Higgs and EW interpretation - theory (SM and BSM) -

Panic 2014

Hamburg, August 25, 2014

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*iCrea INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

The mass conundrum

SM=triumph of Quantum Mechanics + Special Relativity

particles = representations of Poincaré group

these representations are labelled by

(spin, mass)

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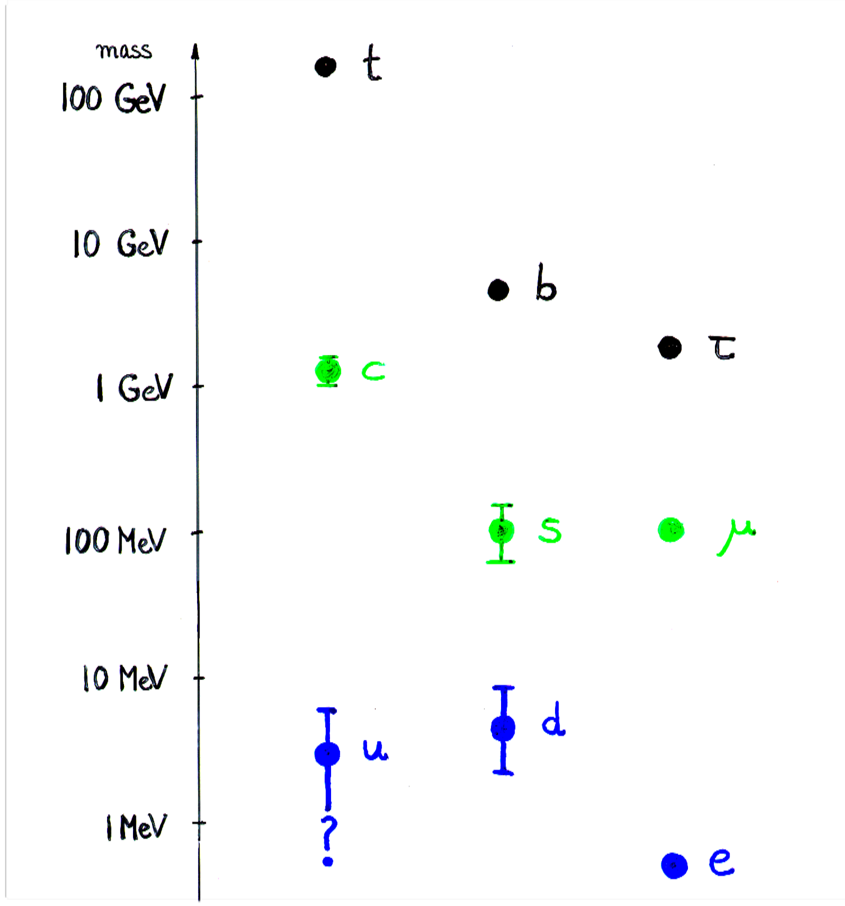

(pictures: courtesy of A. Weiler)

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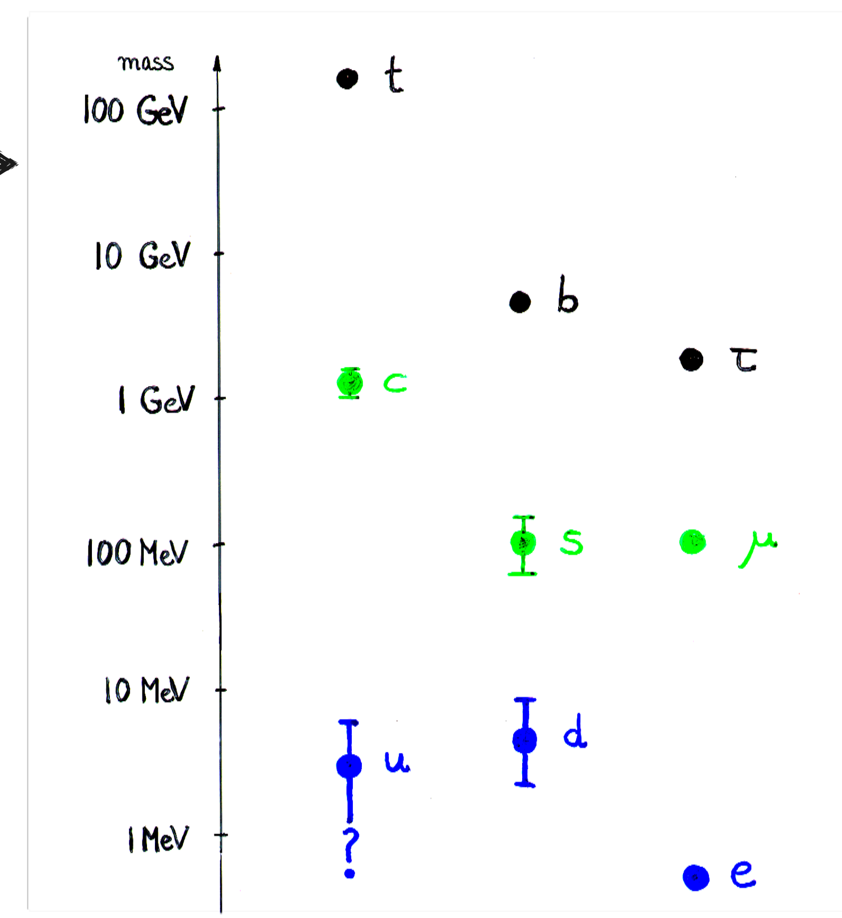


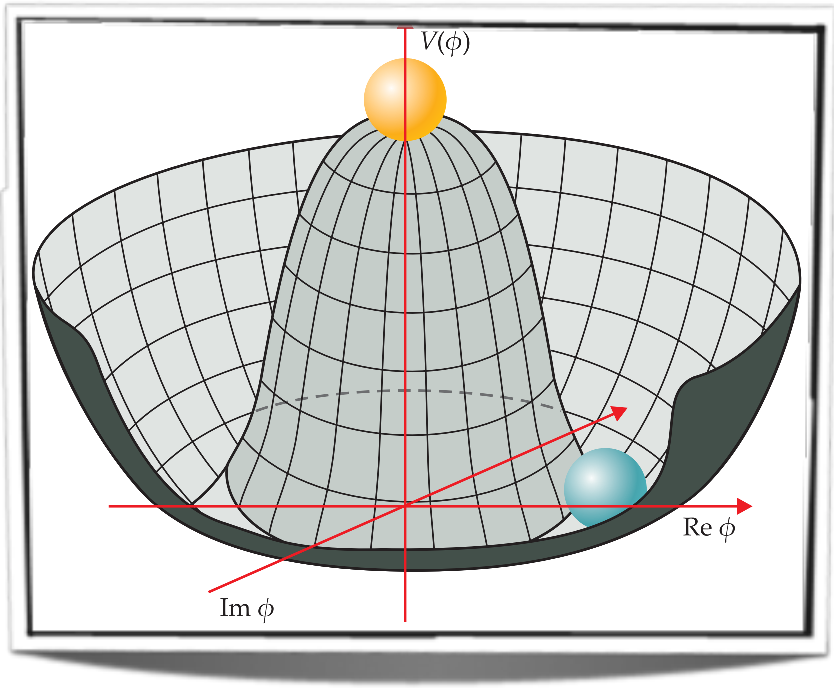
but

incompatible with gauge symmetries
chiral fermion ⇛ m=0 only
gauge boson ⇛ m=0 only

(pictures: courtesy of A. Weiler)

Solution: spontaneous symmetry breaking

The masses are emergent due to a non-trivial structure of the vacuum



vacuum = a space entirely devoid of matter

Oxford English

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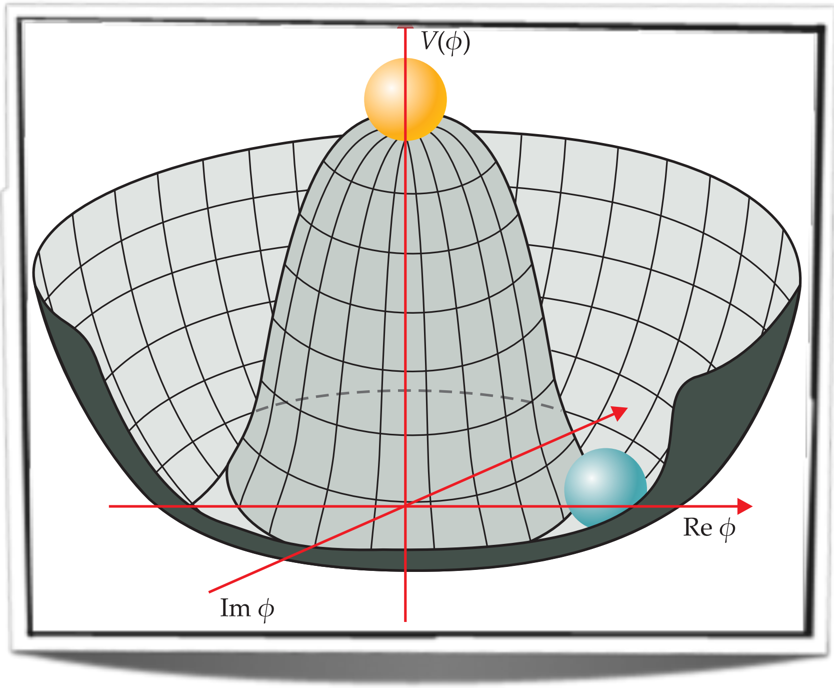

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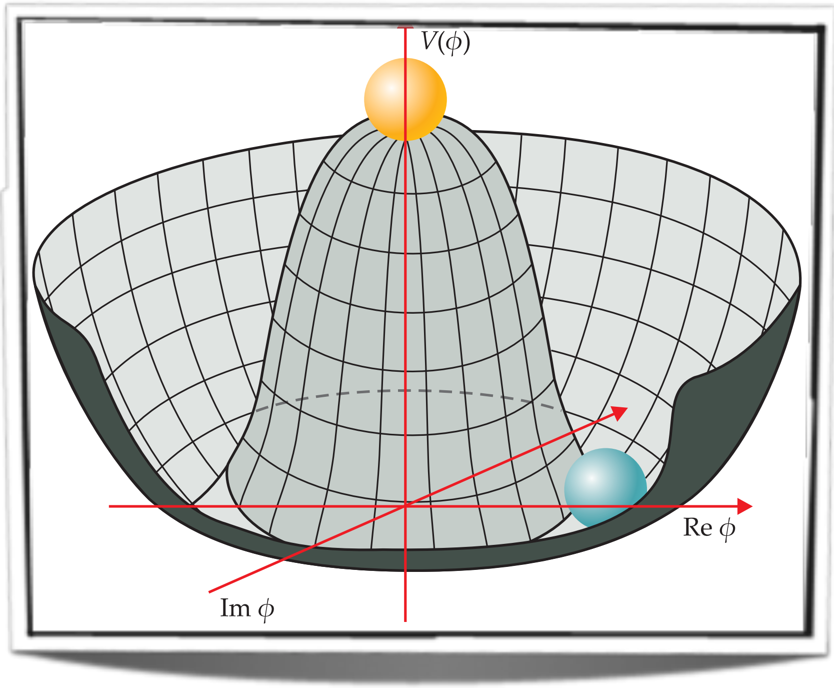

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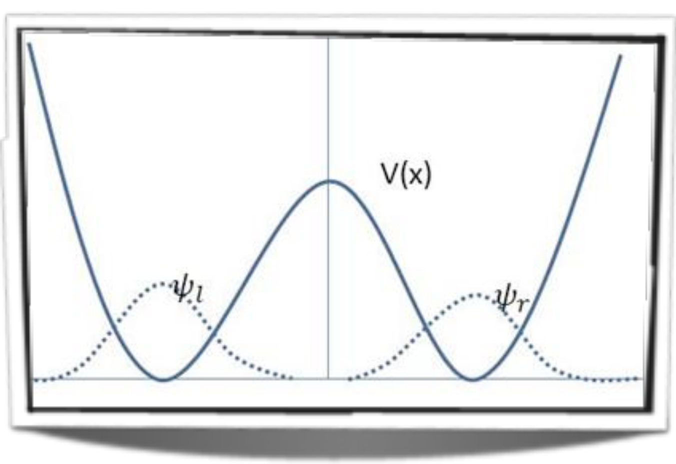
The Brout-Englert-Higgs mechanism is not a trivial thing

(courtesy of J. Lykken@Aspen2014)



ground state of QM double well potential
is a superposition of two states localized on one minimum,
and this superposition preserves the Z_2 symmetry of the potential

the vacuum of the SM breaks $SU(2) \times U(1)$ to $U(1)_{em}$

The HEP landscape after LHC_{8TeV}

Nicely summarized by M. Mangano @Aspen'14:

My key message

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

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The Higgs discovery sets a large part of the agenda for the theoretical and experimental HEP programs over the next couple of decades.

Unless a new major discovery soon (supersymmetry, DM...)!

The open questions about the Higgs

- Is it the SM Higgs?
- Is it an elementary/composite particle?
- Is it unique/solitary?
- Is it eternal/temporary?
- Is it natural?
- Is it the first supersymmetric particle ever observed?
- Is it really "responsible" for the masses of all the elementary particles?
- Is it mainly produced by top quarks or by new heavy vector-like quarks?
- Is it a portal to a hidden world?
- Is it at the origin of the matter-antimatter asymmetry?
- Has it driven the inflationary expansion of the Universe?

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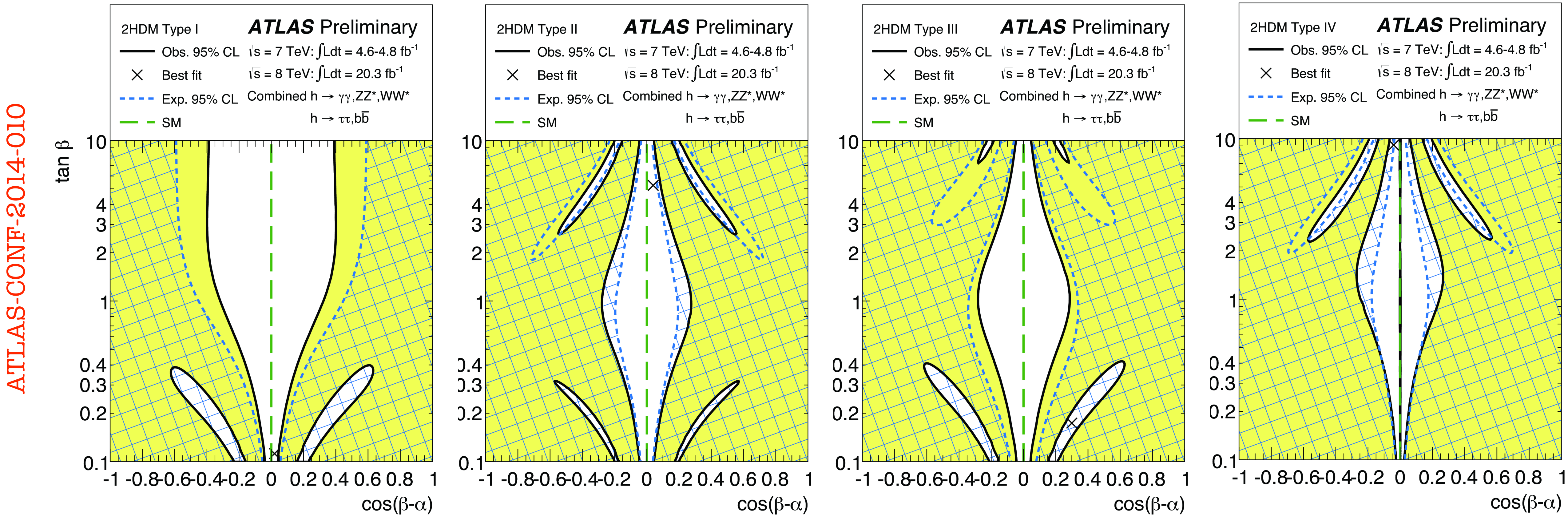
- ... Will it help to discover BSM before the construction of the Hamburg Opera house is over?

1

Is the Higgs solitary?

Is there a second Higgs doublet?

The measurements of the 125GeV Higgs couplings already constrain the existence of a second Higgs



	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
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ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
	$\kappa_V \sim \sin(\beta-\alpha)$ $\kappa'_V \sim \cos(\beta-\alpha)$	Different scaling for up and down fermions	Different scaling for leptons and quarks	Different scaling for up and down quarks, leptons flipped

How to search for a second Higgs?

Reuse the SM searches in the high mass region?

What about new prod./decay modes? New ideas needed!

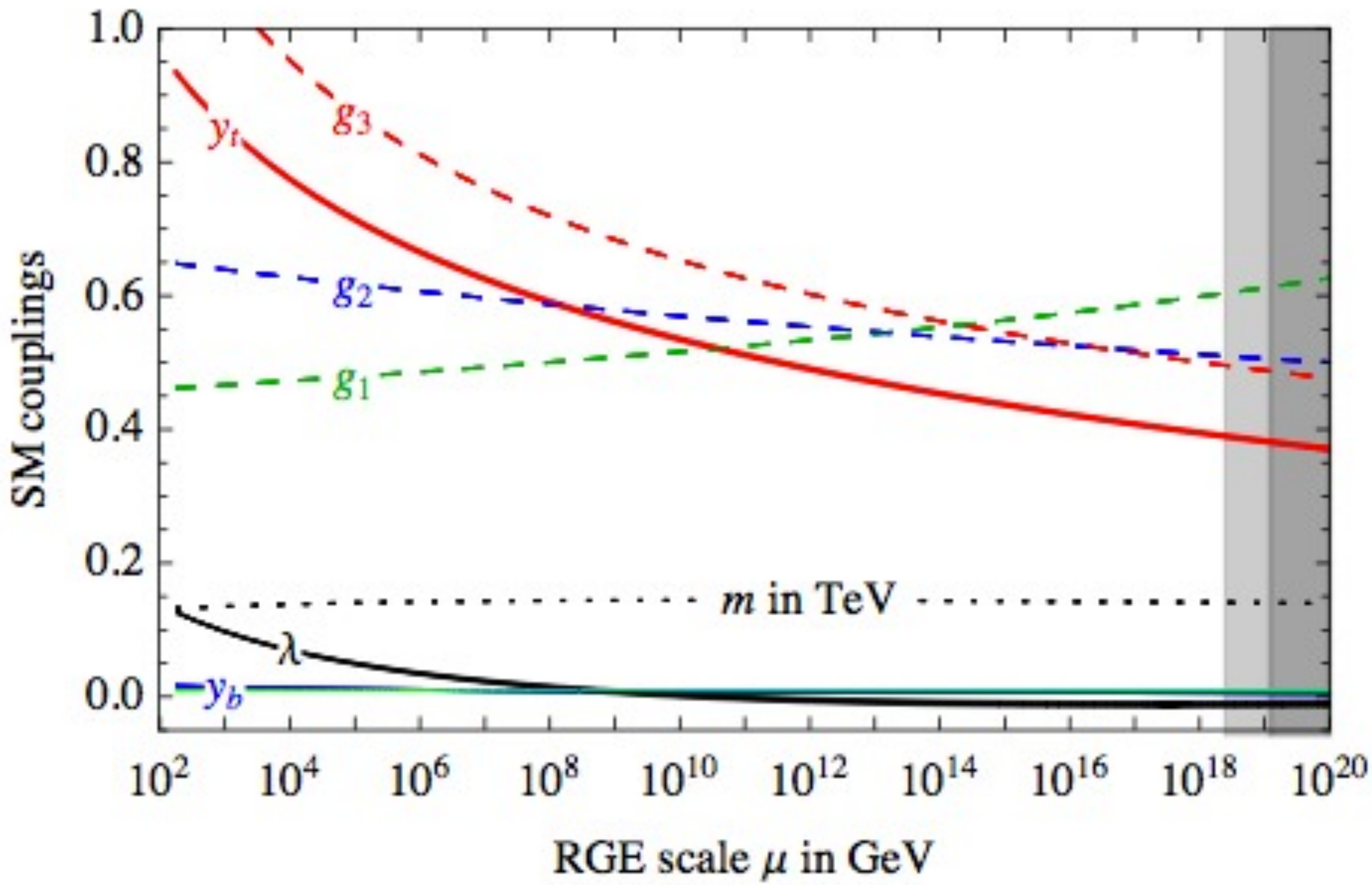
2

Is the Higgs temporary?

aka the fate of the EW vacuum

Can we live without new physics?

Buttazzo et al '13

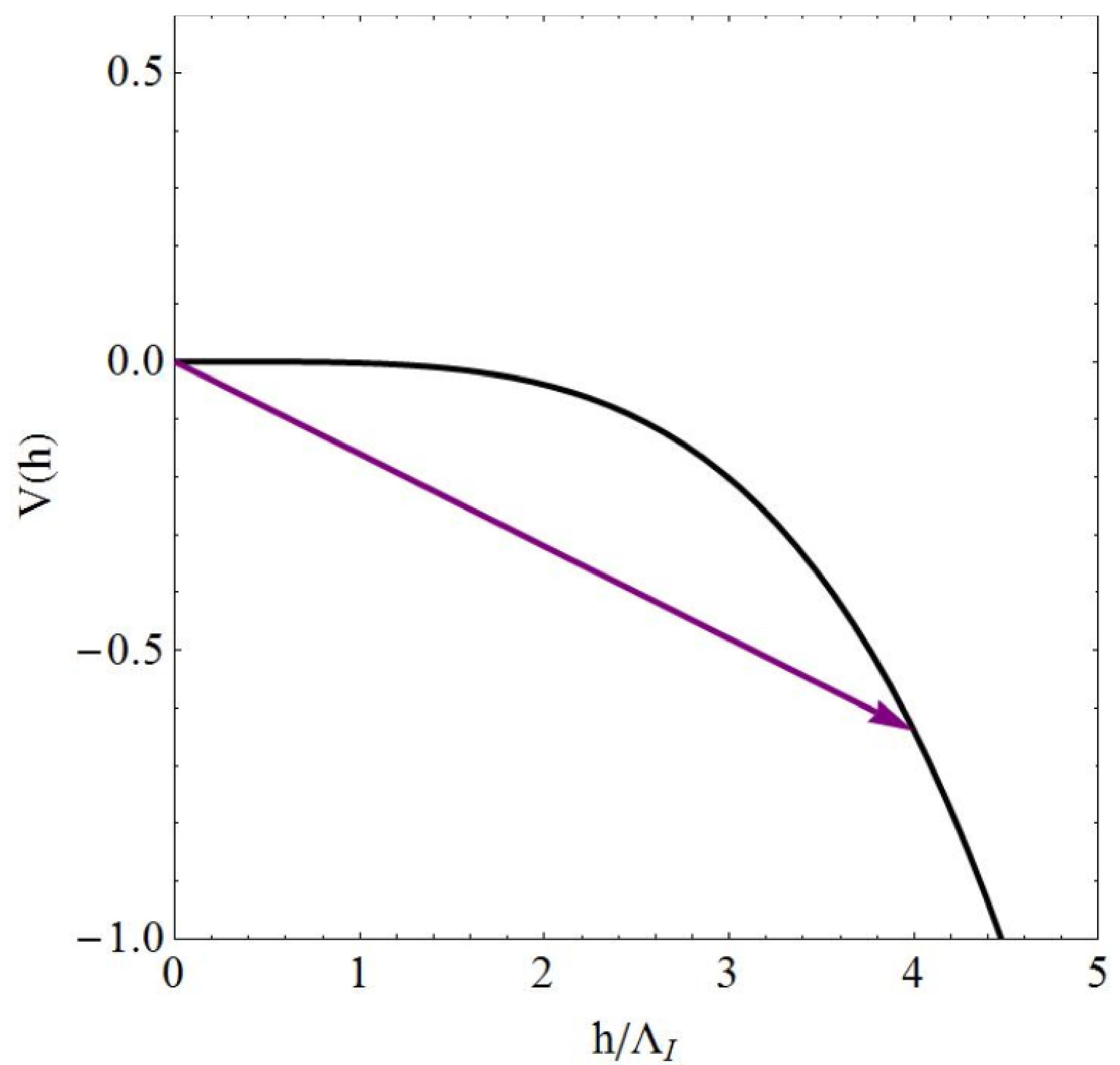


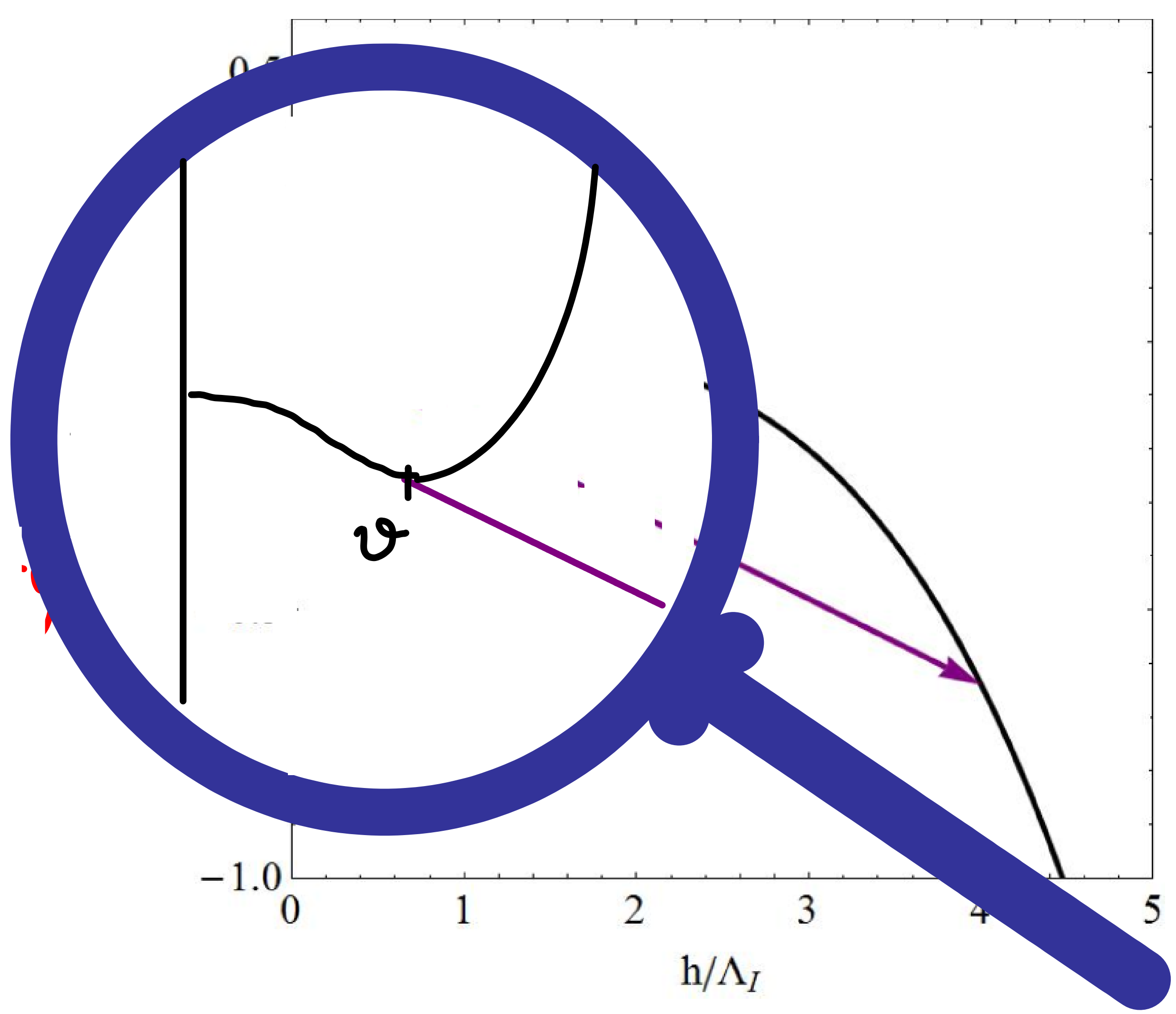
Forgetting the hierarchy problem for a moment, it seems possible to extend the validity of the SM up to M_{Pl} and that it remains weakly coupled?

Is the Higgs temporary?

If λ becomes negative, the EW vacuum is meta/unstable

(courtesy of JR Espinosa)

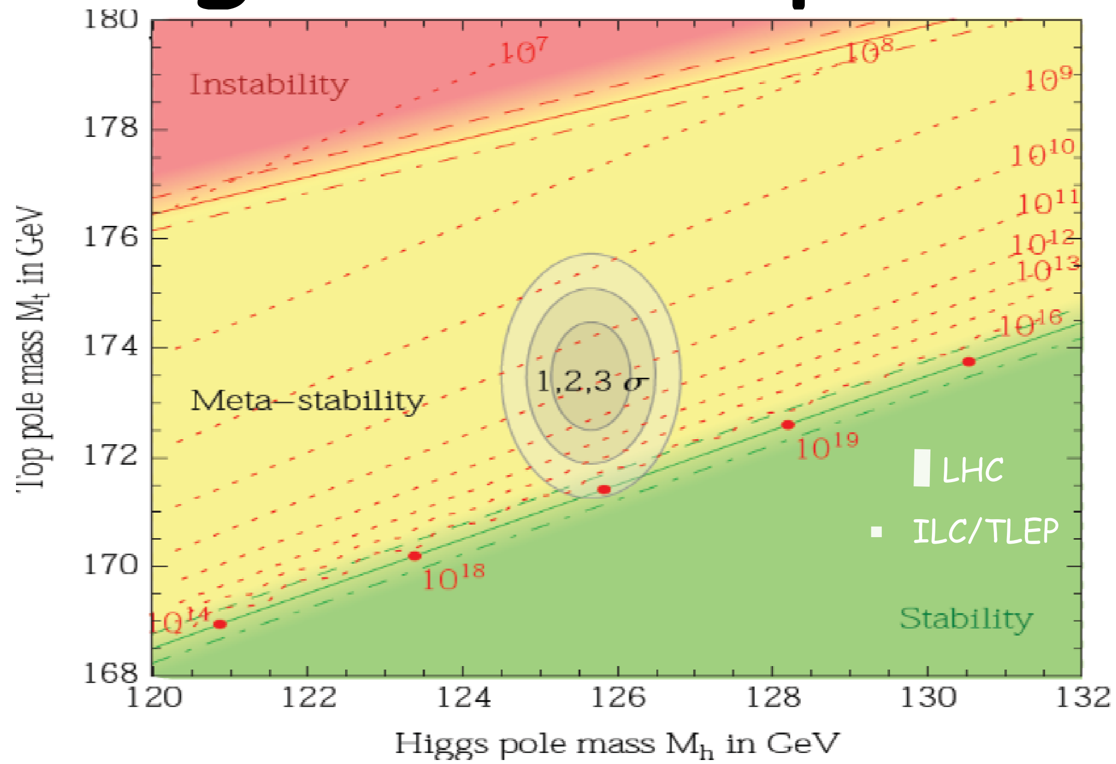




and the Higgs and our EW vacuum are only temporary!

Are we living at a edge of the phase diagram?

Parameter	Present	LHC	ILC/GigaZ	TLEP
M_H [GeV]	0.4	< 0.1	< 0.1	< 0.1
M_W [MeV]	15	8	5	1.3
M_Z [MeV]	2.1	2.1	2.1	0.1
m_t [GeV]	0.9	0.6	0.1	0.08

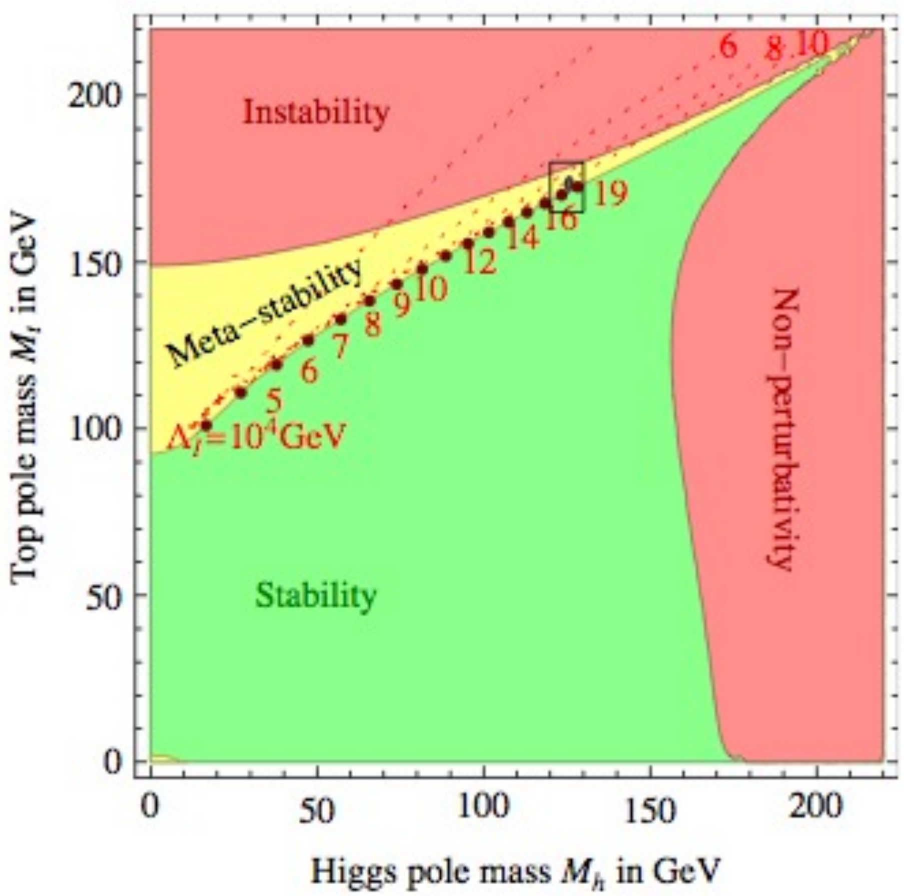


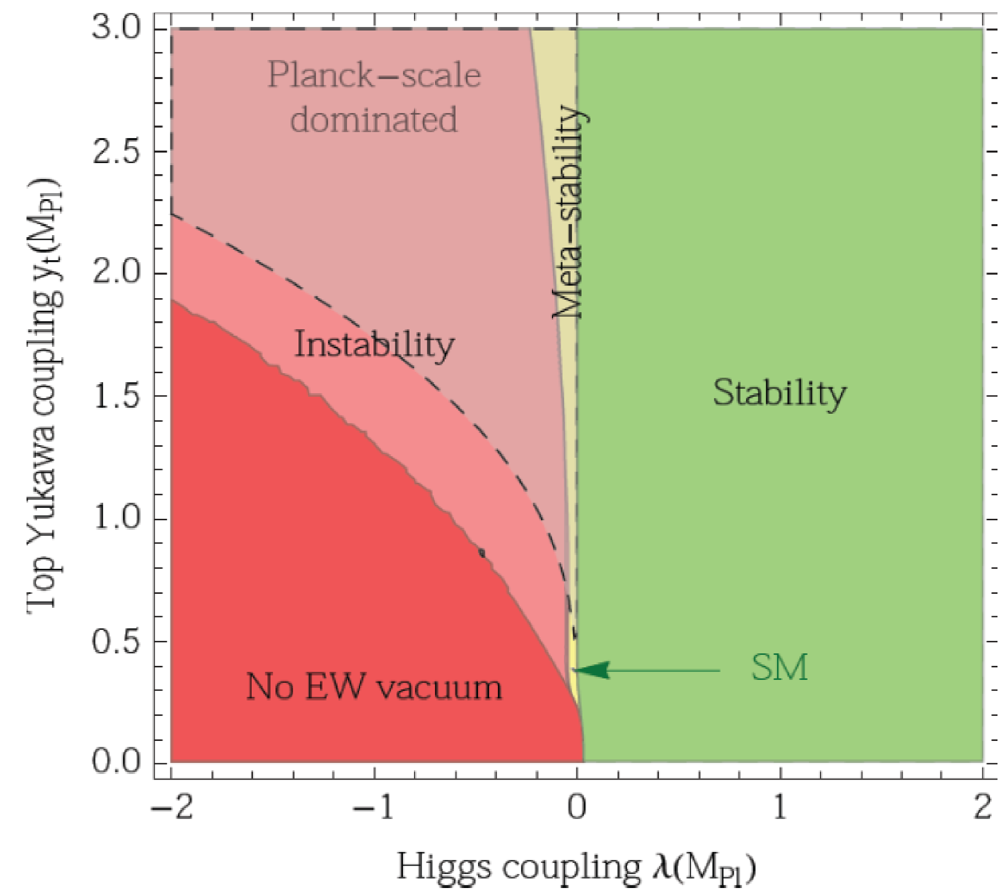
Buttazzo et al '13

see also:

Bezrukov et al '12

Degrassi et al '12





The (near) criticality of our vacuum calls for a precise measurement

3

Is the Higgs a portal to a hidden/dark world?

Is the Higgs a portal to a hidden/dark world?

- the WIMP hypothesis: hierarchy pb ⇒ NP with weak quantum numbers ⇒ DM
- the DM portal models are examples of DM neutral under the SM interactions

DM-portal prime ex.: $\mathcal{L} = \lambda S^2 |H|^2$ (note: fully renormalizable)

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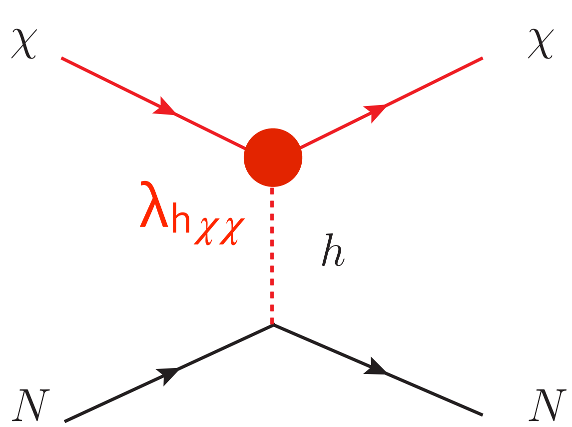
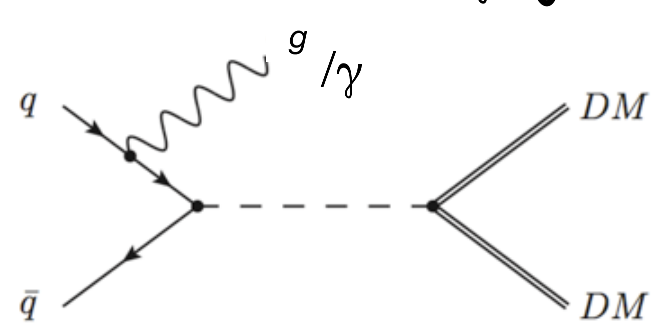
DM direct search

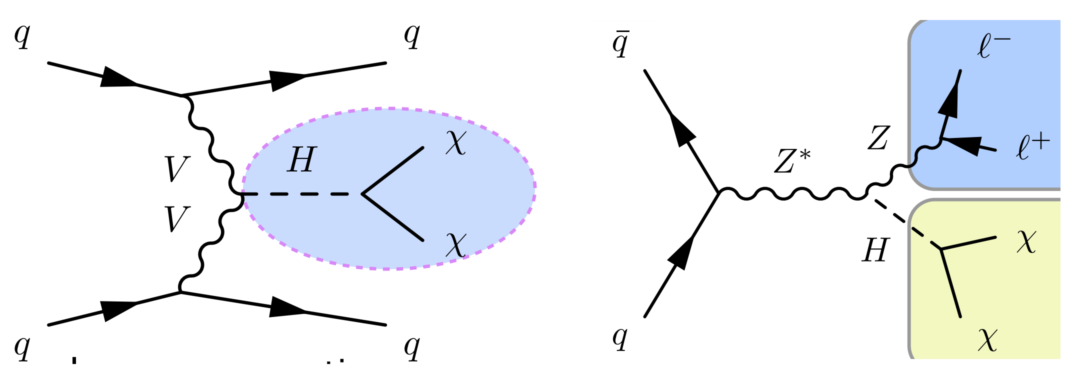


LHC direct search

- MET + mono γ/jet



- VBF & ZH searches



CMS PAS HIG-13-030

ATLAS CONF-2013-011

LHC indirect search

BR_{inv} from Higgs coupling fits

$$\Gamma_{tot} = \Gamma_{tot}^{SM} \cdot \frac{\sum_X \kappa_X^2 \cdot \mathrm{BR}_X^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

CMS PAS HIG-13-005

ATLAS CONF-2014-009

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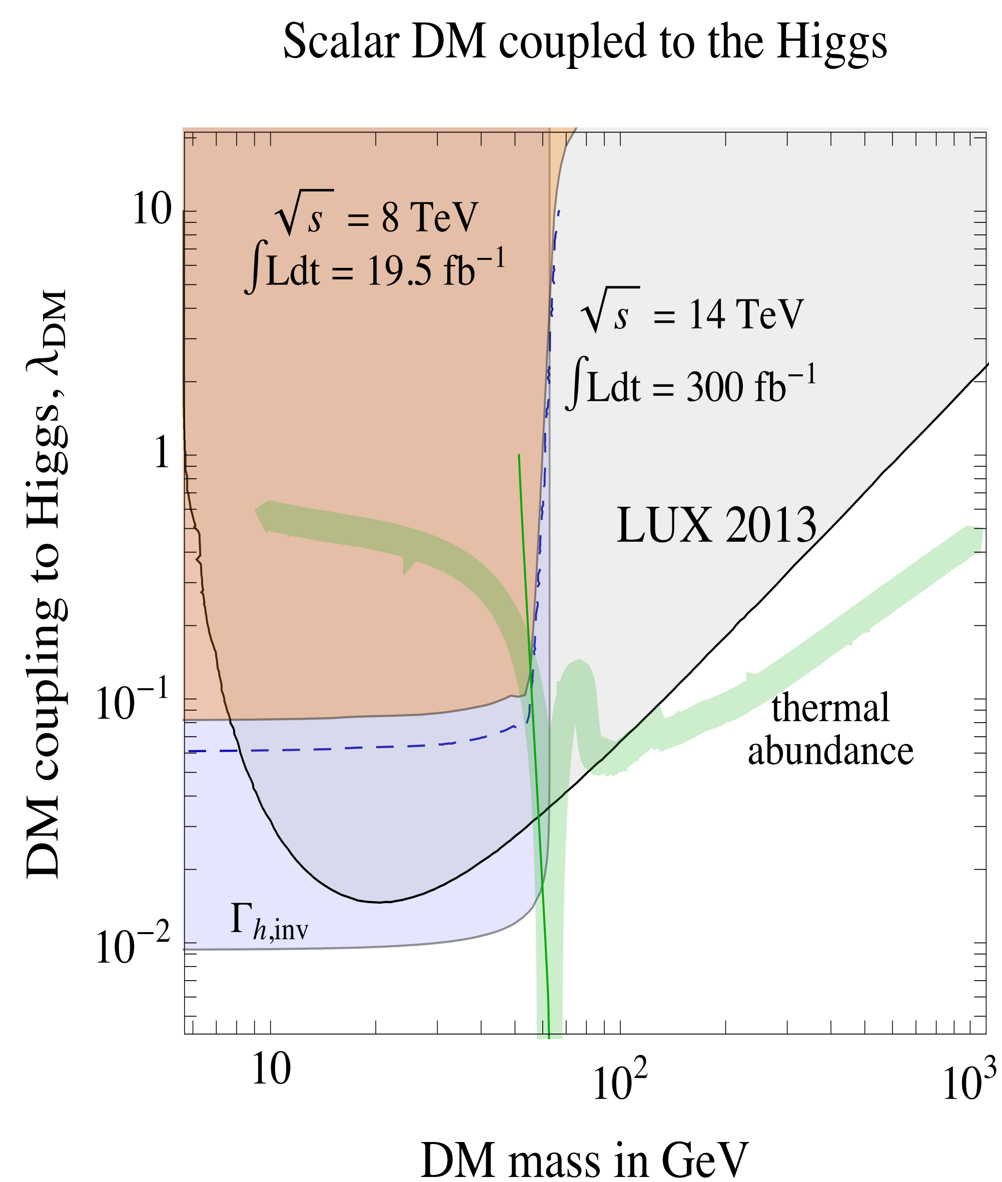


De Simone, Giudice, Strumia '14

the LHC direct searches are not competitive

4

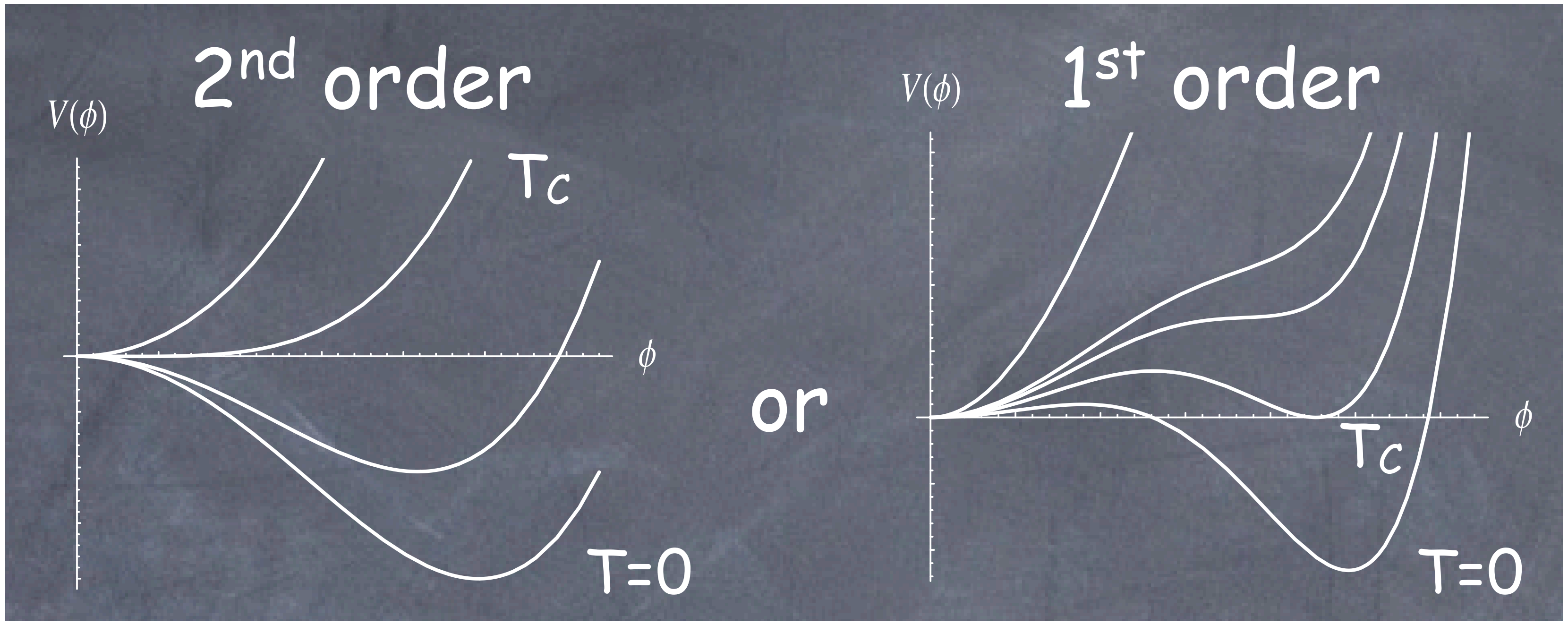
Dynamics of the EW phase transition:

is the Higgs at the origin of the matter-antimatter asymmetry?

Dynamics of EW phase transition and Cosmology

The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

An appealing idea is EW baryogenesis associated to a first order EW phase transition



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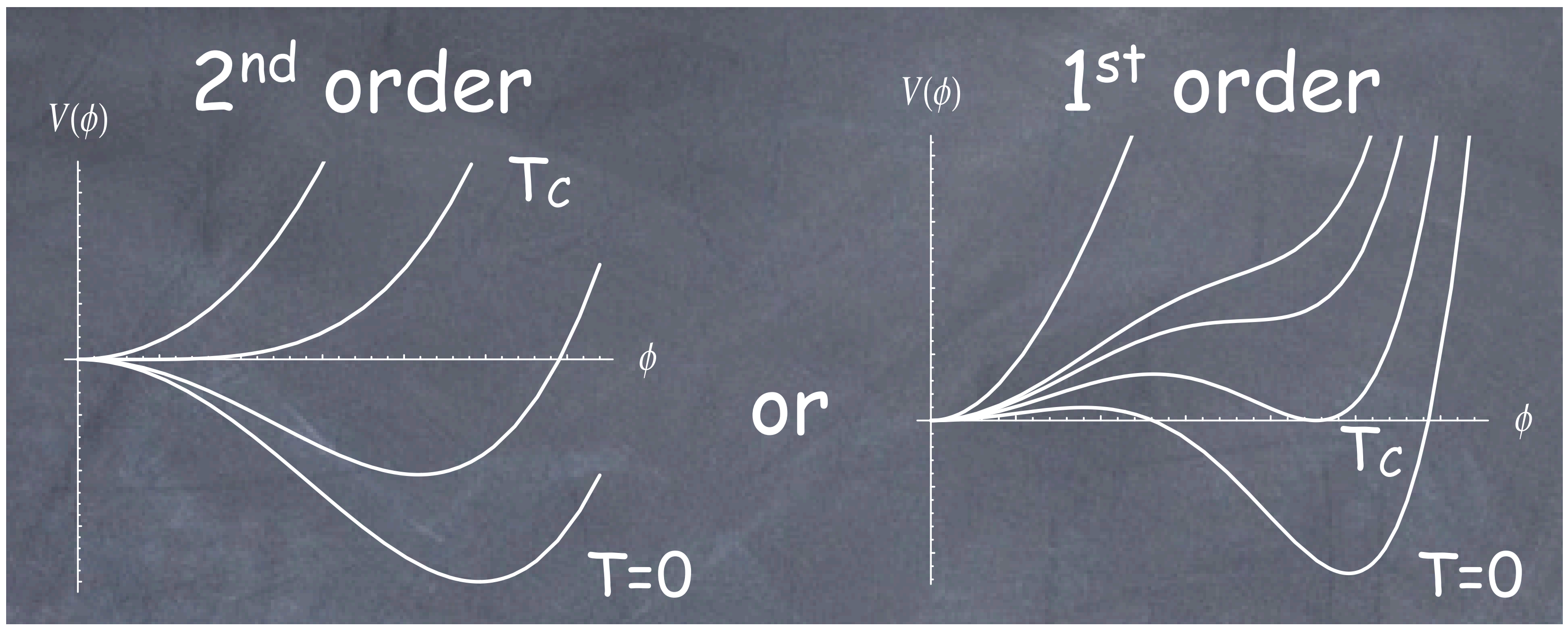
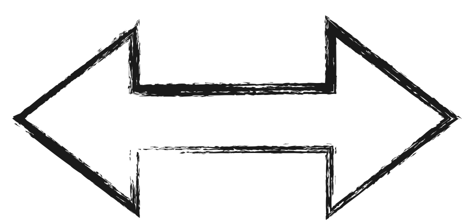


the dynamics of the phase transition is determined by Higgs effective potential at finite T
which we have no direct access to in colliders (LHC≠Big Bang machine!)

finite T
Higgs potential



Higgs couplings
at T=0

SM: first order phase transition iff mH < 47 GeV

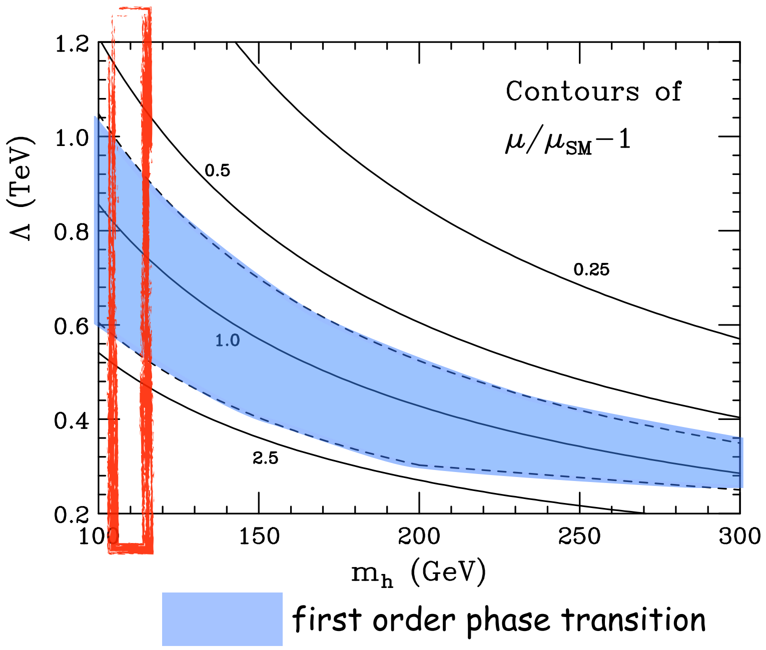
BSM: first order phase transition needs some sizeable deviations in Higgs couplings

Higgs couplings for 1st order EW phase transition

New physics @ tree-level

Grojean, Servant, Wells '04
Noble, Perelstein '07

mixing with other scalars modify the tree-level Higgs potential



$$V(\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 + \frac{1}{\Lambda^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^3$$

1st order phase transition

comes with 80-200% deviations in Higgs self-interaction

$\Downarrow$ $\Downarrow$

visible @ HL-LHC/ILC/TLEP

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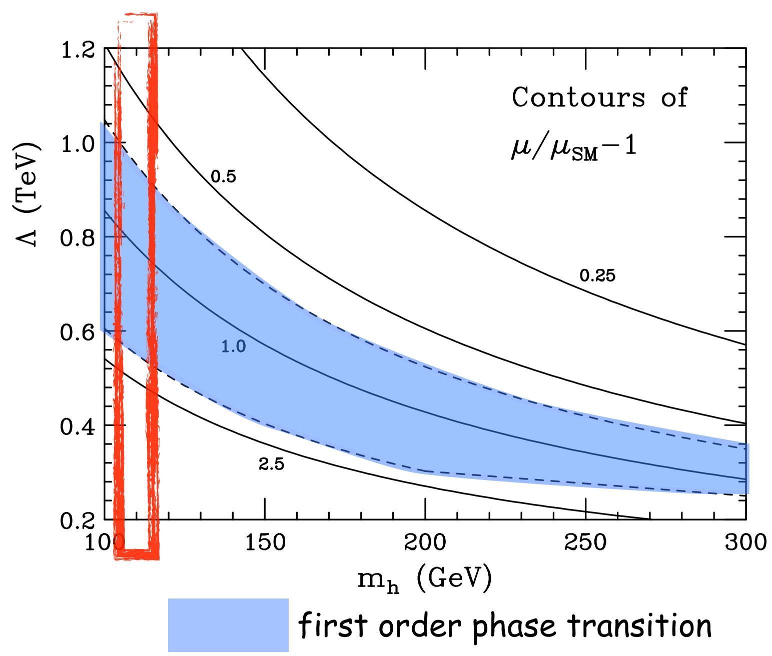

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New physics in loops

Katz, Perelstein '14

new particles, e.g. scalars, coupled to the Higgs without affecting its tree-level potential

$$V \propto \kappa|\Phi|^2|H|^2$$

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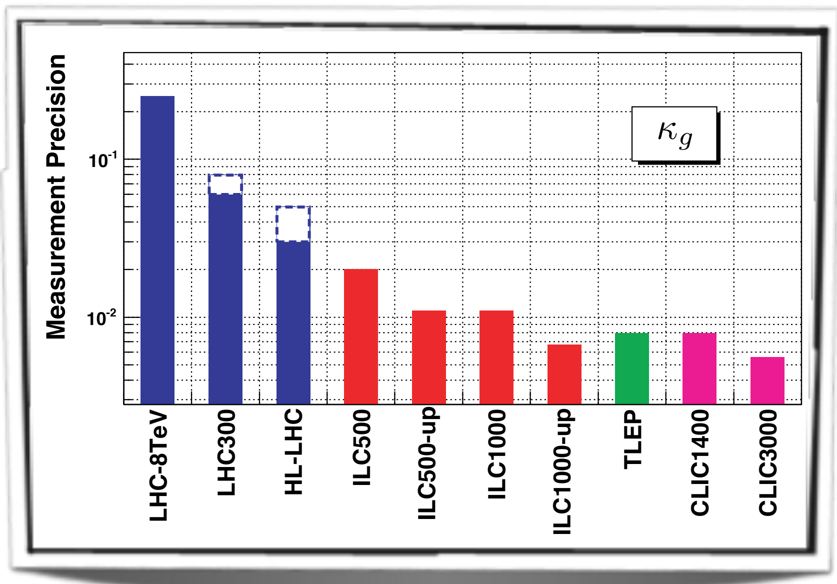

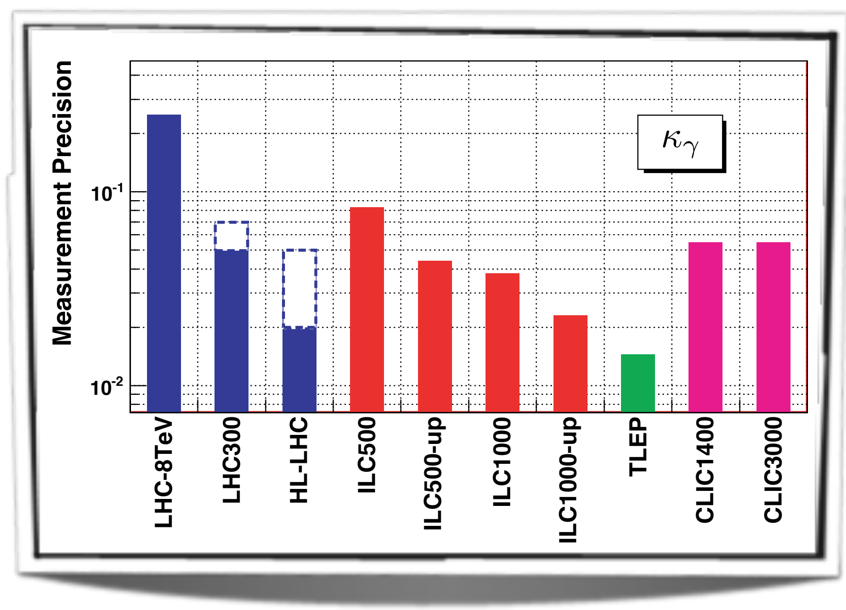

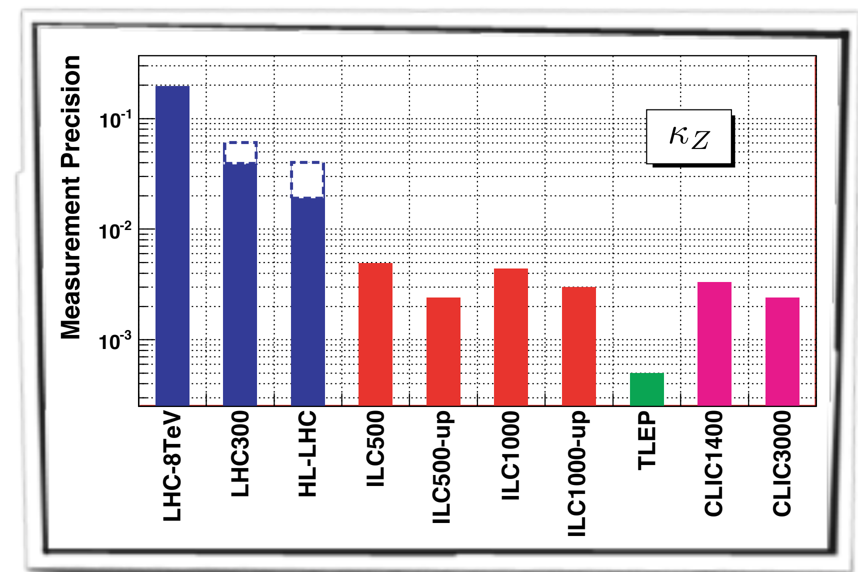

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colored scalars	electrically charged scalars	SM neutral scalars
⇓	⇓	⇓
O(20%) deviation in $h \to gg$	O(5%) deviation in $h \to \gamma\gamma$	O(1%) deviation in $\sigma(ee \to Zh)$
(8%LHC$_{14}$, 5%HL-LHC,1%ILC,<1%TLEP)	(5%LHC$_{14}$, 2%HL-LHC,2%ILC,1%TLEP)	(10%LHC$_{14}$, 2%HL-LHC,0.25%ILC,0.05%TLEP)

5

Is it the SM Higgs?

What is the Higgs the name of?

The SM Higgs couplings are fixed to restore unitarity with mass

$\Sigma = e^{i\sigma^a \pi^a / v}$ Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$ $D_\mu \Sigma = g V_\mu$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right) \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings

For a=1: perturbative unitarity in elastic channels WW → WW

For b = a^2: perturbative unitarity in inelastic channels WW → hh

For ac=1: perturbative unitarity in inelastic WW → $\psi\,\psi$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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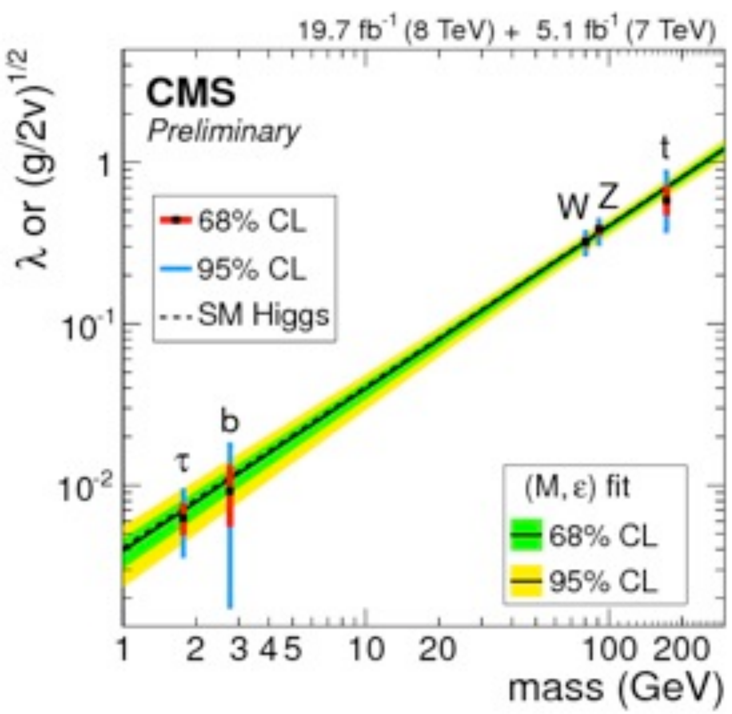

CMS PAS-HIG-14-009

Higgs couplings
are proportional
to the masses of the particles

$$\lambda_\psi \propto \frac{m_\psi}{v}, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

Higgs and Flavor

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij}\bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}} \bar{f}_{L_i} f_{R_j} + \frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

mass

higgs-fermion interactions

both matrices are simultaneously diagonalizable

⇩ ⇩ ⇩

no tree-level Flavor Changing Current induced by the Higgs

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Not true anymore if the SM fermions mix with vector-like partners (*) or for non-SM Yukawa

$$y_{ij} \left(1 + c_{ij} \frac{|H|^2}{f^2}\right) \bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}} \left(1 + c_{ij} \frac{v^2}{2f^2}\right) \bar{f}_{L_i} f_{R_j} + \left(1 + 3c_{ij} \frac{v^2}{2f^2}\right) \frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

(*) e.g. Buras, Grojean, Pokorski, Ziegler '11

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Look for SM forbidden Flavor Violating decays $h \to \mu\tau$ and $h \to e\tau$

(look also at $t \to hc$ ATLAS '14)

- weak indirect constrained by flavor data, eg ($\mu \to e\gamma$): BR<10%
- ATLAS and CMS have the sensitivity to set bounds O(1%)
- ILC/CLIC/FCC-ee can certainly do much better

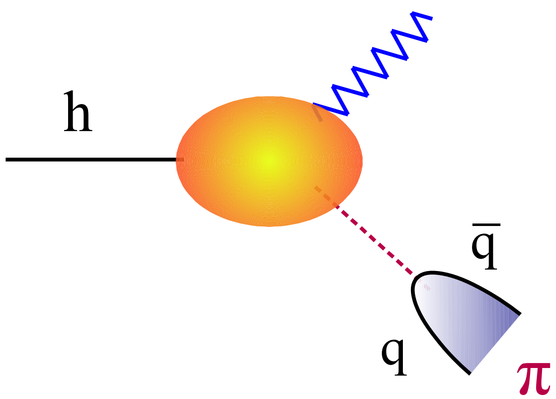
Blankenburg, Ellis, Isidori '12
Celis, Cirigliano, Passemar '13
Harnik et al '12
Davidson, Verdier '12
CMS-PAS-HIG-2014-005

(*) e.g. Buras, Grojean, Pokorski, Ziegler '11

New Physics in Rare Higgs Decays?

(slide courtesy of G. Isidori)

Rare $h \to VP$ decays, where P is a single hadron state (*pseudo-scalar* or *vector-meson*) are a very interesting probe of the vacuum-structure of the theory



$$A^{SM} \propto \frac{f_P}{v}$$

ratio of the two order parameters controlling the $SU(2)_L$ *breaking*

Isidori, Monohar, Trott '13

VP mode	$\mathcal{B}^{SM}$	VP^* mode	$\mathcal{B}^{SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	2.2×10^{-6}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	1.2×10^{-6}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	$Z^0 J/\psi$	1.7×10^{-6}
$h \to \gamma J/\psi$	2.5×10^{-6}	$h \to Z\Upsilon$	1.6×10^{-5}

Sizable modifications possible in various BSM frameworks

Isidori, Monohar, Trott '13

Bodwin, Petriello, Stoynev, Velasco '13

Isidori, Gonzalez-Alonso '14

Is the Higgs produced by top quarks?

- the bearable lightness of the Higgs: rich spectroscopy w/ multiple decays channels
- the unbearable lightness: loops saturate and don't reveal the physics @ energy physics (*)

(*) unless it doesn't decouple (e.g. 4th generation)

m_H(GeV)	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t \to \infty)}$	$\frac{\sigma_{NLO}(m_t, m_b)}{\sigma_{NLO}(m_t \to \infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. Grazzini, Sargsyan '13

the inclusive rate doesn't "see" the finite mass of the top

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

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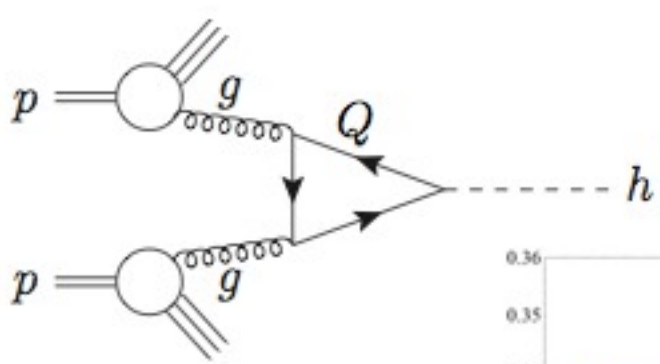
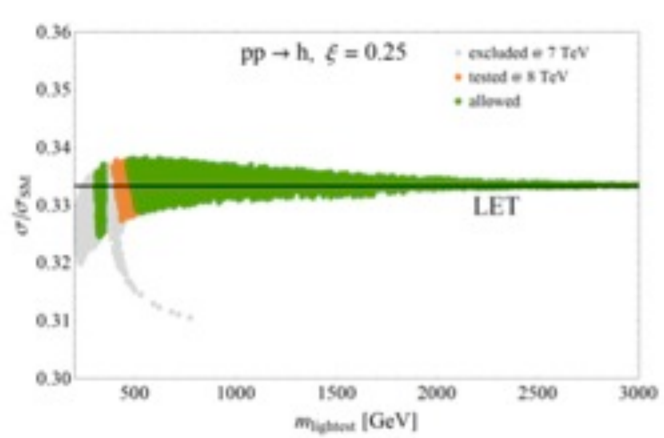
~ current single Higgs processes are insensitive to top partners ~



$\sigma^{SM}_{14\mathrm{TeV}} \approx 50$ pb



two competing effects that cancel:
- ☑ T's run in the loops
- ☑ T's modify top Yukawa coupling

Falkowski '07
Azatov, Galloway '11
Delaunay, Grojean, Perez, '13

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$\Rightarrow$ cannot disentangle
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$\Leftarrow$

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

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

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

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

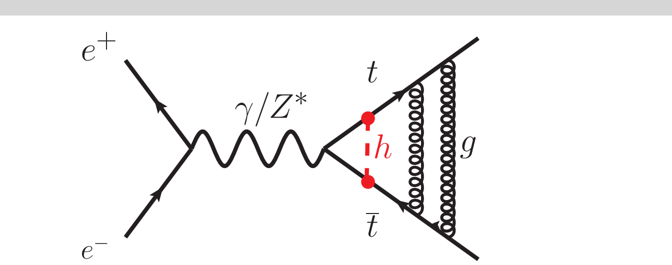
to break the degeneracy

having access to htt̄ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-ILC^{1000}_{1000}

ATLAS CONF-2014-11 μ <4.1

CMS PAS HIG-14-010 μ <3.3

top Yukawa from tt@threshold



6

Future Higgs measurements: Multi Higgs, boosted and off-shell Higgs channels

Beyond single Higgs processes

Producing one Higgs is good. Producing H+X is better

@ 14 TeV

Higgs multiplicty →

Jet multiplicty ↓

Single h	Double h	Triple H
h ~ 50 pb^{gg}	hh ~ 34 fb^{gg}	hhh ~ 44 ab^{gg}
h+j ~ 2 pb $^{p_T(j)>100}$	hh+j	
h+jj ~ 4.2 pb ^{VBF}	hh+jj ~ 2 fb^{VBF}	

- also roughly indicates possible initial states/related kinematics
- Jet multiplicity might be replaced with V=W,Z, top, etc…

(adapted from M. Son@Planck2014)

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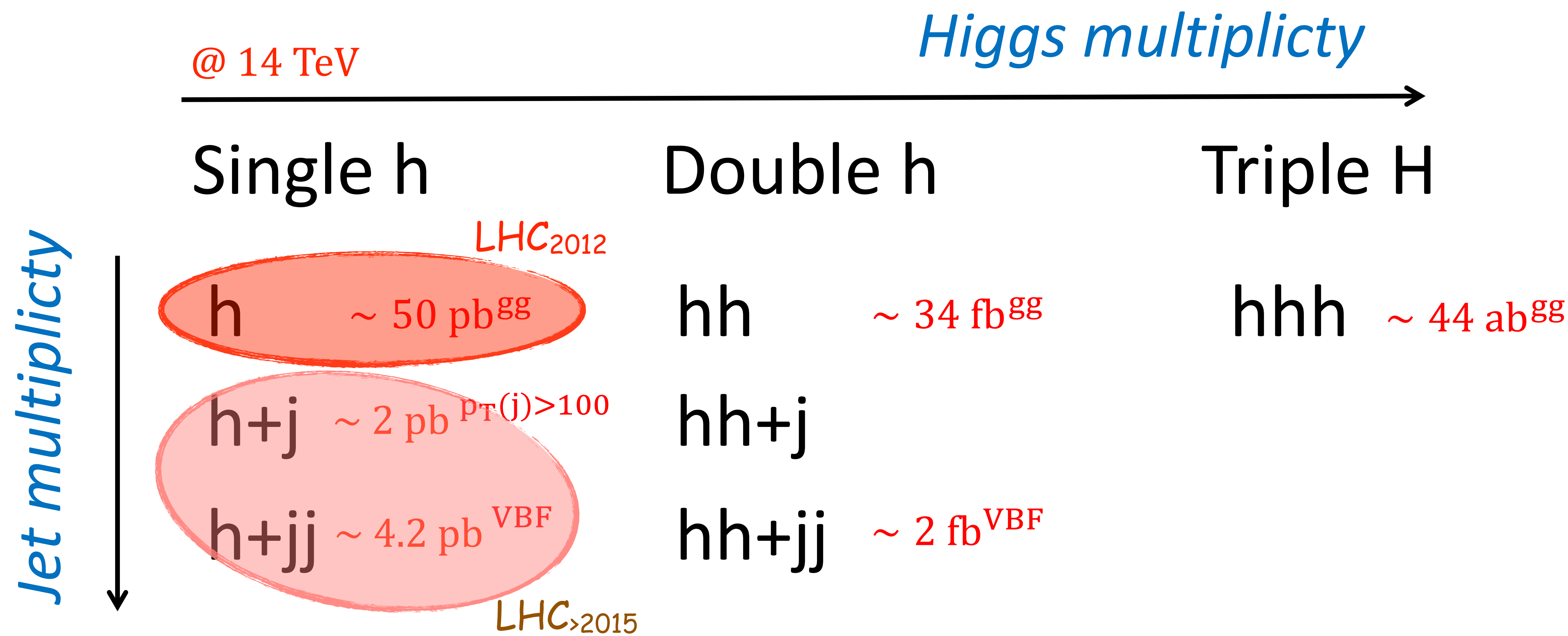

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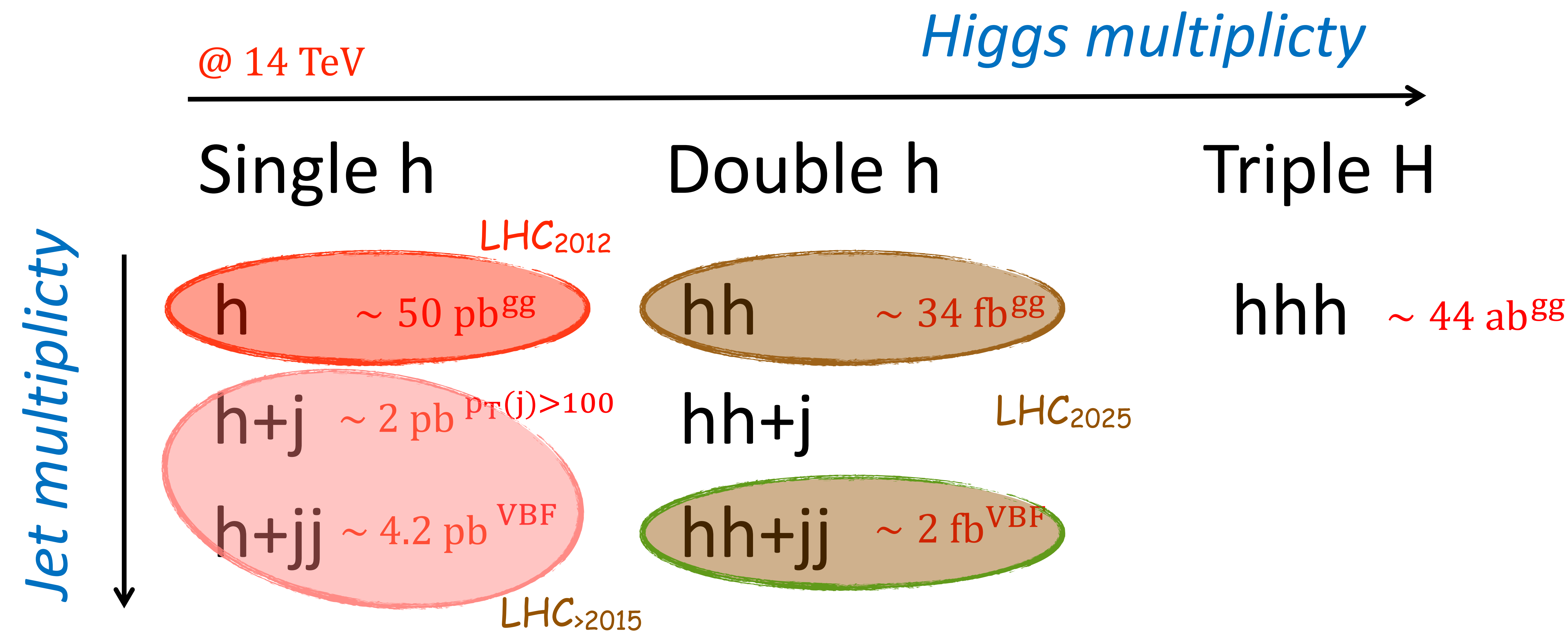

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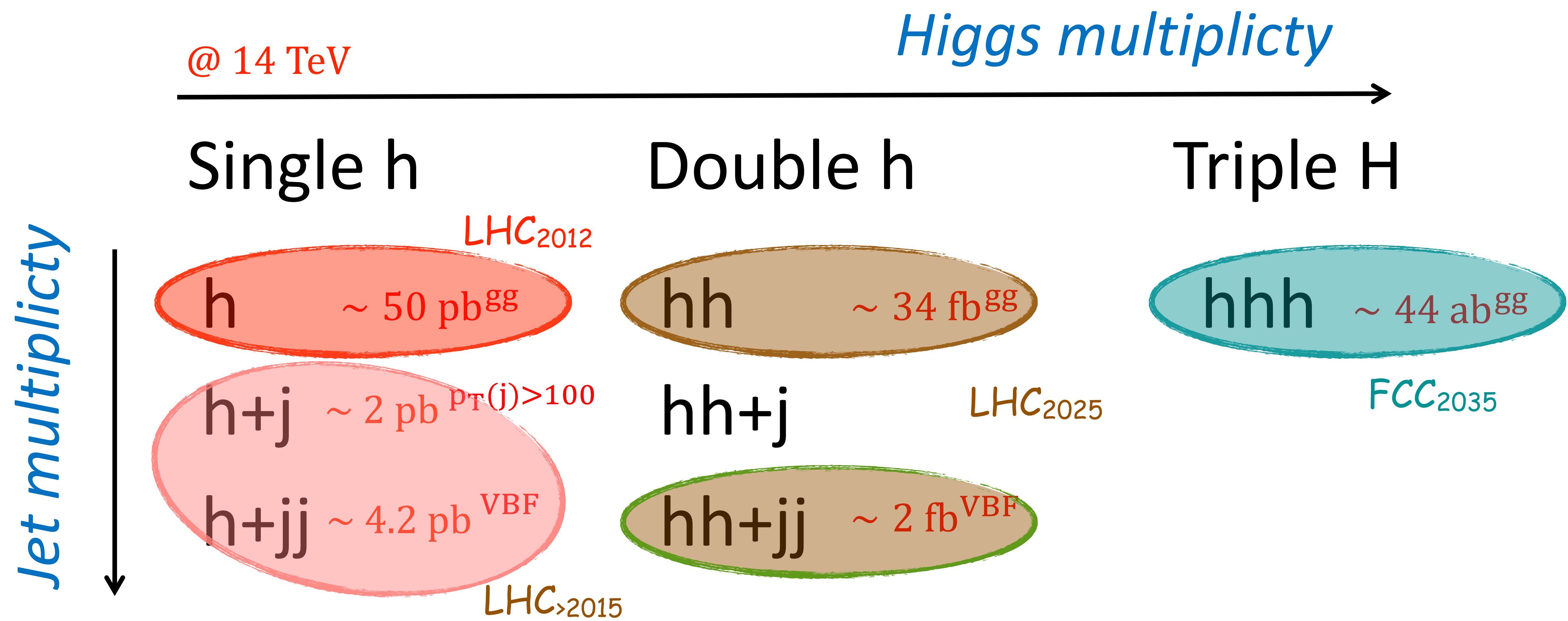

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Beyond single Higgs processes

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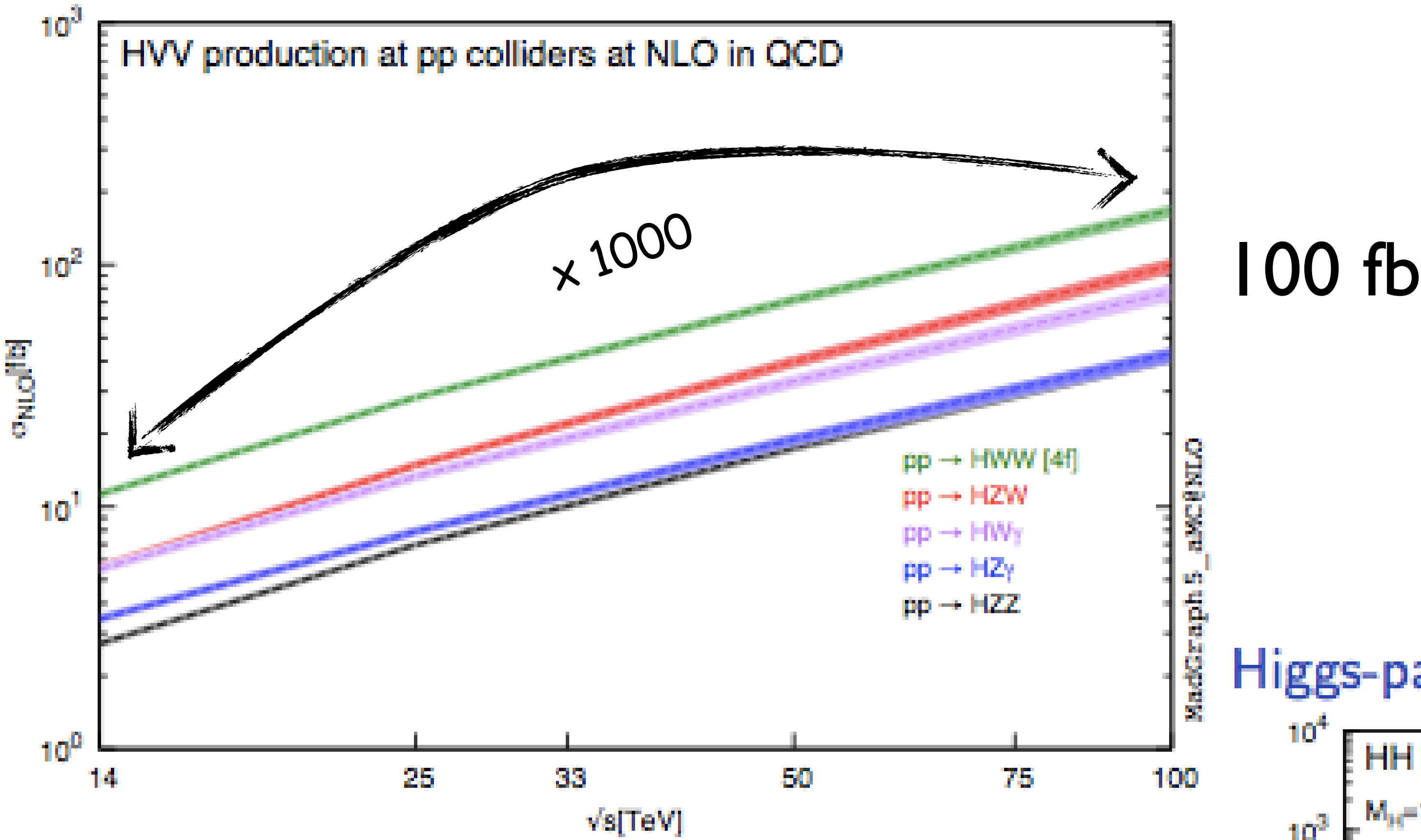
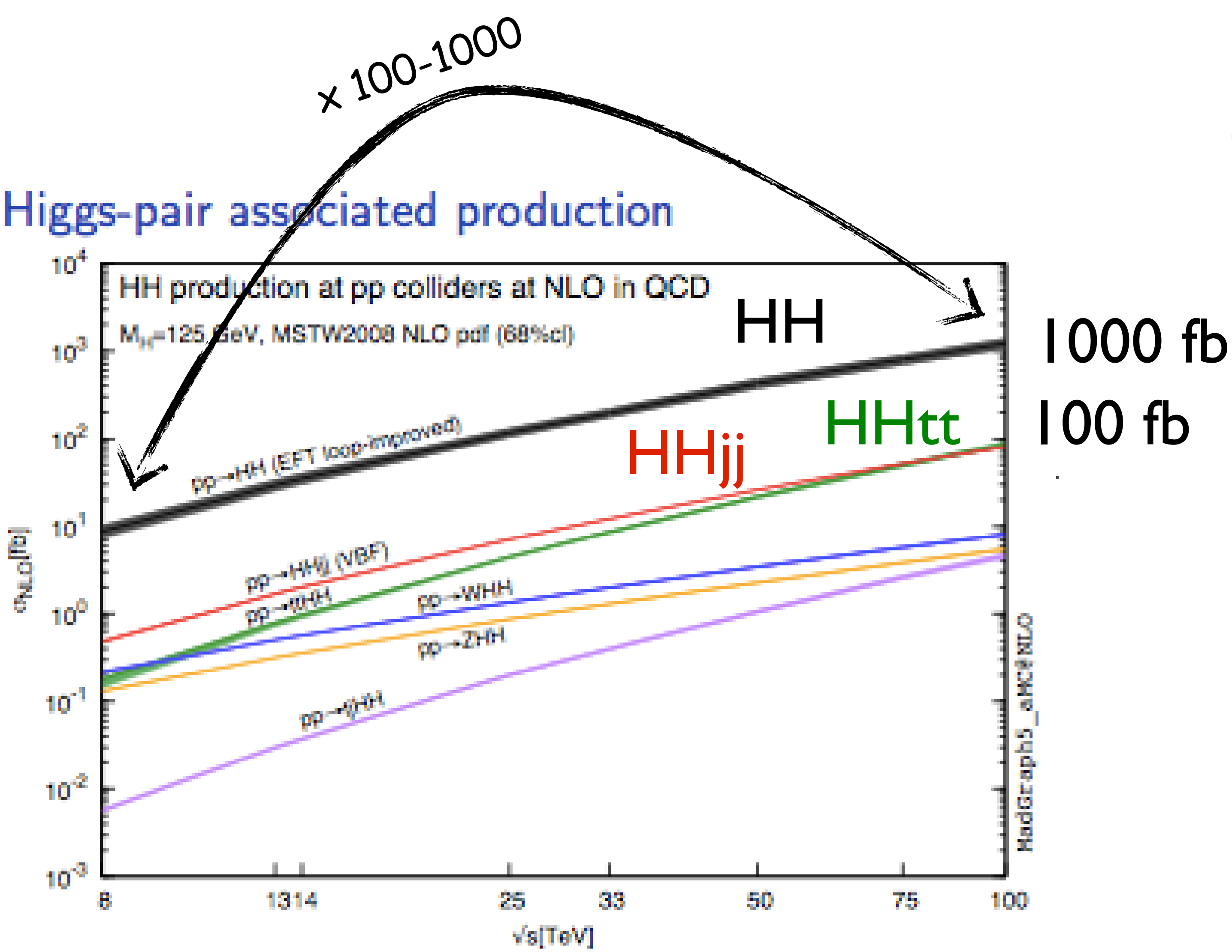
A long term plan?

Higgs-diboson associated production



FCC = H+X factory

Higgs-pair associated production



(Plots from P. Torrielli and MLM, CERN'14)

Why going beyond single Higgs processes?

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in processes with a characteristic scale $\mu \approx m_H$

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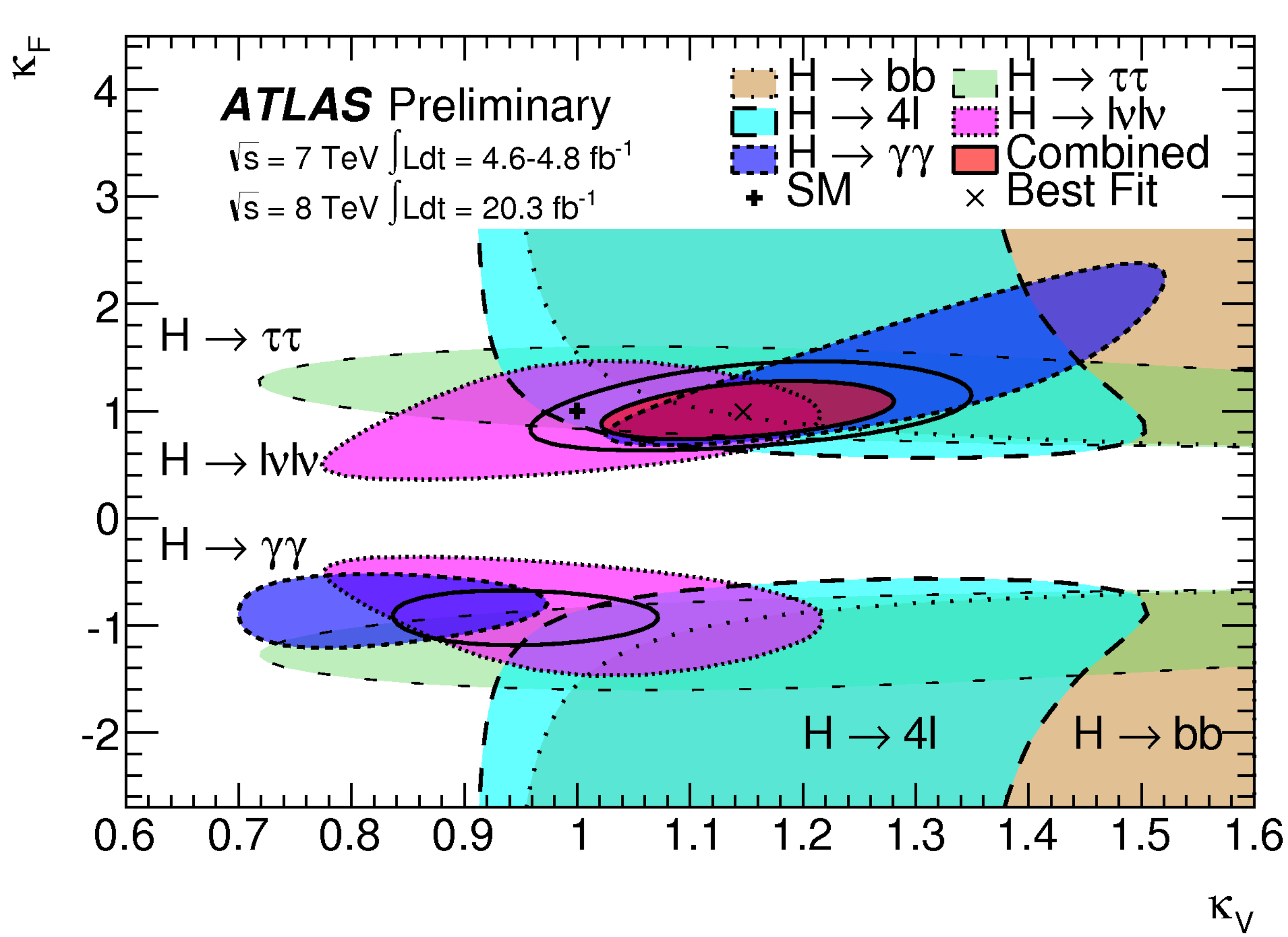

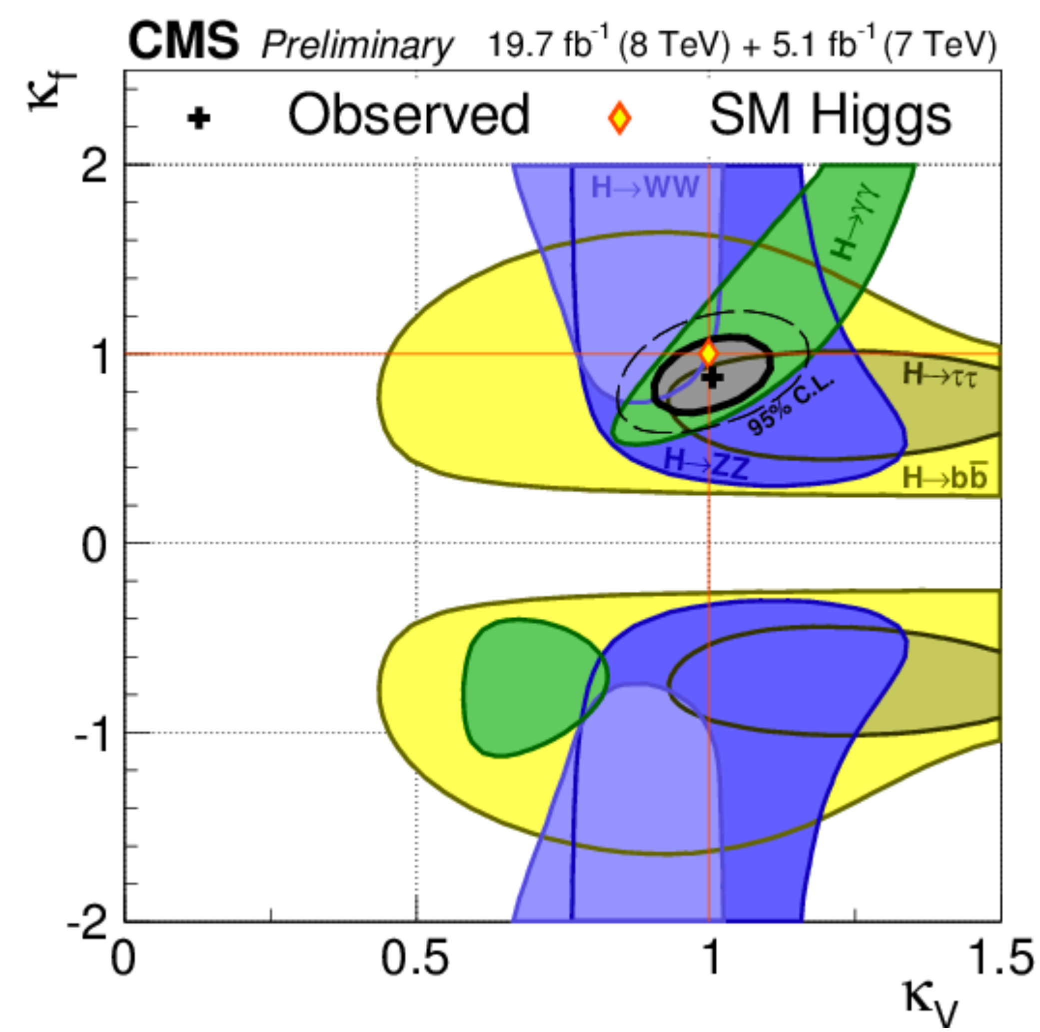

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probe the Higgs couplings @ large energy
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Probing new corrections to the SM Lagrangian?

on-shell Z @ LEP1

constraints on
S and T oblique corrections

off-shell Z @ LEP2

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W and Y oblique corrections
(same order as S and T but cannot be probed @ LEP1)

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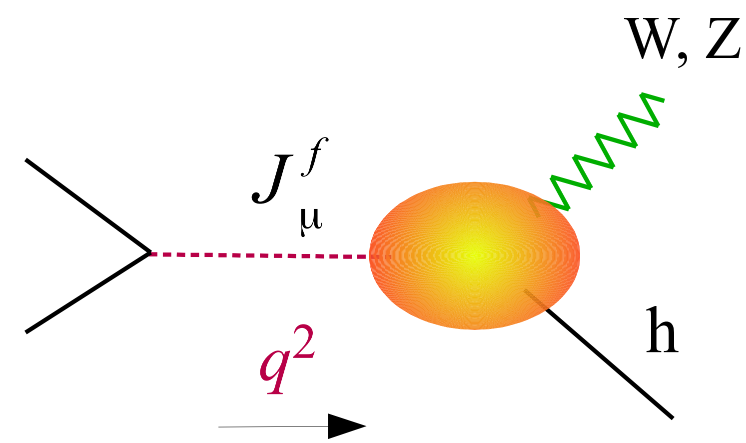
(same order as S and T but cannot be probed @ LEP1)

off-shell Higgs data does not probe new corrections
that are not already constrained by on-shell data

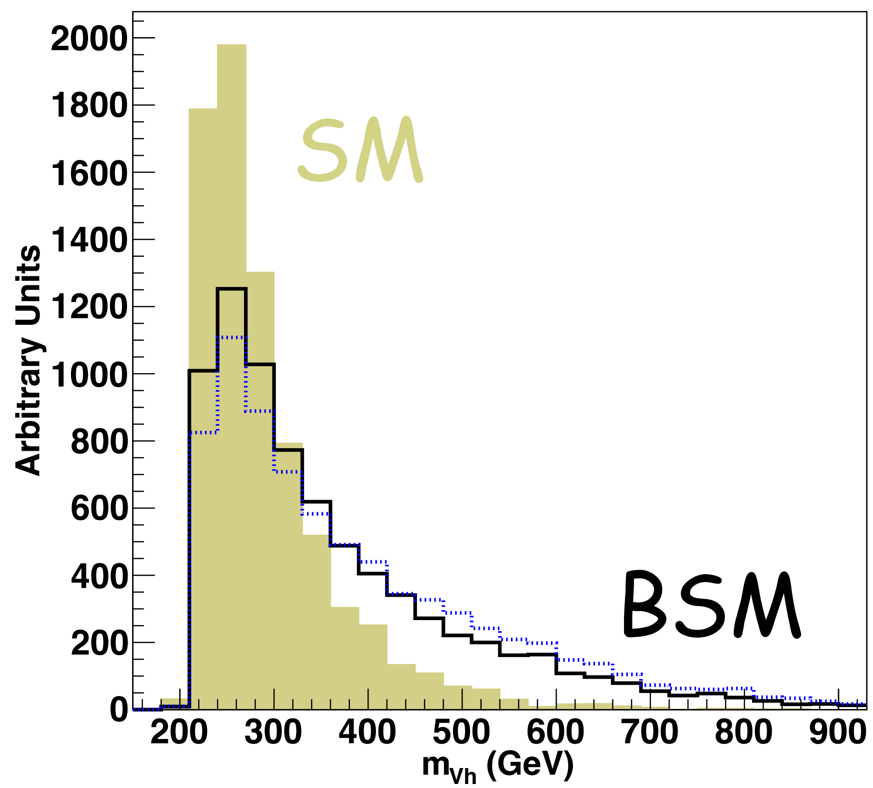
Boosted Higgs in HV production

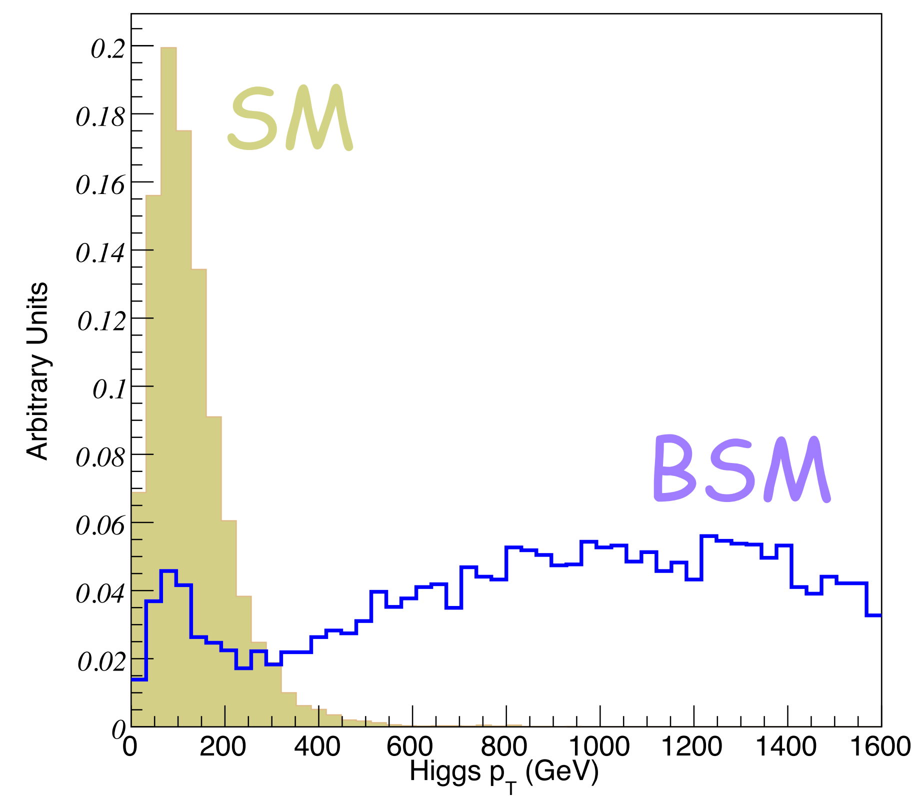
Associate production ff→Vh probe
the high q^2 dependence of the form factors

Isidori, Trott '13



Alloul, Fuks, Sanz '13





The large effects at high p_T or m_{VH} have been used to probe higher dimensional derivative operators

Ellis, Sanz, You '13

Beneke, Boito, Wang '13

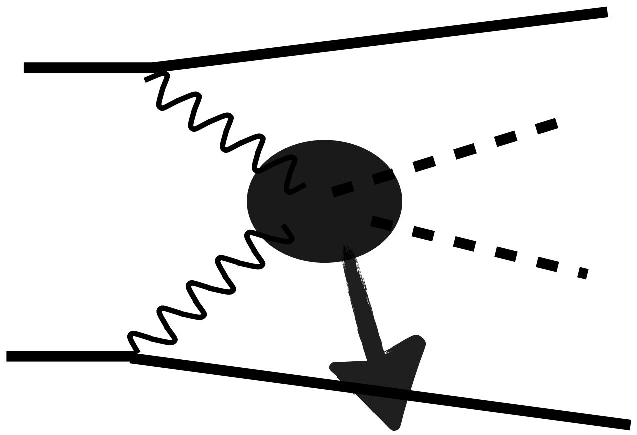
but the validity of the EFT approach is endangered

Biekoetter et al '14

Multiple Higgs interactions in WW→HH

in the SM, the Higgs is essential to prevent strong interactions in EWSB sector

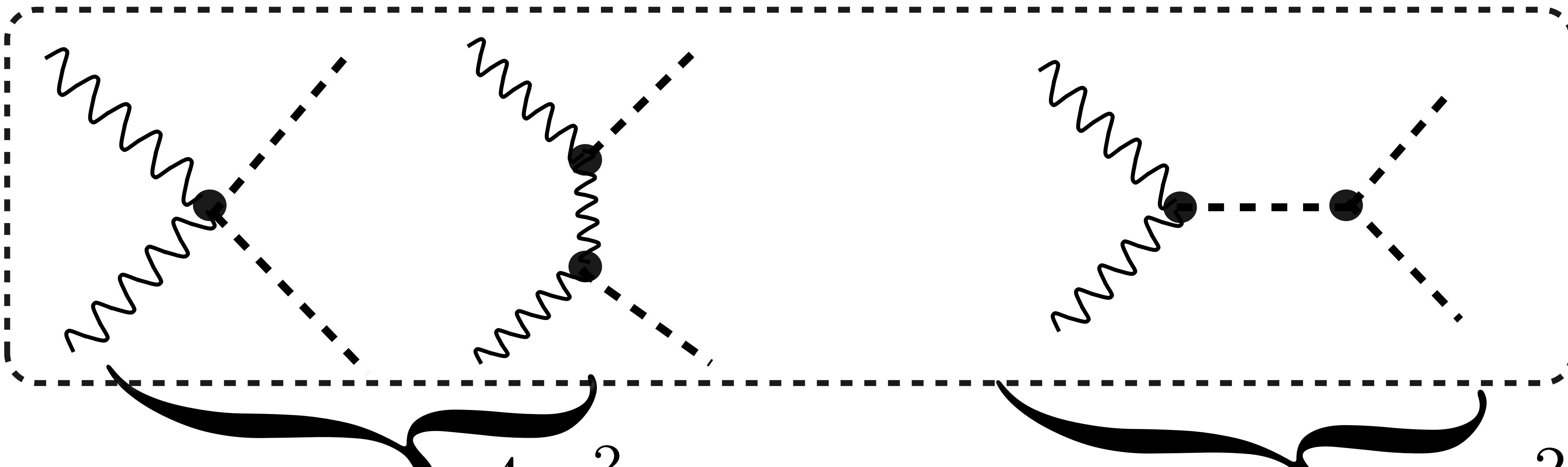
(e.g. WW scattering)



$$\mathcal{L}_{\mathrm{EWSB}} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right)$$

SM: $a=b=d_3=d_4=1$

$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \dots$$



$$\mathcal{A} \underset{m_{hh}^2 \gg m_W^2}{\sim} \left(b - a^2\right)\frac{4m_{hh}^2}{v^2}$$

$$\mathcal{A} \underset{m_{hh}^2 \sim 4m_h^2}{\sim} \mathrm{cst.} + 3ad_3\frac{m_h^2}{v^2}$$

asymptotic behavior
sensitive to strong interaction

threshold effect
anomalous coupling'

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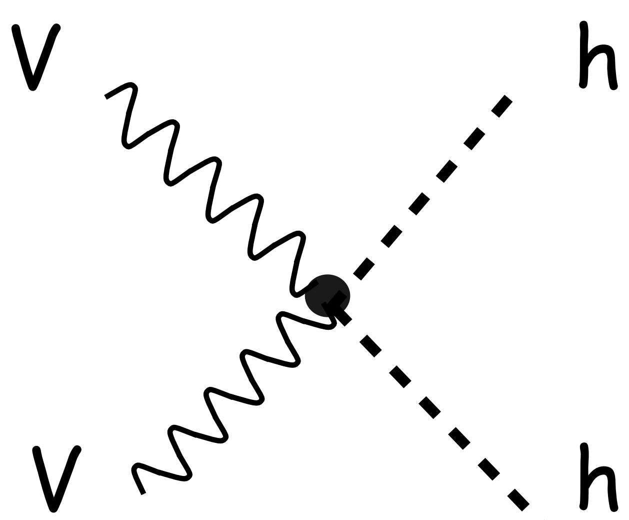
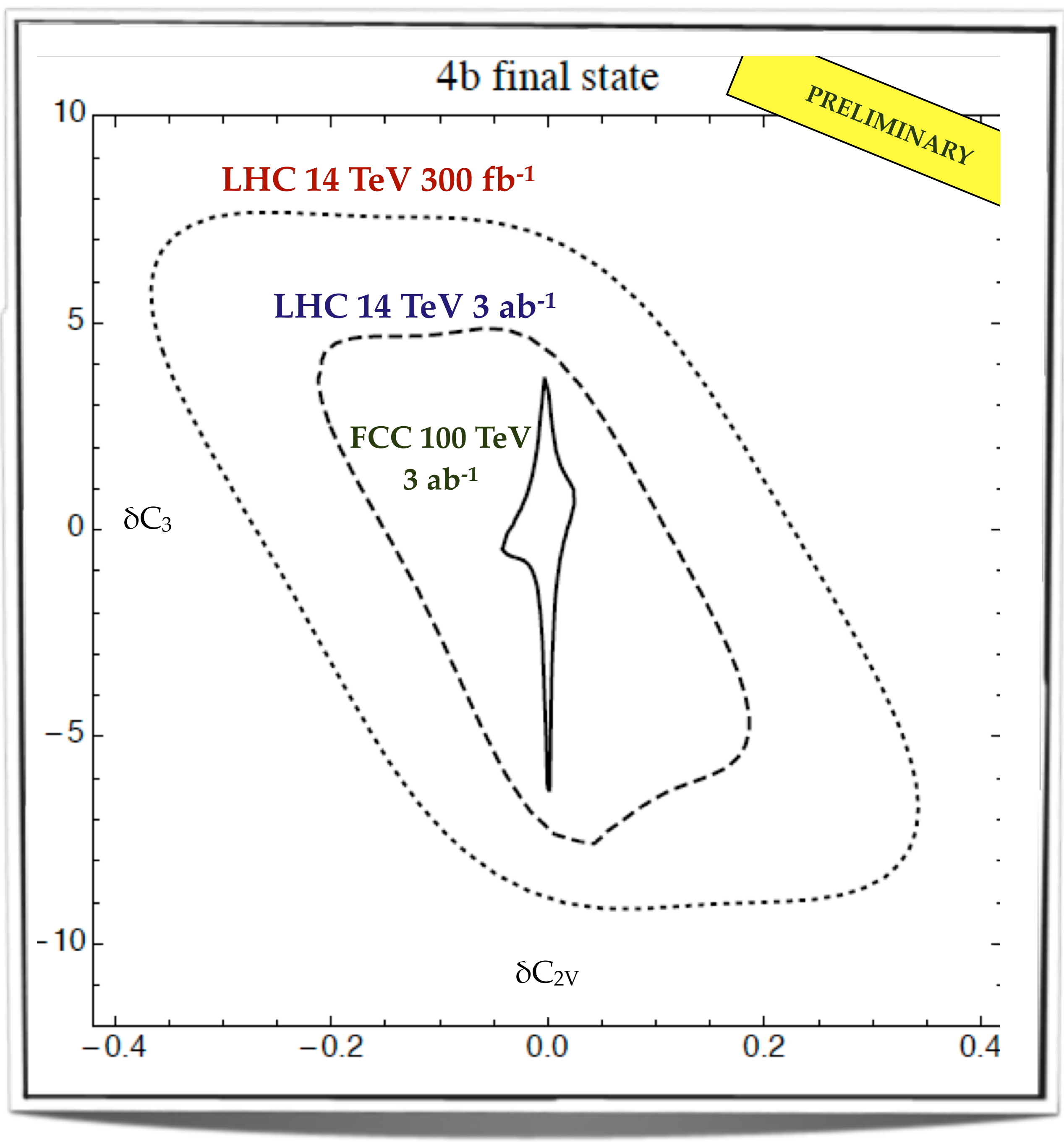
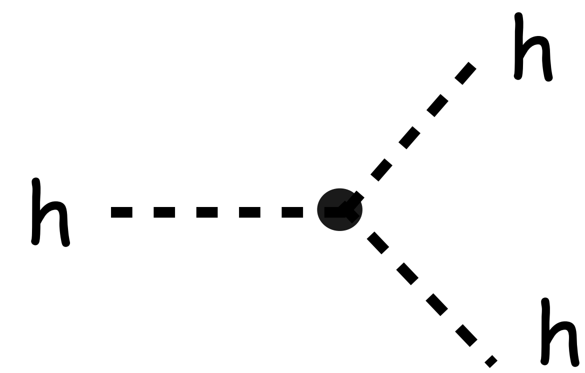


$$g_{VVhh} = c_{2V} * g_{VVhh}^{SM}$$



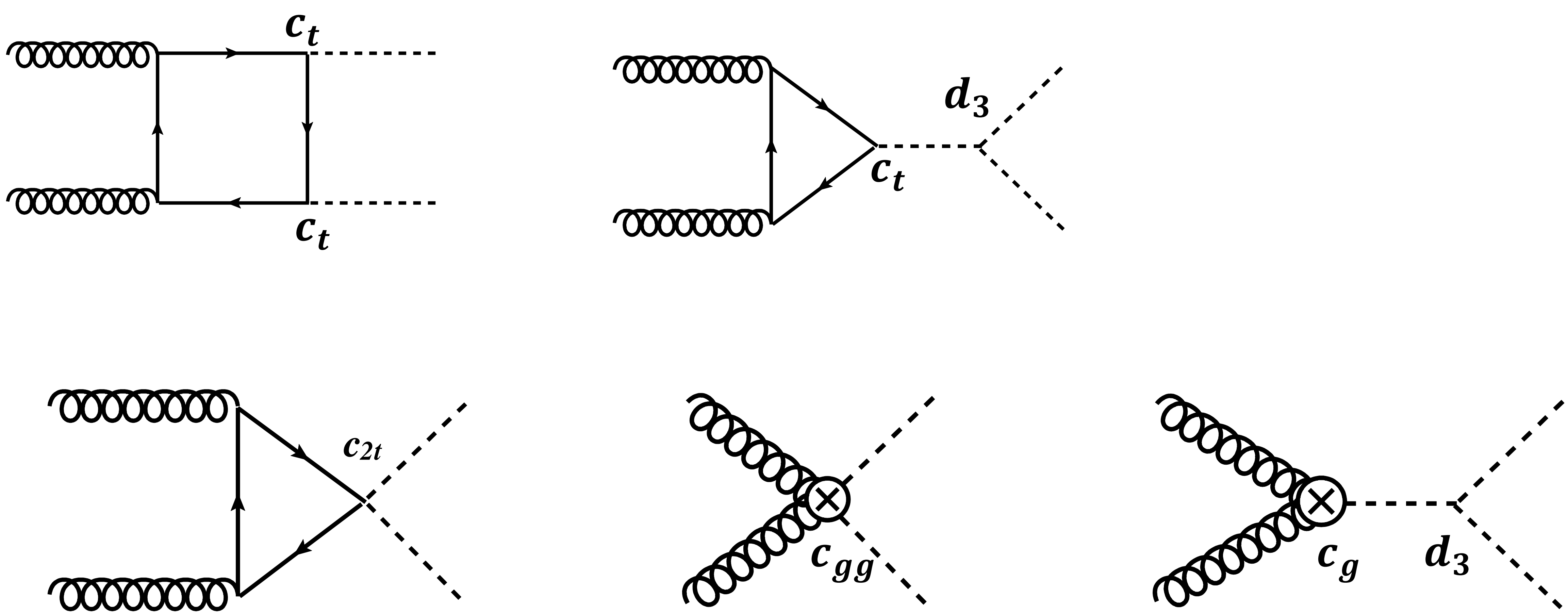


$$g_{hhh} = c_3 * g_{hhh}^{SM}$$

Bondu, Contino, Massironi, Rojo 'to appear

What do we learn from gg→HH?

in principle gg→HH gives access to many new couplings, including non-linear couplings



In practice, if the Higgs is part of an EW doublet,
these new couplings are related to single-Higgs couplings

$$c_{2t} = 3(c_t - 1) \qquad\qquad c_{gg} = c_g$$

In reality single-Higgs processes is unable to differentiate c_t from c_g

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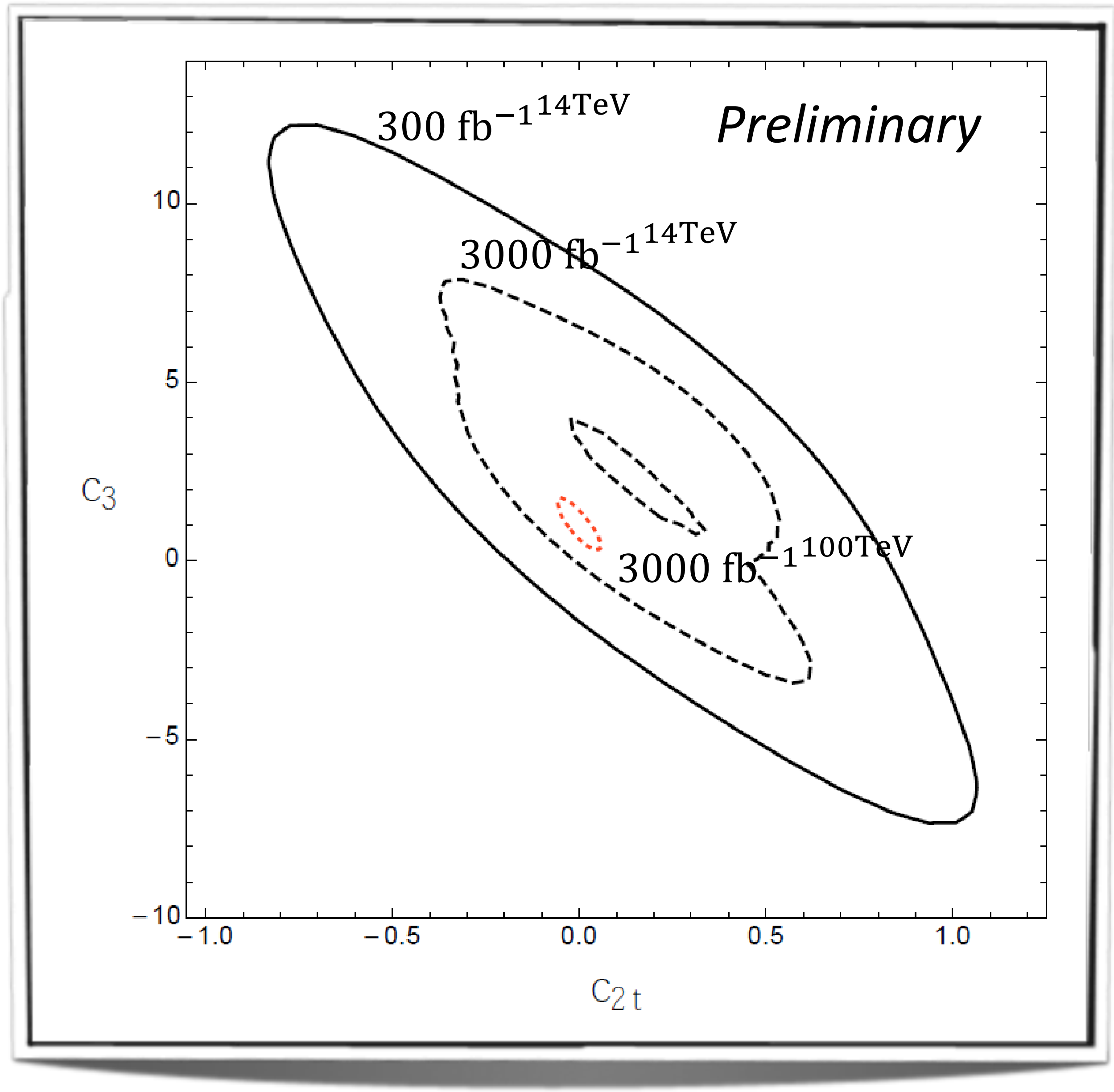


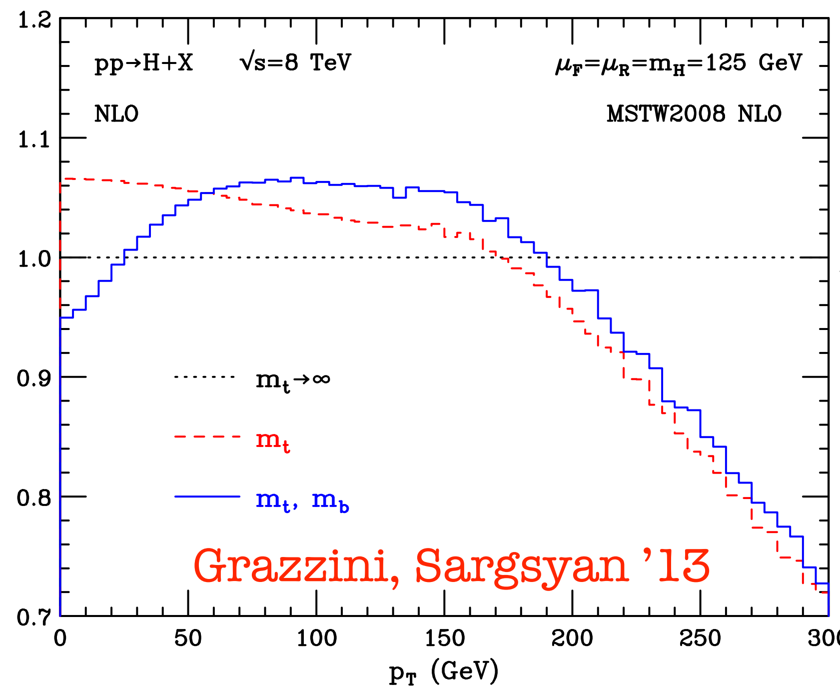
Azatov, Contino, DelRe, Meridiani, Micheli, Panico 'to appear

Resolving top loop: Boosted Higgs

cut open the top loops

high p_T ≈ Higgs off-shell
we "see" the details of the particles running inside the loops

Baur, Glover '90
Langenegger, Spira, Starodumov, Trueb '06



Note: LO only
NLO_{mt} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al '12

the high p_T tail is tens' % sensitive to the mass of top

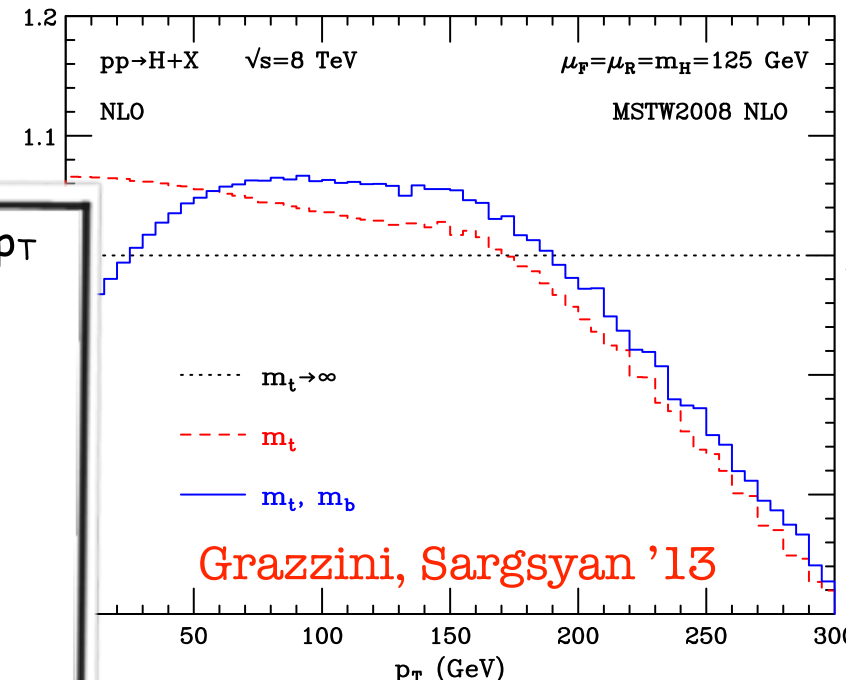
Resolving top loop: Boosted Higgs

cut open the top loops

Don't think it is easy to produce a Higgs with high p_T

$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma^{SM}_{p_T^{\min}}$ [fb]	δ	ϵ	gg, qg [%]
	100	2200	0.016	0.023	67, 31
	150	830	0.069	0.13	66, 32
	200	350	0.20	0.31	65, 34
	250	160	0.39	0.56	63, 36
	300	75	0.61	0.89	61, 38
	350	38	0.86	1.3	58, 41
	400	20	1.1	1.8	56, 43
14	450	11	1.4	2.3	54, 45
	500	6.3	1.7	2.9	52, 47
	550	3.7	2.0	3.6	50, 49
	600	2.2	2.3	4.4	48, 51
	650	1.4	2.6	5.2	46, 53
	700	0.87	3.0	6.2	45, 54
	750	0.56	3.3	7.2	43, 56
	800	0.37	3.7	8.4	42, 57

× 1000 reduction



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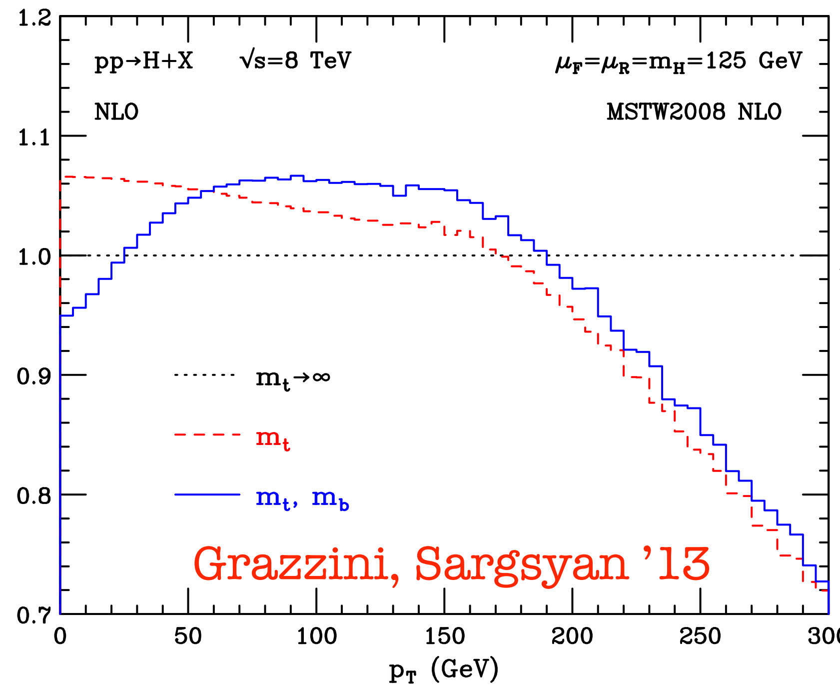

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Harlander et al '12

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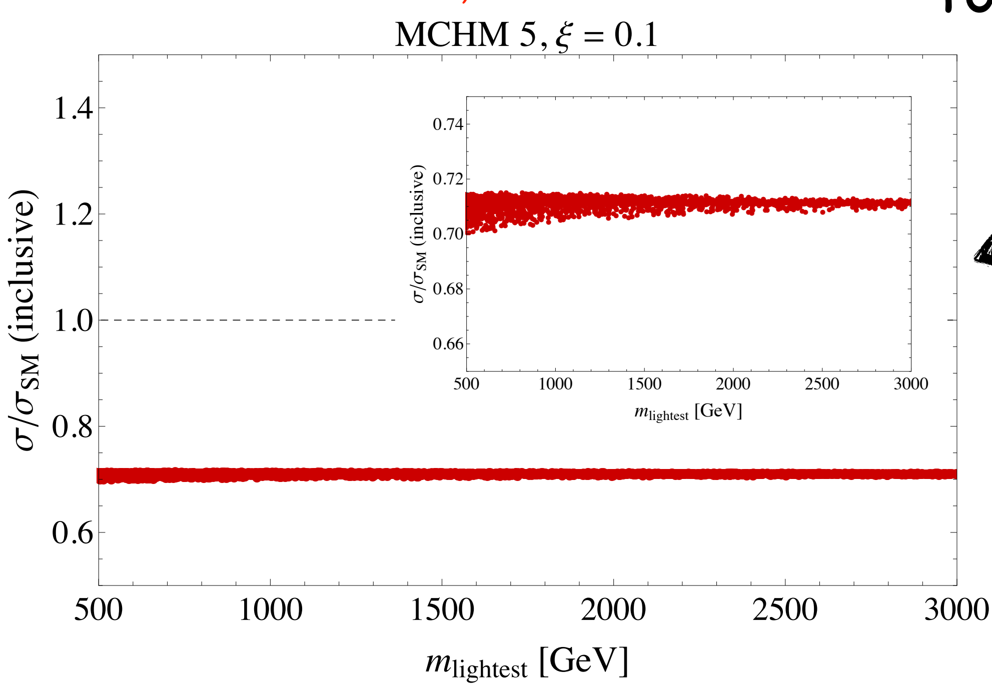
Composite Higgs Model

top partners contributions

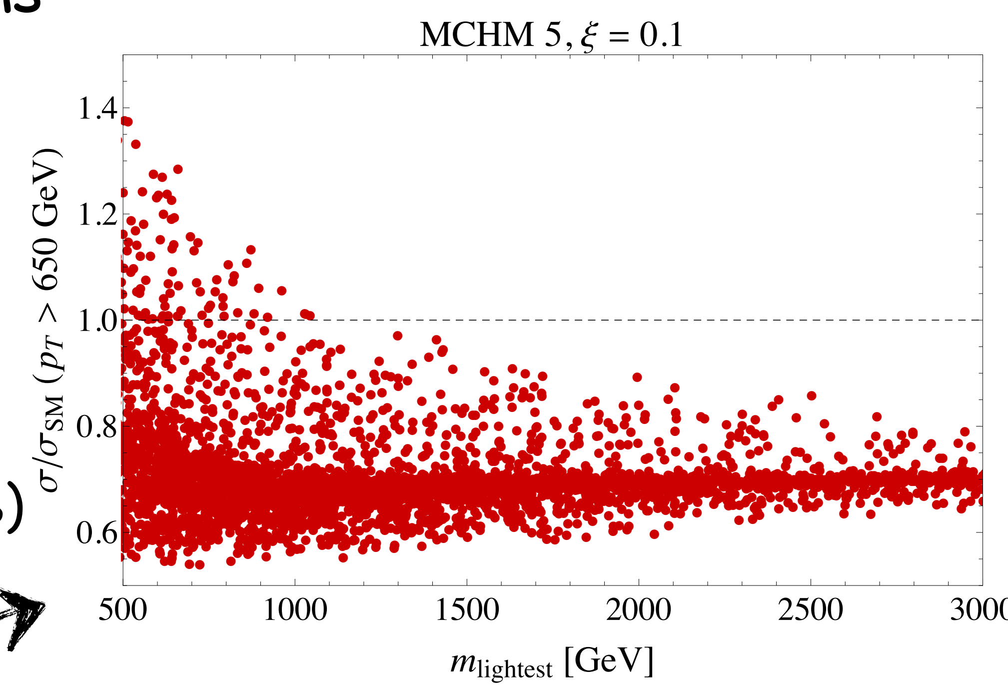
see also Banfi, Martin, Sanz '13
see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler '13



inclusive rate: O(%)

with high-p_T cut: O(x10'%)



high-p_T tail "sees" the top partners that are missed by the inclusive rate

Off-shell Higgs

Off-shell Higgs effects

naively small since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs

but enhancement due to the particular couplings of H to V_L

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Recent analysis of gg→H*→ZZ→4l

CMS PAS HIG-14-002
ATLAS-CONF-2014-042

(about 15% of the Higgs events are far off-shell with m_{4l}>300GeV)

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g_{ggH}g_{HZZ}\frac{F(m_{ZZ})}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H}$$

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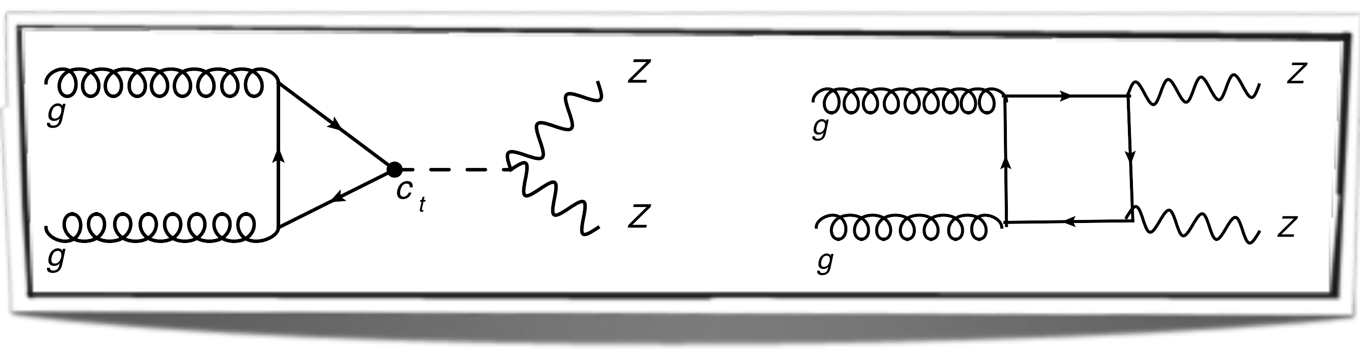
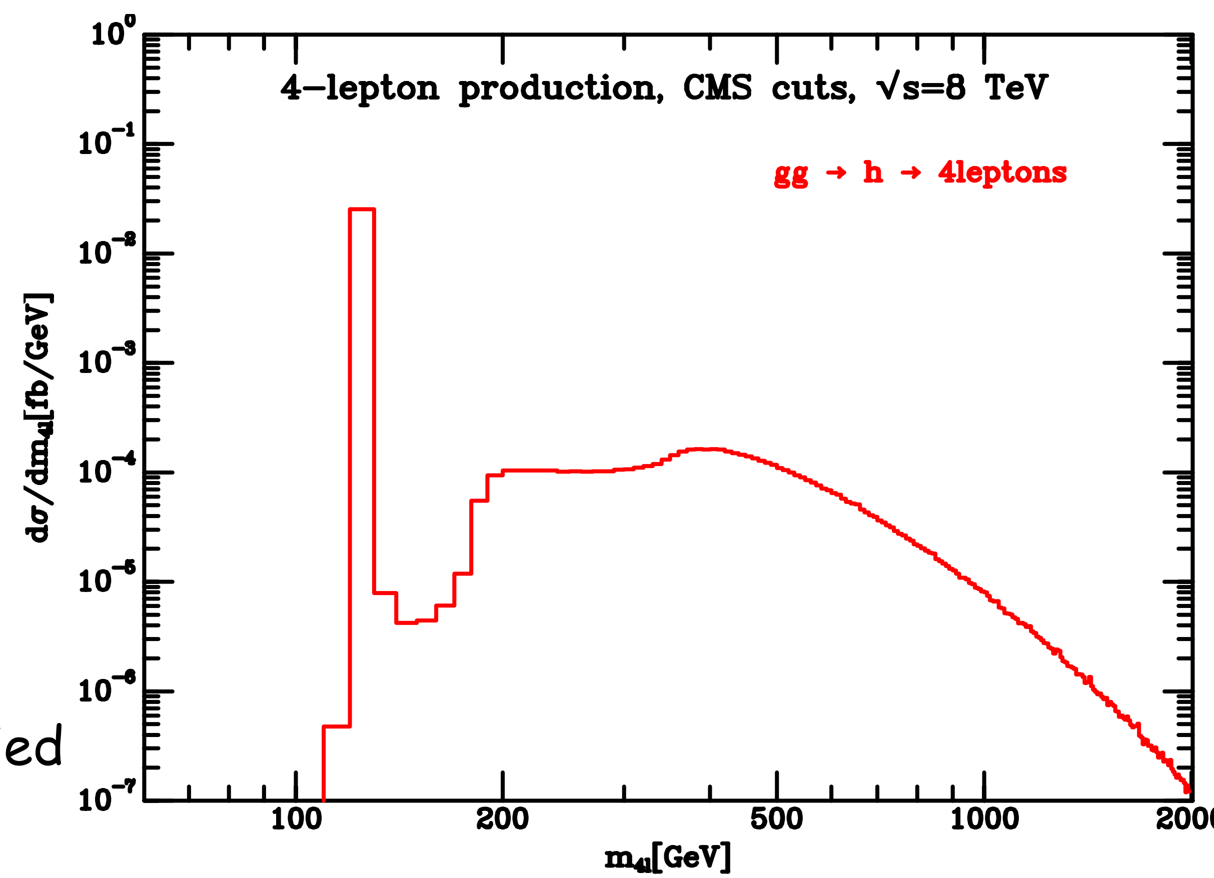
Glover, van der Bij '89



$$\mathcal{M}^{++00}_{\rm Higgs} \sim \log^2\frac{\hat{s}}{m_t^2} \qquad \mathcal{M}^{++00}_{\rm box} \sim -\log^2\frac{\hat{s}}{m_t^2}$$

SM: cancelation forced by unitarity

BSM: deviations of Higgs couplings at large $\hat{s}$ will be amplified



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Access to the Higgs width @ LHC?

often said, it is impossible to measure the Higgs width at the LHC. Not quite true.
it can be done either via off-shell measurements or via the mass shift in gg→h→$\gamma\gamma$

Narrow Width Approx.: on-shell

ratios of κ only

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}$$

no direct access to the width itself

(upper bound if κ_V < 1 is assumed
e.g. Dobrescu, Lykken '12)

off-shell

different width dependence

Γ_H can be fitted w/o assumption

$$\sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$

Kauer, Passarino '12
Caola, Melnikov '13
Campbell et al '13

Off-shell Higgs

Off-shell Higgs effects

naively small since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs

but enhancement due to the particular couplings of H to V_L

Recent analysis of $gg\to H^*\to ZZ\to 4l$

CMS PAS HIG-14-002
ATLAS-CONF-2014-042

(about 15% of the Higgs events are far off-shell with m_{4l}>300GeV)

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g_{ggH}g_{HZZ}\frac{F(m_{ZZ})}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H}$$

Access to the Higgs width @ LHC?

often said, it is impossible to measure the Higgs width at the LHC. Not quite true.
it can be done either via off-shell measurements or via the mass shift in $gg\to h\to\gamma\gamma$

Narrow Width Approx.: on-shell

ratios of κ only

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH}g^2_{HZZ}}{\Gamma_H}$$

no direct access to the width itself

(upper bound if κ_V < 1 is assumed
e.g. Dobrescu, Lykken '12)

off-shell

different width dependence

Γ_H can be fitted w/o assumption

$$\sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH}g^2_{HZZ}$$

Kauer, Passarino '12
Caola, Melnikov '13
Campbell et al '13

What do we learn? BR_{inv} <85%?

Not competitive with global fits on BR_{inv}! BR_{inv} < 20%

Model independent analysis might not be robust because of unitarity issues

($g_i(m_h)$ might be quite different than $g_i(m_{4l})$)

Englert, Spannowski '14

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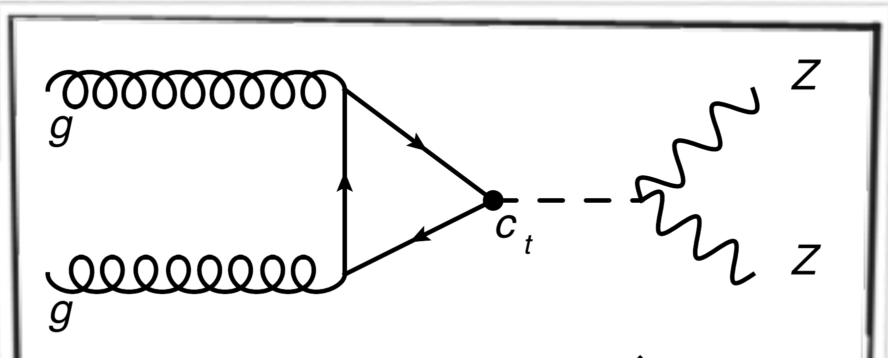
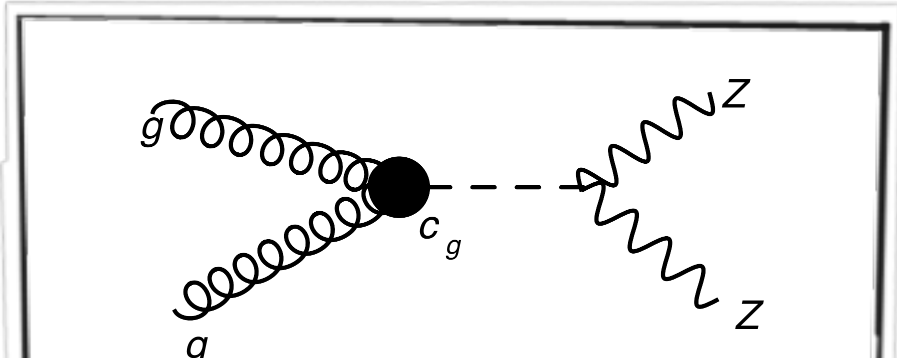
Access to top Yukawa coupling?

strong departure of the Higgs low energy theorem in the far off-shell region

can distinguish c_t from c_g



$$\mathcal{M}_{c_t}^{++00} \sim \log^2 \frac{\hat{s}}{m_t^2}$$



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Cacciapaglia et al. '14

Azatov, Grojean, Paul, Salvioni '14

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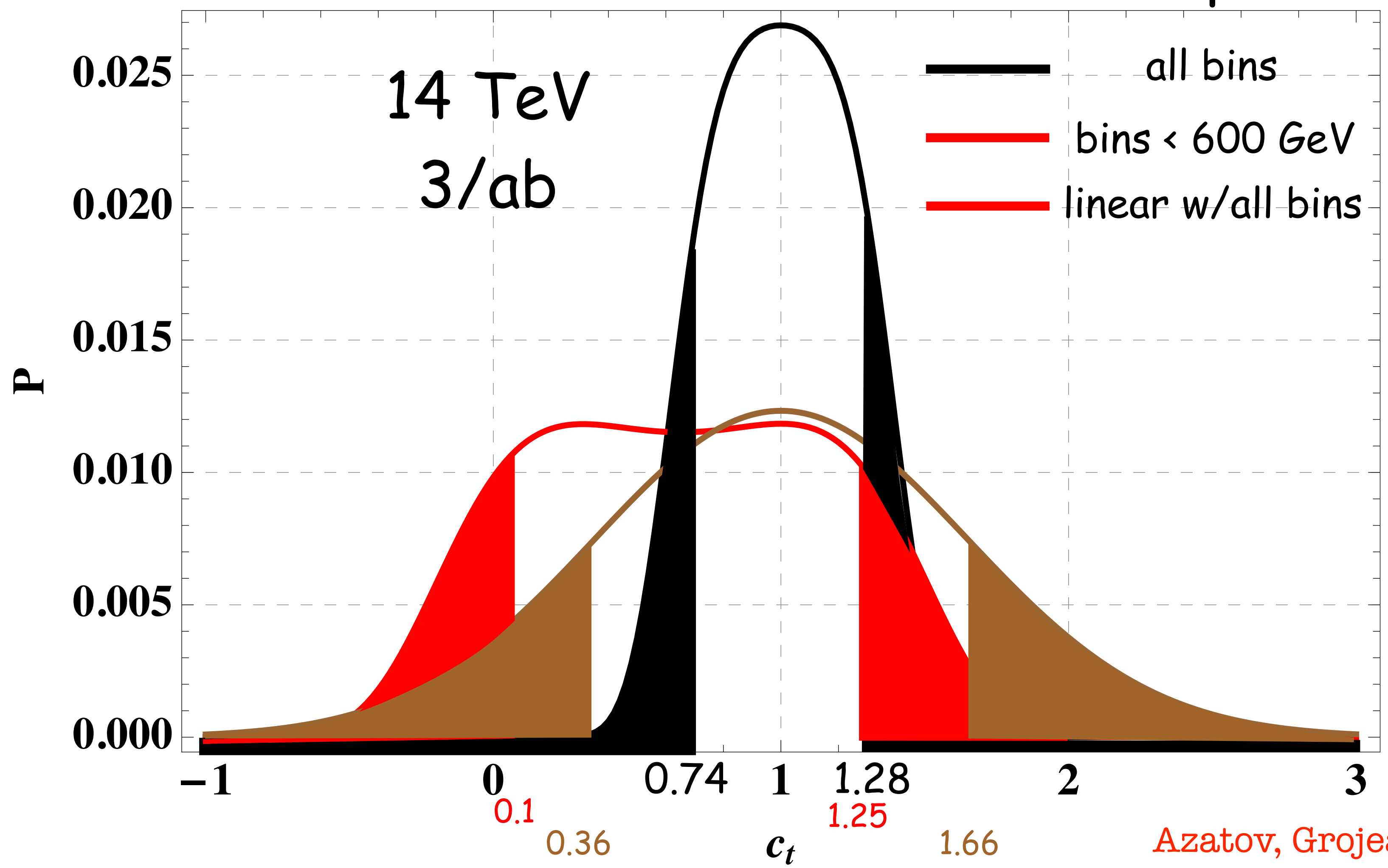
provides an alternative to ttH to measure the top Yukawa coupling



Azatov, Grojean, Paul, Salvioni '14

Conclusions

$$\mathcal{L}_{\text{Higgs}} = V_0 - \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \left(y_{ij}\bar{\psi}_{Li}\psi_{Rj}H + h.c.\right)$$

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cosmological constant

$V_0 \approx (2 \times 10^{-3}\ \text{eV})^4 \ll M_{\text{PL}}^4$

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SUSY?
TeV New Physics?

triviality/stability
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well described
experimentally by CKM
(up to a few exceptions: $A_{FB}^{t\bar{t}}$, ΔA_{CP}^{c}...)

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Higgs = Elementary or Composite?

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Flavor violations: $>10^{8}$ GeV

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New physics should be around the TeV scale
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Precision Higgs physics is on the HEP agenda for the next 2-3 decades
- for a deep understanding of the SM
- for an accurate comparison with experiments
- for an access to BSM

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