Probing Higgs & relaxion physics @ the high energy precision frontier

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Weizmann

1st FCC Physics Workshop

CERN, Jan. 17

Outline

- Higgs & origin of fermion masses at the FCCee. (new: $h \to s\bar{s}$)
- Probing relaxion physics at the FCCee at the Z pole & via precision Higgs.
- Summary.

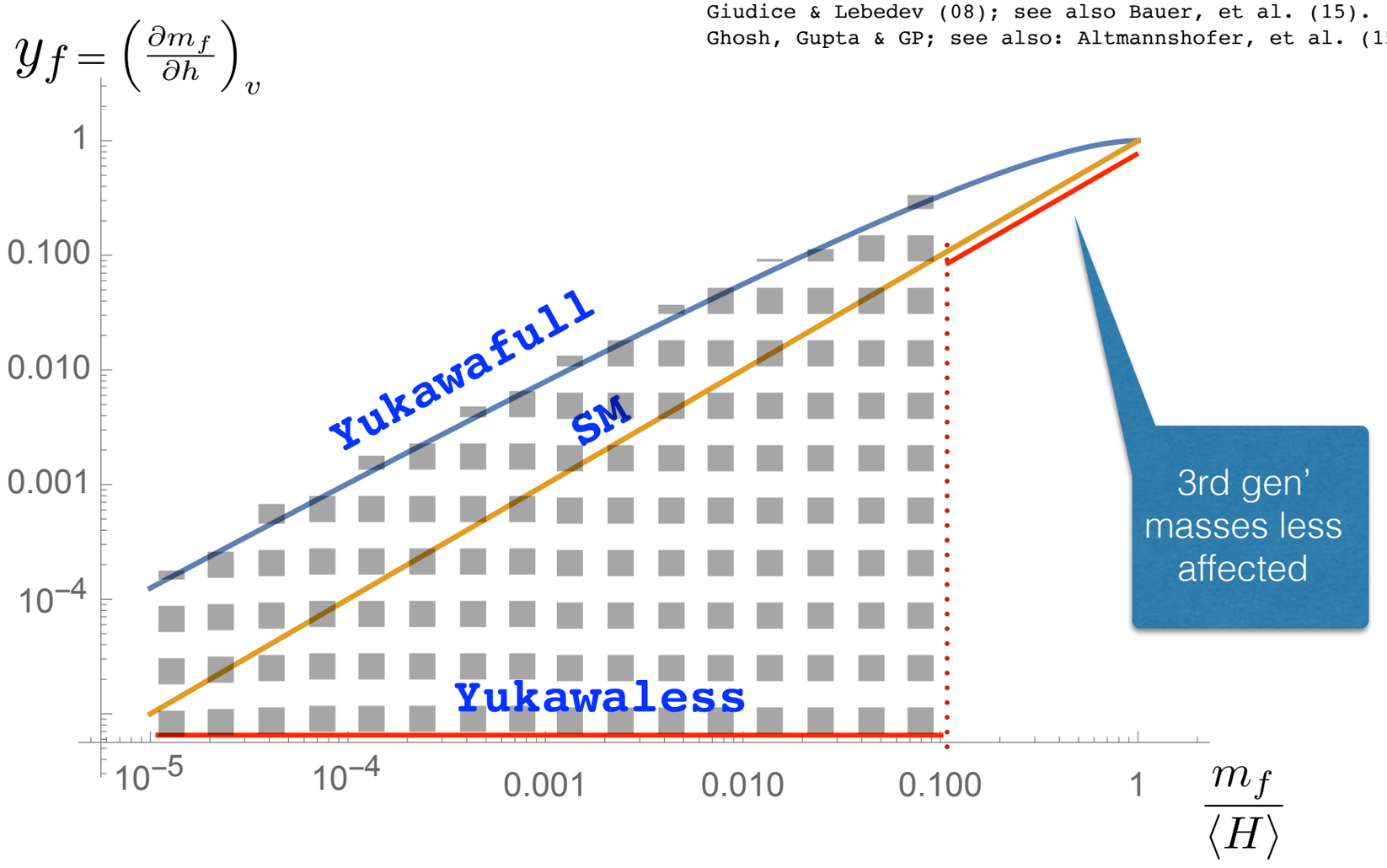
Fermion masses & the flavor puzzle

(i) How are elementary matter masses generated ?

(ii) What sets their hierarchy ?

$$y_f = \left(\frac{\partial m_f}{\partial h}\right)_v$$

Giudice & Lebedev (08); see also Bauer, et al. (15).
Ghosh, Gupta & GP; see also: Altmannshofer, et al. (15).



Flavor physics at the 21st century: can we directly probe the Yukawas ?

(i) Is the Higgs mechanism behind the origin of fermion masses?

(ii) Does it follow the SM prediction (hier' masses = hier' Yukawas)?

Discovery of origin of the top & tau masses (LHC, 2016)

Signal strength: $\mu_x = \dfrac{\sigma^{\rm prod}}{\sigma^{\rm SM}} \times \dfrac{{\rm BR}(h \to x)}{{\rm BR}^{\rm SM}(h \to x)} \quad ({\rm SM\ predicts}\ \mu_x = 1)$

ATLAS+CMS official (tau)
& unofficial (top) combinations:
ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002

$$\mu_{\tau,t} \simeq 1.1 \pm 0.24\,, \quad 2.0 \pm 0.4 \quad \Leftrightarrow \quad 5\,\sigma\,!$$

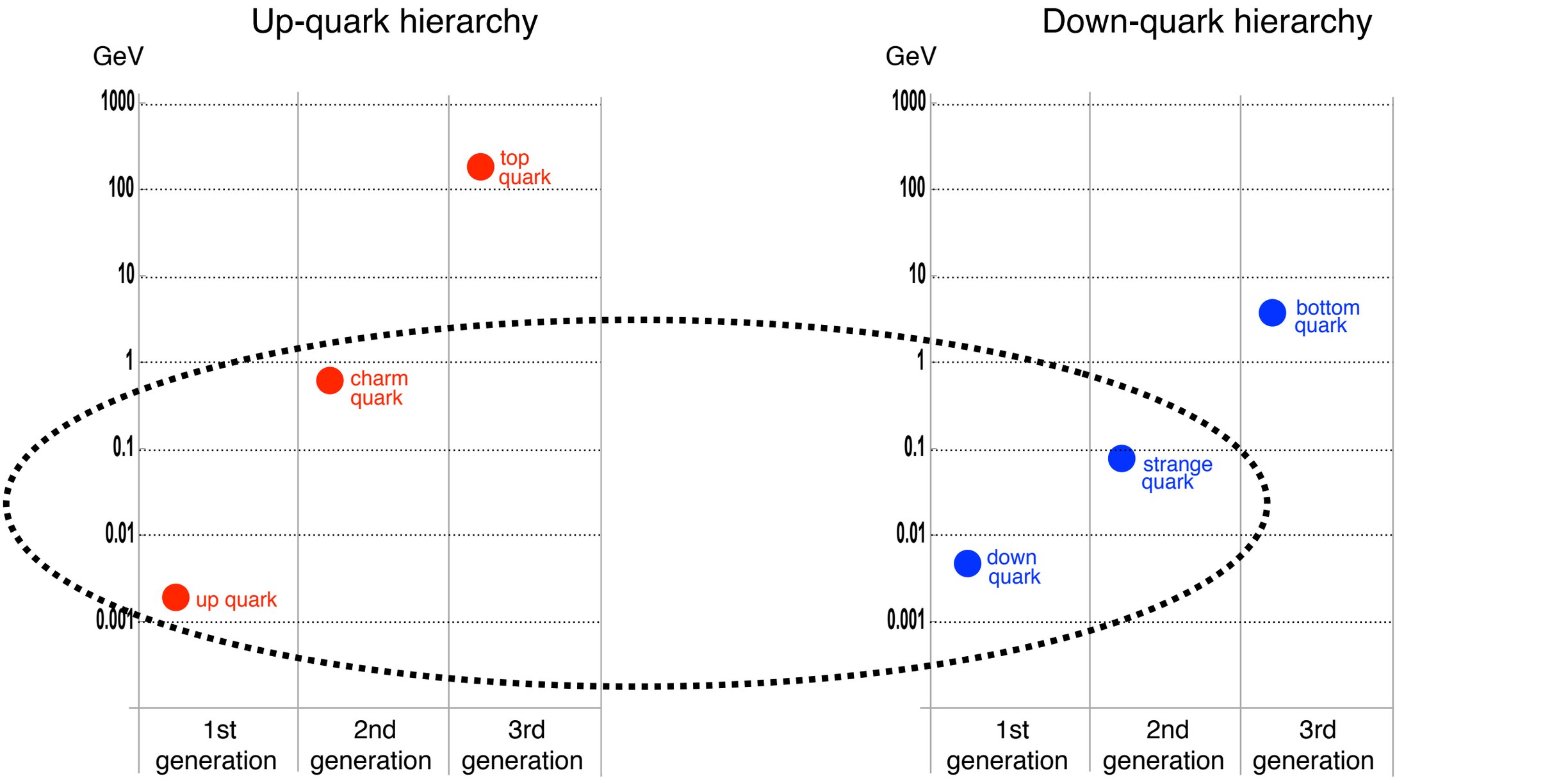
2016: The Higgs mechanism is behind the tau and top masses!

However, what about lighter fermion (quark) masses ?

$$\mu_{\mu,b} \simeq 0.1 \pm 2.5\,, \quad 0.6 \pm 0.25\,.$$ credit: Y. Soreq.

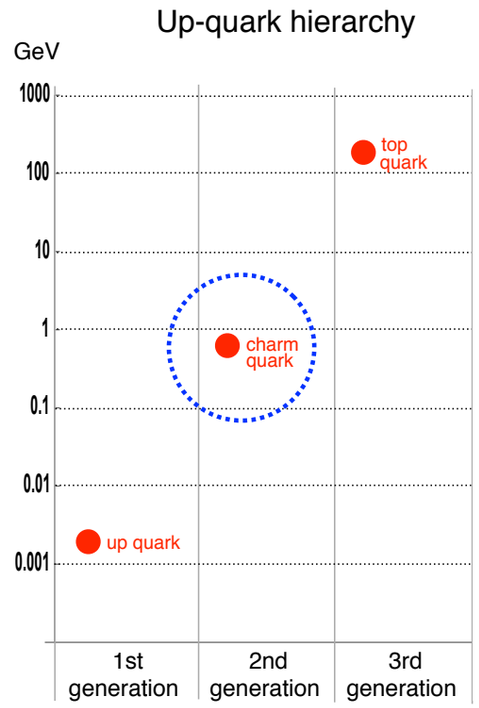
Very weak/non-existing bounds on lighter fermions!

The flavor puzzle, the origin of mass hierarchy

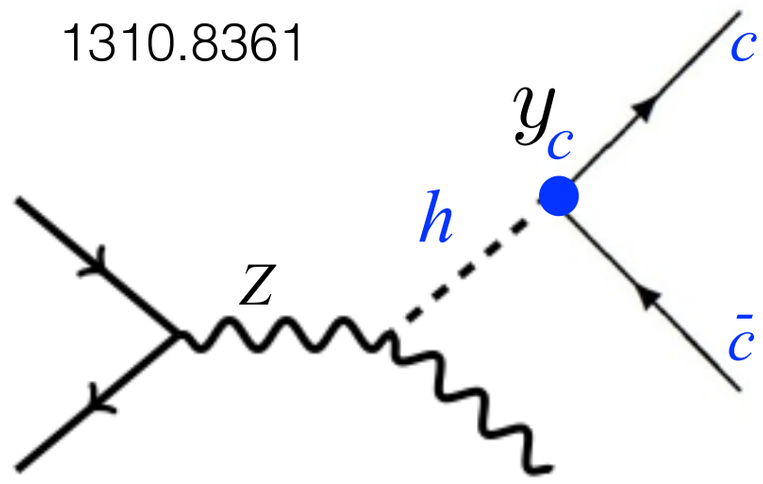


Testing for the Higgs mechanism of light quark masses

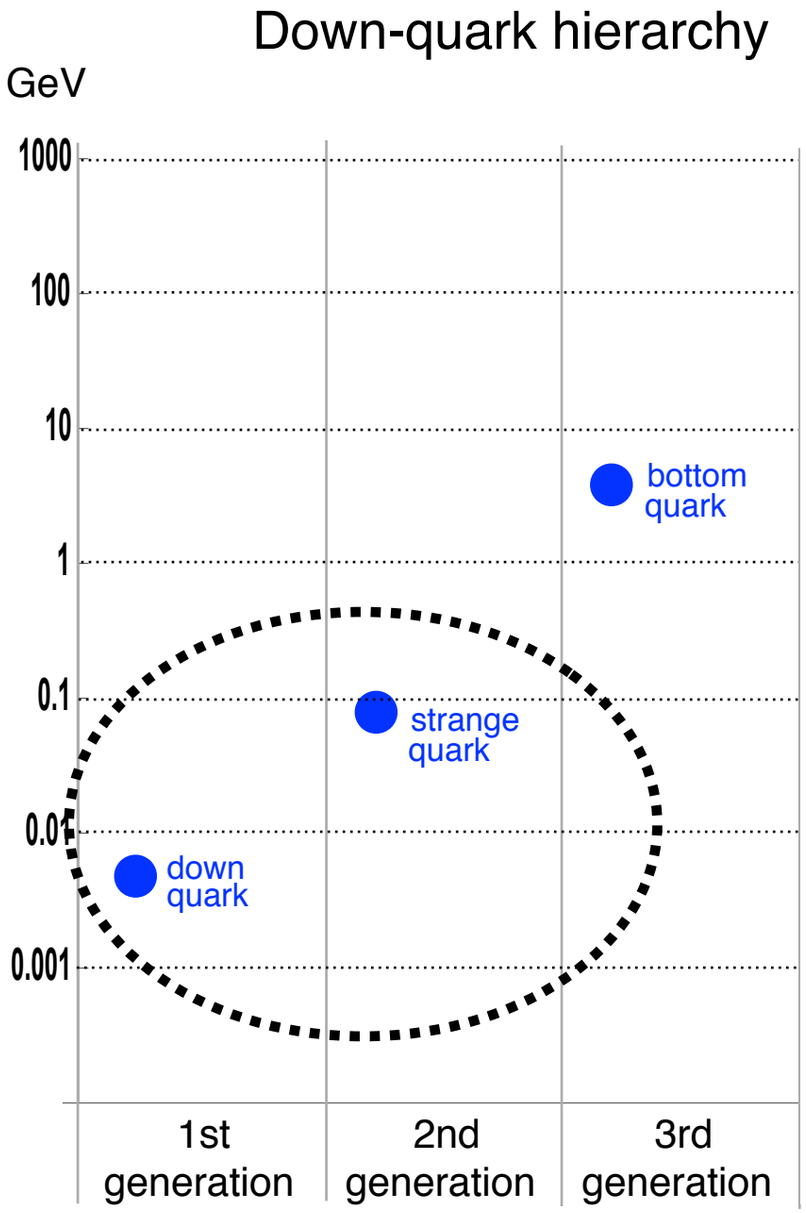
- Higgs decay to light quarks: (*i*) hard to predict; (*ii*) have large backgrounds.



- Yet, charm is heavy enough & its decay is visible =>
  FCCee: coupling will be established at the % level. 1310.8361

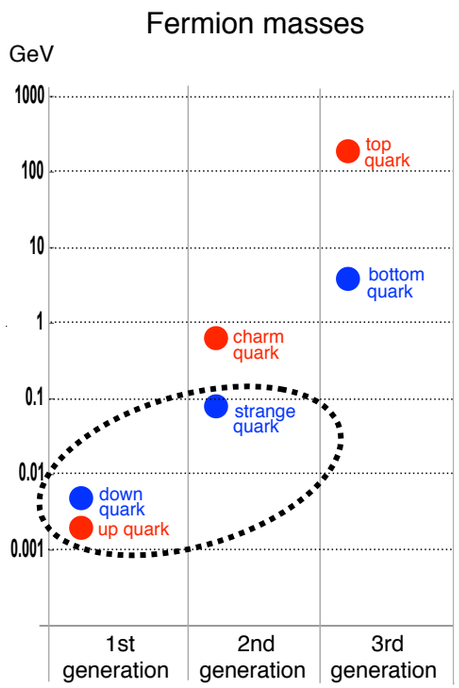


Down sector? lighter quarks?

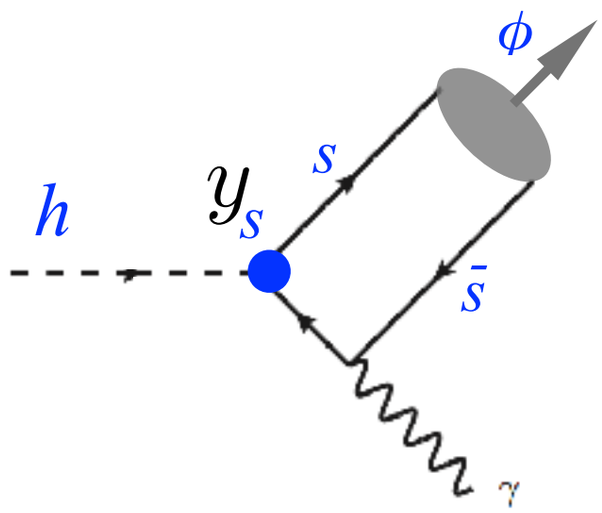


Origin of ultra light (matter constituents) quark masses?

- As $m_{u,d,s} < \Lambda_{\rm QCD}$ their entity/flavor is inaccessible in perturbation theory.



- Different approach: Higgs decay to exclusive states $h \to \phi(s\bar{s})\gamma$:
  (i) reduced backgrounds; (ii) theoretical control via low energy data ("LCDA").



Bodwin, Petriello, Stoynev & Velasco (13);
Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14);
ATLAS (16).

Future: exclusive program, constraining light quark Yukawa

- FCCee: $10^{6\text{-}7}$ Higgses can yield O(40) $h \to \rho\gamma$ events, will give first direct bound on up/down Yukawa, however very weak one.

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14);

- FCChh: large flux of Higgsses, however, new strategy to clean QCD background is required.

GP, Soreq, Stamou & Tobioka #2 (15);

ATLAS (16).

- Indirect probes, via differential distributions can further shed light.

Soreq, Xing Zhu & Zupan; Bishara, Haisch, Monni & Re (2016); Brivio, Goertz & Isidori (15); Yu; Carpenter, Han, Hendricks, Qian & Zhou (16).

FCCee: alternative brute-force approach, observing the strange Yukawa

jordi Duarte-Campderros, GP, Schlaffer & A. Soffer (in preparations)

Strange Yukawa at FCCee

- Already applied to Z:

Measurement of the strange quark forward backward asymmetry around the Z0 peak

DELPHI Collaboration, Eur.Phys.J. C14 (2000)

Light quark fragmentation in polarized Z0 decays

SLD Collaboration, Nucl.Phys.Proc.Suppl. 96 (2001)

- $\mathrm{BR}(h \to s\bar{s}) \simeq 0.02\%$: more than 2000 events with 10^7 Higgses.

- $$\frac{S_{s\bar{s}}}{\sqrt{B_{b\bar{b}}}, \sqrt{B_{gg}}} \sim 1.0, 2.8\,. \quad (10^7 \text{ Higgses})$$

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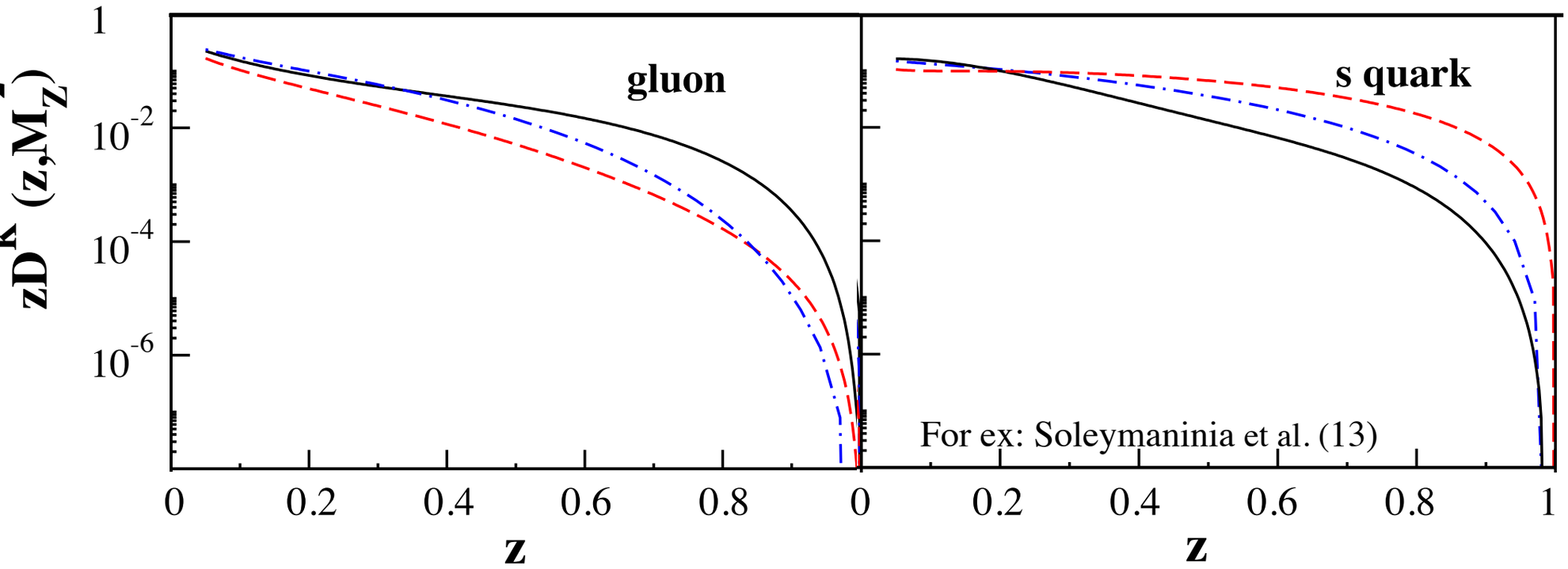
Strategy for digging out higgs to strange decay

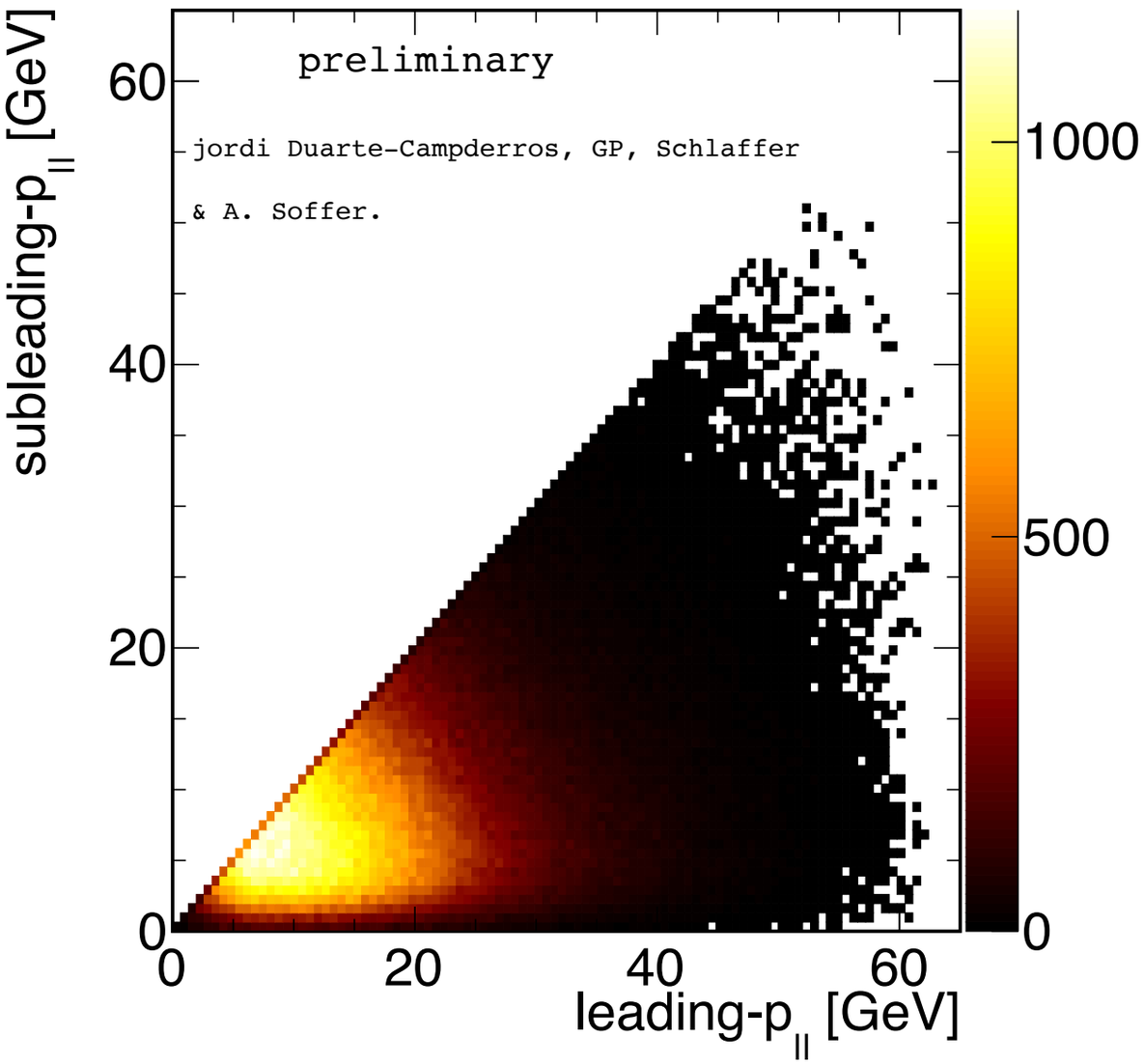
- Looking for 2 leading Kaons that are (i) hard; (ii) prompt.

jordi Duarte-Campderros, GP, Schlaffer & A. Soffer (in preparations)

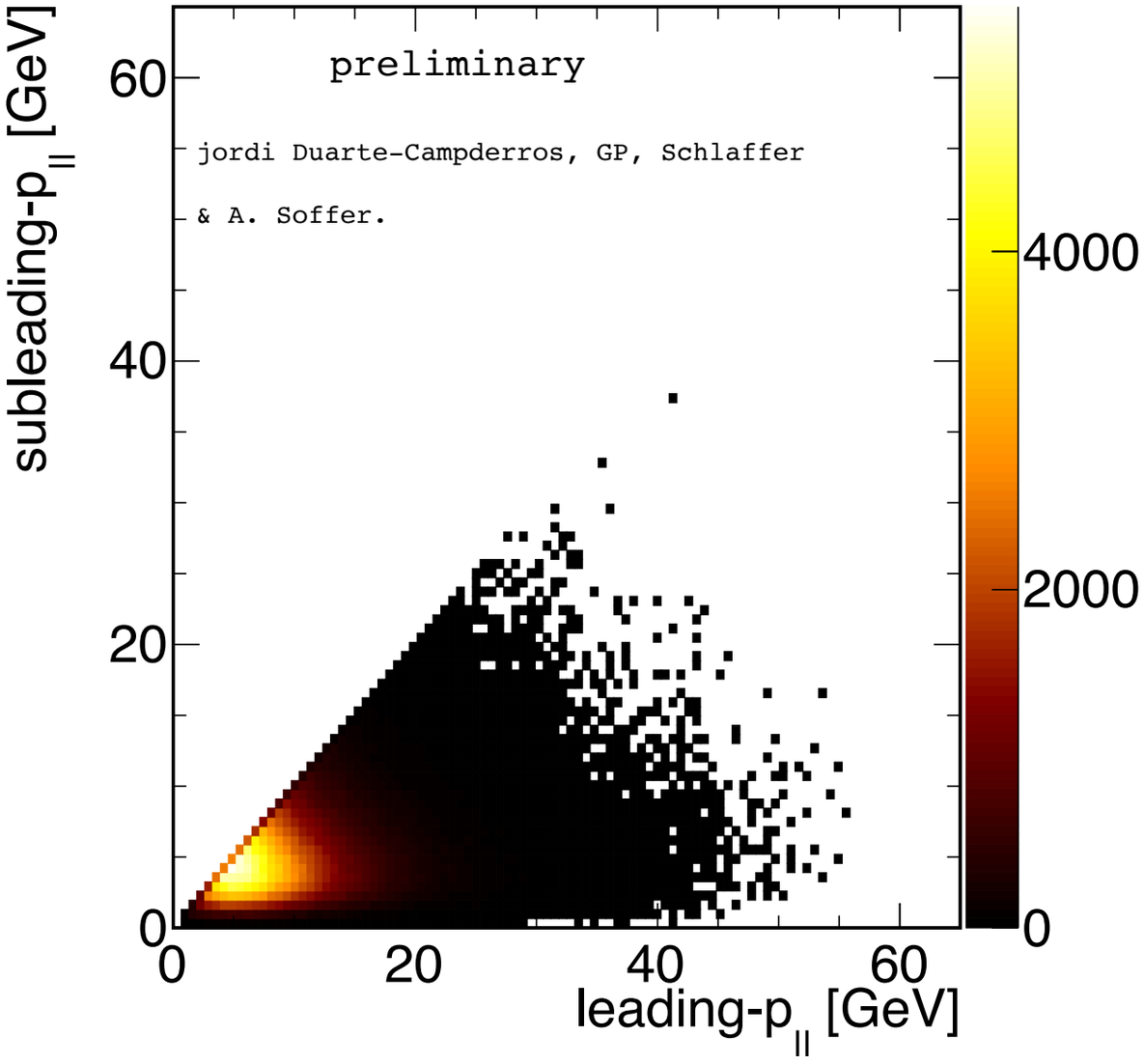


Kaons from Higgs decay are harder (no PID)

$h \to s\bar{s}$



$h \to gg$



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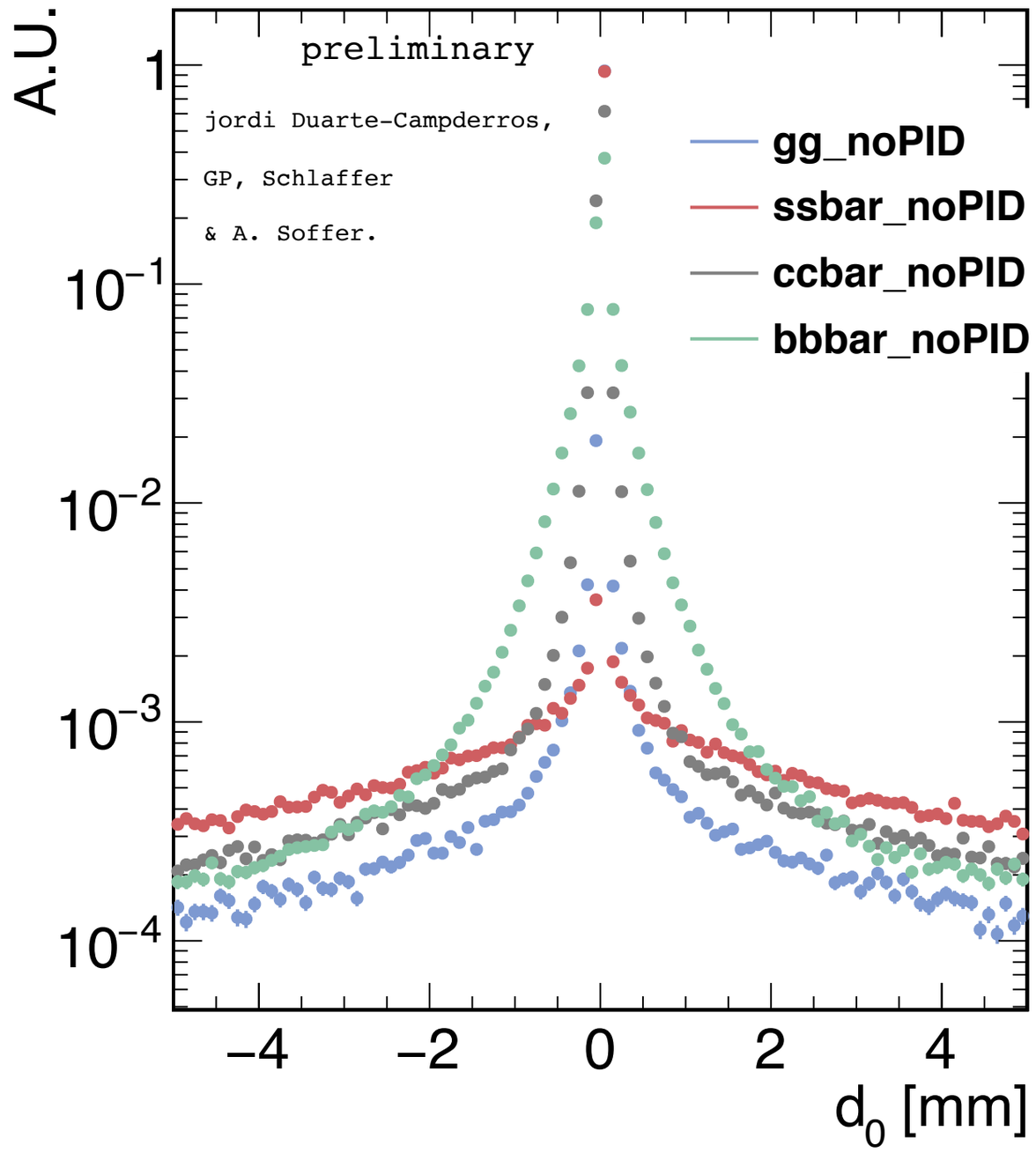
Promptness of charge Kaons



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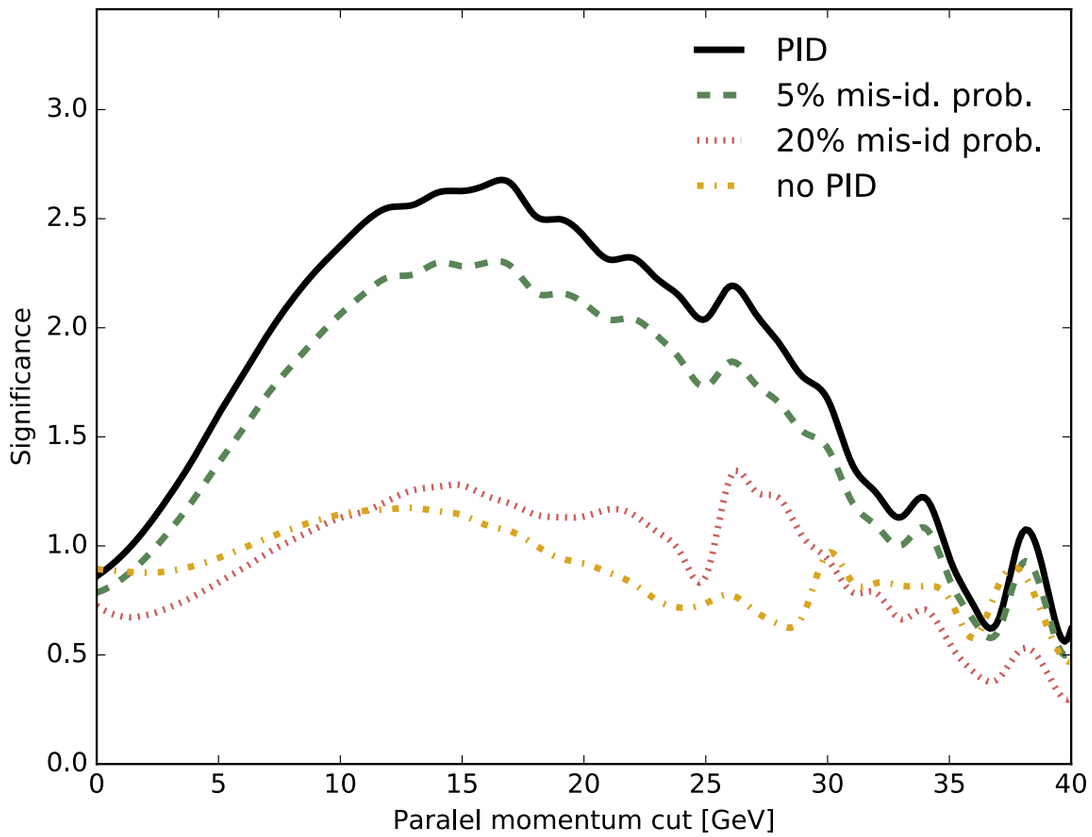
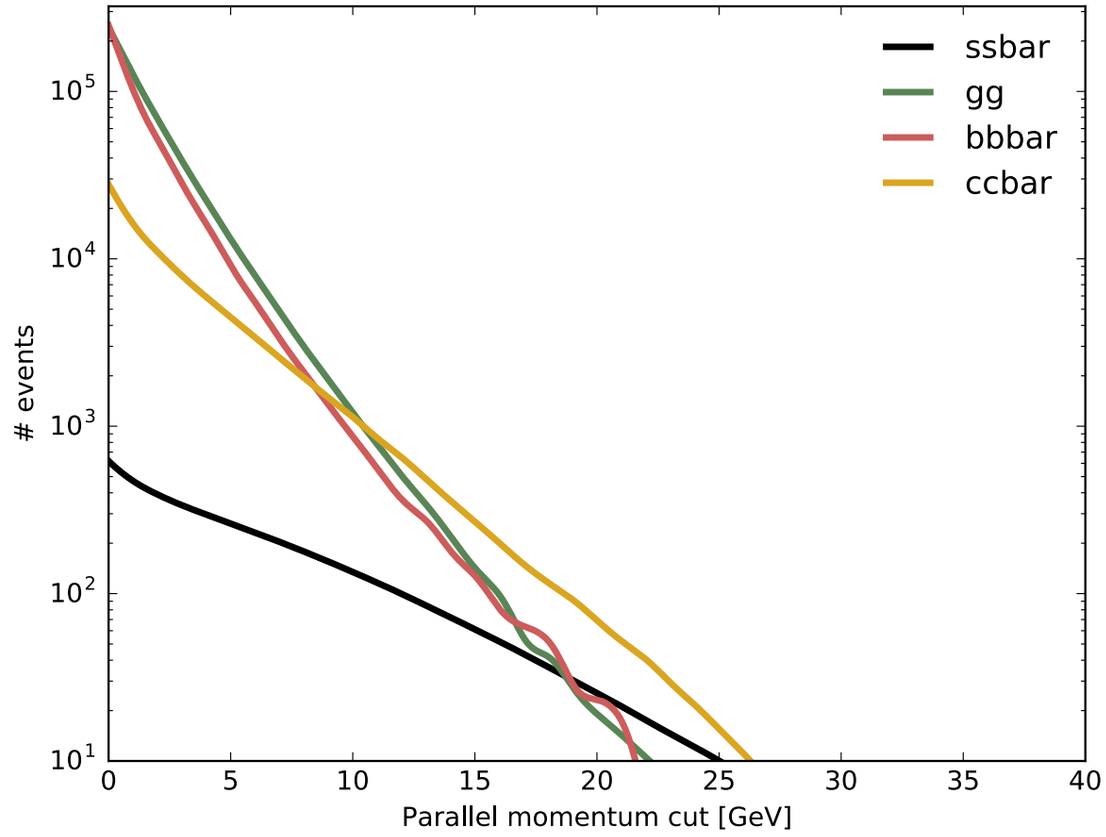
Adding bound on impact parameter and PID

Significance (Impact < 13 mm)



BG decomposition



- Leading charm background can be dealt \w dedicated cuts.

SM strange Yukawa is within the reach of FCCee !

Probing relaxion physics at the FCCee

Flacke, Frugiuele, Fuchs, Gupta & GP (16)

Flacke, Frugiuele, Fuchs, Gupta, GP & Schlaffer (in preparations)

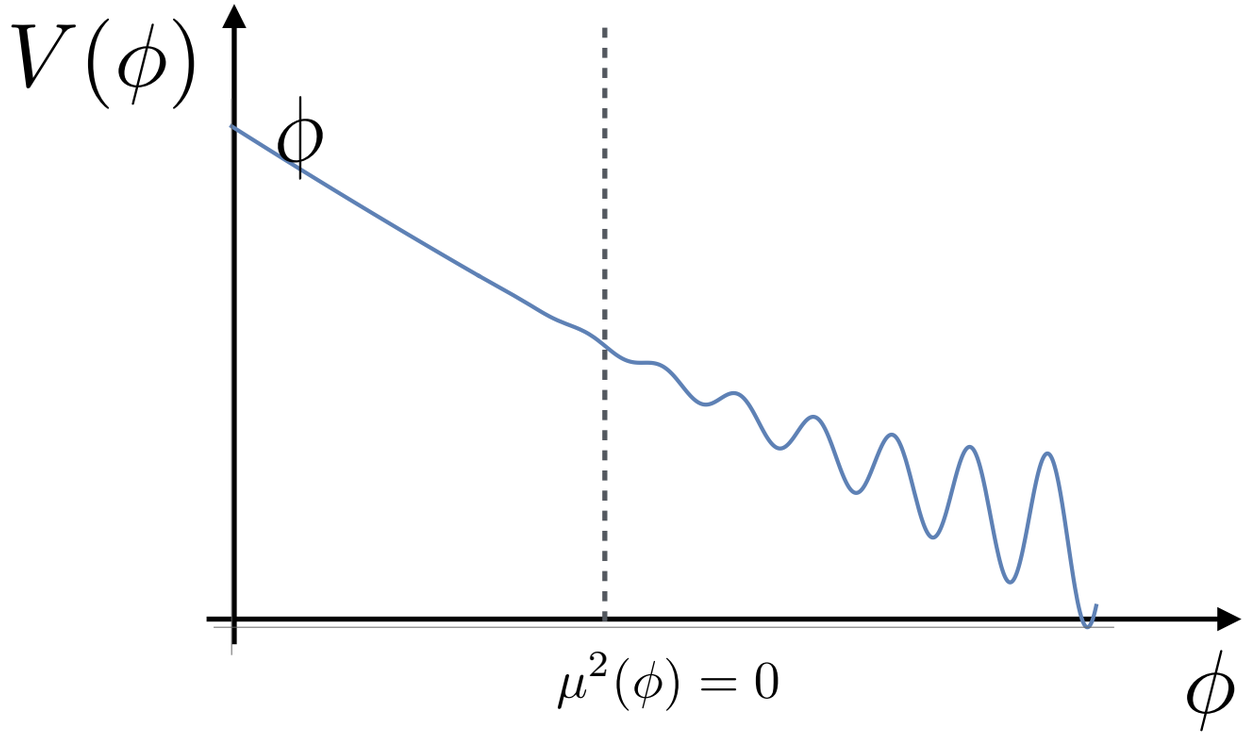
Relaxion's physics

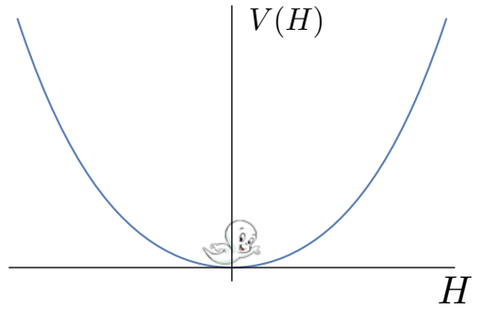
Graham, Kaplan & Rajendran (15)

- A dynamical solution/amelioration of the Higgs fine-tuning problem:

(i) Add a scalar (relaxion) Higgs dependent mass: $\overbrace{\left(\Lambda^2 - g^2\phi^2\right)}^{\mu^2(\phi)} H^\dagger H$.

(ii) ϕ roles till μ^2 changes sign $\Rightarrow \langle H \rangle \neq 0 \Rightarrow$ stops rolling.





Relaxion mechanism

Graham, Kaplan & Rajendran (15)

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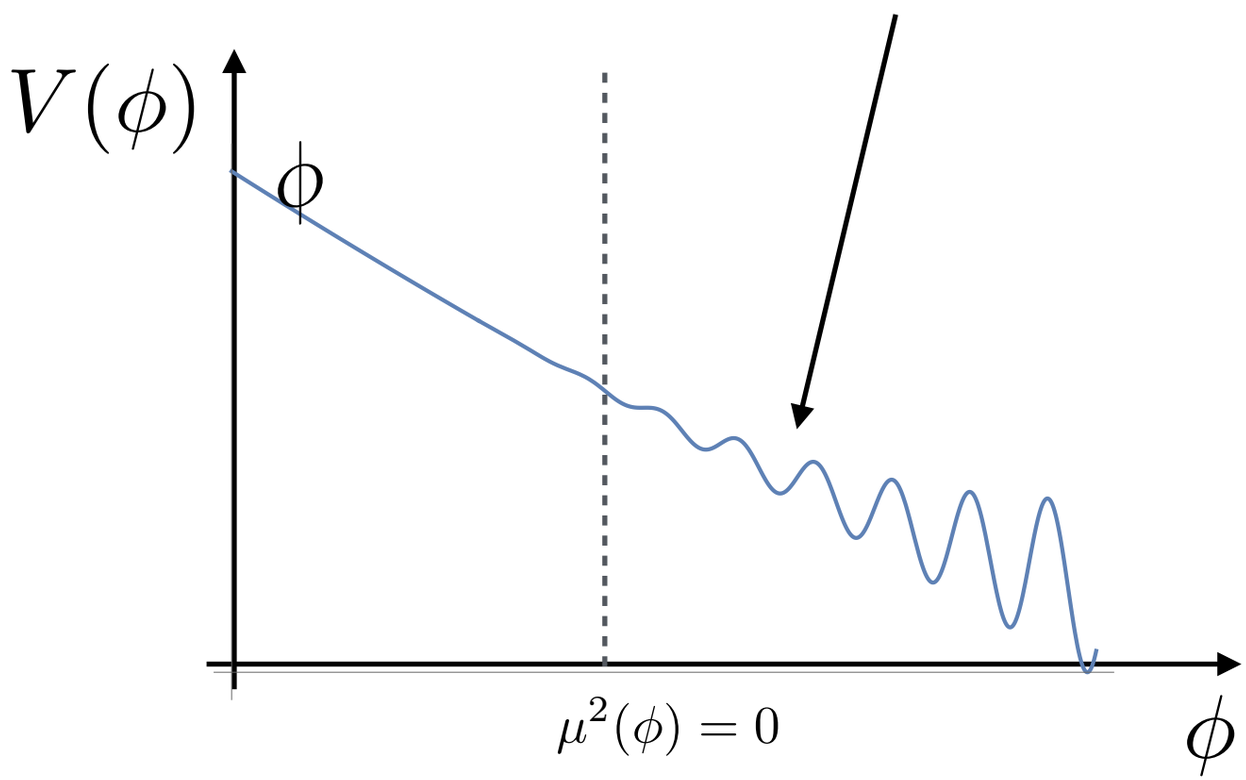

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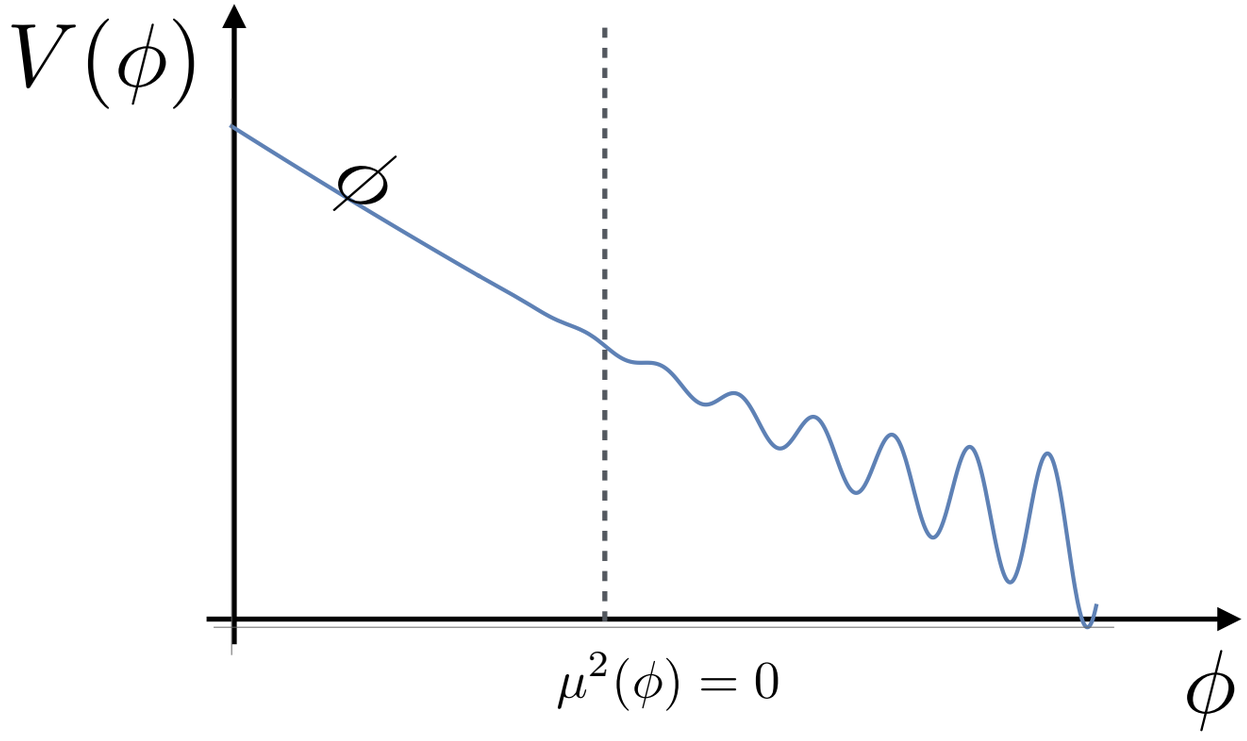

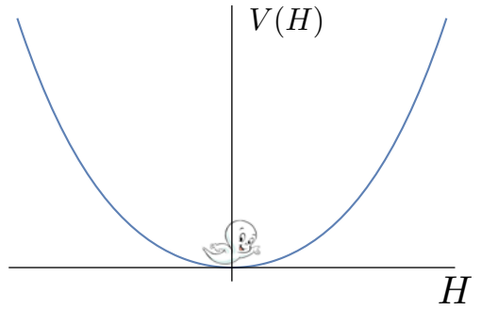

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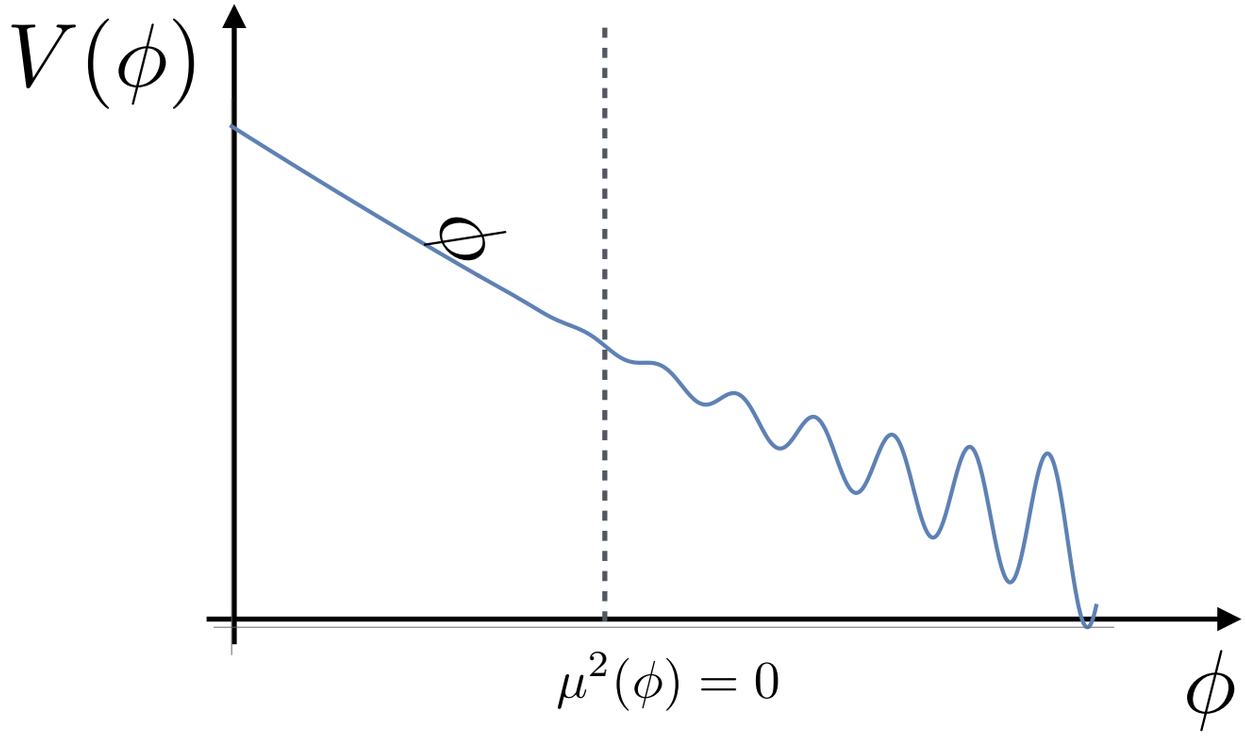

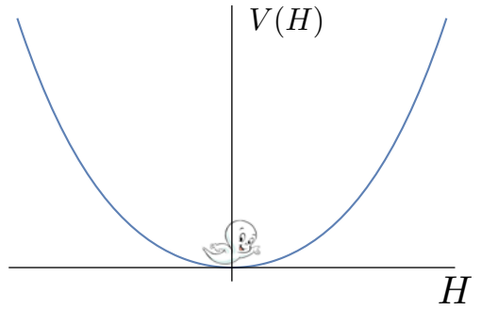

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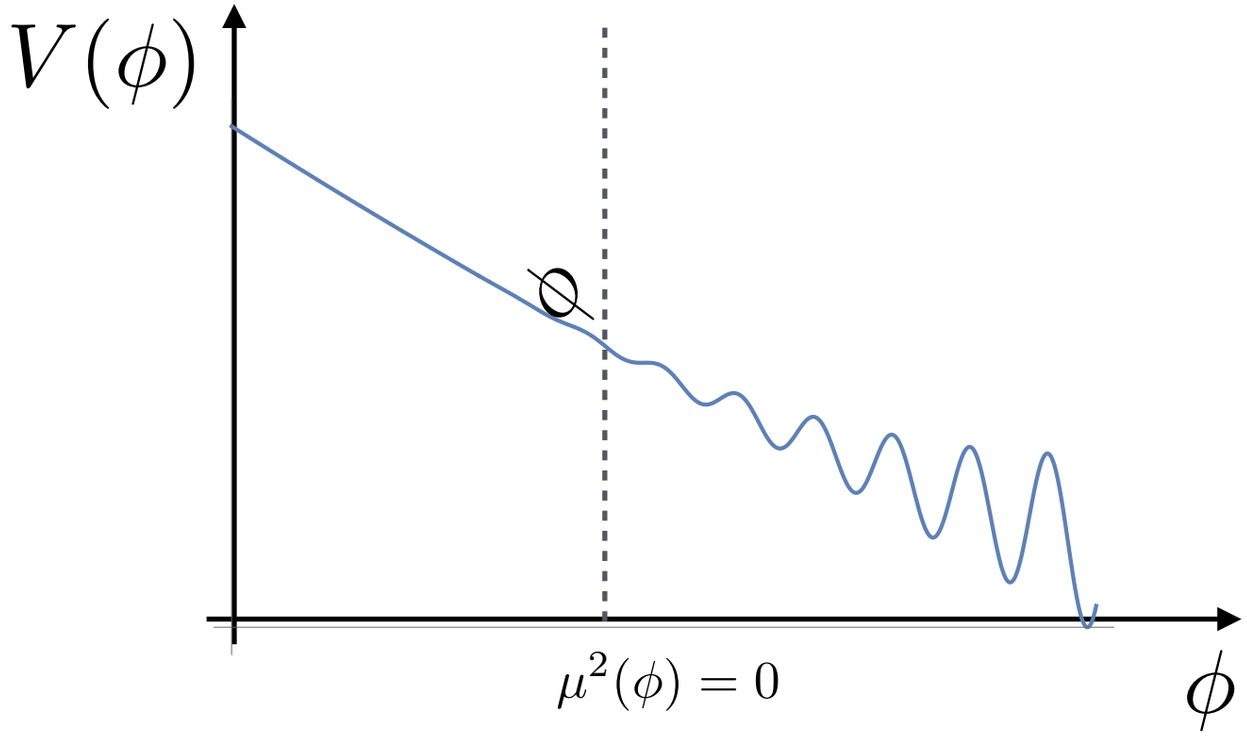

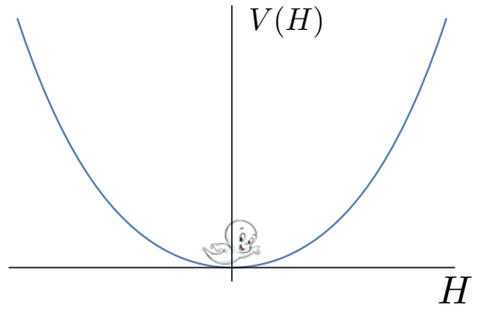

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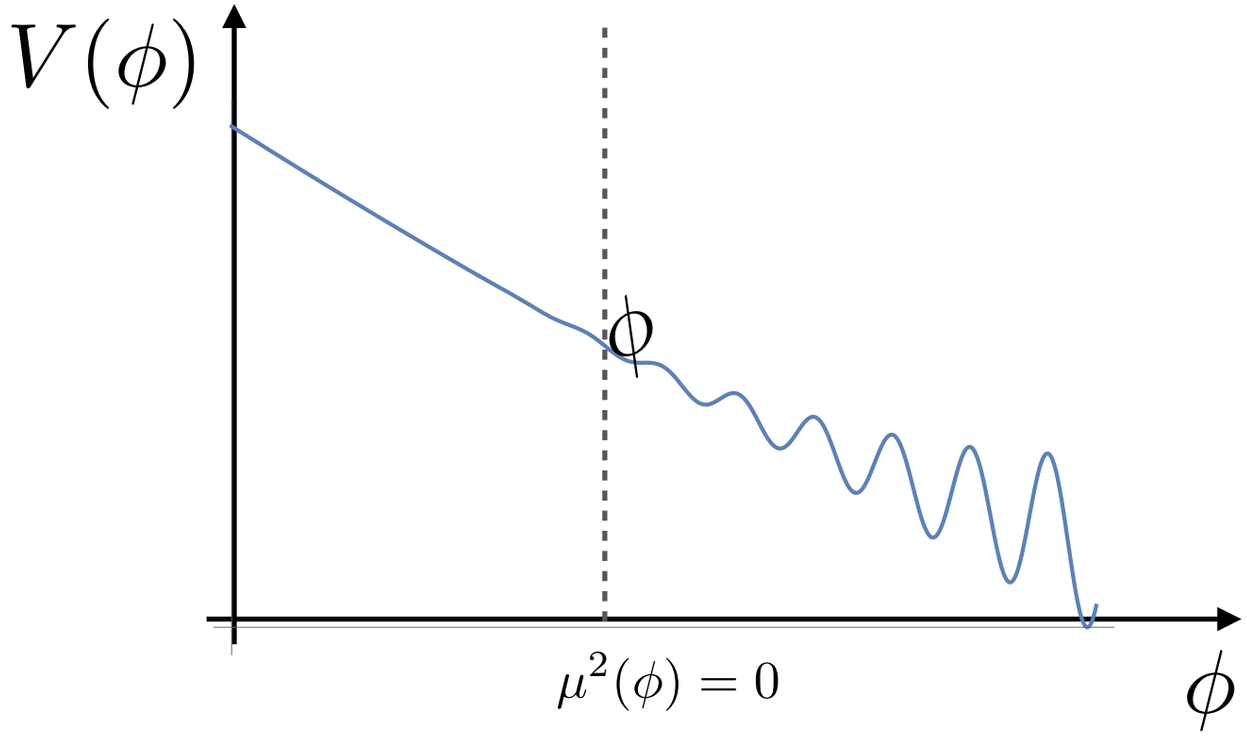

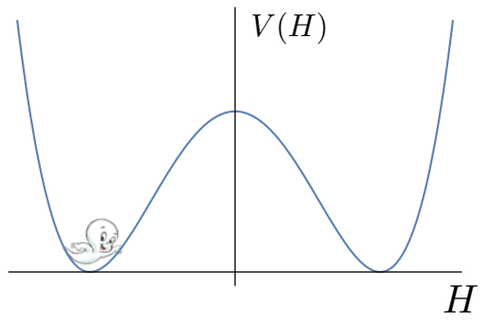

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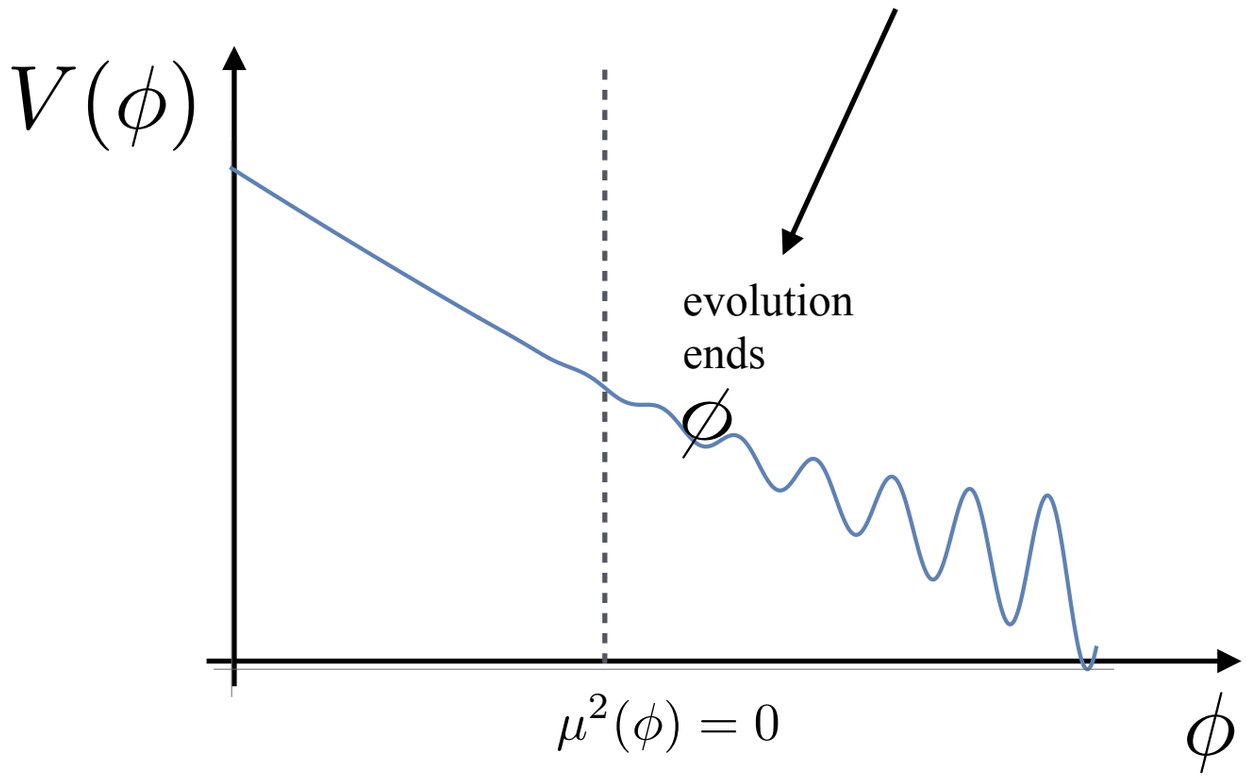
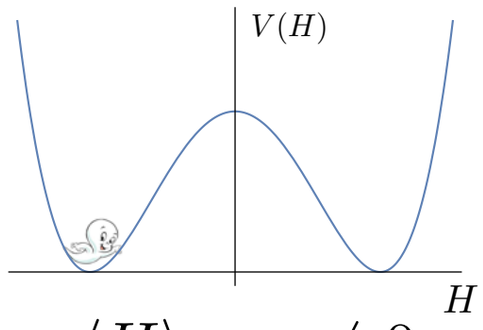




$\langle H \rangle = v \neq 0$

Relaxion pheno'

- Focus shifts from Higgs dynamics to relaxion one:
  different pheno', no partners (stops/t', gauginos/KK Z's …)

- Consider 2 "generic" properties:
  (i) Higgs-relaxion mixing; (ii) coupling to EW gauge, $\frac{\phi}{f}(W,Z)_{\mu\nu}(\tilde{W},\tilde{Z}/\tilde{\gamma})^{\mu\nu}$.

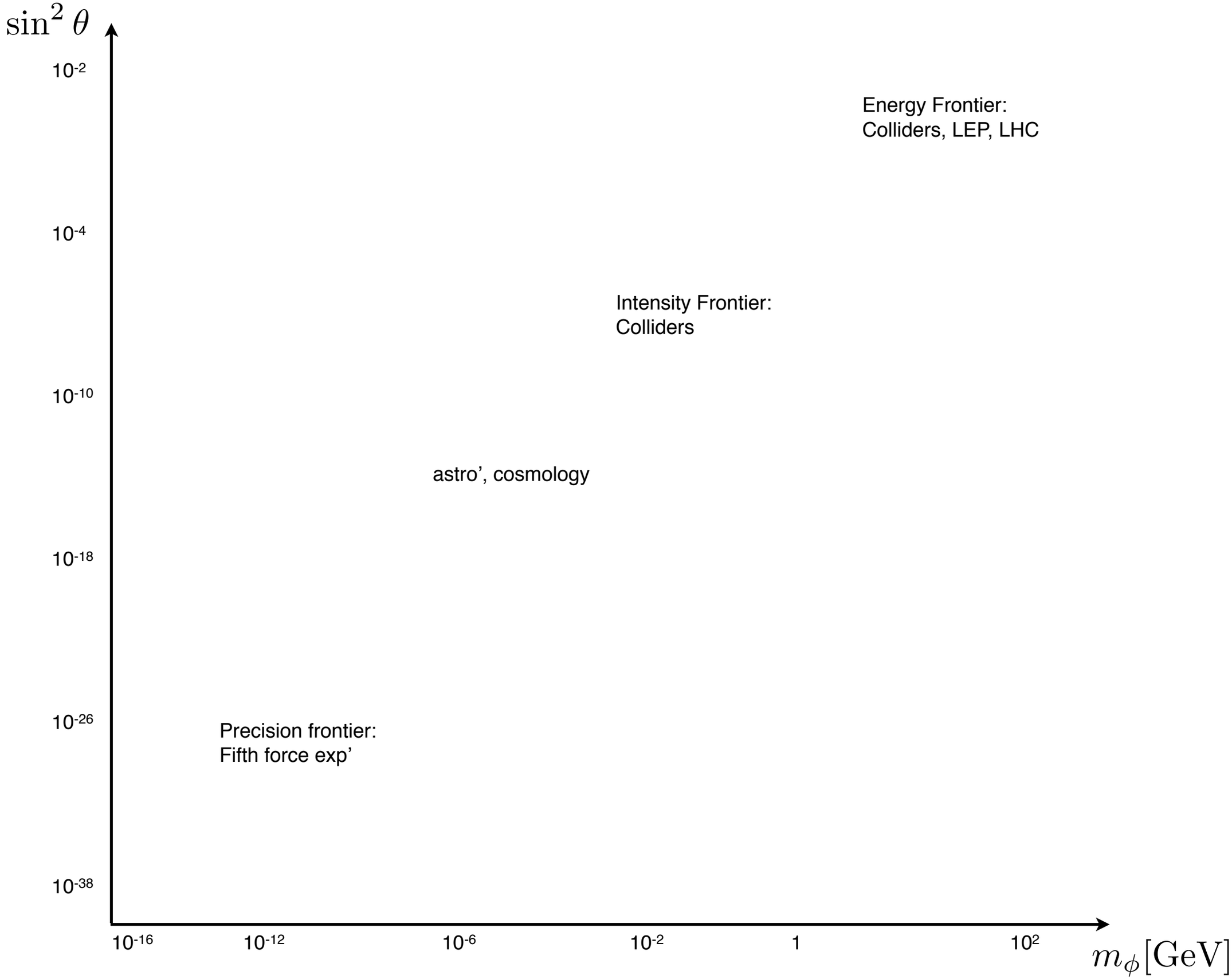
- The relaxion Higgs mixings is: $\sin\theta \sim \frac{\tilde{M}^2 v}{m_h^2 f} \sim 10^{-1} \times \left(\frac{\tilde{M}}{100\,\mathrm{GeV}}\right)^2 \times \frac{1\,\mathrm{TeV}}{\mathrm{f}}$.

Flacke, Frugiuele, Fuchs, Gupta & GP (16)

- The relaxion mass is: $m_\phi \sim \frac{\tilde{M} v}{f} \sim 10\,\mathrm{GeV} \times \frac{\tilde{M}}{100\,\mathrm{GeV}} \times \frac{1\,\mathrm{TeV}}{\mathrm{f}}$. $\left(\sim \sin\theta \times \frac{m_h^2}{\tilde{M}}\right)$

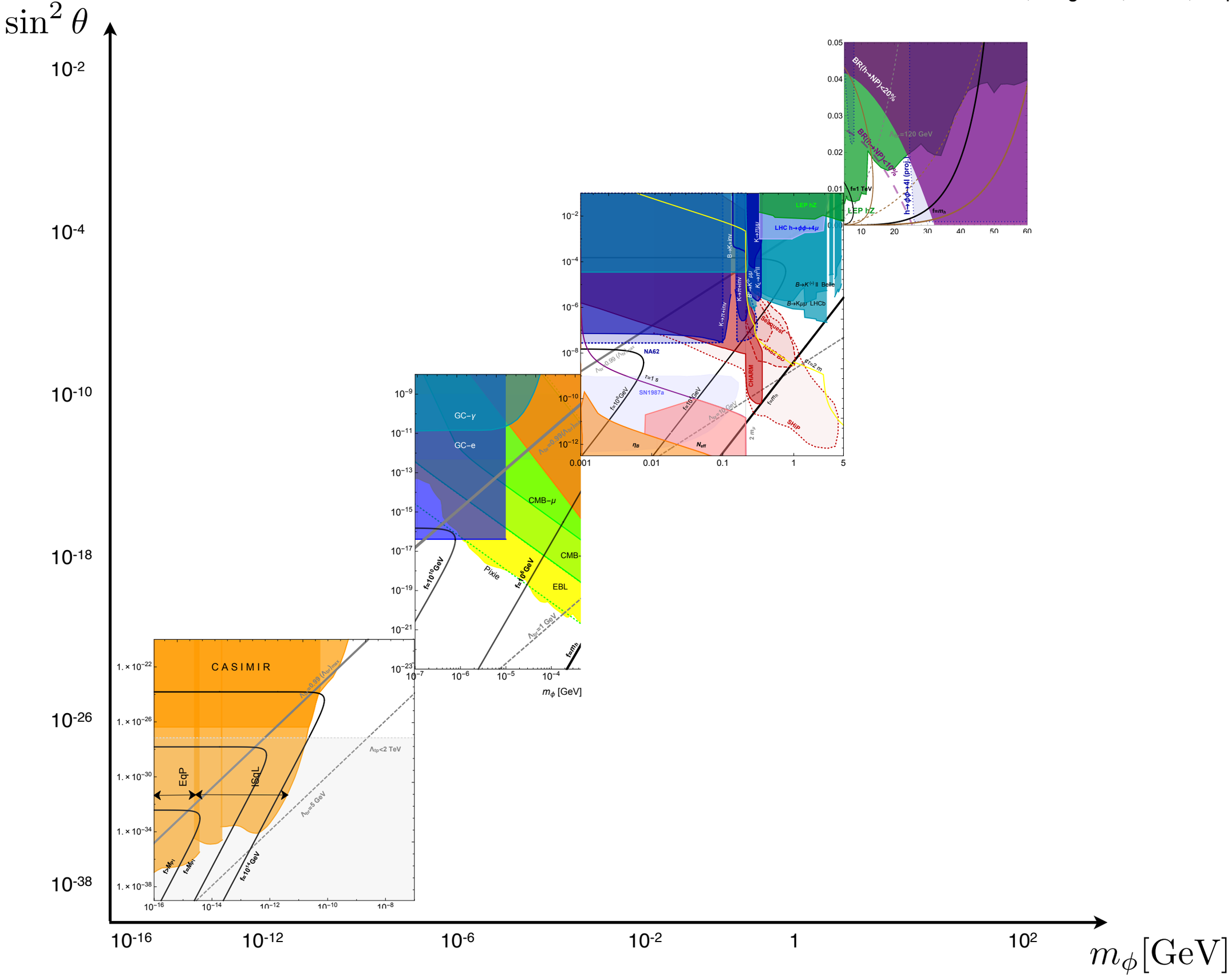
Flacke, Frugiuele, Fuchs, Gupta & GP (16)

How to search for a relaxion?



Current-near-future constraints

Flacke, Frugiuele, Fuchs, Gupta & GP (16)



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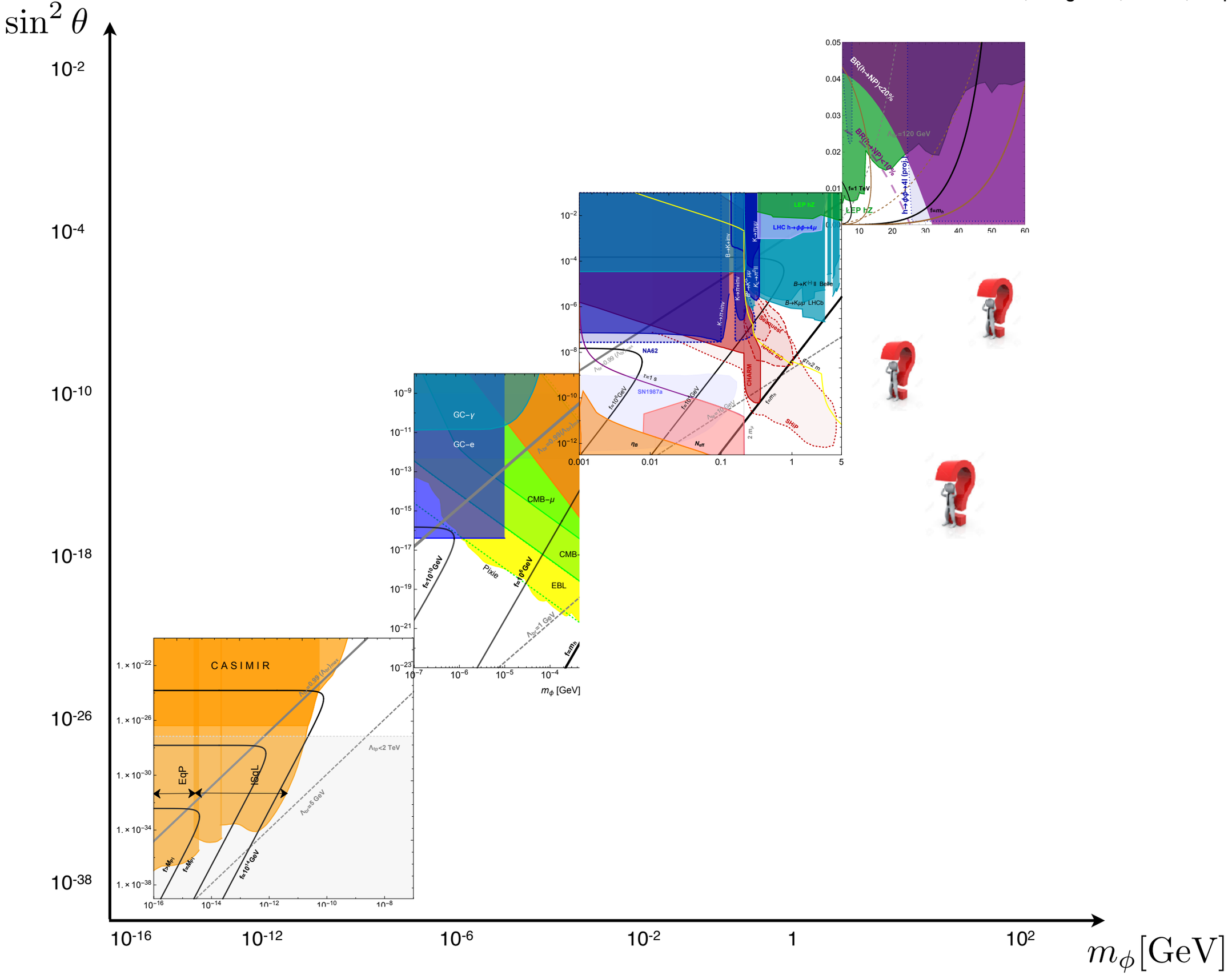


Relaxion pheno' & Higgs/Z factories

Flacke, Frugiuele, Fuchs, Gupta, GP & Schlaffer (in preparations)

- Rescaling LEP to FCCee \w O(10^7 Higgses) & O(10^{13} Zs).

- Higgs prod': simple models: triple couplings only function of m_ϕ : potentially exclude/discover heavy relaxion region above 10 GeV.

- 3-body decay of off-shell Z, very strong bound on mixing angles.

- Also, can constrain direct the scale f via $\frac{\phi}{f}(W,Z)_{\mu\nu}(\tilde{W},\tilde{Z}/\tilde{\gamma})^{\mu\nu}$ coupling robust operator, as in particle production mixing \w Higgs & digamma is small.

Hook & Marques-Tavares (16)

Bounds from Higgs untagged decay

- Rescaling LEP to FCCee \w O(10^6 Higgses) => improvement of 2 orders of magnitude in the constrain on the mixing^2 angle!

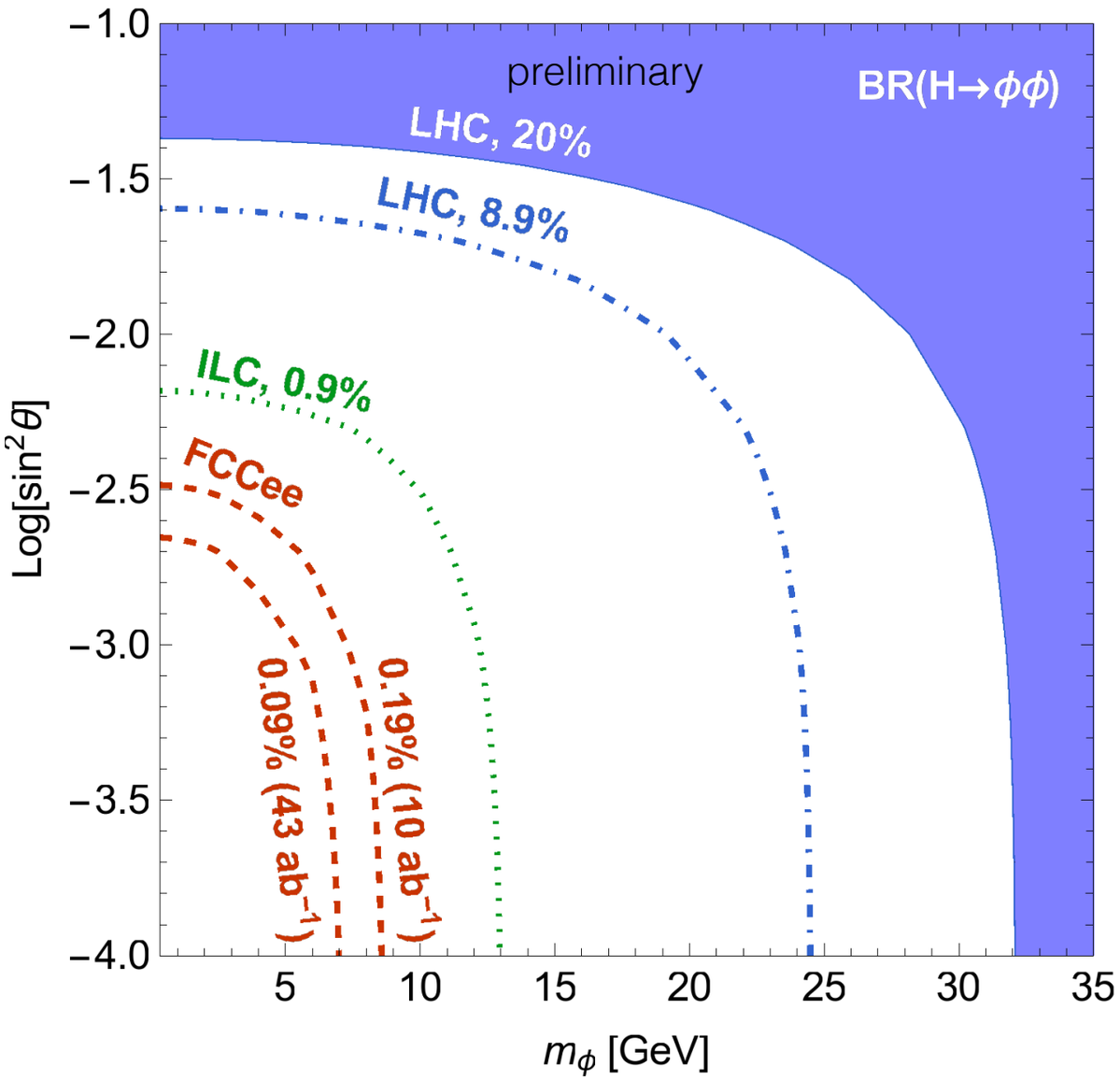
Flacke, Frugiuele, Fuchs, Gupta, GP & Schlaffer (in preparations)

Bound from $H \to$ inv

Collider	$\sqrt{s}$	$\mathcal{L}_{\rm int}$ [fb^{-1}]	BR($H \to$ untagged)
LHC	$7 \oplus 8$ TeV	22	0.2
LHC	$7 - 14$ TeV	300	0.089
HL-LHC	$7 - 14$ TeV	3000	0.05
ILC	250 GeV	250	$9 \cdot 10^{-3}$
FCCee	240 GeV	10^4	$1.9 \cdot 10^{-3}$
FCCee	240 GeV	$4.3 \cdot 10^4$	$9 \cdot 10^{-4}$

. arXiv:1310.8361

Relaxion pheno' & Higgs factories



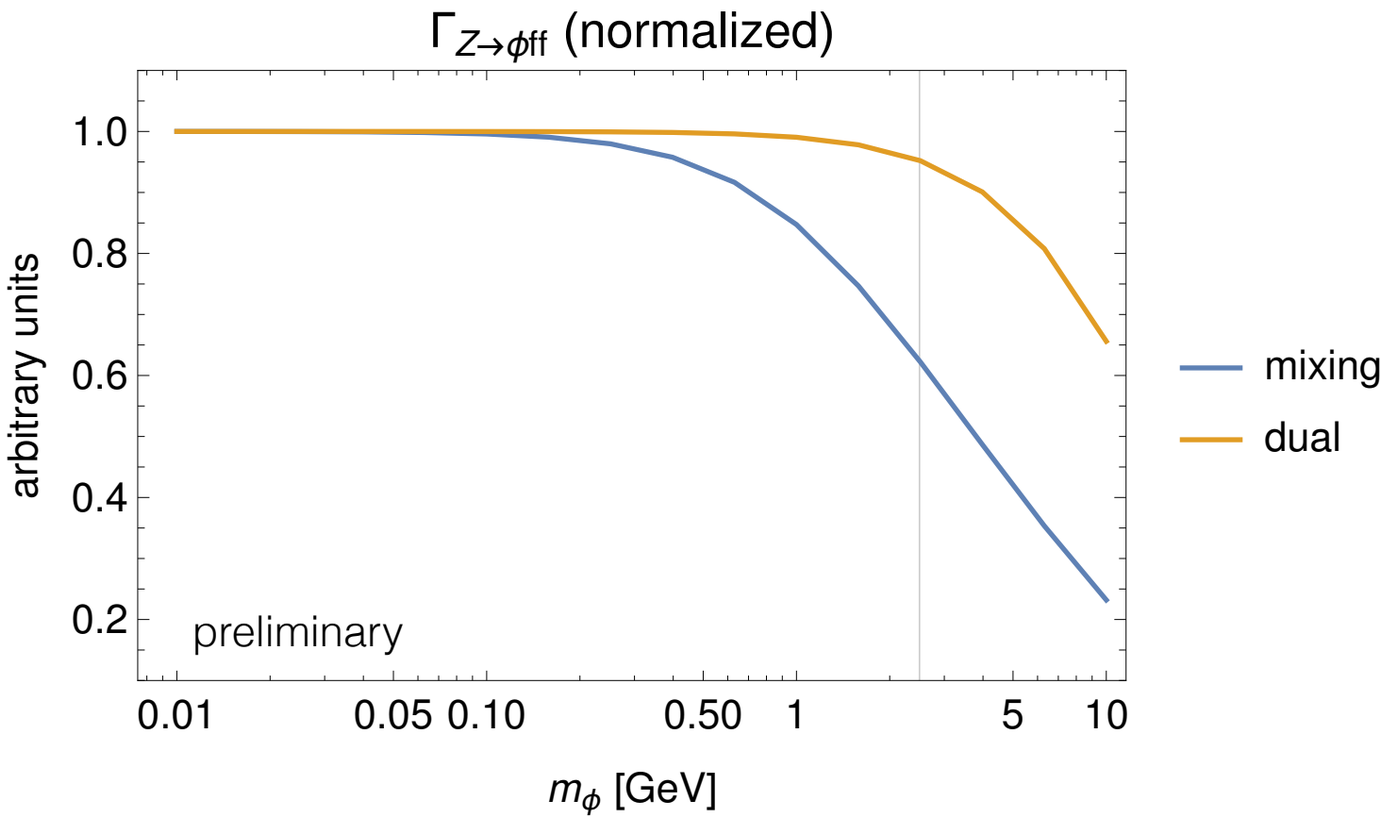
Bounds on $\sin^2\theta$ and m_ϕ from the upper limit on the untagged branching ratio of the Higgs boson, here $H \to \phi\phi$. Current (solid, blue area) and projected (blue, dash-dotted) exclusion from the LHC. Projection for the ILC with $\sqrt{s} = 250\,\text{GeV}$, $\mathcal{L}_{\text{int}} = 250\,\text{fb}^{-1}$ and the FCCee with 4IP, $\sqrt{s} = 240\,\text{GeV}$ and $\mathcal{L}_{\text{int}} = 10\,\text{ab}^{-1}$, $43\,\text{ab}^{-1}$.

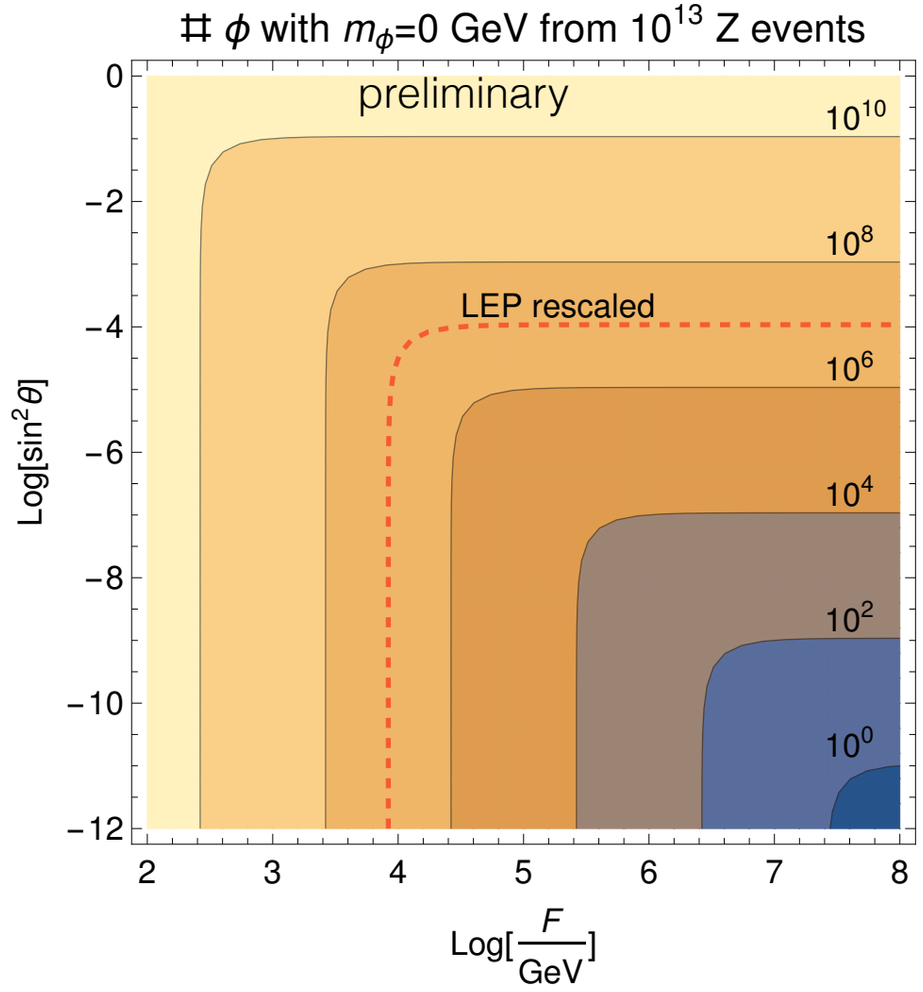
Flacke, Frugiuele, Fuchs, Gupta, GP & Schlaffer (in preparations)

Relaxion pheno' from Z factory

- Probing on shell Z decay to $Z^*(f\bar{f})$+relaxion.

Flacke, Frugiuele, Fuchs, Gupta, GP & Schlaffer (in preparations)





Conclusions

- Is the Higgs-mechanism behind the light quark masses?

- FCCee: direct probe of *all* 2nd generation origin of flavor!

- Relaxion, new approach to hierarchy problem, with potential connection to “flaovor/mass dependent” light mediator.

- FCCee may strongly probe regions of relaxion-models.

Relaxion's basic structure

- QFT consistent constructions are of the form:

Choi, Kim & Yun (2014) Choi & Im; Kaplan & Rattazzi; Gupta, Komargodski, GP & Ubaldi (15)

$$V(\phi, H) = H^\dagger H[\Lambda^2 - M^{\overbrace{2}^{(\text{GKR: } g \sim M/f)}}\cos(\phi/f)] + r\Lambda^2 M^2 \cos(\phi/f) + H^\dagger H \tilde{M}^2 \cos(n\phi/f)\,.$$

$$V'(\phi_*, v) = 0 \;\Rightarrow\; r\Lambda^4 \sin(\phi_*/f) \simeq v^2 n\tilde{M}^2 \sin(n\phi_*/f) \;\not\Rightarrow\; \phi_* \text{ is generic.} \quad (M \sim \Lambda)$$

- It implies that generically:

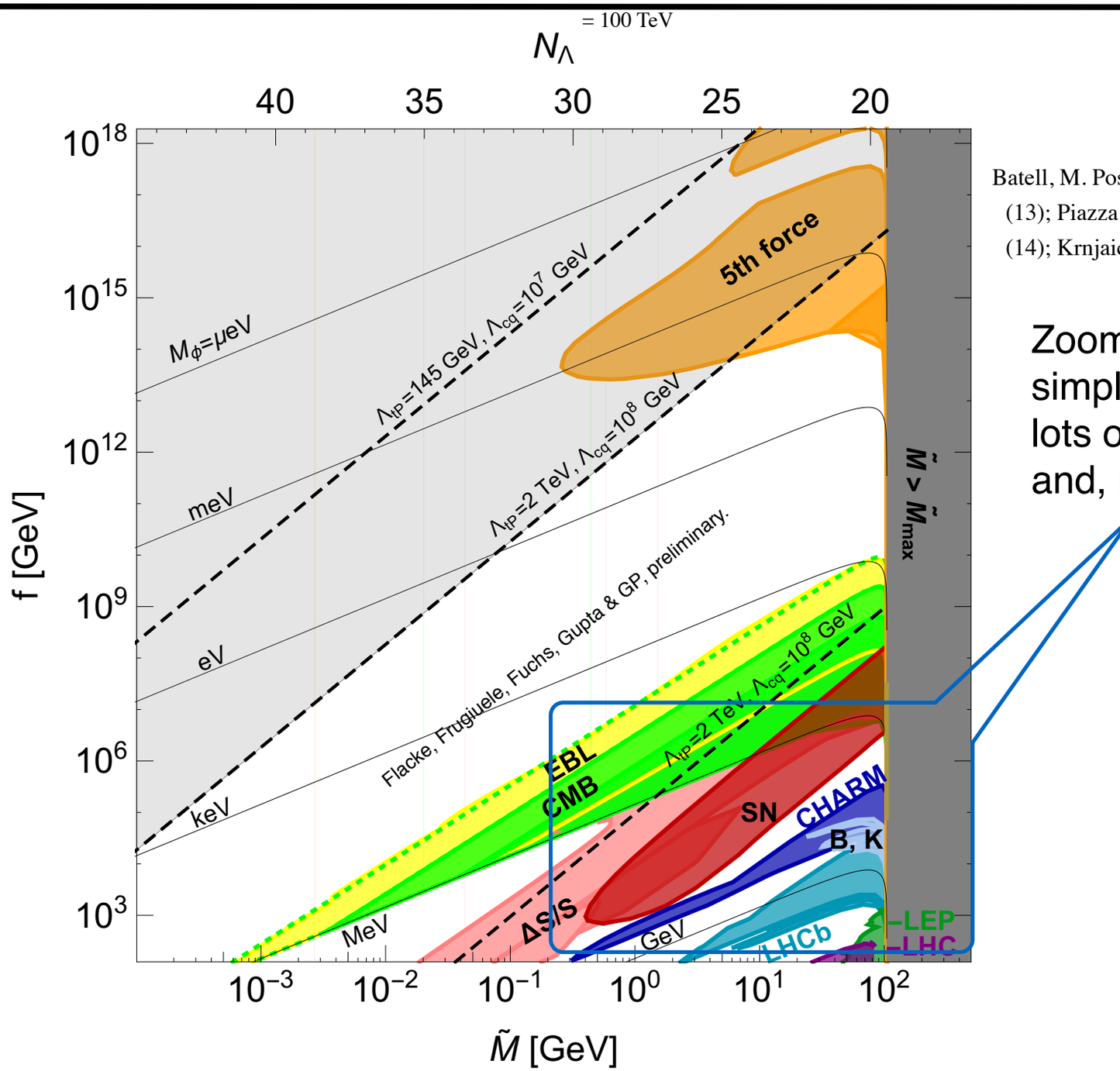
(i) CP violation is spontaneously induced (problematic for axion-relaxion models);

(ii) Higgs-relaxion mixing is induced:

$$V_{\rm mix} \sim \frac{nv\tilde{M}^2}{f} \sin(n\phi_*/f) \times H\phi_{\rm phys} \simeq \frac{r\Lambda^4}{vf} \sin(\phi_*/f) \times H\phi_{\rm phys}\,.$$

Backups

The big picture (prelim)



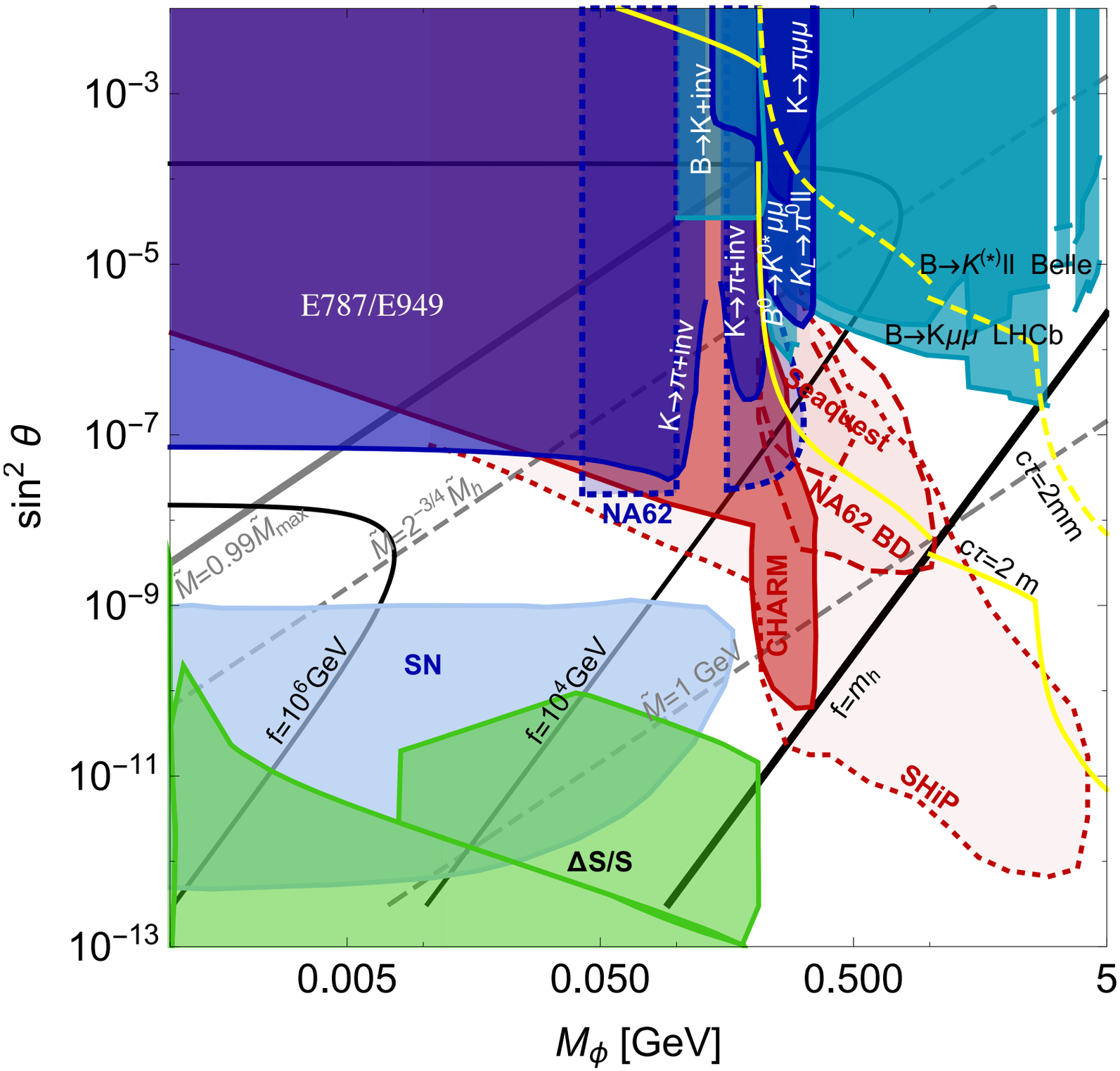
Batell, M. Pospelov, and A. Ritz (09); Clarke, Foot & Volkas (13); Essig, et al. (13); Piazza & Pospelov (10); Dolan, Kahlhoefer, McCabe, Schmidt-Hoberg (14); Krnjaic (15); Dolan et al, (14); Alekhin, et al. SHIP (15)…

Zooming on region \w low cutoff:
simple construction;
lots of progress can be made;
and, relevant to intensity frontier.

5th force exp. (orange), EBL (blue), cosmological entropy injection (pink), supernova (red), CHARM (dark blue), rare B- and K-decays (light blue), LHCb (turquoise), LEP (green). The vertical gray band indicates exclusion due to $\tilde{M} > \tilde{M}_{max}$. The light gray, dotted lines correspond to $\Delta\phi = M_{Pl}$ with $\Lambda = 5$ TeV (upper), $\Lambda = 100$ TeV (lower). The dashed, gray lines show the classical- vs.-quantum condition for $\Lambda = 100$ TeV (upper), $\Lambda = 10^5$ TeV. The thin, black lines indicate M_ϕ from 10^{-15} GeV (uppermost) to 1 GeV (lowest) with a spacing factor of 10^3 .

Relaxion beams, relaxion flavor

Flacke, Frugiuele, Fuchs, Gupta & GP (16).



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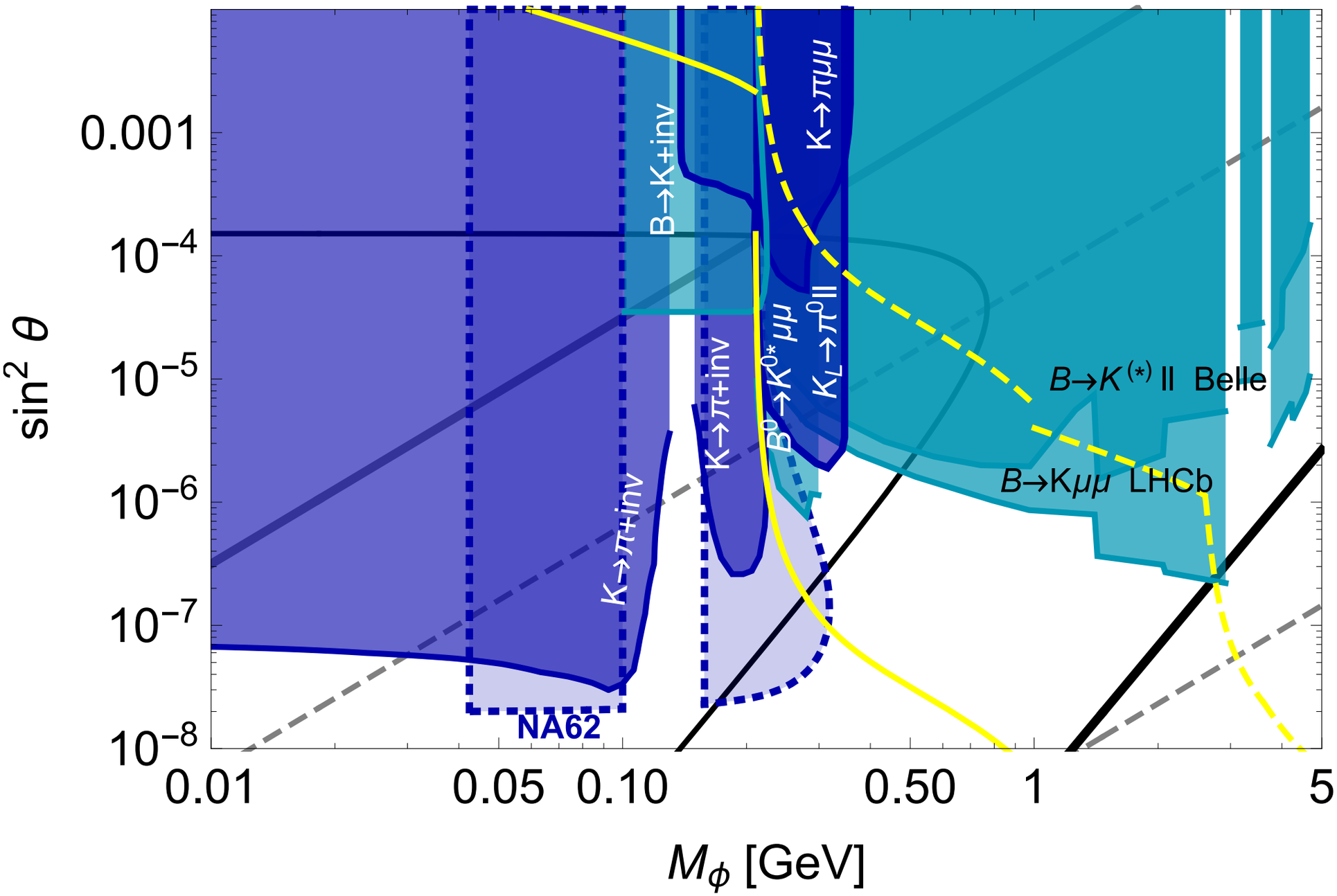
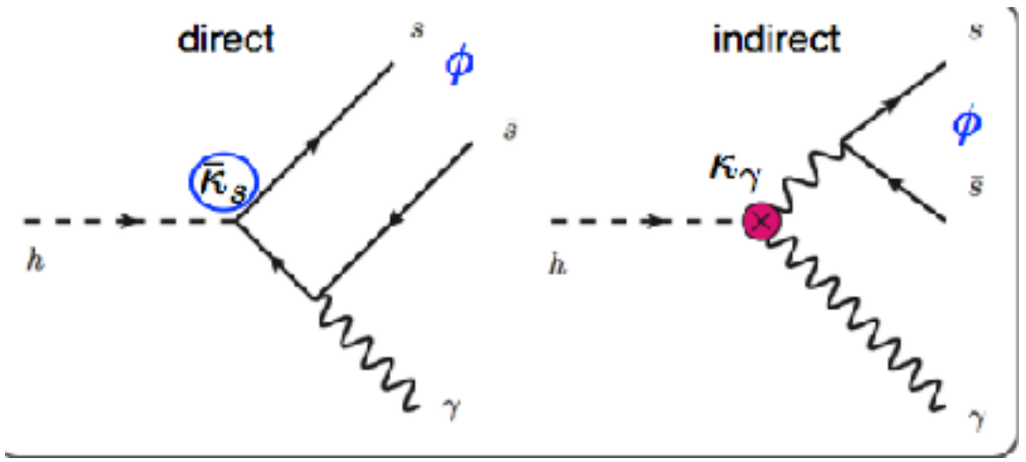


Final result for BR($h \to \phi\gamma$)

$$\Gamma_{h\to\phi\gamma} = \frac{1}{8\pi}\frac{1}{m_h}|M^{\phi}_{ss}|^2,$$



- The resulting sensitivity: $\bar{\kappa}_{u,d,s} = y_q/y_b^{\rm SM}\,,\ \left[\bar{\kappa}^{\rm SM}_{u,d,s} \sim (0.5, 1, 20)\times 10^{-3}\right]$

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(3.0\pm 0.3)\kappa_\gamma - 0.78\bar{\kappa}_s\right]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2},$$

Similar holds for 1st generation:

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm 0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]\cdot 10^{-5}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\mathrm{BR}_{h\to\omega\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.6\pm 0.17)\kappa_\gamma - 0.59\bar{\kappa}_u - 0.29\bar{\kappa}_d\right]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2},$$

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

On King non-linearities, Algebraic intuition

$$
\begin{aligned}
m\delta\nu^{i}_{AA'} &= K_1 + F_i\tilde{\delta}\langle r^2\rangle_{AA'} + H_i AA' \,, \\
&\underset{\text{cont}'}{\Longrightarrow} \\
m\delta\nu(A')^{i} &= K_i + F_i\tilde{\delta}\langle r^2\rangle(A') + H_i AA' \,, \\
&\Downarrow \\
(m\delta\nu^{1,2})' &= F_{1,2}(\tilde{\delta}\langle r^2\rangle)' + H_{1,2}A \,, \quad \text{with prime} \equiv \frac{\partial}{\partial A'} \,.
\end{aligned}
$$

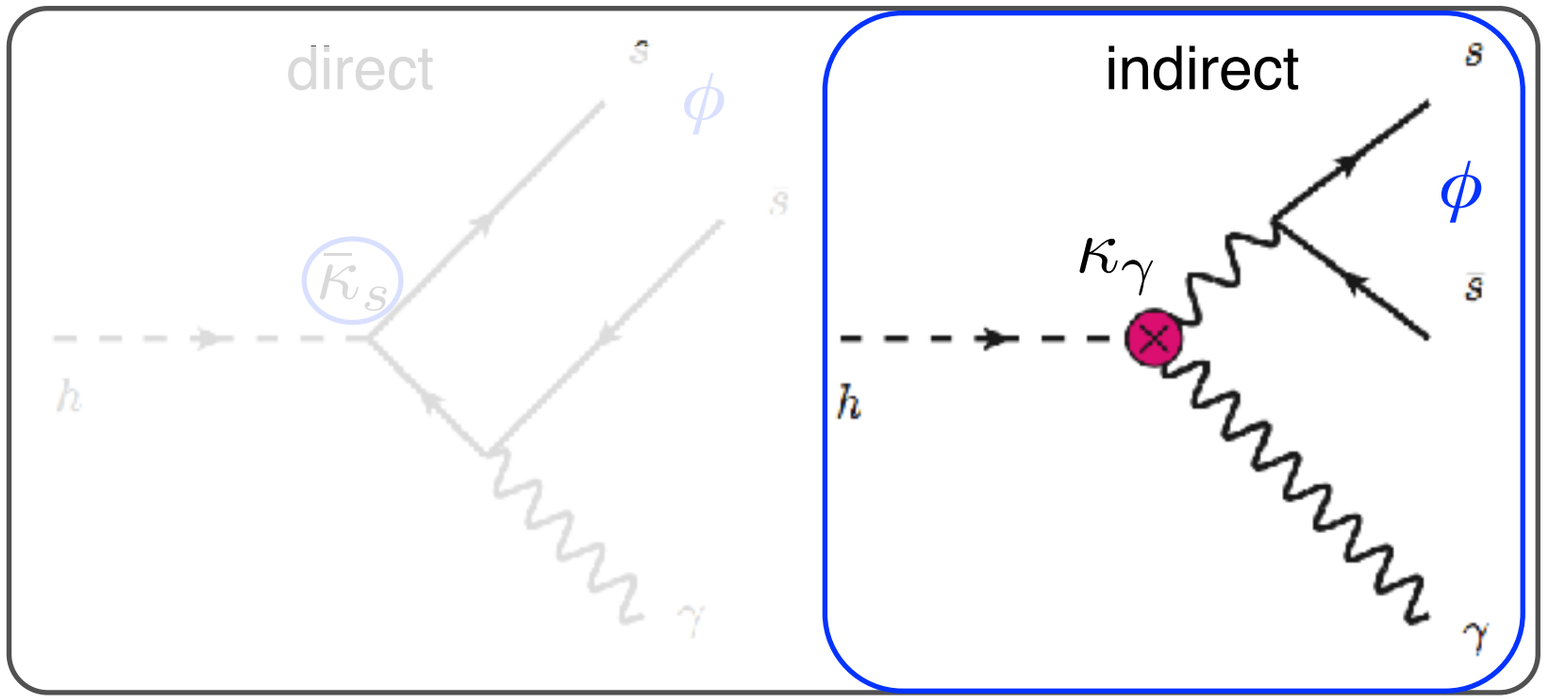
The condition for $m\delta\nu^{1,2}$ to be linearly dependent is that
the Wronskian of $(m\delta\nu^{1,2})'$ vanishes:

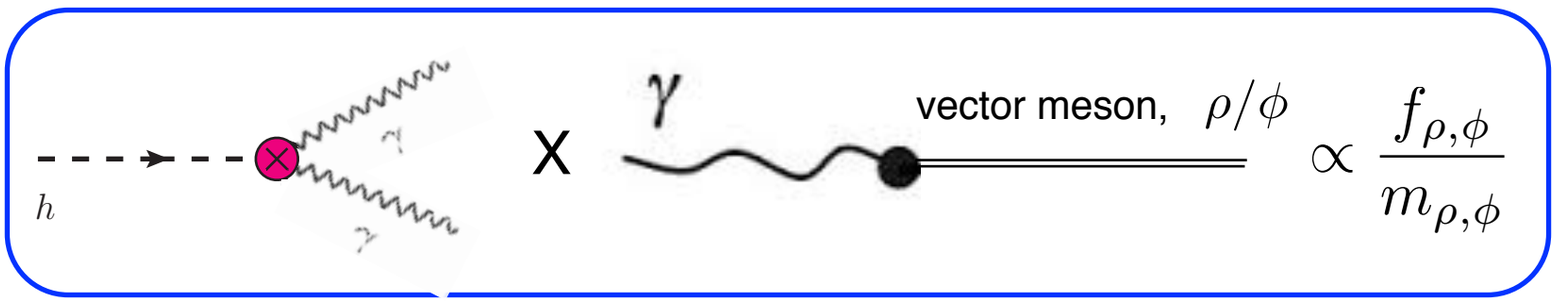
$$
\begin{aligned}
W_{12} &\equiv W[(m\delta\nu^{1,2})'] = (m\delta\nu^{1})'(m\delta\nu^{2})'' - (m\delta\nu^{2})'(m\delta\nu^{1})'' \\
&= (\tilde{\delta}\langle r^2\rangle)''[H_1F_2 - H_2F_1] = -(\tilde{\delta}\langle r^2\rangle)''H_2F_1[1 - F_{21}H_{12}] \,.
\end{aligned}
$$

The Wronskian vanishes if $H_i(n_i, l_i, n_i', l_i') \propto F_i(n_i, l_i, n_i', l_i')$.

Ex.: $h \to \phi\gamma$, indirect contribution

- Two paths to get $h \to \phi\gamma$:





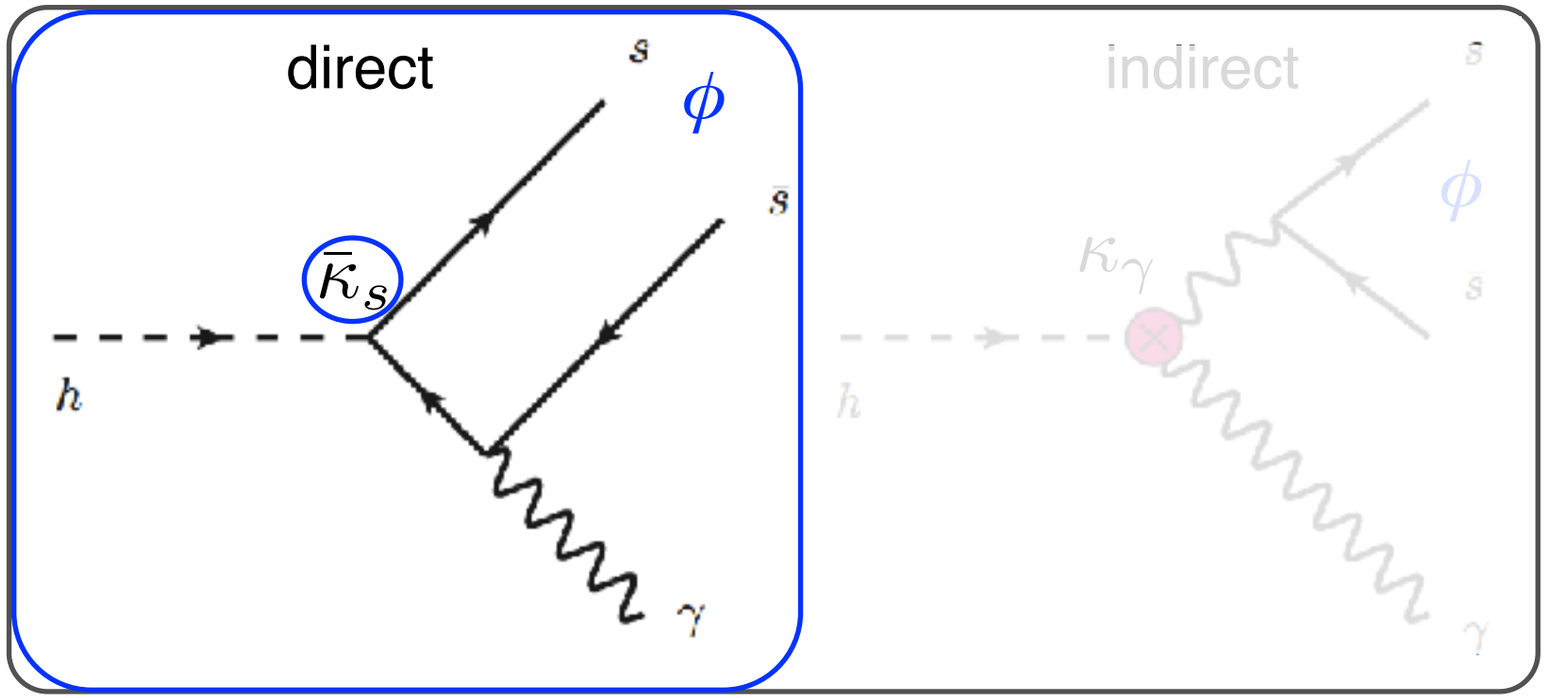
from experiment, $\phi \to e^+e^-$

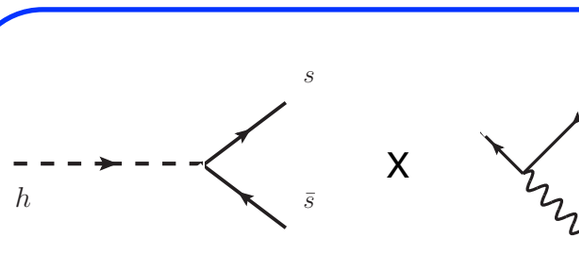
$(f_\phi = 0.235(5)\,\mathrm{GeV}$

$$\left(M_{ss}^{\phi}\right)_{\mathrm{indir}} \approx \frac{f_{\rho,\phi}}{m_{\rho,\phi}}\,\kappa_\gamma A_\gamma \frac{4\alpha m_h^2}{\pi v}$$

Ex.: $h \to \phi\gamma$, direct contribution

- Two paths to get $h \to \phi\gamma$:





$$\propto \frac{\bar{\kappa}_s m_b}{v} \frac{f_{\rho,\phi}^{\perp}}{m_h}$$

("local" structure : $\bar{s}\sigma_{\mu\nu}s \times F^{\mu\nu}$)

from experiment, $\phi \to e^+e^-$

($f_\perp^\phi = 0.191(28)$)

$$\left(M_{ss}^{\phi}\right)_{\rm dir} \approx \frac{\bar{\kappa}_s m_b}{v} f_\phi^\perp$$

Bauer, Pirjol, Stewart (01); Bauer et al. (02);
Beneke, Chapovsky, Diehl, Feldmann (02);
Ball, Braun (1996); Ball et al. (2006, 2007);
Arthur et al. (10)

Future experiments

- only a few events expected at e^+e^- colliders
  - ILC, ILC with luminosity upgrade, CLIC
  - probably too small for observation of $h \to \phi\gamma$
- $\approx$ 30 events expected at FCC-ee (TLEP)
  - too small to probe a deviation from the SM prediction
- $h \to \phi\gamma$ measurements unique to future hadron machines

Experimental sensitivity

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

- focus on $h \to \phi\gamma$, use [illegible]
  - main [illegible] $\pi^+\pi^-\pi^0(15\%)$
  - [illegible] kaons/pions
  - [illegible] ATLAS and CMS
  - adopt the geome[illegible] $Ag = 0.75$
    - do not include other efficiency or trigger factors
- assume $\kappa_\gamma = 1$, negligible background, 3σ reach

$$\mathcal{S} = |\mathrm{BR}_{h\to\phi\gamma} - \mathrm{BR}^{\mathrm{SM}}_{h\to\phi\gamma}|/(\delta\mathrm{BR}_{h\to\phi\gamma}),$$

$$\text{where } (\delta\mathrm{BR}_{h\to\phi\gamma})^2 = \mathrm{BR}_{h\to\phi\gamma}/(\sigma_h \mathcal{L} A_g) + (\delta\mathrm{BR}^{\mathrm{th}}_{h\to\phi\gamma})^2$$

two detectors

one detector

no theory error

$\sqrt{s}$ [TeV]	$\int \mathcal{L}\, dt\, [\mathrm{fb}^{-1}]$	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\mathrm{stat.}} > (<)$
14	3000	770	$0.56\,(-1.2)$	$0.27\,(-0.81)$
33	3000	1380	$0.54\,(-1.2)$	$0.22\,(-0.75)$
100	3000	5920	$0.54\,(-1.2)$	$0.13\,(-0.63)$

5x SM strange Yukawa

Thoughts about experimental strategy

- for $h \to \phi\gamma$ decay most promising $\phi \to K^+K^-$
  - near collinearity of the photon and the ϕ-jet in the transverse plane
  - jet sub-structure information
    - two close high-p_T tracks in a narrow cone
      - di-track invariant mass distribution assuming kaons
        - 1.5% (better than 15 MeV) resolution (CMS)
- can probably be used to significantly cut on the background
  - on jet+γ QCD backgrounds
  - on $h \to \phi\gamma + n\pi^\circ,\ \eta^{(\prime)}(\to neutr.)\,\gamma$
- dedicated trigger probably required to enhance the reach

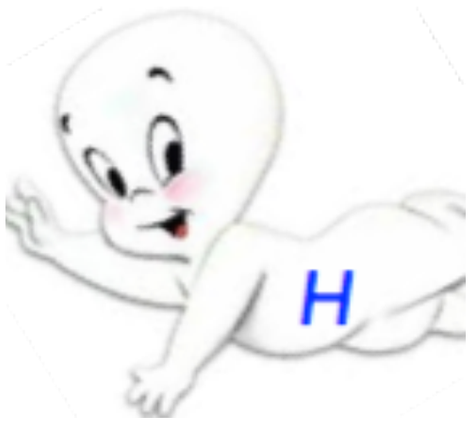
Thoughts about experimental strategy

- $h \to \varrho^{\circ}\gamma$ mode
  - $Br(\varrho^{\circ} \to \pi^{+}\pi^{-}) \sim 100\%$
  - relatively clean mode, similar to $\phi \to K^{+}K^{-}$ decay
- $h \to \omega\gamma$ mode
  - $Br(\omega \to \pi^{+}\pi^{-}\pi^{\circ}) \sim 89\%$
  - harder to trigger on
  - hard-to-identify π° smears the observable quantities
  - a detailed experimental study required

An Exclusive Window onto Higgs Yukawa Couplings to light quarks

Bodwin, Petriello, Stoynev & Velasco (13)
Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

$s\bar{b}$ $s\bar{s}$
$d\bar{b}$ $d\bar{d}$
$d\bar{s}$ $u\bar{u}$



Exclusive path towards Higgs-light quark couplings

- Use the eff. Lagrangian:

$$\mathcal{L}_{\rm eff} = -\sum_{q=u,d,s} \bar{\kappa}_q \frac{m_b}{v} h \bar{q}_L q_R - \sum_{q\neq q'} \bar{\kappa}_{qq'} \frac{m_b}{v} h \bar{q}_L q'_R + h.c.$$
$$+ \kappa_Z m_Z^2 \frac{h}{v} Z_\mu Z^\mu + 2\kappa_W m_W^2 \frac{h}{v} W_\mu W^\mu + \kappa_\gamma A_\gamma \frac{\alpha}{\pi} \frac{h}{v} F^{\mu\nu} F_{\mu\nu} \,,$$

Notice that: $\bar{\kappa}_q = y_q / y_b^{\rm SM}$, (sorry different notation)

in the SM:

$$\bar{\kappa}_s = m_s/m_b \simeq 0.020$$
$$\bar{\kappa}_d = m_d/m_b \simeq 1.0 \cdot 10^{-3}$$
$$\bar{\kappa}_u = m_u/m_b \simeq 4.7 \cdot 10^{-4}$$
$$\kappa_\gamma = \kappa_V = 1$$

Exclusive path towards Higgs-light quark couplings

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

- Use the eff. Lagrangian:

$$\mathcal{L}_{\rm eff} = -\sum_{q=u,d,s} \bar{\kappa}_q \frac{m_b}{v} h \bar{q}_L q_R - \sum_{q\neq q'} \bar{\kappa}_{qq'} \frac{m_b}{v} h \bar{q}_L q'_R + h.c.$$
$$+ \kappa_Z m_Z^2 \frac{h}{v} Z_\mu Z^\mu + 2\kappa_W m_W^2 \frac{h}{v} W_\mu W^\mu + \kappa_\gamma A_\gamma \frac{\alpha}{\pi} \frac{h}{v} F^{\mu\nu} F_{\mu\nu} \,,$$

Notice that: $\bar{\kappa}_q = y_q / y_b^{\rm SM}$,

where generically: $|\bar{\kappa}_u| < 0.98\,, \quad |\bar{\kappa}_d| < 0.93\,, \quad |\bar{\kappa}_s| < 0.70$

varying only one at the time (95%CL)

$|\bar{\kappa}_u| < 1.3\,, \quad |\bar{\kappa}_d| < 1.4\,, \quad |\bar{\kappa}_s| < 1.4$

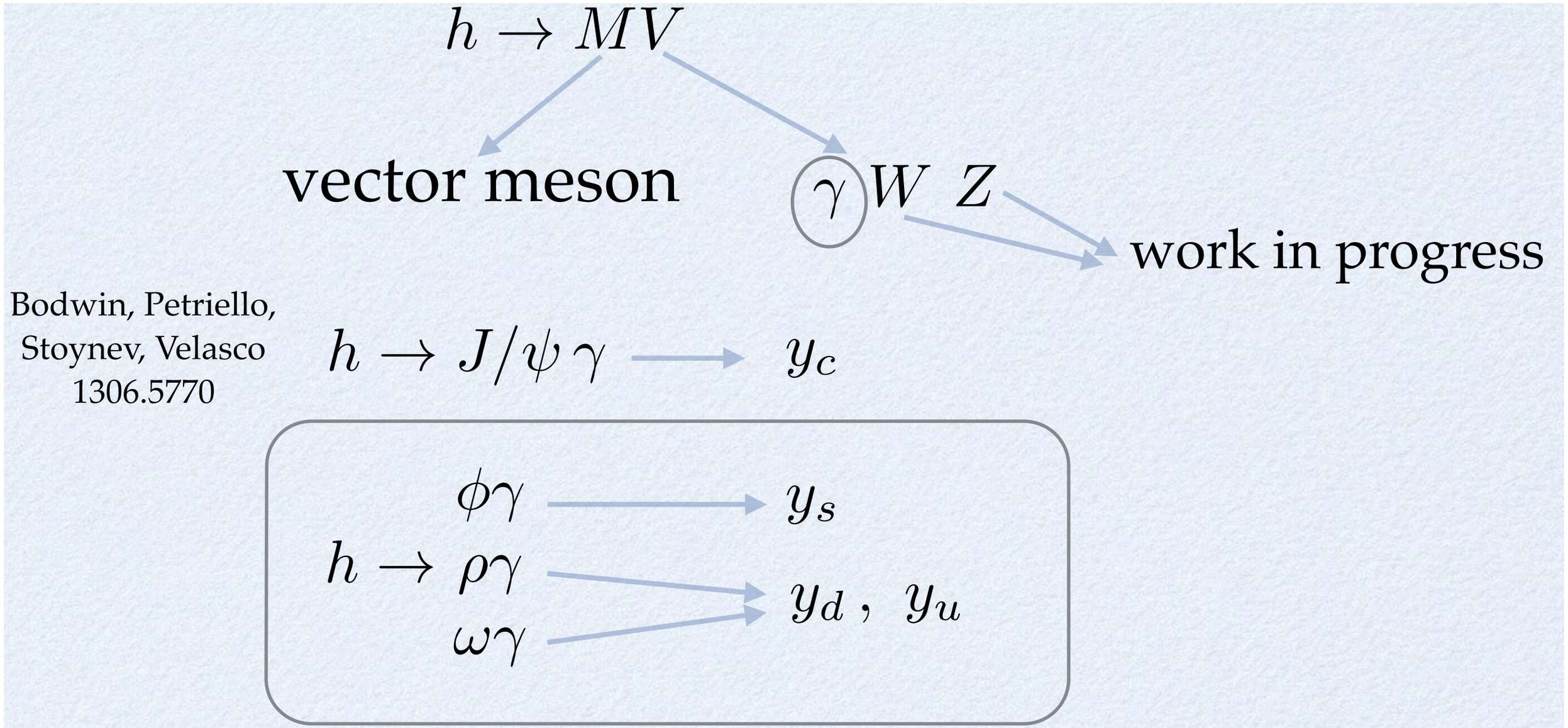
varying all couplings (95%CL)

$|\bar{\kappa}_{qq'}| < 0.6\,(1)$ for $q, q' \in u, d, s, c, b$ and $q \neq q'$

same for the flavor violating case

(FCNC non-robust bound: $|\bar{\kappa}_{bs}| < 8 \cdot 10^{-2}$ Harnik, Kopp & Zupan; Blankenburg, Ellis, Isidori, (12))

The main idea



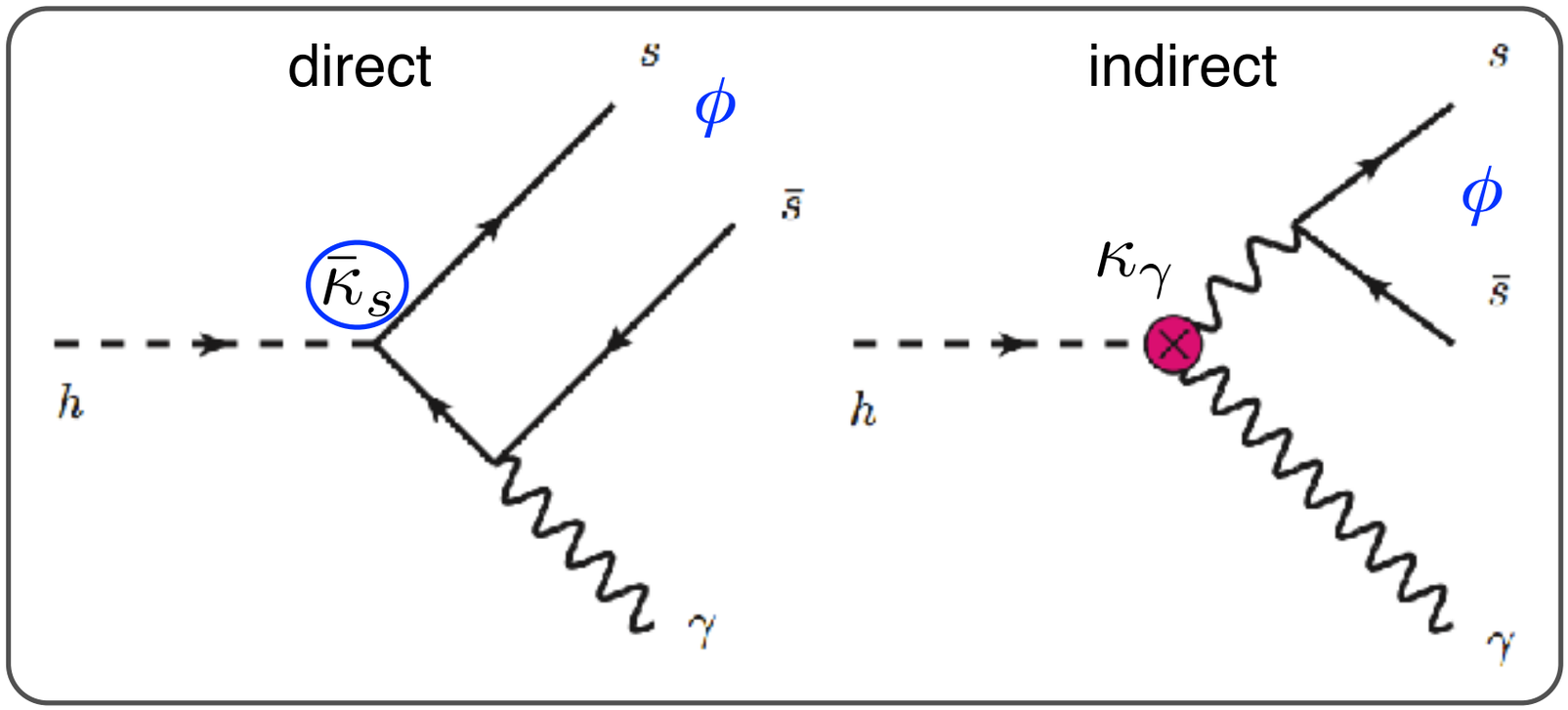
Adding off-diagonal: $h \to \bar{B}^{0*}\gamma$, $h \to \bar{B}^{0*}\gamma$, $h \to K^{0*}\gamma$,$h \to D^{0*}\gamma$

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

Ex.: $h \to \phi\gamma$

$$\Gamma_{h\to\phi\gamma} = \frac{1}{8\pi}\frac{1}{m_h}|M^{\phi}_{ss}|^2,$$

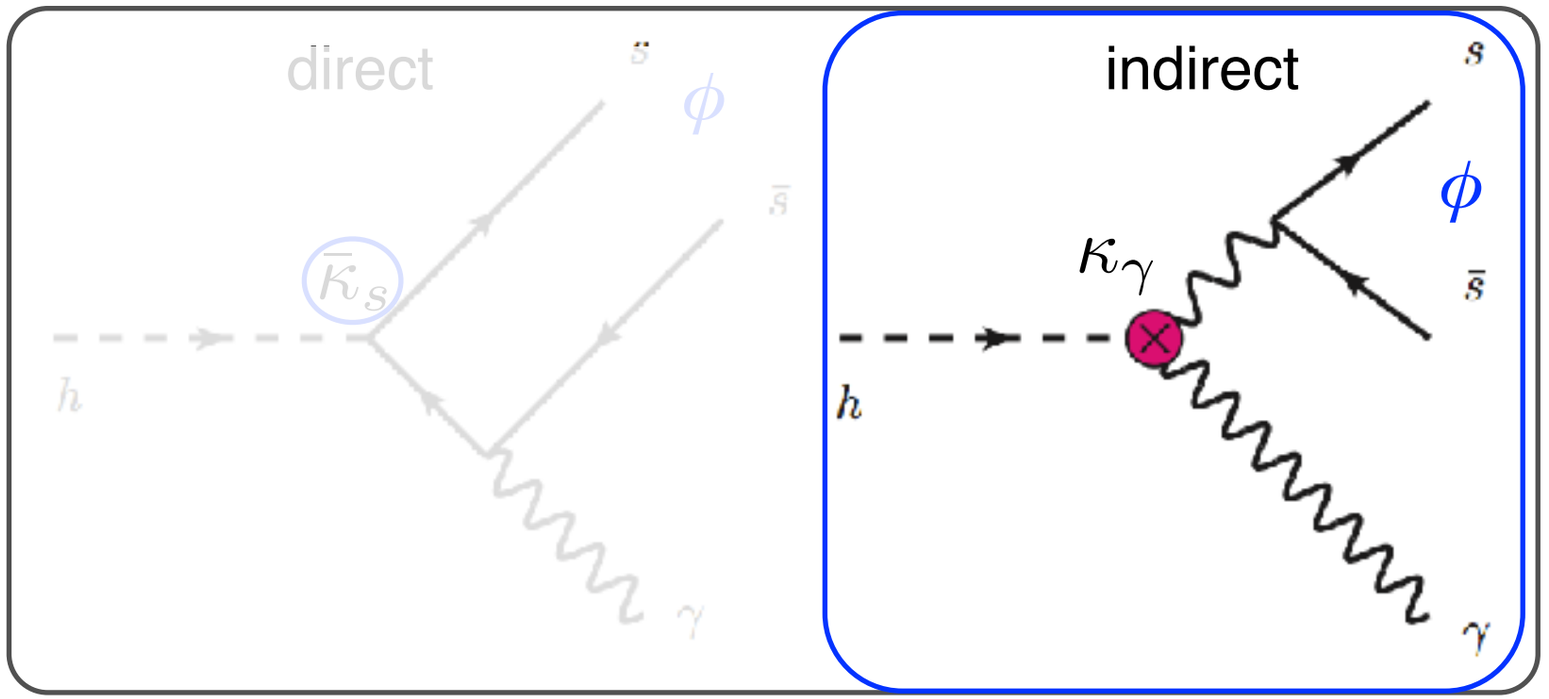
- Two paths to get $h \to \phi\gamma$:

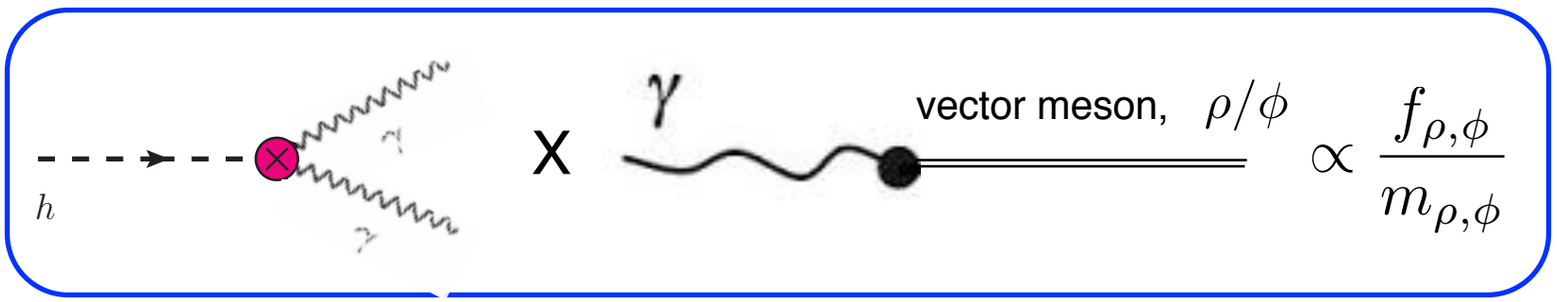


- Let us understand them one by one.

Ex.: $h \to \phi\gamma$, indirect contribution

- Two paths to get $h \to \phi\gamma$:





from experiment, $\phi \to e^+e^-$

($f_\phi = 0.235(5)\,\mathrm{GeV}$

$$\left(M_{ss}^{\phi}\right)_{\mathrm{indir}} \approx \frac{f_{\rho,\phi}}{m_{\rho,\phi}}\,\kappa_\gamma A_\gamma \frac{4\alpha m_h^2}{\pi v}$$

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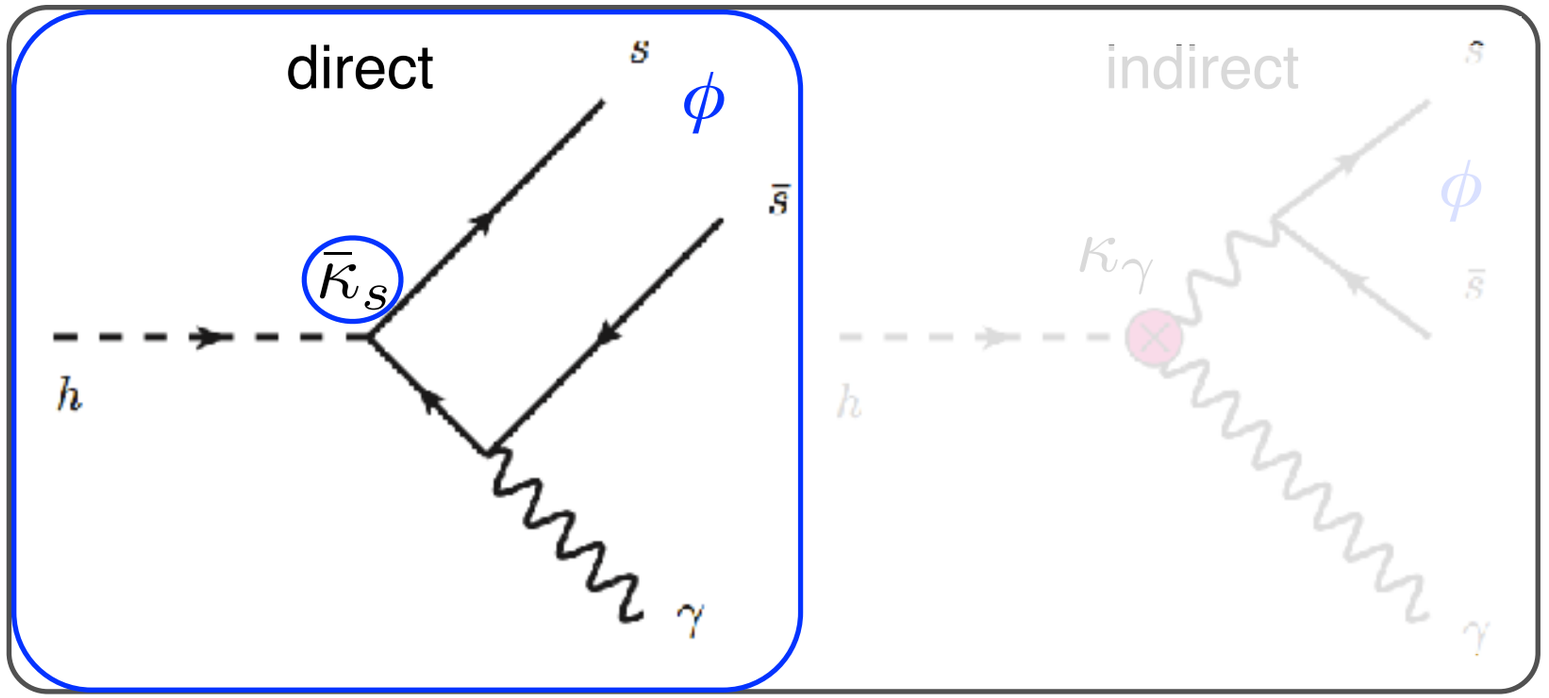
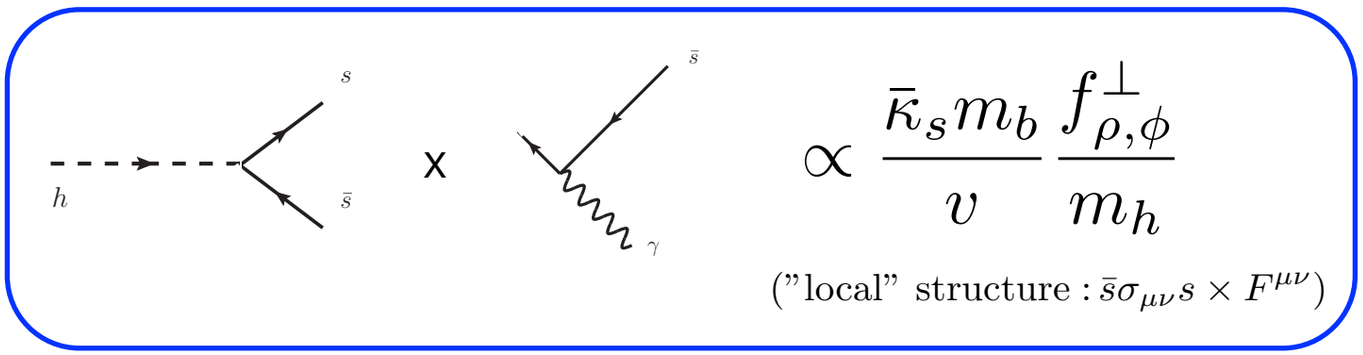




from experiment, $\phi \to e^+e^-$

($f_\perp^\phi = 0.191(28)$)

$$\left(M_{ss}^{\phi}\right)_{\rm dir} \approx \frac{\bar{\kappa}_s m_b}{v} f_\phi^\perp$$

Relaxion's basic structure

- QFT consistent constructions are of the form:

Choi, Kim & Yun (2014) Choi & Im; Kaplan & Rattazzi; Gupta, Komargodski, GP & Ubaldi (15)

$$V(\phi, H) = H^\dagger H[\Lambda^2 - M^2 \overbrace{\cos(\phi/f)}^{(\text{GKR: } g \sim M/f)}] + r\Lambda^2 M^2 \cos(\phi/f) + H^\dagger H \tilde{M}^2 \cos(n\phi/f)\,.$$

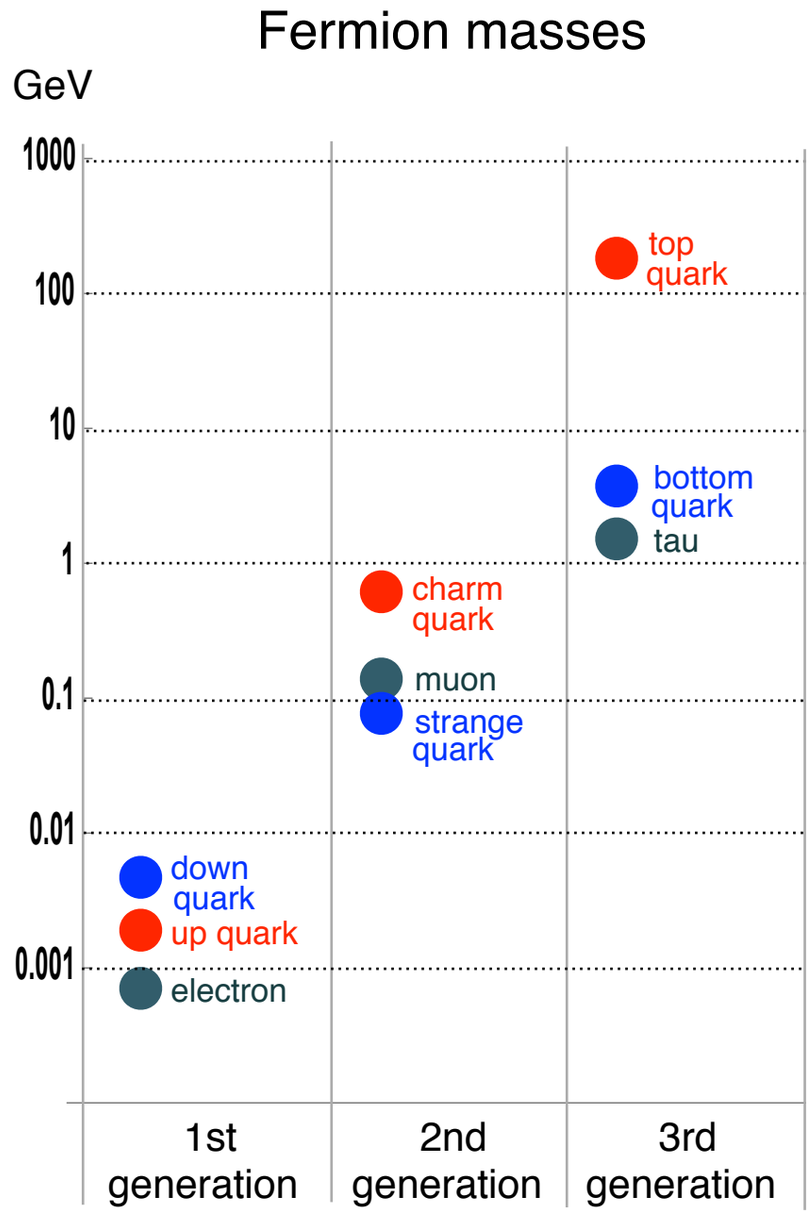
$$V'(\phi_*, v) = 0 \;\Rightarrow\; r\Lambda^4 \sin(\phi_*/f) \simeq v^2 n\tilde{M}^2 \sin(n\phi_*/f) \;\not\Rightarrow\; \phi_* \text{ is generic.} \quad (M \sim \Lambda)$$

- It implies that generically:

(i) CP violation is spontaneously induced (problematic for axion-relaxion models);

(ii) Higgs-relaxion mixing is induced:

$$V_{\rm mix} \sim \frac{nv\tilde{M}^2}{f} \sin(n\phi_*/f) \times H\phi_{\rm phys} \simeq \frac{r\Lambda^4}{vf} \sin(\phi_*/f) \times H\phi_{\rm phys}\,.$$

The flavor puzzle, the origin of mass hierarchy

Known point-like charged particle masses span 5 orders of magnitude.