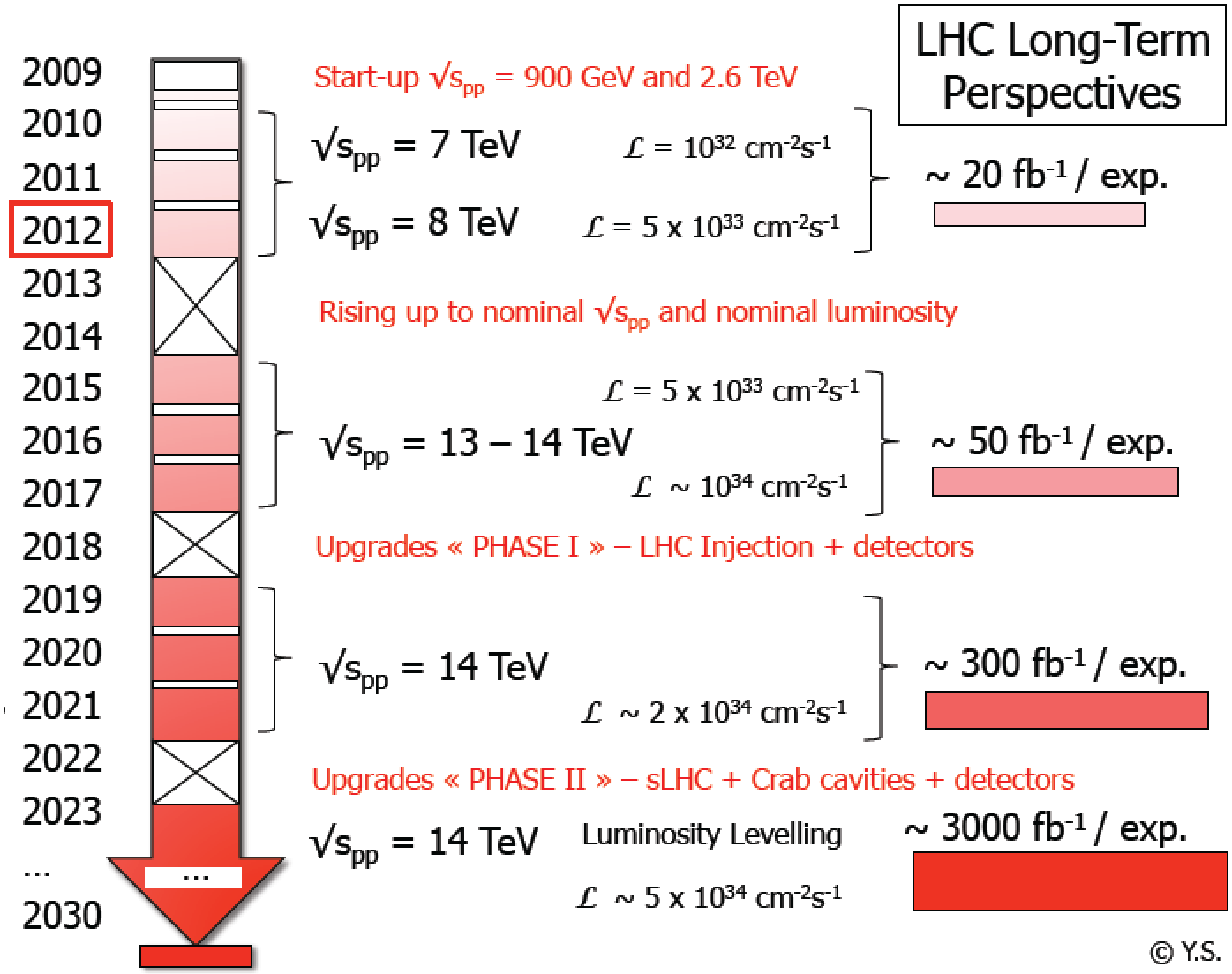
Perspectives de physique au LHC

~2022: 14 TeV 300 fb-1
~2030: 14 TeV 3000 fb-1

Basé essentiellement sur des études d'un groupe de travail ATLAS


LHC Long-Term Perspectives
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
...
2030
Start-up $\sqrt{s_{pp}}$ = 900 GeV and 2.6 TeV
$\sqrt{s_{pp}}$ = 7 TeV
$\mathcal{L} = 10^{32}$ cm^{-2}s^{-1}
$\sqrt{s_{pp}}$ = 8 TeV
$\mathcal{L} = 5 \times 10^{33}$ cm^{-2}s^{-1}
~ 20 fb^{-1} / exp.
Rising up to nominal $\sqrt{s_{pp}}$ and nominal luminosity
$\mathcal{L} = 5 \times 10^{33}$ cm^{-2}s^{-1}
$\sqrt{s_{pp}}$ = 13 – 14 TeV
$\mathcal{L} \sim 10^{34}$ cm^{-2}s^{-1}
~ 50 fb^{-1} / exp.
Upgrades « PHASE I » – LHC Injection + detectors
$\sqrt{s_{pp}}$ = 14 TeV
$\mathcal{L} \sim 2 \times 10^{34}$ cm^{-2}s^{-1}
~ 300 fb^{-1} / exp.
Upgrades « PHASE II » – sLHC + Crab cavities + detectors
$\sqrt{s_{pp}}$ = 14 TeV
Luminosity Levelling
$\mathcal{L} \sim 5 \times 10^{34}$ cm^{-2}s^{-1}
~ 3000 fb^{-1} / exp.
© Y.S.

First ATLAS and CMS studies in 2002 on PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE : F.Gianotti & al, hep-ph/0204087

Topics for 2012 studies for Cracow symposium:

- Higgs (coupling, self-coupling, Spin/CP)
- Vector-boson scattering
- SUSY (mass reach, weak production,3rd generation)
- Exotics (Z', tt-resonances)
- Some prospects with the HE-LHC

2012 strategy for simulation studies with the HL-LHC conditions:

- No time for detailed full simulation of physics processes, as well as full event reconstruction (except for a few studies like WW scattering).
- The approach adopted is based on studies performed using MC truth, applying where simple smearing functions to physics objects, efficiency factors accounting for offline and trigger selection, etc.
- Accounts for changes in key upgraded detector performances aspects under HL-LHC conditions (in particular, jets and MET).

Higgs couplings: present results

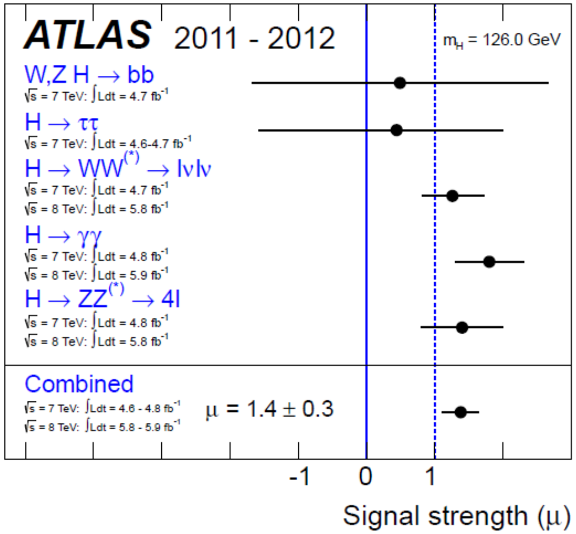
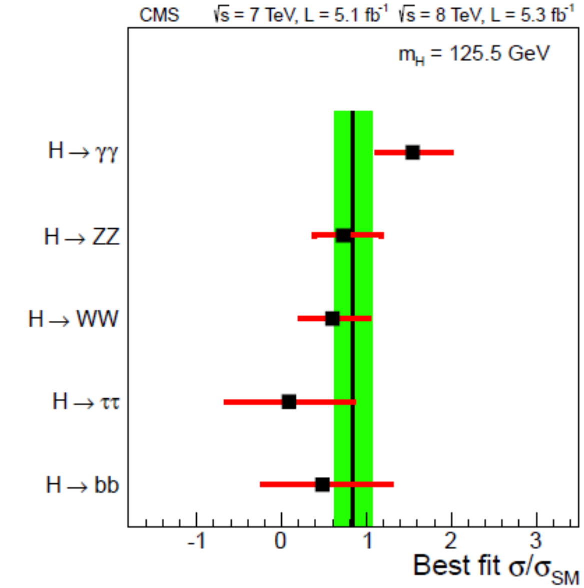


Figure 10: Measurements of the signal strength parameter μ for m_H=126 GeV for the individual channels and their combination.



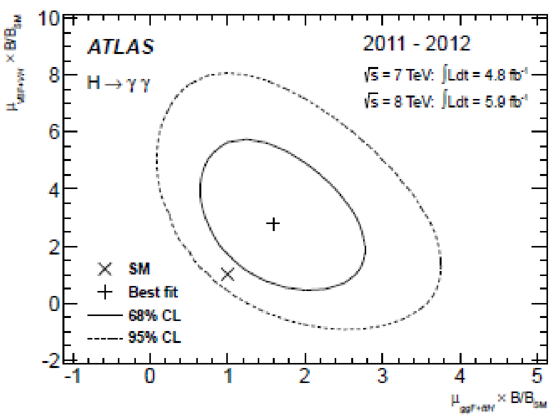
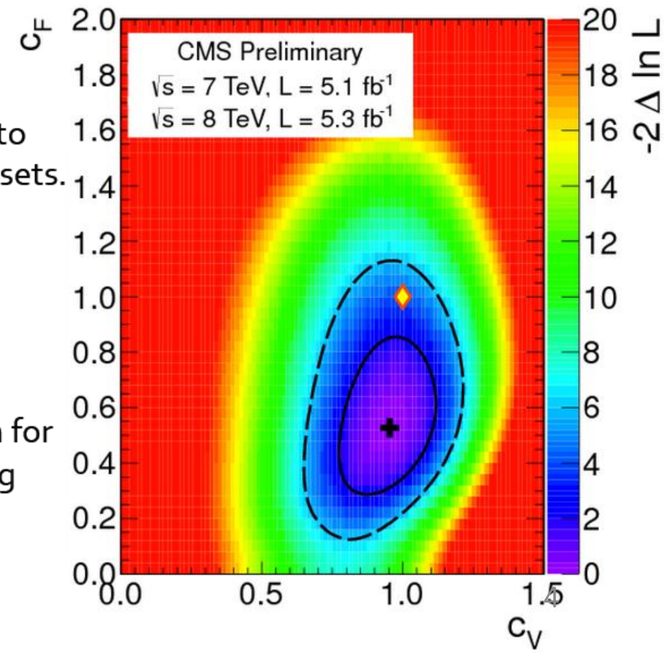


Figure 12: Likelihood contours for the $H \to \gamma\gamma$ channel in the $(\mu_{ggF+t\bar{t}H}, \mu_{VBF+VH})$ plane including the branching ratio factor B/B_{SM}. The quantity $\mu_{ggF+t\bar{t}H}$ (μ_{VBF+VH}) is a common scale factor for the ggF and $t\bar{t}H$ (VBF and VH) production cross sections. The best fit to the data (+) and 68% (full) and 95% (dashed) CL contours are also indicated, as well as the SM expectation (×).

Group the Higgs couplings into "Vectorial" and "Fermionic" sets.

Attach a modifier to the SM prediction
to each of those (C_V and C_F).

Use LO theoretical prediction for loop-induced $H \to \gamma\gamma$, $H \to gg$ couplings.



Measurement of the Higgs spin/CP nature

- Observation in the $\gamma\gamma$ final state -> boson of spin 0 or 2
- Cleanest channel for Spin/CP measurement: H-->ZZ(*)-->4l
- If the new boson is assumed to be a pure state, its spin/CP quantum numbers can be measured to some extent already with the 30 fb^{-1} that should be collected during the present 8 TeV running phase of the LHC.

Tested signal hypothesis (columns); Alternative signal hypothesis (rows)

	0+	0-	1+	1-	2+	2-
0+		2.81	2.15	3.06	1.7	2.45
0-	**3.16**		2.64	3.72	2.82	2.58
1+	**2.15**	2.57		2.54	2.36	2.22
1-	**3.37**	3.67	2.73		3.27	2.89
2+	**1.71**	2.56	2.22	3.77		2.45
2-	**2.54**	2.49	2.19	2.94	2.63	

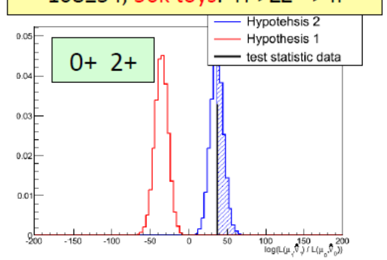
m_H = 126GeV

8 TeV; L = 30 fb^{-1}; S = 24; B = 5.4±2.7; 50k toys.

- Study of the H -> ZZ-> 4l decay can exclude 0^- and 2^- CP states with more than 2σ
- A combination with H -> WW and H ->$\gamma\gamma$ channels will provide a better separation between spin 0+ and spin 2+ hypotheses.

With 300 fb^{-1} at 14 TeV, the spin/CP quantum numbers can be established with a significance of more than 5σ.

14 TeV; L = 300 fb^{-1}; S = 480; B = 108±54; 50k toys. H->ZZ*->4l

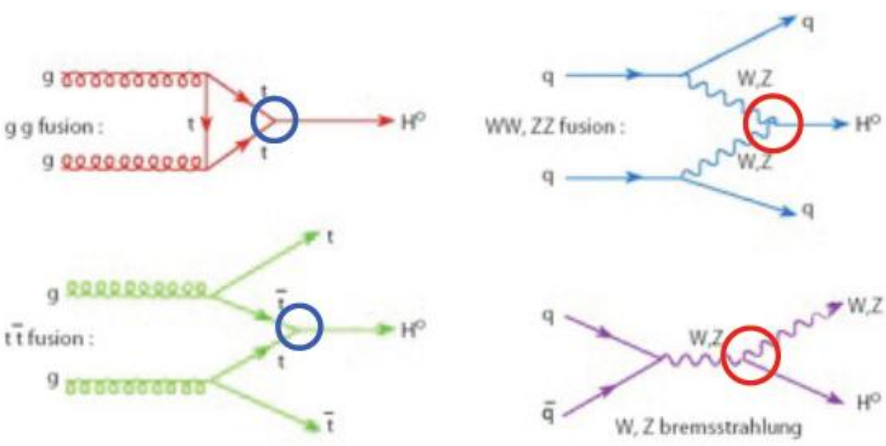


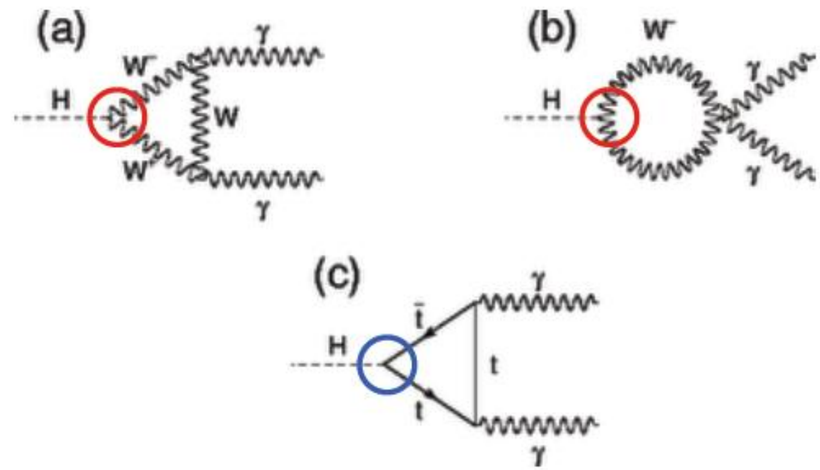
Higgs couplings

Each measurements brings information on :

- The production mode : gg Fusion, VBF, ttbar-H, WH, ZH
- The decay mode: H-> $\gamma\gamma$, WW, ZZ, bbar, τ^{+}-τ^{-}, $\mu\mu$, etc

We have to move from combination of cross sections and branching ratios measurements to couplings determination.





Difficulty:

In the SM, once the Higgs mass is specified, all the couplings of the Higgs to bosons, fermions and to itself are specified within the model. It is therefore not theoretically correct to perform a fit to experimental data within the context of the SM where Higgs couplings are treated as free parameters (problems occurring in NLO loop effects).

Simplification ansatz for introducing deviation from SM Higgs coupling values:
In order to use the currently best available SM predictions for Higgs cross sections (including higher-order QCD and EW corrections), the predicted SM Higgs cross sections and partial decay widths are dressed with scale factors κ_i for the coupling H to particle i:

e.g. for H->γγ in gg-Fusion mode: $(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$

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

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

Total cross section not measured at LHC=> need to make assumptions on undetected final states and on invisible decays to measure the total width Γ_H

Higgs couplings: Studies outside the experiments

arXiv:1205.2699v2

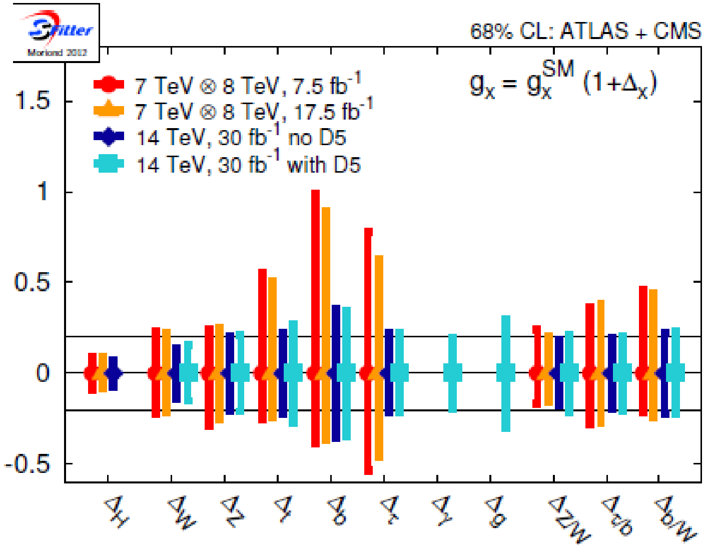
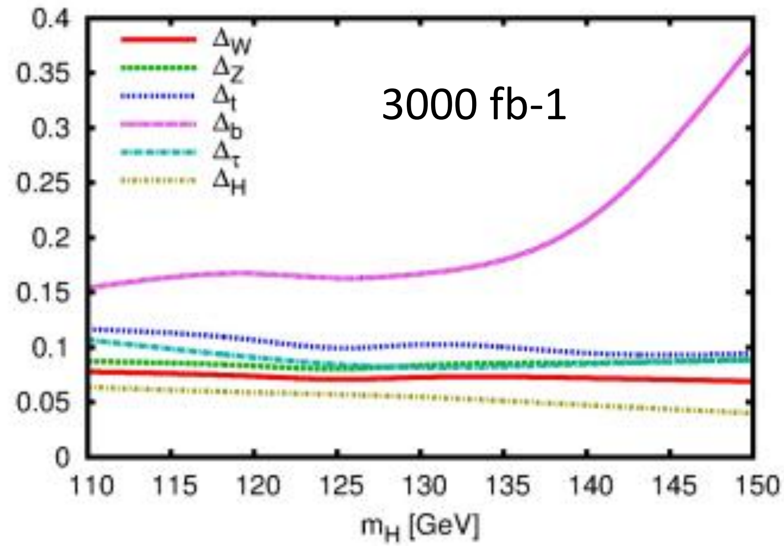
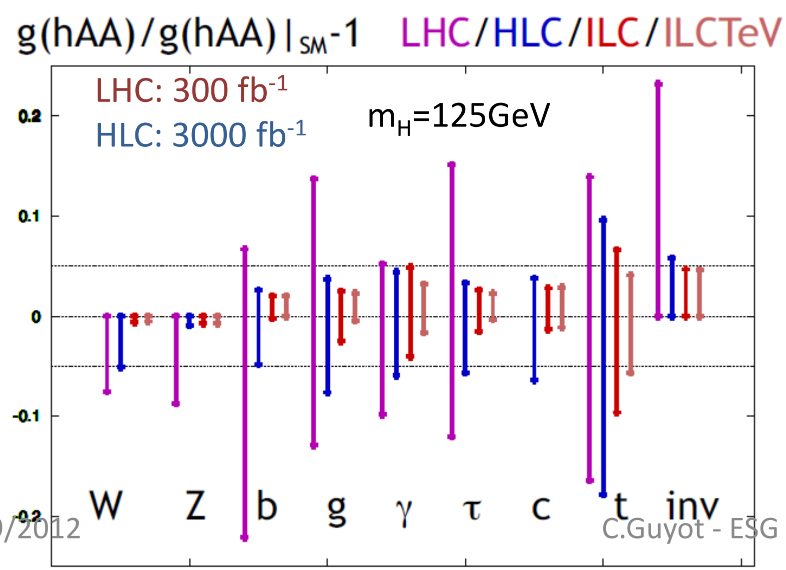


Figure 3: Projections for an assumed SM signal at $m_H = 125$ GeV. The band indicates a ±20% variation.

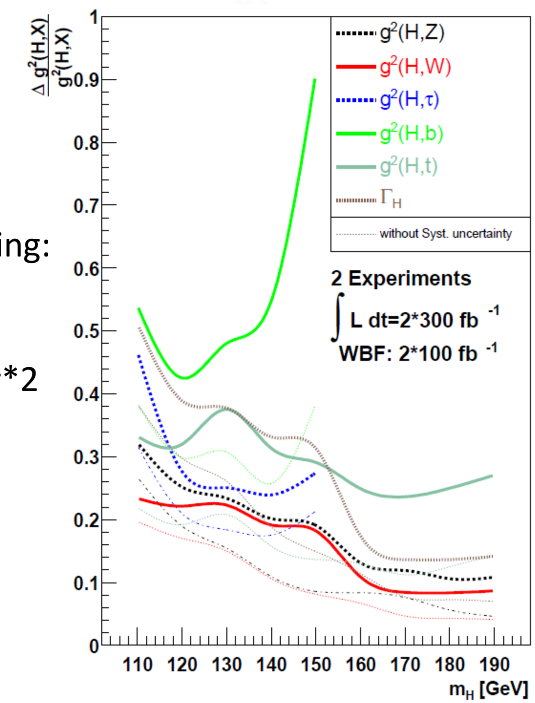


Dirk Zerwas IPNO 2012

M. E. Peskin, arXiv:1207.2516



Warning: g^2 => Error*2



M. Duhrssen et. al. [hep-ph/0406323]

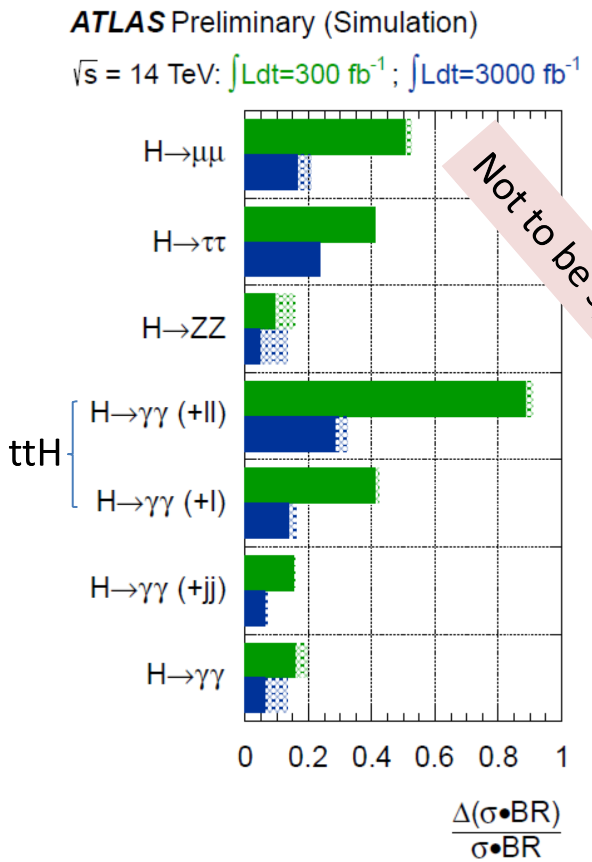
Higgs couplings: preliminary ATLAS studies

Left: Expected measurement precision on the signal strength in all considered channels for luminosities of 300 fb-1 and 3000 fb-1.

Right: Expected measurement precisions on ratios of Higgs boson partial widths without theory assumptions on the particle content in Higgs loops (ggH and H->γγ) or the total width.

$$\sigma \times BR(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

The dashed areas include current theory uncertainties from scale and PDF variations.



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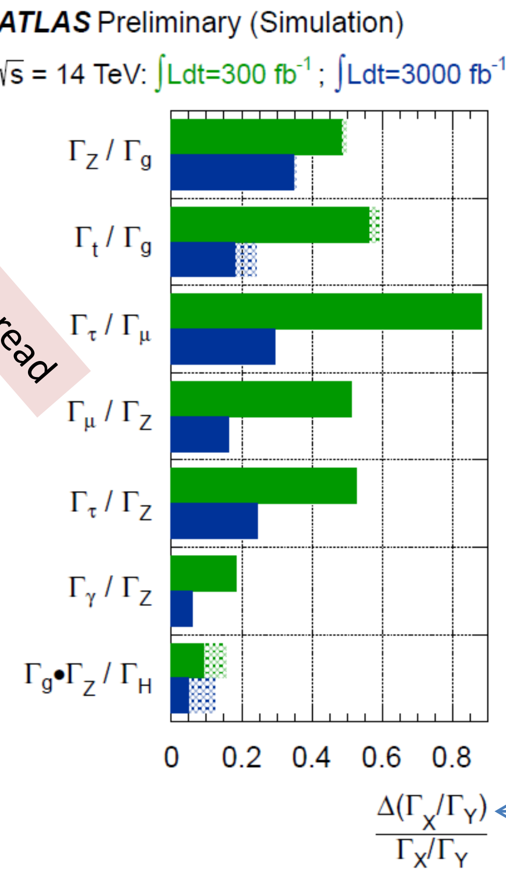

m_H= 126GeV

No result yet on the b-bar final state as jet energy resolution and b-tagging efficiency with the upgraded detector need more careful studies

Corresponds to the square of the scale factor => error*2

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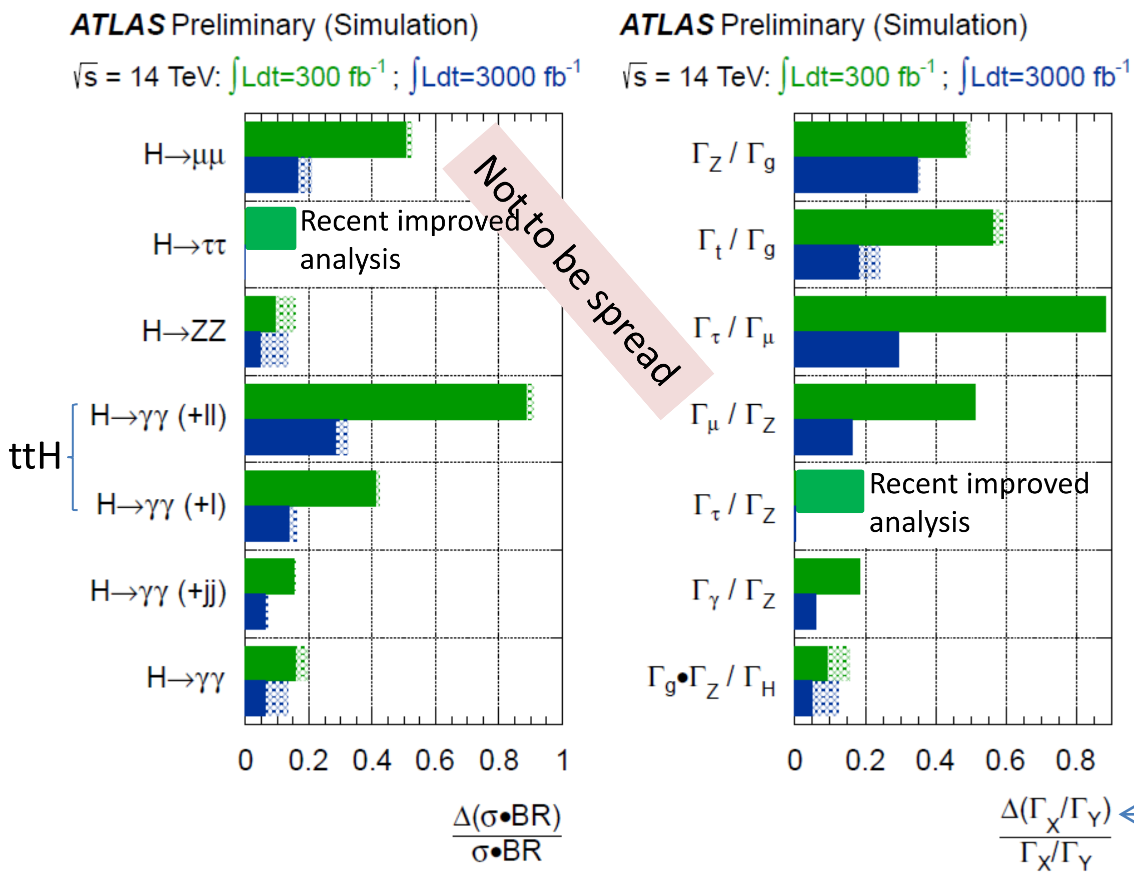

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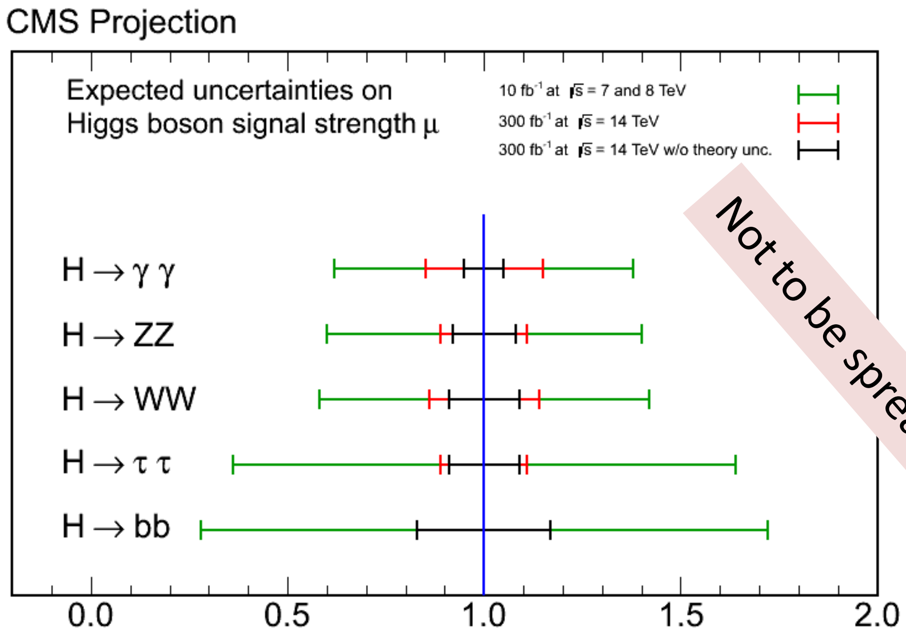
Corresponds to the square of the scale factor => error*2

Higgs couplings: preliminary CMS studies

Estimated precision of the signal strength for a SM-like Higgs boson.. They are shown including or neglecting the systematic errors from theory.

Estimated precision on the measurement of Cγ, Cv, Cg, Cq, and Cl



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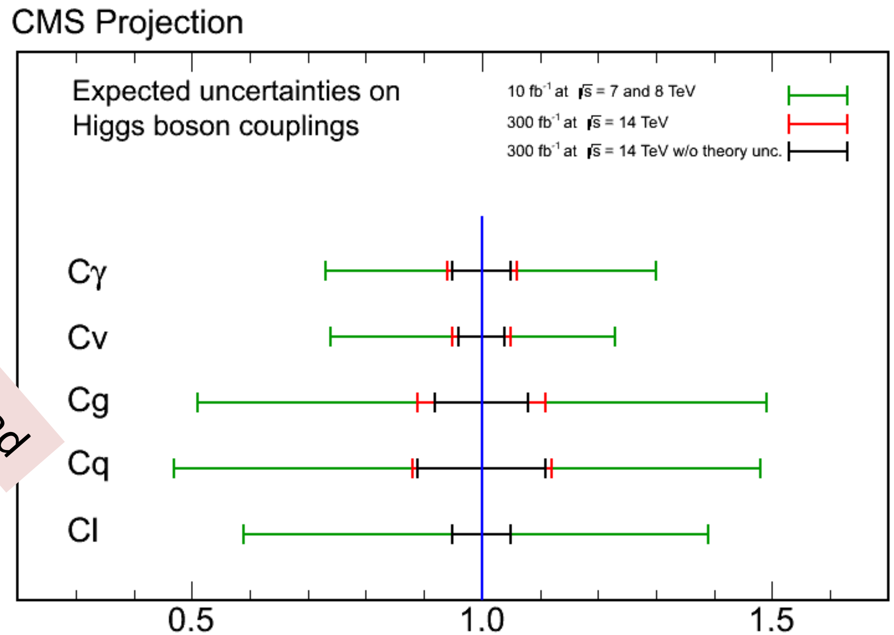


Higgs couplings: comments/conclusions

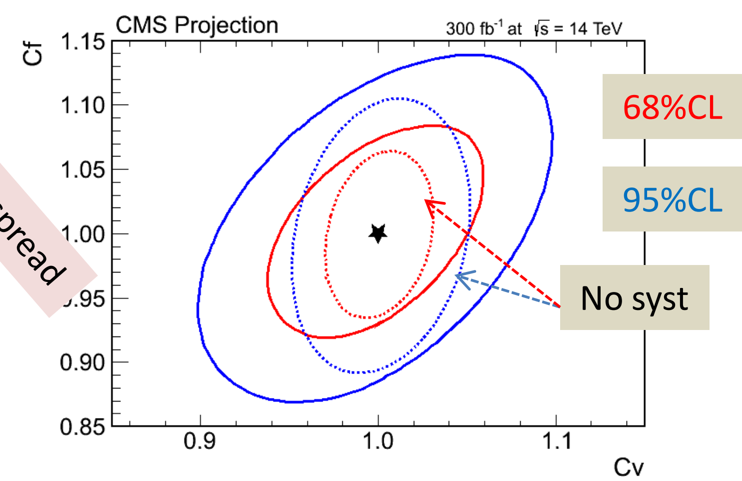
Experiments studies more pessimistic/conservative (in particular ATLAS) than ”independent” analyses. Experimental difficulties at HL-LHC (pile-up, trigger, jet physics, b-tagging, MET) will be significant and are not yet properly estimated (full-sim studies still missing for the 3000fb^{-1} studies)

Some agreement between ATLAS and CMS on the minimal coupling fit with only two independent scale factors for vectors and fermions. No additional BSM contributions allowed.

ATLAS projection:

Scale factor	14 TeV, 300 fb^{-1}		14 TeV, 3000 fb^{-1}	
C_V	+0.062	-0.057	+0.044	-0.042
C_F	+0.124	-0.109	+0.074	-0.069
C_V (w/o theory)	+0.037	-0.036	+0.022	-0.021
C_F (w/o theory)	+0.086	-0.079	+0.033	-0.032

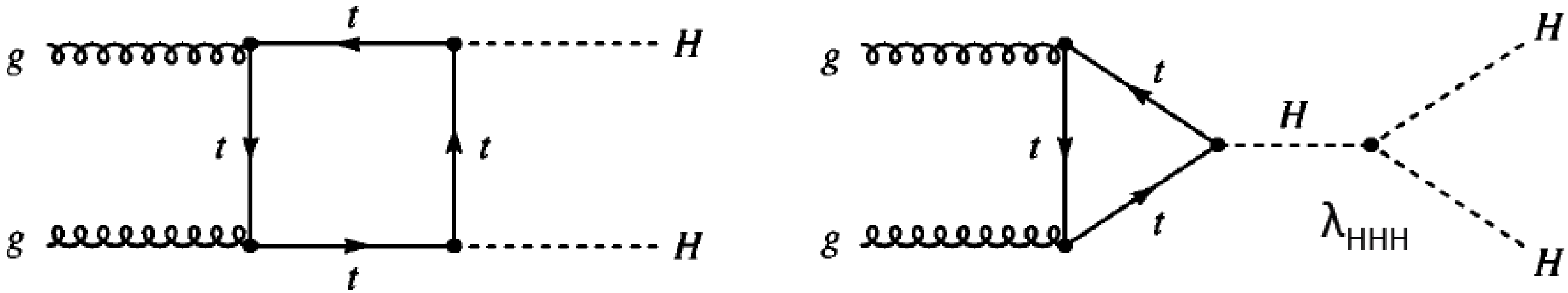
Not to be spread



Theoritical errors are significant and become almost the limiting contribution for several channels above 300fb-1

Higgs self couplings

Higgs pair production sensitive to the tri-linear self-coupling λ_{HHH}



	σ(fb)
$\lambda_{HHH}=0\cdot\lambda_{HHH}^{SM}$	71.0
$\lambda_{HHH}=1\cdot\lambda_{HHH}^{SM}$	33.9
$\lambda_{HHH}=2\cdot\lambda_{HHH}^{SM}$	15.9

(HPAIR, gg→HH at NLO)

	BR (%)	Number of events @3 ab^{-1} (14 TeV)
$b\bar{b}W^+W^-$	25.0	25,000
$b\bar{b}\tau^+\tau^-$	7.4	7,200
$b\bar{b}\gamma\gamma$	0.26	260

HH -> bbWW has the same final state as ttbar production => huge background (S/B ~ 10^{-5})

Analysis cuts reduce the background by only 2 orders of magnitude -> no hope

Higgs tri-linear self-coupling

HH → b b̄ γγ

<u>Event selection</u>

- 2 isolated photons with p_T^{γ}>25 GeV
- $p_T^{jet} > 40/25$ GeV (2 b-tagged jets)
- Angular cuts on b-b, γ-γ, γ-b systems
- $120 < m_{\gamma\gamma} < 130$ GeV, $50 < m_{b\bar{b}} < 130$ GeV
- Veto on isolated lepton and require N_{jet}<5

Process	σ·BR (fb)	Event yield @ 14 TeV, 3 ab^{-1}
$H(\to b\bar{b})H(\to \gamma\gamma)$	0.087	12.3
λ = 0		17.8
λ = 2		5.8
$t\bar{t}H(\to \gamma\gamma)$	1.71	18
$b\bar{b}\gamma\gamma$	111	negligible
$b\bar{b}H(\to \gamma\gamma)$	0.124	negligible

First evidence for double Higgs production can be obtained (S/B =0.7, s/√B = 2.8)
But weak discrimination between the λ=0 and λ=1 cases.

HH → bbττ: Under investigation in ATLAS

- Promising results from ref arXiv:1206.5001 (M.J. Dolan &al, Durham group)
- Based on boosted Higgs pair searches and application of jet substructure techniques on fat jets

	$\xi = 0$	$\xi = 1$	$\xi = 2$	$b\bar{b}\tau\tau$	$b\bar{b}\tau\tau$ [ELW]	$b\bar{b}W^+W^-$
cross section before cuts (fb)	59.48	28.34	13.36	67.48	8.73	873000
reconstructed Higgs from τs	4.05	1.94	0.91	2.51	1.10	1507.99
fatjet cuts	2.27	1.09	0.65	1.29	0.84	223.21
kinematic Higgs reconstruction ($m_{b\bar{b}}$)	0.41	0.26	0.15	0.104	0.047	9.50
Higgs with double b-tag	0.148	0.095	0.053	0.028	0.020	0.15

For 3000 fb^{-1}:
~300 (450) signal events for λ=1 (0) with a background of ~600 evts (discrimination λ=1 vs 0 ~ 5σ_{stat}!)
Exprimental aspects may be largely underestimated.

WW boson scattering (ATLAS studies)

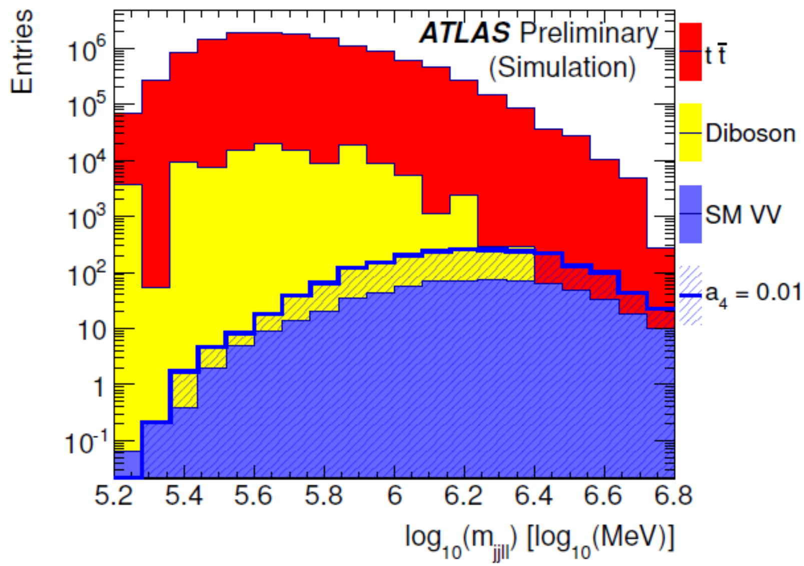
Interest: confirmation that the existence of a Higgs at ~125Gev ensure that unitarity of scattering amplitudes in longitudinal vector boson scattering is maintained at high energy. In alternate models (technicolor like, Little Higgs…), TeV scale resonances can occur which could enhance WW scattering at high energy.

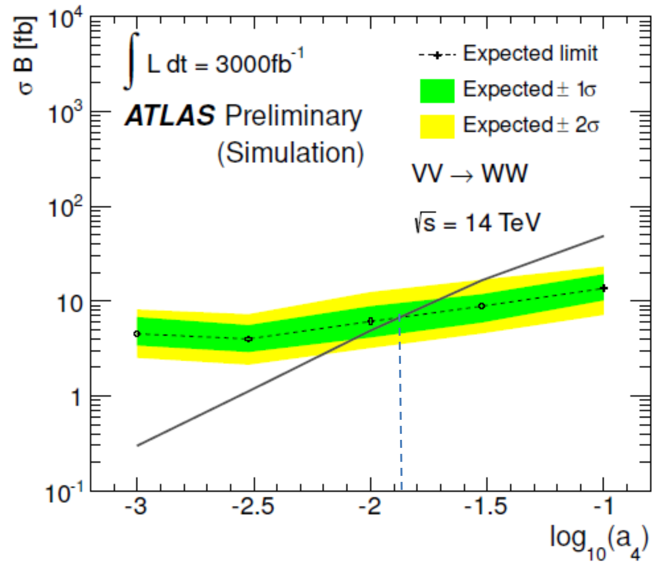
Reference model: PYTHIA implementation of the electroweak chiral Lagrangian with unitarised amplitudes for WW scattering. Non SM effects are parametrized by two coefficients a_4 and a_5 which quantify the importance of extra-SM operators.

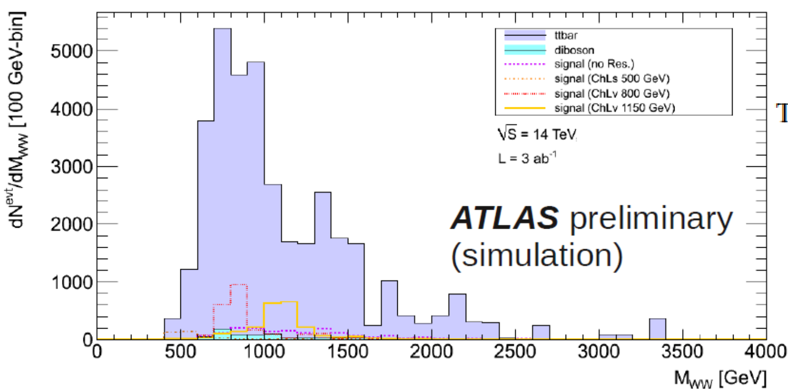
Experimentally: presence of 2 high pT jets in the forward region (as VBF) + rapidity gaps (but difficult to exploit with the pile-up)
Simulation studies:
pp → WW+2j → lν + 4j, used for resonance searches
pp → WW + 2j →e$\nu\mu\nu$+2j : less background, used for enhancement measurement (a_4)
Background: ttbar, W+jets, dibosons

WW boson scattering (ATLAS studies)

pp → WW + 2j → eνμν+2j







pp → WW+2j → lν + 4j

Table 2: Summary of sensitivity to various resonance hypotheses in the semi-leptonic WW channel.

model	baseline	500 GeV scalar	800 GeV vector	1150 GeVvector
(a_4, a_5)	$(0, 0)$	$(0.01, 0.009)$	$(0.009, -0.007)$	$(0.004, -0.004)$
S/B	$(3.3 \pm 0.3)\%$	$(0.7 \pm 0.1)\%$	$(4.9 \pm 0.3)\%$	$(5.8 \pm 0.3)\%$
$S/\sqrt{B}$ $(L = 300\text{fb}^{-1})$	2.3 ± 0.3	0.6 ± 0.1	3.3 ± 0.4	3.9 ± 0.4
$S/\sqrt{B}$ $(L = 3000\text{ fb}^{-1})$	7.2 ± 0.1	1.6 ± 0.1	10.4 ± 0.7	12.4 ± 0.7

Discovery reach (>5σ) obtained for 3000fb^{-1}

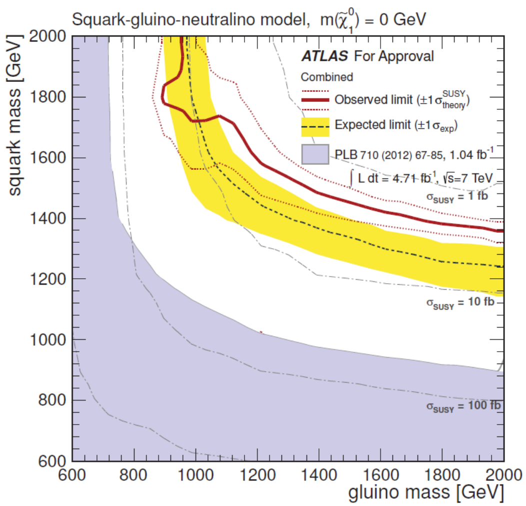
Supersymmetry searches and measurements

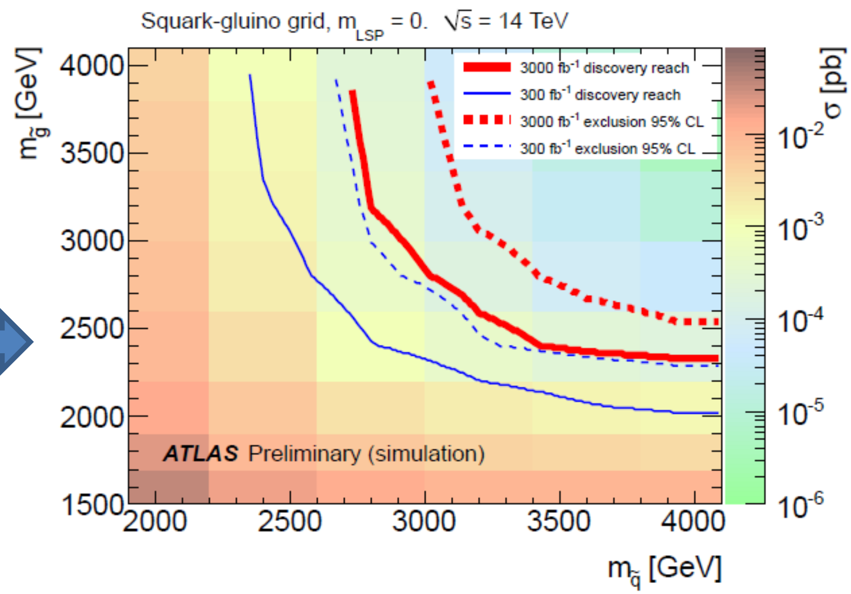
ATLAS

squark (first two generations) and gluino searches:

Simplified squark–gluino model with massless neutralino

Present limits

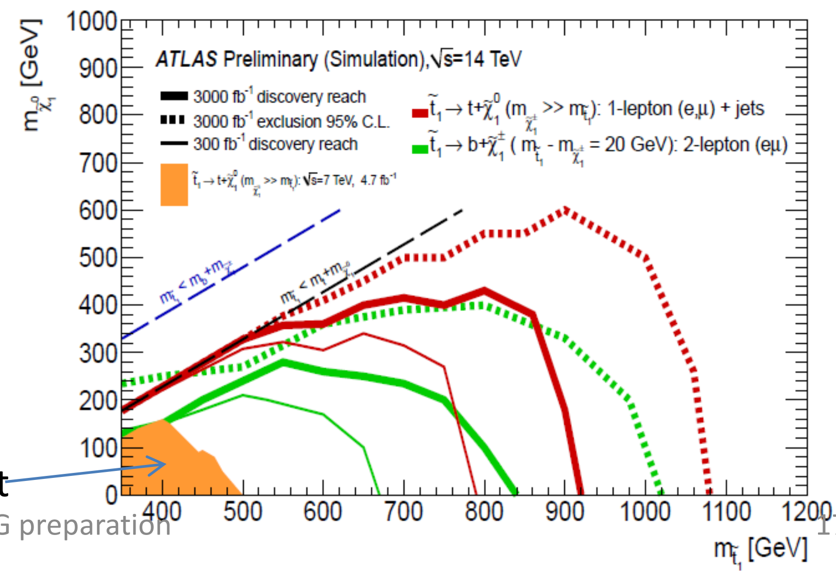




Third generation searches :

Naturalness arguments requires a light stop (<1TeV).

Evidence for new particles found with 300fb^{-1} would be followed by a detailed study (spin, mass, couplings) with 3000fb^{-1}



Present limit

Exotics

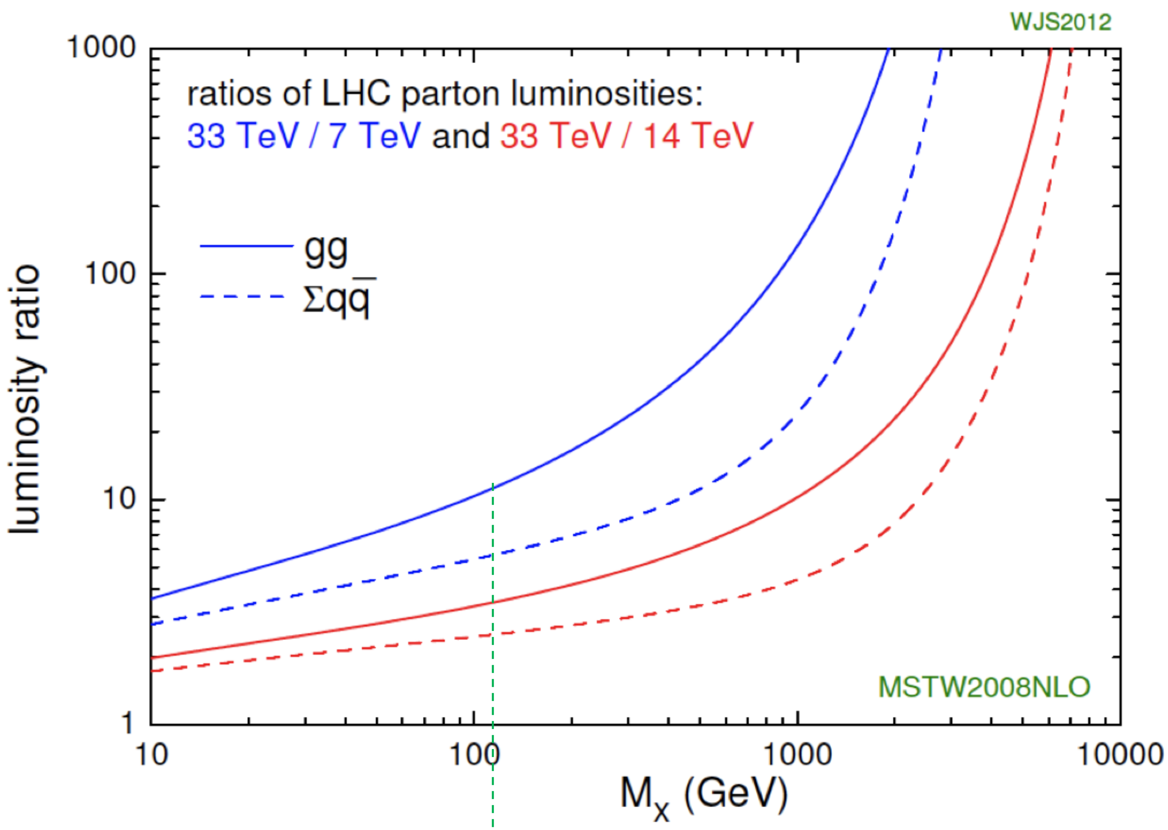
Benchmarks channels: ttbar and dilepton resonances

pp → g_{KK} (Kaluza-Kein gluon) → $t\bar{t}$
pp→ $Z'_{topcolor}$ → $t\bar{t}$
pp → Z'_{SSM} → ll

ATLAS

model	$300\ fb^{-1}$	$1000\ fb^{-1}$	$3000\ fb^{-1}$	Present limit
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)	~1.5 TeV
$Z'_{\mathrm{Topcolour}}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)	
$Z'_{SSM} \rightarrow ee$	6.5	7.2	7.8	~2.5 TeV
$Z'_{SSM} \rightarrow \mu\mu$	6.4	7.1	7.6	

Physics prospects at a High Energy LHC (33TeV, $300fb^{-1}$)

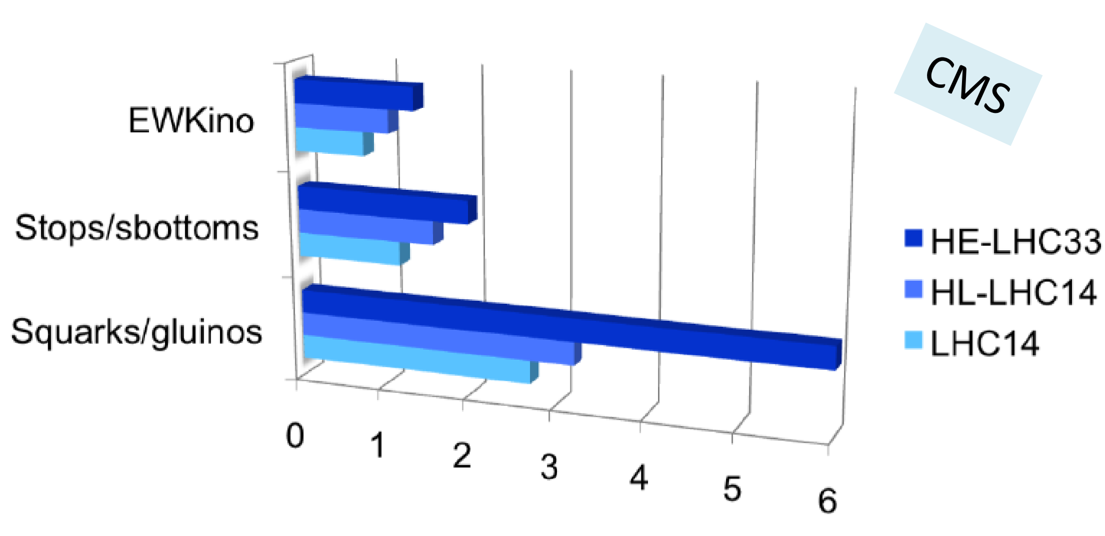


m_H=125 GeV: production cross section factor 2 to 3 w.r.t. 14 TeV
HH prod enhanced by factor 3 to 4

Main interest of HE-LHC: high mass/energy frontier above 1 TeV (to balance favorably a factor 10 loss in integrated luminosity).

Physics prospects at a High Energy LHC (33TeV, 300fb^{-1})

Supersymmetry:



Exotic resonances:

ATLAS

model	$\sqrt{s}$ = 33 TeV 300 fb^{-1}	$\sqrt{s}$ = 33 TeV 3 ab^{-1}	$\sqrt{s}$ = 14 TeV 300 fb^{-1}	$\sqrt{s}$ = 14 TeV 3 ab^{-1}
g_{KK} (Lepton+j (dilepton))	7.1 (6.7)	11.4 (10.1)	4.3 (4.0)	6.7 (5.6)
Z'_{Topcolor} (Lepton+j (dilepton))	4.1 (2.2)	7.6 (4.3)	3.3 (1.8)	5.5 (3.2)
$Z'_{SSM} \to ee$	12.7	15.8	6.5	7.8
$Z'_{SSM} \to \mu\mu$	11.6	15.1	6.4	7.6

Conclusions

- In general, a substantial gain in the physics reach is possible with 3000 fb^{-1}, and some studies are only viable with this high integrated luminosity.

- The precision on σ.Br for most Higgs prod/decay modes can be improved by a factor two to three.
- The rare decay mode of the Higgs boson $H \rightarrow \mu\mu$ only becomes accessible with 3000 fb^{-1}.
- Present studies still very preliminary: detailed experimental effects at HL not yet included.

- Combining both experiments, first evidence for the Higgs self-coupling, and thus a proof that the Higgs mechanism works as predicted, is probably within reach.

- In searches for new particles, the mass reach can be increased by up to 50%.

- The luminosity upgrade would become even more interesting if new phenomena are seen during the 300 fb^{-1} phase of the LHC, as the ten-fold increase in luminosity would give access to measurements of the new physics.

- The largest gain from the HE-LHC can be reached for new particle at high masses

- In such searches a 33 TeV machine roughly doubles the reach of the LHC

- With an integrated luminosity of "only" 300 fb^{-1}, the HE-LHC reach is significantly higher than for the high luminosity LHC with 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV