Istituto Nazionale di Fisica Nucleare
Sezione di Bari

HL-LHC & challenges for CEPC - Higgs

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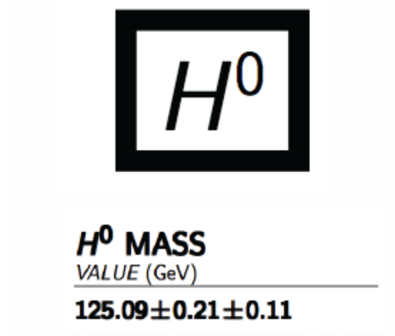
On behalf of RD_FA INFN collaboration

IHEP, November 6-8, 2017, Beijing

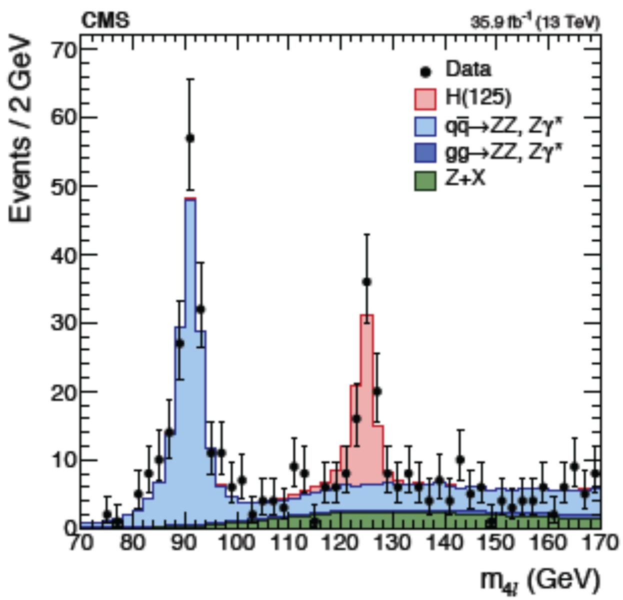
Higgs @ LHC Run 2

- Re-discovery of the Higgs
- measur. Higgs properties
  - cross section (also differential)
  - mass & width
  - couplings:
    - to gauge bosons, to fermions
    - tensor structure and effective couplings in the lagrangian
    - ttH couplings
  - Searches for BSM Higgs

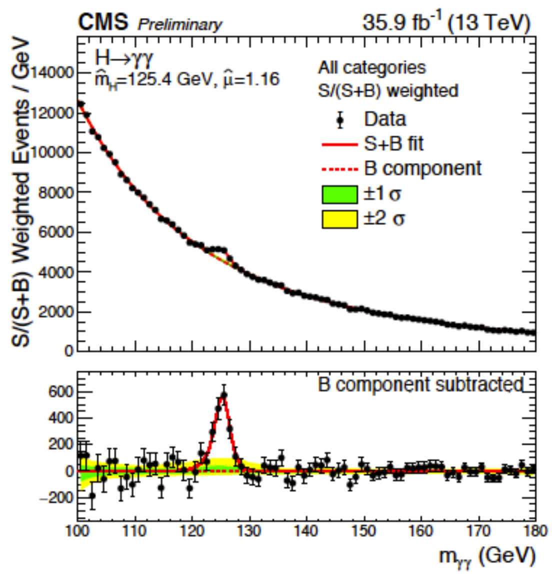


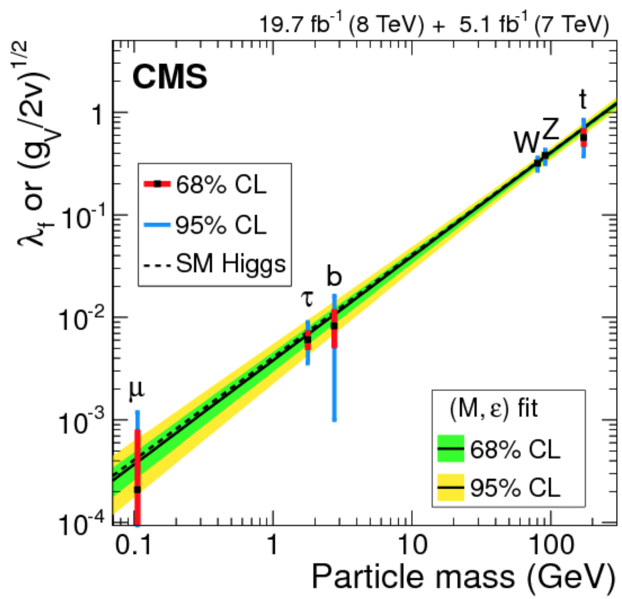
- Mass measured to 0.2%
- Main couplings to ~10%

HIG-16-041



HIG-16-040

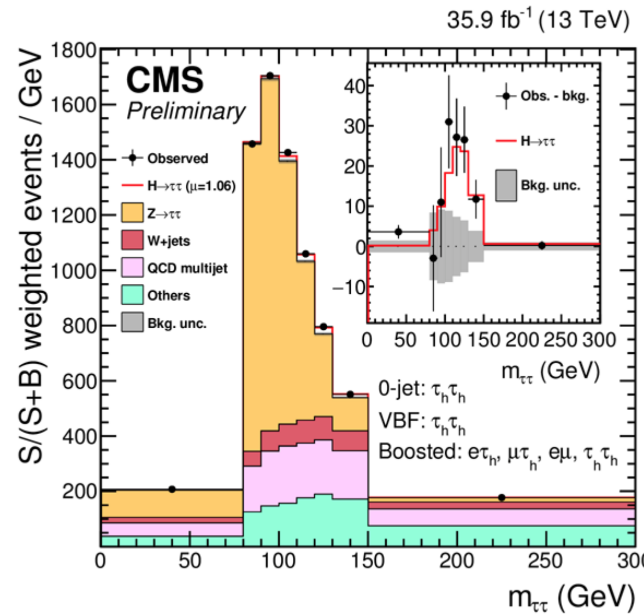




Higgs @ LHC Run 2

H→ ττ :

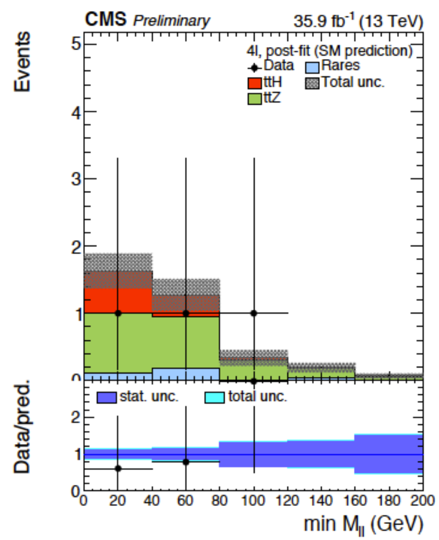
Observation of the SM scalar boson decaying to a pair of τ leptons with the CMS experiment at the LHC (**4.9σ** *vs* 4.7σ expected) → HIG-16-043

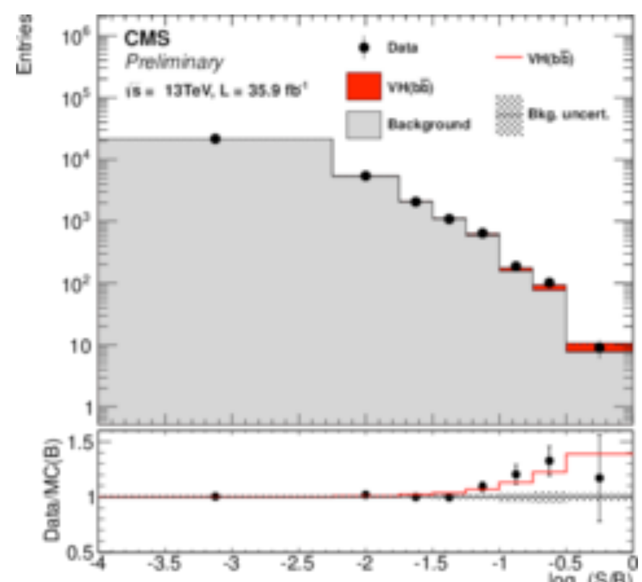


H→bb :

CMS has **3.8σ** evidence (3.8σ expected) for Higgs boson decays to b-quarks and for its production in association with a vector boson → HIG-16-044, arXiv:1709.07497 submitted to Physics Letters B

ttH→ZZ,WW,ττ → multi-leptons: evidence observed (expected) significance of **3.3σ** (2.5σ), by the combination of the 2016 results with 2015 → HIG-17-004





* Similar results from ATLAS

Physics landscape by 2017

A puzzle:

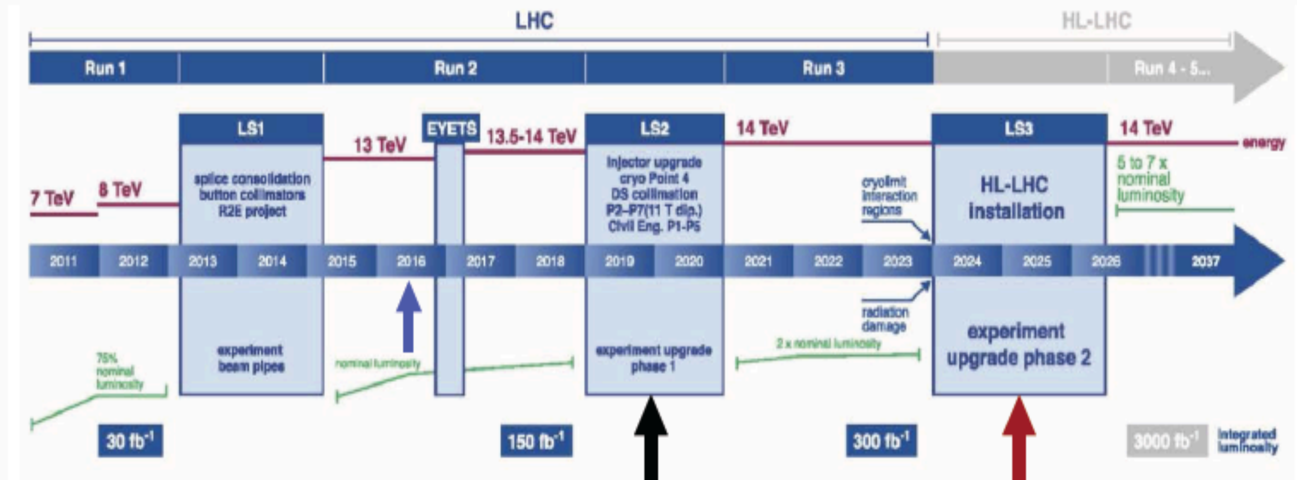
LHC experiments confirms that the SM is strong but is not the ultimate theory of particle physics, because of the many outstanding questions:

- *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 ?*
- *etc…*

→ Run3 + HL-LHC

LHC and HL-LHC

- LHC
  - 300 fb^{-1} by 2023
    - 30 fb^{-1} Run 1
    - >100 fb^{-1} so far
    - …
- HL-LHC
  - ~3000 fb^{-1} by ~2035



LS2 (2019-2020):
- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment @ P1,P5
- ❑ First 11 T dipoles P7; cryogenics in P4
- ❑ Phase-1 upgrade of LHC experiments

LS3 (2024-2026):
- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

ATLAS, CMS Upgrade plan

$8x10^{33}$ Hz/cm^2
30 fb^{-1}
PU ~40

LS1

$2x10^{34}$ Hz/cm^2
300 fb^{-1}
PU ~50

Phase 1 Upgrade

$5x10^{34}$ Hz/cm^2
3000 fb^{-1}
PU ~140

LS3

Phase 2 Upgrade

HL-LHC and Phase II upgrades

Phase II Detector Upgrades:

Significant upgrades of ATLAS and CMS for HL-LHC conditions

- Radiation hardness
- Mitigate physics impact of high pileup

Higgs@HL-LHC:

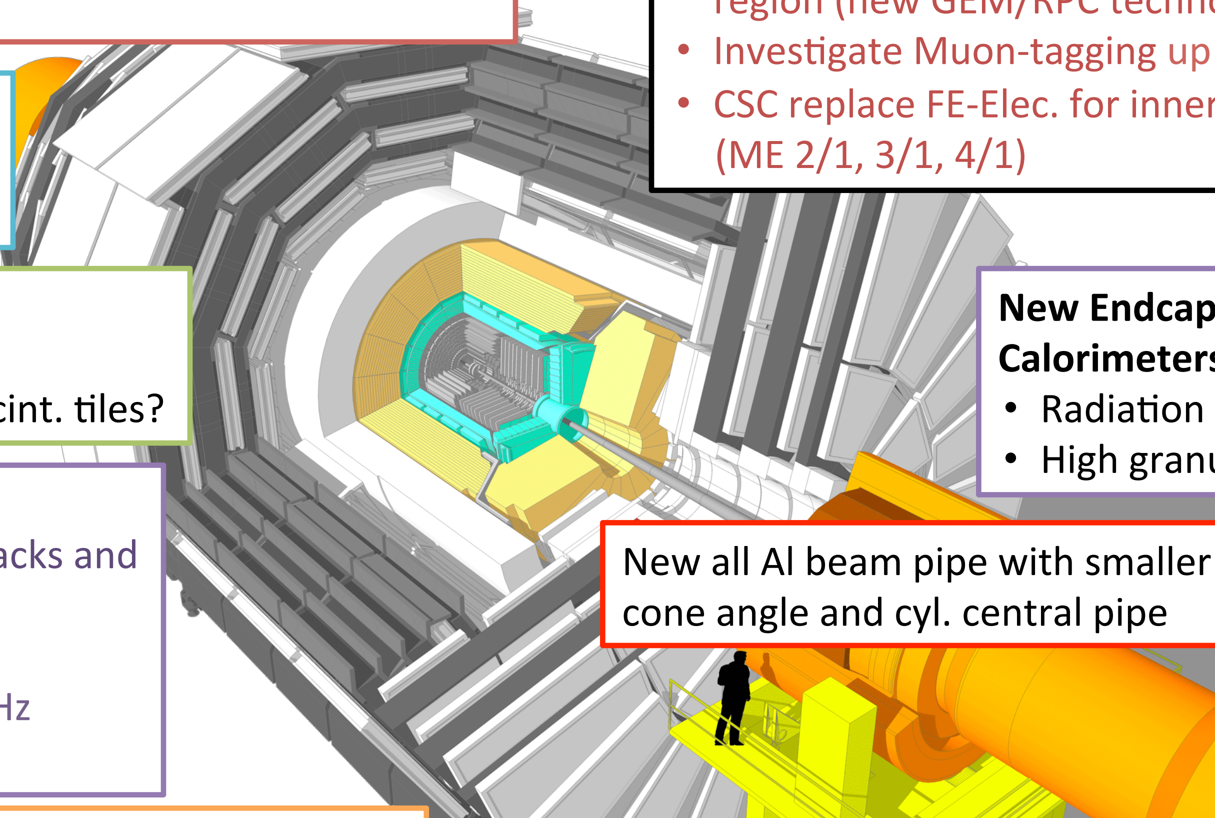
- Precision Measurements (Couplings, Cross Sections, Width, Differential Distributions,…)
- Rare decays and couplings
- Di-Higgs production ➜ self coupling
- BSM Higgs searches: extra scalars, BSM Higgs resonances, exotic decays, anomalous couplings
- VV scattering

CMS Phase 2 upgrade

New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 3
- CSC replace FE-Elec. for inner rings (ME 2/1, 3/1, 4/1)

Barrel ECAL
- Replace FE electronics
- Cool detector/APDs



Barrel HCAL
- Replace HPD by SiPM
- Replace inner layers scint. tiles?

New Endcap Calorimeters
- Radiation tolerant
- High granularity

New all Al beam pipe with smaller cone angle and cyl. central pipe

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 µs
- HLT output rate 7.5 kHz
- New DAQ hardware

Other R&D
- Fast-timing for in-time pileup suppression

Modeling the projections for HL-LHC: ECFA 16

Snowmass '13, ECFA '13, ECFA '16

Goal to **keep** the current performance with the detector and software upgrades

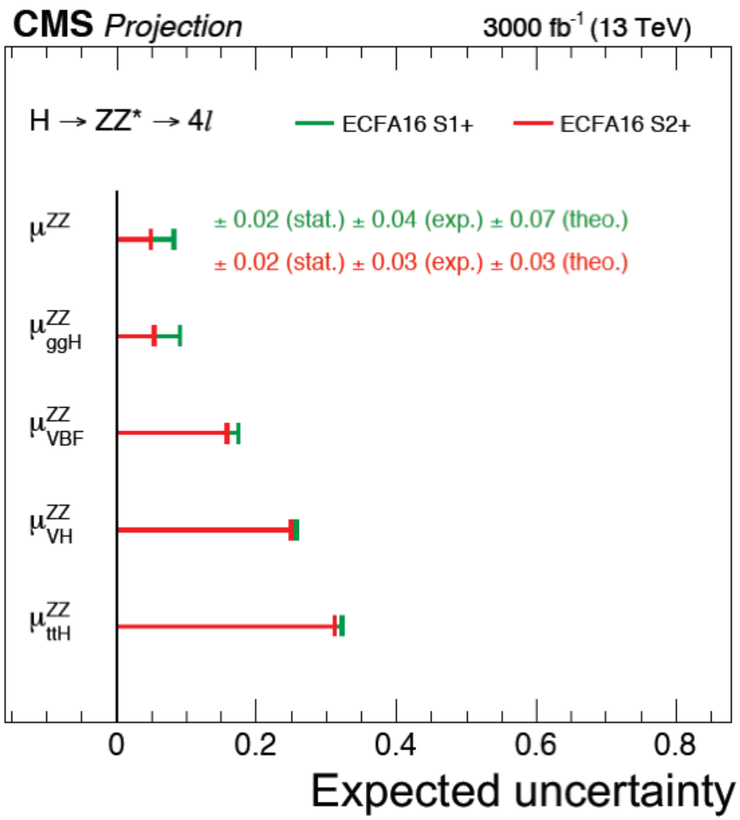
ATLAS:

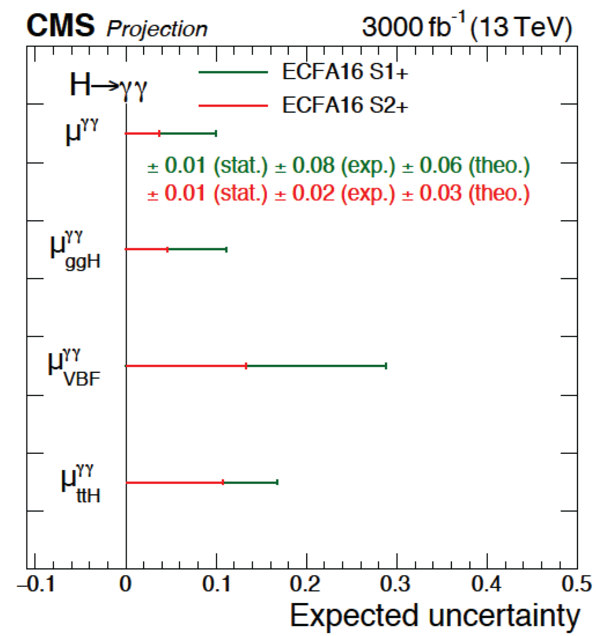
- parametrisation of the detector response (**FAST SIMULATION**) to mimic the effects on selection efficiency and resolution, derived from:
  - full Run 2 detector simulation with pile-up up to $\langle\mu\rangle = 69$
  - full Phase II detector options for $\langle\mu\rangle = 140, 200$ for HL-LHC
- 2 scenarios for uncertainties:
  - systematics based on Run 2, improvements from stat.
  - theory systematics scaled by 1, 0.5 or 0 factor
  - PU and detector upgrades taken into account

CMS:

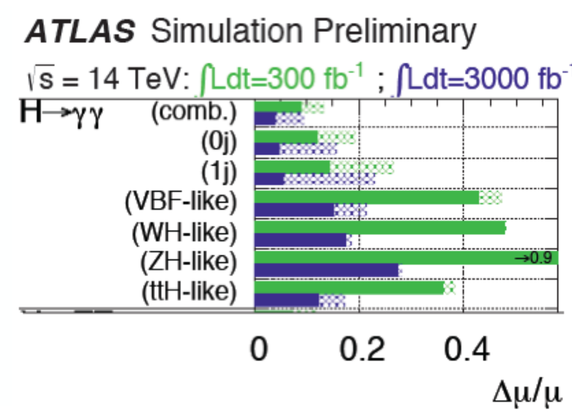
- rescaling of run 2 signal and background yields for 14 TeV with the assumption that current detector performance kept after upgrades.
- 2scenarios for uncertainties:
  - Scenario 1: all systematic uncertainties are kept unchanged with respect to those in current data analyses + PU/detector upgrades (S1+)
  - Scenario 2: the theoretical uncertainties are scaled by a factor of 1/2, while other systematical uncertainties are scaled by $1/\sqrt{L}$ + PU/detector upgrades (S2+)

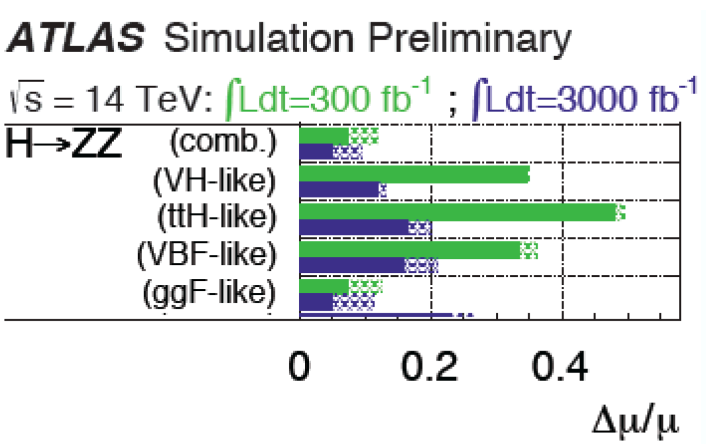
Higgs signal strength: $\mu=\sigma/\sigma_{SM}$ - 3000 fb^{-1}





ECFA 16

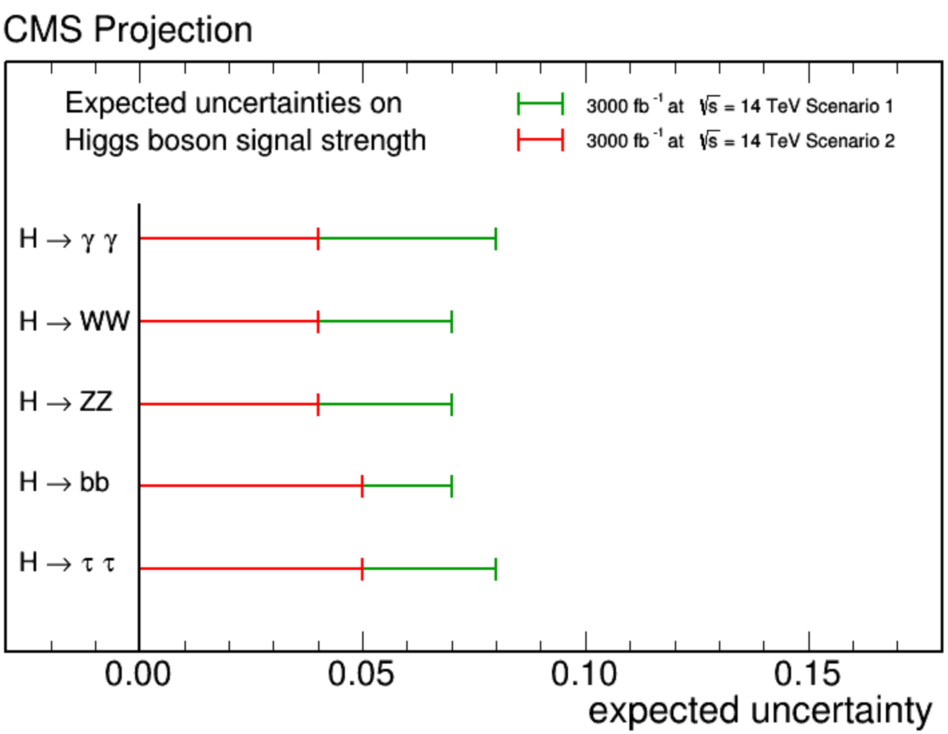


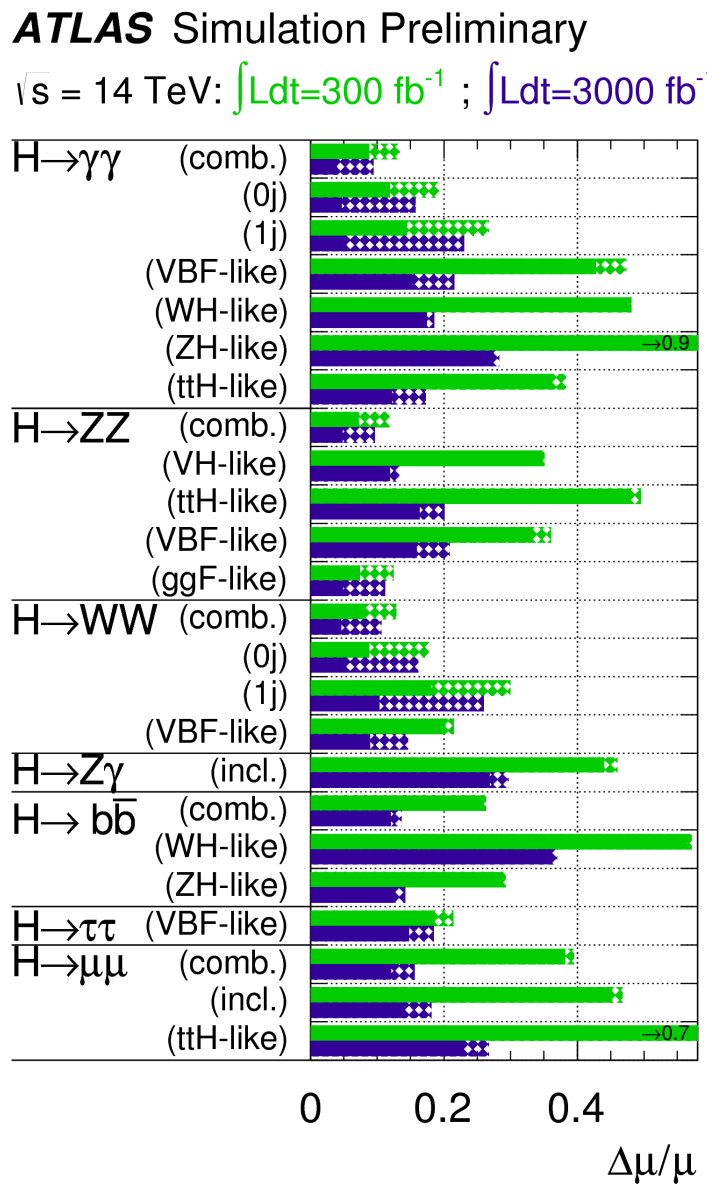


- Similar expected sensitivities between the two experiments
- Precision larger than 5-10%

Higgs signal strength: $\mu=\sigma/\sigma_{SM}$ - 3000 fb^{-1}

Snowmass13 arXiv:1307.7135v2





- Similar expected sensitivities between the two experiments

Higgs couplings formalism

LHC Higgs Xsection WG - arXiv:1307.1347v2

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

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

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

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

- 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

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

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

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

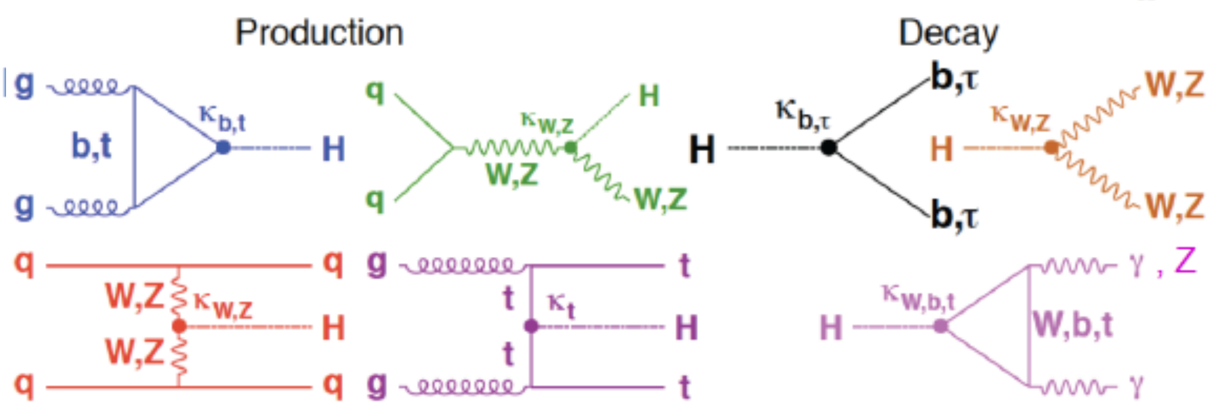
$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

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

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

Total width

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



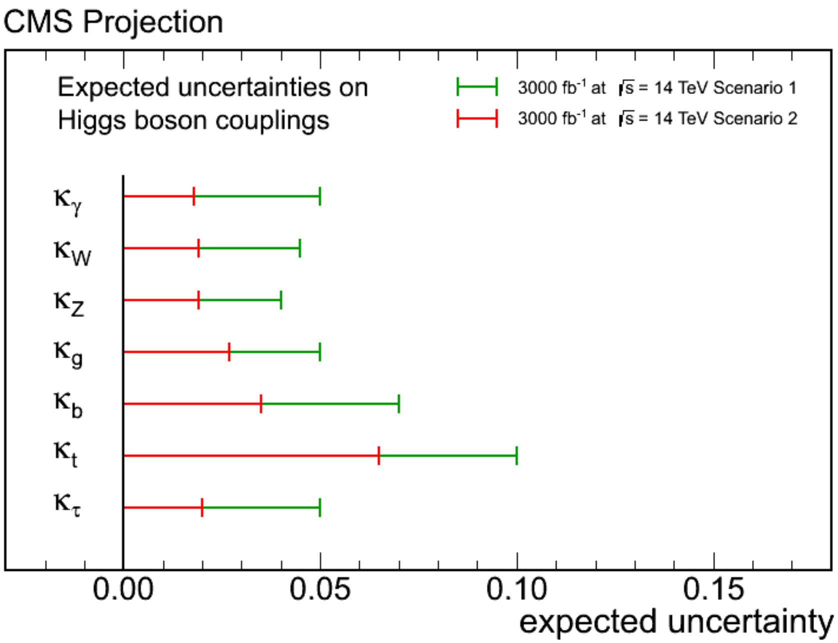
$$\Gamma_H = \Sigma_{SM}\, \Gamma_Y \quad (+\, \Gamma_{BSM})$$

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

Higgs couplings scale factors – 3000 fb^{-1}

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

Snowmass13 arXiv:1307.7135v2



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

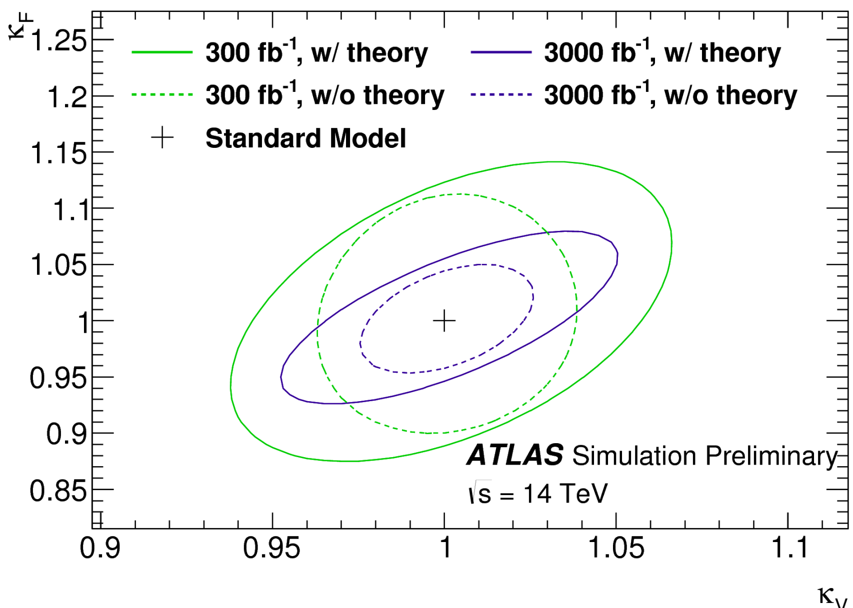
$\sigma(\kappa_V) \approx 3\text{-}5\%$ $\sigma(\kappa_F) \approx 5\text{-}10\%$

Minimal coupling fit:

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

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

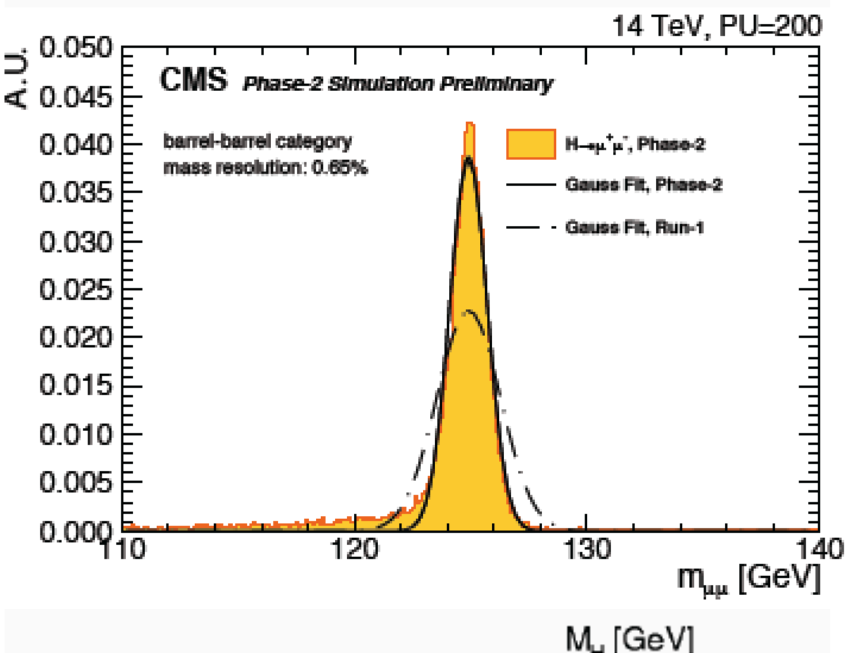
Full line: Scenario 1
Dotted line: Scenario 3

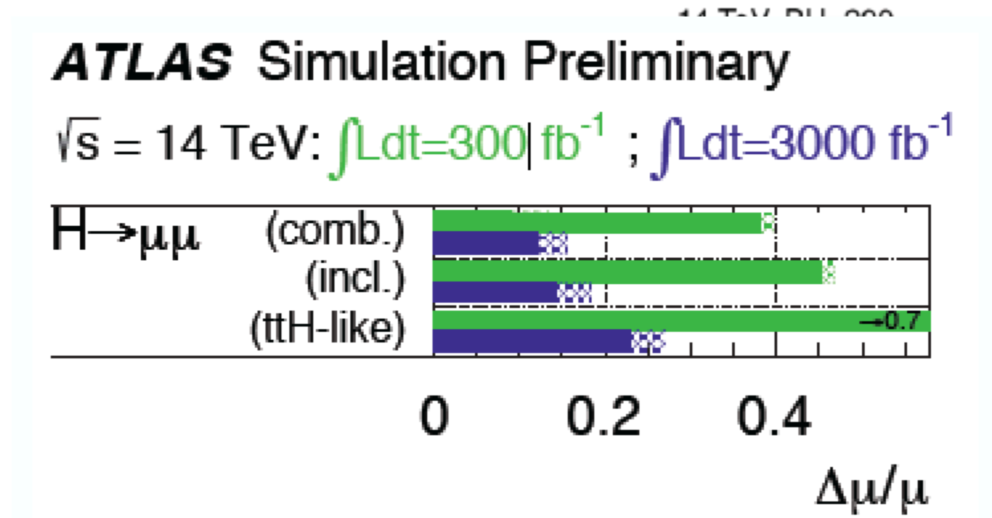


ATLAS: Couplings can be determined with 5 % precision at 3000 fb^{-1}

Rare decays: H→μμ

- **High statistics: rare decays become accessible**
  - 2 OS sign isolated muons, resonant peak at the Higgs mass, very clear signature
  - BR(H→μμ)=0.022. Only visible at HL-LHC
  - CMS projections from Run1: 16% precision on signal strength at 3000 fb^{-1}
  - With improved Phase2 detector:
    mass resolution <1%, uncertainty on H→μμ coupling <5%

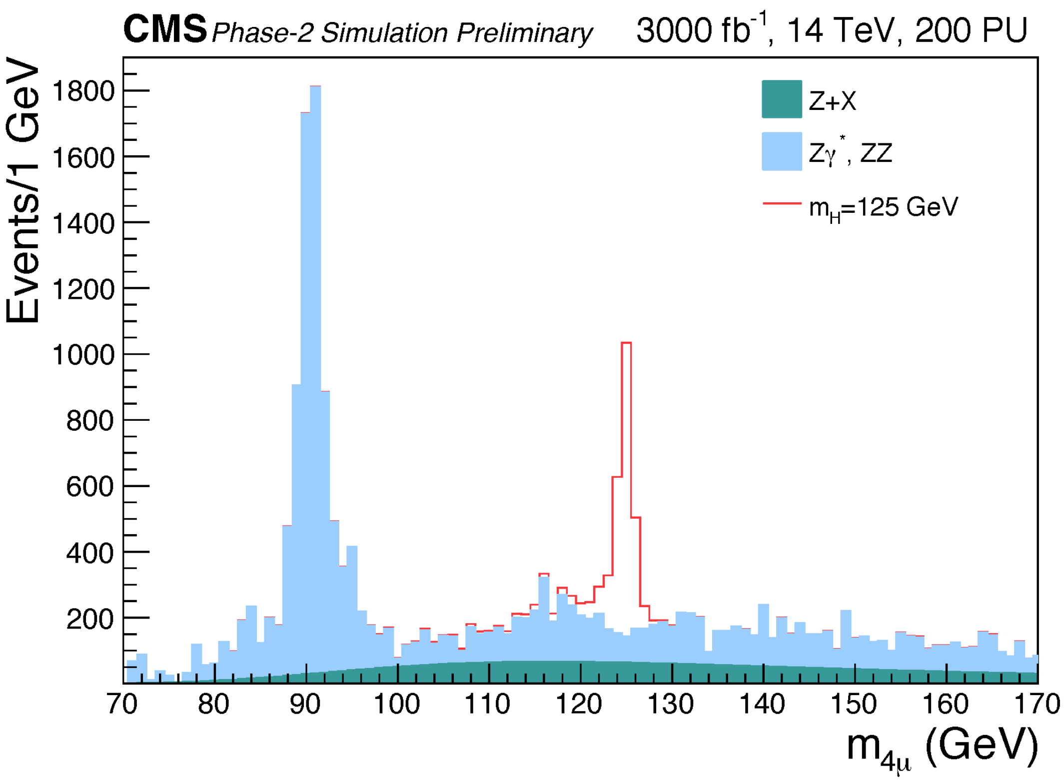


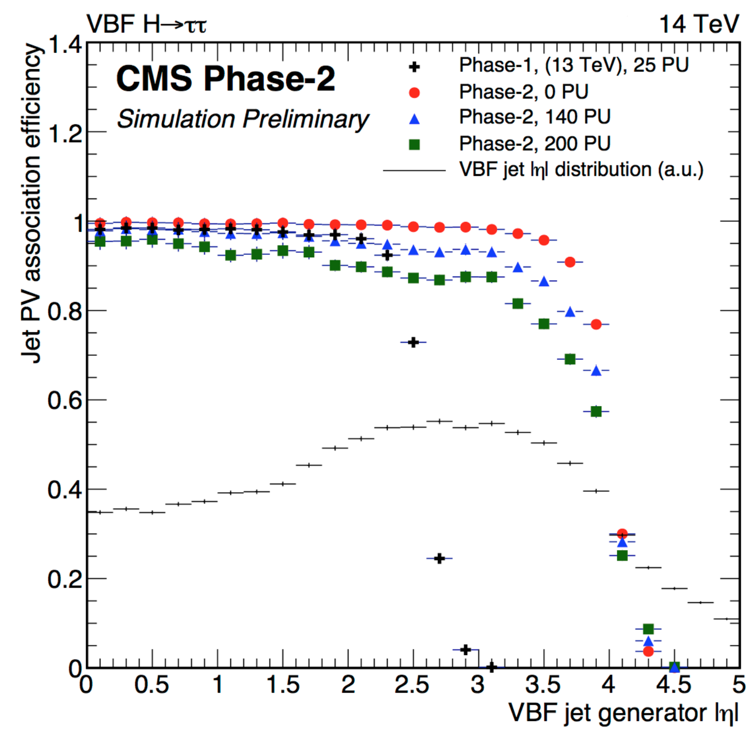


2017 Phase 2 Upgrade TDRs

Not only projections!

- Tracker, Muon, Barrel Calorimeter, Endcap Calorimeters TDRs, DAQ, Trigger and Timing detectors ID in the pipeline
- Focus on detector performance with full simulation updates





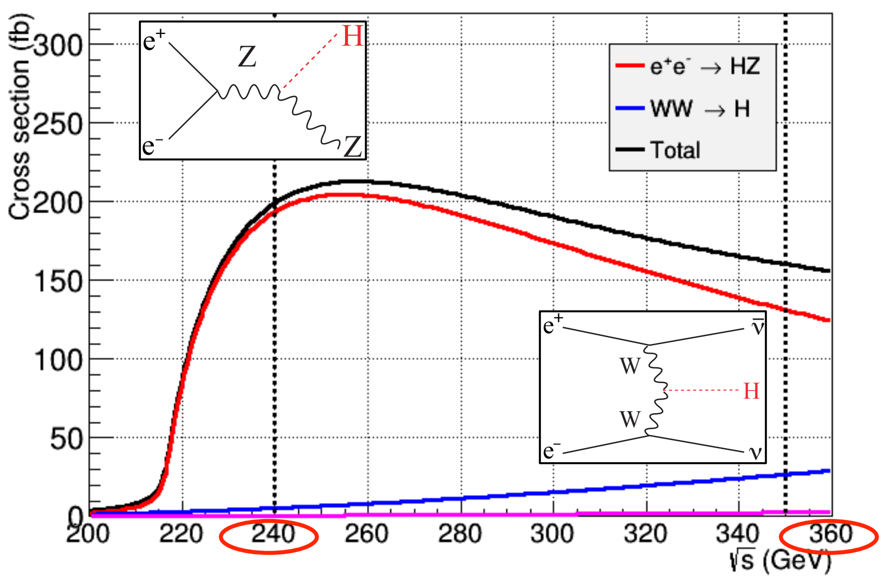
Higgs studies for CepC

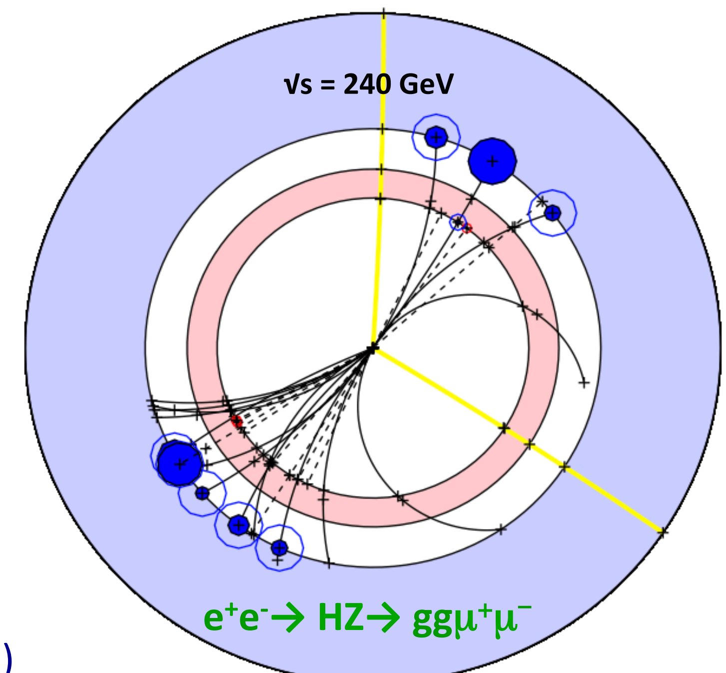
CepC motivation

e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be

FCC-ee/CepC: focus on a 90-250 GeV e^+e^- machine (100 km circumf.)
5 ab^{-1} integrated luminosity to two detectors over 10 years → 10^6 clean Higgs events
→ FCC-ee/CEPC measure the Higgs boson production cross sections and most of its properties with precisions far beyond achievable at the LHC

- Higgs-strahlung (m_H = 125 GeV)



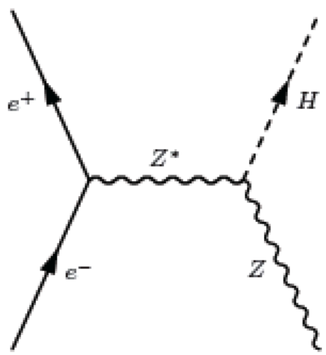


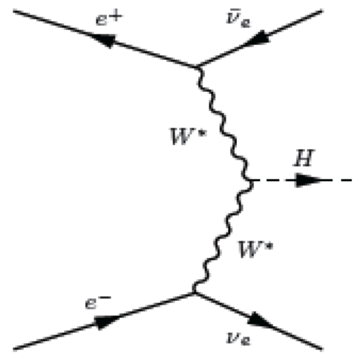
- The gluon can be studied with Higgs decays (BR ~ 10%)

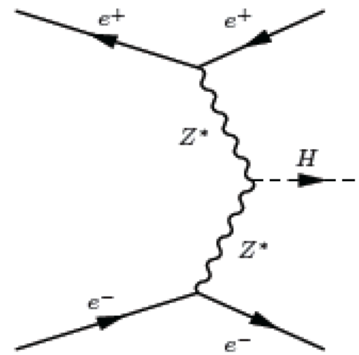
Higgs production at CepC

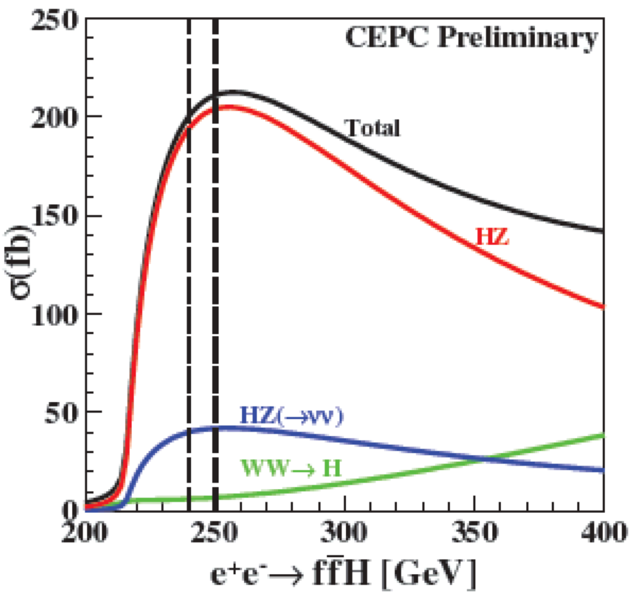
Higgs-strahlung or $e^+e^- \to ZH$

VBF production: $e^+e^- \to \nu\nu H$ (WW fus.), $e^+e^- \to He^+e^-$ (ZZ fus.)

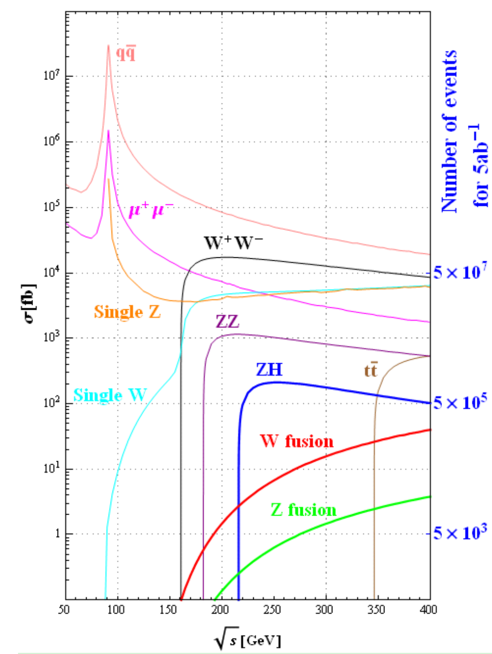








Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6
Background processes, cross section in pb		
$e^+e^- \to e^+e^-$ (Bhabha)	25.1	1.3×10^8
$e^+e^- \to q\bar{q}$	50.2	2.5×10^8
$e^+e^- \to \mu\mu$ (or $\tau\tau$)	4.40	2.2×10^7
$e^+e^- \to WW$	15.4	7.7×10^7
$e^+e^- \to ZZ$	1.03	5.2×10^6
$e^+e^- \to eeZ$	4.73	2.4×10^7
$e^+e^- \to e\nu W$	5.14	2.6×10^7



CepC Higgs factory: $\sqrt{s}$ = 240 GeV

Model-independent precision measurements

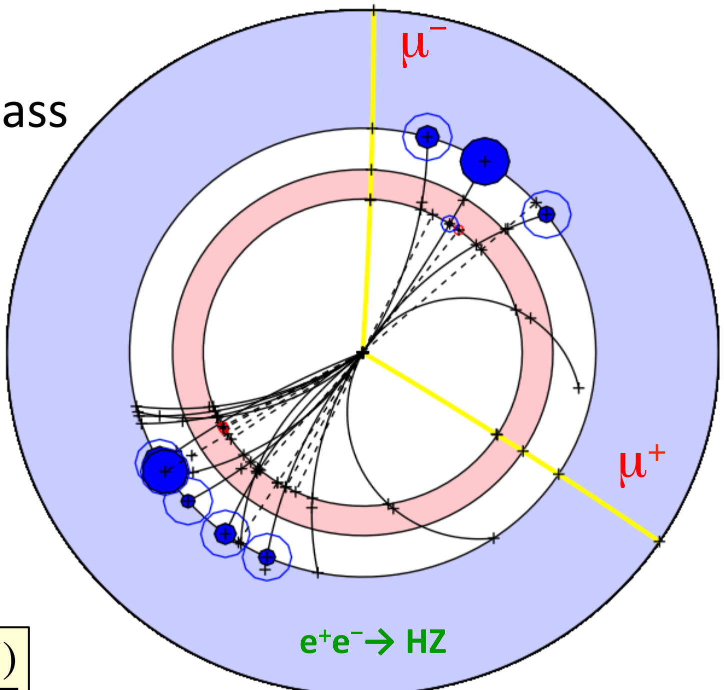
- A Higgs boson is tagged by a Z and the recoil mass

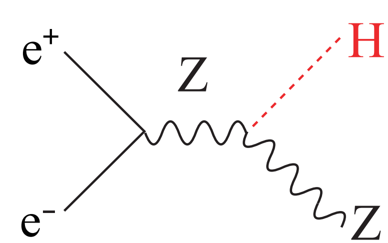
$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

  – Measure $\sigma(e^+e^- \to HZ)$
  – Deduce g_{HZZ} coupling
  – Infer $\Gamma(H \to ZZ)$
  – Select events with $H \to ZZ^*$
  – Measure $\sigma(e^+e^- \to HZ$, with $H \to ZZ^*)$

$$\sigma(e^+e^- \to HZ \to ZZZ) = \sigma(e^+e^- \to HZ) \times \frac{\Gamma(H \to ZZ)}{\Gamma_H}$$

  – Deduce the total Higgs boson width Γ_H
  – Select events with $H \to bb, cc, gg, WW, \tau\tau, \gamma\gamma, \mu\mu, Z\gamma, \ldots$
  – Deduce $g_{Hbb}, g_{Hcc}, g_{Hgg}, g_{HWW}, g_{H\tau\tau}, g_{H\gamma\gamma}, g_{H\mu\mu}, g_{HZ\gamma}, \ldots$
  – Select events with H → "nothing"
  – Deduce $\Gamma(H \to \text{invisible})$





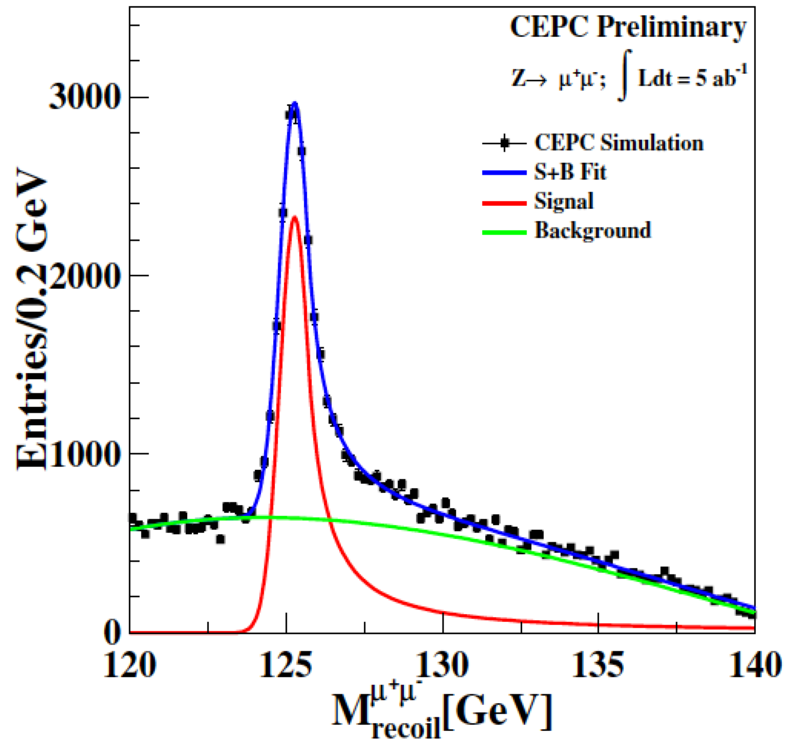
Higgs from recoil mass method

$$m^2_{\text{recoil}} = (\sqrt{s} - E_{f\bar{f}})^2 - p^2_{f\bar{f}} = s - 2E_{f\bar{f}}\sqrt{s} + m^2_{f\bar{f}}$$

- Best mass precision can be achieved with the Z→ll (ee,μμ) decays
- Cross section, ZH and the Higgs-Z boson coupling g(HZZ), can be derived in a model-independent way
- g(HZZ) and Higgs decay branching ratios can be used to derive the total Higgs boson decay width.

- A relative precision of 0.9% for the inclusive cross section has been achieved.
- The Higgs mass can be measured with a precision of 6.5 MeV; the precision is limited by the beam energy spread, radiation effect and detector resolution
- A relative precision of 0.51% on σ(ZH) by combining ee,μμ and qq channels
- g(HZZ) can be extracted from σ(ZH) with a relative precision of 0.25%

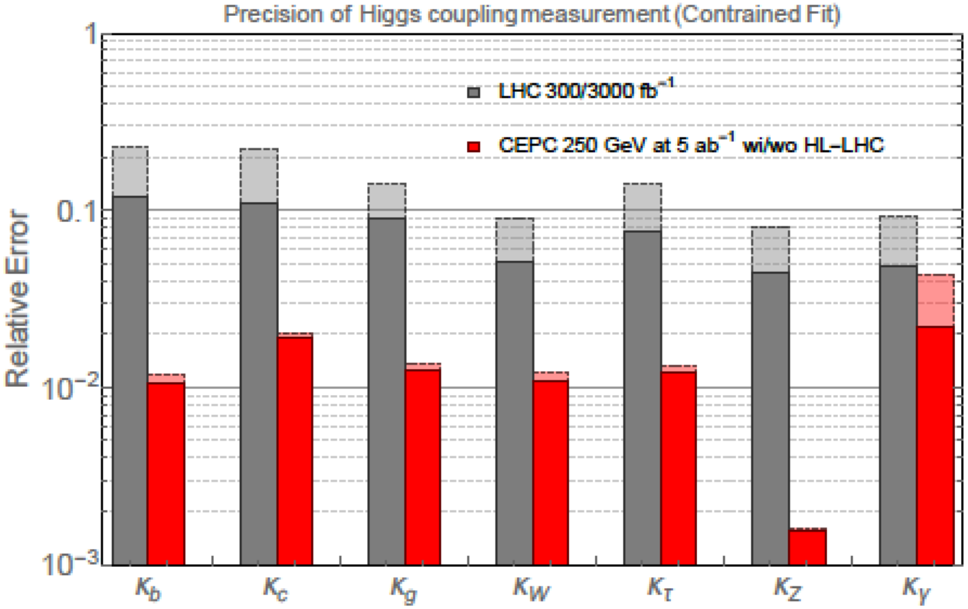
Z decay mode	ΔM_H (MeV)	$\Delta\sigma(ZH)/\sigma(ZH)$	$\Delta g(HZZ)/g(HZZ)$
ee	14	2.1%	
$\mu\mu$	6.5	0.9%	
$ee+\mu\mu$	5.9	0.8%	0.4%
$q\bar{q}$		0.65%	0.32%
$ee+\mu\mu+q\bar{q}$		0.51%	0.25%



Higgs coupling measurements

- 10 parameters $\kappa_b,\ \kappa_c,\ \kappa_\tau,\ \kappa_\mu,\ \kappa_Z,\ \kappa_W,\ \kappa_\gamma,\ \kappa_g,\ \mathrm{BR_{inv}},\ \Gamma_h.$
- assuming lepton universality → 9 parameters $\kappa_b,\ \kappa_c,\ \kappa_\tau = \kappa_\mu,\ \kappa_Z,\ \kappa_W,\ \kappa_\gamma,\ \kappa_g,\ \mathrm{BR_{inv}},\ \Gamma_h.$
- assuming the absence of exotic and invisible decays →7 parameters:

$$\kappa_b,\ \kappa_c,\ \kappa_\tau = \kappa_\mu,\ \kappa_Z,\ \kappa_W,\ \kappa_\gamma,\ \kappa_g$$



Projections for CEPC at 250 GeV with 5 ab^{-1} integrated luminosity and 7 parameters fit

	CEPC				CEPC+HL-LHC			
Luminosity (ab^{-1})	0.5	2	5	10	0.5	2	5	10
κ_b	3.7	1.9	1.2	0.83	2.3	1.5	1.1	0.78
κ_c	5.1	3.2	1.6	1.2	4.0	2.3	1.5	1.1
κ_g	4.7	2.3	1.5	1.0	2.9	1.9	1.3	0.99
κ_W	3.8	1.9	1.2	0.84	2.3	1.6	1.1	0.80
κ_τ	4.2	2.1	1.3	0.94	2.9	1.8	1.2	0.90
κ_Z	0.51	0.25	0.16	0.11	0.49	0.25	0.16	0.11
κ_γ	15	7.4	4.7	3.3	2.6	2.5	2.3	2.0

Concerning $\mathrm{BR_{inv}}$ a high accuracy of 0.25%, while the HL-LHC can only manage a much lower accuracy of 6-17%.

What will we know by 2018/2019 ?

P. Janot (CERN)

- If new physics is found by the end of LHC Run2
  - It will – hopefully – point to the best new accelerator to build
    - Will in turn make it easier to get financial/political/societal support
  - This hypothesis is, unfortunately, getting less and less likely

- Much greater challenge if no new physics is convincingly found
  - Cannot continue indefinitely with R&D towards all possible future facilities
    - A choice will have to be made in 2019-2020

- Physics absolutely need an e^+e^- EW factory with $90 < \sqrt{s} < 400$ GeV
  - Four e^+e^- collider studies on the planet (ILC, CLIC, CEPC, FCC) in the energy range !
  - Exploration of the energy frontier best done with a hadron collider (e.g., FCC-hh/CppS)

Conclusions

HL-LHC: potential for new physics discoveries and precision measurements:

- Higgs couplings modifiers and signal strenghts with precision between 5-15% level
- Measurement on mass, width, CP properties
- Search for additional bosons, dark matter, rare decays, VV scattering
- Similar conclusions from ATLAS and CMS projections in spite of the differences in the assumptions and detector upgrades

FCC-ee/CepC: large potential beyond the HL-LHC

- Measurement of the Higgs mass at few MeV level
- Sub-percent measurement of the higgs couplings
- Model-independent measurement of the Higgs width
- deduce Γ(H→invisible)
- show evidence of BSM Higgs

ΔM_H	Γ_H	$\sigma(ZH)$	$\sigma(\nu\bar{\nu}H) \times \mathrm{BR}(H \to b\bar{b})$
5.9 MeV	2.8%	0.51%	2.8%

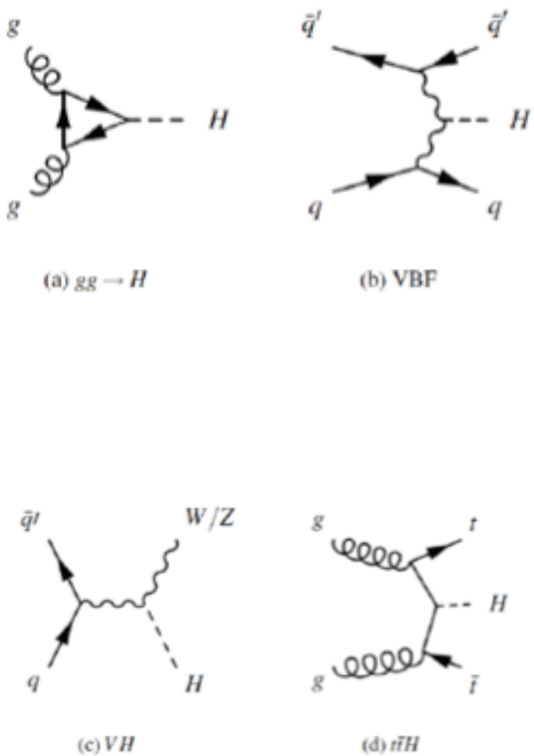
Decay mode	$\sigma(ZH) \times \mathrm{BR}$	BR
$H \to b\bar{b}$	0.28%	0.57%
$H \to c\bar{c}$	2.2%	2.3%
$H \to gg$	1.6%	1.7%
$H \to \tau\tau$	1.2%	1.3%
$H \to WW$	1.5%	1.6%
$H \to ZZ$	4.3%	4.3%
$H \to \gamma\gamma$	9.0%	9.0%
$H \to \mu\mu$	17%	17%
$H \to \mathrm{inv}$	–	0.28%

Backup

SM Higgs production @ LHC: 13 TeV

LHC Higgs Cross Section Working Group

arXiv:1610.07922v2



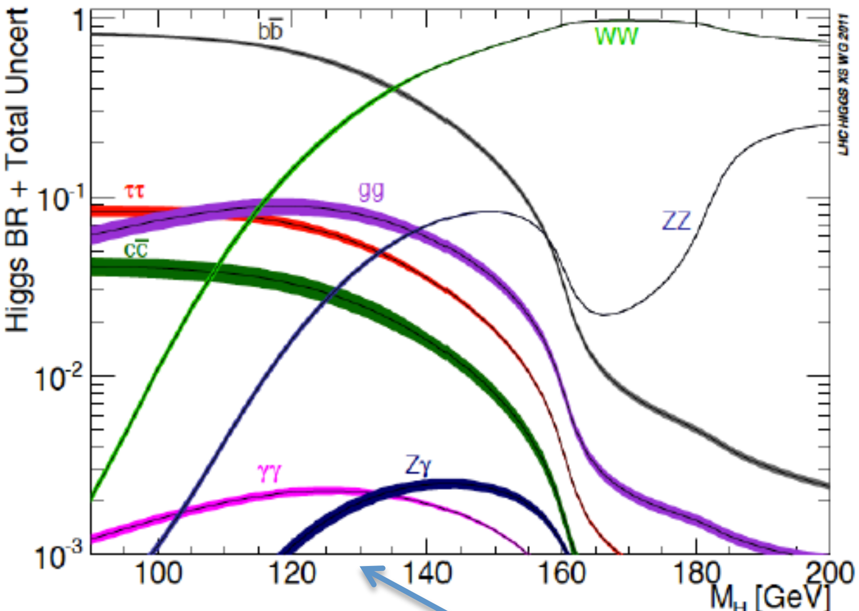
σ [pb] at m_H=125 GeV	13 TeV
ggF	48.58
VBF	3.782
WH	1.370
ZH	0.884
ttH	0.507

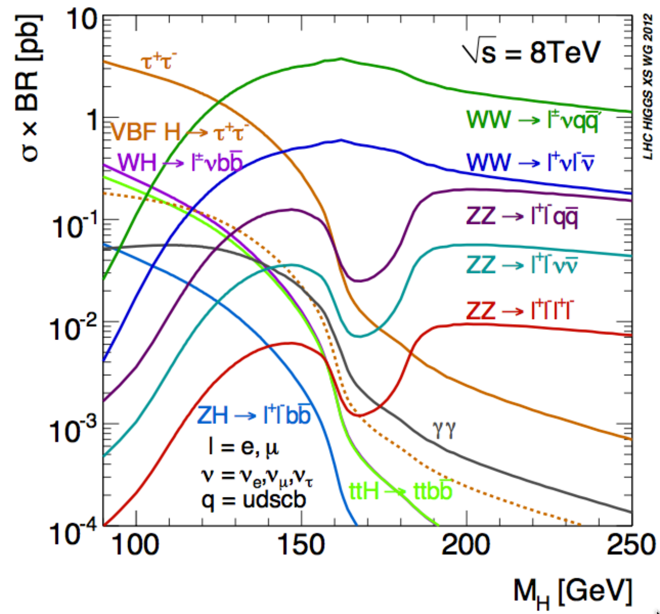
Uncertainty on σ(13TeV) from theory:
@ NNLO/NNLL QCD + NLO EWK

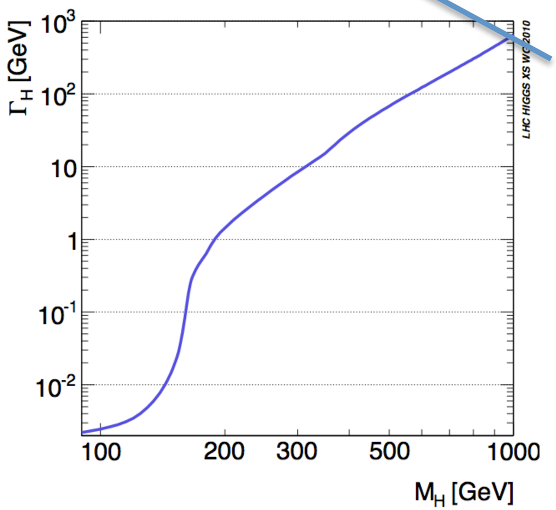
ggF: 8% scale and 7% PDF
VBF: 0.6% scale and 1.7% PDF

Uncertainty on BRs: 3-5%

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%
$(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu$	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
$H \to b\bar{b}, c\bar{c}$	$\sim 0.1\%$	$\sim 1-2\%$	$\sim 2\%$
$H \to \tau^+\tau^-, \mu^+\mu^-$	–	$\sim 1-2\%$	$\sim 2\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW^*/ZZ^* \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$

Theoretical uncertainties

√s =14 TeV

LHC Higgs cross section working group

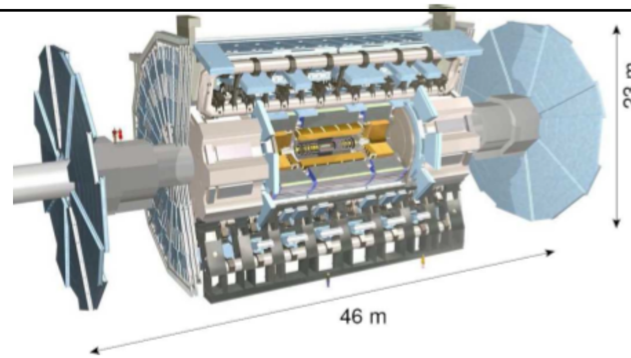
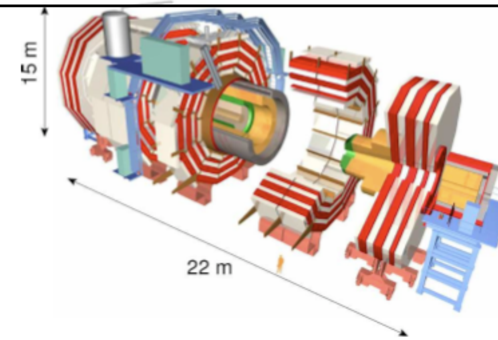
arXiv:1310.8361, Snowmass

Uncertainty on cross section

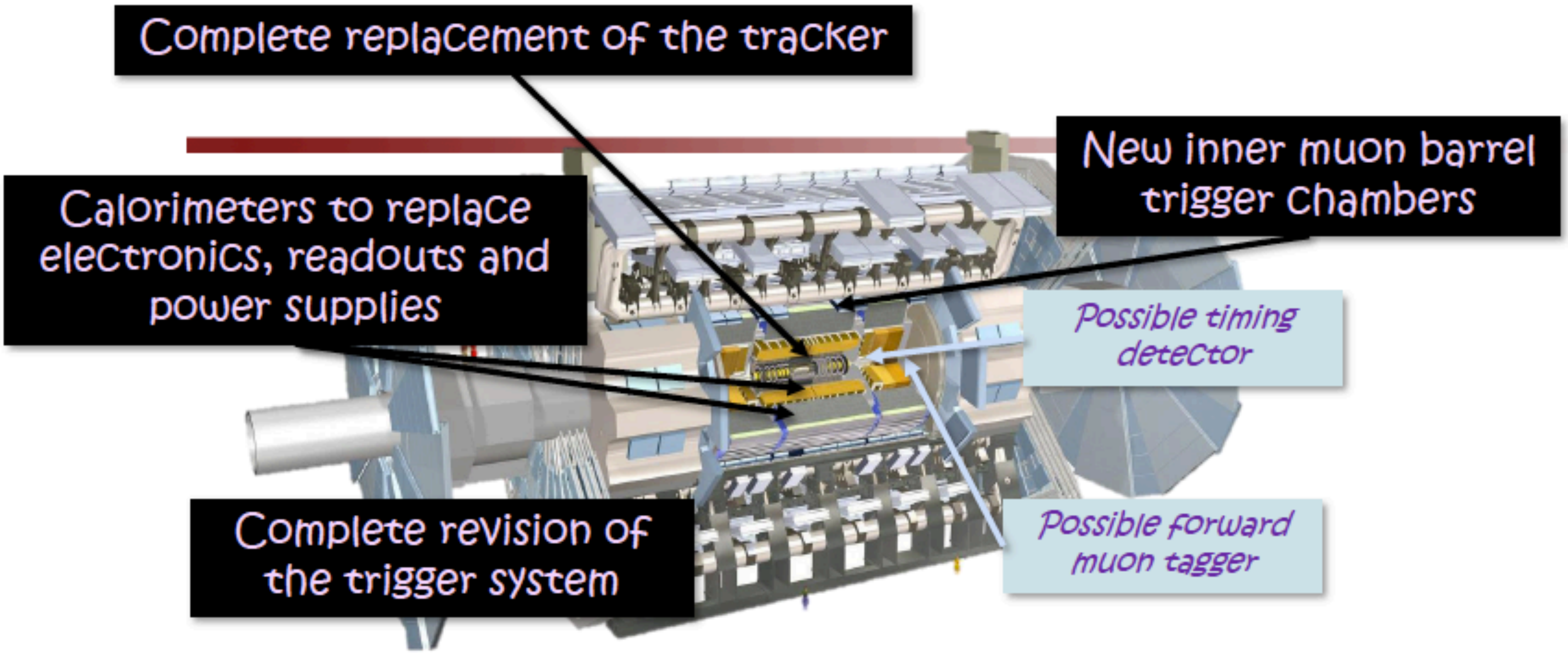
Process	Cross section (pb)	Relative uncertainty in percent: Total	Scale	PDF
Gluon fusion	49.3	$^{+19.6}_{-14.6}$	$^{+12.2}_{-8.4}$	$^{+7.4}_{-6.2}$
VBF	4.15	$^{+2.8}_{-3.0}$	$^{+0.7}_{-0.4}$	$^{+2.1}_{-2.6}$
WH	1.474	$^{+4.1}_{-4.4}$	$^{+0.3}_{-0.6}$	$^{+3.8}_{-3.8}$
ZH	0.863	$^{+6.4}_{-5.5}$	$^{+2.7}_{-1.8}$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

Uncertainty on 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%

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)

ATLAS Phase 2 upgrade



- Complete replacement of the Inner Detector
  - Improved tracking performance and extended coverage!
- Upgrades to the Liquid Argon and Tile calorimeters readouts and electronics to provide more information to be available at L0 trigger
- New barrel trigger chambers to be installed in the Muon Spectrometer to improve trigger acceptance and to maintain current efficiency for HL-LHC

Modeling the projections for HL-LHC: ECFA 16

CMS

- **S1** All systematic uncertainties are kept constant with integrated luminosity. The performance of the CMS detector is assumed to be the unchanged with respect to the reference analysis
- **S1+** All systematic uncertainties are kept constant with integrated luminosity. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account
- **S2** Theoretical uncertainties scaled down by a factor 1/2, while experimental systematic uncertainties are scaled down by the square root of the integrated luminosity until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are not taken into account
- **S2+** Theoretical uncertainties scaled down by a factor 1/2, while experimental systematic uncertainties are scaled down by the square root of the integrated luminosity until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account

	systematics unchanged	exp. sys. scaled* $1/\sqrt{L}$	theo. sys. scaled 1/2	high PU effects
ECFA16 S1	✓	✗	✗	✗
ECFA16 S1+	✓	✗	✗	✓
ECFA16 S2	✗	✓	✓	✗
ECFA16 S2+	✗	✓	✓	✓

(*) until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector.

Modeling the projections for HL-LHC: ECFA 16

CMS extrapolation scenarios:

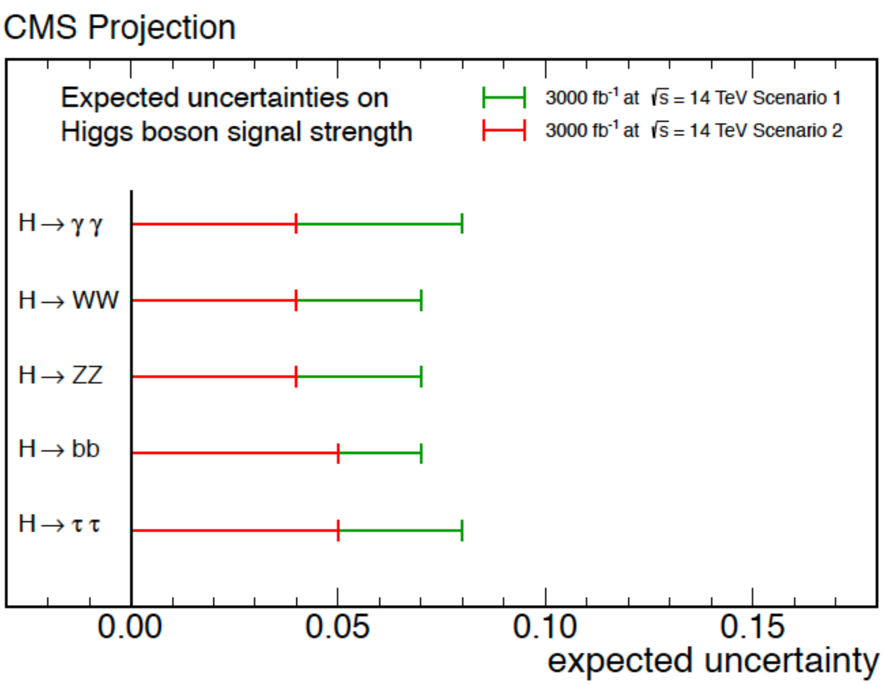
- S1: Systematic uncertainties constant, unchanged detector performances
- S2: Theoretical uncertainties scaled by 0.5, experimental uncertainties scaled by luminosity
- S1/S2+: Includes higher PU and detector upgrades effects

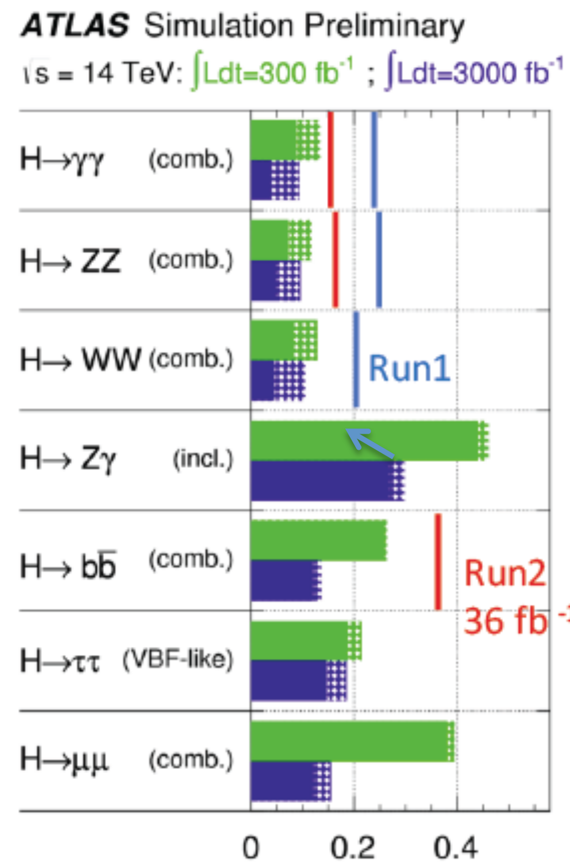
ATLAS extrapolation scenarios:

- Reference, middle and low scenario corresponding to different upgrade designs (from more to less performant)
- PU and upgrades taken into account for projections
- Theoretical uncertainties scaled by 1,0.5 or 0

Higgs signal strength: $\mu=\sigma/\sigma_{SM}$ - 3000 fb^{-1}

Snowmass13 arXiv:1307.7135v2





ATL-PHYS-PUB-2014-016

CMS:

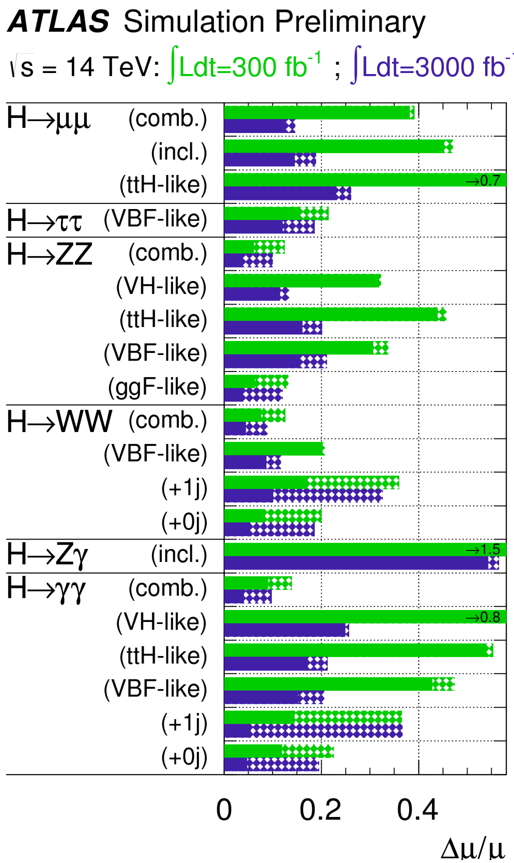
- Extrapolated from 2011/12 results
- scenario 1 and 2 ≈ upper and lower bounds
- precision of **4-8%** on μ

ATLAS:

- Based on parametric simulation
- precision of **1-2%** for main channels, 4-5% on rare models

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**

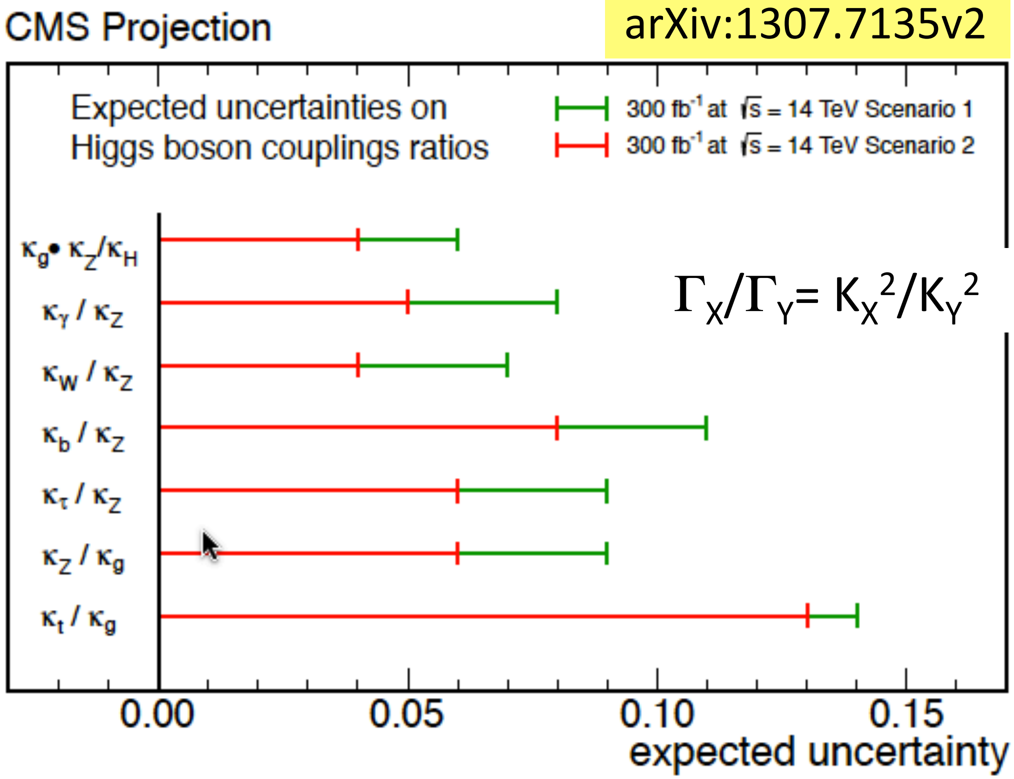
$\int\mathcal{L}dt$ (fb^{-1})	Higgs decay final state							
	$\gamma\gamma$	WW^*	ZZ^*	$b\bar{b}$	$\tau\tau$	$\mu\mu$	$Z\gamma$	BR_{inv}
ATLAS								
300	9 – 14%	8 – 13%	6 – 12%	N/A	16 – 22%	38 – 39%	145 – 147%	< 23 – 32%
3000	4 – 10%	5 – 9%	4 – 10%	N/A	12 – 19%	12 – 15%	54 – 57%	< 8 – 16%
CMS					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

Higgs partial width ratios – 3000 fb^{-1}

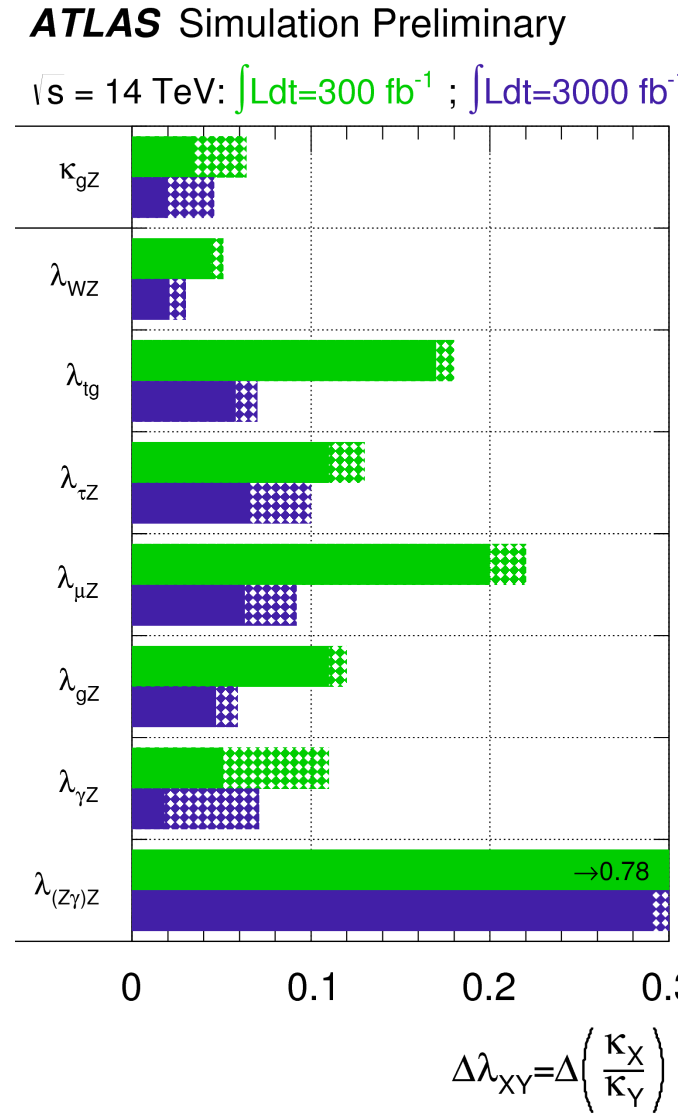
- No assum. on the total H width → ratio of k_i
- many exper. and theor. uncertainties cancel in the ratio

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

arXiv:1307.7135v2



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



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 couplings scale factors

CMS

$L(\text{fb}^{-1})$	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	$300\ \text{fb}^{-1}$ Theory unc.:			$3000\ \text{fb}^{-1}$ Theory unc.:		
		All	Half	None	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:

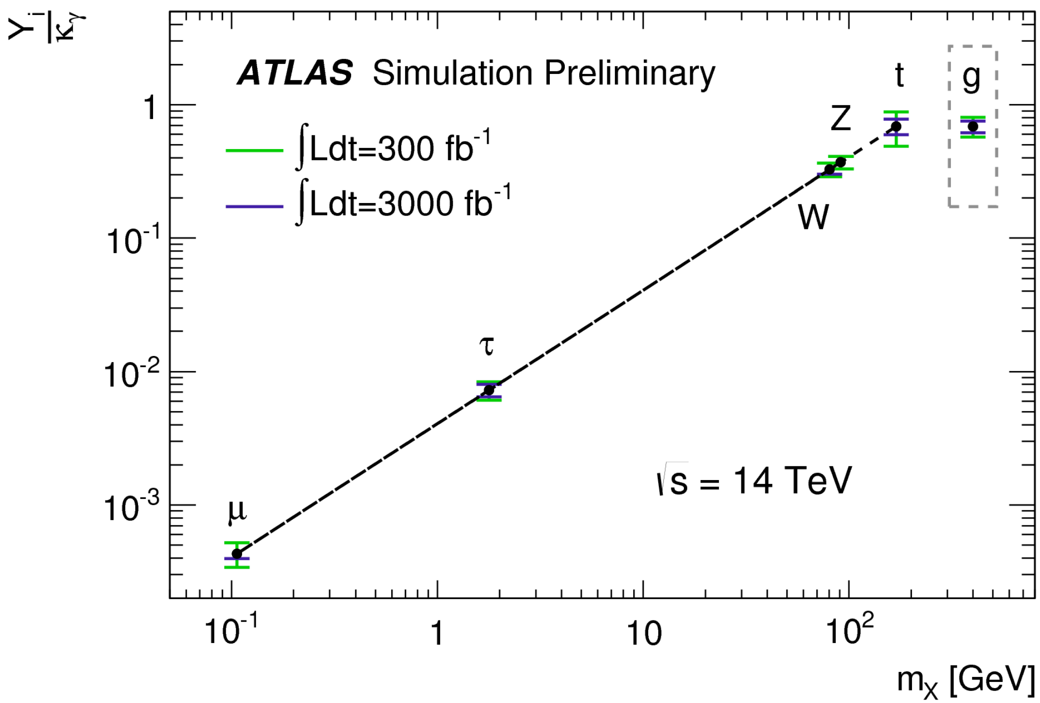
Mass-scaled coupling ratios:

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

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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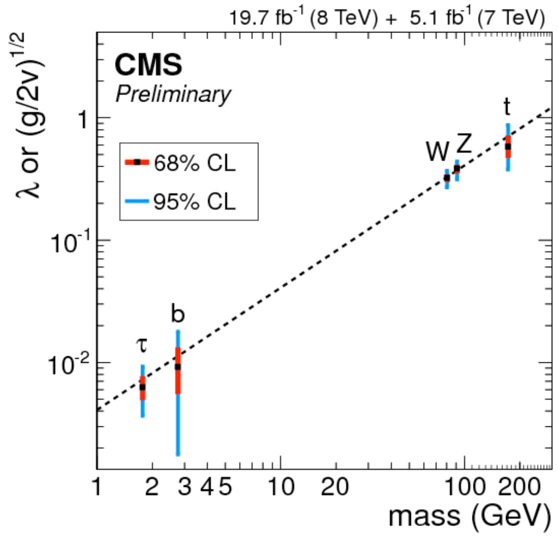


HVV: Anomalous couplings

- Excellent precision on anomalous couplings at HL-LHC
- Different notations in CMS and ATLAS, but both probe tensor-structure and the presence CP violation in the H→VV coupling

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}.$$

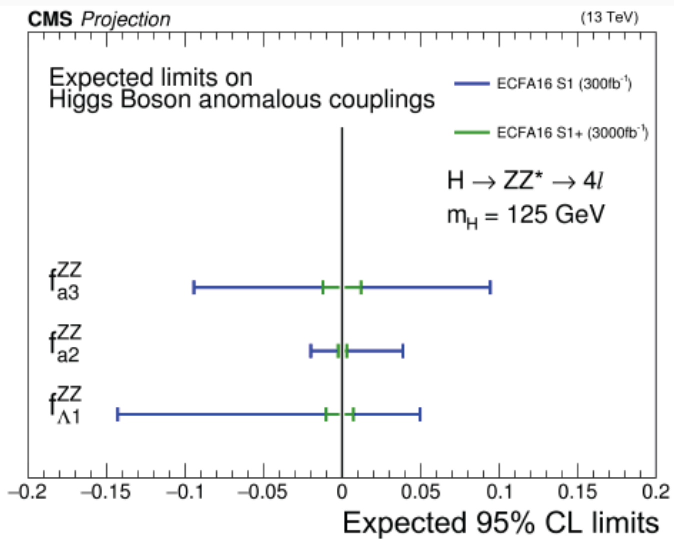
SM

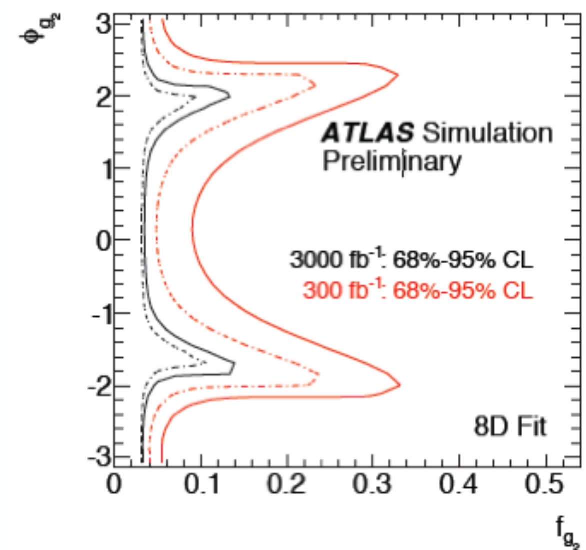
- Test for anomalous couplings:

$$f_{ai} = |a_i|^2\sigma_i \Big/ \sum |a_j|^2\sigma_j$$

$$\phi_{ai} = \arg\left(a_i/a_1\right)$$

- Statistically limited. 1% reach @ 3000 fb^{-1}
- Interference contribution becomes more dominant at smaller values of f_{ai} cos (f_{ai})

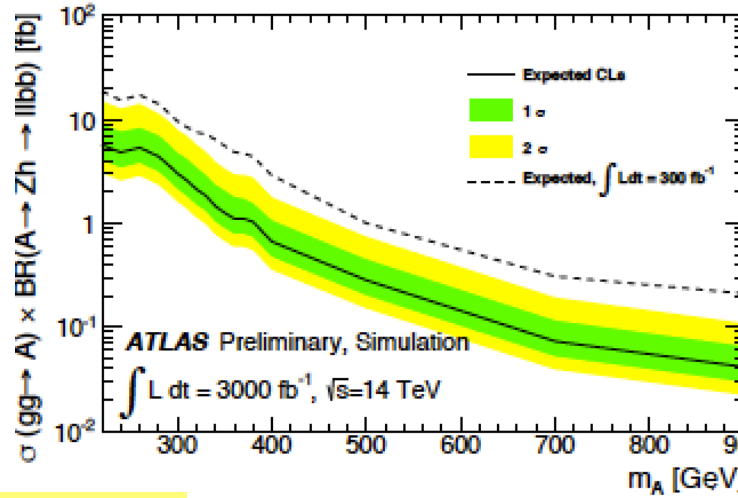




Search for additional Higgs – 3000 fb^{-1}

Two-Higgs-doublet models in many BSM models

- Existence of 5 observable Higgs bosons:



- ***A → Zh*** decay dominant at $m_Z+m_h < m_A < 2\ m_{top}$,
  - Relevant at low tanβ
  - *Consider Z h → llbb decay*
  - 30 % syst. unc. assumed

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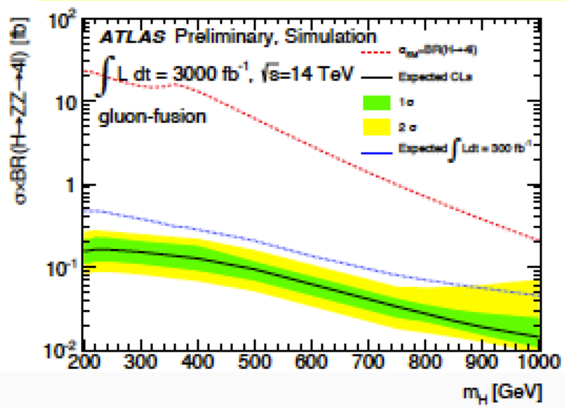
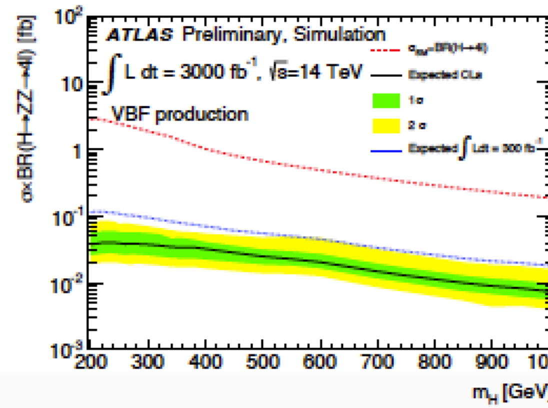
- **Heavy H→ZZ→4l**
  - Extrapolation from Run1 analysis
  - at HL-LHC × 10 – 150 better wrt SM Higgs boson production



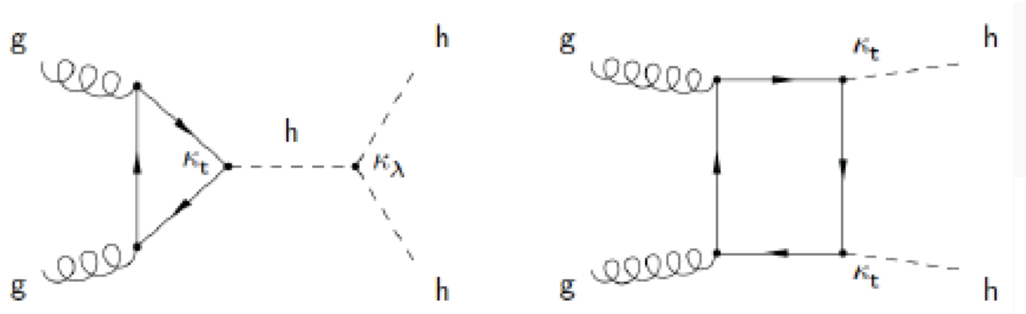


Summary of new ATLAS HL-LHC RESULTS

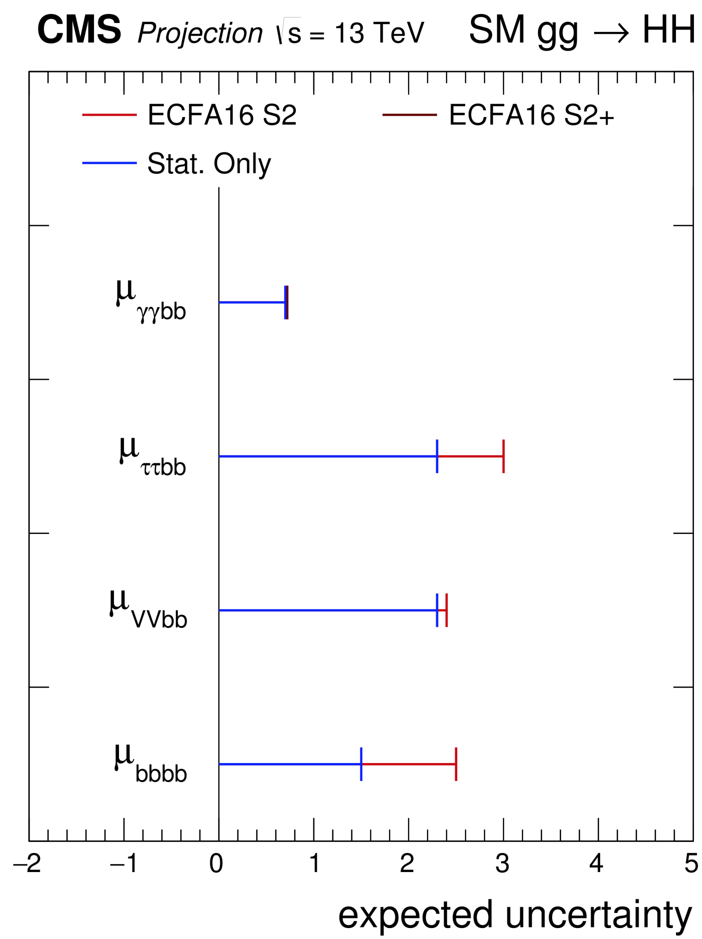
Channel	Result
VBF $H\to W^+W^-$	$\Delta\mu/\mu \simeq$ 14 to 20%
VBF $H\to ZZ\to 4\ell$	$\Delta\mu/\mu \simeq$ 15 to 18%
$ttH, H\to\gamma\gamma$	$\Delta\mu/\mu \simeq$ 17 to 20%
$VH, H\to\gamma\gamma$	$\Delta\mu/\mu \simeq$ 25 to 35%
off-shell $H\to ZZ\to 4\ell$	$\Delta\mu/\mu \simeq$ 50% $\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV
$H\to Z\gamma$	$\Delta\mu/\mu \simeq$ 30% 3.9 σ
$H\to J/\psi\,\gamma$	BR < 44×10^{-6} @95% CL
$t\to Hq$	BR ≲ 10^{-4} @95% CL

HH Channel	Result
$HH\to bb\tau\tau$ (FULL uncertainties)	0.6 σ $-4 < \lambda_{HHH} / \lambda_{SM} < 12$
$HH\to bbbb$ (p_T(jet)> 75 GeV, FULL uncertainties)	$-3.4 < \lambda_{HHH} / \lambda_{SM} < 12$
$HH\to bb\gamma\gamma$ (stat. uncertainties only)	1.3 σ $-1.3 < \lambda_{HHH} / \lambda_{SM} < 8.7$
$ttHH, HH\to bbbb$ (stat. uncertainties only)	0.35 σ

Di-Higgs production



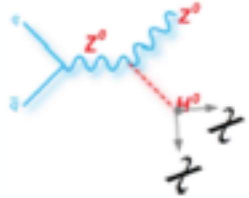
- **ECFA16:** Updated projections from public analyses using 2015 data at 13 TeV
- Updated combination planned for next year
- Also: bbWW → bbjjlv preliminar study with Delphes (sensitivity vs background uncertainty)

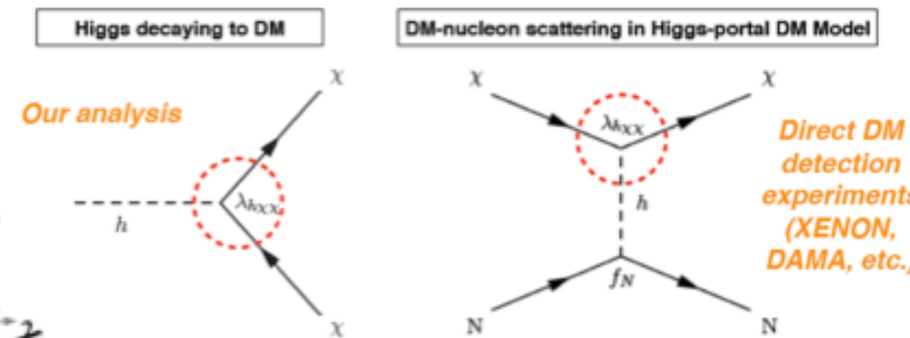


Invisible Higgs as a portal to Dark Matter

ATLAS at 3000 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 $m_h/2$

90% CL UL

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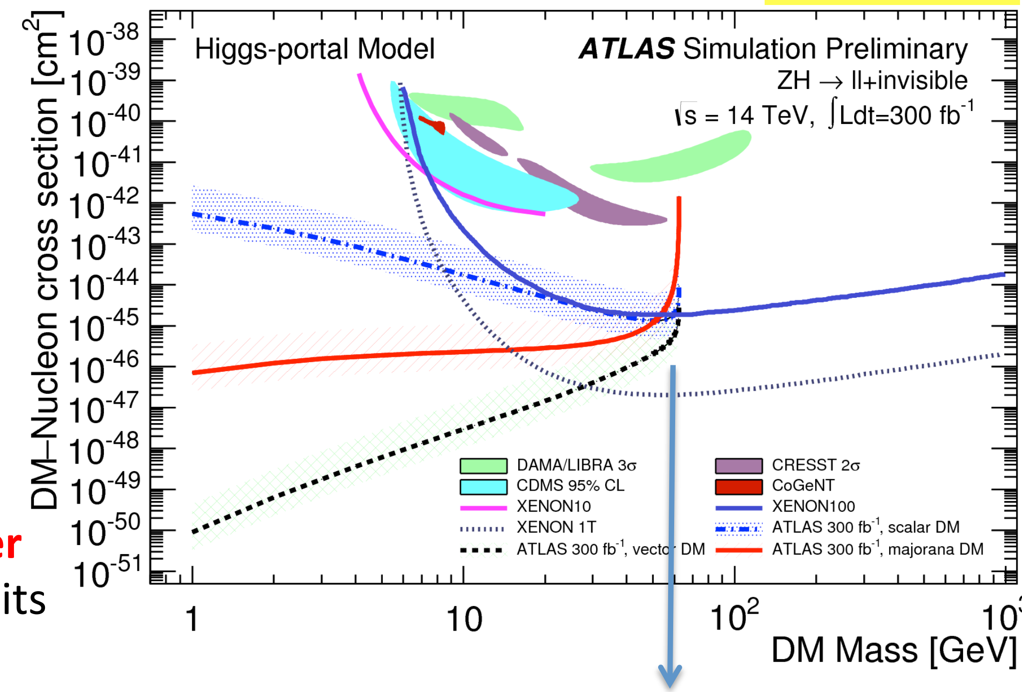


$m_h/2$

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

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

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

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

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

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

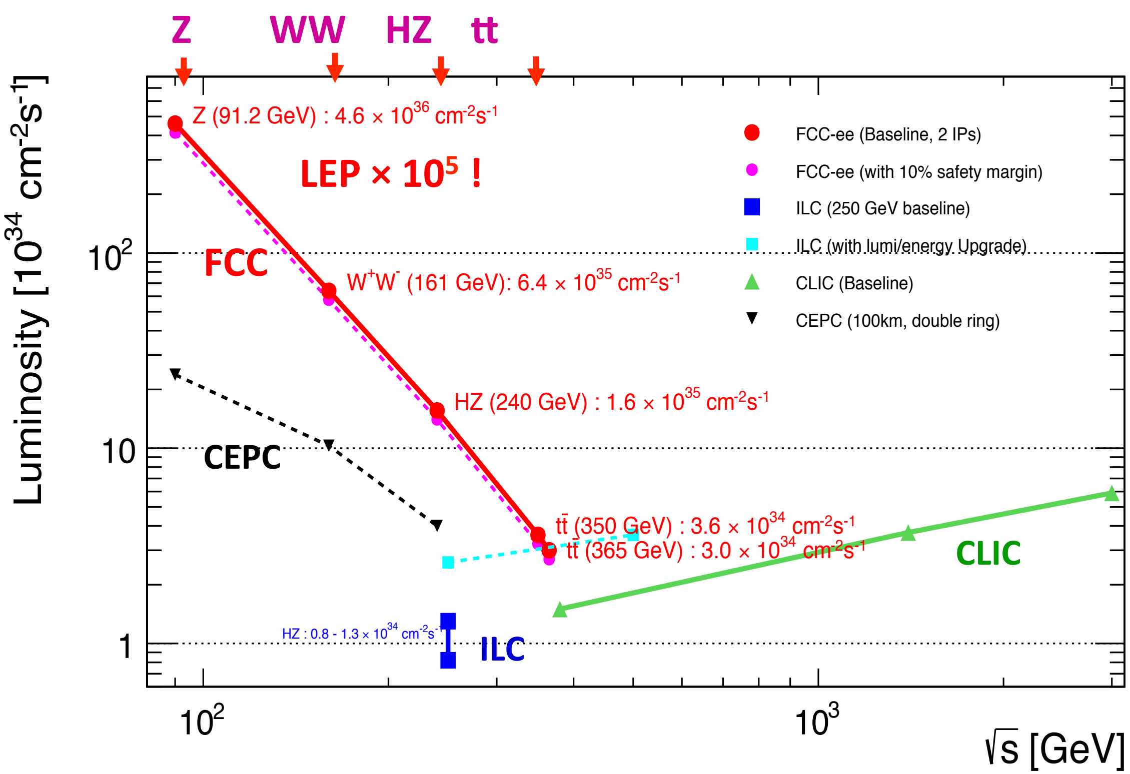
$$\sigma^{\text{Majorana}}_{\chi N} = \frac{\lambda^{2\,\text{Majorana}}_{h\chi\chi}}{4\pi\Lambda^2 m_h^4}\frac{m_\chi^2 m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

CepC challenges

CepC: 5 ab^{-1} integrated luminosity to two detectors over 10 years → 10^6 clean Higgs events will be produced during this period

→ FCC-ee/CEPC measure the Higgs boson production cross sections and most of its properties with precisions far beyond achievable at the LHC

Projection on maximum luminosity.



Compared with hadron collisions at LHC, e^+e^- collisions are not affected by underlying events and pile-up effects.

Tagging of e^+e^- → ZH events through the recoil mass method is independent of the Higgs boson decay

FCC-ee can reach the ttbar threshold

Summary of Higgs measurements at CepC

Percentage level precisions can be achieved for the branching ratio measurements

ΔM_H	Γ_H	$\sigma(ZH)$	$\sigma(\nu\bar{\nu}H) \times \mathrm{BR}(H \to b\bar{b})$
5.9 MeV	2.8%	0.51%	2.8%

Decay mode	$\sigma(ZH) \times \mathrm{BR}$	BR
$H \to b\bar{b}$	0.28%	0.57%
$H \to c\bar{c}$	2.2%	2.3%
$H \to gg$	1.6%	1.7%
$H \to \tau\tau$	1.2%	1.3%
$H \to WW$	1.5%	1.6%
$H \to ZZ$	4.3%	4.3%
$H \to \gamma\gamma$	9.0%	9.0%
$H \to \mu\mu$	17%	17%
$H \to \mathrm{inv}$	–	0.28%

The integrated luminosity can be measured with a precision of 0.1% level, as achieved at LEP

The center-of-mass energy will be known to better than 1 MeV

FCC-ee / CepC discovery potential

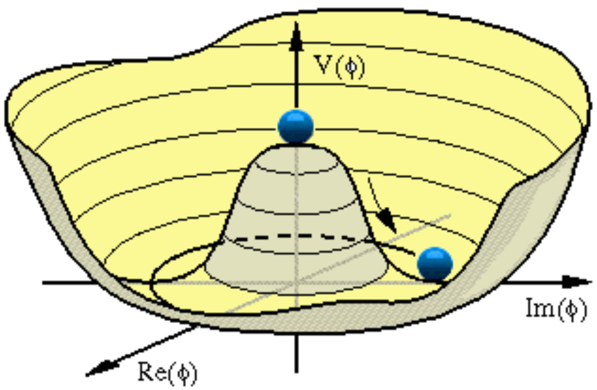
- EXPLORE the 10-100 TeV energy scale
  - With precision measurements of the properties of the Z, W, Higgs
    - 20-50 fold improved precision on ALL electroweak observables
      - m_Z, Γ_Z, m_W, m_{top}, $\sin^2\theta_w^{eff}$, R_b, $\alpha_{QED}(m_z)$, $\alpha_s(m_z)$, top EW couplings …
    - 10 fold more precise and model-independent Higgs couplings measurements
- DISCOVER that the Standard Model does not fit
  - Then extra weakly-coupled and Higgs-coupled particles exist
  - Understand the underlying physics through effects via loops
- DISCOVER a violation of flavour conservation
  - Examples: $Z \to \tau\mu$ in 5×10^{12} Z decays; or $t \to cZ$, cH at $\sqrt{s}$ = 240 or 350 GeV
  - Also a lot of flavour physics in 10^{12} bb events, e.g., with $B^0 \to K^{*0}\tau^+\tau^-$ or $B_S \to \tau^+\tau^-$
- DISCOVER dark matter as invisible decays of Higgs or Z
- DISCOVER very weakly coupled particles in the 5-100 GeV mass range
  - Such as right-handed neutrinos, dark photons, …
    - May help understand dark matter, universe baryon asymmetry, neutrino masses

Today, we do not know how nature will surprise us: other things may come up

Higgs studies for FCC-hh / CppS

The Higgs potential

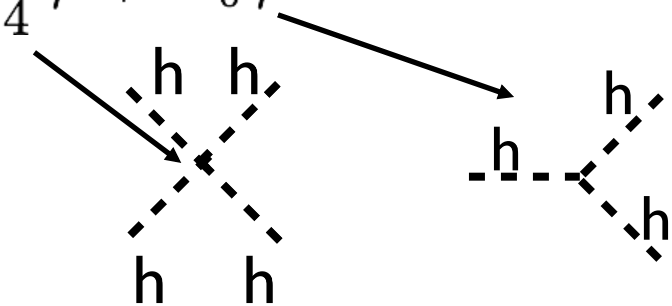
$$V(h) = \mu^2 \frac{h^2}{2} + \lambda \frac{h^4}{4}$$



After spontaneous symmetry breaking:

$$\lambda h_0^2 \eta^2 + \frac{\lambda}{4}\eta^4 + \lambda h_0 \eta^3$$

$$m_h^2 = 2\lambda h_0^2$$



The strength of the triple and quartic couplings is fully fixed by the potential shape.

Why is it relevant?

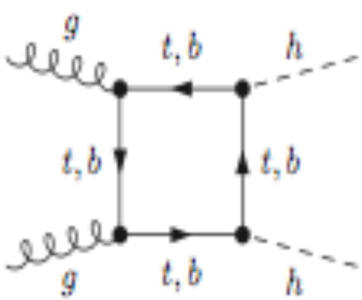
1) it is the last missing ingredient of the SM, like the Higgs boson was the last missing particle, we need to prove that things really behave like we expect;

2) It has implications on the stability of the Vacuum;

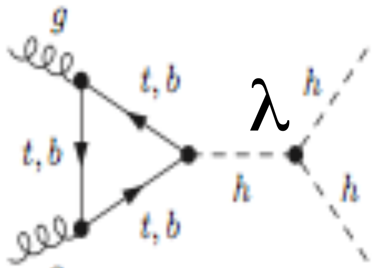
3) It could make the Higgs boson a good inflation field (see backup)

HH production and decay

Standard Model



box

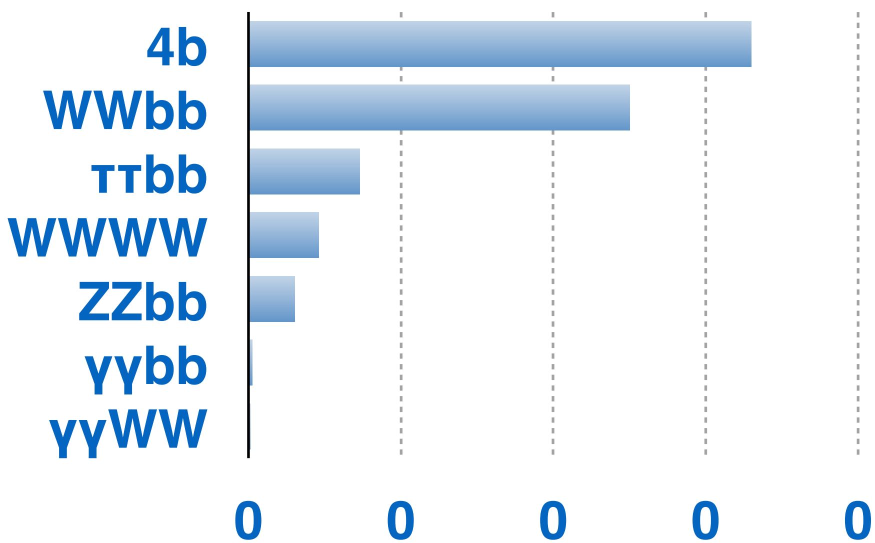


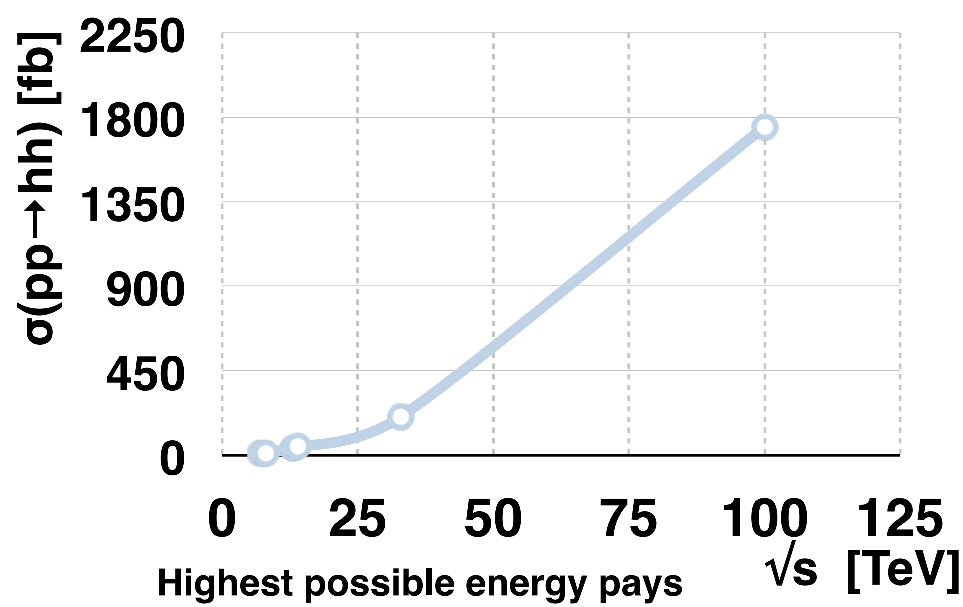
triangle

NNLO with full top mass *NLO $m_t \to \infty$

m_h = 125.09 GeV	σ(fb)	scale unc. (%)	PDF unc. (%)	α_s unc.
√s = 7 TeV	7,71	+4.0/-5.7	± 3.4	± 2.8
√s = 8 TeV	11,17	+4.1/- 5.7	± 3.1	± 2.6
√s = 13 TeV	37,91	+4.3/-6.0	± 2.1	± 2.3
√s = 14 TeV	45,00	+4.4-6.0	± 2.1	± 2.2
√s = 33 TeV*	206,6	+15.1 - 12.5	+5.8/-5.0	
√s = 100 TeV	1748	+5.1/-6.5	± 1.7	± 2.0

Higgs decay branching fraction





Current status @LHC

	√s [TeV]	L (fb^{-1})	σ(fb) 95% C.L.	σ/σ_{SM} 95%C.L.
ATLAS: 4b, bbττ, bbγγ, WWγγ WWWW	8	20,3	< 470	< 48
ATLAS: 4b	13	13,3	< 1000	< 29
CMS: 4b	13	2,32	< 11760	< 310
ATLAS: WWγγ	13	13,3	< 12900	< 340
ATLAS: bbγγ	13	3,2	< 5400	< 142
CMS: bbττ	13	39,5	< 950	< 25
CMS: WWbb	13	36	< 3270	< 86

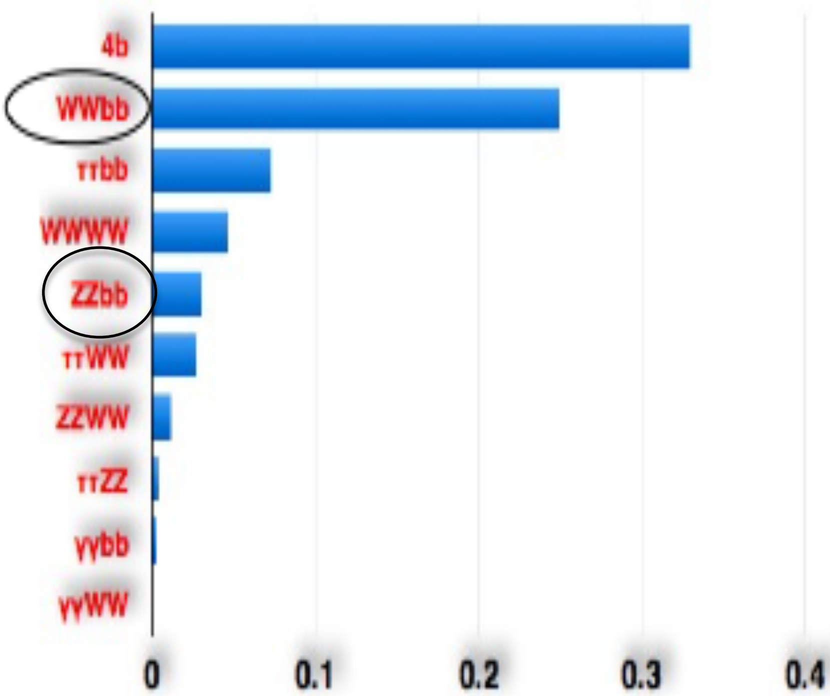
HL-LHC √s = 14 TeV, L = 3000 fb^{-1}	**Exp. sign**	λ/λ_{SM} 95% C.L.	exp σ/σ_{SM}
ATLAS: bbγγ	1.05 σ	[-0.8, 7.7]	< 1.7 [recalc.]
CMS: bbγγ	1.6 σ		< 1.3
ATLAS: 4b	?	$[0.2, 7.0]_{stat.}$, [-3.5, 11]	$< 1.5_{stat.}$, 5.2
CMS: 4b	0,67		$< 2.9_{stat.}$, 7
ATLAS: bbττ	0.6 σ	[-4, 12]	< 4.3
CMS: bbττ	0,39		$<3.9_{stat.}$, 5.2
CMS: VVbb	0,45		$< 4.6_{stat.}$, 4.9

Present best channel 4b, situation will change with higher statistics when syst. dominated channels will saturate their sensitivity.

HL-LHC doesn't seem able to provide a useful constraint on λ, it could probably provide an observation of the whole process.

But advanced analysis techniques are on going...

Current FCC studies for RD_FA



Between the final state from the HH decay:
- 4b, WWbb are dominant
- γγbb, ZZbb are the cleanest

The **Italian community** started to work in 2016 on:
- WWbb, lnuqqbb
- ZZbb, 4lbb
- We used a fast simulation tool (Delphes)
- Pileup simulation with 50, 200, 900 events

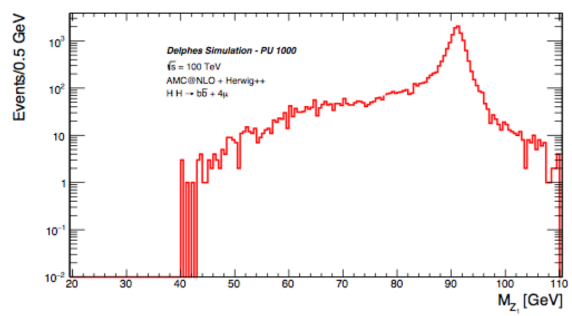
L=30 ab^{-1}	Δσ/σ	Δλ/λ
γγbb	1.3%	2.5%
4b	25% (S/B ~2%)	200%
ZZbb, 4l	~30%	~40%

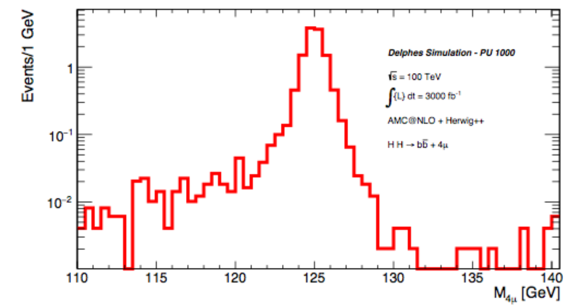
Last contributions to conferences:
- B. Di Micco, IFAE – Trieste – April 19-21 2017
- B. Di Micco, FCC Week – Berlin – May 29 – June 1 2017

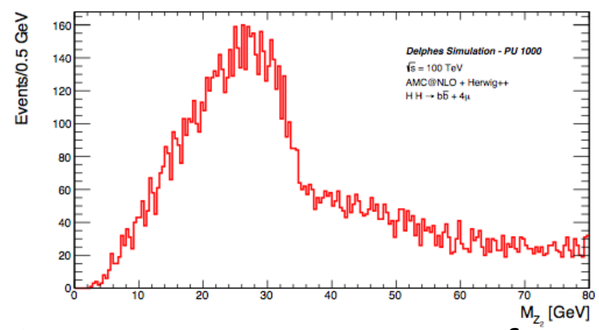
RD_FA: HH→ZZbb→4lbb, l=e,μ

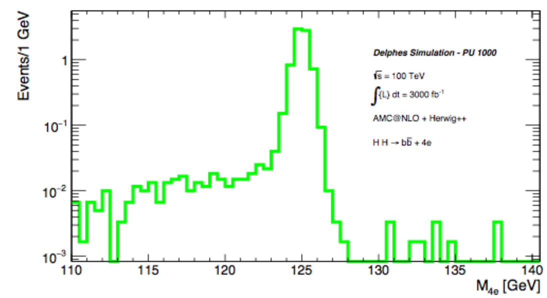
N. De Filippis (Bari), S. Braibant (Bologna)

- ≥ 4 muons with p_T > 5 GeV, |η| < 4.0
- ≥ 4 electrons with p_T > 7 GeV, |η| < 4.0
- Z_1 selection: $\ell^+\ell^-$ pair with mass close to the nominal Z boson mass
  40 GeV < m_{Z1} < 120 GeV
- Z_2 selection: second $\ell^+\ell^-$ pair
  12 GeV < m_{Z2} < 120 GeV
- Among the 4 selected leptons: at least one with p_T>20 GeV and one with p_T>1 GeV
- QCD suppression: $m(\ell^+\ell^-)$ > 4 GeV
- Kinematic cuts: $m_{4\ell}$ > 120 GeV, $m_{4\ell}$ < 130 GeV
- At least 2 b-jets with p_T > 30 GeV









$$\mathcal{L} = 3\,\mathrm{ab}^{-1}$$

	σ·L·Br(hh→ZZbb→4lbb)				
	161	61	12,1	38%	7,4%
	161	40	7,7	25%	4,8%
	322	101	20	31%	6,2%

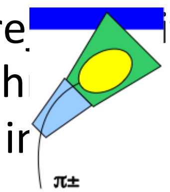
- forward b-tagging can be an important ingredient of the analysis, need to test configuration with fwd dipole
- big impact from lepton isolation cut (not presented here), need to optimise isolation criteria

Object in PU environment [WWbb analysis]

B. Di Micco, M. Testa, M. Verducci (Roma 3)

✦ Particle Flow Reconstruction

- Using charged hadrons, muons, electrons and calorimeter towers to build particle-flow objects
- Tracks from pile-up are re[moved] if $|Z_0 - Z_{\rm PV}| > \sqrt{\sigma^2(Z_0) + \sigma^2(Z_{\rm PV})}$

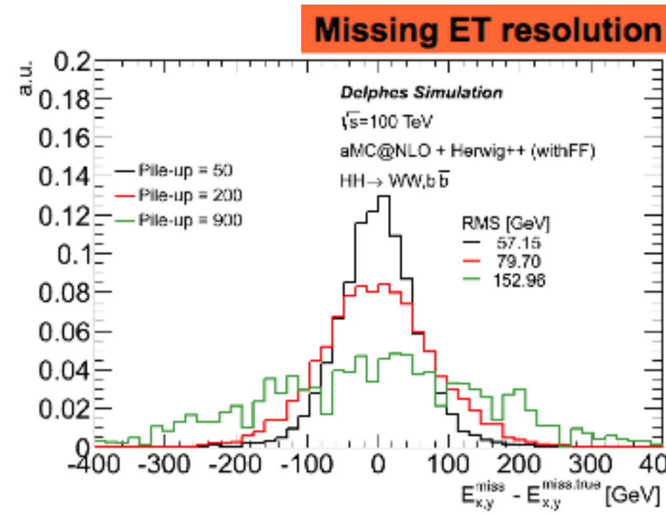


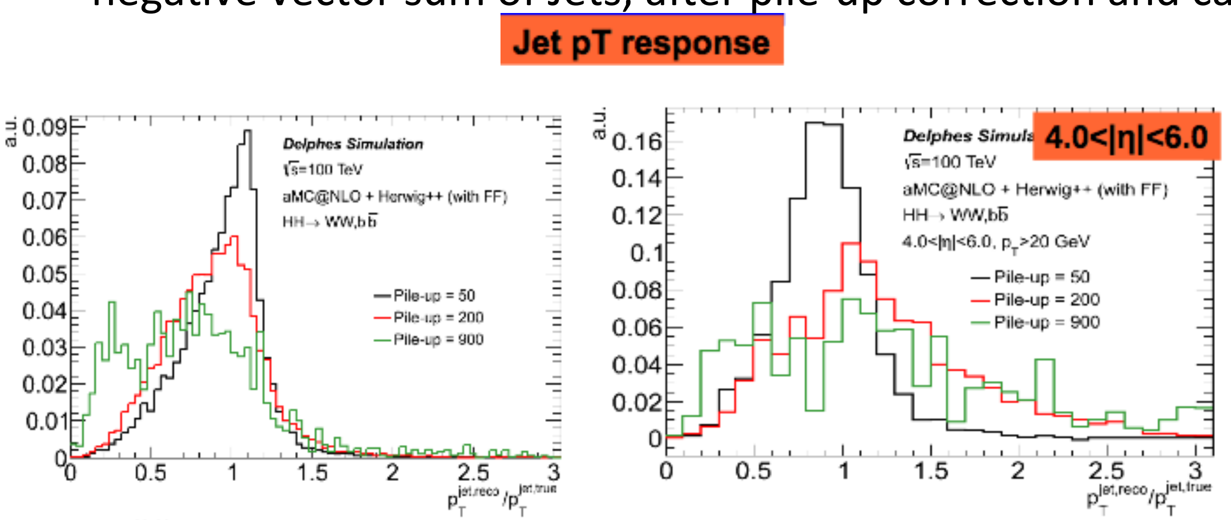
✦ Jets

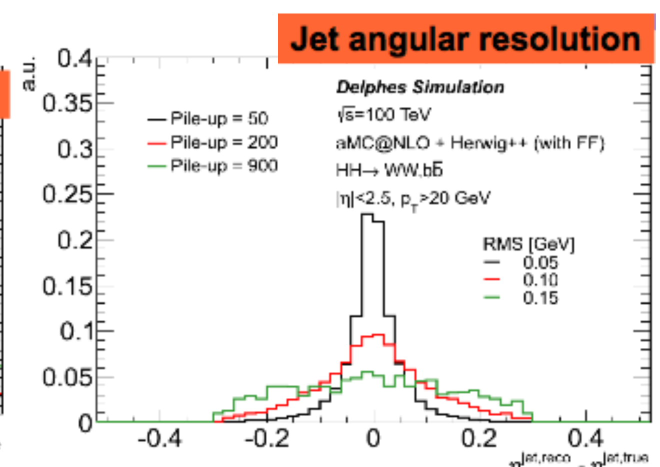
- Anti-Kt (Fast Jet) algorith[m]
- particle-flow objects as i[n]
- R = 0.4
- Jet Area pile-up correction: $p_T^{\rm corrected} = p_T^{\rm raw} - \rho \cdot {\rm JetArea}$
- private calibration to particle level
- $p_T^{\rm jet} > 20$ GeV

✦ Missing Transverse Energy

- Anti-Kt (Fast Jet) algorithm
- negative vector sum of Jets, after pile-up correction and calibration







HH→WWbb→lνqqbb: MVA analysis

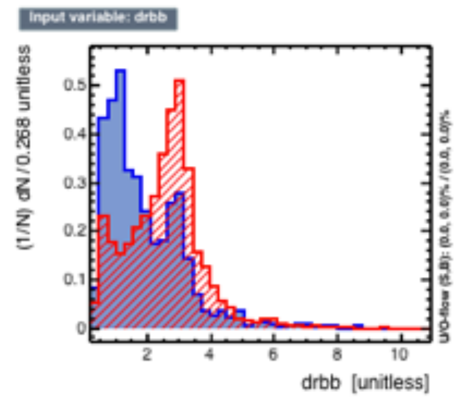
B. Di Micco, M. Testa, M. Verducci (Roma 3)

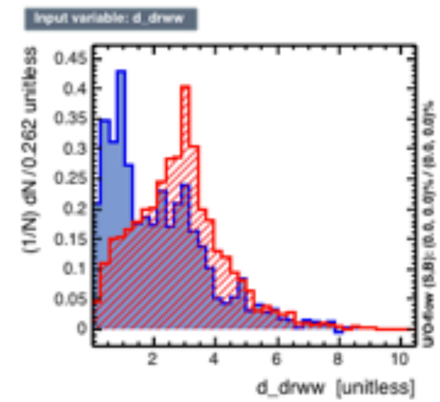
Input variables:

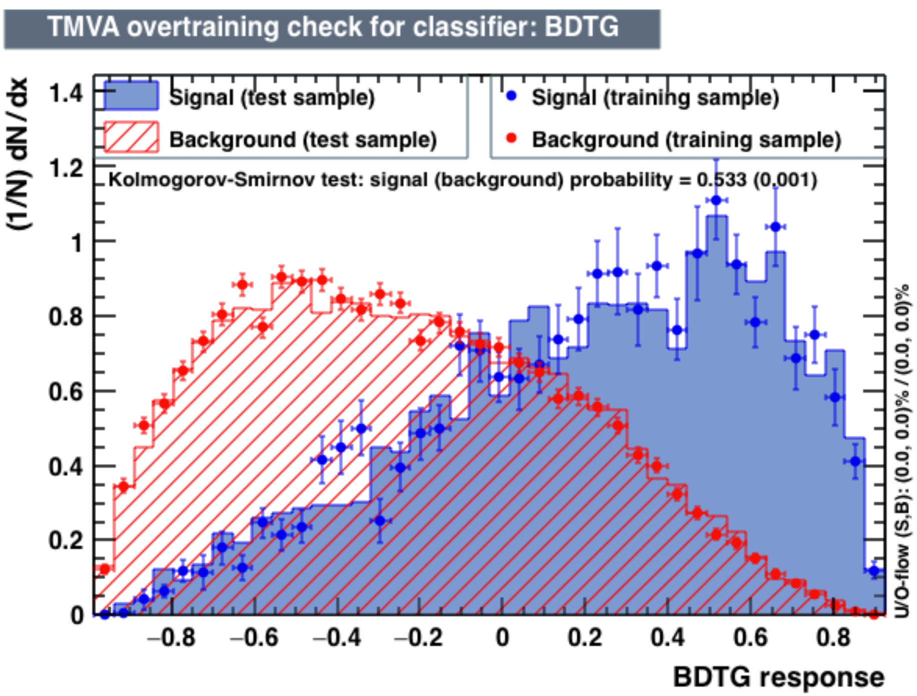
$$\Delta R_{\rm jj},\ \Delta R_{\rm bb},\ \Delta R_{\rm WW},\ m_T^{\rm WW},\ m_{\rm bb}$$
$$m_{\rm jj},\ p_T^{\rm bb},\ p_T^{\rm WW},\ E_T^{\rm miss},\ m_T^{\rm W},\ m_{\rm WW}$$

Pre-training cuts:

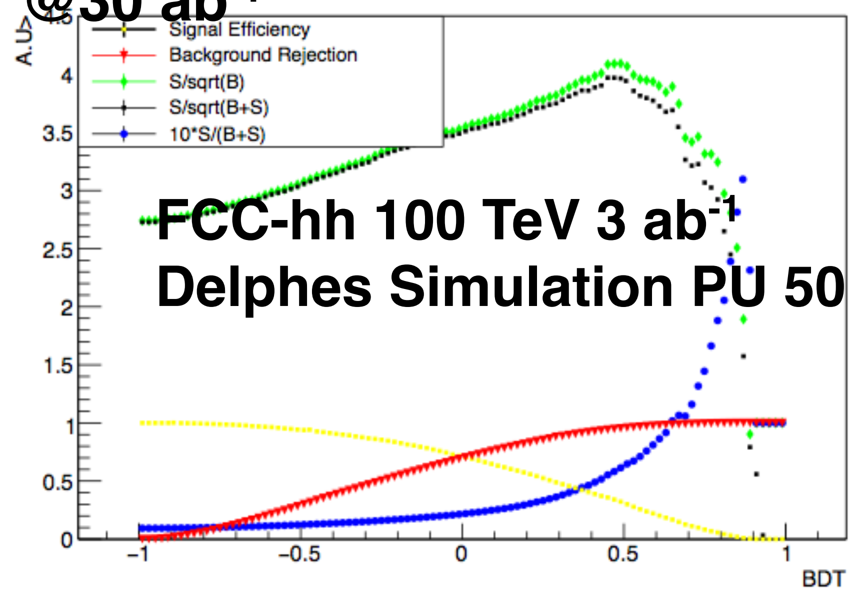
$$p_T^{\rm WW},\ p_T^{\rm bb} > 150,\ 80 < m_{bb} < 180\,{\rm GeV}$$
$$\Delta R_{bb} < 2.0$$







stat. sign. 4.1σ with S/B 0.06, 13σ @30 ab^{-1}



FCC-hh 100 TeV 3 ab^{-1}
Delphes Simulation PU 50