Higgs inflation :updates

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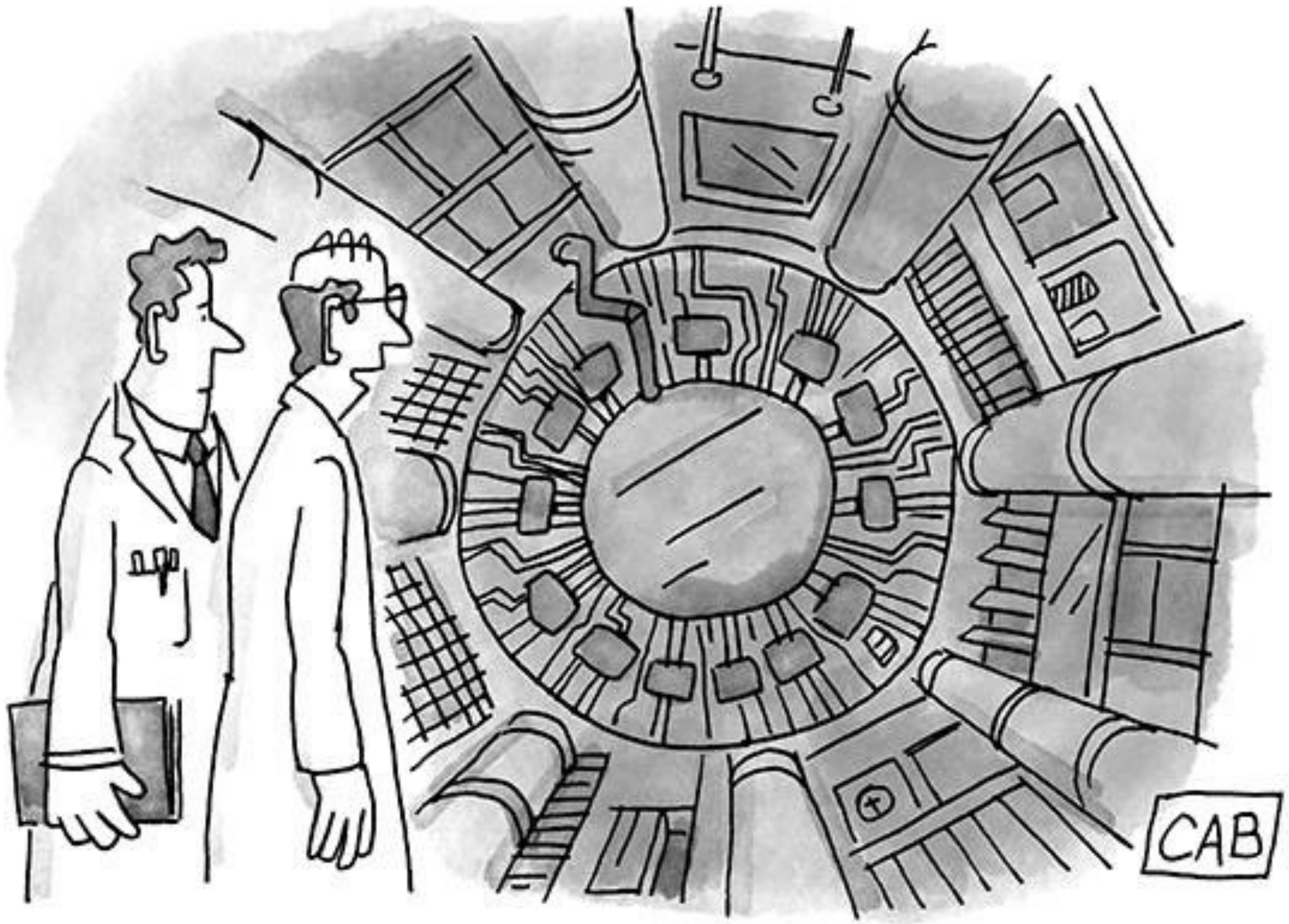
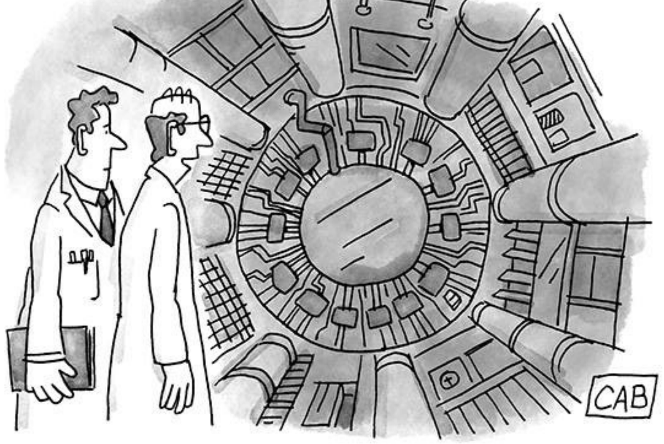


"Once you have a collider, every problem starts to look like a particle."



"Once you have a collider, every problem starts to look like a particle."

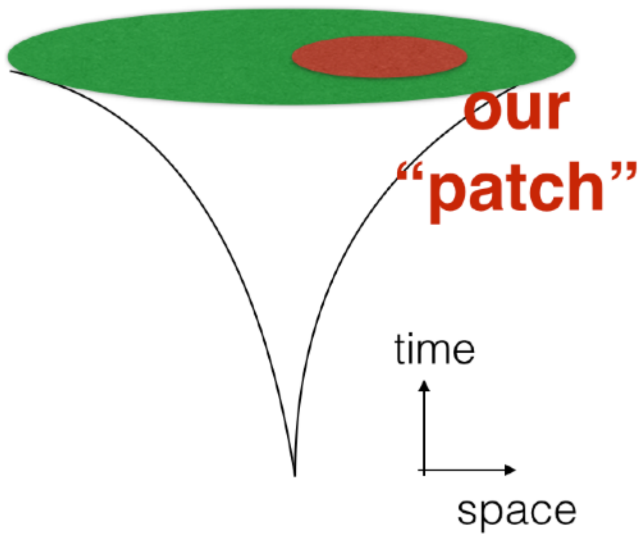
In particle physics, inflation takes place due to a scalar field

N.B. $A^M = (A_5, A^\mu) = (\phi, A^\mu)$

ex) Extra natural inflation [Arcani-Hamed et. al. (2003)]
Orbifold GUT inflation [SCP (2007)]

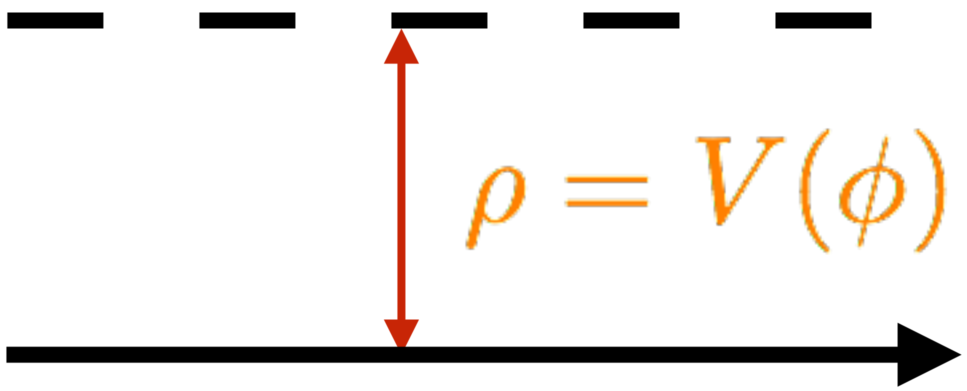
This is what we want: $a(t) = a_0 e^{H(t-t_0)}$

$$ds^2 = dt^2 - a(t)^2 d\vec{x} \cdot d\vec{x}$$



This is the equation: $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_p^2}$

It is realized if the potential is "flat"



"slow-roll conditions"

$$(V'/V)^2 \ll 1$$
$$V''/V \ll 1$$

(ex) $V = \lambda\phi^4, \lambda \sim 10^{-12}$

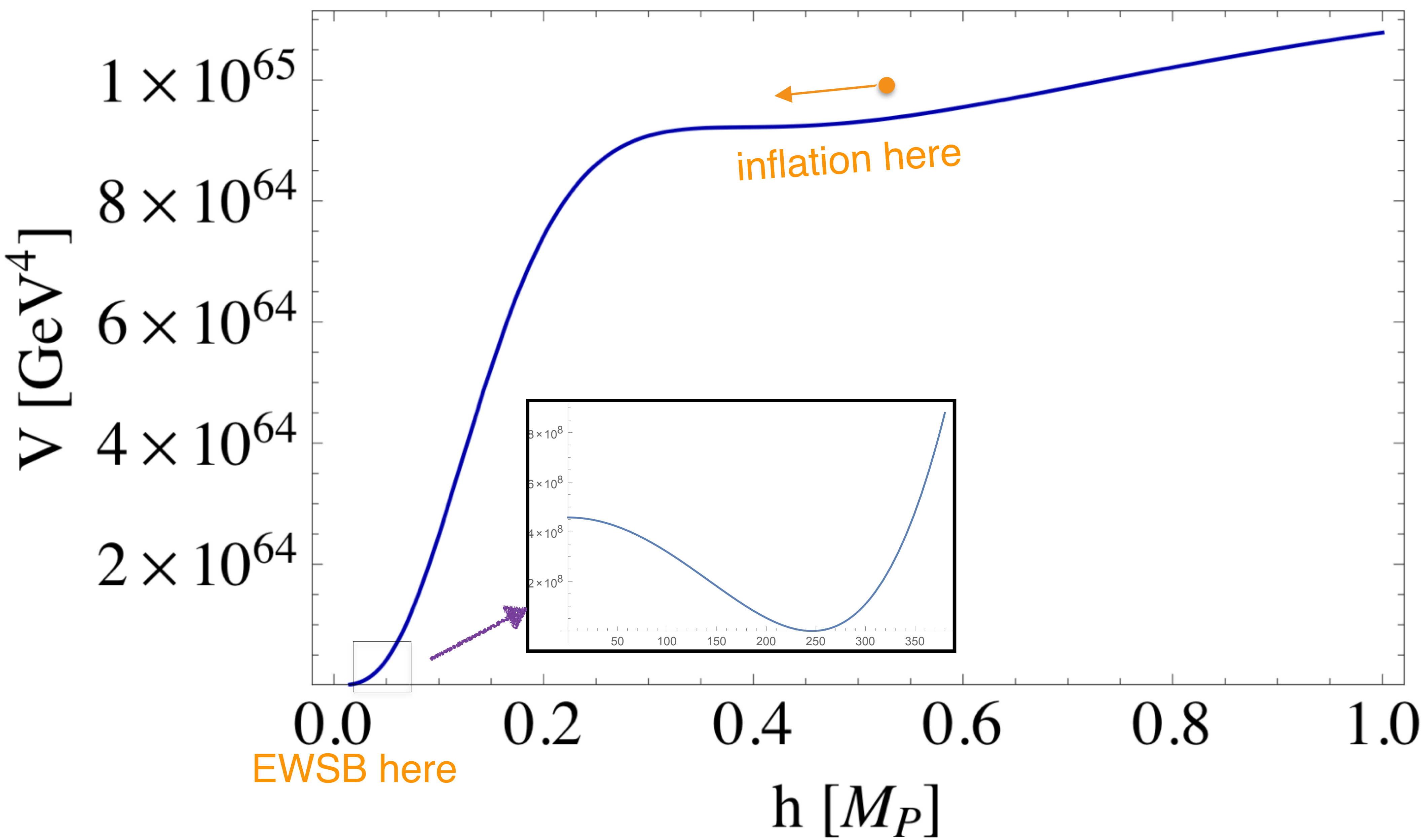
Higgs inflation

An economical and predictive idea

: The SM Higgs = Inflaton field

- at low scale (~100 GeV) responsible for EWSB
- at high scale (~10^{17} GeV) responsible for cosmic inflation

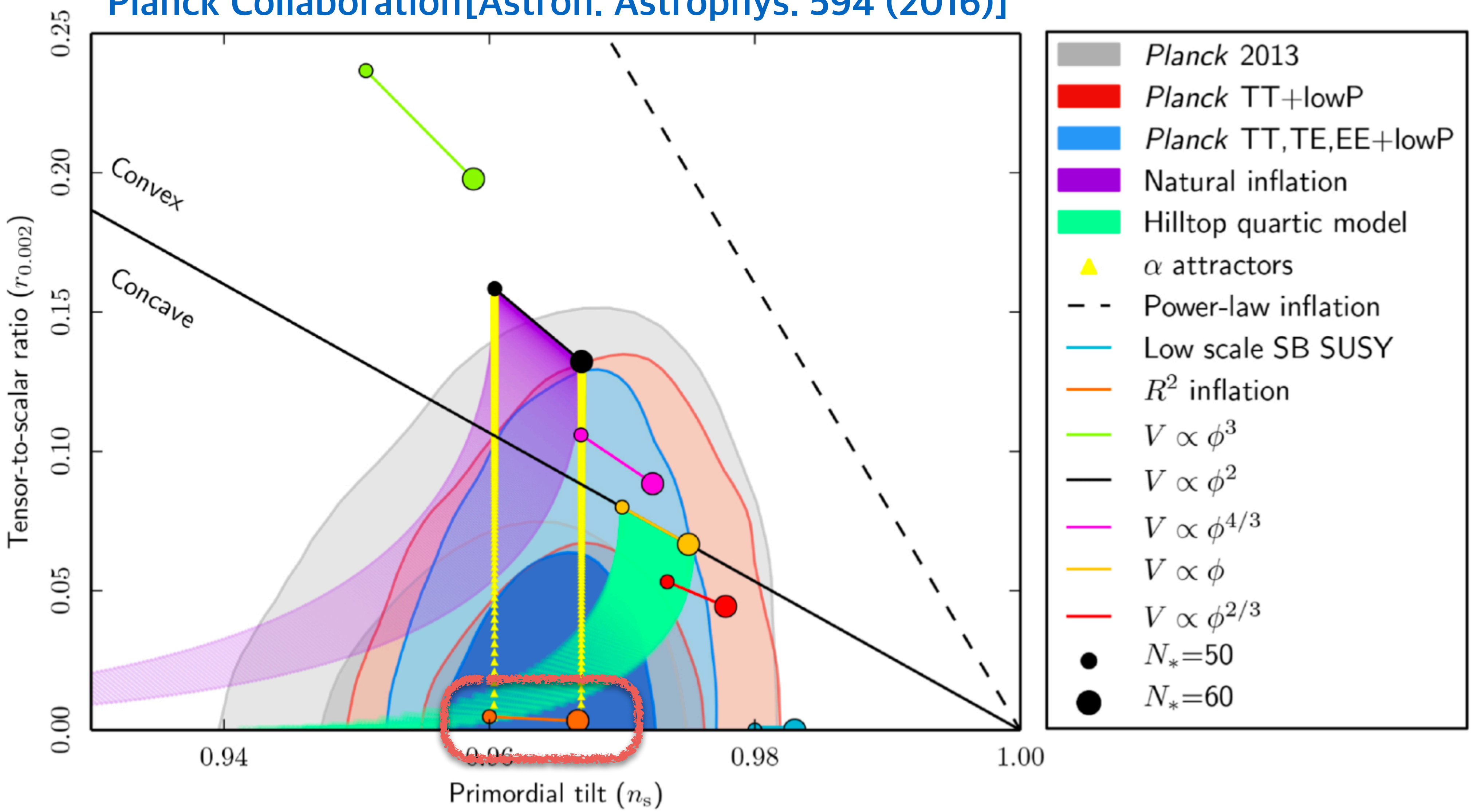
Higgs potential
with RG running and with |H|² R term



- Reheating process is built-in due to the Higgs Decay (as checked by LHC) :-)
- Link EW scale physics to cosmology!

(the best) fit to the 'DATA'

Planck Collaboration[Astron. Astrophys. 594 (2016)]



R² inflation
=Higgs inflation

plan

- Higgs in the SM —status review
- Higgs inflation with RGE
- Discussions on consistency and further implications
- (+one more thing)

The SM_N

- Local gauge symmetry $SU(3) X SU(2) X U(1)_Y$ with Higgs mechanism => $SU(3) X U(1)_{em}$ in broken phase
- N-generations of Weyl spinors: {Q,U,D,L,E,(n)} X N
- Quiz) how many free parameters?

Free parameters in SM_N

- Total (N^2+N+6) free parameters (+ neutrino masses and mixings)
    - ★ gauge couplings (g_3, g_2, g_1) : 3
    - ★ Higgs self coupling + VEV : 2
    - ★ Fermion masses : (2N +N)
    - ★ N(N-1)/2 mixing angles + (N-1)(N-2)/2 complex phases
- N=3 (4th chiral gen. ruled out by the LHC), 18 in total
- 17 known before the LHC

The Higgs potential

$$V(H) = \lambda \left(H^\dagger H - v^2/2\right)^2$$

$$H = \begin{pmatrix} \phi^+ \\ \frac{v+h+i\phi^0}{\sqrt{2}} \end{pmatrix}$$

Lorentz scalar (s=0)
(1,2,1/2) of SU(3)XSU(2)XU(1)

The Higgs potential

$$V(H) = \lambda \left(H^\dagger H - v^2/2\right)^2$$

The most general renormalizable potential with a Tachynonic mass

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(1,2,1/2) of SU(3)XSU(2)XU(1)

The Higgs potential

$$V(H) = \lambda \left(H^\dagger H - v^2/2\right)^2$$

The most general renormalizable potential with a Tachynonic mass

Only two parameters

$$H = \begin{pmatrix} \phi^+ \\ \frac{v+h+i\phi^0}{\sqrt{2}} \end{pmatrix}$$

Lorentz scalar (s=0)
(1,2,1/2) of SU(3)XSU(2)XU(1)

Vacuum expectation value

$$m_W^2 = \frac{g^2 v^2}{4}, \quad m_Z^2 = \frac{(g'^2 + g^2) v^2}{4}$$

$$v = \left(\sqrt{2} G_F\right)^{-1/2} \approx 246 \mathrm{GeV}$$

known since 1970s

The self coupling

the last piece of information within the SM

$$\lambda = \frac{m_h^2}{2v^2} \approx \frac{1}{8}$$

LHC (2012)

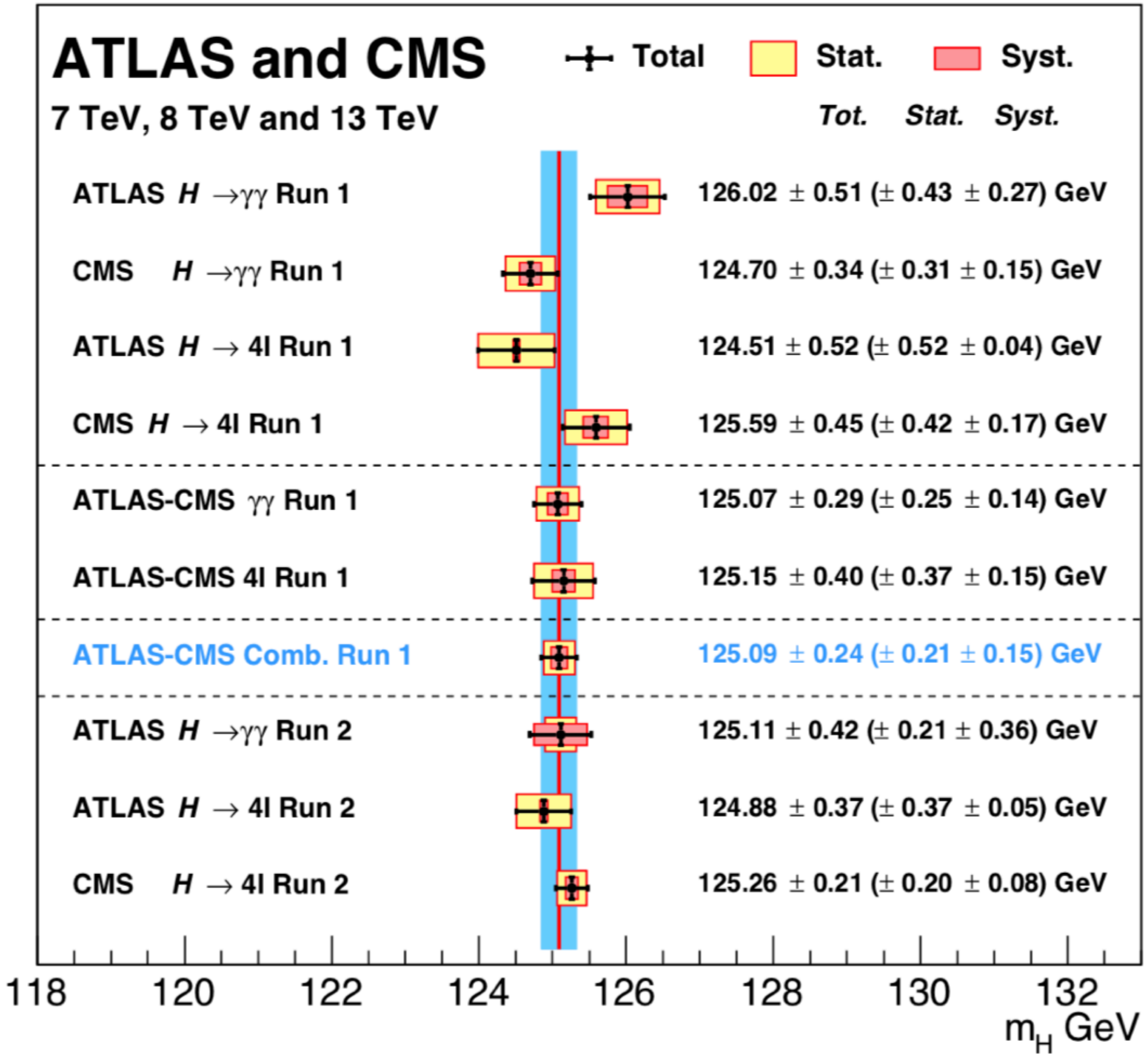
$$m_H = 125.03^{+0.26}_{-0.27}(\text{stat})^{+0.13}_{-0.15}(\text{syst})$$

CMS PAS HIG-14-009

$$m_H = 125.36 \pm 0.37(\text{stat.}) \pm 0.18(\text{syst.})\text{GeV}$$

ATLAS arXiv:1406.3827

The Higgs mass



C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

The SM Higgs potential

$$V(h) = \frac{1}{2}(125\mathrm{GeV})^2 h^2 + \frac{1}{8}(246\mathrm{GeV}) h^3 + \frac{1}{32} h^4$$

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$$\lambda v^2 = \frac{m_h^2}{2}$$

measured

The SM Higgs potential

$$V(h) = \frac{1}{2}(125\text{GeV})^2 h^2 + \frac{1}{8}(246\text{GeV}) h^3 + \frac{1}{32} h^4$$

$$\lambda v^2 = \frac{m_h^2}{2} \qquad \lambda v$$

measured predicted

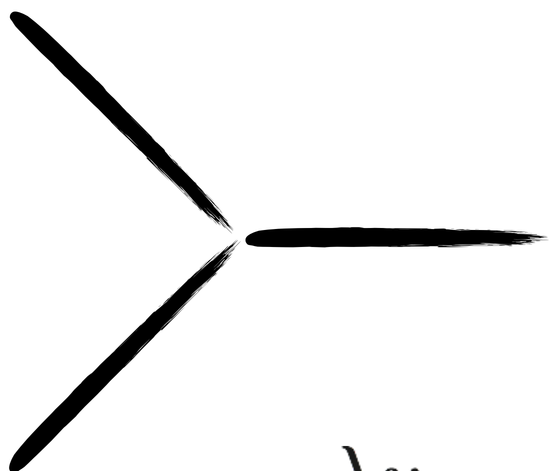
The SM Higgs potential

$$V(h) = \frac{1}{2}(125\mathrm{GeV})^2 h^2 + \frac{1}{8}(246\mathrm{GeV}) h^3 + \frac{1}{32} h^4$$

$$\lambda v^2 = \frac{m_h^2}{2} \qquad \lambda v \qquad \frac{\lambda}{4}$$

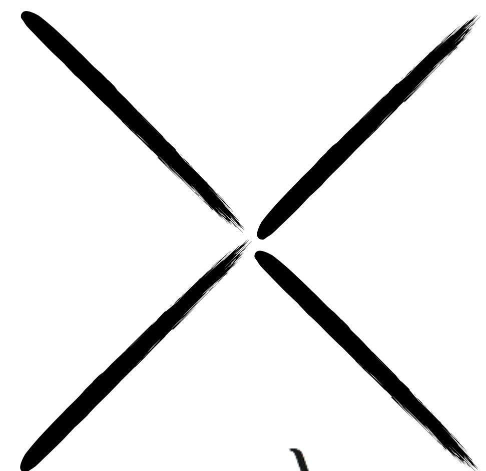
measured — predicted — predicted

HIGGS SELF INTERACTIONS



h-h-h

$$= \frac{\lambda v}{2}$$



h-h-h-h

$$= \frac{\lambda}{4}$$

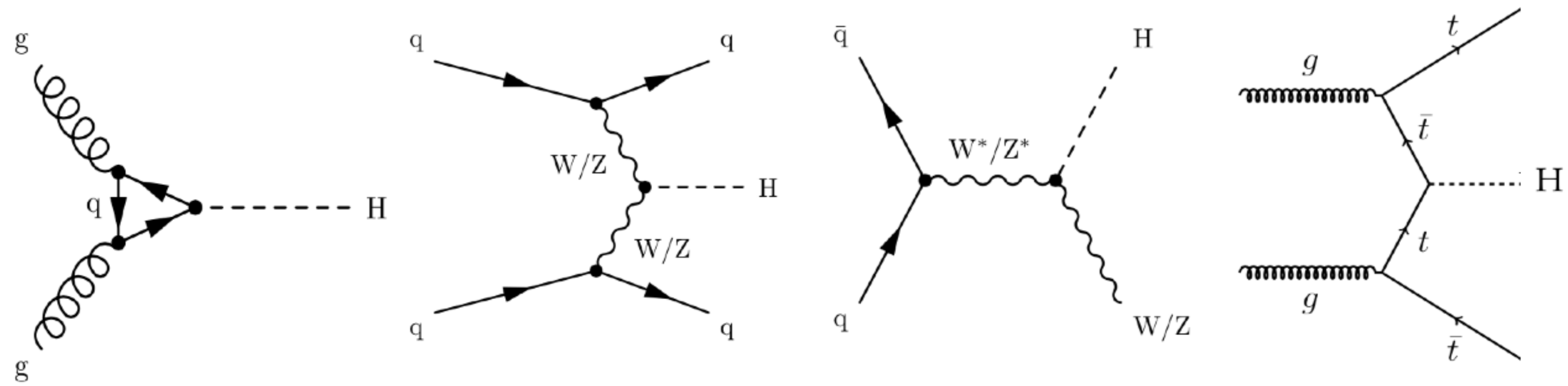
measured+predicted

predicted

Theorists can make models predicting deviations (New physics).

These are good topics for future colliders such as ILC or CEPC …

Observed Higgs-other particle interactions

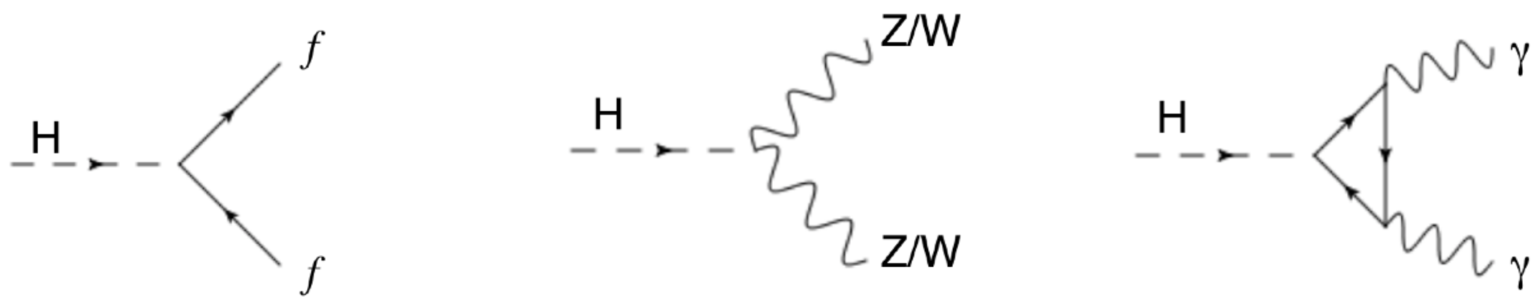


Gluon fusion
ggH (19pb)

Vector Boson Fusion
VBF (1.6pb)

VH (1.1pb)

ttH (0.1pb)



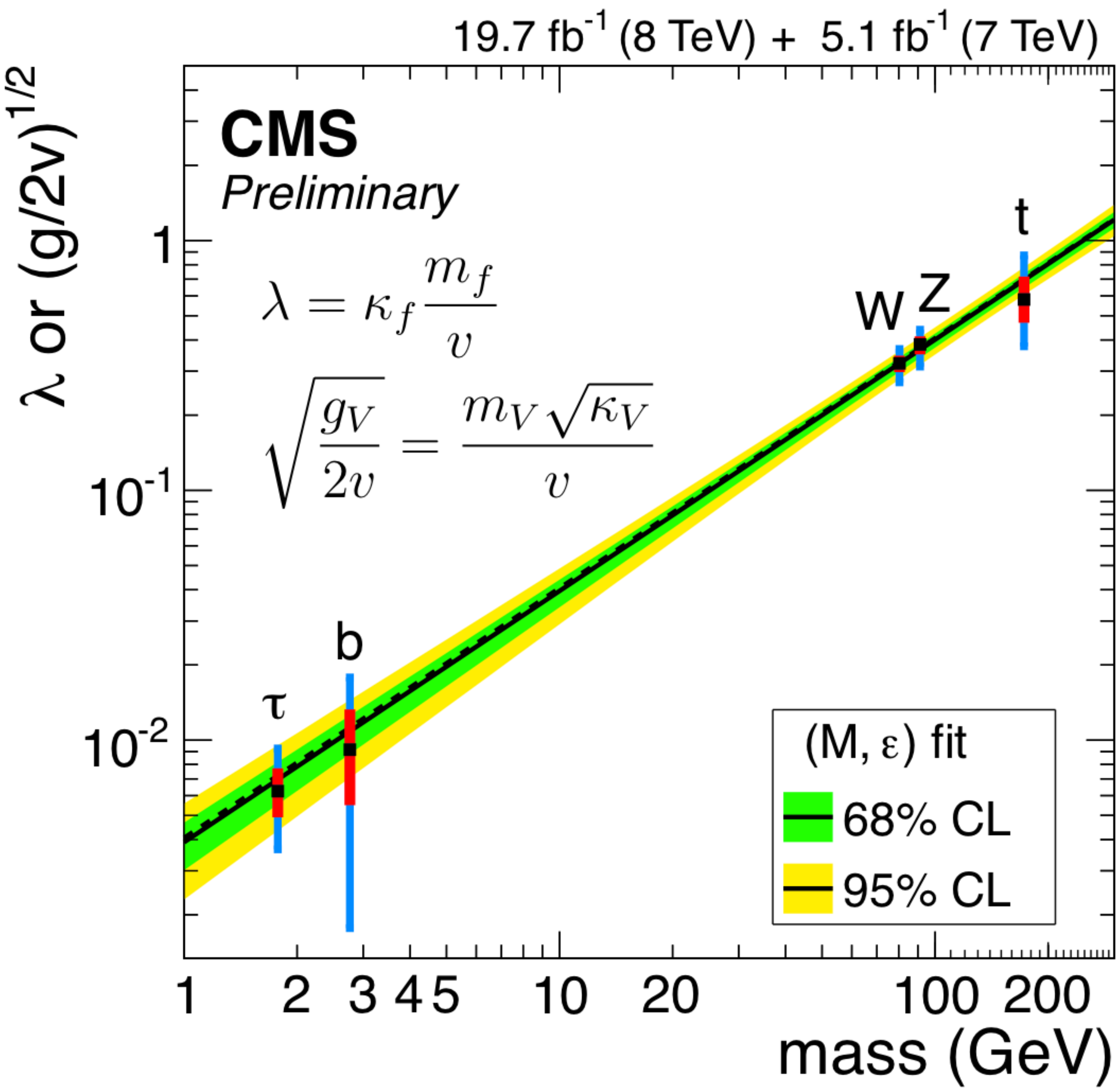
bb (58%)
ττ (6.3%)

WW (21.5%)
ZZ (2.6%)

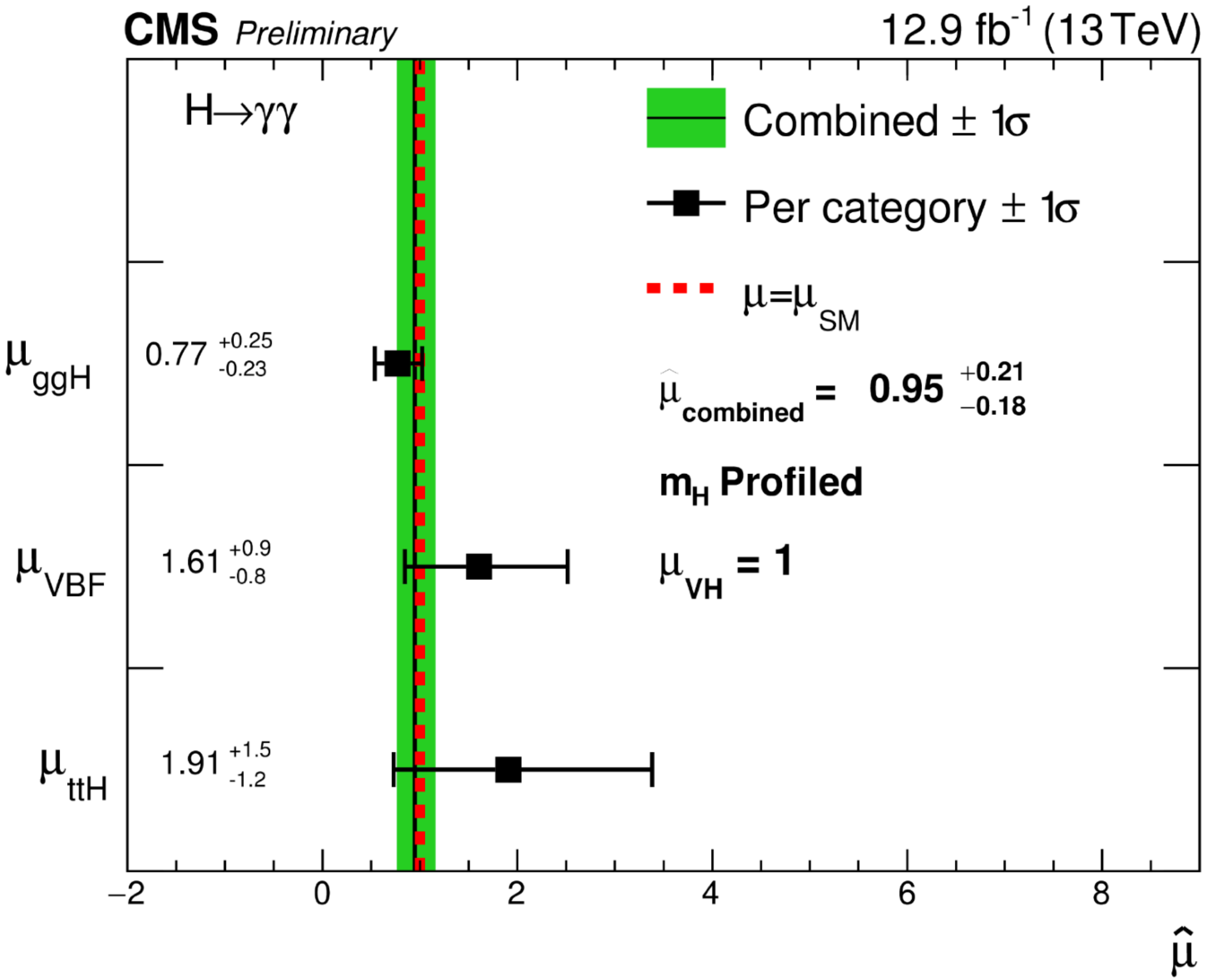
γγ (0.2%)

- Higgs couplings with gauge bosons and some fermions are observed through several processes (indirectly/directly)

All are consistent with the SM



consistent with the SM (LHC Run-2)



The observed Decay pattern of the Higgs is consistent with the SM

$$\mu = \frac{N_{exp}}{N_{theory}}$$

$$\mu = 1.09 \pm 0.07\ (\mathrm{stat})\ \pm 0.04\ (\mathrm{expt})\ \pm 0.03\ (\mathrm{th.\,bkg})\ \pm 0.07\ (\mathrm{th.\,sig})$$

Confidently, we can tell that the observed Higgs is very very close to the SM Higgs!

C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

Beyond the collider energies?

- Let's be more ambitious and ask even more extrapolation of our knowledge further.

- **Q. What's role of the Higgs at very early era of universe, e.g., at the inflationary era?**

- To answer the question, we need to understand high energy & Large field behavior of the Higgs potential.

High energy behavior

- In principle, we can 'calculate' everything $E < \Lambda_{SM}$
- $\Lambda_{SM} > \text{TeV}$, LHC
- $\Lambda_{SM} \sim M_P$, in principle (Don't forget renormalizability!)
- We may be able to see physics **near the Planck energy** assuming that the SM is good (which is not likely though).

Higgs + Gravity

non-minimal coupling

Grav. Mass

Kin. of Higgs
(gauge-Higgs interaction)

$$S_{Higgs} = \int d^4x \left(\frac{M^2 + \xi |H|^2}{2} R + |D_\mu H|^2 - V(H) \right)$$

Ricci curvature
~1/L²
~M²

Pot. of Higgs

Higgs + Gravity

$$V(H) = \lambda \left(|H|^2 - v^2/2\right)^2$$

$$S = \int d^4x \sqrt{g} \left[\frac{M_P^2 + \xi |H|^2}{2} R + |DH|^2 - V(H) + \mathcal{L}_{\rm SM} \right]$$

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- ‘**non-minimal coupling** term’ Dim=4 term (indeed minimally coupled in Einstein frame) is introduced.

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- There could be more terms ~ **$O(4+n)/\Lambda^{n\geq 1}$** w/ strengths to be determined by future experiments or underlying theory you assume.

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- Below, $\mathbf{\Lambda}$, those terms may be neglected.

Non-minimally coupled gravity and chaotic inflation

without RG effect

[T. Futamase, K. Maeda, PRD(1989)]

$$S = \int d^4x\sqrt{-g}\left(\frac{M^2-\xi\phi^2}{2}R + (\partial_\mu\phi)^2 - V(\phi)\right)$$

TABLE I. Chaotic inflationary scenario with a nonminimally coupled scalar. Inflation is realized for "Yes," but not for "No."

ξ (non-minimal) (minimal)	$V=\frac{1}{4}\phi^4$	$V=\frac{1}{2}m^2\phi^2$
$\xi<0$	Yes	No unless $\lvert\xi\rvert\lesssim 10^{-3}$
$\xi=0$	Yes	Yes
$0<\xi<\frac{1}{6}$	Yes if $\xi\lesssim 10^{-8}$	Yes if $\xi\lesssim 10^{-12}$
	Possible but unnatural	Possible but unnatural
(conformal)	if $10^{-8}<\xi\lesssim 10^{-3}$	if $10^{-8}<\xi$
	No if $\xi\gtrsim 10^{-3}$	No if $\xi\gtrsim 10^{-3}$
$\xi=\frac{1}{6}$	No	No
$\xi>\frac{1}{6}$	No	No

Inflation with V=K^2

[SCP, S. Yamaguchi JCAP (2008)]

without RG effect

$$S = \int d^4x \sqrt{-g} \left(\frac{M^2 + K(\phi)}{2} R + (\partial_\mu \phi)^2 - V(\phi) \right)$$

General condition for flat potential at a large field limit:

$$\lim_{\phi \to \infty} \frac{V(\phi)}{K(\phi)^2} = Const. > 0$$

“attractor”!

(ex) monomial functions $K(\phi) = \xi \phi^n, V(\phi) = \lambda \phi^{2n}$

n=2 corresponds to ‘Higgs inflation’

Einstein frame

Bezrukov, Shaposhnikov (2008) for K(phi)=xi phi^2
SCP, Yamaguchi (2008) for general K(phi)

$$S_J = \int d^4x\sqrt{g}\left[\frac{M^2+K(\phi)}{2}R + |DH|^2 + V(H)\right]$$

$$g_{\mu\nu} \to g^E_{\mu\nu} = e^{2\omega} g_{\mu\nu}$$

$$e^{2\omega} = \frac{M^2+K}{M_P^2}$$

$$V_E = \frac{M_P^4}{(M^2+K)^2} V_J$$

$$\frac{\partial H_E}{\partial H_J} = \sqrt{e^{-2\omega} + \frac{3}{2} e^{2\omega} K'^2}$$

$$S_E = \int d^4x\sqrt{g_E}\left[\frac{M_P^2}{2}R_E + |DH_E|^2 - V(H_E)\right]$$

Einstein frame

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for Higgs inflation:

$$V_J = \lambda H_J^4, K = \xi H_J^2$$

Einstein frame

Bezrukov, Shaposhnikov (2008) for K(phi)=xi phi^2
SCP, Yamaguchi (2008) for general K(phi)

$$S_J = \int d^4x\sqrt{g}\left[\frac{M^2+K(\phi)}{2}R + |DH|^2 + V(H)\right]$$

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for Higgs inflation: $V_J = \lambda H_J^4, K = \xi H_J^2$ -> $V_E \to \frac{\lambda}{\xi^2} M_P^4$

Einstein frame

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$$g_{\mu\nu} \to g^E_{\mu\nu} = e^{2\omega} g_{\mu\nu}$$

$$e^{2\omega} = \frac{M^2 + K}{M_P^2}$$

$$V_E = \frac{M_P^4}{(M^2 + K)^2} V_J$$

$$\frac{\partial H_E}{\partial H_J} = \sqrt{e^{-2\omega} + \frac{3}{2} e^{2\omega} K'^2}$$

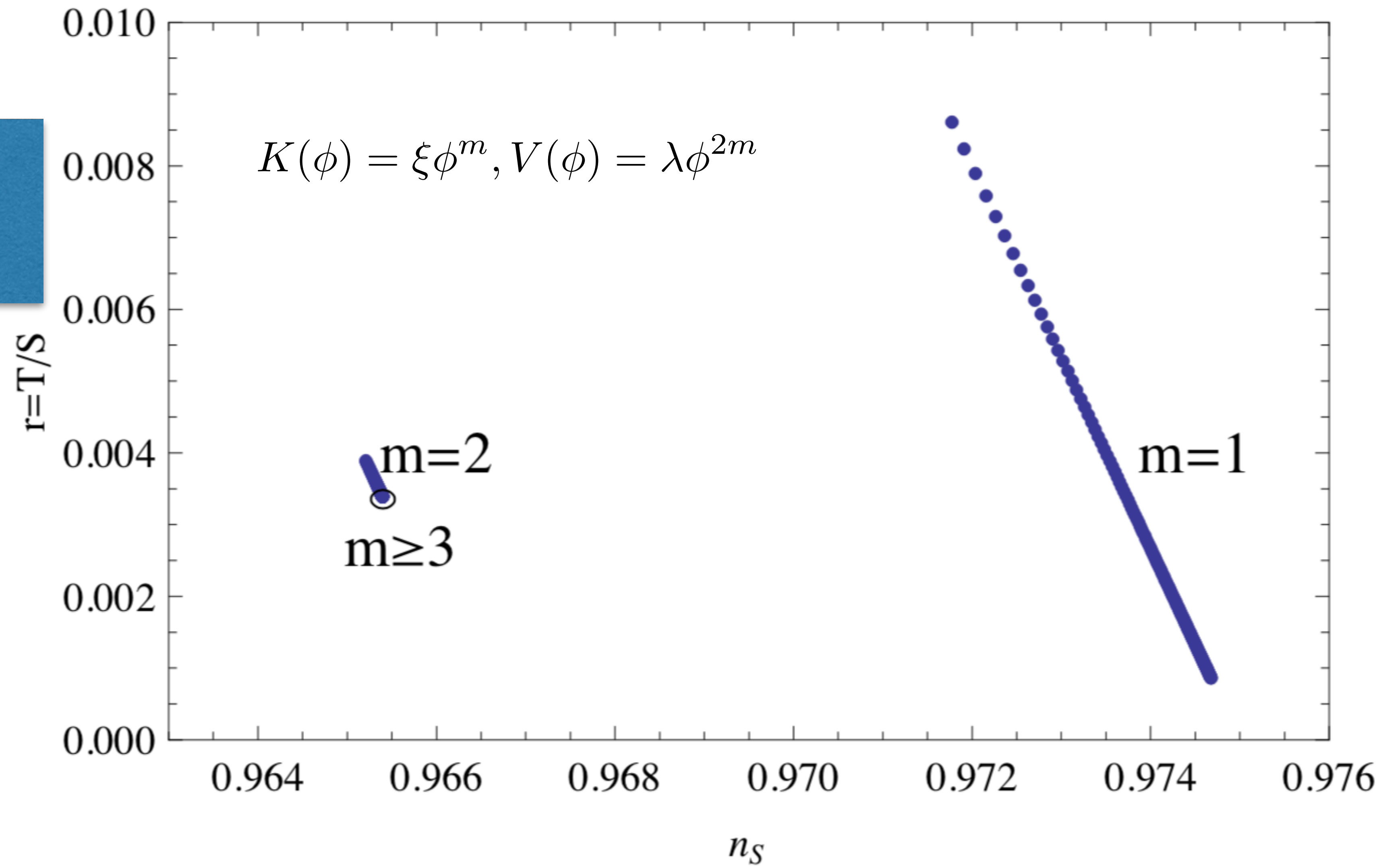
$$S_E = \int d^4x \sqrt{g_E} \left[\frac{M_P^2}{2} R_E + |DH_E|^2 - V(H_E) \right]$$

flat potential

for Higgs inflation: $V_J = \lambda H_J^4, K = \xi H_J^2$ -> $V_E \to \frac{\lambda}{\xi^2} M_P^4$

without RG effect

[SCP, S. Yamaguchi JCAP (2008)]



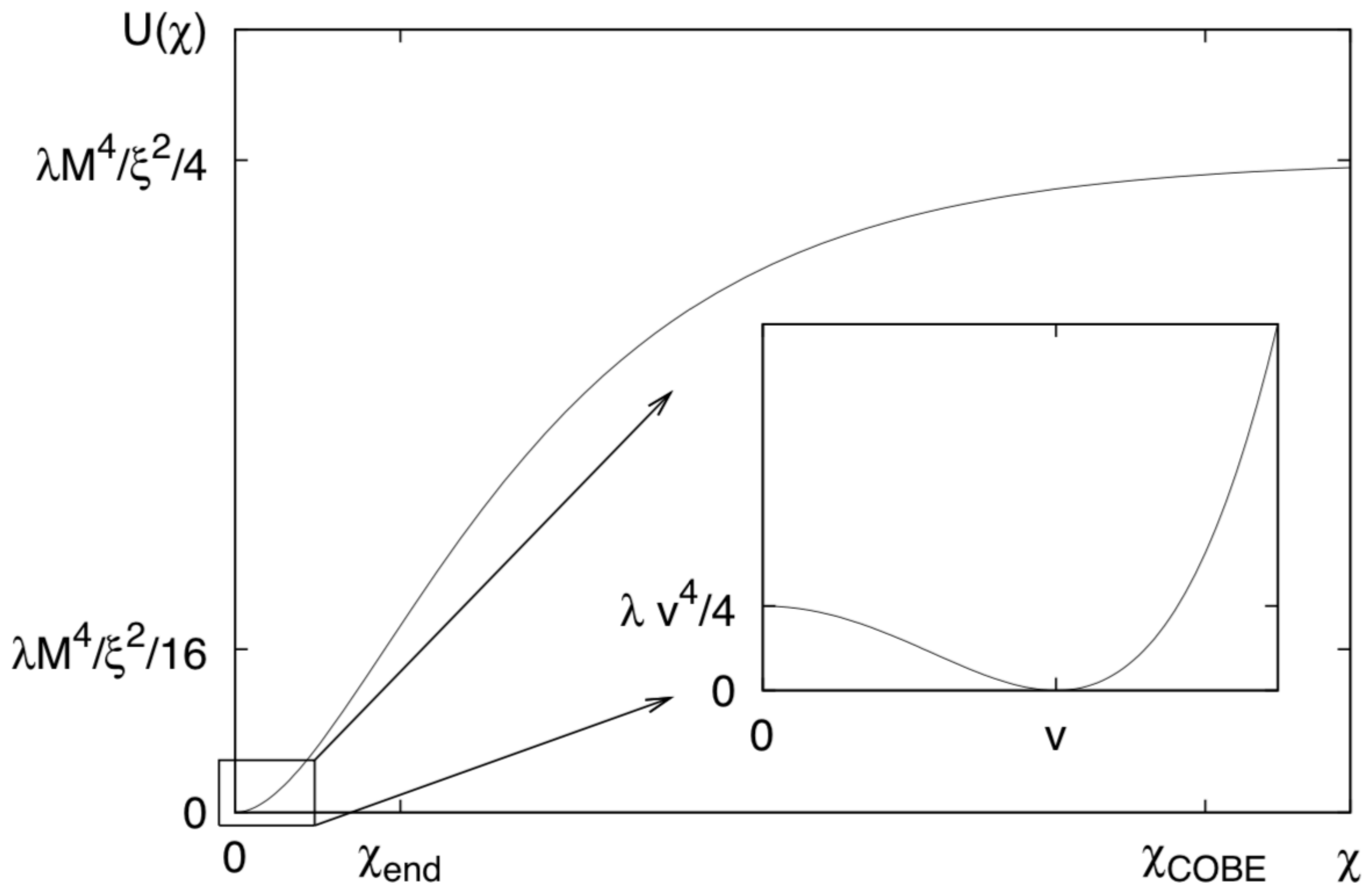
$$n_s = \begin{cases} 1 - \frac{3}{2a_0 N^{3/2}} - \frac{3}{2N}, & (m=1) \\ 1 - \frac{9(1+1/(6a_0))}{2N^2} - \frac{2}{N}, & (m=2) \\ 1 - \frac{9}{2N^2} - \frac{2}{N}, & (m \geq 3) \end{cases}, \qquad r = \begin{cases} \frac{4}{a_0 N^{3/2}}, & (m=1) \\ \frac{12(1+1/(6a_0))}{N^2}, & (m=2) \\ \frac{12}{N^2}, & (m \geq 3) \end{cases}$$

Higgs inflation

without RG effect

[Bezrukov, Shaposhnikov, PLB(2008)]

$$S = \int d^4x \sqrt{-g} \left(\frac{M^2}{2} R + \xi H^\dagger H R + \lambda \left(H^\dagger H - v^2/2 \right)^2 + \cdots \right)$$



COBE normalization

without RG effect

$$\frac{U}{\epsilon} = (0.027 M_{\rm Pl})^4 \quad \Longrightarrow \quad \frac{\lambda}{\xi^2} \approx 10^{10}$$

or $\lambda \sim 1, \xi \sim 10^5$

$$\mathcal{L}_G \ni \frac{M_P^2 + 10^5 \times \phi^2}{2} R + \cdots$$

DOES NOT LOOK GOOD :-(

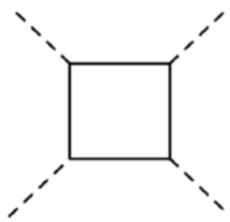
WAIT!

Who told you this? $\lambda \sim 1, \xi \sim 10^5$

Actually, when we take the **quantum** effect into account, the self coupling becomes small!

$$\lambda(100 \text{ GeV}) \approx 1/8 \to \lambda(\mu \gg 100 \text{ GeV}) \ll 1$$

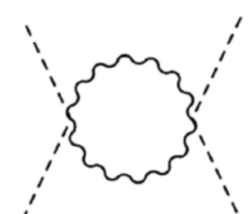
The RGE



self interaction

gauge interactions

$$(4\pi)^2 \frac{d\lambda}{d\ln\bar{\mu}^2} = -3y_t^4 + 6y_t^2\lambda + 12\lambda^2 + \frac{9}{16}\left(g_2^4 + \frac{2}{5}g_2^2 g_1^2 + \frac{3}{25}g_1^4\right) - \frac{9}{2}\lambda\left(g_2^2 + \frac{g_1^2}{5}\right) + \cdots$$



Top quark Yukawa coupling

gauge & self interactions

$$y_t = \frac{\sqrt{2}m_t}{v} = \frac{\sqrt{2}\cdot 172}{246} \approx 0.98$$

Top quark mass

t-Quark Mass (Direct Measurements)

The following measurements extract a t-quark mass from the kinematics of $t\bar{t}$ events. They are sensitive to the top quark mass used in the MC generator that is usually interpreted as the pole mass, but the theoretical uncertainty in this interpretation is hard to quantify. See the review "The Top Quark" and references therein for more information.

OUR AVERAGE of 173.1 ± 0.6 GeV is an average of top mass measurements from LHC and Tevatron Runs. The latest Tevatron average, 174.30 ± 0.35 ± 0.54 GeV, was provided by the Tevatron Electroweak Working Group (TEVEWWG).

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
173.1 ± 0.6 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.				
172.84 ± 0.34 ± 0.61	[1] AABOUD	16T	ATLS	combination of ATLAS
172.44 ± 0.13 ± 0.47	[2] KHACHATRY...	16AK	CMS	combination of CMS
174.30 ± 0.35 ± 0.54	[3] TEVEWWG	16	TEVA	Tevatron combination

• • • We do not use the following data for averages, fits, limits, etc. • • •

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

Top quark mass

PDG (2017 update)

m_t (GeV/c^2)	Source	$\int \mathcal{L}dt$	Ref.	Channel
$172.99 \pm 0.48 \pm 0.78$	ATLAS	4.6	[145]	ℓ+jets+$\ell\ell$
$172.44 \pm 0.13 \pm 0.47$	CMS	19.7	[146]	ℓ+jets+$\ell\ell$+All jets
$172.35 \pm 0.16 \pm 0.48$	CMS	19.7	[146]	ℓ+jets
$172.22 \pm 0.18^{+0.89}_{-0.93}$	CMS	19.7	[152]	$\ell\ell$
$173.72 \pm 0.55 \pm 1.01$	ATLAS	20.2	[158]	All jets
$172.25 \pm 0.08 \pm 0.62$	CMS	35.9	[159]	ℓ+jets
$174.30 \pm 0.35 \pm 0.54$	CDF,DØ (I+II)	$\leq$9.7	[174]	publ. or prelim.
$173.34 \pm 0.27 \pm 0.71$	Tevatron+LHC	$\leq$8.7+$\leq$4.9	[2]	publ. or prelim.

(new) 'smallish' — rows above the dashed line

$m_t(center) = 173.1$

(old) 'largish' — rows below the dashed line

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

Is Higgs vacuum unstable?

- Some of us say that "the Standard Model Higgs potential develops an instability at a scale of the order of 10^{11} GeV"

- This statement is true only when you take 'the current central values of the Higgs and top masses'

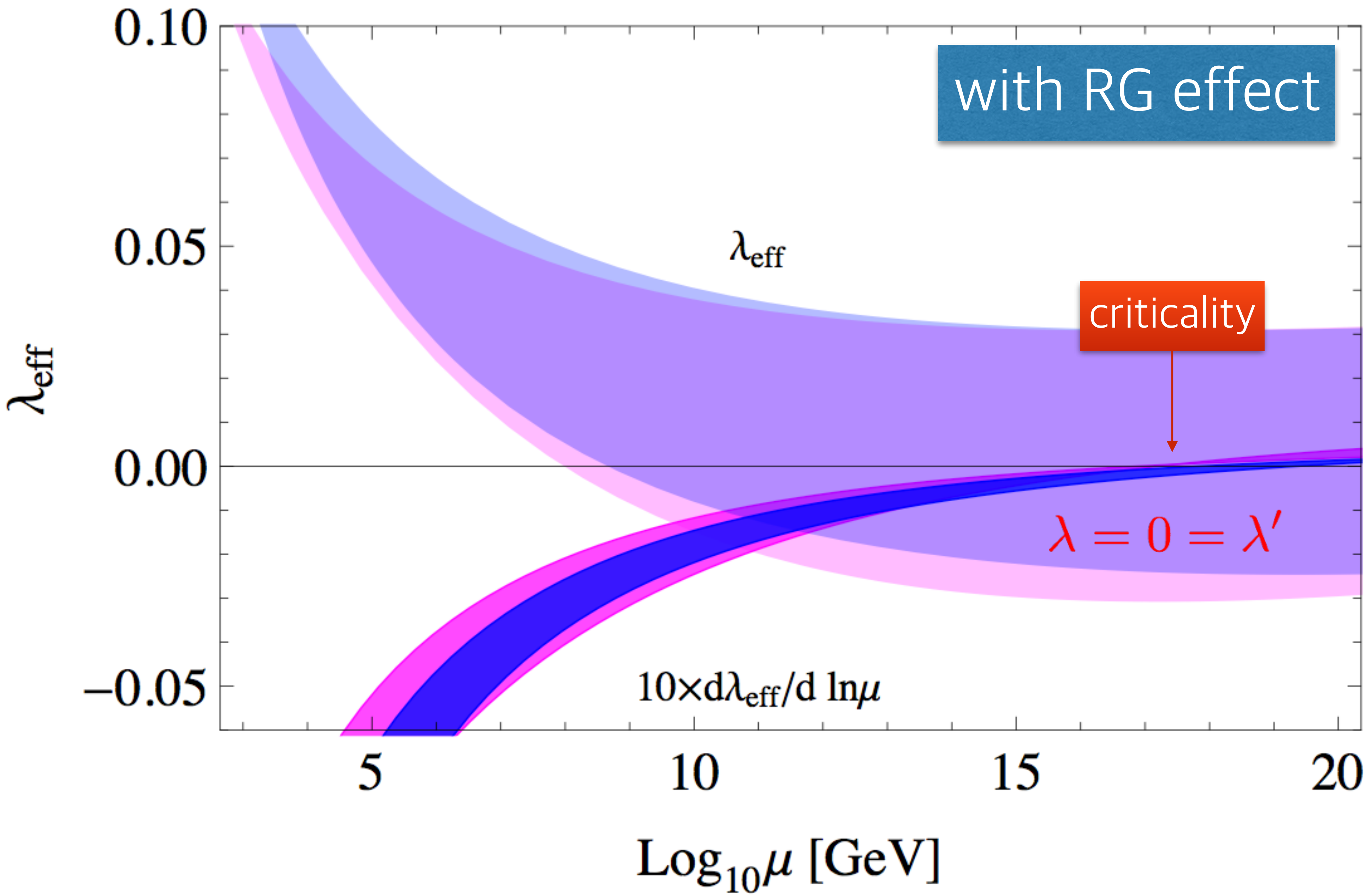
- **thus is premature since large uncertainties are involved**

- we should take the ‘measured top quark mass’ with **a lot of caution**.

- **Maybe our vacuum is stable after all** with a reasonable chance

- The ILC350 can provide more definite answer… (A hadron machine does not help much)

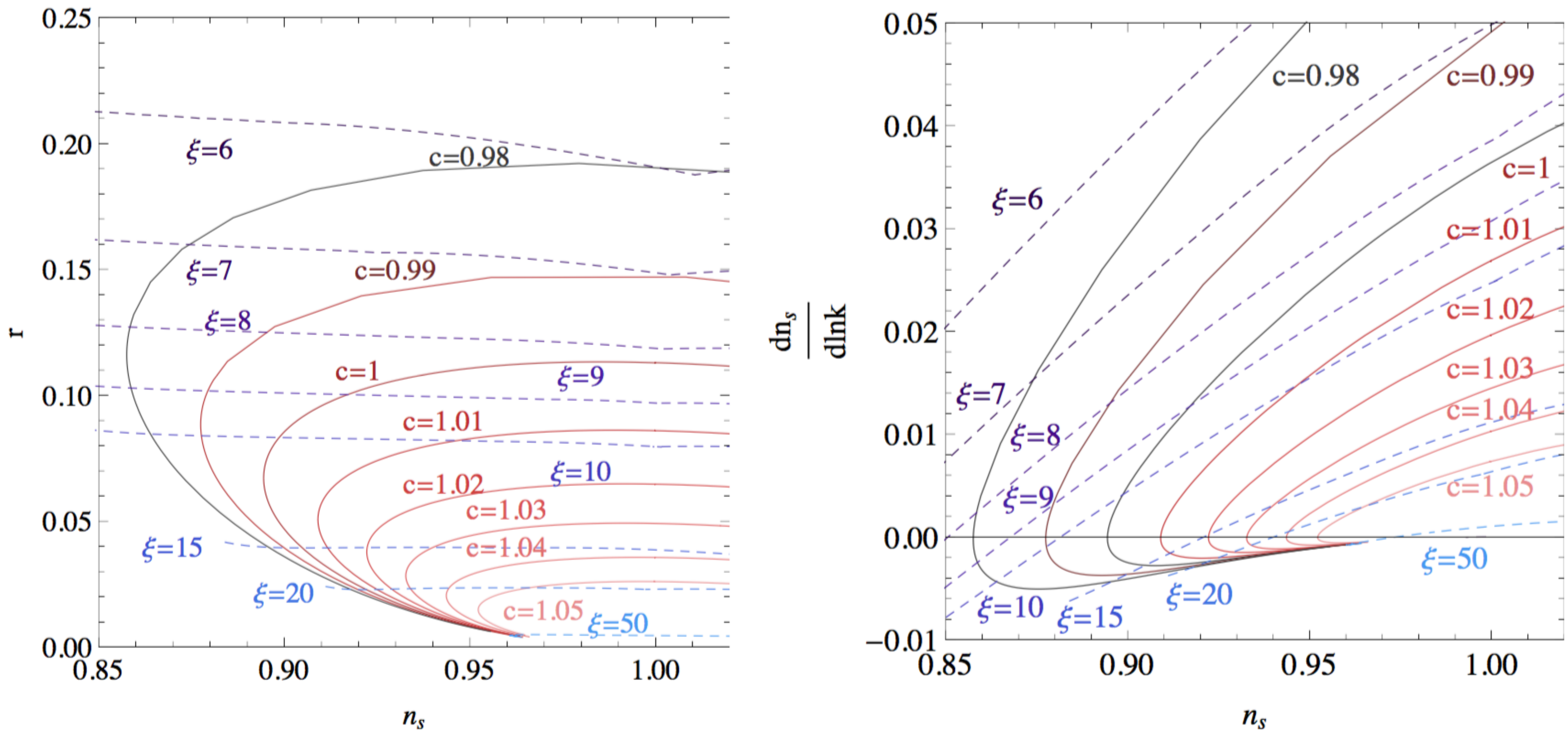
2-loop effective coupling



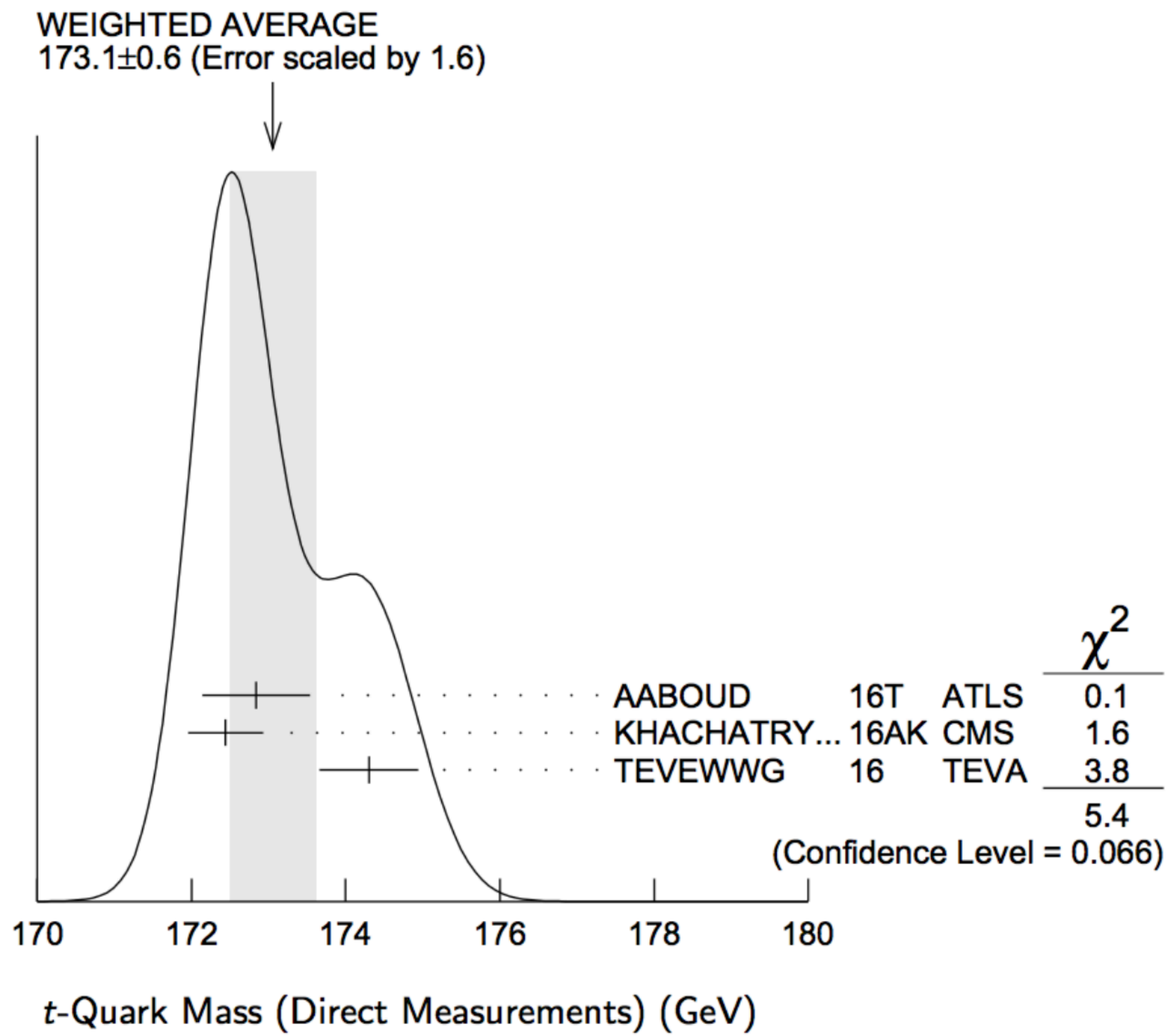
[Hamada, Kawai, Oda, SCP, PRL 2014]

with RG effect

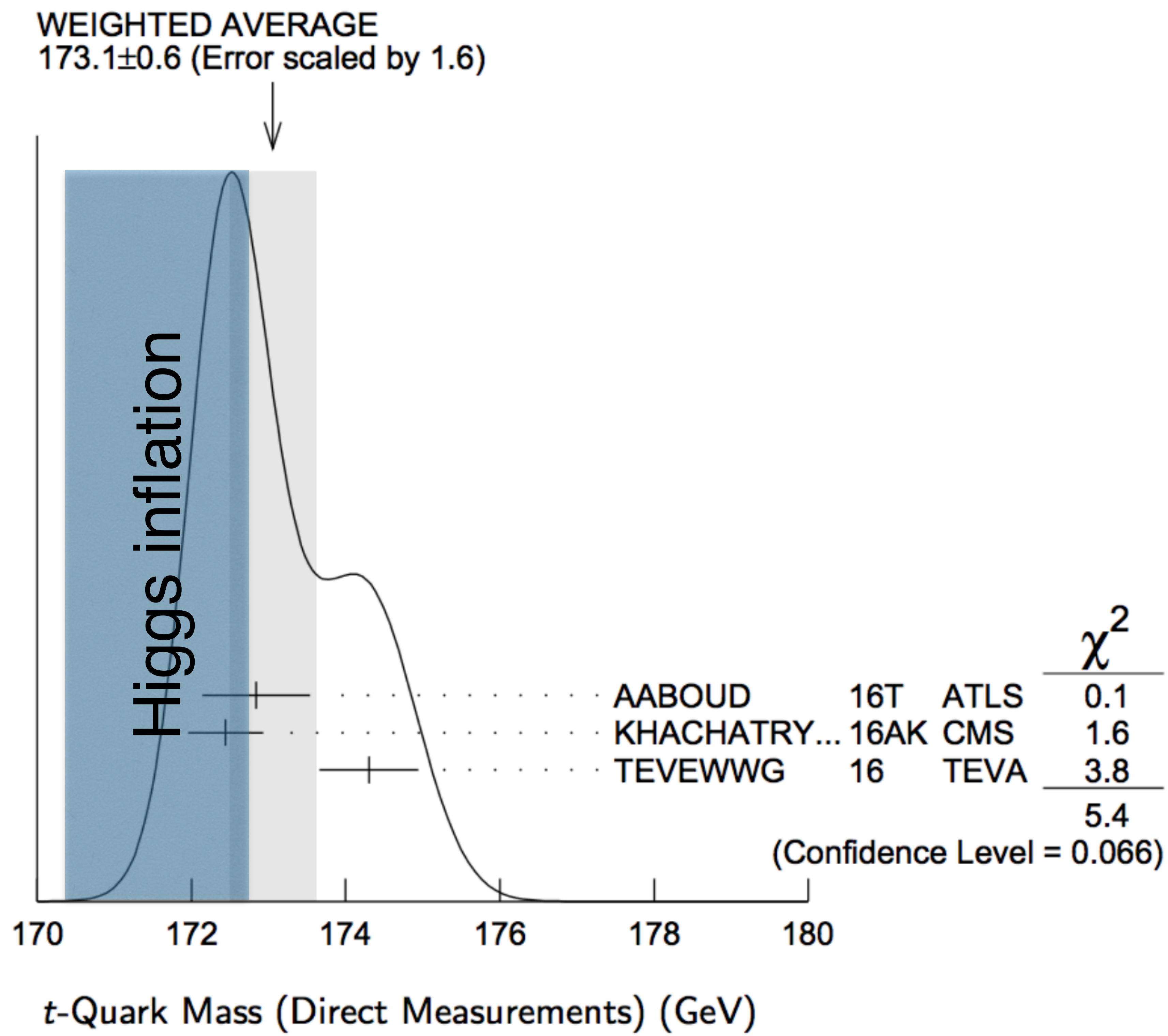
[Hamada, Kawai, Oda, SCP, PRL 2014]
[Hamada, Kawai, Oda, SCP, PRD2015]



$\xi \sim O(1-10)$ This is nice!



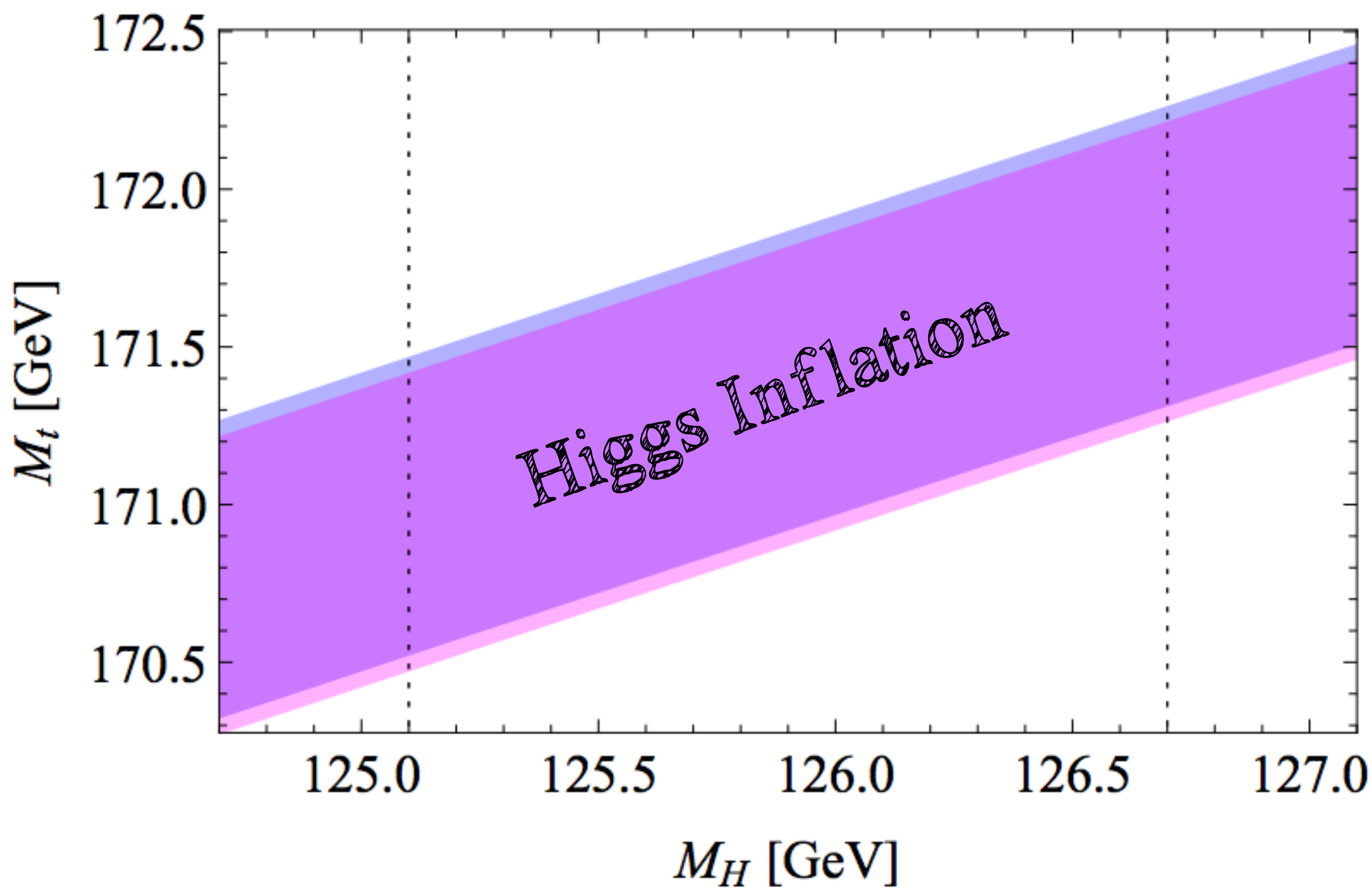
Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update



Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

Mt & MH

from Higgs inflation



Potential Synergy

Cosmological observation

e.g. primordial gravitational wave

=

Precision particle physics experiments

e.g. top quark mass

More discussions

[topic #1]
Cut off

We request $E \ll \Lambda_{cut-off}$

$$E_{inf} \sim V_E^{1/4} = \frac{\lambda^{1/4}}{\sqrt{\xi}} M_P$$

Q. what's cut-off scale?

background dependent cut-off scale

Cut-off depends on background $g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu} \quad \phi = \bar{\phi} + \delta\phi$

The normalized interaction term reads $\mathcal{L}_{int} \ni \frac{1}{\Lambda^J}(\delta\hat{\phi})^2\partial^2\hat{h}$

thus the cutoff scale in Jordan frame:

$$\Lambda^J(\bar{\phi}) = \frac{M_P^2 + \xi\bar{\phi}^2 + 6\xi^2\bar{\phi}^2}{\xi\sqrt{M_P^2 + \xi\bar{\phi}^2}}$$

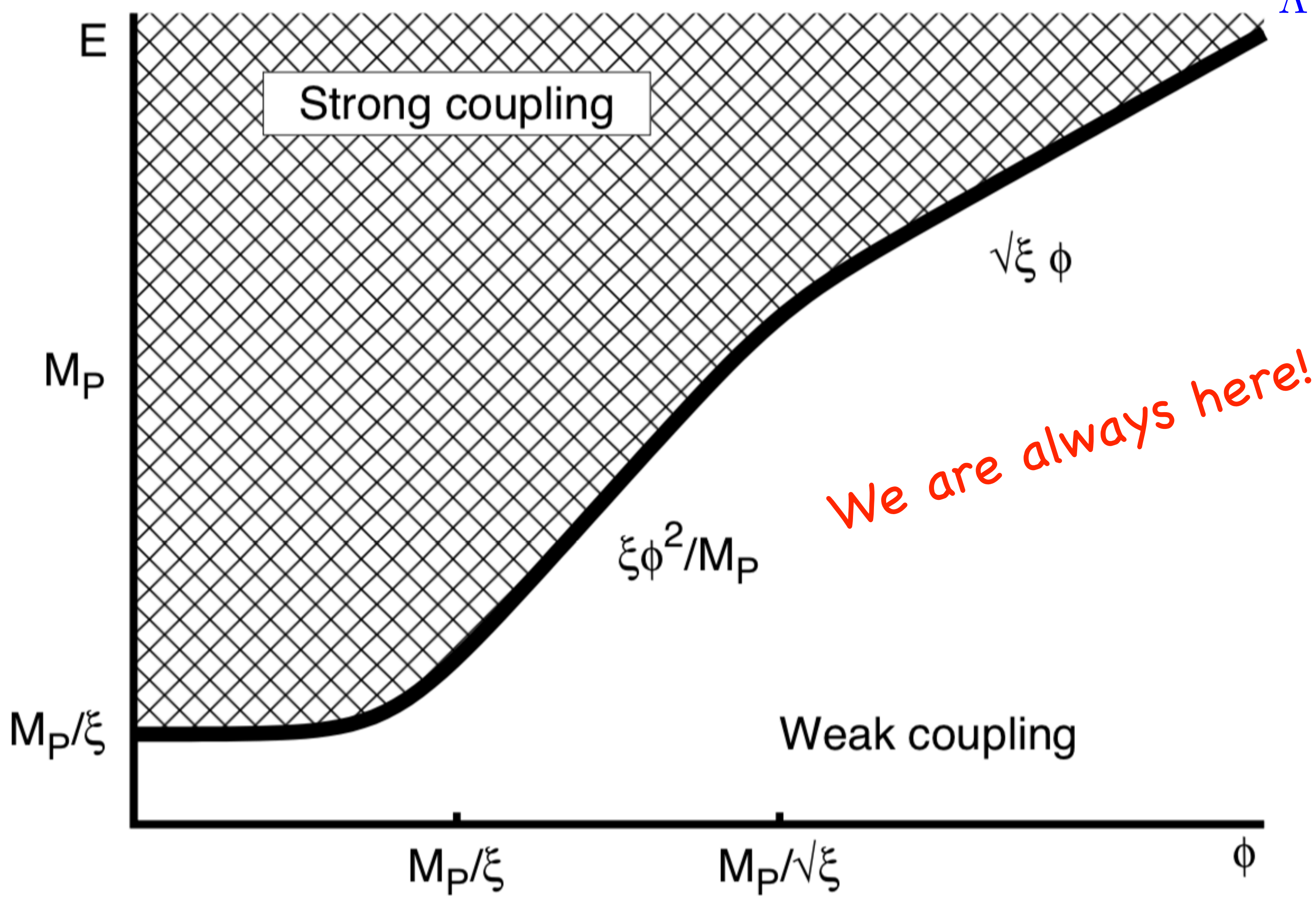
[Bezrukov, Magnin, Shaposhnikov & Sibiryakov, 10']

$\bar{\phi} \ll M_P/\xi$: $\frac{M_P}{\xi}$ [Burgess, Lee & Trott, 09'] [Barbon & Epinosa, 09']

$M_P/\xi \ll \bar{\phi} \ll M_P/\sqrt{\xi}$: $\frac{\xi\bar{\phi}^2}{M_P}$

$\bar{\phi} \gg M_P/\sqrt{\xi}$: $\sqrt{\xi}\bar{\phi}$

$$\Lambda^J(\bar{\phi}) = \frac{M_P^2 + \xi\bar{\phi}^2 + 6\xi^2\bar{\phi}^2}{\xi\sqrt{M_P^2 + \xi\bar{\phi}^2}}$$



Conclusion:
Higgs inflation is consistent and stays perturbative in entire process!

[topic #2]
non-minimal coupling

$$\frac{\xi}{2} H^\dagger H R$$

-same dimension of the Einstein term
-allowed by all symmetries of the SM

therefore you are not allowed to drop this term without a reason

Dim 4 for Ricci

Wait!

$$R \sim (\partial_\rho h_{\mu\nu})^2 / M^2$$

Kinetic term of graviton
Thus, NM term ~

$$\phi^2 (\partial_\rho h_{\mu\nu})^2$$

Dim 6 for graviton dynamics

(sometimes, we should not forget other Dim 6 terms, too)

General Lagrangian

$$S=\int \mathrm{d}^4x\sqrt{-g}\Bigg[\frac{M_P^2}{2}\,A(\varphi)\,\mathcal{R}$$

$$-\frac{1}{2}\,B(\varphi)\,g^{\mu\nu}\left(\partial_\mu\varphi\partial_\nu\varphi+A_\mu A_\nu\varphi^2\right)-V(\varphi)$$

$$-\,C(\varphi)\,\overline{\psi}\gamma^\mu D_\mu\psi-\frac{y}{\sqrt{2}}\,D(\varphi)\,\left(\varphi\overline{\psi}\psi+\mathrm{h.c.}\right)$$

$$-\,\frac{E(\varphi)}{4g_A^2}\,F_{\mu\nu}F^{\mu\nu}\Bigg],$$

$$A(\varphi)=1+a_2\frac{\varphi^2}{M_P^2}+a_4\frac{\varphi^4}{M_P^4}+\cdots\,,\qquad B(\varphi)=1+b_2\frac{\varphi^2}{M_P^2}+b_4\frac{\varphi^4}{M_P^4}+\cdots\,,$$

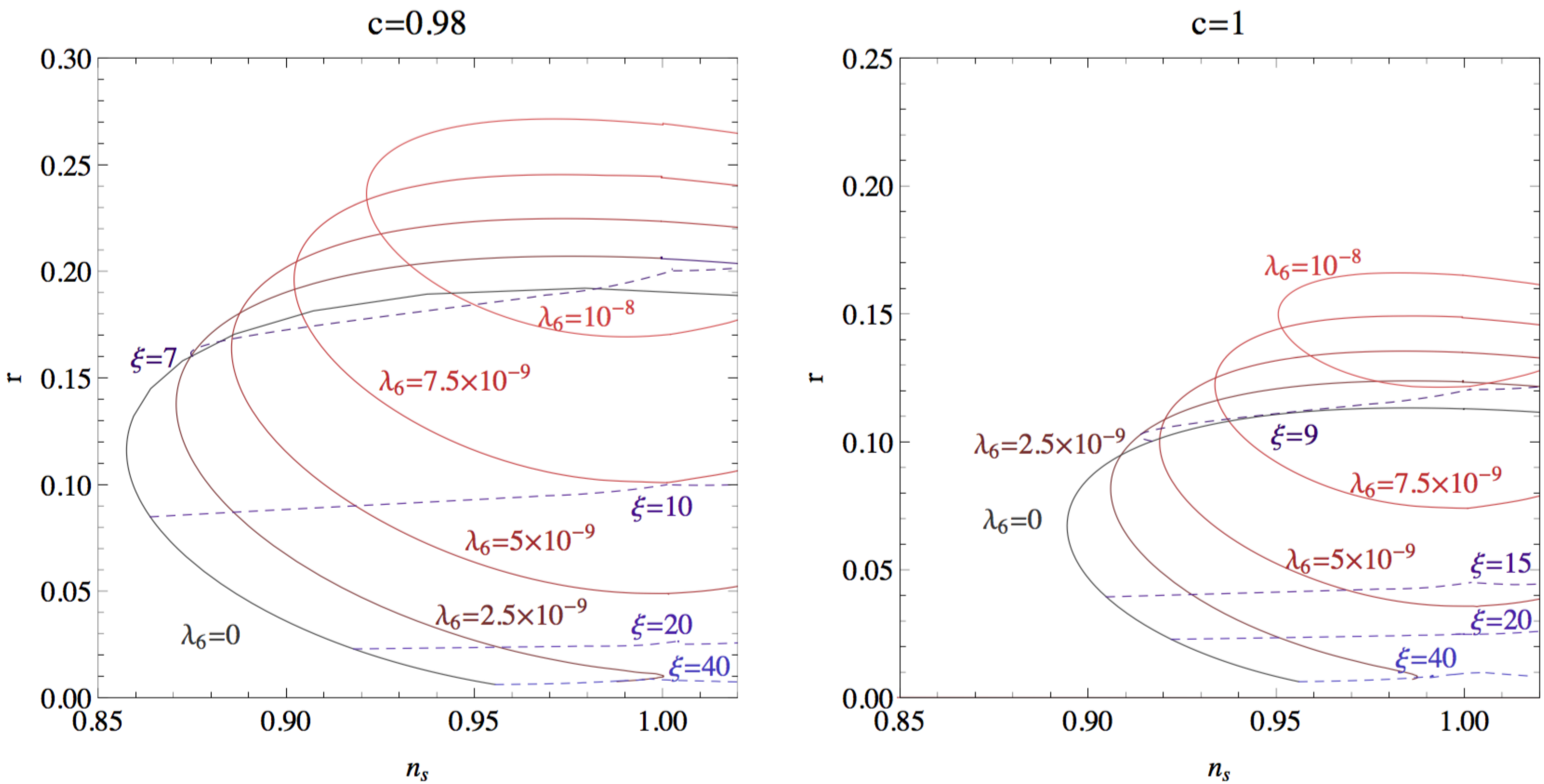
$$V(\varphi)=\frac{m^2}{2}\varphi^2+\frac{\lambda}{4}\varphi^4+\left(\lambda_6\frac{\varphi^6}{M_P^2}+\lambda_8\frac{\varphi^8}{M_P^4}+\cdots\right).$$

[Hamada, Kawai, Oda, SCP, PRD2015]

"higher order terms"

$$V(\varphi) = \frac{m^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 + \left(\lambda_6 \frac{\varphi^6}{M_P^2} + \lambda_8 \frac{\varphi^8}{M_P^4} + \cdots\right)$$

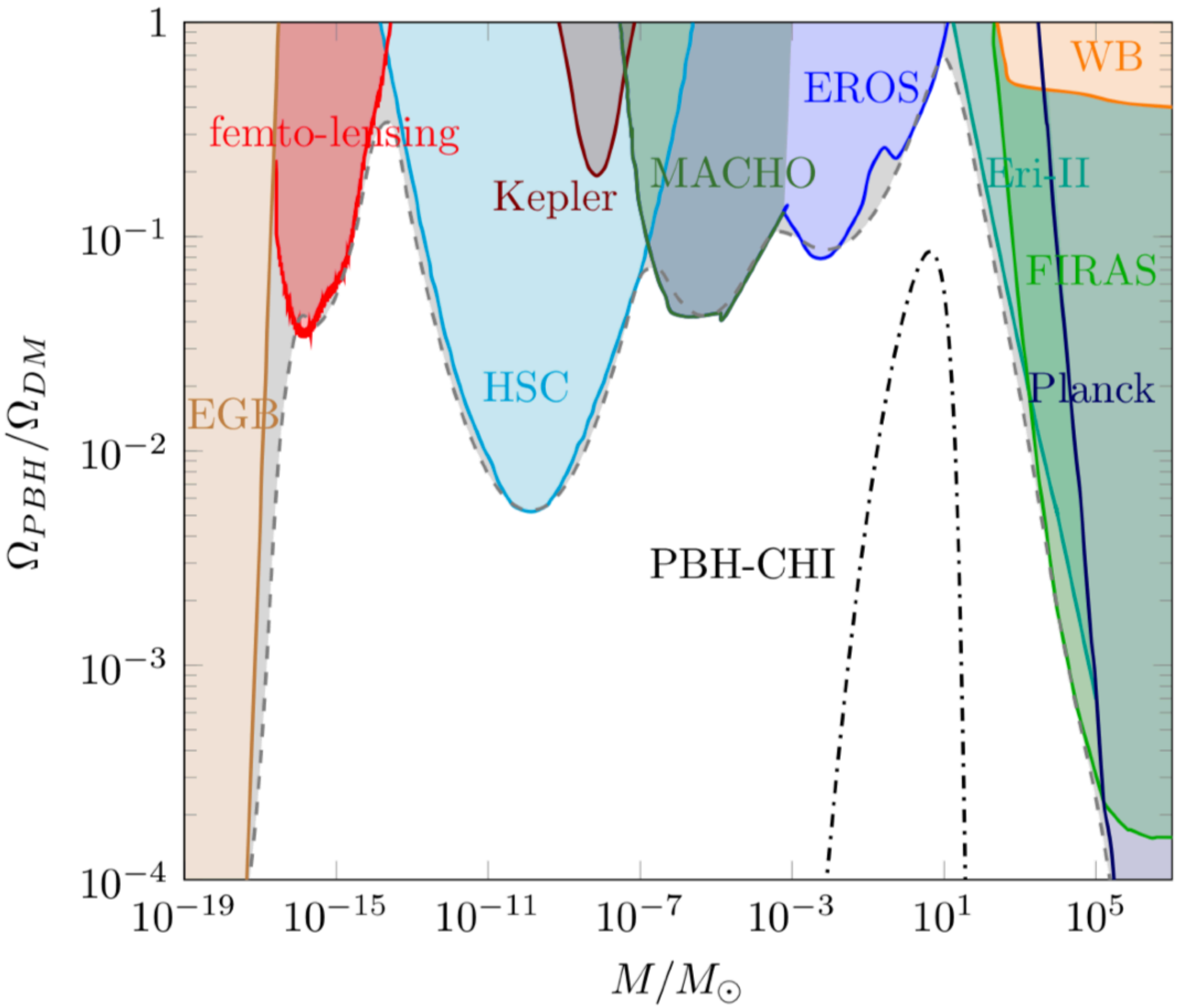
$$\mu_{\rm min} = c\frac{M_p}{\sqrt{\xi}}$$



[Hamada, Kawai, Oda, SCP, PRD2015]

[Topic #3]
PBH in Higgs inflation

J. M. Ezquiaga, J. Garcia-Bellido and E. Ruiz Morales,
``Primordial Black Hole production in Critical Higgs Inflation,''
PLB (776), 345 (2018)



Finally,
take home messages

- Higgs inflation idea is an economic, effective and consistent idea of inflation fitting DATA well.

- Precision measurements of M_t, M_H, self coupling are all very important.

Higgs-f(R) duality

During the inflationary era, two theories effectively describe the same physics

$$S_{\text{Starobinsky}} \leftrightarrow S_{\text{Higgs}}$$

We can enlarge the map in theory space

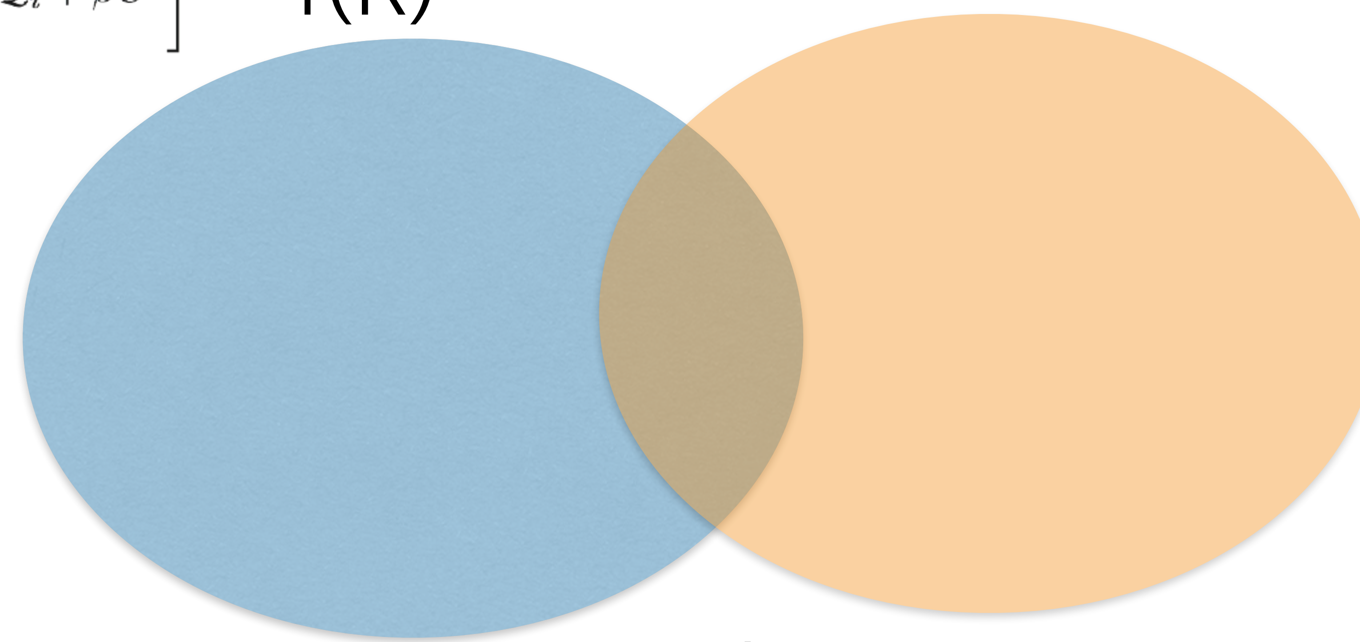
sketch of idea

Starobinsky
f(R)

$$S = \int d^4x\sqrt{-g}\left[f(R) - \sum_i \xi_i(R)\mathcal{Q}_i + \beta C^2\right]$$

Higgs

$$S = \int d^4x\sqrt{-g}\left[\frac{M^2}{2}F(\Phi)R - \frac{1}{2}B(\Phi)g^{\mu\nu}(\partial_\mu\Phi\partial_\nu\Phi + A_\mu A_\nu\Phi^2) -$$



Matching
@Einstein frame

[Gumrukcuoglu, Mukohyama, SCP (in preparation)]