ÉCOLE DOCTORALE PHENIICS

A walk on the Higgs side : From data-analysis To theories beyond the Standard Model

Grégory Moreau

Laboratoire de Physique Théorique d'Orsay

« Habilitation à Diriger des Recherches »

Reviewers :	M. Karim BENAKLI
	M. Aldo DEANDREA
	M. Jean-Marie FRÈRE
Examinators :	M. Abdelhak DJOUADI
	M. François RICHARD
	Mrs. Verónica SANZ

Orsay

- 03/12/2015 -

Introduction

Theoretical side There exist abnormally **small fundamental scales**
not satisfying the ***principle of naturalness*** :

> *« A quantity in nature should be small only if the underlying theory becomes more symmetric as that quantity tends to zero. »*

't Hooft N.Sci.Ser.B 59 (1980) 135

Introduction

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't Hooft N.Sci.Ser.B 59 (1980) 135

Cosmological constant (dark energy?) in G.R. :

Weinberg P.R.L. 59 (1987) 2607

$$\int d^4x \sqrt{g}\Lambda.$$

$\Lambda \sim (10^{-11}\text{GeV})^4$ **<<** $(M_{\text{Planck}})^4$ →

$M_{\text{Planck}} = (\hbar c/G_N)^{1/2}$

«Anthropic principle»

Alternative to naturalness :
multiverse / randomly distributed Λ ?
(landscape of string theories)

Strong CP problem in Q.C.D. :

Peccei, Quinn P.R.L. 38 (1977) 1440

$$\mathcal{L}_\theta = \frac{\theta}{16\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}.$$

θ **<<** 10^{-10} →

Spont. broken global $U(1)_{PQ}$ symmetry ?
And pseudo-GB axion (= dark matter?)

Brout-Englert-Higgs mass in E.W.S.B. sector of the Standard Model :

$$V(\phi) = -\mu^2|\phi|^2 + \frac{\lambda}{4}|\phi|^4.$$

$\mu \sim 10^2$ GeV **<<** M_{Planck}

$\lambda \sim 10^{-1}$ is natural

➡ $M_{Gravity}{}^{5D} \sim 10^3$ GeV
from Extra-dimensions ?

__A__.-Hamed, __D__imopoulos, __D__vali ph/9803315
__R__andall, __S__undrum ph/9905221

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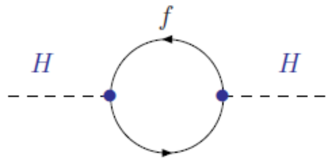
A.-Hamed, Dimopoulos, Dvali ph/9803315
Randall, Sundrum ph/9905221

Instability at quantum level…

Higgs mass : $m_H^2 = m_H^2{}_{\text{bare}} + \delta m_H^2{}_{\text{loop}}$

$\delta m_H^2{}_{\text{loop}} \sim -\frac{Y^2}{8\pi^2}\Lambda_{\text{NP}}^2 \gg m_H^2$ => *Fine-tuning*



$+ \ \ldots$

& **Higgs potential** V (no Landau pole, bounded from below)

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→ $M_{\text{Gravity}}^{5D} \sim 10^3$ GeV from Extra-dimensions ?

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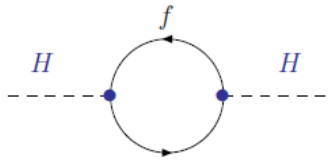


$+ \ \ldots$

→

Supersymmetry *(many references!)*

Pseudo-GB Higgs *[Gauge-Higgs un., Little Higgs, Neutral naturalness…]*

Λ_{NP}^2 taken care of (quantum gravity…)
M_{NP}^2 at TeV scale or Higgs-decoupled
(Leptogenesis, m_ν, GUT…)
«finite naturalness»

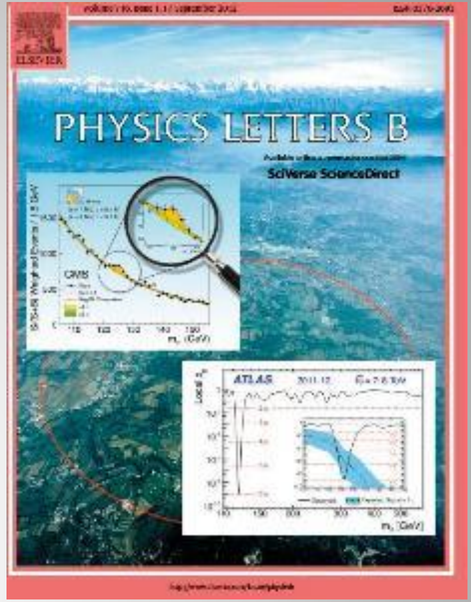
Giudice et al. ph/1412.2769

& **Higgs potential** V (no Landau pole, bounded from below)

Experimental side

The LHC has **discovered** in 2012 a resonance of ~ 125 GeV at the ~ 5σ level

*which is most probably the **B.E.Higgs** boson responsible for **EWSB***



+ ATLAS and CMS Collaborations have collected data at Run 1 with luminosities of ~5 fb^{-1} @ $\sqrt{s}$=7TeV
~20 fb^{-1} @ $\sqrt{s}$=8TeV
and provided measurements of the Higgs rates in **88** channels !

= precious source of **indirect information on physics underlying the SM** since the Higgs couplings might be sensitive to new heavy states.

Outline

I. On the Higgs boson data at the (HL-)LHC

II. Phenomenology: New physics effects on the Higgs sector

III. Theoretical aspects about brane-localized Higgs fields

I. On the Higgs boson data at the (HL-)LHC

[A] The theoretical uncertainties in Higgs rate fits

Global **theoretical uncertainty** on the main gluon-gluon Fusion cross section **(σ_{SM})**
[full Bayesian combination] ~ 10% (QCD, PDF+α_s …)

Typical **experimental errors** on the signal strengths **($\mu_{ex} \approx N_{evts} / \sigma_{SM} B_{SM}$ ε L)**
~ 20%-30% with LHC Run 1 data *ATLAS & CMS combinations, ATLAS-CONF-2015-044*
~ 5% (ɣɣ) - 10% $(\tau\tau, ZZ, WW)$ at $\sqrt{s} = 14\, TeV\ and\ 300\ fb^{-1}$
[for same systematics as today] *European Strategy for Particle Physics CERN-ESG-005*

⇒ **Importance of treating carefully the theoretical uncertainties.
In particular, statistically.**

We have proposed recently a **detailed** statistical implementation of **all** the individual sources of theoretical uncertainty entering the Higgs signal strengths.

*Fichet, **GM***
1509.00472

The starting point being this Likelihood :

$$L(c_V, c_f) = \int \left(\prod_{n,n',X,Y} d\delta_X^n \, d\delta_Y^{n'} \right) \pi_0(\delta_X^n, \delta_Y^{n'}) \times \exp\left[-\frac{1}{2} \sum_{i,j} (\mu_i^{\rm th}[c_V, c_f] - \mu_i^{\rm ex}(1 + \delta_i^\mu \Delta_i^\mu)) \, C_{ij}^{\rm ex\,-1} \, (\mu_j^{\rm th}[c_V, c_f] - \mu_j^{\rm ex}(1 + \delta_j^\mu \Delta_j^\mu)) \right]$$

Bayesian **Marginalisation**
(*frequentist: integ.* => maxim.)

Prior(nuisance parameters)

1σ TH errors

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Bayesian **Marginalisation**
(*frequentist: integ.* => maxim.)

Prior(nuisance parameters)

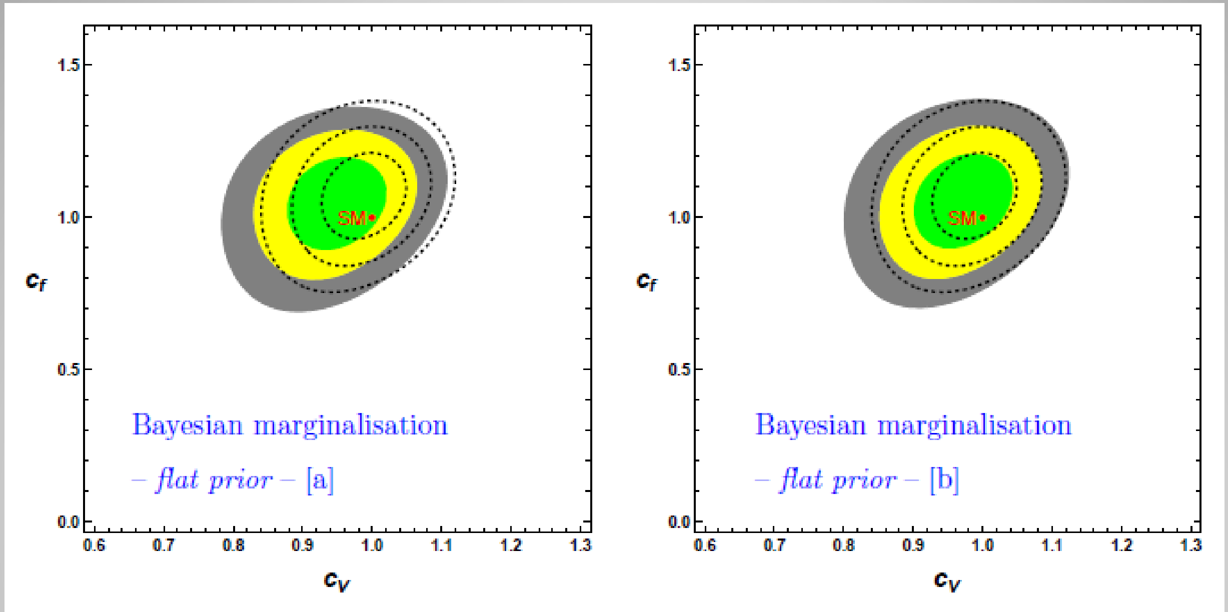
1σ TH errors

Combination (priors and error magnitudes) of each individual uncertainty :

$$L(c_V, c_f) = \int \left(\prod_X d\delta^\mu_X \right) \pi^\mu(\delta^\mu_X) \times \exp \left[-\frac{1}{2} \sum_{i,j} \left(\mu^{\rm th}_i[c_V, c_f] - \mu^{\rm ex}_i (1 + \delta^\mu_{X_i} \Delta^\mu_i) \right) C^{\rm ex\,-1}_{ij} \left(\mu^{\rm th}_j[c_V, c_f] - \mu^{\rm ex}_j (1 + \delta^\mu_{X_j} \Delta^\mu_j) \right) \right]$$

X=ggF,VBF,VH,ttH

Gaussian/Flat priors => Analytical expressions for L(cV,cf) « ready-to-use »



$$\pi^{\mu}(\delta_X) = \pi^{\sigma}_{\rm ggF}(\delta_{\rm ggF})\ \delta(\delta_{\rm ggF}+\delta_{\rm ttH})\ \pi^{\sigma}_{\rm VBF}(\delta_{\rm VBF})$$
$$\delta(\delta_{\rm VBF}-\delta_{\rm ZH})\ \delta(\delta_{\rm VBF}-\delta_{\rm WH})$$

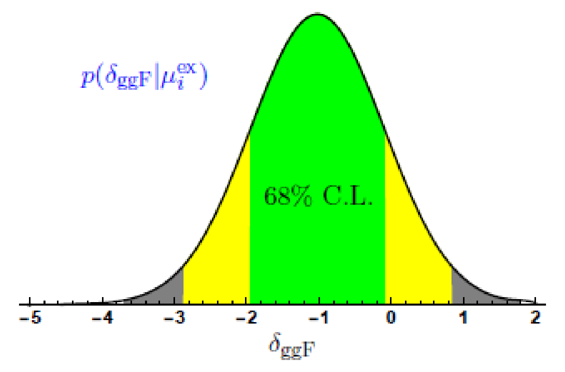
$$\pi^{\mu}(\delta_X) = \pi^{\sigma}_{\rm ggF}(\delta_{\rm ggF})\ \delta(\delta_{\rm ggF}+\delta_{\rm ttH})\ \delta(\delta_{\rm ggF}+\delta_{\rm VBF})$$
$$\delta(\delta_{\rm ggF}+\delta_{\rm ZH})\ \delta(\delta_{\rm ggF}+\delta_{\rm WH})$$

PDF error correlations among X-production modes

[ATL-PHYS-PUB-2011-11, CMS-NOTE-2011-005]

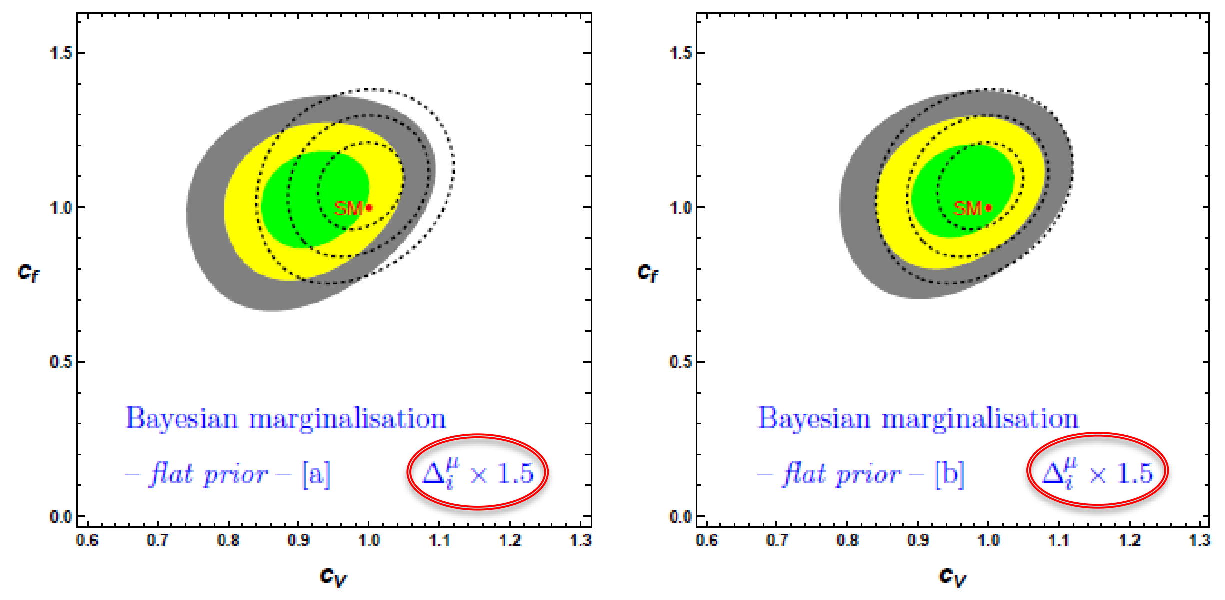
$$p(\delta_{\rm ggF}|\mu_i^{\rm ex}) = \int dc_V\, dc_f\; \pi(c_V,c_f)\; \pi^{\sigma}_{\rm ggF}(\delta_{\rm ggF}) \;\times\; \exp\left[-\frac{1}{2}\sum_{i,j}\left(\mu_i^{\rm th}[c_V,c_f]-\mu_i^{\rm ex}(1\pm\boxed{\delta_{\rm ggF}\Delta_i^{\mu}})\right) C_{ij}^{{\rm ex}\;-1}\left(\mu_j^{\rm th}[c_V,c_f]-\mu_j^{\rm ex}(1\pm\delta_{\rm ggF}\Delta_j^{\mu})\right)\right]$$

Unknown exact prior width (TH error) :
prior set to an **infinite flat** distribution



Information from Higgs data

Additional recommended fit for future data :



Bias approach :

…motivated by the lack of knowledge on the priors *(width and shape)*

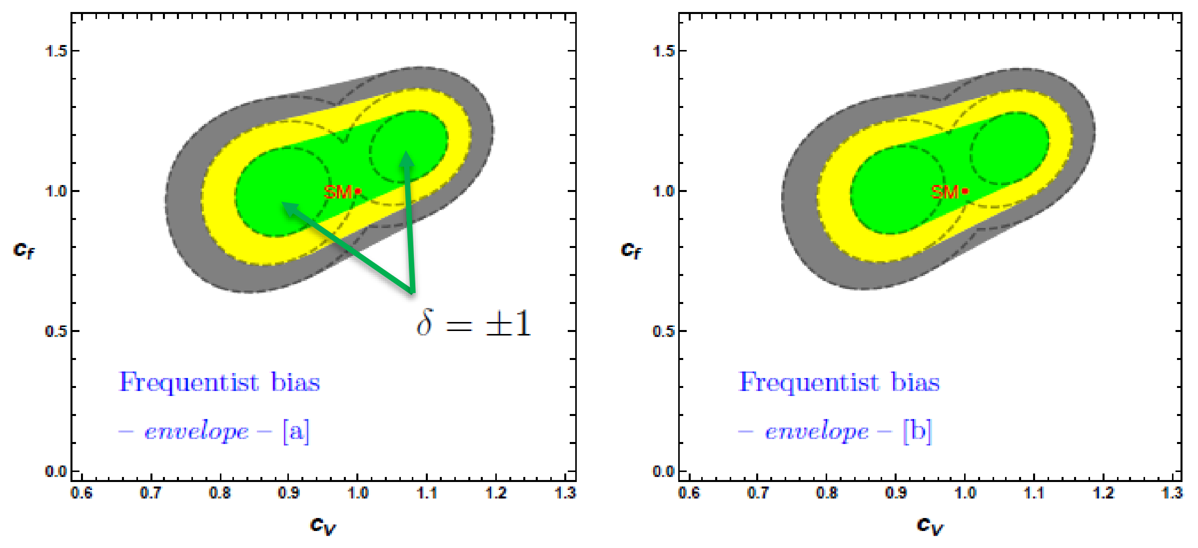
$$L_{\rm bias}(\delta_b) = \exp\left[-\frac{1}{2}\sum_{i,j}\left(\mu_i^{\rm th}[c_V,c_f] - \mu_i^{\rm ex}(1+\delta_b\Delta_i^b)\right) C_{ij}^{{\rm ex}\,-1}\left(\mu_j^{\rm th}[c_V,c_f] - \mu_j^{\rm ex}(1+\delta_b\Delta_j^b)\right)\right]$$

no more int./max. over $\pi(\delta)'s$

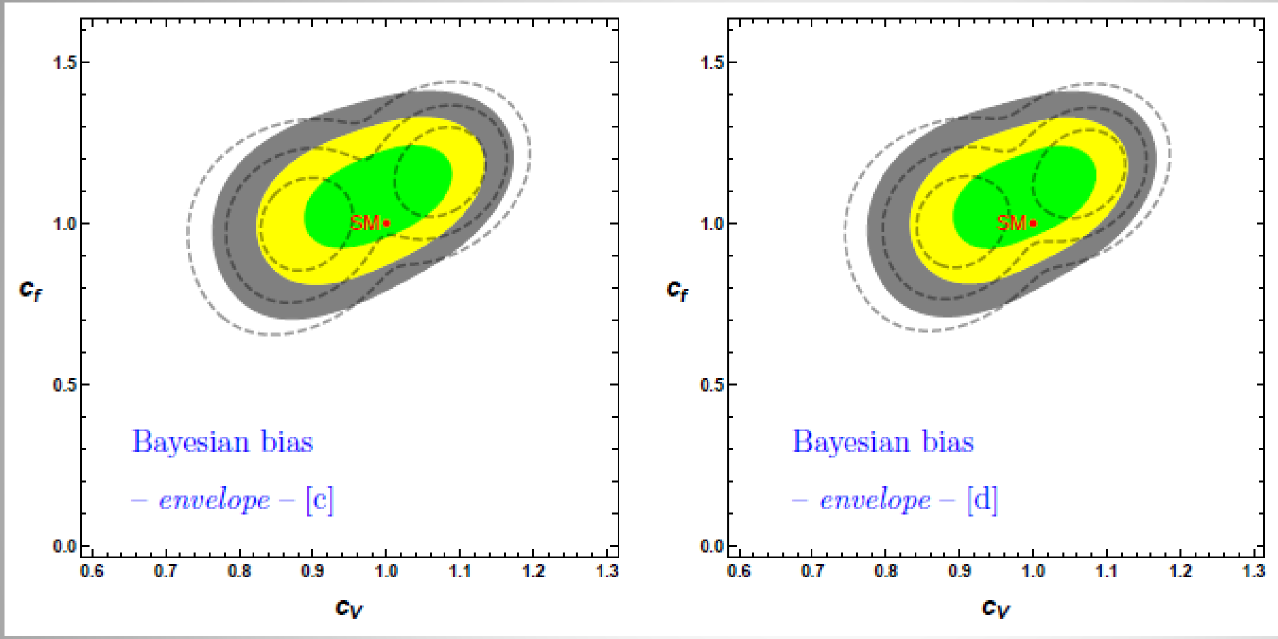
$$\Delta_i^b = \left|\Delta^{\rm P}_{\rm ggF,i} - (\Delta^{\rm P}_{\rm ttH,i} + \Delta^{\rm P}_{\rm VBF,i} + \Delta^{\rm P}_{\rm WH,i} + \Delta^{\rm P}_{\rm ZH,i})\right| + \sum_{Y,a}(\Delta^a_{Y,i} + \Delta_{Y,i})$$

$$\Delta^{\rm P}_{X,i} \hat{=} \frac{\epsilon^i_X \sigma^{\rm SM}_X}{\sum_{X'} \epsilon^i_{X'} \sigma^{\rm SM}_{X'}}\left(\Delta^{\rm amp}_X + \Delta^{{\rm PDF}+\alpha_s}_X\right)$$

**** Direct envelope method ****



⇒ ***« Price to pay »*** **for not relying on unknown priors = more conservative best-fit domains**



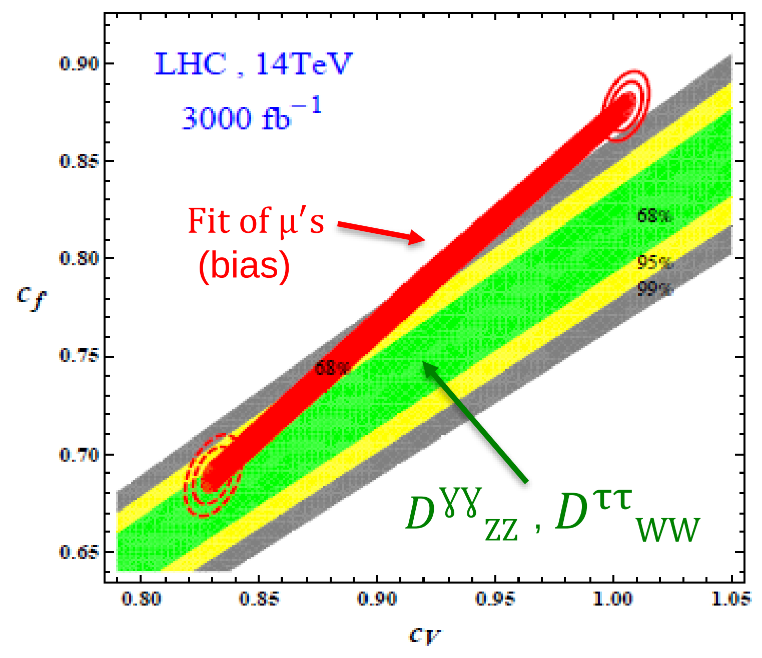
⇒ **Interestingly the *Bayesian* envelope leads to more predictive best-fit regions**

[B] Making the LHC a precision machine for Higgs couplings ?

Djouadi, ***GM*** *1303.6591*

Recall 1st slide: TH uncertainty on Higgs rates might become dominant w.r.t. EXP errors.

$$D^{\rm P}_{XX} = \frac{\sigma^{\rm P}(pp\to H\to XX)}{\sigma^{\rm P}(pp\to H\to VV)} = \frac{\epsilon_X^{gg}\sigma(gg\to H)+\epsilon_X^{\rm VBF}\sigma(Hqq)+\epsilon_X^{HV}\sigma(HV)+\epsilon_X^{t\bar tH}\sigma(t\bar tH)}{\epsilon_V^{gg}\sigma(gg\to H)+\epsilon_V^{\rm VBF}\sigma(Hqq)+\epsilon_V^{HV}\sigma(HV)+\epsilon_V^{t\bar tH}\sigma(t\bar tH)} \times \frac{\Gamma(H\to XX)}{\Gamma(H\to VV)}$$



TH ambiguities on $\Gamma_{\rm total}(H)$ *drop out*

Would be equal/prop. to unity for identical $\boldsymbol{\varepsilon}$*'s [require to adjust kinematical cuts]*

⇒ **main TH error would disappear!**

⇒ **Uncertainty @ 1σ on** $c_{V,f}$ **reduced from ~15% down to ~5%**

II. Phenomenology: New physics effects on the Higgs sector

[A] The constraints of the Higgs rates on the (h)MSSM

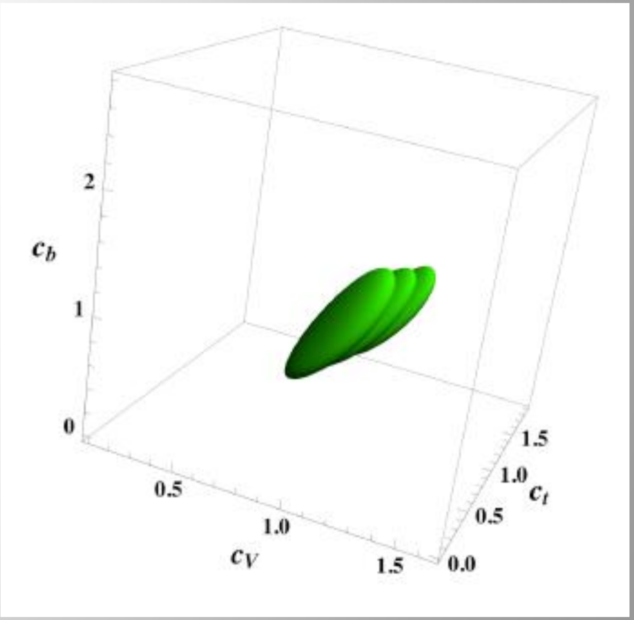
Djouadi et al. 1307.5205

3 effective **light-Higgs coupling** corrective factors, within the **MSSM**, involved in EXP. signal strengths :

$$c_V\ ,\ c_t\ ,\ c_b$$

(c_t definition contains the main *stop* quark contributions to ggH)

3D fit : best-regions (68%C.L.) =>



Including the ***tth*** *associated production in fits would need to introduce another c'$_t$ parameter.*

In the absence of large stop contributions to ggF (**high stop mass**, low L-R mixing) and without strong SUSY-QCD corrections to c_b (**high gluino mass**, low tanβ),

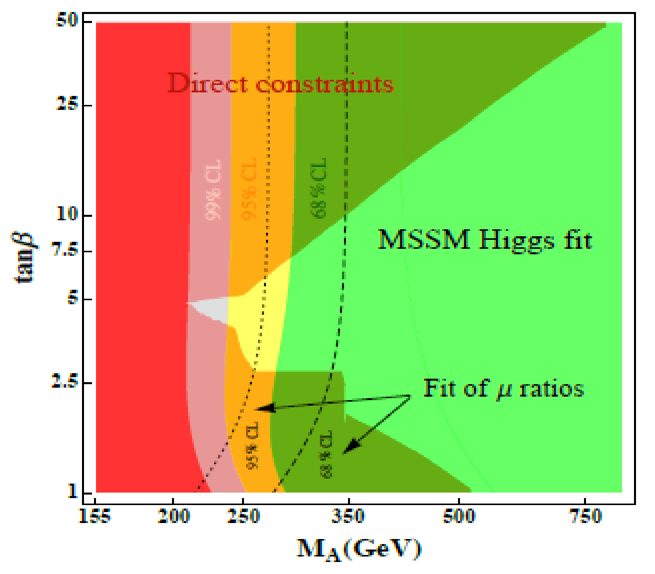
$$c_V^0 = \sin(\beta - \alpha)\ , \quad c_t^0 = \frac{\cos\alpha}{\sin\beta}\ , \quad c_b^0 = -\frac{\sin\alpha}{\cos\beta}$$

The scan-analysis shows that up to two-loop corrections, in a good approximation, the **α**-mixing (CP-even h-H sector) depends solely on the **2** parameters (**hMSSM**) :

M_A , tanβ

Taking the soft SUSY breaking scale M_S>1TeV
(from direct squark/gluino searches)
and using the measured Higgs mass.

2D fit : best-regions (68%C.L.) =>



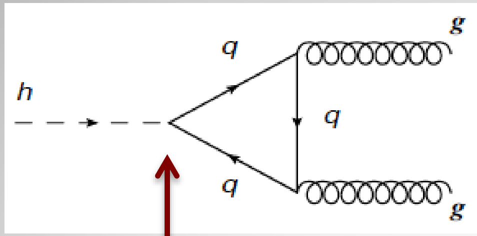
[B] Extra-quarks in the Higgs sector

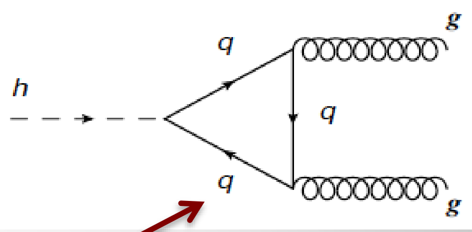
New fermions arise in most *(all?)* of the SM extensions,

- little Higgs *[fermionic partners]*
- supersymmetry *[gauginos / higgsinos]*
- composite Higgs *[excited bounded states]*
- extra-dimensions *[Kaluza-Klein towers]*
- 4*th* generations *[new families]*
- G.U.Theories *[multiplet components]*
- etc…

➡ ***Phenomenology of Extra-fermion(s) = GENERIC BSM approach***

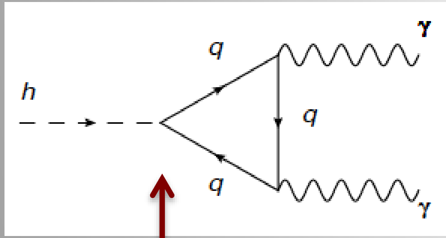
Extra-fermion effect on the Higgs couplings:

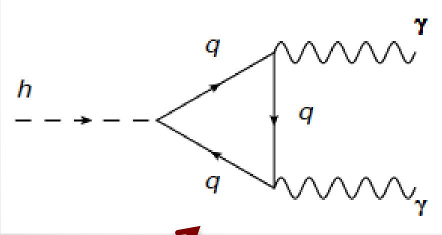




b’ , $q_{5/3}$, …

$$C_{hgg} \;=\; 2C(t)\;A[\tau(m_t)]\;(c_t + c_{gg}) \;+\; 2C(b)\;A[\tau(m_b)]\;c_b \;+\; 2C(c)\;A[\tau(m_c)]$$





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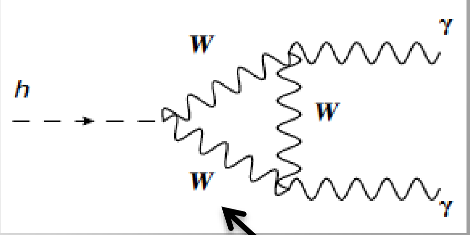


$$C_{h\gamma\gamma} \;=\; \frac{N_c^t}{6}Q_t^2A[\tau(m_t)]\;(c_t + c_{\gamma\gamma}) + \frac{N_c^b}{6}Q_b^2A[\tau(m_b)]\;c_b + \frac{N_c^c}{6}Q_c^2A[\tau(m_c)] + \frac{N_c^\tau}{6}Q_\tau^2A[\tau(m_\tau)]\;c_\tau + \frac{1}{8}A_1[\tau(m_W)]$$

Single Extra-Quark impact on loop-induced Higgs couplings

GM 1210.3977

1. **Single** Extra-Fermion (often good pheno. approx.) => new loop-contributions :

$$c_{gg} = \frac{1}{C(t)A[\tau(m_t)]/v}\left[-C(t')\frac{Y_{t'}}{m_{t'}}A[\tau(m_{t'})] - C(q_{5/3})\frac{Y_{q_{5/3}}}{m_{q_{5/3}}}A[\tau(m_{q_{5/3}})] + \dots\right]$$

$$c_{\gamma\gamma} = \frac{1}{N_c^t Q_t^2 A[\tau(m_t)]/v}\left[-3\left(\frac{2}{3}\right)^2\frac{Y_{t'}}{m_{t'}}A[\tau(m_{t'})] - N_c^{q_{5/3}}\left(\frac{5}{3}\right)^2\frac{Y_{q_{5/3}}}{m_{q_{5/3}}}A[\tau(m_{q_{5/3}})] - Q_{\ell'}^2\frac{Y_{\ell'}}{m_{\ell'}}A[\tau(m_{\ell'})] + \dots\right]$$

2. **Same color** repres.
as the top quark ➡

$$\boxed{\left.\frac{c_{\gamma\gamma}}{c_{gg}}\right|_{q'} = \frac{Q_{q'}^2}{(2/3)^2}}$$

2 realistic assumptions give a quite strong TH prediction

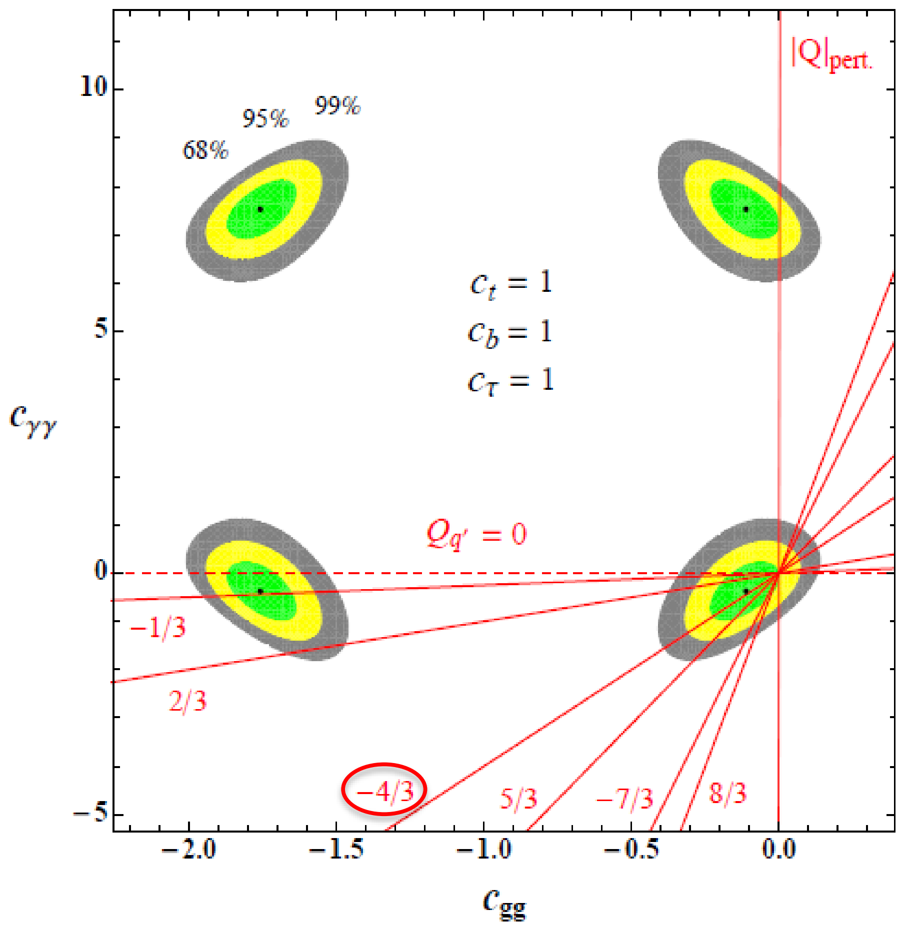
(e.g. any b’, chiral/VL)

Determination of the extra-quark electric charge in case of a deviation w.r.t. SM :

Independently of $Y_{q'}$, masses, $SU(2)_L$ repres.

$$\mathcal{Y}_{q'} = Q_{q'} - I^{q'}_{3L}$$

(2 free parameters)

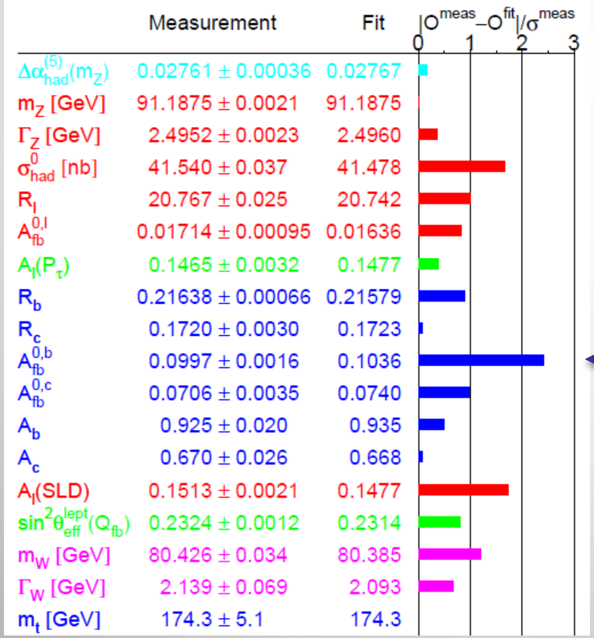


Vector-Like quarks to interpret the LEP and LHC anomalies

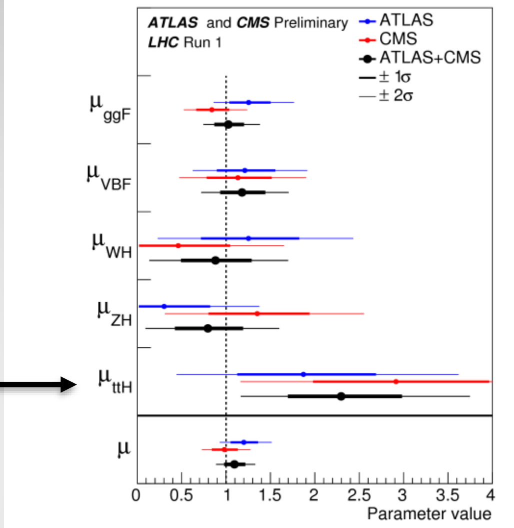
VL quarks appear with :

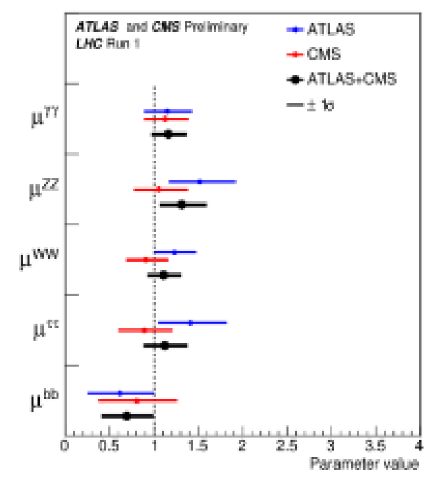
- extra-dimensions *(KK excitations)*
- composite Higgs *(bounded states)*
- etc…

Angelescu,
Djouadi, ***GM***
1510.07527



	Measurement	Fit	$\lvert O^{meas} - O^{fit}\rvert / \sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02767	
m_Z [GeV]	91.1875 ± 0.0021	91.1875	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960	
σ^0_{had} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01636	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477	
R_b	0.21638 ± 0.00066	0.21579	
R_c	0.1720 ± 0.0030	0.1723	
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1036	
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0740	
A_b	0.925 ± 0.020	0.935	
A_c	0.670 ± 0.026	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1477	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.426 ± 0.034	80.385	
Γ_W [GeV]	2.139 ± 0.069	2.093	
m_t [GeV]	174.3 ± 5.1	174.3	

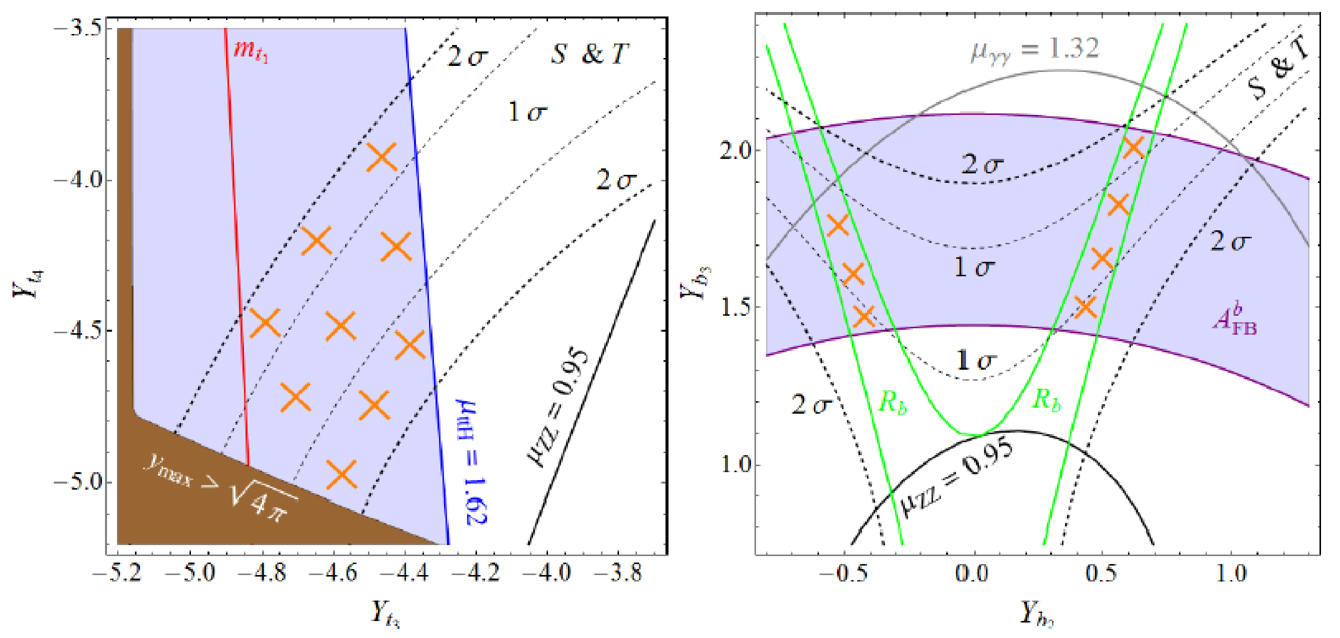




A few VL **b’,t’** models achieve to respect all EXP data, as for instance :

$$T_{L,R},\ B_{L,R},\ Z_{L,R} = \begin{pmatrix} q_{8/3} \\ q'_{5/3} \\ t'' \end{pmatrix}^{Y=5/3}_{L,R} ,\quad b''_{L,R} \text{ and } t'''_{L,R}$$

$$\begin{aligned}\mathcal{L} = {} & Y_{t_1}\,\overline{Q}_L\tilde{H}\,t_R + Y_{t_2}\,\overline{Q}_L\tilde{H}\,t'''_R + \boxed{Y_{t_3}}\,\overline{T}_L H\,t_R + \boxed{Y_{t_4}}\,\overline{T}_L\tilde{H}\,Z_R + Y_{t_5}\,\overline{T}_L H\,t'''_R \\ & + Y_{t_6}\,\overline{Z}_L H\,T_R + Y_{t_7}\,\overline{T}_R H\,t'''_L + Y_{b_1}\,\overline{Q}_L H\,b_R + \boxed{Y_{b_2}}\,\overline{Q}_L H\,b''_R + \boxed{Y_{b_3}}\,\overline{B}_L\tilde{H}\,b_R \\ & + Y_{b_4}\,\overline{B}_L\tilde{H}\,b''_R + Y_{b_5}\,\overline{B}_R\tilde{H}\,b''_L + m_1\overline{T}_L T_R + m_2\overline{Z}_L Z_R + m_3\overline{t}'''_L t'''_R \\ & + m_4\overline{B}_L B_R + m_5\overline{b}''_L b''_R + \text{H.c.},\end{aligned}$$



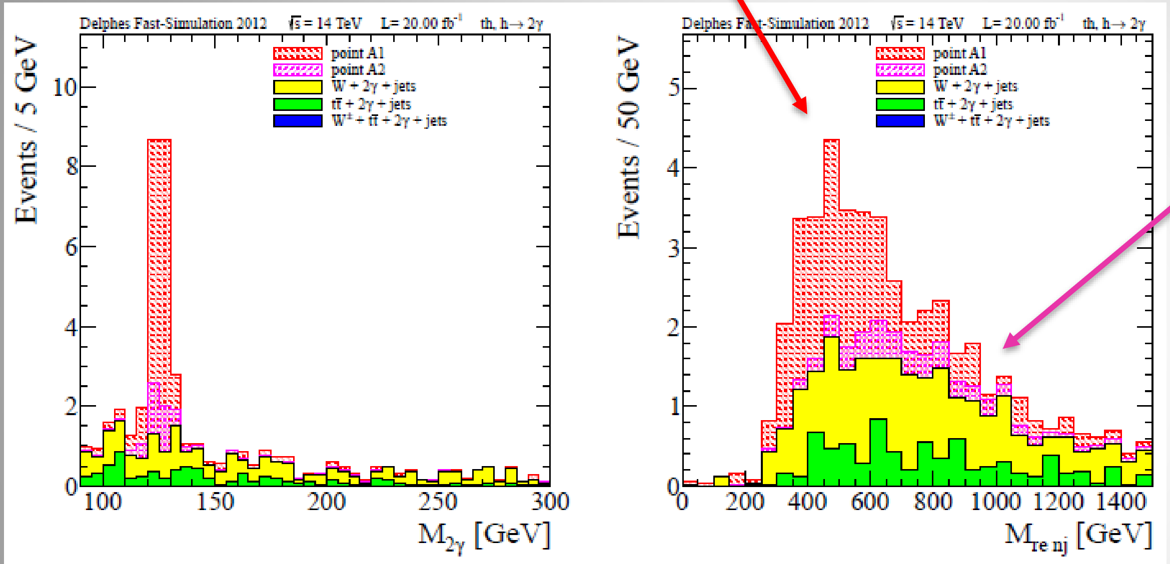
A new Higgs production channel through Vector-Like t’ quark pairs @ LHC

$\mathrm{pp} \rightarrow \mathrm{t}'\mathrm{t}'$

Azatov et al. 1204.0455

$\mathrm{B}(\mathrm{t}' \rightarrow th) = 0.6 \quad S/\Delta B \approx 9$

$\mathrm{B}(\mathrm{t}' \rightarrow th) = 0.3 \quad S/\Delta B \approx 5$



Signal generated with
FeynRules-MadGRAPH
-PYTHIA-DELPHES

Background MC simulated with
ALPGEN-PYTHIA-DELPHES

$\mathrm{t}' \rightarrow th\ ,\ \ h \rightarrow \gamma\gamma$

$(\boldsymbol{top\ jets\ angularly\ close\ to}\ \gamma\gamma)$

$\mathrm{t}' \rightarrow th, tZ, bW$

$(\boldsymbol{jets\ in\ opposite\ hemisphere})$

*Motivation to search for **t’** events in Higgs channels :*

- signature for VL top partners
- correct the standard Higgs production rates

[C] Higgs couplings in warped extra-dimension models

Scenario with warped extra-dimension (TeV-**brane localized Higgs boson**)

= Alternative to SUSY for addressing the gauge hierarchy problem

= Dual via AdS/CFT to composite Higgs models *Maldacena th/9711200*

= Geometrical mechanism for flavour structures *Gherghetta et al. ph/0003129*

+ Custodial symmetry $SU(2)_L$ x $SU(2)_R$ x $U(1)_X$ protect against EWPT

Agashe et al. ph/0308036

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Agashe et al. ph/0308036

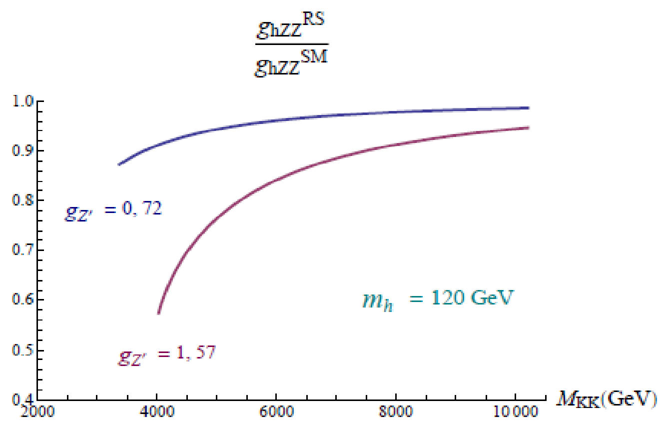
*Bouchart, **GM** 0909.4812*

Higgs **VEV is modified** in the **RS** scenario : Boson Mass <= EWSB + KK MIX

(possible increase of 30%) G_F, M_W, M_Z <= **v**, g, g' (bare) + M_{KK}…

hVV couplings in the RS model

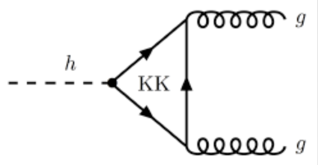
VEV shift can amount to 50% of the correction :

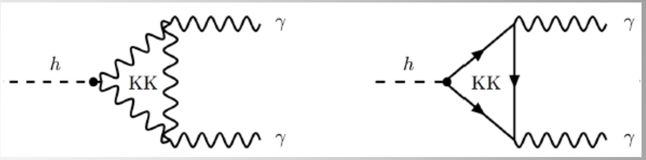


hff couplings in the RS model

VEV shift is the major impact (over KK MIX).

A short review of the Hgg and Hγγ couplings in various RS versions





	Hgg	**Hγγ**	
Gauge-Higgs unification SO(5) *Falkowski 0711.0828*	↘	↘	KK towers contributions subleading due to extra symmetries
Bulk-Higgs (not Pseudo-GB) *Azatov et al. 1006.5939* *Archer et al. 1408.5406*	↗	↘	$Y_5 = Y_5'$ in $Y_5\, \bar{Q}_L H D_R \, + \, Y_5'\, \bar{Q}_R H D_L$
Brane-Higgs / Yukawa *Azatov et al. 1006.5939*	↘↗	↘↗	$Y_5 \neq Y_5'$ (no more 5D Lorentz invariance) Calculation order : $\mathbf{N_{KK}\to\infty}$, $\boldsymbol{\varepsilon\to 0}$
Brane-Higgs - Custodial sym. *Casagrande et al. 1005.4315*	↘	↗	Calculation order : $\boldsymbol{\varepsilon\to 0}$, $\mathbf{N_{KK}\to\infty}$ Under $SU(2)_L$ x $SU(2)_R$ with Parity$_{LR}$: Q_L in (2,2) t_R in (1,1) b_R in (1,3)+(3,1)

	Hgg	**Hγγ**	
Brane-Higgs - Custo. / no P_{LR} *Bouchart, **GM** 0909.4812* *Djouadi, **GM** 0707.3800*	↘	↘↗	Under $SU(2)_L$ x $SU(2)_R$ **without** Parity_{LR} : Q_L mix (2,2) & (2,3) t_R in (1,3) b_R in (1,2)
Brane-Higgs - kinetic terms *Kumar Dey et al. 1507.04357*	↘	(↘)	Brane-kinetic terms for fermions
Departure from AdS5 *Cabrer et al. 1103.1388*		↘ *[via HWW]*	Background metric modif. near TeV-brane

⇨ The increase/decrease of σ_{ggF} and/or Γ(**H**->γγ) could help in the discrimination of RS versions.

(robust predictions for bulk-matter models compatible with EWPT)

	Hgg	**Hγγ**	
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(robust predictions for bulk-matter models compatible with EWPT)

MSSM *Djouadi ph/9806315*	↘↗	↘↗	Higgs-mixing & Sfermion/Gaugino loop-contributions

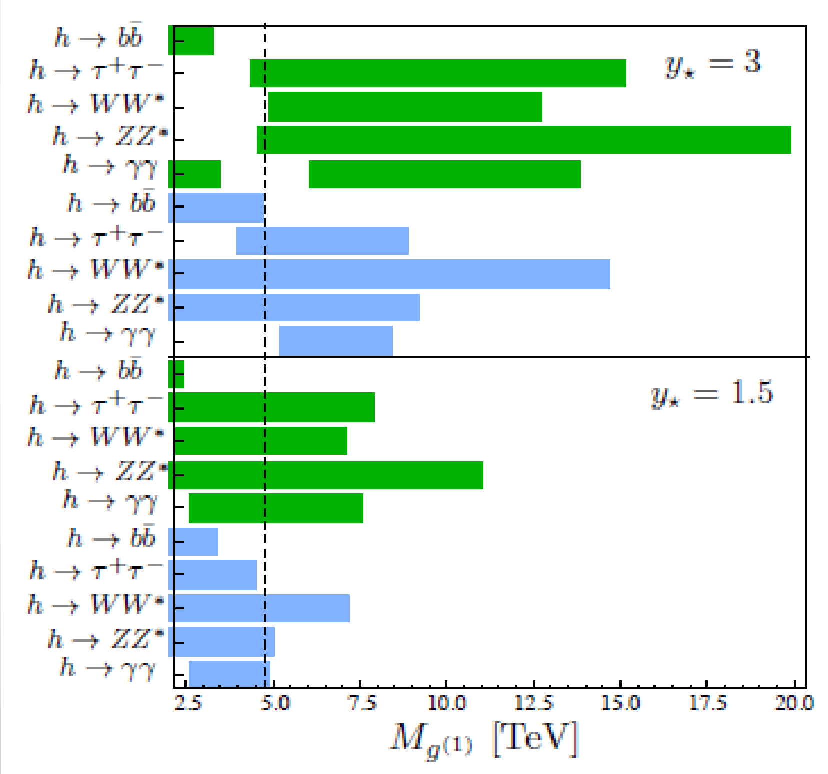
Present bounds on MKK in RS from KK contributions/corrections to the Higgs couplings at LHC Run 1

Malm et al. 1408.4456

(bulk custodial symmetry)

Brane-Higgs

Narrow-bulk Higgs



III. Theoretical aspects about brane-localized Higgs fields

[A] Two types of non-commutativity

Warped extra-dimension model with **brane-Higgs** (bulk matter) includes terms :

$$S_{\mathrm{brane}} = \int d^4x dz\, \delta(z - R') \left(\frac{R}{z}\right)^4 H \left(Y_1^{5D} R \bar{\mathcal{Q}}_L \mathcal{D}_R + Y_2^{5D} R \bar{\mathcal{Q}}_R \mathcal{D}_L + \mathrm{h.c.}\right)$$

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E.O.M. => Well-known **« Jump problem »** on n^{th} wave functions : *ambiguity at z=R'*

$$-m_d q_L - \partial_z q_R + \frac{c_q+2}{z} q_R + v_4 \delta(z-R') Y_1^{5D} R' d_R = 0$$

=> $q_R(R'^-) \neq q_R(R'^+)$

Azatov et al. 0906.1990
Csaki et al. ph/0310355

$(--)$ BC => $q_R(R') = 0$

5D-Need to **regularise** : *e.g.* shift Higgs peak by ε (eliminates the jump) then take ε→0

A first non-commutativity : in the Hgg and Hγγ couplings

Malm et al. 1303.5702
Carena et al. 1204.0008

N_{KK} = Number of KK **eigen-**states exchanged in the Hgg or Hγγ loops
ε = regularisation parameter

Calculation order   4D : $N_{KK} \rightarrow \infty$, $\varepsilon \rightarrow 0$ ⇔ 5D : **Narrow bulk**-Higgs
[Higgs sensitivity to (--) KK modes]

$\not\Updownarrow$

4D : $\varepsilon \rightarrow 0$, $N_{KK} \rightarrow \infty$ ⇔ 5D : **Brane**-Higgs
[Higgs **NOT** sensitivite to (--) KK modes]

☺ This non-commutativity **paradox disappears**
when the hard UV cut-off is applied (or consistent UV regulator).

A second non-commutativity : in the fermion **mass** spectrum

Simplified **flat** extra-dimension model :

$$S_{\text{fermion}} \;=\; \int \mathrm{d}^4x\,\mathrm{d}y\,\Big[\;\delta(y-\pi R)\,\big(Y_5\,\bar{Q}_L H D_R \;+\; Y_5'\,\bar{Q}_R H D_L \;+\; \text{H.c.}\big)\;\Big]$$

5D – Solve BC and 4 **mass** equations (E.O.M. for any *i-th* profile) of type :

(Yukawa in E.O.M.)

$$-\,m\,q_R \;+\; q_L' \;+\; \delta\,\big(y-(\pi-\underset{\substack{\downarrow\\ 0}}{\epsilon})R\big)\,\frac{vY_5'}{\sqrt{2}}\,\underset{\substack{\searrow\\ 0 \text{ at } \pi R}}{d_L} = 0$$

ϵ = regularisation parameter

4D – Solve the characteristic equation for the infinite (0-modes + *i-th* KK modes: **N→∞**) squared **mass** matrix including elements like :

(perturbative Yukawa treatment)

$$\beta_{ji} \;=\; \frac{vY_5'}{\sqrt{2}}\,q_R^i\big((\pi-\overset{\substack{0\\ \uparrow}}{\epsilon})R\big) \times \overset{\substack{0 \text{ at } \pi R\\ \nearrow}}{d_L^j}\big((\pi-\epsilon)R\big) \;\rightarrow 0$$

N = Number of KK modes in spectrum calculation *[interaction basis]* **(≠ N$_{\text{KK}}$)**

Casagrande et al.
0807.4937

Azatov et al.
0906.1990

Table 1 *(shifted Higgs)*	Regularization I	Regularization II
5D CALCULATION	$\boxed{\tan(\pi R\, m) = \frac{vY_5}{\sqrt{2}}}$ no δ-terms for $(--)$-profiles $(--)$ BC at πR, EOM with ϵ	$\boxed{\tan(\pi R\, m) = \frac{\sqrt{2}(1+c)^2 vY_5}{2(1+c)^2 + cv^2 Y_5 Y_5'}}$ δ-terms for $(--)$-profiles EOM with ϵ, $(--)$ BC at πR
4D CALCULATION	$\boxed{\tan^2(\pi R\sqrt{\lvert m\rvert^2}) = \left(\frac{vY_5}{\sqrt{2}}\right)^2}$ no $(--)$-profile rôle $\epsilon \to 0\ ,\ N \to \infty$	$\boxed{\tan^2(\pi R\sqrt{\lvert m\rvert^2}) = \left(\frac{vY_5/\sqrt{2}}{1+v^2Y_5Y_5'/8}\right)^2}$ $(--)$-profile effect $N \to \infty\ ,\ \epsilon \to 0$

$\neq$

Csaki et al.
ph/0310355

Barcelo, Mitra, **GM**
1408.1852

…a new non-commutativity **paradox pointed out**.

Interpretation

Those **2** calculation orderings should be understood as being **2** (5D) regularisations which must be **« experimentally equivalent »** :

$$\mathbf{m}^{\mathbf{I}}\,(v^{\mathbf{I}},\, R^{\mathbf{I}},\, Y_5{}^{\mathbf{I}}) = \mathbf{m}^{\mathbf{II}}\,(v^{\mathbf{II}},\, R^{\mathbf{II}},\, Y_5{}^{\mathbf{II}}\,, Y_5{}')$$

Remark: *future EXP. data could exclude the Regularisation I only.*

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Remark: future EXP. data could exclude the Regularisation I only.

Correct Cut-off Procedure

(1) 4D matrix : **N**$\rightarrow\infty$ allows the 2 regularisations
5D fields : regularisation (**pure 5D**)

[construct 5D theory: calculate masses]

↑

(2) Phenomenology only with mass eigenvalues below the **cut-off Λ** .

(*Higher-dimensional models = Non-renormalisable scenarios*
=> *valid up to an energy scale* **Λ)**

[B] Brane-Higgs regularisation in Supersymmetry

Bouchart, Knochel, ***GM***
1101.0634

5D Superfield content

Warped **Toy model** => extendable to 5D pMSSM :

Brane-localised N=1 4D Chiral superfield H_u^0 and H_d^0

N=1 **5D** (or N=2 4D) hypermultiplets $\{\Phi_L, \Phi_L^{--}\}$ and $\{\Phi_L^c, \Phi_L^{c--}\}$

* Scalar fields $\boldsymbol{\phi}^{c\,--}$

* Fermion chirality
for KK masses

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N=1 **5D** (or N=2 4D) hypermultiplets $\{\Phi_L, \Phi_L^{--}\}$ and $\{\Phi_L^c, \Phi_L^{c--}\}$

- U(1) gauge symmetry -

N=1 4D Vector supermultiplet $V(x^\mu, y; \theta, \bar{\theta})$ ⟵ A_μ

+ N=1 4D Chiral superfield $\Omega(x^\mu, y; \theta, \bar{\theta})^{--}$

* Scalar fields ϕ^{c--}

* Fermion chirality for KK masses

* Scalar fields (Σ - i A_5)

* Chirality for KK gauginos

4D Effective Lagrangian derivation

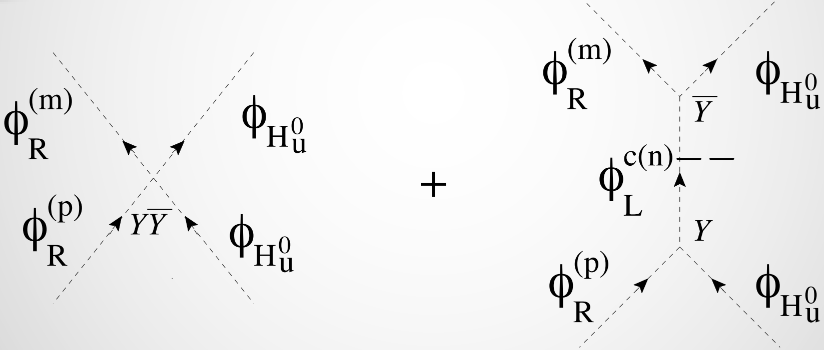
Calculation of the Higgs couplings to the scalar superpartners :

$$\mathcal{L}_{5D} = -\sqrt{G}\left|\mathcal{Y}\delta(y-\pi R_c)\phi_{H_u^0}\phi_R - [\partial_y - (c_L+\frac{3}{2})(\partial_y\sigma)]\phi_L^c\right|^2 -$$

δ from field Lagrangian

δ from EOM solution for auxiliary field **F**

After KK decompos. , integration over y , EOM…



$$\sum_{n=0}^{\infty}\bar{f}_n(y)f_n(y') = \delta(y-y')$$

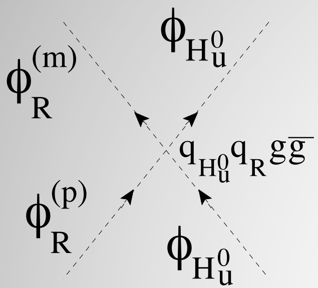
$$-i|\mathcal{Y}|^2\cancel{\delta(0)}\bar{f}_m^{++}(c_R;\pi R_c)f_n^{++}(c_R;\pi R_c)$$

$$i|\mathcal{Y}|^2 f_p^{++}(c_R;\pi R_c)f_m^{++}(c_R;\pi R_c)[\cancel{\delta(0)} - k^2 G_5^{f^{++}(c_L)}(k^2;\pi R_c,\pi R_c)]$$

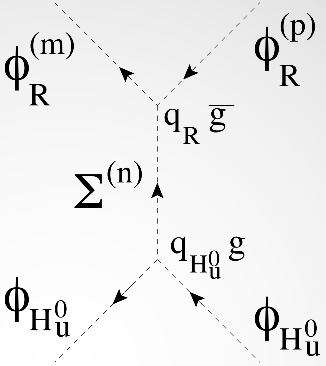
« 5D propagator »

5D regularisation of the δ(0) terms !

Similarly for the **D**-terms…



+



$$\sum_{n=0}^{\infty} \bar{f}_n(y) f_n(y') = \delta(y - y')$$

$$-iq_{H_u^0} q_R \cancel{|g|^2} \bar{f}_m^{++}(c_R;\pi R_c) f_n^{++}(c_R;\pi R_c)$$

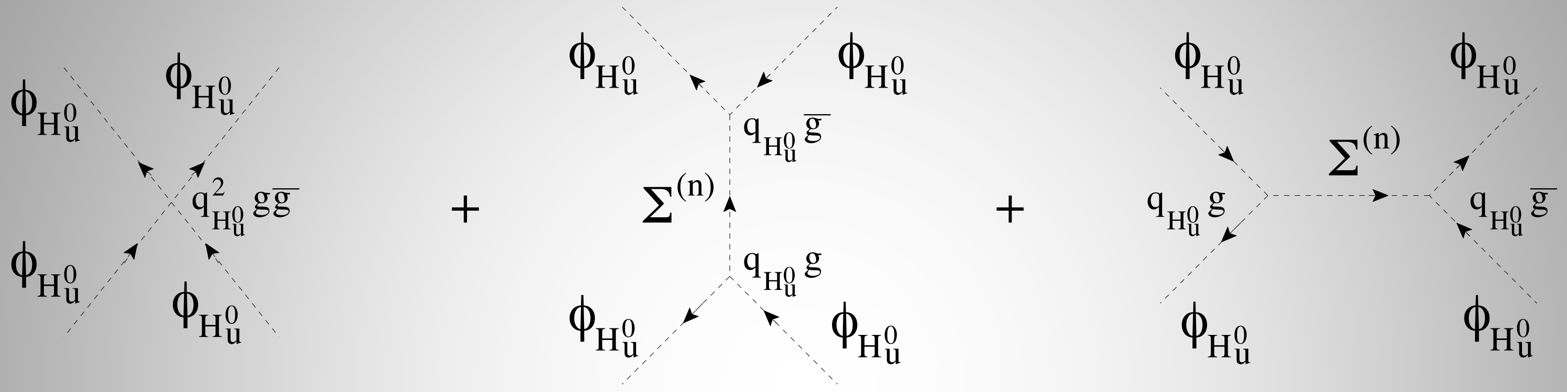
$$+iq_R q_{H_u^0} \cancel{|g|^2} \bar{f}_m^{++}(c_R;\pi R_c) f_p^{++}(c_R;\pi R_c)$$

$$-iq_R q_{H_u^0} |g|^2 \int_{-\pi R_c}^{\pi R_c} dy \bar{f}_m^{++}(c_R;y) f_p^{++}(c_R;y) k^2 G_5^{g^{++}}(k^2;y,\pi R_c)$$

*…generalisable to **5D pMSSM** after EWSB :*

- Higgs-sfermion-sfermion couplings (add KK sfermion mixing)
- squark/slepton mass matrices (infinite matrix diago. or integration out)

Similarly for the Higgs boson **self**-couplings…



$$-\frac{i}{2} q^2_{H_u^0} |g|^2 \cancel{\delta}(0) \times 4$$

$$\sum_{n=0}^{\infty} \bar{f}_n(y) f_n(y') = \delta(y-y')$$

$$i q^2_{H_u^0} |g|^2 [2\cancel{\delta}(0) - k^2 G_5^{g^{++}}(k^2; \pi R_c, \pi R_c) - q^2 G_5^{g^{++}}(q^2; \pi R_c, \pi R_c)]$$

And… $$\frac{\delta^4 i\mathcal{L}_{4D}}{\delta\phi_{H_u^0}\bar{\phi}_{H_u^0}\phi_{H_d^0}\bar{\phi}_{H_d^0}}\Bigg|_{total} = -i q_{H_u^0} q_{H_d^0} |g|^2 k^2 G_5^{g^{++}}(k^2; \pi R_c, \pi R_c)$$

One recovers the order of calculation found out
in the non-SUSY 5D case…

Correct Cut-off Procedure

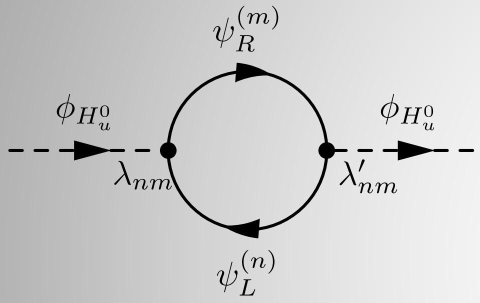
(1) To derive the 4D effective SUSY Lagrangian
=> regularisation at work ***(completeness relation)***
for **N➔∞** (**pure 5D**)

[construct 5D theory:
calculate the Lagr.]

(2) Phenomenology only with mass eigenvalues below the **cut-off Λ** .

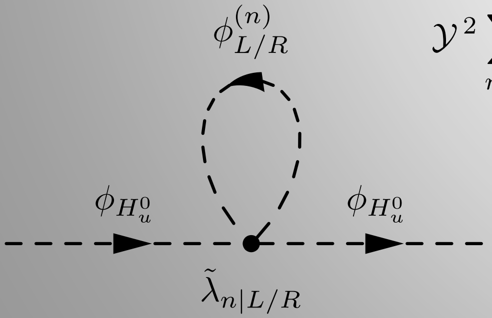
Application : calculation of the quantum corrections to the Higgs mass

Cancellation of the quadratic contributions in 5D, in the **Yukawa** sector :



$$-\,2\mathcal{Y}^2 \sum_{\{n,m\}=0,0}^{N,M} \int \cancel{\frac{d^4k}{(2\pi)^4} k^2 \frac{f_L^n(\pi R_c) f_L^n(\pi R_c)}{k^2 - m_L^{(n)\,2}}} \frac{f_R^m(\pi R_c) f_R^m(\pi R_c)}{k^2 - m_R^{(m)\,2}}$$

« KK level
by KK level »



$$\mathcal{Y}^2 \sum_{n=0}^{N} \int \frac{d^4k}{(2\pi)^4} \left[\frac{[f_L^n(\pi R_c)]^2}{k^2 - m_L^{(n)\,2}} k^2\, G_5^{f_{c_R}^{++}}(k^2;\pi R_c,\pi R_c) + \frac{[f_R^n(\pi R_c)]^2}{k^2 - m_R^{(n)\,2}} k^2\, G_5^{f_{c_L}^{++}}(k^2;\pi R_c,\pi R_c) \right]$$

$$= \; 2\mathcal{Y}^2 \sum_{\{n,m\}=0,0}^{N,M} \int \cancel{\frac{d^4k}{(2\pi)^4} k^2 \frac{[f_R^n(\pi R_c)]^2}{k^2 - m_R^{(n)\,2}}} \frac{[f_L^m(\pi R_c)]^2}{k^2 - m_L^{(m)\,2}}$$

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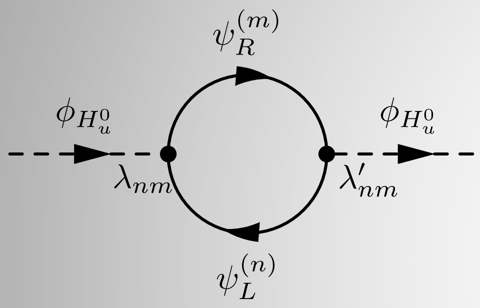
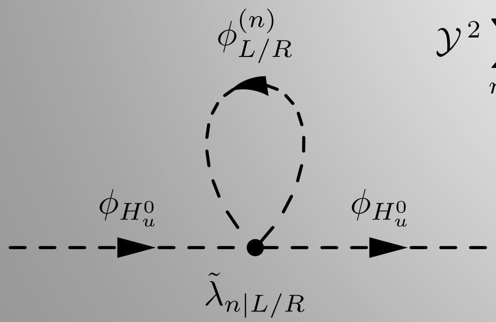


$$-\,2\mathcal{Y}^2 \sum_{\{n,m\}=0,0}^{N,M} \cancel{\int \frac{d^4k}{(2\pi)^4}\, k^2\, \frac{f_L^n(\pi R_c) f_L^n(\pi R_c)}{k^2 - m_L^{(n)\,2}}} \, \frac{f_R^m(\pi R_c) f_R^m(\pi R_c)}{k^2 - m_R^{(m)\,2}}$$

« KK level by KK level »

commute

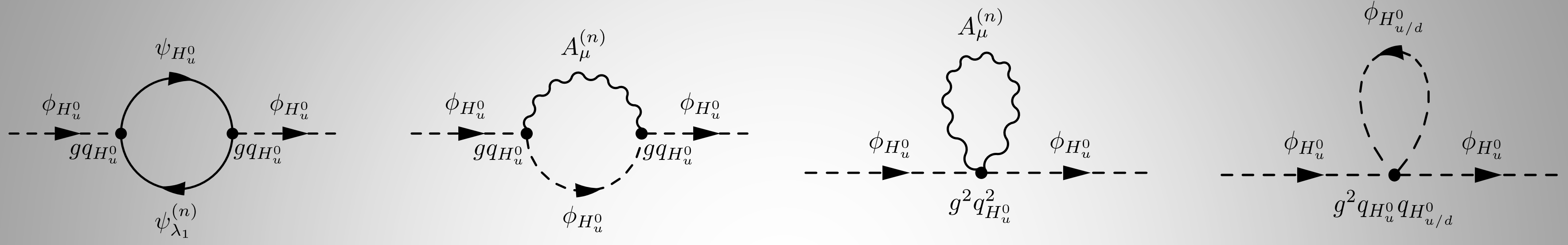
Step **(2)** : cut KK SUM in 5D propagators



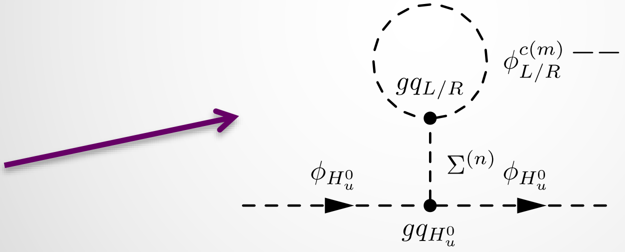
$$\mathcal{Y}^2 \sum_{n=0}^{N} \int \frac{d^4k}{(2\pi)^4} \left[\frac{[f_L^n(\pi R_c)]^2}{k^2 - m_L^{(n)\,2}}\, k^2\, G_5^{f_{c_R}^{++}}(k^2;\pi R_c,\pi R_c) + \frac{[f_R^n(\pi R_c)]^2}{k^2 - m_R^{(n)\,2}}\, k^2\, G_5^{f_{c_L}^{++}}(k^2;\pi R_c,\pi R_c) \right]$$

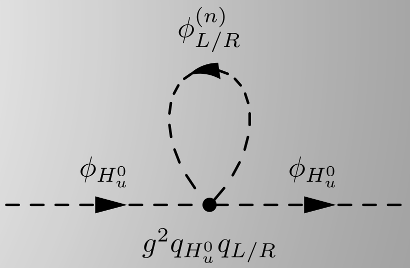
$$=\; 2\mathcal{Y}^2 \sum_{\{n,m\}=0,0}^{N,M} \int \cancel{\frac{d^4k}{(2\pi)^4}\, k^2\, \frac{[f_R^n(\pi R_c)]^2}{k^2 - m_R^{(n)\,2}}} \, \frac{[f_L^m(\pi R_c)]^2}{k^2 - m_L^{(m)\,2}}$$

Cancellation of the quadratic contributions in 5D, in the **gauge** sector :



Pure 5D (KK) tadpole diagram





$$q_{H_u^0}\Big(\underbrace{q_{H_u^0}+q_{H_d^0}+q_L+q_R}_{=\,0\ \text{[4D chiral (A.B.J.) anomaly cancellation]}}\Big)\frac{g^2}{2\pi R_c}\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2} = 0$$

Supersymmetry
Gauge symmetry

} Quadratic m_h correction
cancellation **in 5D**

Interest of this analytical 4D calculation method to prove the cancellation

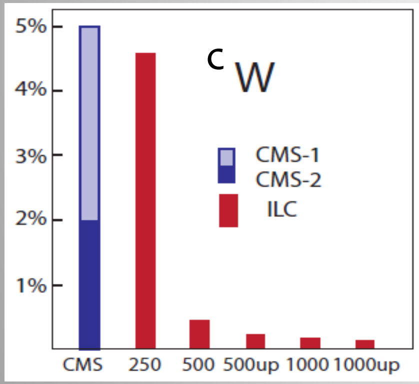
Avoid the problematic so-called « KK regularisation » which was performed in literature - by going through a *non-justified* **commutation** between the infinite loop-exchanged KK-mode summations and the infinite four-momentum loop-integrations.

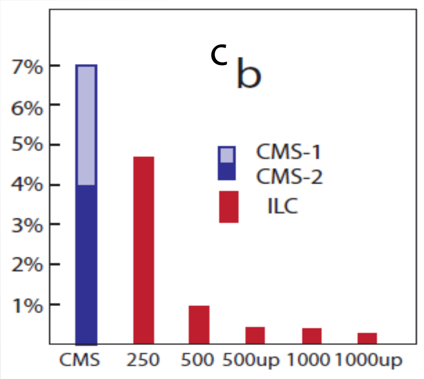
Conclusions

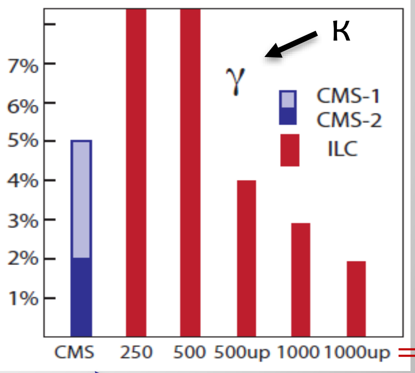
- The data of LHC Run 1 on Higgs rates already imply **non-trivial constraints** on most Beyond-SM theories :
  - *with generic extra-fermions*
  - *higher-dimensional / composite models*
  - *including supersymmetric extensions*

- Special care will be required when analysing the next results from the
  - data side : for **statistical treatments of TH rate uncertainties**
  - theoretical side : for (SUSY) scenarios with **brane-localised Higgs**

Wich next generation colliders will be able to reveal indirect Beyond-SM effects via the Higgs couplings ?







$= \sqrt{s}\ [GeV]$

$= L\ [fb^{-1}]\ (on\ 18\ years)$

<u>Fit prospectives :</u>

<u>Expected accuracies (TH+EXP)</u>

Peskin 1312.4974

(Too) optimistic scenario CMS-2 :

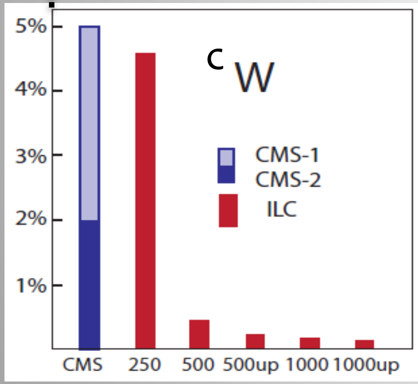
- Systematics improved as statistics
- TH error on σ's halved (PDF…)

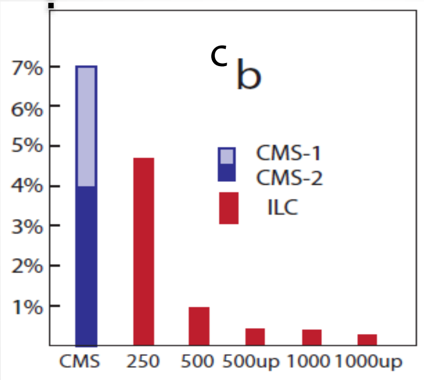
HL-LHC: 14TeV 3000 fb^{-1} (2026-2037)
Run 3: 14TeV 300 fb^{-1} (-2023)
Run 2: 13TeV 100 fb^{-1} (2015-2018)

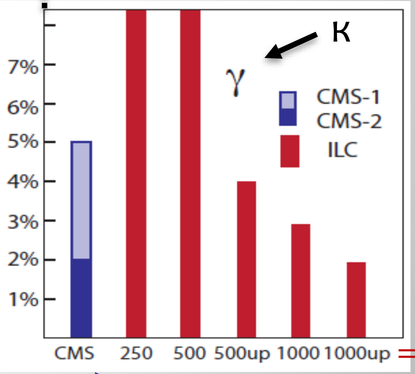
Wich next generation colliders will be able to reveal indirect Beyond-SM effects via the Higgs couplings ?

« ~3σ’s @ HL-LHC would not be impossible »

3σ ?	~ few 10’s %		~ few 10’s %	~ few 10’s %	**…in RS custo.** *Bouchart, **GM** 0909.4812*
	~ 8 %	**3σ ?**	~ few 10’s %		**…comp.-pGB H custo.**
	(< 1 %)	**3σ ?**	~ 10-100% (tanβ-dep.)		**…in the MSSM**
	~ 6 %		~ 6%		**…add. mixed singlet H**







$= \sqrt{s}\ [GeV]$

$= L\ [fb^{-1}]\ \ (on\ 18\ years)$

Gupta et al. 1206.3560

(hypothesis : no BSM state seen directly)

Fit prospectives :
Expected accuracies (TH+EXP)

Peskin 1312.4974

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HL-LHC: 14TeV 3000 fb^{-1} (2026-2037)
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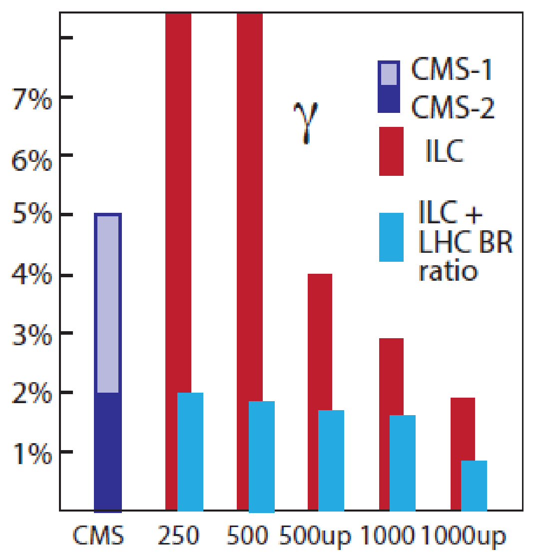
Run 2: 13TeV 100 fb^{-1} (2015-2018)

Combining the LHC and ILC data would improve the pure ILC fit :



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« Thank you

for your attention »

Back up

The Case of Higher-Order Operators

Those 2 calculation orderings become **« analytically equivalent »** to Regul. II if the UV completion induces the Higher-Dimensional operators :

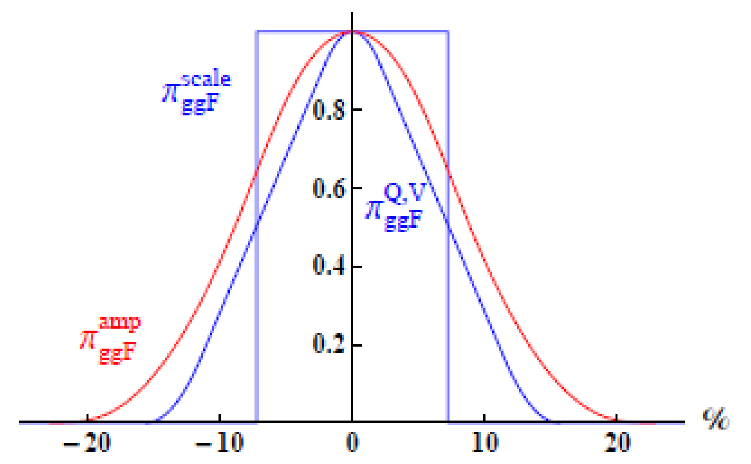
$$\delta(y-\pi R)\; Y_{\rm HO}\; \frac{\partial_y \overline{Q}_R\; H\; \partial_y D_L}{\Lambda^2} \quad \Leftrightarrow \quad \delta\left(y-\left[\pi R-\frac{1}{\Lambda}\right]\right)\; Y_{\rm HO}\; \bar{Q}_R\; H\; D_L$$

5D

$$-\, m\; q_R \;+\; q'_L \;+\; \left\{\delta(y-(\pi-\epsilon)R)\; \frac{vY'_5}{\sqrt{2}} + \delta\left(y-\left[\pi R-\frac{1}{\Lambda}\right]\right)\, \frac{vY^{II}_{\rm HO}}{\sqrt{2}}\right\} d_L \;=\; 0$$

4D

$$\beta_{ji} \;=\; \frac{vY'_5}{\sqrt{2}}\, q^i_R((\pi-\epsilon)R) \times d^j_L((\pi-\epsilon)R) + \frac{vY_{\rm HO}}{\sqrt{2}}\, q^i_R\left(\pi R-\frac{1}{\Lambda}\right) \times d^j_L\left(\pi R-\frac{1}{\Lambda}\right)$$

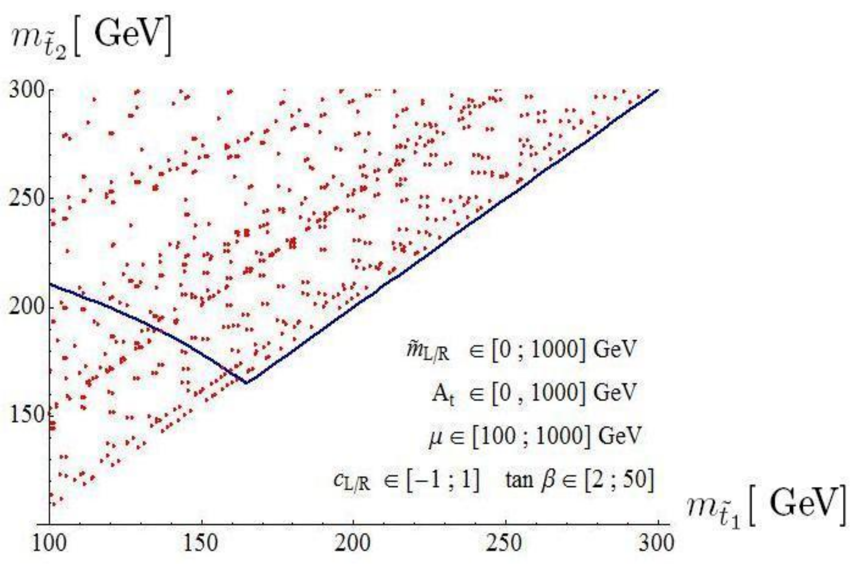

$\pi_{\mathrm{ggF}}^{\mathrm{scale}}$
$\pi_{\mathrm{ggF}}^{\mathrm{Q,V}}$
$\pi_{\mathrm{ggF}}^{\mathrm{amp}}$
0.8
0.6
0.4
0.2
−20
−10
0
10
20
%

$$\delta_i^\mu \Delta_i^\mu = -\delta_i^N \Delta_i^N = -\frac{\sum_X \epsilon_X^i \sigma_X^{\rm SM} \delta_X^\sigma \Delta_X^\sigma}{\sum_{X'} \epsilon_{X'}^i \sigma_{X'}^{\rm SM}} - \delta_{Y_i}^B \Delta_{Y_i}^B$$

$$\delta_X^\sigma \Delta_X^\sigma = \sum_n \delta_X^n \Delta_X^n$$

$$\delta_Y^B \Delta_Y^B = \sum_{Y'} \delta_{Y'}^\Gamma \Delta_{Y'}^\Gamma \left(B_{Y'}^{\rm SM} - \delta_{YY'}\right)$$

$$\delta_Y^\Gamma \Delta_Y^\Gamma = \sum_{n'} \delta_Y^{n'} \Delta_Y^{n'}$$



$$\mathcal{M}^2_{\tilde{t}\tilde{t}}|_{\text{4D SUSY}} = \begin{pmatrix} m_t^2 + Q_Z^{t_L}\cos 2\beta\, m_Z^2 + \tilde{m}_L^2 & A_t - \frac{\mu\, m_t}{\tan\beta} \\ A_t - \frac{\mu\, m_t}{\tan\beta} & m_t^2 - Q_Z^{t_R}\cos 2\beta\, m_Z^2 + \tilde{m}_R^2 \end{pmatrix}$$