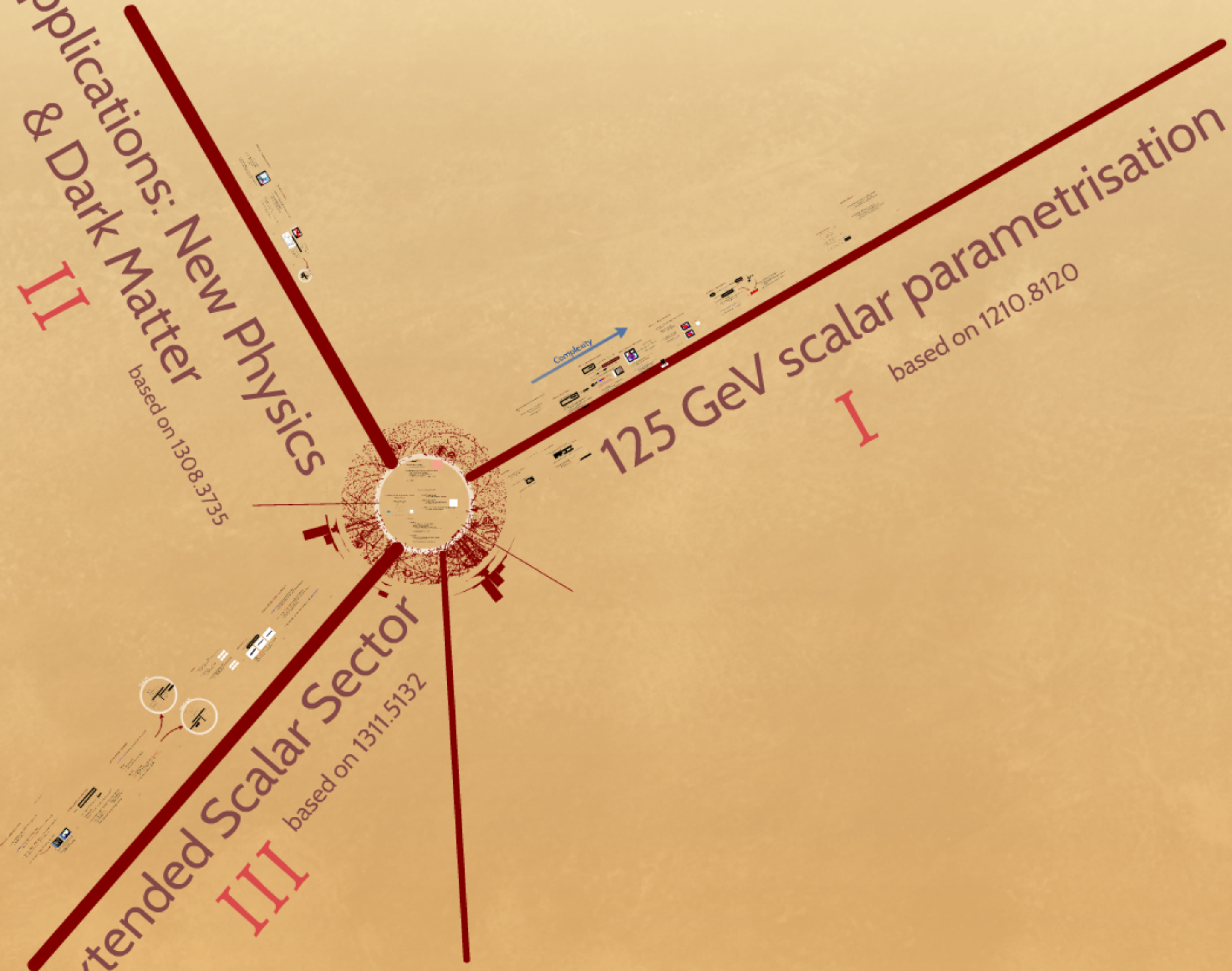

I

125 GeV scalar parametrisation

based on 1210.8120

II

Applications: New Physics & Dark Matter

based on 1308.3735

III

Extended Scalar Sector

based on 1311.5132

Constraining New Physics at the LHC : the SM scalar and Beyond

Guillaume Drieu La Rochelle
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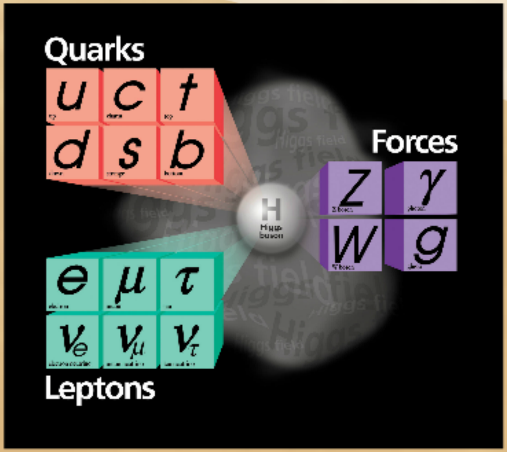
IPNL, Lyon, France

December 6, 2013

Séminaire : Université Libre de Bruxelles - SPT

The Standard ~~Model~~ Theory



- All particles have been found
  - M_{H^0} in good agreement with EWPT
- No indications for "not-too-heavy" New Physics (Terascale)
  - WW scattering is no longer an option.
  - Bounds on new states are approaching the TeV.
  - Flavour physics ➞ No deviations.
    - Rare decay $B_s \to \bar{\mu}\mu$ observed... compatible with SM
- Are we done?

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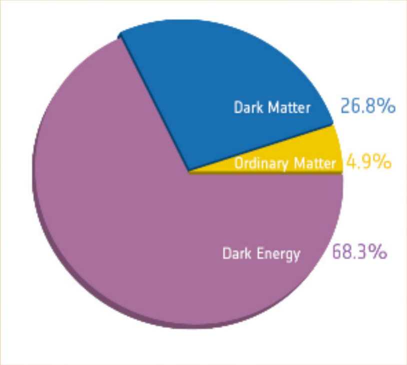
  → One could do with more Naturalness

- The dark matter puzzle:

  → We need one more particle (at least).

  - Or a whole new sector.



- "EWSB + 125 GeV scalar" can be achieved in different ways
  - There is still room for non-SM physics.

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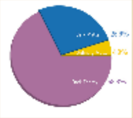

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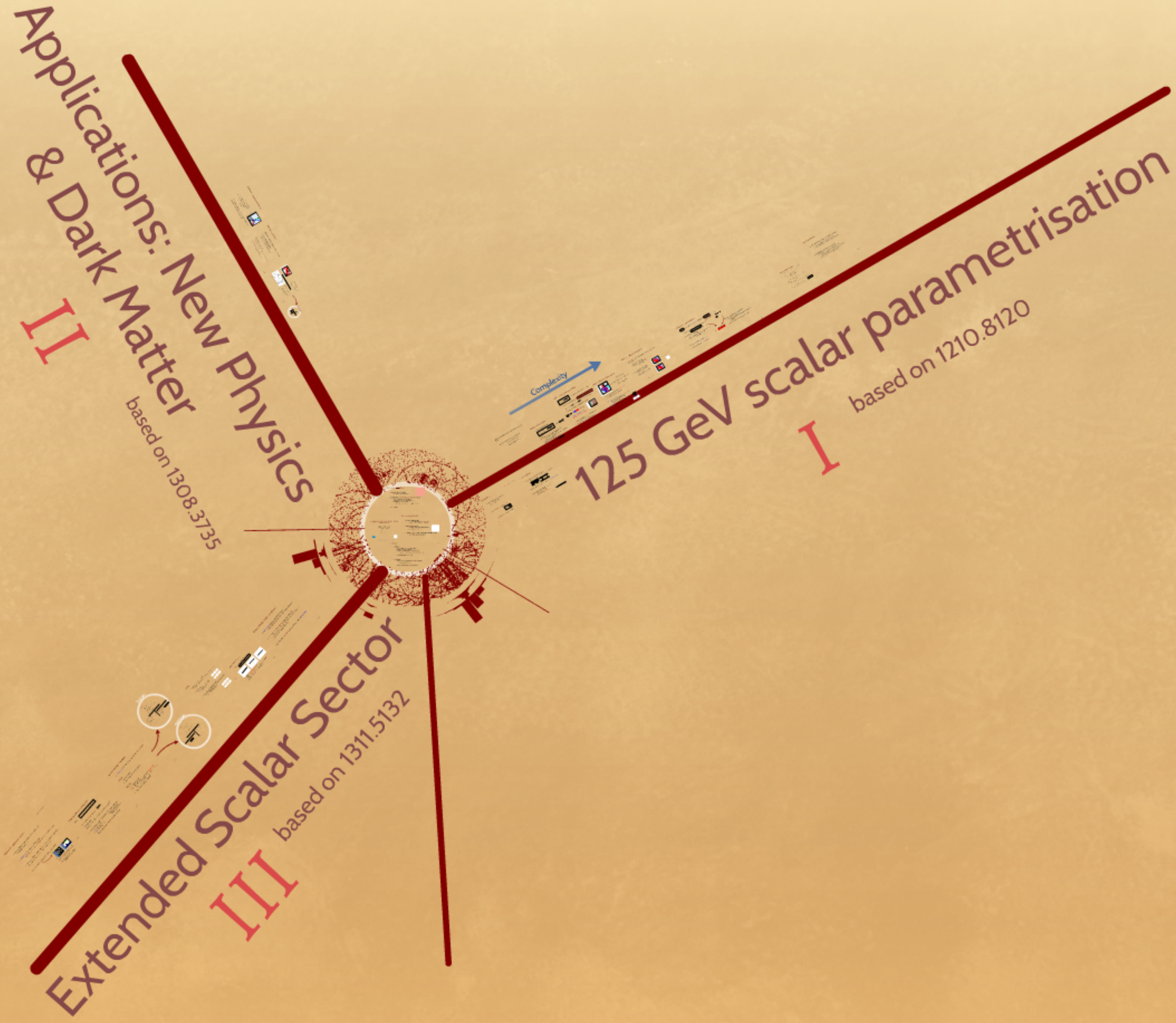
Conclusions

- Summary
  - Tools for using LHC H^0 data in NP studies
  - Importance of a parametrisation
  - How this constraint performs w.r.t other searches
    - e.g. direct searches for heavy state, or Dark matter searches
  - Can help with light states as well.

- Perspectives
  - Some tools are not yet mature (uncertainties, fiducial σ)
    - Hope to improve before Run 2
  - Model-testing will benefit a lot more from LHC.



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based on 1210.8120, 1307.5865

From simple . . .

- Event count for each decay mode :
    - $H \to WW$ ➔ n_{WW}
    - $H \to \gamma\gamma$ ➔ $n_{\gamma\gamma}$
    - . . .

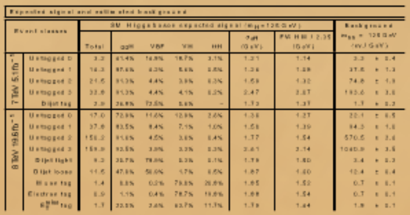
- For convenience, compare to n^{SM}

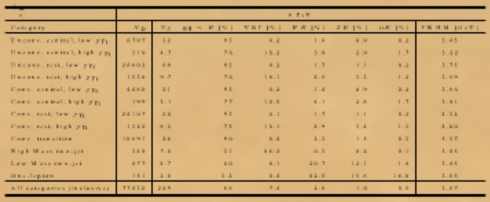
$$\boxed{\widehat{\mu}_{XX} = \frac{n_{XX}}{n^{\mathrm{SM}}_{XX}}}$$

    - $\widehat{\mu}$ indicates which direction is favoured.

. . . to complicated

- One decay mode ➡ several final states
  - $\gamma\gamma$ ➡ $\gamma\gamma|_{p_{T,H}>40\text{ GeV}}$, $\gamma\gamma + 2j$, ... ~ 10-20 subchannels





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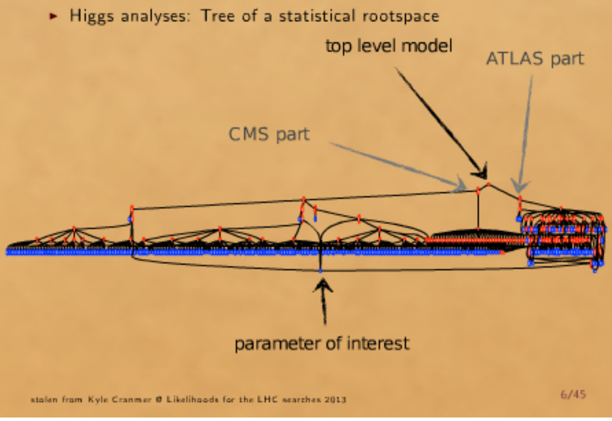
- Many different uncertainties σ_i $(\mu_i \pm \sigma_i)$
  - α_s, PDFs, N^nLO, $\mathcal{L}$, JES...
  - σ_i will be mostly correlated



- Higgs analyses: Tree of a statistical rootspace

stolen from Kyle Cranmer @ Likelihoods for the LHC searches 2013

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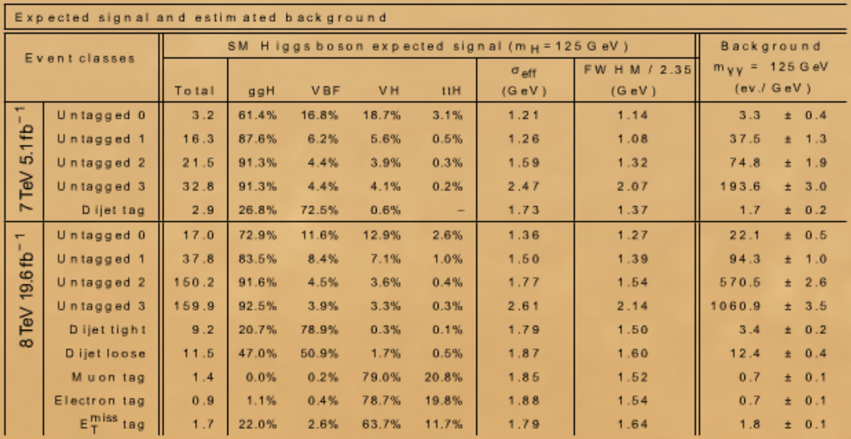
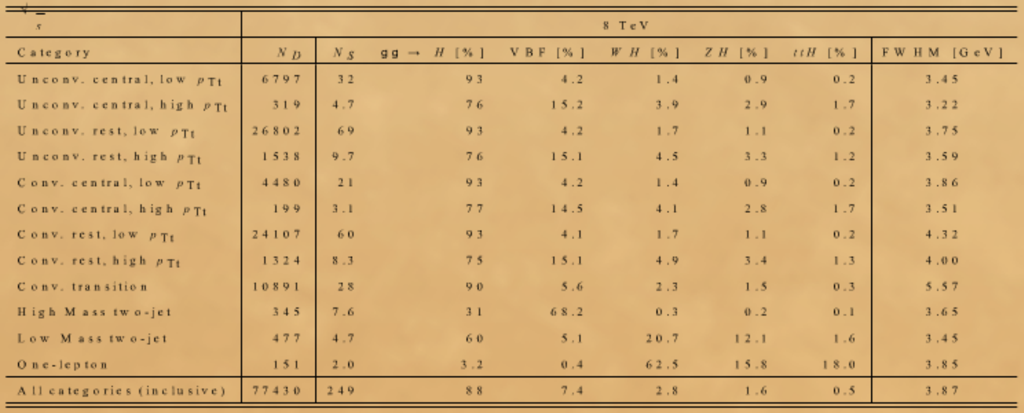


Expected signal and estimated background

Event classes		SM Higgs boson expected signal ($m_H = 125$ GeV)							Background $m_{\gamma\gamma} = 125$ GeV (ev./GeV)
		Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	26.8%	72.5%	0.6%	–	1.73	1.37	1.7 ± 0.2
8 TeV 19.6 fb^{-1}	Untagged 0	17.0	72.9%	11.6%	12.9%	2.6%	1.36	1.27	22.1 ± 0.5
	Untagged 1	37.8	83.5%	8.4%	7.1%	1.0%	1.50	1.39	94.3 ± 1.0
	Untagged 2	150.2	91.6%	4.5%	3.6%	0.4%	1.77	1.54	570.5 ± 2.6
	Untagged 3	159.9	92.5%	3.9%	3.3%	0.3%	2.61	2.14	1060.9 ± 3.5
	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%	1.79	1.50	3.4 ± 0.2
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%	1.87	1.60	12.4 ± 0.4
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%	1.85	1.52	0.7 ± 0.1
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%	1.88	1.54	0.7 ± 0.1
	E_T^{miss} tag	1.7	22.0%	2.6%	63.7%	11.7%	1.79	1.64	1.8 ± 0.1



$\sqrt{s}$	8 TeV							
Category	N_D	N_S	gg → H [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]	FWHM [GeV]
Unconv. central, low p_{Tt}	6797	32	93	4.2	1.4	0.9	0.2	3.45
Unconv. central, high p_{Tt}	319	4.7	76	15.2	3.9	2.9	1.7	3.22
Unconv. rest, low p_{Tt}	26802	69	93	4.2	1.7	1.1	0.2	3.75
Unconv. rest, high p_{Tt}	1538	9.7	76	15.1	4.5	3.3	1.2	3.59
Conv. central, low p_{Tt}	4480	21	93	4.2	1.4	0.9	0.2	3.86
Conv. central, high p_{Tt}	199	3.1	77	14.5	4.1	2.8	1.7	3.51
Conv. rest, low p_{Tt}	24107	60	93	4.1	1.7	1.1	0.2	4.32
Conv. rest, high p_{Tt}	1324	8.3	75	15.1	4.9	3.4	1.3	4.00
Conv. transition	10891	28	90	5.6	2.3	1.5	0.3	5.57
High Mass two-jet	345	7.6	31	68.2	0.3	0.2	0.1	3.65
Low Mass two-jet	477	4.7	60	5.1	20.7	12.1	1.6	3.45
One-lepton	151	2.0	3.2	0.4	62.5	15.8	18.0	3.85
All categories (inclusive)	77430	249	88	7.4	2.8	1.6	0.5	3.87

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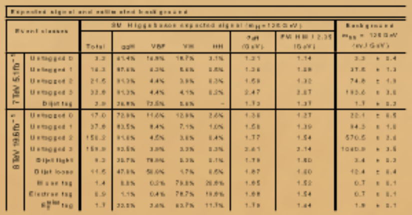

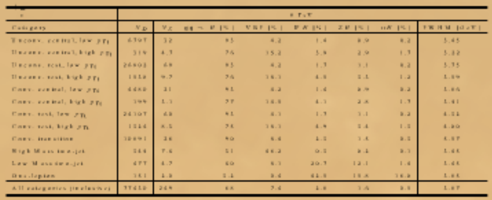

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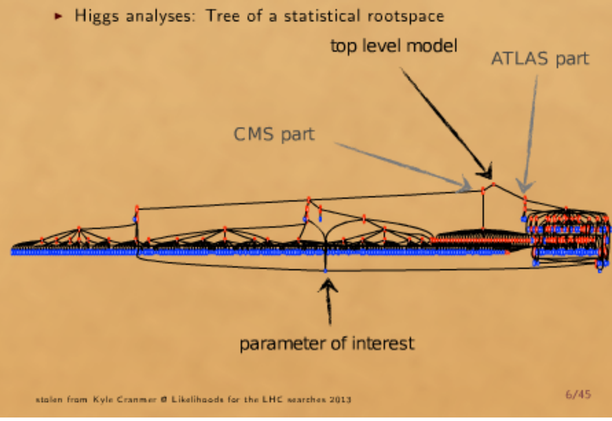

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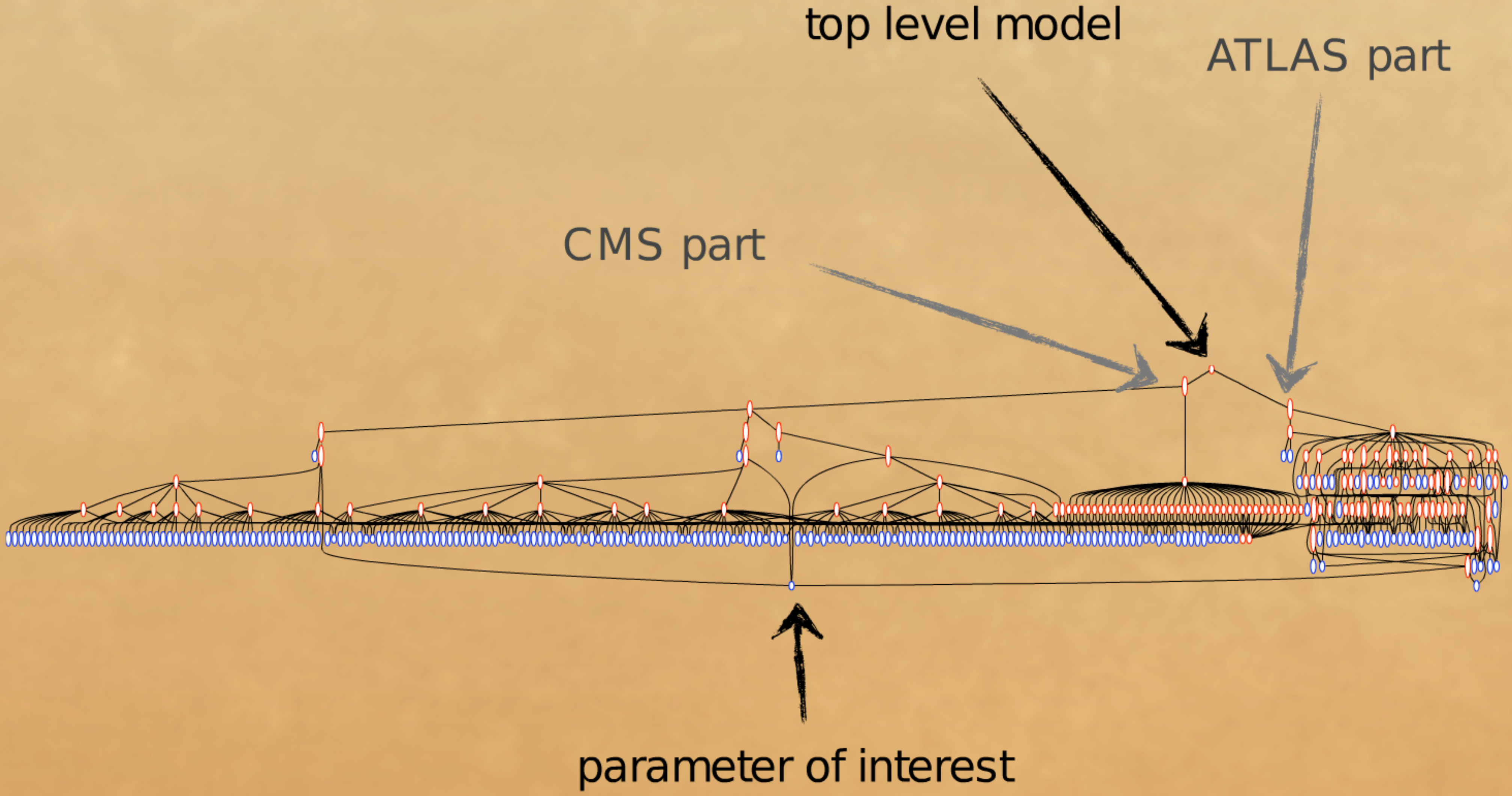

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- Either experimentalists perform the full statistical test on *each* model . . .

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How de we test a model?

How to define a χ^2 ?

Complexity

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How to define a χ^2 ?

Method 1 : the naive guess*

- Compute inclusive quantities

$$\boxed{\chi^2 = \sum_{XX=\gamma\gamma/WW/...} \left(\frac{\mu_{XX} - \widehat{\mu}_{XX}}{\sigma_{XX}}\right)^2} \qquad \mu_{XX} = \frac{\sigma_{pp\to h\to XX}}{\sigma^{SM}_{pp\to h\to XX}}$$

- This is it!
- But experiments can distinguish production modes
  $\longrightarrow (ggH, \text{VBF}, \text{VH}, \bar{t}tH)$
  - At same $\sigma_{pp\to h\to XX}$, fermiophobic scalar and 4th generation scalar are quite different!
  - We must consider experimental cuts in μ

$$\mu_{XX} = \frac{\sigma_{XX}}{\sigma^{SM}_{XX}} = \frac{\sigma_{pp\to h\to XX}\,\epsilon}{\sigma^{SM}_{pp\to h\to XX}\,\epsilon^{SM}}$$

* a.k.a. sweeping the dust under the carpet

Method 2 : the industrious computing

$$\boxed{\chi^2 = \sum_i \left(\frac{\mu_i - \widehat{\mu}_i}{\sigma_i}\right)^2} \qquad i = WW + 0j / WW + 1j / ... / \gamma\gamma + 2j ...$$

- Idea : Re-use SM efficiencies ⚠Only with same productions modes

$$\sigma_{pp\to h\to X_i} = \left(\frac{\sigma_{ggh}}{\sigma^{SM}_{ggh}}\sigma^{SM}_{ggh}\times\epsilon^{SM}_{i,ggh} + \frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}}\sigma^{SM}_{VBF}\times\epsilon^{SM}_{i,VBF} + \dots\right)\times Br_X$$

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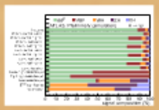

Inclusive : independent of cuts

Exclusive : Cut-dependent, but SM

- Drawback :composition ($n^{SM}_{ggh,i}/n^{SM}_i$) not always public
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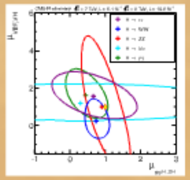
Method 3 : the semi-combined approach



$\vec{\mu} = (\mu_{ggh}, \mu_{VB}$

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- ggh, VBF, VH, $\bar{t}th \Rightarrow \mu_g, \mu_V$
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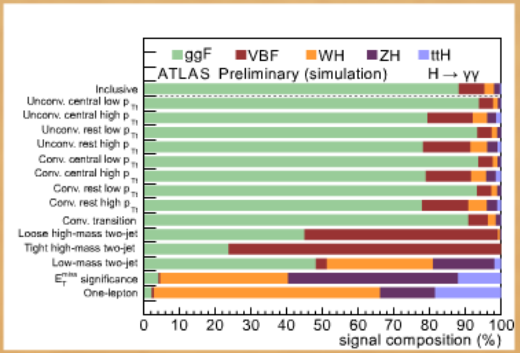

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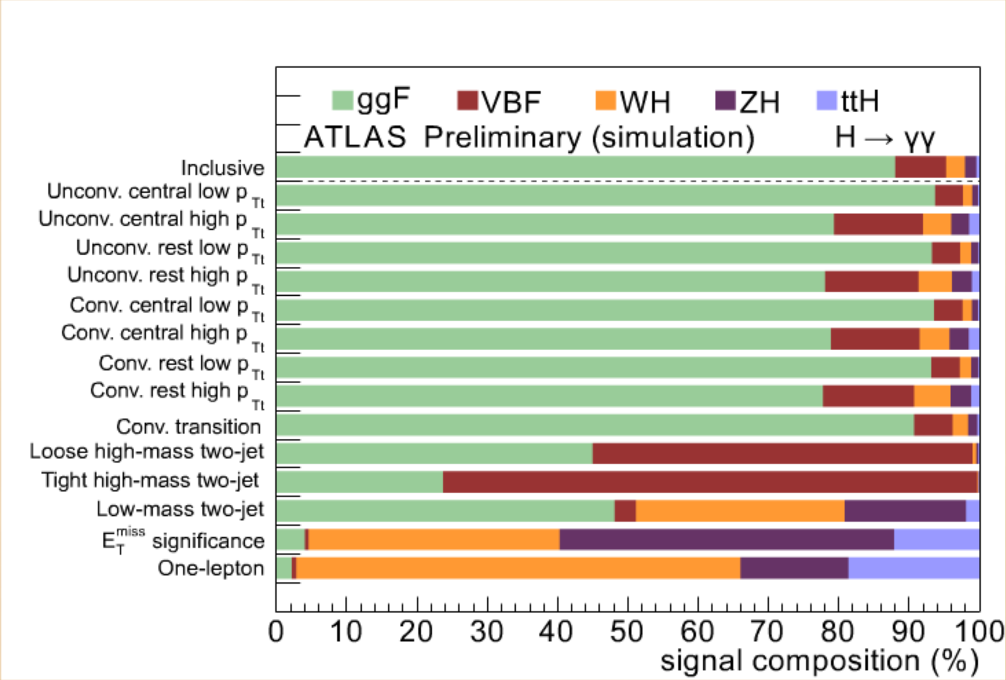
computation in two parts :

$$ \dots \Big) \times Br_X $$



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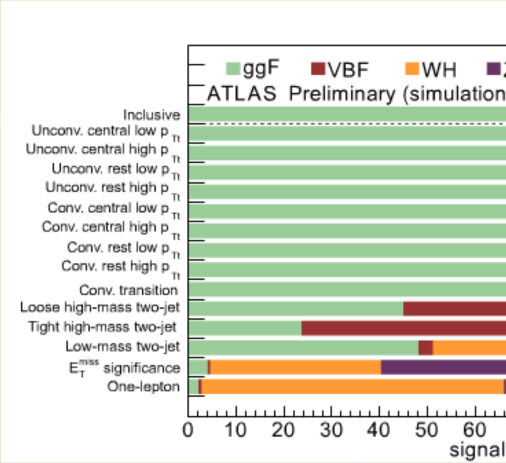

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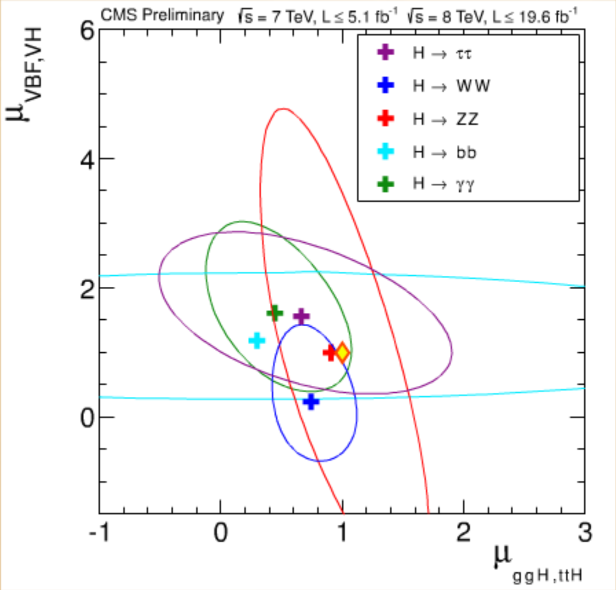

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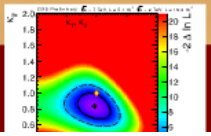
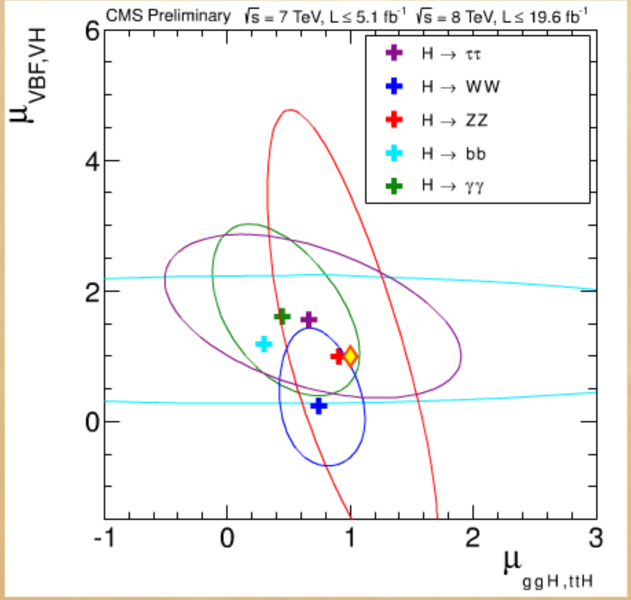
- Collaborations start to release more information





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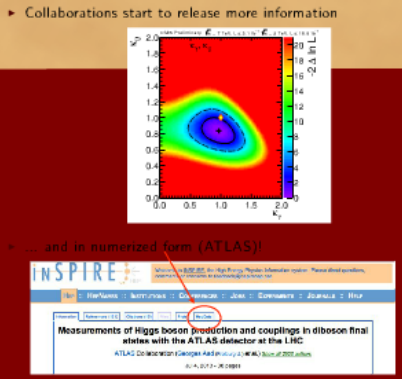

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- ... and in numerized form (ATLAS)!

Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC

ATLAS Collaboration (Georges Aad et al.)

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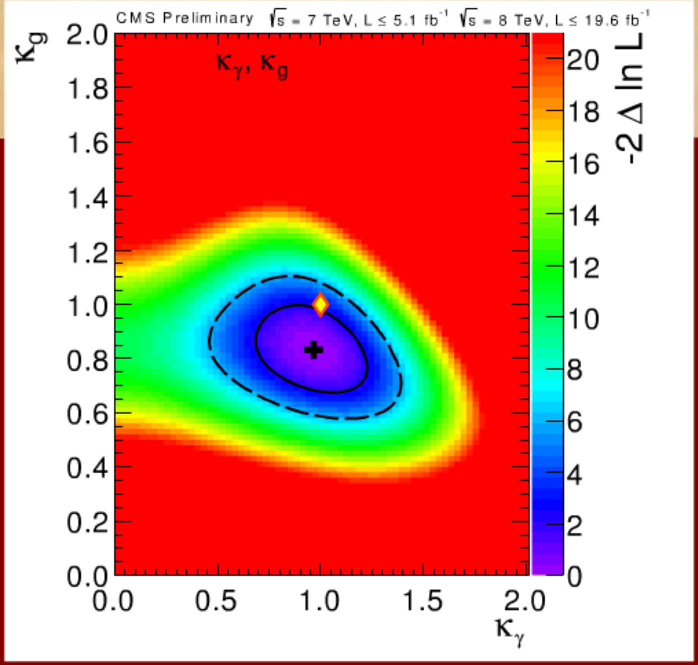

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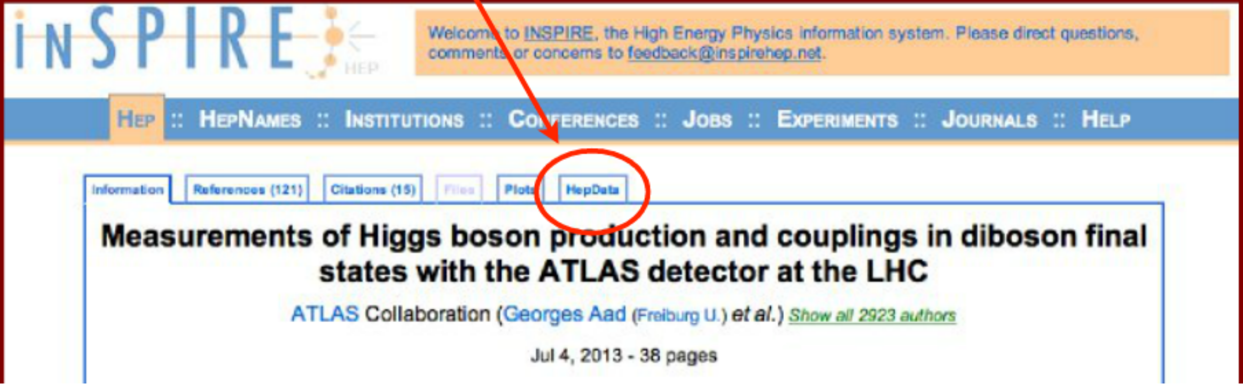

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ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*) *Show all 2923 authors*

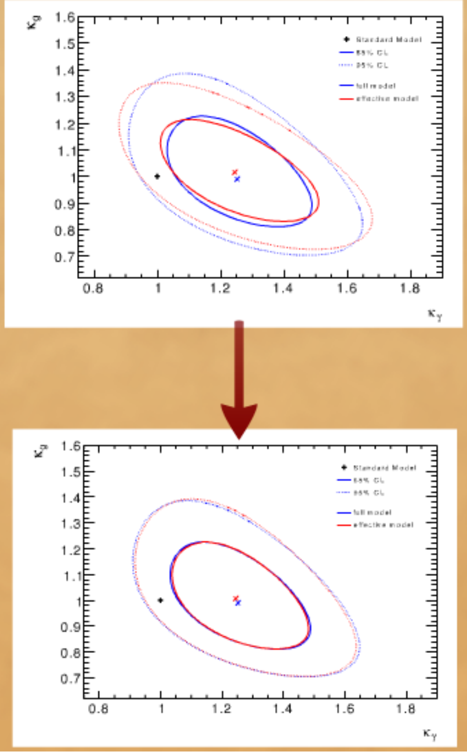
Jul 4, 2013 - 38 pages

Method 4 : Pulling uncertainties out

- Bottom line: common uncertainties should be removed from each decay mode
  - Experimental : luminosity
  - Theoretical : inclusive production σ_{ggh}, $\sigma_{VBF}, \ldots$
    $\rightarrow (\alpha_s$, pdfs,$\ldots)$

$\vec{\widehat{\mu}})$

- Some correlations still remains:
  - Uncertainties on efficiencies ϵ_i
  - specific treatment $(\mu = \mu(\theta))$
    - Cranmer et. al., to appear



- $gg \rightarrow H$ has larg
- Imposing jet veto
  → large lo

stolen from Gavin Salam @ Rencontre

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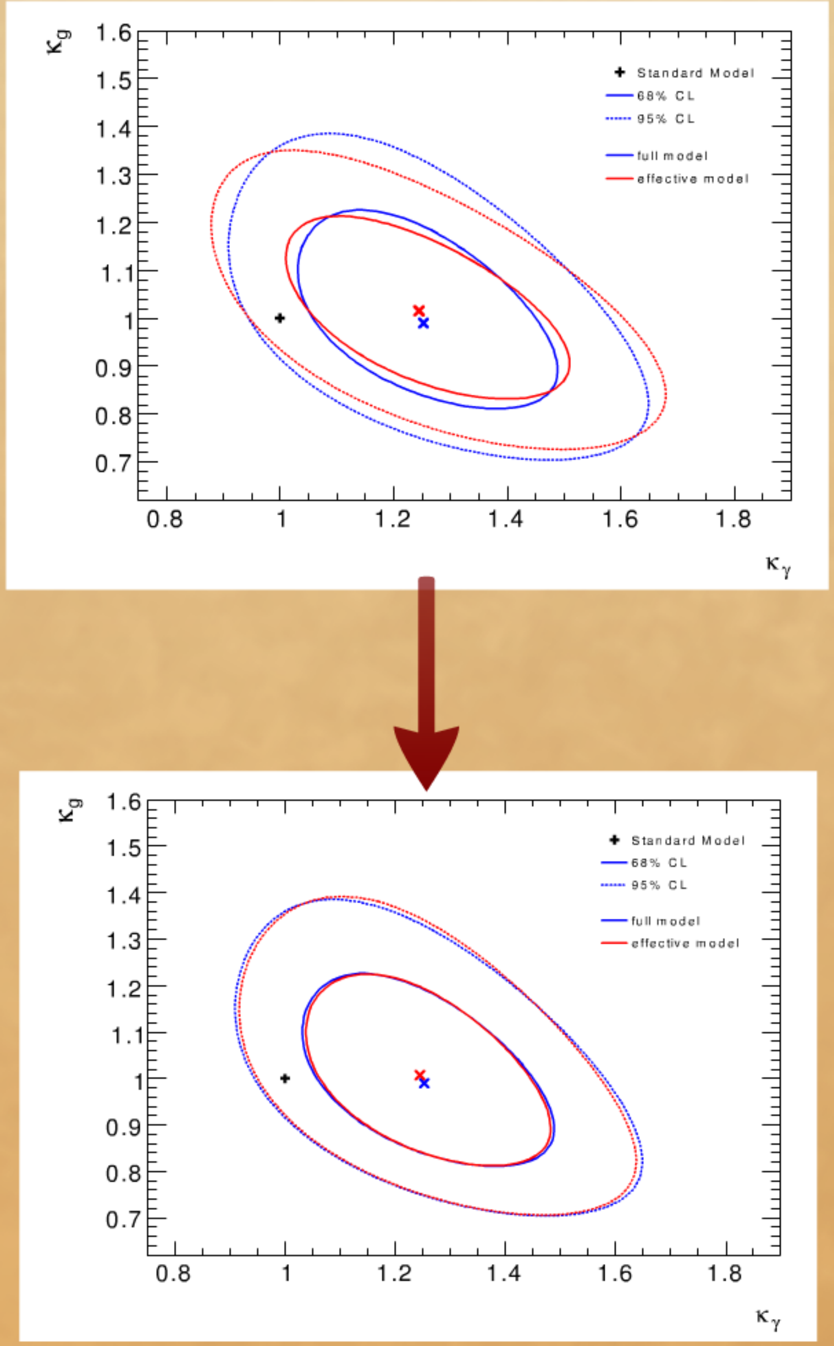
tment $(\mu = \mu(\theta))$

er et. al., to appear

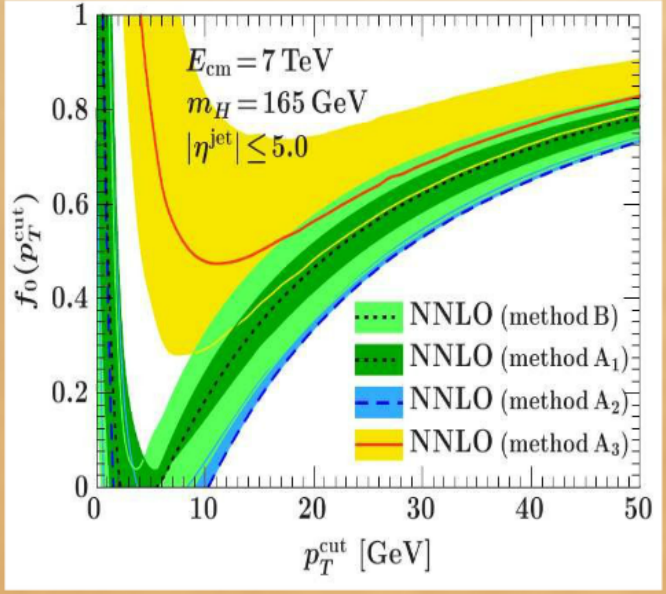


stolen from M. Rauch @ Higgs Couplings 2013

- $gg \to H$ has large contribution from $gg \to H + j,\ H + 2j$.

- Imposing jet veto (or VBF cuts) increases the uncertainty
  $\rightarrow$ large logarithm terms appearing

Higgs jet veto efficiency



stolen from Gavin Salam @ Rencontres de Physique des Particules 2013

Workaround : a parametrisation

Theory → Parametrisation ← Experiments

1. Express all possible deviations as parameters

   ⚠Model-independent

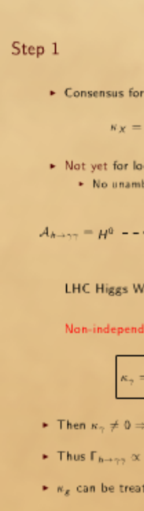
2. Experiments give ranges for parameters

   e.g. $X \in [0.8, 1.2]$

3. Theorists compute parameters in their own model

   e.g. $X = f(\tan\beta, M_{A^0}, \mu, \dots)$

1)



Step 1

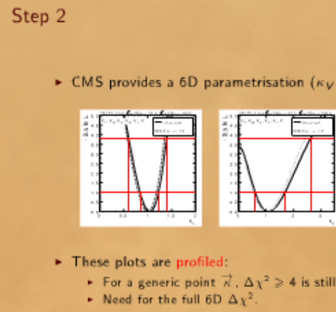
- Consensus for
- Not yet for lo
  - No unamb

LHC Higgs W

Non-independ

- Then $\kappa_\gamma \neq 0 \Rightarrow$
- Thus $\Gamma_{h\to\gamma\gamma} \propto$
- κ_g can be treat

2)



Step 2

- CMS provides a 6D parametrisation (κ_V
- These plots are profiled:
  - For a generic point $\vec{\kappa}$, $\Delta\chi^2 \geqslant 4$ is still
  - Need for the full 6D $\Delta\chi^2$.

- Proposed by different groups

  (see 1207.1717, 1207.1344, 1209.5538. . .)

- Connection with EFT : more later

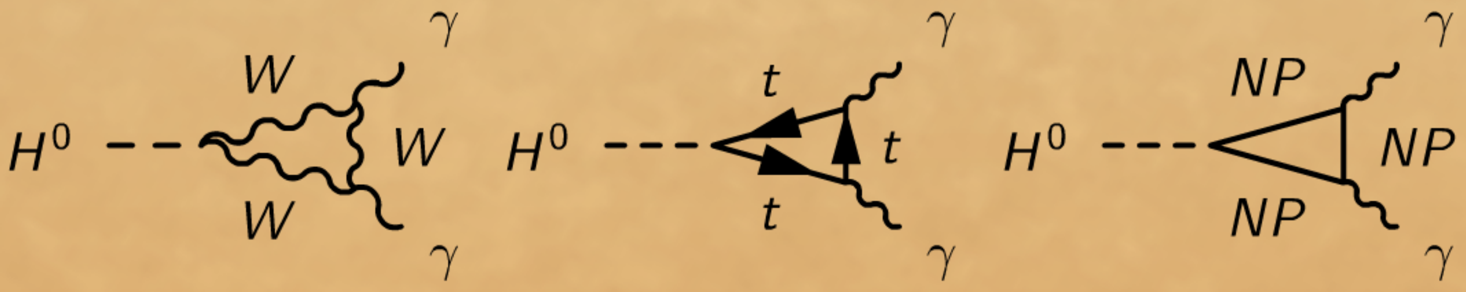
Step 1

- Consensus for tree-level couplings

$$\kappa_X = \frac{g_{hXX}}{g_{hXX}^{\mathrm{SM}}}, \qquad X \in \{W, Z, t, b, \dots\}$$

- Not yet for loop-induced couplings
  - No unambiguous definition

$\mathcal{A}_{h\to\gamma\gamma} =$



LHC Higgs WG ➜ $\kappa_\gamma^2 = \frac{\Gamma_{h\to\gamma\gamma}}{\Gamma_{h\to\gamma\gamma}^{\mathrm{SM}}}$

Non-independent parametrisation: κ_V change $\Rightarrow$ κ_γ change.

$$\boxed{\kappa_\gamma = \frac{\mathcal{A}^{\mathrm{NP}}}{\mathcal{A}^{\mathrm{SM}}}} \qquad \mathcal{A} = \mathcal{A}_{h\to\gamma\gamma}$$

LHC Higgs WG ➞ $\kappa_\gamma^2 = \frac{\Gamma_{h \to \gamma\gamma}}{\Gamma^{\mathrm{SM}}_{h \to \gamma\gamma}}$

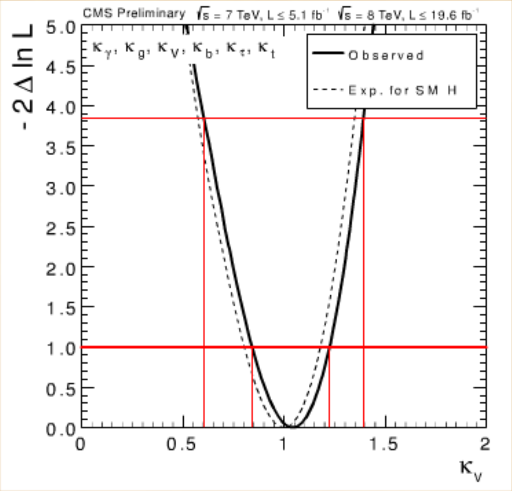
Non-independent parametrisation: κ_V change $\Rightarrow$ κ_γ change.

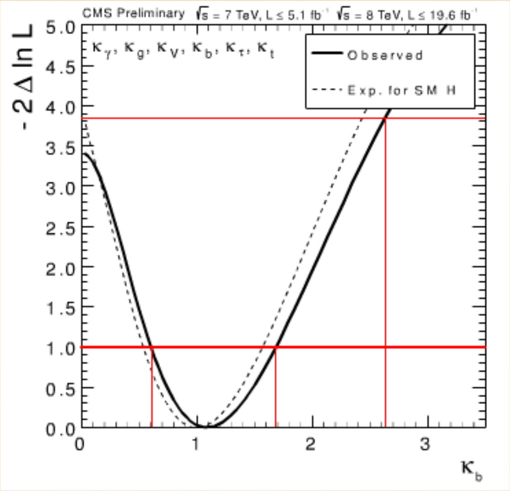
$$\boxed{\kappa_\gamma = \frac{\mathcal{A}^{\mathrm{NP}}}{\mathcal{A}_t^{\mathrm{SM}}}} \qquad \mathcal{A} = \mathcal{A}_{h \to \gamma\gamma}$$

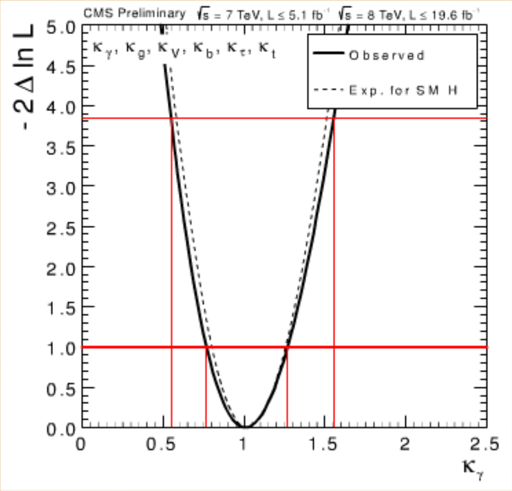
- Then $\kappa_\gamma \neq 0 \Rightarrow$ new particles in the loop.
- Thus $\Gamma_{h \to \gamma\gamma} \propto |\kappa_V \mathcal{A}_W + \kappa_t \mathcal{A}_t + \kappa_b \mathcal{A}_b + \kappa_\gamma \mathcal{A}_t|^2$
- κ_g can be treated similarly.

Step 2

- CMS provides a 6D parametrisation $(\kappa_V, \kappa_b, \kappa_t, \kappa_\tau, \kappa_g, \kappa_\gamma)$







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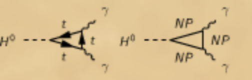


$\frac{\Gamma_{h\to\gamma\gamma}}{\Gamma^{SM}_{h\to\gamma\gamma}}$

risation: κ_V change ⇒ κ_γ change.

$\mathcal{A} = \mathcal{A}_{h\to\gamma\gamma}$

s in the loop.

$\mathcal{A}_t + \kappa_b\mathcal{A}_b + \kappa_\gamma\mathcal{A}_t|^2$

How do we communicate such information?

- assume $\Delta\chi^2(\kappa_V,\dots)$ is gaussian.
  - Then you only need to communicate small number of parameters.
- Not so exact yet ➙ more a long-term scenario

$\kappa_g, \kappa_\gamma)$

What about precision physics?

This parametrisation reaches a hard limit for precision:

- Meaning of each κ is obscured
  - κ_V contributes to $gg \to h$
  - κ_g contributes to VBF, VH
  - ...
- Analysing each production mode is less relevant
- NP generates terms with non-standard Lorentz structure
  - Need for more parameters
  - For instance VH : $ig_W M_W g_{\mu\nu} \to$ $ig_W M_W \left[a g_{\mu\nu} + b(p_{1\mu} p_{2\nu} - g_{\mu\nu} p_1.q_1) + c\epsilon^{\mu\nu\sigma\rho} p_{1\sigma} p_{2\rho}\right]$
- This is the $1-5\%$ precision level

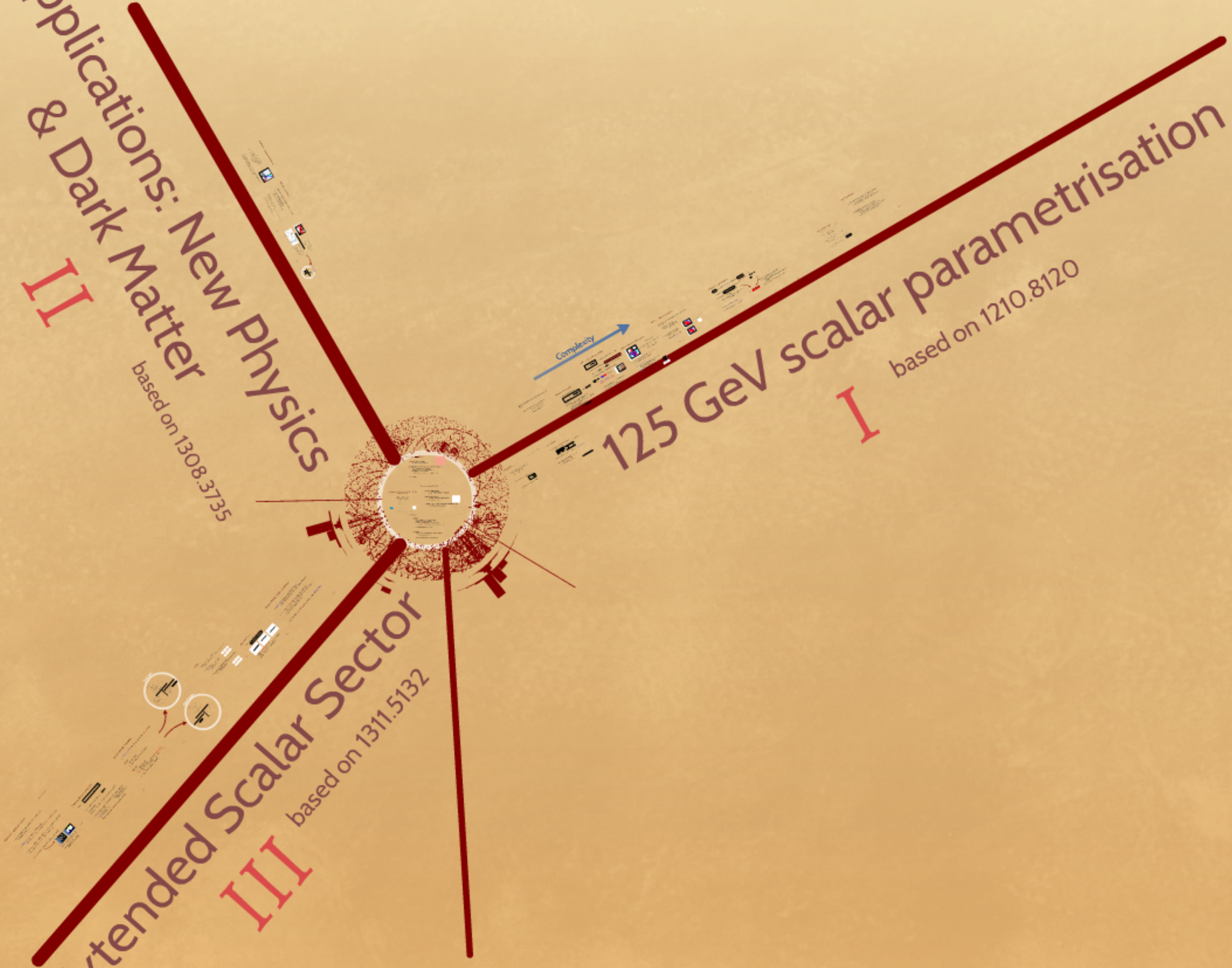
⚠end of LHC

  - The κ parametrisation more relevant for run 2

Part I: Conclusion

- Deviations in scalar sector are tricky to interpret
    - Are we computing the right thing? (ϵ)
    - Are we interpreting correctly experimental data?

- Hopefully, it will become a standard.
    - By using a common parametrisation ($\overrightarrow{\kappa}$)
    - As experimentalists and theorist get along together
    - It all depends on the precision you ask!



125 GeV scalar parametrisation

I

based on 1210.8120

Applications: New Physics & Dark Matter

II

based on 1308.3735

Extended Scalar Sector

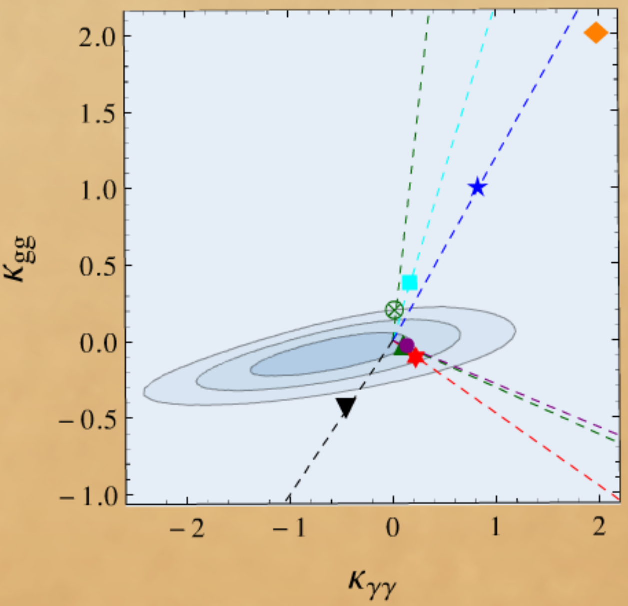
III

based on 1311.5132

Application: constraining New Physics

$$\begin{cases} \kappa_g \to \kappa_g(M) \\ \kappa_\gamma \to \kappa_\gamma(M) \end{cases}$$

- 4th generation
- Warped Higgs
- 6D UED
- SUSY

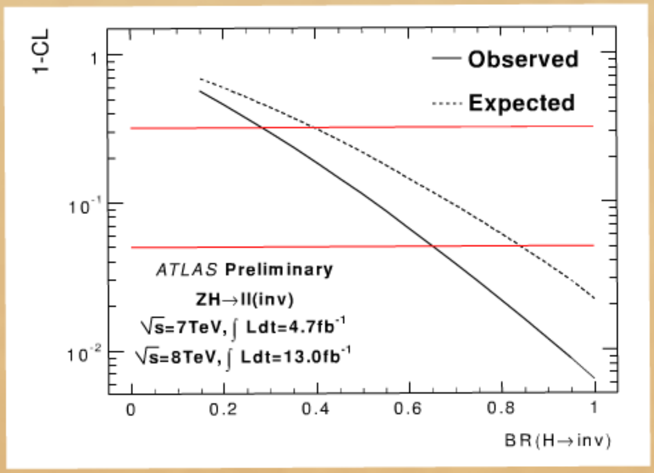


- This indirect limit can be stronger than the direct one.
- Models are lines $f(M)$ starting at SM

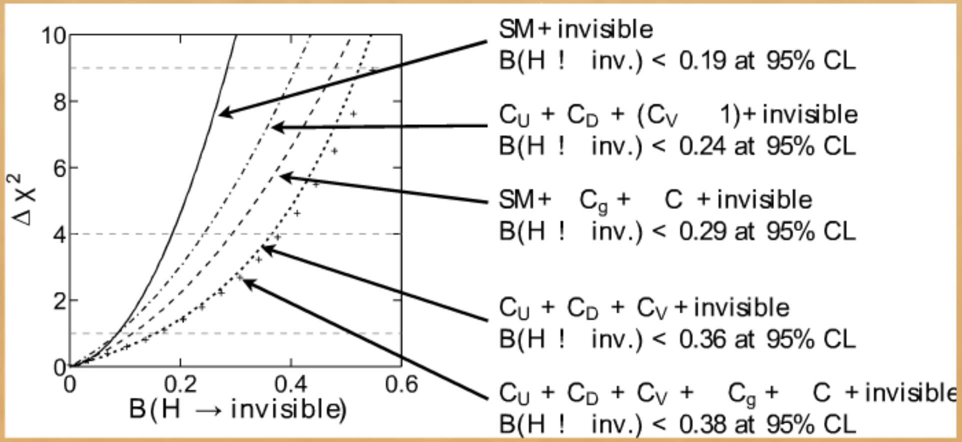
SM scalar & Dark Matter

- If New Physics lighter than $M_H/2$ ➞ new decay $H \to XX$
- Connection with light Dark Matter
  - ➞ Link with direct detection experiments
  - ➞ Another handle on light dark matter
- 2 constraints on scalar sector:
  - Direct observation $pp \to Z(H \to \text{invisible})$, with Z recoil
  - Indirect effect $\Gamma_H \nearrow \quad \Rightarrow \quad \widehat{\mu}_{\text{vis.}} \searrow$

    Affect all visible channels!



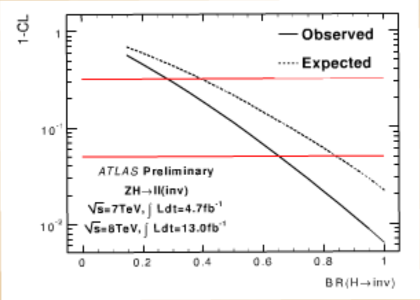
- Direct search ➙ Br $(h \to \text{invisible}) < 0.65$
- Can be improved with monojets



- Stronger limit ➙ Br $(h \to \text{invisible}) < 0.2$
- To go higher, need for special adjustments in $\kappa_g, \kappa_\gamma, \ldots$.

stolen from Sabine Kraml @ New Perspectives on Dark Matter 2013

see 1306.2941



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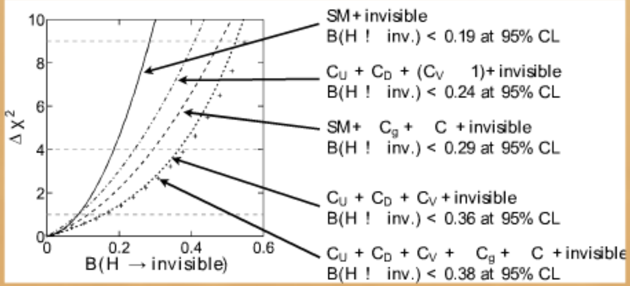

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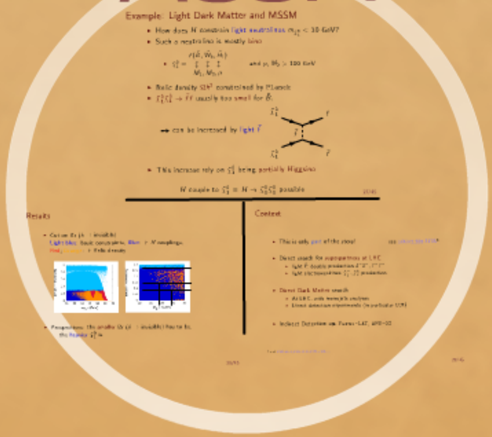
MSSM

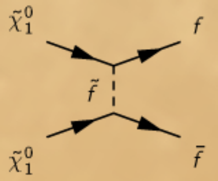


MSSM

Example: Light Dark Matter and MSSM

- How does H constrain light neutralinos $m_{\tilde{\chi}_1^0} < 30$ GeV?
- Such a neutralino is mostly bino
  - $$\tilde{\chi}_1^0 = \begin{array}{c} f(\tilde{B}, \tilde{W}_3, \tilde{H}_i) \\ \updownarrow \ \updownarrow \ \updownarrow \\ M_1, M_2, \mu \end{array} \qquad \text{and } \mu, M_2 > 100 \text{ GeV}$$
- Relic density Ωh^2 constrained by `Planck`
- $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \bar{f} f$ usually too small for $\tilde{B}$.

→ can be increased by light $\tilde{f}$

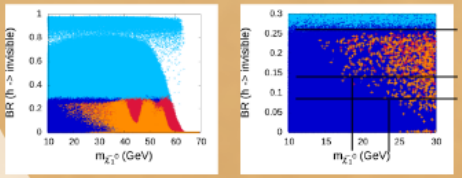


- This increase rely on $\tilde{\chi}_1^0$ being partially Higgsino

H couple to $\tilde{\chi}_1^0 \equiv H \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ possible

Results

- Cut on Br ($h \to$ invisible)
  Light blue: basic constraints, Blue: + H couplings,
  Red/Orange: + Relic density



- Perspectives: the smaller Br ($h \to$ invisible) has to be, the heavier $\tilde{\chi}_1^0$ is.

Context

- This is only part of the story! see arXiv:1308.3735*
- Direct search for superpartners at LHC
  - light $\tilde{\ell}$: double production $\tilde{e}^+\tilde{e}^-, \tilde{\tau}^+\tilde{\tau}^-$
  - light electroweakinos $\tilde{\chi}_1^-, \tilde{\chi}_2^0$ production
- Direct Dark Matter search
  - At LHC, with monojets analyses
  - Direct detection experiments (in particular `LUX`)
- Indirect Detection → `Fermi-LAT`, `AMS-02`

* and 1308.2153,1307.4119,1303.5386,...

Example: Light Dark Matter and MSSM

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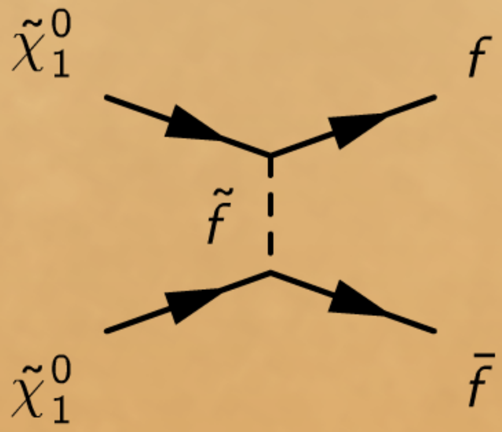

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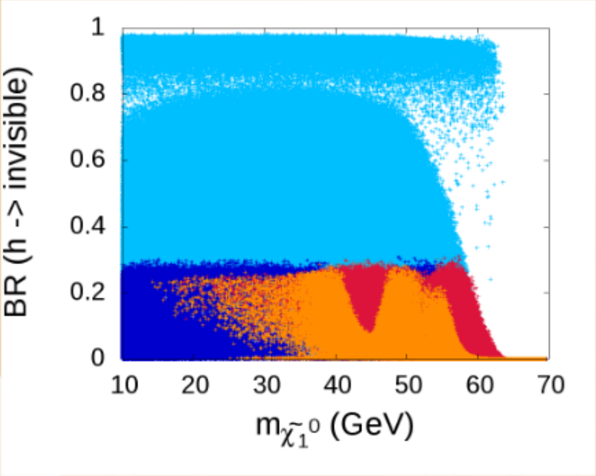

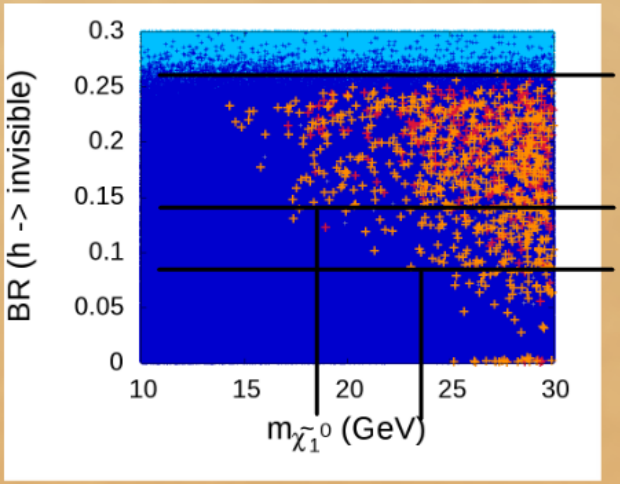

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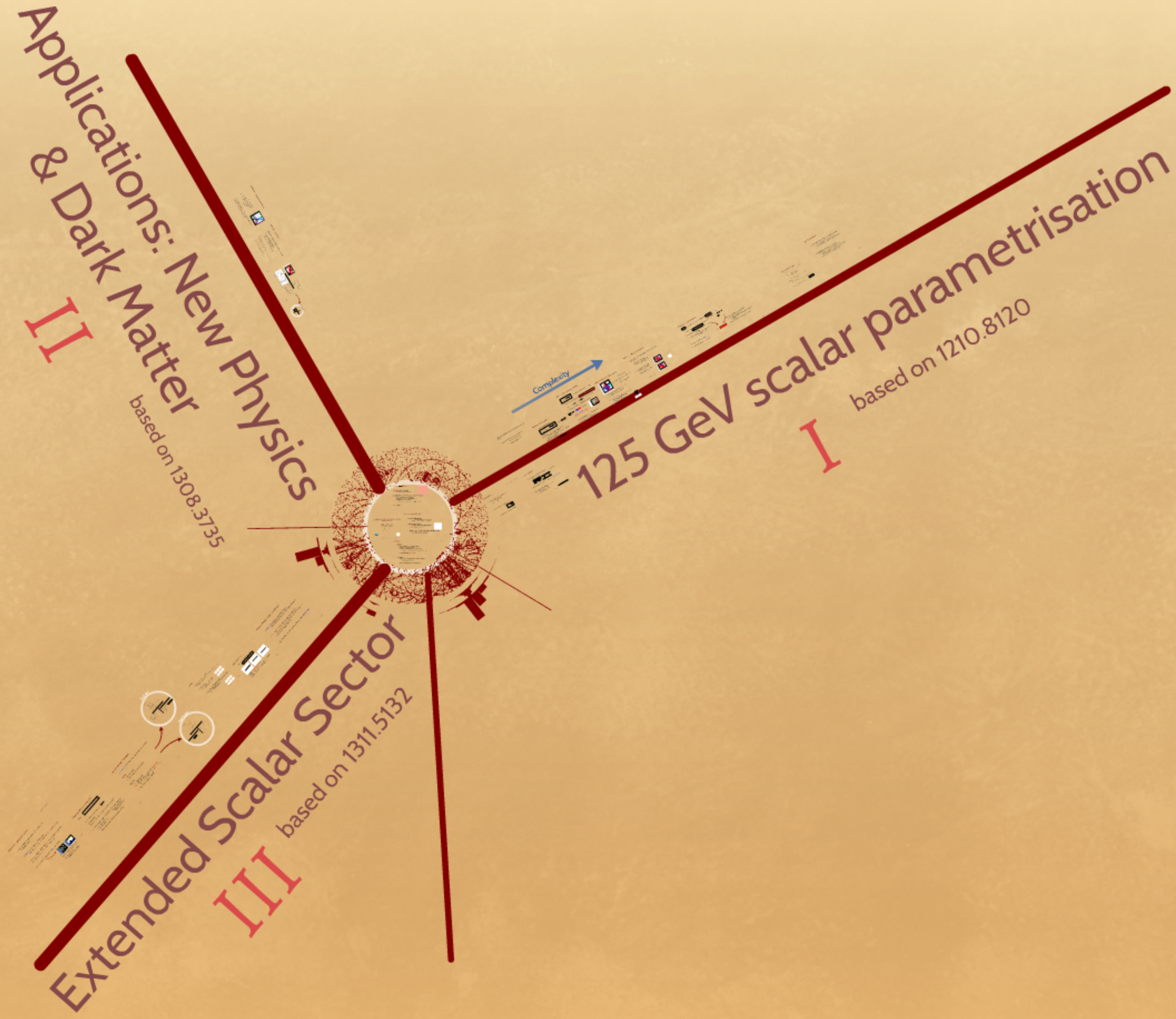


I

125 GeV scalar parametrisation

based on 1210.8120

II

Applications: New Physics & Dark Matter

based on 1308.3735

III

Extended Scalar Sector

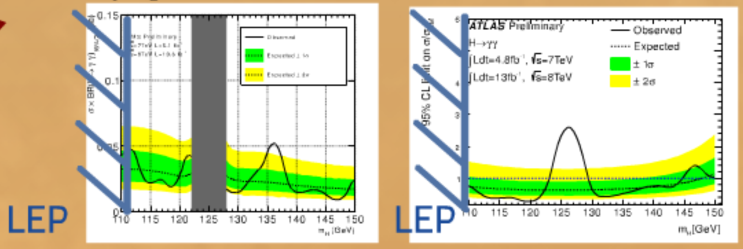
based on 1311.5132

Extension: additional scalars

- Various BSM theories enlarge the scalar sector
    - 2HDM, SUSY, ...
- Correlations between neutral scalars

  $\longrightarrow$ new states are constrained by the observed scalar
- Question: Given our knowledge of the observed scalar, what are our best prospects to find other states?
- Focus: Light additional scalar (< 126 GeV)

- Why lighter?



- But LEP exclusion does not hold for non-SM scalar.
- Aim: Ask collaborations to extend the search range

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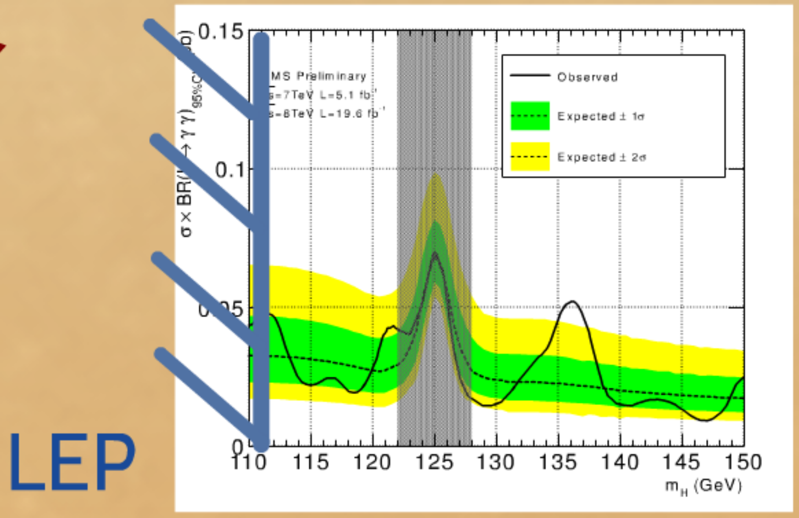
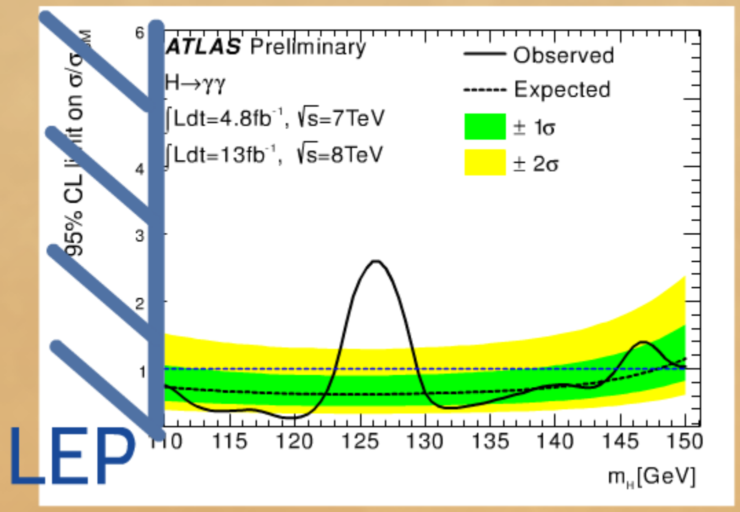




- But LEP exclusion does not hold for non-SM scalar.
- Aim: Ask collaborations to extend the search range.

- Our set-up: two CP-even scalars
  - h_1 : extra **light scalar**, $63 < m_{h_1} < 125.5$ (GeV)
  - h_2 : observed **SM-like scalar**, $m_{h_2} = 125.5$ GeV

Extending the parametrisation

From $\boxed{\kappa_X \longrightarrow \kappa_{X,i} \qquad (i \in \{1,2\})}$

- Loop-induced process $\kappa_{\gamma,i} = \frac{\mathcal{A}^{\mathrm{NP}}_{h_i \to \gamma\gamma}}{\mathcal{A}^{t}_{h_i \to \gamma\gamma}}$

  Partial width:

  $\Gamma_{h_i \to \gamma\gamma} \propto \left|\kappa_{V,i}\mathcal{A}_W + \kappa_{t,i}\mathcal{A}_t + \kappa_{b,i}\mathcal{A}_b + \kappa_{\gamma,i}\mathcal{A}_t\right|^2$

- Test neutral scalars at the level of the parametrisation:
  - LHC ➞ $\Delta\chi^2(\kappa_{X,2})$ (using our method)
  - LEP ➞ $f(m_{h_1}, \kappa_{X,1})$ (using `HiggsBounds`)

  Those tests are independent of the model itself.

Specific models: Examples

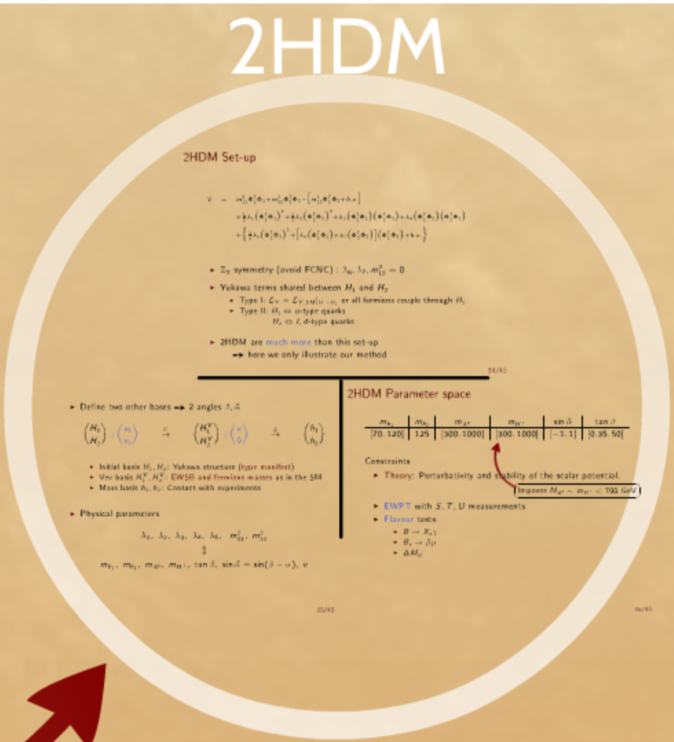
- Correlations between h_1 and h_2 ➞ Choose a scenario

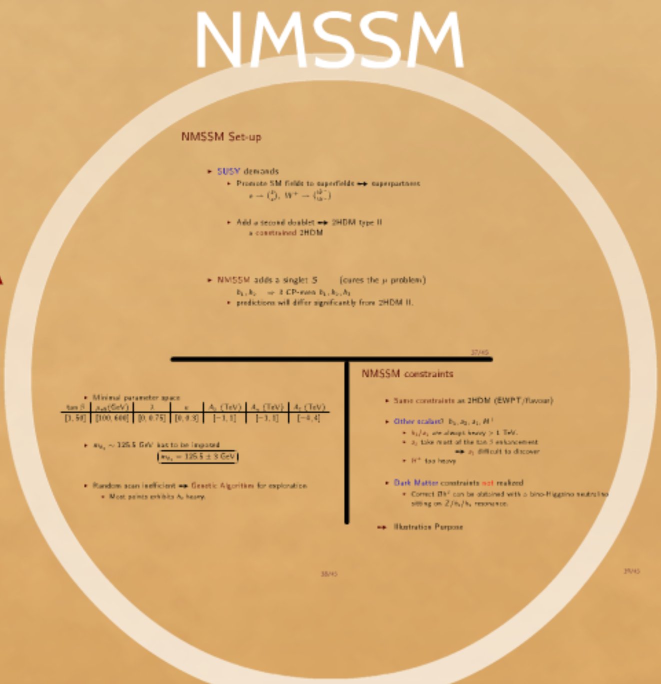
2HDM

- Simple & Rich
- Quite predictive on the whole

NMSSM

- Popular scenario
- Not MSSM ➞ h_2 at 126 GeV disfavoured
  $A^0 \to \bar{\tau}\tau$, flavour ($B \to X_s\gamma$, $B_s \to \bar{\mu}\mu$), . . .
- 3 CP-even scalars ($\neq$ 2HDM)





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2HDM Set-up

$$\begin{aligned}\mathcal{V} \;=\;& m_{11}^2\Phi_1^\dagger\Phi_1+m_{22}^2\Phi_2^\dagger\Phi_2-\left[m_{12}^2\Phi_1^\dagger\Phi_2+h.c.\right]\\ &+\tfrac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2+\tfrac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2+\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right)+\lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)\\ &+\left\{\tfrac{1}{2}\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2+\left[\lambda_6\left(\Phi_1^\dagger\Phi_1\right)+\lambda_7\left(\Phi_2^\dagger\Phi_2\right)\right]\left(\Phi_1^\dagger\Phi_2\right)+h.c.\right\}\end{aligned}$$

- $\mathbb{Z}_2$ symmetry (avoid FCNC) : $\lambda_6, \lambda_7, m_{12}^2 = 0$
- Yukawa terms shared between H_1 and H_2
  - Type I: $\mathcal{L}_Y = \mathcal{L}_{Y,\mathrm{SM}}|_{H\to H_1}$ or all fermions couple through H_1
  - Type II: $H_1 \Leftrightarrow u$-type quarks
    $H_2 \Leftrightarrow l, d$-type quarks
- 2HDM are much more than this set-up
  ⟶ here we only illustrate our method

- Define two other bases ⟶ 2 angles $\beta, \tilde{\alpha}$

$$\begin{pmatrix}H_1\\H_2\end{pmatrix} : \left\langle\begin{matrix}v_1\\v_2\end{matrix}\right\rangle \quad \xrightarrow{\beta} \quad \begin{pmatrix}H_1^V\\H_2^V\end{pmatrix} : \left\langle\begin{matrix}v\\0\end{matrix}\right\rangle \quad \xrightarrow{\tilde{\alpha}} \quad \begin{pmatrix}h_1\\h_2\end{pmatrix}$$

  - Initial basis H_1, H_2: Yukawa structure (type manifest)
  - Vev basis H_1^V, H_2^V: EWSB and fermions masses as in the SM
  - Mass basis h_1, h_2: Contact with experiments
- Physical parameters

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5,\ \ m_{11}^2,\ m_{22}^2$$
$$\Updownarrow$$
$$m_{h_1},\ m_{h_2},\ m_{A^0},\ m_{H^+},\ \tan\beta,\ \sin\tilde{\alpha} = \sin(\beta-\alpha),\ v$$

2HDM Parameter space

m_{h_1}	m_{h_2}	m_{A^0}	m_{H^+}	$\sin\tilde{\alpha}$	$\tan\beta$
$[70, 120]$	125	$[300, 1000]$	$[300, 1000]$	$[-1, 1]$	$[0.35, 50]$

Constraints

- Theory: Perturbativity and stability of the scalar potential.

Imposes $M_{A^0} \sim m_{H^+} < 700$ GeV

- EWPT with S, T, U measurements
- Flavour tests
  - $B \to X_s\gamma$
  - $B_s \to \bar{\mu}\mu$
  - ΔM_d

2HDM Set-up

$$\begin{aligned}\mathcal{V} \quad = \quad & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c. \right] \\ & + \tfrac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \tfrac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) \\ & + \left\{ \tfrac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\right]\left(\Phi_1^\dagger \Phi_2\right) + h.c. \right\}\end{aligned}$$

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- Define two other bases ➞ 2 angles $\beta, \tilde{\alpha}$

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} : \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} \quad \xrightarrow{\beta} \quad \begin{pmatrix} H_1^V \\ H_2^V \end{pmatrix} : \begin{pmatrix} v \\ 0 \end{pmatrix} \quad \xrightarrow{\tilde{\alpha}} \quad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

  - Initial basis H_1, H_2: Yukawa structure (type manifest)
  - Vev basis H_1^V, H_2^V: EWSB and fermions masses as in the SM
  - Mass basis h_1, h_2: Contact with experiments

- Physical parameters

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5,\ \ m_{11}^2,\ m_{22}^2$$
$$\Updownarrow$$
$$m_{h_1},\ m_{h_2},\ m_{A^0},\ m_{H^+},\ \tan\beta,\ \sin\tilde{\alpha} = \sin(\beta - \alpha),\ v$$

2HDM Parameter space

m_{h_1}	m_{h_2}	m_{A^0}	m_{H^+}	$\sin\tilde{\alpha}$	$\tan\beta$
$[70, 120]$	125	$[300, 1000]$	$[300, 1000]$	$[-1, 1]$	$[0.35, 50]$

Constraints

- Theory: Perturbativity and stability of the scalar potential.

Imposes $M_{A^0} \sim m_{H^+} < 700$ GeV

- EWPT with S, T, U measurements
- Flavour tests
    - $B \to X_s \gamma$
    - $B_s \to \bar{\mu}\mu$
    - ΔM_d

NMSSM Set-up

- SUSY demands
  - Promote SM fields to superfields ➞ superpartners
    $e \to \binom{\tilde{e}}{e},\ W^+ \to \binom{\tilde{W}^+}{W^+}$
  - Add a second doublet ➞ 2HDM type II
    a constrained 2HDM
- NMSSM adds a singlet S (cures the μ problem)
  $h_1, h_2 \quad \Rightarrow$ 3 CP-even h_1, h_2, h_3
  - predictions will differ significantly from 2HDM II.

- Minimal parameter space

$\tan\beta$	μ_{eff}(GeV)	λ	κ	A_λ (TeV)	A_κ (TeV)	A_t (TeV)
$[1, 50]$	$[100, 600]$	$[0, 0.75]$	$[0, 0.3]$	$[-1, 1]$	$[-1, 1]$	$[-4, 4]$

- $m_{h_2} \sim 125.5$ GeV has to be imposed

$$\boxed{m_{h_2} = 125.5 \pm 3 \text{ GeV}}$$

- Random scan inefficient ➞ Genetic Algorithm for exploration
  - Most points exhibits h_2 heavy.

NMSSM constraints

- Same constraints as 2HDM (EWPT/flavour)
- Other scalars? h_3, a_2, a_1, H^+
  - h_3/a_2 are always heavy > 1 TeV.
  - a_2 take most of the $\tan\beta$ enhancement
    ➞ a_1 difficult to discover
  - H^+ too heavy
- Dark Matter constraints not realized
  - Correct Ωh^2 can be obtained with a bino-Higgsino neutralino sitting on $Z/h_1/h_2$ resonance.

➞ Illustration Purpose

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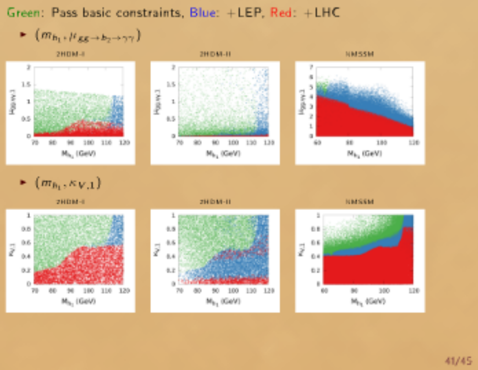
→ Illustration Purpose

Results

- Focus on $gg \to h_1 \to \gamma\gamma$ @LHC
    - In the alignment limit, $h_2 = h^{SM}$ and $gg \to h_1 \to \gamma\gamma \searrow 0$

- In terms of $\kappa_{X,i}$
    - LEP limit for $\sim$ all final states

      ➜ Limits on $(m_{h_1}, \kappa_{V,1})$!

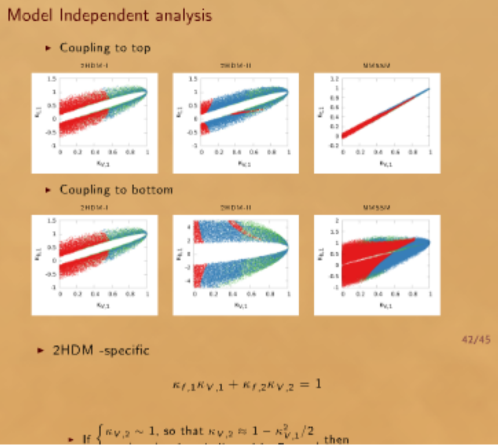


Green: Pass basic constraints, Blue: +LEP, Red: +LHC

- $(m_{h_1}, \mu_{gg \to h_1 \to \gamma\gamma})$
- $(m_{h_1}, \kappa_{V,1})$

    - Behaviour can be understood based on κ
        - e.g. in the NMSSM, $\kappa_{V,1} \sim \kappa_{t,1}$, hence production through $gg \to h$ and VBF scale similarly

E



Model Independent analysis

- Coupling to top
- Coupling to bottom

- 2HDM -specific

$$\kappa_{f,1}\kappa_{V,1} + \kappa_{f,2}\kappa_{V,2} = 1$$

- If $\begin{cases} \kappa_{V,2} \sim 1, \text{ so that } \kappa_{V,2} \approx 1 - \kappa^2_{V,1}/2 \end{cases}$, then

Green: Pass basic constraints, Blue: +LEP, Red: +LHC

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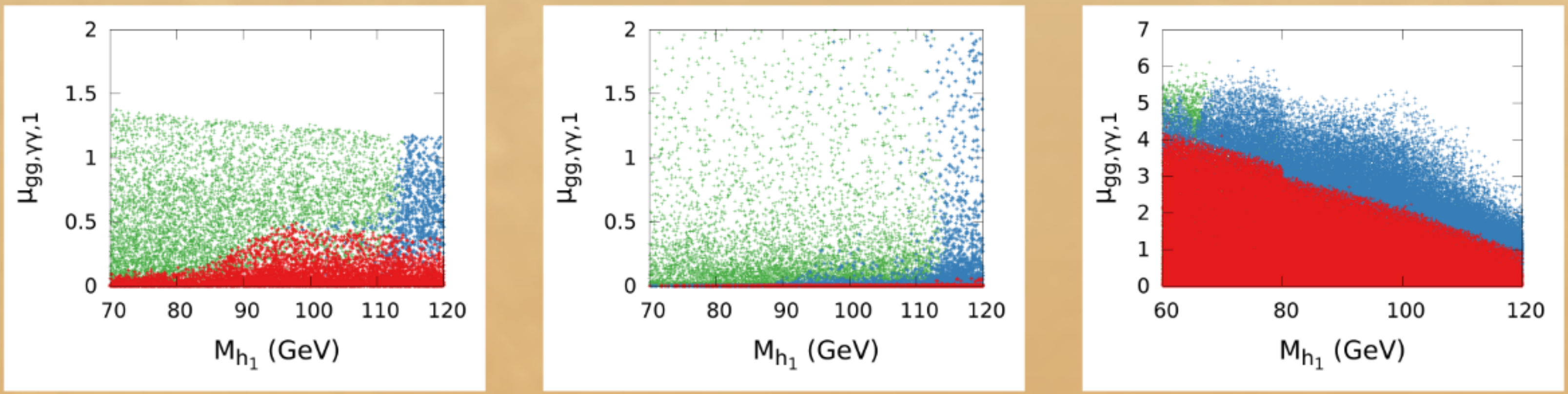
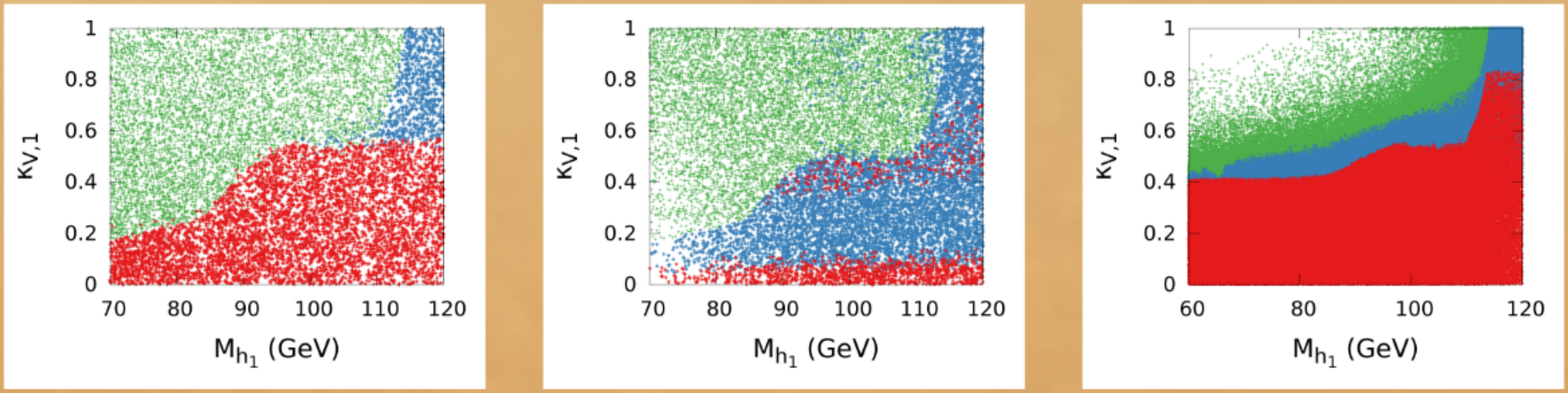


2HDM-I 2HDM-II NMSSM

- $(m_{h_1}, \kappa_{V,1})$



2HDM-I 2HDM-II NMSSM

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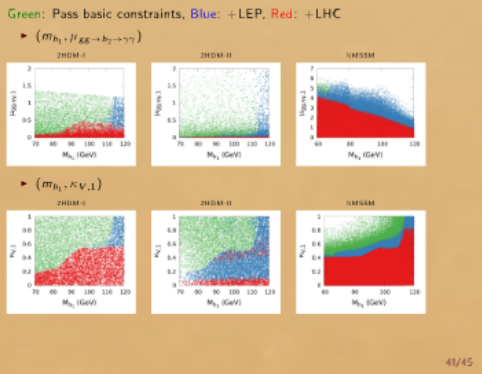

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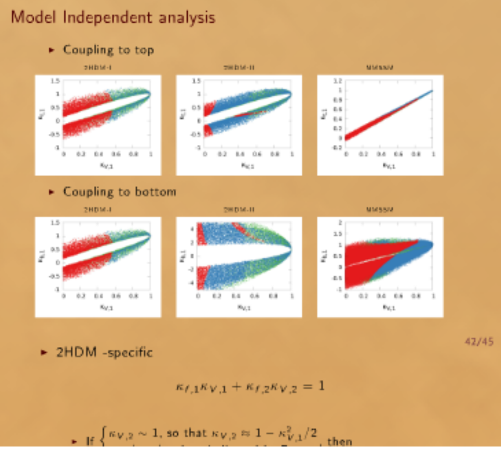

Model Independent analysis

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42/45

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Model Independent analysis

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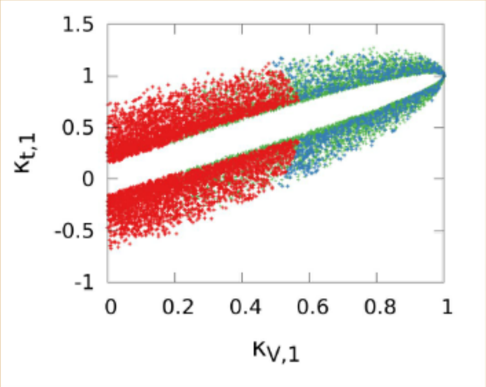
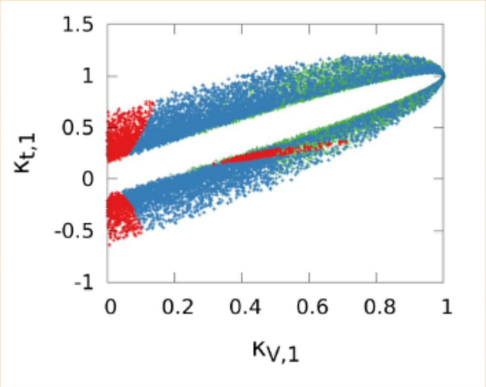
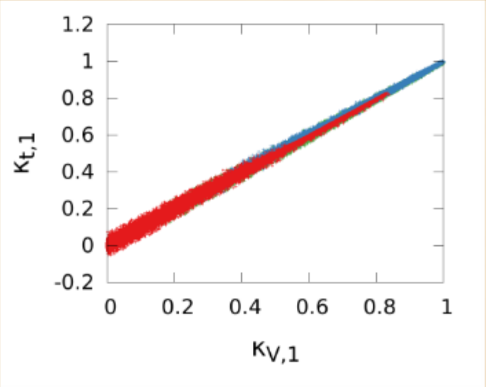
2HDM-I



2HDM-II

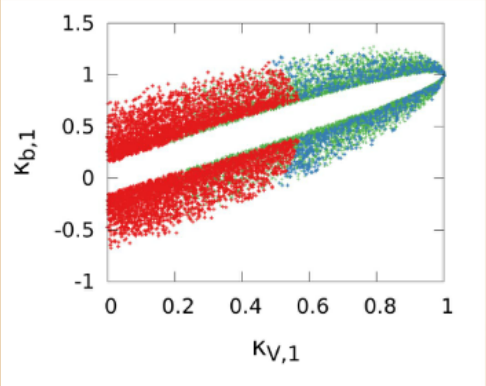


NMSSM

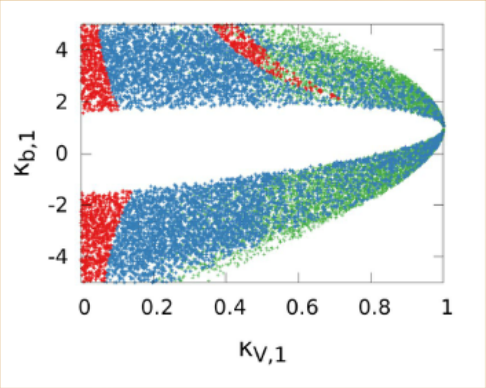


- Coupling to bottom

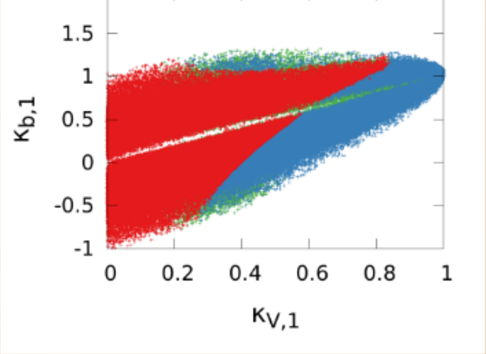
2HDM-I



2HDM-II



NMSSM



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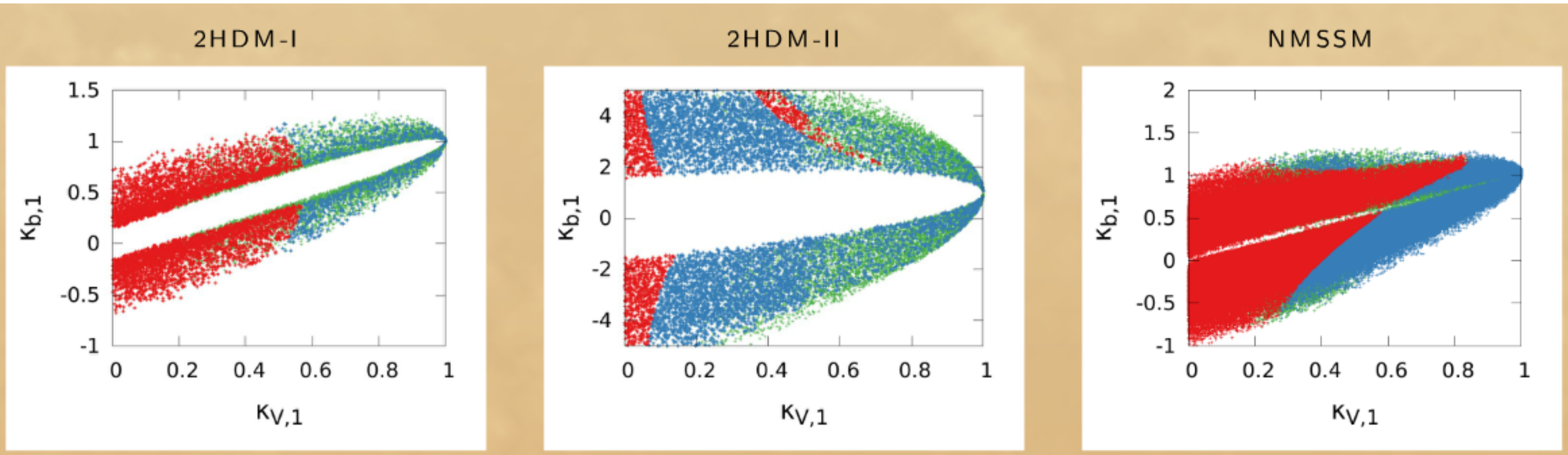

- 2HDM -specific

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- If $\begin{cases} \kappa_{V,2} \sim 1, \text{ so that } \kappa_{V,2} \approx 1 - \kappa_{V,1}^2/2 \\ |\kappa_{f,2}| \approx 1 \text{ as indicated by } \Gamma_h \end{cases}$, then

  $\kappa_{f,1} = \kappa_{V,1}/2$ or $\kappa_{f,1} = 2/\kappa_{V,1}$ depending on $sg(\kappa_{f,2})$

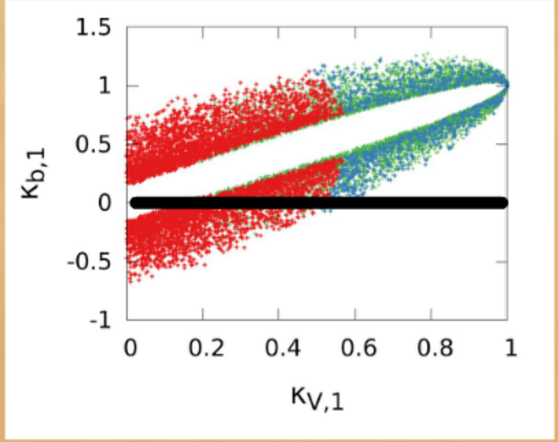
  - In type II, $|\kappa_{V,2}|$ has to be close to one.

Enhancement of $\mu_{h_1 \to \gamma\gamma}$

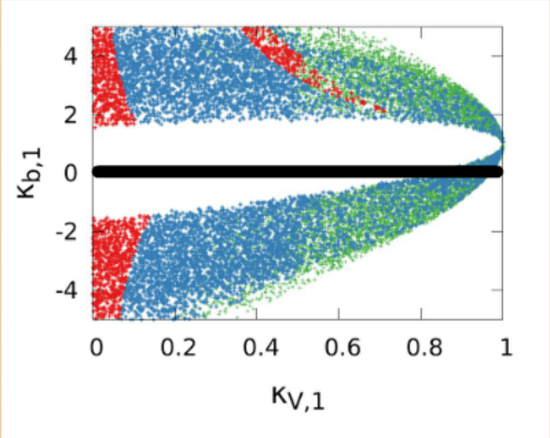
- SM light scalar decay mostly in $\bar{b}b$

➞ if $\kappa_{b,1} \searrow$, then $h_1 \to \gamma\gamma \nearrow$

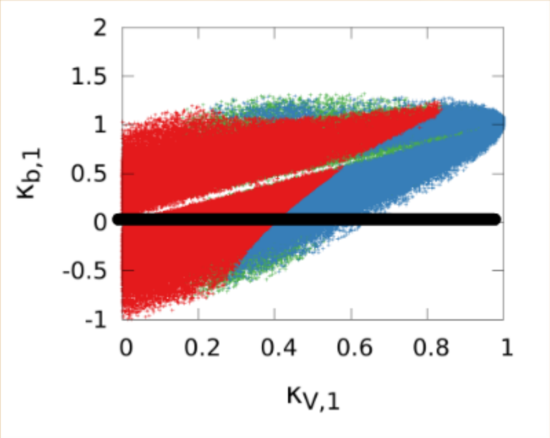
2HDM-I



2HDM-II



NMSSM



- 2HDM-II: ⚠forbidden by flavour
- 2HDM-I: Possible, but $\kappa_{t,1} = \kappa_{b,1}$, so $gg \to h_1$ is reduced
- NMSSM: Possible ➞ $\times 2 - 4$ enhancement.

Additional Light Scalar: Conclusions

- Light scalars arise in many BSM theories

  → Experiments should also target this mass range.

- A combined parametrisation h_1/h_2 is a real plus:
  - Some features appear in a model independent-way ($\kappa_{b,1} \approx 0$)
  - Practical to combine both tests

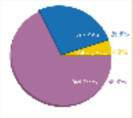
- In particular, can disentangle different models for New Physics

The Standard ~~Model~~ Theory

- All particles have been found
  - M_{H^0} in good agreement with EWPT
- No indications for "not-too-heavy" New Physics (Terascale)
  - *WW* scattering is no longer an option.
  - Bounds on new states are approaching the TeV.
  - Flavour physics → No deviations.
    - Rare decay $B_s \to \bar{\mu}\mu$ observed. . . compatible with SM
- Are we done?

Do we need New Physics?

- Is the SM fully satisfying?
  → One could do with more Naturalness
- The dark matter puzzle:
  → We need one more particle (at least).
  - Or a whole new sector.



- "EWSB + 125 GeV scalar" can be achieved in different ways
  - There is still room for non-SM physics.

Constraining New Physics at the LHC : the SM scalar and Beyond

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Conclusions

- Summary
  - Tools for using LHC H^0 data in NP studies
  - Importance of a parametrisation
  - How this constraint performs w.r.t other searches
    - e.g. direct searches for heavy state, or Dark matter searches
  - Can help with light states as well.
- Perspectives
  - Some tools are not yet mature (uncertainties, fiducial σ)
    - Hope to improve before Run 2
  - Model-testing will benefit a lot more from LHC.

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