I. Global Higgs

II. Systematic uncertainties of the SM Higgs

I. Global Higgs ~ 40 min

II. Systematic uncertainties of the SM Higgs ~ 25 min

The global Higgs as a signal for compositeness at the LHC

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Based on 1607.03125 (JHEP) and 1608.01995 (JHEP) with
Gero von Gersdorff, Eduardo Pontón, Rogerio Rosenfeld

Bethe Forum
30/11/16

1. The composite Higgs paradigm
2. The global Higgs and its properties
3. LHC prospects
4. Outlook

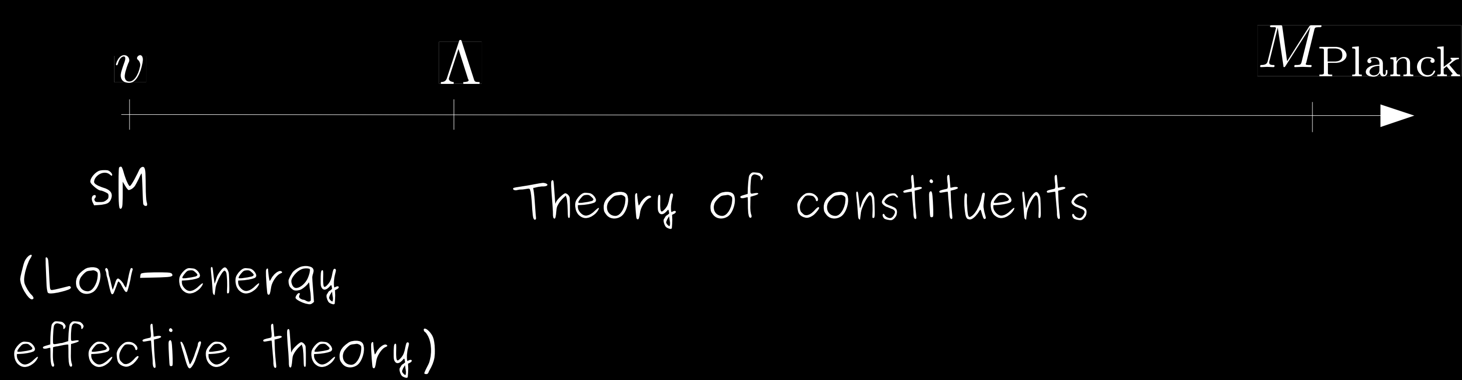
1. The composite Higgs paradigm

Is the Standard Model composite ?

Motivation 1: Why not ?

Motivation 2: $m_h \ll M_{\mathrm{Planck}}$?
Mass of spin-0 particle not protected by a symmetry. The mass of the Higgs boson is technically unnatural.

A solution: NO spin-0 particle. The Higgs is a composite state that dissolves above a scale Λ .



Is the Standard Model composite ?

LHC produced a 125 GeV very SM-like Higgs resonance without revealing any obvious substructure → Binding should be quite strong → Strongly coupled interaction

But the 125 GeV SM-like Higgs is not accompanied by nearby resonances and has a narrow width… Doesn't look like a regular hadron…

Composite pNGB Higgs

Borrow intuition from QCD: the pions are much lighter than other bound states, because they are pseudo Nambu-Goldstone bosons (pNGBs) of a spontaneously broken approximate global symmetry.

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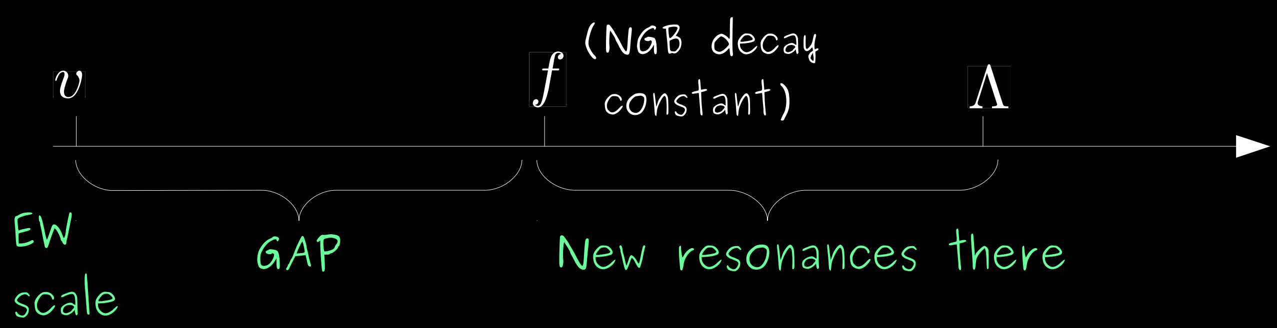
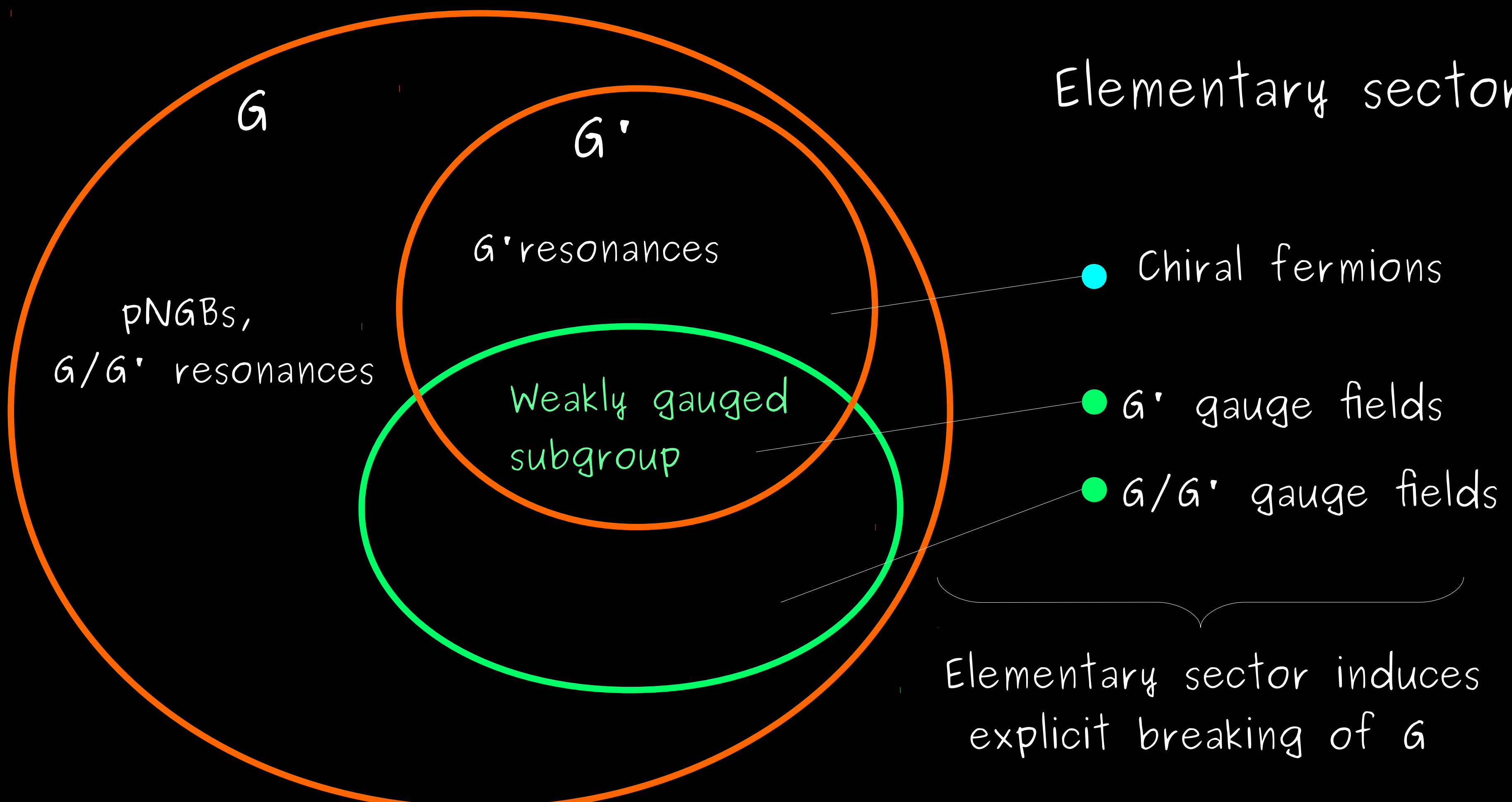
Composite pNGB Higgs

Idea: The Higgs boson and the three longitudinal polarizations of the electroweak (EW) gauge bosons are pNGBs, the 'pions' of a global group **G** broken into **G'**.



The pNGB gap is not arbitrarily large without tuning.
Hence f is expected to be O(TeV) → resonances accessible at LHC

Composite Higgs paradigm

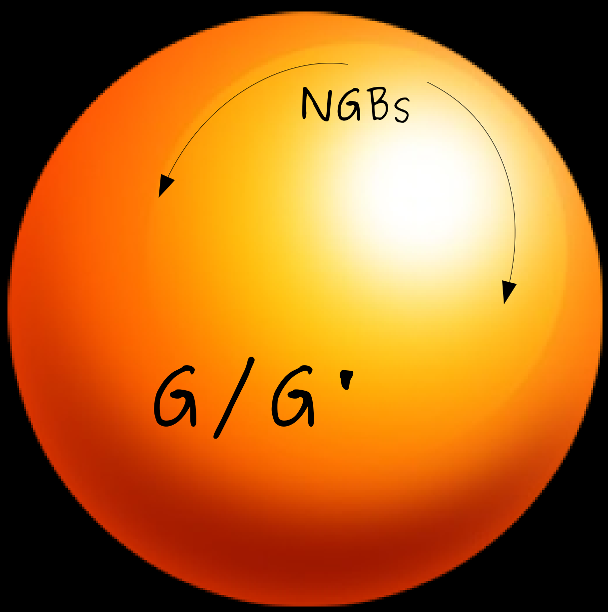


Elementary sector induces explicit breaking of G

2. The global Higgs and its properties

Radius fluctuation

The G/G' coset has a finite radius [in most of constructions], which is assumed to be stable.



The fluctuation of this radius is a massive, CP-even scalar (just like the SM Higgs boson for the SU(2)xU(1)/U(1) coset).

Radius fluctuation

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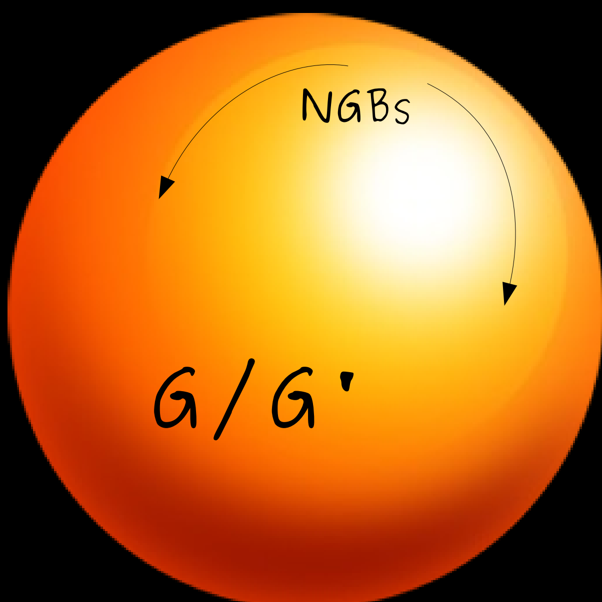

There is another scalar in the composite Higgs picture: the GLOBAL HIGGS, noted ϕ .

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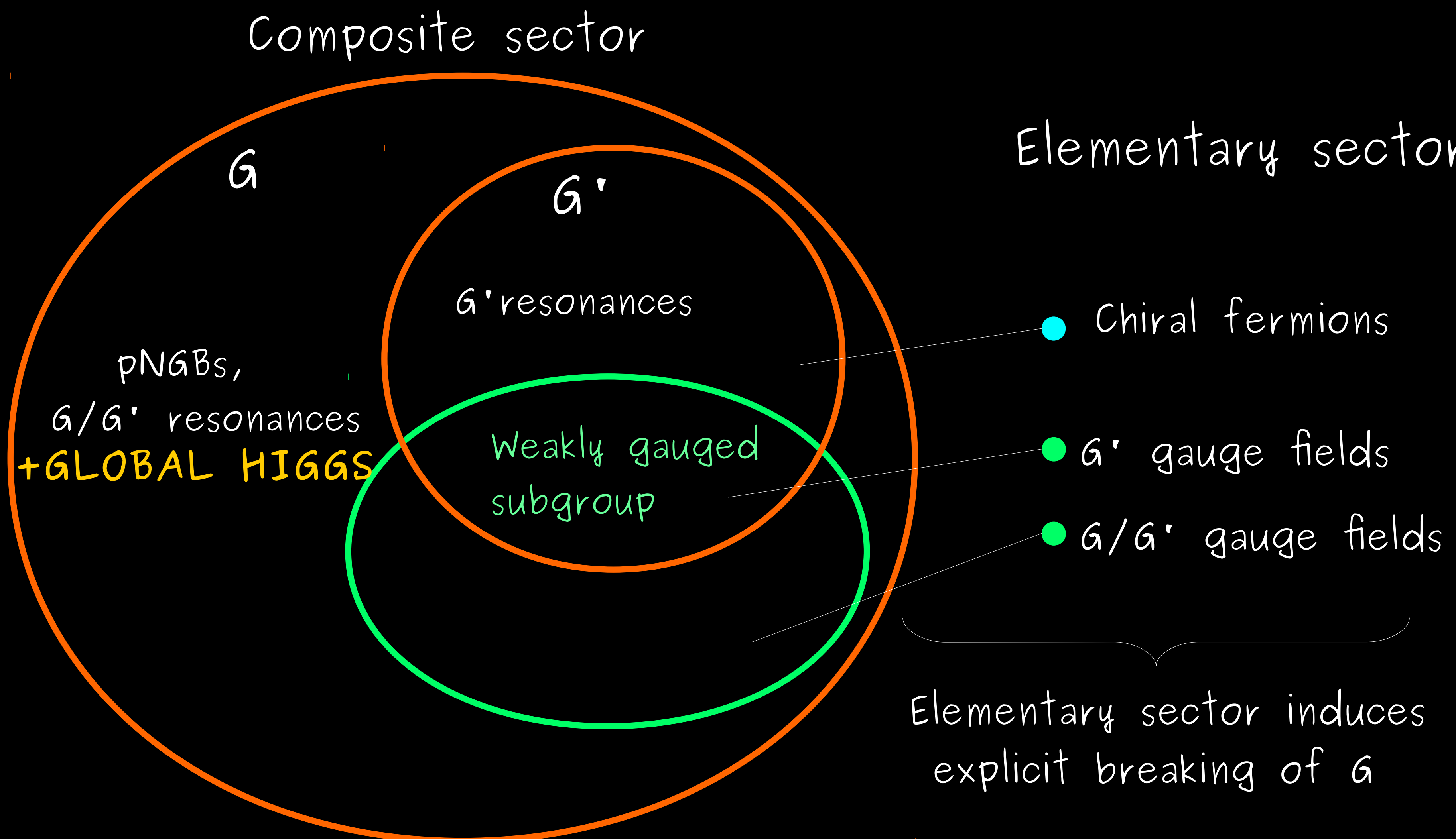


Conceptual step : Global Higgs and pNGBs could be embedded into a multiplet of the unbroken group G (noted Φ).

Qualitative features

- The global Higgs is expected to couple to the NGB's parametrising the coset. Couplings should be derivative by pNGB shift saymmetry
  → One expects a coupling $\phi(\partial_\mu h)^2$, and thus $\phi(Z_\mu)^2$ and $\phi W_\mu^+ W^{\mu-}$ (by gauge invariance)

- Should couple to fermion resonances, as one needs to write proto-Yukawa operators of the form

$$-\xi_{u_i}\mathcal{O}_u(\Phi)\bar{Q}_i U_i - \xi_{d_i}\mathcal{O}_d(\Phi)\bar{Q}_i D_i - \xi_{l_i}\mathcal{O}_l(\Phi)\bar{L}_i E_i + \text{h.c.}$$

- May couple to SM fermions proportionally to their mass,

$$\phi\, m_\psi(\psi_{\rm SM}\psi'_{\rm SM} + \text{h.c.})$$

The SO(5)/SO(4) Higgs

- The G=SO(5), G'=SO(4), choose $\Phi \sim \mathbf{5}$ of SO(5).

$$\underbrace{\Phi = U_5}_{\text{pNGBs}}\underbrace{\mathcal{H}}_{\text{radius}} \qquad \mathcal{H} = (\underbrace{\hat{f}}_{\text{VEV}} + \underbrace{\phi}_{\text{global Higgs}})e_5$$

- Consider quartic expansion of the radius potential:

$$V(\mathcal{H}) = \frac{1}{4}\lambda\left(\mathcal{H}^2 - \hat{f}^2\right)^2 \rightarrow m_\phi = \sqrt{2\lambda}\hat{f}$$

- General bosonic Lagrangian:

$$\mathcal{L}_{\rm bos} = \frac{1}{2}(\nabla_\mu \mathcal{H})^2 - V(\mathcal{H}) + \frac{1}{4}f_\rho^2\left(\mathcal{A}_\mu^A - i[U_5^\dagger D_\mu U_5]^A\right)^2 + \ldots$$

The pNGBs mix with the coset resonances, $f^{-2} = \hat{f}^{-2} + f_\rho^{-2}$

Global Higgs interactions

- Bosonic couplings:
  - SM Higgs and EW gauge bosons: $2\frac{f^2}{\hat{f}^3}\,\phi\,(D_\mu H)^2$
  - Spin-1 (coset) resonances: $\frac{2}{\hat{f}}\phi\mathcal{A}_\mu^{\hat{a}\,2}$

Only two free parameters !

And f should be minimized to reduce EW fine-tuning.

- Fermionic couplings:
  - SM fermions: $-\frac{m_\psi}{\hat{f}}\phi\bar{\psi}\psi$
  - fermion resonances: completely model dependent

Complete realizations

To learn further about the global Higgs properties, one needs to define full realizations of the fermion sector.

We consider four typical models, $\mathrm{MCHM}_{Q,U,D}$, with

$$
\begin{aligned}
(Q,\ U,\ D) = &\ (5_{2/3},\ 1_{2/3},\ 10_{2/3}) \\
&\ (5_{2/3},\ 14_{2/3},\ 10_{2/3}) \\
&\ (14_{2/3},\ 14_{2/3},\ 10_{2/3}) && \leftarrow \text{Higgs in the 14 of } SO(5) \\
&\ (5_{2/3},\ 1_{2/3},\ \times) && \leftarrow \text{No partial compositeness}
\end{aligned}
$$

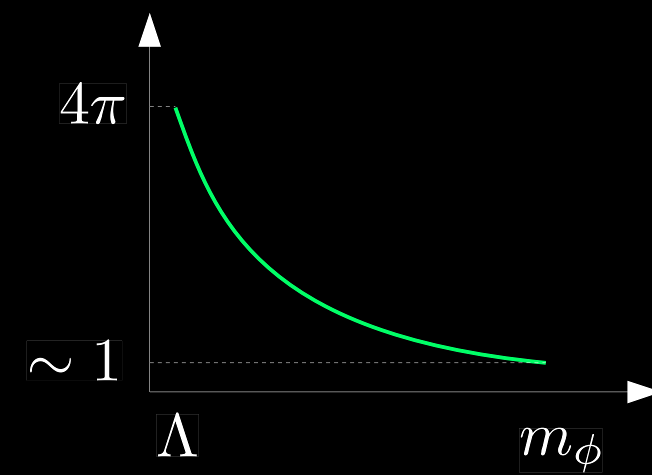
IN SHORT: Yukawa operators and thus couplings of the global Higgs to fermion resonances differ in each scenario (multiplicities, group theoretical factors...)

Renormalization

- Yukawa couplings ξ:

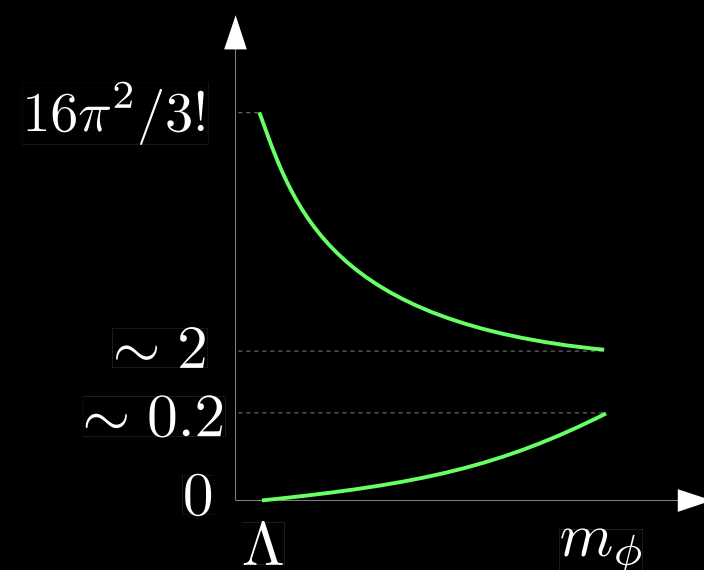
$$\xi_{\text{eff}}^2 = 4N_c\left(N^U\left[\xi_U\xi_U^T + \xi_U'\xi_U'^T\right] + N^D\left[\xi_D\xi_D^T + \xi_D'\xi_D'^T\right]\right)$$

$$\mu\frac{d\xi_{\text{eff}}^2}{d\mu} \approx \frac{\xi_{\text{eff}}^4}{16\pi^2}$$



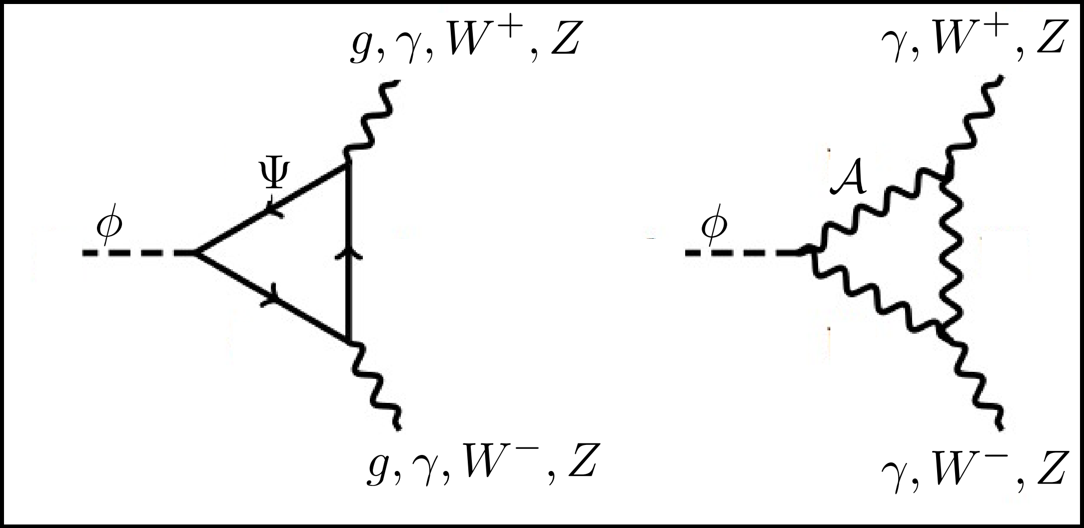
- Global Higgs quartic λ:

$$\mu\frac{d\lambda}{d\mu} \approx \frac{1}{16\pi^2}\left(26\lambda^2 + 2\lambda\xi_{\text{eff}}^2 - \epsilon\,\xi_{\text{eff}}^4\right)$$



One-loop effective couplings

We can now go ahead: The global Higgs couples to many non SM-singlet fermion and vector resonances, which induce loop couplings to SM gauge bosons.

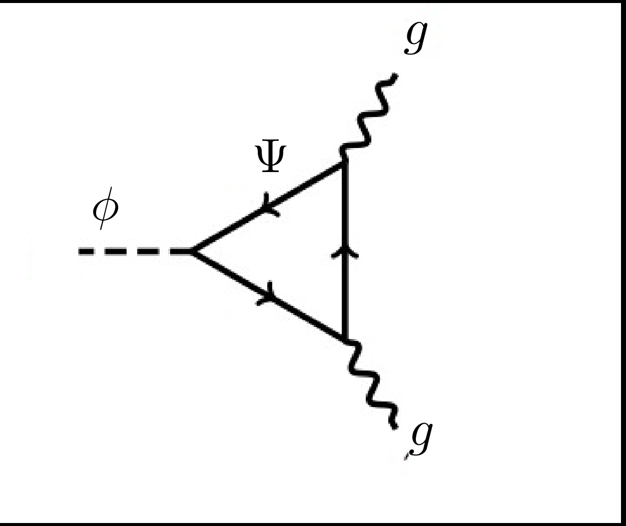


The fermion loops completely depend on the fermion sector (representation, loops, mass matrices). However, for heavy enough vector like masses, compact expressions are obtained.

One-loop effective couplings

For example : gluon coupling

$$\mathcal{L} \supset -\phi \frac{a_{gg}}{\hat{f}} (G^a_{\mu\nu})^2$$



$$a_{gg} = c_{gg} \frac{\hat{f}^2}{M_\psi^2} A_{1/2}\left(\frac{m_\phi^2}{4M_\psi^2}\right)$$

$$c_{gg} = \begin{pmatrix} 0.013 \\ 0.014 \\ 0.011 \\ 0.01 \end{pmatrix} \begin{array}{l} \mathrm{MCHM}_{5,1,10} \\ \mathrm{MCHM}_{5,14,10} \\ \mathrm{MCHM}_{14,14,10} \\ \mathrm{MCHM}_{5,1} \end{array}$$

Very similar for each scenario !

3. Some LHC prospects

Global Higgs parameters

- Global Higgs mass m_Φ
- Global Higgs quartic λ
- Fermion resonances mass scale M_Ψ
- pNGB decay constant f

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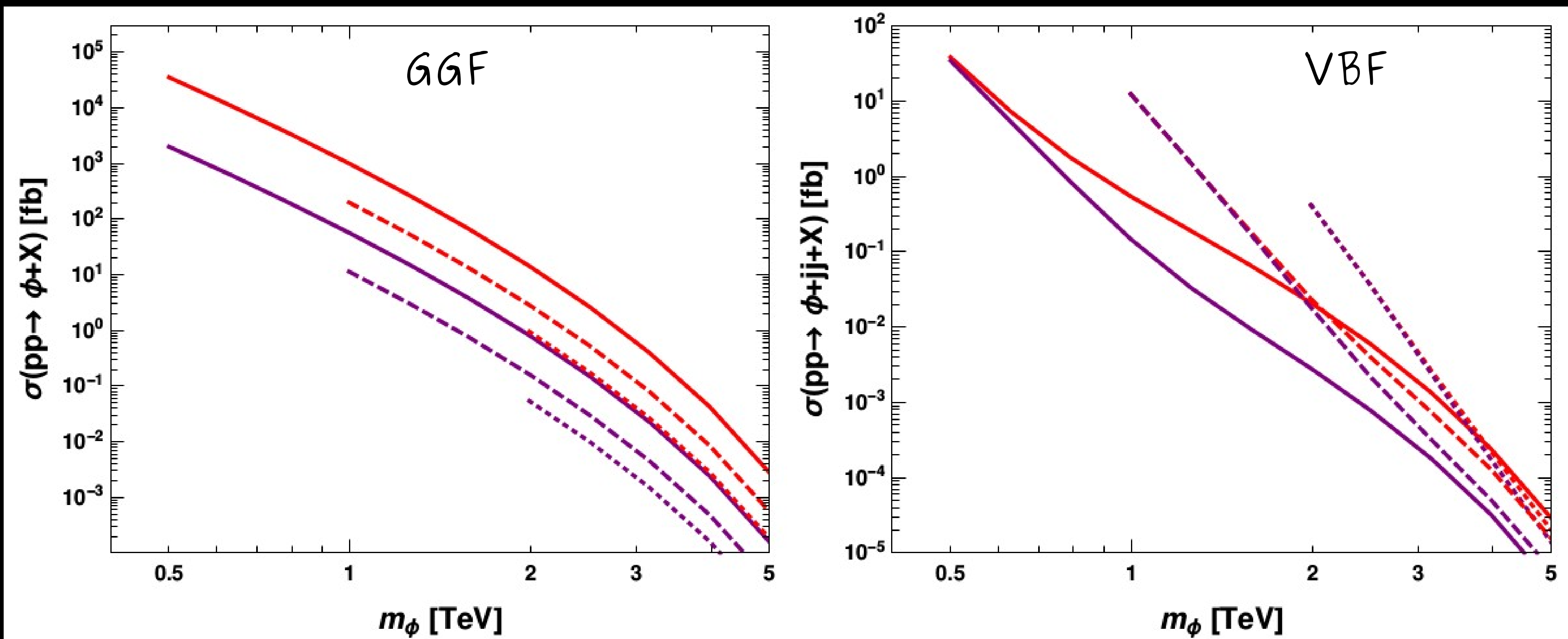
Global Higgs parameters

- Global Higgs mass m_Φ
- Global Higgs quartic $\lambda \in [0.2, 3]$ from RG
- Fermion resonances mass scale M_Ψ
- pNGB decay constant $f = 800\,\mathrm{GeV}$

  from standard LE bounds on composite models. In this work we don't focus on LE effects from the global Higgs.

Production at the 13 TeV LHC

I



Red and purple : $M_\psi = m_\phi$, $M_\psi = 2m_\phi$
Plain, dashed, dotted : $\lambda = 0.2,\ 1,\ 3$

Scenarios

The LHC signals of the global Higgs can be split into two broad cases:

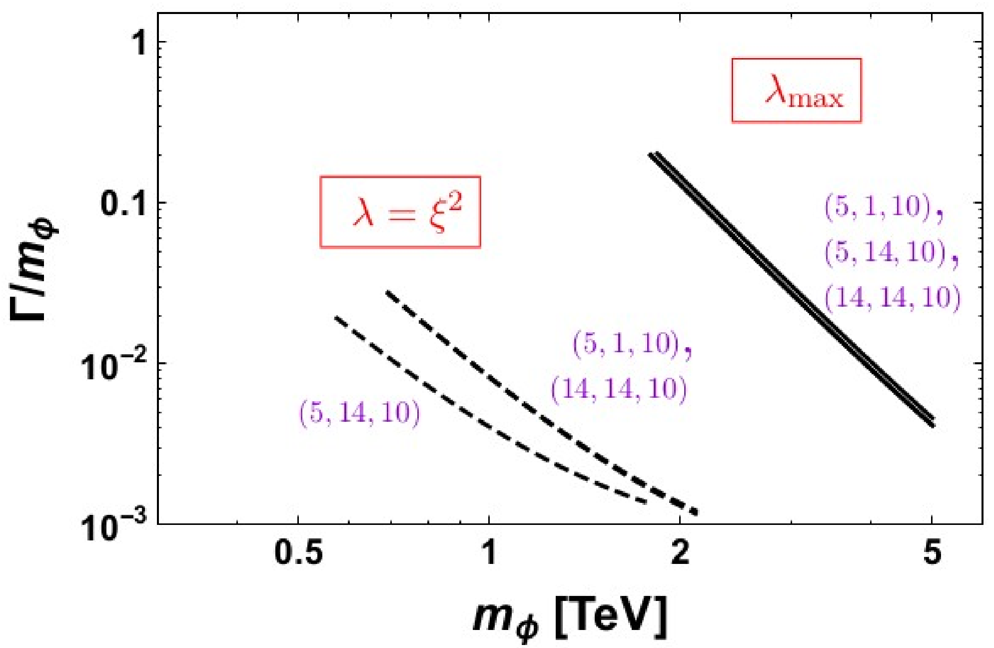
- Case I: All decays involving fermion resonances are closed. The phenomenology is then largely independent of the details of the heavy fermion sector.
  Leading decays are $\phi \to \mathrm{pNGBs}$, $\phi \to t\bar{t}$

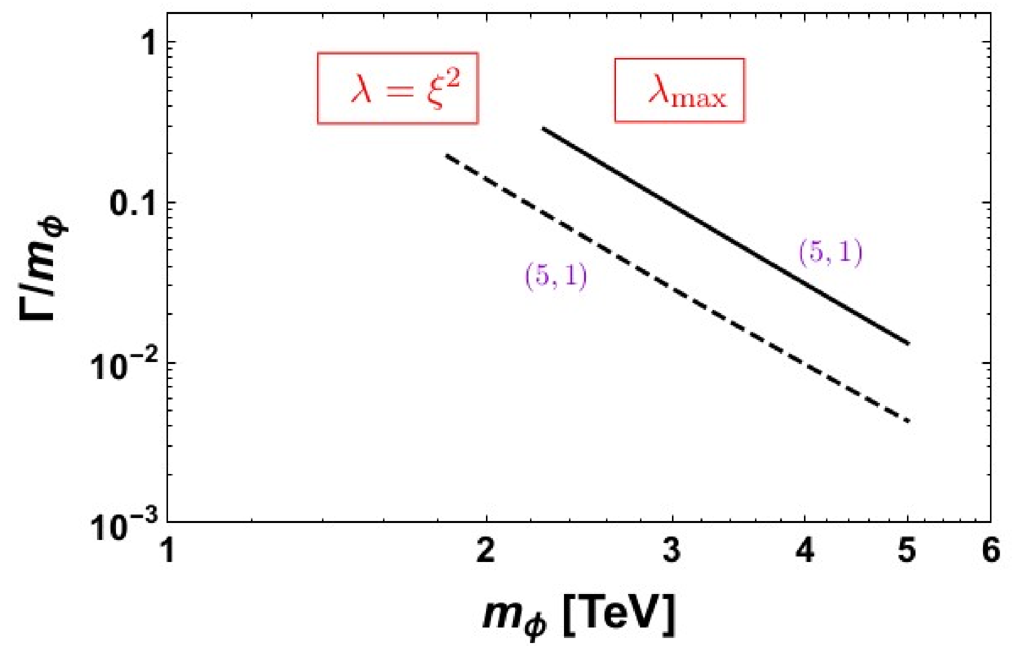
- Case II: Some decays involving fermion resonances $\phi \to \bar{\psi}\psi'$ are also open. The phenomenology depends strongly on the realization of the fermion sector.

Case I

Decays

If no decays to fermion resonances are allowed, the global Higgs mainly decays into Higgs, EW bosons and top quarks.

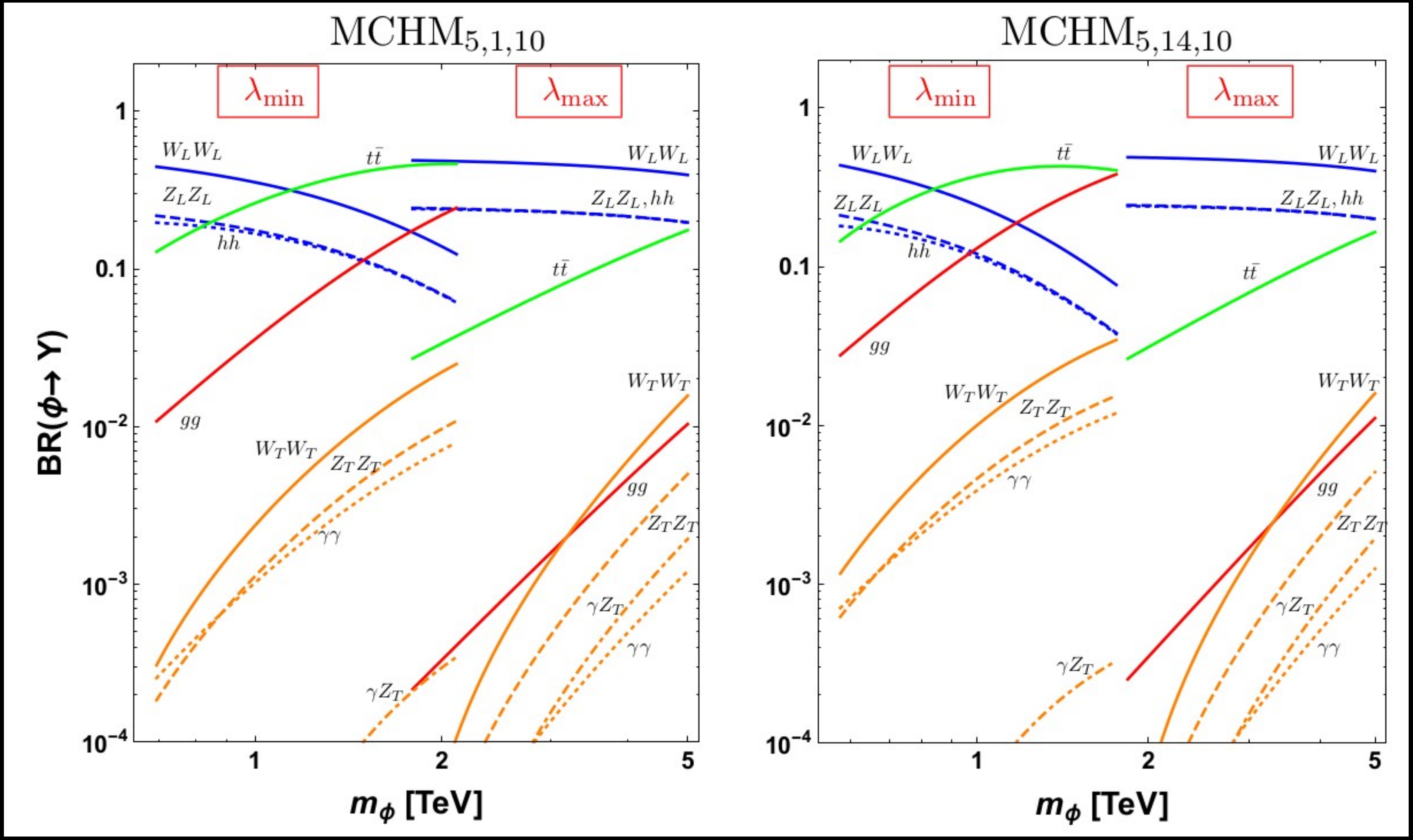




Total width doesn't exceed $\Gamma/m_\phi \sim 0.1$, the global Higgs is a narrow state and NWA applies.

Decays

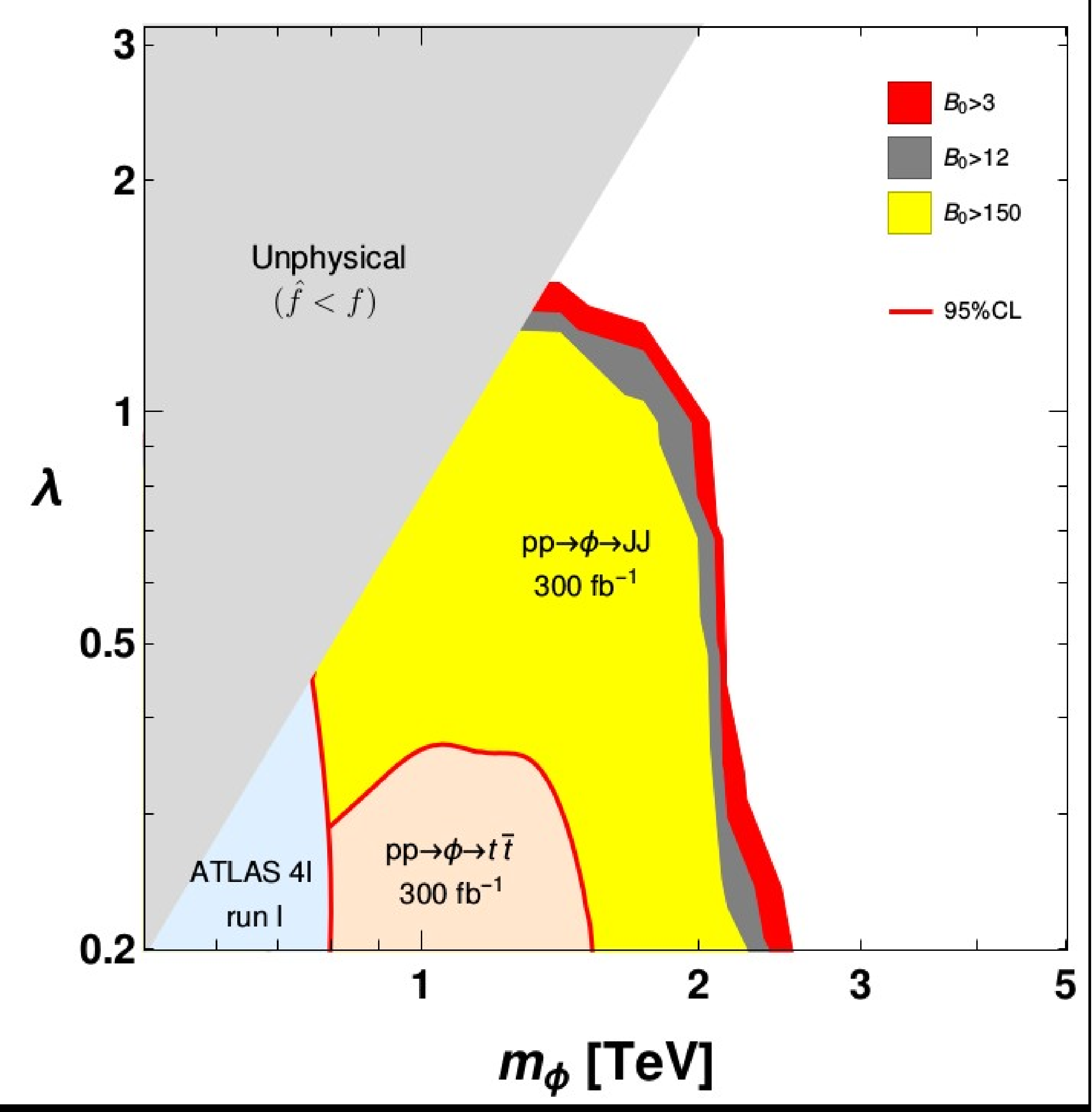
If no decays to fermion resonances, the branching ratios are



Prospects for decays into SM particles

Sensitivities :

- 4l, ttbar directly obtained from exp. sensitivity
- JJ obtained by extrapolating a 8 TeV JJ background from ATLAS



Case II

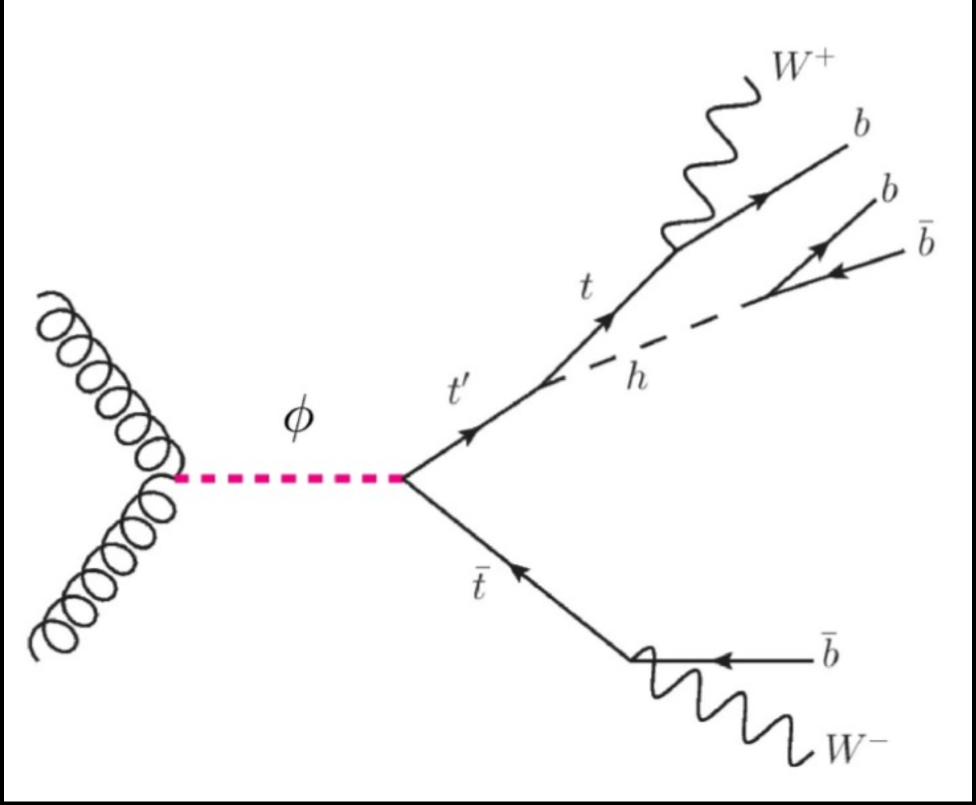
Decays

If decays to fermion resonances are open, the global Higgs width grows. In the extreme limit were all decays are open and masses negligible, one has simply

$$\frac{\Gamma_{\phi\to\bar\psi\psi}}{m_\phi} = \begin{pmatrix} 27/4\pi \\ 54/5\pi \\ 117/20\pi \\ 3/4\pi \end{pmatrix} |\xi|^2 \approx \begin{pmatrix} 0.8 \\ 0.9 \\ 0.7 \\ 0.6 \end{pmatrix}, \quad \begin{matrix} \mathrm{MCHM}_{5,1,10} \\ \mathrm{MCHM}_{5,14,10} \\ \mathrm{MCHM}_{14,14,10} \\ \mathrm{MCHM}_{5,1} \end{matrix}$$

Decays into top partners

When the global Higgs decays into fermion partners, there is a larger model-dependence. We consider the case of decays into top partners (t') only, like



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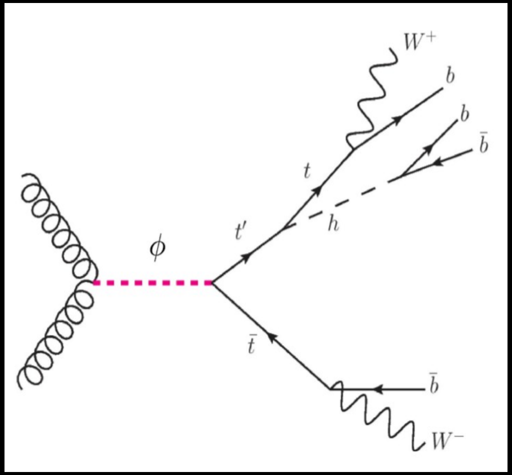


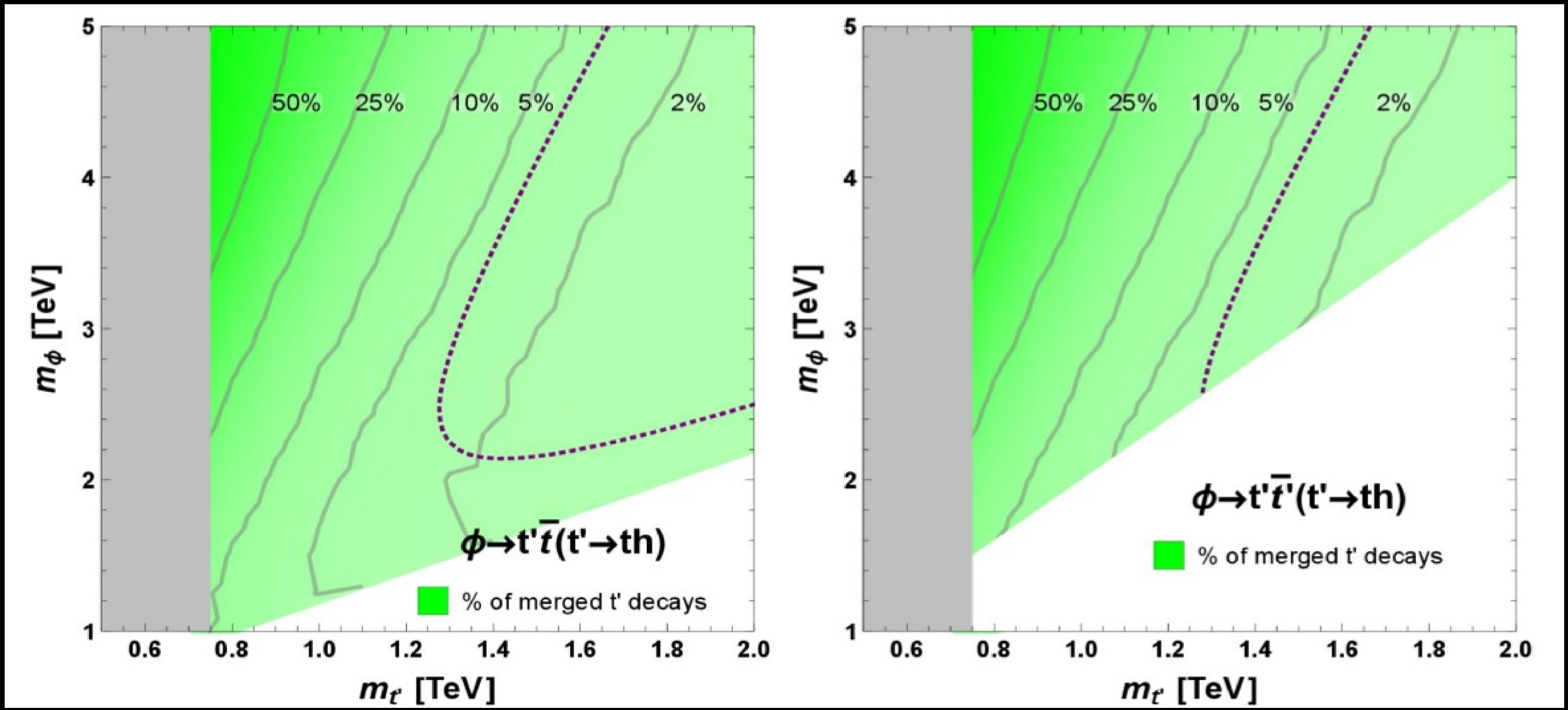
→ A new production mode for t'

→ Resonant topology is useful to reject background (not studied)

→ If hadronic decays, boosted t' may produce large-radius jets

Fat t' jets

Can these actually happen ?



4. Conclusions

Summary (1)

- Composite Higgs models contain another scalar: the excitation of global-symmetry vaccum G/G' -dubbed the global Higgs, coupled in a predictive way to Higgs, Z, W, top.

- We considered complete fermion sector realizations, taking into account renormalization of the composite sector. Sizeable couplings to gauge bosons arise from resonance loops.

- We evaluated the LHC sensitivity to global Higgs resonant production. Our results suggest that these channels can compete with the standard searches for compositeness via SM-produced t'.

Summary (2)

- If the global Higgs decays mostly into NGBs and top quarks, sensitivity in boosted hadronic channels gives a reach up to $m \sim 2.5\text{-}3$ TeV for 300 fb^{-1}. This case is very predictive.

- If global Higgs also decay also into t', such channel can compete with standard t' production. Moreover we find these boosted t' have a sizeable probability to produce t'-jets.

Thanks!

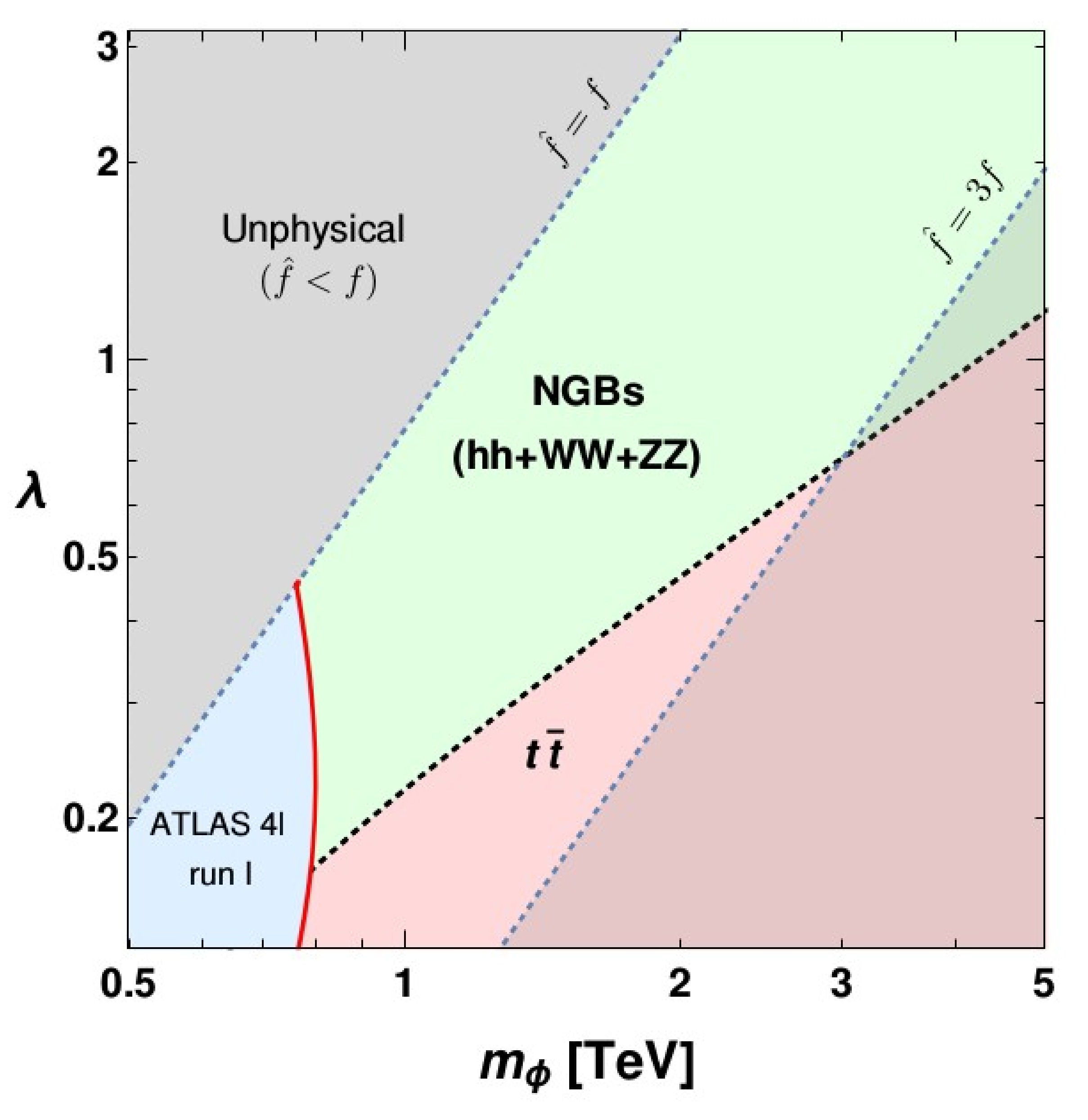
More

Prospects for decays into SM particles

When $\phi \to \bar{\psi}\psi$ closed,

(leading decays are $\phi \to \mathrm{pNGBs}$ $\phi \to t\bar{t}$)

Decays depends on 2 parameters, chosen to be the global Higgs mass and quartic.



Fat t' jets

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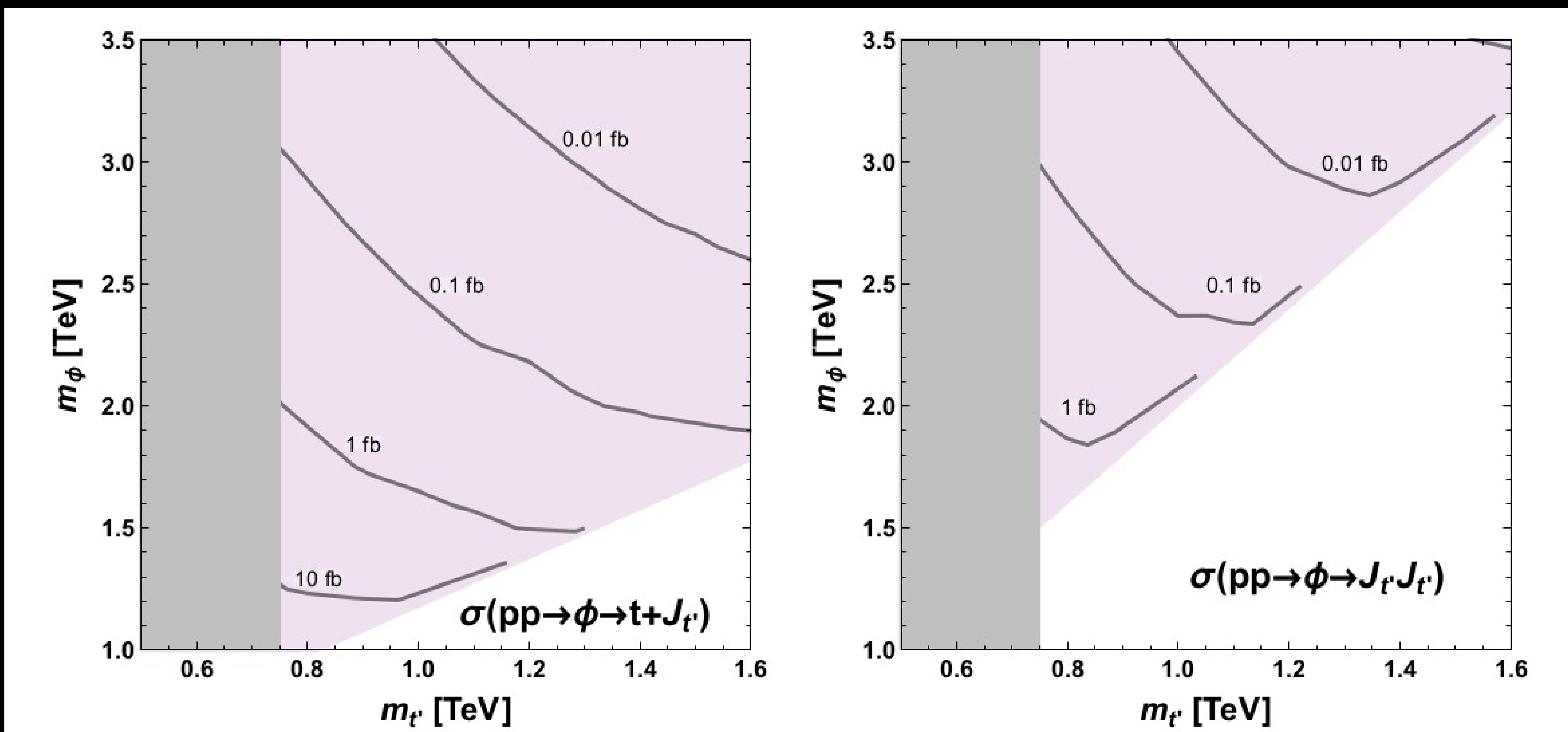

Systematic uncertainties of the SM Higgs

Based on 1603.0361 (NPB), and 1606.00455 (JHEP) with

A. Arbey, N. Mahmoudi, G. Moreau

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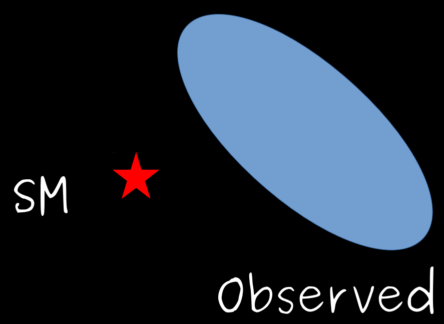
Context

- Systematic uncertainties are becoming increasingly relevant at the LHC. At some point we may face the following situation:



New Physics or systematics ?

→ A flawless treatment of these uncertainties is needed

1. The correlation matrix of Higgs rates
2. Approximate likelihoods

1. The correlation matrix of Higgs rates

“Theoretical“ uncertainties

We take care of the uncertainties affecting the Higgs inclusive rates

- Unknown higher order terms in perturbative calculations
  (ex: renormalization scale dependence)
- Approximations in ME calculations
  (ex: EFT approx. in ggH)
- Modelizations of a physical object
  (ex: sets of parton PDFs)

Truely theoretical
Unknown priors
Hard to quantify

- Uncertainties on auxiliary datas
  (ex: data for PDF, Higgs mass)

Experimental

- Uncertainties on input parameters

It depends

Parametrization of elementary uncertainties

- It is convenient to use a parametrization that make appear the relative magnitudes:

$$A = A^0\left(1 + \sum_{n=1}^{p} \delta_A^n \Delta_A^n + O\left((\Delta_A^n)^2\right)\right), \qquad E[\delta^n] = 0 \quad V[\delta^n] = 1$$

XS, BR...

- We can obtain the covariance matrix (i.e. correlation matrix and error magnitudes) between all rates by just using standard probability computations.

- Our approach is valid in Bayesian and "Gaussian frequentist".

Combination

- Enough to start from two quantities:

$$A = A^0\left(1 + \sum_{n=1}^{p} \delta_A^n \Delta_A^n + O\left((\Delta_A^n)^2\right)\right), \quad B = B^0\left(1 + \sum_{n'=1}^{p'} \delta_B^{n'} \Delta_B^{n'} + O\left((\Delta_B^{n'})^2\right)\right).$$

with general elementary correlations

$$\rho_A^{nm} = \mathrm{Cov}[\delta_A^n, \delta_A^m], \quad \rho_B^{n'm'} = \mathrm{Cov}[\delta_B^{n'}, \delta_B^{m'}], \quad \rho_{AB}^{nn'} = \mathrm{Cov}[\delta_A^n, \delta_B^{n'}].$$

- One gets

$$\boxed{\begin{gathered}(\Delta_A)^2 = \sum_{n,m} \rho_A^{nm} \Delta_A^n \Delta_A^m, \quad (\Delta_B)^2 = \sum_{n',m'} \rho_B^{n'm'} \Delta_B^{n'} \Delta_B^{m'}, \\ \rho_{AB}\Delta_A\Delta_B = \sum_{n,n'} \rho_{AB}^{nn'} \Delta_A^n \Delta_B^{n'}.\end{gathered}}$$

Covariance matrix of the Higgs rates

- We applied this to the Higgs rates:
  - collected all elementary systematics
  - propagated them in the XS and BR
  - combined them
  - results are available on the arxiv in C, F, Mathematica, TeX…

- Only subtelty: renormalization/factorization scale correlations, for which we considered various extreme cases:

  i) All scales independent between each process (no correlations)
  ii) All scales 100% correlated between each process

  This has an important consequence for ttH–ggH correlation:
  i) −1.3% @8TeV, −1.6% @13TeV
  ii) 82% @8TeV, 83% @ 13TeV

Covariance matrix of the Higgs rates

- Relative magnitudes (in %)

$$\begin{array}{lcccccc} & \text{ggH} & \text{VBF} & \text{ZH} & \text{WH} & \text{ttH} & \text{bbH} \\ \Delta_{X_{7\,\text{TeV}}} = & 12.3\ (12.1) & 2.0 & 2.5\ (2.2) & 2.6\ (2.4) & 13.7\ (18.9) & 11.8\ (10.6) \\ \Delta_{X_{8\,\text{TeV}}} = & 12.3\ (11.9) & 2.0 & 2.4\ (2.1) & 2.6\ (2.2) & 13.6\ (18.9) & 11.6\ (10.2) \\ \Delta_{X_{13\,\text{TeV}}} = & 12.3\ (11.2) & 2.1\ (2.2) & 2.4\ (1.8) & 2.5\ (2.0) & 13.6\ (19.0) & 11.0\ (8.9) \\ \Delta_{X_{14\,\text{TeV}}} = & 12.3\ (11.1) & 2.1\ (2.2) & 2.5\ (1.8) & 2.6\ (1.9) & 13.6\ (19.0) & 10.9\ (8.7) \end{array}$$

$$\begin{array}{lcccccccccc} & WW & ZZ & \gamma\gamma & Z\gamma & gg & b\bar{b} & c\bar{c} & s\bar{s} & \tau\bar{\tau} & \mu\bar{\mu} \\ \Delta_Y = & 2.1 & 2.4 & 1.2 & 1.8 & 3.9 & 1.3 & 5.4 & 2.4 & 1.3 & 1.3 \end{array}$$

13 TeV correlation matrix (case i):

	ggH	VBF	ZH	WH	ttH	bbH	WW	ZZ	$\gamma\gamma$	$Z\gamma$	gg	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$\tau\bar{\tau}$	$\mu\bar{\mu}$
ggF	100	9	5	4	−2	3	3	2	10	5	18	−10	−4	−15	10	10
VBF	9	100	50	38	−12	−24	1	0	16	4	28	−14	−6	−23	18	18
ZH	5	50	100	56	−6	−11	−13	−15	14	−9	26	−4	−3	−16	23	23
WH	4	38	56	100	−4	−3	−13	−15	13	−10	24	−3	−3	−14	22	22
ttH	−2	−12	−6	−4	100	9	−4	−4	−2	−4	−2	4	1	3	0	0
bbH	3	−24	−11	−3	9	100	−8	−8	−6	−8	8	4	−5	−16	−3	−3
WW	3	1	−13	−13	−4	−8	100	100	56	99	36	−86	−15	−29	10	10
ZZ	2	0	−15	−15	−4	−8	100	100	49	98	31	−83	−15	−29	2	2
$\gamma\gamma$	10	16	14	13	−2	−6	56	49	100	67	77	−82	−11	−15	88	88
$Z\gamma$	5	4	−9	−10	−4	−8	99	98	67	100	46	−91	−16	−28	24	24
gg	18	28	26	24	−2	8	36	31	77	46	100	−73	−20	−70	70	70
$b\bar{b}$	−10	−14	−4	−3	4	4	−86	−83	−82	−91	−73	100	−1	46	−48	−48
$c\bar{c}$	−4	−6	−3	−3	1	−5	−15	−15	−11	−16	−20	−1	100	25	−4	−4
$s\bar{s}$	−15	−23	−16	−14	3	−16	−29	−29	−15	−28	−70	46	25	100	1	1
$\tau\bar{\tau}$	10	18	23	22	0	−3	10	2	88	24	70	−48	−4	1	100	100
$\mu\bar{\mu}$	10	18	23	22	0	−3	10	2	88	24	70	−48	−4	1	100	100

2. Approximate likelihoods

Collective behaviour of systematics

- When a large number of small independent systematic uncertainties are present in the likelihood, simplifications occur. Elementary uncertainties can be consistently propagated and combined

$$L(\theta,\delta) \equiv \prod_{I=1}^{N} \Pr\Big(\hat{n}_I \,\Big|\, n_I(\theta,\delta),\theta,\delta\Big)$$

Many elementary nuisance parameters with arbitrary distributions

$$\downarrow$$

$$\bar{L}(\theta,\bar{\delta}) \equiv \prod_{I=1}^{N} \Pr\Big(\hat{n}_I \,\Big|\, \bar{n}_{0,I}\exp(\Delta_I\bar{\delta}_I),\theta,\bar{\delta}\Big)$$

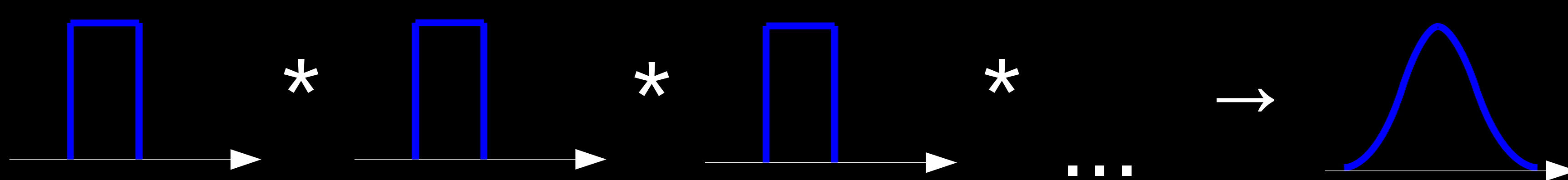
N correlated nuisance parameters with $\sim$multivariate Gaussian distribution

CLTs

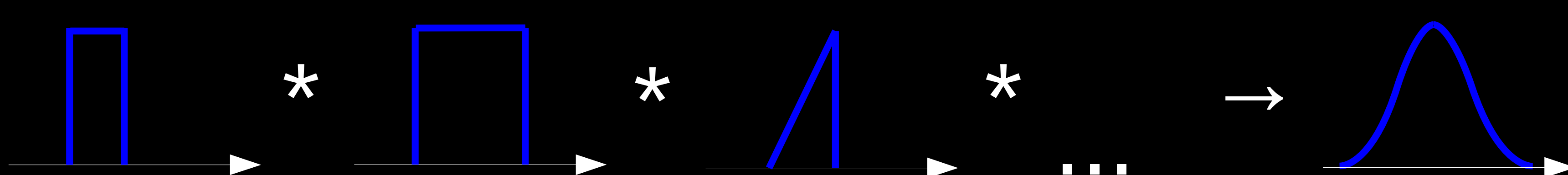
- This is because there is a central limit theorem at work: the elementary uncertainties on the n's enter as

$$n(\delta) = n^0 \exp\left(1 + \sum_r^p \delta_r \Delta_r\right)$$

- Classic CLT



- Lyapunov/Lindberg CLT:



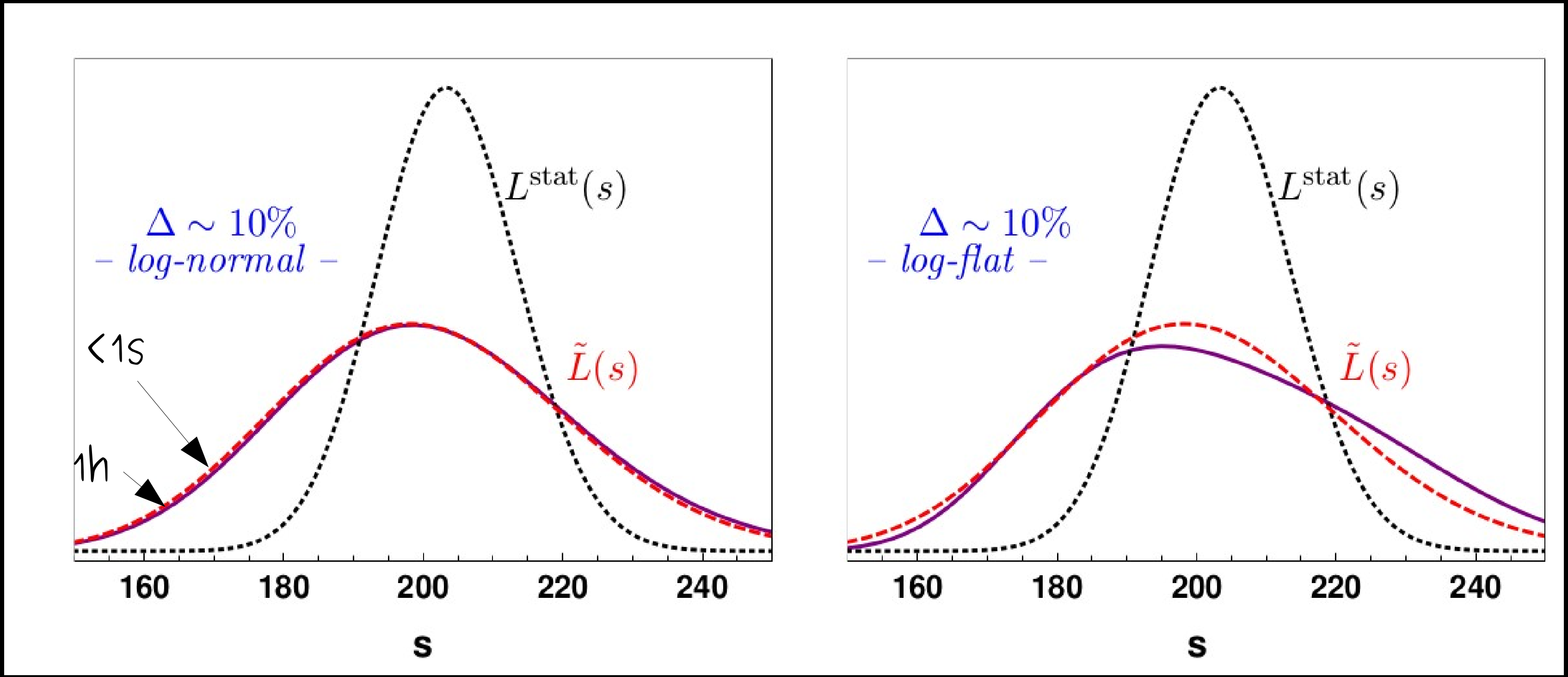
Checks with a toy likelihood

Event rates

Systematics

Channel	A	B	C
$\hat{n}$	280	310	320
$\Delta^{s,1}$	10%	−10%	10%
$\Delta^{s,2}$	5%	10%	10%
$\Delta^{s,3}$	0%	−5%	−5%
$\Delta^{b,1}$	−10%	−10%	10%
$\Delta^{b,2}$	5%	10%	−10%

Checks with a toy likelihood



- Case with Gaussian prior works well. Gives a check of the approximations other than the CLT.

- Discrepancy in the flat prior case comes from unperfect convergence of the CLT. It is expected to decrease with more systematics.

Implications

(thinking in particular about Higgs likelihoods)

i) Much lighter treatment of uncertainties as heavy numerical integrations are reduced or avoided.

ii) Transmission of the information about systematic uncertainties becomes easy and human-readable. Only the magnitudes of elementary uncertainties and derivatives of the expected event rates are needed.

→ One could set up a simplified likelihood framework allowing LHC experiments to easily communicate their systematic effects to the public

Thanks!