Coleman-Weinberg Higgs

Hyung Do Kim
Dept. of Physics and Astronomy
Seoul National University

2013. 07.01
Mainz Institute for Theoretical Physics

Beyond the Standard Model

Why do we need BSM?

electroweak symmetry breaking
dark matter
matter anti-matter asymmetry
inflation
neutrino oscillation
...

BSM before the LHC

LHC will produce many BSM particles.

Confirmation/construction of BSM would be possible from LHC data.

BSM After 3 years of the LHC

LHC discovered 'Higgs-like' particle.

(Confirmation of the Standard Model)

Can we get any hint of BSM from the LHC?

BSM classification

Bottom up

Data as a guiding principle

Direct detection of dark matter : DAMA, CoGeNT,CRESST,CDMSII-Si

Cosmic ray excess (e+,e-,photon) : PAMELA, Fermi-LAT, AMS-02

Tevatron anomalies : D0 dimuon charge asymmetry, CDF Wjj, Top Afb

LHC anomalies : CPV in charm decays, Higgs to diphoton rate

Muon g-2

BSM classification

Bottom up

Data as a guiding principle

Direct detection of dark matter : DAMA, CoGeNT,CRESST,CDMSII-Si

conflict with XENON 10 & XENON 100

Cosmic ray excess (e+,e-,photon) : PAMELA, Fermi-LAT, AMS-02

Astrophysical origin : pulsars?

Tevatron anomalies : ~~D0 dimuon charge asymmetry~~, ~~CDF Wjj~~, ~~Top Afb~~

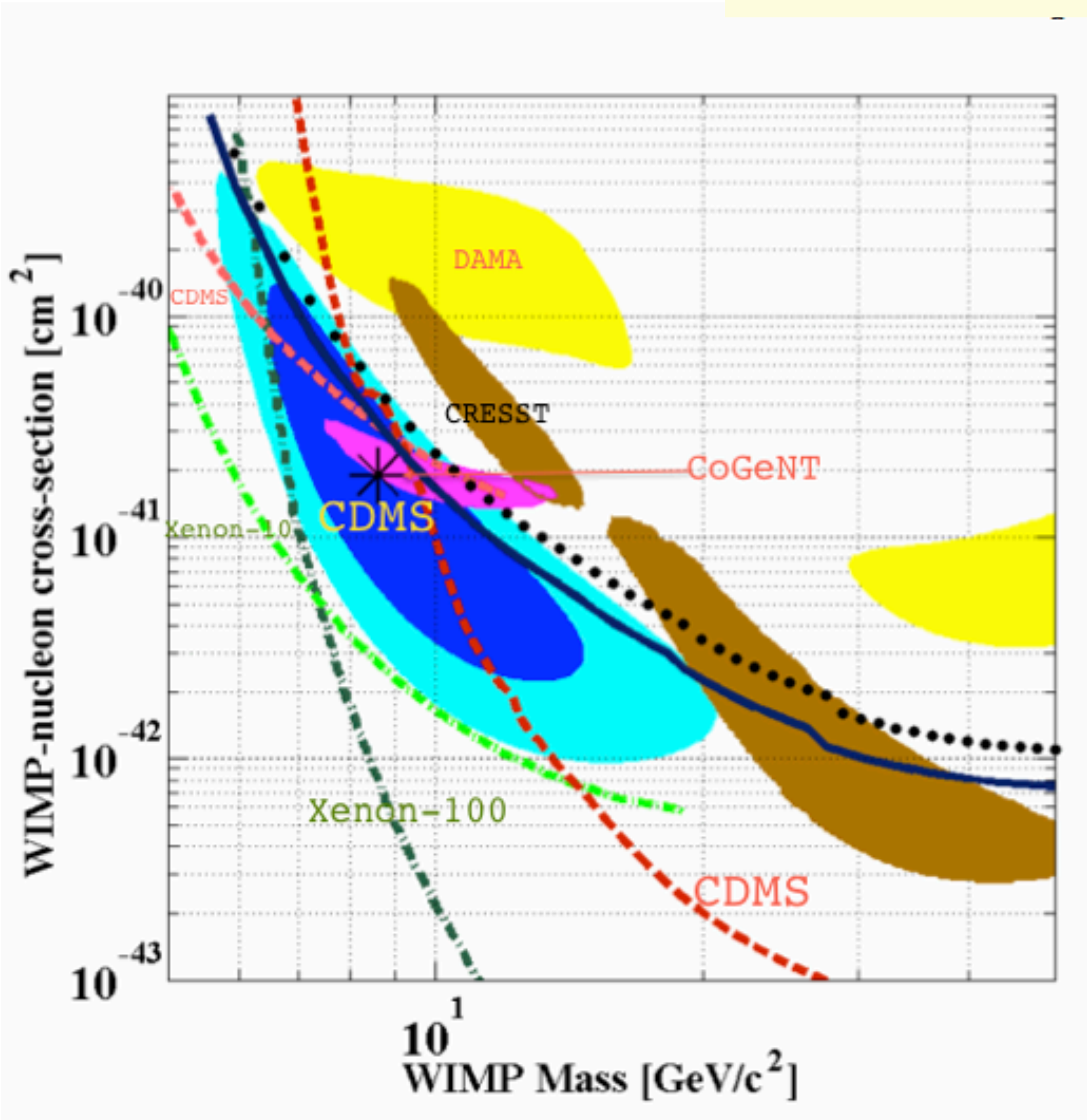
LHC anomalies : ~~CPV in charm decays~~, ~~Higgs to diphoton rate~~

A few percent deviation?

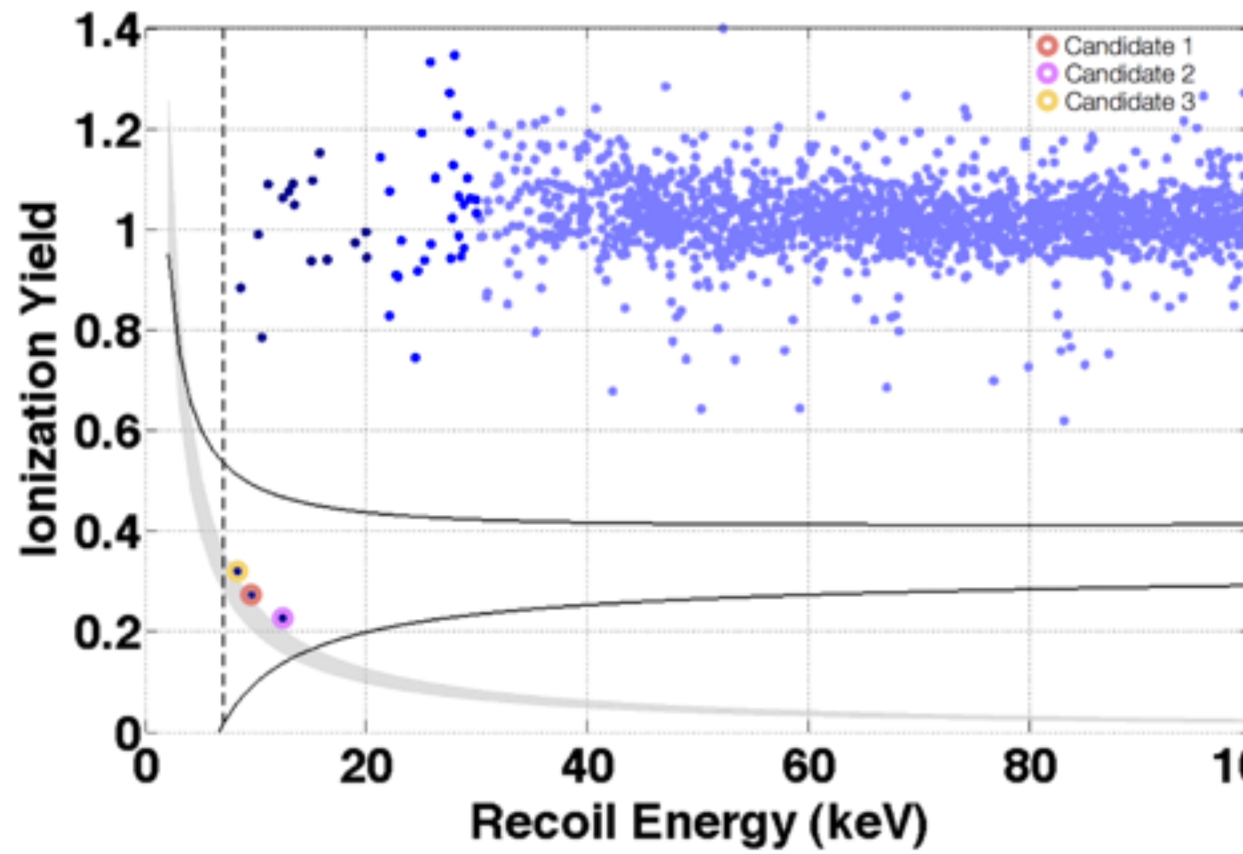
Muon g-2

light by light scattering
theory uncertainty

Light dark matter?

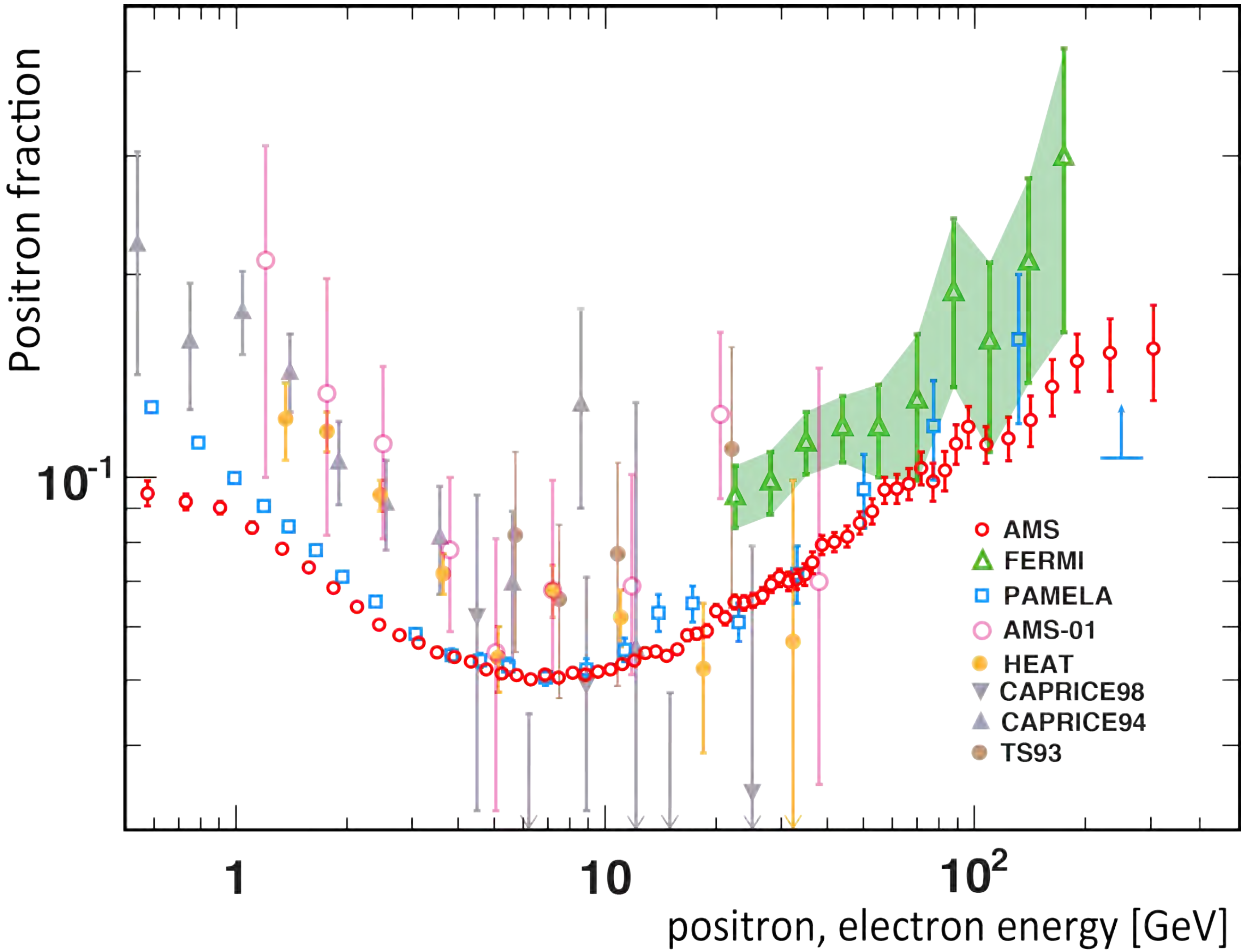


4	vs	2
DAMA,CoGeNT, CRESST,CDMS-Si		XENON 10 XENON 100



Plots from Resonaances blog

Heavy dark matter?



Plot from AMS-02 exp

Three topics to consider

1. electroweak symmetry breaking
2. dark matter
3. baryogenesis

Is the radiative electroweak symmetry breaking possible?

Coleman-Weinberg Higgs

Hyung Do Kim
with Radovan Dermisek and Taehyun Jung

arXiv:1307.xxxx

Higgs self coupling in the SM

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

$$\Big\downarrow$$

$$V(\phi(x)) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

$$H = \frac{1}{\sqrt{2}}\left(\begin{array}{c} 0 \\ v+\phi(x) \end{array}\right)$$

$$\frac{dV}{d\phi} = (-\mu^2 + \lambda\phi^2)\phi|_{\phi=v} = 0 \xrightarrow{v\,=\,246\ \mathrm{GeV}} \mu^2 = \lambda v^2$$

$$m_h^2 = \frac{d^2V}{d\phi^2} = 2\lambda v^2 = 2\mu^2$$

Higgs self coupling in the SM

$$\frac{1}{2}m_h^2\phi^2 + \sqrt{\frac{\lambda}{2}}m_h h^3 + \frac{\lambda}{4}h^4$$

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

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

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

All three definitions give the same quartic coupling.

Coleman-Weinberg mechanism

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

$$m^2 = 0$$

Spontaneous symmetry breaking can occur by radiative corrections.

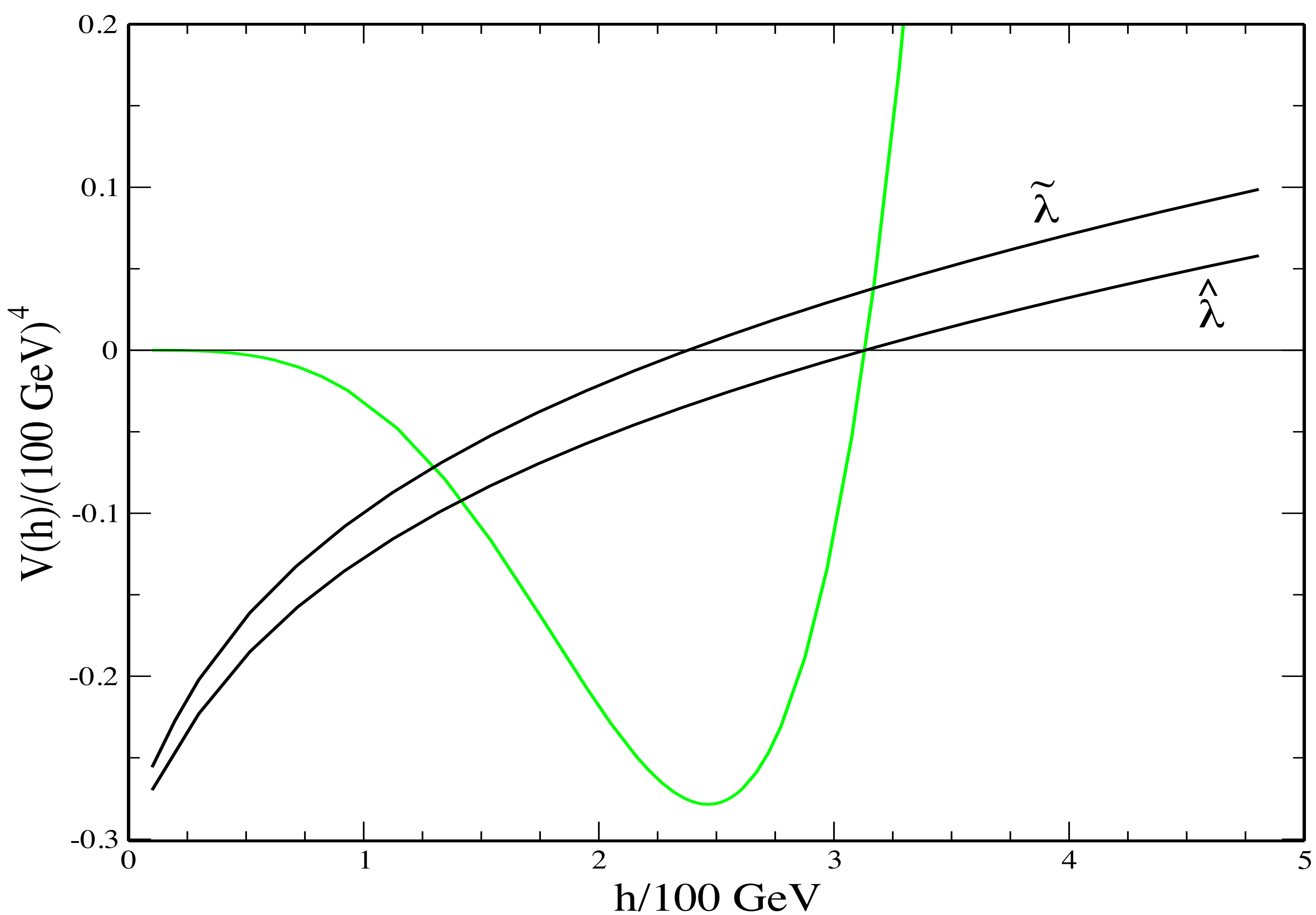
Starting from scale invariant potential

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

RG improved effective potential is then

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

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



Scalar QED

$$V = \frac{\lambda}{4!}\phi_c^4 + \frac{3e^4}{64\pi^2}\phi_c^4\left(\log\frac{\phi_c^2}{\langle\phi\rangle^2} - \frac{25}{6}\right)$$

$$V'(\langle\phi\rangle) = 0 \qquad\qquad \lambda = \frac{3}{8\pi^2}e^4$$ at the minimum

$$e, \lambda \longrightarrow e, \langle\phi\rangle$$

dimensional transmutation

$$V = \frac{3e^4}{64\pi^2}\phi_c^4\left(\log\frac{\phi_c^2}{\langle\phi\rangle^2} - \frac{1}{2}\right)$$

Scalar QED

$$m_h^2 = V''(\langle\phi\rangle) = \frac{3e^4}{8\pi^2}\langle\phi\rangle^2 \qquad m_V^2 = e^2\langle\phi\rangle^2$$

$$\frac{m_h^2}{m_V^2} = \frac{3}{2\pi}\frac{e^2}{4\pi} = \frac{3}{2\pi}\alpha$$

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

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

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

Large top Yukawa prevents CW mechanism in the SM

$$\beta_\lambda \propto -y^4$$

$$\beta_\lambda \propto g^4$$

$$\beta_\lambda \propto \lambda^2$$

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

Coleman-Weinberg Higgs

Classically scale invariant Higgs potential

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

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

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

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

$$\lambda^{(2)}_{\text{eff}} = \frac{1}{2}\frac{m^2}{v^2} \sim \frac{1}{8}$$

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

$$\boxed{\begin{aligned}\lambda^{(3)}_{\text{eff}} &= \frac{5}{3}\lambda^{(2)}_{\text{eff}}, \\ \lambda^{(4)}_{\text{eff}} &= \frac{11}{3}\lambda^{(2)}_{\text{eff}}.\end{aligned}}$$

Scale dependence of the beta function is neglected here.

Higgs portal with extra scalar S

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

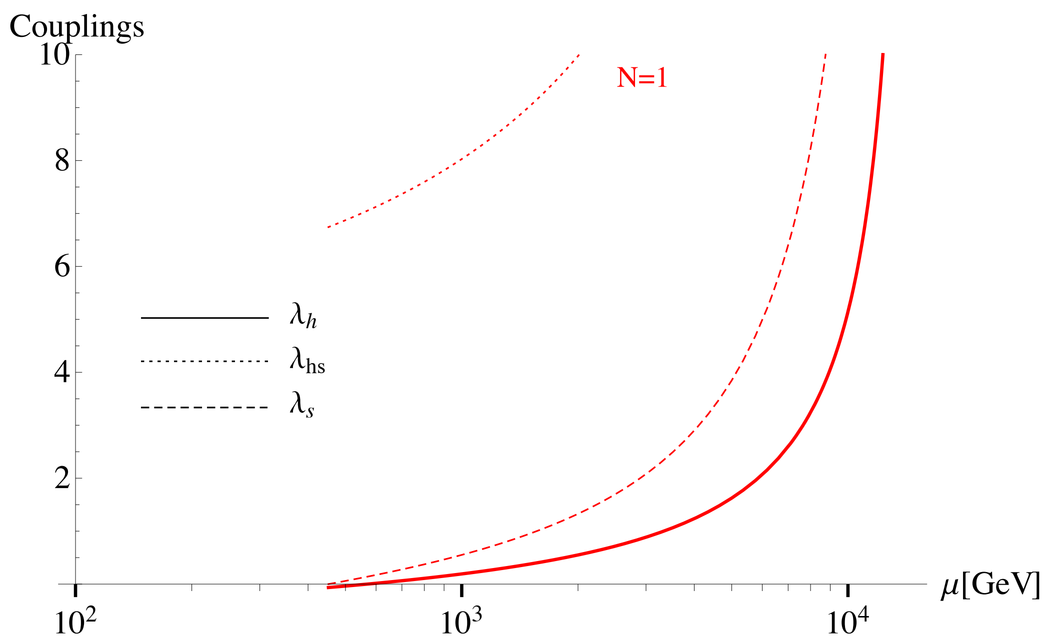
$$16\pi^2 \beta_{\lambda_h} = 24\lambda_h^2 + N\lambda_{hs}^2$$

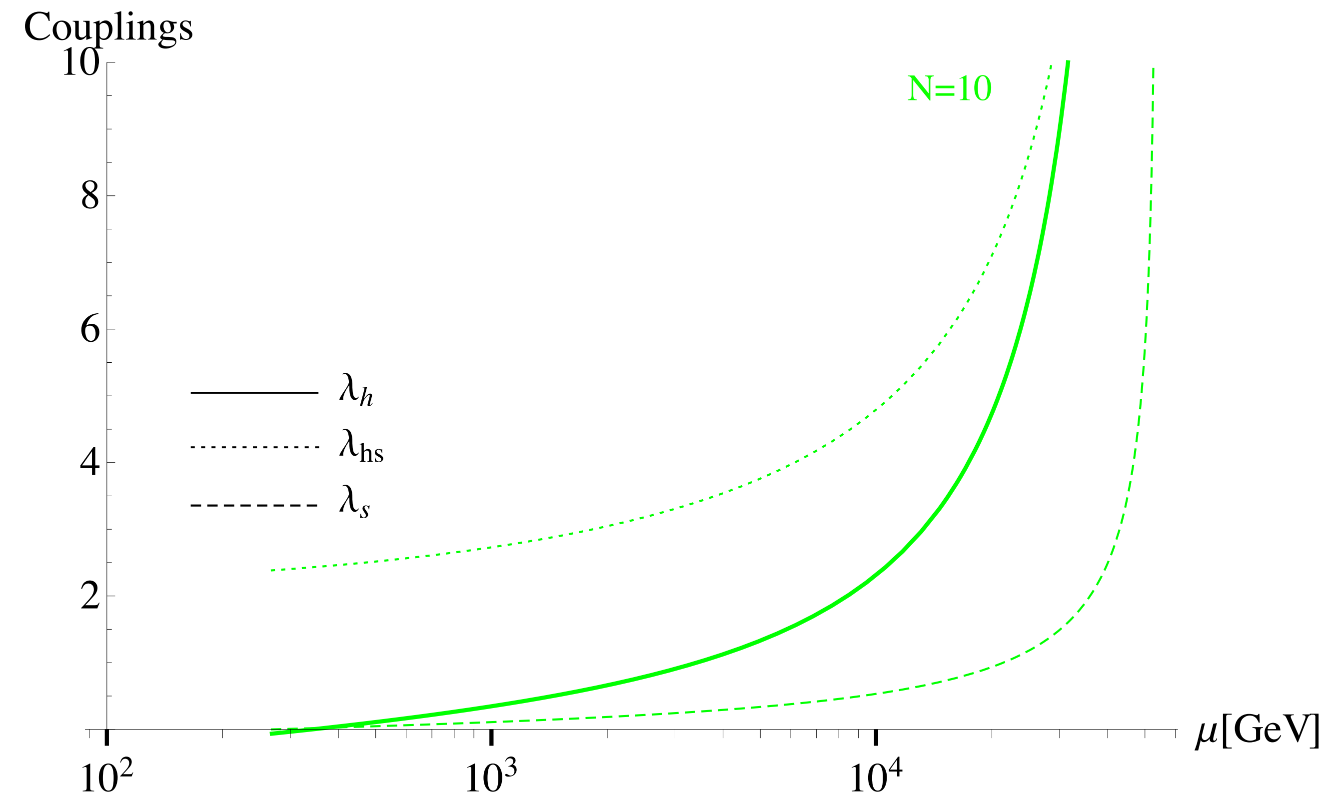
$$16\pi^2 \beta_{\lambda_{hs}} = \lambda_{hs}\left[4\lambda_{hs} + 12\lambda_h + (4N+4)\lambda_{hs}^2\right]$$

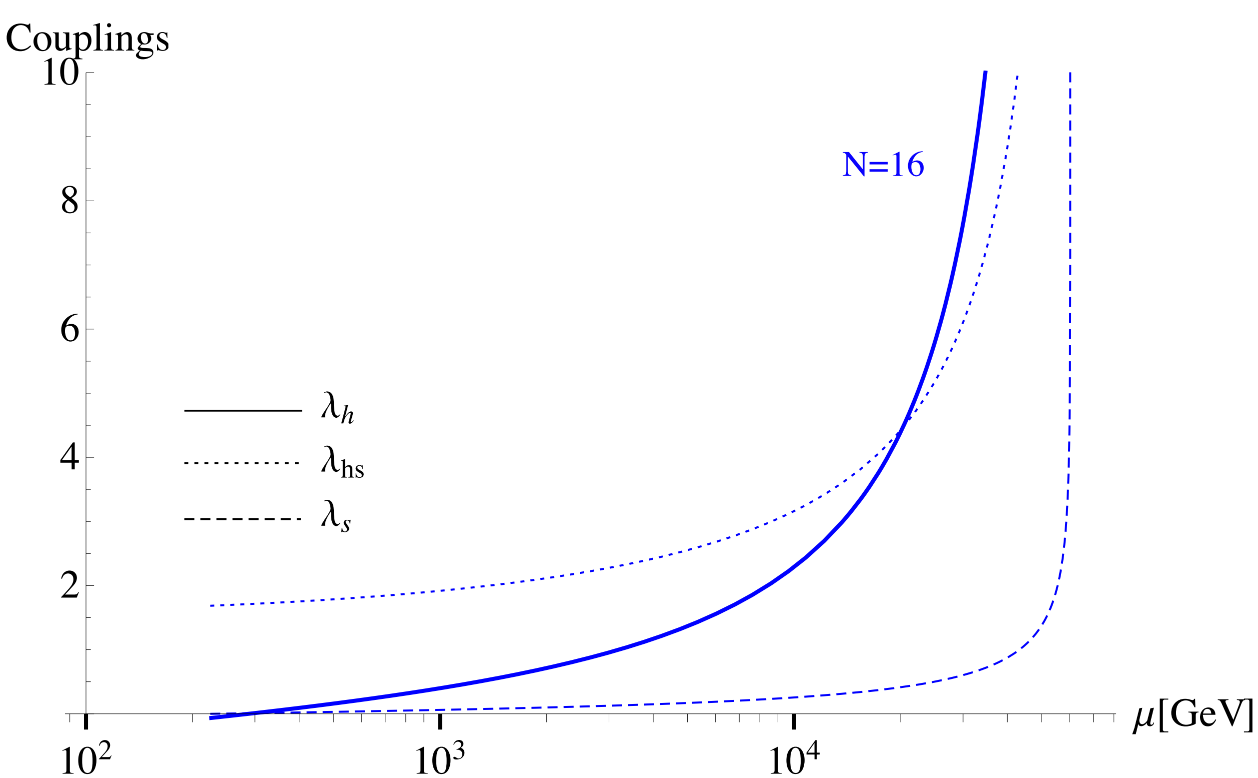
$$16\pi^2 \beta_{\lambda_s} = (16+4N)\lambda_s^2 + 2\lambda_{hs}^2$$

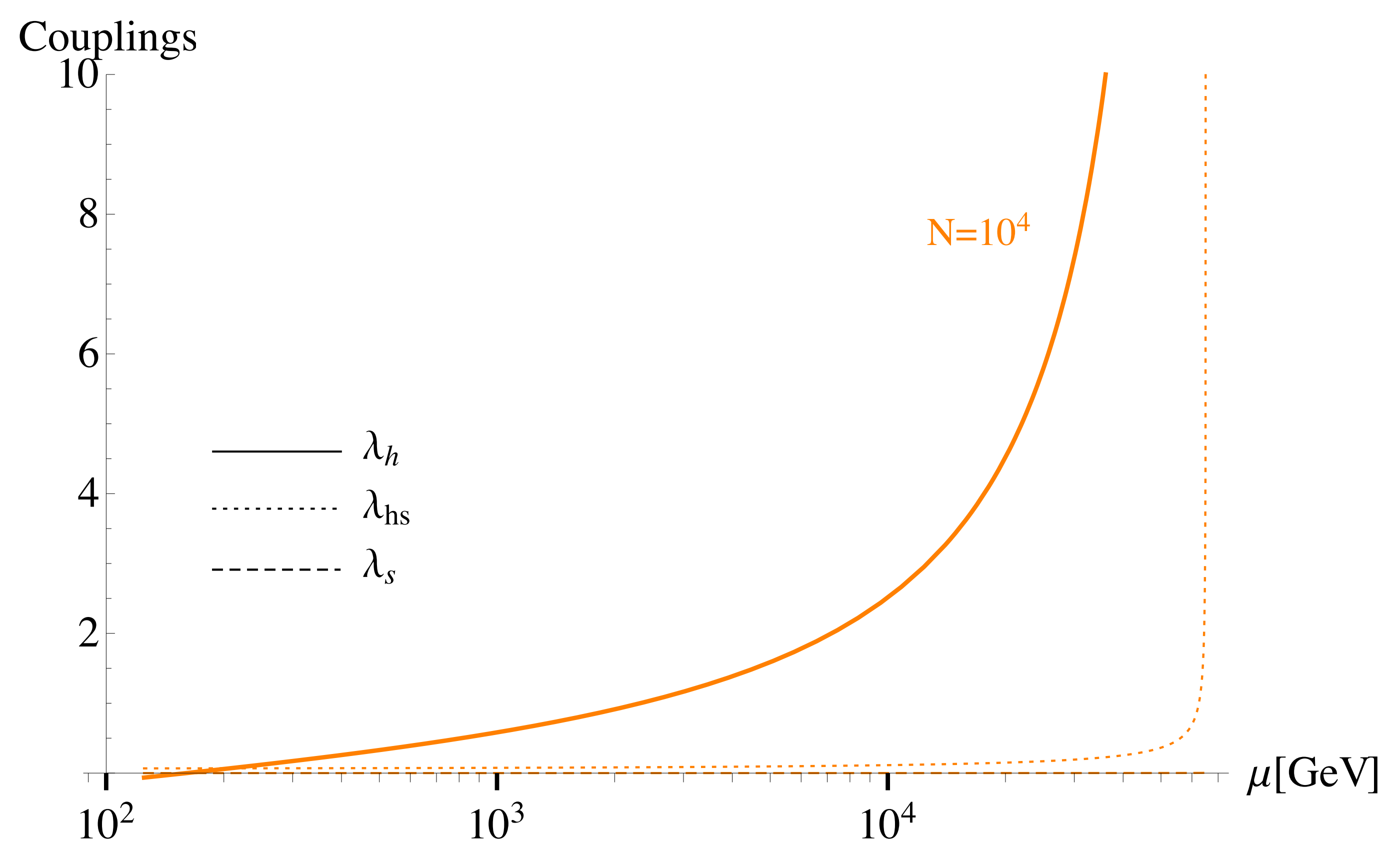
New mixed quartic raises Higgs quartic at high energy

Bound from perturbativity : 20~50 TeV









Bound from perturbativity : 20 TeV

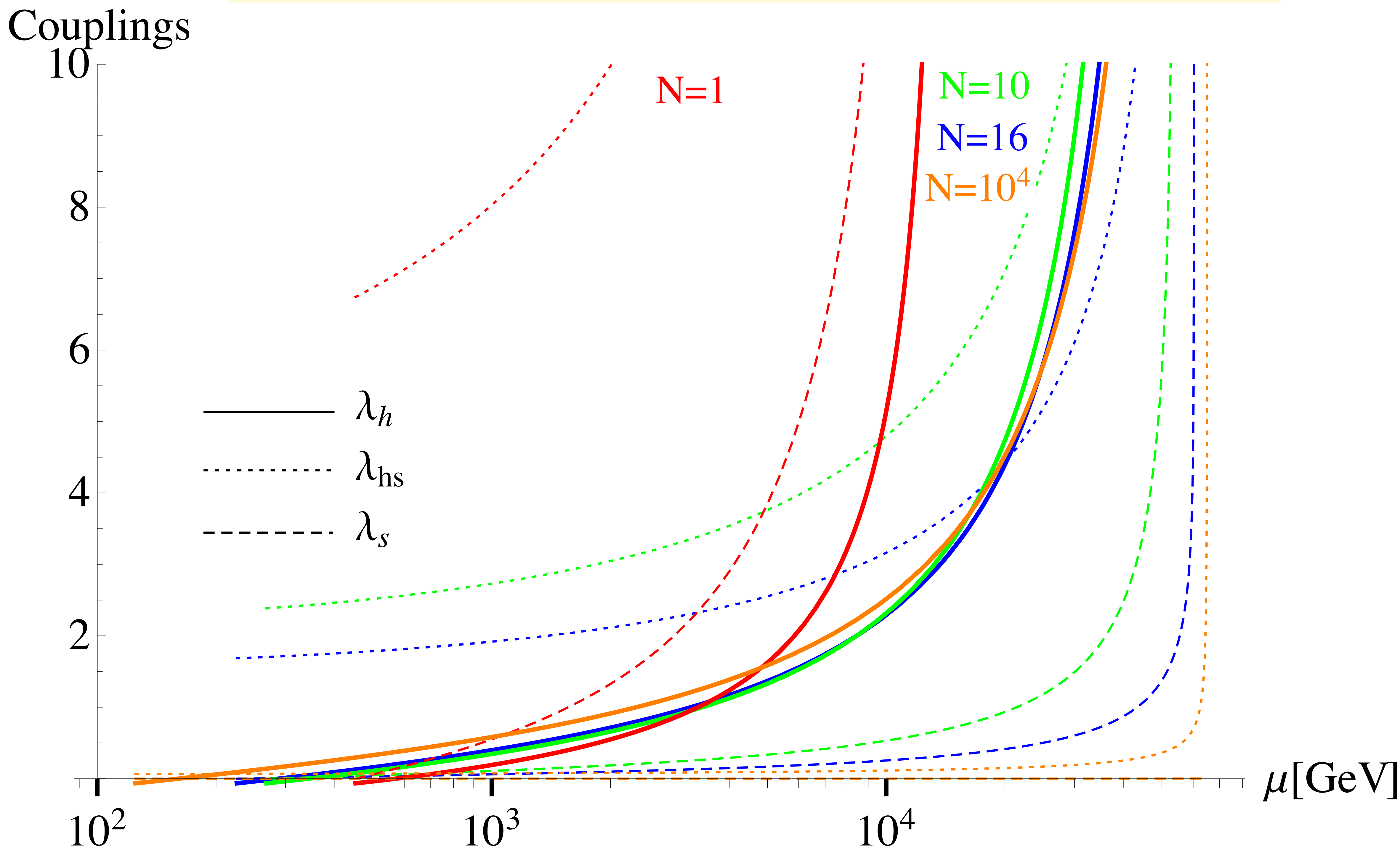
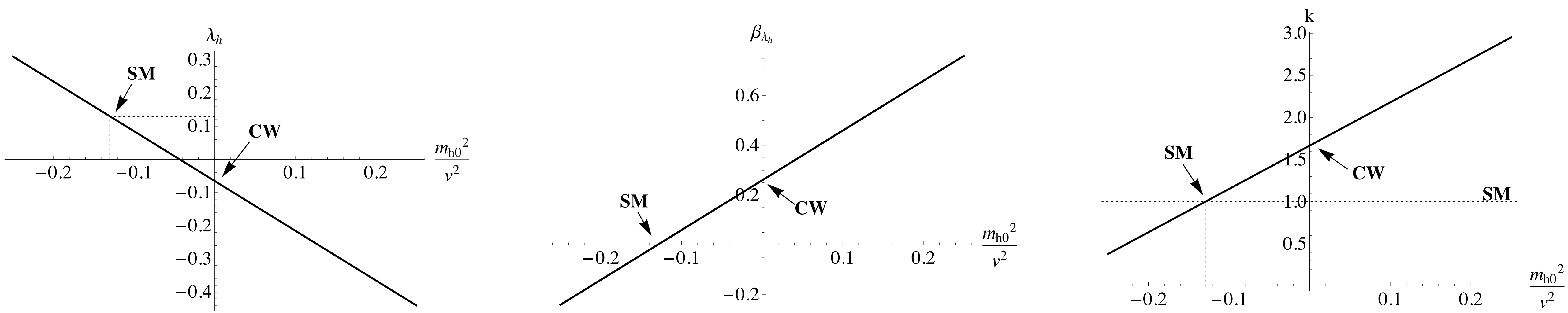


FIG. 1. (rigid, dashed, dotted) : $\lambda_{(h,s,hs)}$, (red, blue, green): $N_S = (1, 10, 16)$.



λ_h
SM
CW
$\frac{m_{h0}^2}{v^2}$
β_{λ_h}
SM
CW
$\frac{m_{h0}^2}{v^2}$
k
SM
CW
SM
$\frac{m_{h0}^2}{v^2}$

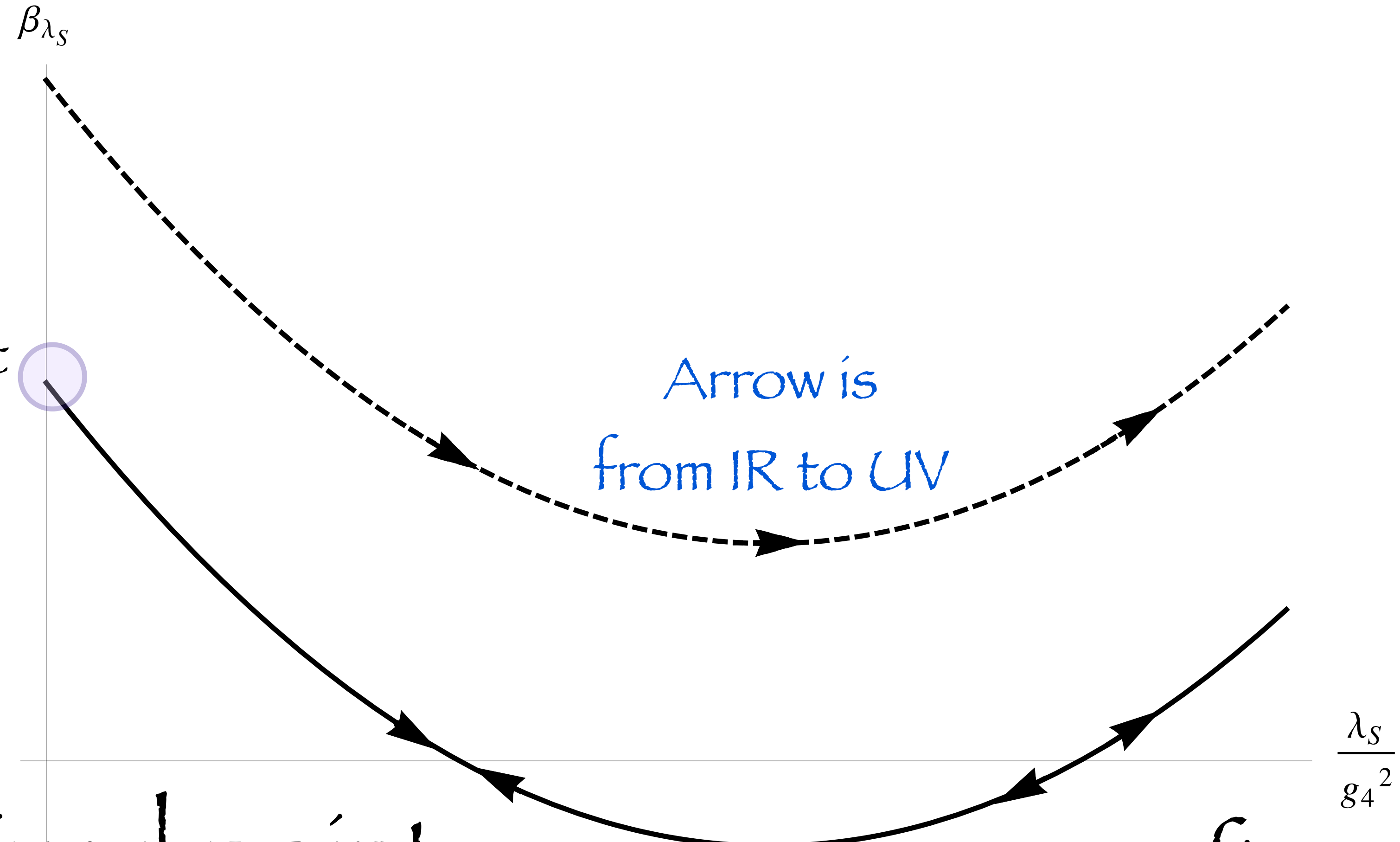
Gauge extension of the scalar S

$SU(N_c)^{N_G}$

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

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

Starting with a small coupling at the weak scale



UV fixed point

IR fixed point

Example : Scalar in 4 of SU(4) :

IR to UV

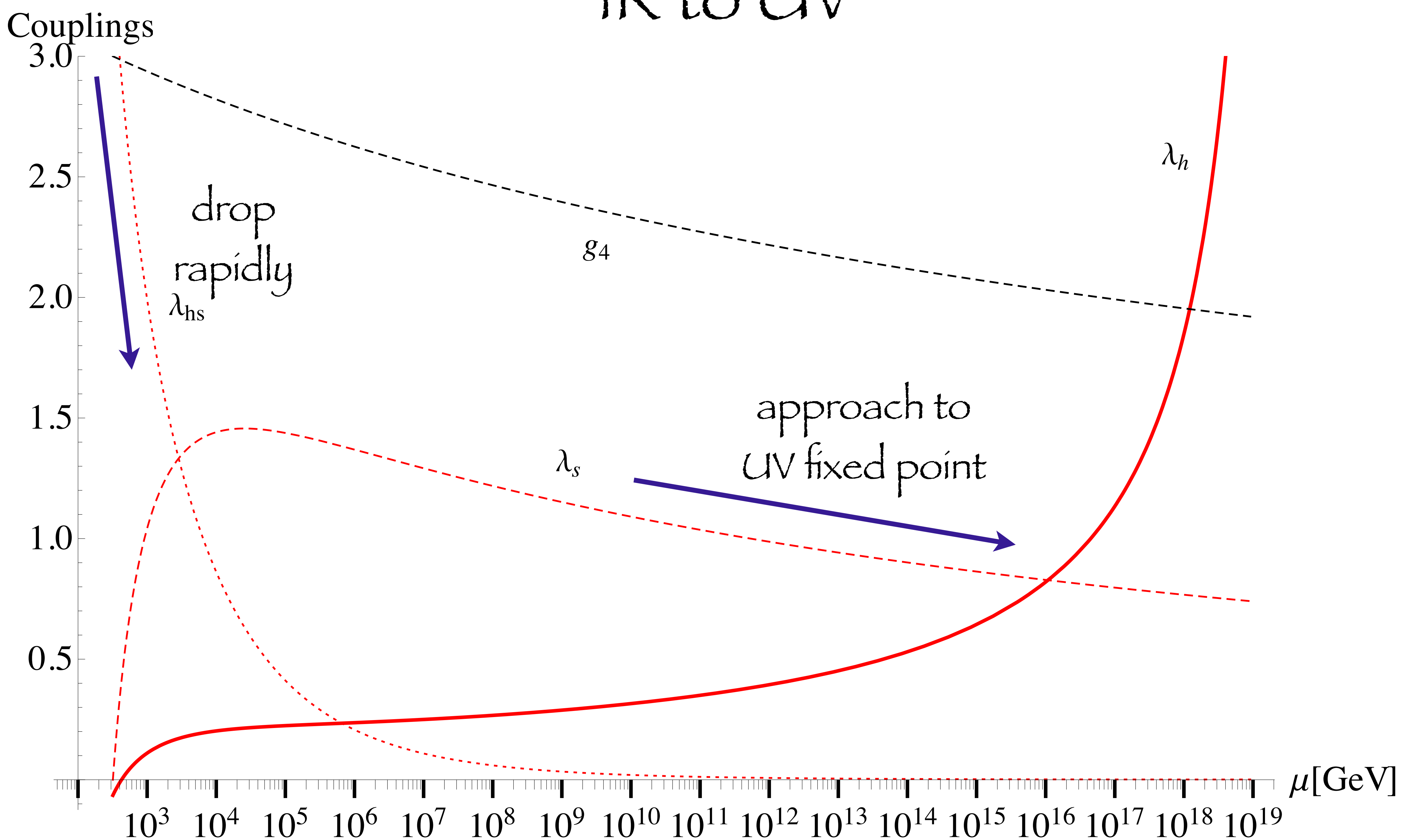


FIG. 2. (rigid, dashed, dotted) : $\lambda_{(h,s,hs)}$

Example : Scalar in 4 of SU(4)

UV to IR

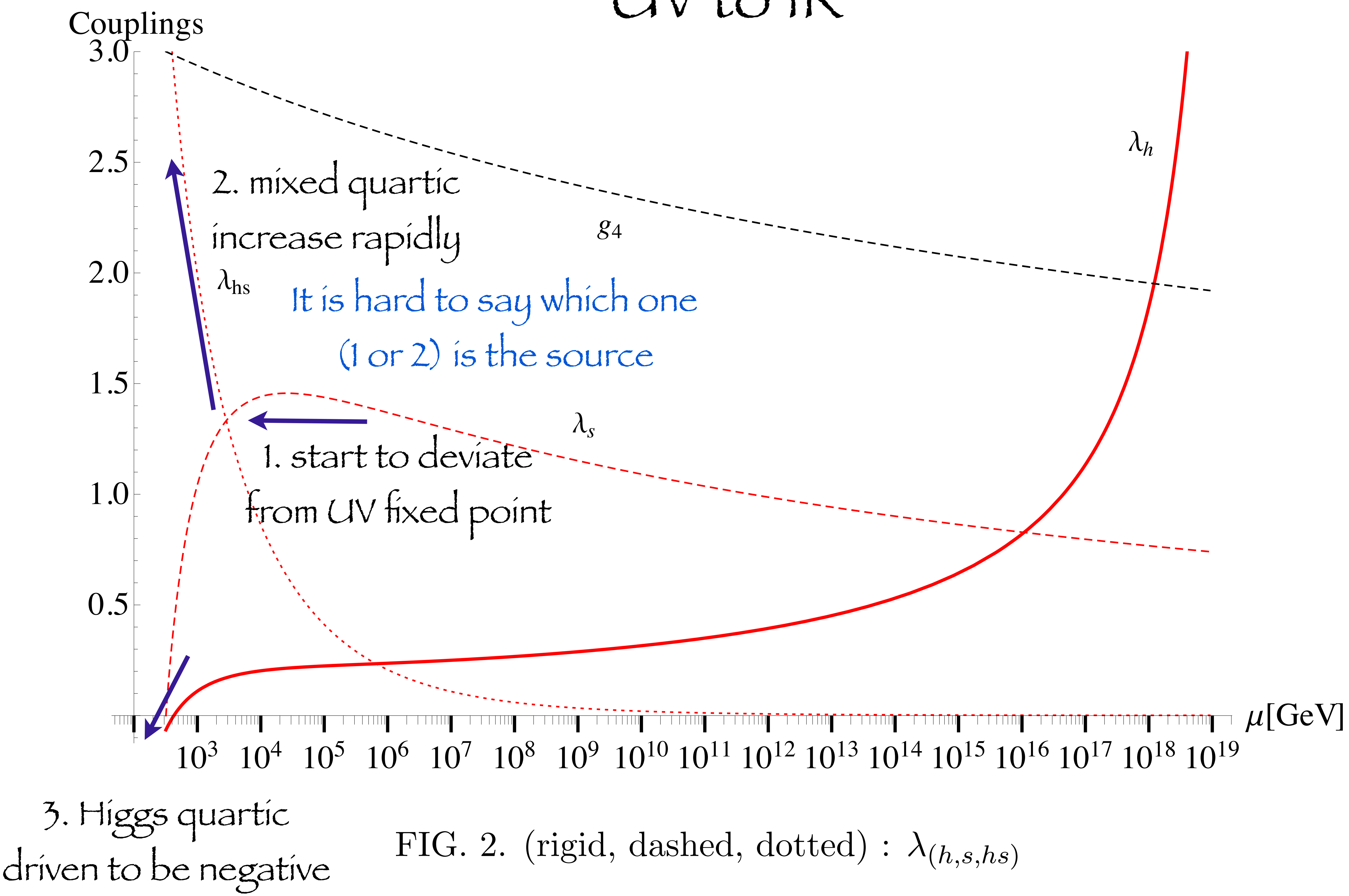


FIG. 2. (rigid, dashed, dotted) : $\lambda_{(h,s,hs)}$

Measuring Higgs self 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

$$\downarrow$$

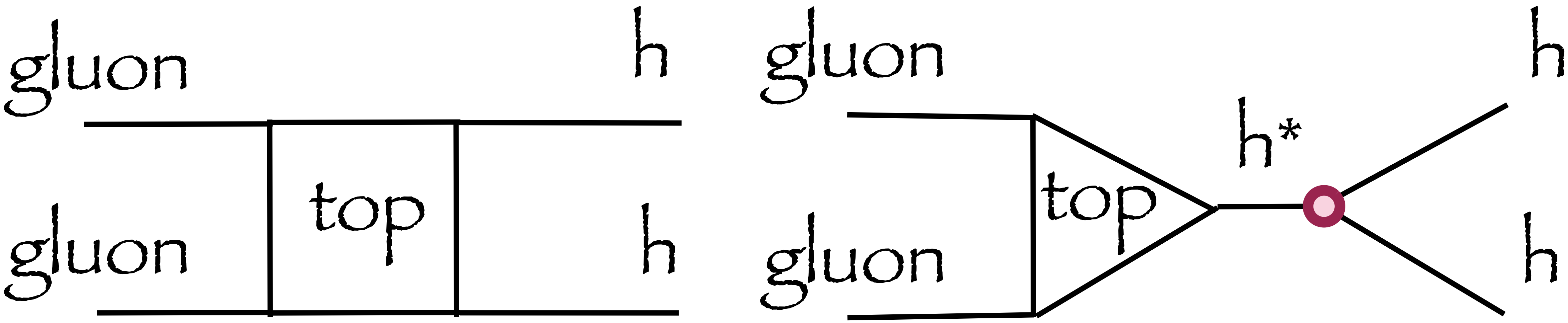
$$\mathcal{L}_{\rm eff} = \frac{1}{4}\frac{\alpha_s}{3\pi v}G^a_{\mu\nu}G^{a\mu\nu}h - \frac{1}{4}\frac{\alpha_s}{6\pi v^2}G^a_{\mu\nu}G^{a\mu\nu}h^2 + \cdots$$

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

destructive interference

leading term

Measuring Higgs self coupling at the LHC



14 TeV @ LHC

$$\sigma^{NLO}(hh+X) = 30fb$$

$$\sigma^{NLO}(h+X) = 17pb$$

$$\sim \frac{1}{500}$$

* Higgs pair production cross section : 300 fb at 33 TeV

Higgs self interactions at the LHC

$$\sigma_{hh}^{NLO} = 70 y_t^4 - 50 \lambda y_t^3 + 10 \lambda^2 y_t^2 \longrightarrow \quad k \quad = \frac{\lambda_{\text{new}}}{\lambda_{\text{SM}}}$$

1 -0.1

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

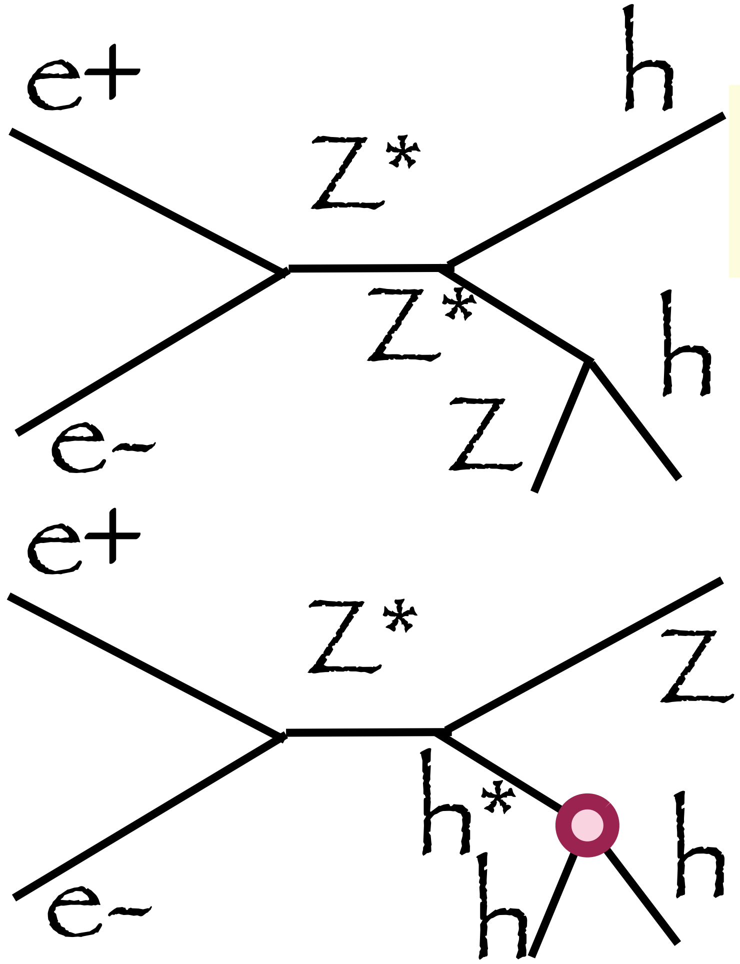
30% uncertainty
(bb tau tau, bbWW, bb gamma gamma)

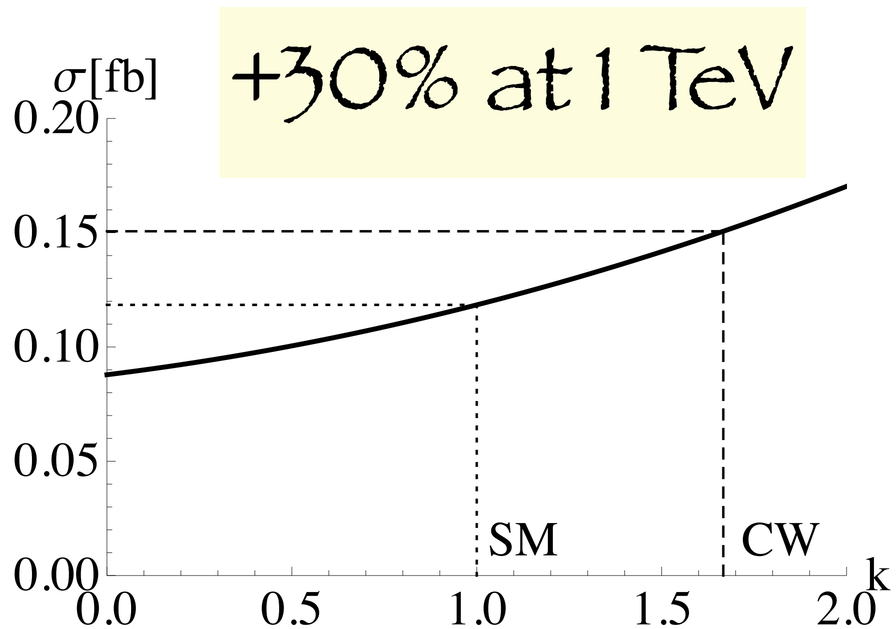
$$3000 fb^{-1} @14 \text{ TeV}$$

It would be difficult to distinguish CW Higgs from SM Higgs at the LHC.

Measuring Higgs self coupling at ILC

ZZhh, WWhh vertex diagram is omitted here





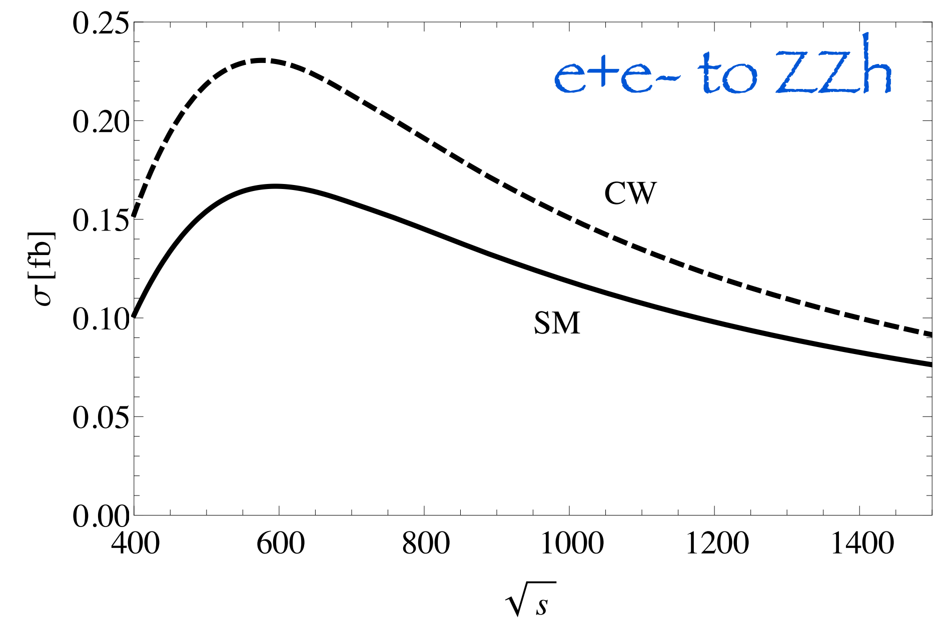
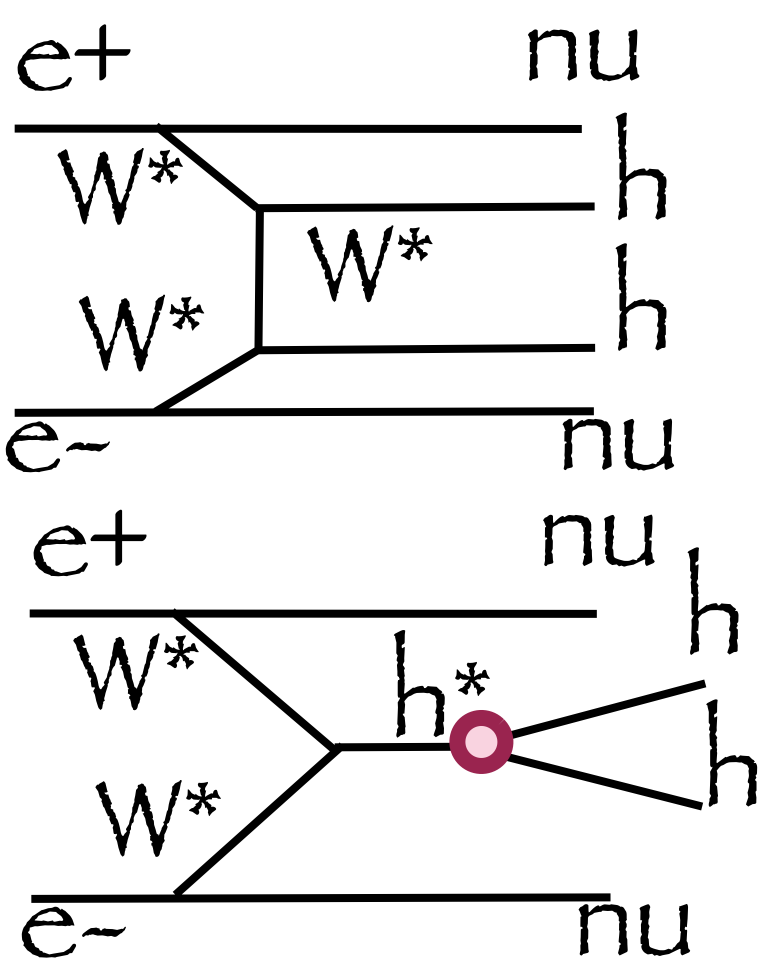
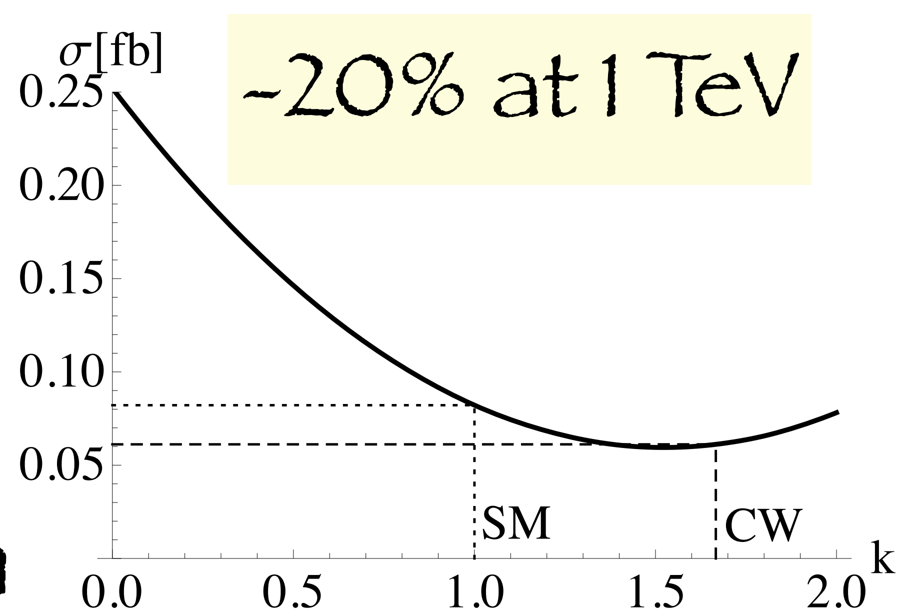


FIG. 7. $e^+e^- \to hhZ$





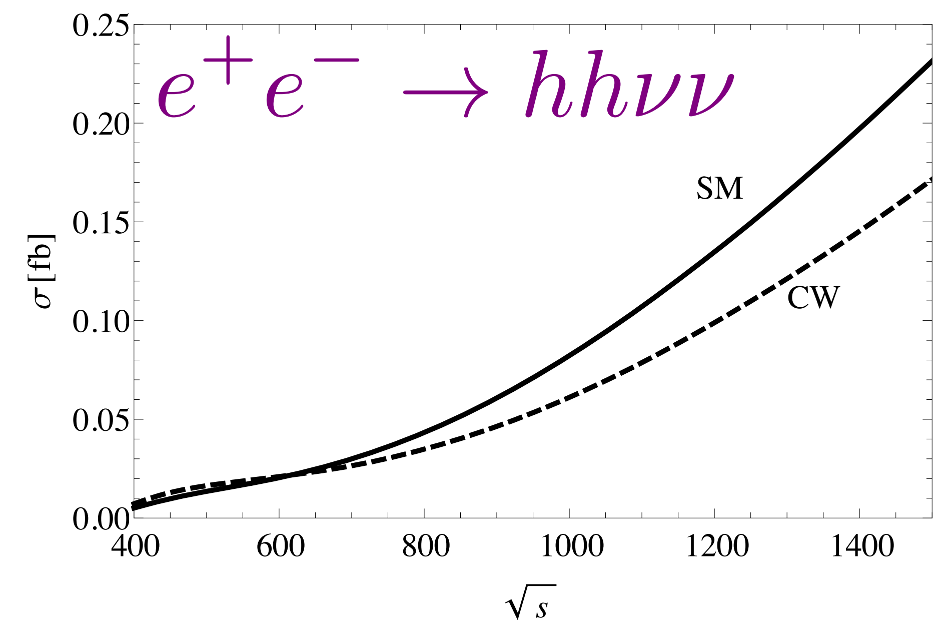
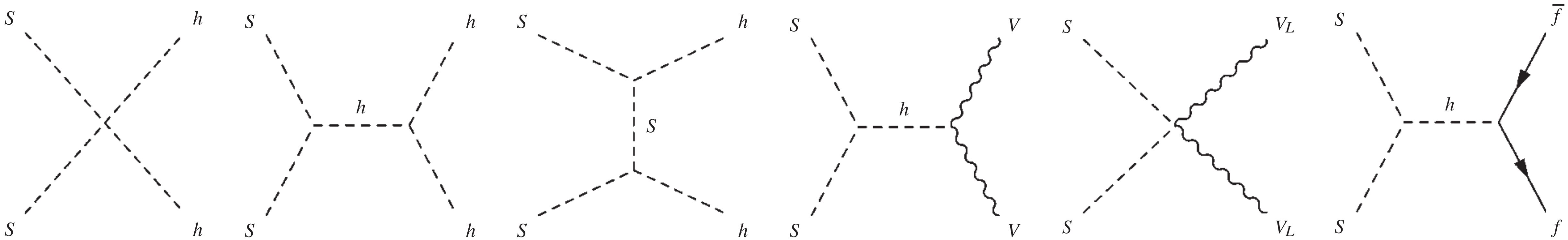
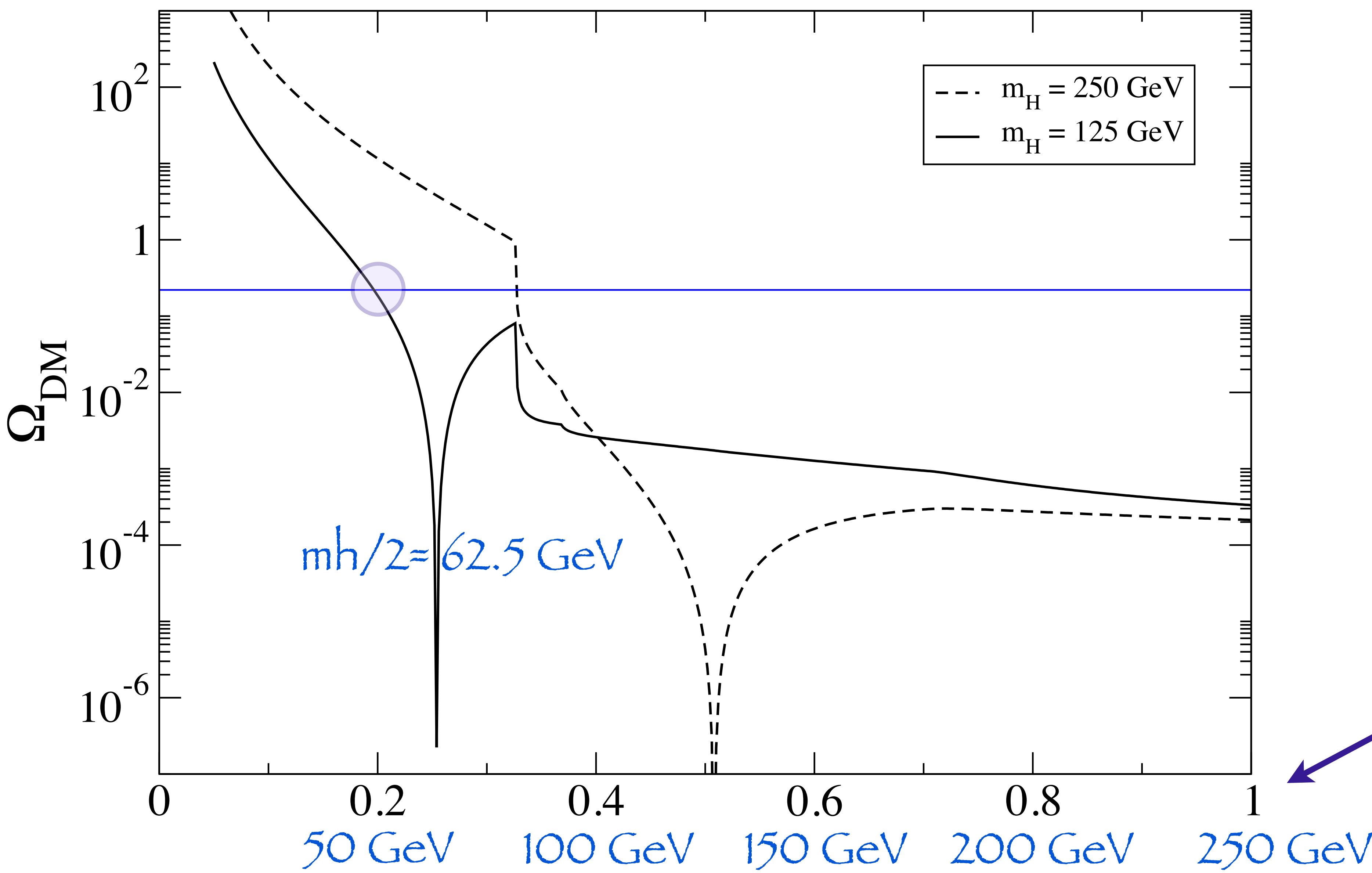


FIG. 8. $e^+e^- \to hh\nu_e\bar{\nu}_e$

Dark matter candidates : relic abundance





Espinosa and Quiros, PRD (2007)

mS > 80 GeV

$$\Omega_S/\Omega_{\rm DM} < 0.01$$

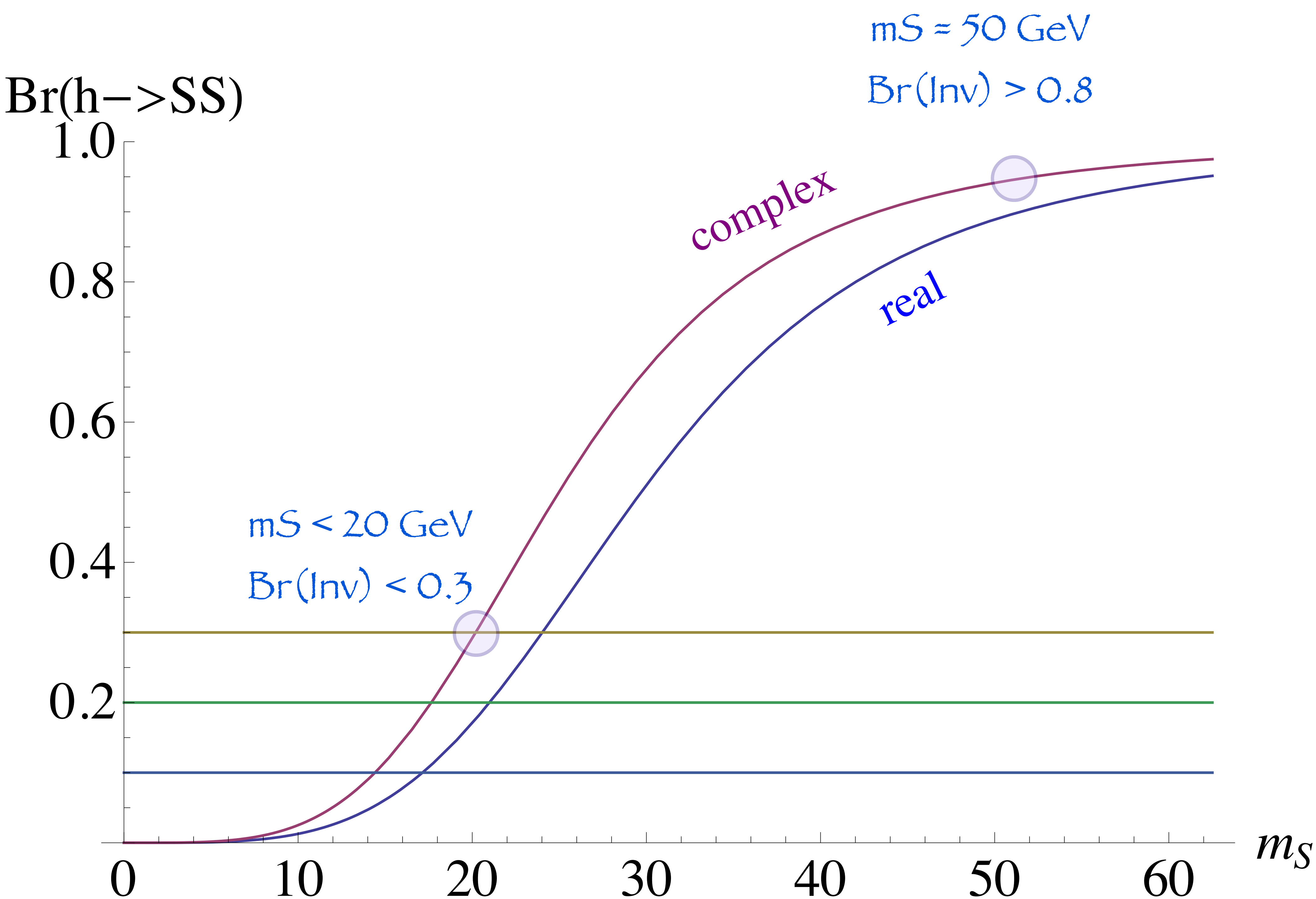
mS < 50 GeV

$$\Omega_S/\Omega_{\rm DM} > 1$$

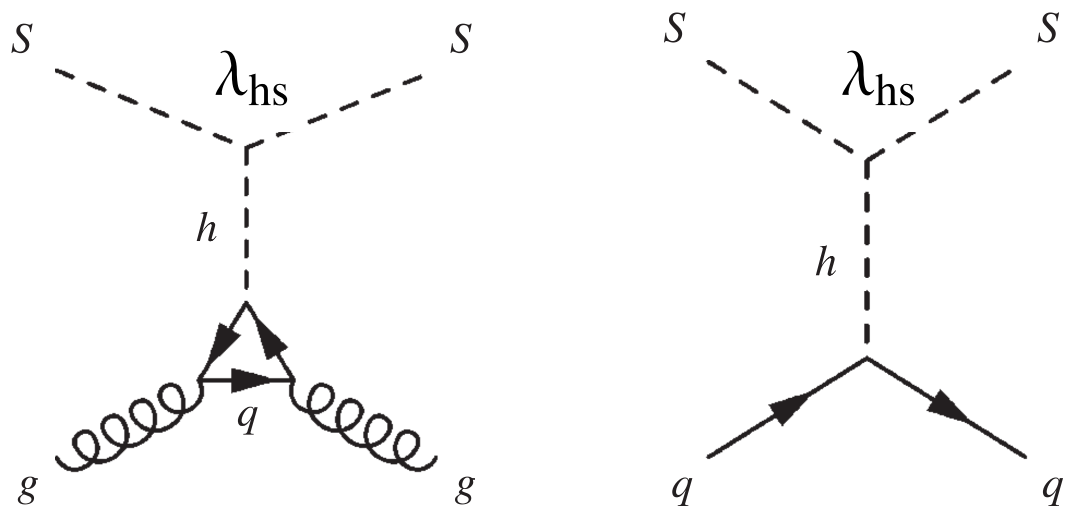
$$\zeta = \sqrt{\frac{\lambda_{hs}}{2}}$$

mS

Dark matter candidates : Higgs Invisible Width



Dark matter candidates : direct detection



S can be a subdominant component of dark matter

$$\tilde{\sigma}^{\rm SI}_{\rm DM} = \sigma^{\rm SI}_{\rm DM} \times \frac{\Omega_S h^2}{\Omega_{\rm DM-WMAP} h^2}$$

1 loop correction : 0.5

Still the direct detection rate is sizeable

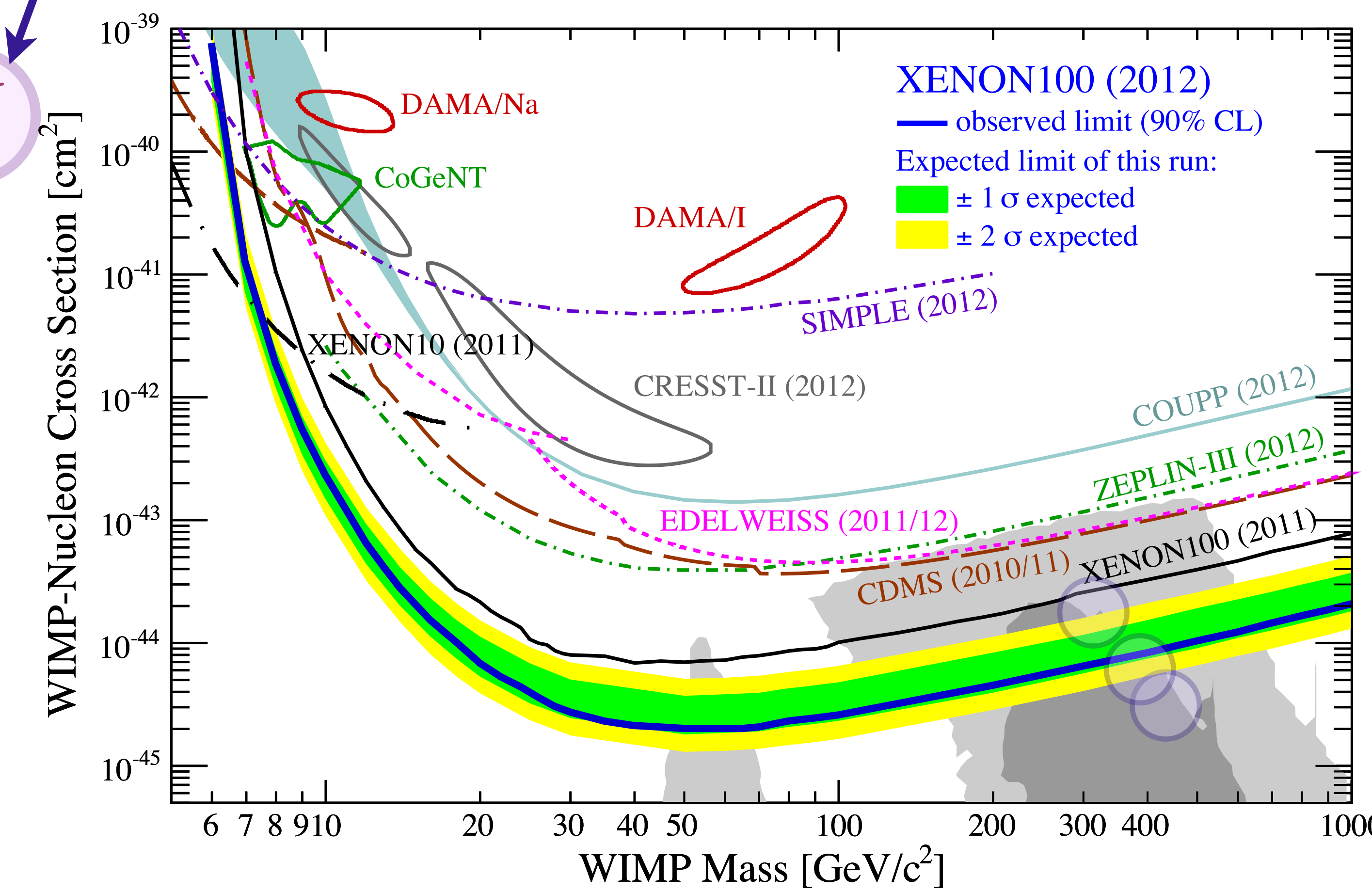
$$\tilde{\sigma}^{\rm SI}_{\rm DM} \simeq N_S \times 5 \times 10^{-45} cm^2 \times K$$

(mS > mh, independent of λ_{hs})

Ns=1 : mS=440 GeV

Ns=2 : mS=370 GeV

Ns=4 : mS=310 GeV



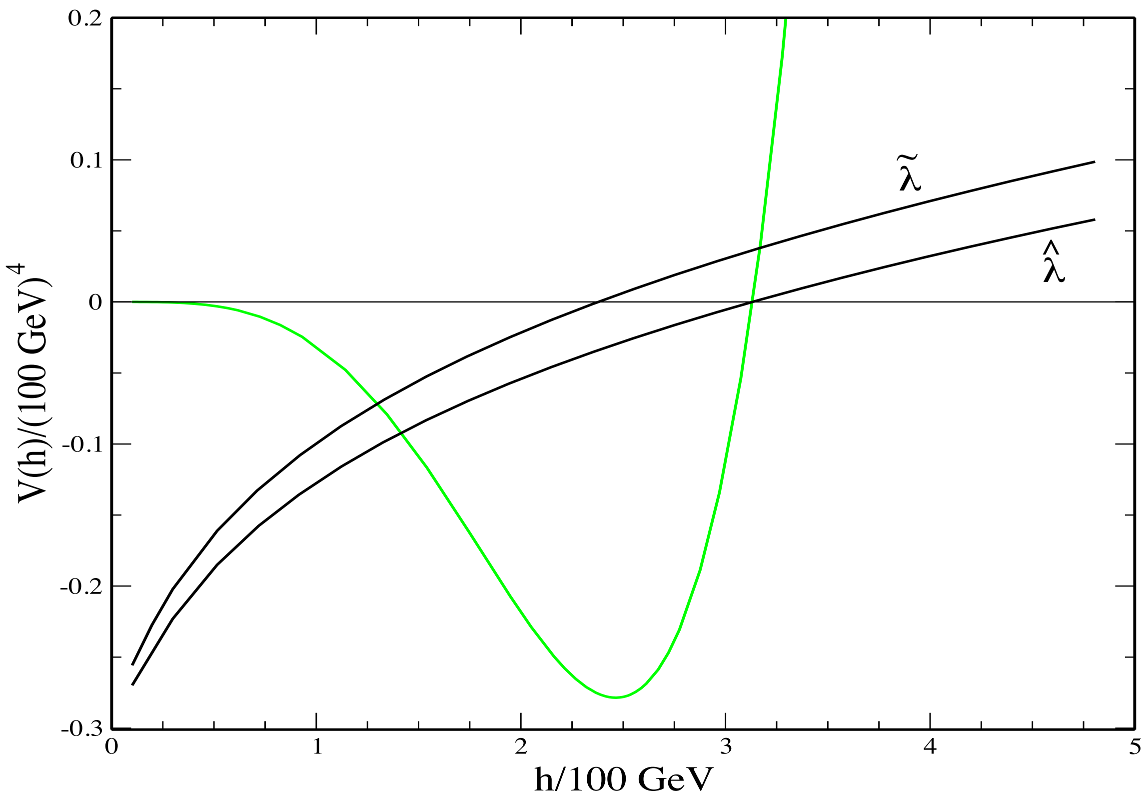
90% CL limit from XENON100(2012)

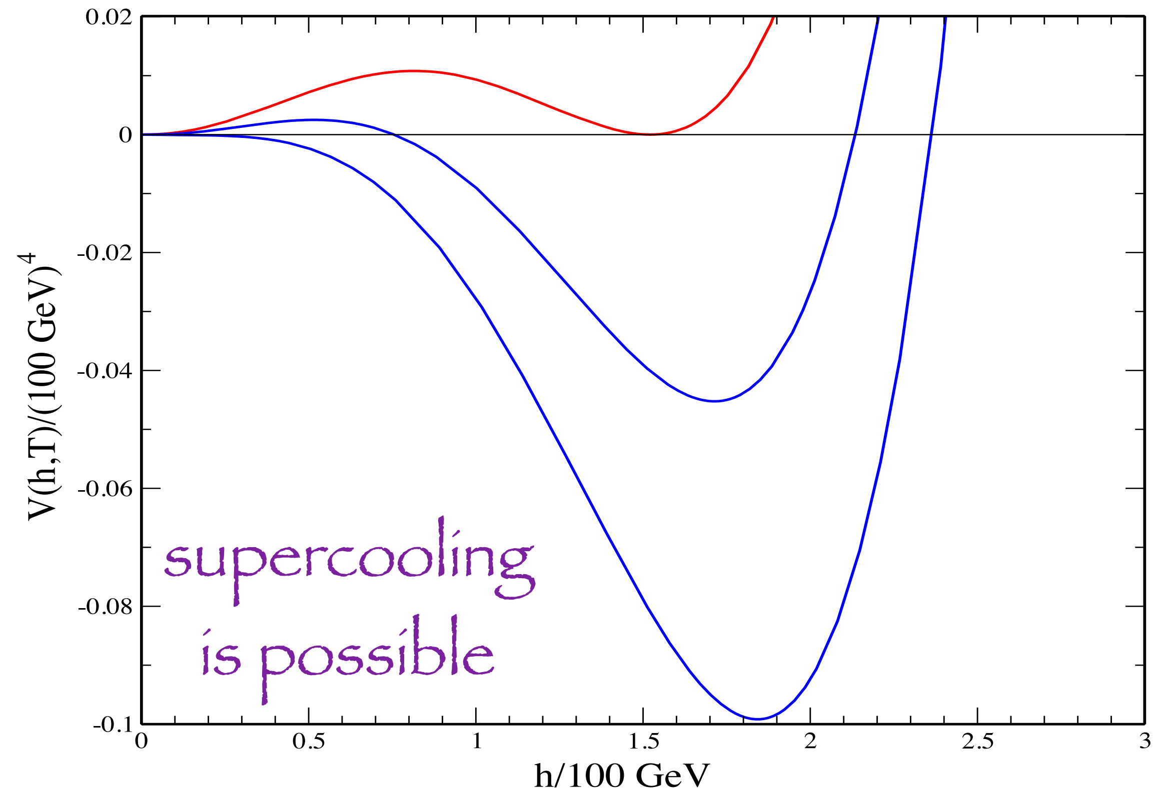
2*10^{-45} cm^2 at mass 55 GeV

10^{-44} cm^2 at mass 500 GeV

Electroweak Baryogenesis

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





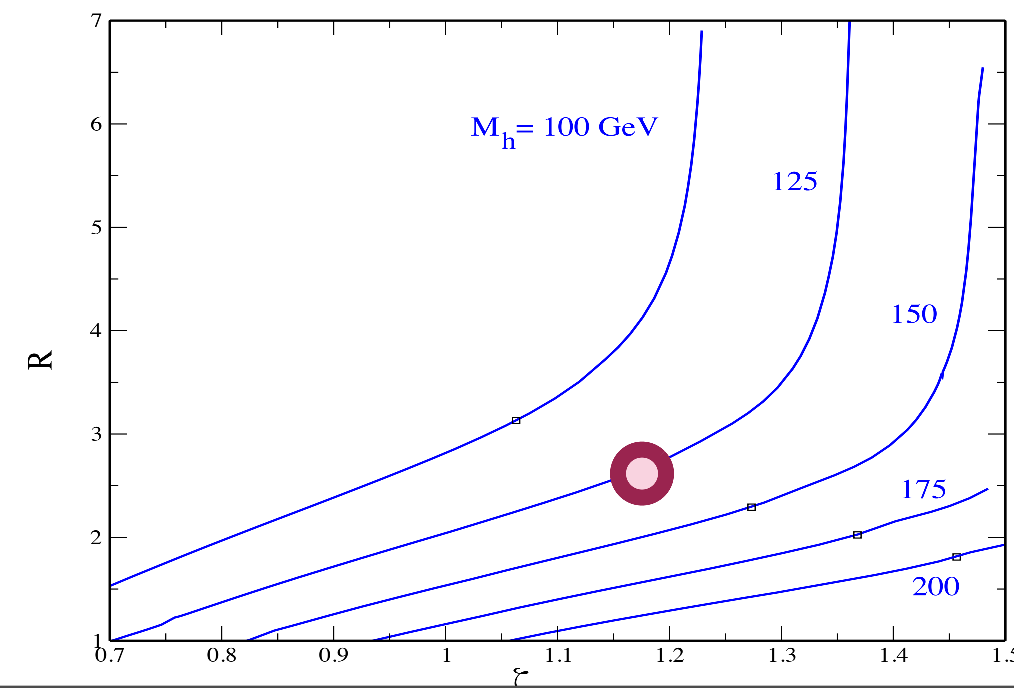
Higgs potential

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

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)



Conclusion

Yet no preference to specific Beyond the SM is given from LHC.

Beyond the SM is needed for dark matter and baryogenesis.

Radiative symmetry breaking is possible with singlet scalars.

→ Coleman-Weinberg Higgs (without mass term)

CW Higgs and SM Higgs can be distinguished by Higgs self coupling measurement at the LHC and the ILC.

Large direct detection rate of (several) subdominant dark matter would strongly indicate the Higgs portal scenario.

Electroweak baryogenesis works in this framework.