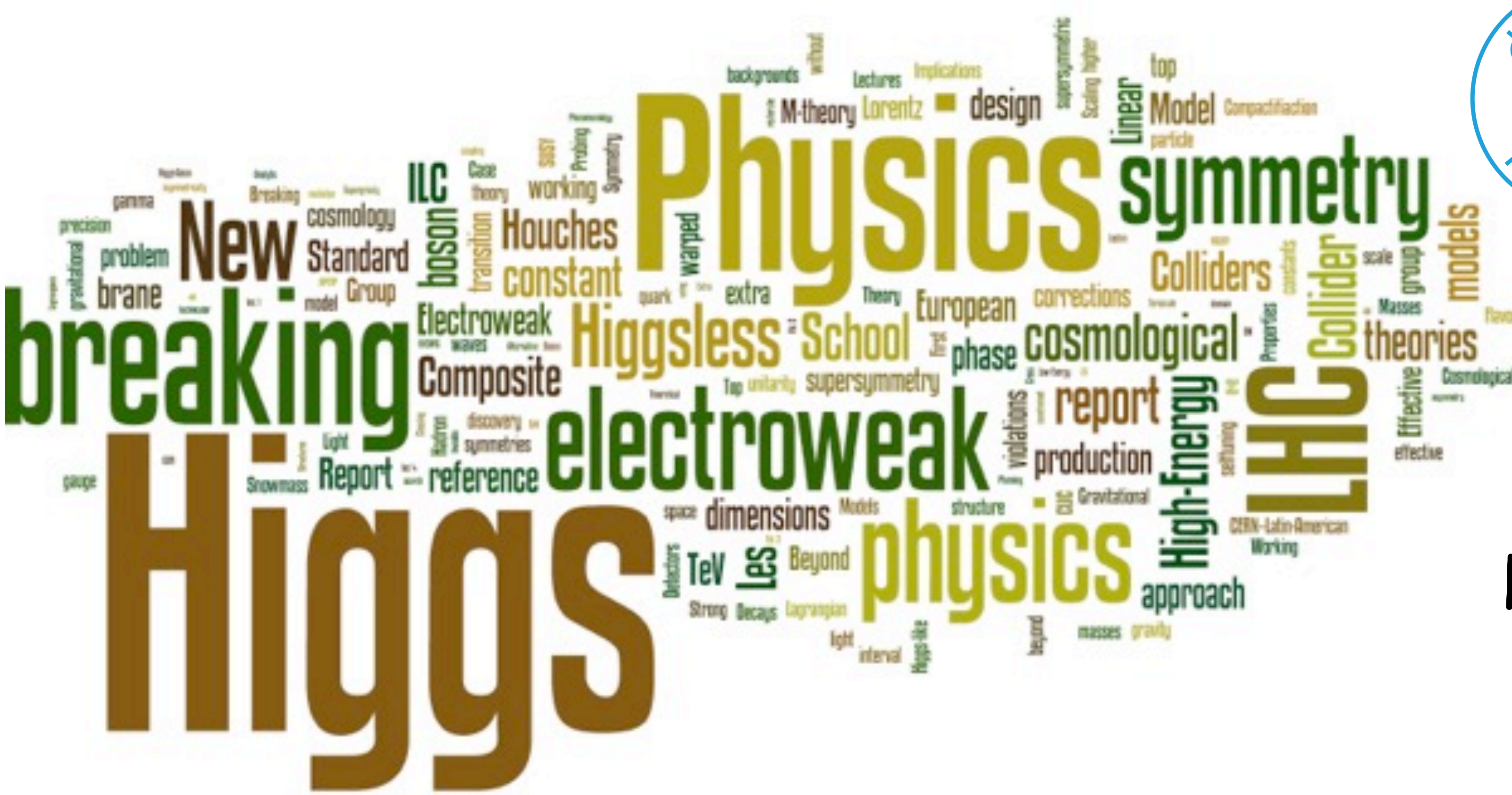
BSM landscape after the Higgs discovery

" Physics in the LHC and the Early Universe "

Tokyo, January 10, 2017



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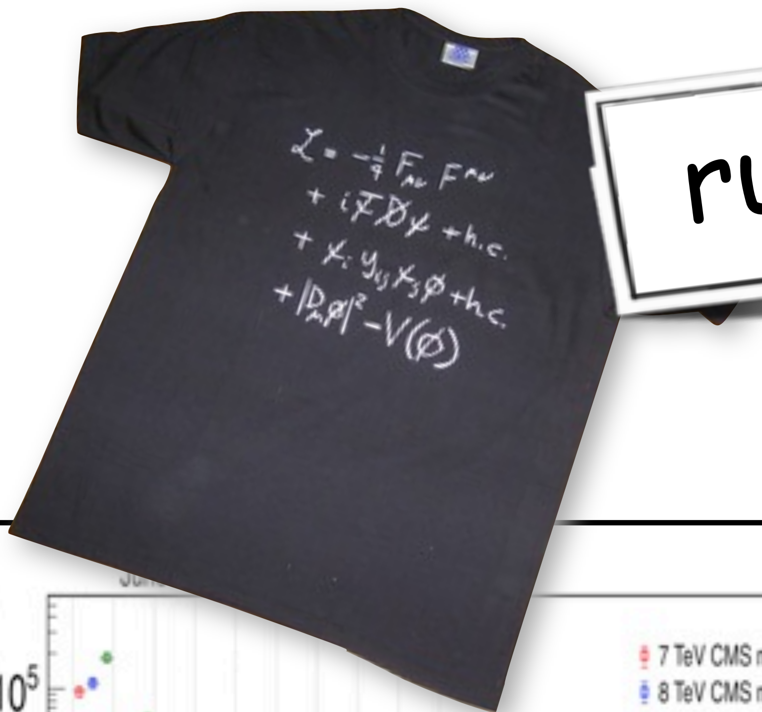
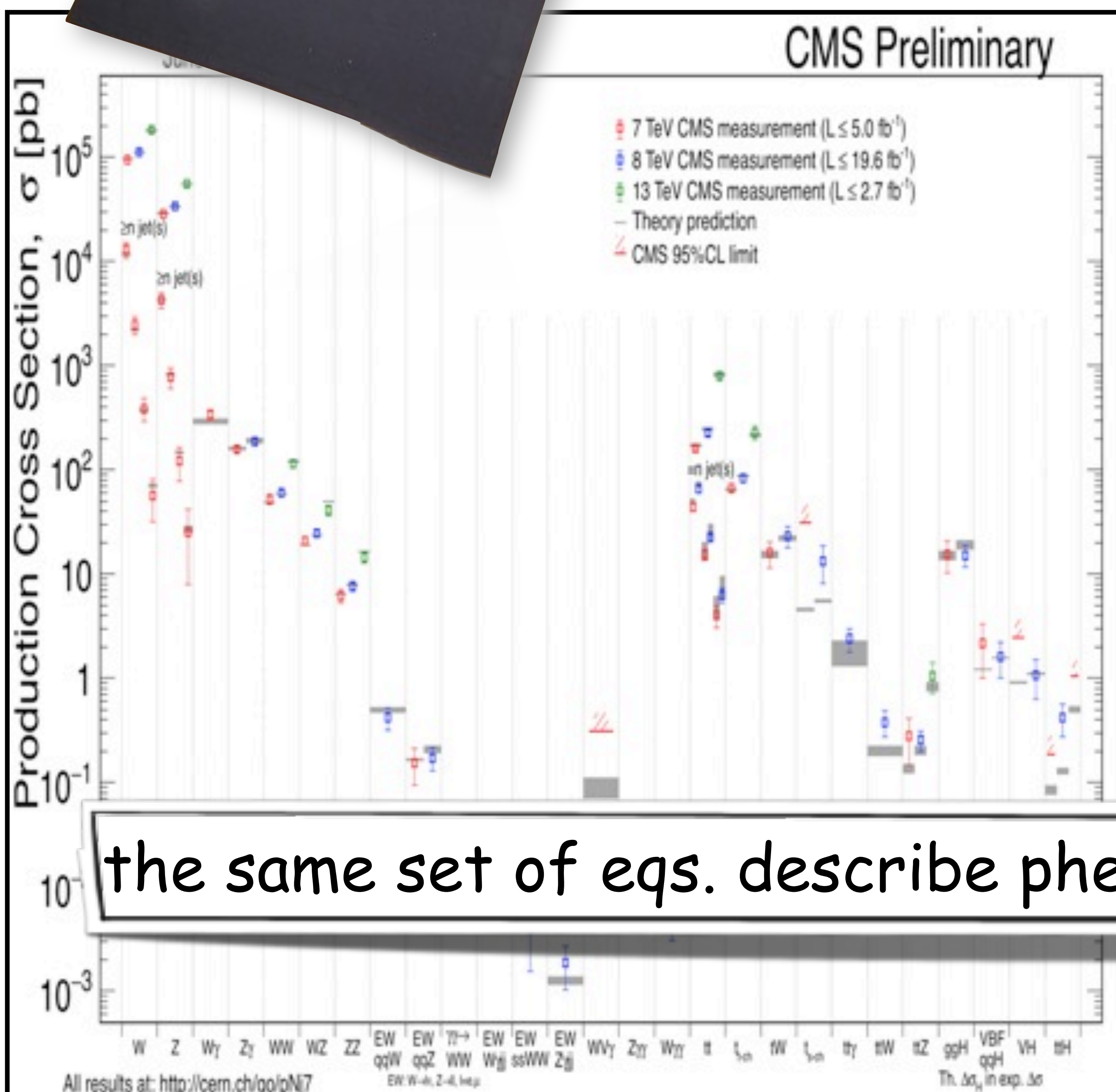
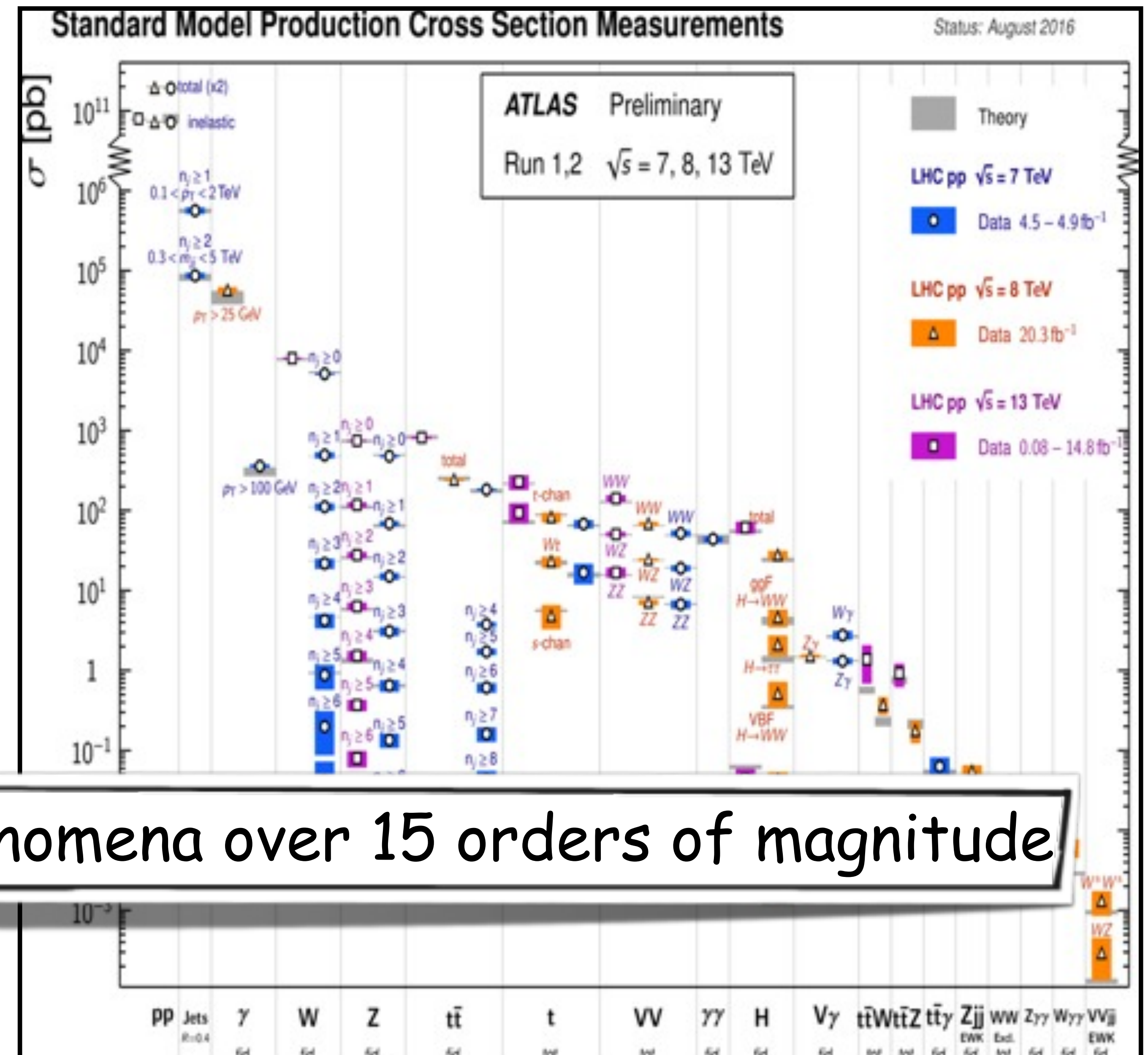
The SM and... the LHC data so far



rules the world!

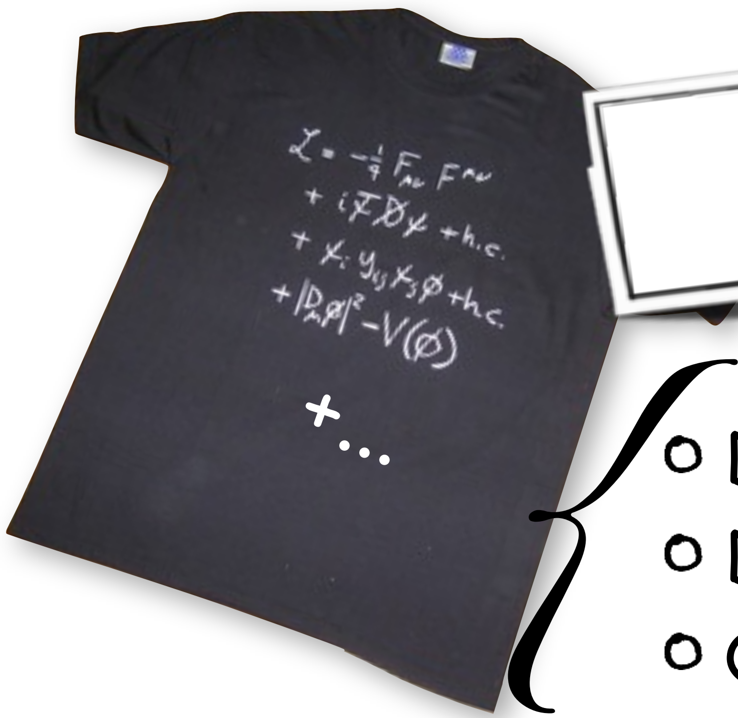
[and we, HEP practitioners, are all entitled for some royalties!]





the same set of eqs. describe phenomena over 15 orders of magnitude

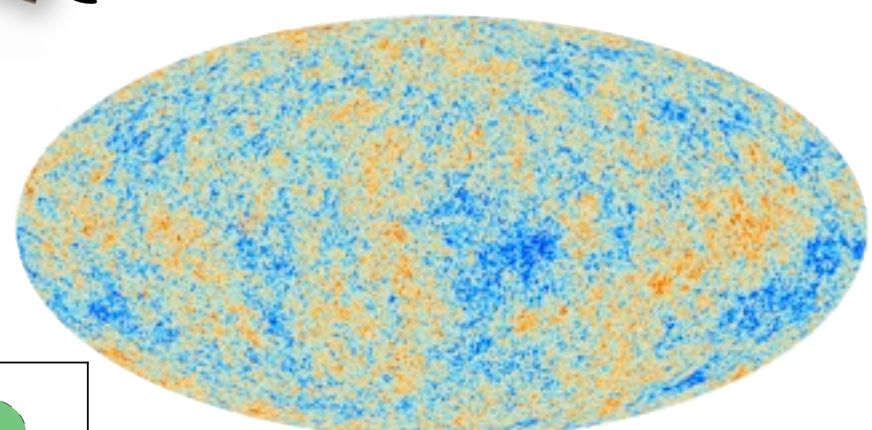
The SM and... the rest of the Universe

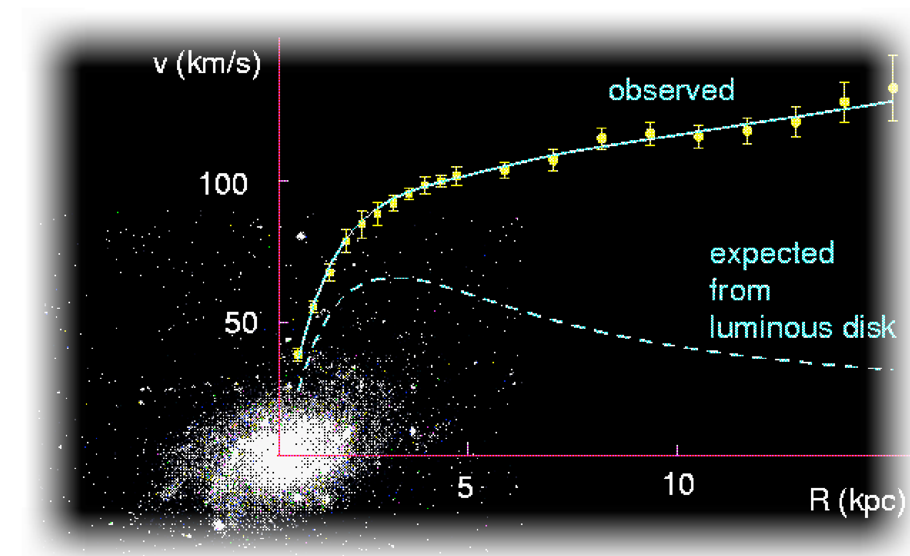


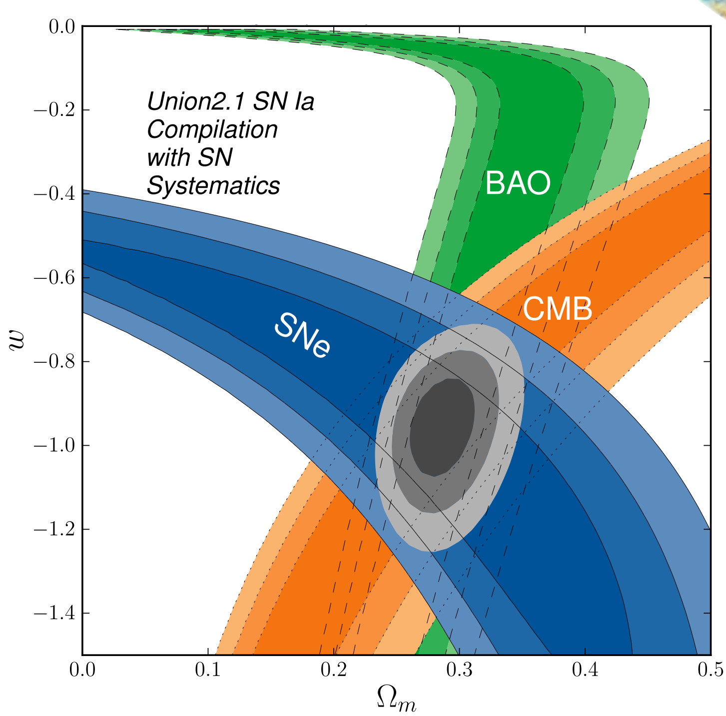
is not enough

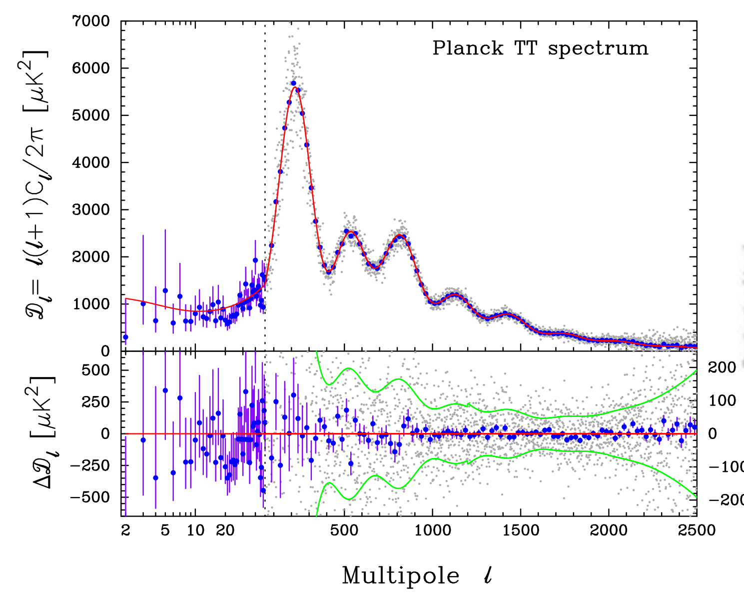
[and we all have to return our royalties!]

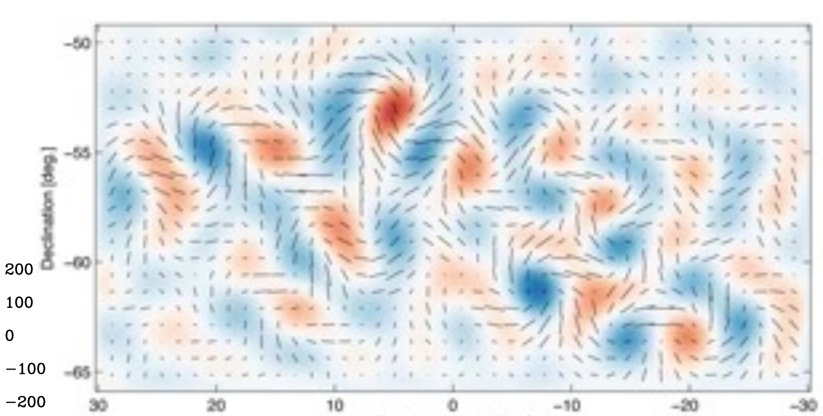
- Dark Matter
- Dark Energy
- Quantum gravity











What is physics beyond the Standard Model?

?

I don't know. Nobody knows [If it were known, it would be part of the SM!]

Plenty of evidences that BSM exist

We just don't know what it is

We have plenty of good ideas. There are rich opportunities

But no guarantee we are on the right track

We should stay open-minded and also learn from our failures

" Looking and not finding is different than not looking"

Sailing to the West with the right tool...

Once upon a time...

Columbus had a great proposal: “reaching India by sailing from the West”

He had a theoretical model

- the Earth is round,
- Eratosthenes of Cyrene first estimated its circumference to be 250’000 stadia
- other measurements later found smaller values ☞Toscanelli’s map
- lost in unit-conversion or misled by post-truth statements, Columbus thought it was only 70’000 stadia, so he believed he could reach India in 4 weeks

He had the right technology

- Caravels were the only ships at that time to sail against the wind, necessary tool to fight the prevailing winds, aka Alizée.

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His proposal was scientifically rejected twice (by Portuguese's & Salamanca U.)
by the decision was overruled by Isabel ... and America became great (already)

Moral(s)

❖ "if your proposal is rejected, submit it again" J. Mnich

❖"you need the right technology to beat your competitors" J. Fuster

❖ "theorists don't need to be right! But progress needs theoretical models to motivate exploration"

❖ "precise data without the big picture might be misleading"

HEP with a Higgs boson

" With great power comes great responsibility "

Voltaire & Spider-Man

which, in physics, really means

" With great discoveries come great measurements "

HEP physicist desperately looking for anomalies
and writing a grant proposal
(true credit: F. Maltoni)

I will take the Higgs boson as an example
but similar story might be made for neutrinos, gravitational waves...

HEP with a Higgs boson

The successes have been breathtaking

- in 4 years, the Higgs mass has been measured to 0.2% (vs 0.5% for the 20-year old top)
- some of its couplings, e.g. κ_γ, have been measured with 1-loop sensitivity (as EW physics at LEP)

The meaning of the Higgs

Particle physics is not so much about particles but more about fundamental principles

- About 10^{-10}s after the Big Bang, the Universe filled with the Higgs substance because it saved energy by doing so:

"the vacuum is not empty"

(even when $\hbar \to 0$, not a Casimir effect)

- The masses are emergent quantities due to a non-trivial vacuum structure
- There are only a finite number of particles (the SM ones) that acquire their mass via the Higgs vev
- There exists a new type (non-gauged) of fundamental forces: matter-dependent forces (e≠μ), e.g. familon, relaxion, Higgs portals...

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Higgs agenda for the LHC-II, HL-LHC, ILC/CLIC, FCC, CepC, SppC, SHiP

multiple independent, synergetic and complementary approaches to achieve **precision** (couplings), **sensitivity** (rare and forbidden decays) and **perspective** (role of Higgs dynamics in broad issues like EWSB and vacuum stability, baryogenesis, inflation, naturalness, etc)

M.L. Mangano, Washington '15

- rare Higgs decays: h→$\mu\mu$, h→γZ
- Higgs flavor violating couplings: h→$\mu\tau$ and t→hc
- Higgs CP violating couplings
- exclusive Higgs decays (e.g. h→J/Ψ+γ) and measurement of couplings to light quarks
- exotic Higgs decay channels:

  h→ $\not{E}_T$, h→4b, h→2b2μ, h→4τ,2τ2μ, h→4j, h →2γ2j, h→4γ, h→γ/2γ+ $\not{E}_T$,

  h→isolated leptons+ $\not{E}_T$, h→2l+ $\not{E}_T$, h→one/two lepton-jet(s)+X, h→bb+ $\not{E}_T$, h→$\tau\tau$+ $\not{E}_T$ ...
- searches for extended Higgs sectors (H, A, $H^\pm$,$H^{\pm\pm}$...)
- Higgs self-coupling(s)
- Higgs width
- Higgs/axion coupling?
- ...

1

Higgs Portrait

Higgs physics vs BSM

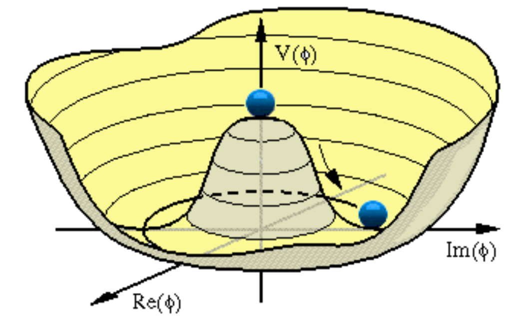
(courtesy of A. Pomarol@Moriond2014)

Several deformations away from the SM affecting Higgs properties are already probed in the vacuum

(assuming EW symmetry linearly realized and that new physics is heavy)

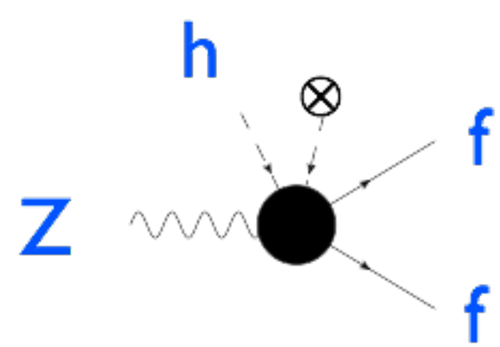
$\phi = v + h$

vacuum

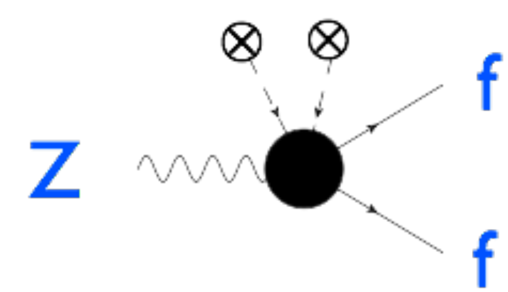


Potentially new BSM-effects in h physics could have been already tested in the vacuum

e.g.



$= \frac{1}{2v} \times$



$H^\dagger D_\mu H \bar{f} \gamma^\mu f$

(assuming that the Higgs boson is part of a doublet)

Modifications in h→Zff related to Z→ff

consistency check not discovery mode

One can use h→ZZ→4l to probe this deformation but hard time to compete with LEP bounds

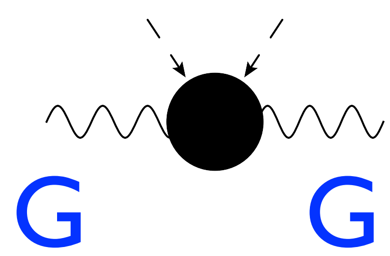
Higgs/BSM Primaries

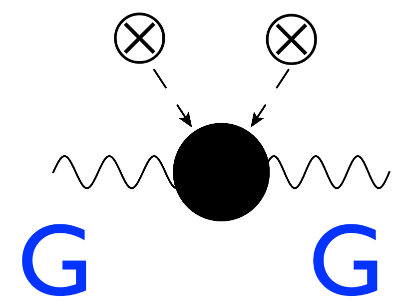
There are others deformations away from the SM that are harmless in the vacuum and need a Higgs field to be probed

e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$

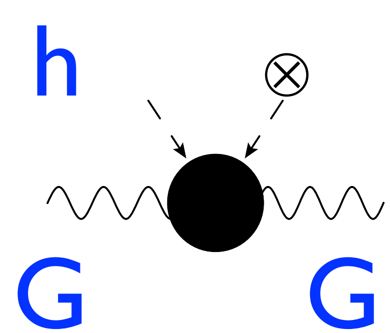
operator is not visible in the vacuum

(redefinition of input parameter)





But can affect h physics:



affects GG →h!

(courtesy of A. Pomarol@HiggsHunting2014)

Higgs/BSM Primaries

How many of these effects can we have?

Pomarol, Riva '13
Elias-Miro et al '13
Gupta, Pomarol, Riva '14

As many as parameters in the SM: **8** for one family

(assuming CP-conservation)

g_s	$\|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	→	GGh coupling
g	$\|H\|^2 B_{\mu\nu} B^{\mu\nu}$	→	hγγ coupling
g'	$\|H\|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$	→	hZγ coupling
m_W	$\|H\|^2 \|D_\mu H\|^2$	→	hVV* (custodial invariant)
m_h	$\|H\|^6$	→	h^3 coupling
m_f (f=t,b,τ)	$\|H\|^2 \bar{f}_L H f_R + h.c.$	→	htt, hbb, h$\tau\tau$

yet to be measured at the LHC

the 6 others have been measured (~15%)

(courtesy of A. Pomarol@HiggsHunting2014)

Higgs/BSM Primaries

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(courtesy of A. Pomarol@HiggsHunting2014)

Almost a 1-to-1 correspondence with the 8 κ's in the Higgs fit

Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
κ_t	22%	21%	20%	11%	8.5%	7.6%
κ_b	23%	22%	22%	12%	11%	10%
κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
κ_g	14%	12%	11%	9.1%	6.5%	5.3%
κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%

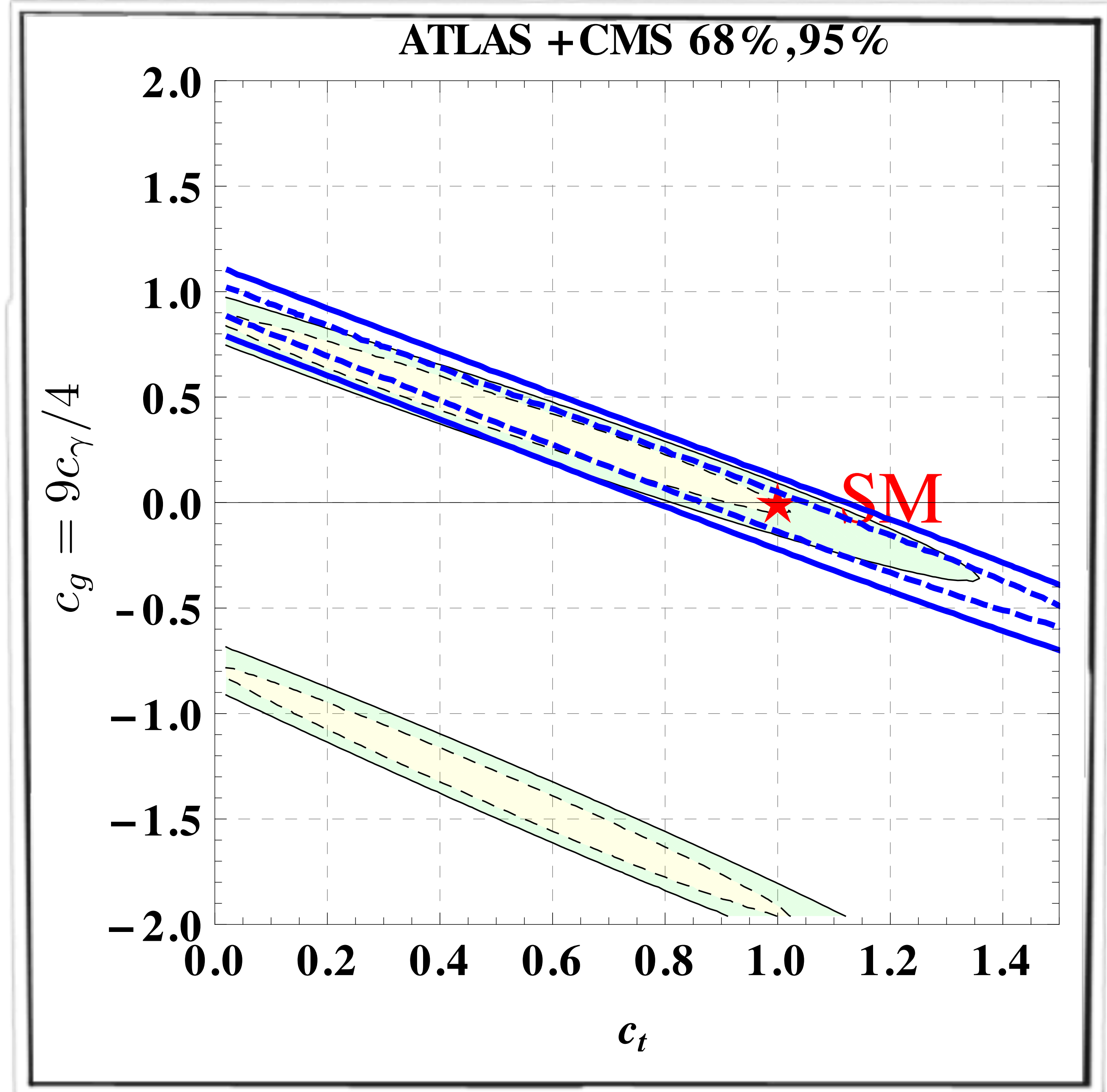
Atlas projection

With some important differences:

1) width hypothesis built-in

2) κ_W/κ_Z is not a primary (constrained by $\Delta\rho$ and TGC)

3) κ_g, κ_γ, $\kappa_{Z\gamma}$ do not separate UV and IR contributions



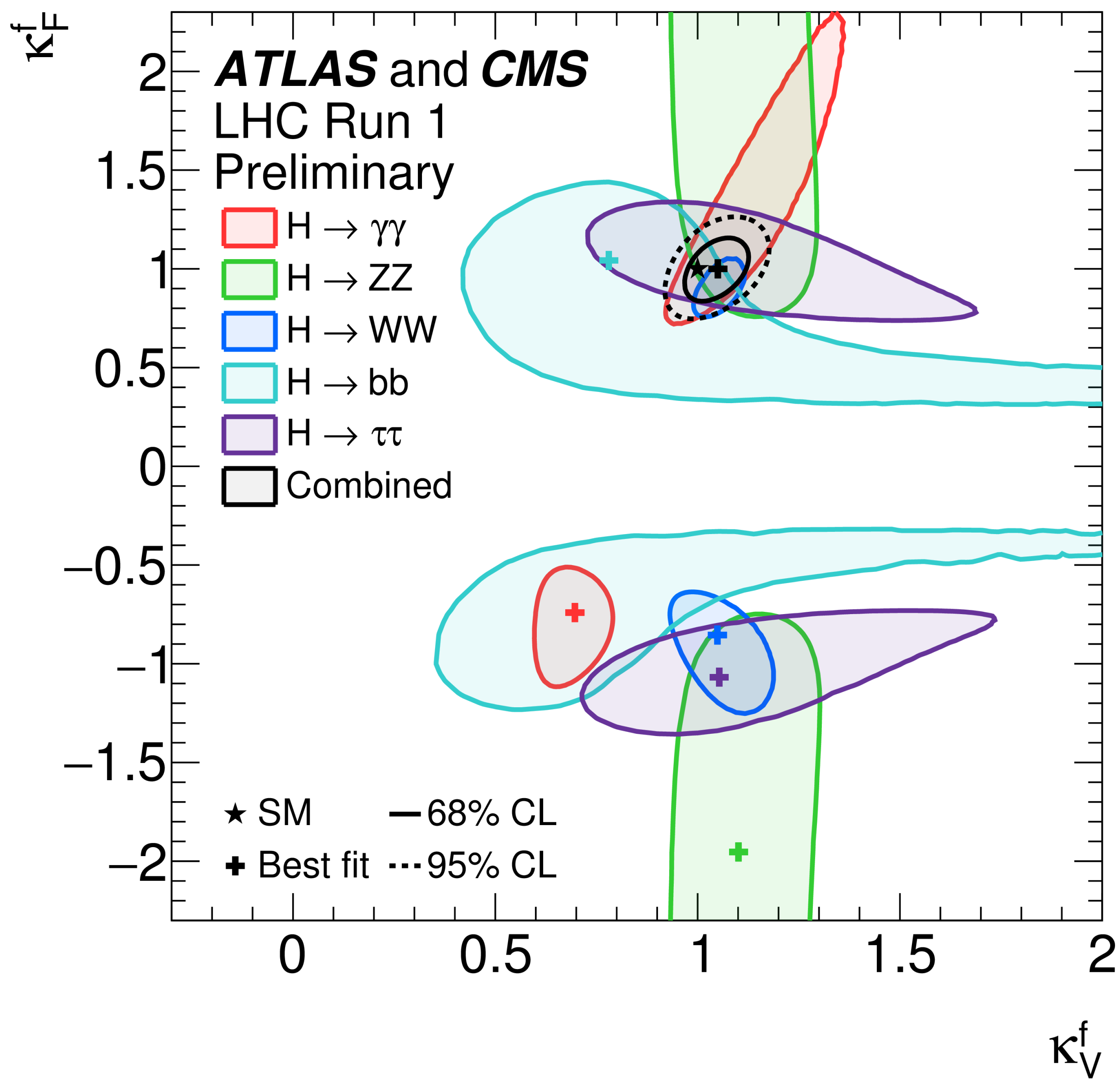
Azatov '15

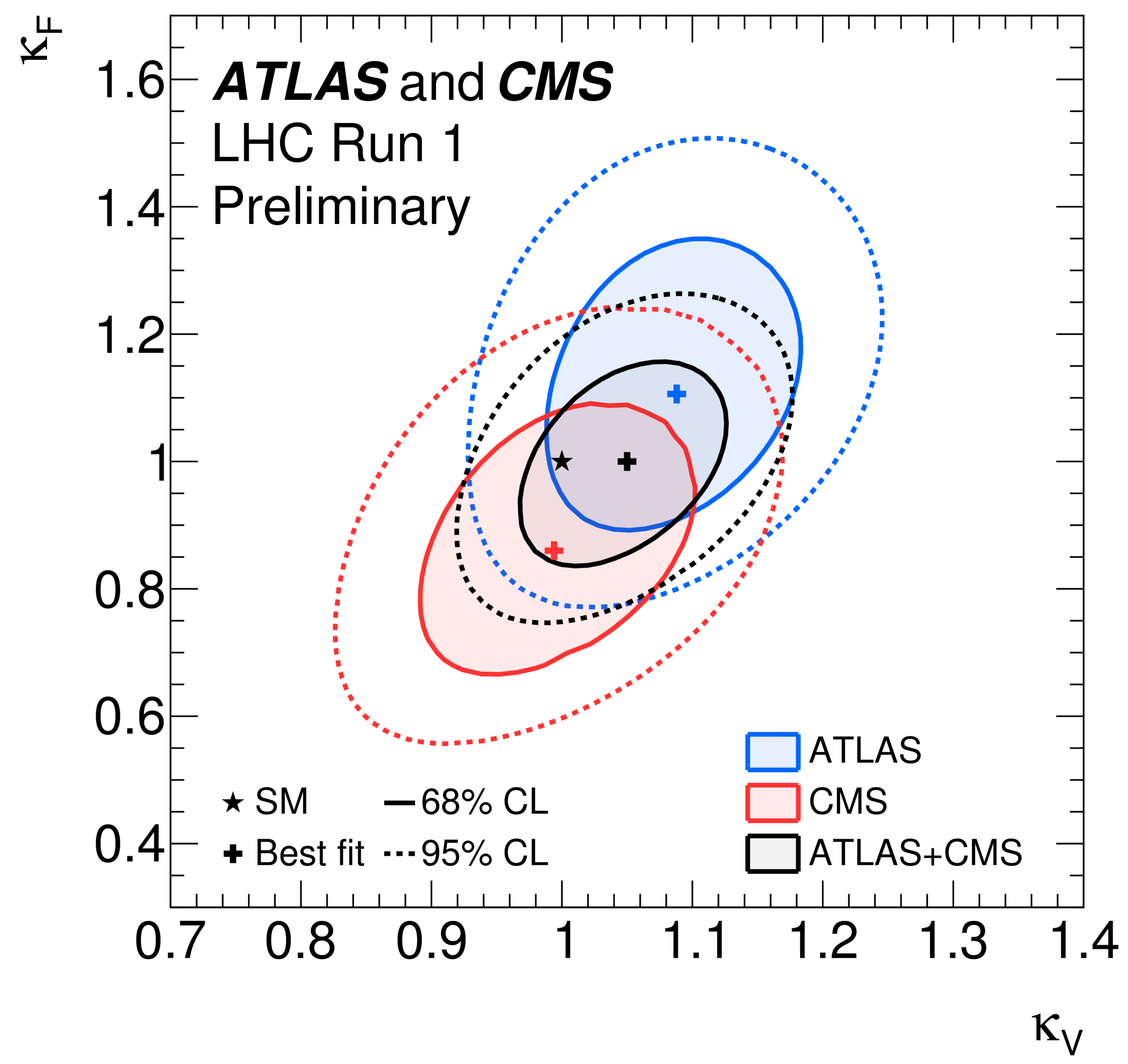
up to a flat direction between between the top/gluon/photon couplings

Why going beyond inclusive Higgs processes?

So far the LHC has mostly produced Higgses on-shell
in processes with a characteristic scale $\mu \approx m_H$

access to Higgs couplings @ m_H





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⇩ ⇩

access to Higgs couplings @ m_H

Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

Examples of interesting channels to explore further:

1. off-shell $gg \to h^* \to ZZ \to 4l$
2. boosted Higgs: Higgs+ high-p_T jet
3. double Higgs production

Why going beyond inclusive Higgs processes?

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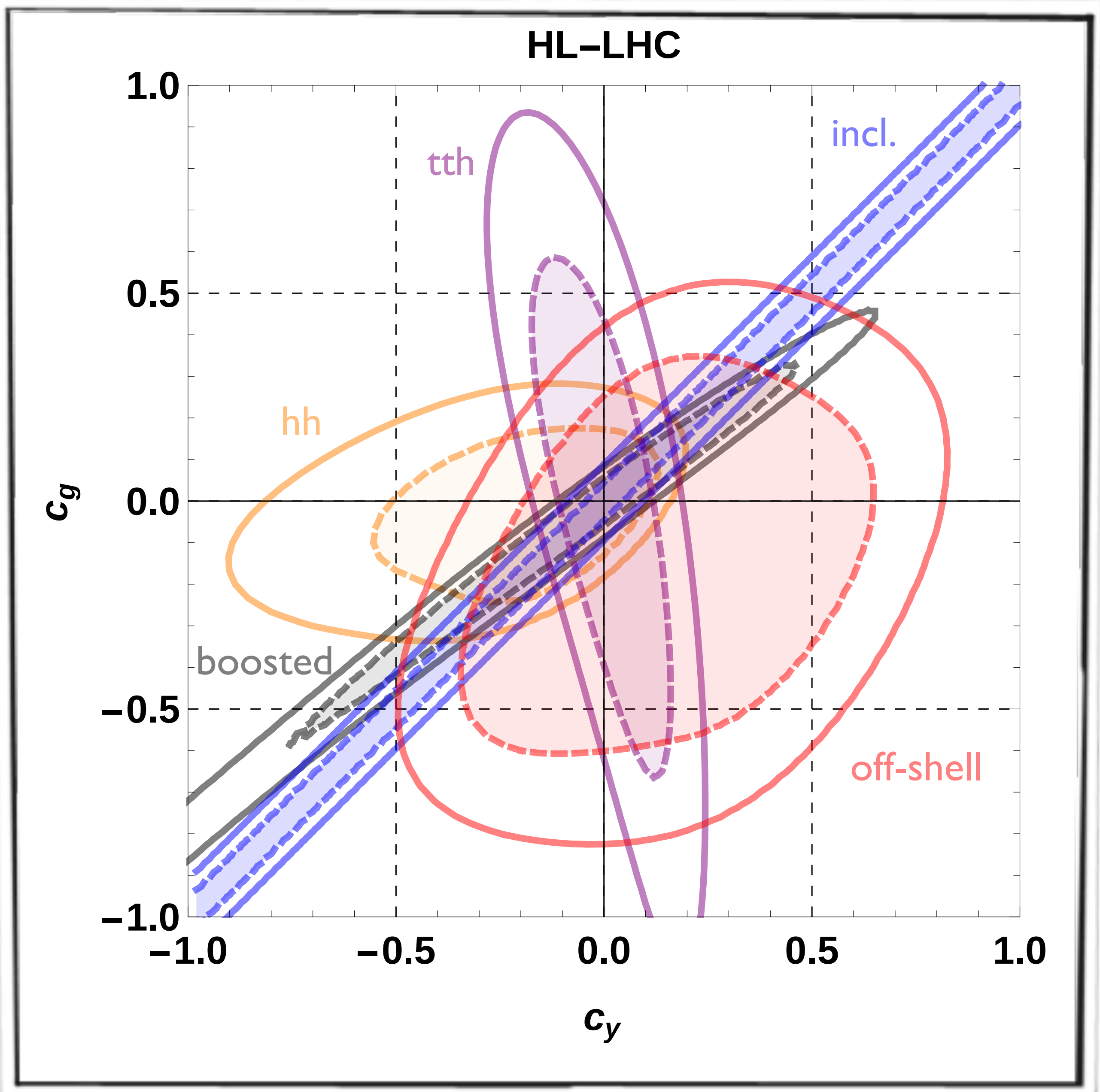
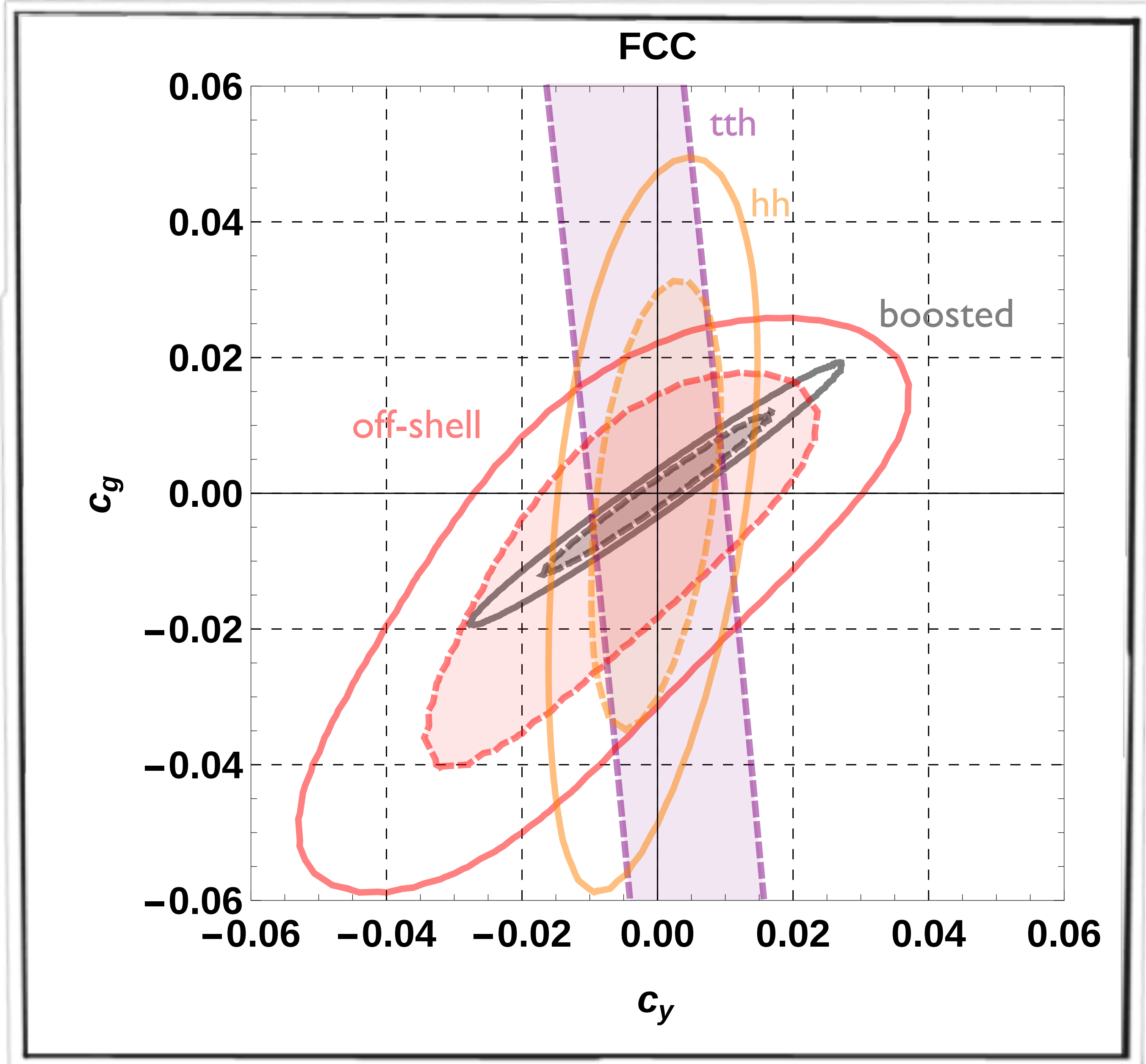




Azatov, Grojean, Paul, Salvioni '16

Usefulness of non-inclusive measurements

In Higgs inclusive measurements, top partners easily hide themselves
lightness of the Higgs makes it impossible to resolve the top-loop
top partners run in the loop and modify top Yukawa couplings ⇒ net effect=0

⇛ cannot disentangle
- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop)

⇚

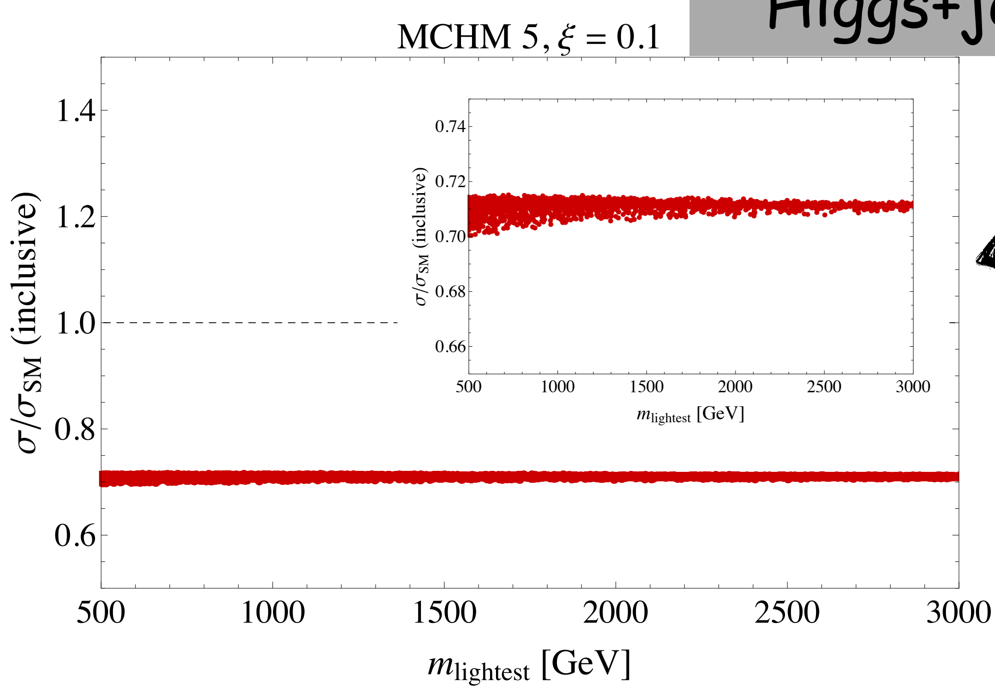
$$\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G^{a\,2}_{\mu\nu} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$$

$$\frac{\sigma(gg\to h)}{\mathrm{SM}} = (1+(c_g - c_t)v^2)^2 \qquad \frac{\Gamma(h\to\gamma\gamma)}{\mathrm{SM}} = (1+(c_\gamma - 4c_t/9)v^2)^2$$

fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$.

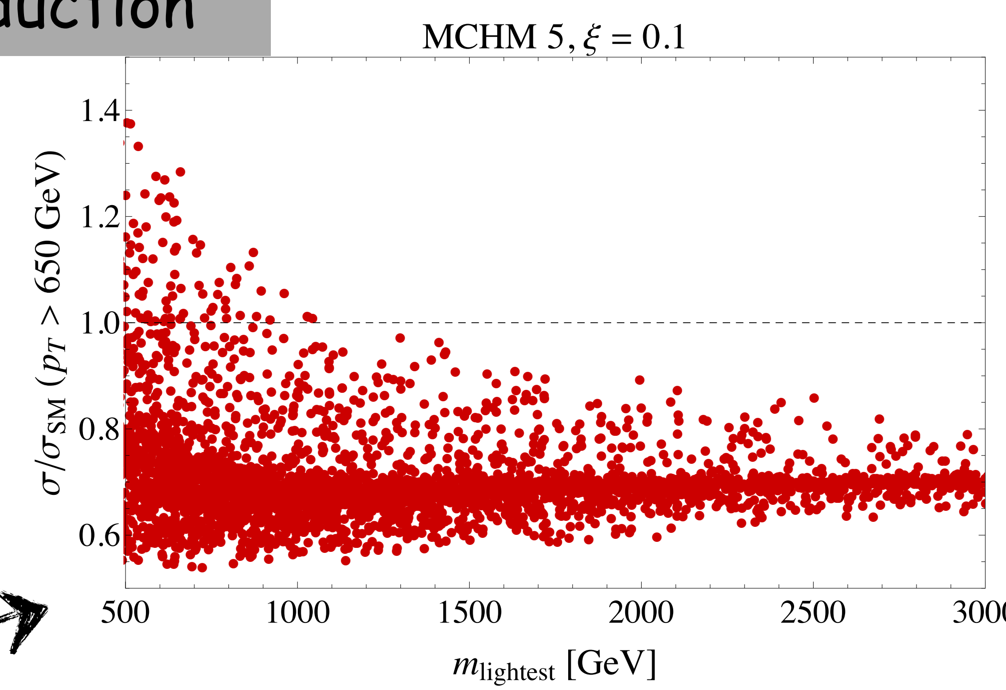
Need to look at differential distributions
Higgs+jet, off-shell Higgs production

Grojean et al '13



inclusive rate

Higgs w/ p_T>500 GeV



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Higgs and BSM physics

Higgs & BSM: a love story

In the context of the SM, there is nothing more to learn from the Higgs

- **This is a blessing and a curse:**
  - **A curse, since we might spend the rest of our lives confirming what we already know**
  - **A blessing, since we now have all ingredients required to assess the (in)consistency of exptl data with the SM itself**

Two extreme BSM scenarios...

- EWSB is intrinsically BSM (e.g. composite Higgs)
  - Higgs properties are directly modified
- EWSB is basically SM, it is not affected by BSM
  - Higgs properties are not visibly modified, but BSM particles manifest themselves through the Higgs (e.g. $\chi_2 \rightarrow h\chi_1$)

- … plus every scenario in between

This makes Higgs physics immensely rich, diverse and challenging

(courtesy of M. Mangano@HiggsCouplings2016)

Higgs & BSM: a love story

There are many ways to look for BSM physics in the Higgs sector...

BSM Higgs searches

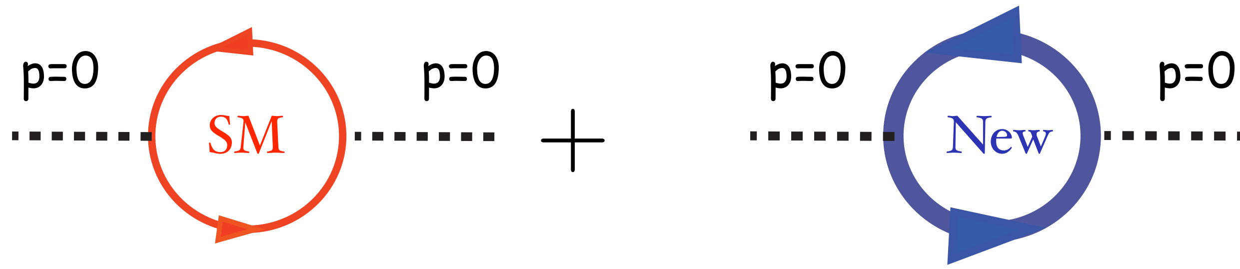
- Neutral heavy Higgs
- Charged Higgs
- Di-Higgs production
- Higgs as a portal to hidden sectors
- BSM constraints from coupling measurements
- Higgs in decay chains
- Higgs exotic decays
- Higgs lepton flavor violating decays

T. Guilemin@Search'16

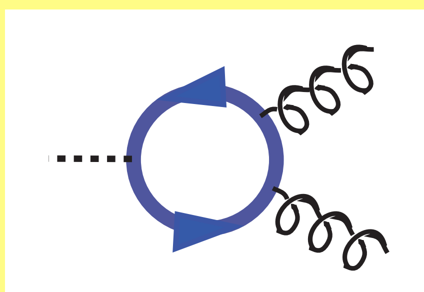
See also yesterday A. Djouadi's talk

Higgs couplings as a test of naturalness

$$-(125\text{ GeV})^2\left(\frac{\Lambda}{600\text{ GeV}}\right)^2 \qquad\qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$

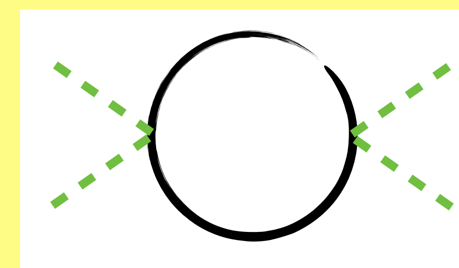
$\delta m_H^2 =$  $\sim m_H^2$

charged particles — *generically* — neutral particles



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$



$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu|H|^2\right)^2$$

$$BR(h\to ii) = BR_{\text{SM}} \qquad \Gamma = \left(1-\frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

$$\delta\sigma_{Zh} = -\frac{g_\star^2}{8\pi^2}\frac{v^2}{m_\star^2}$$

nice to be able to measure Zh & Γ

Colorful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC

aka twin Higgs

Searching for the missing top partners

" Looking and not finding is different than not looking"

giving the null search results, the top partners should either be

- **heavy** (harder to produce because of phase space)
- **stealthy** (easy to produce but hard to distinguish from background, e.g. m_{stop}~m_{top})
- **colorless** (hard to produce, unusual decay)

(C. Verhaaren@NKPI'16)

	Scalar Top Partner	Fermion Top Partner
All SM Charges	SUSY	pNGB/RS
EW Charges	Folded SUSY	Quirky Little Higgs
No SM Charges	???	Twin Higgs

need to go beyond traditional searches

require **hidden QCD** with a higher confining scale:

⇒ 1) hidden glueball (0^{++}) that can mix with Higgs
$h \to G_0 G_0 \to 4l$ with displaced vertices

Curtin, Verhaaren '15

⇒ 2) emerging jets

Schwaller, Stolarski, Weiler '15

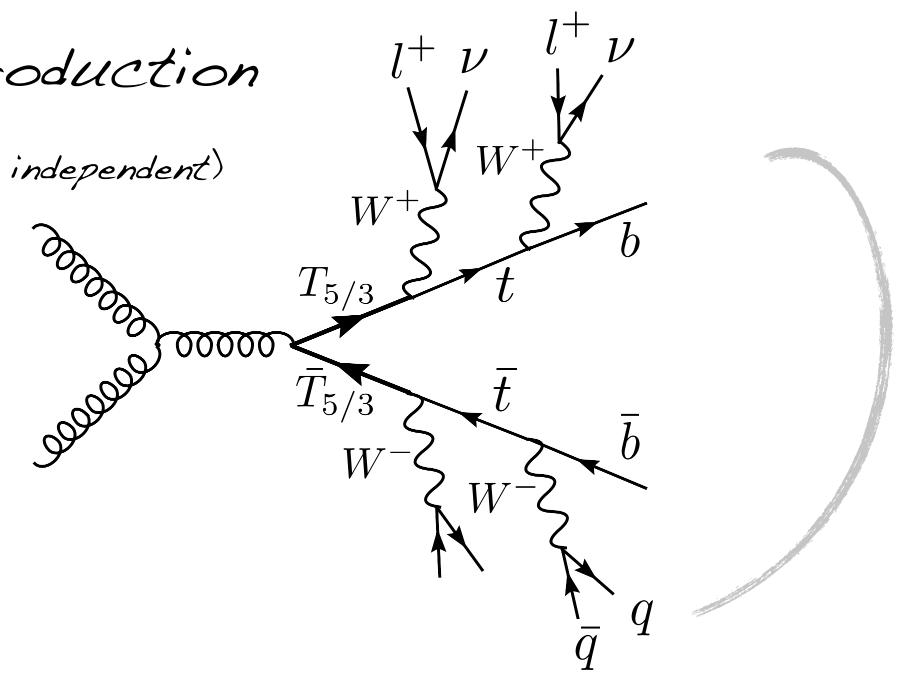
Top partners in Composite Higgs models

top partners searches in composite models:

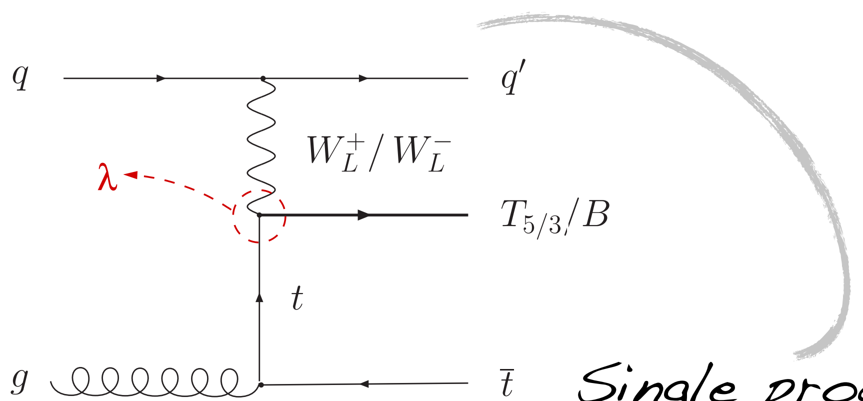
Search in same-sign dilepton events

Pair production

(model independent)

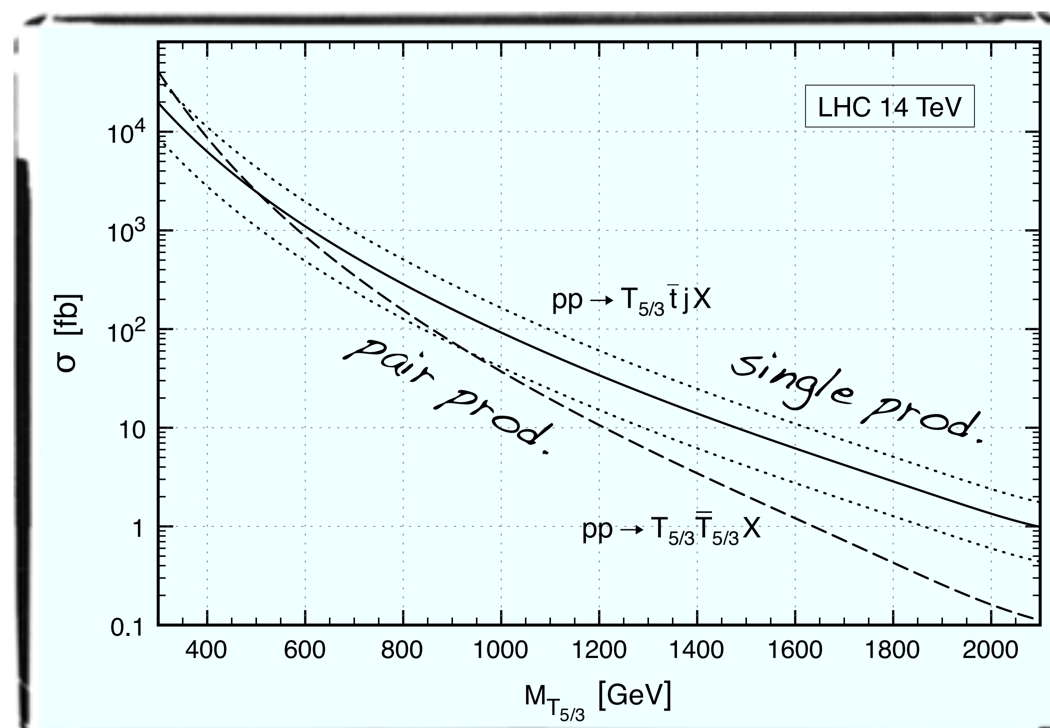


- $t\bar{t}$+jets is not a background [except for charge mis-ID and fake e$^-$]
- the resonant (tW) invariant mass can be reconstructed



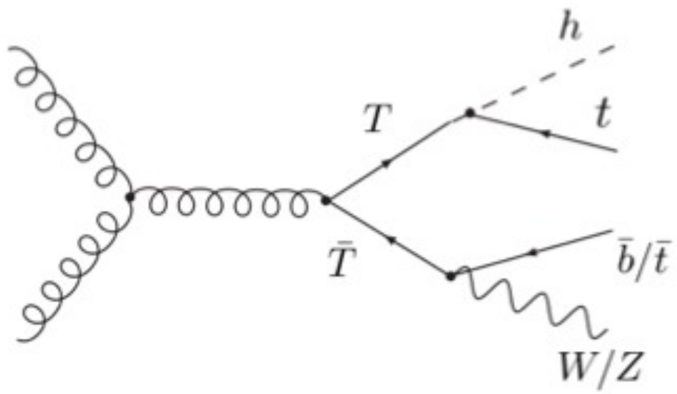
Single production

(model dependent)



[Contino, Servant '08]

Top partners in Composite Higgs models



- $\ell^\pm$ + 4b final state — Aguilar-Saavedra '09

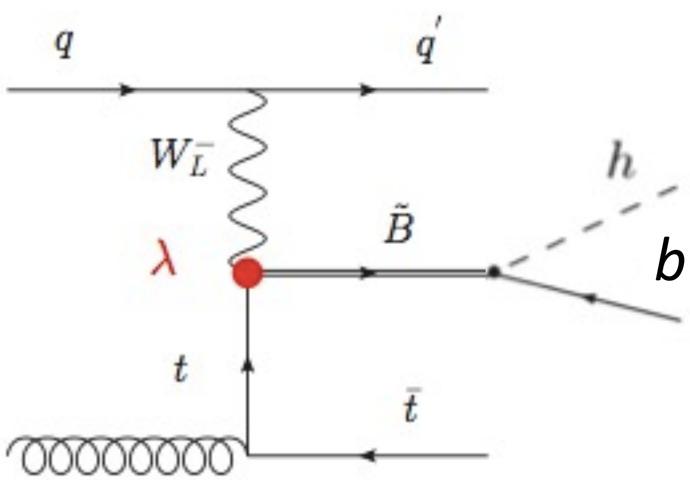
$$T\bar{T} \to HtW^-\bar{b} \to HW^+bW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'\,,$$
$$T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$$

- $\ell^\pm$ + 6b final state — Aguilar-Saavedra '09

$$T\bar{T} \to HtH\bar{t} \to HW^+bHW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'$$

- $\gamma\gamma$ final state — Azatov et al '12

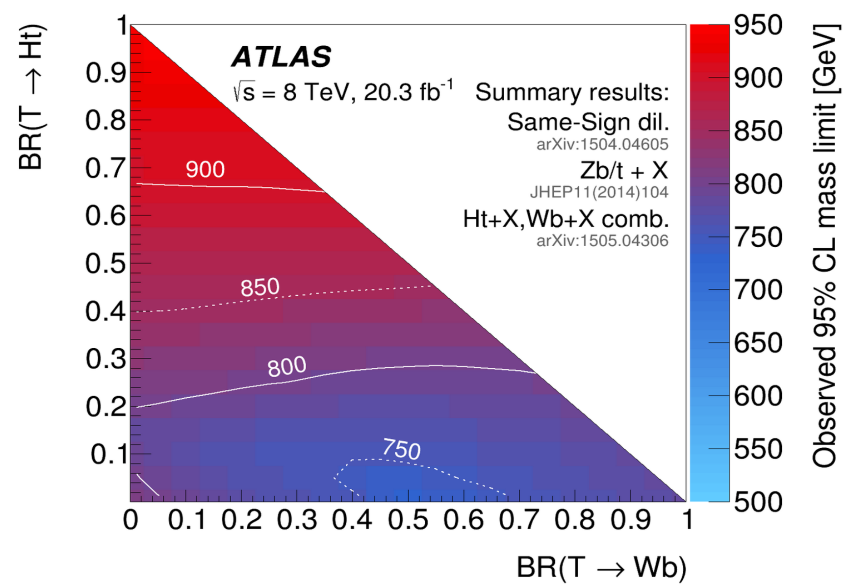
$$thbW/thtZ/thth,\ h \to \gamma\gamma$$



- $\ell^\pm$ + 4b final state — Vignaroli '12

$$pp \to (\tilde{B} \to (h \to bb)b)t + X$$

1505.04306



(*) Not a combination. Only most restrictive individual bounds shown.

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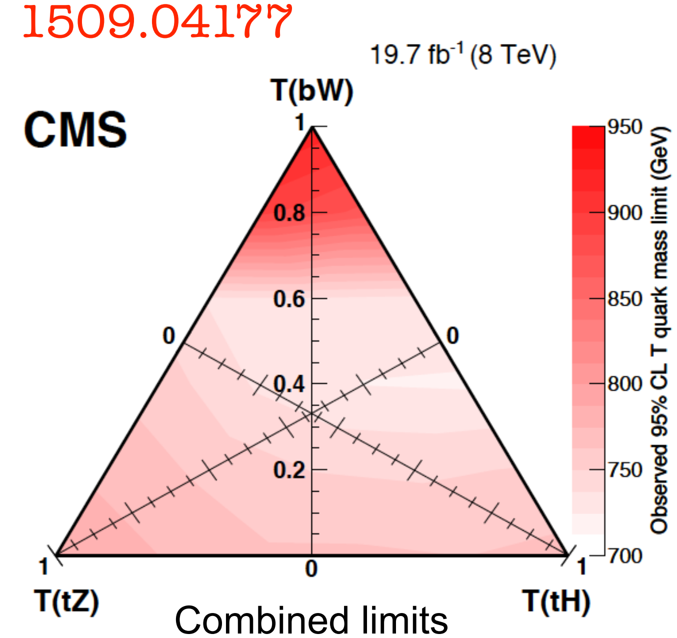


Evading EXP bounds

the stringent bounds from ATLAS/CMS on susy/composite models force theorists to go beyond minimal/simple models

SUSY is Natural but not plain vanilla	composite models involving top partners with really exotic charges

- ~~CMSSM~~
- pMSSM
- NMSSM
- Hide SUSY, e.g. smaller phase space
  - reduce production (eg. split families) Mahbubani et al
  - reduce MET (e.g. ~~R-parity~~, compressed spectrum) Csaki et al
  - dilute MET (decay to invisible particles with more invisible particles)
  - soften MET (stealth susy, stop -top degeneracy) Fan et al

See yesterday D. Shih's talk

"Hyperfolded Composite Higgs"

or how to get spin-1/2 partners with unconventional charges — preliminary

Symmetry breaking pattern:

$$SU(3)_G \times SU(2)_X \times U(1)_Z \to SU(2)_L \times SU(2)_X \times U(1)_Y$$

$$\Phi \sim (\bar{3},1)_{\frac{1}{3}} = \exp\left(-i\frac{\pi^a T^a_G}{f}\right)\begin{pmatrix}0\\0\\f\end{pmatrix} \approx \begin{pmatrix}H\\ f-\frac{H^\dagger H}{2f}\end{pmatrix}$$

SM electroweak group generators:

$$T_L^{1,2,3} = T_G^{1,2,3} \qquad Y = Z - \frac{T_G^8}{\sqrt{3}} + \left(\frac{2}{3} - Y_T\right) T_X^3$$

free parameter, to become the top-partner hypercharge

Since the charge-Y_T partner does not mix with the SM quarks, the usual decays to W/Z/h + quark are absent.

Instead, the decay may proceed via a higher-dimensional operator. For example, the operator

$$\mathcal{L} \propto \bar{X}^\dagger_\alpha \bar{u}^\dagger_{i\beta} \bar{d}^\alpha_j \bar{d}^\beta_k + \text{h.c.}$$

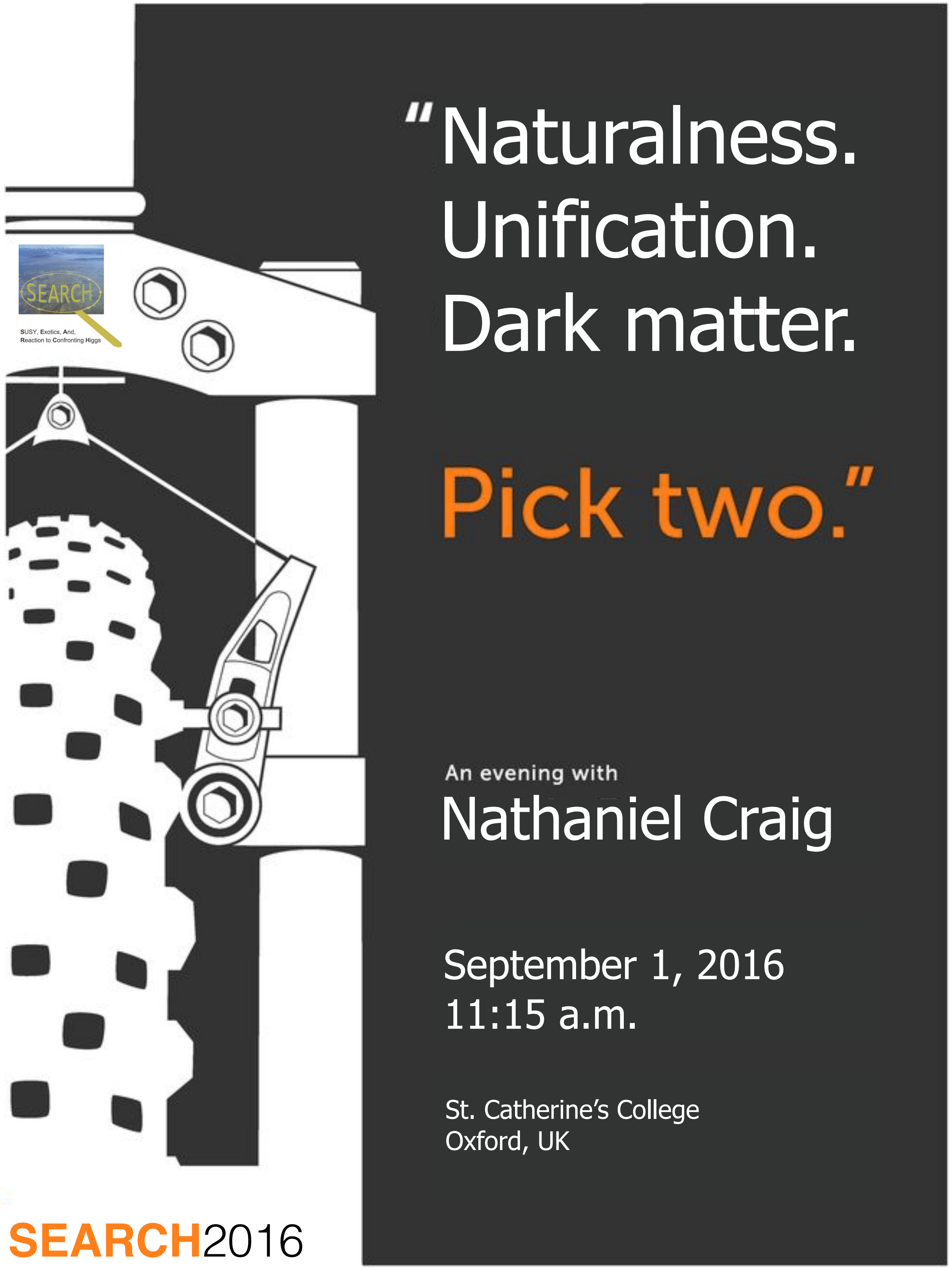
may give the potentially elusive decays

$$X \to jjj,\ tjj$$

Y. Kats @ DESY '16

Status of SUSY model building

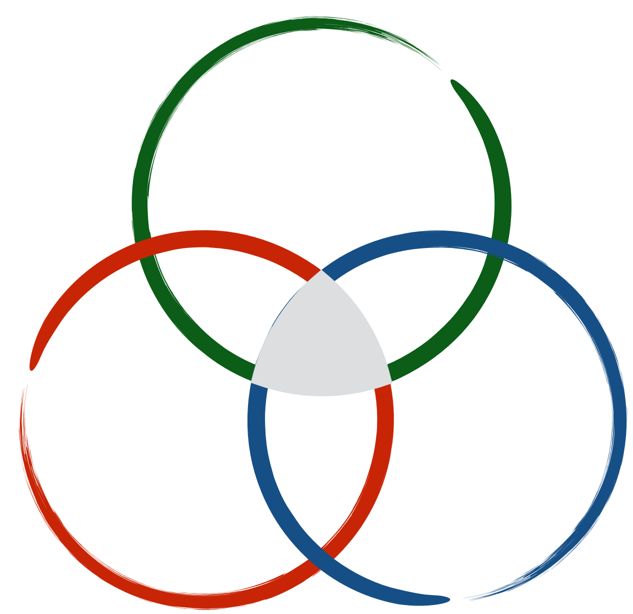
N. Craig@Search'16



Supersymmetry in light of data:

Impossible to have a simple theory that is natural, unifies, and gives WIMP DM.

Picking two is a useful guide.

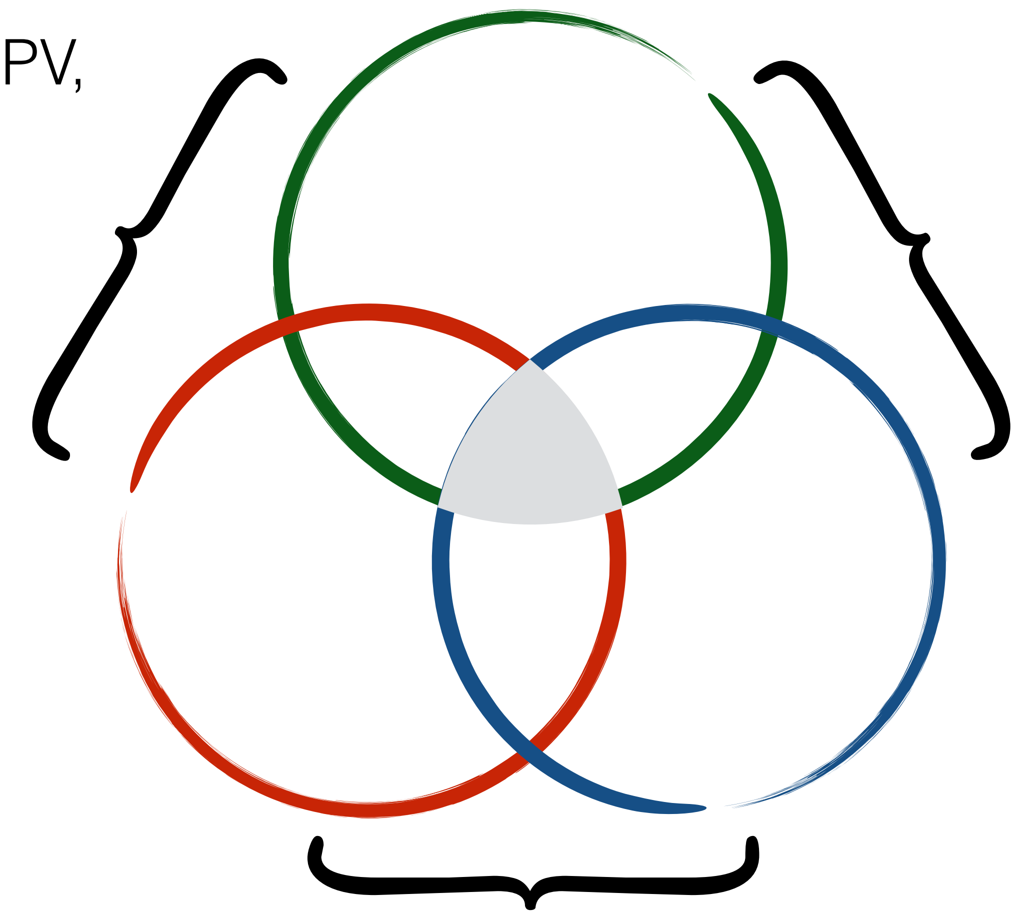


Status of SUSY model building

N. Craig@Search'16

Naturalness & Unification

- Light-flavor UDD RPV, LQD w/ taus
- RPV Higgsino
- Higgs properties
- <Your idea here>



Naturalness & Dark Matter

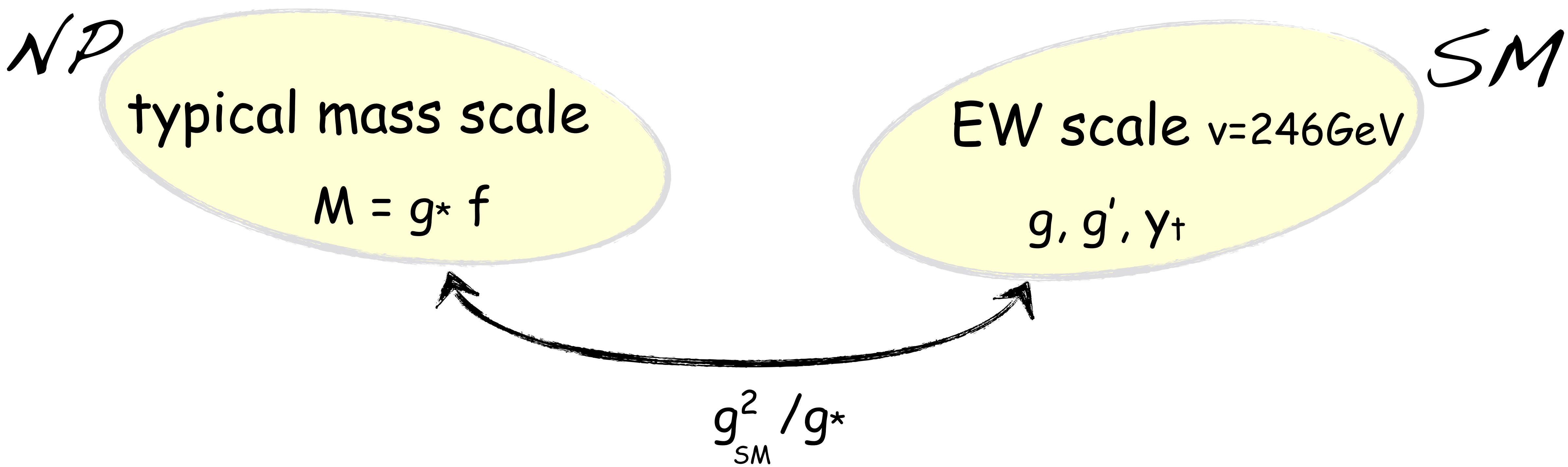
- Additional states near weak scale (sgluon, KK resonances, …)
- Higgs properties
- <Your idea here>

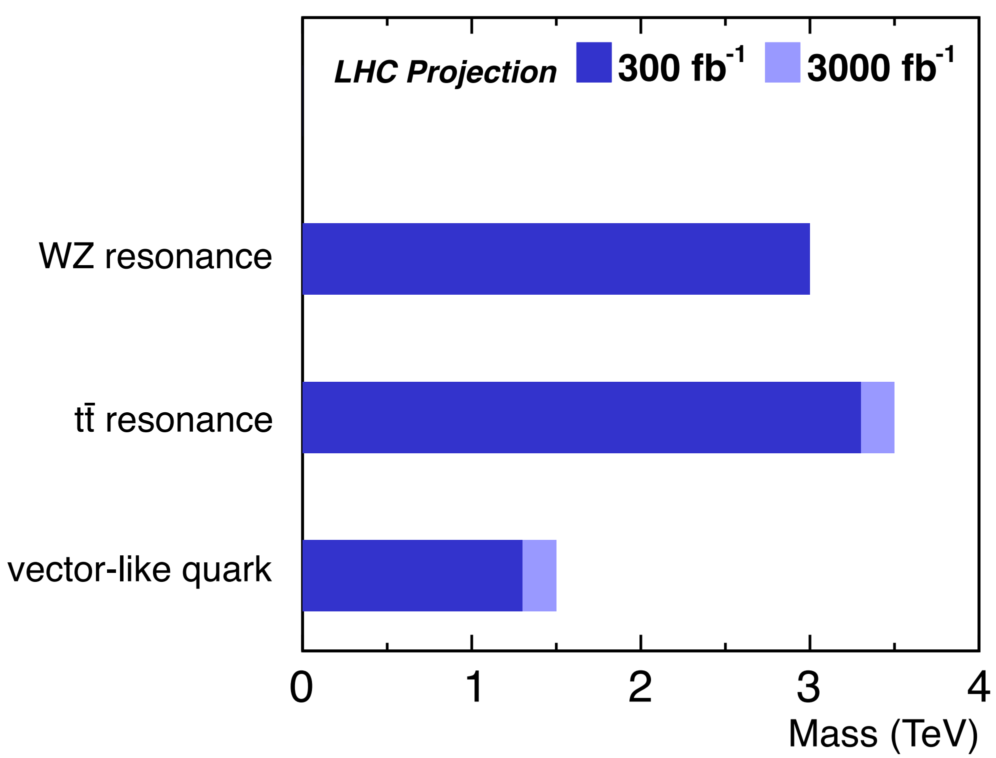
Unification & Dark Matter

- Conventional split SUSY searches
- Pure wino, higgsino LSP
- Extended Higgs sector?
- <Your idea here>

Higgs & New Physics (Vectors)

Precision /indirect searches (high lumi.) vs. direct searches (high energy)





LHC direct search

- Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$
- Direct searches for resonances: $m_\rho \approx g_* f$

Which one is doing best?
it depends on value of g_*

Higgs & New Physics (Vectors)

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

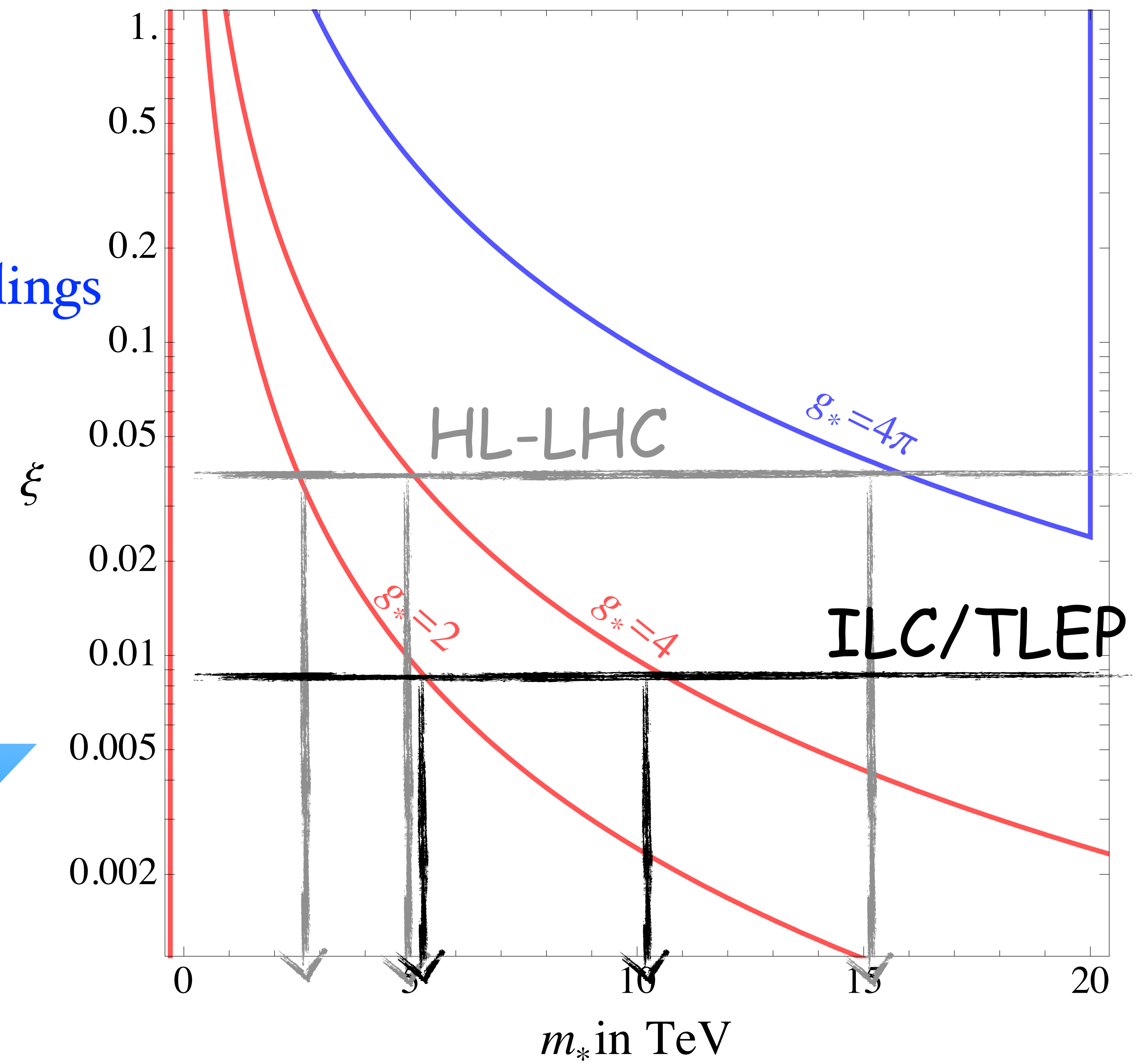
Mass reach:

a deviation in Higgs couplings also teaches us on the maximum mass scale to search for!

e.g. 10% deviation ⇛ m_V < 10TeV

i.e. resonance within the reach of FCC-hh

Higgs couplings



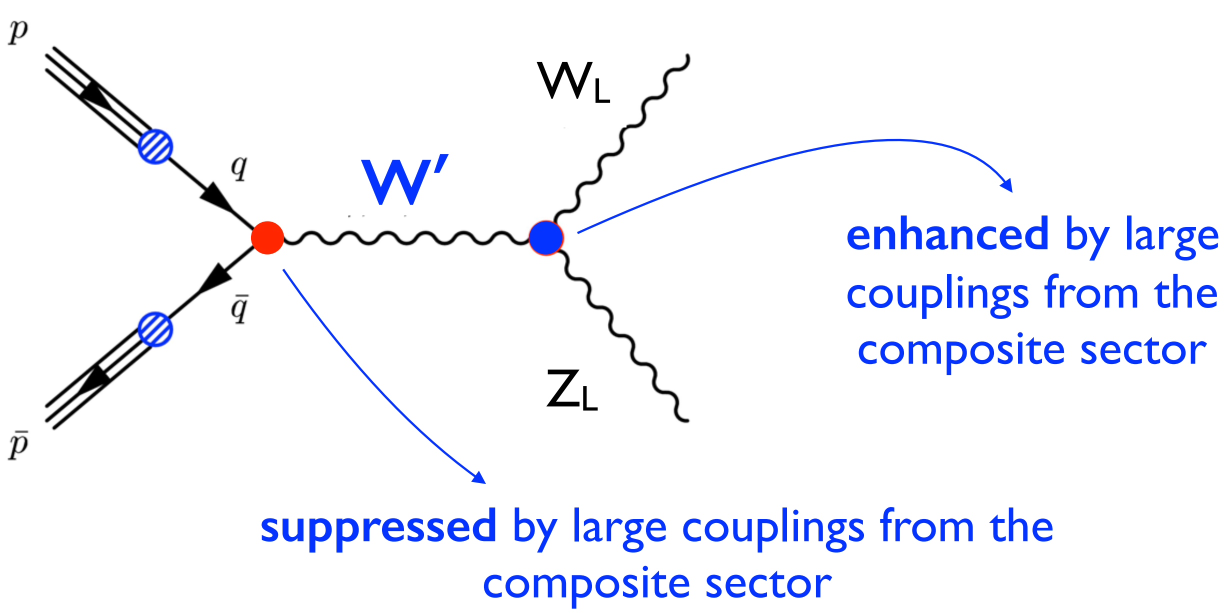
direct searches

Rattazzi, BSM@100TeV, CERN '14

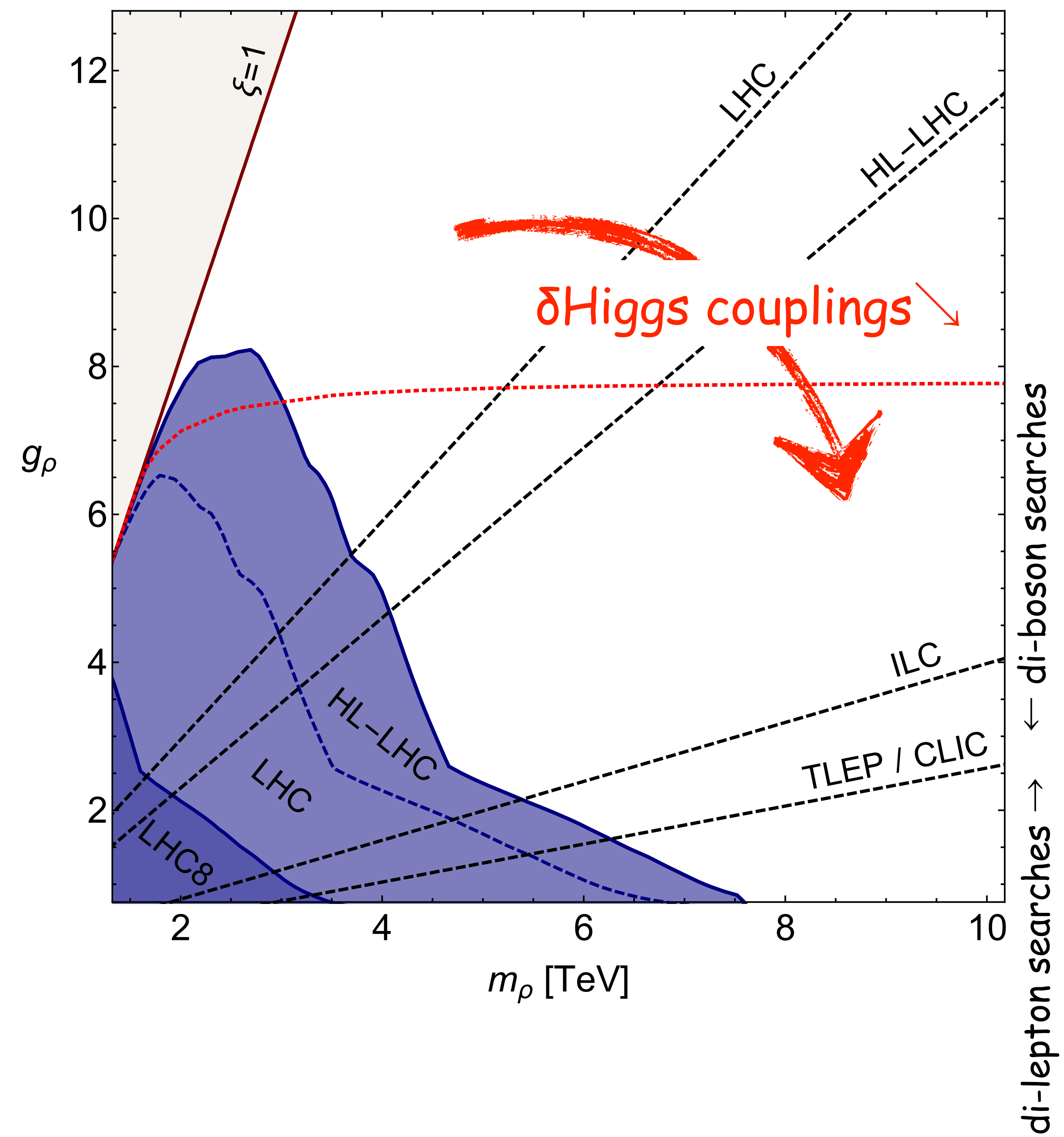
Higgs & New Physics (Vectors)

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Torre, Thamm, Wulzer '15



DY production xs of resonances decreases as $1/g_\rho^2$



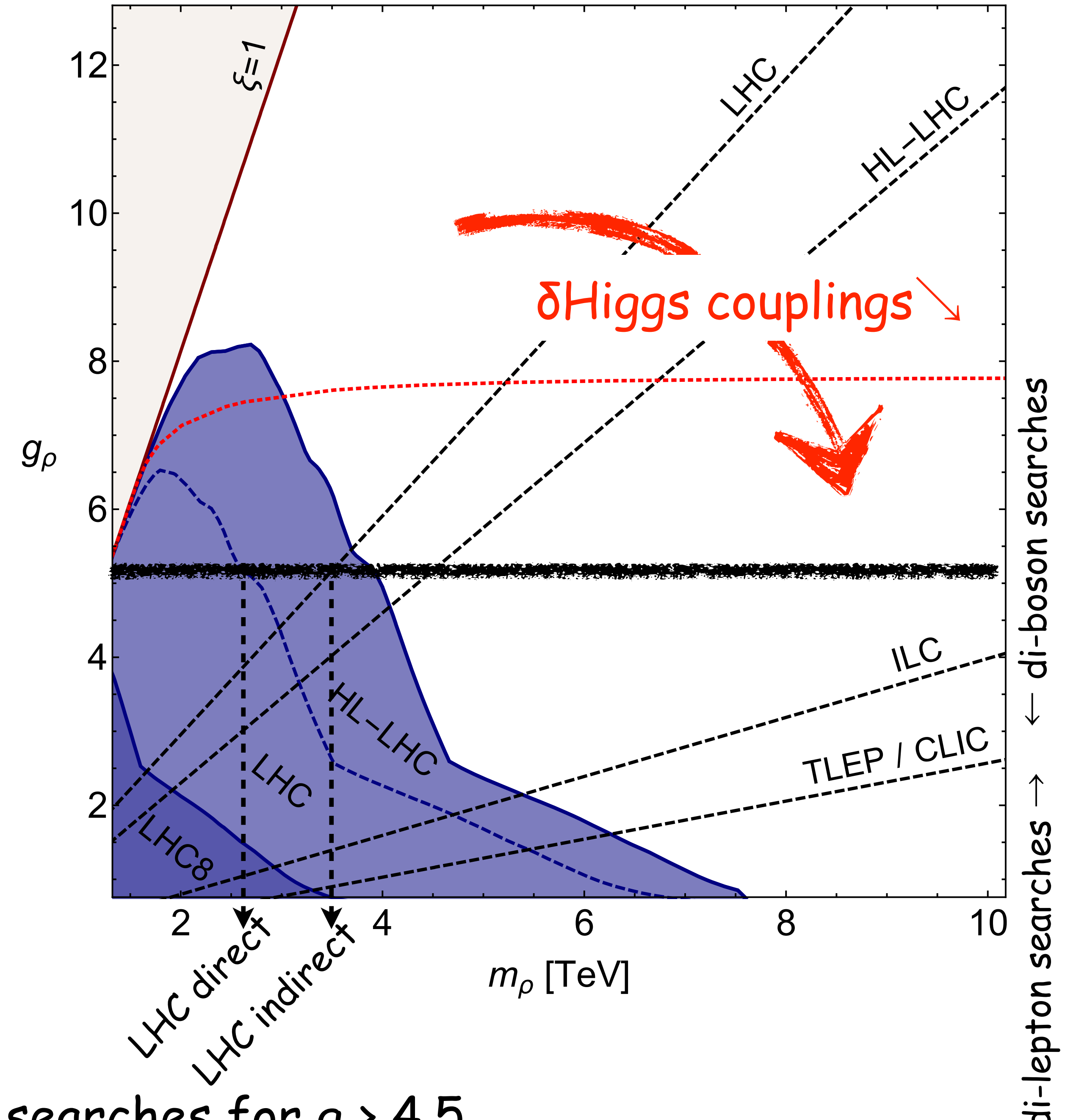
Higgs & New Physics (Vectors)

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Torre, Thamm, Wulzer '15

DY production xs of resonances decreases as $1/g_\rho^2$

Collider	Energy	Luminosity	ξ [1σ]
LHC	14 TeV	300 fb^{-1}	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	3 ab^{-1}	$4 - 10 \times 10^{-2}$
ILC	250 GeV + 500 GeV	250 fb^{-1} 500 fb^{-1}	4.8-7.8 $\times 10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	500 fb^{-1} 1.5 ab^{-1} 2 ab^{-1}	2.2 $\times 10^{-3}$
TLEP	240 GeV + 350 GeV	10 ab^{-1} 2.6 ab^{-1}	2×10^{-3}



- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

e.g.
indirect searches at LHC over-perform direct searches for g > 4.5
indirect searches at ILC over-perform direct searches at HL-LHC for g > 2

Higgs & New Physics (Vectors)

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

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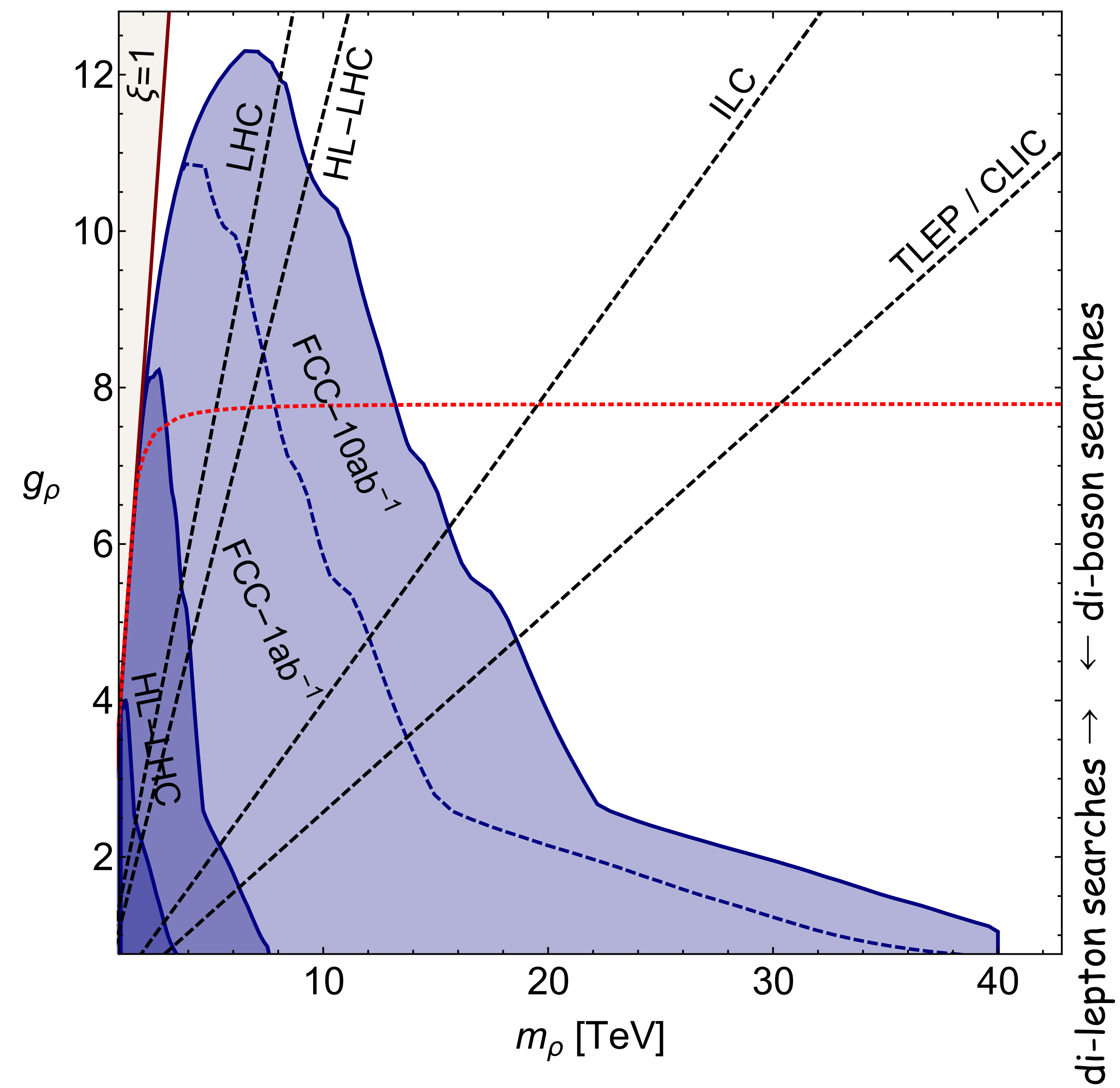

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  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

e.g.

indirect searches at LHC over-perform direct searches for g > 4.5

indirect searches at ILC over-perform direct searches at HL-FCChh for g > 6

Higgs & New Physics: Summary

(courtesy of A. Wulzer@ZPW2017)

Top Partner Searches:
- strongly connected with tuning
- however light Top Partners avoided in peculiar "Twin Higgs" models

Vector Searches:
- less directly related to tuning (but still, higher mass-reach …)
- apply to broader class of comp. models (TC, TH, W-comp.)

Higgs Couplings:
- very model-independent and very strong.
- part of a broad ("SM") exploration program
- slow progresses at run-2

Energy and Accuracy:
- W and Y as a **proof of concept**
- also a way to do **EWPT@LHC!!**
- looking for other channels with similar performances. **Diboson?**

3

BSM Higgs couplings: Baryogenesis

EW scale flavons for EW baryogenesis

Baldes, Konstandin, Servant '16

Electroweak baryogenesis requires:

- A strong first order phase transition
- Sufficient CP violation

However in the SM:

- The Higgs mass is too large
- Quark masses are too small

This negative result is tied to the fact that
Yukawa couplings during EW phase transition are identical the ones afterwards
What if they were larger?
E.g. flavor structure emerges during the EW transition

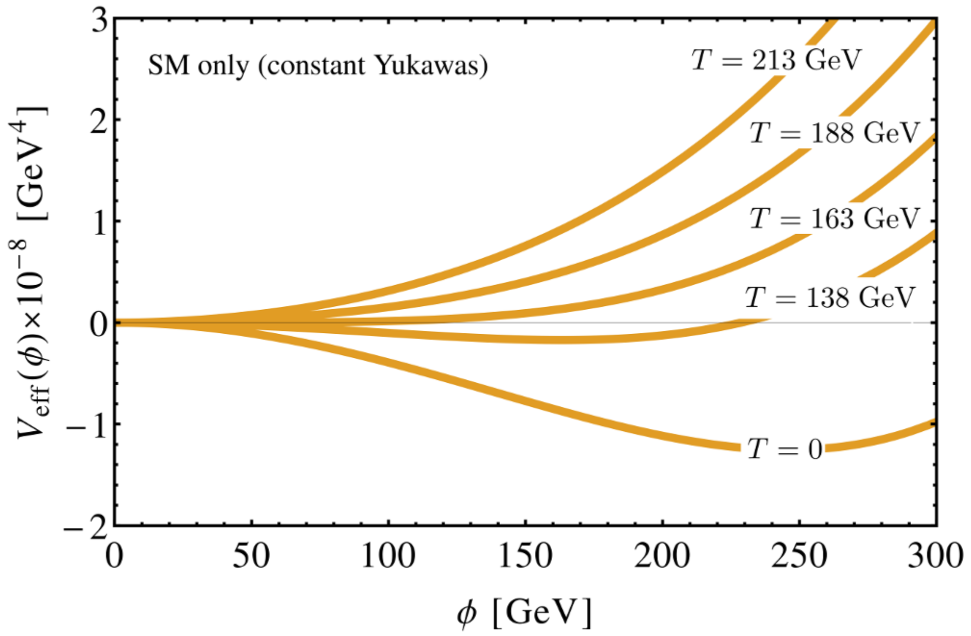
$$y_{ij} \bar{f}_L^i H f_R^j \qquad \Rrightarrow \qquad y_{ij} \left(\frac{\chi}{M}\right)^{q_H + q_j - q_i} \bar{f}_L^i H f_R^j$$

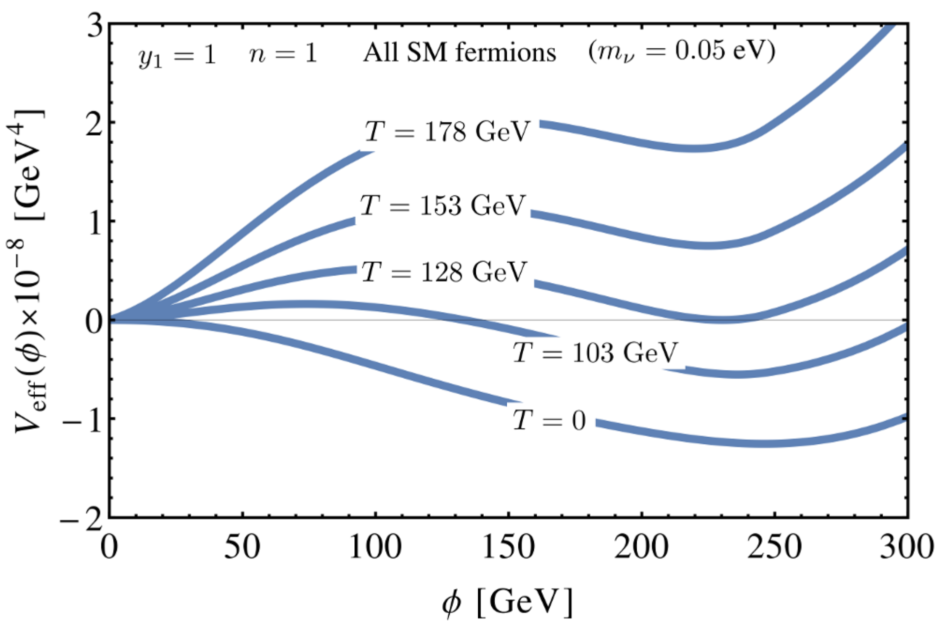
traditionally, M >> v and χ is frozen during EWSB
lowering M and allowing χ to vary leads to totally different phenomenology

EW scale flavons for EW baryogenesis

Baldes, Konstandin, Servant '16

$$y(\phi) = \begin{cases} y_1 \left(1 - \left[\frac{\phi}{v}\right]^n\right) + y_0 & \text{for} \quad \phi \le v, \\ y_0 & \text{for} \quad \phi \ge v. \end{cases}$$





The evolution of the effective potential with temperature in the SM (left) and with varying Yukawas (right) The varying Yukawa calculation includes all SM fermions with y1=1, n=1 and their respective y0, chosen to return the observed fermion masses today (the neutrinos are assumed to have a Dirac m=0.05eV).

In the varying Yukawa case, there is a first-order phase transition with ϕ_c=230GeV and Tc=128GeV (vs. second order transition at Tc=163GeV for the constant Yukawa case).

1st order phase transition + enhanced source of CP

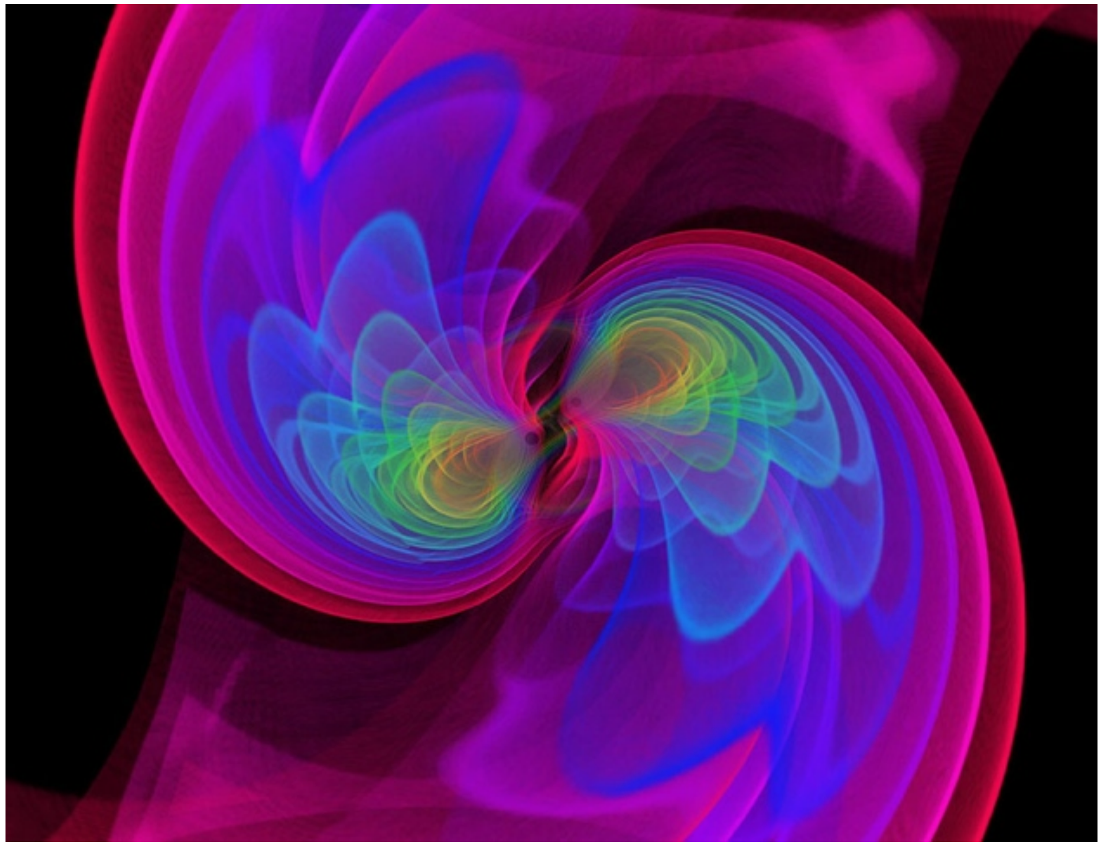
See also yesterday J. Hisano's talk

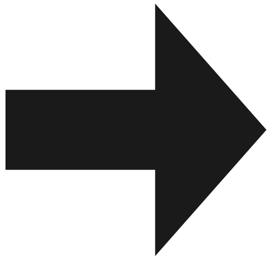
4

Fun with GW: stochastic GW background from phase transitions

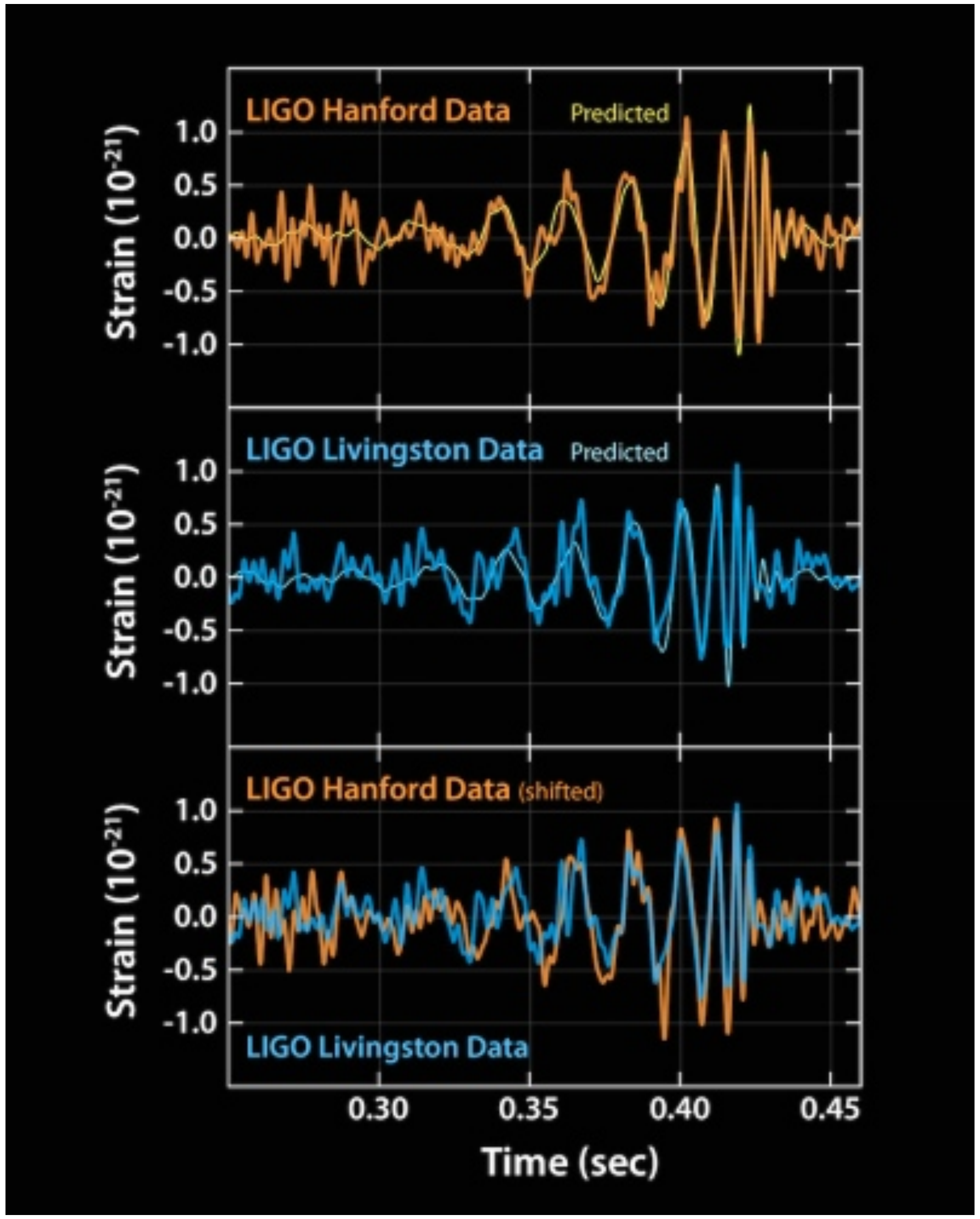
The pictures of 2016

GW150914





1.3 billion years later on earth



what does it teach us?

- never give up against strong background when you know you are right
- $m_g < 10^{-22}$ eV ($c_g - c_\gamma < 10^{-17}$ GRB observed together with GW with the same origin?)
- no spectral distortions: scale of quantum gravity > 100 keV

GW and the ElectroWeak Phase Transition

GW interact very weakly and are not absorbed

direct probe of physical process of the very early universe

possible cosmological sources:

inflation, vibrations of topological defects, excitations of xdim modes, 1st order phase transitions...

ElectroWeak Phase Transition (if 1st order)

typical freq. ~ (size of the bubble)$^{-1}$ ~ (fraction of the horizon size)$^{-1}$

$$@\ T = 100\ \text{GeV}, \qquad H = \sqrt{\frac{8\pi^3}{45}\frac{T^2}{M_{Pl}}} \sim 10^{-15}\ \text{GeV}$$

redshifted freq.

~ today ~

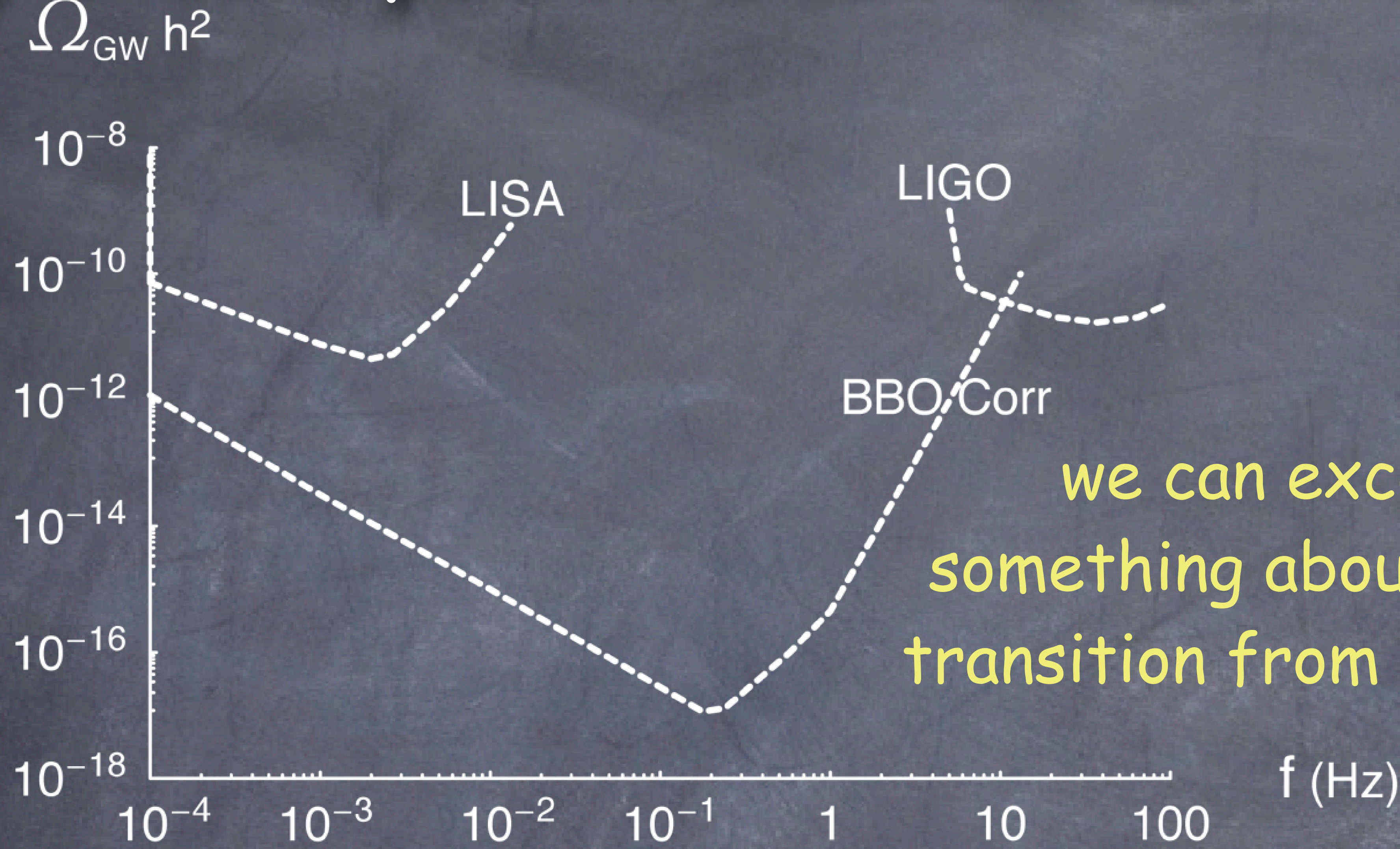
$$f \sim \# \frac{2 \cdot 10^{-4}\ \text{eV}}{100\ \text{GeV}}\ 10^{-15}\ \text{GeV} \sim \# 10^{-5}\ \text{Hz}$$

Grojean, Servant '06

The GW spectrum from a 1st order electroweak PT
is peaked around the milliHertz frequency

Why should you be excited about mHZ freq.?

Grojean, Servant '06



we can except to learn something about the EW phase transition from GW experiments

- test of the dynamics of the phase transition
  (quite important to analyze models of EW baryogenesis!)

redshift

$$\Omega^{\star}_{GW} \Rightarrow \Omega_{GW} = \left(\frac{a_\star}{a_0}\right)^4 \left(\frac{H_\star}{H_0}\right)^2 \Omega^{\star}_{GW} \sim 2{\cdot}10^{-5} h^{-2} \left(\frac{100}{g_\star}\right)^{1/3} \Omega^{\star}_{GW}$$

$$H_0 \sim h \times 2{\cdot}10^{-42}\ \mathrm{GeV}$$

Hunting for phase transitions with GW

P. Schwaller '15

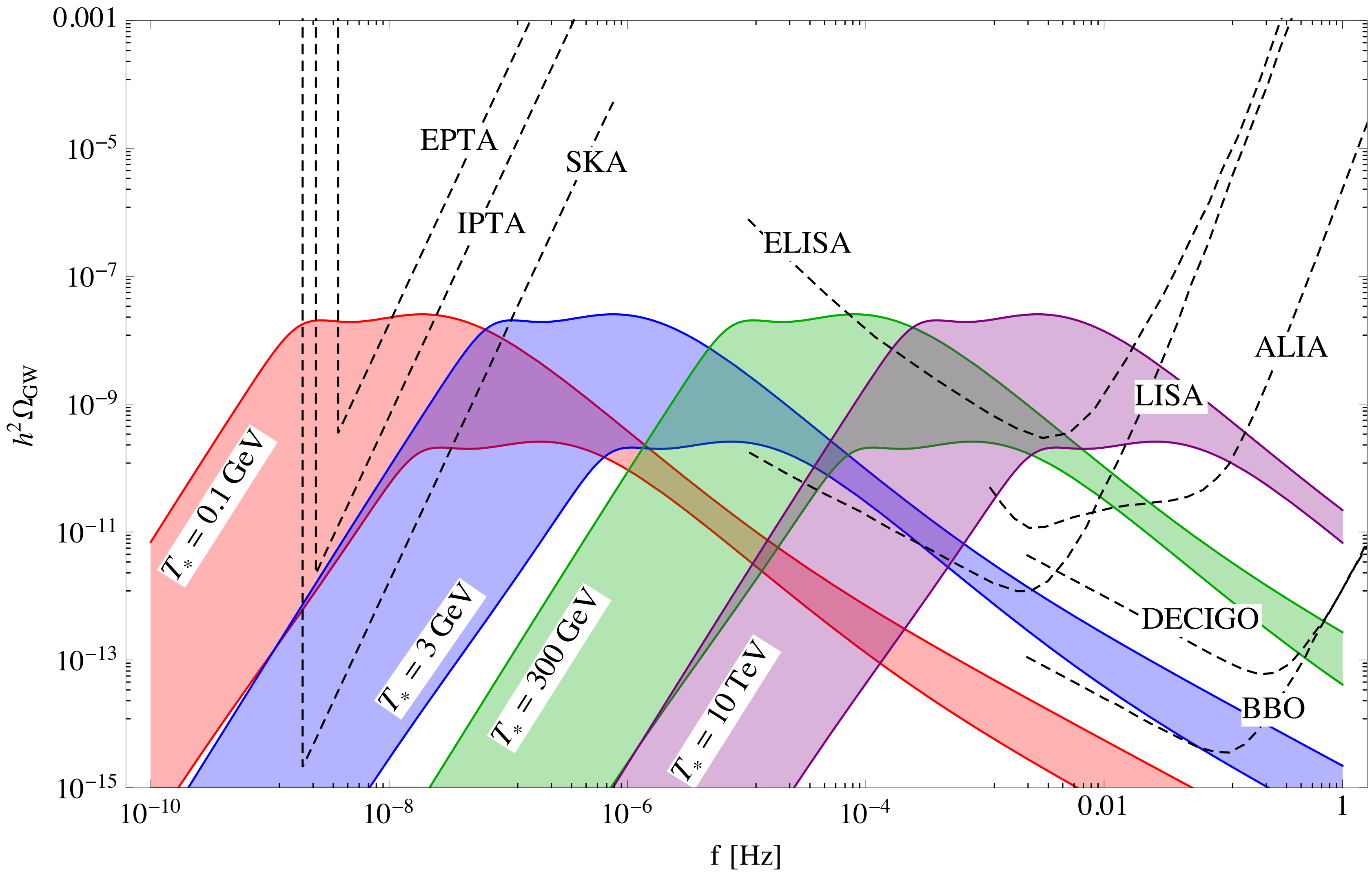


Figure 3: GW spectra $\Omega(f)h^2$ for $T_* = 0.1$ GeV (SIMP), $T_* = 3$ GeV (CDM1, TH models), $T_* = 300$ GeV and $T_* = 10$ TeV (CDM2 models). The upper (lower) edges of the contours correspond to $\beta = \mathcal{H}$ ($\beta = 10\mathcal{H}$), and furthermore $v = 1$ and $\Omega_{S*} = 0.1$ for all curves. The red band $T_* = 0.1$ GeV indicates where a signal of the QCD PT would lie if it was strong. The projected reach of several planned GW detection experiments is shown (dashed).

See also tomorrow
K. Choi's talk

5

Naturalness without TeV-scale New Physics: relax!

The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by time evolution/the age of the Universe

Can this idea be formulated in a QFT language?
In which sense is it addressing the stability of small numbers at the quantum level?

Graham, Kaplan, Rajendran '15

Espinosa et al '15

- Higgs mass-squared promoted to a field
- The field evolves in time in the early universe and scans a vast range of Higgs mass
- The Higgs mass-squared relaxes to a small negative value
- The electroweak symmetry breaking stops the time-evolution of the dynamical system

Self-organized criticality

dynamical evolution of a system is stopped at a critical point due to back-reaction

hierarchies result from **dynamics** not from **symmetries** anymore!

important consequences on the spectrum of new physics

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

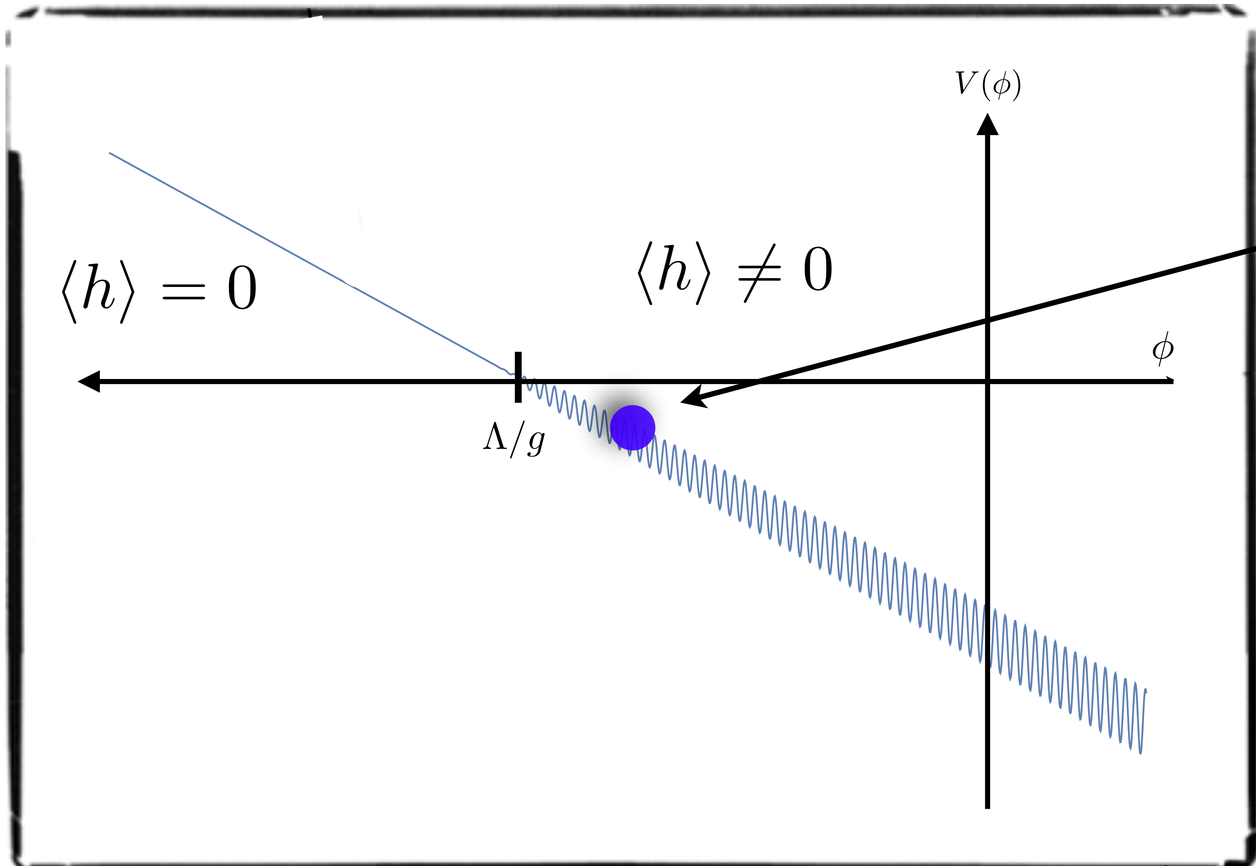
$$\Lambda^2 \left(-1 + f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2 + \Lambda^4 V\left(\frac{g\phi}{\Lambda}\right) + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on ϕ

potential needed to force ϕ to roll-down in time (during inflation)

axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev

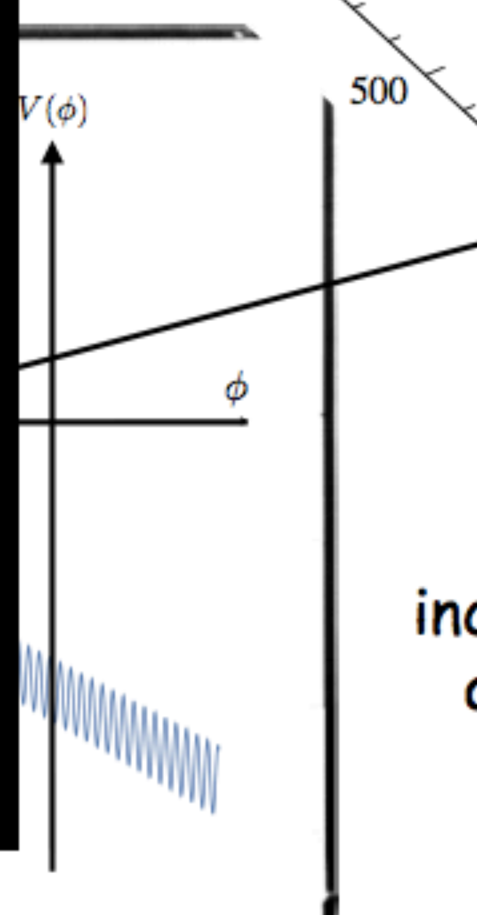
$$\Lambda^3_{\rm QCD}\, h \cos\frac{\phi}{f}$$

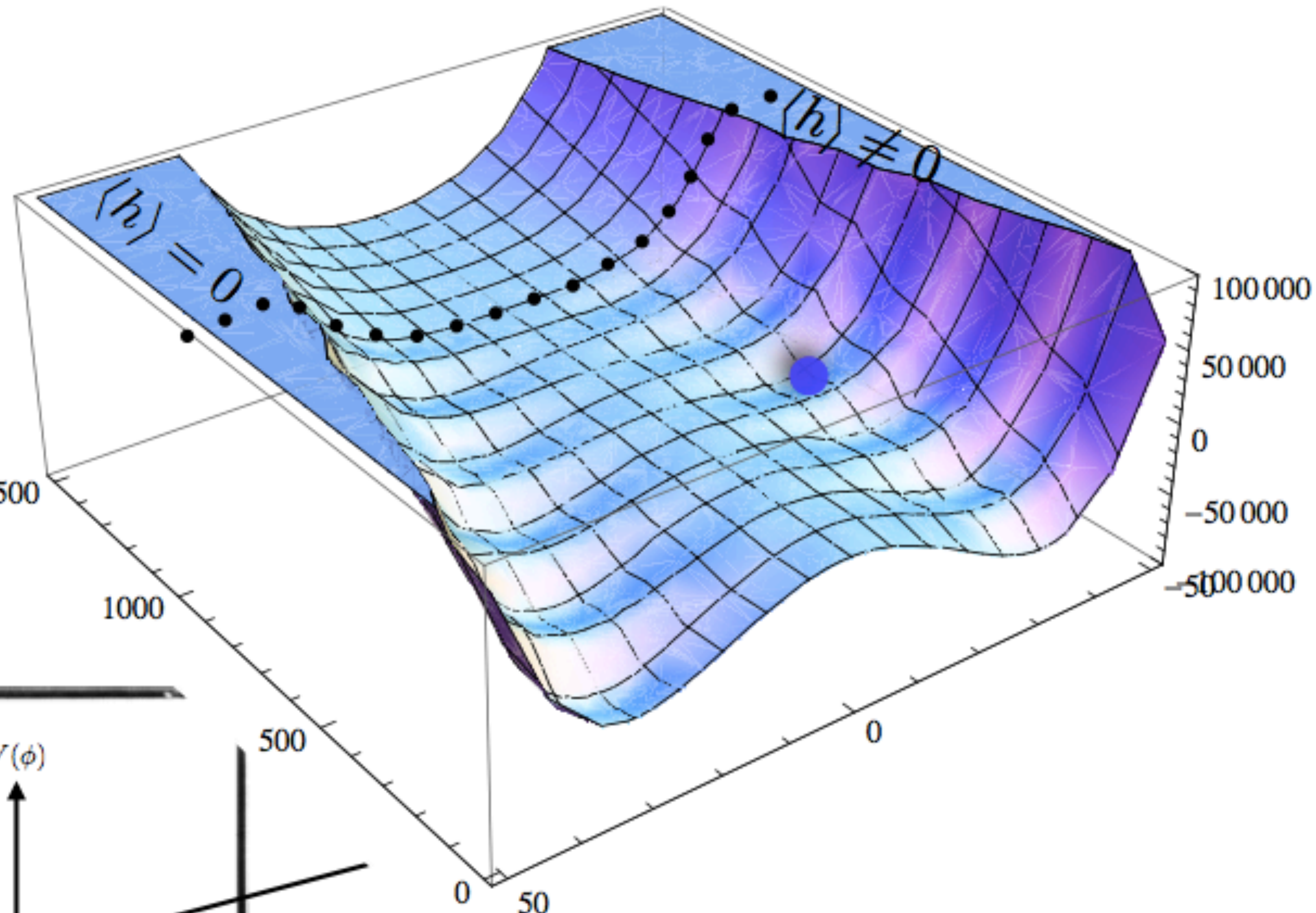


Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ



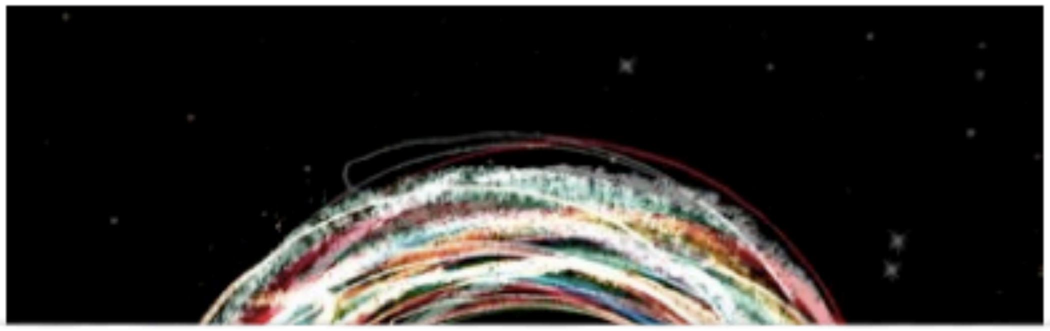


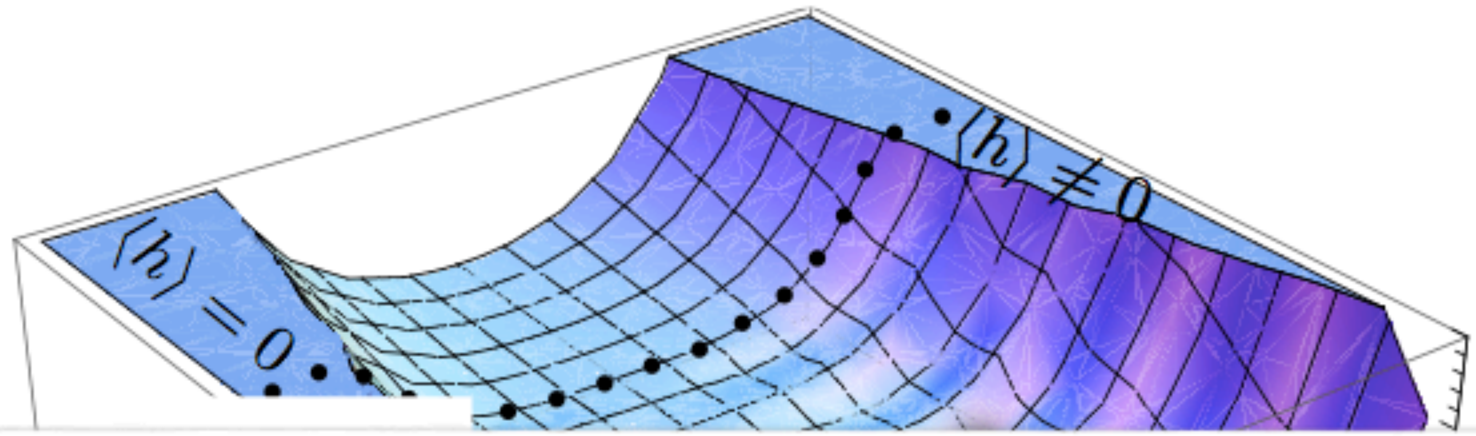
If ϕ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately prevents ϕ from rolling down further

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ





Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics

~interesting cosmology signatures~

- BBN constraints
- decaying DM signs in γ-rays background
- ALPs
- superradiance

~interesting signatures @ SHiP~

- production of light scalars by B and K decays

Phenomenological signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

only BSM physics below Λ

two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim (10^{-20} - 10^2)\,\mathrm{GeV}$$

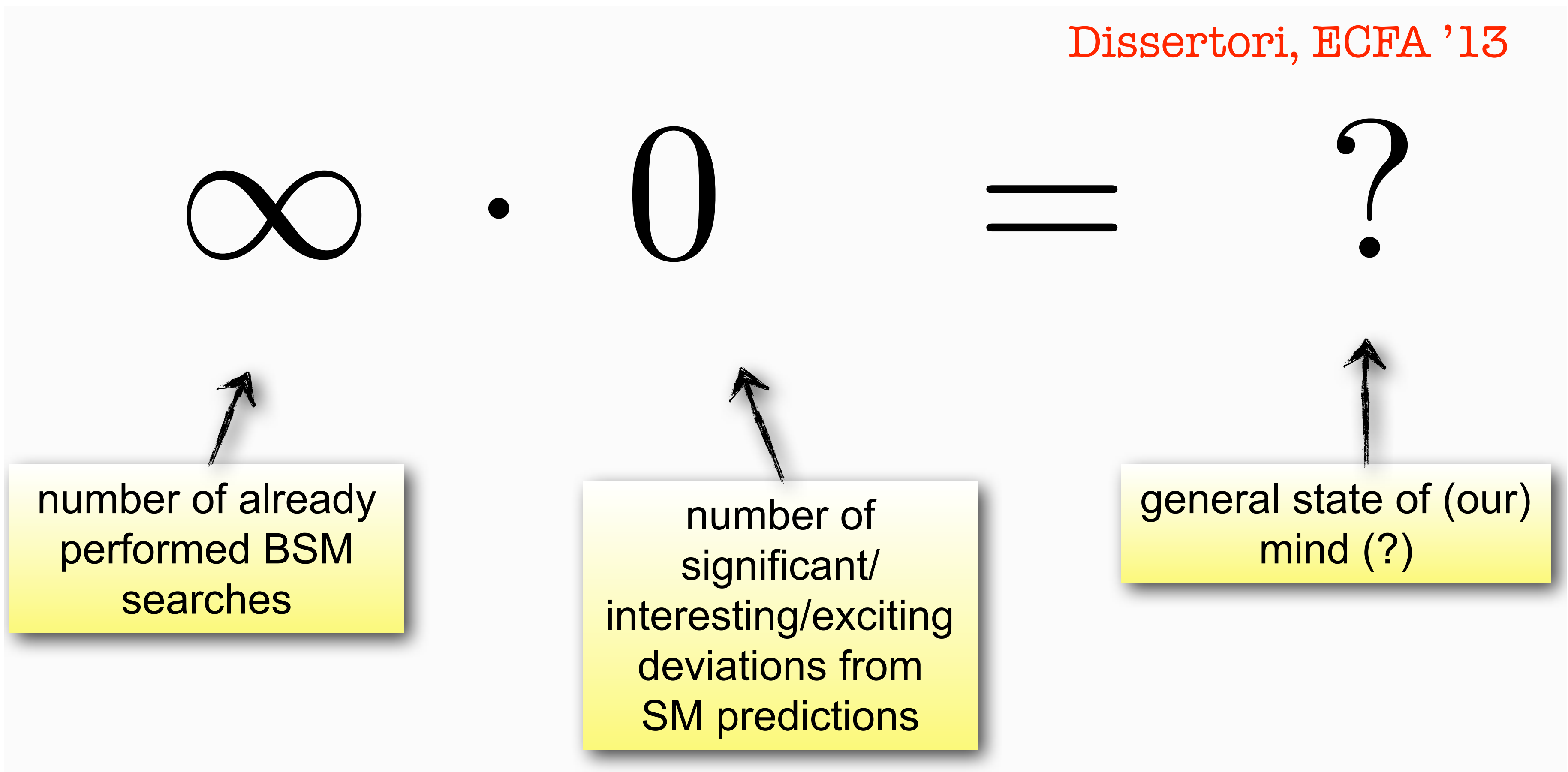
$$m_\sigma \sim (10^{-45} - 10^{-2})\,\mathrm{GeV}$$

interesting signatures in cosmology

Conclusions

Conclusions: Executive Summary

The LHC leaves us with the deepest mathematical pb:



The Higgs boson is the Santa Maria of the 21st century:
understanding the scalar sector of the SM
will help us grasping what lays beyond the SM

We also need the right technological tool (SHiP, ILC, CLIC, CepC, FCC...)
to continue exploring the unknown