Advantages of a Very High Energy Lepton Collider

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Why a High Energy Lepton Collider?

- Recent progress on the feasibility of a high-energy lepton collider: MAP, MICE, LEMMA, Muon Collider coll. @ CERN, PWFA, …

- Colliders are expensive: need a big improvement in *as many as possible different directions*. A Very High Energy Lepton Collider can do that!

- Need for physics potential evaluation (to define energy, luminosity and detector performance goals). Strong interest in the high-energy community:

1807.04743	2003.13628	2006.16277	2009.11287	2012.11555	2102.08386
1901.06150	2005.10289	2007.14300	2012.02769	2101.10334	etc …

- Most considerations here apply equally well to a Muon Collider, to a High-Energy upgrade of a Linear Collider, or any other type of VHELC.

- **Luminosity benchmark:** $$L \gtrsim \frac{\text{5 years}}{\text{time}} \left(\frac{\sqrt{s}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35}\,\text{cm}^{-2}\,\text{s}^{-1}$$

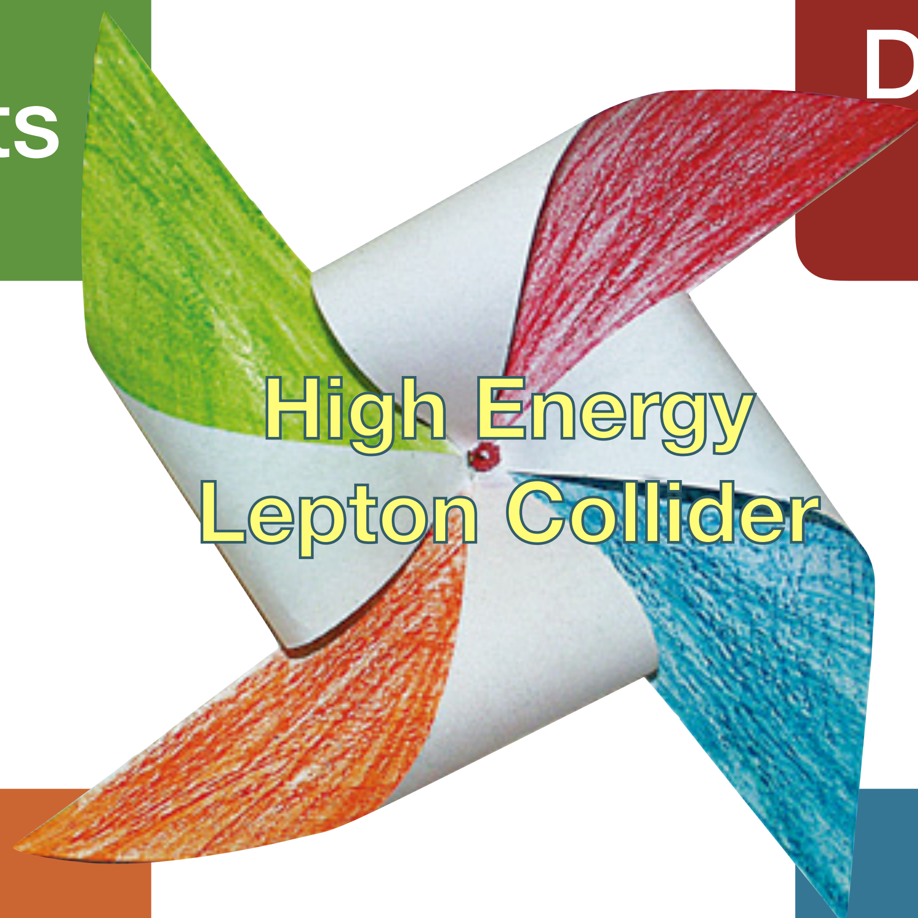
  necessary to perform SM measurements with ~ % precision

Physics cases for a High Energy Lepton Collider

From a theorist's point of view: Energy AND Precision!

High-rate measurements

Direct Searches



Muon-specific physics

High-energy probes

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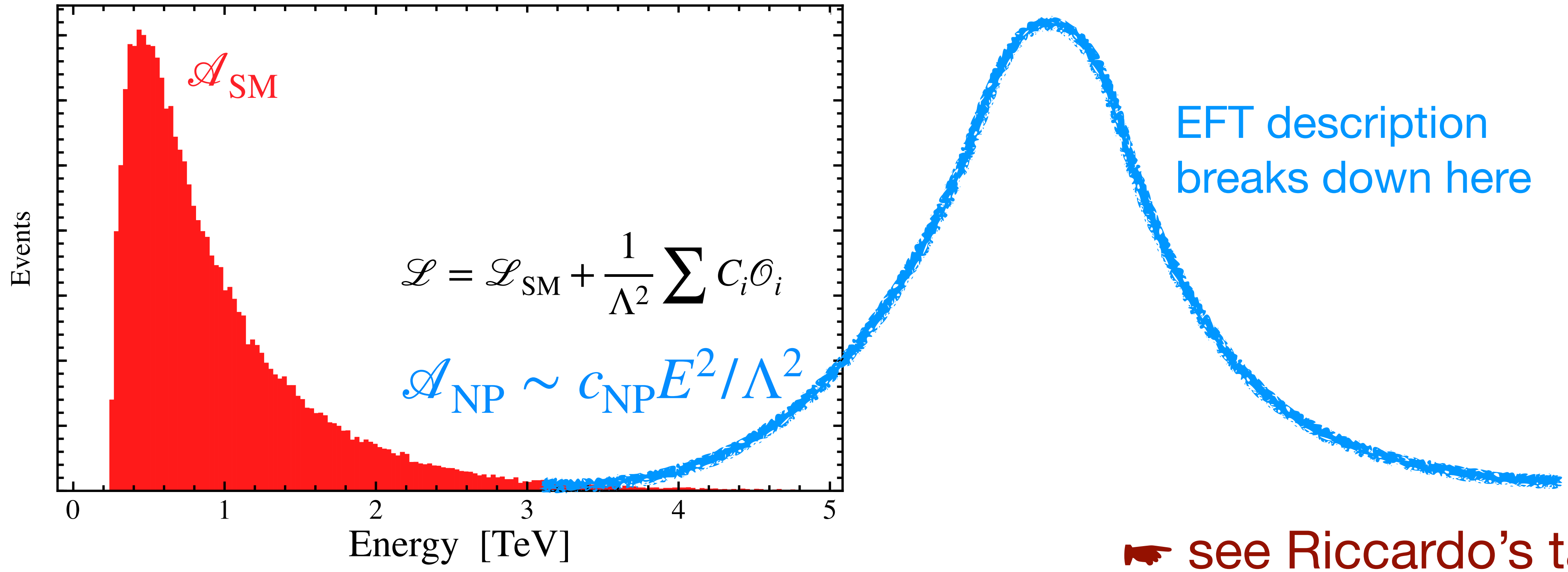
High-energy probes

- NP effects are more important at high energies



☛ see Riccardo's talk

- As simple as this: $$\frac{\Delta\sigma(E)}{\sigma_{SM}(E)} \propto \frac{E^2}{\Lambda^2_{BSM}} \approx \begin{cases} 10^{-6}, & E \sim 100\,\mathrm{GeV} \\ 10^{-2}, & E \sim 10\,\mathrm{TeV} \end{cases}$$

- Effective at LHC, FCC-hh, CLIC: "energy helps precision" 1609.08157 1712.01310

… taken to the extreme at a VHELC with 10's of TeV!

High-energy di-bosons

- Longitudinal 2 → 2 scattering amplitudes at high energy:

Process	BSM Amplitude
$\ell_L^+\ell_L^- \to Z_0 h$ $\bar{\nu}_L\nu_L \to W_0^+W_0^-$	$s\,(G_{3L}+G_{1L})\sin\theta_\star$
$\ell_L^+\ell_L^- \to W_0^+W_0^-$ $\bar{\nu}_L\nu_L \to Z_0 h$	$s\,(G_{3L}-G_{1L})\sin\theta_\star$
$\ell_R^+\ell_R^- \to W_0^+W_0^-\,, Z_0 h$	$s\,G_{lR}\sin\theta_\star$
$\bar{\nu}_L\ell_L^- \to W_0^- Z_0\,/\,W_0^- h$ $\nu_L\ell_L^+ \to W_0^+ Z_0\,/\,W_0^+ h$	$\sqrt{2}\,s\,G_{3L}\sin\theta_\star$

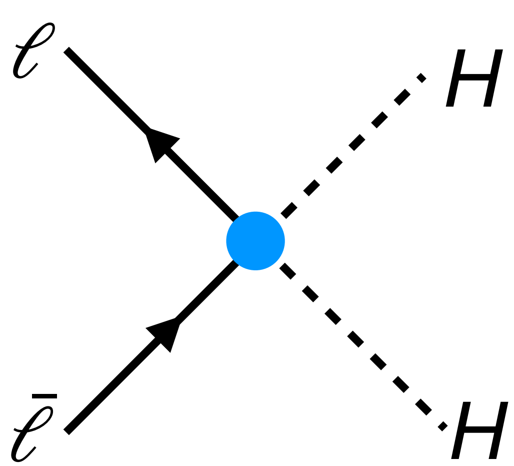
Determined by 3 fermion/scalar current-current interactions (Warsaw):

$$\mathcal{O}_{3L} = \left(\bar{\mathrm{L}}_L\gamma^\mu\sigma^a\mathrm{L}_L\right)\left(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H\right),$$

$$\mathcal{O}_{1L} = \left(\bar{\mathrm{L}}_L\gamma^\mu\mathrm{L}_L\right)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right),$$

$$\mathcal{O}_{lR} = \left(\bar{l}_R\gamma^\mu l_R\right)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right).$$

"high-energy primary effects"



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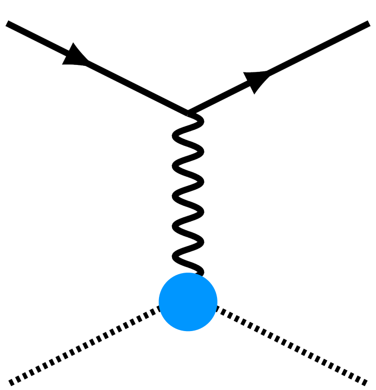
"high-energy primary effects"

- In flavor-universal theories, they are generated by SILH operators (via e.o.m.):



$$G_{1L} = \frac{1}{2} G_{lR} = \frac{g'^2}{4}(C_B + C_{HB})$$

$$G_{3L} = \frac{g^2}{4}(C_W + C_{HW})$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

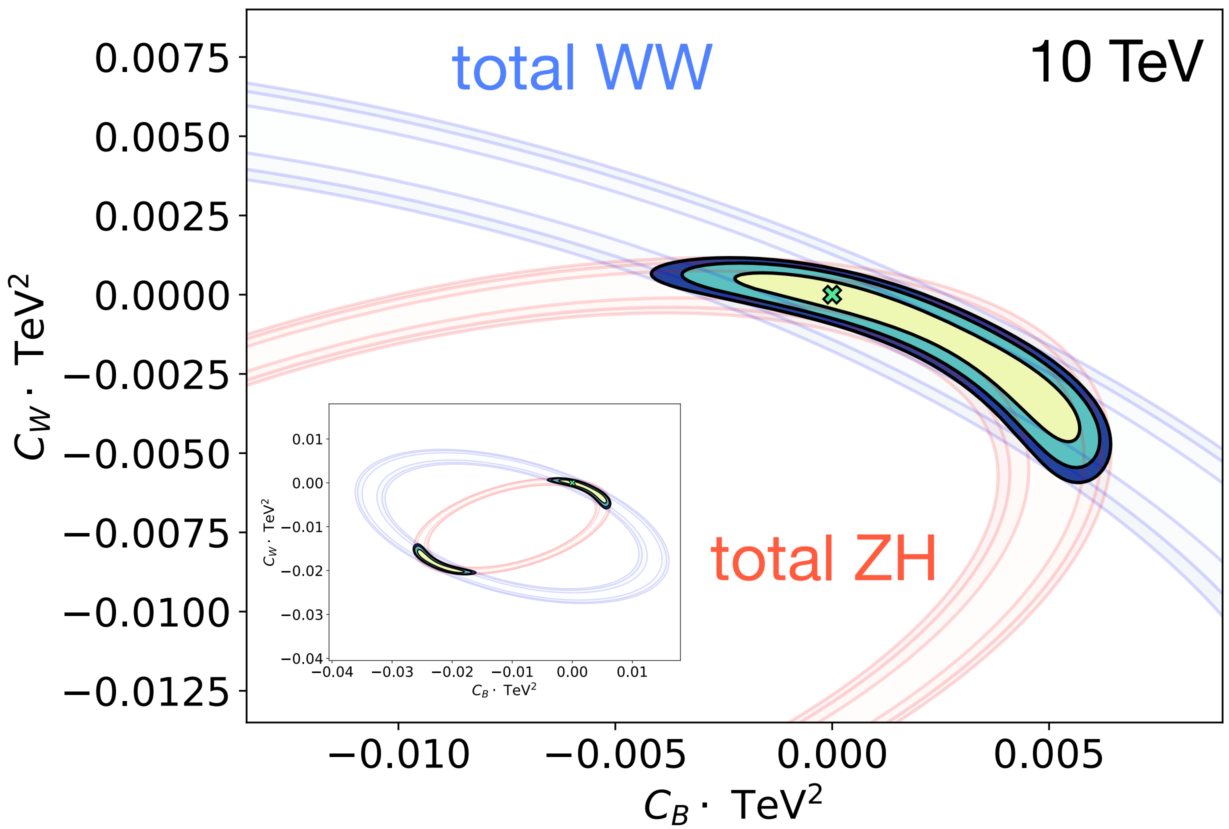
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

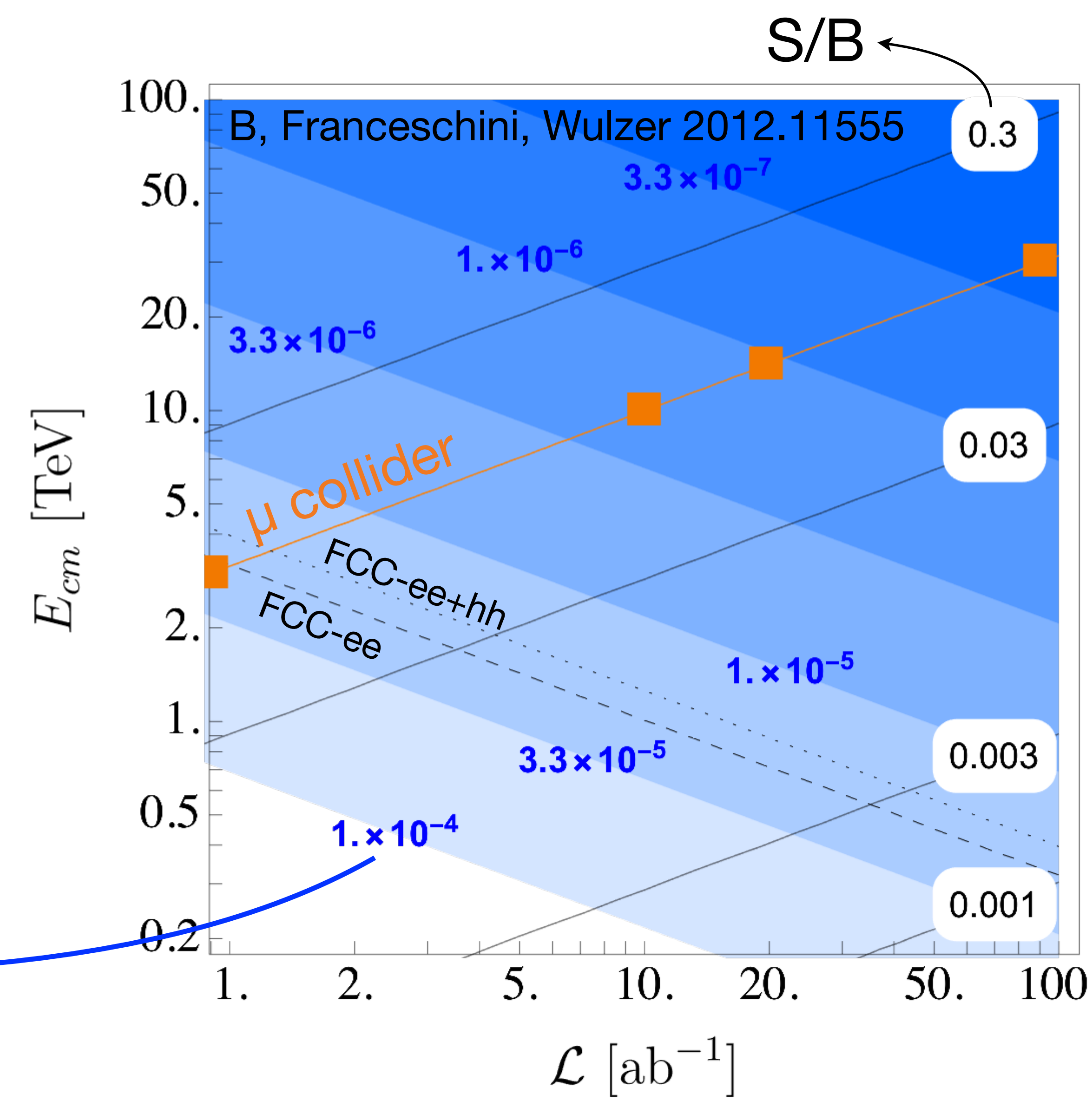
High-energy di-bosons

- C_W and C_B determined from high-energy $\mu^+\mu^- \to ZH,\ W^+W^-$ cross-sections

Limits on $C_{W,B}$ scale as E^2

$$\sigma_{\mu\mu\to ZH} \approx 122\,\text{ab}\left(\frac{10\,\text{TeV}}{E_{\text{cm}}}\right)^2\left[1 + \#\,E_{\text{cm}}^2 C_W + \#\,E_{\text{cm}}^4 C_W^2\right]$$





- In universal theories, $C_{W,B}$ related with EW observables $\hat{S} = m_W^2(C_W + C_B)$

Muon collider:

$$10\,\text{TeV}: \quad C_W \lesssim (40\,\text{TeV})^{-2}, \quad \hat{S} \lesssim 10^{-6}$$

$$30\,\text{TeV}: \quad C_W \lesssim (120\,\text{TeV})^{-2}, \quad \hat{S} \lesssim 10^{-7}$$

LEP : $\hat{S} \lesssim 10^{-3}$

FCC : $\hat{S} \lesssim 10^{-5}$ ← ultimate precision at Z pole

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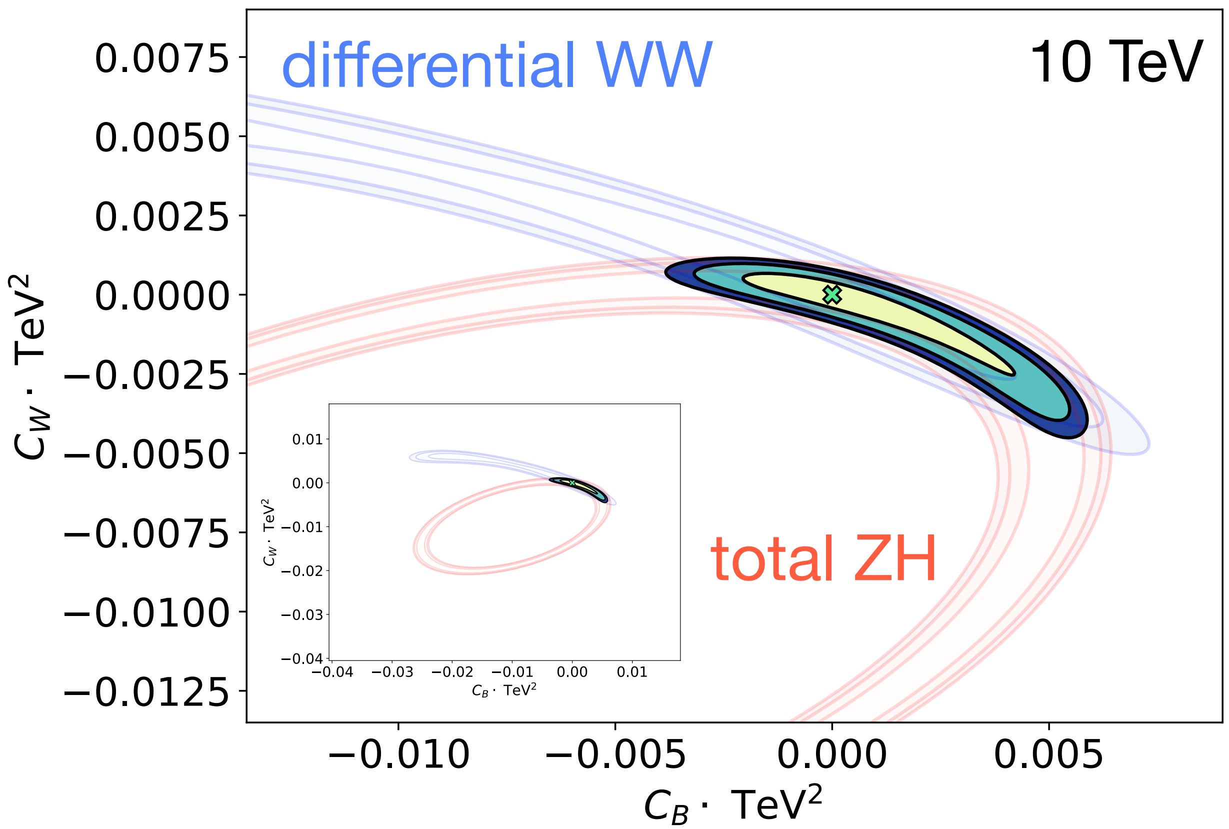

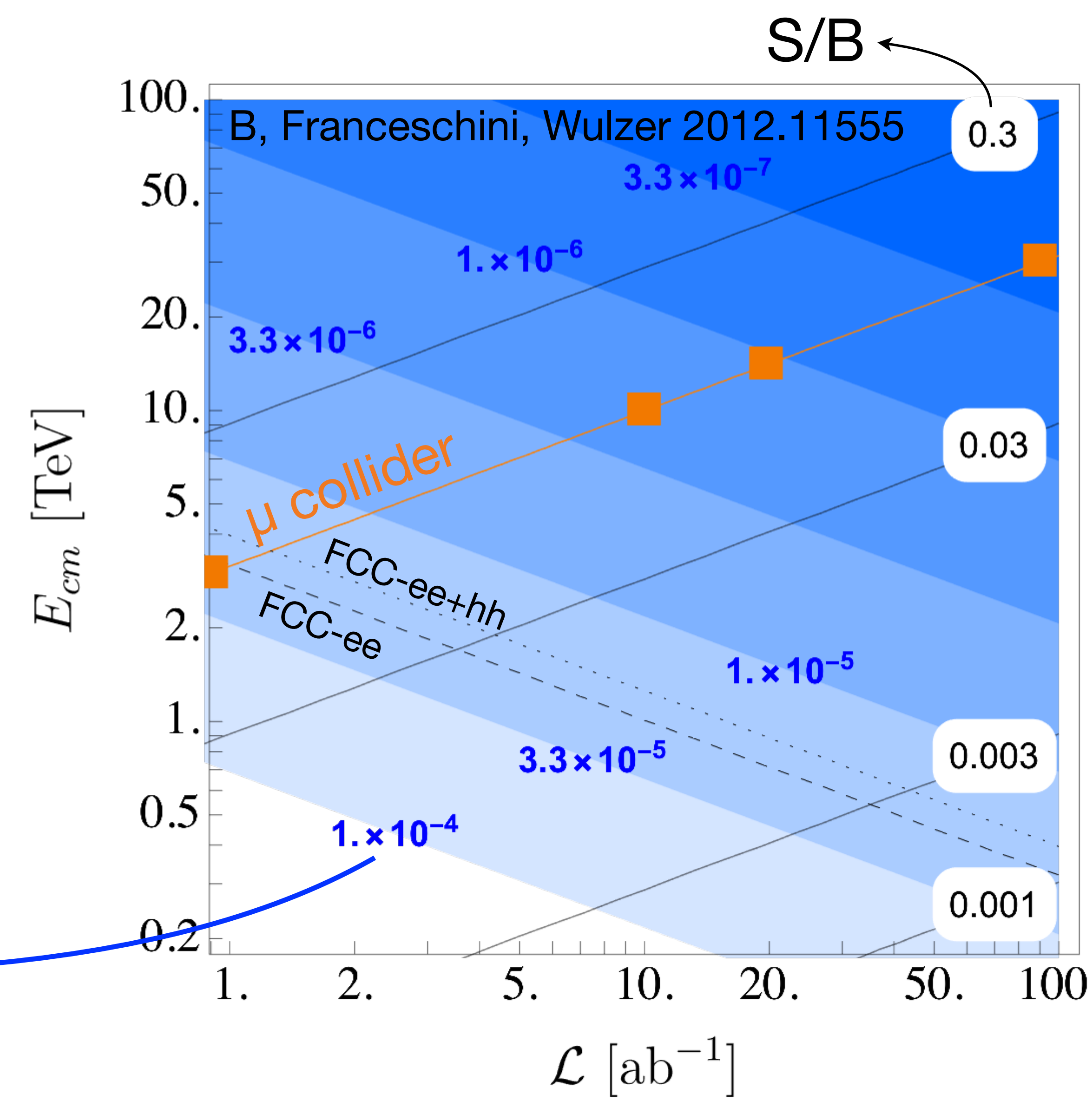

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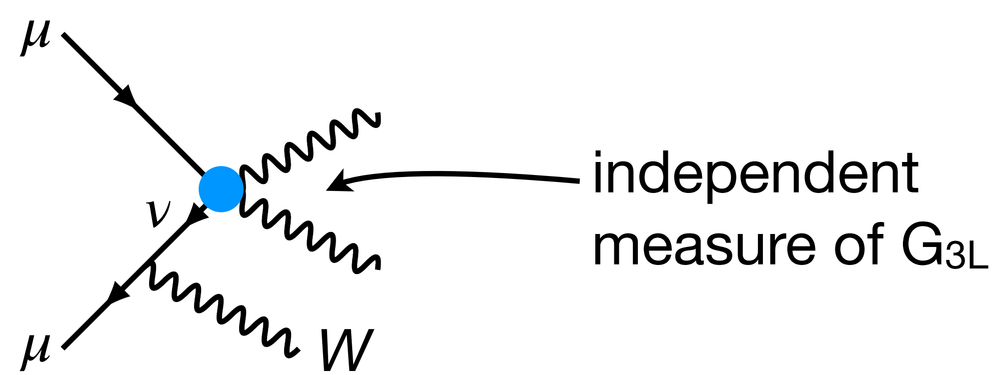
High-energy tri-bosons

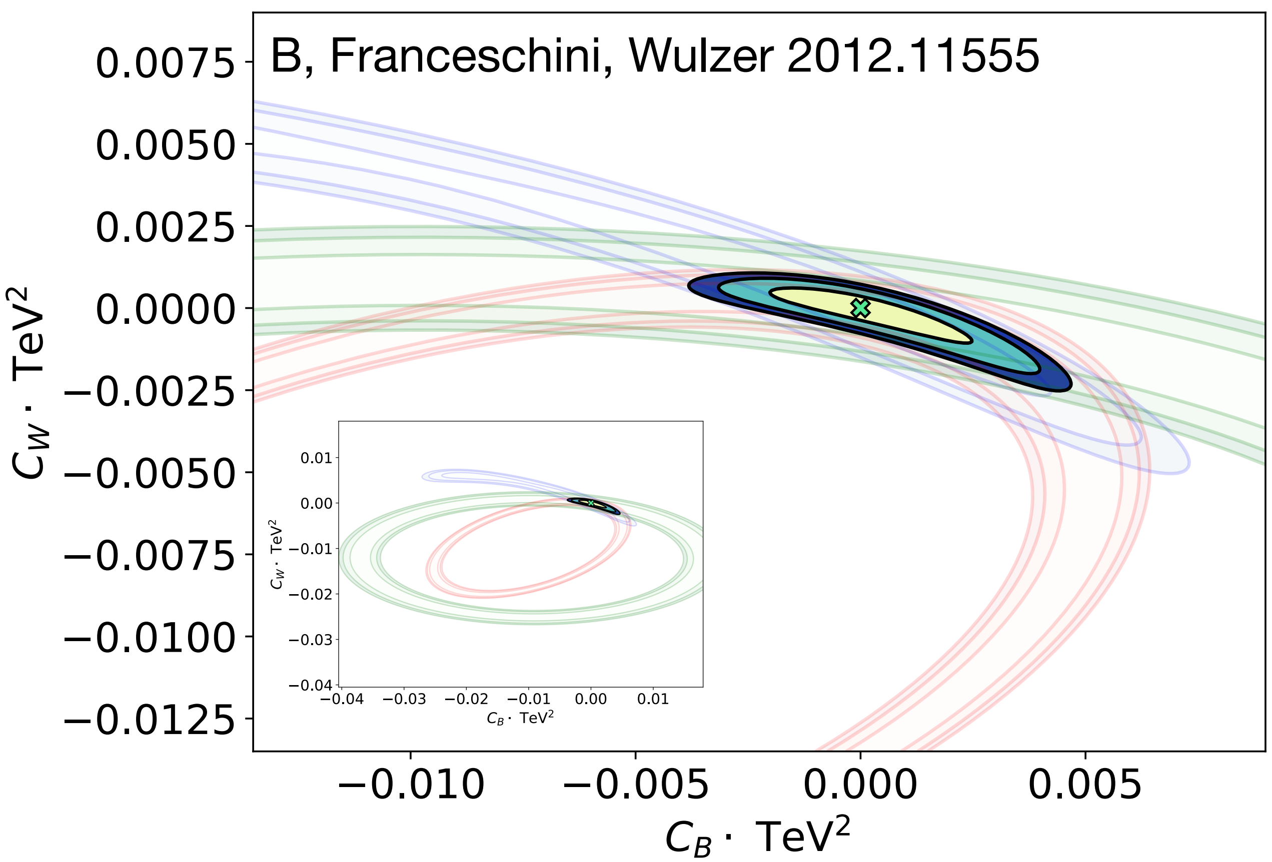
- Gauge boson radiation becomes important at high energies *(Sudakov double-log enhancement of soft-collinear emissions)*

$\mu^+\mu^- \rightarrow VVV$ not much suppressed w.r.t. $\mu^+\mu^- \rightarrow VV$ ($V = W^\pm, Z, H$)

- This allows to access the charged processes $\ell^\pm\nu \rightarrow W^\pm Z, W^\pm H$

"effective neutrino approximation"

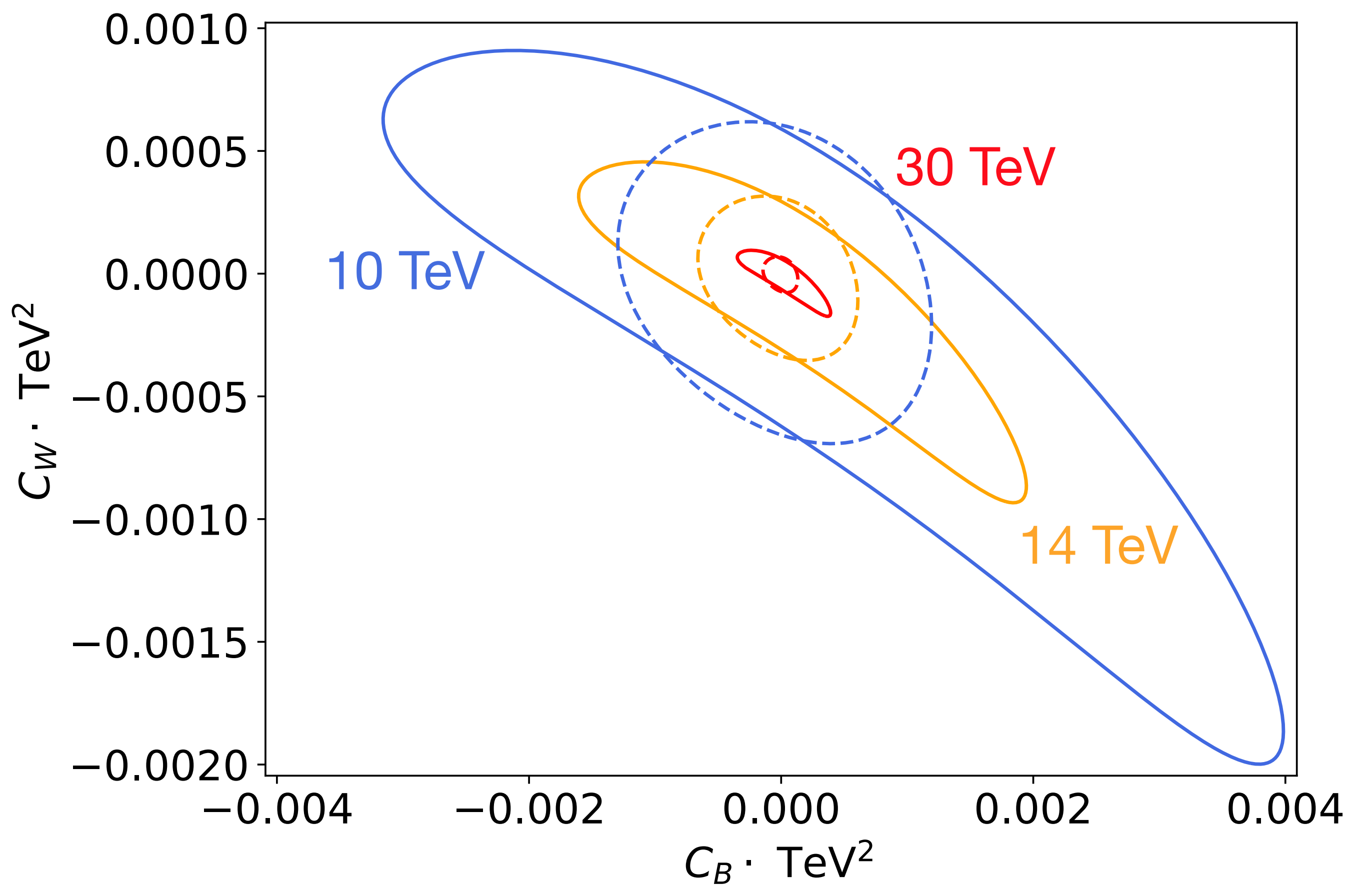


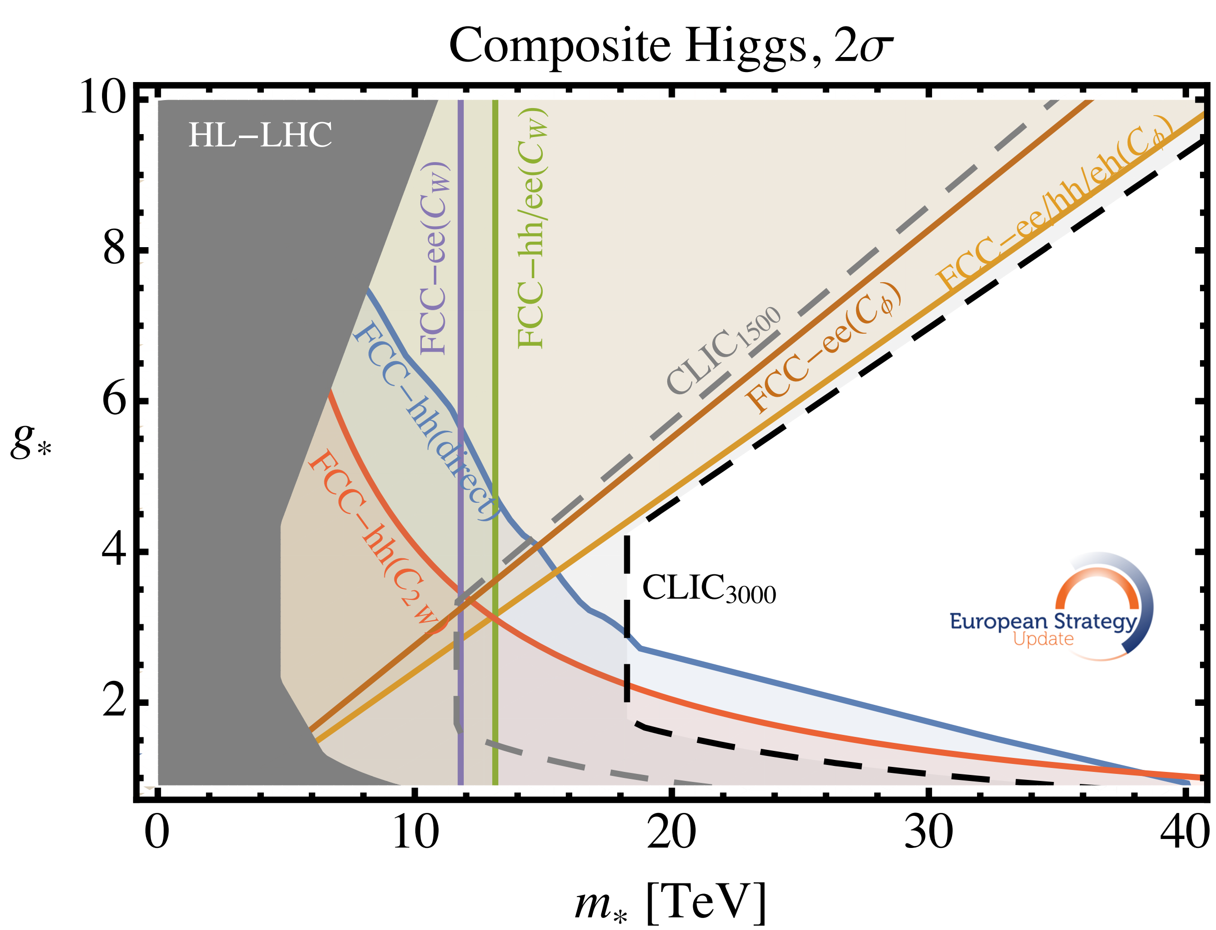


- NB: also 2 → 2 scatterings receive large radiative corrections: "soft" EW radiation must be taken into account properly…

➡ Inclusive NLO study of VV and VVV

- A muon collider is able to probe new physics scales > 100 TeV
  - $\ell^+\ell^- \to VV: \quad \hat{S} \sim m_W^2/m_\star^2 \lesssim 10^{-7}$
  - $VV \to HH: \quad \xi \sim v^2/f^2 \lesssim 10^{-3}$





- Example: Composite Higgs

Almost order of magnitude improvement w.r.t. FCC / CLIC!

High-energy probes: summary

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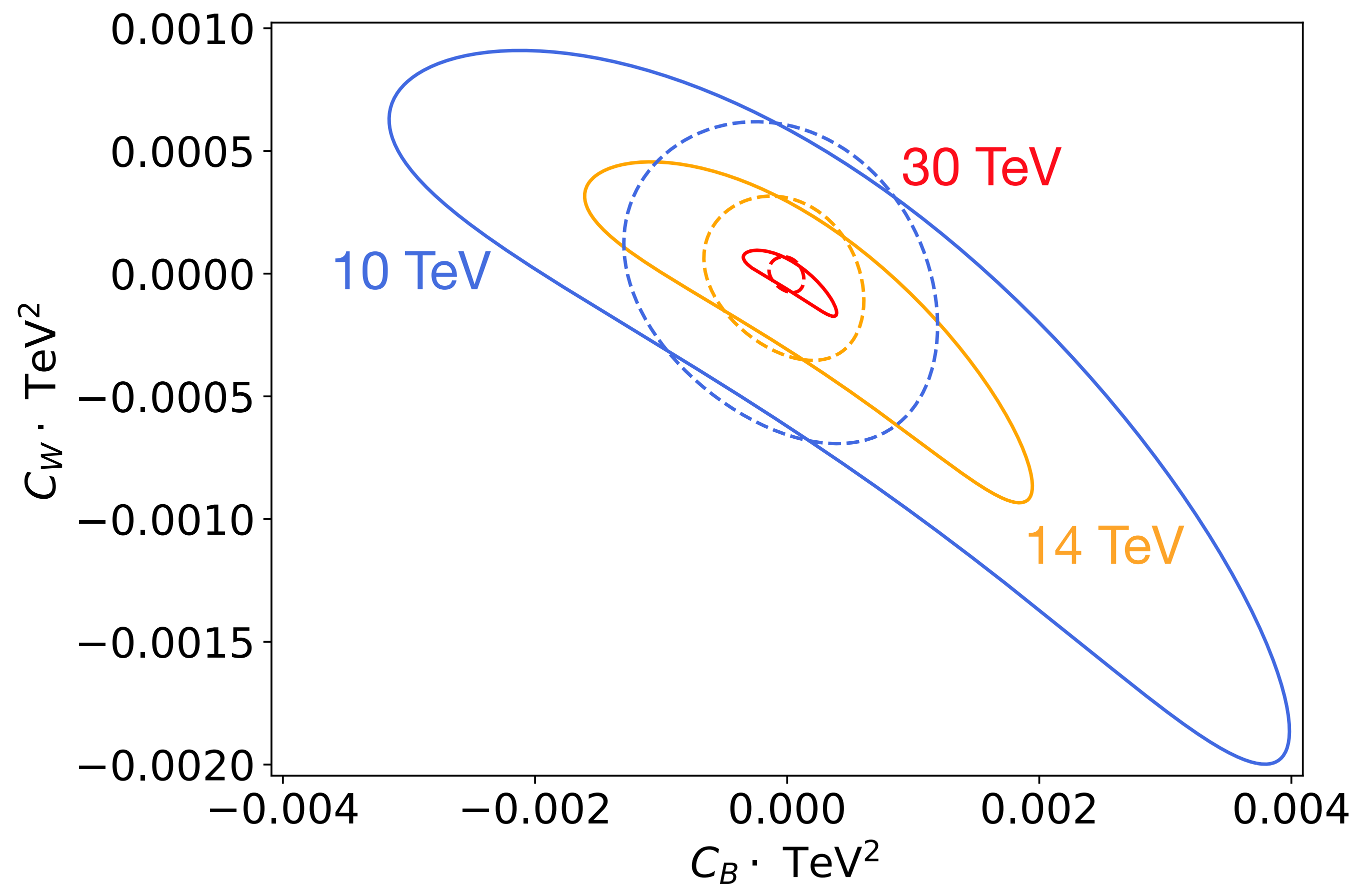

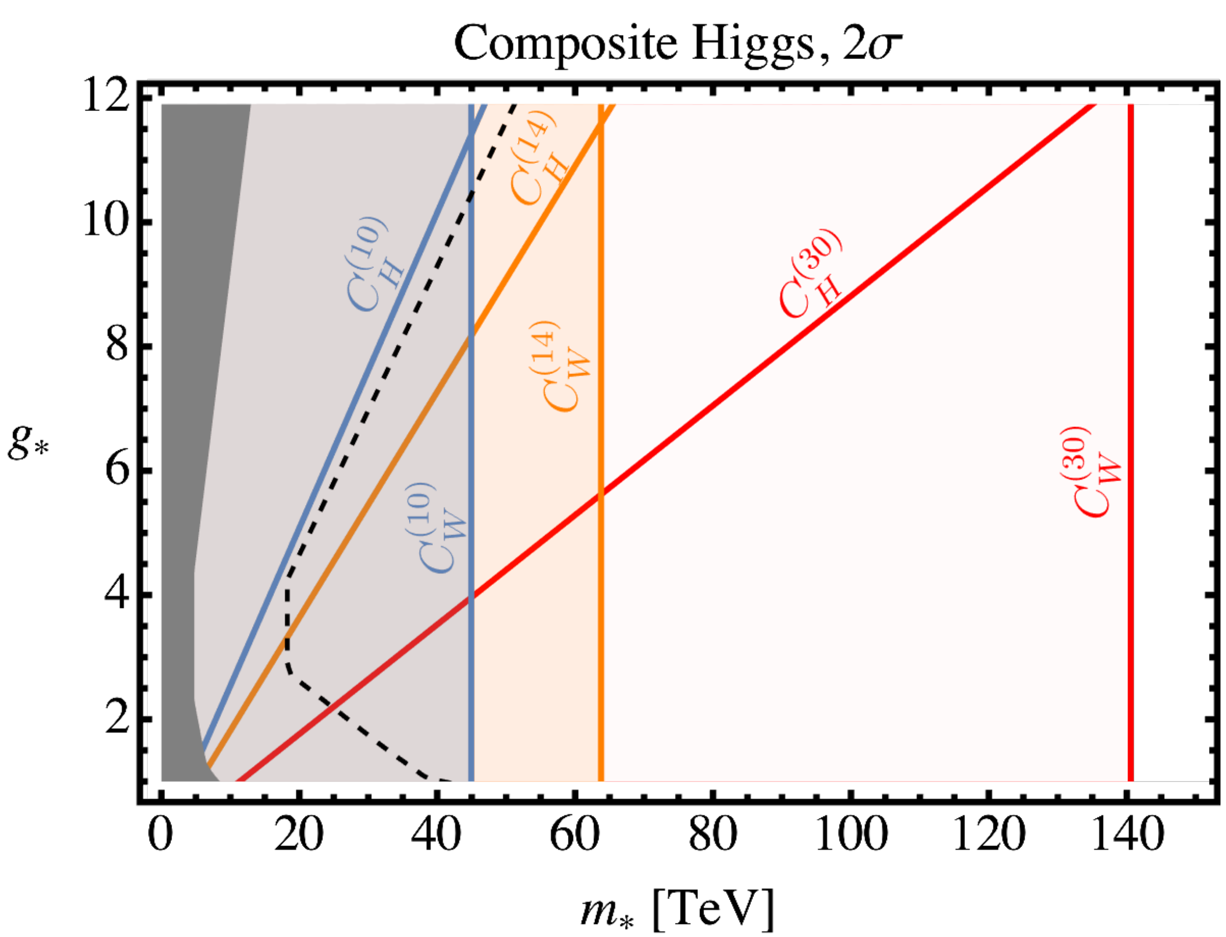

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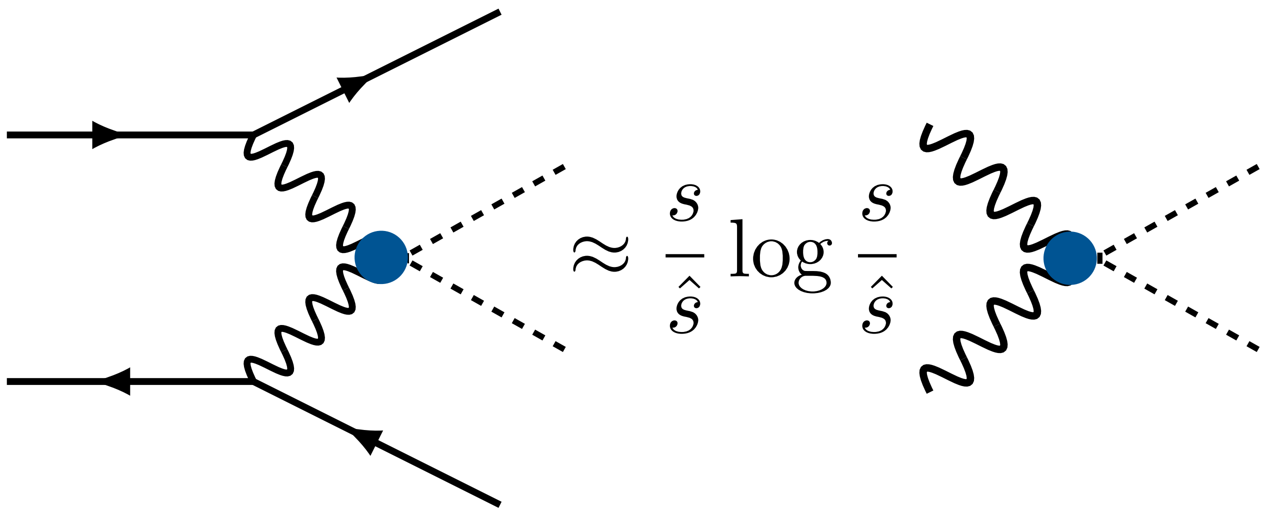
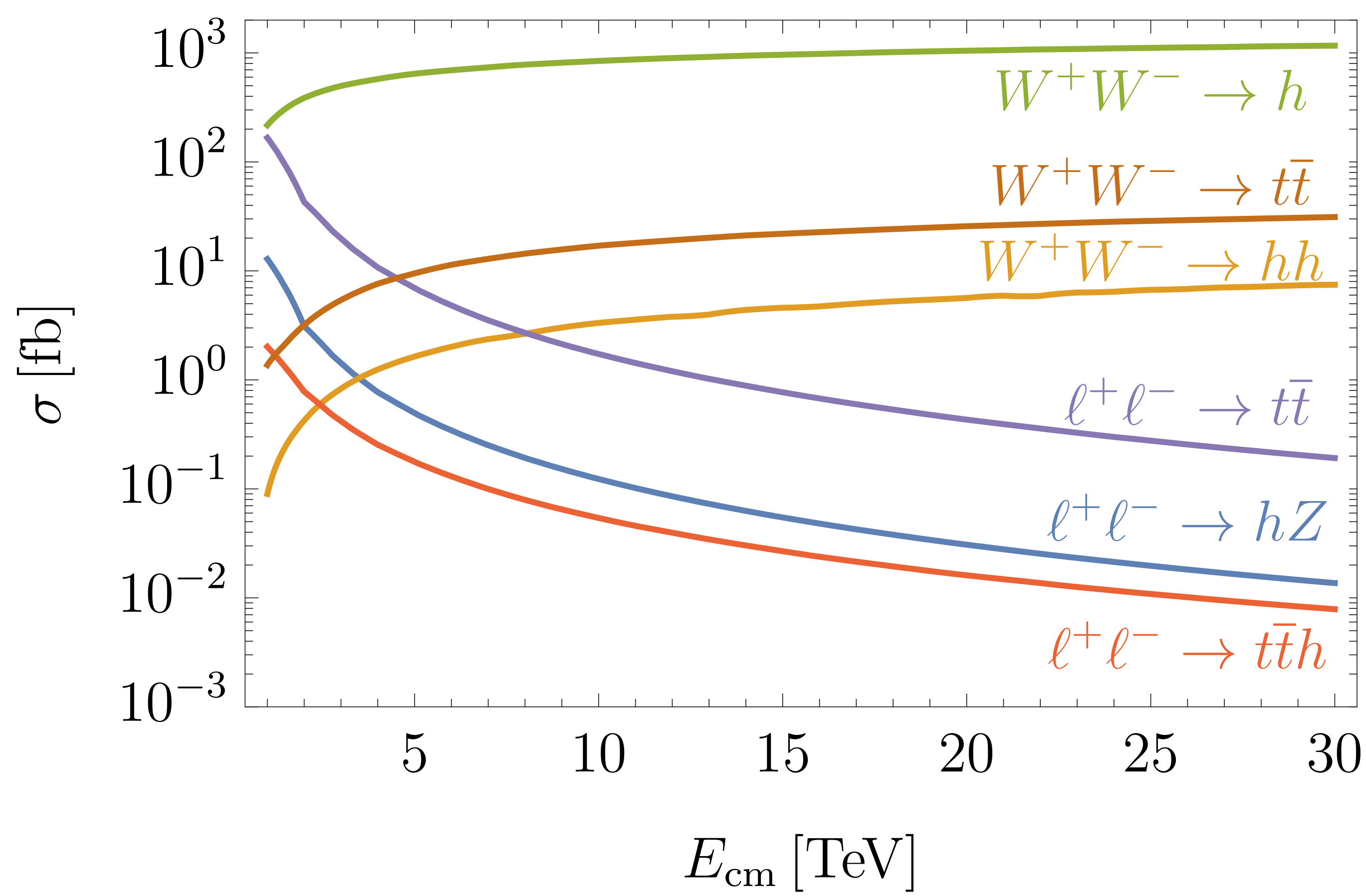
High rate probes: Higgs physics



A High Energy Lepton Collider is a "vector boson collider"

For "soft" final state $\hat{s} \sim m_{\rm EW}^2$ cross-section is enhanced

- ✦ Very large single Higgs VBF rate (10^7–10^8 Higgs bosons)
  - Precision on Higgs couplings driven by systematics: ~ Higgs factory, maybe 1‰
  - Rare/Exotic Higgs decays!
- ✦ Large double Higgs VBF rate
  - Higgs 3-linear coupling

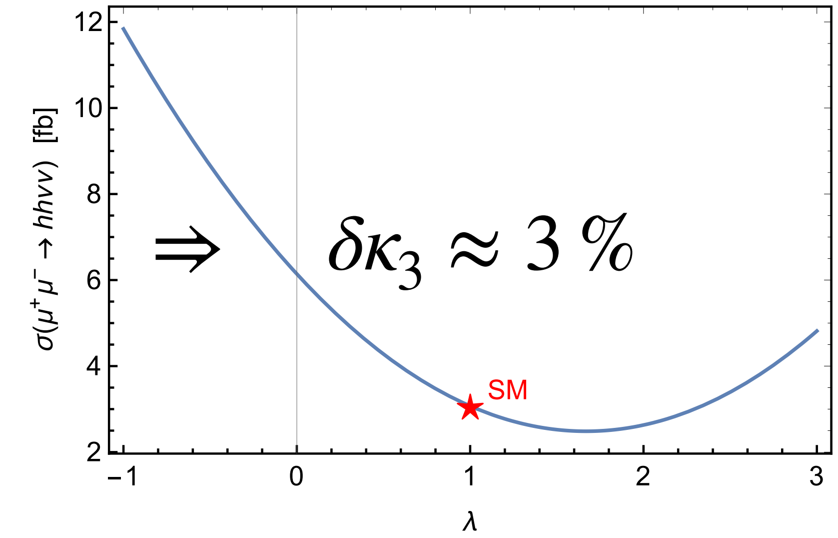


Double Higgs production

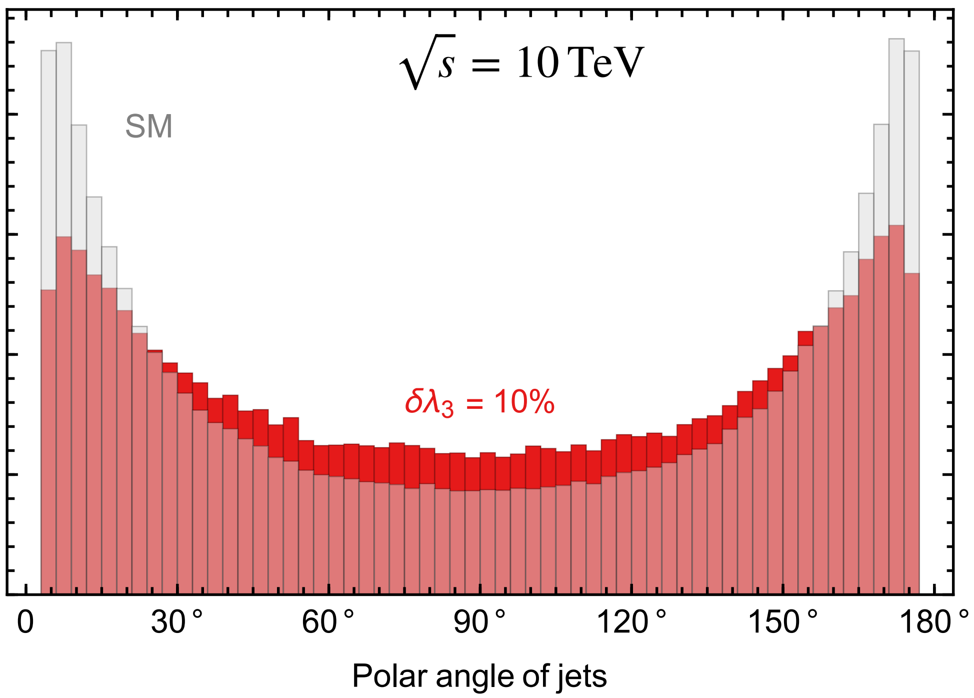
Number of events $\sim s\log(s/m_h^2) \approx 10^5$ at 14 TeV

Naïve estimate of the reach: $\delta\sigma \sim (N\times\epsilon)^{-1/2} \approx 1\,\%$

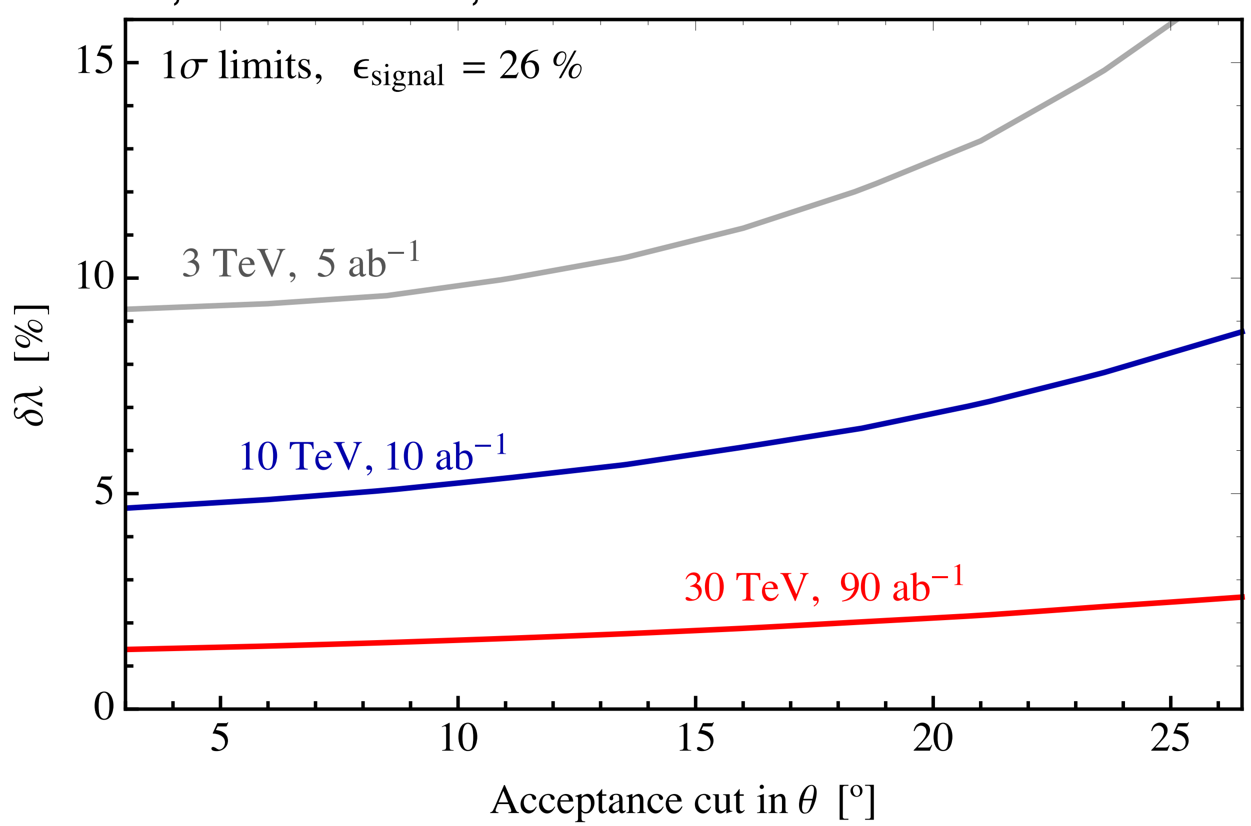
reconstruction eff. $\sim 30\,\%$
$\mathrm{BR}(hh\to 4b) = 34\,\%$
$\Big\}\ \epsilon \sim 10\,\%$



- ✦ **Acceptance cuts** in polar angle θ and p_T of jets:
  - *hh* signal is strongly peaked in forward region



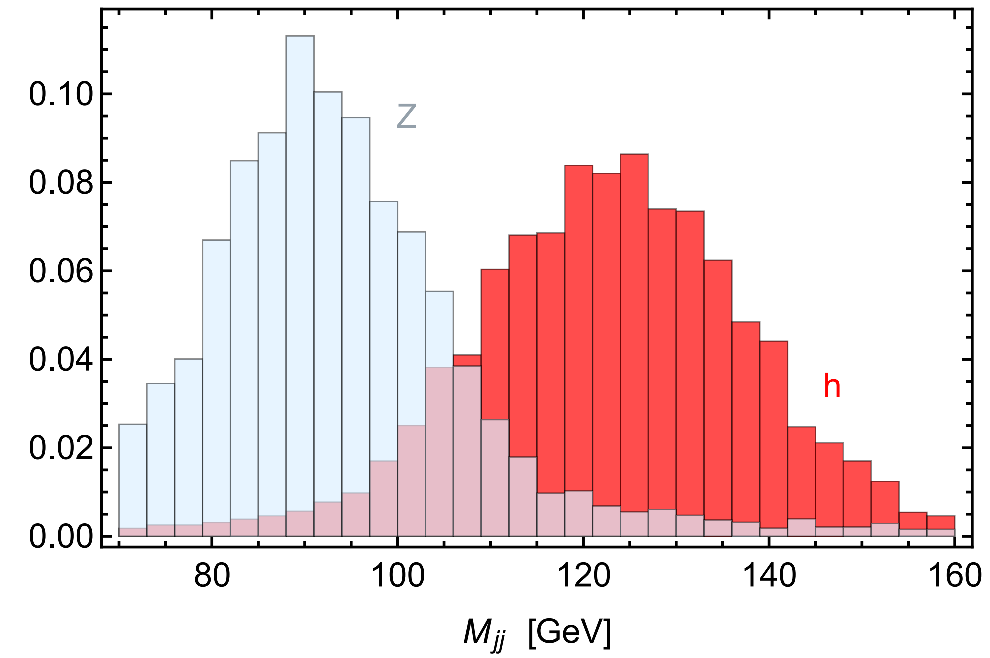
B, Franceschini, Wulzer 2012.11555

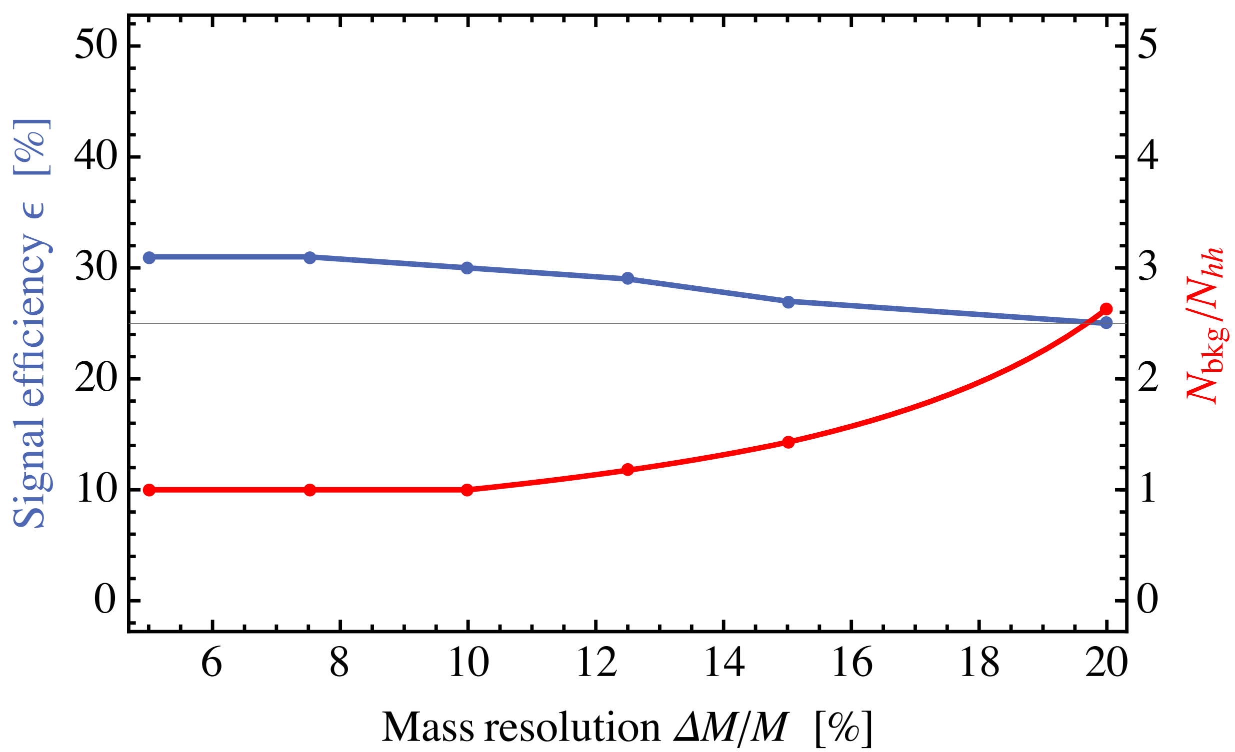


- Contribution from trilinear coupling is more central: loss due to angular cut is less important

Double Higgs production

- **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…
  - Precise invariant mass reconstruction is crucial to isolate signal





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

All this should be done properly with a detector simulation (as has been done for CLIC).

However, perfect agreement with 1901.05897!

B, Franceschini, Wulzer 2012.11555

Double Higgs production

- Reach on Higgs trilinear coupling:

B, Franceschini, Wulzer 2012.11555

see also 2005.12204, 2008.10289

E [TeV]	$\mathscr{L}$ [ab^{-1}]	N_{rec}	$\delta\sigma \sim N_{rec}^{-1/2}$	$\delta\kappa_3$
3	5	170	~ 7.5%	~ 10%
10	10	620	~ 4%	~ 5%
14	20	1340	~ 2.7%	~ 3.5%
30	90	6,300	~ 1.2%	~ 1.5%

  - Weak dependence on detector acceptance
  - Some dependence on detector energy resolution (to remove bkg)

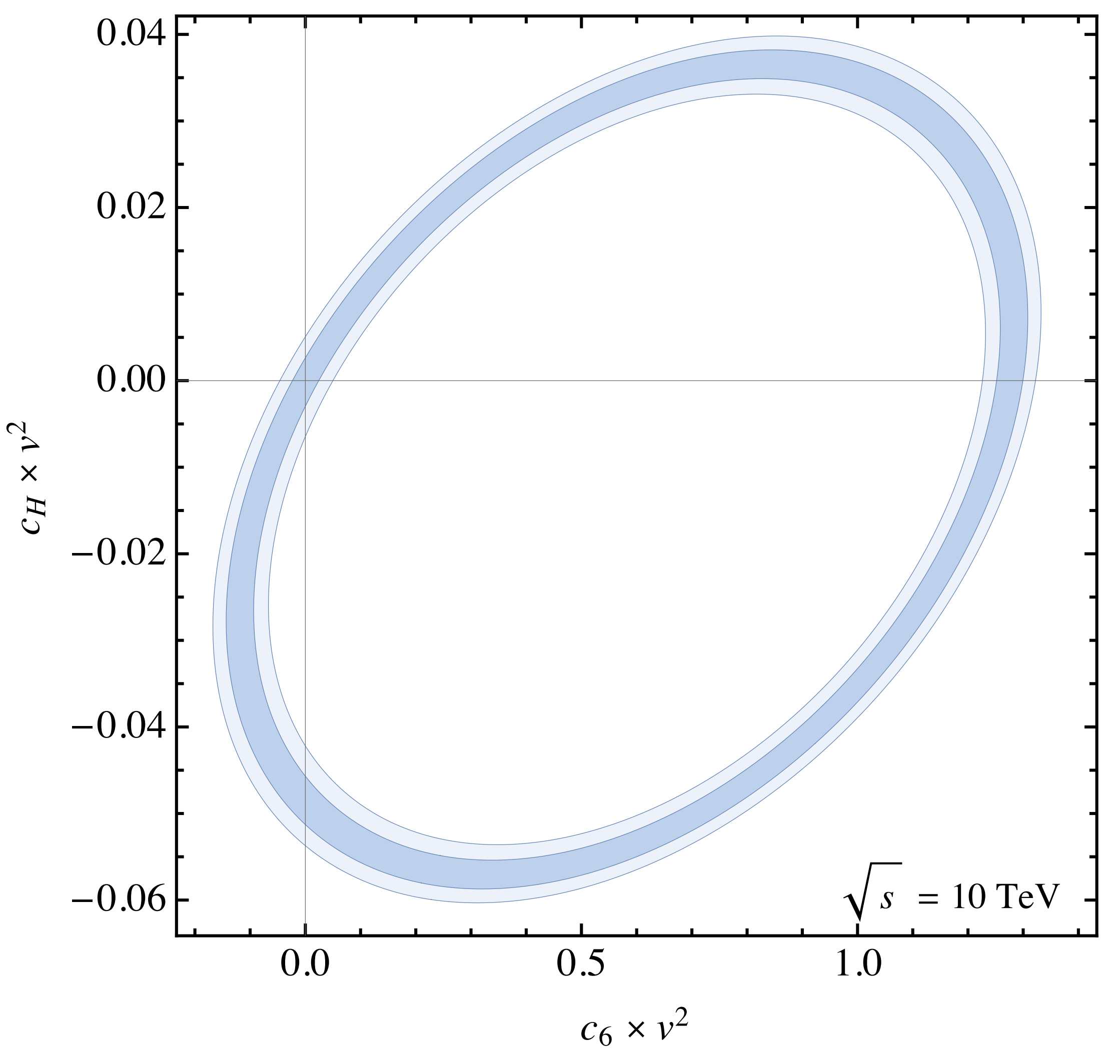
- For comparison, reach of FCC-hh is $\delta\kappa_3$ ~ 3.5% – 8% depending on systematics assumptions

Two-parameter EFT fit

- SM Effective Theory: $\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_i C_i \mathcal{O}_i^{(6)} + \cdots$
- Trilinear coupling is affected by two operators: $\kappa_3 = 1 + v^2\left(C_6 - \frac{3}{2}C_H\right)$

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

O_H also affects single Higgs couplings universally: $\kappa_{V,f} = 1 - v^2 C_H/2$



$$\sigma = \sigma_{\mathrm{SM}} + a_1 C_6 + b_1 C_H + a_2 C_6^2 + b_2 C_H^2 + d_2 C_H C_6$$

large degeneracy in total cross-section: coefficients not determined in general

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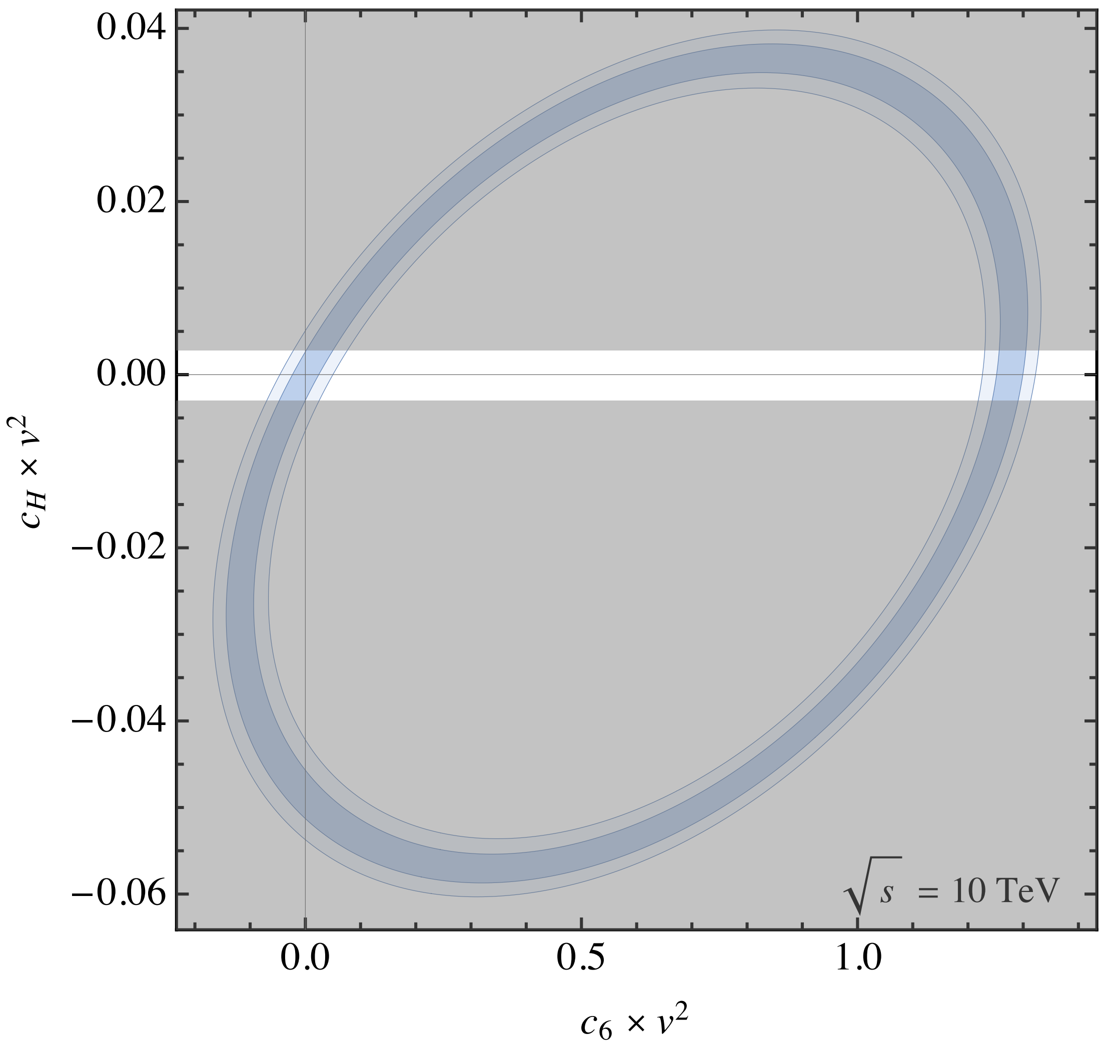

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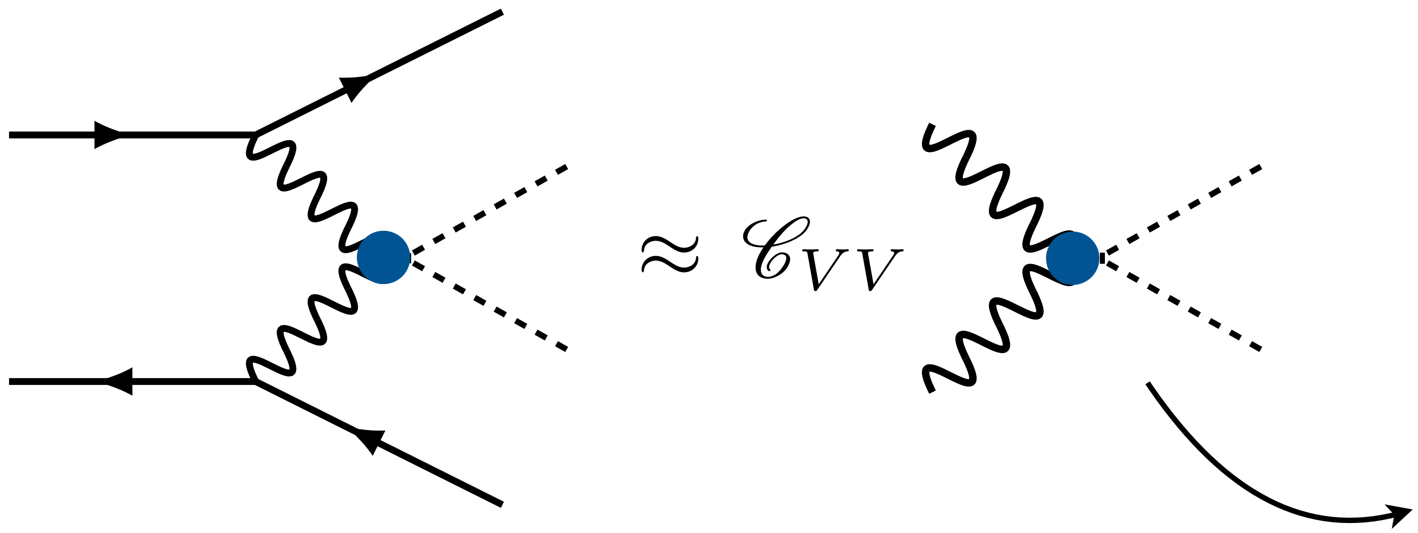
large degeneracy in total cross-section: coefficients not determined in general

c_H can be constrained from Higgs couplings (but indirect measurement)

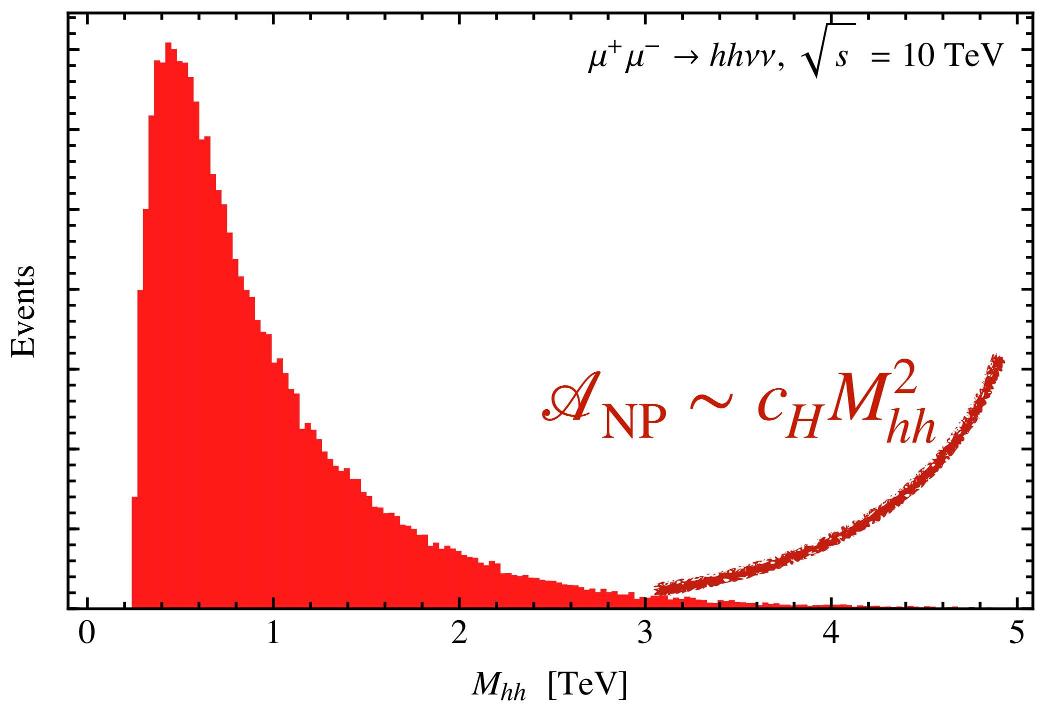
$\Delta\kappa_V \sim C_H v^2 \lesssim$ few $\times 10^{-3}$

Double Higgs at high mass



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

contribution from O_H grows as E^2



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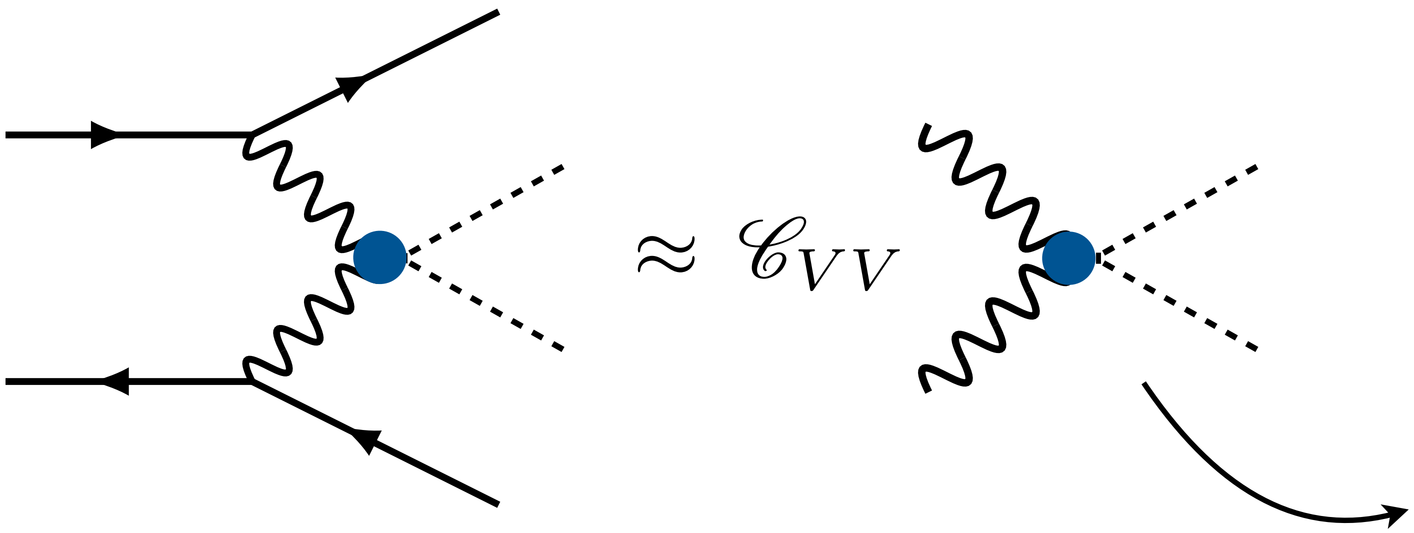

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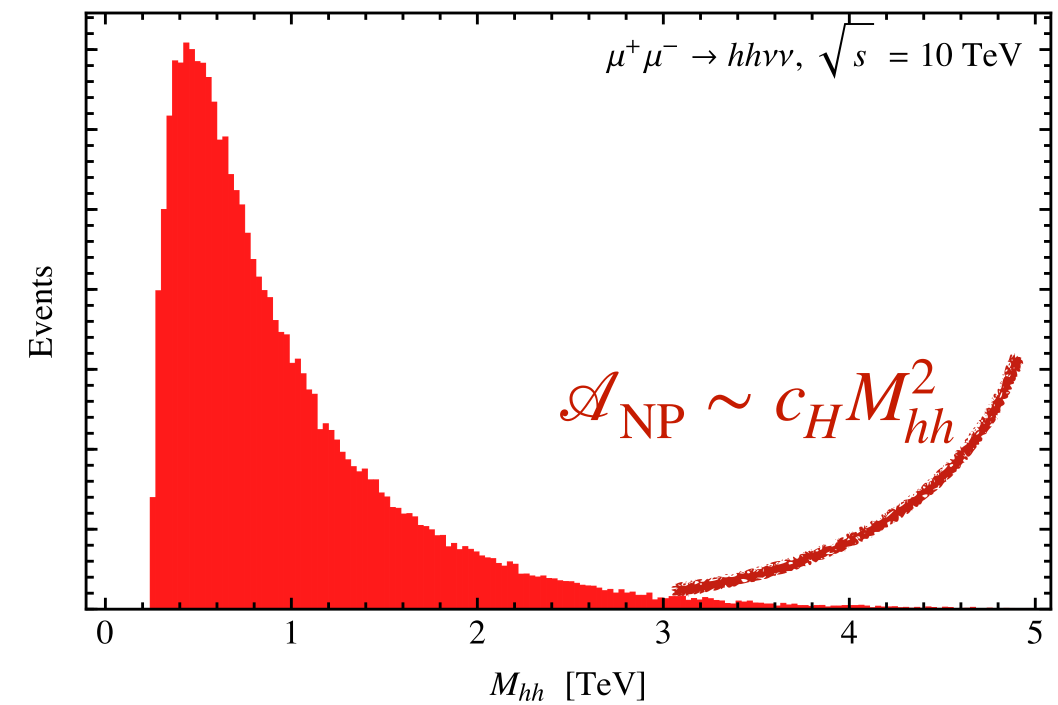

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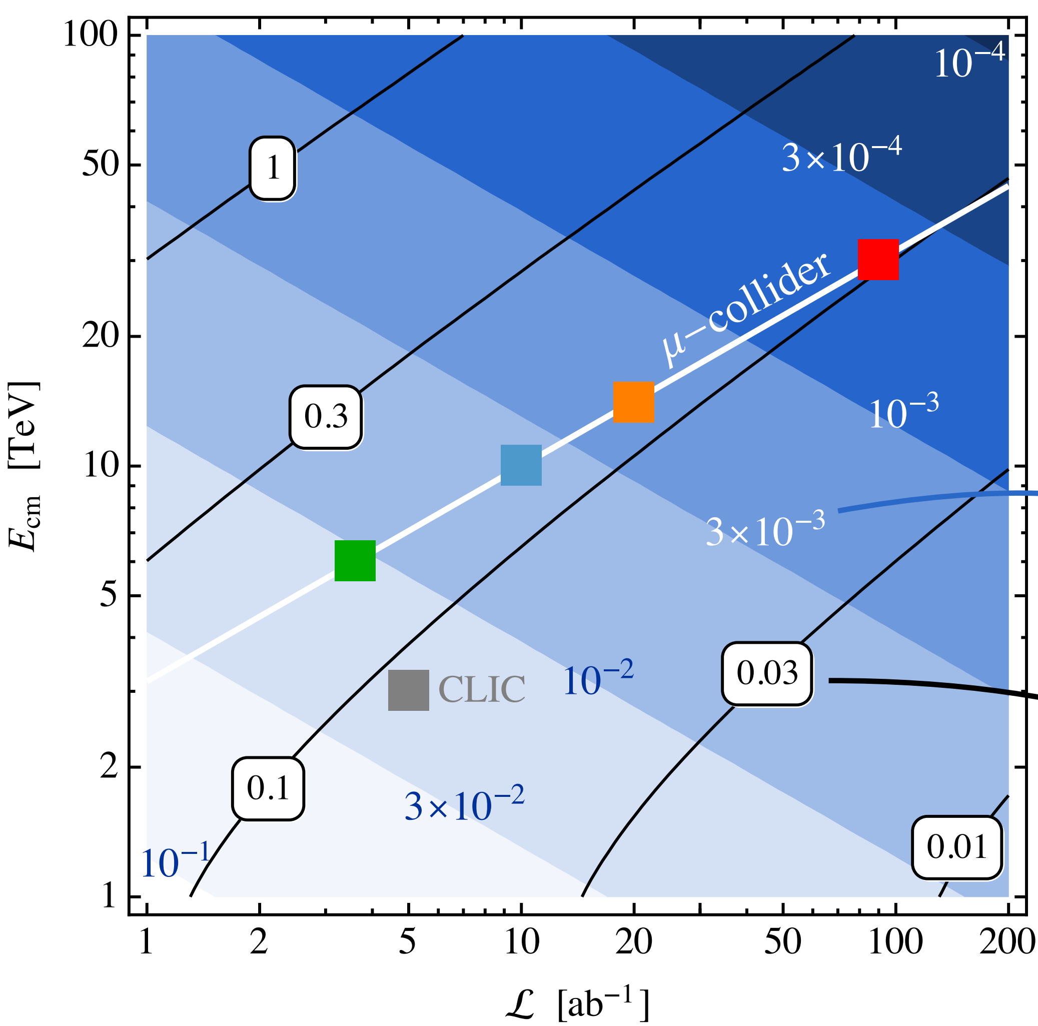


High-energy WW → *hh* becomes more sensitive than Higgs pole physics at energies ≳ 10 TeV

$\xi \equiv C_H v^2$ composite Higgs *v/f*

(see also Contino et al. 1309.7038 for CLIC)

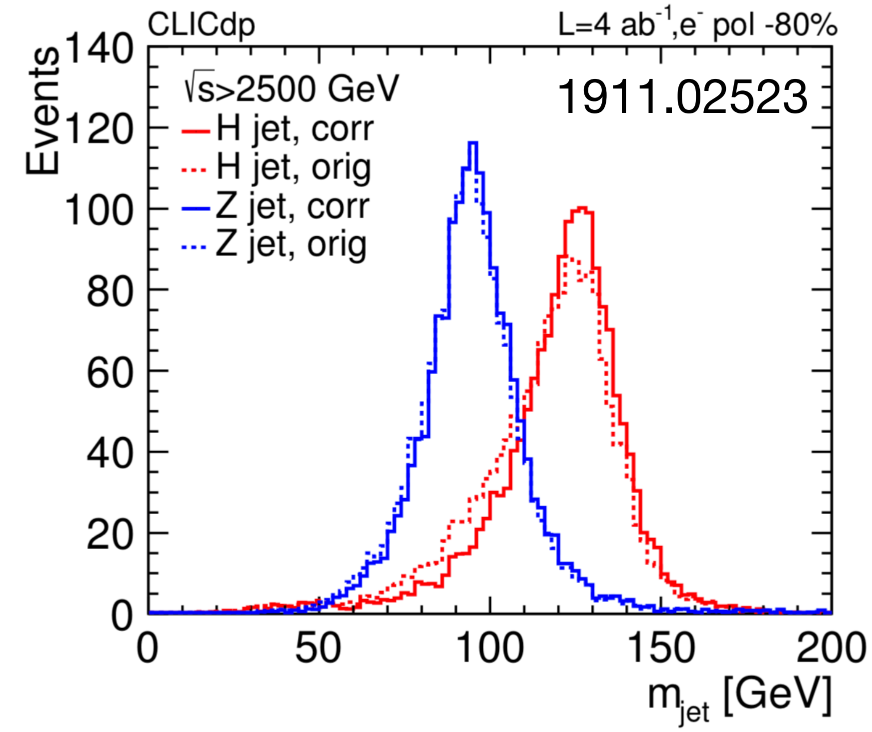
S/B low-precision measurement

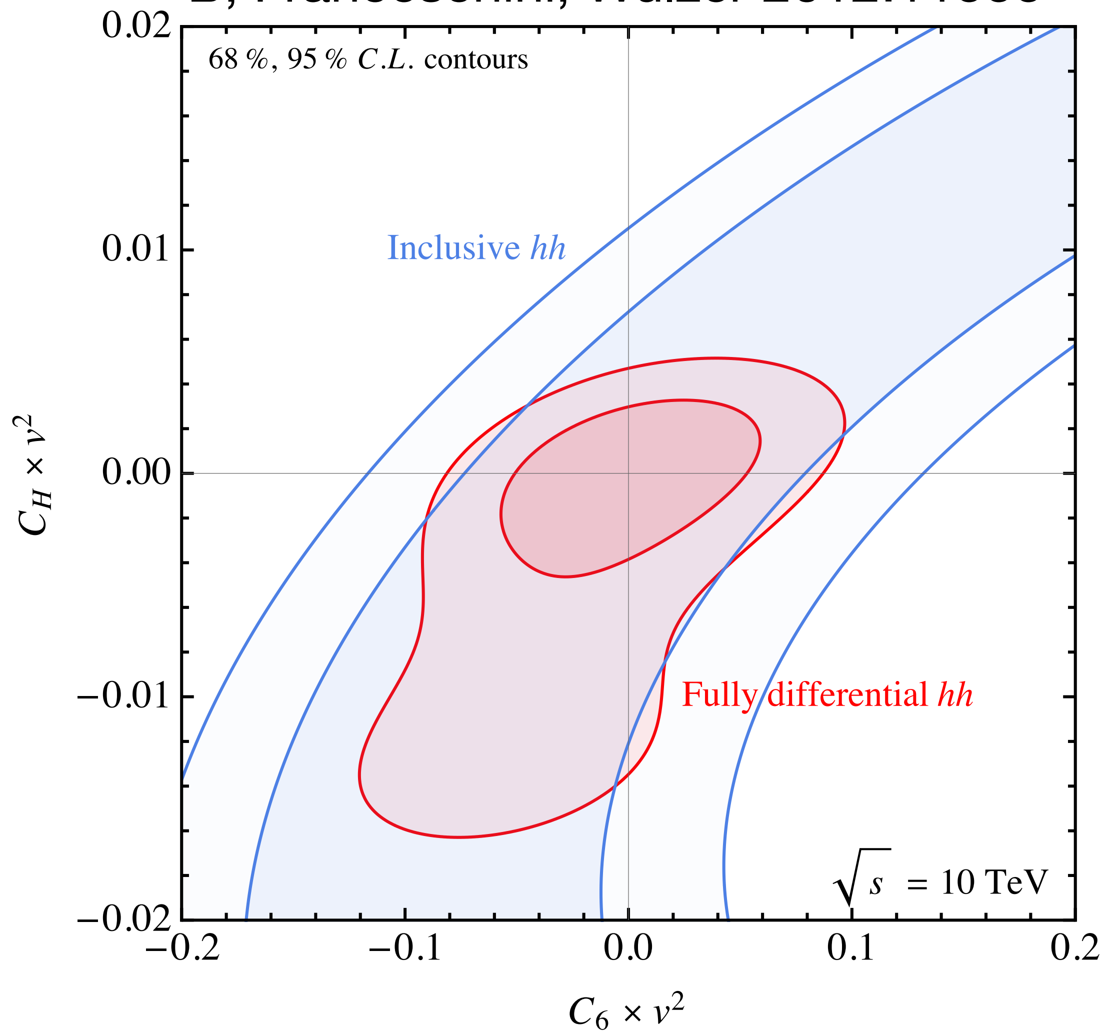
$$\xi \propto \frac{1}{E^2}\frac{1}{\sqrt{N_{\rm bkg}}} \propto \frac{1}{E^2}\frac{1}{\sqrt{\mathcal{L}/E^2}} = \frac{1}{E\sqrt{\mathcal{L}}}$$

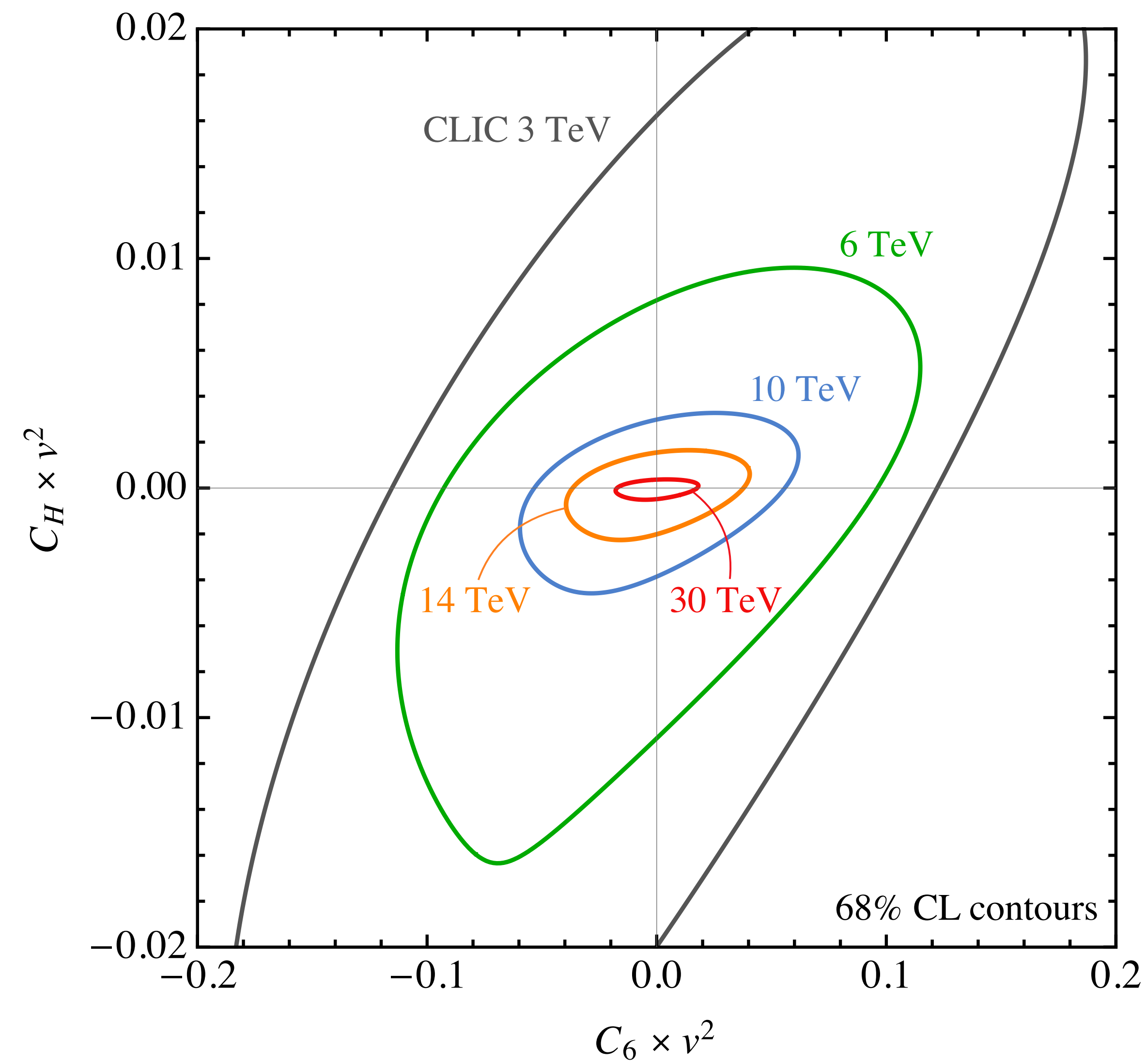
Double Higgs at high mass

- Fully differential analysis in p_T and M_{hh} to optimize combined sensitivity to C_H and C_6
- Very boosted Higgs bosons: treat them as a single h-jet, without reconstructing the 4 b's.

  We assume a boosted-H tagging efficiency ~ 50%

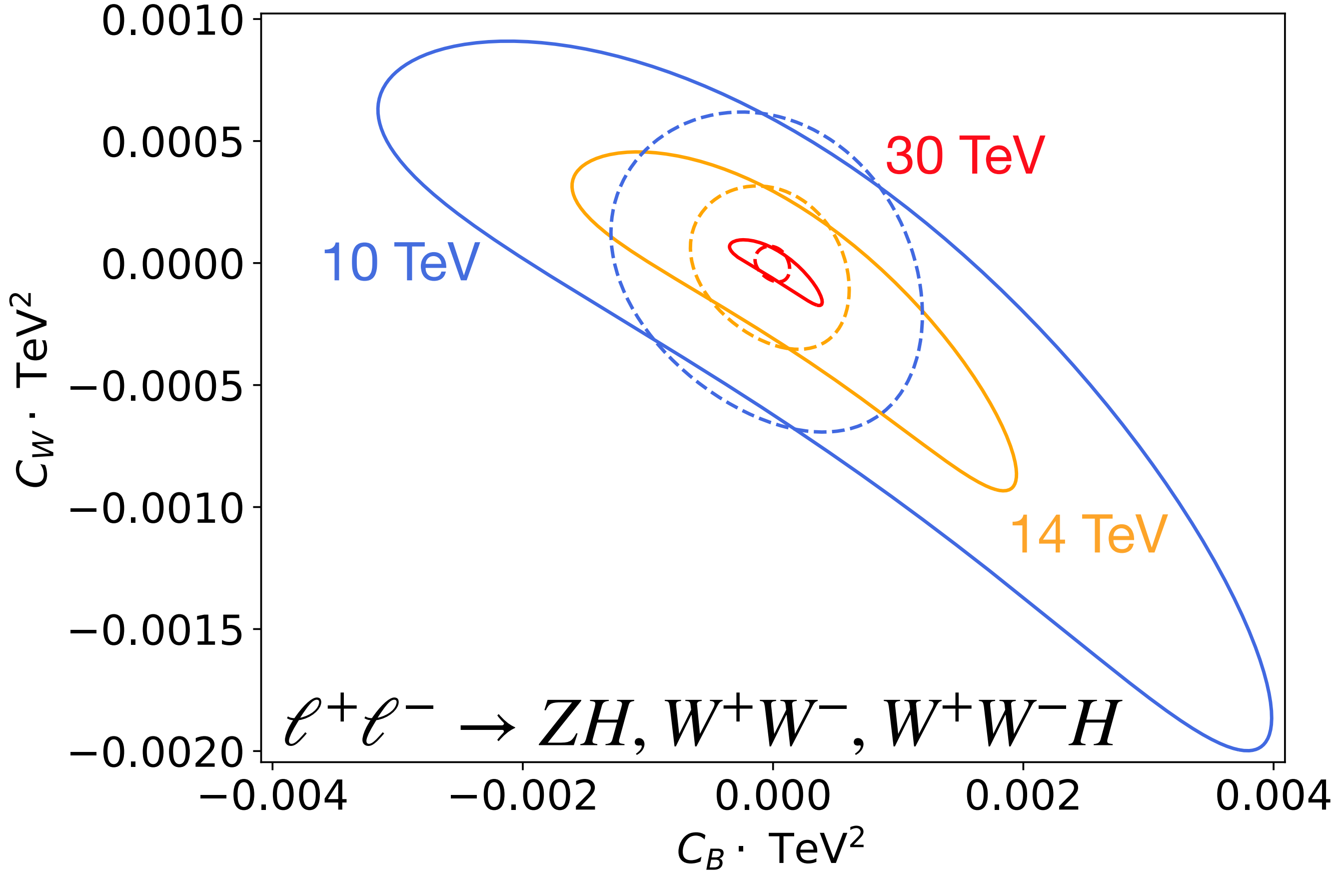


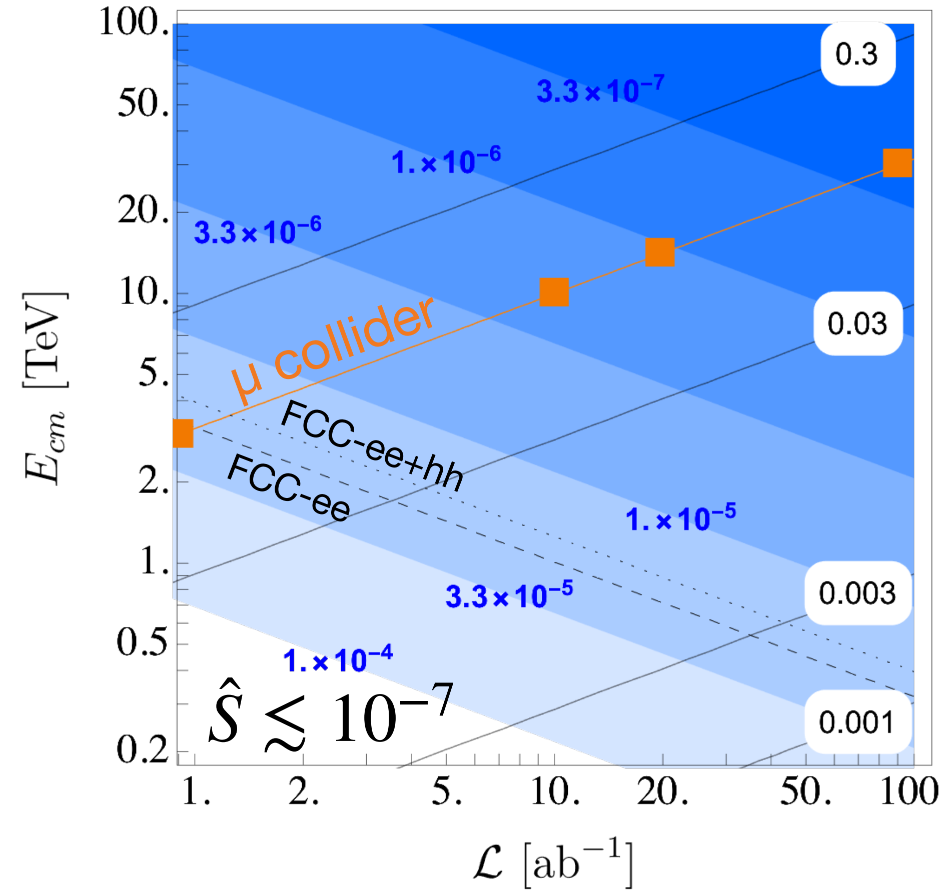




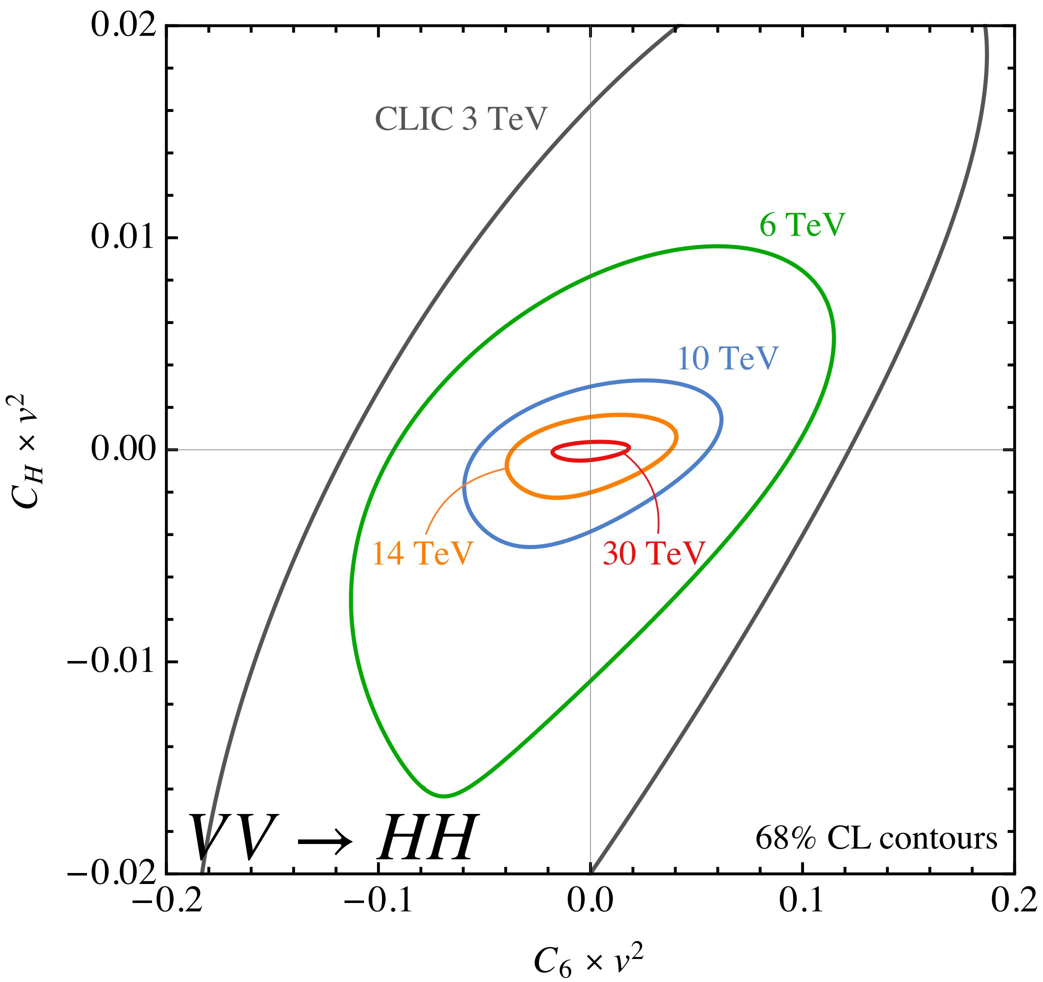
Summary

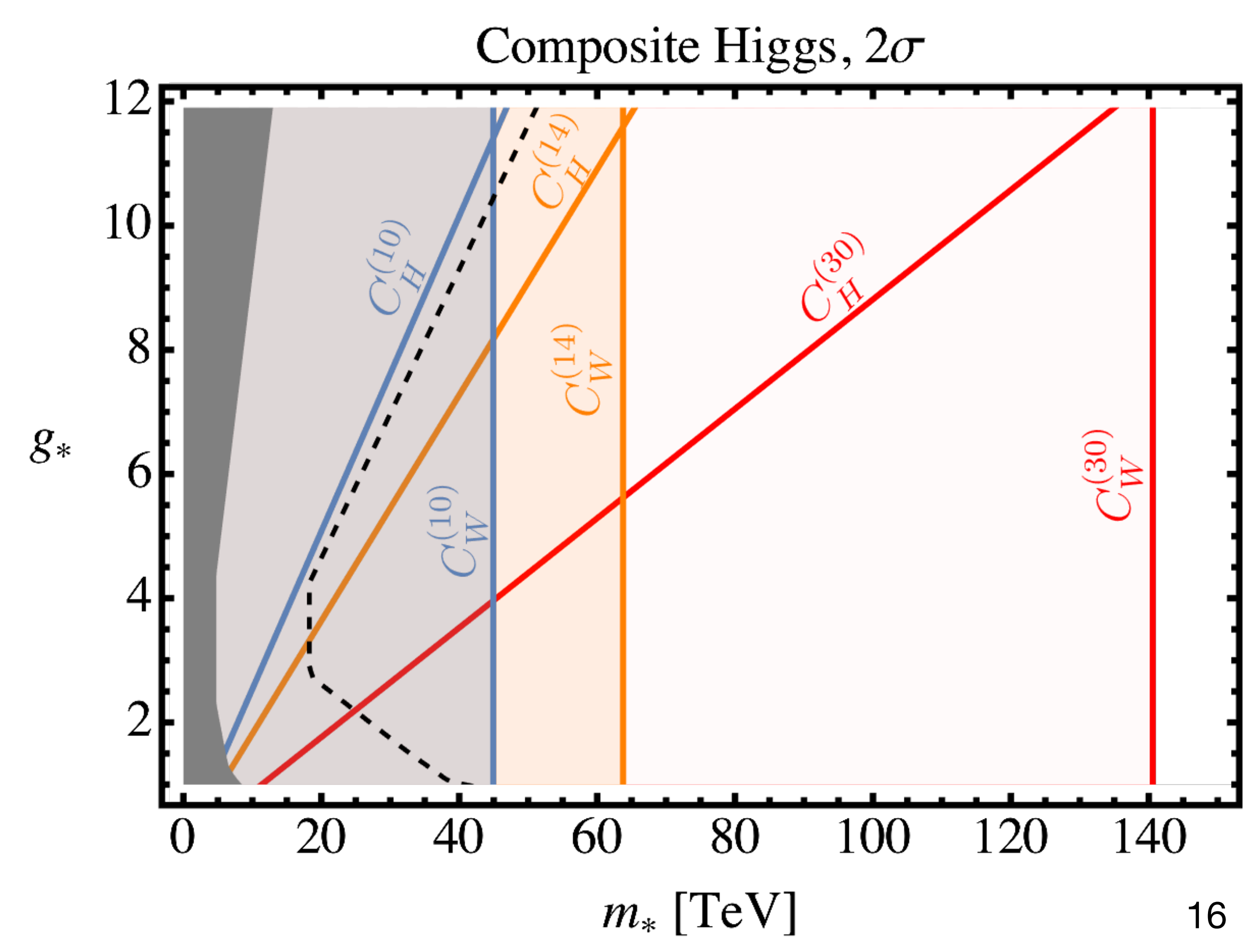
High-energy probes





High-rate measurements





Backup

High-energy WW: angular analysis

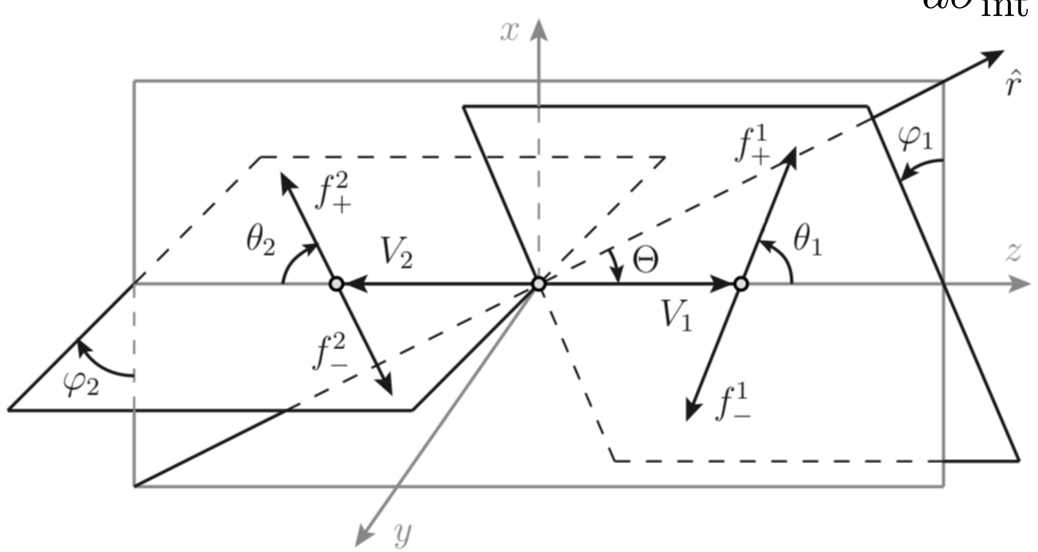
- $O_{W,B}$ contribute to longitudinal scattering amplitudes:

$$\mathcal{A}_{00}^{(\mathrm{NP})} = s\,(G_{1L} - G_{3L})\,\sin\theta_\star$$
$$\mathcal{A}_{-+} = -\frac{g^2}{2}\sin\theta_\star$$
$$\mathcal{A}_{+-} = g^2\cos^2\frac{\theta_\star}{2}\cot^2\frac{\theta_\star}{2}$$

- In the SM, large contribution to $\mu^+\mu^- \to W^+W^-$ from transverse polarizations.

Interference between ±∓ and 00 helicity amplitudes cancels in the total cross-section ⇒ signal suppressed!

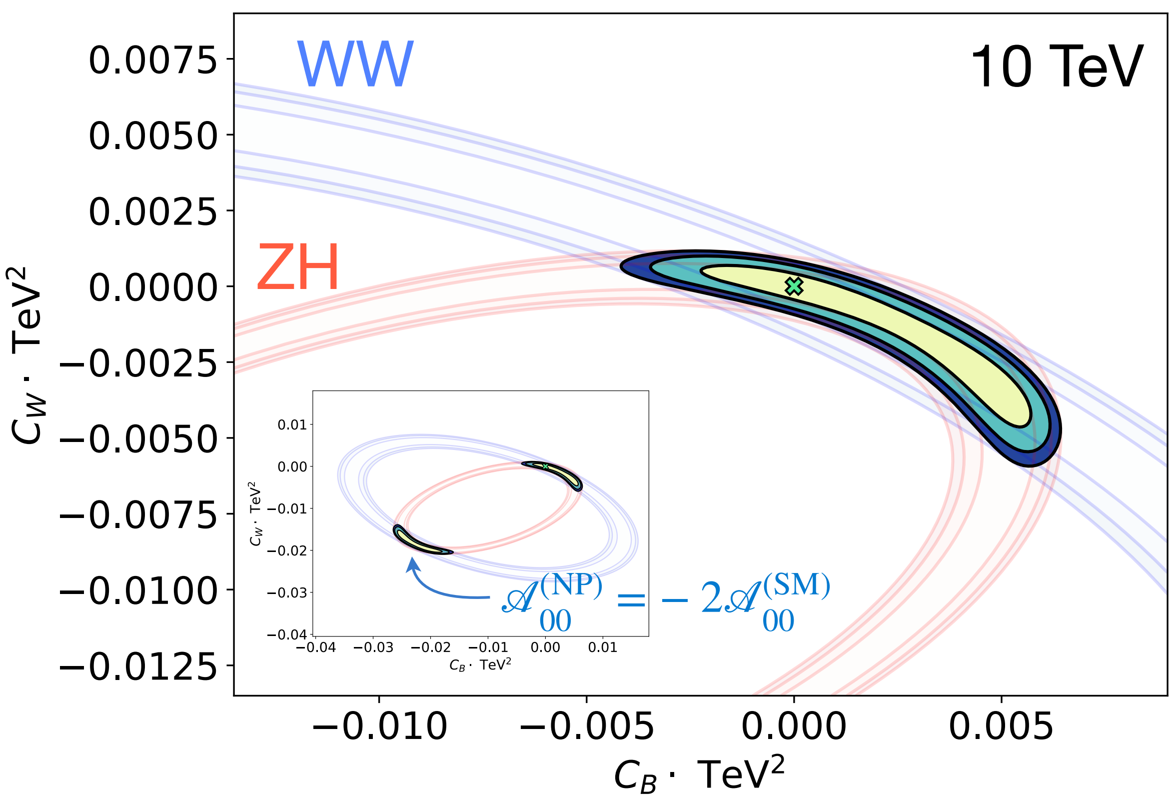
see also Panico et al. 1708.07823, 2007.10356



$$d\sigma_{\mathrm{int}} \propto \mathcal{M}_{00}\mathcal{M}_{+-}\cos(\varphi_+ - \varphi_-)\sin\theta_+(1+\cos\theta_+)\sin\theta_-(1-\cos\theta_-)$$
$$+\mathcal{M}_{00}\mathcal{M}_{-+}\cos(\varphi_+ - \varphi_-)\sin\theta_+(1-\cos\theta_+)\sin\theta_-(1+\cos\theta_-)$$

($\theta_\pm, \varphi_\pm$ polar and azimuthal angle of $W^\pm$ decay products)

- Can exploit the SM/BSM interference by looking at fully differential WW cross-section in scattering and decay angles!



B, Franceschini, Wulzer 2012.11555

High-energy WW: angular analysis

- $O_{W,B}$ contribute to longitudinal scattering amplitudes:

$$\mathscr{A}_{00}^{(\mathrm{NP})} = s\,(G_{1L} - G_{3L})\,\sin\theta_\star$$
$$\mathscr{A}_{-+} = -\frac{g^2}{2}\sin\theta_\star$$
$$\mathscr{A}_{+-} = g^2\cos^2\frac{\theta_\star}{2}\cot^2\frac{\theta_\star}{2}$$

- In the SM, large contribution to $\mu^+\mu^- \to W^+W^-$ from transverse polarizations.

Interference between ±∓ and 00 helicity amplitudes cancels in the total cross-section ⇒ signal suppressed!

see also Panico et al. 1708.07823, 2007.10356

$$d\sigma_{\mathrm{int}} \propto \mathcal{M}_{00}\mathcal{M}_{+-}\cos(\varphi_+ - \varphi_-)\sin\theta_+(1+\cos\theta_+)\sin\theta_-(1-\cos\theta_-)$$
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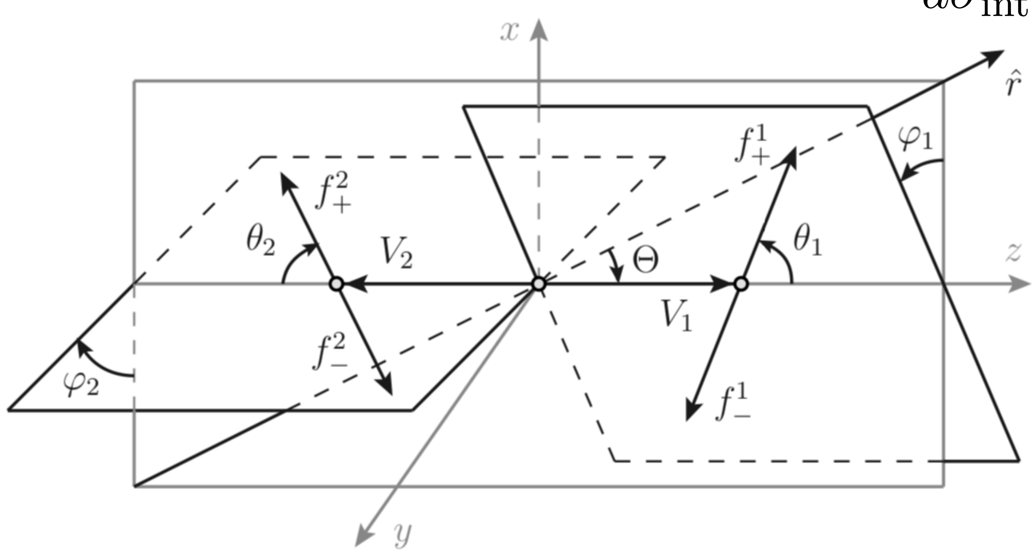
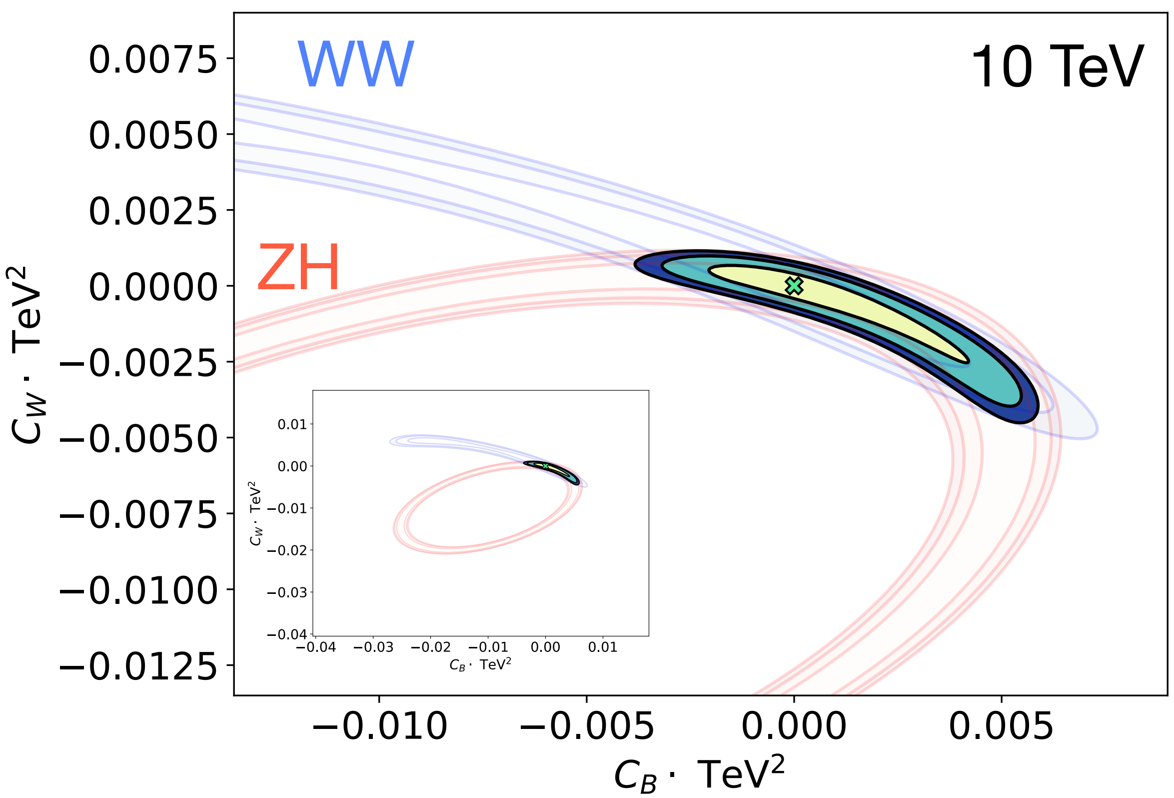




- Can exploit the SM/BSM interference by looking at fully differential WW cross-section in scattering and decay angles!

B, Franceschini, Wulzer 2012.11555

$hh \to 4b$ signal

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

  E.g. for pT > 10 GeV, θ > 10º:

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

BR($hh \to 4b$) = 34%

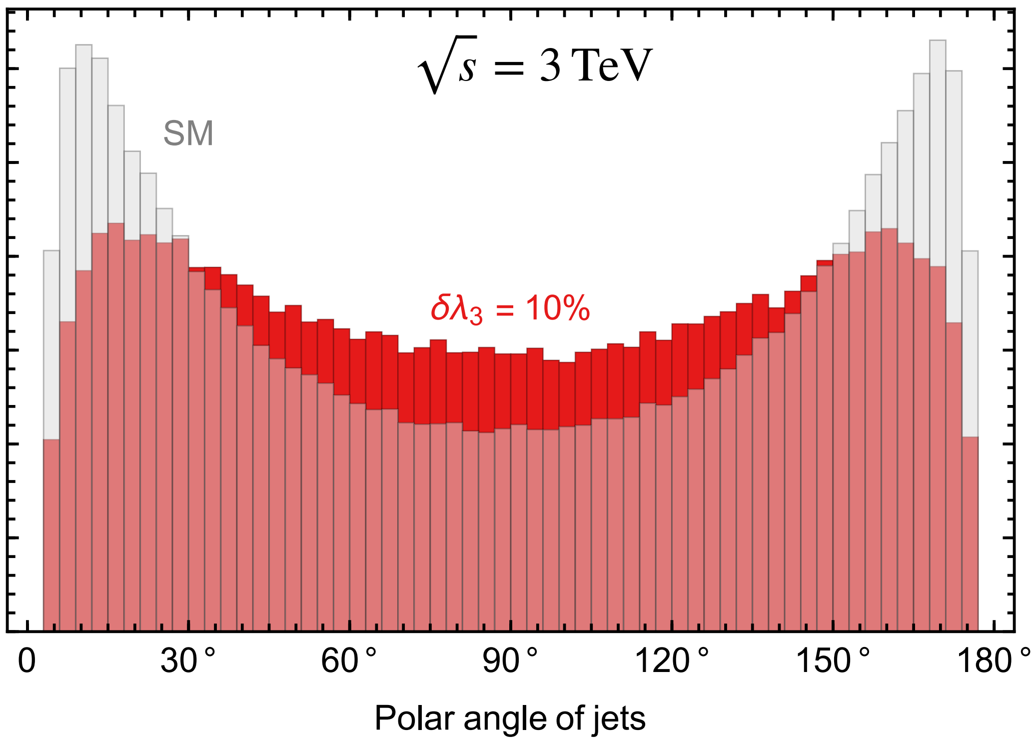
factor 10 loss in xsec at 30 TeV

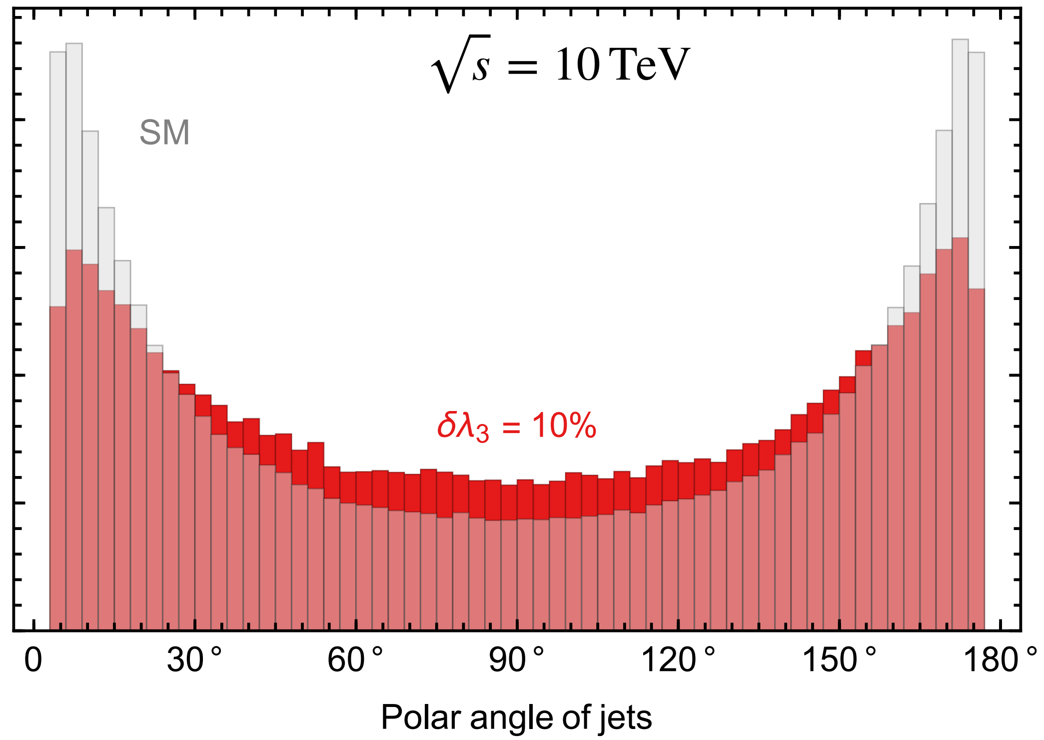
- **Neglect backgrounds** (for the moment)

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

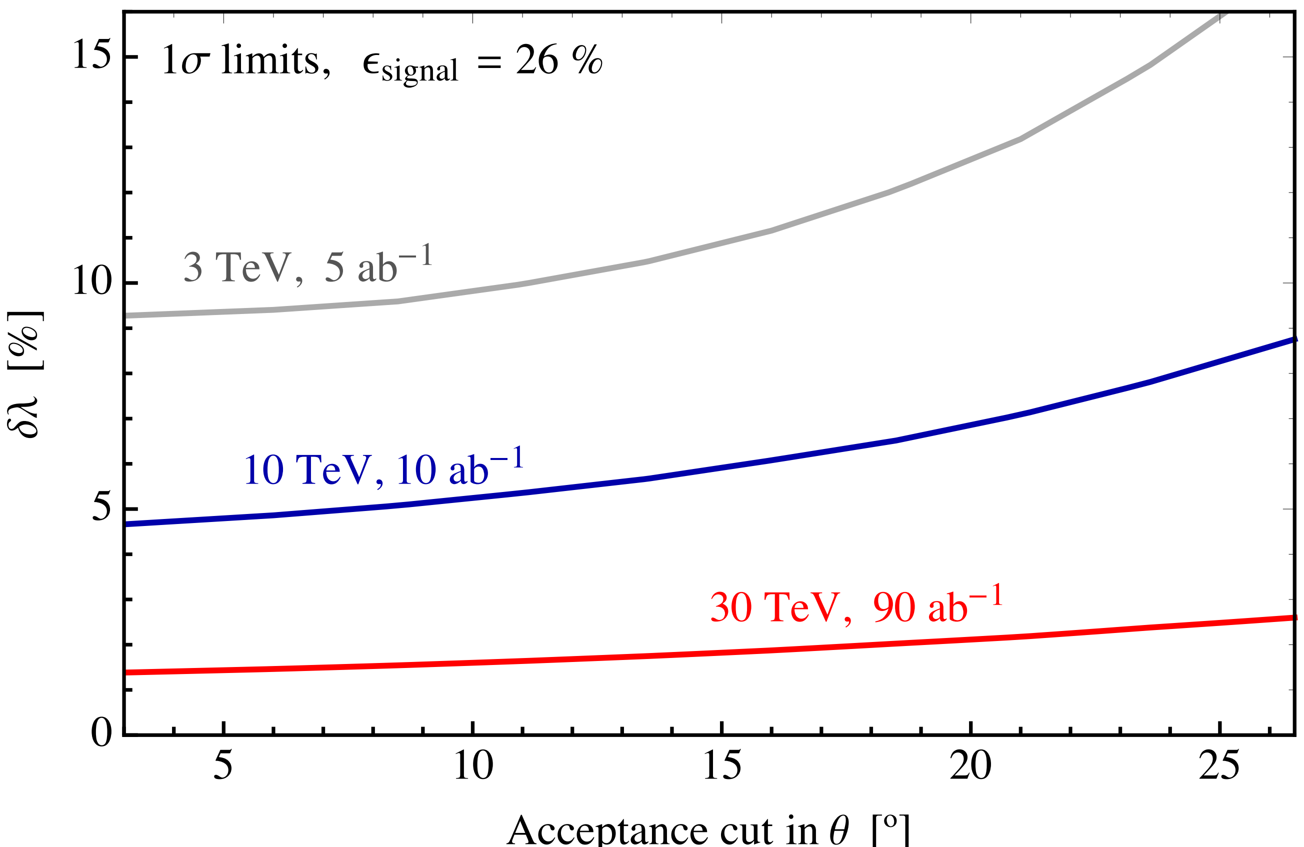
$\sqrt{s}$ [TeV]	L [ab^{-1}]	σ [fb]	N_{rec}	$\delta\sigma \sim N_{\rm rec}^{-1/2}$	$\delta\lambda$
3	5	0.13	170	~ 7.5%	~ 10%
10	10	0.24	630	~ 4%	~ 5%
30	90	0.74	6,300	~ 1.2%	~ 1.5%

Sensitivity to angular acceptance



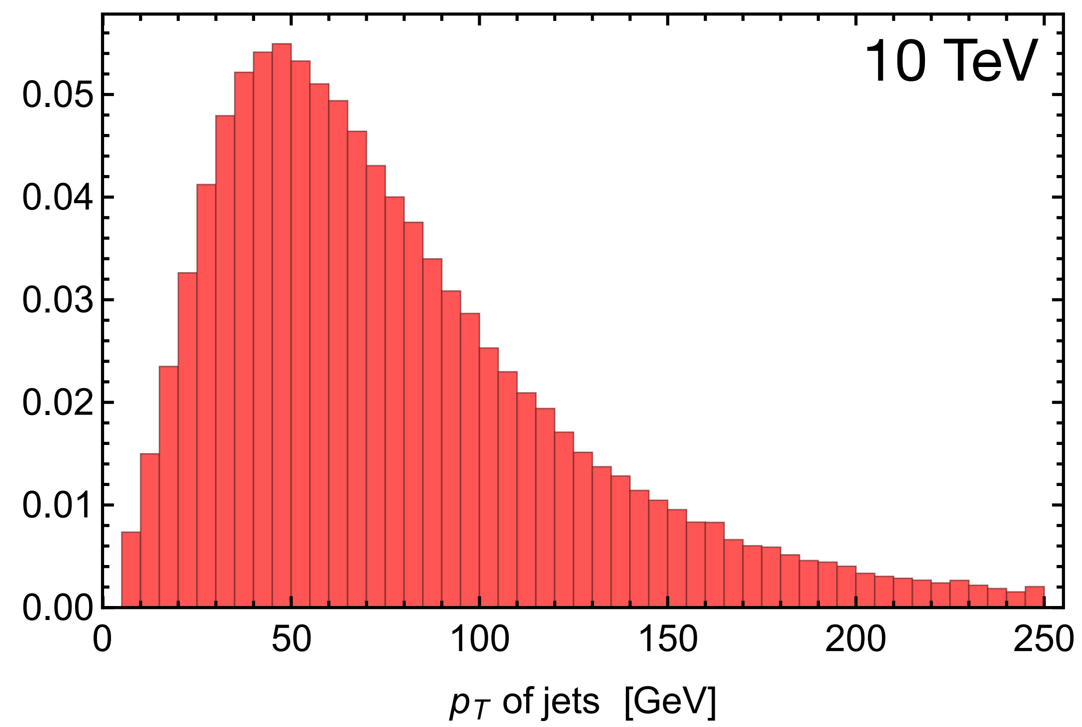


- *hh* signal is strongly peaked in the forward region
- Contribution from trilinear coupling is more central: loss due to angular cut is less important



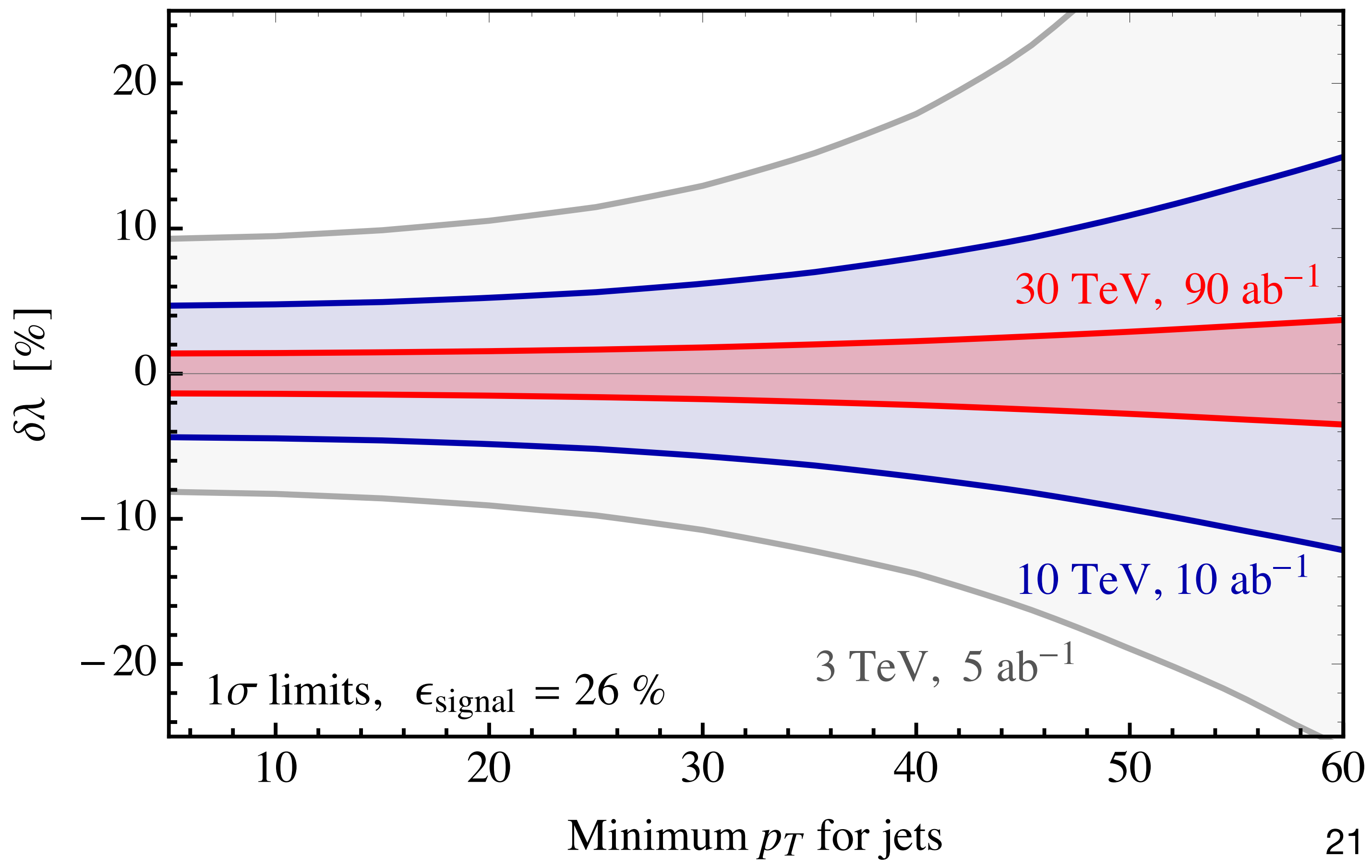
Sensitivity to jet p_T threshold

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



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

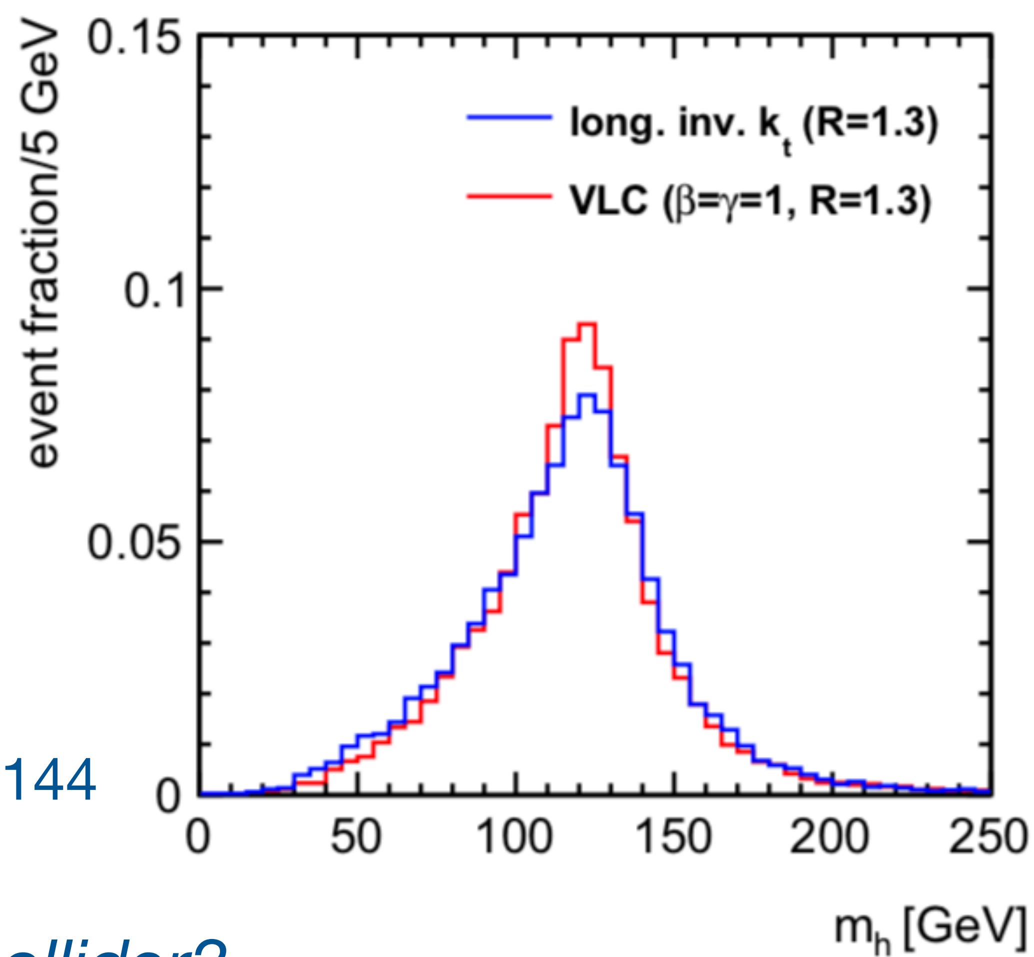
  higher thresholds start to reduce the sensitivity



Backgrounds for HH

- 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

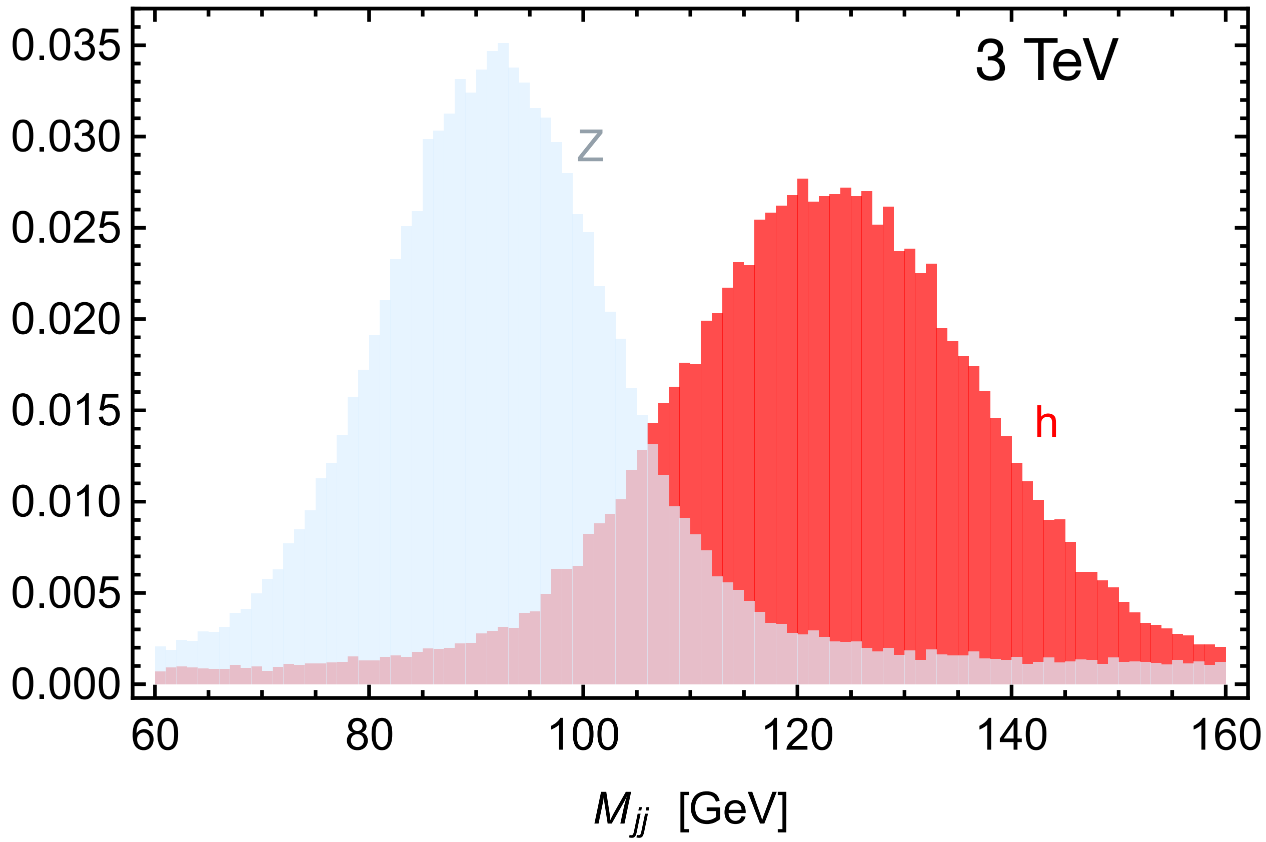
Eur. Phys. J. C (2018) 78:144

what happens at muon collider?

Backgrounds for HH

(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,

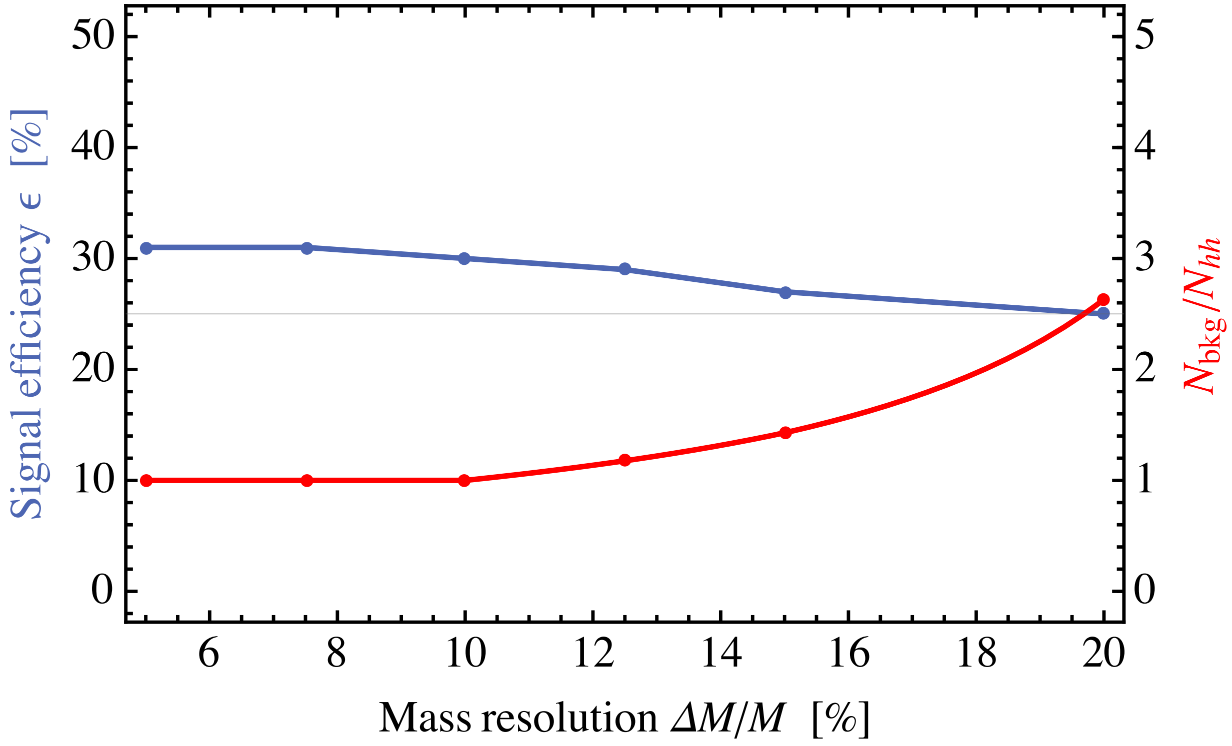
  $n_b = 3.2$

  $\varepsilon_{sig} = 27\%$

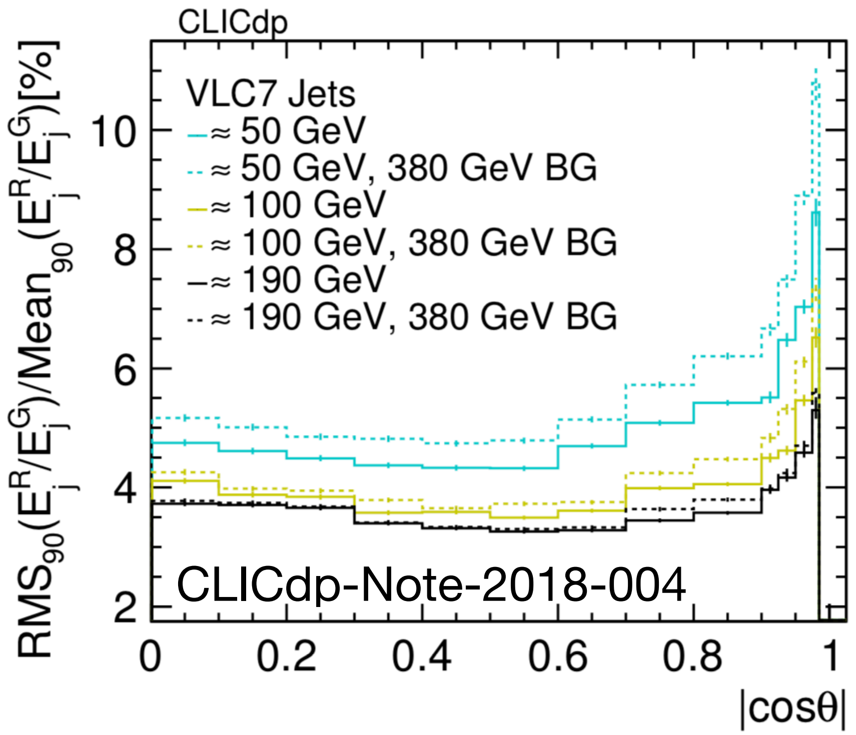
NB: all this should be done properly (and has been done, for CLIC), with a detector simulation

Backgrounds for HH

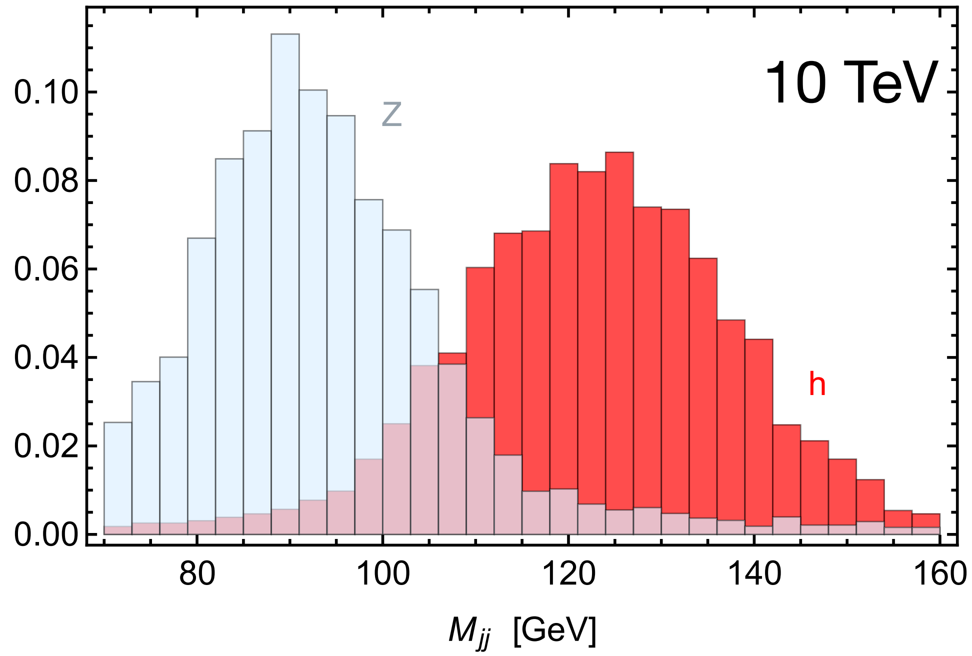
One can now repeat the analysis for different jet energy resolutions:



no real gain using only central events…



… and different energies:



- Optimize cuts to reject bkg:

  $M_{hh} > 105$ GeV,

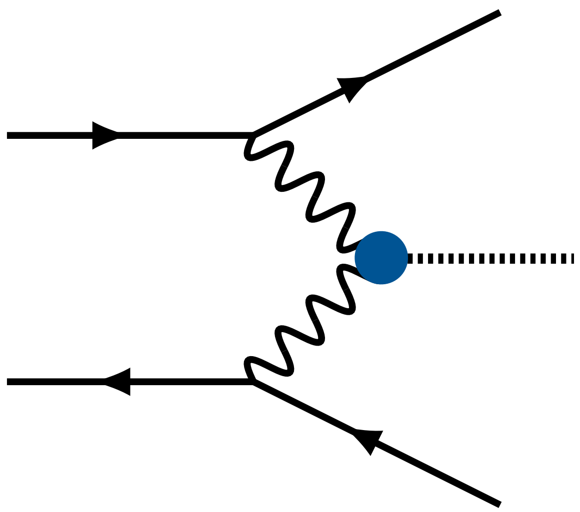
  $n_b = 2.8$

  $\varepsilon_{sig} = 32\%$

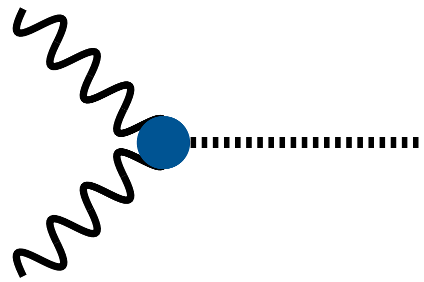
result very similar to 3 TeV

Resonances in VBF

The μ-collider is a "vector boson collider"



$$\approx \frac{E^2}{m_\phi^2}\log\frac{E^2}{m_\phi^2}$$



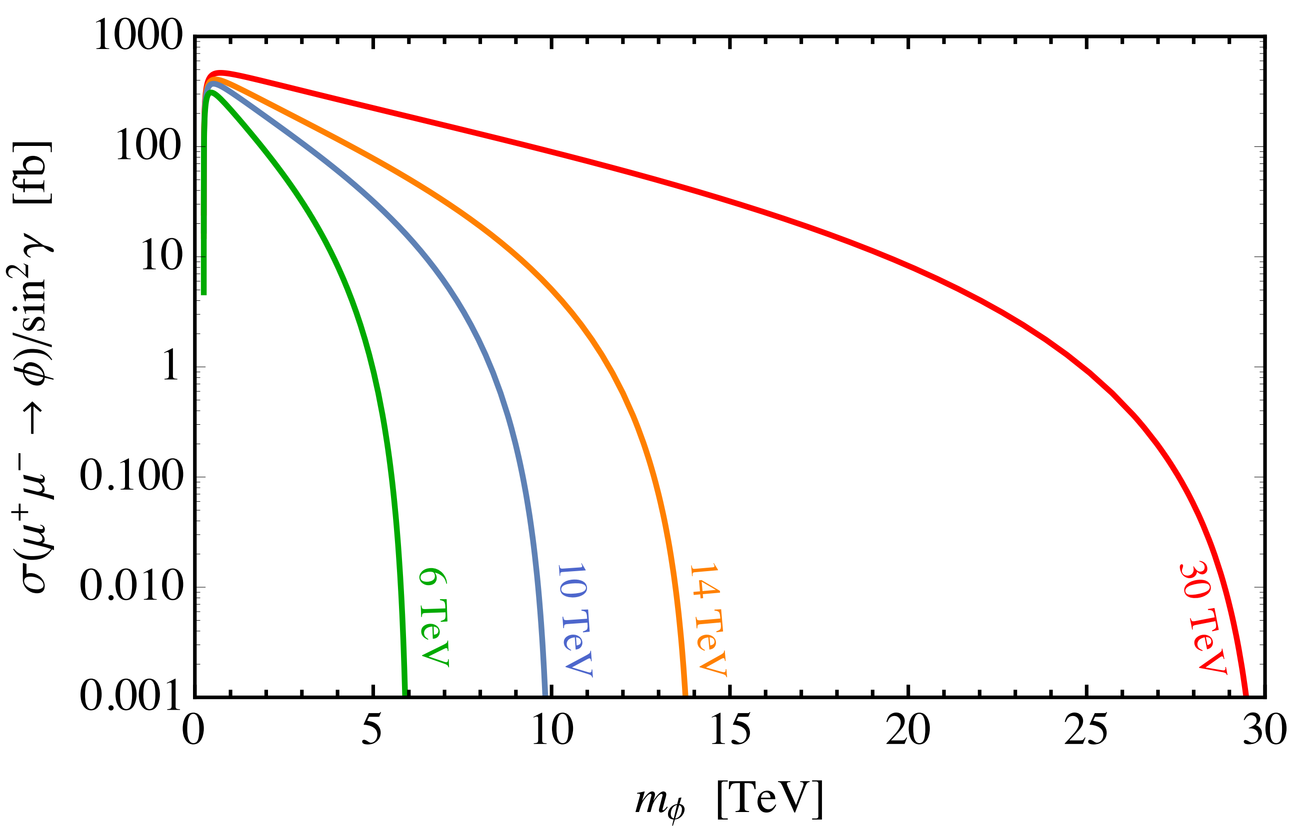
enhanced if the resonance is "light" $m_\phi \ll E$

Dawson 1985

B, Redigolo, Sala, Tesi 1807.04743
Costantini et al. 2005.10289

see also the "Muon Smasher's guide" Arkani-Hamed, Craig et al. to appear soon!

- Example: singlet 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

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

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

A simple example: scalar singlet

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

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

portal coupling

triple couplings:
BR(*ϕ* → *hh*), g_{hhh}

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

mass eigenstates:

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

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

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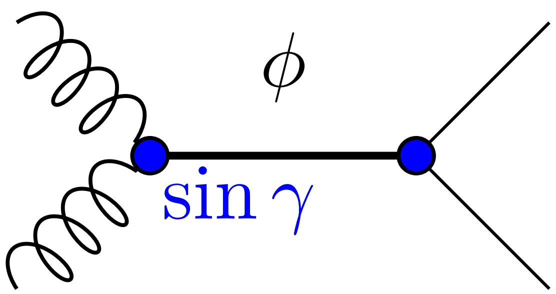
$$\sin\gamma \sim \frac{a_{HS} v}{m_S^2}$$

mass eigenstates:

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

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

- ϕ can be singly produced:

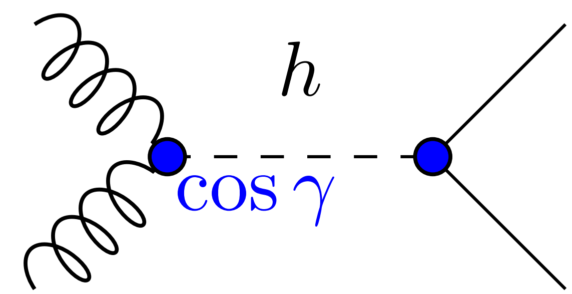


$$\sigma_\phi = \sigma_{\rm SM}(m_\phi) \times \sin^2\gamma$$

- ϕ decays to SM:

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

- Higgs signal strengths:

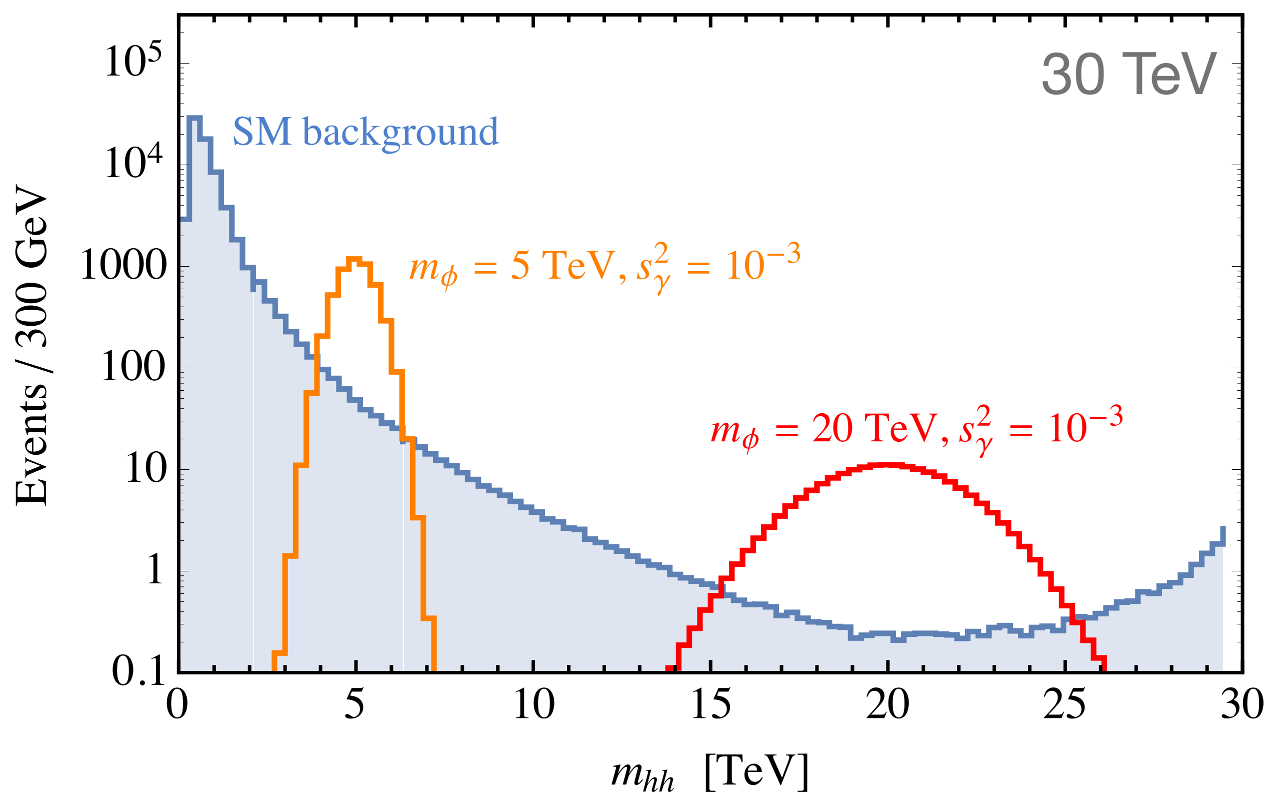


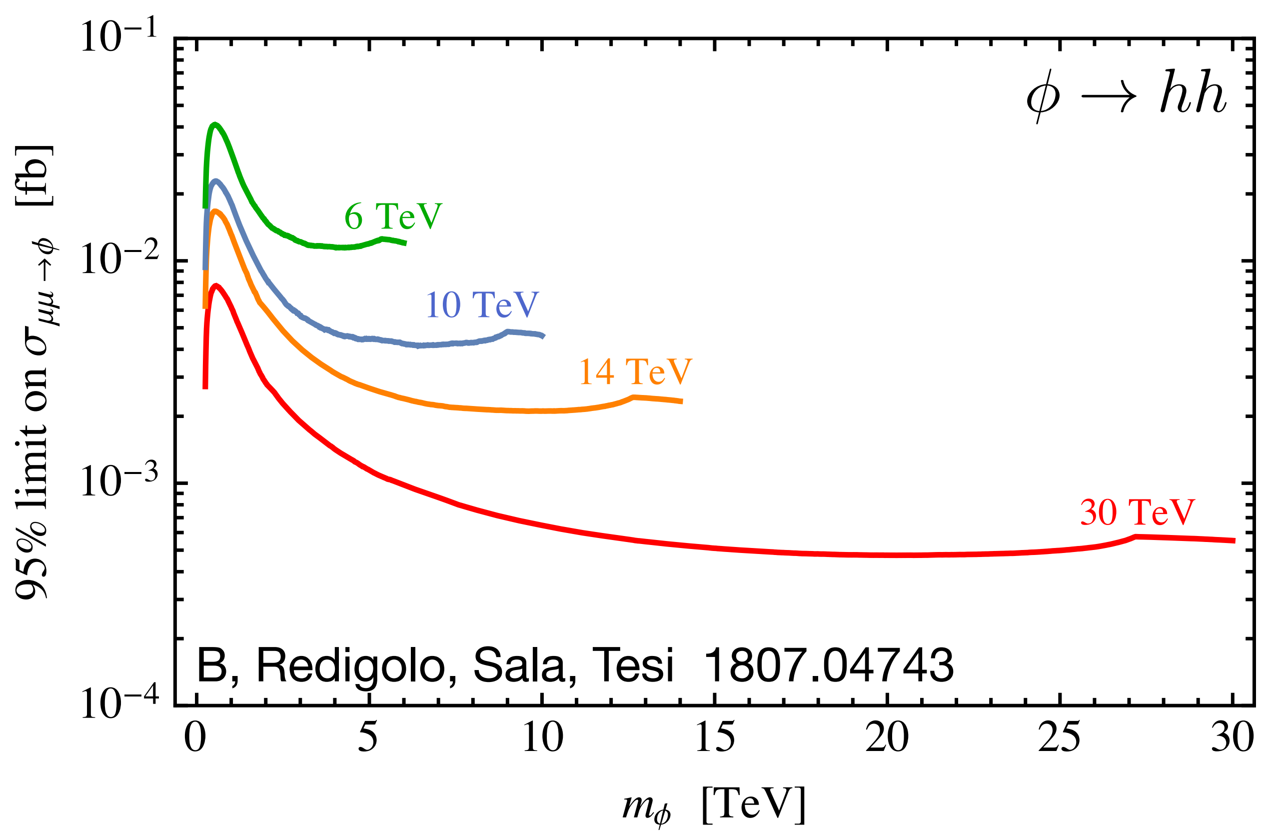
$$\mu_h = \mu_{\rm SM} \times \cos^2\gamma$$

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

hh(4*b*) 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

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

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

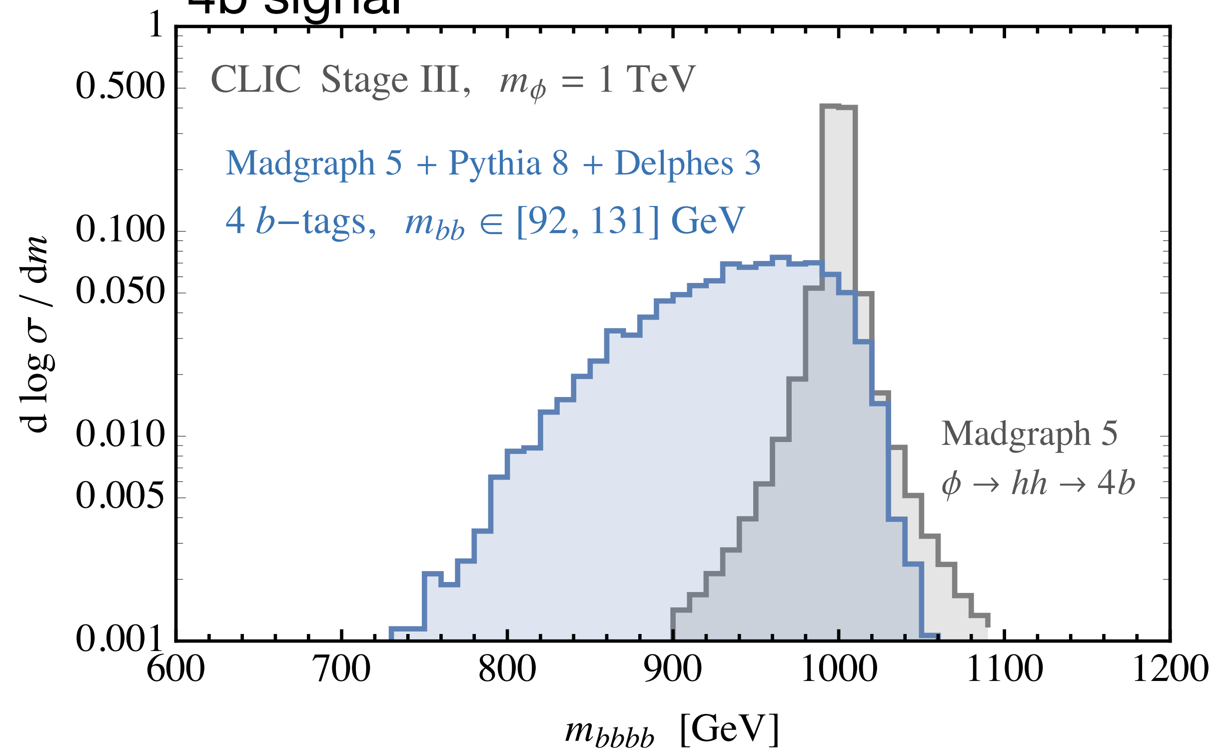
$hh(4b)$ decay channel

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

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: $0.75\, m_\phi < m_{4b} < 1.05\, m_\phi$
- Other cuts: $p_T > 20$ GeV, $|\cos\theta_h| < 0.9$

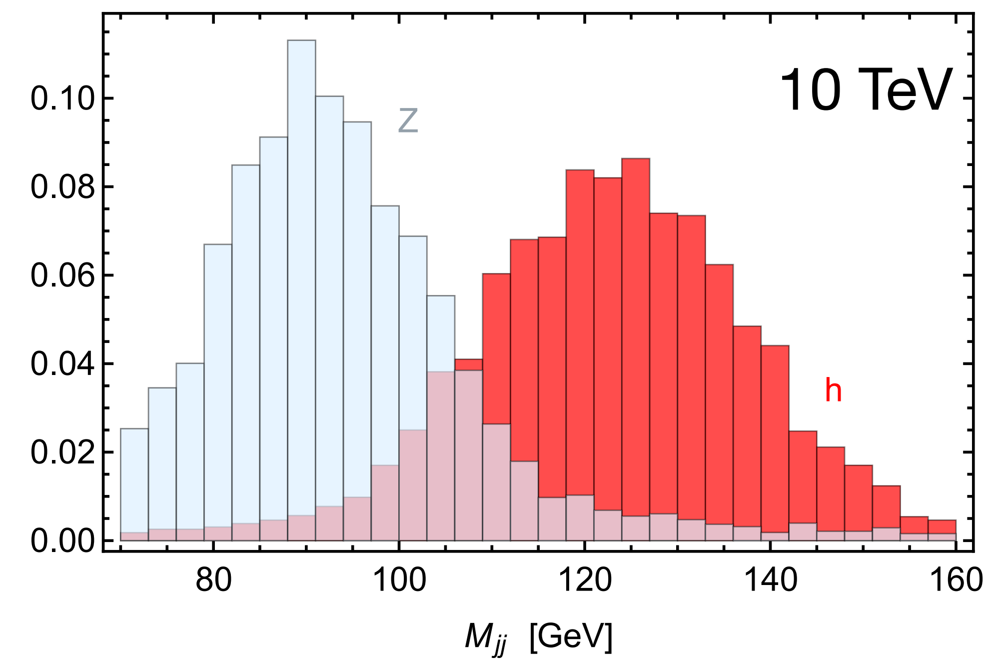
4b signal



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



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%
$\lvert\cos\theta\rvert < 0.94$	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

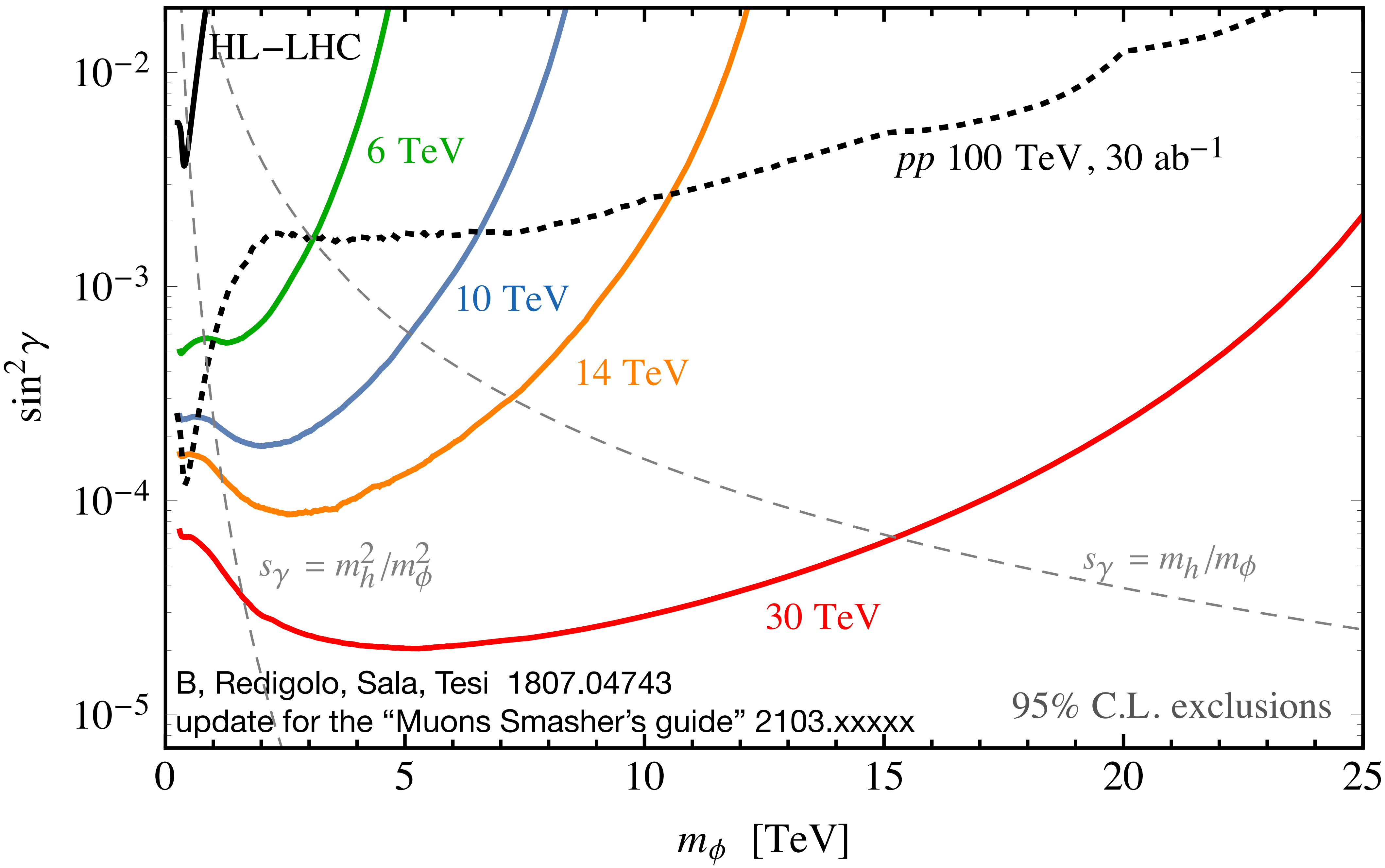
Cut	ϵ_{sig}	$\epsilon_{\text{bkg}}^{4b2\nu}$
$E_{\text{miss}} > 30$ GeV	94%	96%
4 b-tags	51%	33%
$m_{bb} \in [88, 137]$ GeV	60%	15%
$\lvert\cos\theta\rvert < 0.95$	97%	58%
$m_{4b} \in [1.5, 2.04]$ TeV	91%	0.7%
Total efficiency	26%	2×10^{-4}

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

Example: scalar singlet

Compare the reach of very high energy lepton & hadron colliders

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



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

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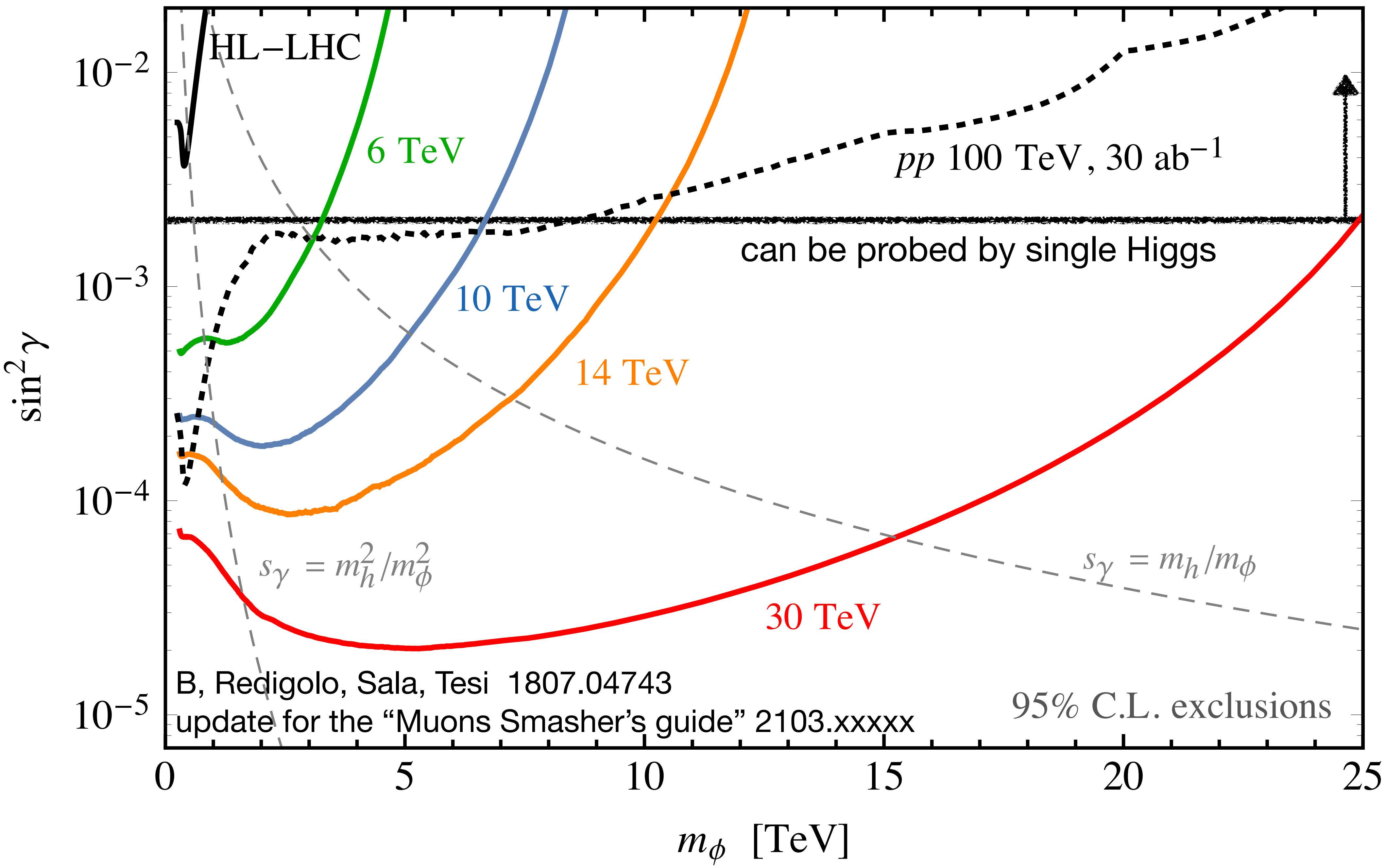

For this class of models, a high-energy $\mu^+\mu^-$ collider has an amazing reach if compared to single Higgs meas. or direct searches at a 100 TeV pp collider