
The H Boson,
Lost Loves,
And New
Hopes
THE BEGINNING IS NEAR
Y. Sirois LLR Polytechnique CNRS-IN2P3

I

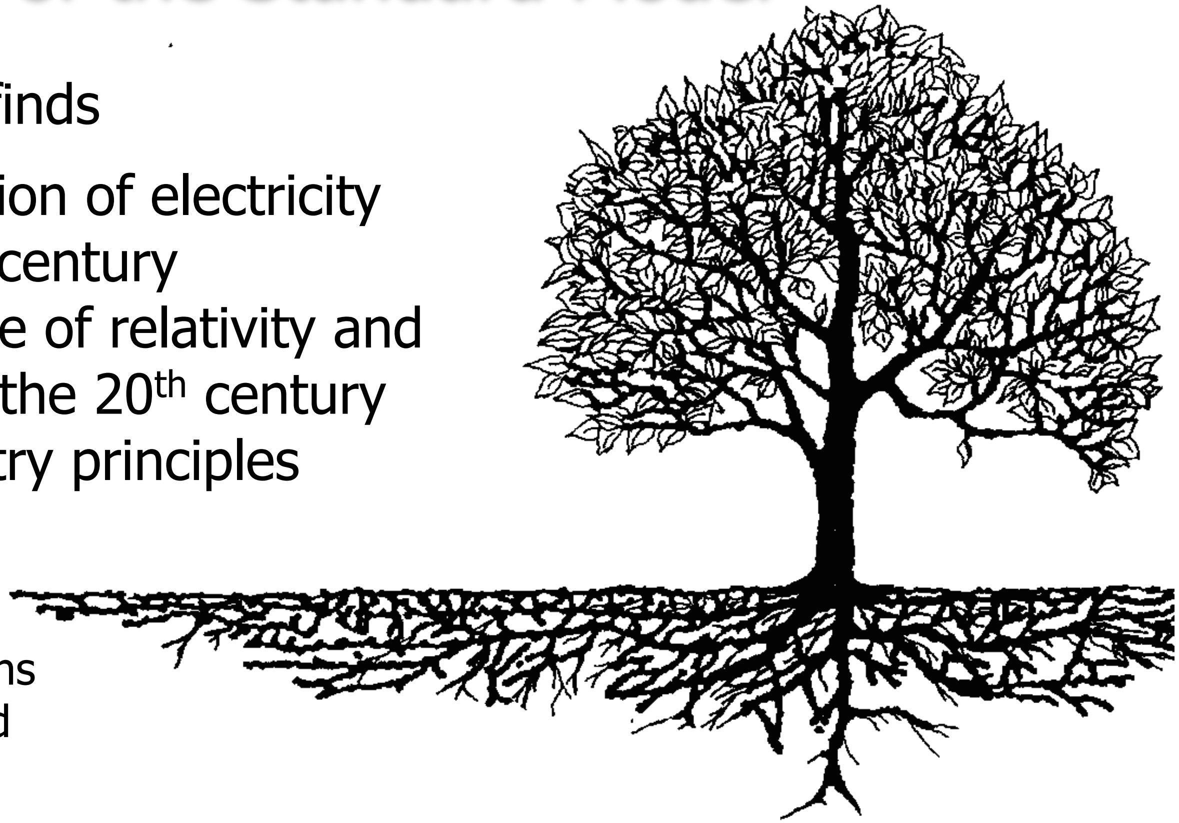
Physics at a Turning Point

The Standard Model and the H Boson at Run I

The Elegance of the Standard Model

The standard model (SM) finds

- Its **roots** in the unification of electricity and magnetism in 19th century
- Its **body** in the marriage of relativity and quantum mechanics in the 20th century
- Its **shape** from symmetry principles (gauge symmetries)



The existence of identical fermions and the marriage of relativity and Quantum mechanics

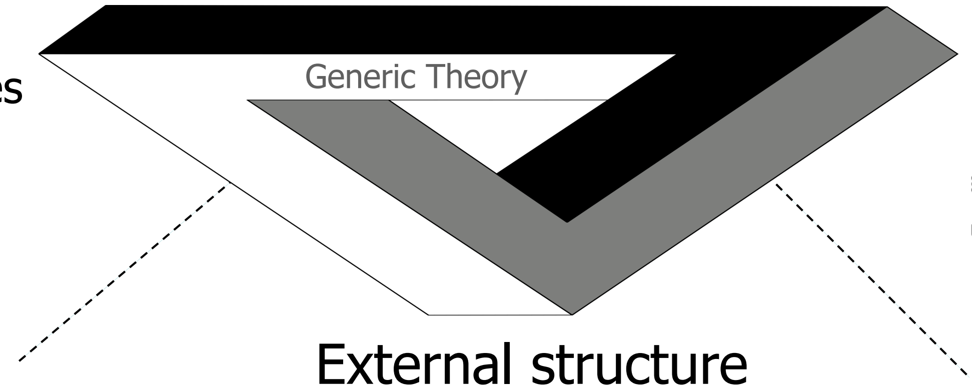
- The "underlying reality" is made of quantum fields
- There are interactions (gauge bosons) as consequence of gauge symmetries
- All "particles" must be massless.
- All ordinary particles must have spin 0, ½, or 1

Notes: Particles with spin 2 (graviton) appear in relation to quantum fluctuations of space-time
Particles of spin 3/2 (gravitino) appear if adding new quantum dimensions (supersymmetry)

The Chronicle of a Death Foretold

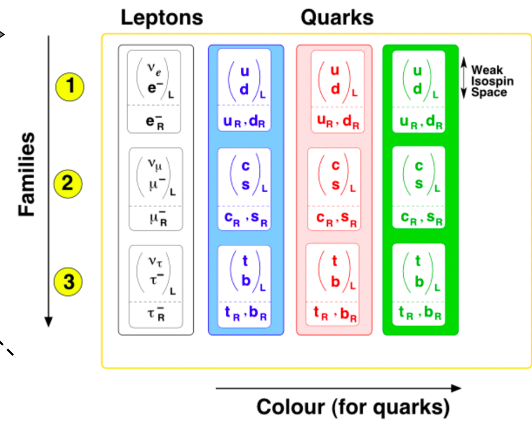
Gauge Bosons

Gauge Symmetries
SU(3)xSU(2)xU(1)



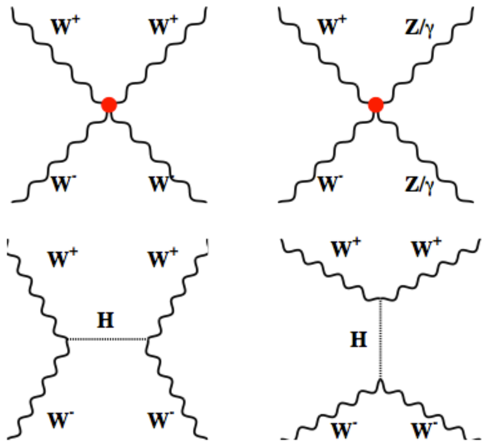
External structure
BEH Mechanism, Higgs boson

Fermions



- There must exist additional structure to explain the origin of mass,
  i.e. to preserve gauge symmetries at the fundamental level
- Additional structure is needed to preserve unitarity

One cannot save the theory by injecting measured observables i.e to allow for renormalization as for electrodynamics



$$A\left(W_L^+W_L^- \to Z_L Z_L\right) = \frac{G_F E^2}{8\sqrt{2}\pi}\left(1 - \frac{E^2}{E^2 - m_H^2}\right)$$

SM limited to E < ~ 1 TeV in absence of regularisation

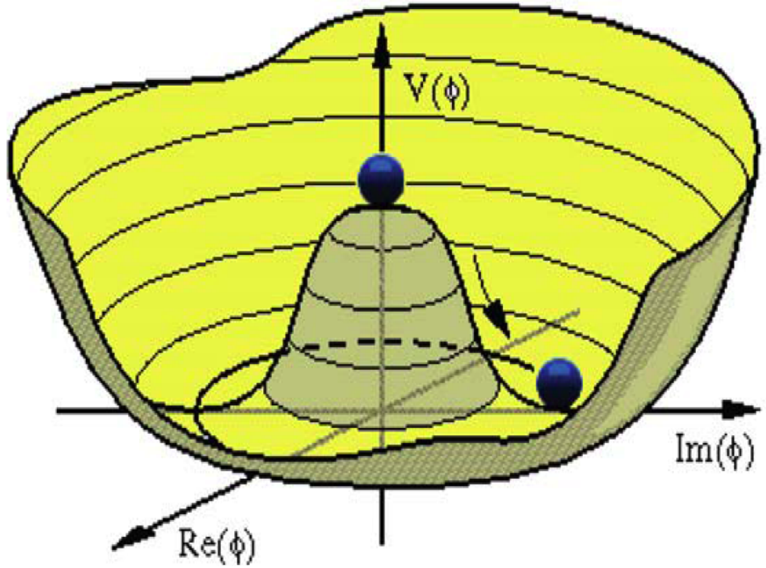
e.g. the H boson allows for exact unitarization

H boson or equivalent or new physics at the TeV scale ?

The BEH Mechanism and the H boson

- One postulates the existence of a scalar field which pervades the Universe
- Below a critical temperature, the potential acquires a minimum at a non-zero value <vev>≠0

  ⇒ **Spontaneous breaking of EWK symmetry**

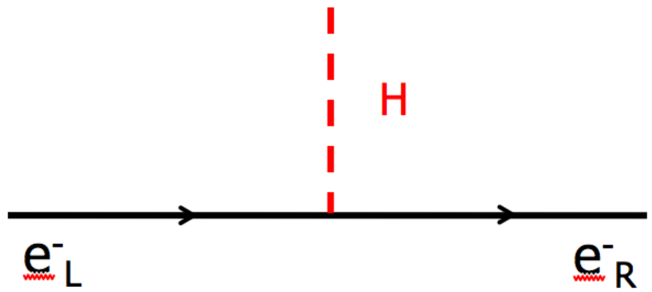


- The Z et W± bosons acquire mass
  (absorb golstone bosons as longitudinal components)

  → Gauge symmetries are preserved at fundamental level
  → The propagation in the physics vacuum breaks the symmetry

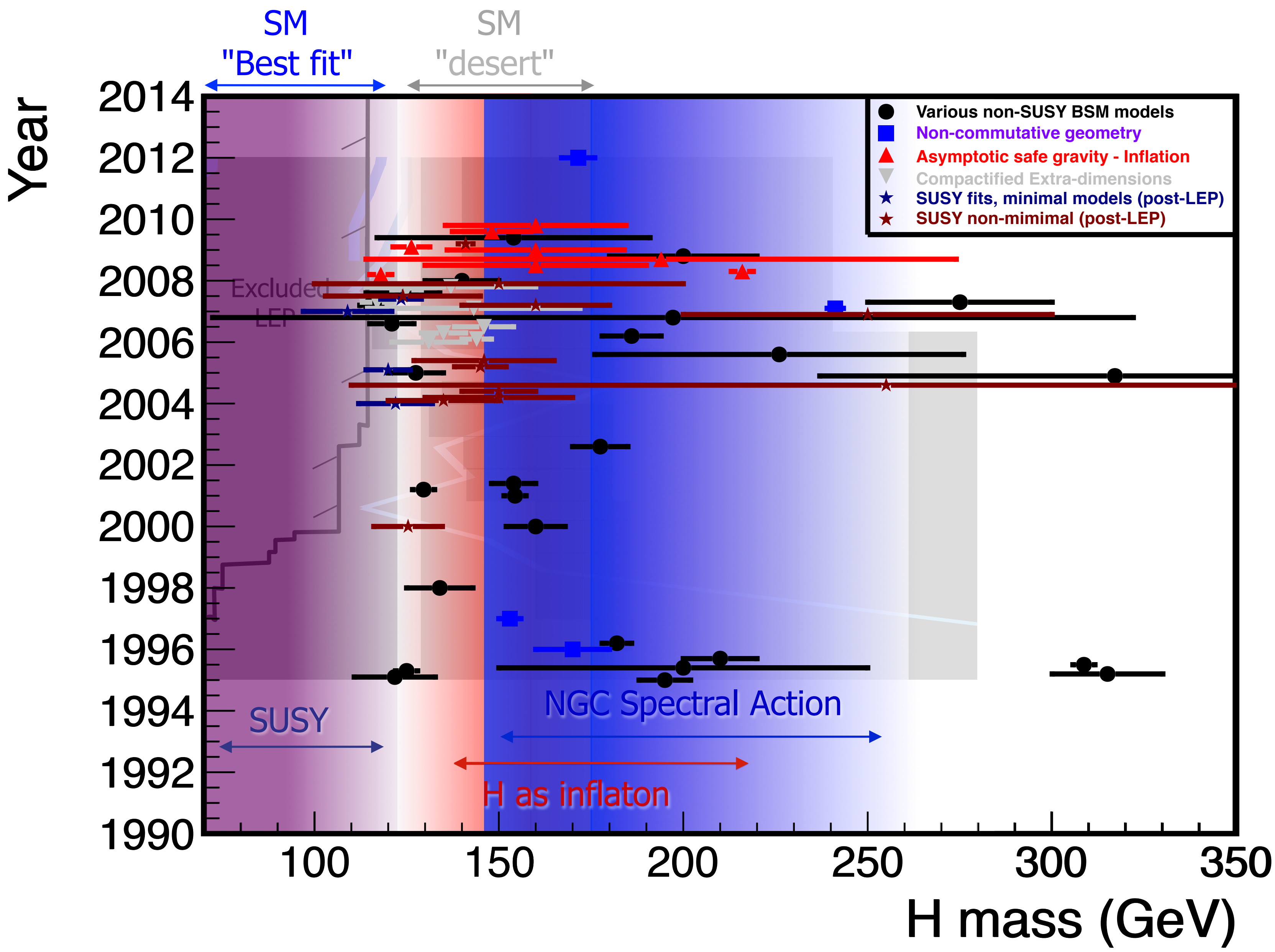
- Elementary fermions interact with the field and acquire mass

  Fields of right- and left-handed chiralities get mixed:



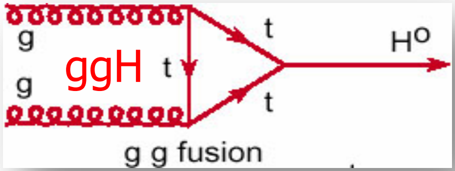
… There exists one physical H boson

The H boson mass : Theory vs Experiment

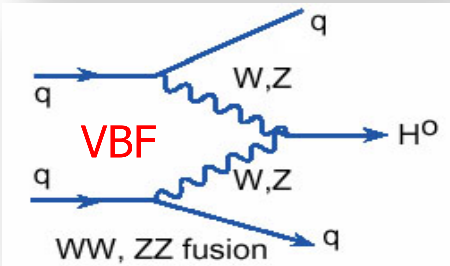


The H Boson Production and Decay

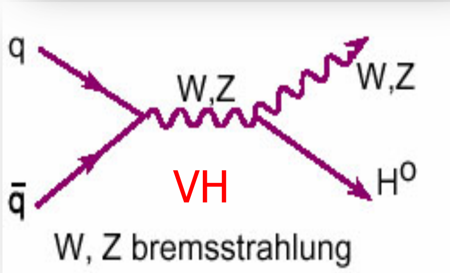
87%



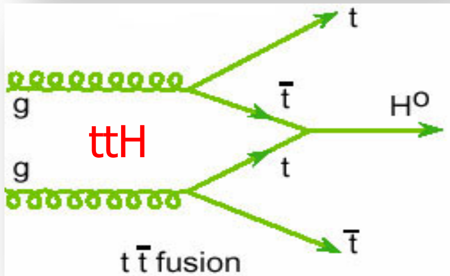
7.1%



4.9%

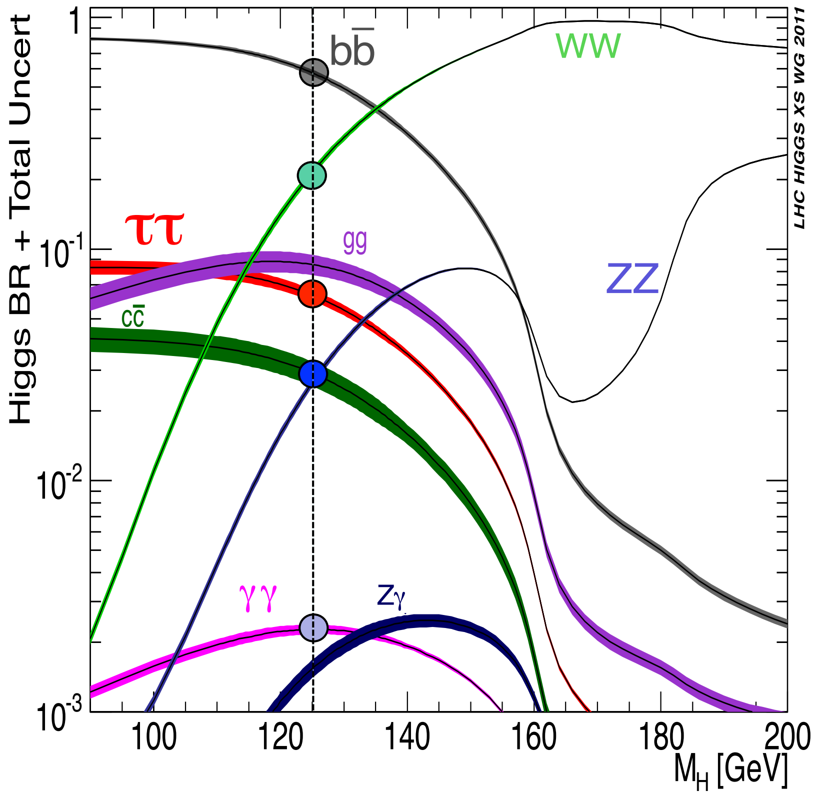


0.6%



⇕

σ/σ_{tot} (M_H = 125 GeV)



ΔM/M ~ 1-2%
High resolution, Rare

H → γγ S/B < 1
H → ZZ* → 4ℓ S/B >> 1

ΔM/M ~ 10-20%
Med. resolution, Abundant

H → bb S/B << 1
H → ττ S/B < 1

ΔM/M > 30%
Low resolution, Common

H → WW*→ 2ℓ2ν S/B < 1

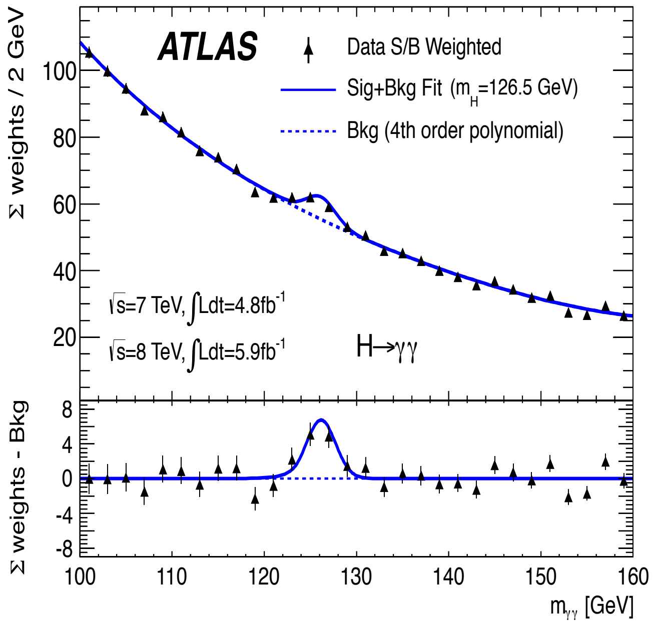
4 production modes × 5 decay modes (γγ, ZZ, WW, ττ, bb)

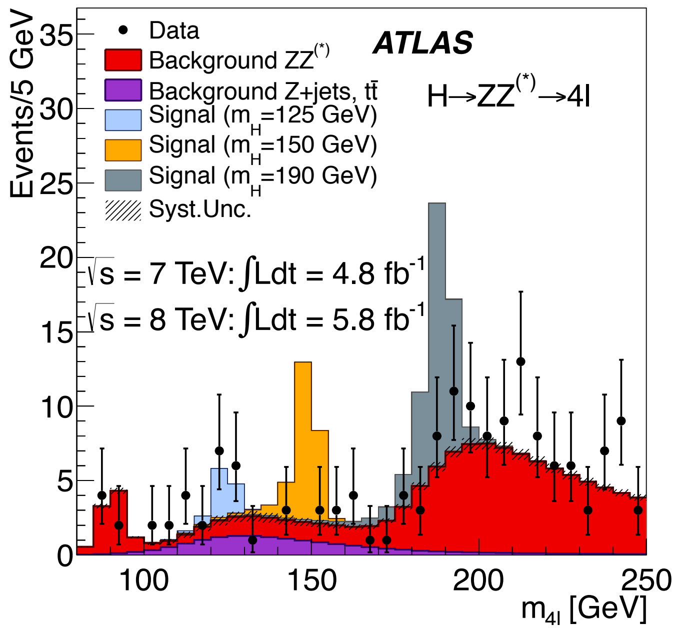
~ 100 exclusive final states (production, decay, event categories) are contributing for M_H ~ 125 GeV !

Where available:
H → γγ and H → ZZ* → 4ℓ as discovery modes

ATLAS

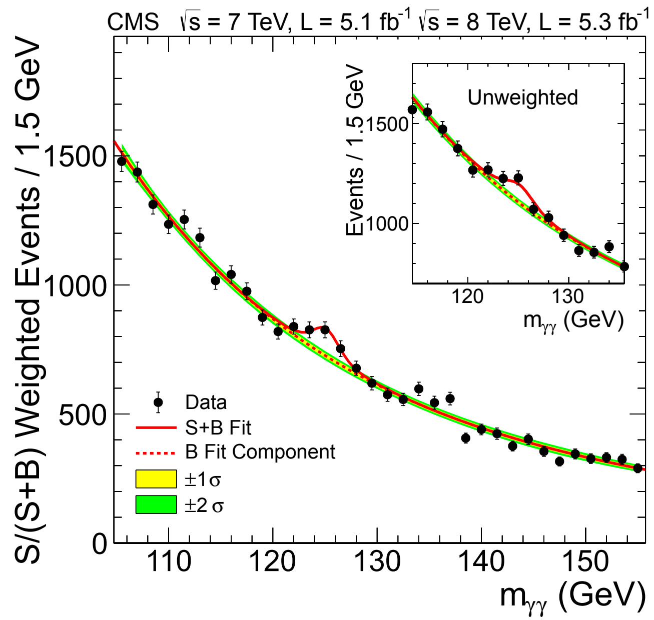
Phys.Lett. B716 (2012) 1-29

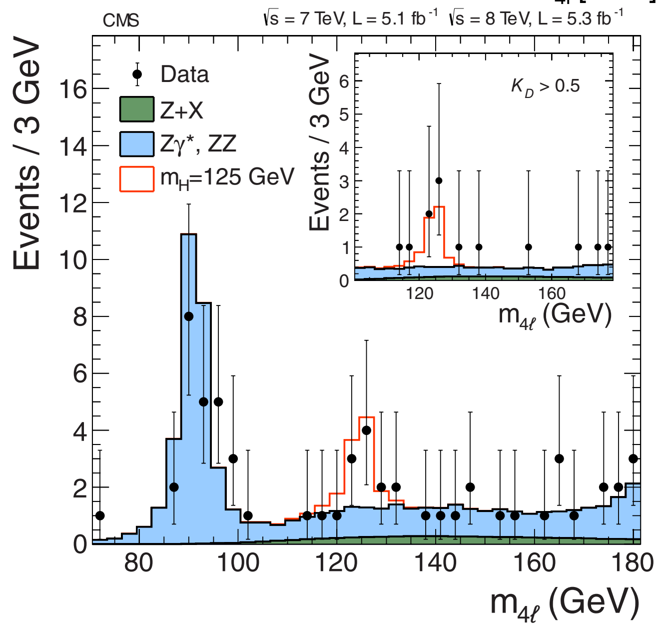




CMS

Phys.Lett. B716 (2012) 30-61

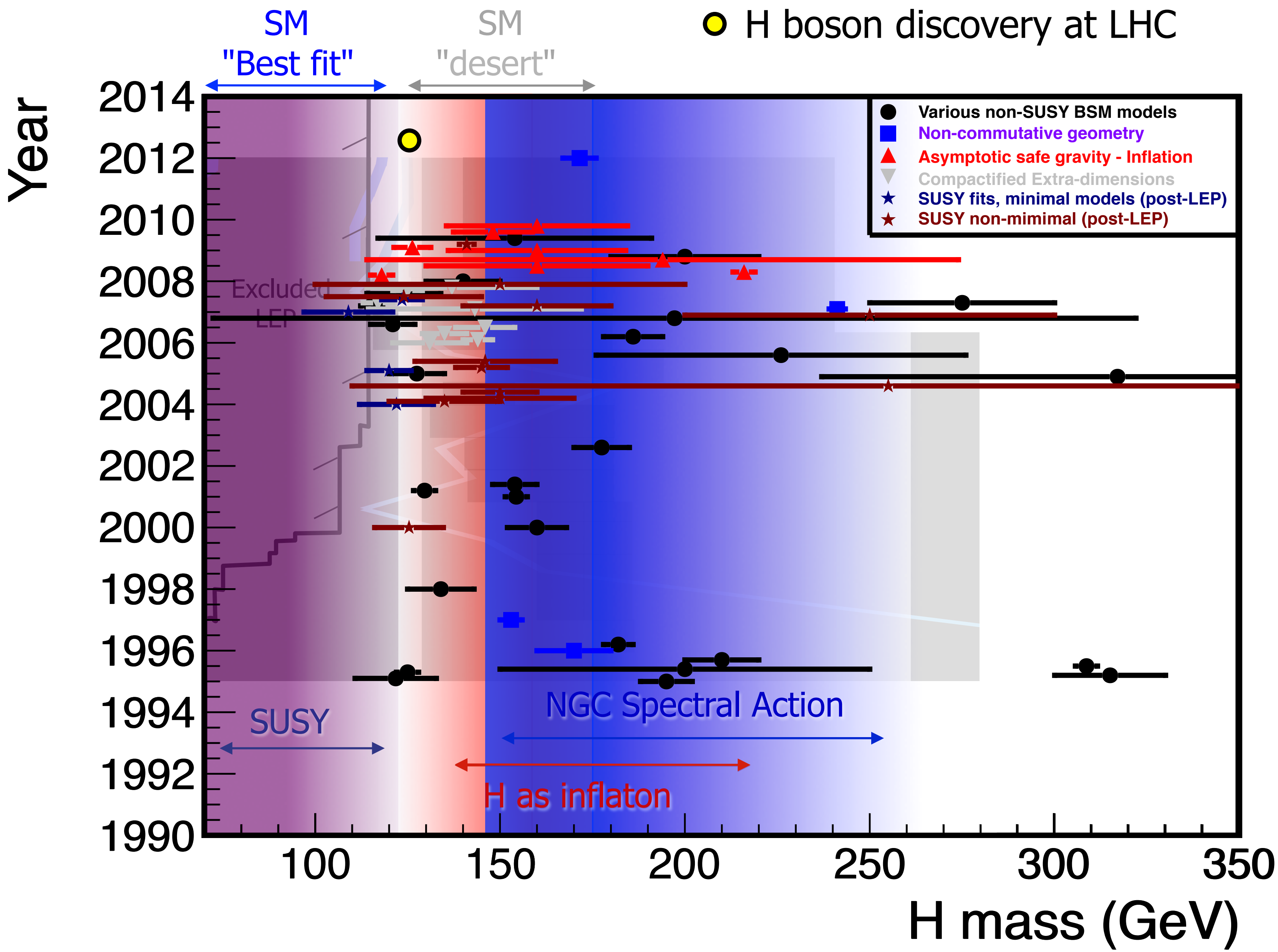




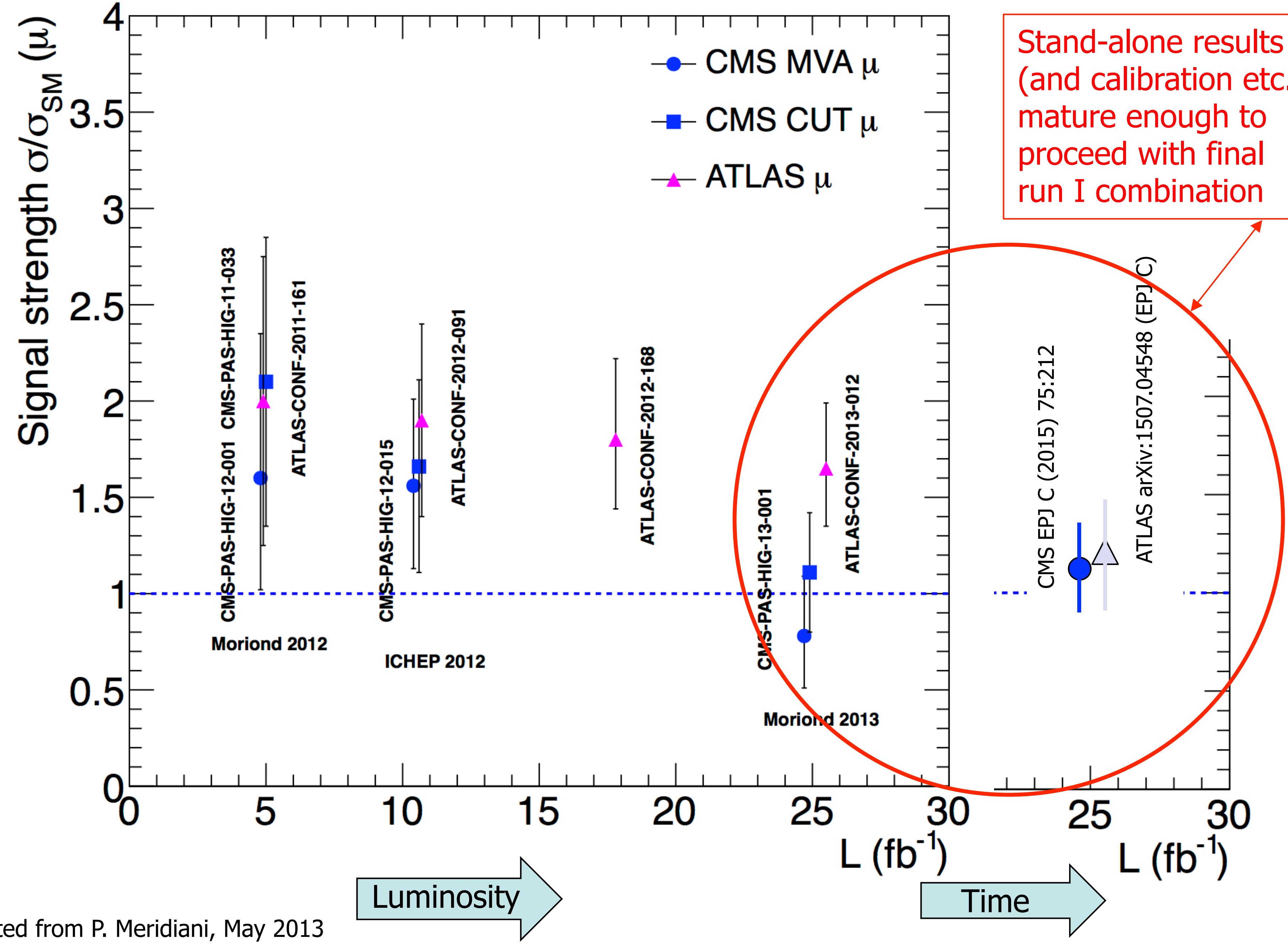
J U L Y 2 0 1 2

Discovery at M_X ~ 125 GeV, in both ATLAS and the CMS experiments combining X → γγ and ZZ* channels (additional evidence from X → WW*)

The H boson mass : Theory vs Experiment



H → γγ signal strength – vs $\mathcal{L}$ and Time

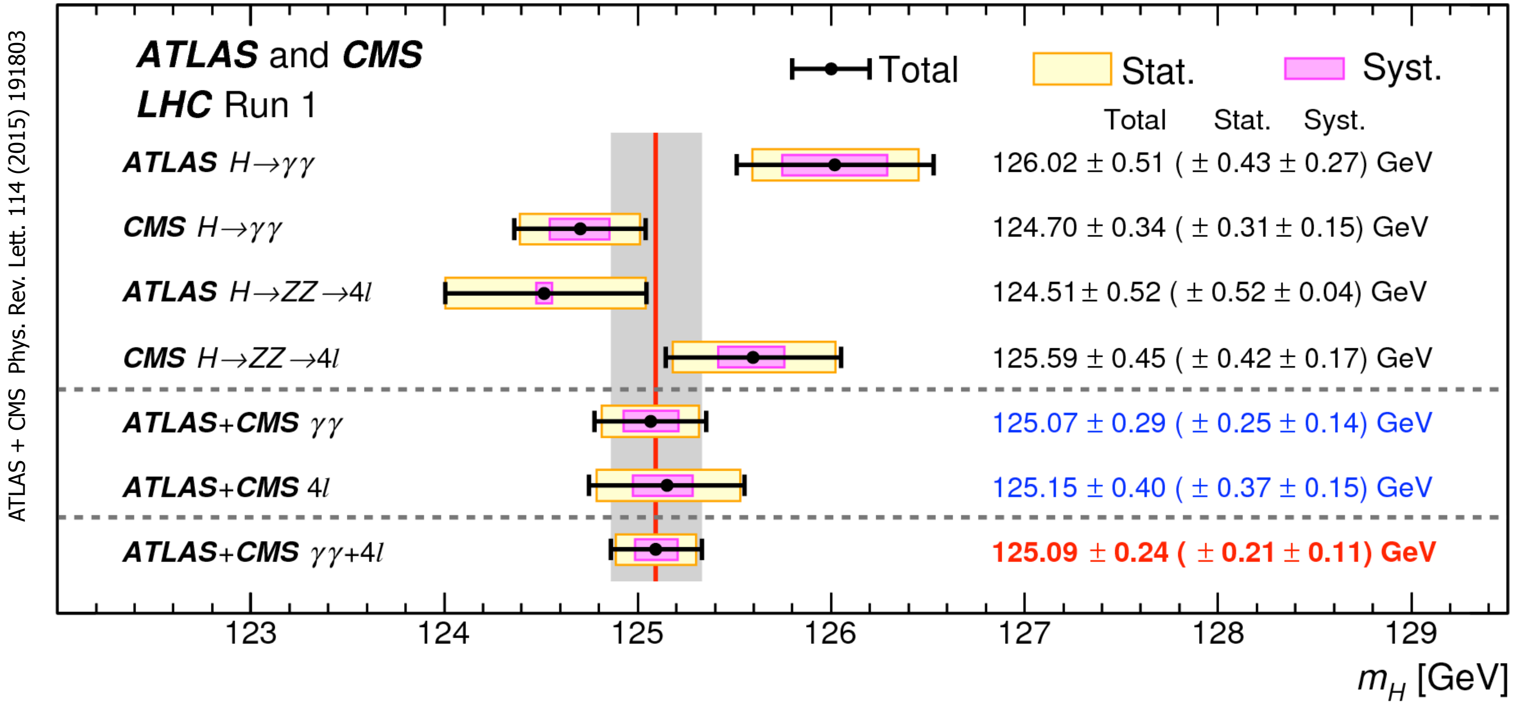


Stand-alone results (and calibration etc.) mature enough to proceed with final run I combination

Adapted from P. Meridiani, May 2013

H boson Mass – LHC Combination

- Mass measured with high precision in γγ and ZZ → 4ℓ channels



- Some tension but opposite for γγ and 4ℓ between ATLAS and CMS; (p-value ~10%) for the four measurements
- Very good agreement in the central values

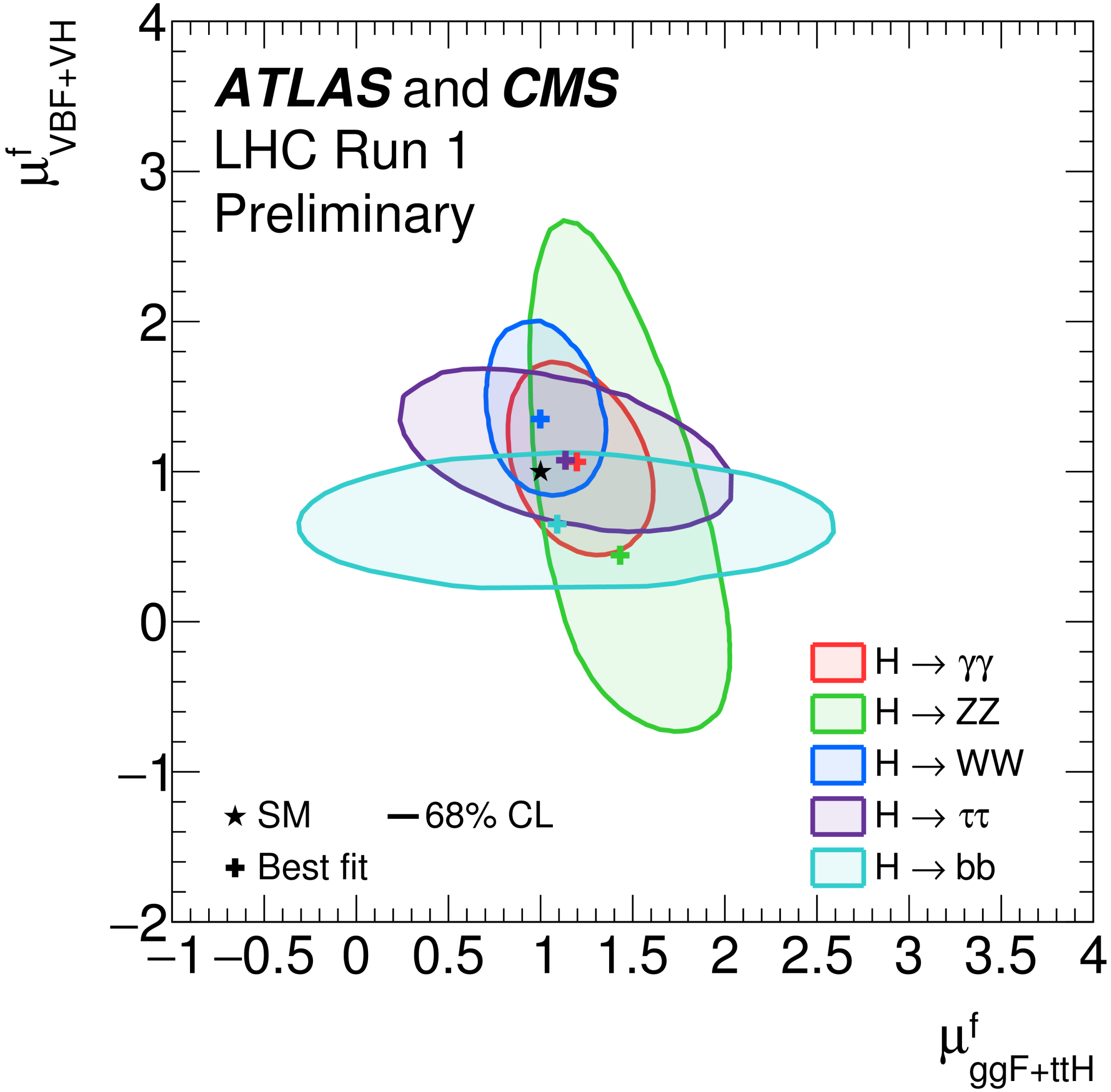
$$m_H^{\gamma\gamma} = 125.07 \pm 0.29 \text{ GeV} = 125.07 \pm 0.25\,(\text{stat.}) \pm 0.14\,(\text{syst.}) \text{ GeV}$$

$$m_H^{4\ell} = 125.15 \pm 0.40 \text{ GeV} = 125.15 \pm 0.37\,(\text{stat.}) \pm 0.15\,(\text{syst.}) \text{ GeV}$$

M_H = 125.09, narrow width, pure CP even state (0^+)

Signal Strength μ: Production and Decay

CMS PAS-15-002, ATLAS CONF-2015-044 (61pp.)

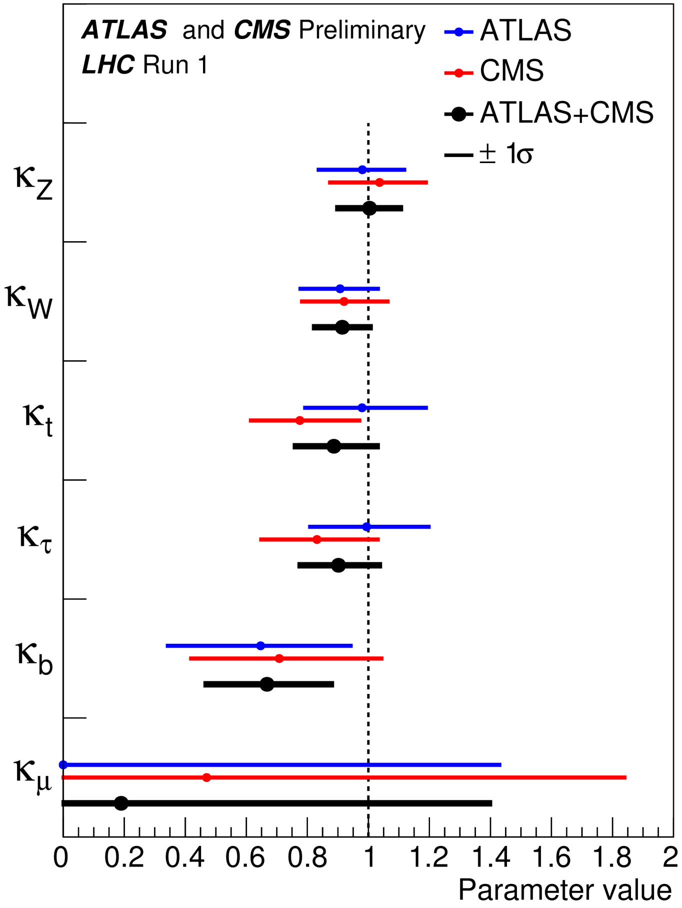


- Assume that μ_F^f and m_V^f are the same for $\sqrt{s}$ = 7 and 8 TeV
- 10-parameter fit of μ_F^f and m_V^f for each of the 5 decay channels

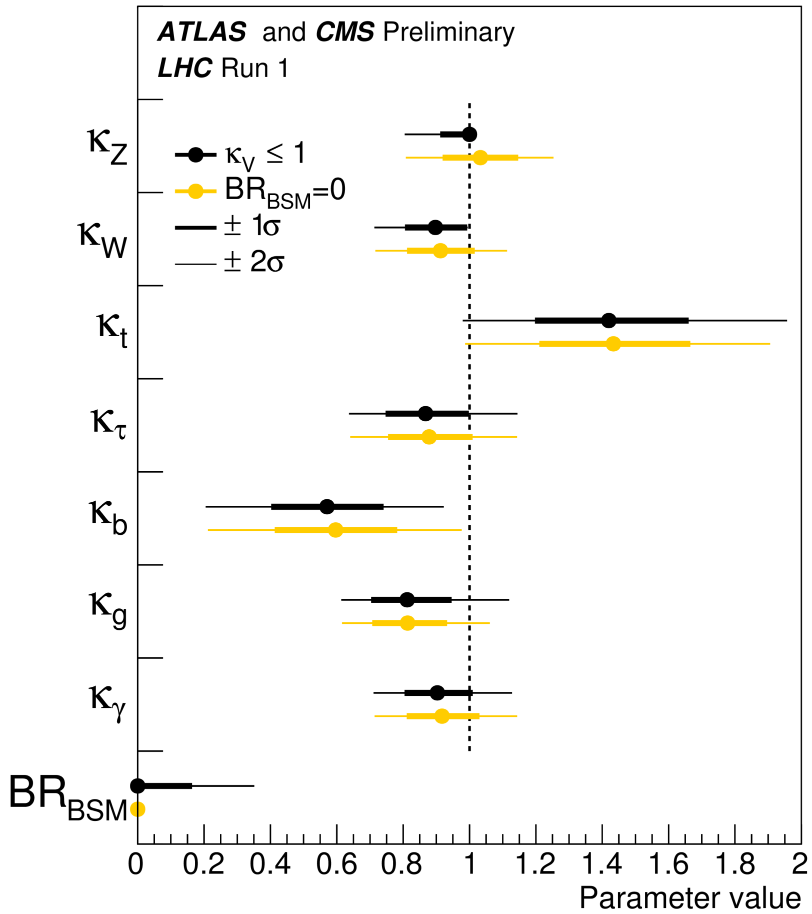
p-value of 88% for the compatibility with SM expectation !!

Test SM Couplings to Fermions and Bosons

Assuming no BSM in the loops:
i.e. assume SM for κ_γ and κ_g



Allowing for BSM in the loops:
i.e. allow effective couplings for κ_γ and κ_g

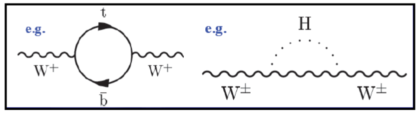


- Signal strengths in different channels are consistent with 1 (SM)
- Tension: Excess at 2.3 σ level for ttH Deficit of 2.4σ in BR^{bb}/BR^{ZZ}

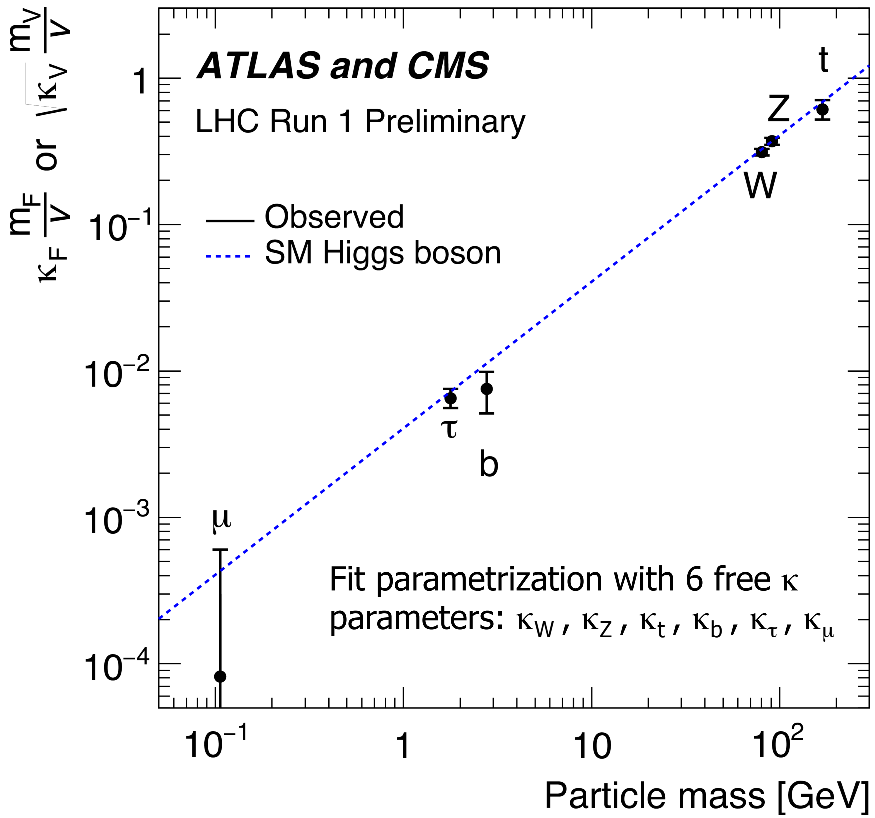
CMS PAS-15-002, ATLAS CONF-2015-044 (61pp.)

State of the Art

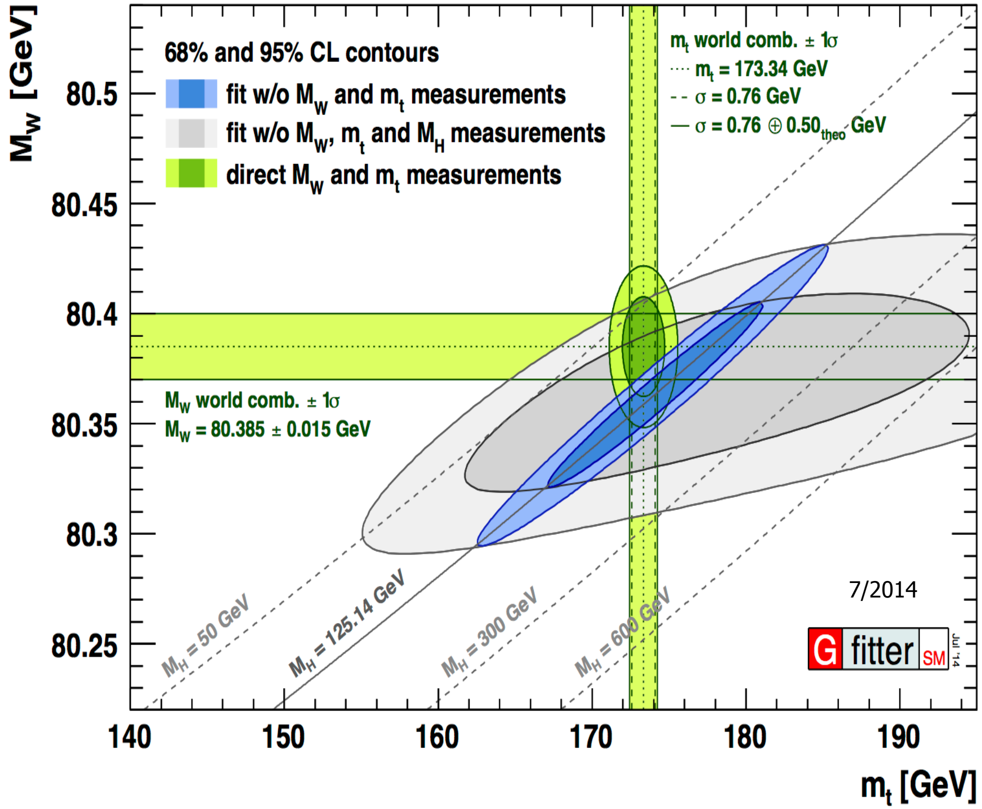
Couplings to fermions and to weak bosons
(verified to ~15-30% precision)

Rad. corrections: 

Run I Legacy M_H = 125.09 ± 0.24 GeV



W, Z meas. sensitive to M_{top} M_H



- SM-like Higgs at ~125 GeV is compatible with global EWK data at 1.3σ (p = 0.18)
- Indirect constraints now superior to some precise direct W, Z measurements

Indirect (EWK fit): M_W = 80.359 ± 0.011
Direct (World average): M_W = 80.385 ± 0.015

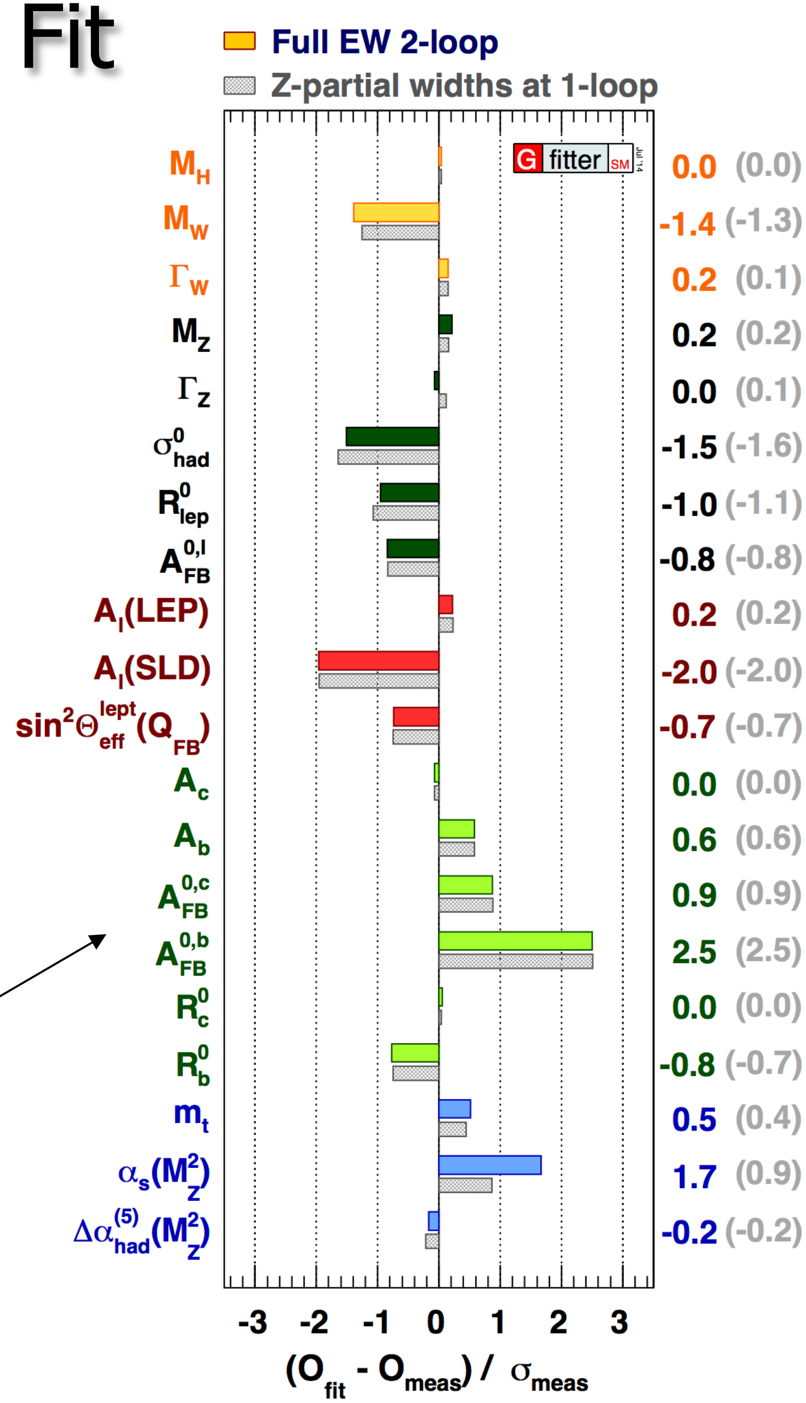
Global EW Fit

Given M_H, it is possible to fully Predict the SM with only a minimal set of input parameters

M_H
The fermions masses
$\alpha_s(M_Z^2)$
+
Three parameters defining the EW sector and its radiative Corrections
e.g. M_Z, G_F and $\Delta\alpha_{had}(M_Z^2)$

Pull values for the SM fit:

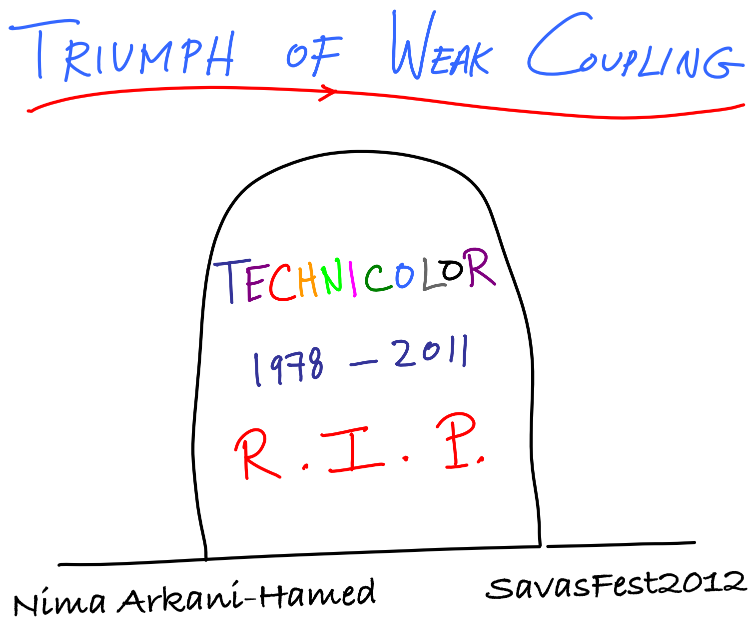
i.e. deviations between experimental measurements and theoretical calculations in units of the experimental uncertainty.



The Standard Model & H Boson Now Firmly Established

A truly astonishing achievement … and a turning point for Physics !

- Our understanding has evolved from the question of the *structure of matter* to that of the *very origin of interactions (local gauge symmetries) and matter (interactions with Higgs field)*
- We understand the quantum origin of mass for particles (scalar field, BEH mechanism) and for hadrons (dynamics in the strong sector)
- Ignoring gravitation, we have for the first time in the history of science a theory which is at least in principle complete, consistent, and coherent at all scales … (up to the Planck scale ?)
- The History of the early universe (and the nature of vacuum) is profoundly changed



We have for the first time a coherent understanding of the history of matter (SM) and of large structures (Cosmology) in the Universe

You have reached your destination!

Game Over

Try Again

II

A Crossing of the Desert

Beyond the Standard Model at Run I

No "Exotic" Discovery at the LHC in Run I

- A considerable amount of "exotic" models have been tested at the LHC up to the ~ TeV range with 2010-2012 data
- Most of the models tested so far really address only some of the many problems of the SM theory !!!

Arbitrariness of the Higgs potential after EWSB
(arbitrary Higgs boson mass, of the self-coupling and sign of μ …)

Origin of the flavour structure of the theory
(three families of fermions, flavour mixing parameters, matter-antimatter asymmetry in the Universe … Scalar sector and the origin of families ($H \rightarrow \mu\mu$, $H \rightarrow \tau\tau$)

Origin of the specific gauge symmetry / set of conserved charges
(cancelation of triangle anomalies, gauge unification ? Scalar sector talking to ν's ($\nu_L \leftrightarrow \nu_R$) ?)

Hierarchy between EWK and the Planck scale (and GUT scale ?)
(metastability of the EWK vacuum, problem of quantum gravity etc.)

- The rise of √s in coming runs at LHC gives access to new territory for the search of the unexpected …
- It is useful to consider how the discovery of the H boson in Run I could serve a a guide towards BSM physics

The Coverage of BSM Theories

	Extension \ Virtues:	Th. motivations									Cosmo/pheno motivations			
		1:QG	2:EW	3:Flav	4:SCP	5:CQ	6:GU	7:Hie	8:Met	9:Cos	1:ν	2:BA	3:DM	4:Infl
+fermions	Heavy ν_R								?		+++	+++		
	Triplet fermions								?		++			
	Vector-like quarks		-	+			+		?					
+ scalars	2 HDM			-				-	+			++		
	Inert doublet								+				++	+?
	H singlet(s)								++				++	+++
	H triplet								+		++			
	Composite H		++					++(?)	?					
	Axions				+++								+++	
+ symmetries	Z'(s)										+?		++	
	SU(5), SO(10)					+++	-	---	-		++	++		+
	L-R Symmetry							-	+		++			+?
	Flavor Symmetry			+++										
+ global	Extra-dimensions	?		+			+	+++	+	+?		?	+	+?
	Little Higgs		+++	?		-	?	-	?				++	
	1-10 TeV Susy-GUT	+	++	-	+?	+++	+++	++(+)	++		+	++	+++	++
	Superstrings	+++	?	?	?	?	?	++	?	?	?	?	?	?

Quantum **G**ravity
EWK Sym. Breaking
Flavour Structure
Strong **CP**
Charge **Q**uant.
Gauge **U**nification
Hierarchy
Vacuum **Met**astability
Cosmo. Constant
ν mass
Baryon **A**ssymetry
Dark **M**atter
Inflation

Supersymmetry

The fundamental concept

Extension of the Poincaré group of space-time symmetries
(translations P_μ, rotations & boosts $M_{\mu\nu}$)

Space-time x^μ $\Rightarrow$ Super-space (x^μ, θ)

Q_α (SUSY transformations) $\{Q, \overline{Q}\} = -2\gamma_\mu P^\mu$ $[Q, P^\mu] = 0$

The virtues

- Solution of the hierarchy problem
- Allows for GUT (convergence of the couplings)
- Promoted to a local symmetry $\Rightarrow$ gravity automatically included
  spin 2 graviton and spin 3/2 fermion added to the spectrum
- Provides a dark matter candidate (with R-parity conservation)
- « Explains » the origin of M_H

SM: $V(H) = -m^2|H|^2 + \lambda^2|H|^4$ $M_h^2 = 2\lambda^2 v^2$

SUSY: at least two Higgs doublets; self-couplings (quartic) connected via SUSY to the weak gauge couplings

$M_H^2 = (g^2 + g'^2)v^2 / 2^2$ $M_H = M_Z$ at tree level

$M_H > M_Z$ with radiative corrections after SUSY breaking

M_H "predicted" !

The SUSY Spectrum

- Necessity to introduce a spectrum of supersymmetric particles
  SUSY is manifestly broken ⇔ need new fermionic / bosonic patners
- Necessity to extend the scalar sector
  To avoid triangular anomalies;
  To satisfy the Glashow-Weinberg condition for 2HDM (avoid FCNCs)

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

- 2 doublets of complex scalar fields
- Type of 2HDM depending on coupling to SM Particles
  e.g. The MSSM has an effective 2HDM of "type II"

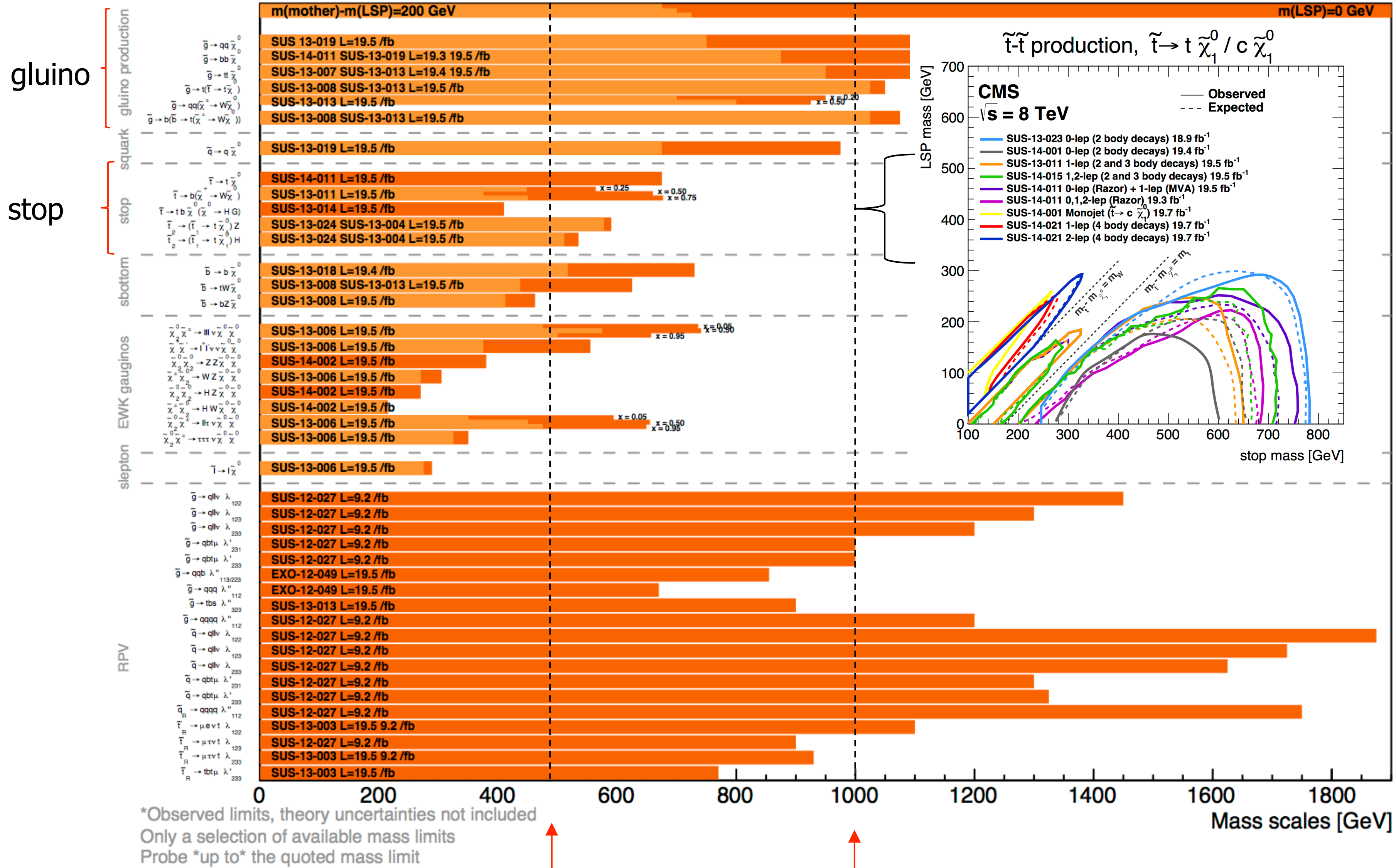
Coupling scale factor	2HDM Type II
κ_V	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$
κ_d	$-\sin(\alpha)/\cos(\beta)$
κ_{lepton}	$-\sin(\alpha)/\cos(\beta)$

e.g. coupling to b quarks and τ leptons enhanced by $\tan^2\beta$ in the MSSM

$\tan\beta = \langle v \rangle_u / \langle v \rangle_d$

SUSY In the Aftermath of Run I

No **s**particle signal found ⇒ set limits



500 GeV

1 TeV

SUSY In the Aftermath of Run I

- Searches for SUSY has been on the agenda of HEP for decades
- So far most of the constraints were derived from the search for supersymmetric matter in various incarnations of minimal models

  (e.g. with contraints from the prejudice of unification applied at GUT scale)

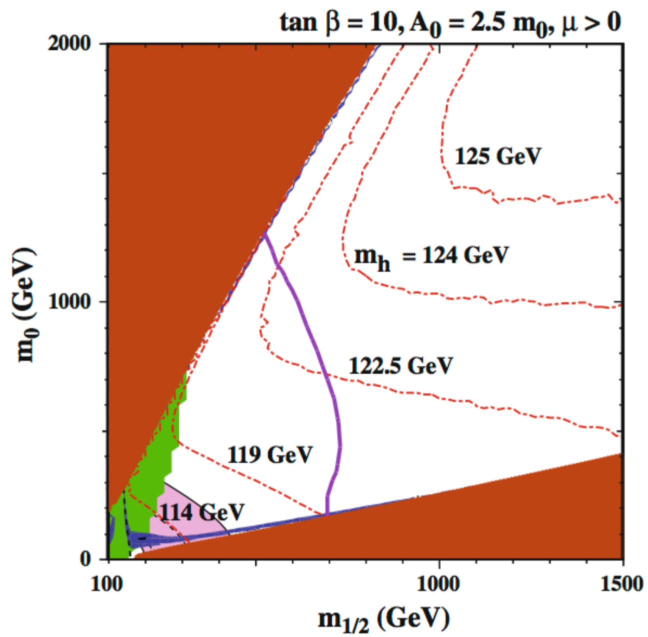
The SM-Like H125 boson discovery dramatically changes the situation

The "h" is SM-like and no other seen so far ⇔ decoupling regime

⇒ The H, A , and $H^{\pm}$ decouples from Z, W and $M_H \sim M_A \sim M_{H\pm}$ with $M_A \gg M_Z$

Only 2 two free parameters needed for the dominant rad. corrections e.g. tanß, M_A

The large mass of the "h" pushes the SUSY spectrum to high scales !!!



It has become difficult to reconcile the rather high mass of the "h", with the necessity to have part of the SUSY spectrum at a low enough mass to preserve a « natural » theory [minimize the fine tuning]

The Problem of Hierarchy

- The "h" boson introduces a major problem of Hierarchy with respect to a GUT scale, and in any case with respect to the Planck scale
(+ metastability of the vacuum)

- In the SM, the mass of the Gauge bosons is protected by gauge symmetries and the mass of the fermions is protected by chiral symmetries … but the mass of the Higgs boson is unprotected

A main virtue of supersymmetric theories is to protect the Higgs mass via a combination of supersymmetry and a chiral symmetry
(in a way consistent with an underlying unified theory or with a EFT picture)

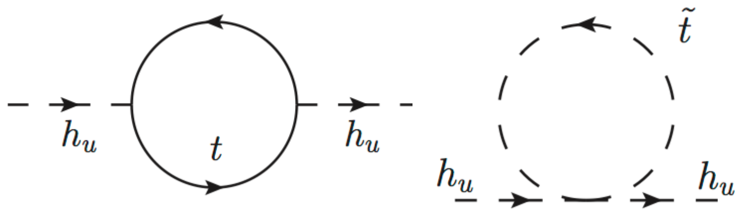
The mass of the h boson is the Z boson mass up to radiative corrections

SUSY stabilizes the scalar sector and ensures stability of the vacuum

Radiative Corrections

- Radiative stability of the weak scale involves the superpartners with Yukawa couplings or order one [gauginos, Higgsinos, stop, and sbottom] (at least for EFT's with cutoff ~ 10 TeV)

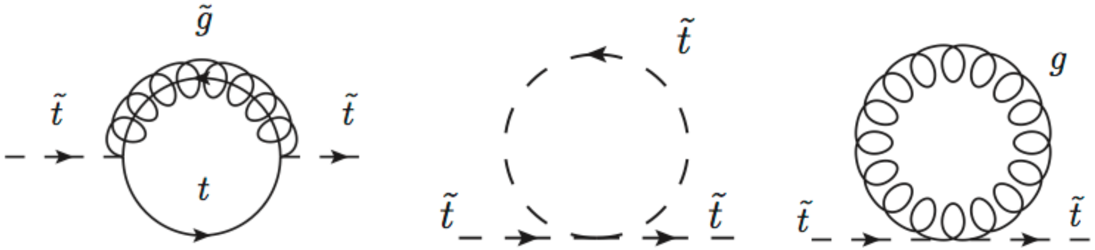
- Radiative corrections to m_h mostly depends on the stop mass



$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\left[\ln\frac{M_S^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

Naturalness requires a stop lighter than a few hundred GeV

- The stop suffer from it's own naturalness problem !



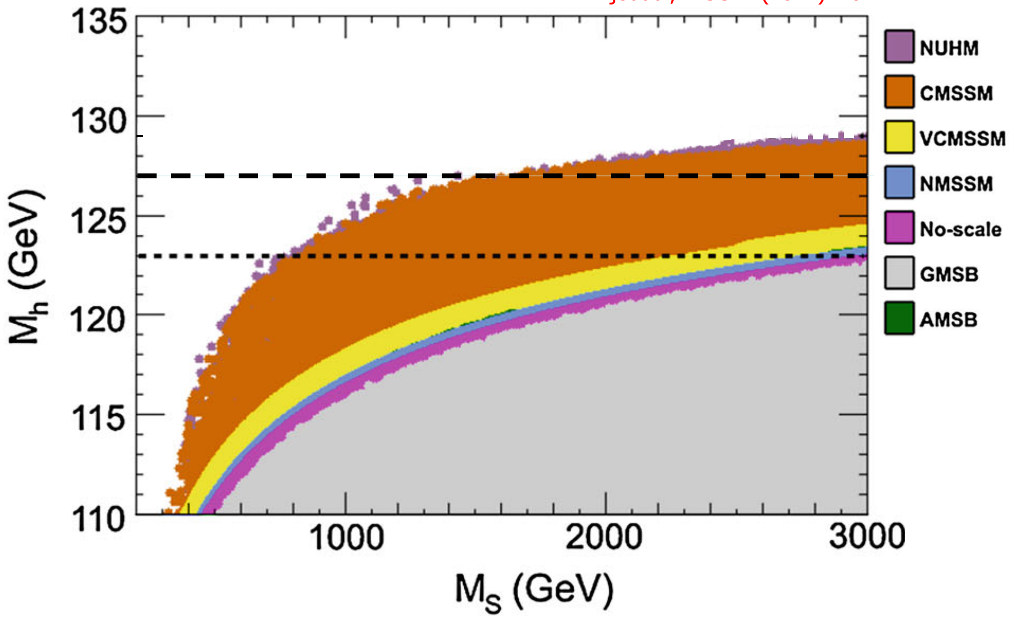
$$\delta m_{\tilde{t}}^2 = \frac{2 g_s^2}{3\pi^2} m_{\tilde{g}}^2 \ln\frac{\Lambda_{UV}}{m_{\tilde{g}}}.$$

Naturalness requires $m_{\tilde{t}} > m_{\tilde{g}} / 2$

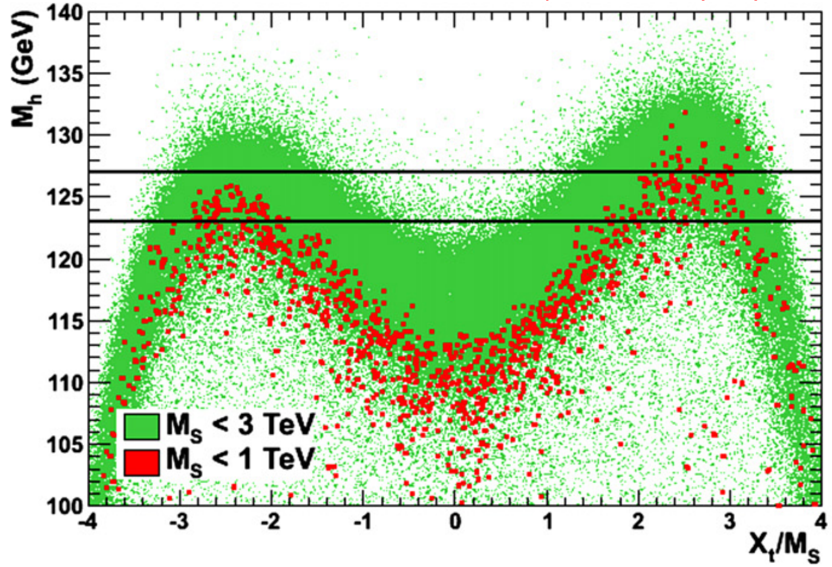
Conflicting requirements: heavy « h », light stop, heavy gluino

The light "h" and Supersymmetry

Djouadi, EPJC 74(2014)2704



Arbey et al. PLB 708(2012)162

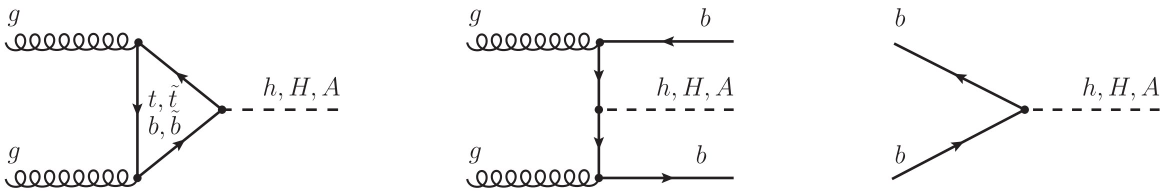


$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ taken as SUSY scale in "phenomelogical MSSM"

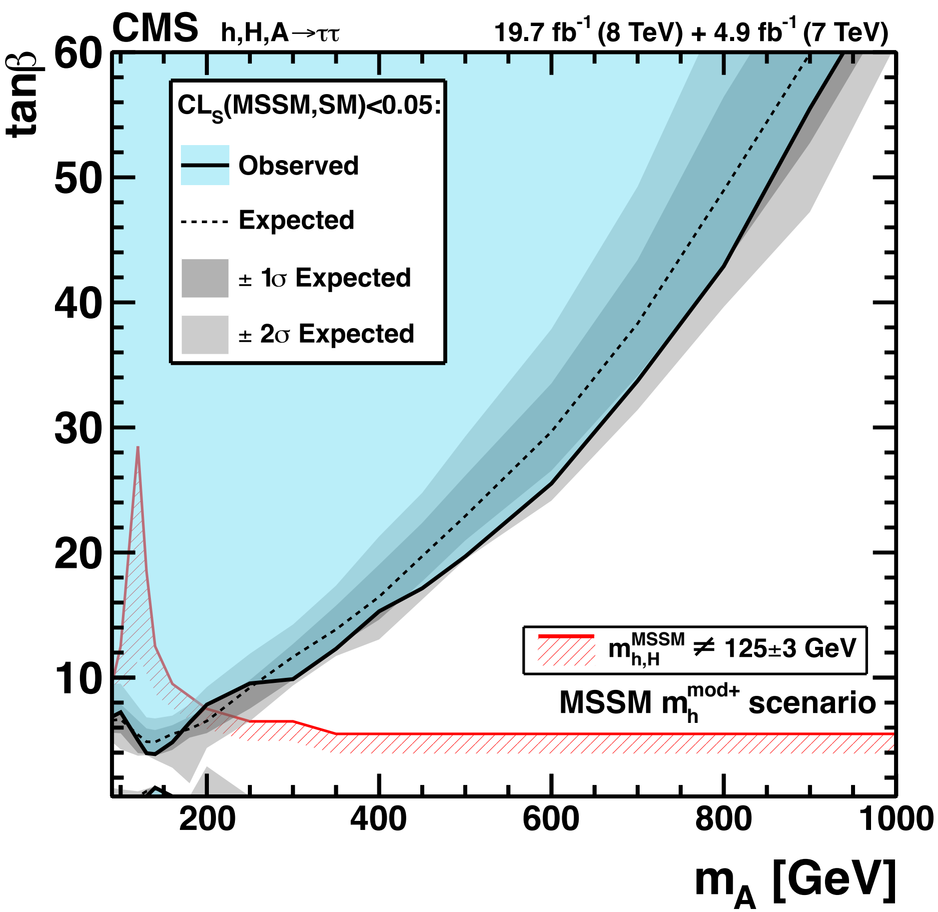
$X_t \equiv$ stop mixing parameter

- M_h can be obtained including the corrections that involve only M_S and X_t
- For M_S < 1 TeV, only the scenarios with X_t/M_S close to maximal mixing survive; in general large M_S and moderate to large tanß is needed
- Light stop state allowed only for large stop mixing and stop mass splitting

Search for an Extended Scalar Sector



- Gluon fusion prod. dominate for small and moderate tanß
- b-quark associated prod. dominates at large tanß



Exclusion limits presented in the MSSM parameter space for different benchmark scenario:

m_h^{max}, $m_h^{mod\pm}$, light-stop, light-stau, τ-phobic, and low-m_H.

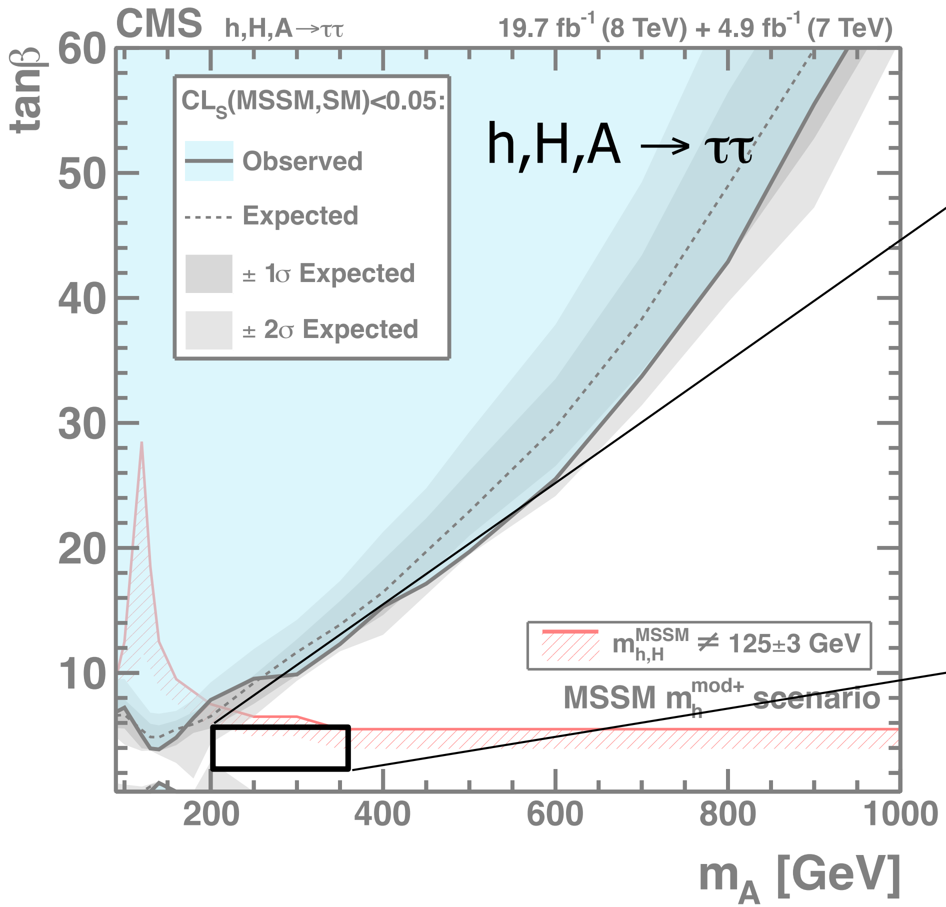
Only a very narrow valley at moderate tanß survives in the m_h^{max} scenario

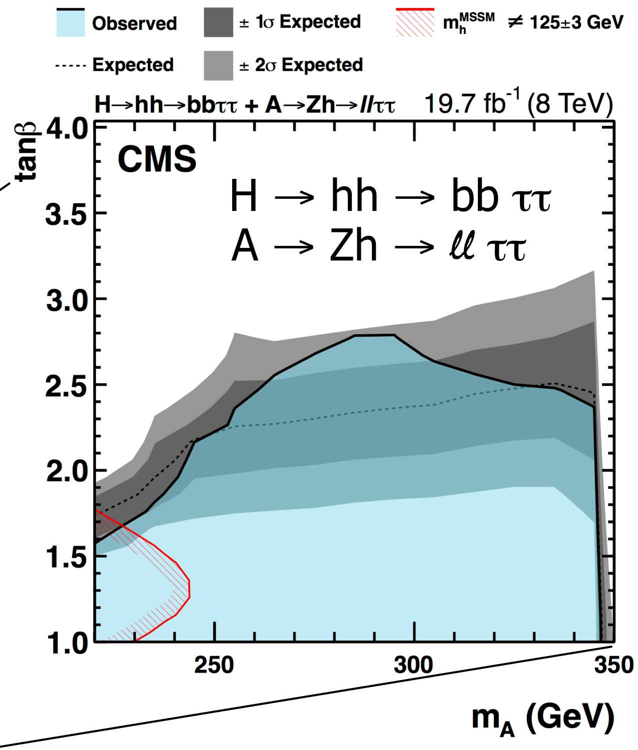
Only large M_A – large tanß allowed in the light stop scenario

Allowed phase space opens up for "modified" stop mixing values

Note: low tan β opens up if MS >> O(TeV)

Search for an Extended Scalar Sector





Also no signal found for the charged Higgs in $H^{\pm} \rightarrow tb$ and $\tau^{\pm} \nu$ decays

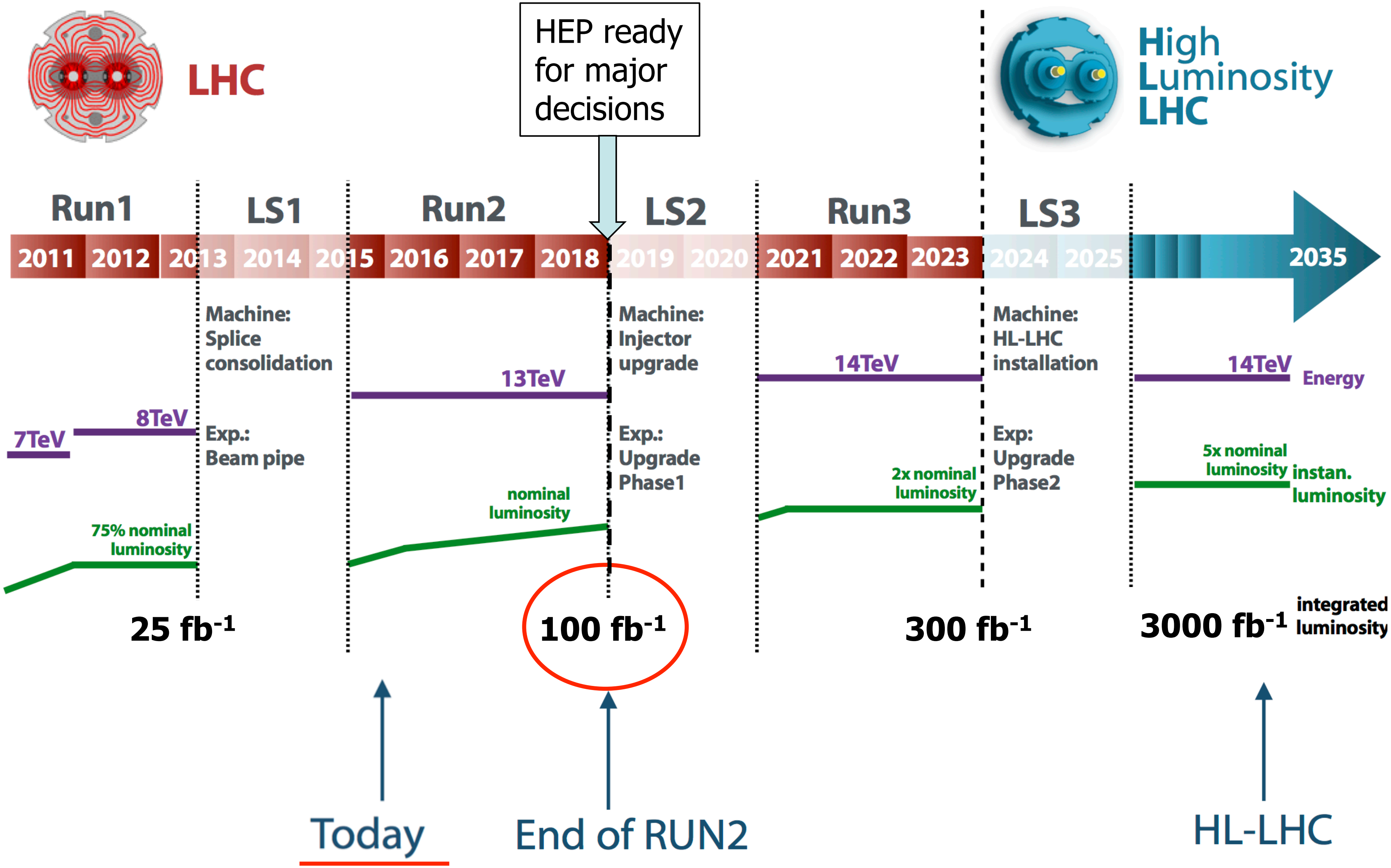
No evidence for an additional Higgs boson in Run I

III

Reaching Unexplored Territories

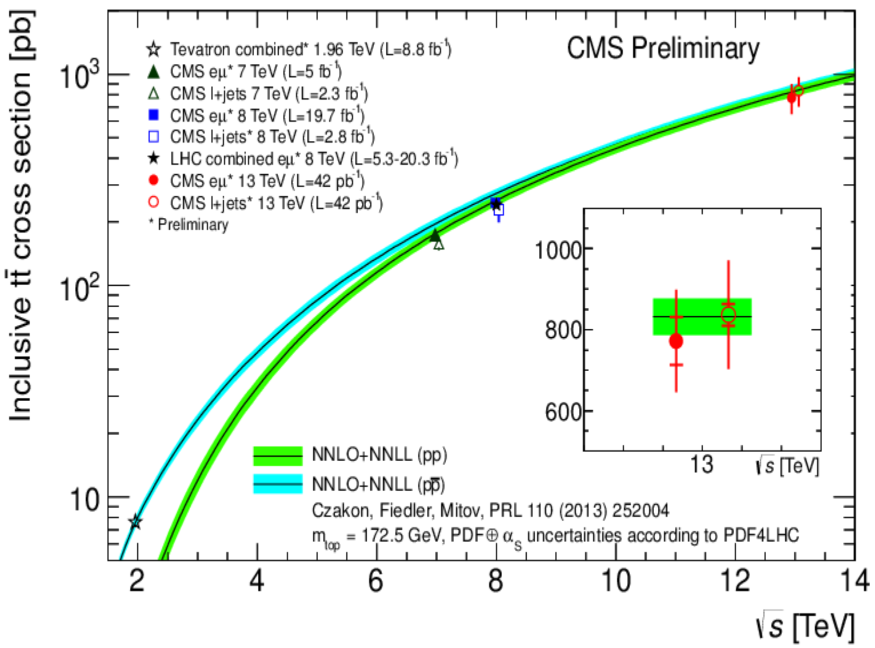
First results from Run II

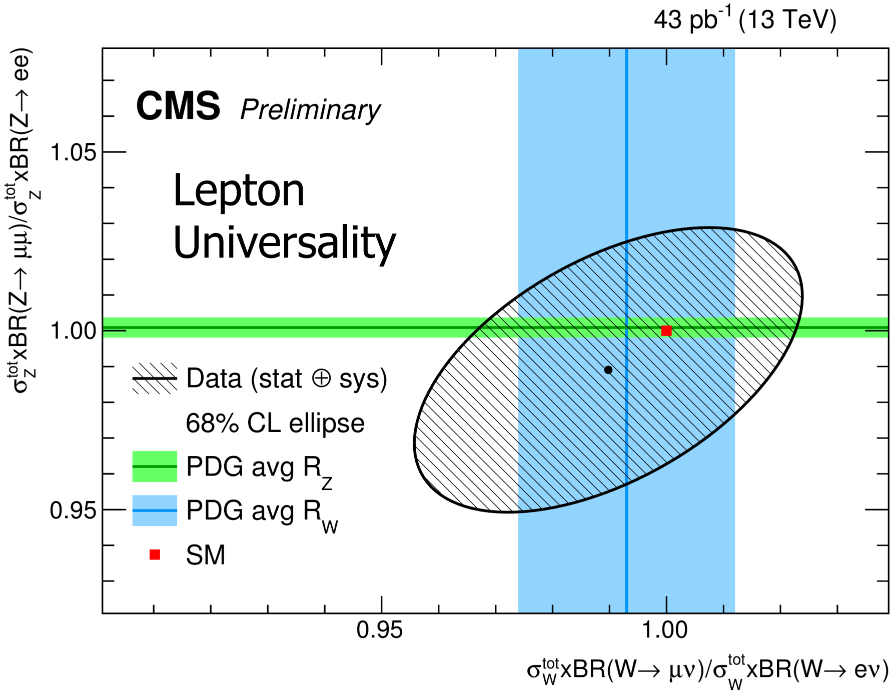
LHC and HL-LHC Plans

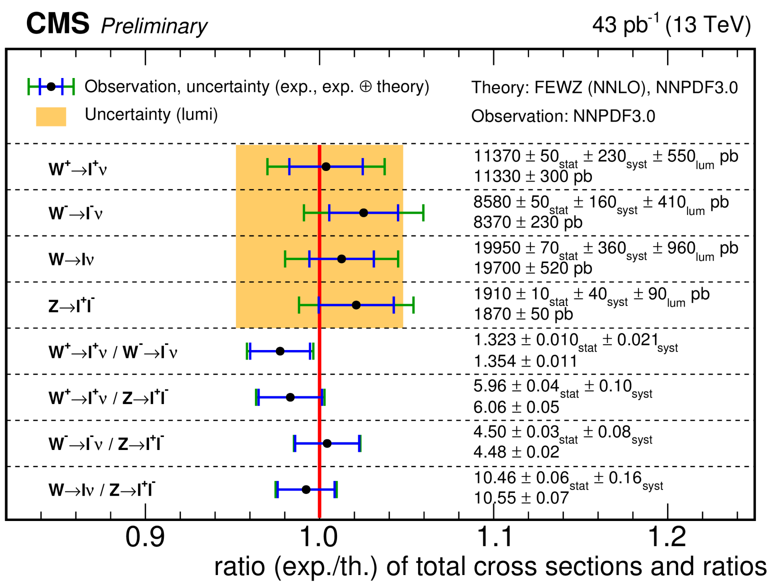


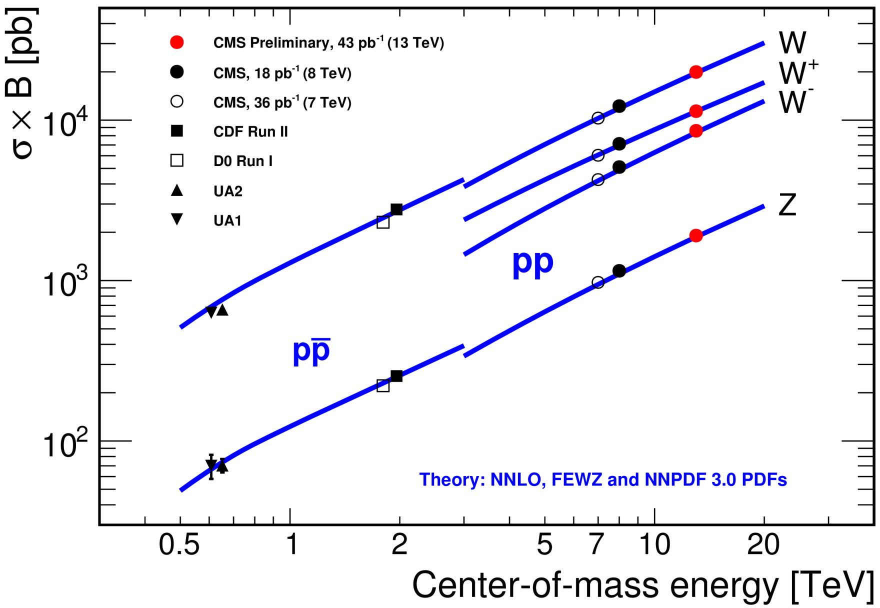
Major LHC and Detector Upgrades needed for HL-LHC

Standard Model Measurements – 13 TeV

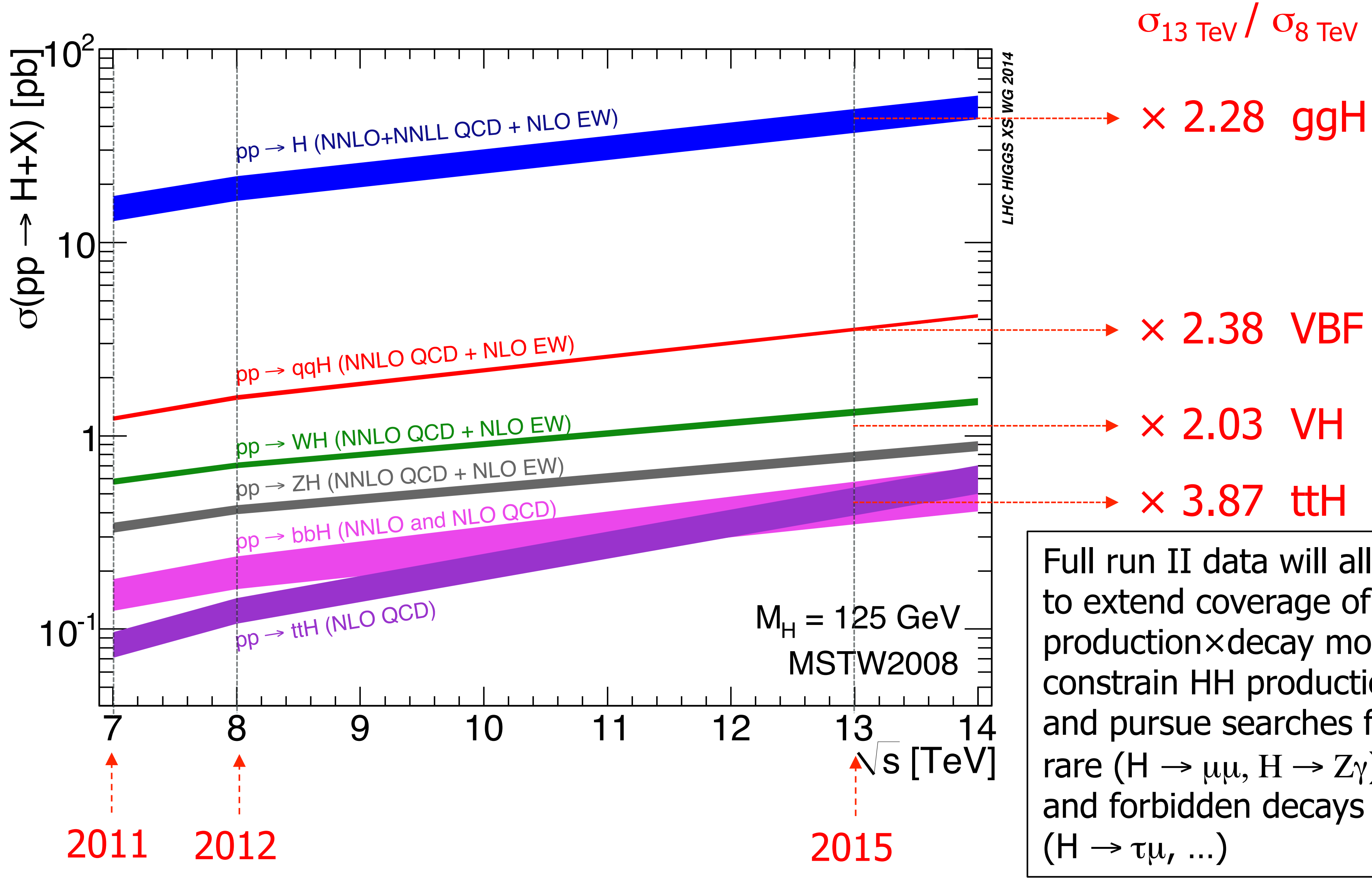








The H125 Boson : From 8 to 13 TeV at the LHC

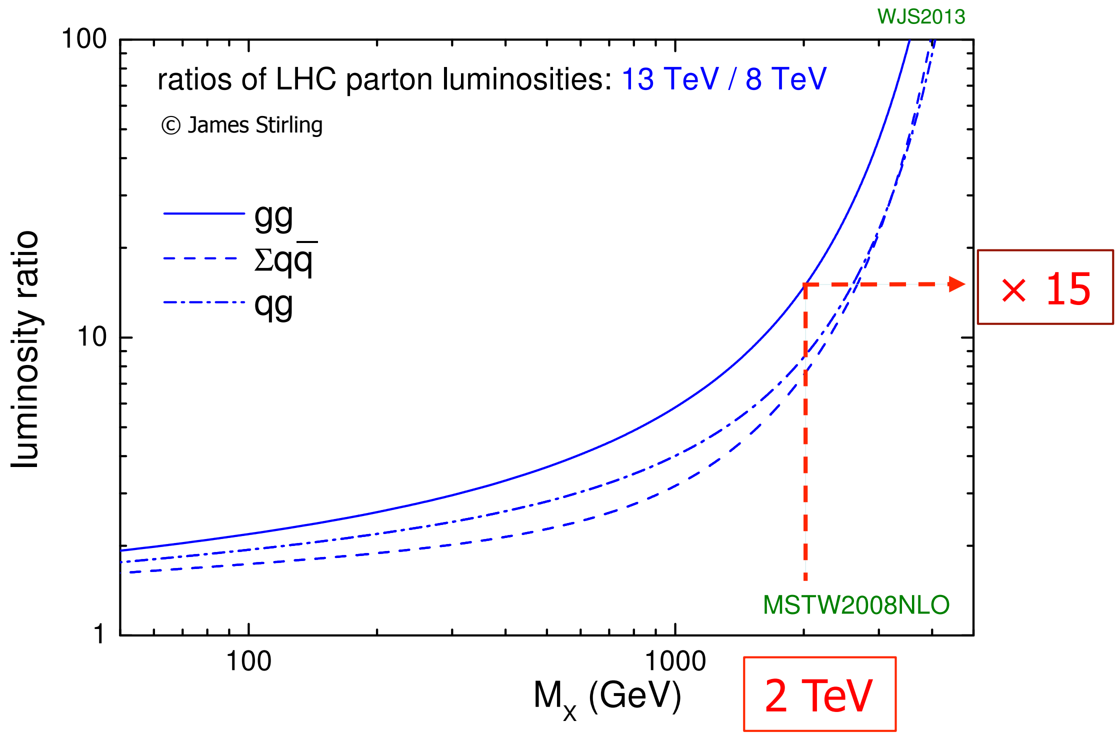


Full run II data will allow to extend coverage of all production×decay modes, constrain HH production and pursue searches for rare ($H \to \mu\mu$, $H \to Z\gamma$) and forbidden decays ($H \to \tau\mu$, …)

- Need ≥5.1 fb-1 (ttH) to 8.7 fb^{-1} (ggH) of 13 TeV data to match with 8 TeV results
- Minimal set of results (proof of existence/consistency) expected by Moriond.

Wait for 2016 data !

Exoticas: From 8 to 13 TeV at the LHC



Run II at √s = 13 TeV

- Considerable extension of the discovery reach

Run III and HL-LHC at √s = 14 TeV

- Further measurements and reconstruction of BSM spectra

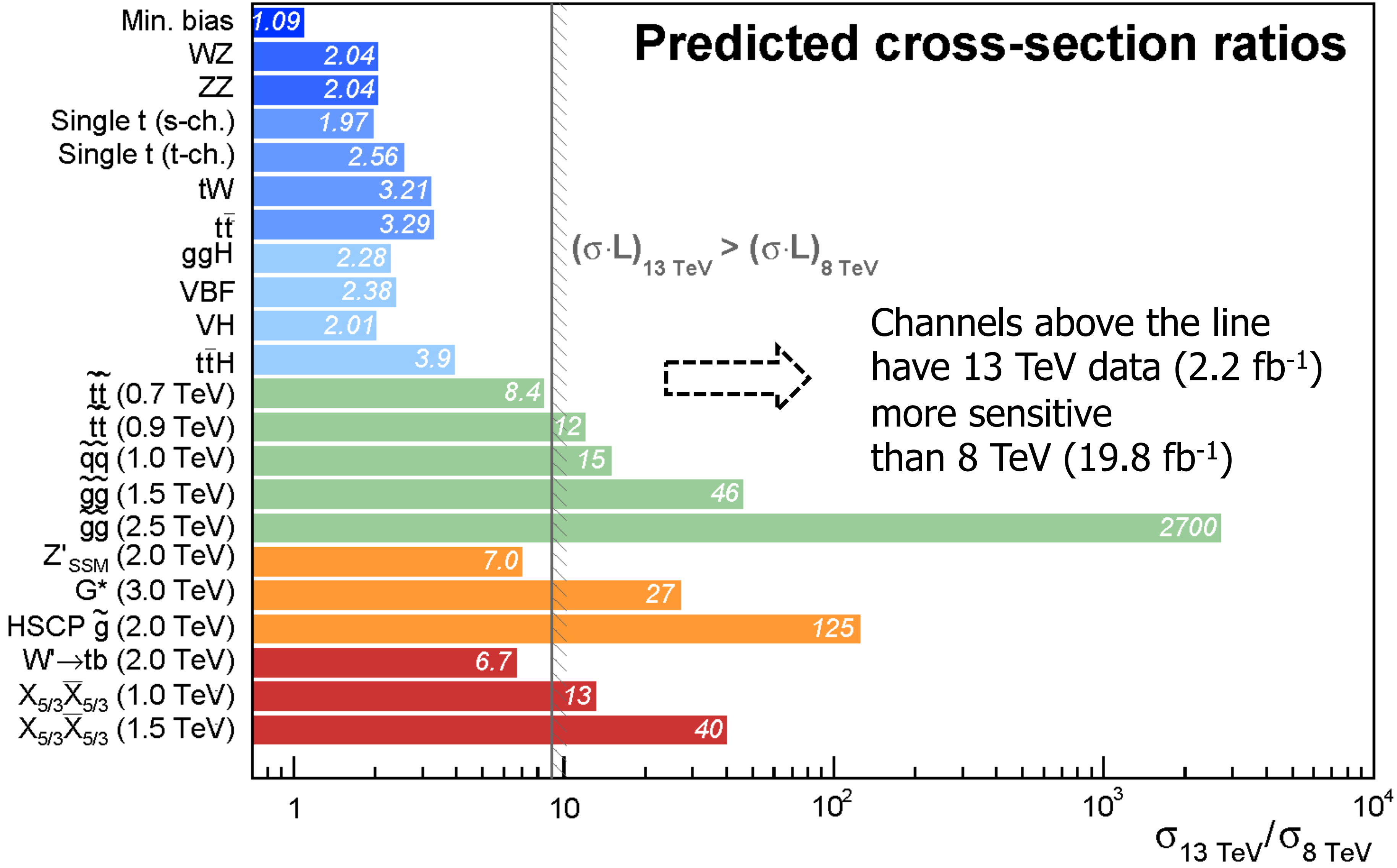
We need more symmetries, more degrees of freedom

Extended Gauge sector → New TeV Resonances

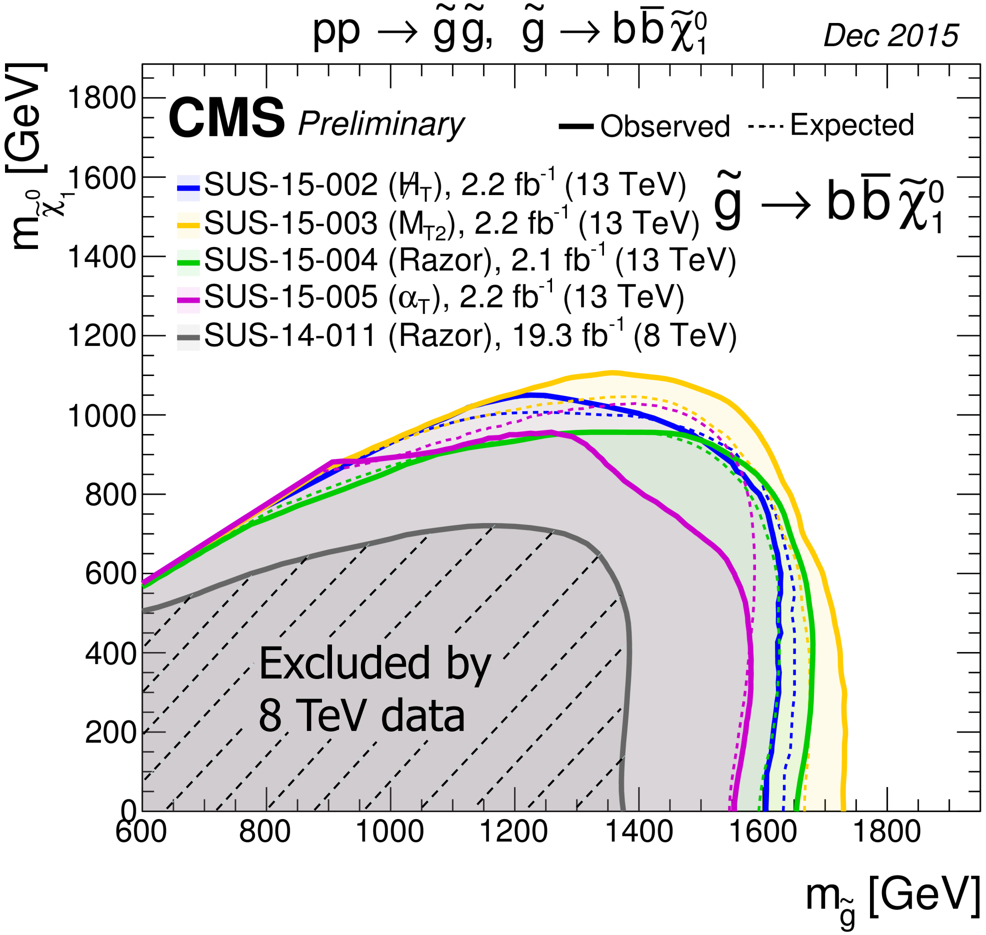
Extended Coordinates (new degrees of freedom)
- Extra-dimensions → New TeV Resonances
- Super space (x^{μ}, θ) → sParticles, Dark Matter, New "Higgs" Bosons

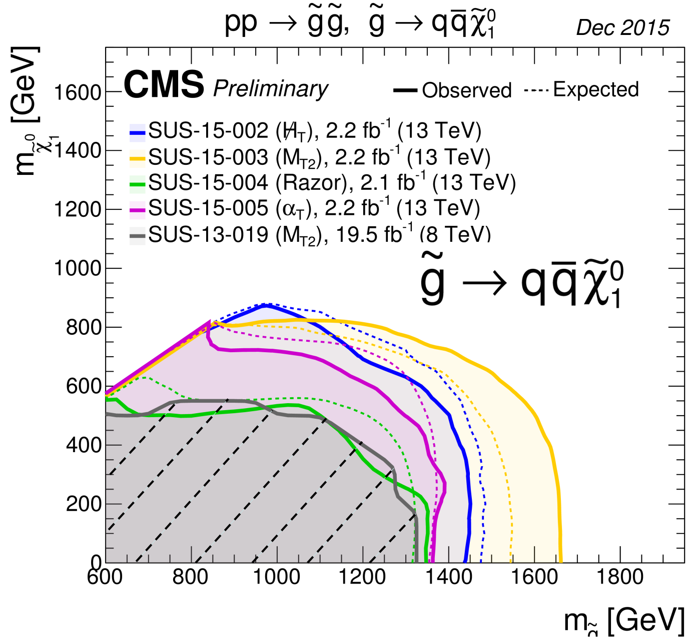
Extended Scalar Sector → New "Higgs" Bosons

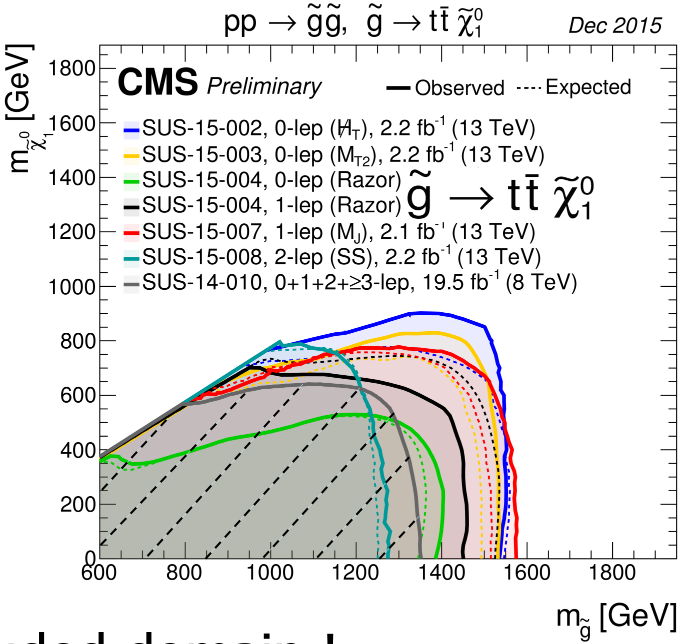
SM and Beyond: From 8 (Run I) to 13 TeV (2015)



Search for Gluinos







Very important increase of the excluded domain !

John Ellis @ CERN

“It's better
to have loved and lost
than
not to have loved at all"

John Ellis

« One year on from the Higgs boson find
has physics hit the buffers »
The Guardian, 6 August 2013

You have reached your destination!

Game Over

Try Again

IV

Looking beyond

High(er) Luminosity Physics

The Scalar Sector and Physics Beyond SM

The Higgs Bosons as a guide !

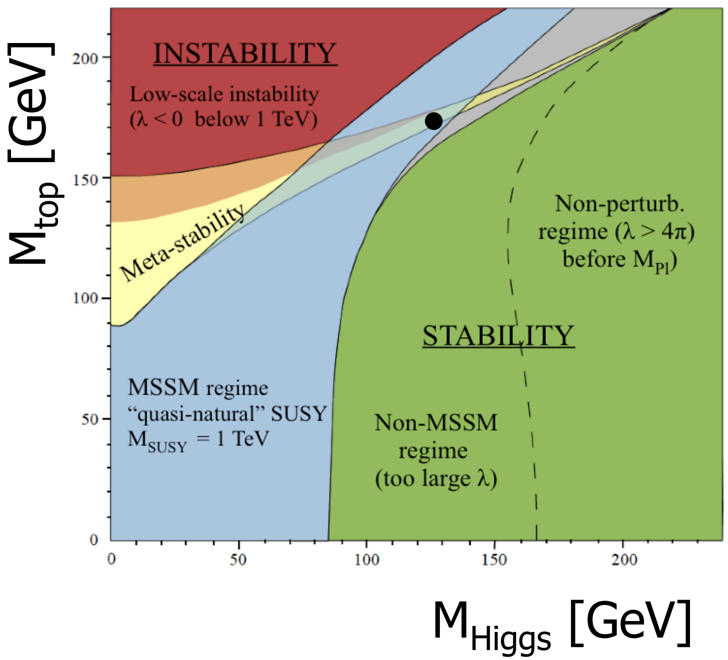
- The complexity of the Standard Model is encoded a scalar sector

$$\mathscr{L}_{SM} = \mathscr{L}_{gauge}(A_a, \psi_i) + \mathscr{L}_{Higgs\ (Symm.\ Break.)}(\phi, A_a, \psi_i)$$

Natural
verified with high precision; stable and highly symmetric (gauge and flavour symmetries)

Ad hoc
Necessary (other mass terms forbidden by EWK gauge symmetries); QM unstable; at the origin of flavour structure and all other problems of the SM

G. Isodori et al.



- Can we avoid the arbitrariness of the Higgs sector ? (get self-coupling via gauge sector ?)

  Does nature requires an extended scalar sector ?

  Can we avoid a Hierarchy problem relative to Planck scale ?

  We have found particles of spin 0, ½, and 1; where are the spin 2 particles connected to gravitation ? (extra-dimension ?)

The H Boson Aftermath at LHC/HL-LHC

Driven by the new scalar boson H discovered during run I:

- Complete precision measurements of the Higgs boson
- Measure trilinear and quartic couplings of weak bosons
- Observe Di-Higgs production and access the self-coupling
- Measure rare decays (e.g. $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$)

1

Driven by the problem of Hierachy, the existence of DM, and the limitations of the SM:

- Search for forbidden H decays (e.g. $H \rightarrow \tau\mu$, $H \rightarrow$ Invisible)
- Search for an extended scalar sector
- Search for supersymmetric or exotic matter
- Search for new resonances at the TeV
- … and be prepared for unexpected surprises [e.g. the 750 GeV ?]

2

The High Luminosity Physics Program is necessary for (1) and the SM

The Future of HEP will be largely determined by (2) with most essential answers already available by 2017-2018

Higgs Self-Coupling

- The shape of the scalar potential depends on self-couplings, at the origin of the spontaneous EWK symmetry breaking:

$$V = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 \qquad V \rightarrow \frac{-M_h^2}{2} h^2 + \lambda_3 h^3 + \lambda_4 h^4$$

- The trilinear (λ_3) and quartic (λ_4) couplings are subject to perturbative evolution
- Given the mass m_H , λ_3 and λ_4 at EWK scale are a prediction of the theory:

$$\lambda_3 = \frac{M_h^2}{2v} \sim 0.13v \qquad \lambda_4 = \frac{M_h^2}{8v^2} \sim 0.03$$

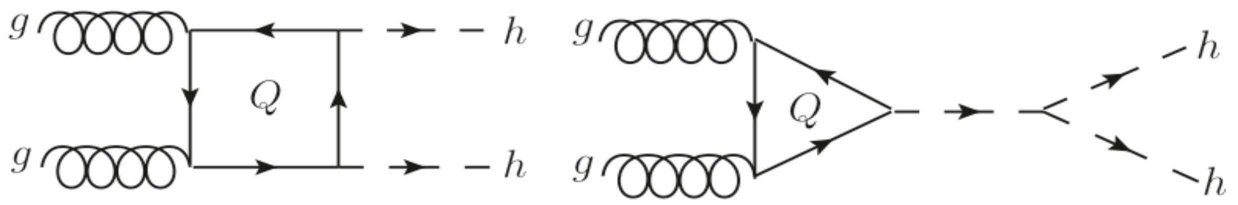
- HH production could ultimately allow to test an important prediction (given m_H) of the theory: the shape of the scalar potential

Q? Can we measure at least λ_3 at the LHC or HL-LHC ?

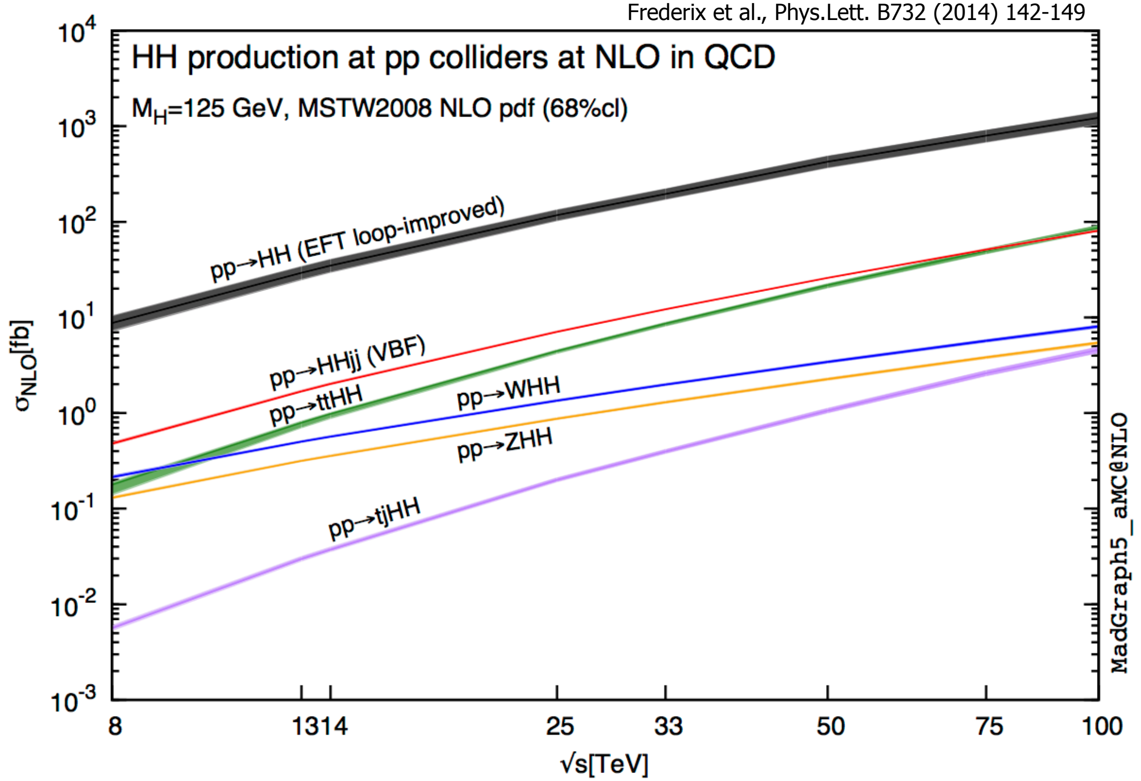
Q? Is there an interest in HH production beyond SM Self-coupling ?

Di-Higgs production at the LHC (1)

- A **strong cancellation** near threshold between the two main production modes via ttH coupling (box diagram) and λ (self-coupling) severely limit the sensitivity



Frederix et al., Phys.Lett. B732 (2014) 142-149



<u>At 13 TeV</u>

Total $\sigma^{NLO}_{prod.}$ = 31.8 ± 4.5 fb

gg → HH = 29.3 ± 4.4 fb
VBF → HH = 1.68 ± 0.02 fb
ttHH = 0.79 ± 0.04 fb

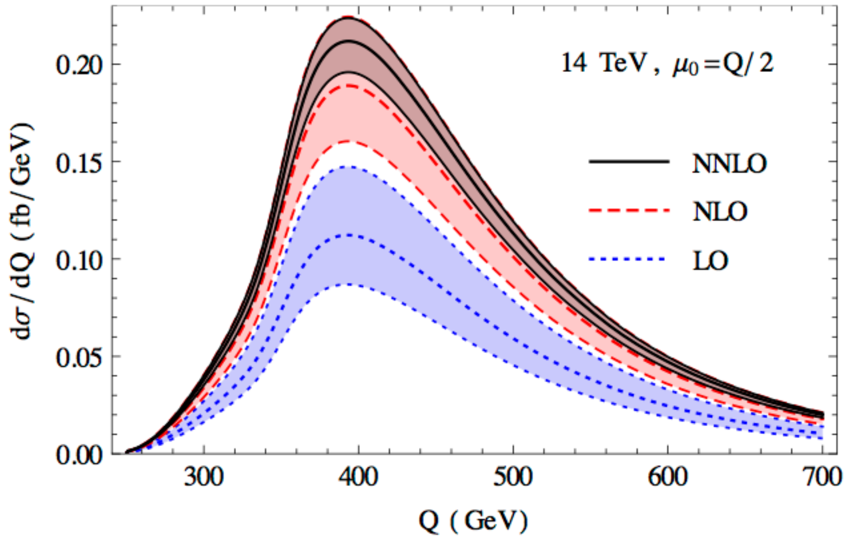
Origin of the ± 15% uncertainty on gg → HH
~ 5 % for the scale
~ 3 % PDF and α_S
~10 % $m_{top} \to \infty$

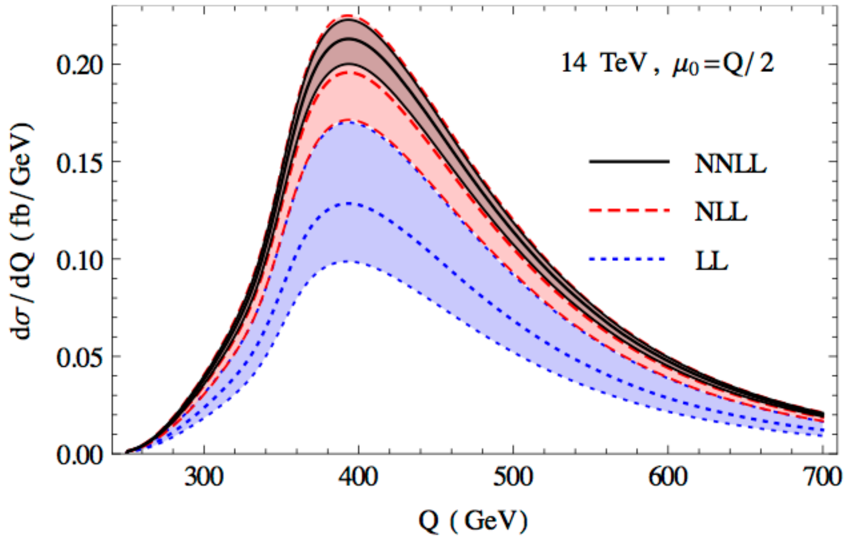
The total production cross-section is small !

Di-Higgs production at the LHC (2)

- Factor two gain on gg → HH production 14 TeV at highest orders !

DeFlorian, Mazzitelli, JHEP 1509 (2015) 053





44.5 ± 2.3 fb at NNLO + NNLL μ_0 = Q/2

43.7 ± 2.4 fb at NNLO + NNLL μ_0 = Q

40.9 ± 3.5 fb at NNLO μ_0 = Q

34.8 ± 4.4 fb at NLO

22.8 ± 6.3 fb at LO

The total production cross-section is small and the theoretical precision is already sufficient for our needs at the LHC !

Di-Higgs production : Decay Channels

Measuring HH given the expected small production cross section is very challenging at HL-LHC

channel ($l = e + \mu$)	BR [%]
$bb\,\tau\tau$	7.3
$bb\,\gamma\gamma$	0.26
$bb\,WW \to bb\,jj\,l\nu$	7.3
$bb\,WW \to bb\,l\nu\,l\nu$	1.2
$bb\,ZZ \to bb\,ll\,ll$	0.014
$bb\,ZZ \to bb\,jj\,ll$	0.29
$bb\,ZZ \to bb\,jj\,jj$	1.5
$ZZ\,\tau\tau \to ll\,ll\,\tau\tau$	0.001
$ZZ\,\tau\tau \to ll\,jj\,\tau\tau$	0.02
$ZZ\,\tau\tau \to jj\,jj\,\tau\tau$	0.1
$\gamma\gamma\,\tau\tau$	0.029
$WW\,\tau\tau$	2.7

Most promising channels
(compromise between BR and S/B)

- Excellent τ_h reconstruction and τ_h / jet separation needed
- Requires a multivariate approach

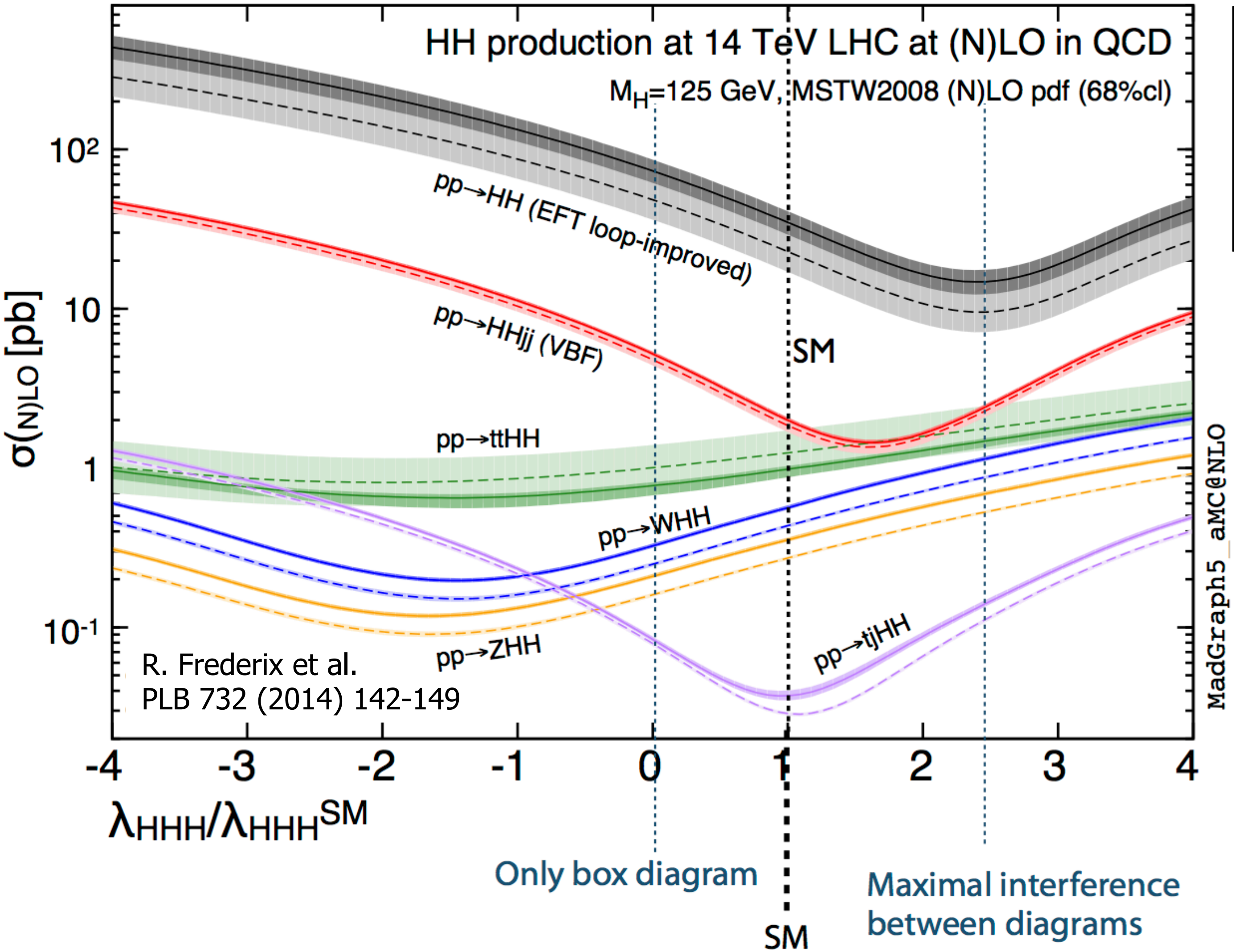
- Simple reconstruction … but very low branching ratio
- Large background rates

A « handful » of measurable events expected for the full Run III with 100 fb-1 (end of 2018), and having ttH and λ_3 contributions entangled !

~ 4000 x 0.073 x 0.6 x $\varepsilon_{accept.}$ = 175 x $\varepsilon_{accept.}(\tau_h\tau_h)$ events for $bb\tau_h\tau_h$

~ 4000 x 0.0026 x $\varepsilon_{accept.}$ = 10.4 x $\varepsilon_{accept.}(\gamma\gamma)$ events for $bb\gamma\gamma$

Di-Higgs production Enhancement Beyond SM



$\lambda_{HHH}/\lambda_{HHH}^{SM}$	σ/σ^{SM}
-4	12
0	2.2
1	1
2.45	0.42
20	105

Significant enhancement possible with respect to the Standard Model from non-standard self-coupling !!!

The Self-Coupling and the Top Quark

- Allowing λ_3 to vary alone is not sufficient ! It is strongly correlated with contributions involving the top quarks (via quantum fluctuations)

e.g. Simple EFT Lagrangian:

$$L \sim L_{SM} + \frac{\alpha_S}{12\pi}\left(c_g \frac{h}{v} + \frac{c_{gg}}{2}\frac{h^2}{v^2}\right) G^{\mu\nu,A} G^A_{\mu\nu} - \delta y_t \frac{m_t}{v} t\bar{t}h + \frac{c_{2h}}{v} t\bar{t}h^2$$

$$-\delta y_3 \frac{M_h^2}{2v} h^3$$

<u>Relevant parameters:</u>

In non-linear EFT: $c_g, c_{gg}, \partial y_t, c_{2h}, \delta\lambda_3$

In linearized EFT*: $c_{gg}, \partial y_t, \delta\lambda_3$ $\quad c_g = c_{gg}, c_{2h} = (3m_t / 2v)\partial y_t$

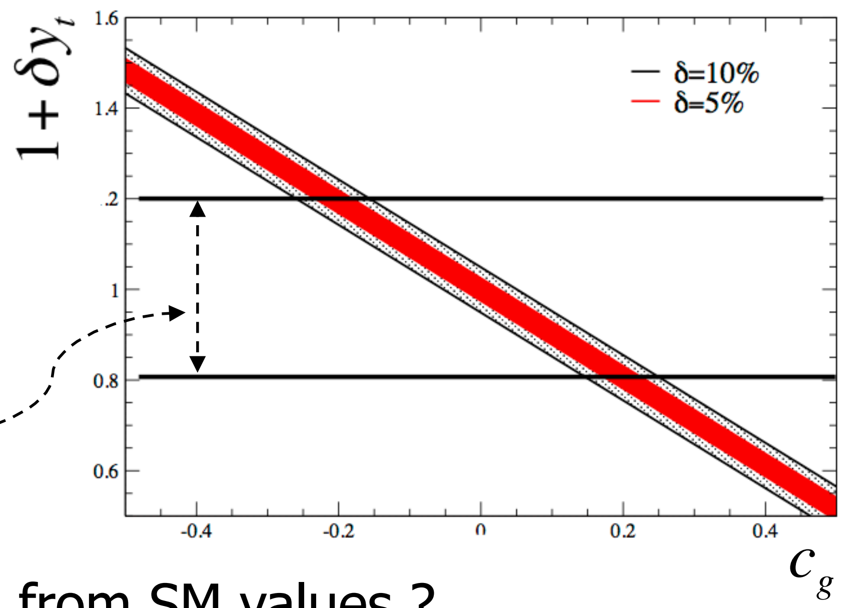
In general, a minimal parameter space involves: the H coupling to gluons, the top Yukawa coupling, and the H self-coupling

*Assuming a doublet of Higgs fields

Constraints on the HH production Parameter Space

- Single Higgs boson production found close to SM expectation

$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{SM}} \sim |cg + \delta y_t|^2$$



20% precision measurement of δy_t

How large are the allowed deviations from SM values ?

Singlet model: $\delta\lambda_3 \sim \pm\left(\frac{v}{M_{H_S}}\right)^2 \sim 0.06\left(\frac{1\times TeV}{M_{H_S}}\right)^2$

Top partner model: $c_g = c_{gg} \sim \left(\frac{\alpha_S \sin^2\theta_t}{12\pi}\right) \sim 0.003\times\sin^2\theta_t$

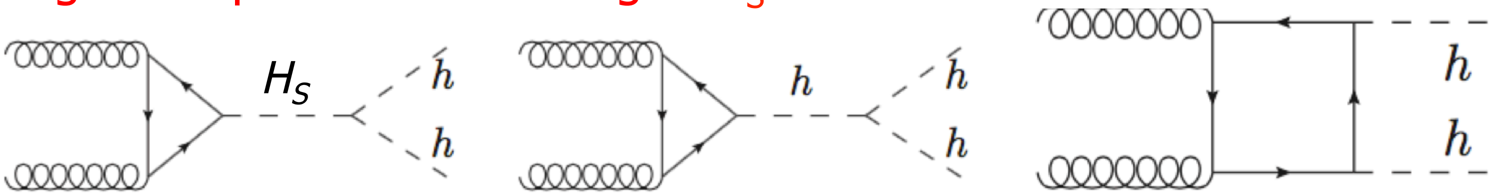
Color Scalar Triplet: $c_g = c_{gg} \sim -\left(\frac{\alpha_S\kappa}{96\pi}\right)\left(\frac{v}{m_s}\right)^2 \sim 2\times10^{-5}\times k\left(\frac{1\times TeV}{m_s}\right)^2$

The allowed deviations to non-resonant HH production appear below the expected experimental sensitivity

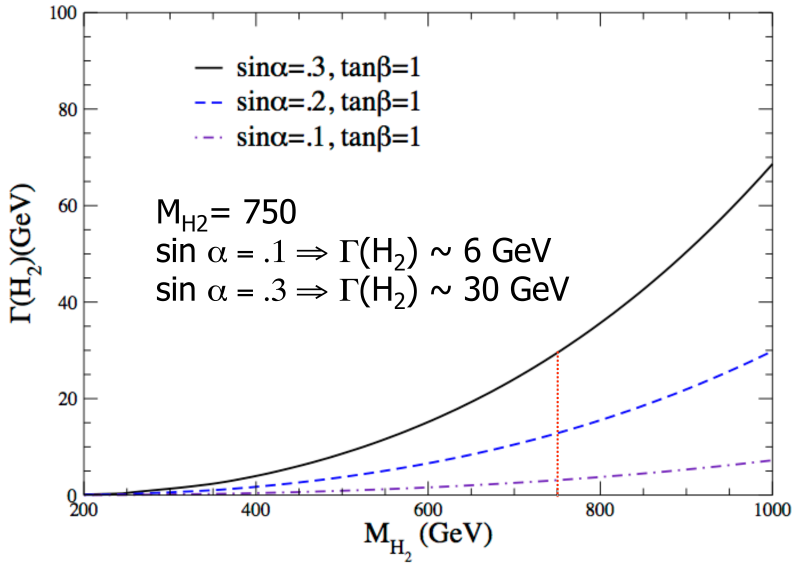
Enhancement via Extended Scalar Sector

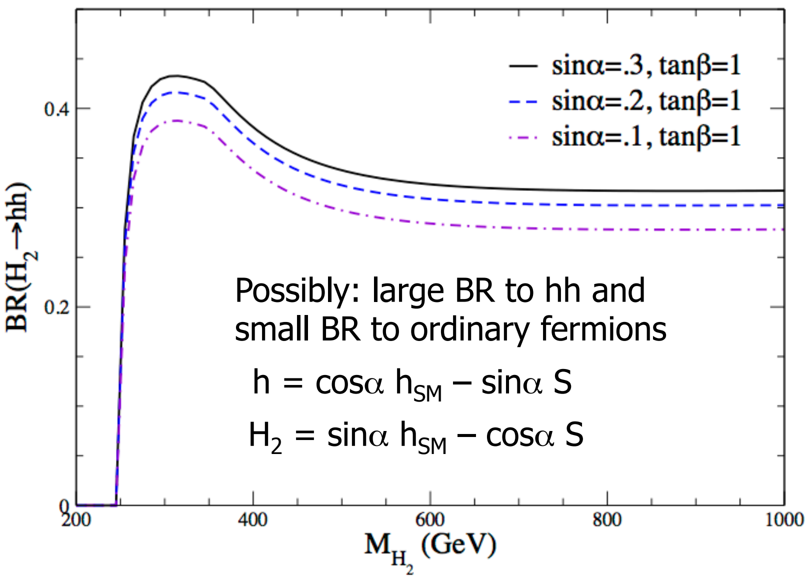
- The h (and hh) production (and decay) rates can be affected by the existence of additional scalar bosons via interference effects and/or new resonances

e.g. Example of a scalar singlet H_S



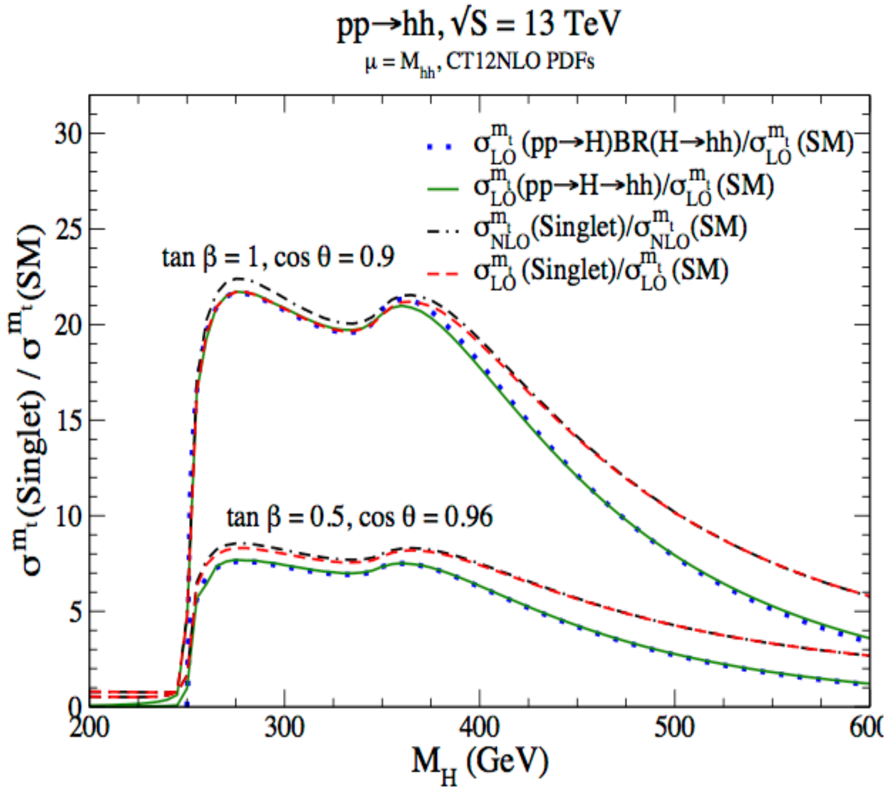
After EWSB, the singlet mixes with the SM Higgs boson
(this could be e.g. a portal to Dark Matter)

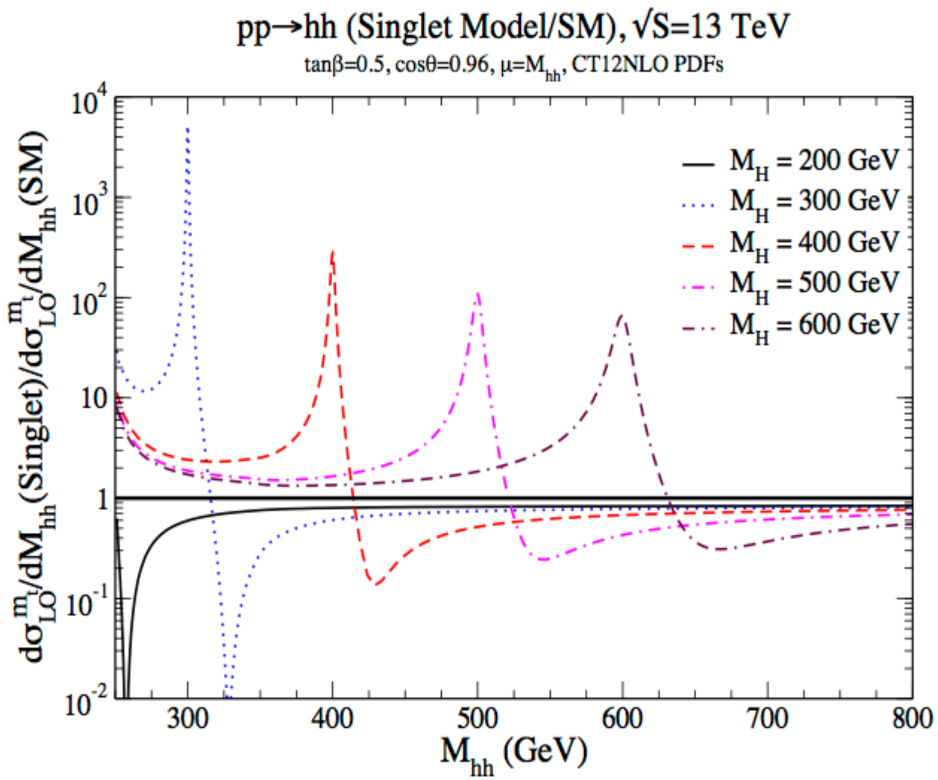




5 Physical parameters: M_h, M_{H2}, α, v, $\tan\beta$ = v/<S>

Enhancement From a New Scalar Resonance





- Enhancement of the hh production cross section up to a factor x 20 possible for M_H below ~ 400 GeV (maximal at ~2 x M_h or 2 x M_{top})
- Large interference effects with the SM hh affecting the observed $d\sigma/dM_{hh}$ resonance
- Similar effects possible in MSSM (2HDM) and NMSSM models

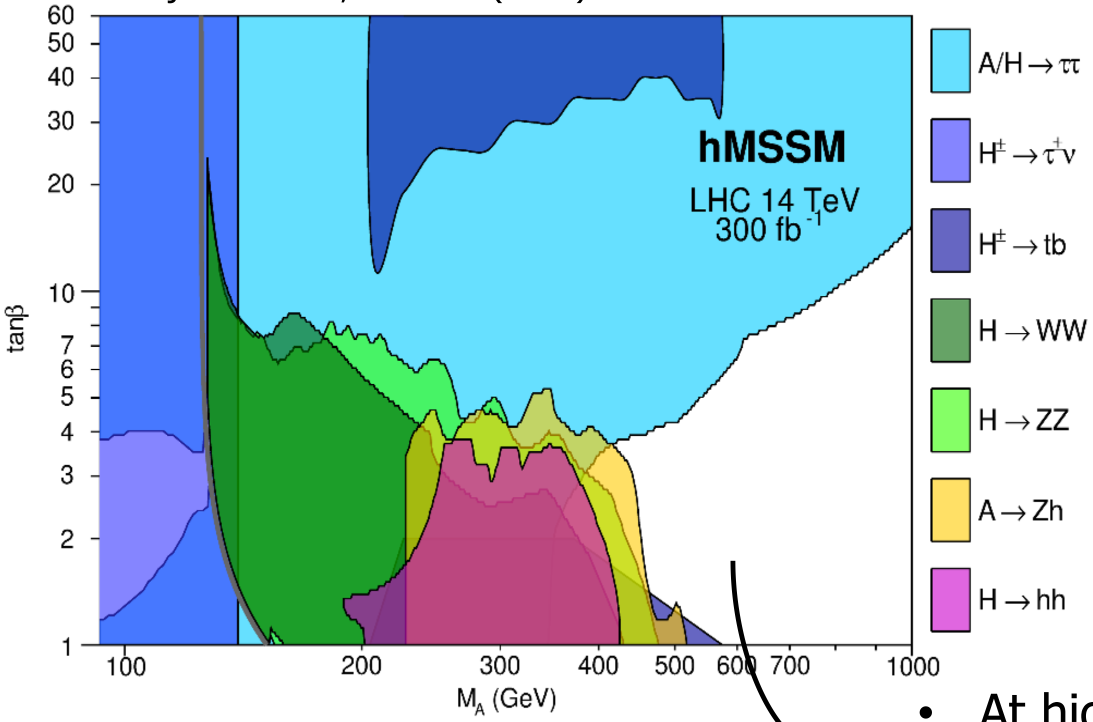
S. Dawson, I.M. Lewis, Phys. Rev. D92 (2015) 9,094023

Covering the MSSM Scalar Sector at the LHC

- Constraints on the MSSM phase space from the precision measurements of the H125 boson
- Direct searches for additional Higgs bosons in the MSSM (or other types of 2HDM), i.e. neutral (ϕ = h,H,A) or charged ($H^{\pm}$) bosons

Covering the scalar sector:

A. Djouadi et al., JHEP 06 (2015) 168

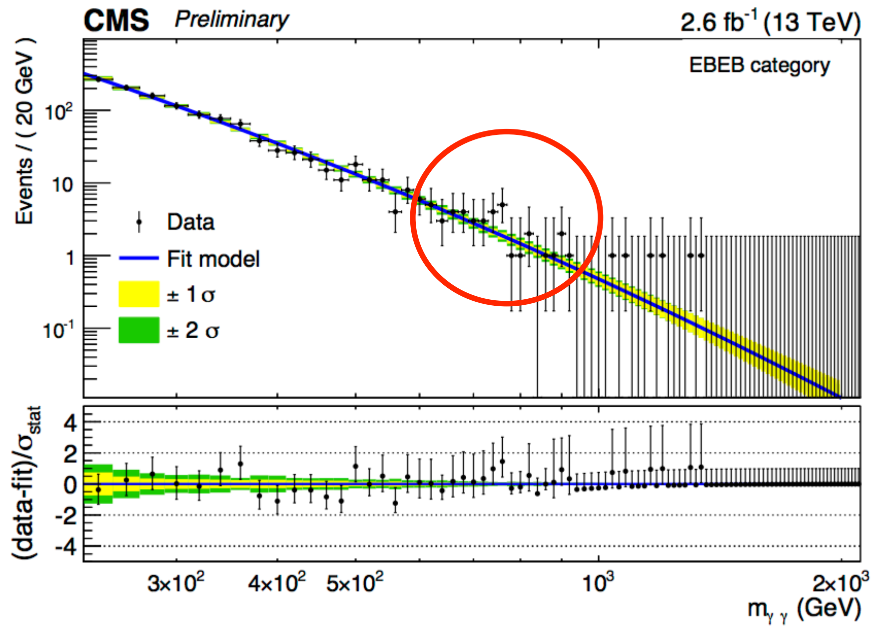


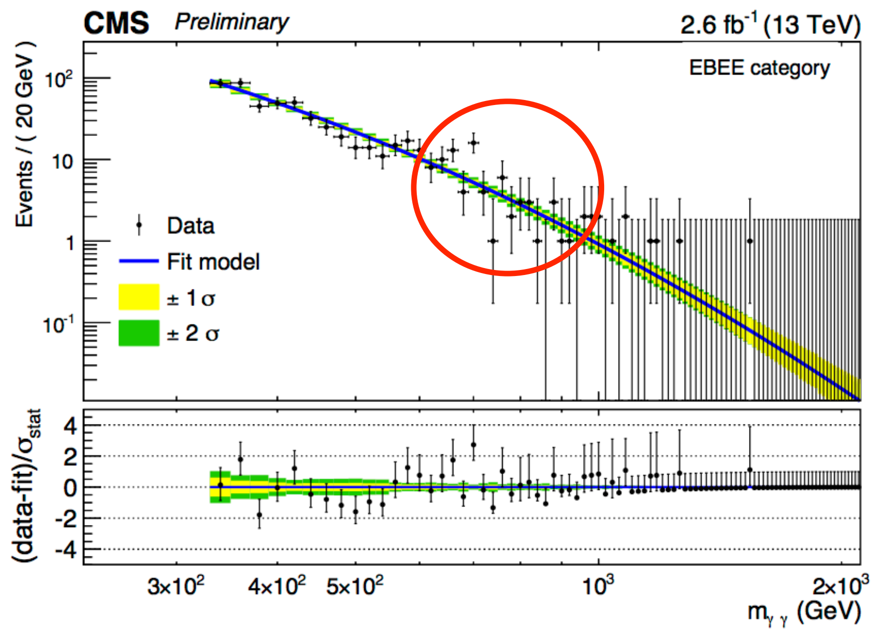
tan β – M_A plane:

- At large tan β
  - large coverage via $\phi \to \tau\tau$
  - coverage via $H^{\pm} \to \tau\nu$
- Towards low MA and at intermediate tan β, some coverage from heavy H → ZZ, WW
- Coverage at low tan β and high M_A from H → hh and A → Zh
- At high M_A and intermediate tan β, H/A → $\chi_i^0 \chi_j^0 \chi_i^+ \chi_j^-$ and H± → $\chi_i^+ \chi_j^0$

CMS – Di-photon Spectrum

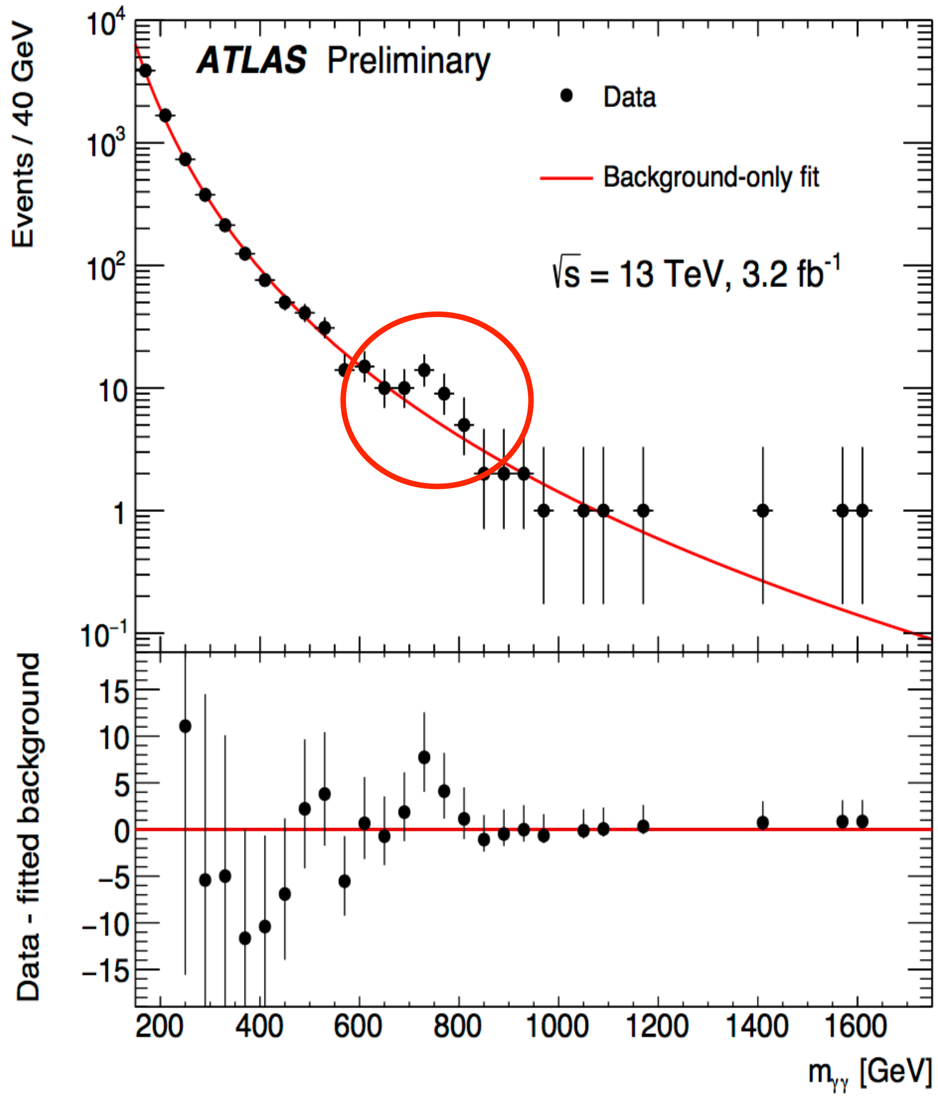
- CMS search motivated by
  Randall-Sundrum gravitons
  coupling: 0.01 (narrow), 0.1, or 0.2 (wide)
- Two categories:
  barrel-barrel (EBEB)
  barrel-endcap (EBEE)
- Simple cuts
  $p_T^{\gamma} > 75$ GeV, γ ID and Isolation
- Efficiency, scale, and resolution well calibrated using $Z \rightarrow ee$ and Drell-Yan events
- Excess in the 600-900 GeV mass range in each category
- Most visible around 750 GeV in category with higher stat. and best expected mass resolution !



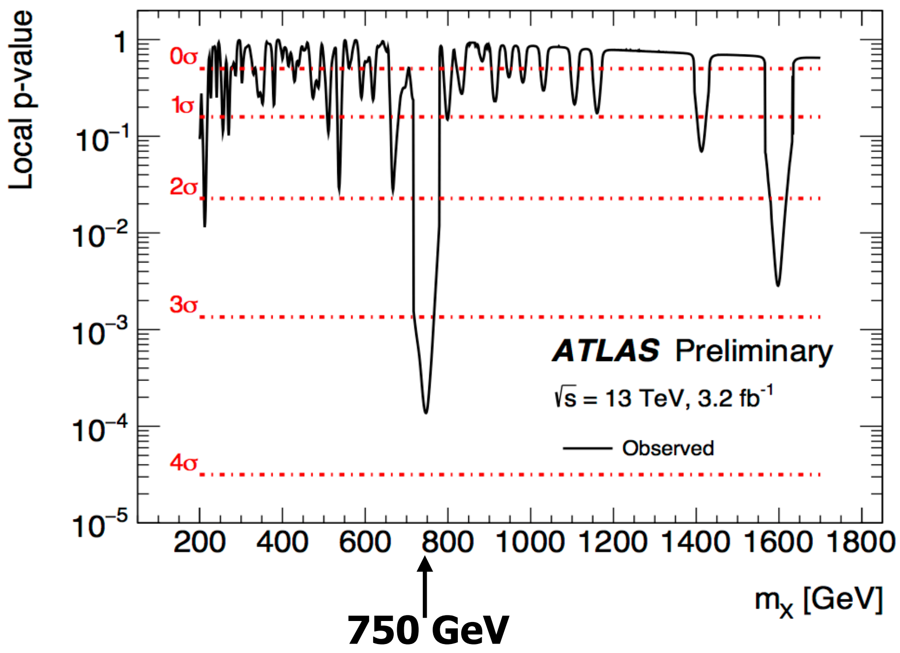


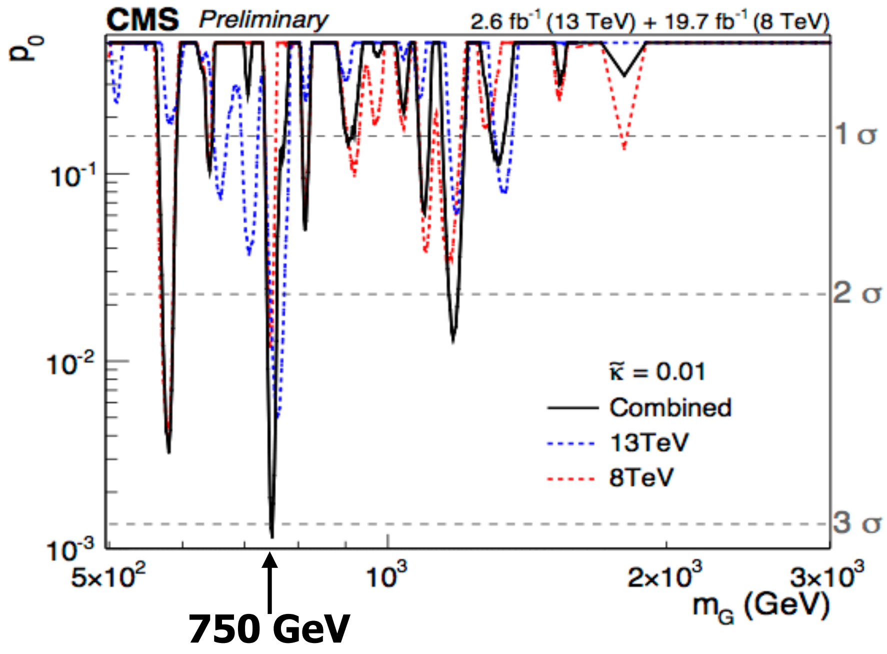
ATLAS – Di-photon Spectrum

- ATLAS search motivated by extended scalar sector
  Intrinsic width taken as as a parameter
- Two categories:
  barrel-barrel (EBEB)
  barrel-endcap (EBEE)
- $E_T^{\gamma 1} / m_{\gamma\gamma} > 0.4$, $E_T^{\gamma 2} / m_{\gamma\gamma} > 0.3$, γ ID and Isolation
- Efficiency, scale, and resolution well calibrated using $Z \rightarrow ee$
- Excess visible around 750 GeV !



Significance of the 750 GeV Di-photon Excess





ATLAS largest excess at 750 GeV

Local significance: **3.6 σ**
Global significance*: 2.0 σ

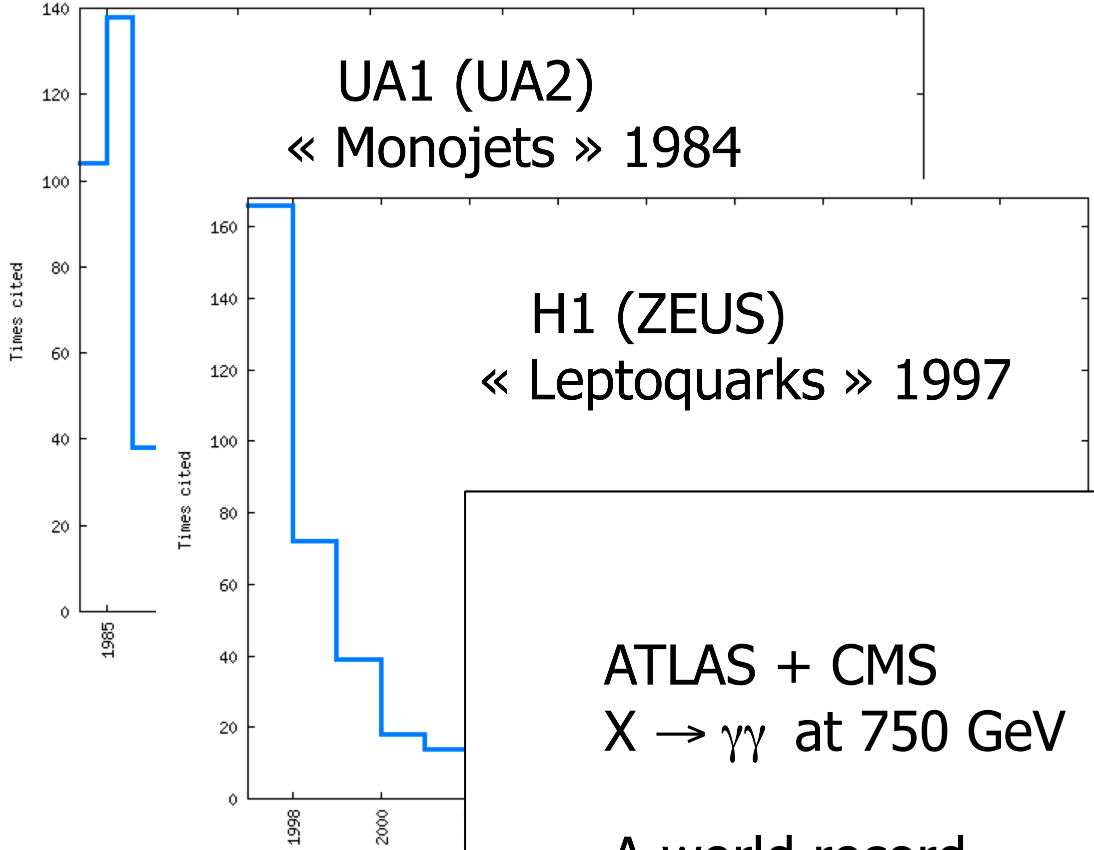
CMS largest excess at 750 GeV

Local significance: **3.2 σ**
Global significance*: 1.6 σ

Combined significance ~ 3.5 σ

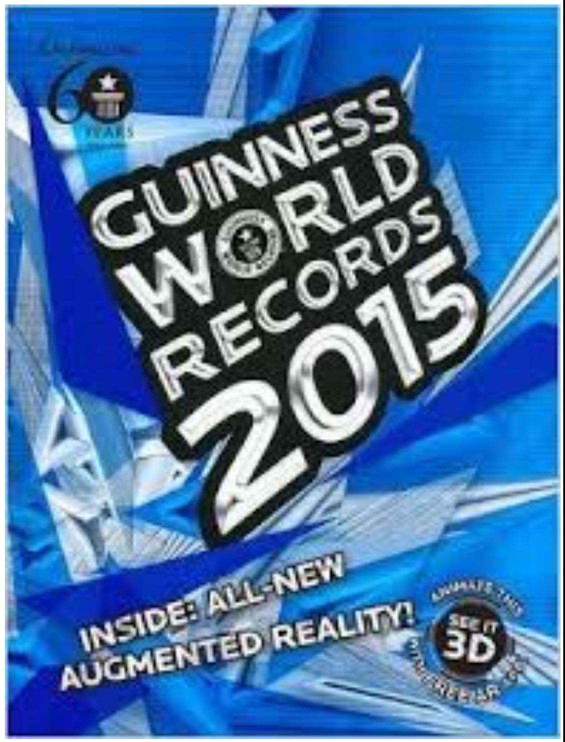
(result with 2D LEE effect close to those obtained via naïve method of picking the mass from one experiment and the significance from the other)

*LEE Effects: E. Gross and O. Vitells, EPJ C70 (2010) 525
2D LEE : A. Read, LEE Stusy, Spåtind, Oslo (2016)



ATLAS + CMS
$X \rightarrow \gamma\gamma$ at 750 GeV

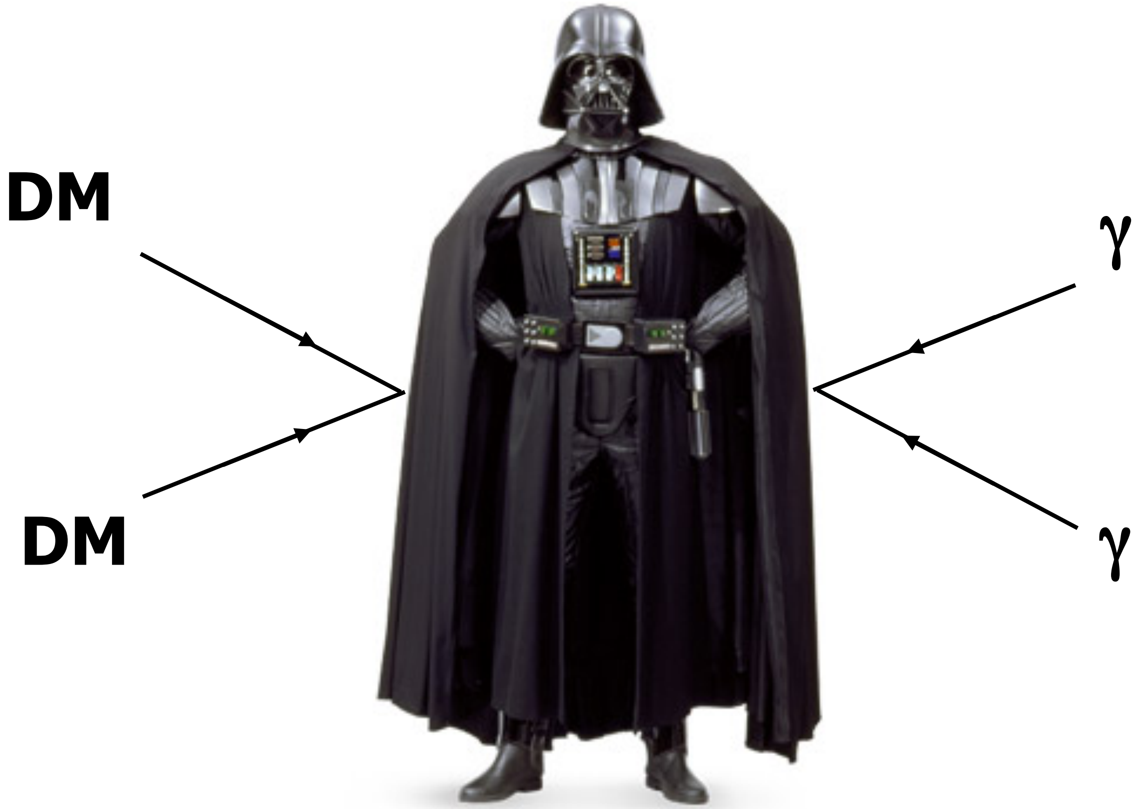
A world record
for a 3σ "excess"
with ~ 100 citations
in 2 weeks !



Interpretation of the 750 GeV Di-photon Excess

More then 150 theory papers so far and 5 main explanations with variants

Simplest explanations: a "statistical fluctuation" OR the **Dark Vador** Boson



Dark Vador Boson

A new « force » (singlet scalar boson ?) connecting
the visible universe to the dark universe

Loop coupling to gluons for production at LHC; decays in DM or photon pairs

Interpretation of the 750 GeV Di-photon Excess

More then 150 theory papers so far and 5 main explanations with variants

A statistical fluctuation ?

Mediator of the Dark Matter / Singlet Scalar ?

Composite state of some new strong dynamics ?
One family walking technipion ?

Massive pseudo-scalar (e.g. 2HDM) from non-minimal SUSY
with new coloured vector like fermions ?

Massive singlet pseudo-golstone boson (e.g. heavy QCD-like axion)
with new coloured vector like fermions ?

Cascade from a higher mass messenger ?

A Higgs-radion of the five-dimensional Randall-Sundrum model ?

… and many more

No need to worry or speculate as experimentalists … this is one of the cleanest and simplest possible analysis .. we just need more data !

CONCLUSIONS

- The discovery of the Higgs boson opens a new chapter in HEP physics
- The Higgs boson appeared somewhat unavoidable, but the discovery at a mass of 125 GeV leaves the Universe unstable and improbable
- The relatively large mass of the SM-Like Higgs boson imposes severe constraints on the new physics needed to stabilize the weak scale

  e.g. Supersymmetry with a light stop and heavy gluinos

- The problem of Hierarchy and the need to explain Dark Matter remain among the best motivations for extension of the scalar sector and new physics at the TeV scale …
- Irrespective of the direct observation of new physics at the TeV scale, there is a rich program at the LHC / LH-LHC

  e.g. Precision Hi boson measurements, rare H decays, HH Production, **Self-couplings …**

- The Run II and III up to 2018 (100 fb^{-1}) will be decisive for the future, with all ingredients on the table for major decisions on future colliders
- We explore new territories and must be ready for surprises