New scalars at High Energy Lepton Colliders

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based on 1807.04743 with D. Redigolo, F. Sala, A. Tesi

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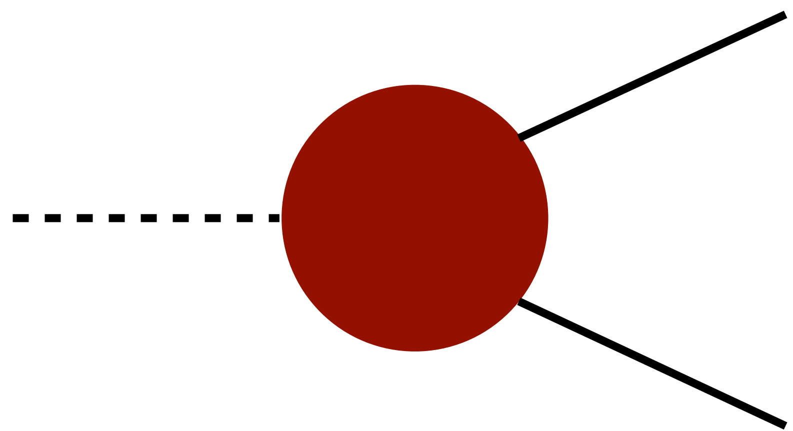
Higgs physics vs. High Energy searches

CLIC will be able to measure Higgs properties with a precision of ~ a few 10^{-3}



$$\sim C_{\text{model}} \times \frac{m_h}{M}$$

mass of new states

If in the few TeV range, it is possible to directly produce the new particles.

Are direct searches for the new states at CLIC able to compete with the sensitivity in Higgs physics?

Reference model: scalar singlet

At the risk of being trivial… Take just the SM + real scalar singlet

- Very simple model: easy enough to test capabilities of a collider with just a few meaningful parameters

- Nevertheless, appears in several motivated physics scenarios
  - Low energy effective theory of Mirror/Twin Higgs models,
  - Realised in the NMSSM,
  - Paradigm for 1st order ElectroWeak phase transition,
  - Non-minimal composite Higgs,
  - More general dark sectors…

- Large (tree-level) Higgs couplings modifications, easily related to direct singlet production cross-section

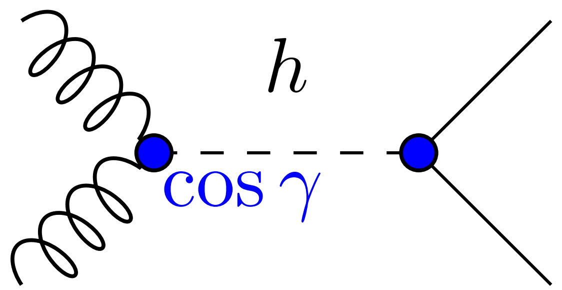
Scalar singlet phenomenology

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}(\partial_\mu S)^2 + \frac{1}{2}m_S^2 S^2 + a_{HS}|H|^2 S + \frac{\lambda_{HS}}{2}|H|^2 S^2 + V(S)$$

- $a_{HS}|H|^2 S$: controls Higgs-singlet mixing ~ **sin γ**
- $\frac{\lambda_{HS}}{2}|H|^2 S^2$: portal coupling
- $V(S)$: enters triple couplings: ***BR(ϕ → hh)***, g_{hhh}

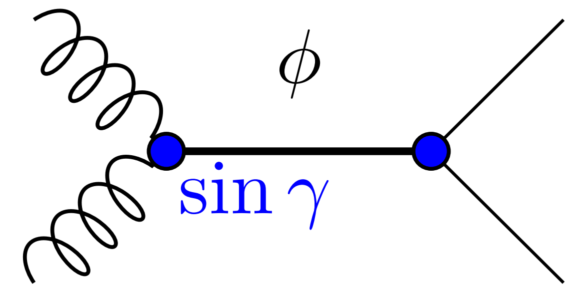
mass eigenstates: $h = c_\gamma H^0 + s_\gamma S, \qquad \phi = -s_\gamma H^0 + c_\gamma S$

- Higgs signal strengths:



$$\mu_h = \mu_{\mathrm{SM}} \times \cos^2\gamma$$

- ϕ can be singly produced:



$$\sigma_\phi = \sigma_{\mathrm{SM}}(m_\phi) \times \sin^2\gamma$$

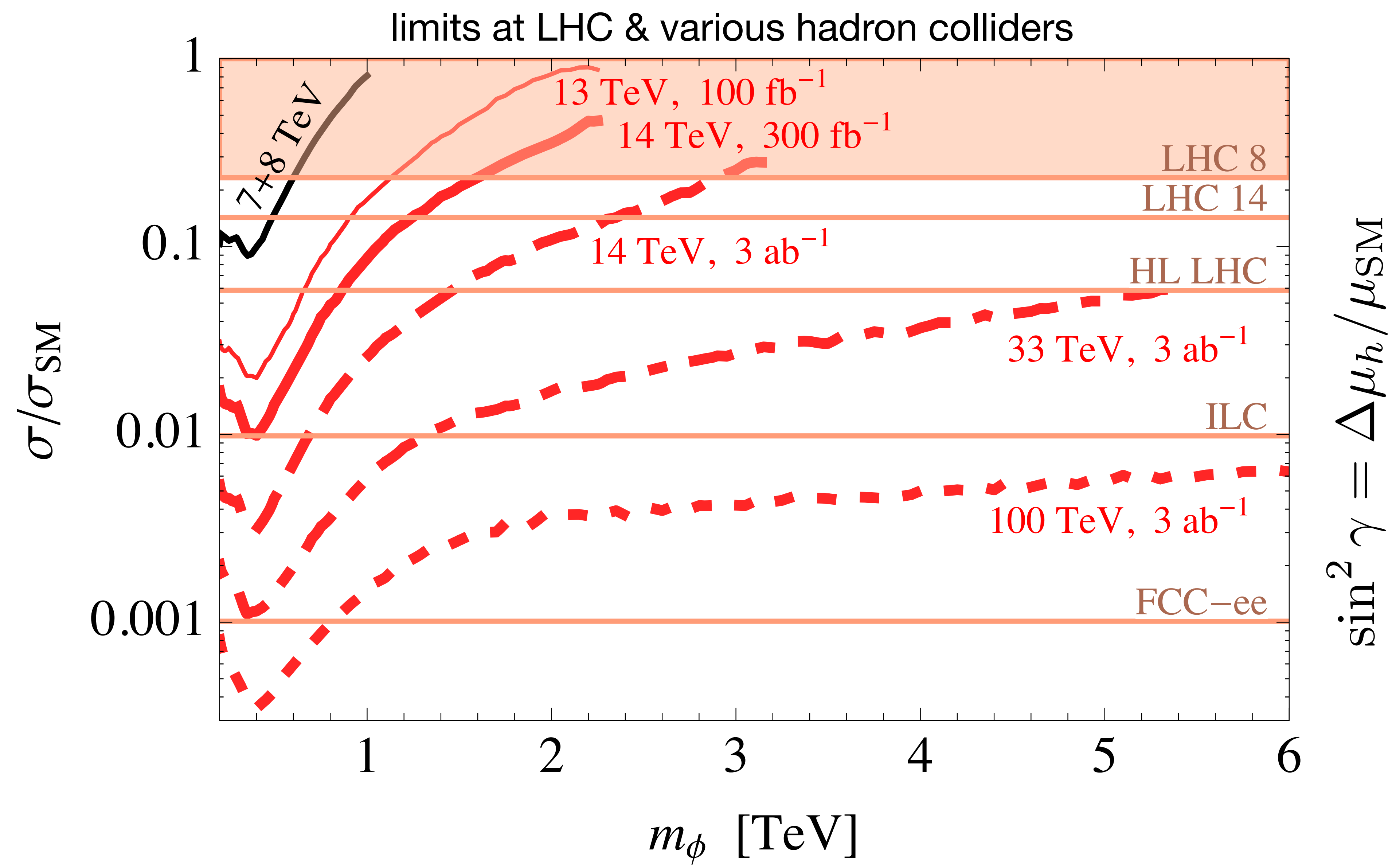
- ϕ decays to SM:

$$\mathrm{BR}_{\phi\to VV,ff} = \mathrm{BR}_{\mathrm{SM}}(m_\phi)\left[1 - \mathrm{BR}_{\phi\to hh}\right]$$

ϕ is like a heavy SM Higgs with narrow width + *hh* channel

Direct vs indirect searches

Very easy to relate direct searches and Higgs couplings: [see also 1505.05488]

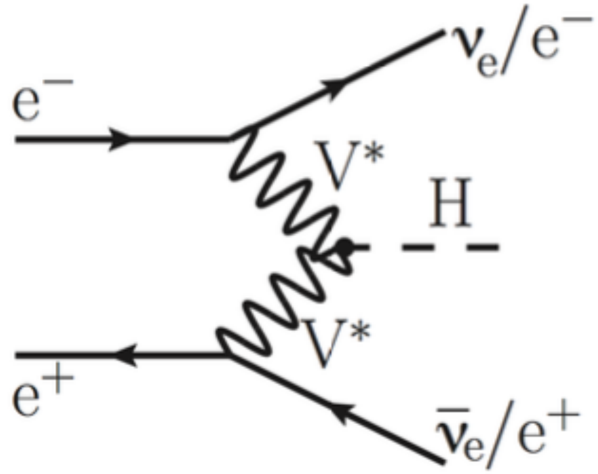


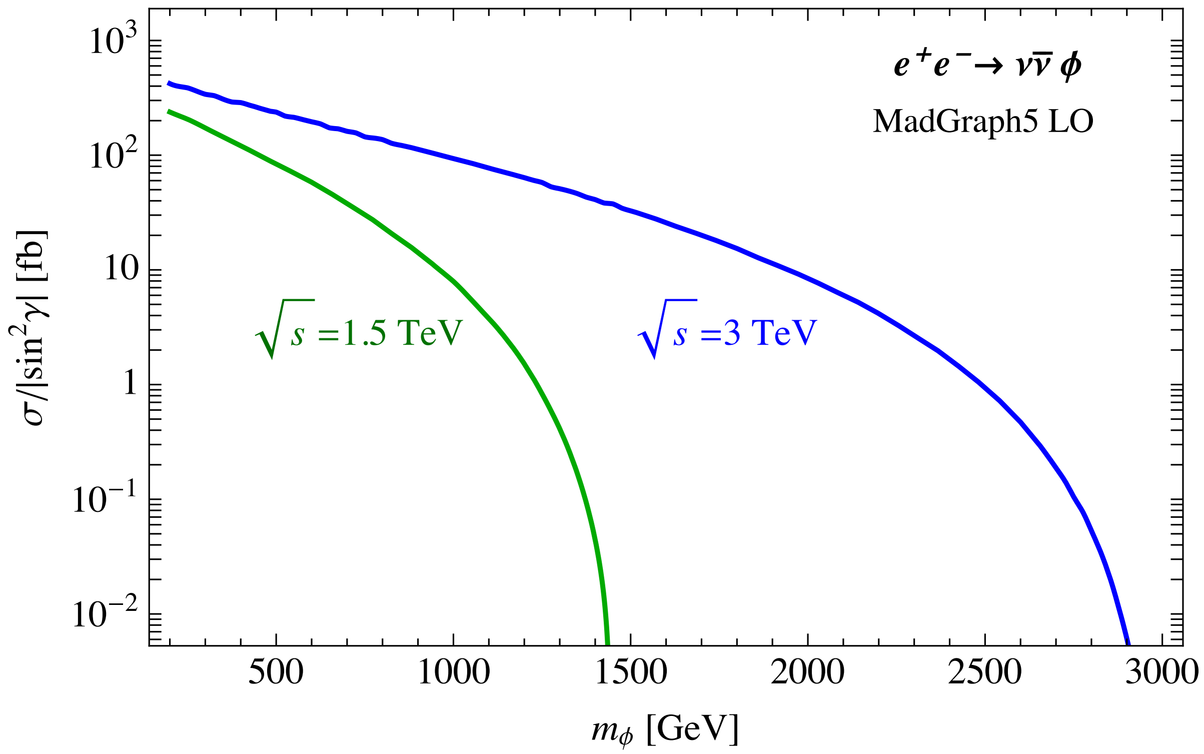
What about CLIC?

Scalar singlets at CLIC

ϕ is like a heavy SM Higgs with narrow width

- At a High Energy Lepton Collider, the dominant production mode is VBF





- The dominant decay modes are into bosons. Equivalence theorem:

$$\mathrm{BR}_{\phi\to hh} = \mathrm{BR}_{\phi\to ZZ} = \frac{1}{2}\mathrm{BR}_{\phi\to WW} \simeq \frac{1}{4}, \qquad m_\phi \gg m_h$$

  - ϕ → *ZZ(4l,2l2j)*: very clean, some EW background; main channel at LHC.
  - ϕ → *hh(4b)*: also clean channel, very sensitive; more challenging at LHC.

$hh(4b)$ decay channel

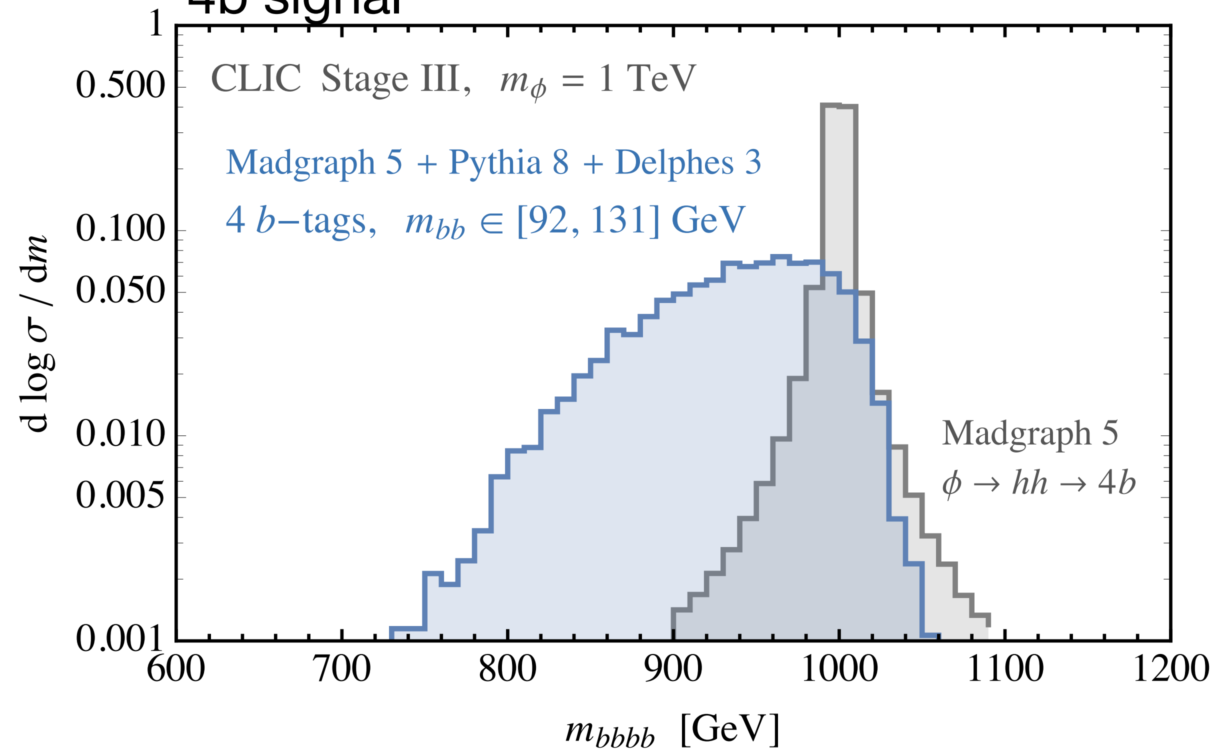
Main backgrounds: hh, ZZ, Zh. We simulate the full e+e- → $4b + 2\nu$

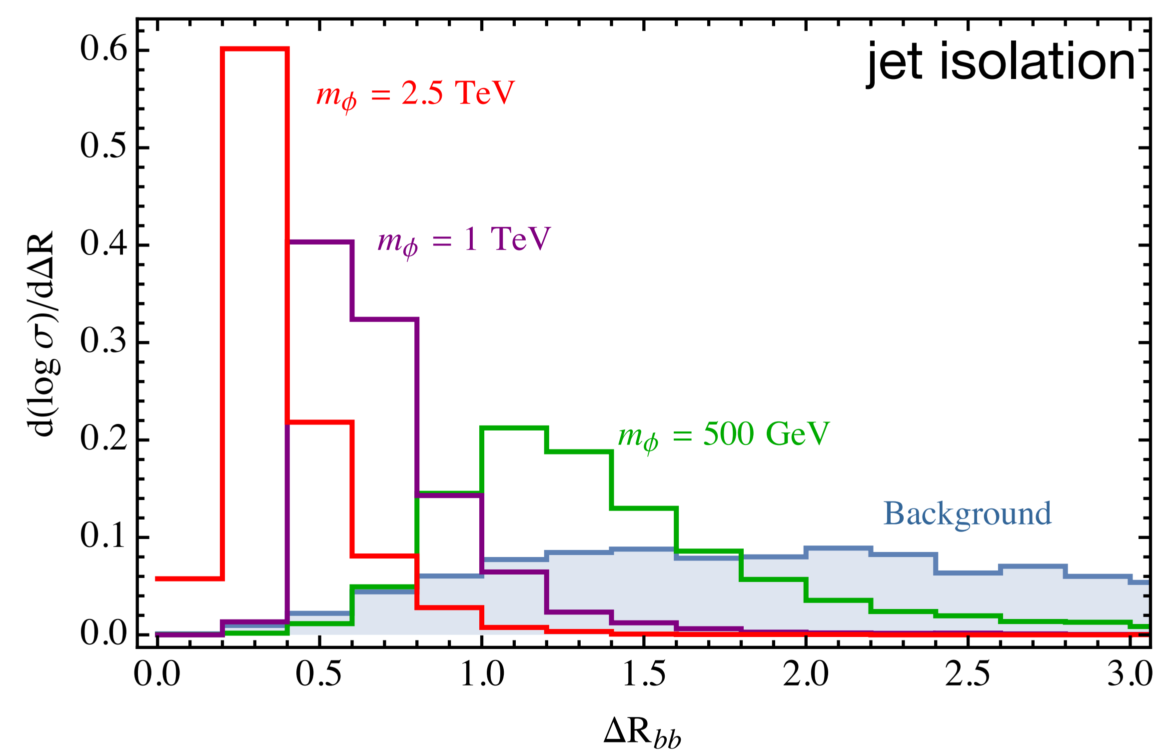
- Detector simulation with CLICdp Delphes card
- VLC exclusive jet reconstruction, N = 4, R = 0.7
- 4 b-tags (loose criterion)
- h reconstruction: select the b pairs that give the best fit to two 125 GeV Higgs bosons, 90 GeV < m_{bb} < 130 GeV
- ϕ reconstruction: $0.75\, m_\phi < m_{4b} < 1.05\, m_\phi$
- Other cuts: $p_T > 20$ GeV, $E_{miss} > 30$ GeV, $|\cos\theta_h| < 0.9$

Signal efficiency $\varepsilon_{sig} \sim 25 - 30\%$

Background reduced by $\varepsilon_{bkg} \sim 10^{-3} - 10^{-4}$

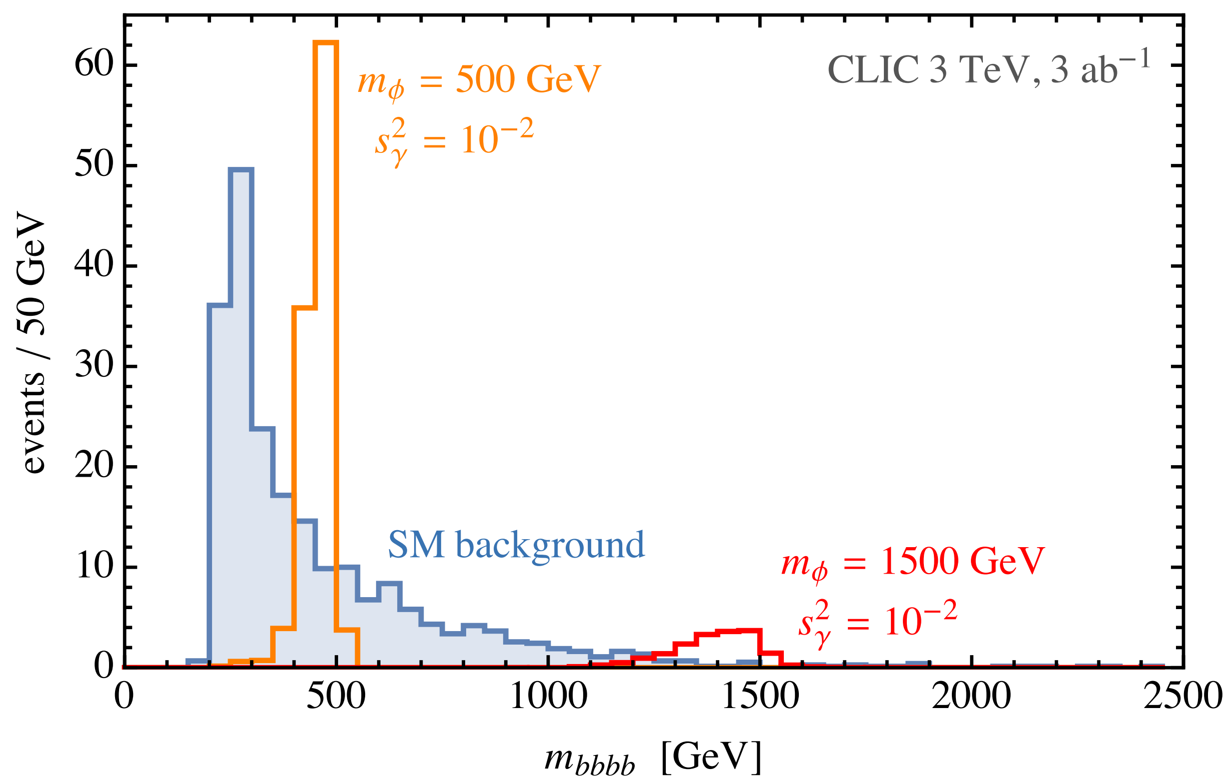
4b signal

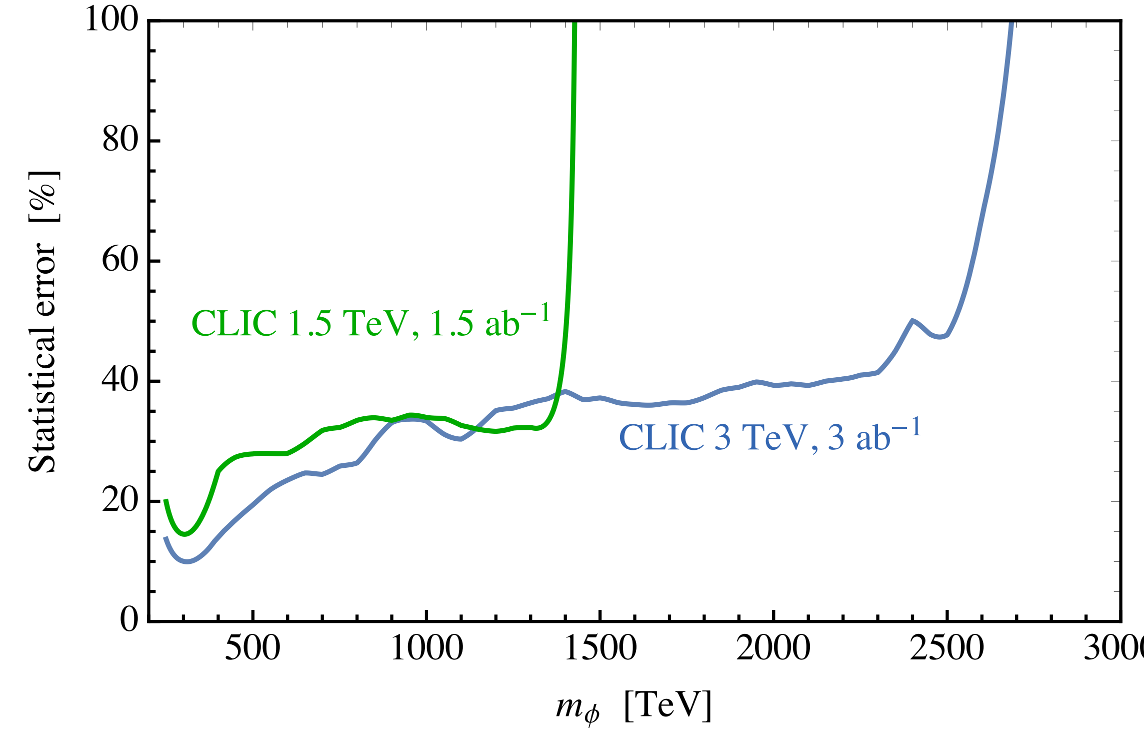




$hh(4b)$ decay channel

Very small background above ~ 500 GeV, the error is dominated by statistics





Cut & count experiment around the resonance peak:

$$\text{significance} = \frac{N_{\text{sig}}}{\sqrt{(N_{\text{sig}} + N_{\text{bkg}}) + \alpha_{\text{sys}}^2 N_{\text{bkg}}^2}}$$

$\alpha_{\text{sys}} = 2\%$ (but it has no impact)

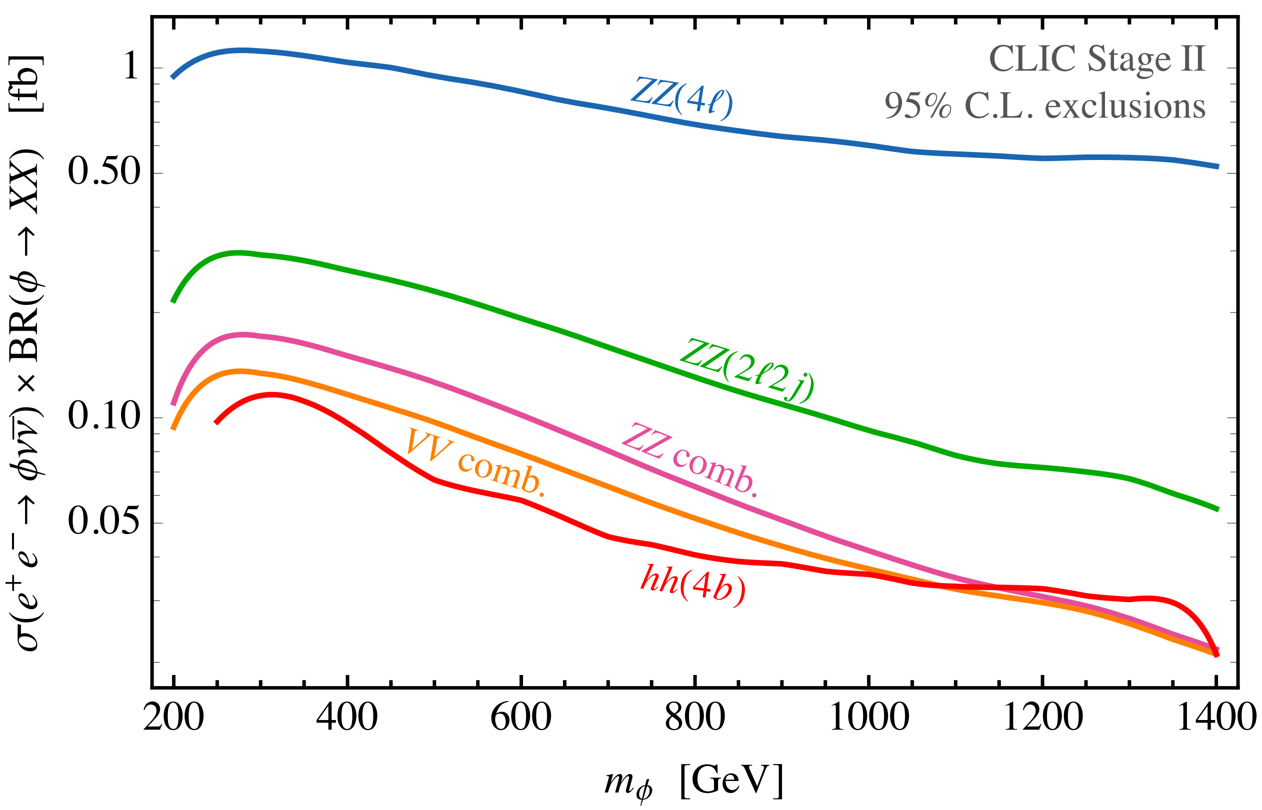
Asymptotic value of excluded cross-section (limit of no bkg):

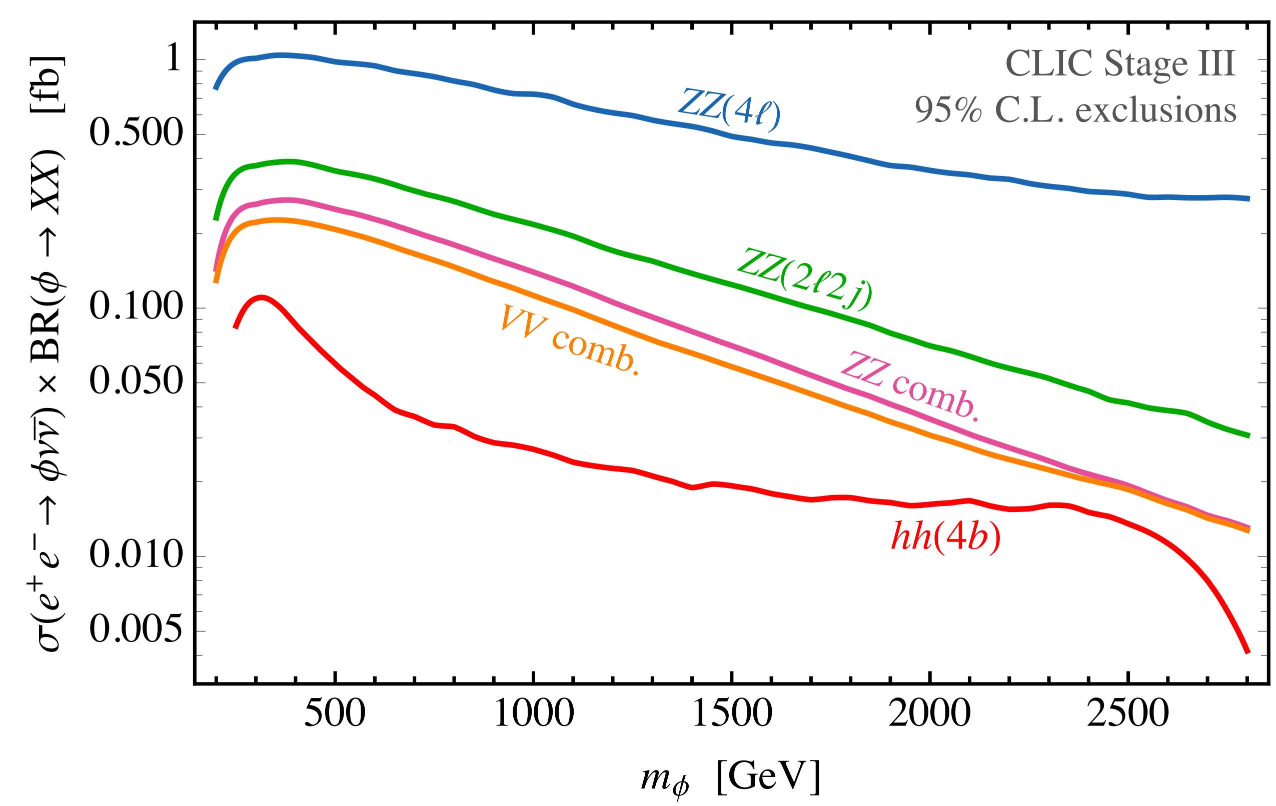
$$\sigma(e^+e^- \to \phi\nu\bar{\nu}) \times \text{BR}(\phi \to f) \simeq 3/L,$$

The reach in di-bosons at CLIC

- For BR(ϕ → hh) ~ 0.25, the most sensitive channel is $\phi \to hh \to 4b$
- Low backgrounds: limits depend weakly on ϕ mass and collider energy
- $\phi \to VV$ less sensitive, but complementary (BR(ϕ → hh) can be small)
- $\phi \to VV$ analysis done at parton-level: ZZ inv. mass in a window around the resonance peak… we checked that it reproduces the full result very well

good agreement with 1807.04284

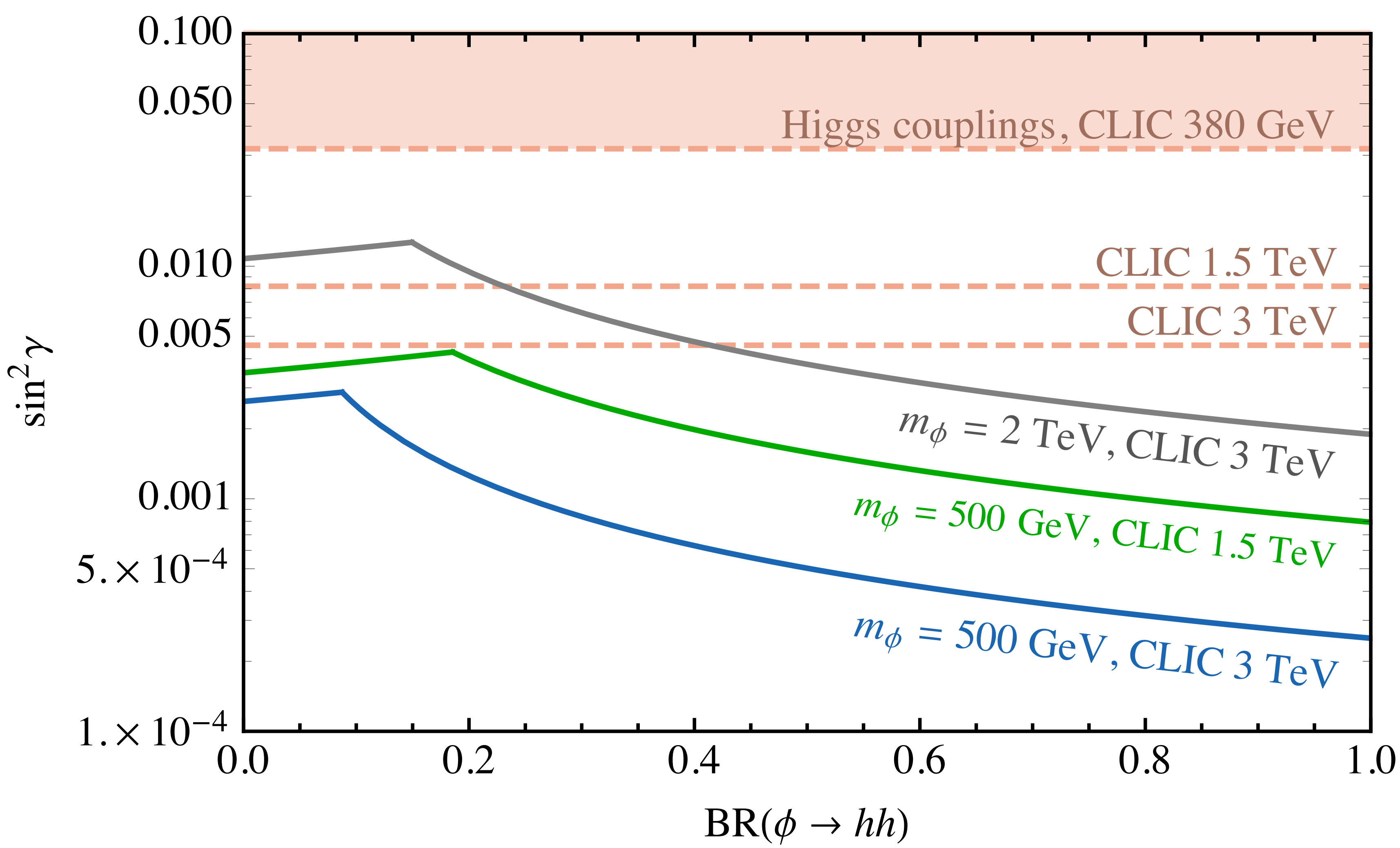




Direct vs indirect reach

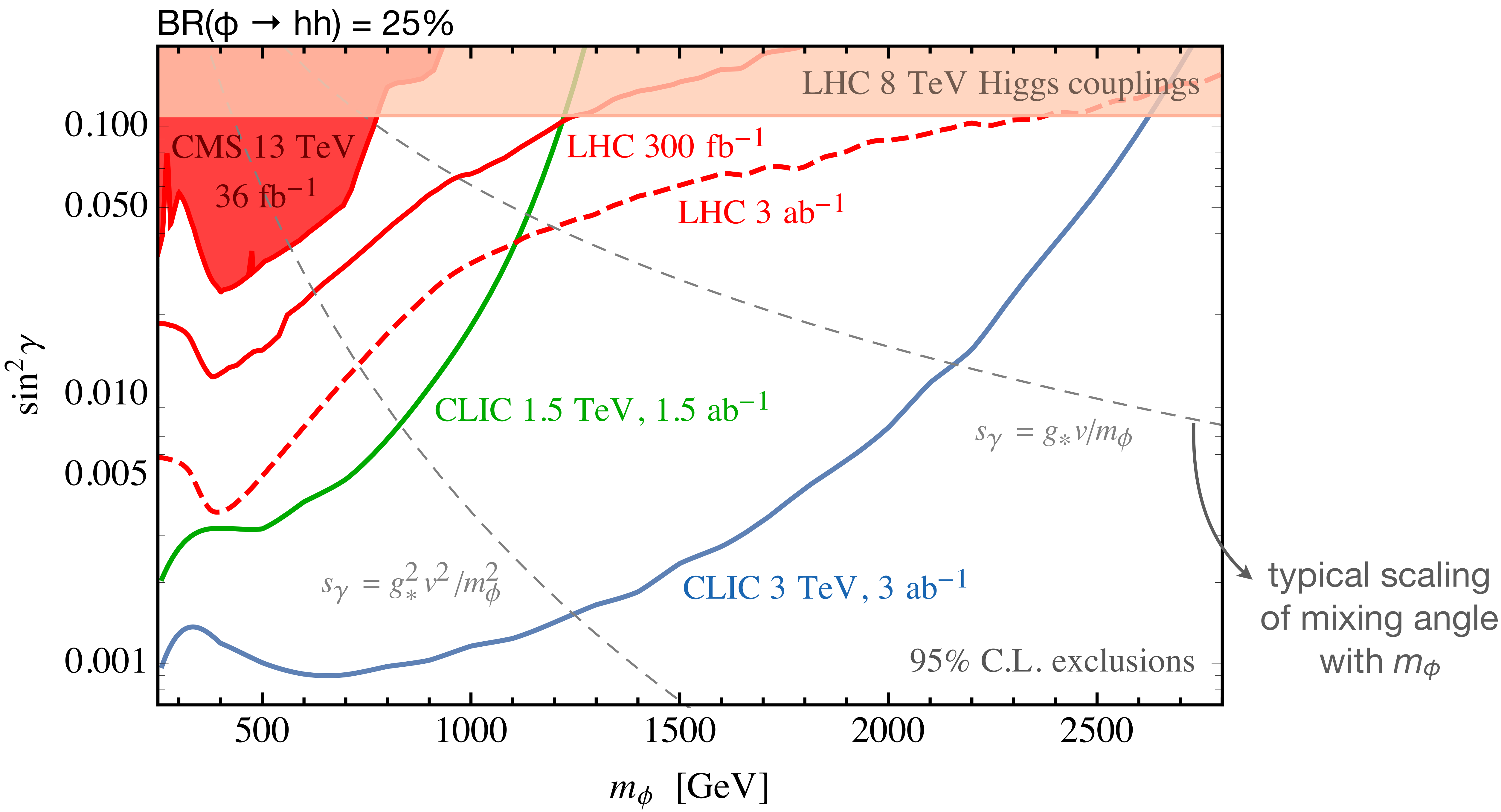
$\phi \to WW, ZZ$ and $\phi \to hh$ searches are complementary:

$$\mathrm{BR}_{\phi\to VV} \approx 1 - \mathrm{BR}_{\phi\to hh}$$



Especially for lower masses, and sizeable BR_{hh} direct searches @ CLIC will be more sensitive than Higgs coupling measurements

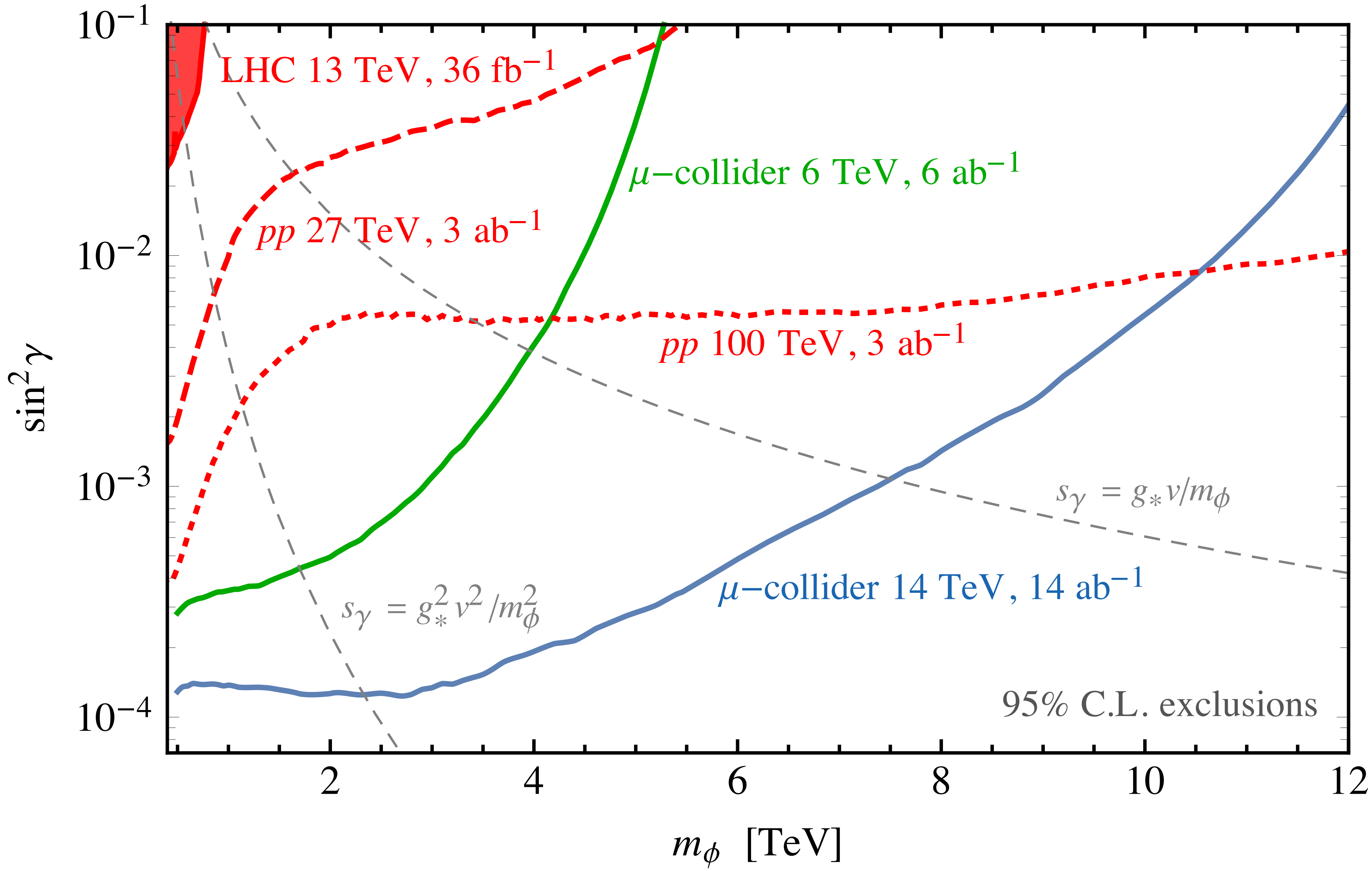
Direct vs indirect reach



CLIC @ 3 TeV is capable to significantly improve over the reach of HL-LHC

Direct vs indirect reach: high energy colliders

- One can compare the reach of very high energy lepton & hadron colliders



- For this class of models, a high-energy μ collider is much more powerful than a 100 TeV pp collider!

SUSY: the NMSSM

$$\mathcal{W} = \mathcal{W}_{\text{MSSM}} + \lambda S H_u H_d + f(S)$$

The singlet can be the lightest new state of the Higgs sector

- ◇ Extra tree-level contribution to the Higgs mass

$$M_{hh}^2 = m_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 + \Delta^2$$

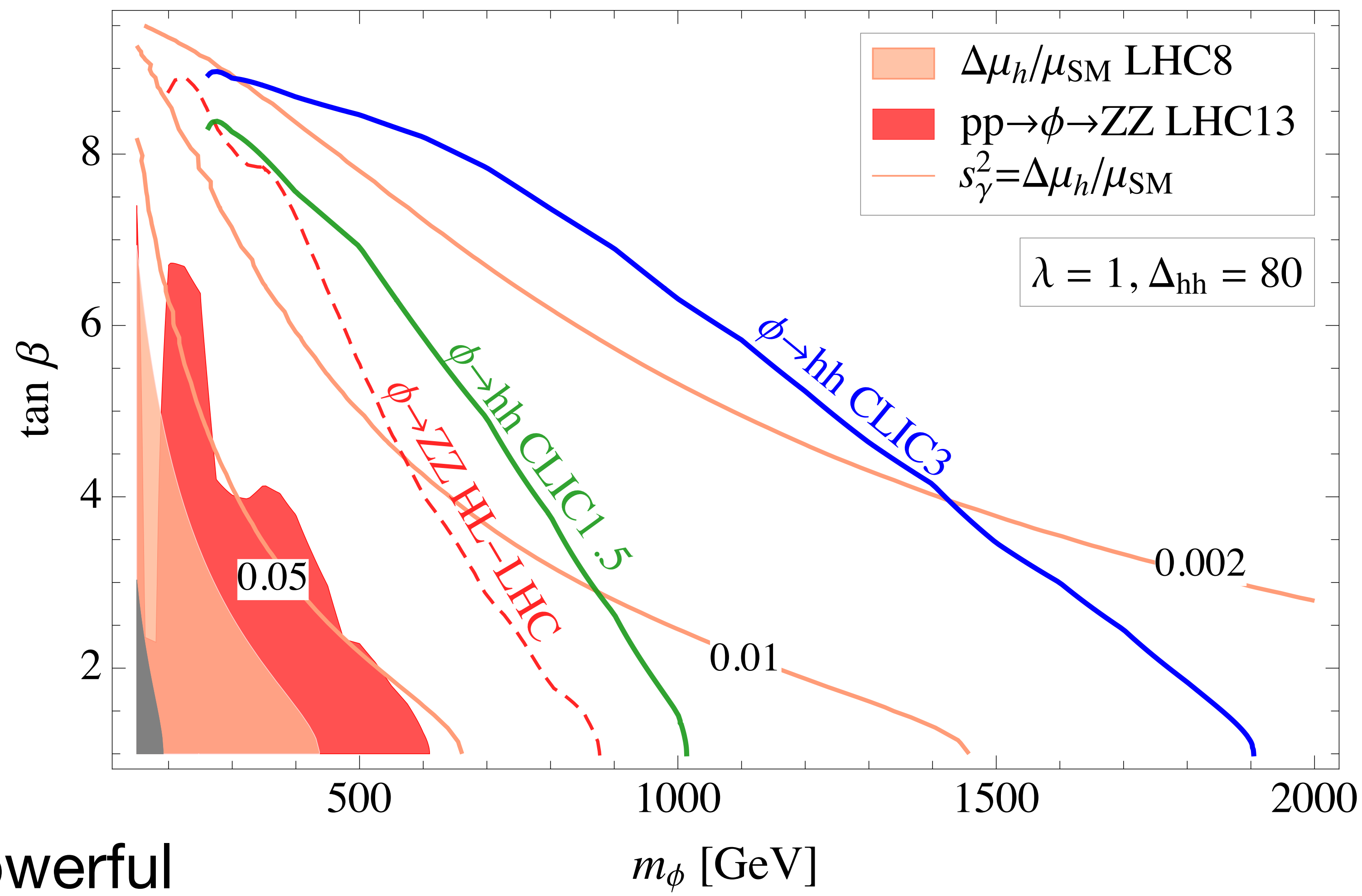
- ◇ Alleviates fine-tuning in v for $\lambda \gtrsim 1$ and moderate $\tan\beta$

Recast the previous bounds:

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

$$M_{hh}^2 = m_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 + \Delta^2$$

loop correction to Higgs mass from top-stop



Weakly coupled: direct searches powerful

Twin Higgs

- Higgs mass is protected from radiative corrections without new light colored states

- Two copies of the SM, with approximate Z_2 symmetry, coupled through the Higgs portal

- Higgs is a pseudo-Goldstone

$$\sin^2\gamma \sim v^2/f^2$$

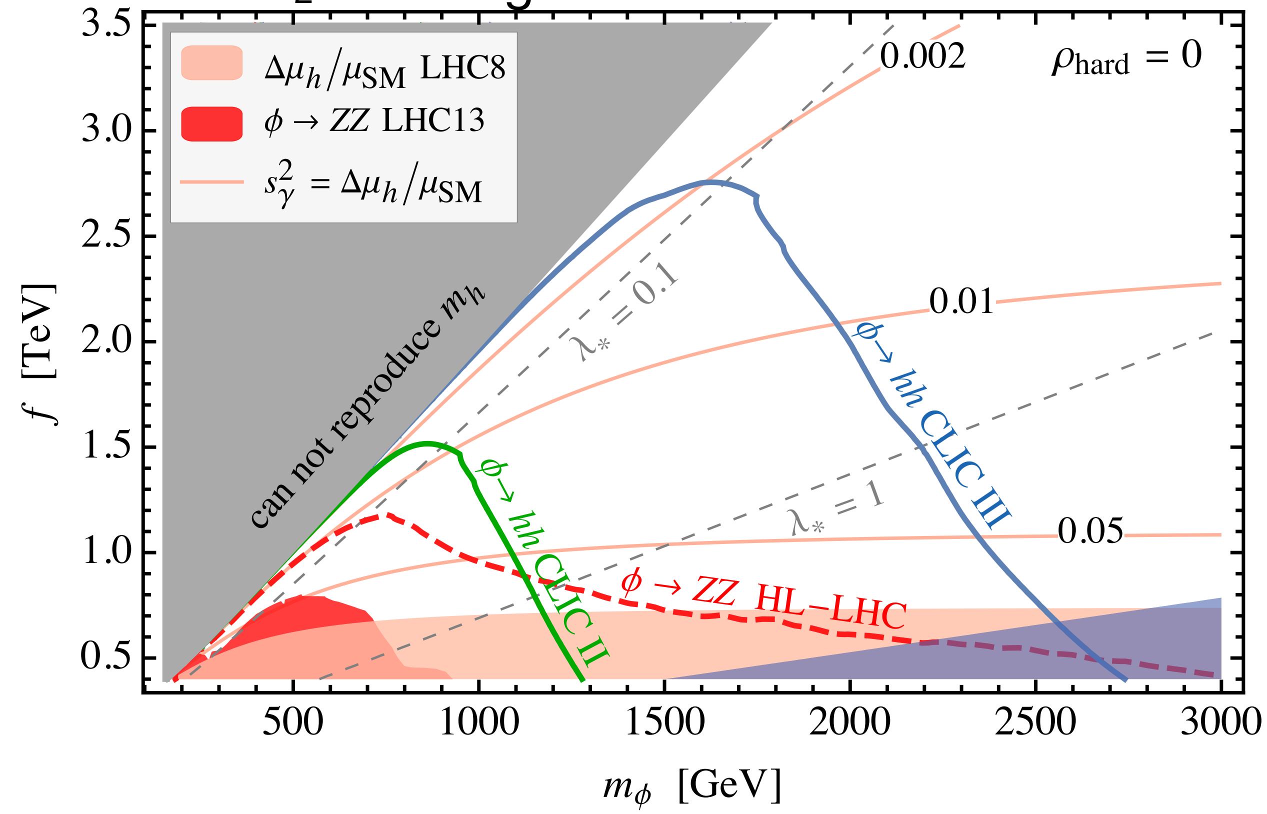
- Model-independent tests:

  ✓ Higgs couplings

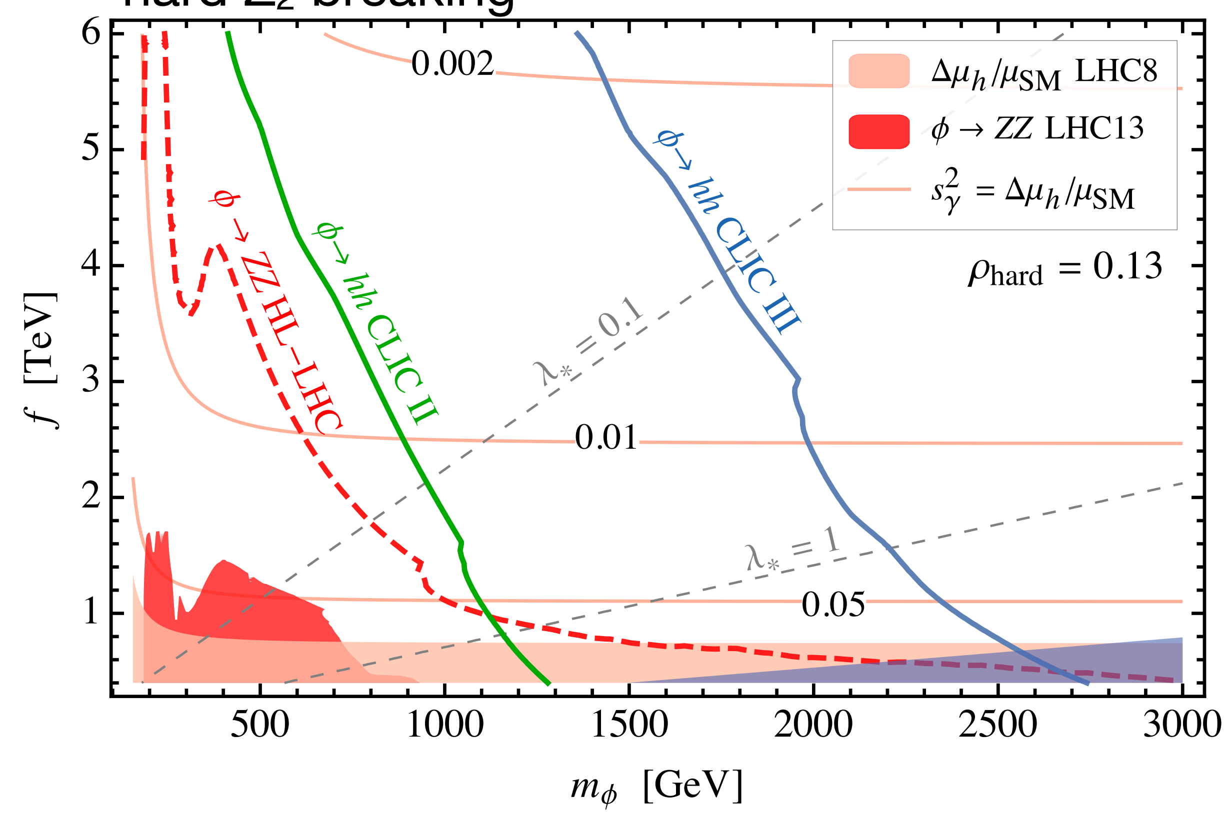
  ✓ Search for the singlet

[see also 1711.05300]

soft Z_2 breaking

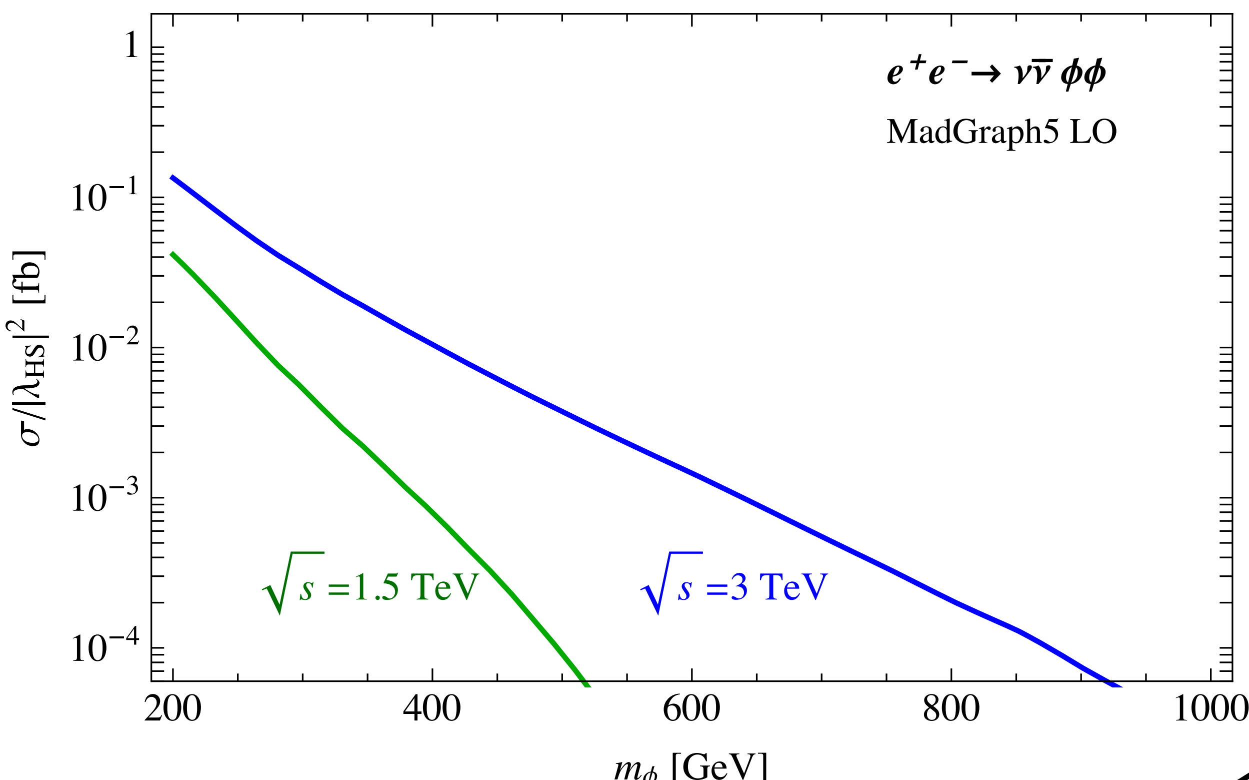


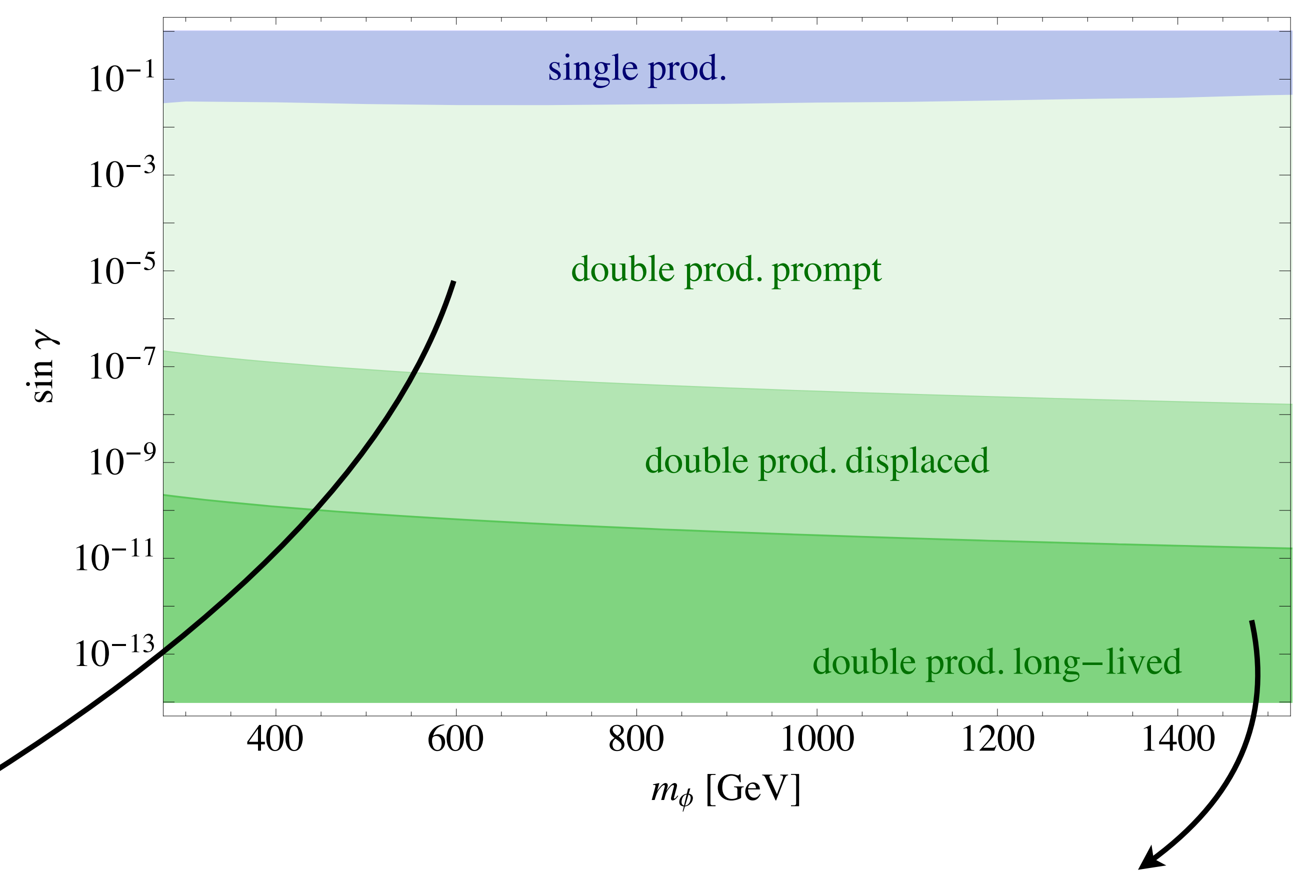
hard Z_2 breaking



Pair production

- In the limit of small mixing angle, the single production rate of ϕ vanishes
  - the Lagrangian has an approximate Z_2 symmetry $\phi \to -\phi$
- The double production rate does not depend on the mixing: controlled by the portal coupling λ_{HS}





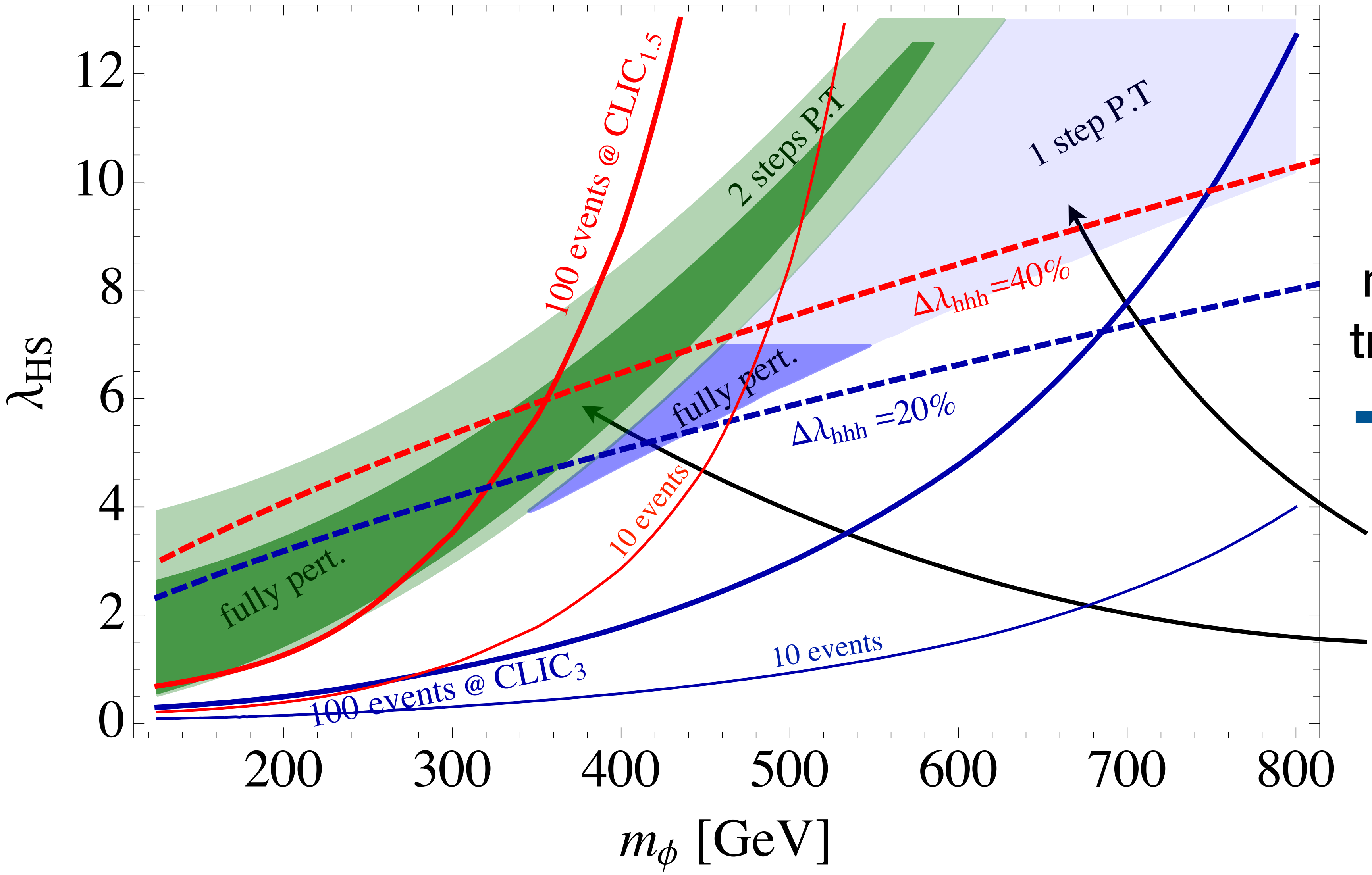
we focus on a region of small non-zero mixing: the singlet decays to SM bosons in the detector

ϕ is invisible: requires a different treatment

[see e.g. 1409.0005]

Pair production: results

- Final states with 4 Higgs (e.g. 8b) or vector bosons: small backgrounds few events are needed to test the model at CLIC



λ_{HS} also induces modifications of the triple-Higgs coupling

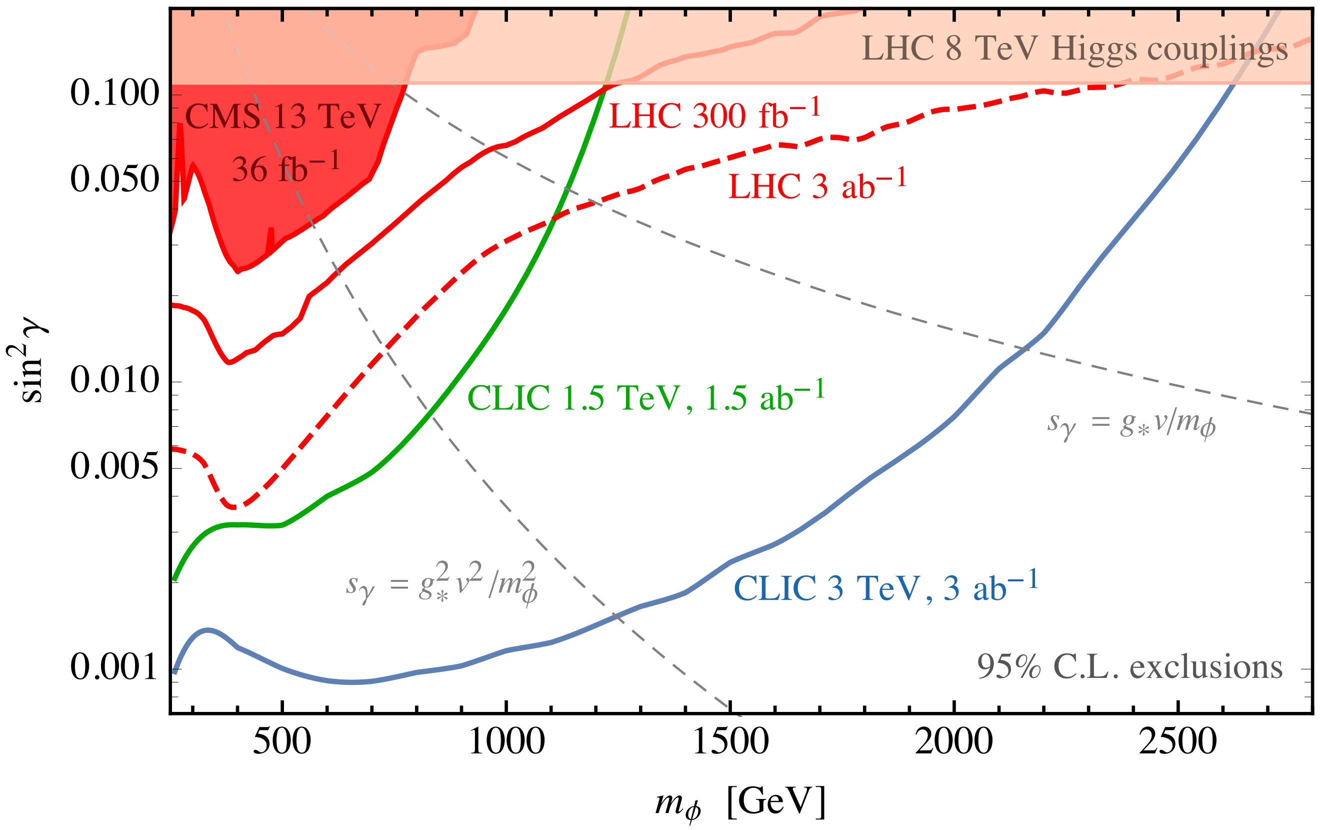
➡ see Ulrike's talk!

regions where 1st order EW phase transition can happen

➡ see Jose's talk!

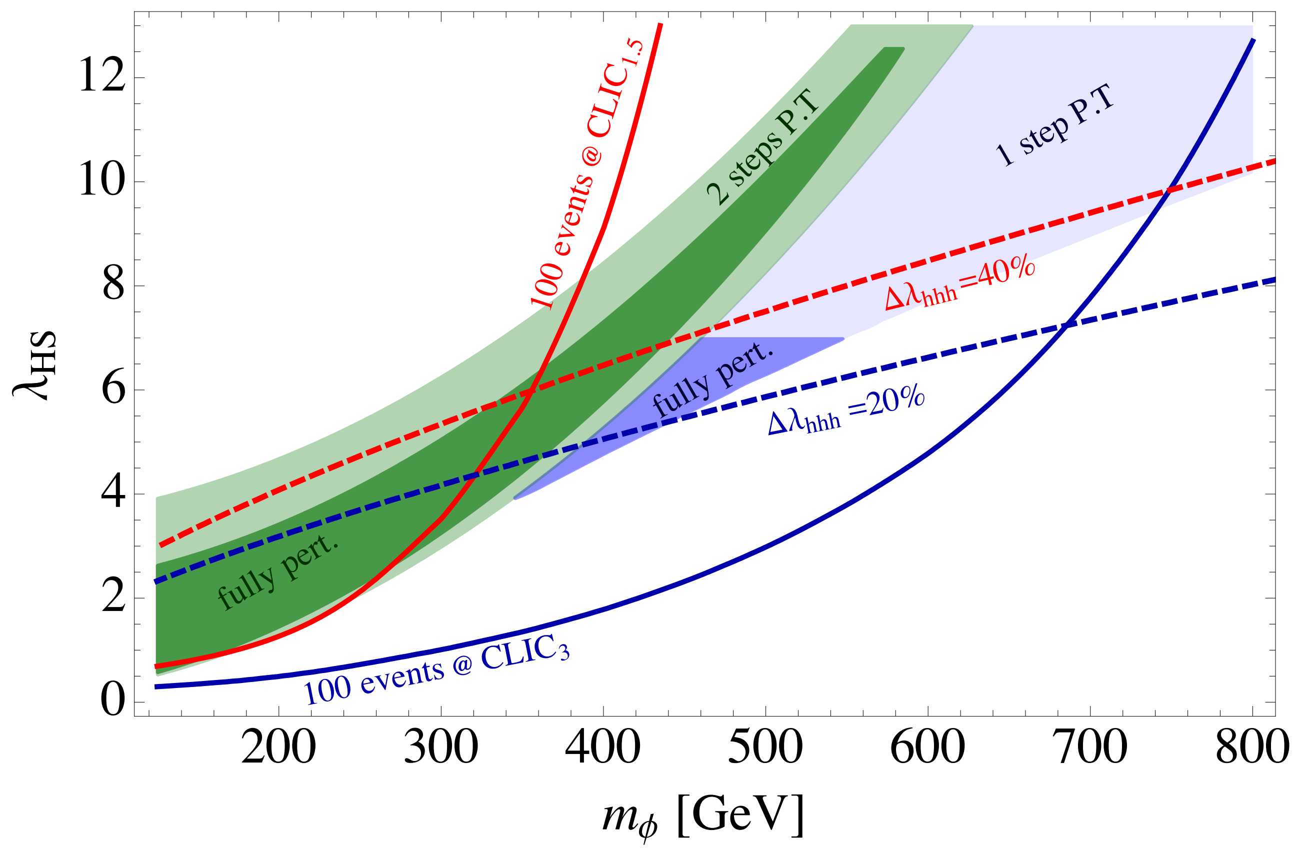
- Even more stringent bounds in the case of displaced decays: virtually all the ϕ can be identified, no background

Summary



HELC are strong discovery machines:
CLIC @ 3 TeV better than HL-LHC

Can directly probe regions with
deviations in Higgs couplings ~ 10^{-3}



Double production:
relevant for small mixing

Can fully test the region
that gives 1st order EWPT

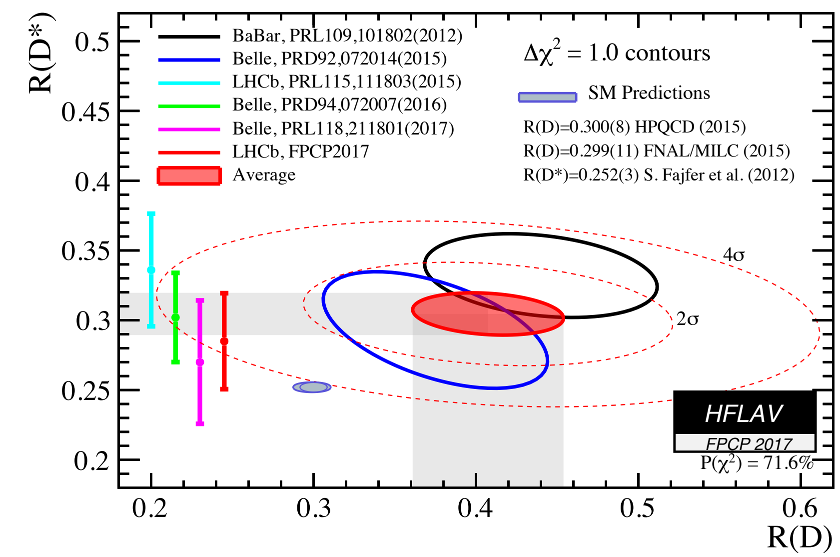

and now for something completely different...

The flavour anomalies

Hints of violations of Lepton Flavour Universality in B-meson decays

- Charged currents: $b \to c\tau\nu$ (tree-level in SM)

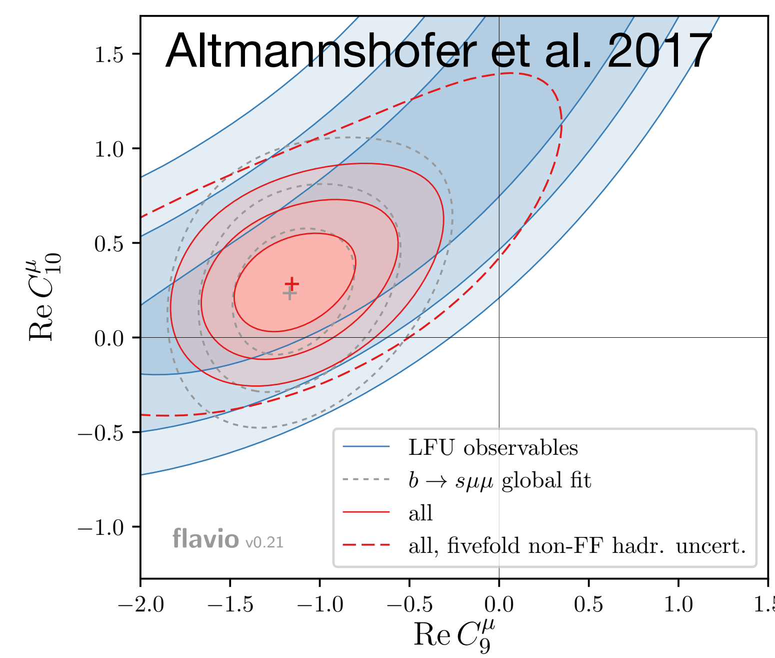
$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\bar{\nu})}{\mathrm{BR}(B \to D^{(*)}\ell\bar{\nu})} \qquad \sim 4\sigma$$



- Neutral currents: $b \to s\mu\mu$ (FCNC: loop in SM)

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} \qquad \sim 5\sigma$$

+ several branching ratios and angular distributions

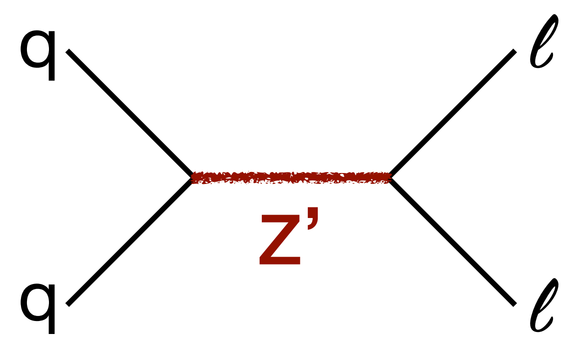


All measurements consistent with NP in LH currents:

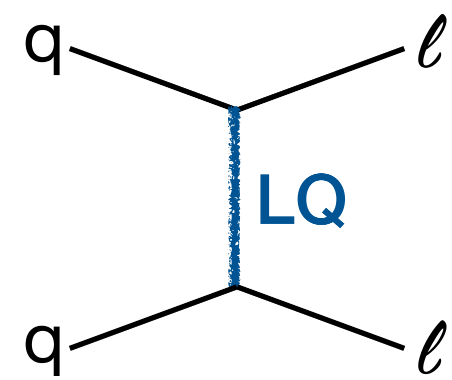
$$\frac{1}{\Lambda_S^2}(\bar{q}_L^i\gamma_\mu q_L^j)(\bar{\ell}_L^\alpha\gamma^\mu\ell_L^\beta) + \frac{1}{\Lambda_T^2}(\bar{q}_L^i\gamma_\mu\sigma^a q_L^j)(\bar{\ell}_L^\alpha\gamma^\mu\sigma^a\ell_L^\beta)$$

Flavour structure reminds Yukawa couplings: larger effect for heavier gen's

Mediators



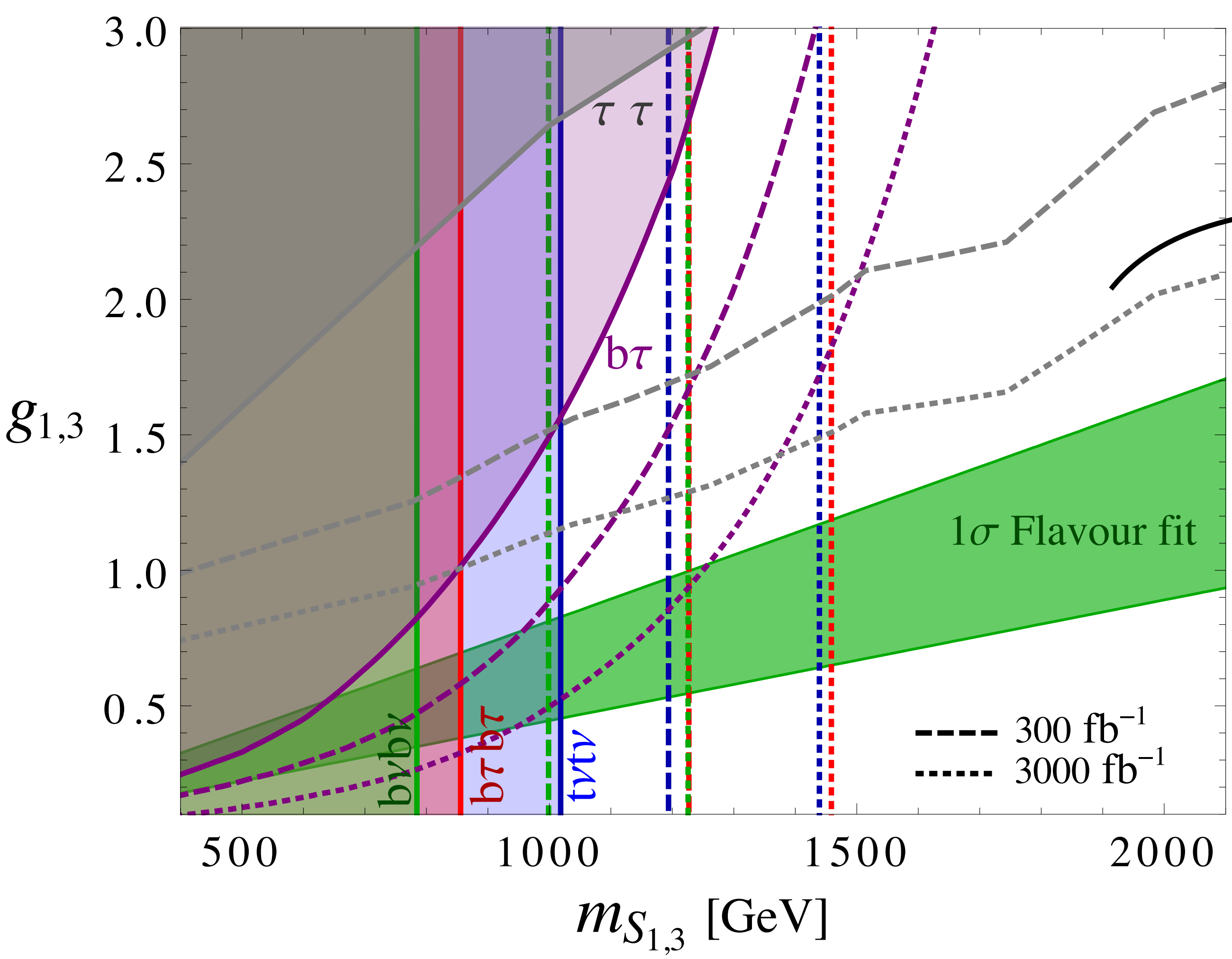
Vector resonances: too large meson mixing + LHC searches



Leptoquarks: best candidates that fit all the anomalies; vector or scalar

Assumption on flavour structure:

Large coupling to third generation, couplings to lighter generations are flavor-suppressed (CKM)



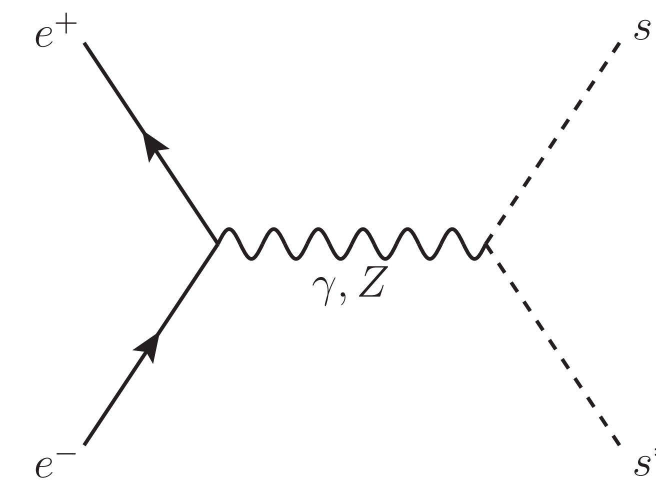
Difficult searches at the LHC: HL-LHC will not probe the full param. space

what is the reach of CLIC in this plane?

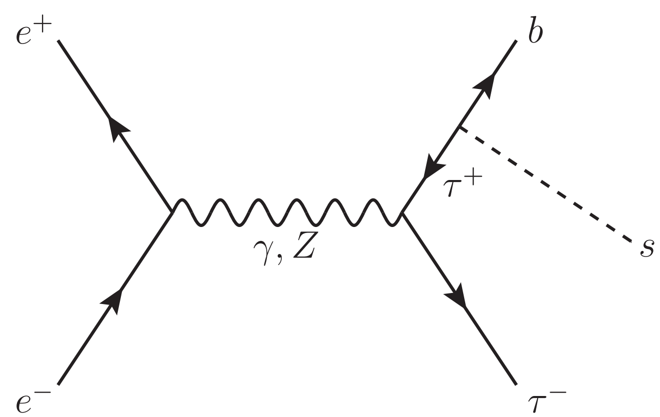
(LHC will exclude up to ~1.5 TeV: consider only CLIC Stage III)

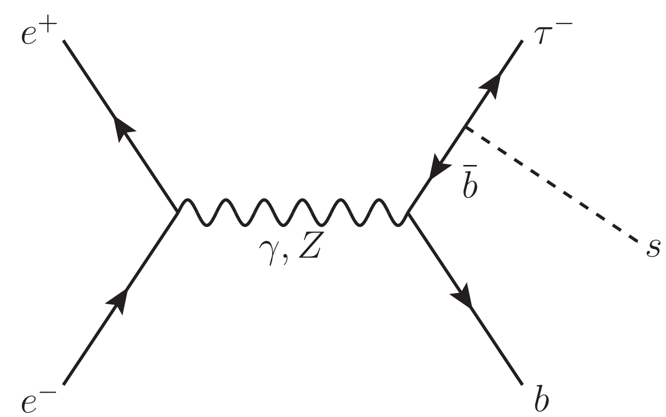
3rd generation leptoquarks @ CLIC

- Pair production: large cross-section when allowed, does not depend on coupling to fermions

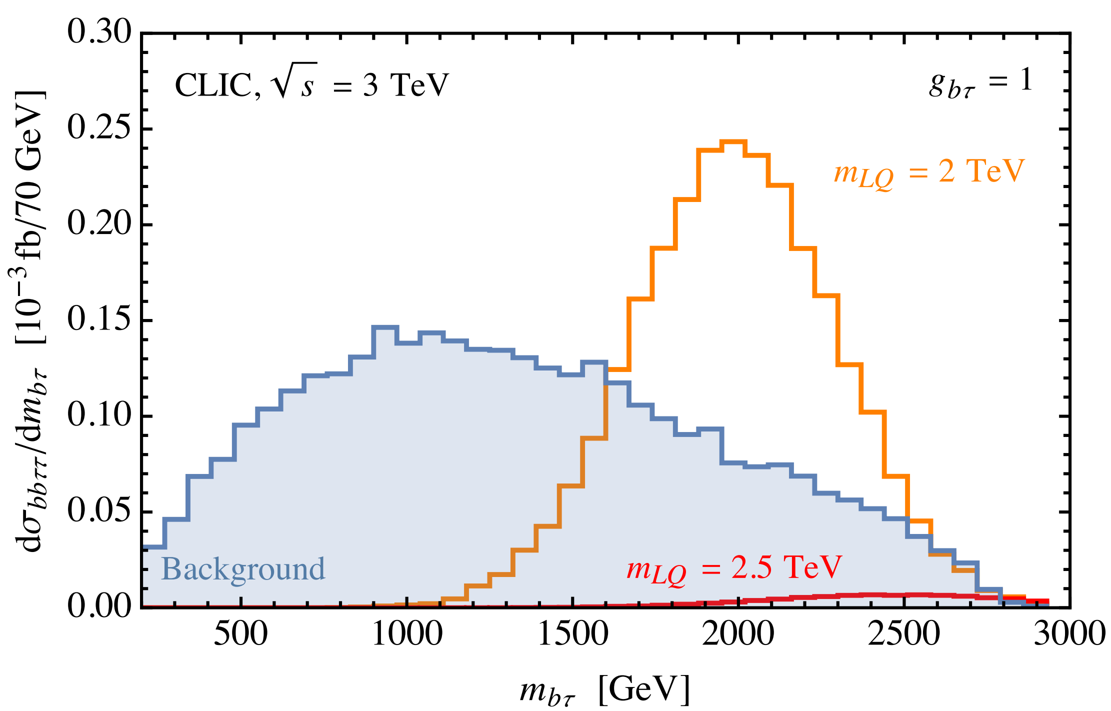


- Single production: radiation from bb or ττ pair

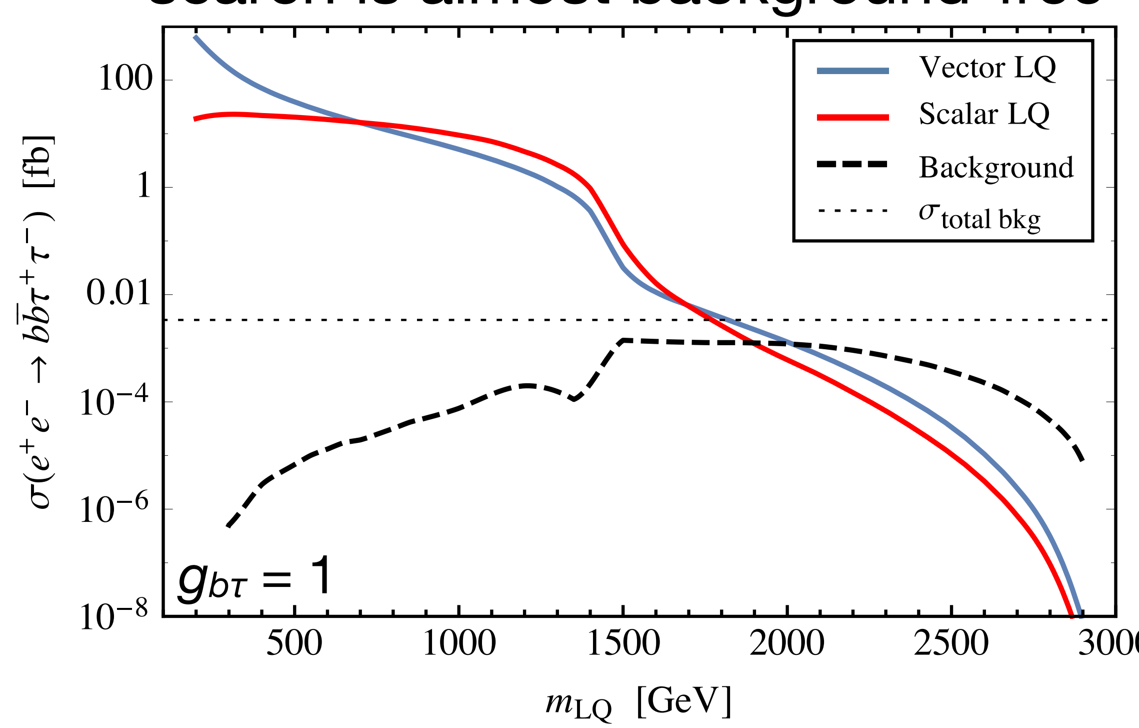




➡ bbττ final state, with $m_{b\tau} \sim M_{LQ}$



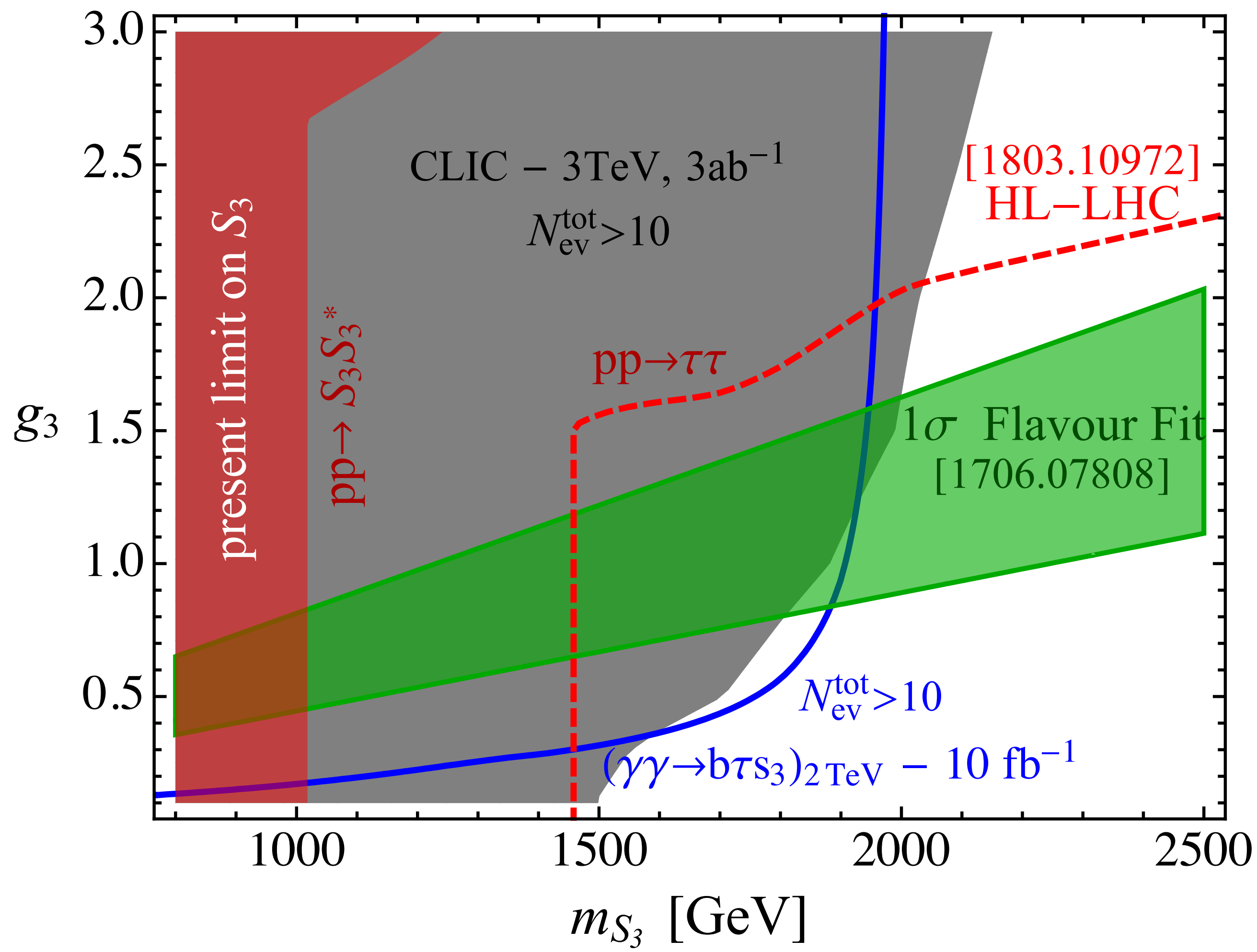
search is almost background-free



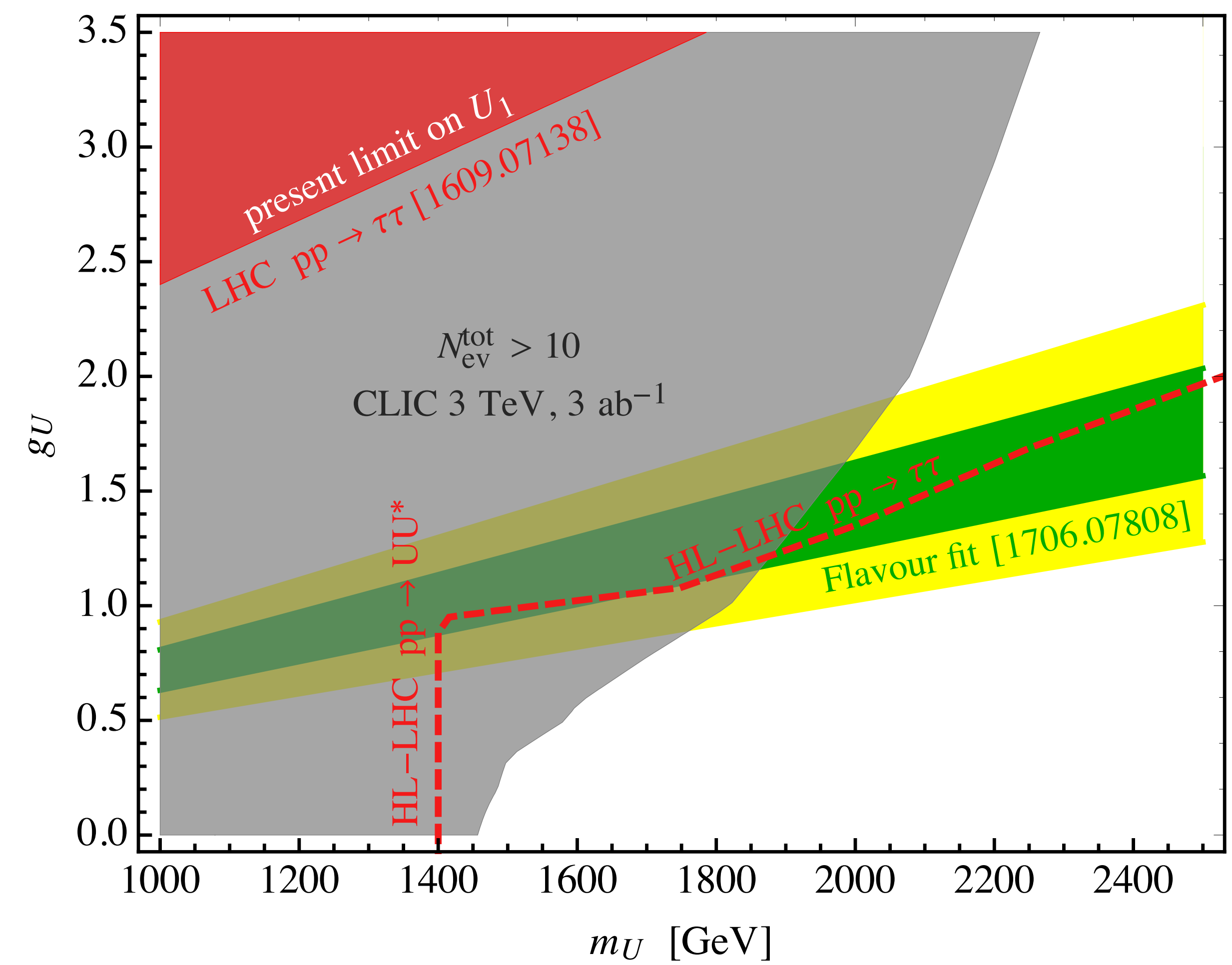
Results

- We require 10 expected signal events to exclude a point: reasonable approximation if background is small

scalar LQ



vector LQ



- CLIC can improve the LHC limit from ~ 1.5 TeV to ~ 1.8 TeV in the region relevant for the anomalies (this can be improved refining the analysis)

Results

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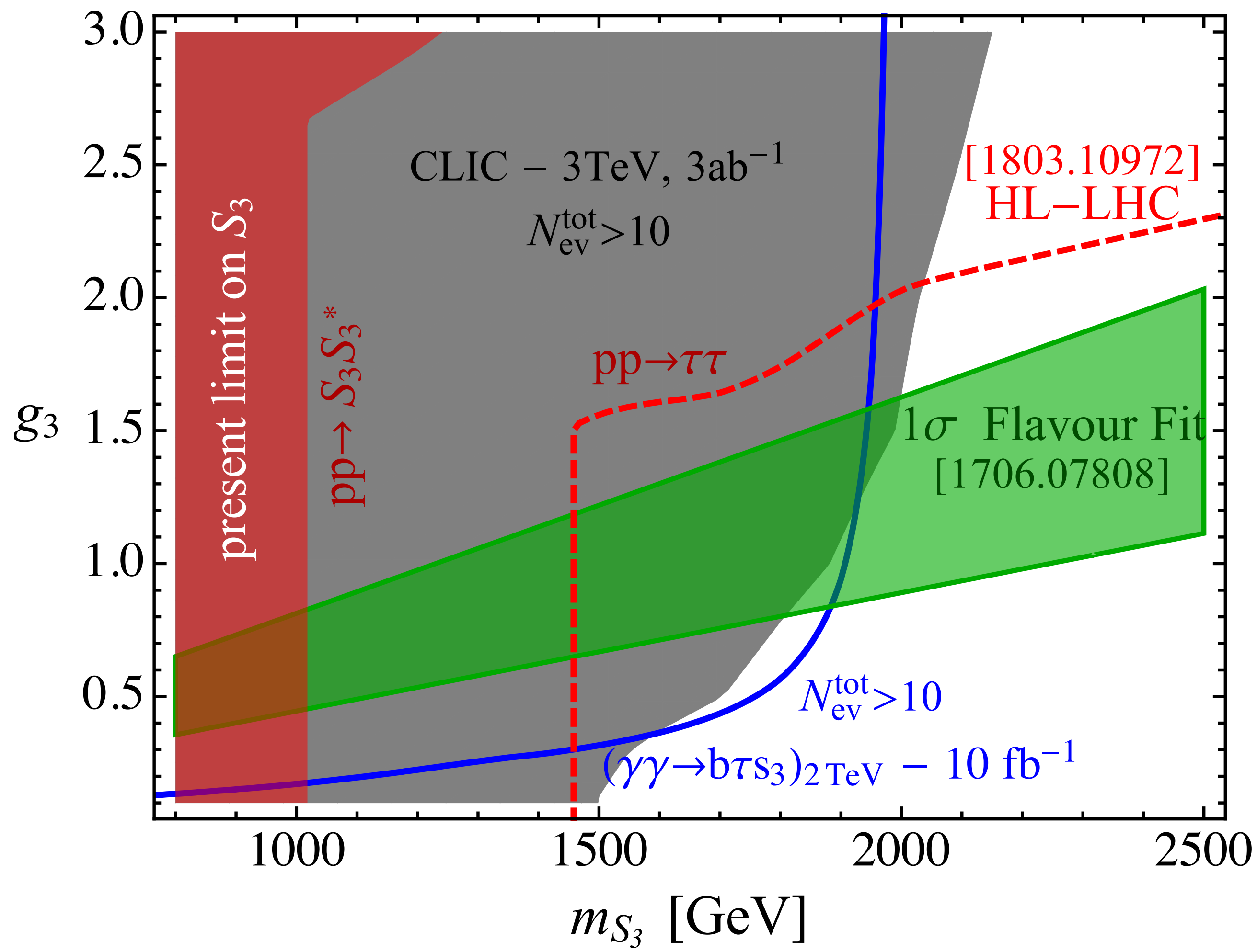

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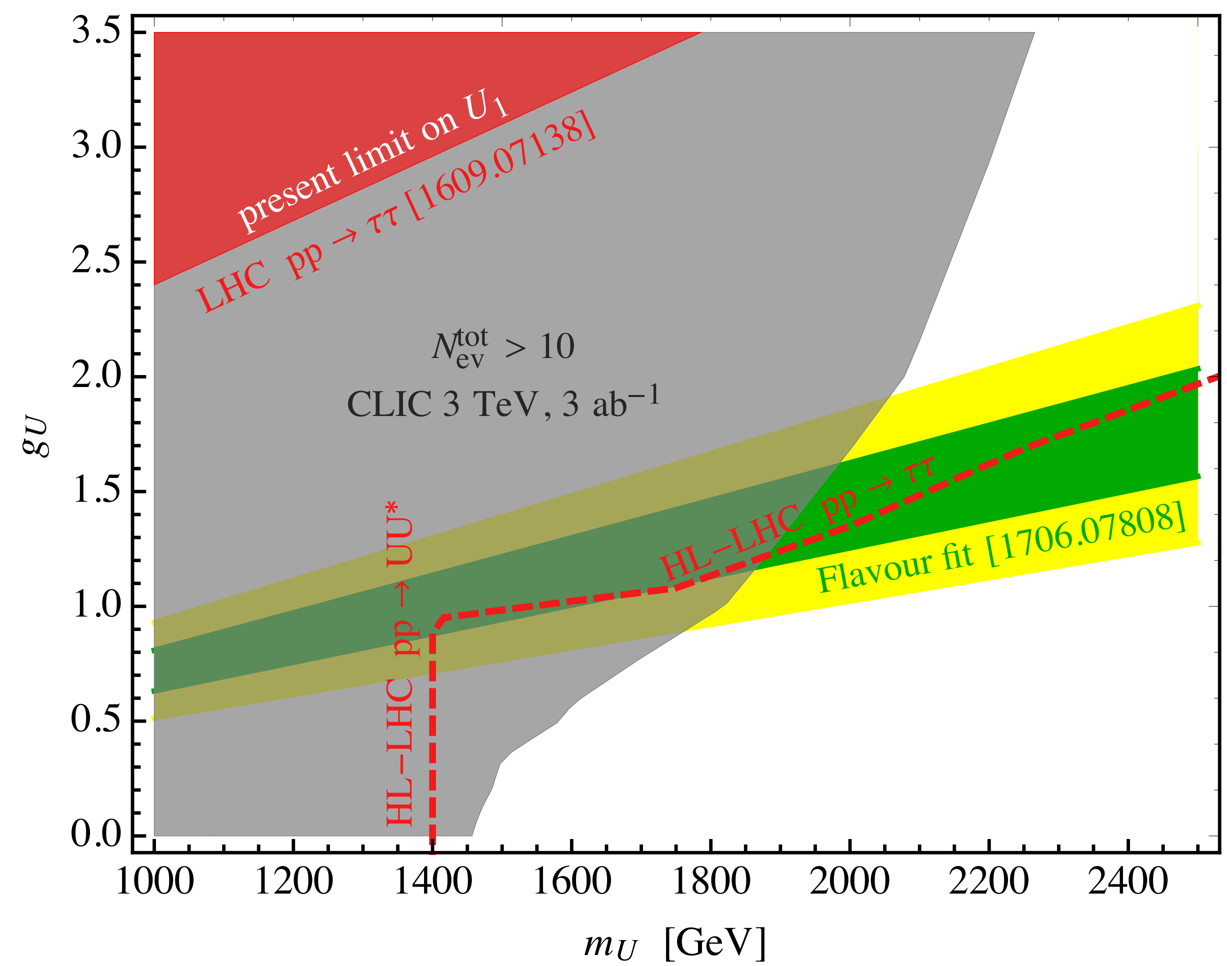

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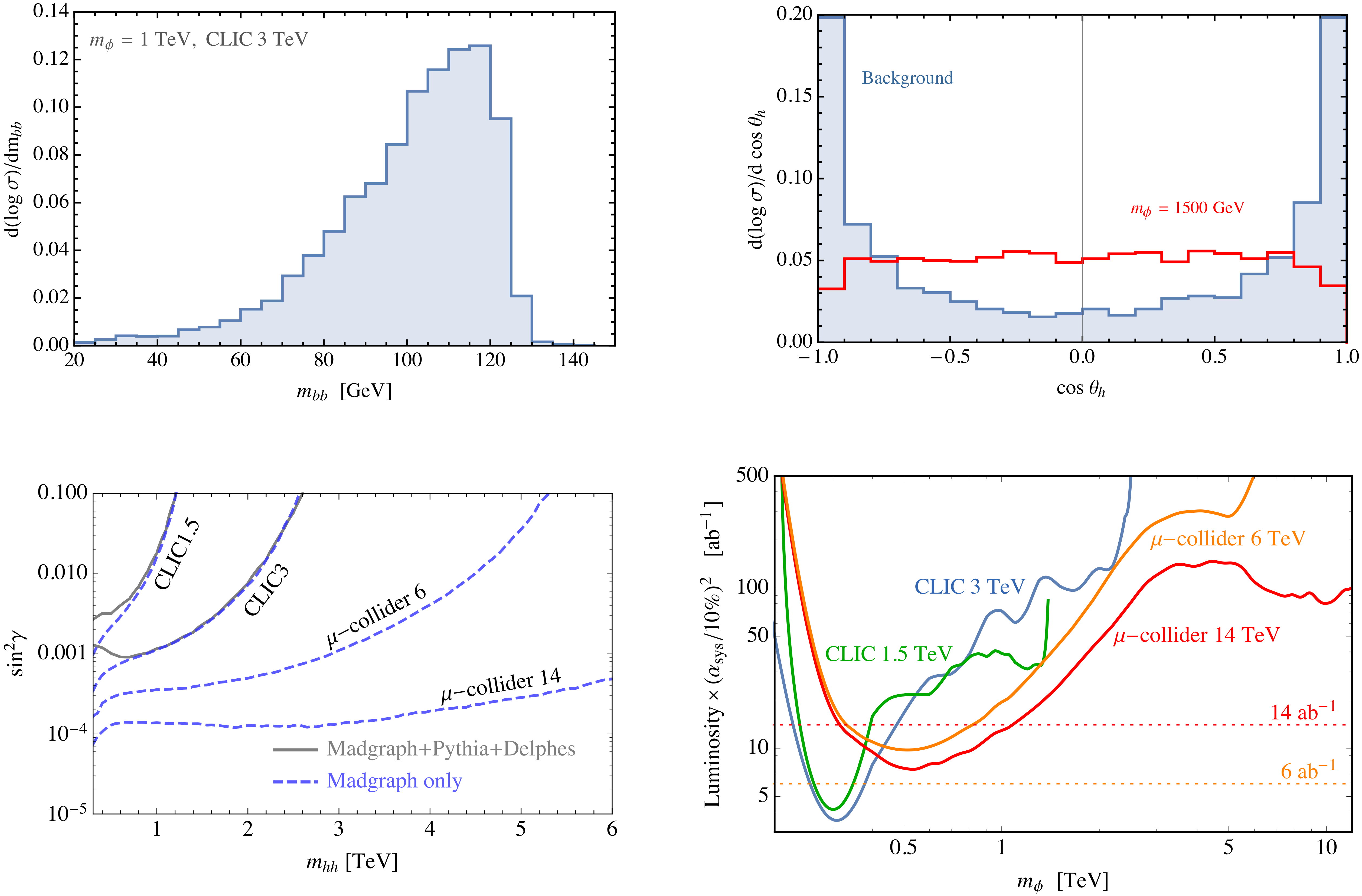
Thank you!

Backup

More details on the *hh*(4*b*) analysis



More details on the $hh(4b)$ analysis

Efficiencies for signal and background:

Cut	ϵ_{sig}	$\epsilon_{\text{bkg}}^{4b2\nu}$
$E_{\text{miss}} > 30$ GeV	90%	95%
4 b-tags	50%	35%
$m_{bb} \in [88, 129]$ GeV	64%	23%
$\|\cos\theta\| < 0.94$	96%	63%
$m_{4b} \in [770, 1070]$ GeV	98%	2.8%
Total efficiency	27%	1.3×10^{-3}

(a) CLIC 1.5 TeV, $m_\phi = 1$ TeV

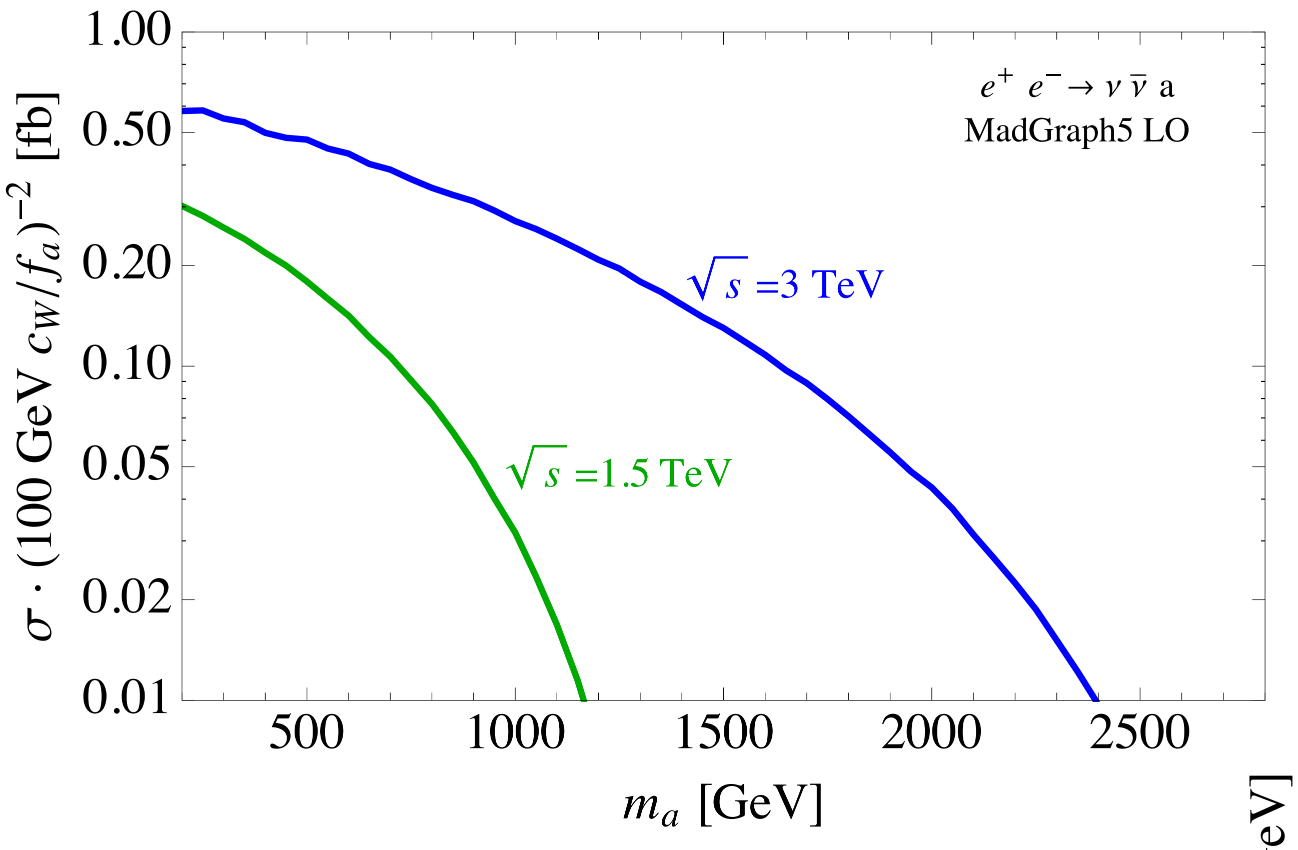
Cut	ϵ_{sig}	$\epsilon_{\text{bkg}}^{4b2\nu}$
$E_{\text{miss}} > 30$ GeV	94%	96%
4 b-tags	51%	33%
$m_{bb} \in [88, 137]$ GeV	60%	15%
$\|\cos\theta\| < 0.95$	97%	58%
$m_{4b} \in [1.5, 2.04]$ TeV	91%	0.7%
Total efficiency	26%	2×10^{-4}

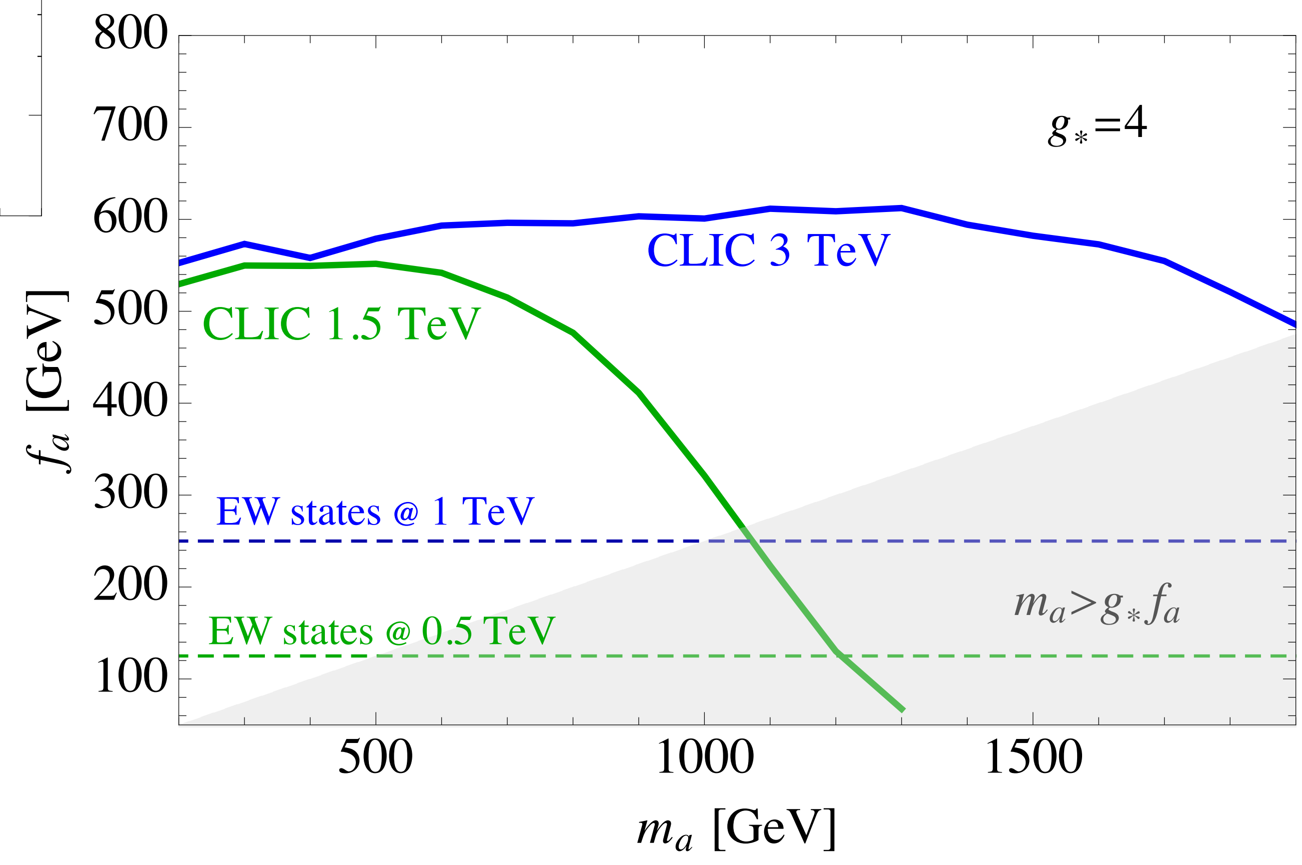
(b) CLIC 3 TeV, $m_\phi = 2$ TeV

EW ALPs

- EW ALPs: $$\mathscr{L}_{\rm ALP} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{c_1\alpha_1}{4\pi}\frac{a}{f_a}B\tilde{B} + \frac{c_2\alpha_2}{4\pi}\frac{a}{f_a}W\tilde{W}$$

also produced in WW fusion (but couple to transverse W's)





WW fusion

- Single and double production cross-sections:

$$\sigma_{e\bar{e}\to\nu\bar{\nu}S} = \sin^2\gamma\,\frac{g^4}{256\pi^3}\frac{1}{v^2}\left[2\Big(\frac{m_\phi^2}{s}-1\Big)+\Big(\frac{m_\phi^2}{s}+1\Big)\log\frac{s}{m_\phi^2}\right] \simeq \sin^2\gamma\frac{g^4}{256\pi^3}\frac{\log\frac{s}{m_\phi^2}-2}{v^2},$$

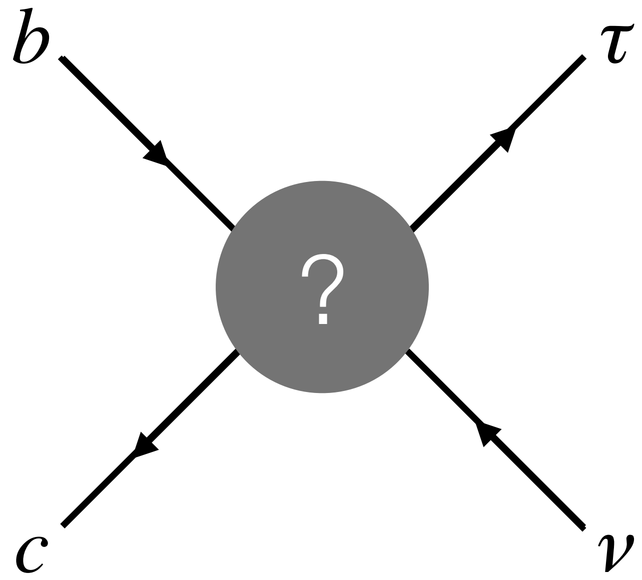
$$\sigma_{e\bar{e}\to\nu\bar{\nu}SS} = \frac{g^4|\lambda_{HS}|^2}{49152\pi^5}\,\frac{1}{m_\phi^2}\Big[\log\frac{s}{m_\phi^2}-\frac{14}{3}+\frac{m_\phi^2}{s}\big(3\log^2\frac{s}{m_\phi^2}+18-\pi^2\big)+\mathcal{O}\Big(\frac{m_\phi^4}{s^2}\Big)\Big],$$

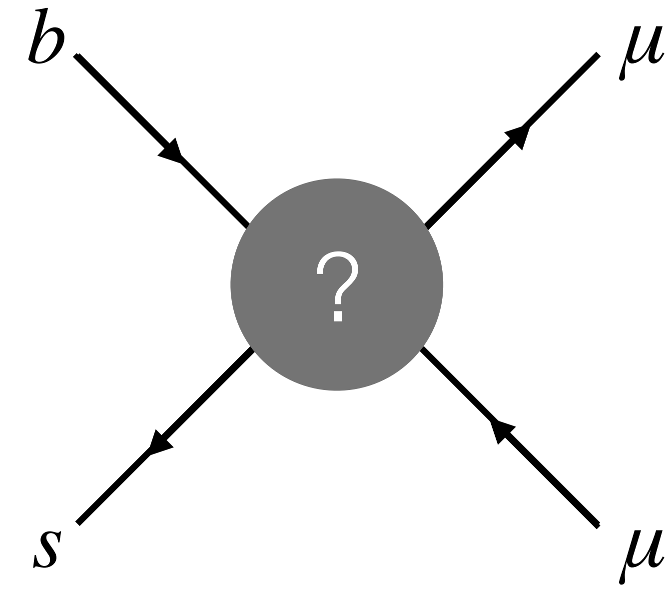
from W-pdf's $\quad \frac{d\sigma}{d\hat{s}} = \frac{\hat{\sigma}_{V_iV_j\to X}(\hat{s})}{s}\,\mathscr{C}_{V_iV_j}(\hat{s}), \quad \text{with} \quad \mathscr{C}_{V_iV_j}(\hat{s}) = \int_{\hat{s}/s}^1 \frac{dx}{x} f_{V_i}(x) f_{V_j}(\frac{\hat{s}x}{s})$

- Approximate limit on mixing angle:

$$\sin^2\gamma \times \mathrm{BR}(\phi\to f) \approx 0.02\left(\frac{1/\mathrm{fb}}{L}\right)\times\left[\log\frac{s}{m_\phi^2}-2+\frac{m_\phi^2}{s}\Big(\log\frac{s}{m_\phi^2}+2\Big)\right]^{-1}$$

Simultaneous explanations of flavour anomalies





$$\frac{1}{\Lambda_D^2}(\bar{b}_L\gamma_\mu c_L)(\bar{\tau}_L\gamma^\mu\nu_\tau)$$

$$\Lambda_D = 3.4\,\mathrm{TeV}$$

$$\frac{1}{\Lambda_K^2}(\bar{b}_L\gamma_\mu s_L)(\bar{\mu}_L\gamma^\mu\mu_L)$$

$$\Lambda_K = 31\,\mathrm{TeV}$$

- I. “vertical” structure: the two operators can be related by $SU(2)_L$

$$(\bar{q}_L\gamma_\mu\sigma^a q_L)(\bar{\ell}_L\gamma^\mu\sigma^a\ell_L)$$

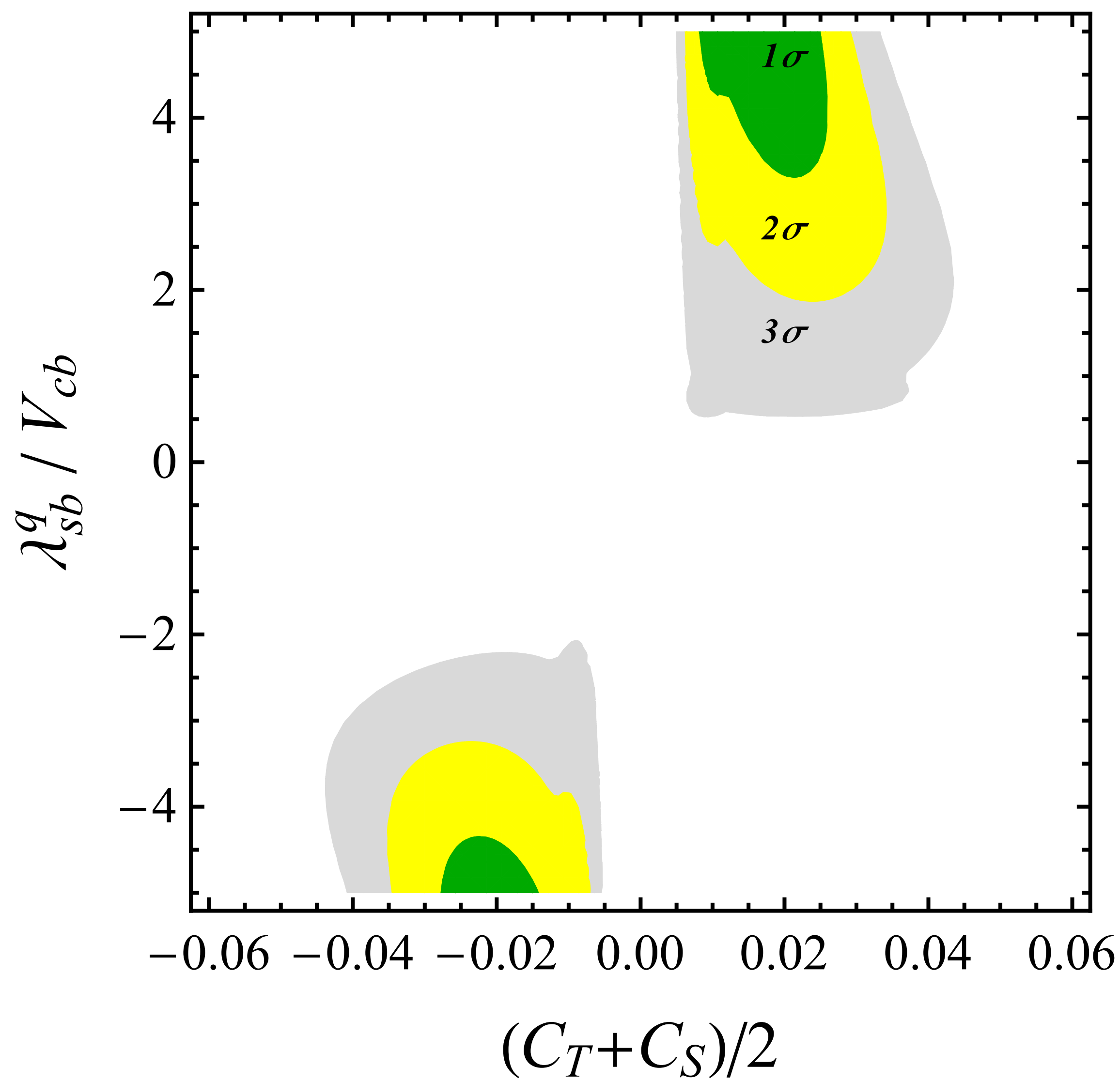
- II. “horizontal” structure: NP structure reminds of the Yukawa hierarchy

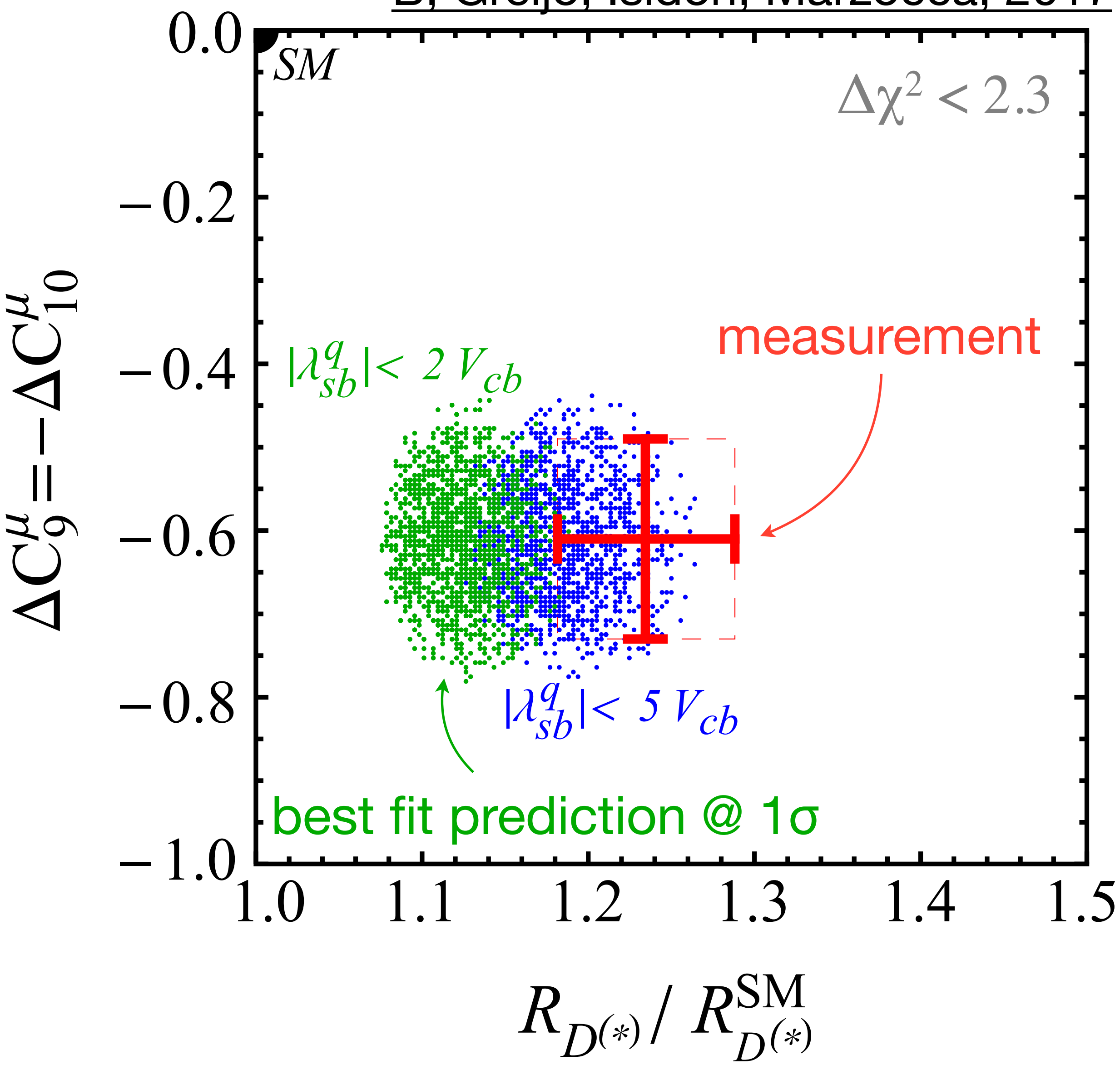
$$\Lambda_D \ll \Lambda_K, \qquad \lambda_{\tau\tau} \gg \lambda_{\mu\mu}$$

Fit to flavour anomalies

- EFT fit to all semi-leptonic observables + radiative corrections to EWPT
- Don't include any UV contribution to other operators
  (they will depend on the dynamics of the specific model)

B, Greljo, Isidori, Marzocca, 2017



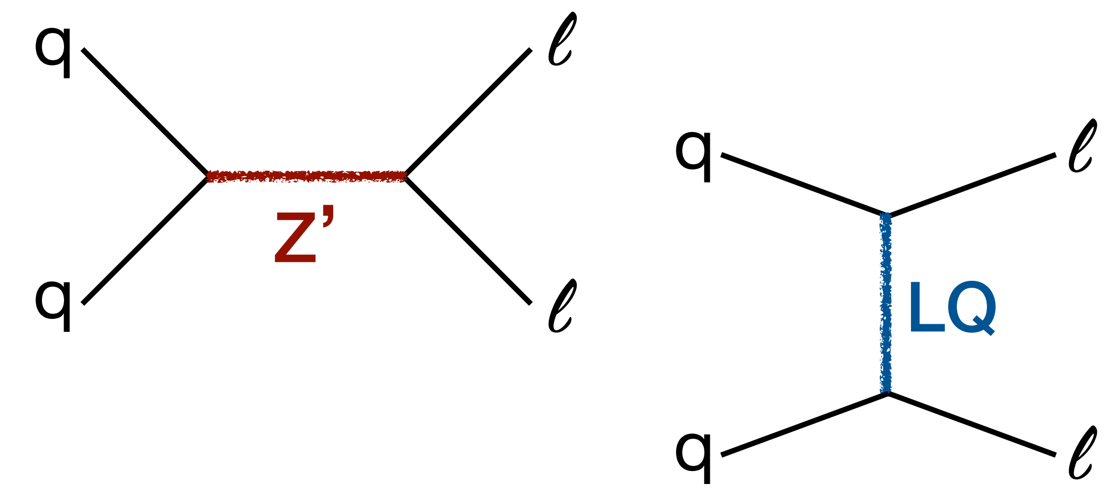


Good fit to all anomalies, with couplings compatible with the U(2) assumption

Simplified models

Mediators that can give rise to the $b \to c\ell\nu$ and $b \to s\ell\ell$ amplitudes:

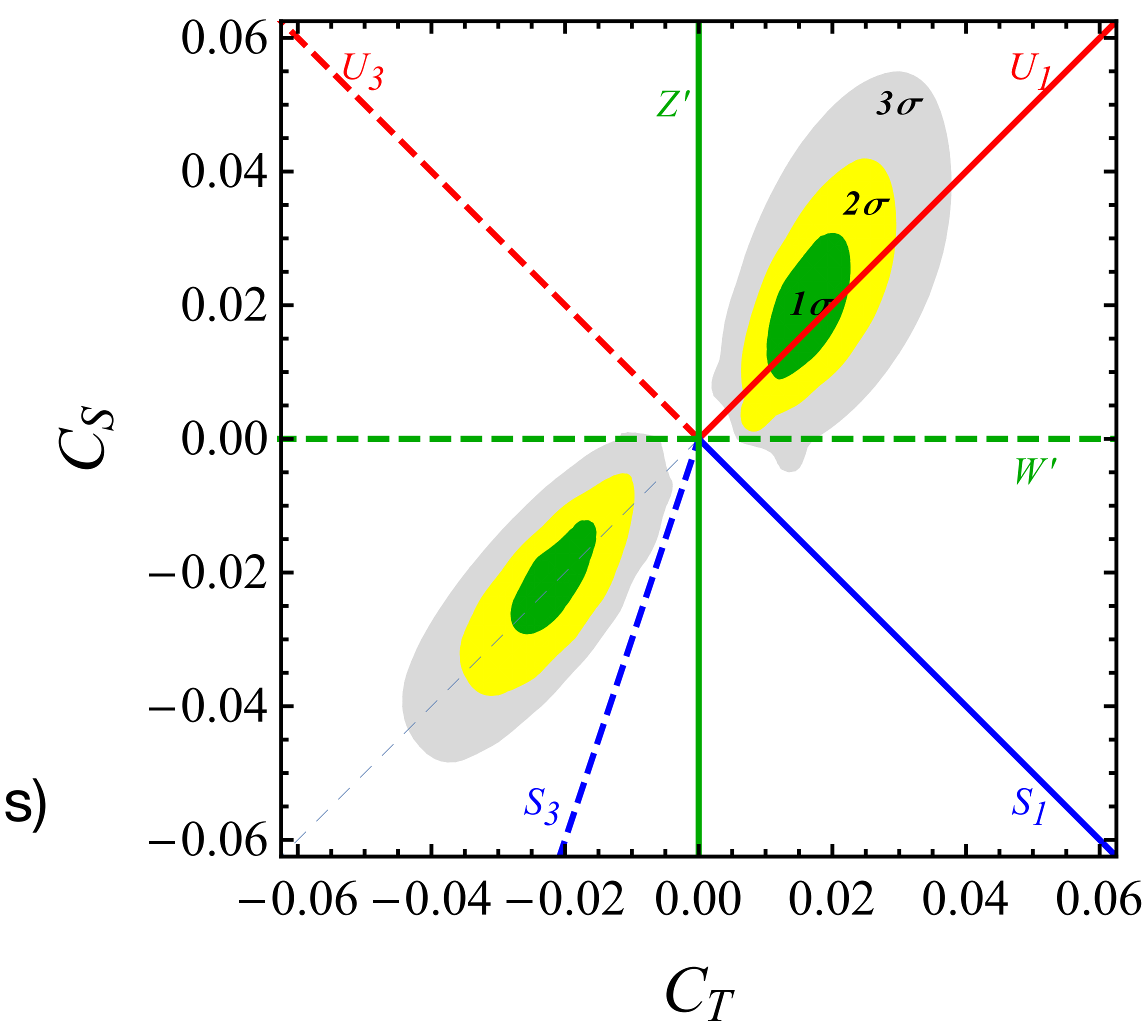
	Spin 0	Spin 1
Colour singlet	~~2HDM~~ no LL operator	Vector resonance
Colour triplet	Scalar lepto-quark	Vector lepto-quark



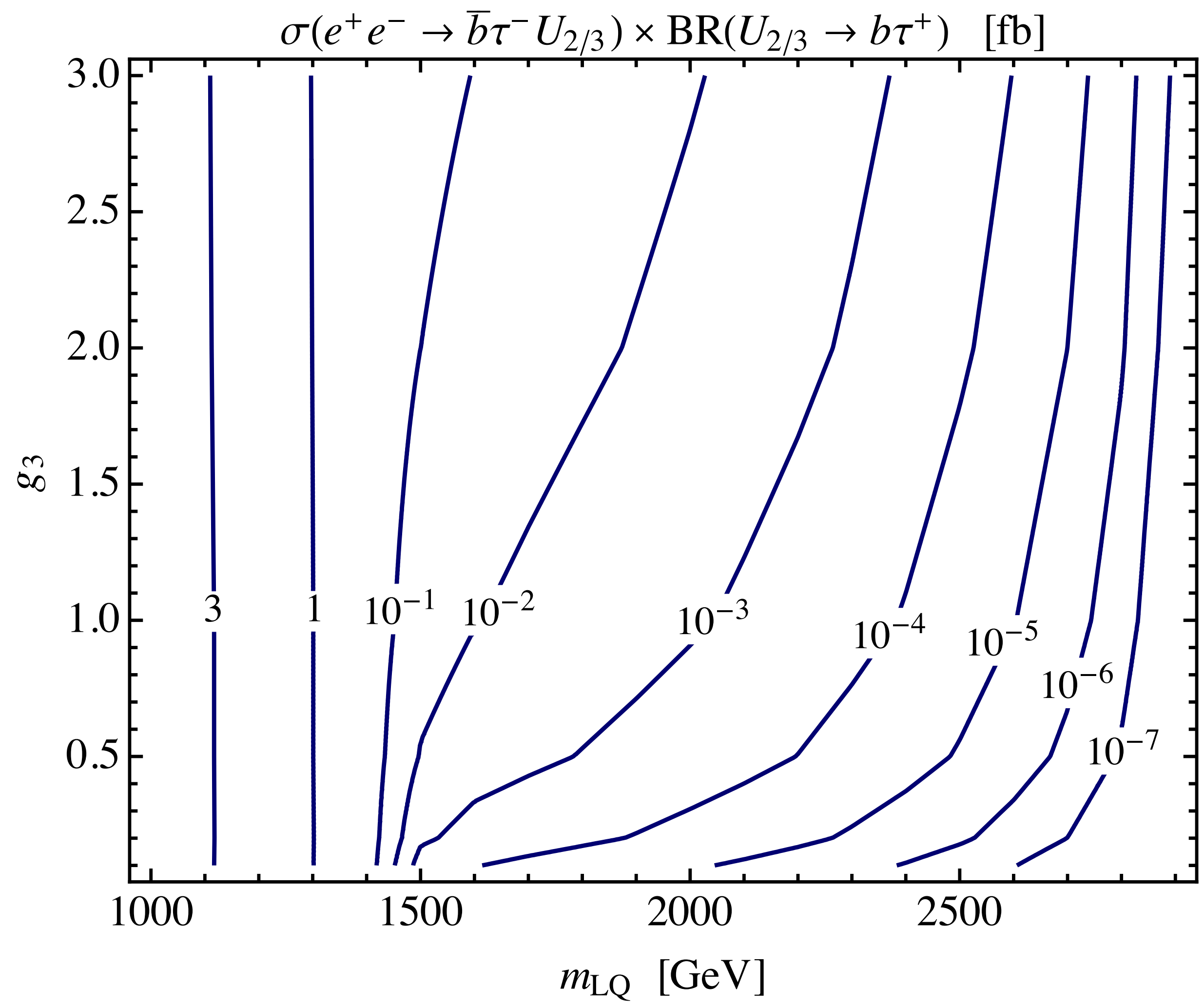
Contributions to C_T and C_S from different mediators:

- A **vector leptoquark** is the only single mediator that can fit all the anomalies alone: $C_T \sim C_S$
- Combinations of two or more mediators also possible (often the case in concrete models)

  large $b \to s\nu\nu$ expected in this case!

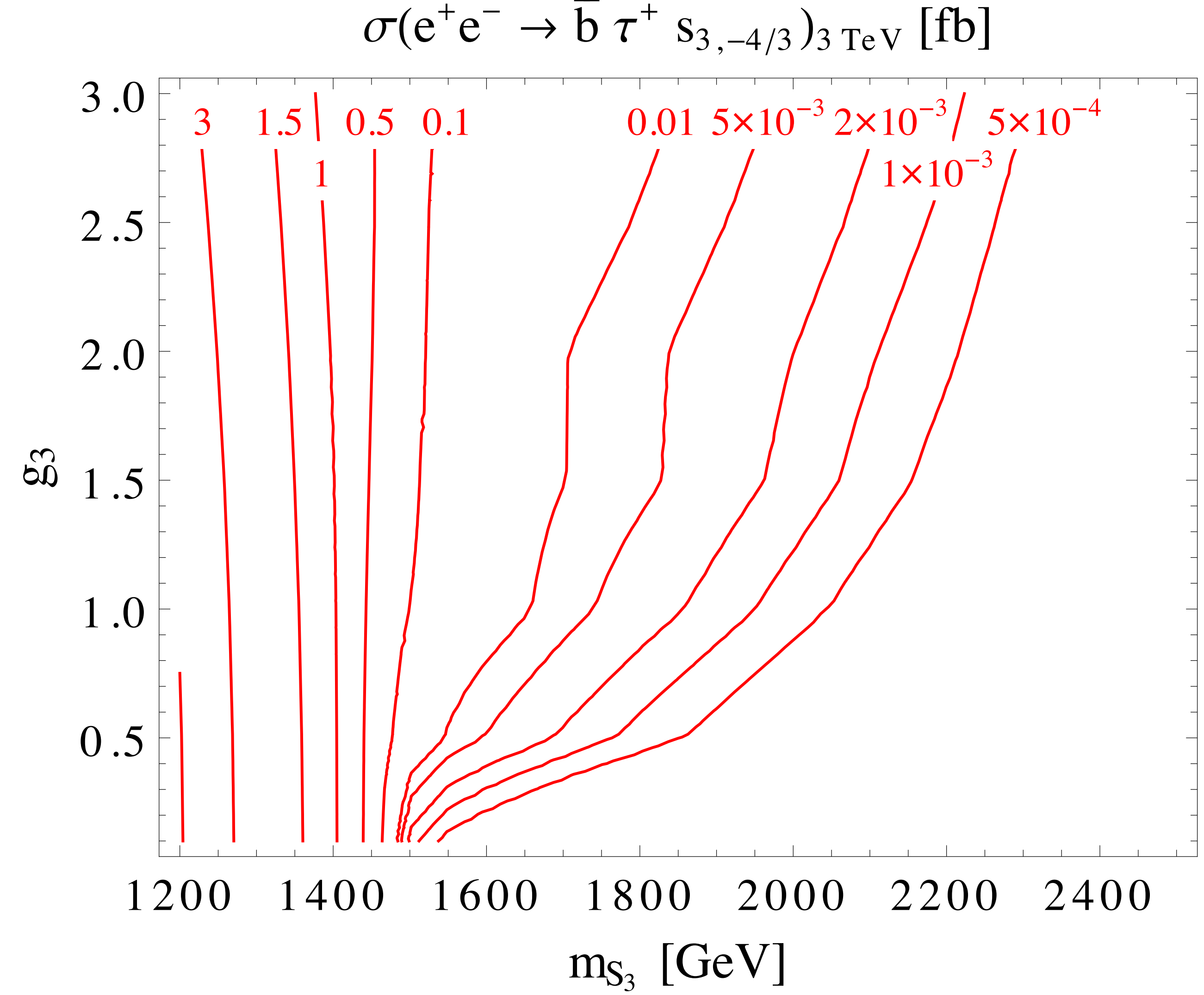


LQ production cross-section at CLIC



vector leptoquark

scalar leptoquark



Photon-fusion at CLIC

Cross-section for scalar LQ