Upgrades & The Future of CMS

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LHC Days in Split 2014
Croatia

Thanks!

To the organizers ! For the very many great talks !

Previous CMS talks at this conference:

G. Landsberg	Status of CMS (Key Physics Results & Preparation for Run 2)
P. Sphicas	What we have learned from the LHC (Broad physics overview)

J.B. Sauvan	Higgs properties
S. Nikitenko	BSM Higgs
F. Pandolfi	Higgs specific channels
M. Nguyen	Heavy Ions
G. Bruno	SUSY and BSM
R. Bartek	Heavy and Excited Quarks
C. Collard	BSM/SUSY prospects

M. Kazana	Long-lived particles
E. Gallo	EWK Physics
J. C. Maestro	Top Physics
O. Kolodova	QCD Physics
C. Grab	B Physics in CMS

D. d'Enterria	LHC vs Particle Astrophysics

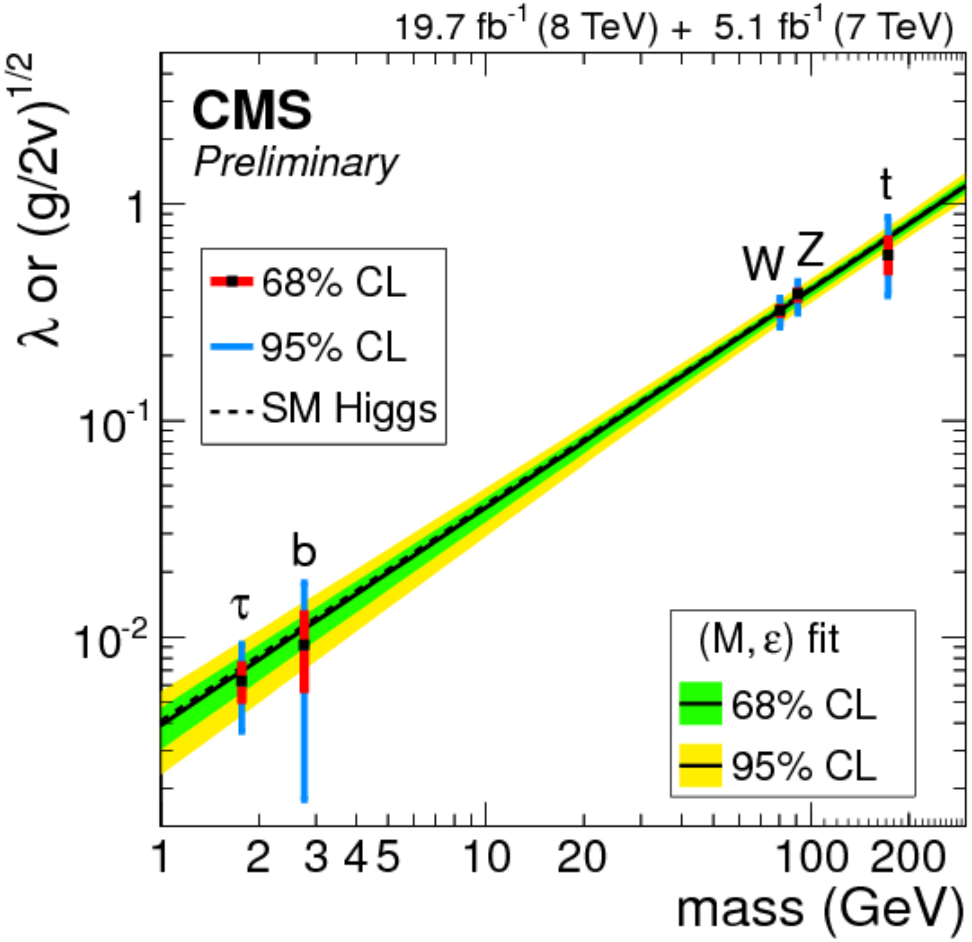
- **The LHC/HL-LHC is on the critical path of every conceivable future*** for High Energy Physics**
- **This talk is about why I find this appropriate and exciting (!) and how we prepare to live for the next 15 years in CMS**

*** FCC's: Futur Circular Collider, Futur Colinear Collider,
Futur CERN Collider, Futur China Collider,
Futur Chicago Collider, etc.

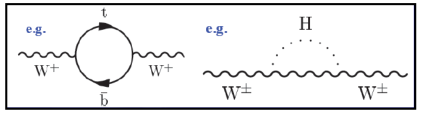
The Higgs Boson Discovery
&
Aftermaths

The Landscape (1)

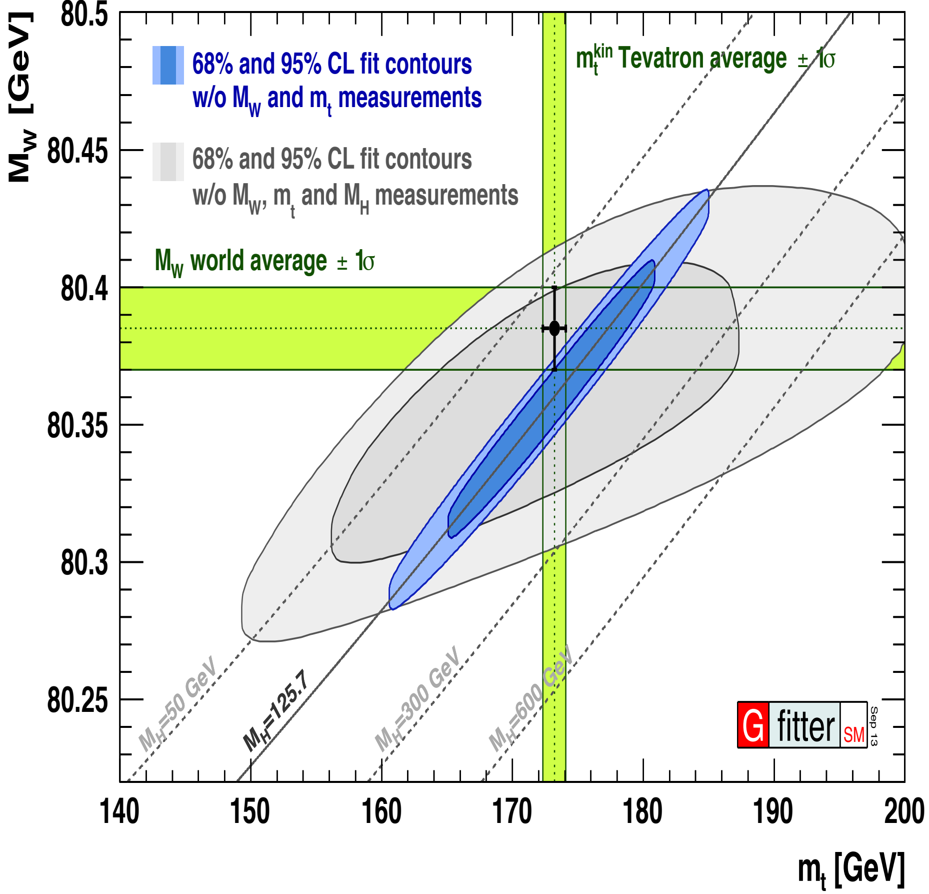
Couplings to fermions and to weak bosons
(verified to ~10-30% precision)



Rad. corrections:



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): $M_W = 80.359 \pm 0.011$
Direct (World average): $M_W = 80.385 \pm 0.015$

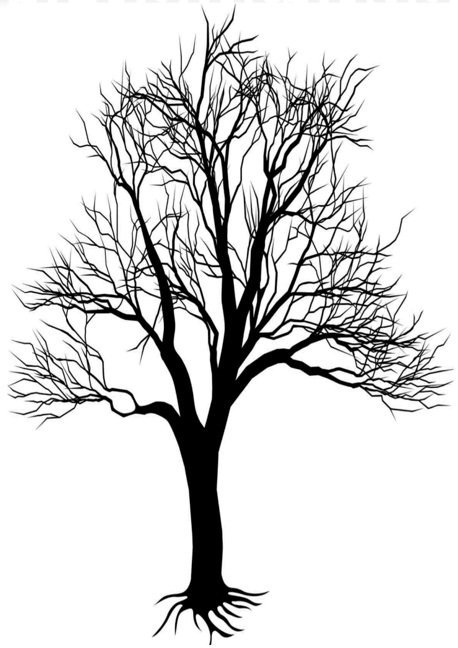
The H Boson discovery is now firmly established

- ✓ M_H ~ 125 GeV
- ✓ Couplings to fermions and to weak bosons (verified to ~10-30% precision) consistent with the minimal scalar sector required for the BEH mechanism
- ✓ Custodial symmetry verified (~ 15% precision) and the existence of a boson with non-universal family couplings established ($\tau\tau$ evidence + no $\mu\mu$ signal)

A truly astonishing achievement !

- Culmination of a reductionism strategy evolving 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 **origin of mass** (i.e. scalar field, BEH mechanism) for particles in a quantum field theory with local (i.e. point like) gauge interactions
- 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 Elegance of the Conceptual Unification



The 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)

Existence of identical fermions + marriage of relativity and QM

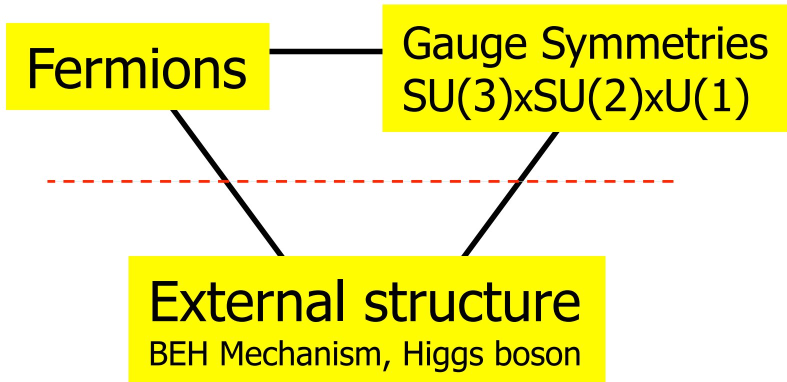
⇒ The "underlying reality" is made of quantum fields

⇒ There are interactions (gauge bosons) as a consequence of gauge symmetries

⇒ All "particles" must be massless.

⇒ All ordinary particles must have spin 0, ½, 1

⇒ There must exist additional ("external") structure to explain the origin of mass, i.e. to preserve gauge symmetries at the fundamental level, and to provide unitarisation of the theory at all scales.

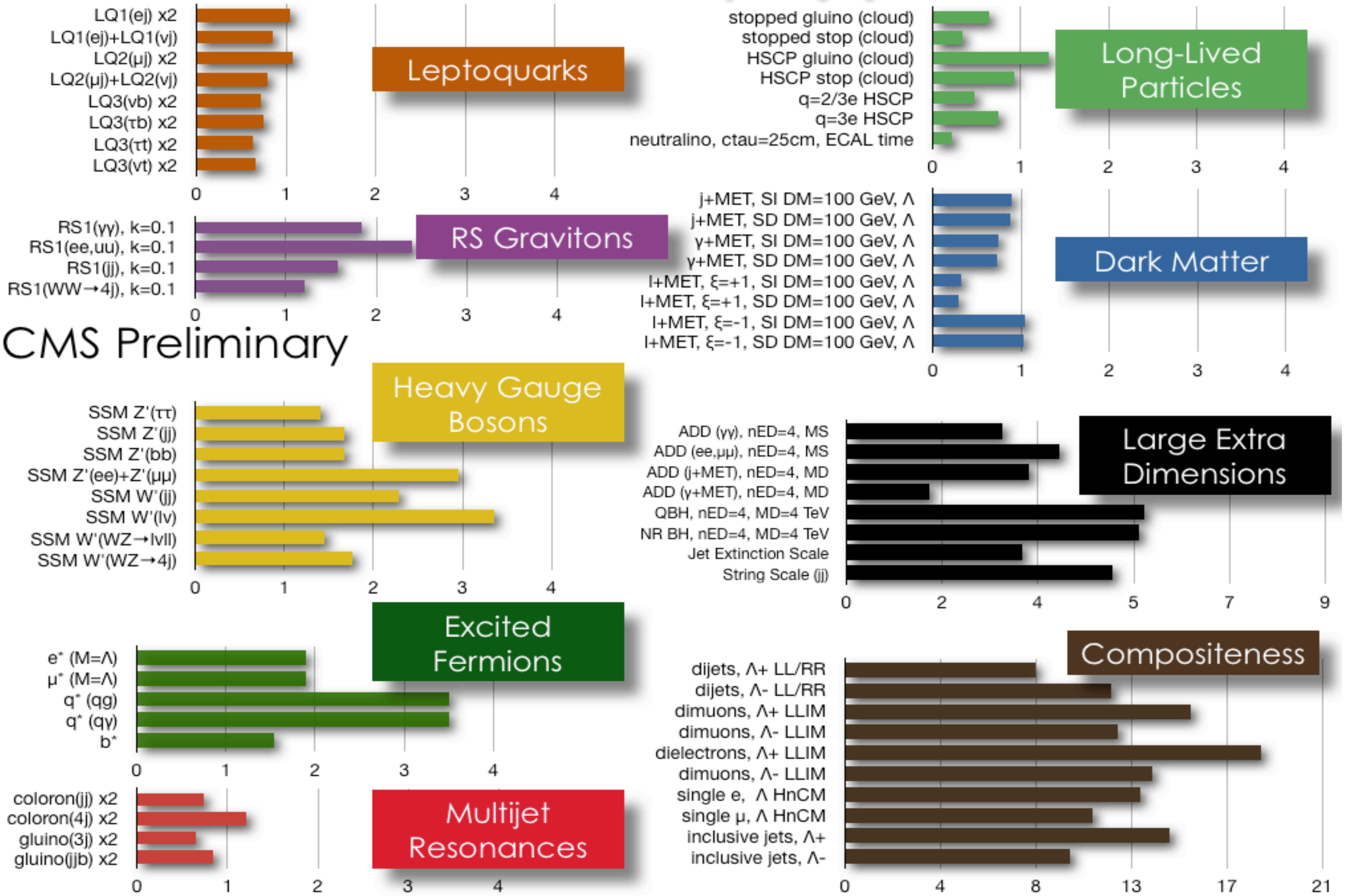


Notes:

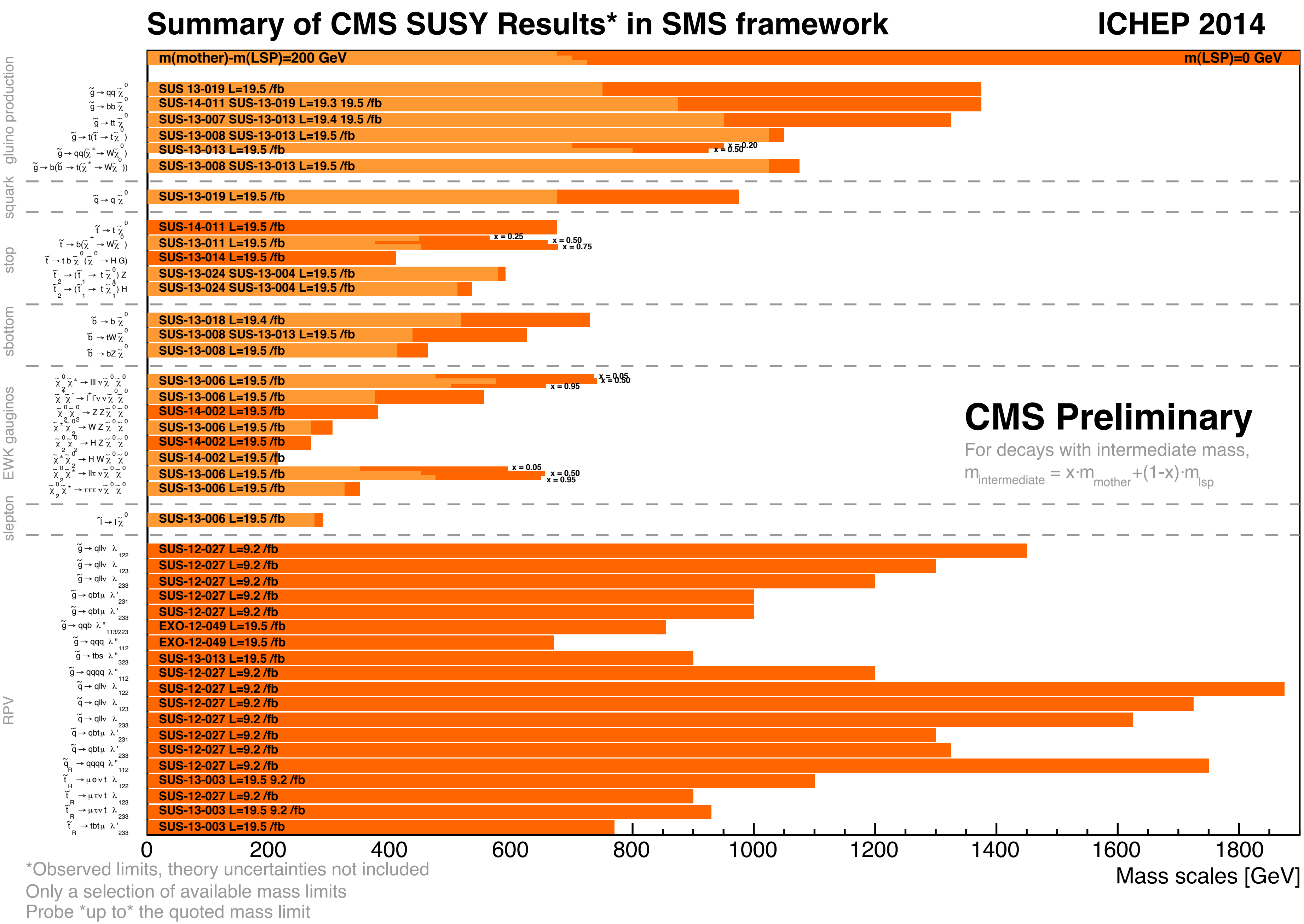
Particles with spin 2 (graviton) appear in relation to quantum fluctuations of space-time

Particles of spin 3/2 (gravitino) appear if adding new quantum dimensions (supersymmetry)

The Landscape (2)



The Landscape (3)



The Higgs boson and nothing else so far ...

« I told you … »

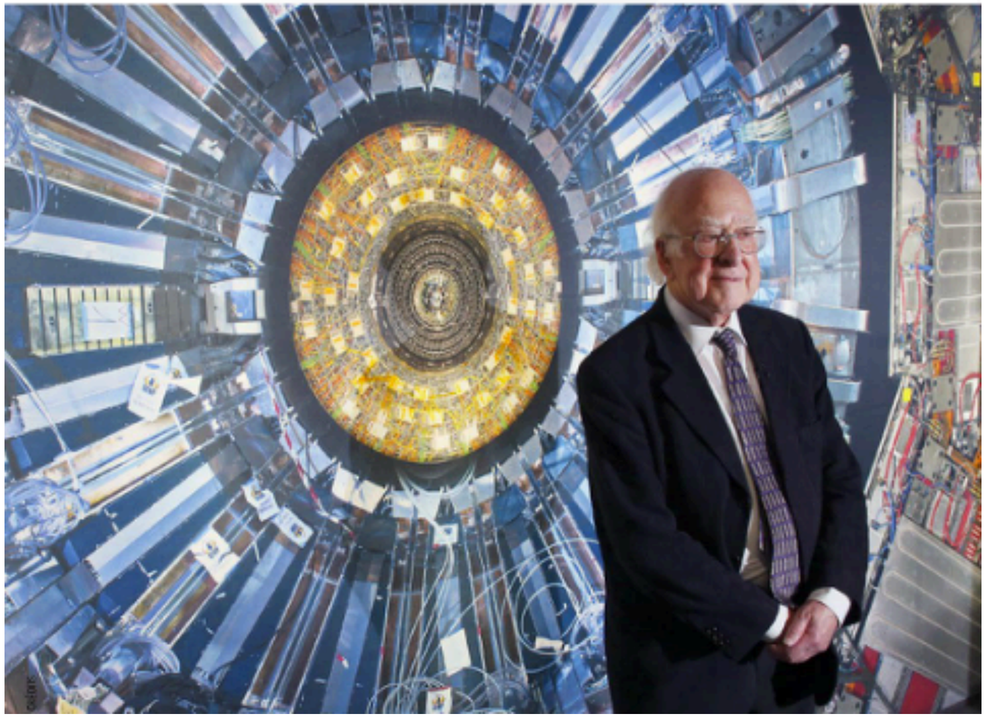
LA Recherche

Février 2914

PETER HIGGS :

« Imaginer que ma théorie était fausse semblait difficile »

Le Prix Nobel de physique 2013 revient sur cinquante ans d'histoire de la physique des particules : de ses travaux théoriques à la découverte du boson de Higgs en passant par la construction du « modèle standard ».



« The End of Particle Physics …"

SCIENTIFIC AMERICAN™

Oct 8, 2013 | By Harry Cliff

Could the Higgs Nobel Be the End of Particle Physics?

Many physicists had hoped that the Large Hadron Collider would also yield a sign of new directions for physics to take, not just a new particle, but that has yet to occur

Oct 8, 2013 | By Harry Cliff and The Conversation

Editor's note: The following essay is reprinted with permission from The Conversation, an online publication covering the latest research.

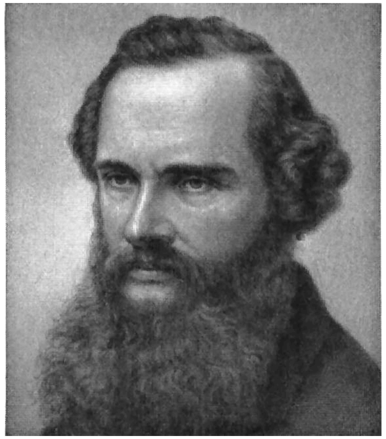
By Harry Cliff, *University of Cambridge*

The 2013 Nobel Prize in Physics has been awarded to François Englert and Peter Higgs for their work that explains why subatomic particles have mass. They predicted the existence of the Higgs boson, a fundamental particle, which was confirmed last year by experiments conducted at CERN's Large Hadron Collider.

Claudia Marcelloni/CERN

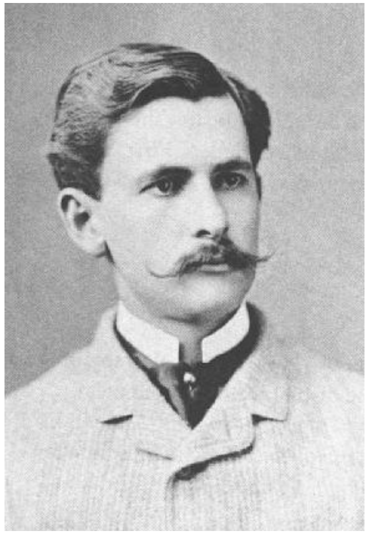
STEPHEN HAWKING SIGNALS THE END OF MODERN PHYSICS

An Historical Precedent ...



"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"

Lord Kelvin 1900



"The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote ..."

Albert Michelson 1903

And then there was

Relativity, Quantum Mechanics, anti-matter, cosmic microwave background, ...

No "Exotic" Discovery at the TeV Scale

- A considerable amount of "exotic" models have been tested at the LHC up to the ~ TeV range
- Only very few of the models tested so far really address more than one of many problems of the 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 …)

Origin of the specific gauge symmetry / set of conserved charges
(cancelation of triangle anomalies, gauge unification ? etc.)

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

- The rise of $\sqrt{s}$ in coming runs at LHC gives access to new territory for the search of the unexpected … but the main excitement is provided by the Higgs boson discovery which opens up new possibilities
- The scalar sector may be the essential key to understand the universe !

The Scalar Sector & The Malicious Higgs Boson (1)

- The Higgs boson is not a gauge boson
  (its mass is not protected by symmetries of the theory)
- Scalar fields "qualitatively" changes the nature of the vacuum

Cosmological problem:
quantum fluctuations at Planck scale involves Planckian energies $\Rightarrow$ space-time gets distorted !
$\rightarrow$ contributes to a vacuum energy density in disagreement with our universe by 10^{120} orders
$\rightarrow$ the principle of locality (a pillar of quantum field theory) breaks down at the Planck scale !
Hierarchy problem:
fine tuning by 10^{30} orders to cancel the scalar field coupling to quantum fluctuations of space-time at the Planck scale

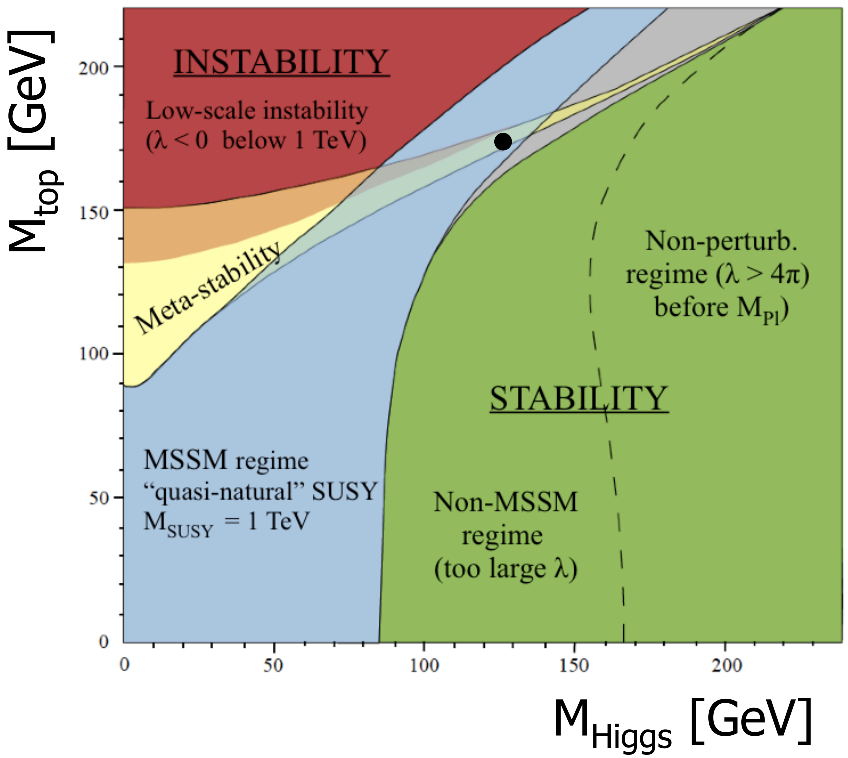
- Scalar fields play a vital role in cosmology: inflation and reheating
- The complexity of the Standard Model is encoded a scalar sector

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

Natural
verified with high precision; stable with respect to quantum corrections; highly symmetric
(gauge and flavour symmetries)

Ad hoc
but necessary (other mass terms forbidden by EWK gauge symmetries); unstable with respect to quantum corrections; at the origin of flavour structure and all other problems of the SM

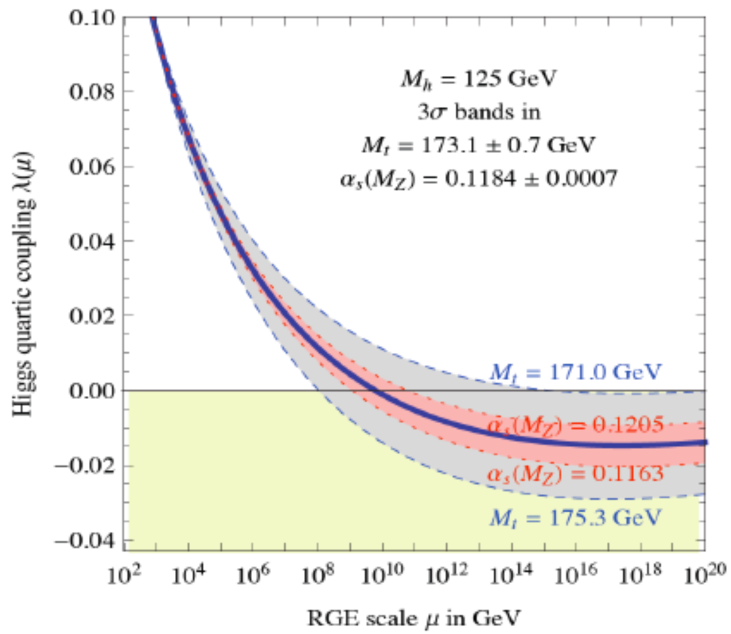
The Scalar Sector & The Malicious Higgs Boson (2)

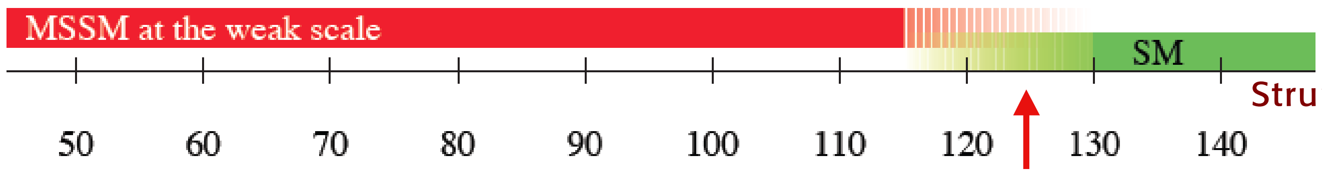


G. Isodori et al.

We live in a very particular corner of parameter space !

Assuming SM up to Planck scale, the fate of the Universe depends on the precise values of M_{top} and M_{Higgs} !





Strumia

The Higgs boson mass at ~ 125 GeV is very special !!! Extrapolation to very large scales seems possible but no indication provided for the scale for SUSY breaking

New questions raised following H boson discovery (1)

"From Particles to the Cosmos"

- Can we avoid the arbitrariness of the scalar sector ?

  Get self-coupling from gauge couplings ? Obtain a more constrained scalar sector ?
  It is not just the M_H problem … but also the problem of arbitrary choices driving the BEH mechanism !

By the geometry ?

Could the Higgs boson emerge from the underlying (quantum) geometry of space-time ?
e.g. non-commutative geometry from Alain Connes (failed to predict MH at 125 GeV)

By the gauge sector ?

Can one get self-couplings starting from gauge couplings ?
Obtain a more constrained scalar sector ?
e.g. Supersymmetry (extended scalar sector) ? Composite Higgs ?

Traditional view (MSSM):

Spin 1	Spin 1/2	Spin 0
gluons g photon γ	gluinos $\tilde{g}$ photino $\tilde{\gamma}$	
$W^{\pm}$ Z	winos $\widetilde{W}^{\pm}_{1,2}$ zinos $\tilde{Z}_{1,2}$ higgsino $\tilde{h}^0$	$\left.\begin{matrix} H^{\pm} \\ h \\ H,\ A \end{matrix}\right\}$ bosons B-E-Higgs
	leptons l quarks q	sleptons $\tilde{l}$ squarks $\tilde{q}$

Alternative interpretation:

gluons photon	gluinos $\tilde{g}$ photino $\tilde{\gamma}$	
$W^{\pm}$ Z	winos $\tilde{W}^{\pm}_{1,2}$ zinos $\tilde{Z}_{1,2}$ Higgsino $\tilde{h}_A$	$\left.\begin{matrix} w^{\pm} \\ z \\ s_A, A \end{matrix}\right\}$ BE-Higgs bosons
	leptons l quarks q	sleptons $\tilde{l}$ squarks $\tilde{q}$

Same superfields
Can describe
W±, Z
and H bosons

$$\textit{spin-1}\ Z \ \overset{SUSY}{\longleftrightarrow}\ \overset{SUSY}{\longleftrightarrow}\ \textit{spin-0}\ \textit{BEH boson}$$

$$\textit{spin-1}\ W^{\pm} \ \overset{SUSY}{\longleftrightarrow}\ \overset{SUSY}{\longleftrightarrow}\ \textit{spin-0}\ H^{\pm}$$

The H boson is possibly a Z without spin !

New questions raised following H boson discovery (2)

"From Particles to the Cosmos"

- Is the Higgs boson sufficient for an exact unitarization of the theory ?
  ⇔ need to test $W_L W_L$ scattering at the multi-TeV scale
- Can the scalar sector destabilize the vacuum ?
  ⇔ interest in most precise measurements of M_{top}, M_{Higgs}, …
- Can we avoid the problem of Hierarchy with respect to Planck scale ?
  ⇔ Supersymmetry, … ? Scalar sector linked to inflation and dark energy ?

Cosmology : needs scalar fields bringing a cosmic repulsion (inflation) and re-heating (energy transferred to massive particles and radiation) bringing new gravitational attraction

LHC : Discovers a (unique ?) scalar field … and the H Boson resulting from the BEH mechanism

Could the Higgs field (and BEH mechanism) be a key element of cosmology ?

New questions raised following H boson discovery (3)

"From Particles to the Cosmos"

- Is the scalar sector responsible for baryogenesis ?

  ⬄ need additional structure in "true" vacuum for baryogenesis at EWPT
  e.g. IDM models – extend scalar sector of SM with a "innert" Higgs doublet
  … interferes only with SM Higgs field …

- Could the scalar « Higgs » sector be a portal towards dark matter ?
  ⬄ need to look for invisible decays and/or invisible DM pairs
  recoiling against the H boson;
  ⬄ deviations of SM Higgs couplings from interference with "innert" Higgs bosons

- Is the scalar sector at the origin of fermion families ?
  ⬄ need precise measurements of $H \rightarrow \mu\mu$, $H \rightarrow \tau\tau$

- Is the scalar sector talking to neutrinos ($\nu_L \leftrightarrow \nu_R$) ?
  What about the fermion flavour structure ?
  ⬄ need for more symmetries (extra gauge bosons)

The CMS Upgrades
@
LHC and HL-LHC

LHC/LH-LHC Characteristics

$\sqrt{s_{pp}}$ = 7-8 TeV

Phase 0

2010-2012

$$\int L\,dt \approx 25\,fb^{-1}$$

$\sqrt{s_{pp}}$ = 13-14 TeV

Phase 1

2015-2022

$$\int L\,dt = 300\,fb^{-1}$$

(LS1 + LS2 ≡ consolidation and phase 1 upgrades)

Phase 2

2023-203x

$$\int L\,dt = 3000\,fb^{-1}$$

(LS3 ≡ phase 2 upgrades)

R&D on-going !!!
Installation in LS3 : 2023-2024

CMS Nominal Design

- Operate at 1×10^{34} cm^{-2} s^{-1} with 25 ns bunch crossing (<PU> ~25)
- Conditions to be realized during run 2 in Phase 1 after LS1 (2015-2017)

CMS Phase 1 Upgrades

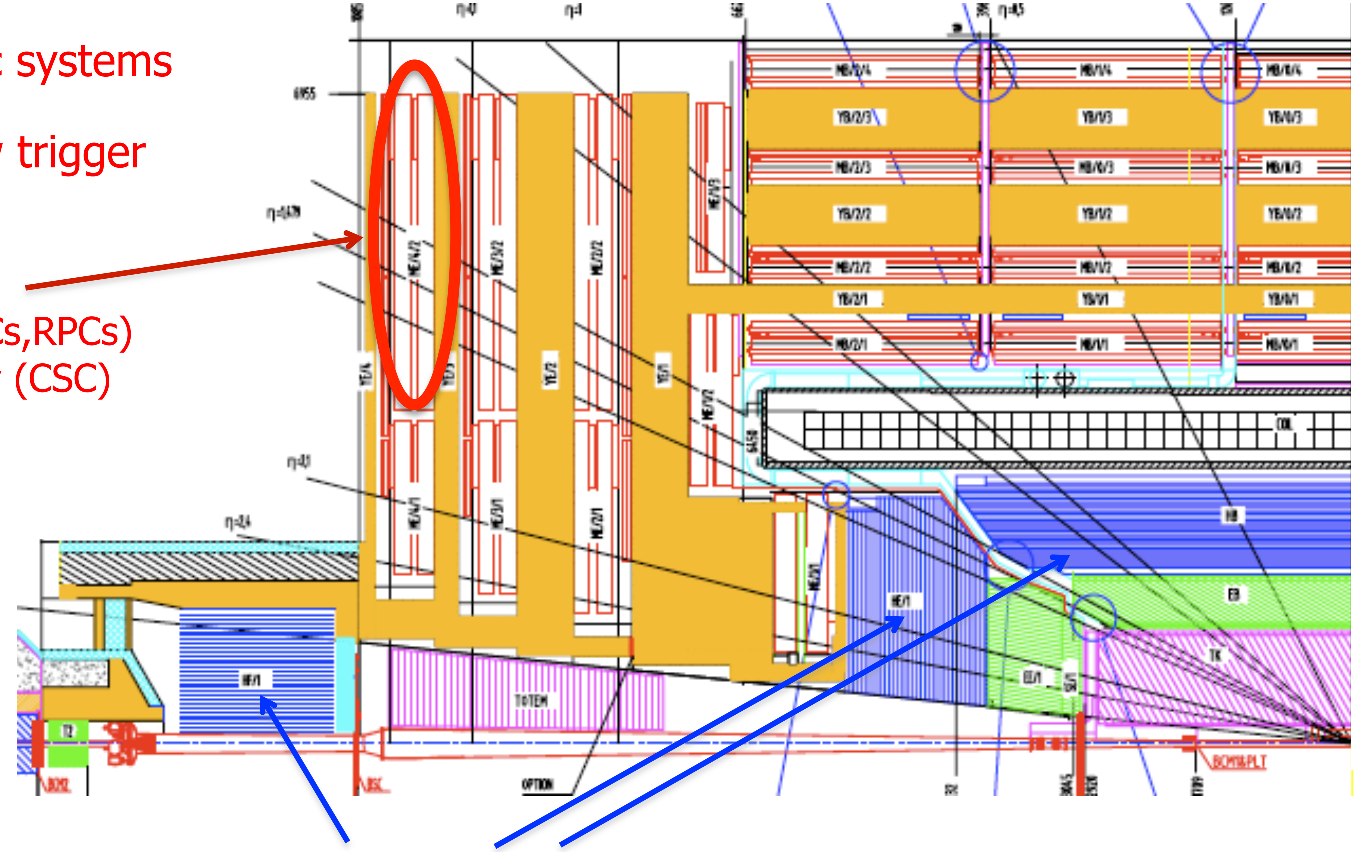
- Deal with 2×10^{34} cm^{-2} s^{-1} and 300 fb^{-1} in run 2 after LS2 (2019-2022)

CMS Phase 1 Detector Upgrades

Prepare for $\mathcal{L}$ = 1.5 x 10^{34} @ 25ns

Trigger/DAQ
New backend electronic systems
(muons and calorimeters)
Optical splitting for new trigger

Muon systems
Complete m coverage (CSCs,RPCs)
Higher read-out granularity (CSC)



+ Tracker going cold for phase 1 longevity
+ μ system upgrades for better L1 trigger
+ New DAQ2 for PU & timing/control
+ New beam pipe to for pixel upgrade
+ μ shielding walls
+ Maintenance & repairs

Hadron calorimeters HF/HE/HB
Replace photo-detectors
and read-out (in LS2)

Pixel detector - Full replacement
(during extended YETS 2016/17)

New beam pipe
(reduced diameter)

Pixel: http://cds.cern.ch/record/1481838?ln=en
L1 Trigger: http://cds.cern.ch/record/1556311?ln=en
HCAL: http://cds.cern.ch/record/1481837?ln=en

CMS Phase 1 Detector Upgrades – LS1

Si tracker operation at -15° C (tested to -20 °C) greater longevity

New CSC and RPC stations:

New beam-pipe with reduced-diameter ⇔ ready for 2017 installation of upgraded pixel

CMS Phase 1 Trigger & Performances

Need to cope with x 2 $\mathcal{L}$ & higher cross sections due to $\sqrt{s}$

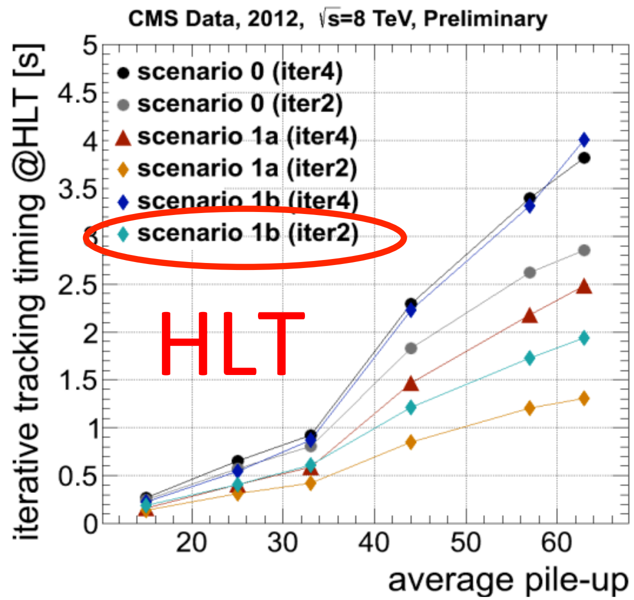
Goal: keep the same physics sensitivity

- Trigger has to select more wisely

Calorimeters: PU subtraction, better e isolation, τ ID
Muons: take advantage of LS1 detector upgrades

HLT higher PU leads to larger reco. times ⇔ improve tracking algorithms

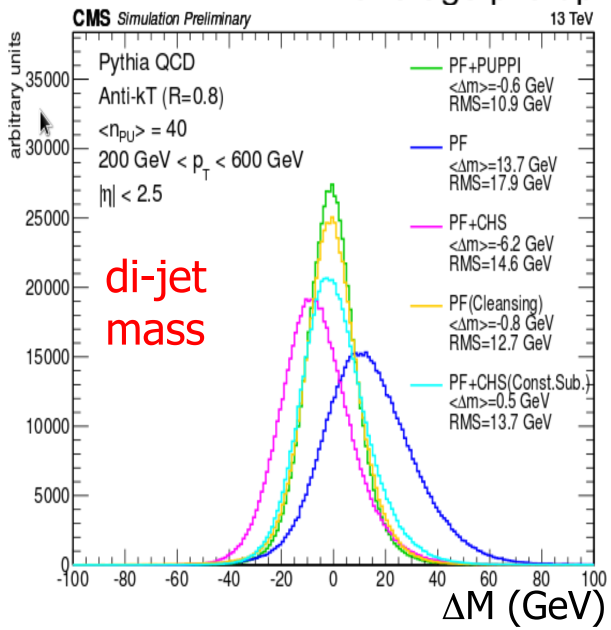
First full menu aimed at PU=40, ΔT=25 ns
now implemented in CMS simulation



- New Pflow technique using per-particle PU

Results based on full reconstruction promising

Improved $\Delta M = M_{reco.} - M_{gener.}$



- First full menu aimed at PU=40, ΔT=25 ns now implemented in CMS simulation

CMS Phase 2 (HL-LHC)-Upgrades

- Operate at leveled luminosity of 5 x 10^{34} cm^{-2} s^{-1} (<PU> ~ 140) to collect 3000 fb-1 from 2023 onward

- Mandatory (radiation damage): change tracker and endcap calorimeters
- Rely on particle-flow (PFLOW) for pile-up mitigation
  1) Increase tracker granularity by a factor ~ 4
  2) Extend tracker up to $|\eta|$ ~ 4
  3) Introduce track info. at L1 trigger (PT ≥ 2 GeV "track-sub" @ 40 MHz)
  4) Increase forward calorimetry granularity (jet ID and resolution)
  5) …

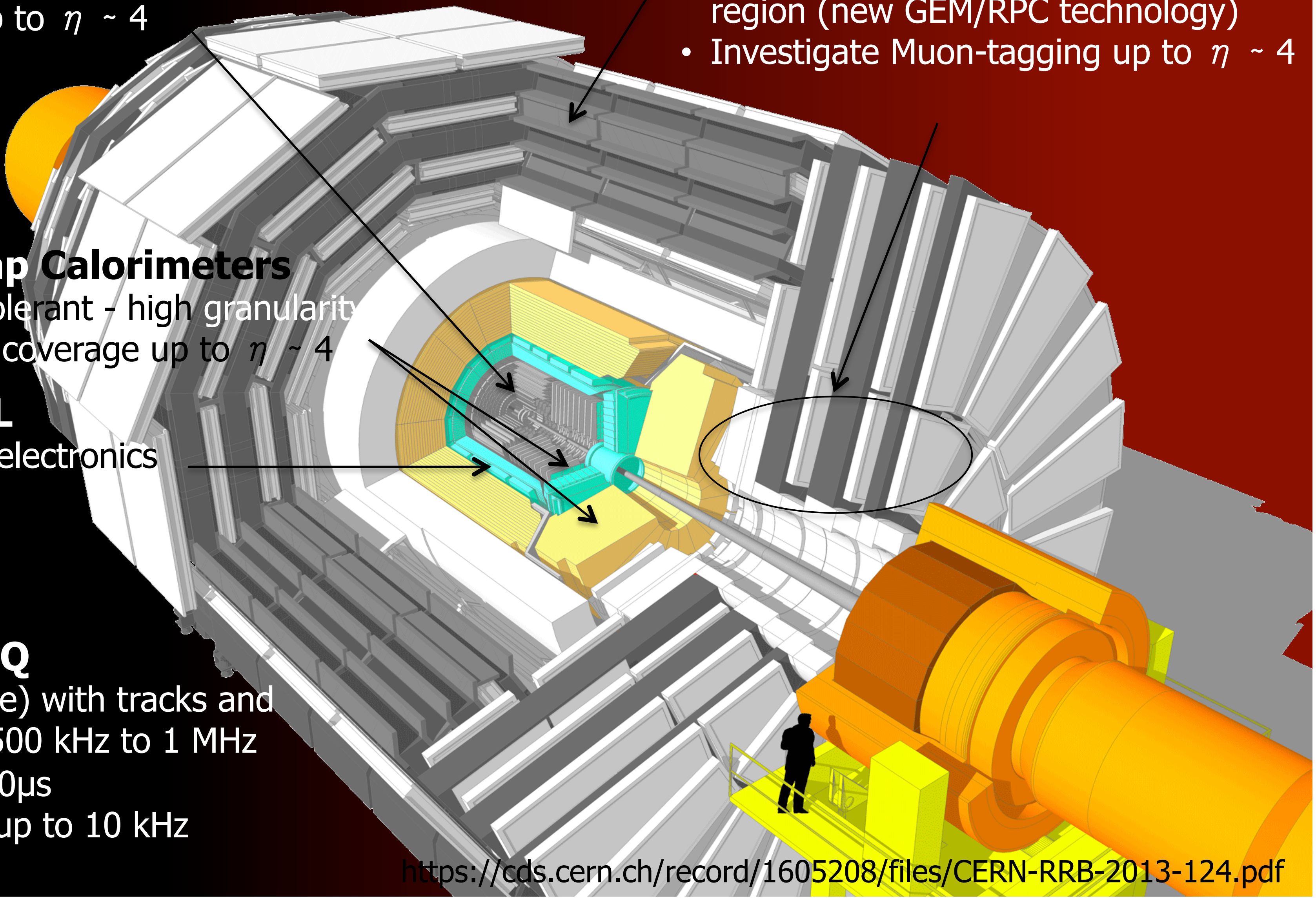
Tracker extension in $|\eta|$ and high granularity calorimetry in forward region allow
→ better cover the peak production region for tag jets in VBF processes
→ Improve on total and E_T^{miss} measurements, improve on b-tagging acceptance …
e.g. could be essential for HH production via self-coupling in VBF processes
→ Improve Jet ID and energy resolution

Preparation of a Technical Proposal - on-going
Decision on forward calorimetry expected in spring 2015
Full Technical Design Reports (TDR) by fall 2017.

CMS Phase 2 Upgrades

New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 4



New Endcap Calorimeters
- Radiation tolerant - high granularity
- Investigate coverage up to η ~ 4

Barrel ECAL
- Replace FE electronics

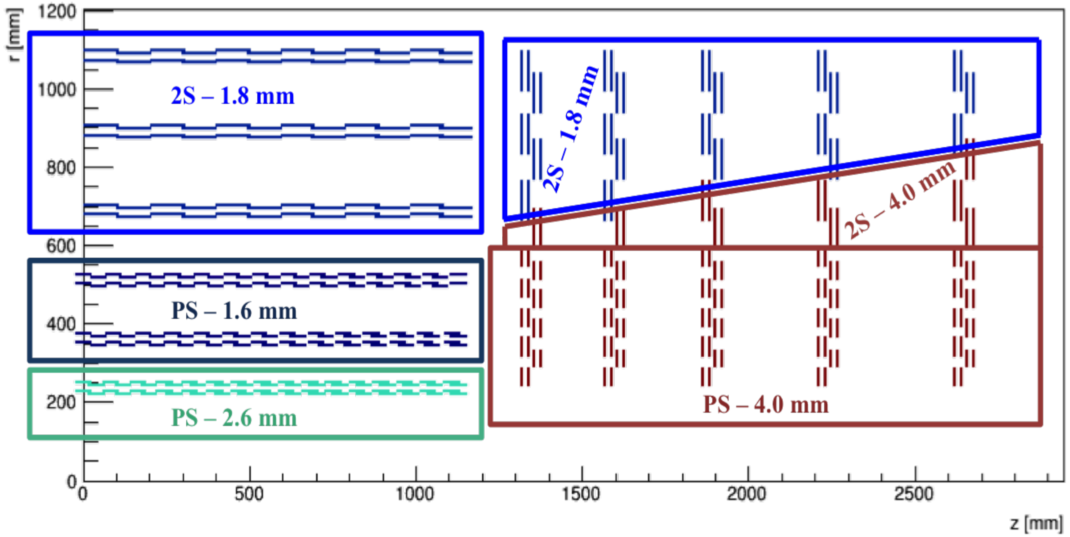
Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 500 kHz to 1 MHz
- Latency ≥ 10μs
- HLT output up to 10 kHz

https://cds.cern.ch/record/1605208/files/CERN-RRB-2013-124.pdf

Tracker Upgrade for Phase 2

Strip and pixel tracker are seriously degraded after Phase 1

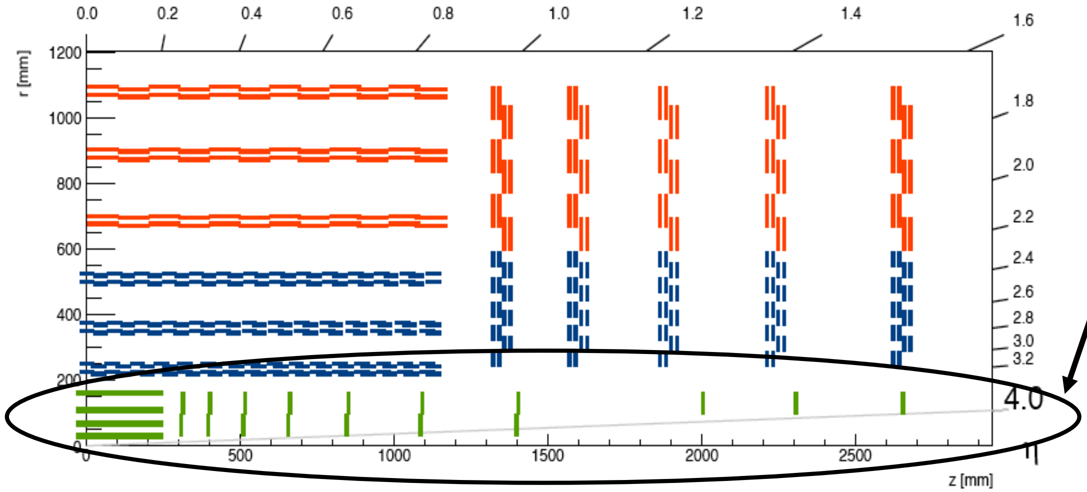
⇔ need rad-hard replacement



Outer Tracker: 2-sensor modules:
Strip-Strip (2S) & Strip-Macro-pixels (PS)
spacing adjusted for trigger data
selective readout of track stubs above (configurable) P_T threshold

⇔ "track-trigger"

- 210 m^2 area - 15500 modules
- 50M strips - 220M macro-pixels
- 90/100 μm^2 pitch (2S/PS modules)
- 2.5/5 cm strips (2S/PS) - 1.5 mm long macro-pixels in PS
- 200 μm active or physical thickness



Pixel Tracker

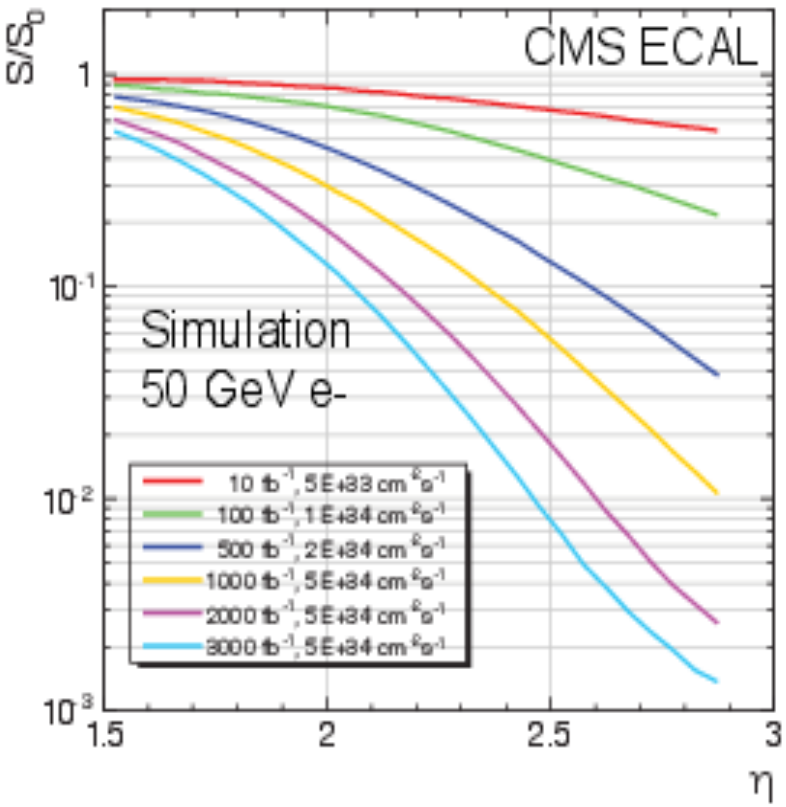
- Total pixel area ~ 4 m^2 - preserve ability to replace inner components
- 10 disks extending coverage to η ~ 4
- 50x50 to 25x100 μm^2 pixels (min. size)
- ≤ 200 μm physical thickness

CMS Forward Calorimeter Aging

At high $|\eta|$, the $PbW0_4$ crystals of ECAL endcap progressively loose transparency

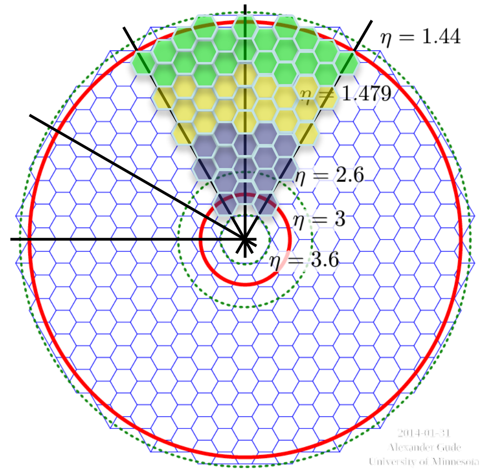
- ECAL trigger noise goes to 200 GeV per tower !
- Cannot replace in situ (absorber is activated), nor only inner portions

⇔ Need replacement !

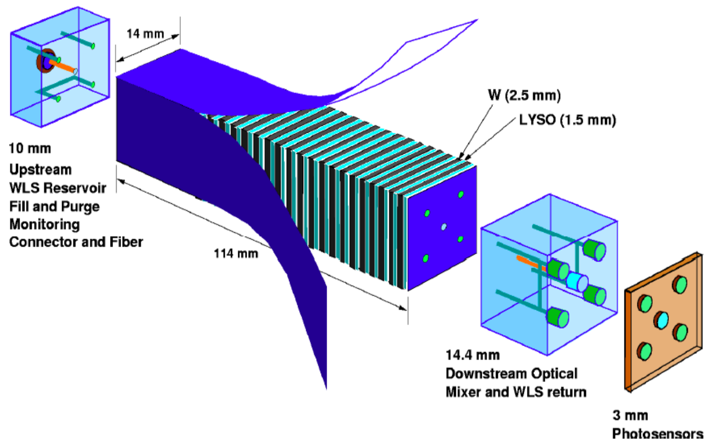


2 possible calorimetry options (decision in 2015)

High Granularity (HGCAL)
Highly Segmented for particle flow



Shashlik – "Conventional dense":



The CMS HGCAL Project

ECAL: ~33 cm, 25 X0, 1 λ, 30 layers:

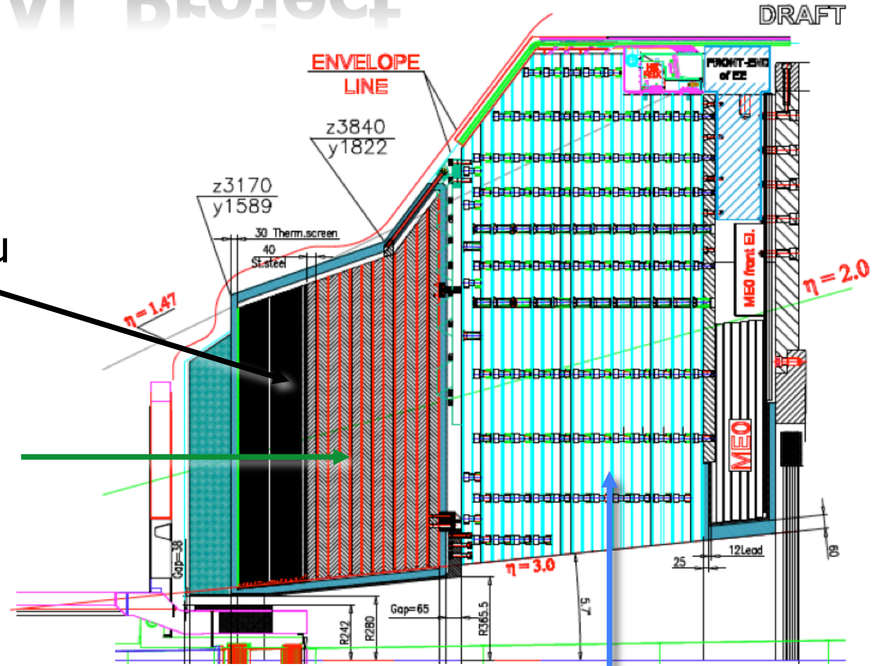
- 10 planes of Si separated by 0.5 X0 of W/Pb/C
- 10 planes of Si separated by 0.8 X0 of W/Pb/C
- 10 planes of Si separated by 1.2 X0 of W/Pb/Cu

Fine grain pads 0.45 & 0.9 cm^2

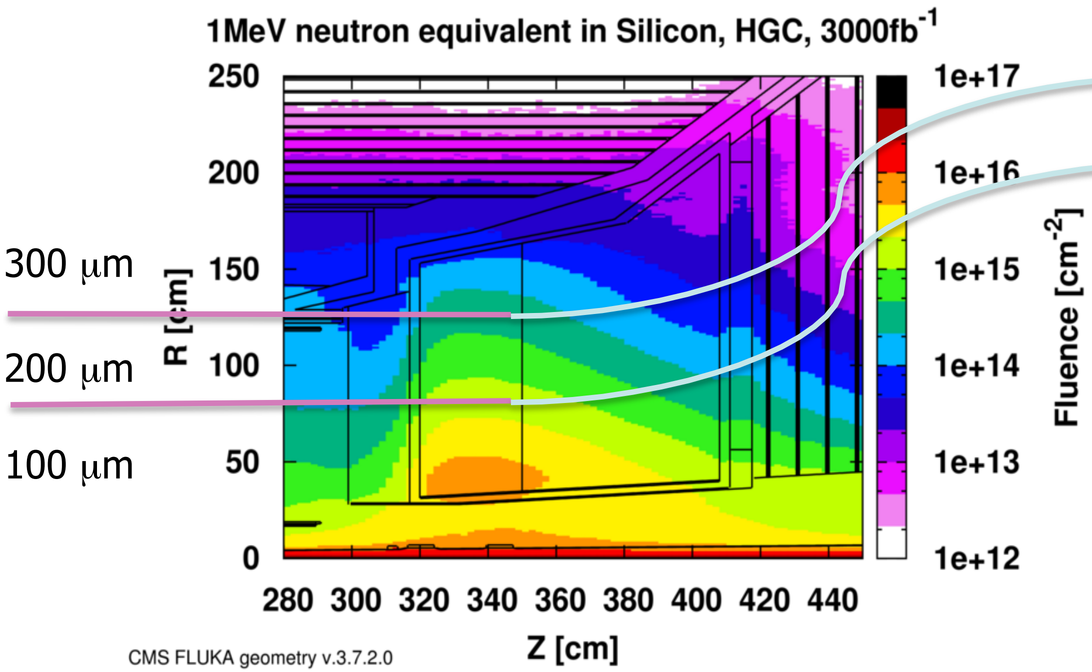
HCAL: ~66 cm, 3.5 λ:

- 12 planes of Si separated by ~0.3λ of absorber

~ 9M channels and 660 m^2 of Silicon



Back HCAL as HE re-build 5 λ with increased granularity



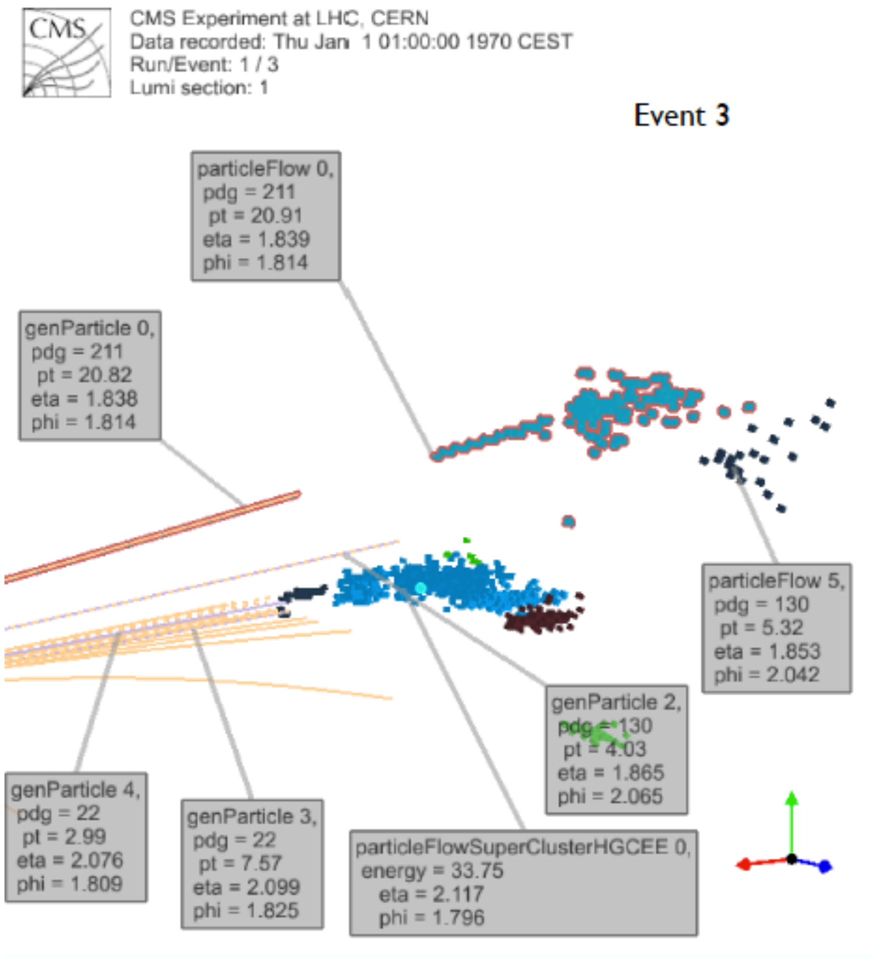
Sensor Parameters:

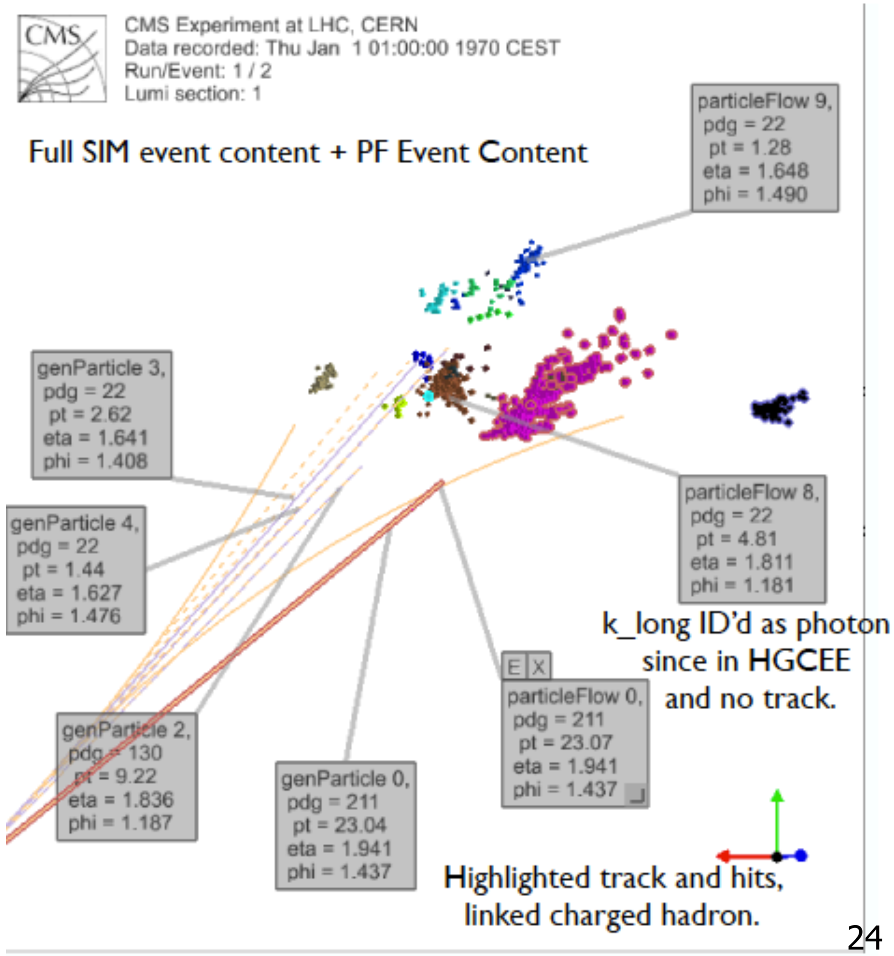
Thickness	300 μm	200 μm	100 μm
Maximum neutron fluence	6×10^{14}	2.5×10^{15}	1×10^{16}
E-HG region	$1.48 < \lvert\eta\rvert < 1.75$	$1.75 < \lvert\eta\rvert < 2.15$	$2.15 < \lvert\eta\rvert < 3.0$
H-HG region	$R > 860$ mm	$R < 860$ mm	-
Cell size (cm^2)	0.9	0.9	0.45
Cell capacitance (pF)	33	50	50
S/N after 3000 fb^{-1}	9.6	4.9	2.4
Si wafer area (m^2)	368	192	97

PFLOW with HGCAL in CMS

- 3D shower reconstruction; Δ(E)/E ~ 20%/$\sqrt{E}$ for e/γ; improved e/γ Iso
- Use detailed shower topology to mitigate PU effect
- Use fine granularity to perform EFLOW (E weighting) for jets (possibly already at trigger level) and improve on jet ID

Pflow:





The Future Physics Program
@
LHC and HL-LHC

CMS LHC/HL-LHC Specific Goals

In addition to all the great SM precision measurements with Z, W and the top quarks, HI Physics, flavour physics etc. …

Driven by the new physics
(i.e. the scalar sector)
Discovered during run I

- Complete precision measurements of the Higgs boson
- Observe Di-Higgs production and access the self-coupling
- Measure trilinear and quartic couplings of weak bosons
- Measure rare decays and search for forbidden H decays
- Search for an extended scalar sector
- Search for extra-structure, supersymmetric matter, Exotica, …

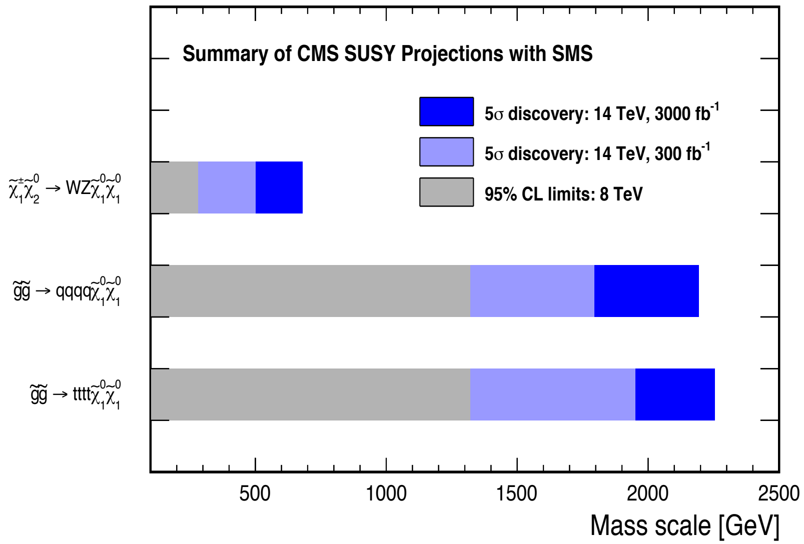
(6) Extra-structure, Supersymmetric Matter, Exotica …

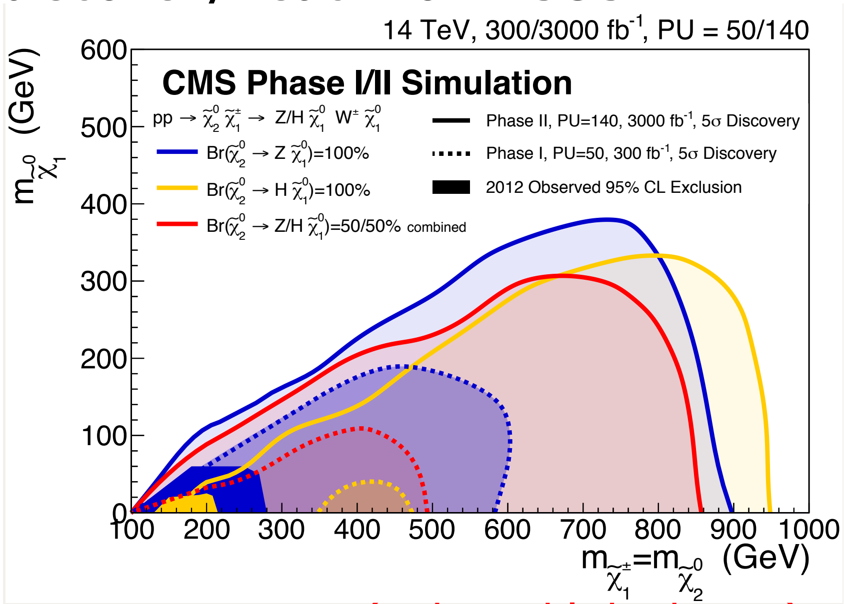
- Considerable extension of the discovery reach for « exotica »

  ⇔ continue and extend searches for leptoquarks, heavy gauge bosons, large extra dimensions, compositeness and excited fermions, vector-like quarks, etc.

  « Rules of thumb » on the discovery reach
  will go up by a factor ~ 2 with respect to Run 1 after ~100 fb-1 at LHC run 2
  will do up by DM = (new – old reach) ~ 0.07 x $\sqrt{s}$ with 10 x $\mathcal{L}$

- Considerable extension of the discovery reach for « SUSY »





CMS studied 5 different SUSY models in 9 generic signatures (to be published soon)

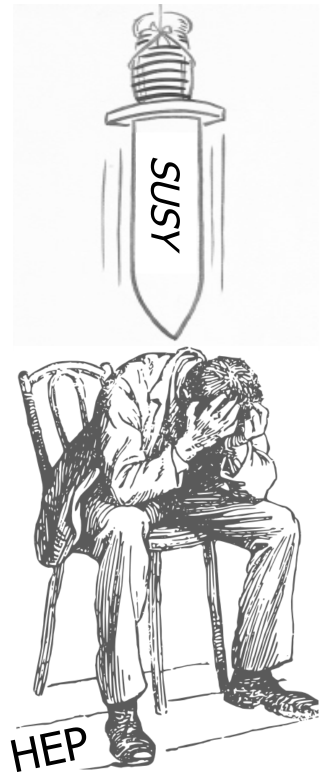
- Deviations to be found in one or the other signature for each model in Phase I (300 fb^{-1})
- Evidence or discovery possible in Phase I
- HL-LHC (Phase 2, 300 fb-1) will be crucial to confirm an evidence or characterize a SUSY discovery made during Phase 1

It would be surprising that Nature would not choose SUSY somehow

- Extension of space-time symmetries to quantum coordinates
- Natural appearance of spin 0 (scalars) and spin 3/2 particles (gravitino)
  bosons ⇔ fermions
- Possibility of a Gauge-Higgs unification (with extra compact spatial dimensions ?)
- Rôle in the Hierarchy between EWK and GUT or Planck scale ?

But it is a big mistake to think that this
must lead to easy discoveries at the LHC
In the few years to come !

e.g. The discovery of the Higgs boson
was made has hard as it possibly
be by Nature with the choice of
M_H ~125 GeV ! …



Science Times ***

The New York Times

TUESDAY, JANUARY 5, 2016

5006 Physicists Report Failure In Search for Supersymmetry

The negative result illustrates the risks of Big Science, and its often sparse pickings.

*** True original article published in 1996 concerning CDF at the TeVatron

Note: 5006 = 2875 (ATLAS) + 2131 (CMS)

CMS LHC/HL-LHC Specific Goals

In addition to all the great SM precision measurements with Z, W and the top quarks, HI Physics, flavour physics etc. …

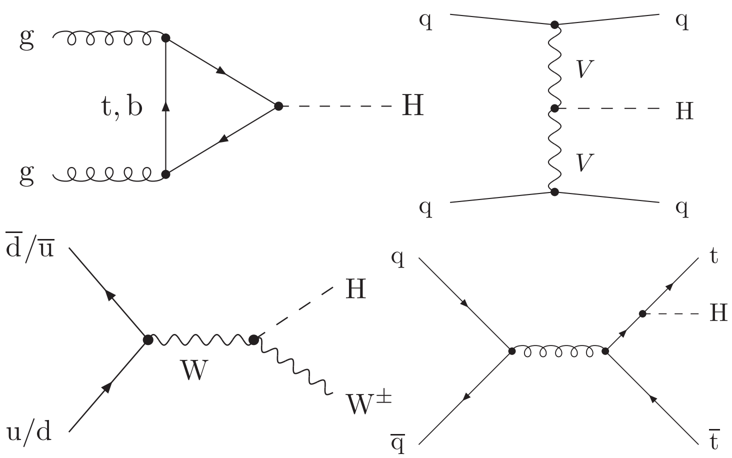
Driven by the new physics (i.e. the scalar sector) Discovered during run I

- Complete precision measurements of the Higgs boson
- Observe Di-Higgs production and access the self-coupling
- Measure trilinear and quartic couplings of weak bosons
- Measure rare decays and search for forbidden H decays
- Search for an extended scalar sector

- Search for extra-structure, supersymmetric matter, Exotica, …

(1) Precision Measurements of the SM-like H boson

Production



Decay

Decay	Production Modes			
	ggH	VVH	VH	$t\bar{t}$H
H→ $b\bar{b}$	- -	○	⋆⋆	⋆
H→ $\tau^+\tau^-$	⋆	⋆⋆	⋆	○
H→ WW*	⋆⋆⋆	⋆⋆	⋆	○
H→ ZZ*	⋆⋆⋆	⋆	○	○
H→ $\gamma\gamma$	⋆⋆⋆	⋆⋆	⋆	○
H→ Z γ	⋆	○	- -	- -
H→ $\mu^+\mu^-$	○	○	- -	- -

State of the Art after run I:

*** = observed (≥ 5σ)
** = evidence (≥ 3σ)
* = sensitivity
° = out-of-reach

√S = from 8 to 13 TeV ⇒

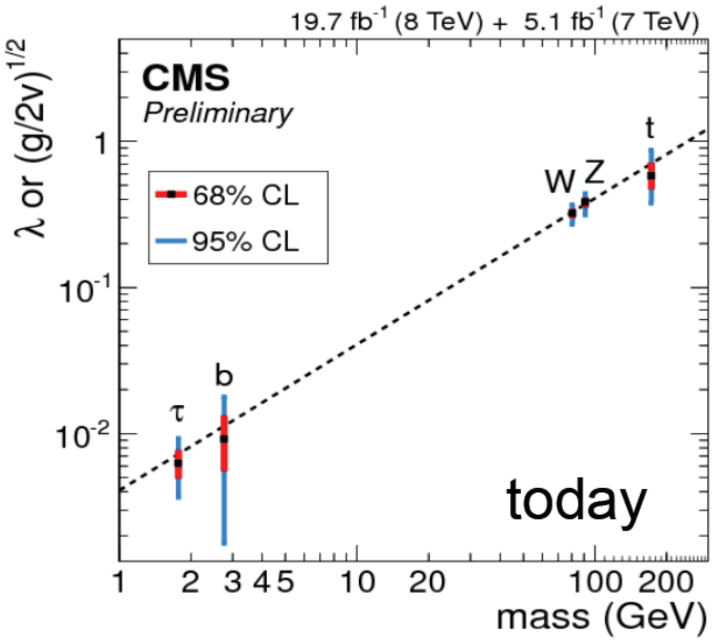
- Gain factor of 2.6 (for ggH, VBF H), 2.1 (VH), and 4.7 (ttH) in σ_H
- All 4 x 5 main production x decay modes observable with 300 fb^{-1}
- Rare decays (H → μμ, H → Zγ) & search forbidden decays (H → τμ, …) at HL-LHC

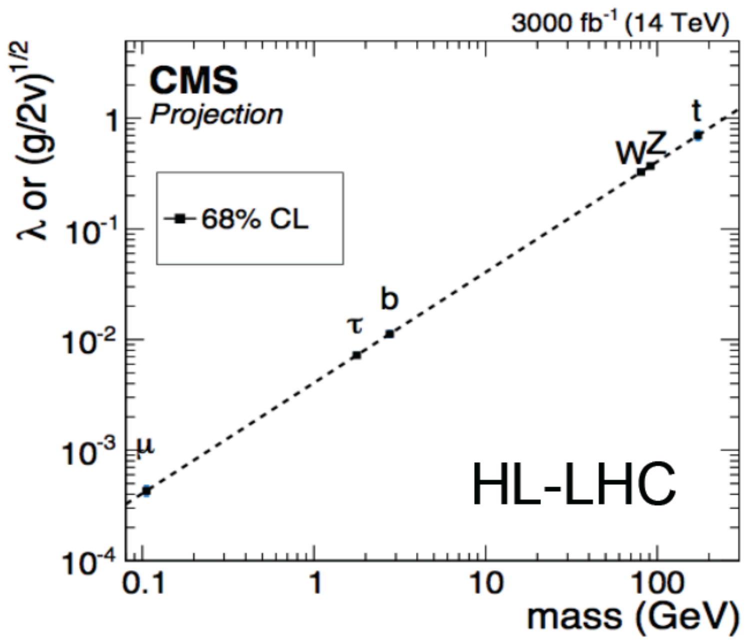
Snowmass 2013 CMS extrapolation

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	BR$_{inv}$
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[7, 11]

HL-LHC experiments will each achieve 2-10% precision on the Hff and HVV couplings

Why Precision at HL-LHC ?: For Discovery





How large are expected deviations on couplings from BSM physics ?

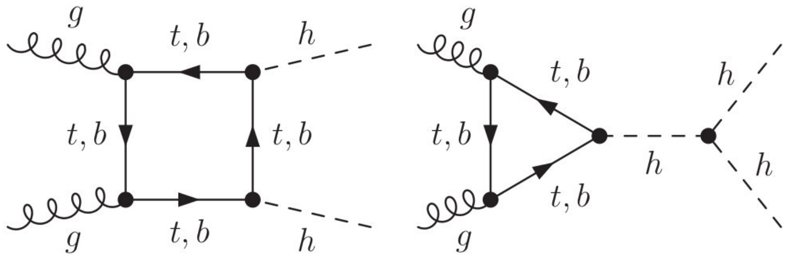
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Gupta, Rzehak & Wells, PRD 2012
Dawson et al., arXiv:1310.8361 (« Snowmass »)

(2) Di-Higgs production and the self-coupling

HL-LHC experiments will each achieve ~30% precision λ in SM case … but HH prod. could be enhanced from BSM

Delicate HH prod. cancellation in SM …
enhanced with anomalous ttH couplings



Production cross-section:

$\sqrt{s}$ (TeV)	Cross sections (fb) and theoretical uncertainties (%)				
	$gg \to HH$ NLO	$qq \to qqHH$ NLO	$q\bar{q} \to WHH$ NNLO	$q\bar{q} \to ZHH$ NNLO	$q\bar{q}/gg \to t\bar{t}HH$ LO
14	$33.89^{+37.2\%}_{-29.8\%}$	$2.01^{+7.6\%}_{-5.1\%}$	$0.57^{+3.7\%}_{-3.3\%}$	$0.42^{+7.0\%}_{-5.5\%}$	1.02

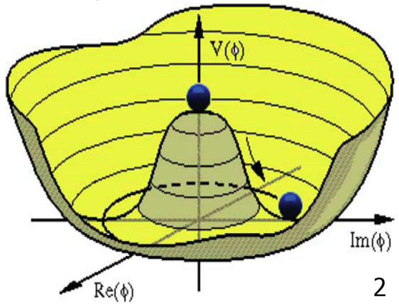
How large are the possible deviations on Triple-H couplings ?

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^{a}$ $\quad -15\,\%^{b}$
NMSSM	$-25\,\%$
LHC 3 ab^{-1} [36]	$[-20\,\%, +30\,\%]$

(3) Trilinear and Quartic Couplings of the Weak Bosons

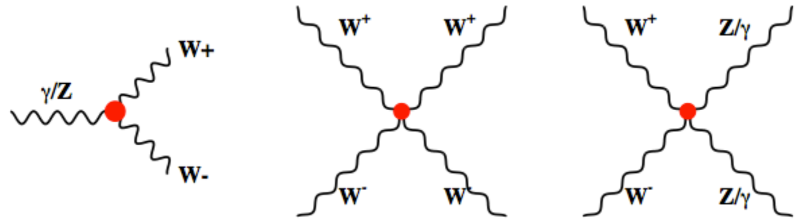
EW gauge boson carry weak charges <=> self-interactions exists (TGC, QGC)

- Non-Abelian gauge structure of the SM predicts the existence of QGCs besides TGCs
- The QGCs are particularly interesting: they can involve four longitudinal components which, according to the equivalence theorem, manifest at high energies as pure Goldstone boson interactions (i.e. independent of SM Gauge couplings)



- Measure SM tri-linear couplings & observe EWK production of WW pairs
  set constraints on aTGC; set first constraints on aQGC; observe WWW prod ?

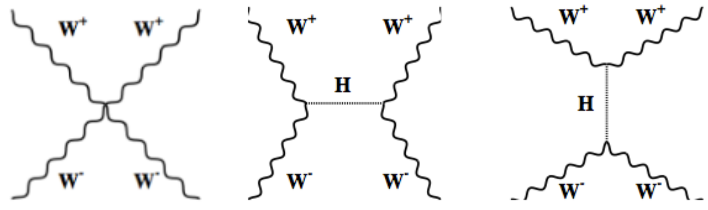
TGC and QGC allowed in SM



Well known

Never observed so far !

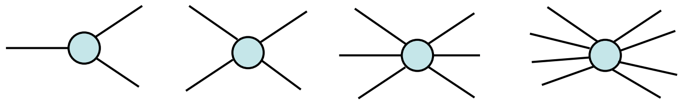
WW → WW to be observed in Phase 1



- Measure VVV prod. at TeV scale; establish the existence of gauge boson quartic self-couplings; set stringent constraints on aQGC

Note: only operators of dimension up to 4 are allowed in a renormalizable QFT;
aTGC and aTGC must be parametrized in terms of an effective theory

A very personnal view of Effective Theories



Animals with more than 4 legs are scary !!!

e.g.
Dimension-8
operators

… but possibly unavoidable

(4) Rare and Forbidden Decays

HL-LHC experiments sensitive to rare decay BSM enhancement (possibly >> 10%)

BSM easily competes with SM decays

... with $H \to bb$, $H \to \tau\tau$ because of small couplings;
… with $H \to ZZ^*$, WW^* because of V off-shell;
… with $H \to \gamma\gamma$, $Z\gamma$ because of loops

$H \to \mu\mu$ expected very small – enhanced in leptonic-Higgs models

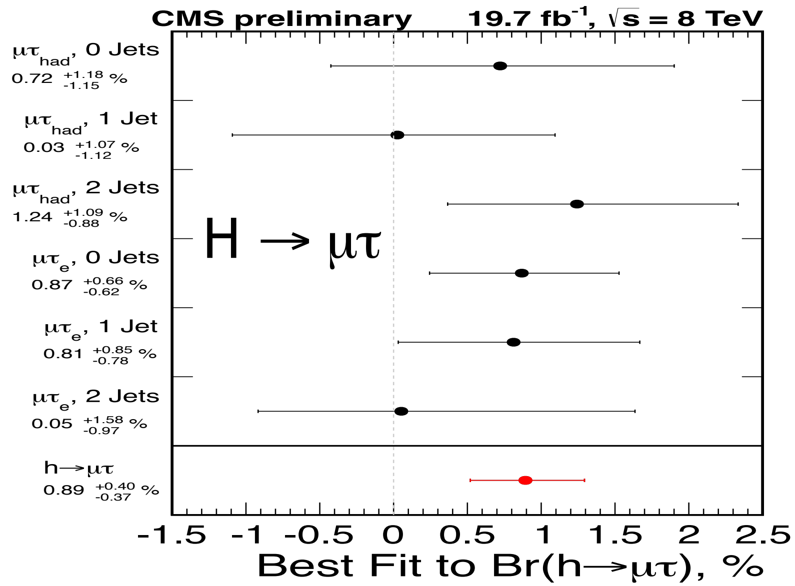
$H \to Z\gamma$ expected small – enhanced alternative (non-Higgs) interpretations

$H \to \tau\mu$ forbidden FCNC – enhanced in some multi-Higgs models

State of the art

$B(H \to \mu\tau) = 0.89 \pm 0.38$

The CMS combined excess is 2.5 σ
(local p-value below 10^{-2} at $M_H \sim 125$ GeV)



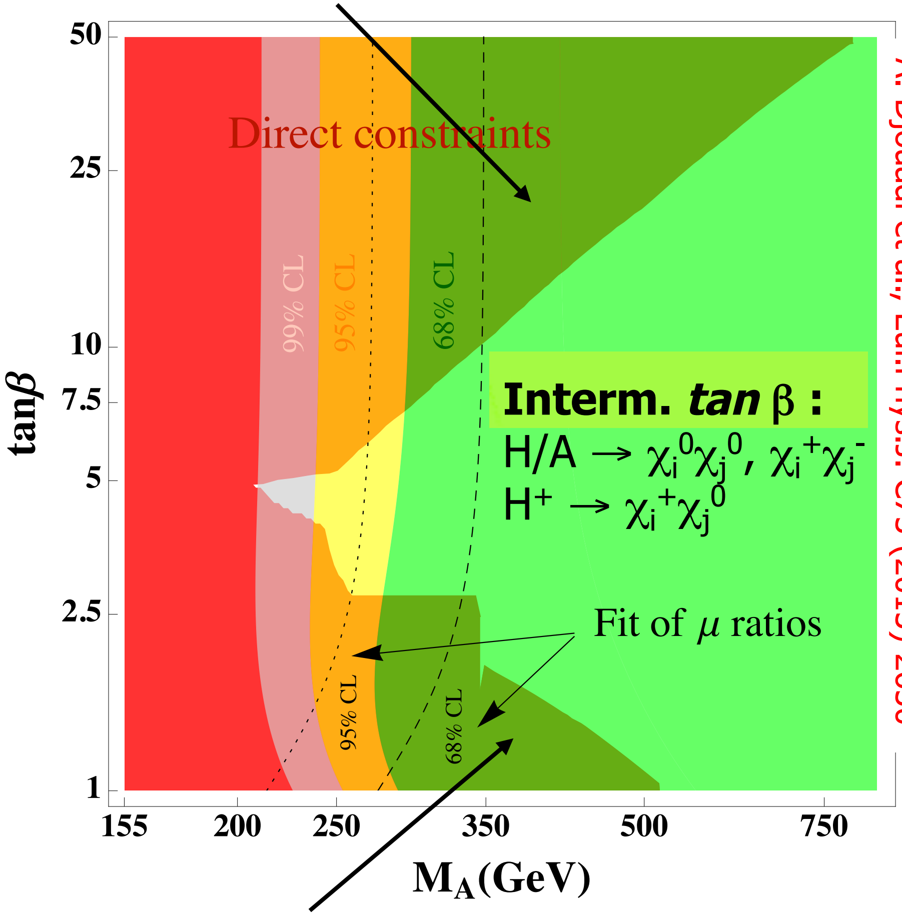
$H \to \gamma$ + Invisible X sensitive to BSM – enhanced e.g. for coupling to DM

X could be a Z ($\to \nu\nu$), a new particle, a pair of new particles, …

(5) Extended Scalar Sector

High *tan* β :

$\phi \rightarrow \tau\tau$, $\phi \rightarrow \mu\mu$; $H^+ \rightarrow \tau\nu$, tb



A. Djouadi et al., Eur.Phys.J. C73 (2013) 2650

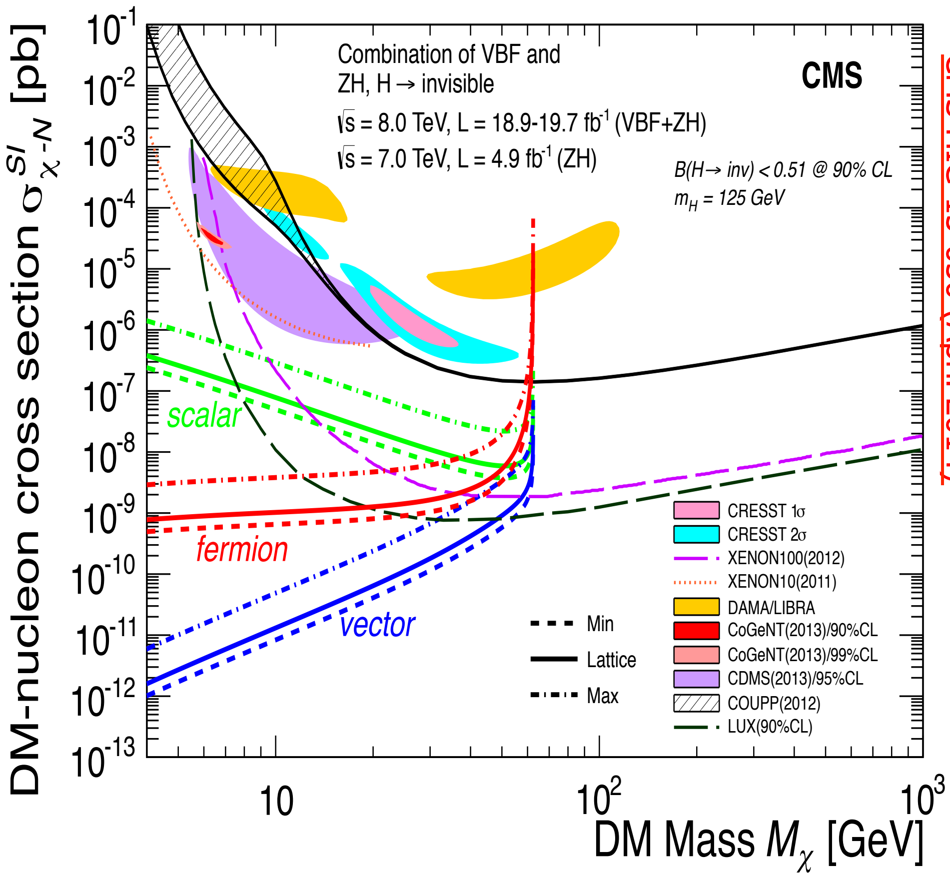
Interm. *tan* β :

$H/A \rightarrow \chi_i^0\chi_j^0$, $\chi_i^+\chi_j^-$

$H^+ \rightarrow \chi_i^+\chi_j^0$

DM Exists – Does it couple to H Sector ?

E.g. use recoil in ZH and VBF H



CMS HIG-13-030 (April 2014)

$\beta\,(H \rightarrow \chi\chi) < 58\%$

Low *tan* β :

$A \rightarrow Zh$; $H \rightarrow hh$, tt;

$H^+ \rightarrow$ cs, cb, tb, Wh

In general: must explore extended scalar sector e.g. effective 2HDM models

Conclusions

- HEP physics is not quite the same after the discovery of a Higgs boson with properties so far consistent with minimal scalar sector of the SM and the BEH mechanism.
- The existence of a scalar field with non-zero v.e.v. qualitatively changes the understanding of the vacuum; could have a major impact on the story of the Universe; and open news domains of HEP physics (extended scalar sector, coupling to DM, etc.)
- The full precision reachable at the LHC or HL-LHC must be exploited to possibly observe deviations caused by extra structure or an extended scalar sector
- One must be prepared now for a non-trivial discovery [if things pop-up quickly at $\sqrt{s}$ ~ 13 GeV, no one will leave or complain anyway !]
- As a consequence, one must not compromise on the quality of the upgraded detectors capable to withstand the PU and radiation.