Camille Flammarion, Universum, 1888

Prospects on SM and Higgs Physics at the HL-LHC

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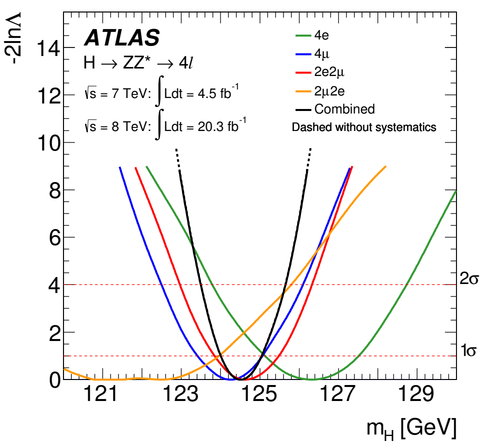
- Higgs results at LHC with Run1 data
- High Energy Physics in the new era: *What Next?*
- Prospects with LHC and the luminosity upgrade, HL-LHC
  - Higgs Coupling Combination
- Summary

See also talk from M. Venturi, M. Pieri - this conference

Higgs boson mass

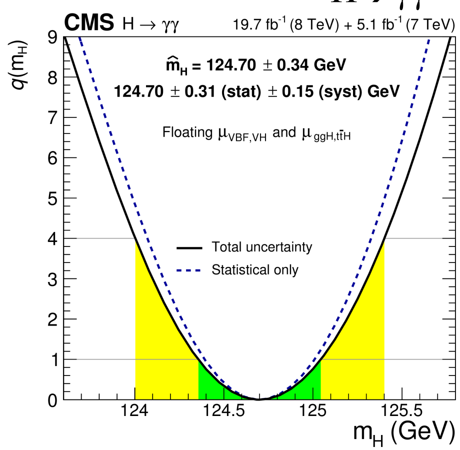
- Combined mass through simultaneous fit to H→4l and H→γγ datasets
  - **Scale accuracy at the level of 0.1%! ← spectrometer & calorimeter calibration important**

H→4l



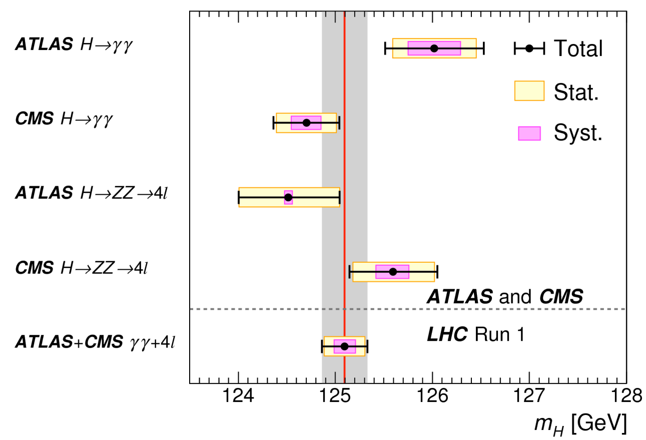
PHYSICAL REVIEW D 90, 052004 (2014)

H→γγ



Eur. Phys. J. C 75 (2015) 212

combination



PHYSICAL REVIEW D 90, 052004 (2014)

	ATLAS	CMS
H→4l	124.51 ± 0.52 ± 0.06	125.6 ± 0.4 ± 0.2
H→γγ	125.98 ± 0.42 ± 0.28	124.70 ± 0.31 ± 0.15
Combination	**125.36 ± 0.37 ± 0.18**	**125.02 $^{+0.26}_{-0.27}$ $^{+0.14}_{-0.15}$**
ATLAS + CMS	**125.09 ± 0.21 (stat) ± 0.11(scale)** ± 0.02 (other) ± 0.01(theory)	

Uncertainty dominated by statistics, it will improve with more data from Run2

See also talk from M. Venturi, M. Pieri - this conference

Higgs boson mass

- Combined mass through simultaneous fit to H→4l and H→γγ datasets
  - **Scale accuracy at the level of 0.1%! ← spectrometer & calorimeter**

- ***m_H was the only fundamental parameter missing to completely set the SM structure***
- ***We just entered a new era: precision tests are now needed in order to "discover" possible deviations from SM***

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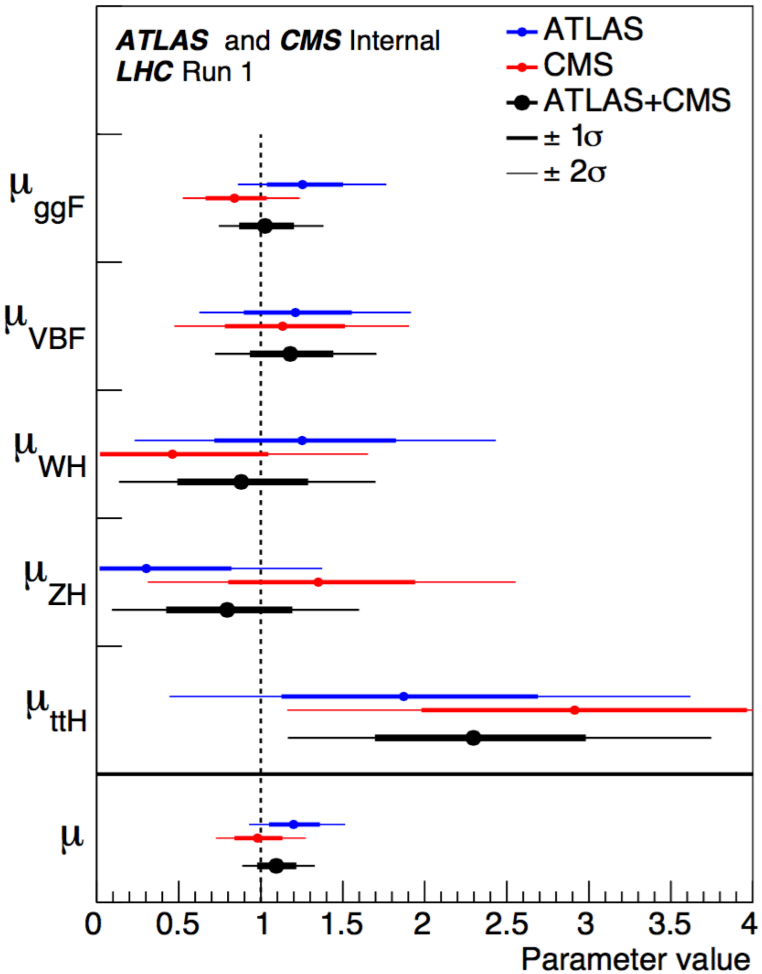
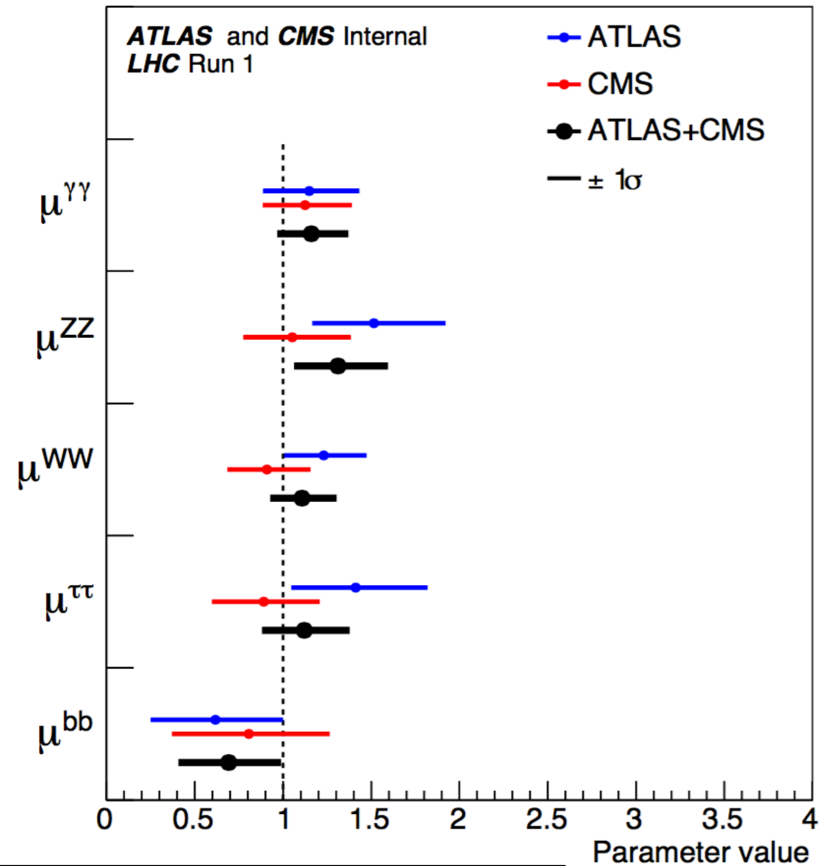
See also talk from M. Pieri, this conference

Signal strength combination: decays

Assume SM values for ratios between different production cross sections



Assume SM values for ratios between different production modes



$\mu(\text{ATLAS}) = 1.20^{+0.15}_{-0.14}$
$\mu(\text{CMS}) = 0.98^{+0.14}_{-0.13}$
$\mu(\text{Comb.}) = 1.09^{+0.11}_{-0.10}$

- Results are fully consistent with SM predictions

See also talk from W. Verkerke and M. Pieri, this conference

k-framework: determination of coupling deviations

Coupling to fermions: $g_F = \kappa_F \frac{\sqrt{2} m_F}{v}$ Coupling to bosons: $g_V = \kappa_V \frac{2 m_V^2}{v}$

Write rates in terms of k_i parameters

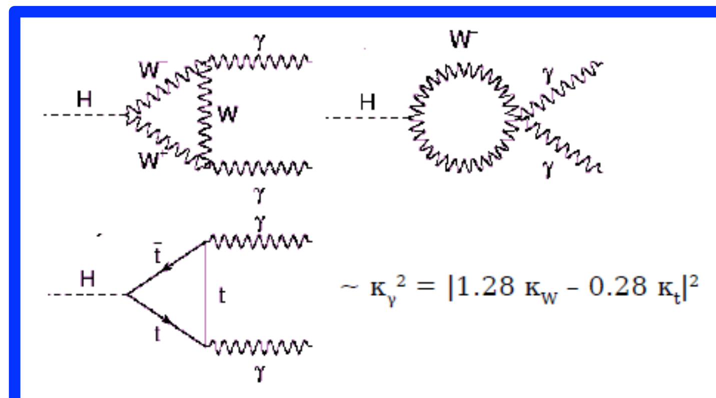
The index *i* is related to each individual elementary particle

- Production: $\sigma_i \sim \kappa_i^2 \, \sigma_i^{SM}$
- Decay: $\Gamma_i \sim \kappa_i^2 \, \Gamma_i^{SM}$
- Total Width: $\Gamma_H = \Sigma_i \, \kappa_i^2 \, \Gamma_i^{SM}$

Total width not measured at LHC (upper limits can be derived from off-shell production studies)

Example:

$$\frac{\sigma \cdot \mathrm{B}\,(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{B}_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$



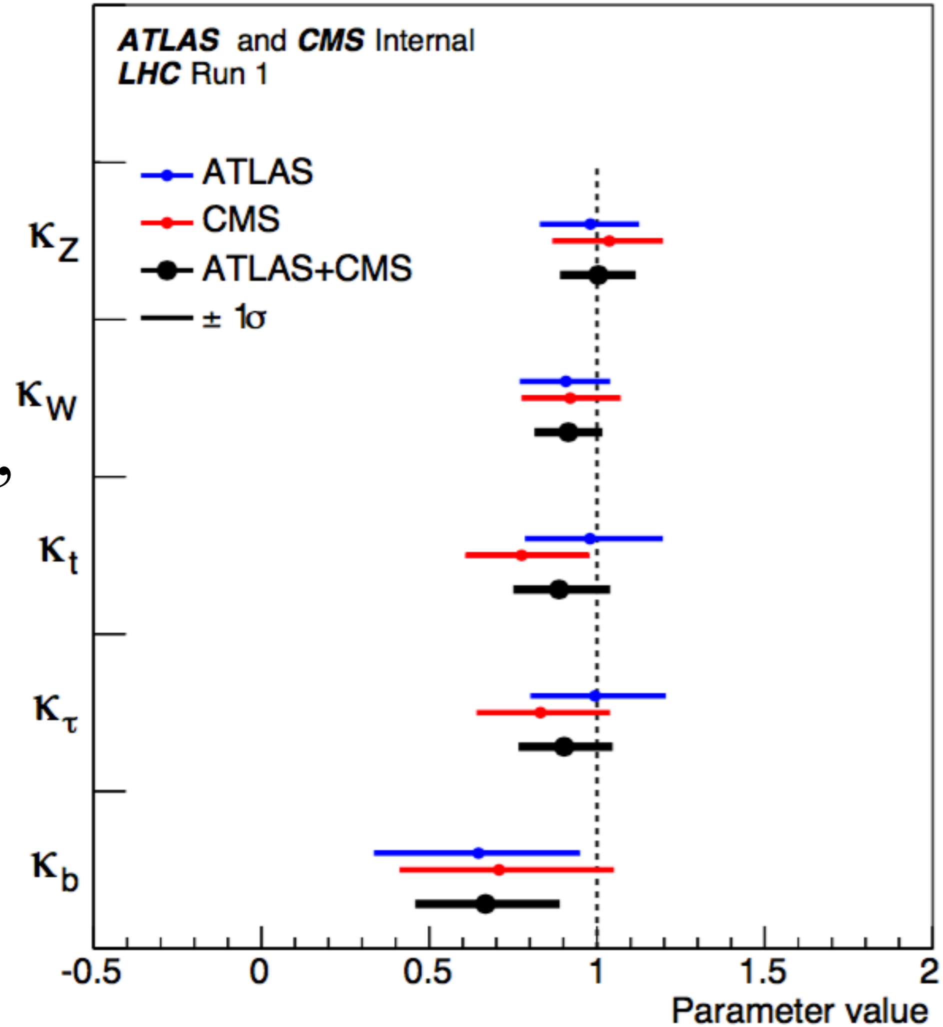
Interference in H→γγ, gg→H, …:
→ some relative sign-ambiguities solved

Assumptions:

- *Only one Higgs boson*
- *Only scalar modifications of the coupling strength: kinematics as in SM*
- $J^P = 0^+$

Absolute coupling deviations

- Absolute coupling determination needs some theory assumption, for example assume no BSM Higgs boson decay, and no BSM particles in the gg→H, H→γγ and H→Zγ loops
- All results compatible between ATLAS and CMS, and with SM



Overview of best-fit values of parameters for the combined measurements with the assumption of the absence of BSM particles in the loops and $BR_{BSM} = 0$.

What's Next

- The discovery of the 125 GeV Higgs boson opens a new era in Particle Physics
- Current data indicate consistency of the 125 GeV new particle with the Higgs boson predicted by SM
- Direct searches of new particles and new phenomena at the 13-14 TeV LHC are of paramount importance; in particular searches for partners of this newly discovered particle is mandatory
- Precision Higgs boson and SM measurements are also essential to verify the properties of this new object and to probe for possible effects from New Physics (approach complementary to direct searches)

What's Next – an example

arXiv:1206.3560v3

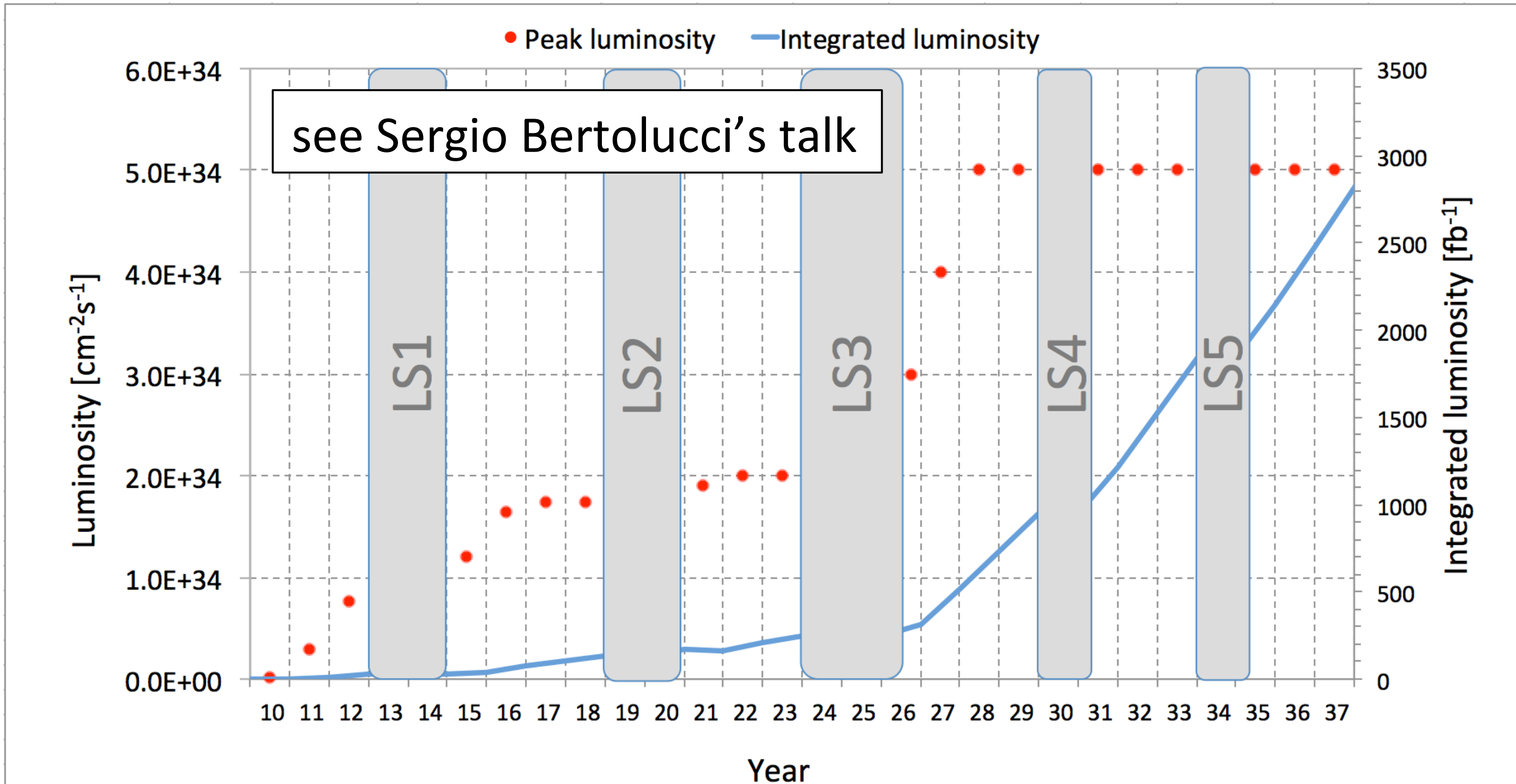
Rick S. Gupta[a,b,c], Heidi Rzehak[a*], James D. Wells[a,b]

	ΔhVV	$\Delta ht\bar{t}$	$\Delta hb\bar{b}$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	10%[a], 100%[b]
LHC Run1 experiment	**~15%**	**~40%**	**~30%**
LHC 14 TeV 300 fb^{-1} (1 exp.)	**~6%**	**~15%**	**~12%**

Quite a few BSM implementations show coupling deviations in the range from few to several %

- 14 TeV & 300 fb^{-1} projections based on what we learnt from early 2011 analyses
  - **Since then more channels have been included in the 125 GeV Higgs boson data analyses**

LHC and HL-LHC timeline

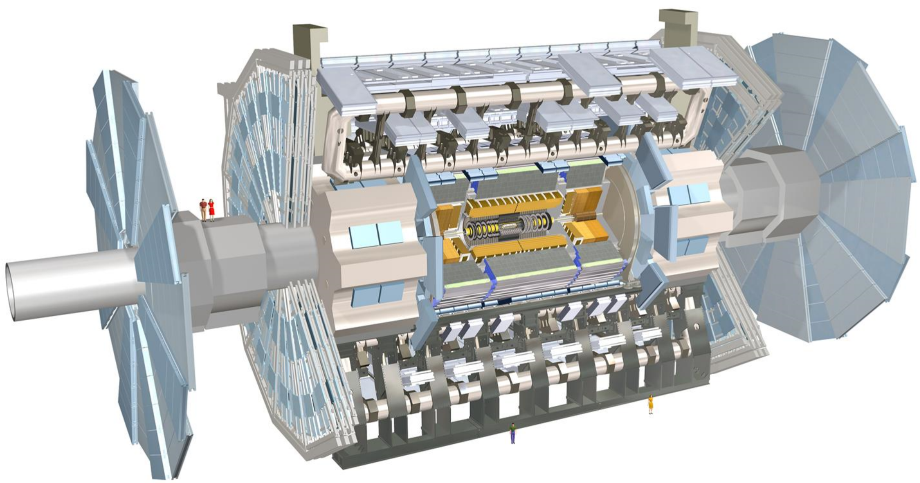


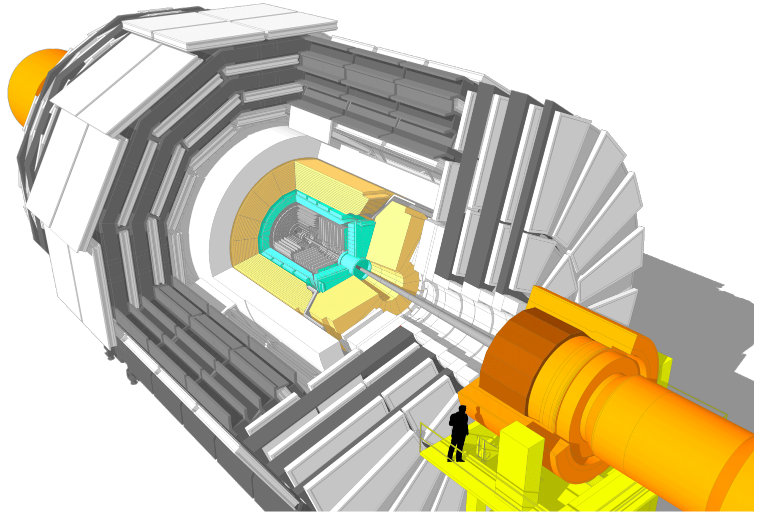
HL-LHC instantaneous (levelled) luminosity: 5.0 (-7.5?) × 10^{34} cm^{-2} s^{-1}

- 2015 √s = 13 TeV – 10 fb^{-1}
- 2015-2018 √s = 13-14 TeV – 100 fb^{-1}
- 2021-2023 √s = 14 TeV – 300 fb^{-1}
- mid 2025-203? √s = 14 TeV – 3000 fb^{-1}

ATLAS and CMS upgrades

- Present ATLAS and CMS detectors have been designed for a vevent pileup level <μ> ~ 23 pp interactions / bunch-crossing
  - And continue to do an excellent job with 35
  - But cannot handle (an average of) 140-200 events of pileup
- See talks on detector upgrade of ATLAS and CMS for the high-luminosity LHC, HL-LHC by:
  - **Lucia Silvestris (CMS)**
  - **Anadi Canepa (ATLAS)**





125 GeV Higgs sector milestones

Run2

time

- Observe the Higgs in ττ and bb decay modes in ATLAS and CMS independently
- Observe the Higgs boson in VBF and VH in ATLAS and CMS independently
- Study Higgs boson differential cross sections
- Observe the Higgs boson in ttH ➔ crucial to investigate the top quark Yukawa coupling
- Search for rare Higgs boson decays: in primis H→μμ
- Higgs coupling precision measurements
- HH production

HL-LHC

- Search for CP mixing in the Higgs sector
- **Direct Search** for partners of the 125 GeV Higgs boson

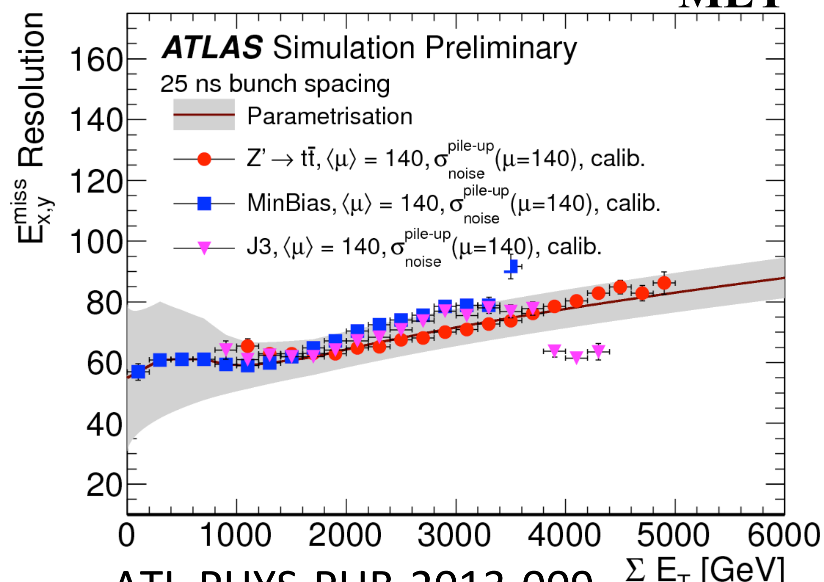
Projection methodology

- ATLAS:
  - Efficiency and resolution functions are applied to physics objects
  - Performance of the new detector will not be worse than the current detector at Run I conditions
- CMS:
  - Scale signal and background yields of current analyses
  - Two scenarios for systematic uncertainties
    - Scenario 1: Systematic uncertainties remain the same
    - Scenario 2: Theoretical uncertainties scaled by ½, other systematic uncertainties scaled by $1/\sqrt{L}$

Full simulation object studies

- Parametrization of object performance in the HL-LHC pile-up environment using full MC samples simulated in the upgraded ATLAS detector
- Some examples here:
  - ATLAS E_T^{miss} resolution with parametrization overlayed
- ATLAS b-tag fake rate for 70% efficiency compared with rate assumed for ES studies
  - ITK brings enhanced tracking
  - Mistag below 0.5% (2%) for <μ>=140 (200) and p_T =100 GeV

MET



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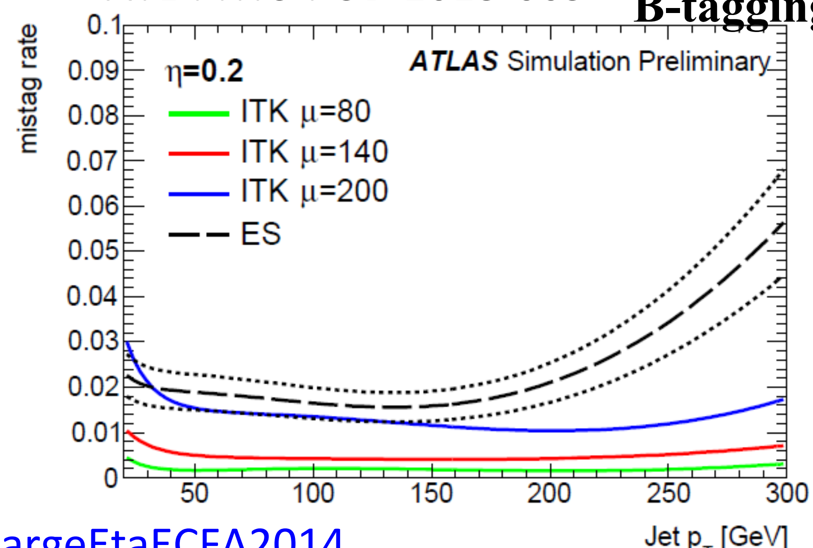
B-tagging



More recent studies available since fall 2014:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LargeEtaECFA2014
http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/UPGRADE/PLOT-UPGRADE-2014-003/

Higgs Coupling studies

	$H\rightarrow\gamma\gamma$	$H\rightarrow ZZ$	$H\rightarrow WW$	$H\rightarrow\tau\tau$	$H\rightarrow bb$	$H\rightarrow Z\gamma$	$H\rightarrow\mu\mu$
gg→H / inclusive	ATLAS CMS	ATLAS CMS	ATLAS CMS	CMS	-	ATLAS CMS	ATLAS CMS
VBF	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS	-	ATLAS CMS	ATLAS CMS
VH	ATLAS CMS	ATLAS CMS	CMS	CMS	ATLAS CMS		CMS
ttH	ATLAS CMS	ATLAS CMS	CMS	ATLAS CMS	CMS		ATLAS

Production and decay modes considered in the projections

$H \rightarrow ZZ^* \rightarrow 4l$

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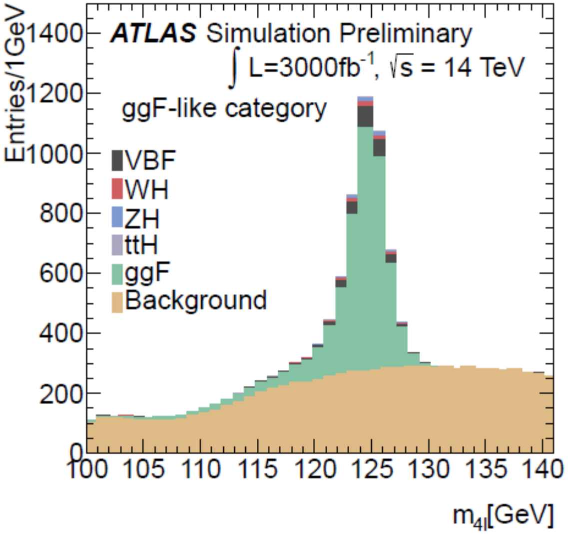
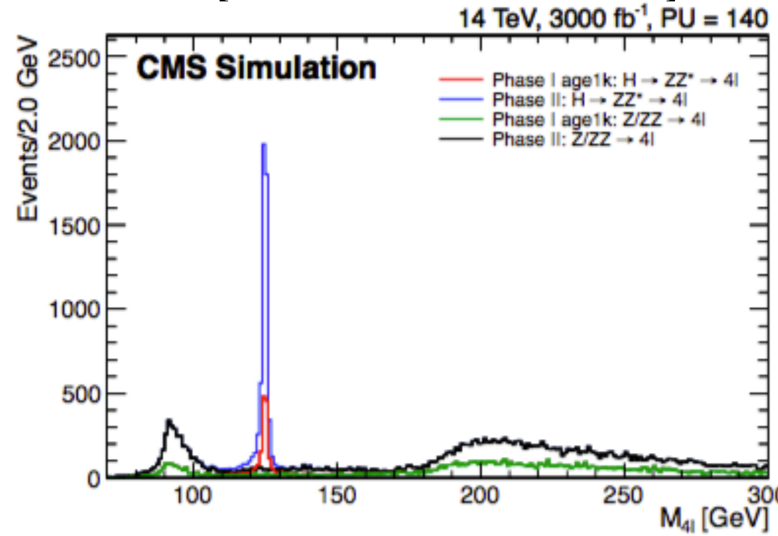


CMS [CERN-LHCC-2015-010]



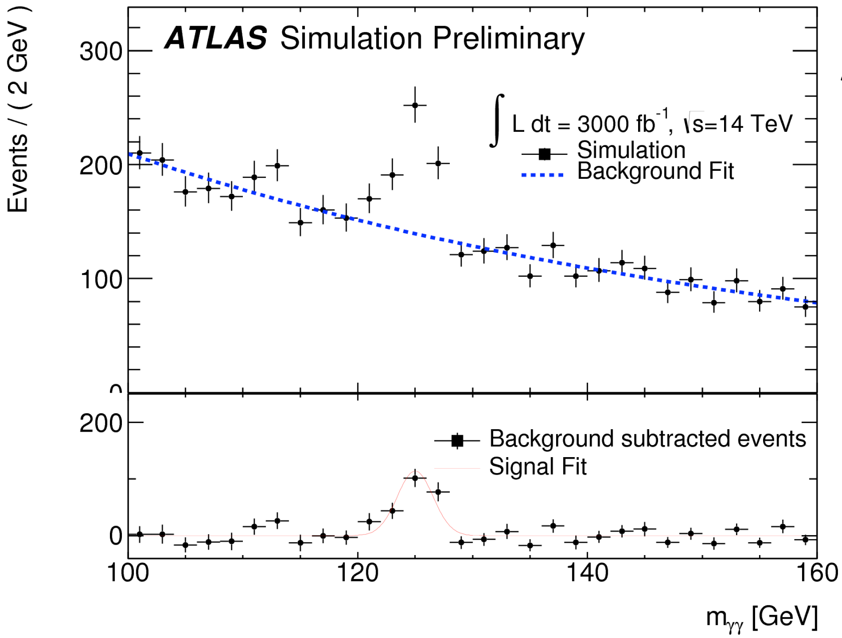
ATLAS Selected signal event rates

	ttH	ZH	WH	VBF	ggH
$3000fb^{-1}$	35	5.7	67	97	3800

- Very high signal purity
- Separate into all 5 production modes
- WH, ZH use lepton tags

ttH only possible at HL-LHC

ttH, H→γγ



ATL-PHYS-PUB-2013-014

- Sensitive to top in both production and decay
- Yields top Yukawa coupling

Experimental uncertainty on ttH signal strength: ~12%

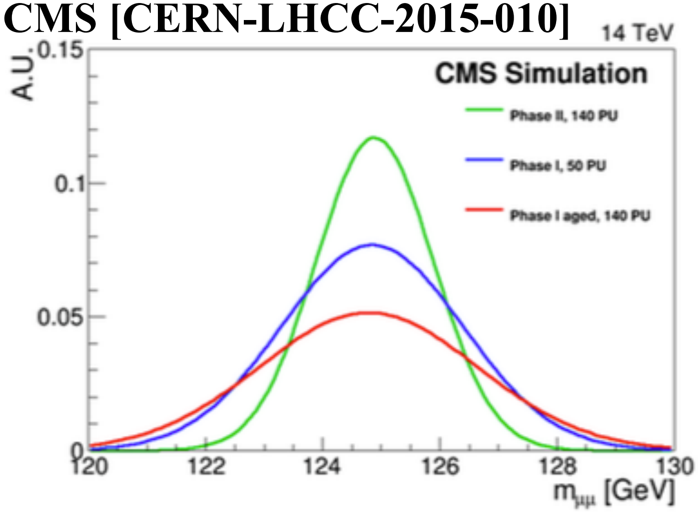
ATL-PHYS-PUB-2014-012

Production mode	$\Delta\hat{\mu}/\hat{\mu}$ (%) Total	Statistical	Experimental	Theoretical
$t\bar{t}H$	$^{+21}_{-17}$	$^{+13}_{-12}$	$^{+5}_{-4}$	$^{+17}_{-11}$
WH	$^{+26}_{-25}$	$^{+21}_{-20}$	$^{+13}_{-12}$	$^{+10}_{-8}$
ZH	$^{+35}_{-31}$	$^{+32}_{-29}$	$^{+7}_{-7}$	$^{+12}_{-8}$
ggF	$^{+19}_{-14}$	$^{+3}_{-3}$	$^{+1}_{-1}$	$^{+19}_{-14}$
VBF	$^{+29}_{-29}$	$^{+18}_{-18}$	$^{+1}_{-1}$	$^{+23}_{-23}$

Rare decays

$H \rightarrow \mu\mu$

CMS [CERN-LHCC-2015-010]



- Allows direct study of coupling to two different leptons
- Test lepton flavour-violation carefully
- Signal significance, ATLAS:
- ***CMS: revised projection, expect 5% on coupling measurement at HL-LHC***

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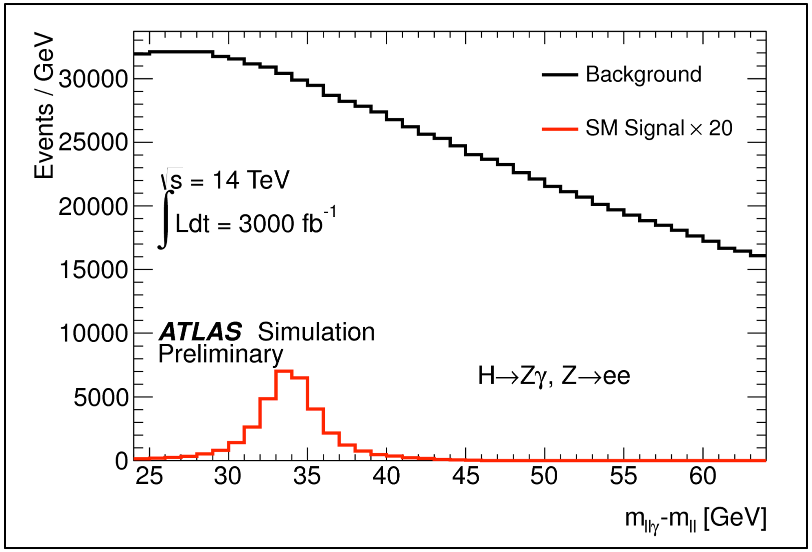
$\mathcal{L}$ [fb^{-1}]	300	3000
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%

$H \rightarrow Z\gamma$

ATL-PHYS-PUB-2014-006

- In Standard Model, this decay proceeds entirely via loops predominantly involving heavy charged particles
- ➔ sensitive to possible new physics
- Observation of the SM decay is possible at HL-LHC



$m_{ll\gamma}$-m_{ll} of signal and background after the full event selection and parameterized lepton and photon reconstruction

Precision on signal strength

channel	Prec. (%) 100 fb^{-1}	Prec. (%) 300 fb^{-1}		Prec. (%) 3000 fb^{-1}	
ttH H→γγ	~65	38	36	17	12
ttH H→ZZ*→4l	~85	49	48	20	16
VBF H→γγ	~80	47	43	22	15
VBF H→ZZ*→4l	~60	36	33	21	16
H→μμ	~70	39	38	16	12
H→ττ	~18	14	8	8	5
H→bb	~20	14	11	7	5
H→γγ	~15	12	6	8	4
H→4l	~15	11	7	9	4
H→4l	~15	11	7	7	4

My personal estimates

ATLAS: experimental & theory uncertianties; only exp. uncertainty

CMS: current exp.l & theory uncertianties; exp. uncertainty ∝ 1/√L and ½ theory unc.

ATLAS assumed luminosity uncertainty: 3%

Higgs Couplings

- VH->bb included in ATLAS, updates for H->Zγ, VH/ttH->γγ (*)
- No BSM Higgs decay modes assumed

–Comparable numbers for κ_W,κ_Z, κ_t, and κ_γ between the two experiments

–Couplings can be determined with 2-10% precision at 3000fb^{-1} (for CMS Scenario 2)

CMS: http://arxiv.org/abs/1307.7135

		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300fb^{-1}	ATLAS	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
300fb^{-1}	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000fb^{-1}	ATLAS	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]
3000fb^{-1}	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

–ATLAS: [no theory uncert., full theory uncert.]

–CMS: [Scenario 2, Scenario1]

(*) ATLAS documents:
ATL-PHYS-PUB-2014-011
ATL-PHYS-PUB-2014-006
ATL-PHYS-PUB-2014-012
ATL-PHYS-PUB-2014-016

Coupling fit with L=300 and 3000 fb^{-1}

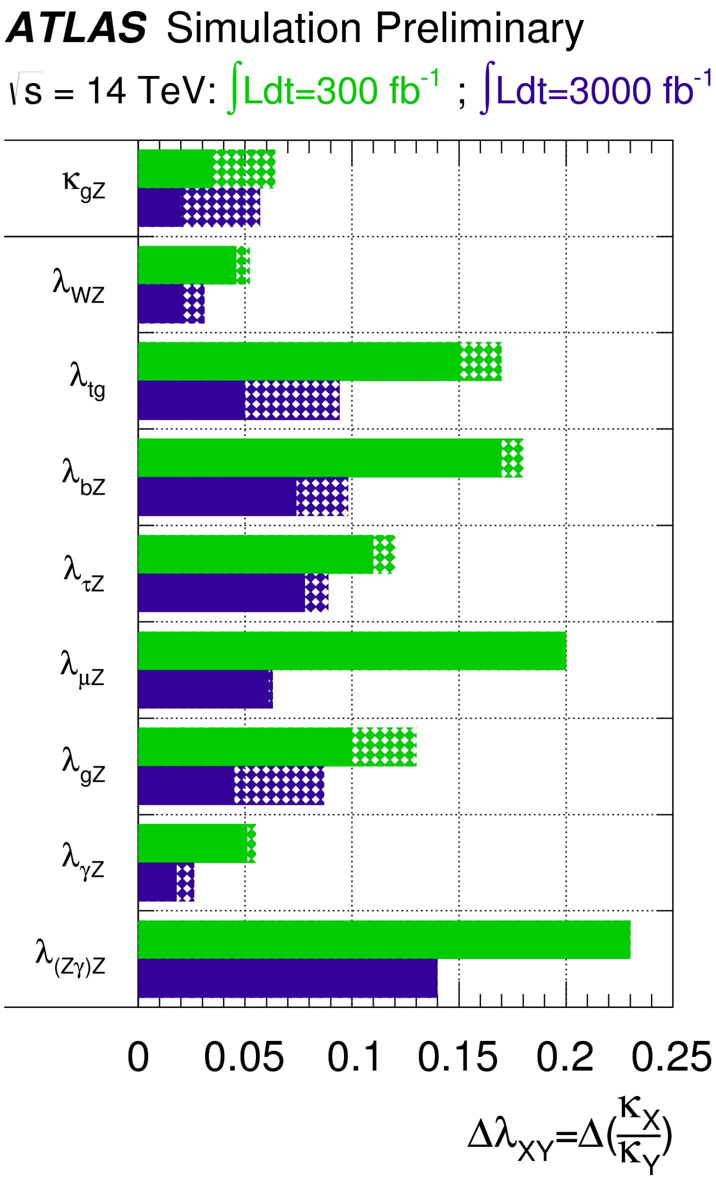
Measurement accuracy per experiment!

Coupling modifier	300 fb^{-1}	3000 fb^{-1}	
$k_{W,Z}$, $k_{\gamma,}$	6%	3%	
k_b	12%	5%	down-quark type
k_t	15%	7%	Top Yukawa coup.
k_τ	10%	5%	lepton coupling
k_μ	22%	7%	2nd generation

based on the results here available

CMS: http://arxiv.org/abs/1307.7135
ATLAS: ATL-PHYS-PUB-2014-016

Higgs Couplings



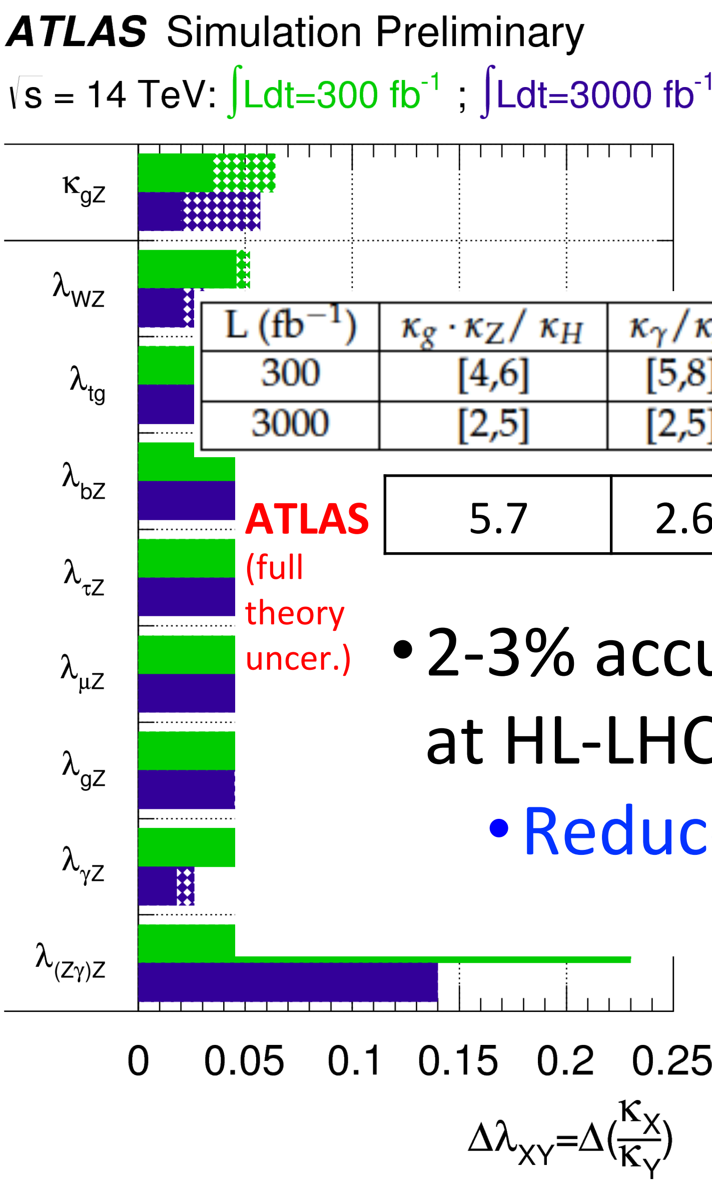
- Most generic model: remove the assumption on the total width
  - Only ratios of the coupling scale factors can be determined at LHC
  - Use given process as a reference

ATL-PHYS-PUB-2015-024

- Total Higgs boson width can be probed at LHC studying the comparison of on-shell and off-shell Higgs boson production
- Recent study by ATLAS indicates that, under a number of assumptions, the (SM) Higgs boson width can be estimated with a **systematic uncertainty of ~ 2 MeV:**

$$\Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1} \text{ MeV (stat+sys)}.$$

Higgs Couplings



CMS [Scenario2,Scenario1]

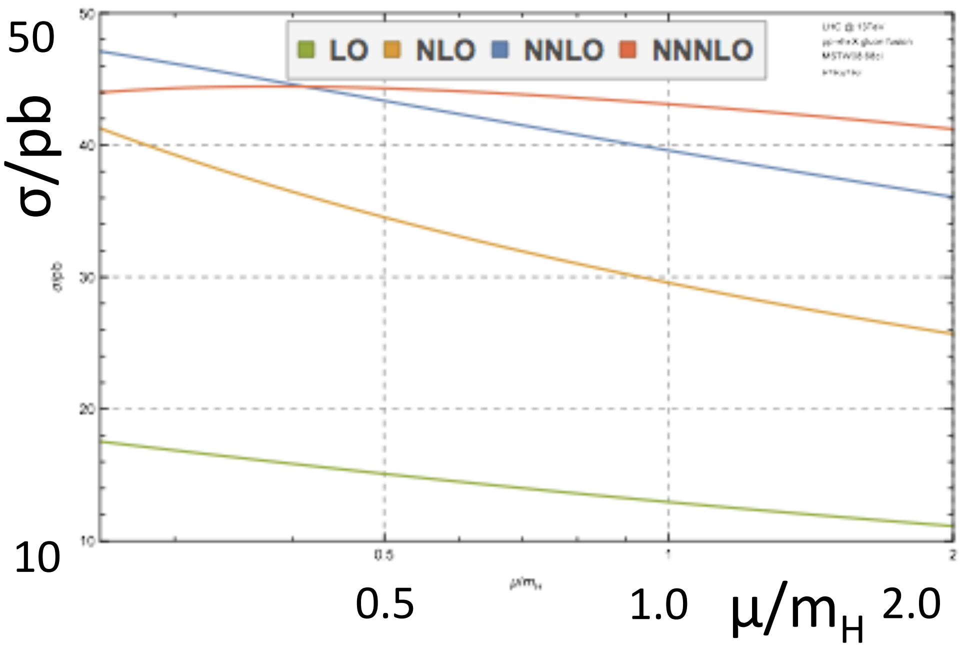
L (fb^{-1})	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ/κ_Z	κ_W/κ_Z	κ_b/κ_Z	κ_τ/κ_Z	κ_Z/κ_g	κ_t/κ_g	κ_μ/κ_Z	$\kappa_{Z\gamma}/\kappa_Z$
300	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

ATLAS (full theory uncer.)

5.7	2.6	3.1	9.8	8.9	8.7	9.4	6.3	14

- 2-3% accuracy on a few coupling constants at HL-LHC
  - Reduced theoretical uncertainties needed

N^3LO ggF production cross section



C. Anastasiou et al.:
http://arxiv.org/abs/1107.0683 ,
http://arxiv.org/abs/1403.4616 ,
http://arxiv.org/abs/1411.3584 ,
http://arxiv.org/abs/1503.06056

FIG. 2: Scale variation of the gluon fusion cross-section at all perturbative orders through N^3LO.

- For renormalisation and factorisation scales equal to half the Higgs mass, the N^3LO corrections are of the order of +2.2%. The total scale variation at N^3LO is 3%, reducing the uncertainty due to missing higher order QCD corrections by a factor of three.
- However the procedure to transfer the scale variations to theory uncertainty on the cross section is not firmly established (why considering a factor 2 and ½, for example?)

[1] http://arxiv.org/abs/1409.5036
[2] http://arxiv.org/abs/1307.1843

Interpretation for BSM Higgs sector

- Use expected accuracy in the couplings k_i of the 125 GeV Higgs boson
- Same decays as in the SM are assumed (b-associated production included as a correction)

h(125) is the light scalar of the 2HDM

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Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

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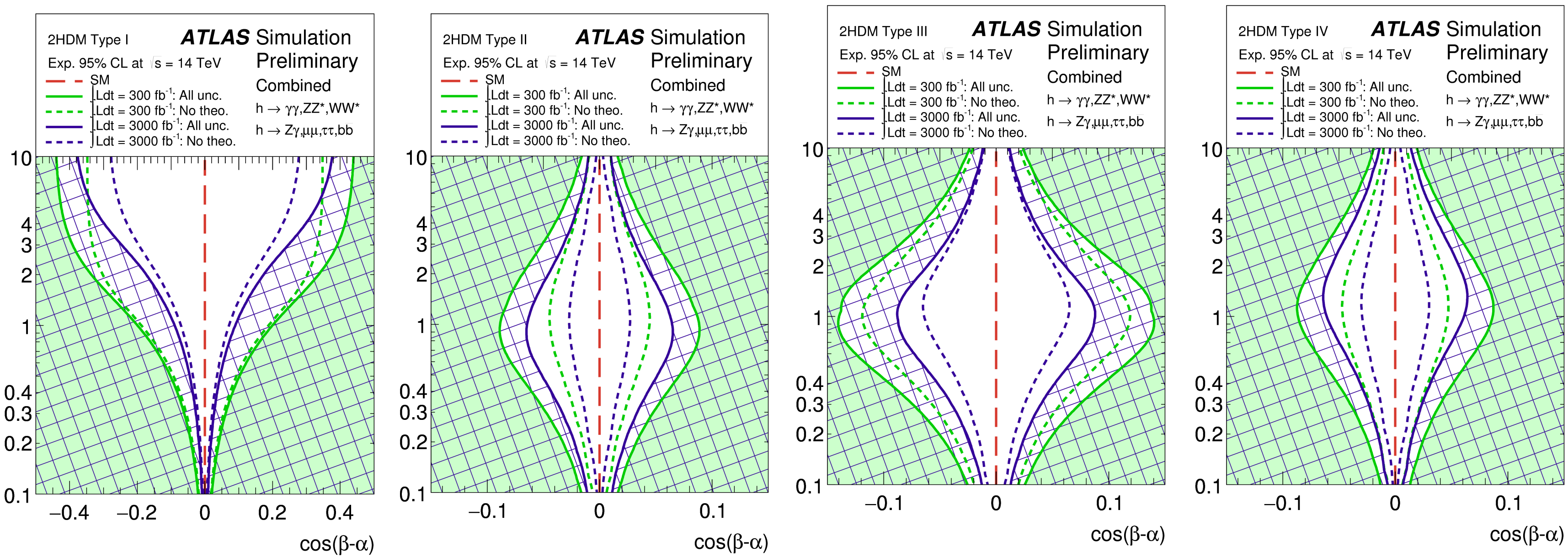
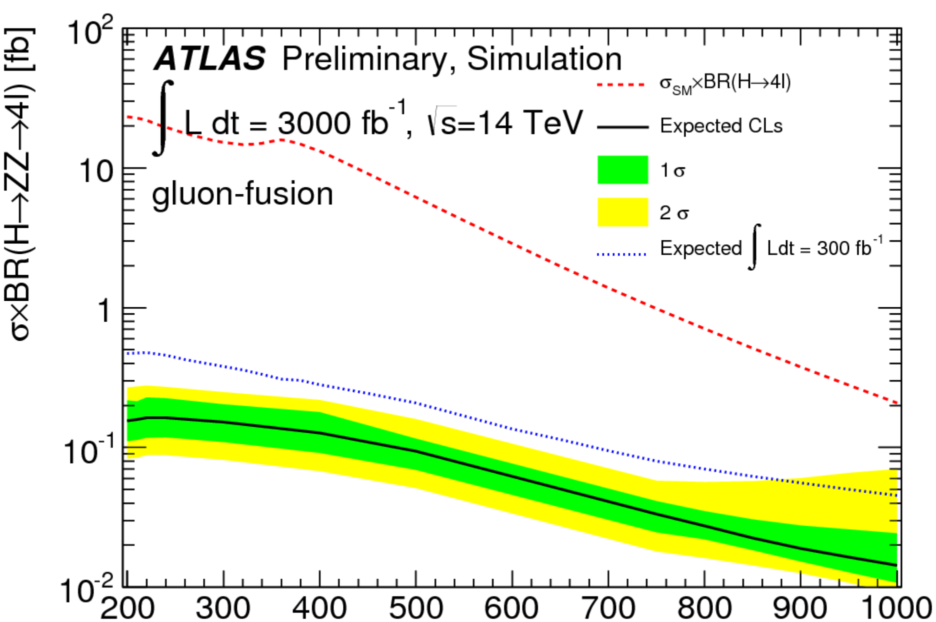


Direct BSM Higgs searches: example H→ZZ→4l

See also talk Pawel Bruckman De Renstrom

- The 4l final state has small cross section but is clean and well reconstructed
- A heavy SM-like Higgs boson decaying to 4l occurs in several extensions of the scalar sector (2HDM,EWK singlet)
- Limits improve by a factor ~3 with 3000 fb^{-1} wrt 300 fb^{-1}
- Similar sensitivity for ATLAS and CMS (~0.01-0.1 fb)



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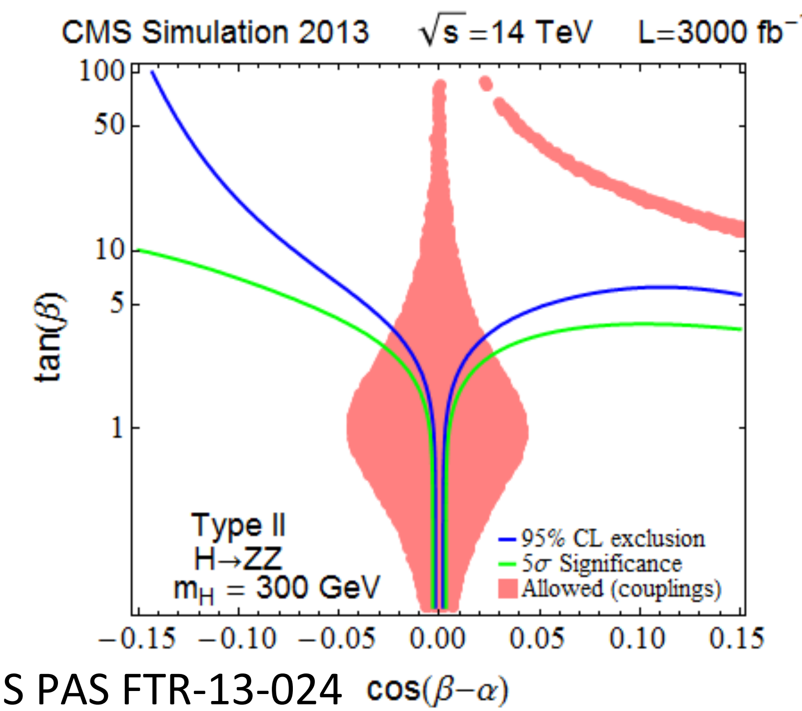


CMS PAS FTR-13-024

HH production and self-coupling

$$V_H = \mu^2 \Phi^\dagger \Phi + \frac{1}{2}\lambda(\Phi^\dagger \Phi)^2 \ ; \quad \lambda = \frac{M_H^2}{v^2} \text{ and } \mu^2 = -\frac{1}{2}M_H^2$$

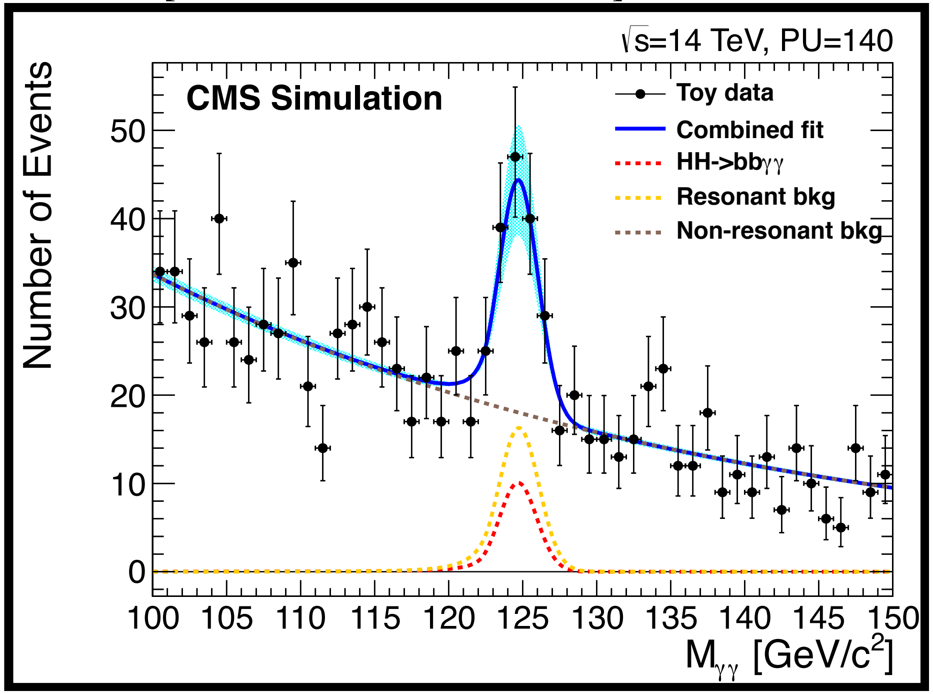
- In the Standard Model, the shape of the Higgs potential is fully determined by the mass of the Higgs boson, now known.
- This is not the case in several BSM implementations ➔ experimental verification is essential, e.g. measuring HH production

- One of the exciting prospects of HL-LHC
  - –Cross section at √s=14 TeV is 40.2 fb [NNLO]
  - –Challenging measurement: small signals and large backgrounds
  - –Preliminary studies performed by ATLAS and CMS are available
  - –Examples: HH→bbγγ, bbττ, bbWW, + many others

See also talk from A. Rizzi, this conference

Double Higgs production

CMS [CERN-LHCC-2015-010]



ATL-PHYS-PUB-2014-019

process	Expected events in 3000 fb^{-1}
SM HH→bbγγ	8.4± 0.1
bbγγ	9.7 ± 1.5
ccγγ, bbγj, bbjj, jjγγ	24.1 ± 2.2
top background	3.4 ± 2.2
ttH(γγ)	6.1 ± 0.5
Z(bb)H(γγ)	2.7 ± 0.1
bbH(γγ)	1.2 ± 0.1
Total background	47.1 ± 3.5
S/√B (barrel+endcap)	1.2
S/√B (split barrel and endcap)	1.3

- Final states investigated: bbγγ, bbττ, bbWW
- CMS estimated accuracy on HH→bbγγ production: 67%
- CMS Combination of HH→bbττ and HH→bbγγ yields a significance of 1.9 standard deviations; measurement accurcay: 54%

- ATLAS HH→bbγγ significance: 1.3 standard deviations

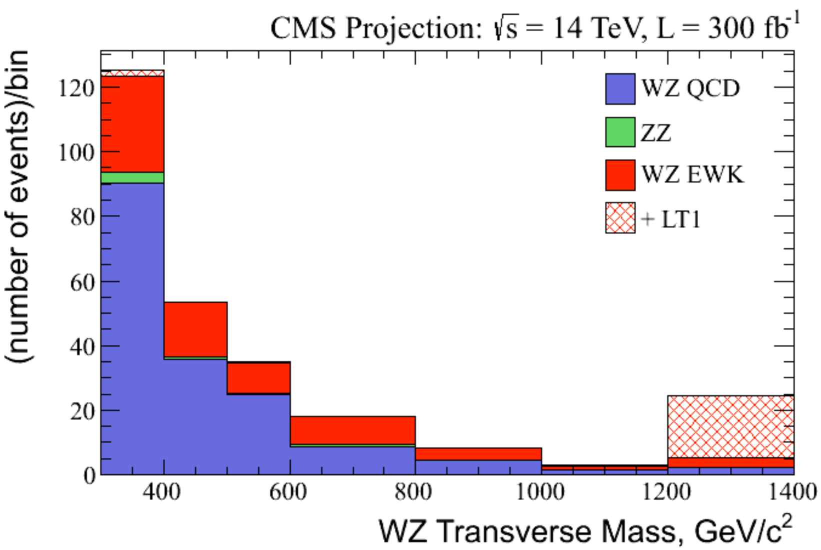
Probing EWK symmetry breaking: QGC

CMS-PAS-FTR-13-006

- In the SM it is the Higgs particle which is responsible for avoiding unitarity violation in the VV cross section at increasing scattering energy.
- It is important to confirm this effect experimentally. Other mechanisms for enhancing/reducing vector boson scattering at high energy are possible, even after the existence of the SM-like Higgs boson is established.
  - Early analyses for HL-LHC made by ATLAS: ATLAS-PHYS-PUB-2012-005
- Recent studies by CMS on *Vector Boson Scattering and Quartic Gauge Coupling Studies in WZ Production at 14 TeV* [CMS-PAS-FTR-13-006]

Probing EWK symmetry breaking: QGC

- EFT approach:
- EFT for modelling aQGCs (no new physics (yet) at the LHC)
- Operator: $L_{T1} = (f_{T1}/\Lambda^4) Tr[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] Tr[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$,
  - involves direct interaction of the gauge boson fields via a field strength tensor operator



WZ transverse mass with 300 fb $^{-1}$.

Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
f_{T1}/Λ^4 at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}

Sensitivities for SM EWK scattering discovery and aQGC. The integrated luminosities for SM EWK discovery at 3σ and 5σ are reported while aQGC prospects for discovery are given in terms of the L_{T1} operator coupling constant

Anomalous couplings studies also by ATLAS: ATL-PHYS-PUB-2013-006

For 3000 fb^{-1} the expected sensitivity to aQGC at 3σ is $f_{T1}/\Lambda^4 = 0.45$ TeV^{-4}, and at 5σ is $f_{T1}/\Lambda^4 = 0.55$ TeV^{-4} using a proposed CMS Phase-2 detector configuration without extended acceptance.

Probing EWK symmetry breaking: QGC

- ATLAS also studied aQGCs from ZZjj, WWjj, WZjj (all VBS) and Z$\gamma\gamma$ for 300 fb^{-1} and 3000 fb^{-1}, at HL-LHC

ATL-PHYS-PUB-2013-006

Parameter	dimension	channel	300 fb^{-1} 5σ	3000 fb^{-1} 5σ
$c_{\phi W}/\Lambda^2$	6	ZZ	34 TeV^{-2}	16 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	10 TeV^{-4}	4.5 TeV^{-4}
f_{T1}/Λ^4	8	WZ	1.3 TeV^{-4}	0.6 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	0.9 TeV^{-4}	0.4 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	2.0 TeV^{-4}	0.7 TeV^{-4}

- The higher integrated luminosity increases the discovery potential for the operators's coefficients here studied by more than a factor of two to three, from 2.0 TeV^{-4} to 0.7 TeV^{-4}

Conclusions

- A Higgs boson SM-like discovered in 2012. Its mass is 125.09 ± 0.24 GeV.
- Standard Model: from "model" to "theory" status
- A data sample of 300 fb^{-1} at the LHC will allow to exclude strong deviations of the Higgs-like particle recently discovered from the Higgs boson predicted by Standard Model
- A complete investigation on the physics properties of this new boson will require the search for rare decay final states, selfcoupling processes, CP violation effects, as well as the reduction of experimental (and theoretical) uncertainties ➔ High-Luminosity LHC with L=3000 fb^{-1} can provide the required statistics with an accuracy on the Higgs couplings in the range of 1-4%;
- HL-LHC extends the searches of LHC of BSM physics, and offers the required data to study the properties of new particles if found at the LHC

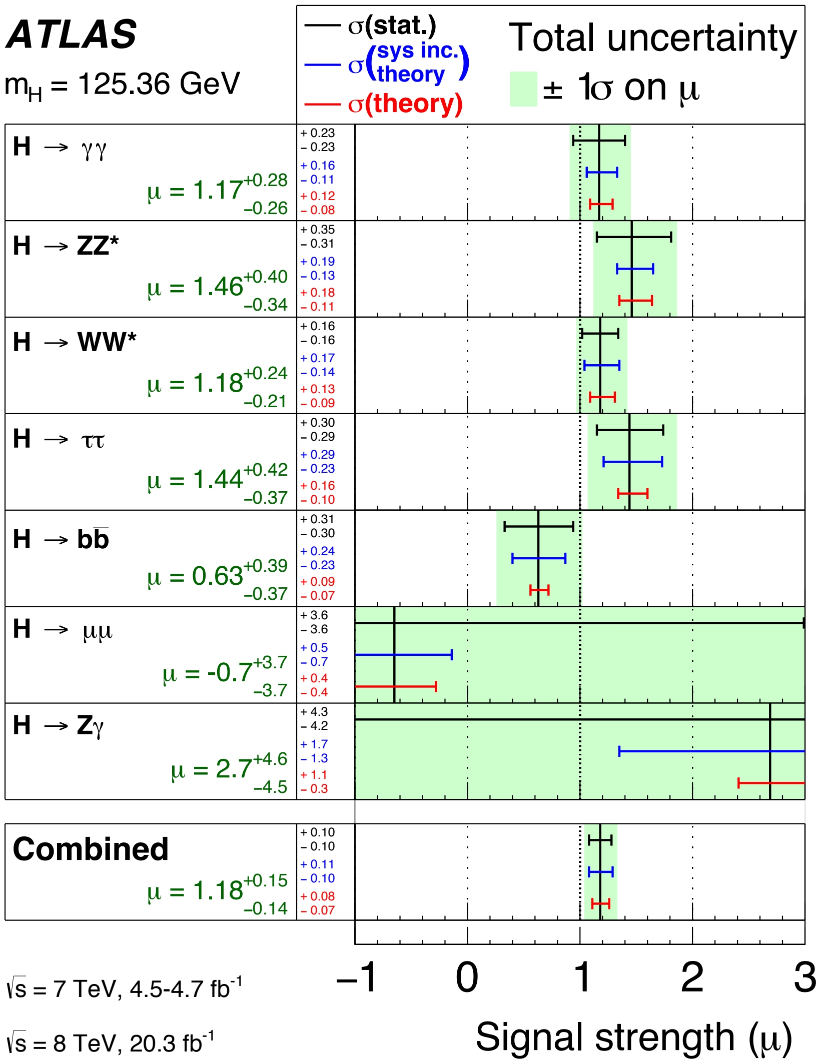
Outlook

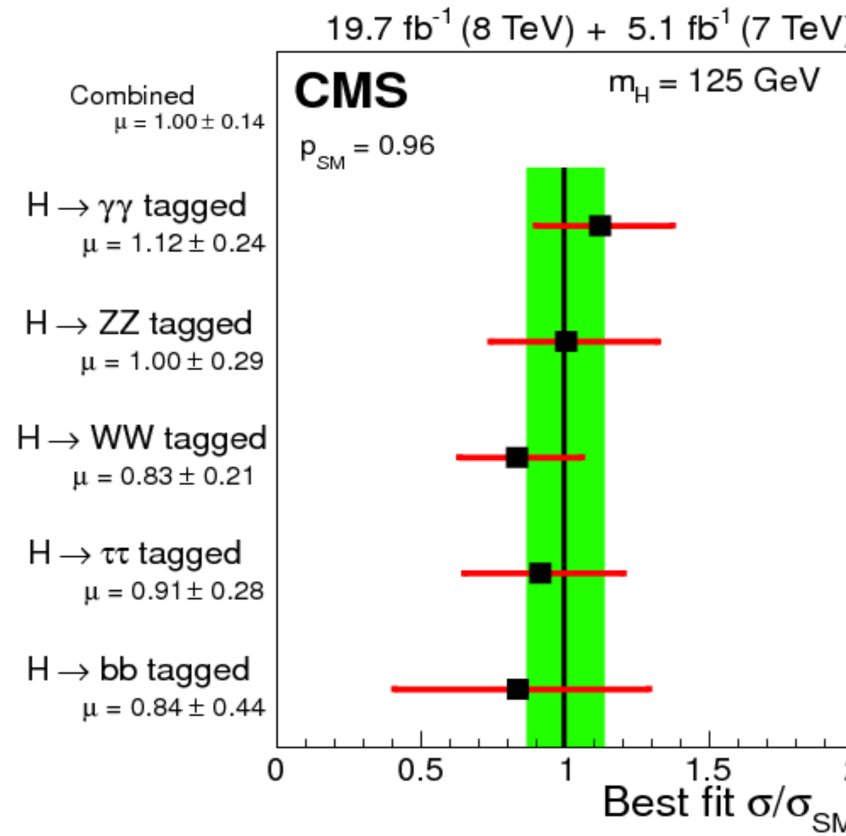
- LHC Run2-100 fb^{-1}:
  - observation of H→bb;
  - Evidence for ttH
  - Differential cross sections
- LHC Run2+3 300 fb^{-1}:
  - Probably observation of ttH
  - Evidence H→μμ
  - Precision measurement of Higgs couplings at the level of 10 %
- HL-LHC 3000 fb^{-1}:
  - Observation ttH
  - Observation of (SM) H→μμ and H→Zγ
  - Precision measurement of Higgs couplings at the level of few %
  - **Evidence for HH production**

backup

Signal strength combination: decays

- Assume SM values for ratios between different production cross sections





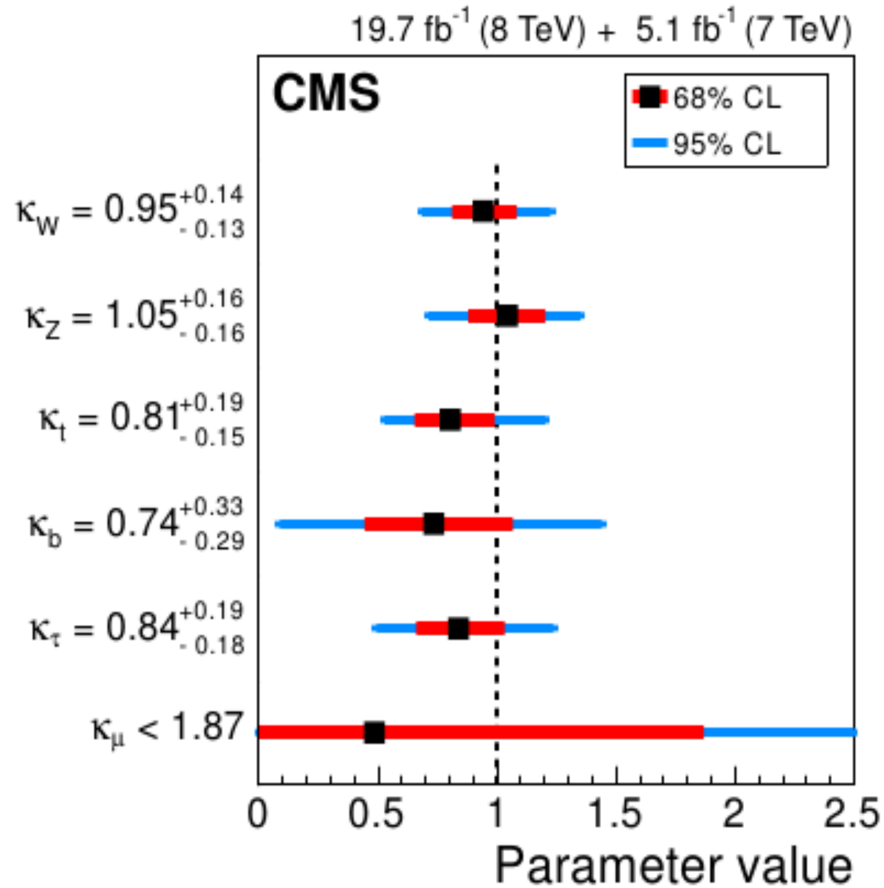
$\mu(\text{ATLAS}) = 1.18^{+0.15}_{-0.14}$
$\mu(\text{CMS}) = 1.00 \pm 0.14$

- Results are fully consistent with SM predictions

See also talk from M. Pieri, this conference

Absolute couplings

- Absolute coupling determination needs some theory assumption, for example assume no BSM Higgs boson decay, and no BSM particles in the gg→H, H→γγ and H→Zγ loops
- All results compatible between ATLAS and CMS, and with SM



Coupling fit (when performing the scan for one parameter, the other parameters in the model are profiled)

Future projects allow precision in the sub-percent range

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs) FCC-ee (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

Table 11: *Expected precisions on the Higgs coupling scaling factors from a constrained 7-parameter fit assuming no non-SM production or decay modes, and $\kappa_i \equiv g_{hii}/g_{hii}^{(SM)}$. The fit assumes generation universality* [34].

HH study requires >1 TeV e+e- collider or FCC-hh

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κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
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κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
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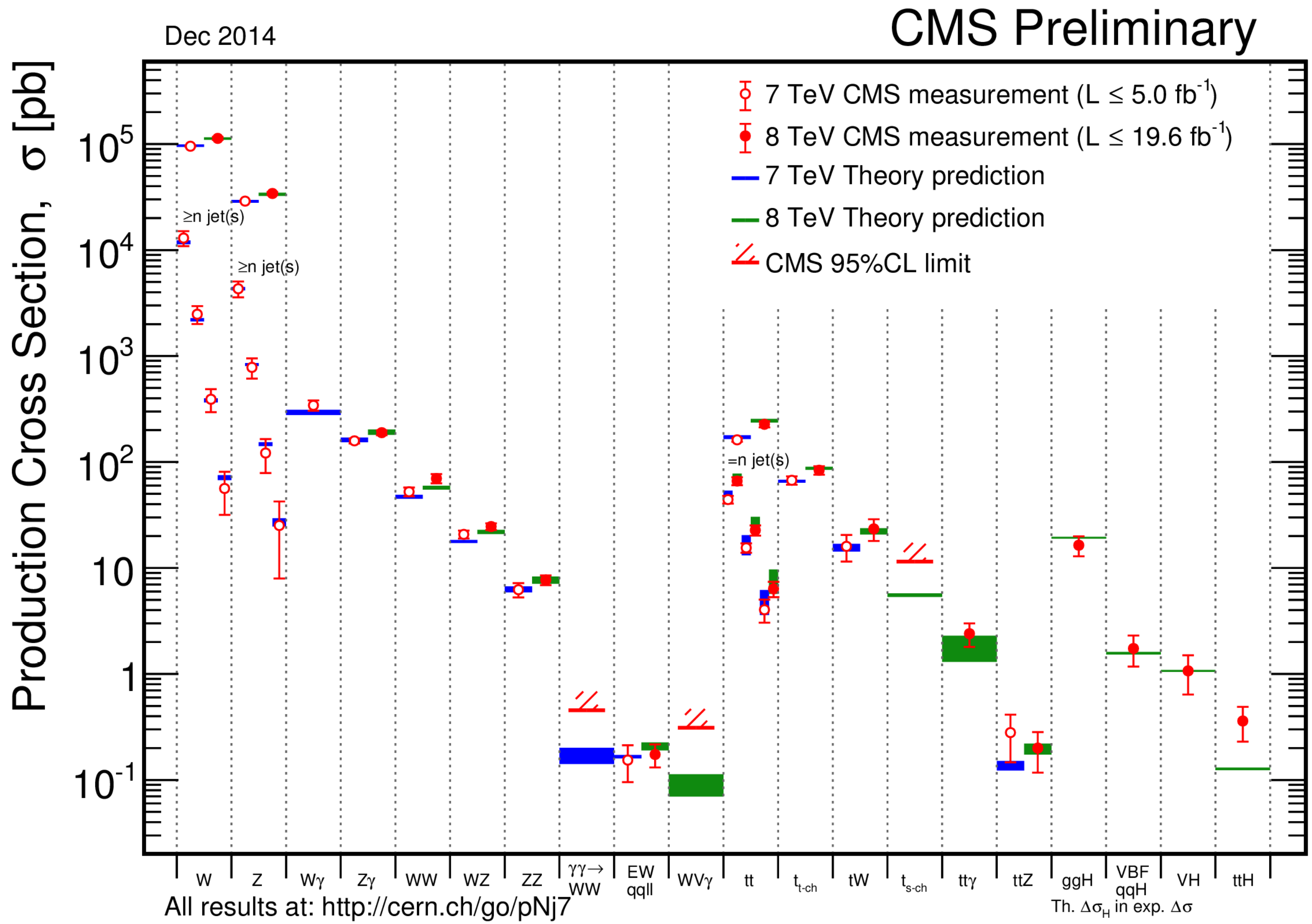
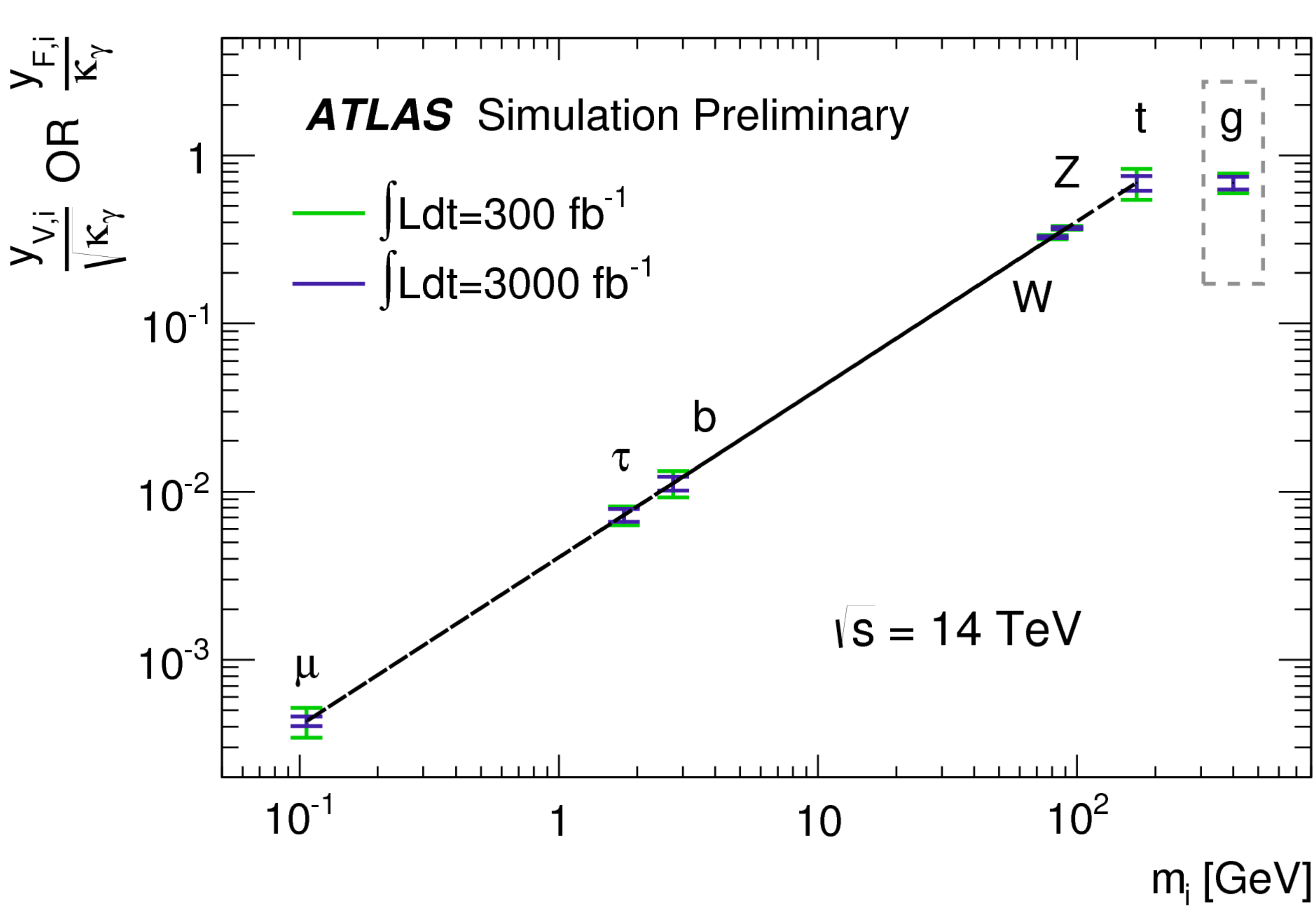
HH study requires >1 TeV e+e- collider or FCC-hh

but need to wait for LHC data at 13-14 TeV before discussing the best solution for future colliders after LHC

The SM @ LHC

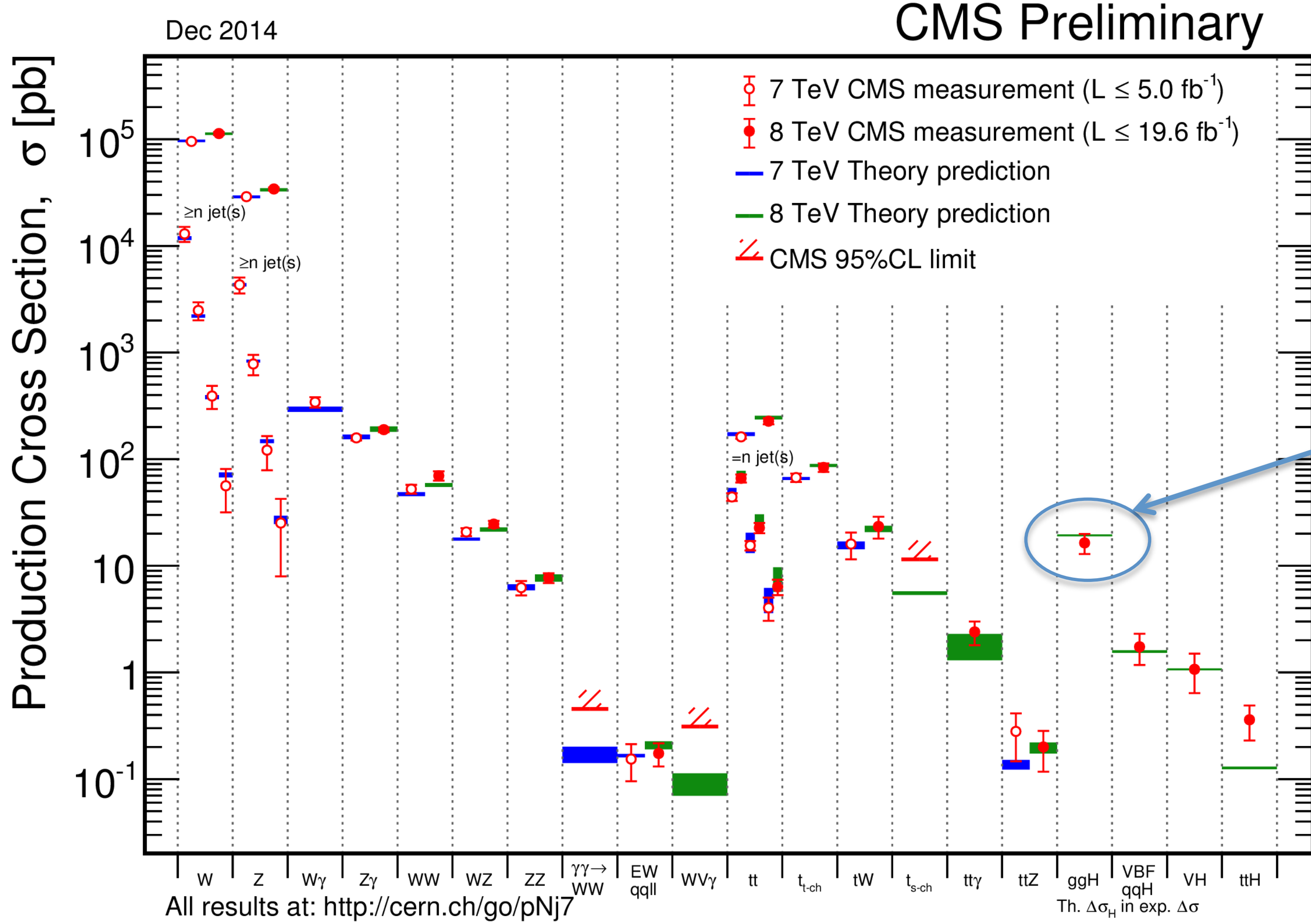


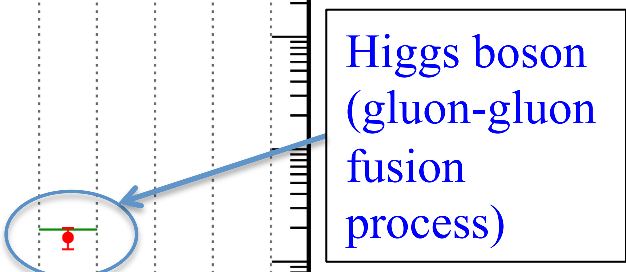
- We have a good understanding/assessment of the Standard Model process at LHC
- Crucial for precision measurement, assesessment of the 125 GeV Higgs boson, and New Physics searches



Fit results for ratios of reduced coupling scaled factors to the photon coupling, $y_{V,i}$ / $\sqrt{\kappa_\gamma}$ for weak bosons and $y_{F,i}$ / κ_γ for fermions, as a function of the mass of particle i, assuming 300/fb and 3000/fb at 14 TeV and a SM Higgs boson with a mass of 125 GeV.

The SM @ LHC





- We have a good understanding/assesment of the Standard Model process at LHC
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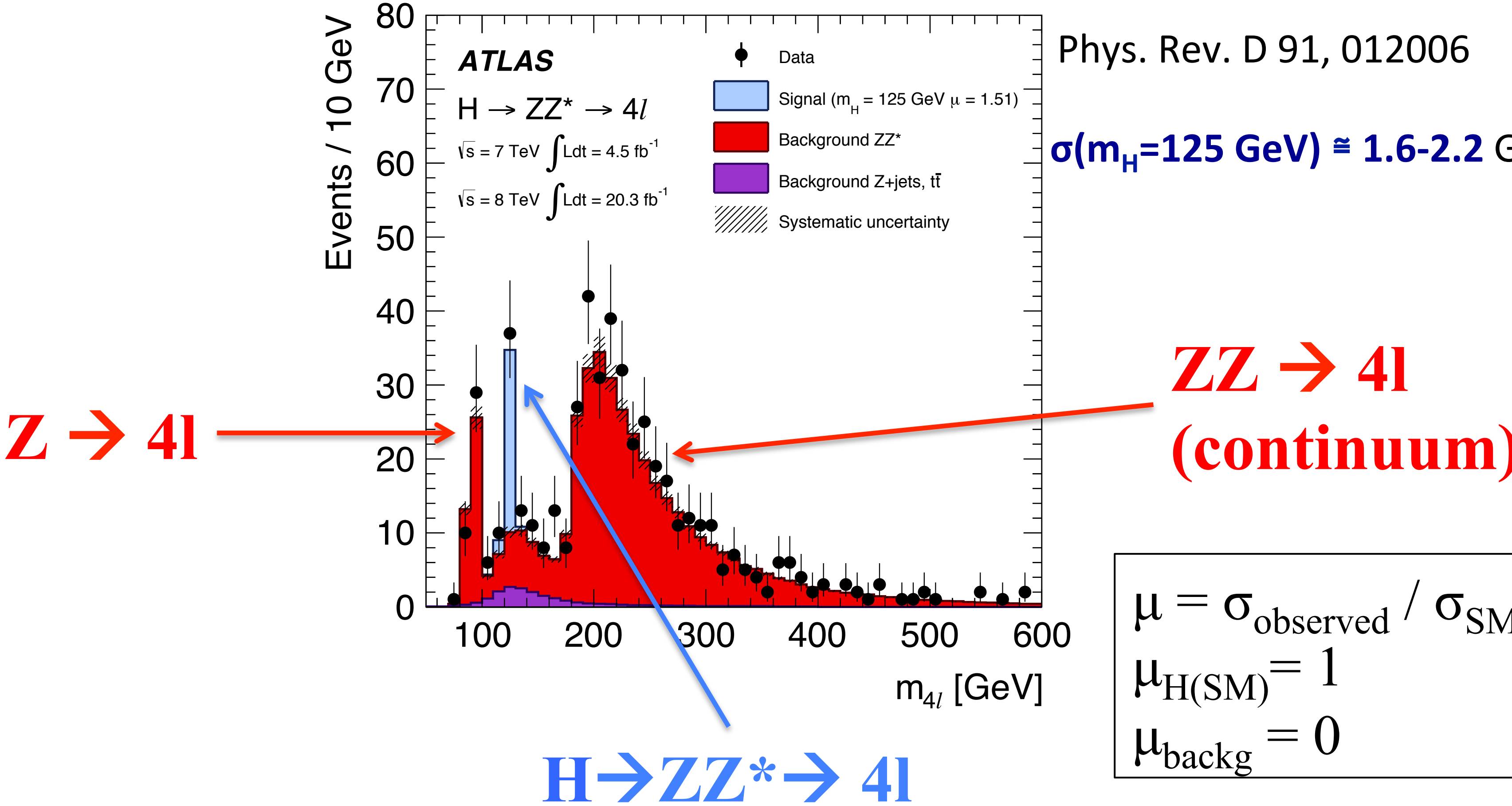
$H \rightarrow ZZ^* \rightarrow 4l$



Phys. Rev. D 91, 012006

$\sigma(m_H=125\ \text{GeV}) \cong 1.6\text{-}2.2$ GeV

$\mu = \sigma_{observed} / \sigma_{SM}$

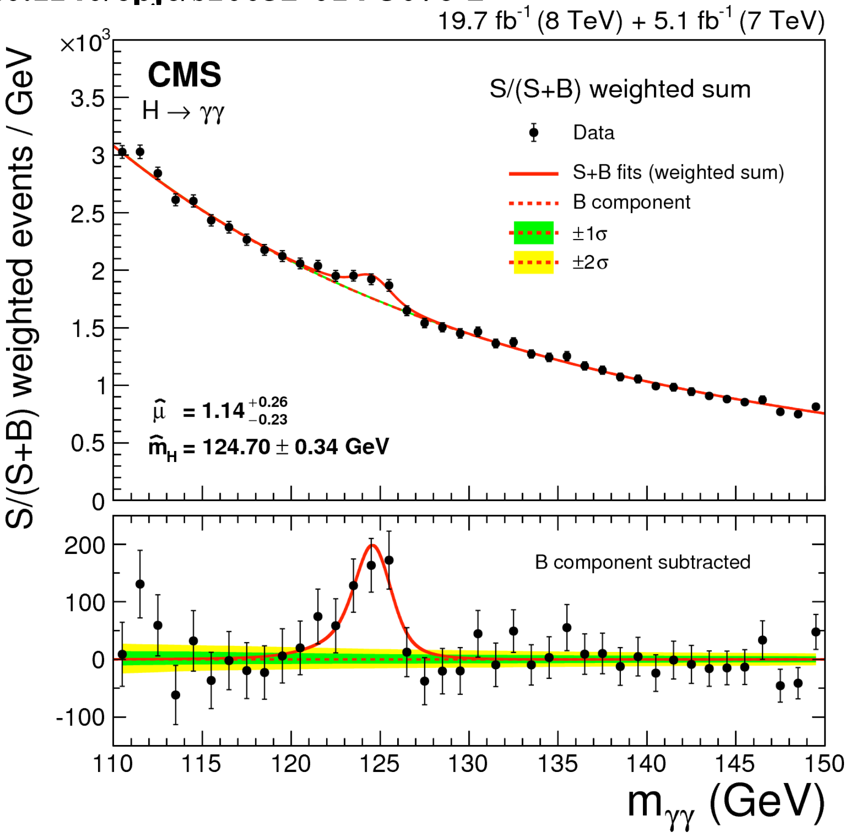
$\mu_{H(SM)} = 1$

$\mu_{backg} = 0$

The distribution of the four-lepton invariant mass, $m_{4\ell}$. The signal expectation shown is for a mass hypothesis of m_H=125 GeV

H→γγ

10.1140/epjc/s10052-014-3076-z



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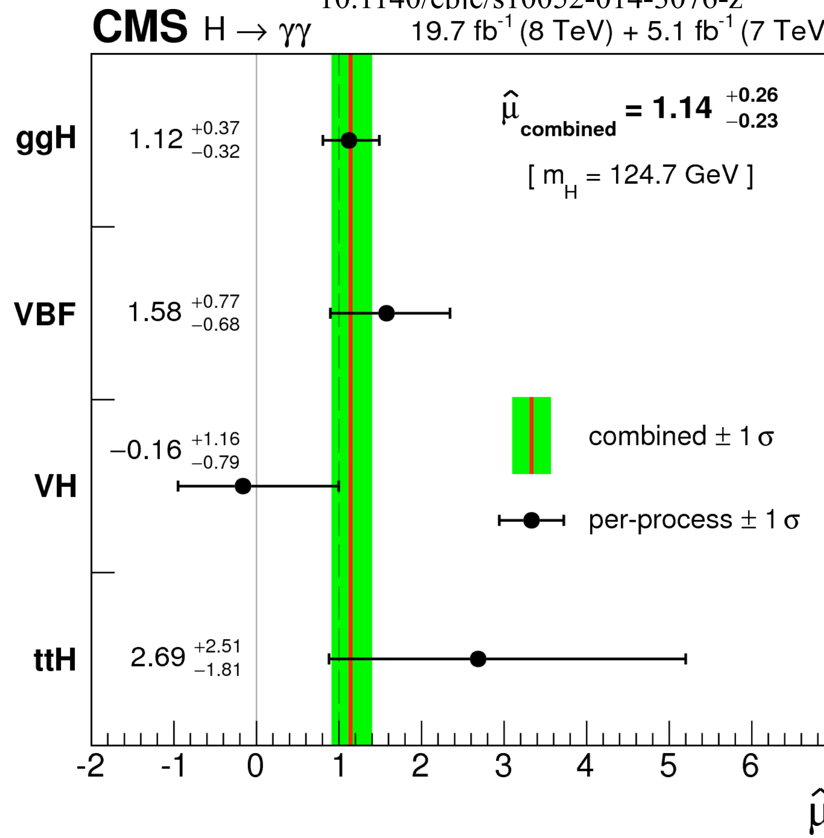
10.1140/epjc/s10052-014-3076-z



Background + Signal fit Sum of the $m_{\gamma\gamma}$ distribution from the 7 and 8 TeV datasets, together with the data binned.

Best-fit signal strength, $\hat{\mu}$