(Weakly) Strong EWSB dynamics

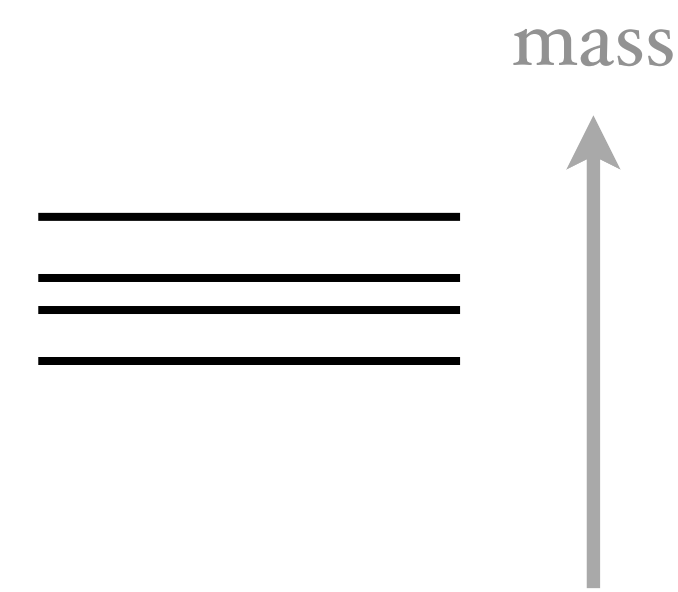
precision tests versus direct searches

chatting with
R. Contino & A. Thamm

EWSB is *broadly* described by

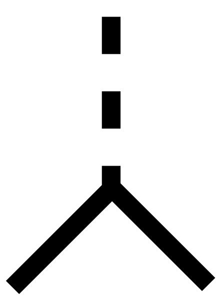
✦ one mass scale m_*

$\sim m_*$ $\Big\{$

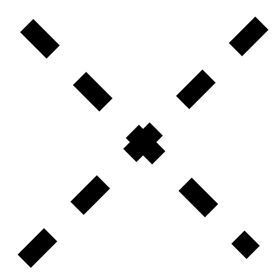


✦ one coupling g_*

Ex.: $g_* \sim \frac{4\pi}{\sqrt{N}}$



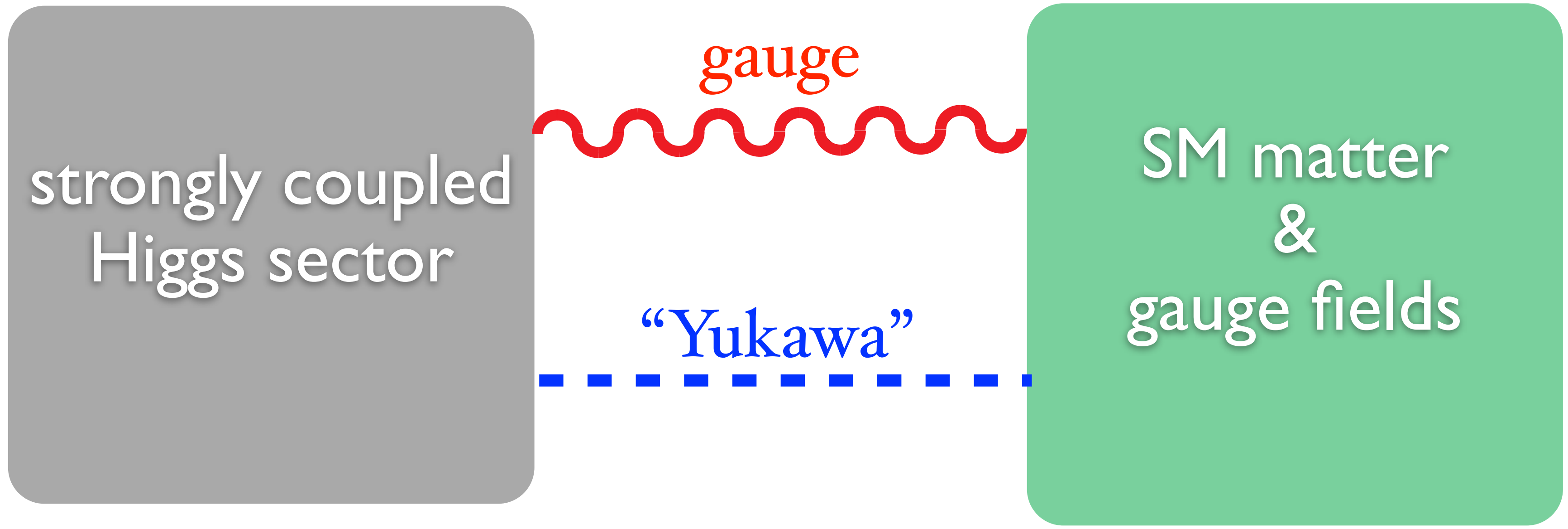
$g_* \, \bar{\Psi}\Psi\Phi$



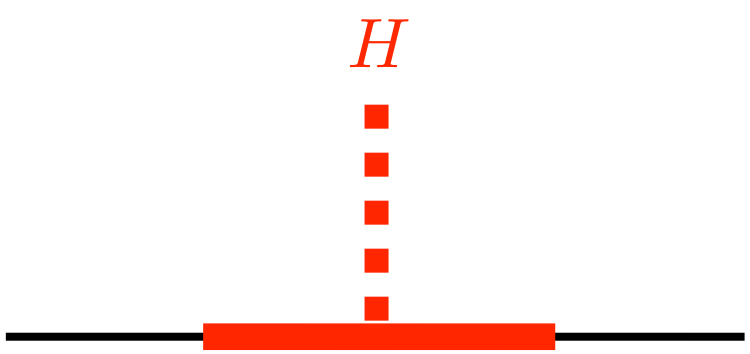
$\frac{g_*^2}{m_*^2}(\pi\partial\pi)^2$

$h \in \pi =$ pseudo-NG

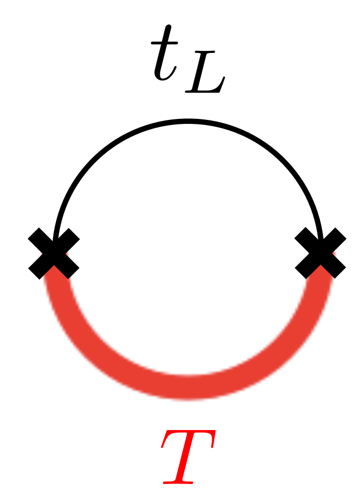
$\frac{g_*}{m_*} \equiv \frac{1}{f}$



$$\mathcal{L}_{int} = g_W W^\mu J_\mu^{comp} + \lambda_i q_i \Psi_i^{comp}$$

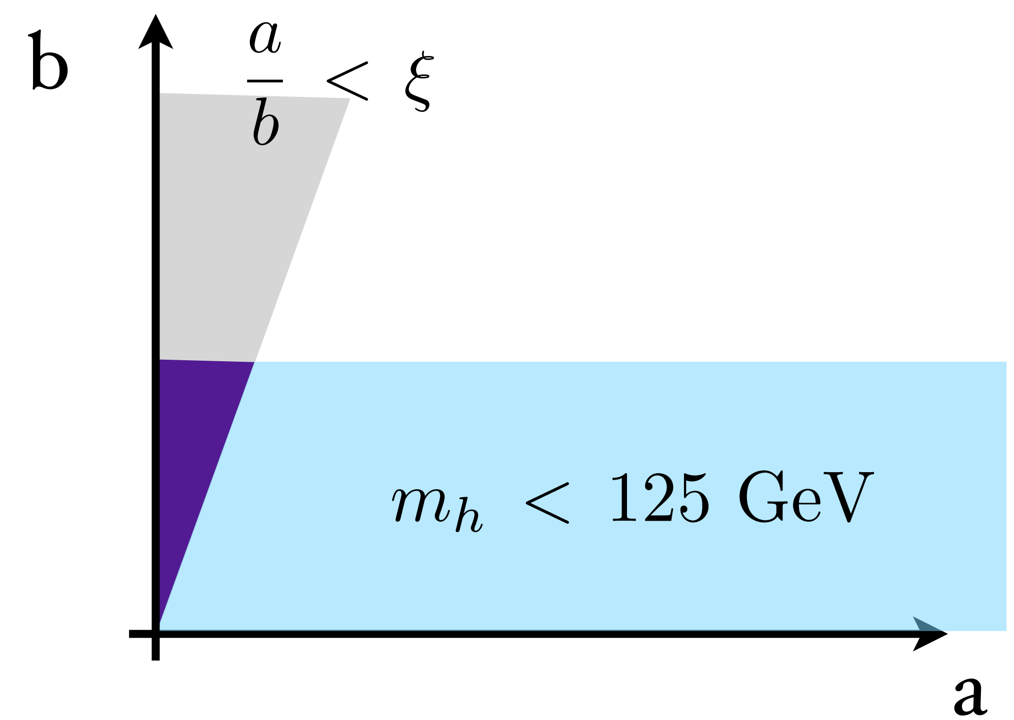


$$Y_{ij} \sim \frac{\lambda_i^L \lambda_j^R}{g_*}$$



Higgs potential

The connection between $g_*,\ m_*,\ m_t$ and m_h



$$V = \frac{3\lambda_t^2 m_*^2}{16\pi^2}\left(a h^2 + b h^4/f^2 + \dots\right)$$

$$\begin{cases} \xi \equiv \dfrac{v^2}{f^2} = \dfrac{a}{b} \\ m_h^2 = b\,\dfrac{3g_*^2}{2\pi^2}\,m_t^2 \sim (125\ \text{GeV})^2\,\dfrac{g_*^2 b}{4} \end{cases}$$

Total tuning ~ area = $a\,b = \left(\frac{430\,\text{GeV}}{m_*}\right)^2 \times \frac{4}{g_*^2}$

Notice impact of 125 GeV Higgs

$$m_h = 125\,\mathrm{GeV} \quad \Longrightarrow \quad a\,b = \left(\frac{430\,\mathrm{GeV}}{m_*}\right)^2 \times \frac{4}{g_*^2}$$

~*weakly* strong EWSB sector and light resonances preferred

$$m_h = 250\,\mathrm{GeV} \quad \Longrightarrow \quad a\,b = \left(\frac{860\,\mathrm{GeV}}{m_*}\right)^2 \times \frac{16}{g_*^2}$$

moderately strong and heavy EWSB sector

EWPT

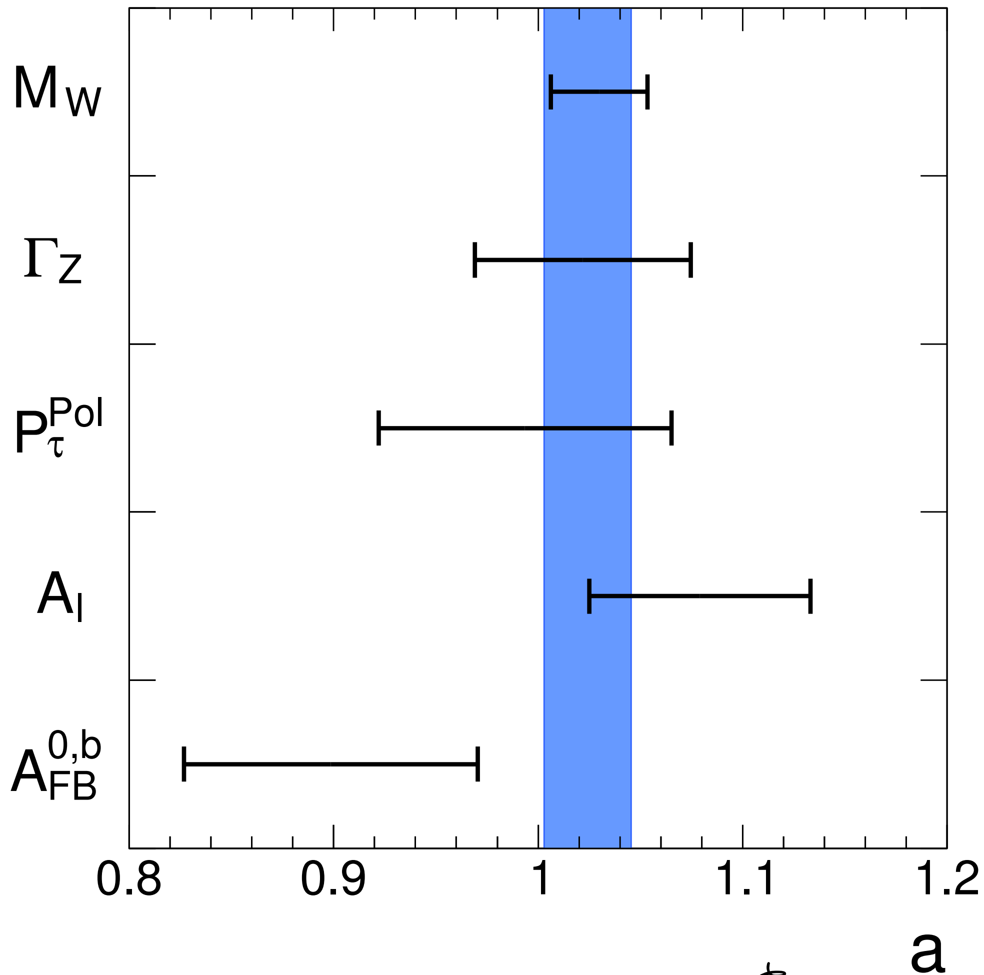
$$\Delta\epsilon_3 \quad = \quad O(1) \times \frac{m_W^2}{m_*^2} \;+\; \frac{g^2}{96\pi^2}\,\frac{v^2}{f^2}\,\ln(m_*/m_h)$$

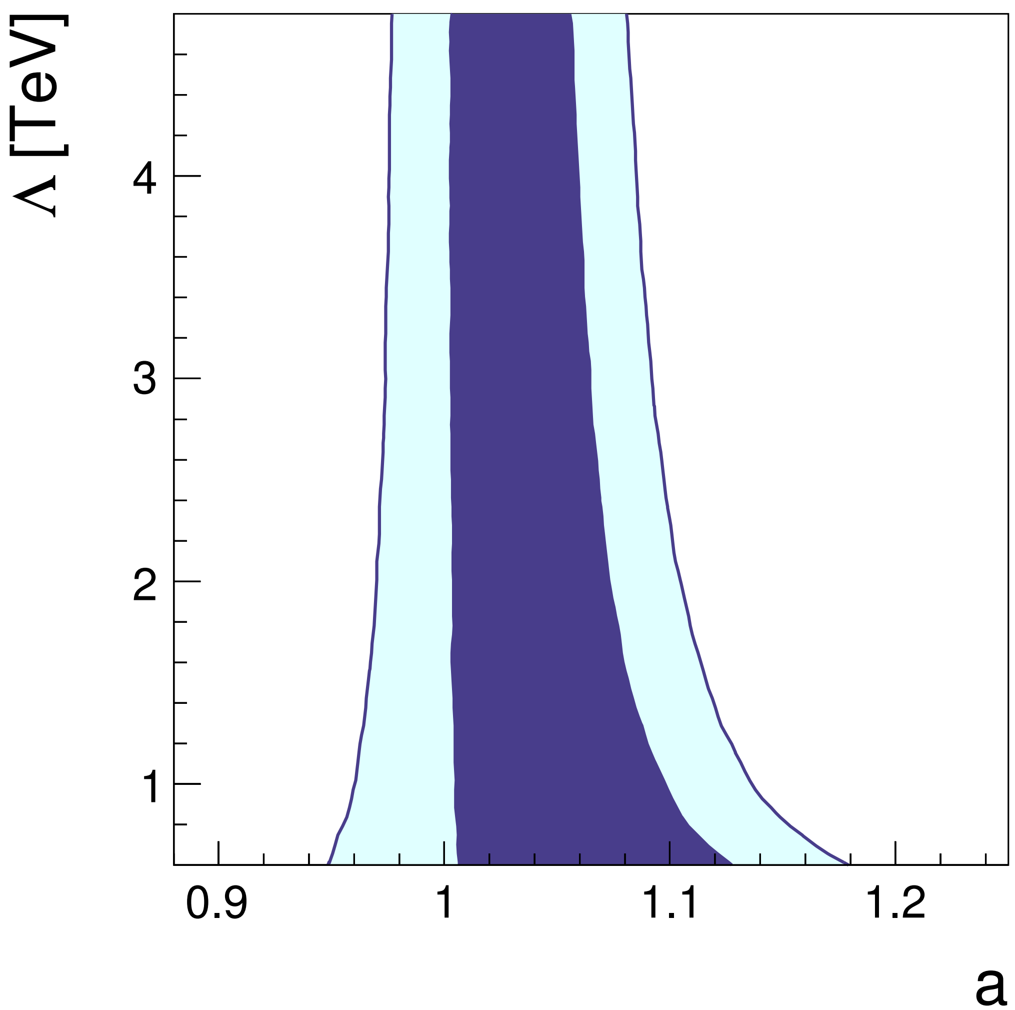
$$m_* \gtrsim 2 \text{ TeV}$$

$$\Delta\epsilon_1 \quad = \quad \delta\rho_{SM} \times \frac{m_t^2}{m_*^2} \;-\; \frac{3g^2 \tan\theta_W^2}{32\pi^2}\,\frac{v^2}{f^2}\,\ln(m_*/m_h)$$

in principle very strong bound : $\xi \equiv \frac{v^2}{f^2} \lesssim 0.05$

in practice it could be relaxed by short distance contribution





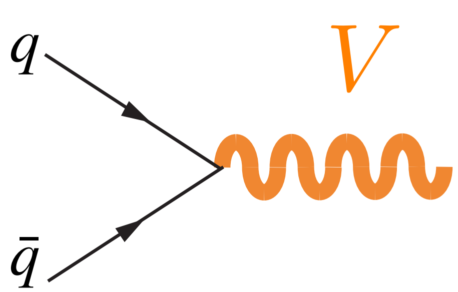
$$a = 1 - \frac{\xi}{2}$$

Franco, Mishima, Silvestrini 2013

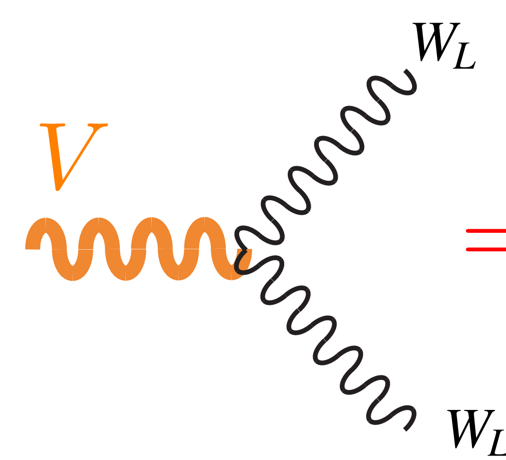
Direct searches (LHC 8TeV)

- Top partners (Q=-1/3, 2/3, 5/3) $m_* \gtrsim 1\,\text{TeV}$

- Vector resonances



$= \frac{g_W^2}{g_*} < g_W$



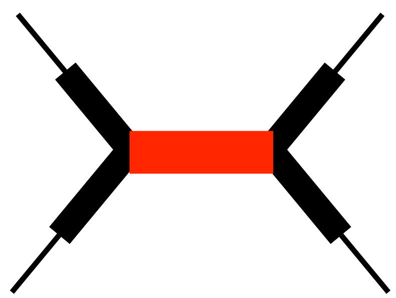
$= g_*$

CMS data
Pappadopulo, Thamm, Torre, Wulzer 2014

$$\begin{cases} g_* = 1 & m_* > 3\,\text{TeV} \\ g_* = 3 & m_* > 2\,\text{TeV} \end{cases}$$

Flavor

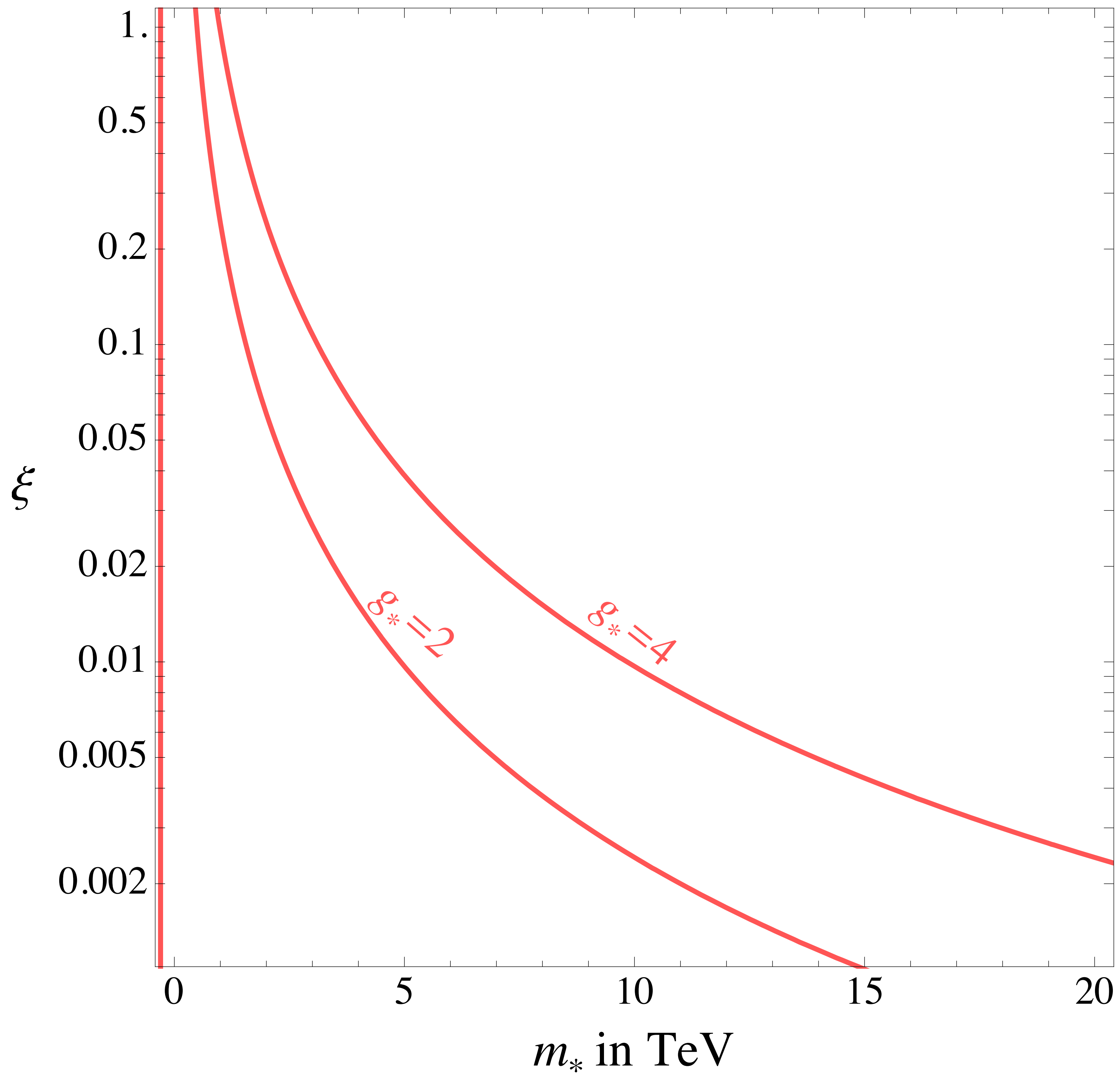
$\Delta F=2$



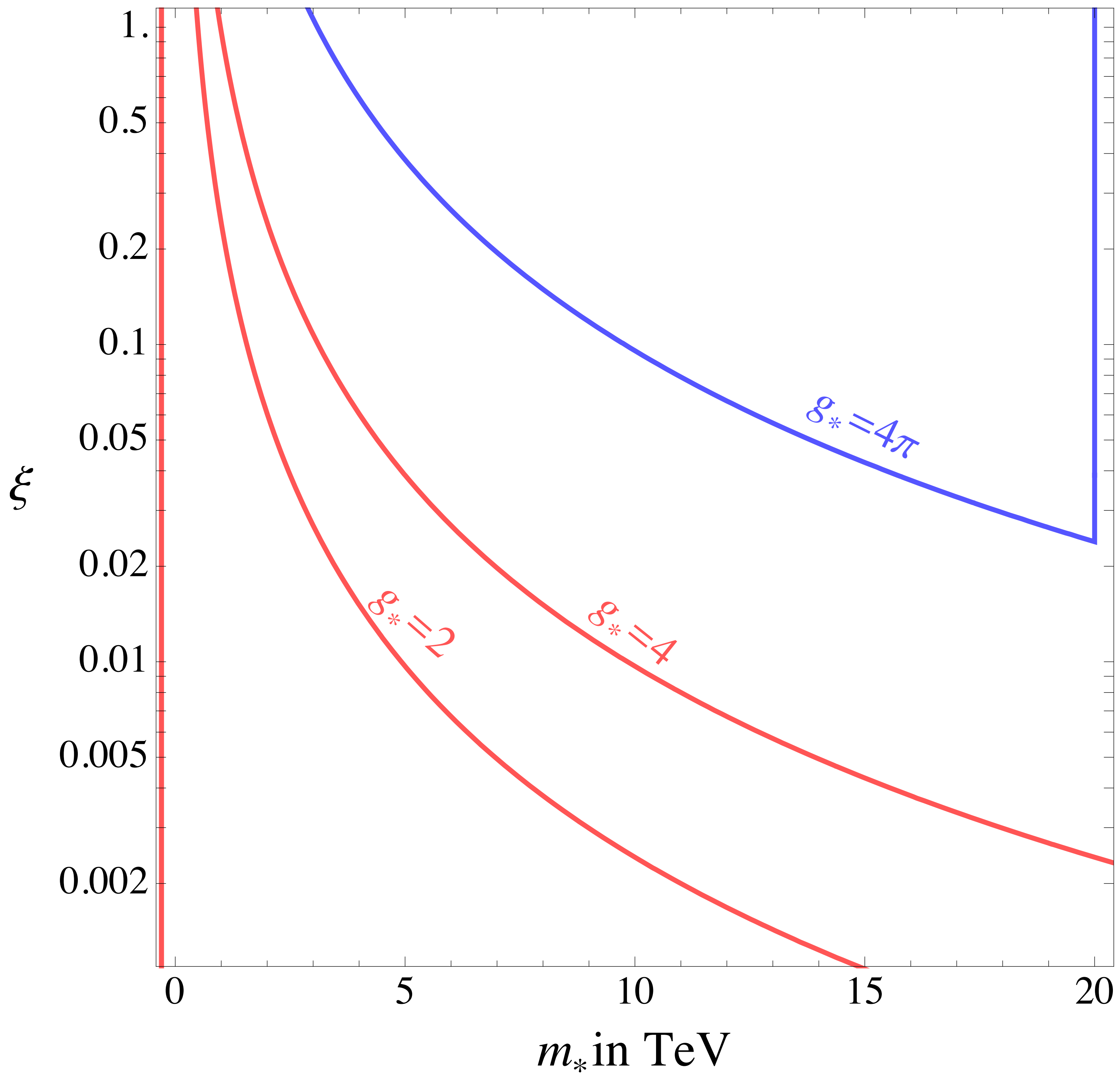
$\Delta F=1$

$$m_* > 10 - 40 \text{ TeV}$$

unless additional flavor symmetries in place



$$\xi \; = \; \frac{g_*^2}{m_*^2} \, v^2$$



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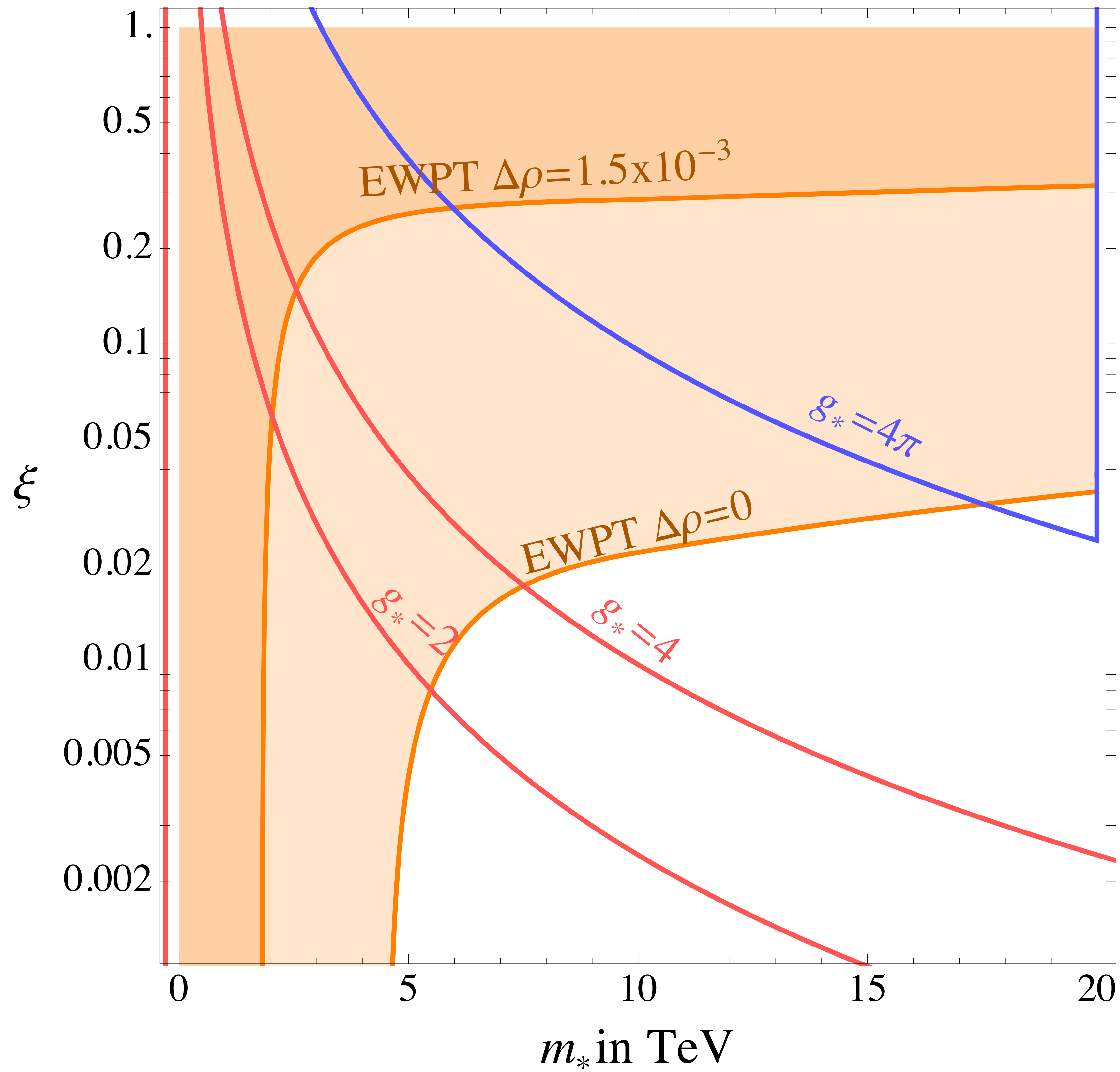
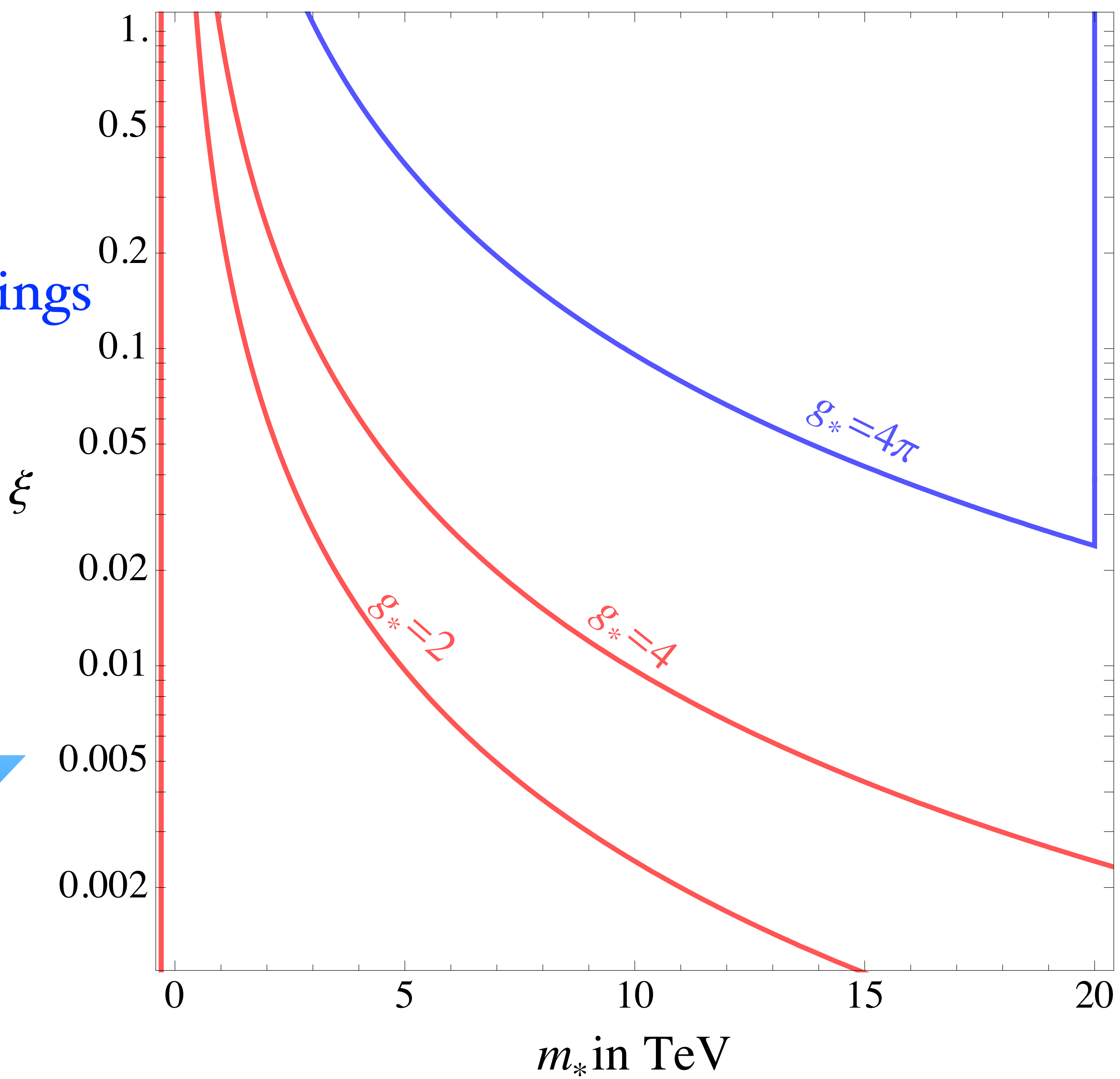


1.
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.002
0
5
10
15
20
ξ
m_* in TeV
EWPT Δρ=1.5x10^-3
EWPT Δρ=0
g_*=4π
g_*=2
g_*=4

$$\xi = \frac{g_*^2}{m_*^2} v^2$$

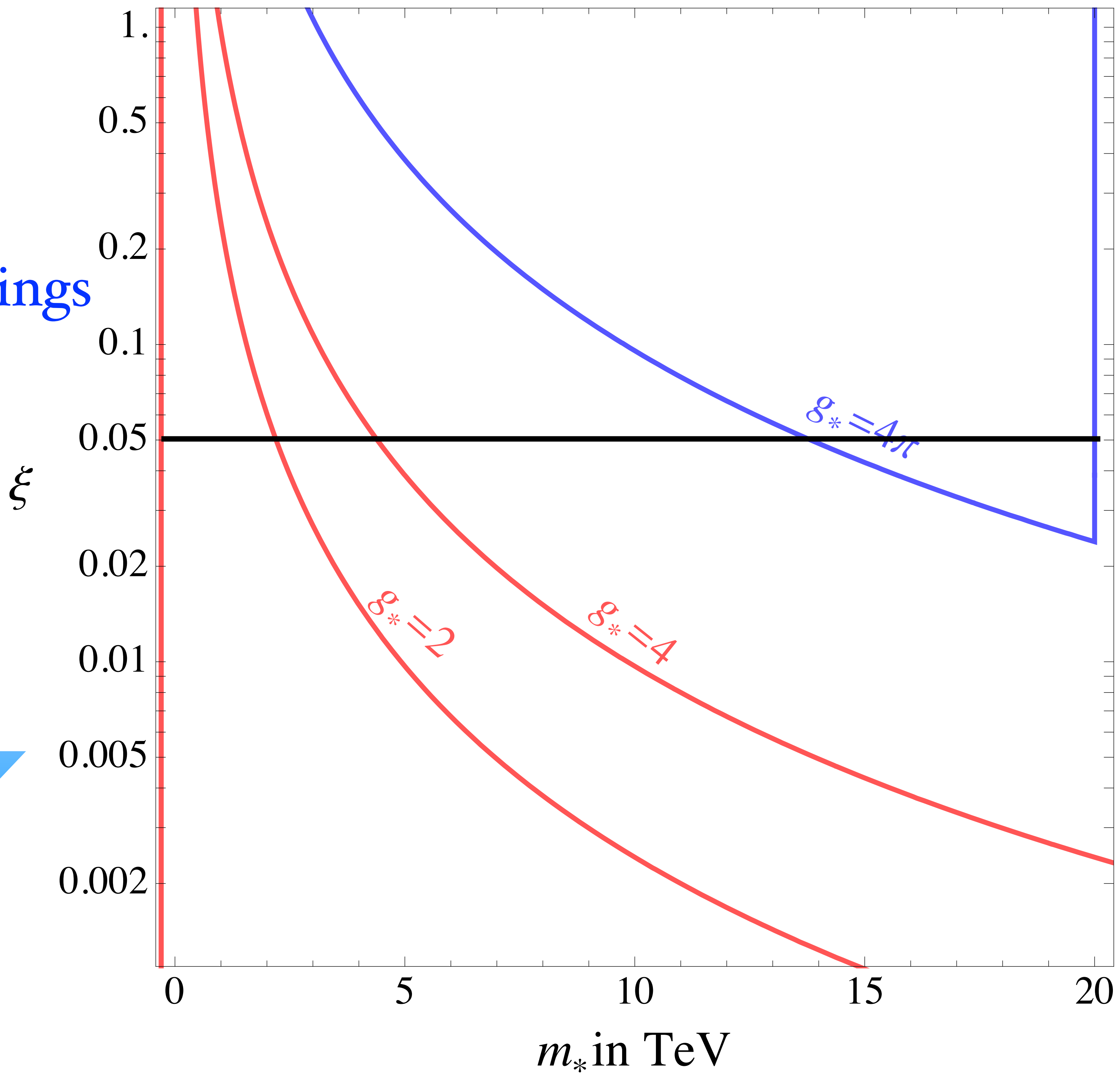
Higgs couplings



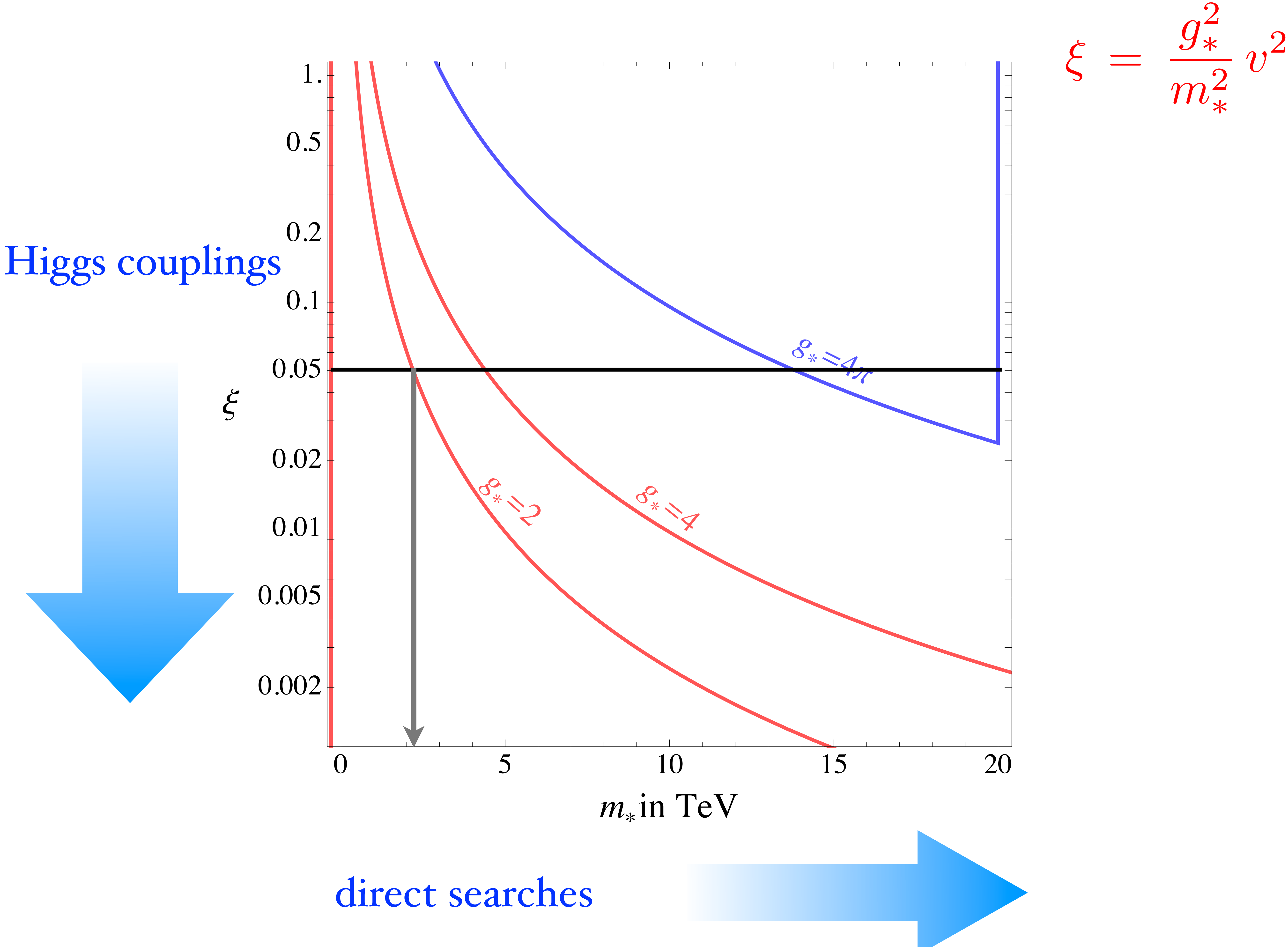
direct searches

$$\xi = \frac{g_*^2}{m_*^2} v^2$$

Higgs couplings



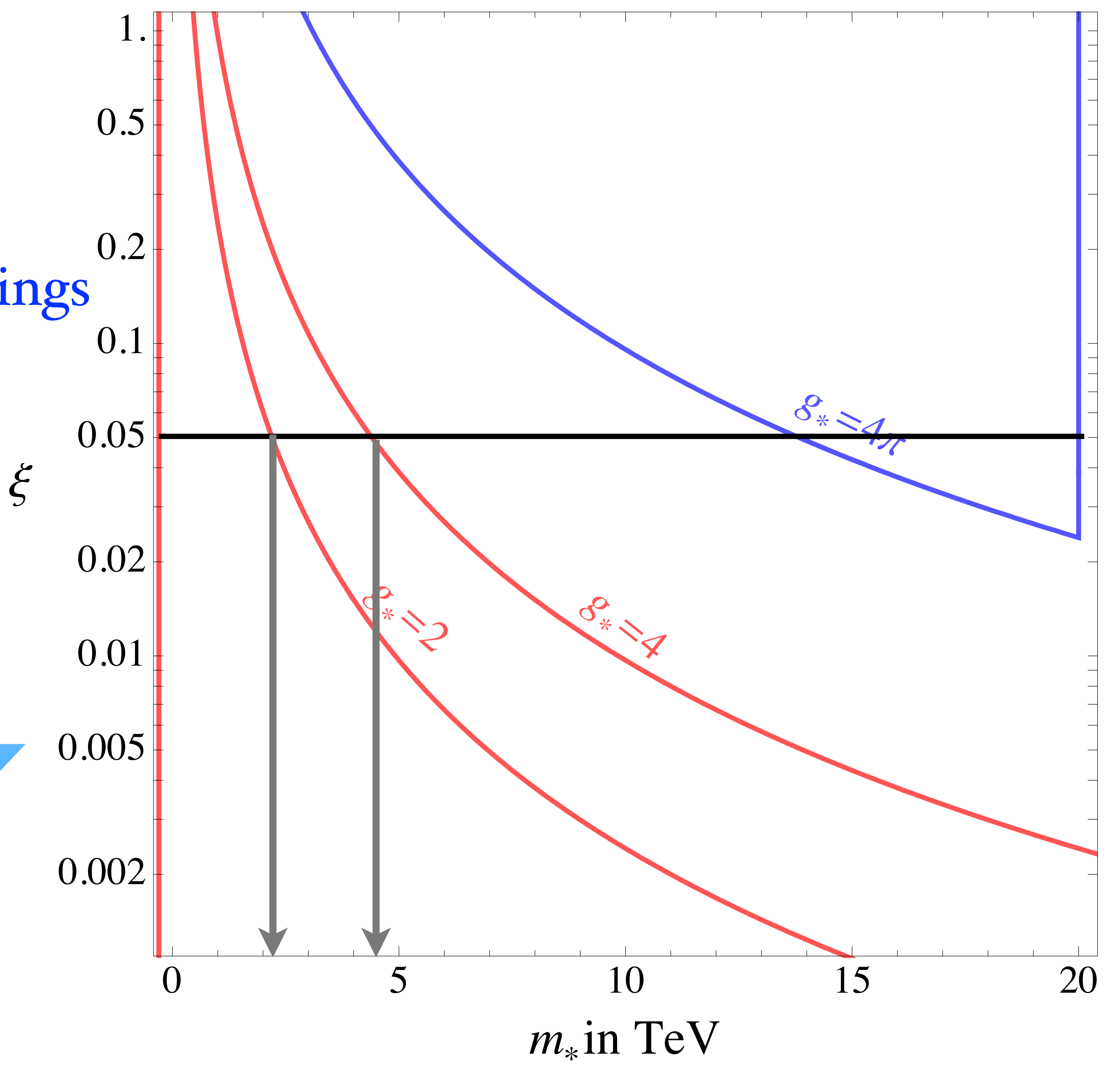
direct searches



$\xi = \frac{g_*^2}{m_*^2} v^2$
Higgs couplings
direct searches
ξ
m_* in TeV
1.
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.002
0
5
10
15
20
$g_* = 2$
$g_* = 4$
$g_* = 4\pi$

$$\xi = \frac{g_*^2}{m_*^2} v^2$$

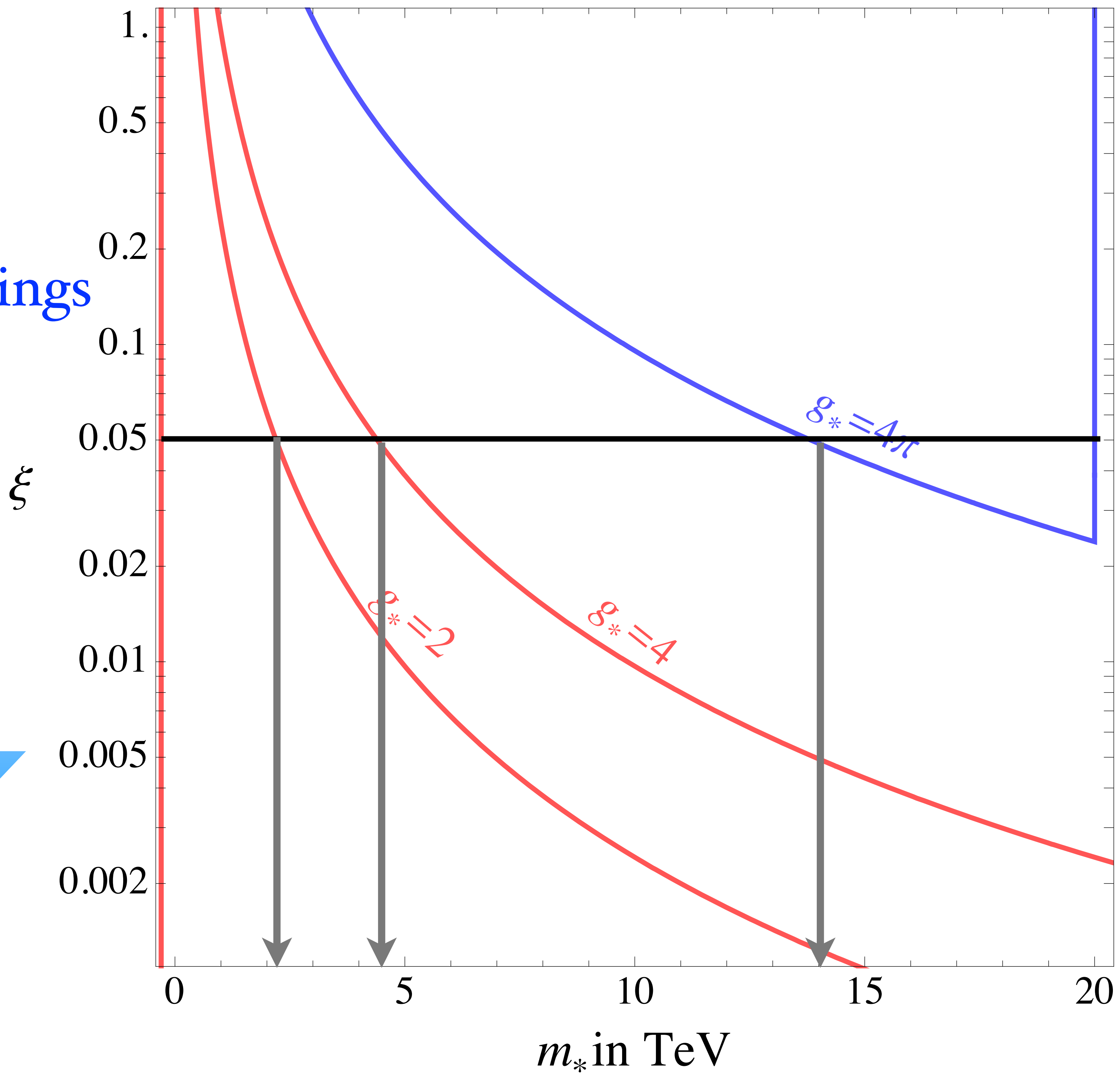
Higgs couplings



direct searches

$$\xi = \frac{g_*^2}{m_*^2} v^2$$

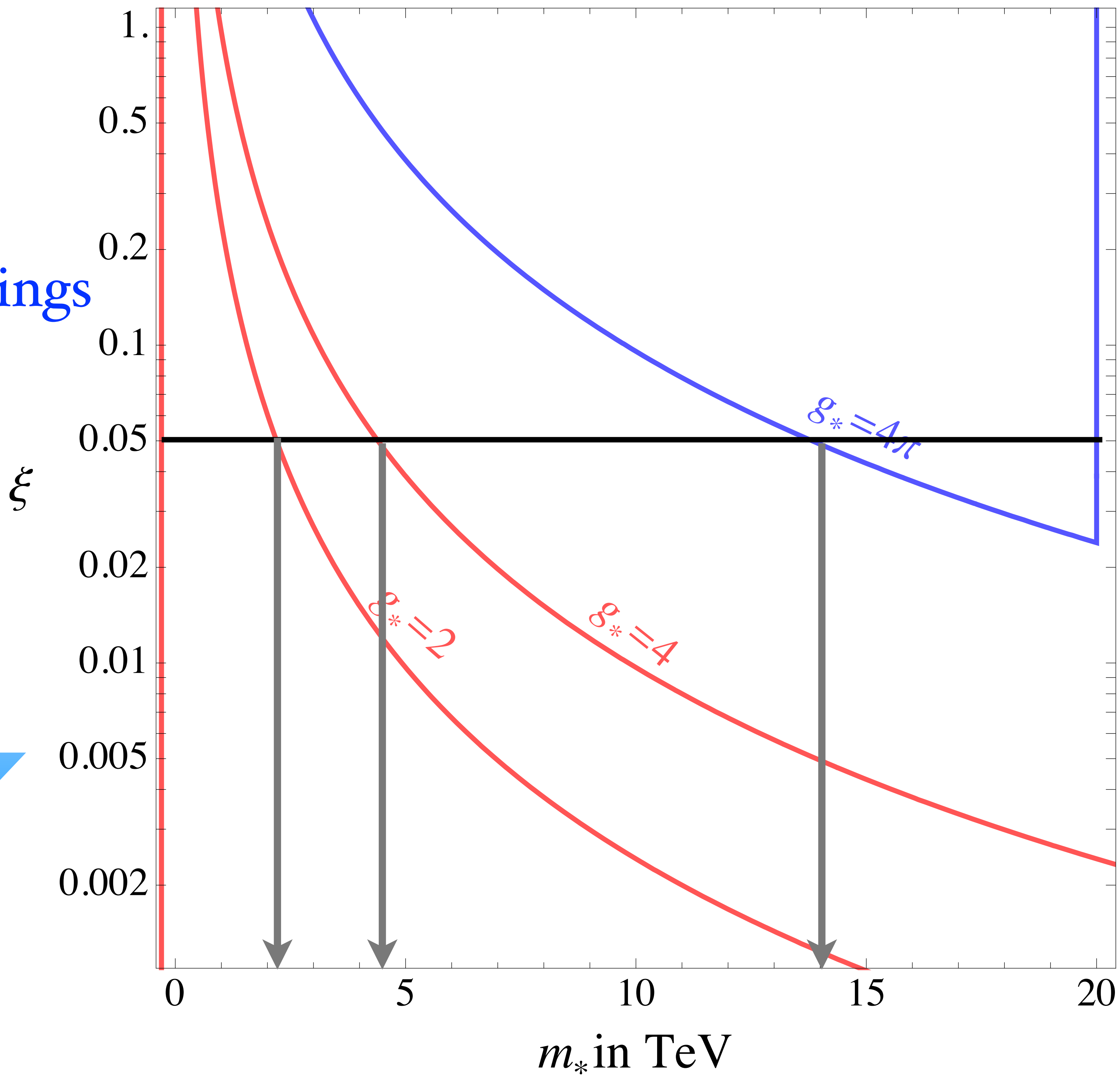
Higgs couplings



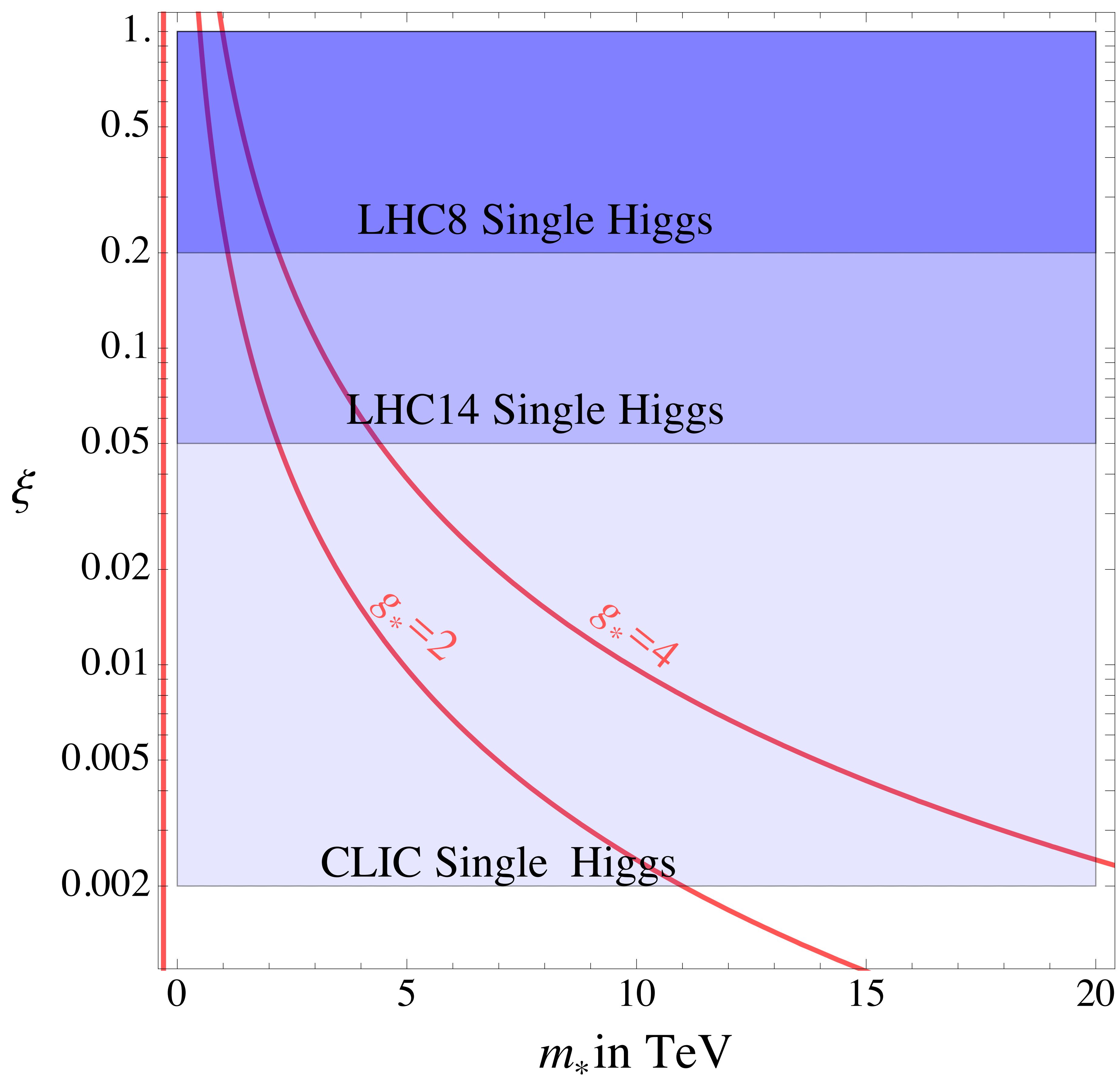
direct searches

$$\xi = \frac{g_*^2}{m_*^2} v^2$$

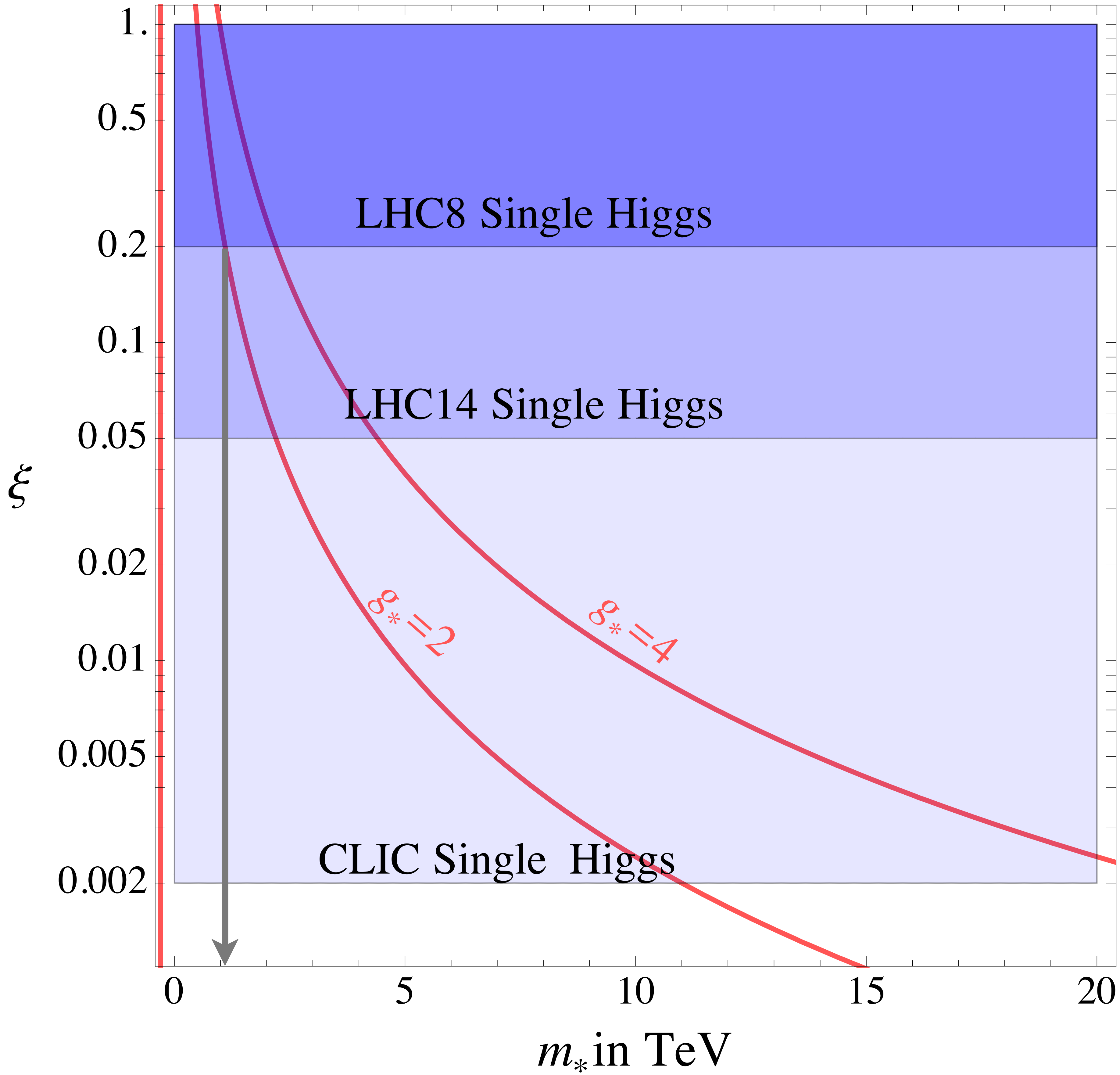
Higgs couplings



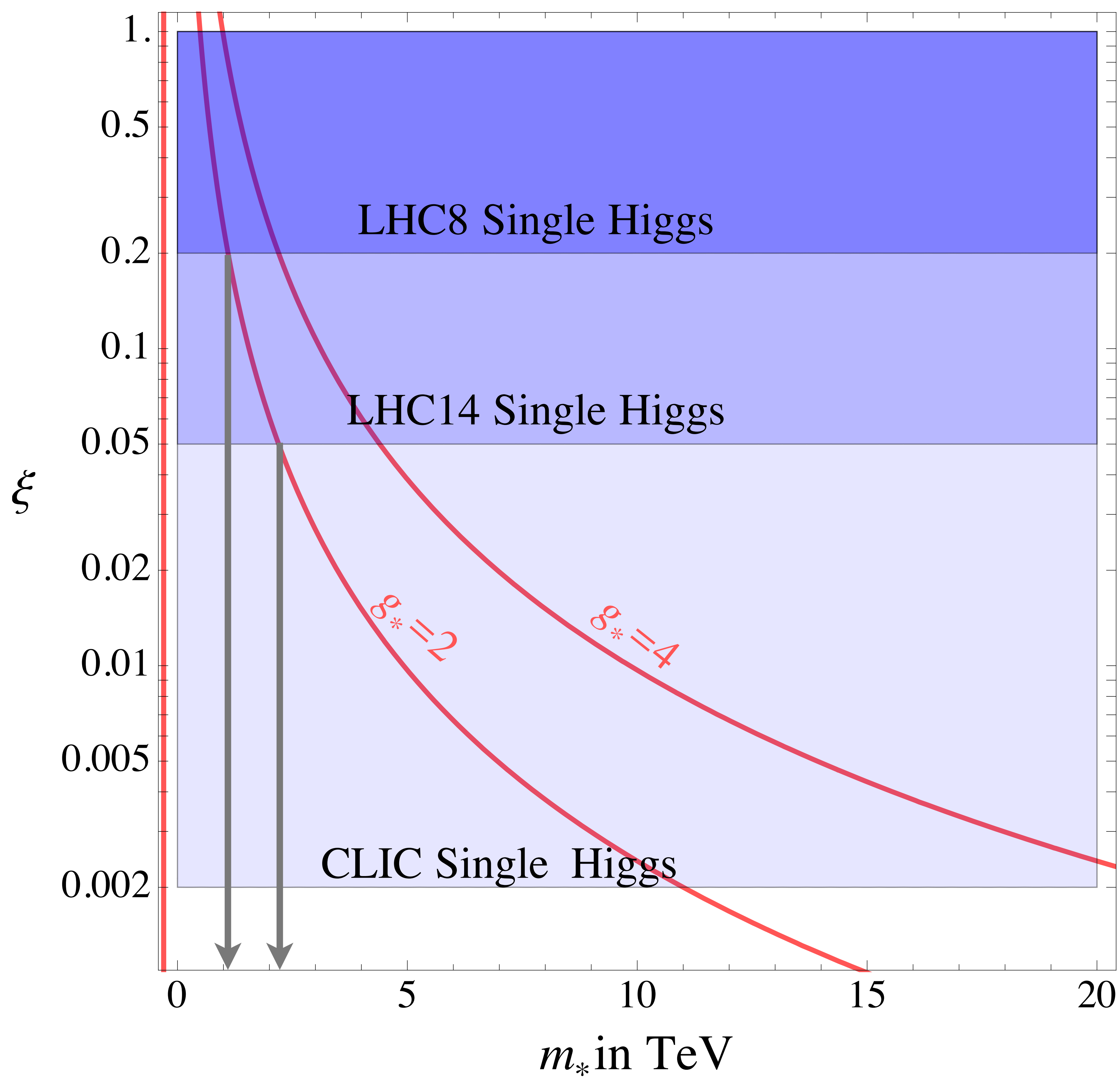
the stronger g_* the more relevant the precision measurements

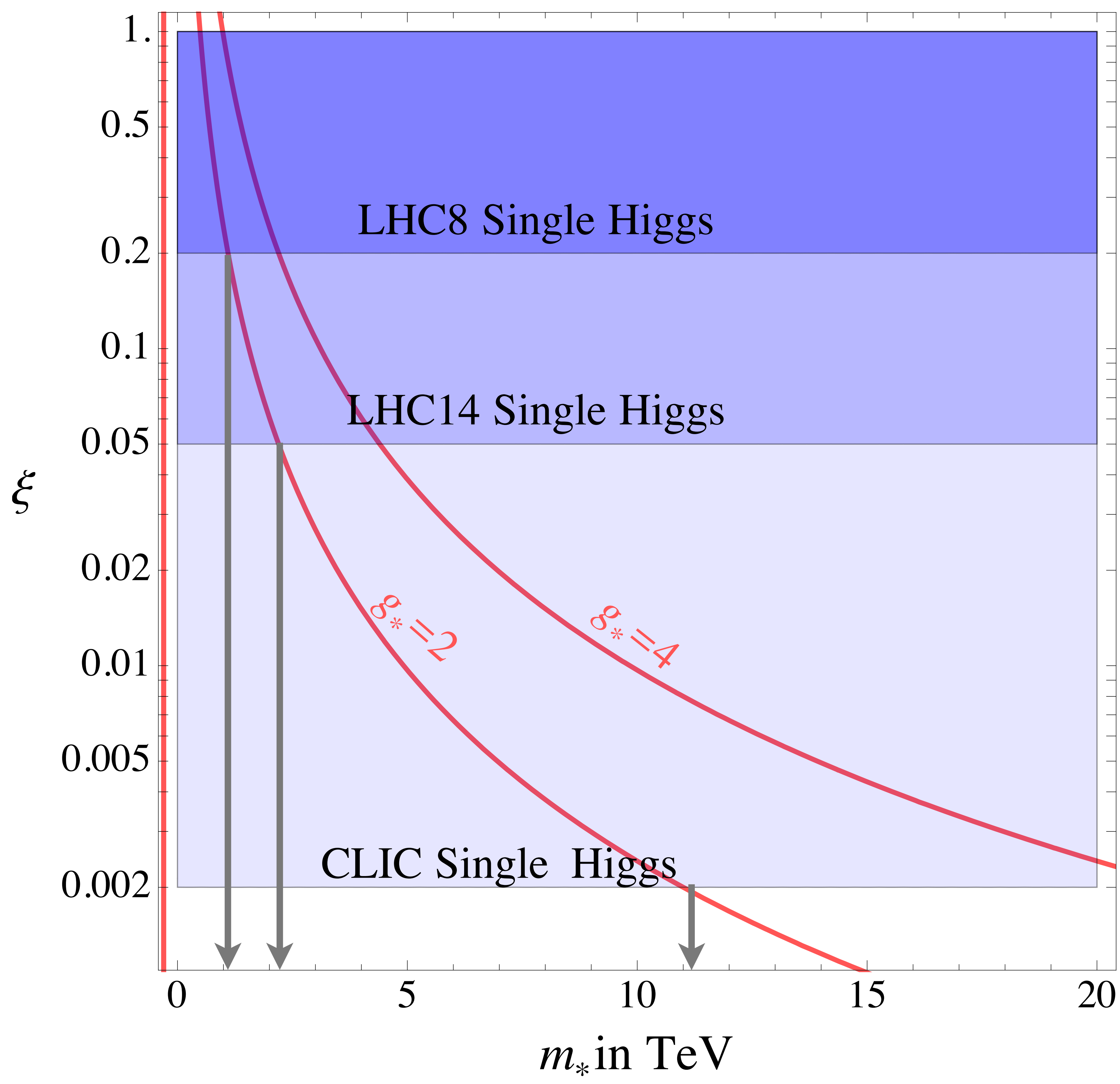


LHC8 Single Higgs
LHC14 Single Higgs
CLIC Single Higgs
$g_*=2$
$g_*=4$
ξ
1.
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.002
0
5
10
15
20
m_* in TeV



1.
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.002
ξ
LHC8 Single Higgs
LHC14 Single Higgs
CLIC Single Higgs
g* =2
g* =4
0
5
10
15
20
m* in TeV


1.
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.002
ξ
LHC8 Single Higgs
LHC14 Single Higgs
CLIC Single Higgs
g* =2
g* =4
0
5
10
15
20
m* in TeV



1.
0.5
0.2
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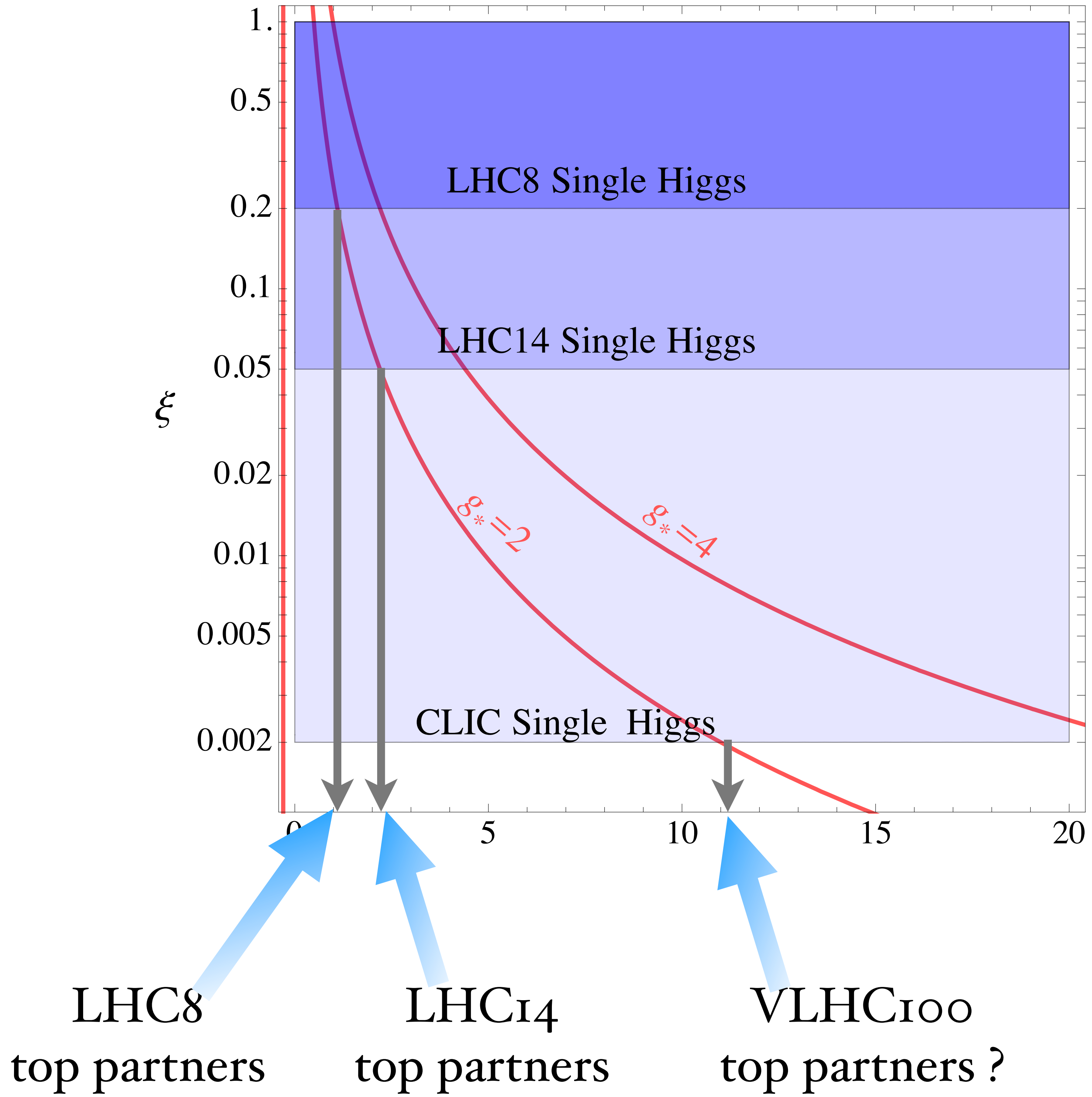
ξ
LHC8 Single Higgs
LHC14 Single Higgs
CLIC Single Higgs
g*=2
g*=4
0
5
10
15
20
m* in TeV



1.
0.5
0.2
0.1
0.05
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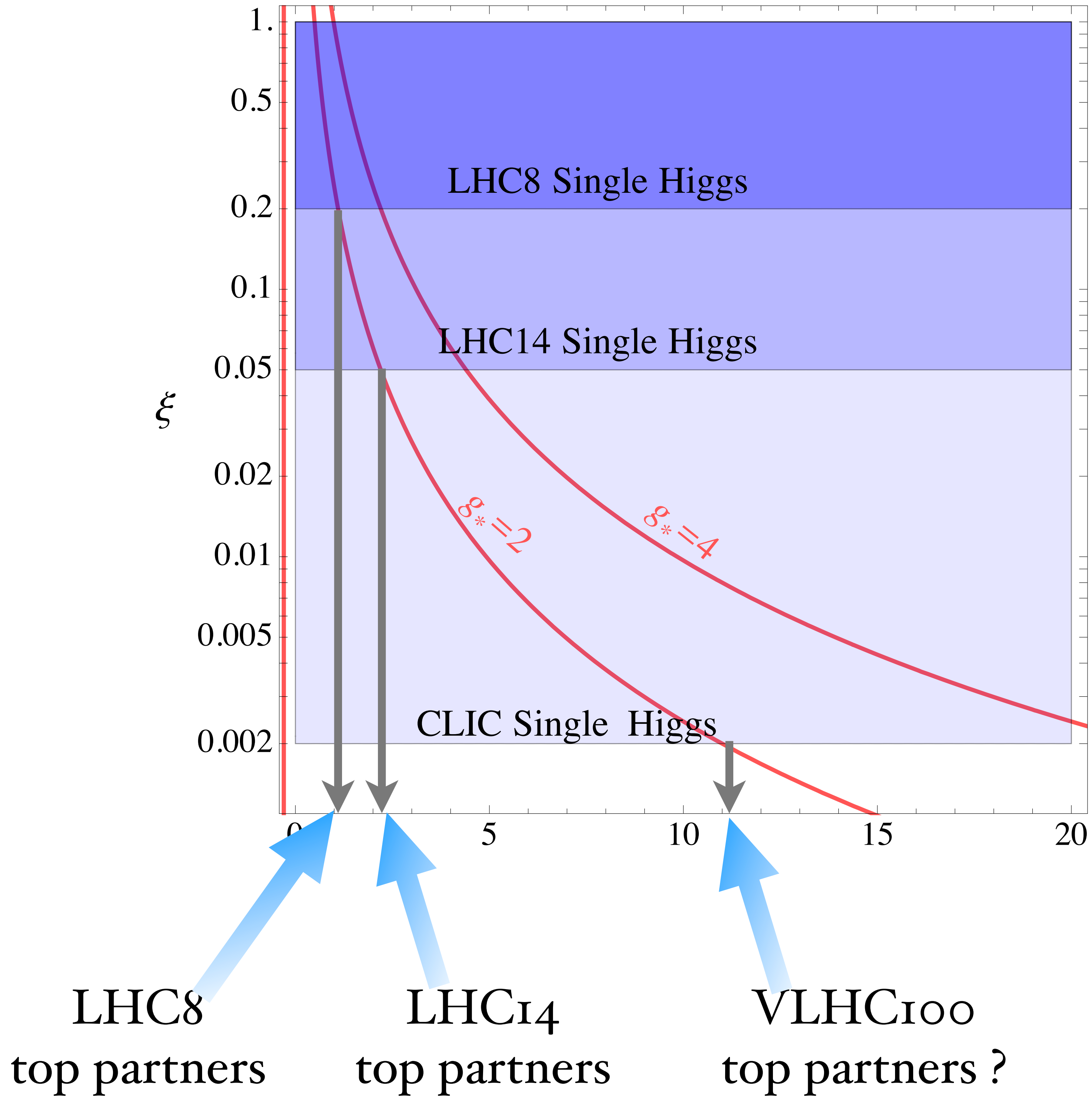
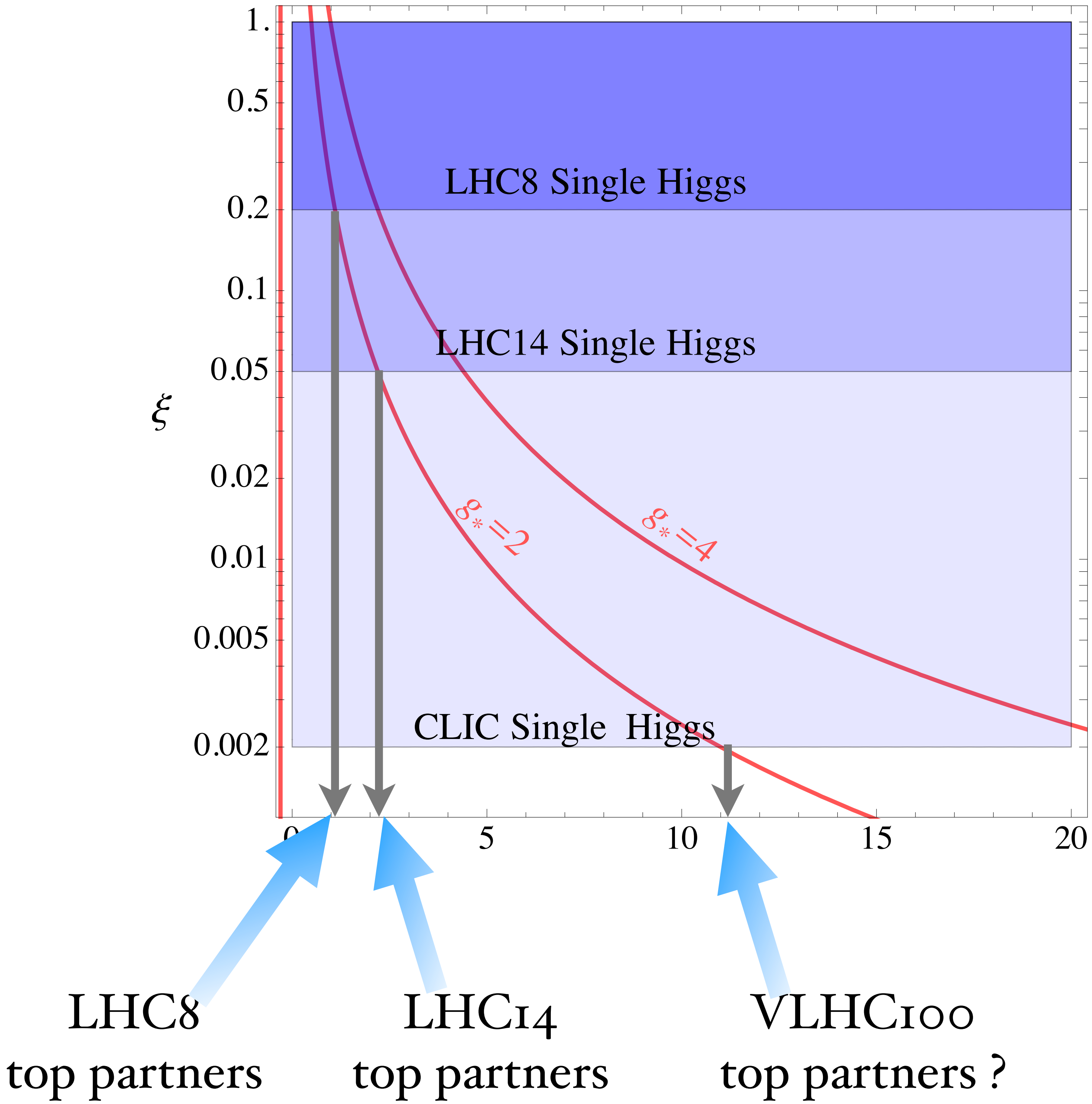
0.01
0.005
0.002
ξ
0
5
10
15
20
LHC8 Single Higgs
LHC14 Single Higgs
CLIC Single Higgs
$g_*=2$
$g_*=4$
LHC8
top partners
LHC14
top partners
VLHC100
top partners ?



In the weakly strong scenario the reach of precision measurements matches the competing direct searches



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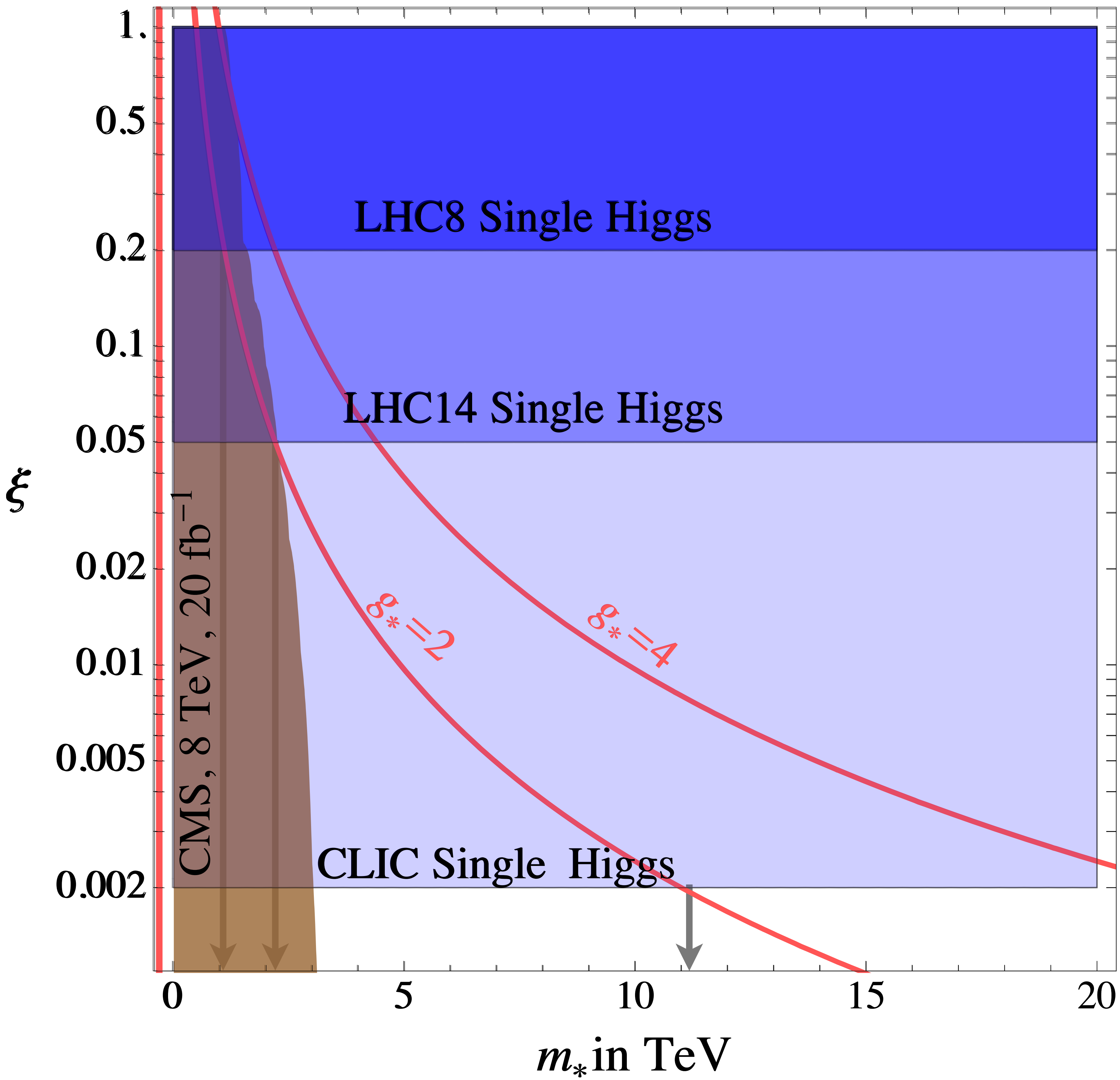
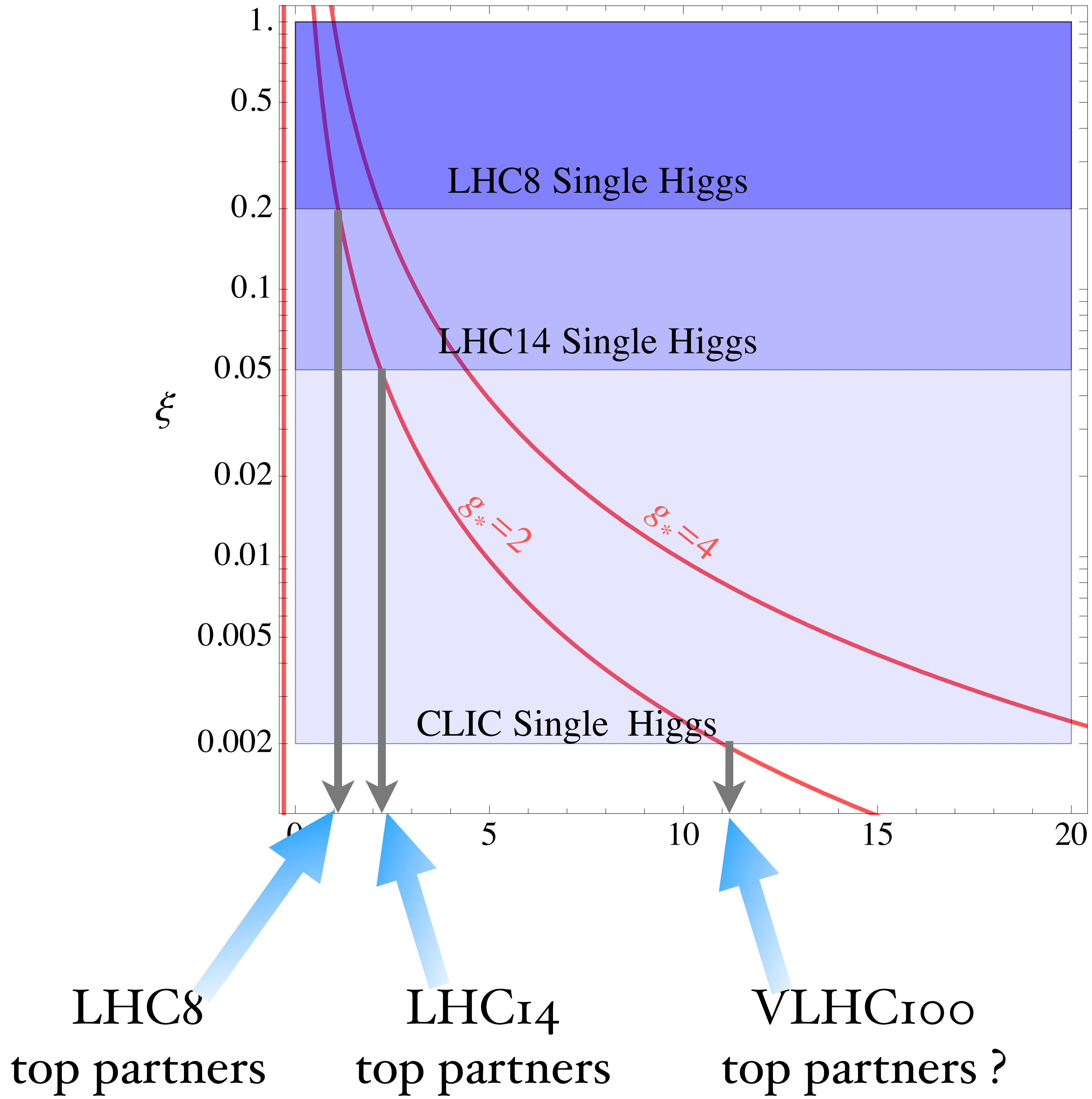
In the moderately strong case CLIC may have some advantage

search for vectors in DY





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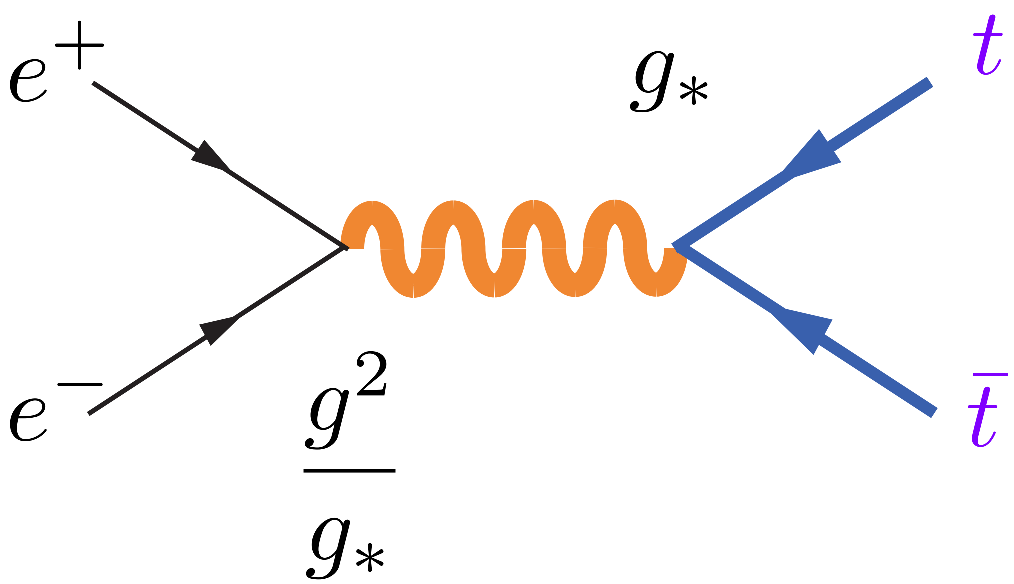


$$\sim \frac{g^2}{g_*} \frac{1}{m_*^2} g_* \sim \frac{g^2}{m_*^2}$$

CLIC study estimates sensitivity $m_* \sim 15 \text{ TeV}$

Battaglia et al., 2013

On the use of effective theory in WW-scattering

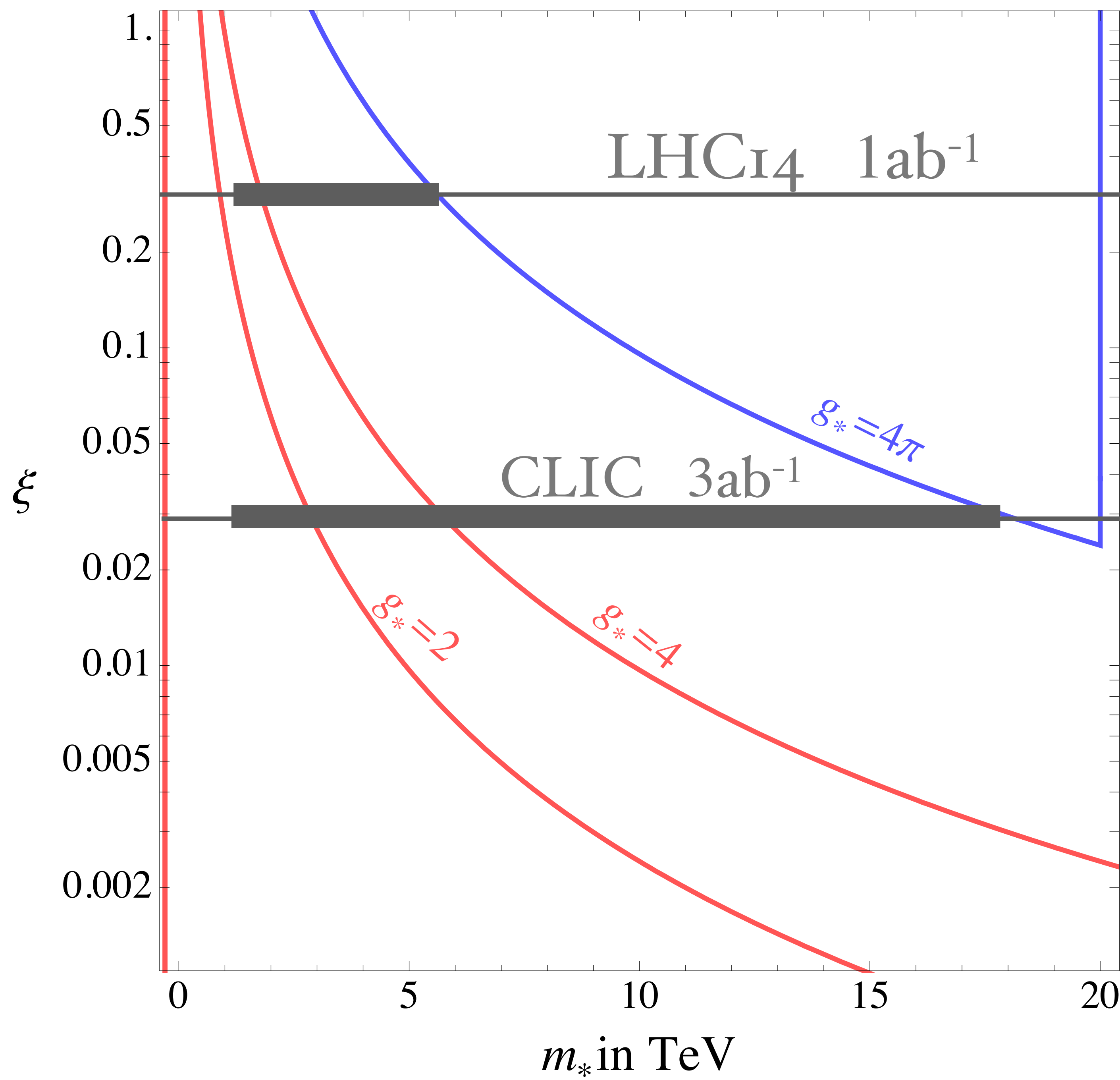
$$\mathcal{A}(2\to 2) = \frac{s}{f^2}\left(1+\frac{s}{m_*^2}+\dots\right) \longleftarrow g_*^2\,\frac{s}{-s+m_*^2}$$

$$\mathcal{A}(2\to 2) = \frac{s}{f^2}\left(1+\frac{1}{g_*^2}\frac{s}{f^2}+\dots\right)$$

a given collider is sensitive to $\frac{s}{f^2} > g_{min}^2$

when $g_{min}^2 > g_*^2$ resonances become essential

$WW \to WW$ $\qquad$ $WW \to hh$



$g_{min} \sim 2$

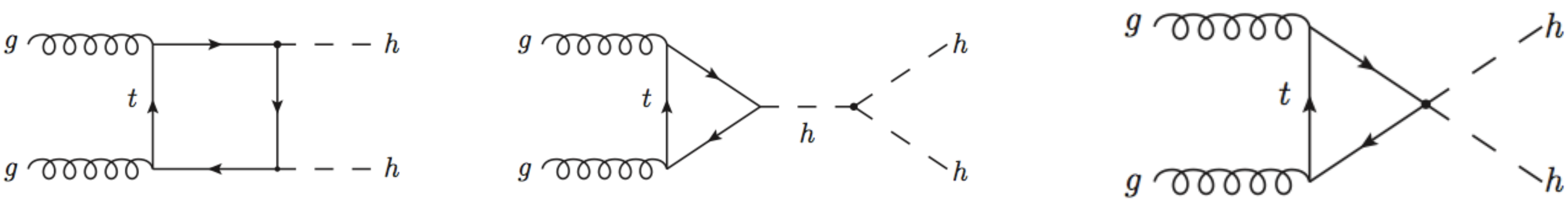
$g_{min} \sim 0.7$

Roughly expect same g_{min} at LHC and 100 TeV pp

EFT approach: good rule of thumb, but disfavored by light Higgs

Would perhaps be worth considering reach of gg →hh

LHC ab^{-1} : $\frac{v^2}{f^2} \sim 0.1$



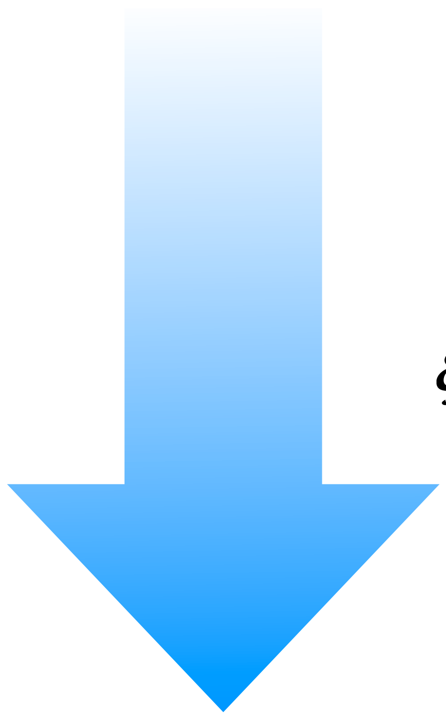
Grober, Muhlleitner 2010
Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer 2012

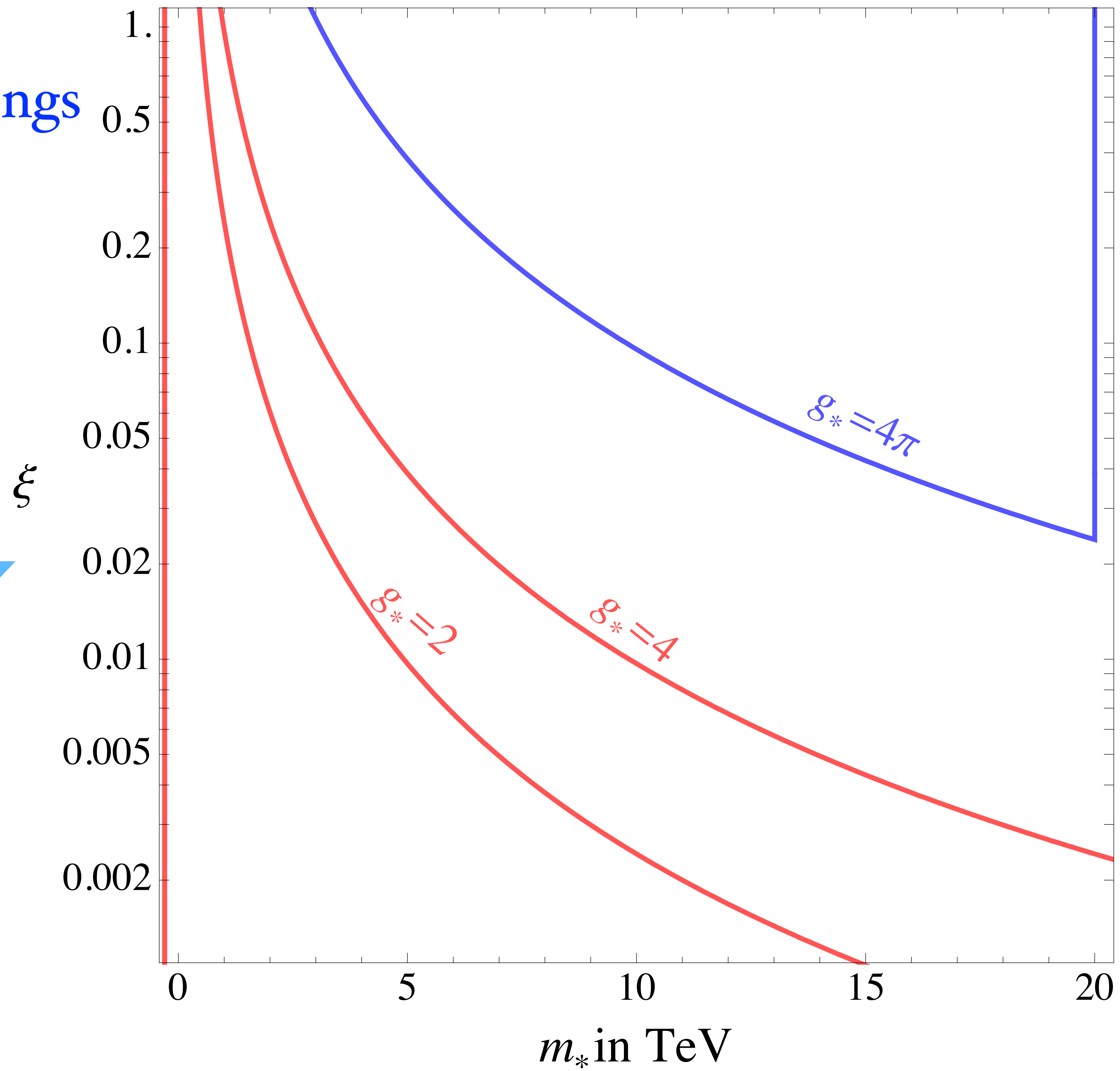
In conclusion...

- ✦ Strong -Weak duality : hadron colliders for weakly coupled theories and lepton colliders for strongly coupled ones

- ✦ 125 GeV Higgs speaks in favor of weaker than stronger dynamics (though fine tunings can always undo the favor)

Higgs couplings





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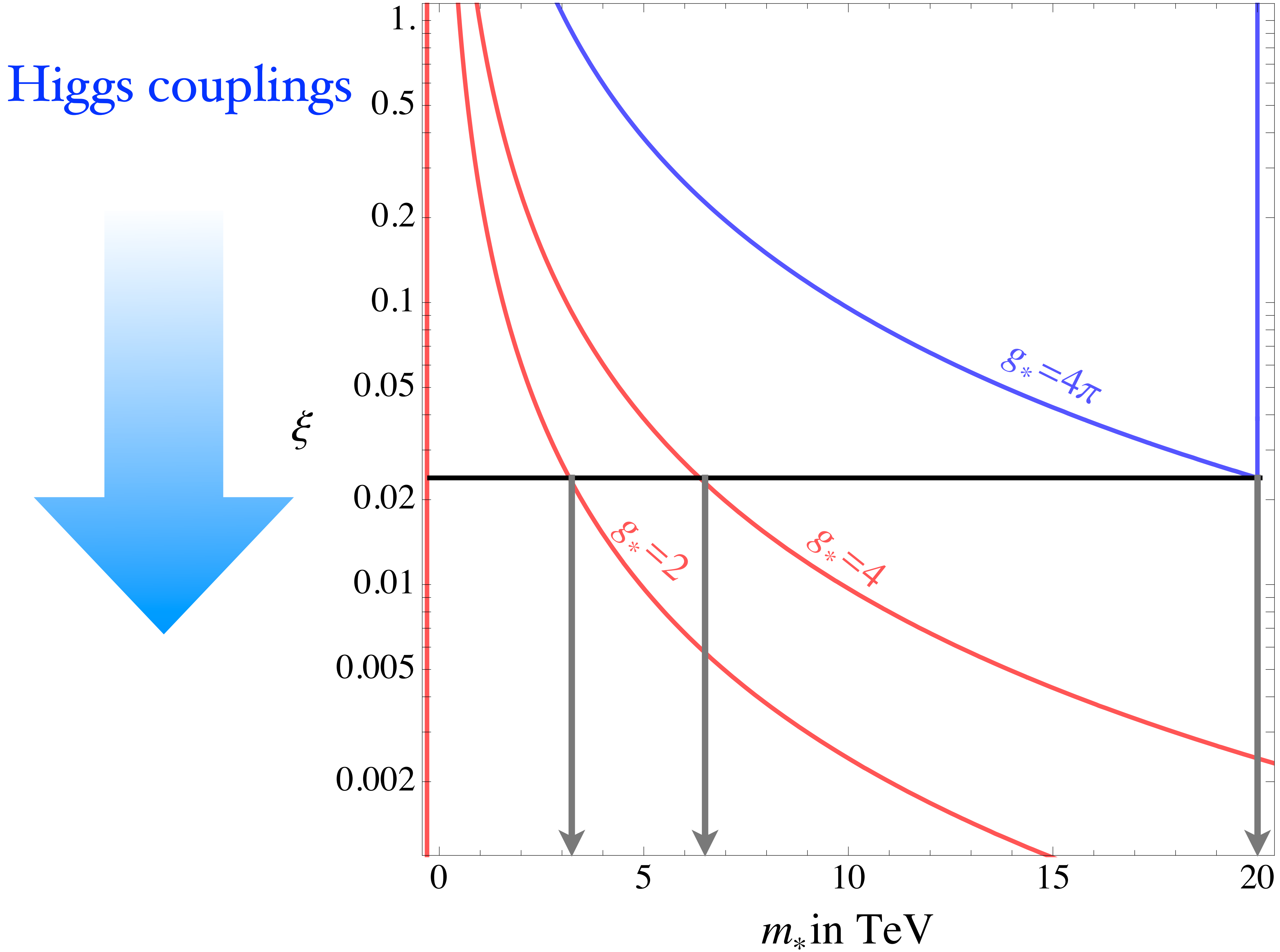
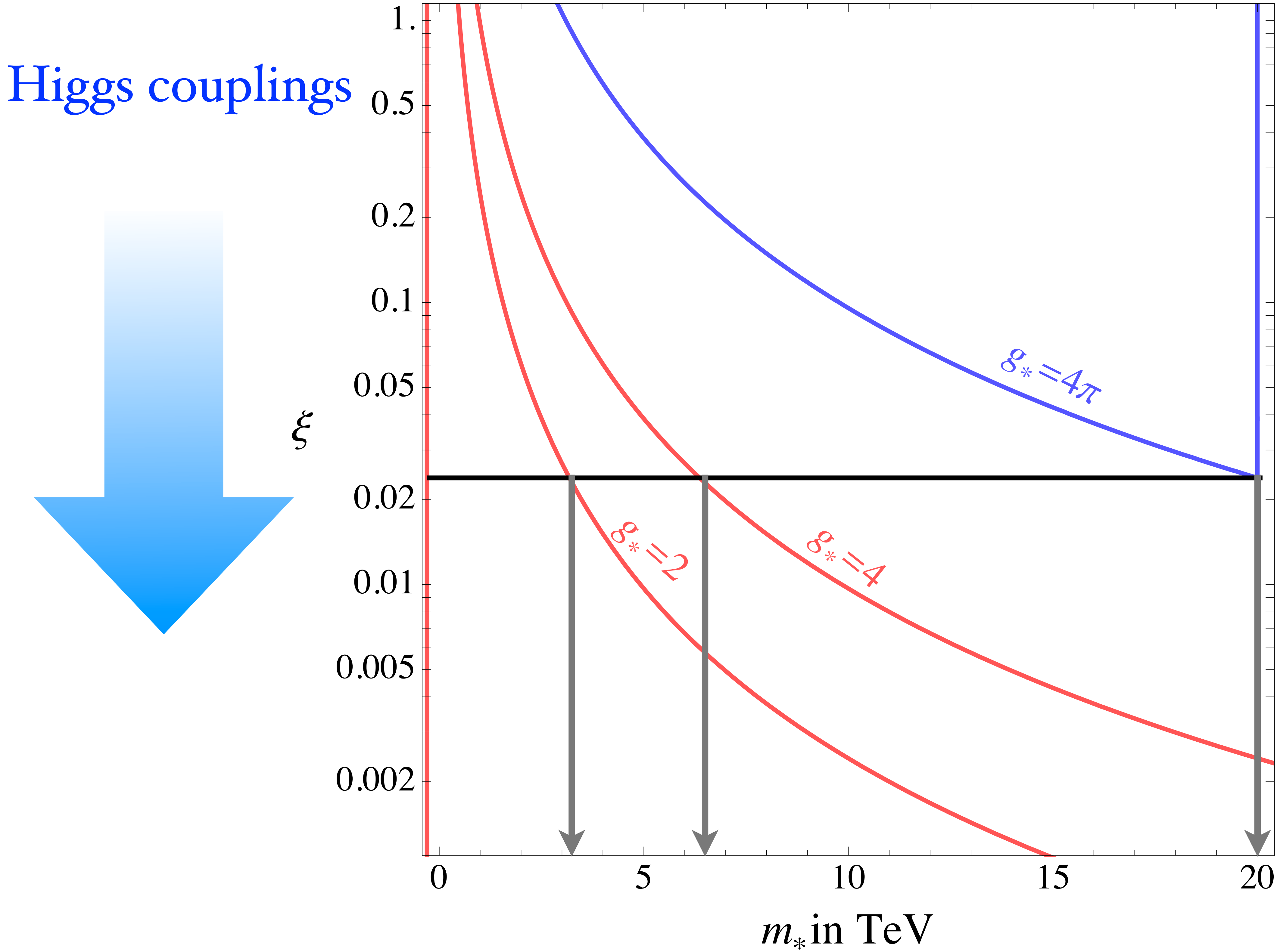
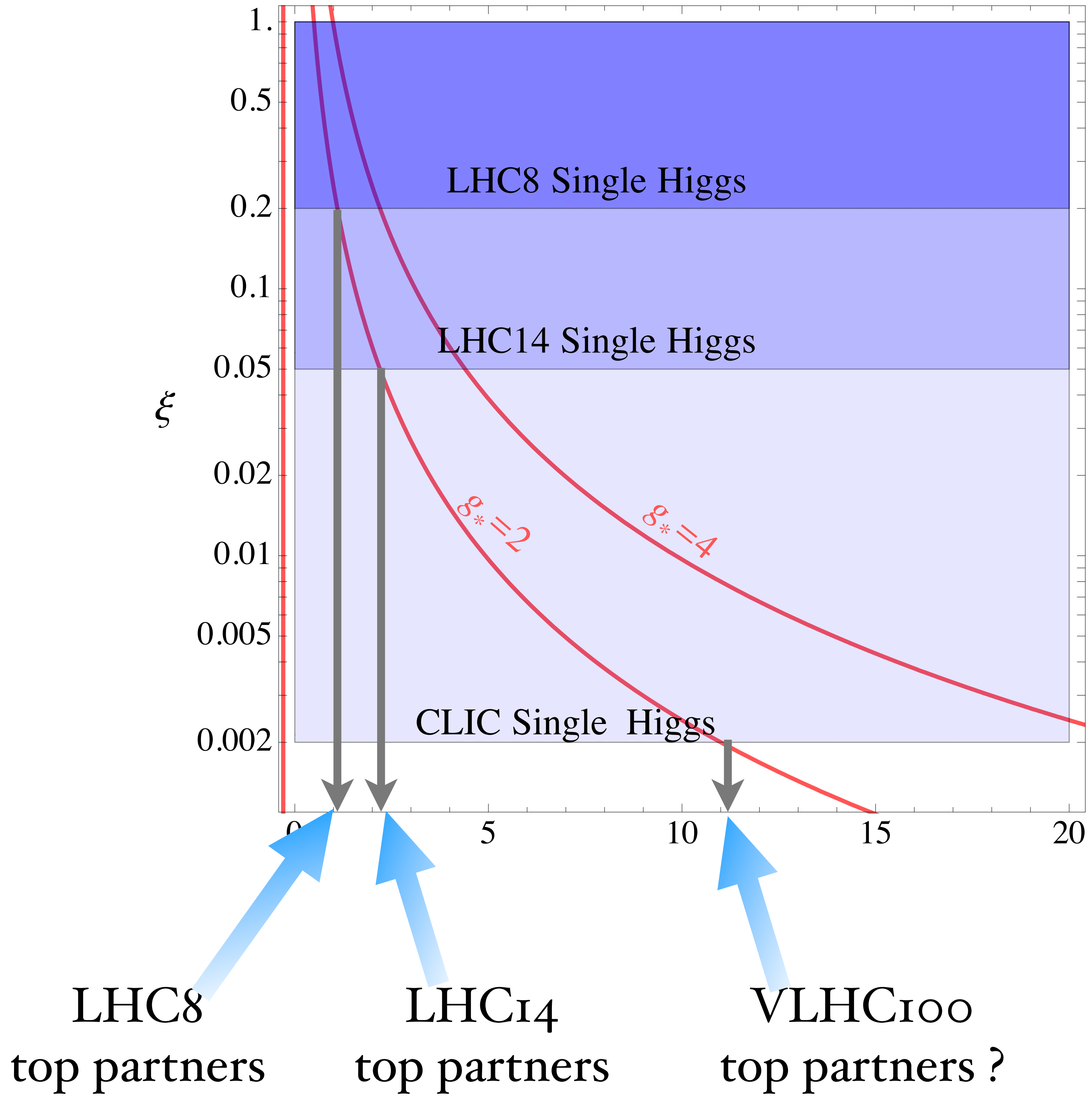




the weaker g_* the more relevant the direct searches at pp machine



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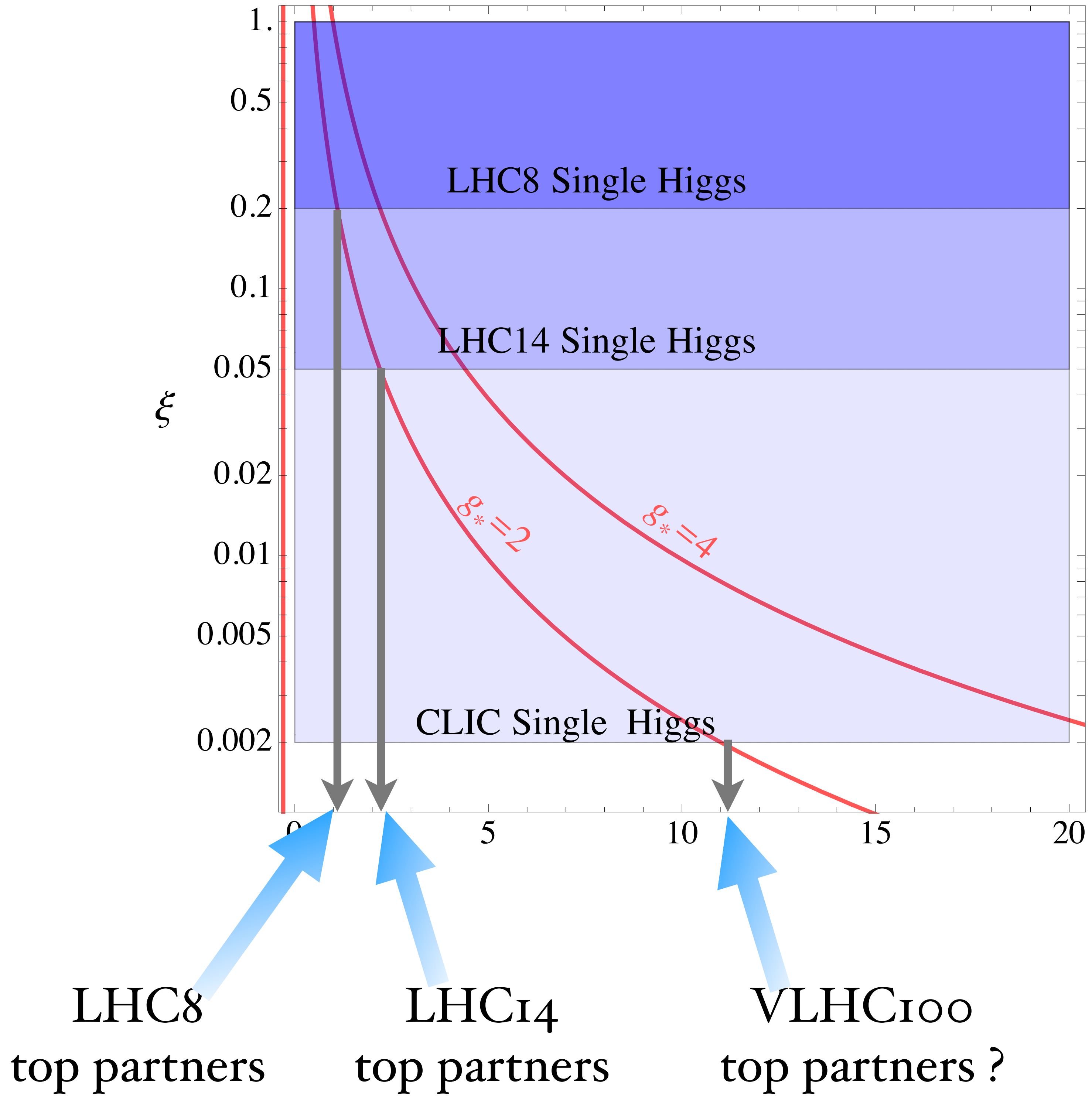

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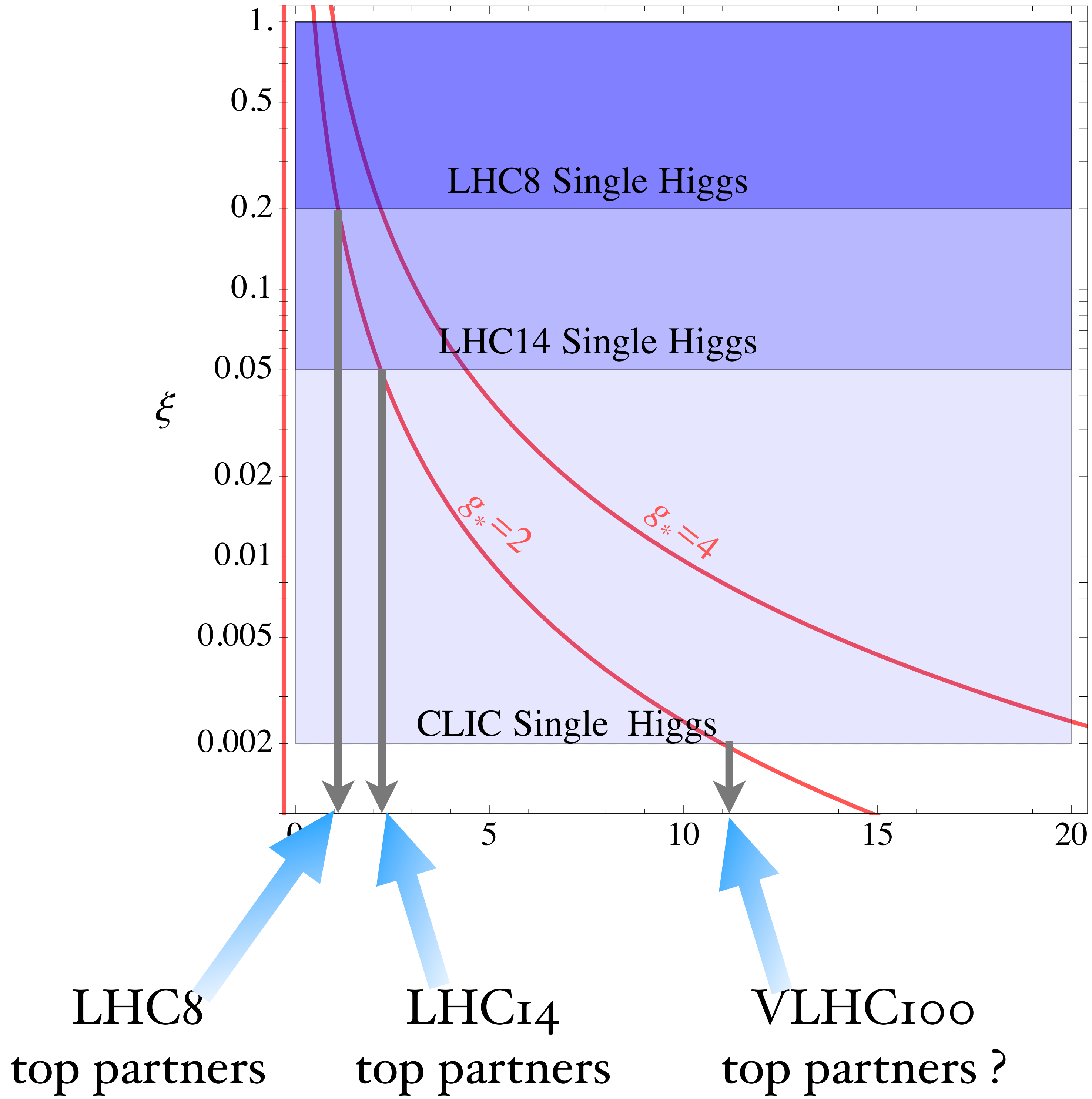

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