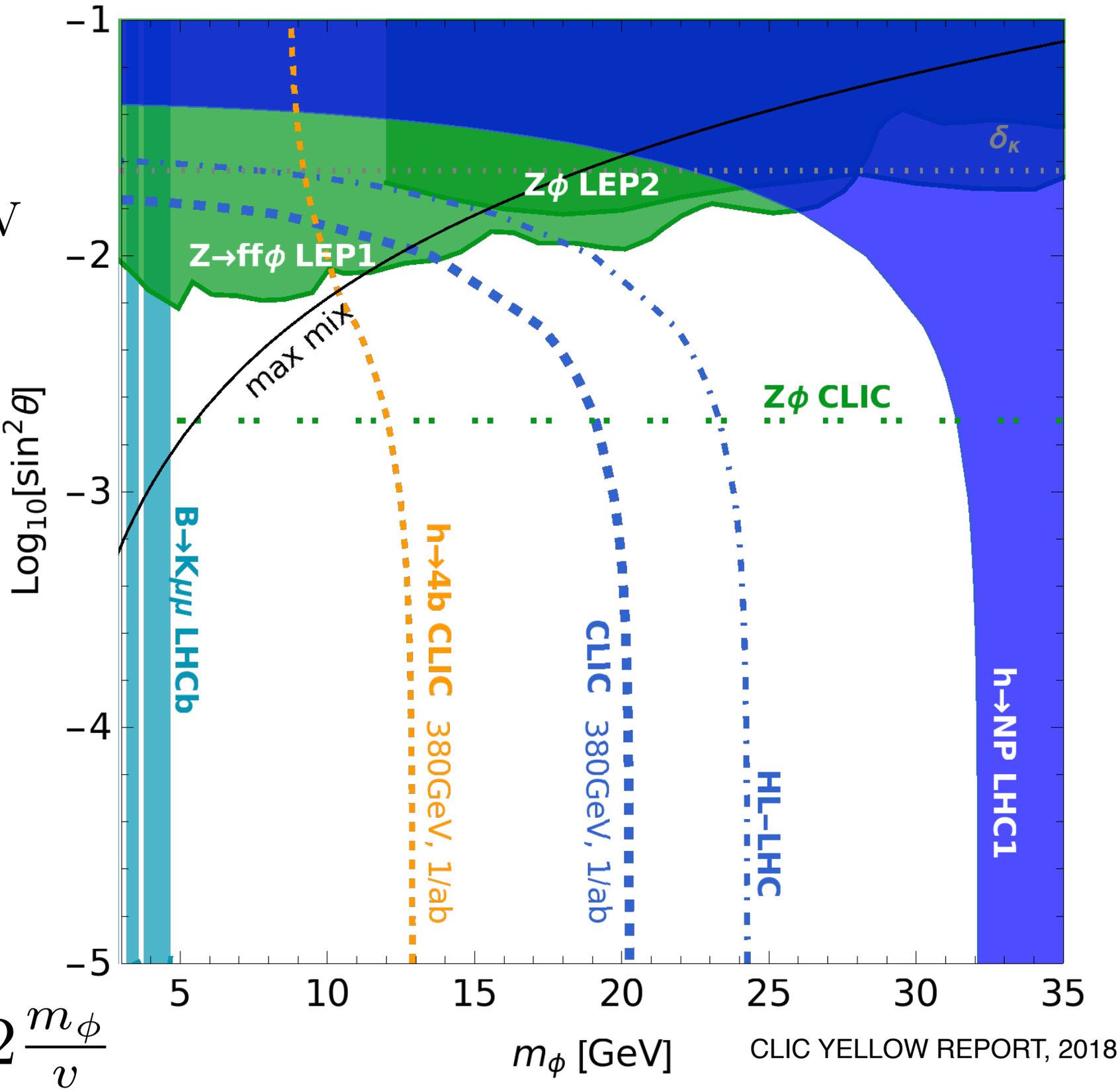
What about future lepton colliders?

Relaxion @ CLIC

Projections for CLIC

$3\ \mathrm{ab}^{-1}$

$\sqrt{s} = 380\ \mathrm{GeV}$

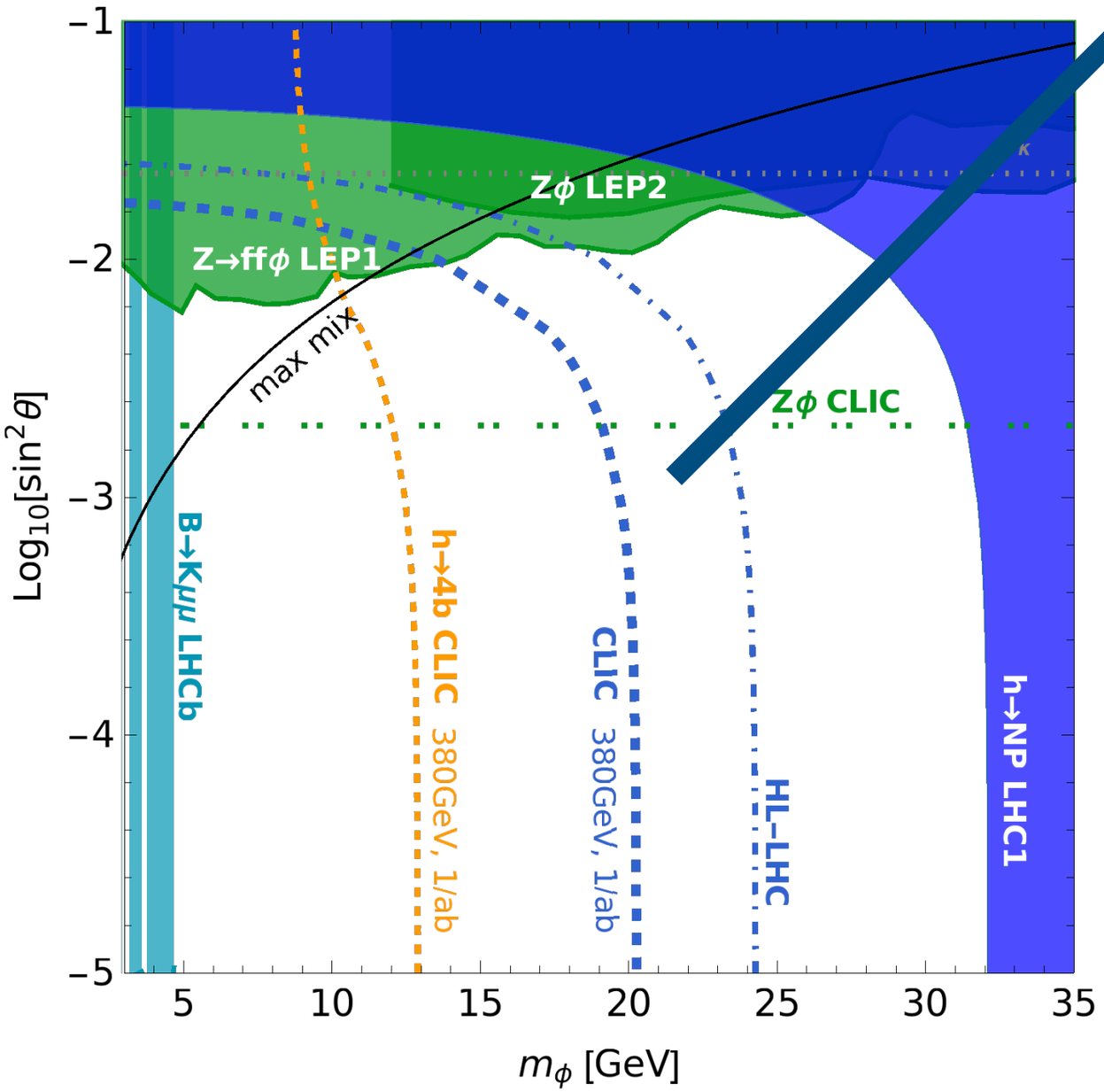


$\sin\theta \leq 2\frac{m_\phi}{v}$

CLIC YELLOW REPORT, 2018

Projections for CLIC

$$BR(h \to \phi\phi) \leq BR(h \to \text{unt})_{\text{CLIC}} = 4.6\%(95\%\text{CL})$$



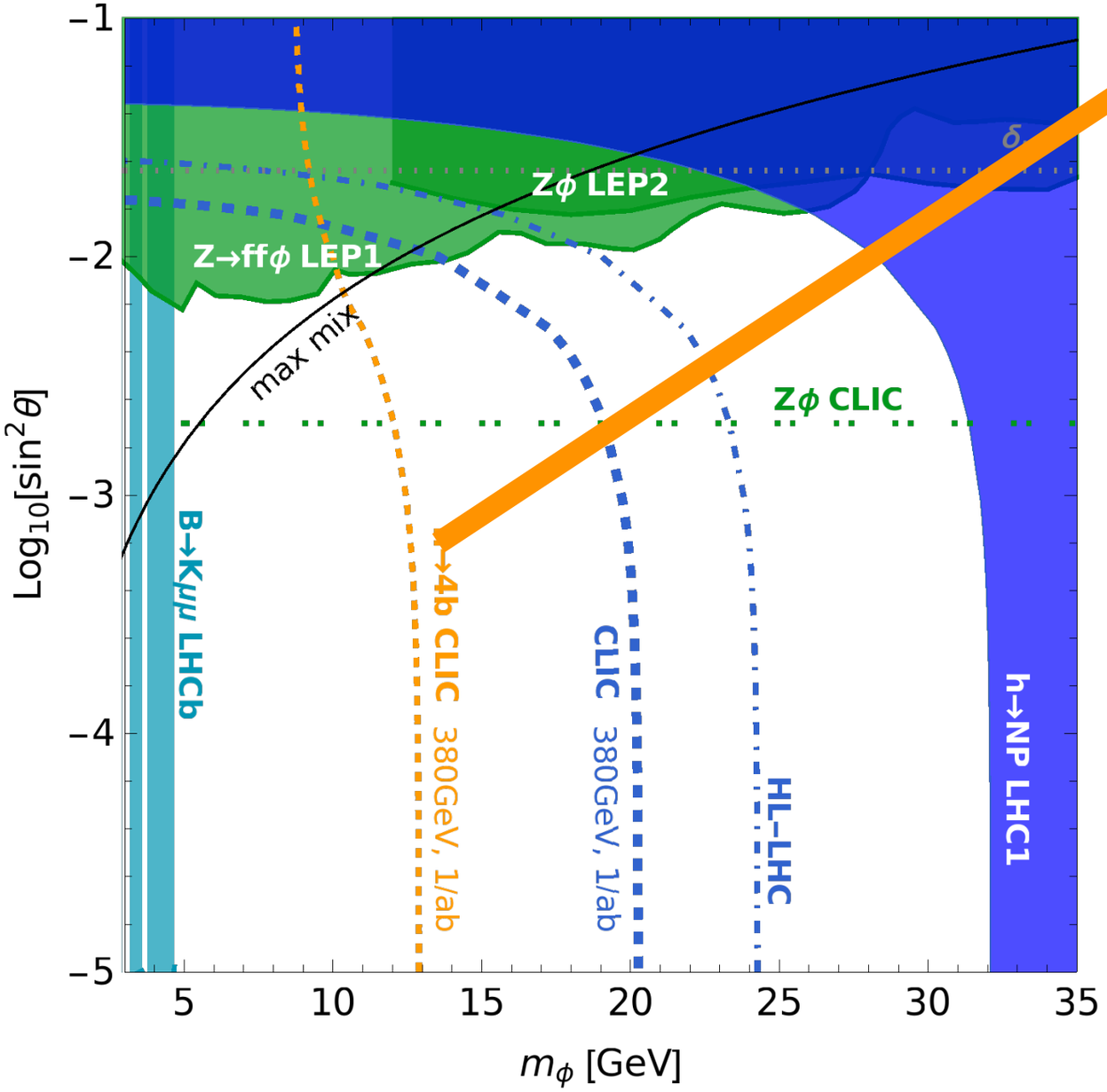
$$c_{\phi\phi H} \simeq \frac{m_\phi^2}{2v}$$

Small mixing limit

Projections for CLIC

Rescaling of the projection for 240GeV-250 GeV CEPC run by the square root of the total Higgs events

Z.Liu,L.Wang,H.Zhang, 2015



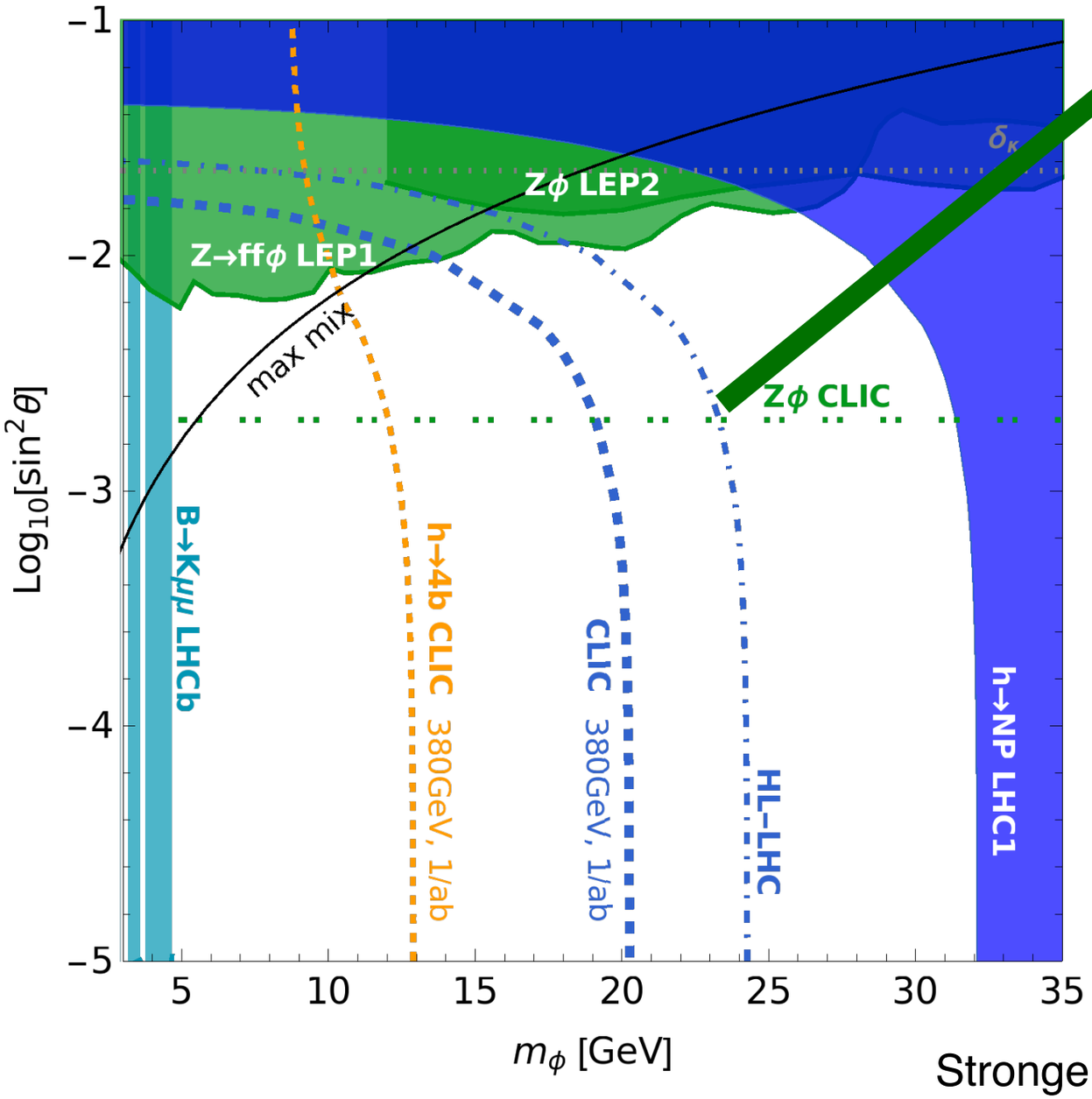
Possible room for improvement at higher energy runs for CLIC. Dedicated study needed

Projections for CLIC

Rescaling from ILC study via Z recoil techniques

arXiv:1801.09662

Bound independent from relaxion decay mode



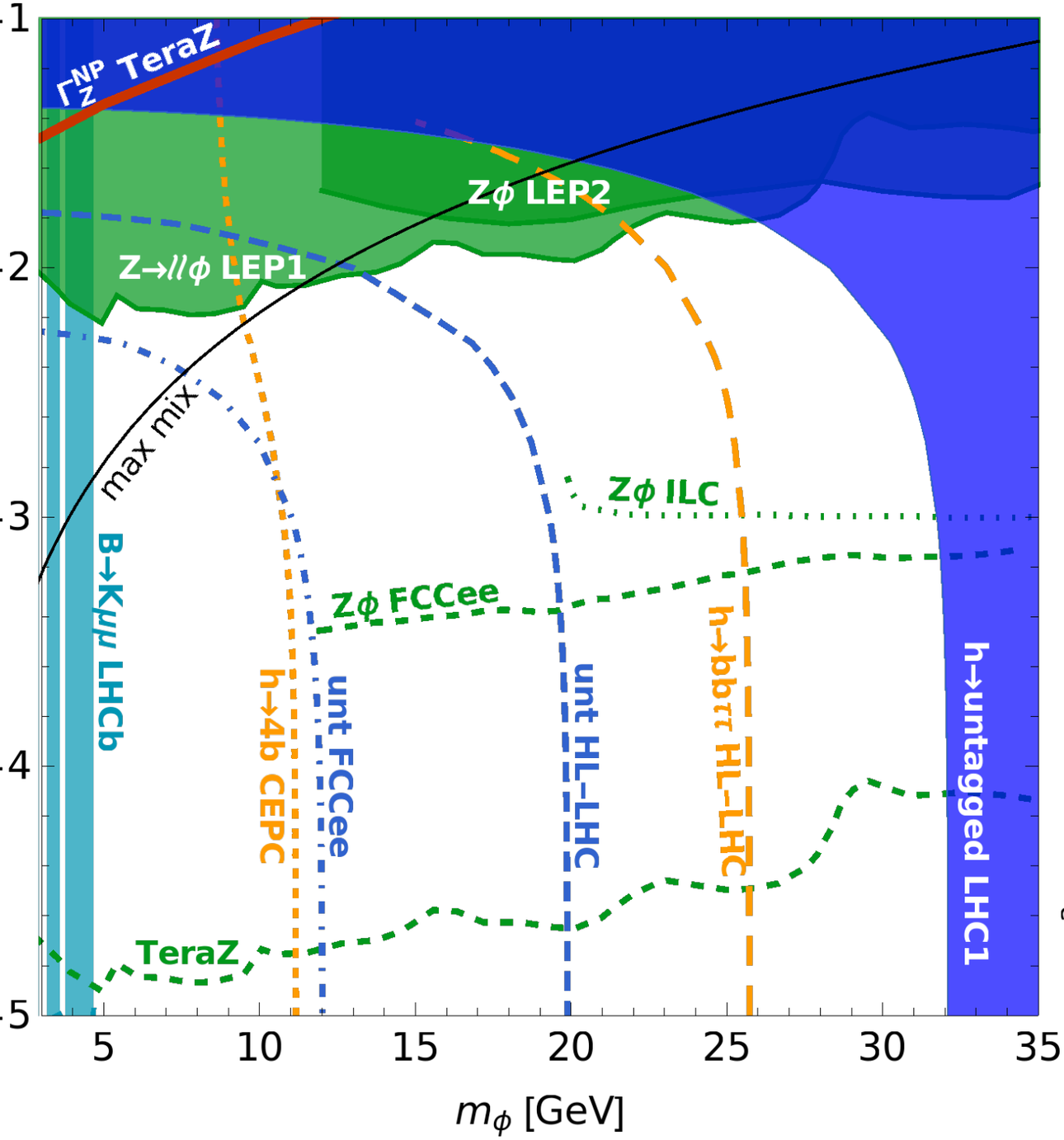
This applies to Higgs portals models in general
Possible connections to dark matter?

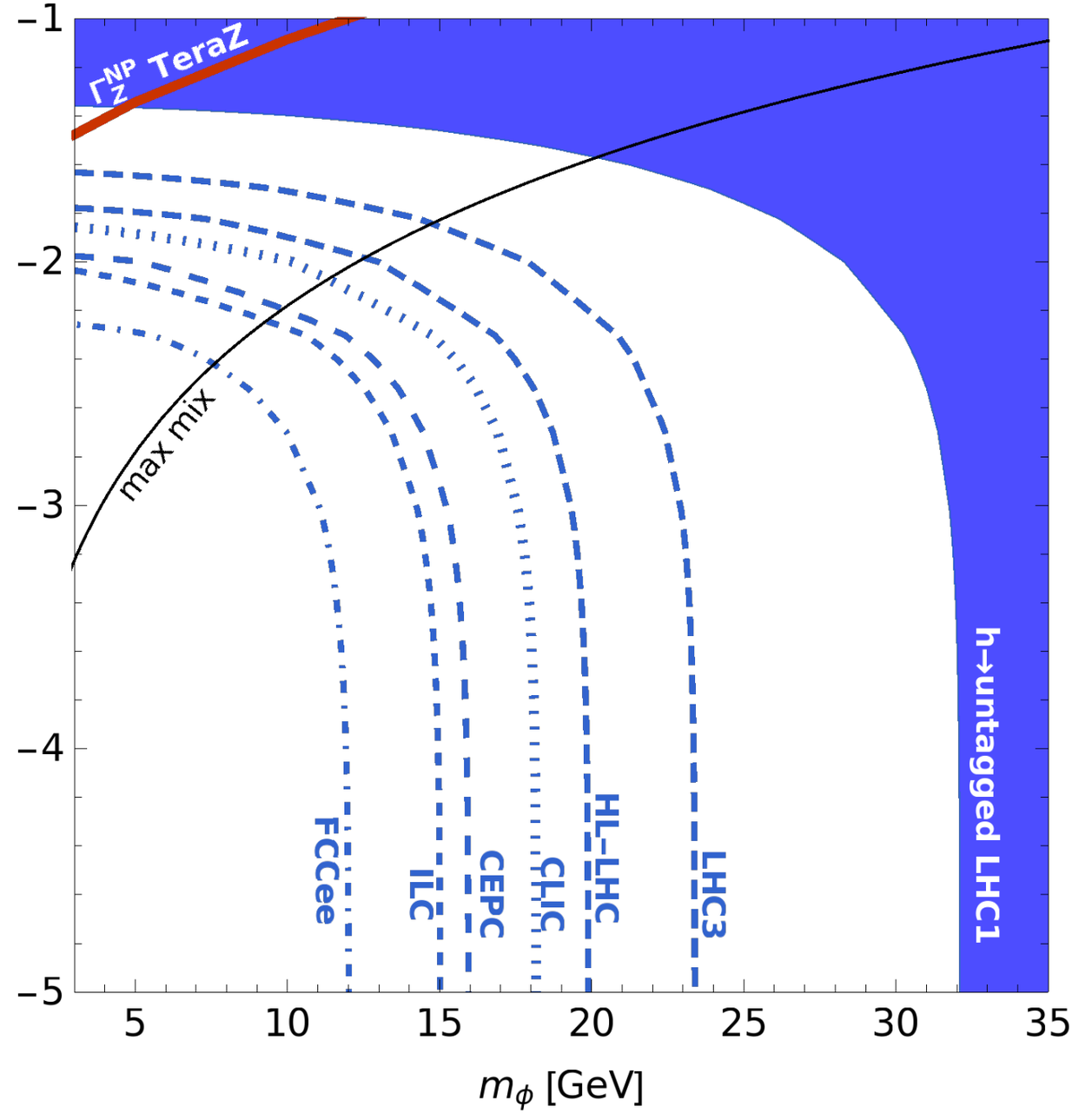
Stronger sensitivity might arise from model dependent
Studies, e.g. relaxion into b's decay

Outlook

Improvement of the sensitivity to relaxion parameter space with respect HL-LHC

Sensitivity to models with generic light scalars mixed with the Higgs


Γ_Z^{NP} TeraZ
Zϕ LEP2
Z→llϕ LEP1
max mix
Zϕ ILC
Zϕ FCCee
B→Kμμ LHCb
h→4b CEPC
unt FCCee
unt HL–LHC
h→bbττ HL–LHC
h→untagged LHC1
TeraZ
−1
−2
−3
−4
−5
5
10
15
20
25
30
35
m_ϕ [GeV]


Γ_Z^{NP} TeraZ
max mix
FCCee
ILC
CEPC
CLIC
HL–LHC
LHC3
h→untagged LHC1
$\mathrm{Log}_{10}[\sin^2\theta]$
−1
−2
−3
−4
−5
5
10
15
20
25
30
35
m_ϕ [GeV]