HL–LHC Prospects for SM $H \to \mu^+\mu^-$ with ATLAS

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Physics at the Terascale
December 3, 2013

Overview

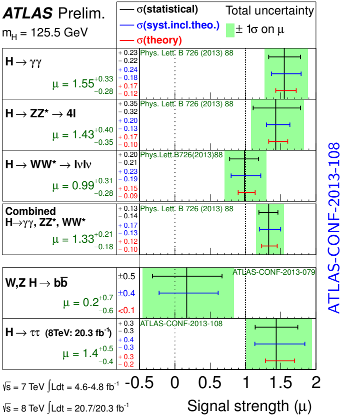
$H \to \mu^+\mu^-$ studies carried out as part of prospects for combined Higgs boson coupling determination.

- As part of two series of notes about prospects of Higgs boson physics at the HL–LHC.
  - 2012: Input to European Strategy Briefing Book
  - 2013: ECFA HL–LHC Workshop
- Two studies have been performed:
  1. Inclusive $H \to \mu^+\mu^-$ @ 300 fb^{-1} and 3000 fb^{-1}
  2. Exclusive ttH, $H \to \mu^+\mu^-$ @ 3000 fb^{-1}

The Properties of the Discovered Higgs Boson

What kind of Higgs boson was discovered by ATLAS and CMS?

- Discovered first in decays to $\gamma\gamma$, ZZ^* and W^+W^-.
  - Evidence also in $\tau^+\tau^-$.
- Measured mass of $\sim 125.6\,\text{GeV}$.
- All measured properties consistent with SM Higgs boson hypothesis.
- No definite statement on Higgs boson nature possible yet.
  - Still considerable uncertainties.
  - Particularly in fermionic sector.

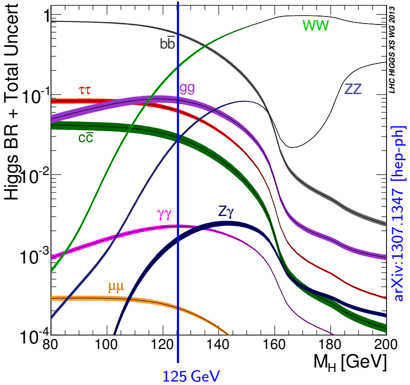


Higgs Boson Decays to $\mu^+\mu^-$

The SM Higgs boson with $m_H = 125\,\text{GeV}$ decays to many final states with considerable rates.

Experimentally accessible channels at LHC:

- $H \to b\bar{b}$ (57 %)
- $H \to W^+W^-$ (22 %)
- $H \to \tau^+\tau^-$ (6.2 %)
- $H \to ZZ^*$ (2.8 %)
- $H \to \gamma\gamma$ (0.23 %)
- $H \to Z\gamma$ (0.16 %)
- $H \to \mu^+\mu^-$ (0.022 %)



The decay $H \to \mu^+\mu^-$

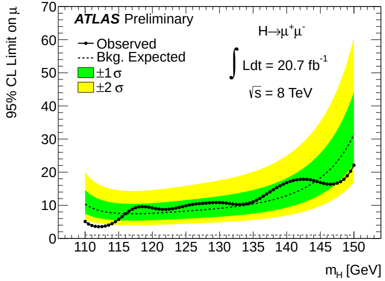
- Experimentally challenging due to:
  - Small branching fraction of $\sim 10^{-4}$.
  - Large irreducible $Z/\gamma^* \to \mu^+\mu^-$ background.
- Clean final–state signature.
- High mass resolution ($\sim$ 2%).
- Only channel to probe second generation fermion couplings of Higgs boson.

$H \to \mu^+\mu^-$ Searches in 8 TeV ATLAS Data

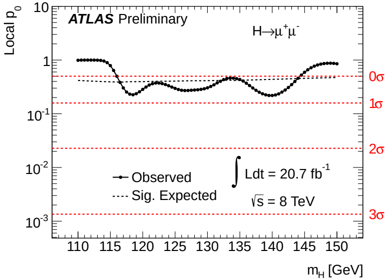
Inclusive search performed on 8 TeV data in mass range of 110 to 150 GeV.

[ATLAS–CONF–2013-010]

CL$_s$ Limit



Local p_0–value



Results for $m_H = 125\,\text{GeV}$:

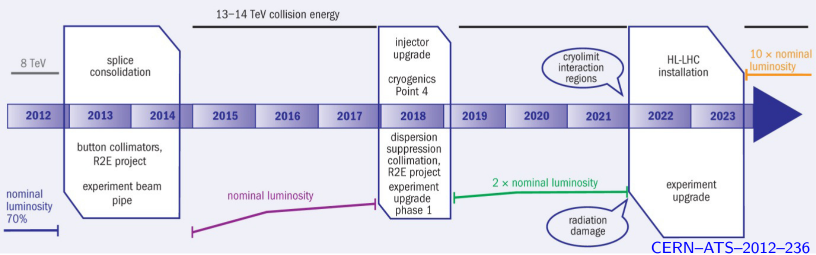
- Exclusion of 9.8× SM prediction (expected: 8.2).
- Expected signal significance: $\sim 0.3\,\sigma$.

Much larger data set needed to become sensitive!

LHC Upgrade Prospects

Approved LHC Physics Schedule:

- Run II (2015 – 2017): 13 – 14 TeV collisions in 2015, reach nominal luminosity.
- Run III (2019 – 2021): operation at 2 – 3 times the design luminosity.
- Goal of approved physics programme: collect 300 fb^{-1} by end of 2021.



Possible High–Luminosity LHC Upgrade:

- Luminosity upgrade needed to sustain statistical gain.
- After 3rd long shutdown: 5 – 10 times the nominal luminosity ($\mu = 140 - 200$).
- Ulimate goal of LHC life cycle: 3000 fb^{-1} by end of 2030.

Expected ATLAS Detector Performance

Detector design for HL–LHC phase not yet completed.

Goal: Performance of upgraded detector not below current Run–I–performance @ $\mu \approx 20$.

Expected Muon Performance Assumptions:

- Single muon trigger efficiency expected to be as in 2012.
  - $\epsilon_{\text{trig}} = 0.70$ for $|\eta| < 1.05$
  - $\epsilon_{\text{trig}} = 0.86$ for $|\eta| > 1.05$
  - p_{T}–thresholds comparable: e.g. 24 GeV
- "Flat" muon ID efficiency maps:
  - Standalone: $\epsilon_{\text{ID}} = 0.99$ for $|\eta| < 2.7$
  - Combined: $\epsilon_{\text{ID}} = 0.97$ for $0.1 < |\eta| < 2.5$ and $\epsilon_{\text{ID}} = 0.54$ for $|\eta| < 0.1$
- Resolution smearing functions for combined muon reconstruction
  - Phase–I ID and MS setup.
  - Improved Phase–II configuration after ITK upgrade.

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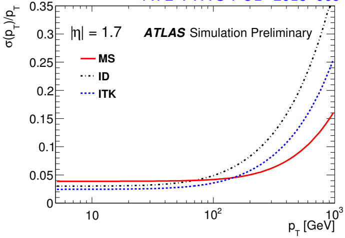

Inclusive $H \to \mu^+\mu^-$ Search

- Inclusive $H \to \mu^+\mu^-$ prospects based on search in 8 TeV data [ATL–PHYS–PUB–2013–014].
- Signal and background processes generated for $\sqrt{s} = 14\,\text{TeV}$.
- Generator objects modified according to efficiency and resolution functions.

Simple event selection:

- At least two muons with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.5$.
- At least one with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ triggered.
- Track isolation emulated using efficiency from Run–I data.
- Opposite sign muon pair with $m_{\mu\mu} > 70\,\text{GeV}$.

Mass resolution (assuming no ITK):

- Central region ($|\eta_{1,2}| < 1.0$): 1.4 %.
- Non–central ($|\eta_{1/2}| > 1.0$): 1.9 %.

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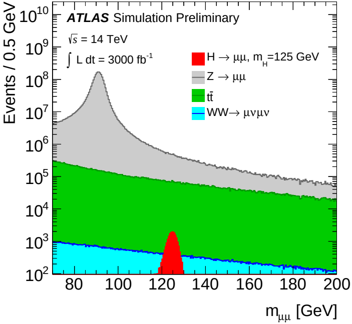

Expected Signal and Background

Number of expected events in ± 3 GeV mass window around 125 GeV:

- Extracted from combined S+B fit to $m_{\mu\mu}$
- Using analytic parametrizations of signal and background shapes.

$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
$\Delta^{\mathrm{sys}}_{Bkg}$ (model)	68	110
$\Delta^{\mathrm{sys}}_{Bkg}$ (fit)	190	620
$\Delta^{\mathrm{stat}}_{\mathrm{S+B}}$	750	2380

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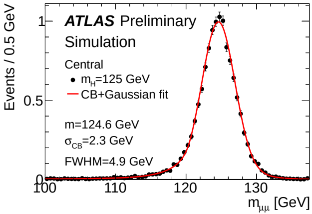

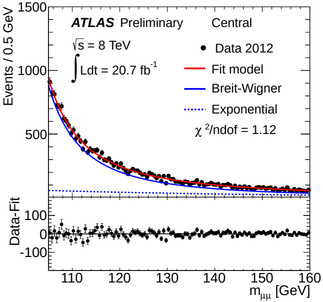

$H \rightarrow \mu^+\mu^-$ Sensitivity Prospects

- Expected sensitivity with ultimate LHC and HL–LHC data sets extracted from combined fit to $m_{\mu\mu}$.
- Accounting for theory uncertainties and systematic uncertainties in background modelling.

$\mathcal{L}$ [fb^{-1}]	300	3000
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	19%

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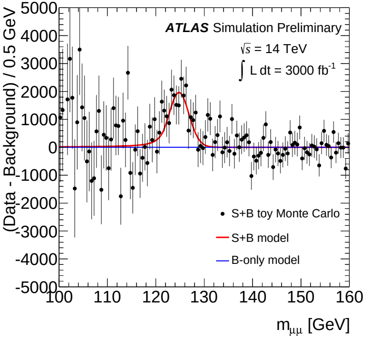
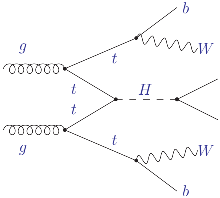


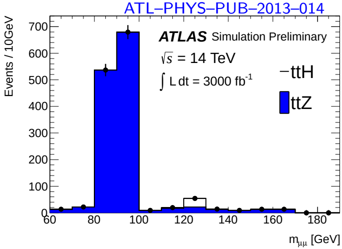
Search for $t\bar{t}H$, $H \to \mu^+\mu^-$



Probes product of top and μ–Yukawa couplings and CP nature of discovered resonance.

Event selection:

- At least two opposive sign muons with $p_{\mathrm{T}} > 35\,\mathrm{GeV}$.
- Reconstruct one "hadronic top" (hadronic W plus b jet).
- Not more than four leptons.
- At least four jets.
- Higgs candiate mass window: 120 to 130 GeV



Despite small production rate, this channel is observable at the HL–LHC.

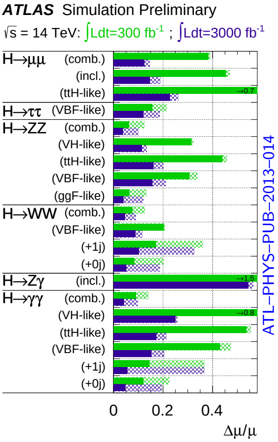
- Expected signal events: 33
- Expected background: 22
- $\Delta\mu/\mu \approx 25\,\%$

Combined Coupling Fit

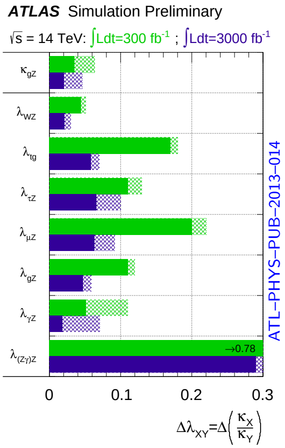
Combination of various channels studied for ES & ECFA to determine Higgs boson couplings:

Using the leading–order κ–framework of HXSWG [arXiv:1209.0040 [hep-ph]]

Relative strenght of different channels:



Expected precision in coupling scale factor ratios:



Summary

- Fermionic decay channels essential to pin down nature of discovered Higgs boson.
- Rare decays become important in Run II and beyond.
- Sensitivity potential of $H \rightarrow \mu^+\mu^-$ have been evaluated for ultimate LHC and HL–LHC data sets.
- Improve combined coupling determinations in fermionic sector.
- ES and ECFA studies showed the importance of HL–LHC upgrade for precision Higgs boson physics.

backup

Minimal Coupling Fit

Assuming universal vector boson and fermion couplings (κ_V, κ_F).

Comparison with Run–I measurements:

- Strong contrain in κ_V already with 300 fb^{-1}.
- Improvement with 3000 fb^{-1} mostly in κ_F.

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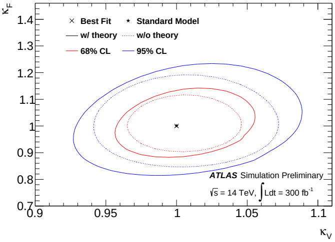
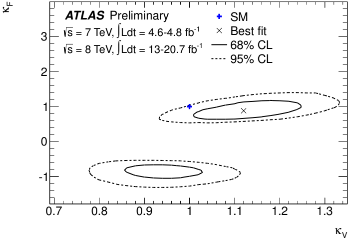


ATLAS–CONF–2013–034



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