Higgs and Beyond at the LHC

Selected topics mostly on Higgs physics at the LHC, some comments about Run 2

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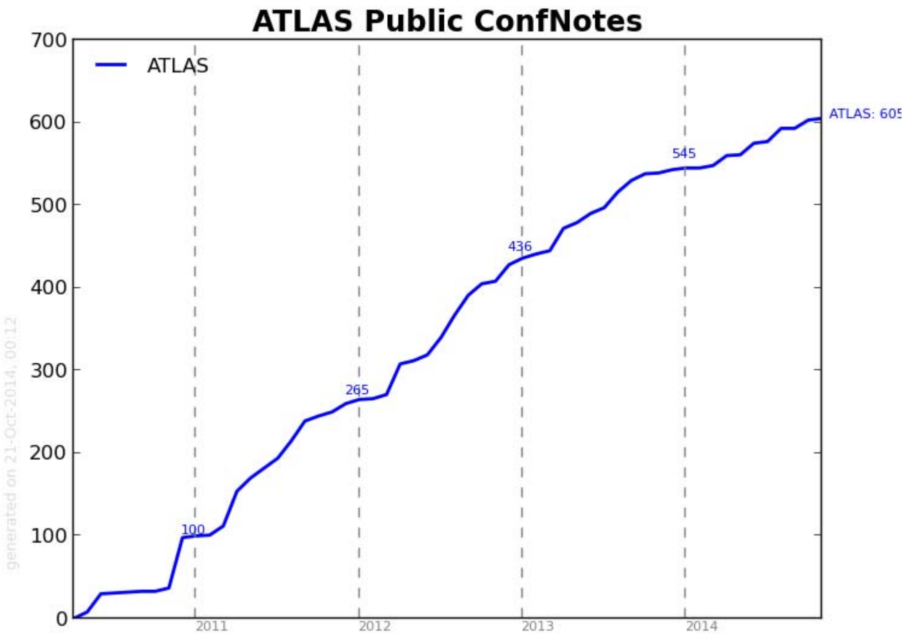
Preliminary remarks and Disclaimer

- The LHC physics program is incredibly vast!

- This talk will mostly be centered on Higgs physics but will not cover all aspects of Higgs physics

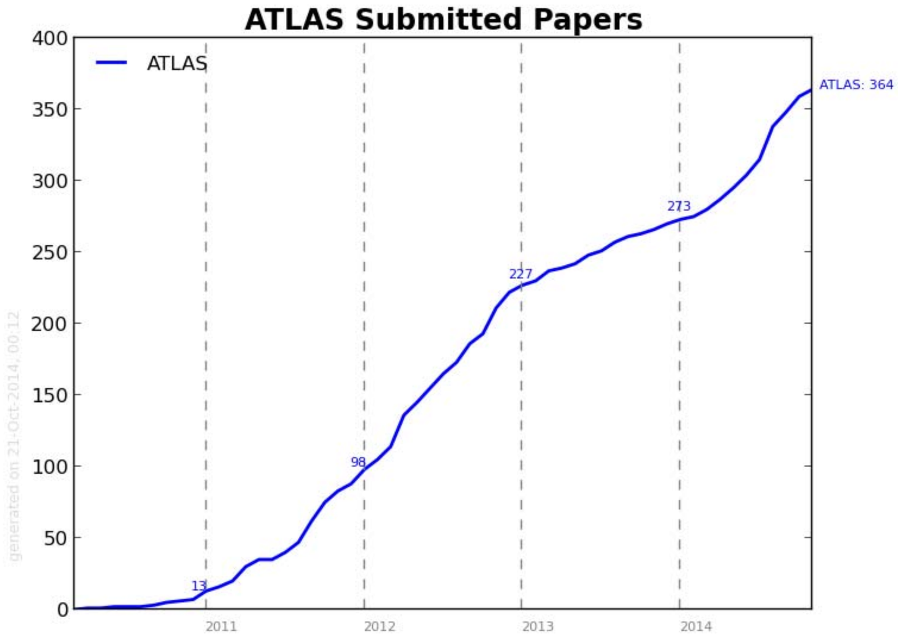
- We have not fully done our home work for Run 2 projections (we have Run 3 and HL-LHC) !

The Run 1 of the LHC has been extremely productive



Conference Notes

Similar numbers for CMS



Papers

Similar numbers for CMS

… and successful!

The two main outcomes of the LHC (so far)

- The celebrated discovery of the Higgs boson !

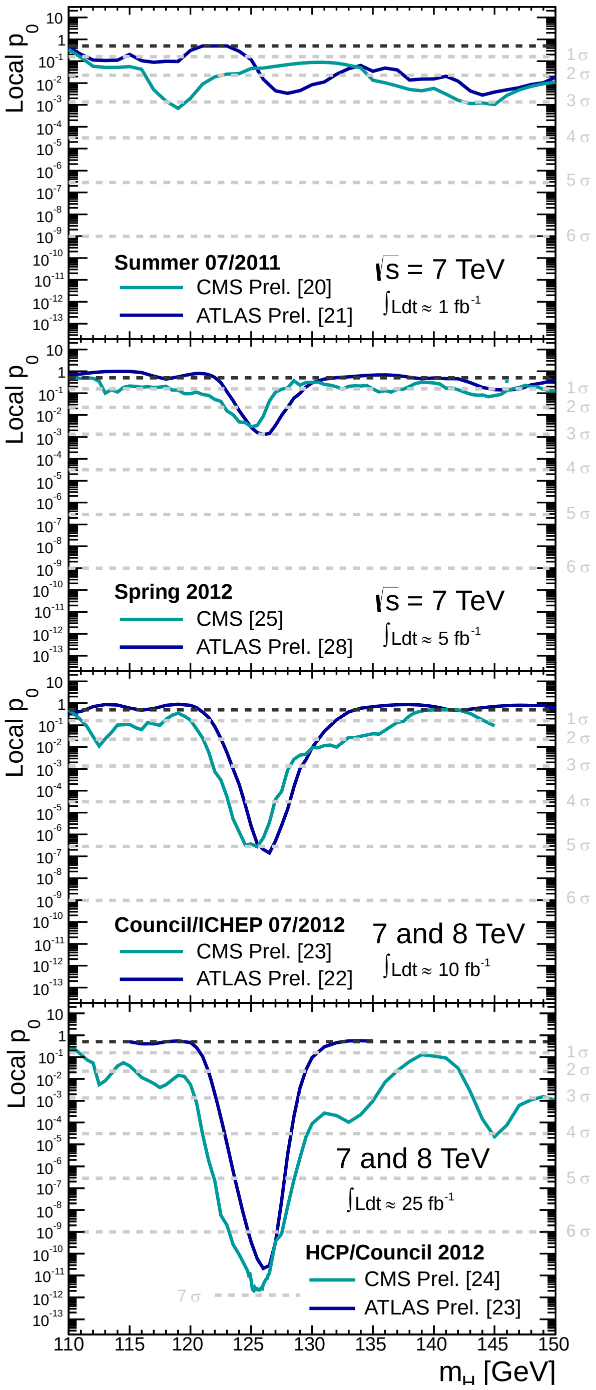
THE BEH-MECHANISM,
INTERACTIONS WITH SHORT RANGE FORCES
AND
SCALAR PARTICLES

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

- And nothing else…

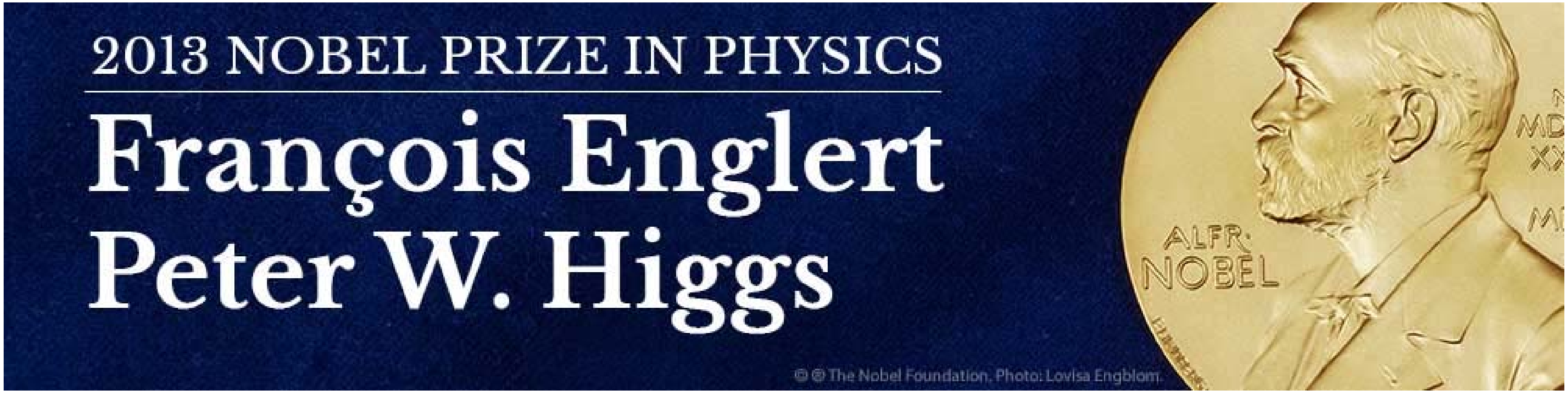
(surprise despite the absence of deviations in precision EW and flavor measurement)

[PDG, review of Particle Physics]



A Textbook and Timely Discovery

- Summer 2011: EPS and Lepton-Photon
  First (and last) focus on limits (scrutiny of the p_0)
- December 2011: CERN Council
  First hints
- Summer 2012: CERN Council and ICHEP
  Discovery!
- December 2012: CERN Council
  Begining of a new era

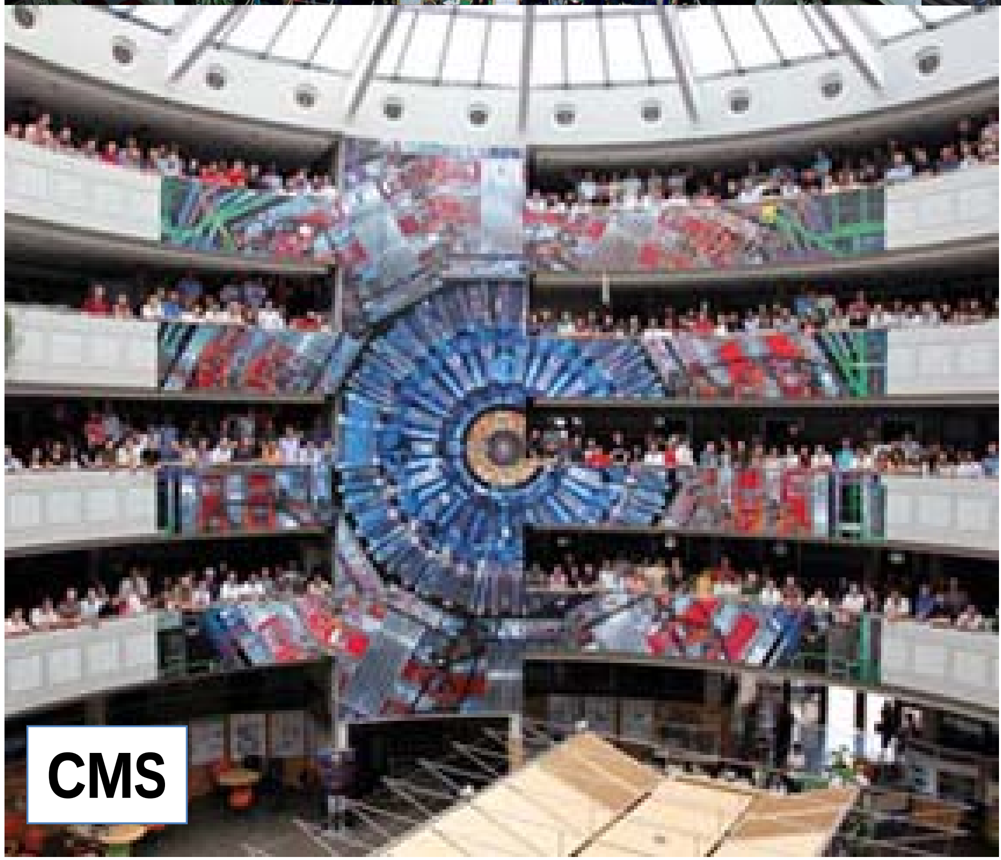


8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert and Peter 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”



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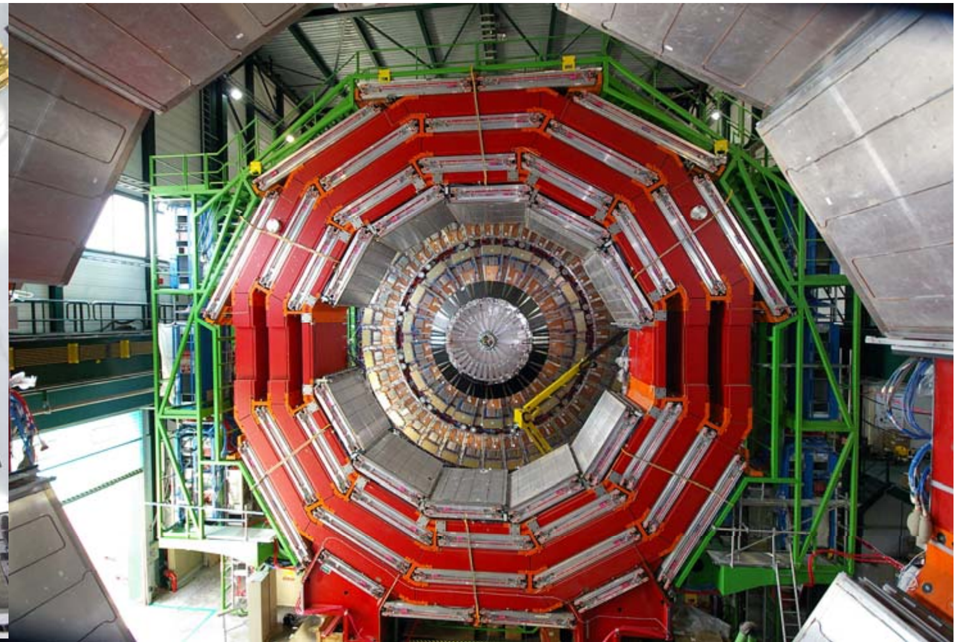
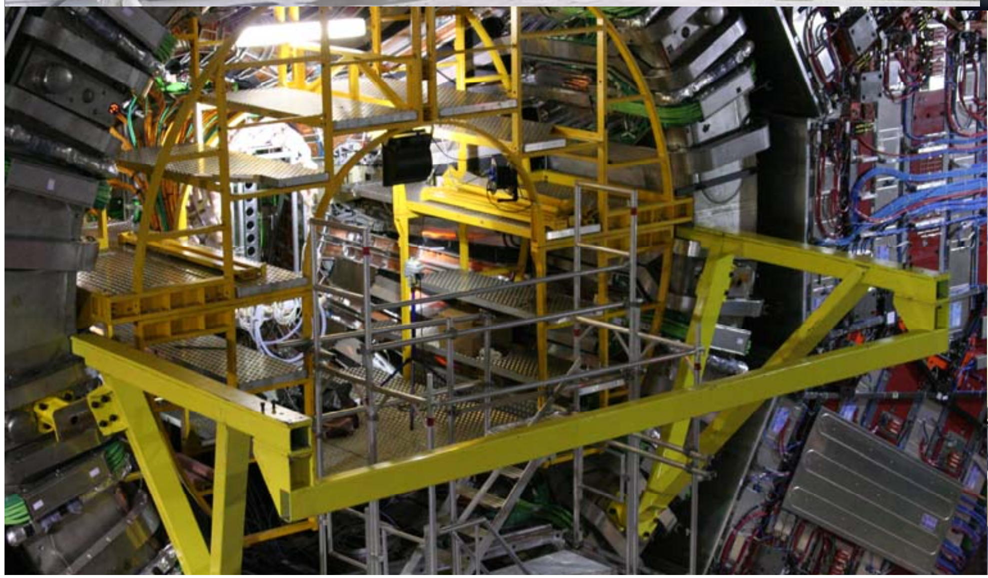
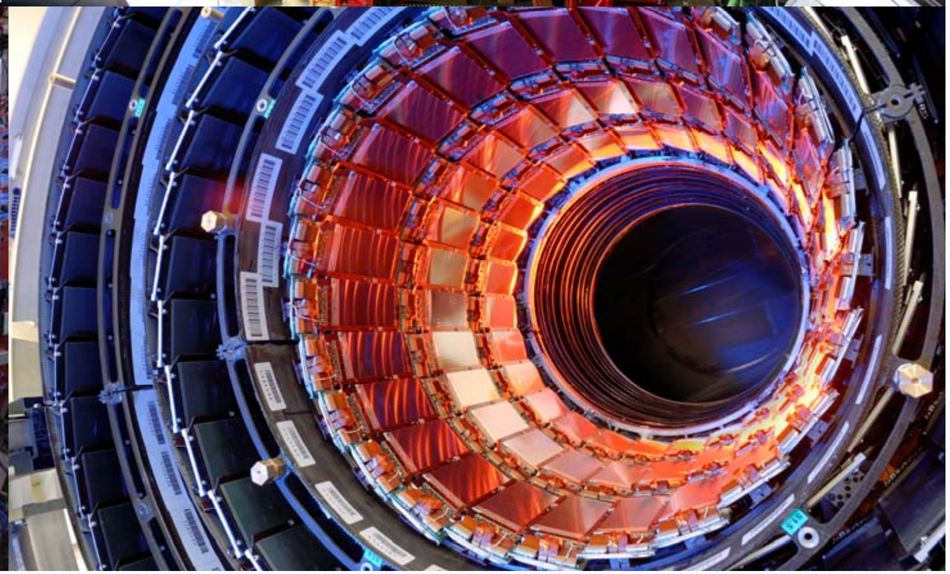
Years of Design, Construction and Commissioning of the LHC

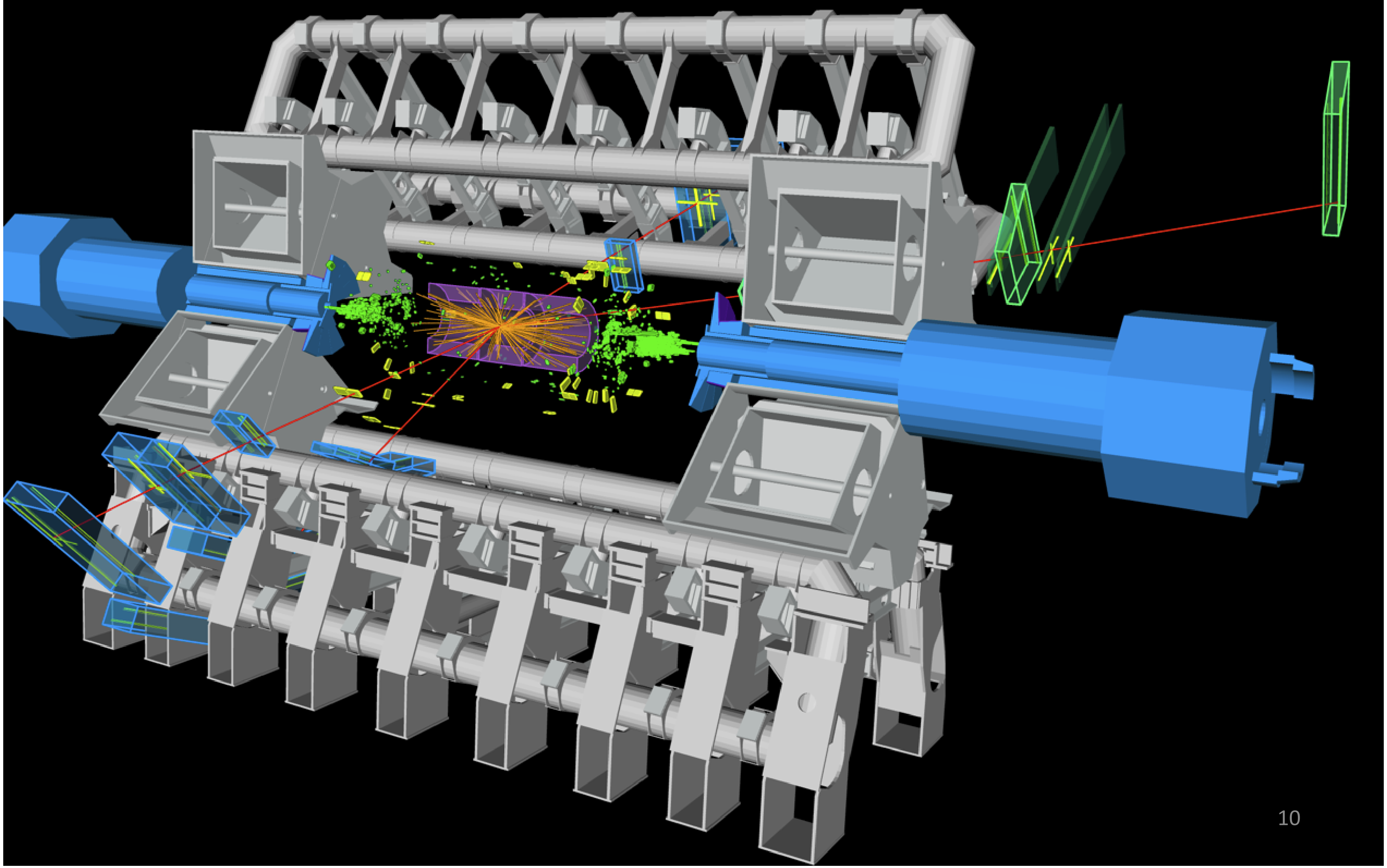
Years of Design, Construction and Commissioning of Experiments



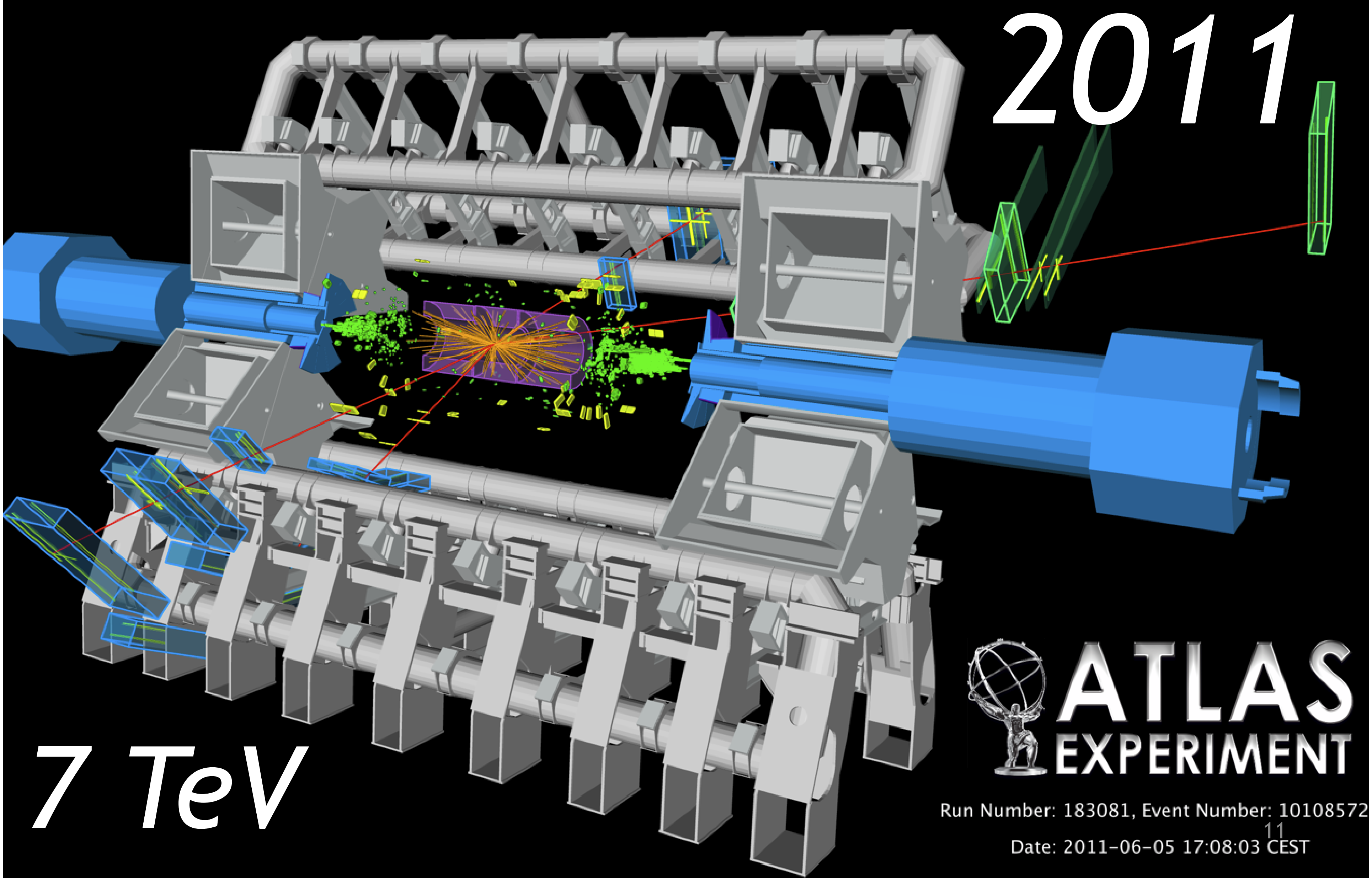


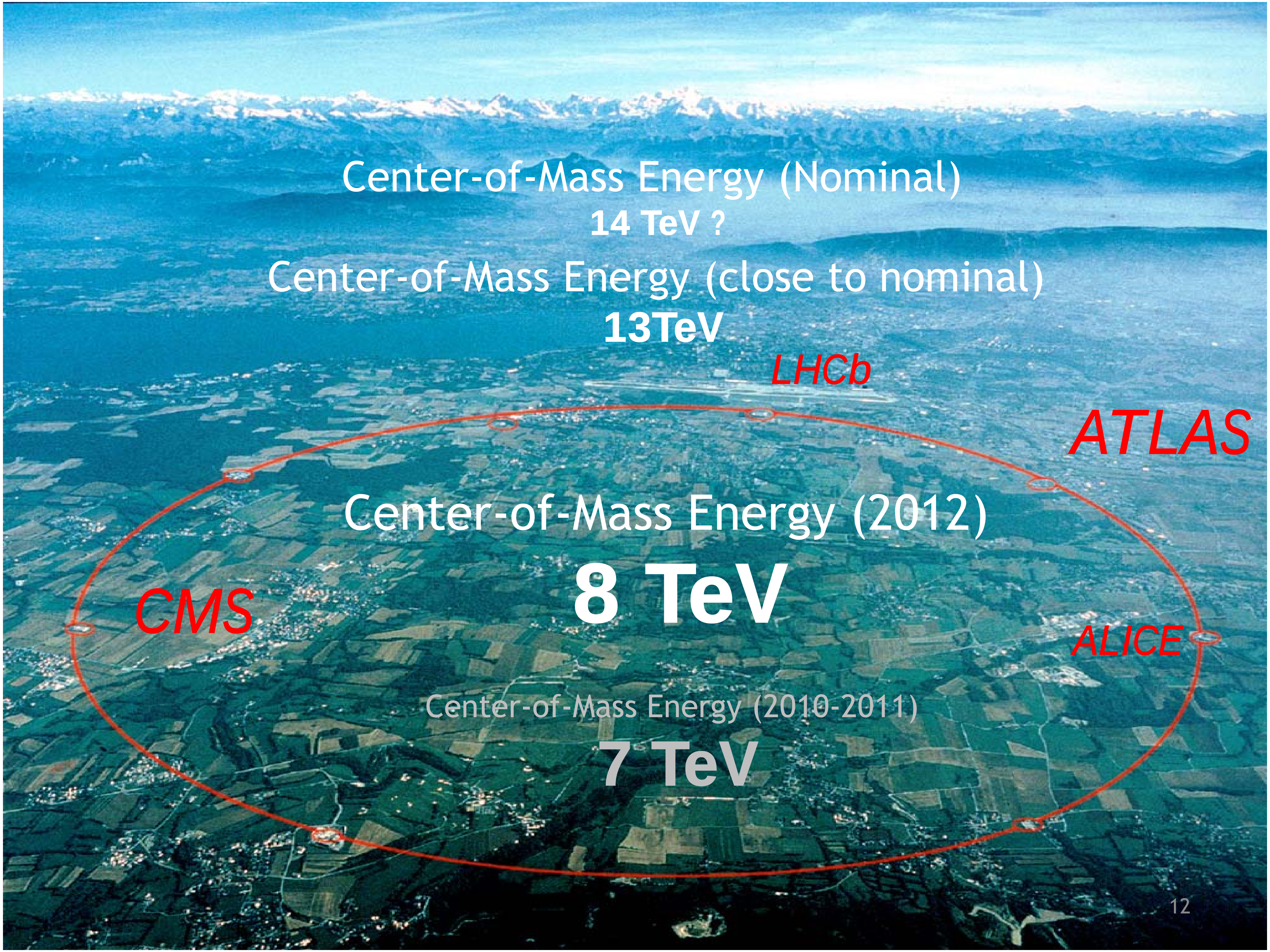


20 Years, projecting, constructing and Simulating…

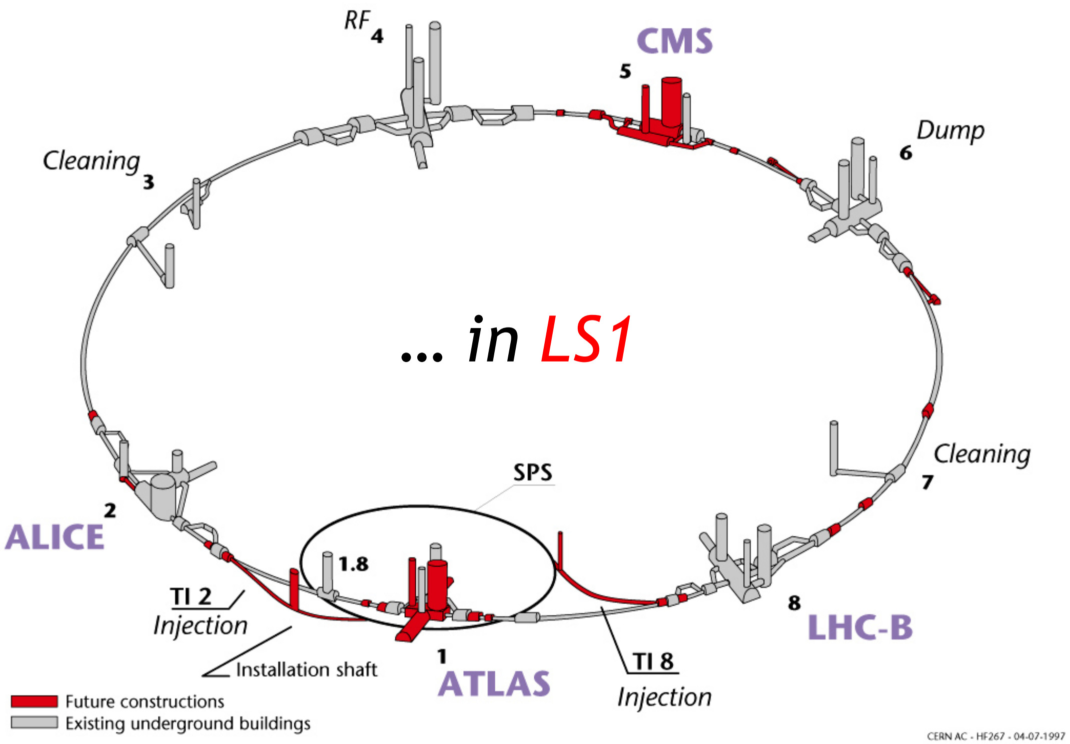


4 μ event … *Standard EW only or Higgs?*




Center-of-Mass Energy (Nominal)
14 TeV ?
Center-of-Mass Energy (close to nominal)
13TeV
LHCb
ATLAS
Center-of-Mass Energy (2012)
8 TeV
CMS
ALICE
Center-of-Mass Energy (2010-2011)
7 TeV

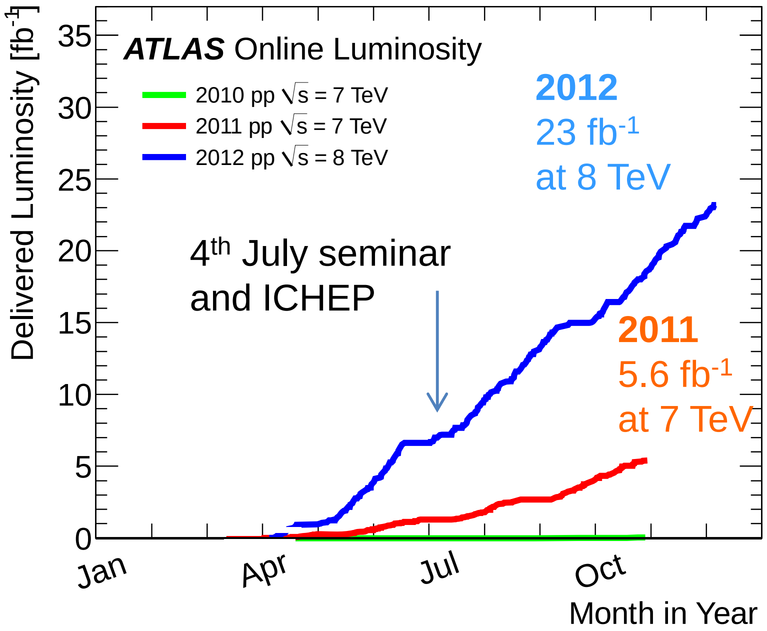
First LHC Run Completed



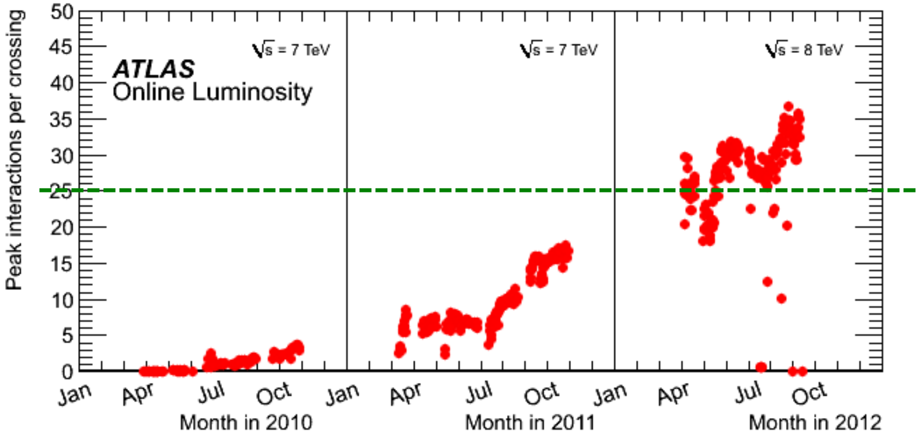
$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Parameter	2010	2011	2012	Nominal
C.O.M Energy	7 TeV	7 TeV	8 TeV	14 TeV
Bunch spacing / k	150 ns / 368	50 ns / 1380	50 ns /1380	25 ns /2808
ε (mm rad)	2.4-4	1.9-2.3	2.5	3.75
β* (m)	3.5	1.5-1	0.6	0.55
L ($cm^{-2}s^{-1}$)	$2x10^{32}$	$3.3x10^{33}$	$\sim 7x10^{33}$	10^{34}

The first LHC run



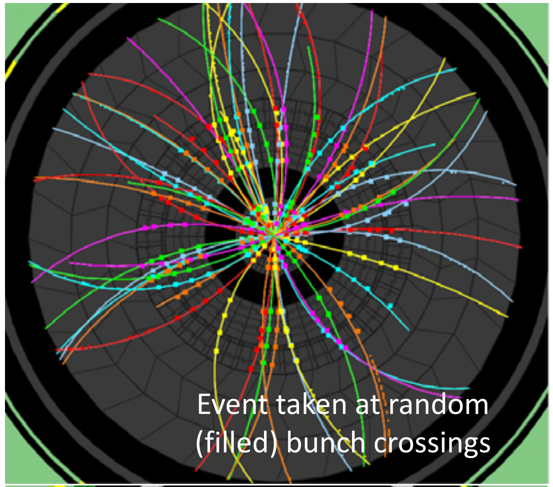
2010
0.05 fb^{-1}
at 7 TeV



2010

O(2) Pile-up events

150 ns inter-bunch spacing



2011

O(10) Pile-up events

50 ns inter-bunch spacing

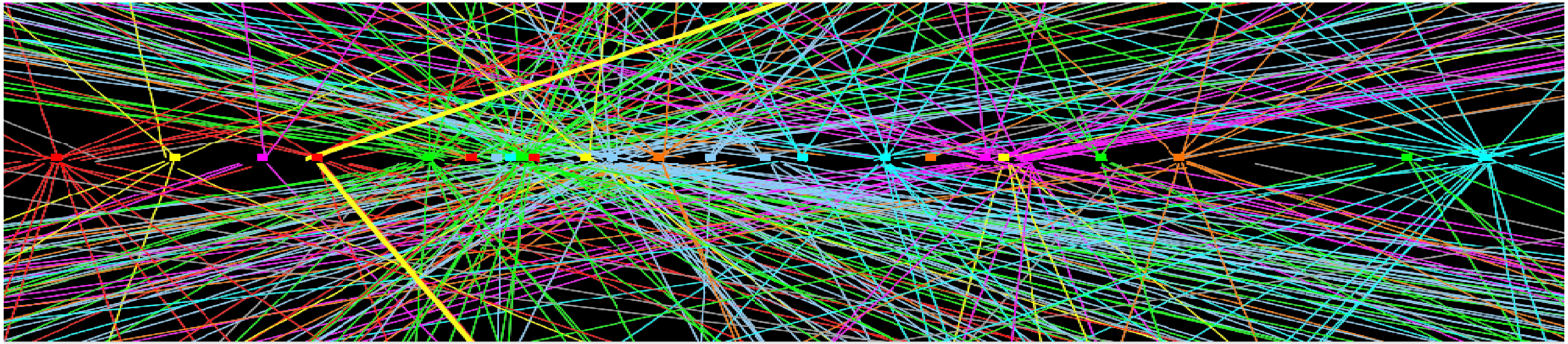
Design value
(expected to be
reached at $L=10^{34}$!)

2012

O(20) Pile-up events

50 ns inter-bunch spacing

Detector Challenges (Highlights)



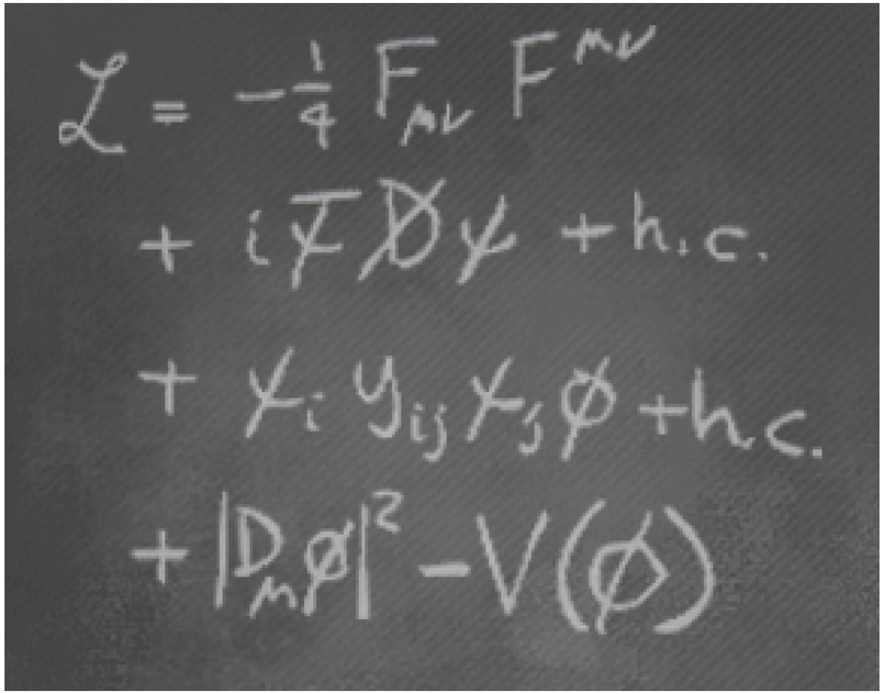
- Trigger Challenge : How to select 400 out of 20M events per second while keeping the interesting (including unknown) physics

- Computing Challenge : How to reconstruct, store and distribute 400 increasingly complex events per second and their simulation (over 100 PB per experiment)

- Analysis Challenge : Maintain high (and as much as possible stable) reconstruction and identification efficiency for physics objects (e, μ, τ, jets, E^T_{mis}, b-jets) up to the highest pile-up

The Standard Model

With one doublet of complex scalar field



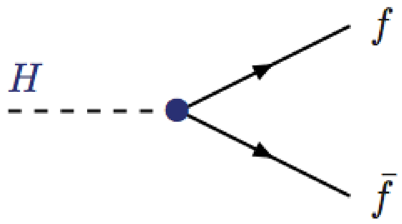
The elegant gauge sector

The ugly Higgs sector

- Non universal interactions not governed by a symmetry
- Bares most of the free parameters of the SM

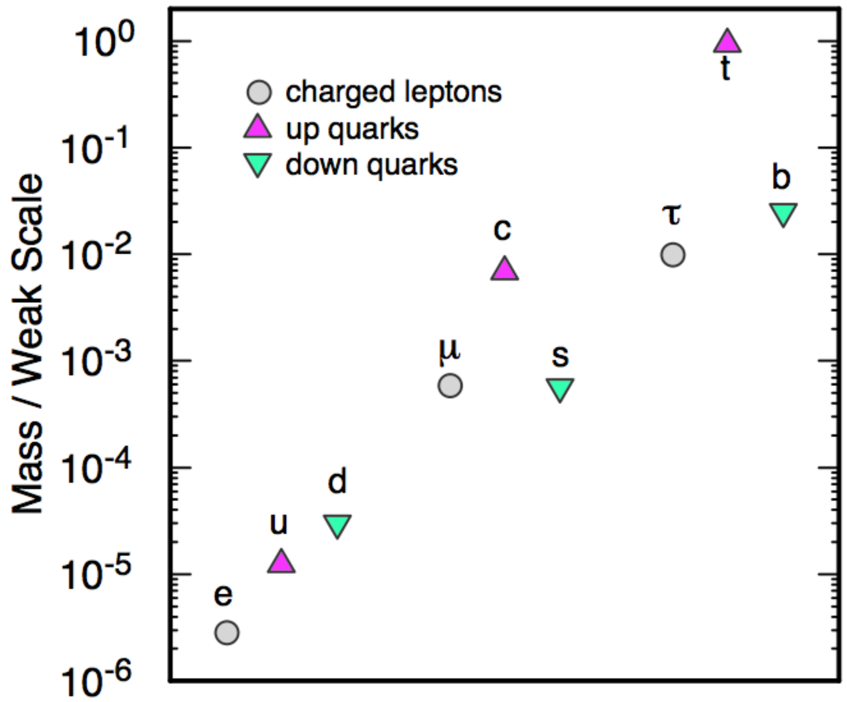
+ Dark matter ?
+ BSM ?

… but testable!



$$g_{Hff} = m_f/v$$

(and masses of fermions)

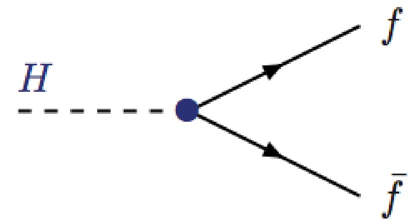


~6 orders of magnitude

Neutrinos are not even on the scale!

Not explaining the flavor Hierarchy

Replacing mass terms by Yukawa couplings



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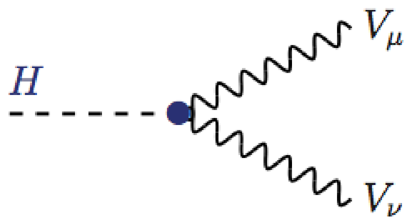
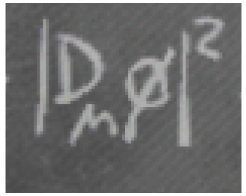
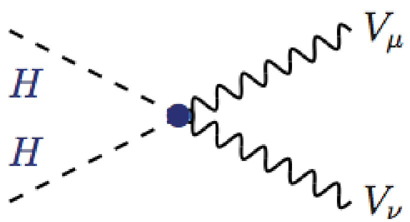


$$g_{HVV} = 2M_V^2/v$$

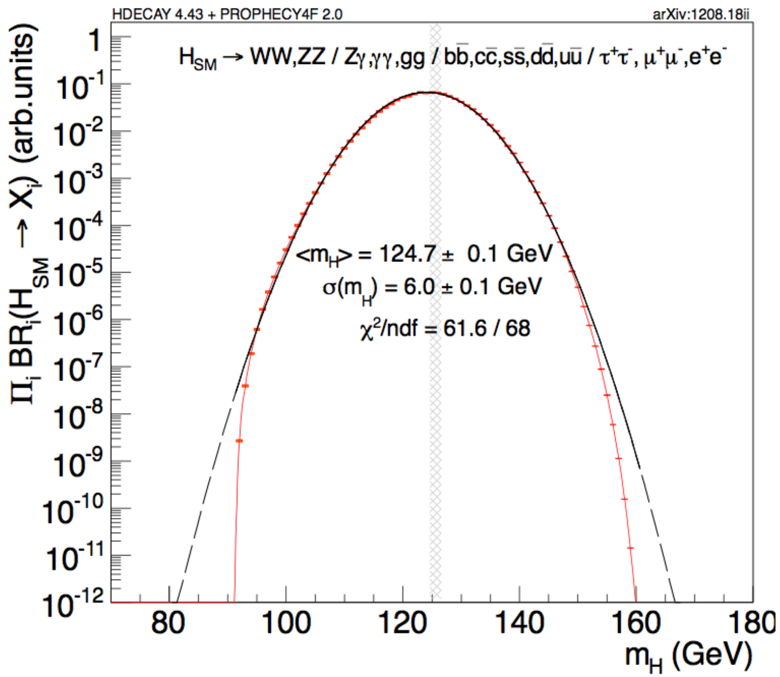
Proof of condensate !



(and masses of gauge bosons)

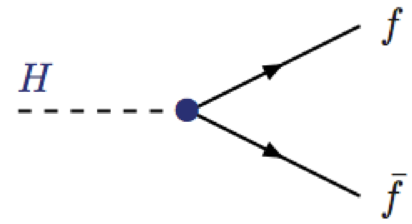


$$g_{HHVV} = 2M_V^2/v^2$$



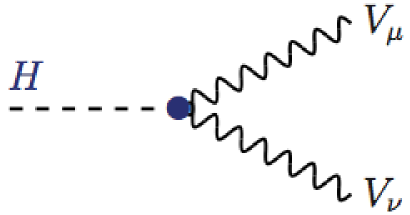
The Gift of Nature

at 125 GeV



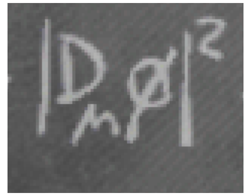
$$g_{Hff} = m_f/v$$

(and masses of fermions)



$$g_{HVV} = 2M_V^2/v$$

Proof of condensate !



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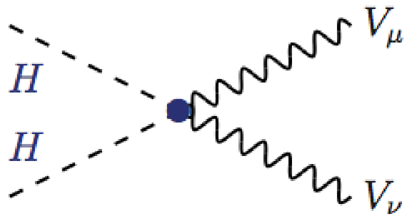
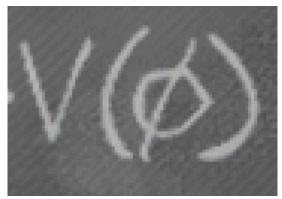
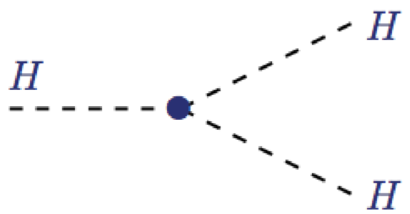


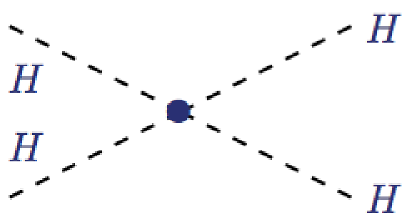
$$g_{HHVV} = 2M_V^2/v^2$$





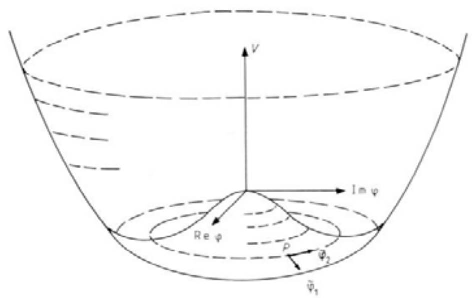
$$g_{HHH} = 3M_H^2/v$$

$$V(\varphi) = \mu^2 \varphi^* \varphi + \lambda(\varphi^* \varphi)^2$$



$$g_{HHHH} = 3M_H^2/v^2$$

$$v = -\frac{\mu^2}{\lambda}$$



The discovery did not exactly come as a surprise!

Prediction of the Model

$$\rho = 1$$

Protected by cutsodial symmetry

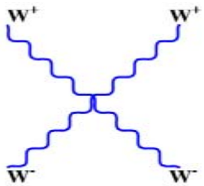
$$\frac{M_W}{M_Z} = \rho \frac{g^2}{g^2 + g'^2} = \rho \cos^2 \theta_W$$

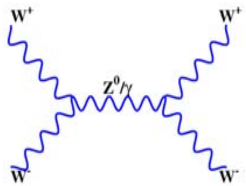
F. Wilczek at the LEP Celebration :

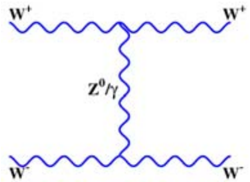
The Higgs mechanism is corroborated at 75%

The Higgs and the No Loose theorem* at the LHC

The longitudinally polarized amplitude of: $W^+W^- \rightarrow W^+W^-$





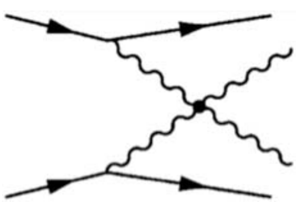


Does not preserve perturbative unitarity.

Introducing a Higgs boson ensures the unitarity of this process PROVIDED that its mass be smaller than :

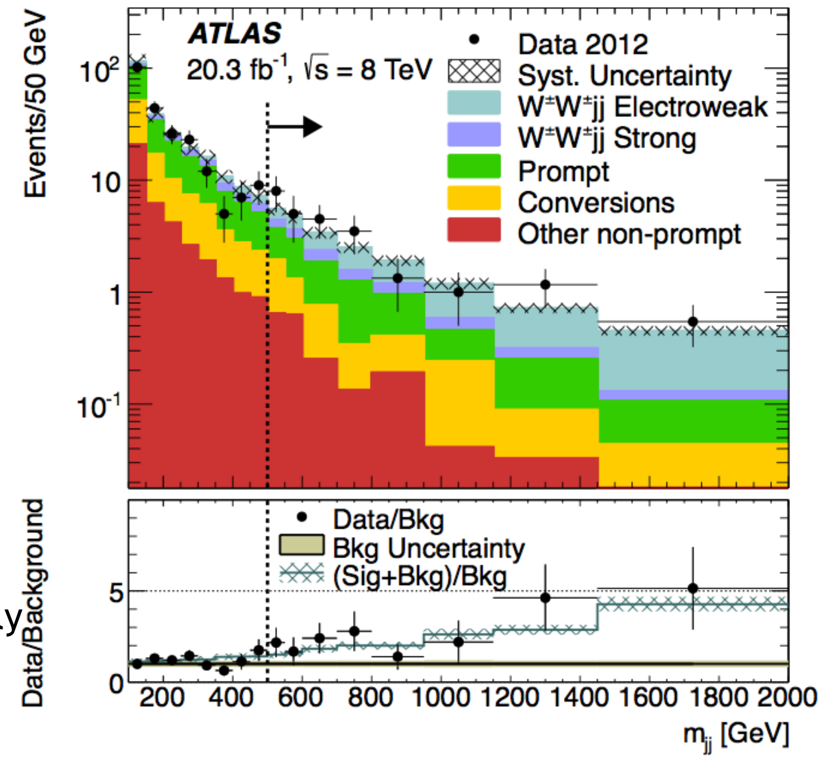
$$\sqrt{4\pi\sqrt{2}/3G_F} \sim 1 \text{ TeV}$$

Still very important to check :



Just starting…

- Overall same sign WW
- 4.5 s observed (3.4 s exp.)
- Still a long way to go to precisely test polarized VBS



*approximate No Loose theorem

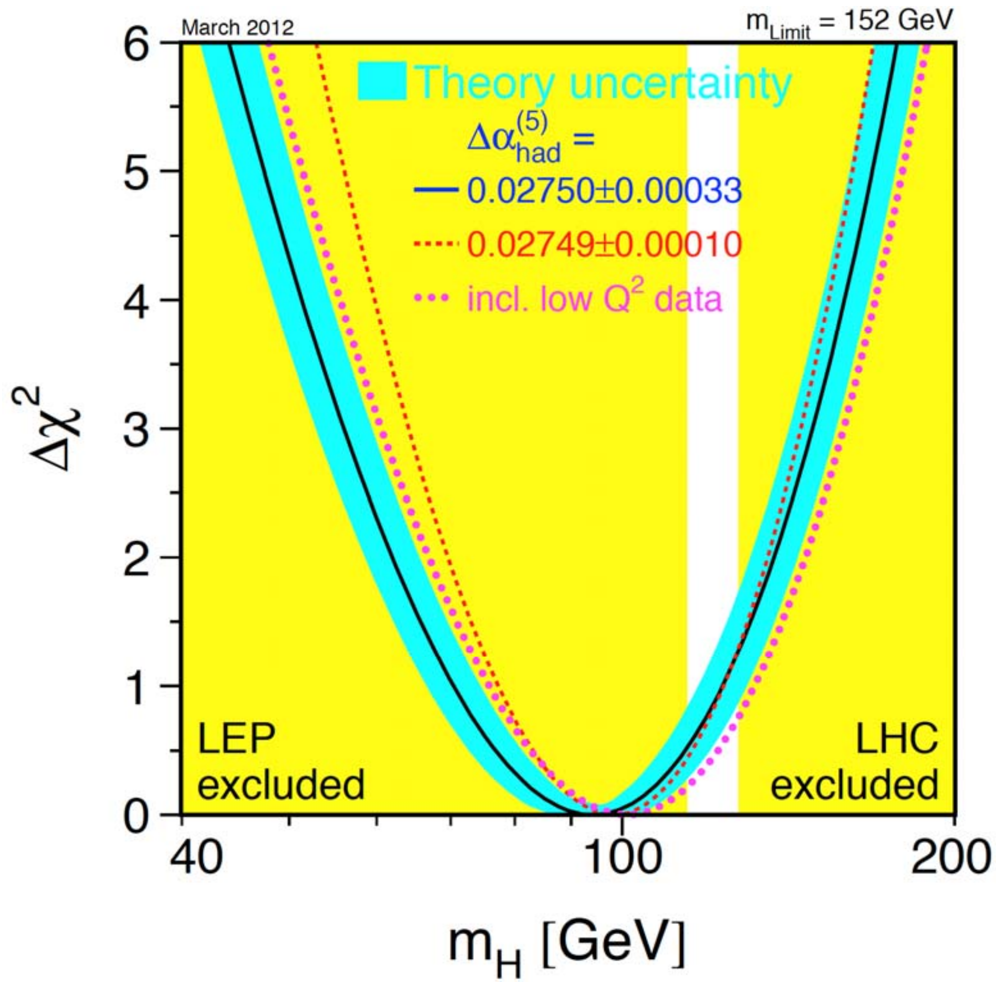
The mass did not exactly come as a surprise either!

Precision EW data

$$\Delta r \propto \log\left(\frac{m_H}{m_W}\right)$$

$$m_H \sim 90 GeV$$

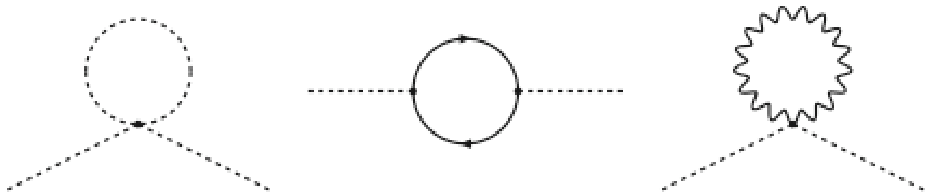
Is there a Higgs?



Why "nothing else" came as a fundamental observation and a surprise?

The Hierarchy Problem, Naturalness and fine tuning

The Higgs potential is fully renormalizable, but…



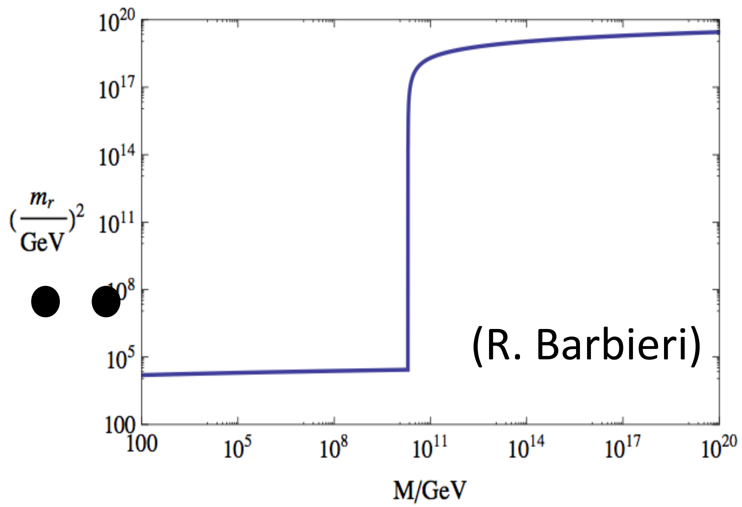
Loop corrections to the Higgs boson mass…

…are quadratically divergent :

$$\Delta m^2 \propto \int^{\Lambda} \frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi^2}$$

Not really a problem unless there is a scale L !

$$m_H = m_0 + \Delta m + \ldots$$



(R. Barbieri)

Possible Solutions

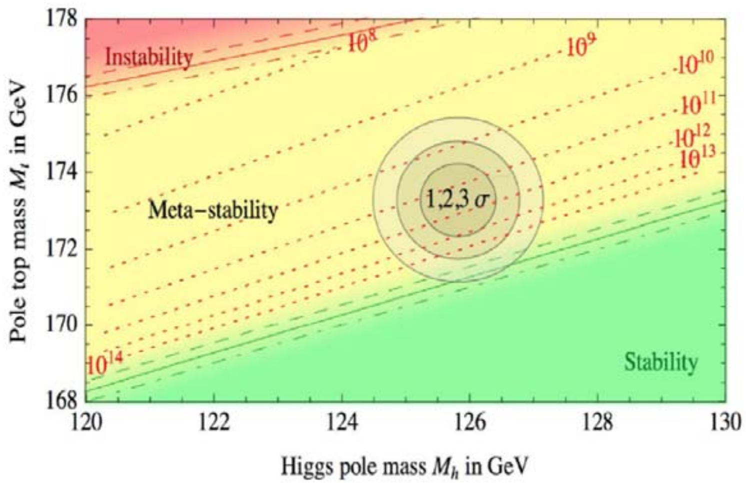
1.- Elegant: Mechanisms that protect the Higgs boson mass

- Supersymmetry
- Composite Higgs, Higgs as a pseudo goldstone boson
- Large extra dimensions

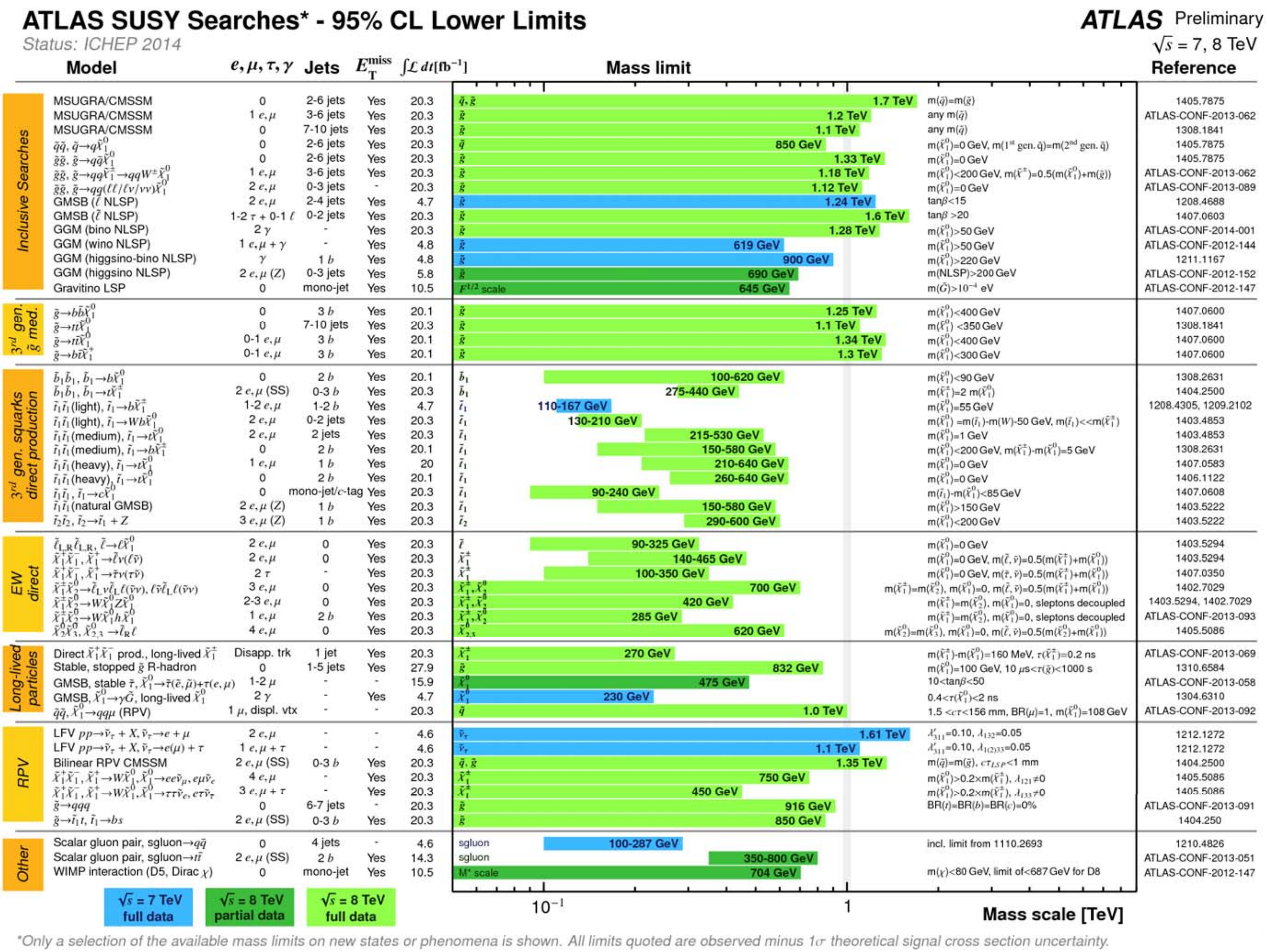
All more or less in trouble (G. Altarelli)

2.- The multiverse and accepting fine tuning:

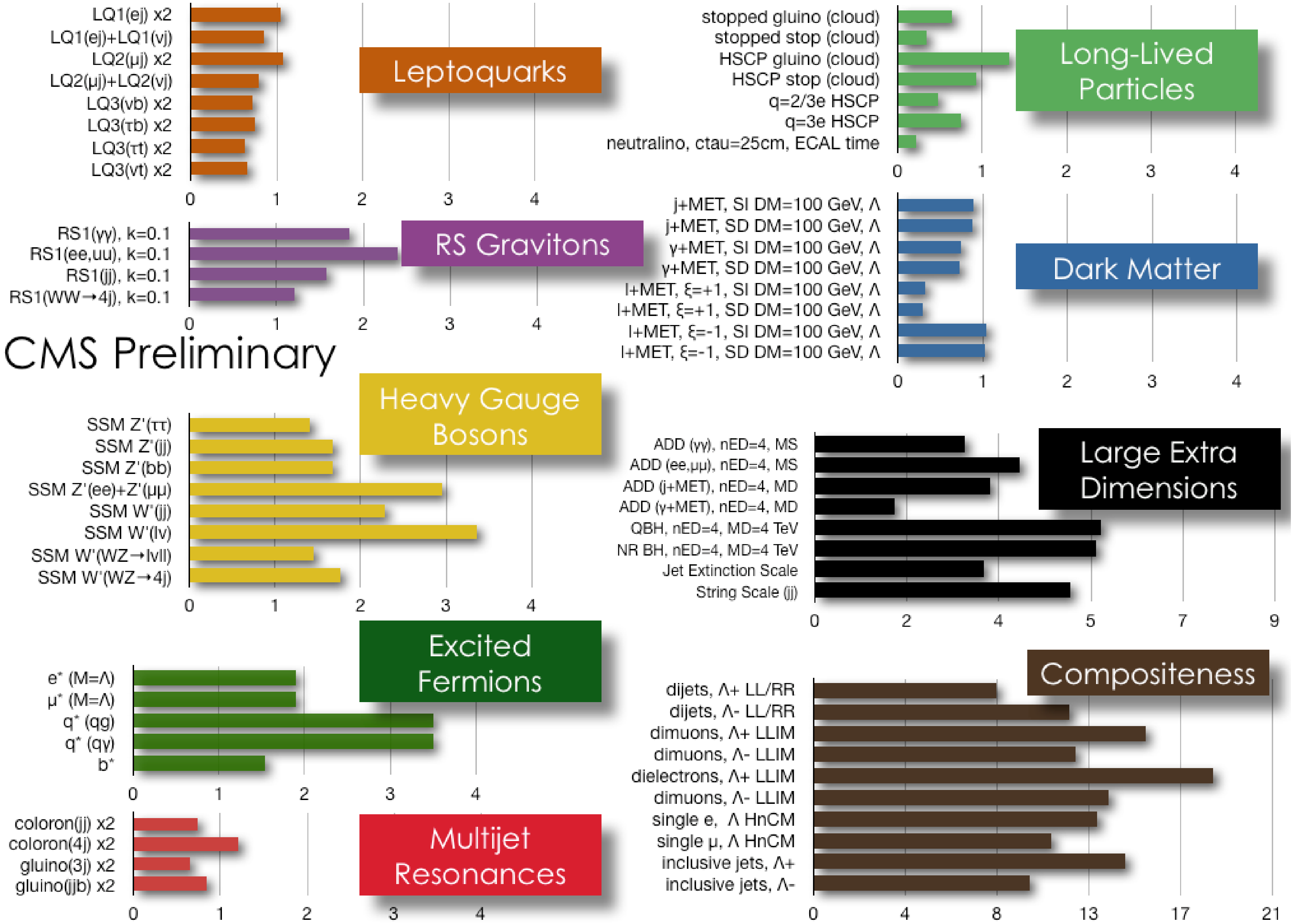
- The anthropic principle
- Near criticality of our universe (metastable vacuum)



Nothing Else (1)



Nothing Else (2)



Landscape Redefined

Flurry of new ideas !

Precision
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- Off Shell couplings and width
- Interferometry

Rare decays
- $Z\gamma$, $\gamma\gamma^*$
- Muons $\mu\mu$
- LFV $\mu\tau$, $e\tau$
- $J/\Psi\gamma$, $Z\Upsilon$, WD etc…

$$H^0$$

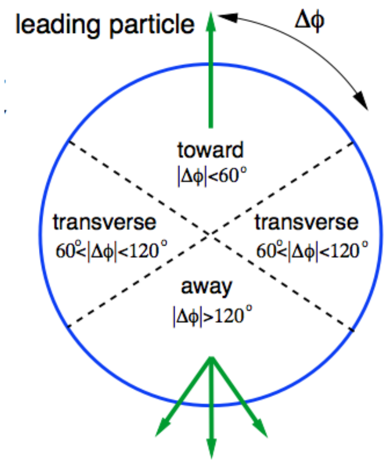
Is the SM minimal?
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

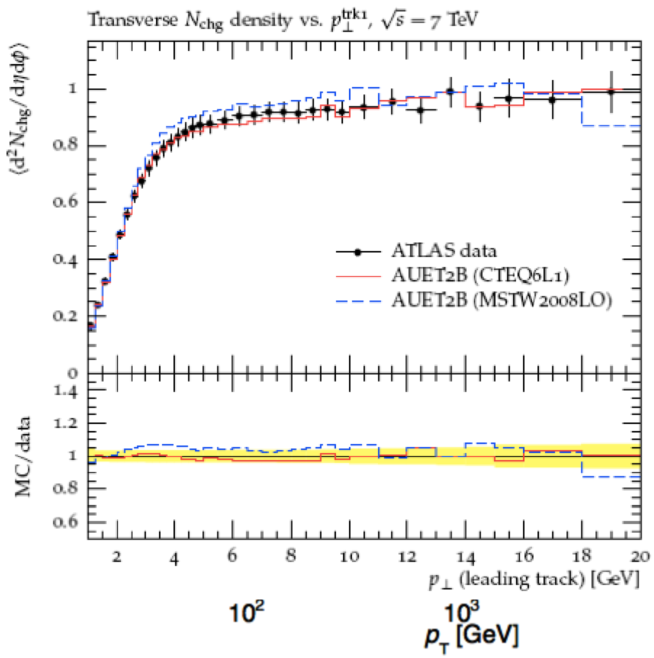
Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)

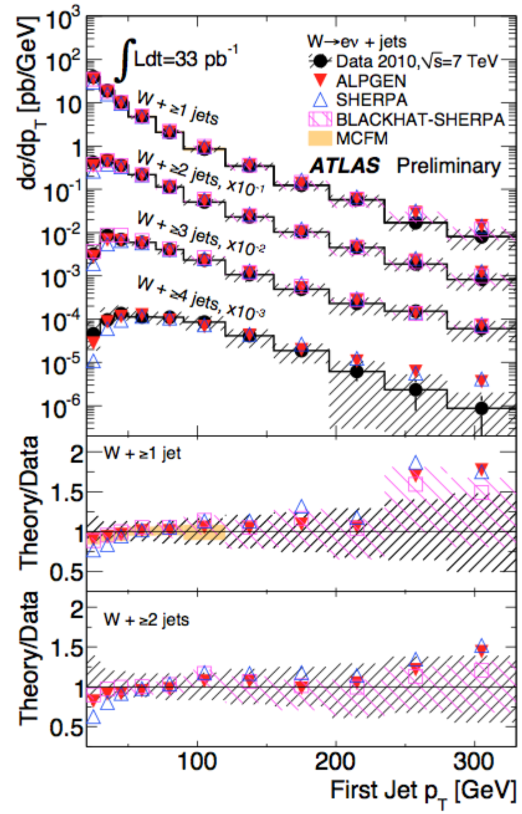
…and More!
- FCNC top decays
- Di-Higgs production
- Trilinear couplings prospects
- Etc…

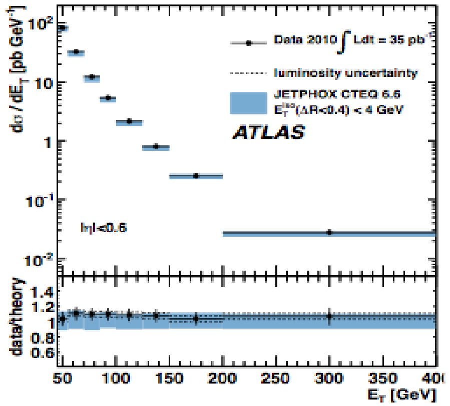
One of the first goals : focus our efforts to extract most of the physical content of our data!

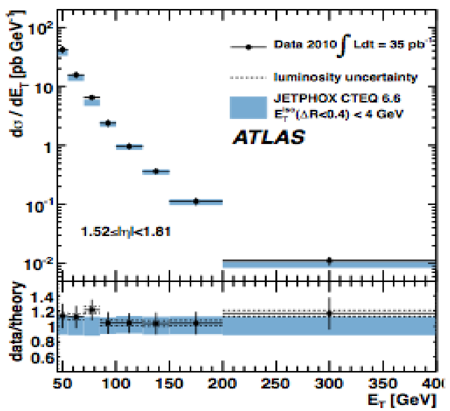
QCD

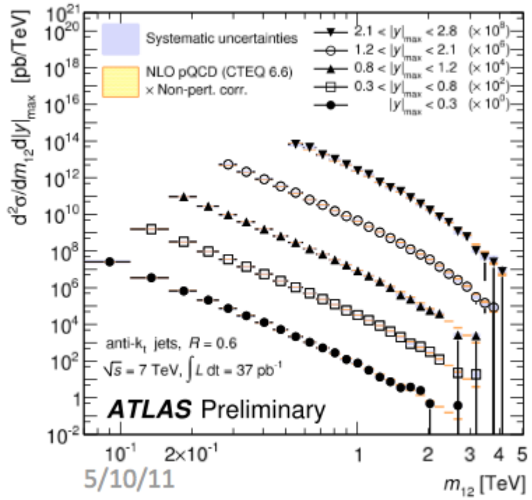

leading particle
Δϕ
toward
|Δϕ|<60°
transverse
60°<|Δϕ|<120°
transverse
60°<|Δϕ|<120°
away
|Δϕ|>120°


Transverse N_{chg} density vs. $p_\perp^{trk1}$, $\sqrt{s} = 7$ TeV
ATLAS data
AUET2B (CTEQ6L1)
AUET2B (MSTW2008LO)
MC / data
$p_\perp$ (leading track) [GeV]
10^2
10^3
p_T [GeV]

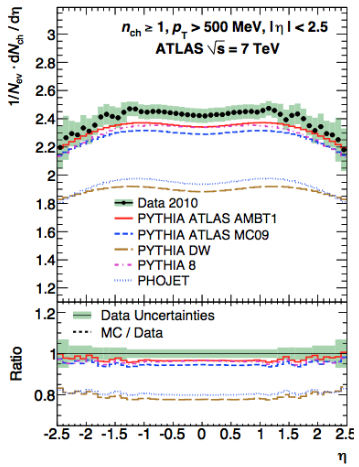

$\int$Ldt=33 pb^{-1}
W→eν + jets
Data 2010,√s=7 TeV
ALPGEN
SHERPA
BLACKHAT-SHERPA
MCFM
ATLAS Preliminary
W + ≥1 jets
W + ≥2 jets, x10^{-1}
W + ≥3 jets, x10^{-2}
W + ≥4 jets, x10^{-3}
dσ/dp$_T$ [pb/GeV]
Theory/Data
W + ≥1 jet
W + ≥2 jets
First Jet p$_T$ [GeV]

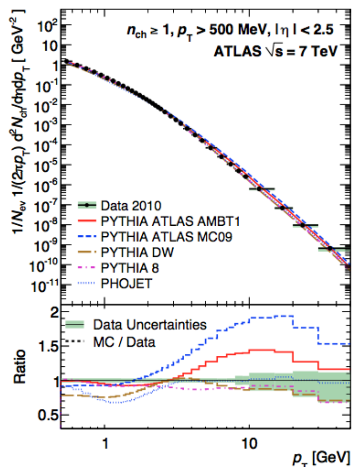

Data 2010 $\int$ Ldt = 35 pb^{-1}
luminosity uncertainty
JETPHOX CTEQ 6.6
ATLAS
|η|<0.6
dσ / dE$_T$ [pb GeV^{-1}]
data/theory
E$_T$ [GeV]


Data 2010 $\int$ Ldt = 35 pb^{-1}
luminosity uncertainty
JETPHOX CTEQ 6.6
ATLAS
1.52≤|η|<1.81
dσ / dE$_T$ [pb GeV^{-1}]
data/theory
E$_T$ [GeV]


Systematic uncertainties
NLO pQCD (CTEQ 6.6)
× Non-pert. corr.
anti-k$_t$ jets, R = 0.6
√s = 7 TeV, $\int$ L dt = 37 pb^{-1}
ATLAS Preliminary
d^{2}σ/dm$_{12}$d|y|$_{max}$ [pb/TeV]
m$_{12}$ [TeV]

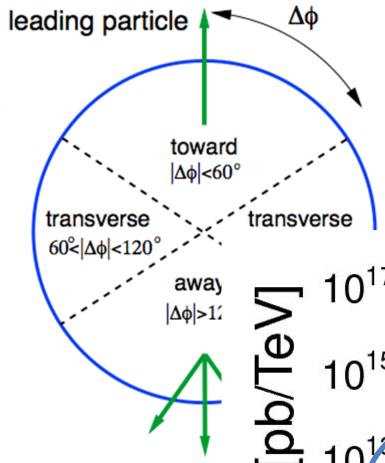
5/10/11

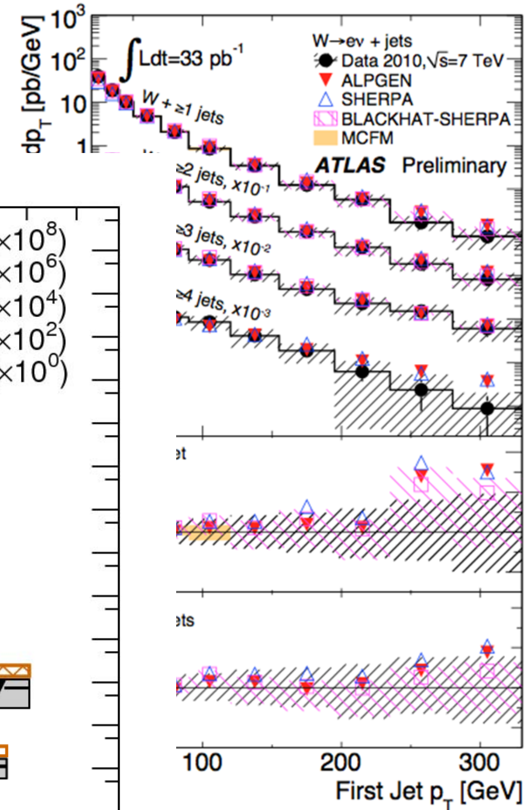

n$_{ch}$ ≥ 1, p$_T$ > 500 MeV, | η | < 2.5
ATLAS √s = 7 TeV
Data 2010
PYTHIA ATLAS AMBT1
PYTHIA ATLAS MC09
PYTHIA DW
PYTHIA 8
PHOJET
Data Uncertainties
MC / Data
Ratio
η

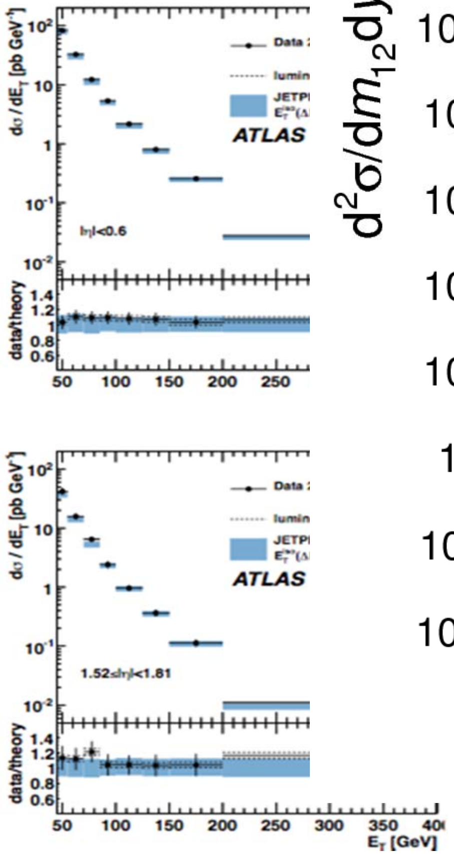

n$_{ch}$ ≥ 1, p$_T$ > 500 MeV, | η | < 2.5
ATLAS √s = 7 TeV
Data 2010
PYTHIA ATLAS AMBT1
PYTHIA ATLAS MC09
PYTHIA DW
PYTHIA 8
PHOJET
Data Uncertainties
MC / Data
Ratio
p$_T$ [GeV]

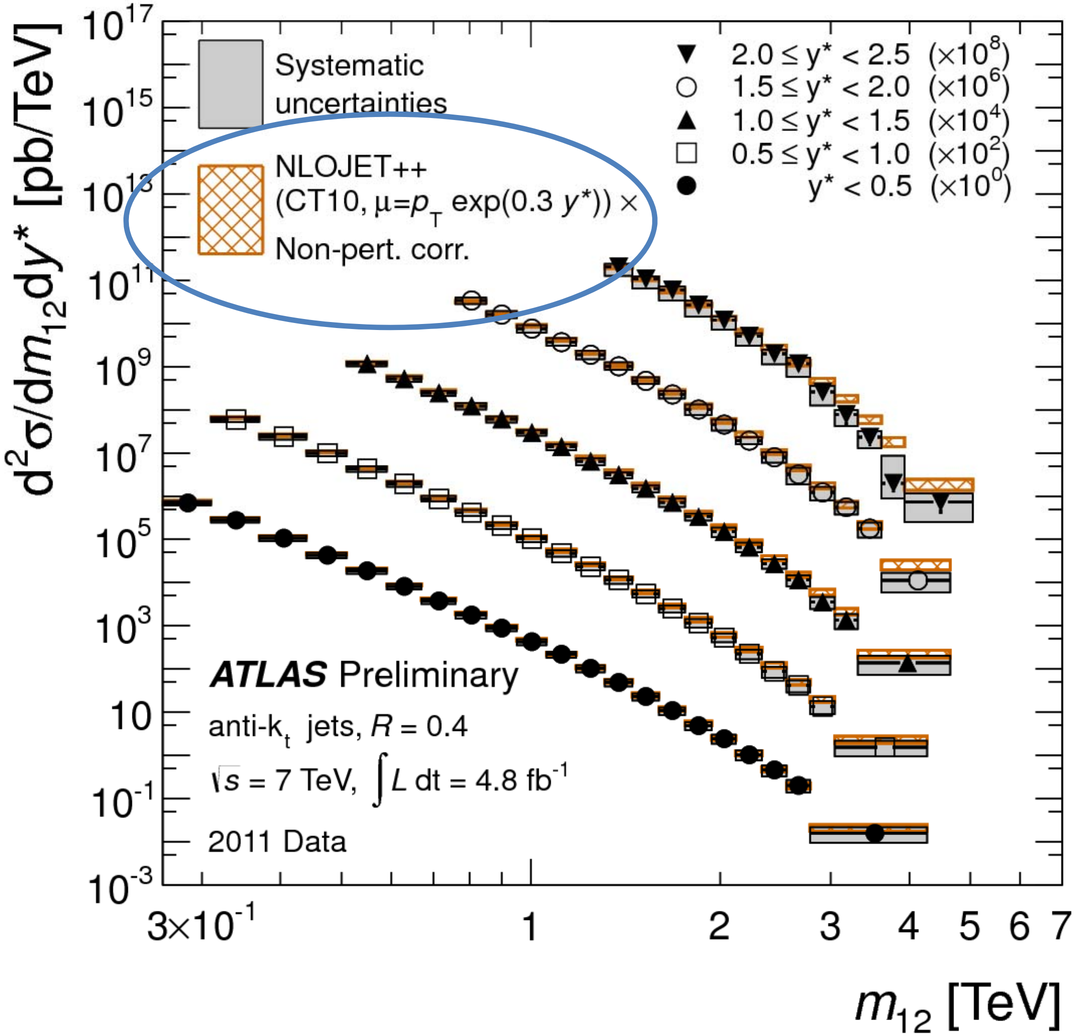
QCD

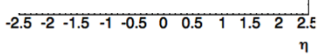
Testing predictions over
8 orders of magnitude !

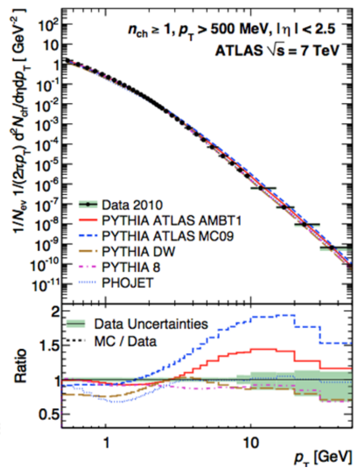




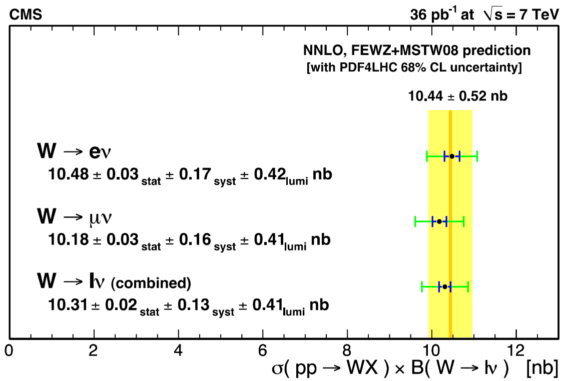


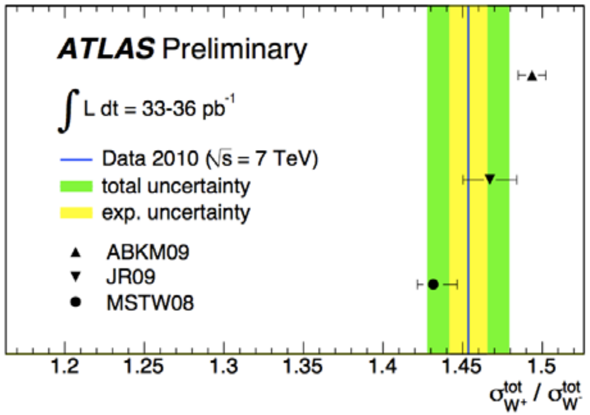


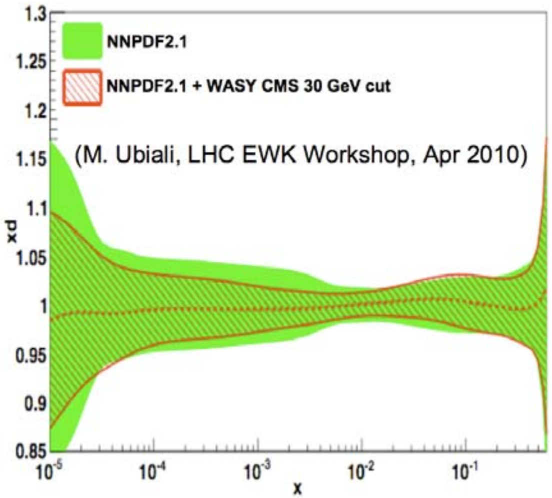


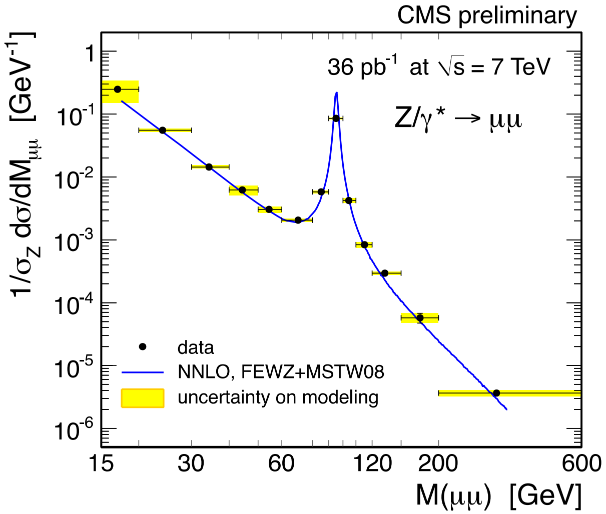


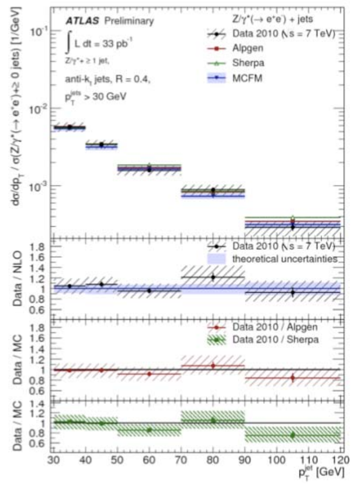
EW

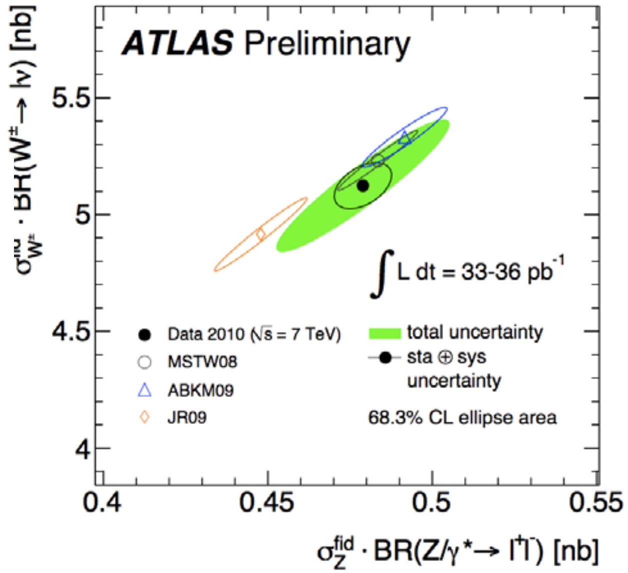

CMS
36 pb^{-1} at $\sqrt{s}$ = 7 TeV
NNLO, FEWZ+MSTW08 prediction
[with PDF4LHC 68% CL uncertainty]
10.44 ± 0.52 nb
W → eν
10.48 ± 0.03 stat ± 0.17 syst ± 0.42 lumi nb
W → μν
10.18 ± 0.03 stat ± 0.16 syst ± 0.41 lumi nb
W → lν (combined)
10.31 ± 0.02 stat ± 0.13 syst ± 0.41 lumi nb
0 2 4 6 8 10 12
σ(pp → WX) × B(W → lν) [nb]

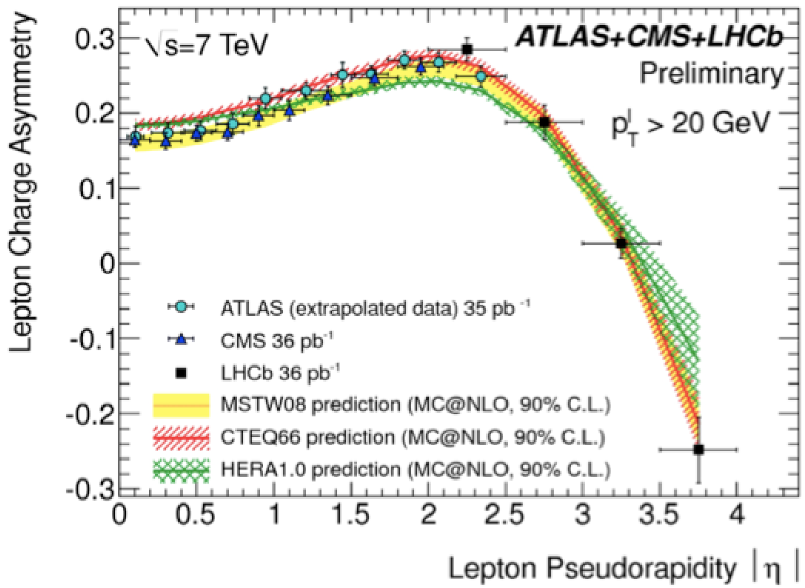

ATLAS Preliminary
∫ L dt = 33-36 pb^{-1}
Data 2010 ($\sqrt{s}$ = 7 TeV)
total uncertainty
exp. uncertainty
ABKM09
JR09
MSTW08
1.2 1.25 1.3 1.35 1.4 1.45 1.5
$\sigma^{tot}_{W^+} / \sigma^{tot}_{W^-}$


NNPDF2.1
NNPDF2.1 + WASY CMS 30 GeV cut
(M. Ubiali, LHC EWK Workshop, Apr 2010)
xd
x


CMS preliminary
36 pb^{-1} at $\sqrt{s}$ = 7 TeV
Z/γ* → μμ
data
NNLO, FEWZ+MSTW08
uncertainty on modeling
$1/\sigma_Z\, d\sigma/dM_{\mu\mu}$ [GeV^{-1}]
15 30 60 120 200 600
M(μμ) [GeV]


ATLAS Preliminary
Z/γ*(→ e+e-) + jets
Data 2010 ($\sqrt{s}$ = 7 TeV)
Alpgen
Sherpa
MCFM
Data / NLO
Data / MC
p_T^{jet} [GeV]


ATLAS Preliminary
∫ L dt = 33-36 pb^{-1}
Data 2010 ($\sqrt{s}$ = 7 TeV)
MSTW08
ABKM09
JR09
total uncertainty
sta ⊕ sys uncertainty
68.3% CL ellipse area
$\sigma^{fid}_{W^\pm} \cdot$ BR(W$^\pm$ → lν) [nb]
$\sigma^{fid}_{Z} \cdot$ BR(Z/γ* → l$^+$l$^-$) [nb]

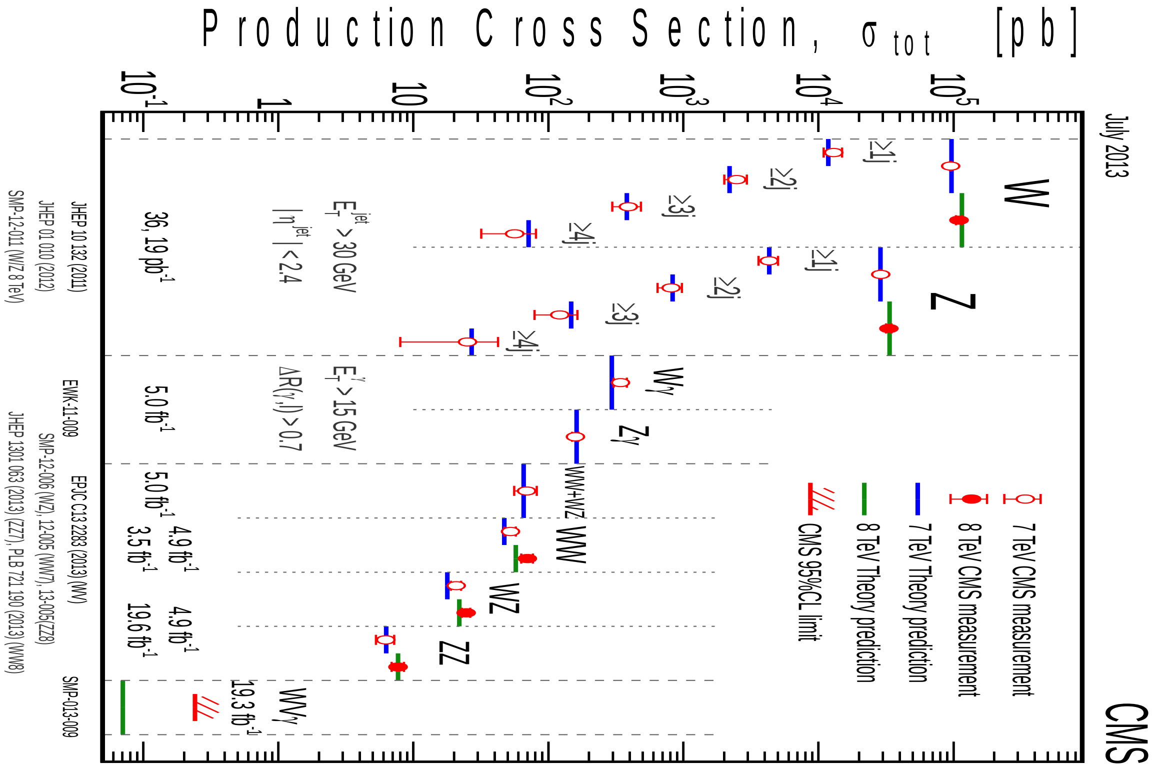

$\sqrt{s}$=7 TeV
ATLAS+CMS+LHCb
Preliminary
p_T^l > 20 GeV
ATLAS (extrapolated data) 35 pb^{-1}
CMS 36 pb^{-1}
LHCb 36 pb^{-1}
MSTW08 prediction (MC@NLO, 90% C.L.)
CTEQ66 prediction (MC@NLO, 90% C.L.)
HERA1.0 prediction (MC@NLO, 90% C.L.)
Lepton Charge Asymmetry
Lepton Pseudorapidity |η|

Overview of Cross Sections

Expected Standard Model and Higgs Productions

Theory and simulation "Next-to…" (r)evolution :

- NNLO PDFs sets
- Calculations at unprecedented order in perturbation theory
- Parton Shower (and Matrix Element matching) improvements



Overview of Cross Sections

Expected Standard Model and Higgs Productions

Theory and simulation "Next-to…" (r)evolution :

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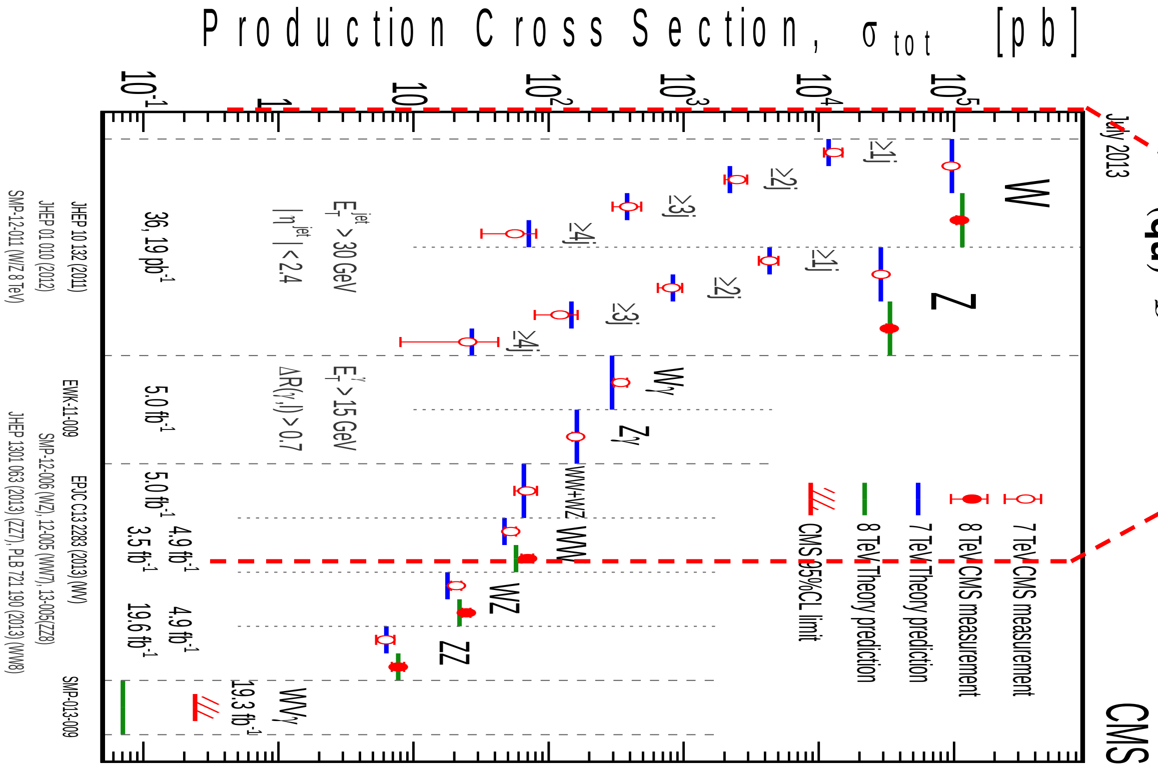
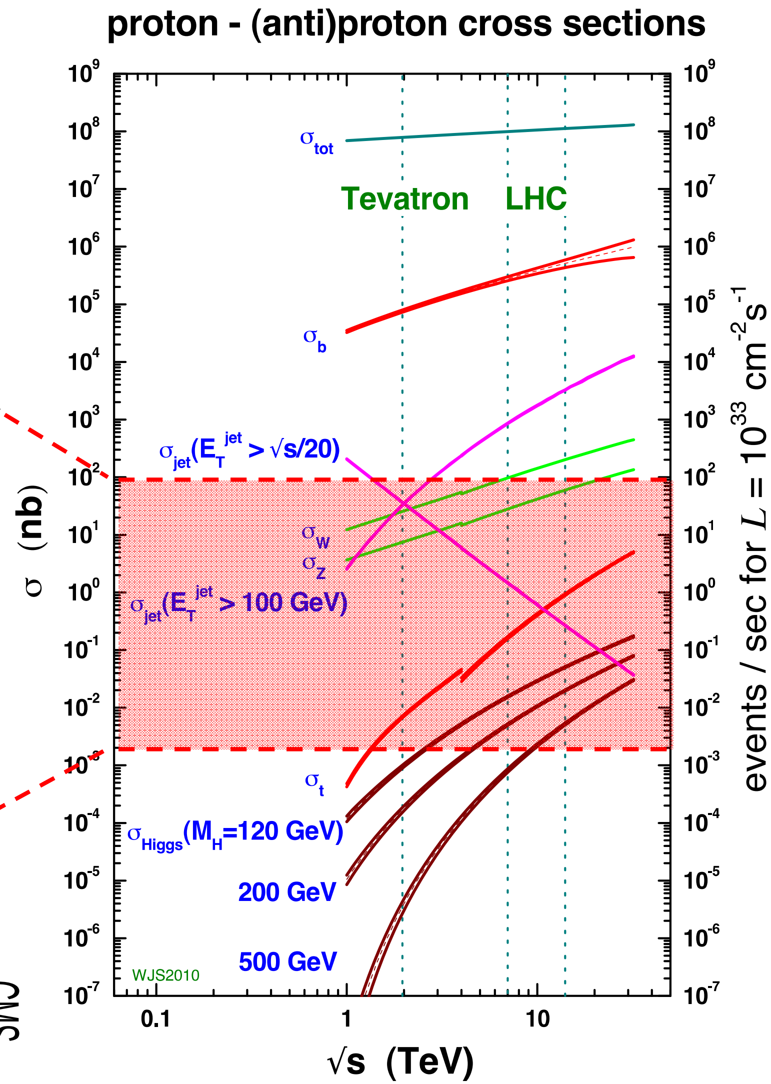
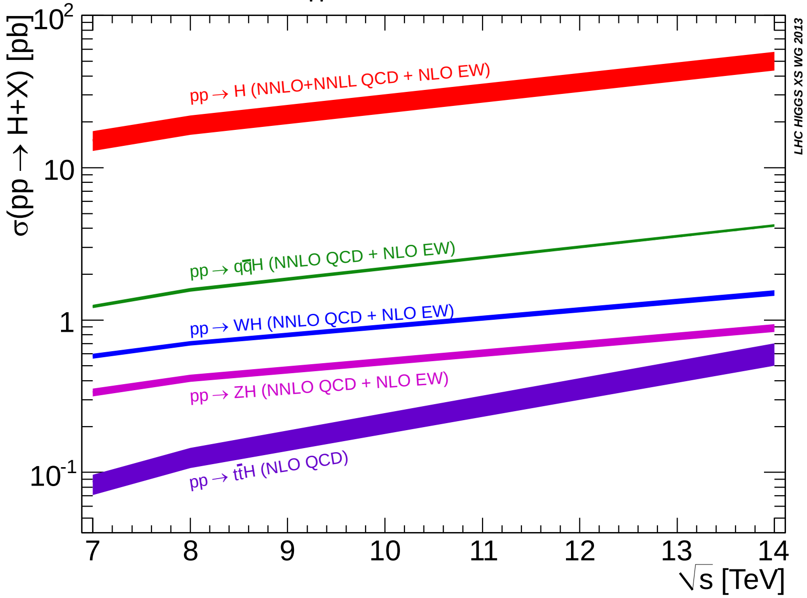
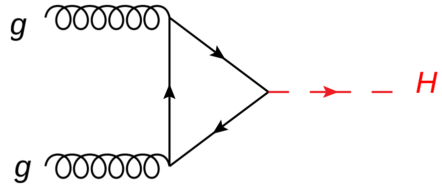




Higgs Production Modes

κ for m_H = 125.5 GeV

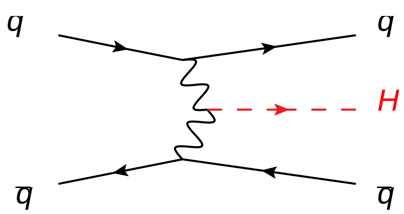




Gluon fusion process

NNnLO ~O(10%)

~0.5 M events produced

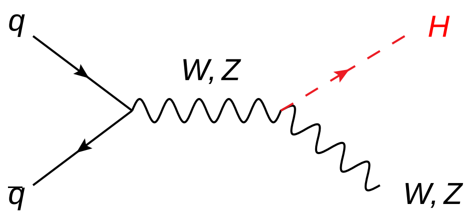


Vector Boson Fusion

NLO TH uncertainty ~O(5%)

Two forward jets and a large rapidity gap

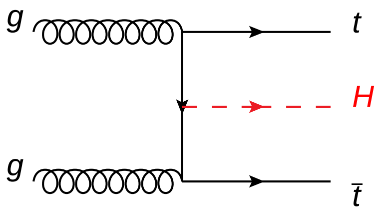
~40 k events produced



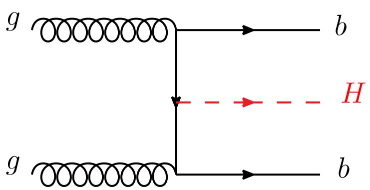
W and Z Associated Production

NNLO TH uncertainty ~O(5%)

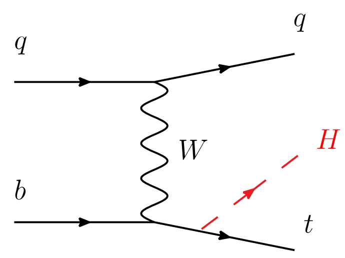
~20 k events produced



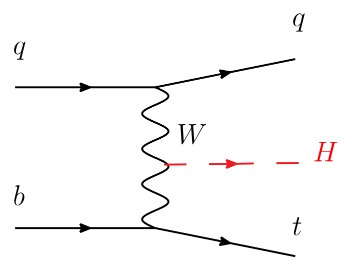
Top Assoc. Prod. ~3 k evts produced



B-quark Assoc. Prod. ~5 k evts produced

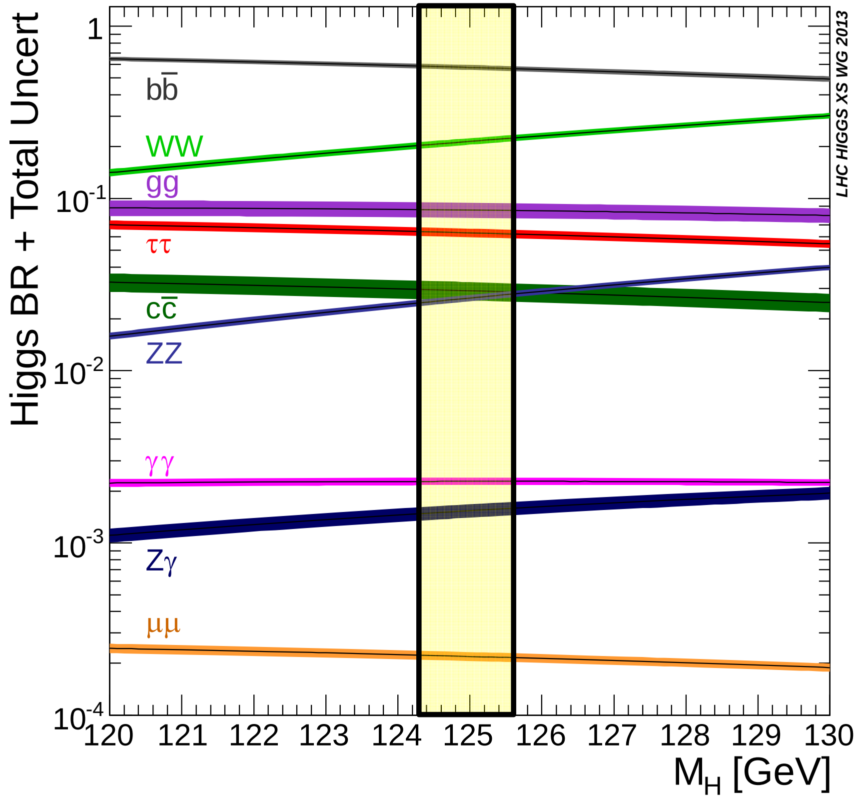


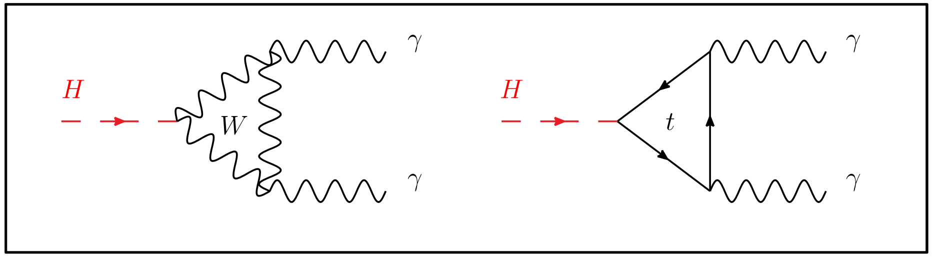
tH



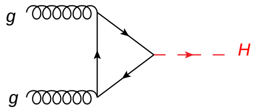
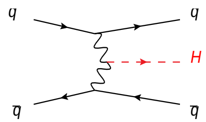
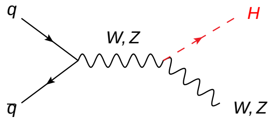
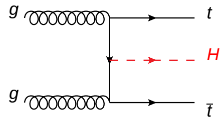
Higgs Decay Channels

- Dominant: bb (57%)
- WW channel (22%)
- ττ channel (6.3%)
- ZZ channel (3%)
- cc channel (3%)
  Extremely difficult
- The γγ channel (0.2%)
- The Zγ (0.2%)
- The μμ channel (0.02%)

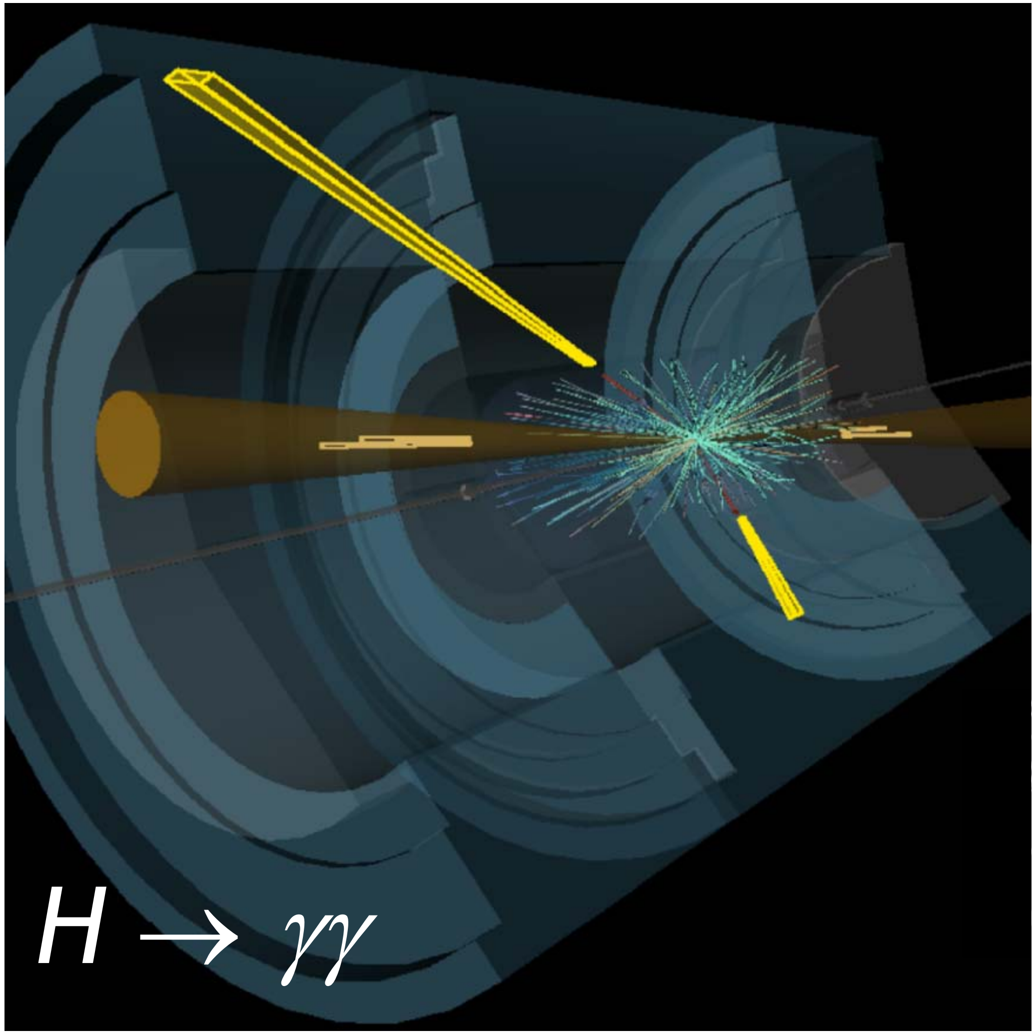


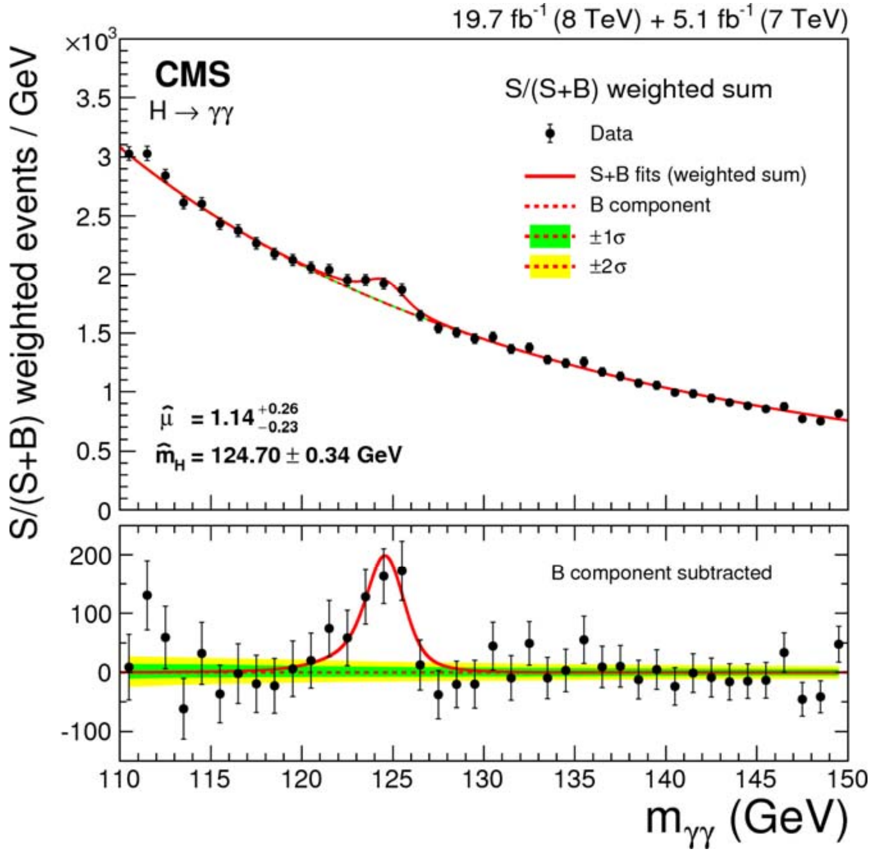


Panorama of Higgs Analyses

Channel categories	ggF 	VBF 	VH 	ttH 
$\gamma\gamma$	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	
WW ($l\nu l\nu$)	✓	✓	✓	✓
$\tau\tau$	✓	✓	✓	✓
bb		✓	✓	✓
Zγ and $\gamma\gamma^*$	✓	✓		
$\mu\mu$	✓	✓		
Invisible	✓	✓	✓	✓ (1408.011)

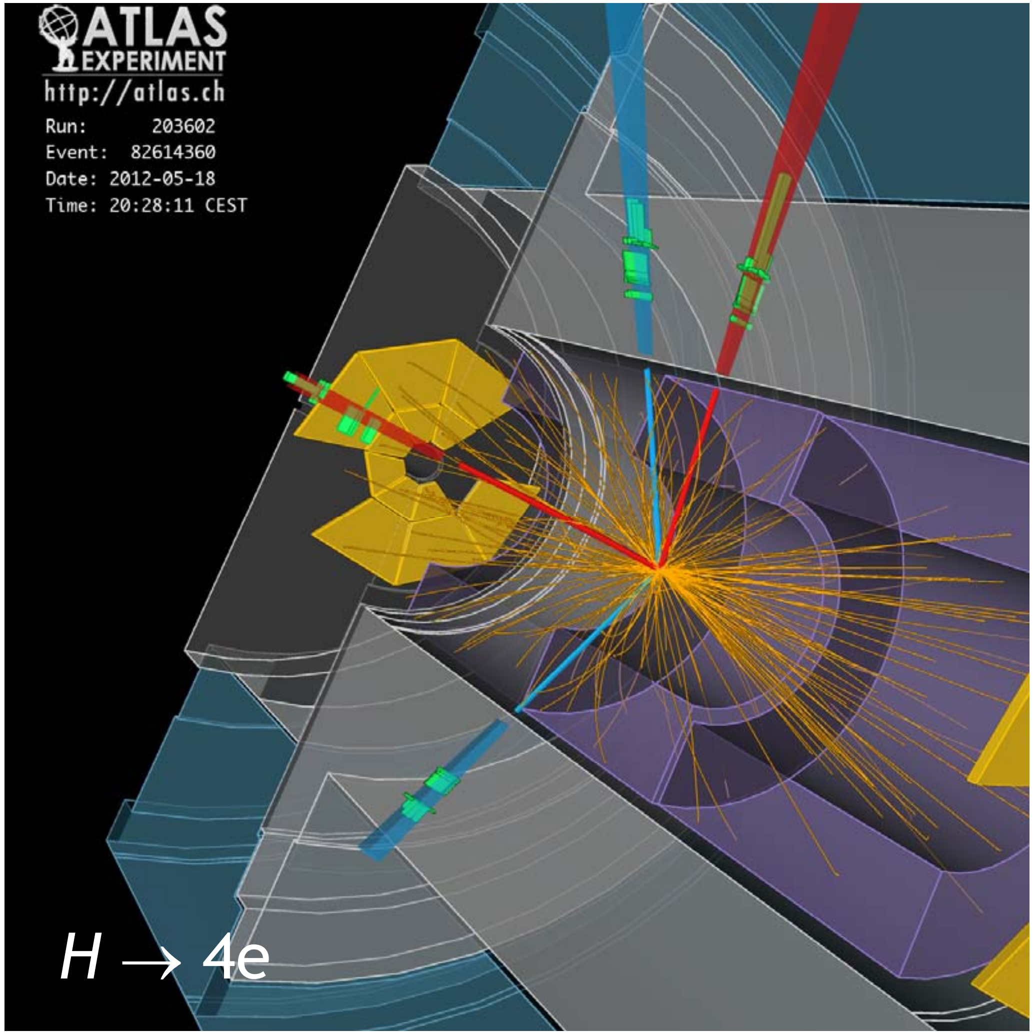
The diphoton decay channel
(covers all production modes)

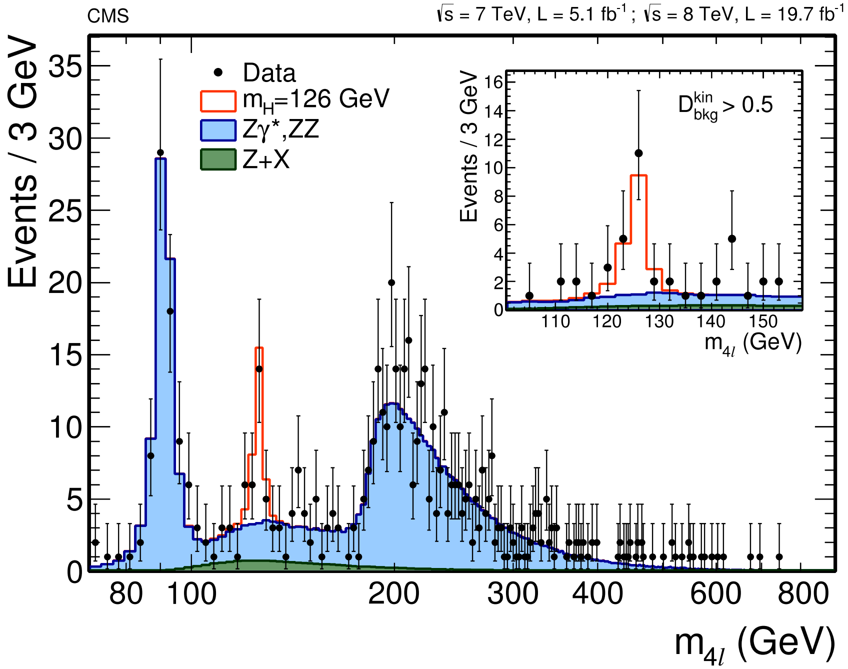




- s/b ratio ranging from few % to approximately 30%
- Excellent mass resolution

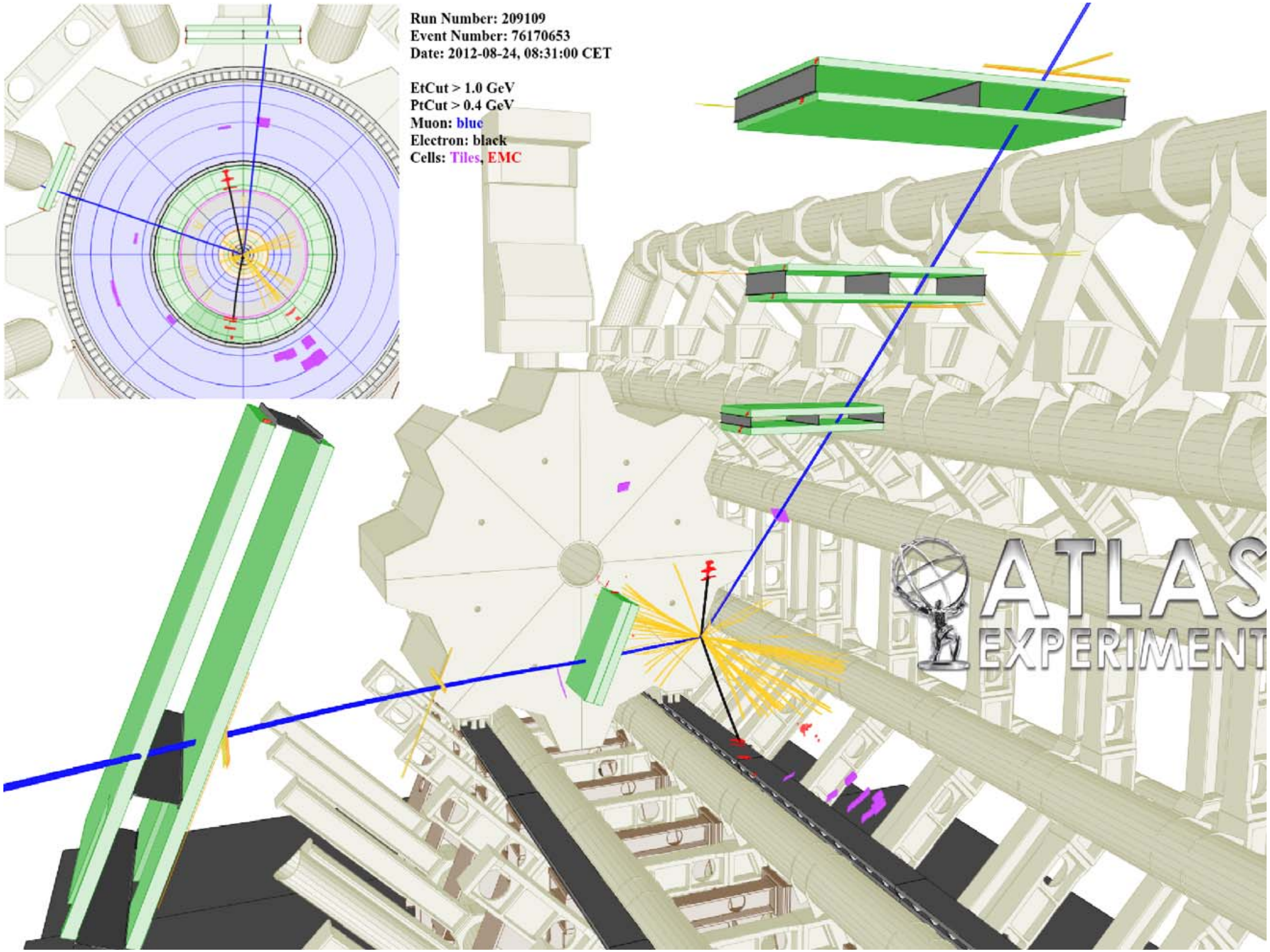
Four Lepton decay channel
(covers most production modes)





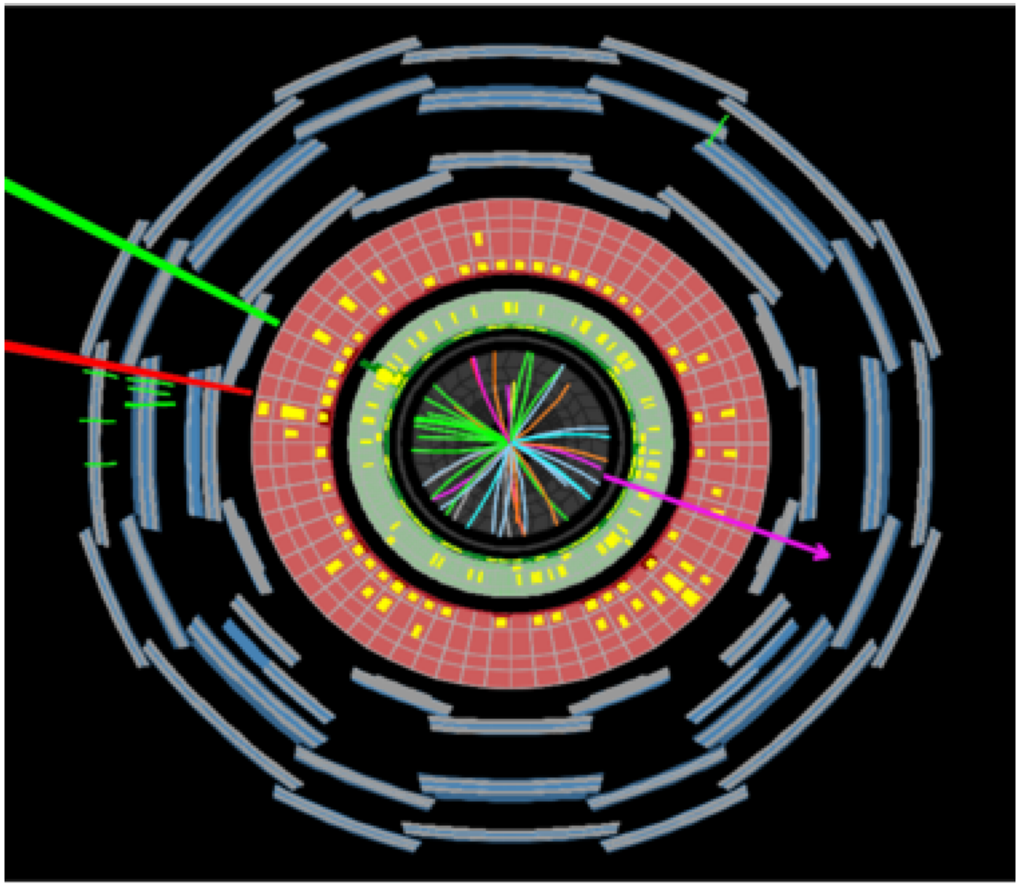
- High s/b ratio starting from approximately 1.5 and reaching more than 10.
- Excellent mass resolution

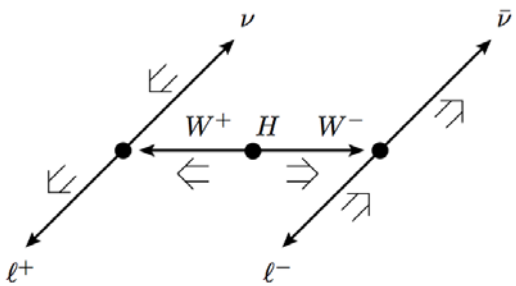
$H \rightarrow$ 4l Single Highest Purity Candidate Event (2e2μ)

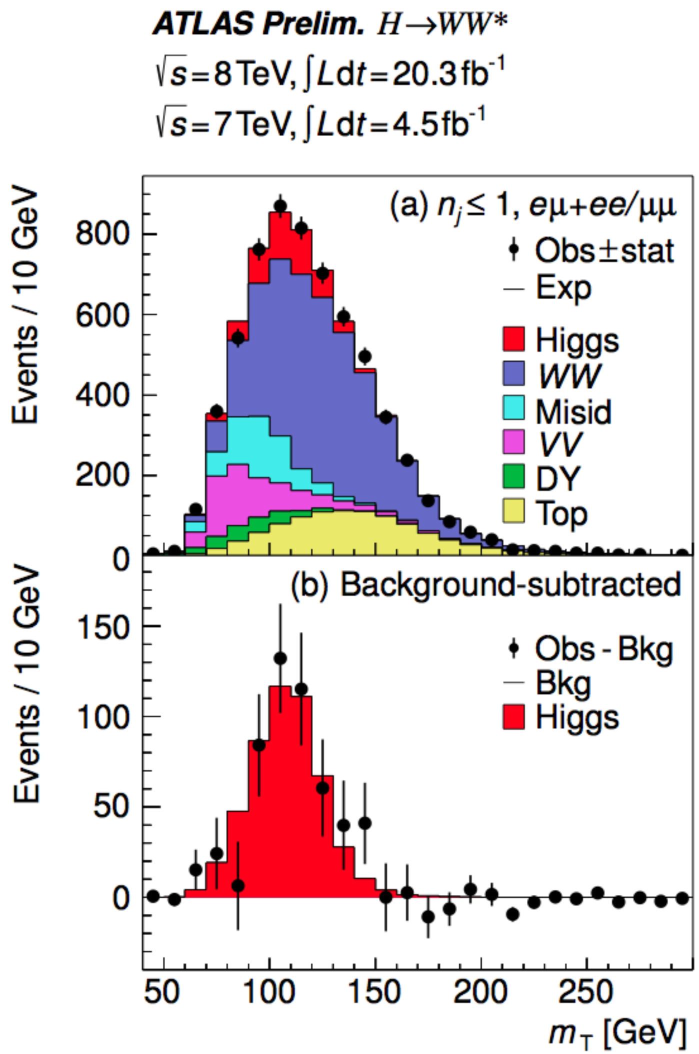


$H \to WW^{(*)} \to l\nu l\nu$

(covers most production modes)

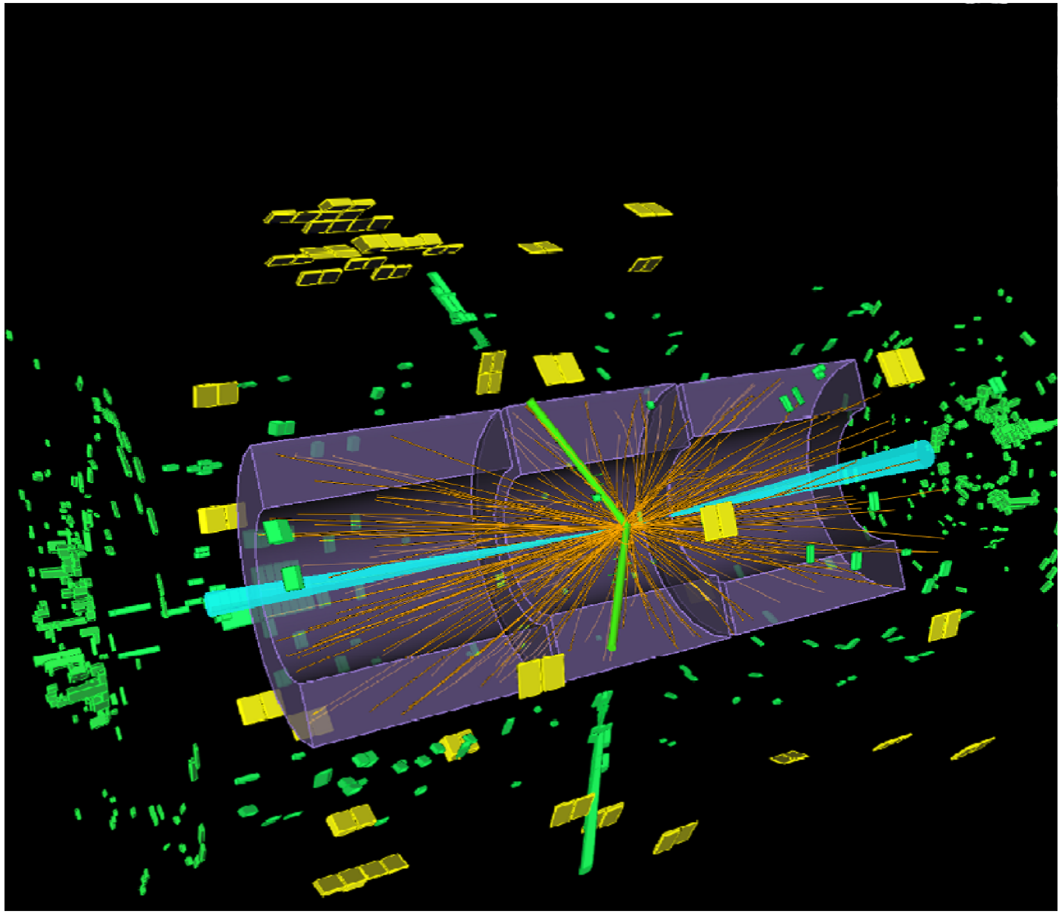


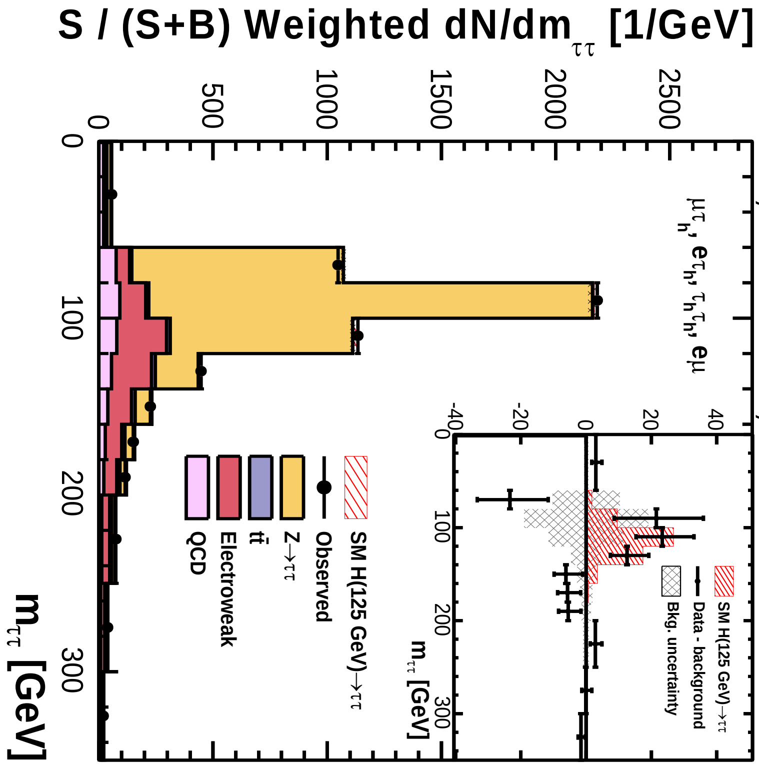




- Intricate analysis
- Moderate s/b ratio starting from approximately 1.5 and reaching more than 10.
- Poor mass resolution

(Mostly) VBF $H \to \tau\tau$

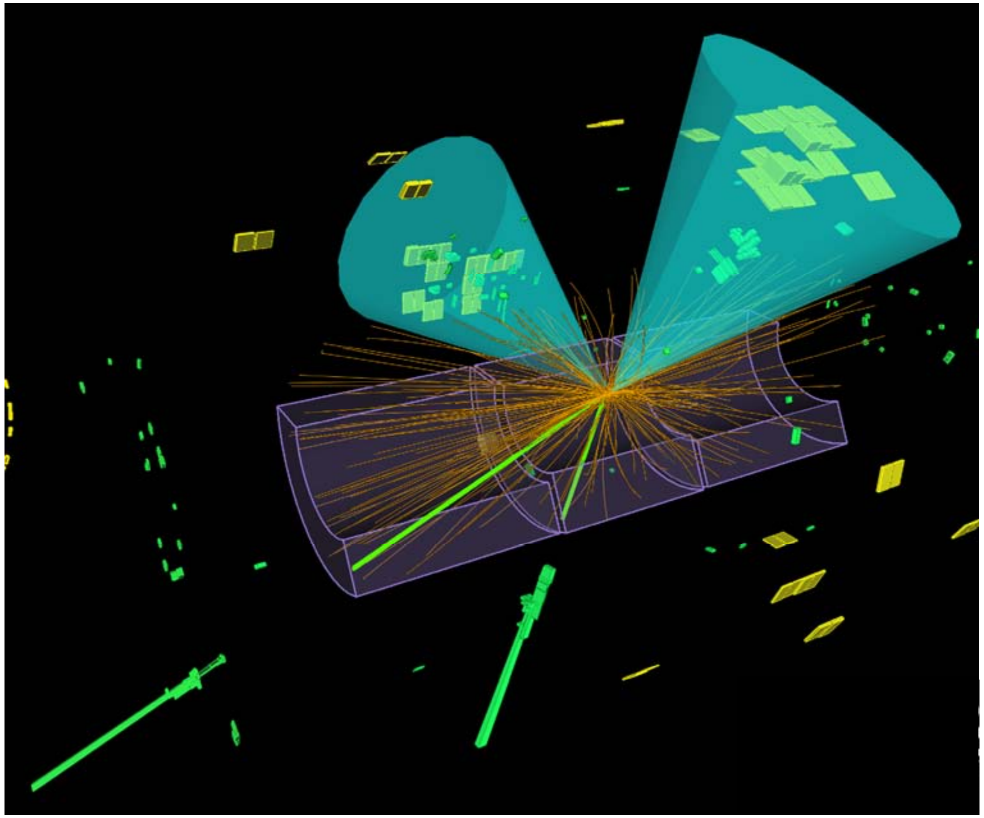


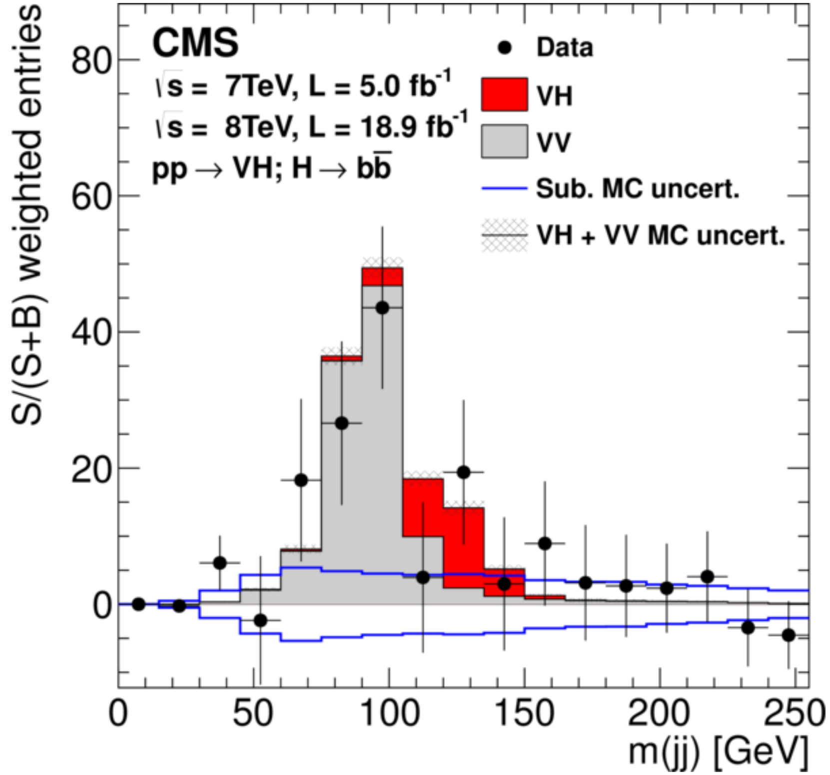


- Intricate analysis
- Moderate s/b ratio starting from approximately few percent to approximately 30%.

VH production with $H \rightarrow bb$

Also a VBF analysis (CMS)

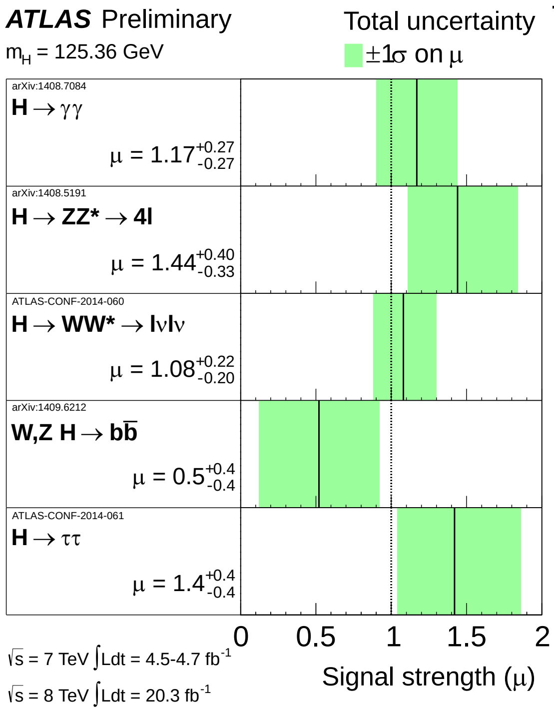


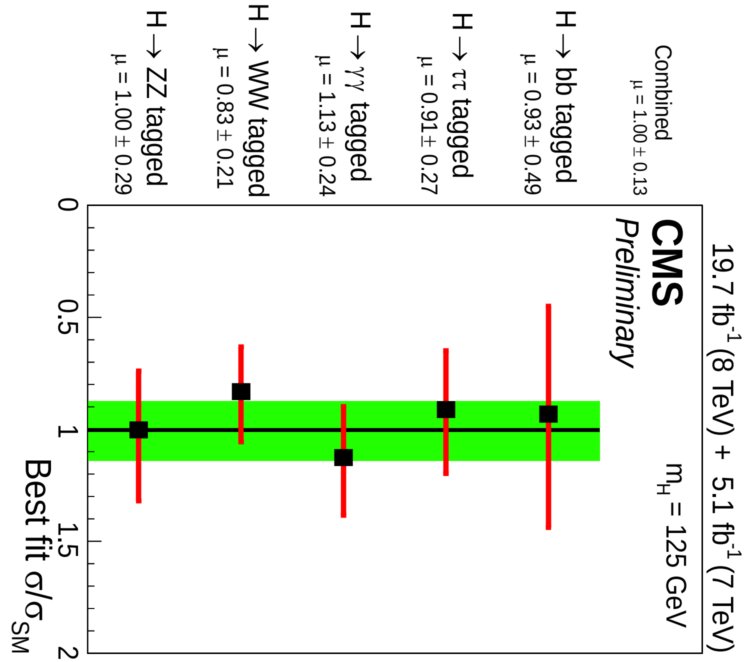


- Intricate analysis
- Moderate s/b ratio starting from approximately few percent to approximately 30%.

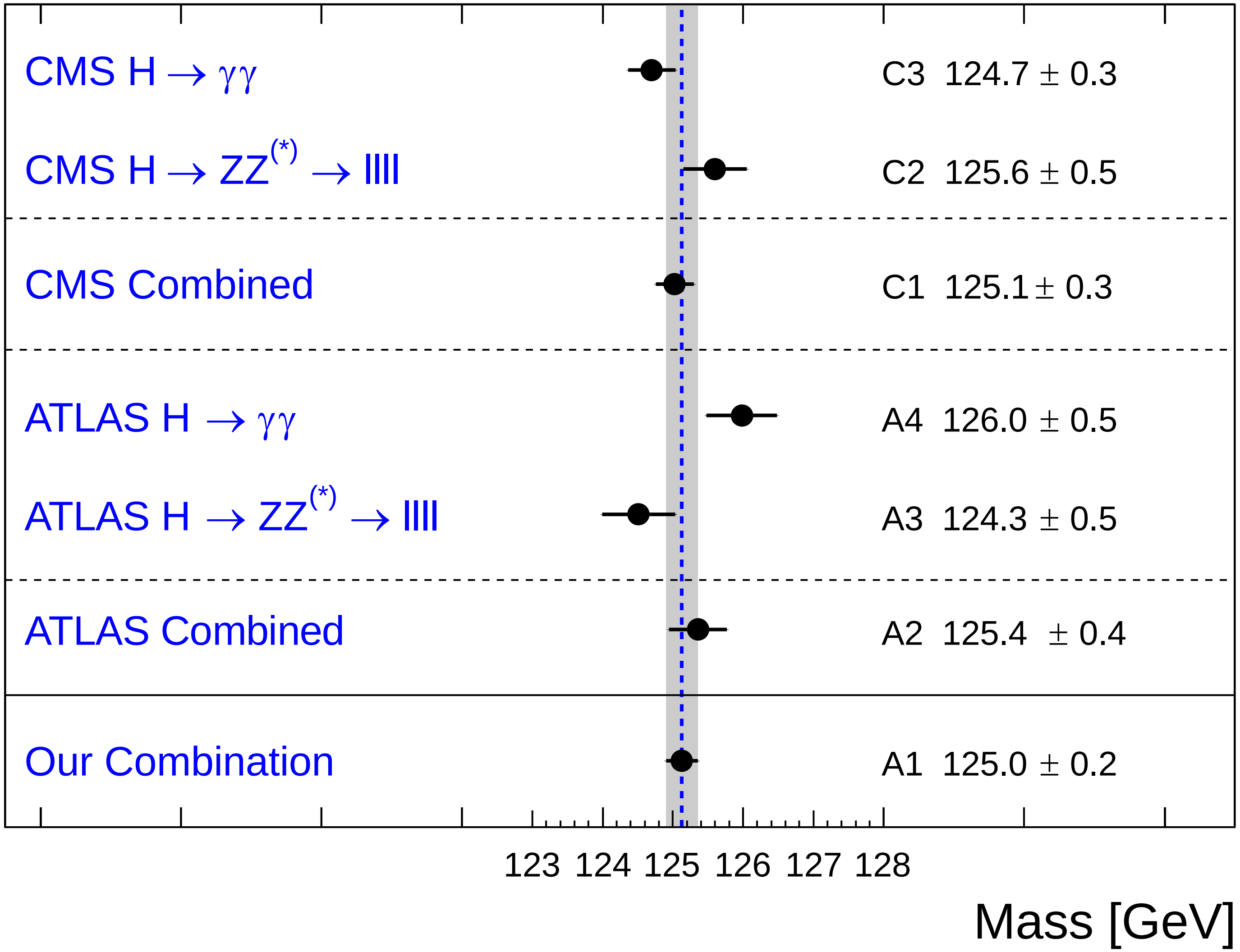
Main decays channels inputs

Channel categories	ATLAS				CMS			
	μ (at 125.4 GeV)	Z exp	Z obs	M (GeV)	μ	Z exp	Z obs	M (GeV)
γγ	1.2±0.3	4.6	5.2	126.0±0.5	1.1±0.2	5.2	5.7	124.7±0.3
ZZ (llll)	1.4±0.4	6.2	8.1	124.3±0.5	1.0±0.3	6.2	6.2	125.6±0.5
WW (lnln)	1.1±0.2	5.8	6.1	-	0.8±0.2	5.3	3.9	-
ττ	1.4±0.4	3.5	4.5	-	0.9±0.3	3.7	3.2	125^{+9}_{-7}
W,Z H (bb*)	0.5±0.4	2.6	1.4	-	0.9±0.5	2.1	2.1	-
Combination	-	-	-	125.4±0.4	1.00±0.13	-	-	125.1±0.3





Precision through Combinations



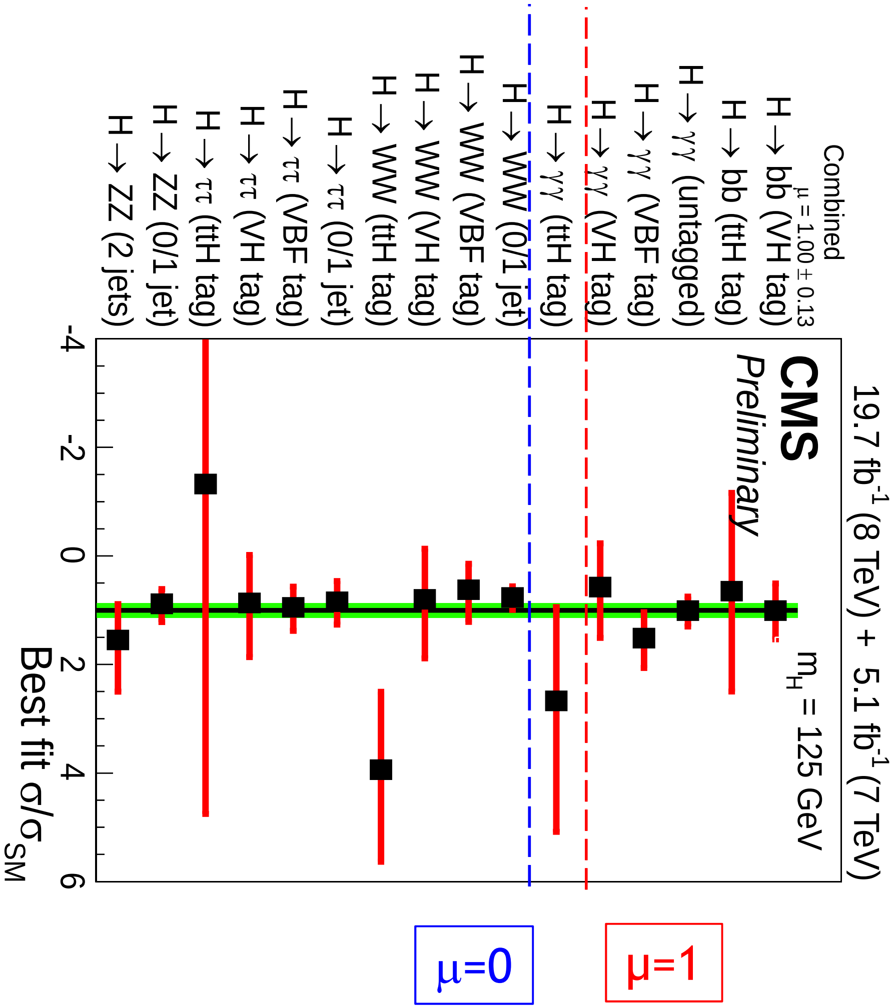
Currently Measured at ~0.16%

(still some gain from Stat, Syst more difficult!)

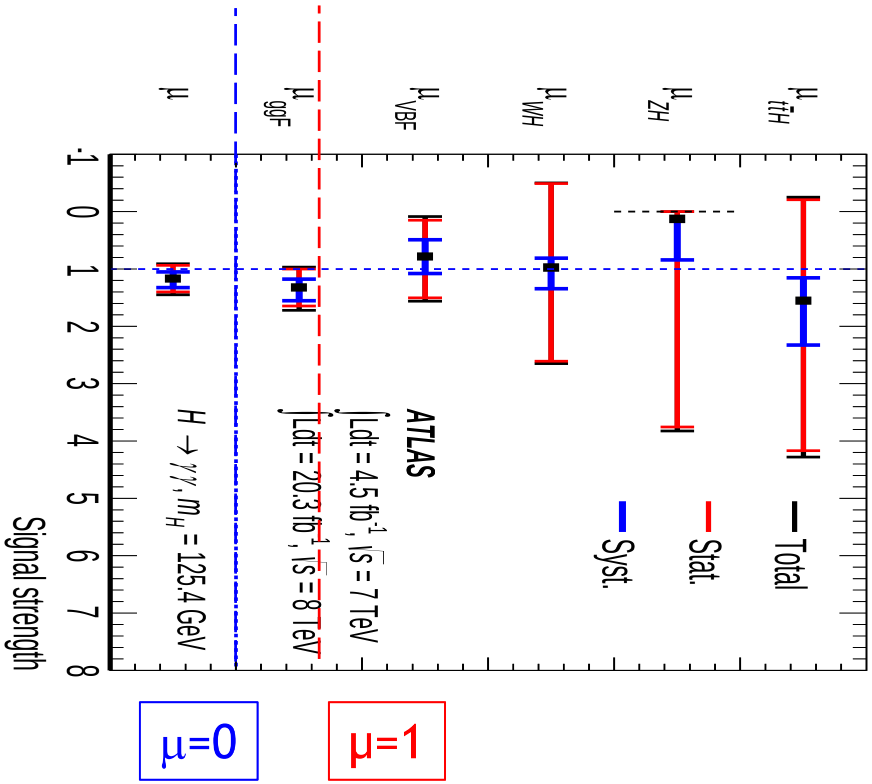
Digression on Information Format

$$n_s^c = \left(\sum_{i \in \{ggF, VBF, VH, ttH\}} \mu^i \sigma^i_{SM} \times A^{ic} \times \varepsilon^{ic} \right) \times \mu^f Br^f \times L^c$$

Sub-channel signal strengths



Production mode signal strengths (per channel)



The Natural Width of the Higgs Boson

$$\Gamma_{SM} = 4.2\ \text{MeV}$$

Is small therefore small couplings to the Higgs can be easily visible: tool for discovery!

At LHC only cross section x branching ratio, no direct access to the Higgs total cross section (unlike e^+e^- collider from recoil mass spectrum)

- Direct measurement (on-shell) with the ZZ(4l) and $\gamma\gamma$ channels [obs. (exp.)]:

  Γ_{4l} < 2.6 (3.5) GeV *[exp. 6.5 for μ=1]* and $\Gamma_{\gamma\gamma}$ <5.0 (6.2) GeV

- Only measure ratio of couplings or coupling modifiers with specific assumptions
- Coupling properties measurements
- Constraints from invisible (and exotic decays)

Total width: Interference in diphoton

(SM shift of approximately 30 MeV)

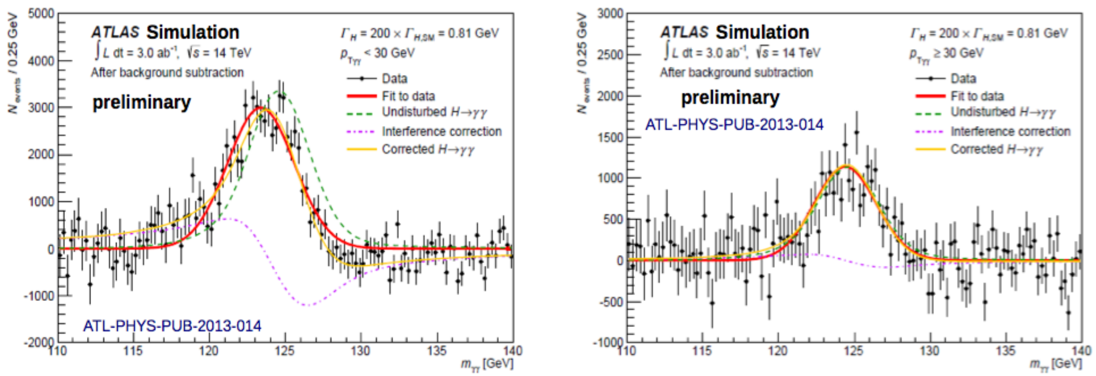
Use pT dependence of shift

(~200 MeV limit expected for 3 ab^{-1})

Total width:

Through off shell couplings

ATL-PHYS-PUB-2013-014



Interpreting our Data

First step towards an global EFT analysis:

From the number of signal events fitted in analysis categories

$$n_s^c = \underline{\mu} \left(\sum_{i \in \{processes\}} \underline{\mu^i} \sigma_{SM}^i \times \mathrm{A}^{ic} \times \varepsilon^{ic} \right) \times \underline{\mu^f} Br^f \times L^c$$

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- Link to an effective Lagrangian and use scale factors

$$\begin{aligned}\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\ + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\ - \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H\end{aligned}$$

Interpreting our Data

First step towards an global EFT analysis:

From the number of signal events fitted in analysis categories

$$n_s^c = \mu \left(\sum_{i \in \{processes\}} \mu^i \sigma_{SM}^i \times A^{ic} \times \varepsilon^{ic} \right) \times \mu^f Br^f \times L^c$$

- Link to an effective Lagrangian and use scale factors

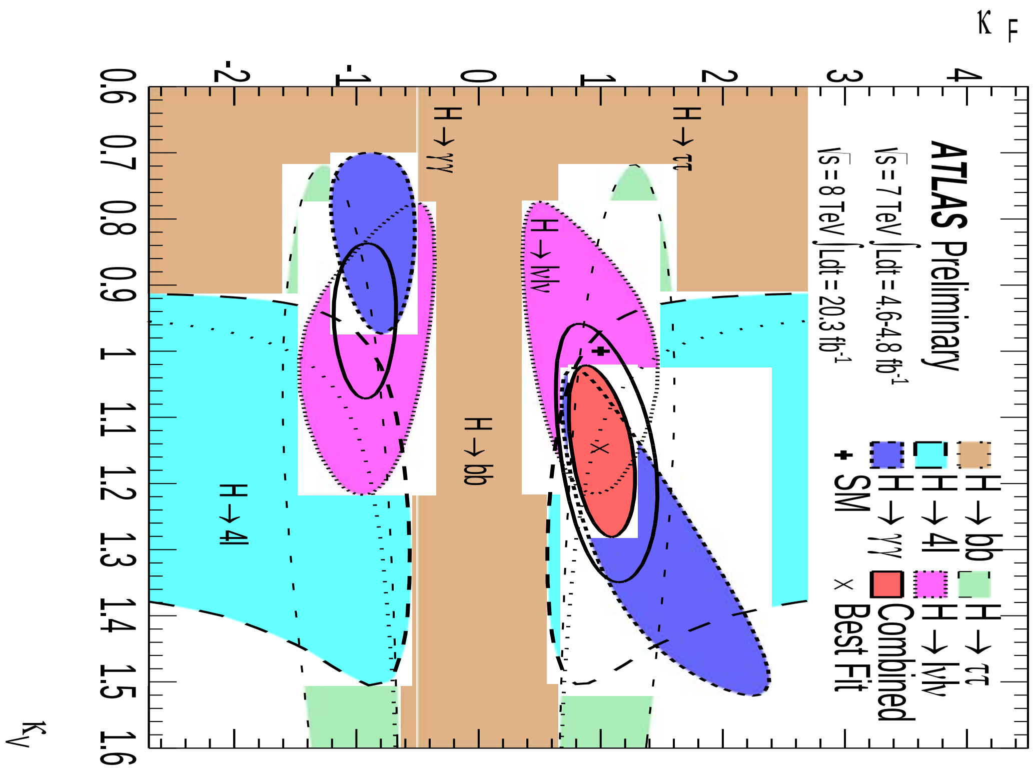
$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H - \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$

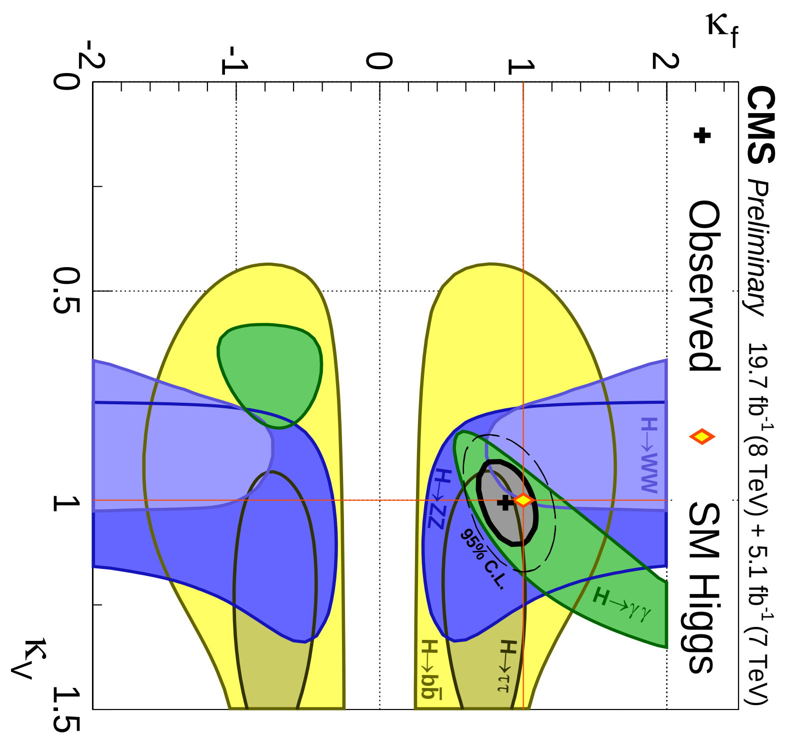
- Assuming narrow width approximation
- Assume the same tensor structure of the SM Higgs boson : $J^{CP} = 0^{++}$

For example, the main contribution (ggF) to the gg channel can be written as (under the assumption that couplings to SM particles are SM):

$$\mu^i = \kappa_g^2 \qquad \mu^f = \frac{\kappa_\gamma^2}{\kappa_H^2} \qquad \kappa_H^2 = 0.085 \times \kappa_g^2 + 0.0023 \times \kappa_\gamma^2 + 0.91$$

Main results I : Probing the coupling to SM particles

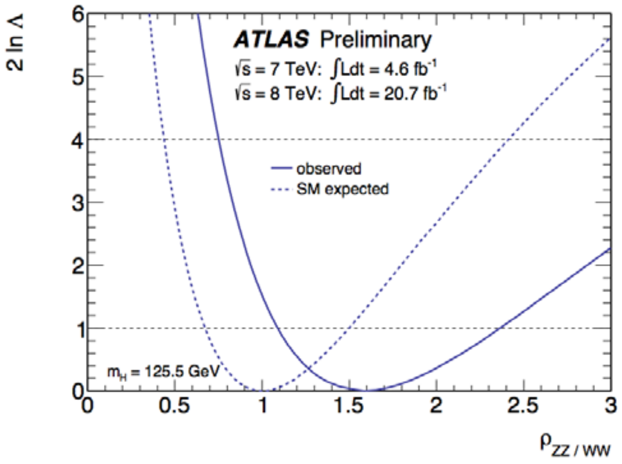


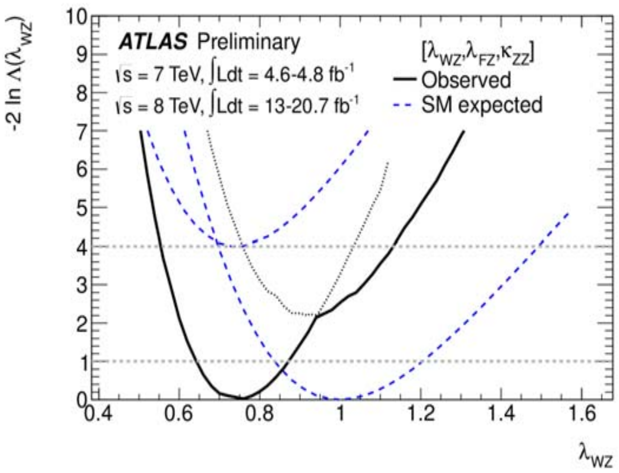


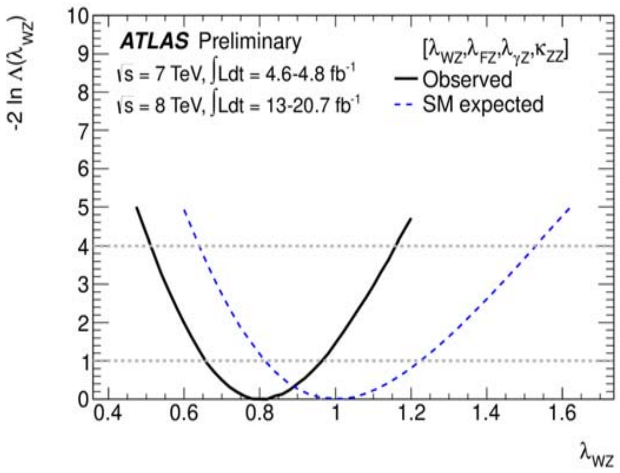
- Checking the direct and indirect couplings to fermions

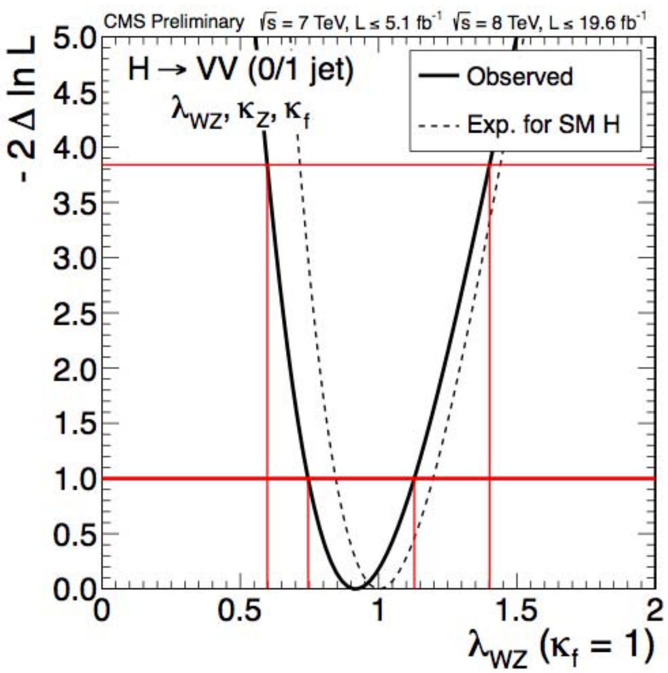
- Probing specific composite models

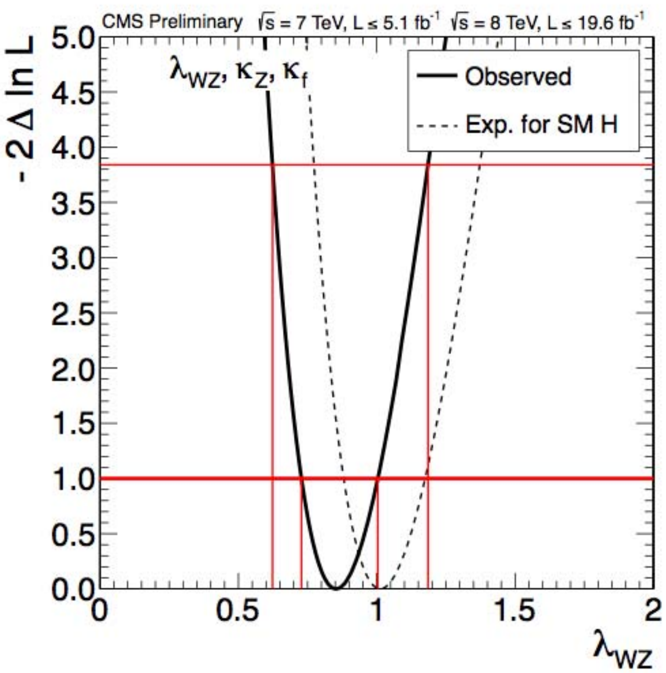
Main results II : Probing the W to Z ratio (custodial symmetry)





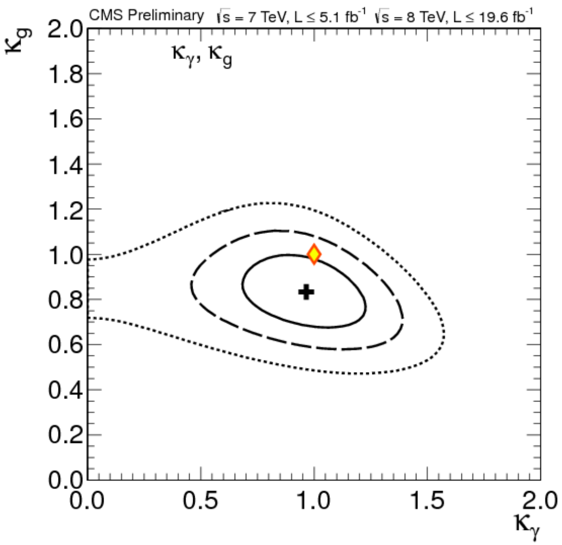


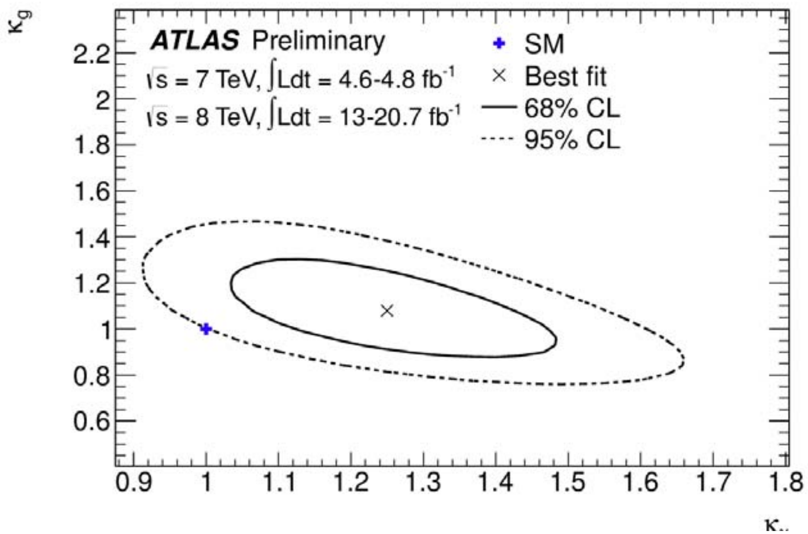




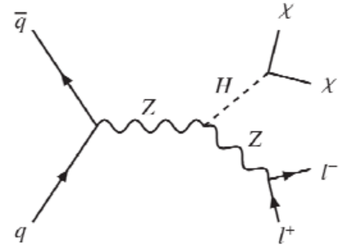
Main results III : Probing physics beyond the Standard Model

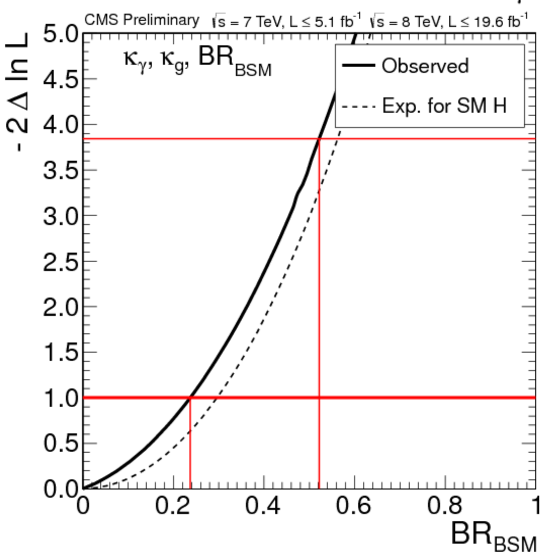
(In the decays and/or in the loops)

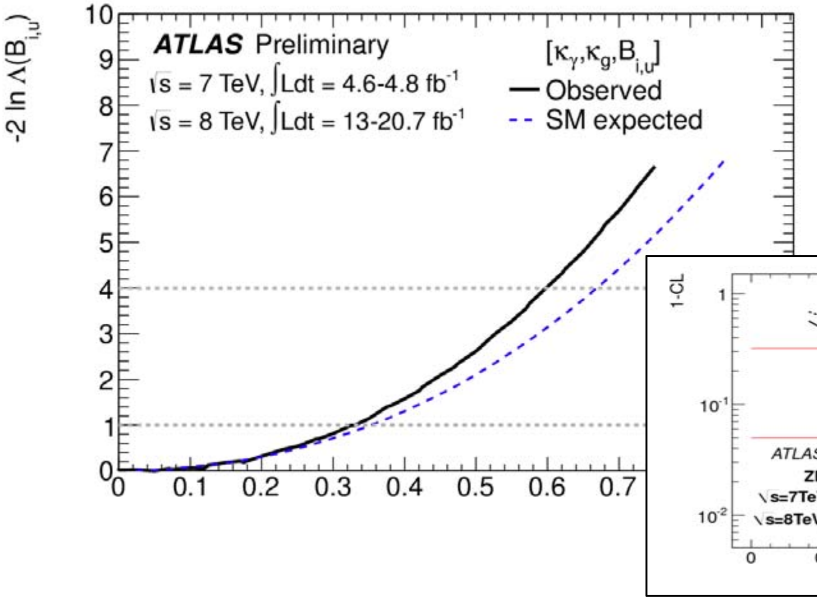


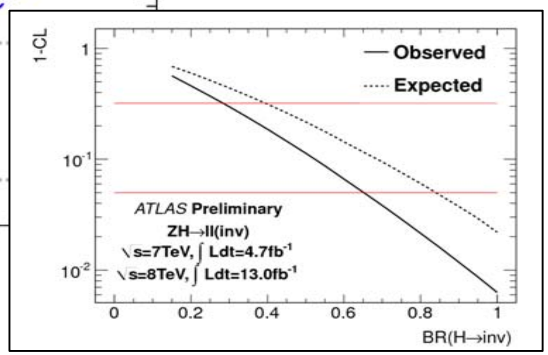


Also direct invisible only search

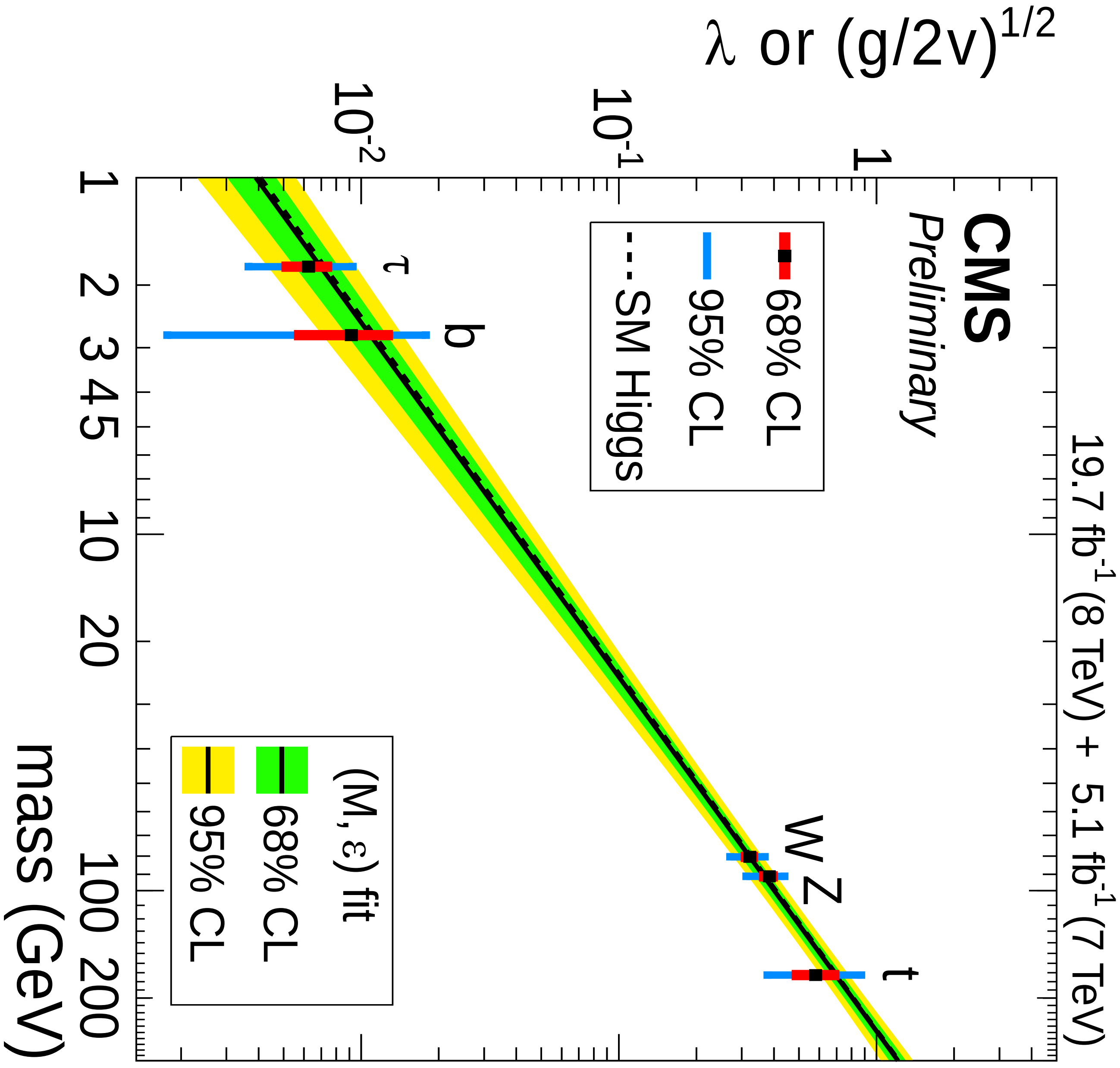




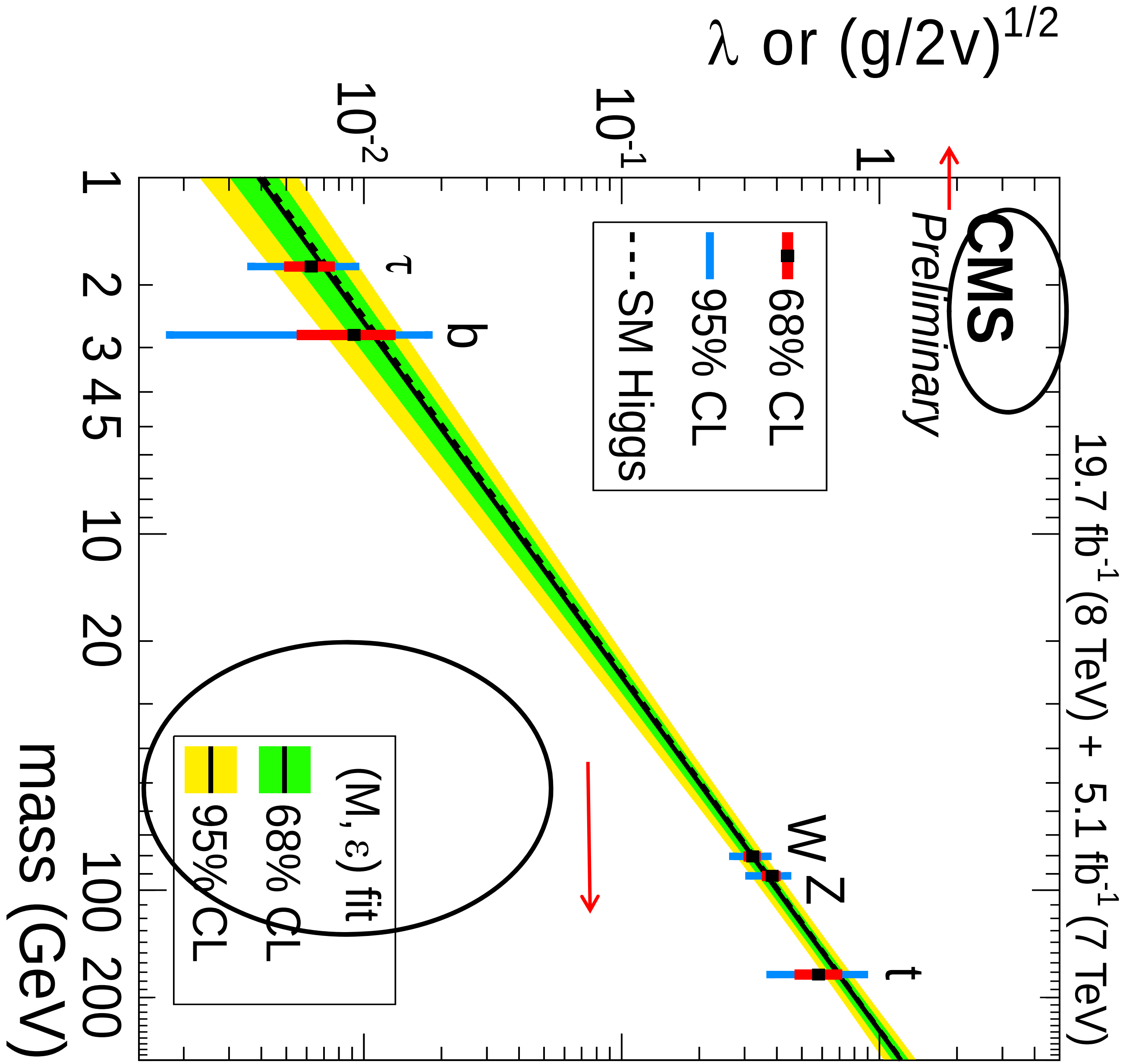




There are important signs not to be missed!

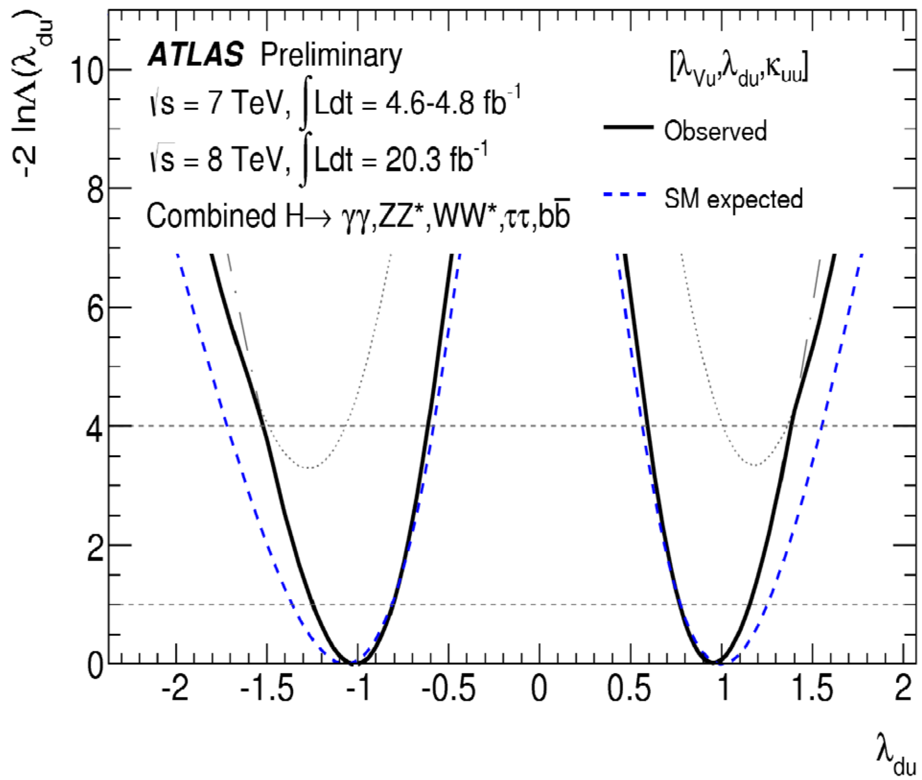


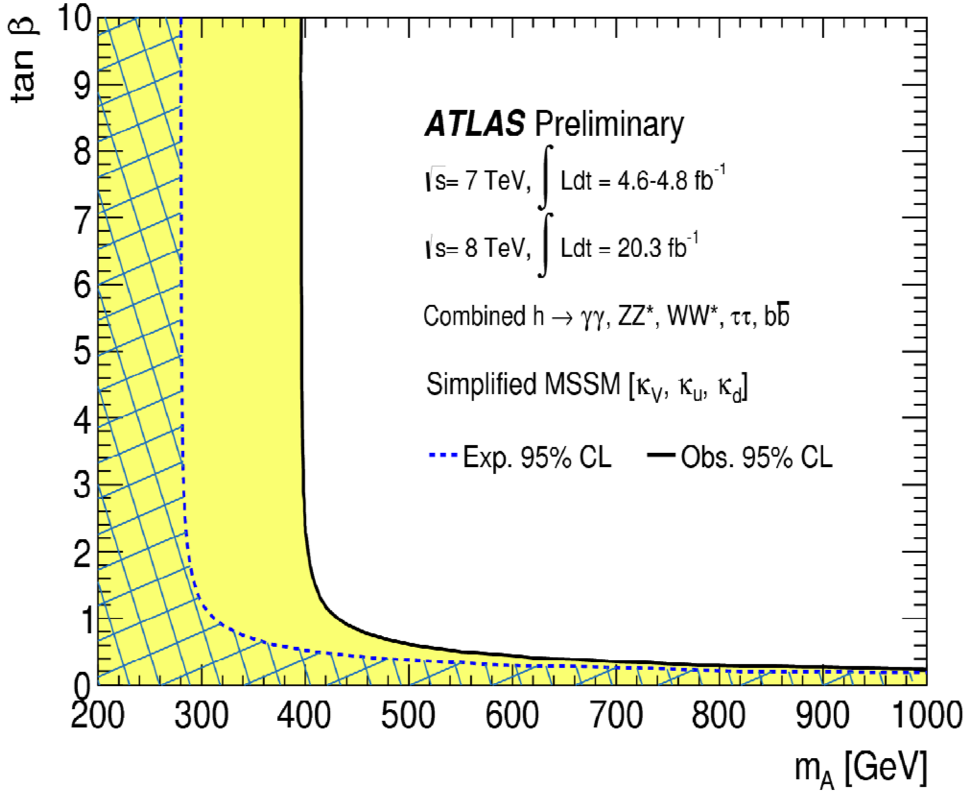
Test of SUSY (and 2 HDMs)



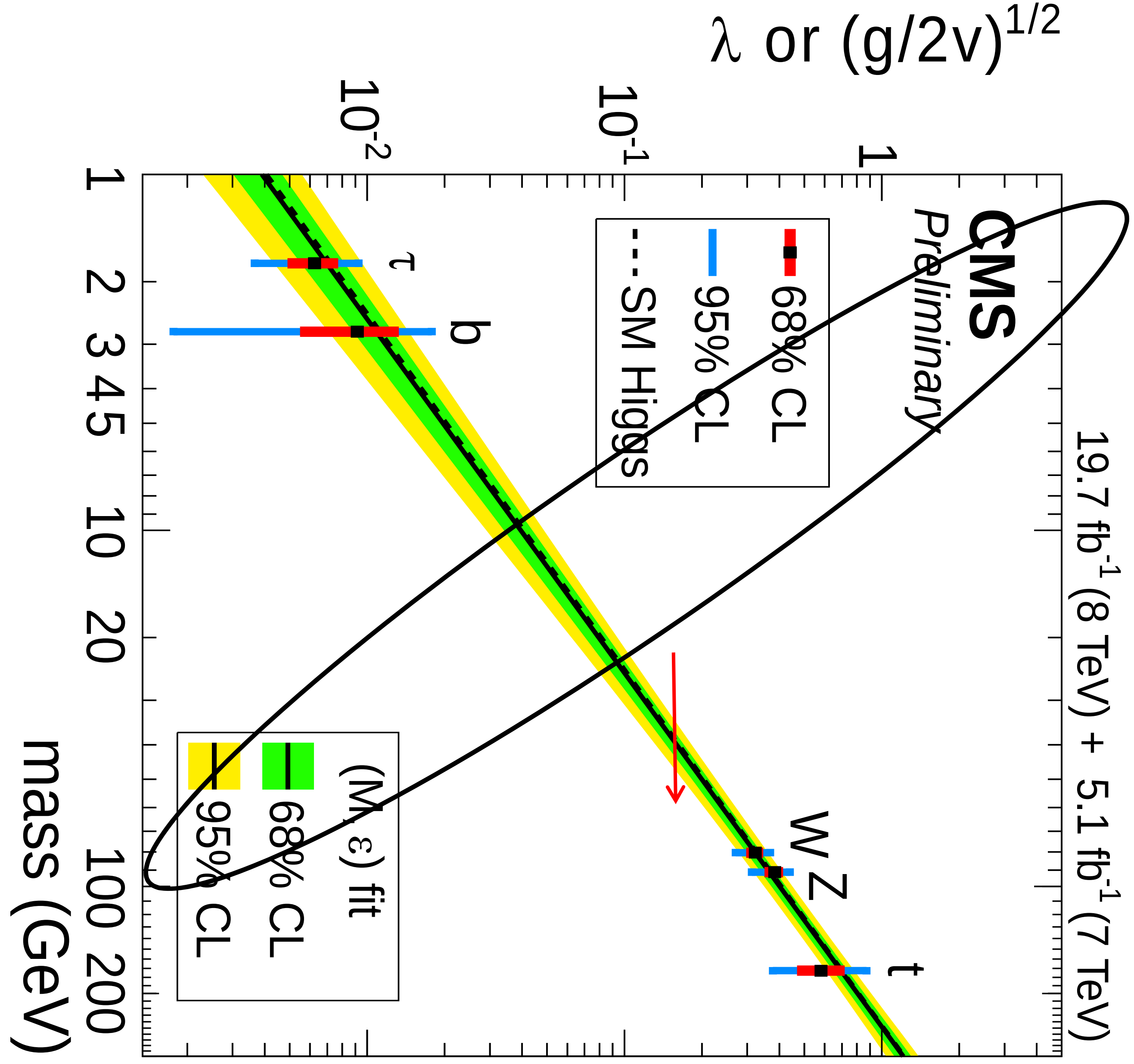
SUSY

Test of SUSY (and 2 HDMs)



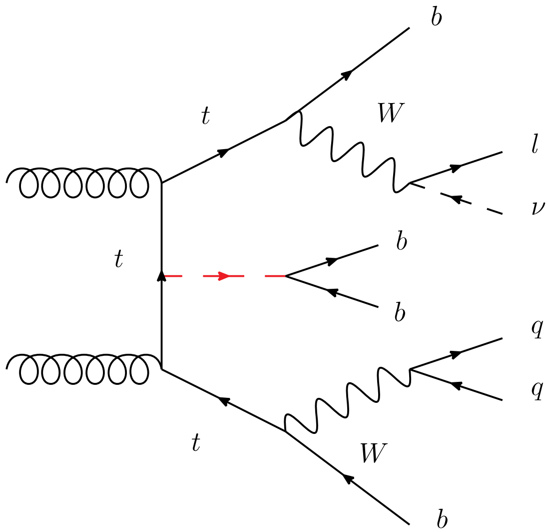


Test of Compositness



Cornering the Top Yukawa Coupling

Cornering (directly) the top Yukawa coupling



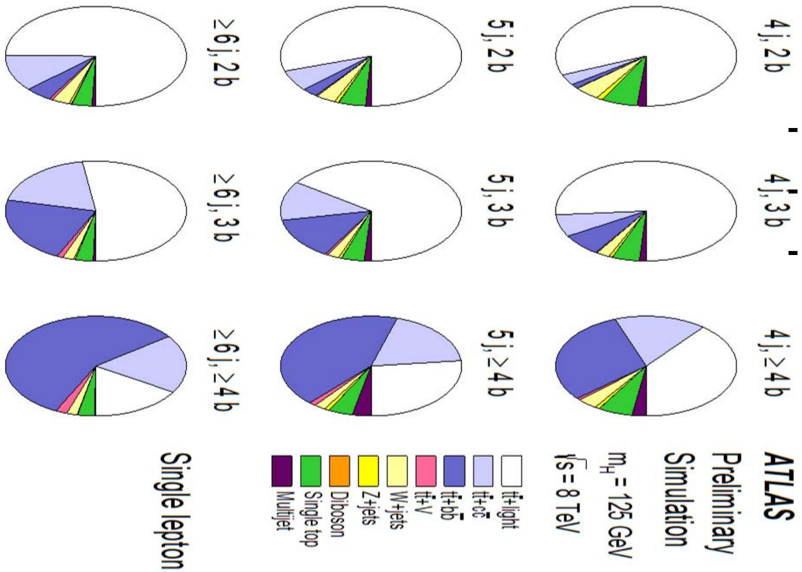
ATLAS-CONF-2014-011

ttH(bb) Analysis strategy

- 2 channels t(lvb)t(qqb)H(bb) and t(lvb)t(lvb)H(bb)
- Challenging tt+jets background…
- tt+jets and tt+HF tamed

Cornering (directly) the top Yukawa coupling

ATLAS-CONF-2014-011



ttH(bb) Analysis strategy

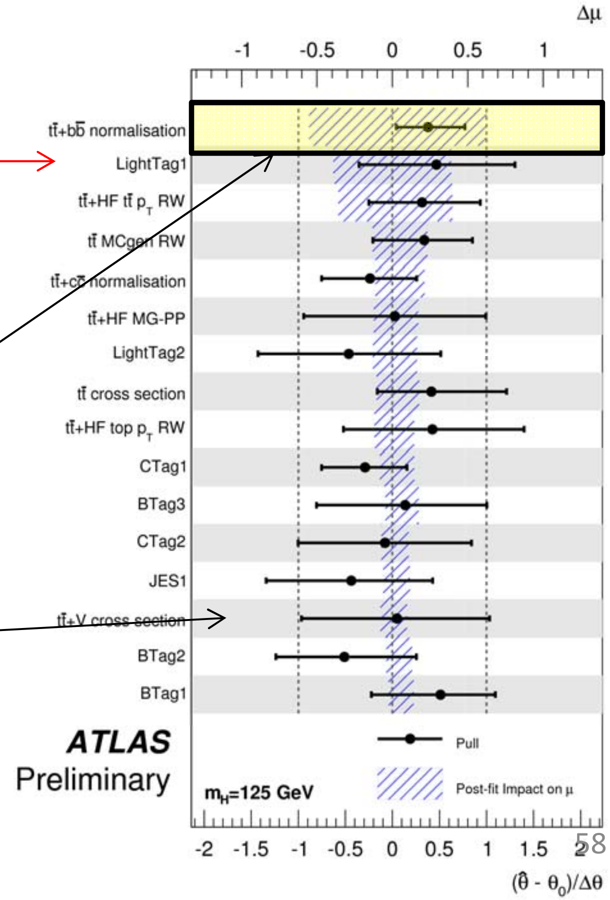
- 2 channels t(lvb)t(qqb)H(bb) and t(lvb)t(lvb)H(bb)
- Challenging tt+jets background…
- tt+jets and tt+HF tamed

	5 jets, ≥ 4 *b*-tags	≥ 6 jets, 3 *b*-tags	≥ 6 jets, ≥ 4 *b*-tags
$t\bar{t}H$ (125)	11 ± 1 ± 9	69 ± 3 ± 57	28 ± 2 ± 23
$t\bar{t}$+ light	78 ± 9	2380 ± 130	78 ± 11
$t\bar{t} + c\bar{c}$	45 ± 12	750 ± 190	75 ± 19
$t\bar{t} + b\bar{b}$	149 ± 20	1160 ± 170	300 ± 40
$t\bar{t} + V$	3.3 ± 1.0	44 ± 13	8.9 ± 2.7
non-$t\bar{t}$	23.2 ± 2.5	218 ± 23	18.8 ± 2.2
Total	309 ± 11	4620 ± 80	507 ± 27
Data	283	4671	516

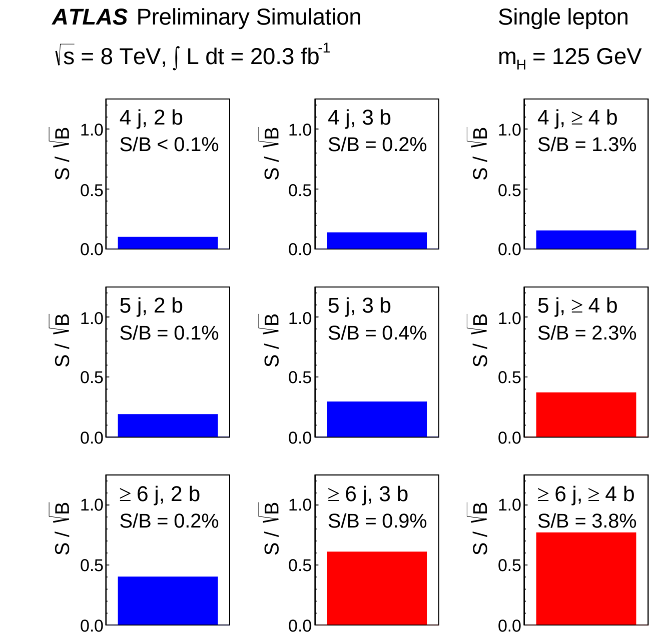
Light rejection crucial

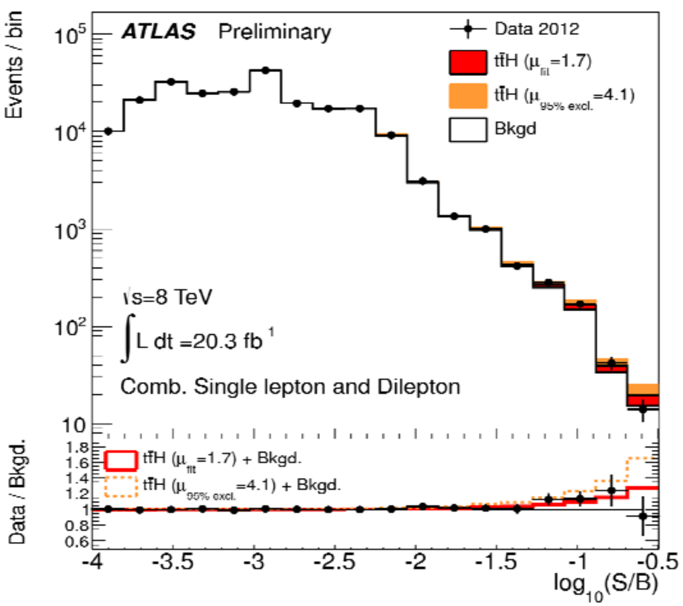
13%

Irreducible not critical



Cornering (directly) the top Yukawa coupling

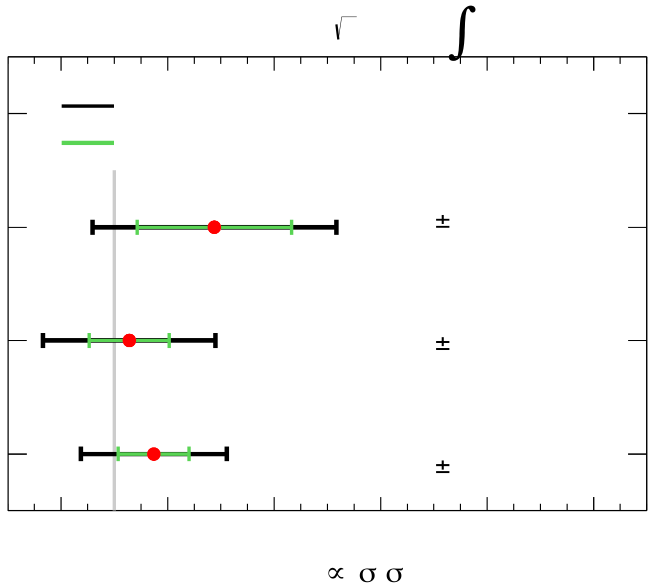




ATLAS-CONF-2014-011

ttH(bb) Analysis strategy

- 2 channels t(lvb)t(qqb)H(bb) and t(lvb)t(lvb)H(bb)
- Challenging tt+jets background…
- tt+jets and tt+HF tamed
- Also used kinematic discrimination to further constrain backgrounds and discriminate signal
- Results:

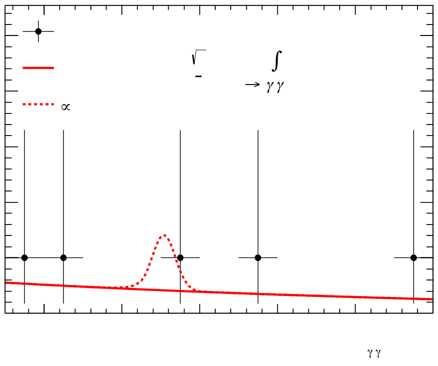


Cornering the top Yukawa coupling

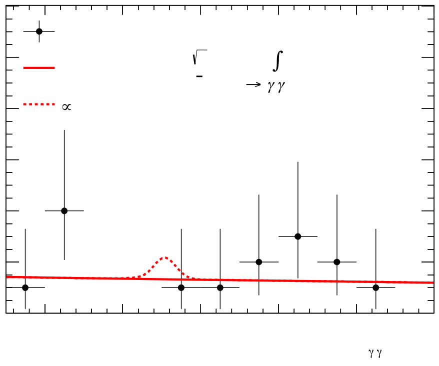
$t(t)H(\gamma\gamma)$

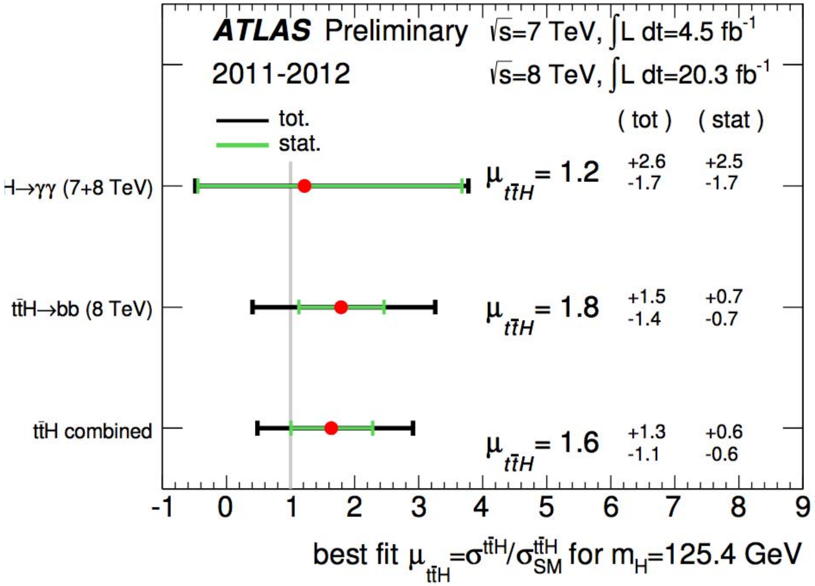
ATLAS-CONF-2014-043

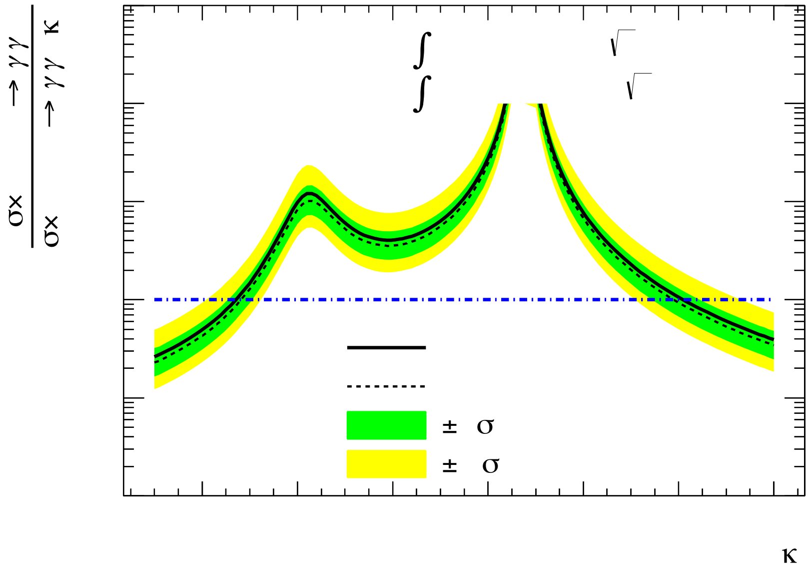
Leptonic channel



Hadronic channel



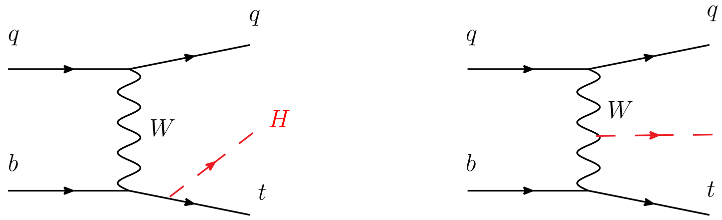




Analysis reinterpretation

Inclusive $\gamma\gamma$ limit from process assuming $\kappa_W = 1$

tH contribution at negative κ_t



$$\propto 3.3\times\kappa_W^2 - 5.1\times\kappa_t\kappa_W + 2.8\times\kappa_t^2$$

95% CL exclusion $]-\infty,1.3]\cup[8.1,+\infty[$ $(]-\infty,1.2]\cup[7.9,+\infty[)$

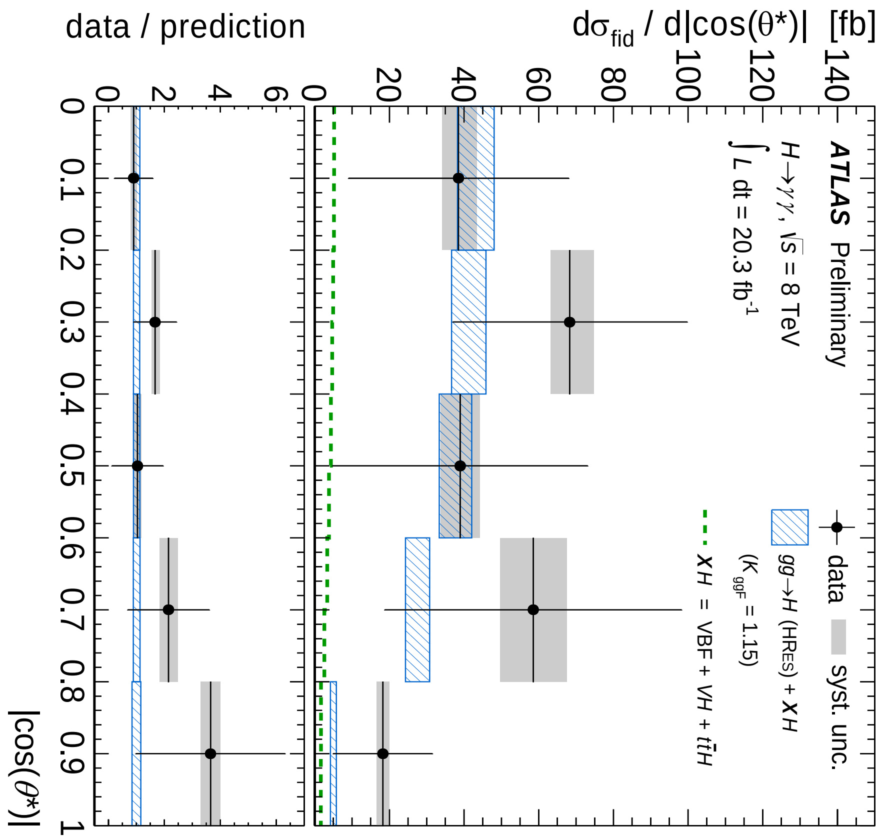
Measurements of Differential Cross Sections

Differential Cross sections (II)

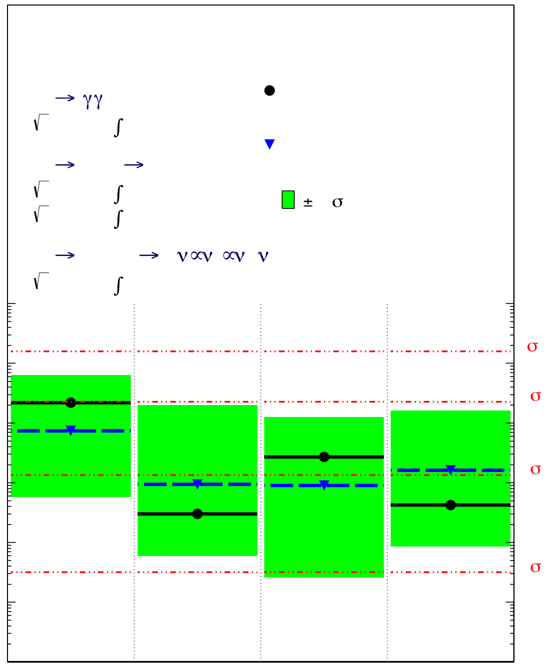
More to learn from differential distributions which are sensitive to the main quantum numbers Spin and CP in many channels

PLB 726 (2013)

$H \to \gamma\gamma$



Evidence for Spin 0 Nature

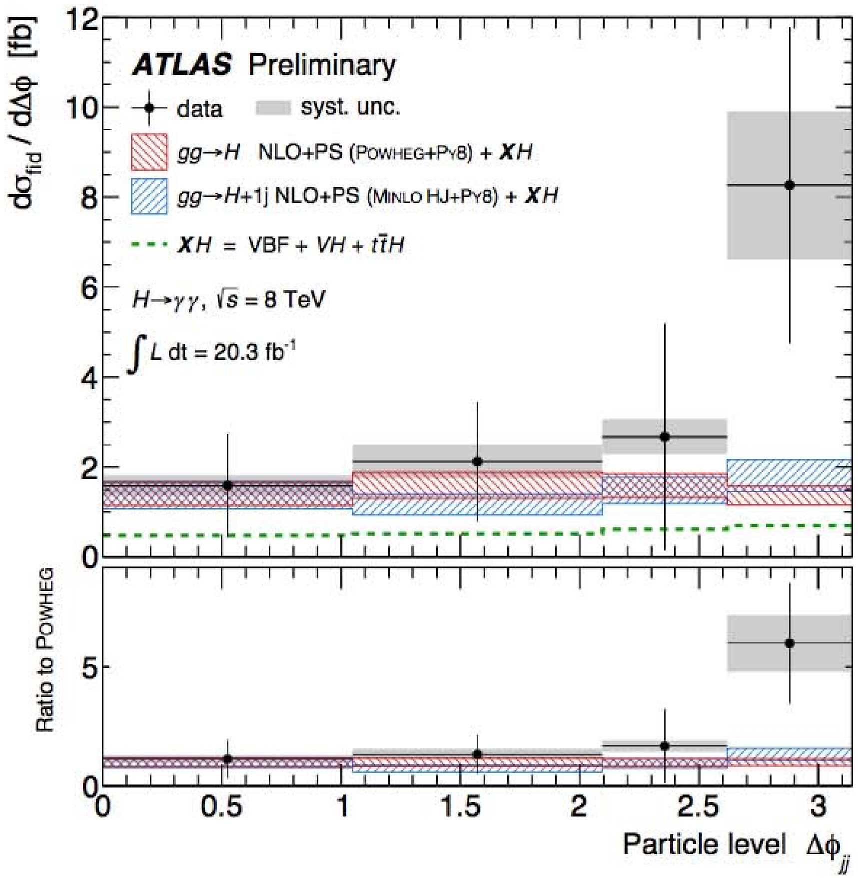


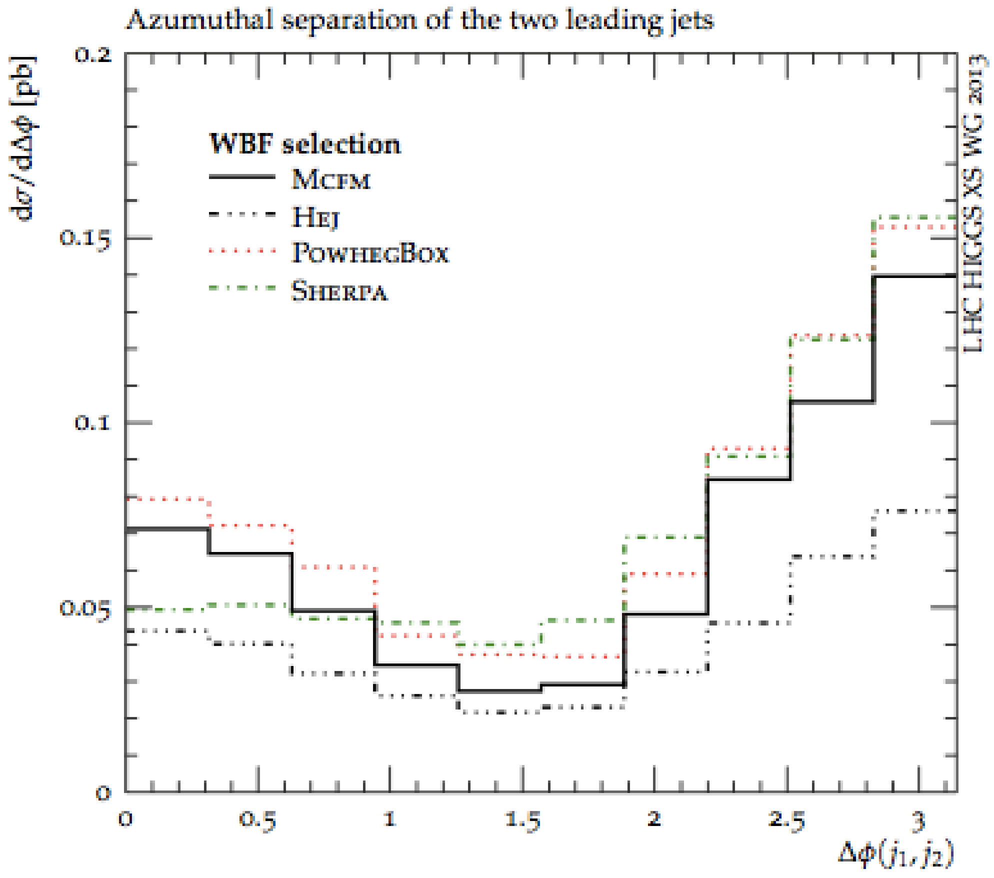
To be submitted soon and ATLAS-CONF-2013-072

PLB 726 (2013)

Differential Cross Sections

(Differential and fiducial cross sections in dijet - Diphoton channel)





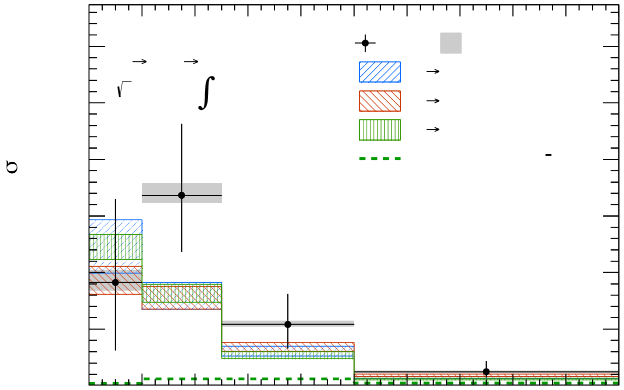
Experimental as well as TH endeavor !

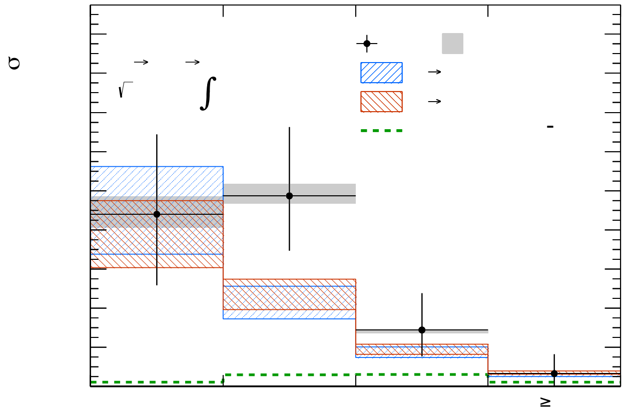
Differential Cross sections

- Our results rely on the Higgs transverse momentum or jet multiplicities
- Sensitive to new physics in the content of the production loop

$H \rightarrow 4l$

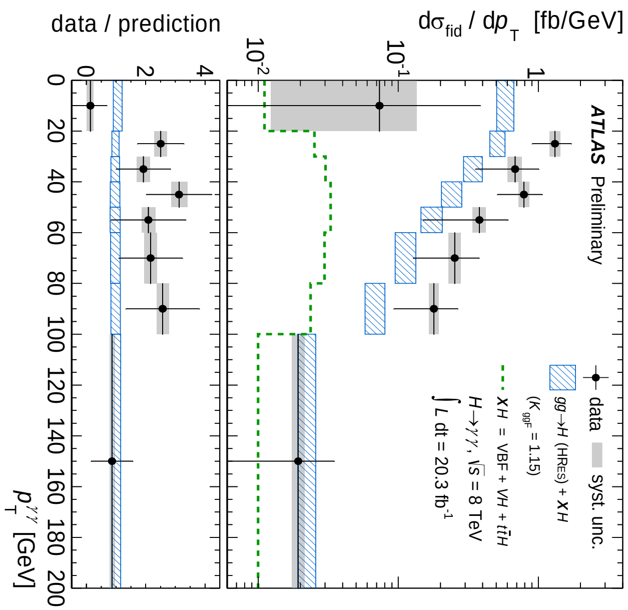
ATLAS-CONF-2014-044

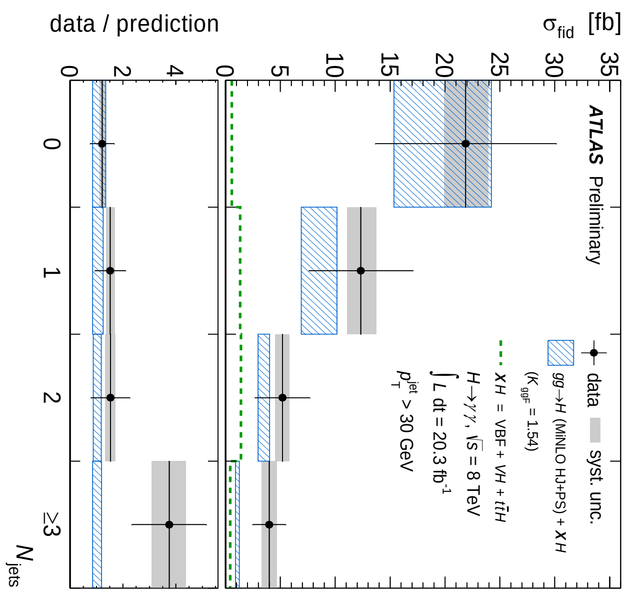




$H \rightarrow \gamma\gamma$

To be submitted soon and ATLAS-CONF-2013-072

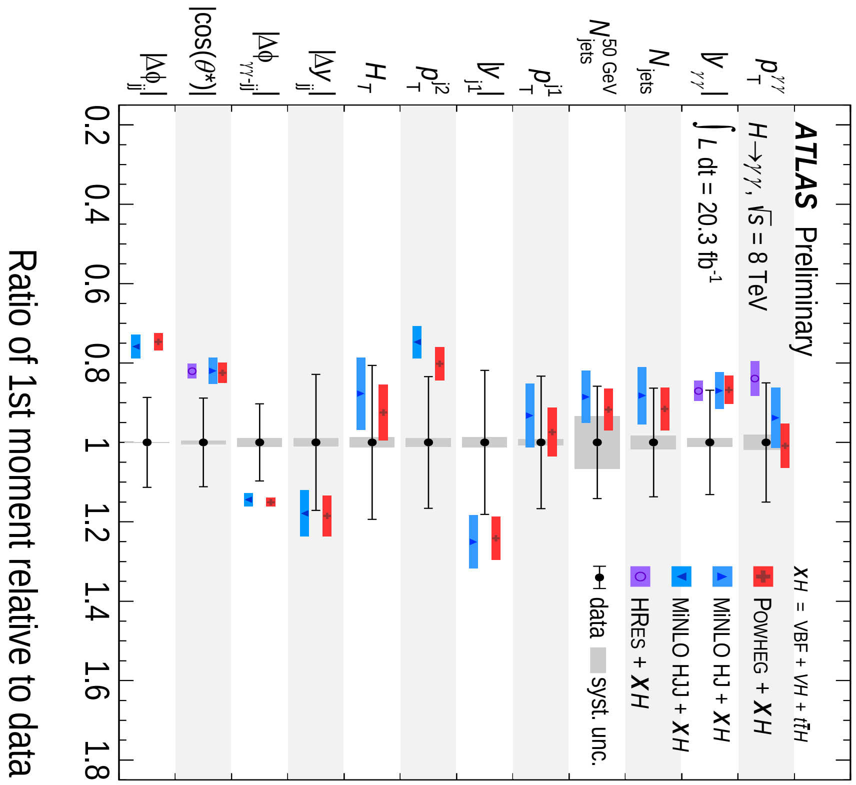


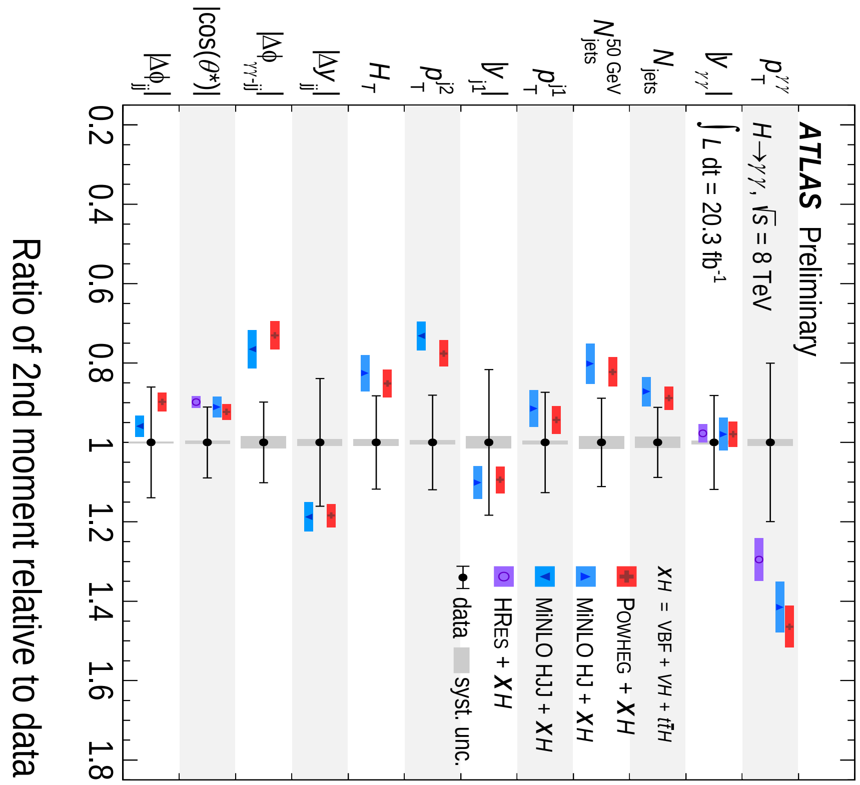


Differential Cross sections

- Large number of observable tested
- Higgs started to provide Rivet routines!
- Entering also HEP data

$H \rightarrow \gamma\gamma$





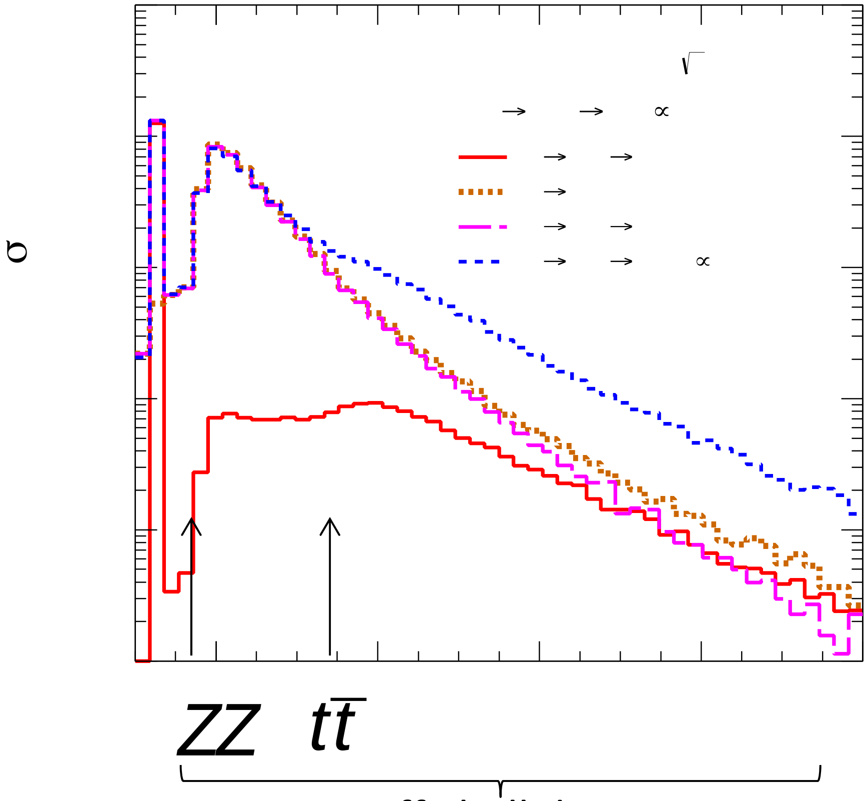
To be submitted soon and ATLAS-CONF-2013-072

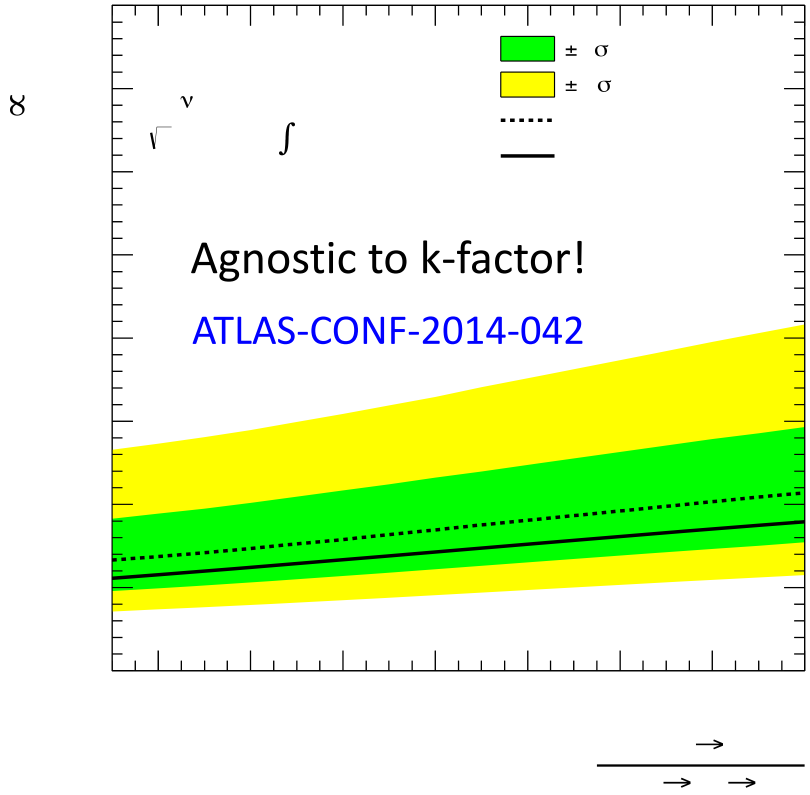
Exploring the far Off Shell mass region and the Off Shell couplings

Off Shell Couplings

Extremely interesting analysis:

- The constraint on the total width is of limited interest
- Investigate more the EFT approach (See Christophe's talk)





R=1 (Verified in the soft colinear approximation)
(G. Passarino)

95% CL limit obs. (exp.)
$\mu_{OffShell}$ < 6.7 (7.9)

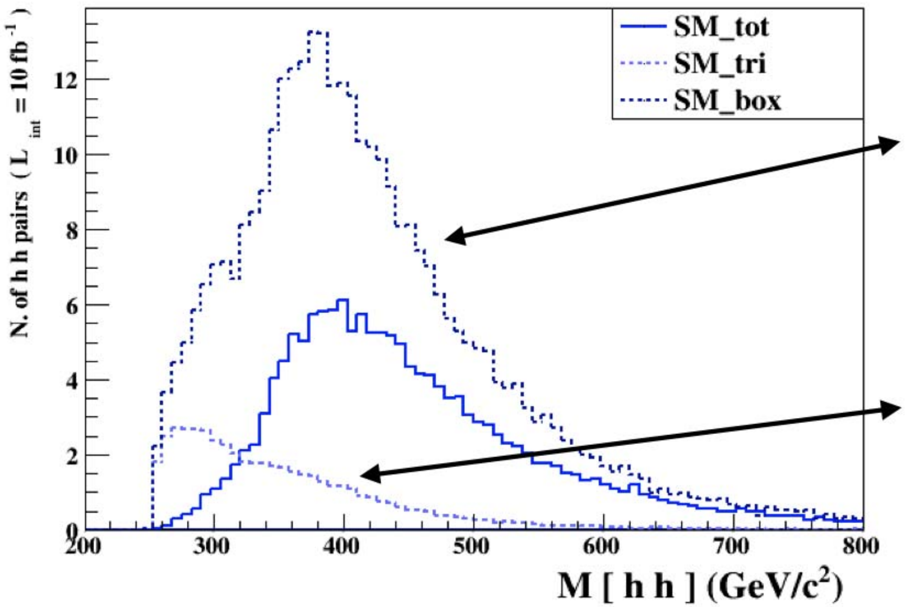
Inspiring … For self couplings

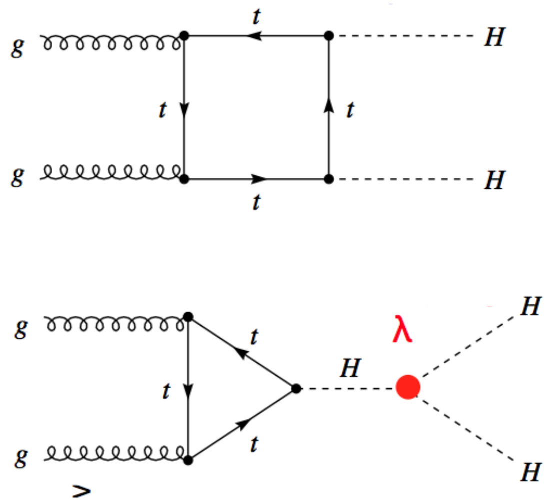
- Determination of the scalar potential, essential missing ingredient : **self couplings** $\lambda_3 \sim m_H^2/(2v)$, $\lambda_4 \sim m_H^2/(8v^2)$!

- Very similar analysis as the off shell couplings!

λ_4 : hopeless in any planed experiment (?)

λ_3 : very very hard in particular due to the double H production, which also interferes with the signal…



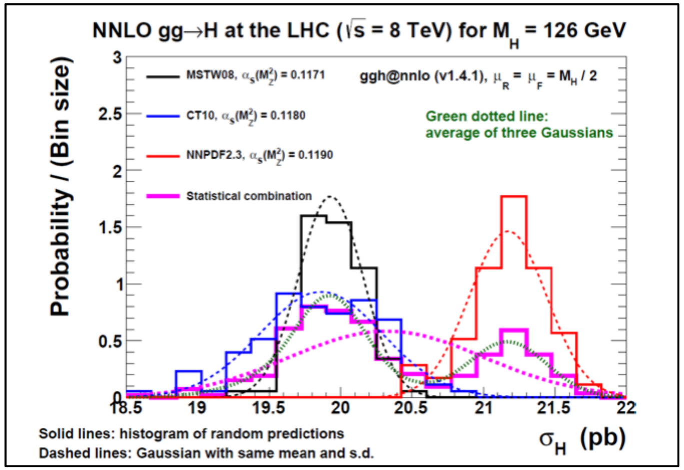


… some hope? pp $\rightarrow$ HH $\rightarrow$ $bb\gamma\gamma$ or $bb\tau^+\tau^-$ (under study)

Extremely challenging!

Towards Precision Higgs Physics

1.- Improve/consolidate the current channels



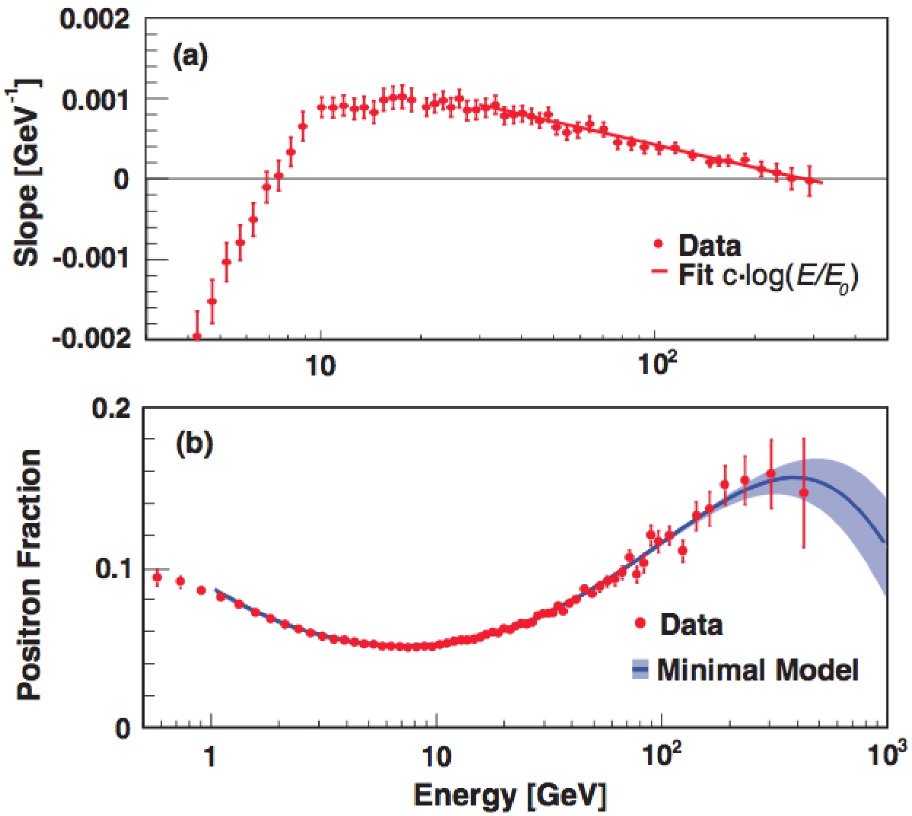
2.- Synergy with Theory

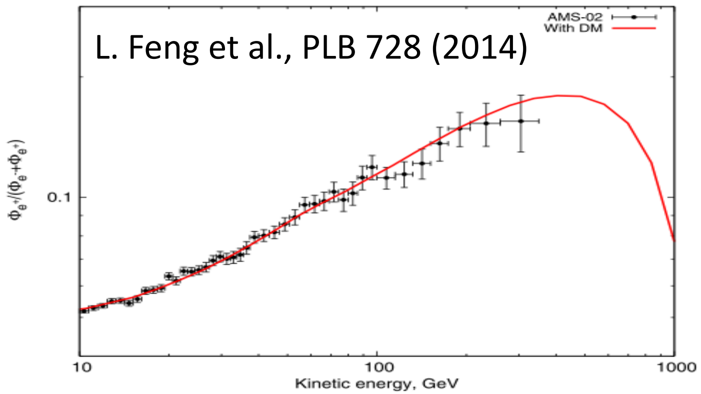
- Signal
  - Need an improved PDF prescription
  - N^3LO
- Backgrounds
  - Top transverse momentum and jet mult.
  - V+jets
  - NNLO diboson

3.- Exploration of the power of EFT has started

- Yield a more precise and robust framework for the couplings analysis
- Yield a framework to define the sensitive observables (see Christophe's talk)
- Yield a very general framework for indirect tests of new physics through the overall consistency of all EW and Higgs measurements

Higgs and Dark Matter





L. Feng et al., PLB 728 (2014)

- Light DM in the total width of the Higgs boson?

- Heavier DM production of DM at LHC through direct searches of (increased interest):
  - Mono jet
  - Mono photon
  - Mono W or Z
  - Mono Higgs!

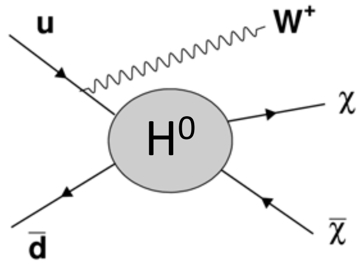
Covered in a seminar by
I. Vivarelli November 11, 2014

Invisible Higgs Channels I

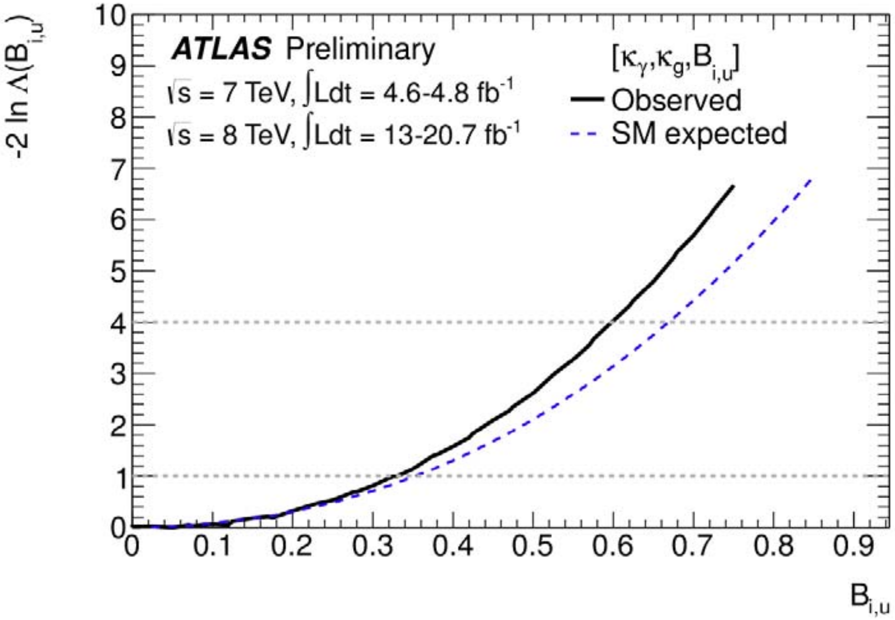
- Indirect constraints on the invisible and undetected Branching

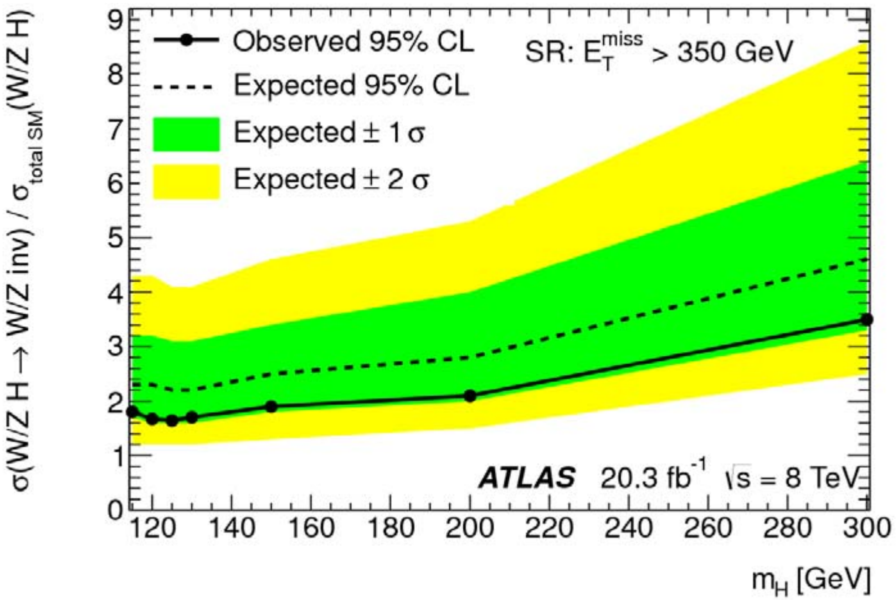
  (*a fortiori* on the invisible branching)

- Re-interpretation of mono-jet and mono-W or Z analyses



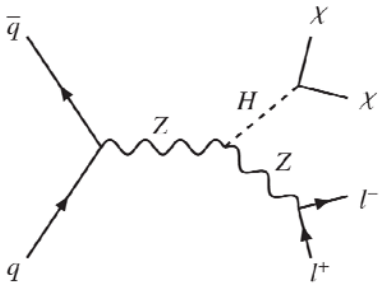
$$\kappa_g, \kappa_\gamma, Br_{\text{inv,undet}}$$



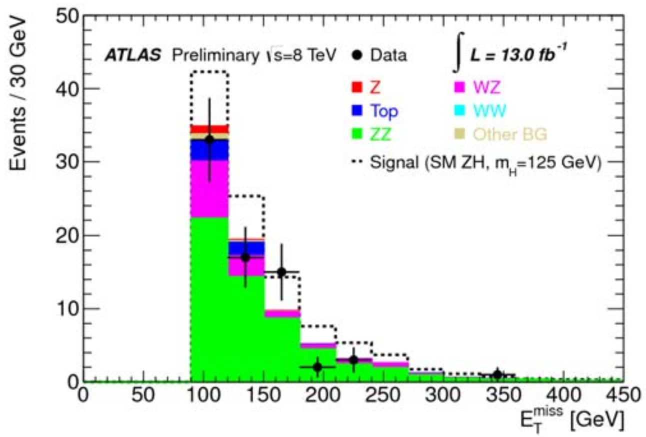


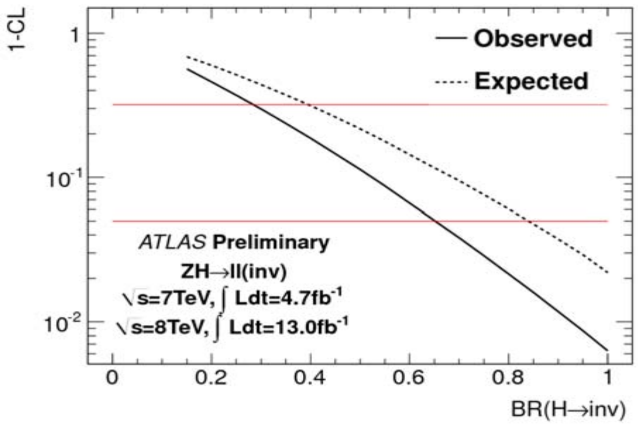
For a 125 GeV Higgs: $\sigma Br_{inv}/\sigma_{SM}$ < 1.6 at 95%CL (obs)

Invisible Higgs Channels I



- Search for a dilepton pair compatible with a Z and missing transverse energy
- Analyses using fits to MET (ATLAS) or MT (CMS)





For a 125 GeV Higgs:

- ATLAS

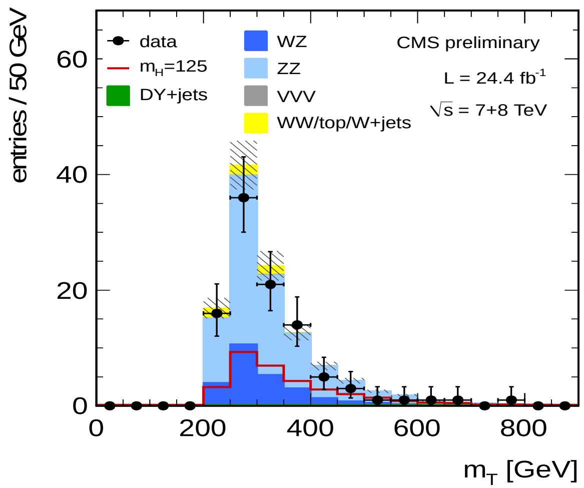
  Br_{inv} < 65% at 95%CL (obs)

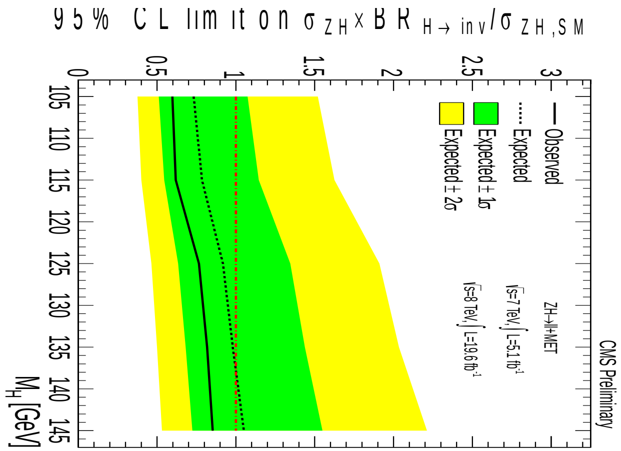
  Br_{inv} < 84% at 95%CL (exp)

- CMS

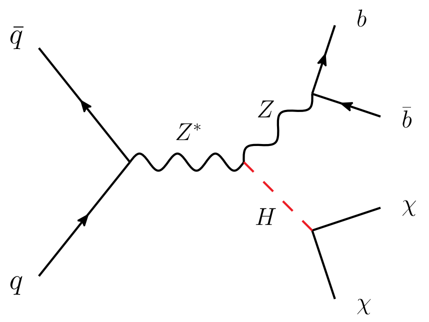
  Br_{inv} < 75% at 95%CL (obs)

  Br_{inv} < 91% at 95%CL (exp)

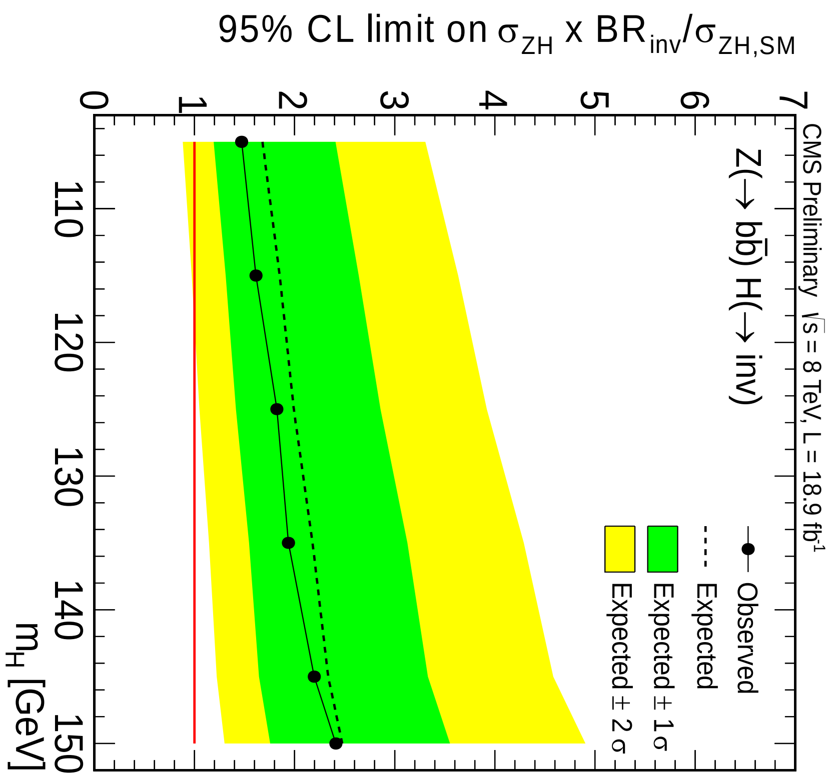


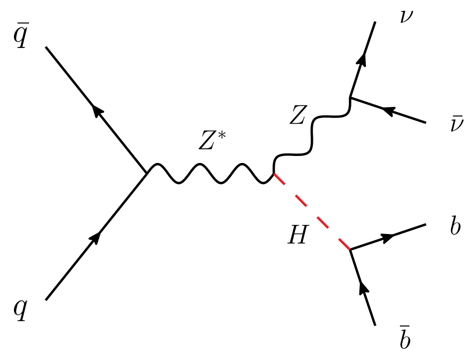


Invisible Higgs Channels II



- Associated production with a Z in bb (CMS only)
- Search following closely VH(bb)
- Contribution from VH(bb) has very little impact





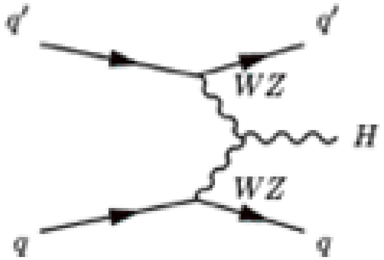
For a 125 GeV Higgs:

$\sigma Br_{inv}/\sigma_{SM}$ < 1.8 at 95%CL (obs)

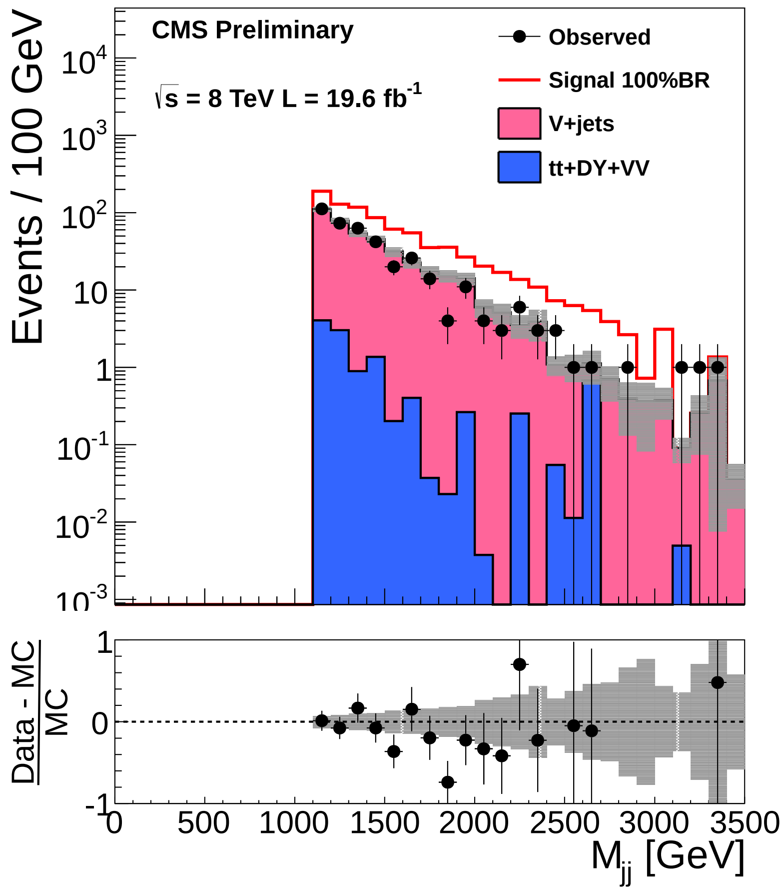
$\sigma Br_{inv}/\sigma_{SM}$ < 2.0 at 95%CL (exp)

CMS-PAS-HIG-13-028

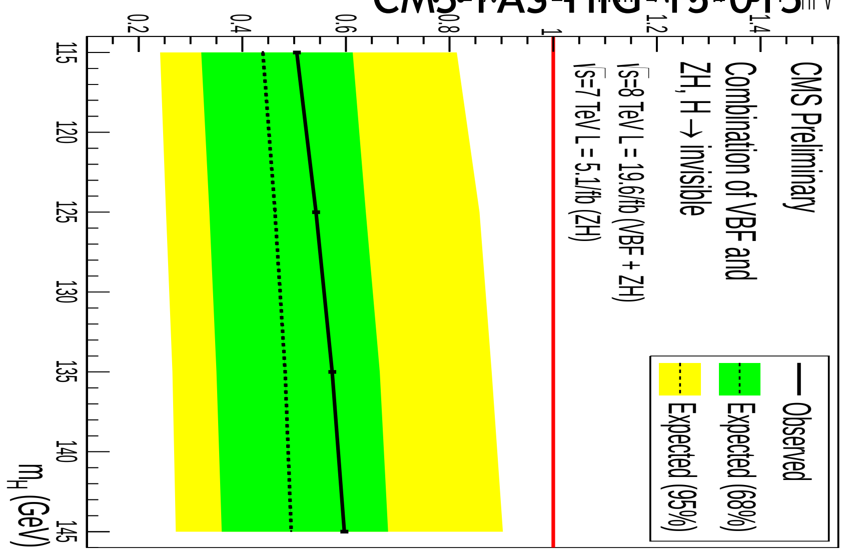
Invisible Higgs Channels IV



- Search in the VBF production mode
- Main selection on M_{jj}, $\Delta\eta_{jj}$, and large MET



CMS-PAS-HIG-13-013



For a 125 GeV Higgs:

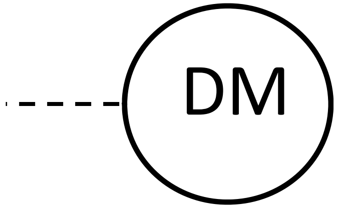
- CMS

  Br_{inv} < 69% at 95%CL (obs)

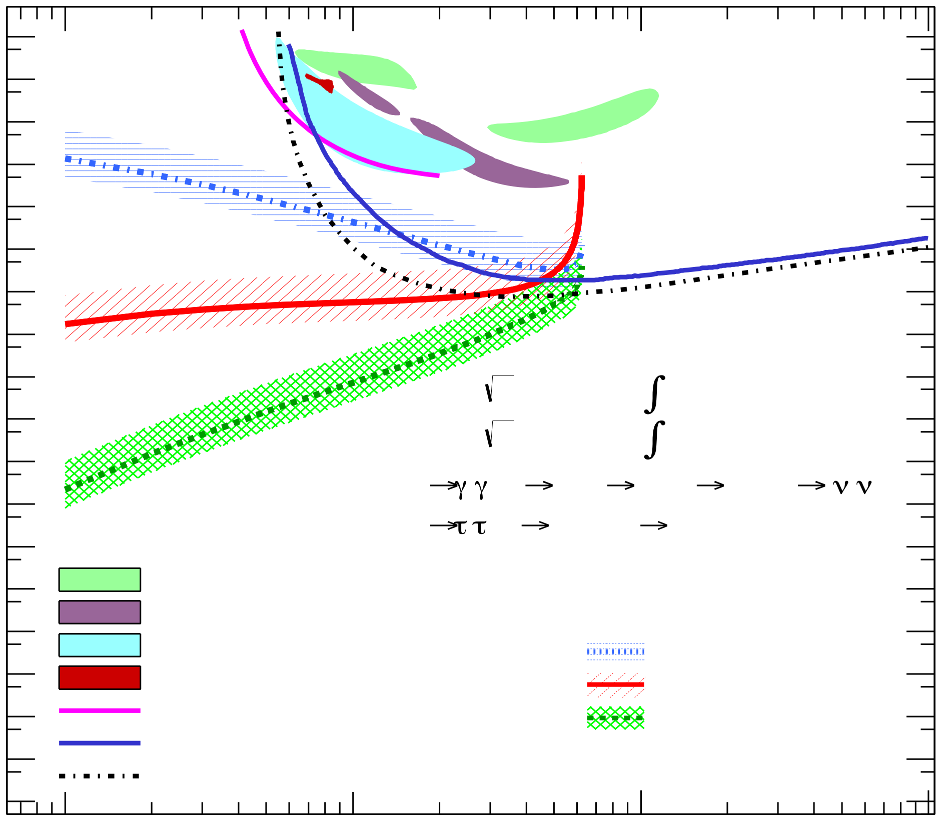
  Br_{inv} < 53% at 95%CL (exp)

Interpretation

$H^{\dagger}H$



Pure Higgs portal interpretation



Searches for Additional Higgs bosons

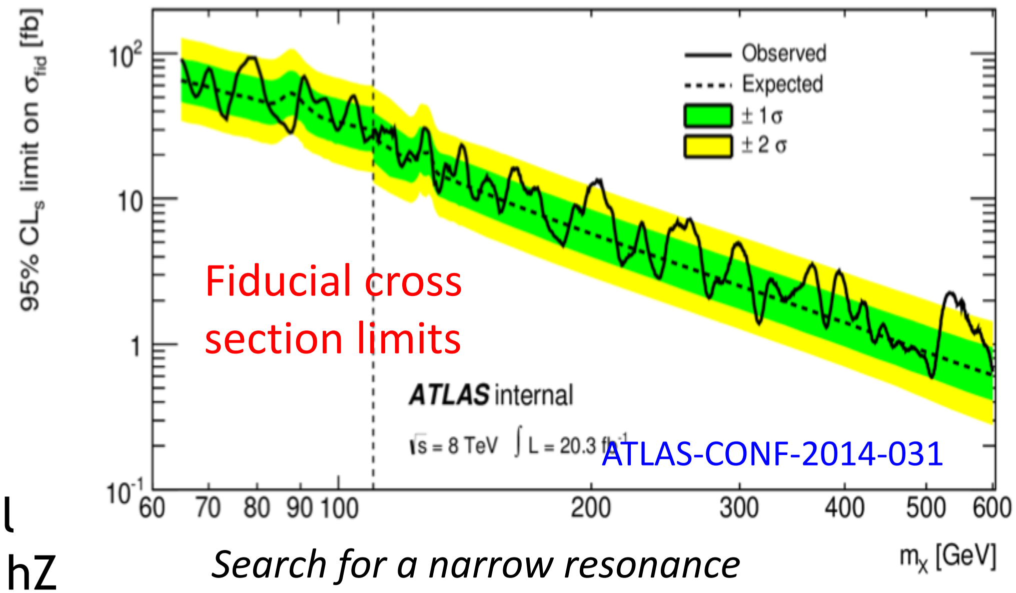
Extremely important to search for additional states of the EW breaking sector

e.g. SUSY requires at least two doublets of complex scalar fields (therefore additional scalar states are expected)

Nano Review of BSM Channels

- Charged Higgs
  - Main current analysis $H^{\pm}$ to $\tau\nu$
  - $H^{\pm}$ to cs
  - High mass specific $H^{\pm}$ to AW
  - High mass specific $H^{\pm}$ to tb
- Additional CP Odd/Even
  - Nice results on $\tau\tau$
  - Also searched for in $\mu\mu$
  - Also searched for in bb(b)
  - Needs searches in the tt channel
  - New results on hh, soon coming hZ
  - $\gamma\gamma$ extending mass domain
  - ZZ in 4l, llqq, llvv, vvqq
  - WW in lvlv and lvqq
- NMSSM (mainly low mass)
  - Direct low mass $\mu\mu$
  - Exotic cascades h to aa to four photons, or four taus, $\tau\tau\mu\mu$, etc…

$H \to \gamma\gamma$

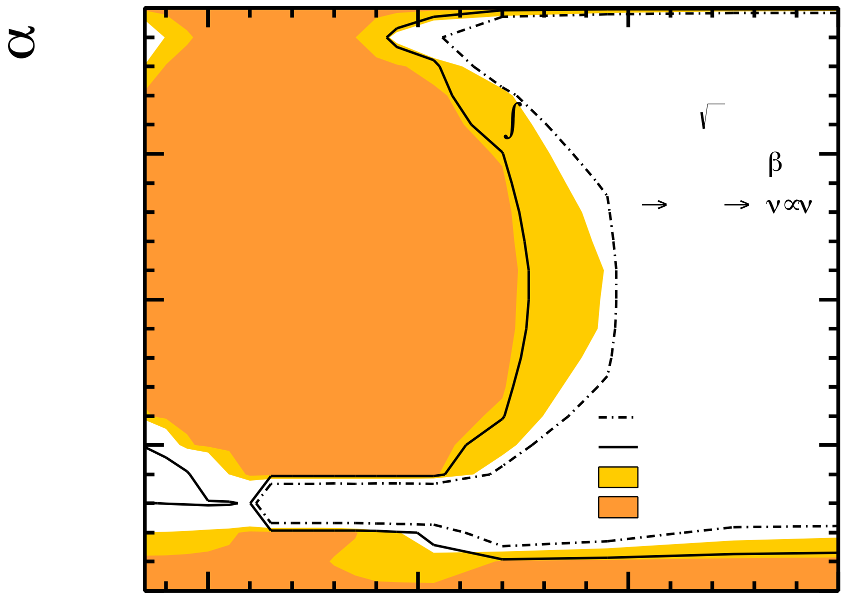


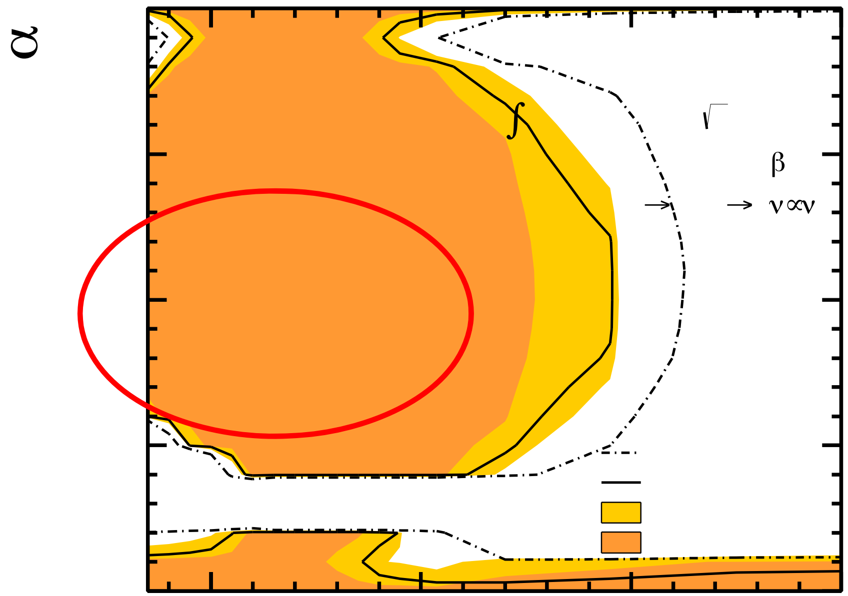
Search for a narrow resonance decaying to a pair of photons

Nano Review of BSM Channels

Specific model dependent searches

Search for two states in the spectrum in this case h and H together!





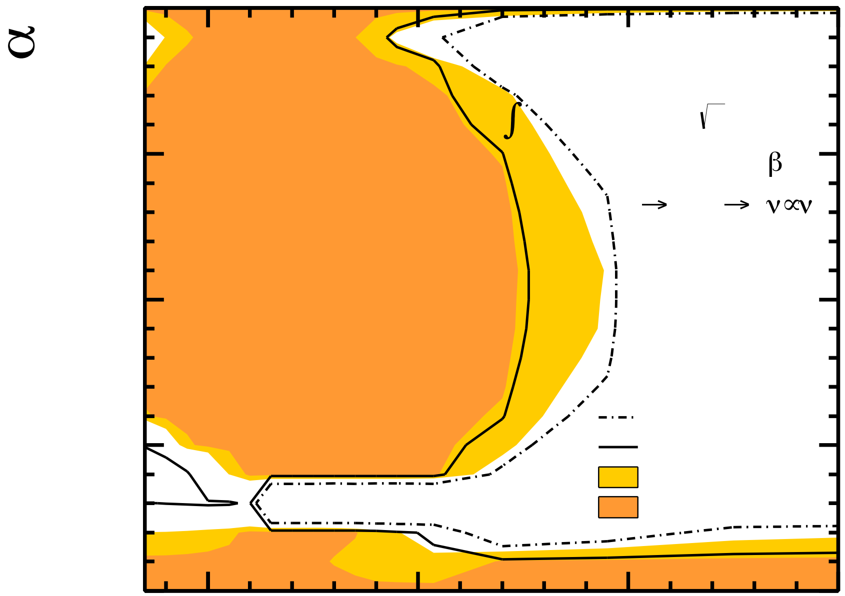
Becoming a standard! (see Roger's talk)

… and much more !

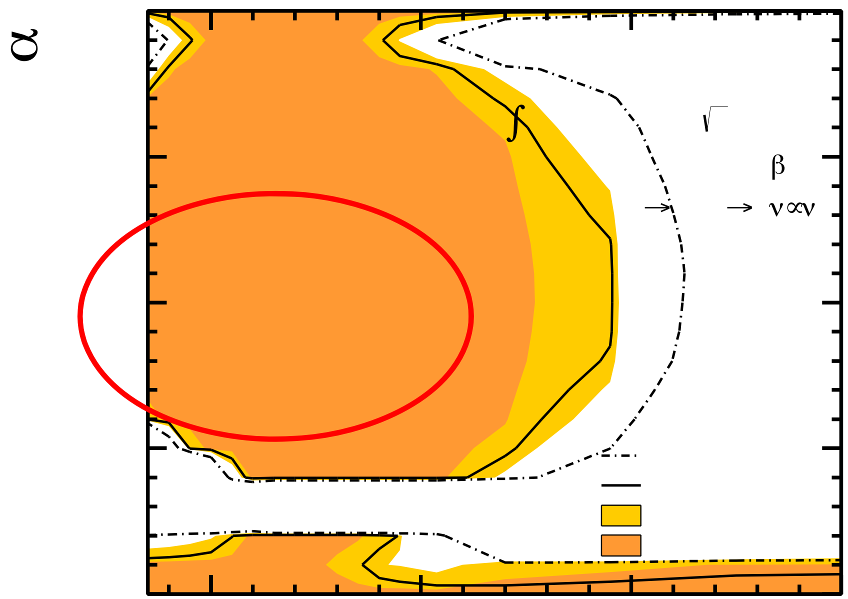
- Doubly charged Higgs
- Cascade decays
- Higgs decays to dark Z, hidden valley pions
- Model independent searches for H(gg) + X

Nano Review of BSM Channels

Specific model dependent searches



Search for two states in the spectrum in this case h and H together!



Becoming a standard! (see Roger's talk)

… and much more !

- Doubly charged Higgs
- Cascade decays
- Higgs decays to dark Z, hidden valley pions
- Model independent searches for H(gg) + X

… and more !

- NMSSM A_s and H_s w/ 6γ's, etc…

(Thanks Margarete)

- Specific Higgs SUSY decays

(Thanks Georg)

Run 2
A new era of exploration
and precision…

… No « No Loose Theorem » anymore…

ATLAS Upgrades

Phase 0 Upgrade

- Additionnal insertable b-layer (Pixels)
- New beam pipe
- Complete muon coverage
- Repairs (TRT, LAr, Tile)

Phase 1 Upgrade

- New Small Wheel (Forward muons) for L1 muon trigger
- Topological L1 trigger processors
- High granularity L1 Calorimeter trigger

Phase 2 Upgrade

- Completely new tracker (large eta?)
- Calorimeter eletronics upgrade
- Possible L1 track trigger
- Possible change to the forward calorimeters

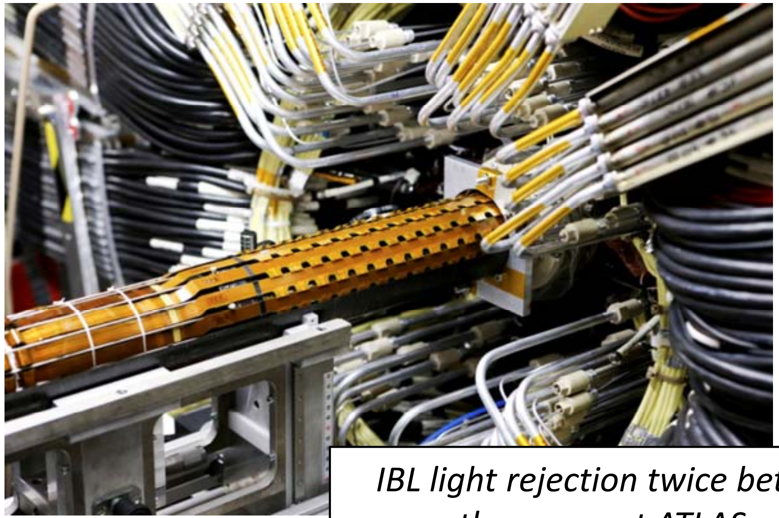
CMS Upgrades

Phase 0 Upgrade

- Complete muon coverage
- Replace HCAL photodetectors (forward and outer)

Phase 1 Upgrade

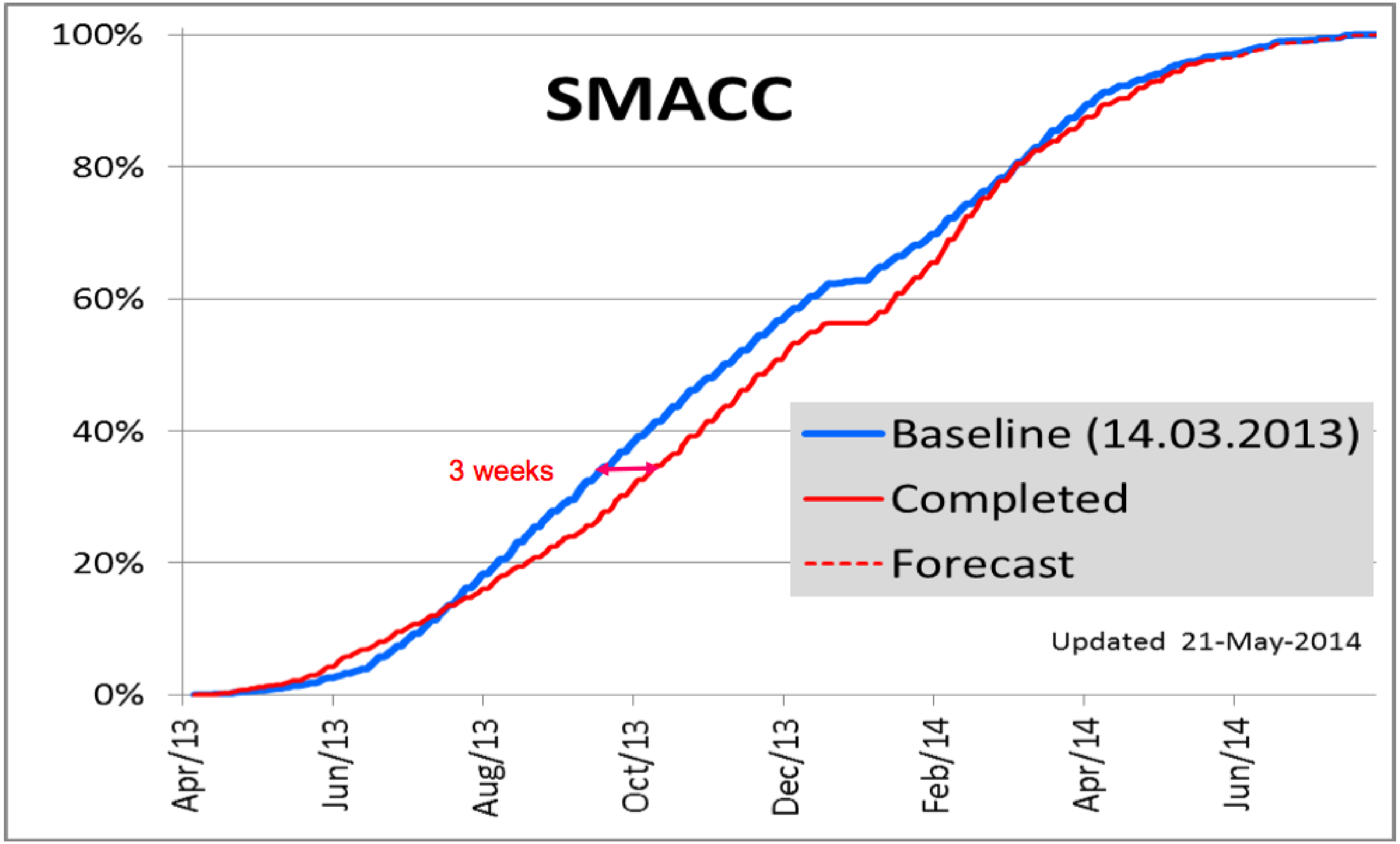
- New pixel detector
- New beam pipe
- L1 trigger upgrade
- HCAL electronics



IBL light rejection twice better than current ATLAS

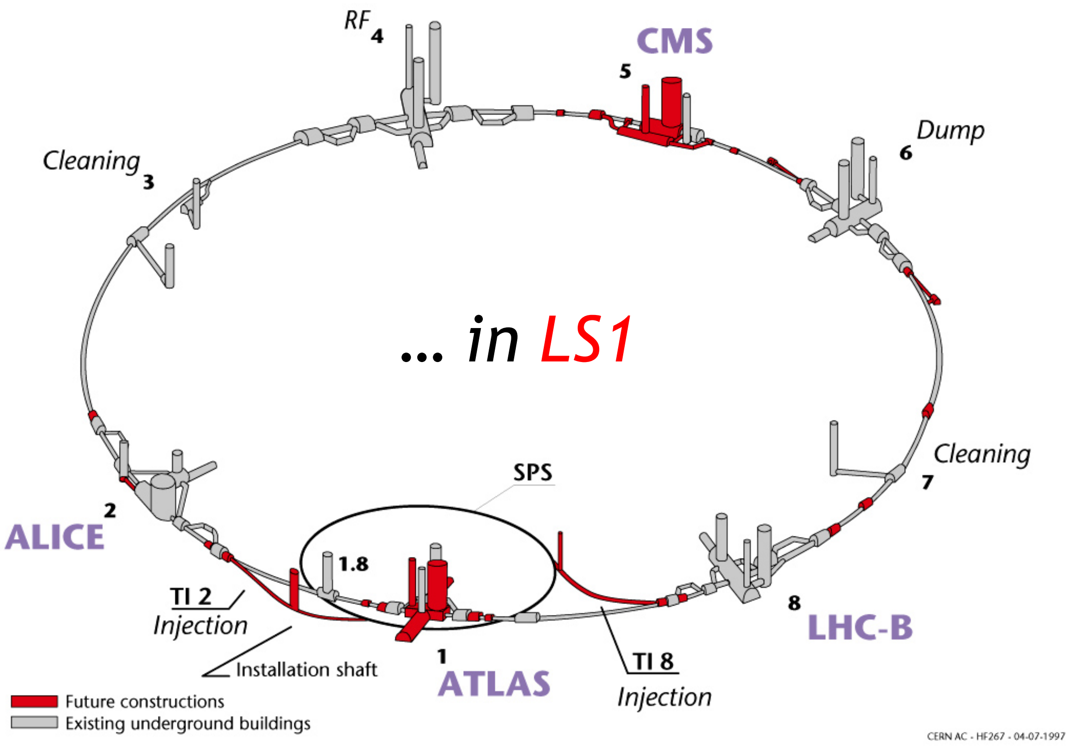
How to get to Run-2?

How do we get to Run-2?



SMACC (Superconducting Magnets and Circuits Consolidation)

A New Machine at a New Energy Forntier



$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Parameter	2010	2011	2012	Run 2
C.O.M Energy	7 TeV	7 TeV	8 TeV	13 TeV
Bunch spacing / k	150 ns / 368	50 ns / 1380	50 ns /1380	25 ns /2508
ε (mm rad)	2.4-4	1.9-2.3	2.5	1.9
β^* (m)	3.5	1.5-1	0.6	< 0.6
L ($cm^{-2}s^{-1}$)	$2x10^{32}$	$3.3x10^{33}$	$\sim 7x10^{33}$	$1.6\ 10^{34}$

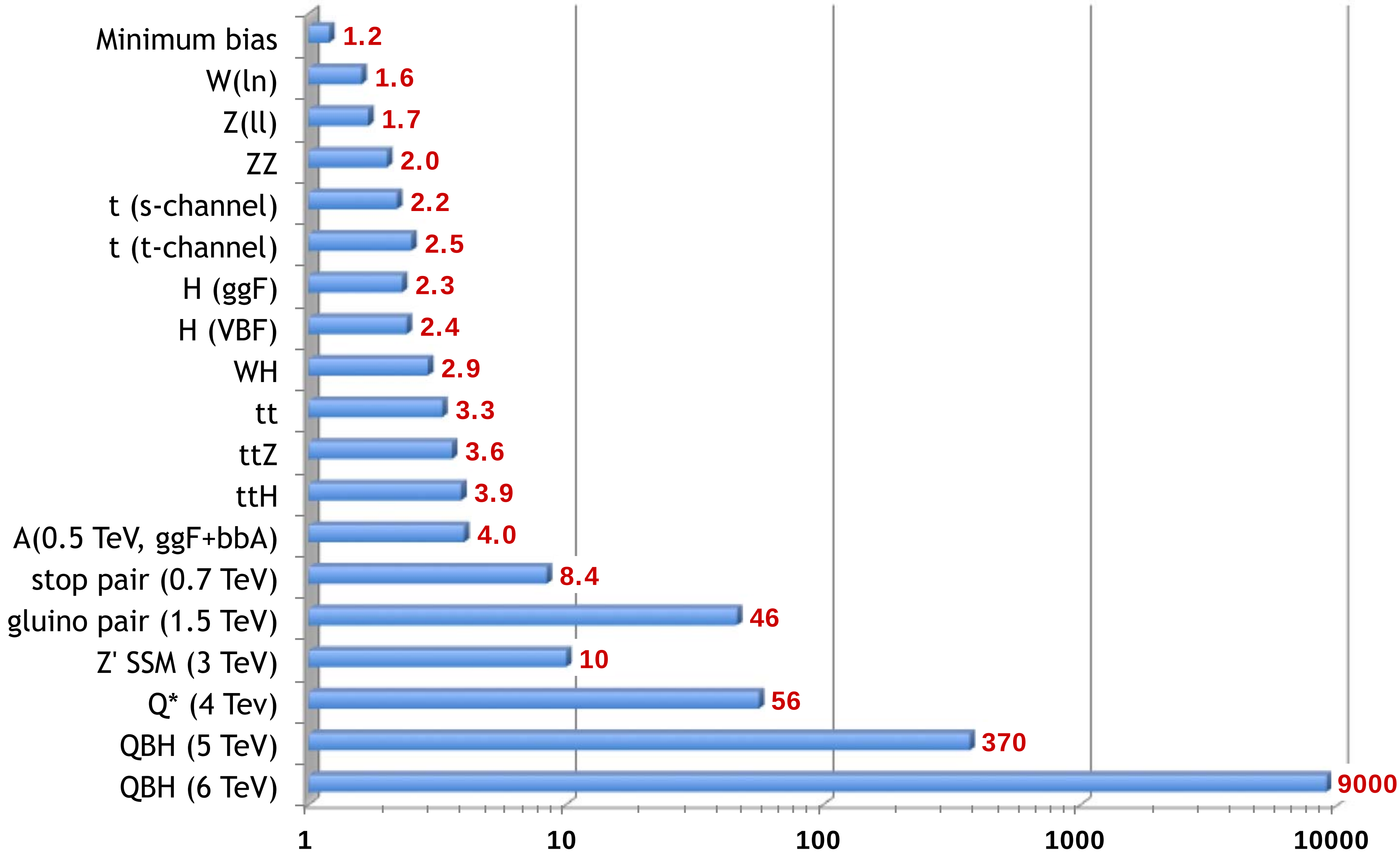
What can we expect?

- Elaborate a concrete analysis program based on the following scenarios
  - Spring-Summer 2015 0-1 fb^{-1} at 50 ns
  - EPS 2015 < 1 fb^{-1} at 50ns
  - LHCP - LP 2015 1 fb^{-1} at 50ns
  - Full 2015 10- fb^{-1} at 25ns
  - Full Run II 75-100 fb^{-1} at 25ns

- Moriond 2016

Important milestone for the entire physics program

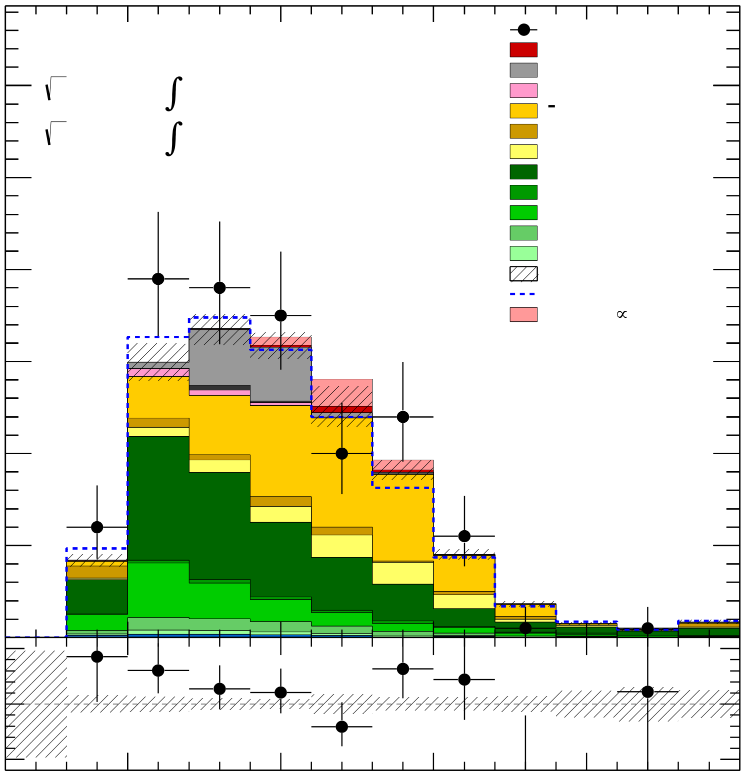
The rough Picture...

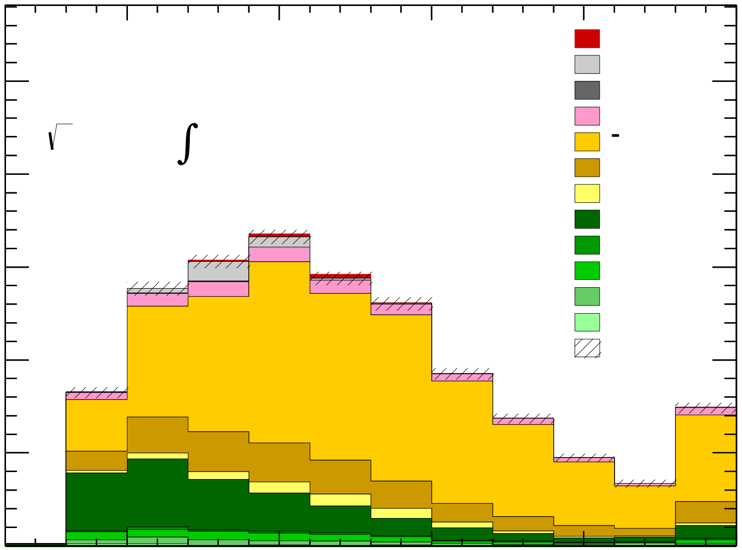


The critical b-Yukawa

~60% of the width

- Projections: Validating the parametrization with data!
- Estimate the sensitivity vi the llbb (eventually most sensitve) and lvbb
- Of course includes the increase top background estimates





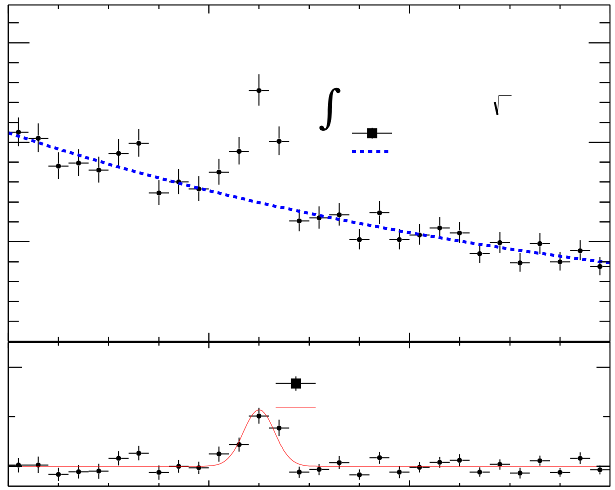
300 fb-1 O(60) PU events: 4σ

This is without the very sensitive vvbb channel!

Run 2 could be saying a strong word on this channel possibly have an observation at more than 3σ)

The Crucial ttH Channels

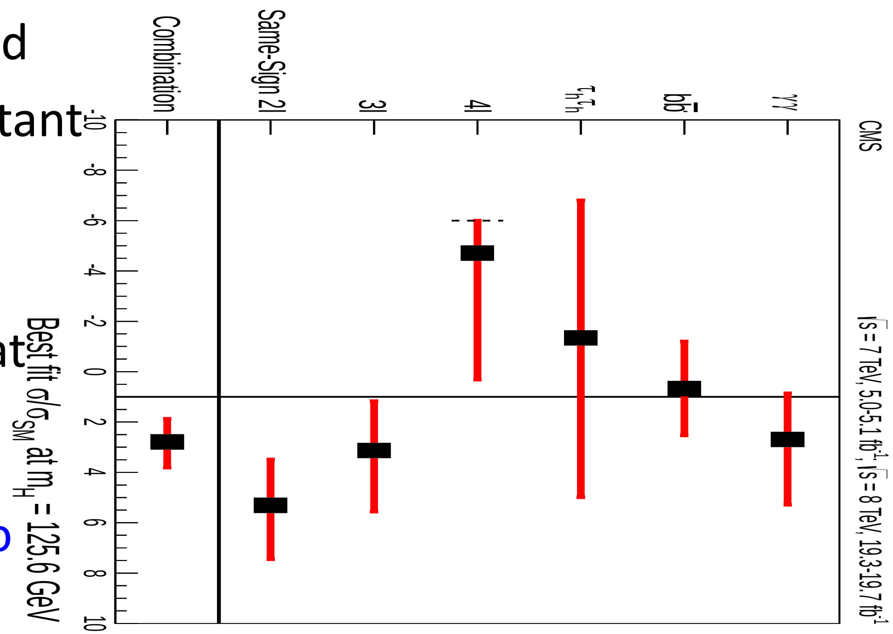
- Long term analyses:
  - ttH (μμ)
  - ttH (γγ)
- Current channels:
  - ttH (bb) 1 and 2-leptons
  - ttH (gg) semi and fully hadronic
  - ttH (WW and tt) multileptons and taus



- Not trivial to project without systematics!
  - Diphoton ε O(200%) stat. Dominated
  - Multileptons ε O(100%) syst. Important

    Not trivial to improve
  - bb channel ε O(150%) syst. Critical

    Even harder
- Combination Hopefully an observation at Run-2 (3σ)!
- Combination ATLAS-CMS crucial but also extremely intricate!



Conclusions

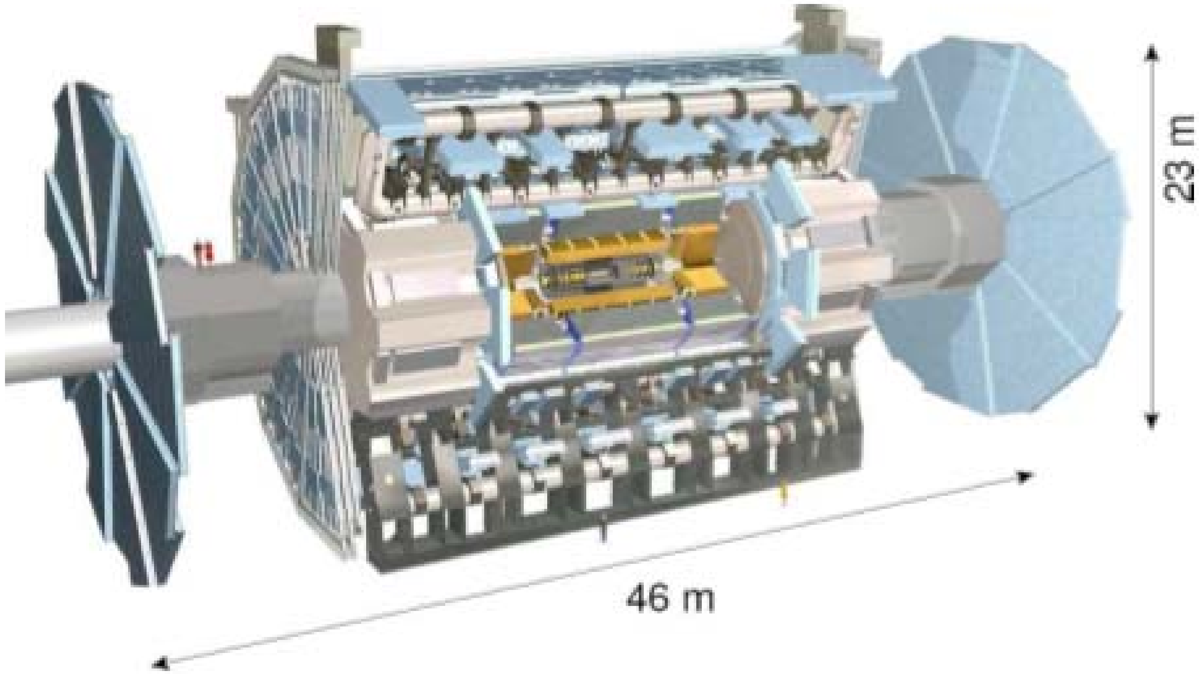
- Run-1 has been an amazing success !

- The discovery of the Higgs boson is a success of the experimental **and** TH community

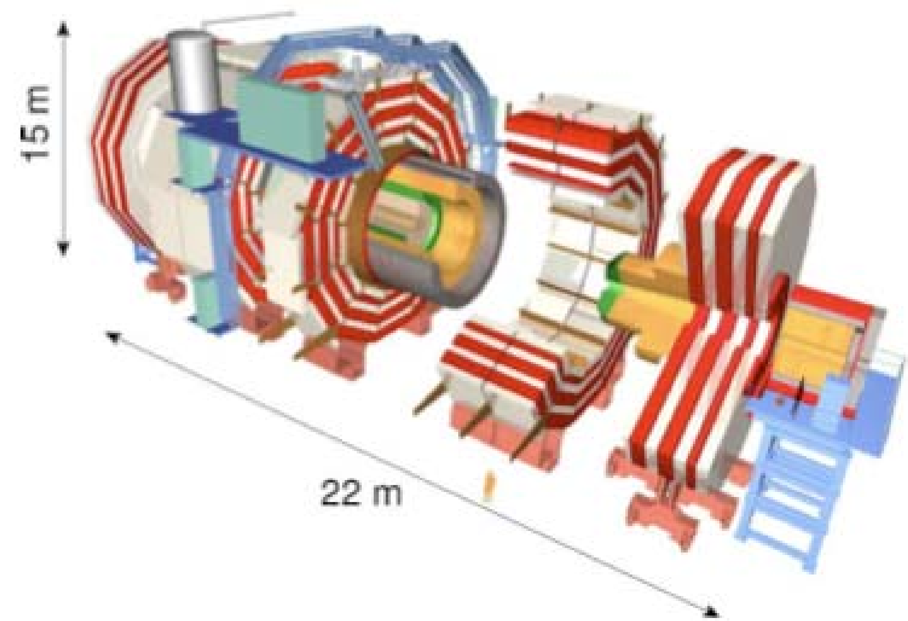
- Run-2 is an imminent new machine

    - Close to double centre-of-mass energy
    - Should deliver approximately four times the Run-1 Luminosity
    - Exciting opportunities for discoveries (leave no stone unturned)
    - Continue our vast precision program

- Now is the perfect time to start a PhD at LHC!

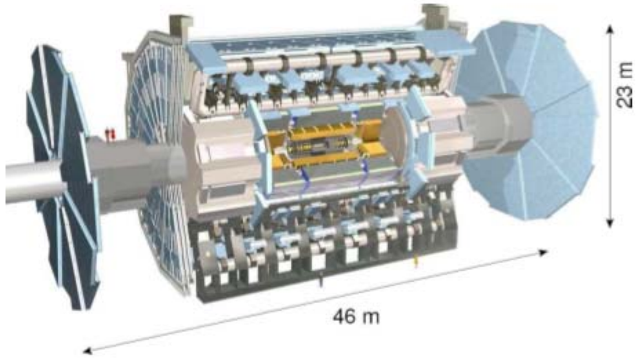
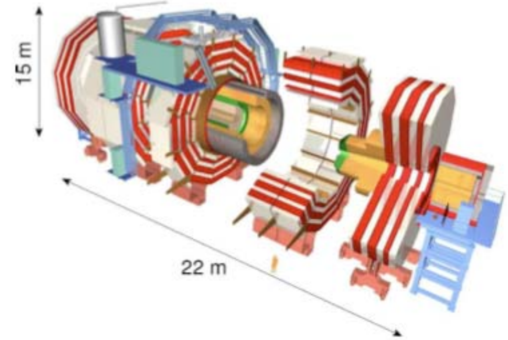


The ATLAS detector



The CMS detector

Preamble I: The ATLAS and CMS Detectors In a Nutshell

Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5\times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5\times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)