Higgs boson physics: prospects for the Run 2 and 3

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On behalf of ATLAS and CMS collaborations

Higgs Hunting

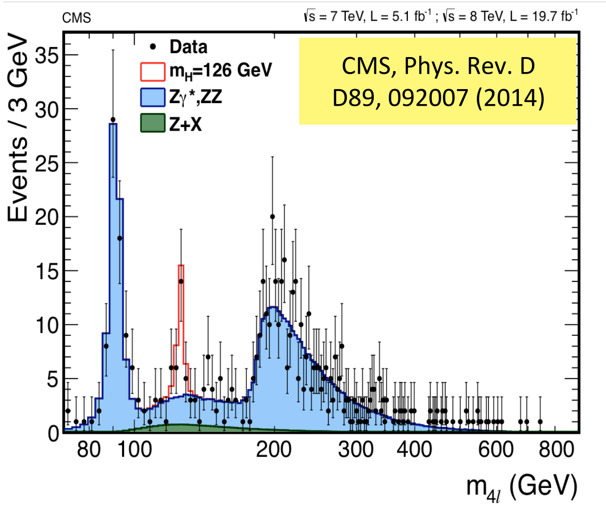
July 21-23, 2014

LAL-Orsay

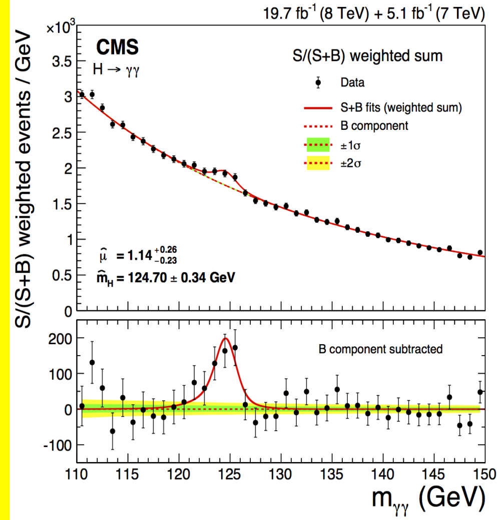
Outline

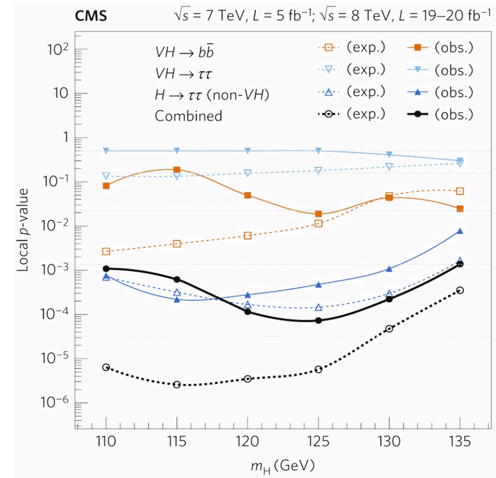
- The LHC/Higgs Run 1 era
- Landscape for 2015
- Changes: 8TeV → 13 TeV
- ATLAS and CMS upgrade
- Higgs physics prospects for Run 2 and 3
- Projections at 13 TeV
- Conclusions

The LHC/Higgs era at Run 1

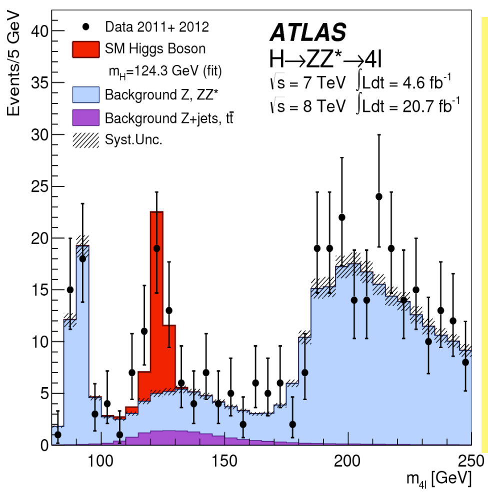


arXiv: 1407.0558, submitted to Eur. Phys. J. C

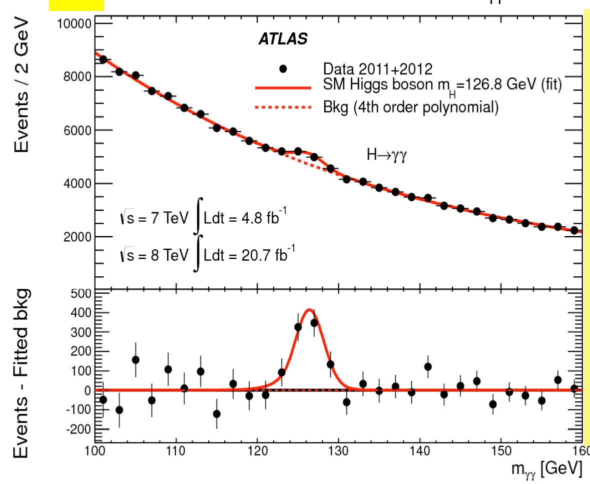




Nature Physics (2014)



Phys. Lett. B 726 (2013), pp. 88-119



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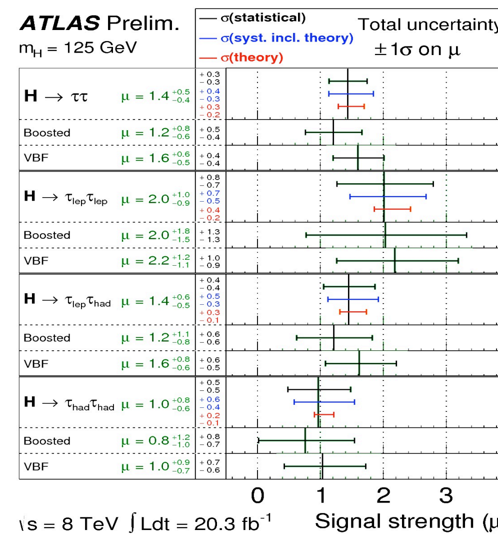
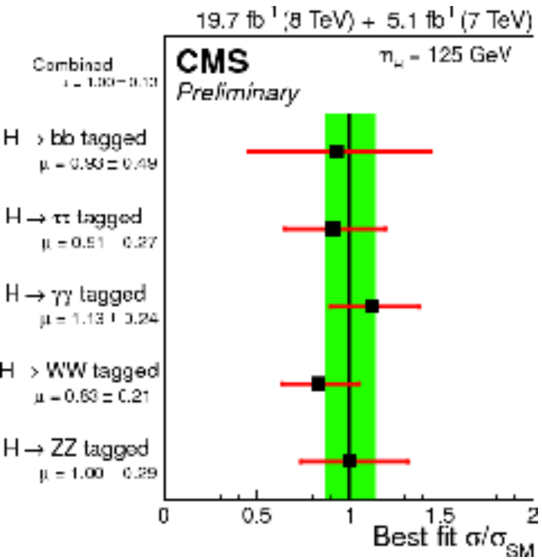
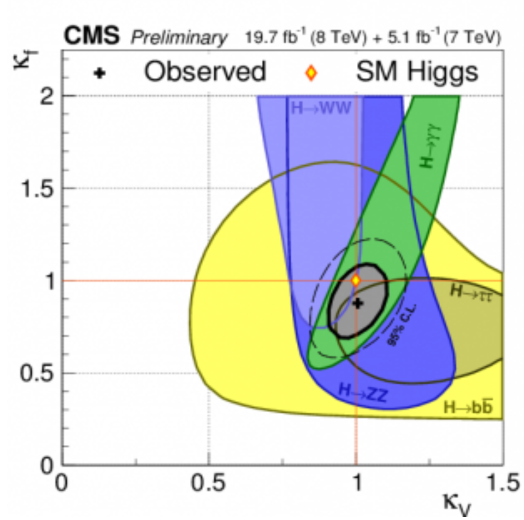


ATLAS-CONF-2013-108/

$4l/\gamma\gamma$	CMS	ATLAS
Measured mass	**125.03 $^{+0.26}_{-0.27}$(stat) $^{+0.13}_{-0.15}$(syst) GeV**	**125.36+-0.37(stat)+-0.18(syst) GeV**
Syst. Uncert.	Electron e/p-scale ≈ 0.1-0.3%	Electron e/p-scale ≈ 0.2-0.4%
	Muon p-scale ≈ 0.1%	Muon p-scale ≈ 0.1-0.2%

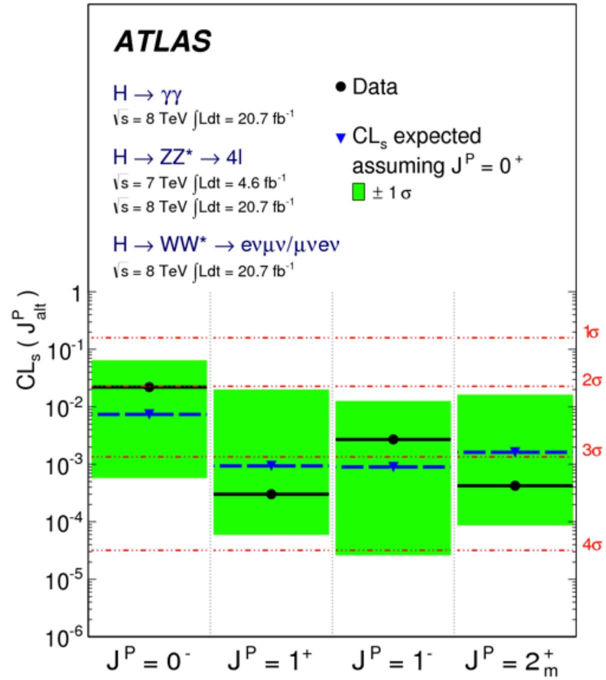
The LHC/Higgs era at Run 1

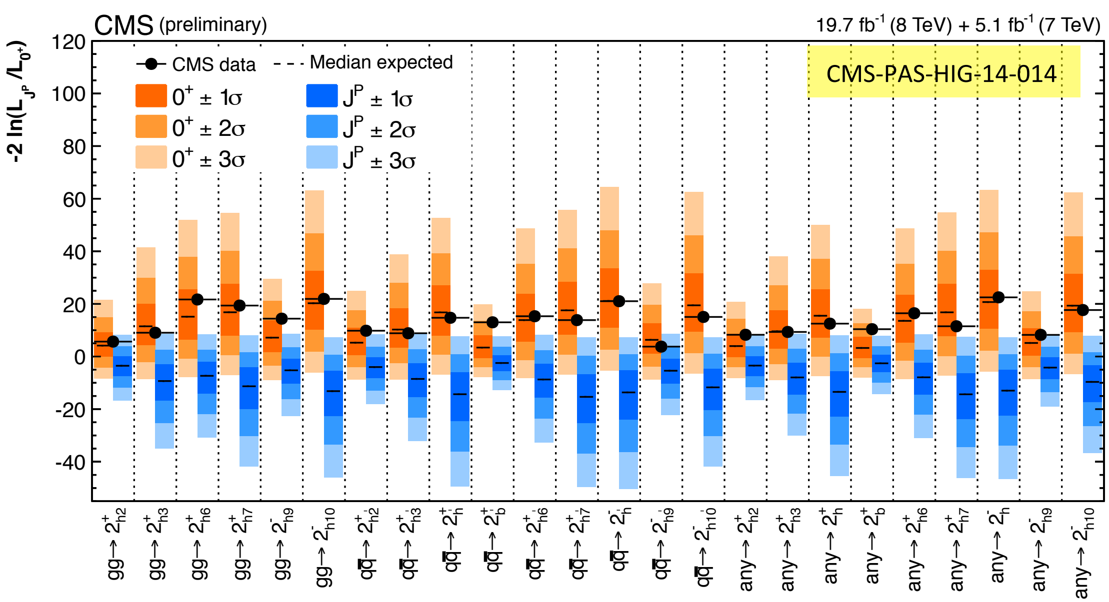




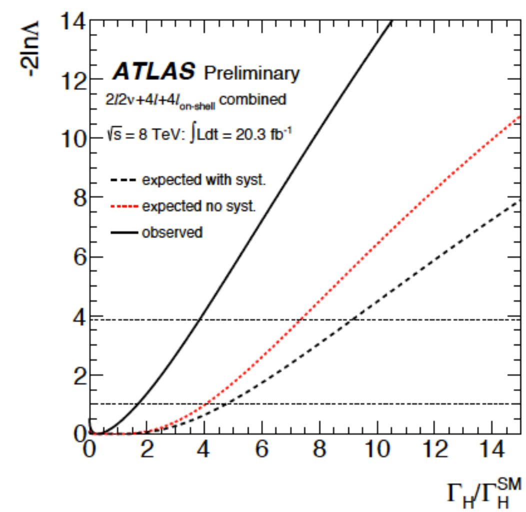
CMS-PAS-HIG-14-009

Phys. Lett. B 726 (2013), pp. 120-144





CMS-PAS-HIG-14-014



ATL-COM-CONF-2014-052

Physics remarks at Run 1

Consolidated the SM:

- Immense set of measurements at 7-8 TeV
  - Precision measurements in EW and QCD
  - Rare processes, sensitive to new Physics, like $B_s \rightarrow \mu\mu$

Completed the SM: Higgs boson discovery

- $\geq 5\ \sigma$ from each of $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$ per experiment
- $\approx 3\ \sigma$ from $H \rightarrow \tau\tau$ per experiment and
- $\approx 2\ \sigma$ from W/ZH, $H \rightarrow bb$ for CMS
- separation $0^+/2^+$ and pure $0^+/0^-$ at $> 3\sigma$ level
- some couplings measured with precision of 20-30 %

NO evidence of any new physics

4 July 2014 – ICHEP 2014
Happy Birthday Higgs Boson

Physics landscape by 2015

A Puzzle:

The SM is not the ultimate theory of particle physics, because of the many outstanding questions:

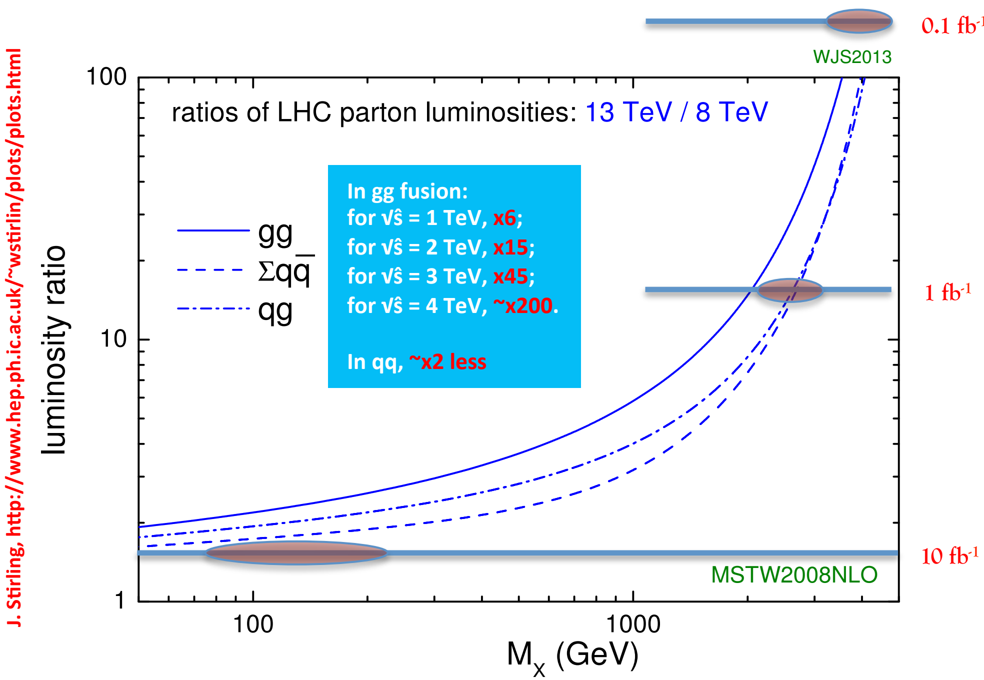
- *why is the Higgs boson so light ("naturalness"/fine-tuning/hierarchy problem) ?*
- *what is the the nature of the dark part (96% !) of the universe ?*
- *what is the origin of the matter-antimatter asymmetry ?*
- *why is gravity so weak ?*

The expected integrated luminosity of the Run 2 implies

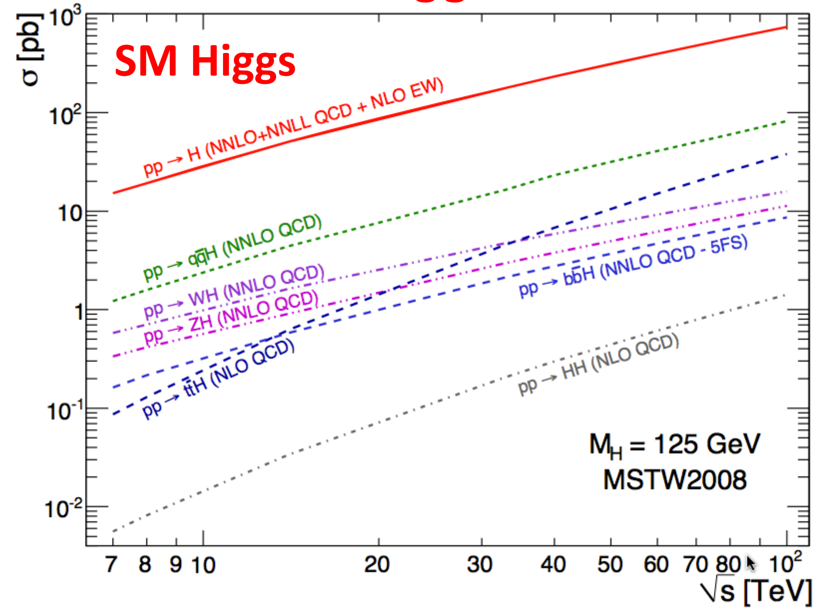
- if New Physics exists at the TeV scale hints of discovery at $\sqrt{s}$ = 13 TeV can happen already in Run 2

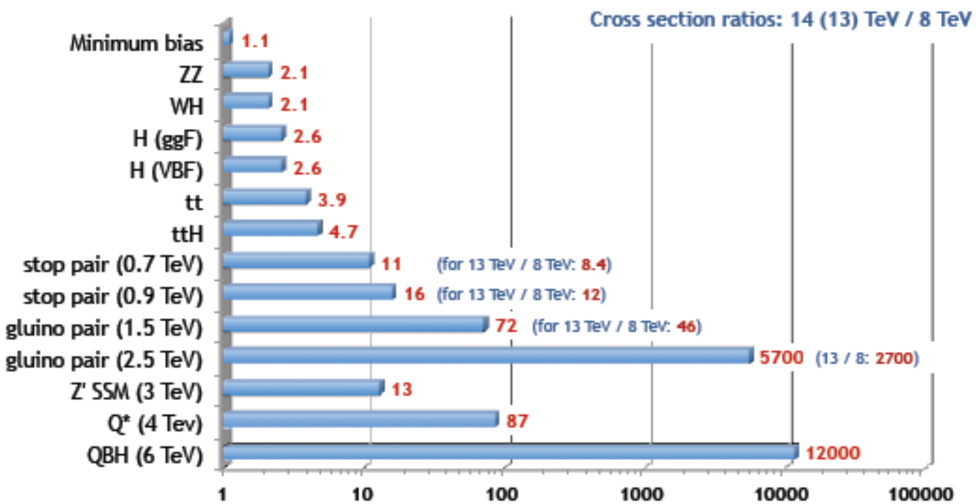
→ Run 2 will focus on **precision studies** and search for **small signals**

8 TeV → 13 TeV: What does it change ?



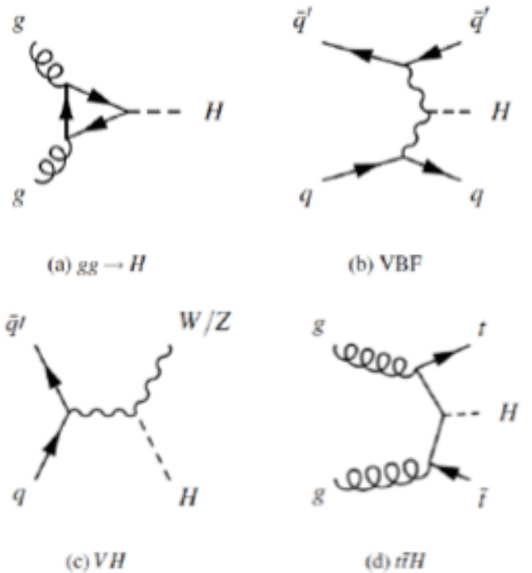
LHC Higgs Xsection WG





- SM Higgs is light, so the gluon fusion cross section doesn't get that much boost (x2, 19.1 → 43.6 pb)
- **Background cross sections increase too**

SM Higgs production at LHC: 8 vs 13 TeV



σ [pb] at m_H=125.5 GeV	8 TeV	13 TeV	Ratio
ggF	19.1	43.62	2.6
VBF	1.6	3.727	2.6
WH	0.7	1.362	2.1
ZH	0.4	0.8594	2.1
ttH	0.1	0.5027	4.7

It's very important to repeat the discovery of SM Higgs at 13 TeV as a part of physics commissioning

- could be possible during Run 1 at 13 TeV data
- an important exception: **ttH** production, which gets a boost by a factor of 4 (0.13 → 0.50 pb)
  - could potentially see it for the first time during Run 2 @13 TeV
  - But, this is a challenging analysis because of background increase

Uncertainty on σ(13TeV) from theory:
@ NNLO/NNLL QCD + NLO EWK

ggF: 8% scale and 7% PDF
VBF: 0.6% scale and 1.7% PDF

Uncertainty on BRs: 3-5%

Theoretical uncertainties

√s =14 TeV

LHC Higgs cross section working group

arXiv:1310.8361, Snowmass

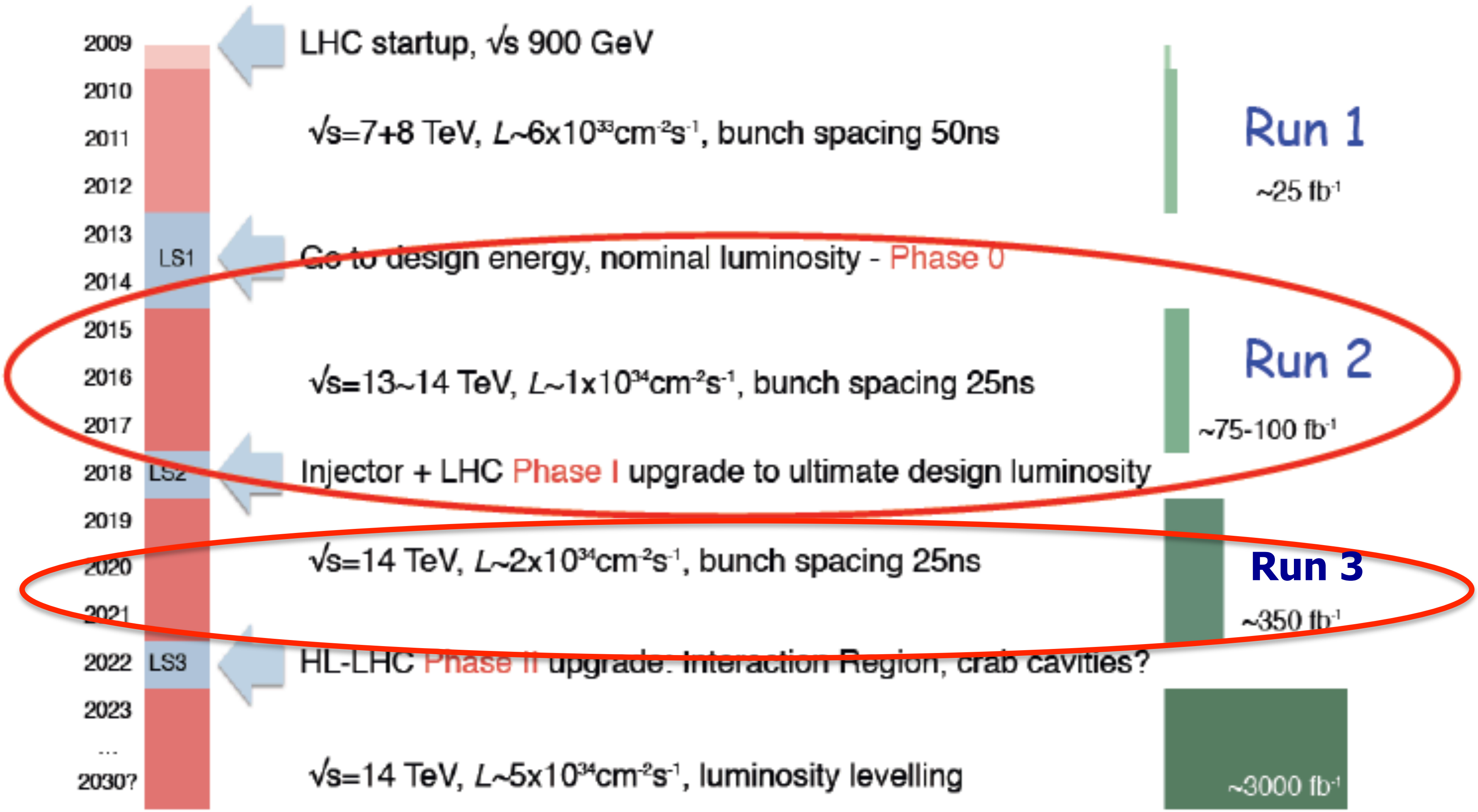
Uncertainty on cross section

Process	Cross section (pb)	Relative uncertainty in percent: Total	Scale	PDF
Gluon fusion	49.3	$^{+19.6}_{-14.6}$	$^{+12.2}_{-8.4}$	$^{+7.4}_{-6.2}$
VBF	4.15	$^{+2.8}_{-3.0}$	$^{+0.7}_{-0.4}$	$^{+2.1}_{-2.6}$
WH	1.474	$^{+4.1}_{-4.4}$	$^{+0.3}_{-0.6}$	$^{+3.8}_{-3.8}$
ZH	0.863	$^{+6.4}_{-5.5}$	$^{+2.7}_{-1.8}$	$^{+3.7}_{-3.7}$

Uncertainty on branching ratio

Decay	QCD Uncertainty	Electroweak Uncertainty	Total
$H \to b\bar{b}, c\bar{c}$	$\sim 0.1\%$	$\sim 1-2\%$	$\sim 2\%$
$H \to \tau^+\tau^-, \mu^+\mu^-$	–	$\sim 1-2\%$	$\sim 2\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW^*/ZZ^* \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$

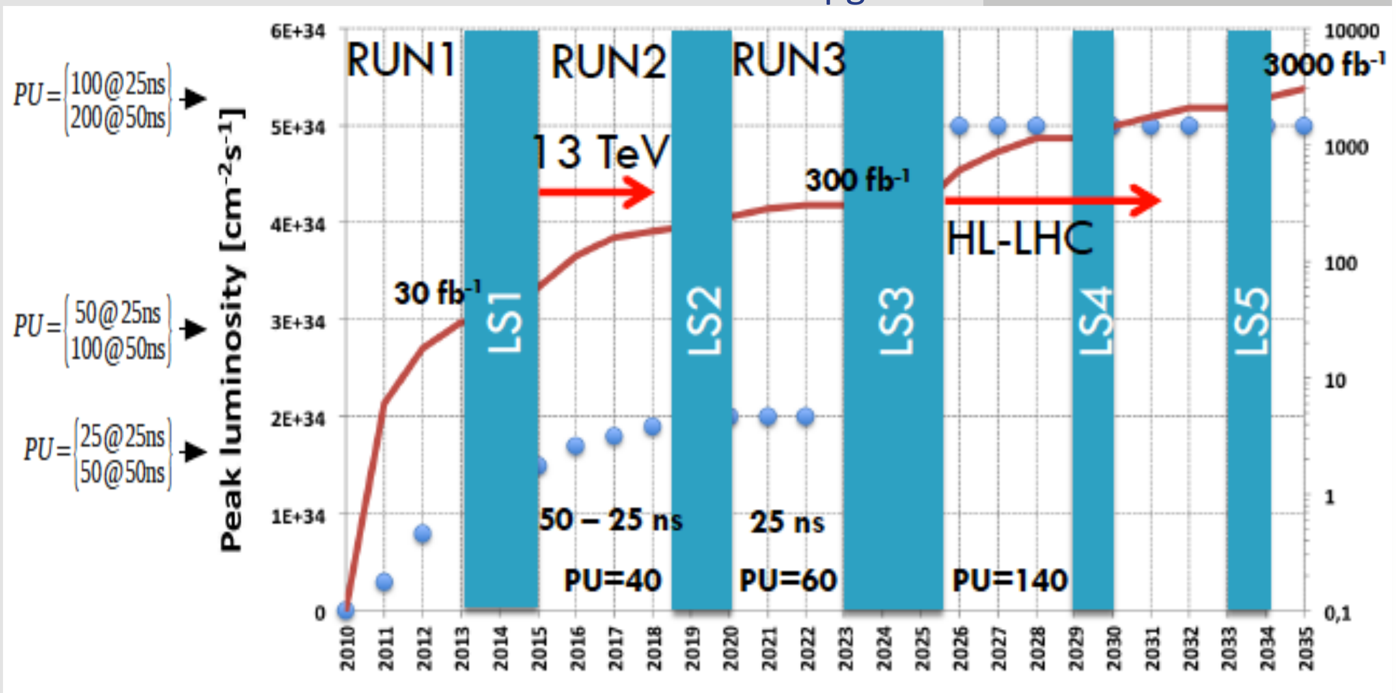
LHC plans



2009
LHC startup, $\sqrt{s}$ 900 GeV
2010
2011
$\sqrt{s}$=7+8 TeV, L~6×10^{33}cm^{-2}s^{-1}, bunch spacing 50ns
2012
Run 1
~25 fb^{-1}
2013
LS1
2014
Go to design energy, nominal luminosity - Phase 0
2015
2016
$\sqrt{s}$=13~14 TeV, L~1×10^{34}cm^{-2}s^{-1}, bunch spacing 25ns
2017
Run 2
~75-100 fb^{-1}
2018
LS2
Injector + LHC Phase I upgrade to ultimate design luminosity
2019
2020
$\sqrt{s}$=14 TeV, L~2×10^{34}cm^{-2}s^{-1}, bunch spacing 25ns
2021
Run 3
~350 fb^{-1}
2022
LS3
HL-LHC Phase II upgrade: Interaction Region, crab cavities?
2023
...
2030?
$\sqrt{s}$=14 TeV, L~5×10^{34}cm^{-2}s^{-1}, luminosity levelling
~3000 fb^{-1}

Luminosity evolution

LHC | Energy increase 8 TeV to 13/14 TeV | Injection upgrade | HL-LHC



LS= Long Shutdown

ATLAS, CMS Upgrade plan

8×10^{33} Hz/cm^2
30 fb^{-1}
PU ~40

LS1

2×10^{34} Hz/cm^2
300 fb^{-1}
PU ~50

Phase 1 Upgrade

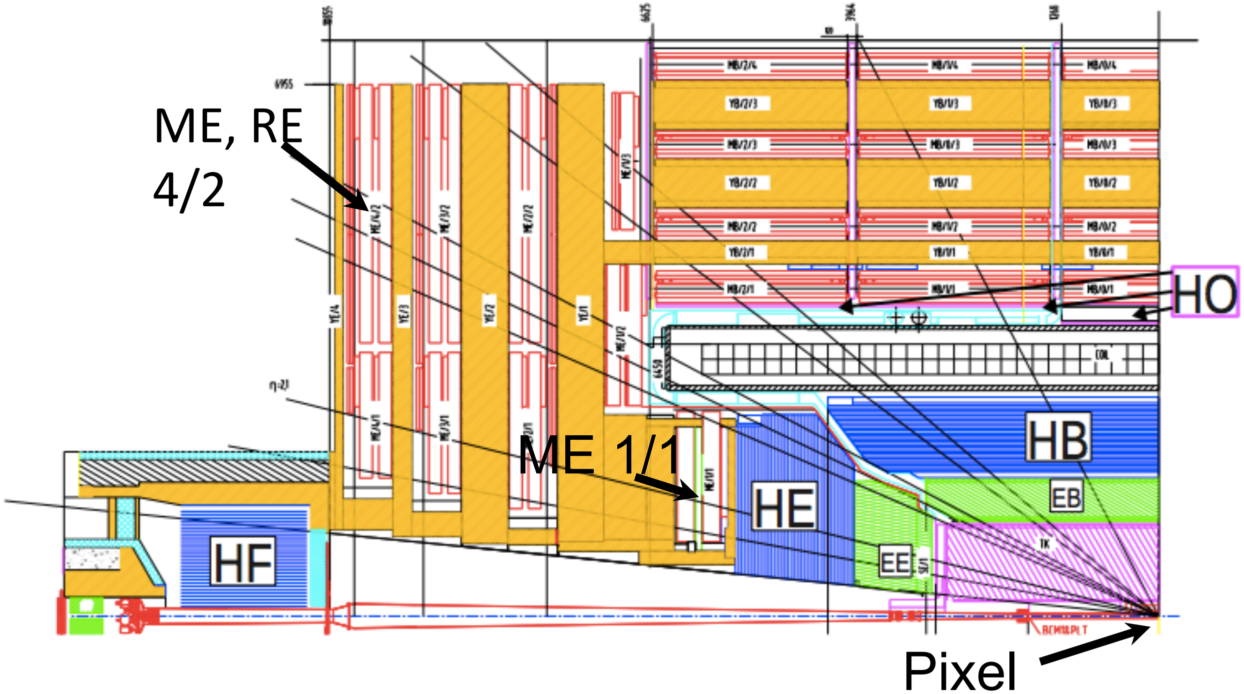
Interaction region upgrade

LS3

5×10^{34} Hz/cm^2
3000 fb^{-1}
PU ~140

Phase 2 Upgrade

CMS upgrade program



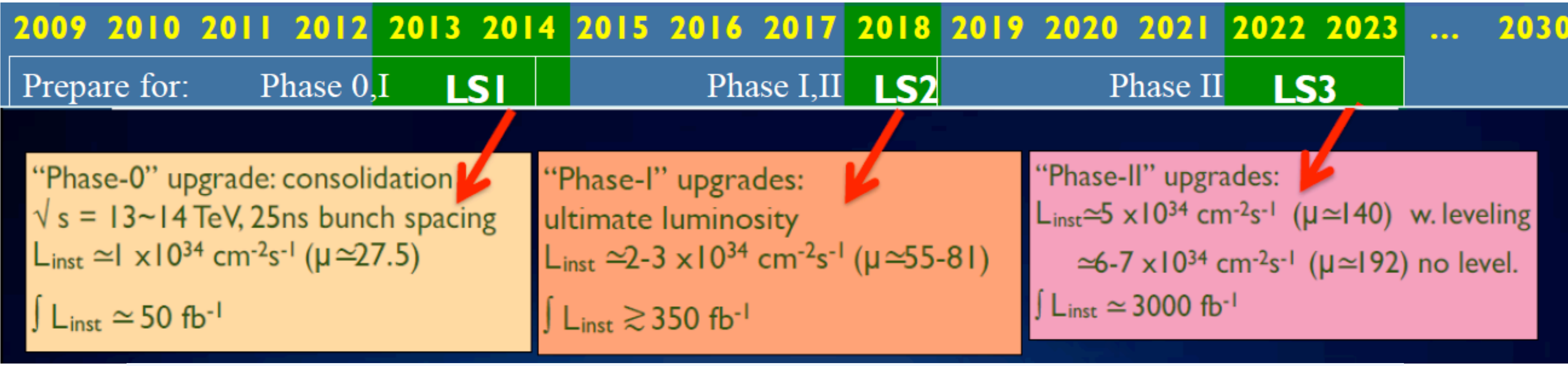
LS1 Projects:

- Complete Muon coverage (ME,RE4)
- Improve muon operation, DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPMs)

Phase 1 Upgrades

- New Pixel detector, HCAL electronics and L1-Trigger upgrade
- GEMs for forward muon det.
- New beam pipe for pixel upgrade

ATLAS upgrade program



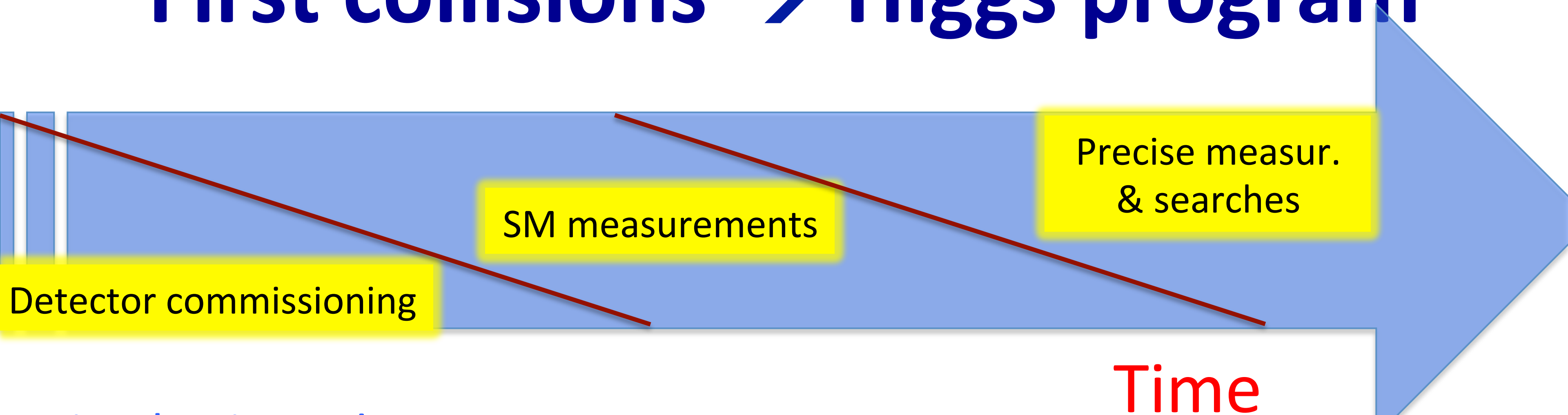
ATLAS has devised a 3 stage upgrade program

- **4th insertable pixel b-layer** (IBL)
- New Al beam pipe
- New pixel services
- Complete installation of EE muon chambers – muon coverage
- Consolidation of detector services
- New neutron shielding
- Upgrade magnet cryogenics
- Repairs: TRT, Lar, and tile

- New Small Wheel (nSW) for the forward muon Spectrometer
- High Precision Calorimeter L1-Trigger
- Fast TracKing (FTK) for L2-trigger
- Topological L1-trigger processors
- New forward diffractive physics detectors (AFP)

- Completely new tracking detector
- Calorimeter electronics upgrades
- Upgrade part of the muon system
- Possible L1-trigger track trigger
- Possible changes to the forward calorimeters

First collisions → Higgs program



Simple picture!

- **Precise measurements** and searches rely on work on detector commissioning and SM physics measurement
- physics objects need to be validated, tracking detectors re-aligned
- MC to data corrections for detector performance need to be derived
- MC might not describe 13 TeV collisions physics out of the box
- all of this is similar to 2010, though simpler (the detector is not totally new, the collision energy step is smaller, we benefit from the software developed in run I)

Higgs physics prospects

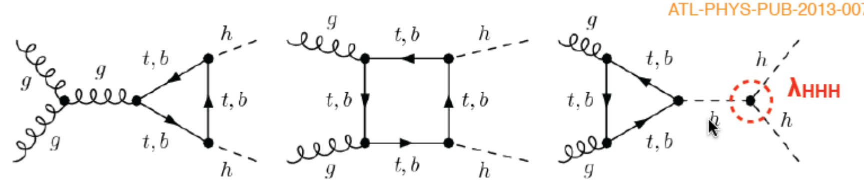
Run 2 and 3 (starting at 2015):

- re-discovery of the Higgs
- measur. Higgs properties
  - cross section (also differential via unfolding)
  - mass & width
  - couplings
    - to gauge bosons
    - to fermions
    - CP-odd admixture
    - tensor structure and effective couplings in the lagrangian
- ttH couplings
- searches for BSM Higgs:
  - additional boson in EWK singlet model
  - search for H → hh and A → Zh in 2HDM
  - search for H^+, dark matter

High Luminosity-LHC (see next talks):

- precision measurements → 2x improvement in precision
- search for rare decays and couplings
- search for CP-violation in the Higgs sector
- HH production - Higgs self-coupling
- Search for BSM decays (invisible, t→cH)
- VV scattering

ATL-PHYS-PUB-2013-007



Modeling the projections for Run 2/3

European Strategy '12, Snowmass '13, ECFA '13

Goal to **keep** the current performance in Run 2/3 for maximum 2x PU level with the detector and software upgrades (pixel det. and trigger system)

ATLAS:

- parametrisation of the detector response (**FAST SIMULATION**) to mimic the effects on selection efficiency and resolution, derived from:
  - full Run 1 detector simulation with pile-up up to $\langle\mu\rangle$ = 69
  - full Phase I detector simulation for $\langle\mu\rangle$ up to 80 and 14 =TeV
  - full Phase II detector options for $\langle\mu\rangle$ = 80, 140, 200 for HL-LHC.
- 2 scenarios for uncertainties:
  - systematics based on Run 1, improvements from stat.
  - w/o theory systematics

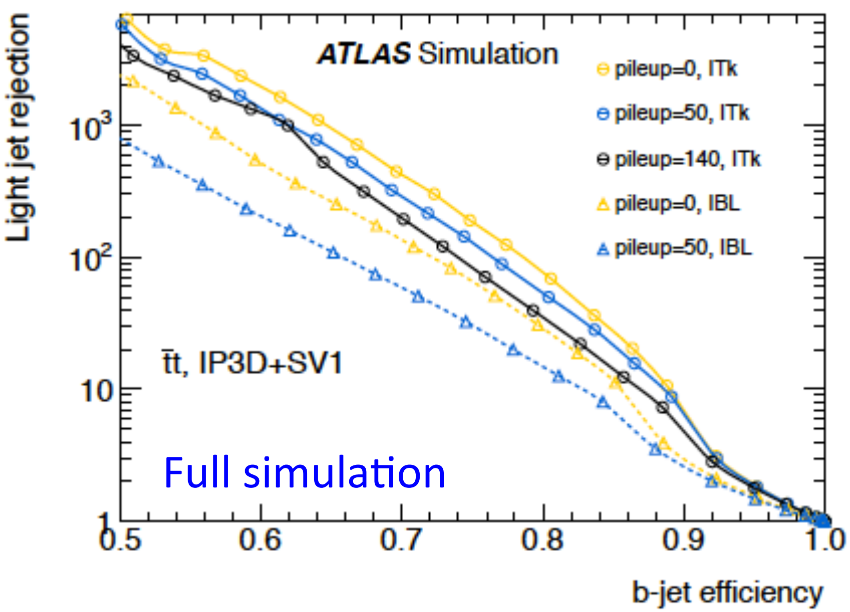
CMS:

- rescaling of run 1 signal and background yields for 14 TeV with the assumption that current detector performance kept after upgrades.
- 3 scenarios for uncertainties:
  - Scenario 1: all systematic uncertainties are kept unchanged with respect to those in current data analyses
  - Scenario 2: the theoretical uncertainties are scaled by a factor of 1/2, while other systematical uncertainties are scaled by $1/\sqrt{L}$
  - Scenario 3: set theoretical uncertainties to zero, leave other syst. as in 2012

Detector upgrade performance for Run 2/3

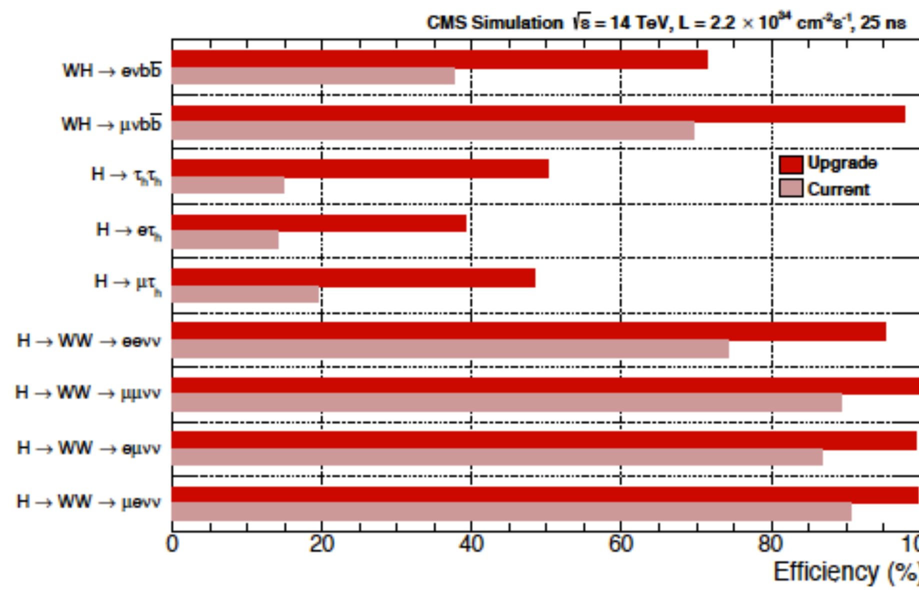
- Detector upgrades for high-luminosity in run 2 & 3 mainly in pixel detectors and trigger →
- Main improvements in b-tagging performance and trigger efficiency, E_T^{miss}

ATLAS b-tagging efficiency dependence on PU and silicon tracker upgrade



ATLAS-PHY-PUB-2013-007, arXiv 1307:7292

Improvement of the CMS trigger efficiency for Higgs channel for Run 3 at L=$2x10^{34}cm^{-2}s^{-1}$



CMS PAS 13-002

Input channels for the projections

CMS

H decay	prod. tag	exclusive final states	cat.	res.
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	1-2%
	VBF-tag	$\gamma\gamma + (jj)_{\mathrm{VBF}}$	2	<1.5%
	VH-tag	$\gamma\gamma + (\mathrm{e}, \mu, \mathrm{MET})$	3	<1.5%
	ttH-tag	$\gamma\gamma$ (lep. and had. top decay)	2	<1.5%
$ZZ \to 4\ell$	$N_{\mathrm{jet}} < 2$	4e, 4μ, $2e2\mu$	3	1-2%
	$N_{\mathrm{jet}} \geq 2$		3	
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\times$ (0 or 1 jets)	4	20%
	VBF-tag	$\ell\nu\ell\nu + (jj)_{\mathrm{VBF}}$ (DF or SF dileptons)	2	20%
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	2	
$\tau\tau$	0/1-jet	$(\mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu, \mu\mu) \times$ (low or high p_T^{τ})	16	15%
	1-jet	$\tau_h\tau_h$	1	
	VBF-tag	$(\mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu, \mu\mu, \tau_h\tau_h) + (jj)_{\mathrm{VBF}}$	5	
	ZH-tag	$(\mathrm{ee}, \mu\mu) \times (\tau_h\tau_h, \mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu)$	8	
	WH-tag	$\tau_h\mu\mu, \tau_h\mathrm{e}\mu, \mathrm{e}\tau_h\tau_h, \mu\tau_h\tau_h$	4	
bb	VH-tag	$(\nu\nu$, ee, $\mu\mu$, $\mathrm{e}\nu$, $\mu\nu$ with 2 b-jets$)\times$x	13	10%
	ttH-tag	(ℓ with 4, 5 or $\geq$6 jets) $\times$ (3 or $\geq$4 b-tags);	6	
		(ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-jets)	3	
$Z\gamma$	inclusive	$(\mathrm{ee}, \mu\mu) \times (\gamma)$	2	
$\mu\mu$	0/1-jets	$\mu\mu$	12	1-2%
	VBF-tag	$\mu\mu + (jj)_{\mathrm{VBF}}$	3	
invisible	ZH-tag	$(\mathrm{ee}, \mu\mu) \times (\mathrm{MET})$	2	

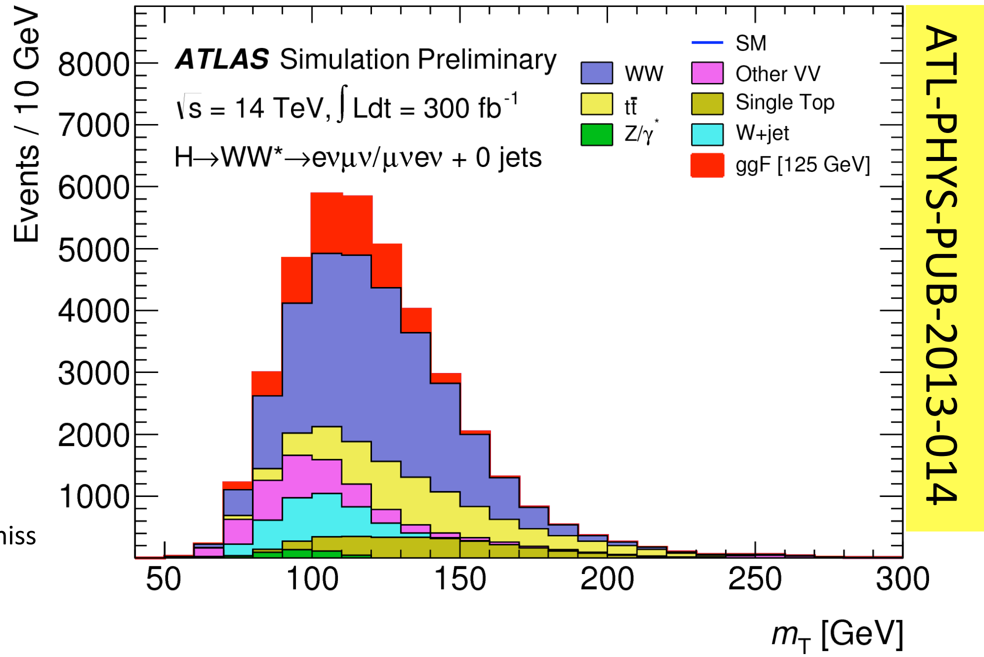
ATLAS

- H→γγ in the 0-, 1- and 2-jet/VBF final states, ttH H→γγ, WH/ZH H→γγ
- H→ ZZ →4l, ggF, ttH, ZH, WH, VBF
- H→WW→lνlν in the 0-, 1- and the 2-jet/VBF
- H→ττ in the 2-jet final state with a VBF selection
- H->Zγ, H→μμ
- ttH H→μμ, VH H->bb ← NEW since ECFA

Example: H→WW→lνlν – 300 fb^{-1}

ATLAS

- Analysis with 0, 1 or 2 jets final states based on 8 TeV samples
- extrapolated to the 14 TeV conditions by
  - PDF reweighting
  - emulation of performance of ATLAS with PU=50 events
    - evaluation of the loss in the trigger eff.
    - additional jet p_T smearing
    - degradation of the resolution of the E_T^{miss}
    - stability of the b-tagging efficiency



- Background: SM WW, tt/single top, Wγ/WZ/ZZ), Z/γ+jets, W+jets

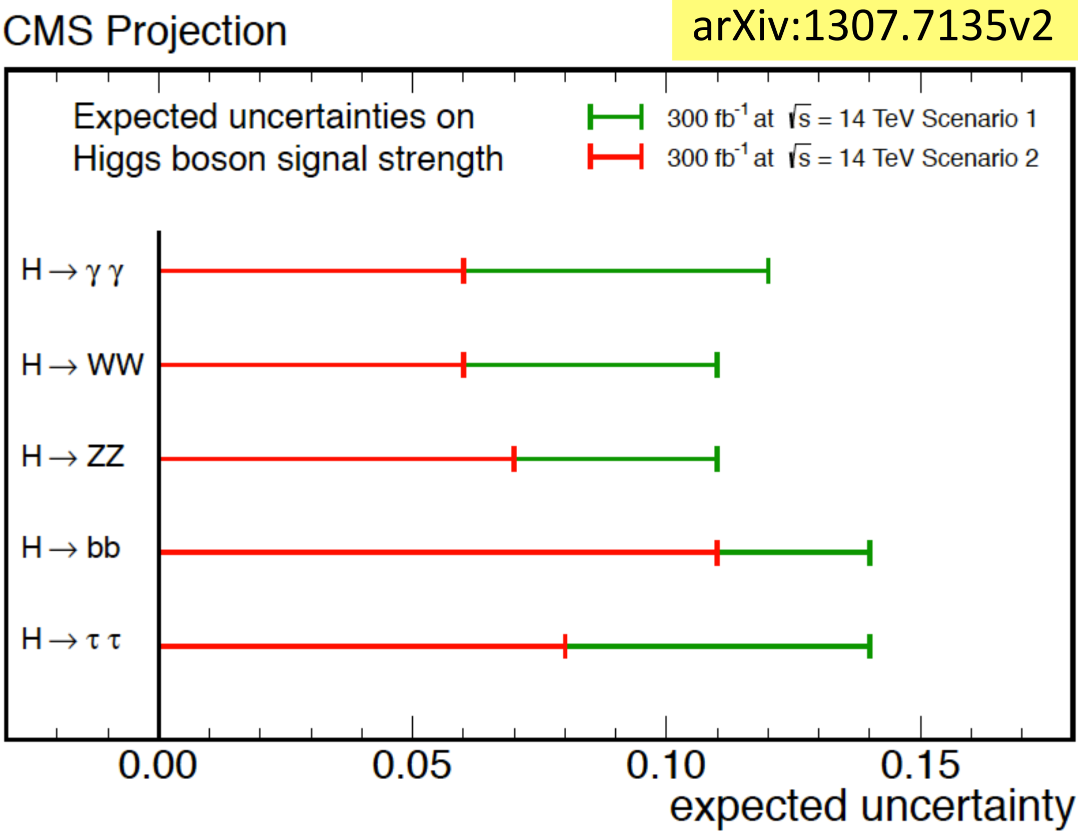
- systematic uncertainties on background
  - smaller with the increased statistics
  - Better modelling of the bkg in the control regions

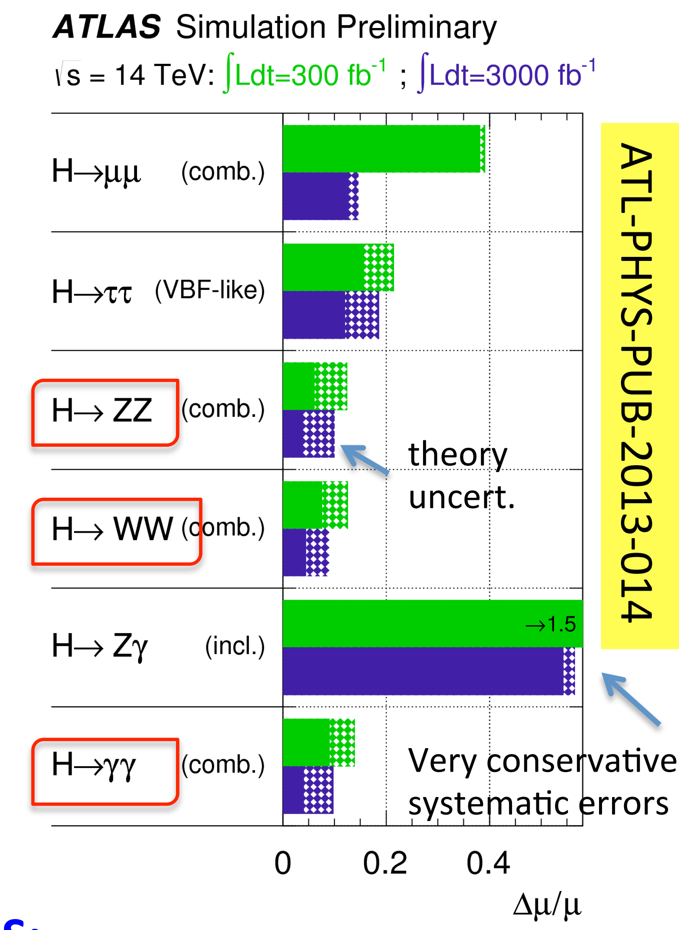
European Strategy

	$N_{jet}=0$			$N_{jet}=1$			$N_{jet}\geq 2$		
	14 TeV	ES	8 TeV	14 TeV	ES	8 TeV	14 TeV	ES	8 TeV
WW	1.5	5	5	5	-	6.5	10	10	30
VV	2	15	15	5	-	20	10	20	20
$t\bar{t}$	7	7	12	8	-	23	10	15	33
$tW/tb/tqb$	7	7	12	8	-	23	10	15	33
Z+jets	10	10	15	10	-	18	10	10	20
W+jets	20	30	30	20	-	30	20	100	30

Higgs signal strength: $\mu=\sigma/\sigma_{SM}$ - 300 fb^{-1}

arXiv:1307.7135v2





ATL-PHYS-PUB-2013-014

CMS:

- Extrapolated from 2011/12 results
- scenario 1 and 2 ≈ upper and lower bounds
- precision of **6-14%** on μ

ATLAS:

- Based on parametric simulation
- precision of **6-20%** on μ
- H→bb not yet included

Higgs couplings formalism

LHC Higgs Xsection WG - arXiv:1307.1347v2 :

- Single resonance with mass of 125 GeV.
- Zero-width approximation

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- the tensor structure of the lagr. is the SM one → observed 0^+
- coupling scale factors K_i are defined in such a way that:
  - the cross sections σ_i and the partial decay widths Γ_i scale with K^2_i compared to the SM prediction
- deviations of K_i from unity → new physics BSM
- Results from fits to the data using the profile likelihood ratio with κ_i couplings
  - as parameters of interest or
  - as nuisance parameters, according to the measurement

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{WW}^{(*)}}} = \kappa^2_{\mathrm{W}}$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{ZZ}^{(*)}}} = \kappa^2_{\mathrm{Z}}$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{b\bar{b}}}} = \kappa^2_{\mathrm{b}}$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{\mathrm{SM}}_{\tau^-\tau^+}} = \kappa^2_{\tau}$$

Higgs couplings formalism

arXiv:1307.1347v2

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}}$$

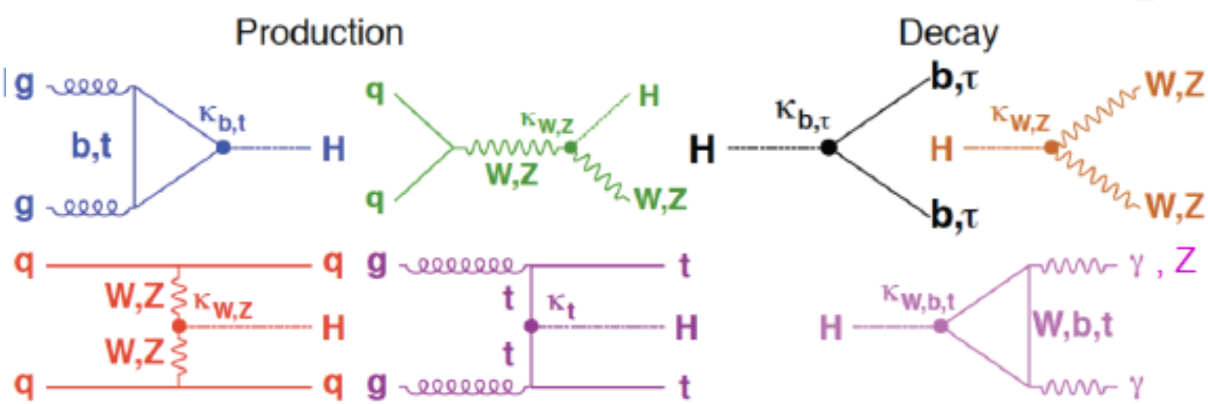
$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$



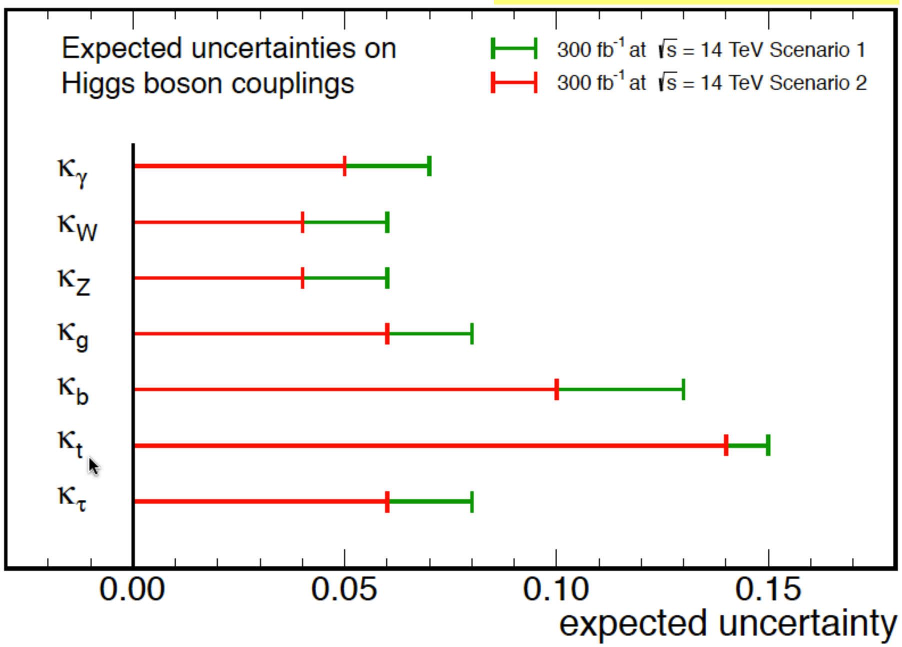
$$\Gamma_H = \Sigma_{SM}\,\Gamma_Y \;\; (+\,\Gamma_{BSM})$$

Contributions from **new physics** through Γ_{BSM} and loop processes

Higgs couplings scale factors – 300 fb^{-1}

Assump. : No extra BSM Higgs decays → absolute couplings can be extracted

arXiv:1307.7135v2



CMS: uncertainties on K_i limited by theoretical uncertainties on production and decay rates

$\sigma(\kappa_V) \approx$ 3-6% $\sigma(\kappa_F) \approx$ 5-15%

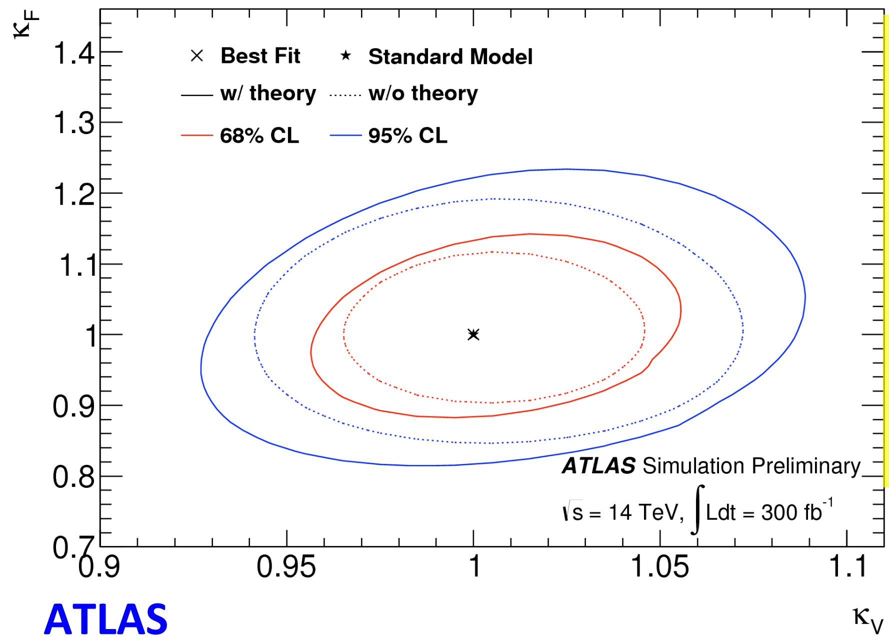
Minimal coupling fit:

$$\kappa_V = \kappa_Z = \kappa_W$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$$

Full line: Scenario 1

Dotted line: Scenario 3



ATL-PHYS-PUB-2013-014

ATLAS

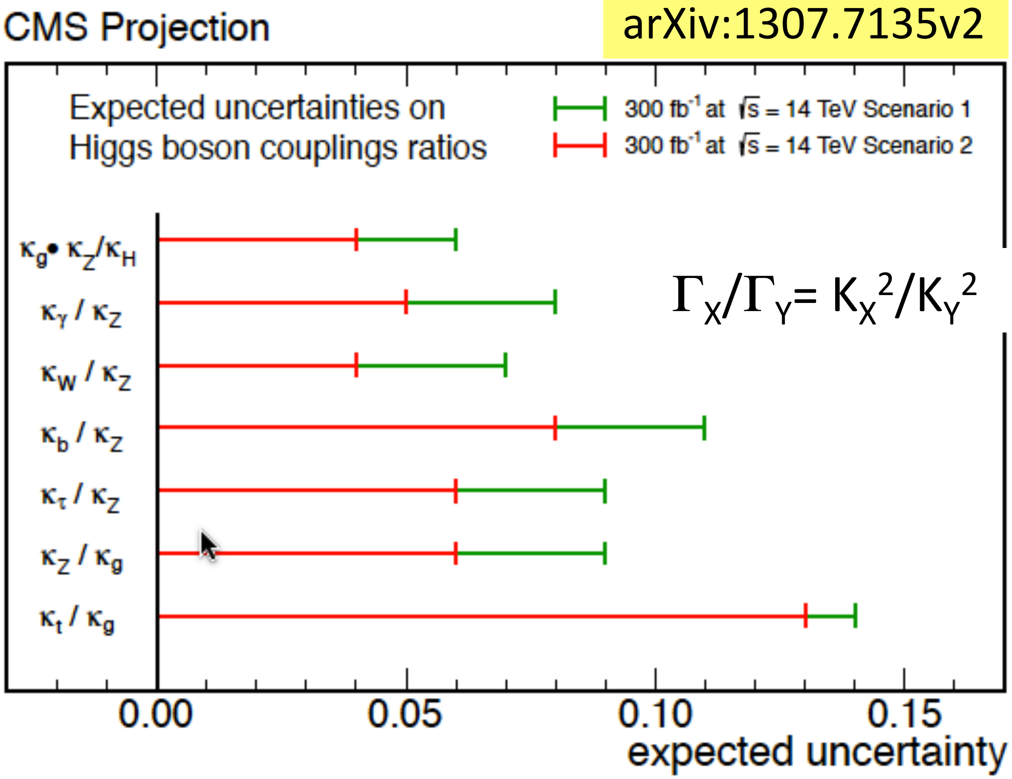
Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None
2	$\kappa_V = \kappa_Z = \kappa_W$	3.3%	2.8%	2.7%
	$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$	8.6%	7.5%	7.1%

Higgs partial width ratios – 300 fb^{-1}

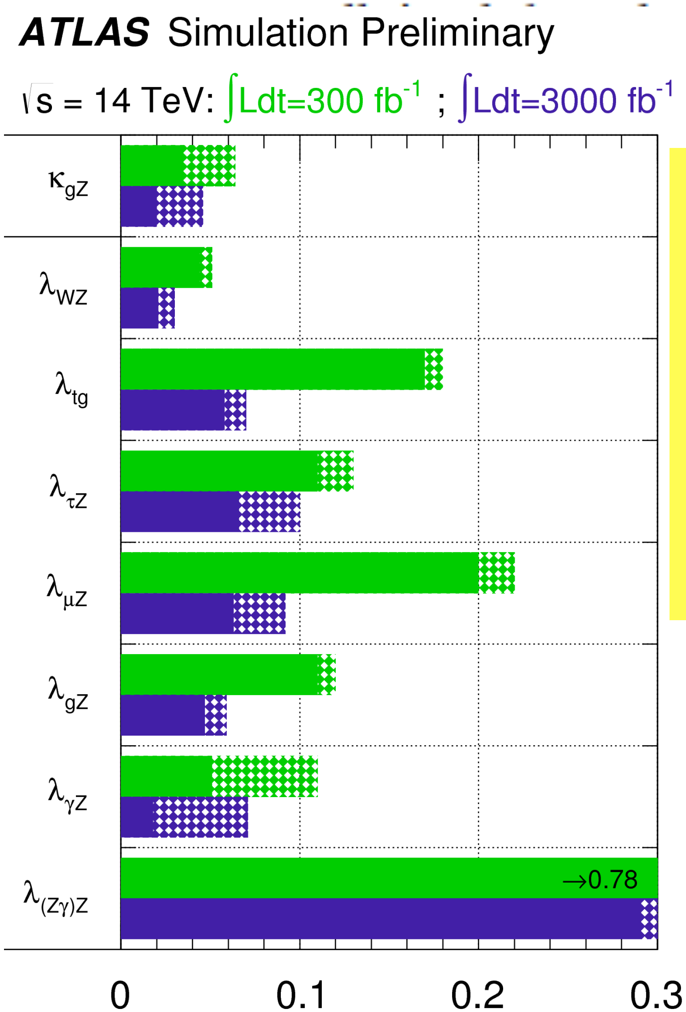
- No assum. on the total H width → ratio of k_i
- many exper. and theor. uncertainties cancel in the ratio

$$\sigma \cdot B(i \to H \to f) \sim \lambda_{iY}^2 \cdot \kappa_{YY'}^2 \cdot \lambda_{fY}^2$$

arXiv:1307.7135v2



$\Gamma_X/\Gamma_Y = K_X^2/K_Y^2$



$\Delta\lambda_{XY} = \Delta\left(\frac{\kappa_X}{\kappa_Y}\right)$

ATL-PHYS-PUB-2013-014

CMS: With 300 fb^{-1} the uncertainties on the Higgs coupling scale factor ratios are expected in the range 4-15%

Higgs mass – 300 fb^{-1}

Run 1

4l/γγ	CMS	ATLAS
Measured mass	**125.03 $^{+0.26}_{-0.27}$(stat) $^{+0.13}_{-0.15}$(syst) GeV**	**125.36 ± 0.37(stat) ± 0.18(syst) GeV**
Syst. Uncert.	Electron e/p-scale ≈ 0.1-0.3%	Electron e/p-scale ≈ 0.2-0.4%
	Muon p-scale ≈ 0.1%	Muon p-scale ≈ 0.1-0.2%

Following Snowmass report: arXiv:1310.8361

- 2.5 increase in Higgs cross section from 8 TeV to 14 TeV → the statistical uncertainty is expected to be reduced to
  - **50 MeV with 300 fb^{-1}**
  - 15 MeV with 3000 fb^{-1}
- the precision of the future measurement will likely be dominated by systematics.
  - knowledge of the energy/momentum scale of photons, electrons and muons, which should improve with increasing statistics.
- If one makes the optimistic assumption that that the systematics also scales with statistics, the expected systematic uncertainty is
  - **70 MeV with 300 fb^{-1}**
  - 25 MeV with 3000 fb^{-1}

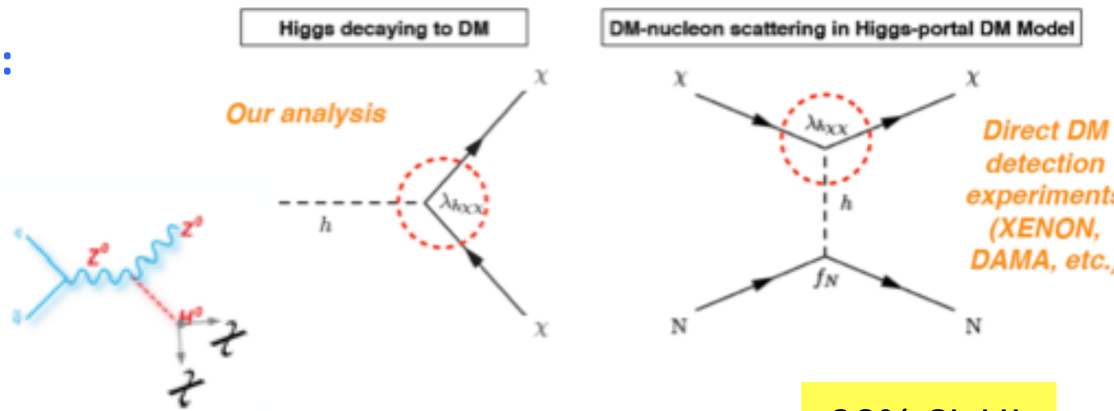
TDR (1999): ATLAS estimates that a relative precision of **0.07%** is achievable with 300 fb^{-1}

TDR (2007): CMS projects a statistical uncertainty of **0.1%** with 300 fb^{-1}

Invisible Higgs as a portal to Dark Matter

ATLAS at 300 fb^{-1}

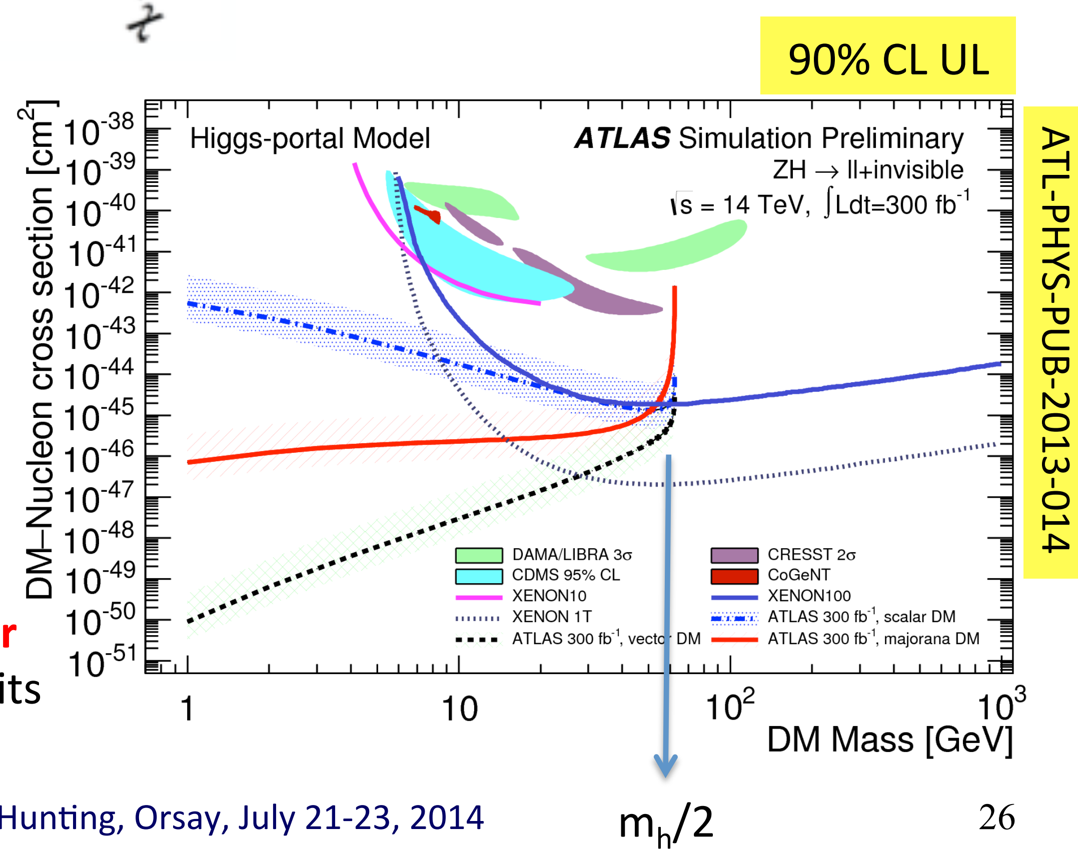
- **Indirect constraints on BR(H->inv):**
  - from Higgs coupling fit
  - BR(H→inv) < 28% @ 95% CL
- **Direct search**
  - ZH→ee/μμ+ET_{miss}
  - BR(H→inv) < 32% @ 95% CL



- Possible to **convert** the limits on BR(H→inv) into the strenght of the interaction between dark matter and Higgs boson, $\lambda_{h\chi\chi}$
- Bound on $\lambda_{h\chi\chi}$ can be mapped into scattering cross section of dark matter on a nuclei

→ **comparison with direct searches**

- Limits from ATLAS at low mass **better** than those from direct detection limits
- degrade as m_χ approches $m_h/2$



Conclusions

- ATLAS and CMS provided wonderful results during Run 1 at LHC:
  - proving the existence of the Higgs boson and measuring its properties precisely, consistent with the prediction of the SM, etc….
  - exceeding their design performances during the first LHC run with different pileup conditions
- A new energy domain with a vast potential for new physics discoveries and precision measurements will open with the Run 2 and 3 at $\sqrt{s}$=13 TeV
  - with instantaneous luminosities up to $2\times10^{34} cm^{-2}s^{-1}$
  - integrated luminosity up to 300 fb^{-1}
- It is a challenging project involving upgrades of ATLAS and CMS detectors and the experience gained in Run 1 gives us confidence that the experiments will meet the physics prospects:
  - Higgs couplings to gauge bosons at 3-6%, to fermions at 5-15% level
  - Measurement on mass, width, CP properties
  - Search for additional boson, dark matter, rare decays, VV scattering (HL-LHC)
- Similar conclusions from ATLAS and CMS projections in spite of the differences in the assumptions

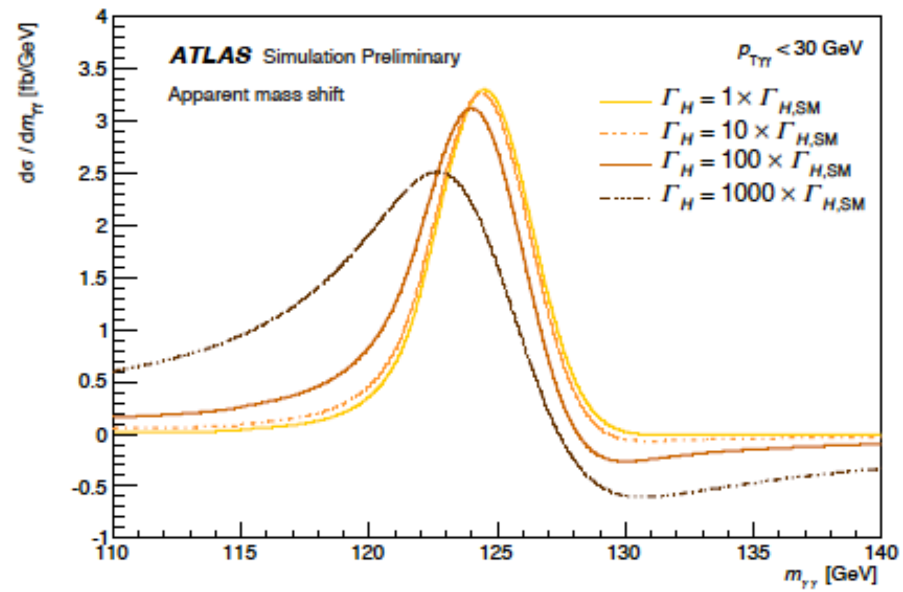
Backup

Higgs width – 300 fb^{-1}

- SM → Γ_{SM} = 4.15 MeV at m_H=125.6 GeV
  - Direct measurement limited by experimental resolution

- Interference: **ATLAS**
  - H→γγ and γγ background
  - expected shift in mass in SM
    - 54.4 MeV

(L.J. Dixon and Y.Li, arXiv:1305:3854, Sep. 2013, S.P. Martin, arXiv:1303:3342, March 2013).

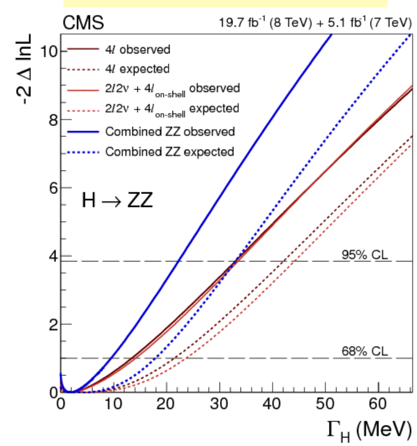


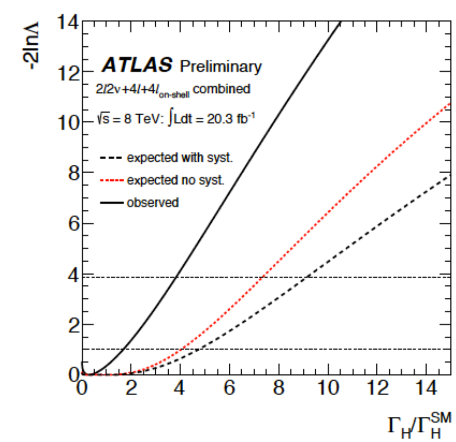
ATL-PHYS-PUB-2013-014

- Projection at 14 TeV: **ATLAS**
  - Γ_H < 920 MeV (300 fb^{-1})

- **From off-shell production:**
  - CMS Run 1
    - $\Gamma_H < 5.4\ \Gamma_{SM}$, Γ_H < 22 MeV
  - ATLAS Run 1
    - $\Gamma_H < 5.6\text{-}9\ \Gamma_{SM}$

arXiv:1405.3455v1

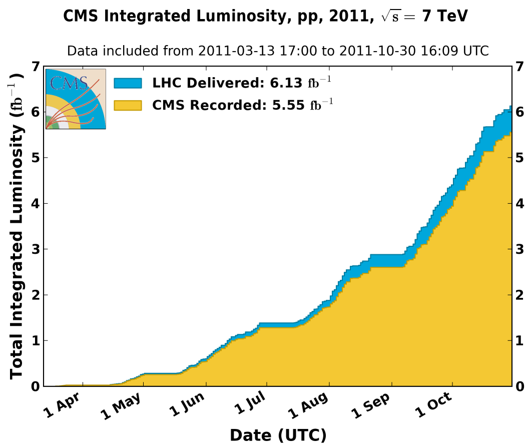


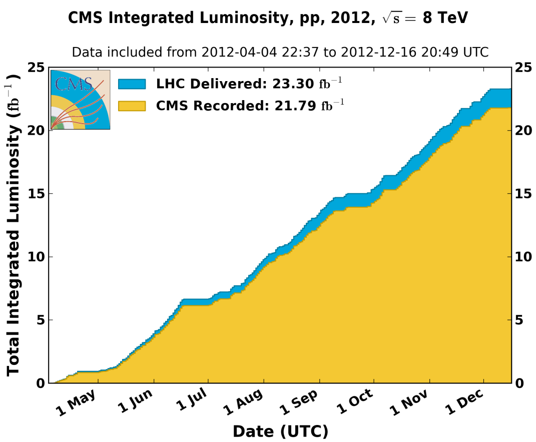


ATL-COM-CONF-2014-052

Data samples for Run 1: CMS / ATLAS

- Excellent machine and detector performance
- Very high quality data
  - ≈ 95% of delivered data were recorded
  - ≈ 90% certified and used in physics analyses

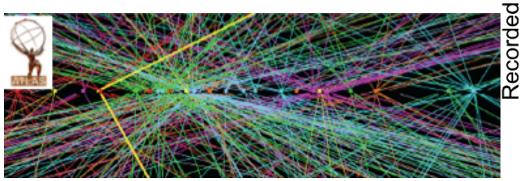


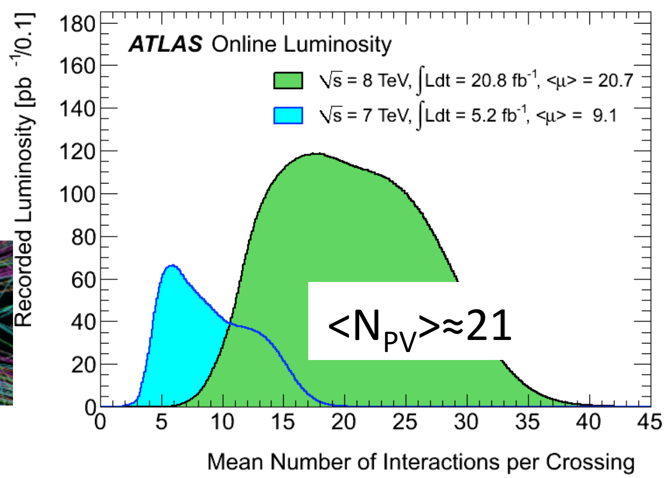


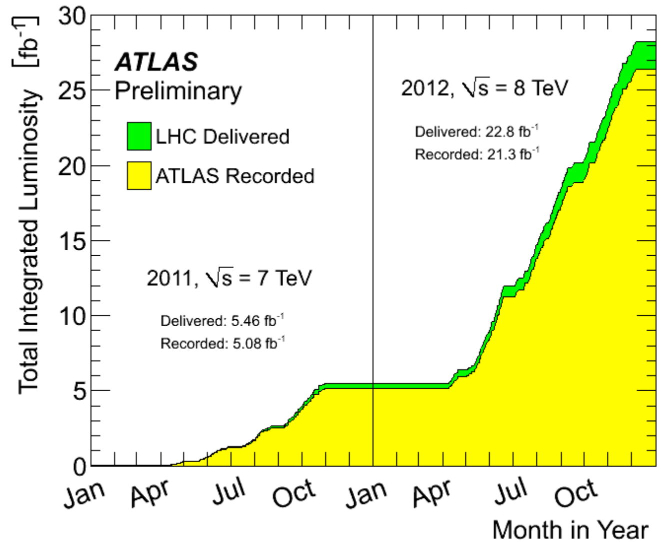
- Dataset of 2011-2012 of :

L = 5.1 (CMS) – 4.7 (ATLAS) fb^{-1} (7 TeV)
L = 19.7 (CMS) – 20.7 (ATLAS) fb^{-1} (8 TeV)

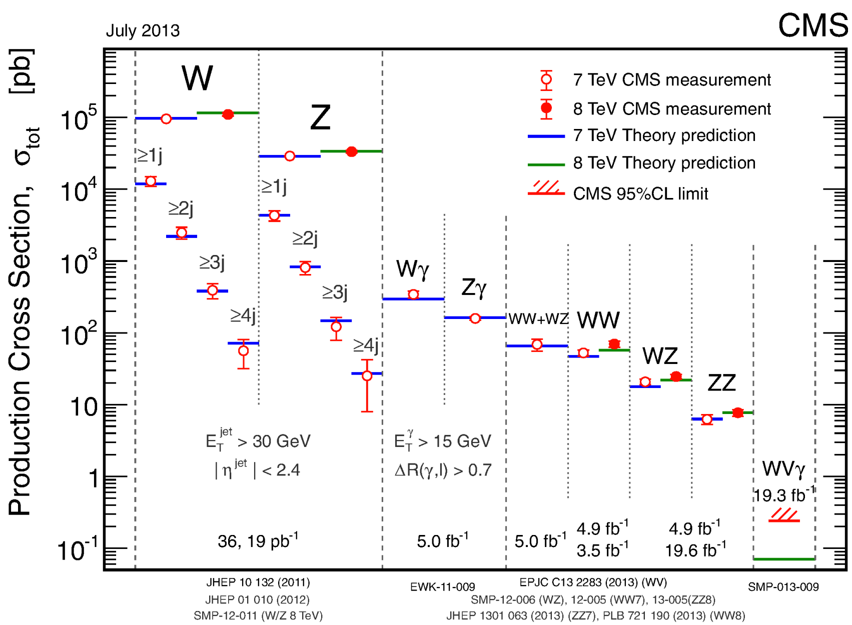
- Successfull pileup handling

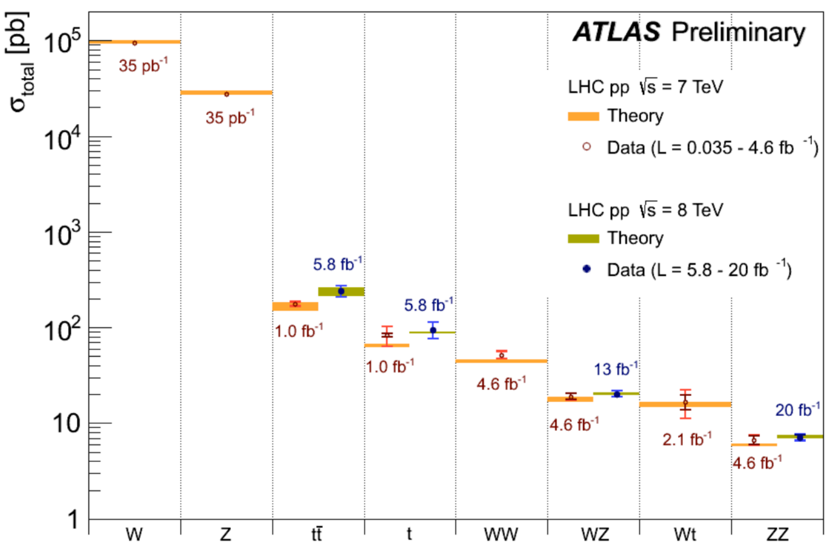


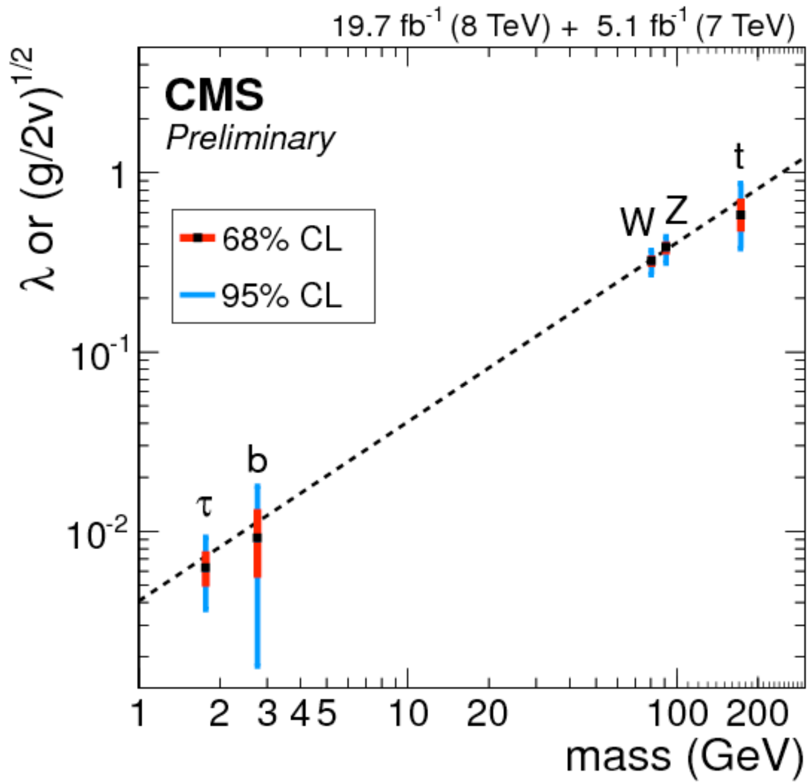




The LHC/Higgs era at Run 1







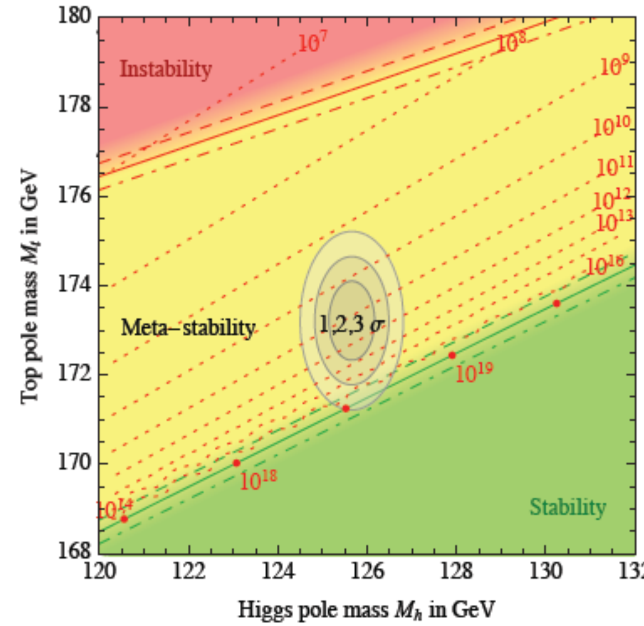
Meta-stability of the Higgs vacuum

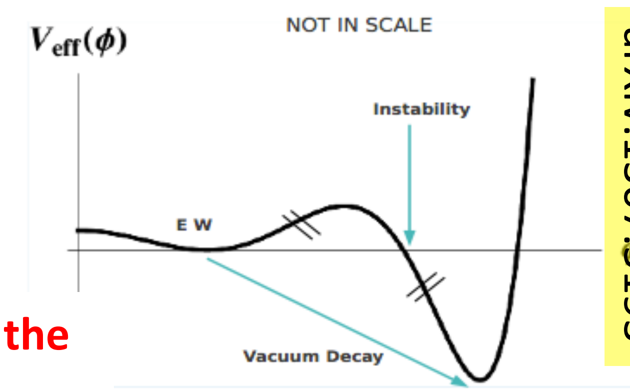
arXiv:1205.6497v2

arXiv:1307.3536v2

Intriguing outcome of the higgs discovery:

- Assuming the validity of the SM up to very high energy scales (Planck mass)
- the measured values of m_H and m_t place the EW vacuum at the border between stability and metastability → near-criticality ←Higgs vacuum in a **metastable** state
- motivates NNLO calculation of the SM Higgs potential → improved calculation of the Higgs quartic coupling to very high scales $V_0 = -\frac{m_0^2}{2}|H_0|^2 + \lambda_0|H_0|^4$ @tree level
- Stability of the Higgs potential: the measured SM parameters correspond to the minimum values of the Higgs quartic coupling and of the top Yukawa coupling y_t → long-lived EW vacuum
- The Higgs potential can develop further minima at high scales **→ new physics at Planck scale can modify the tunneling time**

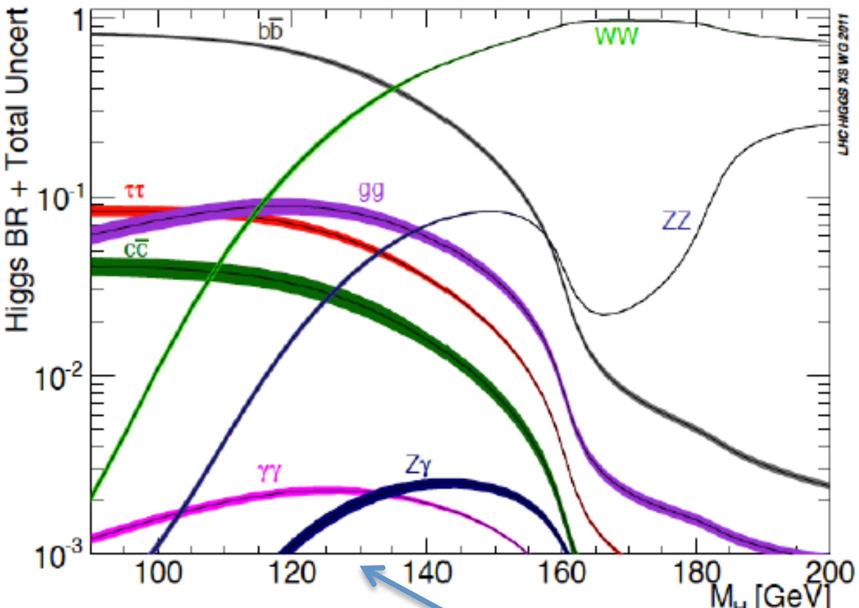


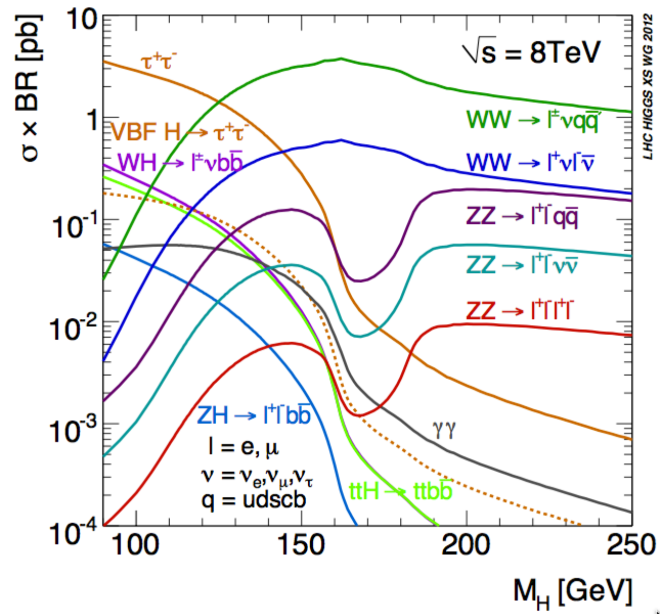


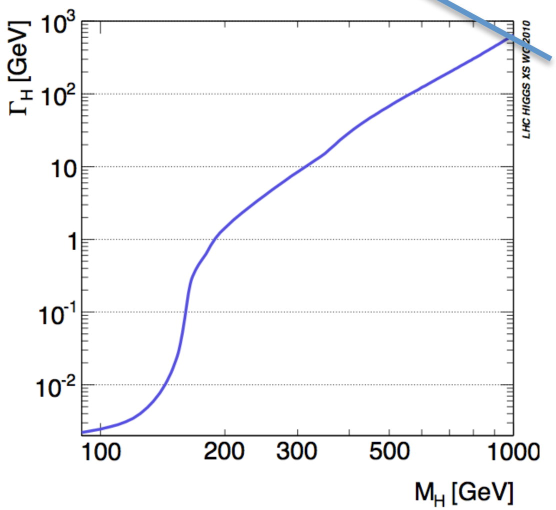
True Vacuum

arXiv:1307.5193

Higgs decay channels







At m_H =125 GeV:

- H(bb) ≈ 57%
- H(WW) ≈ 22%
- H(ττ) ≈ 6.2%
- H(ZZ) ≈ 2.8%
- H(γγ) ≈ 0.23%

Channel	m_H resolution
$H \to \gamma\gamma$	1–2%
$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$	20%
$H \to \tau\tau \to \mu\mu + X$	20%
$WH \to e\mu\tau_h/\mu\mu\tau_h + \nu's$	20%
$(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu\nu)$	10%
$H \to WW^* \to 2\ell 2\nu$	20%
$WH \to W(WW^*) \to 3\ell 3\nu$	20%
$H \to ZZ^{(*)} \to 4\ell$	1–2%
$H \to ZZ^{(*)} \to 2\ell 2q$	3% 3%
$H \to ZZ \to 2\ell 2\tau$	10–15%
$H \to ZZ \to 2\ell 2\nu$	7%

Theoretical uncertainties

√s =14 TeV

LHC Higgs cross section working group

arXiv:1310.8361, Snowmass

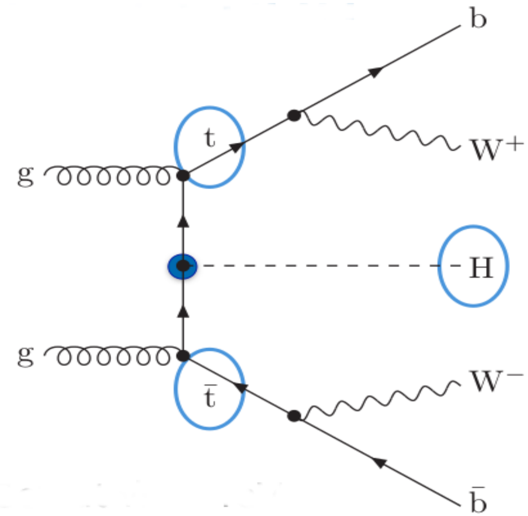
Uncertainty on cross section

Process	Cross section (pb)	Relative uncertainty in percent		
		Total	Scale	PDF
Gluon fusion	49.3	$^{+19.6}_{-14.6}$	$^{+12.2}_{-8.4}$	$^{+7.4}_{-6.2}$
VBF	4.15	$^{+2.8}_{-3.0}$	$^{+0.7}_{-0.4}$	$^{+2.1}_{-2.6}$
WH	1.474	$^{+4.1}_{-4.4}$	$^{+0.3}_{-0.6}$	$^{+3.8}_{-3.8}$
ZH	0.863	$^{+6.4}_{-5.5}$	$^{+2.7}_{-1.8}$	$^{+3.7}_{-3.7}$

Uncertainty on branching ratio

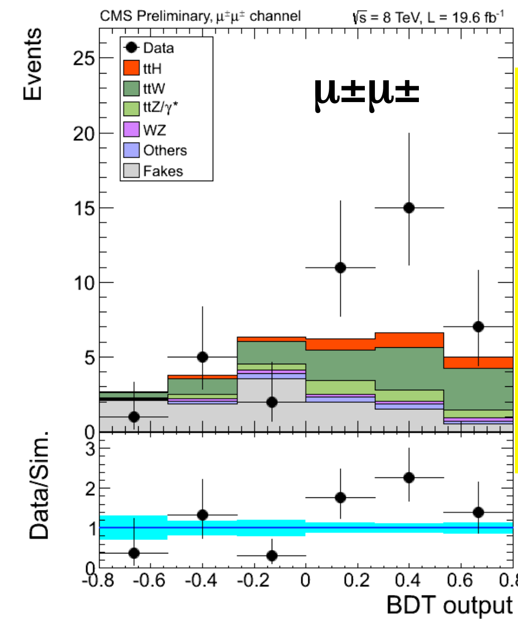
Decay	QCD Uncertainty	Electroweak Uncertainty	Total
$H \to b\bar{b}, c\bar{c}$	$\sim 0.1\%$	$\sim 1-2\%$	$\sim 2\%$
$H \to \tau^+\tau^-, \mu^+\mu^-$	–	$\sim 1-2\%$	$\sim 2\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW^*/ZZ^* \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$

Probing the top couplings at Run 1



Top coupling can be probed at tree level via ttH production

- Very low cross section but unique signature → bbWWH
- Expected uncertainty on signal strength ~ 100%



CMS PAS HIG-12-020

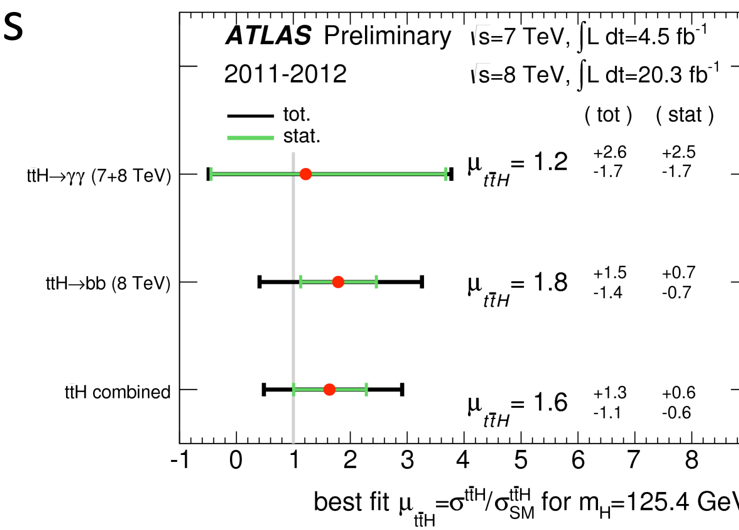
CMS ttH analysis for **Run 1**:

- **2σ excess** observed in SS di-muon events

CMS

JHEP 05 (2013) 145

Channel	μ^{fit}	$\Delta\mu^{fit}$
ttH, H→bb	0.65	-1.8/+1.8
ttH, H→$\tau_{had}\tau_{had}$	-1.3	-3.6/+6.1
ttH, H→leptons	3.9	-1.4/+1.7
ttH, H→γγ	2.7	-1.7/+2.4
ttH tagged	2.76	-0.92/+1.05



ATLAS-CONF-2014-043

Latest CMS public documents

[1] The CMS Collaboration, "Observation of the diphoton decay of the Higgs boson and measurement of its properties", arXiv: 1407.0558, submitted to Eur. Phys. J. C.

[2] CMS Collaboration, "Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks", Phys. Rev. D 89 (2014) 012003, doi:10.1103/PhysRevD.89.012003.

[3] CMS Collaboration, "Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states", JHEP 01 (2014) 096, doi:10.1007/JHEP01(2014)096.

[4] CMS Collaboration, "Measurement of the properties of a Higgs boson in the four-lepton final state", Phys. Rev. D 89 (2014) 092007, doi:10.1103/PhysRevD.89.092007.

[5] CMS Collaboration, "Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons", JHEP 05 (2014) 104, doi:10.1007/JHEP05(2014)104.

[6] The CMS Collaboration, "Precise determination of the mass of the Higgs boson and studies of the compatibility of its couplings with the standard model", Physics Analysis Summary, CMS-PAS-HIG-14-009, http://cds.cern.ch/record/1728249?ln=en

Latest CMS public documents

[7] The CMS Collaboration, "Constraints on Anomalous HWW Interactions using Higgs boson decays to W+W- in the fully leptonic final state", Physics Analysis Summary, CMS-PAS-HIG-14-012, http://cds.cern.ch/record/1728250?ln=en

[8] The CMS Collaboration, "Constraints on anomalous HVV interactions using H to 4l decays", Physics Analysis Summary, CMS-PAS-HIG-14-014, http://cds.cern.ch/record/1728251?ln=en

[9] The CMS Collaboration, "Evidence for the direct decay of the 125 GeV Higgs boson to fermions", Nature Physics advance online publication (2014), doi:10.1038/nphys3005.

Latest ATLAS public documents

New Higgs Results for Summer 2014

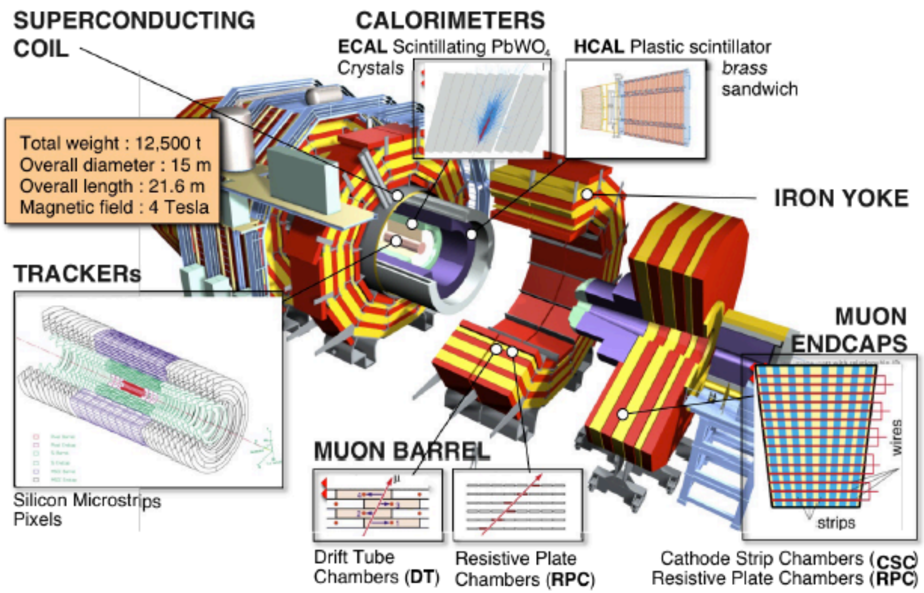
Channel	Documentation	L	Date
Higgs mass measurement	ATLAS-HIGG-2013-12	25 fb^{-1}	15/06/2014
Search for double Higgs production in the H→gamgam and H→bb decay channels	ATLAS-HIGG-2013-29	25 fb^{-1}	19/06/2014
Search for the Standard Model Higgs boson decay to mu+ mu- with the ATLAS detector	ATLAS-HIGG-2013-07	25 fb^{-1}	30/06/2014
Limits on fiducial cross sections of additional Higgs states in the gamma gamma final state	ATLAS-CONF-2014-031	25 fb^{-1}	31/05/2014
Determination of the off-shell Higgs boson signal strength in the high-mass ZZ final state with the ATLAS detector	ATLAS-CONF-2014-042	20 fb^{-1}	3/07/2014
Search for $H \to \gamma\gamma$ produced in association with top quarks and constraints on the top quark-Higgs boson Yukawa coupling	ATLAS-CONF-2014-043	20 fb^{-1}	3/07/2014
Measurement of inclusive and differential fiducial cross-sections of the Higgs boson in the $H \to ZZ^* \to 4$ decay channel	ATLAS-CONF-2014-044	20 fb^{-1}	4/07/2014

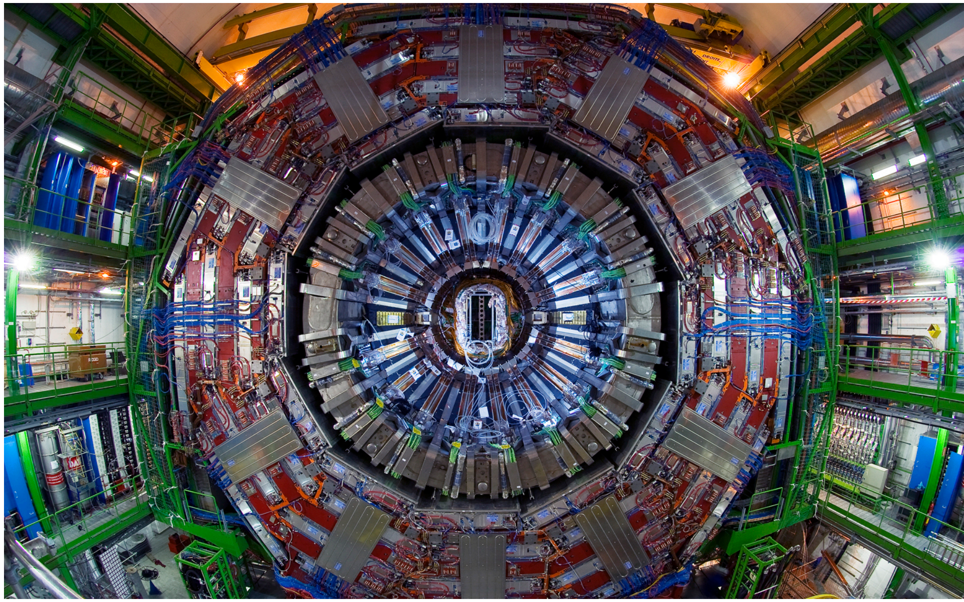
PUBLISHED Search for top quark decays $t \to qH$ with $H \to \gamma\gamma$ using the ATLAS detector	JHEP	Figures, Inspire, arXiv	JHEP06(2014)008 (Submitted: 2014/03/26)
PUBLISHED Search for Invisible Decays of a Higgs Boson Produced in Association with a Z Boson in ATLAS	PRL	Figures, Inspire, Synopsis, arXiv	Phys. Rev. Lett. 112, 201802 (2014) (Submitted: 2014/02/13)
PUBLISHED Search for the Standard Model Higgs boson decay to a photon and a Z boson in pp collisions at $\sqrt{s}$ = 7 and 8 TeV with the ATLAS detector	PLB	Figures, Inspire, arXiv	Phys. Lett. B 732C (2014), pp. 8-27 (Submitted: 2014/02/13)

Higgs Group Public Notes

Reference	Full Title	Publication Date	Groups
ATL-PHYS-PUB-2014-012	HL-LHC projections for signal and background yield measurements of the Higgs boson production in association with t quarks, W or Z bosons, in the diphoton decay channel	2014/07/06	HIGG
ATL-PHYS-PUB-2014-009	ATLAS interpretation of the combined measurements of coupling properties of the Higgs boson in terms of its production cross sections	2014/07/04	HIGG
ATL-PHYS-PUB-2014-011	A study of Standard Model Higgs boson production in the decay mode $H \to bb$ in association with a W or Z boson for High Luminosity LHC Running	2014/07/04	HIGG

CMS in a nutshell





|η|<2.5 : Tracker

$\sigma/p_T \approx 10^{-4}p_T \oplus 0.005$

|η|<4.9 : EM Calorimeter

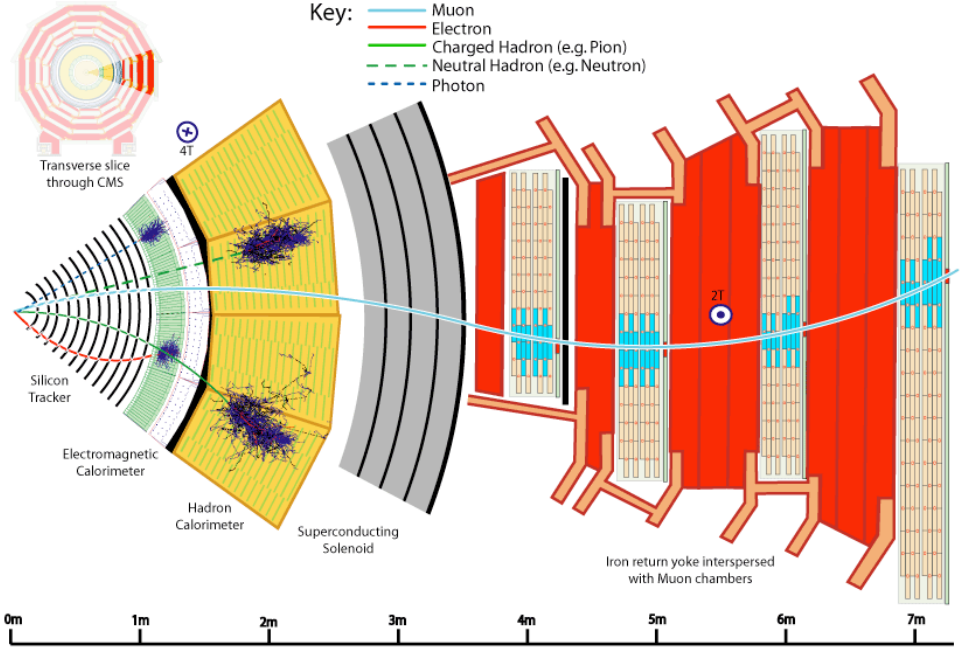
$\sigma/E \approx 0.03/\sqrt{E} + 0.003$

|η|<4.9 : HAD Calorimeter

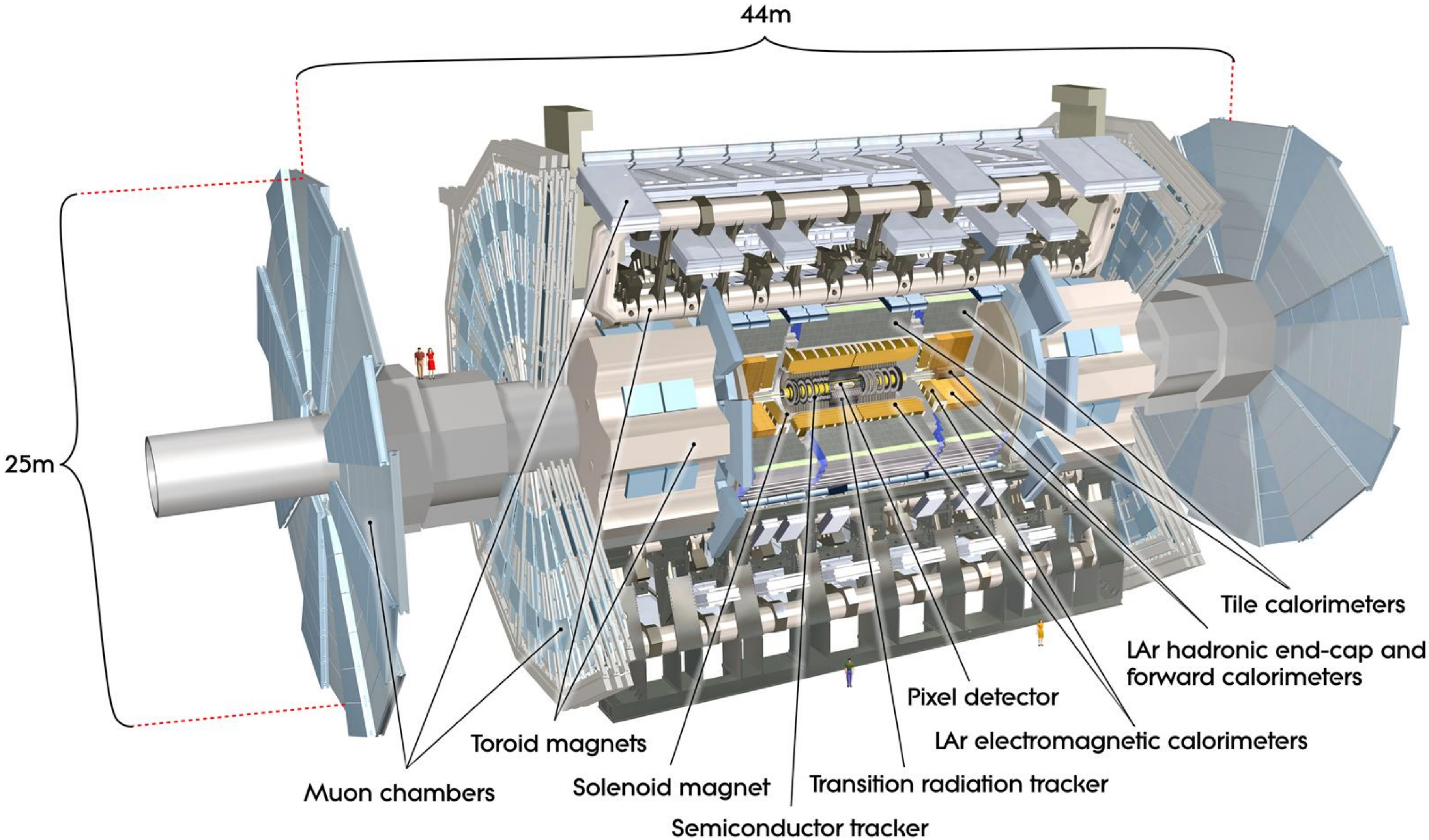
$\sigma/E \approx 1.0/\sqrt{E} + 0.05$

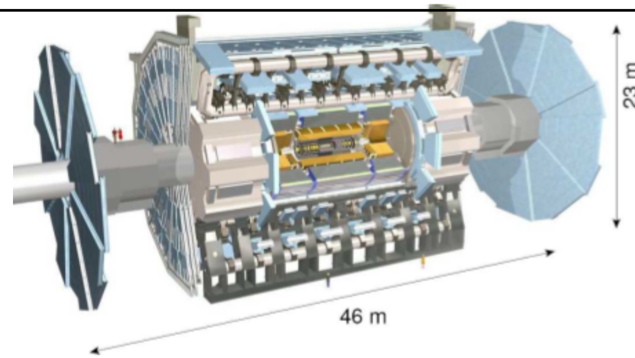
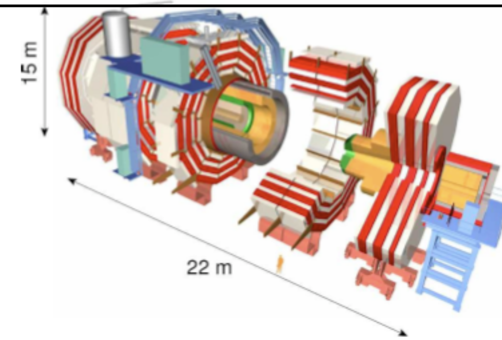
|η|<2.4 : Muon spectrometer

$\sigma/p_T \approx 0.10$ *(1TeV muons)*



ATLAS 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)

Theoretical constraints on m_H

Unitarity: WW scattering

$$M_H < 700 - 800 \ GeV/c^2$$

Triviality: **Higgs self-coupling finite**

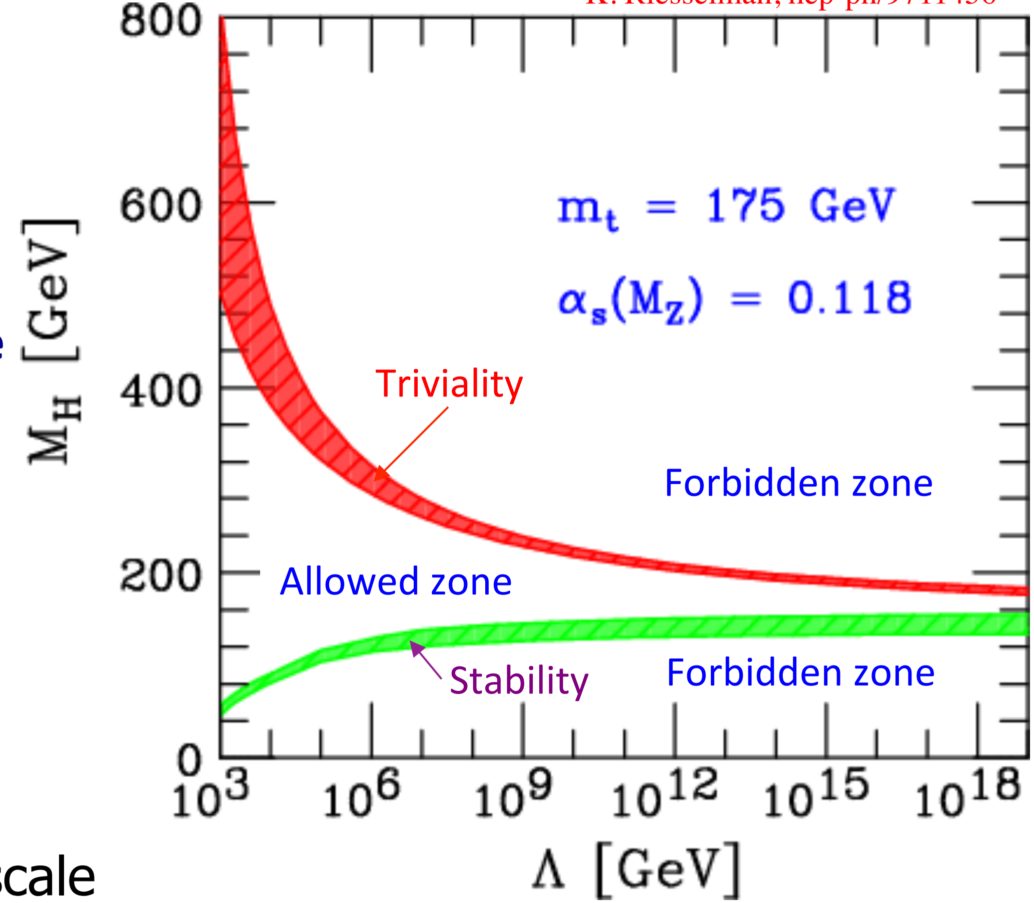
$$M_H^2 < \frac{4\pi^2 v^2}{3\ln(\Lambda/v)}$$

Stability **of vacuum:**

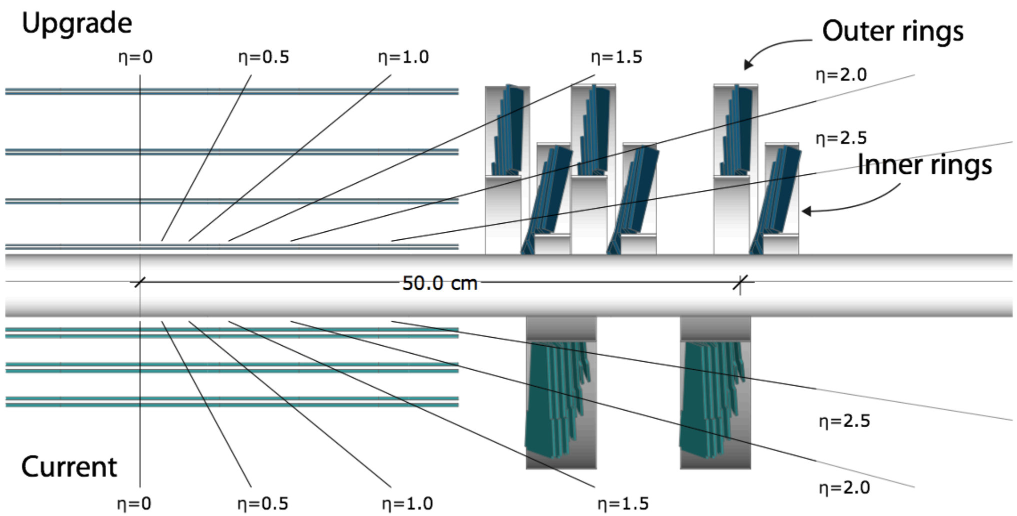
$$M_H^2 > \frac{4m_t^4}{\pi^2 v^2}\ln(\Lambda/v)$$

Λ = cut-off scale

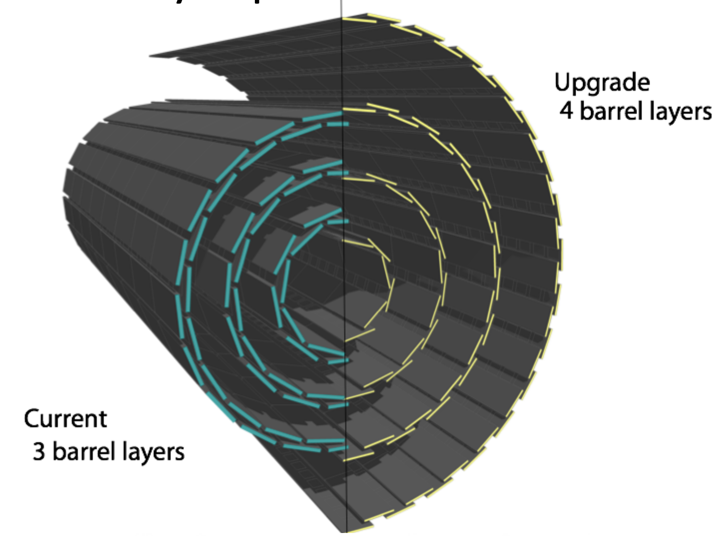
K. Riesselman, hep-ph/9711456



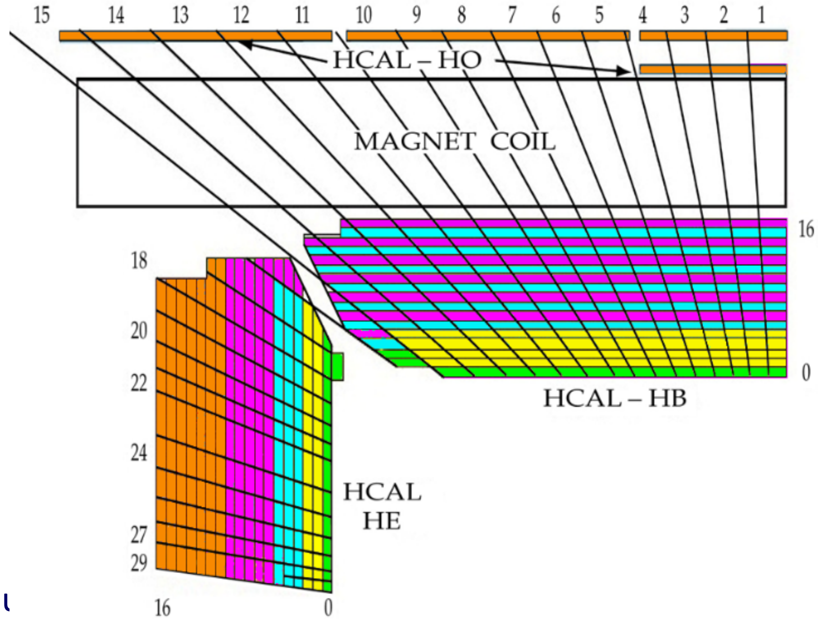
CMS pixel and HCAL phase 1



New 4-layer pixel detector Pixel



- Upgraded HCAL
  - New photodetectors
  - New electronics (frontend, backend)
  - Improved longitudinal segmentation
  - Improved background rejection, Missing E_T resolution and Particle Flow reconstruction



Run II – Early 2015

- 100/pb-1/fb program:
  - Dijet resonances
  - Black holes
  - Excited leptons
  - Leptoquarks
  - Heavy neutrino
  - W', Z'
  - Gluino-mediated SUSY searches
  - W/Z, tt, VV, Y, inclusive jet, direct photon cross sections
  - UE, particle multiplicity
- 1-10/fb program:
  - Direct third generation searches
  - Full program of Higgs physics
  - Possible observation of ttH production
  - Single top quark cross section
  - Searches with top quarks (tt resonances, top partners, etc.)
  - EWK SUSY production

Higgs physics plans for the future

Production and decays:

- Cross sections (also differential via unfolding), Branching fractions
  - Rare, invisible, or non-standard decays (HL-LHC)
- Couplings to bosons and fermions
  - ***Top quark Yukawa coupling***
- Test of standard model
  - Most models affect couplings at few % level
- Higgs ***self-coupling*** (HL-LHC)
- Mass measurement in several channels
- Measurement of the Higgs ***width***

Search for additional Higgs bosons

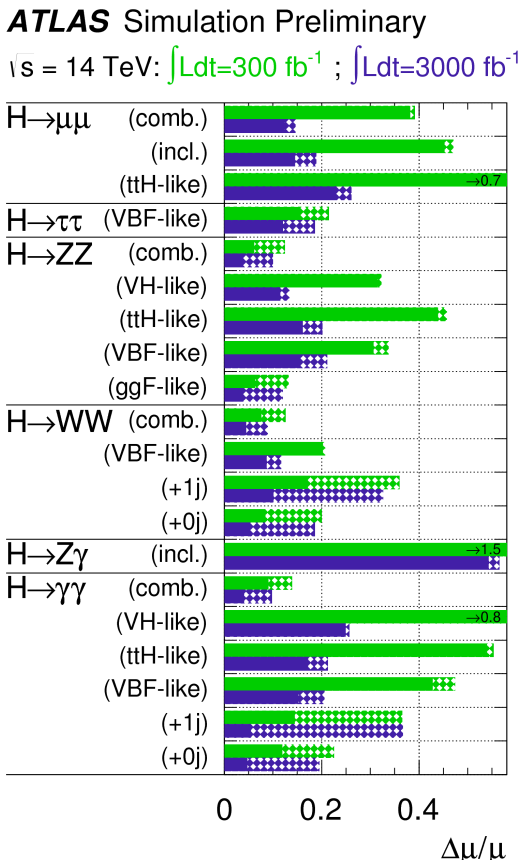
- Direct and indirect searches

Spin and CP properties

- Possible CP mixing contributions

Higgs signal strength: $\mu=\sigma/\sigma_{SM}$

ATLAS:



$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H\to\mu\mu$ (comb.)	0.39	0.38	0.15	0.12
(incl.)	0.47	0.45	0.19	0.15
(ttH-like)	0.73	0.72	0.26	0.23
$H\to\tau\tau$ (VBF-like)	0.22	0.16	0.19	0.12
$H\to ZZ$ (comb.)	0.12	0.06	0.10	0.04
(VH-like)	0.32	0.31	0.13	0.12
(ttH-like)	0.46	0.44	0.20	0.16
(VBF-like)	0.34	0.31	0.21	0.16
(ggF-like)	0.13	0.06	0.12	0.04
$H\to WW$ (comb.)	0.13	0.08	0.09	0.05
(VBF-like)	0.21	0.20	0.12	0.09
(+1j)	0.36	0.17	0.33	0.10
(+0j)	0.20	0.08	0.19	0.05
$H\to Z\gamma$ (incl.)	1.47	1.45	0.57	0.54
$H\to\gamma\gamma$ (comb.)	0.14	0.09	0.10	0.04
(VH-like)	0.77	0.77	0.26	0.25
(ttH-like)	0.55	0.54	0.21	0.17
(VBF-like)	0.47	0.43	0.21	0.15
(+1j)	0.37	0.14	0.37	0.05
(+0j)	0.22	0.12	0.20	0.05

ATLAS vs **CMS**

$\int\mathcal{L}dt$ (fb^{-1})	Higgs decay final state							
	$\gamma\gamma$	WW^*	ZZ^*	$b\bar{b}$	$\tau\tau$	$\mu\mu$	$Z\gamma$	BR$_{inv}$
ATLAS								
300	9 – 14%	8 – 13%	6 – 12%	N/A	16 – 22%	38 – 39%	145 – 147%	$<$ 23 – 32%
3000	4 – 10%	5 – 9%	4 – 10%	N/A	12 – 19%	12 – 15%	54 – 57%	$<$ 8 – 16%
CMS								
300	6 – 12%	6 – 11%	7 – 11%	11 – 14%	8 – 14%	40 – 42%	62 – 62%	$<$ 17 – 28%
3000	4 – 8%	4 – 7%	4 – 7%	5 – 7%	5 – 8%	14 – 20%	20 – 24%	$<$ 6 – 17%

Theoretical uncertainties

√s =14 TeV

LHC Higgs cross section working group

Uncertainty on cross section

Process	Cross section (pb)	Relative uncertainty in percent: Total	Scale	PDF
Gluon fusion	49.3	$^{+19.6}_{-14.6}$	$^{+12.2}_{-8.4}$	$^{+7.4}_{-6.2}$
VBF	4.15	$^{+2.8}_{-3.0}$	$^{+0.7}_{-0.4}$	$^{+2.1}_{-2.6}$
WH	1.474	$^{+4.1}_{-4.4}$	$^{+0.3}_{-0.6}$	$^{+3.8}_{-3.8}$
ZH	0.863	$^{+6.4}_{-5.5}$	$^{+2.7}_{-1.8}$	$^{+3.7}_{-3.7}$

Uncertainty on partial width

Channel	$\Delta\alpha_s$	Δm_b	Δm_c	Theory Uncertainty	Total Uncertainty
$H \to \gamma\gamma$	0%	0%	0%	±1%	±1%
$H \to b\bar{b}$	∓2.3%	$^{+3.3\%}_{-3.2\%}$	0%	±2%	±6%
$H \to c\bar{c}$	$^{-7.1\%}_{+7.0\%}$	∓0.1%	$^{+6.2\%}_{-6.1\%}$	±2%	±11%
$H \to gg$	$^{+4.2\%}_{-4.1\%}$	∓0.1%	0%	±3%	±7%
$H \to \tau^+\tau^-$	0%	0%	0%	±2%	±2%
$H \to WW^*$	0%	0%	0%	±0.5%	±0.5%
$H \to ZZ^*$	0%	0%	0%	±0.5%	±0.5%

arXiv:1310.8361, Snowmass

Higgs couplings scale factors

CMS

$L(fb^{-1})$	Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$
300	ATLAS	[8,13]	[6, 8]	[7, 8]	[8, 11]	N/a	[20, 22]	[13, 18]	[78, 79]	[21, 23]
	CMS	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]
3000	ATLAS	[5, 9]	[4, 6]	[4, 6]	[5, 7]	N/a	[8, 10]	[10, 15]	[29, 30]	[8, 11]
	CMS	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]

ATLAS:

Nr.	Coupling	$300\ fb^{-1}$ Theory unc.: All	Half	None	$3000\ fb^{-1}$ Theory unc.: All	Half	None
1	κ	3.2%	2.7%	2.5%	2.5%	1.9%	1.6%
2	$\kappa_V = \kappa_Z = \kappa_W$	3.3%	2.8%	2.7%	2.6%	1.9%	1.7%
	$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$	8.6%	7.5%	7.1%	4.1%	3.5%	3.2%
3	κ_Z	8.4%	7.3%	6.8%	6.3%	5.0%	4.6%
	κ_W	8.0%	6.7%	6.2%	6.1%	4.8%	4.3%
	κ_t	11%	9.0%	8.3%	7.0%	5.6%	5.1%
	$\kappa_{d3} = \kappa_\tau = \kappa_b$	18%	14%	13%	14%	11%	10%
	κ_μ	22%	20%	20%	10%	8.1%	7.5%
4	κ_Z	8.0%	7.0%	6.6%	5.2%	4.3%	4.0%
	κ_W	7.7%	6.8%	6.5%	4.9%	4.2%	3.9%
	κ_t	19%	18%	18%	7.7%	6.7%	6.3%
	$\kappa_d = \kappa_\tau = \kappa_\mu = \kappa_b$	16%	13%	12%	11%	8.2%	7.2%
	κ_g	8.9%	7.9%	7.5%	4.3%	3.8%	3.6%
	κ_γ	13%	9.3%	7.8%	9.3%	5.9%	4.2%
	$\kappa_{Z\gamma}$	79%	78%	78%	30%	30%	29%
5	κ_Z	8.1%	7.1%	6.7%	6.2%	4.9%	4.4%
	κ_W	7.9%	6.9%	6.5%	5.9%	4.8%	4.4%
	κ_t	22%	20%	20%	10%	8.4%	7.8%
	$\kappa_{d3} = \kappa_\tau = \kappa_b$	18%	15%	13%	15%	11%	9.7%
	κ_μ	23%	21%	21%	11%	8.5%	7.6%
	κ_g	11%	9.1%	8.5%	6.9%	5.5%	4.9%
	κ_γ	13%	9.3%	7.8%	9.4%	6.1%	4.6%
	$\kappa_{Z\gamma}$	79%	78%	78%	30%	30%	29%

Theory uncertainty not improved over today's values → pessimistic numbers

Higgs couplings scale factor ratios

CMS

L (fb^{-1})	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ / κ_Z	κ_W / κ_Z	κ_b / κ_Z	κ_τ / κ_Z	κ_Z / κ_g	κ_t / κ_g	κ_μ / κ_Z	$\kappa_{Z\gamma} / \kappa_Z$
300	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

ATLAS:

Theory uncertainty not improved over today's values → pessimistic numbers

Nr.	Coupling ratio	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
1	κ_{VV}	7.6%	7.1%	6.9%	4.1%	3.3%	3.0%
	λ_{FV}	8.5%	7.7%	7.5%	3.7%	3.2%	3.0%
2	κ_{ZZ}	10%	9.3%	8.9%	6.1%	4.7%	4.1%
	λ_{WZ}	4.7%	4.0%	3.7%	2.8%	2.0%	1.6%
	λ_{FZ}	9.4%	8.6%	8.4%	4.5%	3.9%	3.6%
3	κ_{uu}	13%	11%	10%	6.3%	5.0%	4.5%
	λ_{Vu}	10%	8.9%	8.5%	4.6%	3.8%	3.5%
	λ_{du}	11%	9.1%	8.2%	7.1%	5.6%	4.9%
4	$\kappa_{\tau\tau}$	22%	18%	16%	17%	14%	12%
	$\lambda_{V\tau}$	12%	11%	9.8%	9.3%	7.2%	6.4%
	$\lambda_{q\tau}$	12%	9.6%	8.7%	9.1%	7.0%	6.1%
	$\lambda_{\mu\tau}$	24%	22%	21%	12%	9.6%	8.8%
5	κ_{gZ}	6.4%	4.4%	3.5%	4.6%	2.9%	2.0%
	λ_{WZ}	5.1%	4.6%	4.4%	3.0%	2.3%	2.1%
	λ_{tg}	18%	18%	17%	7.0%	6.1%	5.8%
	$\lambda_{\tau Z}$	13%	11%	11%	10%	7.6%	6.6%
	$\lambda_{\mu Z}$	22%	21%	20%	9.2%	7.2%	6.3%
	λ_{gZ}	12%	11%	11%	5.9%	5.0%	4.7%
	$\lambda_{\gamma Z}$	11%	6.9%	5.1%	7.1%	3.9%	1.8%
	$\lambda_{(Z\gamma)Z}$	78%	78%	78%	30%	29%	29%
6	$\kappa_{\gamma\gamma}$	22%	16%	13%	14%	8.3%	5.4%
	$\lambda_{Z\gamma}$	11%	6.9%	5.1%	7.1%	3.9%	1.8%
	$\lambda_{W\gamma}$	11%	7.3%	5.6%	7.4%	4.2%	2.2%
	$\lambda_{t\gamma}$	27%	23%	21%	14%	9.7%	7.7%
	$\lambda_{\tau\gamma}$	15%	12%	11%	10%	7.7%	6.7%
	$\lambda_{\mu\gamma}$	21%	20%	20%	7.2%	6.6%	6.3%
	$\lambda_{g\gamma}$	18%	13%	11%	11%	6.8%	5.0%
	$\lambda_{(Z\gamma)\gamma}$	77%	76%	76%	29%	29%	29%

Higgs couplings vs mass

To derive the mass dependence of the Higgs boson couplings we define:

Mass-scaled coupling ratios:

$$Y_f = \kappa_f \frac{m_f}{v}$$

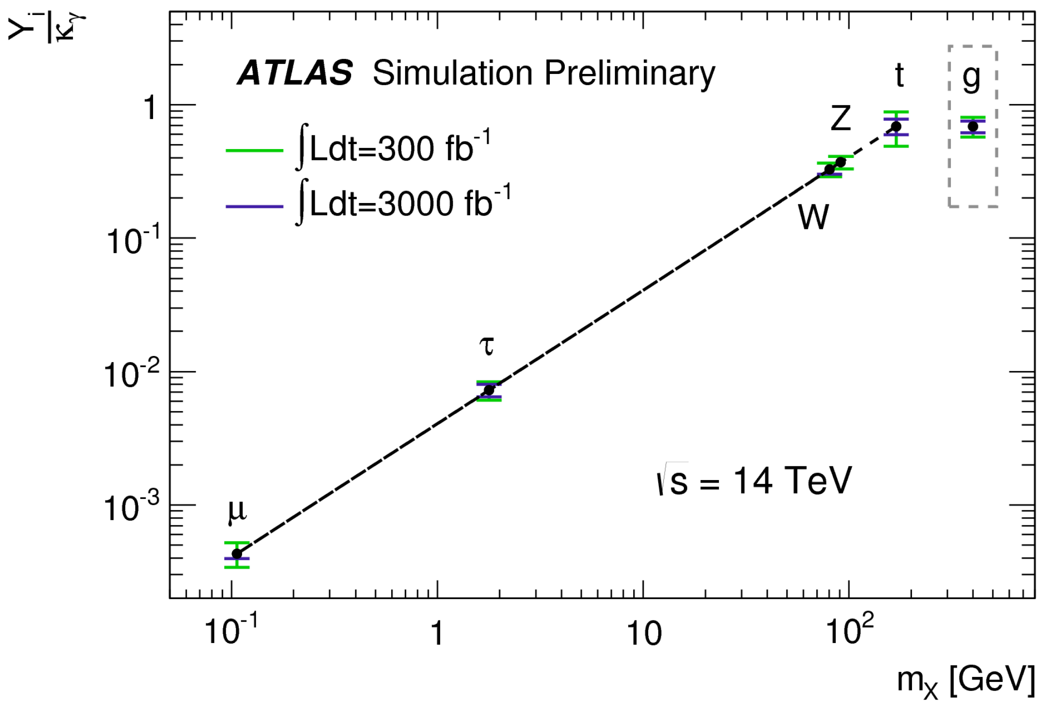
$$Y_f/\kappa_\gamma = \kappa_f/\kappa_\gamma \frac{m_f}{v}$$

for fermions

$$Y_V = \kappa_V \frac{m_V}{v}$$

$$Y_V/\kappa_\gamma = \kappa_V/\kappa_\gamma \frac{m_V}{v}$$

for bosons



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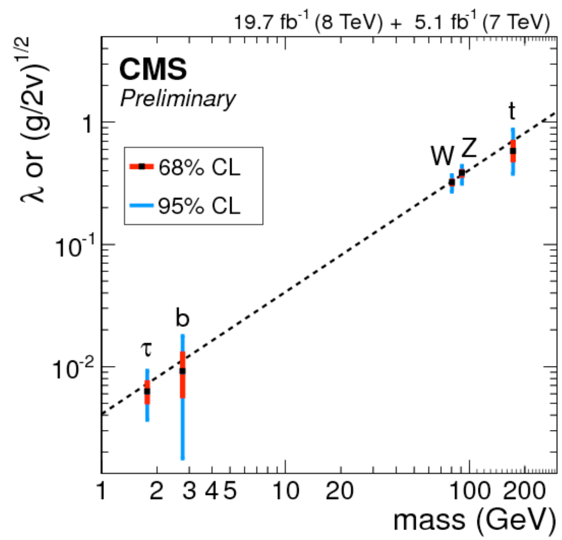
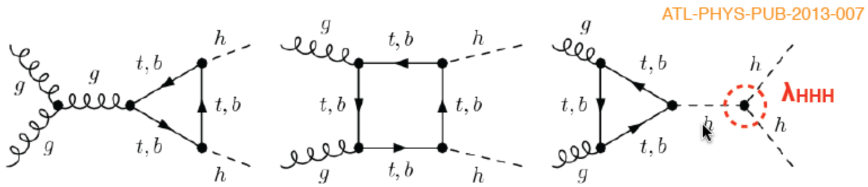


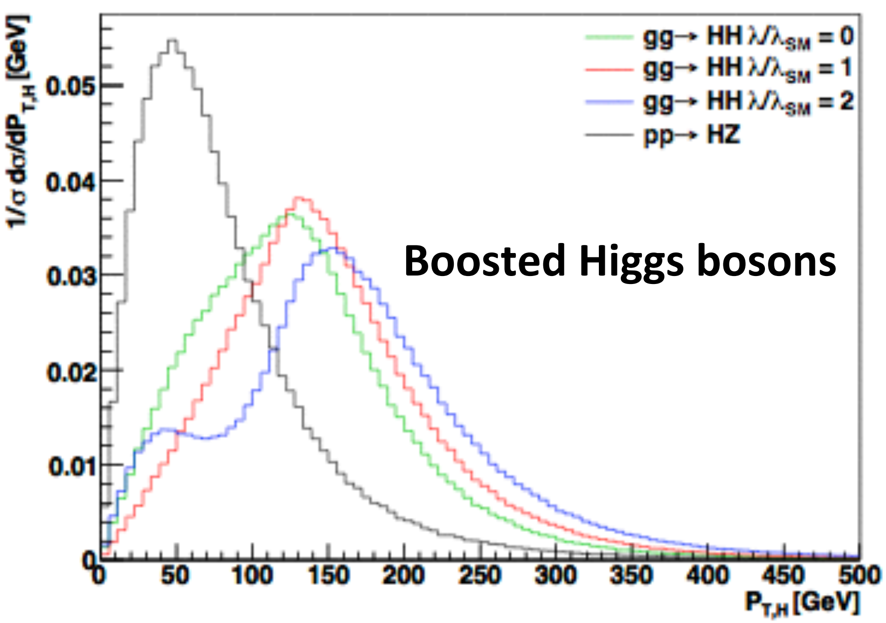
Higgs self coupling (1)



Very challenging search / meas.

Cross section at NNLO
arXiv:1309.6594

E_{cm}	8 TeV	14 TeV
$\sigma_{\rm NNLO}$	9.76 fb	40.2 fb
Scale [%]	$+9.0-9.8$	$+8.0-8.7$
PDF [%]	$+6.0-6.1$	$+4.0-4.0$
PDF+α_S [%]	$+9.3-8.8$	$+7.2-7.1$



HL-LHC required to reach SM sensitivity!

BSM increase in yields can be substantial!

Ebullient discussion of di-Higgs production by theory community!

Experimentalists very conservative

Higgs self coupling (2)

Channels and Sensitivity

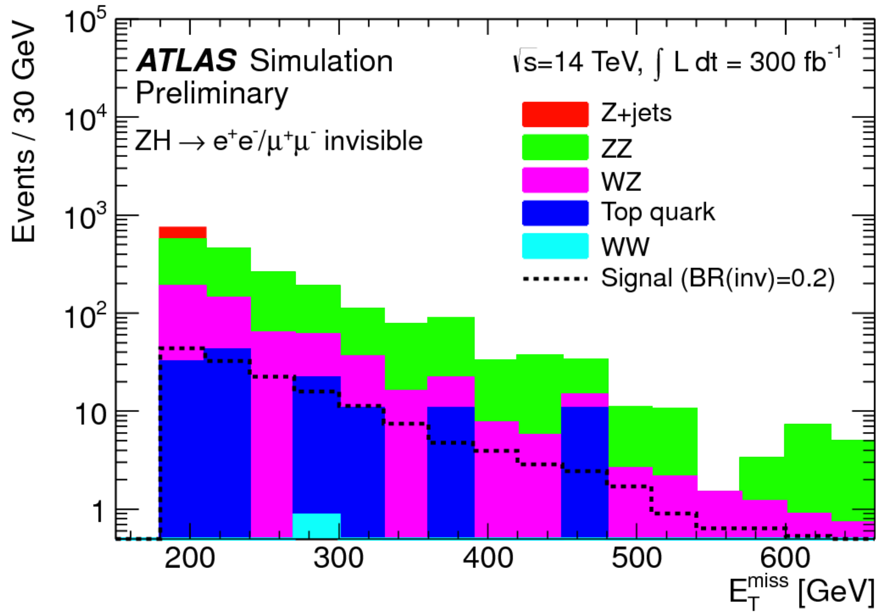
Promising final states $HH \to b\bar{b}\gamma\gamma$ $HH \to b\bar{b}\tau^+\tau^-$

- Difficulties in background estimation
- esp. fake rate or mistag estimates!
- Expected sensitivity $\frac{\delta\lambda_{HHH}}{\lambda_{HHH}} = \mathcal{O}(30\%)$
- Sensitivity enhanced using event shapes
- ATLAS & CMS are developing a program for HL-LHC di-Higgs measurements
- Lepton collider need very large datasets at high energy or extreme precision g_{ZH} measurements

Invisible Higgs decays →Dark Matter

ATLAS: L = 300 fb^{-1}

- **Indirect constraints:**
  - from Higgs coupling fit
  - BR(H→inv) < 28% @ 95% CL
- **Direct search**
  - ZH→ee/μμ+ET_{miss}
  - BR(H→inv) < 32% @ 95% CL



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Mapping & DM-types

Higgs invisible decay | **Higgs-DM coupling** | **DM-nucleon xsec**

$$\Gamma(h \to \chi\chi) \Leftrightarrow \lambda^2_{h\chi\chi} \Leftrightarrow \sigma_{N\chi}$$

$$BR(h \to \chi\chi) = \frac{\Gamma(h \to \chi\chi)}{\Gamma(h \to \chi\chi) + \Gamma(h \to SM)}$$

We consider three DM types: scalar, vector, majorana fermion

$$\Gamma^{\rm Scalar}(h \to \chi\chi) = \frac{\lambda^{2\,\rm Scalar}_{h\chi\chi} v^2}{64\pi m_h}\left[1-\left(\frac{2m_\chi}{m_h}\right)^2\right]^{1/2}$$

$$\sigma^{\rm Scalar}_{\chi N} = \frac{\lambda^{2\,\rm Scalar}_{h\chi\chi}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

$$\Gamma^{\rm Vector}(h \to \chi\chi) = \frac{\lambda^{2\,\rm Vector}_{h\chi\chi} v^2}{256\pi m_\chi^4 m_h}\left[m_h^4 - 4m_\chi^2 m_h^2 + 12 m_\chi^4\right]\left[1-\left(\frac{2m_\chi}{m_h}\right)^2\right]^{1/2}$$

$$\sigma^{\rm Vector}_{\chi N} = \frac{\lambda^{2\,\rm Vector}_{h\chi\chi}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

$$\Gamma^{\rm Majorana}(h \to \chi\chi) = \frac{\lambda^{2\,\rm Majorana}_{h\chi\chi} v^2 m_h}{32\pi\Lambda^2}\left[1-\left(\frac{2m_\chi}{m_h}\right)^2\right]^{3/2}$$

$$\sigma^{\rm Majorana}_{\chi N} = \frac{\lambda^{2\,\rm Majorana}_{h\chi\chi}}{4\pi\Lambda^2 m_h^4}\frac{m_\chi^2 m_N^4 f_N^2}{(m_\chi + m_N)^2}$$