Higgs and New Physics

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Outline

Brief Overview
Higgs searches at LHC

Simplified model
Simplified scalar sector

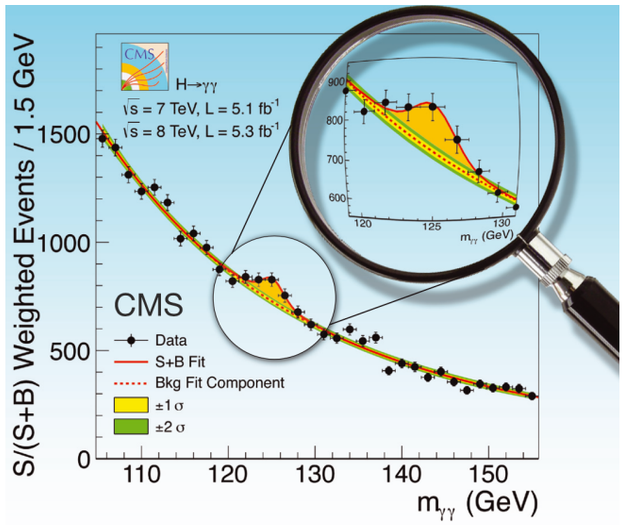
1 2 3 4

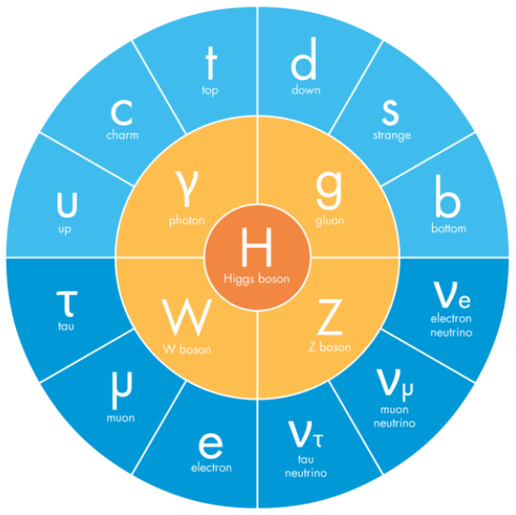
Top down approach
Naturalness solutions

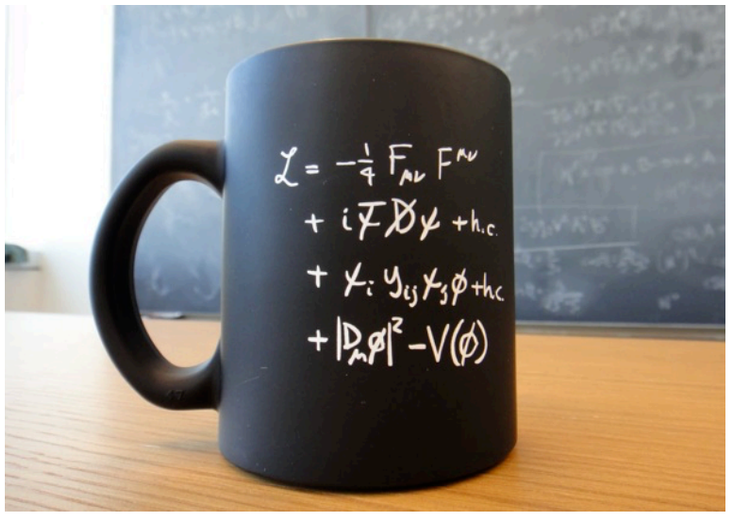
Bottom up Approach
Higgs effective theory

Higgs Boson

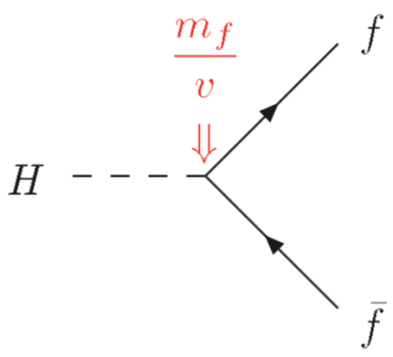
Higgs discovery completes the standard model spectrum

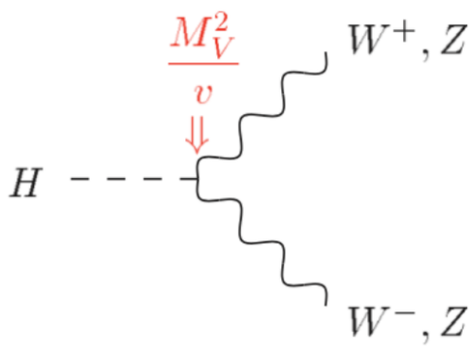


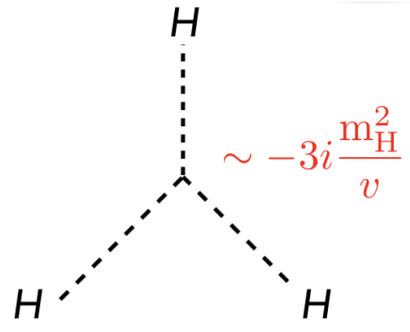




Knowing m_{Higgs}, all the Higgs coupling parameters are predicted!



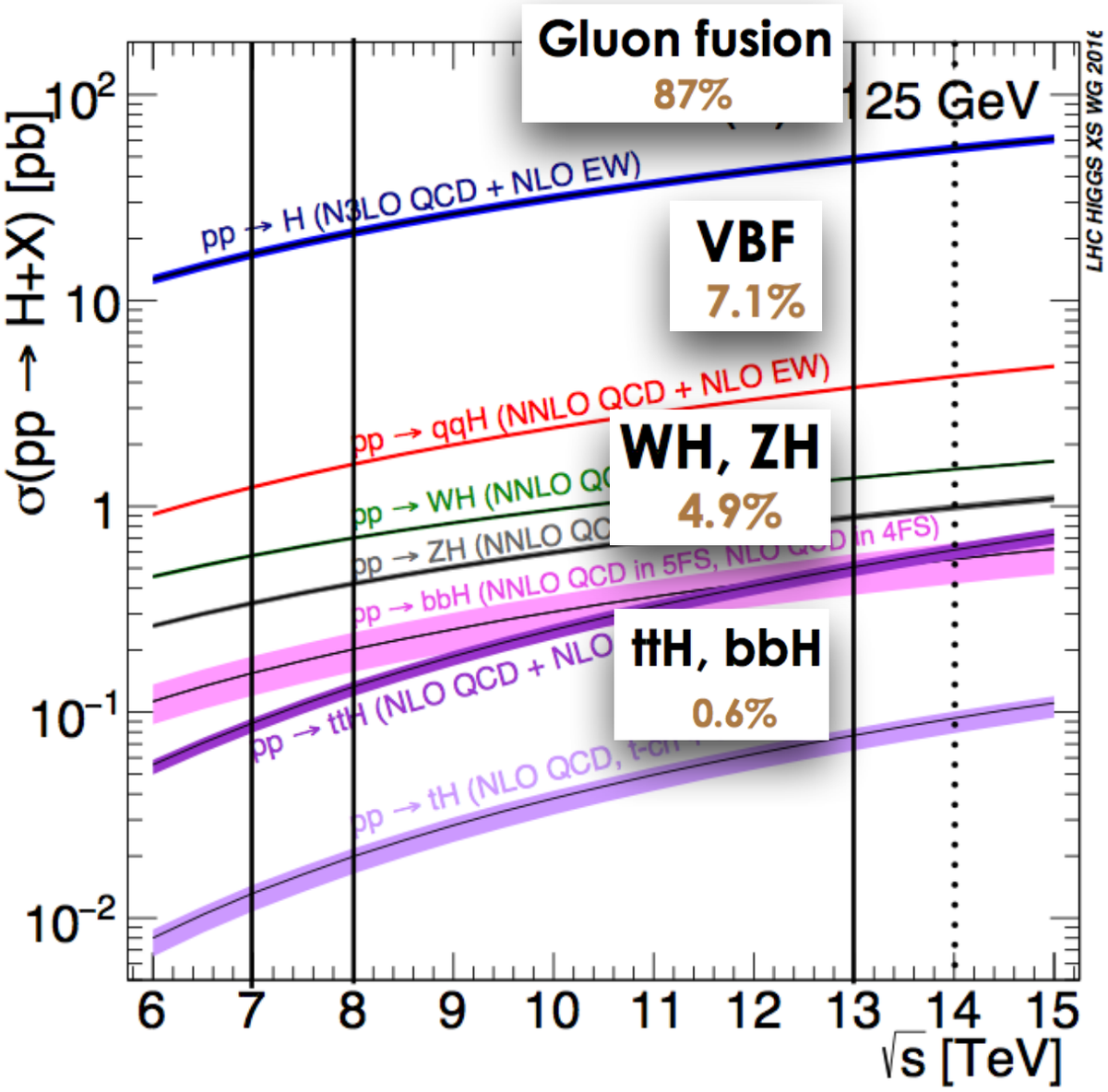


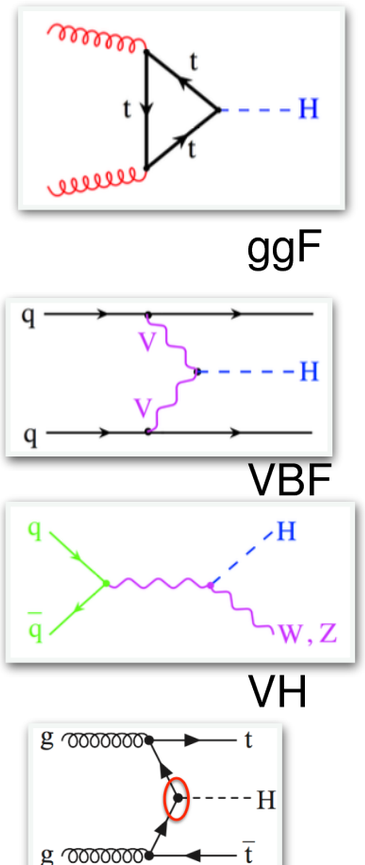


Coupling ~ mass, due to Higgs mechanism

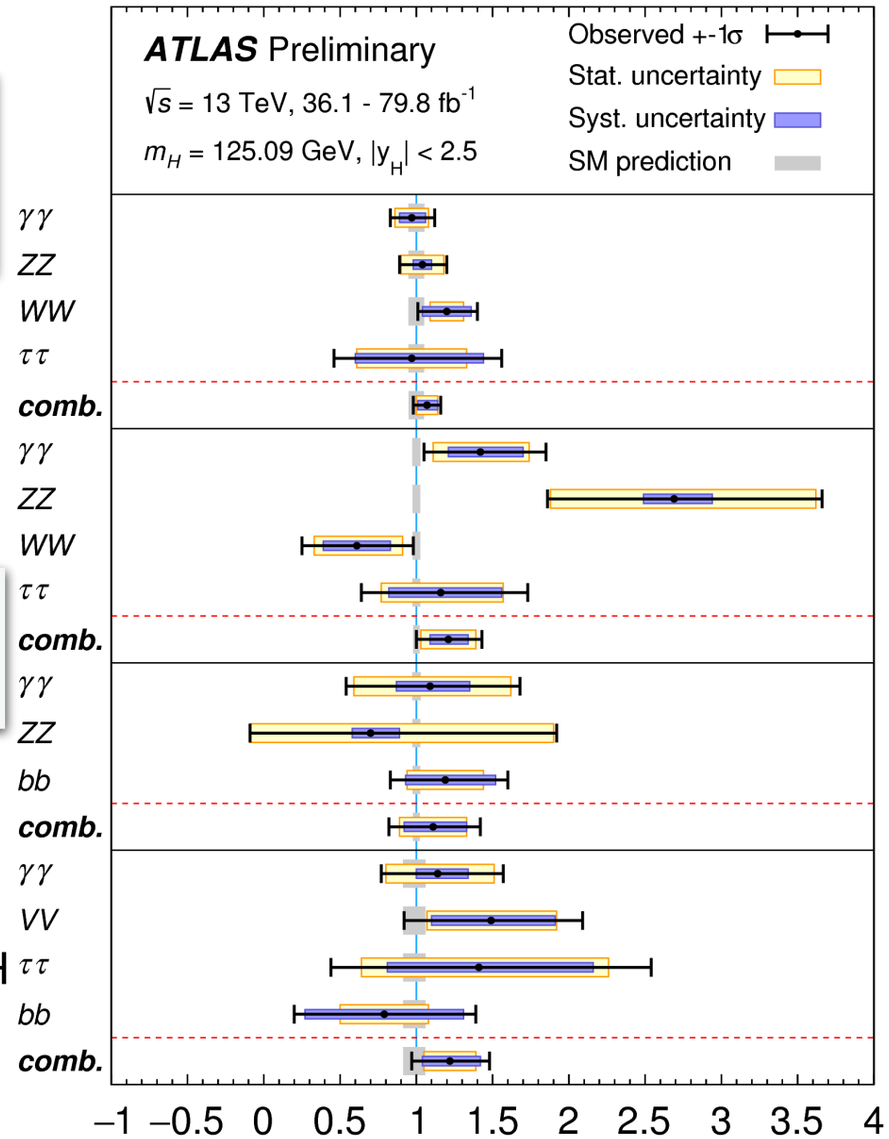
Higgs Production at the LHC

Predicted

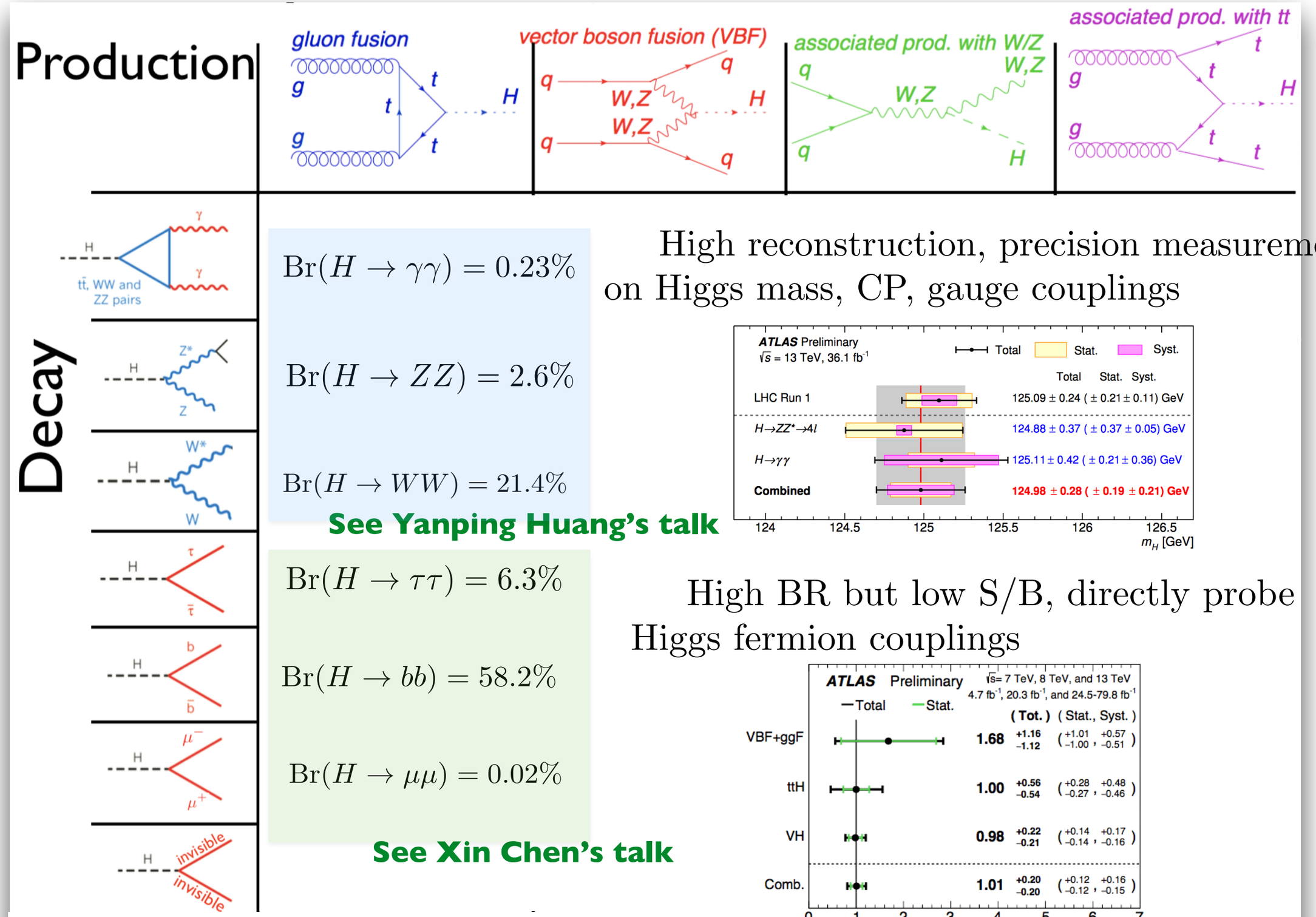




Measured



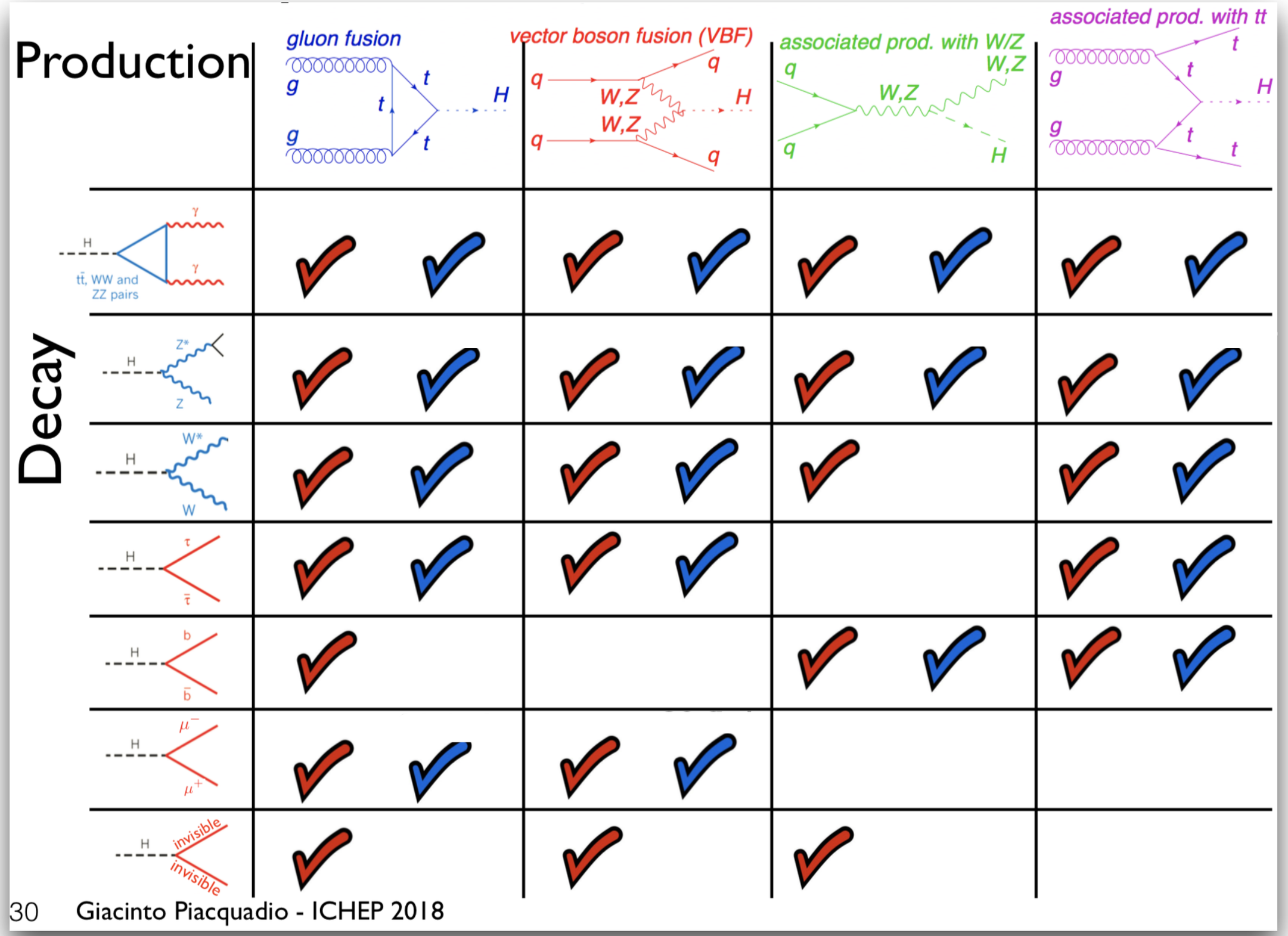
Higgs Decay Channels



High reconstruction, precision measurements on Higgs mass, CP, gauge couplings

High BR but low S/B, directly probe Higgs fermion couplings

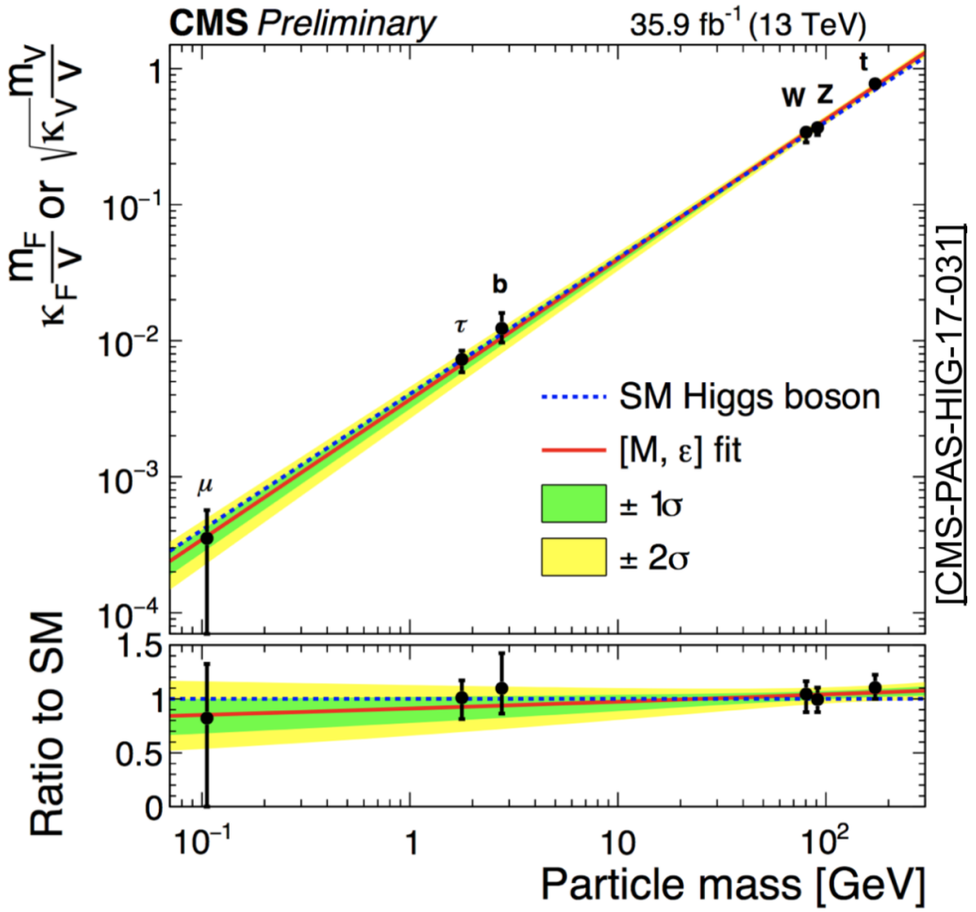
Current Status at the LHC

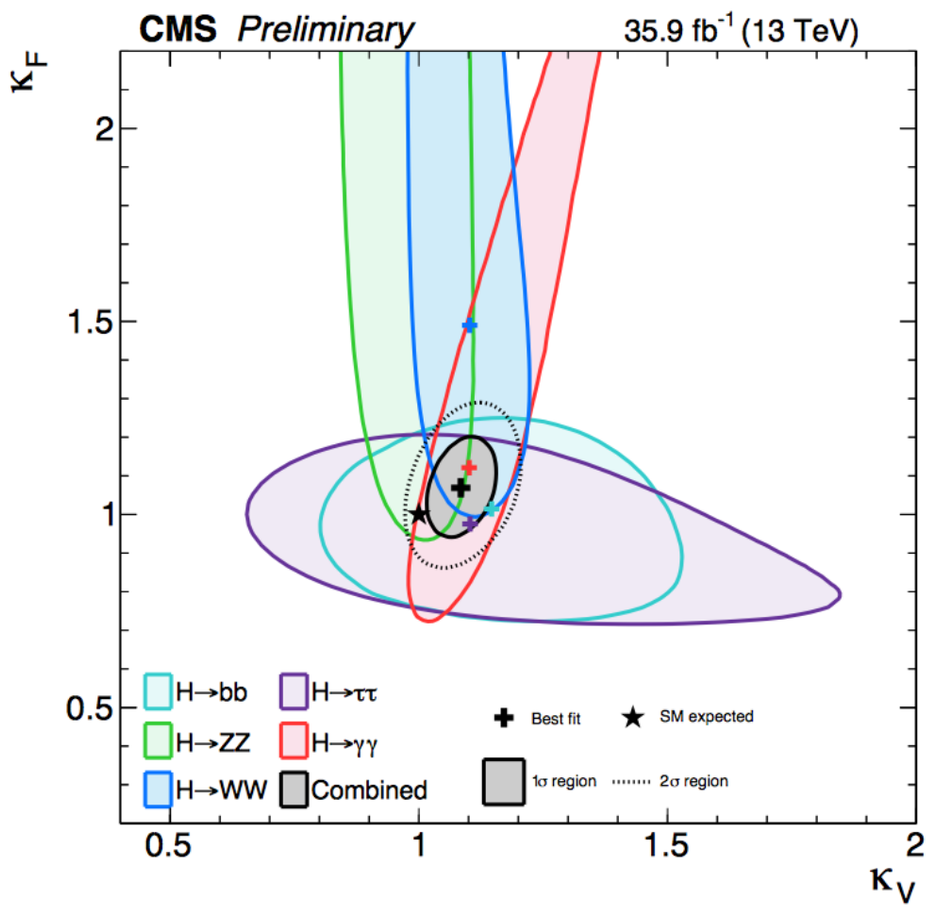


CMS

ATLAS

Known Known





Deviation

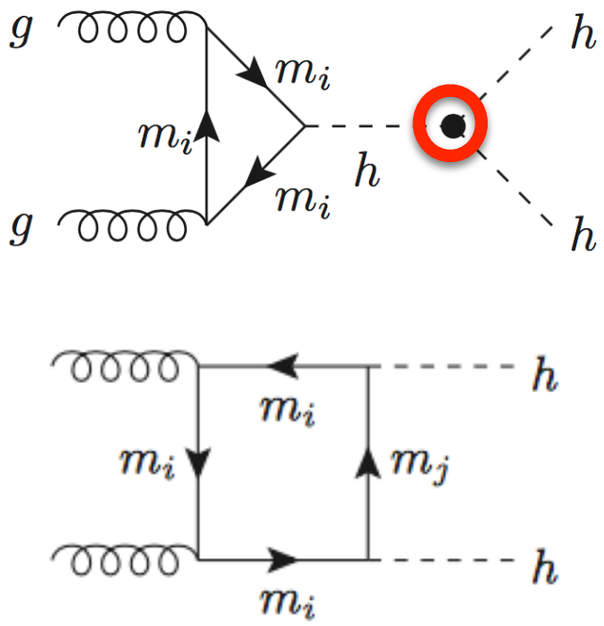
from SM

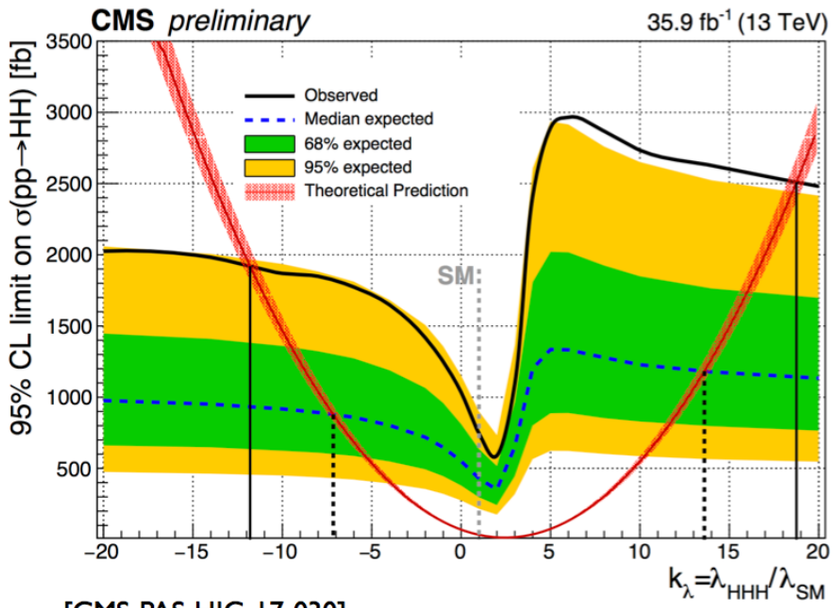
Higgs couplings

Any deviation from SM couplings is new physics!

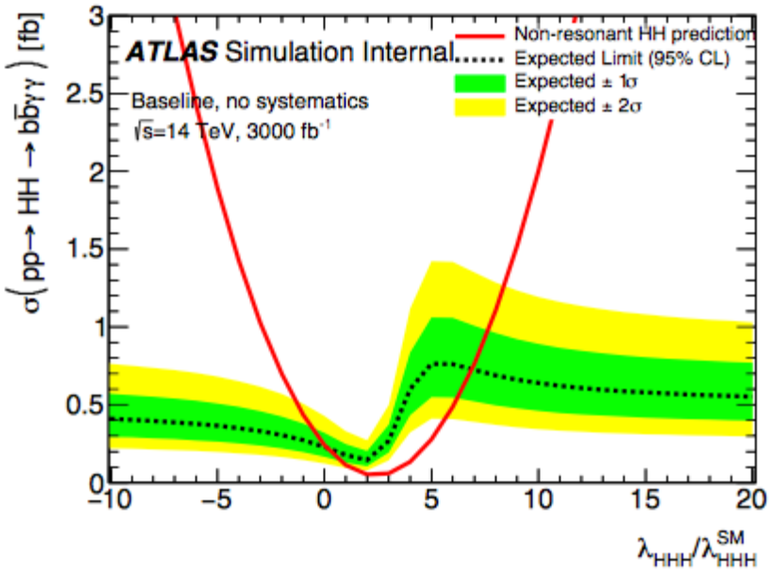
Known Unknown

Higgs self coupling, Higgs rare decay (charm, electron), not yet determined





[CMS-PAS-HIG-17-030]



$-11.8 < k_\lambda < 18.8$

Without systematics: $0.2 < \lambda_{hhh}/\lambda^{\mathrm{SM}}_{hhh} < 6.9$

Different Potential

than SM Higgs potential

Shape of Higgs potential could be different from SM!

Known Unknown

New Couplings

other than SM
Higgs couplings

CP violating Higgs coupling, Higgs exotic decay are well motivated!

New scalars

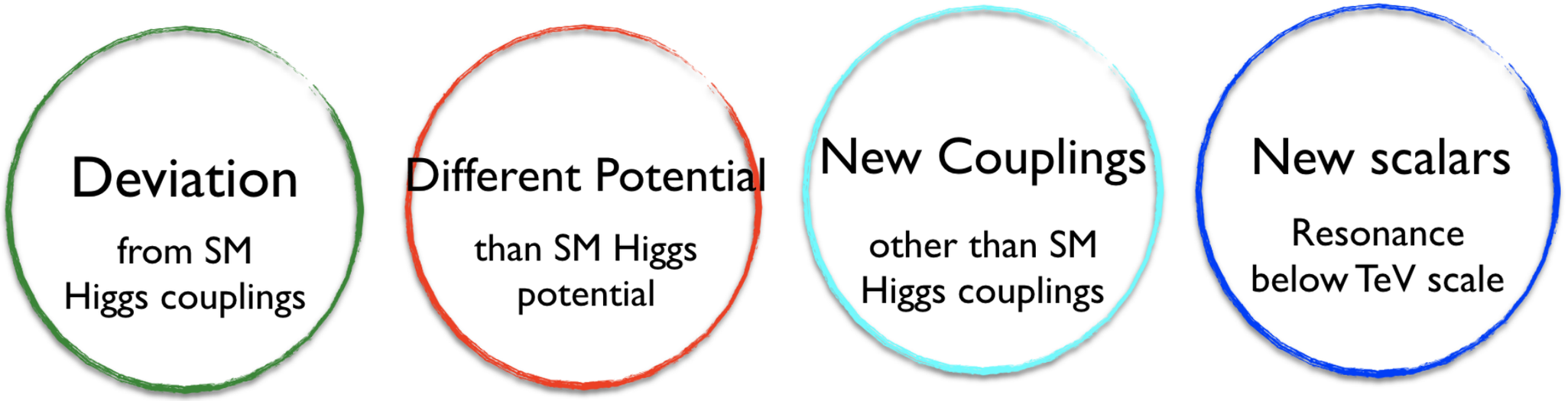
Resonance
below TeV scale

New neutral scalar, charged scalar, light scalar are direct sign of new physics!

See Muhammad Ahmad's talk

Higgs Portal to New Physics

Top-down approach: new physics models

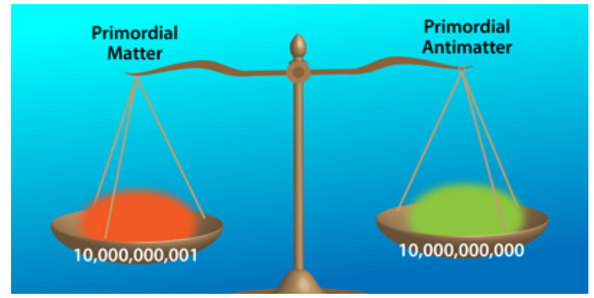


Bottom-up approach: Higgs effective field theory (HEFT)

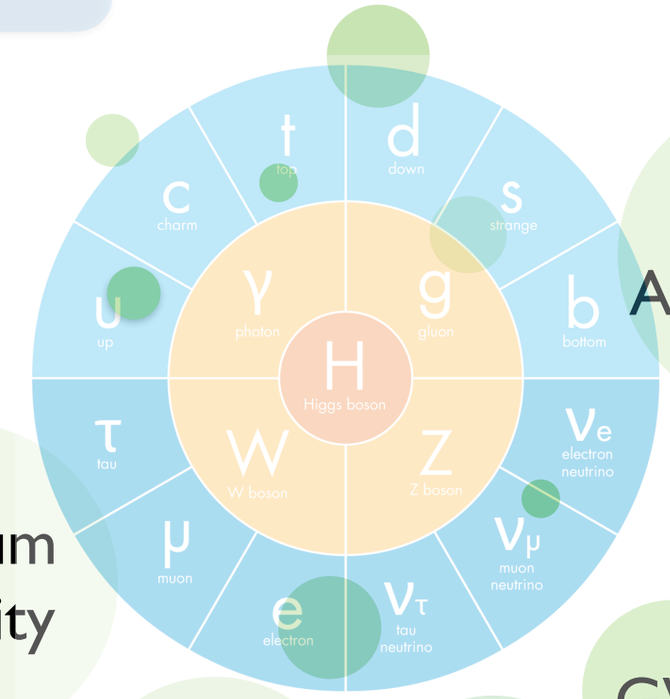
Top Down Approach

Motivations for new physics beyond the SM

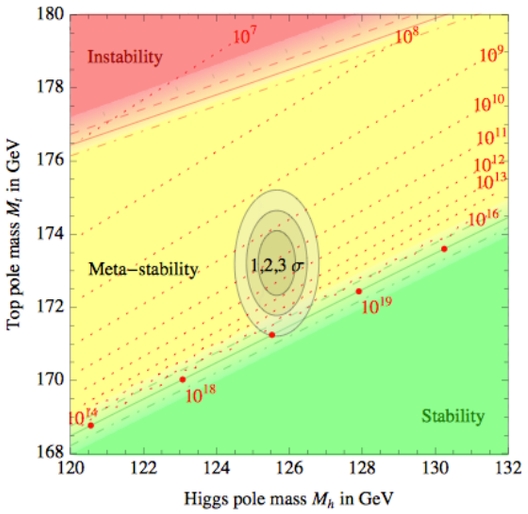
$$m^2_{\text{Higgs}} = \quad + \quad \begin{matrix} t \\ y_t \end{matrix}$$



Naturalness

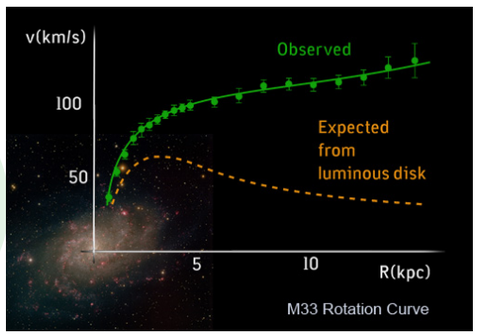


Baryon Asymmetry



Vacuum Stability

Dark matter

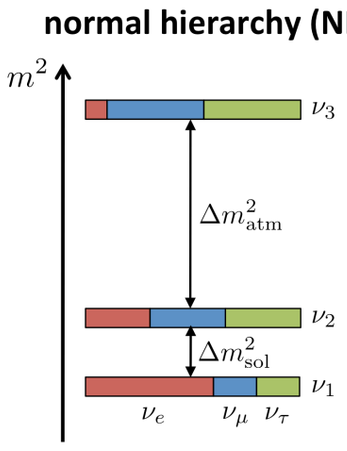


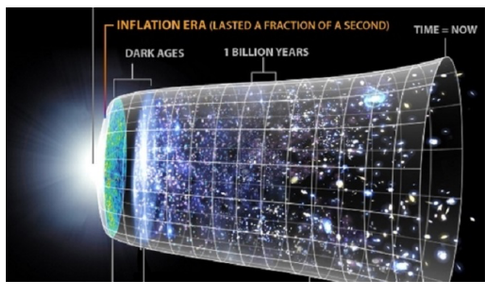
GW

Neutrino Mass

Inflation

normal hierarchy (NH)



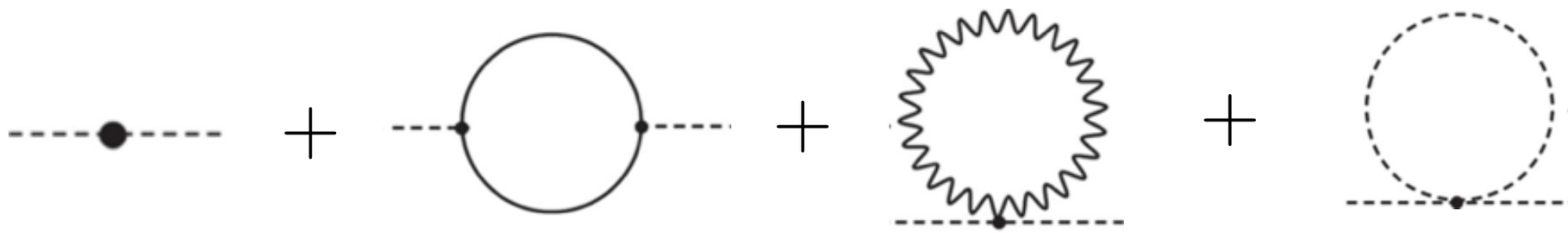


Naturalness

Among all the motivations

naturalness directly addresses nature of Higgs boson

Higgs mass parameter

$-(100\ \mathrm{GeV})^2 =$  $+ \cdots$

$$= (m^0)^2 + \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{3}{4}(3g^2 + g'^2) + 6\lambda\right)$$

Take $\Lambda = M_{\mathrm{pl}}$ Susskind 1979; t'Hooft 1980; Veltman, 1981; Witten, 1981

$$-(100\ \mathrm{GeV})^2 = +\,3612789098478930739452093287892807398\ \mathrm{GeV}^2$$
$$-\,3612789098478930739452093287892817398\ \mathrm{GeV}^2$$

Need fine tuning, hierarchy problem!

Naturalness Solutions

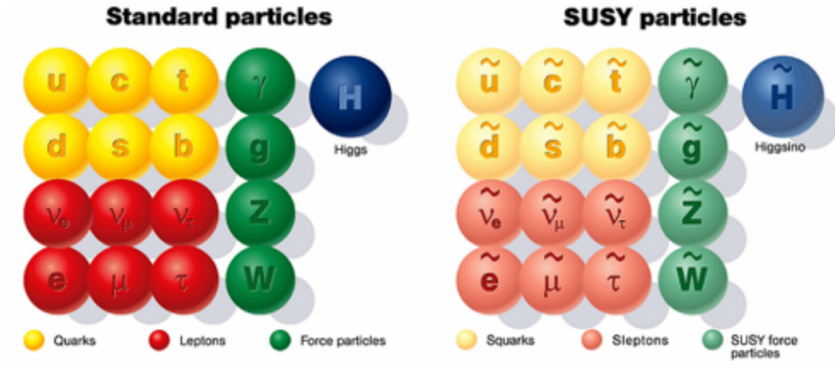
Introduce new symmetry for the Higgs Boson

Supersymmetry

$H \leftrightarrow \tilde{H}$

Higgs Higgsino

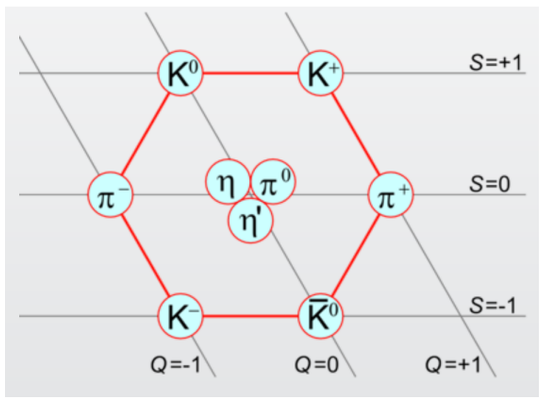
Hierarchy Problem Solutions



See Jun-Jie Cao's talk

Composite Higgs

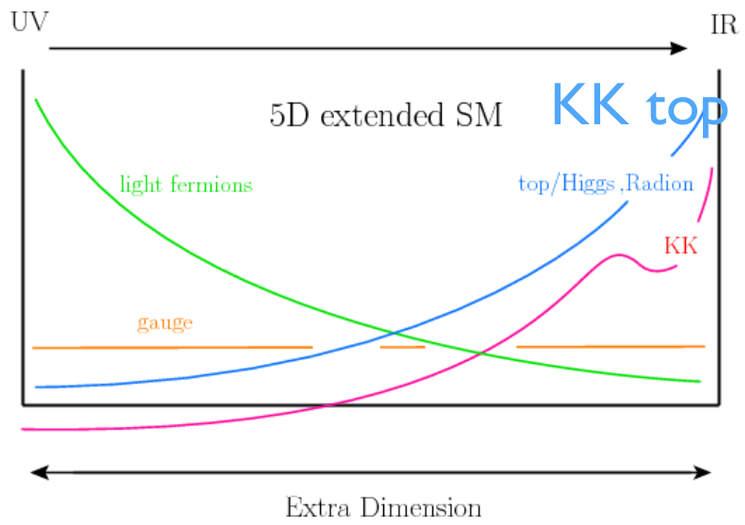
shift: $h \to h + a$



Higgs similar to pion

Extra Dimension

Conformal: $h \to e^{\omega} h$



Higgs as 5D gauge boson

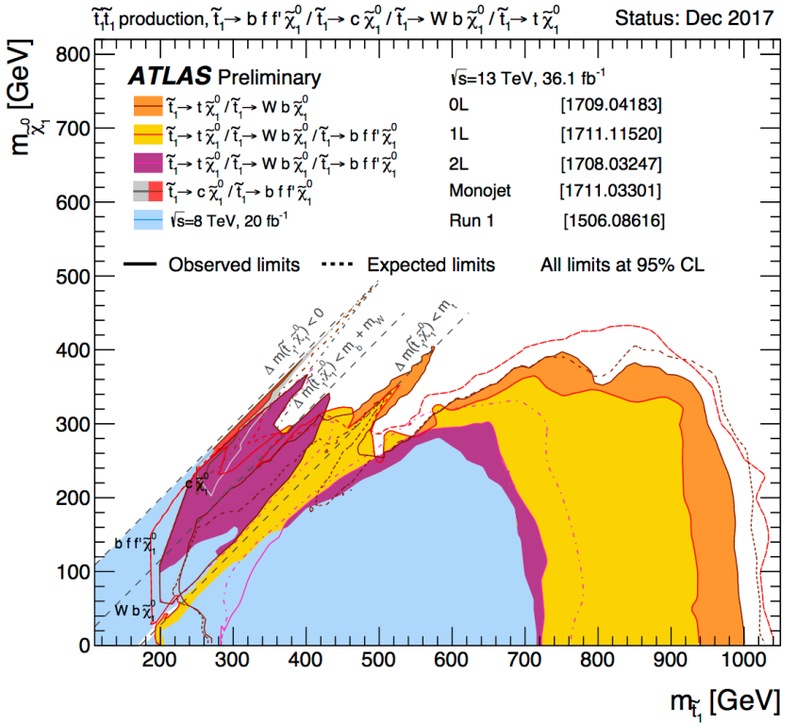
Top Partner Searches

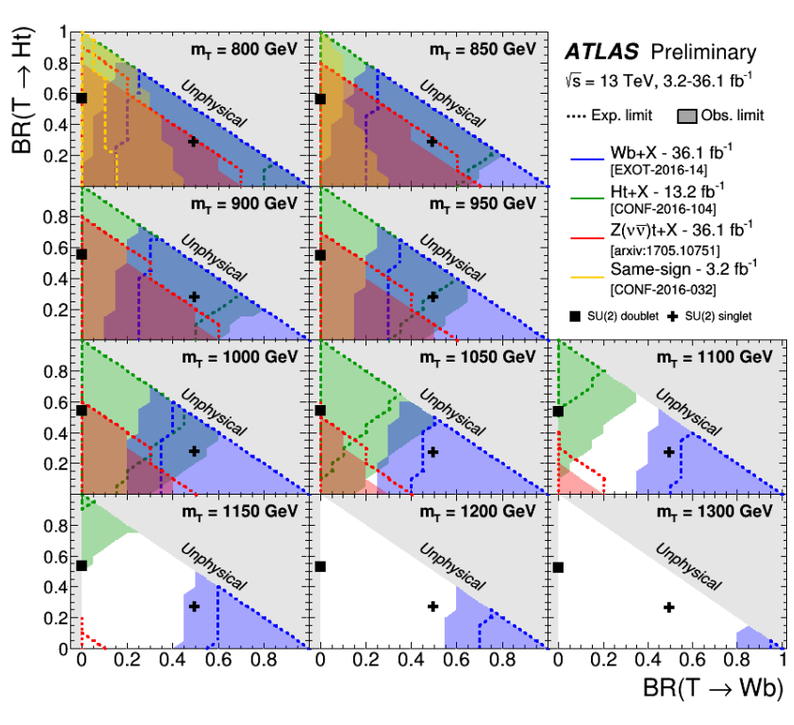
How to protect the Higgs mass?

$$-(100\ \text{GeV})^2 = \quad \text{---}\bullet\text{---} \quad + \quad \text{---}\overset{y_t}{\bigcirc}\overset{t}{\bigcirc}\overset{y_t}{}\text{---} \quad + \quad \text{---}\overset{y_t^2}{\bigcirc}\overset{\tilde{t}}{\bigcirc}\text{---} \quad + \quad \text{---}\overset{-\frac{y_t}{2f}}{\bigcirc}\overset{y_t f \times \quad T}{\bigcirc}\text{---}$$

$$= \quad (m^0)^2 \quad + \quad \cancel{\frac{\Lambda^2}{16\pi^2}\left(-6y_t^2+6y_t^2\right)} \quad + \quad \frac{6y_t^2}{16\pi^2} m_{t'}^2 \log\frac{\Lambda^2}{m_{t'}^2}$$

Smoking-gun signature: sub-TeV top partner





Little hierarchy problem!

Two Opinions

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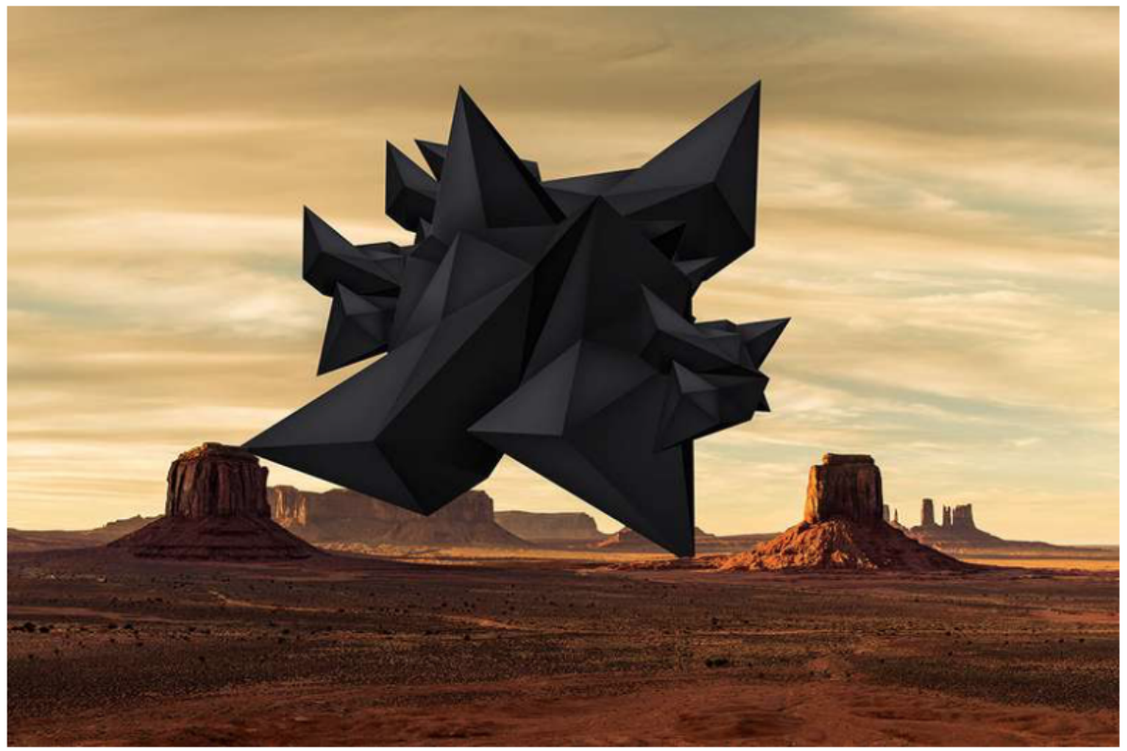
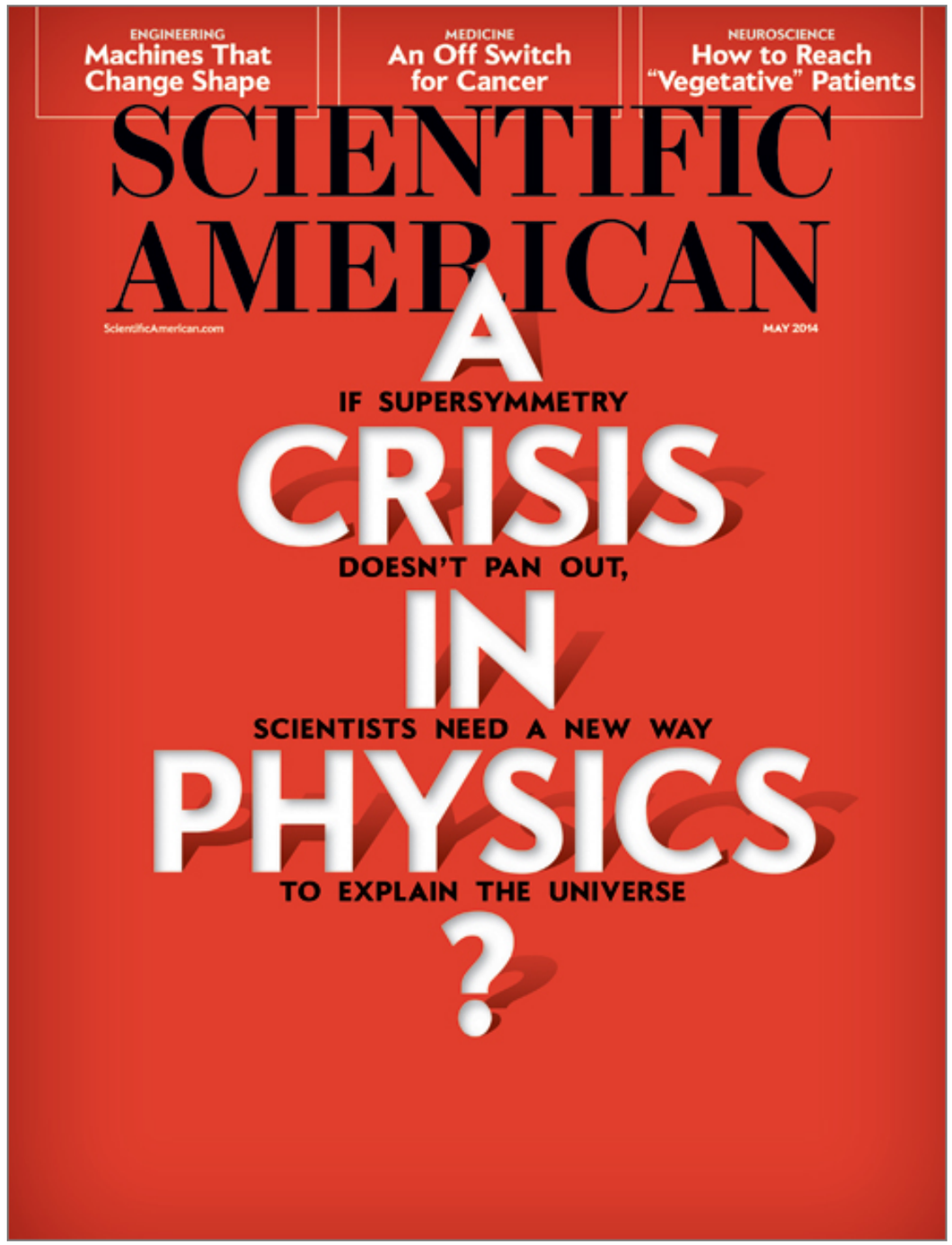
FEATURE 28 February 2018, updated 9 March 2018

Truth before beauty: Our universe is uglier than we thought

Our cosmos is failing to meet the rigorous beauty standards set by physicists. Is it time to face up to the fact we may live in an uglyverse?





Post-Naturalness Era

Giudice 2017: We are entering into post-naturalness era!

G. F. Giudice, 1710.07663

Supersymmetry
Composite Higgs
Extra Dimensions

Neutral Naturalness in UV

Dynamical selection in IR

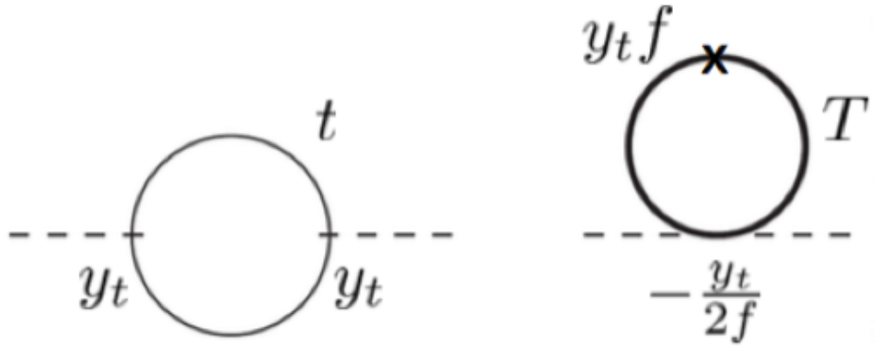
Relaxion
NNaturalness
…

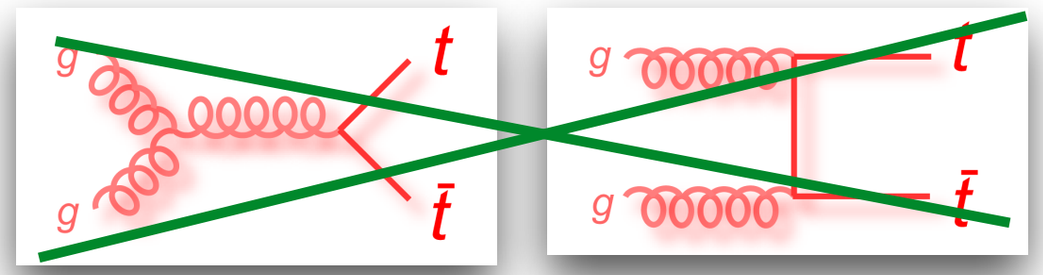
Seems Naturalness paradigm runs out of mileage …

Neutral Naturalness

Neutral naturalness = QCD neutral top partner

N. Craig, A. Katz, M. Strassler, R. Sundrum JHEP07(2015)105





Light top partner, solve little hierarchy problem!

Top quark loop has 3 d.o.f

Top partner is charged under hidden SU(3)color sector

Twin Higgs	Folded SUSY	Quirky little Higgs	Trigonometric Higgs	Minimal neutral naturalness
Z. Chacko, H.-S. Goh, R. Harnik PRL96(2006)231802	G. Burdman, Z. Chacko, H.-S. Goh, R. Harnik JHEP0702(2007)009	H. Cai, H.-C. Cheng, J. Terning JHEP0905(2009)045	C. Csaki, T. Ma, J. Shu PRL121(2018)231801 J. Serra, R. Torre PRD97(2018)035017	L.-X. Xu, JHY, S.-h. Zhu 1810.01882
JHY, PRD94(2016)111704				

Mirror Twin Higgs

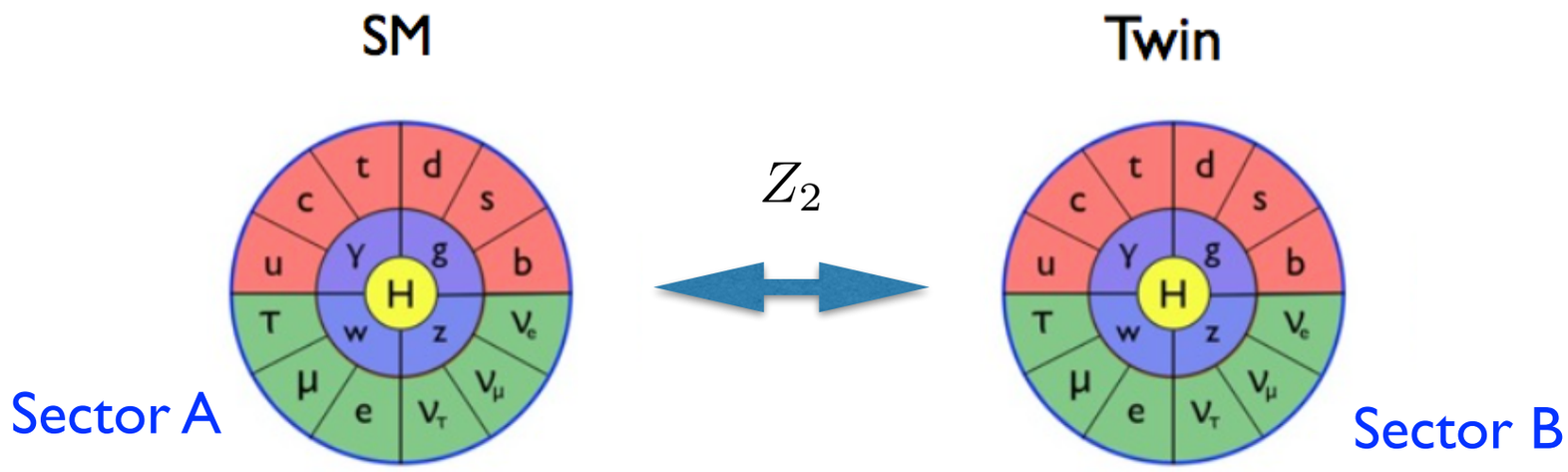
Mirror Standard Model

Z. Chacko, H.-S. Goh, R. Harnik PRL96(2006)231802

N. Craig, S. Knapen, P. Longhi, PRL114(2015)061803

JHY, PRD94(2016)111704

JHY, JHEP1612(2016)143



Top partner carries twin QCD color, twin EW symmetry

Accidental SU(4) symmetry for Higgs Boson

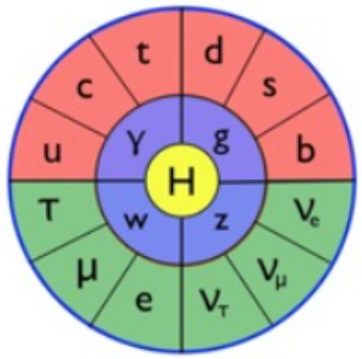
$$H \equiv \left(\begin{array}{c} H_A \\ H_B \end{array} \right) \begin{array}{l} \leftarrow SU(2)_A \\ \leftarrow SU(2)_B \end{array} \Bigg\} \; SU(4) \to SU(3) \quad \text{Higgs as one of 7 PNGBs}$$

Too many particles in hidden sector, Neff problem!

Minimal Neutral Naturalness

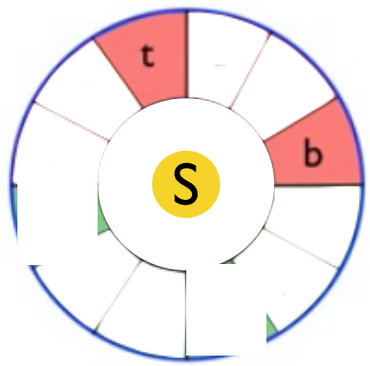
Minimal matter content: two hidden QCD vector-like top partners

SM



$SU(6)$

Minimal Hidden Sector



L.-X. Xu, JHY, S.-h. Zhu 1810.01882

Also L.-X. Xu's talk

Minimal Higgs symmetry: SO(5)/SO(4)

Higgs as one of 4 Goldstone Bosons in SO(5)/SO(4) breaking

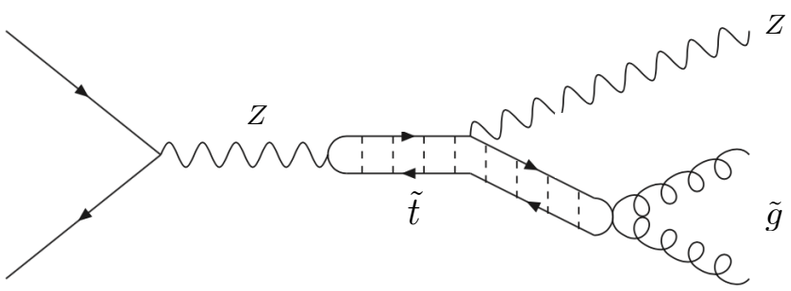
Top partners carry hidden QCD, form quirk hadrons, glueball

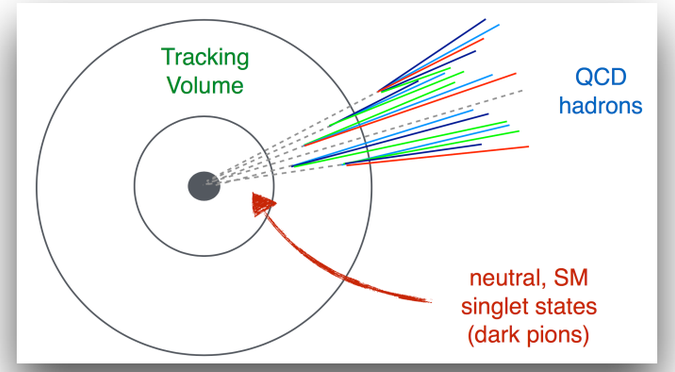
No tree-level potential, radiatively generate Higgs potential

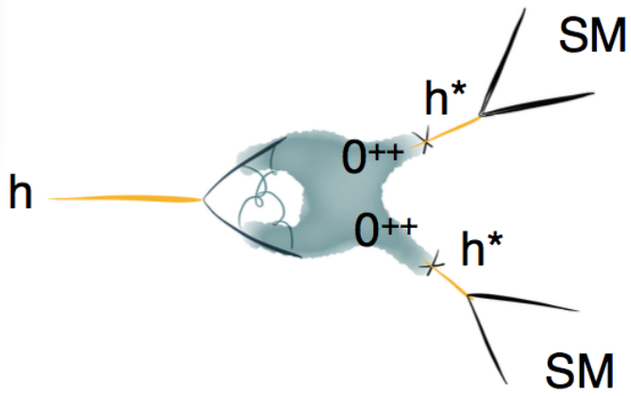
Pheno on Neutral Naturalness

Introduce new particles only in dark sector: dark matter, cosmo

Top partner (in dark sector) cannot be searched via typical channels







mono-Z or Z + displaced vertices

Higgs displaced vertices signature

N. Craig, A. Katz, M. Strassler, R. Sundrum JHEP07(2015)105

New Physics Models

Naturalness	Baryon asymmetry	Neutrino Mass	Dark Matter	Gauge Unification
MSSM	Higgs Singlet	Type-I seesaw	Higgs portal DM	U(1) extensions
NMSSM	Higgs Doublet	Type-II seesaw	Minimal DM	G221
Little Higgs	Higgs Triplet	Type-III seesaw	Singlet-doublet dark matter	G331
Composite Higgs	Type-I seesaw	Inert doublet	Scalar Portal DM	Pati-Salam
Randall-Sundrum	Vector Fermion	Leptoquark	Fermion Portal	SU(5) GUT
Twin Higgs	4th gen. quark		Z-prime Portal	SO(10) GUT
Minimal neutral naturalness	Top Seesaw		Hidden U(N)	
Trigonometric Higgs				

Some models address several problems together

Apologize if not including your favorite model …

Model Classifications

Higgs is not elementary

- Little Higgs
- Composite Higgs
- Randall-Sundrum
- Gauge-Higgs
- Twin Higgs
- Minimal neutral naturalness
- Trigonometric Higgs
- Top Seesaw

Higgs is elementary

- MSSM
- NMSSM
- Higgs Singlet
- Higgs Doublet
- Higgs Triplet
- Type-II seesaw
- Vector Fermion
- 4th gen. quark
- Higgs portal DM
- Minimal DM
- Singlet-doublet dark matter
- Scalar Portal DM
- Fermion Portal
- Z-prime Portal
- Hidden U(N)
- Inert doublet
- U(1) extensions
- G221
- G331
- Pati-Salam
- SU(5) GUT
- SO(10) GUT

Simplified Models

UV model

Higgs is not elementary

UV model

Integrate out TeV heavy states

Higgs is elementary

UV model

Simplified model

Goldstone Higgs, other Goldstone scalar

Higgs, additional scalar, EW fermion
neutralino, etc

Goldstone Higgs

could have other light Goldstone

Only Higgs

SM Higgs

with exotic decay

Higgs + scalar

Extended scalar model

Integrate out sub-TeV scalar

Higgs EFT

Strongly interacting Higgs EFT

Weakly interacting Higgs EFT

Higgs as Pseudo-Goldstone

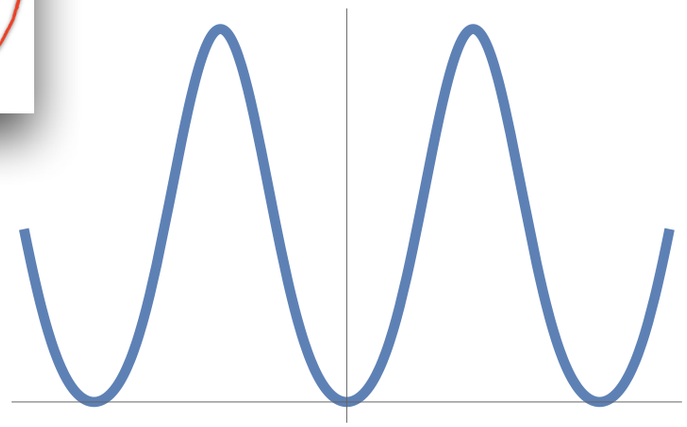
Deviation from SM Higgs couplings

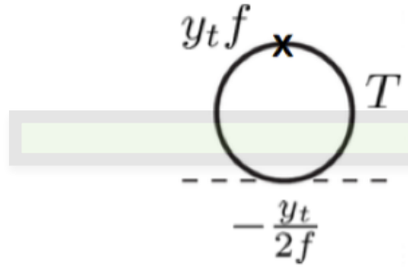
Higgs couplings deviate SM couplings (misalignment, form factor)

$$\frac{g_{hff}}{g_{h_{\rm SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \text{TeV}}{f}\right)^2 \qquad \frac{g_{hhtt}}{g_{h_{\rm SM}tt}} \sim -3\% \left(\frac{1\text{TeV}}{f}\right)^2$$

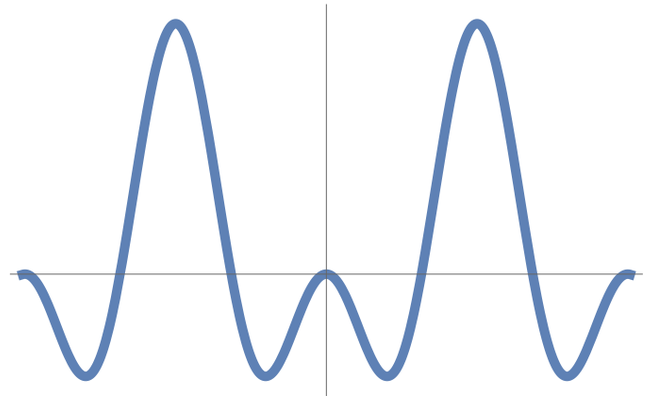
Different Potential than SM Higgs potential

Pion potential





Pseudo-Goldstone Higgs



$$V(\phi) = -a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

Radiative symmetry breaking mechanism

diHiggs signature!

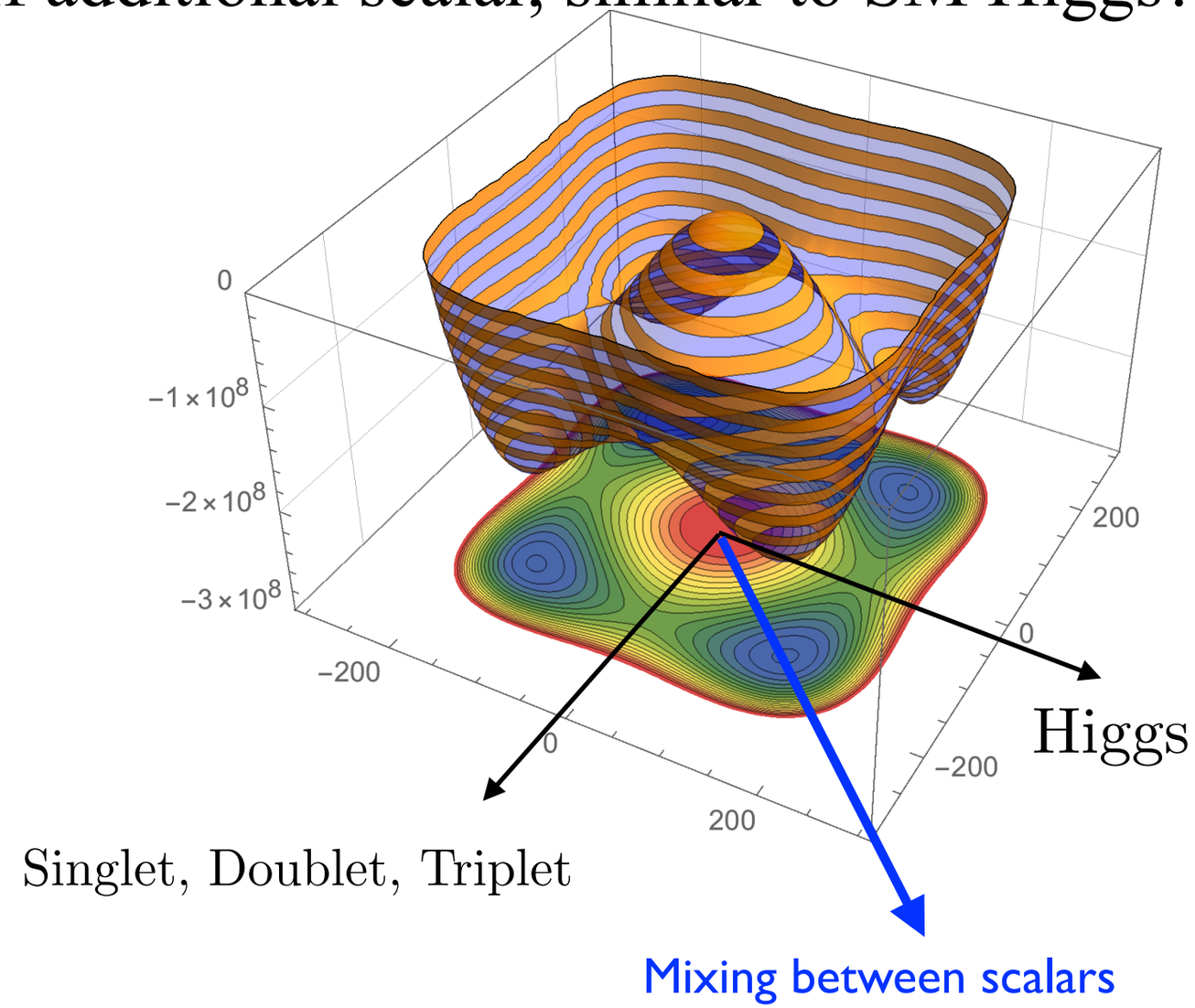
JHY, PRD94(2016)111704
JHY, JHEP1612(2016)143
Foadi, J. Laverty, C. Schmidt, JHY, JHEP1006(2010)026

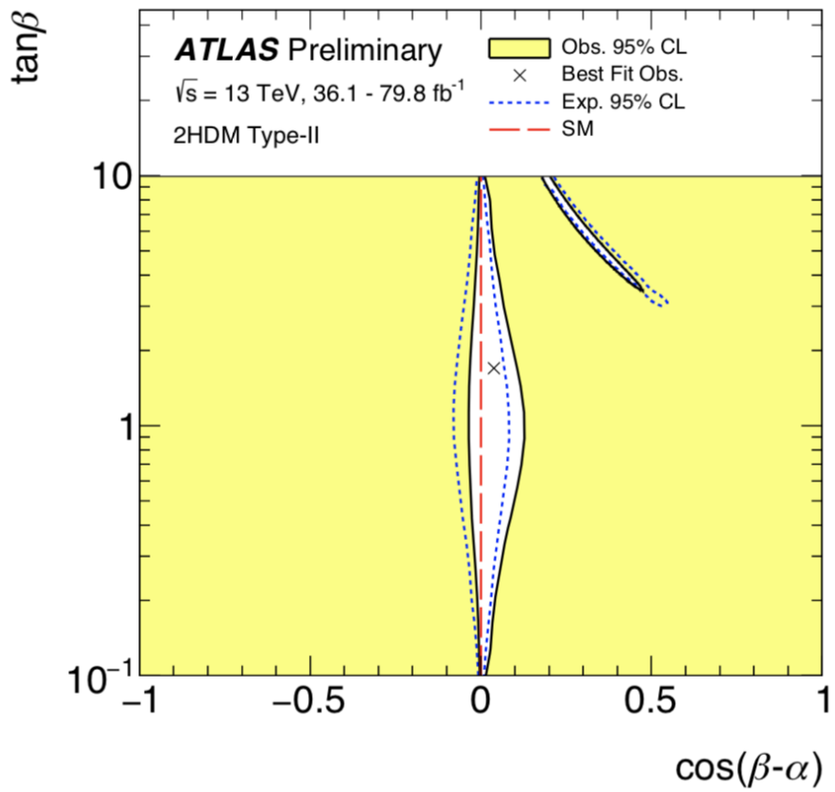
Csaki, Ma, Shu, JHY, 1810.07704
Csaki, Ma, Shu, PRL119(2017)131803
Marzocca, Serone, Shu, JHEP 1208(2012)013

Higgs as Elementary Scalar

If no additional scalar, just SM Higgs (could have invisible decay)

If additional scalar, similar to SM Higgs? New scalar could have VEV





If VEV is zero, no mixing, scalar could be dark matter!

Extended Scalar Models

Higgs Singlet

NMSSM limit

Higgs Doublet

MSSM Higgs

Higgs Triplet

Type-II seesaw

Inert Higgs

Deviation
from SM
Higgs couplings

$\frac{g_{hff}}{g_{h_{\rm SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{\rm SM}VV}} \sim$ mixing angle

$g_{hff} \sim \tan\beta, \cot\beta$

No mixing

New scalars
Resonance
below TeV scale

$H \to hh$

$H^+ \to \tau\nu$ $A \to hZ$

$H^+ \to hW^+$ $H \to AZ$

$H \to hh, AA, bb, tt$

$H^{++} \to \ell^+\ell^+$

$H^{++} \to W^+W^+$

$H^+ \to WZ$

$H^+ \to W^+ + \text{MET}$

J.-Y. Cen, J.-H. Chen, X.-G. He, G. Li, J.-Y. Su, W. Wang, 1811.00910

J. Ren, R.-Q. Xiao, M. Zhou, Y. Fang, H.-J. He, W. Yao, JHEP1806(2018)090

F. Kling, J. M. No, S. Su, JHEP1609(2016)093

X. F. Han, L. Wang, J. M. Yang, MPLA31(2016)1650178

N. Chen, J. Li, Y. Liu, Z.w. Liu, PRD91(2015)075002

N. Craig, F. D'Eramo, P. Draper, S. Thomas, H. Zhang, JHEP 1506(2015)137

Z. Kang, J. Li, T.-j. Li, Y. Liu, G.-Z. Ning, EPJC75(2015)574

J. Hajer, Y.-Y. Li, T. Liu, J. Shiu, JHEP1511(2015)124

Q.-H. Cao, X. Wan, X.-p. Wang, S.-h. Zhu, PRD87(2013)055022

Du, Dunbrack, Ramsey-Musolf, JHY, 1810.09450

Y. Cai, T. Han, T. Li, R. Ruiz, F.Phy6(2018)40

Z.-L. Han, R. Ding, Y. Liao, PRD92(2015)033014 PRD91(2015)033014

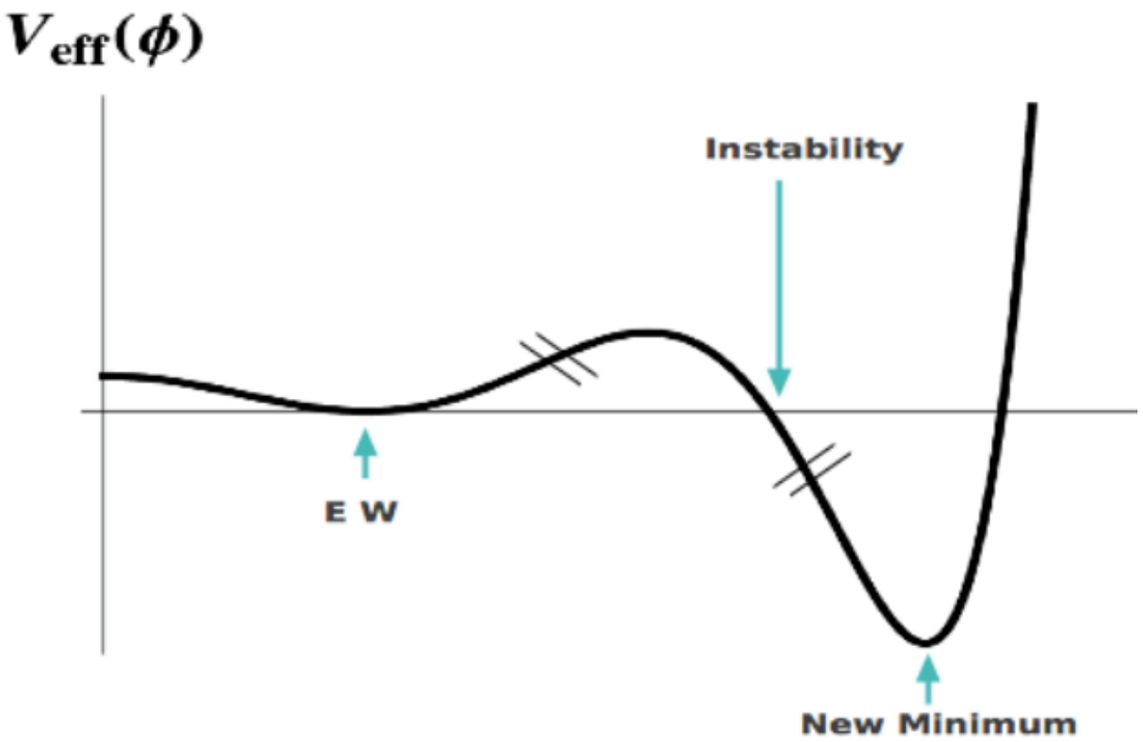
P. F. Perez, H. Patel, M. Ramsey-Musolf, K. Wang, PRD79(2009)055024

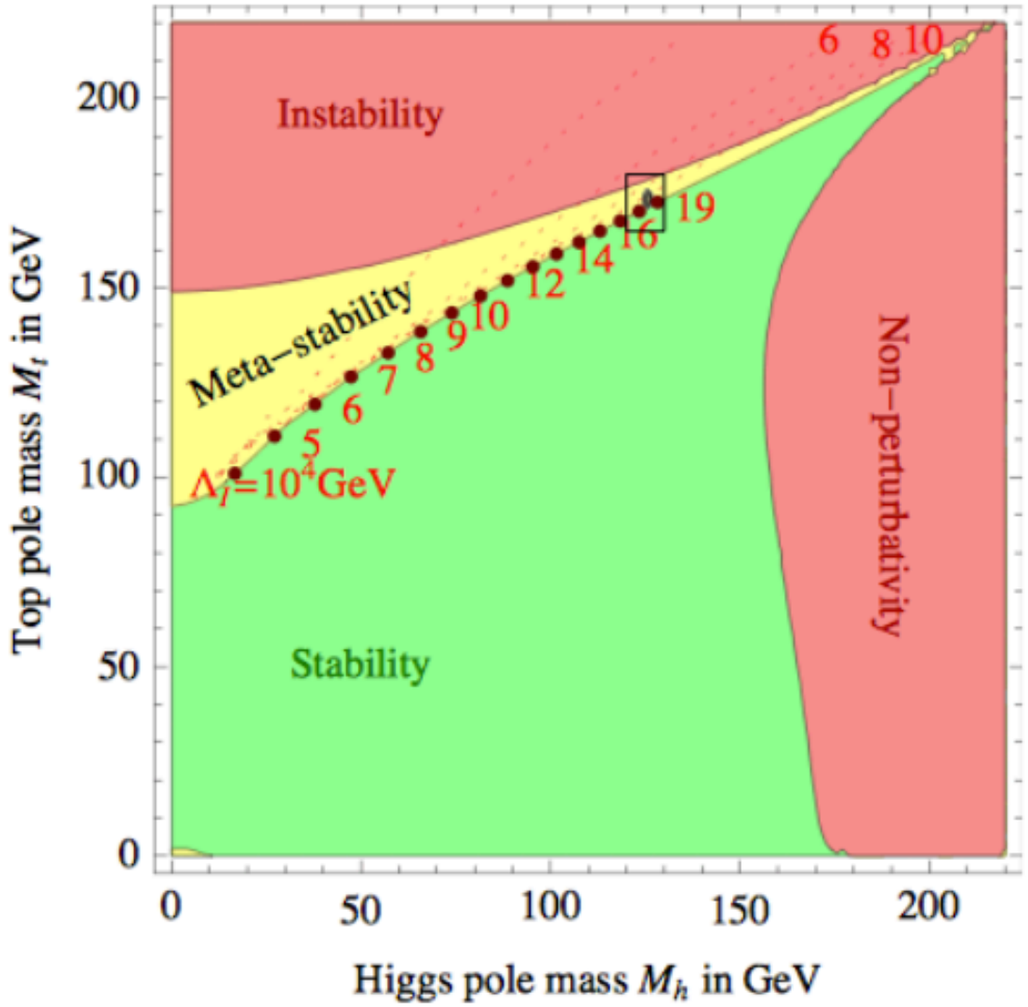
Q.-H. Cao, E. Ma, G. Rajasekaran, PRD76(2007)095011

P. F. Perez, T. Han, G. Huang, T. Li K. Wang, PRD78(2008)015018

Vacuum Stability

Higgs potential at large field value





$$\mu\frac{d\lambda(\mu)}{d\log(\mu)} = (\ \#\ \lambda^2\ + \ldots\ -\#\ h_t^4\ + \ldots) + \ldots$$

Buttazzo, Degrassi, Giardino, et.al, 13'

Additional scalar helps Higgs quartic positive up to Planck scale

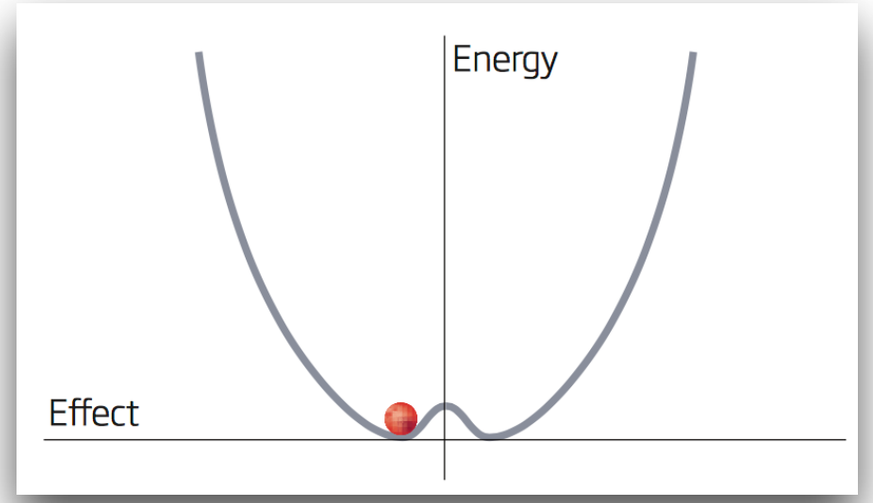
Other Goldstone or
New elementary scalar

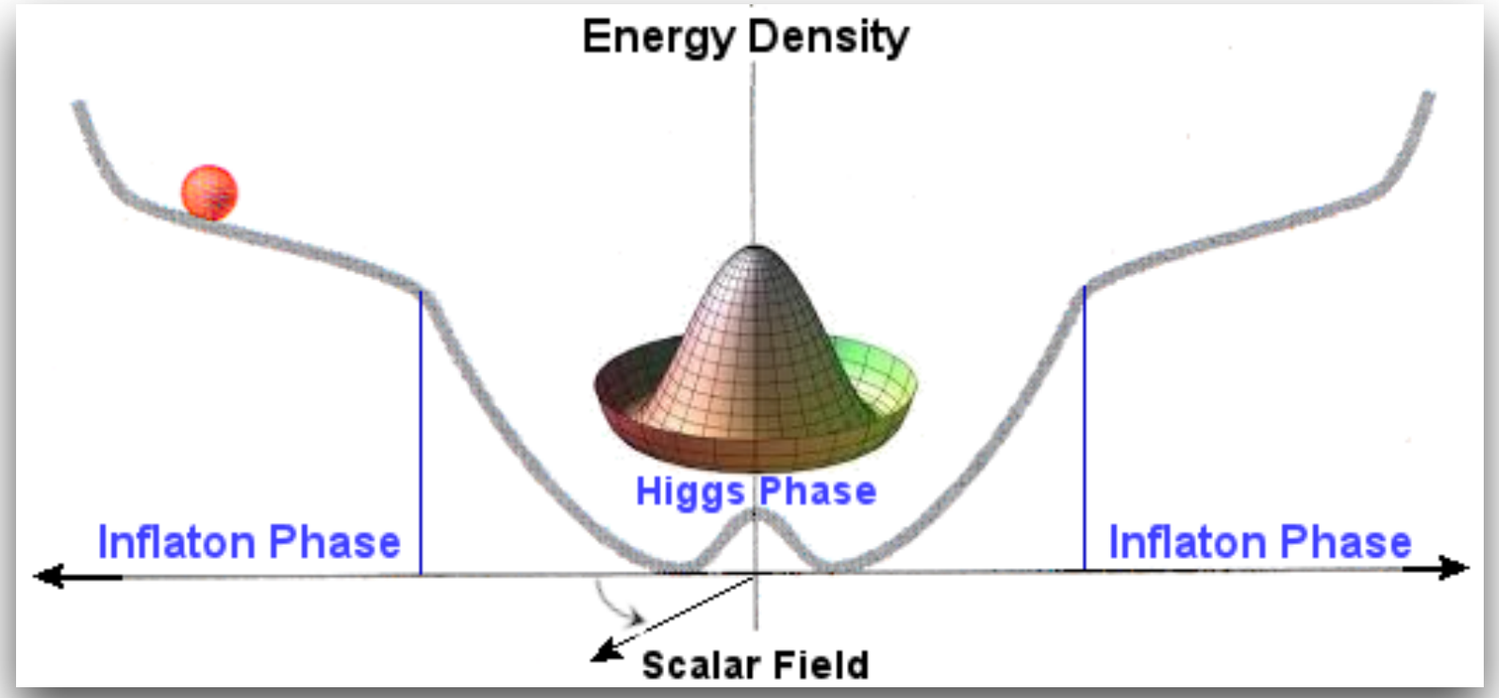
J. Elias-Miro, J. Espinosa, G. Giudice, A. Strumia, JHEP1206(2012)031

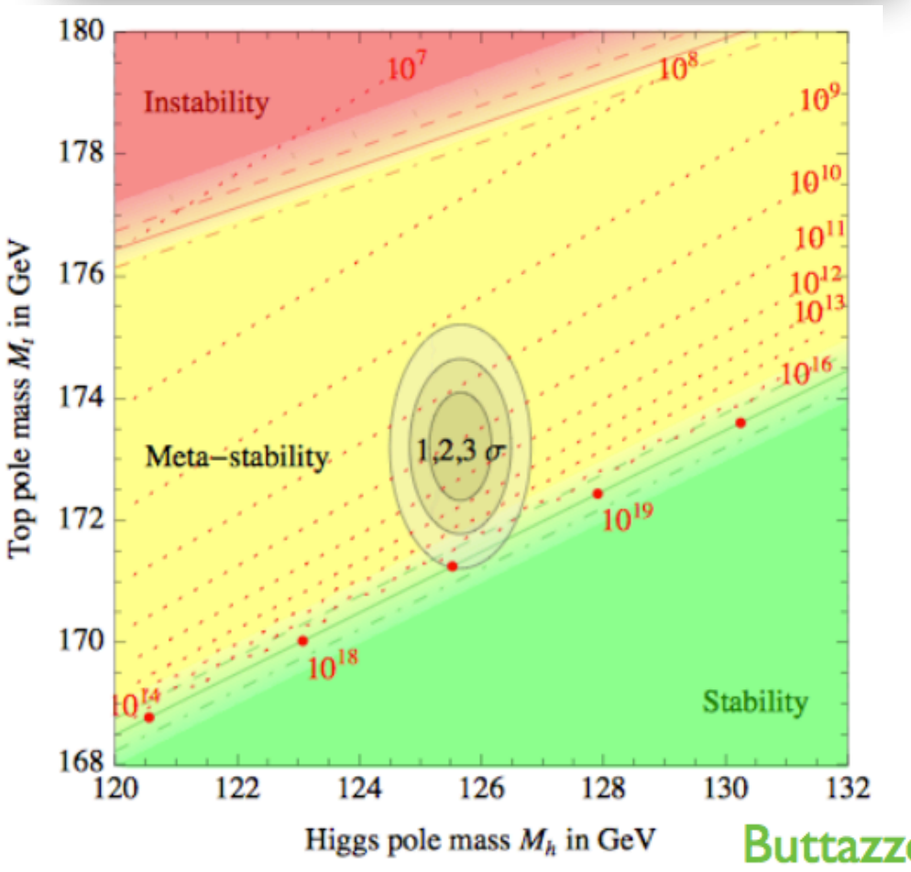
M.-L. Xiao, JHY, PRD90(2014)014007

Higgs Inflation

$$S = \int d^4x\sqrt{-g}\left(\xi H^2 R + \mathcal{L}_{\rm Higgs} + \cdots\right)$$







$$V_E = \frac{\lambda\phi^4}{4(1+\xi\phi^2/M_p^2)^2} \rightarrow \text{flat at large } \phi$$

Additional scalar helps Higgs inflation!

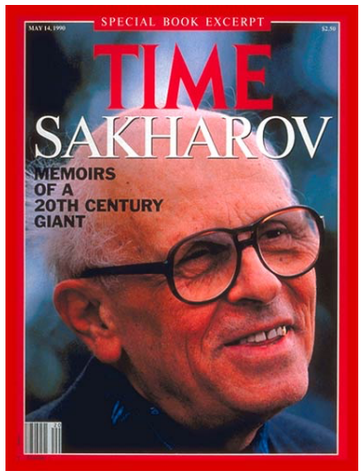
Aravind, Xiao, JHY, PRD93(2016)123513

H.-J. He, Z.-Z. Xianyu, JCAP1410(2014)019

H.-Y. Chen, I. Gogoladze, S. Hu, T.-j. Li, L. Wu, 1805.00161

Buttazzo, Degrassi, Giardino, et.al, 13'

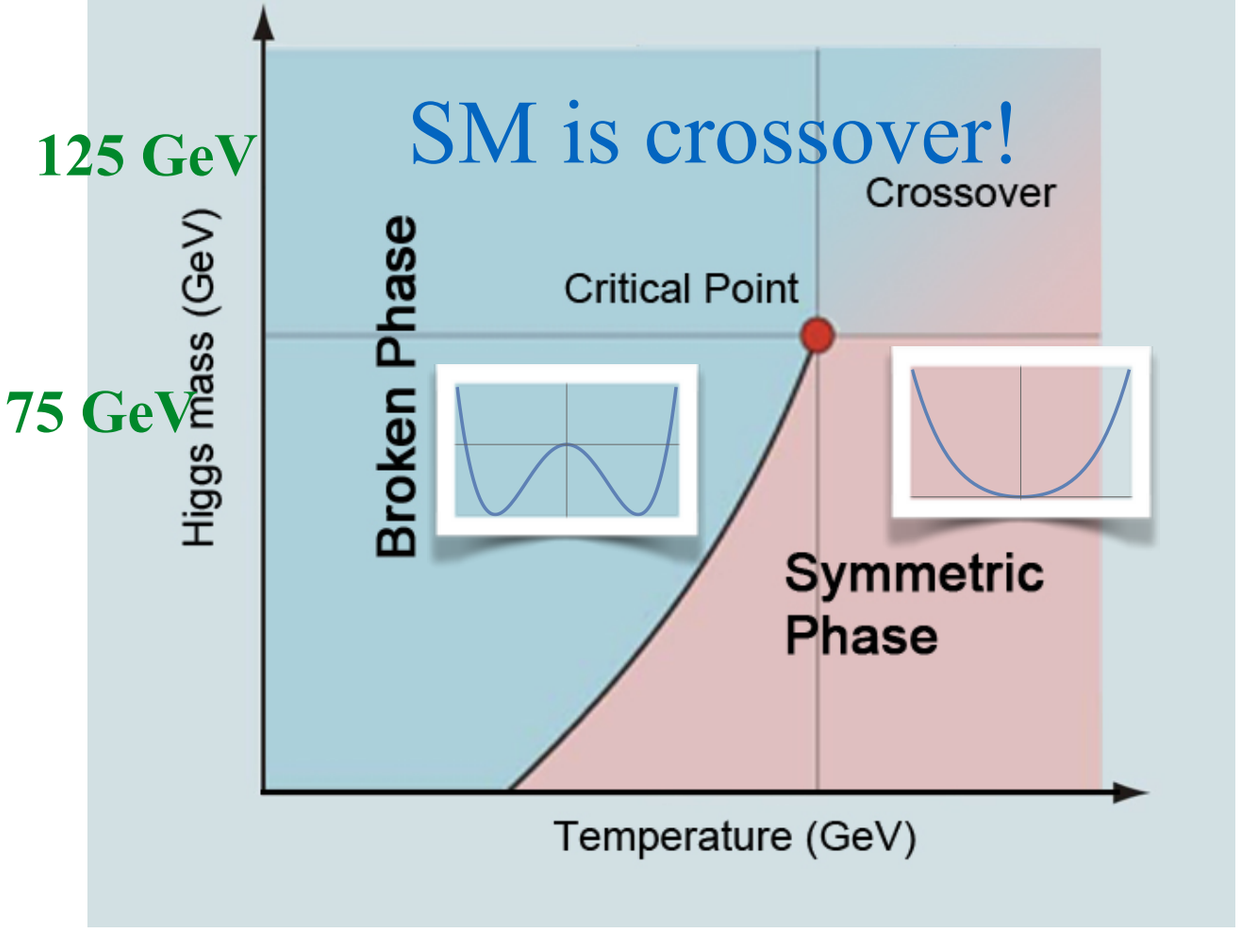
Electroweak Baryogenesis

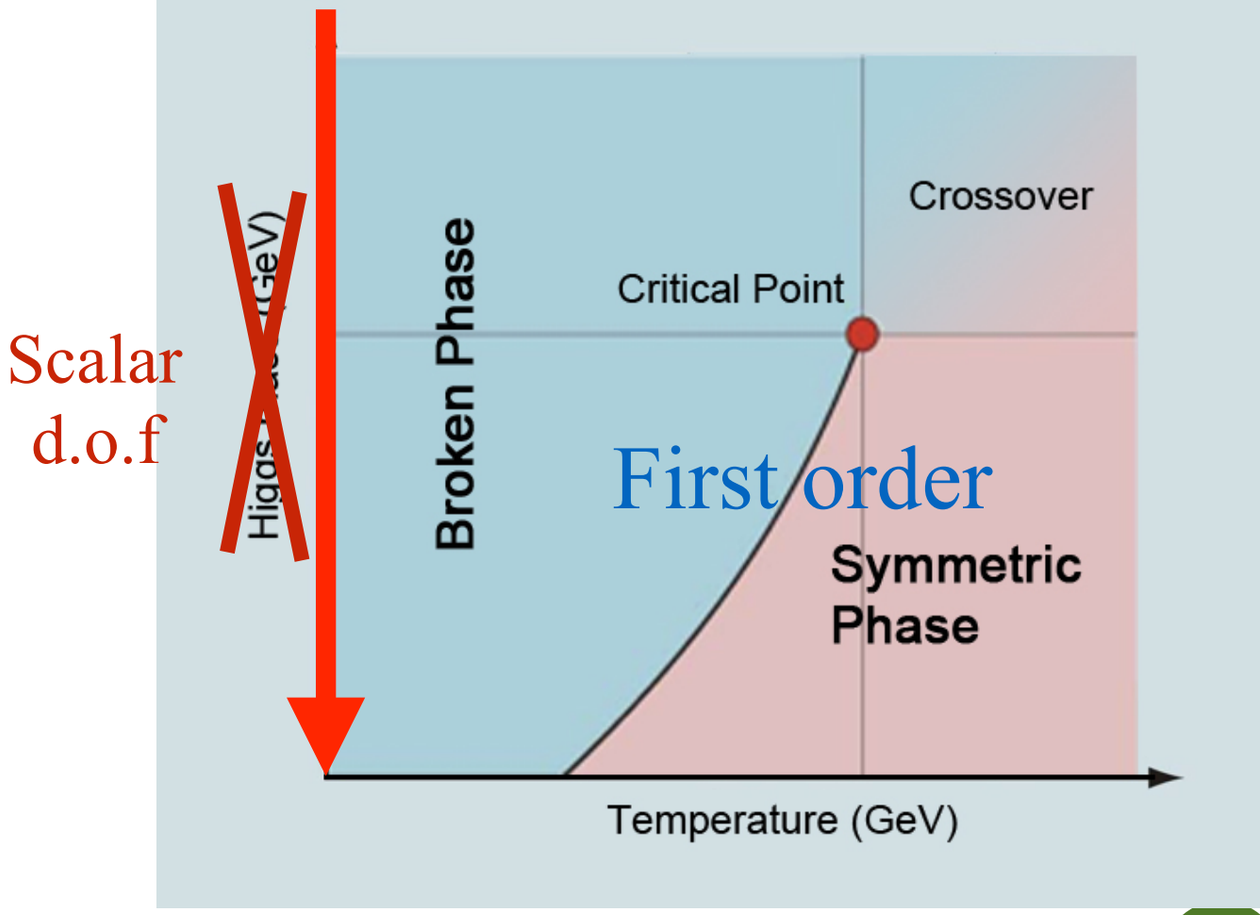


Baryon number violation

C and CP violation

Departure from equilibrium at early universe!

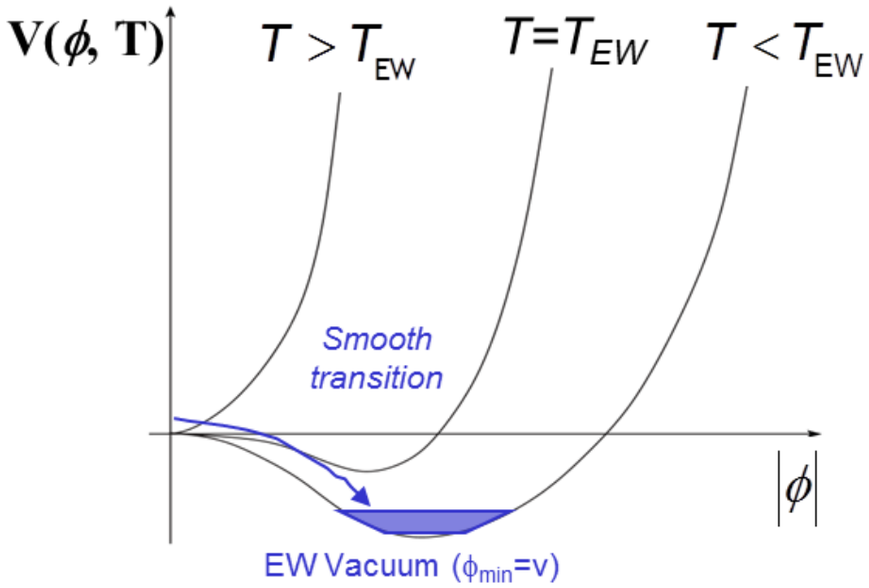


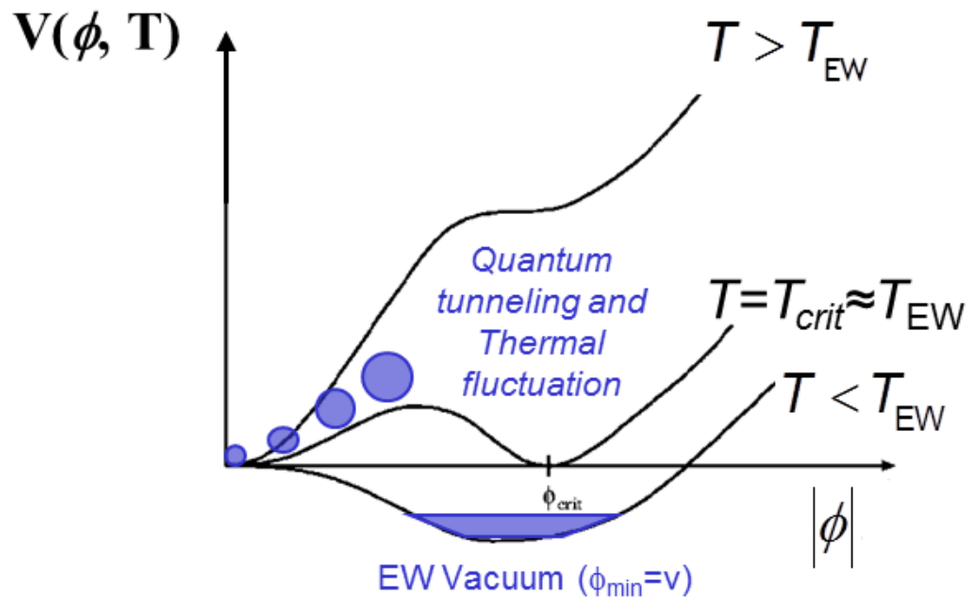


First Order Phase Transition

Additional scalar helps develop loop or tree level barrier

(Other Goldstone or New elementary scalar)





$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$

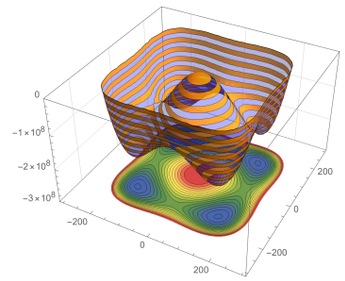
- *Loop level barrier*

$$E = \frac{1}{2\pi v_0^3}\left(2m_W^3 + m_Z^3 + \text{new scalar mass}\right)$$

Huang, JHY, PRD98(2018)095022

A. Katz, M. Perelstein, M. Ramsey-Musolf, P.Winslow, PRD92(2015)095019

- *Tree level barrier*



M.-L. Xiao, JHY, PRD94(2016)015011

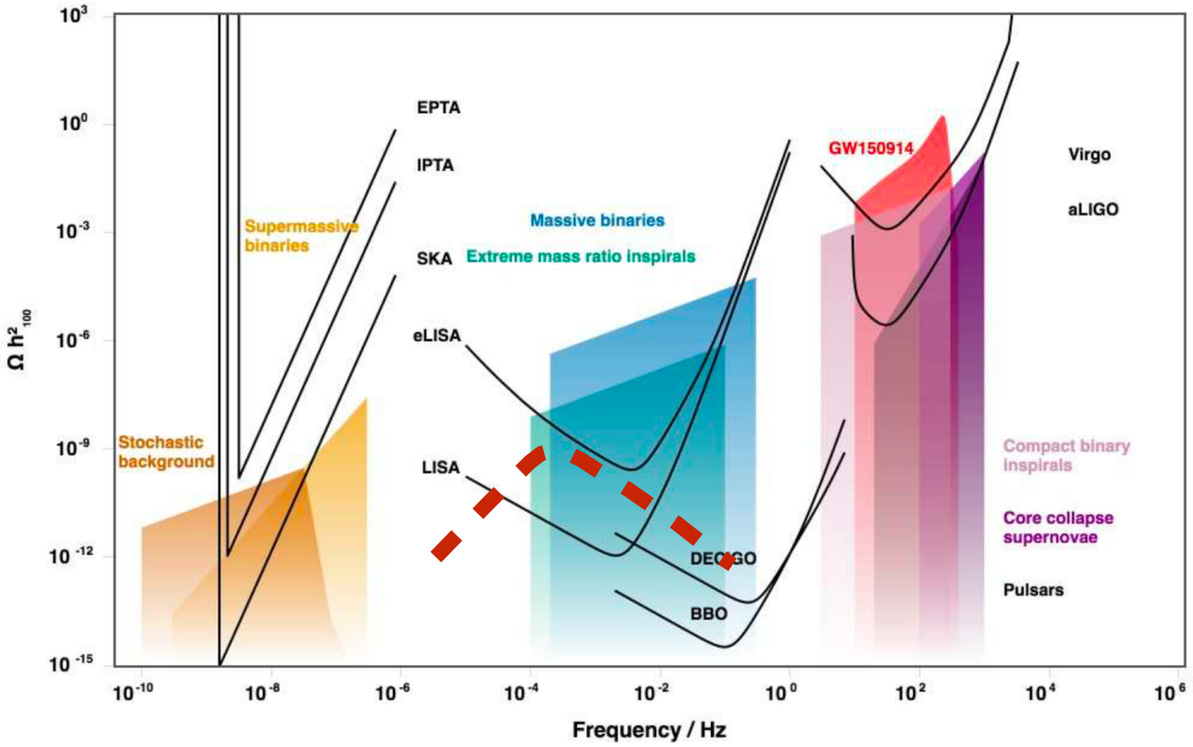
W. Huang, Z. Kang, J. Shu, P.Wu, J.-M.Yang, PRD91(2015)025006

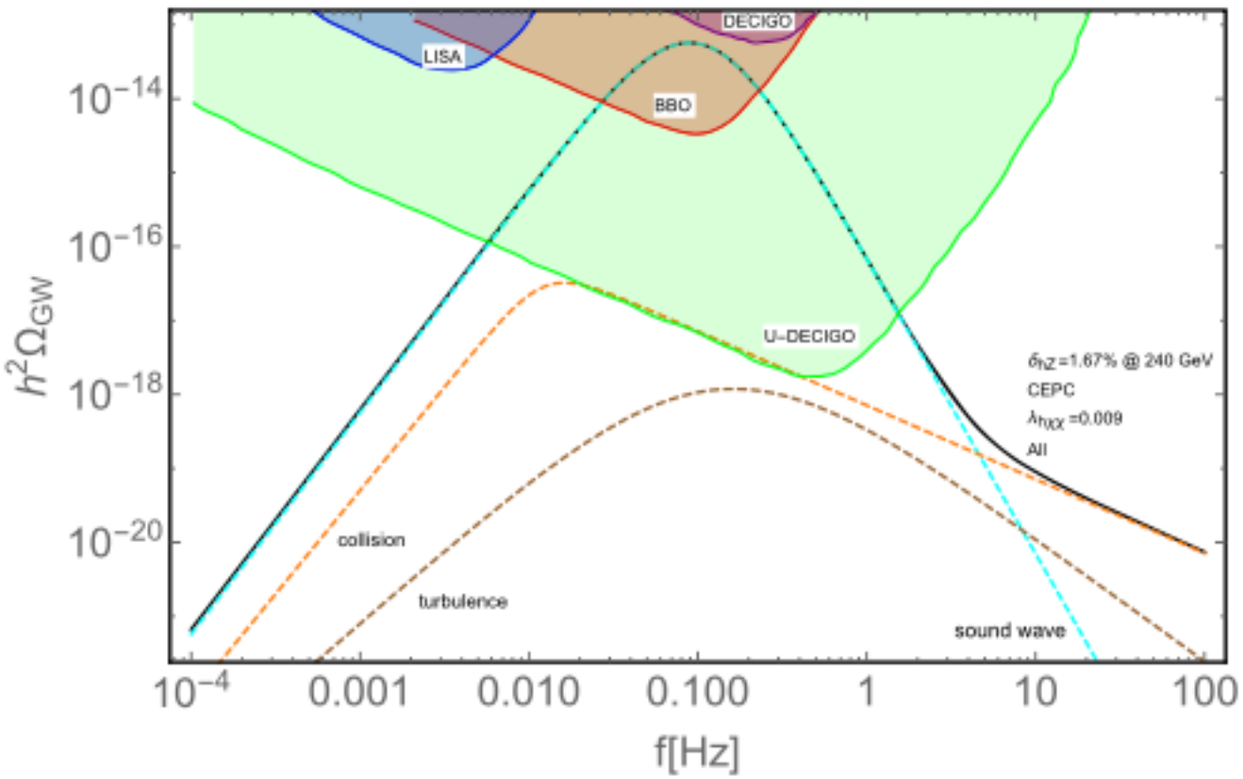
S. Profumo, M. Ramsey-Musolf, C.Wainwright, P.Winslow, PRD91(2015)035018

Gravitational Wave (GW)

First order phase transition generates GW signal

Interplay among baryon asymmetry, collider and GW signatures





F. P. Huang, JHY, PRD98(2018)095022

Q.-H. Cao, F. P. Huang, K.-P. Xie, X.-m.Zhang, CPC42(2018)023103

W. Chao, H.-K. Guo, J. Shu, JCAP 1709(2017)009

R.-G. Cai, M. Sasaki, S.-J. Wang, JCAP 1708(2017)004

F. P. Huang, P.-H. Gu, P.-F.Yin, Z.-H.Yu, X.-m. Zhang, PRD93(2016)103515

Bottom up Approach

UV model

Higgs is not elementary

Higgs is elementary

Integrate out TeV heavy states

Simplified Model

Goldstone Higgs

Only Higgs

SM Higgs

with exotic decay

Higgs + scalar

Extended scalar model

Integrate out sub-TeV scalar

Higgs EFT

Strongly interacting Higgs EFT

SILH basis

Weakly interacting Higgs EFT

Warshaw basis

Electroweak breaking scale

Higgs effective couplings

m_{Higgs}

Light Scalar Still Alive!

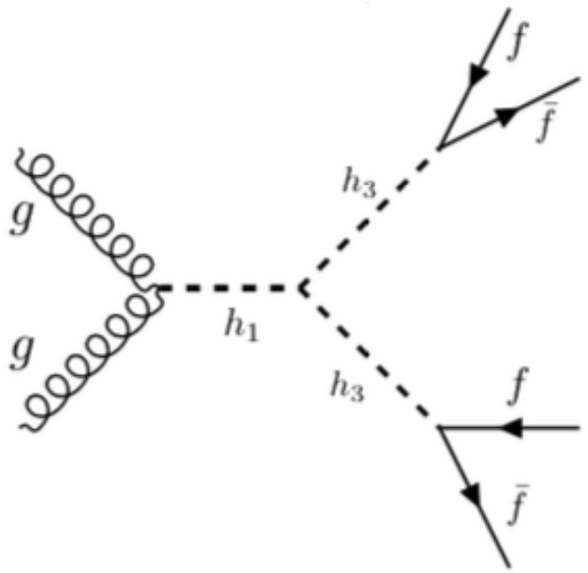
Caveat: light scalar (lighter than 100 GeV) cannot be integrated out!

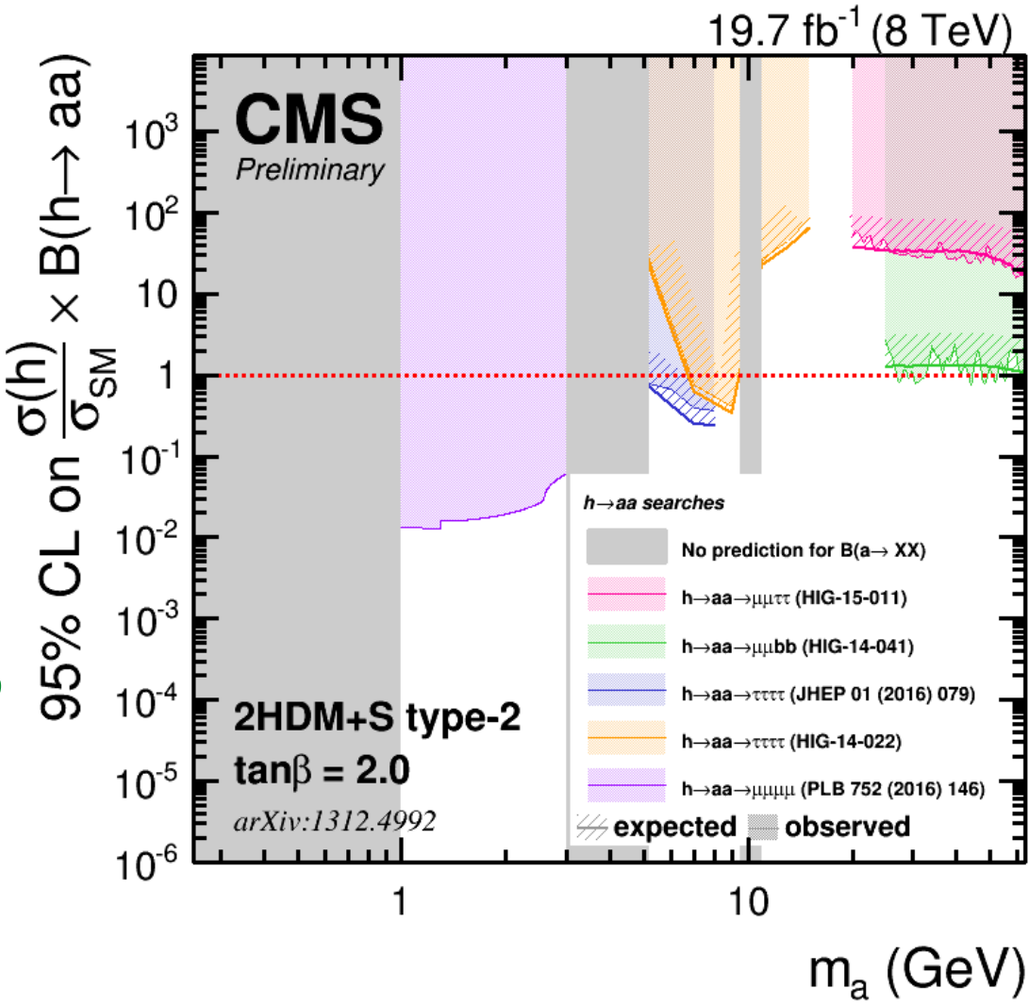
Light pseudo-Goldstone

Pseudo-scalar in Complex Higgs Singlet

NMSSM

Higgs to aa searches





L. Wang, J.-M. Yang, M. Zhang, Y. Zhang, PLB788(2019)519

J. Liu, Y.-L. Tang, C. Zhang, S.-h. Zhu, EPJC77(2017)457

X. Liu, L. Bian, X.-Q. Li, J. Shu, NPB909(2016)507

W. Chao, M. Ramsey-Musolf, JHY, PRD93(2016)095025

Higgs Effective Field Theory

If new physics states are heavy, Higgs effective theory

New physics scale

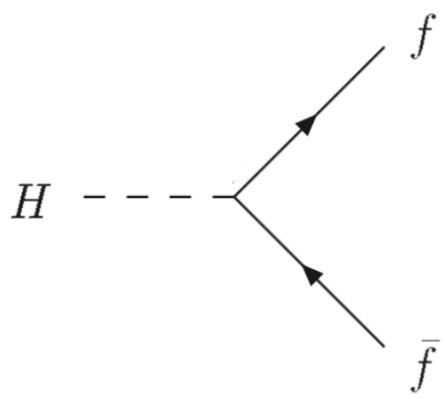
$$\mathcal{L} = \mathcal{L}^{\text{eff}}_{\text{Gravity}} + \underbrace{\mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{EW}}}_{\mathcal{L}_{SM}} + \mathcal{L}^{NP}_{\text{heavy}}$$

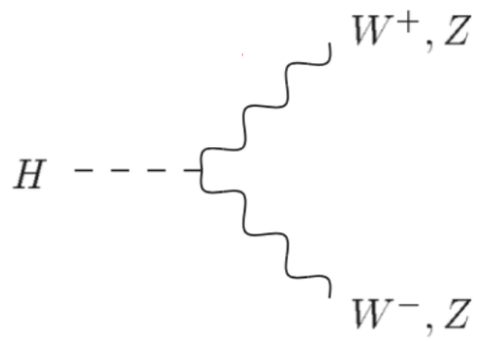
New Physics Model

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{C_i^{(5)}}{\Lambda_{NP}} Q_i^{(5)} + \frac{C_i^{(6)}}{\Lambda_{NP}^2} Q_i^{(6)} + \cdots$$

$SU(2)_L \times U(1)_Y$ invariant
Effective Field Theory

$v \sim 246$ GeV





Effective Couplings
with anomalous couplings
and exotic decays

$m_{\text{Higgs}} = 125$ GeV

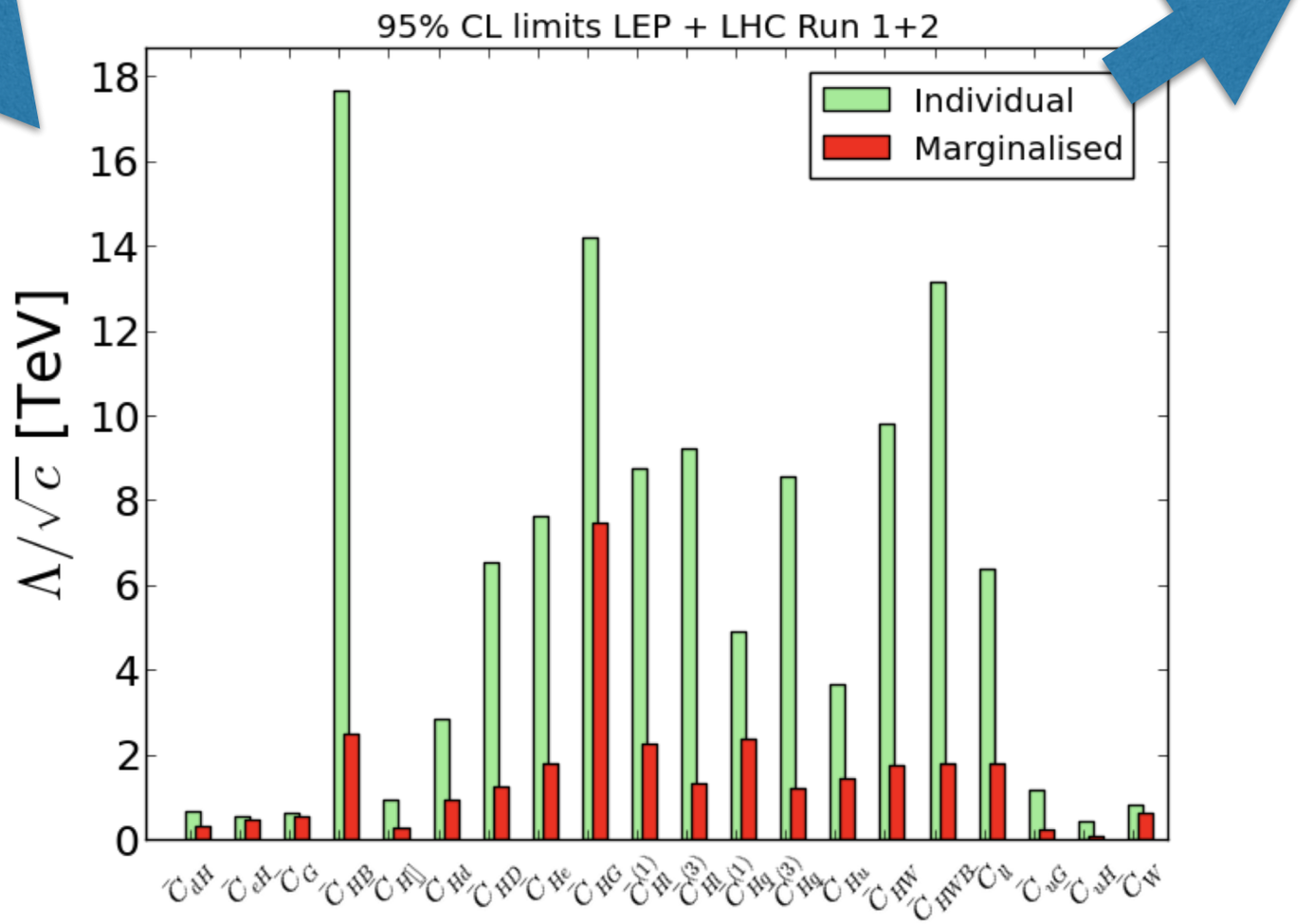
Global Fit on Higgs EFT

Higgs EFT Operators

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H \rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H \rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H \rvert^2 \bar{Q}_L \tilde{H} u_R + \text{h.c.}$
$\mathcal{O}_{BB} = g'^2 \lvert H \rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H \rvert^2 \bar{Q}_L H d_R + \text{h.c.}$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H \rvert^2 \bar{L}_L H e_R + \text{h.c.}$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^{b}_{\nu\rho} W^{c\,\rho\mu}$

Higgs EFT

New Physics models



J. Ellis, C. Murphy, V. Sanz, T. You, JHEP1806(2018)146

Additional Scalar

UV model

Higgs is not elementary

Higgs is elementary

Integrate out TeV heavy states

Simplified Model

Goldstone Higgs

Only Higgs

SM Higgs

with exotic decay

Higgs + scalar

Extended scalar model

Integrate out sub-TeV scalar

Higgs EFT

Strongly interacting Higgs EFT

SILH basis

Weakly interacting Higgs EFT

Warshaw basis

Electroweak breaking scale

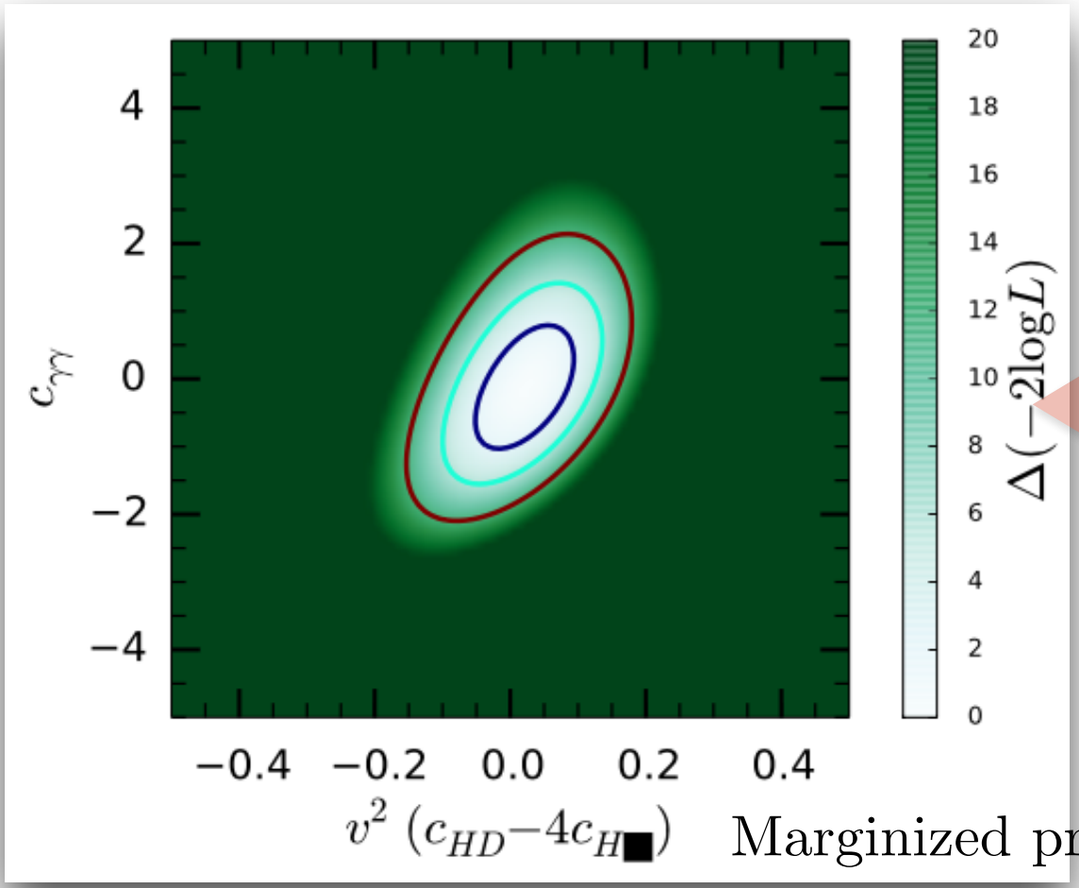
Higgs effective couplings

m_{Higgs}

Scalar Models and HEFT

Higgs EFT

$$
\begin{aligned}
Q_H &= (H^\dagger H)^3, & Q_{eH} &= (H^\dagger H)(\bar{L} e_R H), \\
Q_{H\Box} &= (H^\dagger H)\Box(H^\dagger H), & Q_{uH} &= (H^\dagger H)(\bar{Q} u_R \tilde{H}), \\
Q_{HD} &= (D^\mu H)^\dagger H H^\dagger (D_\mu H), & Q_{dH} &= (H^\dagger H)(\bar{Q} d_R H).
\end{aligned}
$$



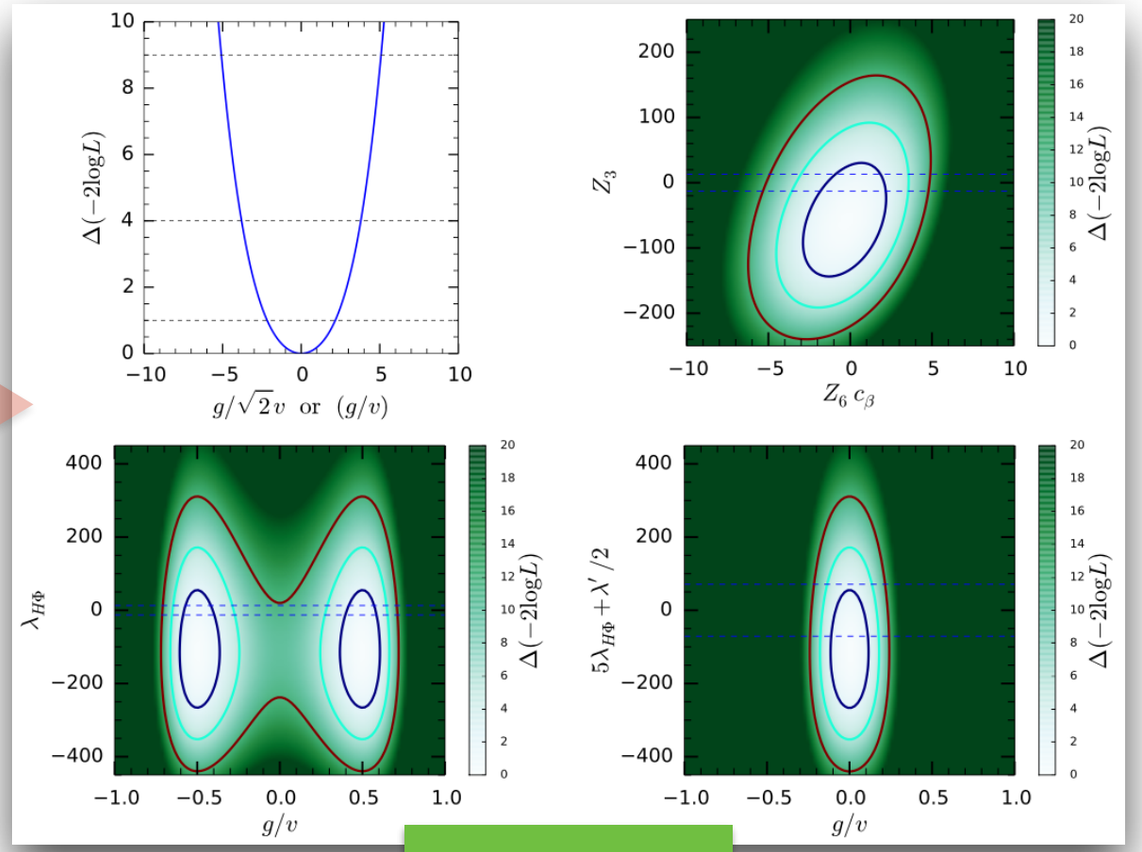
Marginized profile

Extended scalar

Model parameters

Higgs Singlet

Higgs Doublet



Higgs Triplet

T. Corbett, A. Joglekar, H.-L. Li, JHY, JHEP1805(2018)061

Higgs at HL-LHC and CEPC/SppC

Deviation from SM Higgs couplings

Different Potential than SM Higgs potential

New Couplings other than SM Higgs couplings

New scalars Resonance below TeV scale

See Qing-Hong Cao's talk on CEPC physics

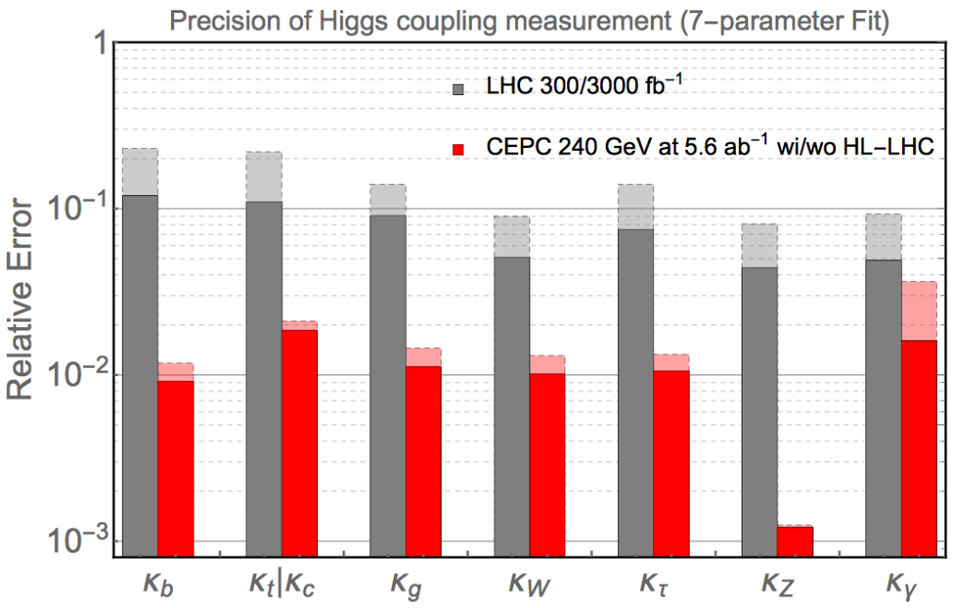
Precision Higgs Coupling

Deviation
from SM
Higgs couplings

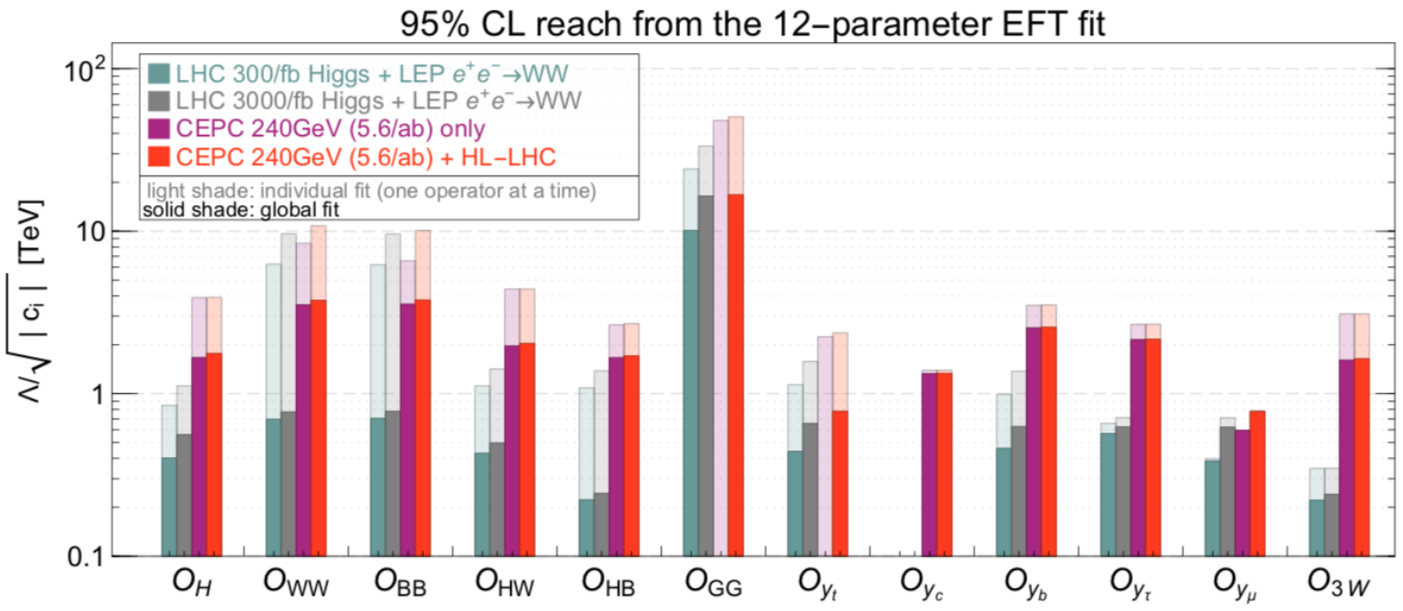
Deviation from SM coupling is indirect sign of new physics!

$$\kappa \equiv \frac{\delta g_h}{g_h} \sim 10\%(\mathrm{HL-LHC}) \rightarrow 1\%(\ \mathrm{CEPC})$$

effective couplings



Higgs EFT



F. An, et.al. Precision Higgs Physics at CEPC, 1810.09037

S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, JHEP1802(2018)178

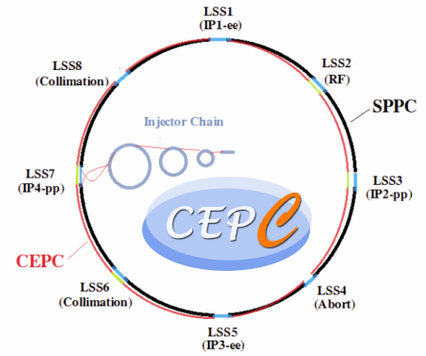
W. H. Chiu, S. C. Leung, T. Liu, K. F. Lyu, L.-T. Wang, JHEP1805(2018)081

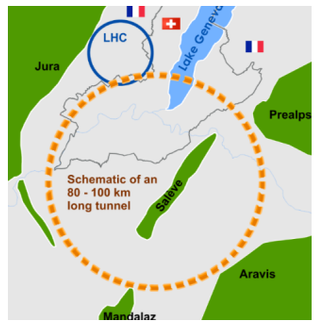
S.-F. Ge, H.-J. He, R.-Q. Xiao, JHEP1610(2016)007

Higgs Self Coupling

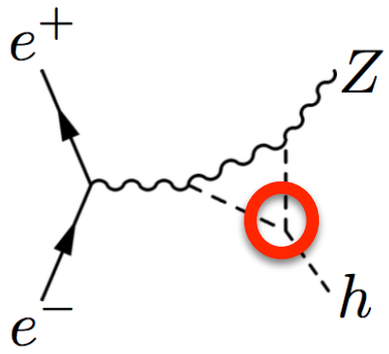
Different Potential than SM Higgs potential

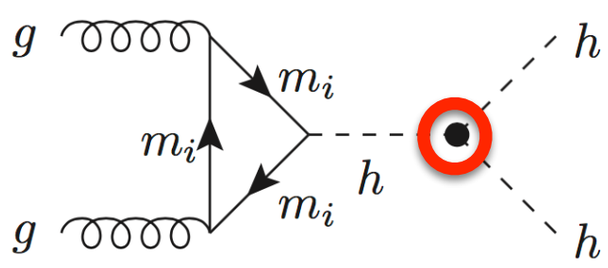
Could determine self coupling, address nature of Higgs





$$\frac{\delta\lambda}{\lambda} \sim 25\%(\text{CEPC}) \to 8\%(100\ \text{TeV})$$





D. Goncalves, T. Han, F. Kling, T. Plehn, M. Takeuchi, PRD97(2018)113004

Q.-H. Cao, G. Li, B. Yan, D.-m. Zhang, H. Zhang, PRD96(2017)095031

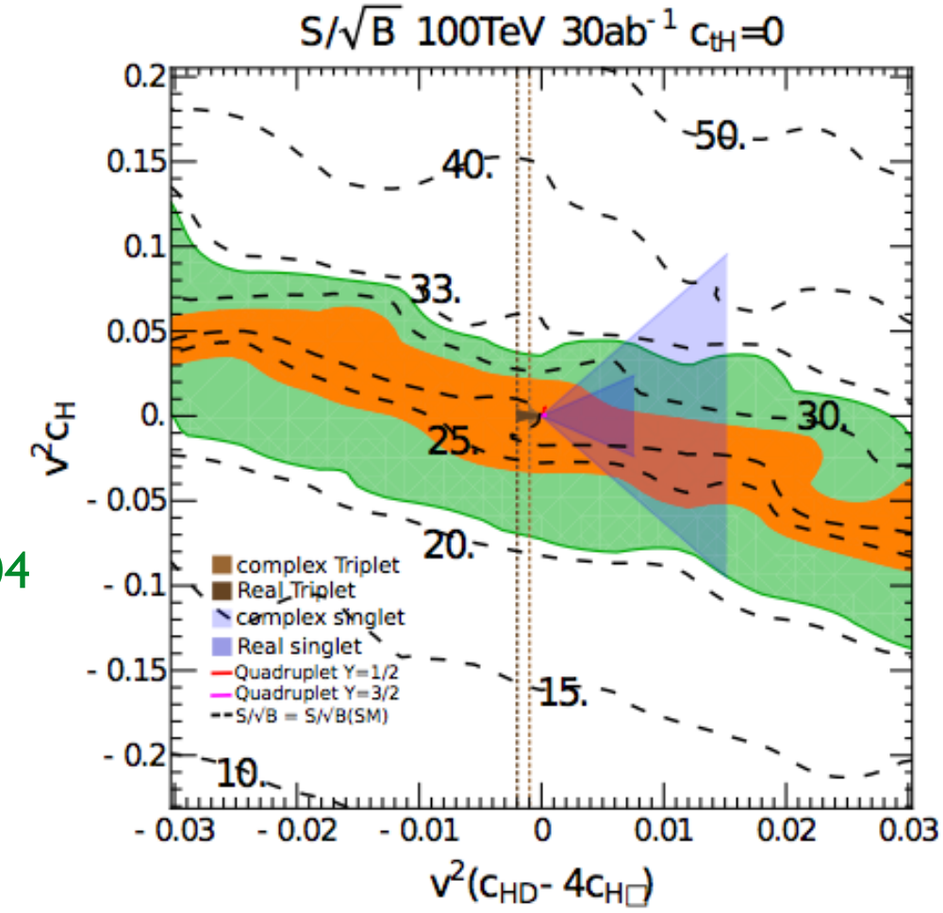
X. Zhao, Q. Li, Z. Li, Q.-S. Yan, CPC41(2017)023105

H. J. He, J. Ren, W. Yao, PRD93(2016)015003

F. Goertz, A. Papaefstathiou, L. L. Yang, J. Zurita, JHEP1504(2015)167

L. Wu, J. M. Yang, C.-P. Yuan, M. Zhang, PLB747(2015)378

Distinguish different scalar multiplet



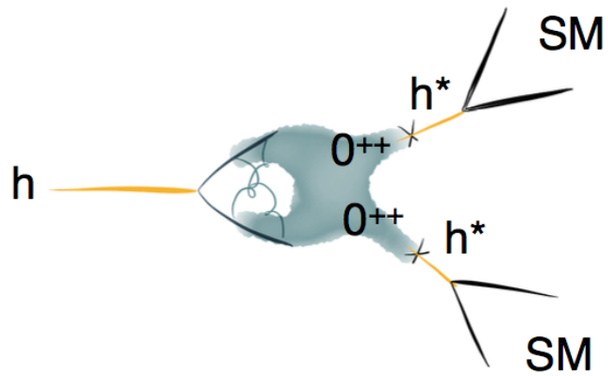
T. Corbett, A. Joglekar, H.-L. Li, JHY, JHEP1805(2018)061

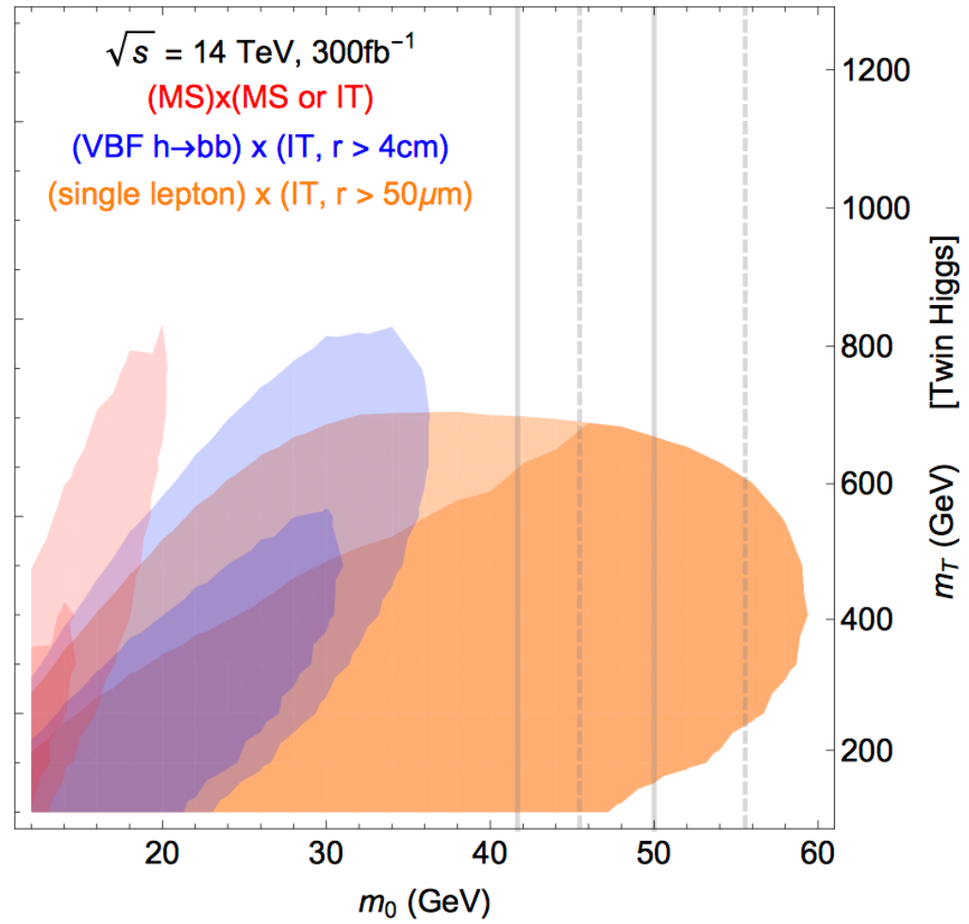
Higgs Exotic Couplings

New Couplings

other than SM Higgs couplings

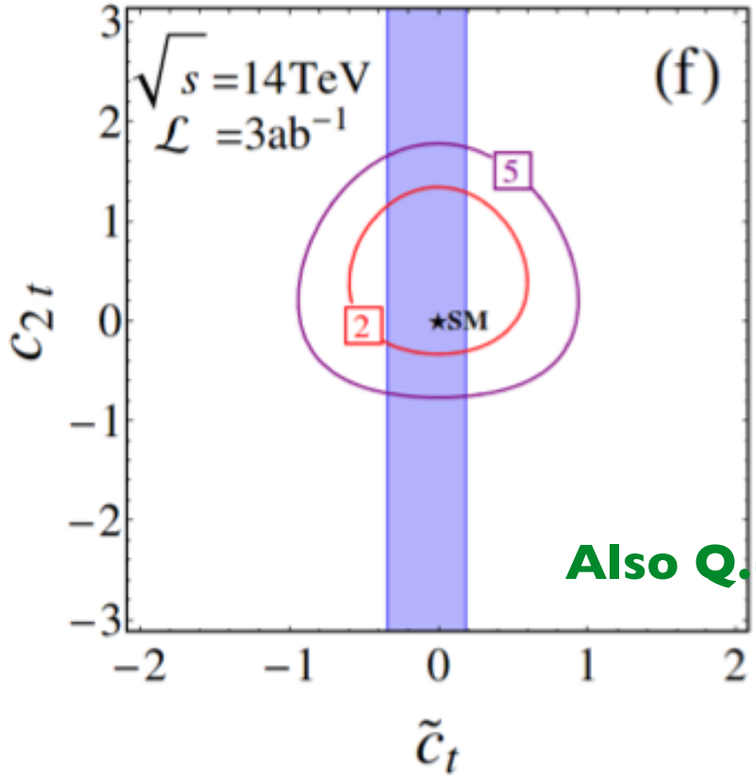
Displaced vertices





Z. Chacko, D. Curtin, C. Verhaaren, PRD94(2016)011504

CP-odd tth and tthh coupling

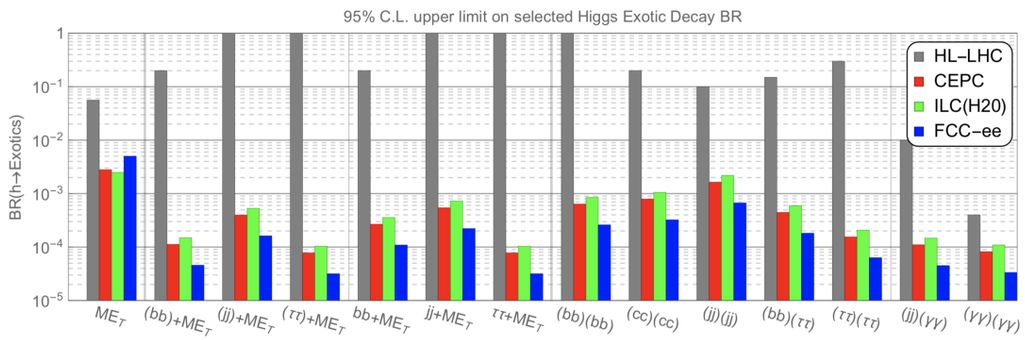


Also Q.-H. Cao's talk

Q.-H. Cao, S.-L. Chen, Y. Liu, PRD95(2017)053004

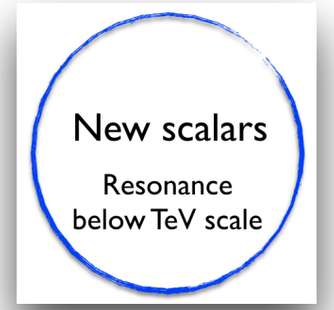
J. Li, Z.-G. Si, L. Wu, J. Yue, PLB779(2018)72

Higgs exotic decay



Z. Liu, L.-T. Wang, H. Zhang, CPC41(2017)063102

New Scalar Signatures

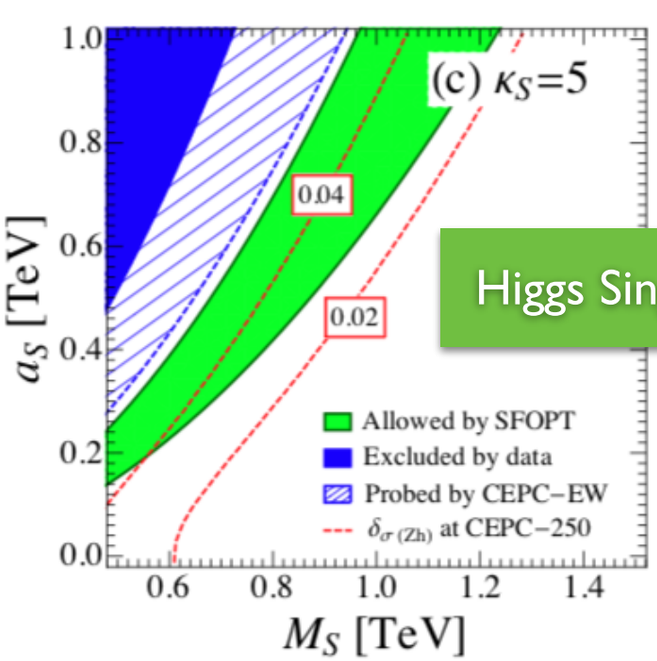


More powerful probe of heavy neutral/charged Higgses!

Fermonic channels, ff, are being constrained at LHC Run-2

Bosonic decay channels, such as hV, AV, hh, AA, VV

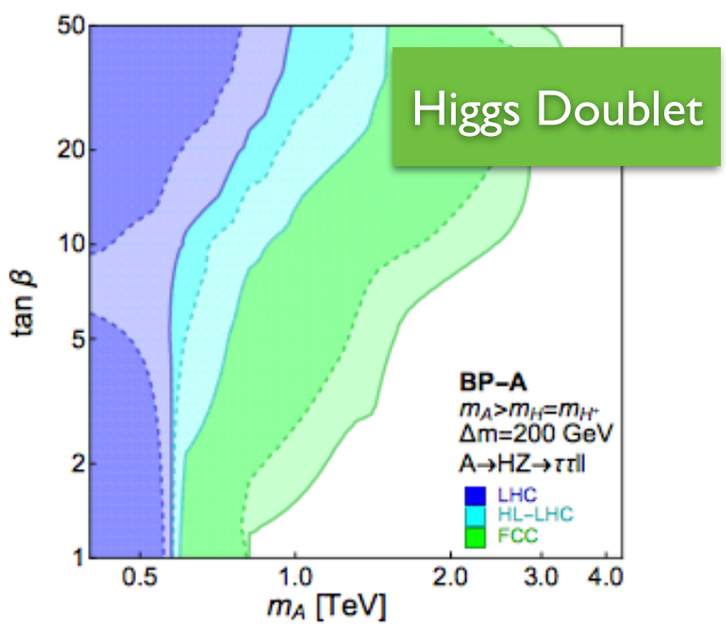
CEPC



Higgs Singlet

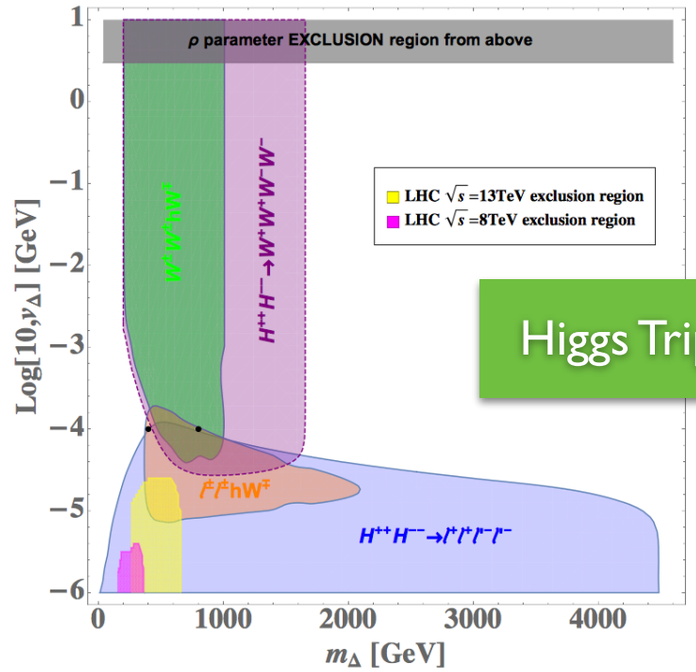
Q.-H. Cao, F. P. Huang, K.-P. Xie, X.-m.Zhang, CPC42(2018)023103

100 TeV Collider



Higgs Doublet

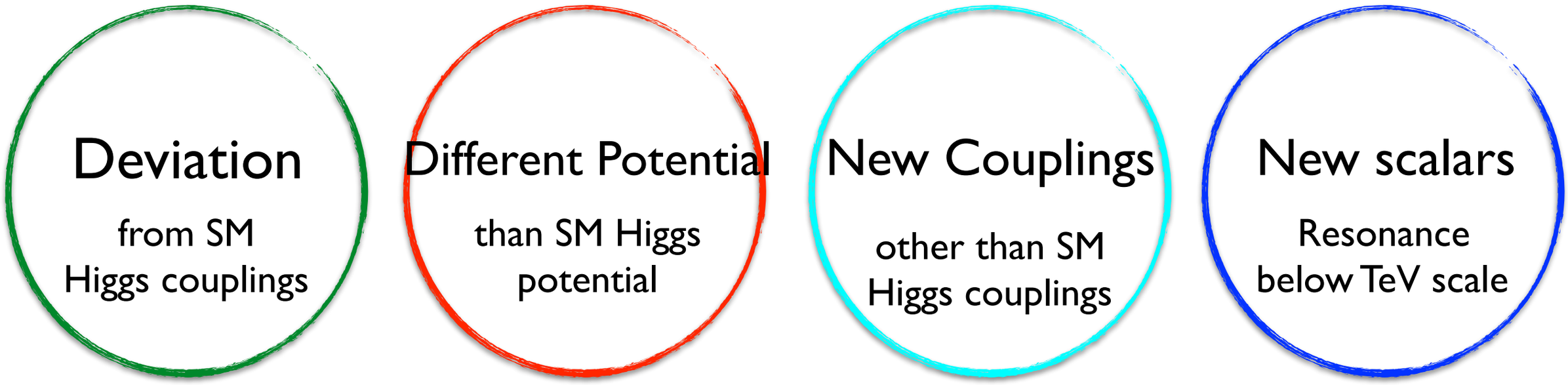
F. Kling, H. Li, A. Pyarelal, H. Song, S. Su, 1812.01633



Higgs Triplet

Y. Du, A. Dunbrack, M. Ramsey-Musolf, JHY, 1810.09450

Summary



Higgs effective theory
(precision Higgs measurement)

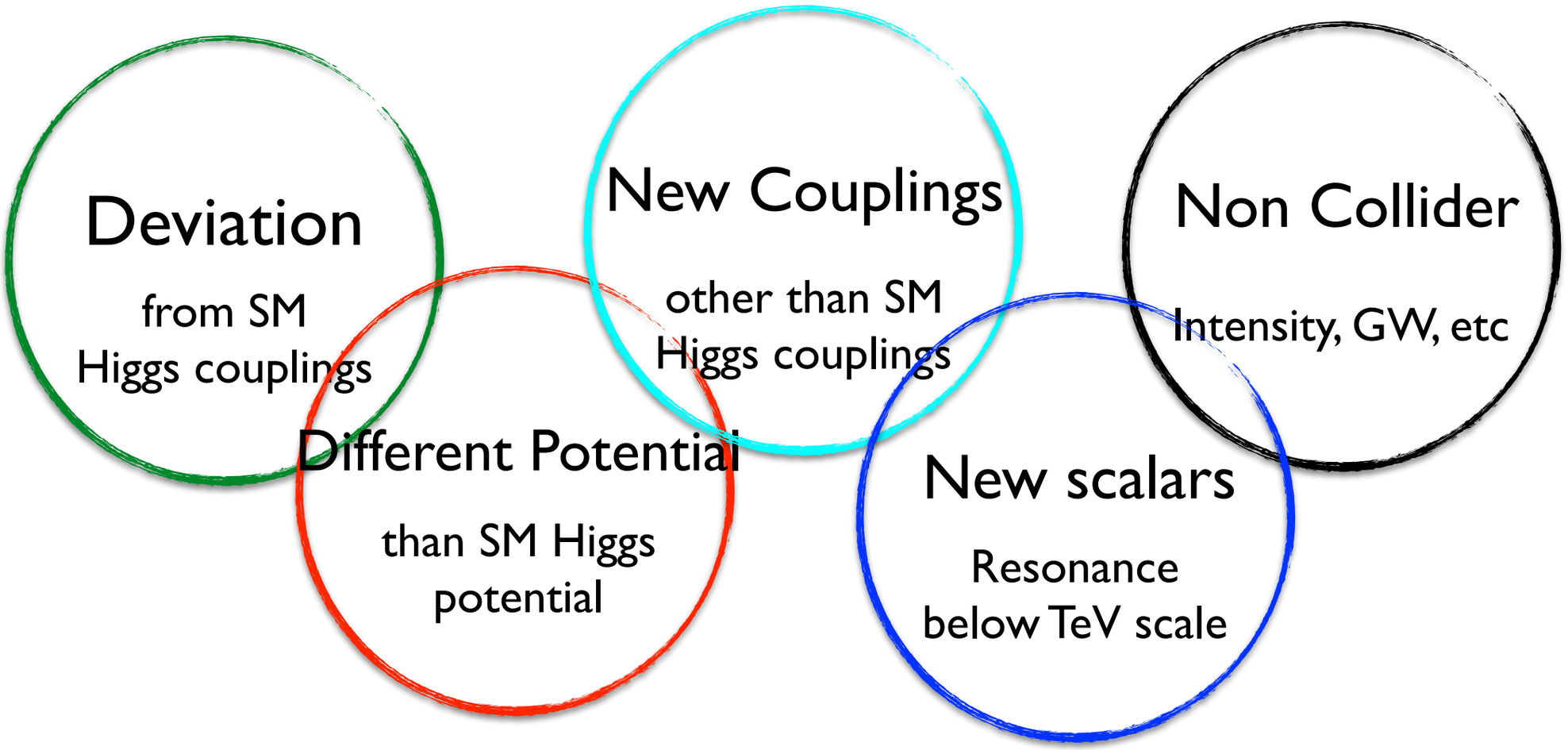
Neutral Naturalness
(diHiggs and displaced vertices signature)

Simplified scalar sector
(search for new scalars)

Topics are chosen based on my personal perspective

Apologize if your work is not included/covered in this 20 min talk…

Higgs Physics Olympics



Who will get gold medal in this race for new physics?

Thank You For Your Attention!

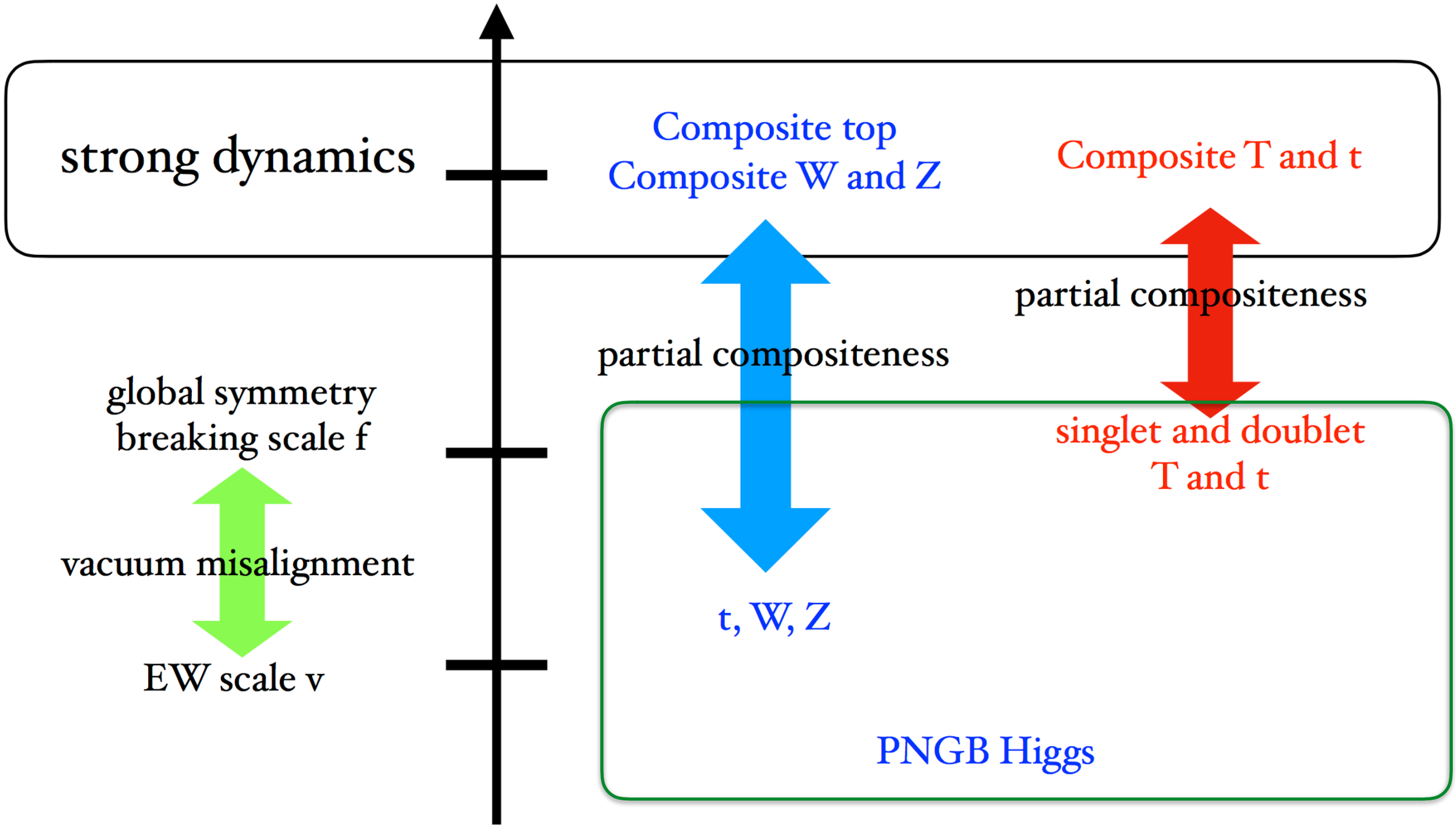
Backup Slides

Connect HEFT and Scalar Models

Theory:	c_H	$c_{H\Box}$	c_{HD}	c_{eH}	c_{uH}	c_{dH}
$\mathbb{R}$ Singlet	$-\frac{\lambda_{HS}}{2}\frac{g_{HS}^2}{M^4}$	$-\frac{g_{HS}^2}{2M^4}$	-	-	-	-
$\mathbb{C}$ Singlet	$-\left(\frac{\lvert g_{HS}\rvert^2\lambda'_{H\Phi}}{2M^4}+\frac{\mathrm{Re}[g_{HS}^2\lambda_{H\Phi}]}{M^4}\right)$	$-\frac{\lvert g_{HS}\rvert^2}{M^4}$	-	-	-	-
2HDM, Type I	$\frac{\lvert Z_6\rvert^2}{M^2}$	-	-	$\frac{Z_6}{M^2}Y_l c_\beta$	$\frac{Z_6}{M^2}Y_u c_\beta$	$\frac{Z_6}{M^2}Y_d c_\beta$
Type II:	$\frac{\lvert Z_6\rvert^2}{M^2}$	-	-	$-\frac{Z_6}{M^2}Y_l s_\beta$	$\frac{Z_6}{M^2}Y_u c_\beta$	$-\frac{Z_6}{M^2}Y_d s_\beta$
Lepton-Specific:	$\frac{\lvert Z_6\rvert^2}{M^2}$	-	-	$-\frac{Z_6}{M^2}Y_l s_\beta$	$\frac{Z_6}{M^2}Y_u c_\beta$	$\frac{Z_6}{M^2}Y_d c_\beta$
Flipped:	$\frac{\lvert Z_6\rvert^2}{M^2}$	-	-	$\frac{Z_6}{M^2}Y_l c_\beta$	$\frac{Z_6}{M^2}Y_u c_\beta$	$-\frac{Z_6}{M^2}Y_d s_\beta$
$\mathbb{R}$ Triplet $(Y=0)$	$-\frac{g^2}{M^4}\left(\frac{\lambda_{H\Phi}}{8}-\lambda\right)$	$\frac{g^2}{8M^4}$	$-\frac{g^2}{2M^4}$	$\frac{g^2}{4M^4}Y_l$	$\frac{g^2}{4M^4}Y_u$	$\frac{g^2}{4M^4}Y_d$
$\mathbb{C}$ Triplet $(Y=-1)$	$-\frac{\lvert g\rvert^2}{M^4}\left(\frac{\lambda_{H\Phi}}{4}+\frac{\lambda'}{8}-2\lambda\right)$	$\frac{\lvert g\rvert^2}{2M^4}$	$\frac{\lvert g\rvert^2}{M^4}$	$\frac{\lvert g\rvert^2}{2M^4}Y_l$	$\frac{\lvert g\rvert^2}{2M^4}Y_u$	$\frac{\lvert g\rvert^2}{2M^4}Y_d$
$\mathbb{C}$ Quadruplet $(Y=1/2)$	$\frac{\lvert\lambda_{H3\Phi}\rvert^2}{M^2}$	-	$\frac{2\lvert\lambda_{H3\Phi}\rvert^2v^2}{2M^4}$	-	-	-
$\mathbb{C}$ Quadruplet $(Y=3/2)$	$\frac{\lvert\lambda_{H3\Phi}\rvert^2}{M^2}$	-	$\frac{6\lvert\lambda_{H3\Phi}\rvert^2v^2}{2M^4}$	-	-	-

T. Corbett, A. Joglekar, H.-L. Li, JHY, JHEP1805(2018)061

Minimal Neutral Naturalness



L.-X. Xu, JHY, S.-h. Zhu 1810.01882