BSM benchmarks at a muon collider: few results and many ideas

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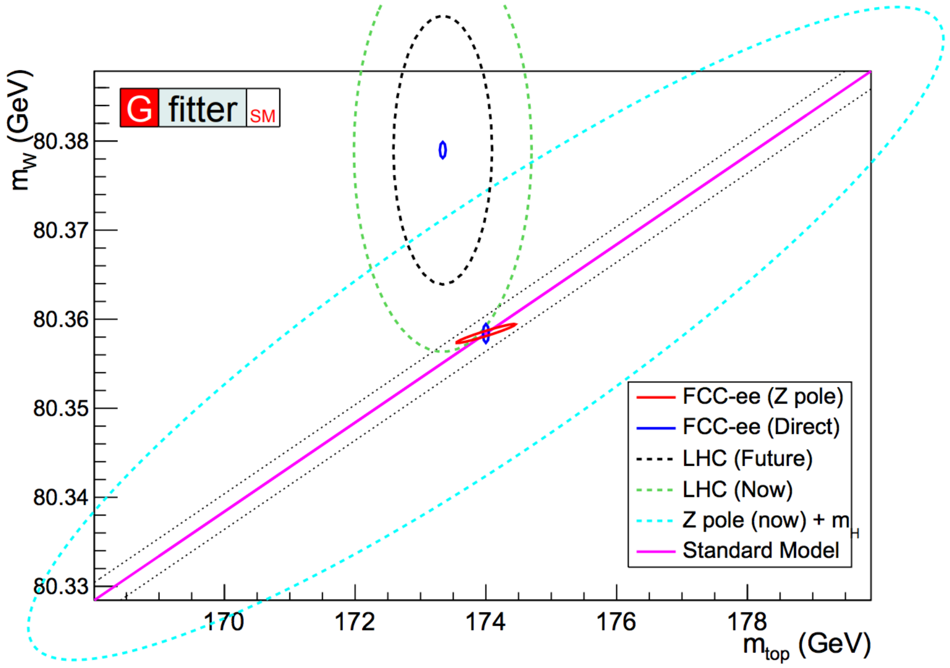
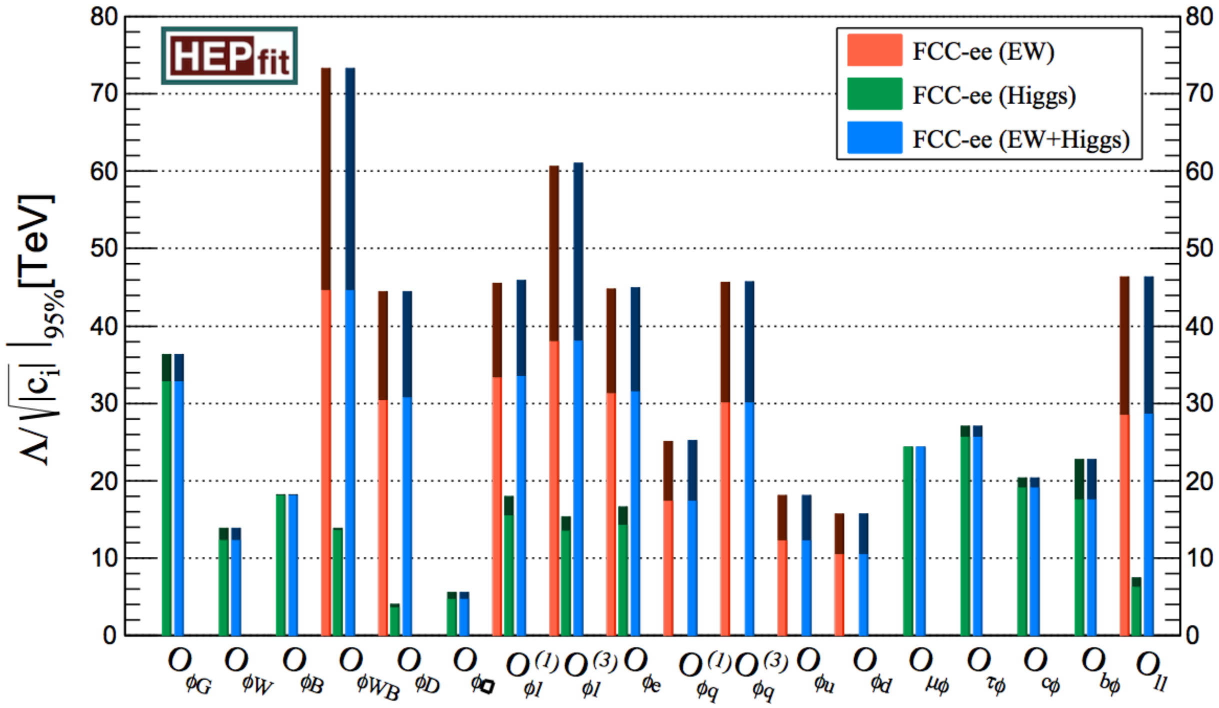
Why a High Energy Lepton Collider?

- High-Intensity Lepton Colliders: ultimate **precision on EW/Higgs physics**



  - FCC-ee can measure Z-pole parameters with a precision of a few 10^{-5}



  - FCC-ee/ILC/CLIC can measure Higgs pole parameters with a precision of a few 10^{-3}

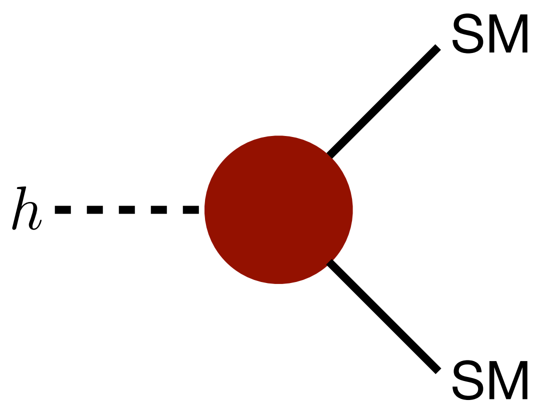
(these measurements are limited by systematic/parametric uncertainties)

- **Energy frontier:** FCC-hh can directly probe c.o.m. energies > 10 TeV

Can a very High Energy Lepton Collider tell us more?

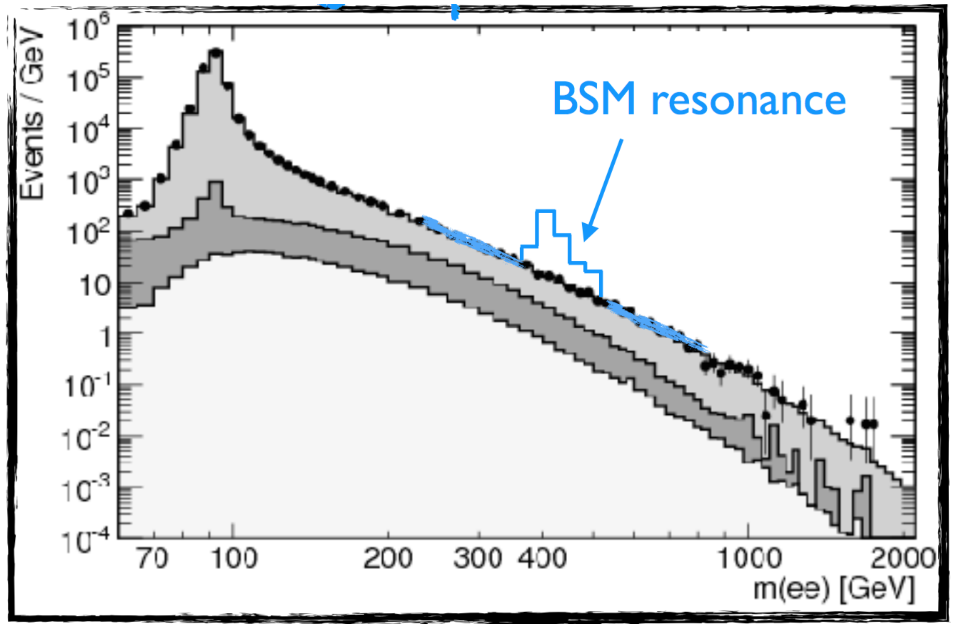
Precision vs Energy

I. New physics is light enough: direct searches



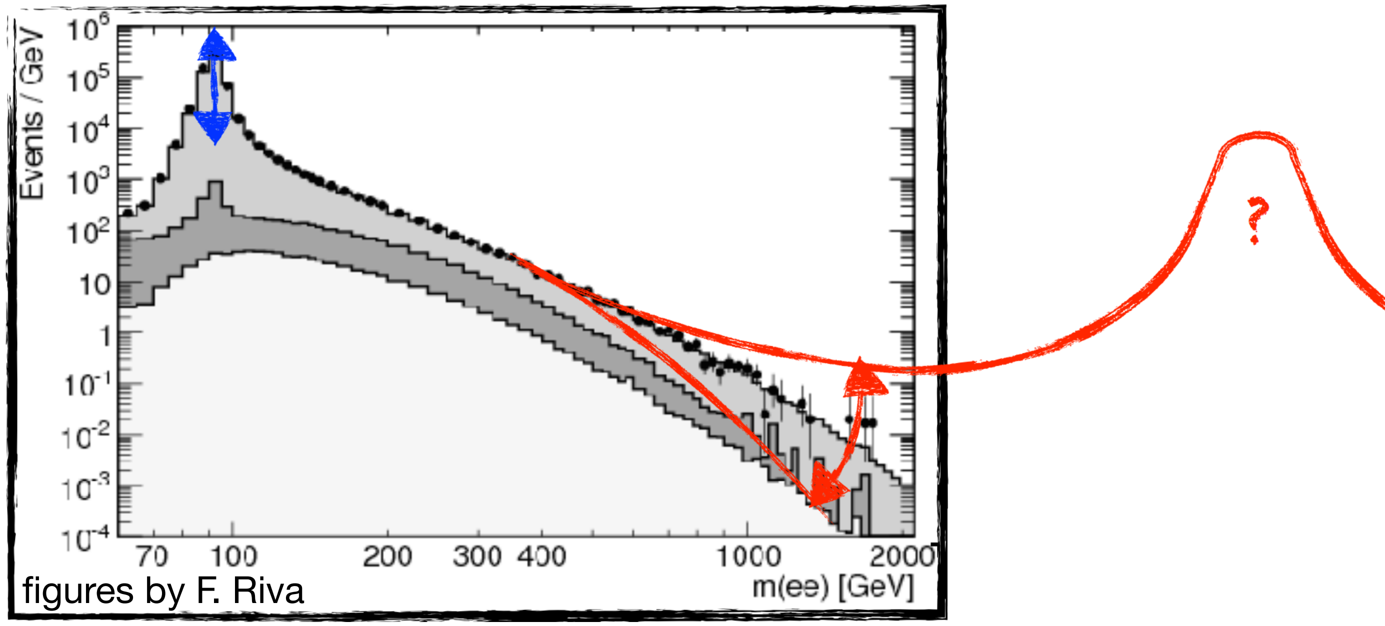
$\sim C_{\text{model}} \times \frac{m_h}{M}$

mass of
new states



II. New physics is heavy: EFT

- pole observables $\propto m_{\text{EW}}^2/M^2$
- high energy tails $\propto E^2/M^2$



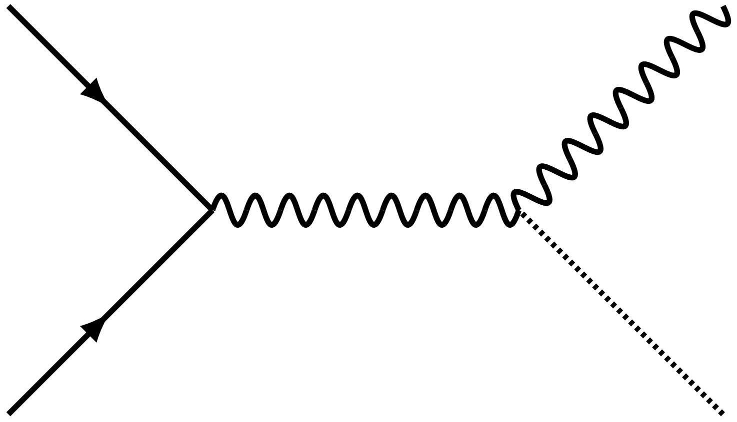
figures by F. Riva

With the same experimental accuracy, high-energy measurements yield a precision gain of E^2/m_{EW}^2

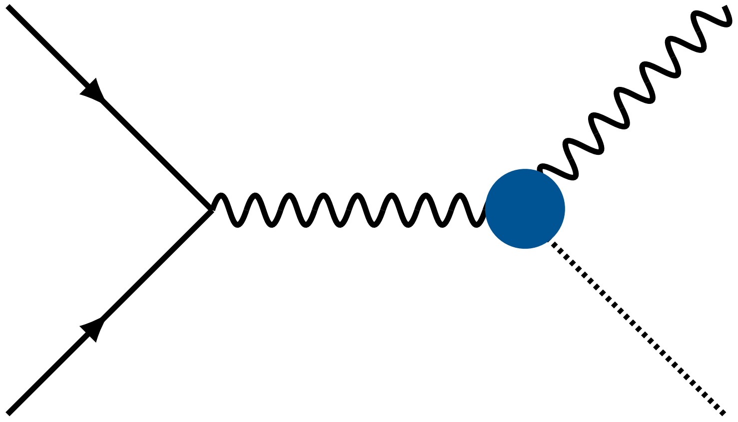
Example: Zh & S parameter

Consider the dim. 6 operator $\mathcal{O}_W = \frac{g}{M^2} D^\mu W^a_{\mu\nu} (H^\dagger \sigma^a D^\nu H)$

- contribution to $\ell^+\ell^- \to Zh$ scattering



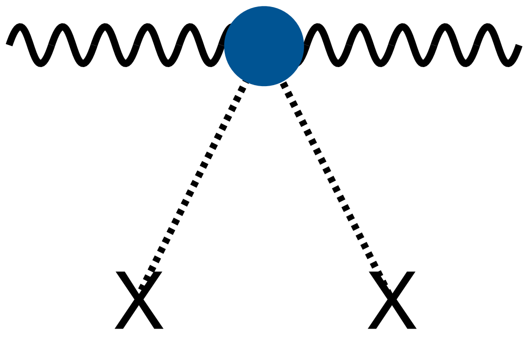
$\sim g^2$



$\sim g^2 E^2/M^2$

grows
with energy

- contribution to Z-pole observables (S parameter)



$\sim m_W^2/M^2$

(also contribution from $\mathcal{O}_B = \partial^\mu B_{\mu\nu} (H^\dagger \partial^\nu H)$

can be constrained with $\ell^+\ell^- \to WW$

$\hat{S} = c_W + c_B$)

Higgs couplings not relevant here…

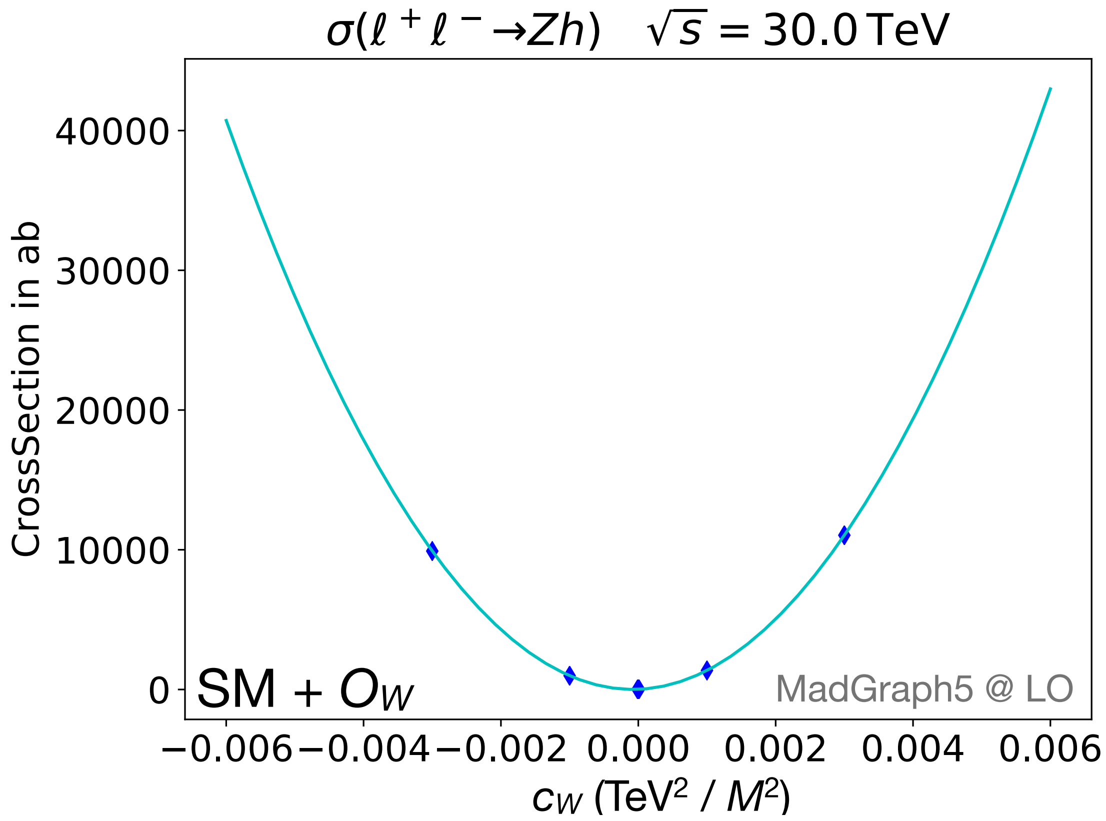
➡ see Andrea's talk

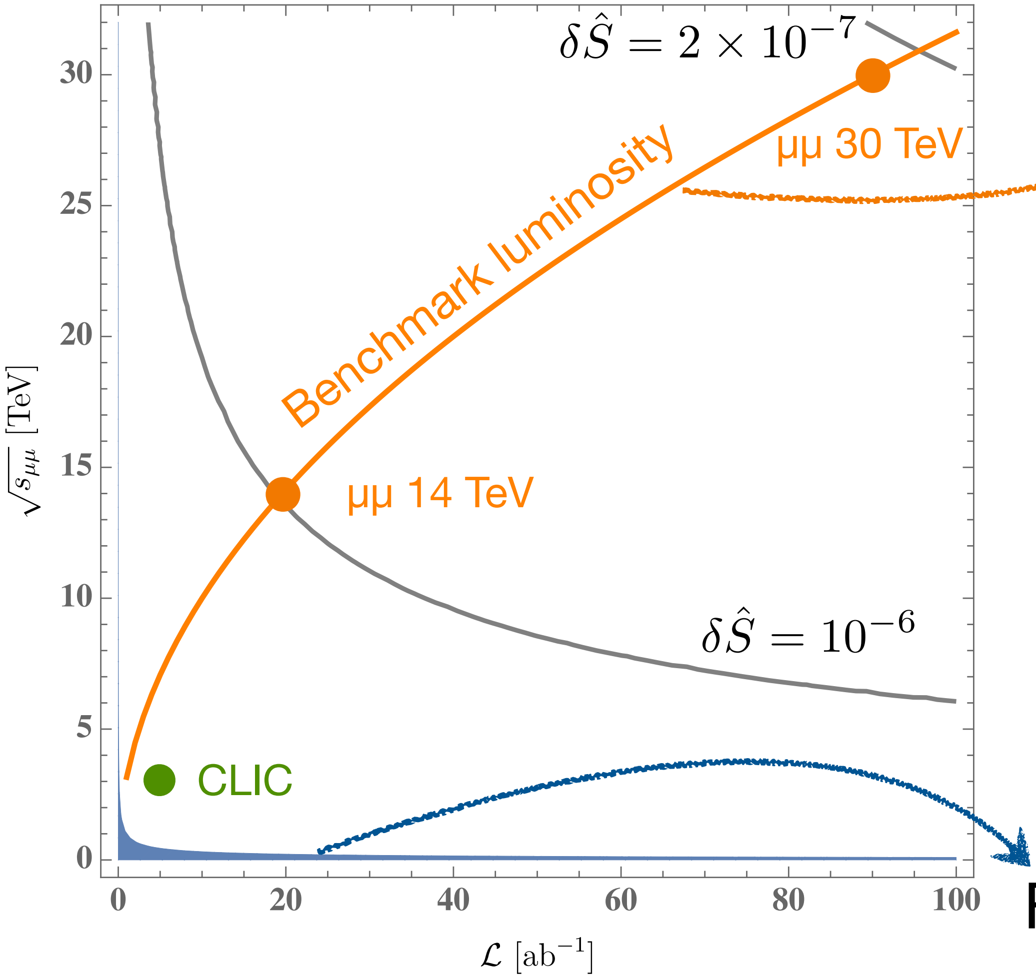
Example: Zh & S parameter

$\sqrt{s}$ [TeV]	$\sigma_{\rm SM}$ [ab]	$\mathcal{L}$ [ab^{-1}]	$M_{95\%\,\rm CL}$ [TeV]
3	1363	2	[12.8, -12.2]
14	62.3	20	[58, -55]
30	13.5	90	[124, -118]

Expected precision on cross-section (statistical only): $\delta\sigma_{95\%} = 2\sqrt{\sigma_{\rm SM}/\mathcal{L}}$

⇒ bound on c_W/M^2 (or equivalently on $\hat{S}$)





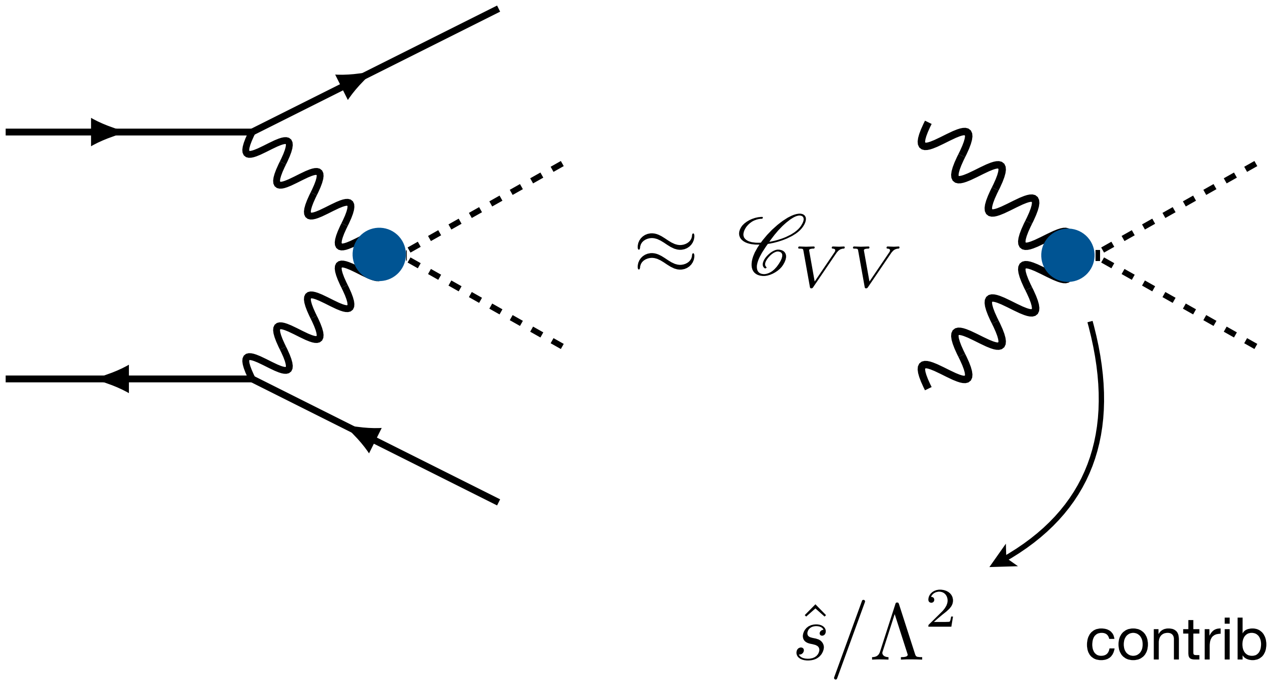
$\mathcal{L} = 10\,{\rm ab}^{-1}\,\frac{s}{(10\,{\rm TeV})^2}$ (talk by Andrea)

A multi-TeV collider (already CLIC) can reach much better precision than the maximal one achievable on $\hat{S}$ at FCC

14 TeV μ-collider: $\hat{S} < 10^{-6}$ ⇒ $M > 80$ TeV

FCC-ee Z-pole fit: $\hat{S} < 6{*}10^{-5}$

Double Higgs production



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

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

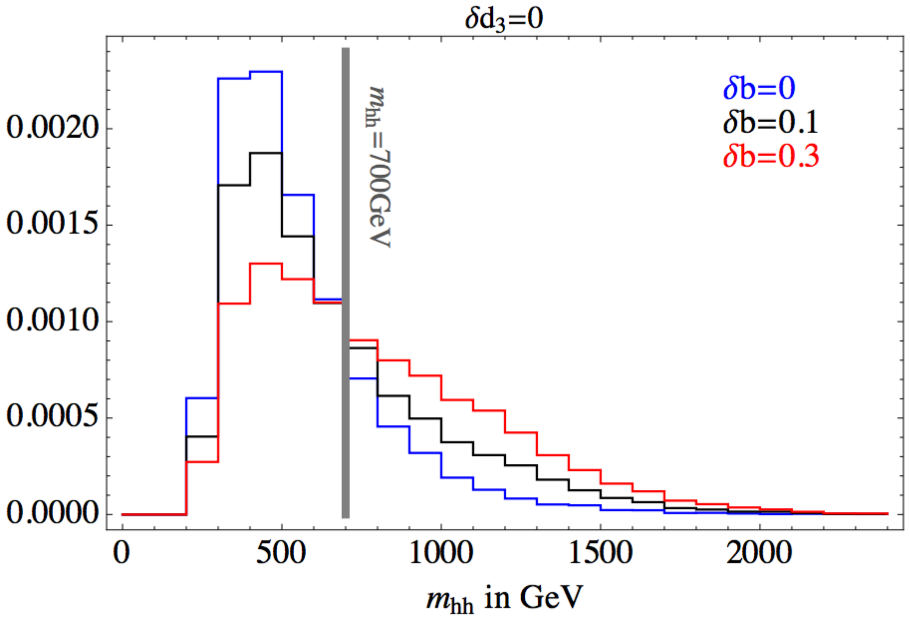
Dawson, 1984

contribution from operator $\mathcal{O}_H = \frac{c_H}{f^2}(\partial_\mu |H|^2)^2$

- From measurement of high invariant mass $e^+e^- \to hh\nu\nu$ cross-section at 3 TeV CLIC:

$$\xi = \frac{v^2}{f^2} \lesssim 0.01$$

Contino et al. 1309.7038



- Higgs couplings modification from O_H: $\Delta g_{hWW} \propto v^2/f^2 \lesssim 10^{-3}$

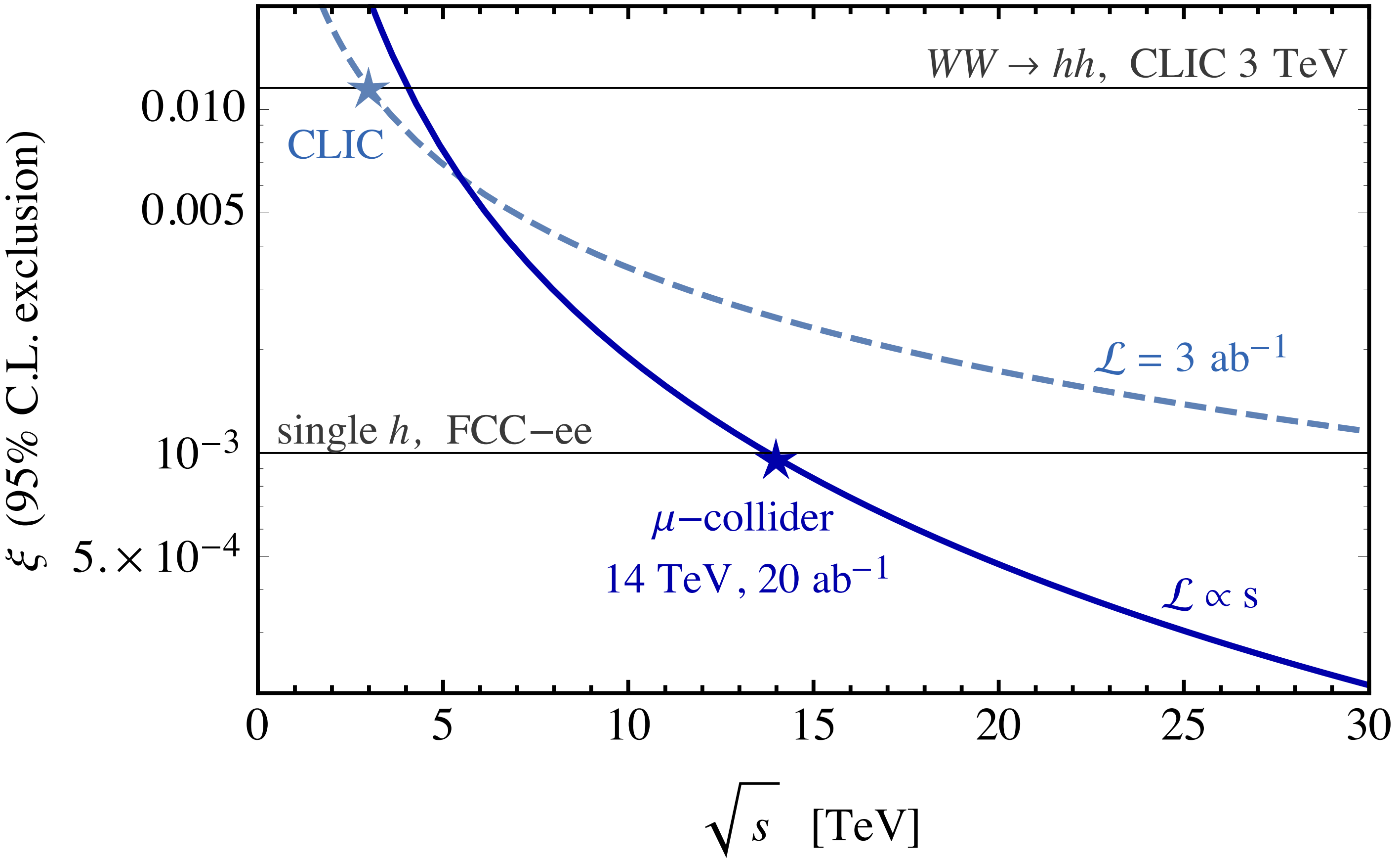
High energy *VV* → *hh* at CLIC is not able to compete with single Higgs

Double Higgs production

- E = 3 TeV, $\mathcal{L}$ = 3 ab^{-1}: $\xi = v^2/f^2 \lesssim 0.01$ 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

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

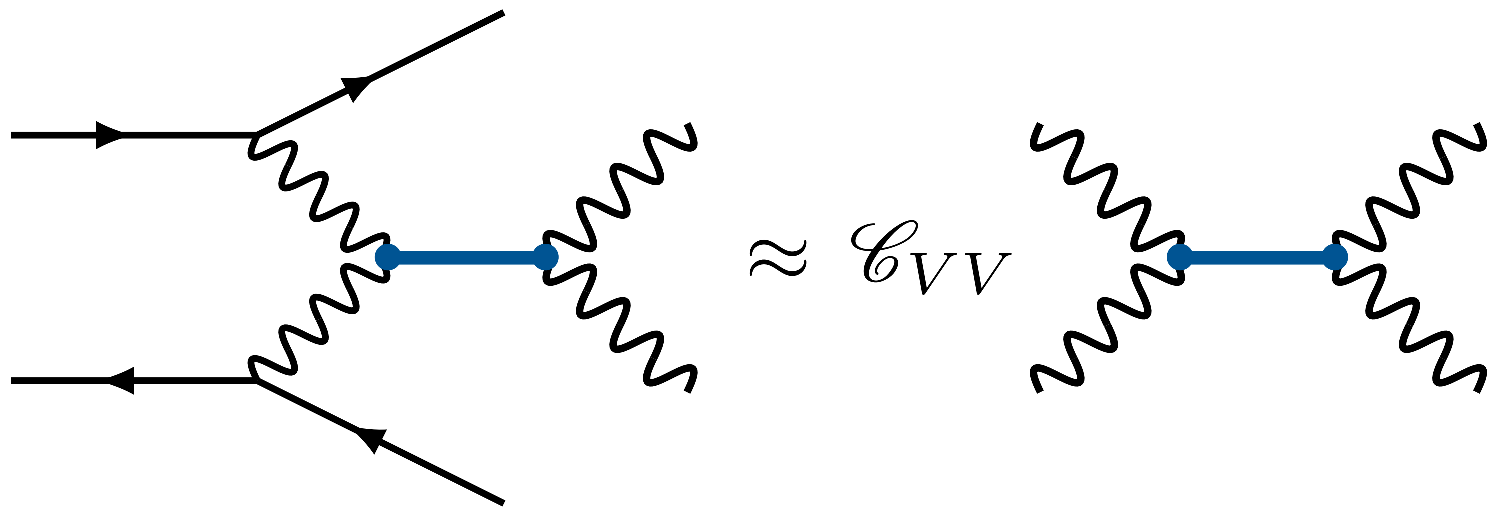
$\xi < 10^{-3} \qquad f > 8\,\mathrm{TeV}$

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

$\xi < 2\times 10^{-4} \qquad f > 17\,\mathrm{TeV}$

Resonance searches

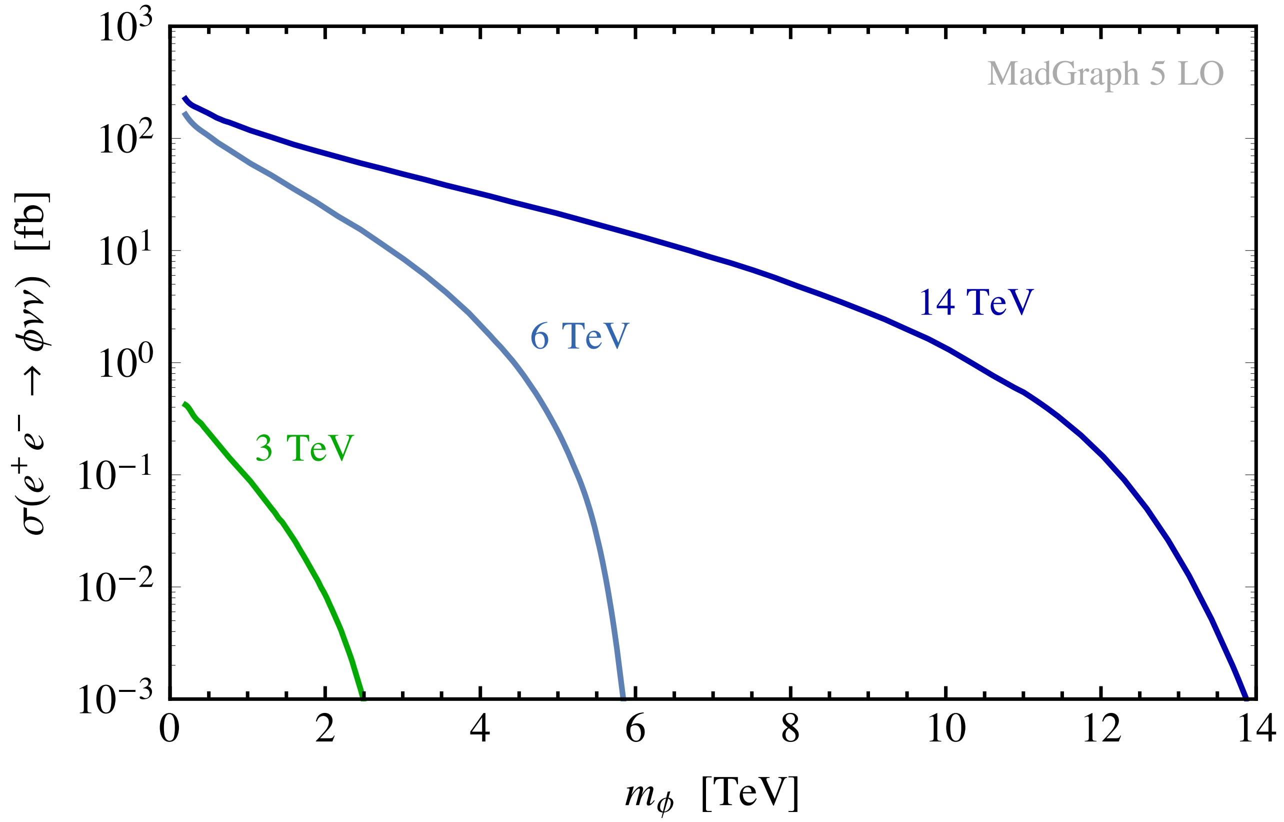
A High Energy Lepton Collider is a “vector boson collider”



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

Dawson, 1984

VBF resonance production cross-section enhanced by $\log s/m_\phi^2$



- Example: scalar production

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

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

A simple example: scalar singlet

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

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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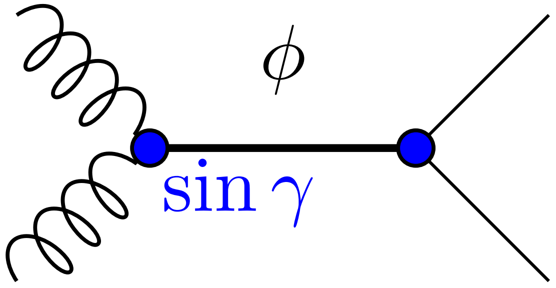
- ϕ can be singly produced:

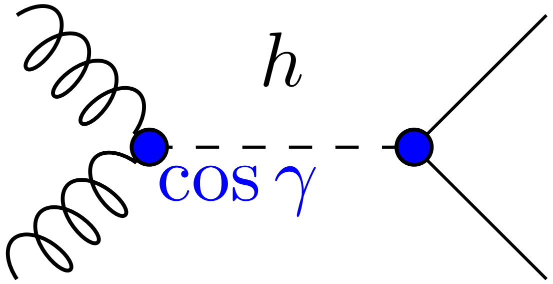


$$\sigma_\phi = \sigma_{\rm SM}(m_\phi) \times \sin^2\gamma$$

- 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:



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

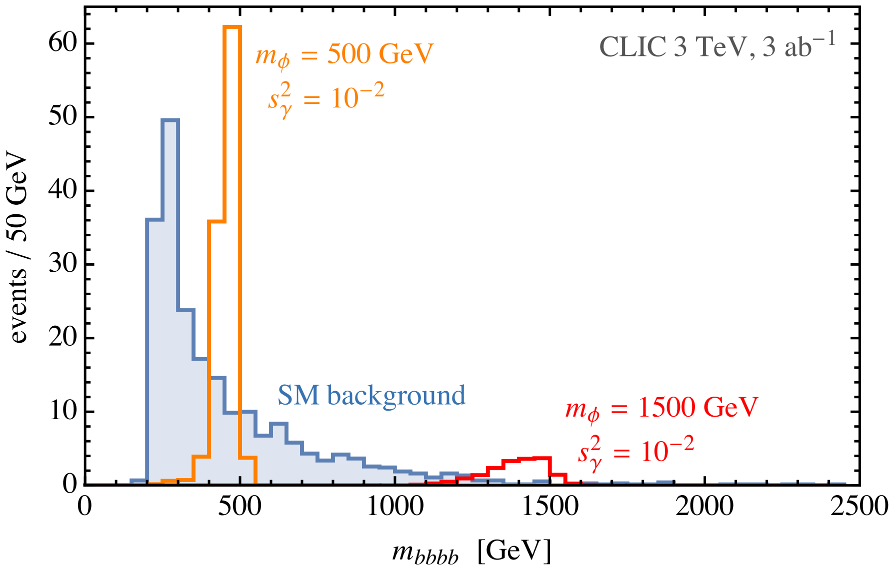
ϕ is like a heavy SM Higgs with narrow width + *hh* channel

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



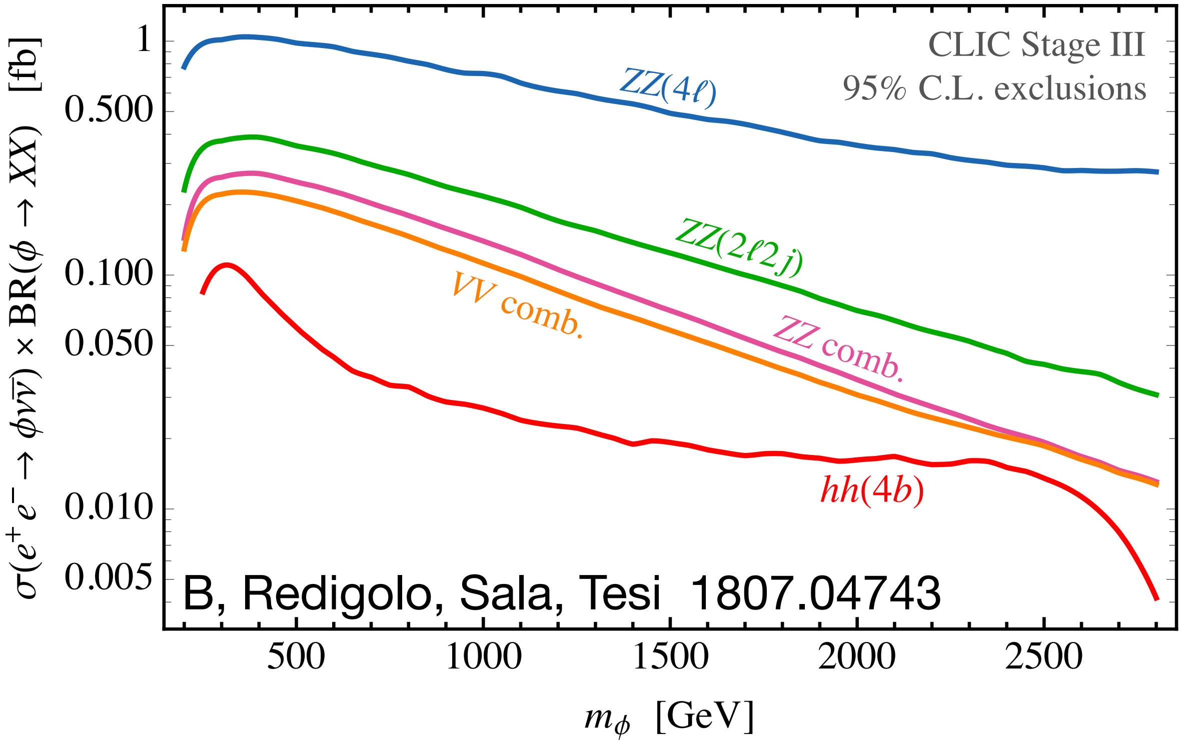
- Very small background at high masses, the error is dominated by statistics

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

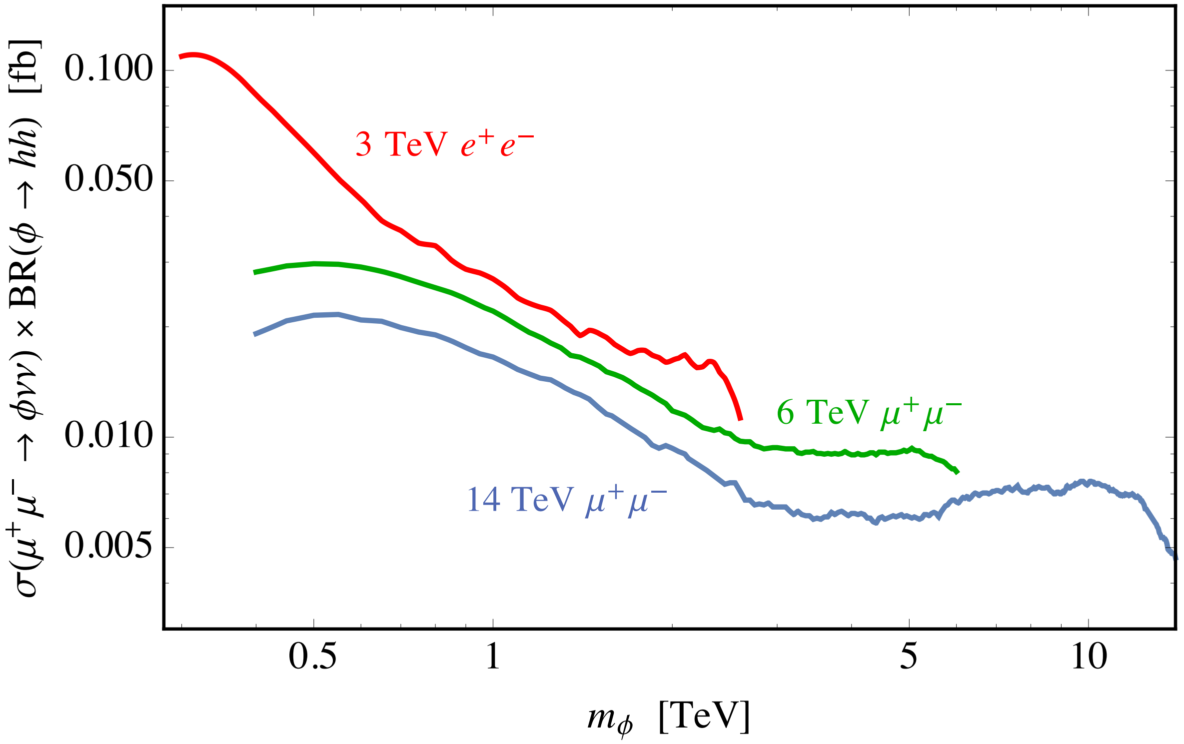
- Parton-level analysis for *ϕ → hh(4b)*:

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

  (validated with simulation at 3 TeV CLIC)



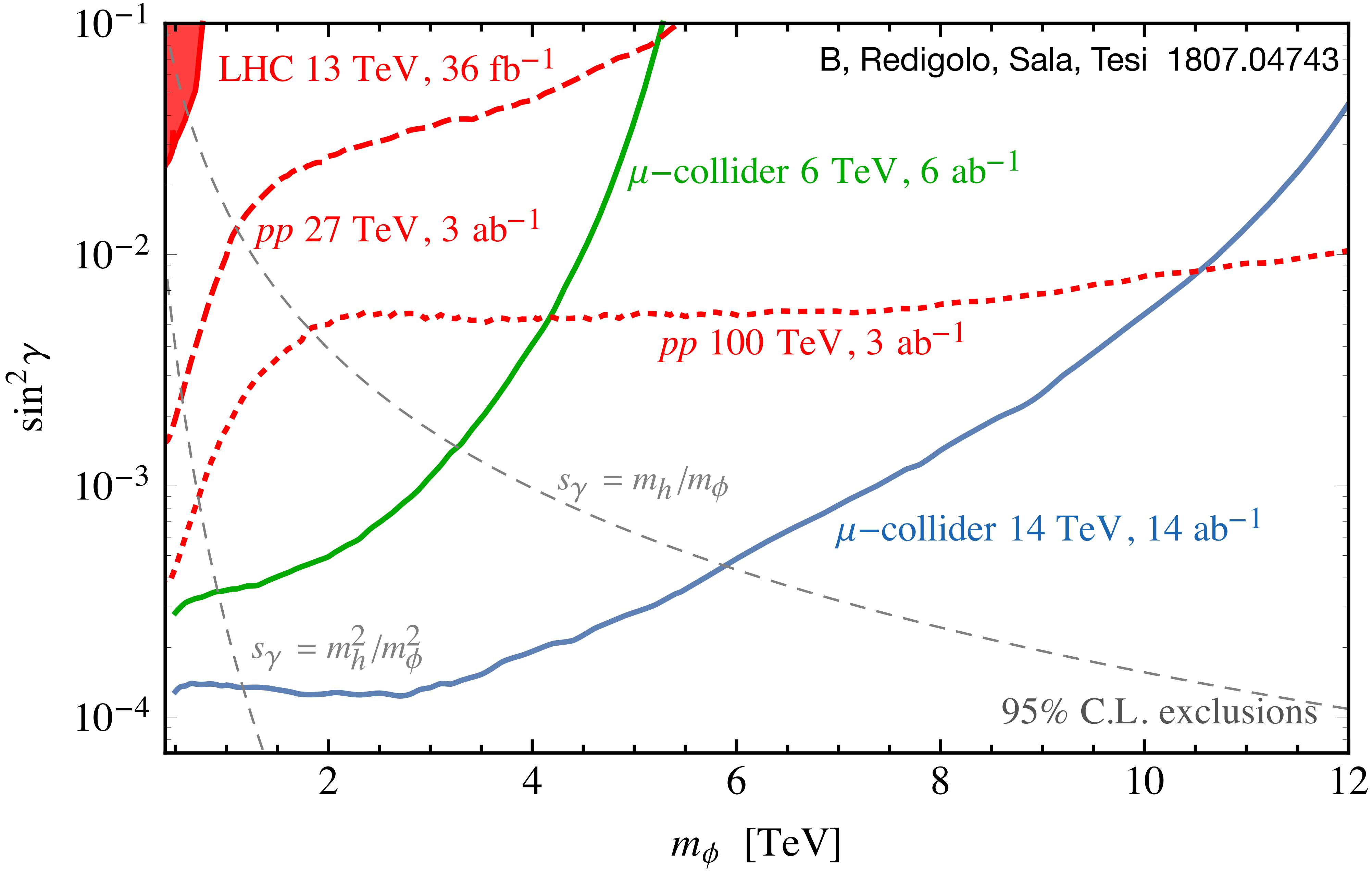
B, Redigolo, Sala, Tesi 1807.04743



Direct vs indirect

Compare the reach of very high energy lepton & hadron colliders

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



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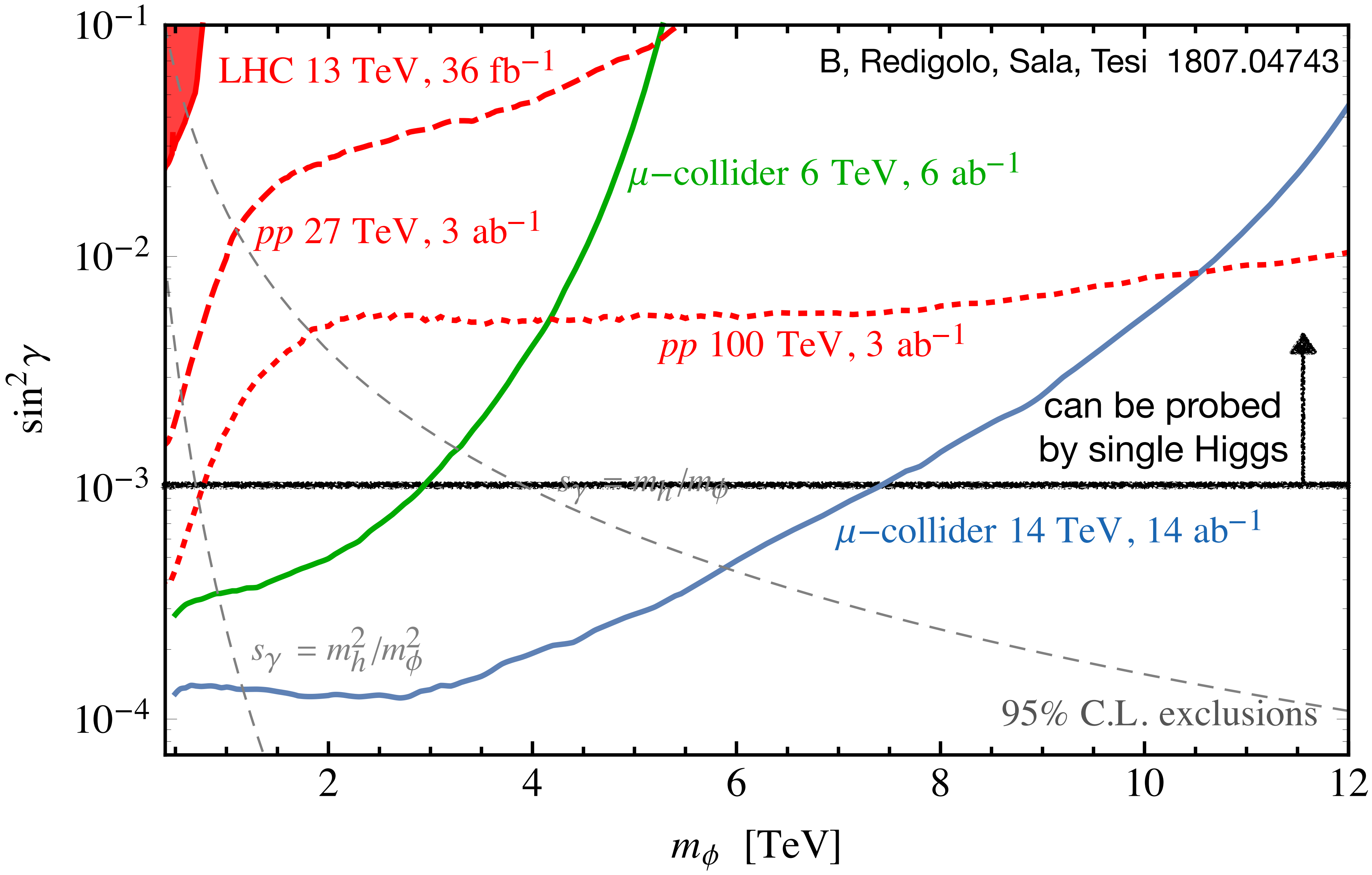


For this class of models, a high-energy $\mu^+\mu^-$ collider has an amazing reach if compared to single Higgs meas. or direct searches at a 100 TeV pp collider

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

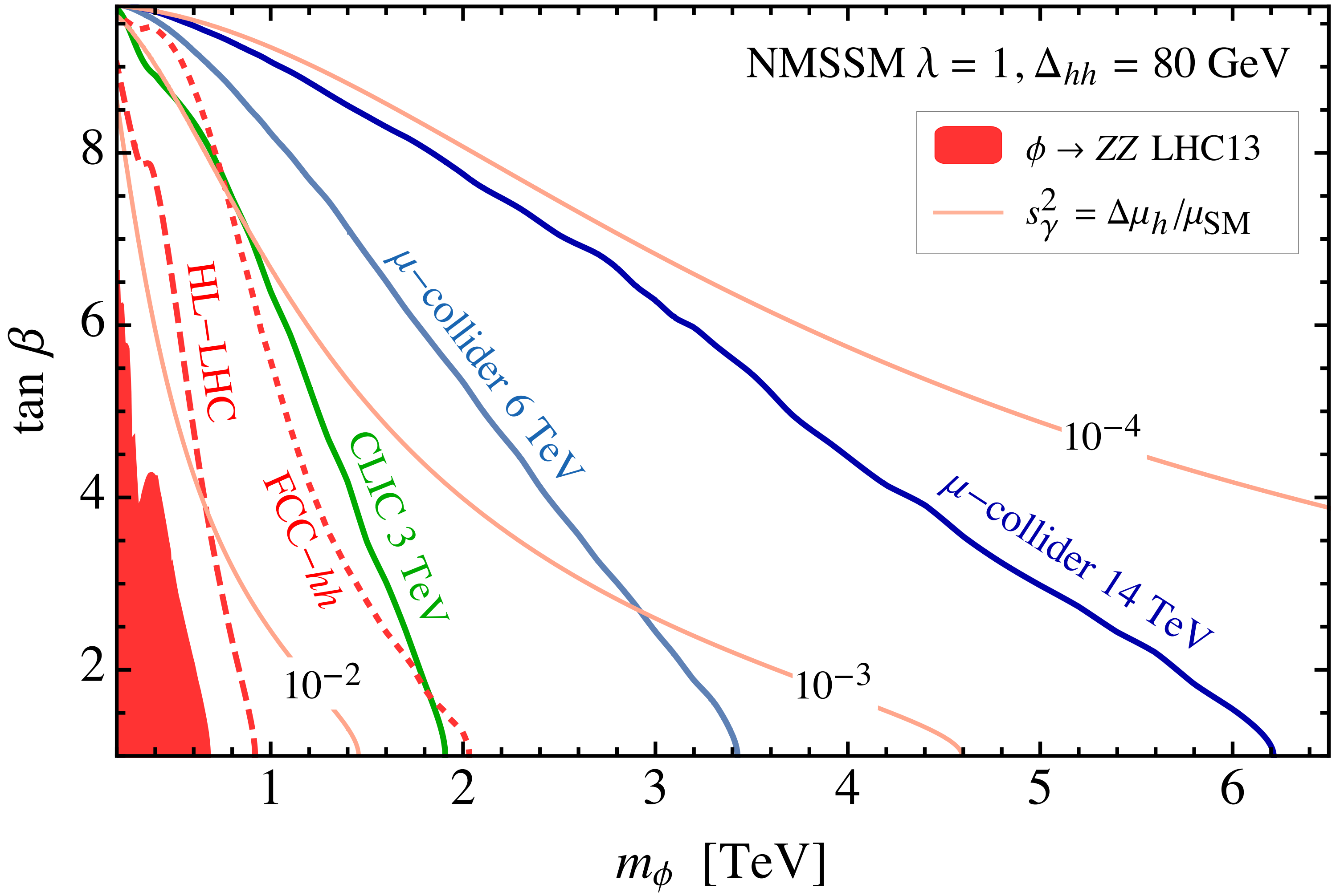
The singlet can be the lightest new state of the Higgs sector

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



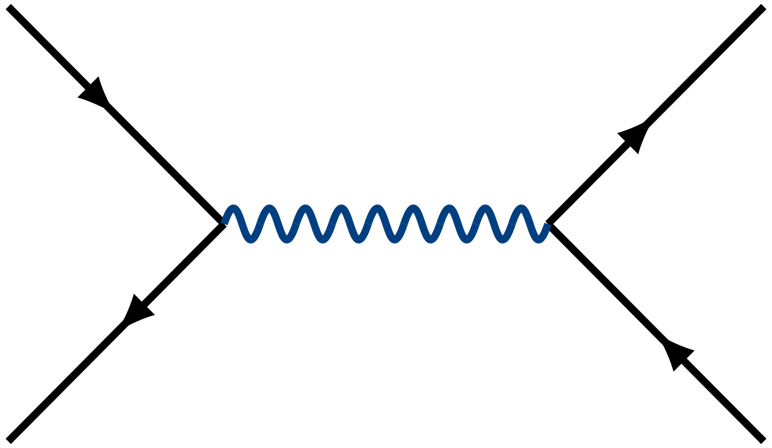
Weakly coupled & low mass:
direct searches very powerful!

➡ see Andrea's talk for sparticle production!

More resonances: Z’

Most typical example of direct search:

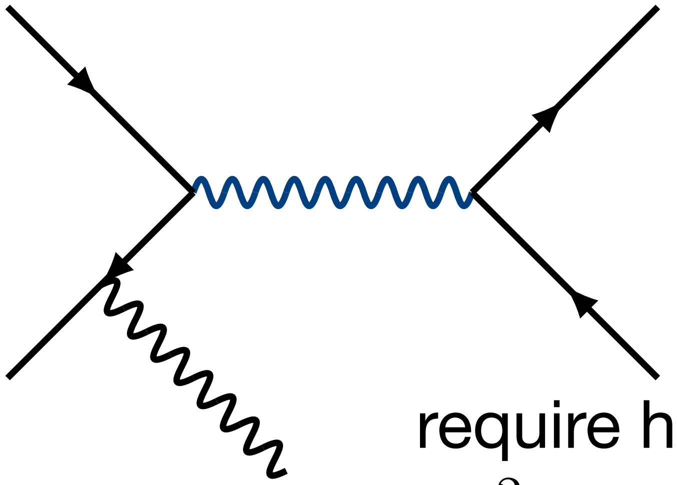
heavy s-channel resonance produced in Drell-Yan



If Z’ produced on-shell, very large cross-section

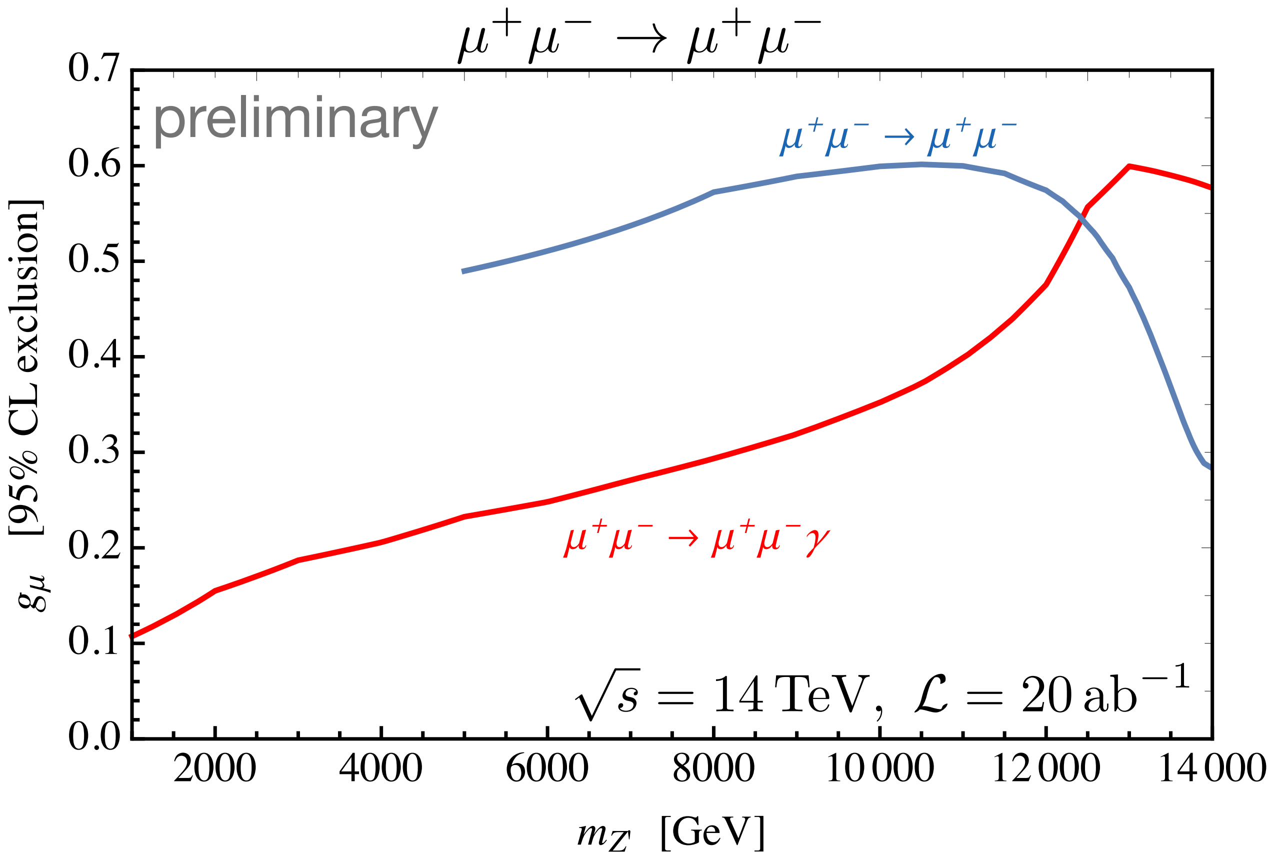
Problem: how do we look for resonances of unknown mass at fixed √s?

I. “Radiative return”: produce resonance on-shell with ISR



require hard photon

$$M^2 = m_{\ell\ell}^2 = s - 2\sqrt{s}E_\gamma$$



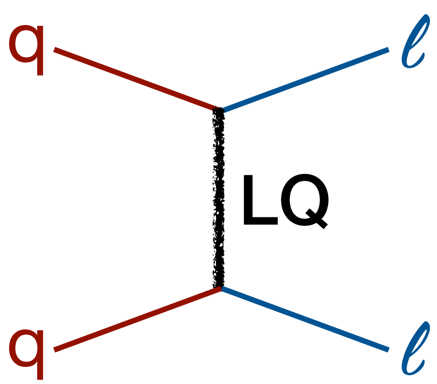
II. Off-shell Z’ exchange

(μμ → ff cross-section)

kinematical cuts: $p_T > 20\,\mathrm{GeV}, \quad |\theta| > 5°$

QED corrections $\approx \dfrac{2\alpha}{\pi} \log \dfrac{s}{m_\mu^2} \lesssim 10\%$

Coloured resonances: 3rd generation leptoquarks



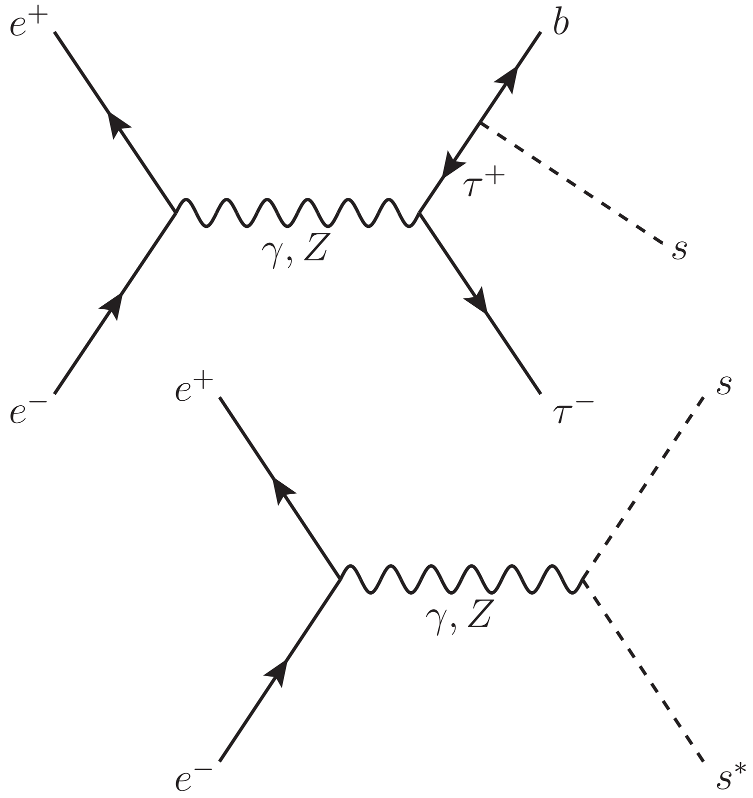
- Different signature compared to more “standard” BSM
- Interesting: NP coupled to 3rd generation fermions (*B physics anomalies!*)
- Can be either scalar or vector
- Difficult searches at LHC: High Lumi reach ~ 1.5 TeV

➡ $\sqrt{s} > 3$ TeV interesting range for lepton colliders

3rd generation LQ production at a lepton collider:

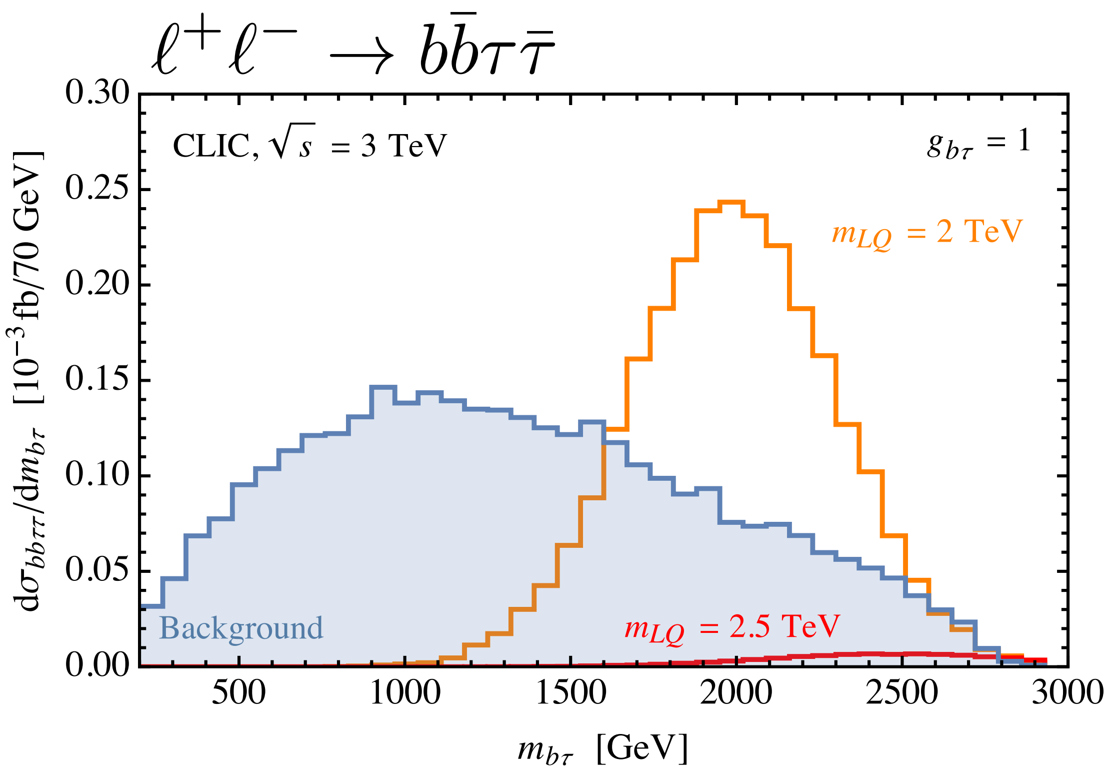
- Pair production: large cross-section when allowed, does not depend on coupling to fermions
- Single production: radiation from bb or ττ pair

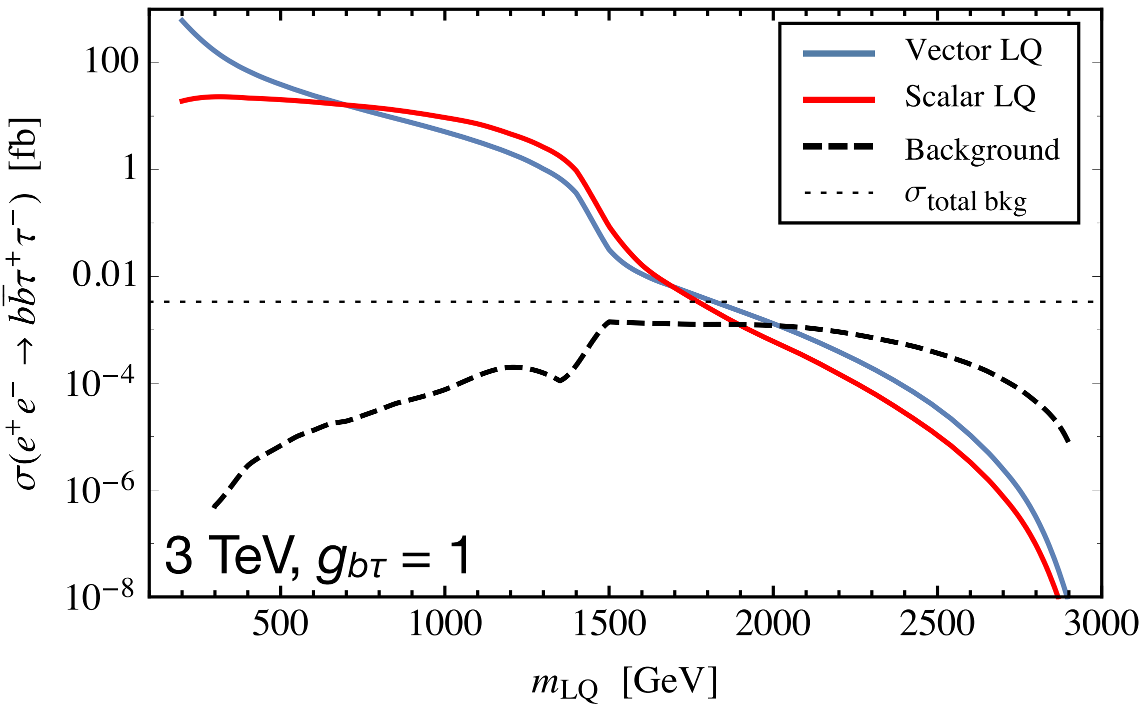
➡ bbττ final state, with $m_{b\tau} \sim M_{LQ}$



B, Greljo, Marzocca, Nardecchia 2018

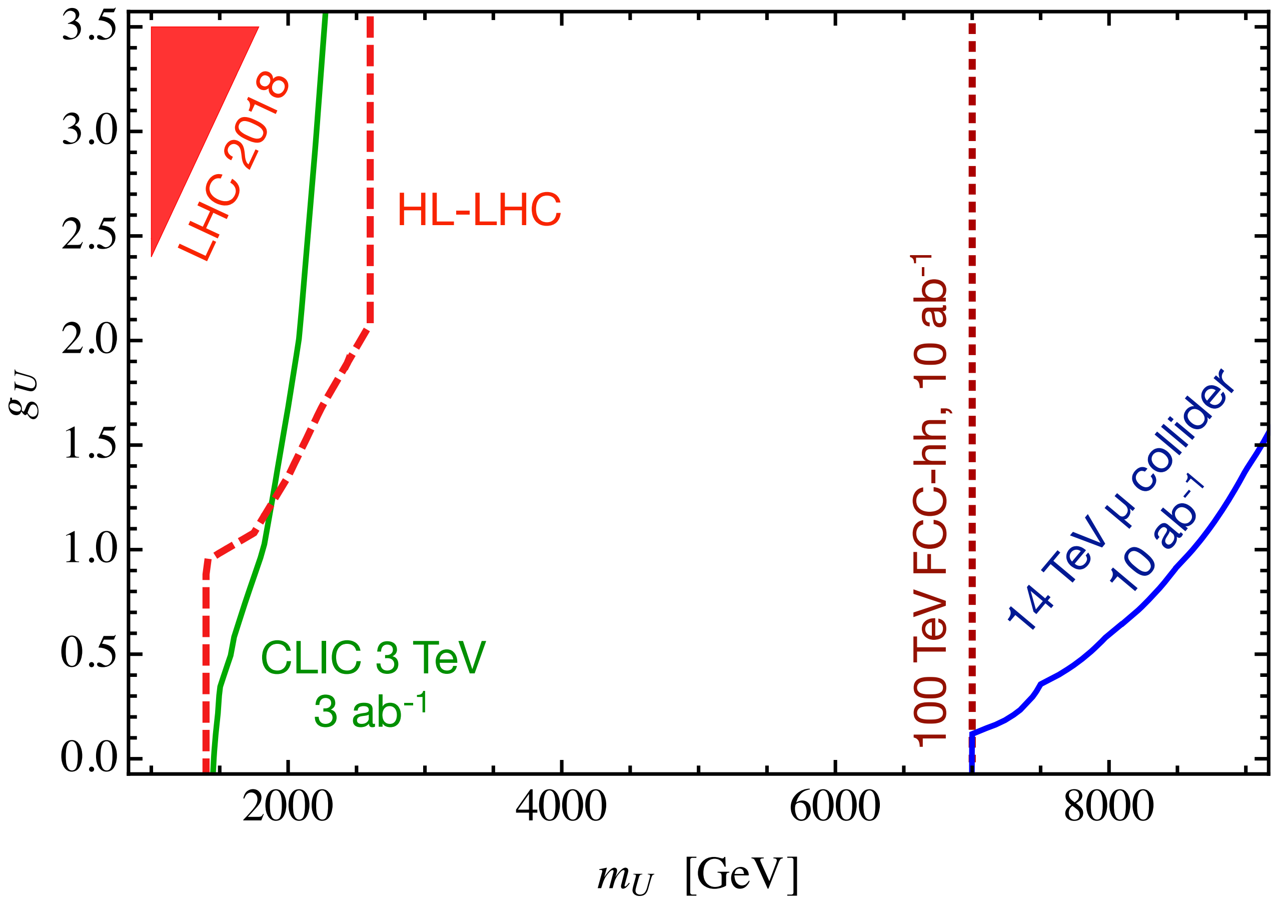
Coloured resonances: Leptoquarks





- Search is almost background-free: We set a bound simply by requiring 10 signal events

- The main limitation for CLIC is the c.o.m. energy: room for huge improvement at a μ-collider



Conclusions

A muon collider would be a “dream machine” for BSM physics:

a way to access multi-TeV c.o.m. energies in a clean environment

✦ Would allow to reach **unmatchable precision in EW & Higgs physics**
by means of high-energy scattering processes
(in some cases corresponding to a 10^{-7} *accuracy in pole observables)*

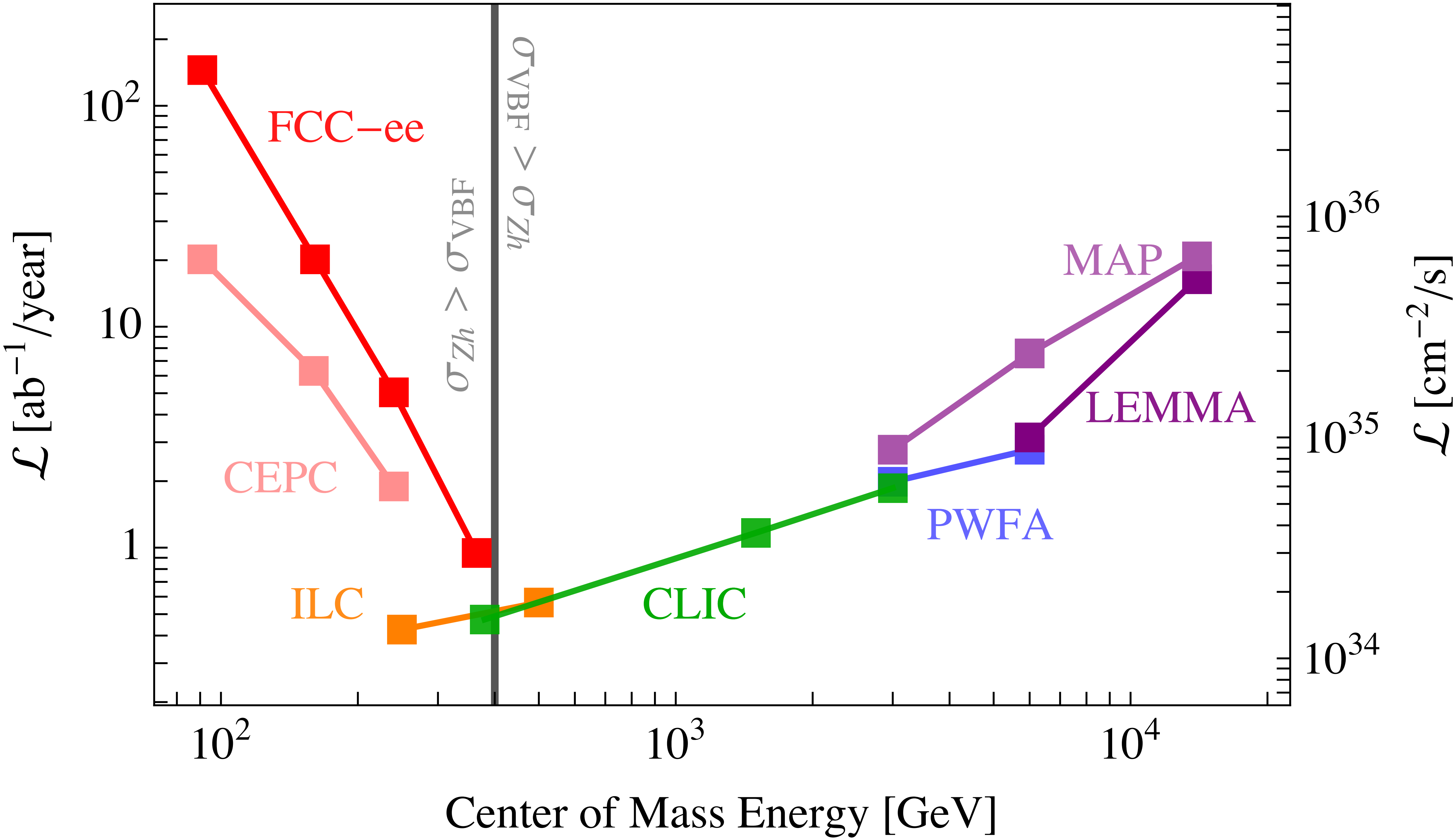
✦ **Powerful discovery machine**: direct reach often much better than what is attainable both at hadron machines and through precision measurements
EW scalars, vector resonances, coloured objects…

(Unfortunately) this is not a comparison with other future colliders…

… but a motivation to study the feasibility of such a machine

Backup

High Energy Lepton Colliders



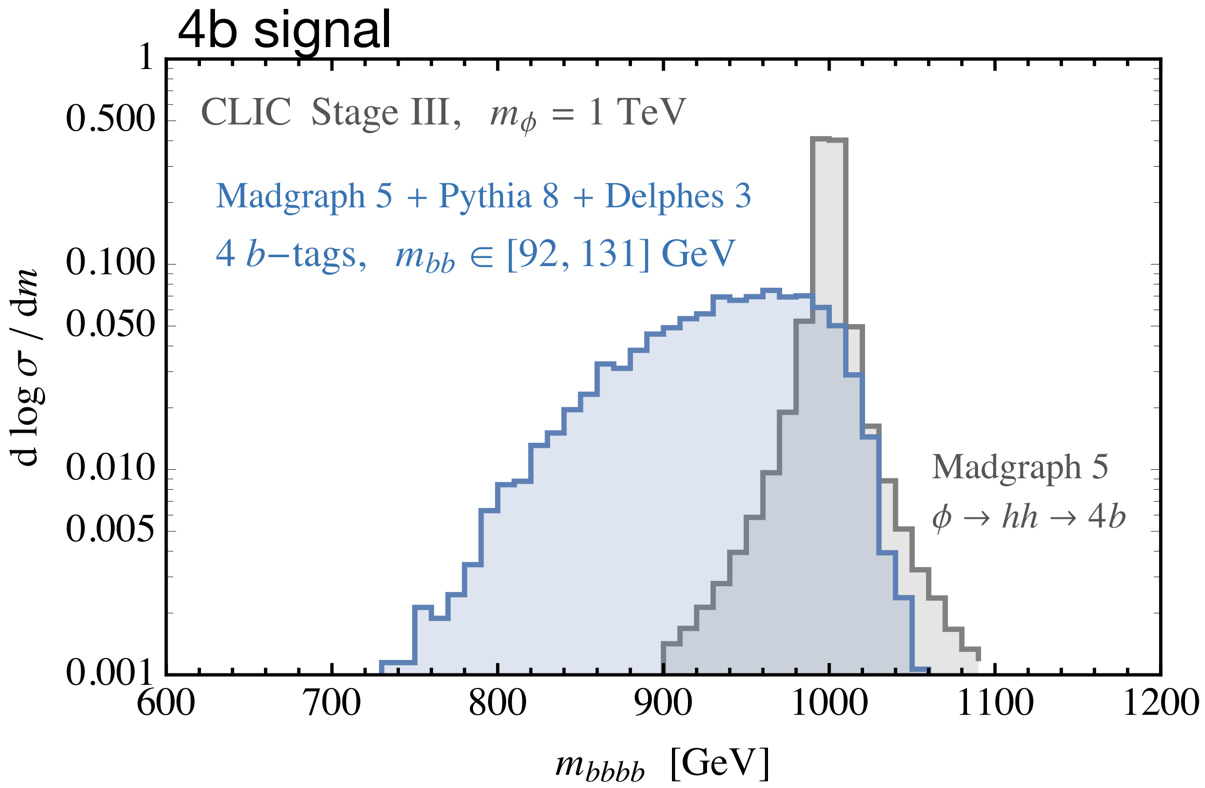
$hh \to 4b$ at CLIC

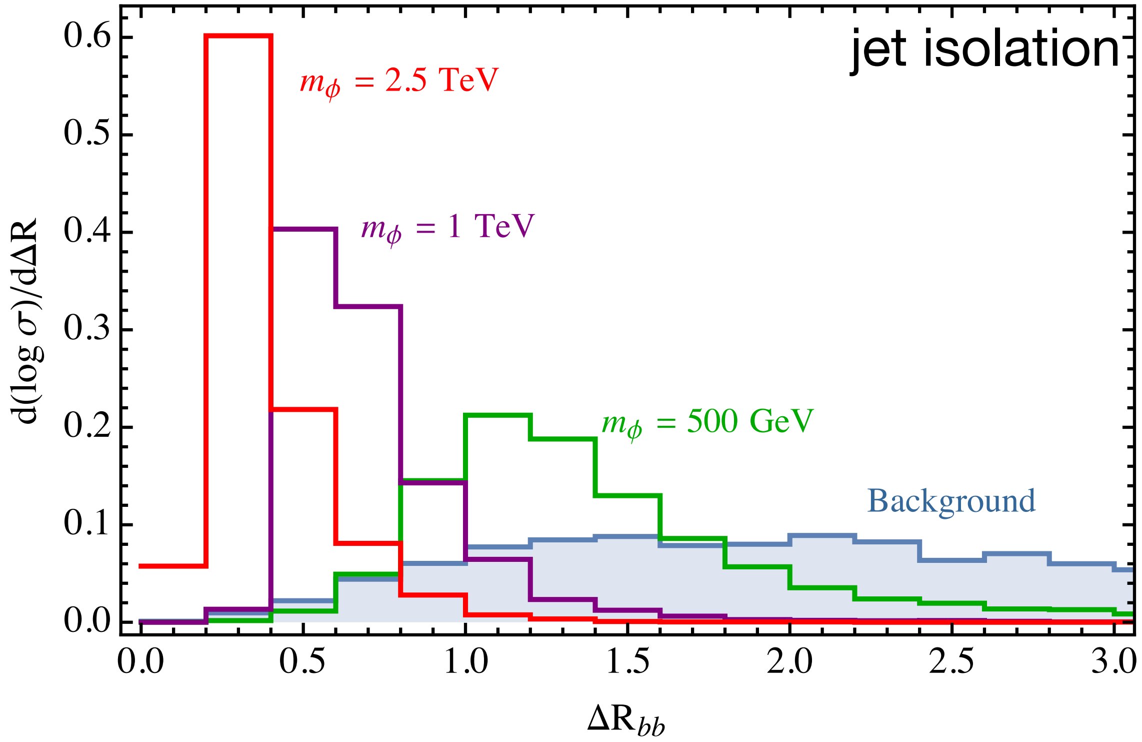
Main backgrounds: *hh*, *ZZ*, *Zh*. We simulate the full process $e^+e^- \to 4b + 2\nu$

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

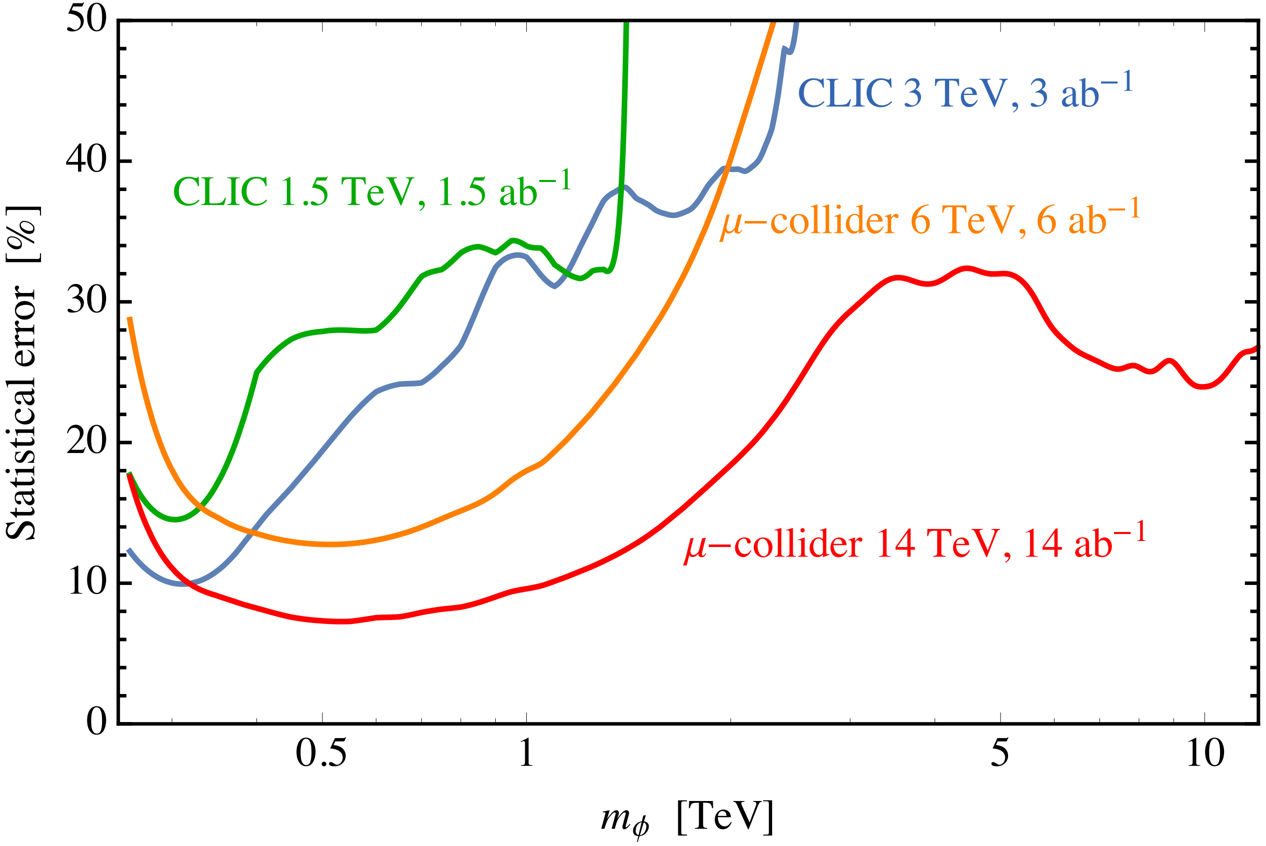
Background reduced by $\varepsilon_{bkg} \sim 10^{-3} - 10^{-4}$



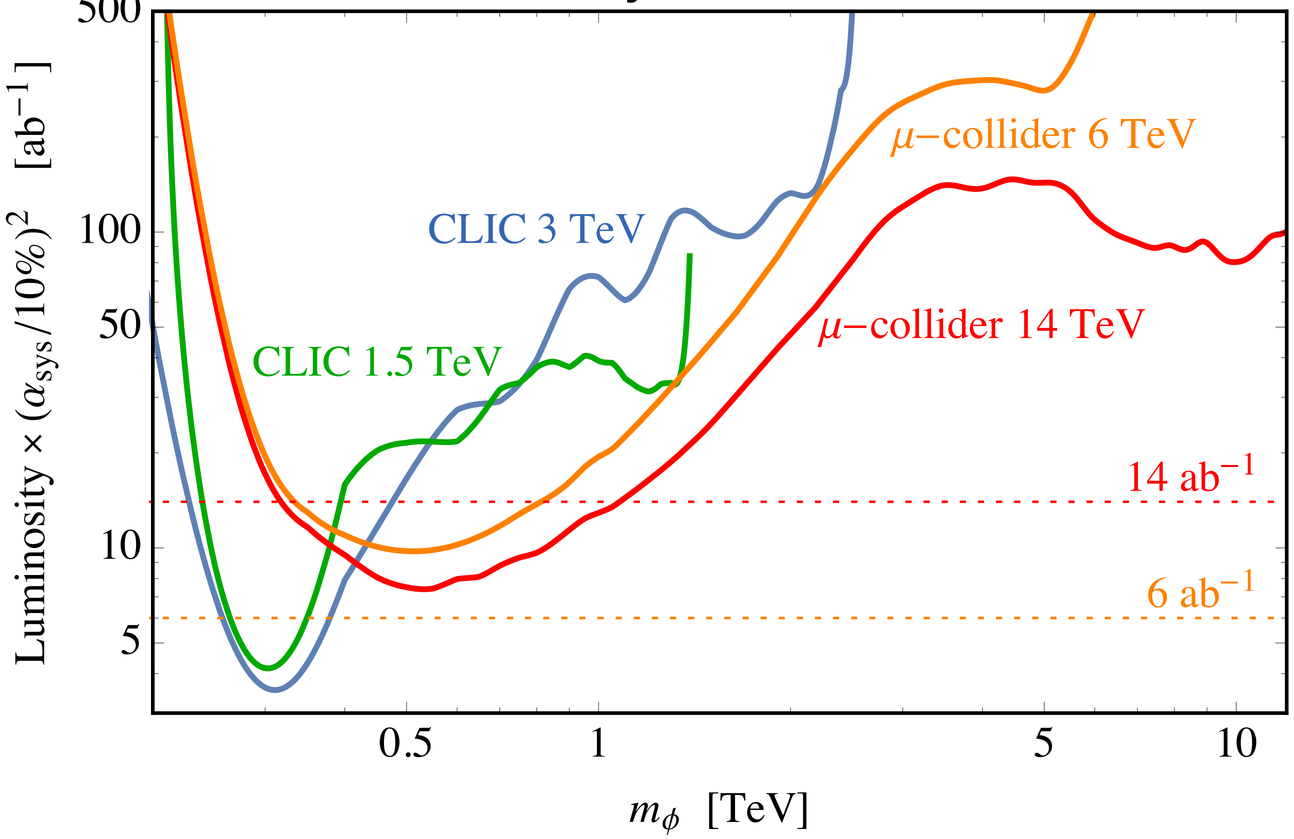


Statistical vs systematic error

Statistical error $\sqrt{N_{sig} + N_{bkg}}$



Lumi for which systematics dominate:



Applications: Twin Higgs

- If the Higgs is a pseudo-Goldstone boson, $\sin^2\gamma \sim v^2/f^2$

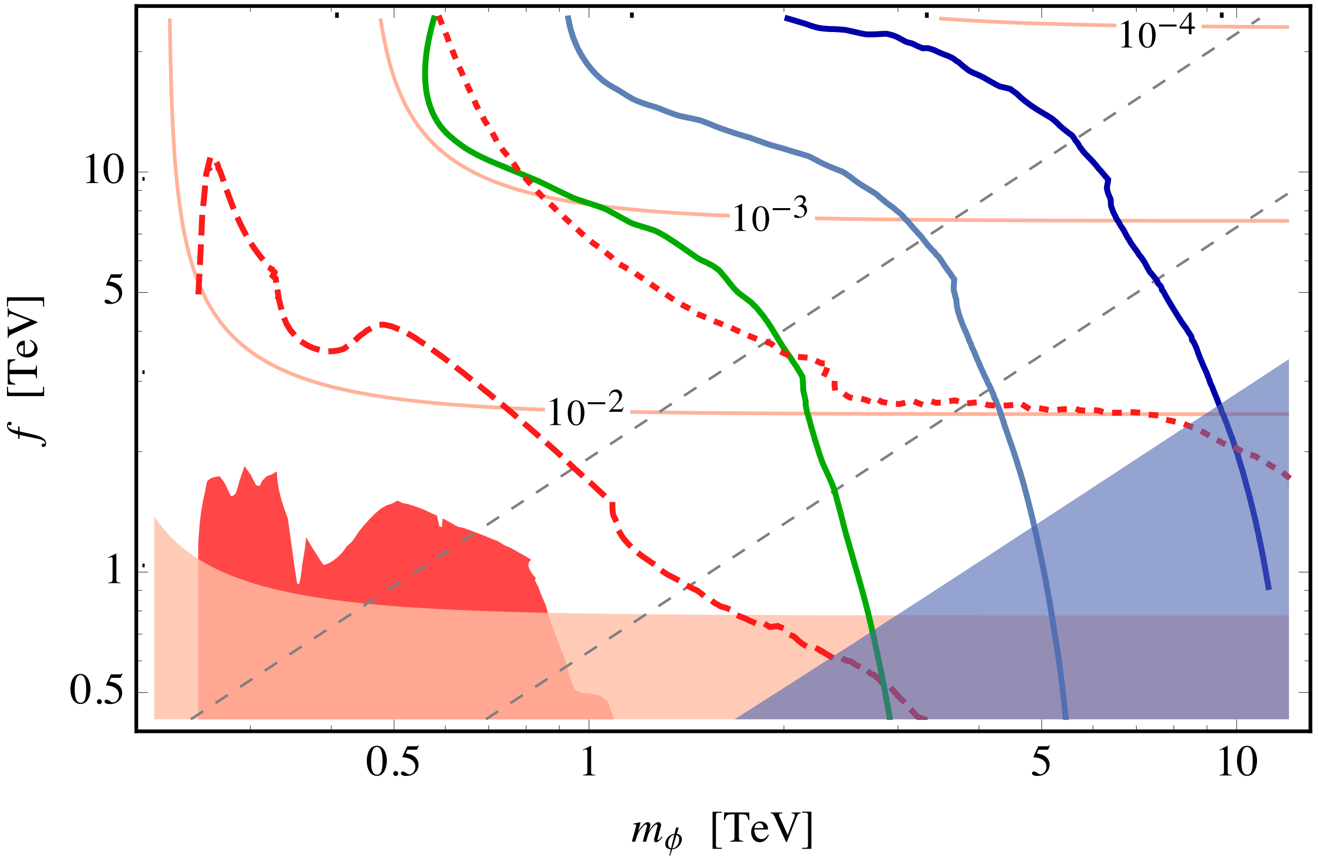
- **Example:** Twin Higgs

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

  Model-independent tests:

  ✓ Higgs couplings

  ✓ Search for the singlet



B, Redigolo, Sala, Tesi 1807.04743

(see also 1711.05300)