What the *Higgs* is going on? (beyond the SM)

Cédric Delaunay

LAPTH – Annecy-le-vieux, France

enigmass@lpsc.fr

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~Menu~

- a SM Higgs discovery: good and bad news

- new physics in Higgs phenomenology at the LHC

Implications of
a ~125GeV SM Higgs discovery

why did we need a Higgs boson?

- mass of the universe? *NO!* it comes from Λ_{QCD} (*+dark-matter?*)
- mass of W/Z bosons + SM fermions? *NO!* they come from ***spontaneous breaking*** of EW gauge invariance

nlσm:

$$\mathcal{L}_{mass} = \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger (D^\mu\Sigma)\right] - \frac{v}{\sqrt{2}}\sum_{i,j}\left(\bar{u}_L^{(i)} d_L^{(i)}\right)\Sigma\begin{pmatrix}\lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)}\end{pmatrix} + h.c.$$

Goldstone's

$$\Sigma(x) = \exp(i\sigma^a\chi^a(x)/v),$$

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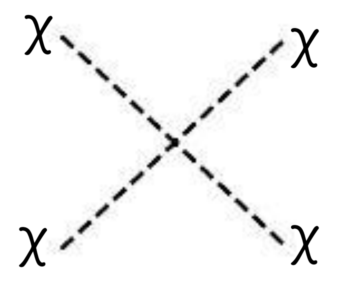
- to restore unitarity >o(1 TeV) in $W_L W_L$ scattering? *YES*!



$\sim E^2/v^2$

unitarity lost
at $\sim 4\pi v$

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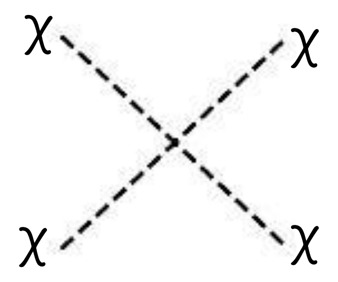
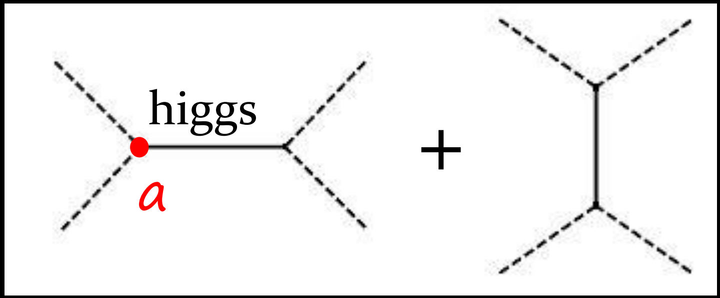


~ E^2/v^2

unitarity lost at ~$4\pi v$

+



~<TeV

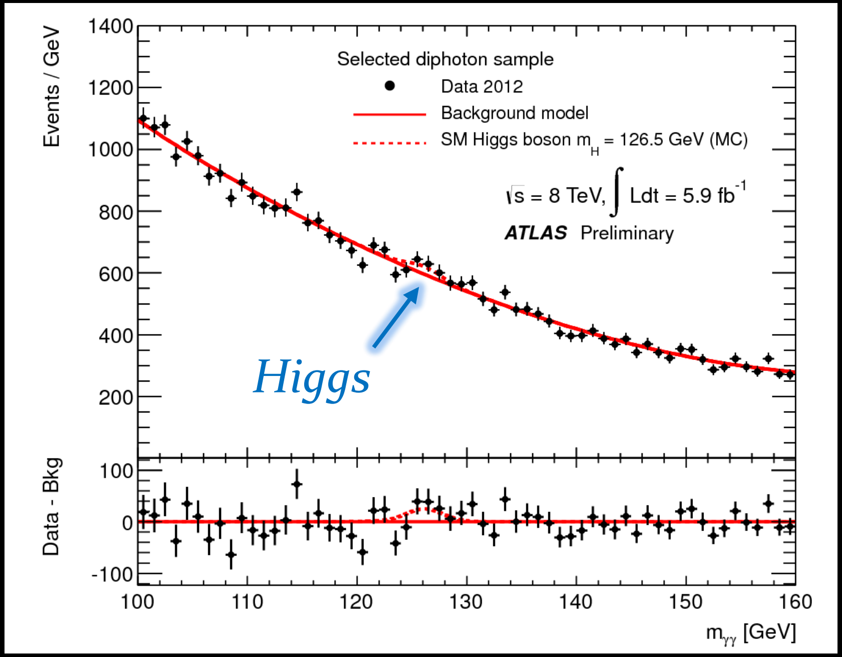
~ $E^2/v^2(1-a^2)$ + $o(m_h^2/E^2)$

unitarity up to $4\pi v/\sqrt{(1-a^2)}$

SM predicts $a=1$ → valid theory of EW interactions down to very short distances!

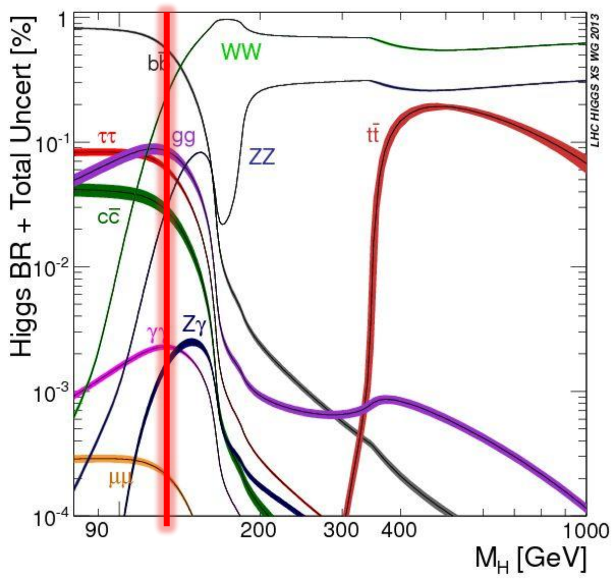
Higgs discovery = EXP+TH+Nature effort

- *EXP*: dig out a faint signal in a huge bkgd

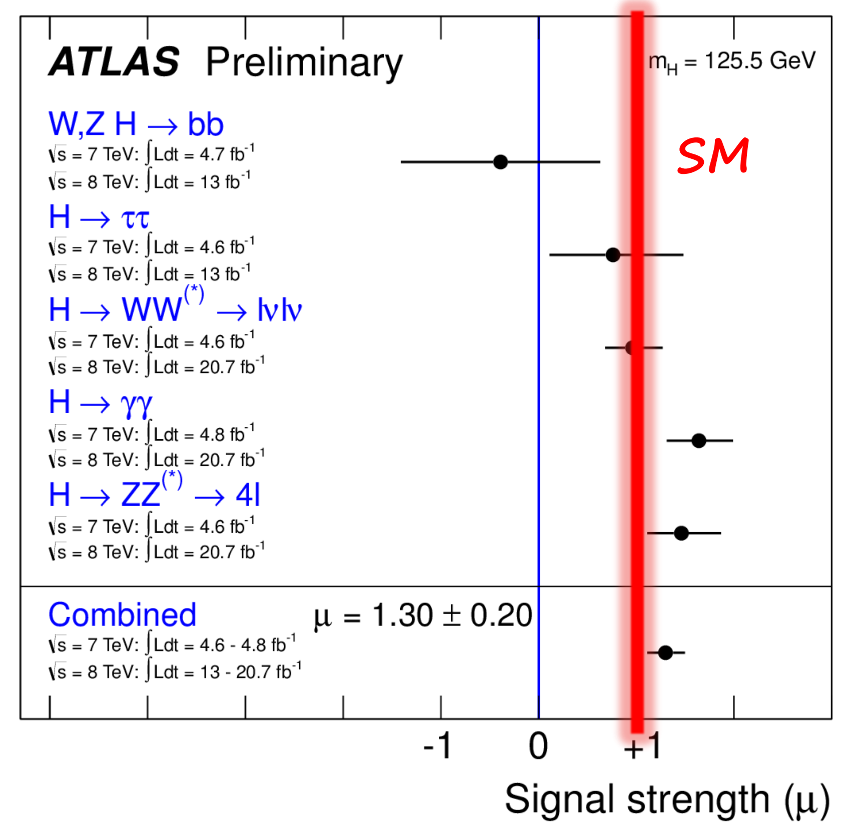


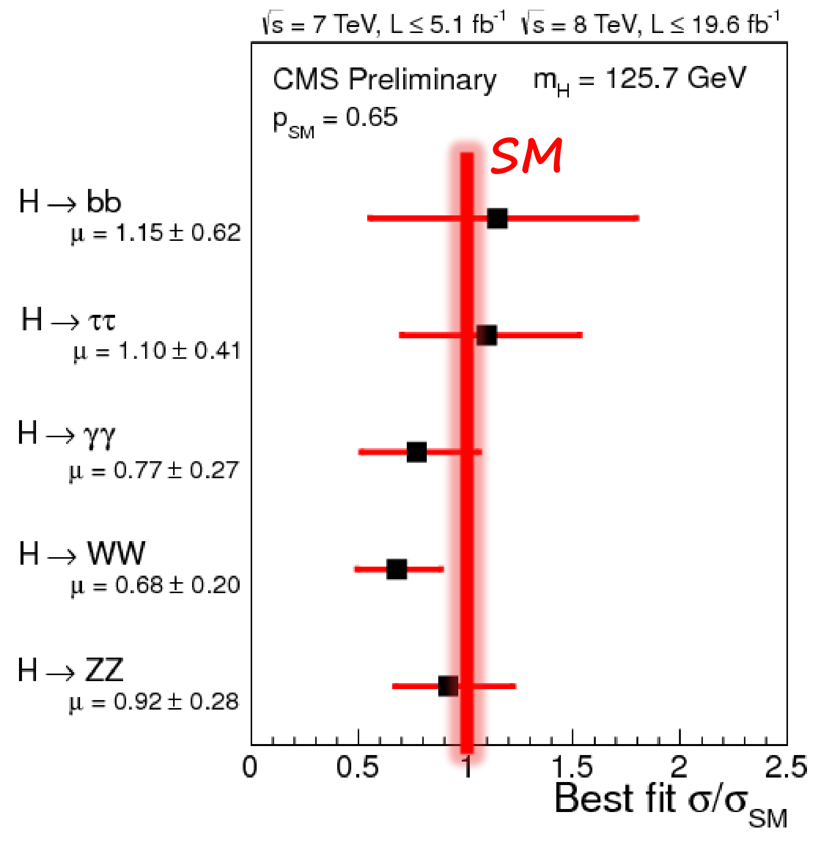
- *TH*: NNLO H x-section → larger *expected* signal

- *Nature*: kind enough to yield a light state visible in clean channels like $h \to \gamma\gamma$



The observed Higgs is thus far SM-like:





in particular its coupling to W/Z is inferred (through fits) to be:

1.04±0.03 in units of SM value

see *e.g.* Falkowski-Riva-Urbano ‘12

what do we learn from a 125GeV SM Higgs?

Good news:

- SM is consistent picture down to very short distances, potentially up to gravity scale ($\sim 10^{19}$GeV)

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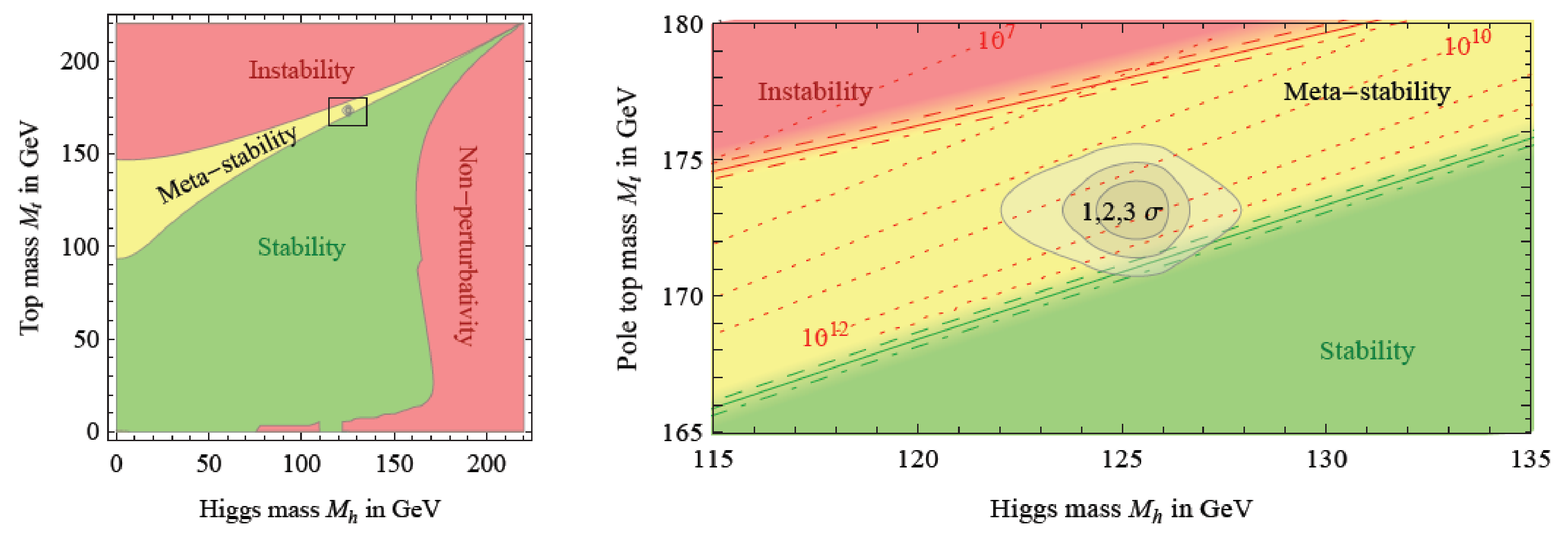
Degrassi et al. ‘12



Higgs quartic turns negative at $\Lambda \approx 10^{11}$GeV: $d\lambda / d\log\mu \propto - N_c\, y_t^4/16\pi^2$

had y_{top} been ~3% larger, we wouldn’t have been here…

what do we learn from a 125GeV SM Higgs?

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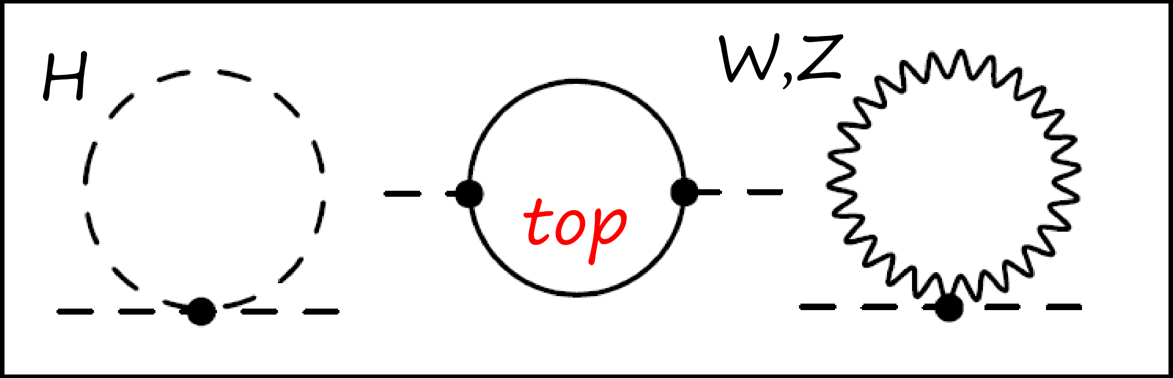
- SM is consistent picture down to very short distances, potentially up to gravity scale (~10^{19}GeV)

$\delta m^2 =$



$\sim \frac{g^2\Lambda^2}{16\pi^2}$

The SM Higgs dilemma:

full restoration of unitarity induces a huge UV sensitivity!

SM-like Higgs is not naturally light

i.e. doesn't break any symmetry

't Hooft '84

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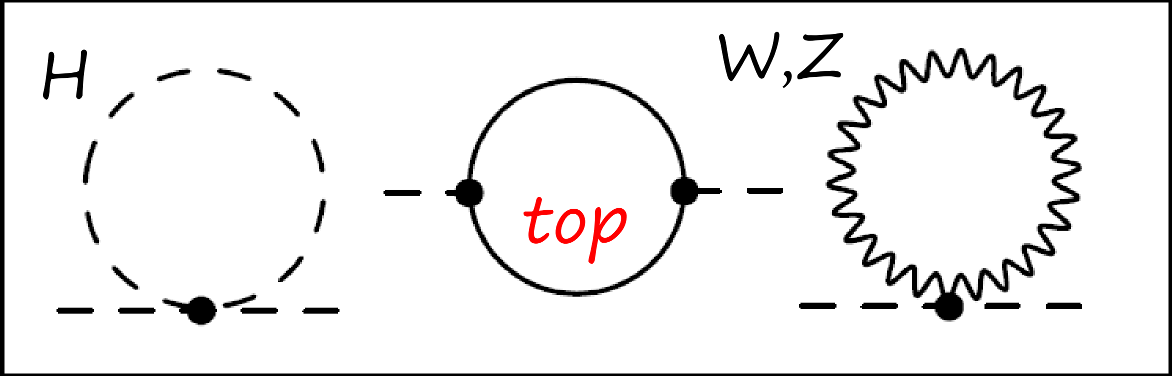

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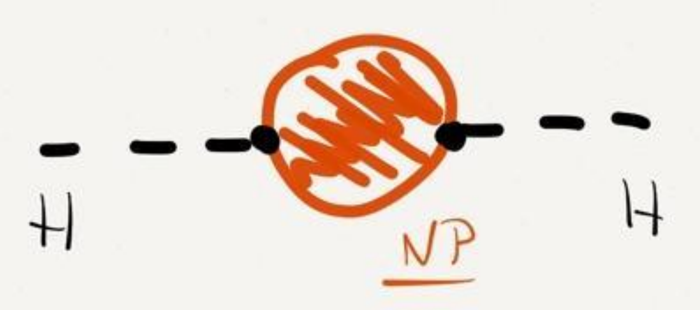

$= \log(\Lambda)$ or finite

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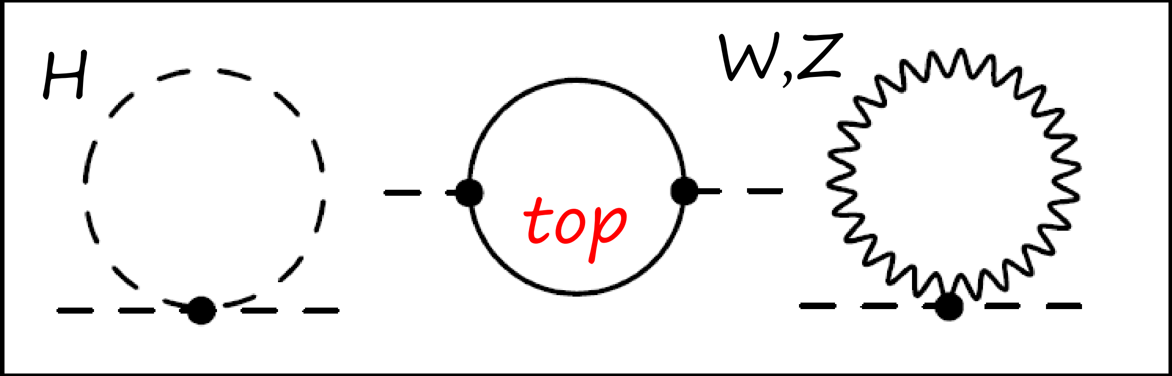

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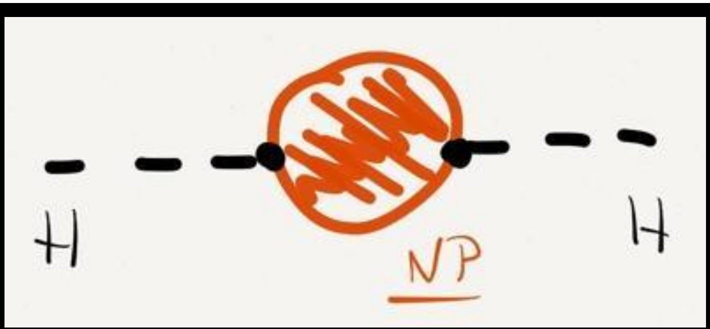


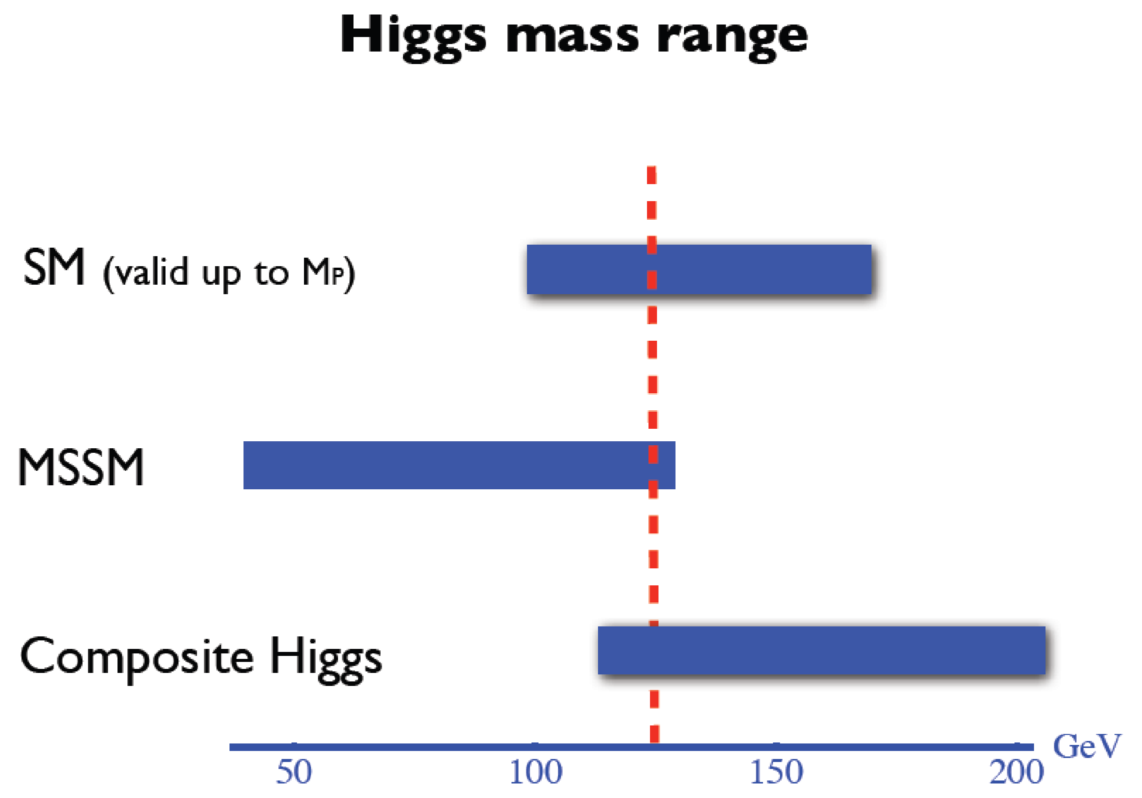
$= \log(\Lambda)$ or finite

Nature is natural → $\Lambda \sim \mathrm{TeV}$ 2 ***new physics*** paths:

- $\Lambda \sim M_{Pl}$ but new symmetry kicks in at TeV scale
  e.g. supersymmetry
- SM fields couple to a new strong dynamics with $\Lambda \sim \mathrm{TeV}$
  e.g. composite Higgs models

Understanding whether EW scale stabilization mechanism is weakly or strongly coupled is still a fundamental open question

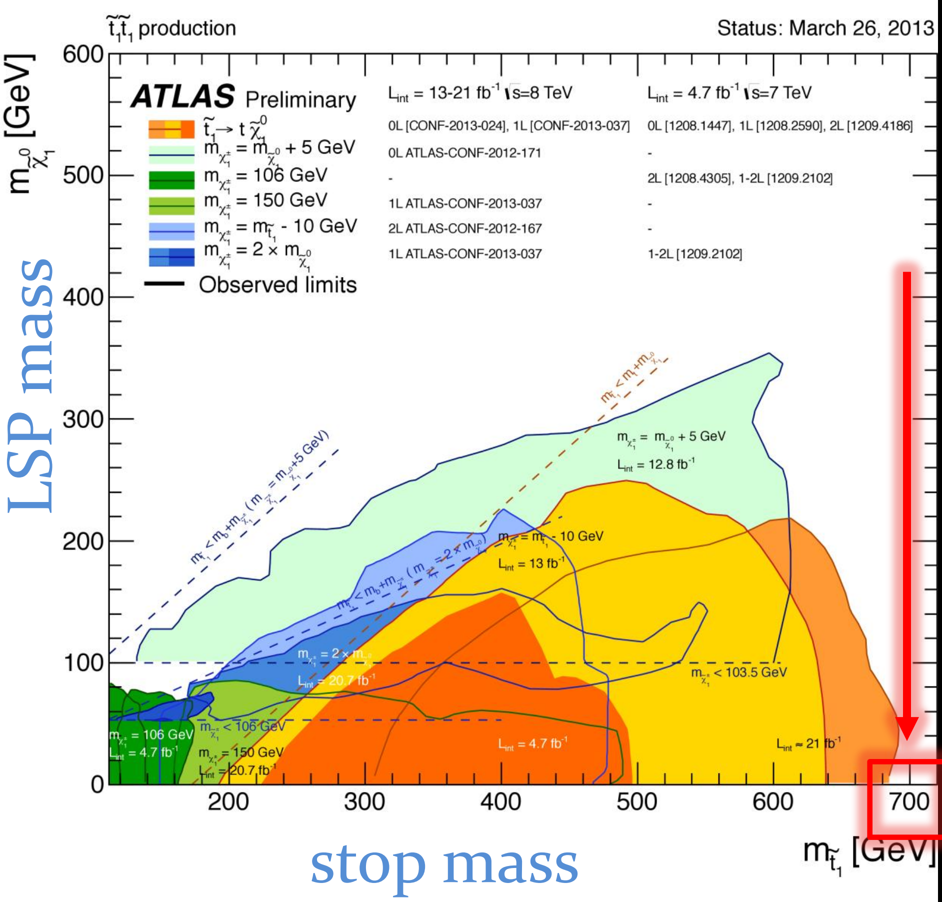
125GeV Higgs mass leaves no clear-cut answer:



[Pomarol ICHEP '12]

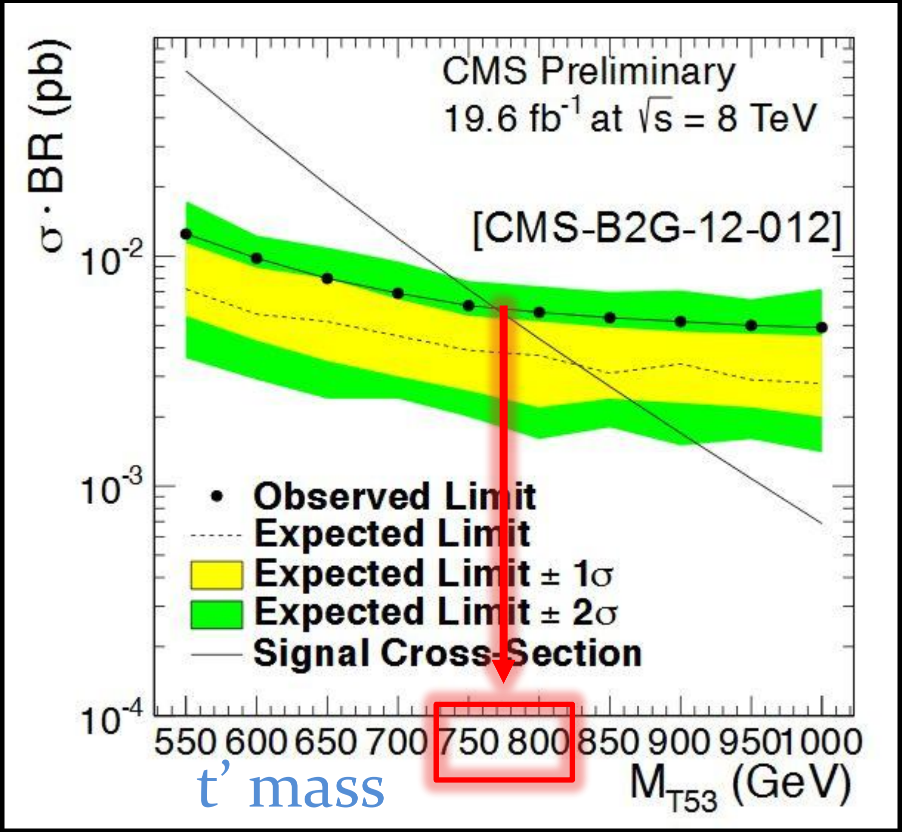
be it weakly or strongly coupled,
natural BSM theories have
top partners $< \mathcal{O}(1\ \mathrm{TeV})$
to soften the UV sensitivity of the Higgs mass

be it weakly or strongly coupled, natural BSM theories have **top partners < o(1 TeV)** to soften the UV sensitivity of the Higgs mass



LSP mass

stop mass



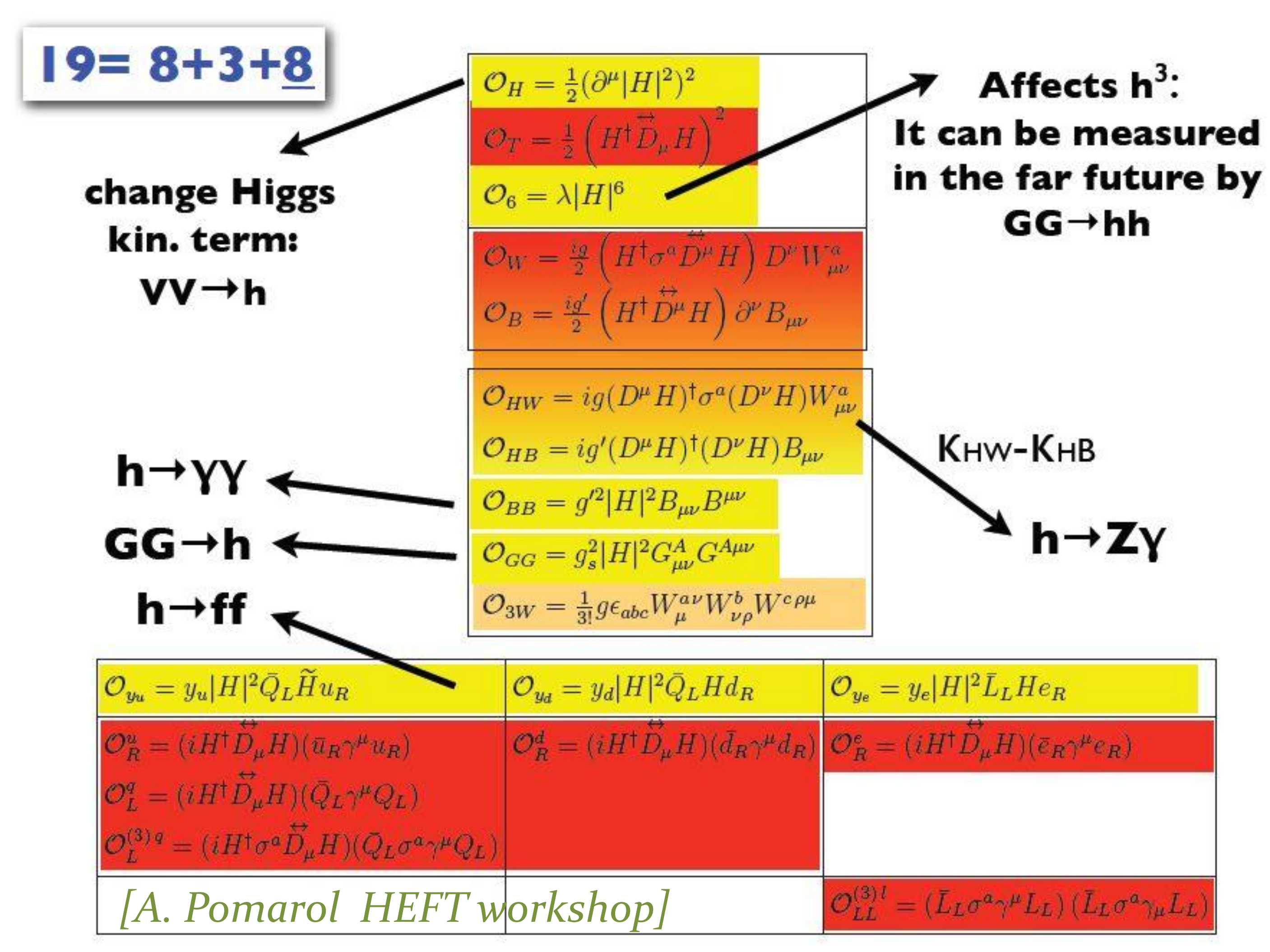
t’ mass

Probing new physics in Higgs pheno at the LHC

through precision Higgs measurements:

SM-like Higgs → heavy new physics → effective approach
→ small $o(E^2/\Lambda^2)$ effects → precision measurements

8 operators involving Higgs are probed only by the LHC



19= 8+3+8

$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$

$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overset{\leftrightarrow}{D}_\mu H\right)^2$

$\mathcal{O}_6 = \lambda |H|^6$

$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overset{\leftrightarrow}{D^\mu} H\right) D^\nu W^a_{\mu\nu}$

$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overset{\leftrightarrow}{D^\mu} H\right) \partial^\nu B_{\mu\nu}$

$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$

$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$

$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$

$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$

$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\nu}_\mu W^b_{\nu\rho} W^{c\rho\mu}$

$\mathcal{O}_{y_u} = y_u \|H\|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \|H\|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \|H\|^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}^q_L = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}^{(3)q}_L = (iH^\dagger \sigma^a \overset{\leftrightarrow}{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}^d_R = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
		$\mathcal{O}^{(3)l}_{LL} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$

change Higgs kin. term:
VV→h

Affects h³:
It can be measured in the far future by GG→hh

h→γγ

GG→h

h→ff

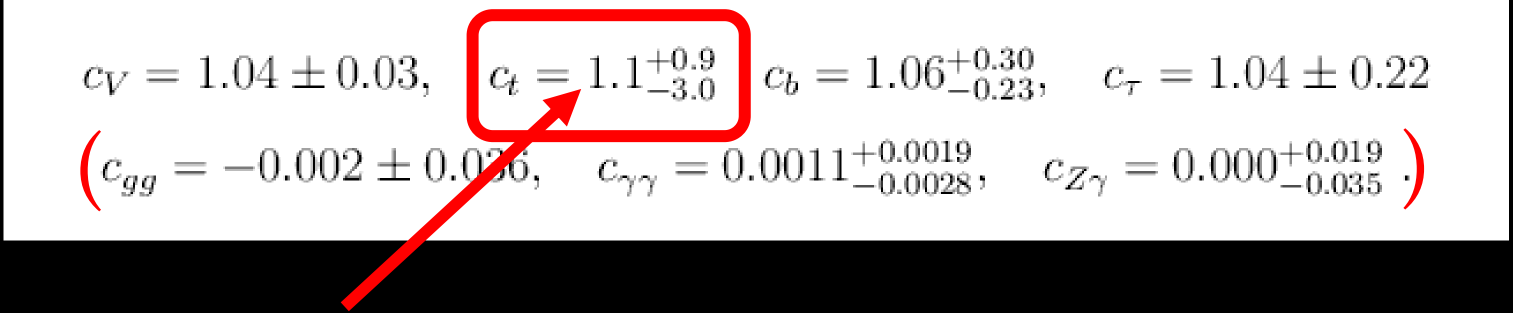
κ_{HW}-κ_{HB}

h→Zγ

[A. Pomarol HEFT workshop]

low-energy precision measurements have limited scope:

indirect constraints on Higgs couplings from LHC run 1 data
best fit + 68% CL intervals: (w/EWPTs)



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$$\left(c_{gg} = -0.002 \pm 0.036, \quad c_{\gamma\gamma} = 0.0011^{+0.0019}_{-0.0028}, \quad c_{Z\gamma} = 0.000^{+0.019}_{-0.035} . \right)$$

SM-like top-Higgs coupling favored,
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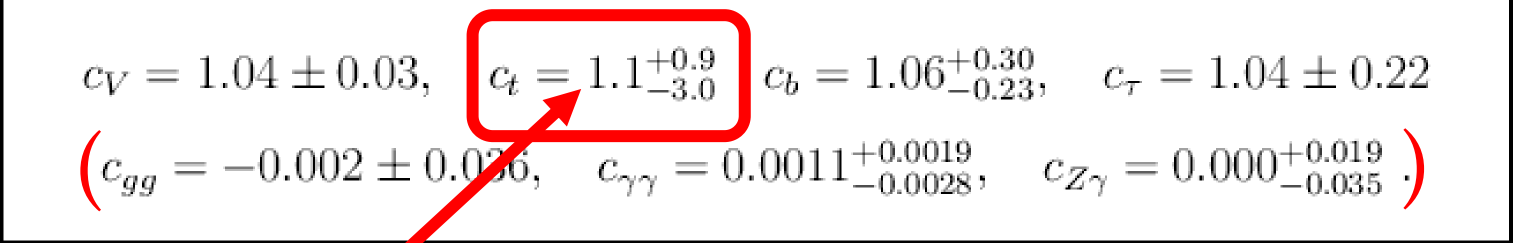

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SM-like top-Higgs coupling favored,
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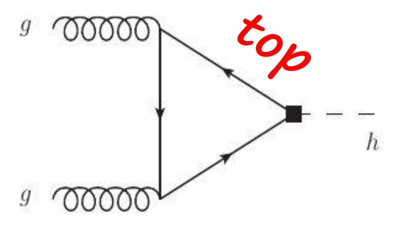
...because of a "blind direction":

$$\sigma_{gg\to h} \propto \left| \overset{\text{BSM loop}}{c_{gg}} + \frac{\alpha_s \overset{\text{top loop}}{c_t}}{3\pi} \right|^2$$



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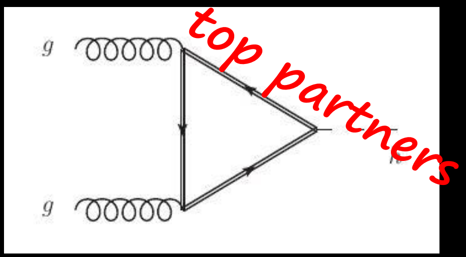
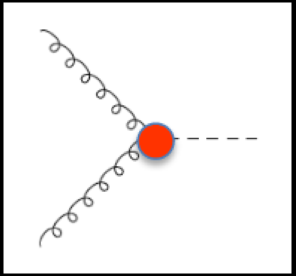


→

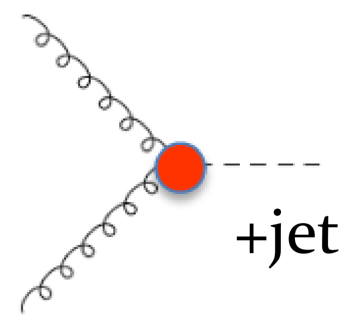


$$= h\, G^{\mu\nu} G_{\mu\nu}$$

one could, besides Higgs+tt production,
access top coupling in very boosted Higgs production:

Banfi-Martin-Sanz '13 ,
Grojean-Salvioni-Weiler *in prep'* ,
Spannowsky-Takeuchi-Wymant *in prep'*

demanding an extra hard jet w/ $m_{top} << \text{jet } p_T << M_{top\ partner}$
resolves the top loop in gluon fusion



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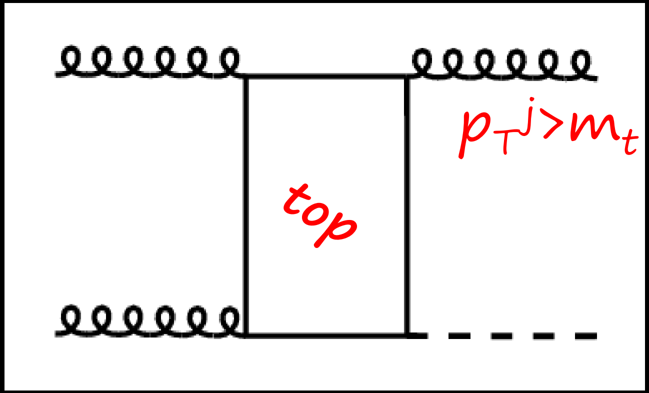

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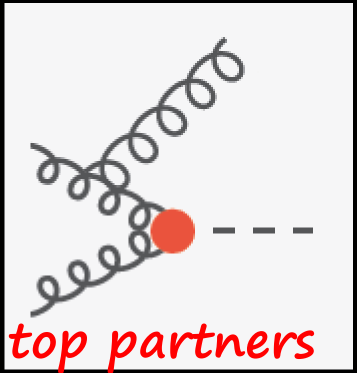
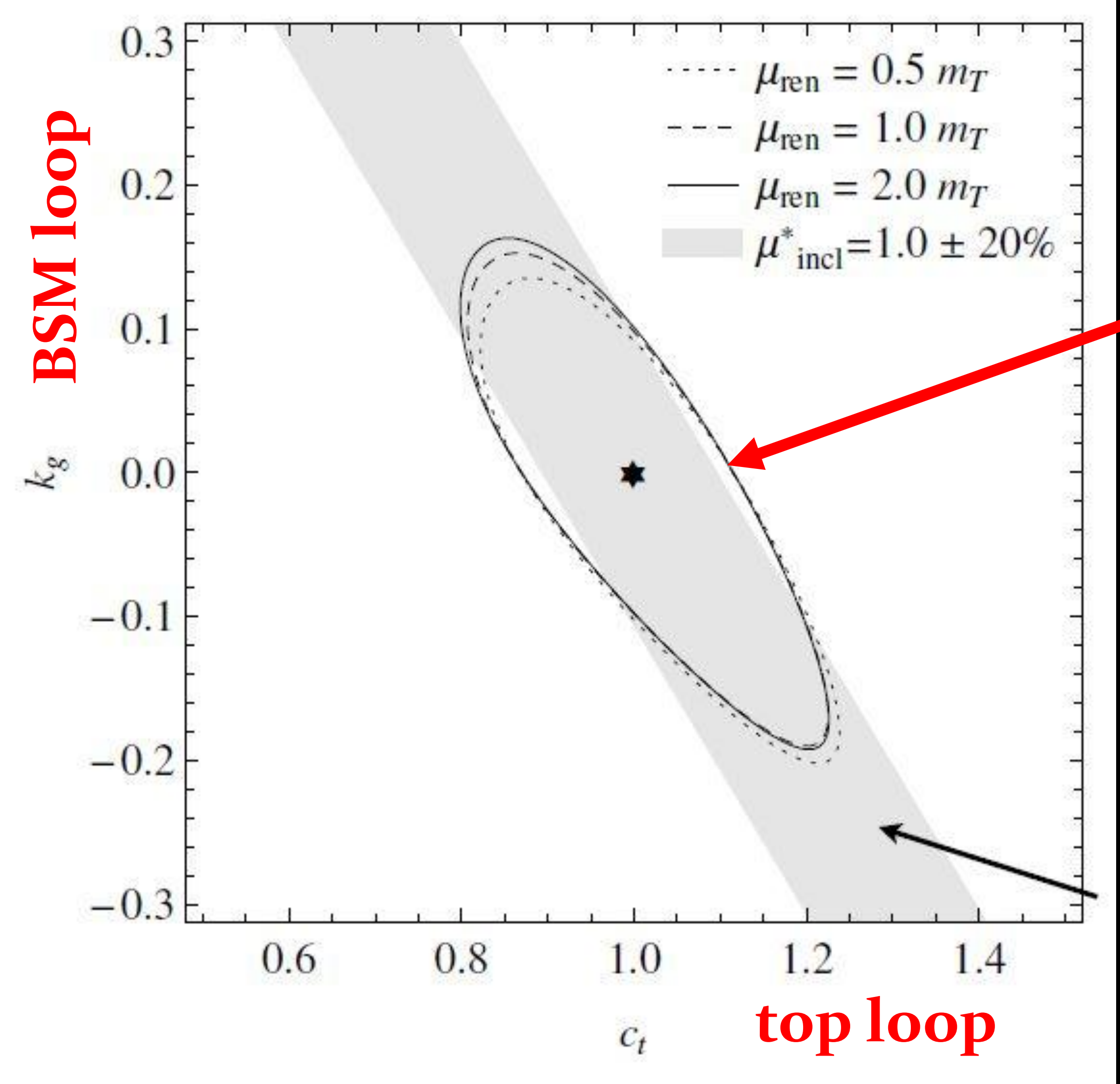


EFT in terms $h\, G^{\mu\nu} G_{\mu\nu}$ breaks down,
→ need to integrate the top in!

[A. Weiler HEFT workshop ‘13]



BSM loop

top loop

expected sensitivity
for p_T>650GeV
@LHC14, 3/ab

blind direction
@inclusive level

Are we doomed to search for small effects in Higgs phyics?

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...not necessarily.

125GeV light Higgs is rather narrow

→ most of its couplings to other SM fields are small

(*e.g.* Higgs-bottom coupling is ~0.02 in the SM)

→ this leaves plenty of room for *o(1)* effects!

Example #1:

“charming the Higgs”

[CD-Golling-Perez-Soreq ‘13]

Higgs decay to charm pair:

- *Common lore:* *H→cc within the SM* is not visible @LHC:
  - * BR(H→cc) ~ $\frac{m_c^2}{m_b^2}$ BR(H→bb) ~ 1/16 x 60% ~ 4%
  - * hard to resolve charm jets → huge QCD dijet bkg

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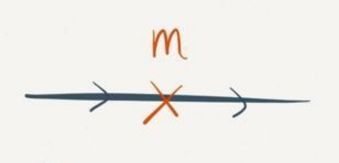
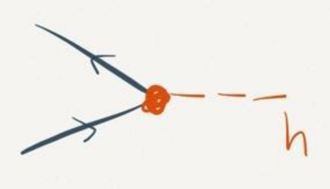
– *Hcc* coupling significantly larger due to newphysics:

$$\mathcal{L}_{\rm EFT} \supset \lambda^u_{ij}\bar{Q}_i\tilde{H}U_j + \frac{g^u_{ij}}{\Lambda^2}\bar{Q}_i\tilde{H}U_j\left(H^\dagger H\right) + {\rm h.c.}$$



$$= \frac{v}{\sqrt{2}}\left(\lambda^u_{ij} + g^u_{ij}\frac{v^2}{2\Lambda^2}\right),$$



$$= \frac{1}{\sqrt{2}}\left(\lambda^u_{ij} + 3g^u_{ij}\frac{v^2}{2\Lambda^2}\right).$$

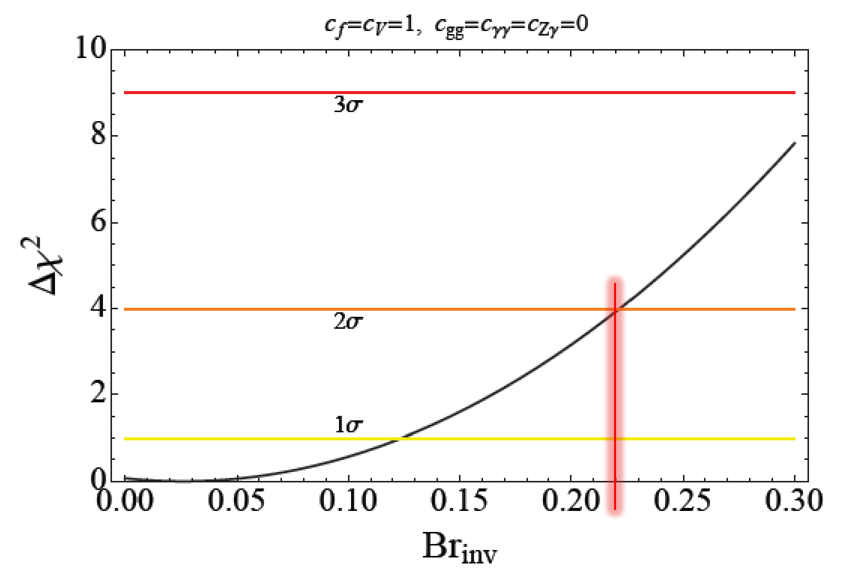
$$\Lambda \simeq \frac{44\,{\rm TeV}}{\sqrt{c_c - 1}}.$$

Hcc enhancement

yet, modulo an accidental cancellation of o(1/few)

What's the sensitivity to larger charm coupling in Higgs data?

- indirectly constrained through the invisible width:



[Falkowski-Riva-Urbano '13]

if all other "visible" couplings set to SM values:

$\mathrm{Br_{inv}}$ ~< 22% @95%CL

adding a new physics source of ggh: $\mathrm{Br_{inv}}$ ~< 50% @95%CL

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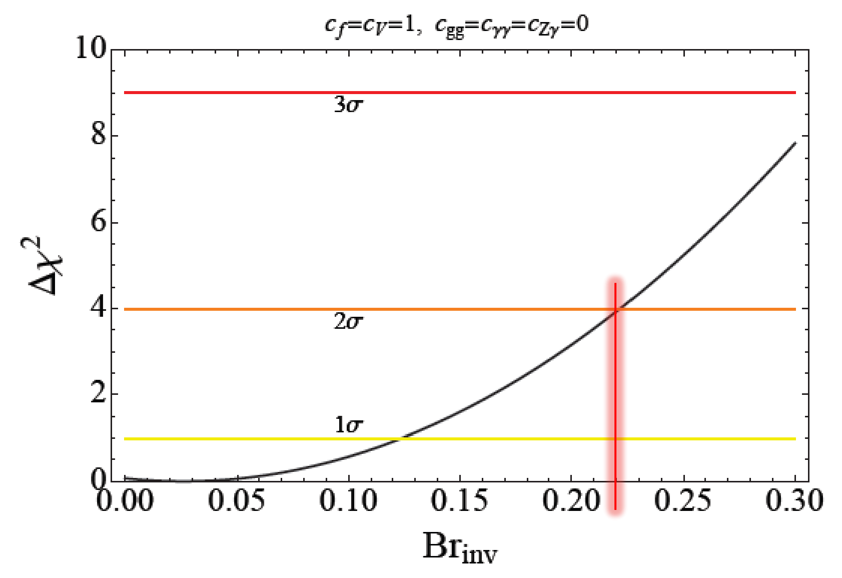

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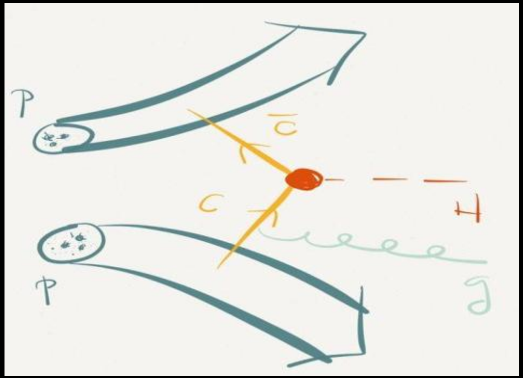
- charm fusion opens up as a significant H prod. mechanism



@NLO: $\sigma_{cc} \approx 0.003\, \sigma_{gg}$ in the SM

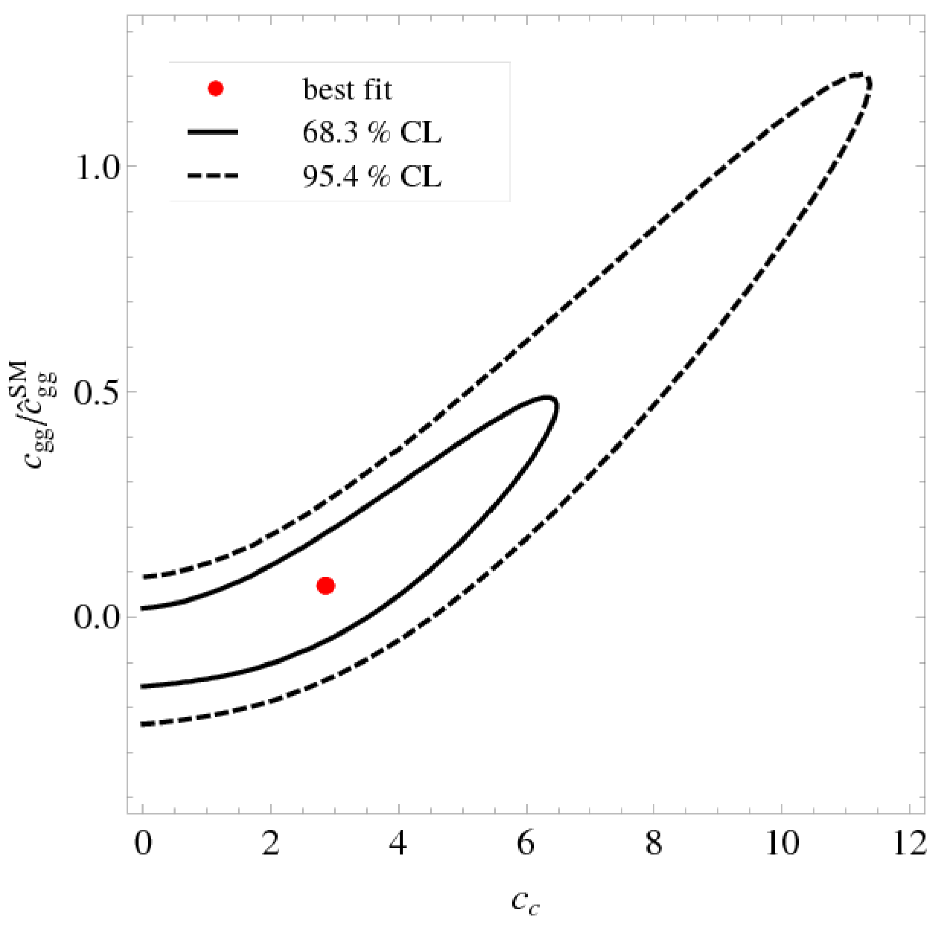
$\sim o(10\%)$ increase in $\sigma_{pp\to h}$ if Hcc 5x larger

What's the sensitivity to larger charm coupling in Higgs data?

we perform a global Higgs fit within the EFT framework*:

only allowing c_c to float: c_c ~< 4 @2σ

allowing a new physics source in ggh: c_c ~< 8 @2σ



a fairly large coupling allowed by current Higgs data

*we assume similar efficiencies for cc and gg fusion

This yields significant change (V)H→bb channel:

BR(*H→bb*) is significantly suppressed:

with $c_{gg}>0$

$$\mathrm{BR}_{h\to b\bar{b}} = \frac{\mathrm{BR}^{\mathrm{SM}}_{h\to b\bar{b}}}{1+(|c_c|^2-1)\mathrm{BR}^{\mathrm{SM}}_{h\to c\bar{c}}} \,. \approx 40\% \; (20\%)$$

but most charm fusion events rejected after VH-enriching cuts:

$$\to \; \mu_{bb} \approx 0.7 \; (0.4)$$

with $c_{gg}>0$

large part of *bb* signal expected @ATLAS/CMS could be lost!

in the benefit of charm…

one can use charm tagging technique to capture *H→cc*:

build *cc*-enriched *bb* signal = "*charming the Higgs*":

$$\mu_{b\bar{b}+c\bar{c}} \equiv \frac{\sigma_{pp\to h}\left(\epsilon_b^2\mathrm{BR}_{h\to b\bar{b}}+\epsilon_c^2\mathrm{BR}_{h\to c\bar{c}}\right)}{\sigma^{\mathrm{SM}}_{pp\to h}\left(\epsilon_b^2\mathrm{BR}^{\mathrm{SM}}_{h\to b\bar{b}}+\epsilon_c^2\mathrm{BR}^{\mathrm{SM}}_{h\to c\bar{c}}\right)} \approx 0.9 \; (0.75)$$

assuming 40% efficiency in c-tagging

Example #2:
“up/down Higgs CP asymmetry”

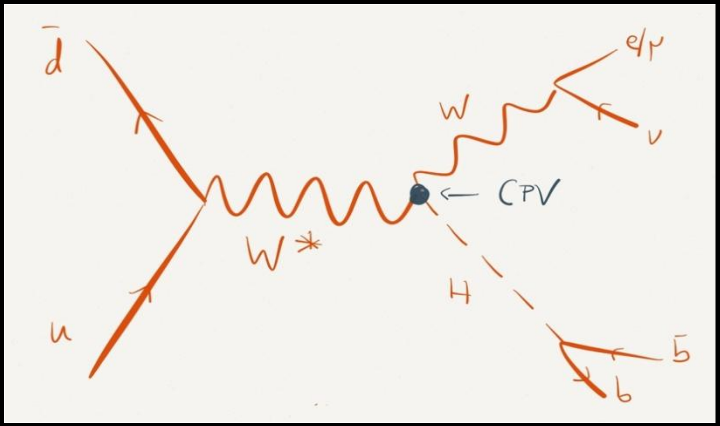
[CD-Perez-de Sandes-Skiba ‘13]

large CPV effects in Higgs physics:

Consider $WH \to l\nu bb$:

[CD-Perez-de Sandes-Skiba '13]

parton level process →



H–V_μ–V_ν :

$$-ig_V m_V \left[\boxed{A_V \eta_{\mu\nu} + B_V p_{1\nu} p_{2\mu}} + \boxed{C_V \epsilon_{\mu\nu\alpha\beta} p_1^\beta p_2^\alpha}\right]$$

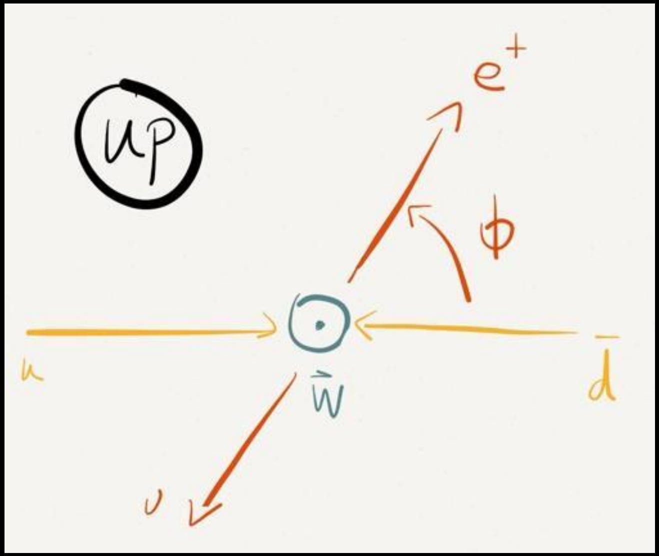
CP-even

CP-odd

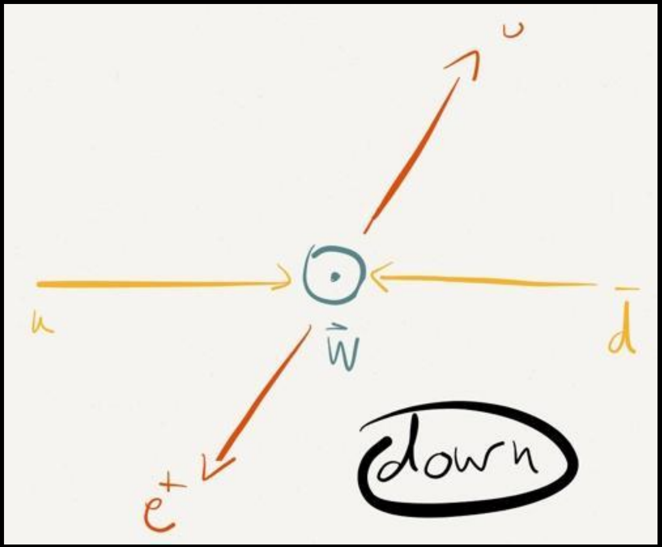
induces **P**-odd triple product

$t = \vec{\ell} \cdot (\vec{H} \times \vec{u})$ + **CP**-even couplings → **CP** asymmetry in t

asymmetry in t is an up/down asymmetry in terms of l^+



vs.



$$A_{up/down} = -\frac{9\pi}{16}\sin\gamma\left(\frac{\mathcal{A}_T\mathcal{A}_L}{2\mathcal{A}_T^2+\mathcal{A}_L^2}\right)$$

@partonic level

$$\tan\gamma = \frac{C_W\,\hat{s}\beta}{2A_W}$$

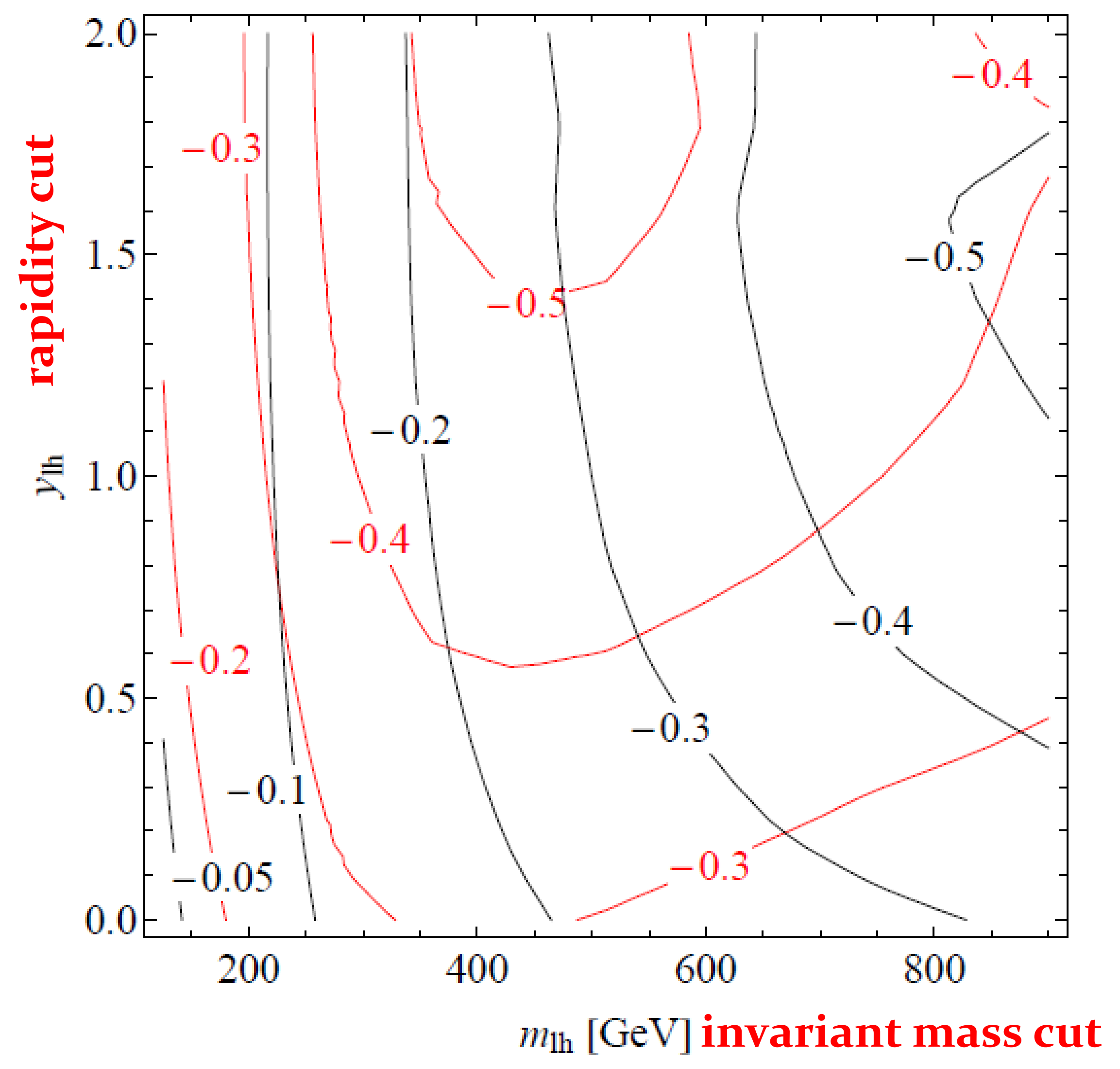
"weak" phase

"strong" phase: $M_{W_\lambda \to l^+\nu} \propto e^{i\lambda\phi}$

large CPV effects in Higgs physics:

LHC@14TeV w/ $A=A_{SM}=1$, $B=B_{SM}=0$ and $C=4/\Lambda^2$

[CD-Perez-de Sandes-Skiba ‘13]



$\Lambda=1$TeV
$\Lambda=500$GeV

scale of $g^2WW\sim$

cutoff ~ $4\pi\Lambda/g$

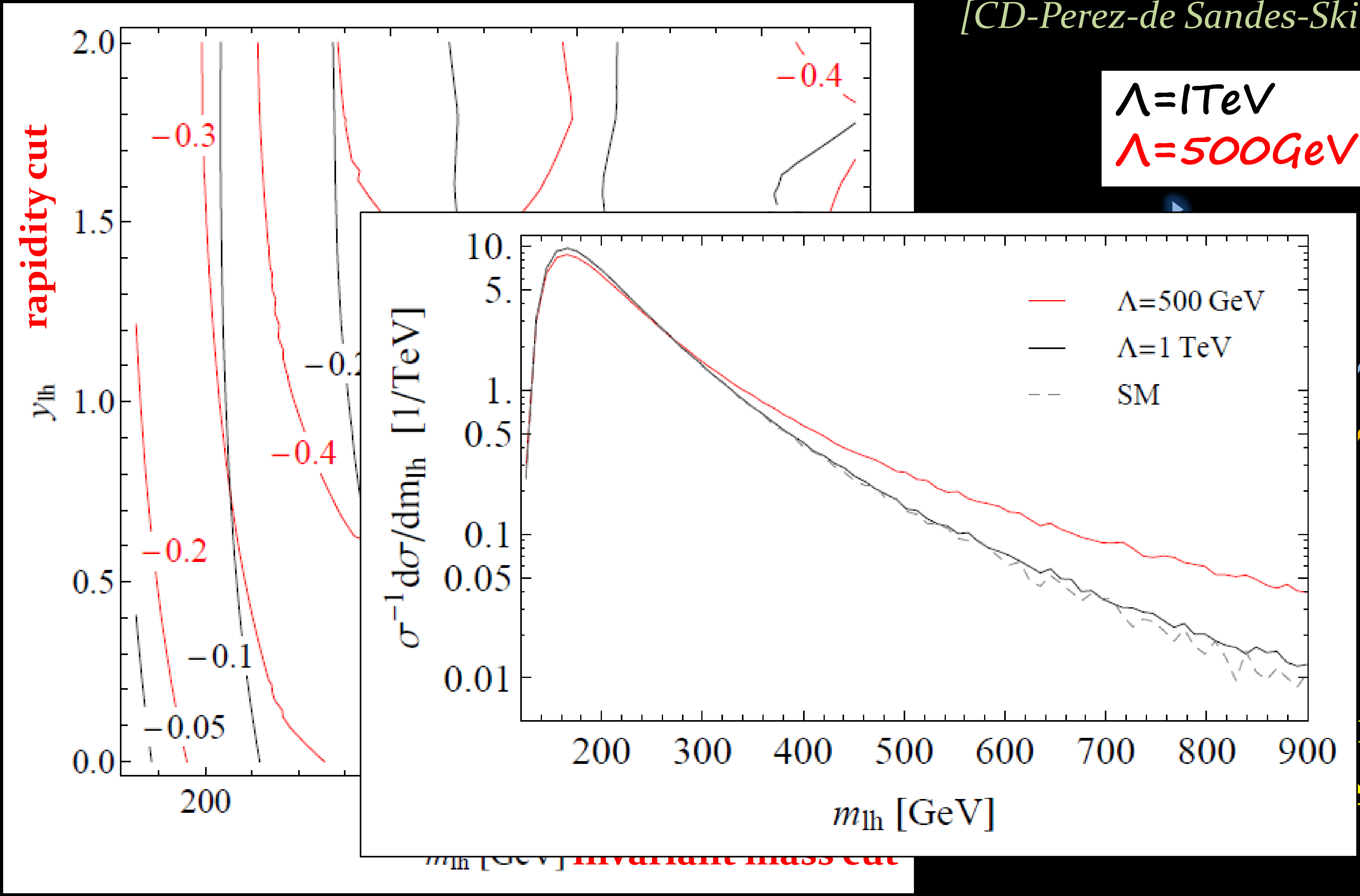
$o(1)$ asymmetryies
easy to measure

large CPV effects in Higgs physics:

LHC@14TeV w/ $A=A_{SM}=1$, $B=B_{SM}=0$ and $C=4/\Lambda^2$

[CD-Perez-de Sandes-Skiba '13]

Λ=1TeV
Λ=500GeV



N~

Λ/g

ies

e

conclusions:

- SM-like Higgs → SM = consistent theory down to very short distances, but a very UV sensitive theory!

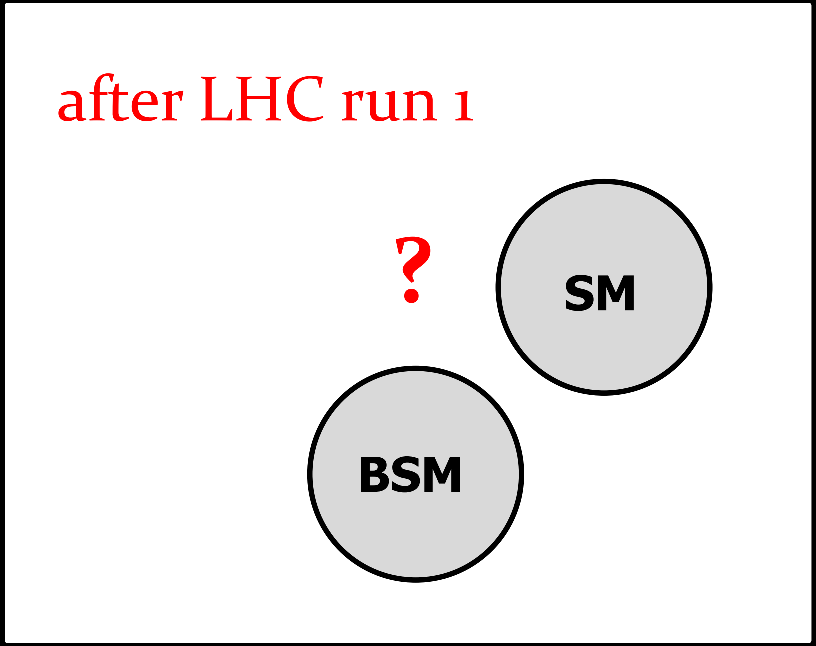
- Naturalness is the only guiding principle which predicts a new scale (other than gravity) beyond the SM, Λ~TeV

- TeV scale will continue to be probed at the LHC through:
  - precision Higgs measurements
  - direct searches of top partners

- also, still plenty of room for new physics in Higgs pheno:
  - $O(1)$ CPV in Wh
  - Higgs could decay dominantly to charm pairs
  - $O(1)$ deviation in $h \to Z\gamma$ (not indirectly constrained)

→ to study all Higgs properties at LHC is an exciting/vast program!

is the observed Higgs really the SM Higgs ?



after LHC run 1

more data

more anything?