Higgs boson:
CMS recent results and future perspectives

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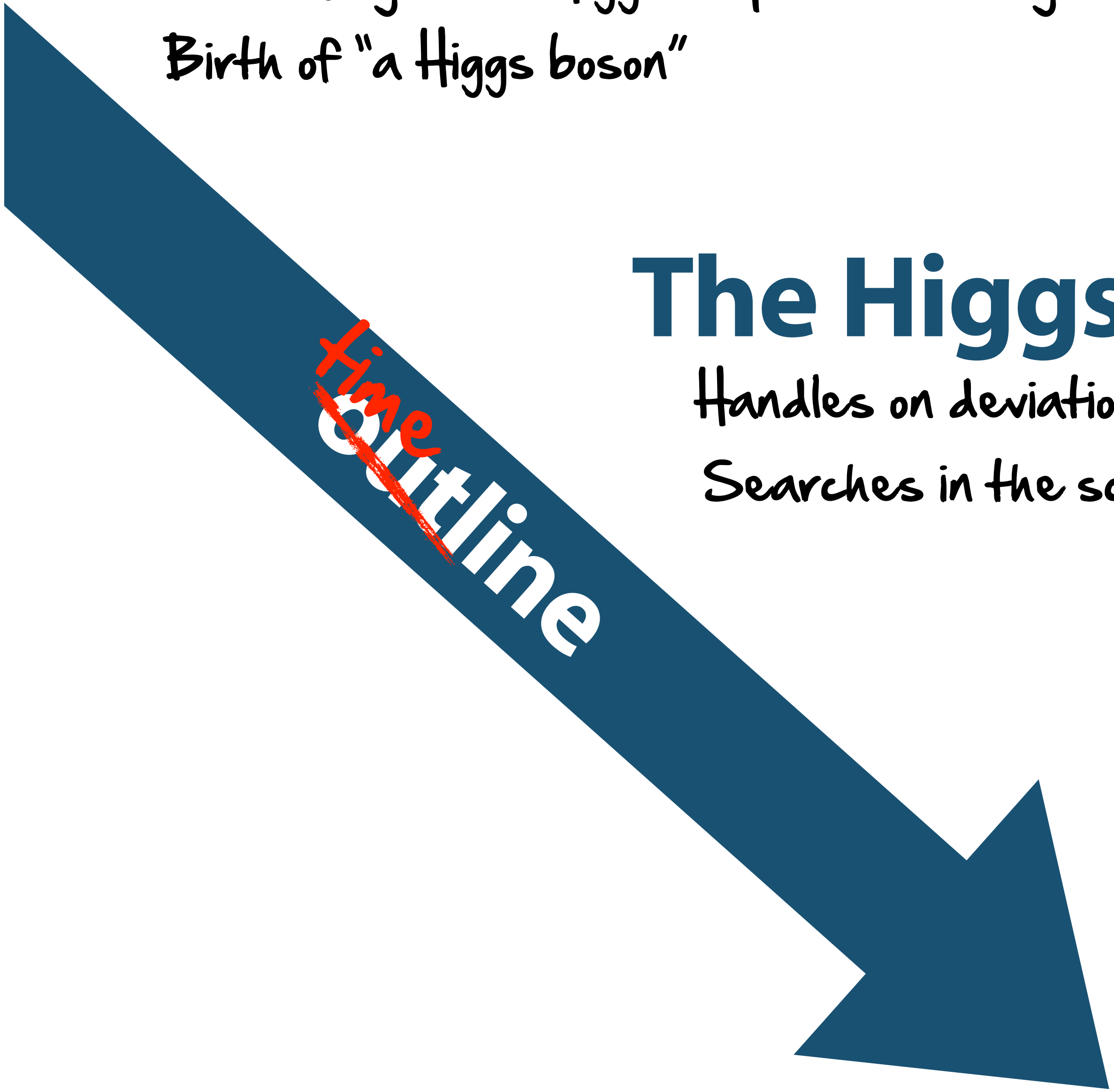
The quest for the Higgs boson

Nothing else in the horizon

4th of July 2012: Higgs-dependence day

Birth of "a Higgs boson"



The Higgs boson profile

Handles on deviations

Searches in the scalar sector: BSM Higgs

Next on the road

RUN2, end of Phase1, HL-LHC

The quest for the Higgs boson

Nothing else in the horizon

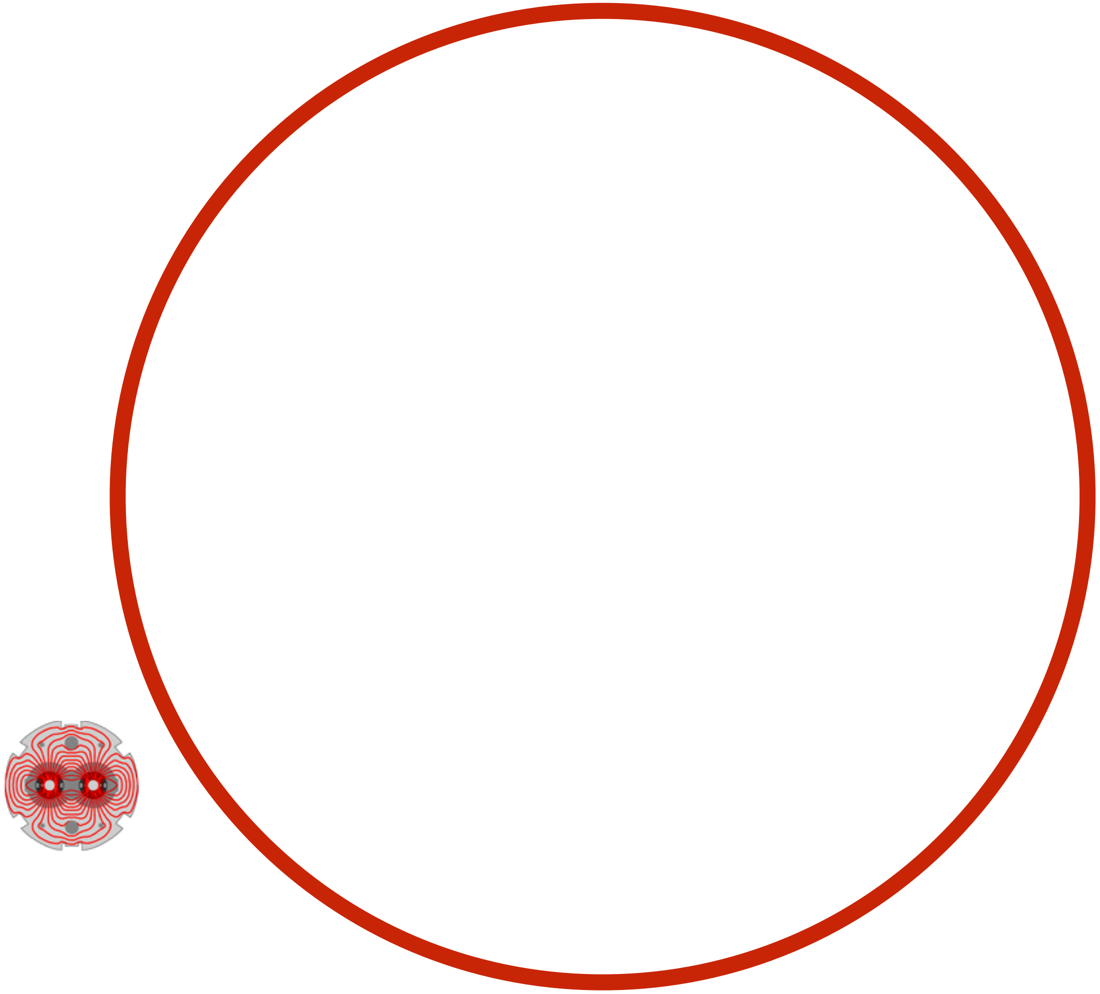
4th of July 2012: Higgs-dependence day

Birth of "a Higgs boson"

~~Out~~timeline

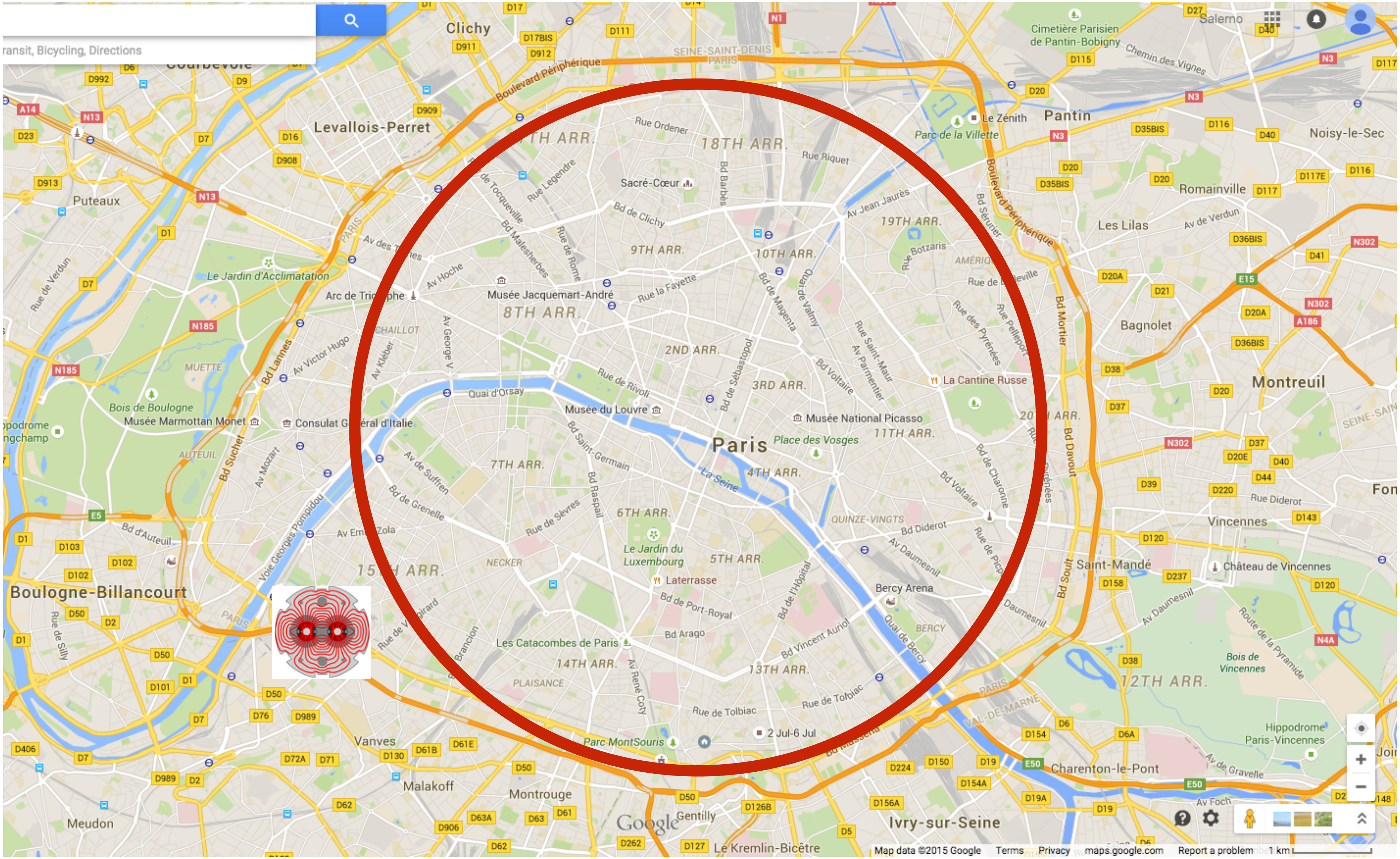
Contestants engage in epic challenges during the journey of a lifetime

LHC ...

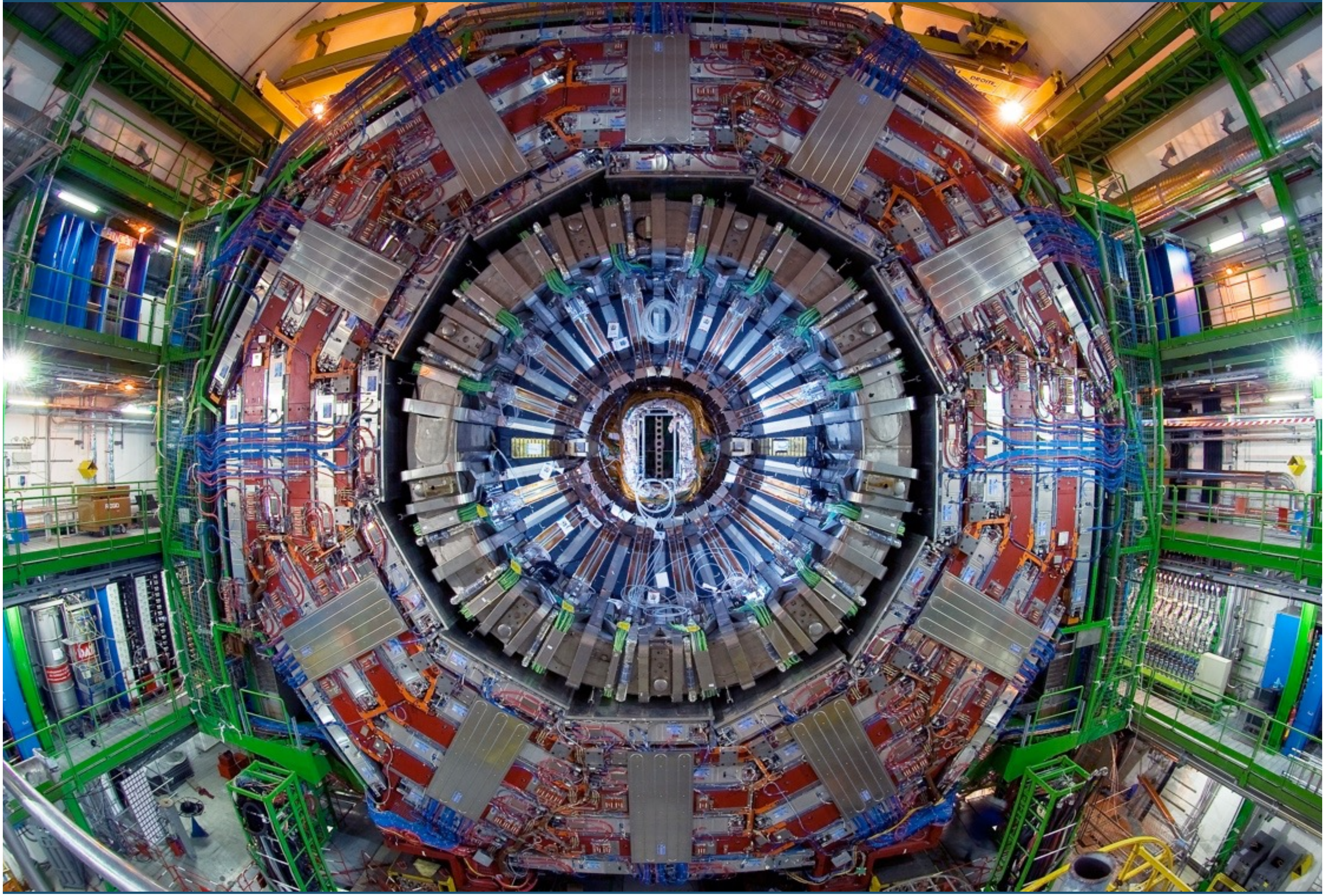


LHC ...

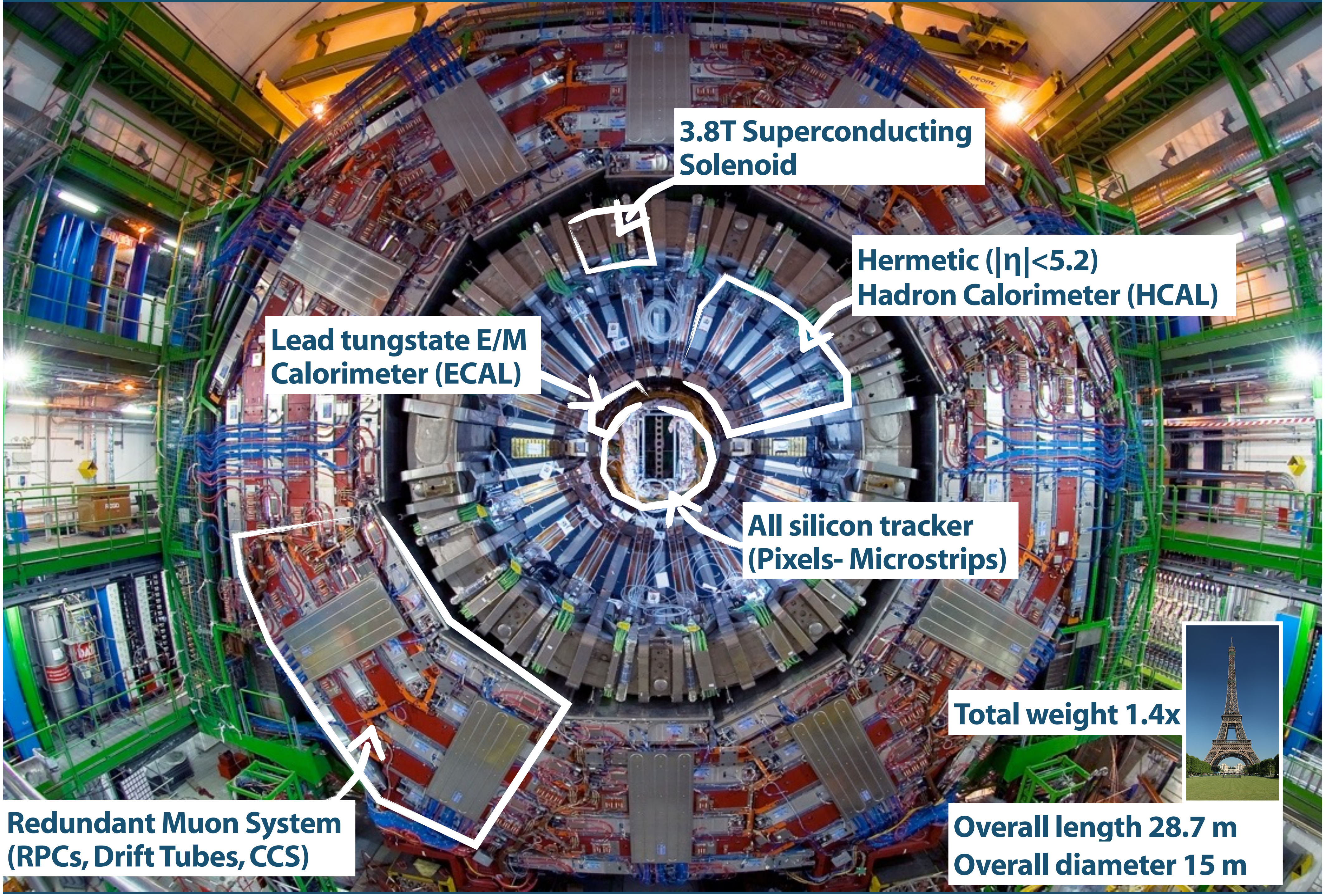
...inscribed in Boulevards des Maréchaux



The CMS detector



The CMS detector



3.8T Superconducting Solenoid

Hermetic (|η|<5.2) Hadron Calorimeter (HCAL)

Lead tungstate E/M Calorimeter (ECAL)

All silicon tracker (Pixels- Microstrips)

Total weight 1.4x

Redundant Muon System (RPCs, Drift Tubes, CCS)

Overall length 28.7 m

Overall diameter 15 m

The Rise and Fall of SM Higgs boson(*)

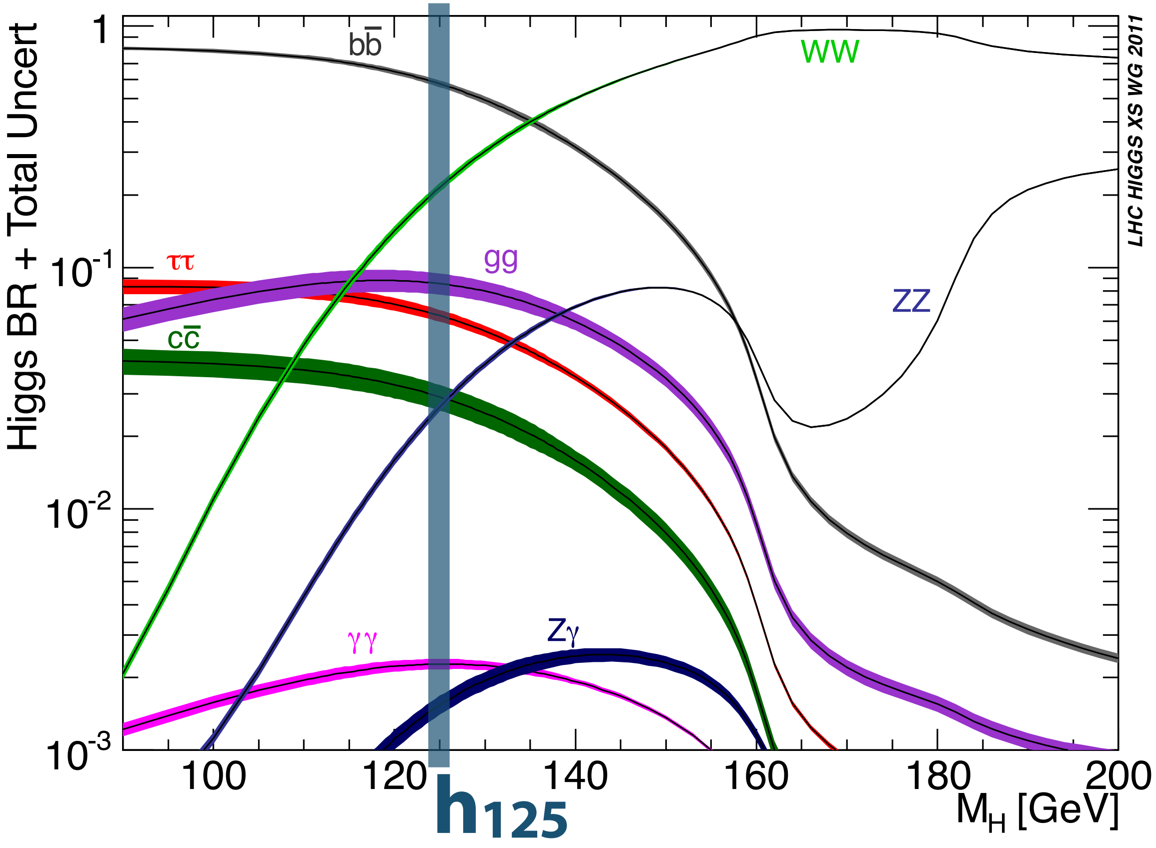
Production cross section at 8 TeV

>20K Higgs/fb

Process	Cross Section (pb)
gg	19.5 (±14%)
VBF	1.6 (±3%)
WH	0.70 (±4%)
ZH	0.39 (±5%)
ttH	0.13 (±17%)

Decay branching ratio

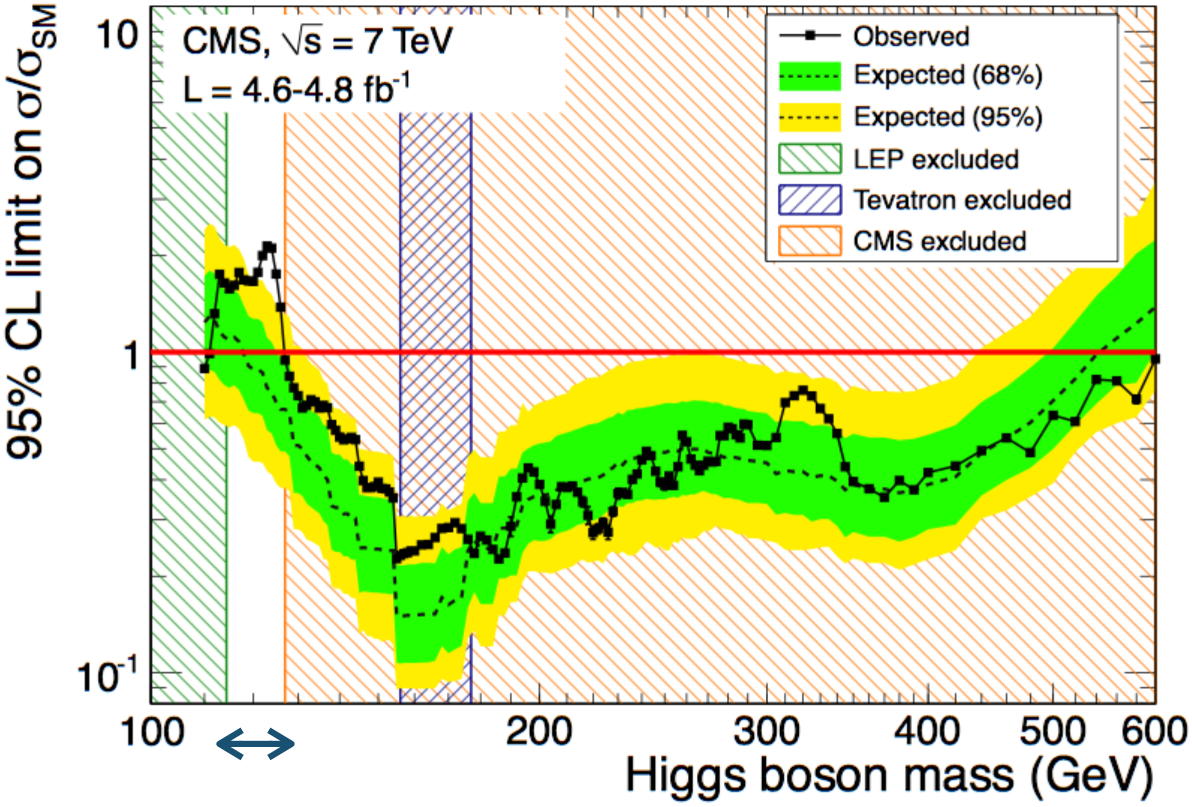
Process	Branching ratio
H → bb	5.77×10^{-1}
H → cc	2.91×10^{-2}
H → ττ	6.32×10^{-2}
H → μμ	2.20×10^{-4}
H → gg	8.57×10^{-2}
H → γγ	2.28×10^{-3}
H → Zγ	1.54×10^{-3}
H → WW	2.15×10^{-1}
H → ZZ	2.64×10^{-2}
Γ_H [GeV]	4.07×10^{-3}

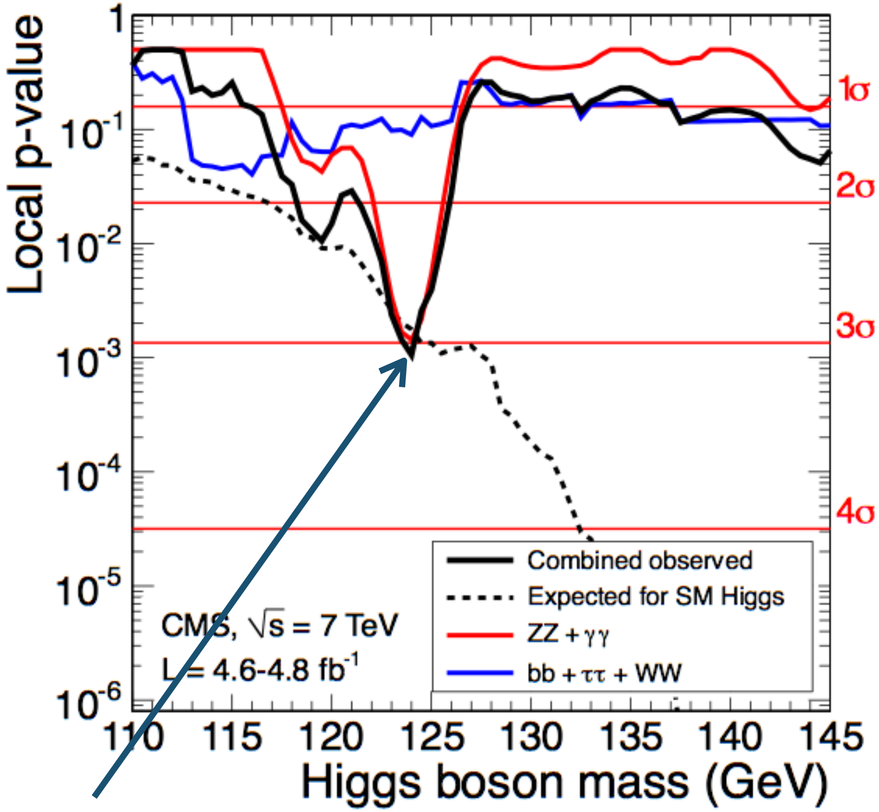


* Credit D. Bowie

The exclusion

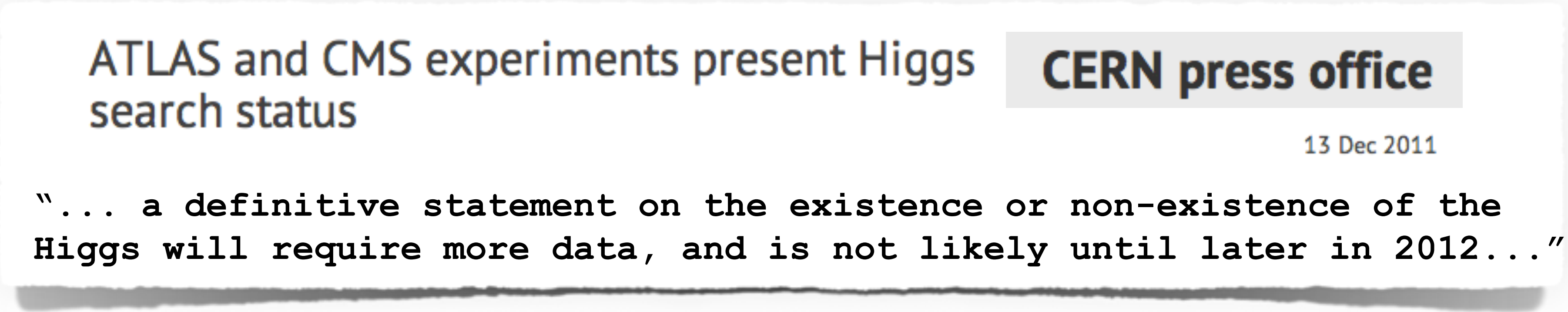
5 fb^{-1} at 7 TeV





114.4–127 GeV
Allowed m_H range
for the SM Higgs boson

3.1σ max significance in
non-excluded region ~125 GeV



ATLAS and CMS experiments present Higgs search status

CERN press office

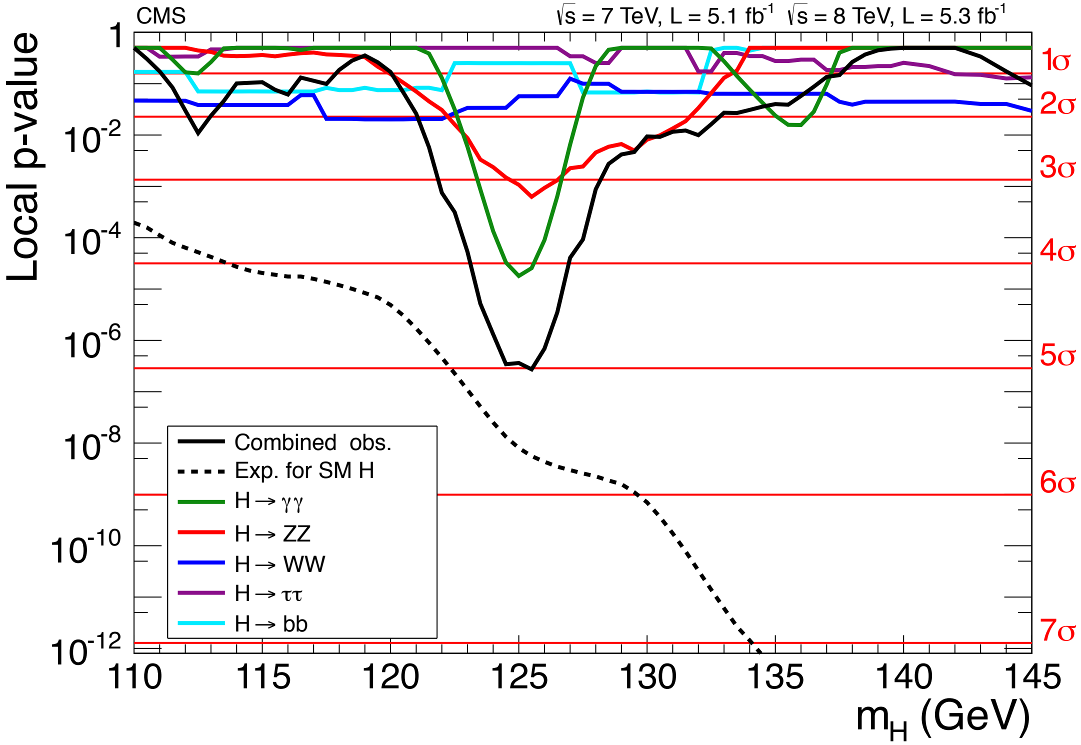
13 Dec 2011

`"... a definitive statement on the existence or non-existence of the Higgs will require more data, and is not likely until later in 2012..."`

The “Higgs-dependence” day

5 fb^{-1} at 7 TeV
5 fb^{-1} at 8 TeV

Observation of a new boson

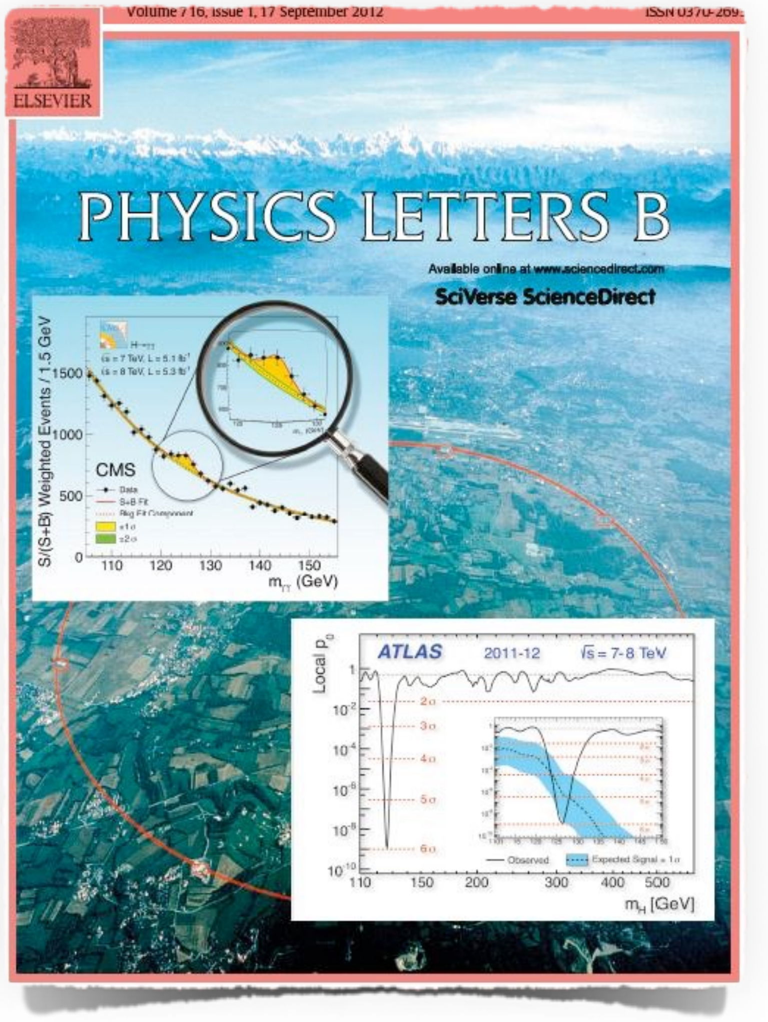


Local significance of excess 5σ

Signal strength $\sigma/\sigma_{SM} = 0.80 \pm 0.20$

$m_H = 125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$

The white paper



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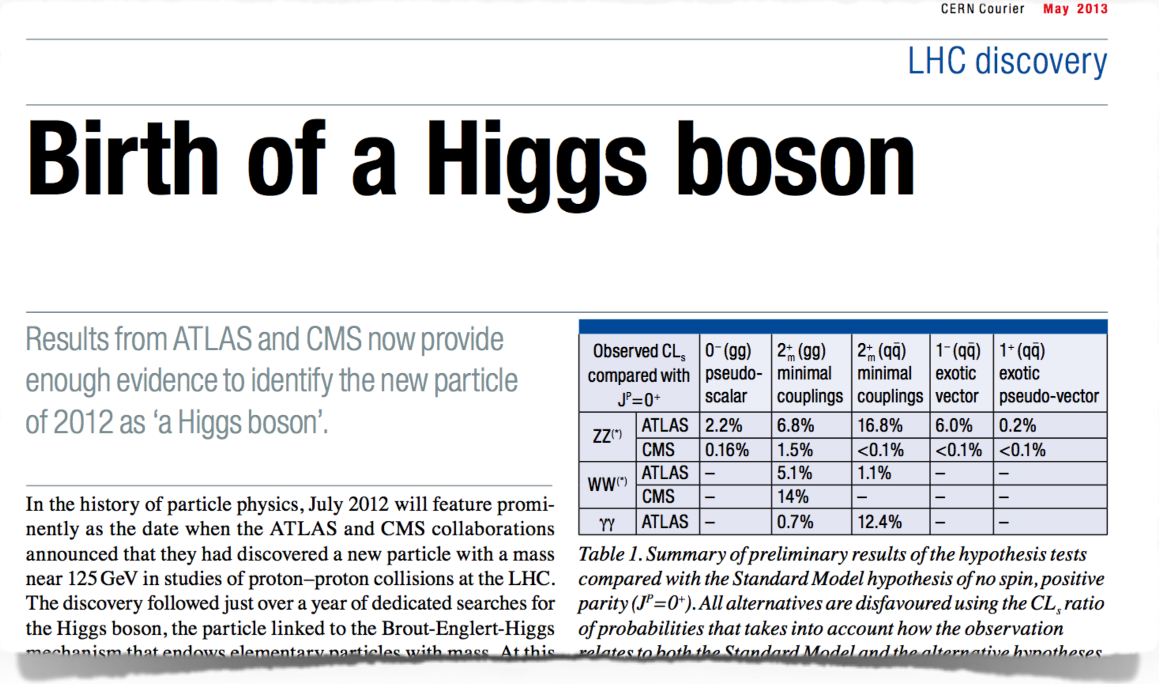
> 4500 citations…
…and counting

Birth of "a Higgs Boson"

5 fb^{-1} at 7 TeV
20 fb^{-1} at 8 TeV



CERN Courier May 2013

LHC discovery

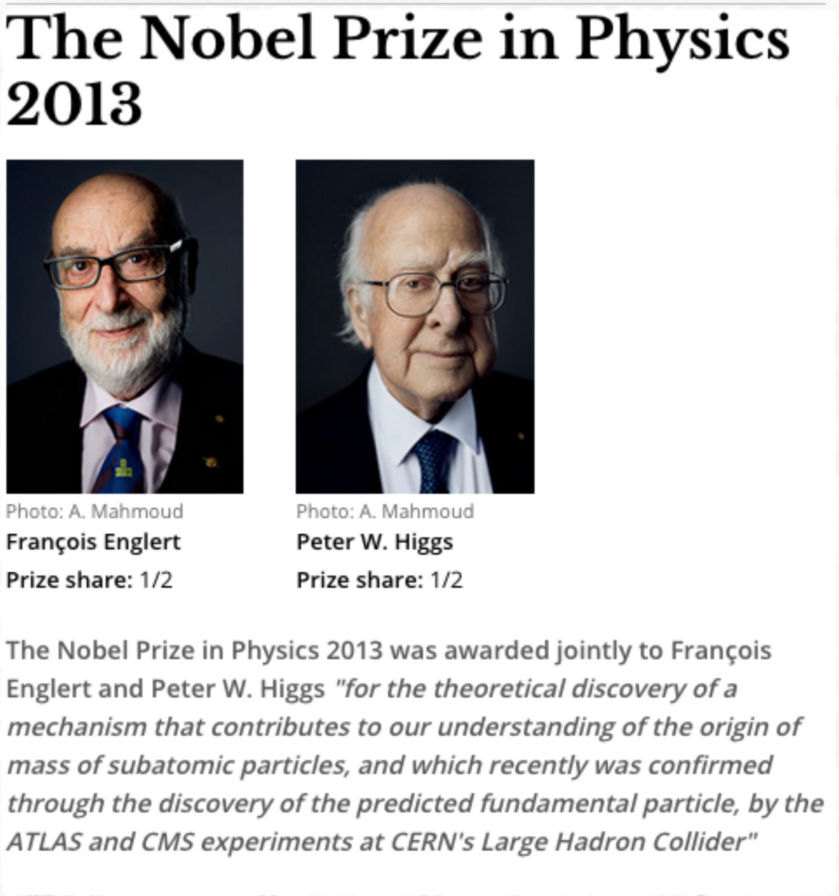
Birth of a Higgs boson

Results from ATLAS and CMS now provide enough evidence to identify the new particle of 2012 as 'a Higgs boson'.

In the history of particle physics, July 2012 will feature prominently as the date when the ATLAS and CMS collaborations announced that they had discovered a new particle with a mass near 125 GeV in studies of proton–proton collisions at the LHC. The discovery followed just over a year of dedicated searches for the Higgs boson, the particle linked to the Brout-Englert-Higgs mechanism that endows elementary particles with mass. At this

Observed CL_s compared with $J^P=0^+$		0^- (gg) pseudo-scalar	2^+_m (gg) minimal couplings	2^+_m ($q\bar{q}$) minimal couplings	1^- ($q\bar{q}$) exotic vector	1^+ ($q\bar{q}$) exotic pseudo-vector
$ZZ^{(*)}$	ATLAS	2.2%	6.8%	16.8%	6.0%	0.2%
	CMS	0.16%	1.5%	<0.1%	<0.1%	<0.1%
$WW^{(*)}$	ATLAS	–	5.1%	1.1%	–	–
	CMS	–	14%	–	–	–
$\gamma\gamma$	ATLAS	–	0.7%	12.4%	–	–

Table 1. Summary of preliminary results of the hypothesis tests compared with the Standard Model hypothesis of no spin, positive parity ($J^P=0^+$). All alternatives are disfavoured using the CL_s ratio of probabilities that takes into account how the observation relates to both the Standard Model and the alternative hypotheses



The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

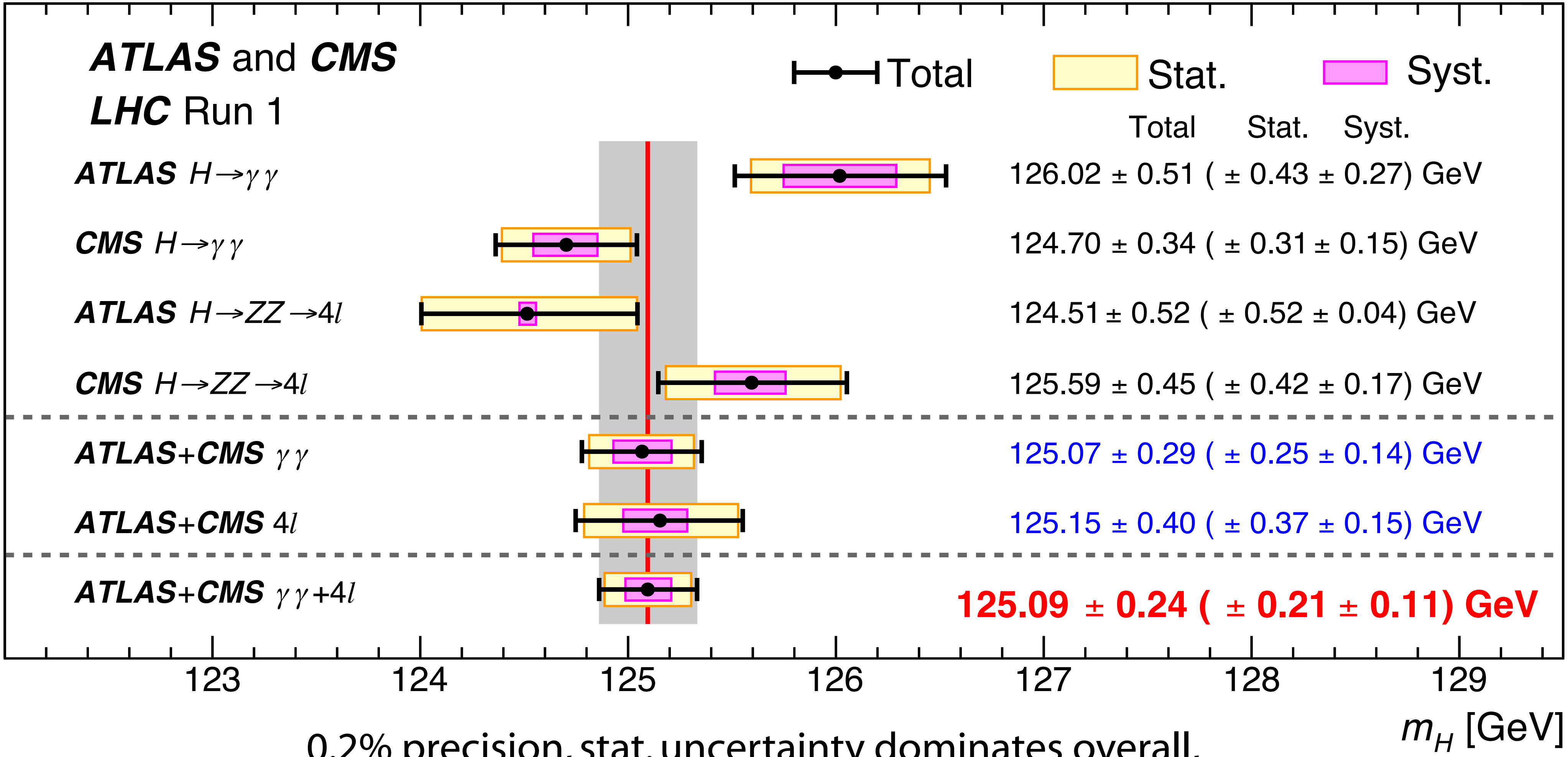
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Mass: a massive problem

5 fb^{-1} at 7 TeV
20 fb^{-1} at 8 TeV

In the SM the Higgs sector is determined by a single parameter $\boldsymbol{m_H}$

Once m_H is fixed the Higgs couplings are **determined**
(given the known particle masses OR within the precision of known particle masses)



	Total	Stat.	Syst.
ATLAS $H\rightarrow\gamma\gamma$	126.02 ± 0.51	(± 0.43	± 0.27) GeV
CMS $H\rightarrow\gamma\gamma$	124.70 ± 0.34	(± 0.31	± 0.15) GeV
ATLAS $H\rightarrow ZZ\rightarrow 4l$	124.51 ± 0.52	(± 0.52	± 0.04) GeV
CMS $H\rightarrow ZZ\rightarrow 4l$	125.59 ± 0.45	(± 0.42	± 0.17) GeV
ATLAS+CMS $\gamma\gamma$	125.07 ± 0.29	(± 0.25	± 0.14) GeV
ATLAS+CMS $4l$	125.15 ± 0.40	(± 0.37	± 0.15) GeV
ATLAS+CMS $\gamma\gamma+4l$	**125.09 ± 0.24**	**(± 0.21**	**± 0.11) GeV**

0.2% precision, stat. uncertainty dominates overall,
syst. uncertainty has big energy scale contribution (can be improved)
Among the most precise parameters of the EWK fit

The Higgs boson profile

time~~out~~line

Handles on deviations

Searches in the scalar sector: BSM Higgs

Xavier Cortada | art@CMS

The big picture

Productions

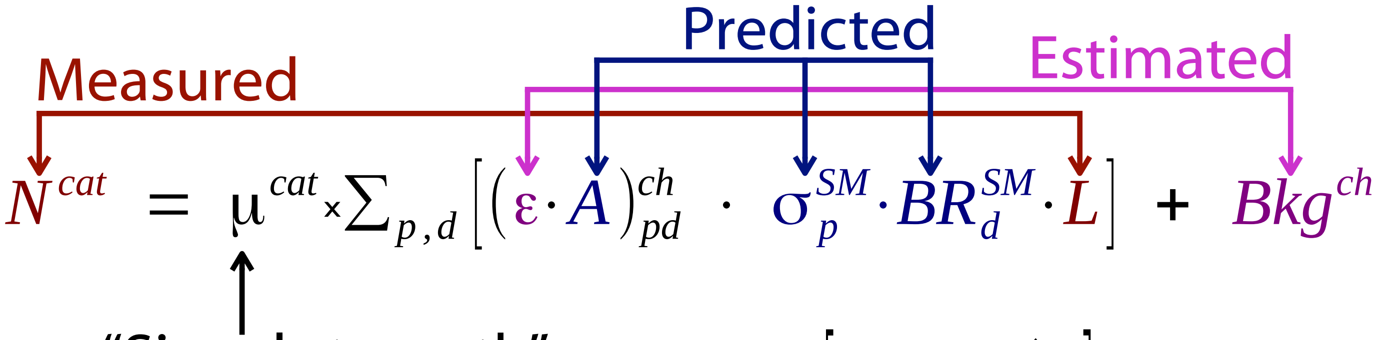
Decays

	ggH	VBF	VH	ttH	Observed (Expected) Significance	σ_m/m
$H\rightarrow ZZ$	✔	✔	✔		6.5 (6.3) σ	1-2%
$H\rightarrow WW$	✔	✔	✔	✔	4.7 (5.4) σ	15%
$H\rightarrow\gamma\gamma$	✔	✔	✔	✔	5.6 (5.3) σ	1-2%
$H\rightarrow\tau\tau$	✔	✔	✔	✔	3.8 (3.9) σ	10-20%
$H\rightarrow bb$		✔	✔	✔	2.0 (2.6) σ	10%
$H\rightarrow Z\gamma$	✔				<0.1 (0.4) σ	1-2%
$H\rightarrow\mu\mu$	✔	✔			-	
$H\rightarrow$invisible		✔	✔		-	

Characterising the Higgs boson

PRL 114 (2015) 191803

Properties of the Higgs boson can be inferred correlating the event rates measured in all the channels



Predicted

Estimated

Measured

$$N^{cat} = \mu^{cat} \times \sum_{p,d} \left[\left(\varepsilon \cdot A \right)^{ch}_{pd} \cdot \sigma^{SM}_{p} \cdot BR^{SM}_{d} \cdot L \right] + Bkg^{ch}$$

“Signal strength”

inferred via a statistical model $q(\mu) = -\ln \left[\frac{\mathcal{L}(data|\mu;\hat{\theta}_{\mu})}{\mathcal{L}(data|\hat{\mu};\hat{\theta})} \right]$

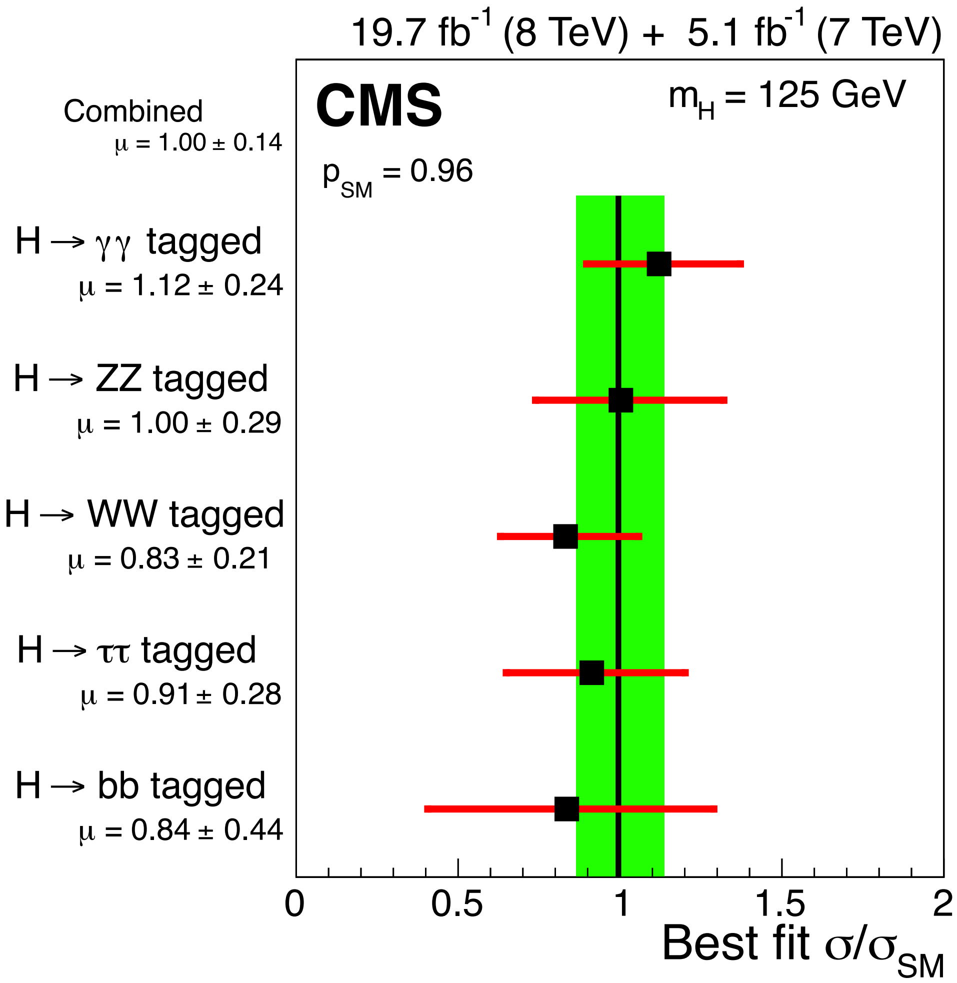
Simplest model: one overall signal strength

$$\hat{\mu} = 1.00^{+0.14}_{-0.13} \left[\pm 0.09 \left(stat \right) {}^{+0.08}_{-0.07} \left(theo \right) \pm 0.07 \left(syst \right) \right]$$

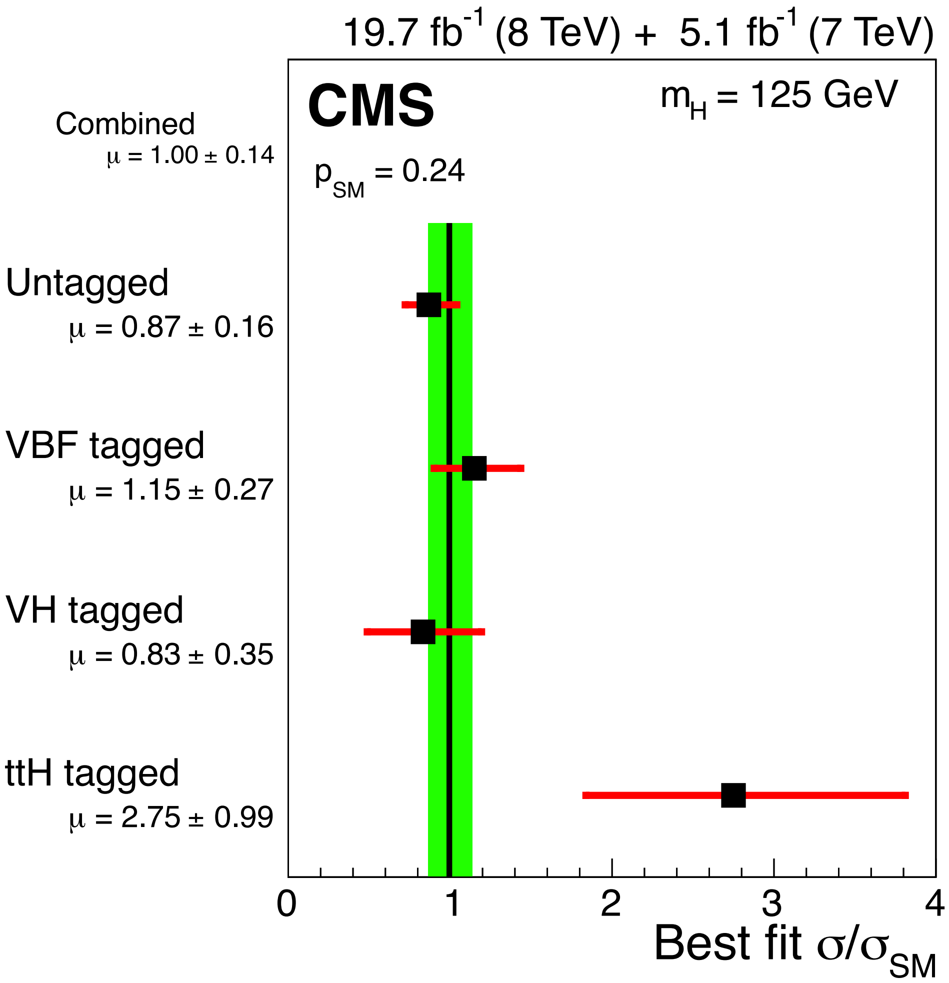
Grouping channels….

PRL 114 (2015) 191803

…by decay mode



…by production mechanism



I KEEP AN EYE ON YOU!!!

Signal strength for ttH tagged channels ~2σ higher than SM prediction
Mostly driven by excess in same-sign di-lepton channel

From signal strengths to coupling modifiers

Simplest parametrization of Higgs-couplings deviations from SM values

Assumptions

The signals observed in the different channels originate from a single narrow resonance

Zero-width approximation for the state

The tensor structure of the couplings is assumed to be the same as in the SM prediction (pure CP-even state)

$$(\sigma \times \mathrm{BR})(ii \rightarrow \mathrm{H} \rightarrow ff) = \sigma_{\mathrm{SM}}(ii \rightarrow \mathrm{H}) \times \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \rightarrow ff) \times \frac{k_i^2 k_f^2}{k_{\mathrm{H}}^2}$$

tested scaling factors

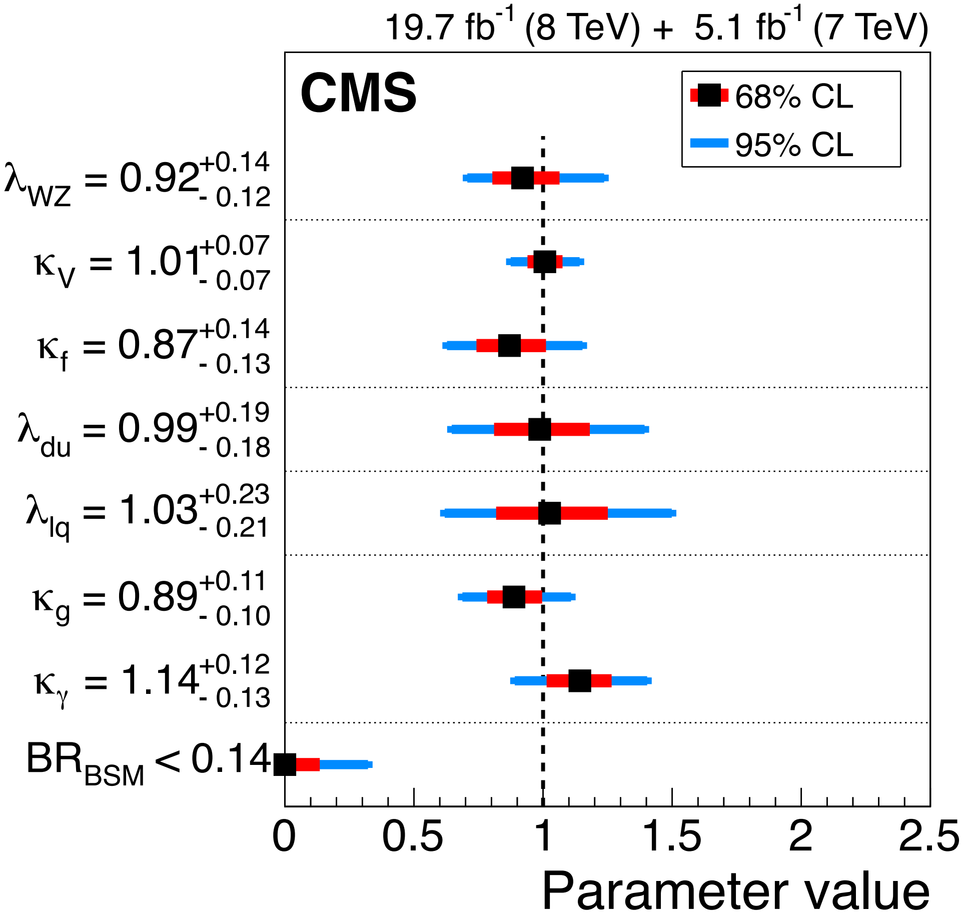
Scaling coupling thorough loop defined either:

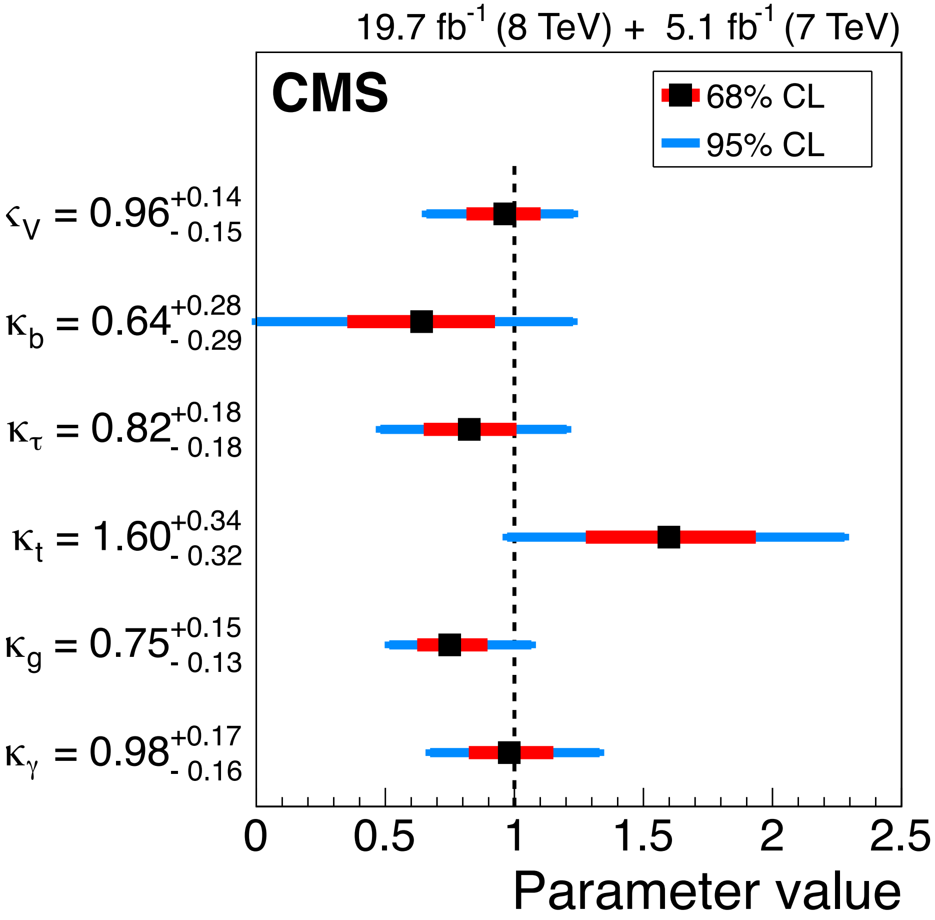
- as function of scale factors for the fields in the loop (resolved at NLO accuracy)
- as additional free parameter

Parametrise µ's in terms of k's

...models, models, models...

Custodial Symmetry
Fermion and vector boson couplings
Asymmetries in couplings to fermions
Search for BSM Physics in Loops and Decays
BSM in loops: gluons and photons.
Extra width: BR_{BSM}
Generic search for deviations





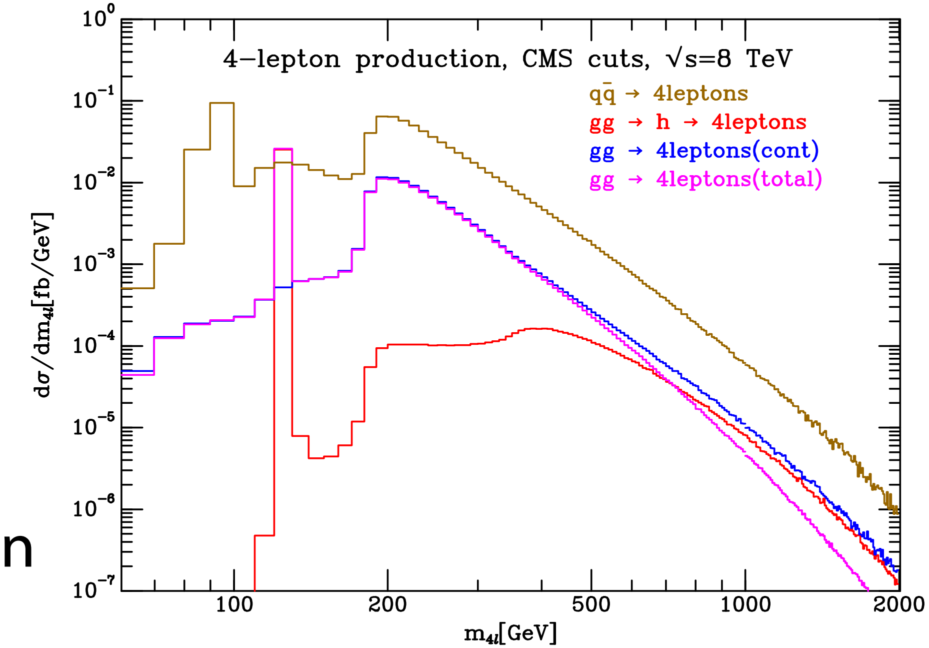
Off-shell width measurement

PLB 736 (2014) 64

The idea

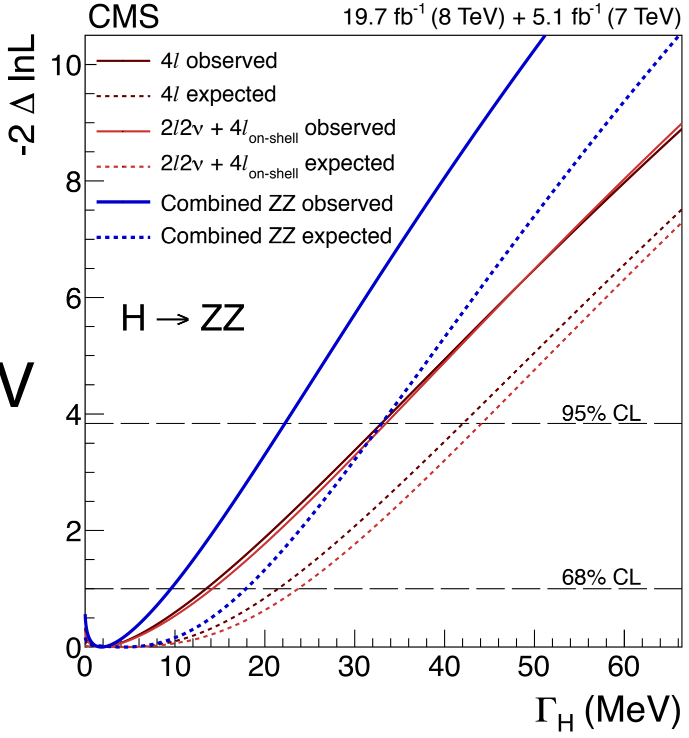
Off-shell production sizeable at high mass

About 7.6% of total cross-section, but can be enhanced by experimental cuts



On-shell / Off-shell productions comparison constraints the width

$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{(2m_Z)^2} \qquad \sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}$$



$\Gamma < 22\ (33)$ MeV

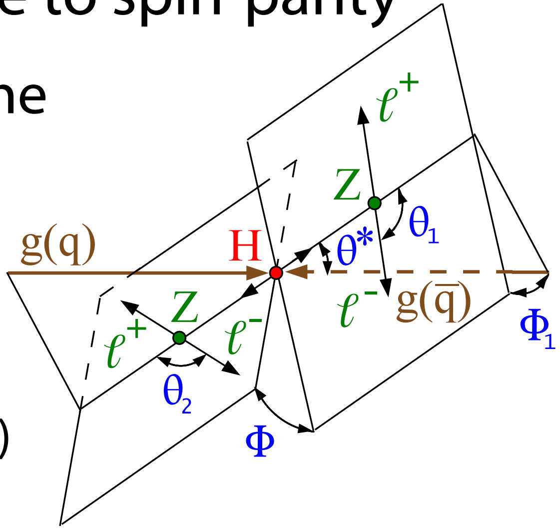
$\Gamma = 1.8^{+7.7}_{-1.8}$ MeV

CAVEAT: assuming same off-shell/on-shell couplings, i.e. no BSM particles in the off-shell loop

Spin/Parity

arXiv:1411.3441
Accepted by PRD

Kinematics of the production and decay are sensitive to spin-parity

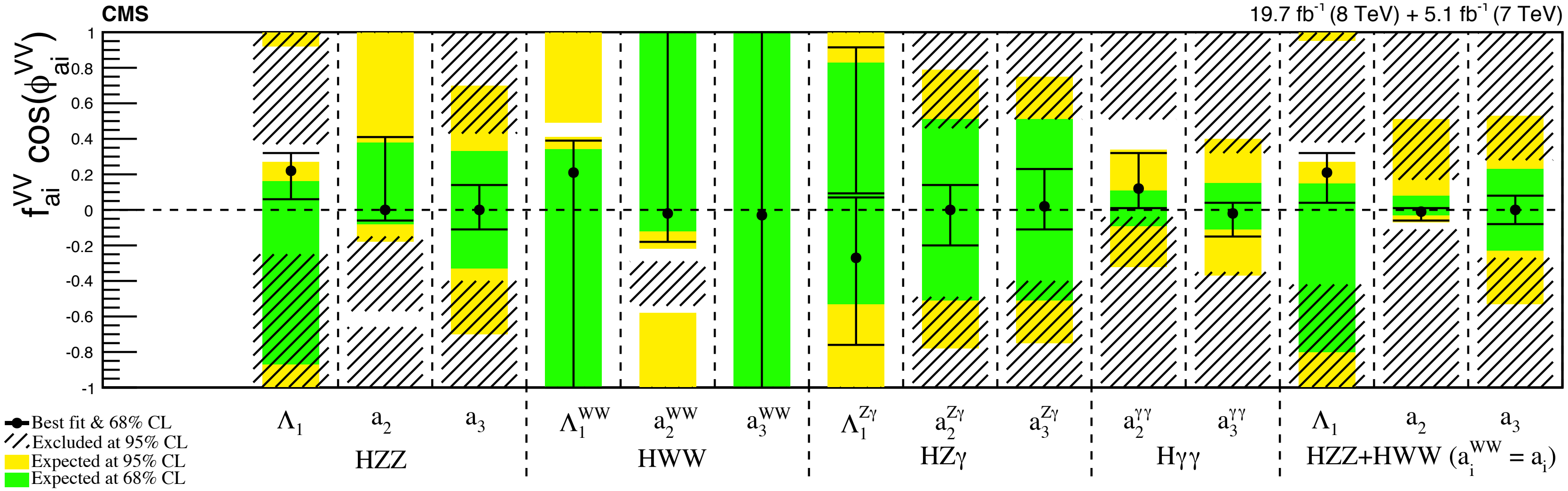


For example in H→ZZ→4ℓ to characterize the kinematics of the 2→4 process are used in a kinematical discriminant

- 5 non-trivial angles
  - production angles (θ^* ϕ)
  - helicity angles, independent of production (θ_1 θ_2 ϕ_1)
- the invariant masses of the two-fermion final states ($m^1_{\ell\ell}$ $m^2_{\ell\ell}$)

Anomalous CP couplings on Spin-0

$$A(H \to VV) \sim \left(a_1 - e^{i\phi_{\Lambda_1}} \frac{q_1^2 + q_2^2}{(\Lambda_1)^2} \right) m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + a_3 f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}$$



BSM Higgs searches

The properties of Higgs boson at the current level of precision appear to be in accord with the SM… but …

- the detailed structure of the Higgs sector is still unclear
- the SM cannot be a final theory

Beyond the SM (2HDM, MSSM/NMSSM) might hold the answer

- Exotic Higgs decays
    - Search for lepton flavour violating decays of Higgs boson
    - Search for exotic decays of a Higgs boson into undetectable particles and photons

- Low mass Higgs
    - Search for pair production of new light bosons decaying into muons

- High mass Higgs
    - Search for pseudoscalar A boson decaying into a Z boson and H_{125} boson
    - Search for scalar boson decaying into a VV bosons

- Invisible Higgs decays

Lepton Flavour Violating: H→μτ

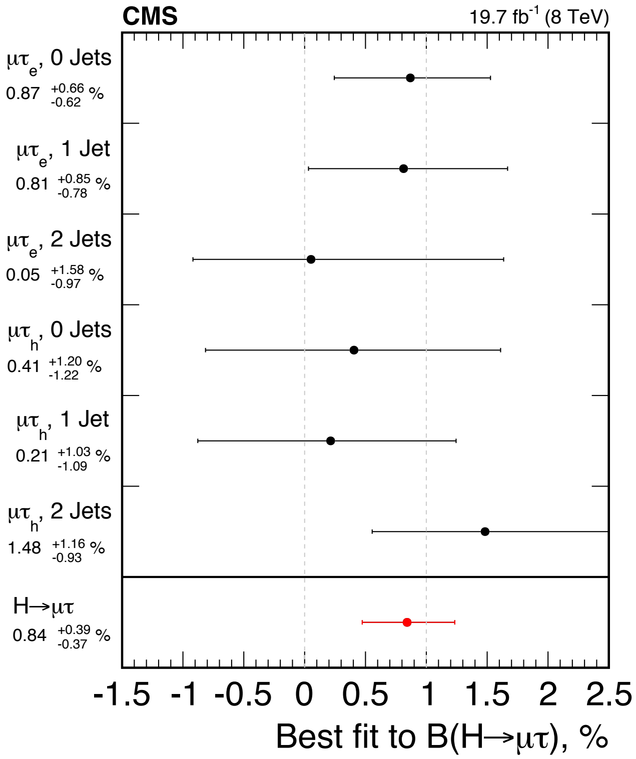
arXiv:1502.07400
Submitted to PLB

Lepton Flavour Violating (LFV) decays are not allowed in SM

exception can occur in case it is a theory valid only to a finite mass scale

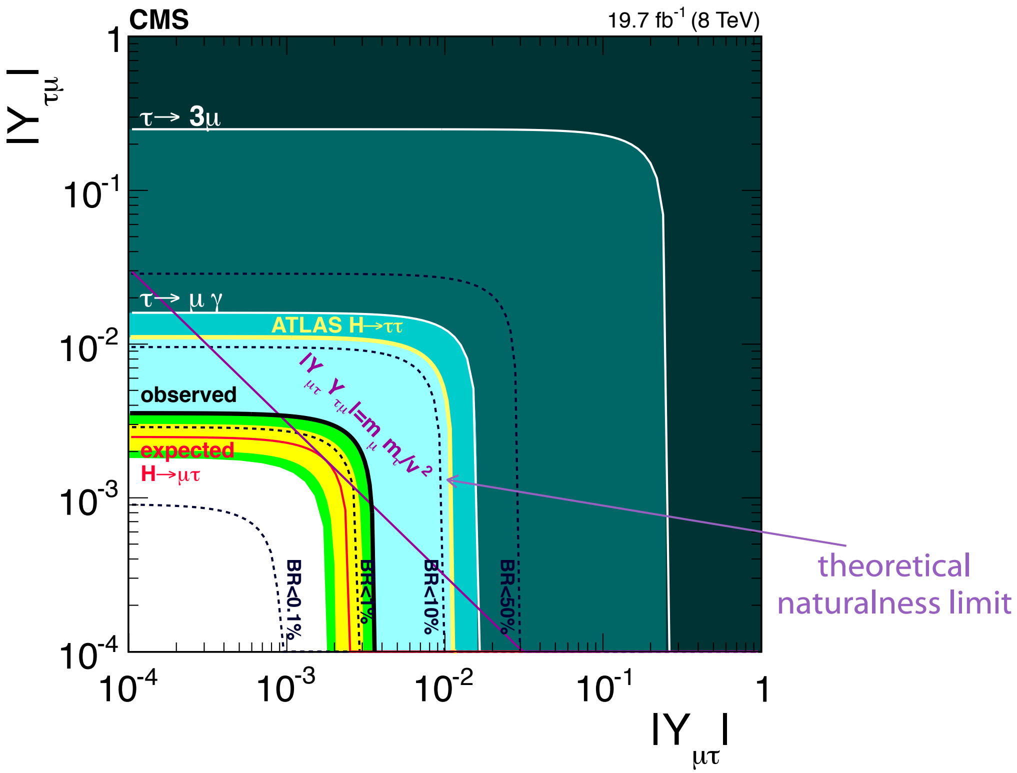
LFV decays can occur in 2-Higgs Doublet Models (2HDM), and others…

$$\begin{pmatrix} y_{ee} & y_{e\mu} & y_{e\tau} \\ & y_{\mu\mu} & y_{\mu\tau} \\ & & y_{\tau\tau} \end{pmatrix}$$



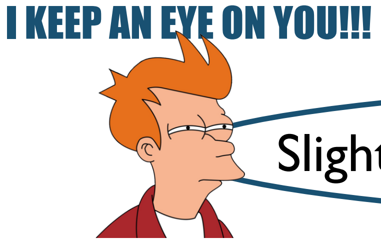
Interpreted as a signal:

$B(H \to \mu\tau) = (0.89^{+0.40}_{-0.37})\%$



Yukawa Couplings $Y_{\mu\tau}$ and $Y_{\tau\mu}$

97% C.L.: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}$

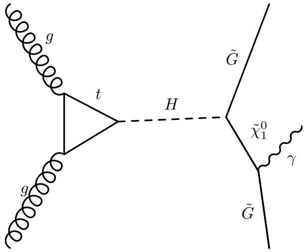


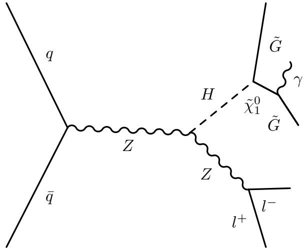
Slight excess of signal events with a significance of 2.5σ is observed in 8 TeV data

Undetectable particles and photons decays

arXiv:1507.00359
Submitted to PLB

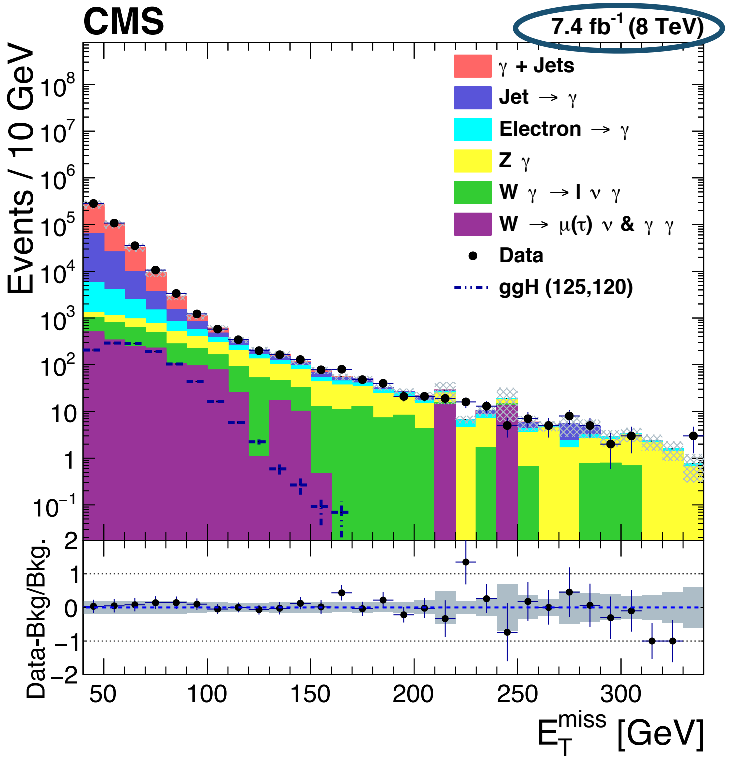
In certain low-scale SUSY models, the Higgs bosons are allowed to decay into a gravitino and a neutralino or a pair of neutralinos

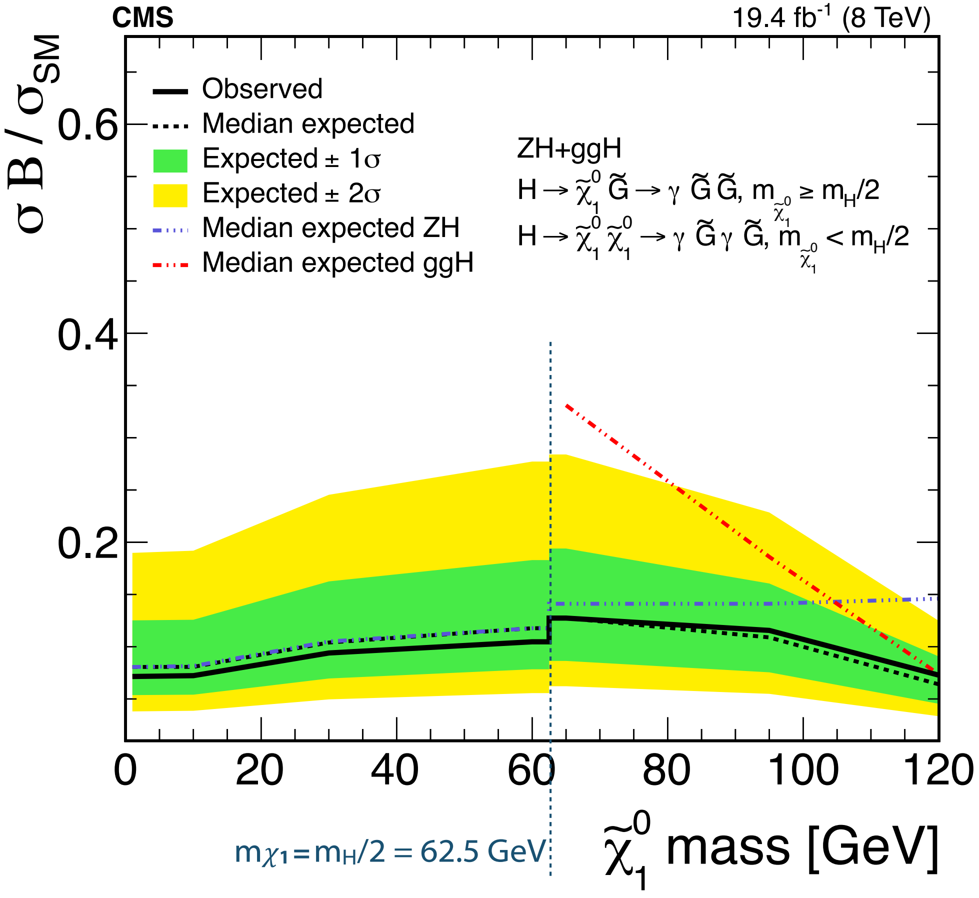




$m_{\chi_1} > m_H/2$

For $H \rightarrow \gamma$+MET final state using trigger from CMS **"data parking"** program





$m_{\chi_1} = m_H/2 = 62.5$ GeV

Upper limit in the range of 7 to 13%

Low mass Higgs

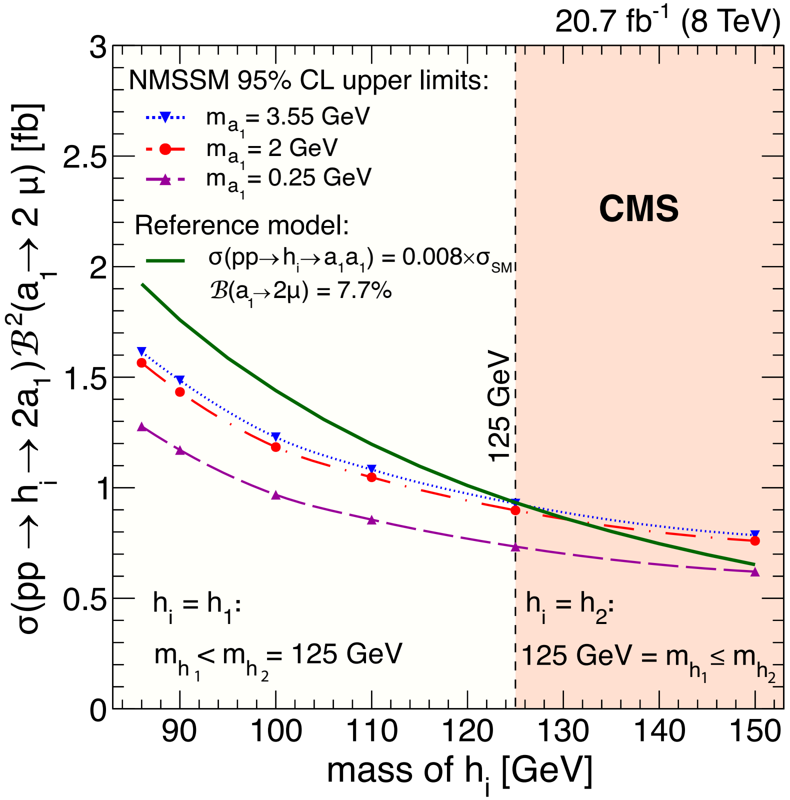
arXiv:1506.00424
Submitted to PLB

Search of light Higgs boson $h \to 4\mu$ model independent search motivated by several models beyond SM

Benchmark 1

NMSSM $h_{1,2} \to 2a_1 \to 4\mu$

Minimal extension of the MSSM adding a scalar singlet to 2HDM



$h_{1,2} \to 2a_{1,2}$ can have a significant BR

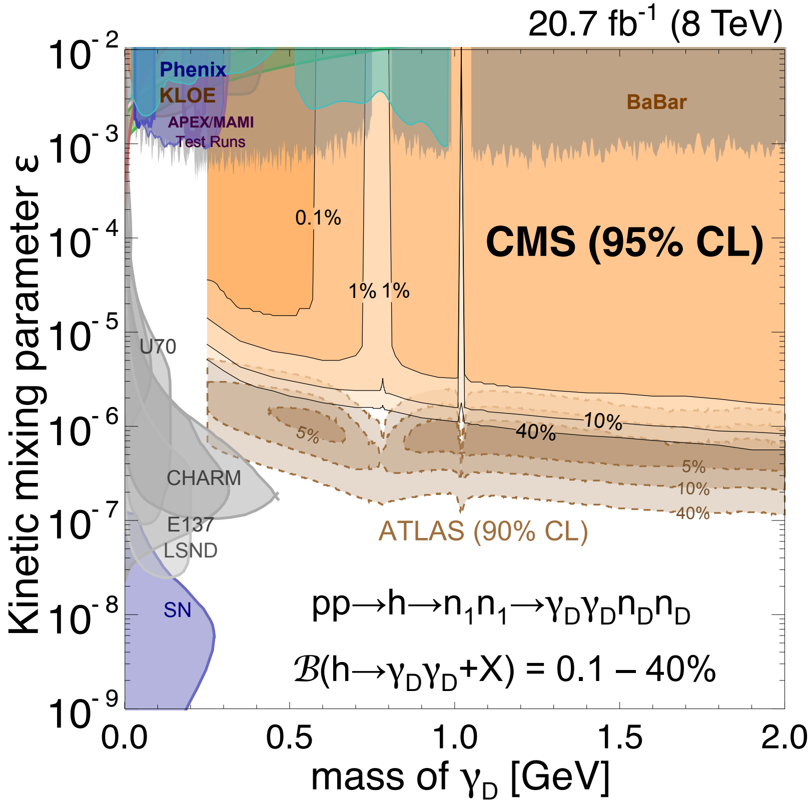
$a_{1,2} \to 2\mu$ for $2m_\mu < m_{a1} < 2m_\tau$

$BR(a_1 \to 2\mu) \approx 7.7\%$ for $2m_{a1} = 2$ GeV

Benchmark 2

Dark SUSY $h \to 2n_1 \to 2n_D + 2\gamma_D \to 4\mu$

able to explain the positron excess in cosmic rays observed by PAMELA, Fermi



n_D escapes to detection

$BR(\gamma_D \to 2\mu) > 45\%$

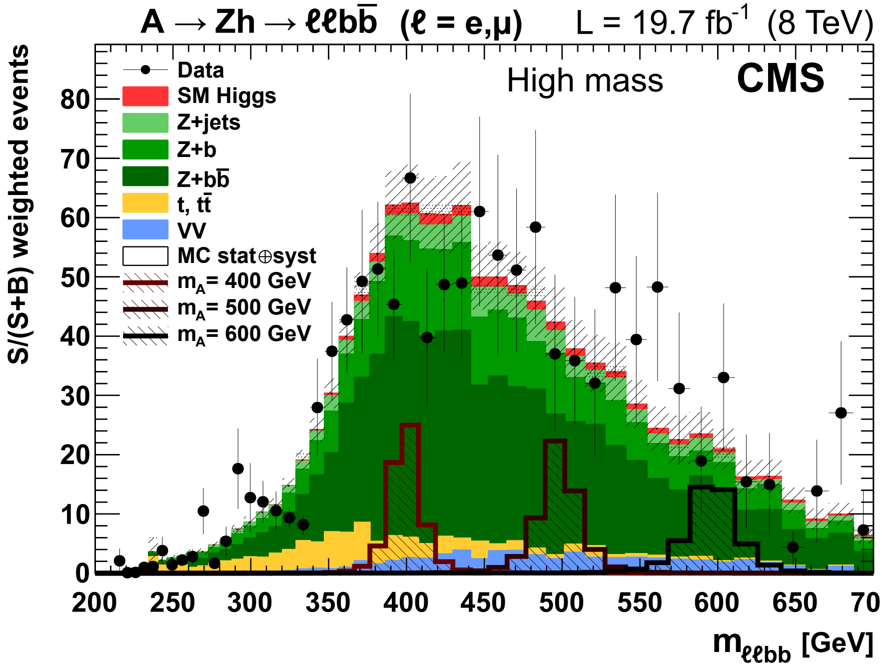
High mass Higgs: A → Zh → llbb

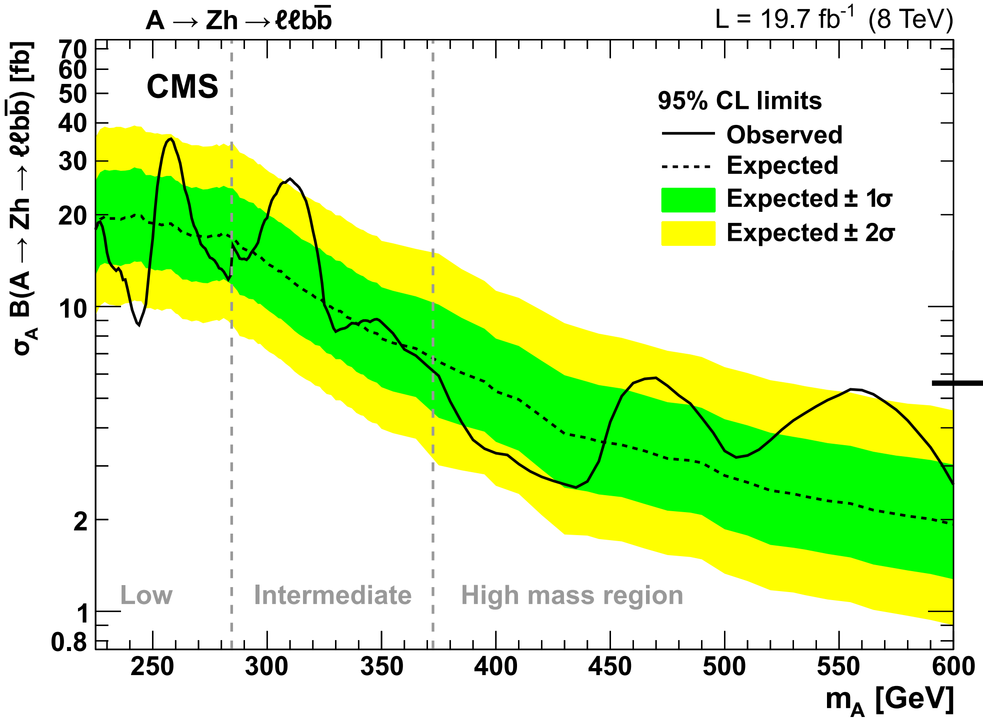
arXiv:1504.04710
Submitted to PLB

Searches for a heavy Higgs decaying into lighter Higgs in the MSSM

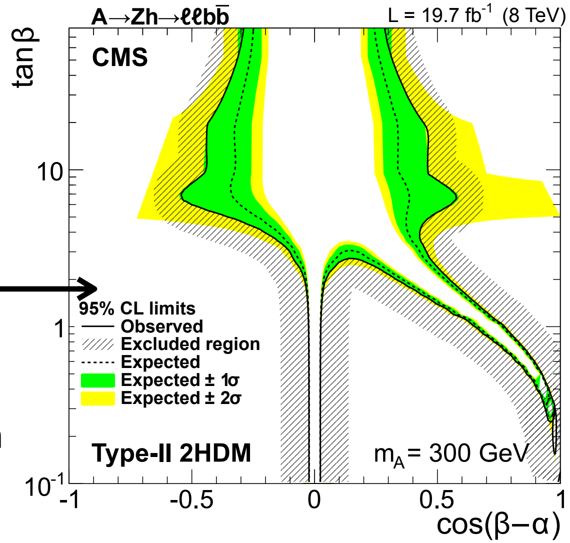
In addition to the SM Higgs scalar doublet, a second one is added to these models, giving rise to five physical states, the model is described in terms of free parameters tanβ and cos(β-α)

	Type I	Type II
K_u	sinα/sinβ	sinα/sinβ
K_d	sinα/sinβ	cosα/cosβ
K_f	sinα/sinβ	cosα/cosβ
K_V	cos(β-α)	cos(β-α)





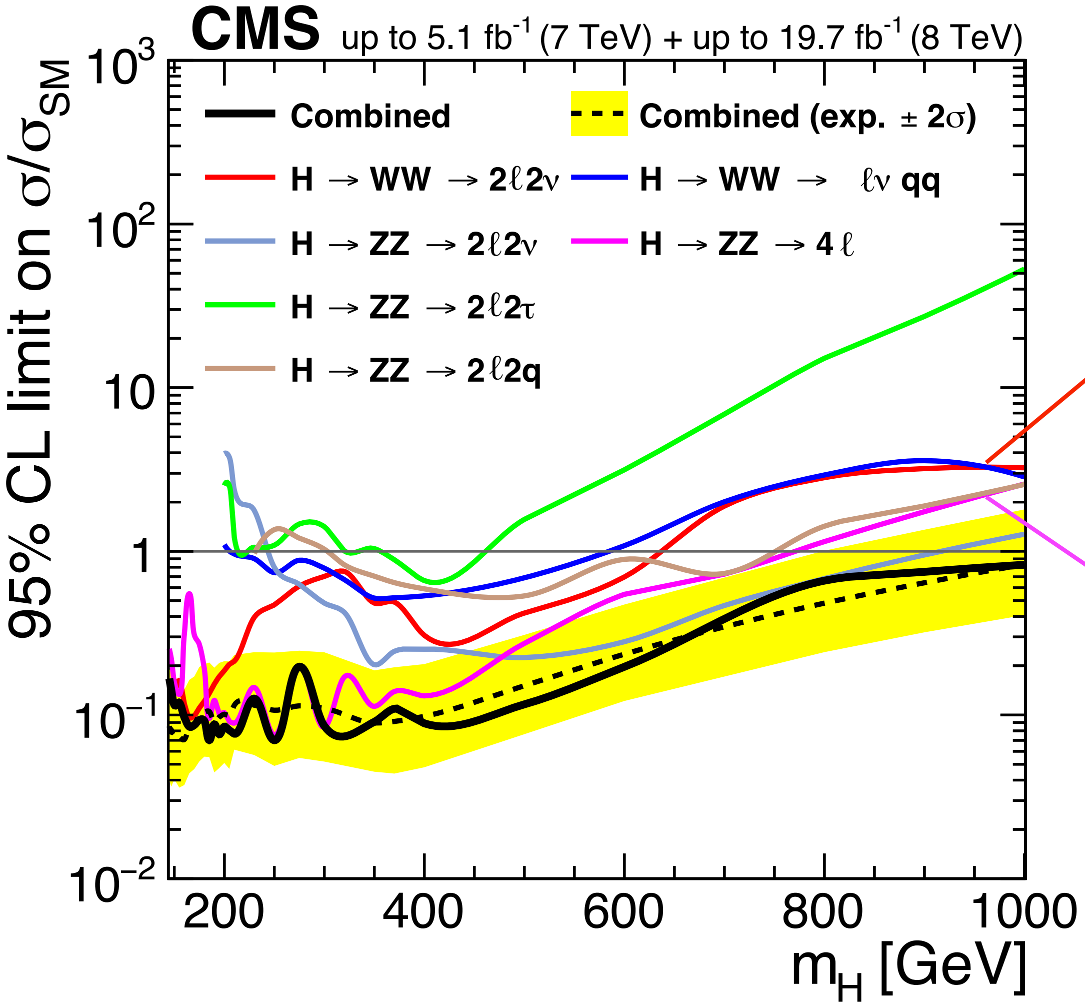
Exclusion limit for Type-I and Type-II models projected in (tanβ, cos(β-α))

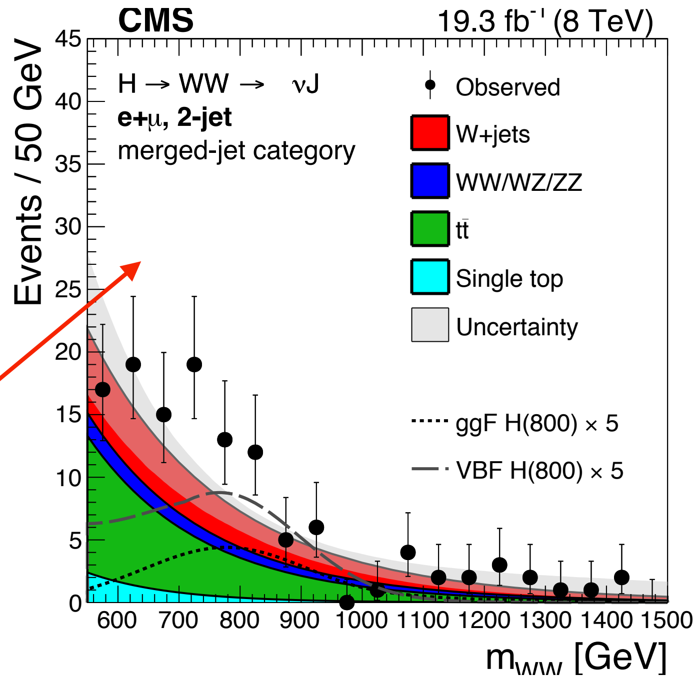


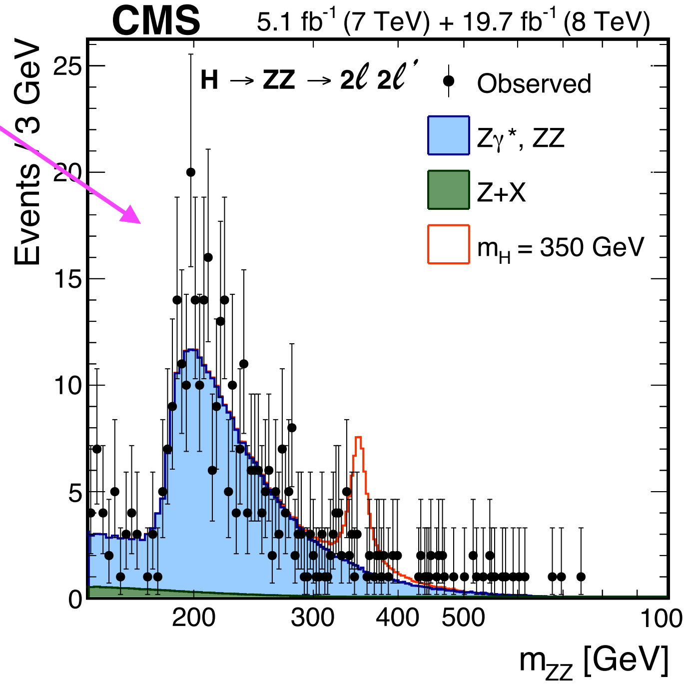
High mass Higgs: VV resonances

arXiv:1504.00936
Submitted to JHEP

Combined WW→ℓνℓν, ℓνqq′; ZZ→ℓℓℓℓ, ℓℓνν, ℓℓqq





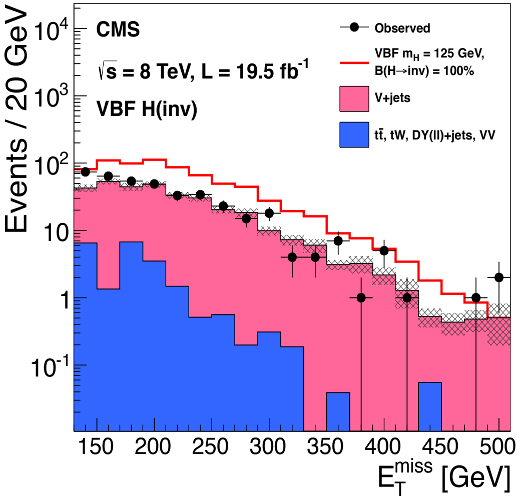


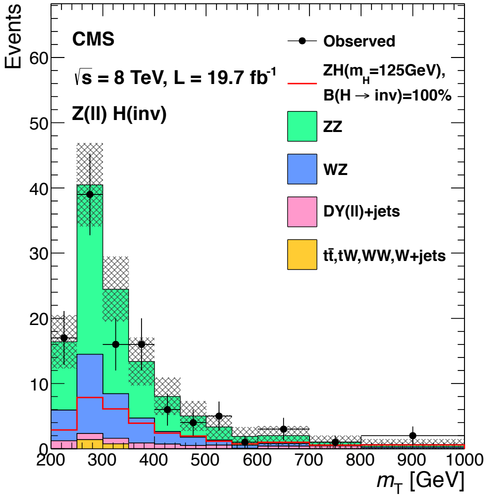
Assuming SM couplings and decays:
95% C.L. exclusion in the **145 GeV < m_H < 1 TeV** range
Also interpreted as bounds on EW singlet parameters

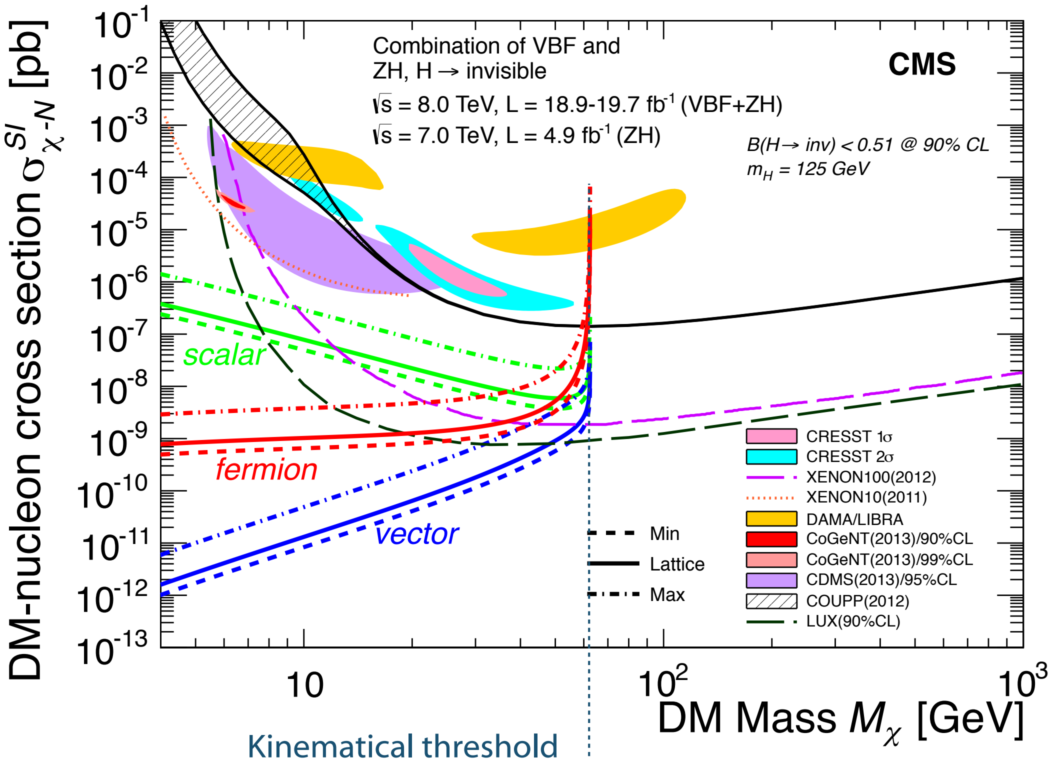
Invisible decays

EPJC 75 (2015) 212

A search for invisible decays of Higgs bosons is performed using the vector boson fusion and associated ZH production modes







Kinematical threshold
$m_{DM} = m_H/2 = 62.5$ GeV

95% CL limits on BR at m_H=125 GeV

Channel	Observed	Expected
qqH	0.57	0.40
ZH, Z→ll	0.83	0.86
ZH, Z→bb	1.82	1.99
Combined	0.47	0.35

$$\sigma^{SI}_{S-N} = \frac{\lambda^2_{hSS}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_S + m_N)^2}$$

Scalar DM

$$\sigma^{SI}_{V-N} = \frac{\lambda^2_{hVV}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_V + m_N)^2}$$

Vector DM

$$\sigma^{SI}_{f-N} = \frac{\lambda^2_{hff}}{4\pi \Lambda^2 m_h^4} \frac{m_N^4 M_f^2 f_N^2}{(M_f + m_N)^2}$$

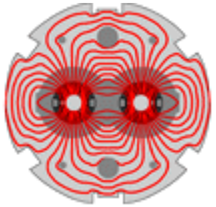
Majorana DM

time ~~Out~~line

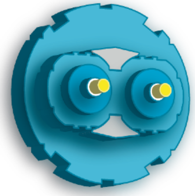
Next on the road

RUN2, end of Phase1, HL-LHC

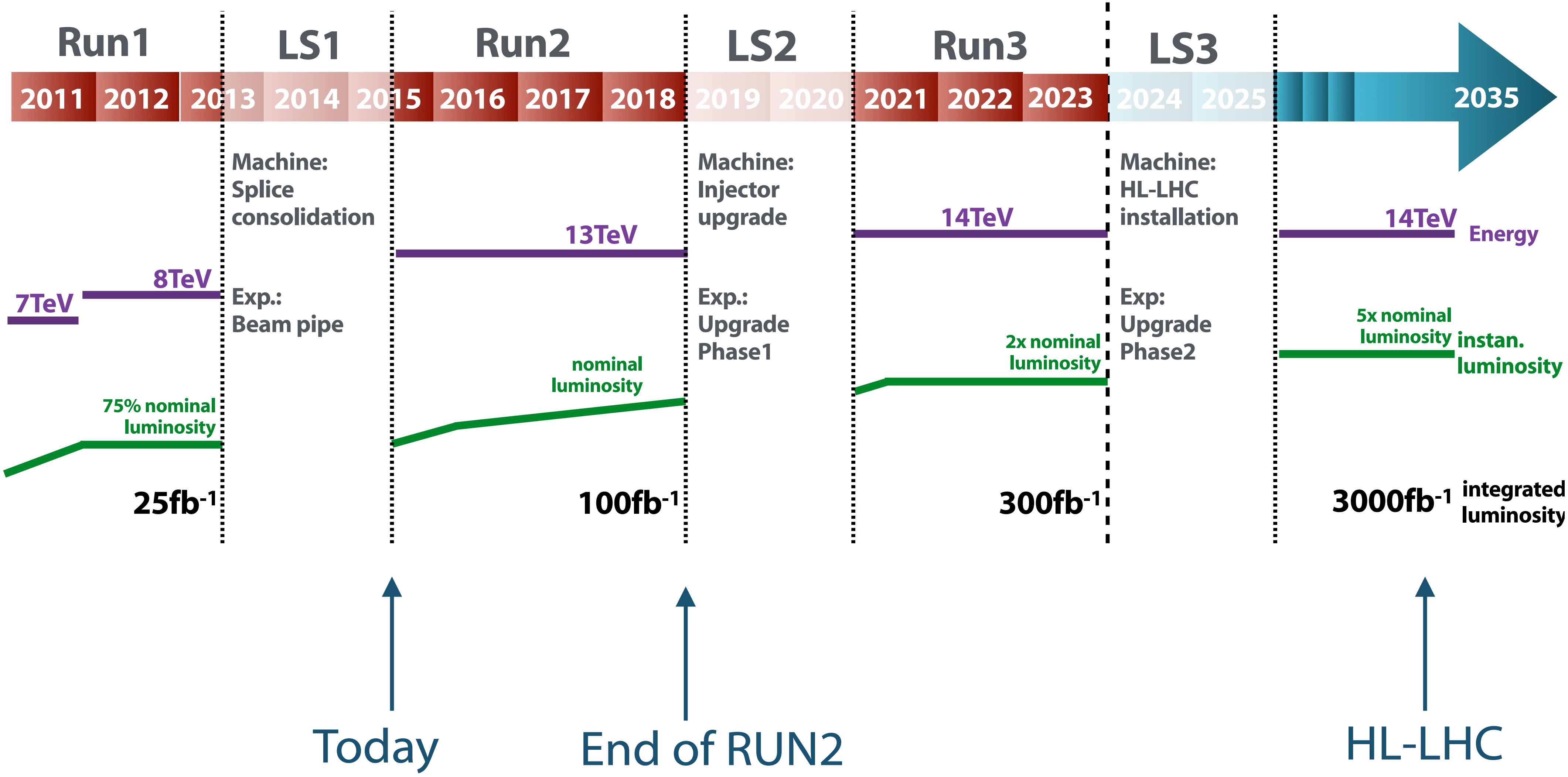
LHC and HL-LHC plans



LHC



High Luminosity LHC



Run1 | LS1 | Run2 | LS2 | Run3 | LS3

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2035

Machine: Splice consolidation

Exp.: Beam pipe

Machine: Injector upgrade

Exp.: Upgrade Phase1

Machine: HL-LHC installation

Exp: Upgrade Phase2

7TeV 8TeV 13TeV 14TeV 14TeV Energy

75% nominal luminosity | nominal luminosity | 2x nominal luminosity | 5x nominal luminosity instan. luminosity

$25 fb^{-1}$ $100 fb^{-1}$ $300 fb^{-1}$ $3000 fb^{-1}$ integrated luminosity

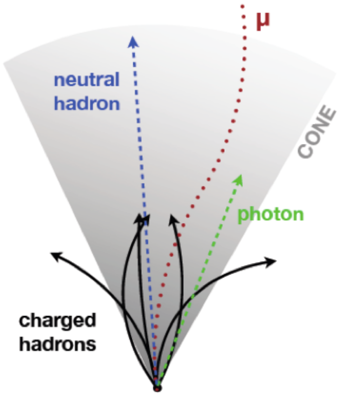
Today

End of RUN2

HL-LHC

Before RUN2 start

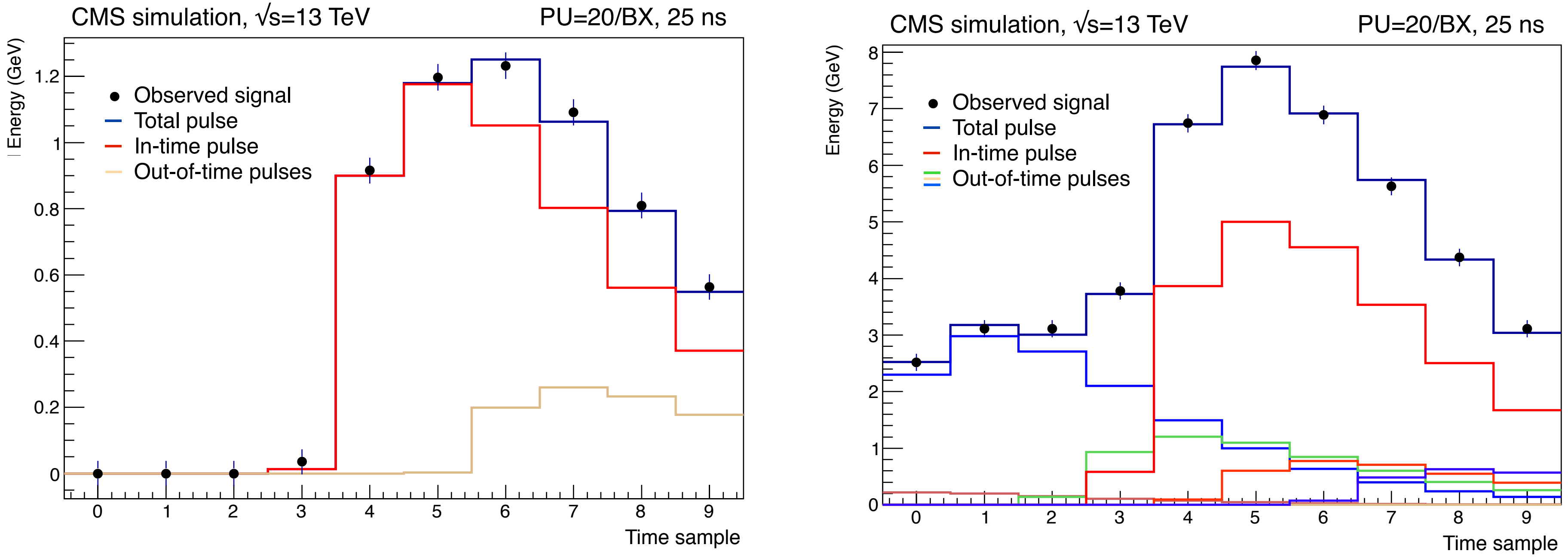
Incorporating knowledge/experience/developments/optimization from Higgs analyses into default reconstruction (Global Event Description)



Improved Monte Carlo simulation

- NLO+PS QCD description for all Higgs production modes
- merged NLO+PS QCD accuracy for additional jets

New calorimeter local reconstruction to mitigate out-of-time pileup with 25ns bunch spacing



Higgs boson physics at Run2 100fb^{-1}

Rediscover the Higgs boson at 13 TeV

First 13 TeV fiducial/differential cross-section measurements

Observe the Higgs boson more exclusive production and decay modes

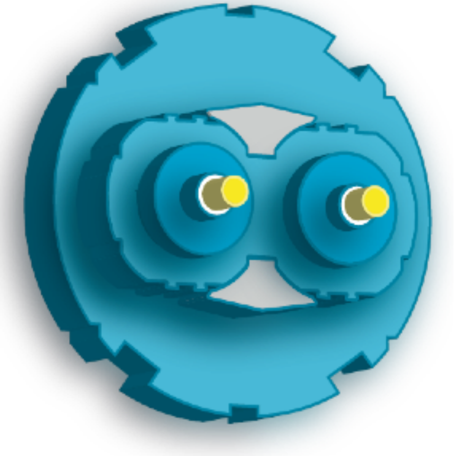
Follow the few excess of signal events (LFV, ttH, …) observed in Run1 data

Look for additional Higgs-like particles or partners at high masses

Extension to the Higgs Effective Field Theory

- Major change of paradigm
  - → Analyses not designed only for signal but also for pseudo-observables
  - → Our understanding of backgrounds will change too
  - → Including LEP data?

Higgs boson physics at HL-LHC $3000fb^{-1}$



SM Higgs

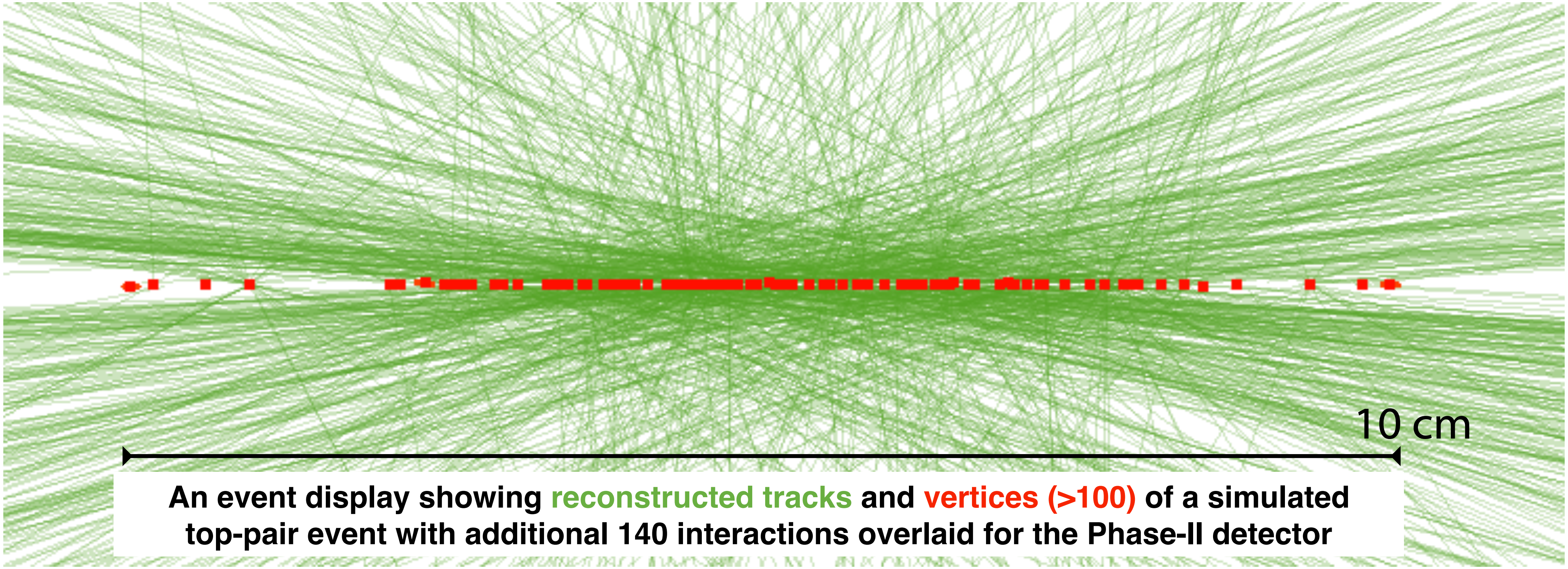
- Possibility to measure all the production modes
- High precision coupling measurements
- Rare decays
- Higgs boson pair production

BSM Higgs

- Extended scalar sector (direct/indirect searches)
  - heavy Higgs, charged Higgs, composite Higgs, MSSM
- Couplings to Dark Matter

The main challenge

Harsh pile-up conditions and instantaneous rate



An event display showing reconstructed tracks and vertices (>100) of a simulated top-pair event with additional 140 interactions overlaid for the Phase-II detector

Necessary conditions:

→ maintain event reconstruction performances

→ trigger in a high luminosity environment

The CMS Phase2 Upgrade

Trigger / HLT /DAQ

Track information at L1 trigger

L1-trigger – 12.5 μs latency / 750 kHz output

HLT output 7.5 kHz

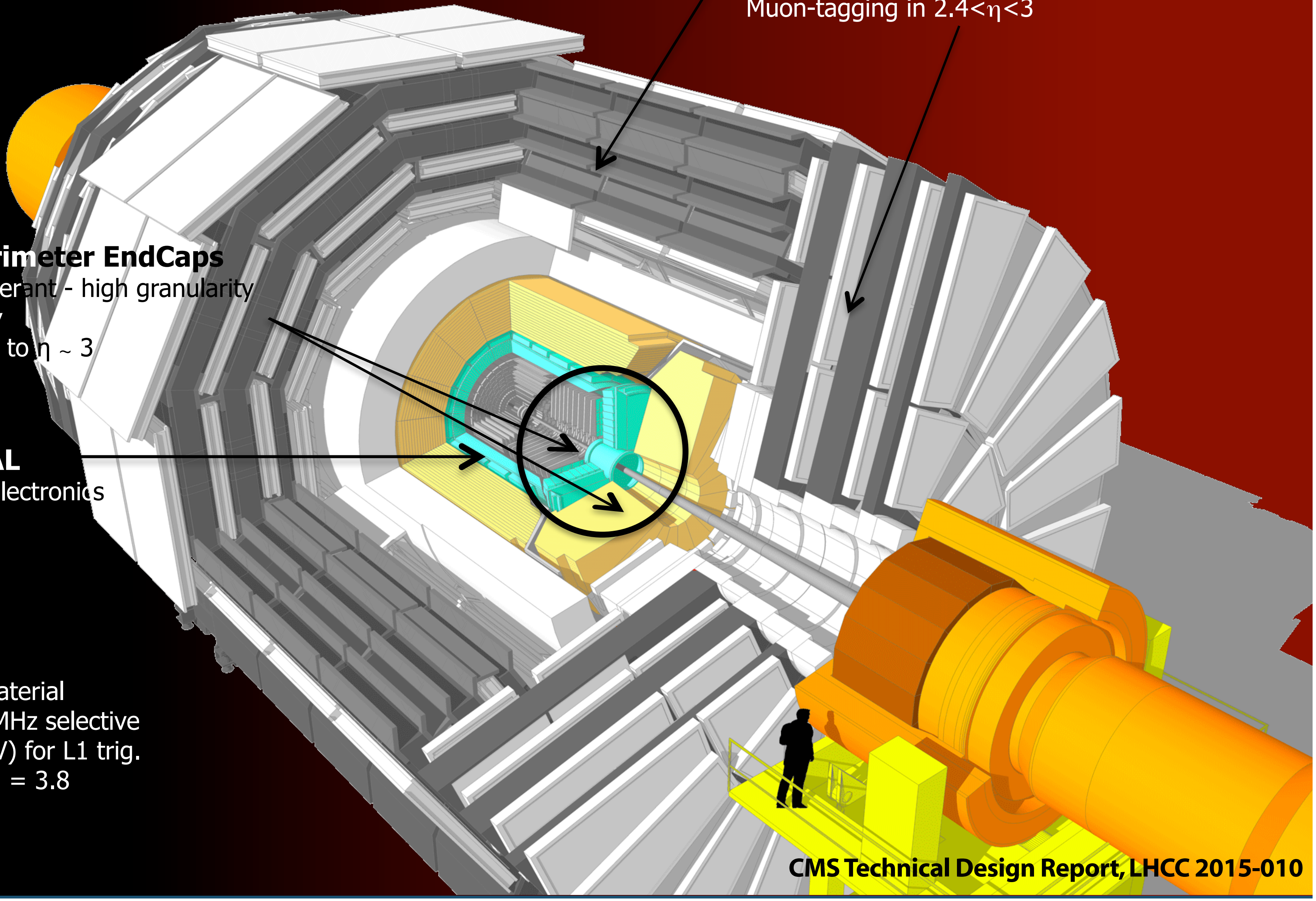
Muons

Replace DT & CSC FE+BE electronics

Complete RPC coverage in $1.5<\eta<2.4$

(new GEM/RPC technology)

Muon-tagging in $2.4<\eta<3$



New Calorimeter EndCaps

Radiation tolerant - high granularity

5D capability

Coverage up to $\eta \sim 3$

Barrel ECAL

Replace FE electronics

New Tracker

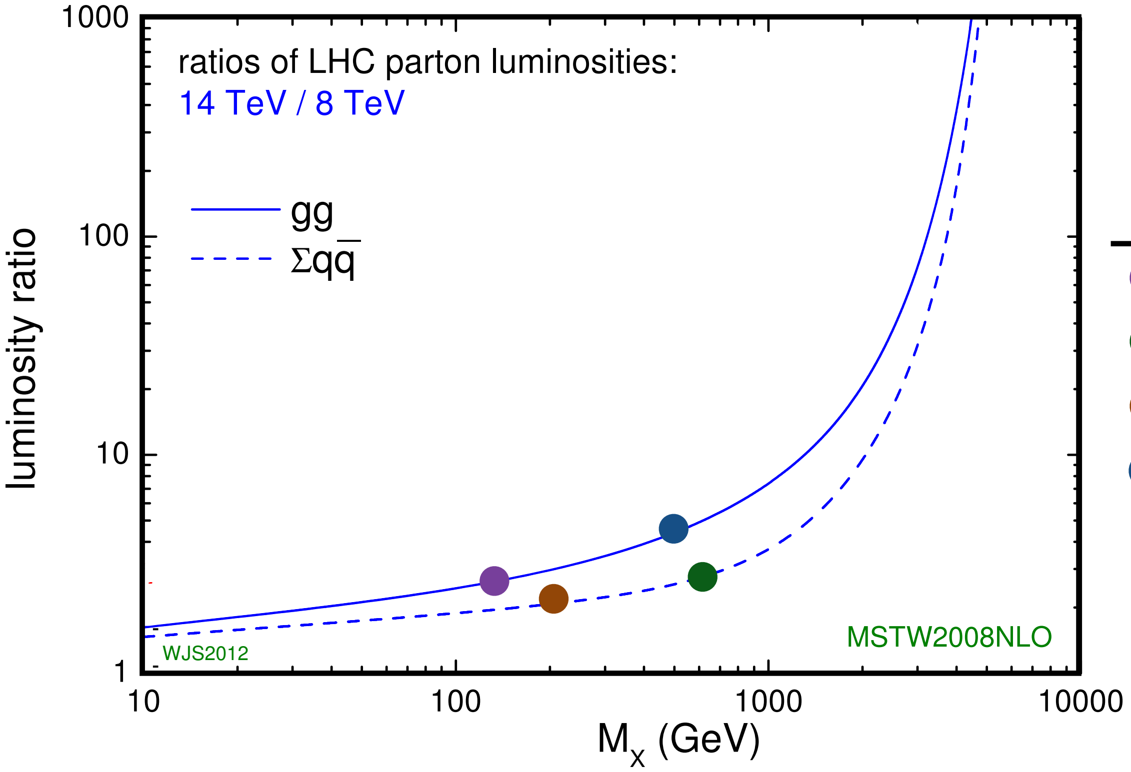
Rad. tolerant – low material

High granularity – 40MHz selective readout (P_T > 2 GeV) for L1 trig.

Extend coverage to η = 3.8

CMS Technical Design Report, LHCC 2015-010

HL-LHC is a Higgs boson factory



	$\sigma_{14TeV}/\sigma_{8TeV}$	σ_{14TeV} [pb]
● gg→H	2.6(M_X=M_H)	49.5
● qq→qqH	2.6(high M_X)	4.2
● qq→VH	2.1(M_X=M_V+M_H)	1.5/1
● gg→ttH	4.7(M_X=2M_t+M_H)	0.6

Higgs boson candidates for 3000 fb^{-1} at 14 TeV:

ggF	**VBF**	**WH**	**ZH**	**ttH**	**total**
148M	**13M**	**4.6M**	**2.9M**	**1.8M**	**170M**

→ have access to rare(r) Higgs boson production and decay modes

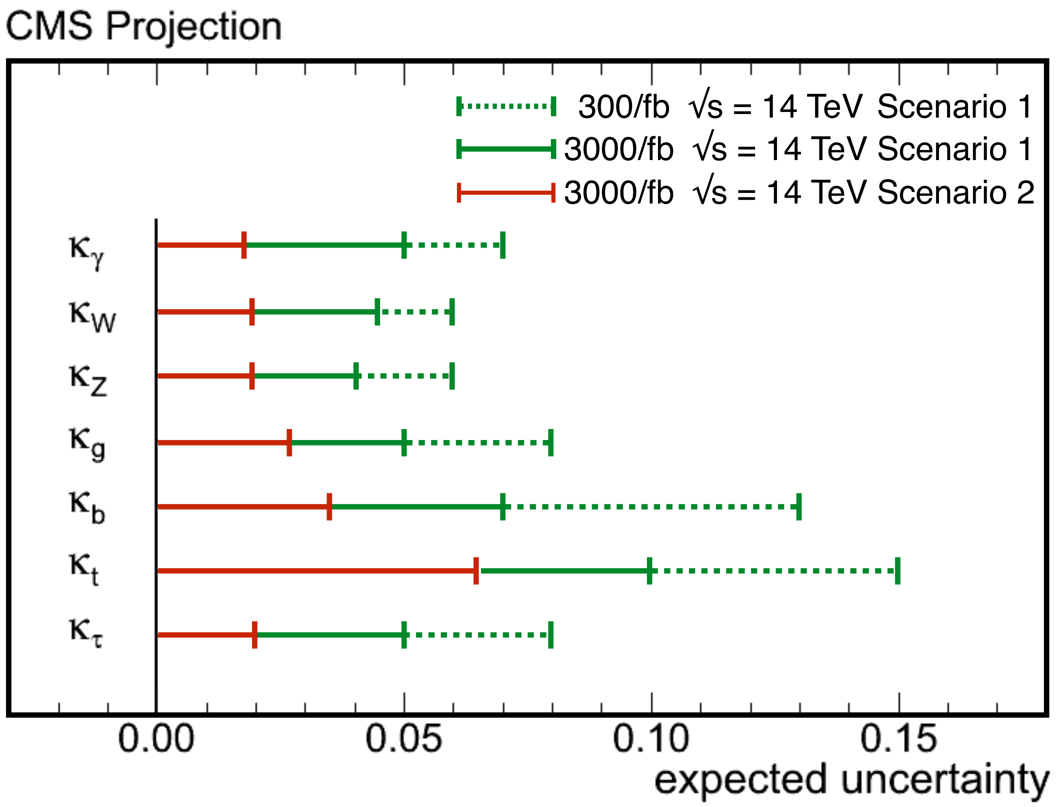
260K tH candidates, 140K HH candidates

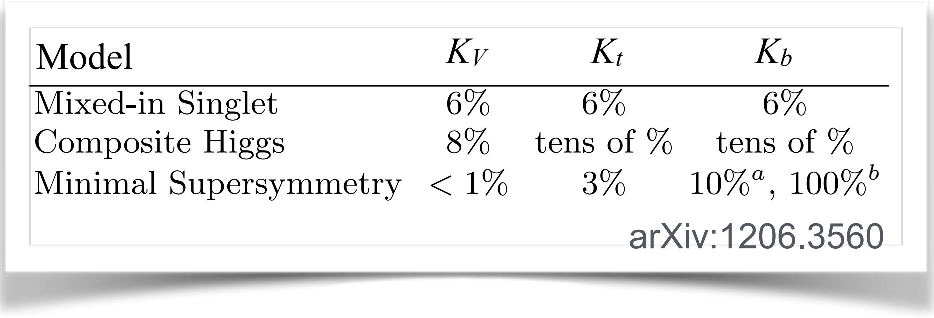
$BR_{H\rightarrow\mu\mu}$ = 0.021% $BR_{H\rightarrow Z\gamma}$ = 0.15% ($BR_{H\rightarrow Z\gamma\rightarrow ll\gamma}$ = 0.01%)

High precision coupling measurements

CERN-LHCC-2015-010

Expected uncertainties on Higgs boson couplings





Model	K_V	K_t	K_b
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	$10\%^a$, $100\%^b$

arXiv:1206.3560

Maximum deviation in (plausible) BSM scenarios for which there are not another EWSB states accessible at LHC

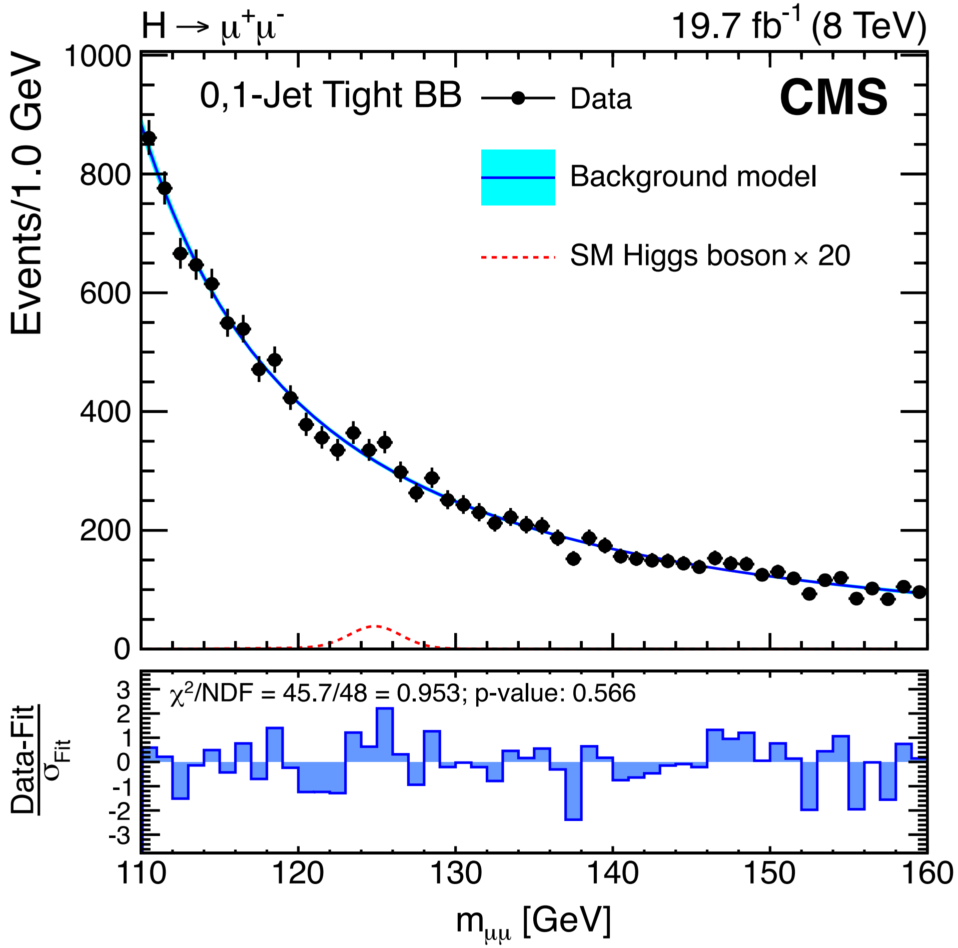
Scenario 1 : uncertainties as in Run1

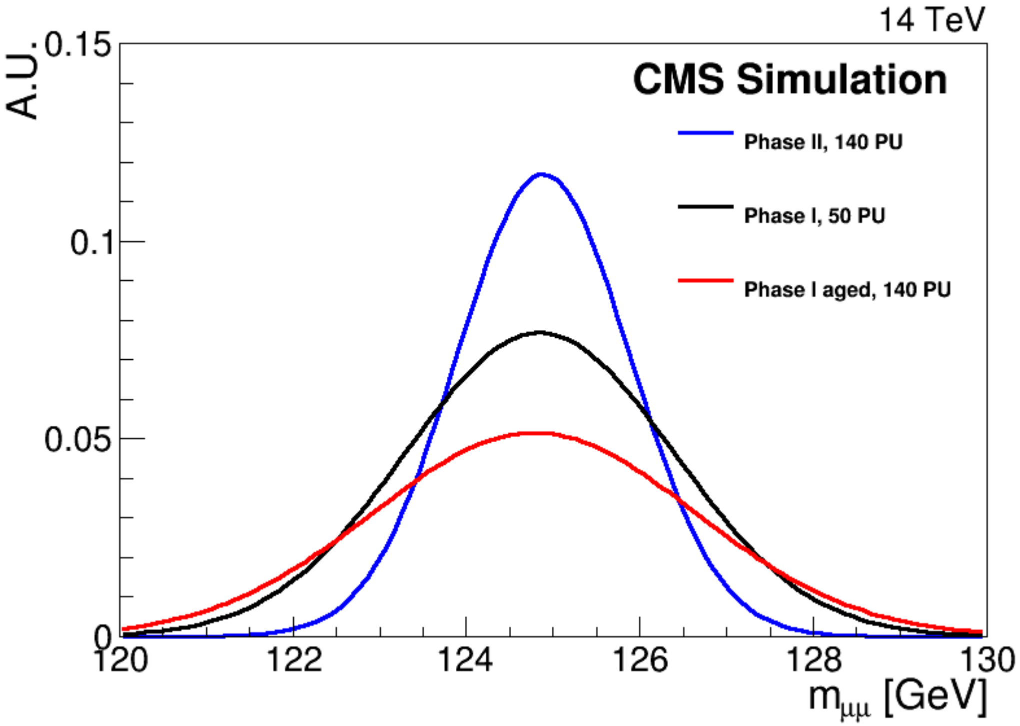
Scenario 2 : theoretical uncertainties/2
experiment systematic/sqrt($\mathcal{L}$)

Rare decay : H→μμ

Main channel to measure Yukawa coupling to 2nd generation fermions

$BR_{H\to\mu\mu}$ = 0.021% : ~100 events produced during RUN1 w.r.t. 34k events at HL-LHC





Moving from **PhaseI aged** to **PhaseII** detector

better mass resolution (40%)

higher μ resolution efficiency (20%)

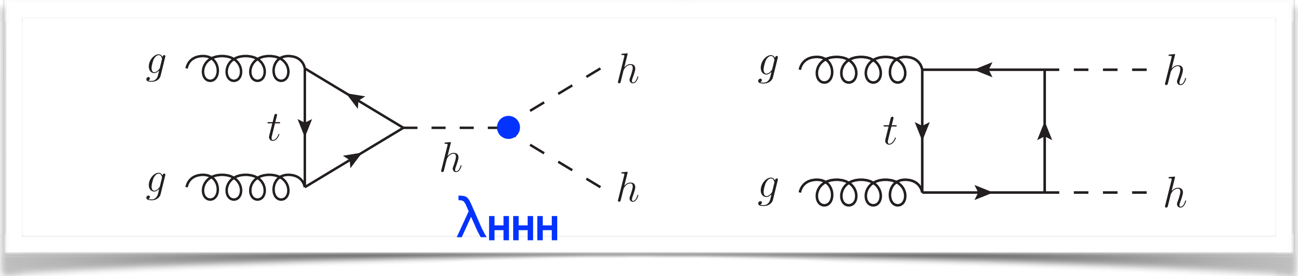
due to better spatial measurement of tracker

>7σ observation and 5% uncertainty on K_μ are expected

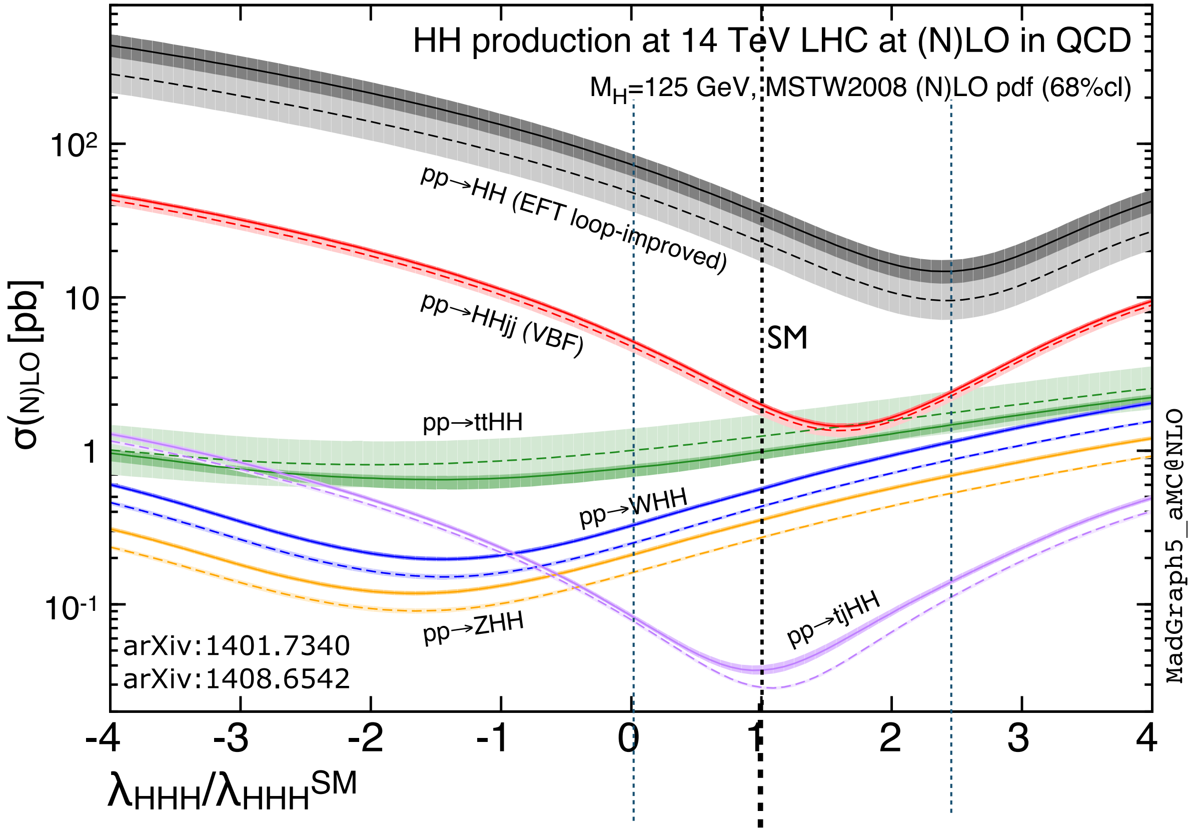
Test of models with deviations in couplings to 2nd generation fermions

Higgs boson pair production

A process like HH production has not been observed in nature



Destructive interference



Only box diagram

SM

Maximal interference between diagrams

At 14 TeV

$gg \rightarrow HH$ = 40.7 fb
VBF = 6.8 fb
ttHH = 0.7 fb

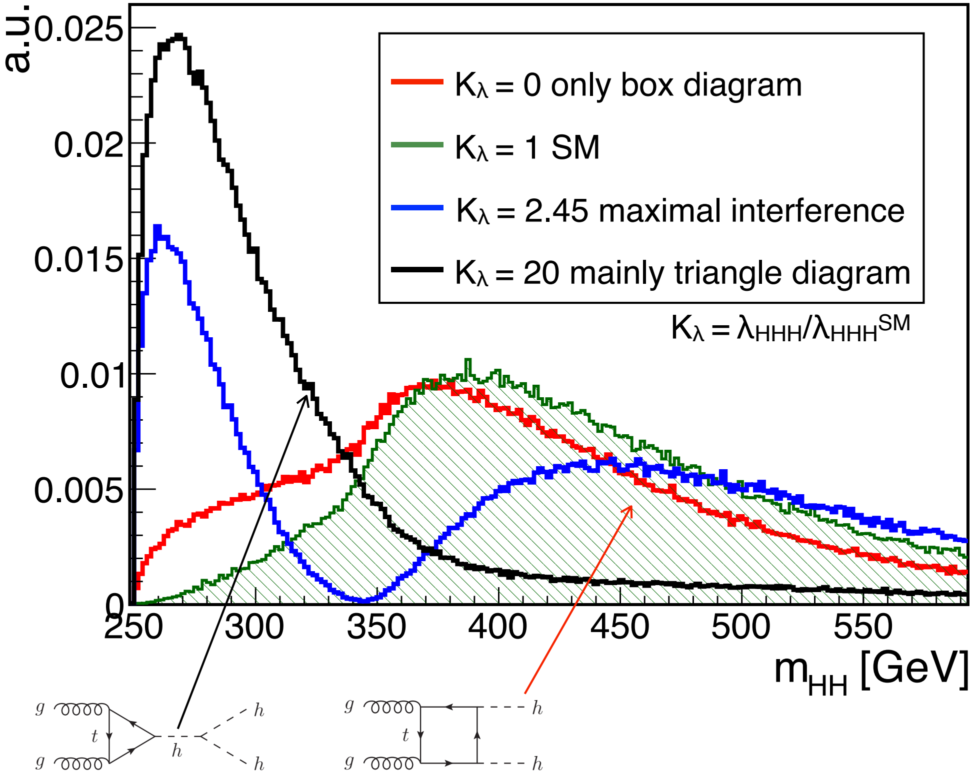
$\lambda_{HHH}/\lambda_{HHH}^{SM}$	σ^{SM}
-4	12
0	2.2
1	1
2.45	0.42
20	105

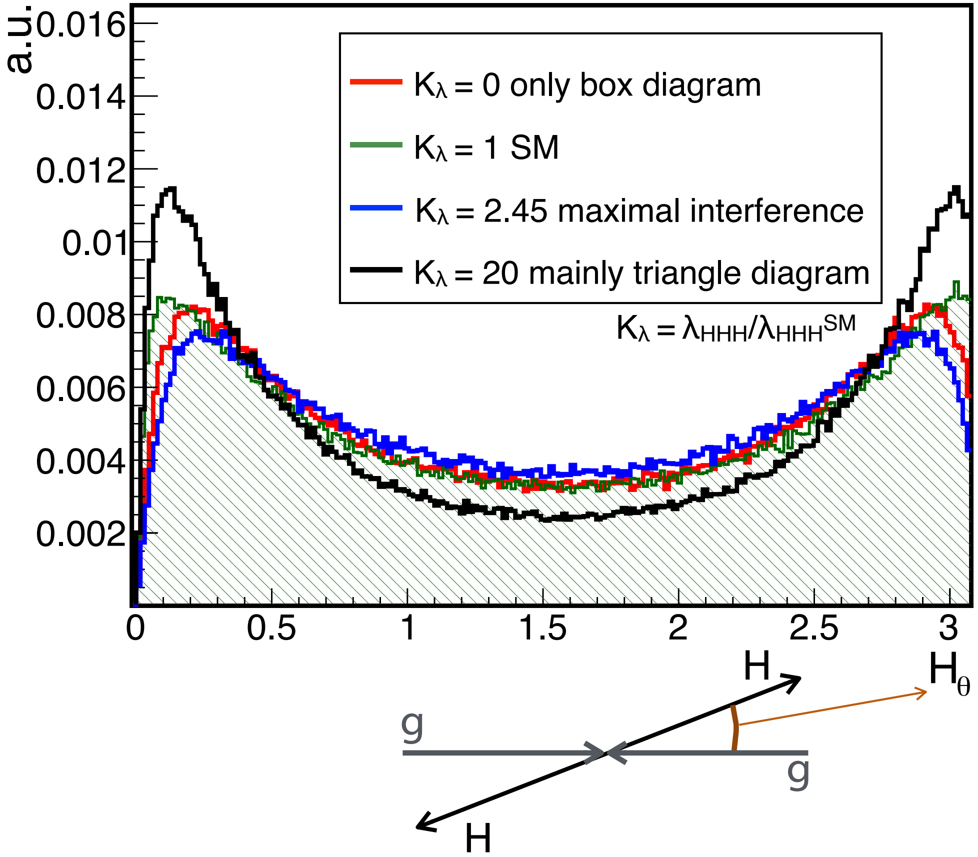
Significant enhancements w.r.t. SM

HH : signal kinematics

At LO a 2→2 scattering process is completely determined by two variables (e.g. “S and T” or “E and scattering angle”)

All SM and BSM effects covered by double-differential measurement of two variables





The triangle diagram that depends on the Higgs trilinear coupling (λ_{HHH}) is always suppressed at higher invariant masses → its contribution affects the process mostly at threshold.

HH : where is sensitivity located?

Measuring this small cross section in an inclusive search is very challenging at HL-LHC: compromise between branching ratio and cleanliness of the signal

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

Most promising channels

Tau reconstruction tough
Largest bkg tt
m_{T2} / BDT

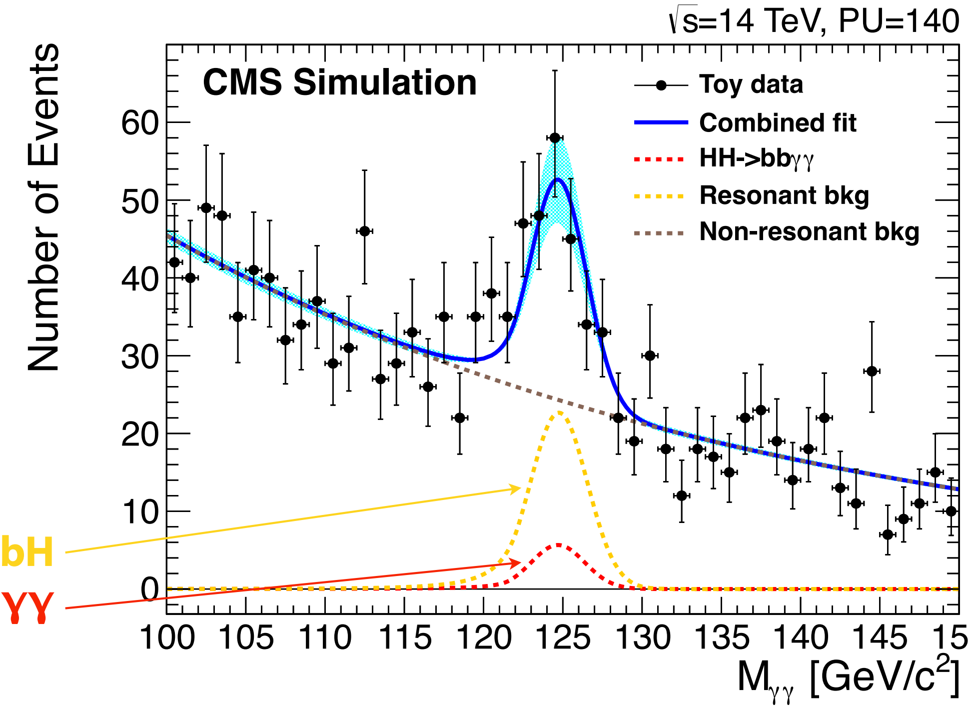
Signal small
Bkg. large and difficult to asses
Simple reconstruction

HH→bbγγ

CERN-LHCC-2015-010

Rate: 300 events for 3000/fb

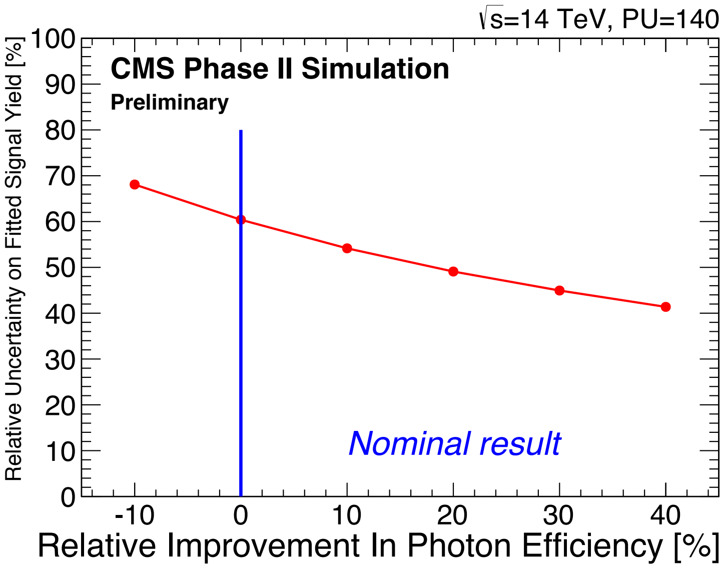
Di-photon mass distribution for the estimated signal and background contributions. The data points show the result of a pseudo-experiment.

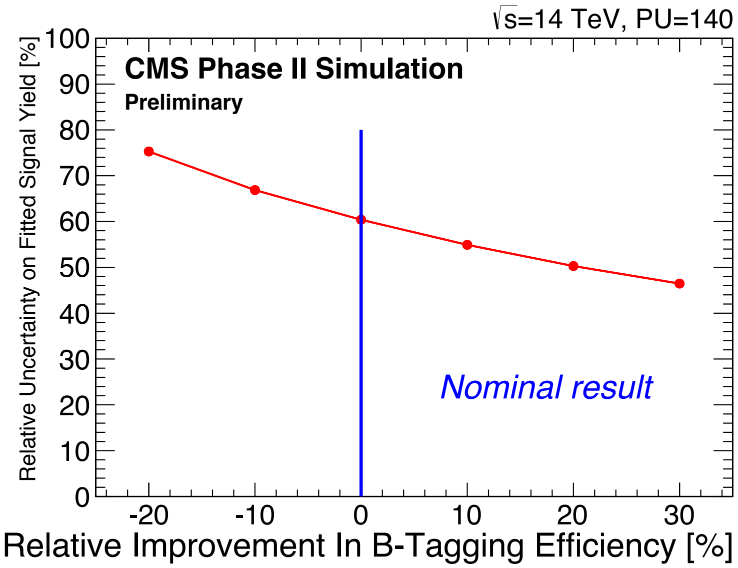


background : ZH,ttH,bbH

signal : HH → bbγγ

Impact on the analysis from improvements on the detector





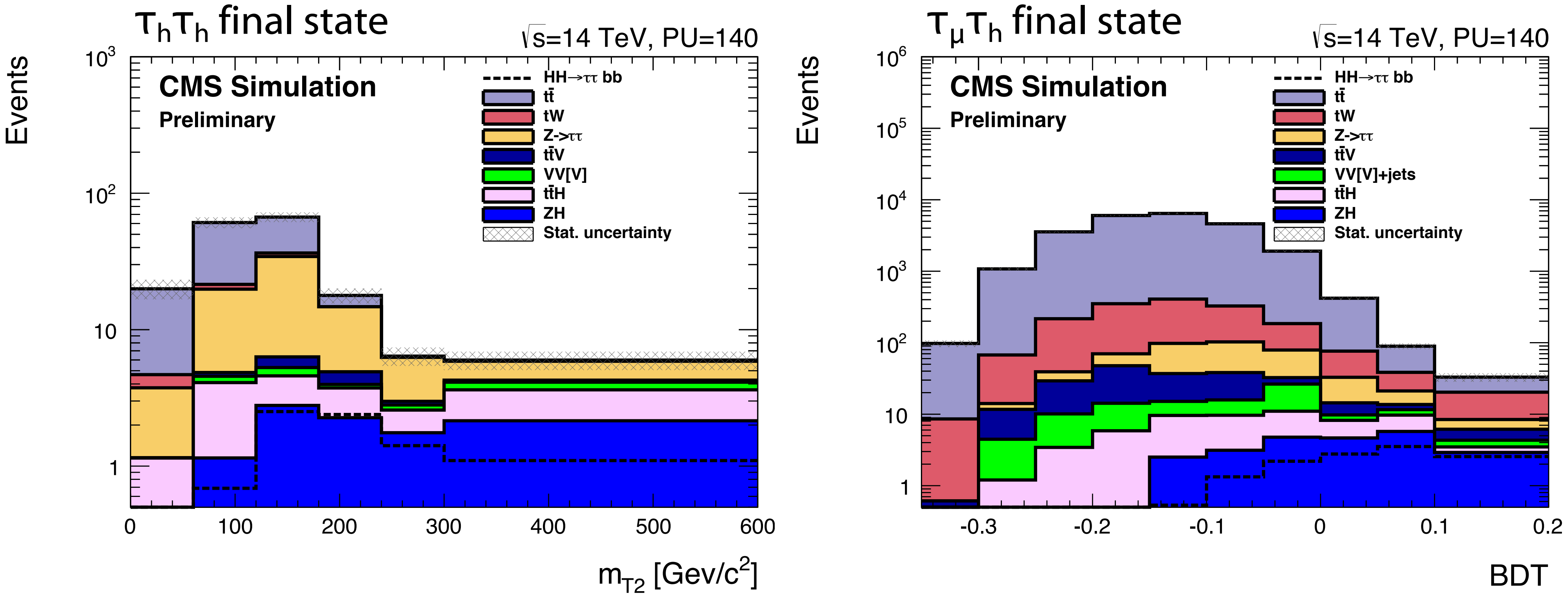
HH→bbττ

Rate: 9000 events for 3000/fb

Challenging analysis, overwhelming ttbar background

The most sensitive final states: $\tau_\mu\tau_h$ and $\tau_h\tau_h$

m_{T2} mass/BDT for signal extraction method

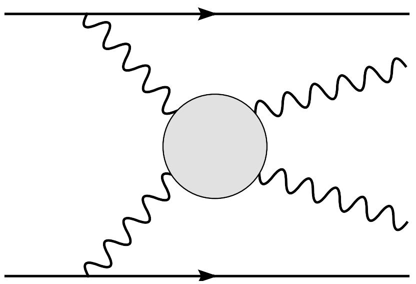


Uncertainty on the cross section: ~115%

Vector Boson Scattering

Assess VBS sensitivity using same-sign WW and WZ

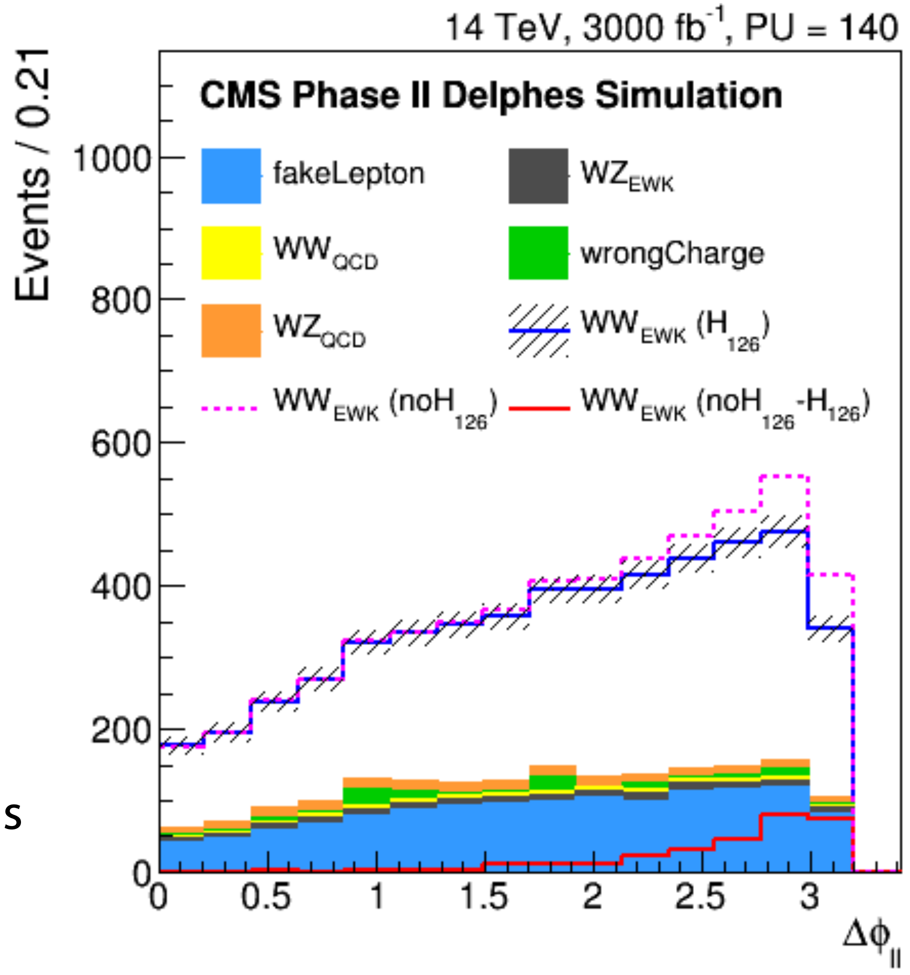
EWK scattering cross-section
non-unitarized scenarios simulated as the absence of Higgs
anomalous couplings in the EFT approach



SM scenario

No-Higgs scenario : extreme case when the Higgs boson does not play any role in the unitarization of VBS.

Difference : analysis sensitivity to models where the Higgs boson performs a partial unitarization of VBS.



Δφ between the two final state charged leptons for the same-sign WW scattering, after the VBS selections

Conclusions

ATLAS and CMS have established the existence of a Higgs boson

Higgs mass measured with and 0.2% precision

The Higgs boson profile

Overall $\sigma/\sigma_{SM} = 1.00 \pm 0.14$

No significant deviation from SM is observed but there are few channels to keep an eye on

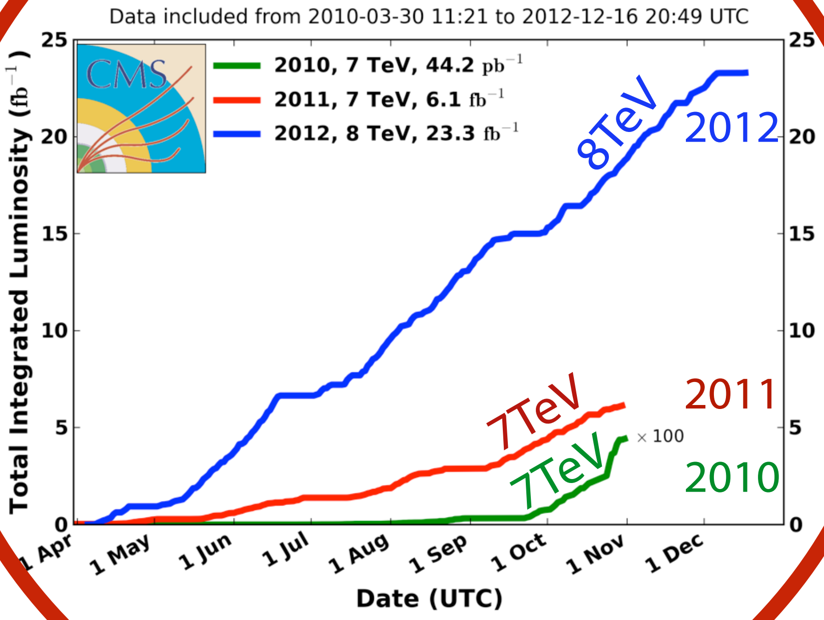
Reach program of searches for deviation(s) from SM or for extra states in the scalar sector

A glimpse of the rich Higgs physics programme that will be performed at HL-LHC has been presented

It will be strongly motivated by the discovery in the scalar sector at RunI of LHC

Additional material

LHC delivered integrate luminosity



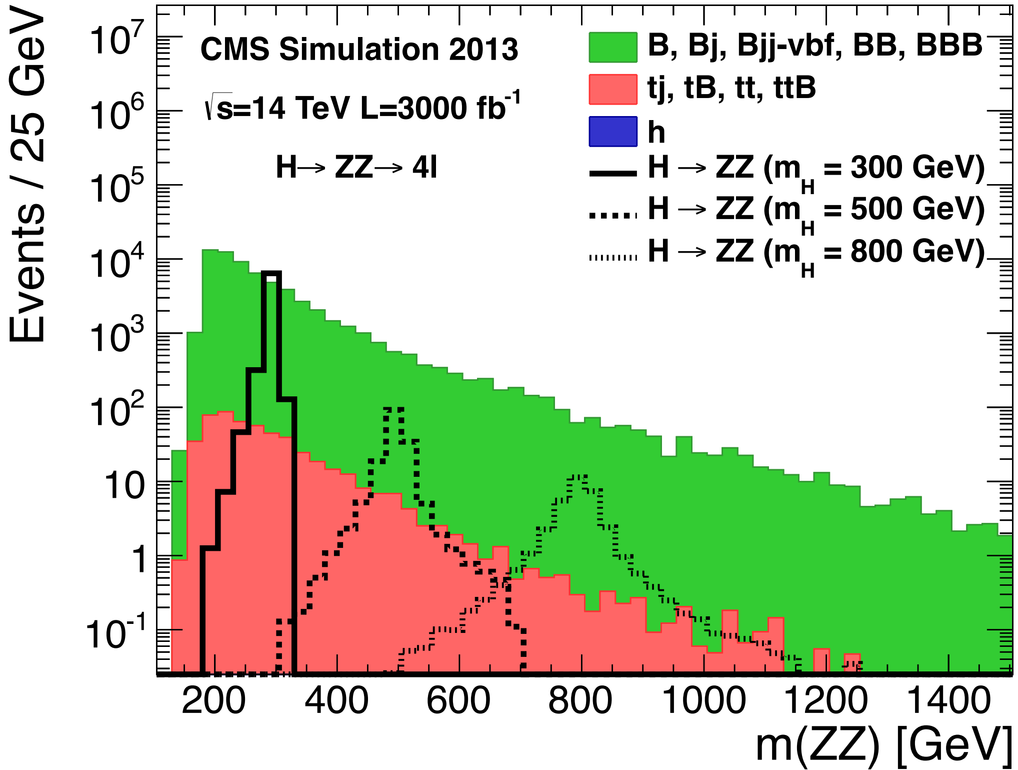
LHC

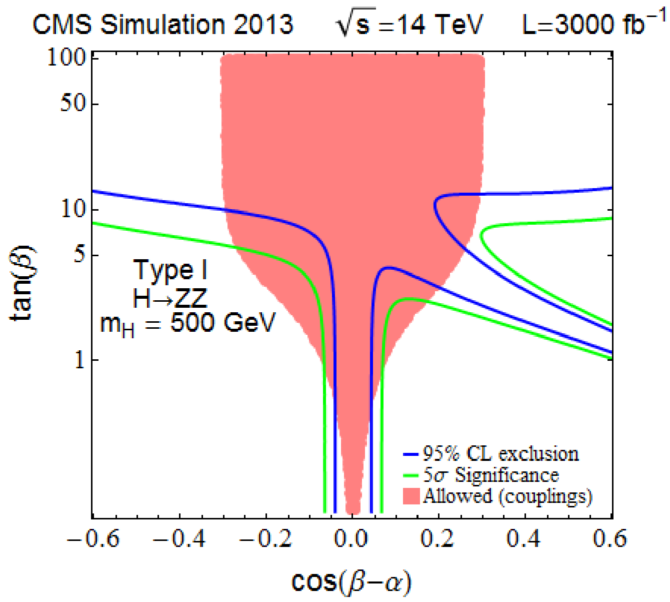
BSM Higgs : direct search 2HDM

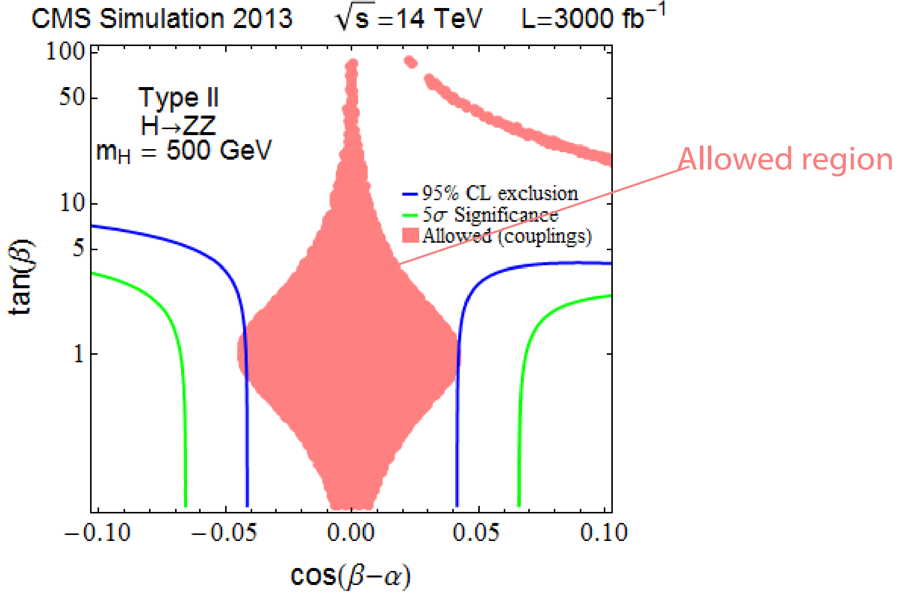
Potential to exclude or discover heavy (scalar/pseudo-scalar) neutral Higgs bosons in the context of 2HDM

Free parameters: $m_h, m_H, m_A, m_{H\pm}, m_{12}, tg\beta, \alpha$

	Type I	Type II
K_u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
K_d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
K_f	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
K_V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$

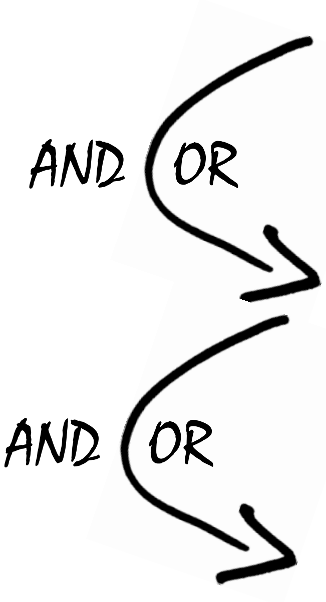






SUSY

Motivation for SUSY has never been stronger, discovery of the Higgs gives new urgency to find "natural" explanation for gauge hierarchy



HL-LHC will investigate the SUSY spectrum of new particles to be discovered at LHC

HL-LHC will allow to firmly establish an evidence of SUSY particle observed at LHC

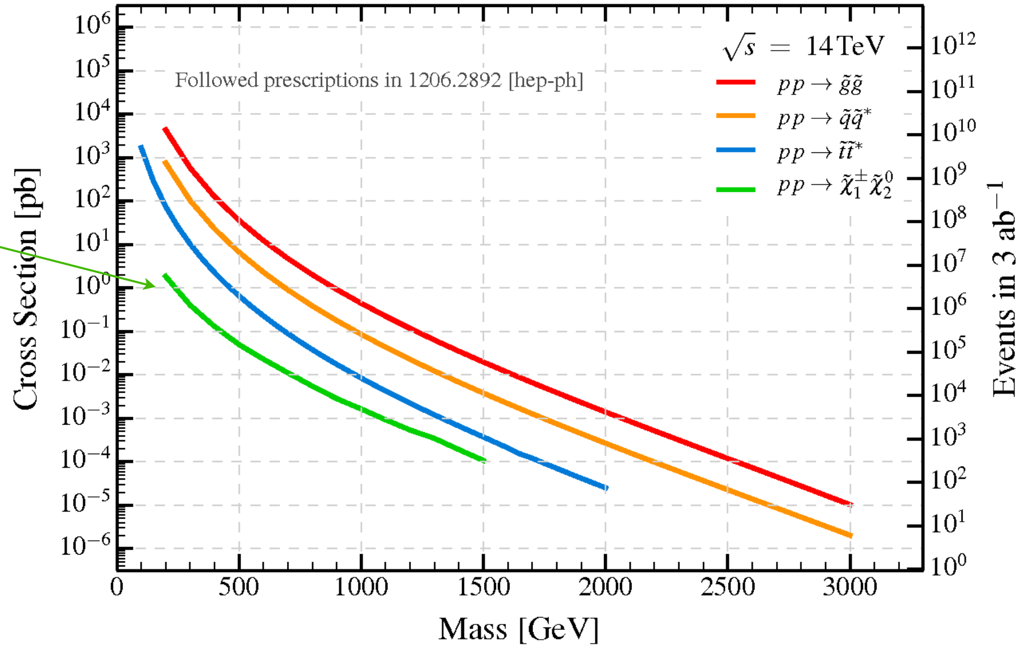
HL-LHC will slightly expands discovery reach of LHC

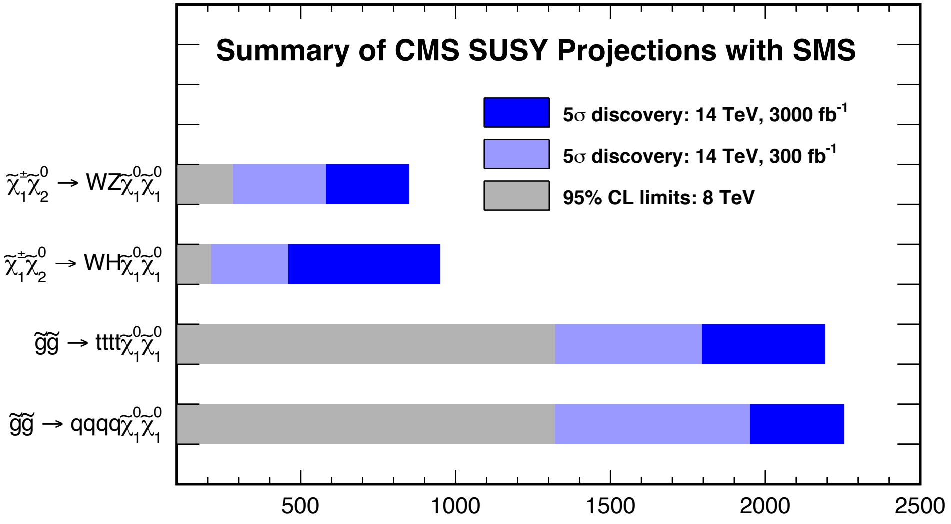
Expand SUSY discovery reach

Electroweak searches benefit from large integrated luminosity

Cross section for production **$pp\rightarrow\chi^{\pm}\chi^{0}$** ranges from 1pb to 1fb, going from masses of 300 to 1100 GeV

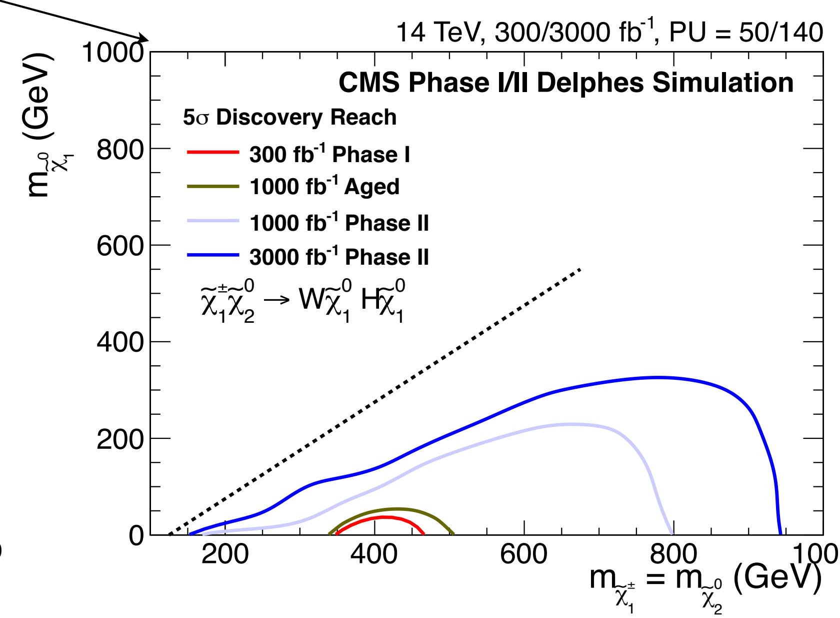
The full HL-LHC dataset is needed for high mass sensitivity





Probe *up to* the quoted mass

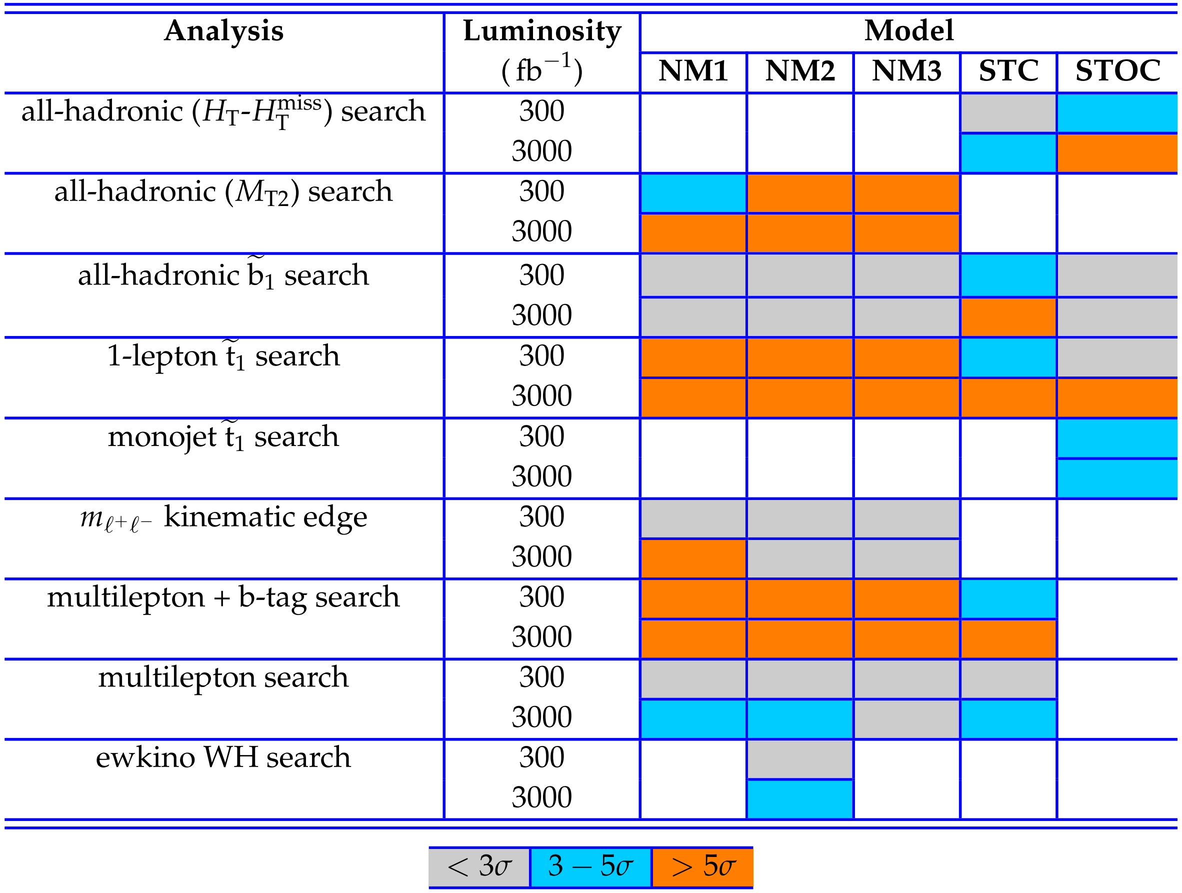
Mass scales [GeV]



Investigating SUSY spectrum

Exploring SUSY model space

Exploring experimental signature space



Analysis	Luminosity (fb^{-1})	Model				
		NM1	**NM2**	**NM3**	**STC**	**STOC**
all-hadronic (H_T-H_T^{miss}) search	300				▨	🟦
	3000				🟦	🟧
all-hadronic (M_{T2}) search	300	🟦	🟧	🟧		
	3000	🟧	🟧	🟧		
all-hadronic $\tilde{b}_1$ search	300	▨	▨	▨	🟦	▨
	3000	▨	▨	▨	🟧	▨
1-lepton $\tilde{t}_1$ search	300	🟧	🟧	🟧	🟦	▨
	3000	🟧	🟧	🟧	🟧	🟧
monojet $\tilde{t}_1$ search	300					🟦
	3000					🟦
$m_{\ell^+\ell^-}$ kinematic edge	300	▨	▨	▨		
	3000	🟧	▨	▨		
multilepton + b-tag search	300	🟧	🟧	🟧	🟦	
	3000	🟧	🟧	🟧	🟧	
multilepton search	300	▨	▨	▨	▨	
	3000	🟦	🟦	▨	🟦	
ewkino WH search	300		▨			
	3000		🟦			

▨ $< 3\sigma$ 🟦 $3-5\sigma$ 🟧 $> 5\sigma$

SUSY EWK searches

Different types of SUSY models lead to different patterns of discoveries in different final states after different amounts of data.

HL-LHC measurements can be crucial to illuminate a Run 3 discovery, and thus answer fundamental questions about gauge hierarchy or dark matter.