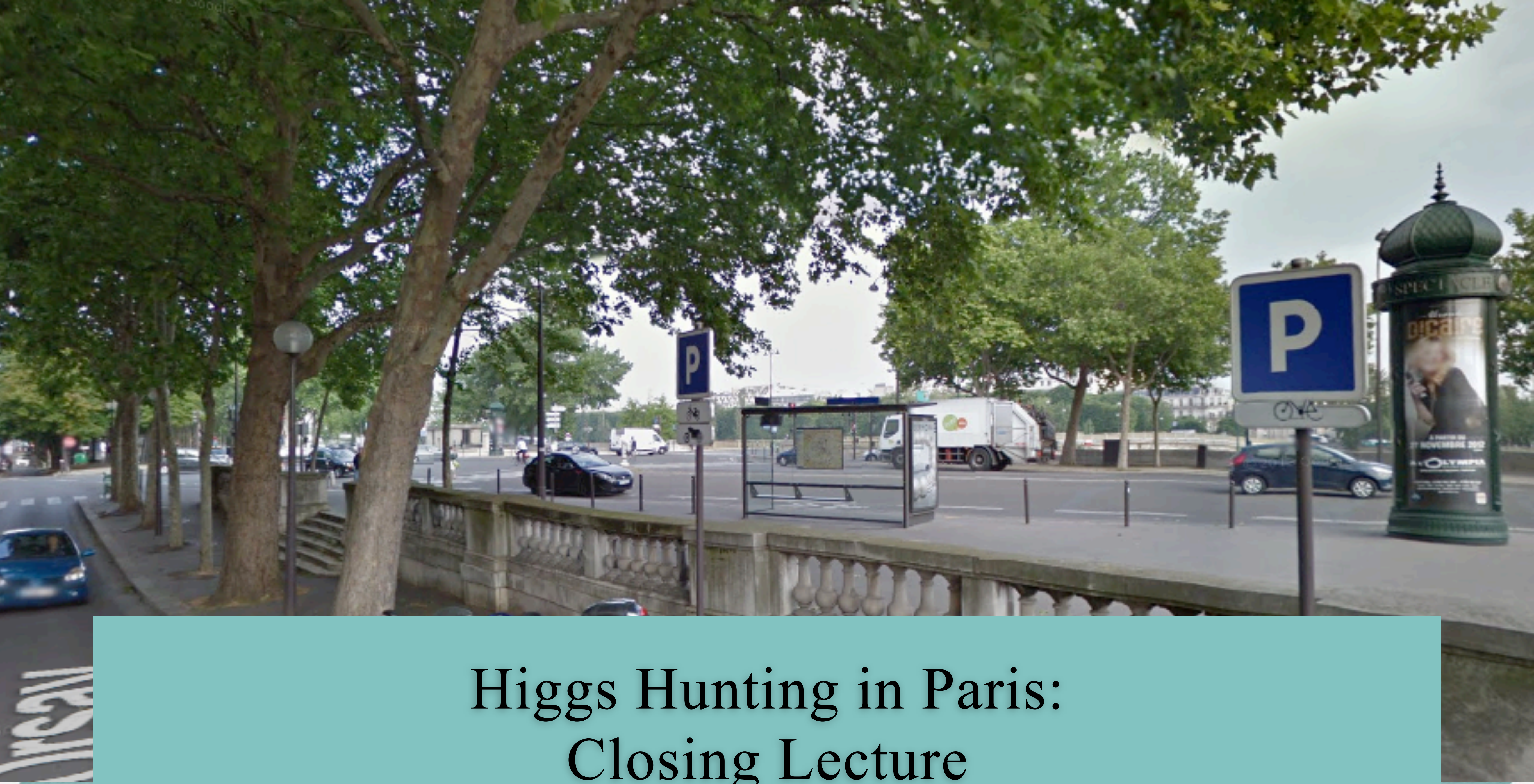


Higgs Hunting in Paris: Closing Lecture

Luciano Maiani, Sapienza Universita' di Roma
and
INFN Sezione di Roma

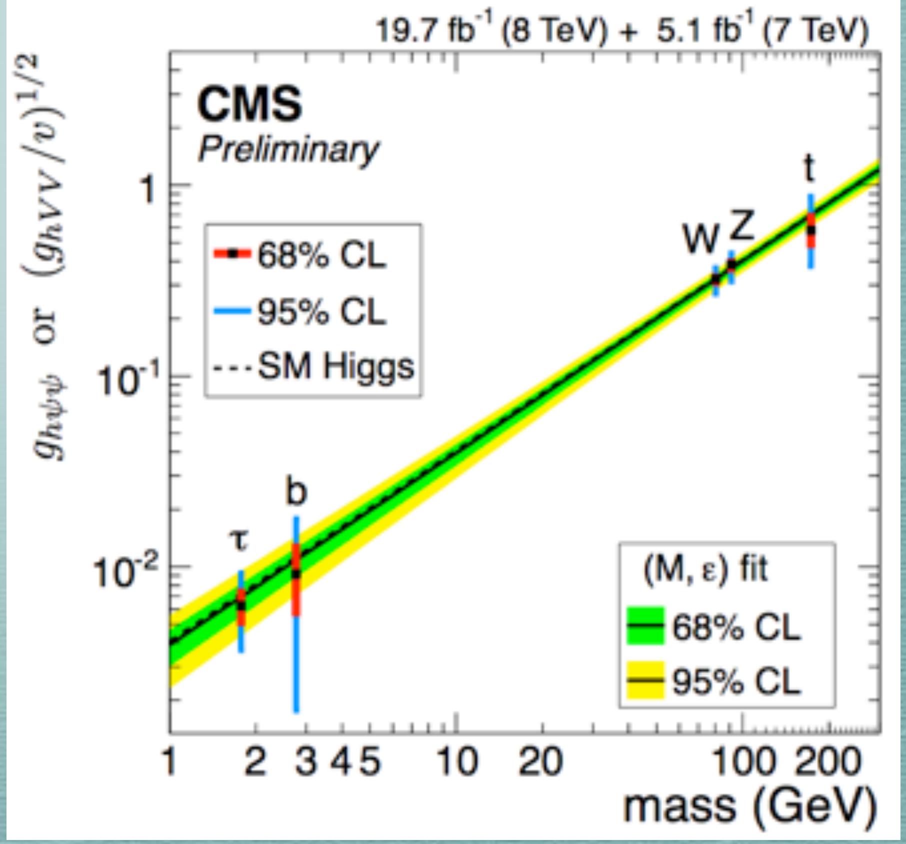
SUMMARY

- Being the Higgs Boson
- Physics @ the Hadron Collider
- Unexpected:
  - The Higgs boson width
  - Lepton flavor violations?
- Unnatural: what is it ?
- Precursors
- Probing SUSY in the Higgs Sector
- Higgs boson as a PseudoGoldstone
- Flavor Symmetry and Flavor Symmetry Breaking
- A new “light” vector boson?
- LHC @ 14 TeV and Beyond.

1. Being the Higgs boson: couplings to the other particles

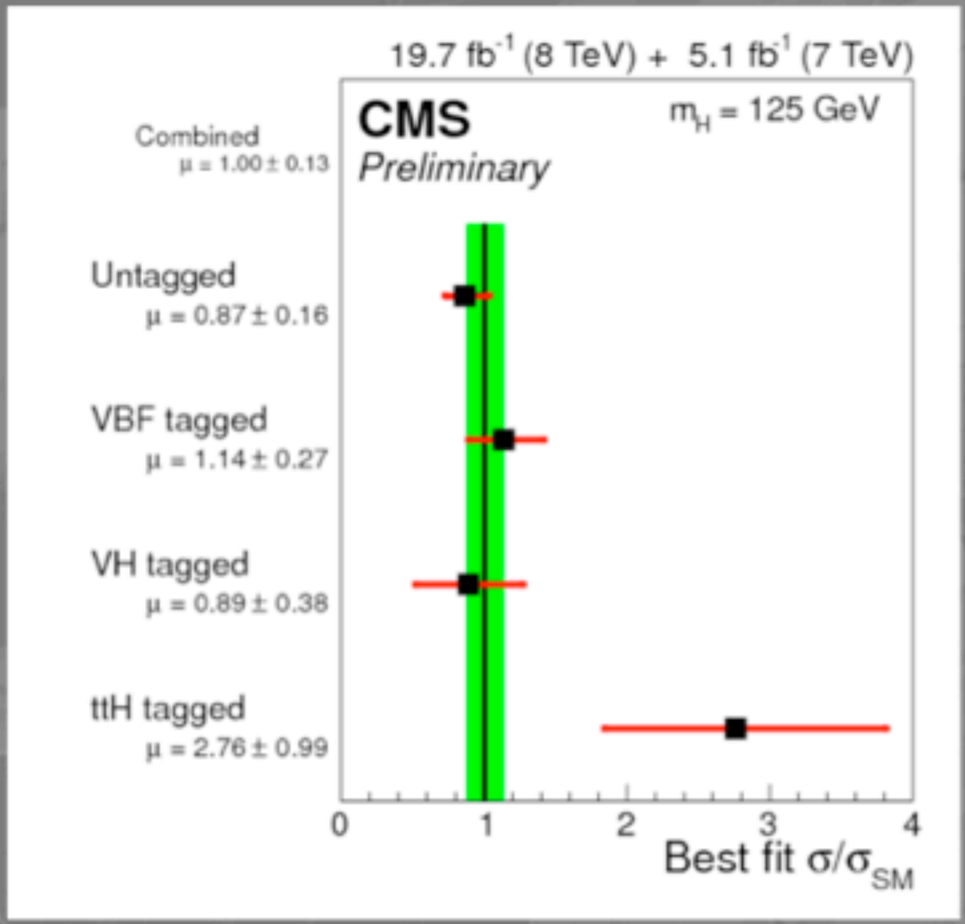
- With the Higgs boson we are probing a physics which is very different from the one we are used with the gauge interactions
- In lowest order, the couplings of H to other particles are related to the masses:
  - g(H-f fbar) $\propto m_f$ (no e-μ universality !)
  - g(H-VV) $\propto m_V^2$ (coupling to the photon only in higher orders)
- large variations
- this is the signature of being the Higgs boson!

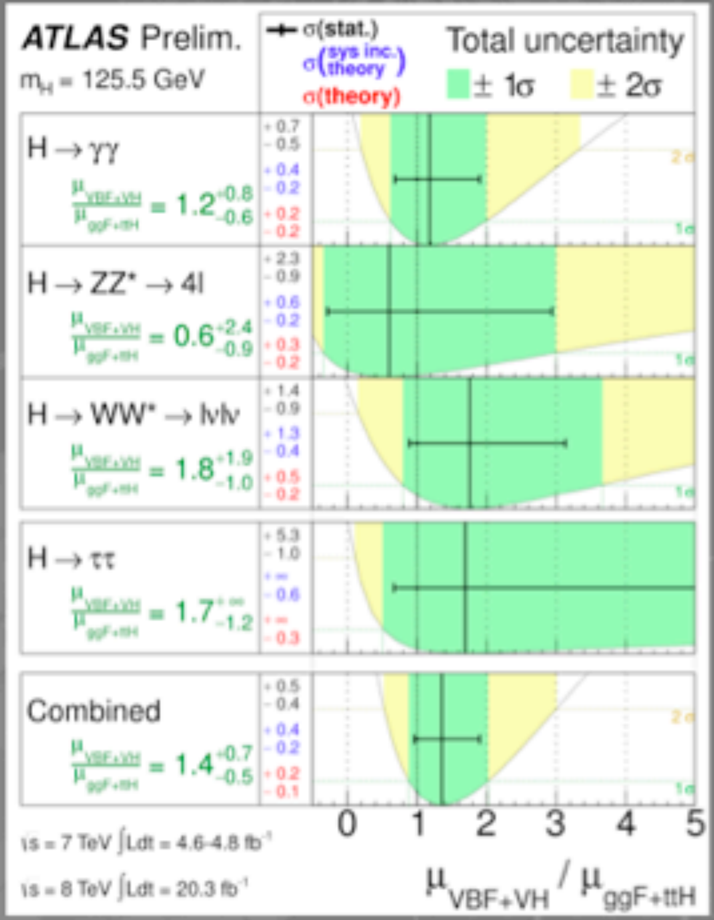
- After all, this is the most important message: mass vs. coupling correlation for all known particles



Higgs Boson Summary (J. Ocariz @ Invisibles)

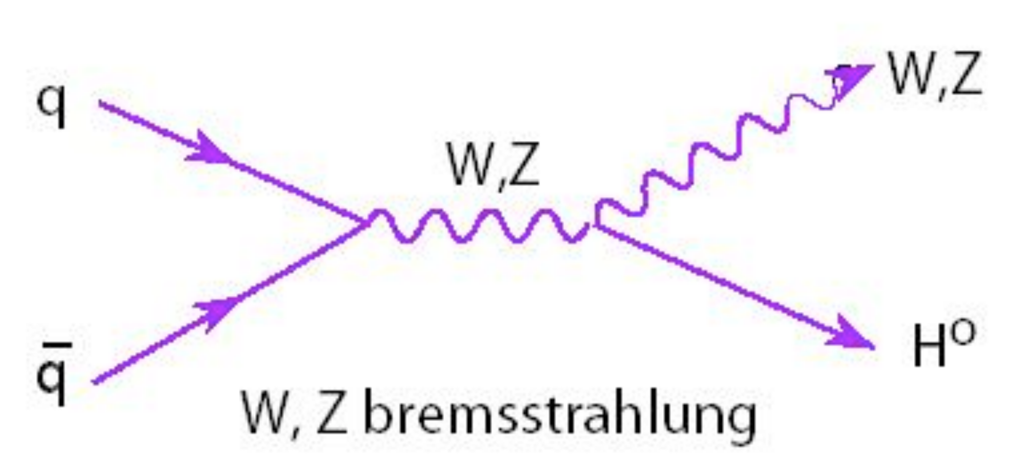
CMS-PAS-HIG-14-009

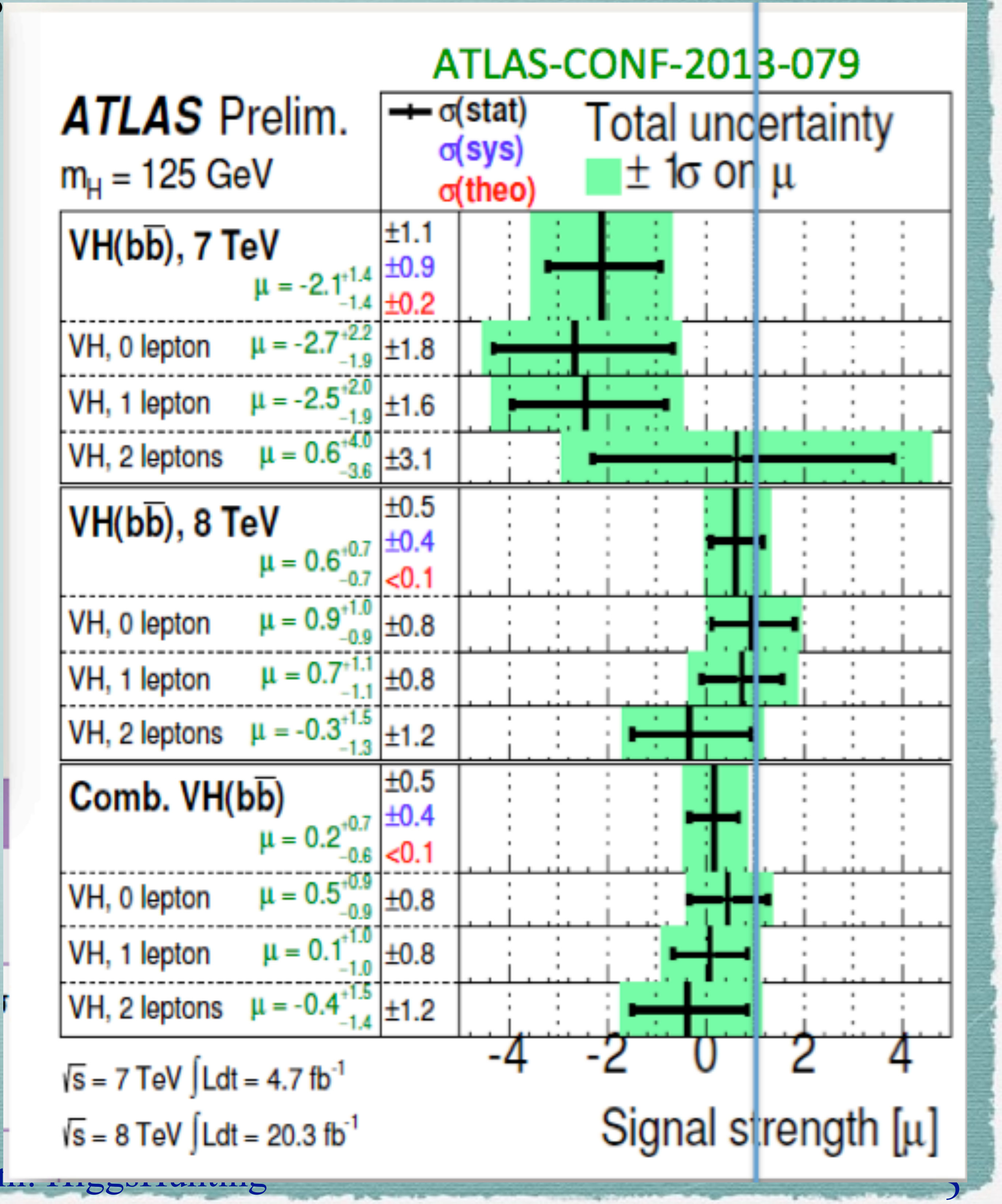




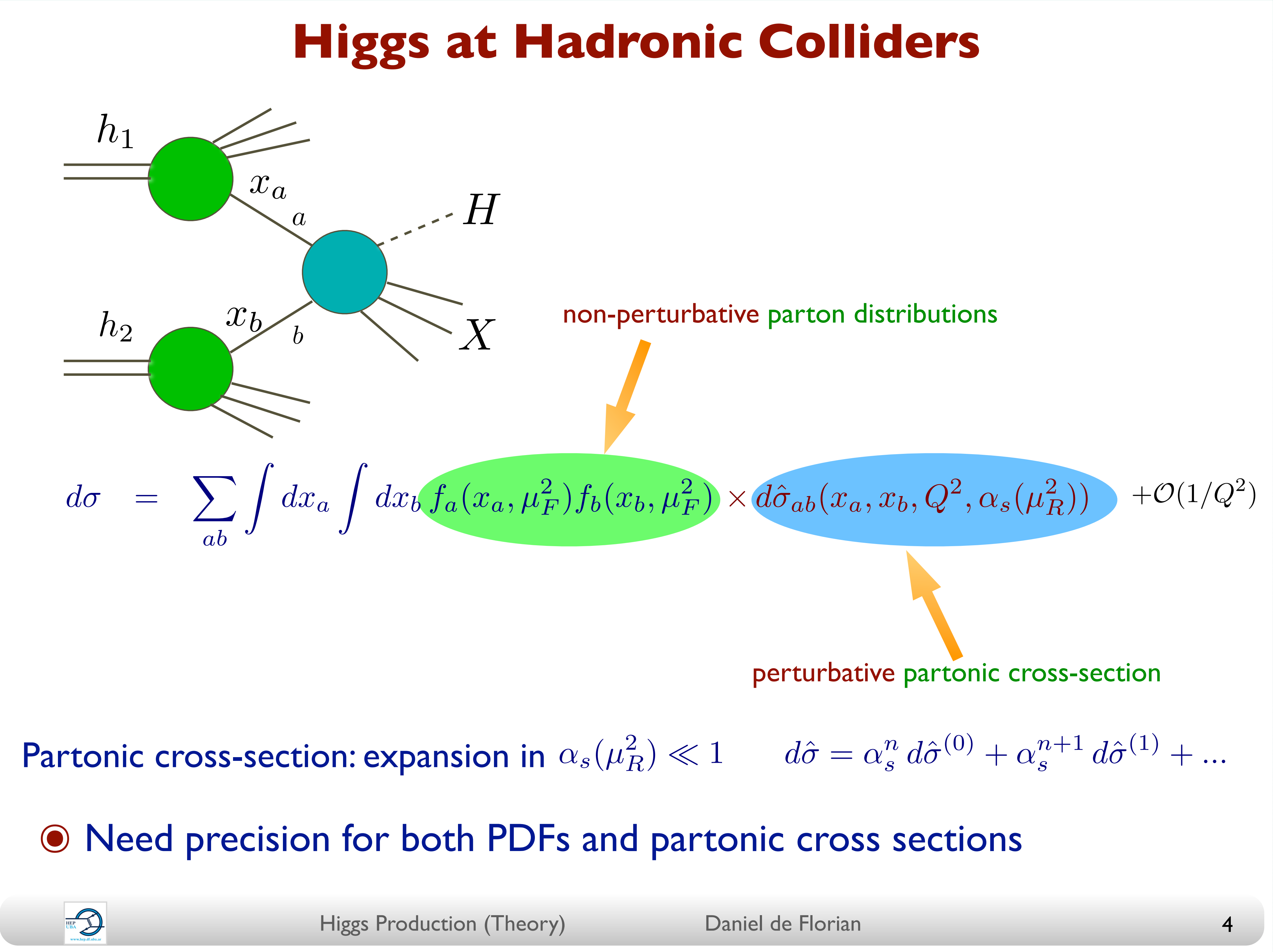
ATLAS-CONF-2014-009

- the b-b bar channel is one of the most interesting but also most elusive because of large background
- a strategy is to select for VH events





2. Physics @ the Hadron Collider



Higgs at Hadronic Colliders

non-perturbative parton distributions

$$d\sigma = \sum_{ab} \int dx_a \int dx_b\, f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \times d\hat{\sigma}_{ab}(x_a, x_b, Q^2, \alpha_s(\mu_R^2)) \quad + \mathcal{O}(1/Q^2)$$

perturbative partonic cross-section

Partonic cross-section: expansion in $\alpha_s(\mu_R^2) \ll 1$ $\quad d\hat{\sigma} = \alpha_s^n\, d\hat{\sigma}^{(0)} + \alpha_s^{n+1}\, d\hat{\sigma}^{(1)} + \ldots$

- Need precision for both PDFs and partonic cross sections

Higgs Boson at the LHC

- SM Higgs boson can be discovered at ≈ 5 σ after ≈1 year of operation (10 fb^{-1}/ experiment) for m_H ≈ 150 GeV
- Discovery faster for larger masses
- Whole mass range can be excluded at 95% CL after ~1 month of running at 10^{33} cm^{-2} s^{-1}.

Discovered by each expt

results are conservative:

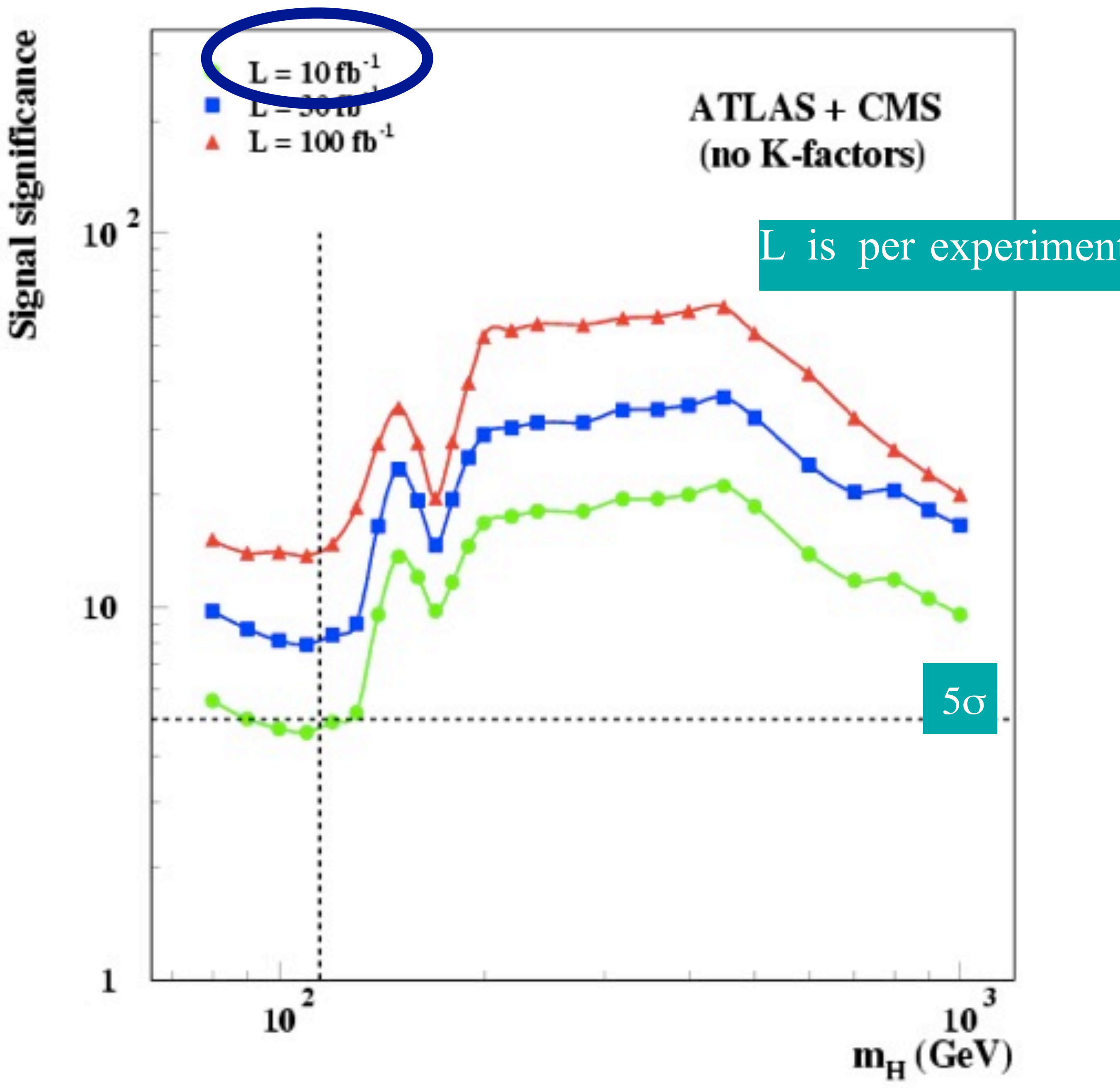
-- no k-factors

-- simple cut-based analyses

-- conservative assumptions on detector performance

-- channels where background control is difficult not included, e.g $WH \to l\nu bb$

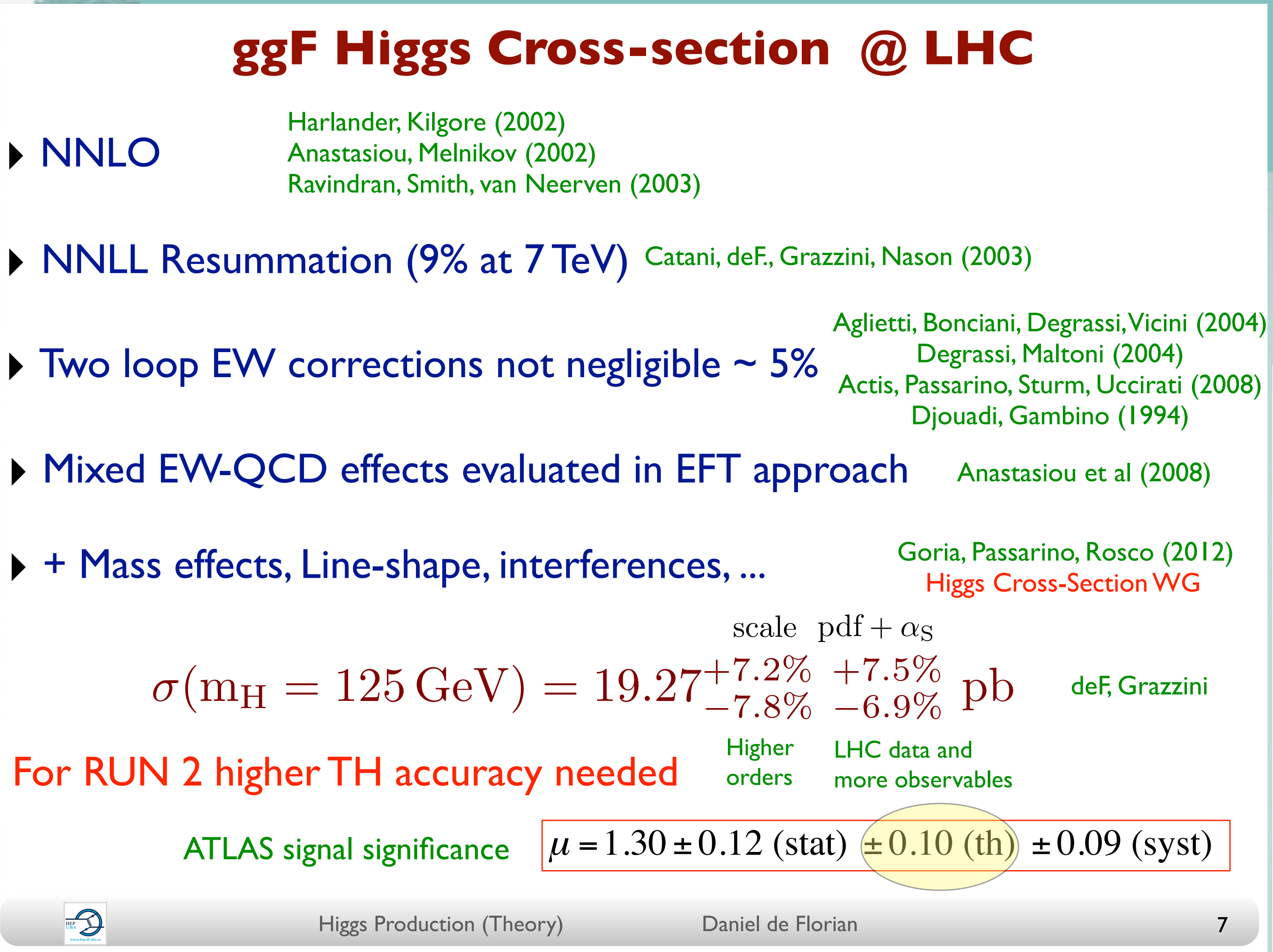
Discovered in the difficult region with $20 fb^{-1}$ for each expt.



L is per experiment

5σ

F. Gianotti



ggF Higgs Cross-section @ LHC

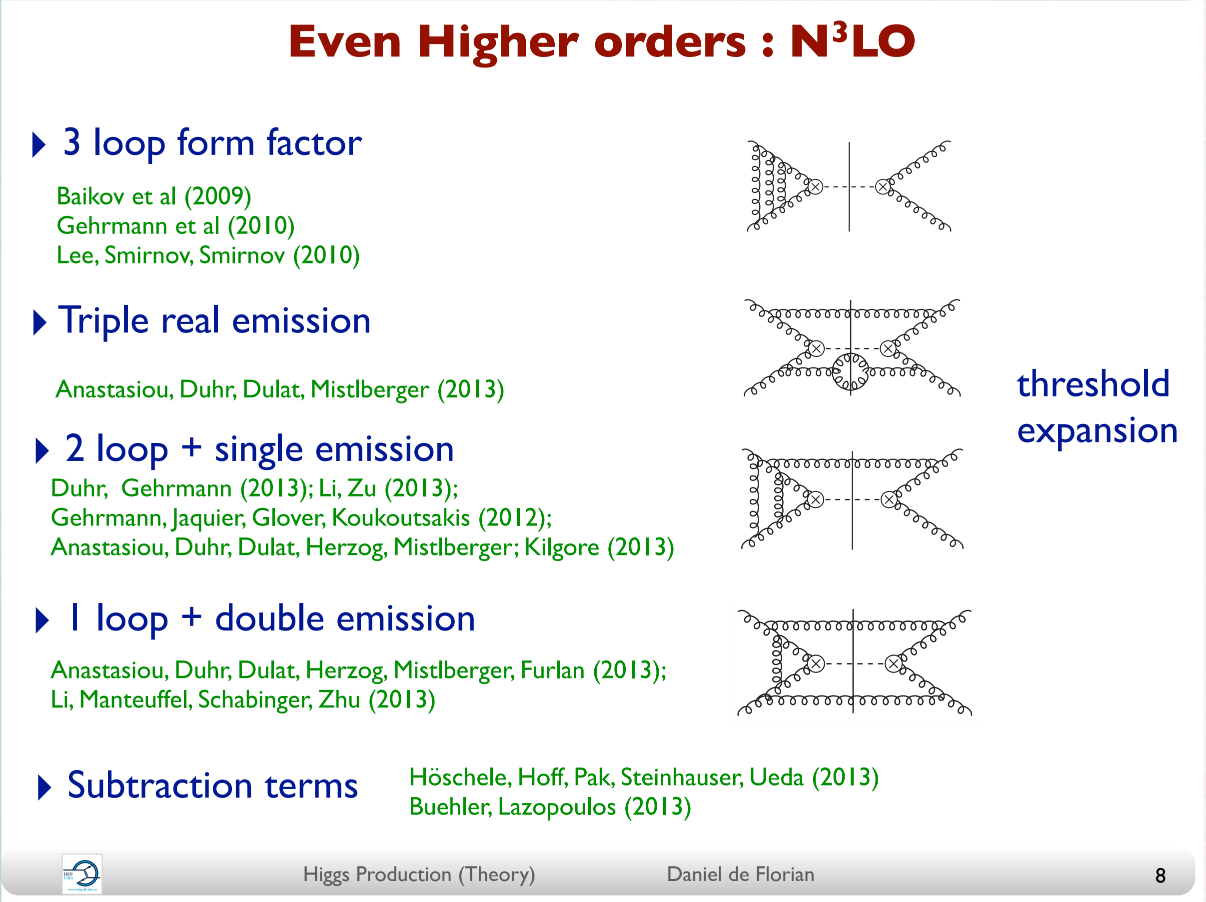
- NNLO — Harlander, Kilgore (2002)
  Anastasiou, Melnikov (2002)
  Ravindran, Smith, van Neerven (2003)
- NNLL Resummation (9% at 7 TeV) — Catani, deF., Grazzini, Nason (2003)
- Two loop EW corrections not negligible ~ 5% — Aglietti, Bonciani, Degrassi, Vicini (2004)
  Degrassi, Maltoni (2004)
  Actis, Passarino, Sturm, Uccirati (2008)
  Djouadi, Gambino (1994)
- Mixed EW-QCD effects evaluated in EFT approach — Anastasiou et al (2008)
- \+ Mass effects, Line-shape, interferences, ... — Goria, Passarino, Rosco (2012)
  Higgs Cross-Section WG

$$\sigma(\mathrm{m_H} = 125\,\mathrm{GeV}) = 19.27\overset{\text{scale}}{\underset{\text{Higher orders}}{{}^{+7.2\%}_{-7.8\%}}}\;\overset{\text{pdf}+\alpha_S}{\underset{\text{LHC data and more observables}}{{}^{+7.5\%}_{-6.9\%}}}\ \mathrm{pb}$$

deF, Grazzini

For RUN 2 higher TH accuracy needed

ATLAS signal significance $\mu = 1.30 \pm 0.12\ (\text{stat})\ \pm 0.10\ (\text{th})\ \pm 0.09\ (\text{syst})$



Even Higher orders : N^{3}LO

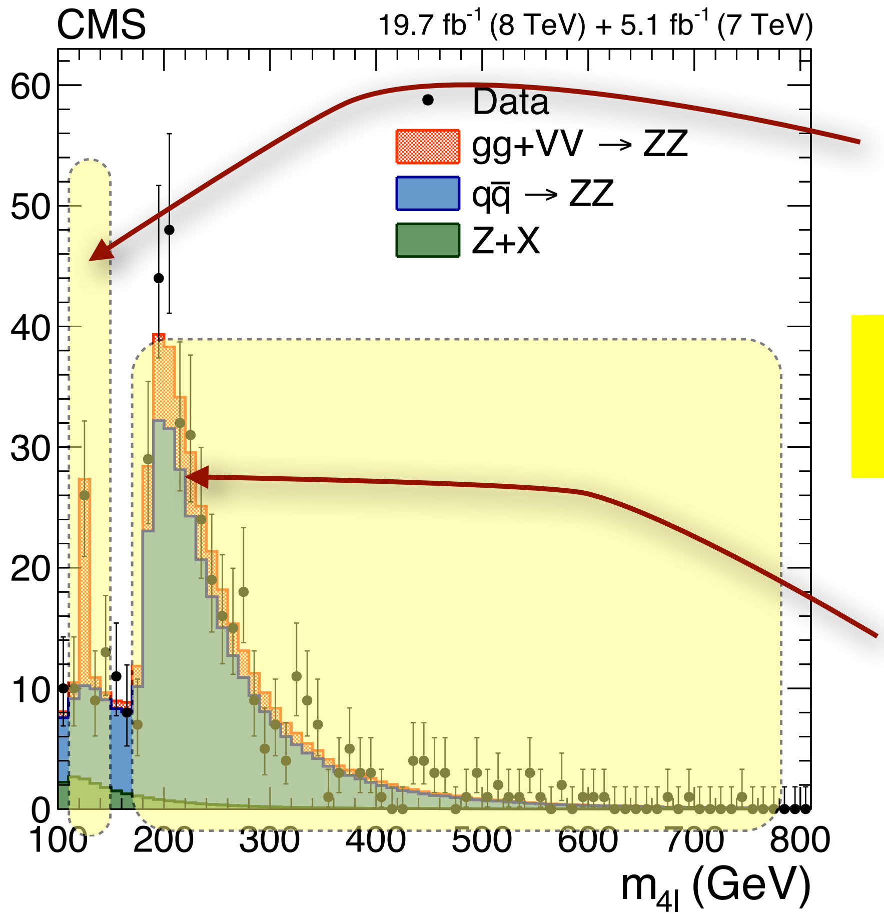
- 3 loop form factor
  Baikov et al (2009)
  Gehrmann et al (2010)
  Lee, Smirnov, Smirnov (2010)
- Triple real emission
  Anastasiou, Duhr, Dulat, Mistlberger (2013)
- 2 loop + single emission
  Duhr, Gehrmann (2013); Li, Zu (2013);
  Gehrmann, Jaquier, Glover, Koukoutsakis (2012);
  Anastasiou, Duhr, Dulat, Herzog, Mistlberger; Kilgore (2013)
- 1 loop + double emission
  Anastasiou, Duhr, Dulat, Herzog, Mistlberger, Furlan (2013);
  Li, Manteuffel, Schabinger, Zhu (2013)
- Subtraction terms — Höschele, Hoff, Pak, Steinhauser, Ueda (2013)
  Buehler, Lazopoulos (2013)

threshold expansion

3. Unexpected 1: the width

Width measurement from off-shell

Caola, Melnikov



$$\sigma^{\text{on}} \int_{M_H^2-\Delta^2}^{M_H^2-\Delta^2} dq^2 \frac{|A_{gg\to H\to VV}|^2}{(q^2-M_H^2)+\Gamma_H^2 M_H^2} \sim \frac{g_{ggH}^2(M_H^2)\, g_{HVV}^2(M_H^2)}{\Gamma_H}$$

the off-shell behavior is reliable!
see K. Ellis @ Higgs Hunting 2014

$$g = \xi\, g^{SM}$$
$$\Gamma_H = \xi^4\, \Gamma_H^{SM}$$

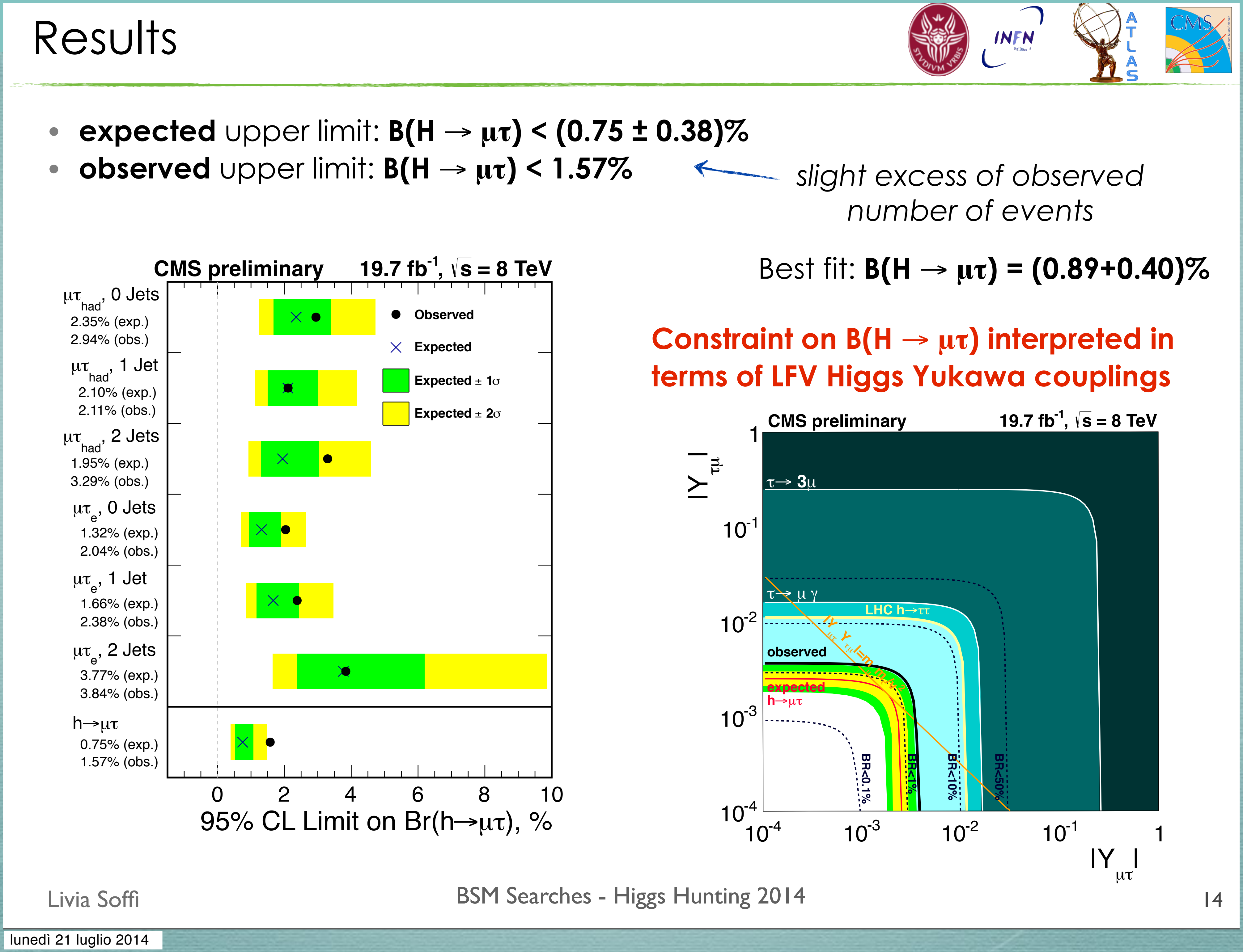
$$\sigma^{\text{off}} \int_{q^2\gg M_H^2} dq^2 \frac{|A_{gg\to H\to VV}|^2}{(q^2-M_H^2)+\cancel{\Gamma_H^2} M_H^2} \sim \int dq^2 g_{ggH}^2(q^2)\, g_{HVV}^2(q^2)$$

SM assumptions on couplings (running)

$$\sigma^{\text{exp}} = \sigma^{\text{back}} + \sigma^{\text{on}} + \sigma^{\text{off}} \times \frac{\Gamma_H}{\Gamma_H^{SM}} + \sigma^{\text{int}} \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

CMS	$\Gamma_H < 22\,\text{MeV}$ (5.4 SM)
ATLAS	$\Gamma_H < 24\,\text{MeV}$ (5.7 SM)

Unexpected 2: lepton flavor violation?



Results

- **expected** upper limit: **B(H → μτ) < (0.75 ± 0.38)%**
- **observed** upper limit: **B(H → μτ) < 1.57%**

← *slight excess of observed number of events*

Best fit: **B(H → μτ) = (0.89+0.40)%**

Constraint on B(H → μτ) interpreted in terms of LFV Higgs Yukawa couplings

Livia Soffi

BSM Searches - Higgs Hunting 2014

14

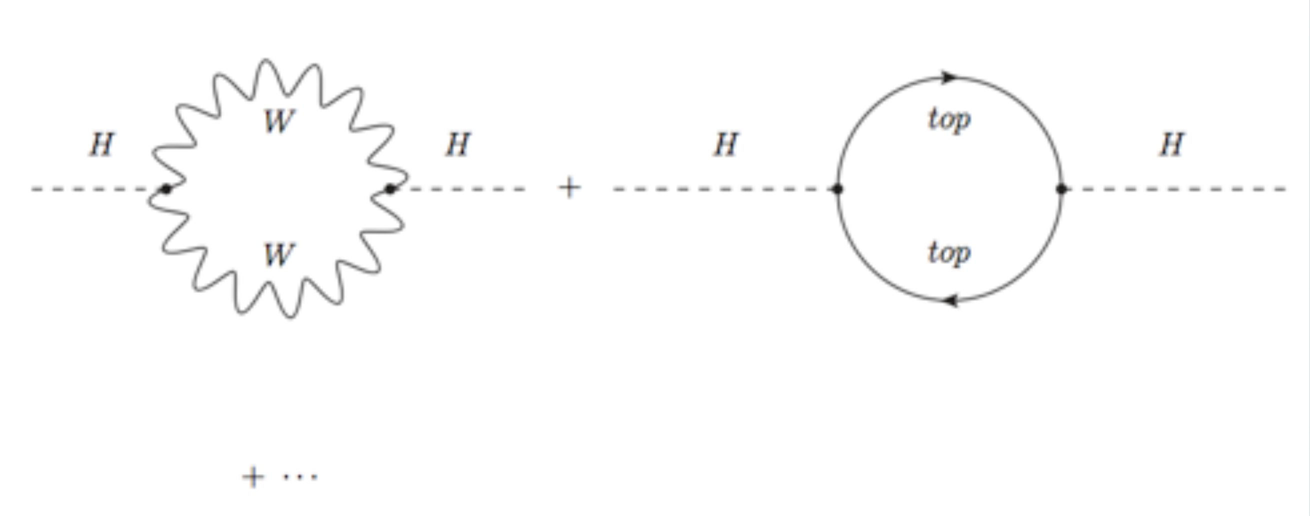
lunedì 21 luglio 2014

4. Unnatural: what is it?

- The Standard Theory is incomplete: missing parts imply mass scale >> W mass
  - -Gravity: regulated by the Planck mass $M_P=1/\sqrt{G_{Newton}} = 10^{19}$ GeV
  - -Unification of the three gauge interactions of ST, Grand Unification mass $M_{GUT} = 10^{14}$ GeV
- How is it possible to have a low energy sector almost decoupled from the high energy scales?
- Spin 1/2 and 1 particles: in the zero mass limit a new symmetry is gained (chiral symmetry for spin 1/2, gauge symmetry for spin 1)
- higher order corrections to the mass do vanish in the limit where the bare mass vanishes
- thus, e.g. for the electron mass: $m_e(q^2)=m_0 \, \mathrm{Log}(q^2/M_{GUT})$ and the large mass is locked into Logs.
- In the Standard Model, no increased symmetry is gained by letting the mass of the elementary scalar to vanish: ST is “unnatural” (‘t-Hooft, 1979).

quadratic divergences

- Sometime unnaturalness of the Higgs is tyed to quadratic divergences and unnatural tuning between bare mass and rad corrections



$$\mu^2 = \mu_0^2 + \frac{\alpha}{\pi} \times Cost \times \Lambda^2 + \cdots$$

- this is however not necessary: even in regularization schemes with no quad div (e.g. dimensional reg. or Lee-Wick ghosts) the large mass will end up into the finite corrections, unless a symmetry reason does not prevent it.

alternatives

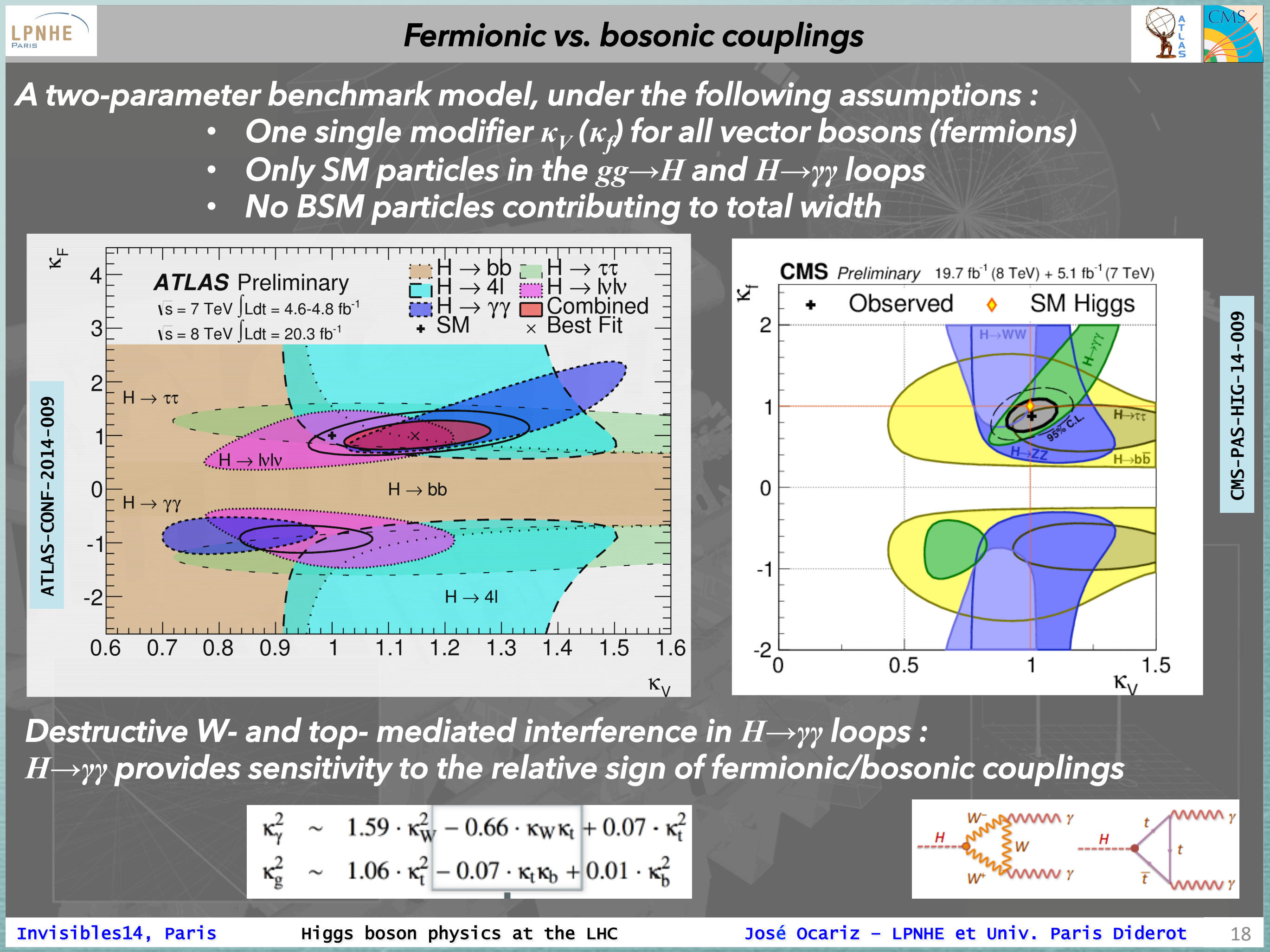
- ***Low energy supersymmetry*** relates scalars and fermions, whose mass is protected by chiral symmetry, and reduces the cutoff scale to M_{SUSY}, needed to be O(1TeV) for not too unnatural tuning, ... or
- ***No elementary scalars***, the Higgs boson is composite by fermion fields, tied together by forces at a scale O(1 TeV), called generically Technicolor forces.
- H could be much lighter than the high energy strong interactions scale, if it is a ***would-be-Goldstone boson*** of some symmetry.
- New strong-interactions at high energy: not indicated by electroweak precision data (which are becoming high-precision data).
- The value found for the Higgs boson mass speaks in favour of SUSY
- but we should keep ***both options*** open...for the time being.
- Important: it is not a matter of a factor of 2 or 4...
- The third option, which is becoming popular, is to ignore the problem...an anthropic solution?

If this is the answer...what was the question? (Financial Times)

5. Precursors

- Before finding the particles implied by SUSY or by the extra strong interactions at high energy, one should detect ***anomalous couplings*** of the Higgs particle to vectors and fermions; deviations at few percent levels could be seen;
- the pattern of couplings may be quite complicated, but some simplification may help to orient us

present status is somewhat represented here:



LPNHE PARIS

Fermionic vs. bosonic couplings

A two-parameter benchmark model, under the following assumptions :

- *One single modifier κ_V (κ_f) for all vector bosons (fermions)*
- *Only SM particles in the $gg \to H$ and $H \to \gamma\gamma$ loops*
- *No BSM particles contributing to total width*

Destructive W- and top- mediated interference in $H \to \gamma\gamma$ loops :
$H \to \gamma\gamma$ provides sensitivity to the relative sign of fermionic/bosonic couplings

$$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 \boxed{- 0.66 \cdot \kappa_W \kappa_t} + 0.07 \cdot \kappa_t^2$$

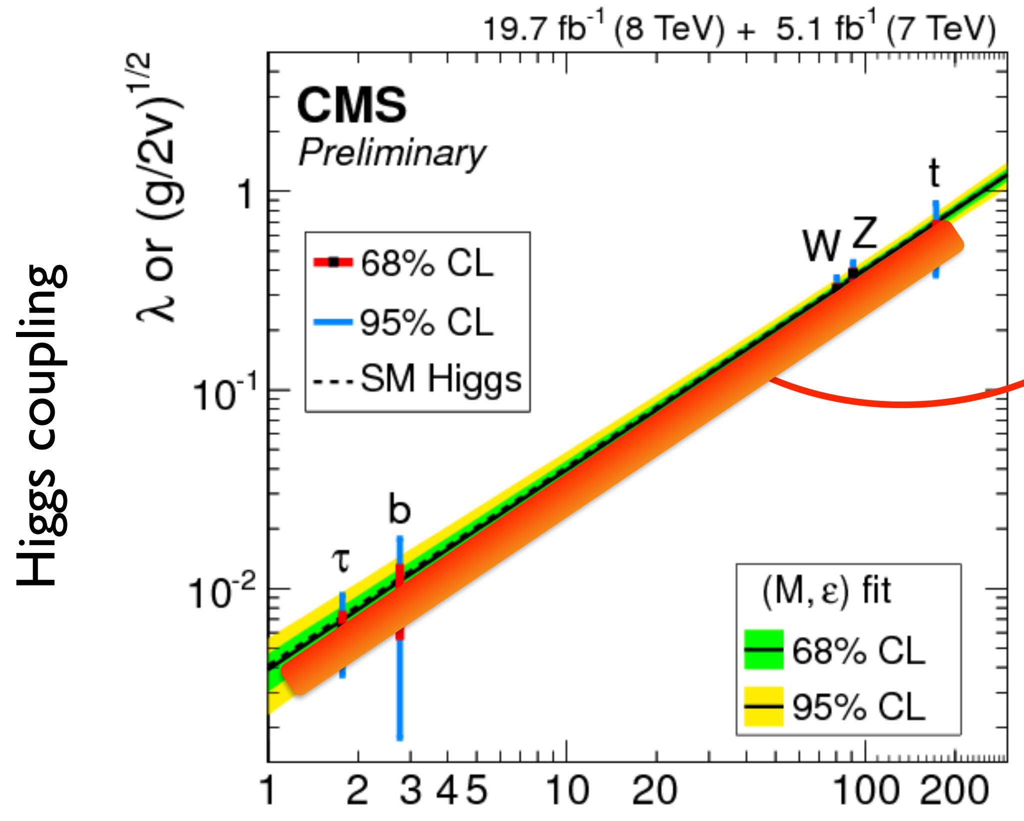
$$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 \boxed{- 0.07 \cdot \kappa_t \kappa_b} + 0.01 \cdot \kappa_b^2$$

Invisibles14, Paris   Higgs boson physics at the LHC   José Ocariz – LPNHE et Univ. Paris Diderot   18

Looking for precursor signals in h decay: strategy

A better perspective to understand how close to a SM Higgs:

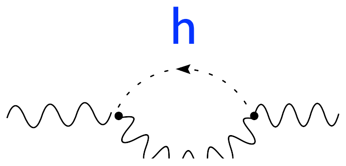
A. Pomerol @ Higgs Hunting 2014



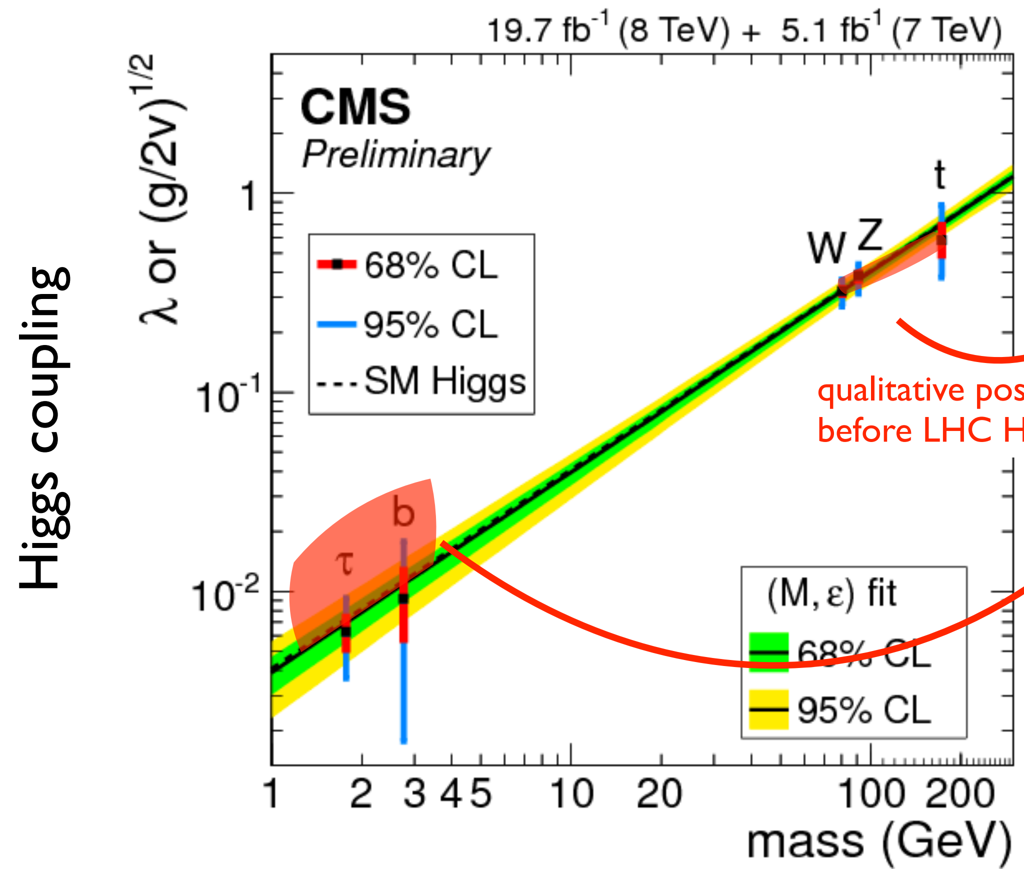
Composite Higgs

(reduction of couplings)

small effects already expected,
as EWPT (LEP1) put strong limits
to the coupling hVV
since it affects the Z propagator:



A better perspective to understand how close to a SM Higgs:



MSSM light Higgs

qualitative possible ranges
before LHC Higgs data

6. Probing SUSY in the Higgs Sector

L. Maiani, A.D. Polosa , V. Riquer, New J. Phys. **14** (2012) 073029.:

ORSAY-ROMA Collab.: A. Djouadi, L. Maiani, G. Moreau, A. Polosa, J. Quevillon1 , V. Riquer, EPJ C in press, arXiv: 1307.5205

- Two Higgs doublets required (Dimopoulos & Giorgi): H_u, H_d

Recent work:
P.Giardino, et al.arXiv:1303.3570 [hep-ph];
A.Djouadi, J.Quevillon,arXiv:1304.1787 [hep-ph];
NMSSM model:
G.~Belanger et al., JHEP **1301**(2013) 069;
R.Barbieri, et al., arXiv:1304.3670 [hep-ph];
Two Higgs Doublets:
B.Grinstein,P.Uttayarat,arXiv:1304.0028 [hep-ph];
O.~Eberhardt et al., arXiv:1305.1649 [hep-ph].

$$\langle 0|H_u^0|0\rangle = v\sin\beta;\quad \langle 0|H_d^0|0\rangle = v\cos\beta;\quad 0 < \tan\beta < +\infty$$

$$v^2 = (2\sqrt{2}G_F)^{-1} = (174\ \mathrm{GeV})^2$$

Physical H bosons: $h:\ 125\ \mathrm{GeV}$

$H,\ A,\ H^{\pm}\ \ ???$

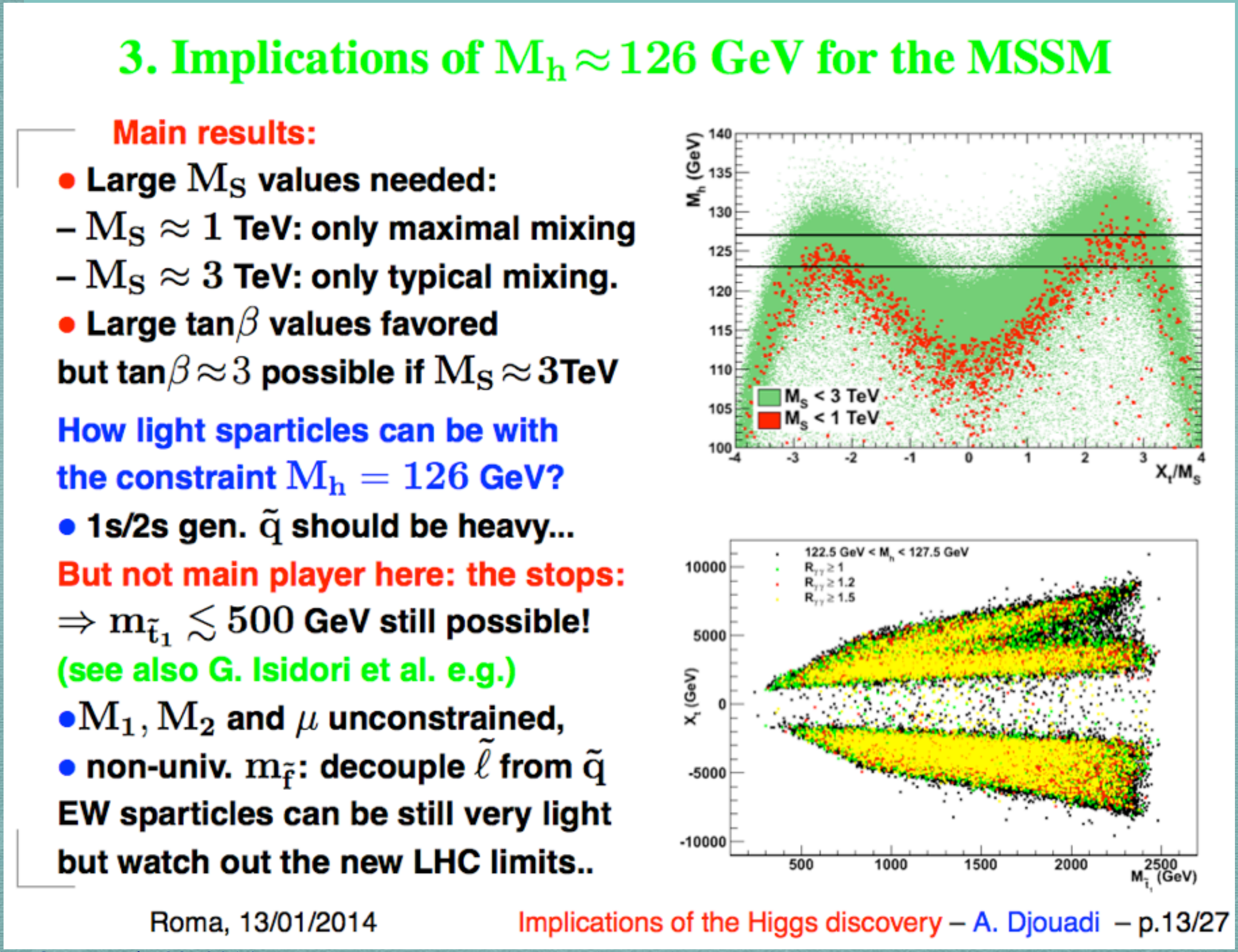
$$\mathcal{M}_S^2 = M_Z^2\begin{pmatrix}\cos^2\beta & -\cos\beta\sin\beta\\ -\cos\beta\sin\beta & \sin^2\beta\end{pmatrix} + M_A^2\begin{pmatrix}\sin^2\beta & -\cos\beta\sin\beta\\ -\cos\beta\sin\beta & \cos^2\beta\end{pmatrix} + \begin{pmatrix}0 & 0\\ 0 & \frac{\delta}{\sin^2\beta}\end{pmatrix}$$

- h, H mass matrix contains M_Z, M_A, tanβ , δ

- EW interactions control the quartic potential, hence M_Z

- δ embodies the leading radiative corrections related to the top-sector and summarizes all details and variations of the MSSM;

- ***with M_h=125 GeV, we can obtain δ= δ(M_A, tan β) and determine all quantities in the Higgs sector as function of M_A, tan β, or M_H, tan β.***



3. Implications of $M_h \approx 126$ GeV for the MSSM

Main results:

- Large M_S values needed:

– $M_S \approx 1$ TeV: only maximal mixing

– $M_S \approx 3$ TeV: only typical mixing.

- Large tanβ values favored

but tan$\beta \approx 3$ possible if $M_S \approx 3$TeV

How light sparticles can be with the constraint $M_h = 126$ GeV?

- 1s/2s gen. $\tilde{q}$ should be heavy...

But not main player here: the stops:

$\Rightarrow m_{\tilde{t}_1} \lesssim 500$ GeV still possible!

(see also G. Isidori et al. e.g.)

- M_1, M_2 and μ unconstrained,
- non-univ. $m_{\tilde{f}}$: decouple $\tilde{\ell}$ from $\tilde{q}$

EW sparticles can be still very light

but watch out the new LHC limits..

Checks

A. Djouadi *et al*.

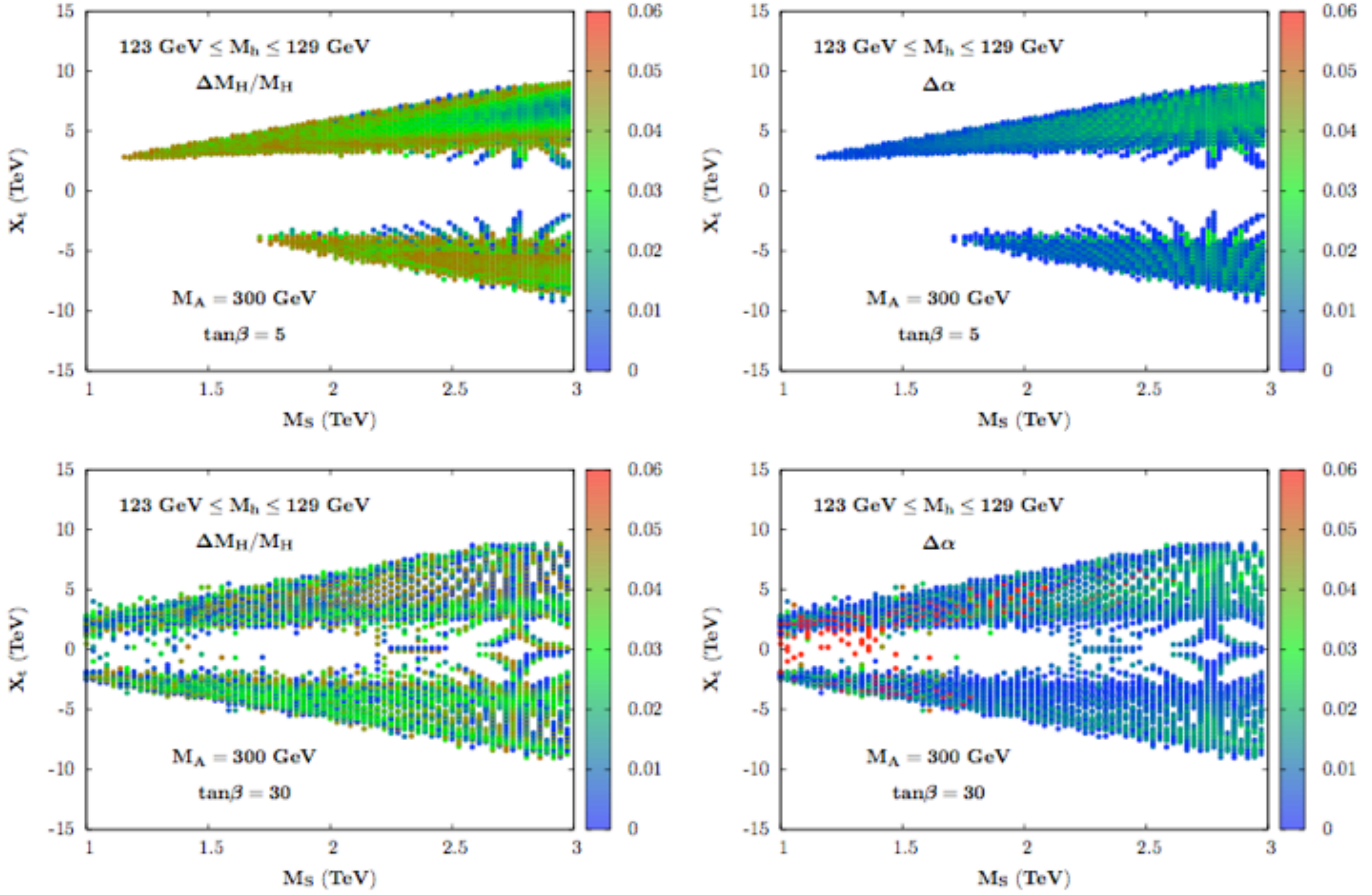
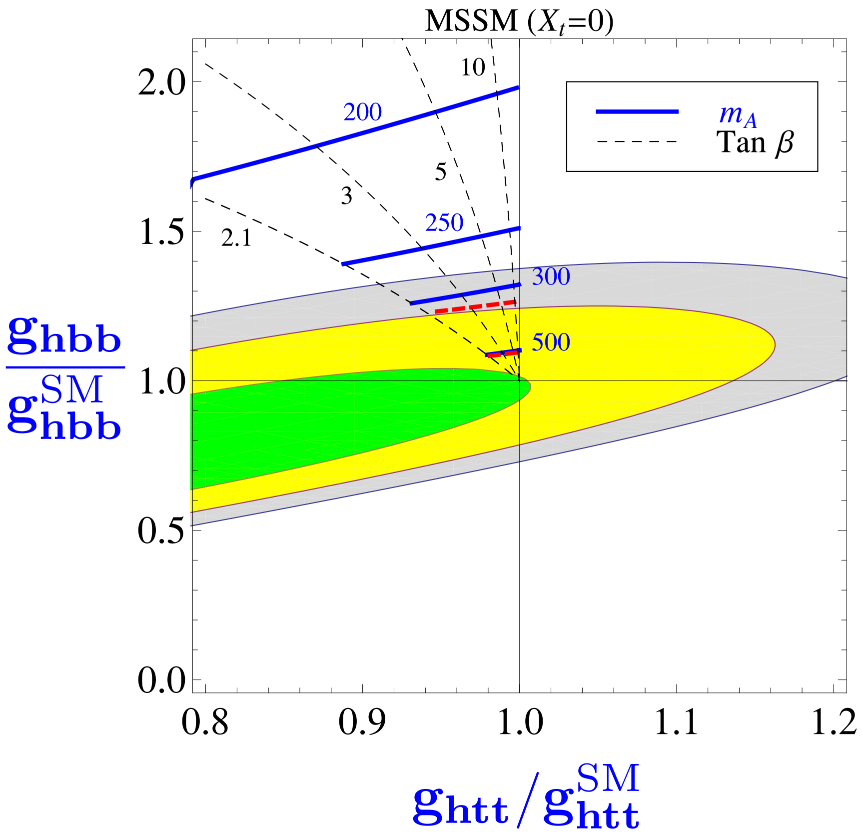


Figure 3: The variation of the mass M_H (left) and the mixing angle α (right), are shown as separate vertical colored scales, in the plane $[M_S, X_t]$ when the full two loop corrections are included with and without the subleading matrix elements $\Delta\mathcal{M}^2_{11}$ and $\Delta\mathcal{M}^2_{12}$. We take $M_A = 300$ GeV, $\tan\beta = 5$ (top) and 30 (bottom) and the other parameters are varied as described in the text.

where we stand: MSSM

Relevant plane for susy Higgs couplings:

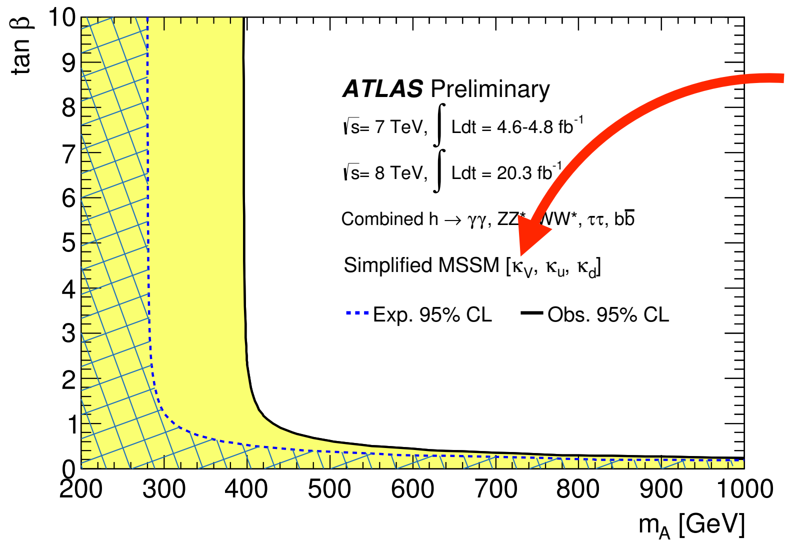
A. Pomerol @ Higgs Hunting 2014



from arXiv:1212.524

(data before Moriond 13)

Higgs coupling measurements are already **ruling out** susy-parameter space



$\kappa_V \ll \kappa_u, \kappa_d$

(not needed in the fit)

7. Higgs Boson as a PseudoGoldstone

The Minimal composite Higgs model
K.Agashe, R. Contino, A. Pomarol, **Nucl.Phys. B719** (2005) 165.

A simple example:

- Technicolor forces are symmetric under O(5)
- O(5) breaks sontaneously to O(4)=$SU(2)_L \otimes SU(2)_R$
- 4 Goldstone Bosons = complex doublet under $SU(2)_L \otimes U(1)$
- EW interactions break O(5) -> O(4) in a different direction and generate a potential for T_{45}: 3 GBs give mass to W and Z and the 4th field is the, naturally light, Higgs boson.

- *O(5) generators= 5x5, real, antisymmetric matrices=$T_{ij}=-T_{ji}$*
- *O(4) generators= T_{ij}, i, j, = 1,..4*
- *broken O(5) generators correspond to T_{5j} , j=1,..4, a vector under O(4) and a (1/2,1/2) under $SU(2)_L \otimes SU(2)_R$*

Higgs particle = would be Goldstone Boson ?

Luca Merlo@Moriond 2014

- A **strong dynamics** at the scale $\Lambda_s \sim \mathcal{O}(\mathrm{TeV})$ can provide a solution to the Hierarchy problem: in Composite Higgs models, the Higgs arises as a NGB, with an induced mass protected from large quantum corrections.
- In CH models, the resonance corresponds to a composite object, singlet under SM symmetries: **light CP-even singlet scalar *h***
- The Lagrangian can be written in terms of these building blocks:

$$\mathbf{U}(x) = e^{i\sigma_a \pi^a(x)/v} \qquad\qquad h$$

$\mathbf{U}(x)$ is a 2x2 **adimensional** matrix. This leads to a fundamental difference between the linear and chiral Lagrangians:

Linear Lagrangian

- The GBs are in the Higgs doublet Φ
- Φ has dimension 1 in mass
- d=4+n operators are suppressed by Λ_{NP}^n

Chiral Lagrangian

- The $\mathbf{U}(x)$ matrix is adimensional and any its extra insertions do not lead to any suppression

31 parameters

Luca Merlo@Moriond 2014

$$\mathcal{P}_B(h) = -\frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h)$$

$$\mathcal{P}_W(h) = -\frac{g^2}{4} W^a_{\mu\nu} W^{a\mu\nu} \mathcal{F}_W(h)$$

$$\mathcal{P}_G(h) = -\frac{g_s^2}{4} G^a_{\mu\nu} G^{a\mu\nu} \mathcal{F}_G(h)$$

$$\mathcal{P}_C(h) = -\frac{v^2}{4} \mathrm{Tr}(\mathbf{V}^\mu \mathbf{V}_\mu) \mathcal{F}_C(h)$$

$$\mathcal{P}_T(h) = \frac{v^2}{4} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathcal{F}_T(h)$$

$$\mathcal{P}_1(h) = g g' B_{\mu\nu} \mathrm{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h)$$

$$\mathcal{P}_2(h) = i g' B_{\mu\nu} \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h)$$

$$\mathcal{P}_3(h) = i g \mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_3(h)$$

$$\mathcal{P}_4(h) = i g' B_{\mu\nu} \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h)$$

$$\mathcal{P}_5(h) = i g \mathrm{Tr}(W_{\mu\nu} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_5(h)$$

$$\mathcal{P}_6(h) = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu))^2 \mathcal{F}_6(h)$$

$$\mathcal{P}_7(h) = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \partial^\nu \mathcal{F}_7(h)$$

$$\mathcal{P}_8(h) = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \partial^\mu \mathcal{F}_8(h) \partial^\nu \mathcal{F}'_8(h)$$

$$\mathcal{P}_9(h) = \mathrm{Tr}((\mathcal{D}_\mu \mathbf{V}^\mu)^2) \mathcal{F}_9(h)$$

$$\mathcal{P}_{10}(h) = \mathrm{Tr}(\mathbf{V}_\nu \mathcal{D}_\mu \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{10}(h)$$

$$\mathcal{P}_{11}(h) = (\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2 \mathcal{F}_{11}(h)$$

$$\mathcal{P}_{12}(h) = g^2 (\mathrm{Tr}(\mathbf{T} W_{\mu\nu}))^2 \mathcal{F}_{12}(h)$$

$$\mathcal{P}_{13}(h) = i g \mathrm{Tr}(\mathbf{T} W_{\mu\nu}) \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_{13}(h)$$

$$\mathcal{P}_{14}(h) = g \varepsilon^{\mu\nu\rho\lambda} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{14}(h)$$

$$\mathcal{P}_{15}(h) = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathcal{D}_\nu \mathbf{V}^\nu) \mathcal{F}_{15}(h)$$

$$\mathcal{P}_{16}(h) = \mathrm{Tr}([\mathbf{T}, \mathbf{V}_\nu] \mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{16}(h)$$

$$\mathcal{P}_{17}(h) = i g \mathrm{Tr}(\mathbf{T} W_{\mu\nu}) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{17}(h)$$

$$\mathcal{P}_{18}(h) = \mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu, \mathbf{V}_\nu]) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_{18}(h)$$

$$\mathcal{P}_{19}(h) = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu \mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\nu \mathcal{F}_{19}(h)$$

$$\mathcal{P}_{20}(h) = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \mathcal{F}_{20}(h) \partial^\nu \mathcal{F}'_{20}(h)$$

$$\mathcal{P}_{21}(h) = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \mathcal{F}_{21}(h) \partial^\nu \mathcal{F}'_{21}(h)$$

$$\mathcal{P}_{22}(h) = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu) \partial^\mu \mathcal{F}_{22}(h) \partial^\nu \mathcal{F}'_{22}(h)$$

$$\mathcal{P}_{23}(h) = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{23}(h)$$

$$\mathcal{P}_{24}(h) = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu) \mathcal{F}_{24}(h)$$

$$\mathcal{P}_{25}(h) = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2 \partial_\nu \partial^\nu \mathcal{F}_{25}(h)$$

$$\mathcal{P}_{26}(h) = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2 \mathcal{F}_{26}(h)$$

RED $\mathcal{F}_i(h) \equiv g(h, f)$

new Higgs couplings in the AL basis, and new operators with derivatives of h

A first look: Composite PseudoGoldstone Higgs

A. Pomerol @ Higgs Hunting 2014

Composite PGB Higgs couplings

Couplings dictated by symmetries (as in the QCD chiral Lagrangian)

Giudice,Grojean,AP,Rattazzi 07
AP,Riva 12

$$\frac{g_{hWW}}{g_{hWW}^{\mathrm{SM}}} = \sqrt{1-\frac{v^2}{f^2}}$$

f = Decay-constant of the PGB Higgs

(model dependent but expected f ~ v)

$$\frac{g_{hff}}{g_{hff}^{\mathrm{SM}}} = \frac{1-(1+n)\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}}$$

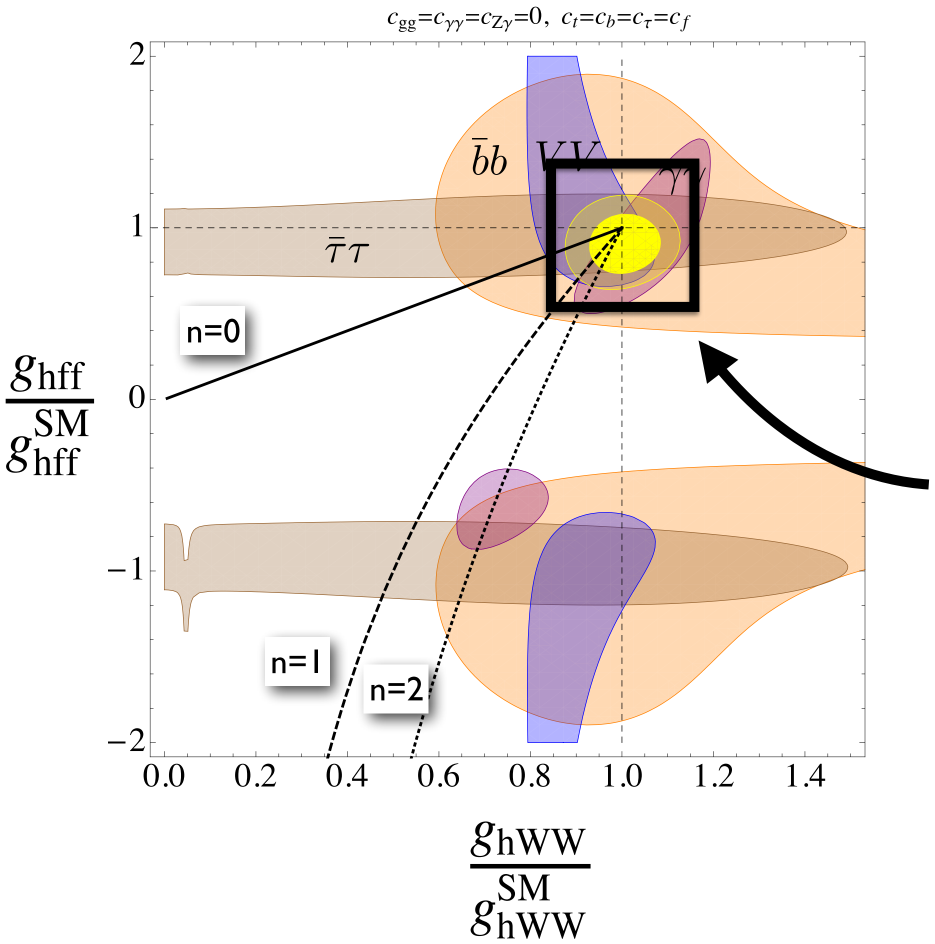
$n = 0, 1, 2, \ldots$

MCHM4 MCHM5

small deviations on the h$\gamma\gamma$(gg)-coupling due to the Goldstone nature of the Higgs

$$\xi \leq 0.1 \text{ from EW precision tests}$$

ATLAS+CMS:



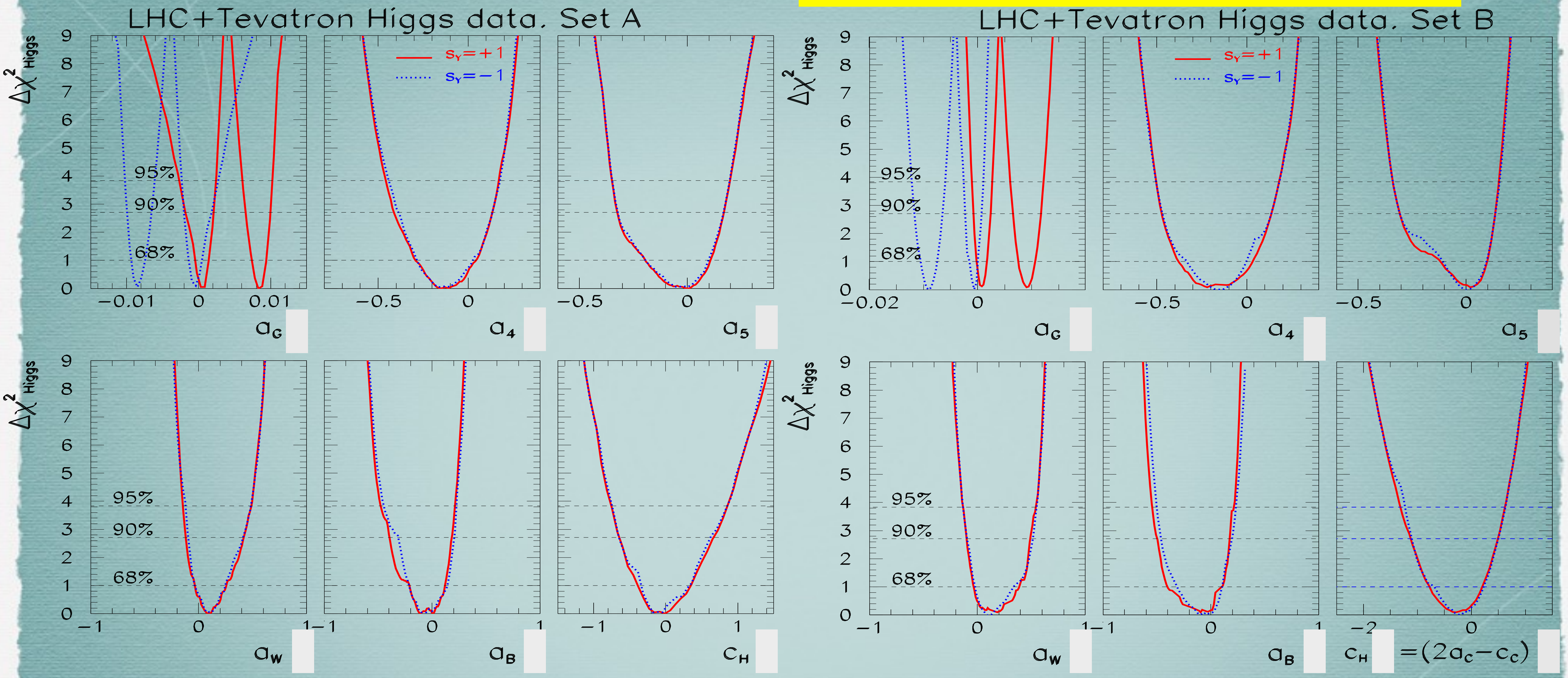
arXiv:1303.1812

getting into the interesting region

Set A : $a_G\ ,\ a_4\ ,\ a_5\ ,a_B\ ,\ a_W\ ,\ c_H\ ,\ 2a_C - c_C = 0$ HVV = Hff

Set B : $a_G\ ,\ a_4\ ,\ a_5\ ,a_B\ ,\ a_W\ ,\ c_H = 2a_C - c_C$ HVV ≠ Hff

Fit by B. Gavela and coll.; Luca Merlo@Moriond 2014



$|\chi^2_{min,A} - \chi^2_{min,B}| < 0.5$

Data: Tevatron D0 and CDF Collaborations and LHC, CMS, and ATLAS Collaborations at 7 TeV and 8 TeV for final states γγ, W^+W^-, ZZ, Zγ, $b\bar{b}$, and $\tau\bar{\tau}$

8. Flavor Symmetry and (Minimal) Flavor Symmetry Breaking

- The symmetry group commuting with the ST gauge group, for three generations, is:

$$\underleftrightarrow{SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R}} \otimes \underleftrightarrow{SU(3)_{\ell_L} \otimes SU(3)_{E_R}}$$

Chivukula& Georgi, no right-handed neutrinos, or:

$$\underleftrightarrow{SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R}} \otimes \underleftrightarrow{SU(3)_{\ell_L} \otimes SU(3)_{E_R} \otimes \mathcal{O}(3)}$$

to trigger see-saw.

- O(3) is the maximal symmetry with three generations of right-handed neutrinos, N, endowed with a degenerate, Majorana mass, M.
- a set of Yukawa couplings break the symmetry, providing masses to all particles:

$$m_a = Y_a < H >, \;\; a = U, D, E$$

$$m_\nu =< H >^2 \frac{Y_\nu^T Y_\nu}{M}$$

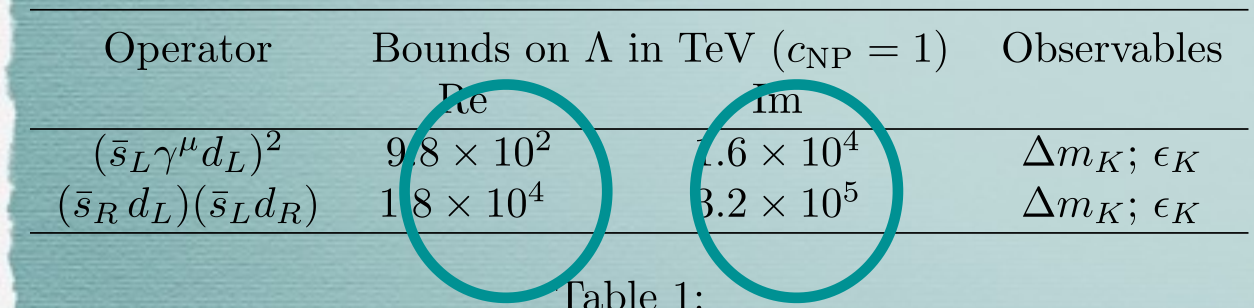
- Y_ν are not particularly suppressed for very small ν masses:

$$|Y_\nu| \sim \sqrt{\frac{m_\nu M}{< H >^2}} \sim \text{normal coupling}$$

Minimal Flavor Violation for quarks

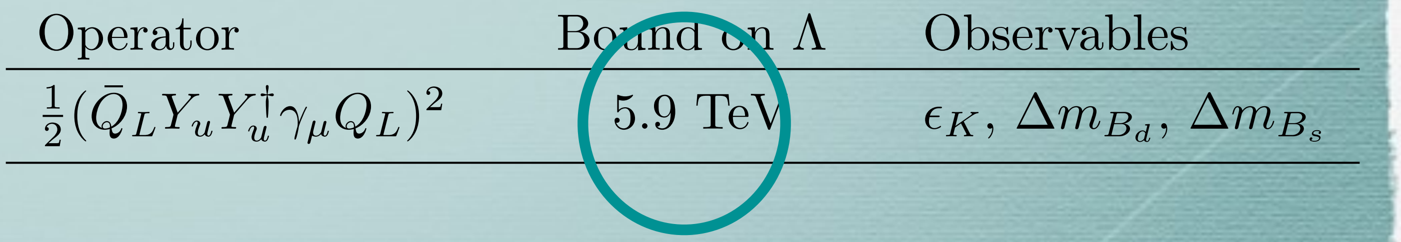
- Ys must appear in all Flavor Violating effective lagrangians arising from the heavy particles from New Physics (Technicolor or SUSY), in such a way as to make the effective lagrangian to be symmetric under the Flavor Group (see G. Isidori's talk);
- MFV is very effective in reducing the lower bounds to the scale of New Physics, obtained from the non observed deviations from ST in flavor changing neutral current effects (an extension of the GIM mechanism):

$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2}(\bar{s}_L \gamma_\mu d_L)^2 \to \frac{1}{\Lambda^2}\left(\bar{Q}_L Y_U Y_U^\dagger \gamma_\mu Q_L\right)^2$$



Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$)		Observables
	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	Δm_K; ϵ_K

Table 1:



Operator	Bound on Λ	Observables
$\frac{1}{2}(\bar{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}

Table 1:

- Λ is further reduced if effects come from 1-loop diagrams, a factor of g^2 in the numerator

The scale of the Flavor Symmetry Breaking

- For the particles of the ST, but neutrinos, the scale of symmetry breaking is given by Y<H> ;
- Y may be “universal”, but I find it unlikely that the same <H> will convert Y into GeV;
- the more so if Y=<S> with S a completely new field: this is indicated as ***dynamical Yukawa couplings***.
- In Technicolor (Chivukula and Georgi), Y ∝ preon masses/V, V some new scale;
- if so in SUSY, and the scale of FSB is of the order of M_{SUSY}, s-quarks and s-leptons of different flavor could be ***not so degerate*** as normally expected
- and lepton flavor violation not so far !!!

10. A new "light" vector boson?

- In a recent paper we have assumed that Yukawa couplings are VEV's of scalar fields, determined by a minumum principle

R. Alonso, M. B. Gavela, G. Isidori and L. Maiani, JHEP **1311** (2013) 187 [arXiv:1306.5927 [hep-ph]].

- a natural solution is found for neutrinos, with ***large mixing angles and degenerate masses***
- the solution, including diagonal masses for charged leptons, admits a conserved charge (with respect to the lepton flavor group $SU(3)_{\ell_L} \otimes SU(3)_{E_R} \otimes \mathcal{O}(3)$)

$$Q_{cons} = \lambda_3' \oplus \mathbf{1} \oplus \mathbf{1} + \mathbf{1} \oplus \lambda_3' \oplus \mathbf{1} + \mathbf{1} \oplus \mathbf{1} \oplus \lambda_7$$
$$\lambda_3' = \mathrm{diag}(0, 1, -1)$$

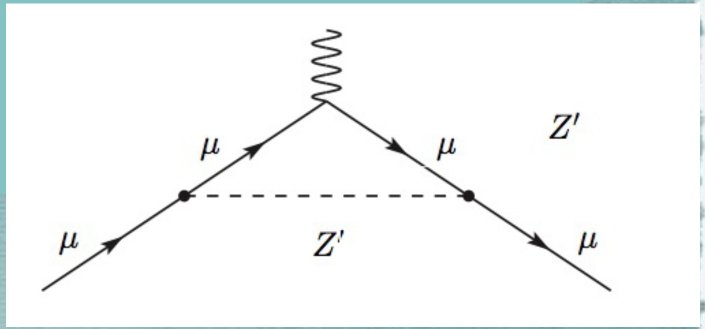
- gauging the flavor symmetry we would be left with one massless vector boson, Z', coupled to the conserved current

$$J_\lambda = \left[\bar{\ell}_L^{(\mu)} \gamma_\lambda \ell_L^{(\mu)} + \bar{\mu}_R \gamma_\lambda \mu_R\right] - [\mu \to \tau] + N^T \gamma^0 \gamma_\lambda \lambda_7 N$$

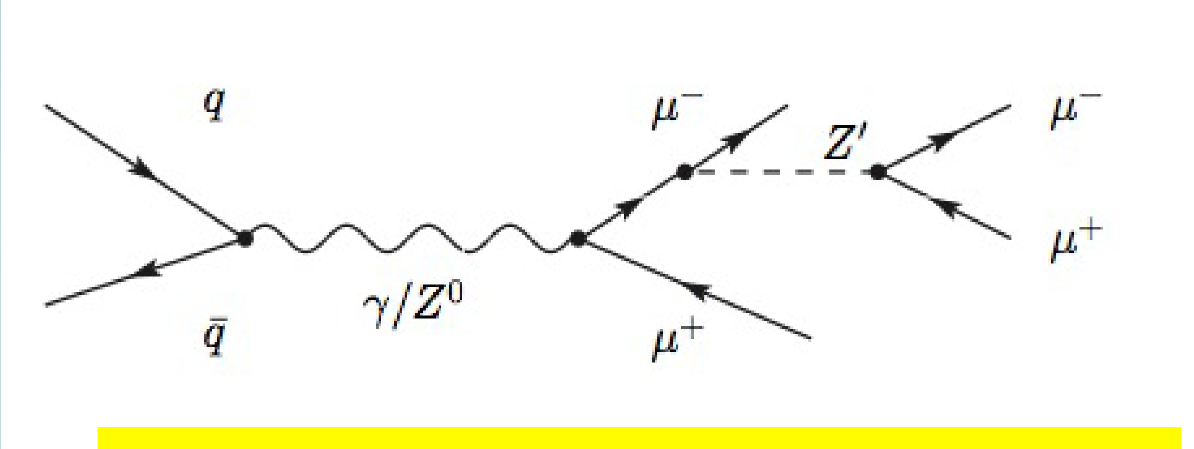
- One may assume that small perturbations to remove the neutrino degeneracies, will be able to give the Z' a mass, which may be much smaller than the general mass scale of flavons.
- A"light" Z' coupled to Lμ-Lτ, was proposed, on different grounds, by several authors, see J. Heeck and W. Rodejohann, 2011.

J. Heeck and W. Rodejohann, Phys. Rev. D **84** (2011) 075007 [arXiv:1107.5238].

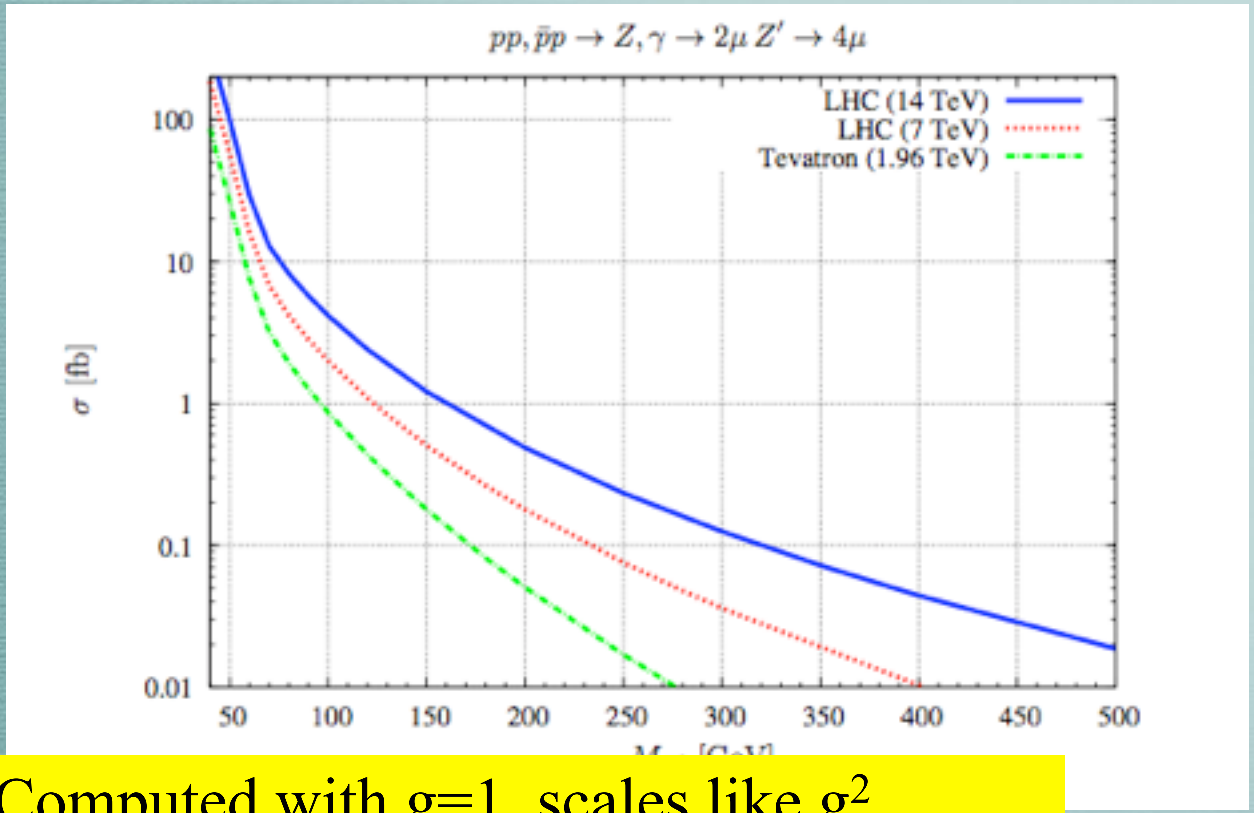
Z’ coupled to Lμ-Lτ



- explains discrepancy in the muon g-2 if: M/g ~ 200 GeV
- not directly coupled to electron or quarks, would be produced by final state muons at LEP and LHC:

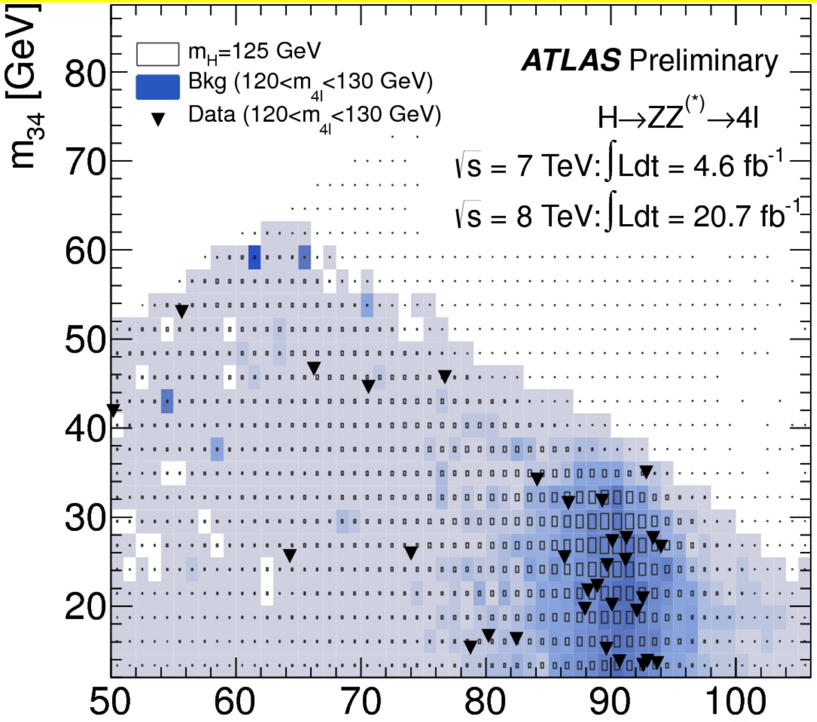


- limits from LEP, M>50 GeV
- cross section at LHC:



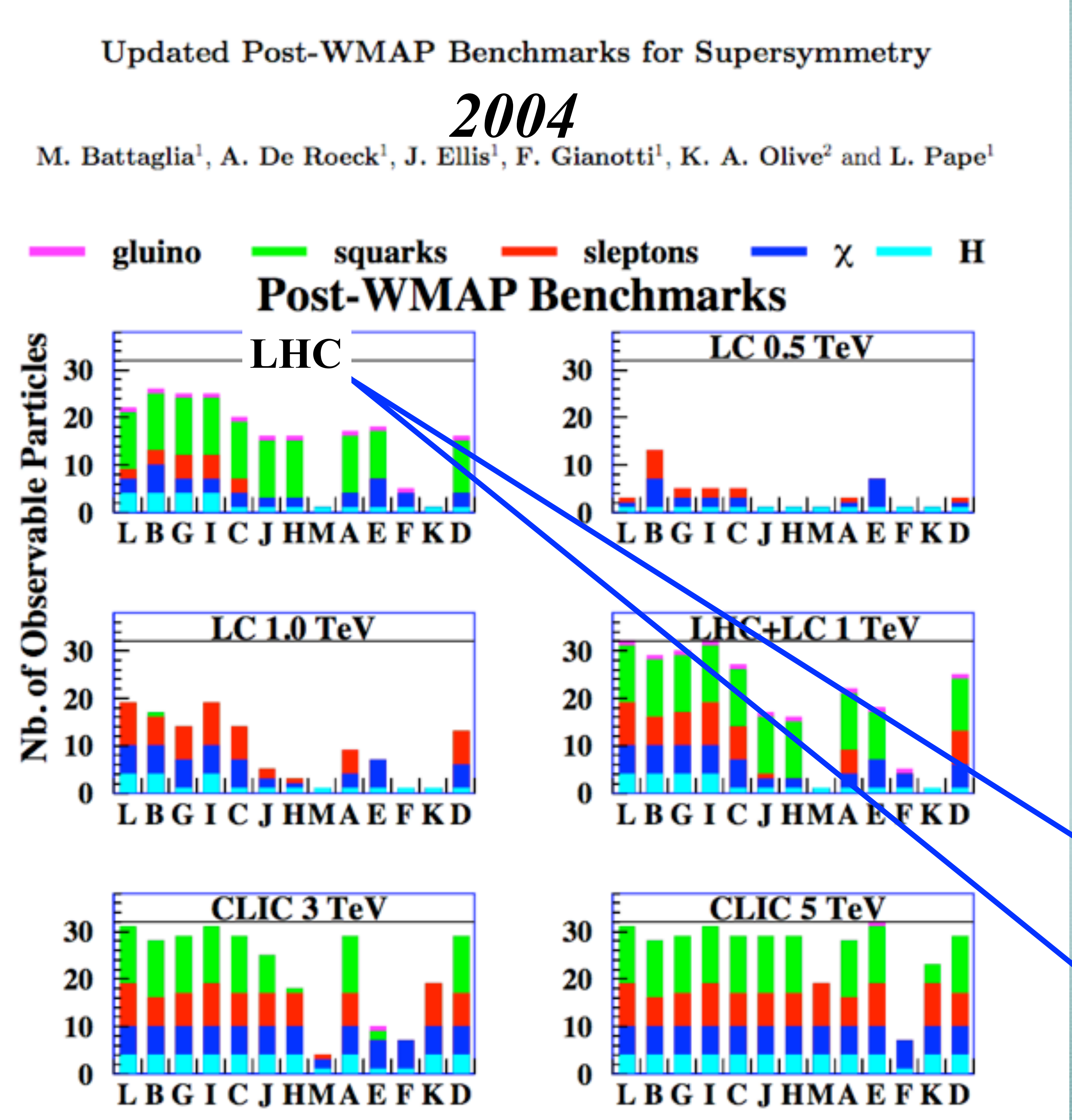
Computed with g=1, scales like g^2
σ~(1-10) x g^2 fb
(from Heeck and W. Rodejohann, 2011)

You have to find a line in the plot of the dimuon masses: low vs. high, and fight against the Z background



Yesterday sensation is the signal of today and the background of tomorrow

LHC @ 14 TeV And Beyond



Updated Post-WMAP Benchmarks for Supersymmetry

2004

M. Battaglia[1], A. De Roeck[1], J. Ellis[1], F. Gianotti[1], K. A. Olive[2] and L. Pape[1]

- Numbers and types of MSSM particles discovered, for representative regions of SUSY parameters
- LHC: E_{cm}=14 TeV ; integrated luminosity =100 fb^{-1}
- with a little luck we could be able to see the tail...