Double Higgs production at a muon collider: energy *and* precision

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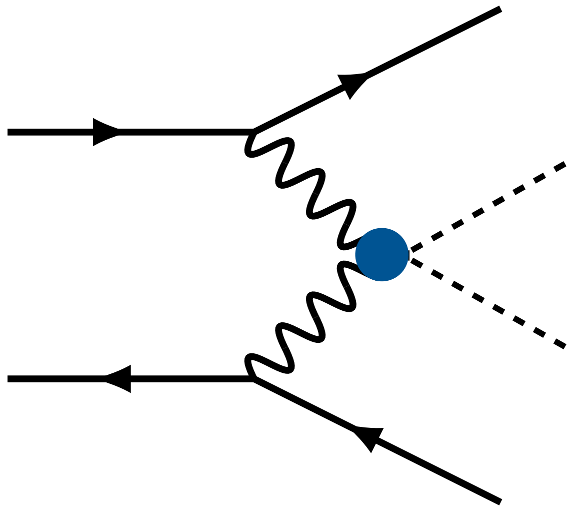
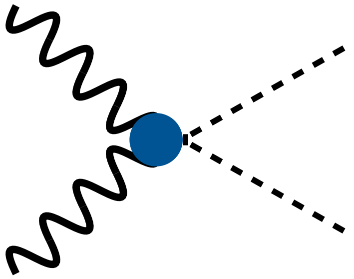
Double Higgs production



$\approx \mathscr{C}_{VV}$



A High Energy Lepton Collider is a “vector boson collider”

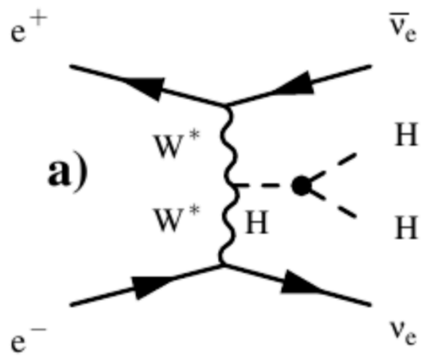
$$\mathscr{C}_{VV} \approx \frac{s}{\hat{s}} \log \frac{s}{\hat{s}}$$

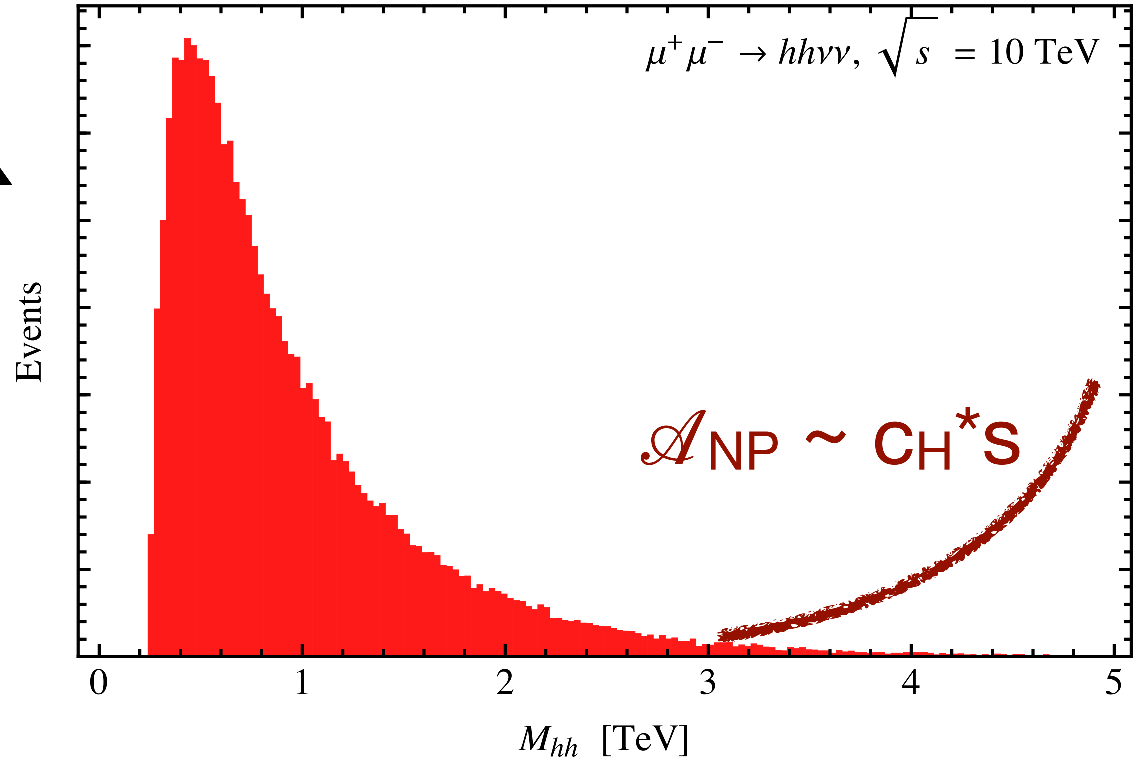
Dawson, 1984

For “soft” final state $\hat{s} \sim 4m_h^2$, cross-section is enhanced as

$$\sigma \approx \log(s/m_h^2)$$

For high partonic energies $\hat{s} \gg m_h^2$ amplitude for longitudinal W scattering grows as $\mathcal{A} \sim \hat{s}$





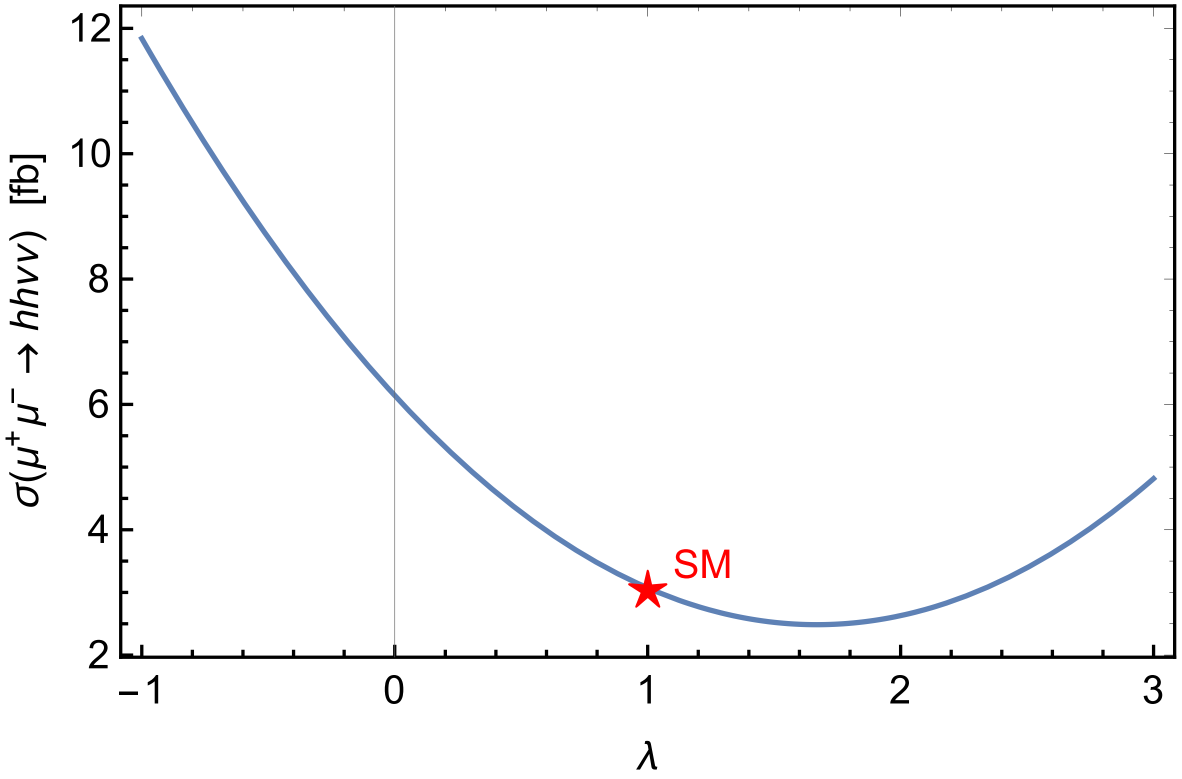
Double Higgs production

Number of events: N ~ s log(s/m_h^2)

assume overall efficiency ~ 10%

Naïve estimate of the reach:

$\sqrt{s}$ [TeV]	L [ab^{-1}]	σ [fb]	N_{SM}	$\delta\sigma \sim (N_{SM} * \mathrm{eff})^{-1/2}$	$\delta\lambda$
3	1	0.82	800	~ 10%	~ 15%
10	10	3.1	31'000	~ 1.8%	~ 4%
14	20	4.4	88'000	~ 1%	~ 3%
30	90	7.4	660'000	~ 0.4%	~ 1.5%



Cross-section dependence on δλ

$$\sigma = \sigma_{\rm SM} + a_1(\delta\lambda) + a_2(\delta\lambda)^2$$

hh → 4*b* signal

- **Acceptance cuts** in polar angle θ and p_T of b-jets.

  E.g. for pT > 10 GeV, $\theta > 10^o$:

$$\begin{aligned}\sigma_{\rm cut}(3\,{\rm TeV}) &= 0.13\left[1-0.87(\delta\lambda)+0.74(\delta\lambda)^2\right]\ {\rm fb},\\ \sigma_{\rm cut}(10\,{\rm TeV}) &= 0.24\left[1-0.81(\delta\lambda)+0.71(\delta\lambda)^2\right]\ {\rm fb},\\ \sigma_{\rm cut}(30\,{\rm TeV}) &= 0.27\left[1-0.79(\delta\lambda)+0.78(\delta\lambda)^2\right]\ {\rm fb}.\end{aligned}$$

BR(*hh* → 4*b*) = 34%

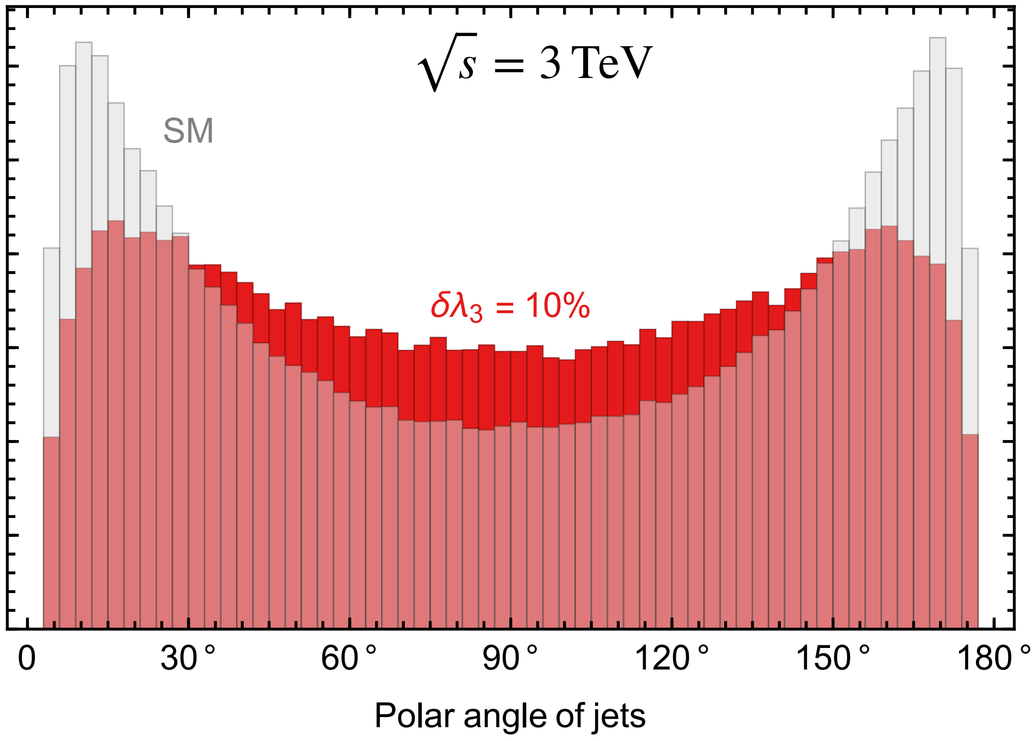
factor 10 loss
in xsec at 30 TeV

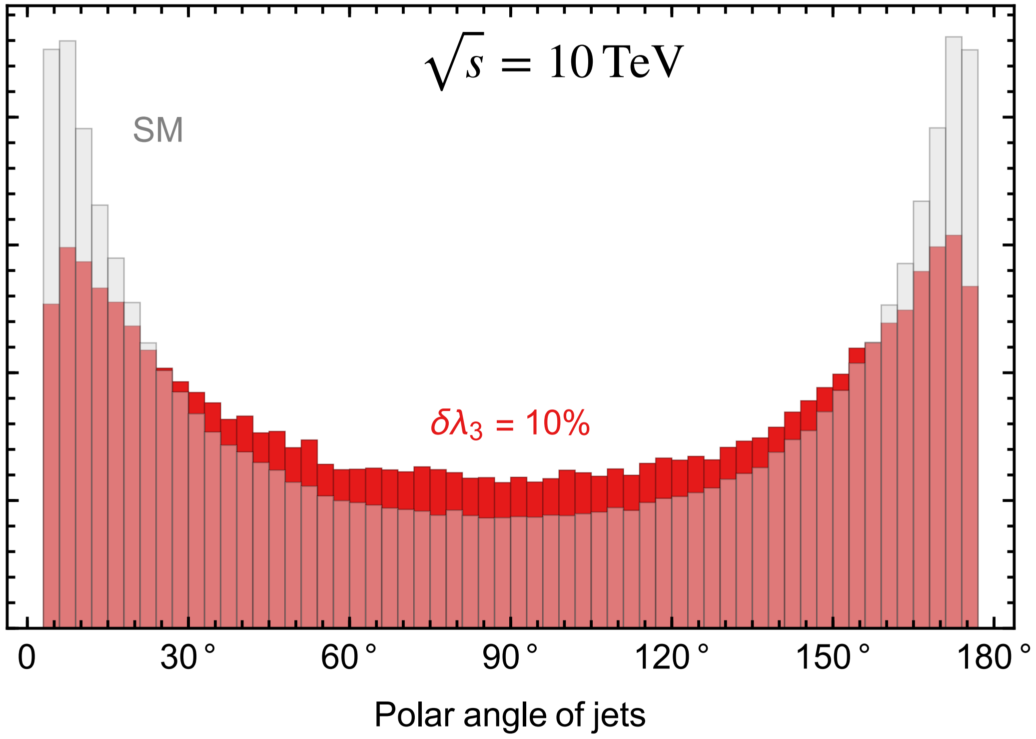
- **Neglect backgrounds** (for the moment)

- Assume signal **reconstruction efficiency** ε ~ 25% as CLIC [1901.05897]: mainly from invariant-mass cuts and b-tag

$\sqrt{s}$ [TeV]	L [ab^{-1}]	σ [fb]	N$_{\rm rec}$	$\delta\sigma \sim N_{\rm rec}^{-1/2}$	$\delta\lambda$
3	5	0.13	170	~ 7.5%	~ 10%
10	10	0.24	630	~ 4%	~ 5%
30	90	0.74	6'300	~ 1.2%	~ 1.5%

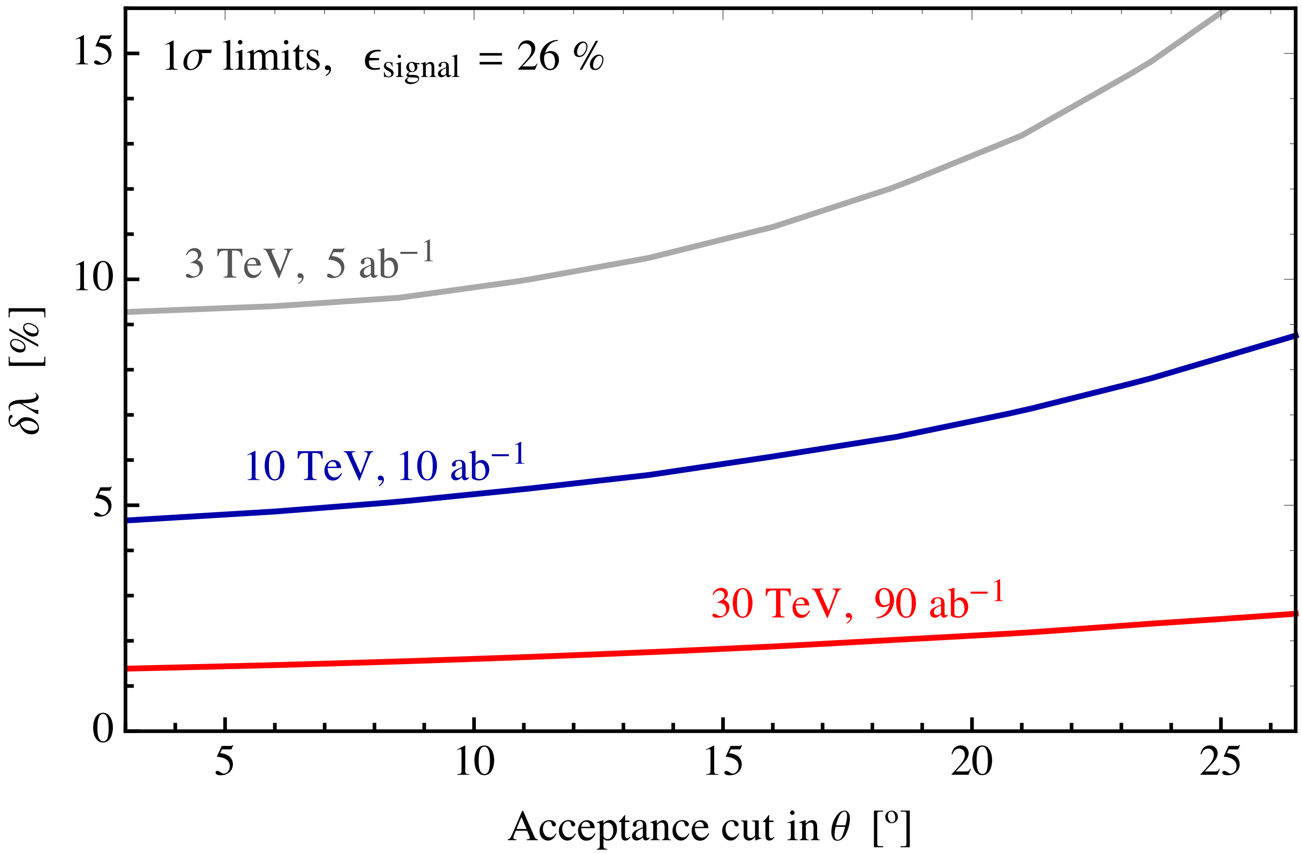
Sensitivity to angular acceptance





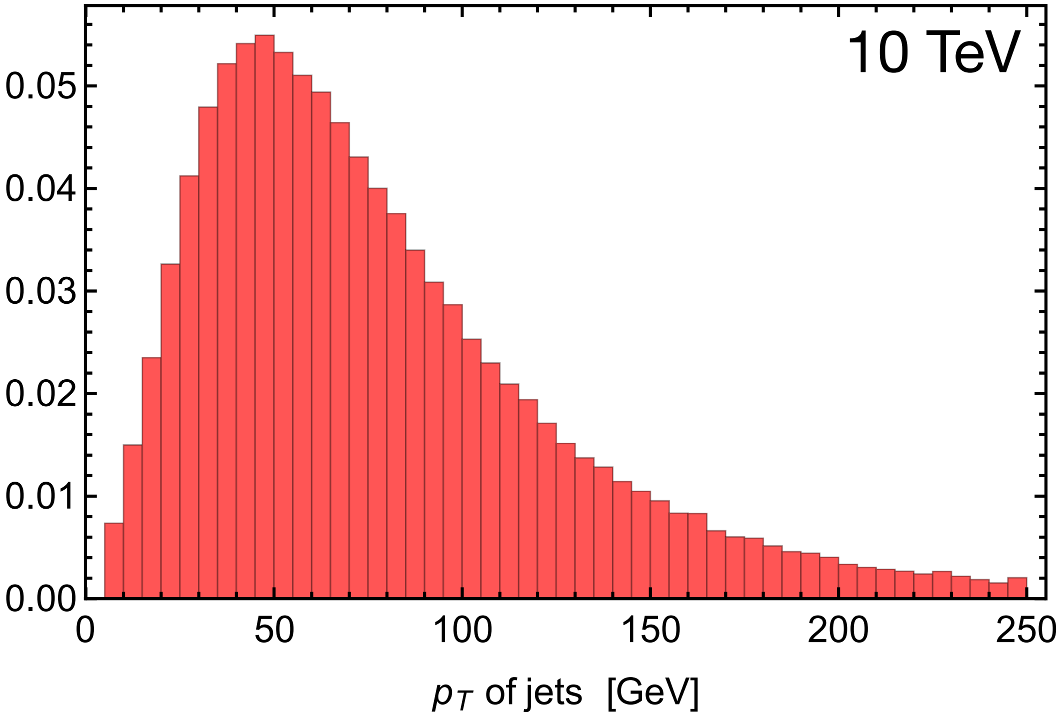
- *hh* signal is strongly peaked in the forward region

- Contribution from trilinear coupling is more central: loss due to angular cut is less important



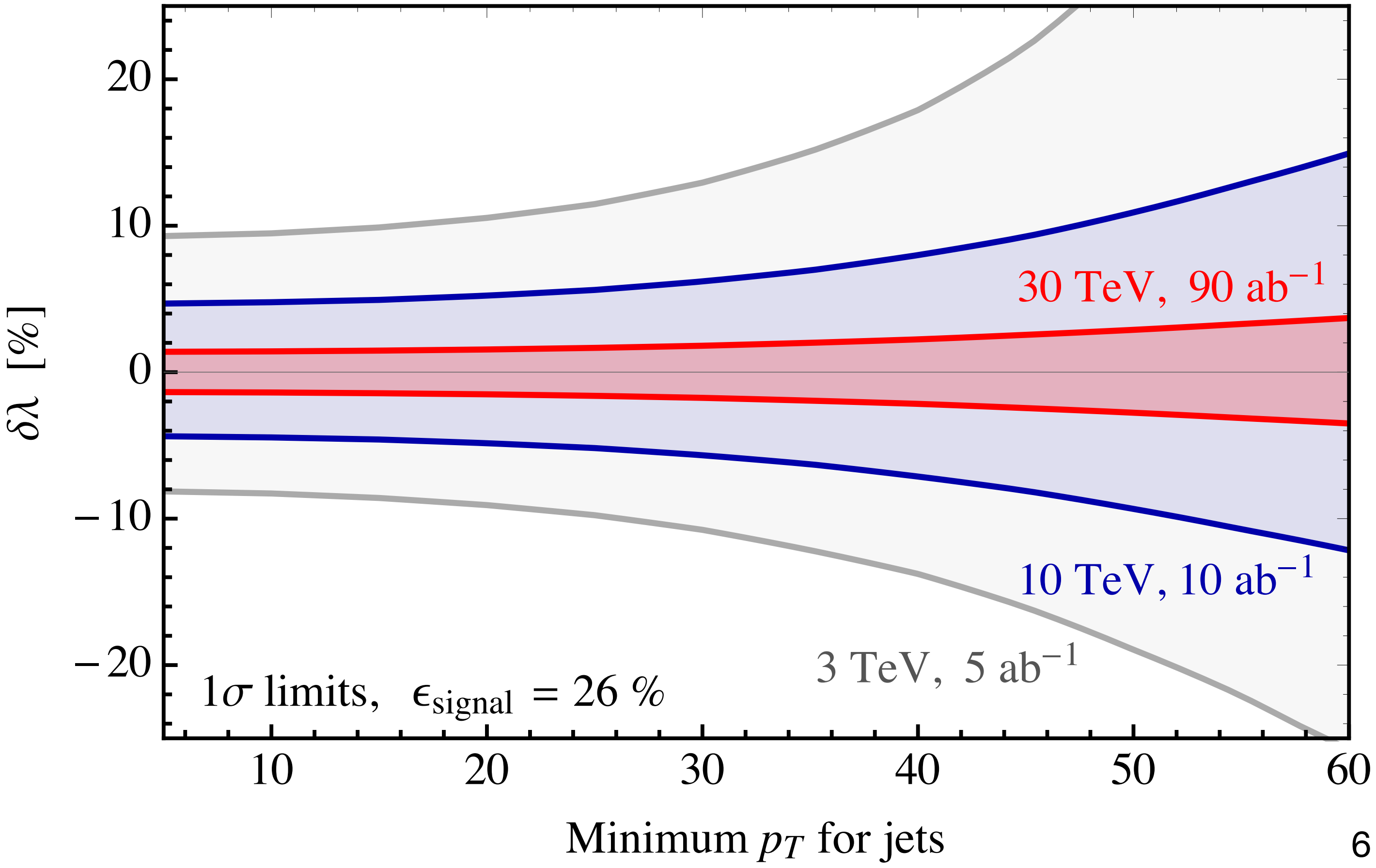
Sensitivity to jet p_T threshold

- Jets come from Higgs decays: typical momentum ~ $m_h/2$



- No significant impact if $pT_{min} \lesssim$ 40–50 GeV

  higher thresholds start to reduce the sensitivity



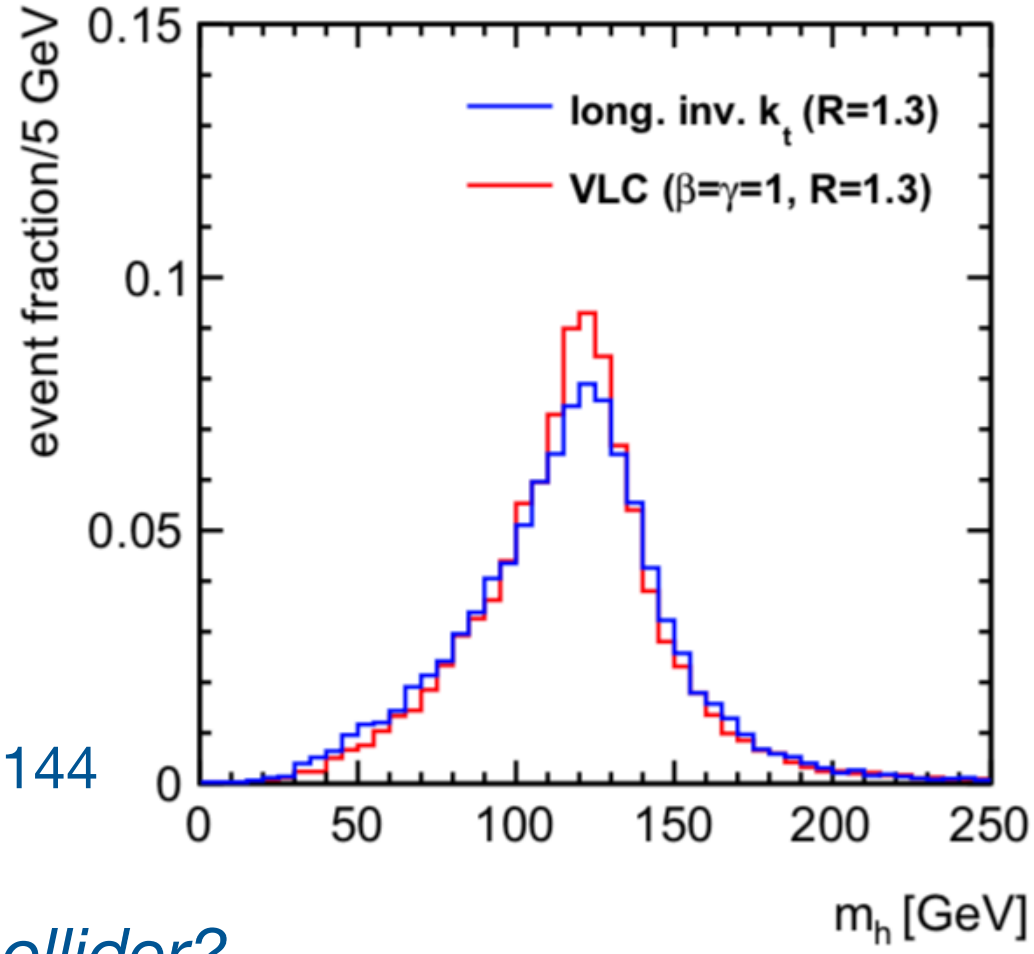
Backgrounds

- 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

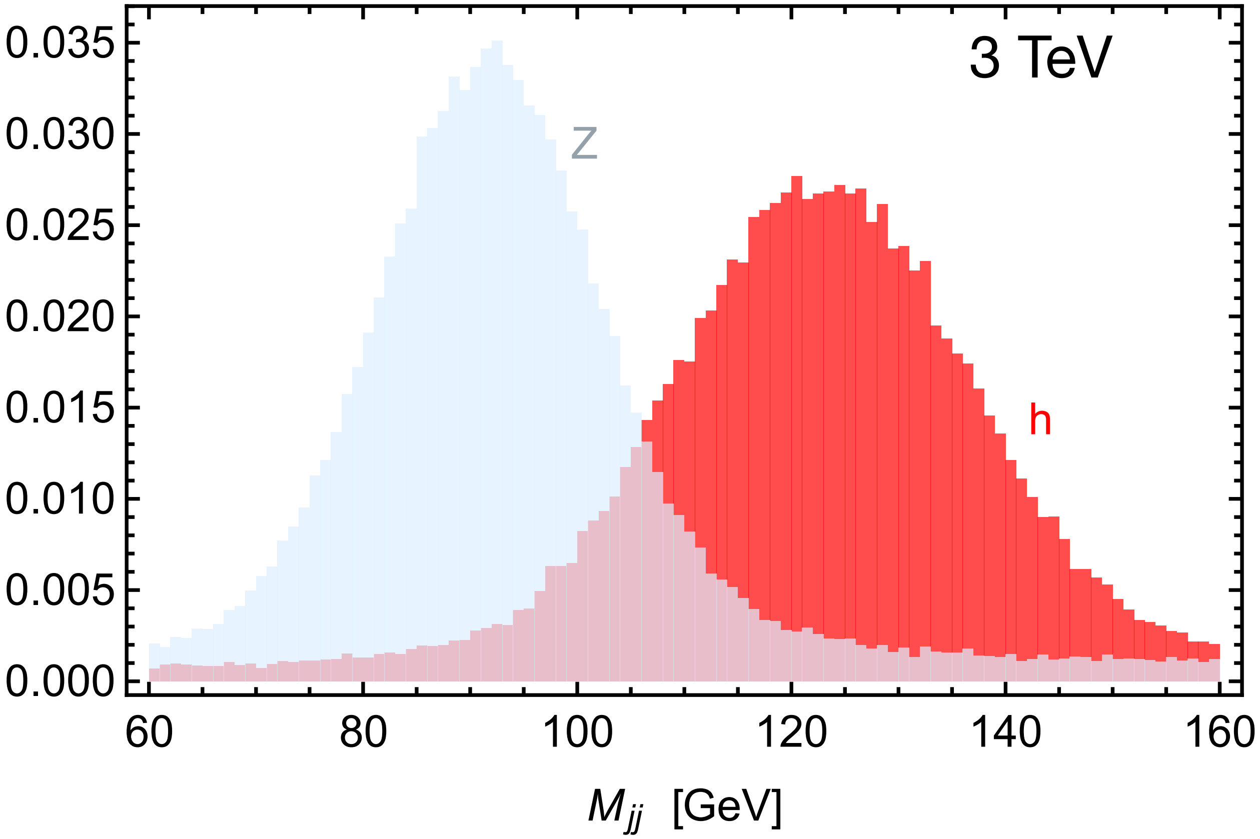
Eur. Phys. J. C (2018) 78:144

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,

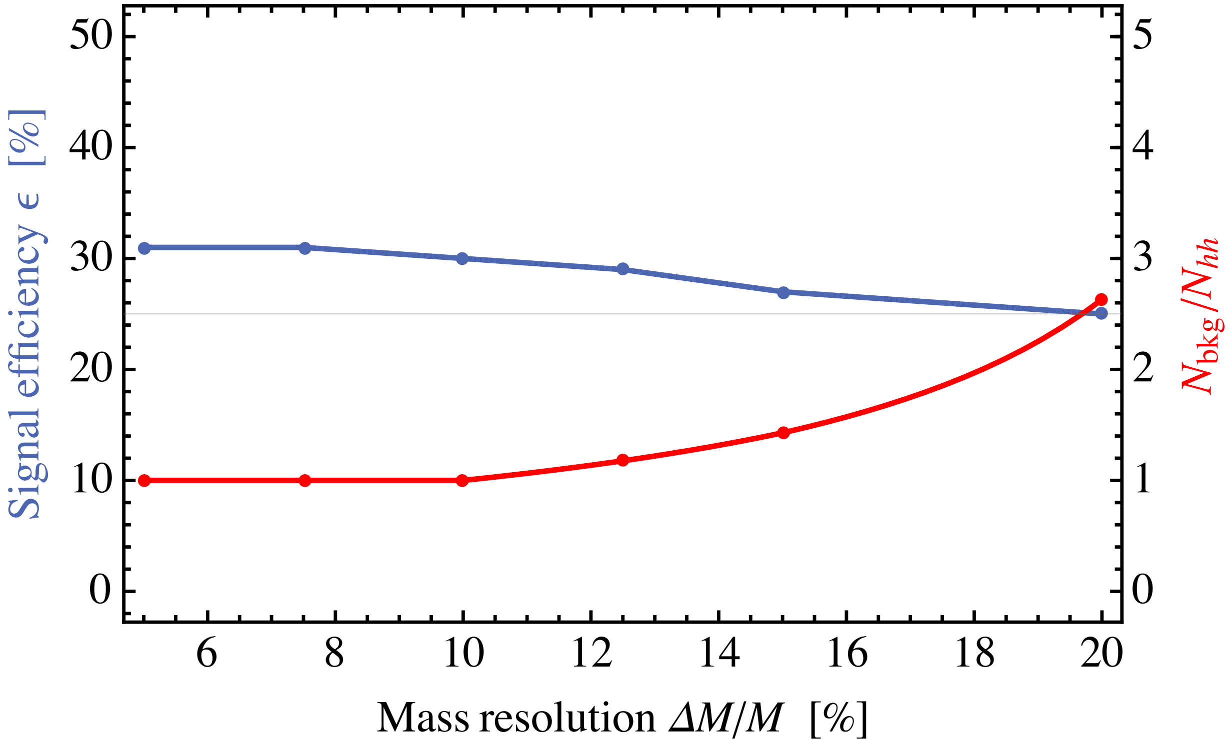
  $n_b = 3.2$

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

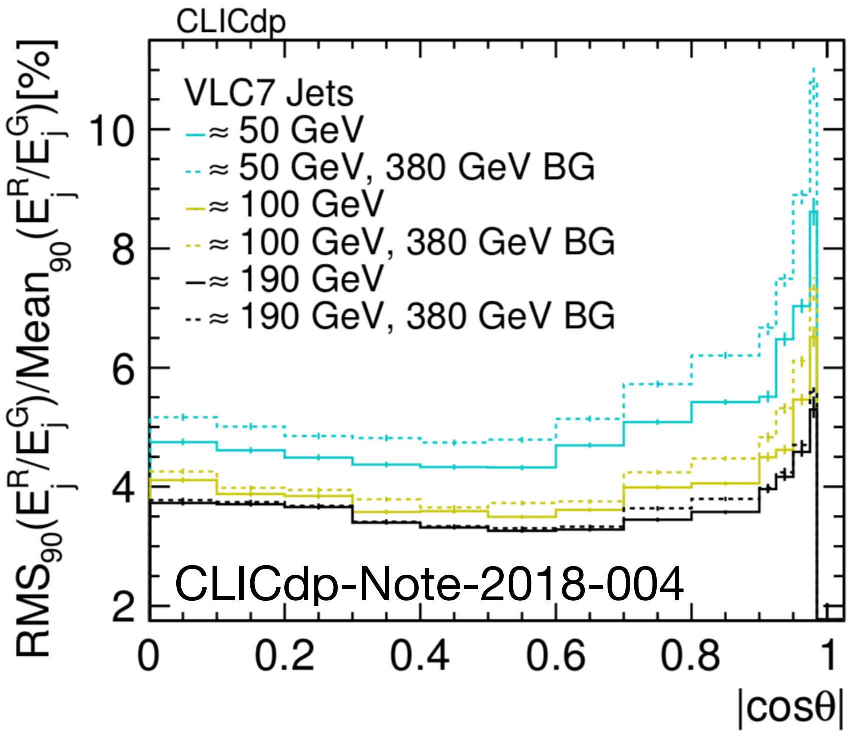
NB: all this should be done properly (and has been done, for CLIC), with a detector simulation

Backgrounds

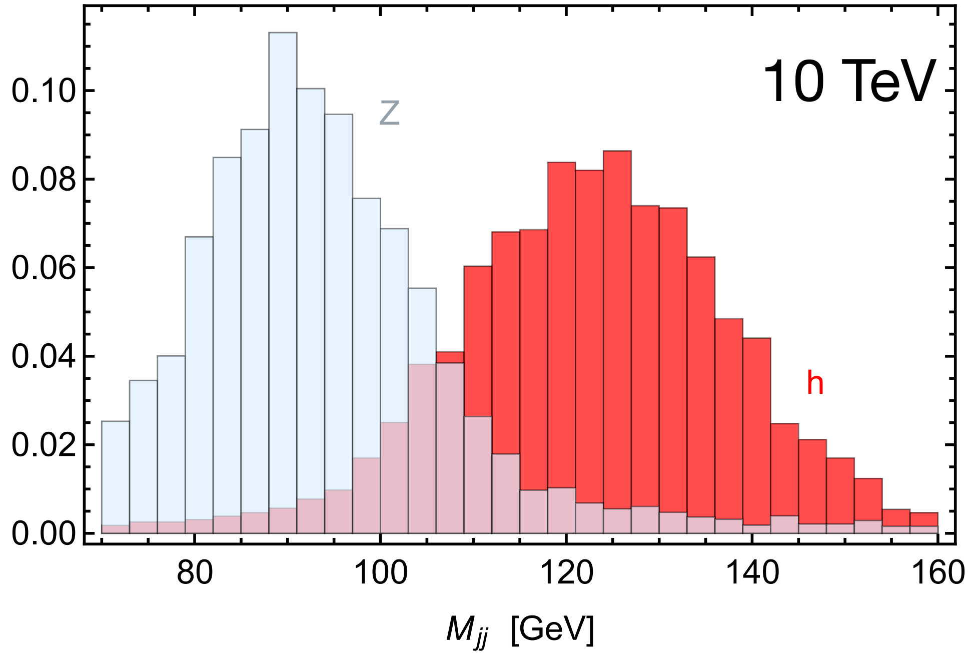
One can now repeat the analysis for different jet energy resolutions:



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

Two-parameter fit

- *hhh* coupling is affected by two operators in SMEFT:

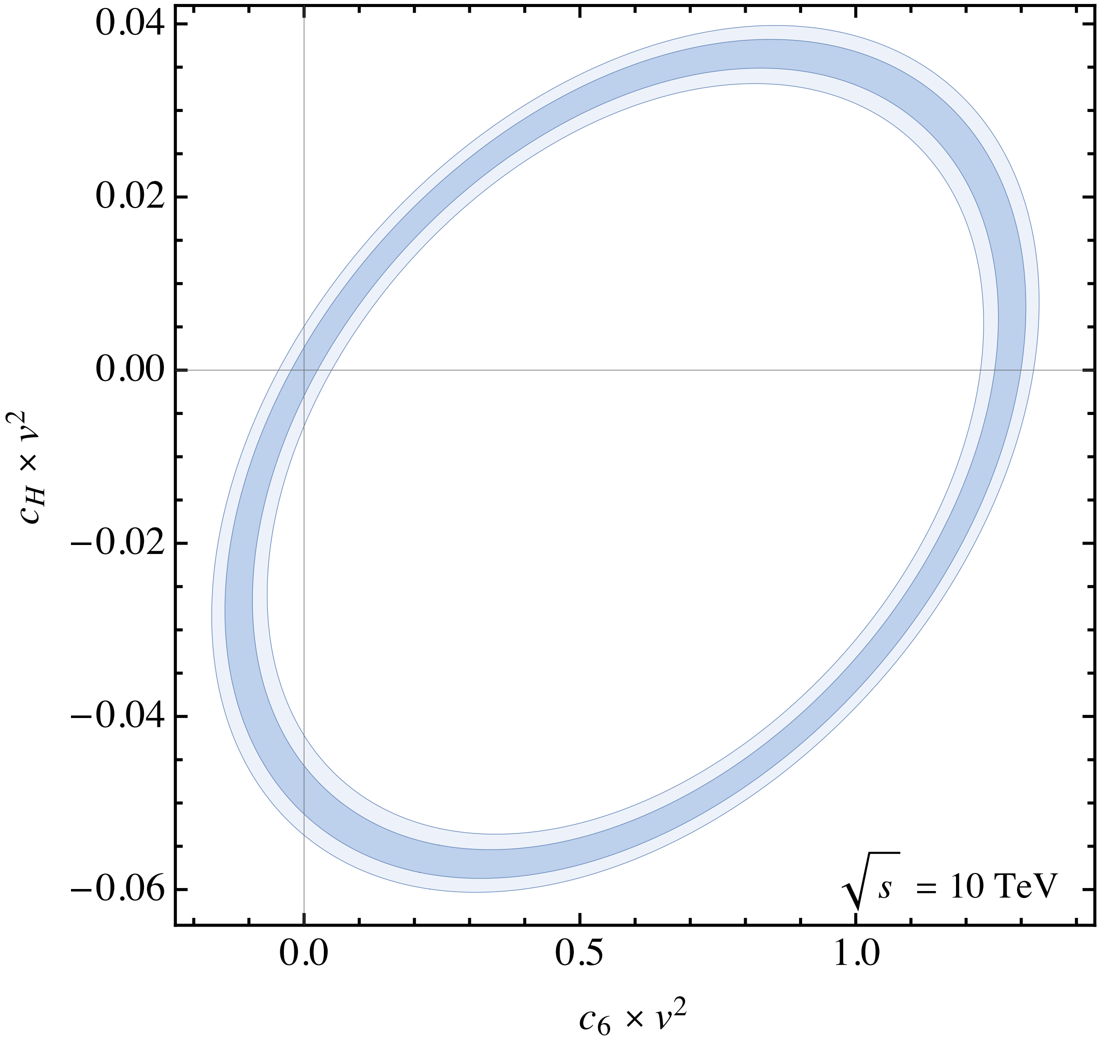
$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \qquad \mathcal{O}_6 = -\lambda |H|^6$$

$$g_{hhh} = g_{hhh}^{\mathrm{SM}}\left(1 + v^2\left(c_6 - \frac{3}{2}c_H\right)\right)$$

trilinear coupling

$$g_{hWW} = g_{hWW}^{\mathrm{SM}}\left(1 - v^2\frac{c_H}{2}\right)$$

O_H also affects single Higgs couplings universally



$$\sigma = \sigma_{\mathrm{SM}} + a_1 c_6 + a_2 c_6^2 + b_1 c_H + b_2 c_H^2 + d_2 c_H c_6$$

large degeneracy: coefficients not determined in general

Two-parameter fit

- *hhh* coupling is affected by two operators in SMEFT:

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \qquad \mathcal{O}_6 = -\lambda |H|^6$$

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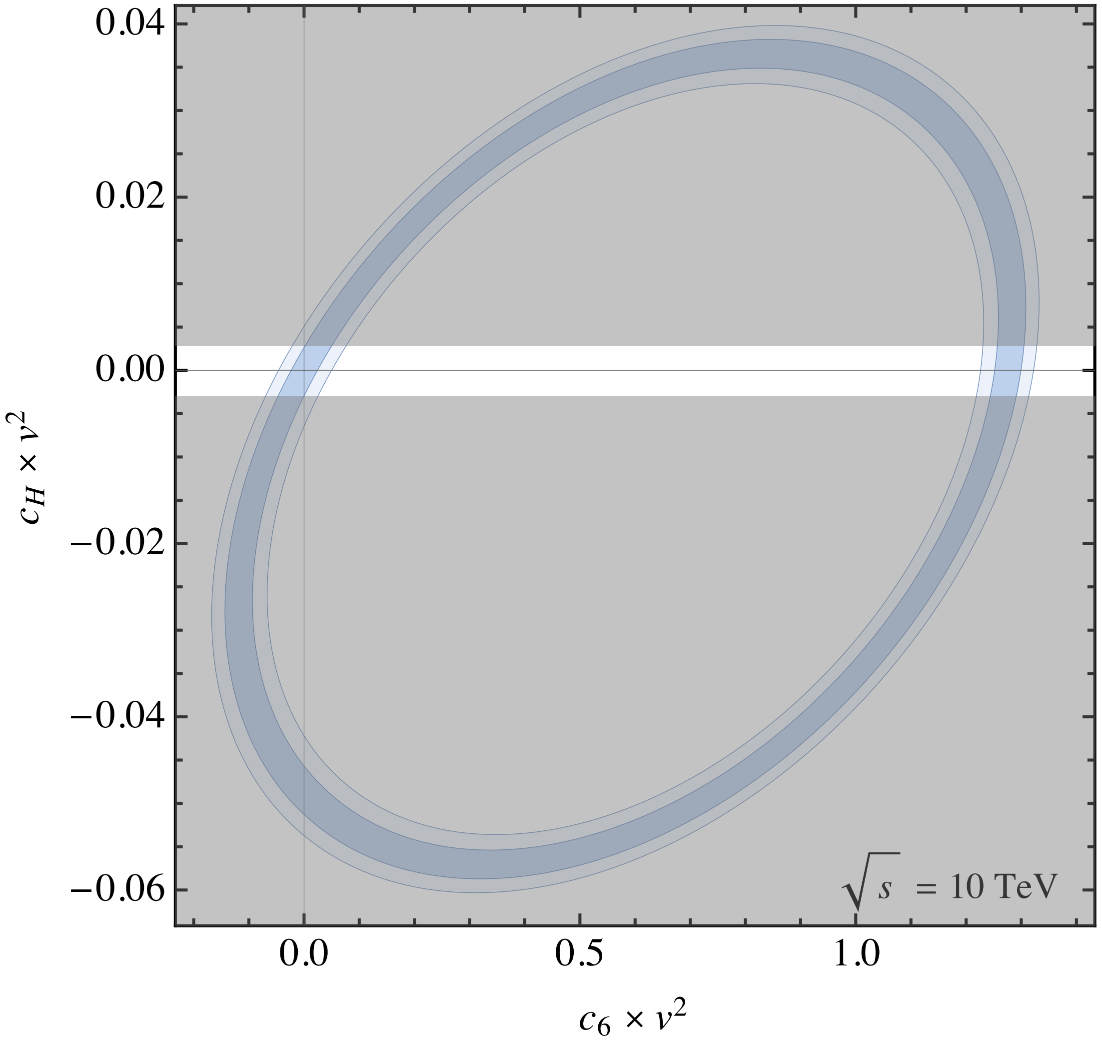
O$_H$ also affects single Higgs couplings universally



$$\sigma = \sigma_{\mathrm{SM}} + a_1 c_6 + a_2 c_6^2 + b_1 c_H + b_2 c_H^2 + d_2 c_H c_6$$

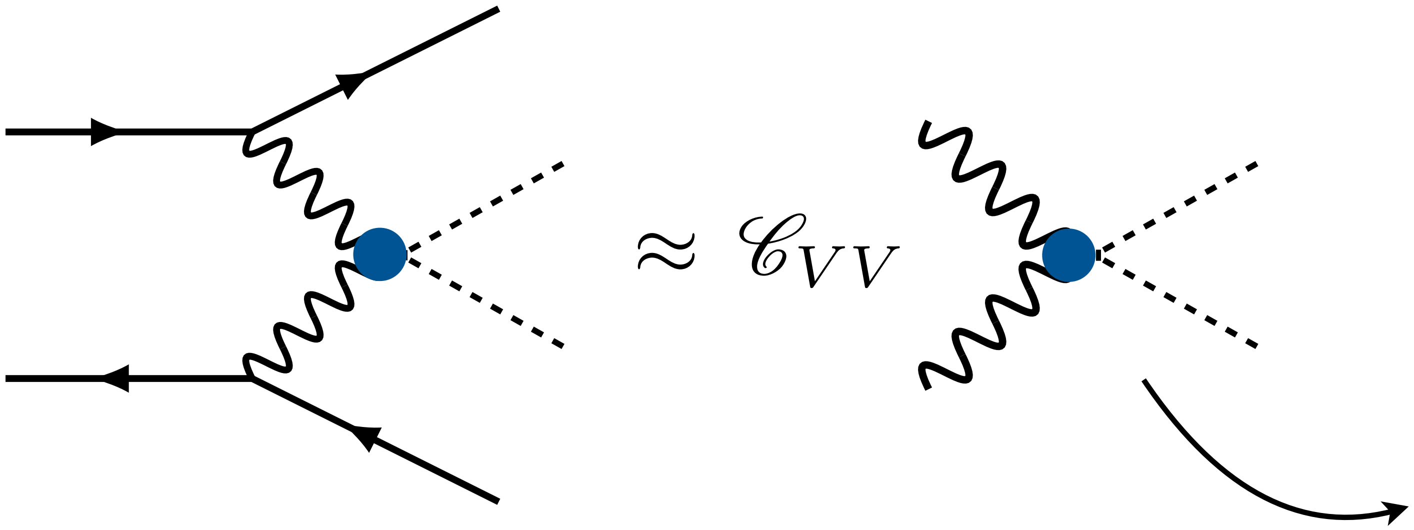
large degeneracy: coefficients not determined in general

c$_H$ can be constrained from Higgs couplings

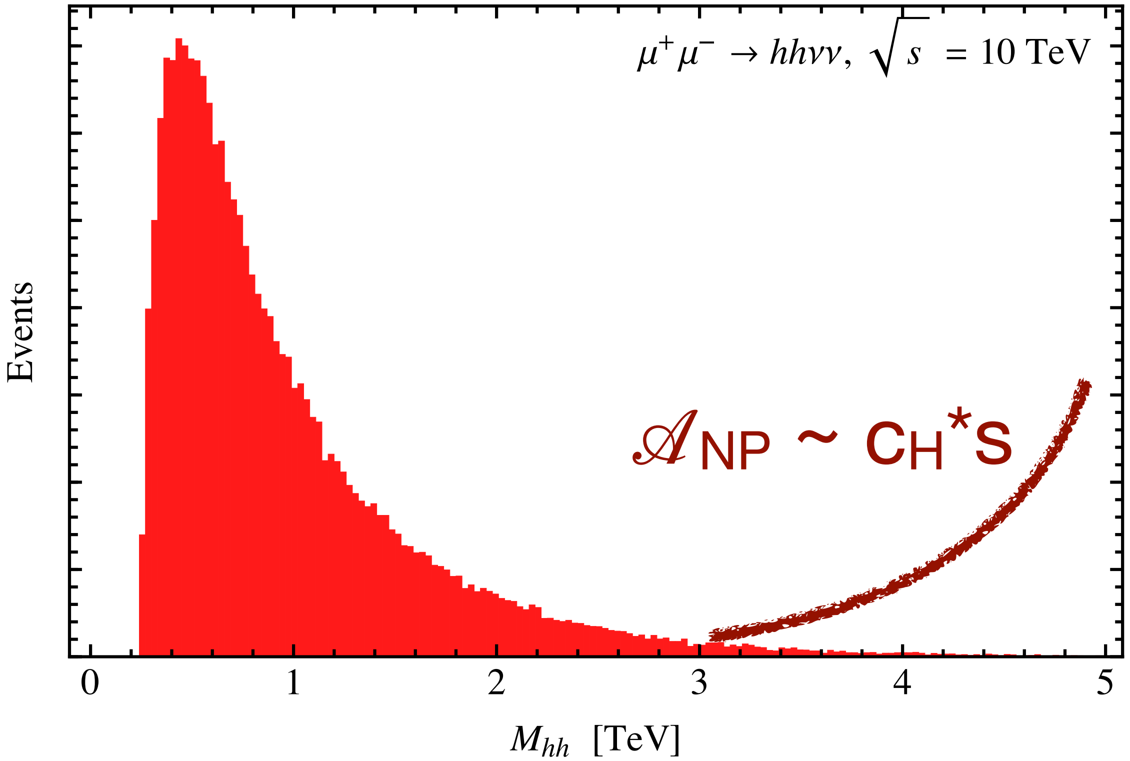
(but indirect measurement)

$$\Delta g_{hWW} \propto v^2/f^2 \lesssim 10^{-3}$$

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:

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

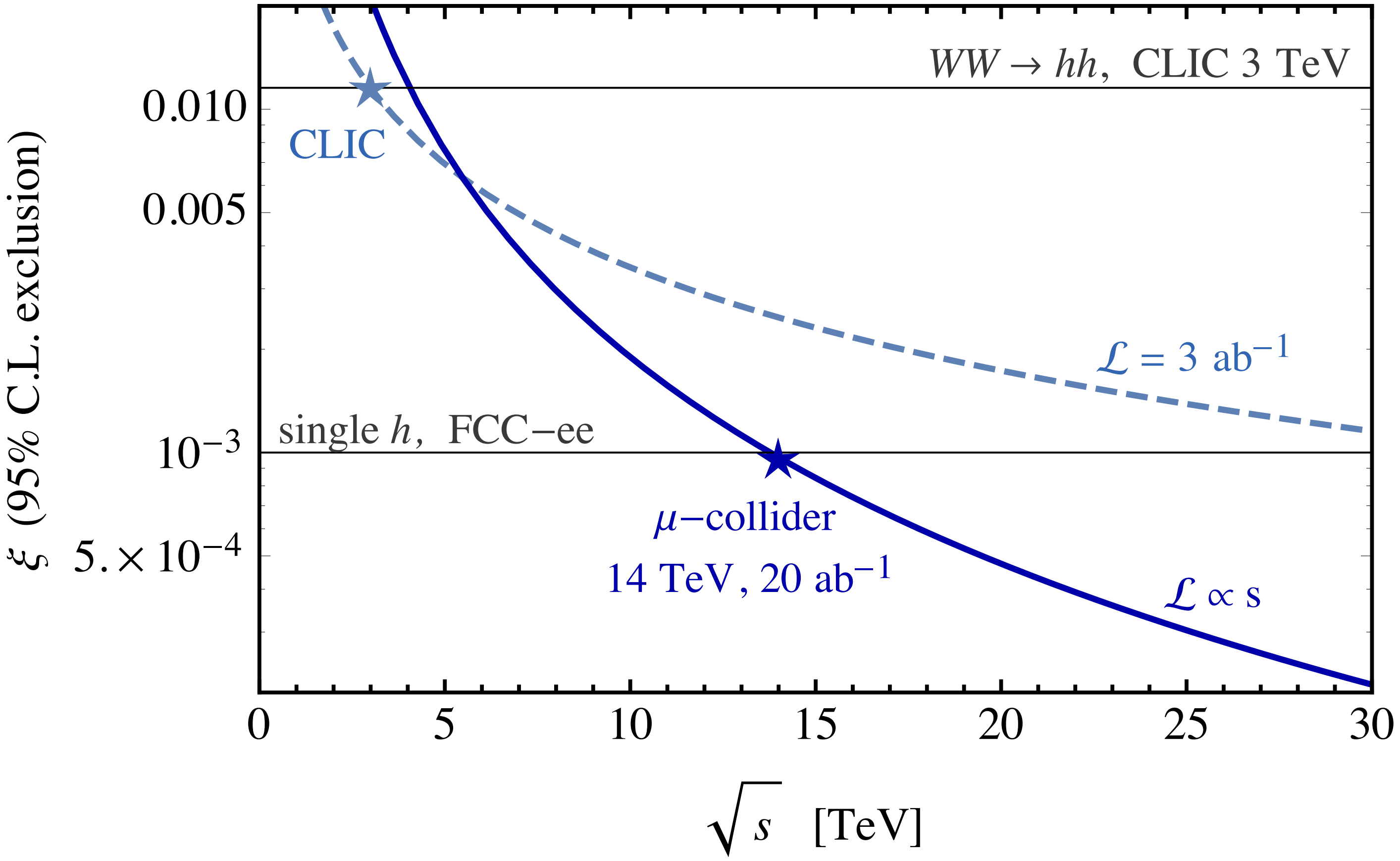
Contino et al. 1309.7038

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: $\xi \propto \frac{1}{E^2}\frac{1}{\sqrt{N_{\text{bkg}}}} \propto \frac{1}{E^2}\frac{1}{\sqrt{\mathcal{L}/E^2}} = \frac{1}{E\sqrt{\mathcal{L}}}$

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



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

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

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

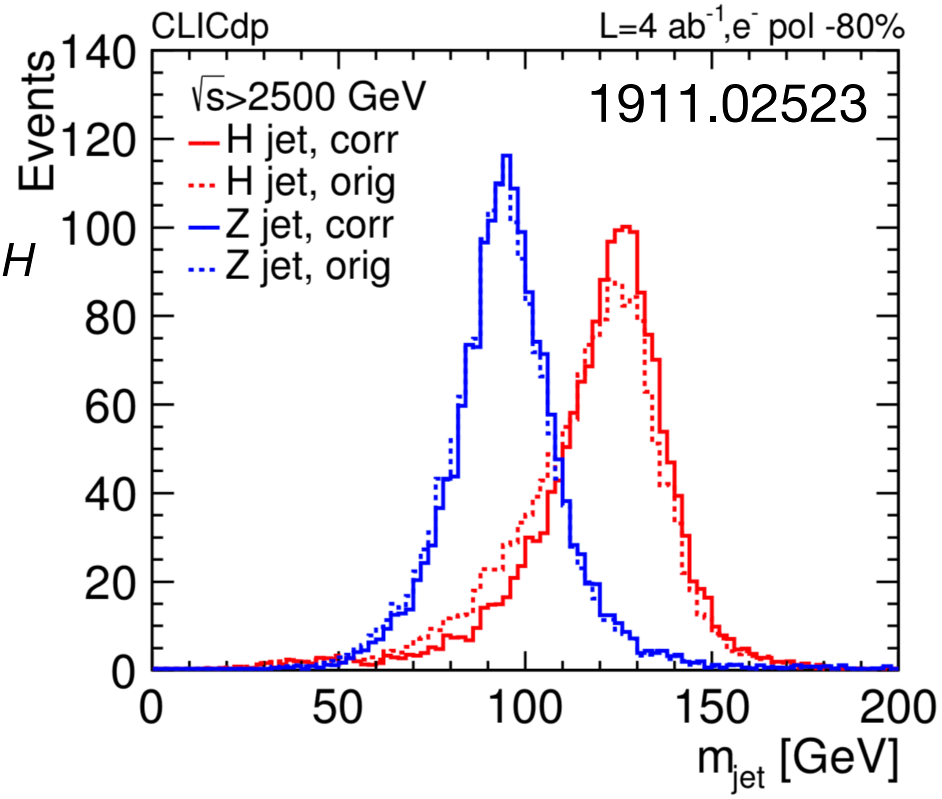
$\sqrt{s} = 30\,\text{TeV},\ \mathcal{L} = 90\,\text{fb}^{-1}$

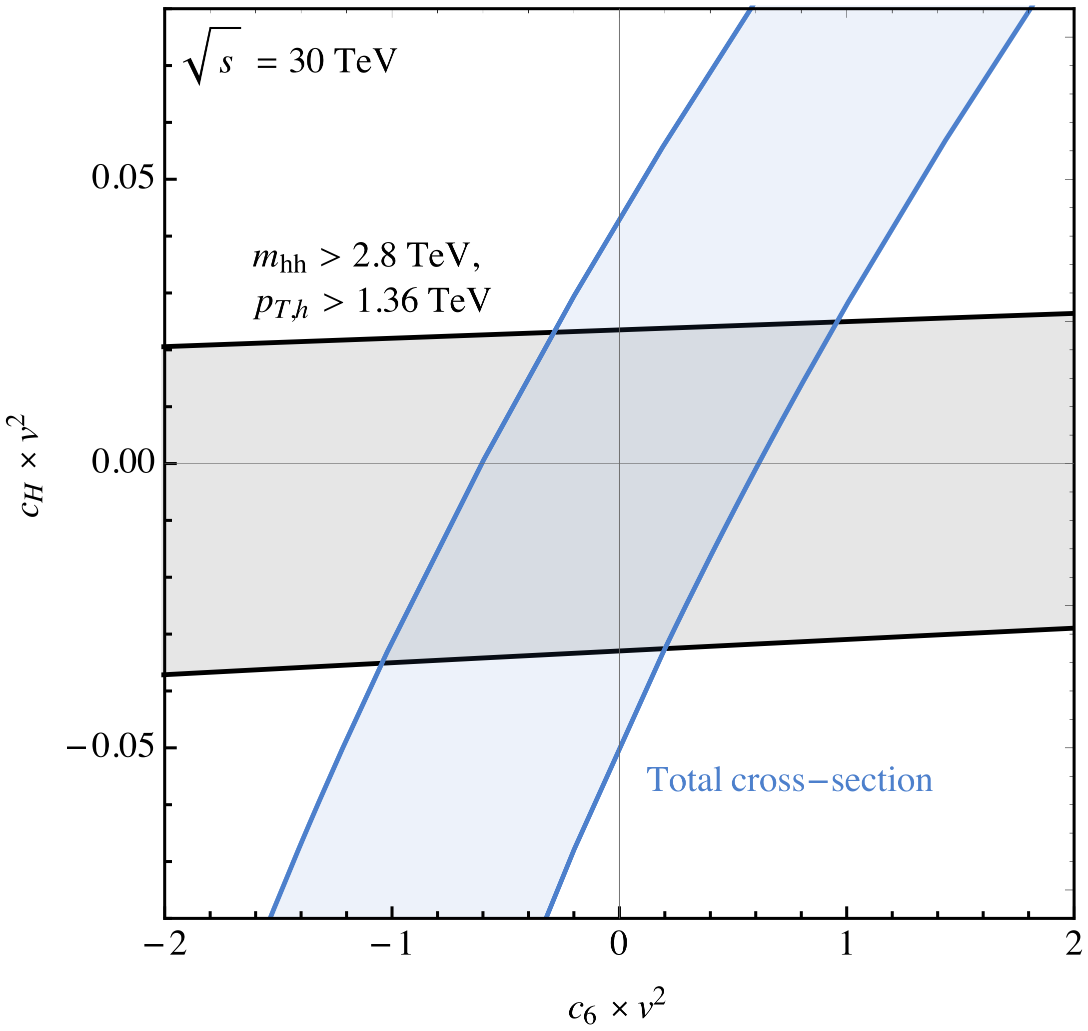
$\xi < 2\times 10^{-4} \qquad c_H^{-1/2} > 17\,\text{TeV}$

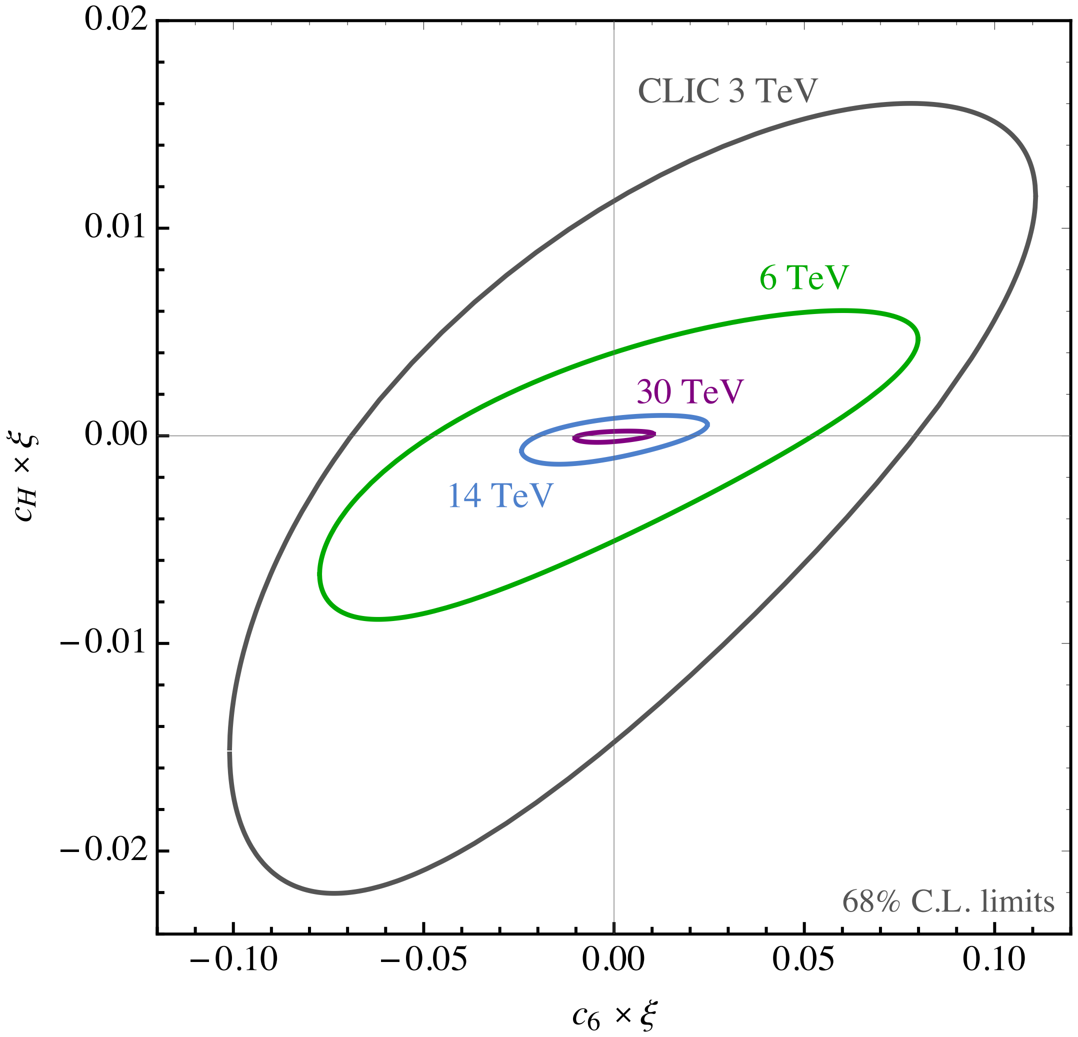
hh at high mass

- 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%

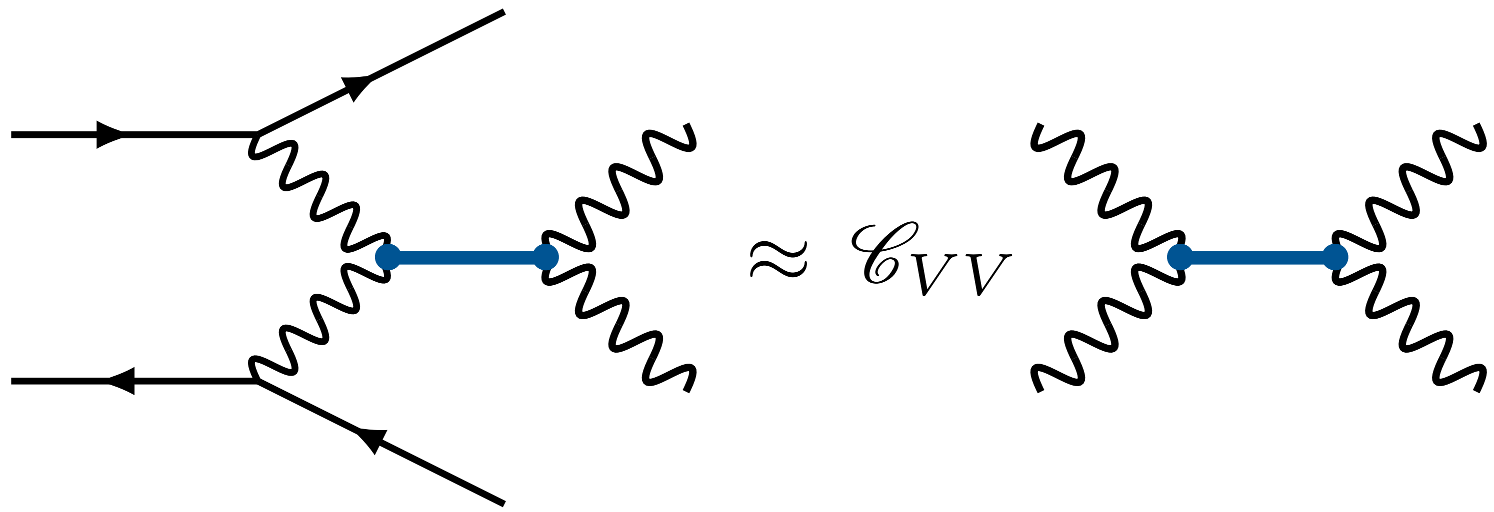






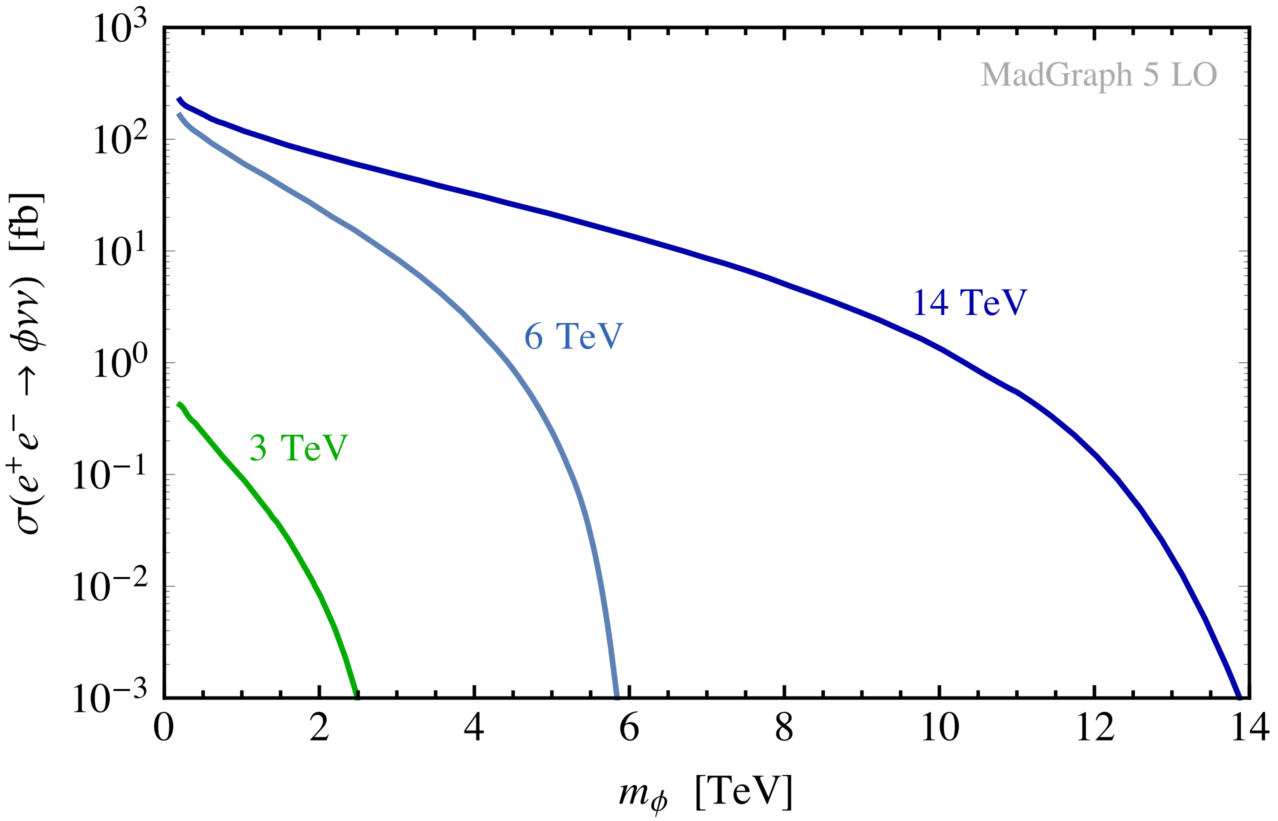
Resonance searches

VBF resonance production cross-section



enhanced if the resonance is light

- Example: scalar production $\mu^+\mu^- \to \phi\nu\nu, \quad \phi \to hh, W^+W^-, ZZ$



It's like a heavy Higgs with narrow width + *hh* decay

$$\sigma(\ell^+\ell^- \to h\nu\bar{\nu}) \approx \frac{g^4}{256\pi^3 v^2}\left[\log\frac{s}{m_h^2} - 2\right]$$

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

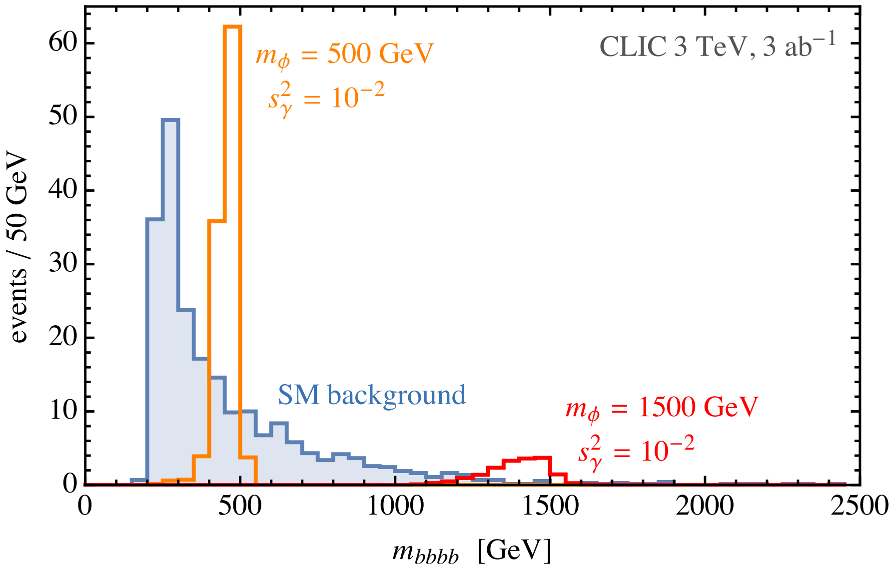
Resonant hh & VV searches

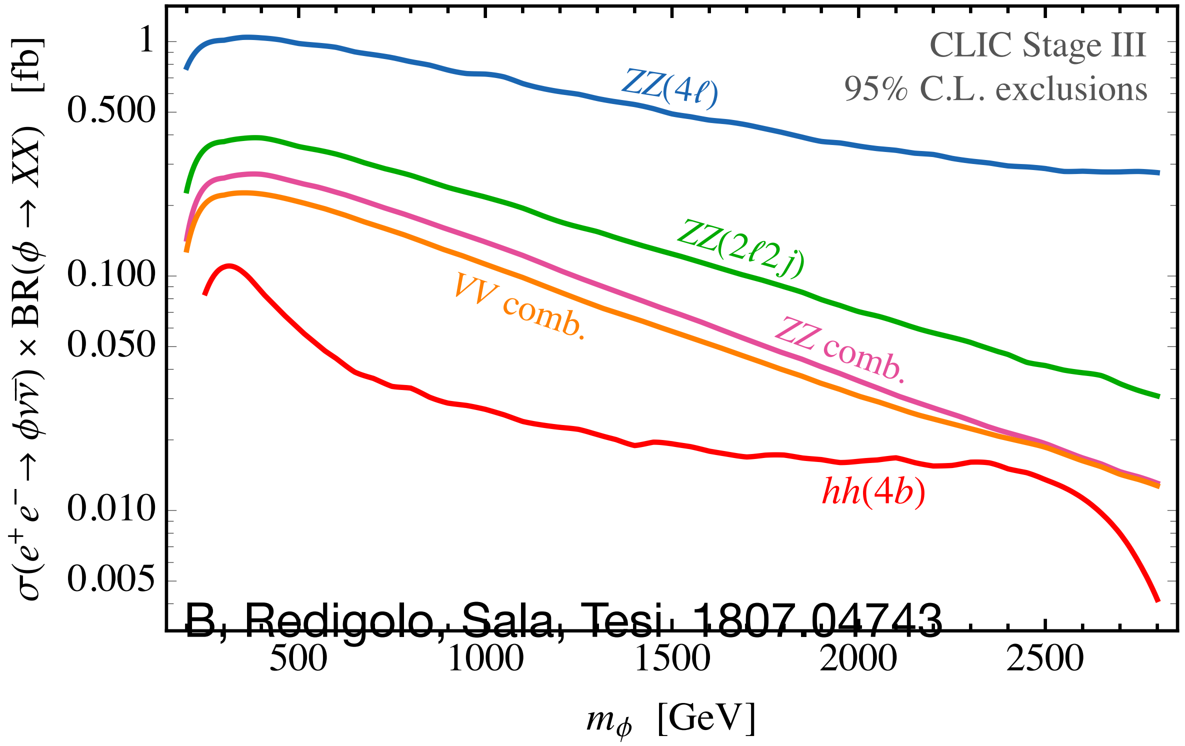
Main decay channels: *ϕ → hh, WW, ZZ.*

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

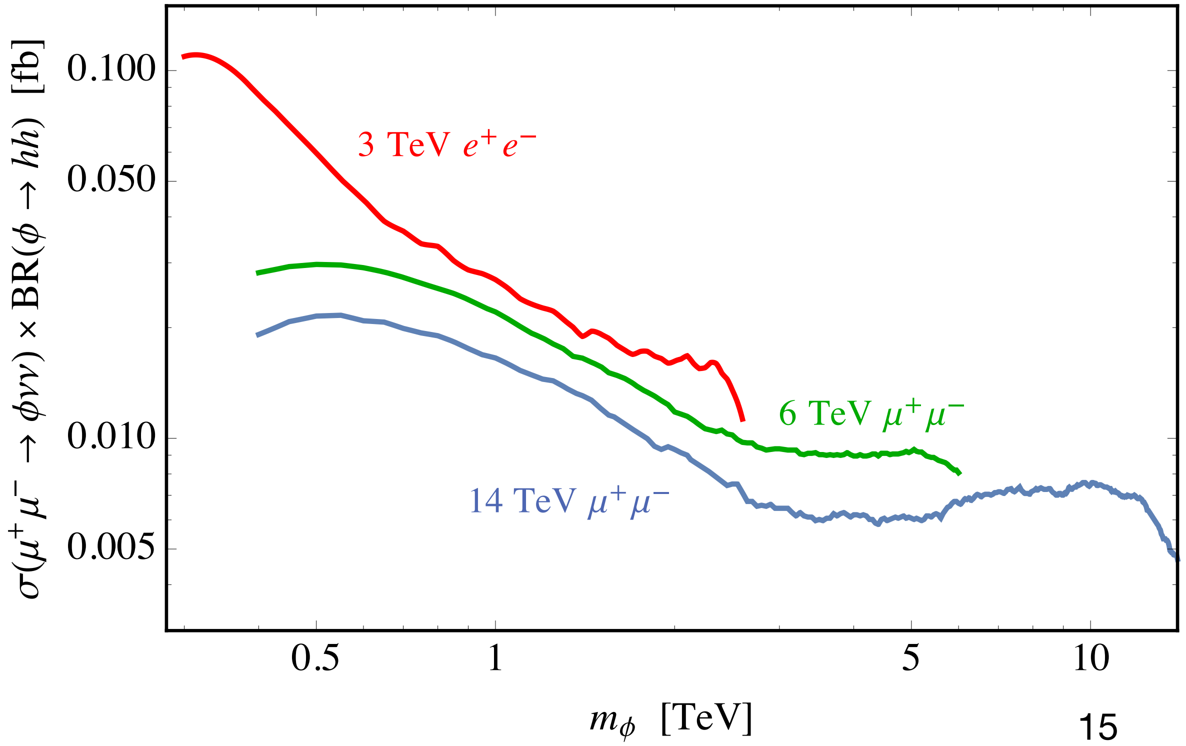
VV and *hh* channels are complementary

- Cut & count experiment around resonance





B, Redigolo, Sala, Tesi, 1807.04743



- Very small background at high masses, the error is dominated by statistics

  In the limit of no bkg: $[\sigma_{95\%} \times \mathrm{BR}] \simeq 3/\mathcal{L}$

- Parton-level analysis for *ϕ → hh(4b)*:

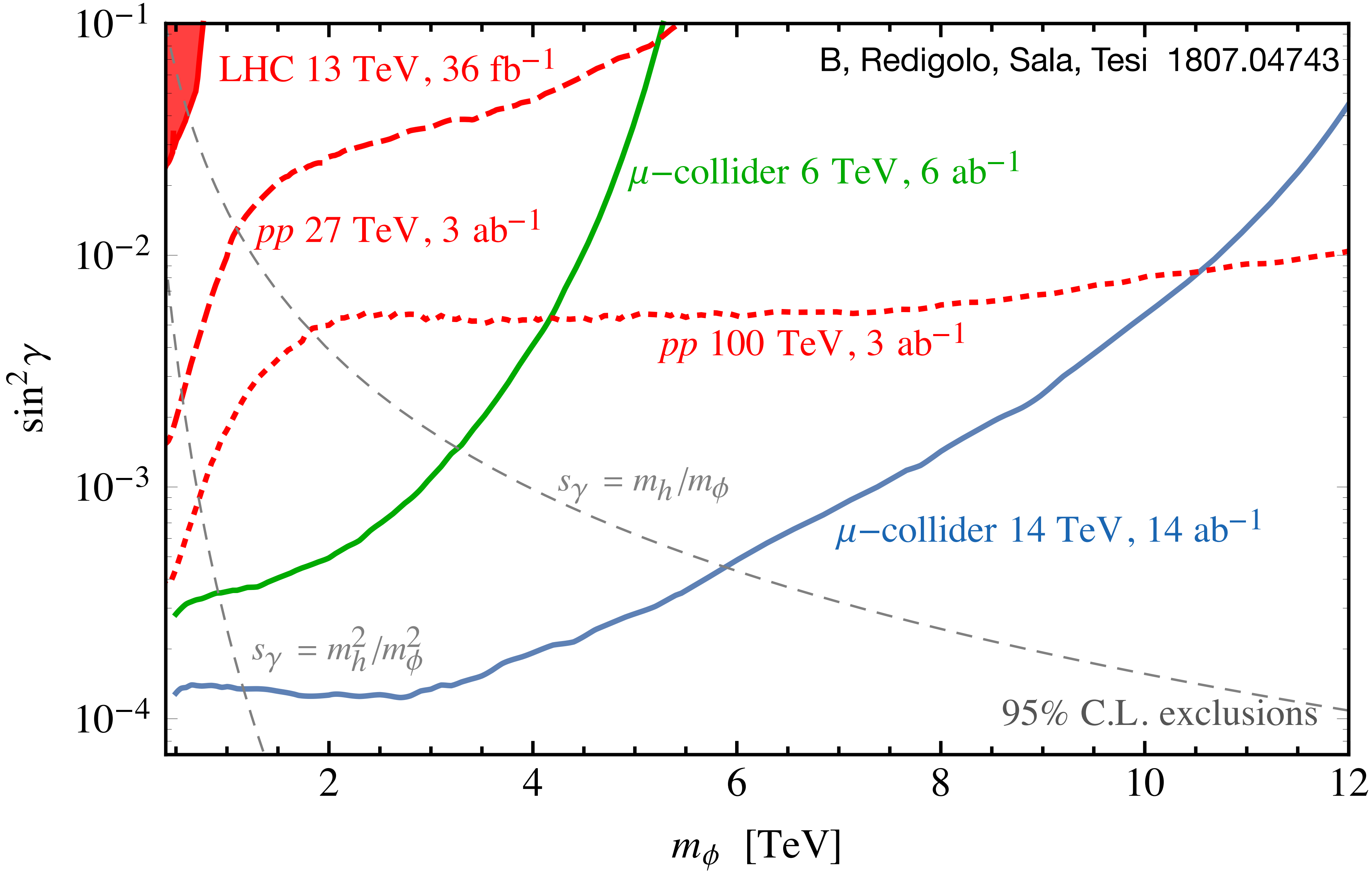
  Identification cut: $m_{4b} = m_\phi \pm 15\%$
  b-tag efficiency 30%

  (validated with simulation at 3 TeV CLIC)

Example: scalar singlet

Compare the reach of very high energy lepton & hadron colliders

$$\sin^2\gamma \approx \Delta\mu_h/\mu_h^{\rm SM} \approx \sigma_{VV\to\phi}/\sigma_{VV\to h}^{\rm SM}$$



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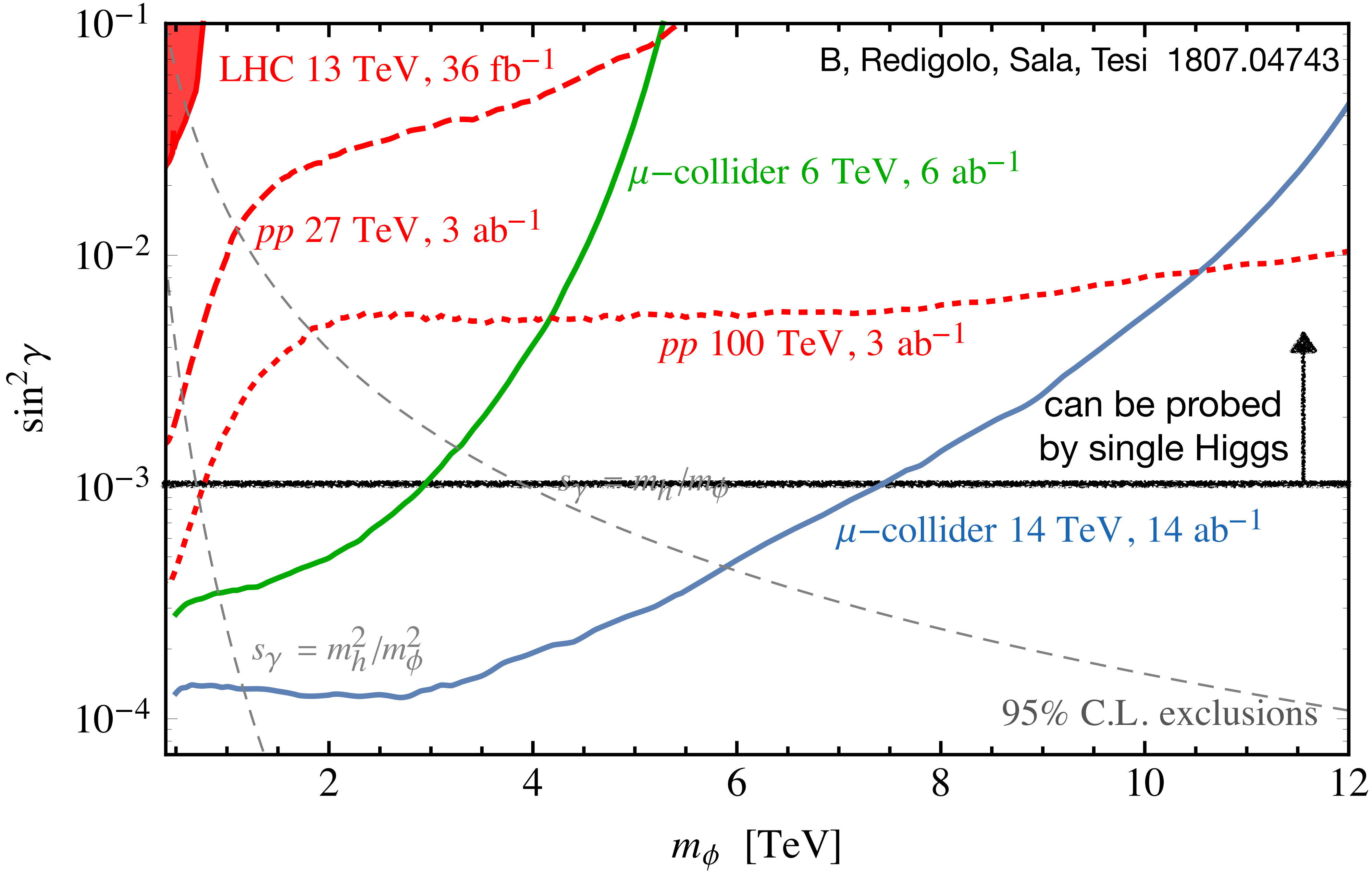
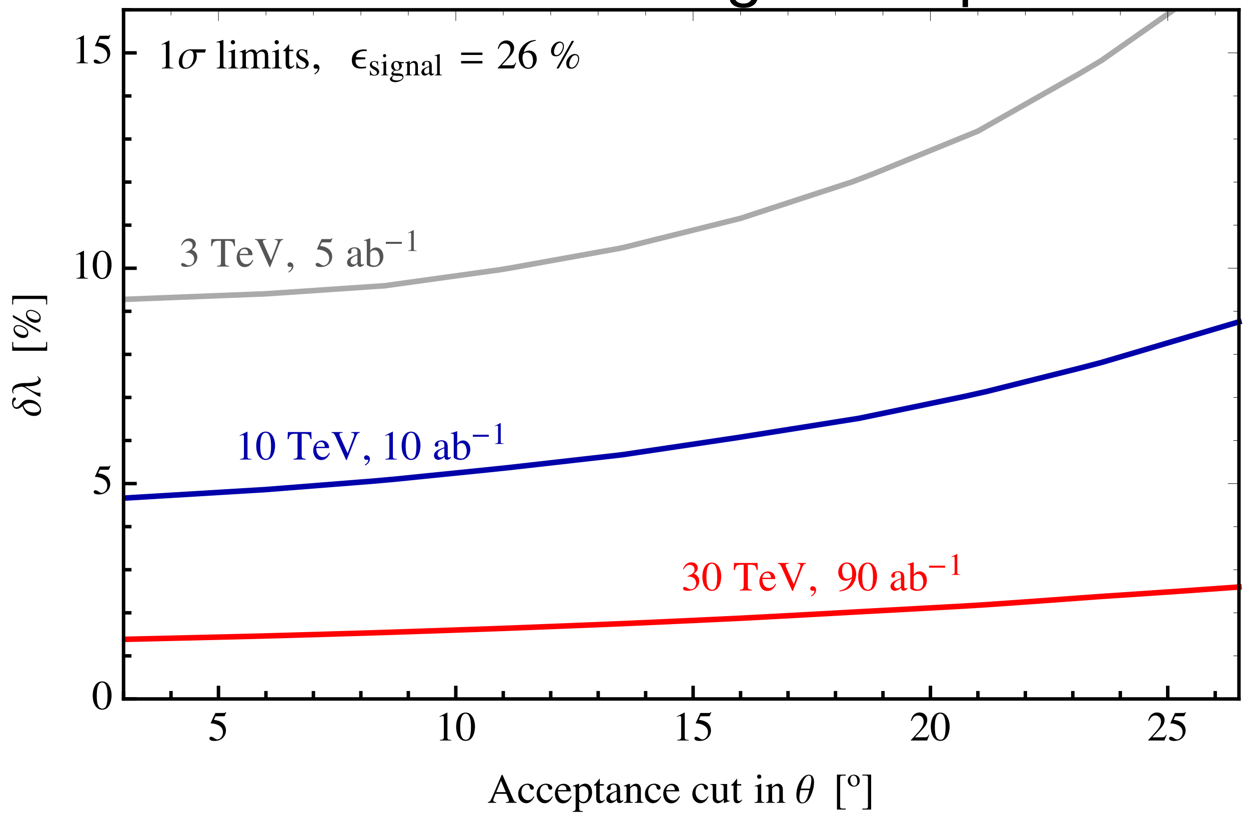


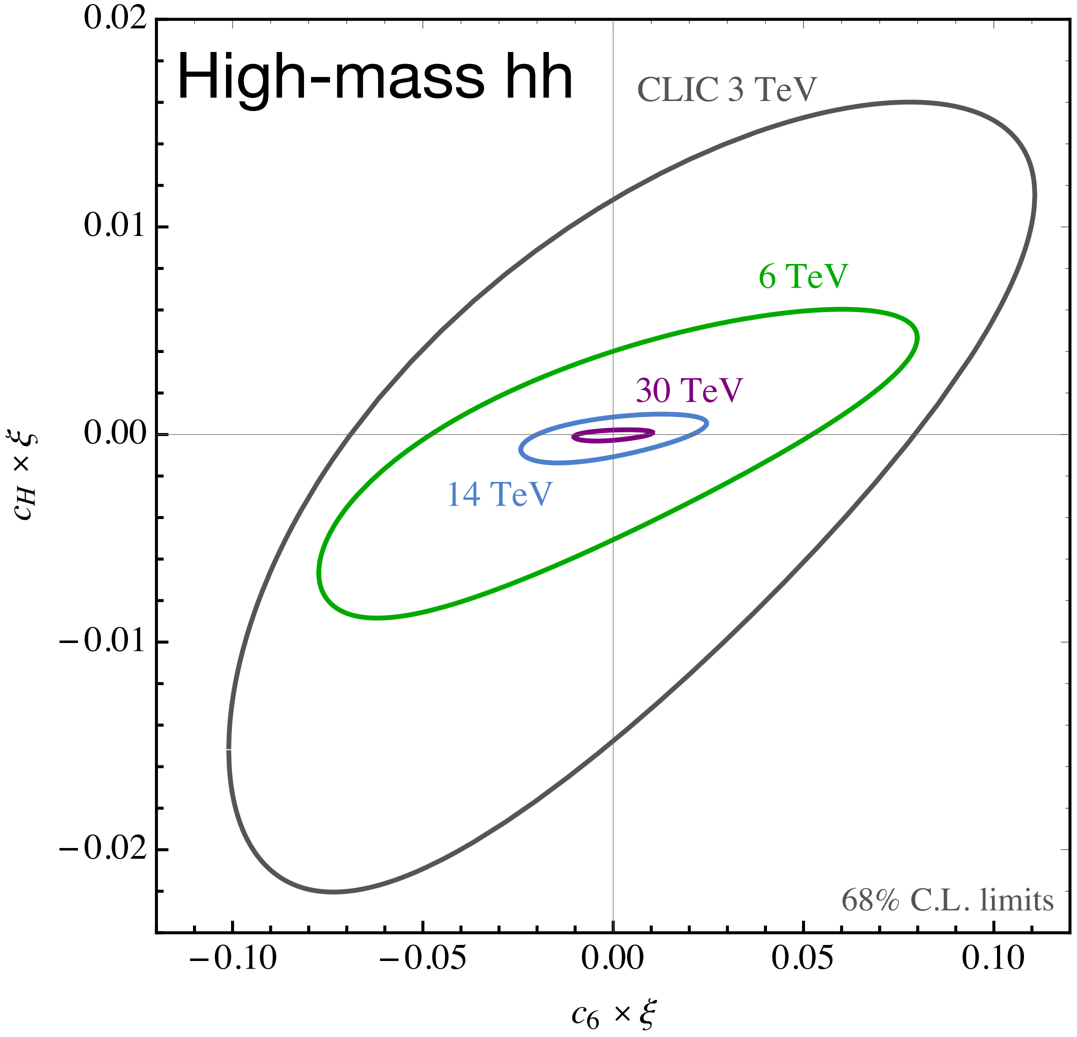
For this class of models, a high-energy μ⁺μ⁻ collider has an amazing reach if compared to single Higgs meas. or direct searches at a 100 TeV pp collider

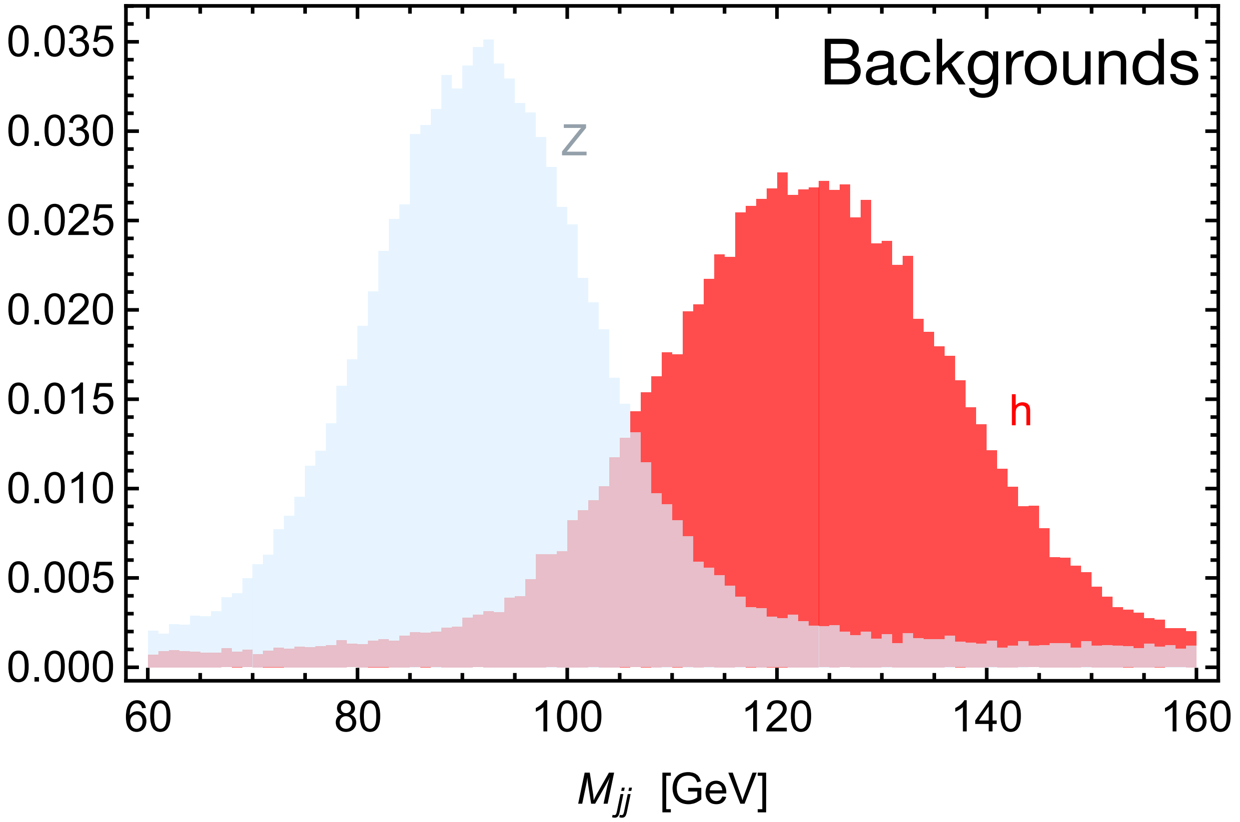
Summary

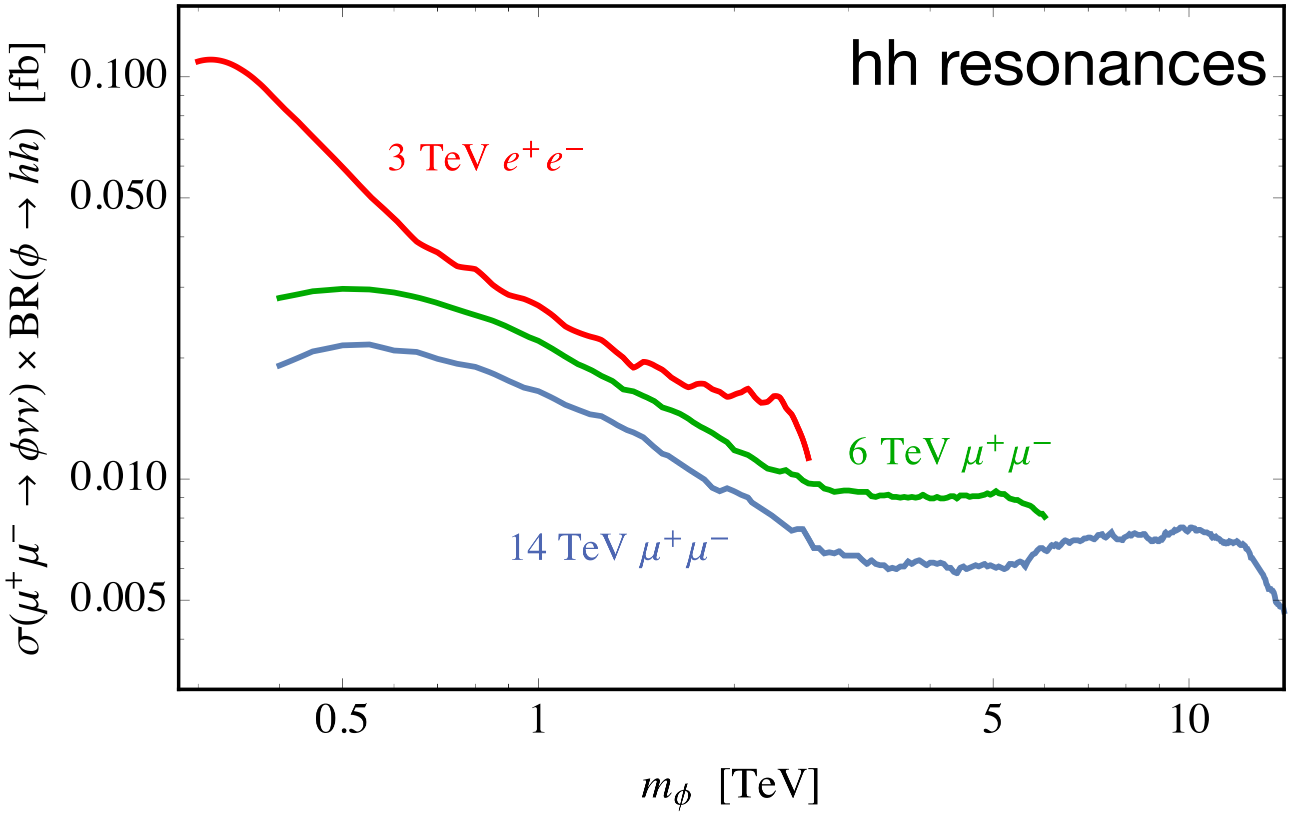
Limit on trilinear & angular dependence



High-mass hh







Backup

Cross-sections

- Total cross-section (acceptance θ > 10° & pT > 10 GeV):

$$\sigma_{3\text{ TeV}} = \left[0.13 + 0.51\, c_H\, v^2 - 0.11\, c_6\, v^2 + 3.5\, c_H^2 v^4 + 0.10\, c_6^2 v^4 - 0.73\, c_H\, c_6\, v^4\right] \text{fb},$$

$$\sigma_{10\text{ TeV}} = \left[0.24 + 1.73\, c_H\, v^2 - 0.19\, c_6\, v^2 + 46.9\, c_H^2 v^4 + 0.17\, c_6^2 v^4 - 2.01\, c_H\, c_6\, v^4\right] \text{fb},$$

$$\sigma_{30\text{ TeV}} = \left[0.27 + 3.48\, c_H\, v^2 - 0.21\, c_6\, v^2 + 376.7\, c_H^2 v^4 + 0.21\, c_6^2 v^4 - 3.74\, c_H\, c_6\, v^4\right] \text{fb}.$$

- High-mass:

$\sqrt{s}$	M_{hh} cut	$p_{T,h}$ cut	$\sigma(\mu^+\mu^- \to hh\nu\nu)$ [fb]
3 TeV	250 GeV	150 GeV	$0.01 + 0.98\, c_H\, v^2 - 0.09\, c_6\, v^2 + 10.2\, c_H^2 v^4 + 0.08\, c_6^2 v^4 - 1.26\, c_H\, c_6\, v^4$
6 TeV	680 GeV	300 GeV	$0.05 + 1.49\, c_H\, v^2 - 0.04\, c_6\, v^2 + 44.4\, c_H^2 v^4 + 0.03\, c_6^2 v^4 - 1.61\, c_H\, c_6\, v^4$
14 TeV	1500 GeV	690 GeV	$0.01 + 1.78\, c_H\, v^2 - 0.01\, c_6\, v^2 + 254.3\, c_H^2 v^4 + 0.007\, c_6^2 v^4 - 1.88\, c_H\, c_6\, v^4$
30 TeV	2800 GeV	1360 GeV	$0.005 + 2.11\, c_H\, v^2 - 0.003\, c_6\, v^2 + 1214\, c_H^2 v^4 + 0.002\, c_6^2 v^4 - 2.2\, c_H\, c_6\, v^4$

Resonant *hh* → *4b* at CLIC

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

- Detector simulation with CLICdp Delphes card (thanks to Ulrike Schnoor for support!)
- 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, $90 \text{ GeV} < m_{bb} < 130 \text{ GeV}$
- 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 $\varepsilon_{bkg} \sim 10^{-3} - 10^{-4}$