New scalars at High Energy Lepton Colliders

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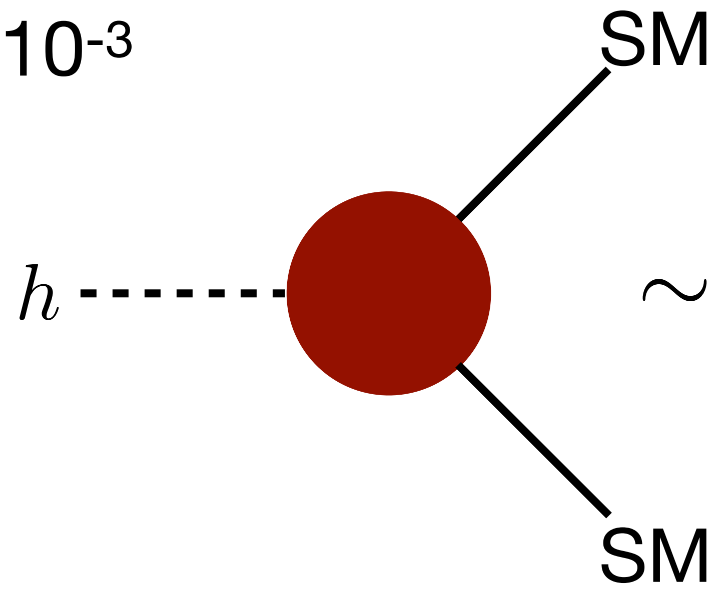
based on 1807.04743 with D. Redigolo, F. Sala, A. Tesi
and work in progress

Fourth Muon Collider Physics Potential meeting — 11.12.2020

Higgs physics vs. High Energy searches

A Higgs factory will be able to measure couplings with a precision of 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.

1. *Assess the reach of a HELC for new particles coupled to Higgs/EW*
2. *How do direct searches for the new states compare 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

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

controls Higgs-singlet mixing ~ **sin γ**

portal coupling

enters triple couplings:
BR(*ϕ* → *hh*), *g*

$$\sin\gamma \sim \frac{a_{HS} v}{m_S^2}$$

mass eigenstates:

$$h = \cos\gamma\, H^0 + \sin\gamma\, S$$

$$\phi = -\sin\gamma\, H^0 + \cos\gamma\, S$$

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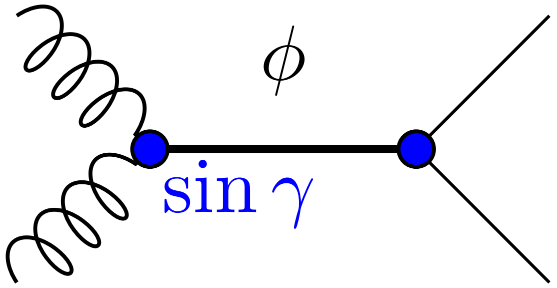
- ϕ can be singly produced:

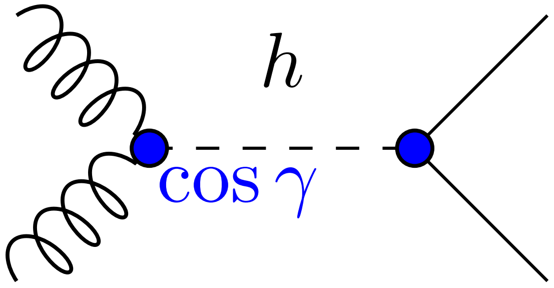


$$\sigma_\phi = \sigma_{\text{SM}}(m_\phi) \times \sin^2\gamma$$

- ϕ decays to SM:

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

- Higgs signal strengths:

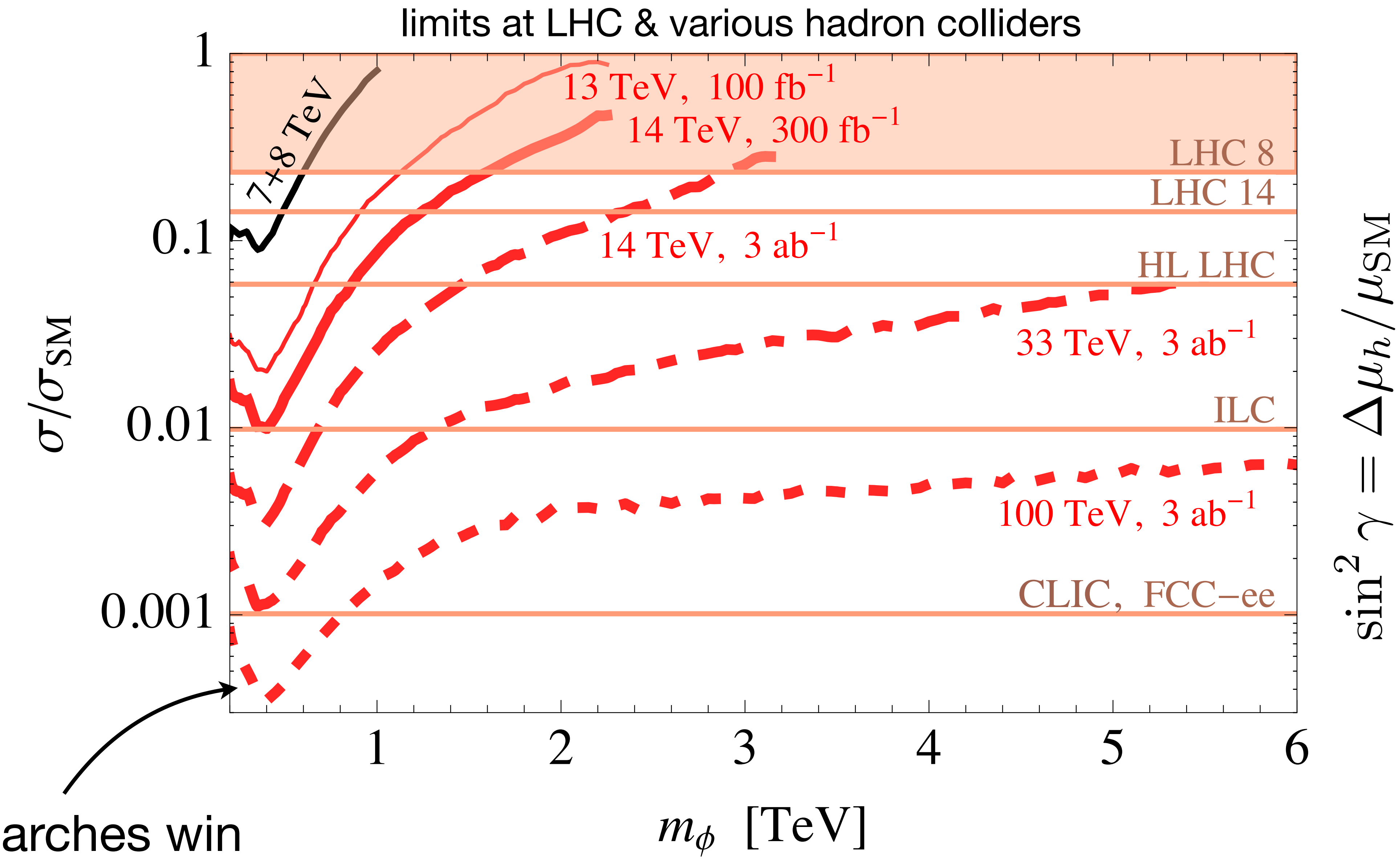


$$\mu_h = \mu_{\text{SM}} \times \cos^2\gamma$$

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]



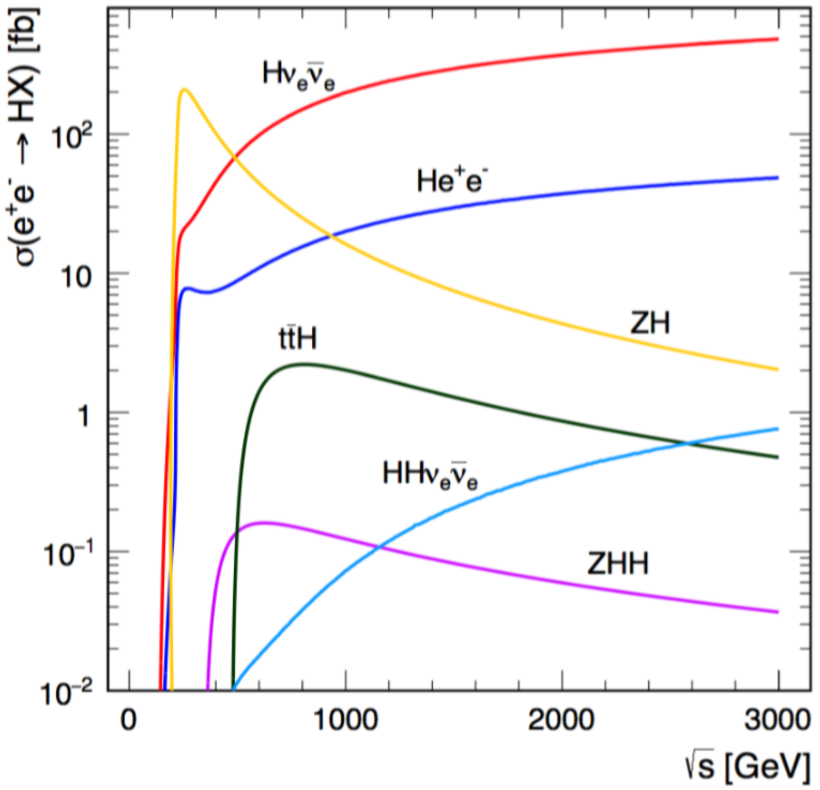
direct searches win at lower masses

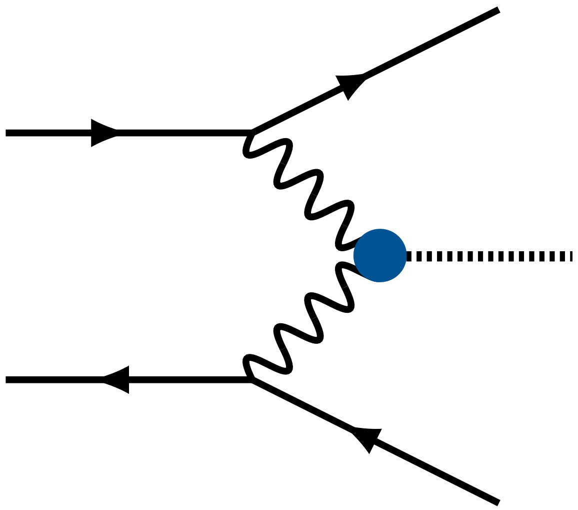
What about a Muon Collider?

Scalar singlets at a HELC

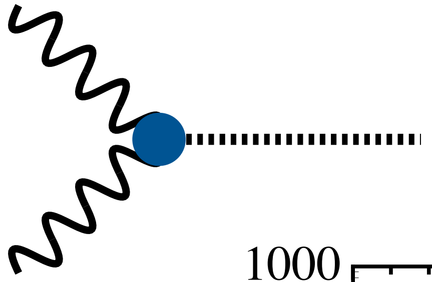
- ϕ is like a heavy SM Higgs with narrow width:
  At a High Energy Lepton Collider,
  the dominant production mode is VBF

  the μ-collider is a "vector boson collider"



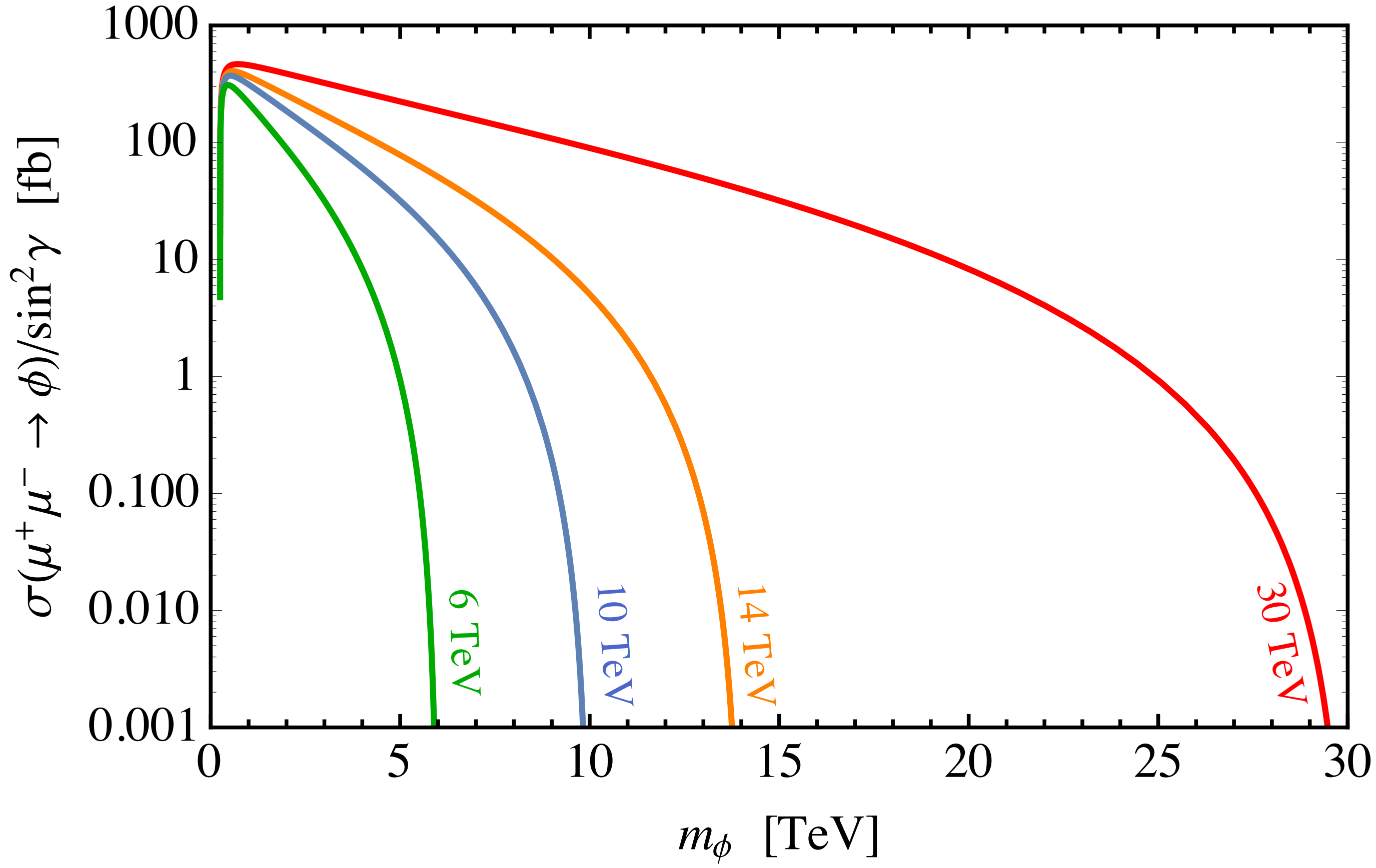


$$\approx \frac{s}{\hat{s}} \log \frac{s}{\hat{s}}$$



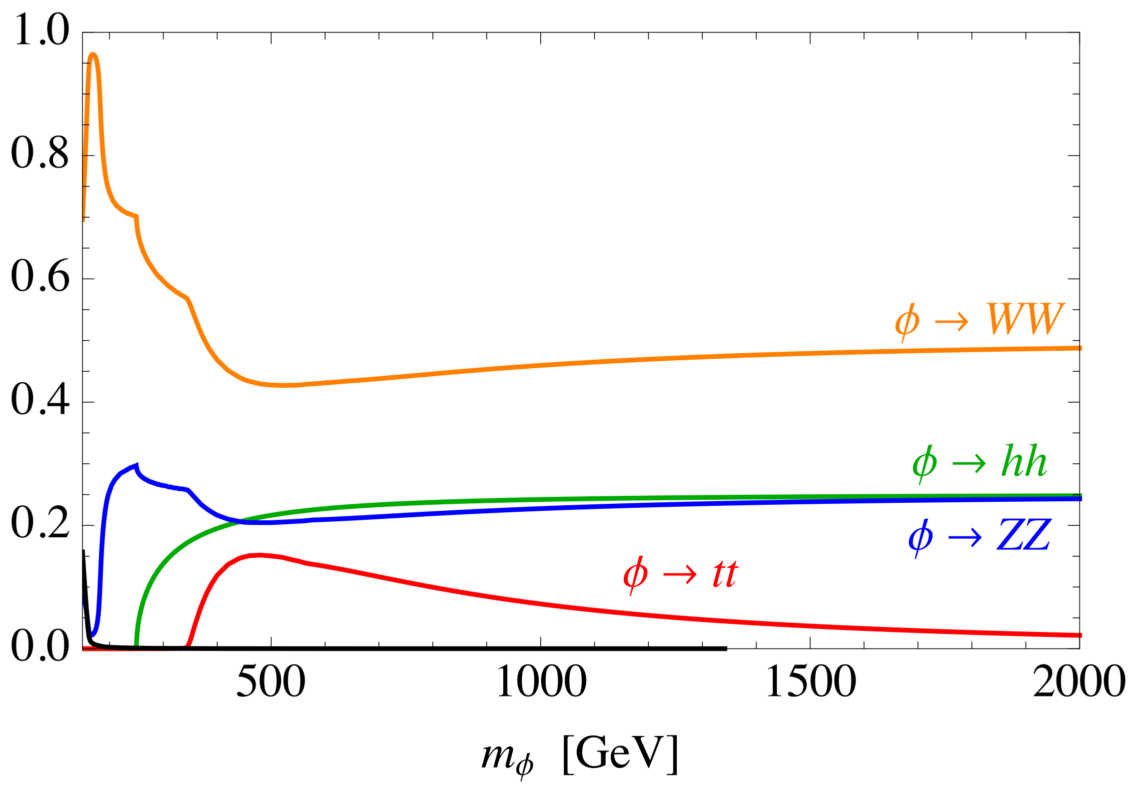
$$\sigma_{\mu\mu\to\phi\nu\nu} \approx \frac{g^4\, s_\gamma^2}{256\pi^3 v^2} \log \frac{s}{m_\phi^2}$$

cross-section grows at high energy
due to longitudinal W-fusion



Scalar singlets at a HELC

- ϕ is like a heavy SM Higgs with narrow width: Dominant decay modes are into (longitudinal) bosons.

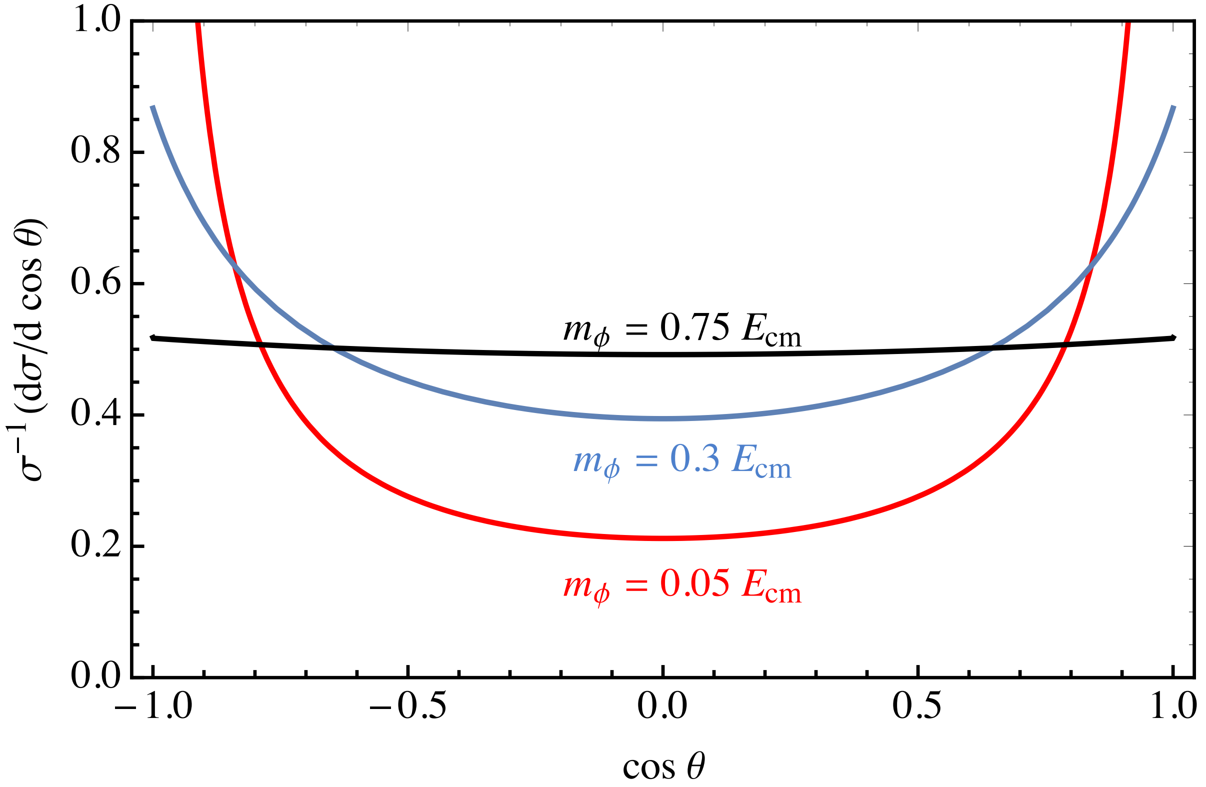


Goldstone boson equivalence theorem:

$$\mathrm{BR}_{\phi\to hh} = \mathrm{BR}_{\phi\to ZZ} = \frac{1}{2}\mathrm{BR}_{\phi\to WW} \simeq \frac{1}{4}$$

$$m_\phi \gg m_h$$

- Golden channels:
  - **ϕ → ZZ(4l,2l2j):** very clean, some EW background; most sensitive channel at LHC.
  - **ϕ → hh(4b):** also clean and very sensitive at l^+l^- collider; more challenging at LHC due to QCD background

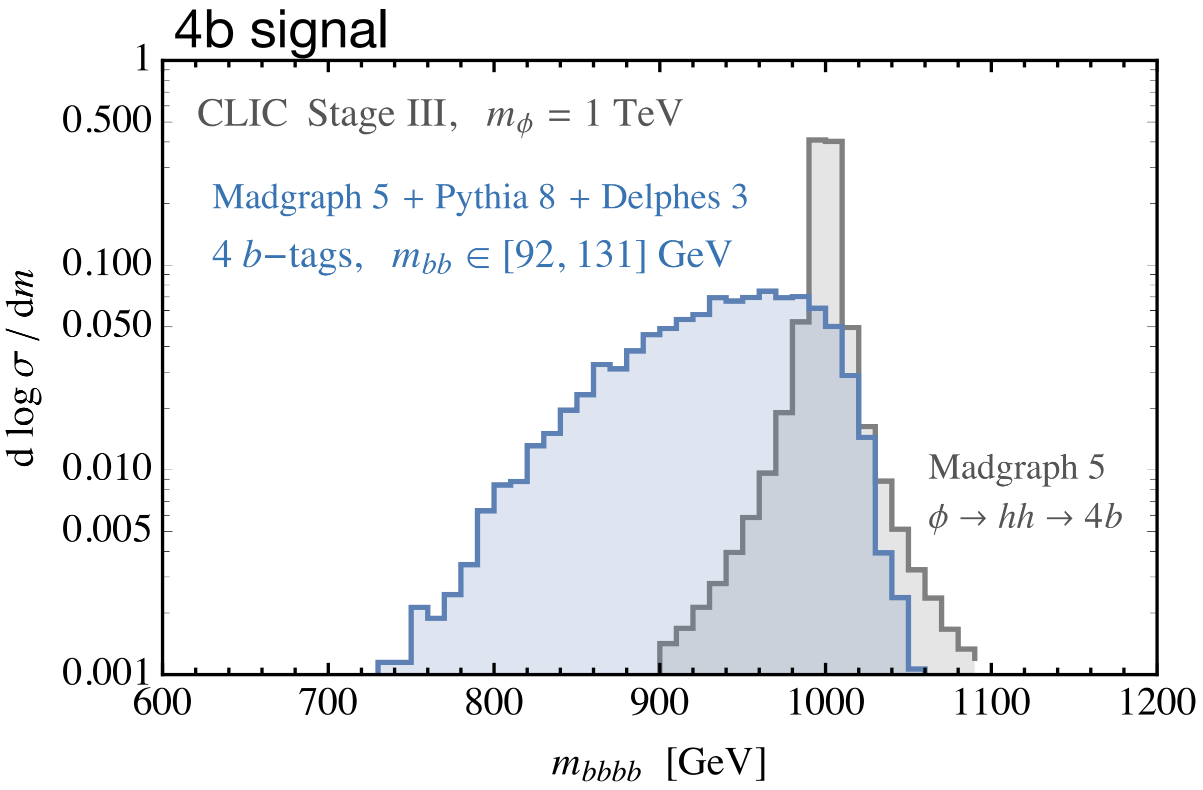


hh(4*b*) decay channel

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

1807.04743 — 3 TeV CLIC

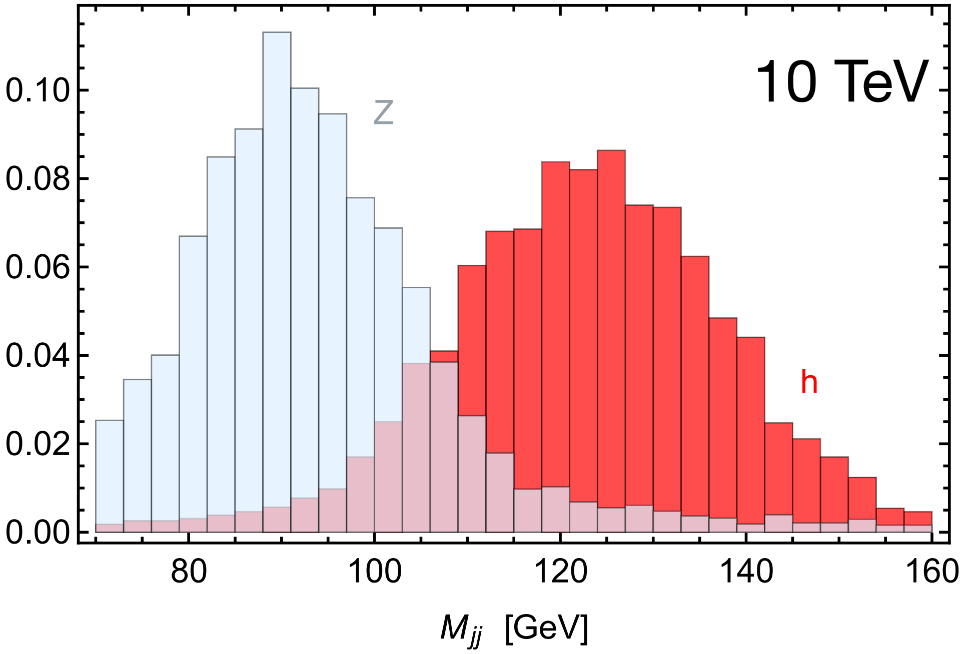
- Detector simulation with CLICdp Delphes card
- VLC exclusive jet reconstruction, N = 4, R = 0.7 + 4 b-tags (loose tagging algorithm)
- h reconstruction: select the b pairs that give the best fit to two 125 GeV Higgs bosons, 90 GeV < m_{bb} < 130 GeV
- ϕ reconstruction: 0.75 $m_\phi < m_{4b} <$ 1.05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


4b signal

Signal efficiency ε_{sig} ~ 25 – 30%

Background reduced by ε_{bkg} ~ 10^{-3} – 10^{-4}

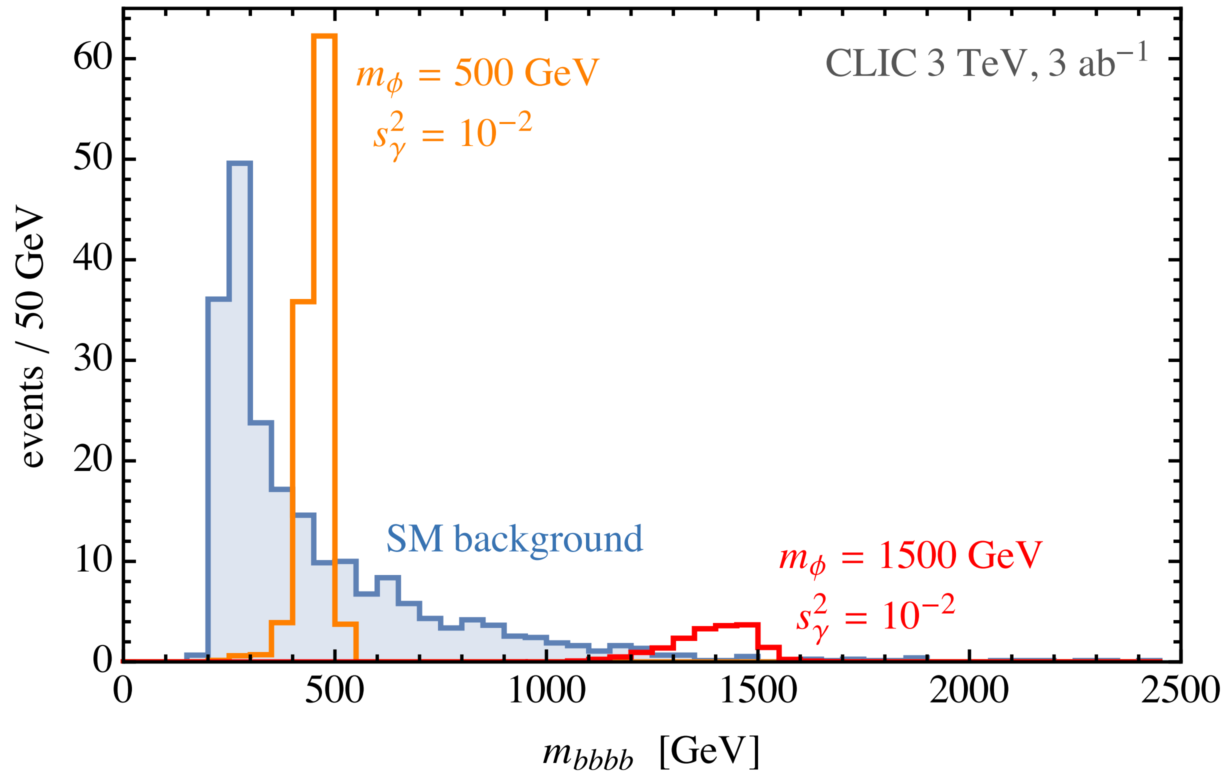
Checked (at parton level) that results still hold at 10 TeV: ε_{sig} ~ 30% assuming similar detector performance

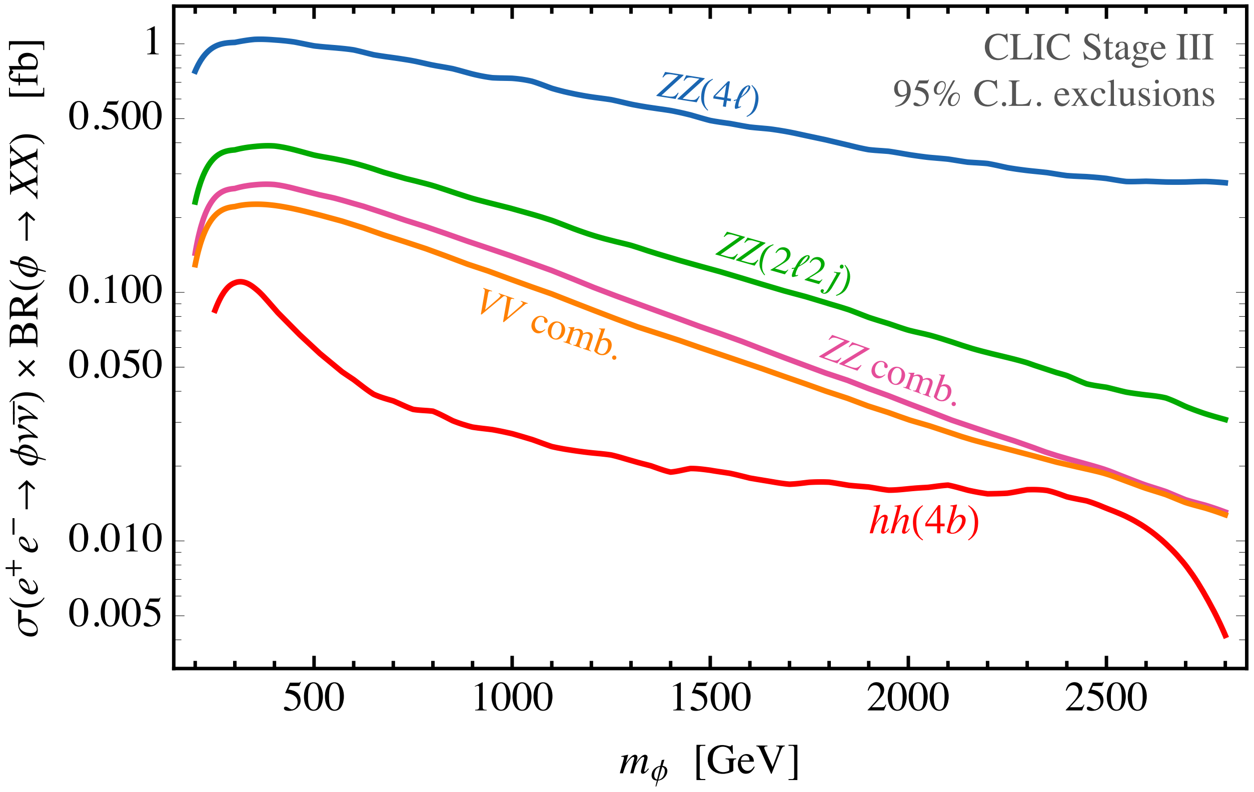


(see also my talk of last month)

$hh(4b)$ decay channel

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)

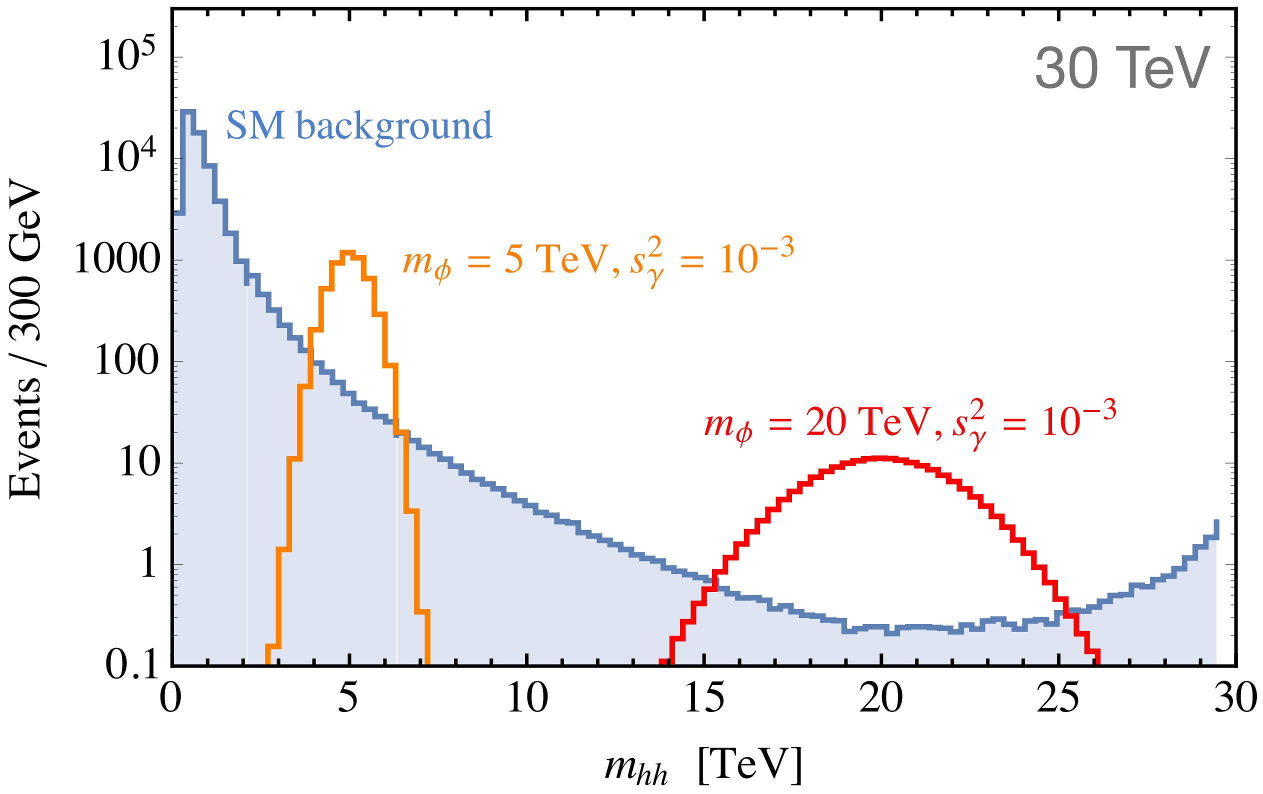
- ✦ Small background at high invariant-mass:
  - ‣ error is dominated by statistics
  - ‣ limits depend weakly on ϕ mass and collider energy

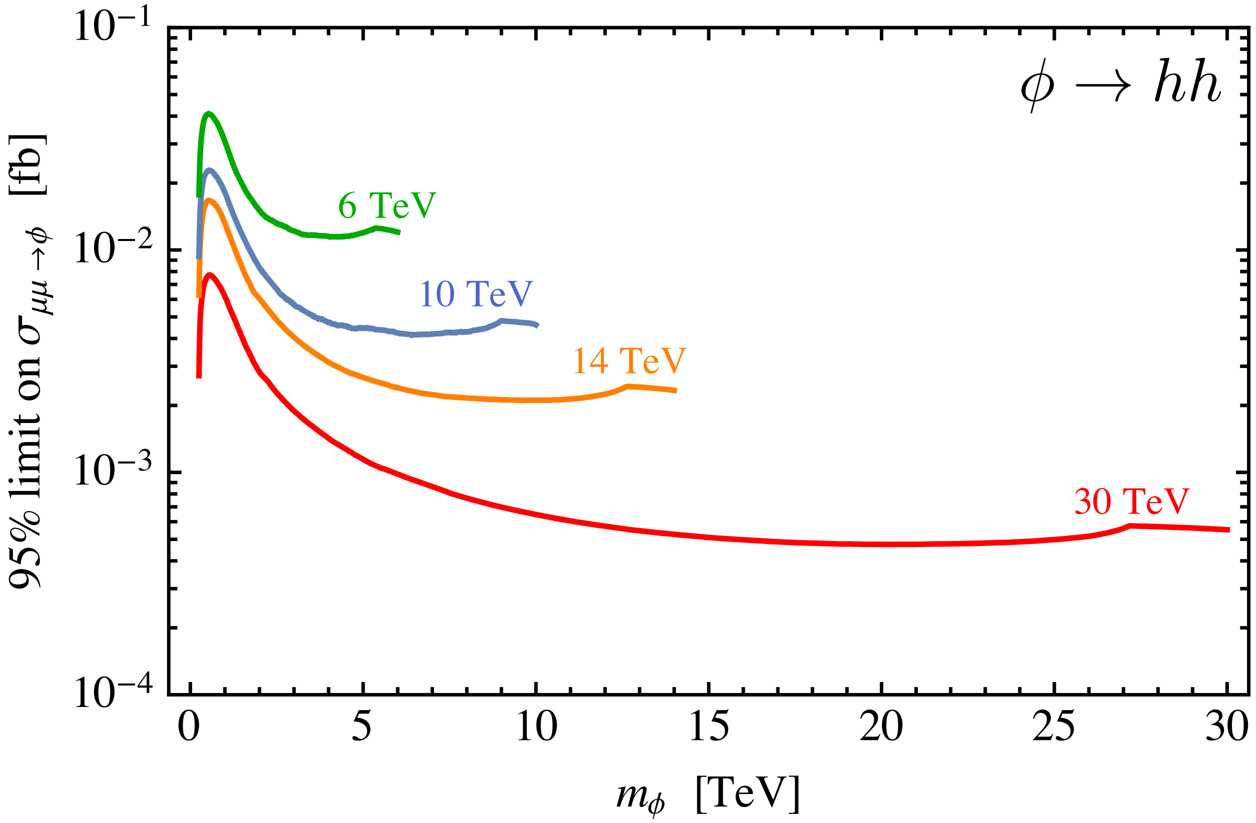
$$\sigma(e^+e^- \to \phi\nu\bar{\nu}) \times \mathrm{BR}(\phi \to f) \simeq 3/L,$$

- ✦ For BR(ϕ → *hh*) ~ 0.25, most sensitive channel is ϕ → *hh(4b)*
  - ‣ ϕ → *VV* less sensitive, but complementary if BR(ϕ → *hh*) small

hh(4*b*) decay channel

Cut & count experiment around the resonance peak:





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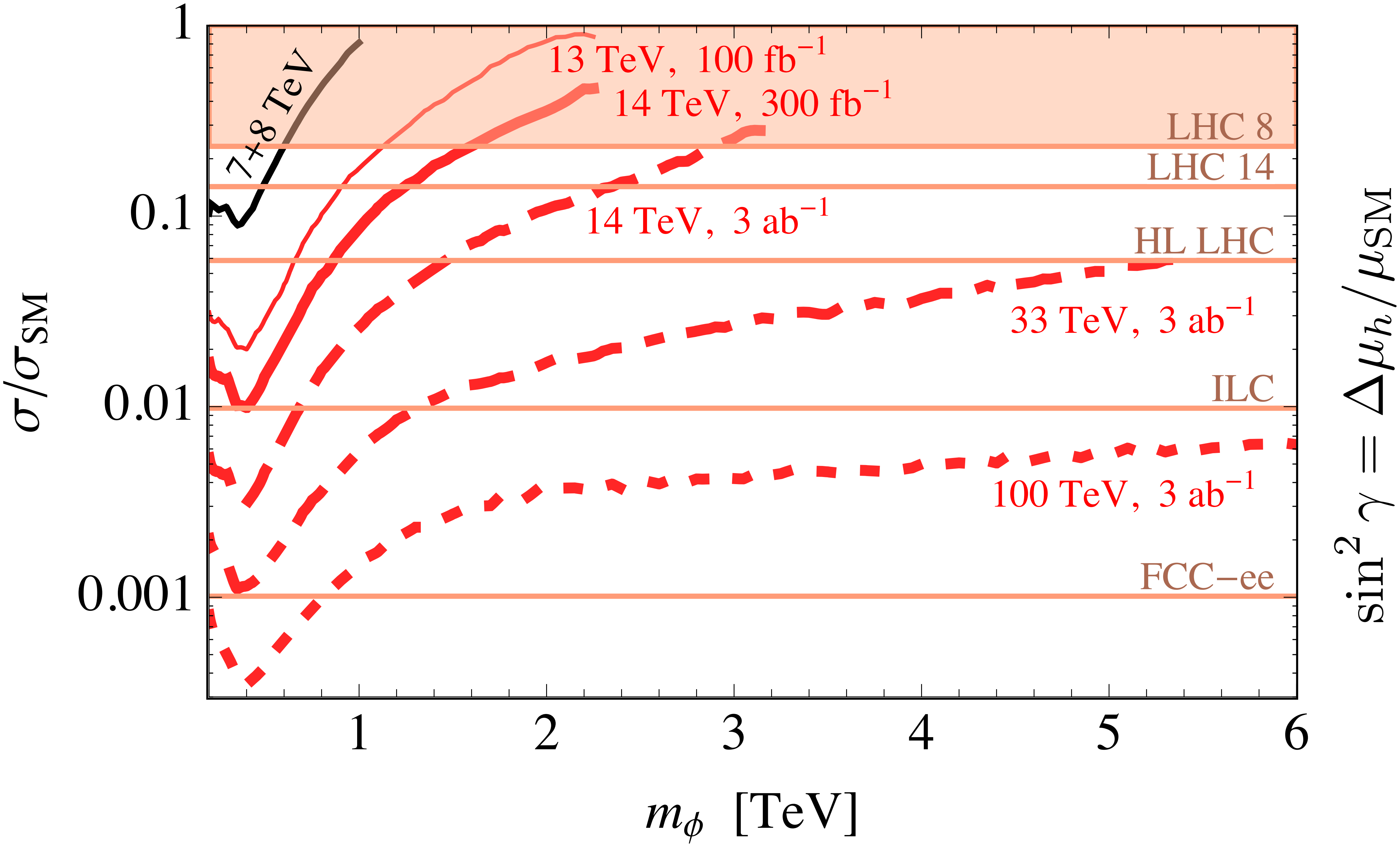
High Energy Lepton colliders

Compare the reach of very high energy lepton & hadron colliders



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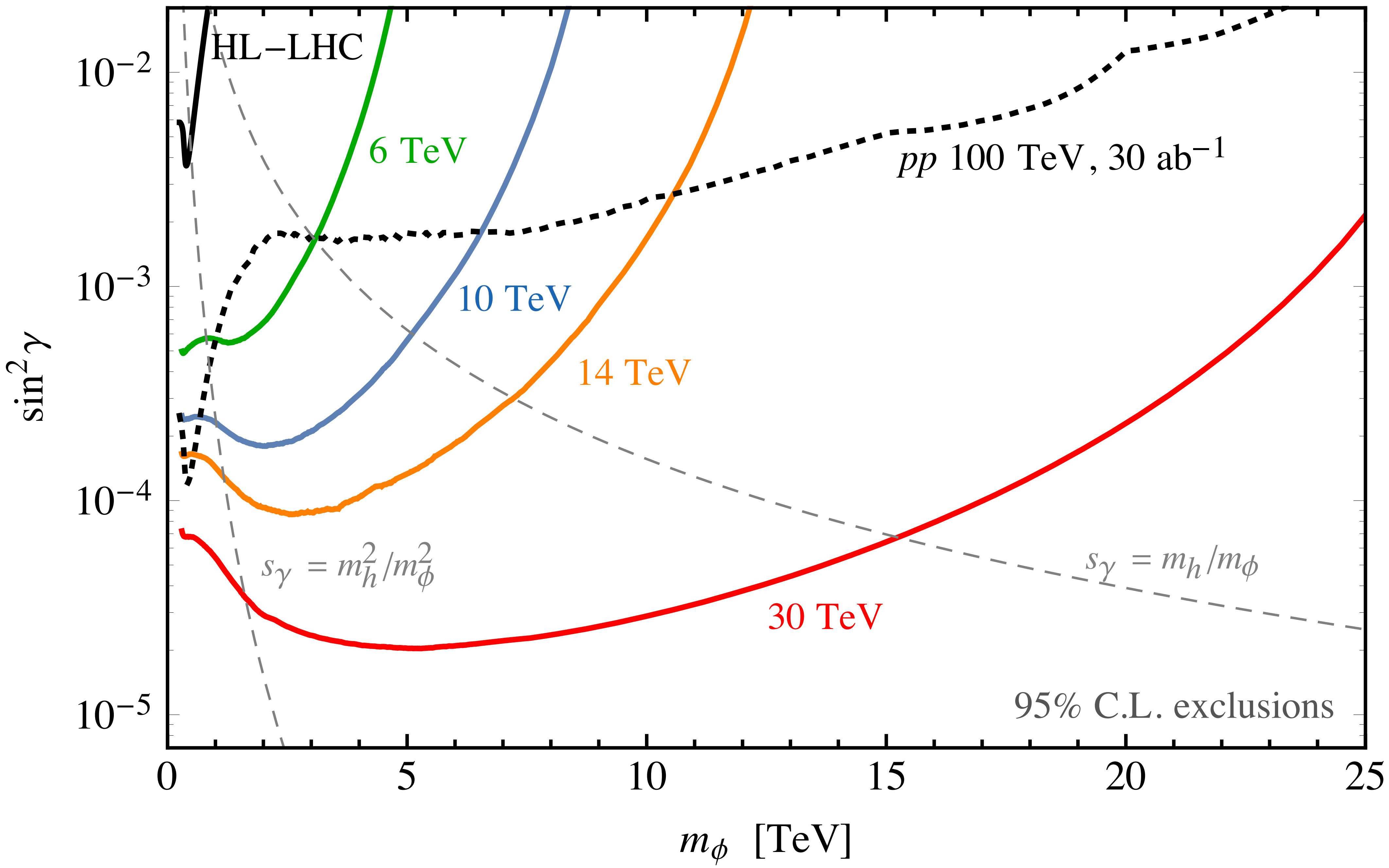

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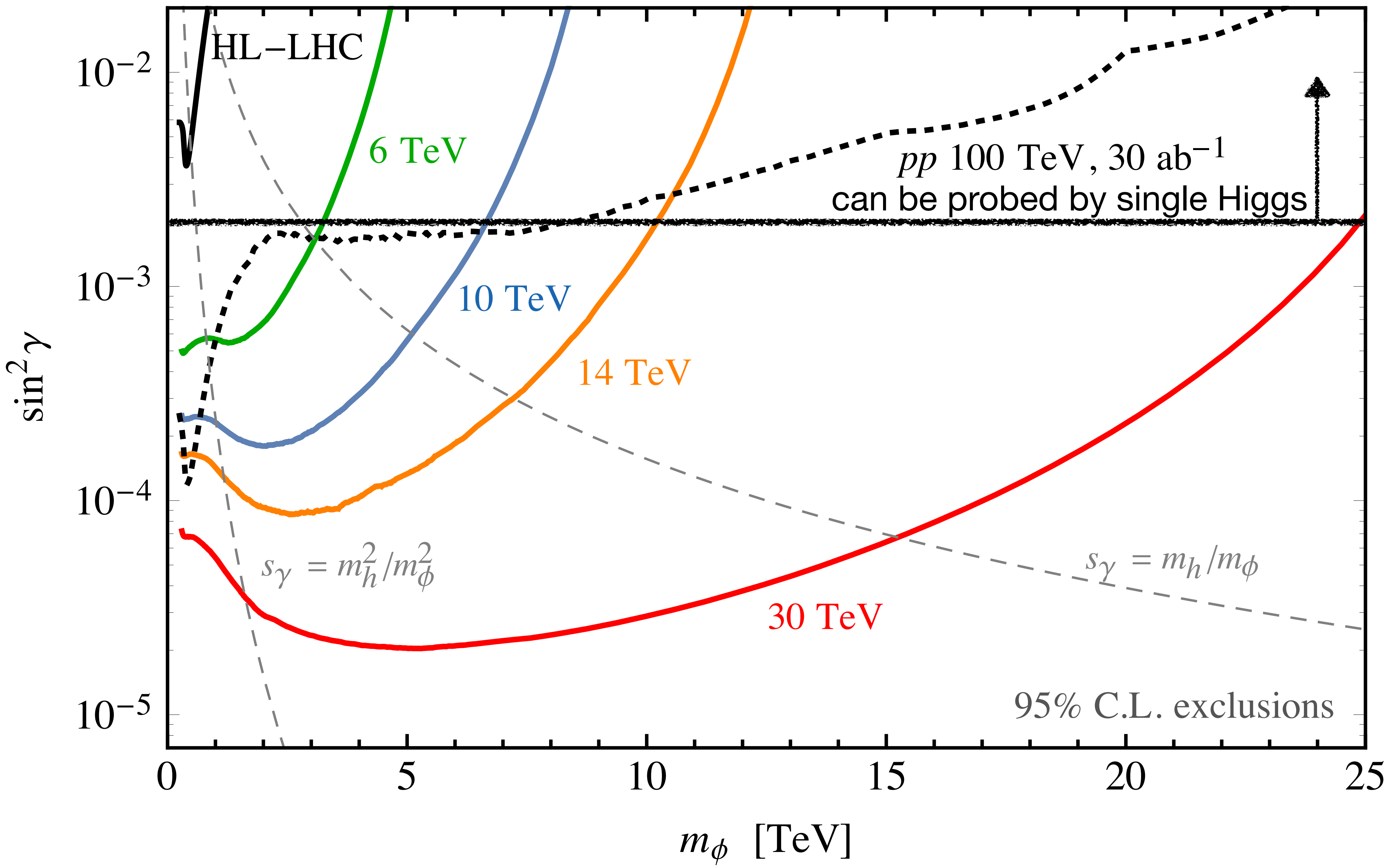
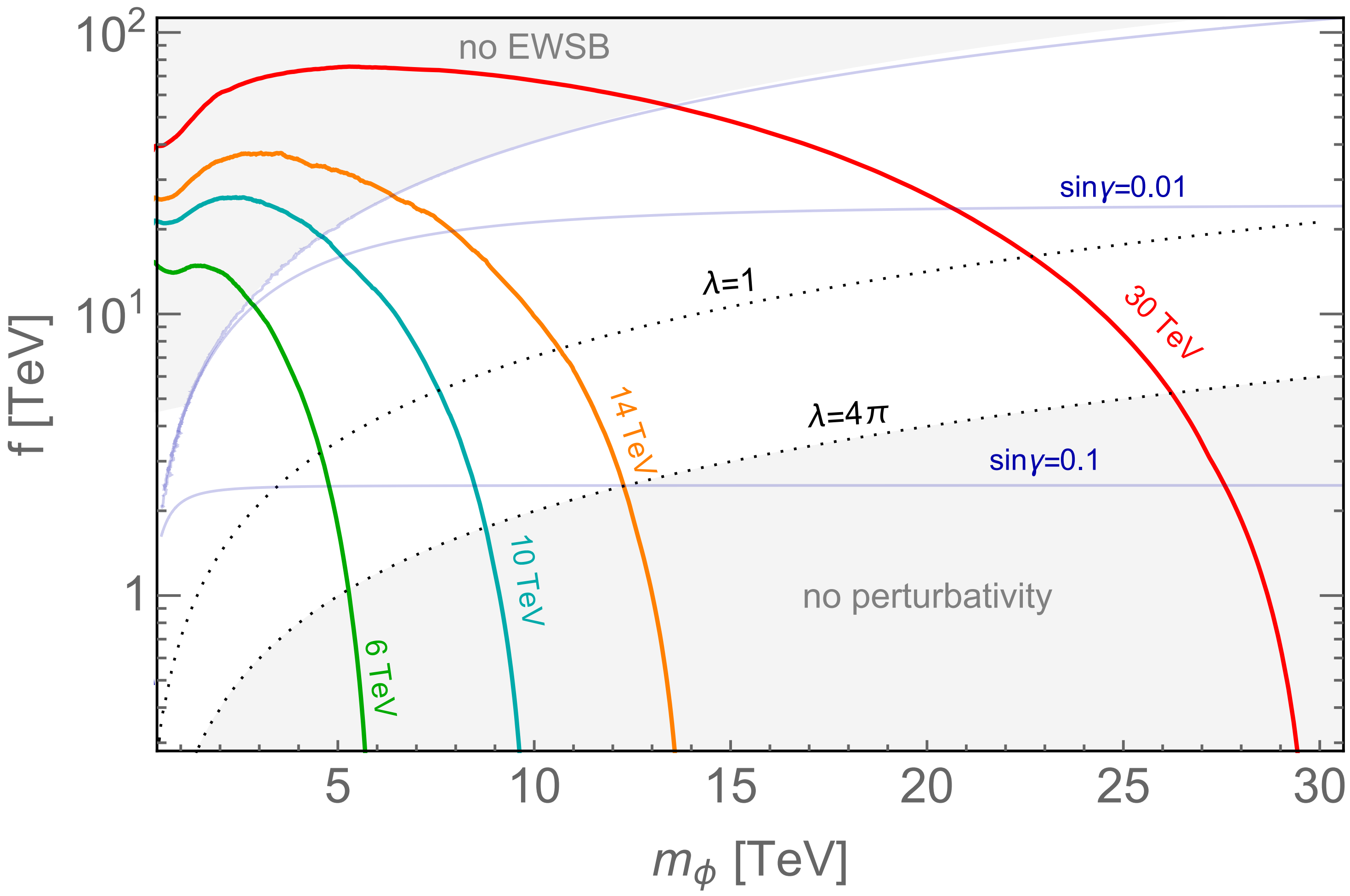


For this class of models, a high-energy $\mu^+\mu^-$ collider has an amazing reach if compared to single Higgs meas. or direct searches at a 100 TeV pp collider

Goldstone bosons (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 Higgs portal
- Higgs is a pseudo-Goldstone

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

- Model-independent tests:
  - ✓ Higgs couplings
  - ✓ Search for the singlet

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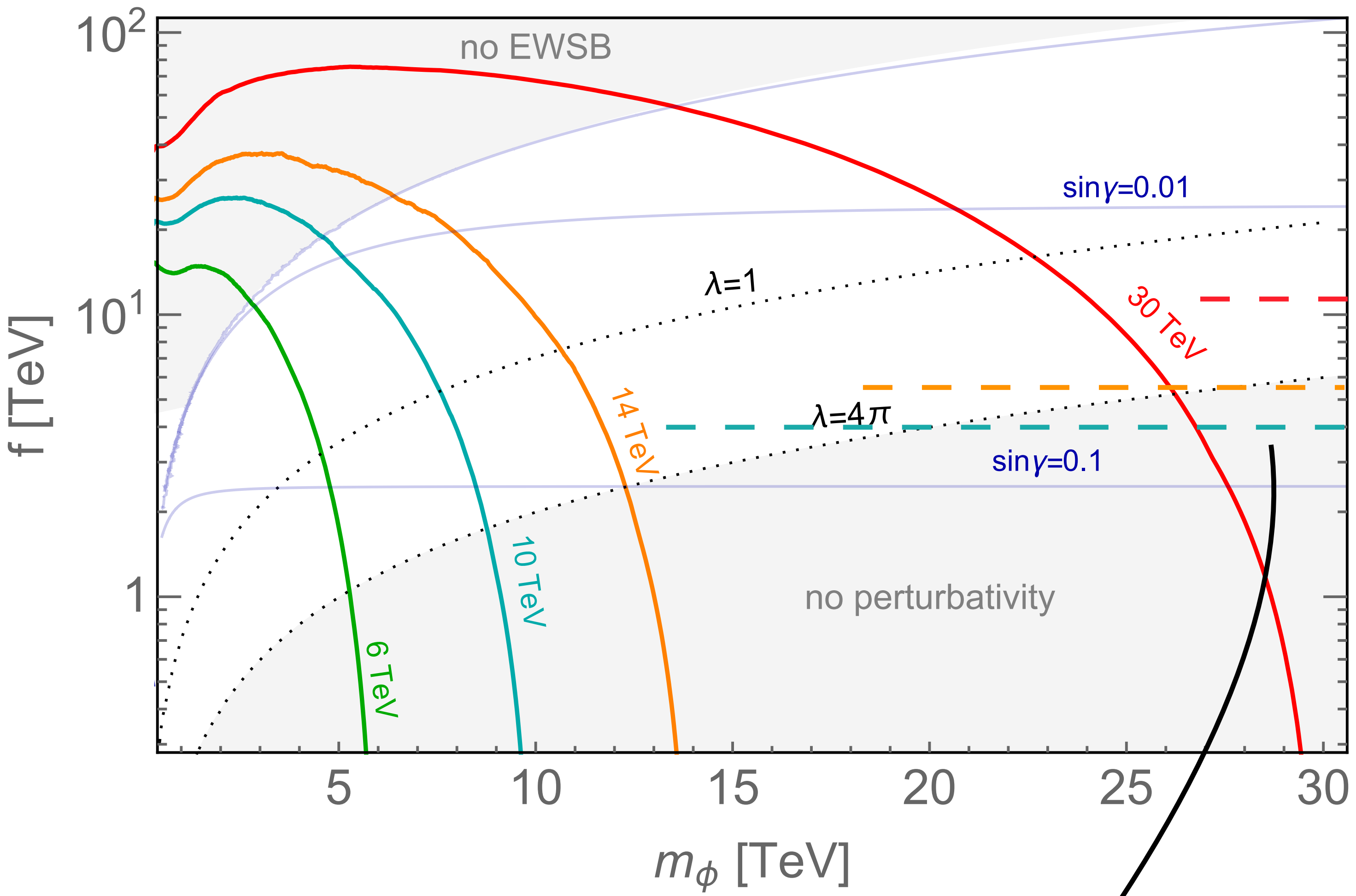
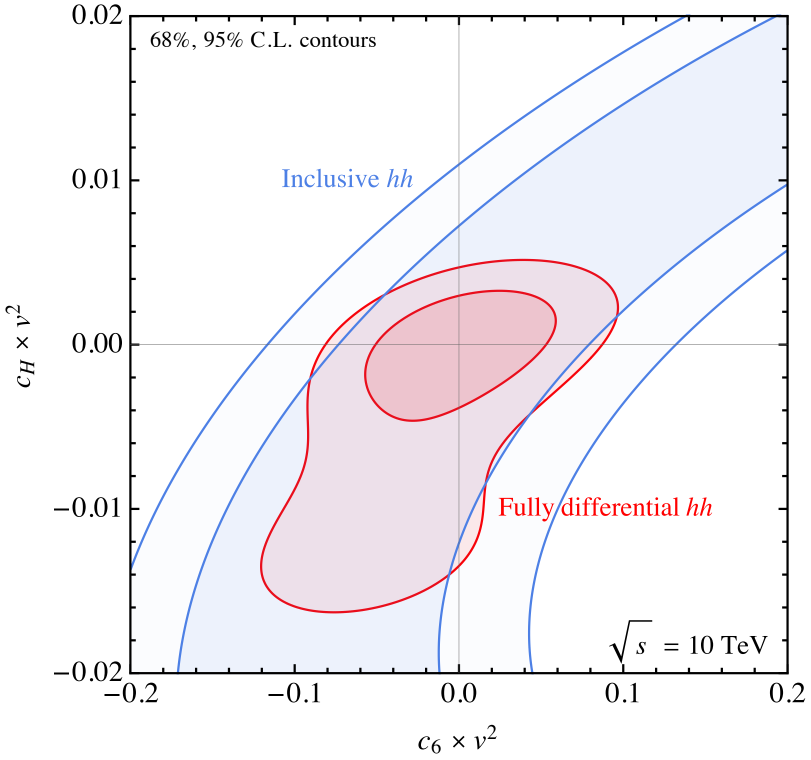


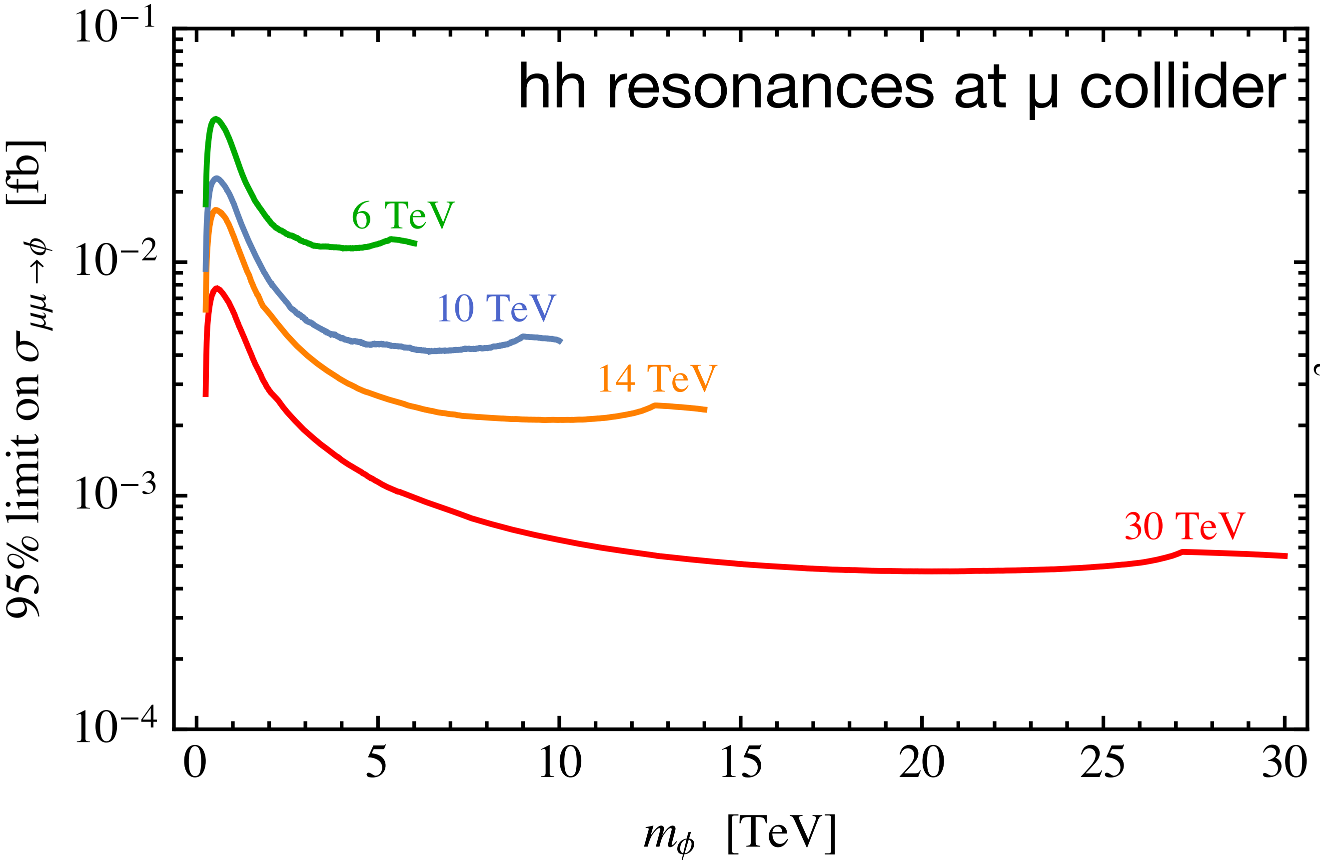


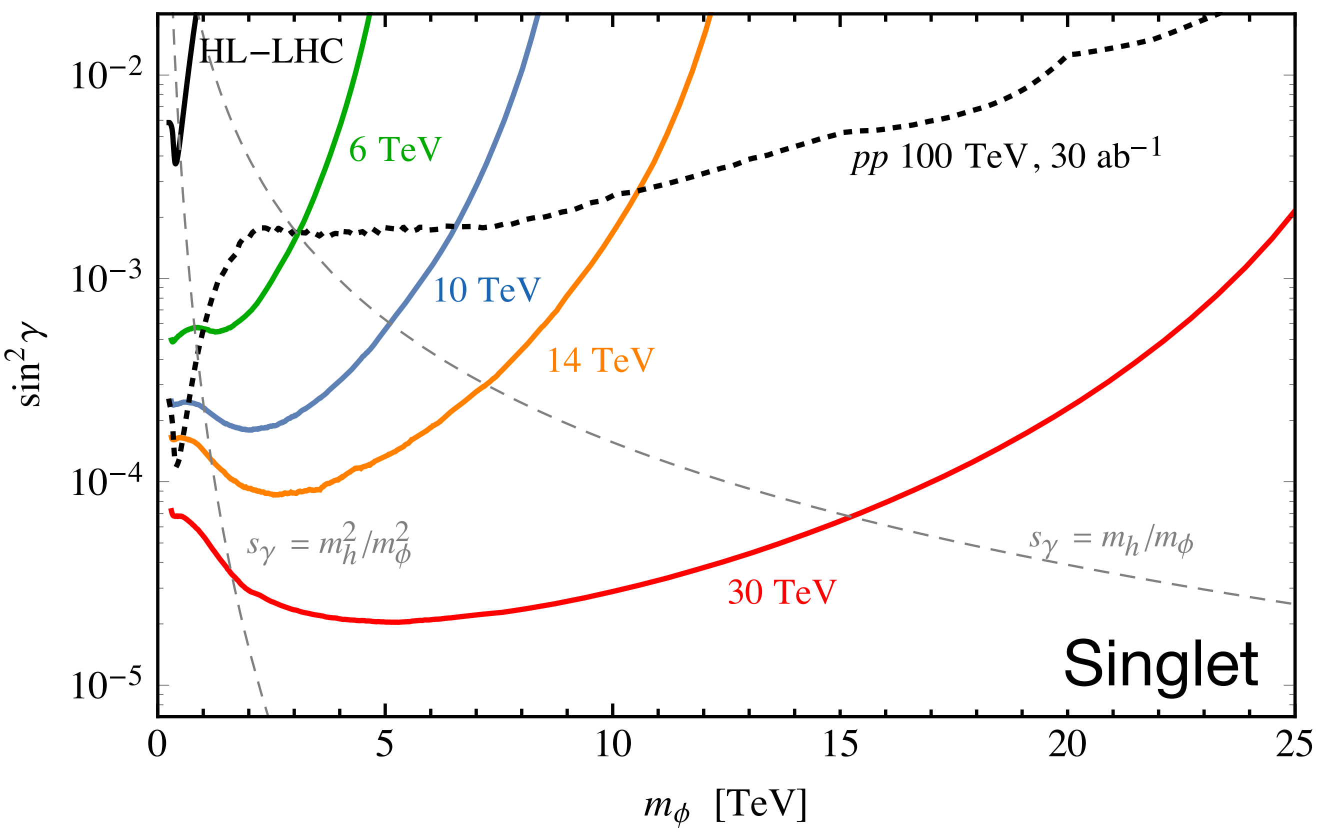
If ϕ heavy, no resonance search but EFT applies

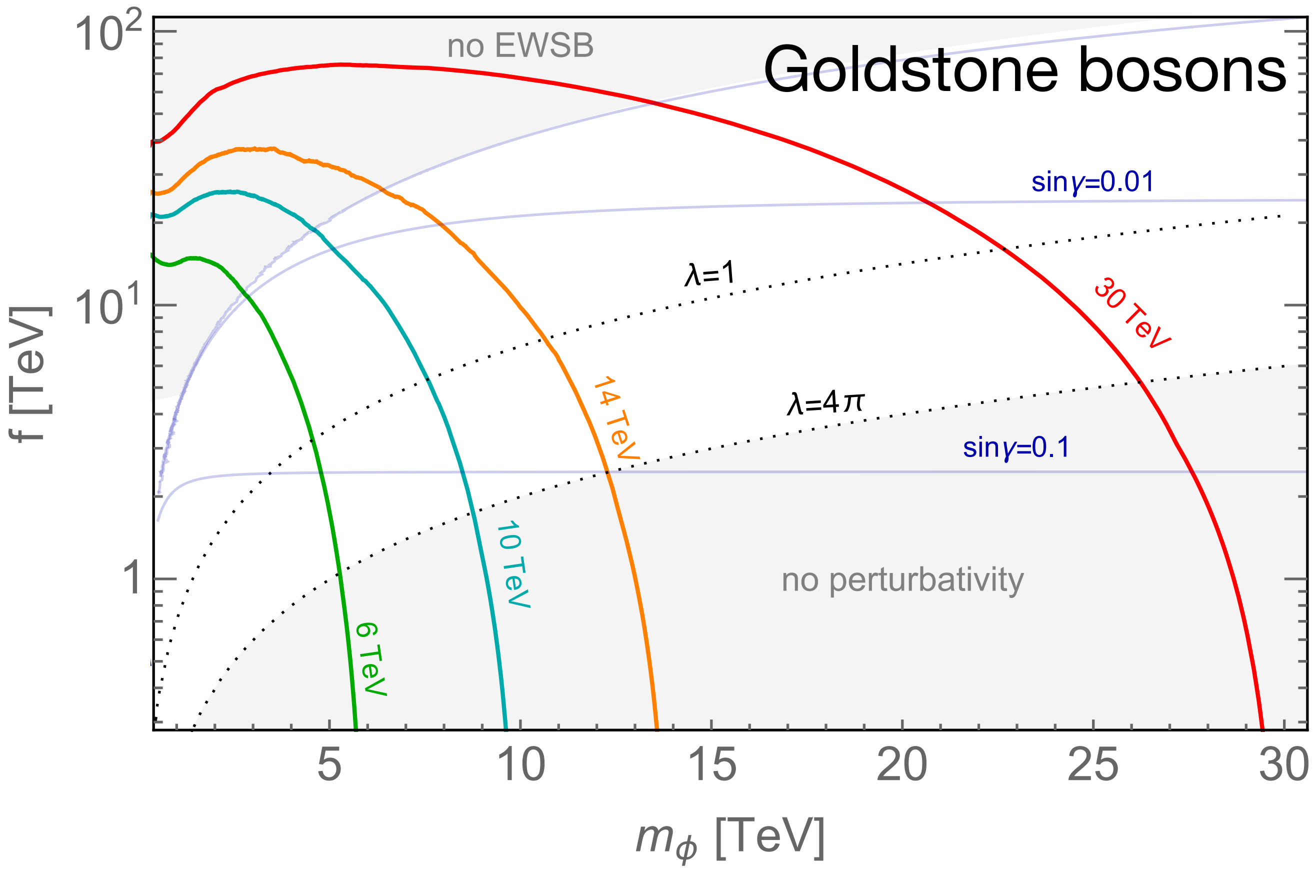
μμ → hh still useful

B, Franceschini, Wulzer, 2012.xxxxx

Summary







A high-energy μ collider
is simply amazing!

Backup

SUSY: the NMSSM

Three Higgs fields: H_u, H_d doublets + S singlet $\mathcal{W} = \mathcal{W}_{\rm MSSM} + \lambda S H_u H_d + f(S)$

- ◇ Extra tree-level contribution to the Higgs mass

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

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

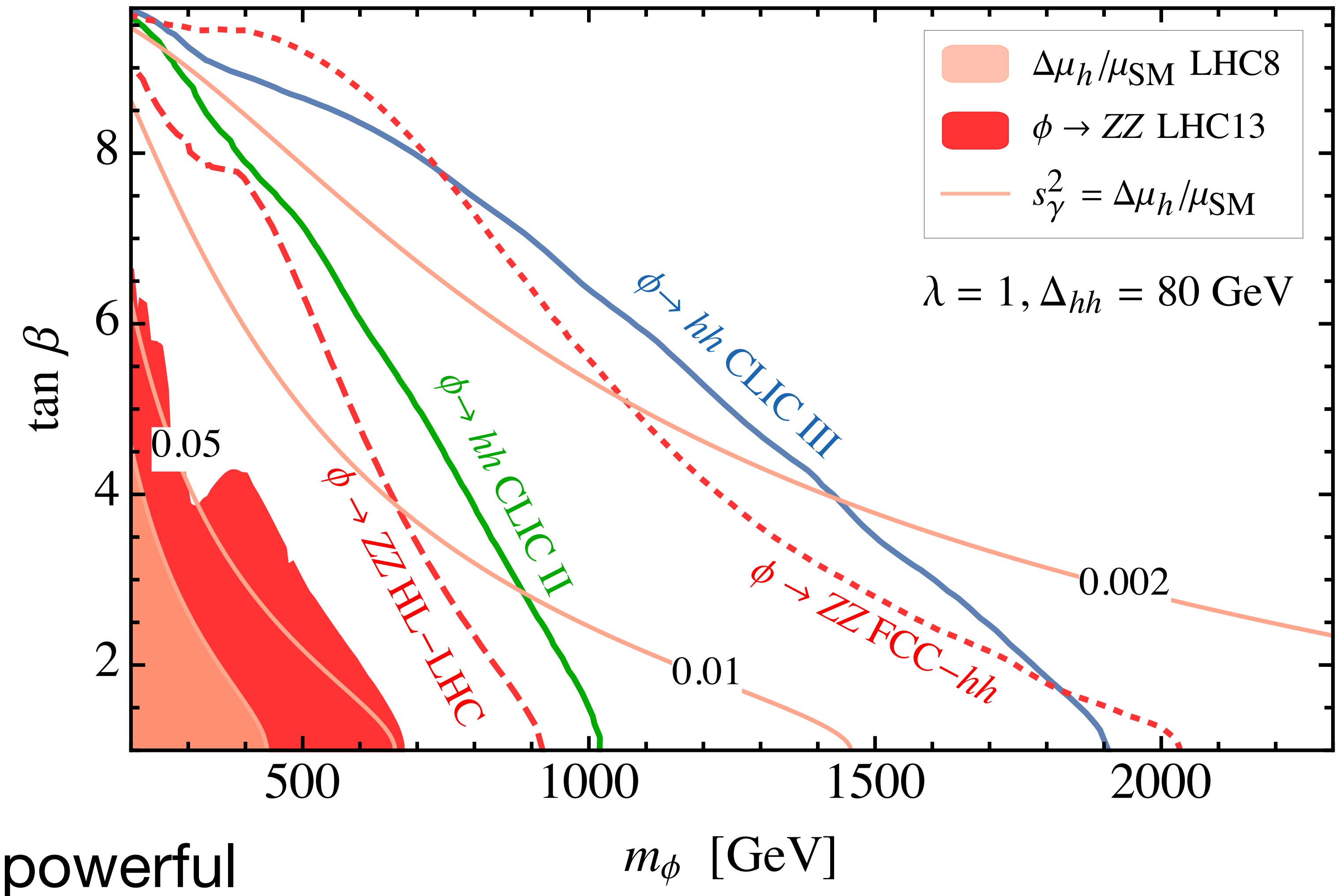
- ◇ Alleviates fine-tuning in v for $\lambda \gtrsim 1$ and moderate $\tan\beta$

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

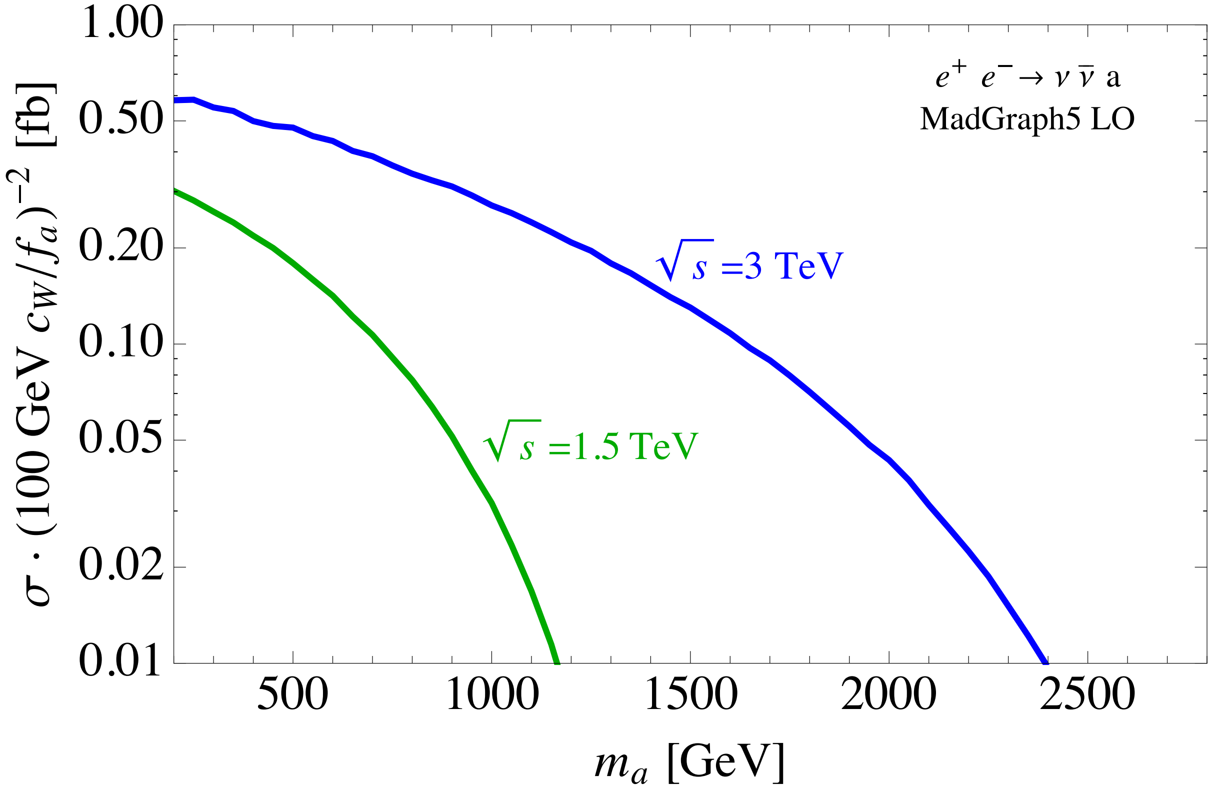


Weakly coupled: direct searches powerful

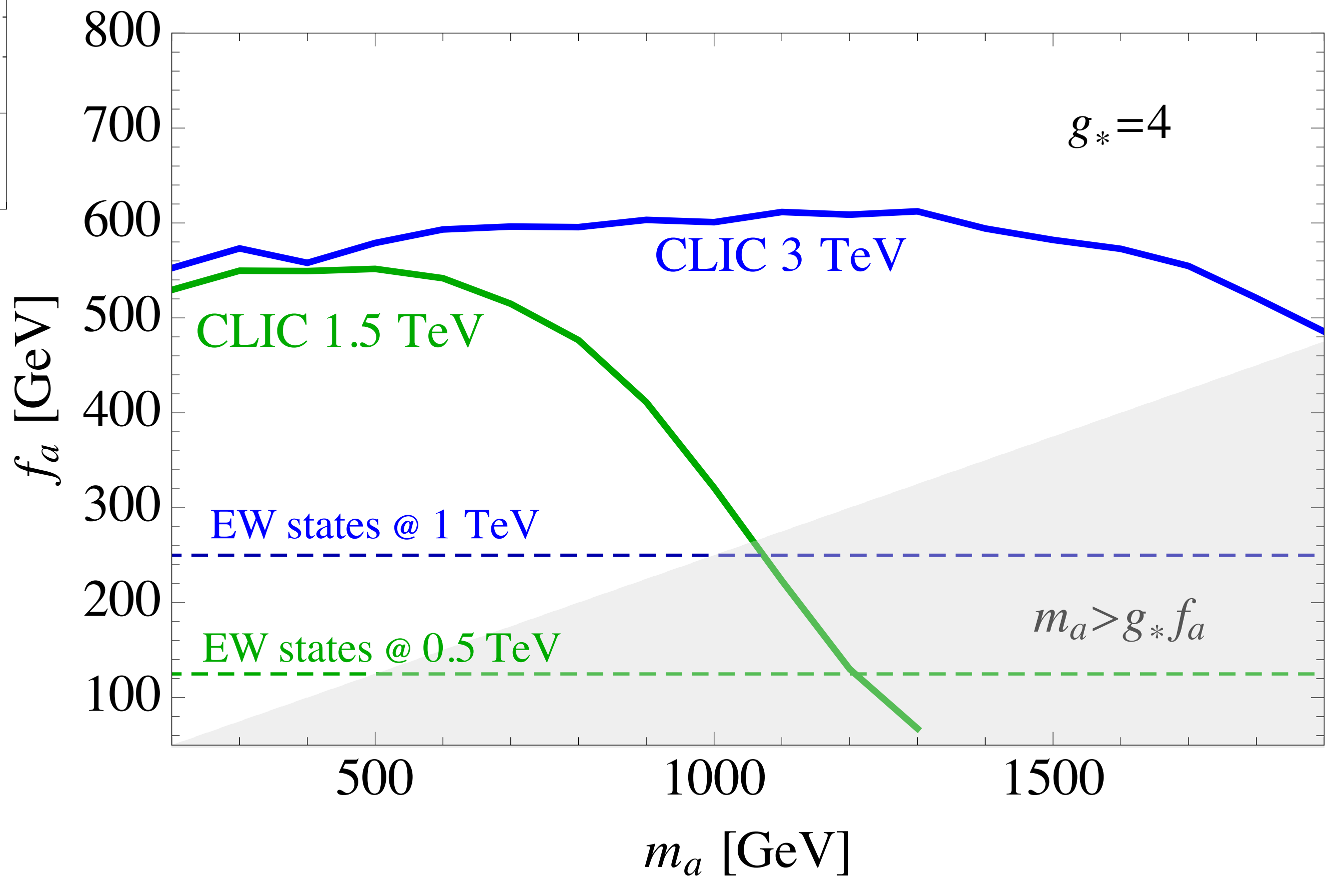
Axion-like particles (ALPs)

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

  SSB of a U(1) at scale f_a (**not** the QCD axion), physical cut-off at $g_* f_a$



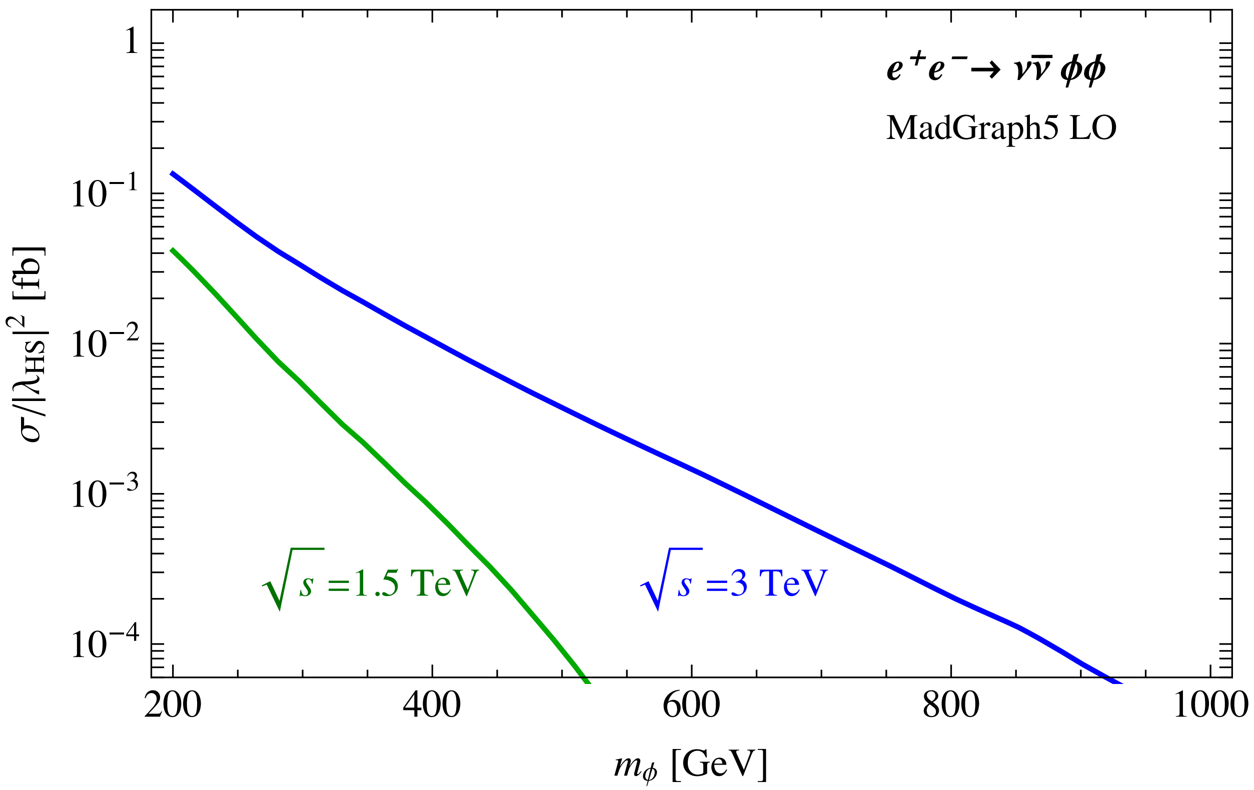
- Produced in W-fusion (but couple to transverse W's), and decay to vectors

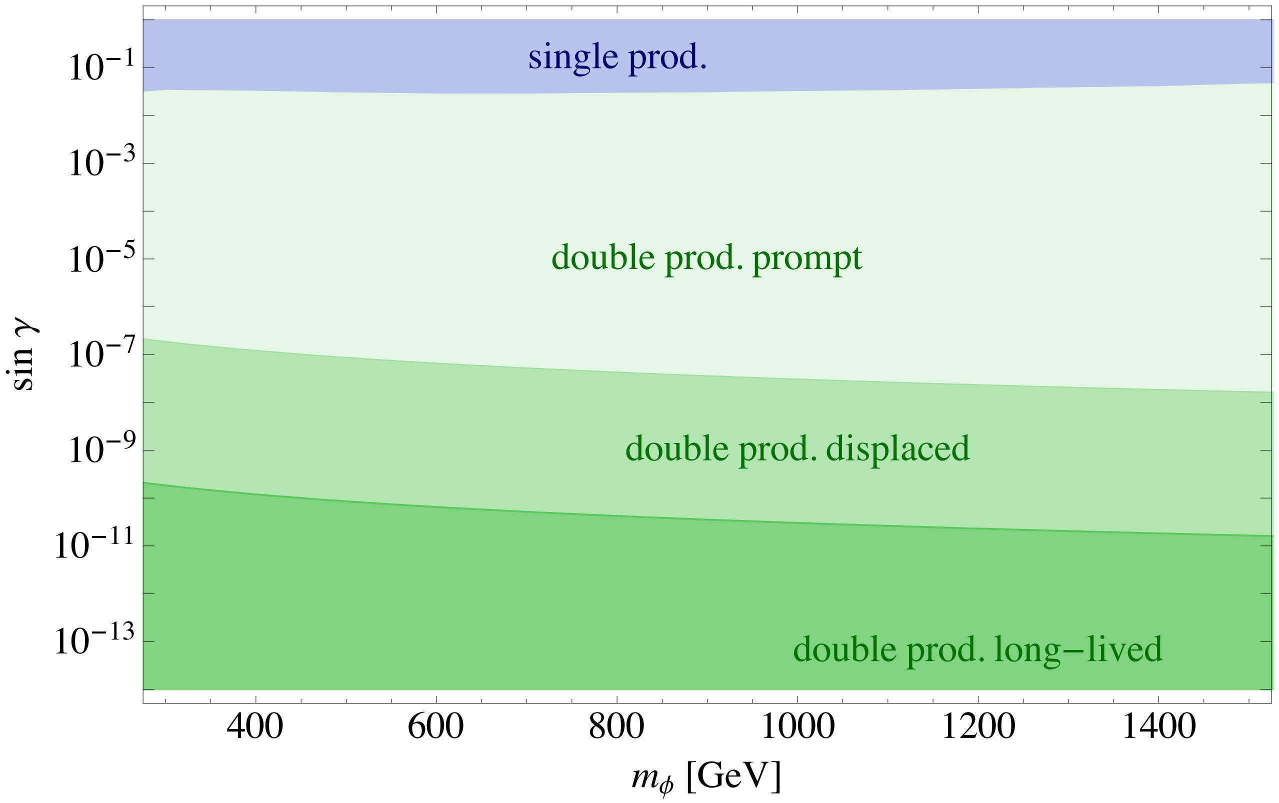


- In general, a → γγ is a golden channel, but could be suppressed for particular values of c_1, c_2 (photophobic ALP)

Pair production

- In the limit of small mixing angle, the single production rate of ϕ vanishes
  - the Lagrangian has an approximate Z_2 symmetry $\phi \rightarrow -\phi$ $\cancel{a_{HS}|H|^2 S}$
- Double production rate does not depend on the mixing: controlled by the portal coupling $\lambda_{HS}\, S^2|H|^2$





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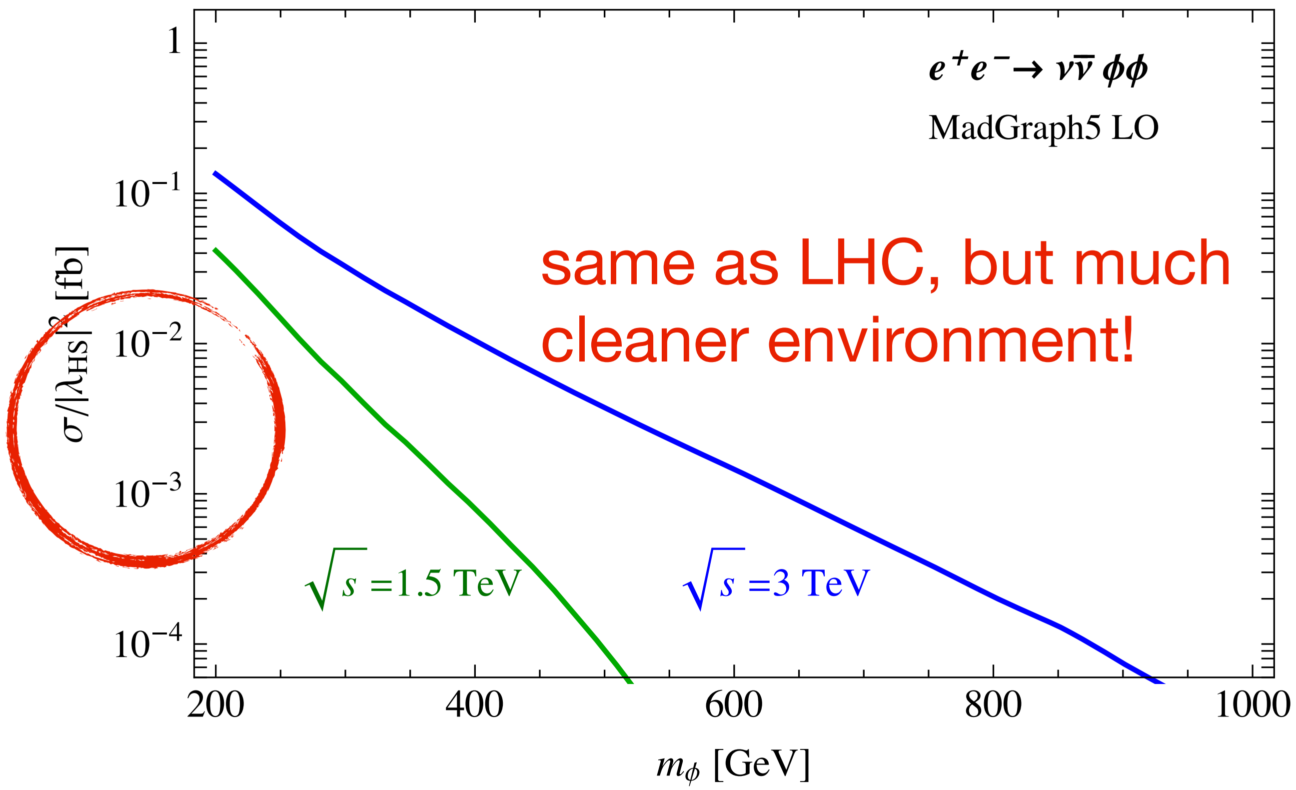
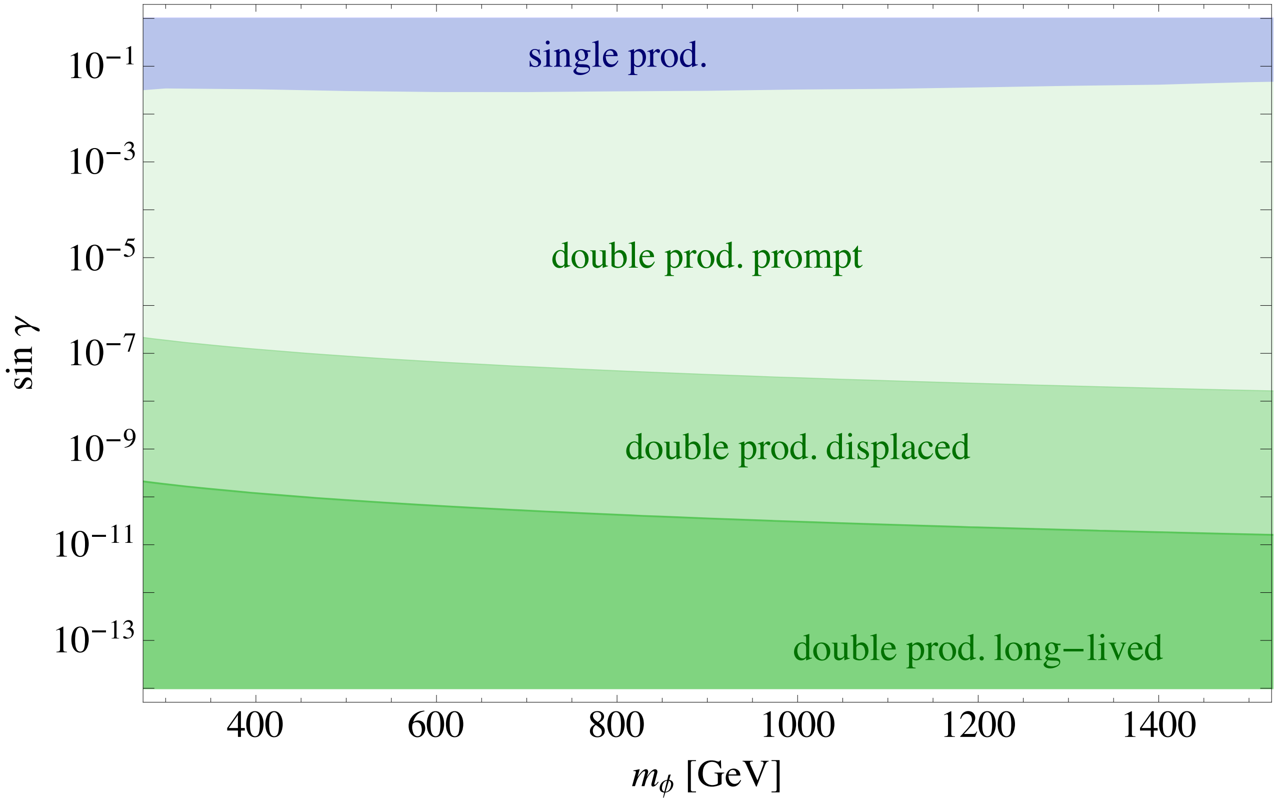


same as LHC, but much cleaner environment!



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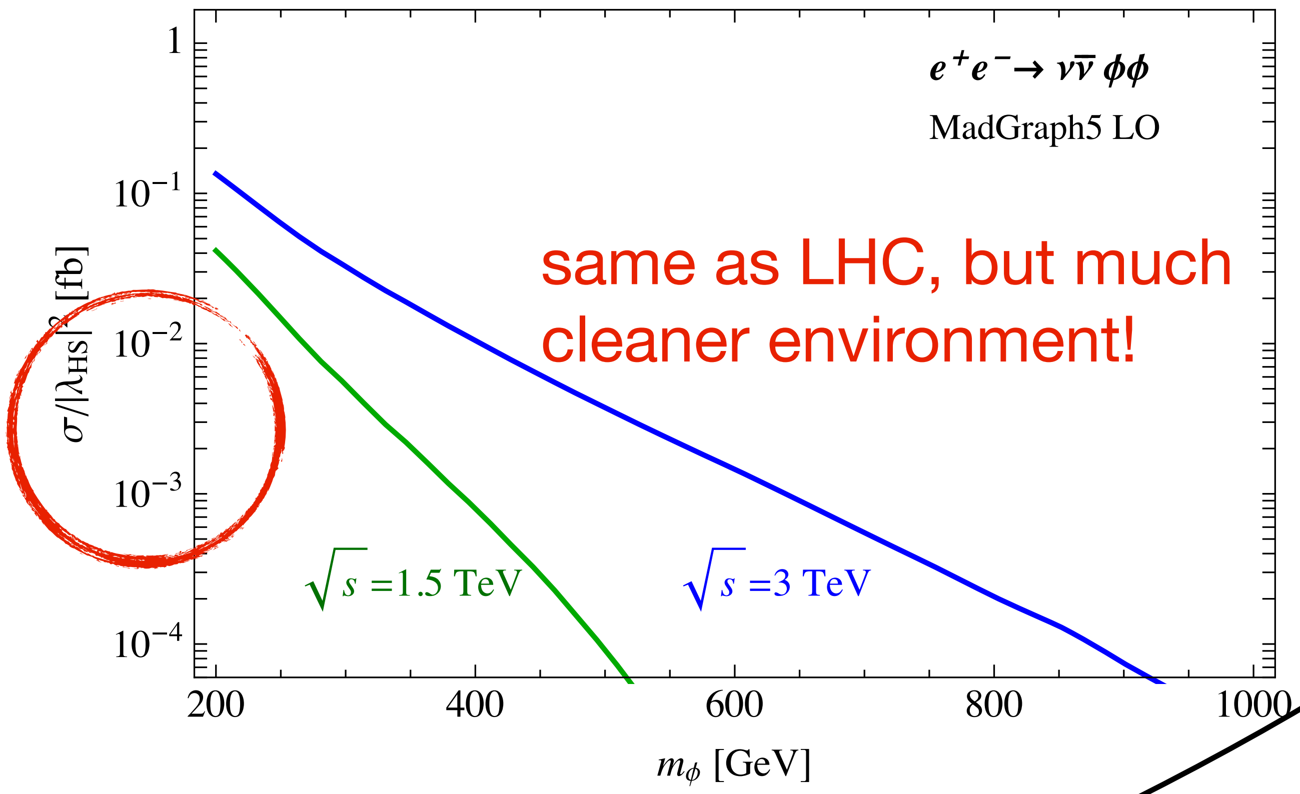

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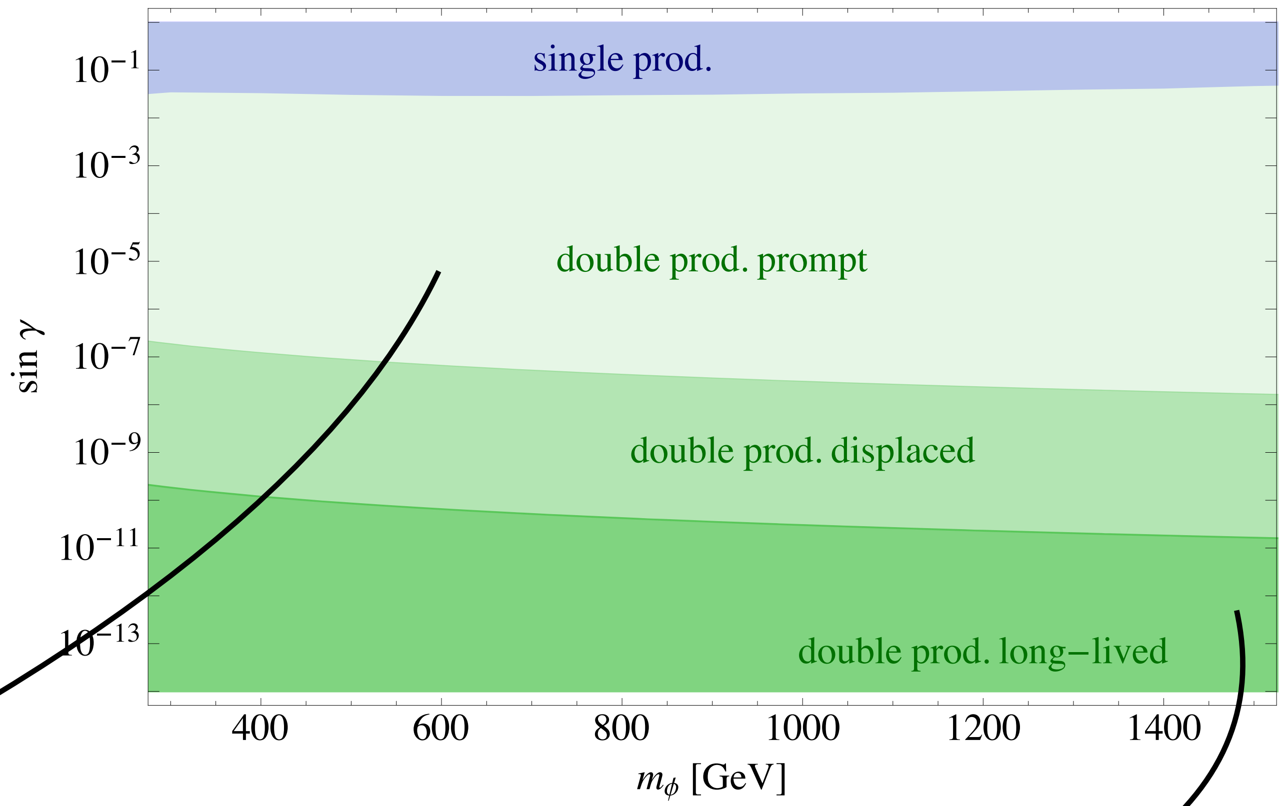


we focus on a region of small non-zero mixing: the singlet decays to SM bosons in the detector

ϕ is invisible: requires a different treatment

[see e.g. 1409.0005 and talk by R. Franceschini]

Electroweak phase transition

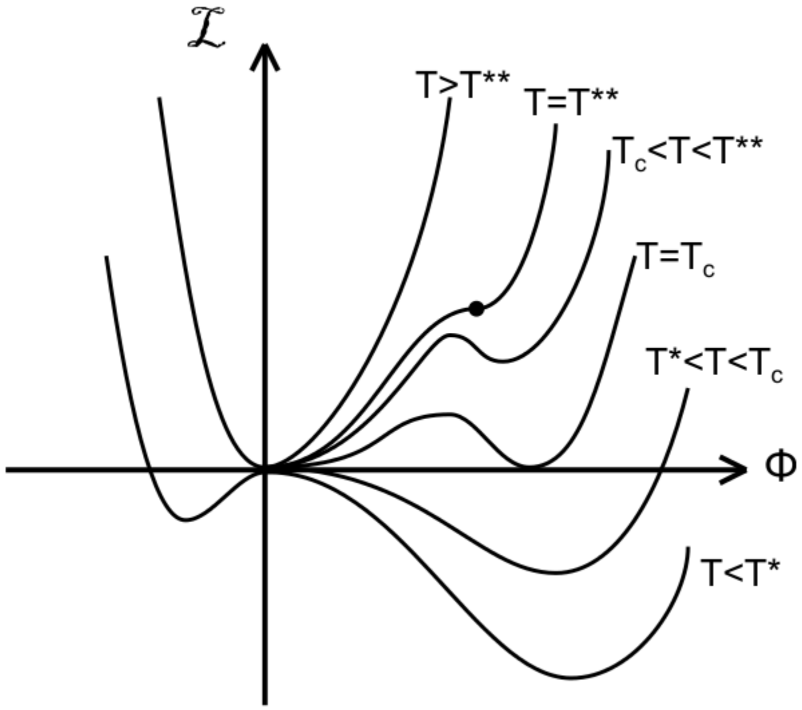
- In the SM, the EW phase transition is 2nd order (smooth $v(T)$ dependence)
  - ➡ 1ST order PT crucial for (EW) baryogenesis: need to be strongly out-of-equilibrium!

- Additional scalar singlets can give a 1st order PT:

1. Phase transition in the singlet potential:

   “light state with large coupling to Higgs”

$$m_S^2 = m_\phi^2 - \lambda_{HS}^2 v^2/2 < 0$$

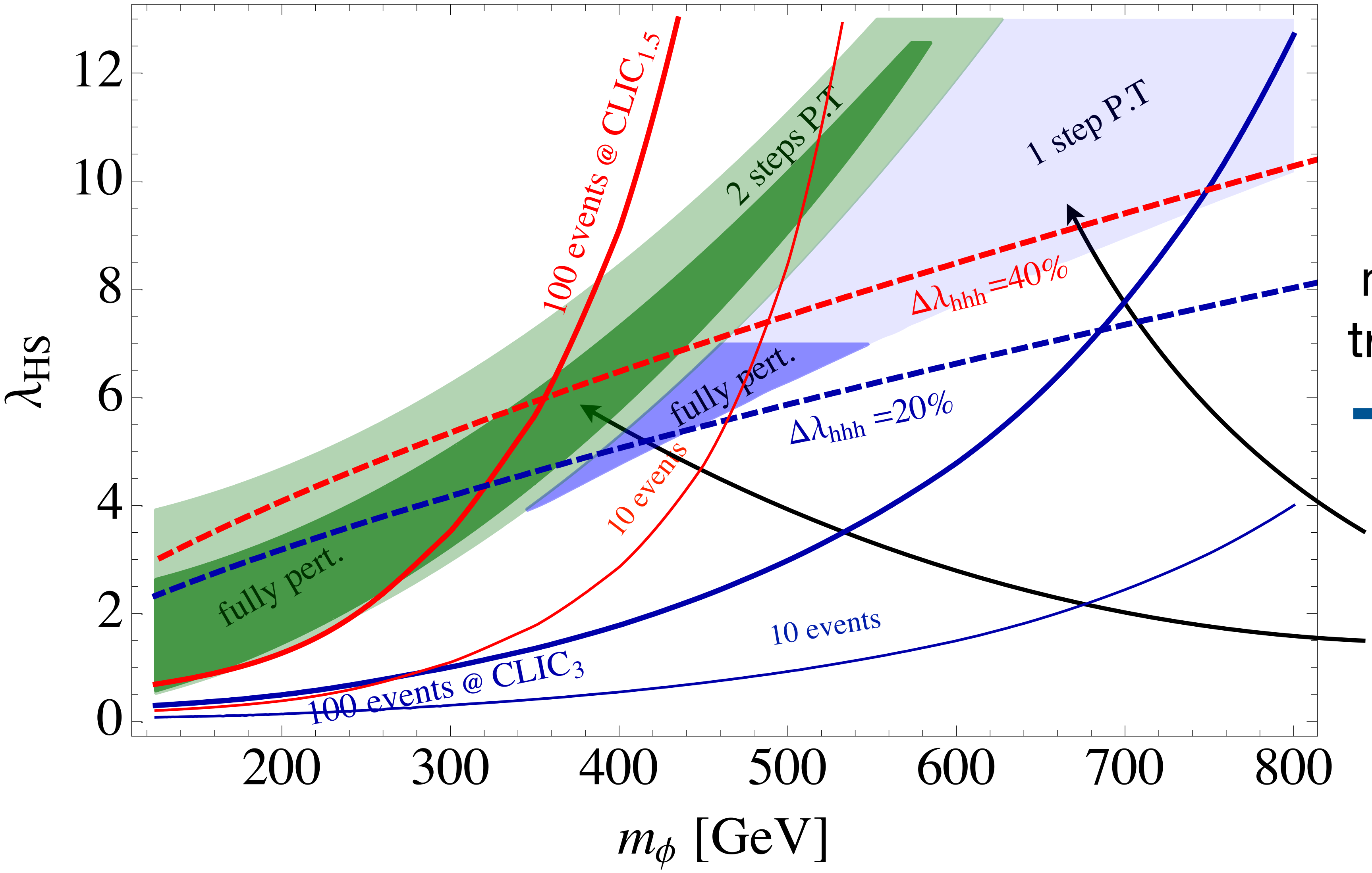


see talk by G. Panico

2. Singlet induces a negative effective quartic coupling for the Higgs $\lambda_h^{\text{eff}}(m_\phi, \lambda_{HS}) < 0$

Pair production: results

- Final states with 4 Higgs or vector bosons (e.g. $e^+e^- \rightarrow 8b + E_{miss}$): very small backgrounds, few events are needed to test the model at CLIC
- Even more stringent bounds in the case of displaced decays (smaller mixing): virtually all the ϕ can be identified, no background



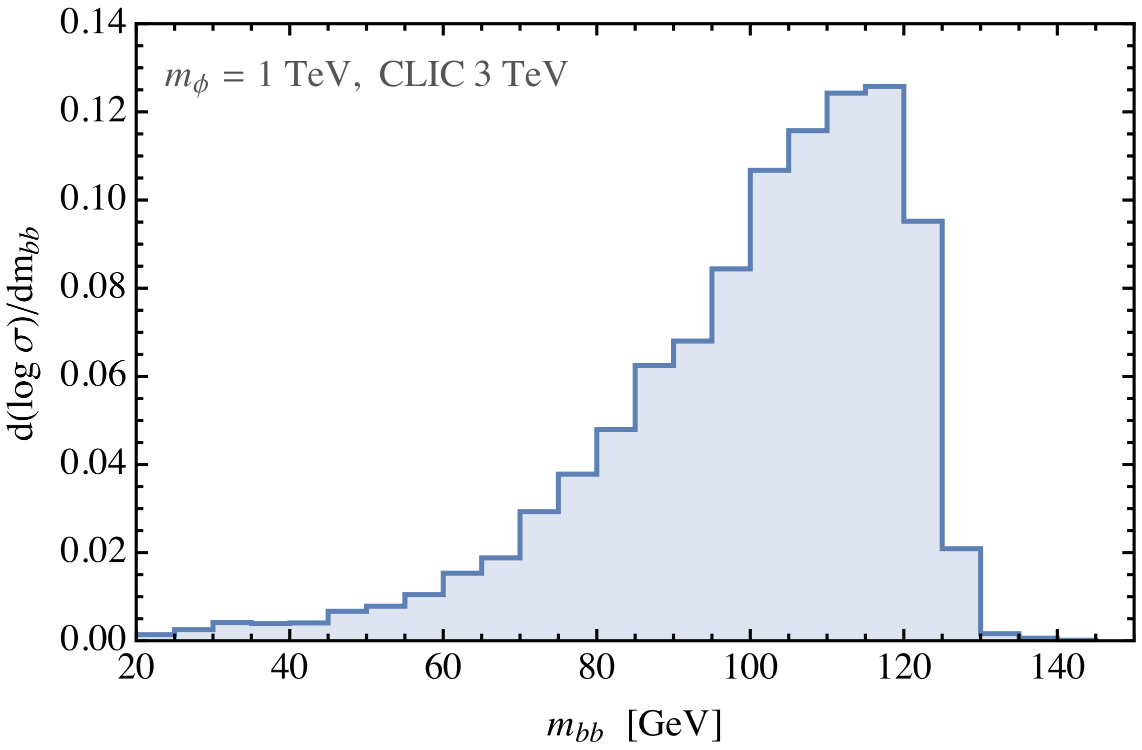
λ_{HS} also induces modifications of the triple-Higgs coupling

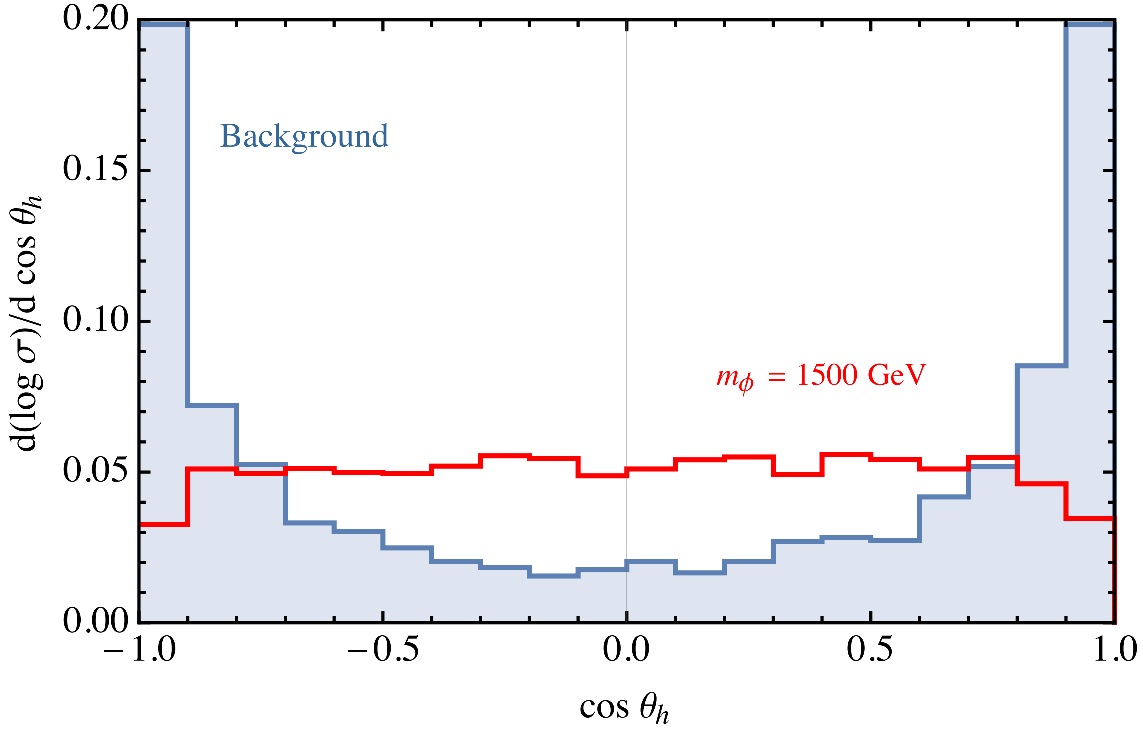
➡ see talk by G. Panico

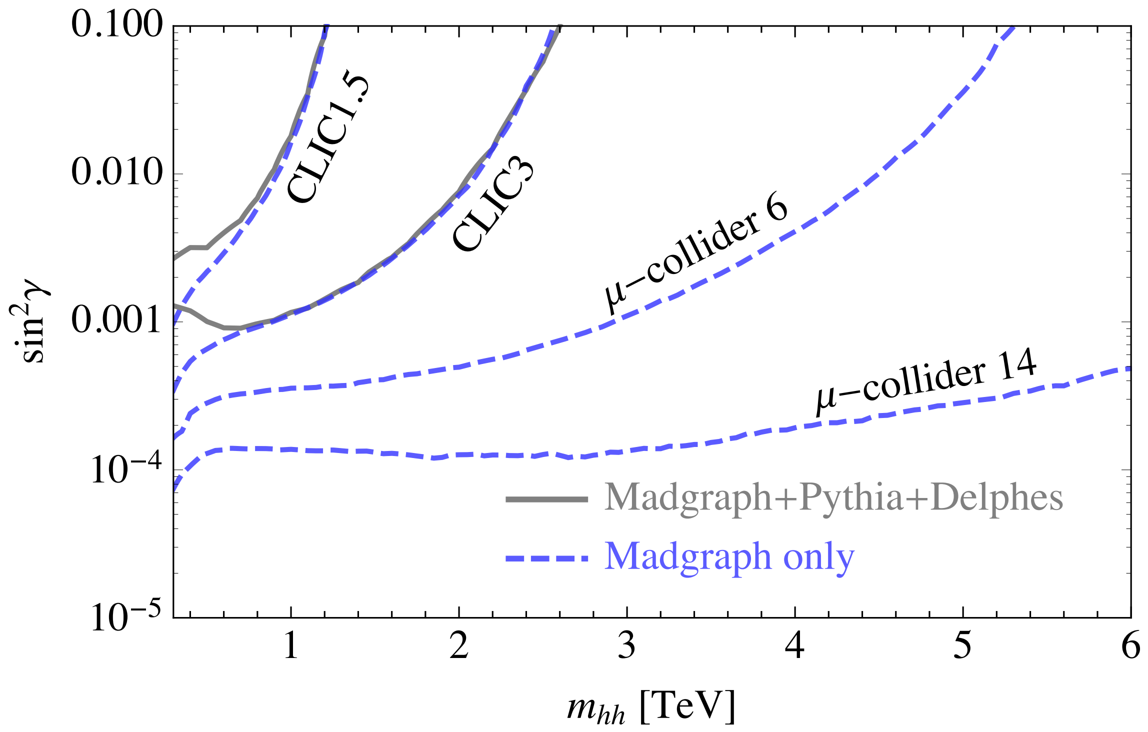
regions where 1st order EW phase transition can happen

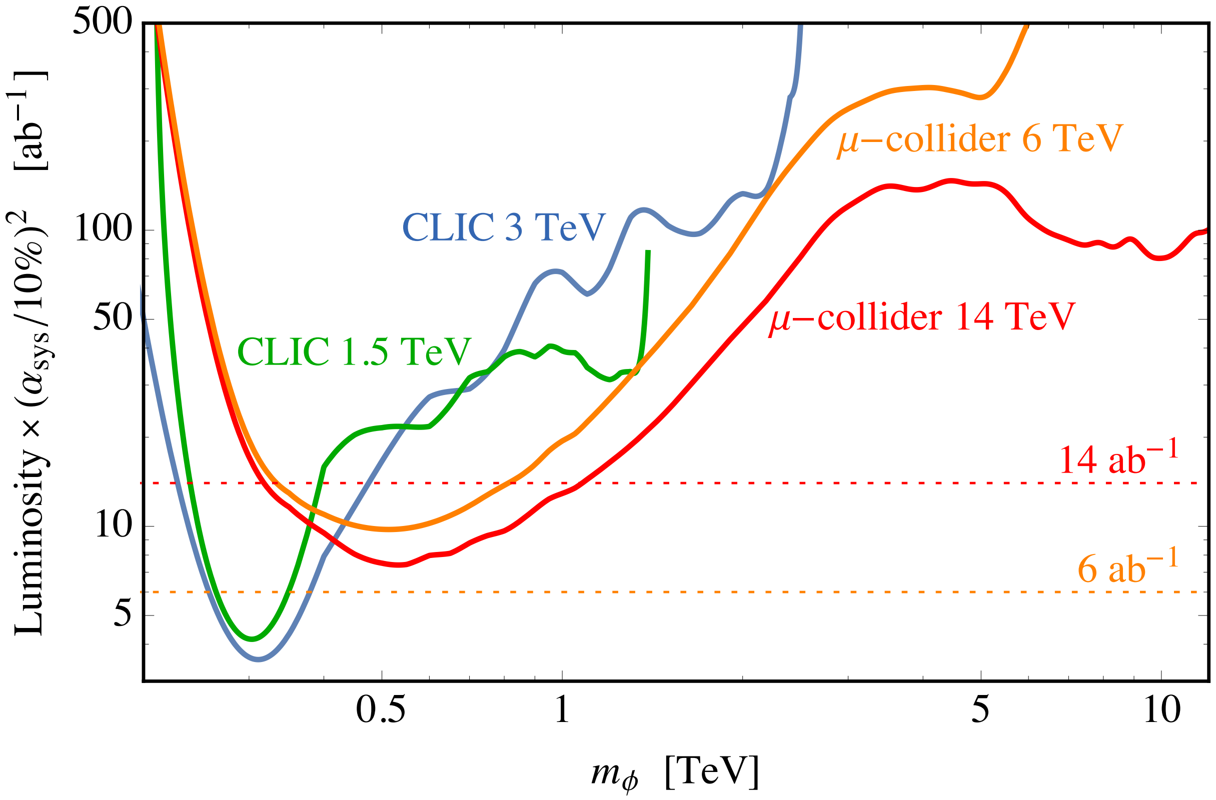
CLIC can fully test the region where singlet gives 1st order phase transition!

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





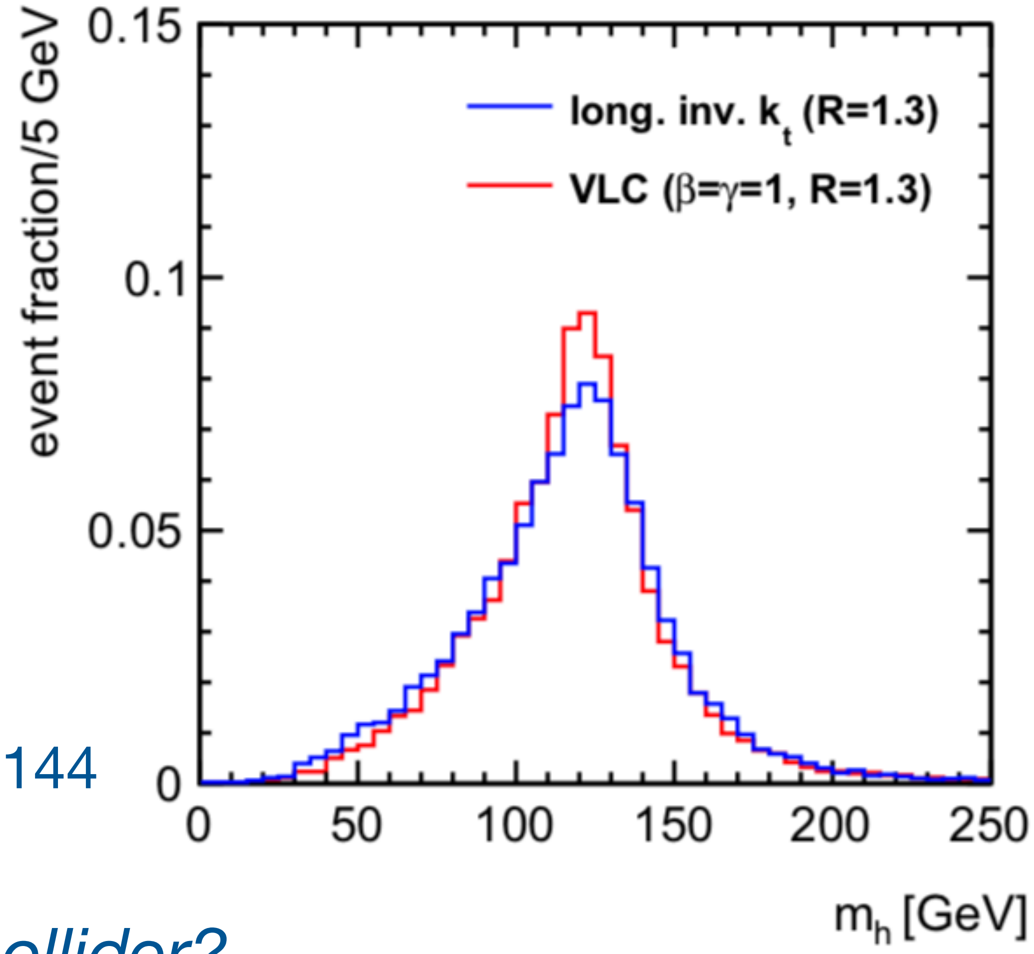




Backgrounds

- Backgrounds are important and cannot be neglected
  (see also CLIC study [1901.05897])
- Mainly VBF di-boson production: Zh & ZZ, but also WW, Wh, WZ…
  other backgrounds are easily rejected with cut on tot. inv. mass
- Precise invariant mass reconstruction is crucial to isolate signal
  - resolution on Z inv. mass ~ 6–7% at 3 TeV [CLICdp-Note-2018-004]
  - for Higgs energy resolution is worse: 10% on jet energy, ~ 15% on inv. mass (neutrinos in semi-leptonic b decay, too forward tracks missed)

thanks to Philipp
for discussion



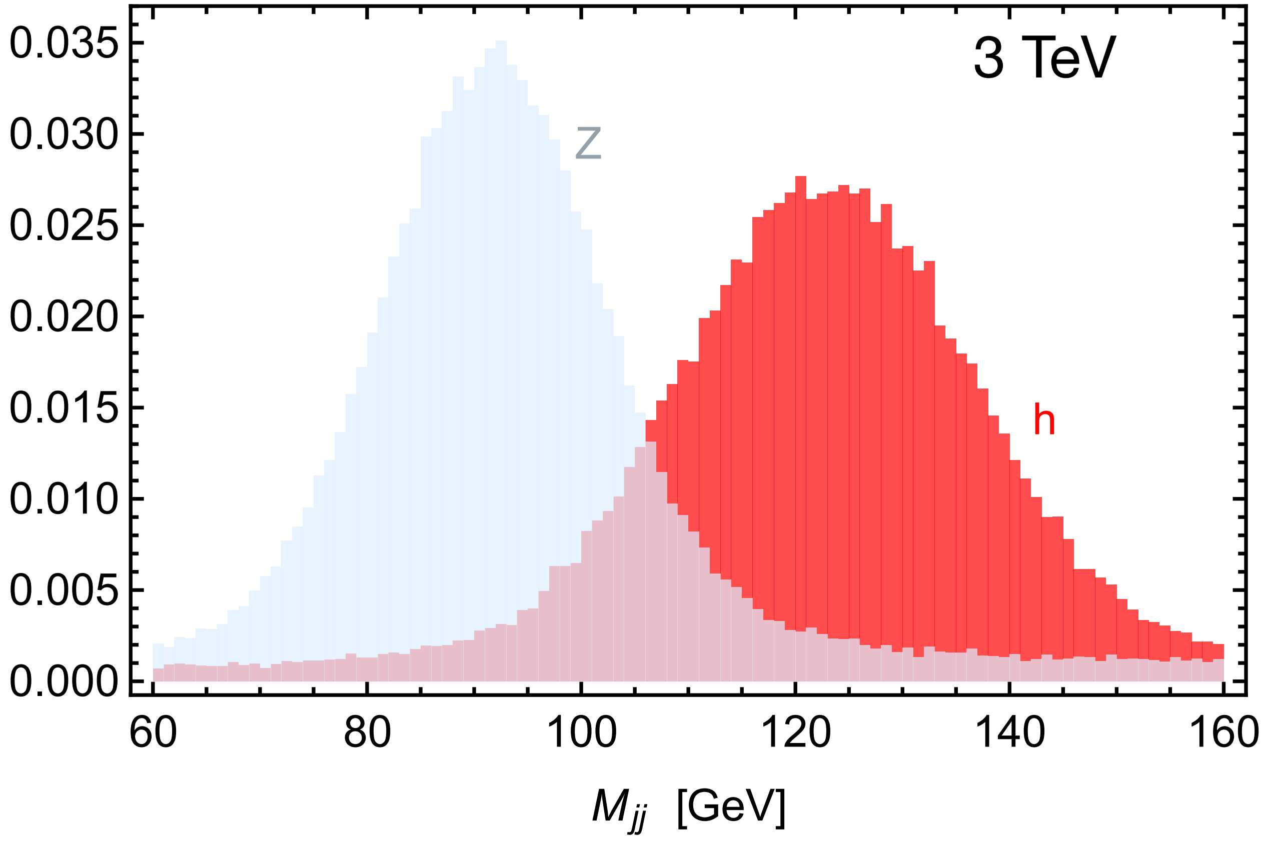
Eur. Phys. J. C (2018) 78:144

what happens at muon collider?

Backgrounds

(Very!) simplified background analysis *(at parton level!)*

- Include all VV → VV processes (Zhνν, ZZνν, WWνν, Whν, WZν)
- Apply gaussian smearing to jets, assuming 15% energy resolution
- Reconstruct bosons by pairing jets with minimal $|m(j_1 j_2) - m(j_3 j_4)|$



- Optimize cuts to reject bkg: dijet inv. mass, n. of b-tags

$M_{hh} > 105$ GeV,

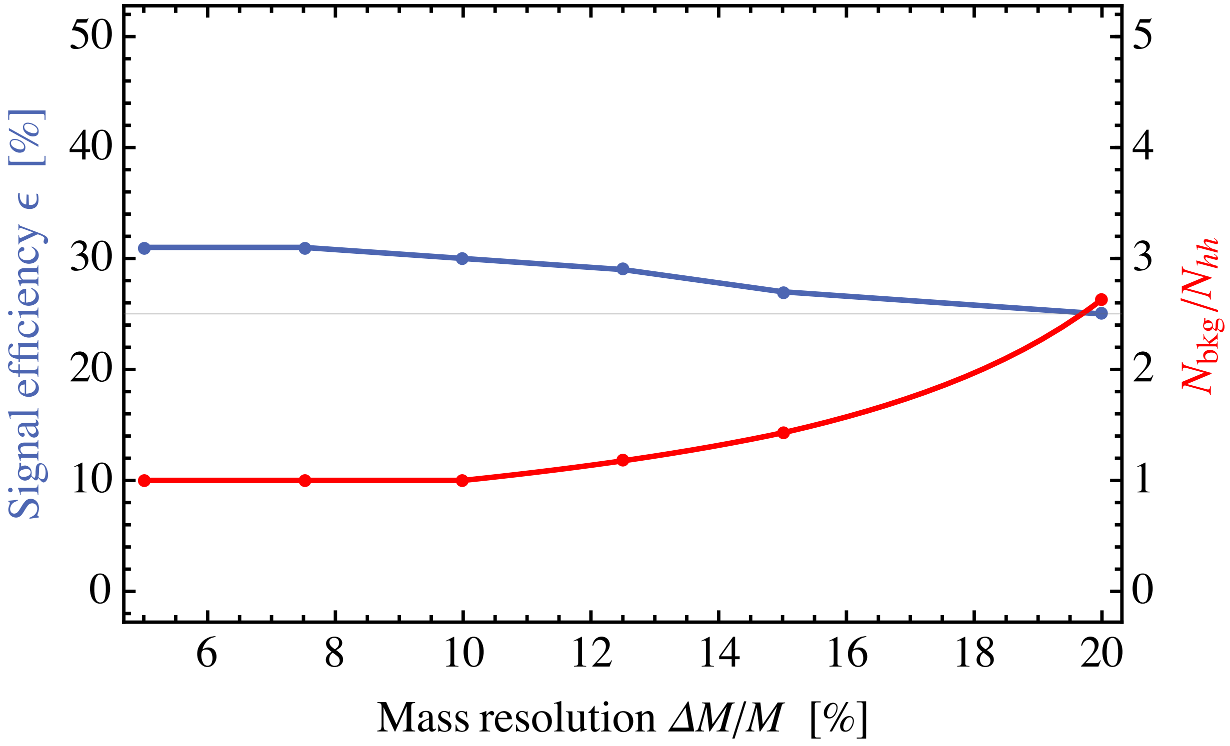
$n_b = 3.2$

$\varepsilon_{\text{sig}} = 27\%$

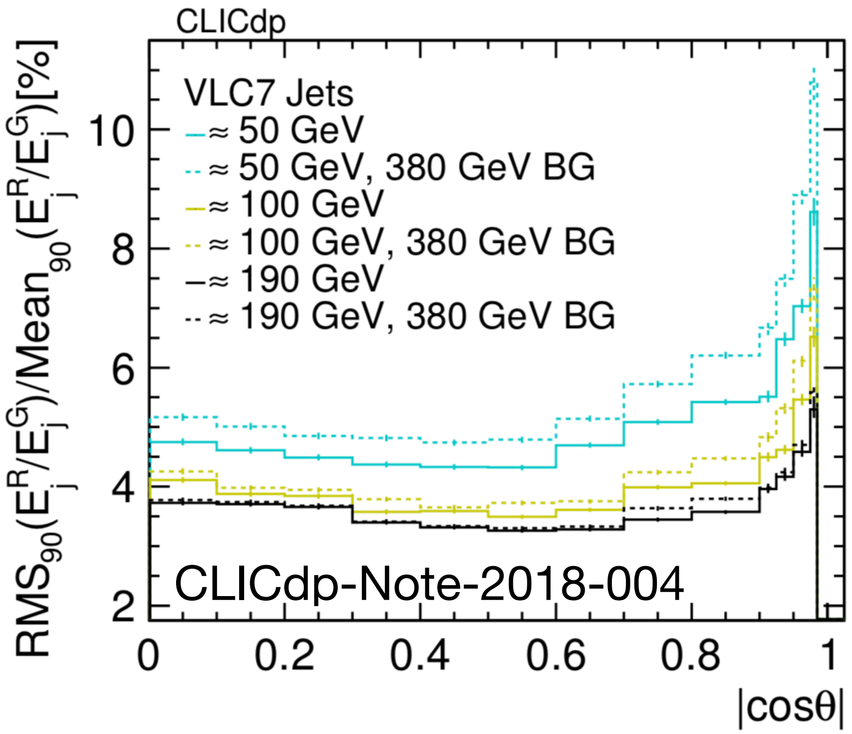
NB: all this should be done properly (and has been done, for CLIC), with a detector simulation

Backgrounds

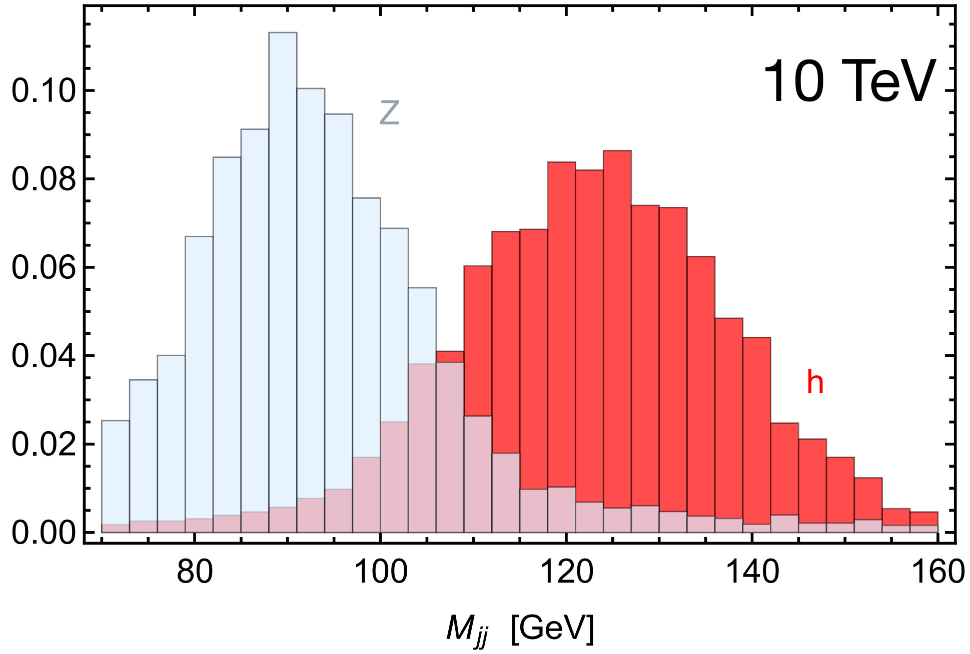
One can now repeat the analysis for different jet energy resolutions:



no real gain using only central events…



… and different energies:



- Optimize cuts to reject bkg:

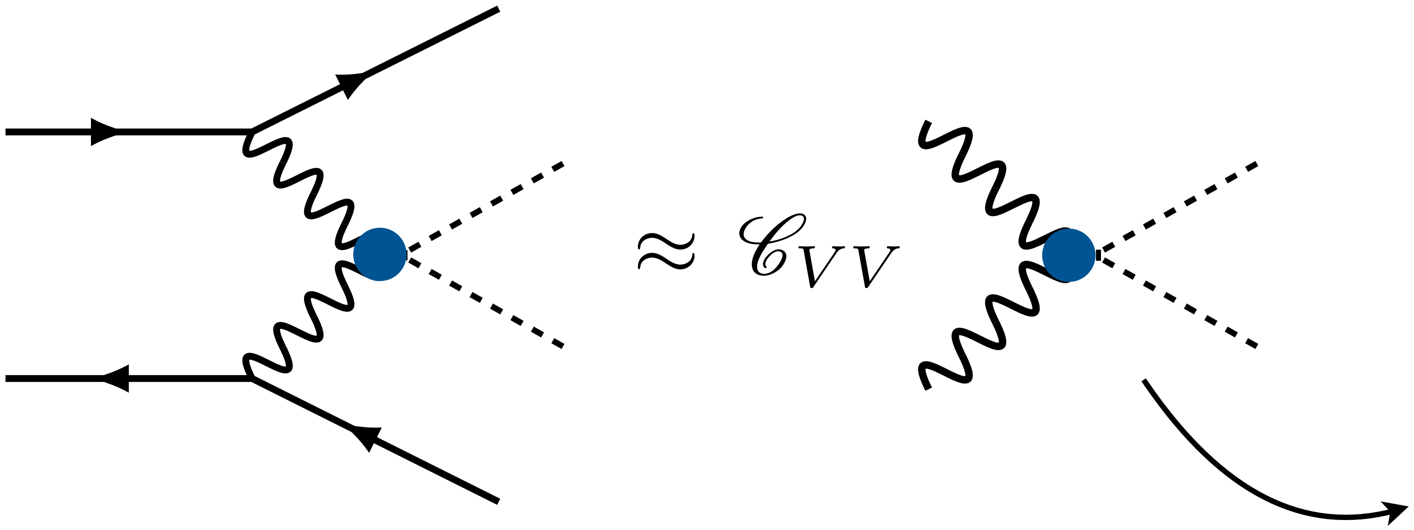
  $M_{hh} > 105$ GeV,

  $n_b = 2.8$

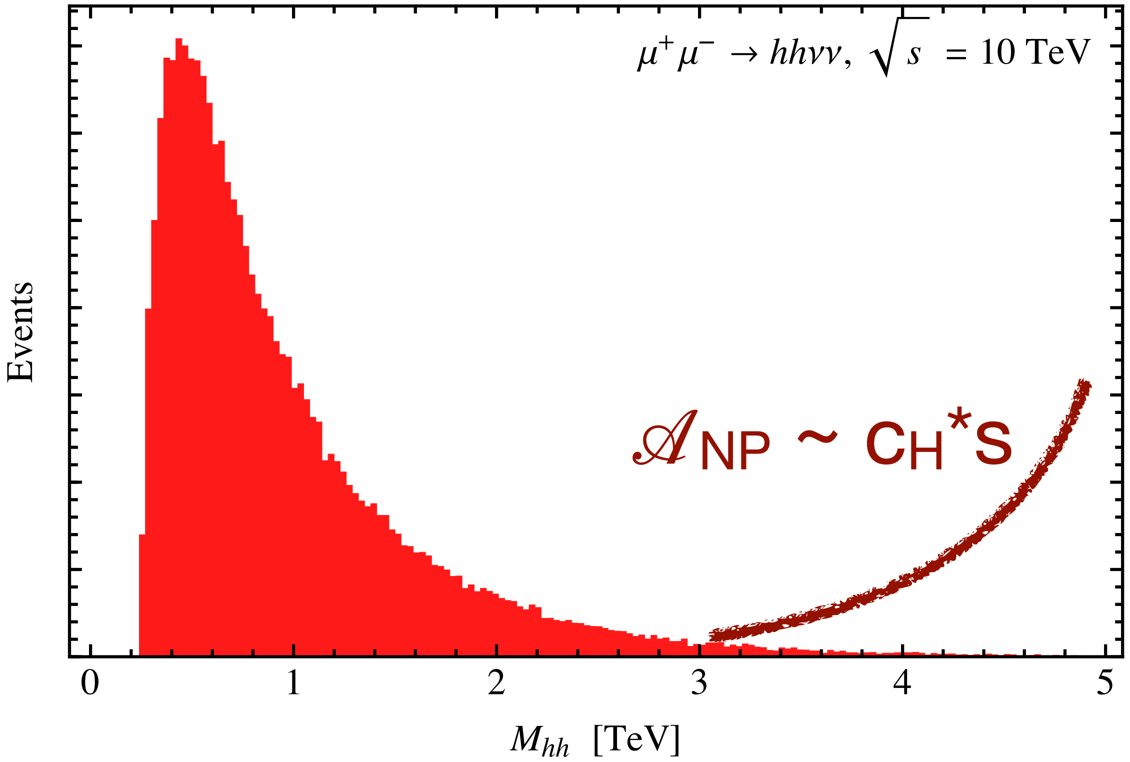
  $\varepsilon_{\rm sig} = 32\%$

result very similar to 3 TeV

Double Higgs at high mass



contribution from O_H grows with s



High invariant-mass tail gives a *direct* measurement of cH (*WWhh* coupling)

High energy *VV* → *hh* at 3 TeV CLIC:

$$\xi = c_H v^2 \lesssim 0.01$$

Contino et al. 1309.7038

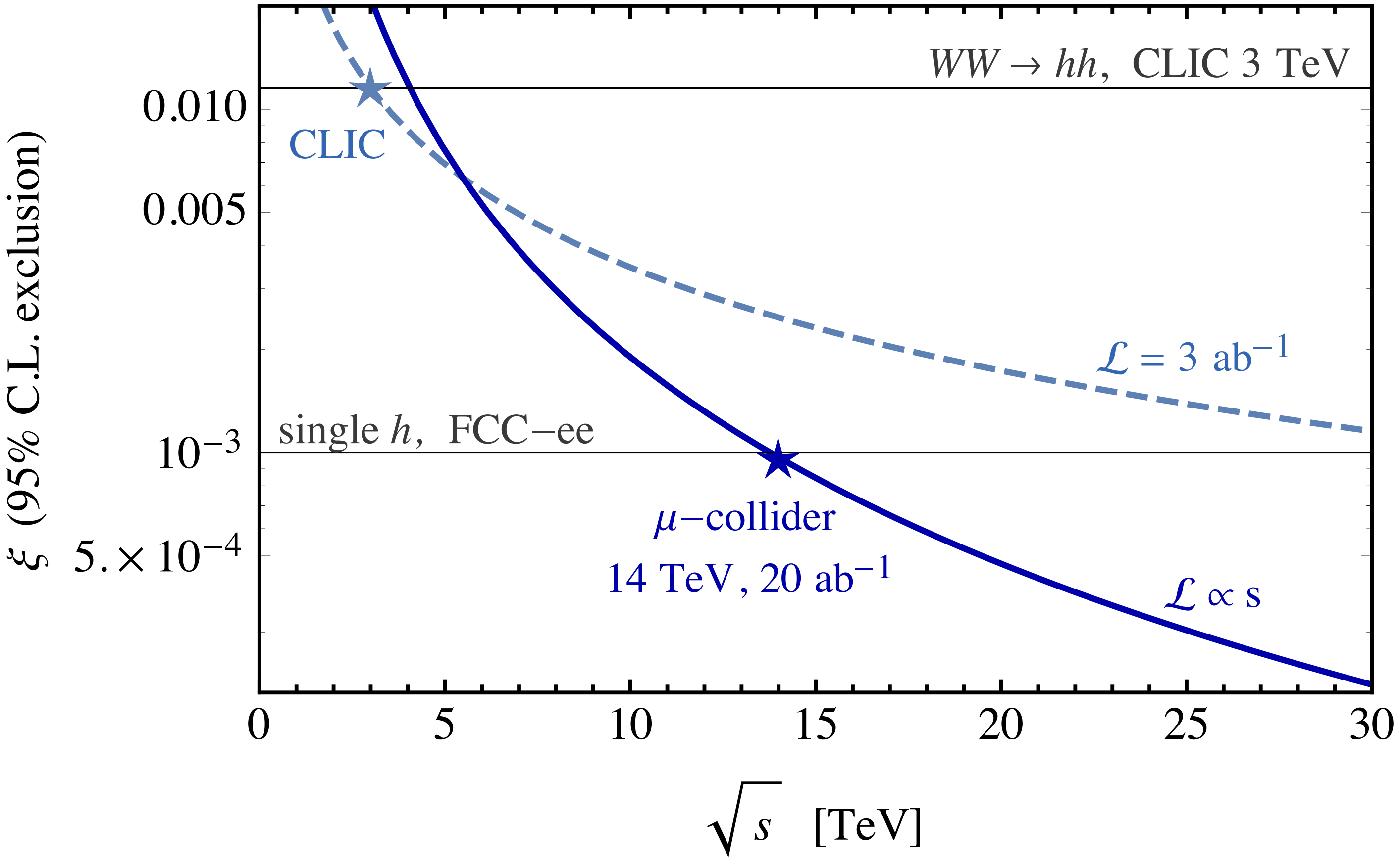
not able to compete with single Higgs, ξ ~ few*10^{-3}

hh at high mass

- E = 3 TeV, $\mathcal{L}$ = 3 ab^{-1}: $\xi = c_H v^2 \lesssim 0.01$ Contino et al. 1309.7038

- Rescale to higher energies: $\xi \propto \frac{1}{E^2}\frac{1}{\sqrt{N_{\rm bkg}}} \propto \frac{1}{E^2}\frac{1}{\sqrt{\mathcal{L}/E^2}} = \frac{1}{E\sqrt{\mathcal{L}}}$

  (assumption: cuts rescaled with E, and bkg composition unchanged)



High-energy WW → *hh* becomes more sensitive than Higgs pole physics at energies > 14 TeV

$\sqrt{s} = 14\,\mathrm{TeV},\ \mathcal{L} = 20\,\mathrm{fb}^{-1}$

$\xi < 10^{-3}$ $c_H^{-1/2} > 8\,\mathrm{TeV}$

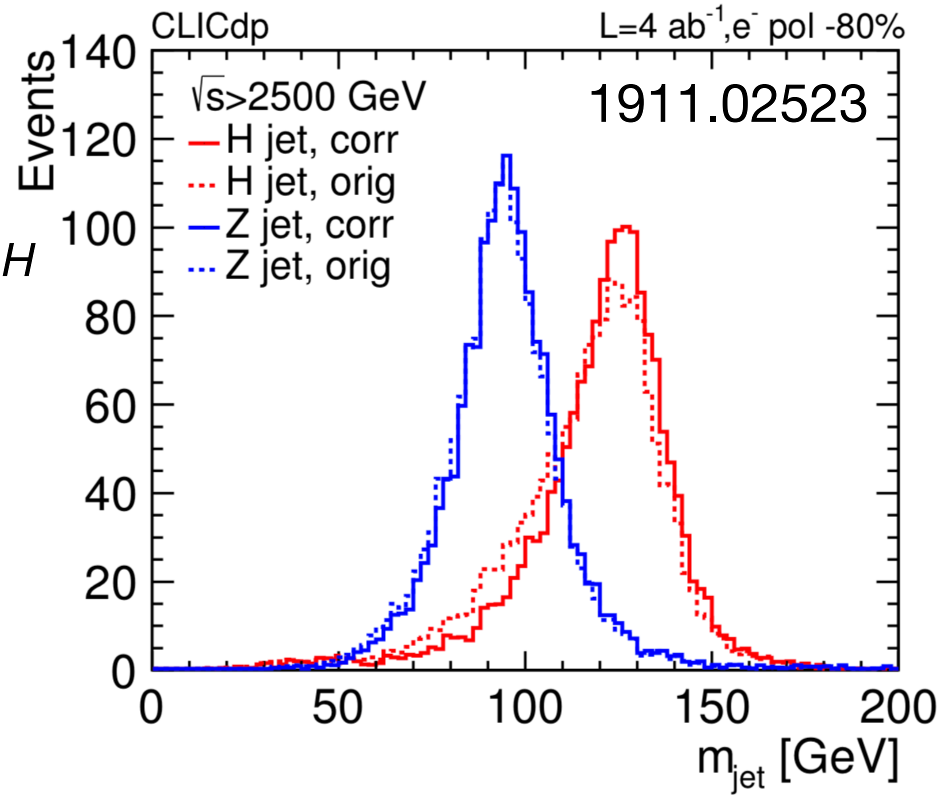
$\sqrt{s} = 30\,\mathrm{TeV},\ \mathcal{L} = 90\,\mathrm{fb}^{-1}$

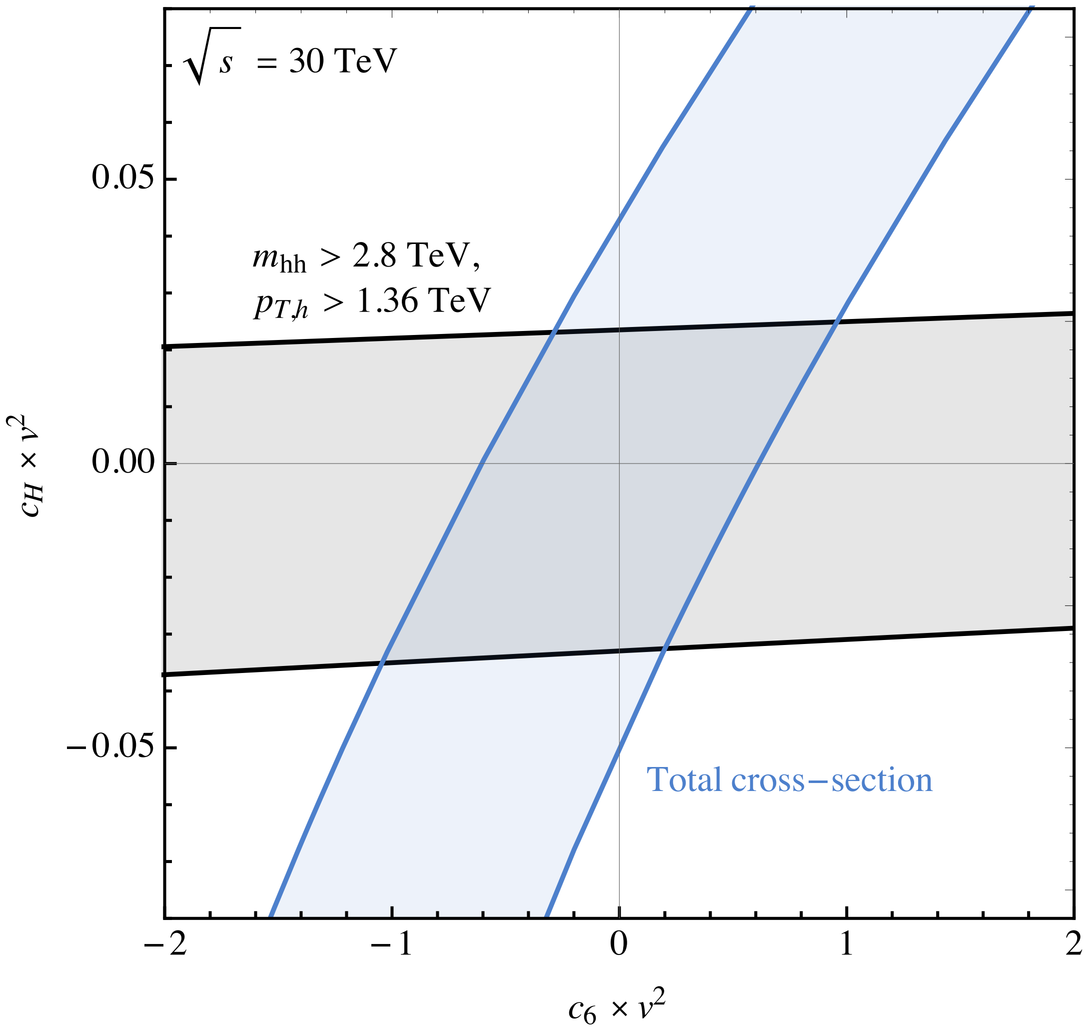
$\xi < 2 \times 10^{-4}$ $c_H^{-1/2} > 17\,\mathrm{TeV}$

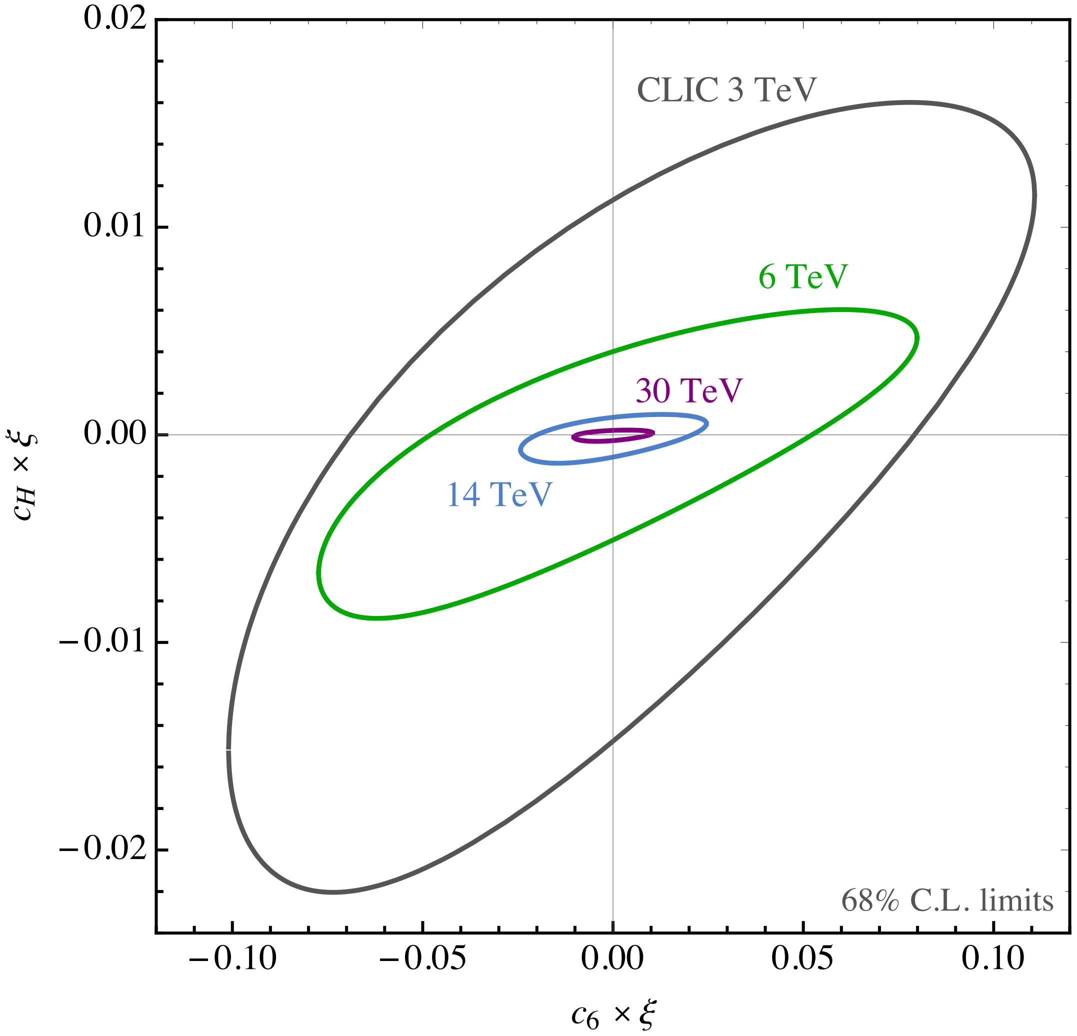
hh at high mass

- Simulate hh events in high-p_T / high-mass region
- Choose p_T and M_{hh} cuts to optimize sensitivity to c_H
- Very boosted Higgses: tag them as a single h-jet, without reconstructing the 4 b's.

We assume a boosted-H tagging efficiency ~ 50%







More details on the *hh*(4*b*) 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%
$\lvert\cos\theta\rvert < 0.94$	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%
$\lvert\cos\theta\rvert < 0.95$	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

WW fusion

- Single and double production cross-sections:

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

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

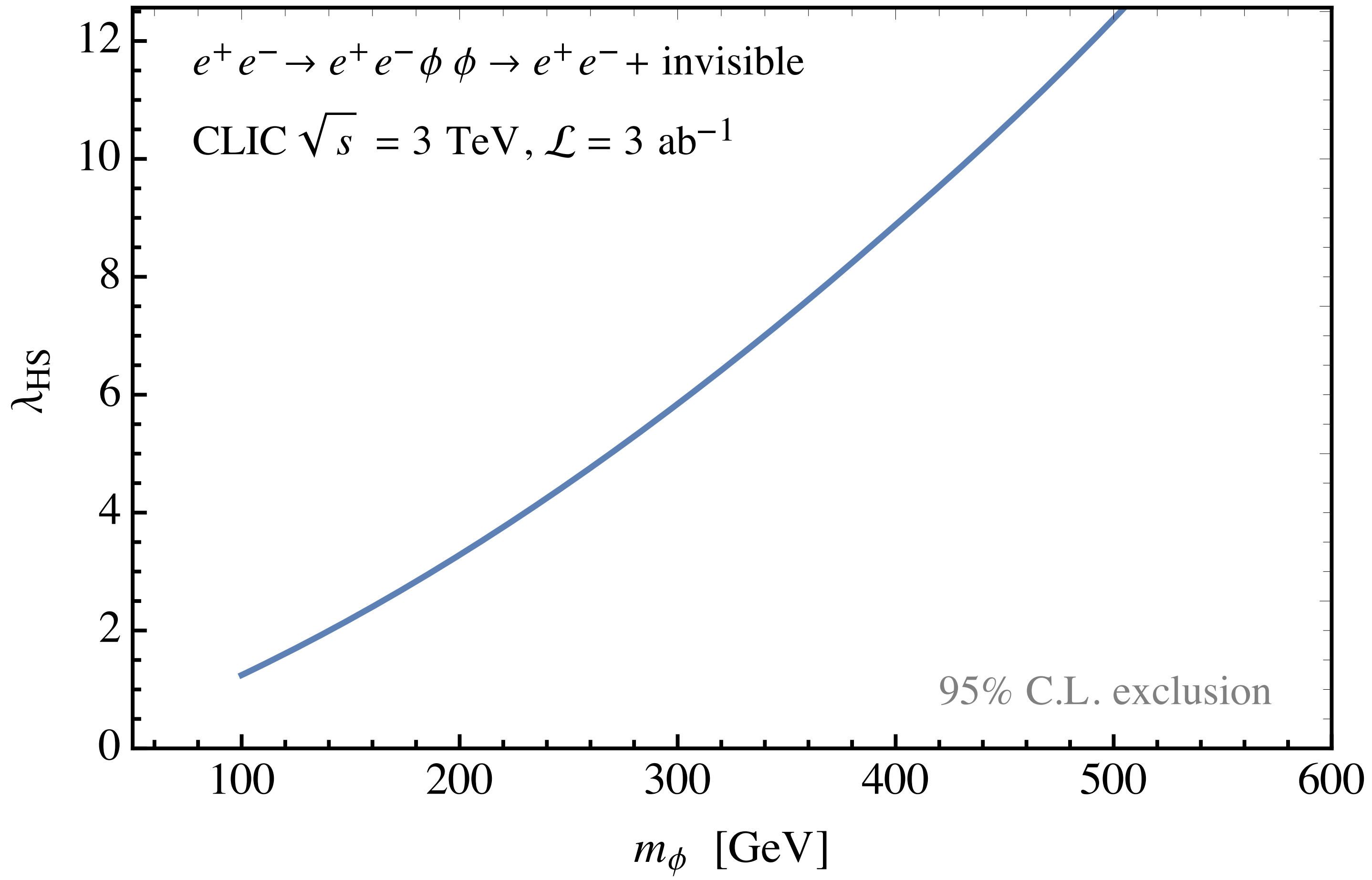
from W-pdf's $$\frac{d\sigma}{d\hat{s}} = \frac{\hat{\sigma}_{V_iV_j\to X}(\hat{s})}{s}\,\mathscr{C}_{V_iV_j}(\hat{s}), \quad \text{with} \quad \mathscr{C}_{V_iV_j}(\hat{s}) = \int_{\hat{s}/s}^{1}\frac{dx}{x}f_{V_i}(x)f_{V_j}(\frac{\hat{s}x}{s})$$

- Approximate limit on mixing angle:

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

Invisible singlet

- Double production of singlet in Z-fusion, singlet decays invisibly



cuts on missing mass
and e+e- invariant mass