Higgs and Electroweak Physics
[theory summary]

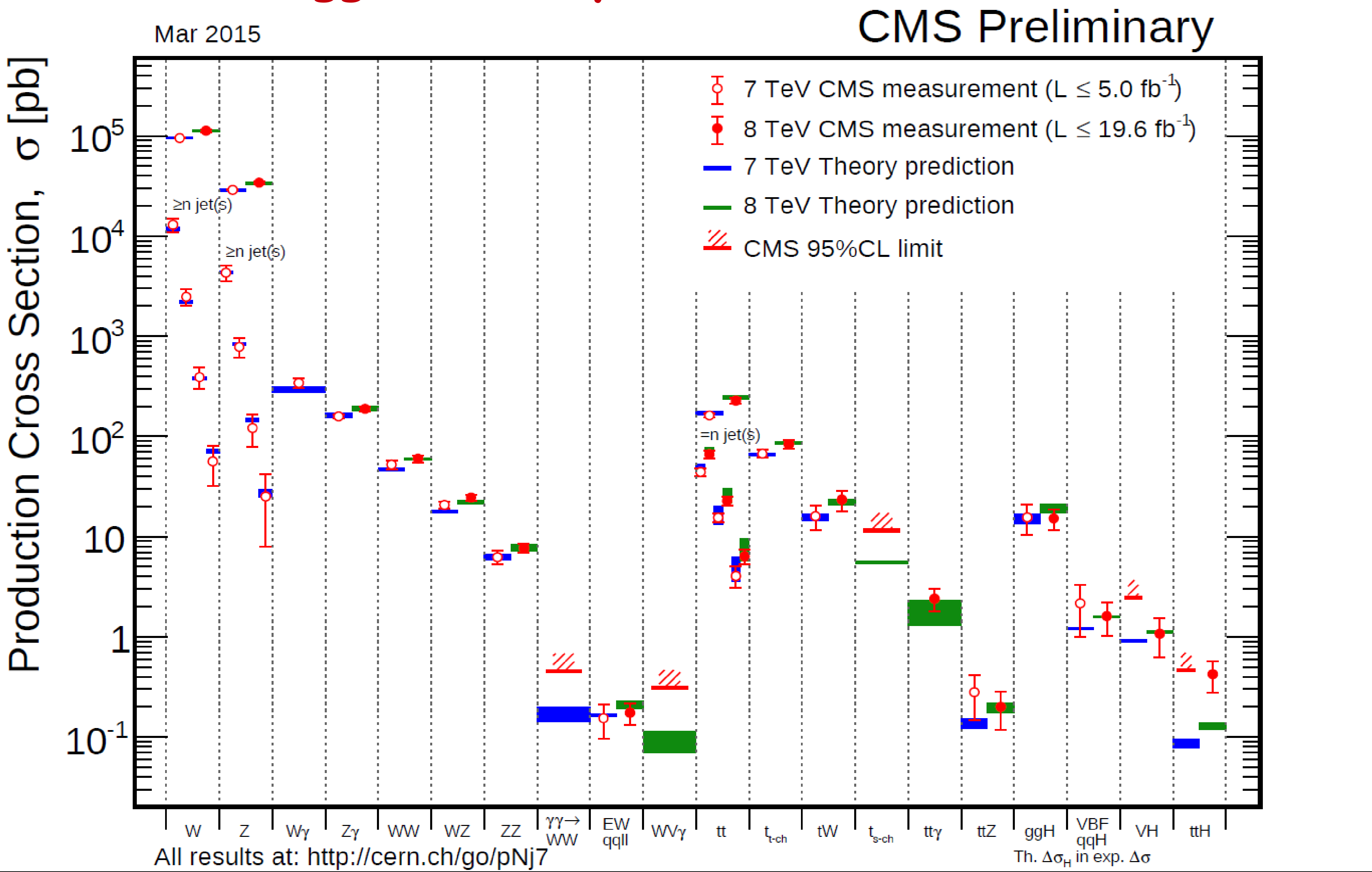
Alexander Belyaev

Southampton University & Rutherford Appleton LAB

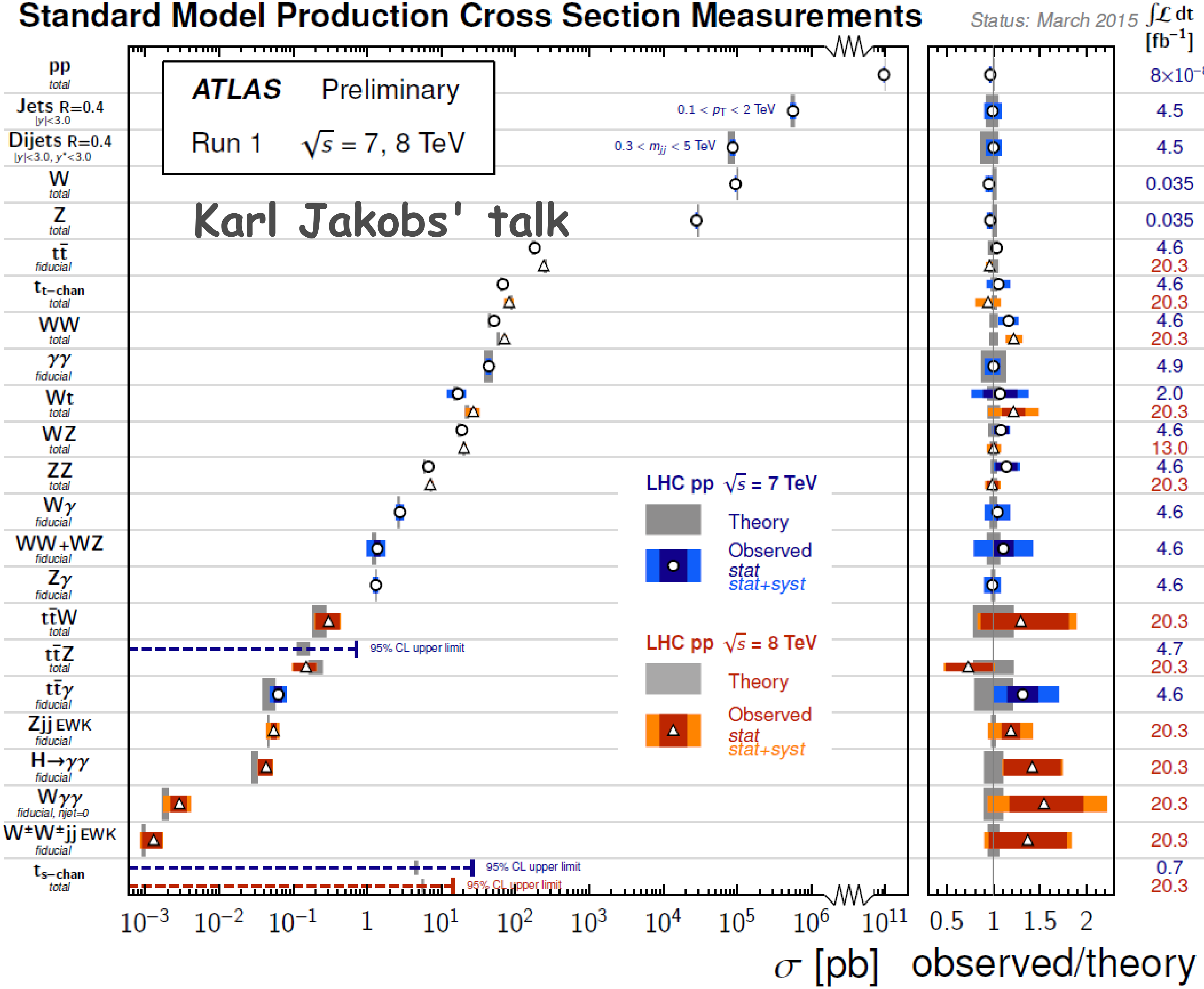
WIN2015

June 12, 2015, MPIK Heidelberg

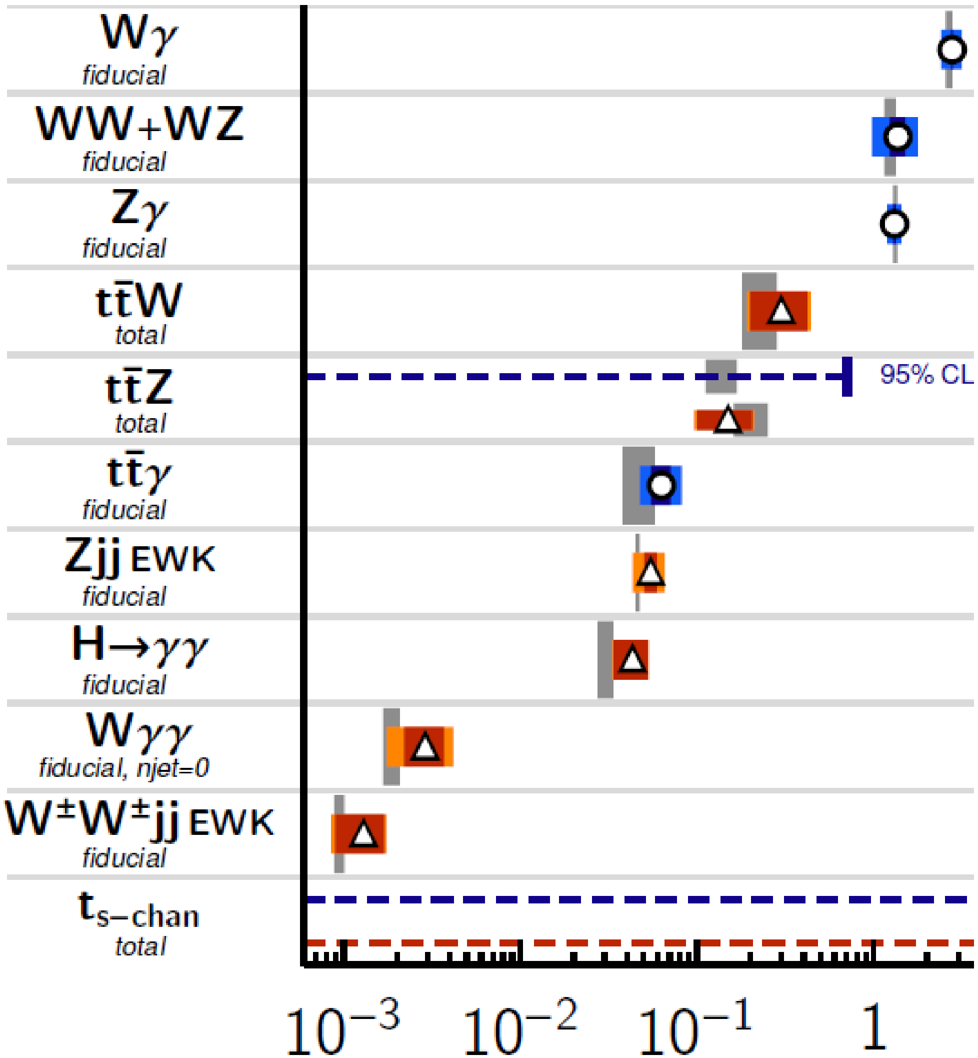
Present: impressive success of LHC RUN 1 on the Higgs&EW Physics measurements!

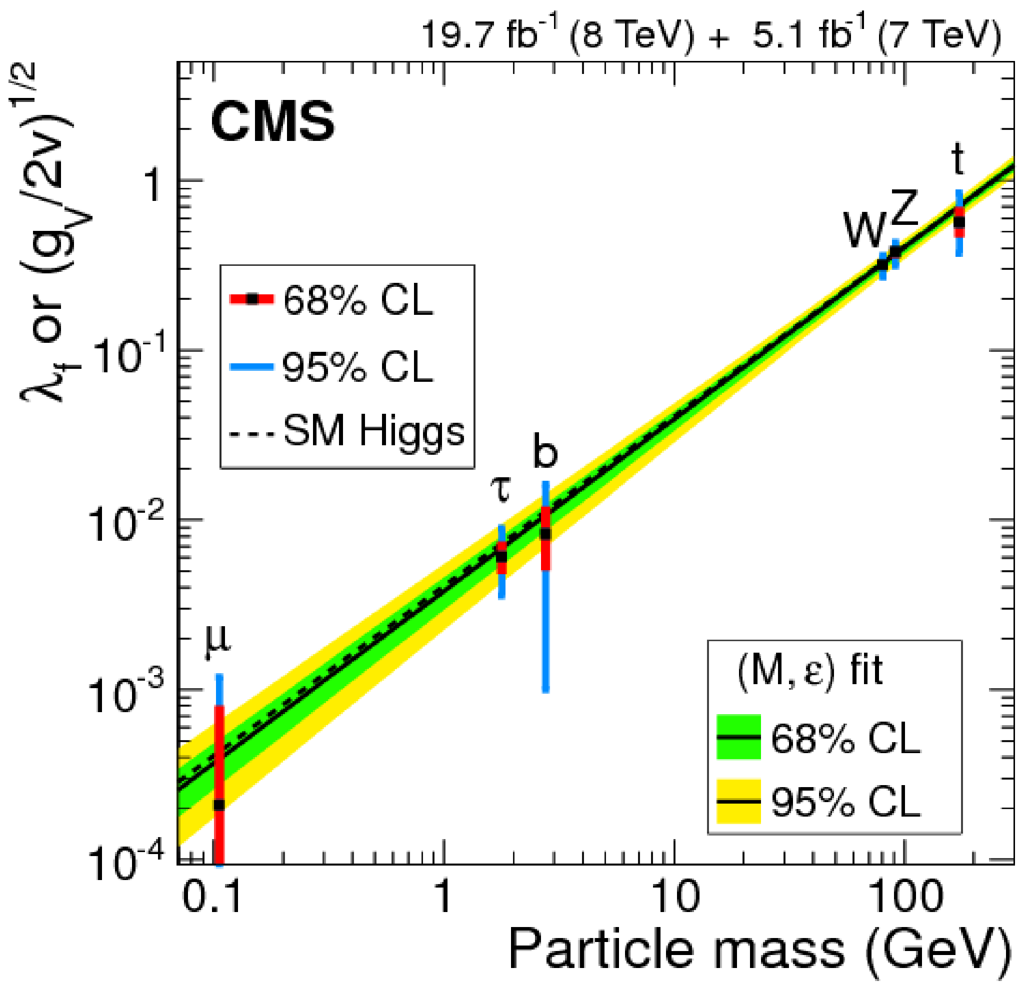


Standard Model Production Cross Section Measurements



Present: no deviations from SM ...





Higgs Boson Discovery has completed the puzzle of the Standard model ...

But it has raised even more questions than the number of answers it has given!

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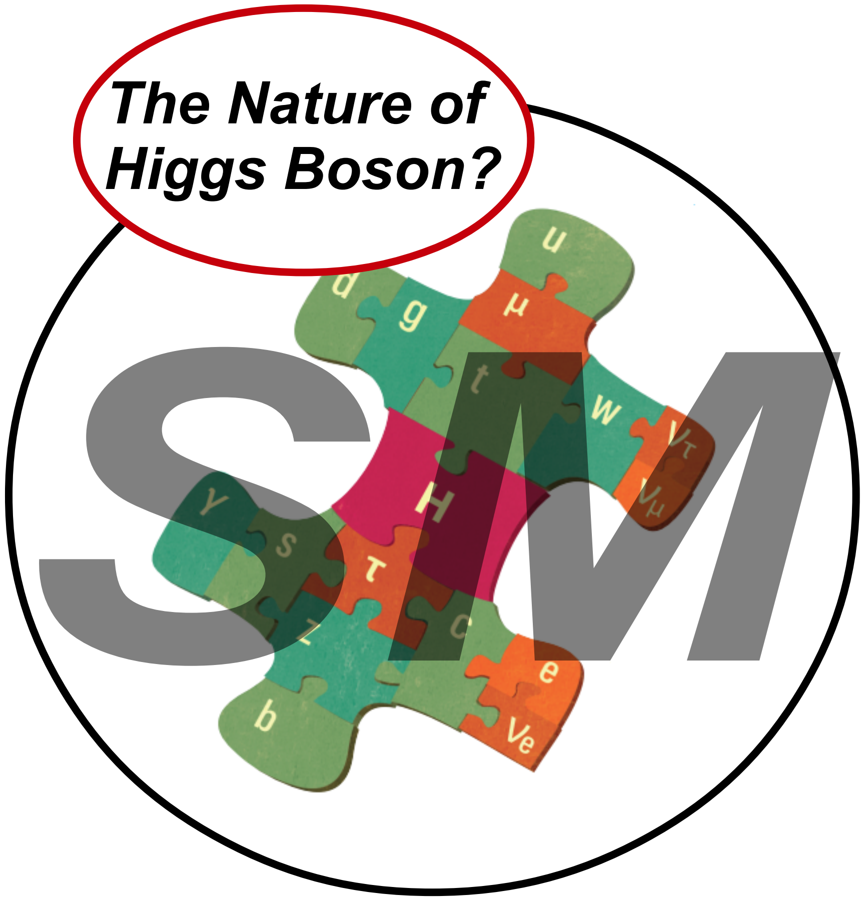

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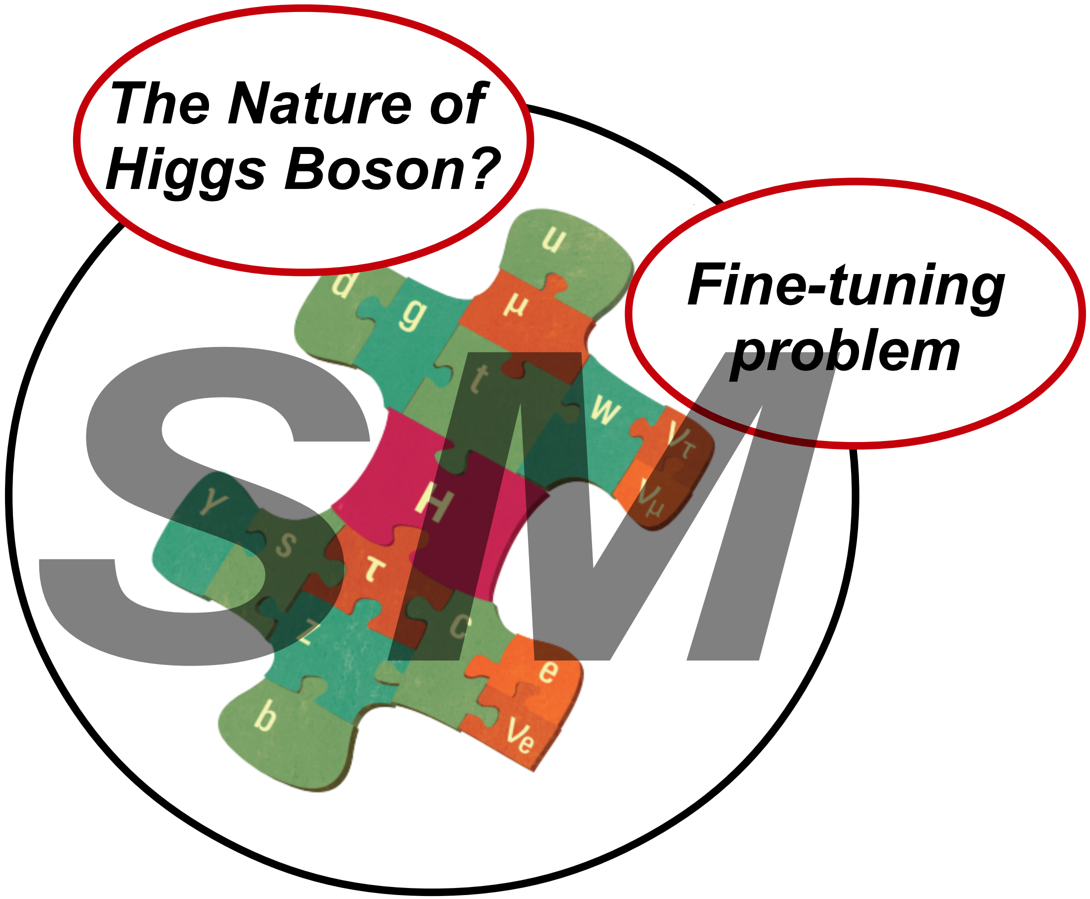

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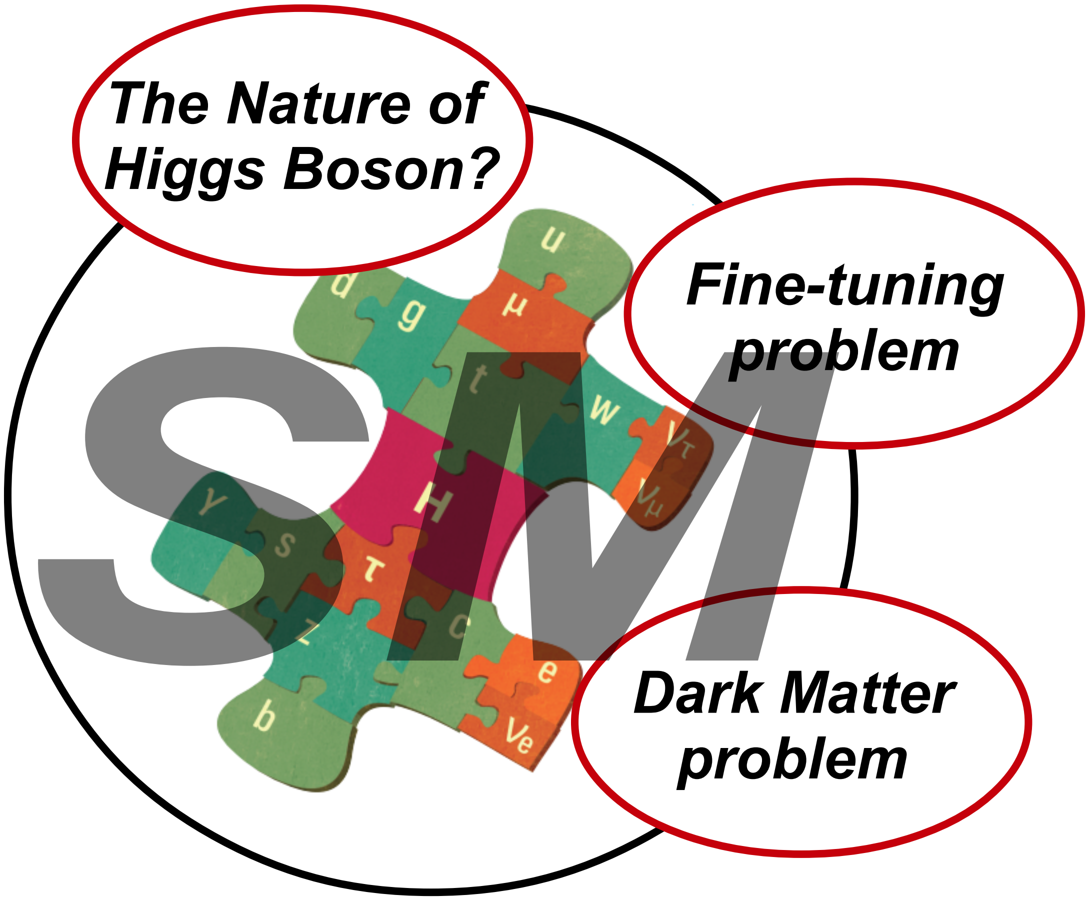

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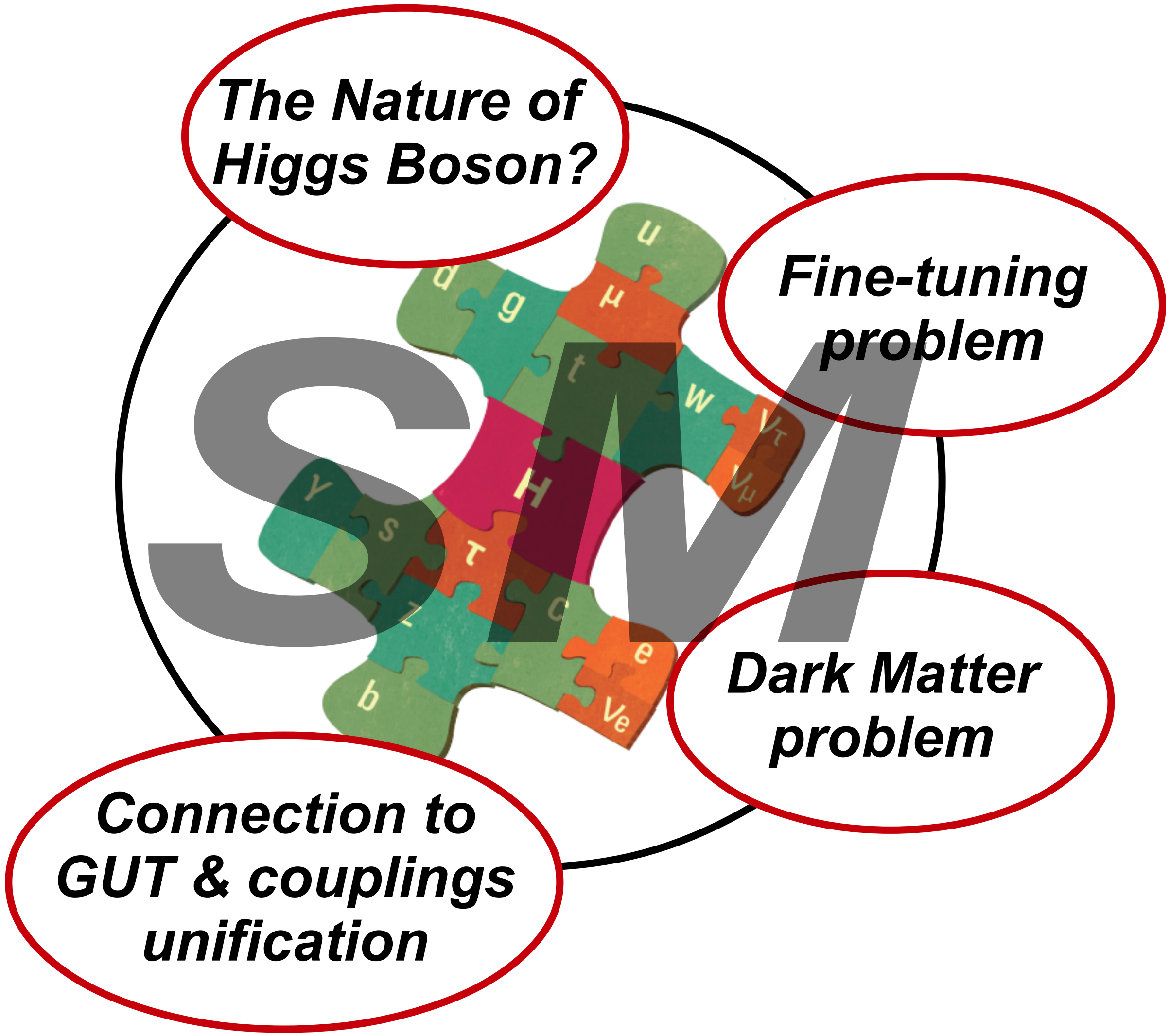

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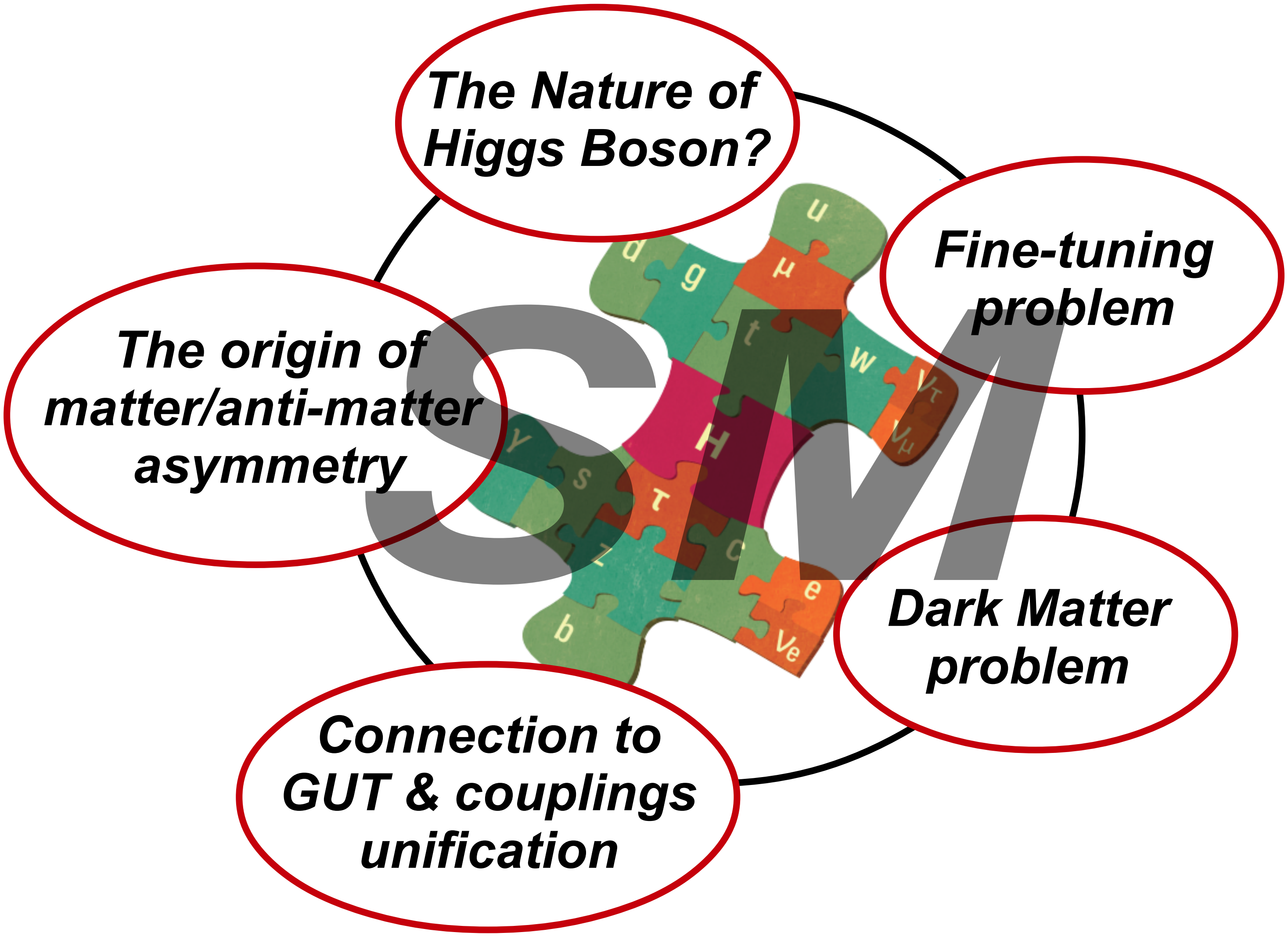
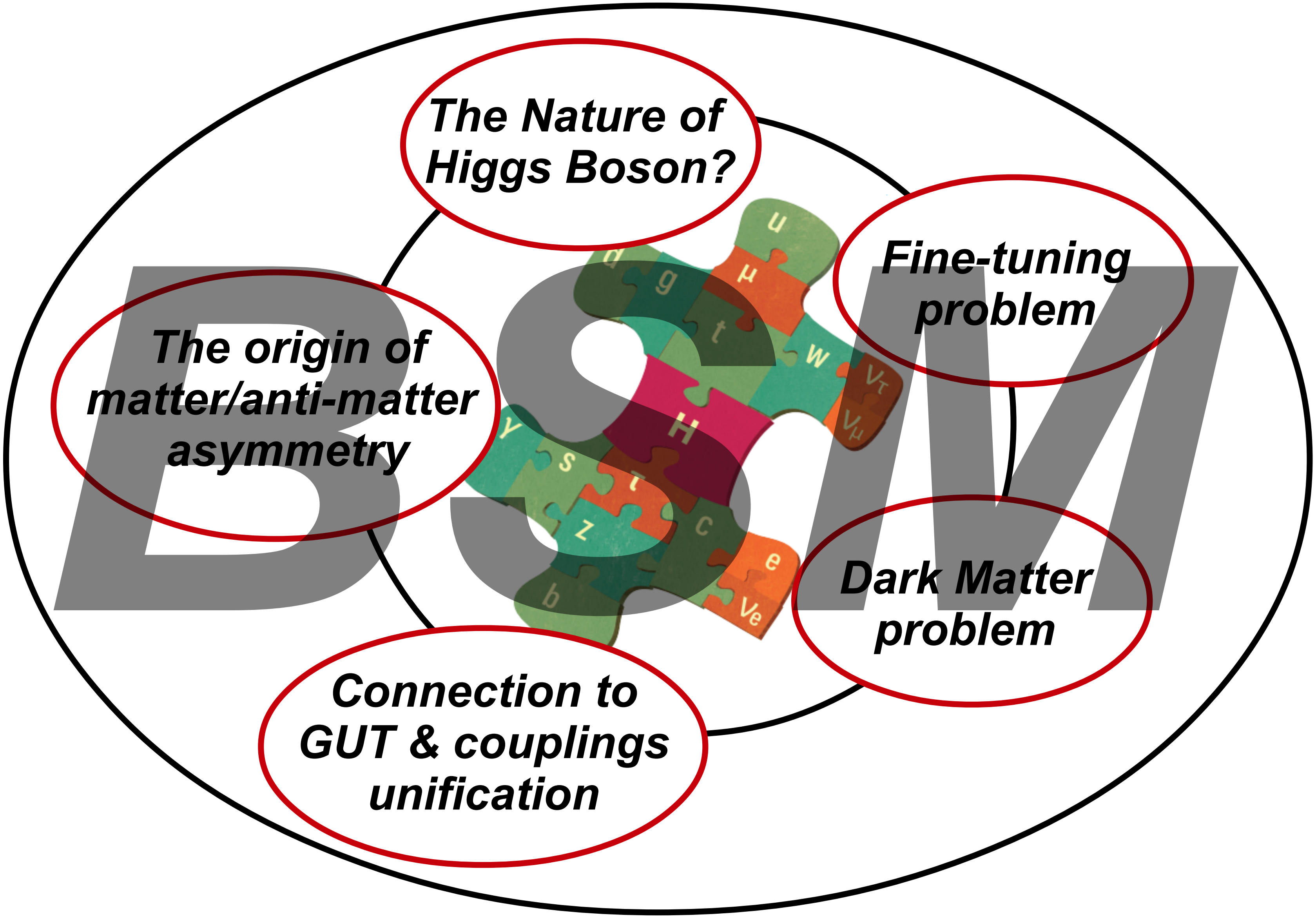
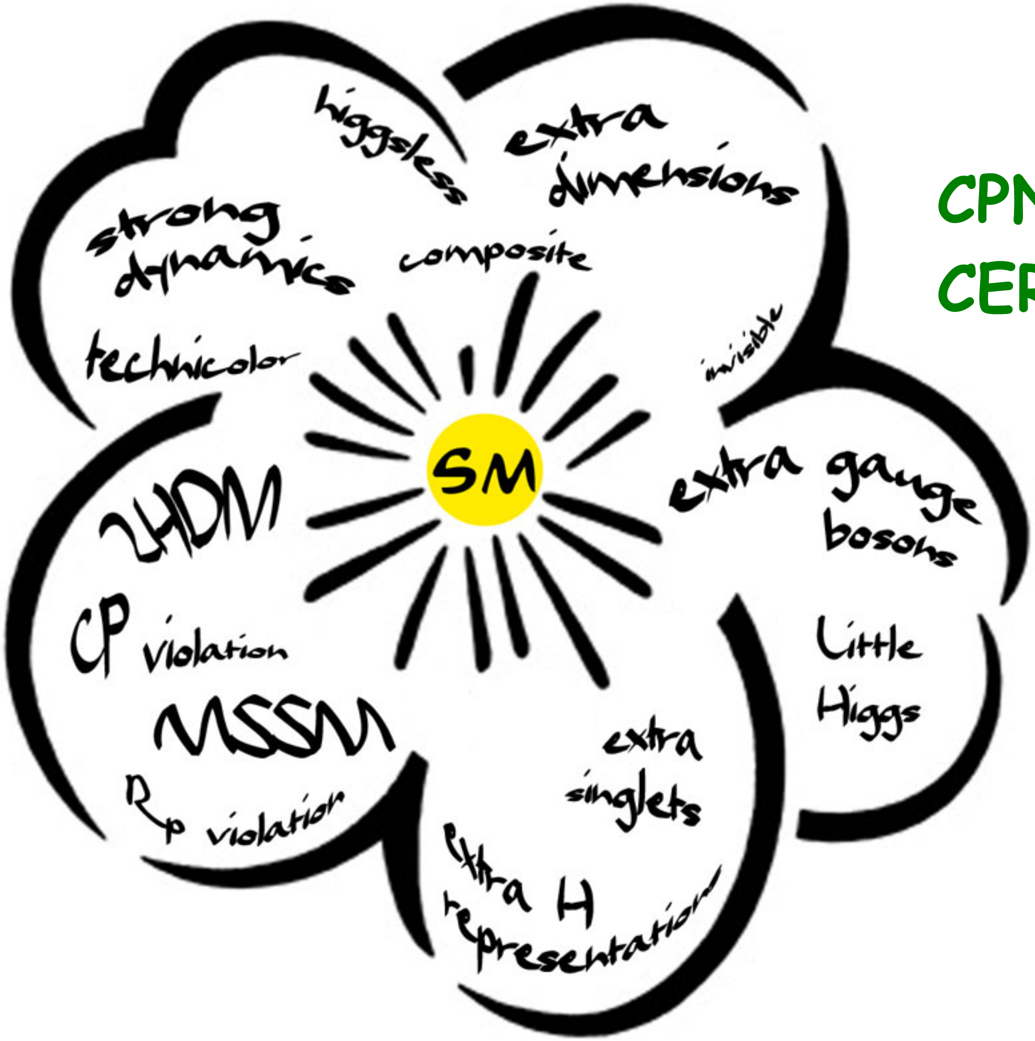


Higgs boson properties are consistent with main compelling BSM theories, so the pattern we have is just a piece of a much bigger puzzle!



Beyond the Higgs discovery

- Higgs properties are amazingly consistent with all main compelling underlying theories (except higgsless ones!)
  Some parameter space of BSM theories was eventually excluded.



CPNSH workshop
CERN 2006-009

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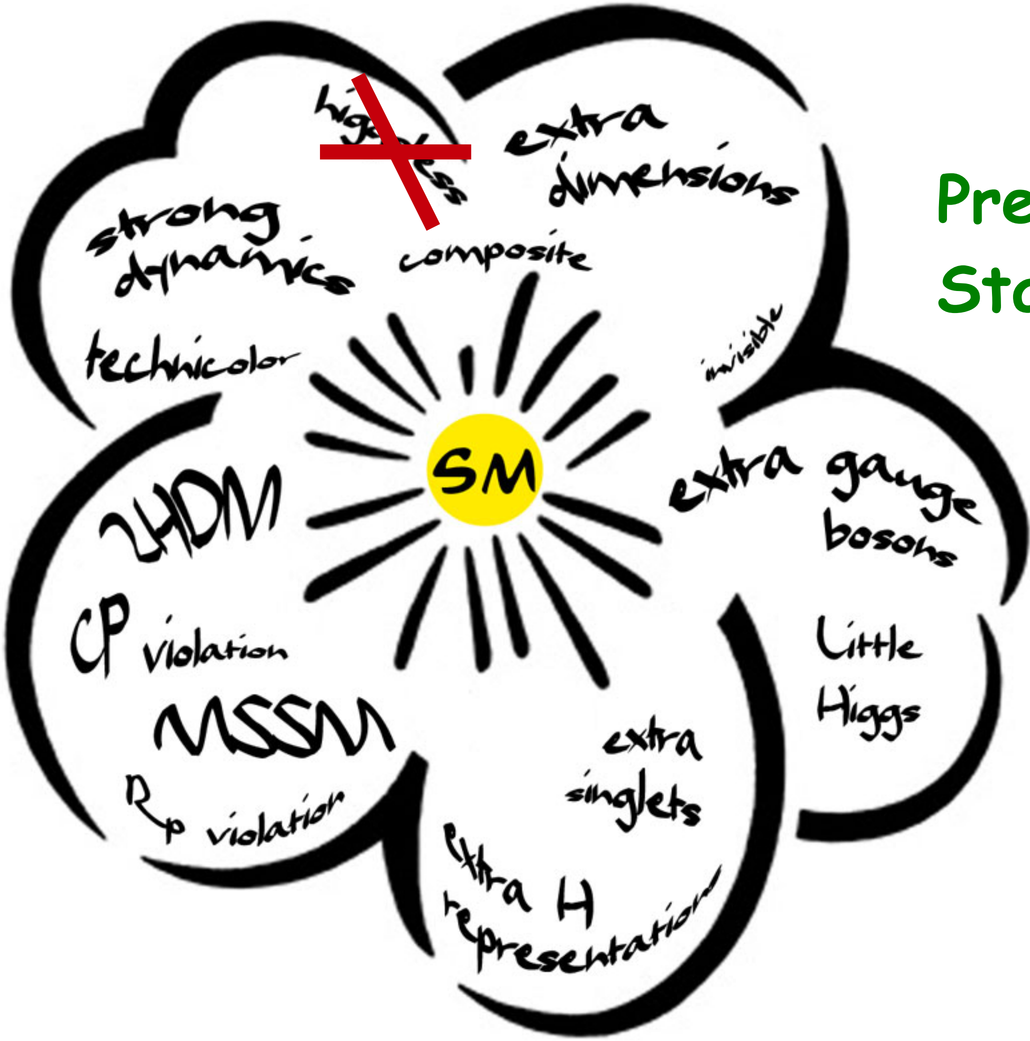

Present Status

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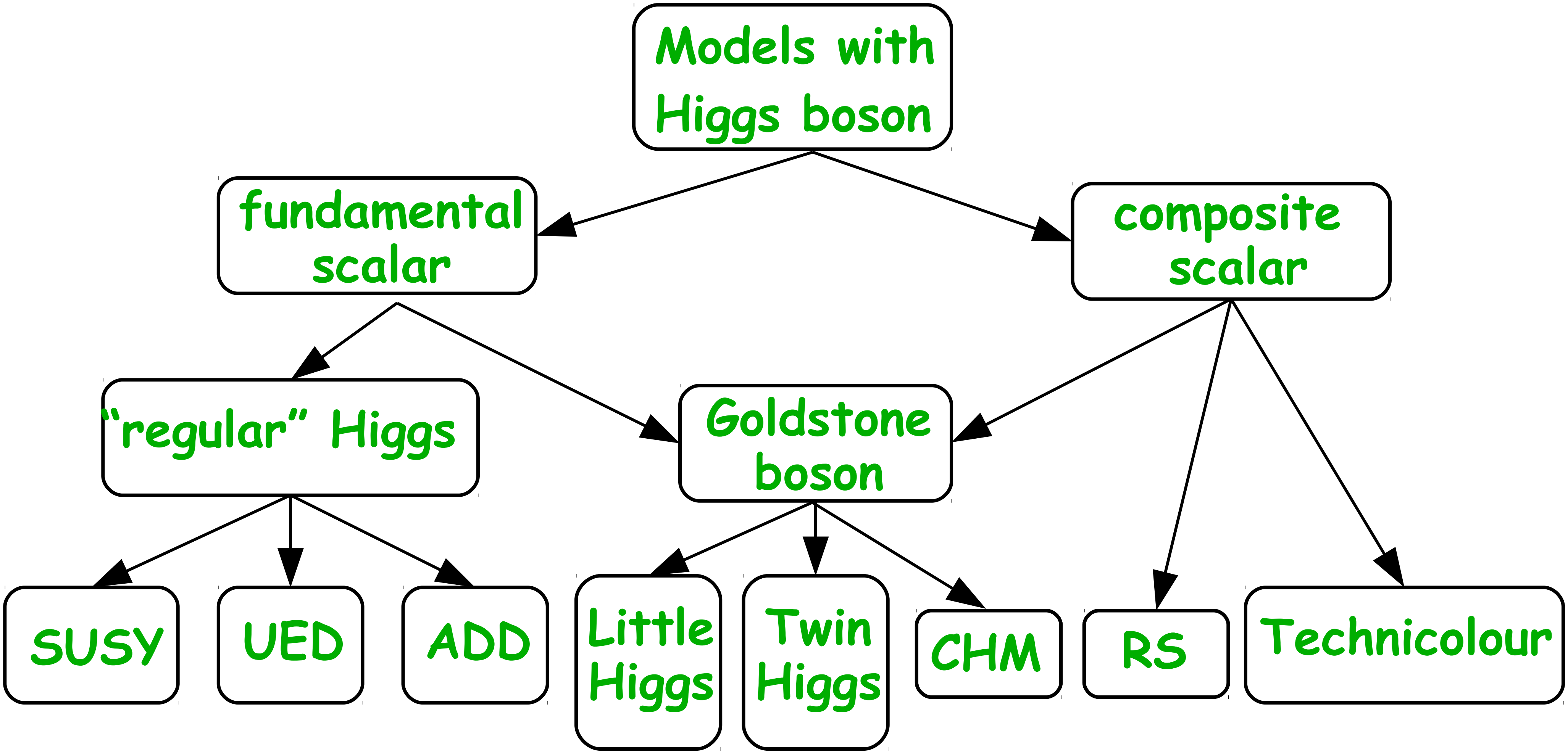

What do we know about BSM?

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It does exist!

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And Higgs & EW sector is the perfect (may be the best) place to probe it! [see also Alex Pomarol's talk]

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And Higgs & EW sector is the perfect (may be the best) place to probe it! [see also Alex Pomarol's talk]

- Higgs production cross sections, coupling determination, model-independent analysis (higher-dimensional operators)
- Higgs width
- New Higgs Decays
- Longitudinal Vector Boson scattering ($V_L V_L$), unitarity considerations, new vector and scalar resonances
- New states decaying into Higgs – SUSY, TC, CHM
- Dark Matter Connections – Higgs and/or EW bosons portals
- Connection to inflation
- Neutrino Physics
- Flavour Physics
- ....

Higgs&EW group at WIN2015

23 talks, great TH<->EXP dialog, new results!

“Measurements of the Higgs Boson Coupling and Properties at the LHC”	[***Marcello Fanti***]
“Search for the Higgs the associate production ttH at the LHC”	[***Daniele Zanzi***]
“Search for additional higgs-like resonances with heavy masses at the LHC”	[***Matthias Ulrich Mozer***]
“Unified approach to composite Higgs phenomenology”	[***Mads Frandsen***]
“Multiboson production and searches for anomalous gauge couplings at the LHC”	[***Zhaoru Zhang***]
“VBF and multi-boson production, Higgs anomalous couplings”	[***Marc Thomas***]
“New developments in SUSY Higgs area	[***Sven Heinemeyer***]
“Searches for Supersymmetric Higgs signatures at the LHC”	[***Nicolaos Rompotis***]
"Fully covering the MSSM Higgs sector at the LHC"	[***Jeremie Quevillon***]
“Chances for SUSY-GUT in the LHC Epoch”	[***Marco Chianese***]
“Higgs Signatures from NMSSM”	[***Dilip Ghosh***]
“Higgs-DM connection and the Scale of New Physics”	[***Michael Scherer***]
“Searches exploiting the the Higgs boson as a Dark/Hidden portal at the LHC”	[***James Baker Beacham***]
"Classically Conformal SM extension with DM"	[***Stefano Di Chiara***]
“Discovering a second Higgs doublet via A → Z H”	[***Glauber Carvalho Dorsch***]
“Higgs to fermions at the LHC”	[***Silvio Donato***]
“Search for the Higgs the associate production excluding ttH at the LHC”	[***Prolay Kumar Mal***]
“The SM Vacuum and Higgs inflation”	[***Javier Rubio***]
“EFT approach to the Higgs physics and LHC data fits”	[***Tevong You***]
“The Higgs Legacy of the LHC Run I “	[***Juan Gonzalez Fraile***]
"Higgs width and coupling constraints from the high-mass H→VV process"	[***Nikolaus Kauer***]
“Measurements of the Higgs width at the LHC	[***Roberto Covarelli***]
“HL-LHC. beyond Run 2. prospective”	[***Monica Trovatelli***]

Higgs Couplings measurements/analysis

“Measurements of the Higgs Boson Coupling and Properties at the LHC”	[***Marcello Fanti***]
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EWPTs and Higgs+TGC constraints on dim-6 operators

Tevong You

$$\mathcal{L}_{\rm SM}^{\rm dim\text{-}6} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Juan González Fraile

Operator	Coefficient
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W - c_B)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}c_{HW}$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}c_{HB}$
$\mathcal{O}_{3W} = \frac{1}{3!}g\epsilon_{abc}W^{a\,\nu}_{\mu}W^b_{\nu\rho}W^{c\,\rho\mu}$	$\frac{m_W^2}{\Lambda^2}c_{3W}$
$\mathcal{O}_g = g_s^2\lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$	$\frac{m_W^2}{\Lambda^2}c_g$
$\mathcal{O}_\gamma = g'^2\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}c_\gamma$
$\mathcal{O}_H = \frac{1}{2}(\partial^\mu\lvert H\rvert^2)^2$	$\frac{v^2}{\Lambda^2}c_H$
$\mathcal{O}_f = y_f\lvert H\rvert^2\bar{F}_L H^{(c)} f_R + \text{h.c.}$	$\frac{v^2}{\Lambda^2}c_f$

$$\mathcal{O}_{GG} = \Phi^\dagger\Phi\, G^a_{\mu\nu}G^{a\mu\nu},$$
$$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right),$$
$$\mathcal{O}_{e\Phi,33} = (\Phi^\dagger\Phi)(\bar{L}_3\Phi e_{R,3}),$$

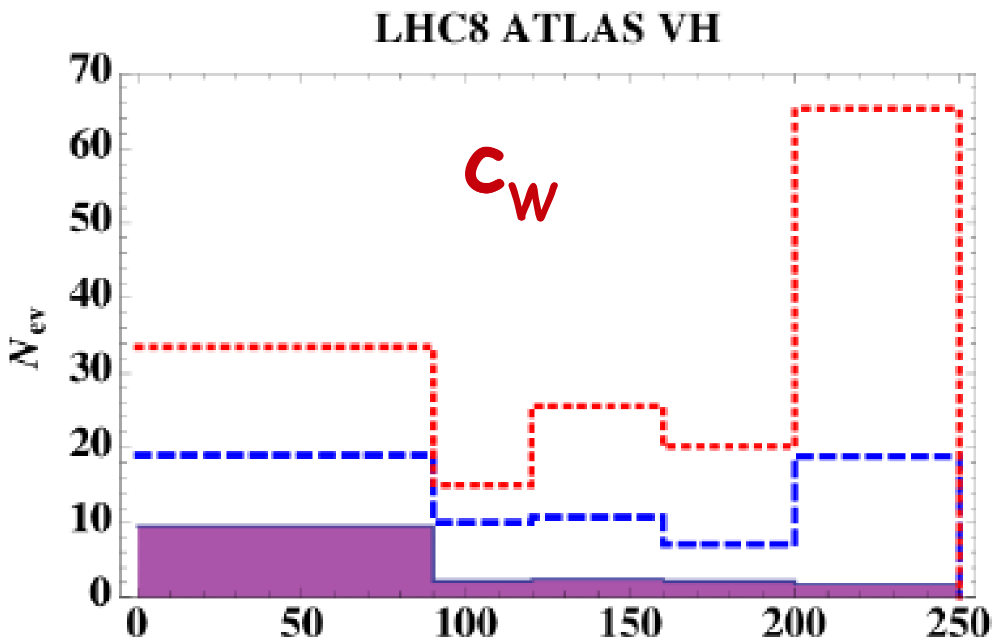
$$\mathcal{O}_{WW} = \Phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi,$$
$$\mathcal{O}_W = (D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\Phi),$$
$$\mathcal{O}_{u\Phi,33} = (\Phi^\dagger\Phi)(\bar{Q}_3\tilde{\Phi}u_{R,3}),$$

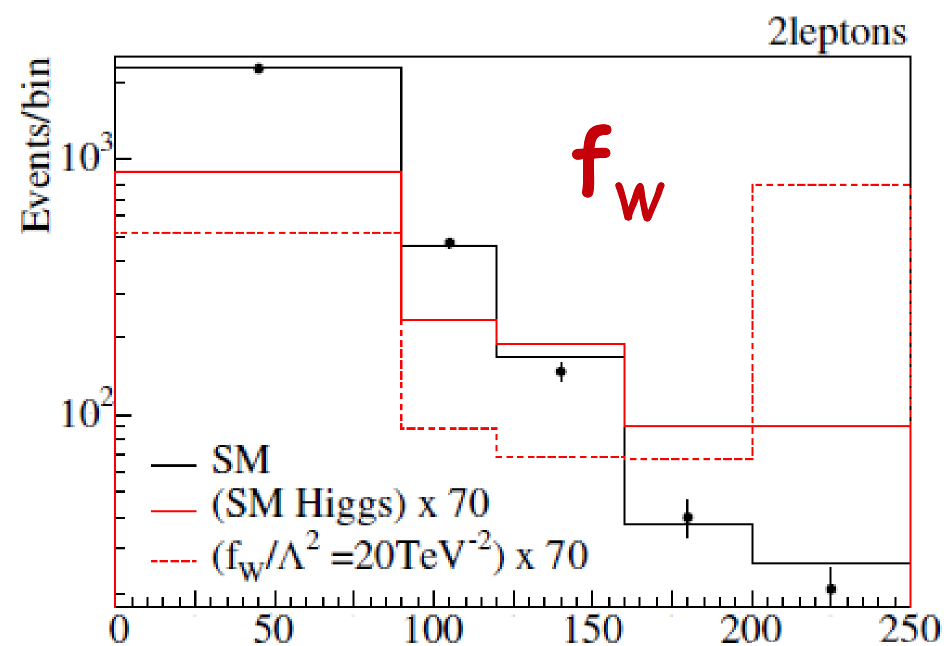
$$\mathcal{O}_{BB} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi,$$
$$\mathcal{O}_B = (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi),$$
$$\mathcal{O}_{d\Phi,33} = (\Phi^\dagger\Phi)(\bar{Q}_3\Phi d_{R,3}),$$

The role of the change of kinematics

Tevong You

Juan González Fraile





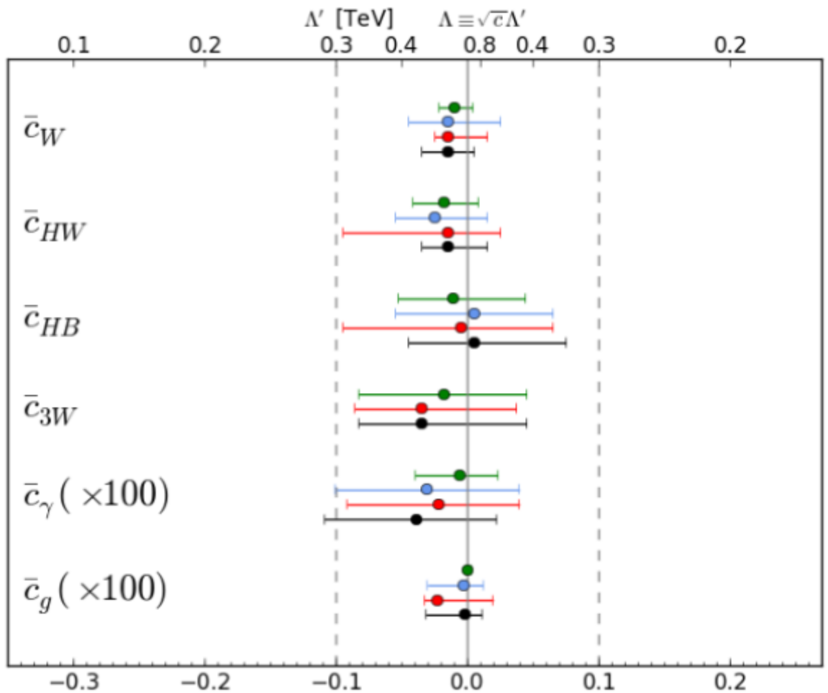
p_T^V in associated production

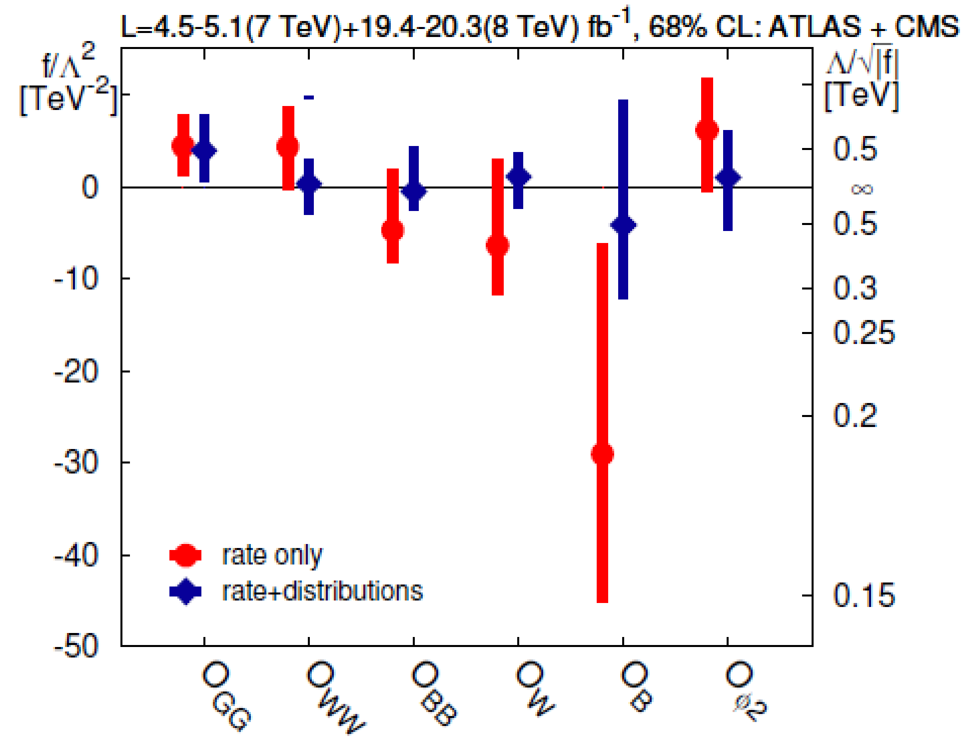
Some operators affect not only the Higgs signal rate but also differential distributions. Taking it into account could significantly increase sensitivity to a new physics!

EWPTs and Higgs+TGC constraints on dim-6 operators taking into account kinematics

Tevong You | **Juan González Fraile**

x 10 TeV





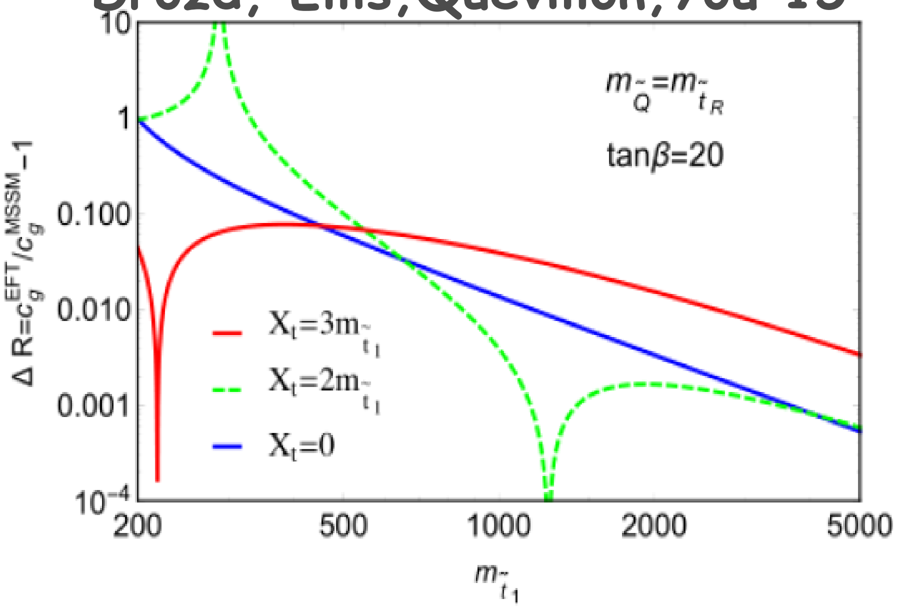
for c_i=1 LHC probes ~ 0.5–5 TeV scale range of Λ with Higgs+TGC couplings
Taking it into account kinematics does increase sensitivity!

Indirect constraints on stops and validity of EFT

Tevong You

- Compare EFT dim-6 vs full MSSM amplitude

Drozd, Ellis, Quevillon, You'15



Coeff.	Experimental constraints		95 % CL limit	deg. $m_{\tilde{t}_1}$, $X_t = 0$
$\bar{c}_g$	LHC	marginalized	$[-4.5, 2.2] \times 10^{-5}$	$\sim$ 410 GeV
		individual	$[-3.0, 2.5] \times 10^{-5}$	$\sim$ 390 GeV
$\bar{c}_\gamma$	LHC	marginalized	$[-6.5, 2.7] \times 10^{-4}$	$\sim$ 215 GeV
		individual	$[-4.0, 2.3] \times 10^{-4}$	$\sim$ 230 GeV
$\bar{c}_T$	LEP	marginalized	$[-10, 10] \times 10^{-4}$	$\sim$ 290 GeV
		individual	$[-5, 5] \times 10^{-4}$	$\sim$ 380 GeV
$\bar{c}_W + \bar{c}_B$	LEP	marginalized	$[-7, 7] \times 10^{-4}$	$\sim$ 185 GeV
		individual	$[-5, 5] \times 10^{-4}$	$\sim$ 195 GeV

below 500 GeV, the EFT breaks down; above 500 GeV EFT provides description with the accuracy better than 10%

Vector Boson Fusion (VBF) and multi-boson Production

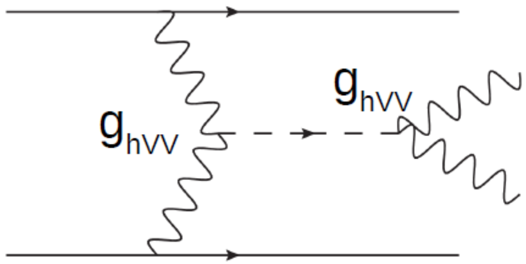
"Multiboson production and searches for anomalous gauge couplings at the LHC" [***Zhaoru Zhang***]

"VBF and multi-boson production, Higgs anomalous couplings" [***Marc Thomas***]

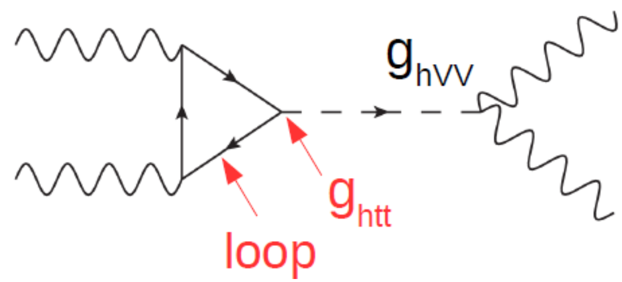
VBF sensitivity to Higgs and new physics

Marc Thomas

- VBF is more model-independent



vs



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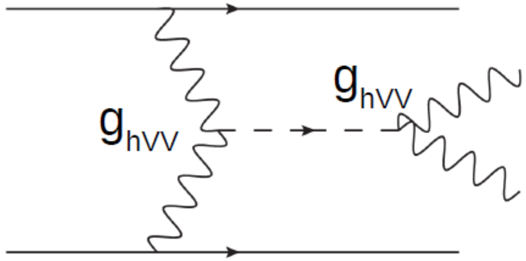
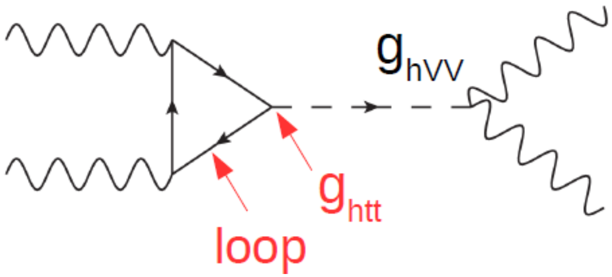
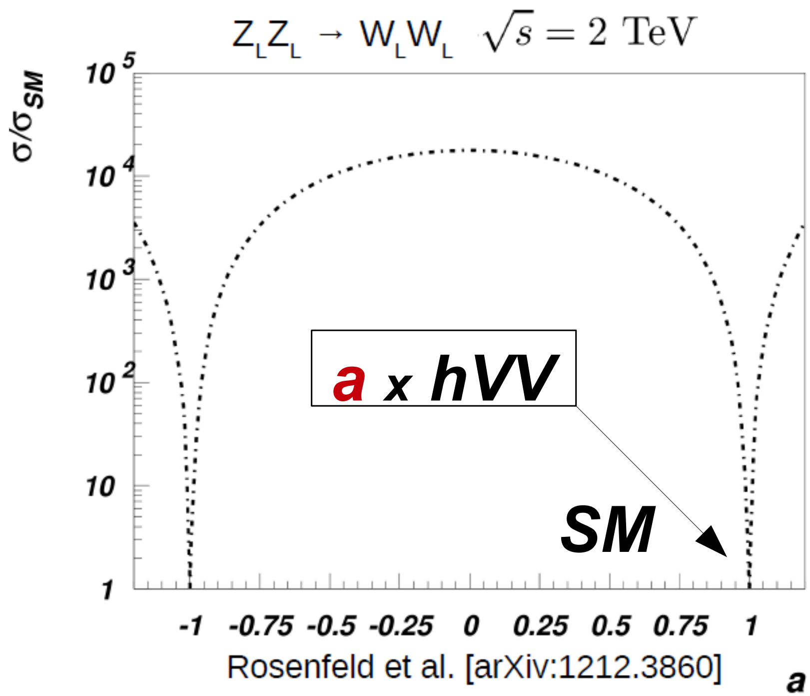


VS



- VBF is sensitive to the lack of cancellation in $V_L V_L$ scattering amplitude



Rosenfeld et al. [arXiv:1212.3860]

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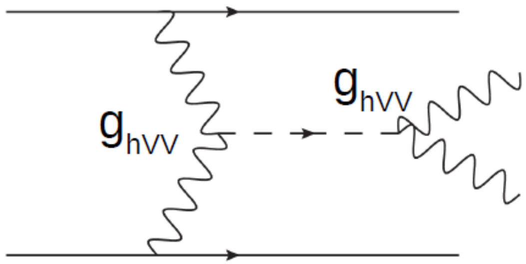

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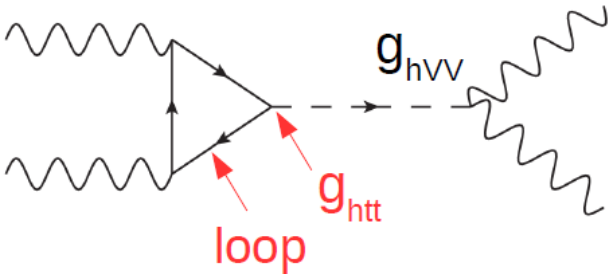

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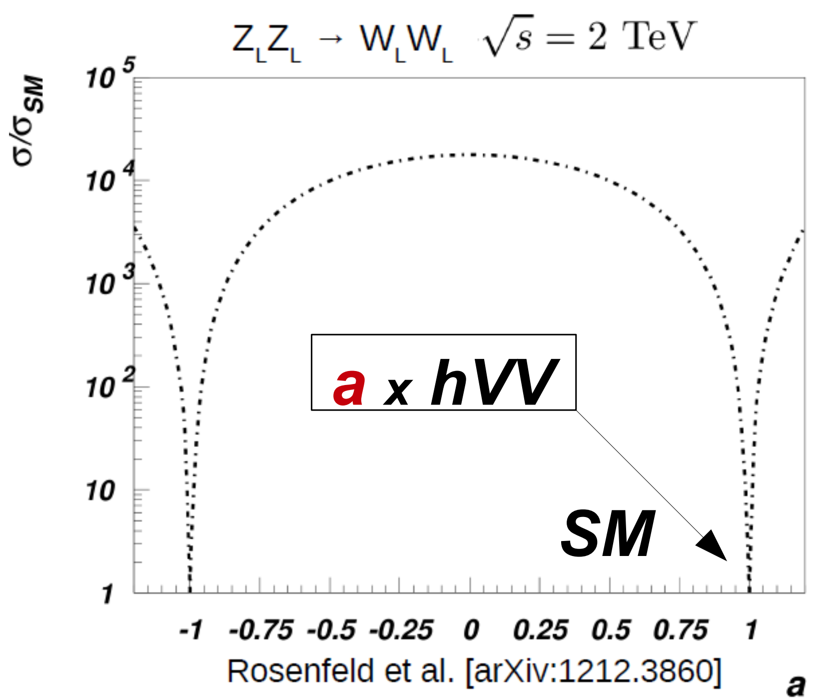

Rosenfeld et al. [arXiv:1212.3860]

- for g_{hVV} deviation from SMthe cross section faster increases with energy for larger numbers of final state particles

$$A_{NL\sigma M}(2 \to n) \sim \frac{s}{v^n}$$

$$\sigma(2 \to n) \sim \frac{1}{s}\left(\frac{s}{v^n}\right)^2 s^{n-2} = \frac{s^{n-1}}{v^n}$$

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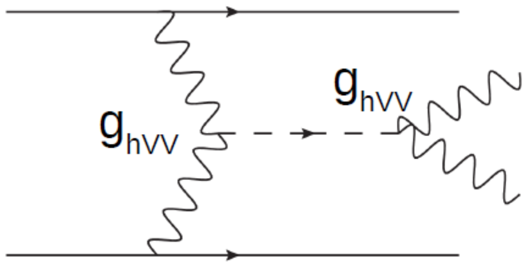

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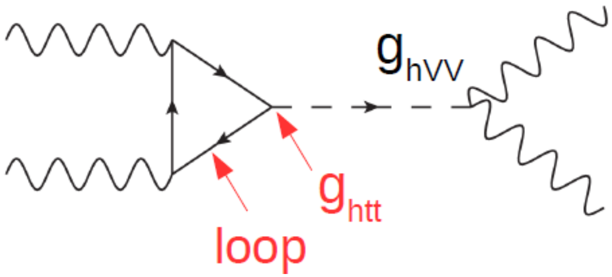

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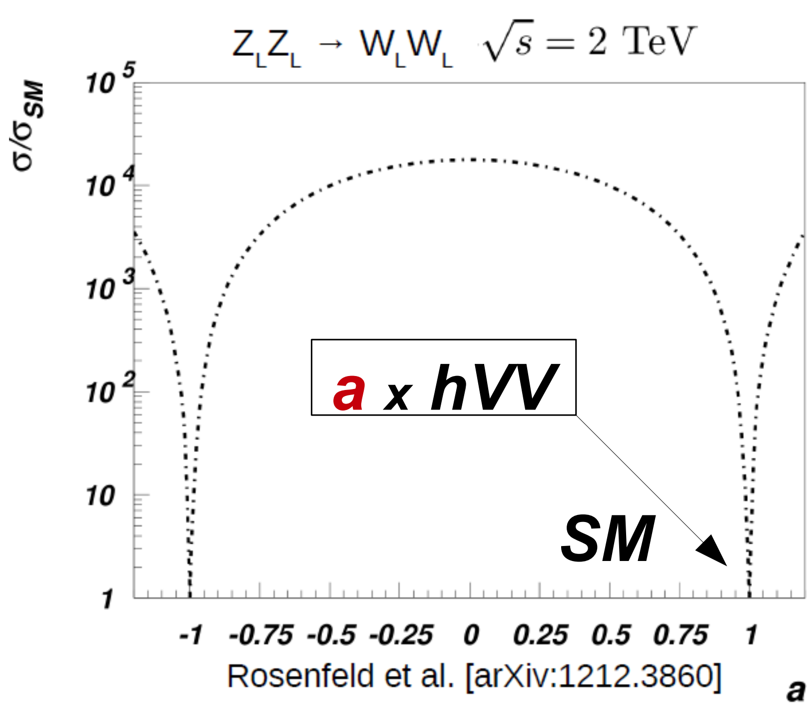

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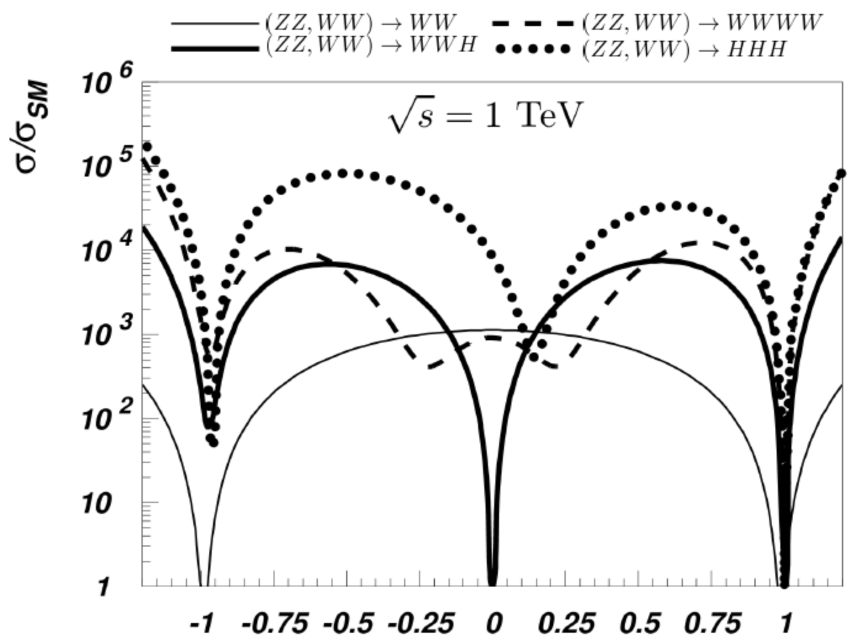
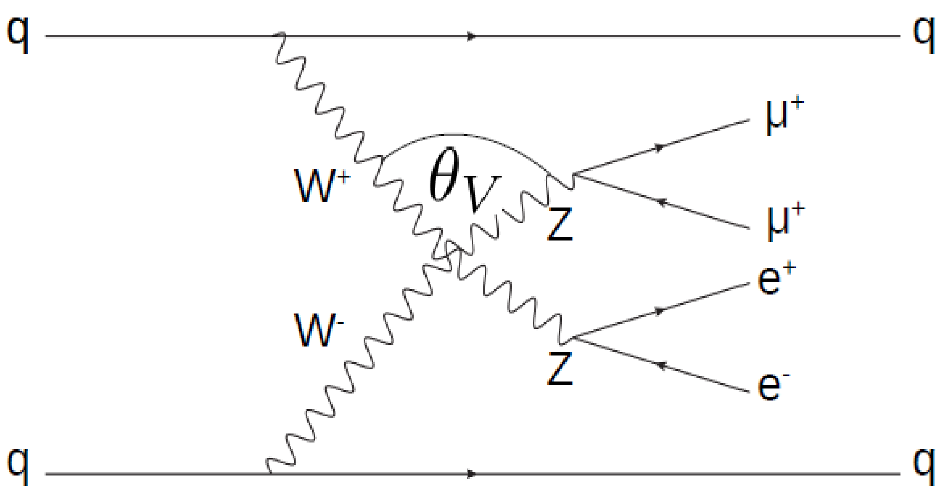


VBF at proton-proton level

Process (14 TeV)	SM (a = 1)	a = 0.9
$pp \to jjW^+W^-$	95.2 fb	99.3 fb
$pp \to jjW^+W^-h$	0.011 fb	0.0088 fb
$pp \to jjhhh$	1.16×10^{-4} fb	0.0566 fb

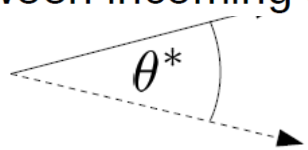
Marc Thomas

- $W_LW_L \to W_LW_L$ enhancement is hidden under the large transverse "polution"
- WW->hhh enhancement is impressive, but rates are too low for the LHC
- To measure g_{hVV} from $W_LW_L \to W_LW_L$ one needs suppress W_T contribution



Observables $\theta_V, \theta^*, \sqrt{s_{VV}}$

- θ_V, angle **in rest frame** of vector boson scattering between incoming and outgoing vector.

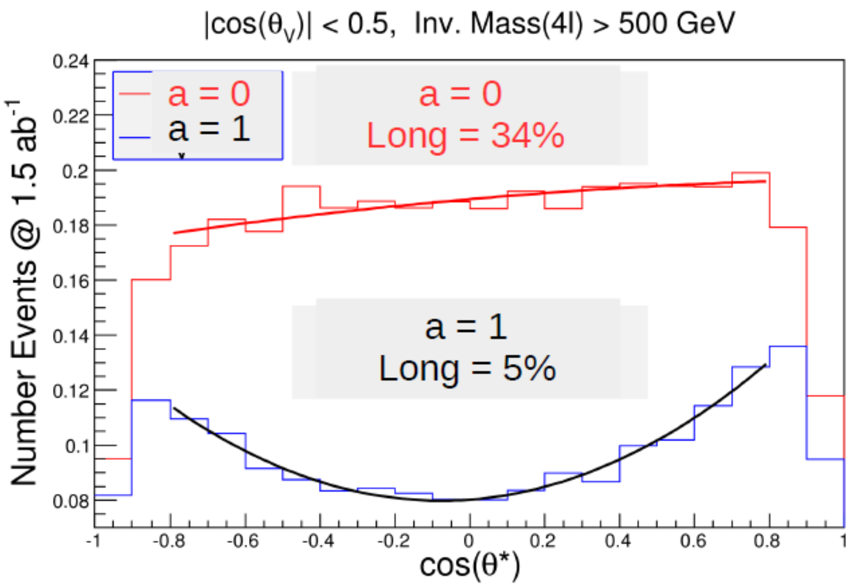


Direction of boost to go to rest frame of Z

- $\sqrt{s_{VV}}$ = invariant mass of all decay products

Results on the VBF sensitivity

Marc Thomas



$$pp \to jjZZ \to e^+e^-\mu^+\mu^-jj$$

- $|\cos\theta_V| < 0.5$
- Invariant mass (4l) > 500 GeV.

- **Large increase in longitudinal fraction** from 0.05 to 0.34, for a = 1 vs a = 0.
- Very small cross section for studied process, but should be ~ x 250 if semi-leptonic decays and complete set of processes (ZZ, WW, WZ) included.
- Expect sensitivity to a at approx 20% with 100 fb^{-1}.

$$P(\cos\theta^*) = f_L P_L(\cos\theta^*) + f_+ P_+(\cos\theta^*) + f_- P_-(\cos\theta^*)$$

$$P_L(\cos\theta^*) = \frac{3}{4}(1-\cos^2\theta^*) \qquad P_\pm(\cos\theta^*) = \frac{3}{8}(1\pm\cos\theta^*)^2$$

cuts reduce transversely polarised background and make measurement of HVV coupling from VBF viable, providing model-independent way of measuring of HVV coupling

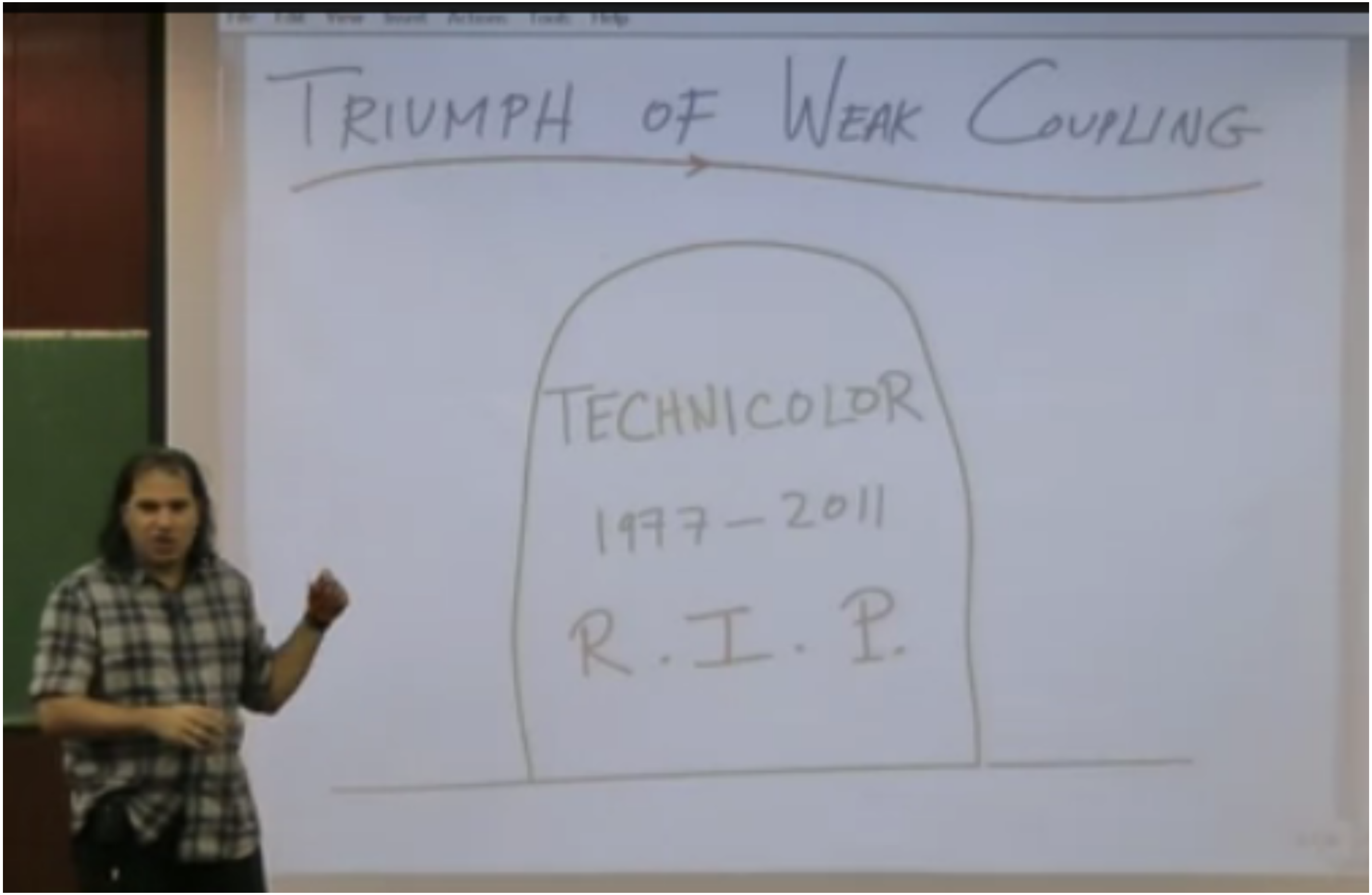
Connection to Composite Higgs and Technicolor models

"Search for additional higgs-like resonances with heavy masses at the LHC" [***Matthias Ulrich Mozer***]

"Unified approach to composite Higgs phenomenology" [***Mads Frandsen***]

Is Technicolor really dead?

Mads Frandsen



Is Technicolor really dead?

If title contains question, then the answer is ...Mads Frandsen

NO!

Two time-honoured extensions

Mads Frandsen

- **New Strong Dynamics**
  - Expect new states at $4\pi f_{Strong}$?
  - Atleast one state needs to be quite a bit lighter…*known since LEP!*
  - Finding a light scalar did not change established picture *that* much…

- **Supersymmetry**
  - Expect new states below v_{EW}?
  - Nature likes SUSY heavy (and fine-tuned?) since LEP

m_h^{NSD}

m_h^{obs}

m_h^{SUSY}

New Strong Dynamics

Mads Frandsen

- **The Technicolor Composite Higgs**
  - 'Higgs' is the lightest scalar isospin-0 resonance of strong dynamics
  - Compare with the $f_0(500)$ in QCD

m_σ^{TC}

m_h^{obs}

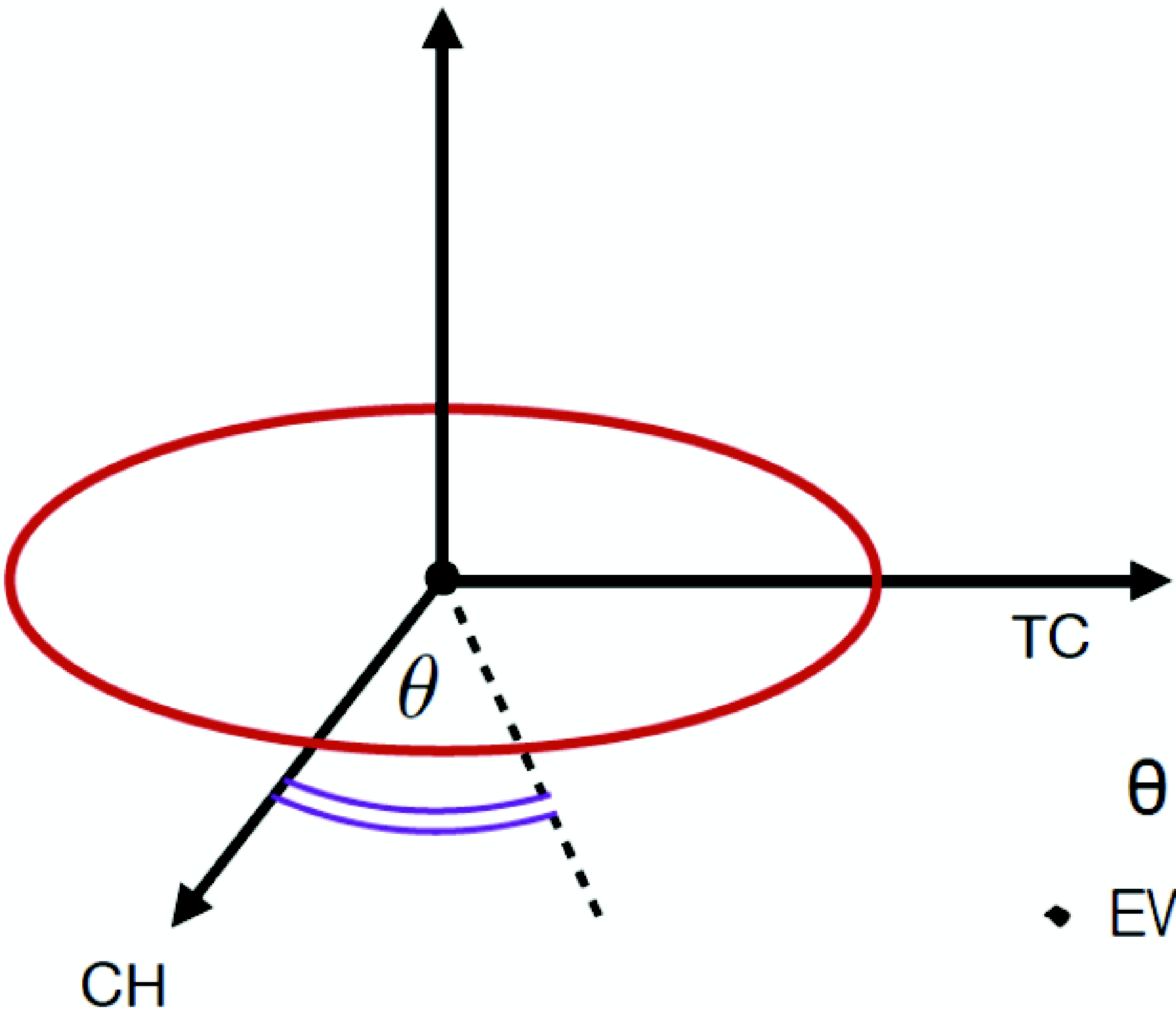
- **The *Composite Higgs* Composite Higgs**
  - The Higgs doublet arises as goldstone bosons of global symmetry breaking
  - Electroweak symmetry breaks through vacuum misalignment

$m_h^{\rm CH}$

Technicolor vs Composite Higgs

Mads Frandsen

(Galloway, Evans, Tacchi & Luty '10
G. Cacciapaglia & F. Sannino '14)



$\theta = 0$

- EW does not break
- Higgs is exact GB

$\theta = \pi/2$

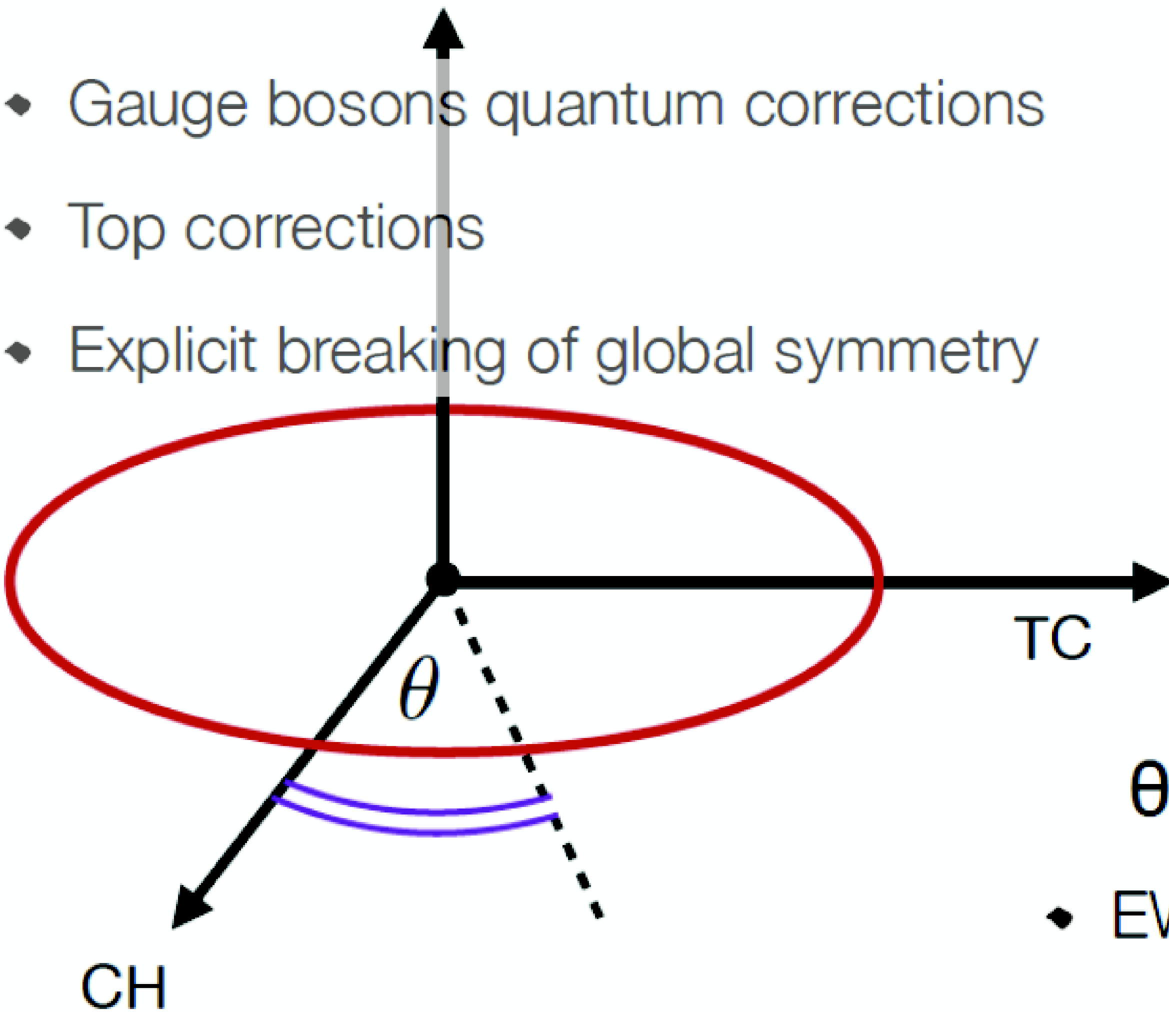
- EW breaks
- Higgs is massive excitation

Technicolor vs Composite Higgs

Mads Frandsen

(Galloway, Evans, Tacchi & Luty '10
G. Cacciapaglia & F. Sannino '14)

- Gauge bosons quantum corrections
- Top corrections
- Explicit breaking of global symmetry



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- EW does not break
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TC Higgs

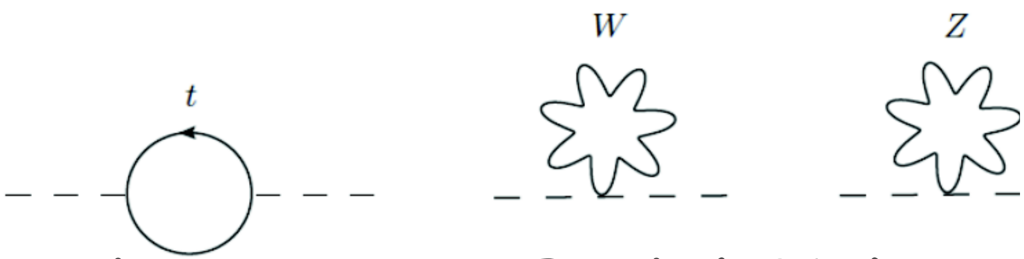
Minimal chiral symmetries: 3 GB's + Custodial + DM.

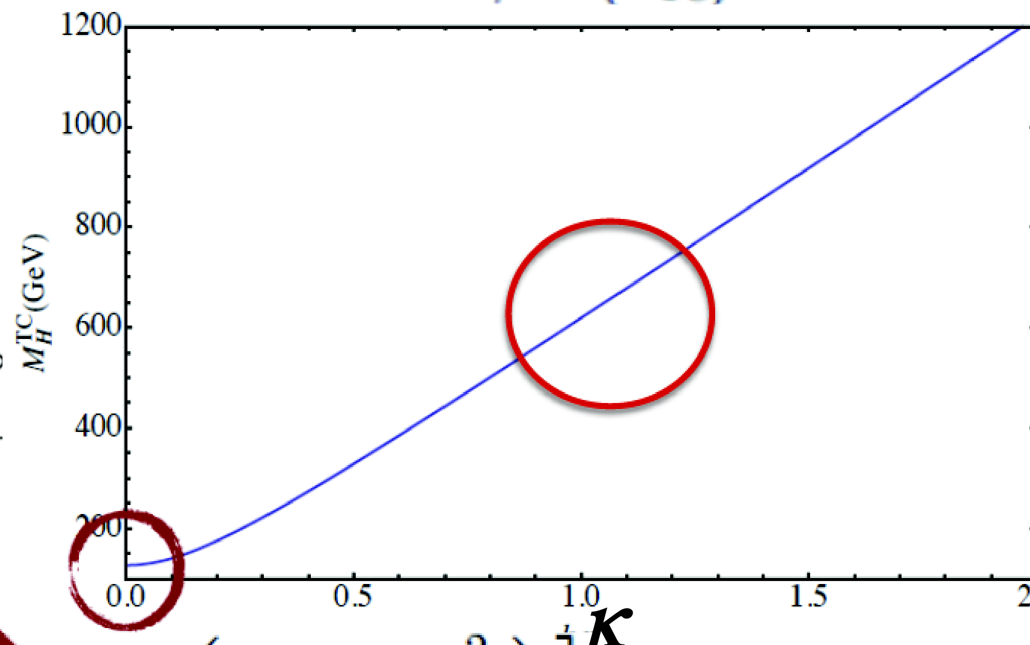
$$SU_L(2) \times SU_R(2) \times U_{TB}(1) \rightarrow SU_V(2) \times U_{TB}(1) \; .$$

Minimal fermion content:
2 Dirac technifermions in a weak doublet,
TC charge but no QCD charges

$$Q_L^a = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_L , \quad Q_R^a = (U_R^a, D_R^a),$$
$$a = 1, \ldots d(\mathcal{R}_{TC})$$

Higgs as Techni-scalar can be dynamicall light !





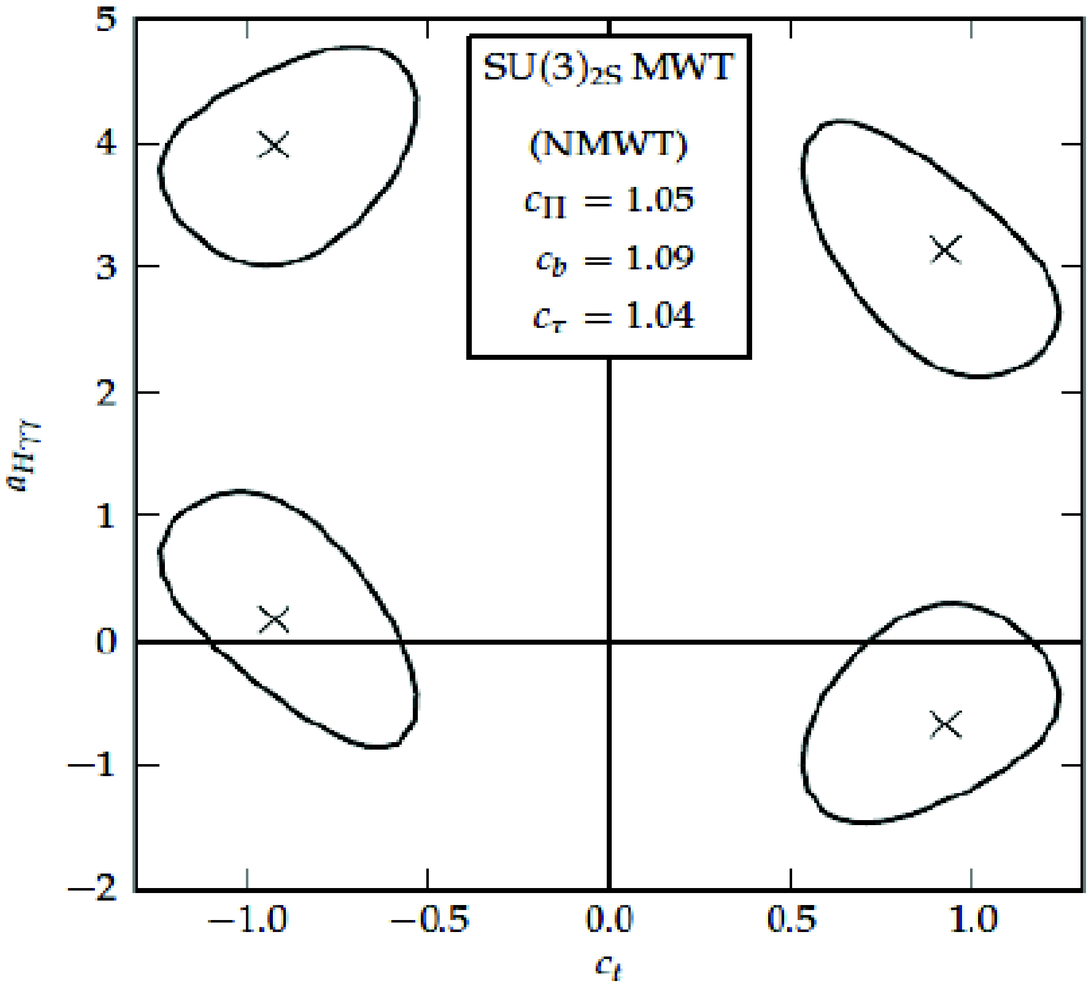
Frandsen, Sannino, Foadi (2012)

$$M_H^2 = (M_H^{TC})^2 + \frac{3(4\pi\kappa F_\Pi)^2}{16\pi^2 v^2}\left[-4r_t^2 m_t^2 + 2s_\pi\left(m_W^2 + \frac{m_Z^2}{2}\right)\right] + \Delta_{M_H^2}(4\pi\kappa F_\Pi)$$

TC Higgs vs data

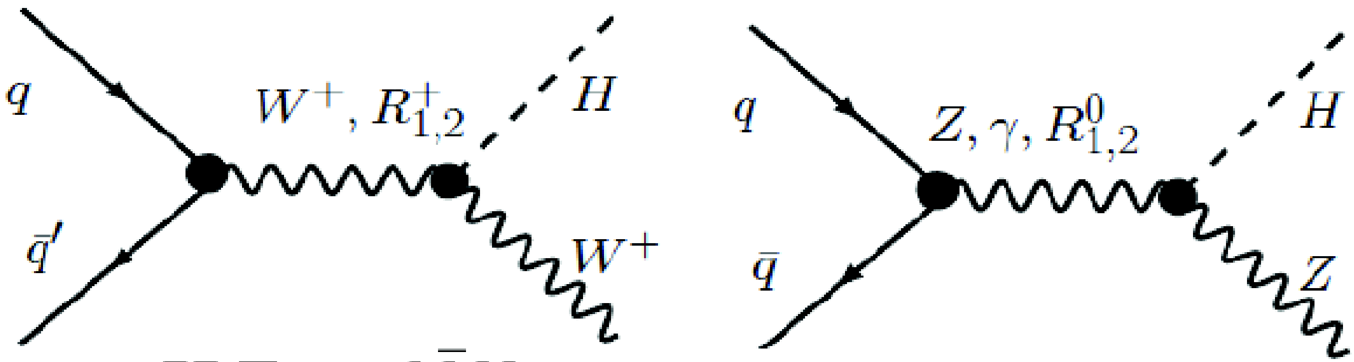
$$g^{TC}_{H\gamma\gamma} = \frac{\alpha}{8\pi}\left| c_\Pi\,[F_1(\tau_W) - 2] + \sum_f c_f\, N_c^f\, Q_f^2\, F_{1/2}(\tau_f) + a_{H\gamma\gamma}\, d(R_{TC}) \sum_F N_c^F\, Q_F^2\, F_{1/2}(\tau_F) \right|$$

Fit to LHC data

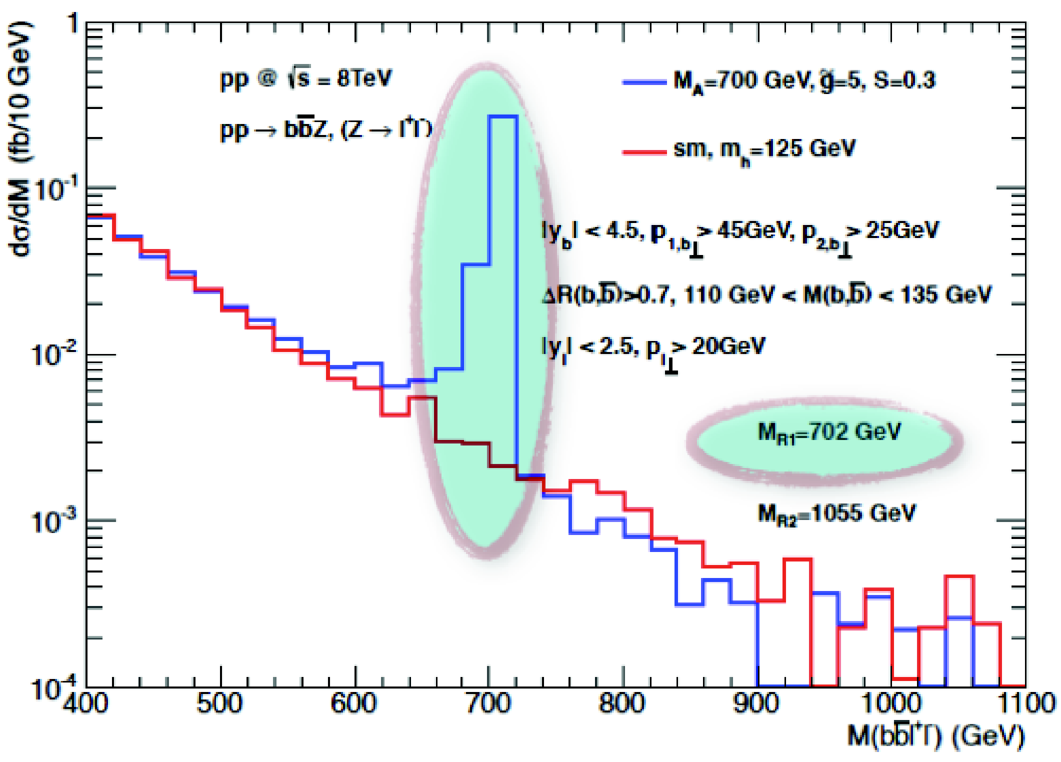


Belyaev, Brown, Foadi, Frandsen (2012)

TC Phenomenology



$$pp \to HZ \to b\bar{b}ll$$



Belyaev, Frandsen, Foadi, Jarvinen, Sannino 2008
Hapola, Sannino 11

- Resonances couples to TC Higgs
- Resonances couples to W,Z
- The search for di-boson signatures is important!
- Setting limits on the TC scale will strongly constrain the lower limit on TC-Higgs mass

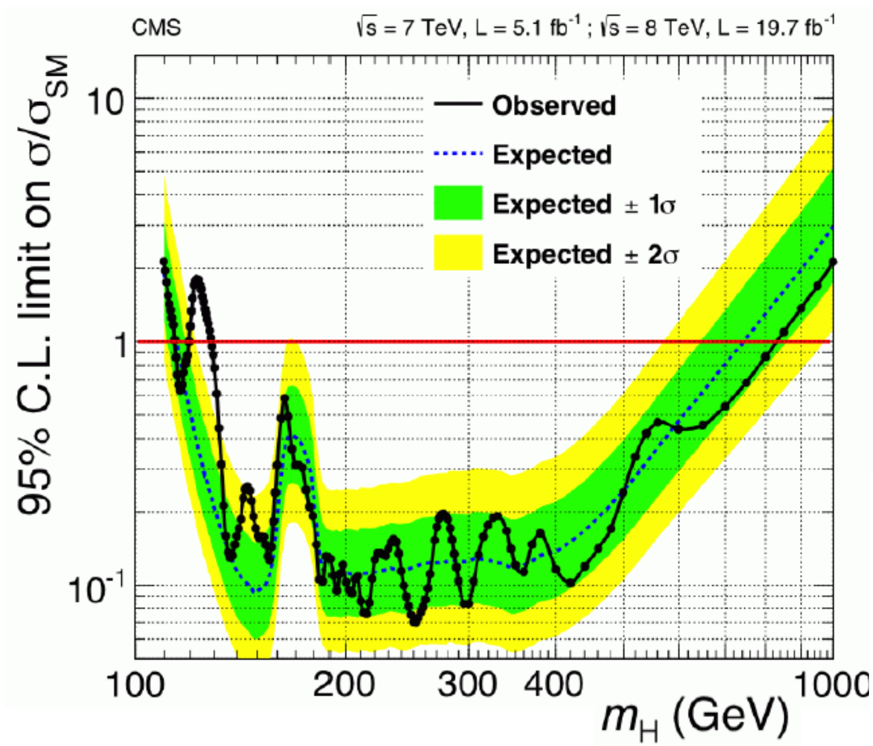
Higgs in SUSY models

“New developments in SUSY Higgs area	[*Sven Heinemeyer*]
“Searches for Supersymmetric Higgs signatures at the LHC”	[***Nicolaos Rompotis***]
"Fully covering the MSSM Higgs sector at the LHC"	[*Jeremie Quevillon*]
“Chances for SUSY-GUT in the LHC Epoch”	[*Marco Chianese*]
“Higgs Signatures from NMSSM”	[*Dilip Ghosh*]

SUSY reinterpretation of LHC Higgs results

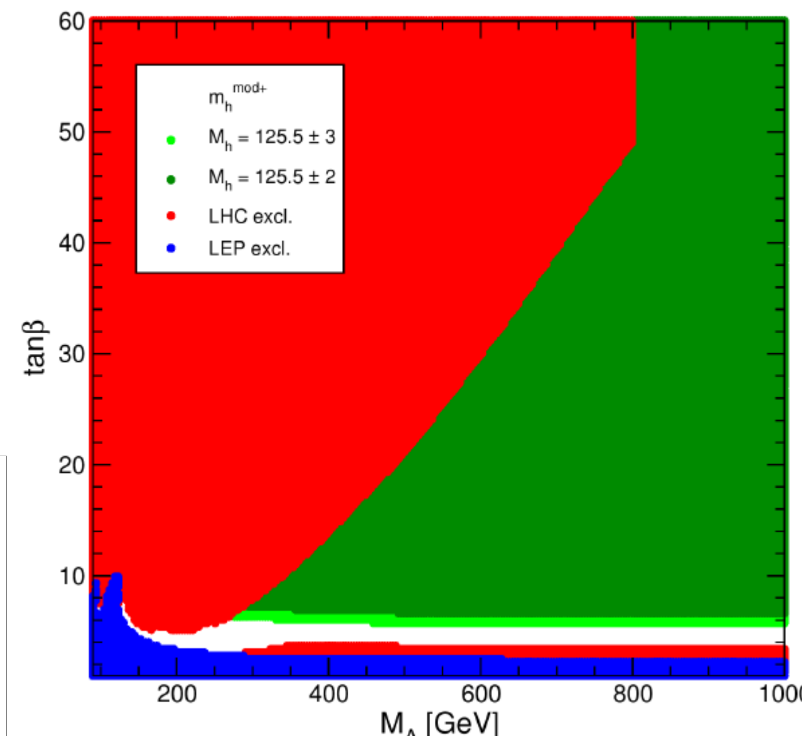
Sven Heinemeyer

$$g^2_{hVV} = \sin^2(\beta-\alpha)\, g^2_{HVV,\mathrm{SM}}, \quad g^2_{HVV} = \cos^2(\beta-\alpha)\, g^2_{HVV,\mathrm{SM}}$$



$m_h^{\mathrm{mod}+}$ scenario:

$$m_t = 173.2\ \mathrm{GeV},$$
$$M_{\mathrm{SUSY}} = 1000\ \mathrm{GeV},$$
$$\mu = 200\ \mathrm{GeV},$$
$$M_2 = 200\ \mathrm{GeV},$$
$$X_t^{\mathrm{OS}} = 1.5\, M_{\mathrm{SUSY}}$$
$$A_b = A_\tau = A_t,$$
$$m_{\tilde g} = 1500\ \mathrm{GeV},$$
$$m_{\tilde l_3} = 1000\ \mathrm{GeV}\ .$$



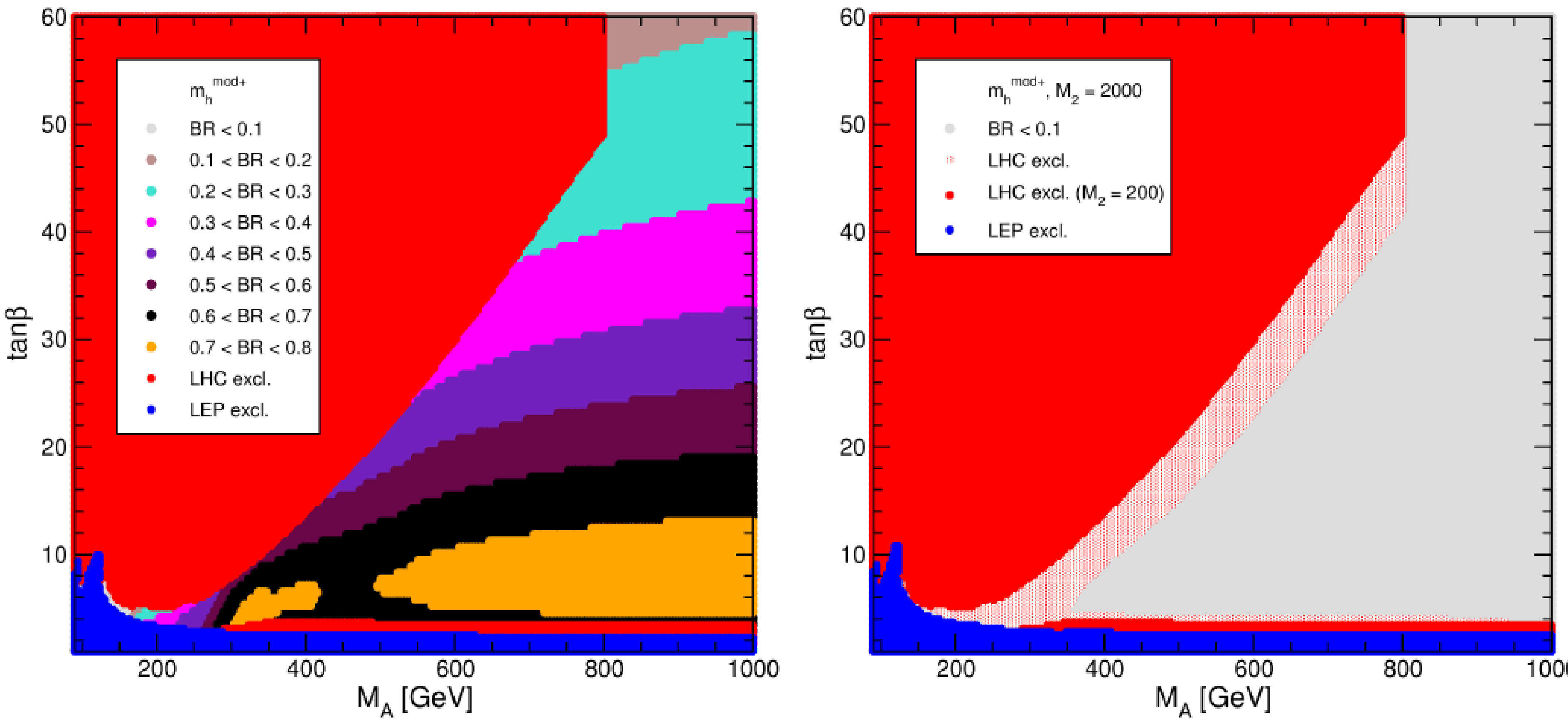
$\Rightarrow M_h \approx 125$ GeV nearly "everywhere"

SUSY reinterpretation of LHC Higgs results

Sven Heinemeyer

$m_h^{\text{mod}+}$ scenario:

⇒ effect of non-SM Higgs decays:



⇒ strong impact from $H/A \to \tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_k^\pm \tilde{\chi}_l^\mp$

⇒ disover heavy Higgses and SUSY at the same time!

SUSY reinterpretation of LHC Higgs results

Sven Heinemeyer

The general possibility:
the discovered Higgs is the second-lightest one

– more contrived in the MSSM with real parameters

– "easier" (?) possible in the MSSM with complex parameters

– "easier" (!) possible in the NMSSM
$\Rightarrow$ light Higgs can be singlet like
can more easily escape detection

Is such a light Higgs detectable at the LHC?

– $h_2 \to h_1 h_1$ possible, but strongly suppressed for $M_{h_1} \gtrsim 63$ GeV

– so far few (and "weak") LHC searches for a Higgs with $M_{h_1} \lesssim 100$ GeV

– Possible: SUSY $\to$ SUSY h_1 , e.g. $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h_1$

Fully Covering the MSSM Higgs Sector at the LHC

Jeremie Quevillon

The hMSSM

In the basis (H_d, H_u), the CP–even Higgs mass matrix can be written as:

$$M_S^2 = M_Z^2 \begin{pmatrix} c_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & s_\beta^2 \end{pmatrix} + M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta\mathcal{M}_{11}^2 & \Delta\mathcal{M}_{12}^2 \\ \Delta\mathcal{M}_{12}^2 & \Delta\mathcal{M}_{22}^2 \end{pmatrix}$$

$\Delta\mathcal{M}_{ij}^2$: radiative corrections

One derives the neutral CP-even Higgs boson masses and the mixing angle α:

$$\begin{aligned} M_{h/H}^2 &= f_{h/H}(M_A, \tan\beta, \Delta\mathcal{M}_{11}, \Delta\mathcal{M}_{12}, \Delta\mathcal{M}_{22}) \\ \tan\alpha &= f_\alpha(M_A, \tan\beta, \Delta\mathcal{M}_{11}, \Delta\mathcal{M}_{12}, \Delta\mathcal{M}_{22}) \end{aligned}$$

Higgs mass should be used as input!

The post-Higgs MSSM scenario:

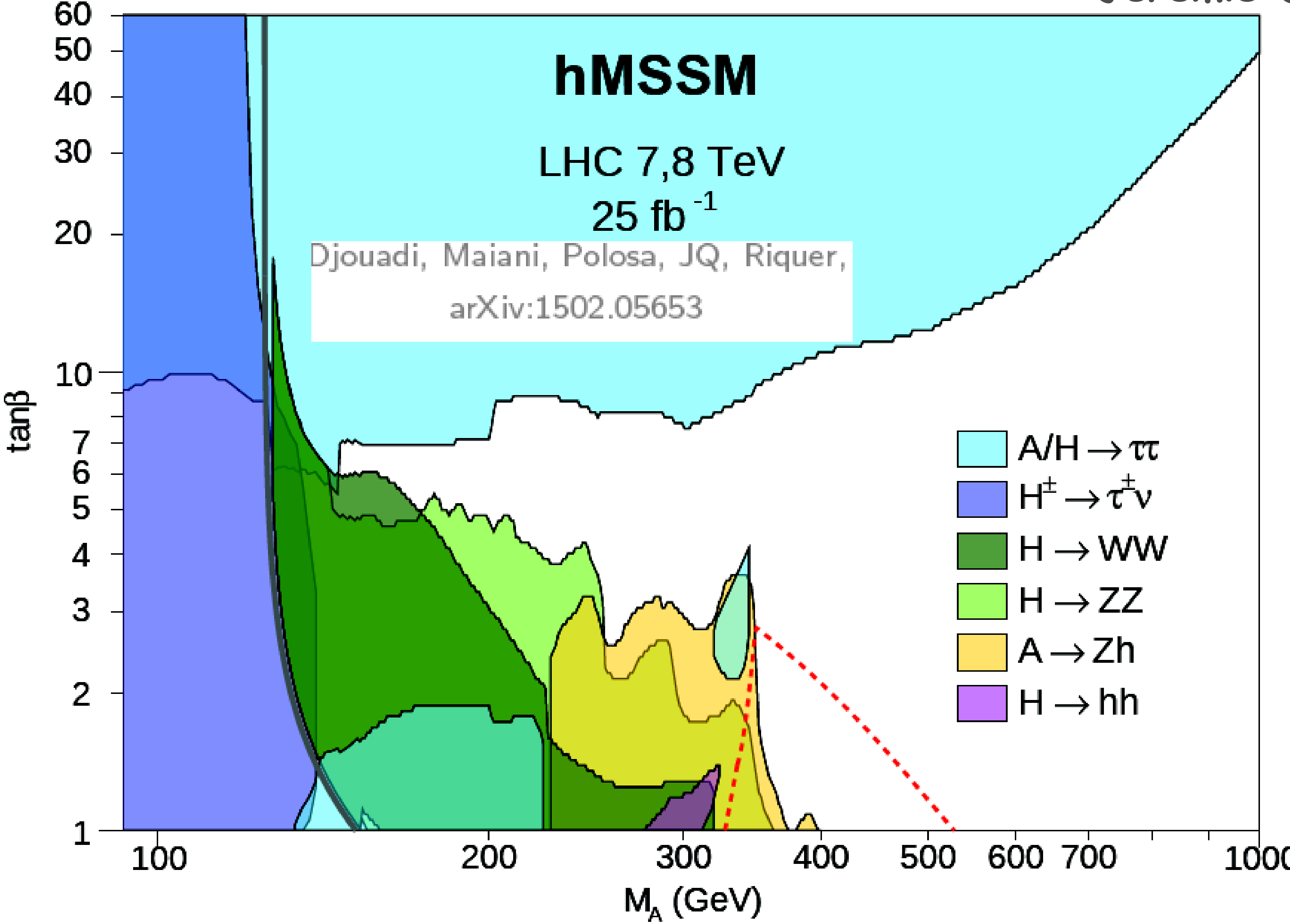
- observation of the lighter h boson at a mass of $\approx 125\ GeV$
- non-observation of superparticles at the LHC

MSSM $\Rightarrow$ SUSY–breaking scale rather high, $M_S \gtrsim 1$ TeV.

Higgs sector is defined effectively at tree-level by $\tan(\beta)$ and M_A!

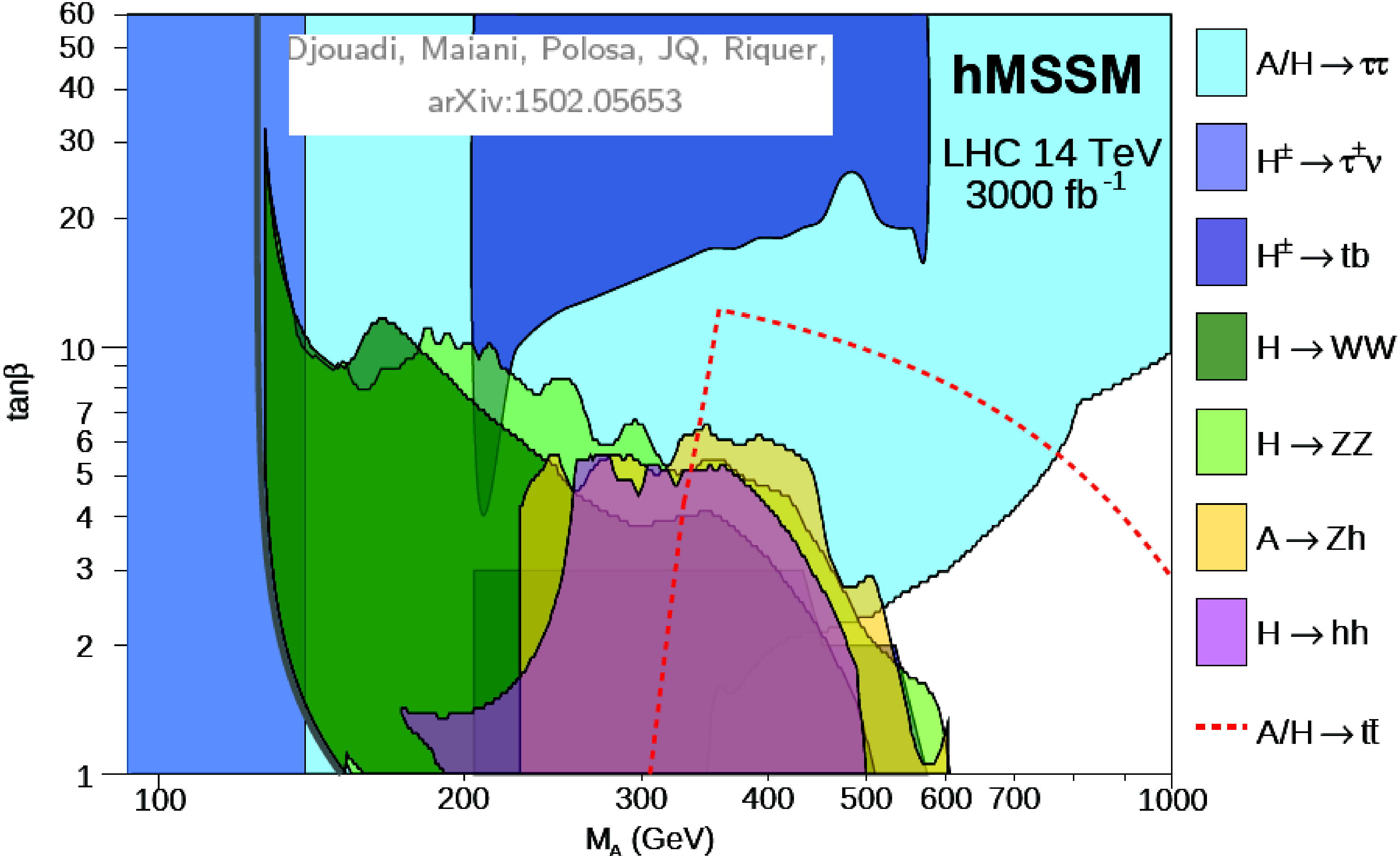
Fully Covering the MSSM Higgs Sector at the LHC

Jeremie Quevillon



Fully Covering the MSSM Higgs Sector at the LHC

Jeremie Quevillon



Note: decays to SUSY particles are absent here!

Chances for SUSY-GUT in the LHC Epoch

Marco Chianese

- The set of input parameters are

SU(5) framework

$$\{\tilde{m}_h, \tilde{m}_g, \tilde{m}_{sq}, \chi, \tan\beta\}$$

- The outputs are

$$\{\alpha_3(M_Z), M_{GUT}, \alpha_{GUT}, y_t(M_{GUT}), y_b(M_{GUT}), y_\tau(M_{GUT})\}$$

The Higgs Σ, which breaks SU(5) down to the MSSM, can have mass M_Σ smaller than M_{GUT}.

$$V_\Sigma = \frac{M_\Sigma}{2}\Sigma^2 + \frac{\lambda_\Sigma}{2}\Sigma^3$$

$$\chi = \frac{M_{GUT}}{M_\Sigma}$$

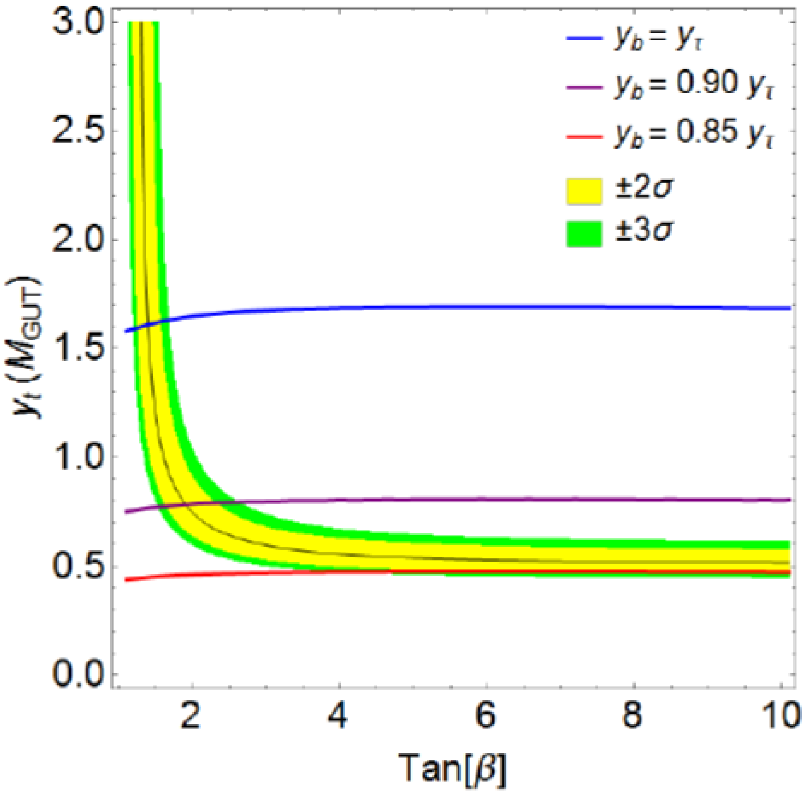
$$\lambda_\Sigma = \frac{\sqrt{2\pi\alpha_{GUT}}}{\chi} = \mathcal{O}(1)$$

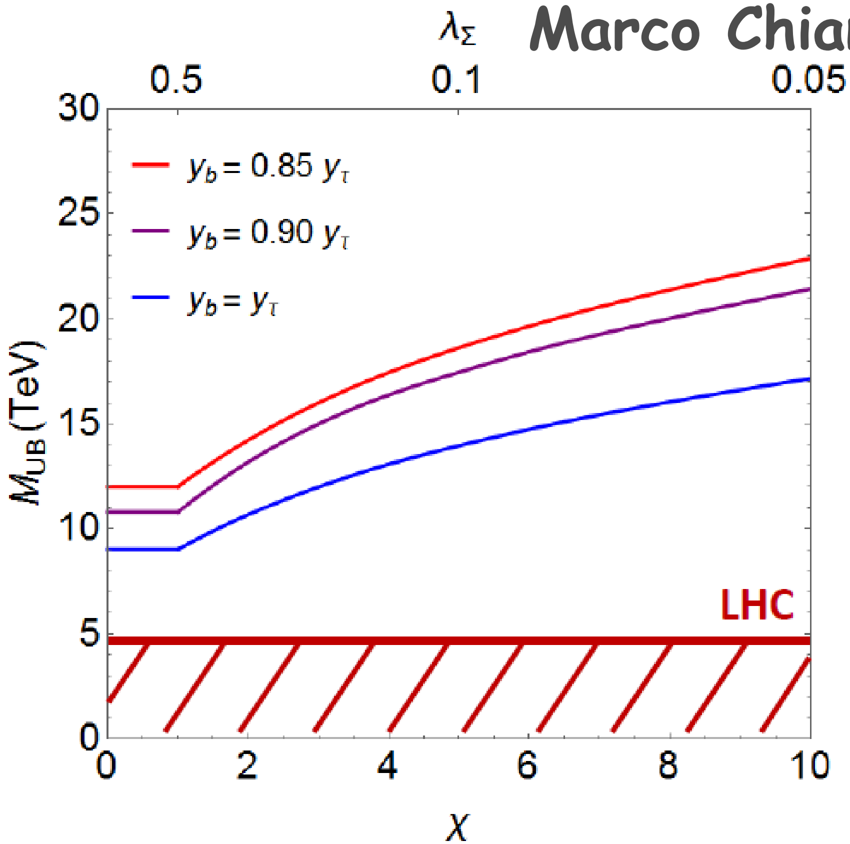
Naturalness

Chances for SUSY-GUT in the LHC Epoch

Upper bound for SUSY physics

Marco Chianese





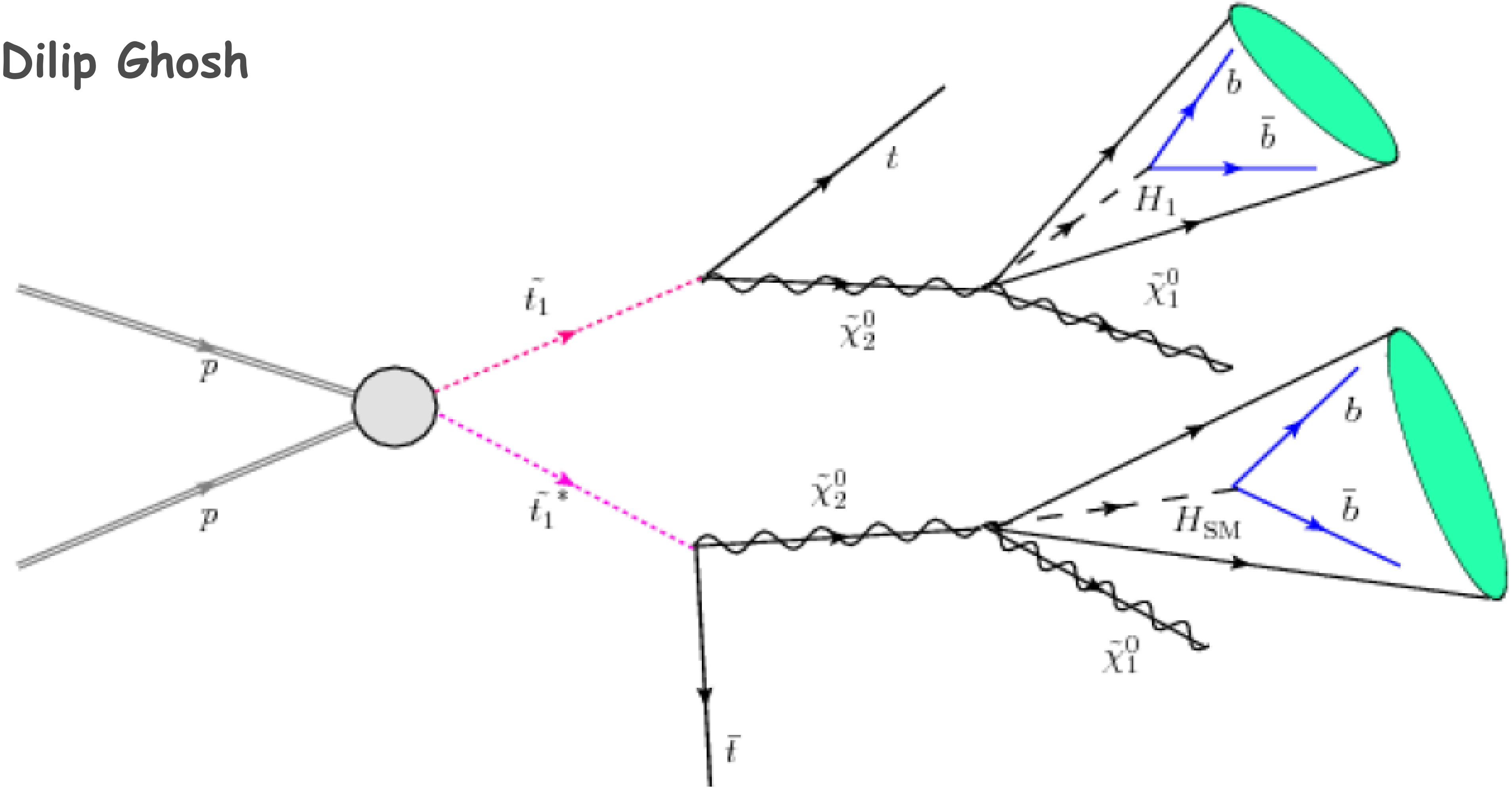
- Larger values for GUT threshold χ are not allowed since:
  - naturalness requirement implies $\lambda_\Sigma \sim \mathcal{O}(1)$;
  - M_{GUT} unnaturally approaches M_{Plack}.

→ $M_{UB} \sim 20$ TeV

The limit is based – on naturalness of λ principles!

NMSSM Higgs signatures from stop decays

Dilip Ghosh



Analysis divided into two parts:

→ Jet substructure technique to analyze boosted Higgs (if $m_{\tilde{\chi}_i^0} - m_{\tilde{\chi}_1^0}$ is large).

→ Standard leptonic search st the LHC.

NMSSM Higgs signatures from stop decays

Dilip Ghosh

- NMSSM can accommodate 125 GeV Higgs boson at tree-level.
- We studied Higgs signatures from the cascade decay of the light stop ($\tilde{t}_1$) in this framework.
- Our benchmark points are consistent with current data on Higgs, LHC constraints on SUSY particles, DM relic density & direct detection constraints as well as heavy flavour physics constraints.
- We probe this channel using the jet substructure method and via the conventional leptonic searches.
- Jet substructure method : we can discover $m_{\tilde{t}_1}$ up to 1.0 TeV with 300 fb^{-1} luminosity.
- di-lepton channel: discover $m_{\tilde{t}_1}$ up to 1.2 TeV with 300 fb^{-1} luminosity.

Higgs-jet ID efficiency can be high in the high-PT Higgs region, so Higgs-jet can be generically used for BSM hunting!

Higgs connection to Cosmoogy:
Dark Matter, Baryogenesis and Inflation

"Higgs-DM connection and the Scale of New Physics"	[*Michael Scherer*]
"Searches exploiting the the Higgs boson as a Dark/Hidden portal at the LHC"	[***James Baker Beacham***]
"Classically Conformal SM extension with DM"	[*Stefano Di Chiara*]
"Discovering a second Higgs doublet via A → Z H"	[*Glauber Carvalho Dorsch*]
"The SM Vacuum and Higgs inflation"	[*Javier Rubio*]

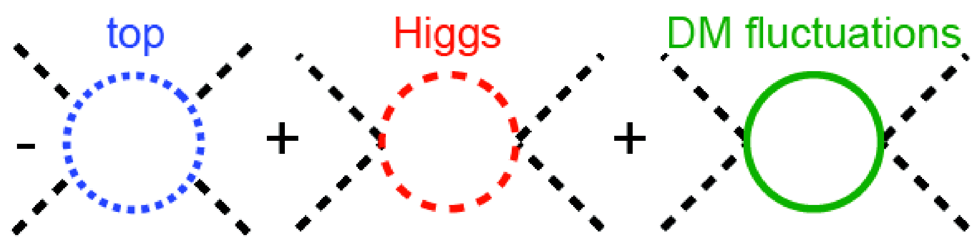
Higgs-Dark Matter Connection and the Scale of New Physics

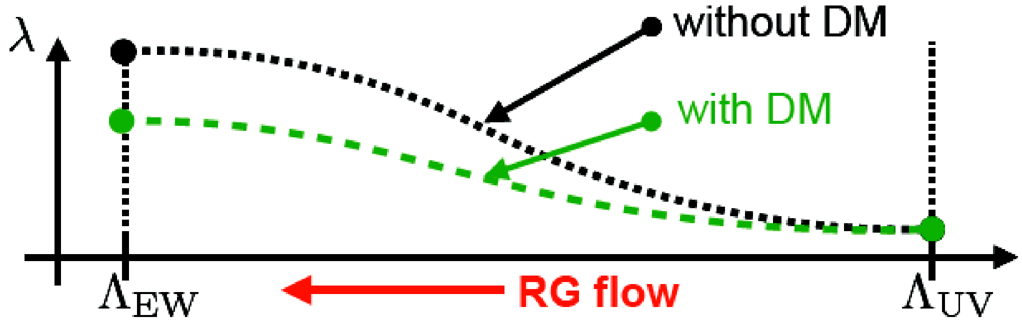
Michael Scherer

Effect of Dark Matter on Higgs Mass

- **Running Higgs self-coupling:**

$\beta_\lambda = -$





$\lambda_{11} > 0$: lower Higgs mass

Gauged Higgs-Top Model - Higher-dimensional operators

$$S_\Lambda = \int d^4x \left[\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu\varphi)^2 + V_{\text{eff}}(\Lambda) + i\sum_{j=1}^{n_f} \bar\psi_j \not{D} \psi_j + i\frac{y}{\sqrt{2}} \sum_{j=1}^{n_y} \varphi \bar\psi_j \psi_j \right]$$

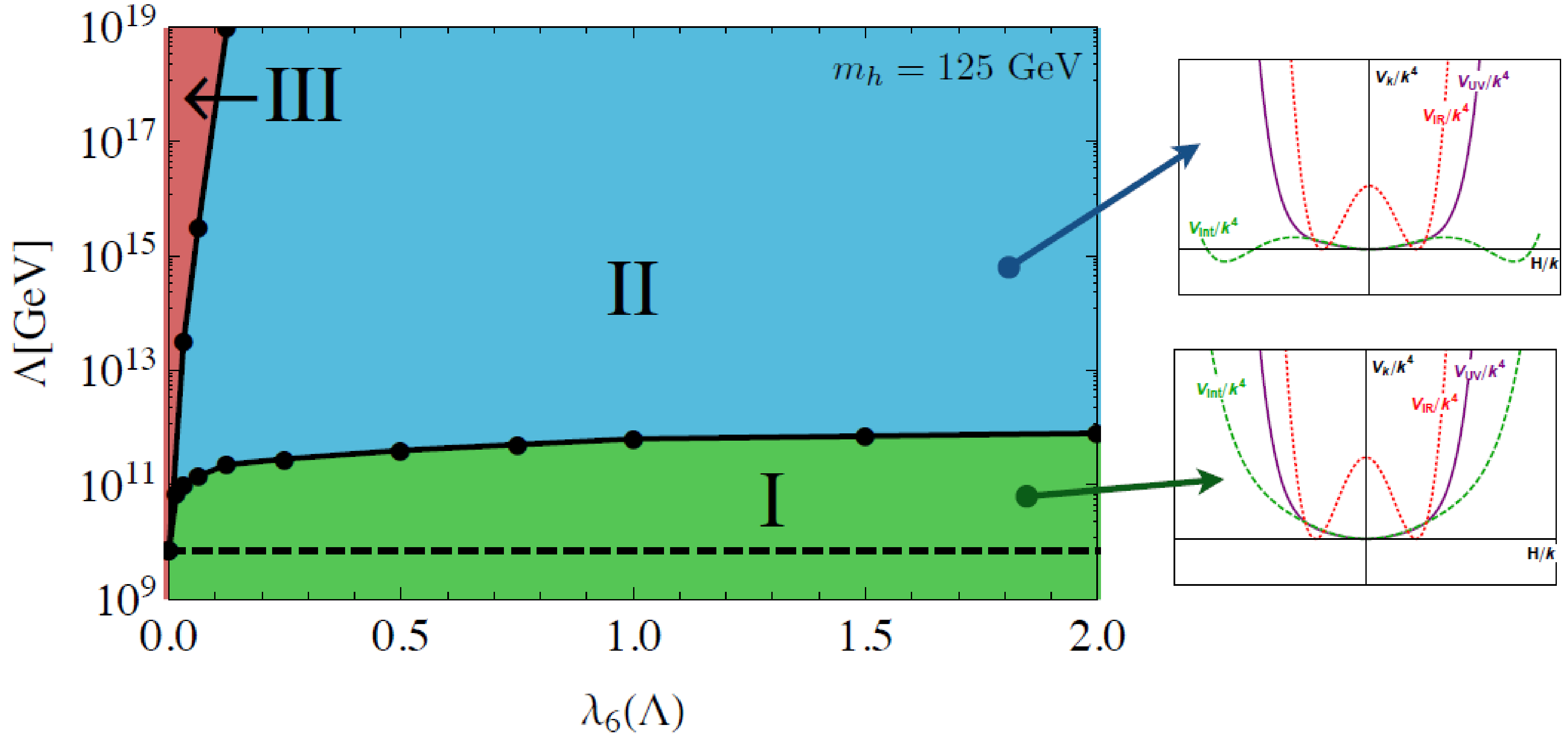
- **Potential at UV scale:** completely stable with unique minimum at $H=0$

$$V_{\text{UV}} = \frac{\lambda_4(\Lambda)}{4} H^4 + \frac{\lambda_6(\Lambda)}{8\Lambda^2} H^6 + \ldots$$

Higgs-Dark Matter Connection and the Scale of New Physics

Michael Scherer

Stability Regions



- Moderately small $\lambda_6(\Lambda)$ extend UV cutoff by 2 orders of magnitude at full stability (green)
- Pseudo-stable region (blue) - allows for more orders of magnitude

Minimal SU(N) Vector Dark Matter

Stefano Di Chiara

All SM fields singlets of $\mathrm{SU}(N)_D$, Φ singlet of $\mathcal{G}_{SM}$, then minimal (no mass terms) potential is

$$V = \frac{\lambda_h}{2}\left(H^\dagger H\right)^2 + \frac{\lambda_\phi}{2}\mathrm{Tr}\left(\Phi^\dagger\Phi\right)^2 - \lambda_p H^\dagger H \mathrm{Tr}\Phi^\dagger\Phi, \quad H = \frac{1}{\sqrt{2}}\begin{pmatrix} \pi^+ \\ h + i\pi^0 \end{pmatrix}$$

Potential minimum at

$$\langle H\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_h \end{pmatrix}, \quad \langle\Phi\rangle = \frac{v_\phi}{\sqrt{N^2-1}} I \quad \Rightarrow \quad m_A = \frac{g_D}{\sqrt{N - N^{-1}}}$$

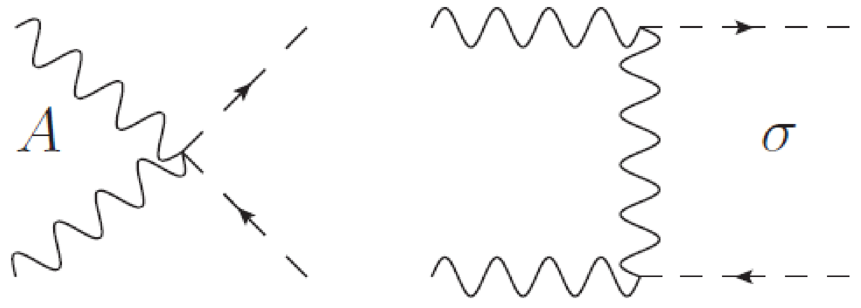
Residual $\mathrm{SO}(N)$ global symmetry makes massive vector bosons A^a stable $\Rightarrow$ viable DM candidates

Mass terms generated radiatively via dimensional transmutation $\Rightarrow$ quantum corrections to m_H^2 depend on $\log\Lambda_{\mathrm{UV}}$: no fine tuning needed; f.t. problem traded with that of justifying zero tree level mass terms

DM Abundance

Higgs couplings are SM-like $\Rightarrow \cos\alpha \sim 1$. In the limit of no-mixing, the dark vector annihilation process is

Stefano Di Chiara



with $\sigma \sim h_2$ eventually decaying to h_1. In semi-annihilation process one σ replaced by A. Thermally averaged cross sections

LHC Pheno Viability

All SM couplings (except λ_h) and v_h set to SM values; λ_h & λ_ϕ set by V minimization conditions; v_ϕ set by requiring $m_{h_1} = 125$ GeV; Only two free parameters: g_D, λ_s. We collect 10^5 random data points in interval

$$0 < g_D < 1.4, \boxed{0 < \lambda_p < 0.12}$$

→ **H_1/H_2 mixing**

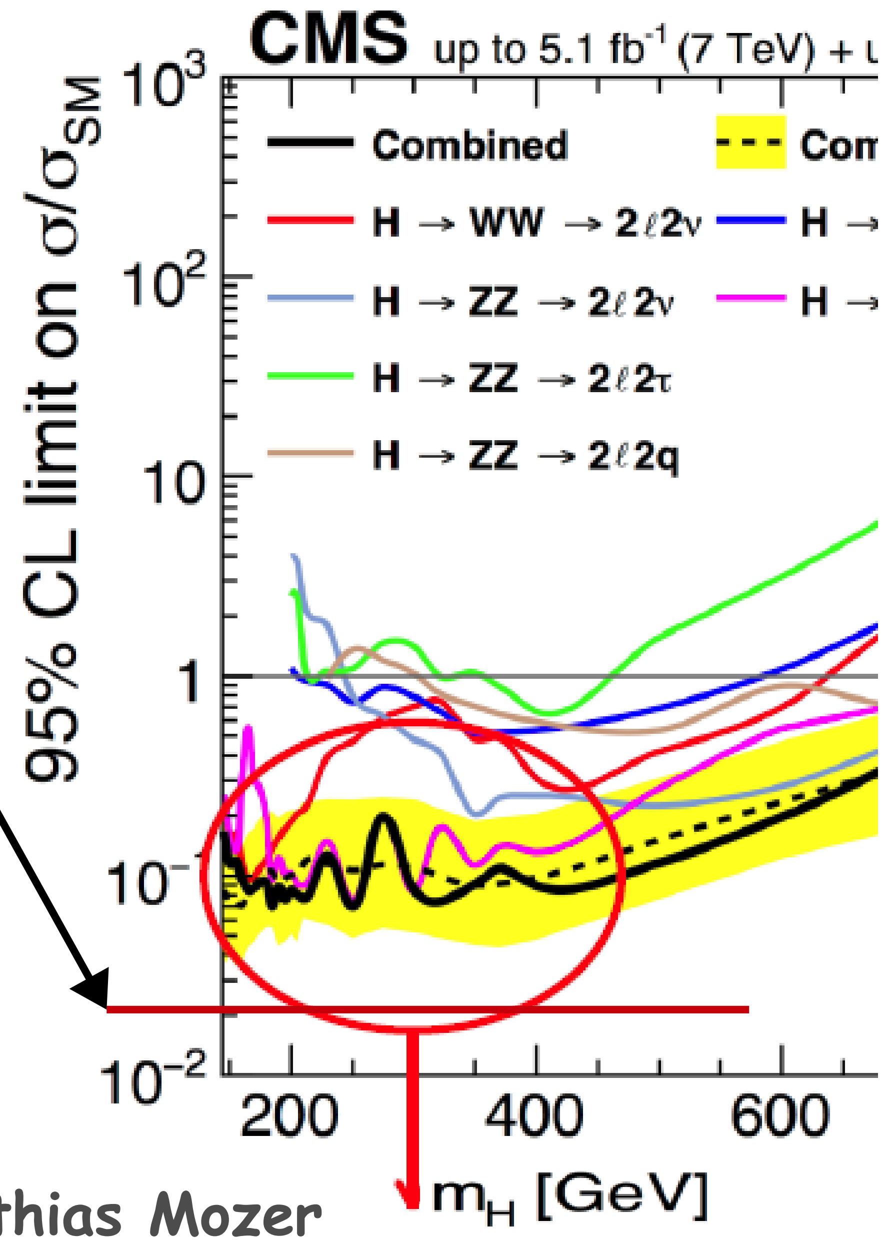
The model can be probed and potentially completely excluded at the LHC@13 TeV !

Stefano Di Chiara

$$N = \begin{cases} 2 \\ 3 \\ 4 \end{cases}, \quad \lambda_p = \begin{matrix} 0.020 \pm 0.011 \\ 0.019 \pm 0.011 \\ 0.019 \pm 0.010 \end{matrix},$$

and dark Higgs and vector boson masses

$$N = \begin{cases} 2 \\ 3 \\ 4 \end{cases}, \quad m_{h_2}/\mathrm{GeV} = \begin{matrix} 175 \pm 10 \\ 175 \pm 10 \\ 175 \pm 9 \end{matrix}$$



Matthias Mozer

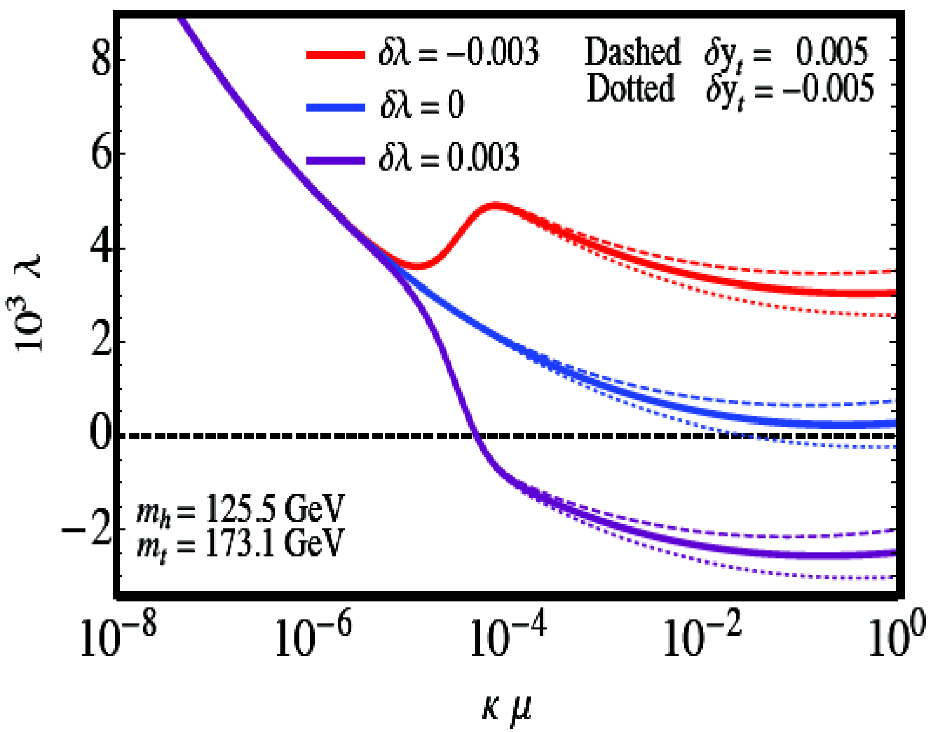
THE SM VACUUM AND HIGGS INFLATION

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_P^2 + \xi_h h^2}{2} R - \frac{1}{2}(\partial h)^2 - \frac{\lambda}{4}(h^2 - v_{EW}^2)^2$$

Scale invariance at $h \gg M_P/\sqrt{\xi_h}$

Javier Rubio

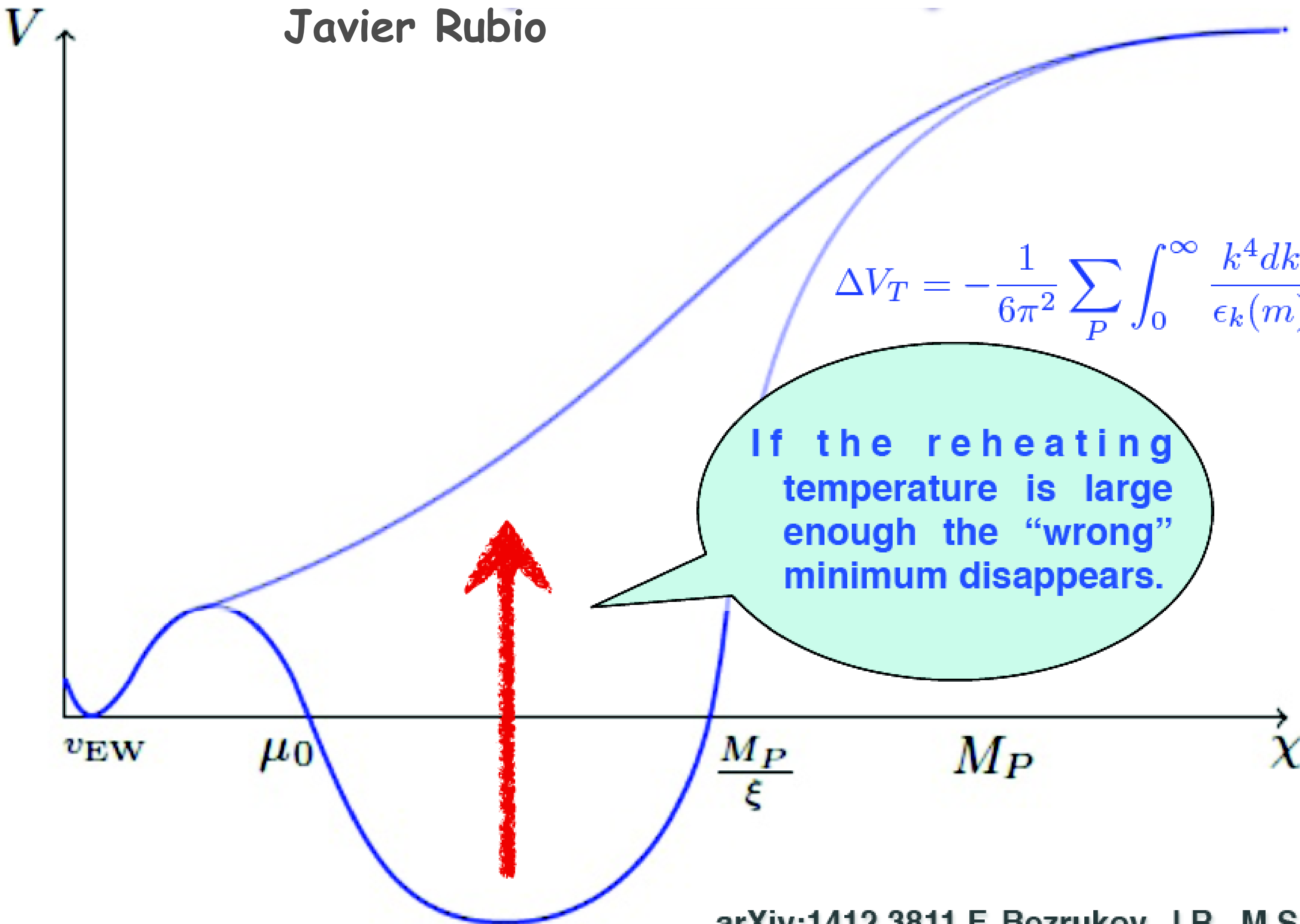
Interaction with gravity introduc Higher dimensional operators
Which change running of λ



$$\lambda(\mu) \longrightarrow \lambda(\mu) + \delta\lambda \left[\left(F'^2 + \frac{1}{3} F'' F \right)^2 - 1 \right]$$

THE SM VACUUM AND HIGGS INFLATION

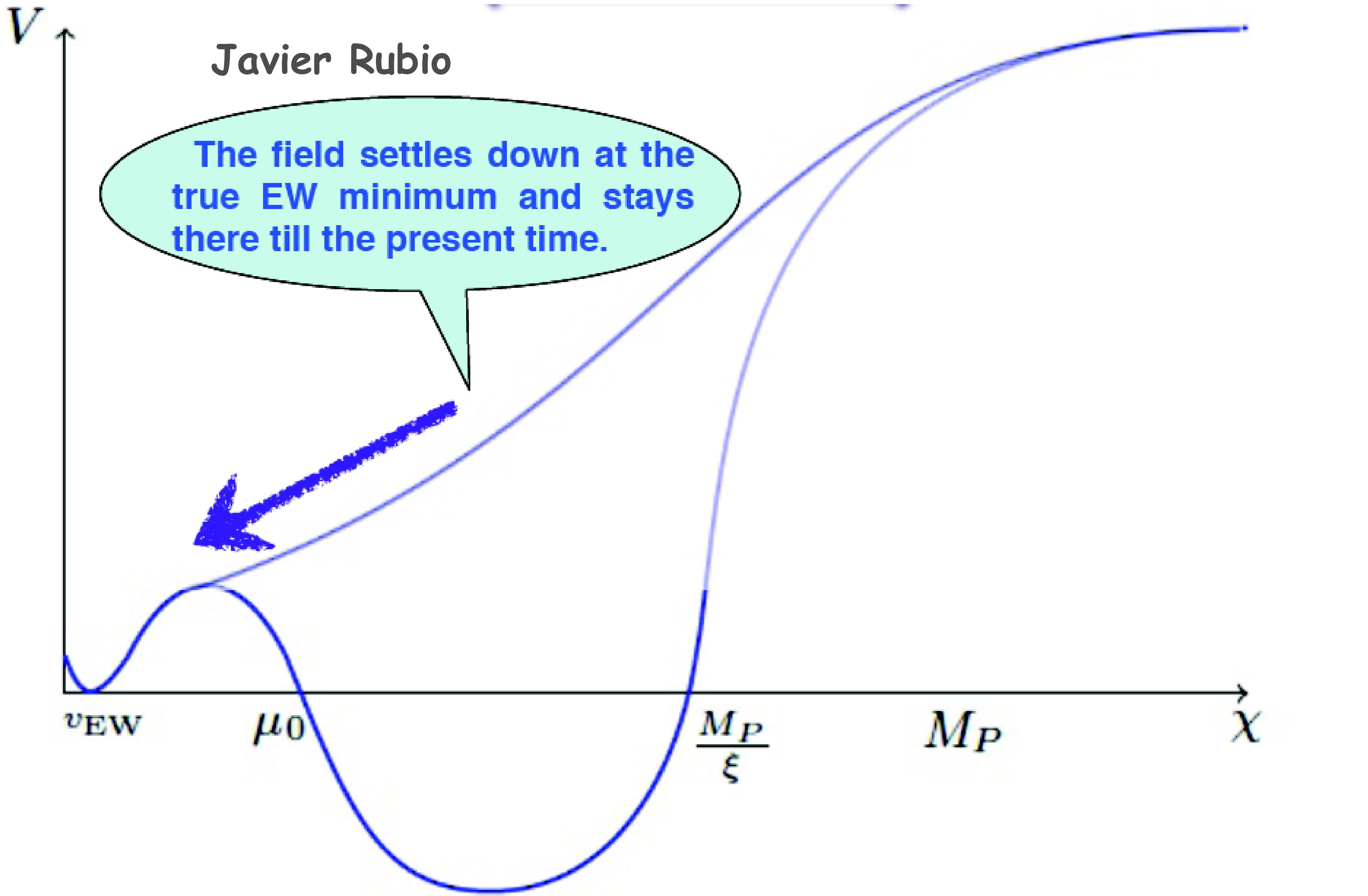
Javier Rubio



$$\Delta V_T = -\frac{1}{6\pi^2}\sum_P \int_0^\infty \frac{k^4 dk}{\epsilon_k(m)} \frac{1}{e^{\epsilon_k(m)T} \mp 1}$$

arXiv:1412.3811 F. Bezrukov, J.R., M.Shaposhnikov

THE SM VACUUM AND HIGGS INFLATION

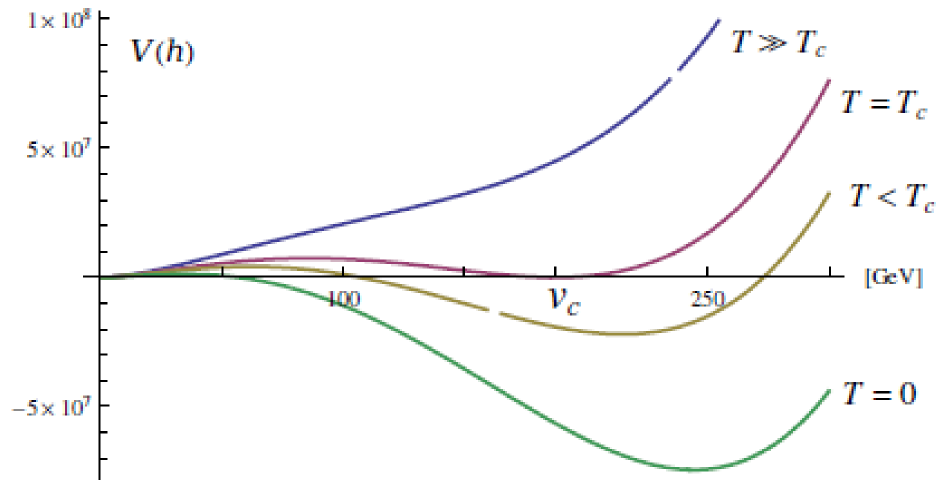


Discovering a second Higgs doublet via $A^0 \to ZH^0$ and connection to EW baryogenesis

Gláuber Carvalho Dorsch

- To freeze out the generated BAU inside bubble, EWPT must be strongly first order (supercooling):

$$v_c/T_c \gtrsim 1.0$$



- ✘ Not realized in the SM for $m_h \gtrsim m_W$.
- ✘ Also, CP violation from CKM matrix insufficient!

very hard in MSSM, but possible in 2HDM

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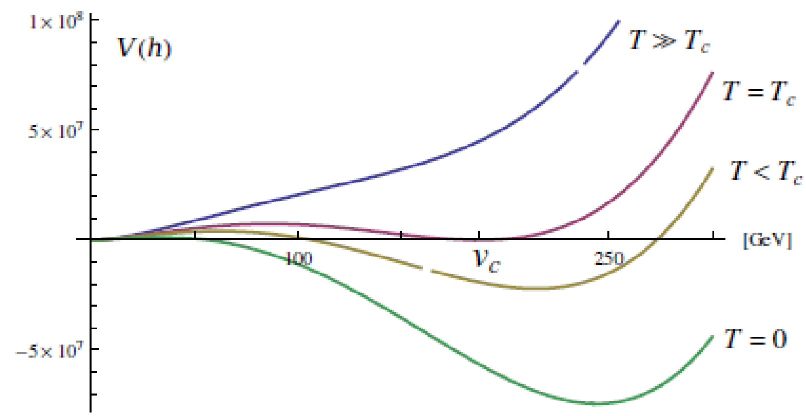

- ✗ Not realized in the SM for $m_h \gtrsim m_W$.
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very hard in MSSM, but possible in 2HDM

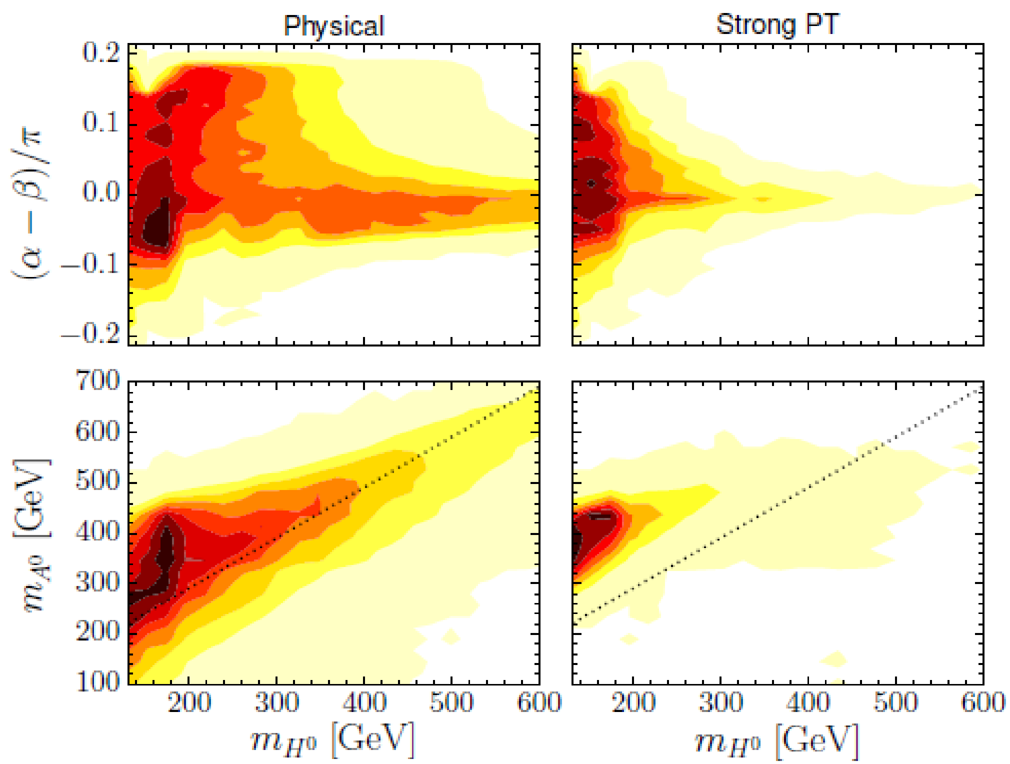
- One of the simplest extensions of SM: Two $SU(2)_L$ scalar doublets: Φ_1 and Φ_2 .
- Various heavy scalars $(h_0, H_0, A_0, H^{\pm})$ increase EWPT strength.
- Additional source of CP violation (explicit or spontaneous).
- Testable at LHC @ 14 TeV!

2HDM and the EWPT

Gláuber Carvalho Dorsch

- We study the EWPT by looking for the minima of the 1-loop thermal effective potential. *GCD, S. J. Huber, J. M. No, JHEP 1310 (2013) 029*
  - EW symmetry is restored at high temperatures.
  - At critical temperature T_c the potential has two degenerate minima at 0 and at v_c.
  - Phase transition is strong when $v_c/T_c > 1$.

- SM-like h_0 favoured.
- As m_{H_0} increases, strong PT requires $\langle H_0 \rangle \sim \sin(\alpha - \beta) \to 0$.
- But for $m_{H_0} \lesssim 200$ GeV, $\alpha - \beta \sim 0.1\pi$ is acceptable!
- $m_{A_0} \gtrsim 300$ GeV, with $m_{A_0} \gtrsim m_{H_0} + m_Z$.



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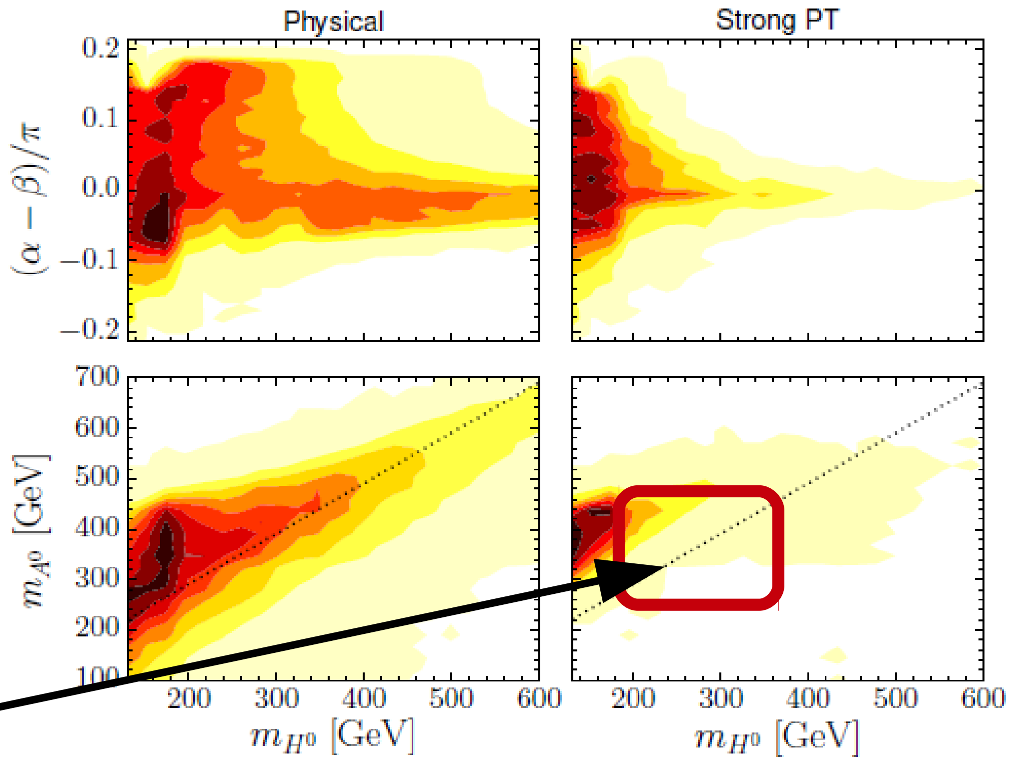
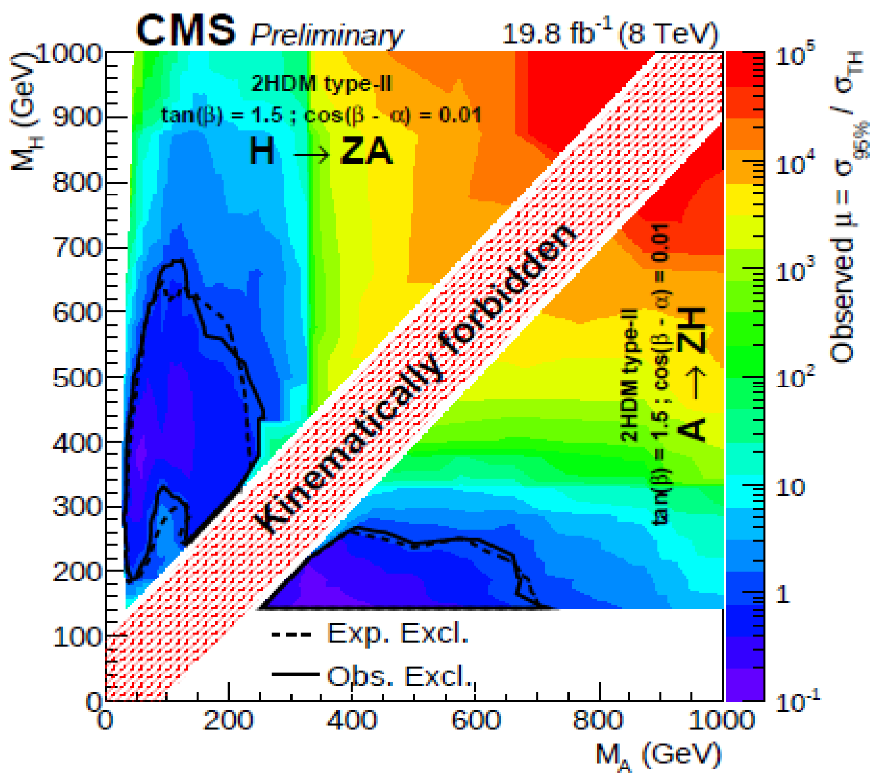


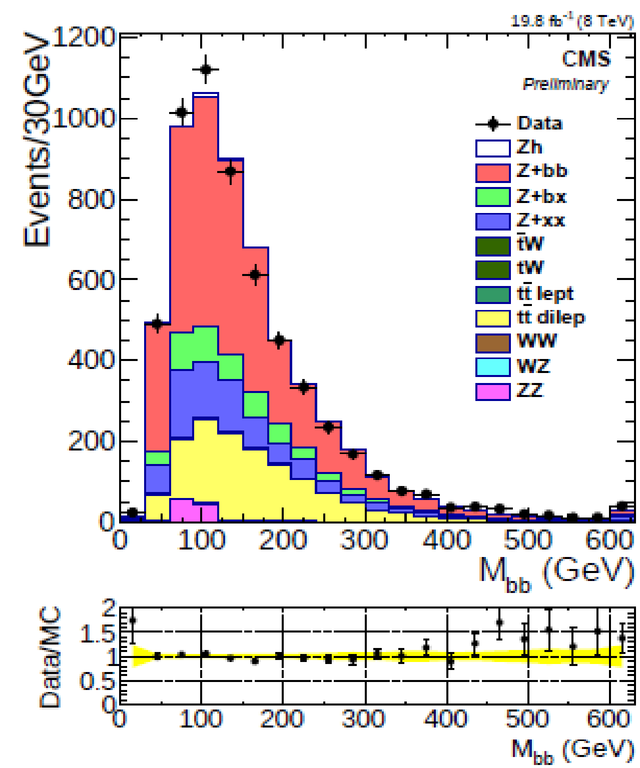
Requires sizable M_A-M_H mass split

Prospects with 8 TeV data

Gláuber Carvalho Dorsch

- This work motivated a recent search in this channel (as well as in $H_0 \to ZA_0$) by the CMS collaboration *CMS-PAS-HIG-15-001*
- New exclusion limits; new search channel!
- Further investigation of 8 TeV data granted, and already on its way!





LHC sensitivity to Higgs width

"Higgs width and coupling constraints from the high-mass H→VV process" [*Nikolaus Kauer*]
“Measurements of the Higgs width at the LHC [*Roberto Covarelli*]

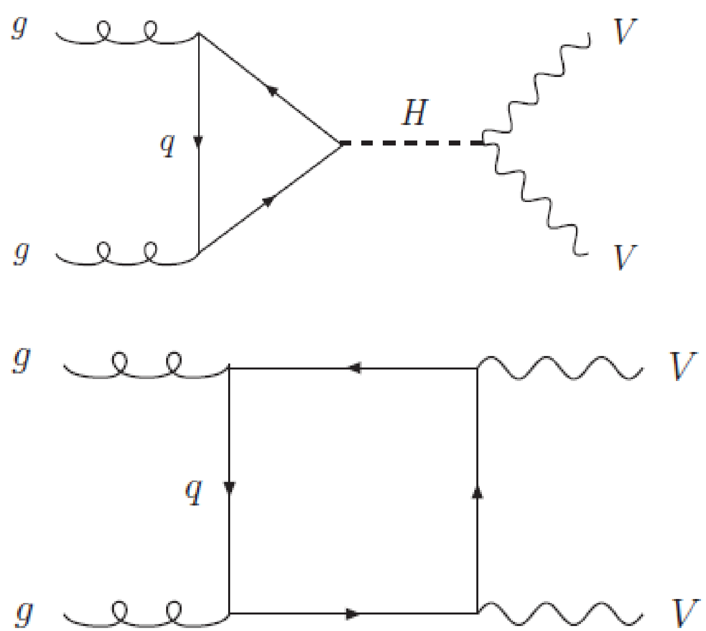
Higgs width and coupling constraints from the high-mass H → V V process

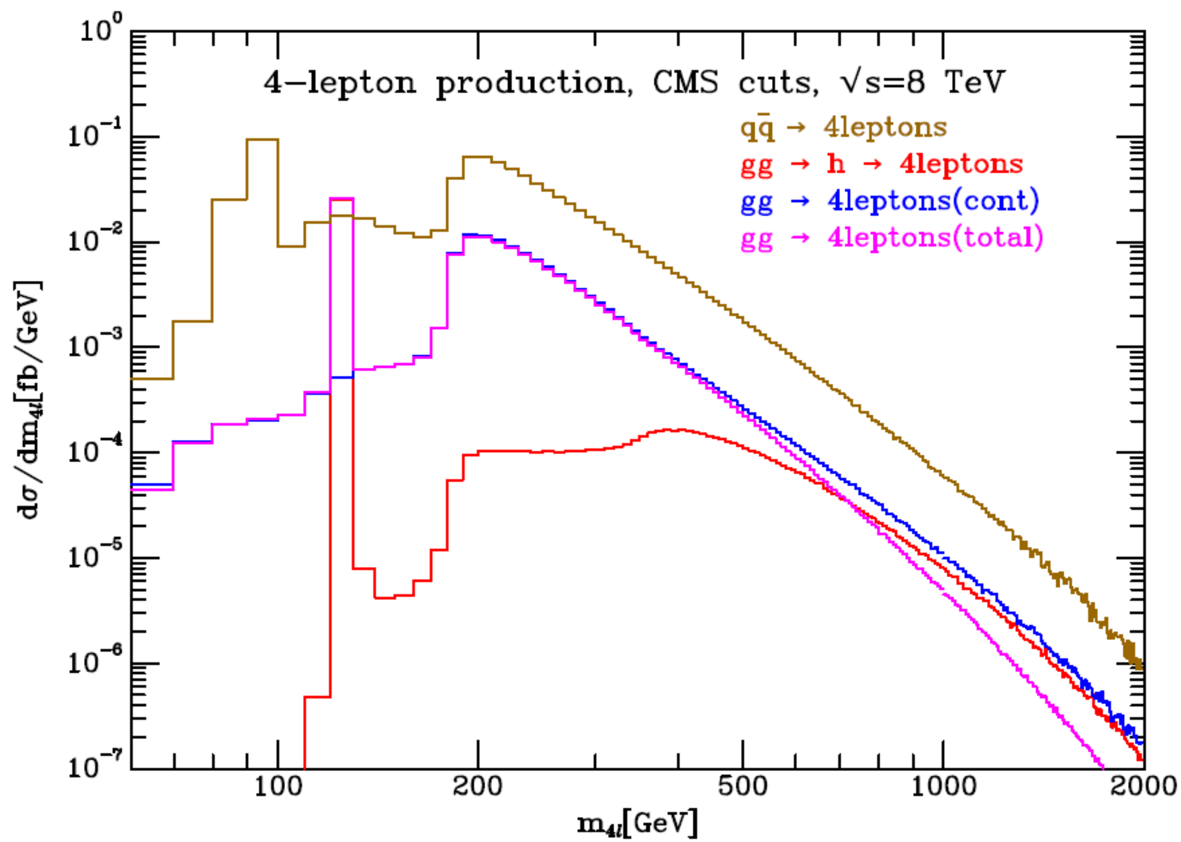
Higgs – SM BG interference is the key point for the sensitivity to the Higgs width!

Nikolas Kauer
also in talk by
Juan González Fraile

$$\sigma_{i\to H\to f} \overset{\text{NWA}}{\propto} \frac{g_i^2 g_f^2}{\Gamma_H}$$

$$\sigma_{i\to H\to f}\left(\sqrt{p_H^2} - M_H \gg \mathcal{O}(\Gamma_H)\right) \propto g_i^2 g_f^2$$





Higgs width and coupling constraints from the high-mass $H \to V\,V$ process

Nikolas Kauer

- $H \to ZZ, WW$ in ggF & VBF @ LHC: $\mathcal{O}(10\%)$ off-shell high-mass Higgs signal contribution with large Higgs(-Higgs)-continuum interference: now taken into account, provides complementary physics information (similar at high-energy linear collider)

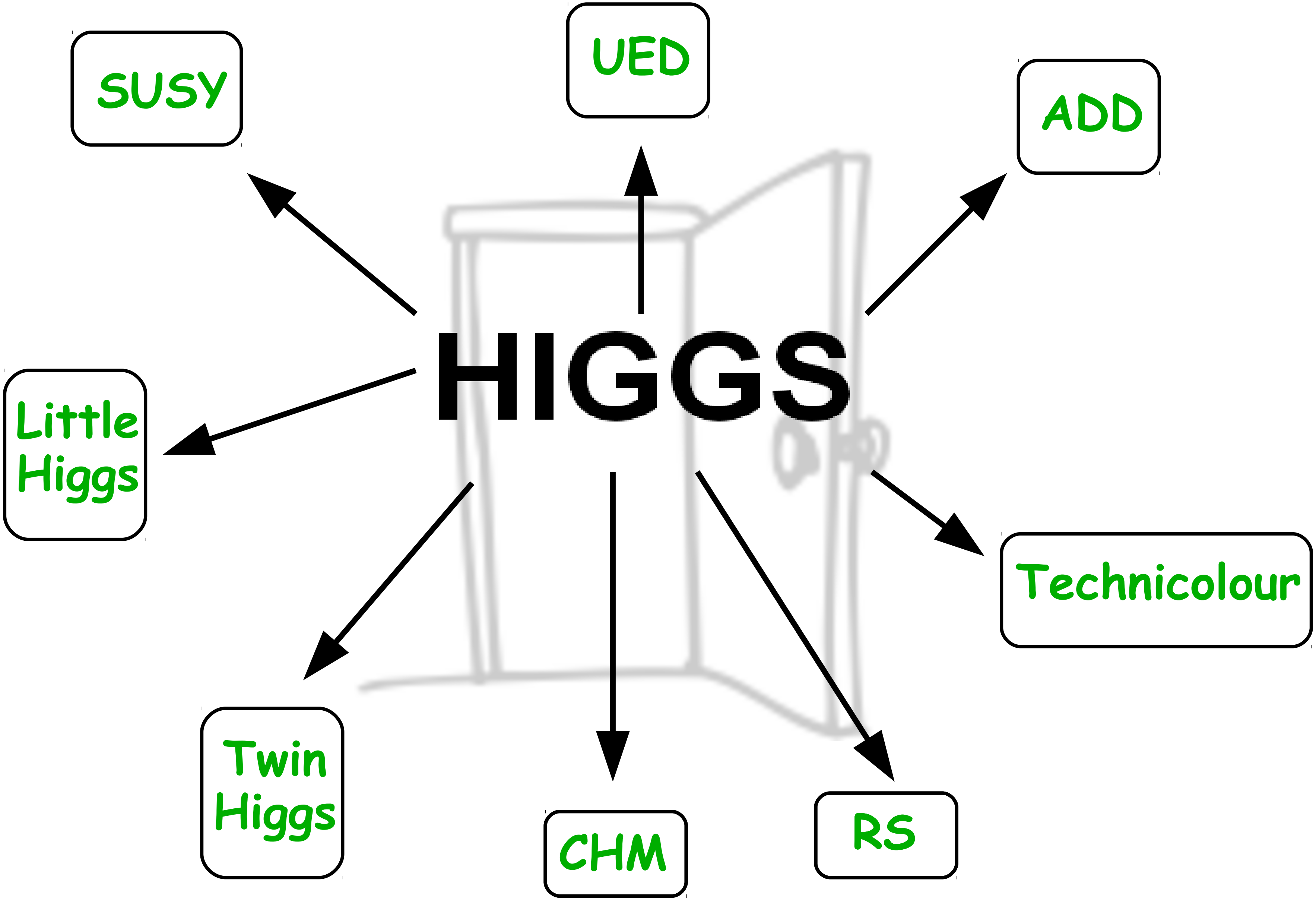
- Direct Higgs width measurement at LHC limited by mass resolution: $\Gamma_H < 600\,\Gamma_H^{SM}$

- high-mass Higgs tail not Higgs width dependent $\longrightarrow$ provides complementary constraints on Higgs couplings and Higgs width Γ_H (when combined with on-peak data)

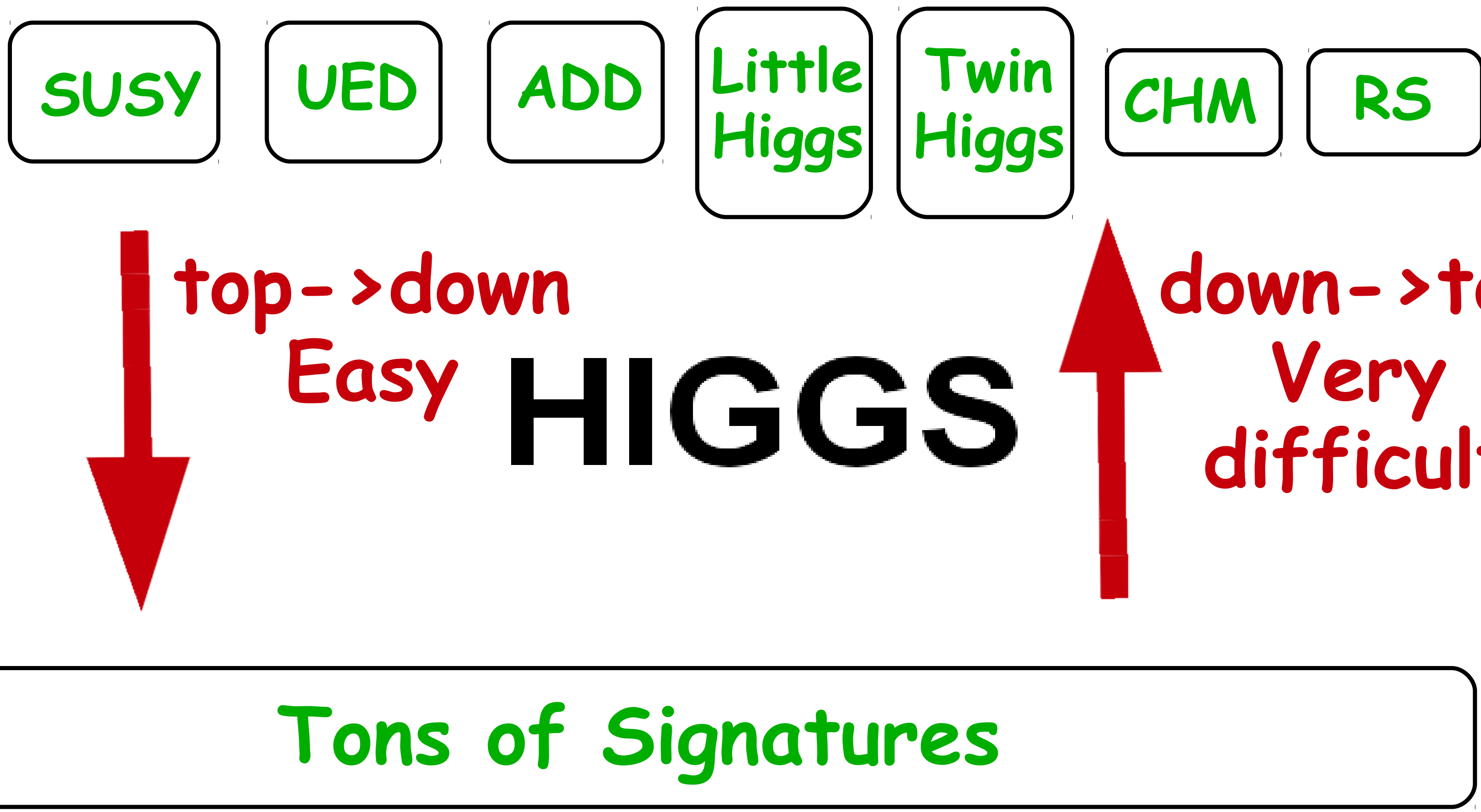
- $H \to \gamma\gamma$: interference-facilitated bound $\Gamma_H < 15\,\Gamma_H^{SM}$ (14 TeV, 3 ab^{-1}, 95% CL)

Bounds are model-dependent!

Higgs boson is opening door to comprehensive test of underlying theory of Nature!



The main problem is to decode an underlying theory from the complicated set of signatures: down -> top



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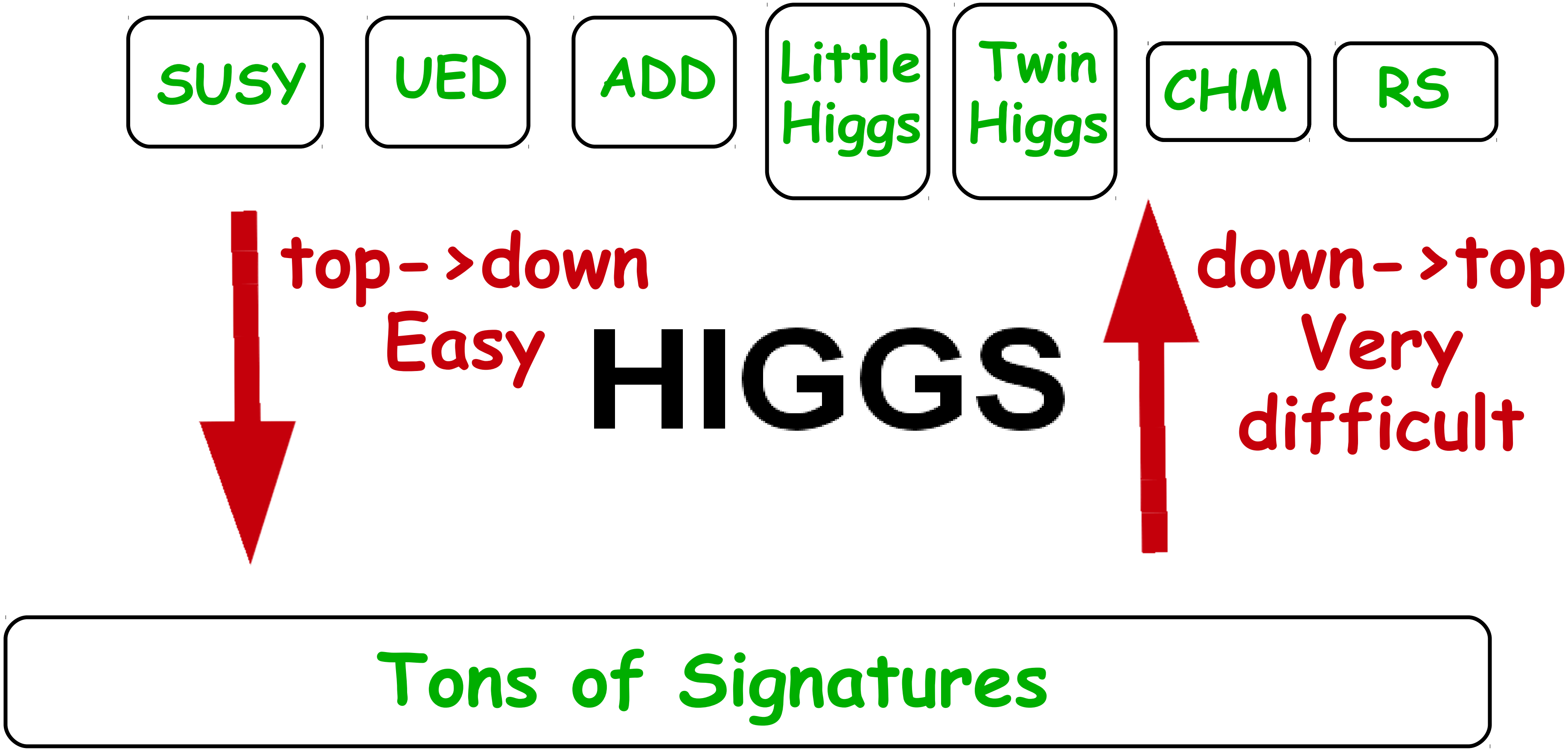

HEPMDB

High Energy Physics Models DataBase

https://hepmdb.soton.ac.uk/

THANK YOU!

- To all organizers and particular to Manfred for fantastic workshop and weather (especially at the excursion!)
- To all speakers for very inspiring talks!
- Thanks to everybody!