Coleman-Weinberg Higgs

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Hyung Do Kim

(Seoul National University
& Institute for Advanced Study)

What if there is no mass term
from the beginning?

$$m^2 = 0$$

This condition was shown to lead to symmetry breaking through radiative corrections. ⋯ This argument is quite speculative, particularly since no theory has even been found in which the "zero bare mass" condition is really natural. But it is interesting to pursue the consequences of assuming that scalars satisfying this condition exist. ⋯

E. Witten (1981)

The final blunder was a claim that scalar elementary particles were unlikely to occur in elementary particle physics at currently measurable energies unless they were associated with some kind of broken symmetry. ⋯ But this claim makes no sense when one becomes familiar with the history of physics. ⋯
This blunder was potentially more serious, if it caused any subsequent researchers to dismiss possibilities for very larger or very small values for parameters that now must be taken seriously. ⋯The lesson from history is that sometimes there is a need to consider seriously a seemingly unlikely possibility.

K. Wilson (2003)

What is important in science is not the solution of some particular scientific problems of one's own day, but understanding the world. ⋯
The Alexandrians concentrated on understanding specific phenomena, where real progress could be made. ⋯
Again and again, it has been an essential feature of scientific progress to understand which problems are ripe for study and which are not. ⋯

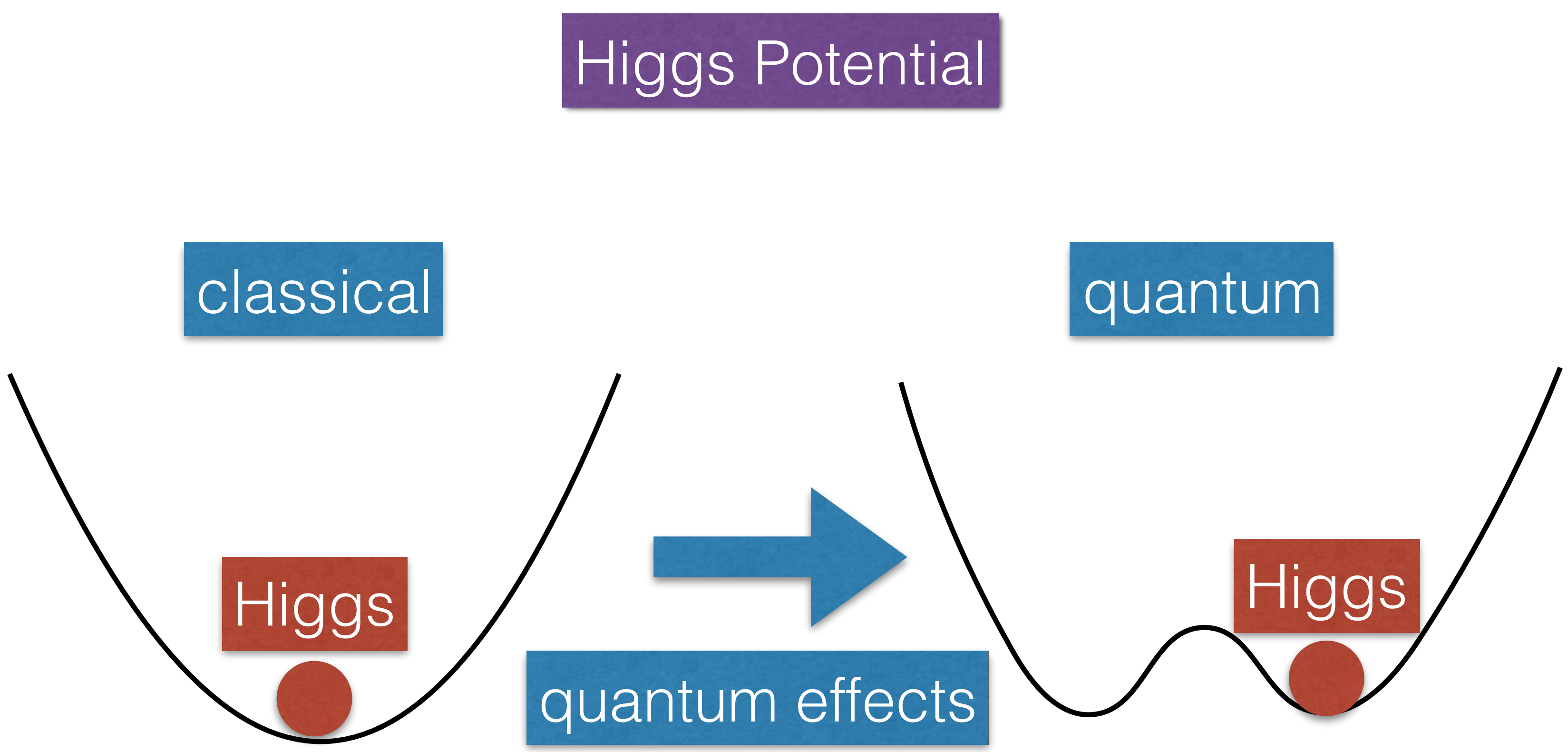
S. Weinberg (2015)

One simple question.
Can we still make electroweak symmetry breaking possible without mass term?

Coleman-Weinberg Higgs

with D Chway, R Dermisek and TH Jung, PRL(2014)

with D Chway, R Dermisek, D Mo and TH Jung, to appear



start from classically scale invariant theory

Higgs self coupling in the SM

$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

$\mu^2 = \lambda v^2$ at the minimum of the potential

$$m_h^2 = 2\lambda v^2$$

All three definitions give the same quartic coupling.

$$\lambda_{\text{eff}}^{(2)SM} = \frac{m^2}{2v^2} \longrightarrow \frac{1}{2!}\frac{d^2 V}{d\phi^2}\Big|_{\phi=v}\frac{1}{v^2}$$

$$\lambda_{\text{eff}}^{(3)SM} = \frac{1}{3!}\frac{d^3 V}{d\phi^3}\Big|_{\phi=v}\frac{1}{v}$$

$$\lambda_{\text{eff}}^{(4)SM} = \frac{1}{3!}\frac{d^4 V}{d\phi^4}\Big|_{\phi=v}$$

Coleman-Weinberg mechanism

$$V(\phi) = m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$m^2 = 0$$

(second derivative of V at the origin)

Spontaneous symmetry breaking can occur
by radiative corrections.

Starting from scale invariant potential

$$V(\phi) = \lambda(\phi^\dagger \phi)^2$$

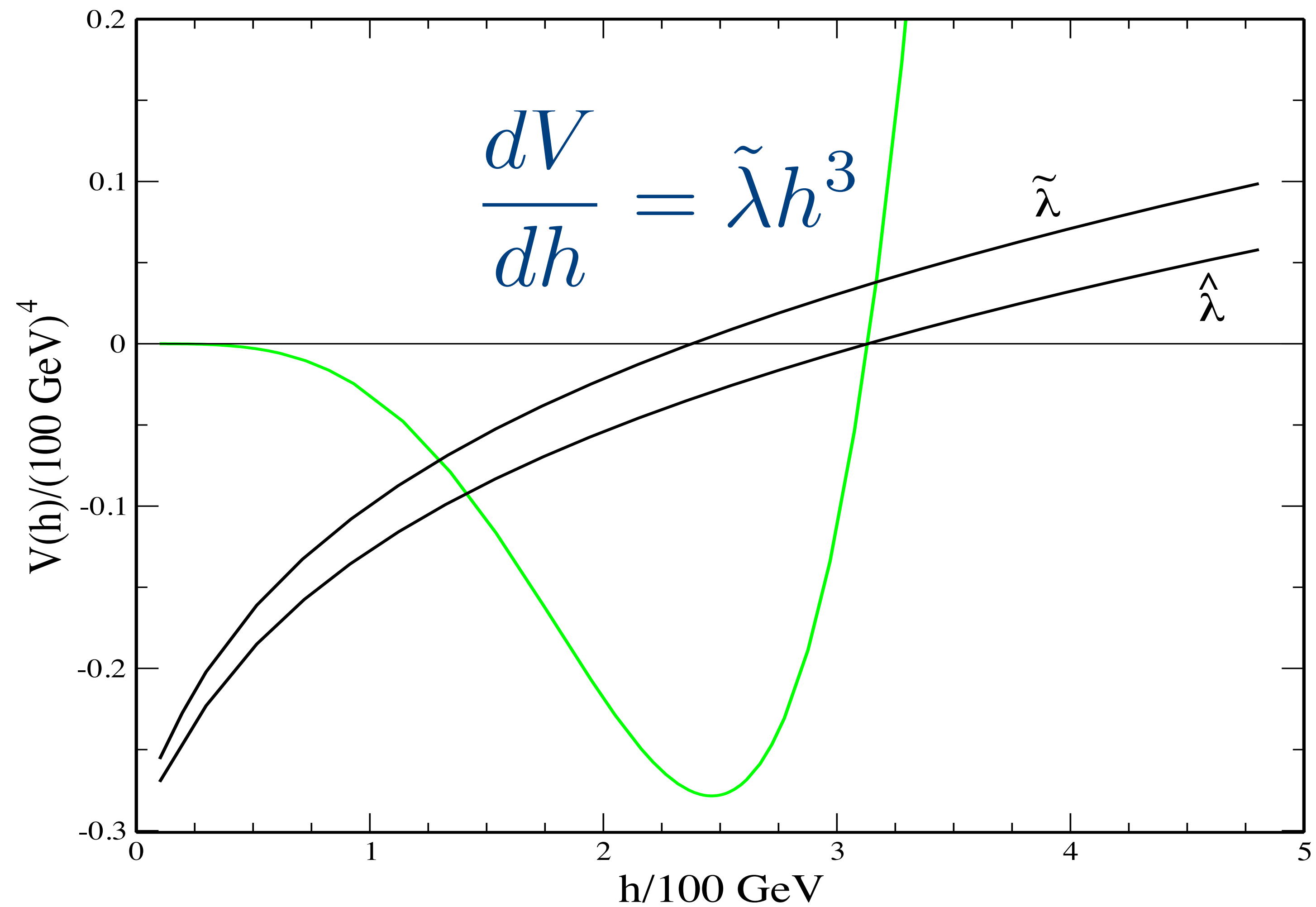
RG improved effective potential is then

$$V(\phi) = \lambda(\phi)(\phi^\dagger \phi)^2$$

$$V(h) = \frac{\hat{\lambda}}{4} h^4$$

If the quartic changes sign at low energy, nontrivial minimum is developed

$$\frac{dV}{dh} = \tilde{\lambda} h^3$$



Espinosa and Quiros, PRD (2007)

Scalar QED and Standard Model in 1970s

$$\frac{m_h^2}{m_V^2} = \frac{3}{2\pi}\frac{e^2}{4\pi} = \frac{3}{2\pi}\alpha \qquad\qquad m_V^2 = e^2\langle\phi\rangle^2$$

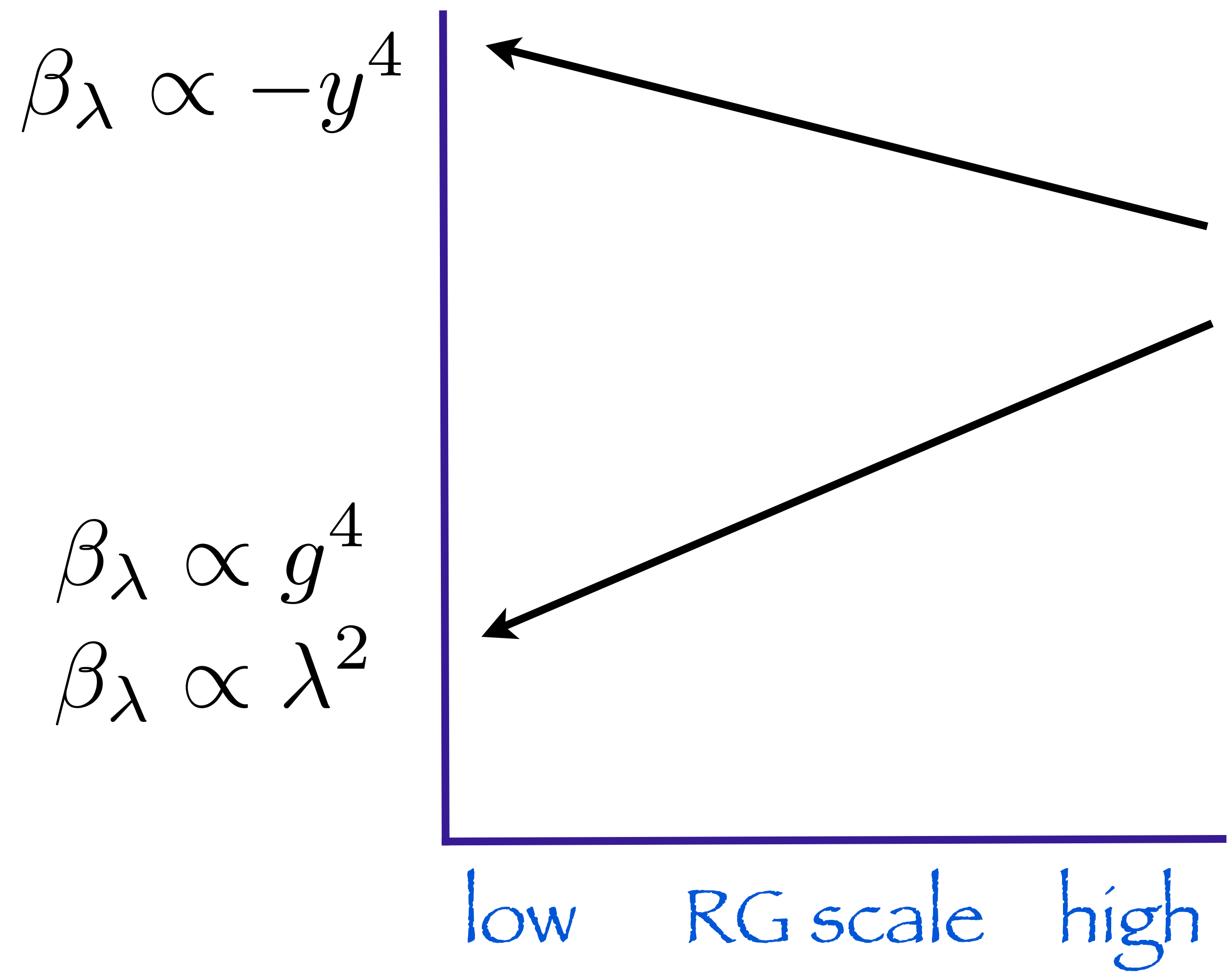
$$m_h^2 = \frac{3}{32\pi^2}\left[2g^2 m_W^2 + (g^2 + g'^2)m_Z^2\right]$$

SM with W and Z (without top) : mh ~ 10 GeV

Radiatively generated Higgs mass is one loop suppressed compared to the vector boson mass

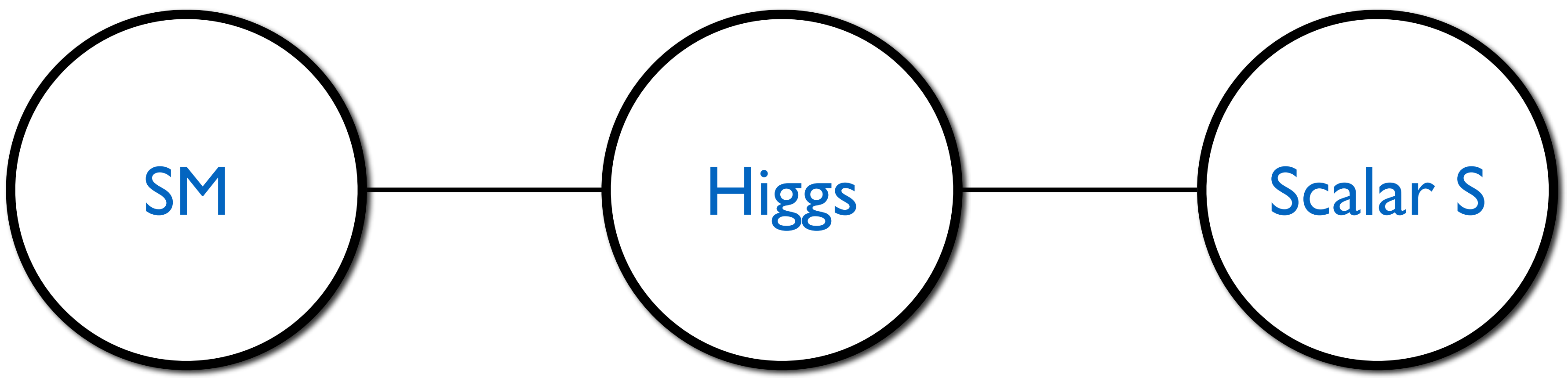
Superconductor :
Coherence length is much longer than London penetration length

Top Yukawa prevents CW mechanism in the SM



Radiative symmetry breaking is possible
with gauge or mixed quartic interactions.

New particles interacting with Higgs



$$V(h) \propto h^4 \log h$$

Coleman-Weinberg Higgs

$$V(\phi) = \frac{\lambda(t)}{4}\phi^4$$

$$t = \log \phi$$

$$\frac{dV}{d\phi} = \frac{dt}{d\phi}\frac{\beta_\lambda}{4}\phi^4 + \frac{\lambda}{4}\cdot 4\phi^3$$

$$= (\lambda + \frac{\beta_\lambda}{4})\phi^3|_{\phi=v} = 0$$

-75% (tree) + 175% (loop)

$$m^2 = \frac{d^2V}{d\phi^2}|_{\phi=v} = (\beta_\lambda + \cancel{\frac{\beta'_\lambda}{4}})v^2$$

$$\lambda_{\rm eff}^{(2)} = \frac{1}{2}\frac{m^2}{v^2} \sim \frac{1}{8}$$

(precisely = 0.129)

$$\boxed{\beta_\lambda \sim \frac{1}{4}}$$

$$\boxed{\lambda_{\rm eff}^{(3)} = \frac{5}{3}\lambda_{\rm eff}^{(2)}, \quad \lambda_{\rm eff}^{(4)} = \frac{11}{3}\lambda_{\rm eff}^{(2)}.}$$

Scale dependence of the beta function is neglected here.

Higgs portal with extra scalar S

$$V = \lambda_h (H^\dagger H)^2 + \lambda_{hs} H^\dagger H S^\dagger S + \lambda_s (S^\dagger S)^2$$

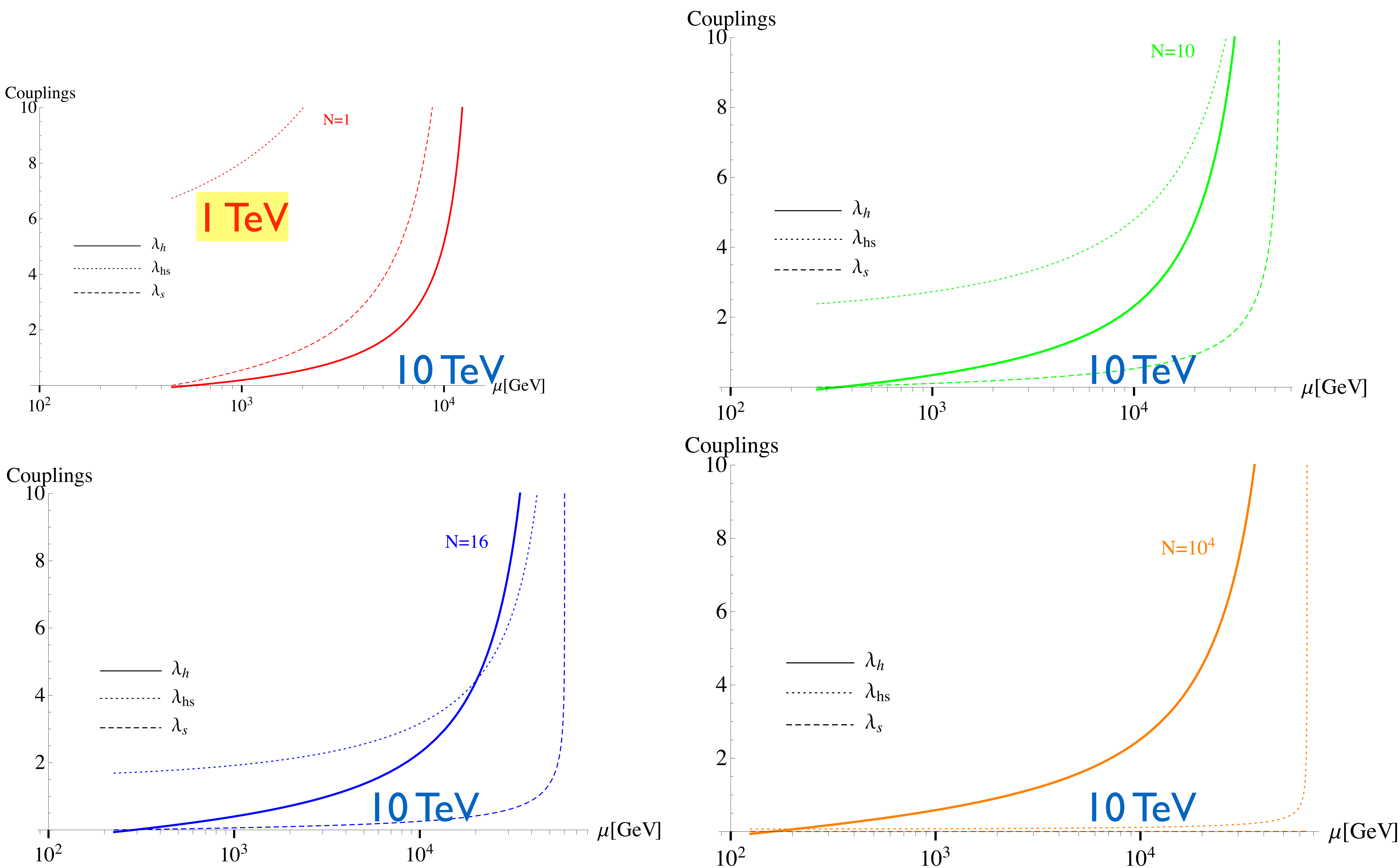
$$16\pi^2 \beta_{\lambda_h} = 24\lambda_h^2 + N\lambda_{hs}^2$$

$$16\pi^2 \beta_{\lambda_{hs}} = \lambda_{hs}\left[4\lambda_{hs} + 12\lambda_h + (4N+4)\lambda_{hs}\right]$$

$$16\pi^2 \beta_{\lambda_s} = (16+4N)\lambda_s^2 + 2\lambda_{hs}^2$$

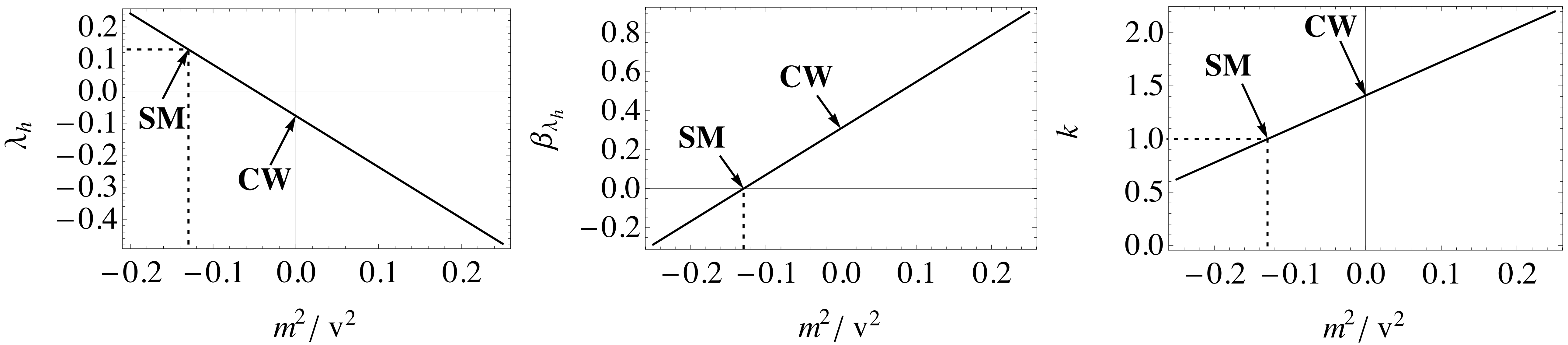
New mixed quartic raises Higgs quartic at high energy

Non-perturbative at 20TeV for Ns〉1



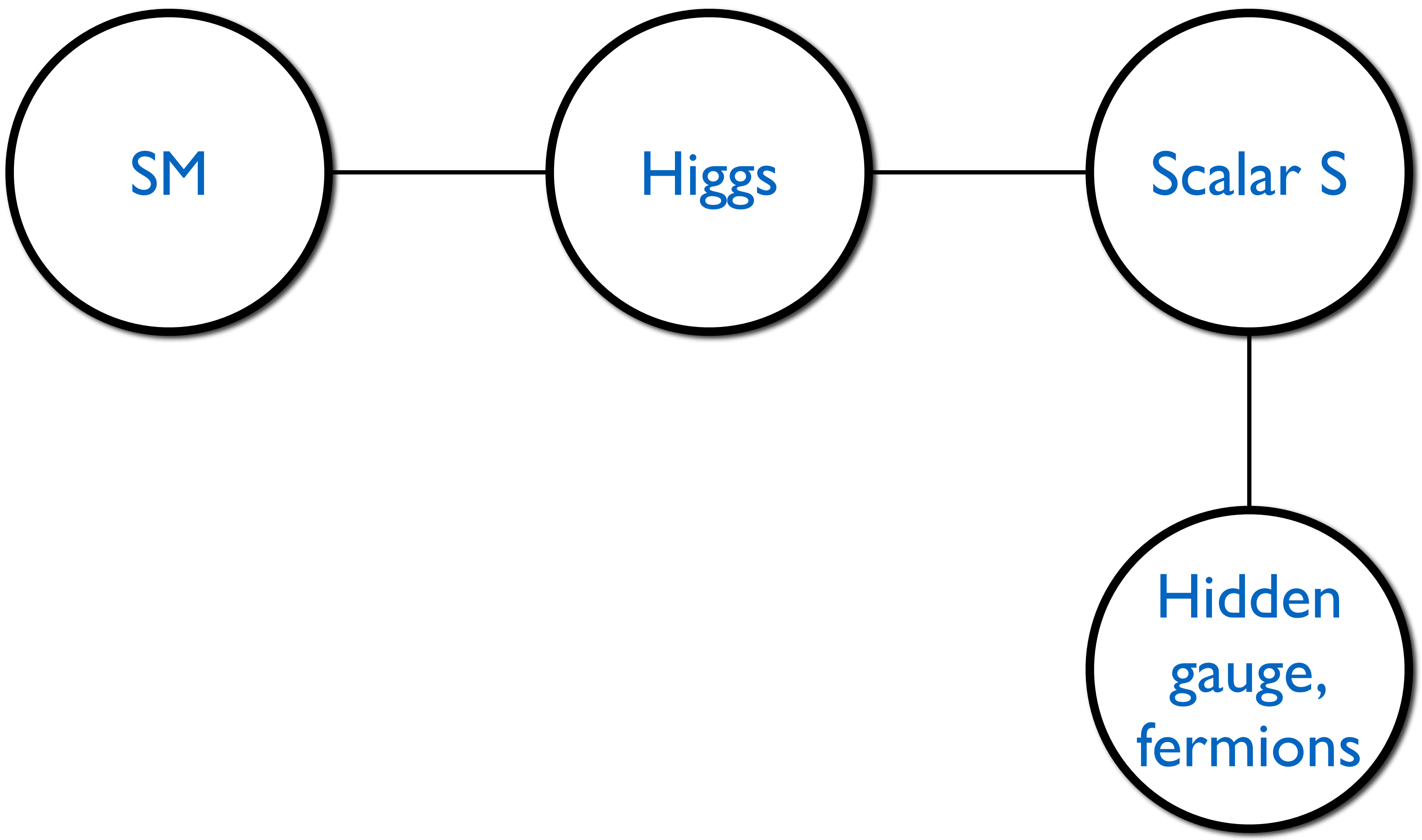
New parameter space with running couplings

m=0 is a one point in the extended parameter space



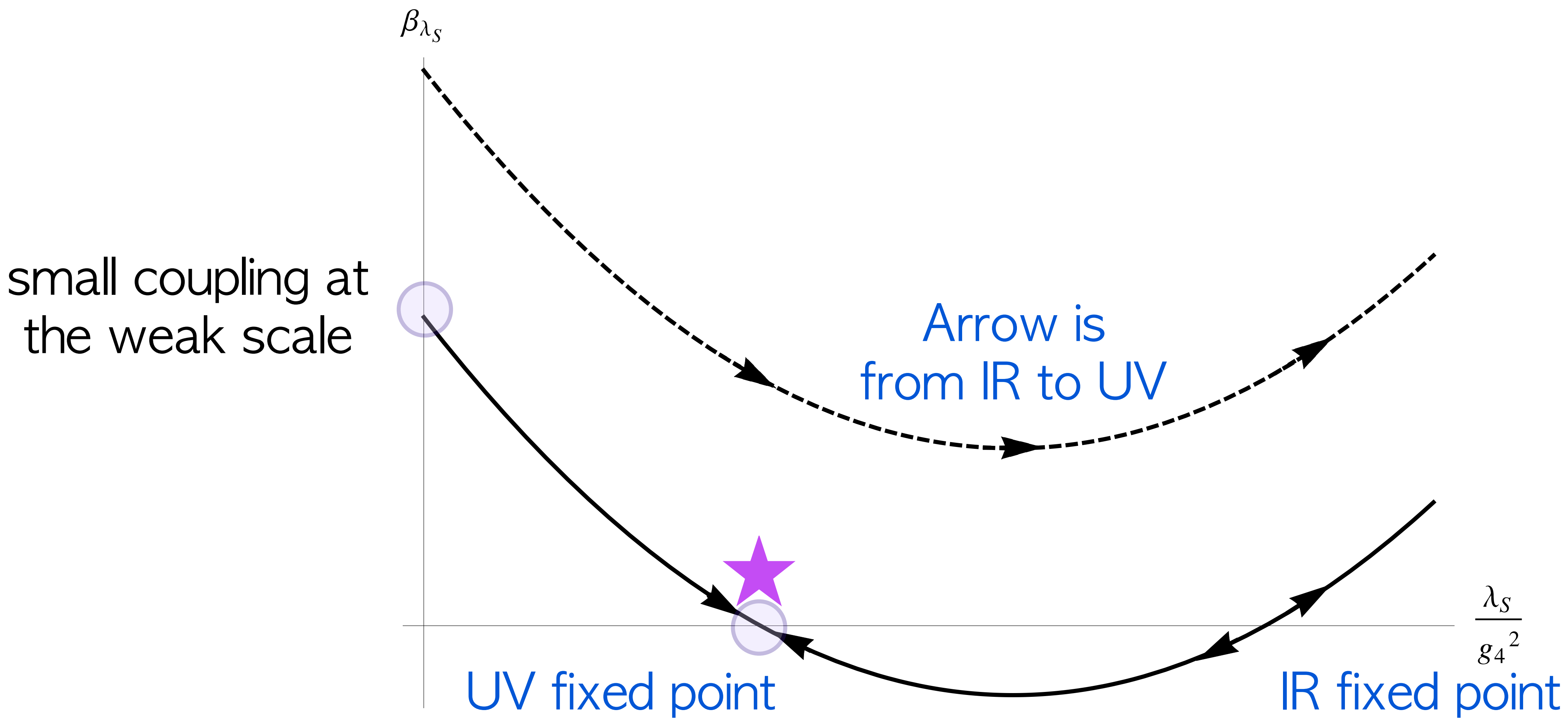
k: Relative strength
of Higgs cubic couplings
with respect to SM

Gauge extension of hidden sector

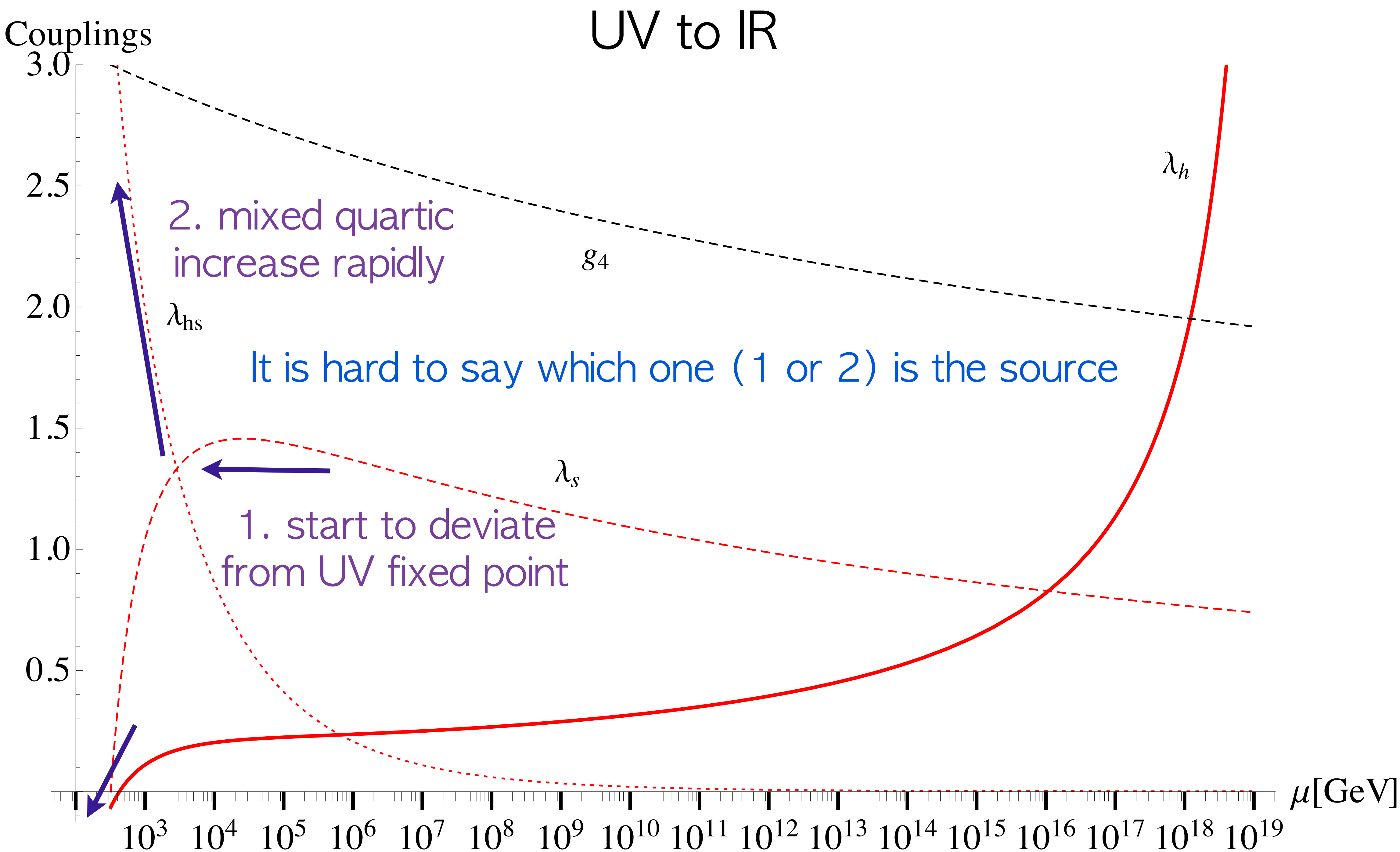


$$16\pi^2\frac{d\lambda_s}{dt}=\frac{3}{4}\Big(\frac{N_S^3+N_S^2-4N_S+2}{N_S}\Big)g_4^4-6\Big(\frac{N_S^2-1}{N_S}\Big)g_4^2\lambda_s+4(4+N_S)\lambda_s^2+2\lambda_{hs}^2$$

$$16\pi^2\frac{d\lambda_{hs}}{dt}=\lambda_{hs}\left[4\lambda_{hs}+12\lambda_h+(4N_S+4)\lambda_s-3\Big(\frac{N_S^2-1}{N_S}\Big)g_4^2\right]$$



Example : Scalar in 4 of SU(4) :

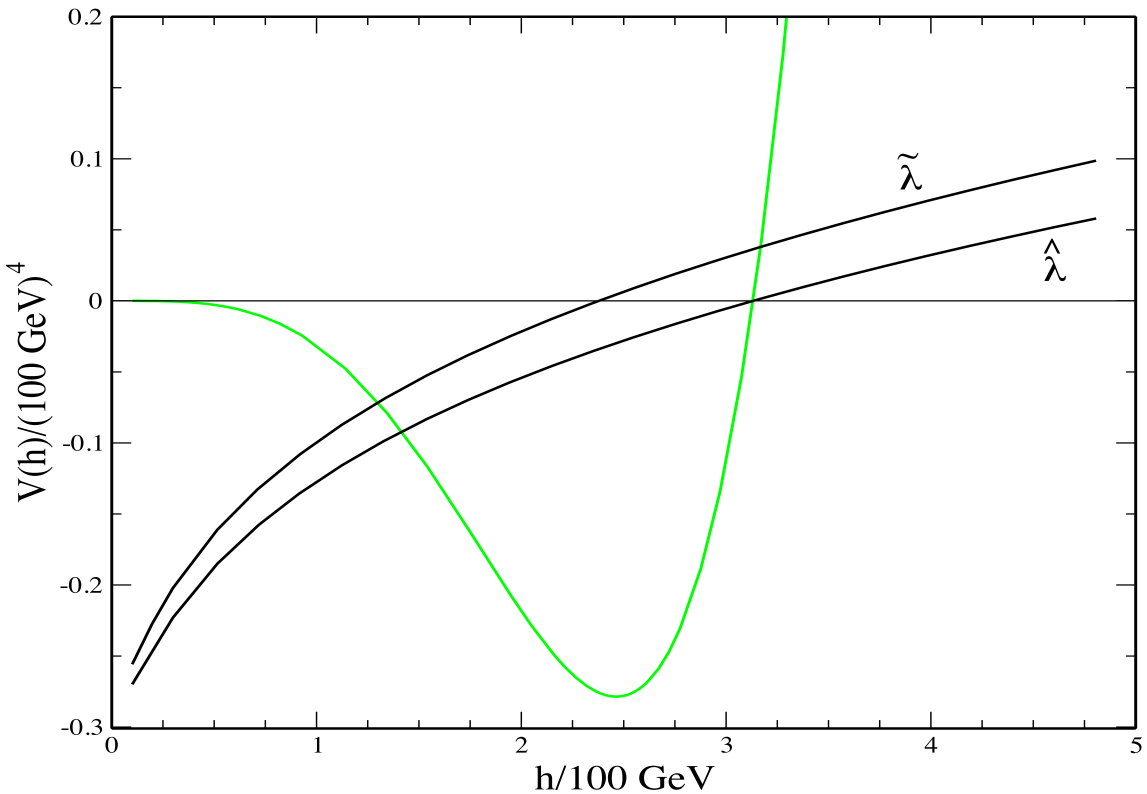


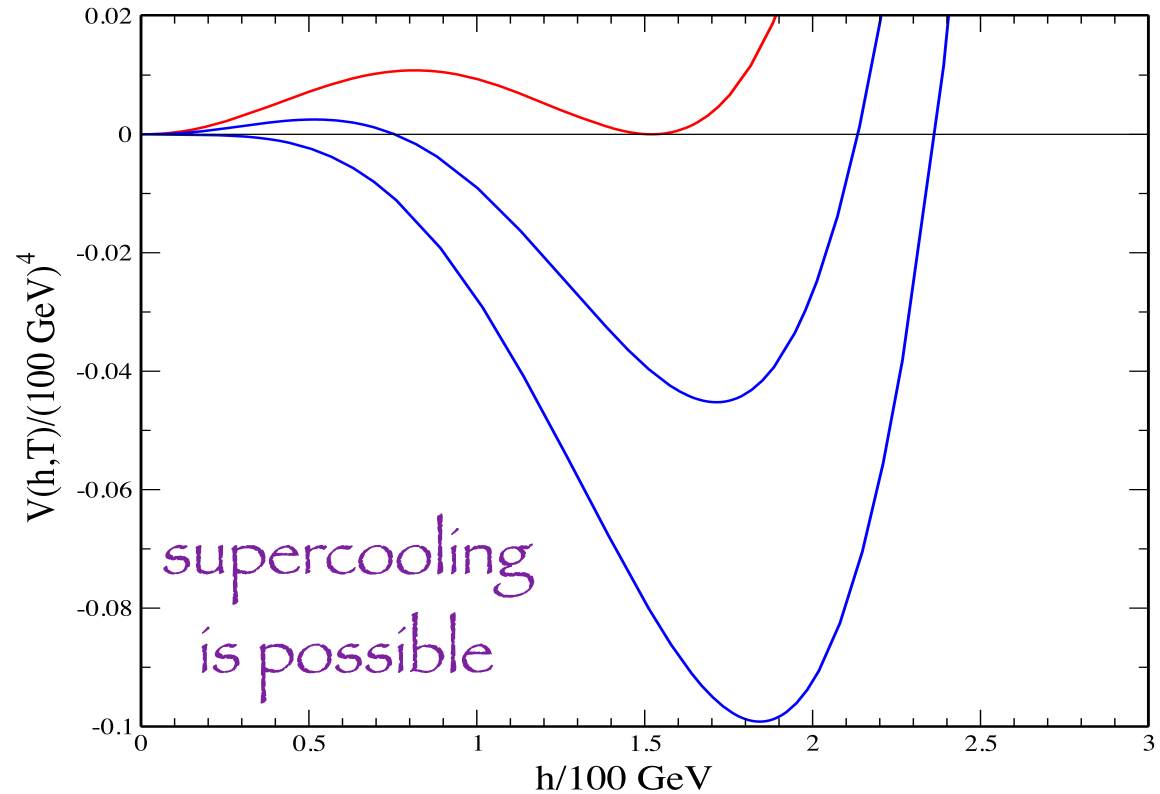
3. Higgs quartic driven to be negative

FIG. 2. (rigid, dashed, dotted) : $\lambda_{(h,s,hs)}$

Electroweak Baryogenesis

$$V = \lambda_h (H^\dagger H)^2 + \lambda_{hs} H^\dagger H S^\dagger S + \lambda_s (S^\dagger S)^2$$

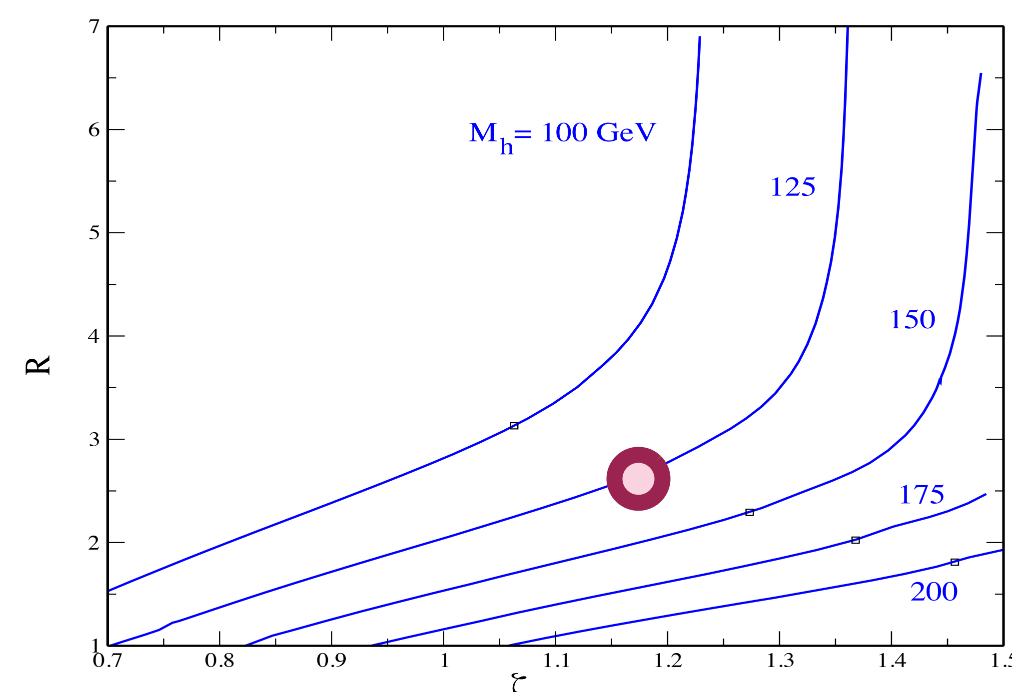




Higgs potential

$$R \equiv \langle h(T_c) \rangle / T_c$$

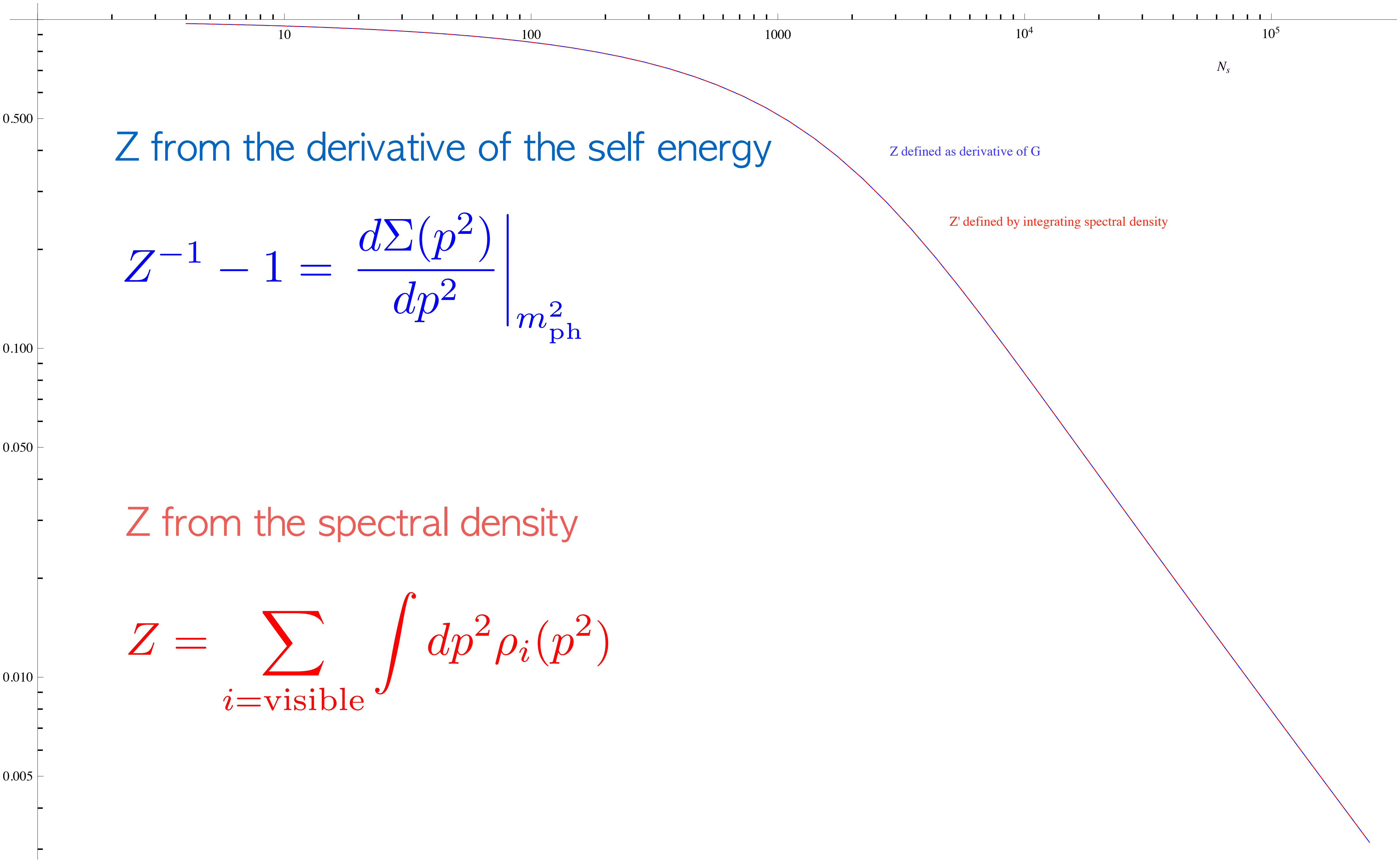
1. Strong 1st order phase transition
2. New source of CP violation exists



$$\lambda_{hS} H^\dagger H S^\dagger S \ + \ \theta G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Espinosa and Quiros, PRD (2007)

Two definitions agree with each other



Z from the derivative of the self energy

$$Z^{-1} - 1 = \left. \frac{d\Sigma(p^2)}{dp^2} \right|_{m_{\mathrm{ph}}^2}$$

Z from the spectral density

$$Z = \sum_{i=\text{visible}} \int dp^2 \rho_i(p^2)$$

Phenomenology of Higgs with singlets (no hidden gauge group)

Off-shell Higgs invisible decay

Suppression of Higgs couplings to all SM particles

Higgs self coupling

Electroweak precision

Higgs potential is stabilised by the balance of tree and one loop.

All one loop correction to Higgs mass should be kept.

There is only one parameter, the number of singlet scalars.

Higgs portal with hidden scalar S

$$V = \lambda_h (H^\dagger H)^2 + \lambda_{hs} H^\dagger H S^\dagger S + \lambda_s (S^\dagger S)^2$$

$$16\pi^2 \beta_{\lambda_h} = 24\lambda_h^2 + N\lambda_{hs}^2 \sim 40$$

$$m_S \simeq \frac{440}{N_S^{1/4}} \text{ GeV}$$

Mass of hidden scalar S is entirely fixed from Higgs VEV and N.

Lower bound on hidden scalar mass exists
when Higgs self energy is taken into account.

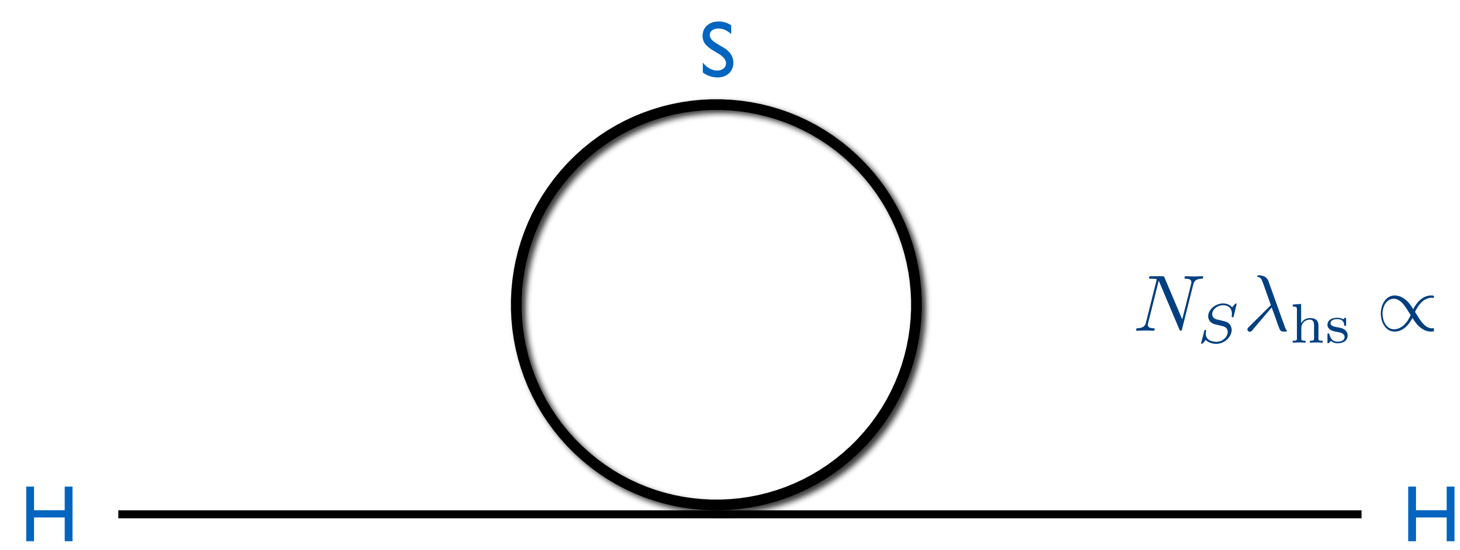
$$m_S = (1 + \frac{2}{\pi^2}) \frac{m_h}{2}$$

momentum dependent correction

$$G^{-1} = p^2 - \left[\beta_\lambda v^2 - 2\beta_\lambda v^2\left(1 - \hat{\beta}\tan^{-1}\frac{1}{\hat{\beta}}\right)\right]$$

$$\geq \frac{1}{2}$$

$$\hat{\beta} = \sqrt{\frac{4m_S^2}{p^2} - 1}$$



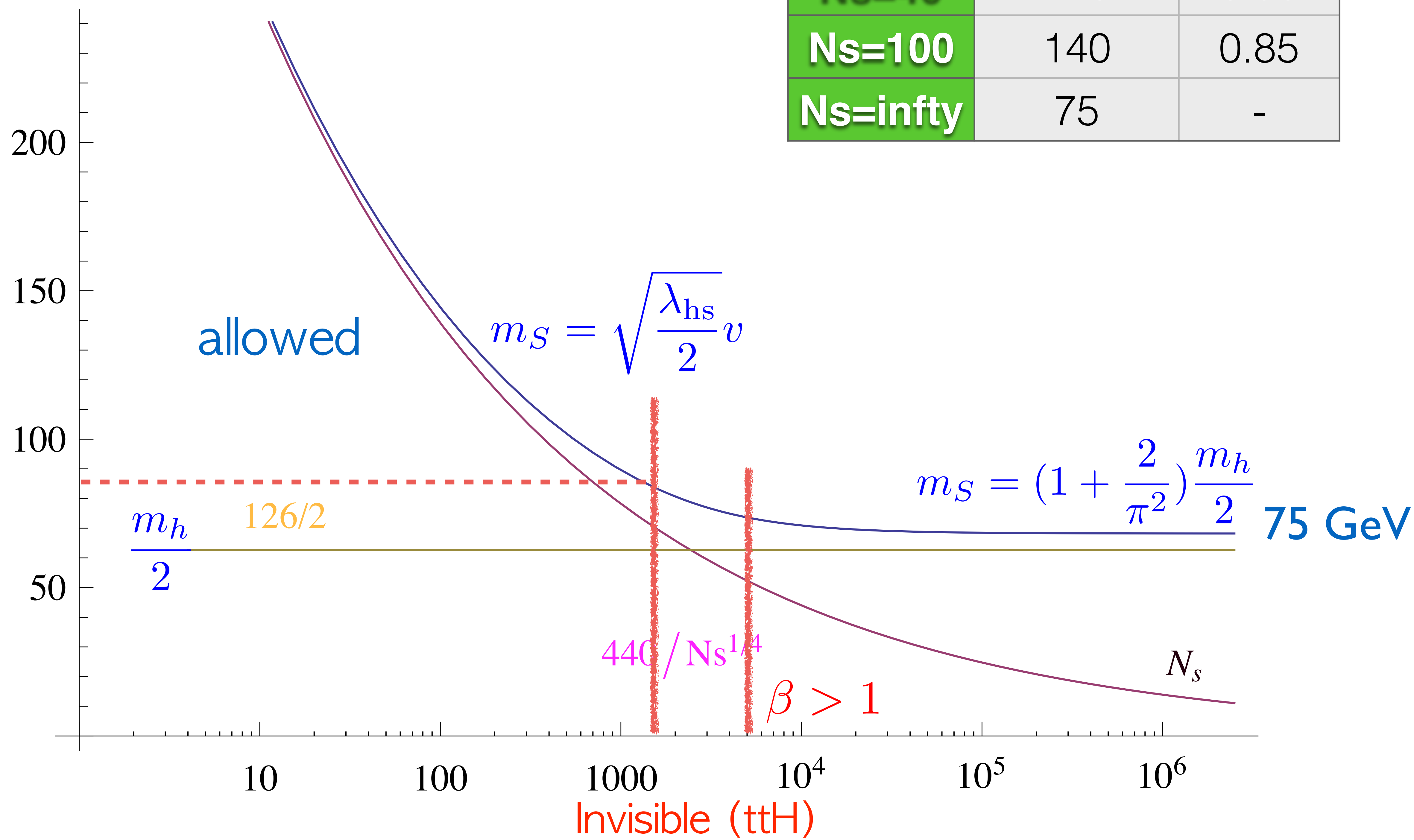
$$N_S \lambda_{\mathrm{hs}} \propto \sqrt{N_s}\beta_\lambda$$

As Ns becomes larger, this diagram is more important and should be kept in all computations.

Hidden scalar mass

$$m_S \simeq \frac{440}{N_S^{1/4}}\ \mathrm{GeV}$$

	Ms (GeV)	Z
Ns=10	250	0.95
Ns=40	175	0.90
Ns=100	140	0.85
Ns=infty	75	-



Measuring Higgs cubic coupling at the LHC

$$\mathcal{L}_{\rm eff} = \frac{1}{4}\frac{\alpha_s}{3\pi} G^a_{\mu\nu} G^{a\mu\nu} \log(1+\frac{h}{v})$$ from top loop

$$\downarrow$$

$$\mathcal{L}_{\rm eff} = \frac{1}{4}\frac{\alpha_s}{3\pi v} G^a_{\mu\nu} G^{a\mu\nu} h - \frac{1}{4}\frac{\alpha_s}{6\pi v^2} G^a_{\mu\nu} G^{a\mu\nu} h^2 + \cdots$$

$$\downarrow \times \lambda v h^3$$

destructive interference

leading term

Higgs cubic coupling at the LHC

$$\sigma_{hh}^{NLO} = 70y_t^4 - 50\lambda y_t^3 + 10\lambda^2 y_t^2$$

1 ~0.1

Vainshtein theorem*

multi-Higgs production amplitudes
vanish in the heavy top limit

The cross section only vary by 10% for order one change of Higgs self coupling.

$$3\ ab^{-1}$$

50% uncertainty at 14 TeV LHC
(bb tau tau, bbWW, bb gamma gamma)

Higgs cubic coupling at the ILC

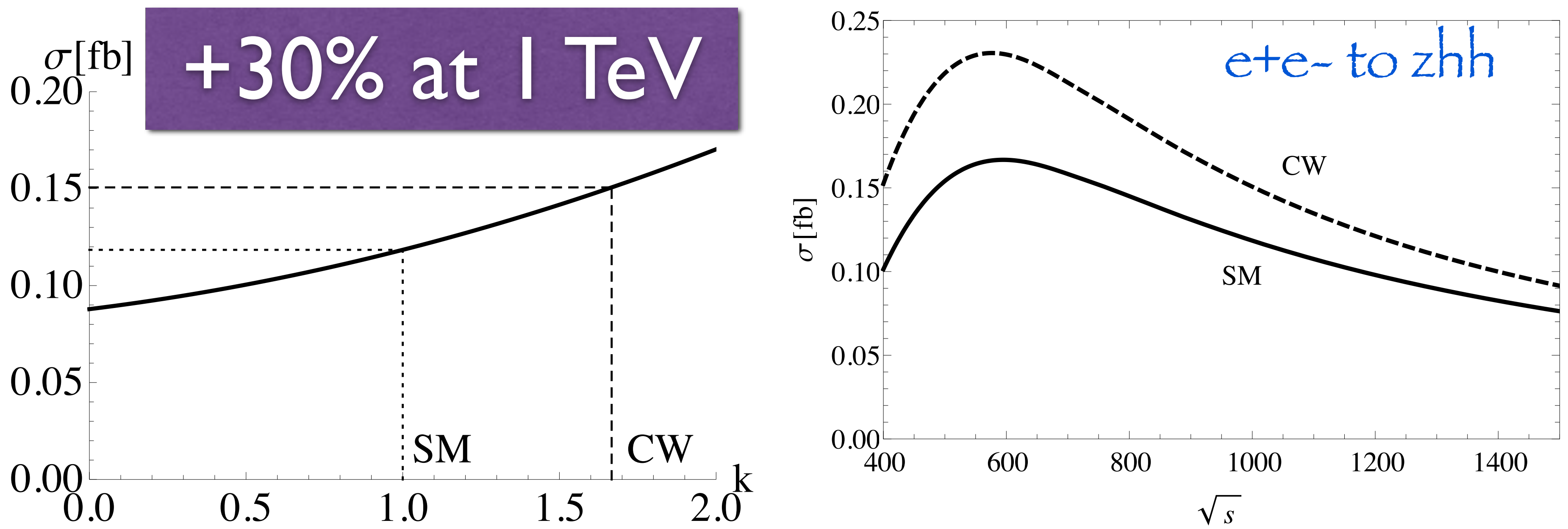


FIG. 7. $e^+e^- \to hhZ$

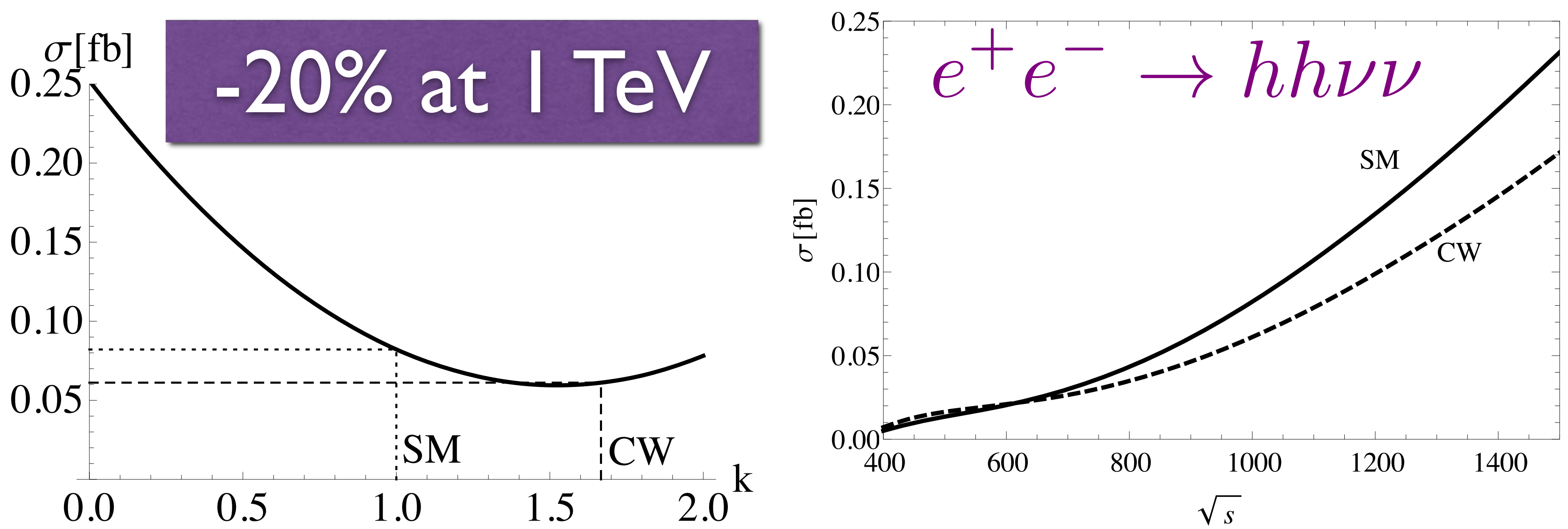
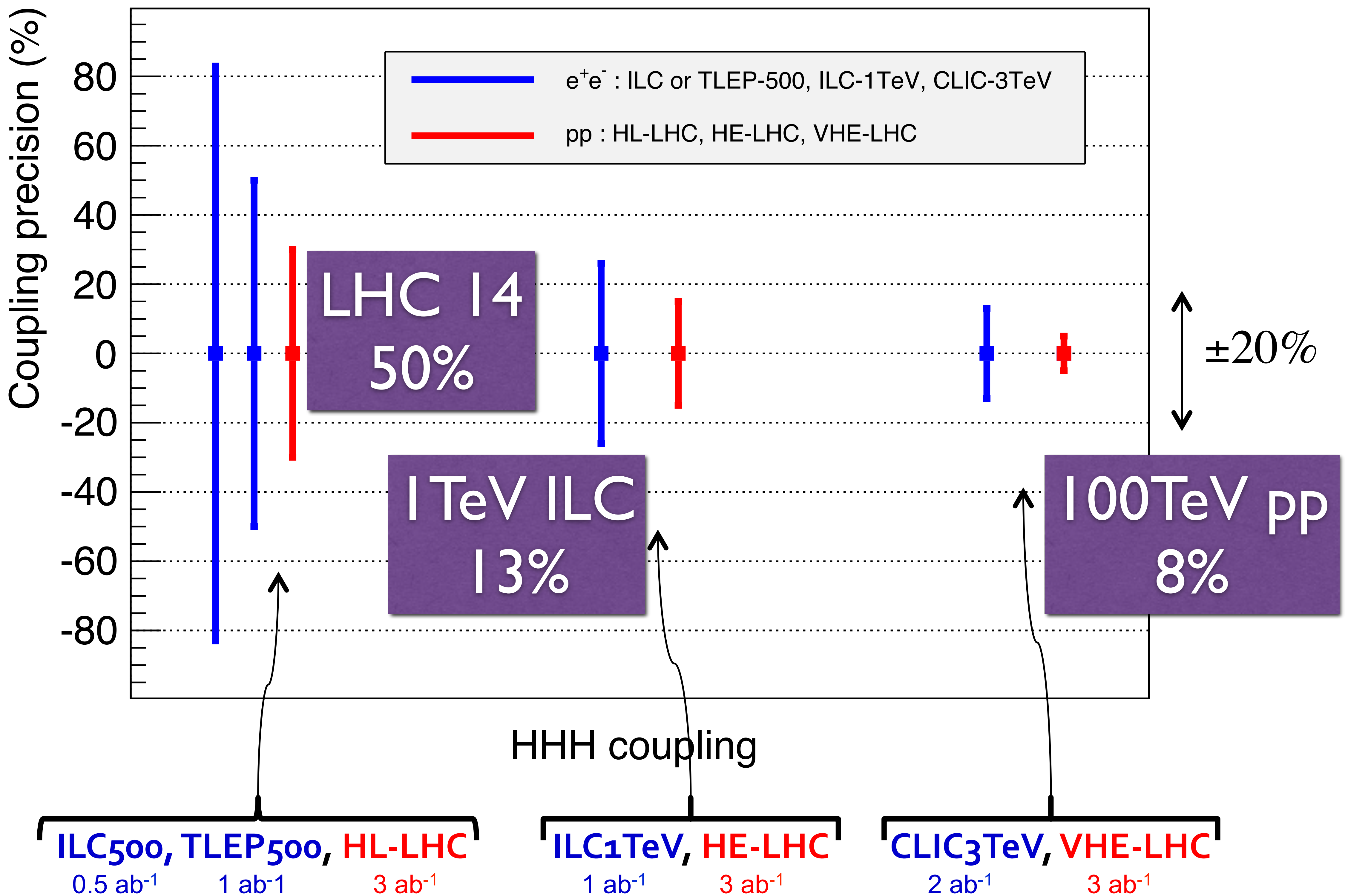


FIG. 8. $e^+e^- \to hh\nu_e\bar{\nu}_e$

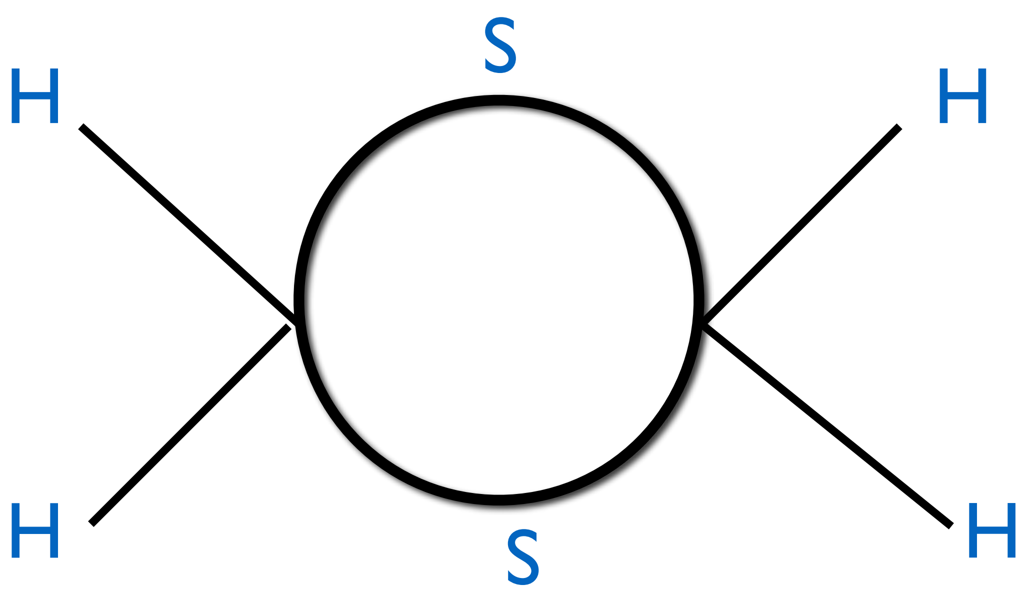
Higgs cubic coupling measurement

TLEP design study working group, 1308.6176



Suppression of Higgs couplings to the SM

Expected precision for hZZ
LHC : 2% to 5%
Higgs factory 1% to 0.4%



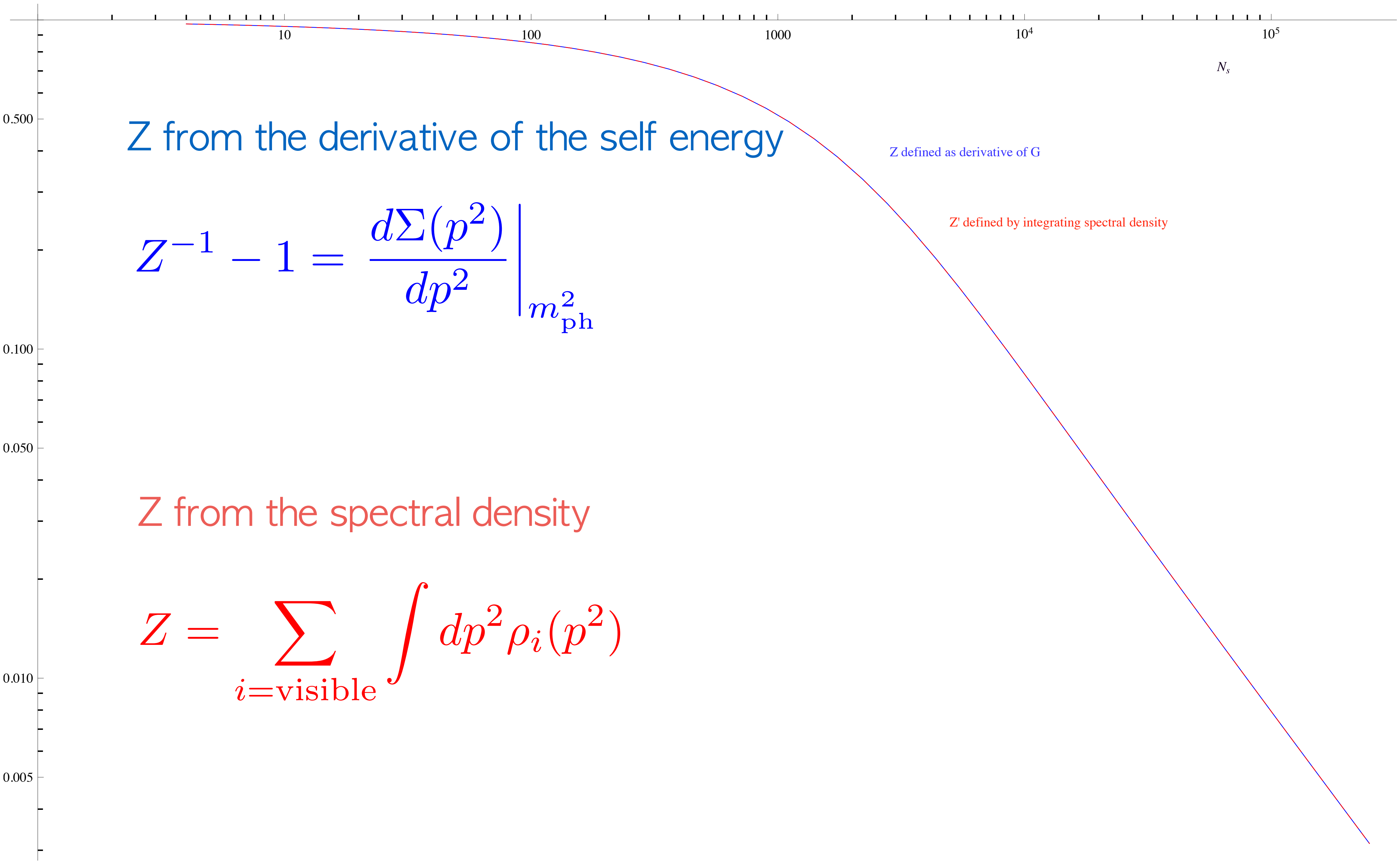
$$\frac{1}{p^2 - m_h^2 + \Sigma(p^2)}$$
$$\simeq \frac{Z}{p^2 - m_h^2 + (Z^{-1} - 1)(p^2 - m_h^2) + i m_h \Gamma_h}$$
$$= \frac{Z}{p^2 - m_h^2 + i m_h Z \Gamma_h}$$

expansion at the resonance
can not be valid for off-shell

Generate dimension 6 operator

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_H}{m_\phi^2}\left(\frac{1}{2}\partial_\mu |H|^2 \partial^\mu |H|^2\right) + \ldots$$

Two definitions agree with each other



Z from the derivative of the self energy

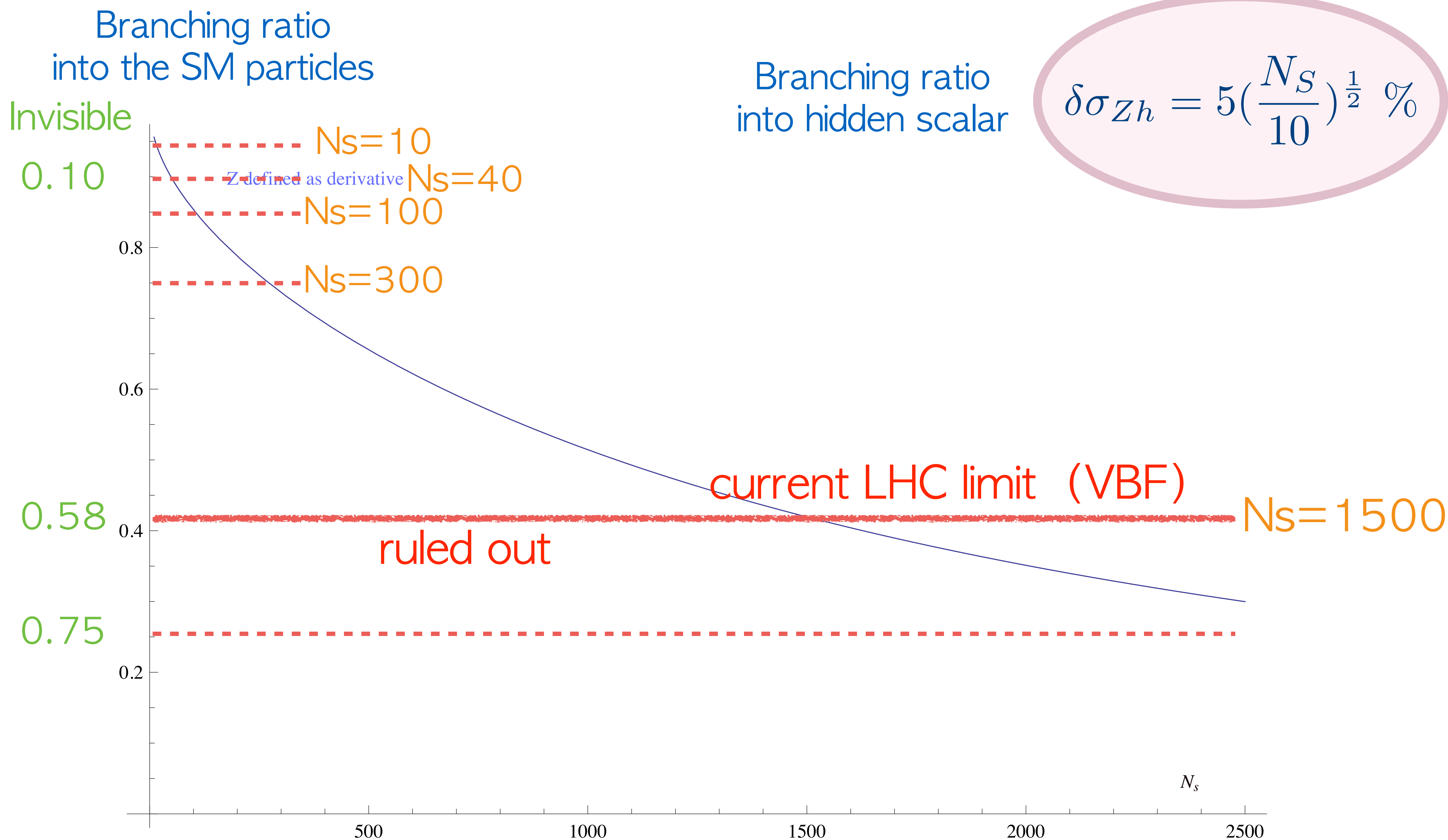
$$Z^{-1} - 1 = \left. \frac{d\Sigma(p^2)}{dp^2} \right|_{m^2_{\rm ph}}$$

Z from the spectral density

$$Z = \sum_{i=\text{visible}} \int dp^2 \rho_i(p^2)$$

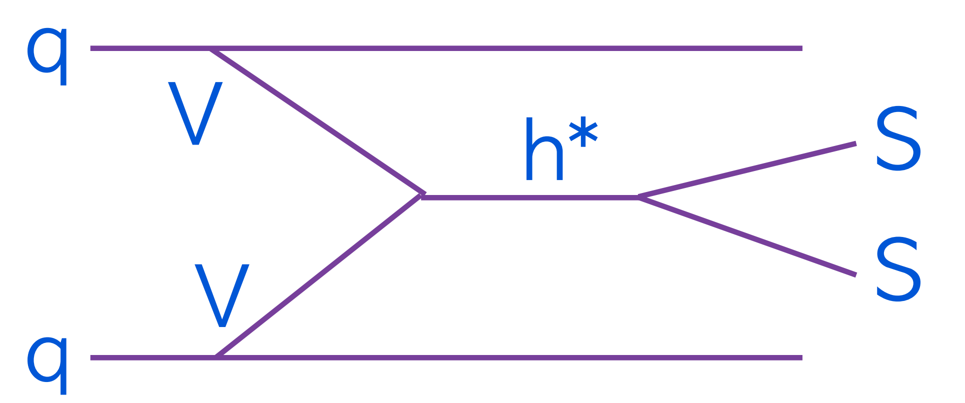
Suppressed ZZh coupling as an invisible decay

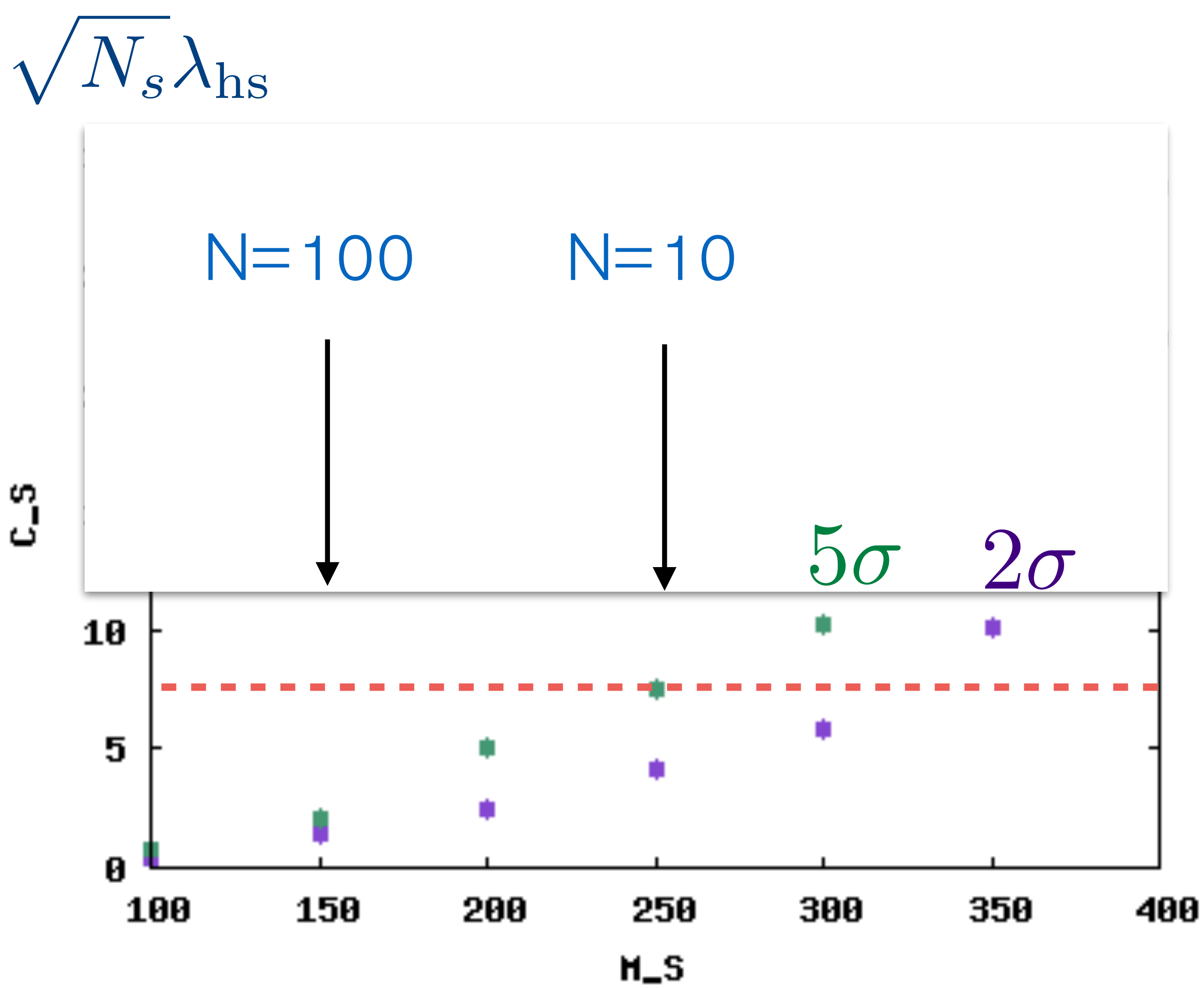
$$\delta\sigma_{Zh} = 5\left(\frac{N_S}{10}\right)^{\frac{1}{2}} \%$$



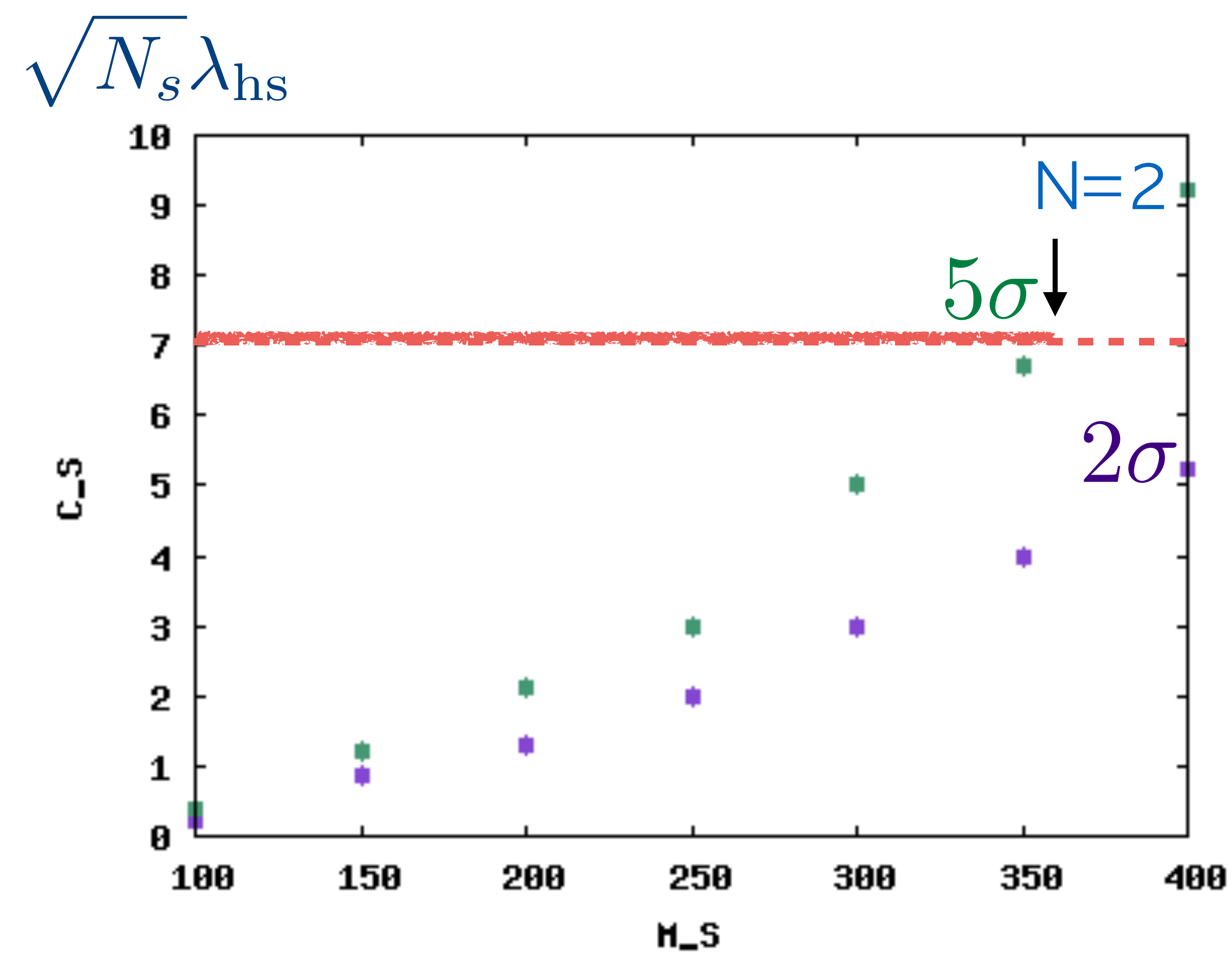
Off-shell Higgs decay : VBF

(e.g.,N=10,Ms=250 GeV)





LHC 14 TeV

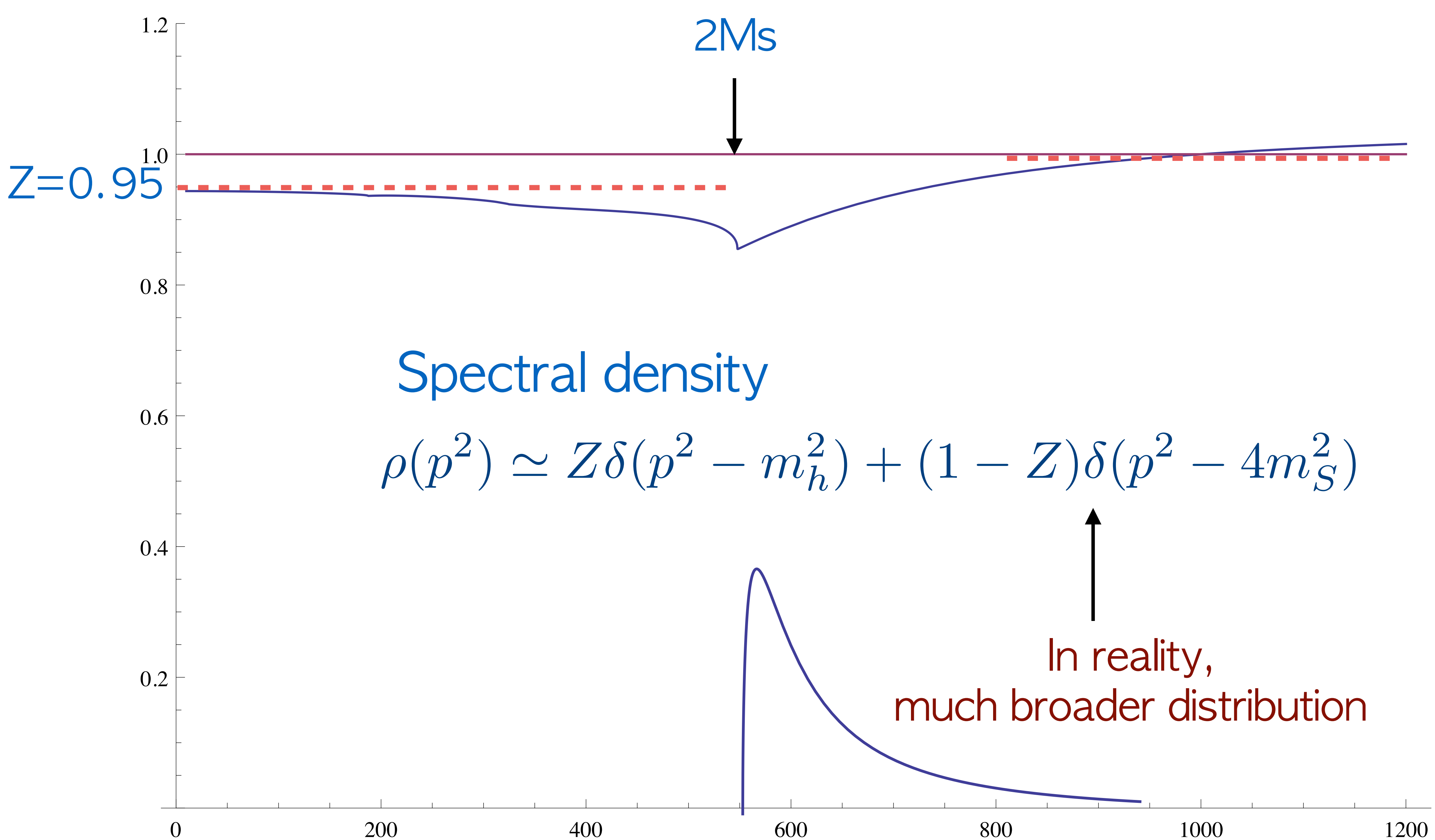


100 TeV

$\frac{v}{E}$ suppression for scalar cubic

Relative suppression of the propagator

$$\frac{\frac{1}{p^2 - m_h^2 + \Sigma(p^2)}}{\frac{1}{p^2 - m_h^2 + i m_h \Gamma_h}}$$



Spectral density

$$\rho(p^2) \simeq Z\delta(p^2 - m_h^2) + (1 - Z)\delta(p^2 - 4m_S^2)$$

(N=10,Ms=250 GeV)

Physics of Higgs with singlets using spectral density

$$\frac{1}{p^2 - m_h^2 + \Sigma(p^2)} = \int_0^\infty dq^2 \, \frac{\rho(q^2)}{p^2 - q^2 + \imath\epsilon}$$

$$\rho(p^2) \simeq Z\delta(p^2 - m_h^2) + (1 - Z)\delta(p^2 - 4m_S^2)$$

schematically the momentum dependence is captured by

$$\frac{Z}{p^2 - m_h^2 + i\epsilon} + \frac{1 - Z}{p^2 - 4m_S^2 + i\epsilon}$$

is approximated by delta function

Electroweak precision

$$\Delta S = (1 - Z)\frac{1}{6\pi}\log\frac{2m_S}{m_h}$$

$$\Delta T = -(1 - Z)\frac{3}{8\pi\cos^2\theta_W}\log\frac{2m_S}{m_h}$$

Preliminary result

	Ms	Z	1-Z	T
Ns=10	250	0.95	0.05	-0.011
Ns=40	175	0.90	0.10	-0.013
Ns=100	140	0.85	0.15	-0.020
Ns=300	120	0.75	0.25	-0.022

Summary

Singlet mass	$M_S = 250(\frac{10}{N_S})^{\frac{1}{4}}$ GeV	$N_S \geq 10$ reach : 250 GeV VBF from LHC 14
On-shell suppression	$\delta\sigma_{Zh} = 5(\frac{N_S}{10})^{\frac{1}{2}}$ %	$N_S \geq 10$ or 40 95% CL on 4~10% from LHC 14 all N_S(1~2% from ILC)
Higgs pair production	$\lambda^{(3)}_{\mathrm{CW}} = \frac{5}{3}\lambda_{\mathrm{SM}}$	50% from LHC14 13% from ILC 1TeV $N_S \leq 40$
Electroweak precision	$\Delta T < -0.02$	maximum at Ns=330

Conclusions

Quantum loop can explain the electroweak symmetry breaking.

Ginzburg-Landau $-\alpha\phi^2 + \beta\phi^4$ vs Coleman-Weinberg $\phi^4 \log \frac{\phi}{\langle\phi\rangle}$

Conclusions

Quantum loop can explain the electroweak symmetry breaking.

Ginzburg-Landau vs Coleman-Weinberg

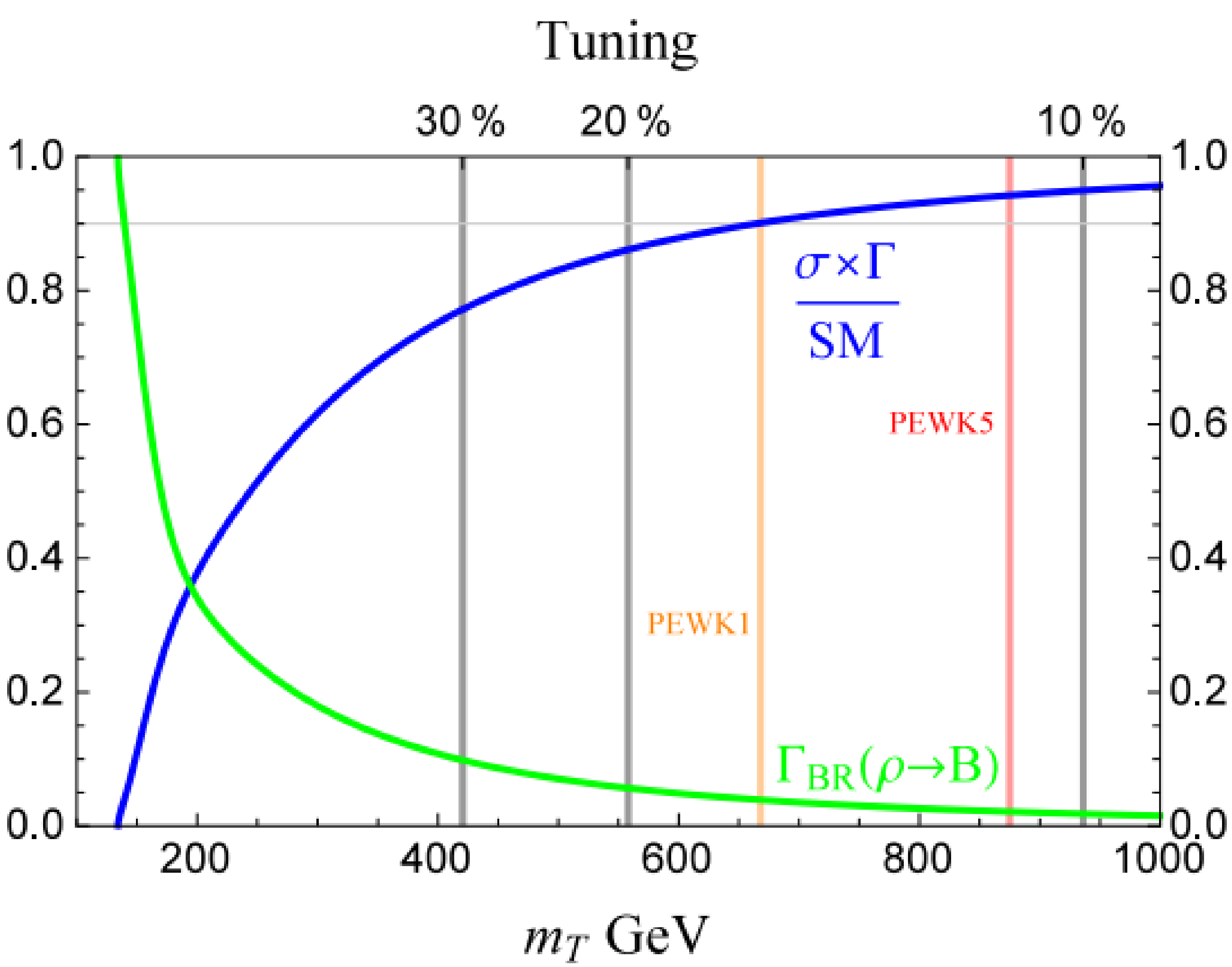
$$-\alpha\phi^2 + \beta\phi^4 \qquad \text{vs} \qquad \phi^4 \log \frac{\phi}{\langle\phi\rangle}$$

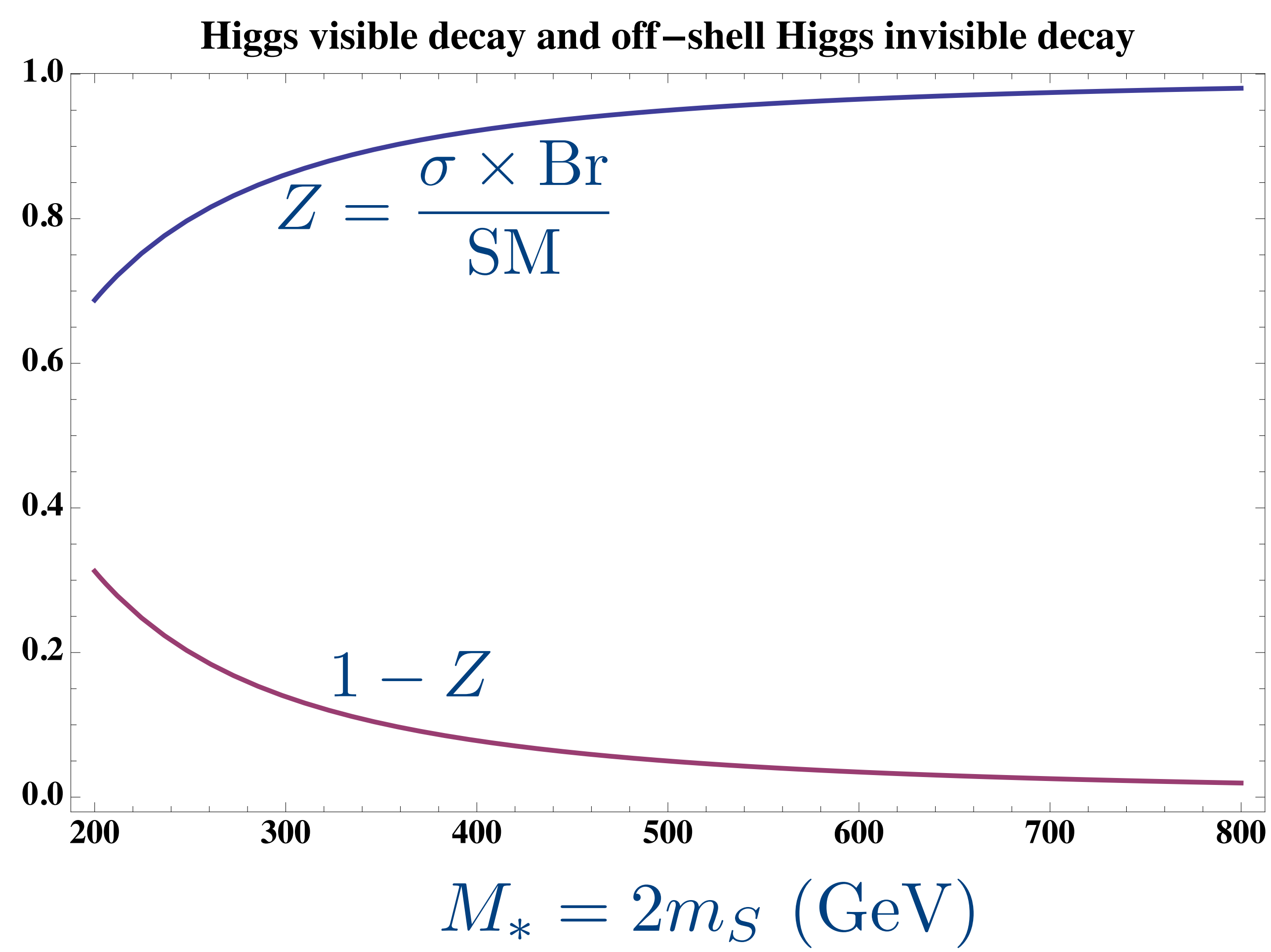
Even though there is no mixing with the singlets, the off-shell physics is very similar to mixing case.$(2M_S \text{ instead of } M_S)$

LHC14 can cover Ns〉10, only the crazy parameter space.
Singlets coupled strongly to the Higgs would survive after LHC14.

Coleman-Weinberg vs Twin phenomenology

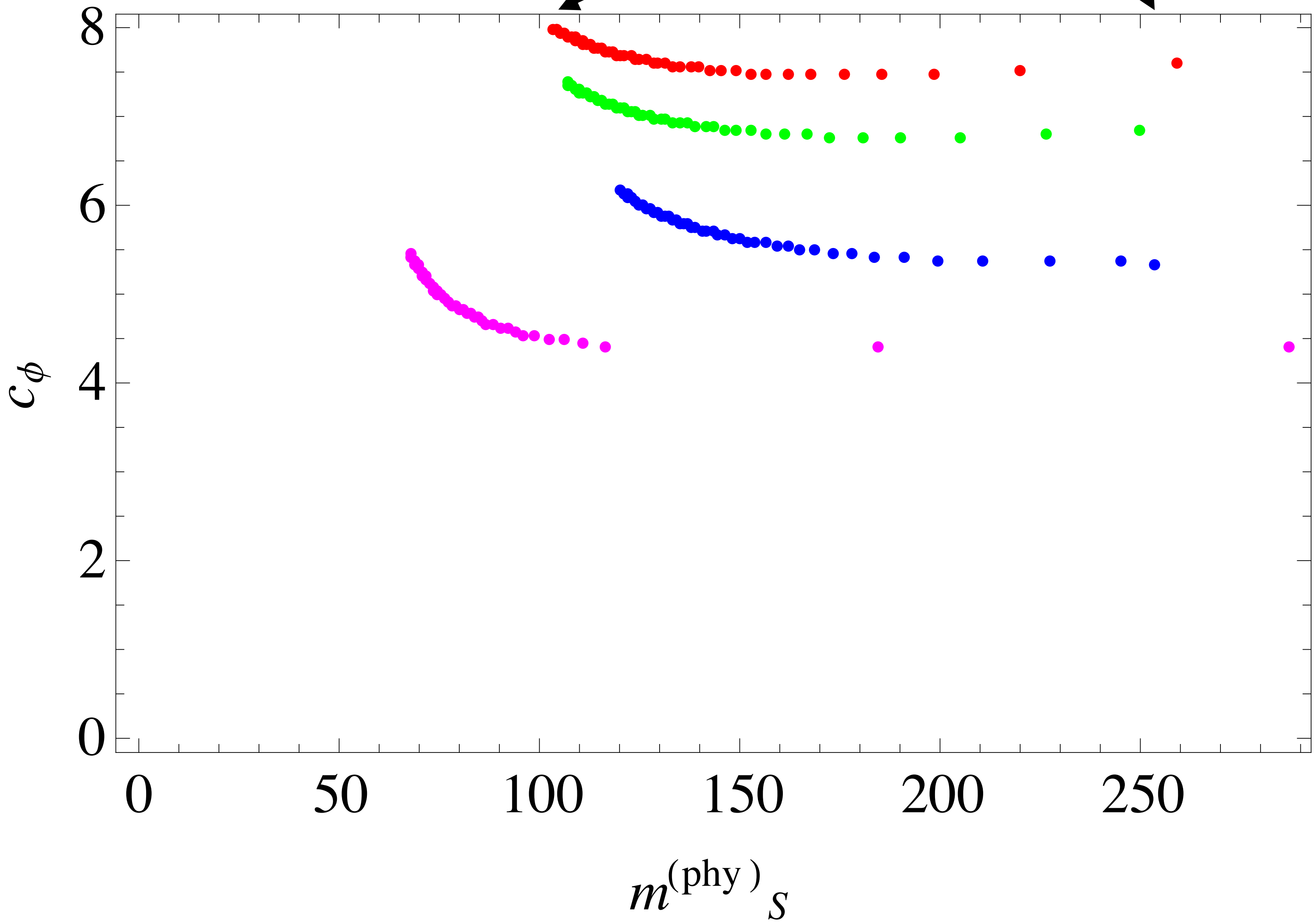
Suppression of Higgs couplings disappear at high energy $E > 2m_S$.





Thank you

Red dots : Ns= 300 ~ 10



Unstable particles

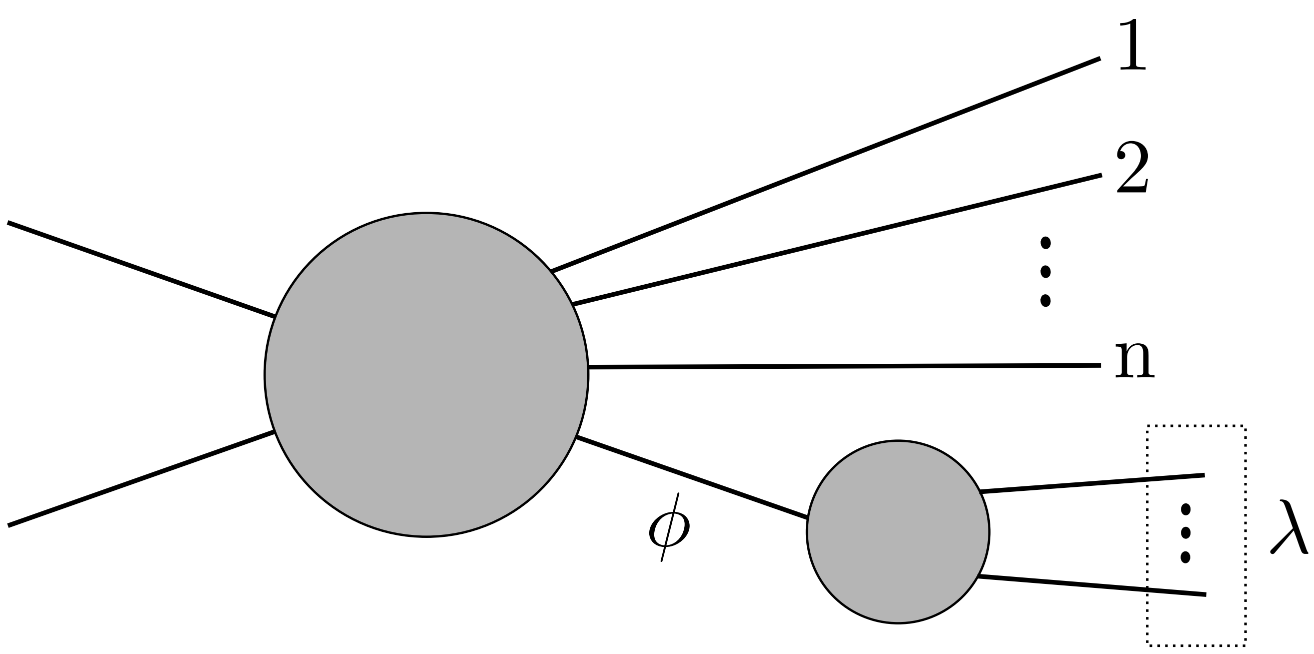
Unitarity of S-matrix requires only stable particles

R. Peierls 1955
J. Schwinger 1960
M. Veltman 1964

Narrow width approximation(NWA) :
Unstable particles are treated as if it is stable as long as the decay width is much smaller than its mass

NWA breaks down when the resonance is at a threshold

Unstable particles : Factorization



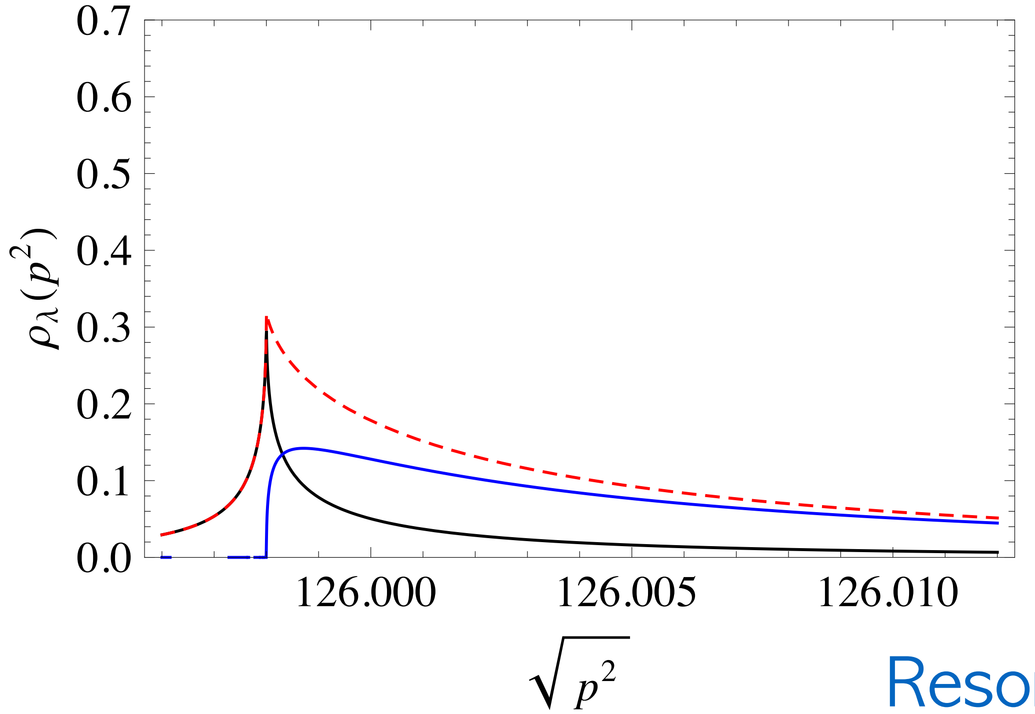
$$\sigma(\text{initial} \to 1, 2, \cdots, n, \lambda) = \int_{S_{\min}}^{S_{\max}} \sigma(\text{initial} \to m_1, m_2, \cdots, m_n, \sqrt{S})\rho_\lambda(S)$$

$$\simeq \sigma(\text{initial} \to m_1, m_2, \cdots, m_n, m_\lambda) \int_{S_{\min}}^{S_{\max}} \rho_\lambda(S)$$

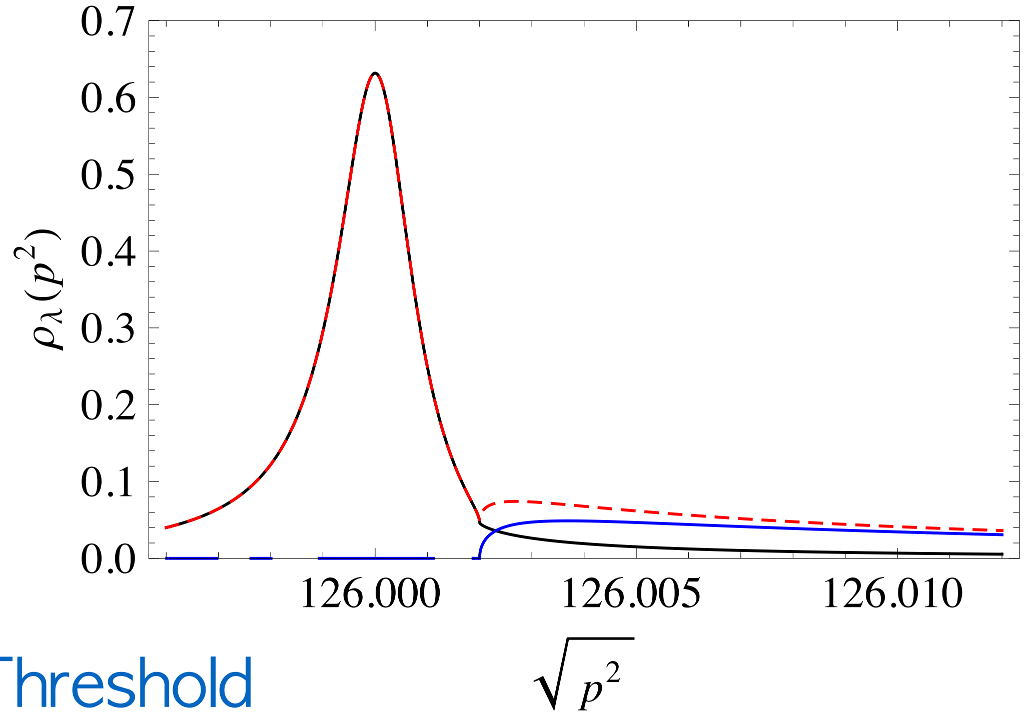
Spectral density of toy example

Higgs to bb and SS

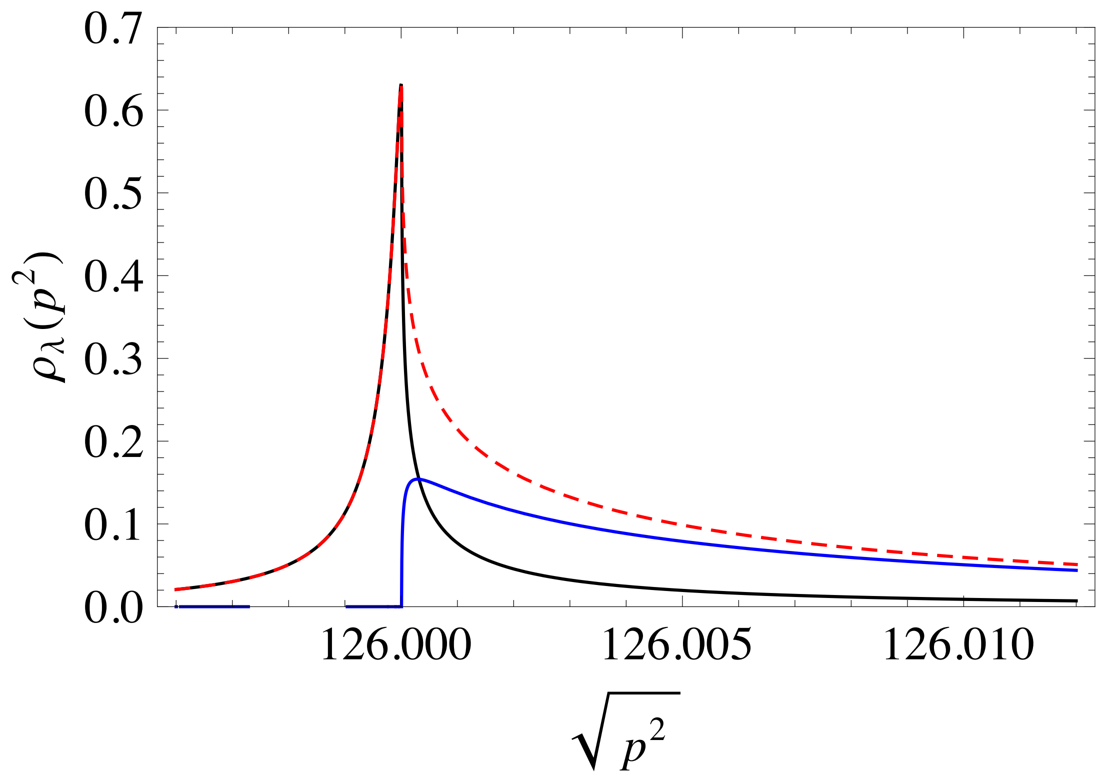
Resonance 〉 Threshold



Resonance 〈 Threshold



Resonance = Threshold



No definition of single width works

Flatte parametrization (1976)

Wave function renormalisation vs. Branching ratio

$$Z_i = \int_{S_{\min}}^{S_{\max}} \rho_i(S)$$

$$Z' = \sum_i Z_i$$

for relevant decay modes

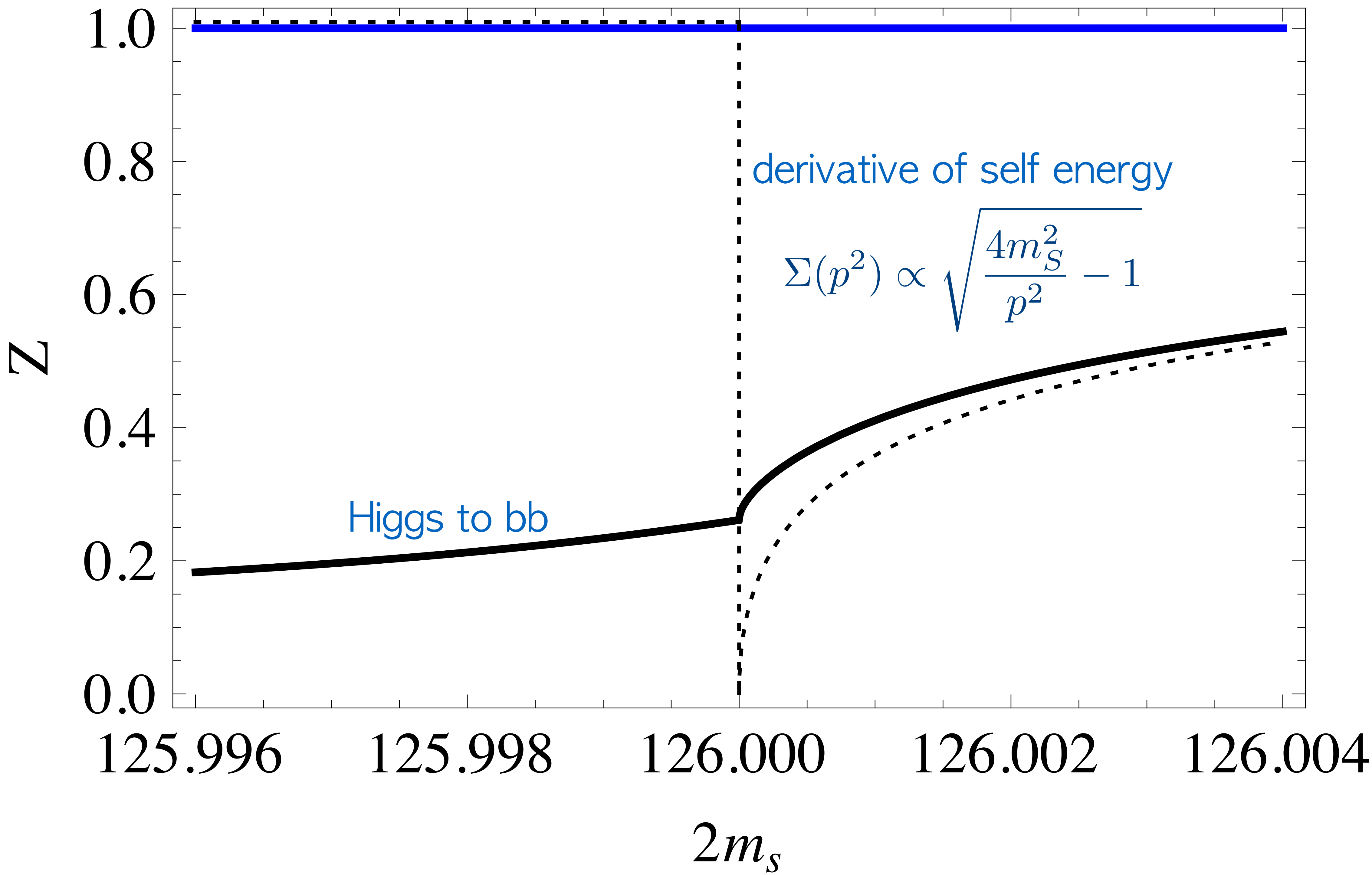
$$\mathrm{Br}_\lambda = \frac{Z_\lambda}{Z'}$$

$$\sigma(\text{initial} \to 1, 2, \cdots, n, \lambda) = \int_{S_{\min}}^{S_{\max}} \sigma(\text{initial} \to m_1, m_2, \cdots, m_n, \sqrt{S})\rho_\lambda(S)$$

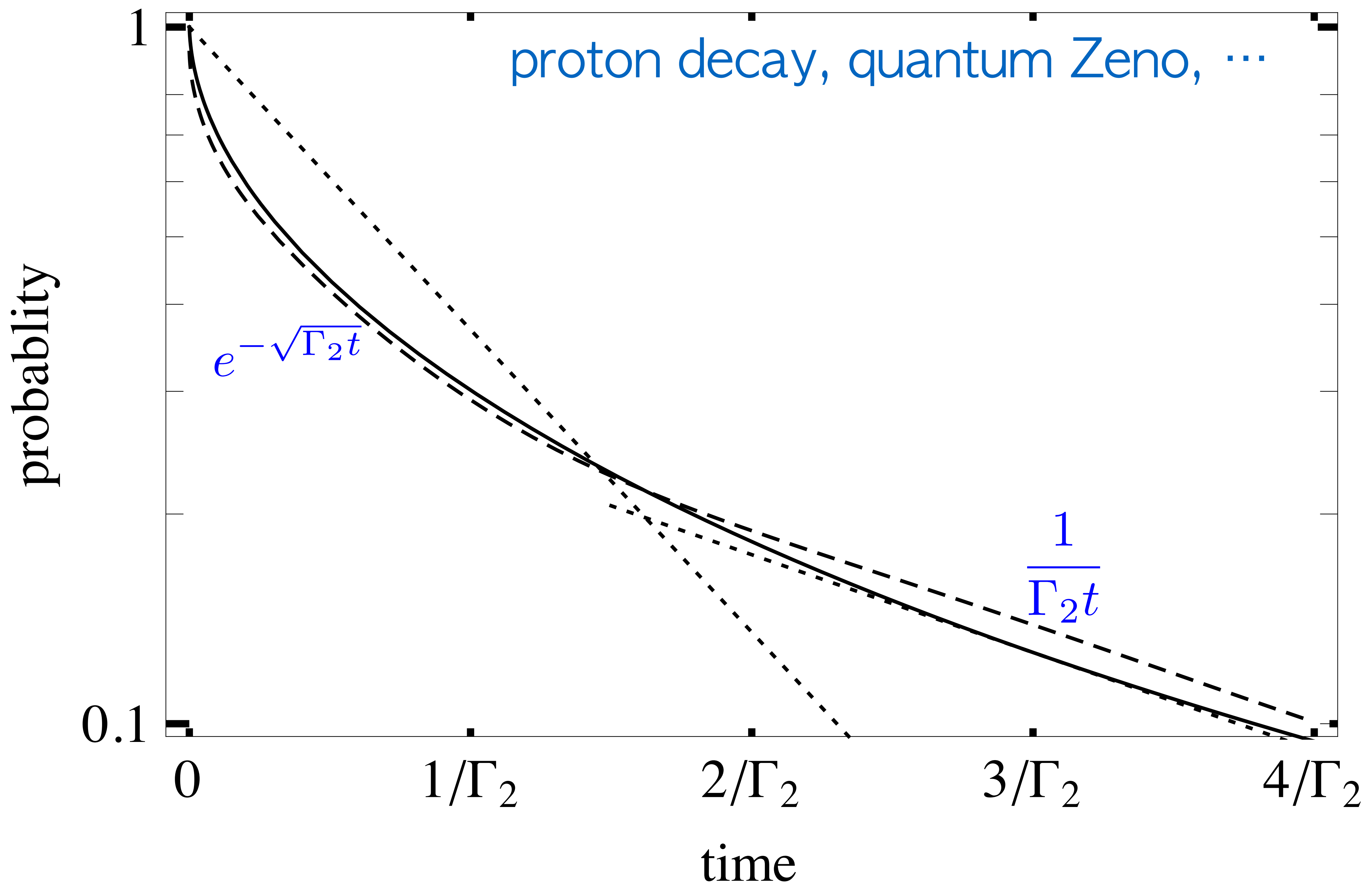
$$\simeq \sigma(\text{initial} \to m_1, m_2, \cdots, m_n, m_\lambda) \int_{S_{\min}}^{S_{\max}} \rho_\lambda(S)$$

$$Z' \mathrm{Br}_\lambda$$

Branching ratios (threshold at resonance)



Non-exponential decay



Mass and width of unstable particles

Complex mass/pole scheme

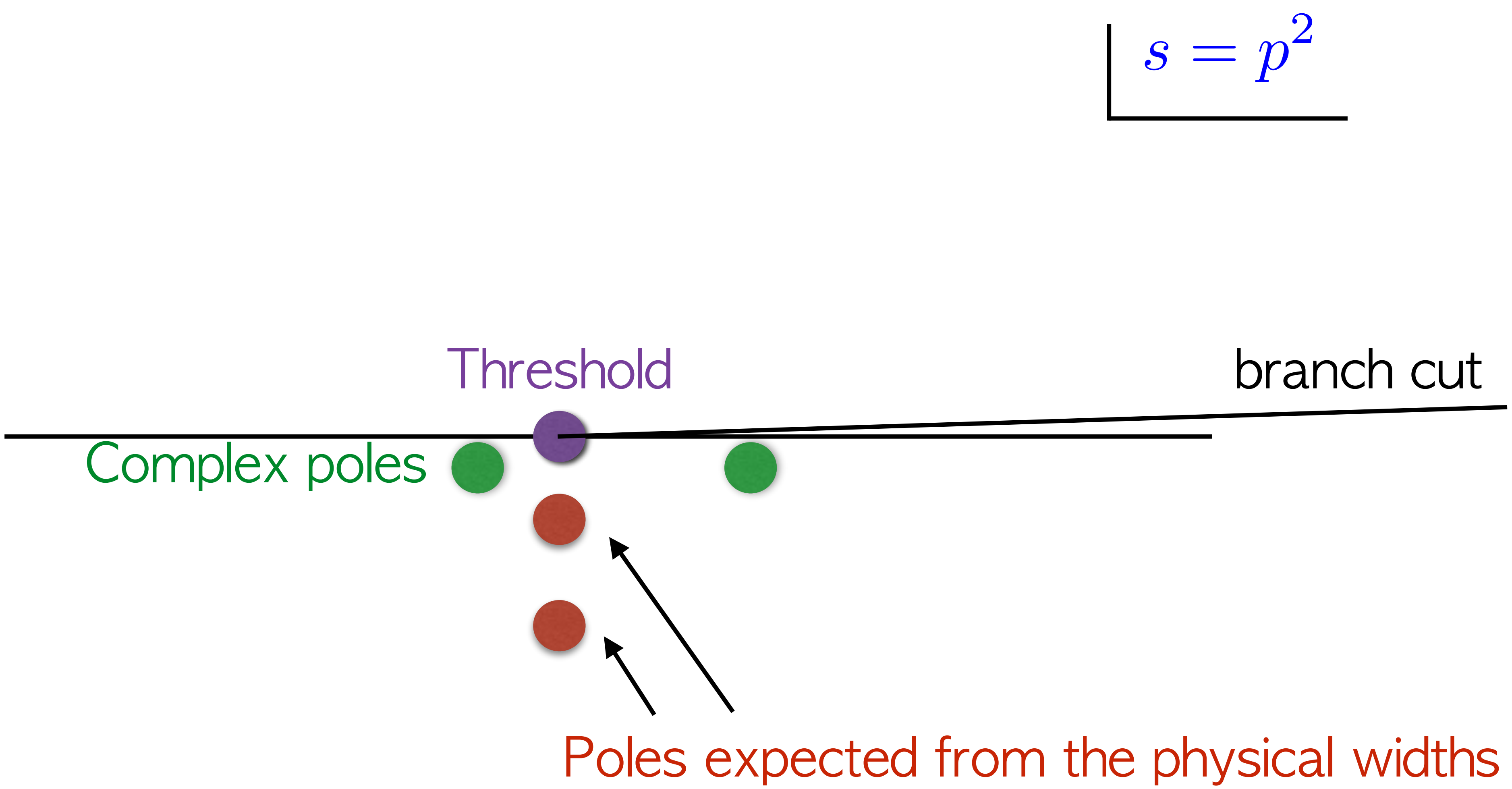
The Dyson resumed propagator has a pole in the unphysical second Riemann sheet.
The real value is the mass and the imaginary value is the width.

$$S_* = M^2 - iM\Gamma$$

In the previous example, there are two solutions and two physical widths correspond to the shift in the real value rather than the imaginary value.

Mass and width of unstable particles

Complex mass/pole scheme



The mass and width obtained from the complex pole does not carry any physically meaningful information.