FUTURE PROSPECTS FOR HIGGS PHYSICS AT THE LHC AND BEYOND

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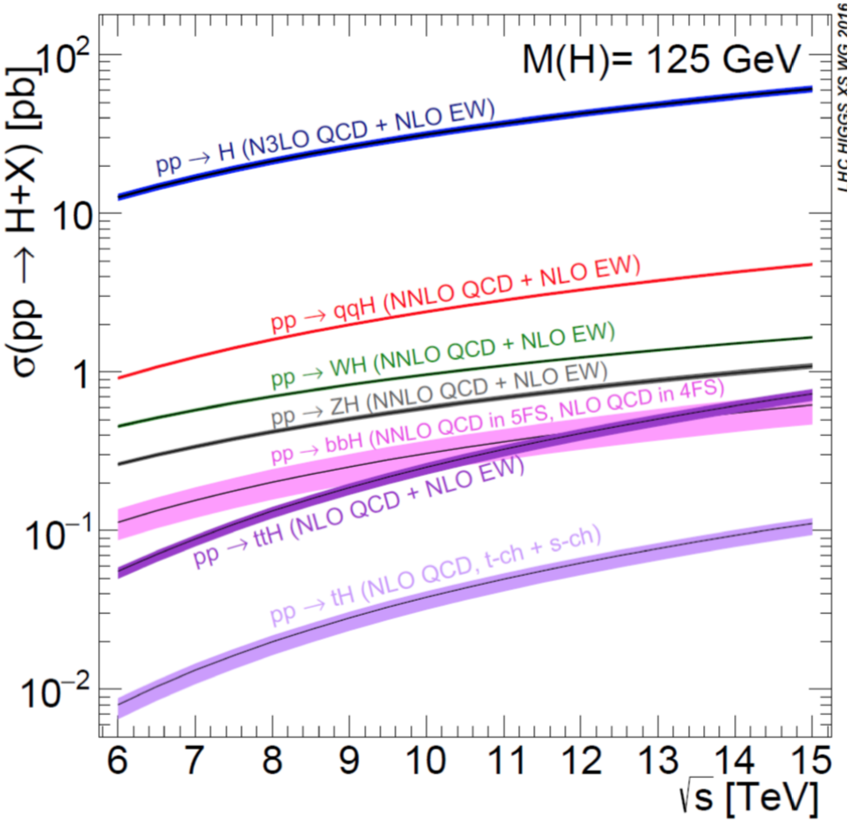
Outline

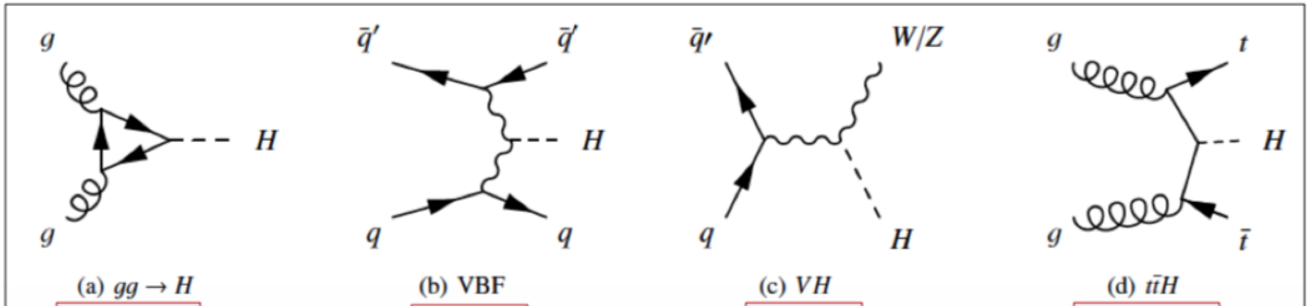
- Highlights for Higgs physics @ Run 2
  - H→bb observation
- HL-LHC and Higgs prospects
  - Selected results
  - Studies for L1 TDR trigger preparation
- Higgs physics for Future colliders

SM Higgs production at the LHC



- ggF: dominant, larger initial state radiation from gluons
- VBF: two forward jets with high mass and large rapidity gap
- VH: vector boson (lν, ll’, qq’)
- ttH: many b-jets, leptons, E_T^{miss}

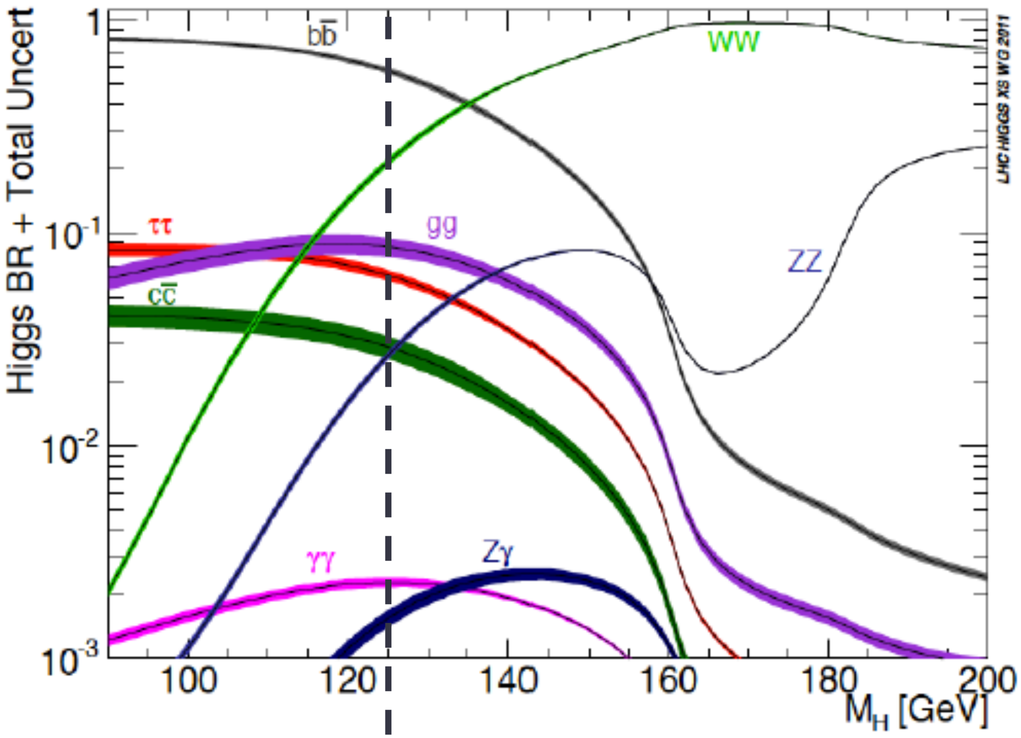
Total cross-section = 56 pb at 13 TeV

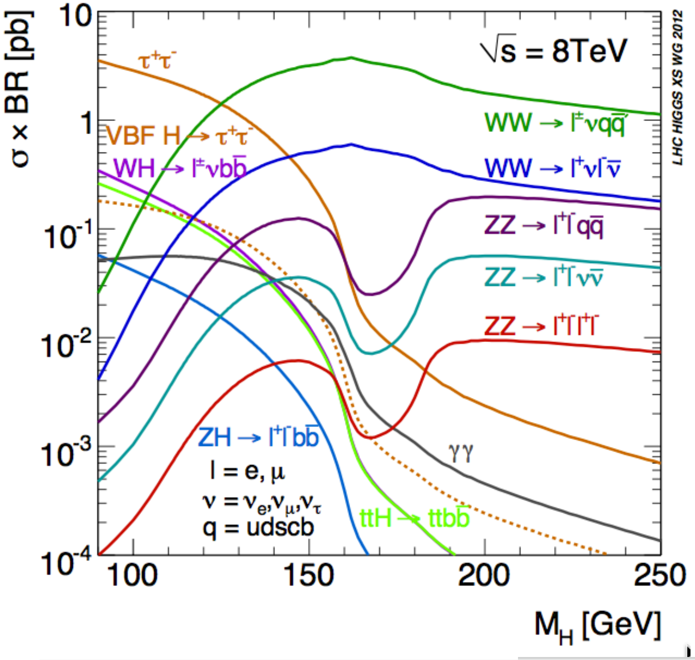


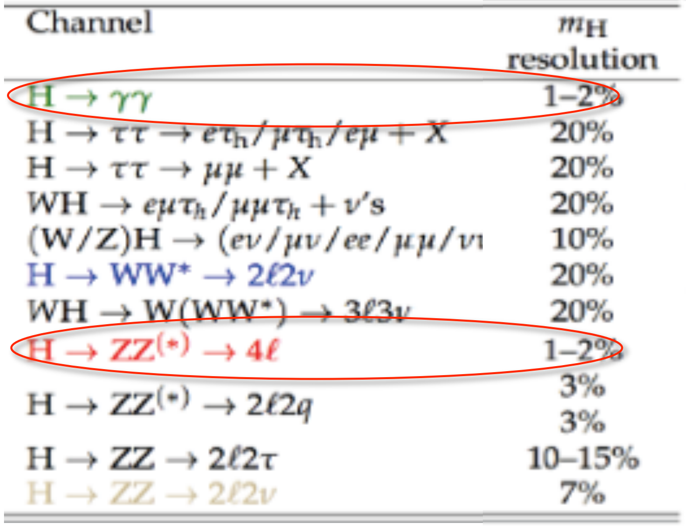
(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

87% 7% 5% <1%

Higgs decay channels







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%

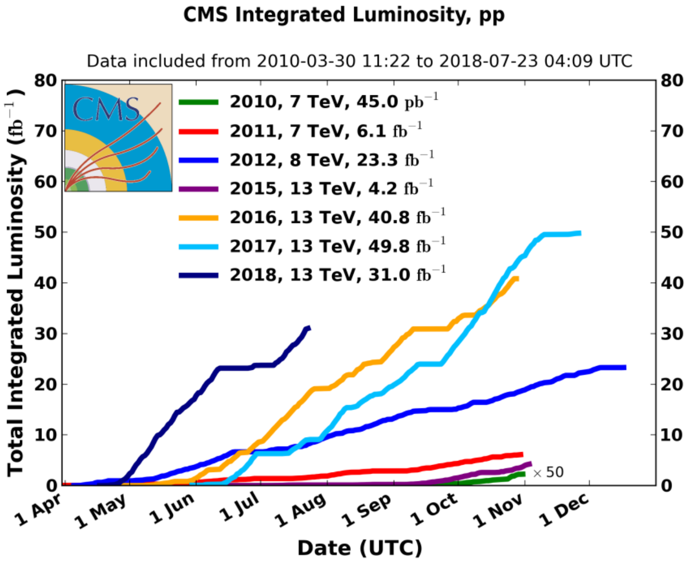
At m_H =125 GeV:

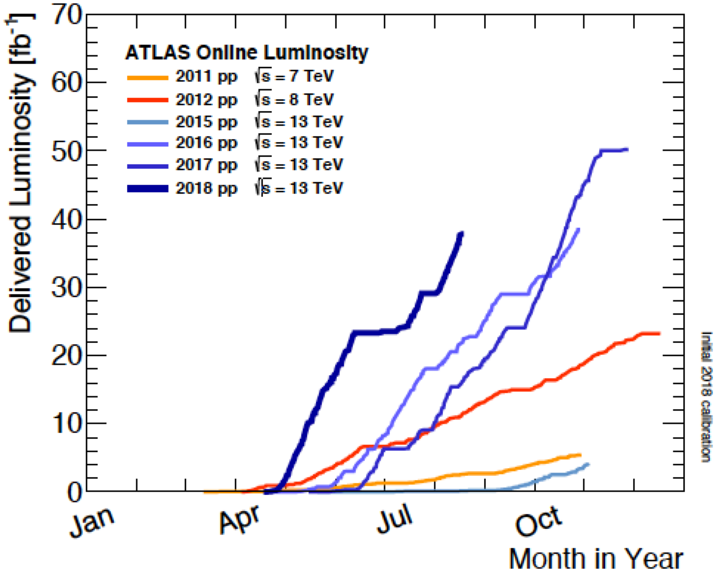
- H(bb) = 57.8%
- H(WW) = 21.4%
- H(gg) = 8.19%
- H(ττ) = 6.27%
- H(ZZ) = 2.62%

- H(cc) = 2.89%
- H(γγ) = 0.23%
- H(Zγ) = 0.15 %
- H(μμ) = 0.02%

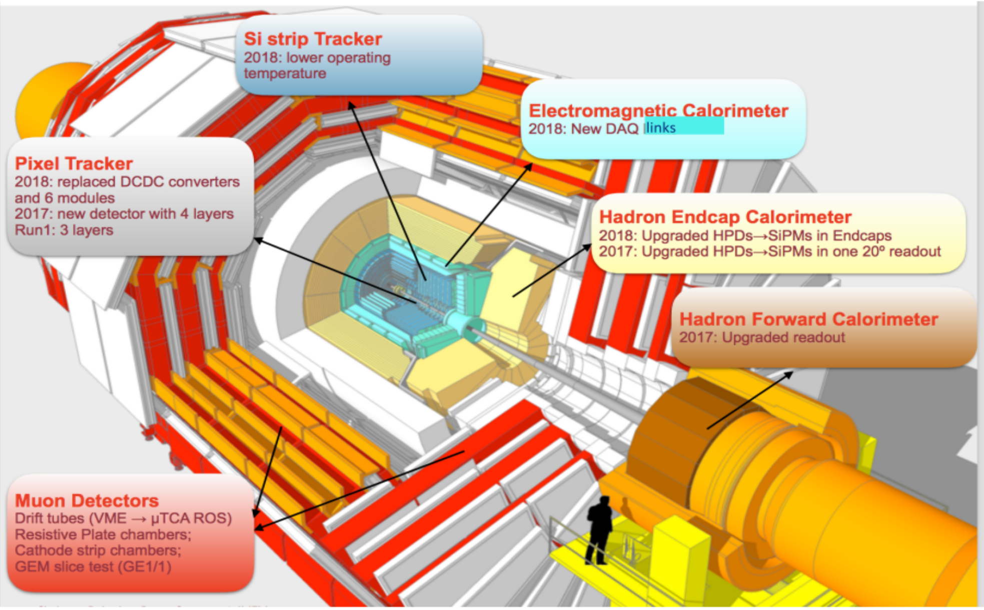
LHC Run 2

- LHC has produced **> 3 years of 13 TeV** data with fantastic performance
  - **>150 fb^{-1}** data by the end of the 2018 run
  - Maximum peak luminosity ~$2\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ with mean pileup ~33 in 2017, ~38 in 2018
  - DESIGN peak luminosity exceeded by a factor of 2!





CMS/ATLAS in 2017/2018 (after LS1)



Si strip Tracker
2018: lower operating temperature

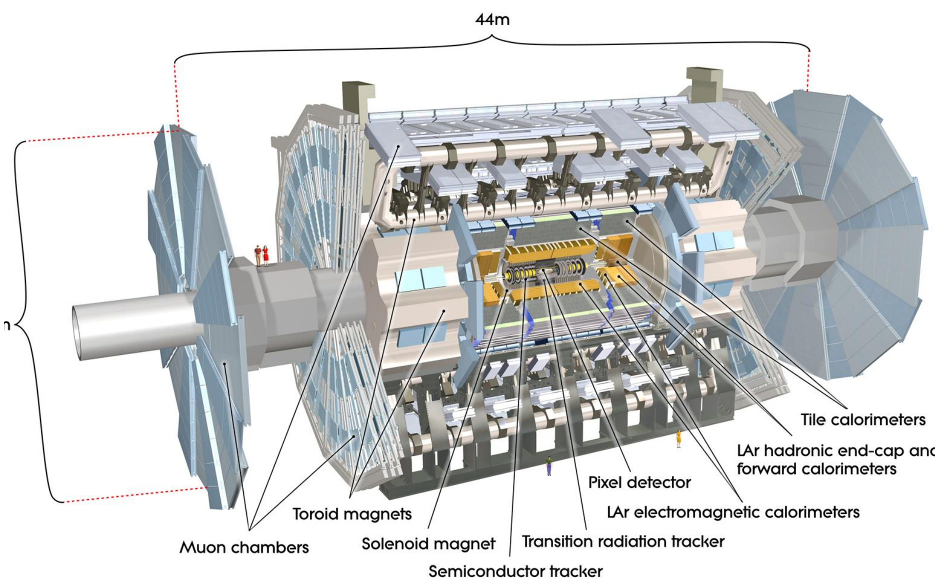
Electromagnetic Calorimeter
2018: New DAQ links

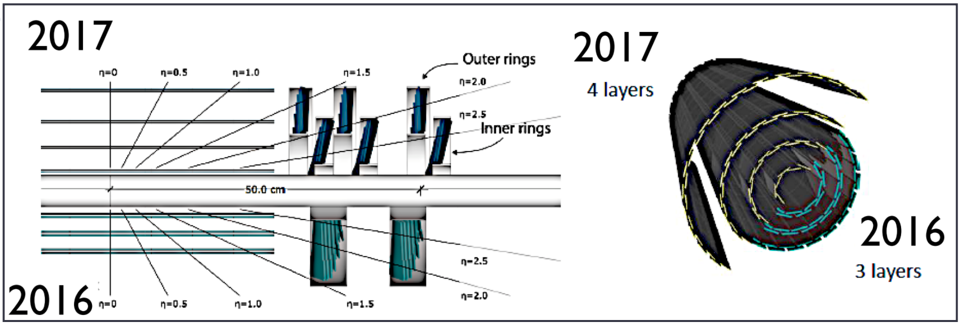
Pixel Tracker
2018: replaced DCDC converters and 6 modules
2017: new detector with 4 layers
Run1: 3 layers

Hadron Endcap Calorimeter
2018: Upgraded HPDs→SiPMs in Endcaps
2017: Upgraded HPDs→SiPMs in one 20° readout

Hadron Forward Calorimeter
2017: Upgraded readout

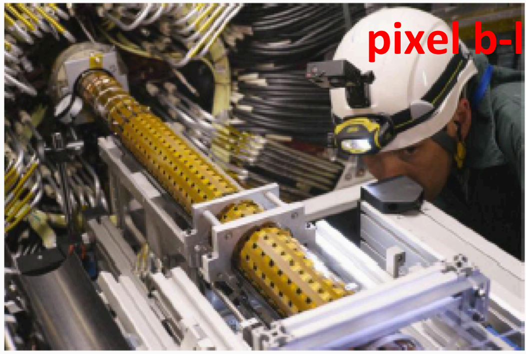
Muon Detectors
Drift tubes (VME → µTCA ROS)
Resistive Plate chambers;
Cathode strip chambers;
GEM slice test (GE1/1)





- New IBL detector installed in LS1 (2013-2014)
- Tracking optimized for high-PU and high-p_T environments
- Better ML algorithms

4th insertable pixel b-layer (IBL)



Large impact on b-tagging performance

H→bb

Motivation:

- H→ bb has the largest BR (58%) for m_H=125 GeV
- Unique final state to measure coupling with down-type quarks
- Drives the uncertainty of the total Higgs boson width
- Primary decay mode for searches at LEP and Tevatron
  → a long history or searches

First H→bb searches started at LEP...

Physics Letters B 565 (2003) 61–75

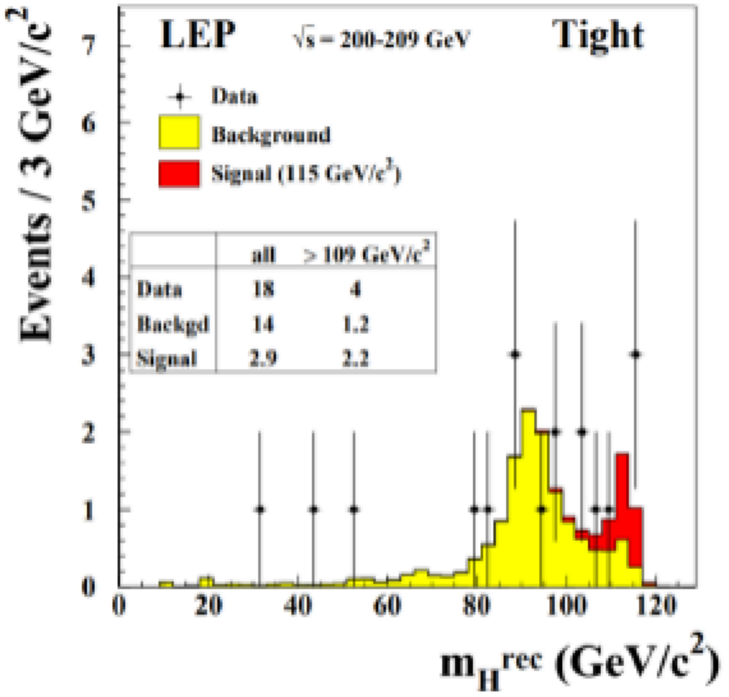
ELSEVIER

Search for the Standard Model Higgs boson at LEP

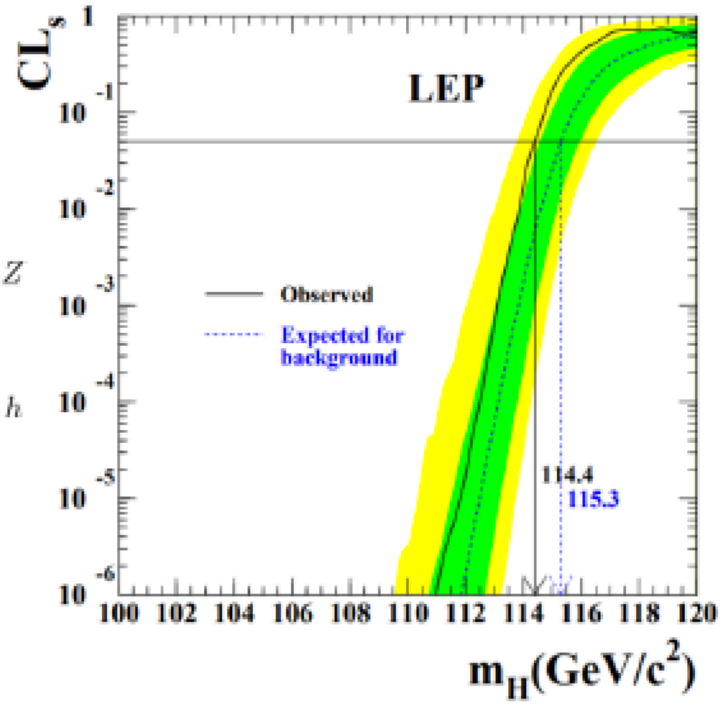
ALEPH Collaboration[1] DELPHI Collaboration[2] L3 Collaboration[3] OPAL Collaboration[4]
The LEP Working Group for Higgs Boson Searches[5]

PHYSICS LETTERS B

$m_H > 114.4$ GeV @ 95%CL



	all	> 109 GeV/c²
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2

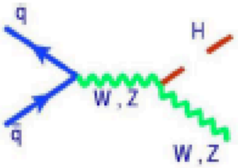


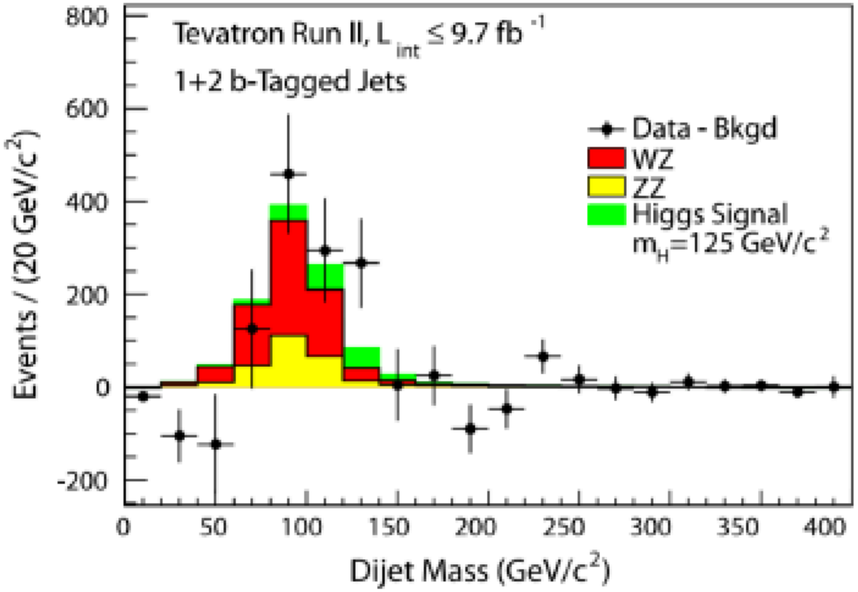
... and continued at Tevatron

PRL **109,** 071804 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Evidence for a Particle Produced in Association with Weak Bosons and Decaying to a Bottom-Antibottom Quark Pair in Higgs Boson Searches at the Tevatron

(*CDF Collaboration)
(†D0 Collaboration)



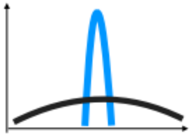


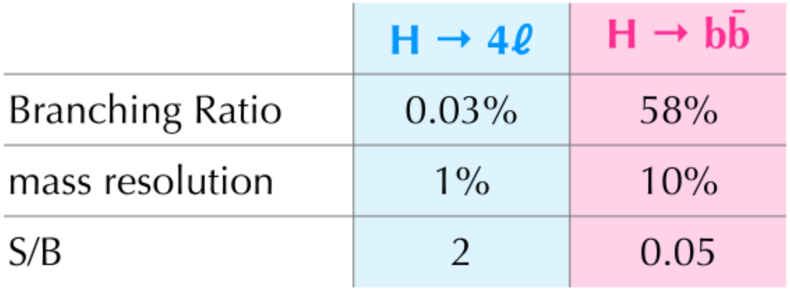
Significance

2.8σ observed @ 125 GeV

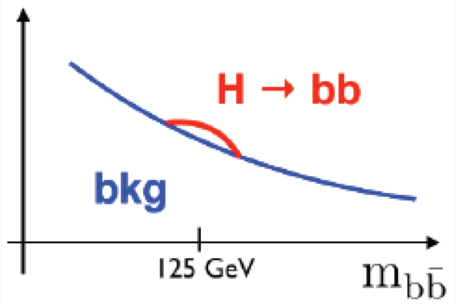
H→bb search challenge:

- **Needs:**
  - Good **b-jets identification** performance: 70% efficiency with < 1% q/g mis-identification probability
  - Best possible **resolution on m(bb)**
  - Capability to exploit all possible information from the event to **improve S/B**
- **H(bb) compared with discovery channel**



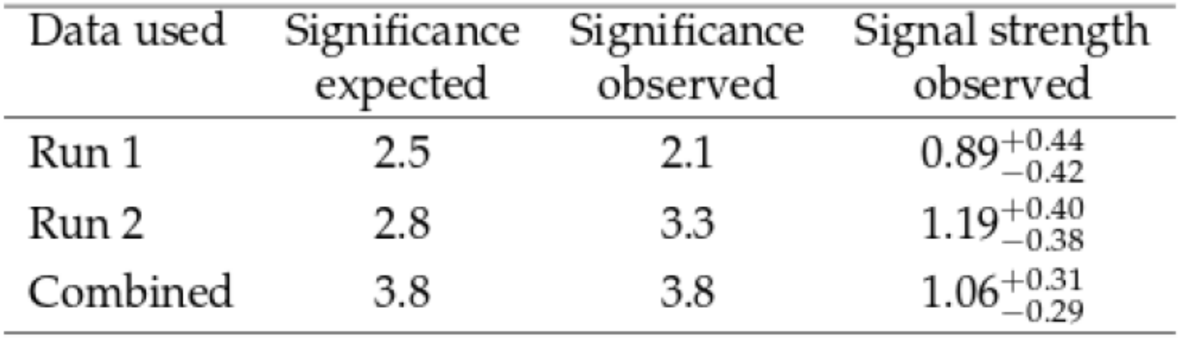


	$H \to 4\ell$	$H \to b\bar{b}$
Branching Ratio	0.03%	58%
mass resolution	1%	10%
S/B	2	0.05



- **Higgs-strahlung - VH (4%) is the most sensitive channel**
  - leptons, E_T^{miss} to trigger and high p_T V to suppress backgrounds

@CMS so far
Evidence established in 2017
Phys. Lett. B 780 (2018) 501

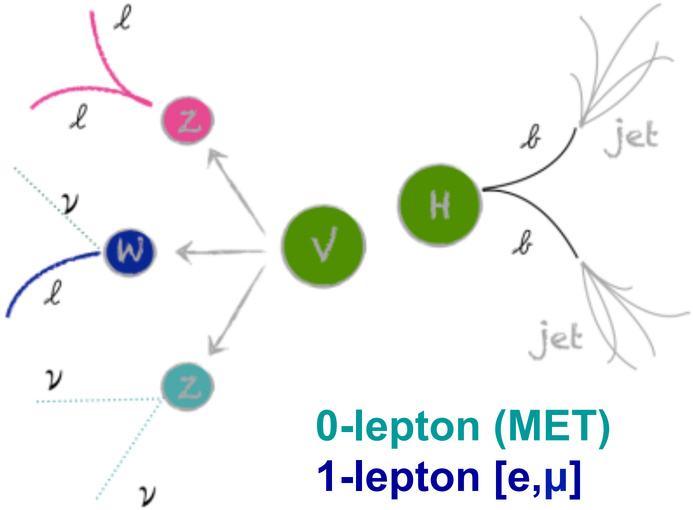


Data used	Significance expected	Significance observed	Signal strength observed
Run 1	2.5	2.1	$0.89^{+0.44}_{-0.42}$
Run 2	2.8	3.3	$1.19^{+0.40}_{-0.38}$
Combined	3.8	3.8	$1.06^{+0.31}_{-0.29}$

VH(H→bb): analysis strategy

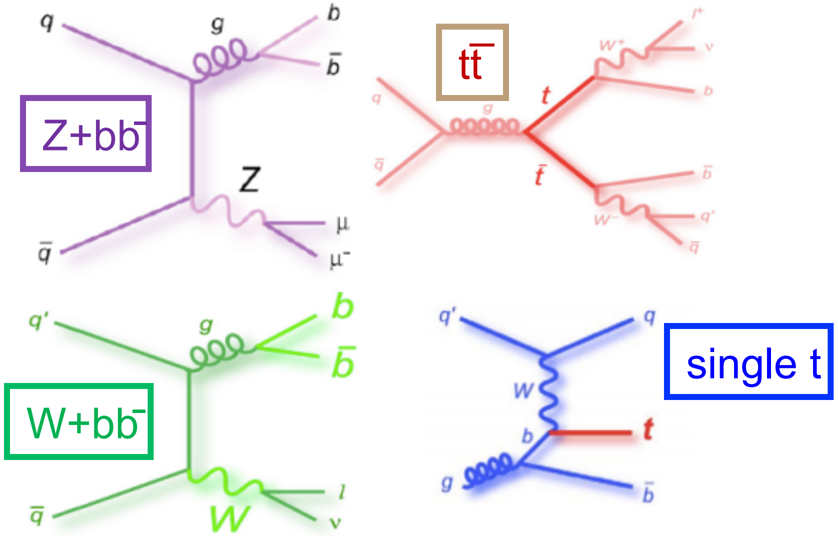
- **Analysis strategy:**
  - **3 channels** with 0, 1, and 2 leptons and 2 b-tagged jets
    - To target Z(vv)H(bb), W(lv)H(bb) and Z(ll)H(bb) processes
  - **Signal region designed to increase S/B**
    - **Large boost** for vector boson
    - **Multivariate analysis** exploiting the most discriminating variables ($m_{b\bar{b}}$, $\Delta R_{b\bar{b}}$, b-tagging)
  - **Control regions**: to validate background samples and control/constrain background normalization and systematics

signal



0-lepton (MET)
1-lepton [e,μ]
2-leptons [ee,μμ]

irreducible backgrounds

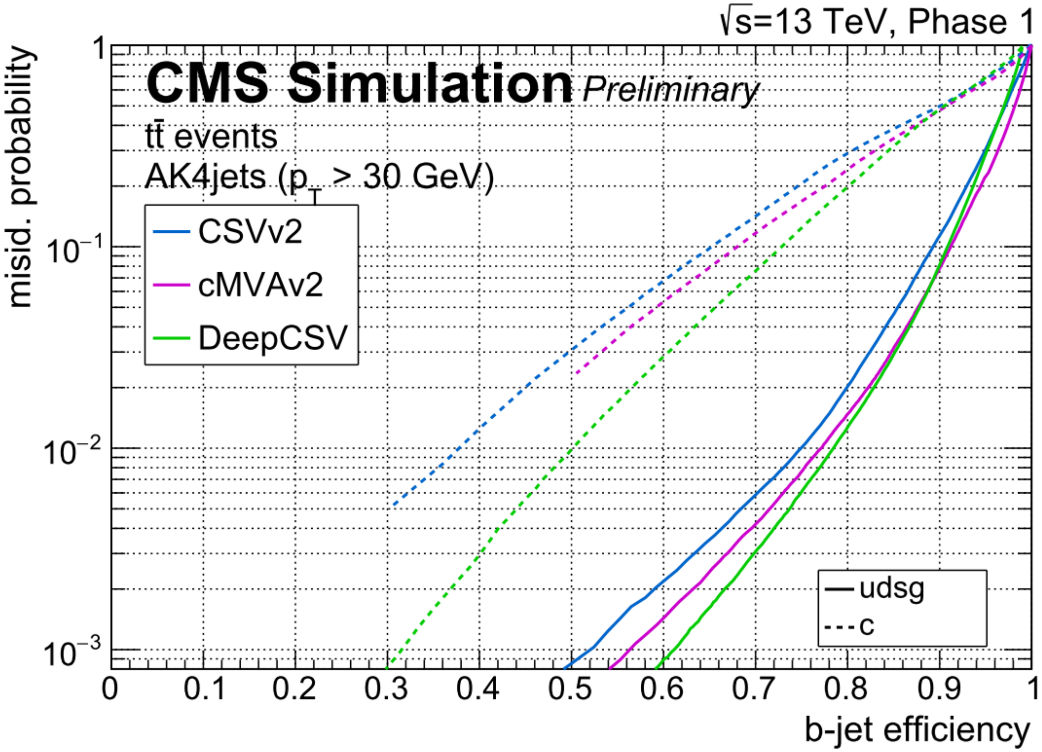


normalization from data, shapes from MC

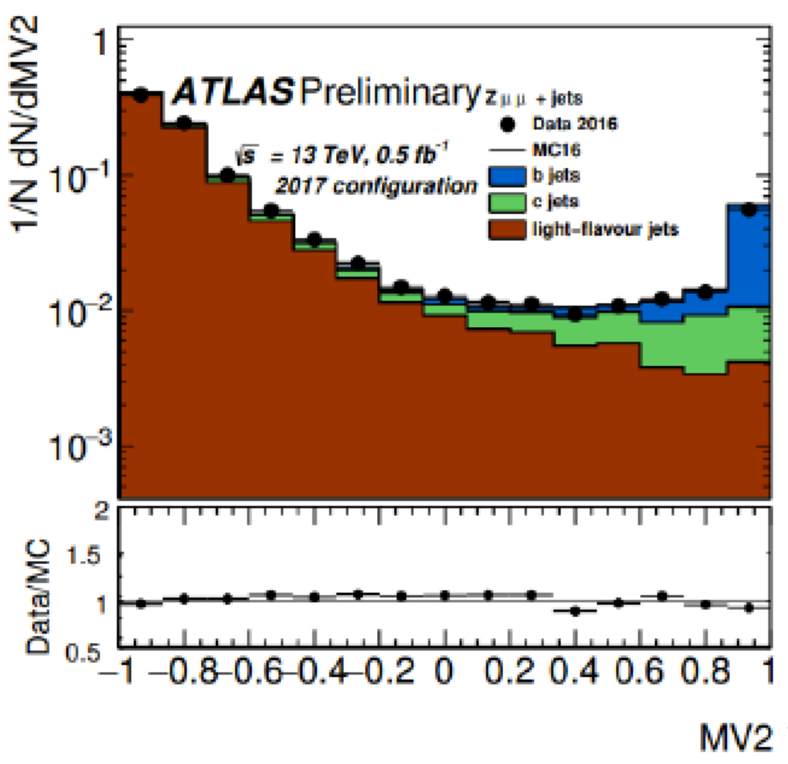
Improvement of b-tagging

CMS: better mis-identification rate and data/MC agreement with Phase 1 pixel detector and DeepCSV algorithm

- Efficiency ~70% per fake rate at < 1%

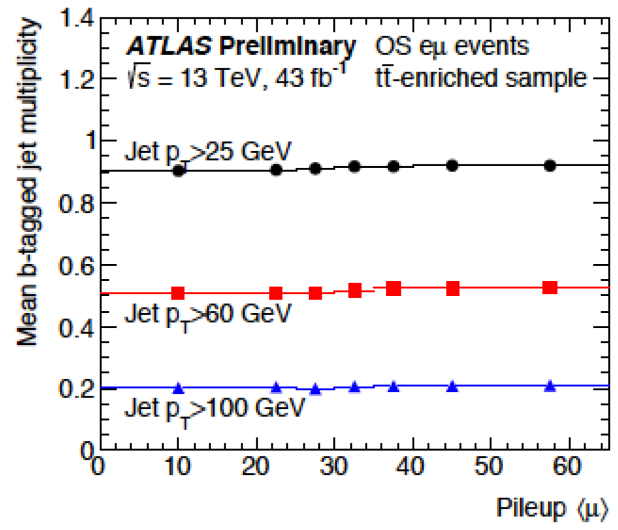


b-tagging discriminant

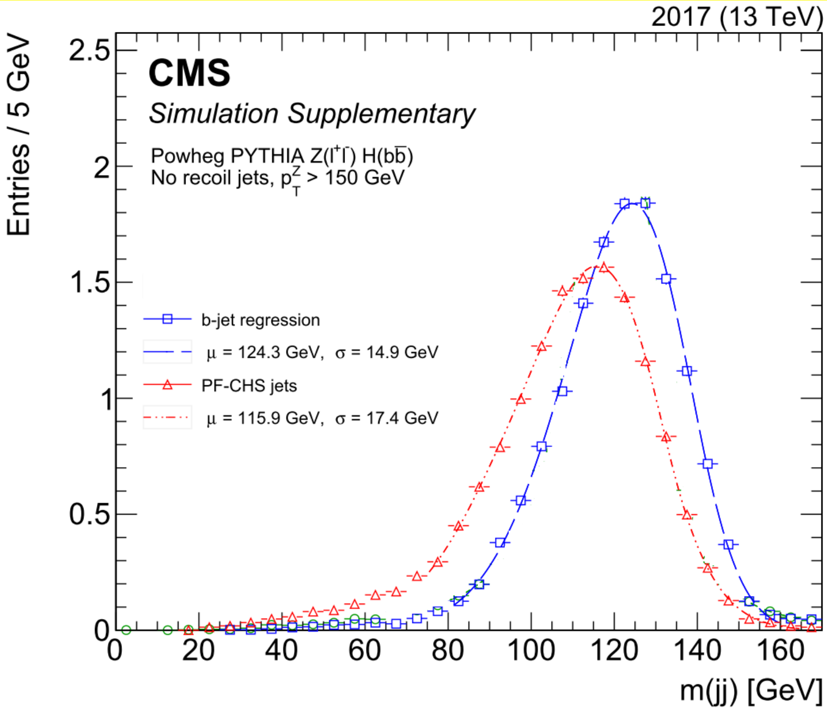


ATLAS:

- rejection of light/c jets 300/8 at 70% b-jet efficiency
- Good performance even at high PU

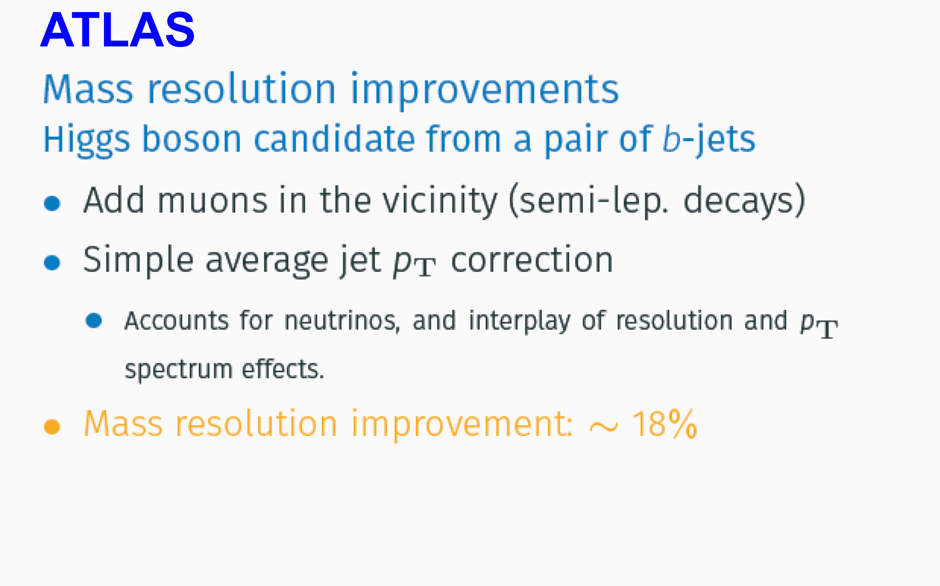


Improvement of di-jet mass resolution



CMS:

- Regression mainly recovers missing energy in the jet due to neutrino
- Extended set of input variables now including lepton flavour (μ/e), jet mass, p_T wrt to lepton axis, energy fractions in ΔR rings
- Significant m(bb) resolution improvement → σ/peak down to 11.9% in 2017 wrt 13.2% in 2016

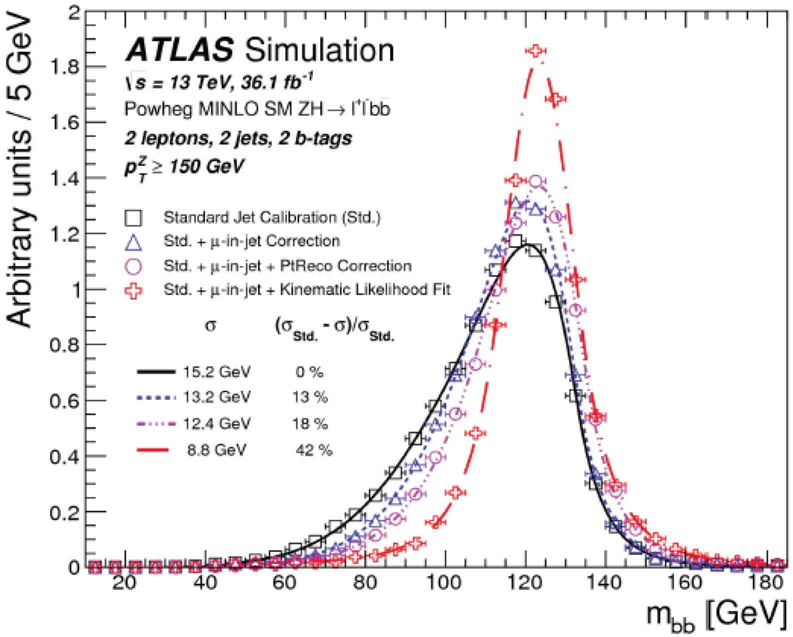


ATLAS

Mass resolution improvements

Higgs boson candidate from a pair of *b*-jets

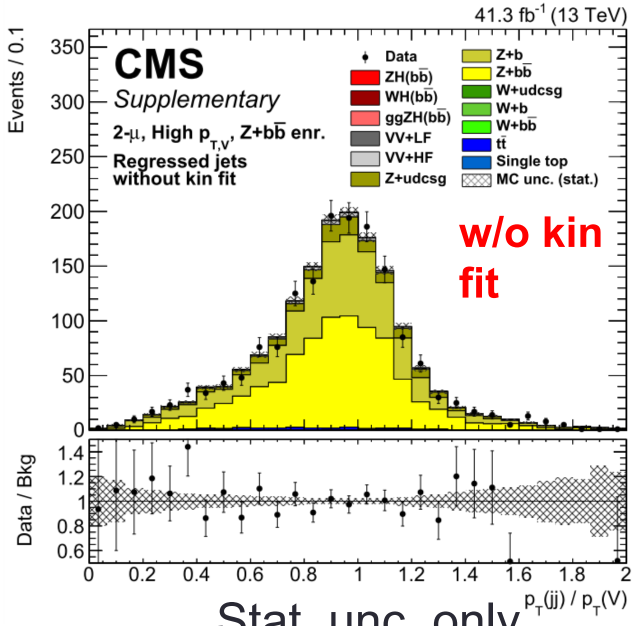
- Add muons in the vicinity (semi-lep. decays)
- Simple average jet p_T correction
  - Accounts for neutrinos, and interplay of resolution and p_T spectrum effects.
- Mass resolution improvement: ∼ 18%



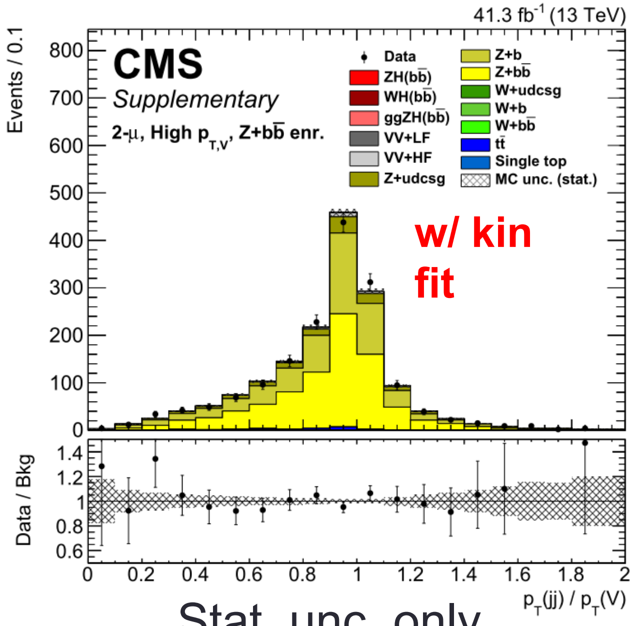
Kinematic fit in 2-lepton channel

CMS:

- No intrinsic missing energy in the $Z(ll)H(b\bar{b})$ process
- Improve jet p_T measurement through kinematic fit procedure
  - Constrain dilepton system to Z mass
  - Balance the ll+bb system in the (p_x,p_y) plane
- Improvement of up to 36% on $m(b\bar{b})$ resolution

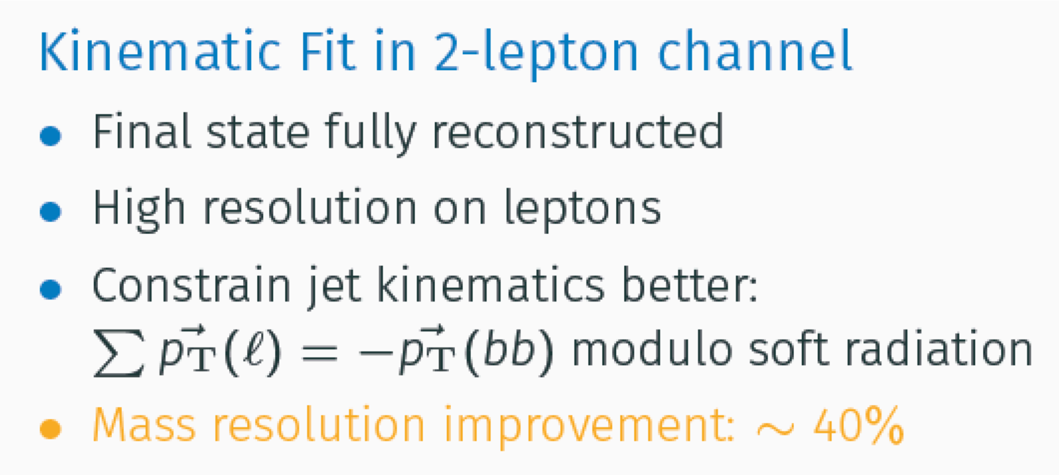


Stat. unc. only



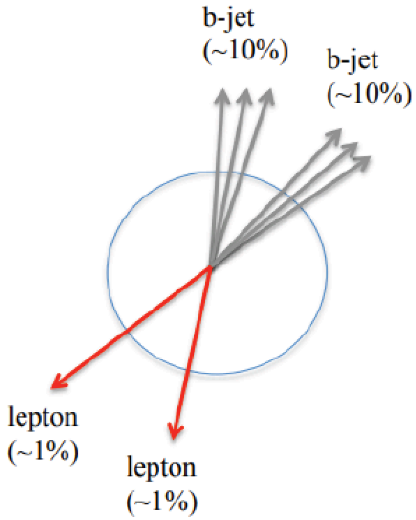
Stat. unc. only

ATLAS:



Kinematic Fit in 2-lepton channel

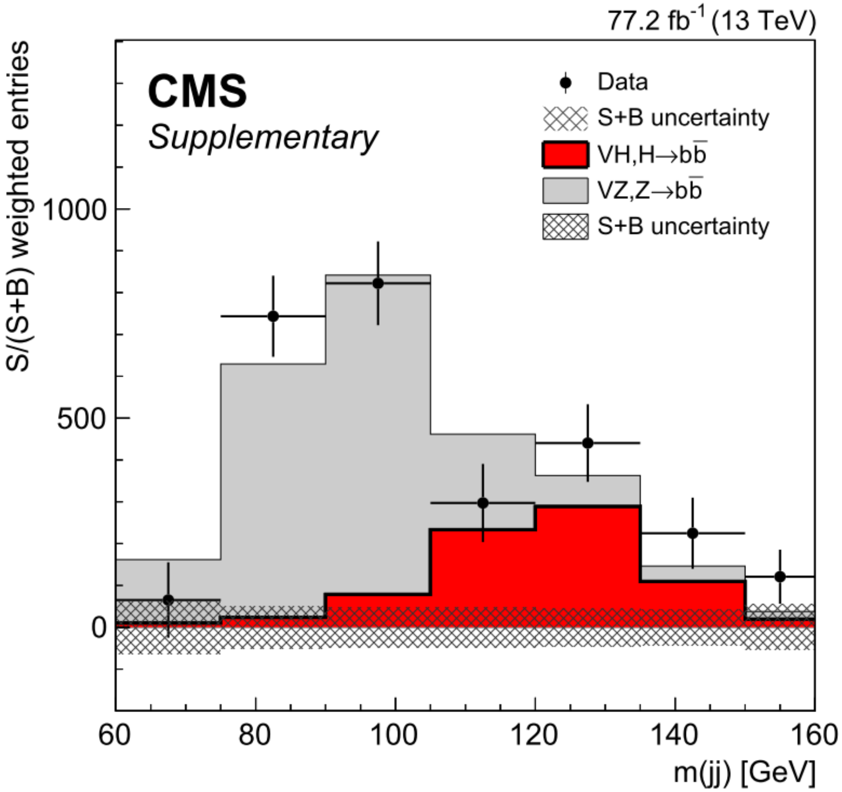
- Final state fully reconstructed
- High resolution on leptons
- Constrain jet kinematics better:
  $\sum \vec{p_T}(\ell) = -\vec{p_T}(bb)$ modulo soft radiation
- Mass resolution improvement: $\sim 40\%$



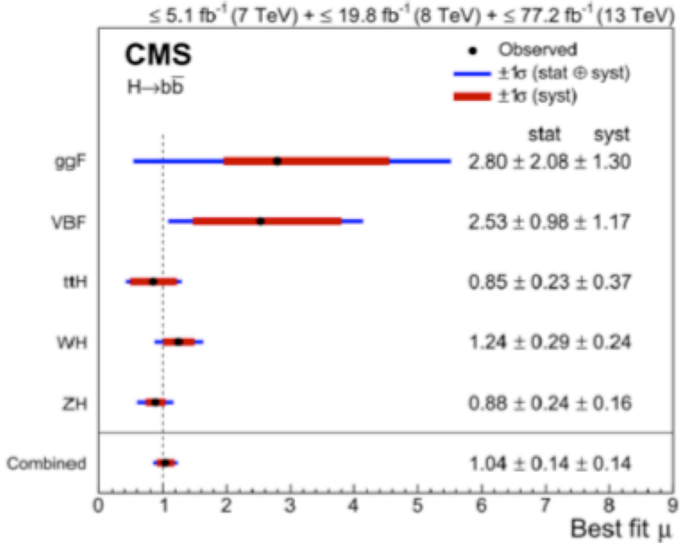
Run 1 + Run 2 results (CMS)

VH(H→bb)

	Significance (σ)		
Data set	Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23



Combining all the channels:



Significance
5.5σ expected
5.6σ observed

Observation of the H→bb decay by the CMS Collaboration

Physics landscape at the end of Run 2

LHC experiments confirm that the SM is robust but it should not be the ultimate theory of particle physics, because of many 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 ?*
- *Is supersymmetry realized in Nature?*
- *Inflation*

No excess in data for direct signs of new physics:

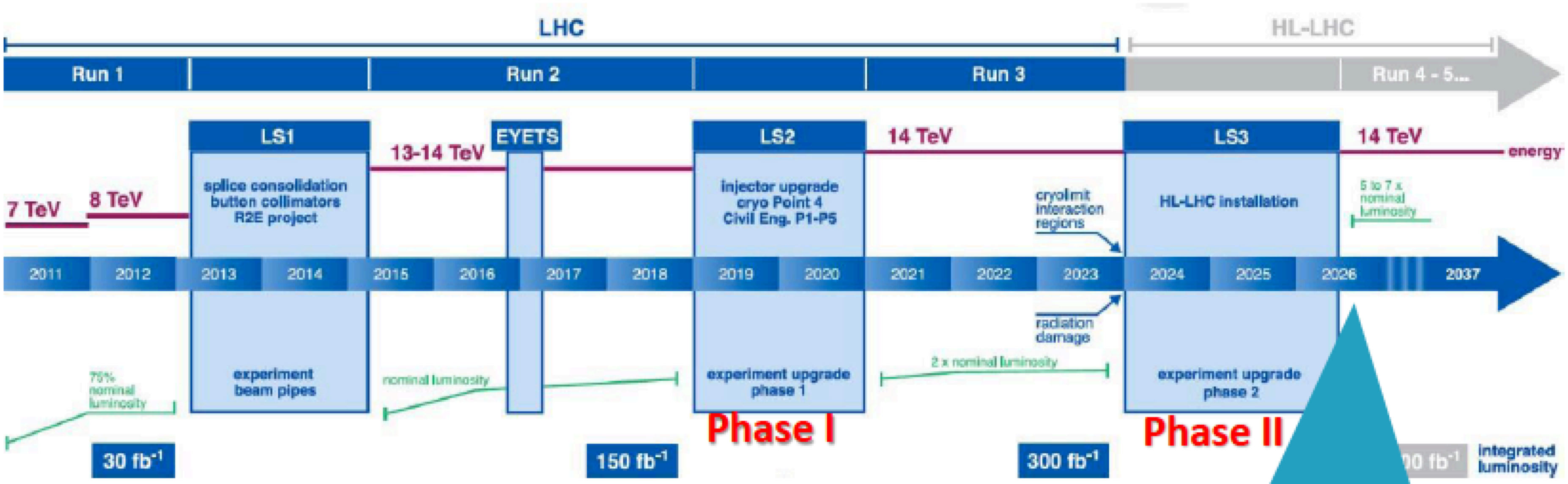
- Supersymmetry
- Long-lived particles
- New heavy resonances
- Dark Matter and its nature

Doing Precision measurements (Couplings, Cross Sections, Width, Differential Distributions,…) which might be an indirect sign of BSM physics

The Big Questions

- **The four big questions for Higgs physics**
  - How well can the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?
  - How do precision electroweak observables inform us about the Higgs boson properties and/or BSM physics?
  - What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?
  - What is the best path towards measuring the Higgs potential?
- **The four big questions for BSM (@colliders):**
  - To what extent can we tell whether the Higgs is fundamental or composite?
  - Are there new interactions or new particles around or above the electroweak scale?
  - What cases of thermal relic WIMPs are still unprobed and can be fully covered by future collider searches?
  - To what extent can current or future accelerators probe feebly interacting sectors?

LHC and HL-LHC schedule

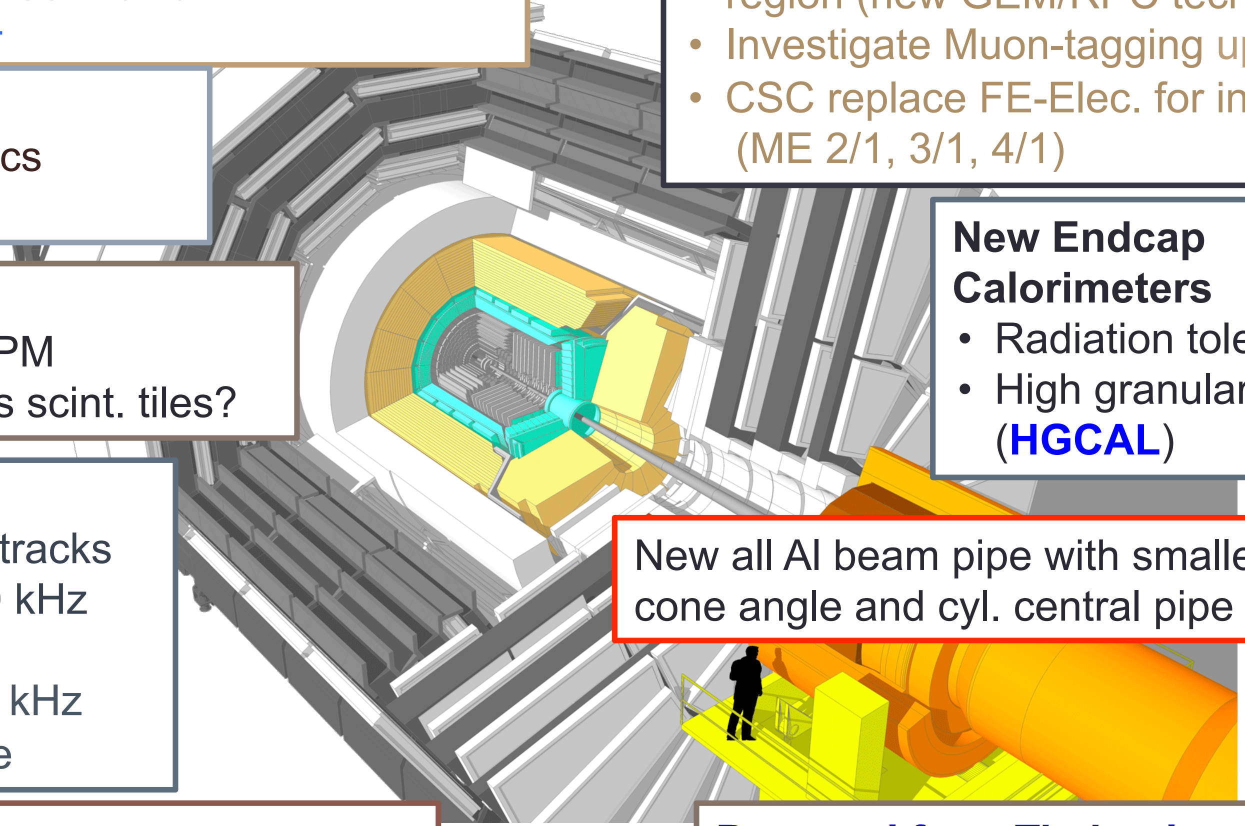


Luminosity

Nominal scenario: $\mathcal{L} = 5\times10^{34}$ cm^{-1}s^{-1}
for 3000/fb; Pile-up = 140

Ultimate Scenario: $\mathcal{L} = 7.5\times10^{34}$ cm^{-1}s^{-1}
for 4000/fb; Pile-up = 200
⇒25% increase in integrated lum.

CMS Phase 2 upgrade



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

Barrel ECAL
- Replace FE electronics
- Cool detector/APDs

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

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

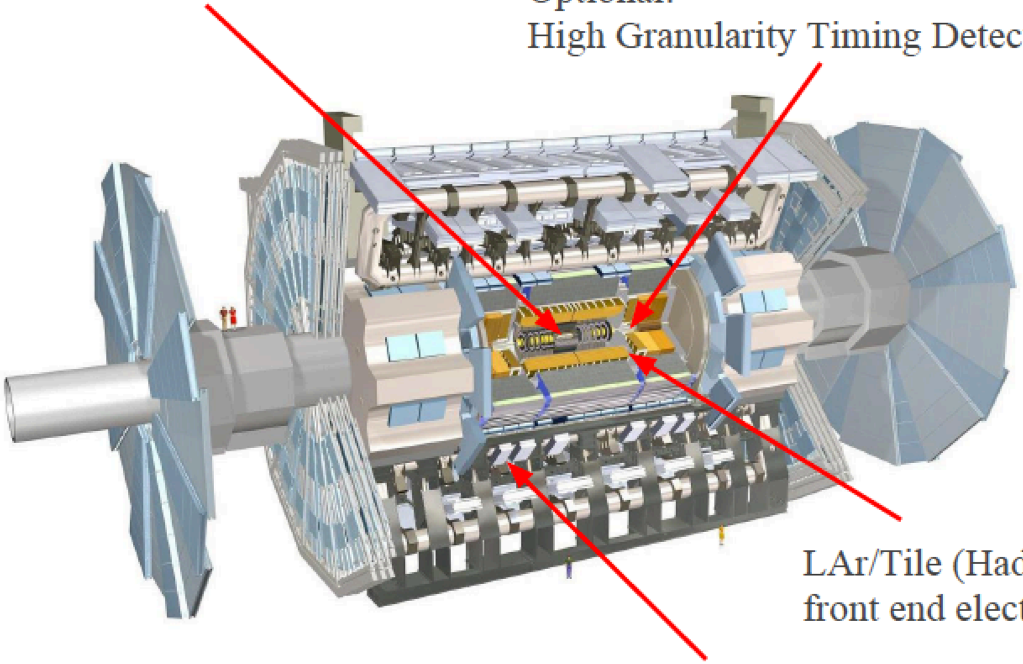
Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 3
- CSC replace FE-Elec. for inner rings (ME 2/1, 3/1, 4/1)

New Endcap Calorimeters
- Radiation tolerant
- High granularity (**HGCAL**)

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

Proposal for a Timing layer
- Timing resolution ~ 10 ps
- Space resolution ~ 10’s of μm

ATLAS Phase 2 upgrade



New silicon Inner Tracker (ITk)

Optional:
High Granularity Timing Detector (HGTD)

LAr/Tile (Hadronic cal.)
front end electronics

New muon chambers and front
end readout electronics

DAQ off detector electronics:

- L0 hardware triggers will provide trigger decisions within a latency of 10 µs.
  - Based on muon and calorimeter data + their combinations in the topological processors.
- The L1Track trigger processes L0 RoIs to search for ITk tracks with high transverse momentum.
- The L1Global uses full-granularity calorimeter information and improved granularity for the entire detector.

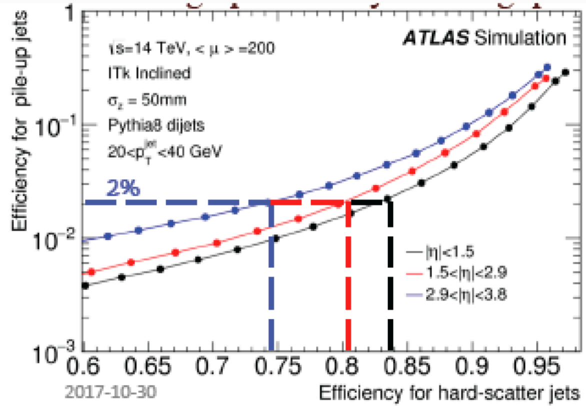
Itk: All-silicon tracker which provides **coverage for tracking for up to |η| < 4.0.**
Optional: A new High Granularity Timing Detector (HGTD) instrumenting the gap region between the two LAr cryostats
Muon: new RPCs and sTGCs which are able to cope with the high rate trigger

Detector performance for Phase 2 upgrade

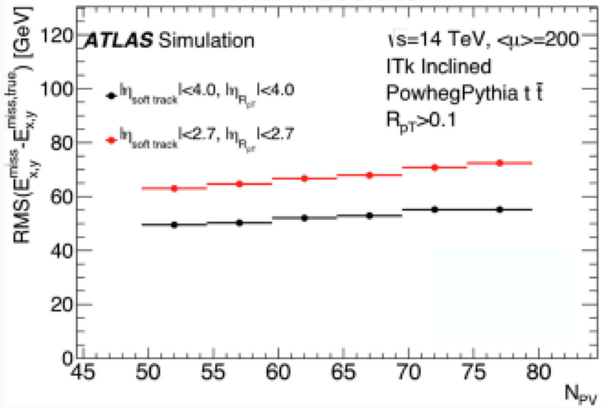
Detector performance after Phase-2 upgrades:

- Effective pileup mitigation
- Overall performance similar or better than during Run 2
- Extended capabilities with new algorithms

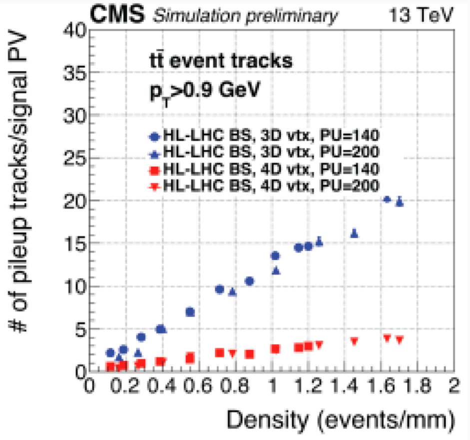
Jets



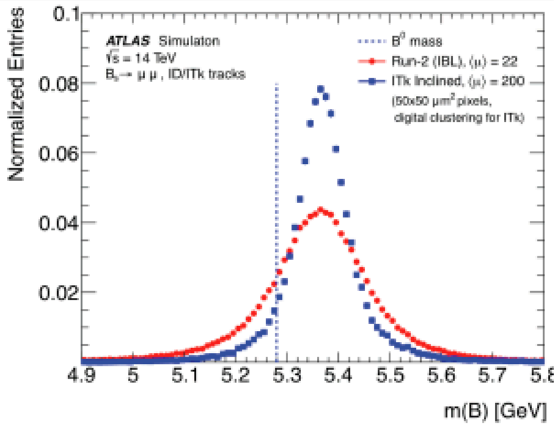
MET resolution



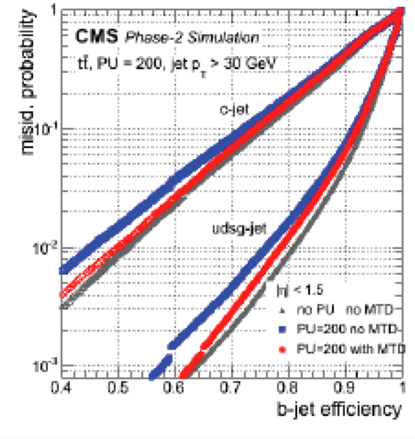
Pile-up suppression



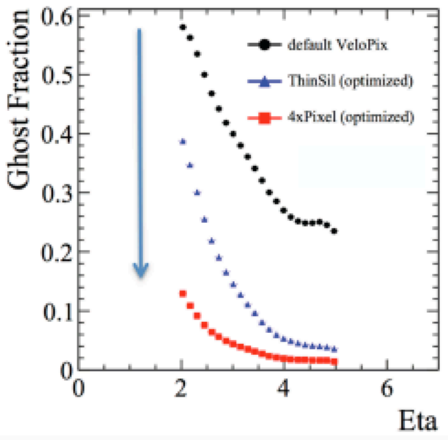
Mass resolution



B-tagging



LHCb Vertex Locator



Strategy for Higgs physics @ HL-LHC

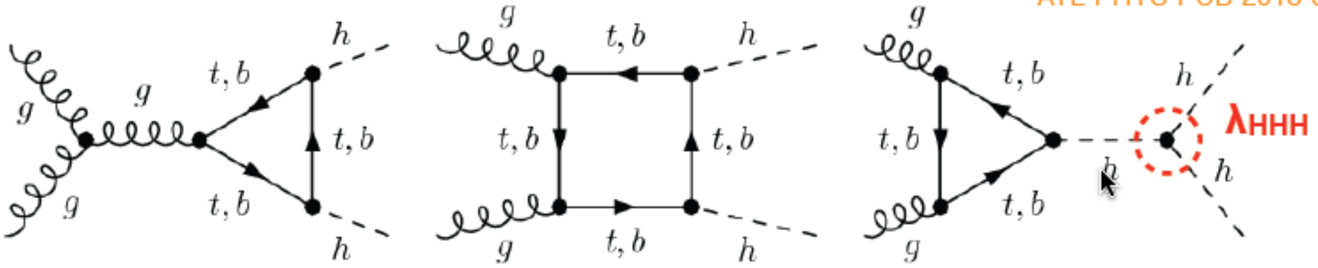
Phase II Detector Upgrades:

- Radiation hardness
- Mitigate physics impact of high pileup
- → Object reconstruction efficiencies, resolutions and fake rates are assumed to be similar in the Run-2 and HL-LHC environments

Higgs@HL-LHC:

- Precision Measurements (Couplings, Cross Sections, Width, Differential Distributions,…) → looking for deviations from the SM
- BSM Higgs direct searches: extra scalars, BSM Higgs resonances, exotic decays, anomalous couplings
- VBS scattering
- Rare decays and couplings
  - Di-Higgs production ➜ Higgs self coupling

ATL-PHYS-PUB-2013-007



Analysis approaches for HL-LHC

- **Method 1: Full simulation (CMS)**: use of the most advanced geometry, algorithms and tuning, PU simulation

- **Method 2: Full analysis with parameterized detector performance (CMS)**: use DELPHES with up-to-date phase-2 detector performance (tracking, vertexing, timing, dedicated PUPPI jet algorithms, increased acceptance, performance of new detectors)

- **Method 3: truth + smearing (ATLAS):** truth-level events overlaid with jets (full sim) from pileup library, reconstruct particles (electrons, muons, jets, MET) from MC truth+overlay and smear their energy and p_T using appropriate smearing functions
  - Cross checked with some of the 'real' data analyses

- **Method 4: projections (mostly CMS and LHCb)**
  - Existing signal and background samples (simulated at 13 TeV) scaled to higher lumi and √s luminosity and 14 TeV. Analysis steps (cuts) from present analyses
  - 2 scenarios 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+)

Modeling the projections for HL-LHC

Experimental uncertainties:

- Estimates of **ultimately achievable accuracy** based on the upgraded Phase-2 detectors studies (TDRs).
- Assumption that **sufficiently large simulation samples** will be available

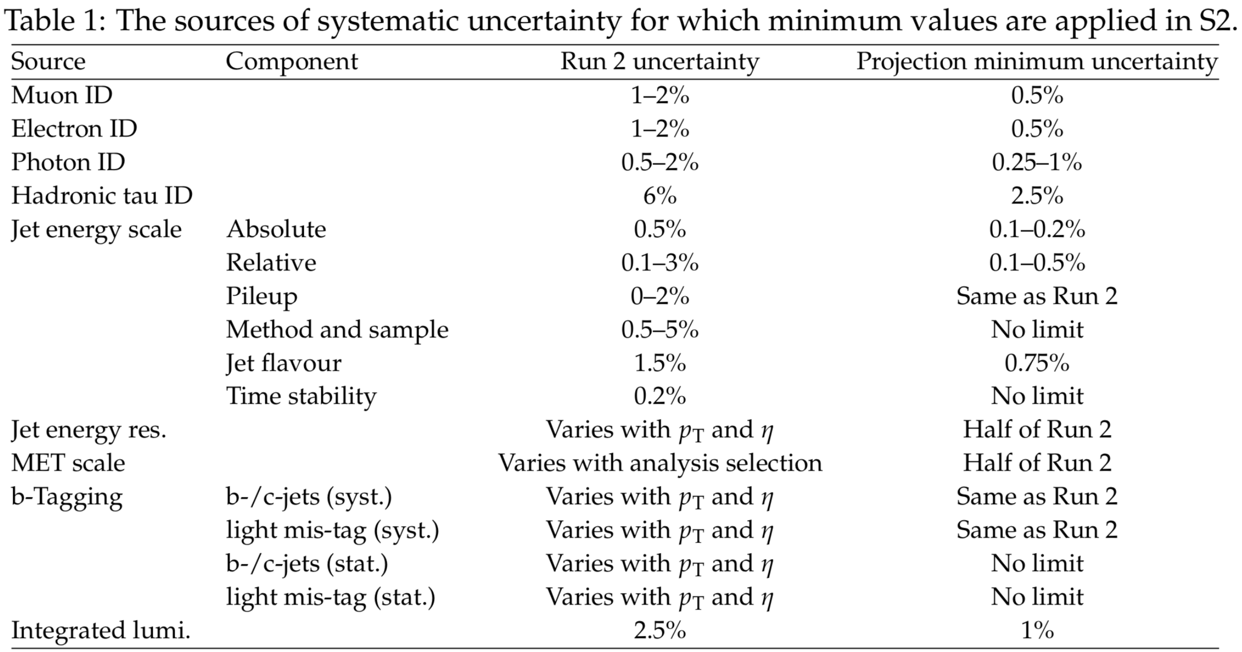


Table 1: The sources of systematic uncertainty for which minimum values are applied in S2.

Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

Theoretical uncertainties:

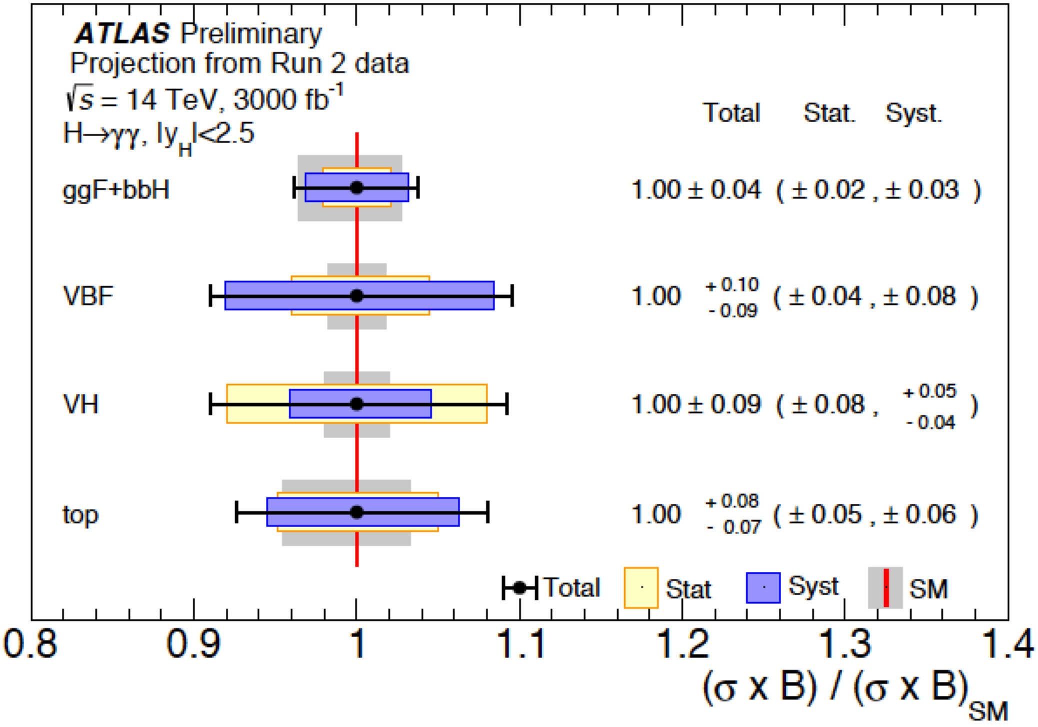
- Build upon existing/recent TH progress/studies
- Assume a scaling down by a constant factor
- **QCD calculations (1/2), understanding of** PDFs (1/3), **top pT (1/2), etc.**

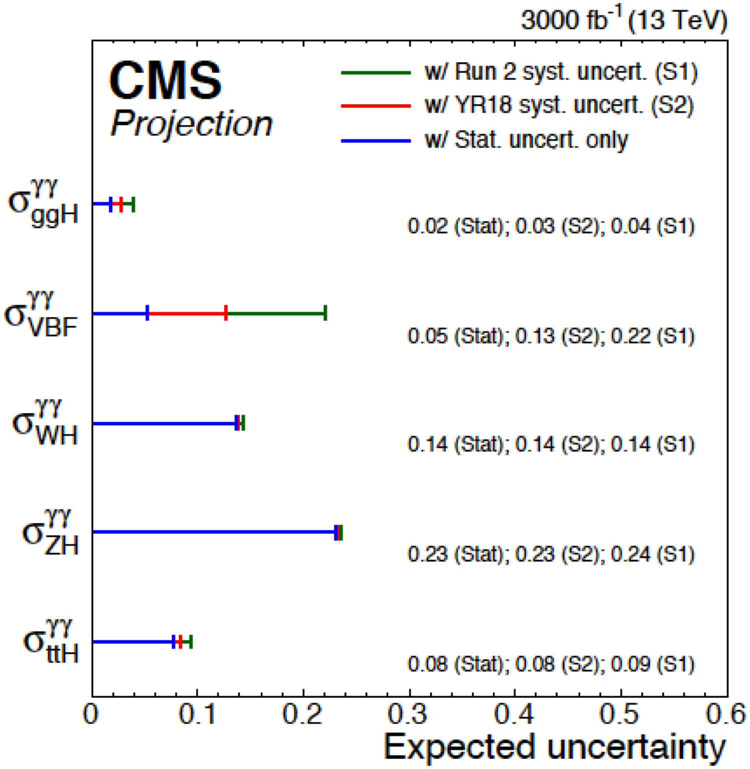
H→γγ

Projections for:
- H→γγ (ggH, VBF, VH, ttH)

two isolated photon candidates passing good quality requirements in the precision regions of the detectors

The main systematic uncertainties affecting the results are the background modeling uncertainty, missing higher order uncertainties causing event migrations between the bins, photon isolation efficiencies and jet uncertainties



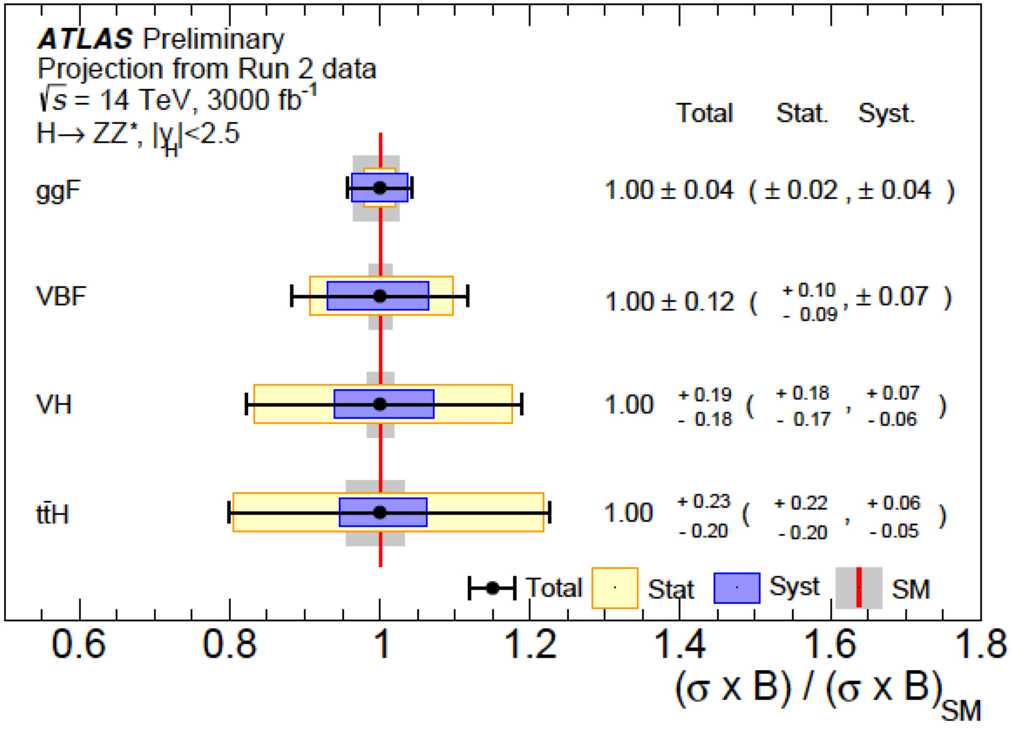


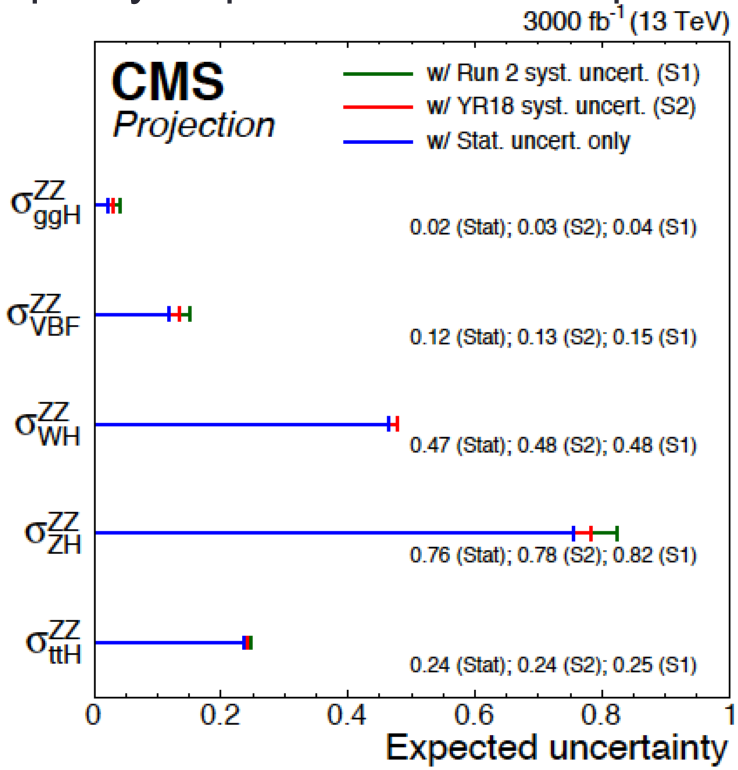
Achievable precision @3000 fb^{-1} : less than 10 % (VH dominated by stat uncert.)

H→ZZ→4l

Projections for:
- H→ZZ→4l (ggH, VBF, VH, ttH)

at least two same-flavor opposite-sign di-lepton pairs, chosen from isolated e and μ candidates passing good quality requirements in acceptance





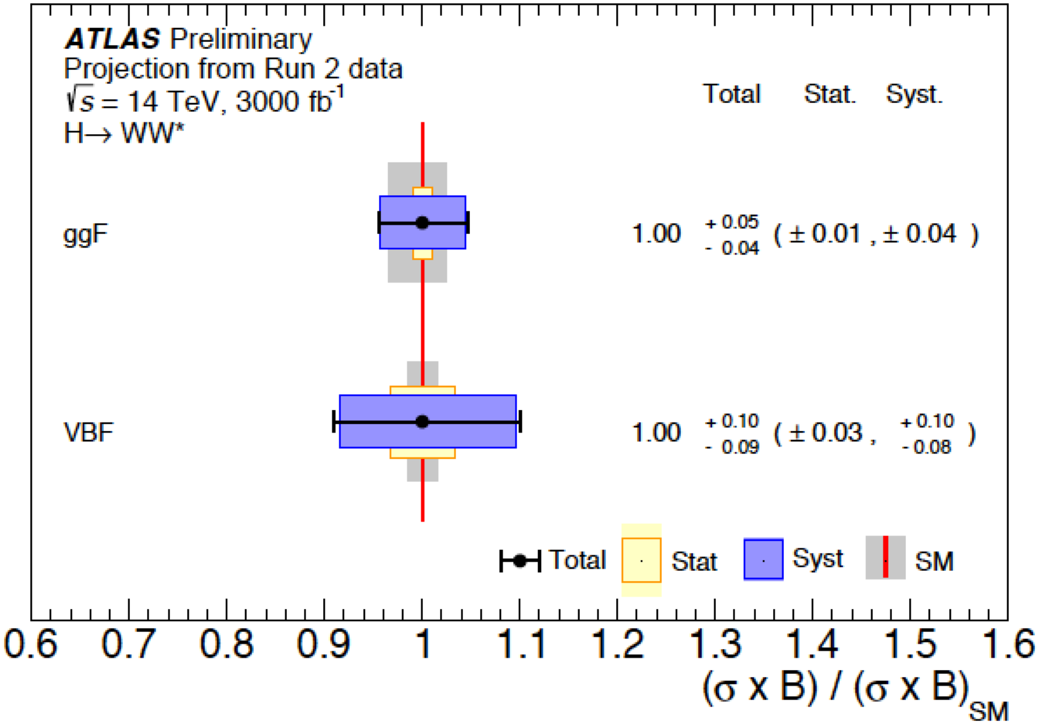
Dominant systematic uncertainties:
- for ggH: on the lepton reconstruction and identification efficiencies, and pile-up modelling uncertainties.
- for VBF and VH: on the jet energy scale and resolution, and by the missing higher order uncertainties + the parton shower modelling for ttH.

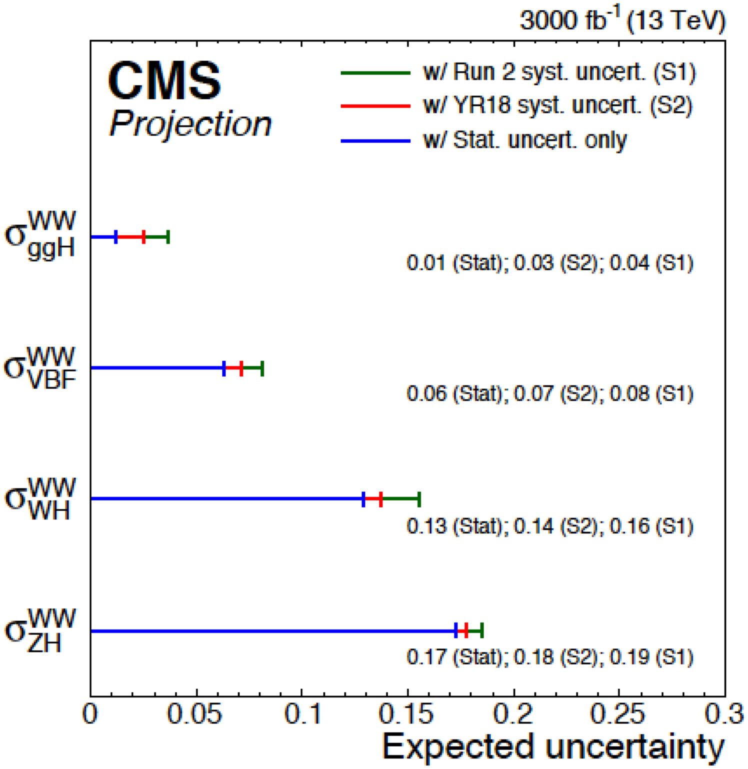
$H \rightarrow WW \rightarrow 2l2\nu$

Projections for:

- $H \rightarrow WW \rightarrow 2l2\nu$ (ggH, VBF, VH)

events that contain two opposite-charged isolated leptons passing good quality requirements in the precision region of the detectors and missing transverse momentum





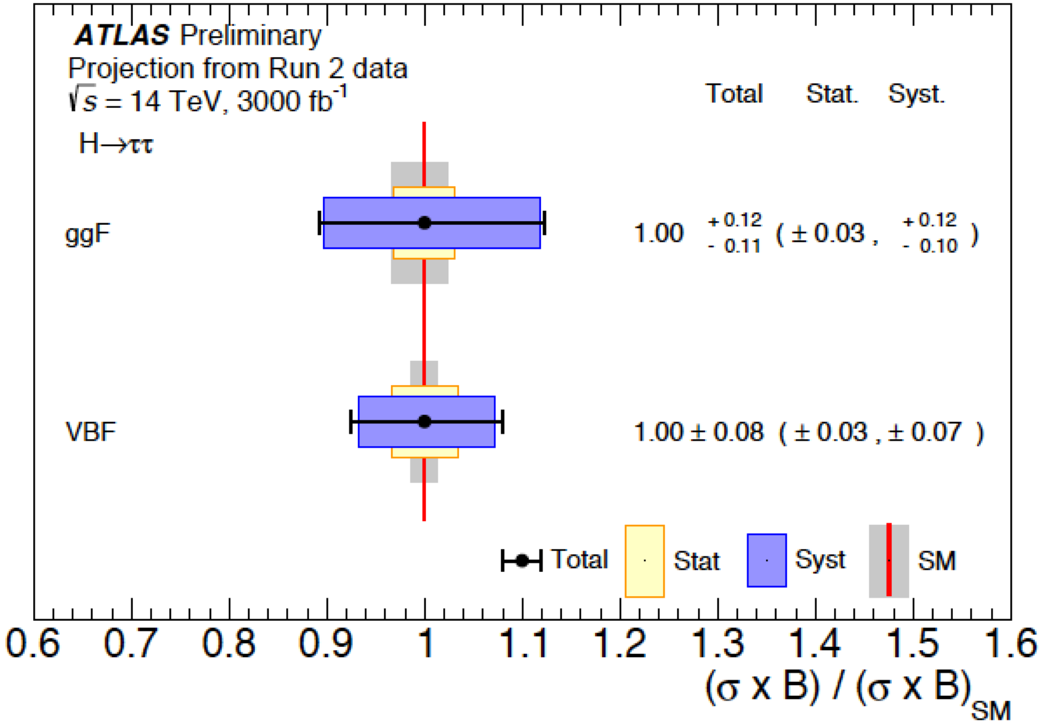
The measurement of the ggH cross section by branching fraction is dominated by theoretical PDF uncertainty, followed by experimental uncertainties affecting the signal acceptance, including uncertainties on the jet energy scale and flavour composition, and lepton mis-identification.

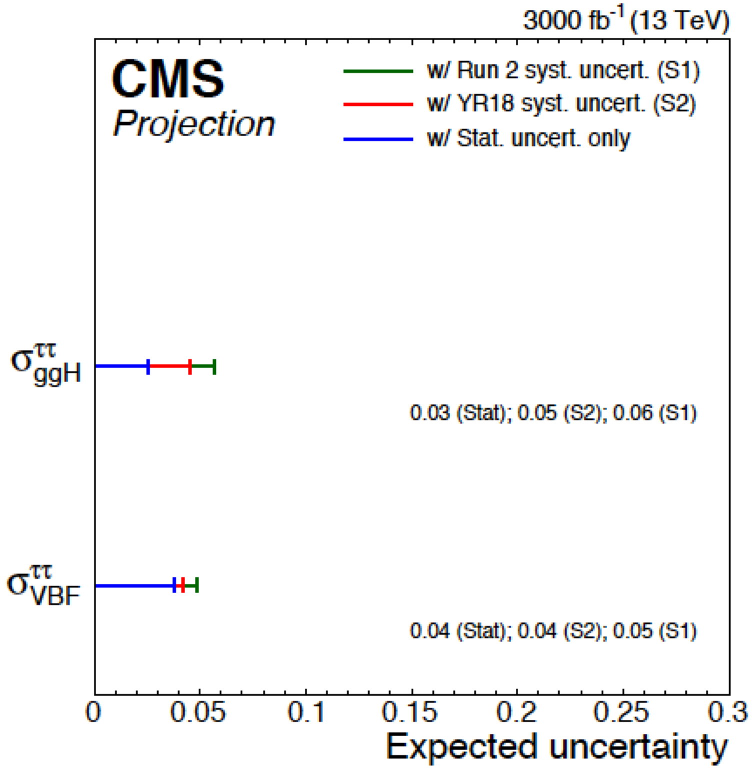
H→ττ

Projections for:

- H→ττ (ggH, VBF)

Three subs-channels ($\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$) are defined by requirements on the number of hadronically decaying τ-leptons candidates and leptons (electrons or muons)





The dominant contributions to the systematic uncertainty come from:

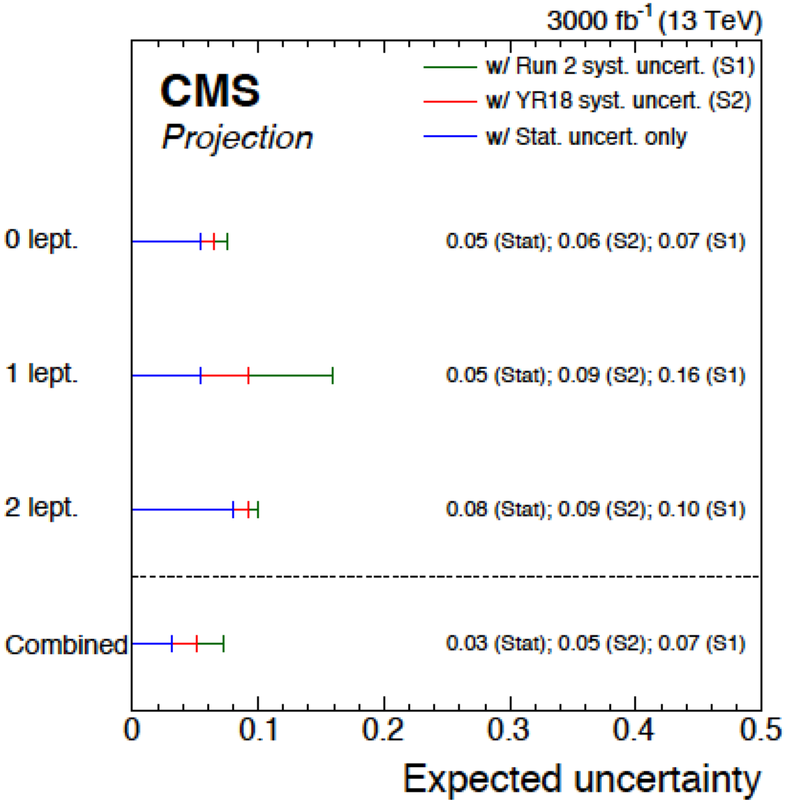
- the experimental and background modeling errors
- the uncertainties on jet calibration and resolution, on the reconstruction of the E_t^{miss}
- the determination of the background normalization from signal and control region

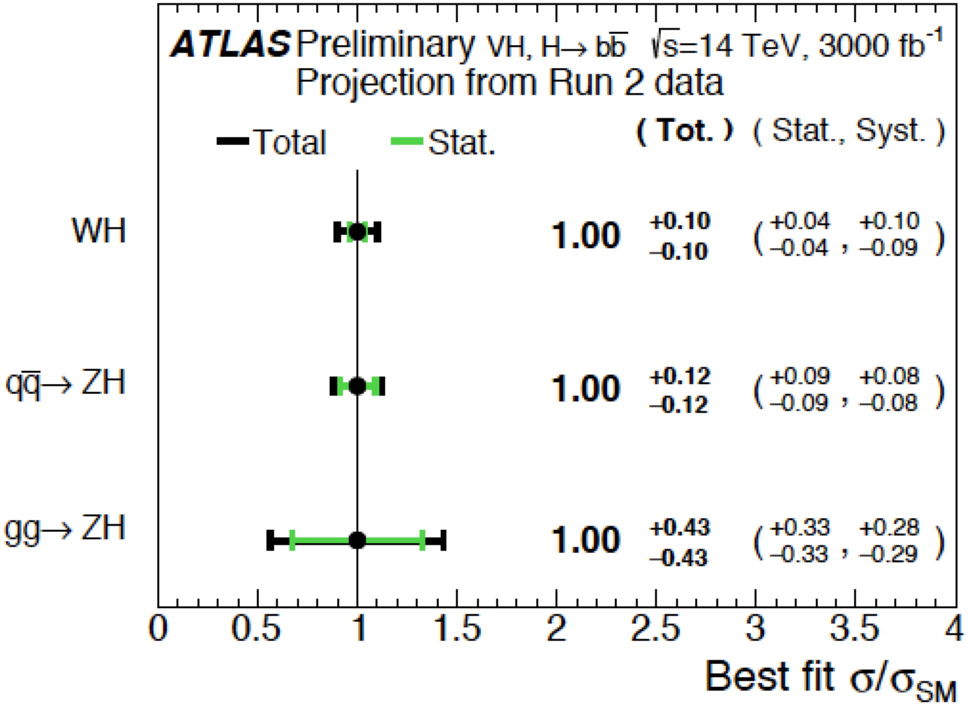
H→bb

Projections for:

- VH, H→bb and boosted H→bb

- Leptonic decays of the vector boson for triggering and to reduce the multi-jet background
- Final states: two b-jets and either zero, one or two electrons or muons.

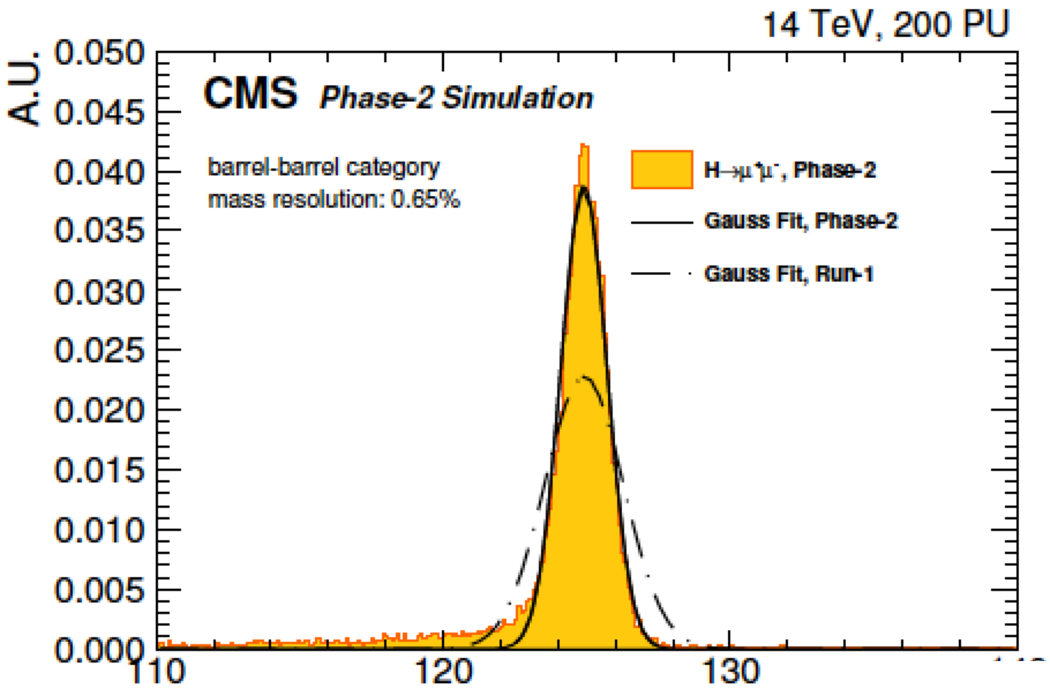


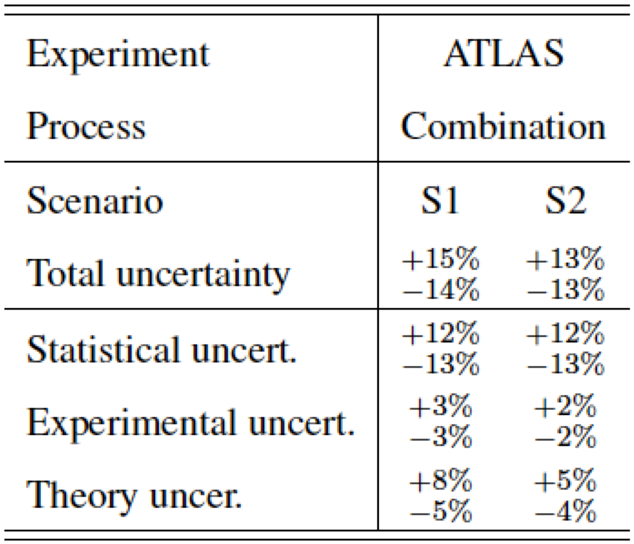


The largest component of the systematic uncertainty is theoretical. This arises from the uncertainty in the gluon-induced ZH (gg→ZH) production cross section due to QCD scale variations

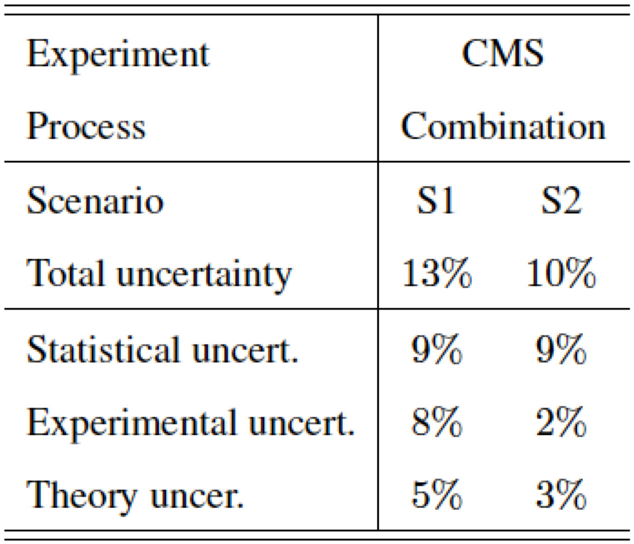
Rare decays: H→μμ

- Signature: 2 OS isolated muons, resonant peak at the Higgs mass
- **BR(H→μμ)=0.022**. Only visible at HL-LHC
- di-muon invariant mass width is reduced in order to match the expected increase in performances due to the upgrade in the tracking system





Experiment	ATLAS	
Process	Combination	
Scenario	S1	S2
Total uncertainty	$^{+15\%}_{-14\%}$	$^{+13\%}_{-13\%}$
Statistical uncert.	$^{+12\%}_{-13\%}$	$^{+12\%}_{-13\%}$
Experimental uncert.	$^{+3\%}_{-3\%}$	$^{+2\%}_{-2\%}$
Theory uncer.	$^{+8\%}_{-5\%}$	$^{+5\%}_{-4\%}$



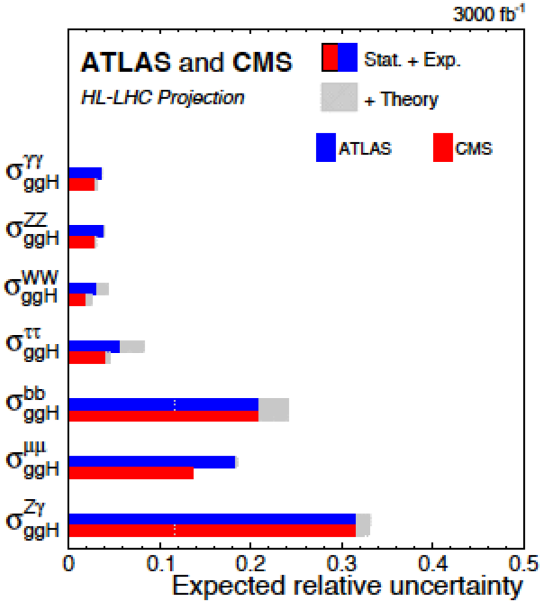
Experiment	CMS	
Process	Combination	
Scenario	S1	S2
Total uncertainty	13%	10%
Statistical uncert.	9%	9%
Experimental uncert.	8%	2%
Theory uncer.	5%	3%

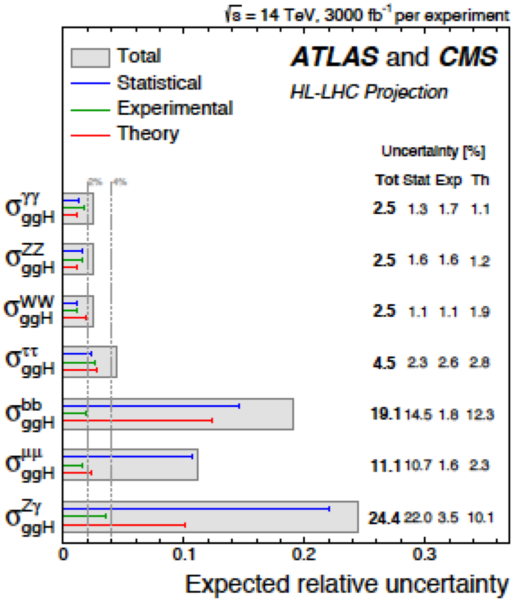
CMS detector will be able to reach in the best category a di-muon mass resolution down to 0.65%

Higgs boson cross section

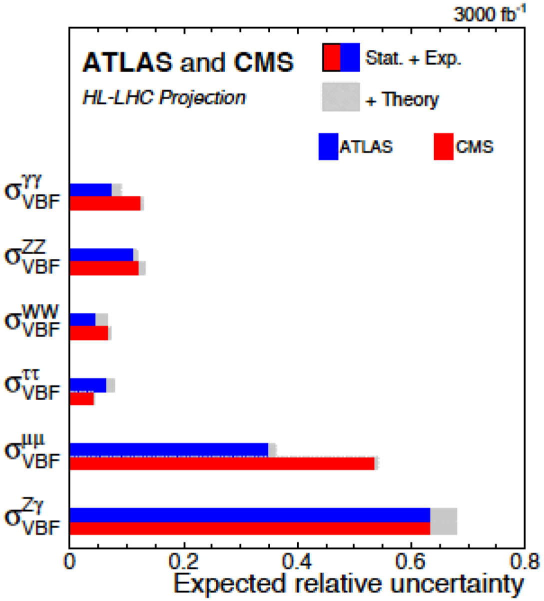
Projections for:

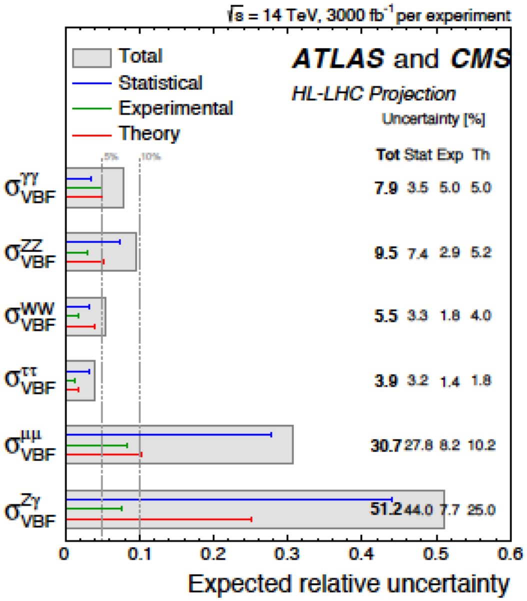
- H→ZZ→4l (ggH, VBF, VH, ttH)
- H→WW→2l2ν (ggH, VBF, VH)
- H→$\gamma\gamma$ (ggH, VBF, VH, ttH)
- H→$\tau\tau$ (ggH, VBF)
- VH, H→bb and boosted H→bb
- H→$\mu\mu$ (ggH and VBF)
- ttH, H→leptons, H→bb
  + studies about tH



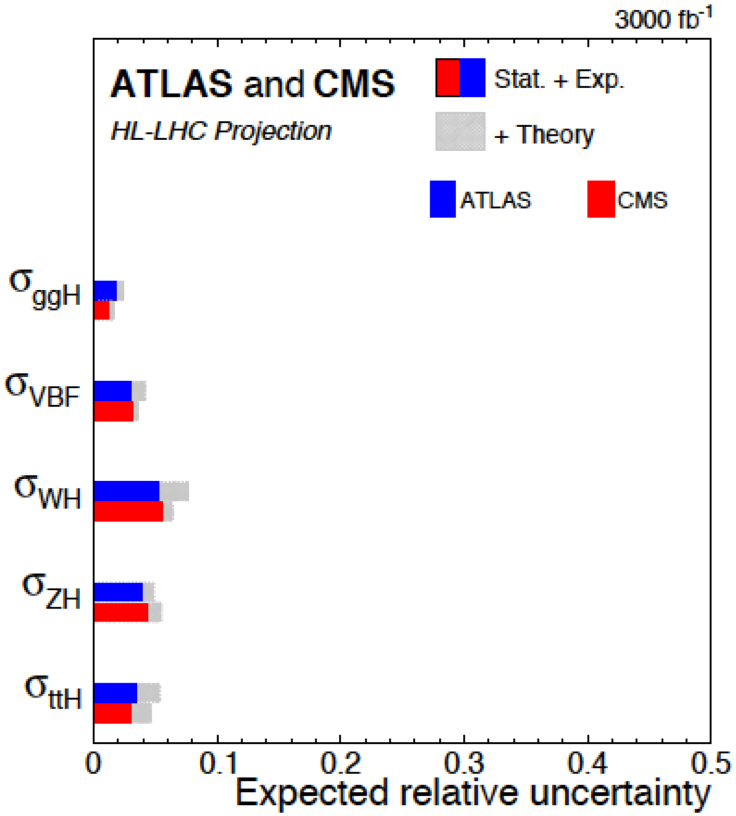


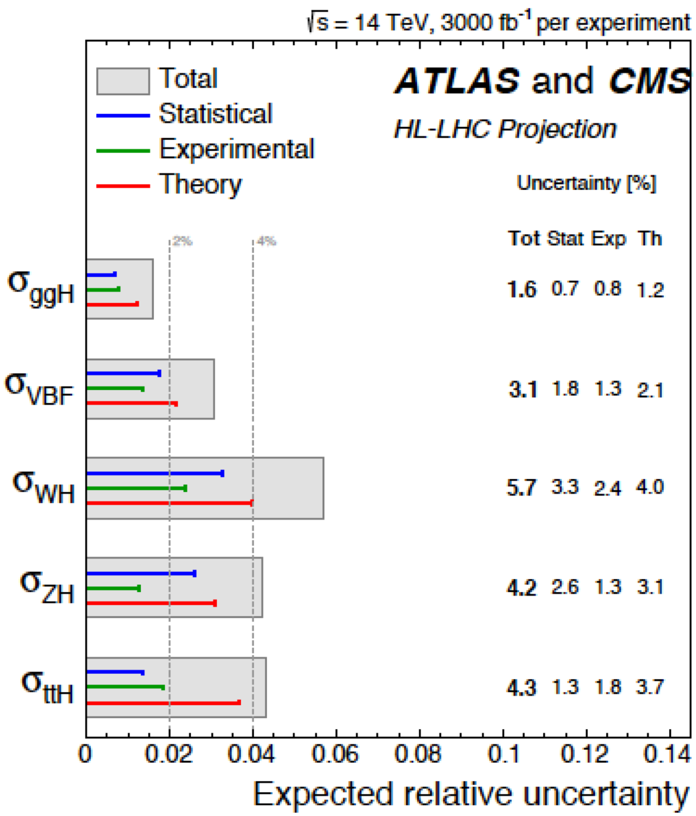
Systematic uncertainties will dominate, in particular theoretical uncertainties on signal and background are the main component for S2 scenario





Higgs boson cross section

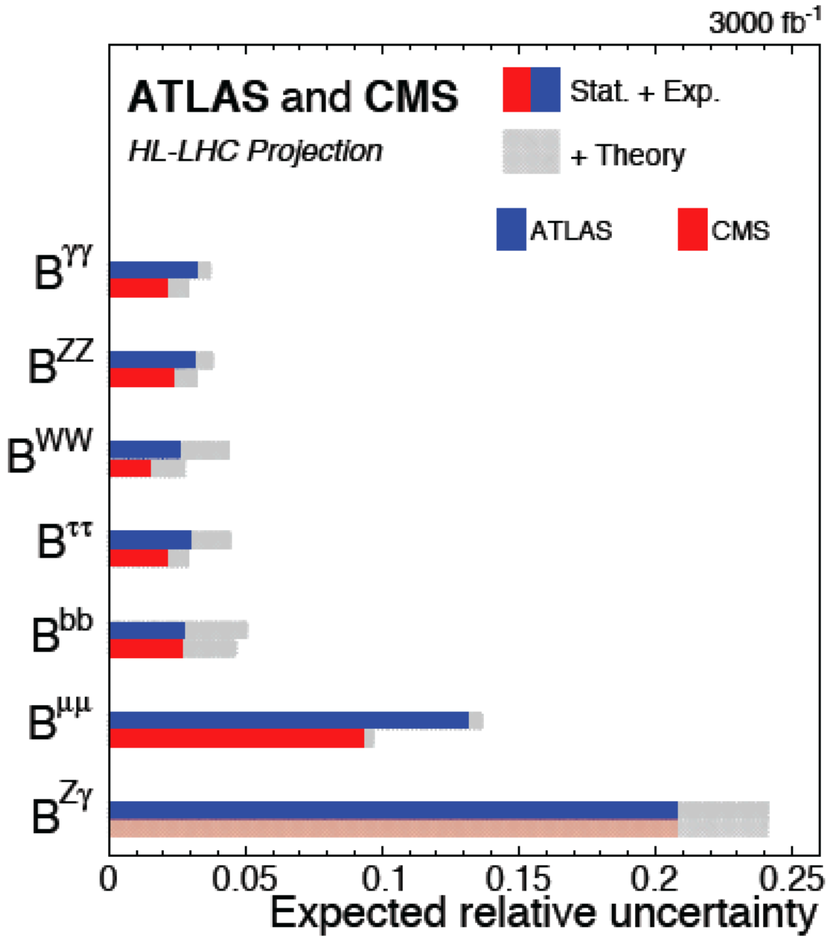


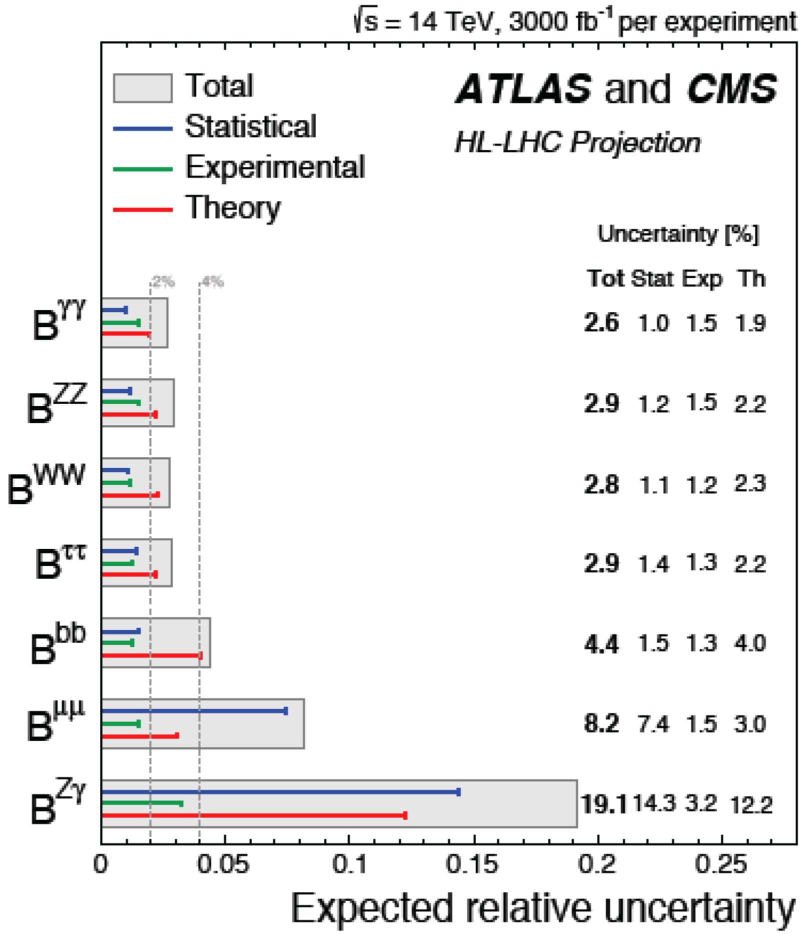


ATLAS						
		3000 fb^{-1} uncertainty [%]				
		Total	Stat	Exp	SigTh	BkgTh
σ_{ggH}	S1	3.5	0.8	2.1	2.1	1.6
	S2	2.4	0.8	1.7	1.2	1.0
σ_{VBF}	S1	5.5	2.0	2.7	3.7	2.1
	S2	4.2	2.0	2.3	2.2	1.7
σ_{WH}	S1	9.3	4.0	4.0	5.1	5.4
	S2	7.7	4.0	3.4	3.3	4.5
σ_{ZH}	S1	6.2	3.4	2.4	3.4	3.0
	S2	4.8	3.4	1.8	2.0	2.1
σ_{ttH}	S1	6.7	1.9	3.1	3.7	4.3
	S2	5.3	1.9	2.8	2.4	3.3

CMS						
		3000 fb^{-1} uncertainty [%]				
		Total	Stat	Exp	SigTh	BkgTh
$\sigma_{ggH\|}$	S1	2.4	0.8	1.2	1.6	0.9
	S2	1.7	0.8	0.9	0.9	0.6
σ_{VBF}	S1	4.1	2.6	2.1	2.0	1.3
	S2	3.5	2.6	1.6	1.8	0.3
σ_{WH}	S1	8.1	4.6	5.2	2.6	3.3
	S2	6.4	4.6	3.2	1.5	2.7
σ_{ZH}	S1	6.7	3.9	2.1	4.3	2.5
	S2	5.4	3.9	1.7	2.4	2.3
σ_{ttH}	S1	5.8	1.8	3.1	1.9	4.1
	S2	4.6	1.8	2.4	1.1	3.4

Higgs boson branching ratios





	Tot	Stat	Exp	Th
$B^{\gamma\gamma}$	2.6	1.0	1.5	1.9
B^{ZZ}	2.9	1.2	1.5	2.2
B^{WW}	2.8	1.1	1.2	2.3
$B^{\tau\tau}$	2.9	1.4	1.3	2.2
B^{bb}	4.4	1.5	1.3	4.0
$B^{\mu\mu}$	8.2	7.4	1.5	3.0
$B^{Z\gamma}$	19.1	14.3	3.2	12.2

For the combined ATLAS-CMS extrapolation

- uncertainty range from 2 to 4%, with the exception of that on B($\mu\mu$) at 8% and on B($Z\gamma$) at 19%.

Higgs couplings formalism

LHC Higgs Xsection WG - arXiv:1307.1347v2

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$
$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$
$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$
$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

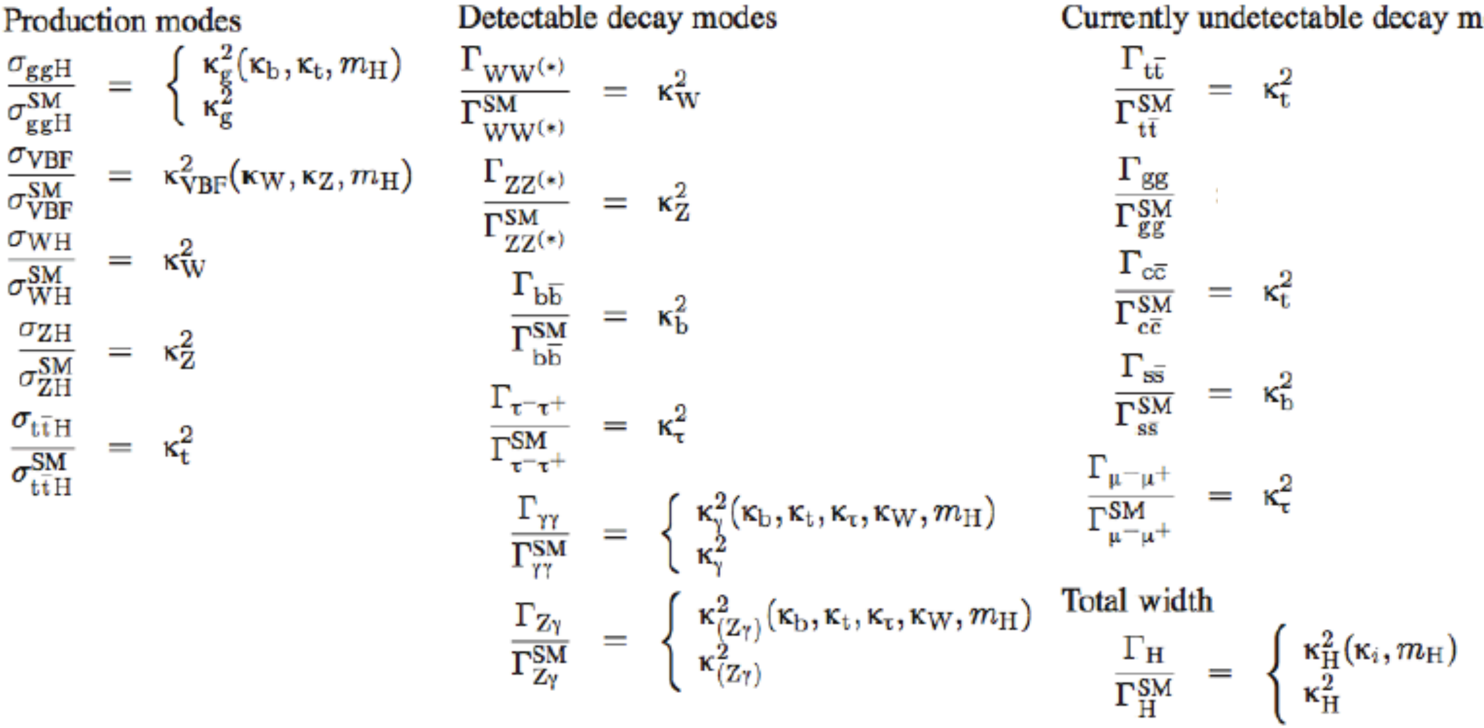
- Single resonance with mass of 125 GeV.
- Zero-width approximation

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

- 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

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

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

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

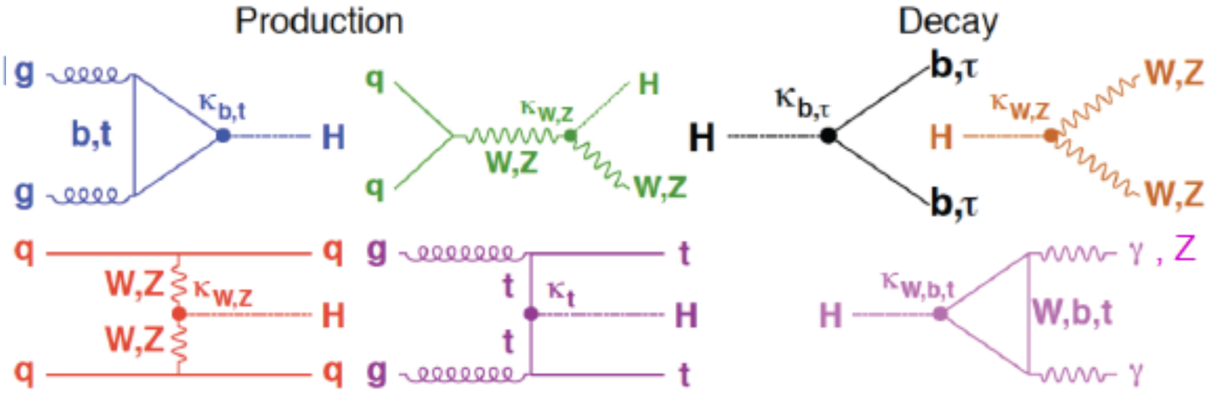
$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

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

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

Total width

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

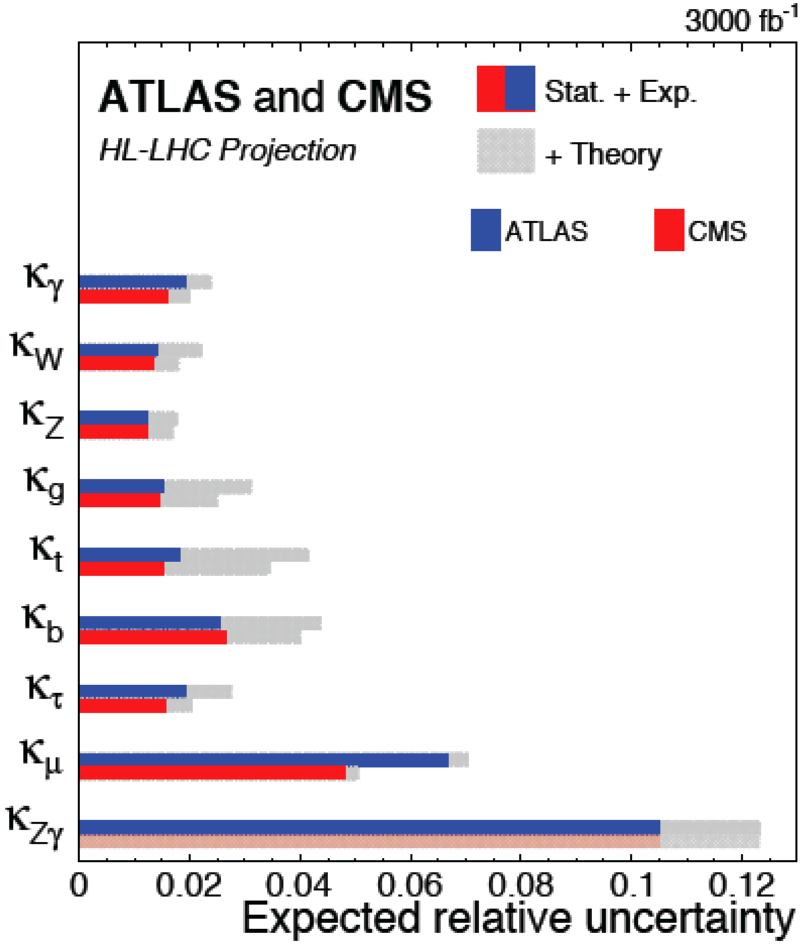


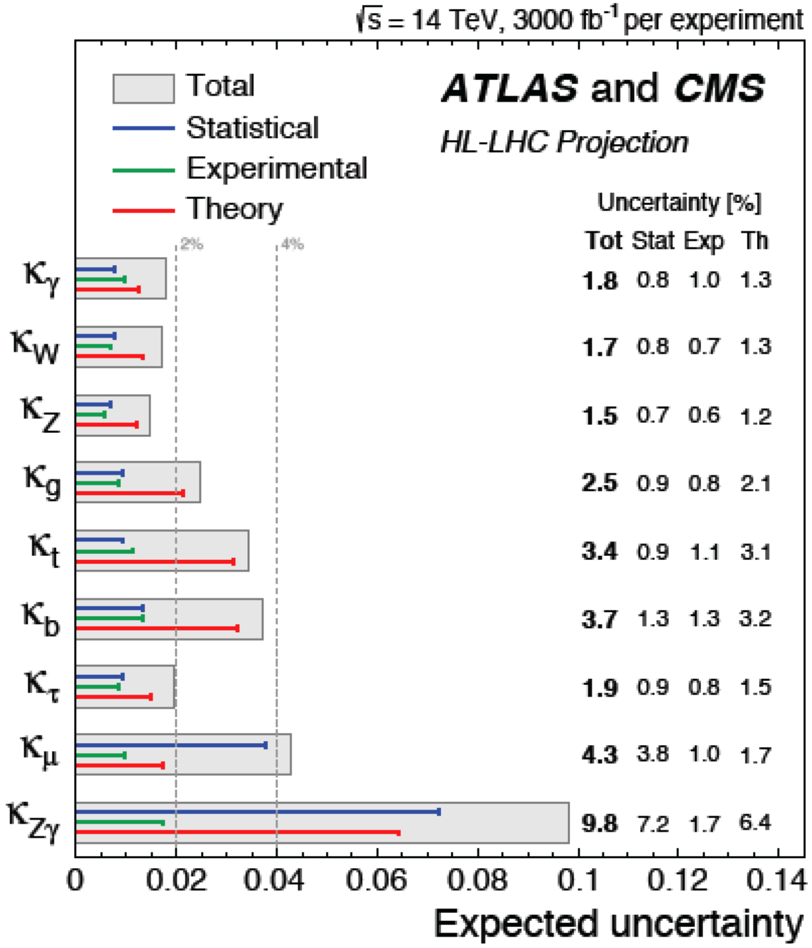
$$\Gamma_H = \Sigma_{SM}\, \Gamma_Y \quad (+\, \Gamma_{BSM})$$

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

Higgs boson couplings

- Results for couplings in κ-framework
- Six coupling modifiers corresponding to the tree-level Higgs boson couplings are defined: κ_t, κ_b, κ_τ, κ_μ, κ_W, κ_Z (+ κ_g, κ_γ, $\kappa_{Z\gamma}$)





Uncertainties on the κ's 2-5%, apart from Zγ

Mostly limited by theoretical uncertainties

Anomalous HVV interactions

Performance to be estimated using the H→ 4ℓ analysis @13 TeV.

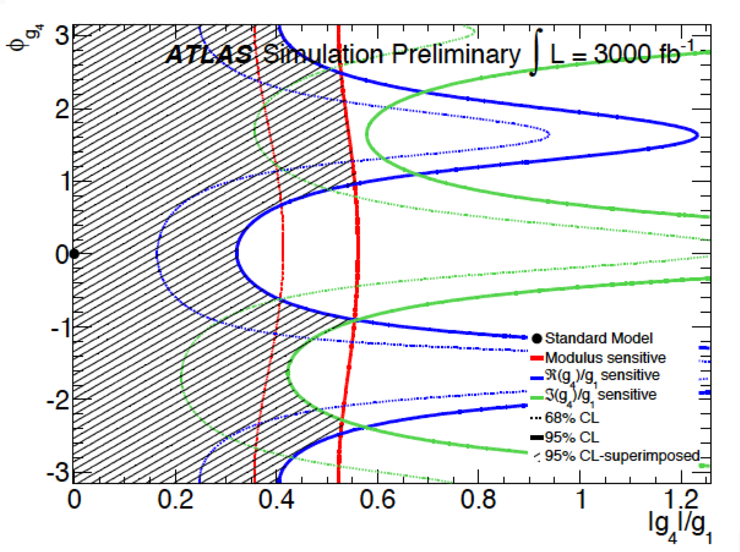
- Parameterisation of decay amplitude:

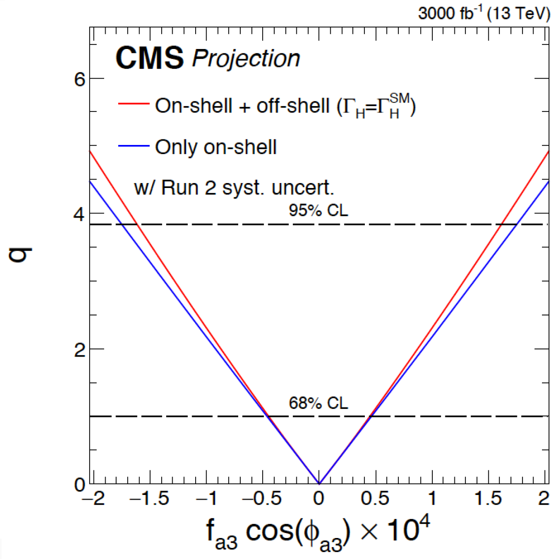
SM | leading momentum expansion | higher order cp-even | cp-odd

$$A = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV} (q_1 + q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Powerful constraints on anomalous couplings:

- Exploiting information from:
  - H decay (on-shell)
  - H on-shell production
  - H off-shell production:
- Sensitivity driven by on-shell production-level info. Some model dependance from assumption on HWW/HZZ relation.





Parameter	Information from	95% CL interval
f_{a3}	decay	$\pm 120 \cdot 10^{-4}$
f_{a3}	decay & production	$\pm 1.8 \cdot 10^{-4}$
f_{a3}	decay & production & off-shell	$\pm 1.6 \cdot 10^{-4}$

Constraints on fractional CP-odd presence $<1.6 \cdot 10^{-4}$

Differential Higgs cross sections

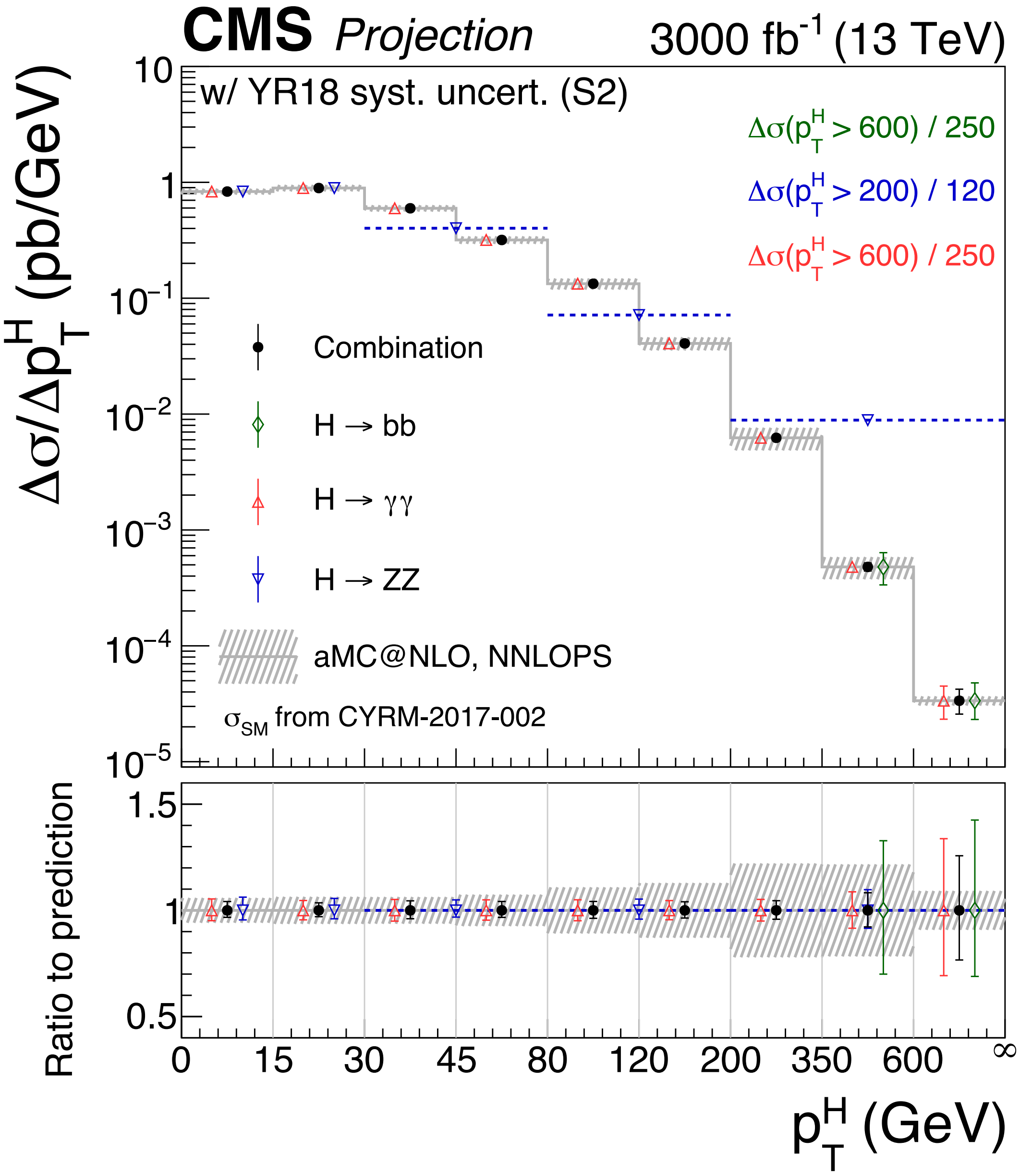
Combined differential cross sections using:

- $H\to\gamma\gamma$, $H\to ZZ\to 4l$
- Plus boosted $H\to bb$ in the high p_T^H tail

Looking at distortions of differential distributions

With respect to the uncertainties at the current integrated luminosity the uncertainties at 3000 fb^{-1}:

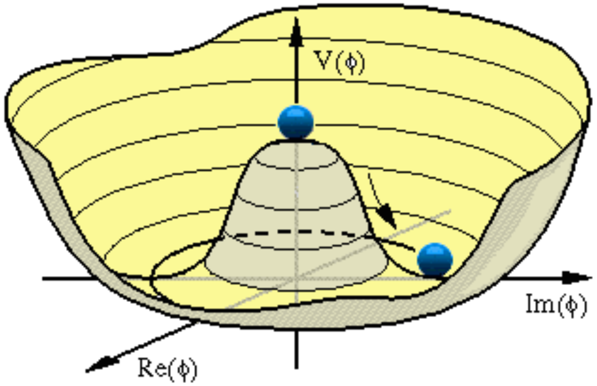
- in the higher p_T^H region are about a factor of ten smaller (statistically dominated)
- in the lower p_T^H region the reduced systematic uncertainties in S2 yield a reduction in the total uncertainty of up to 25% compared to S1 (no statistically dominated)



THE HIGGS POTENTIAL

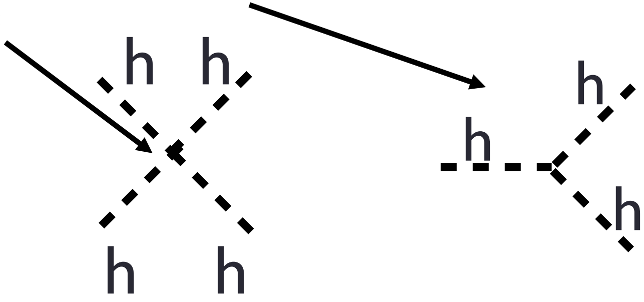
After spontaneous symmetry breaking:

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



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

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



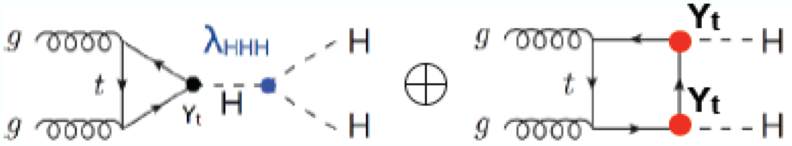
The strength of the triple and quartic couplings is fully fixed by the potential shape.

Why is it relevant?

- 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 expected
- It has implications on the stability of the Vacuum
- it could make the Higgs boson a good inflation field

Double Higgs production

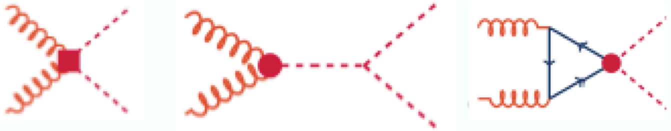
Main probe for trilinear Higgs coupling λ_{HHH}. Diagrams interfere destructively in SM



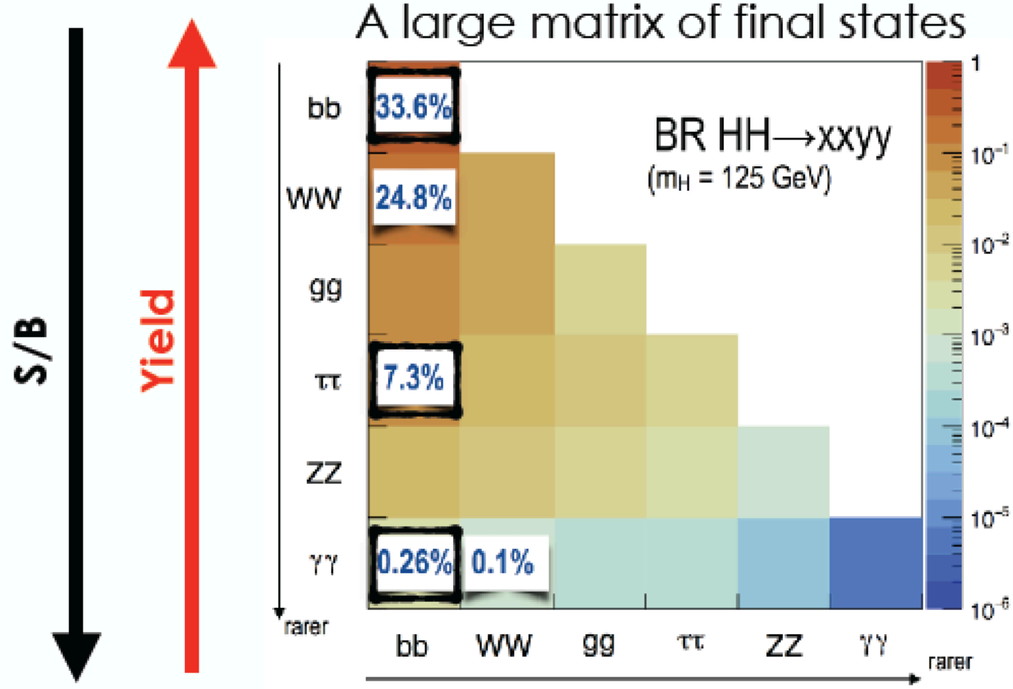
$\sigma_{gg\to HH} = 33.49^{+4.3}_{-6.0}$ (scale) ± 2.1 (PDF) ± 2.3 (α_s) fb

[13 TeV, NNLO + NNLL with top mass effects, HXSWG, arXiv:1610.07922]

sensitive to possible BSM contributions



A large matrix of final states



bbbb largest statistics

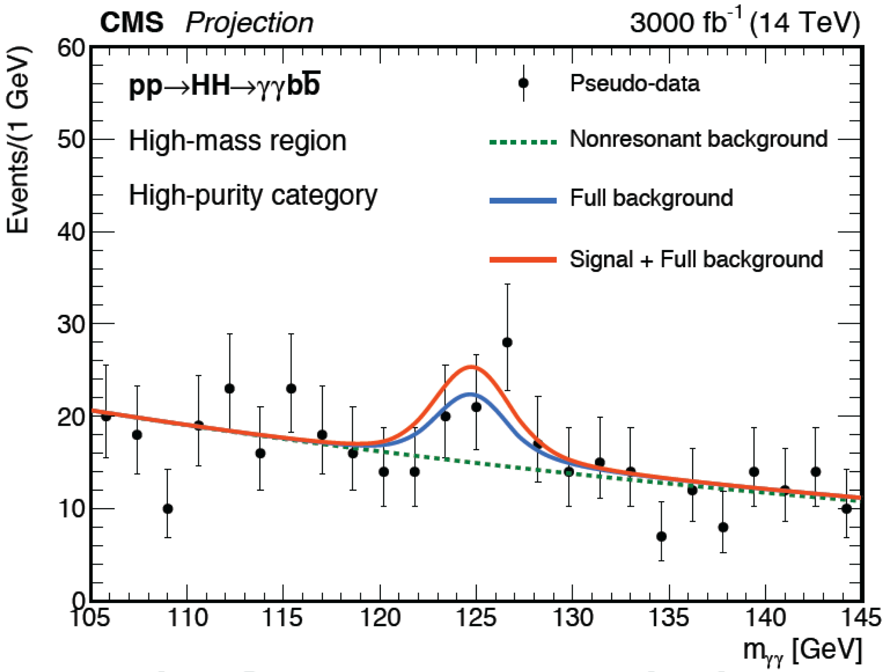
bb(γγ,ττ) good compromise between statistics and S/B

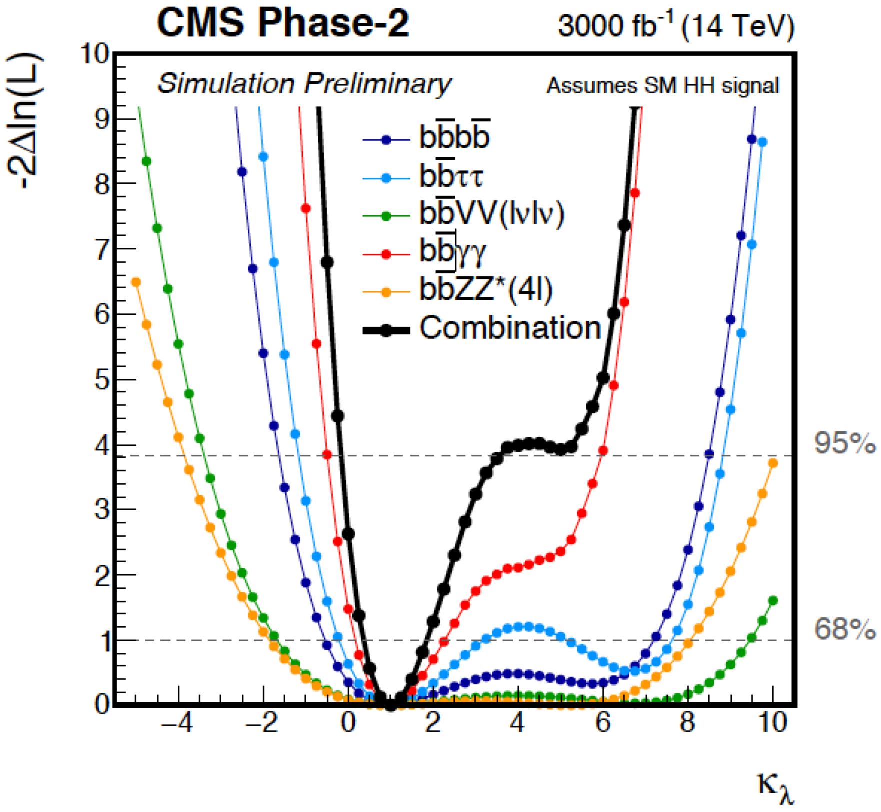
Not enough data in Run 2 to approach the SM sensitivity

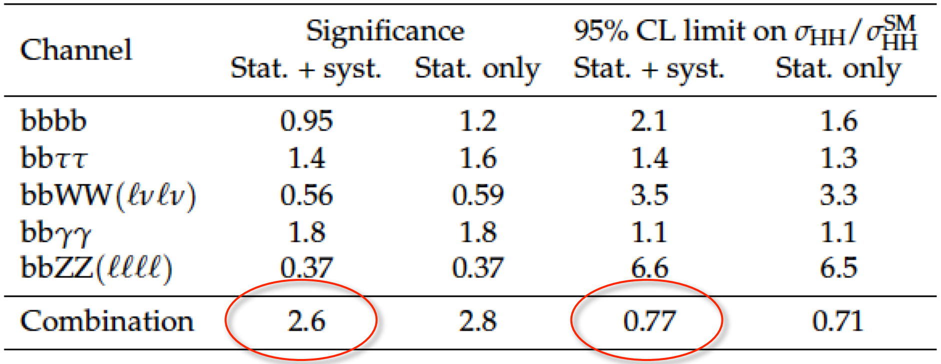
Prospects for HH measurements

Search of Higgs boson pair (HH) production and the measurement of the Higgs boson self-coupling (λ_{HHH})

Decay channels: HH→ bbbb, **bb$\tau\tau$**, bbWW(→llνν), **bbγγ (most sensitive)**, bbZZ(→4l)







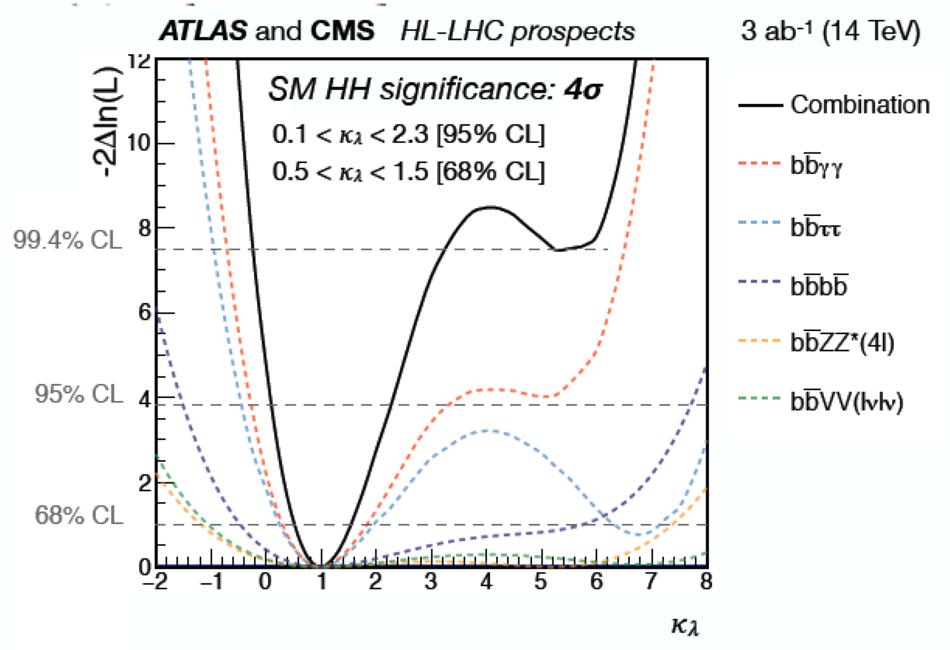
Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma^{SM}_{HH}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
bb$\tau\tau$	1.4	1.6	1.4	1.3
bbWW($\ell\nu\ell\nu$)	0.56	0.59	3.5	3.3
bb$\gamma\gamma$	1.8	1.8	1.1	1.1
bbZZ($\ell\ell\ell\ell$)	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

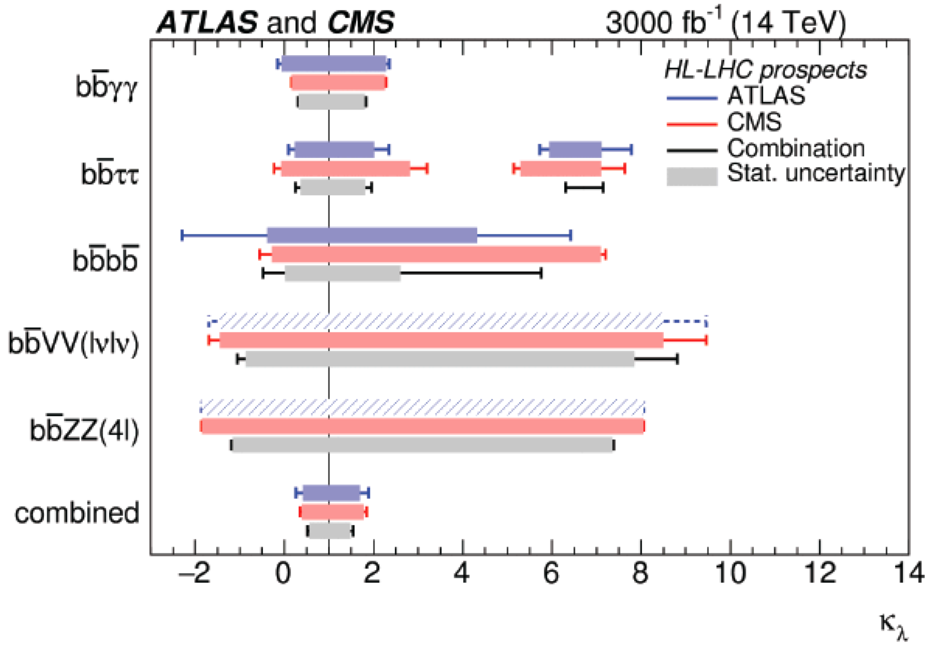
Measurement of the $k_\lambda=\lambda_{HHH}/\lambda^{SM}_{HHH}$ in the range [0.4, 1.9] at the 68% CL

HH: CMS and ATLAS combined

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

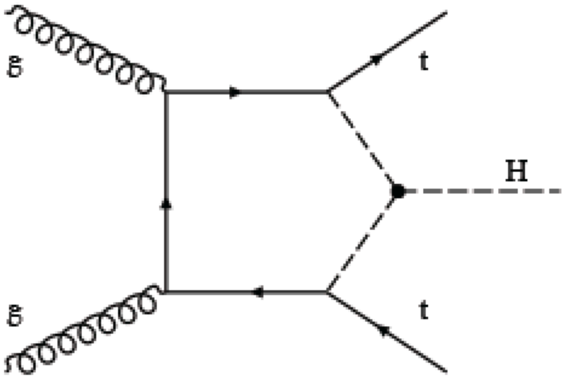
$$\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}.$$

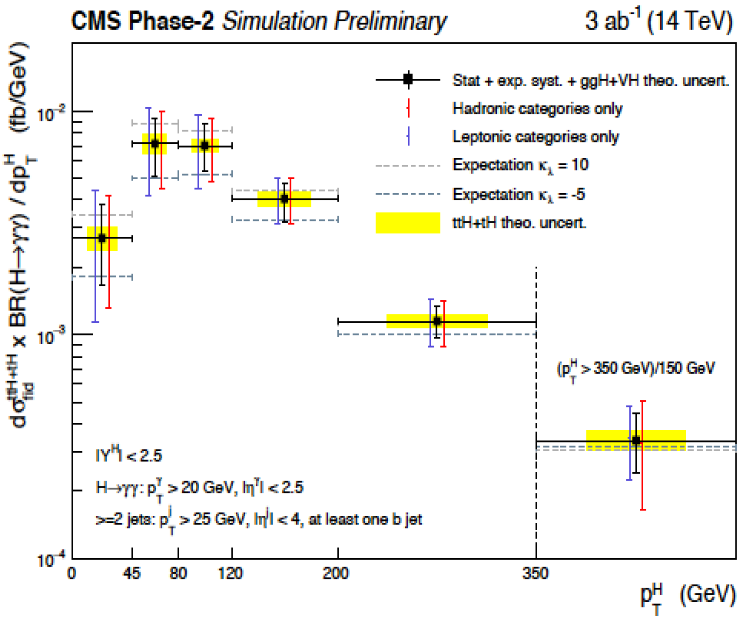


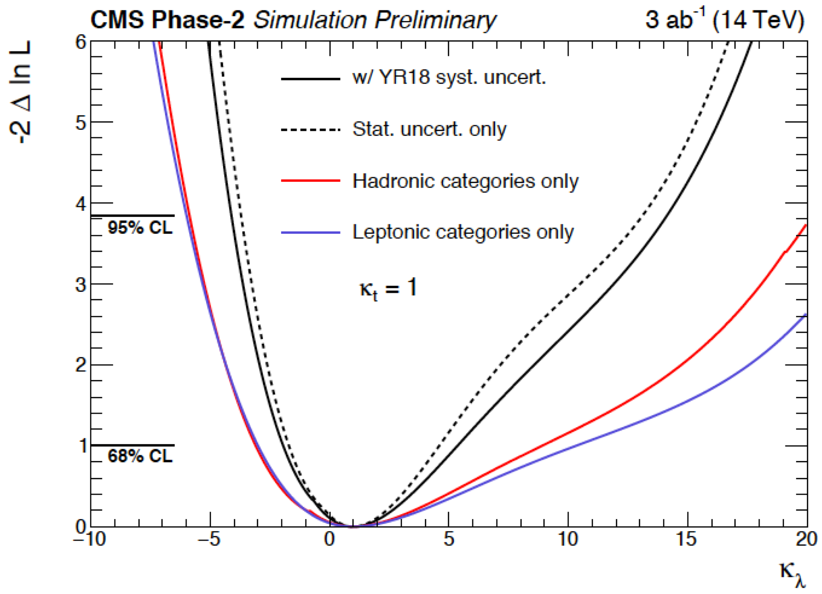


Differential XS and limits on self coupling

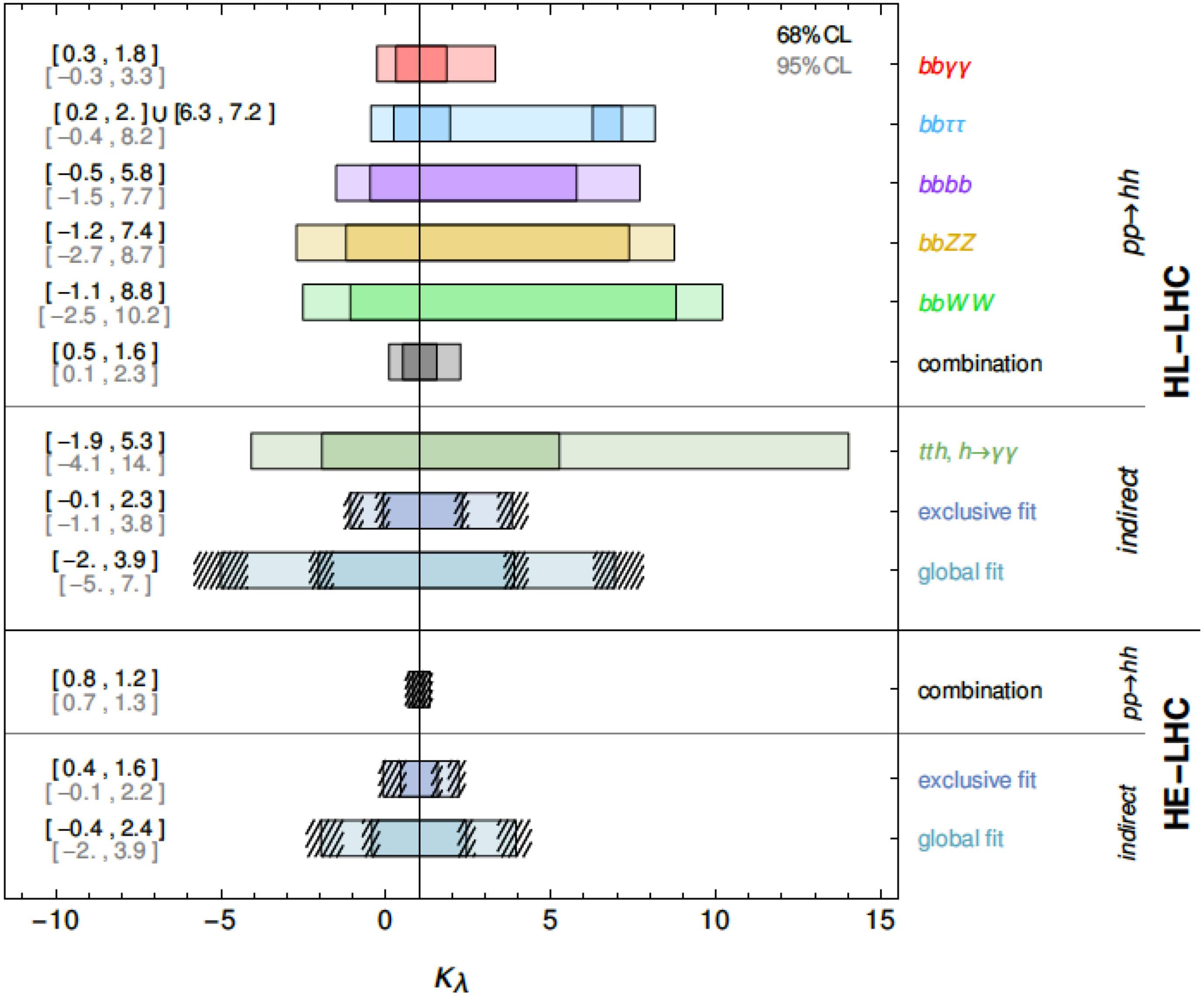
- At NLO Higgs boson production modes include contributions involving the trilinear Higgs coupling ➔ ttH most sensitive
- Focus on ttH, H➔γγ using Delphes simulation
- At 95% CL: $-4.1<\kappa_\lambda<14.1$ ➔ complementary to the stronger constraints from direct di-Higgs production





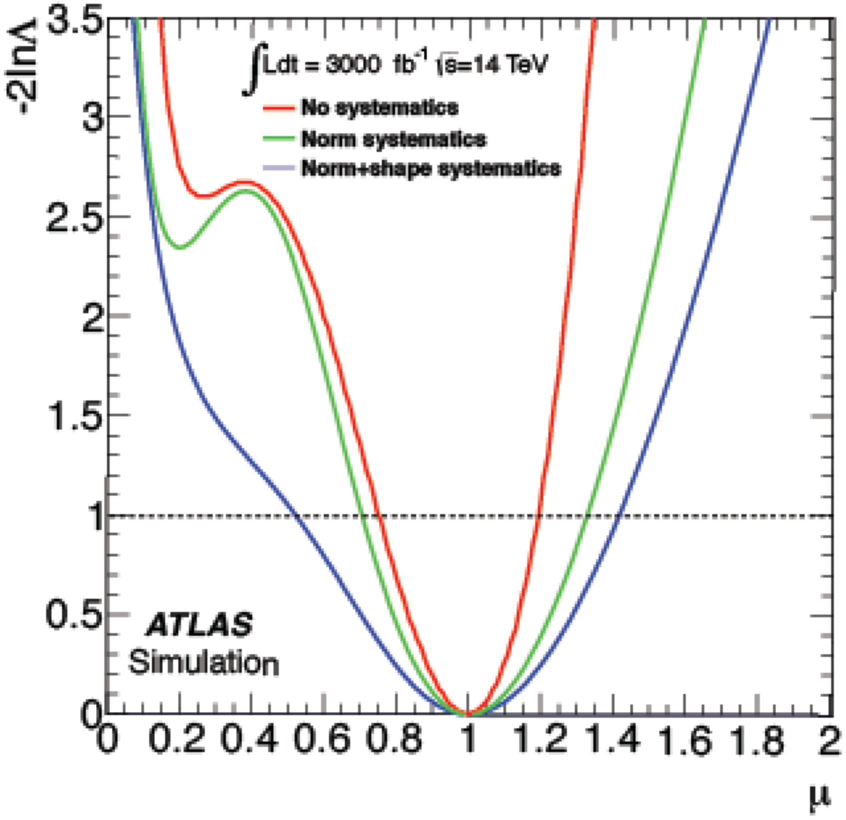


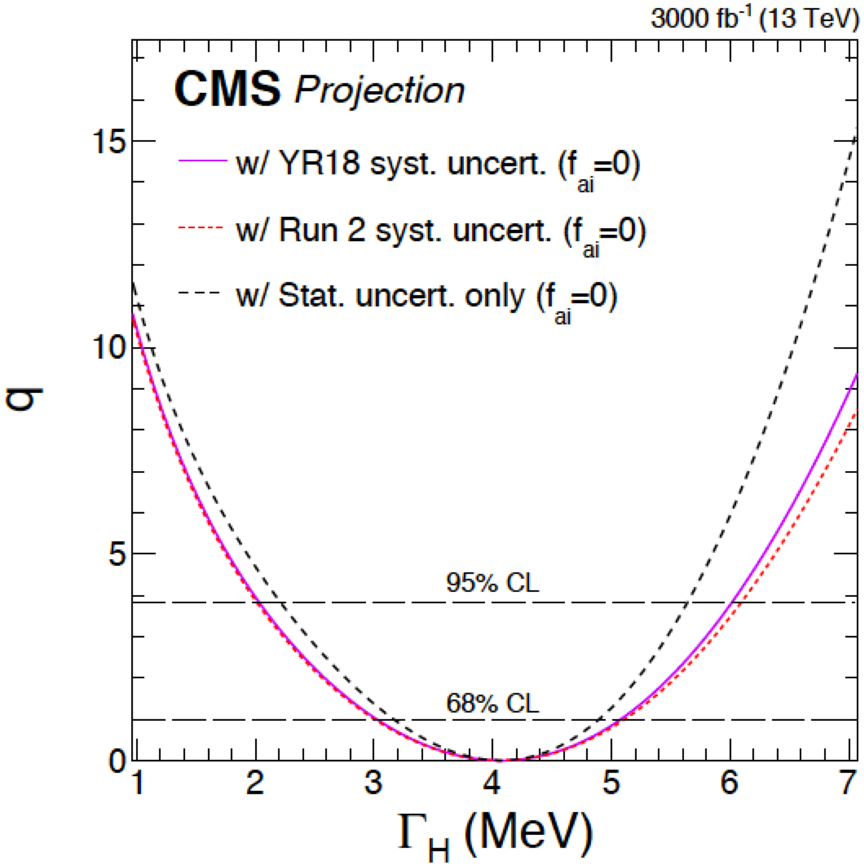
Constraints on the trilinear coupling



Limits on the Higgs width

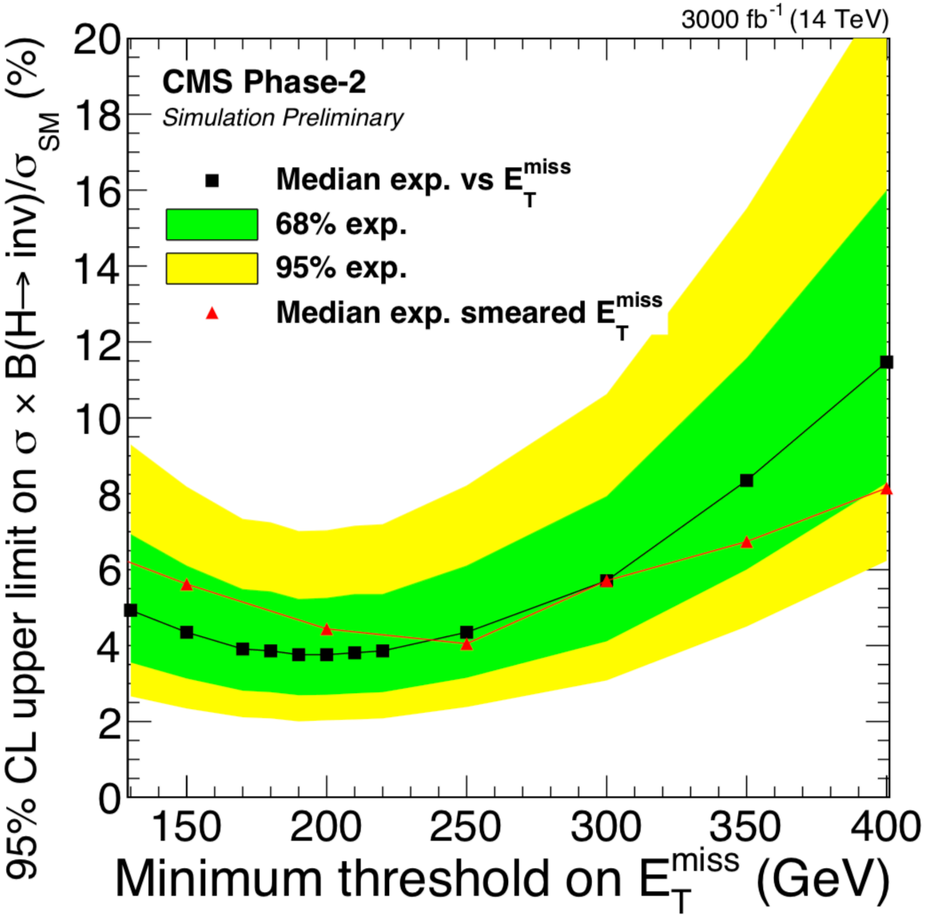
- Comparison of on- and off-shell rates in H→ZZ→4l can constrain the Higgs boson width. Current constraint: $\Gamma<14.4$ MeV (ATLAS), $\Gamma<9.2$ MeV (CMS)
- CMS projection: $4.1^{+1}_{-1.1}$ MeV, ATLAS projection: $4.1^{+1.5}_{-2.1}$ MeV
  - ATLAS projection based on Run I analysis, used large theoretical uncertainties that have been reduced in the meantime
- Assuming ATLAS analysis would have same sensitivity as CMS analysis at HL-LHC, combined constraint on the width **$4.1^{+0.7}_{-0.8}$ MeV**





Higgs to Invisible decays

- Current observed (expected) limits on B_{inv} at 95% CL:
  - ATLAS: < 26% (17%)
  - CMS: < 22% (17%)
- VBF production mode dominates sensitivity → HL-LHC sensitivity studied using Delphes simulation
- With optimised selection: **B_{inv}<3.8%** at 95% CL with 3000 fb^{-1} at HL-LHC
- Degradation of E_T^{miss} resolution does not impact the sensitivity significantly
- Combining with previous ATLAS projection of VH channel, and assuming both experiments would perform equally well in both channels: **B_{inv}<2.5%** at 95% CL



What has been the focus now?

FUTURE HIGGS PLANS WITH NEW L1 TRIGGER DESIGN FOR PHASE 2

HIG-related plans for L1 Trigger TDR

General goal:
Evaluate the impact of Phase-2 L1 Trigger on benchmark physics analyses → Phase-2 L1 Trigger TDR

Phase-2 L1 Trigger Menu & seeds:
Some recent progress/developments by L1 trigger team

Displaced muons seeds - check if sustainable
- double muon path with displaced muons algos **($h\rightarrow\gamma_D\gamma_D\rightarrow\mu\mu XX$)**

Extended η Seeds - check rates
- standard double Muon(Electron) paths up to η 2.8(3) **(HWW,HZZ)**
- HT+QuadJets with extended jets up to 3.5 **(HH,bbbb)**

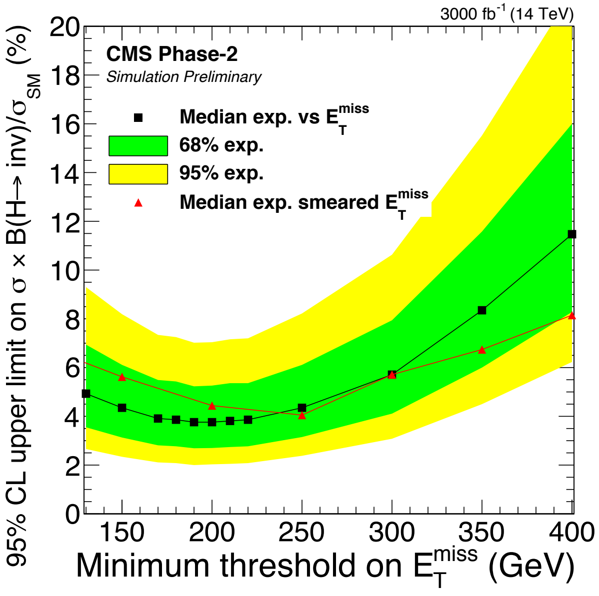
New cross triggers to lower thresholds
- MET+VBF **(VBF H→invisible)**
- HT+QuadJet+softMu-within-jet **(HH,bbbb)**
- τ+m+m, τ+τ+m, τ+τ+softMu-within-jet **($h\rightarrow aa\rightarrow bb\tau\tau$, $\mu\mu\tau\tau$)**
- VBF+softMu-within-jet **(VBF h→aa→bbbb)**

VBF H→invisible

HE/HL-LHC YR analysis: FTR-18-016

Some analysis details:

- Current VBF H→invisible analysis relies on pure MET triggers.
- For 2017-2018 data: VBF L1 trigger in menu - still to be integrated into the analysis→ gain in signal efficiency in a complementary low MET - high M_{jj} phase-space



Plans for the future:

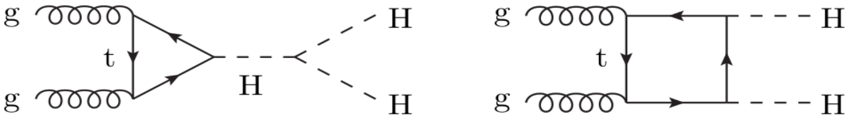
- Investigating a 2nd **complementary VBF-based trigger**:
  - minimum one pair of jets with pT > 110, 35 GeV, Mjj > 650 GeV.
  - at HLT: MET> 110 GeV
  - Additional criteria to loosen the jet p_T thresholds:
    - min($\Delta\phi$(jets,MET)): to reject QCD multi-jets $\Delta\phi$(jj): background rejection sensitive to HIG CP nature.
    - loose MET criteria.
  - Depends on:
    - PU-resilience of jets and MET at L1.
    - Feasibility of implementing corresponding algorithms in firmware → need L1 experts for a VBF jet+MET trigger with jets p_T , M_{jj} and (jets,MET) criteria.

HH→bbbb

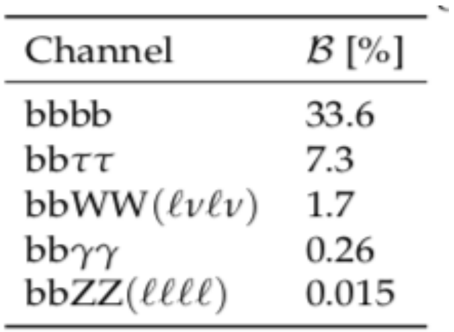
Some analysis details:

HE/HL-LHC YR analysis: FTR-18-019

Gluon fusion production gg →HH



$$\sigma_{14TeV}[fb] = 36.69^{+2.1\%}_{-3.9\%}(scale) \pm 3.1\%(PDF) \pm 2.1\%(\alpha_s) \pm 2.1\%(top)$$



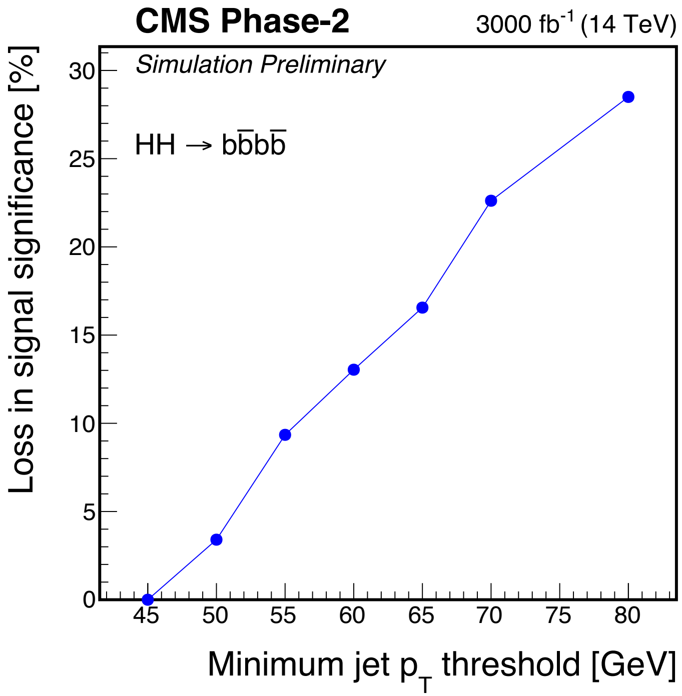
Channel	$\mathcal{B}$ [%]
bbbb	33.6
$bb\tau\tau$	7.3
$bbWW(\ell\nu\ell\nu)$	1.7
$bb\gamma\gamma$	0.26
$bbZZ(\ell\ell\ell\ell)$	0.015

HH→bbbb to measure/constraint Higgs self couplings λ_3:

"Resolved" topology:

- four jets from reconstructed separately,
- usage of BDT explored to efficiently discriminate the signal from overwhelming multi-jet QCD background.

Studies performed for the HL/HE YR showed the importance of low jet thresholds to ensure enough signal acceptance (and then the significance)



Plans for the future:

- Study the impact of lowered threshold and of the jet η extension on the sensitivity
- Study effect of p_T-asymmetric & jet+HT triggers
  - like : p_T> 90,70,40,40 GeV + H_T > 350 Gev

ggF H→ϕϕ→ bbbb (displaced jets)

HE/HL-LHC YR analysis: FTR-18-018

Some analysis details:

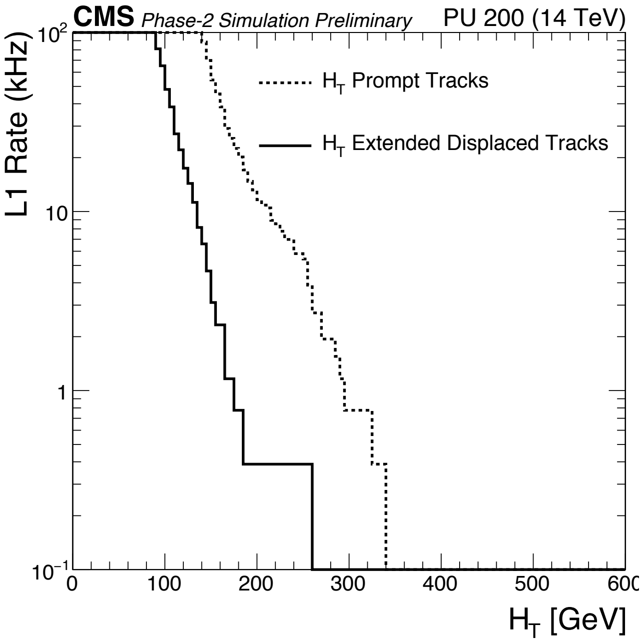
Consider scalar ϕ with a macroscopic decay length (1-50mm) → displaced jets

The team already investigated the capabilities of L1 track finding to increase the L1 trigger efficiency for such signals via:

- a jet clustering algorithm that uses the L1 tracks with a primary vertex constraint
- extension of the L1 track finder to off-pointing tracks (Kinks), and develop a jet lifetime tag for tracks with $|\eta| < 1.0$.

Plans for the future:

- Expanding the off-pointing track finding at L1 to the full acceptance of the outer tracker
- Matching track jets with high transverse momentum (p_T) deposits in ECAL; and finding new ways to evaluate track quality to suppress "fake" tracks



H→aa→ bbττ, μμττ

HE/HL-LHC YR analysis: FTR-18-035

Some analysis details:

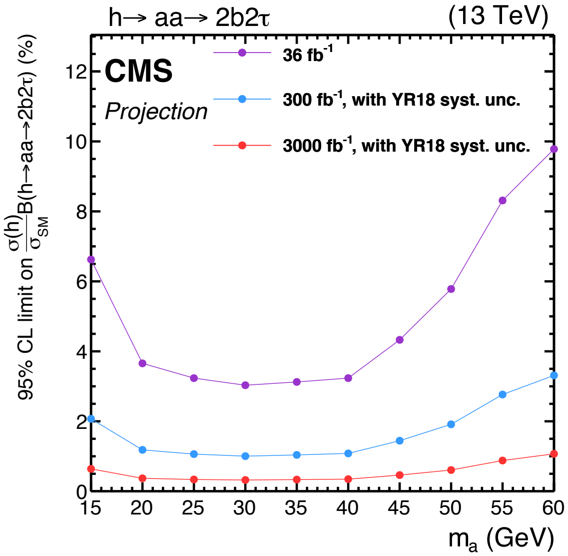
Exotic decays of the Higgs boson to a pair of light pseudoscalar bosons explored:

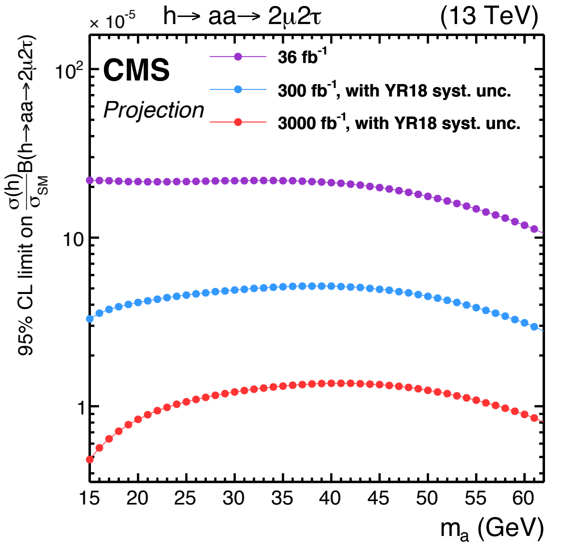
h→aa→2b2τ:

- currently trigger on e+mu, e+tau, single-e, single-mu, and mu+tau
- no study the final state with two hadronic taus because of the lack of triggers. This final state could be analyzed using a low-mass di-tau trigger. Such a trigger was deployed at end of the 2018 data taking

h→aa→2μ2τ:

- may benefit from a mu+mu+tau trigger





Future colliders

European Strategy Group
from Granada workshop
& more

ILC, CLIC, FCC-ee/hh,CepC/SppC

ILC Candidate site in Kitakami, Tohoku

20km

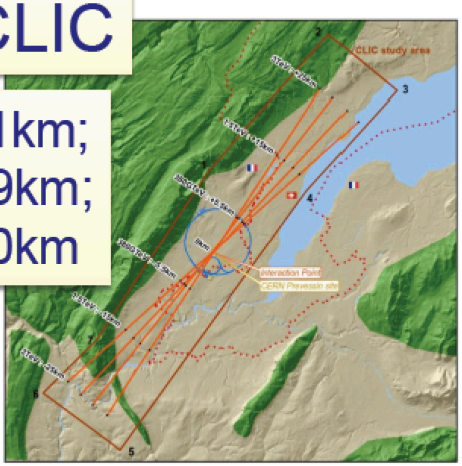
Qinhuangdao site

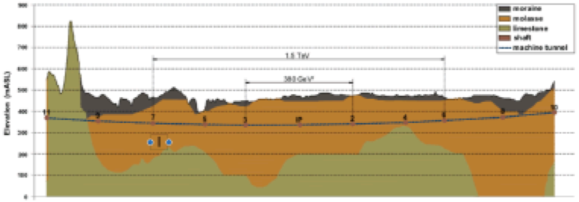
100 km

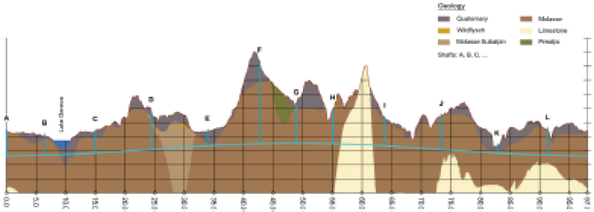
CEPC: multiple candidate sites in China

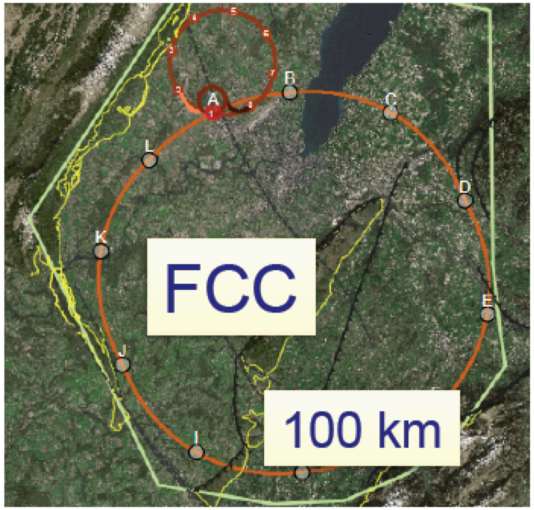
CLIC

11km;
29km;
50km





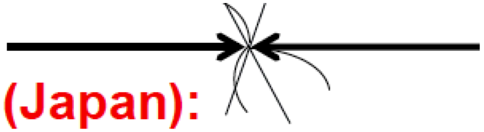




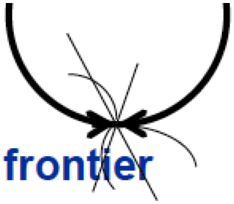
FCC

100 km

ILC, CLIC, FCC-ee/hh,CepC/SppC

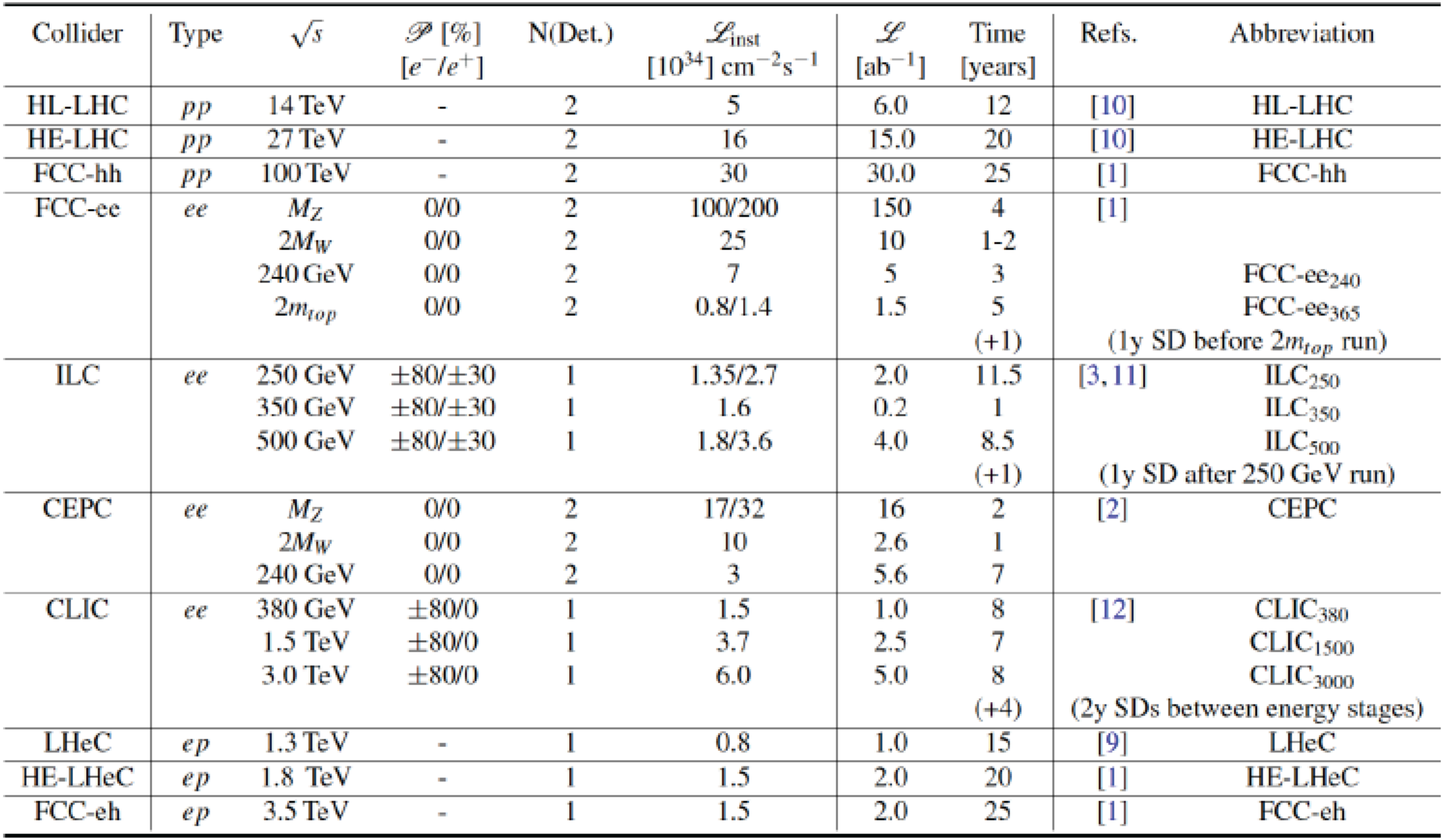


- **ILC (Japan):**
  - Linear collider with high-gradient superconducting acceleration
  - Ultimate: 0.5-1(?) TeV
  - To secure (…) funding: reduce cost by starting at 250 GeV (H factory)
- **CLIC (CERN):**
  - Linear collider with high gradient normal-conducting acceleration
  - Ultimate: multi-TeV (3) e+e⁻ collisions
  - Use technology to overcome challenges
  - Stages, for physics and funding



- **FCC-ee/FCC-hh (CERN):**
  - Protons to extend energy frontier
  - 100 km ring with 16T magnets
  - Use FCC-hh tunnel for e+e⁻ collider
  - Technology for ee: “standard”
- **CEPC/SppC**
  - Essentially an FCC-ee, then hh with (a) more conservative luminosity estimates and (b) in China
- **Outliers:**
  - LHeC/FCC-eh; extend LHC with minimal cost; FCC-eh: intermediate machine? PDFs?
  - “Low-field” (7T) magnets @ FCC (?)

Future accelerators: comparison



Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee_{240}
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee_{365}
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC_{250}
		350 GeV	±80/±30	1	1.6	0.2	1		ILC_{350}
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC_{500}
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC_{380}
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC_{1500}
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC_{3000}
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

The challenges

- Linear ee colliders:
  - Acceleration gradient
    - ILC: 30 MV/m; CLIC: 72 MV/m
  - Luminosity (to be partially recovered by polarization)
    - +loss: e.g. at 3000 GeV, 1/3 at >0.99√s
  - Tiny beam spot:
    - v: 8nm for ILC; 3 nm for CLIC3000.
  - Power consumption
    - ILC: 130-300 MW
    - CLIC: 170-590 MW
- Circular ee colliders:
  - Power consumption: 260-350 MW
  - Luminosity drops with E
- hh collider:
  - Magnets!
    - Need 16 TeV (x2 LHC); they do not exist today
  - High stored beam energy (8-9 GJ)
    - Beam handling, beam dumping
    - Collimation
  - High synchrotron radiation inside magnets: several MW
  - Beam screen design and cryogenic efficiency;
  - Power consumption: 580 MW
- Costs (GU):
  - ILC: 5.0 (for 250 GeV); 7.8 (500 GeV)
  - CLIC: 5.9 or 7.3 (for 380 GeV) + 5.1 (1500 GeV) + 7.1 (3000 GeV) (Tot: 19.5)
  - FCC-ee: 11.6; but 7.1 is the tunnel
  - FCC-hh: tunnel + 17 (Tot: 24)

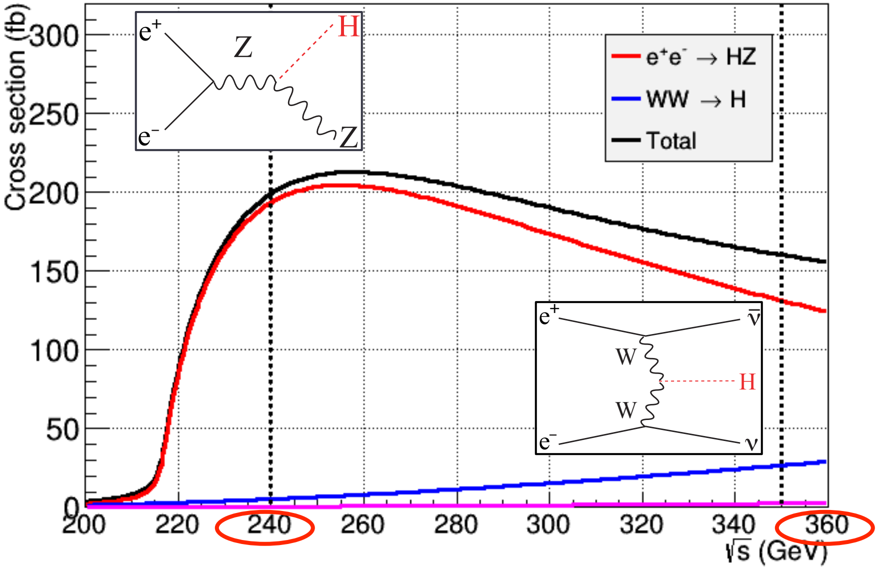
Higgs studies for FCC-ee/CepC

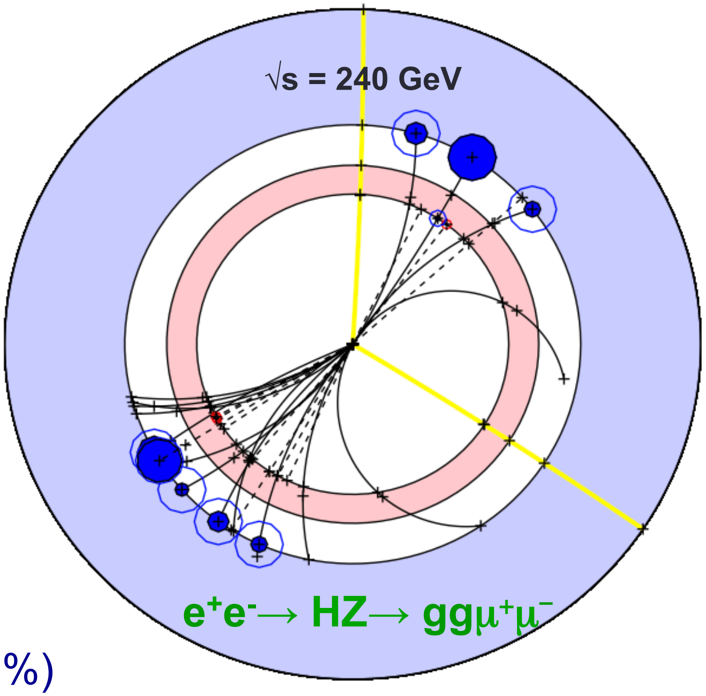
FCC-ee/CepC motivation

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 can 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)





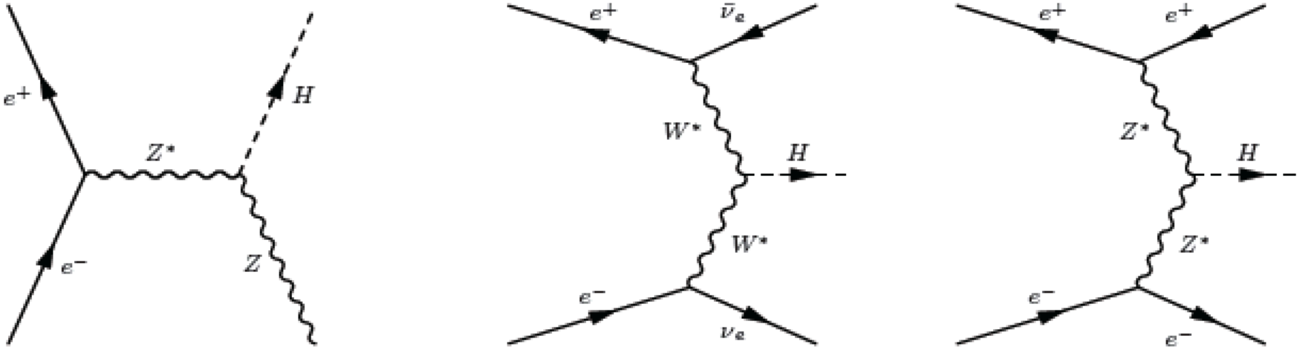
- The gluon can be studied with Higgs decays (BR ~ 10%)

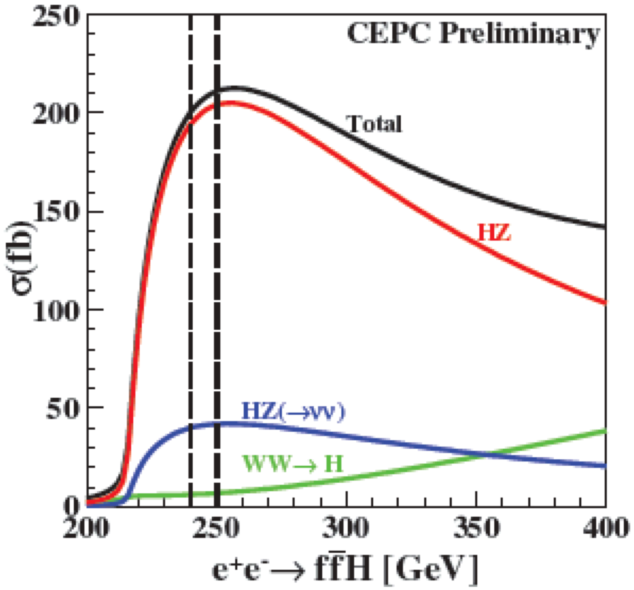
Higgs production at FCC-ee/CepC

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

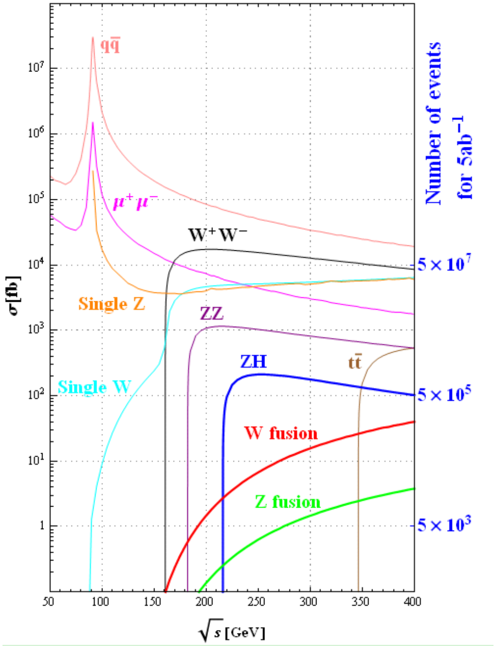
VBF production:

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



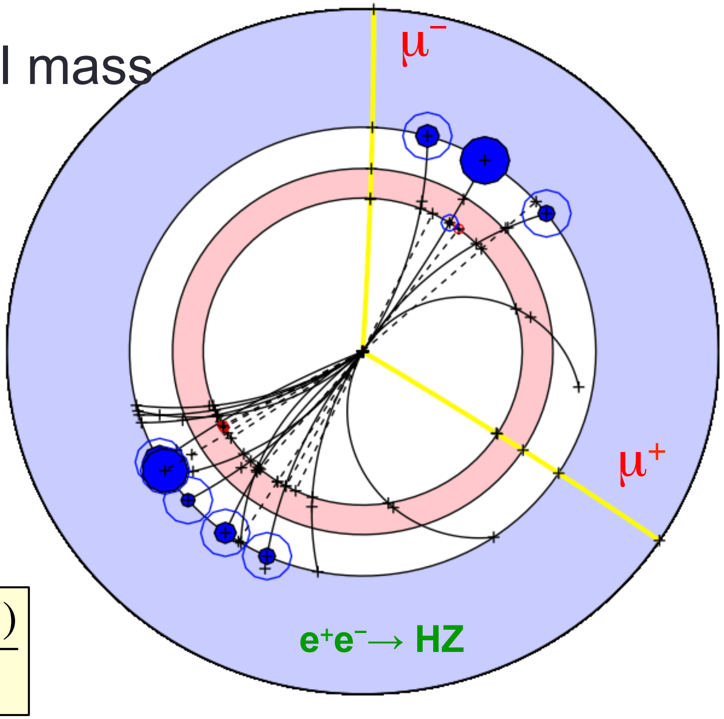


Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6
Background processes, cross section in pb		
$e^+e^- \to e^+e^-$ (Bhabha)	25.1	1.3×10^8
$e^+e^- \to q\bar{q}$	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



FCC-ee/CepC Higgs factory: √s = 240 GeV

Model-independent precision measurements



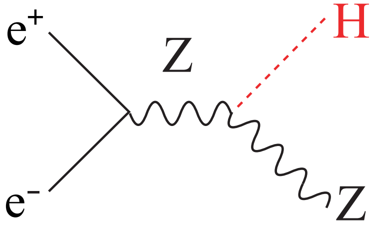
- A Higgs boson is tagged by a Z and the recoil mass

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

  - 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 $H\to ZZ^*)$

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

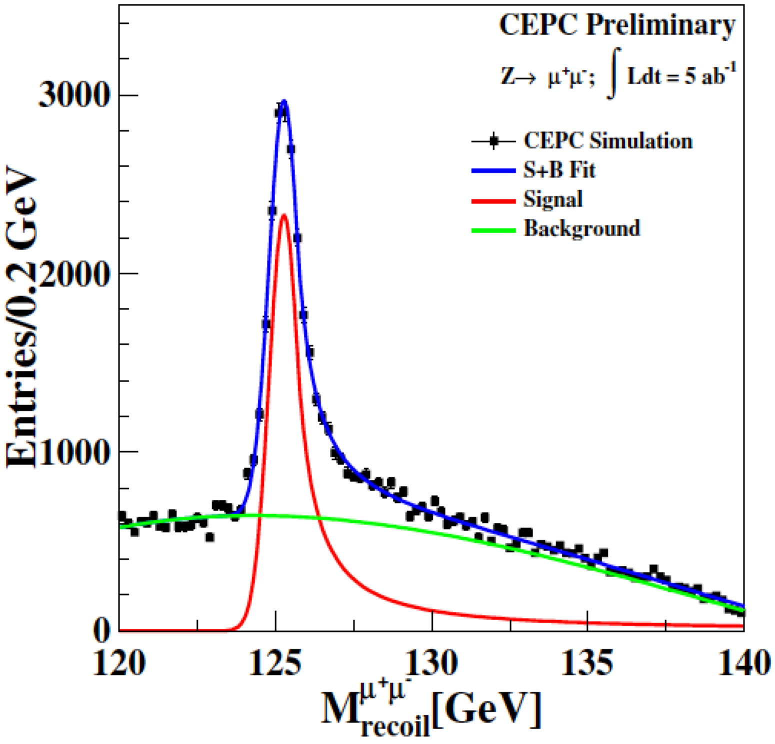
  - Deduce the total Higgs boson width Γ_H
  - Select events with $H \to$ bb, cc, gg, WW, $\tau\tau$, $\gamma\gamma$, $\mu\mu$, $Z\gamma$, …
  - Deduce g_{Hbb} , g_{Hcc} , g_{Hgg} , g_{HWW} , $g_{H\tau\tau}$, $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, $g_{HZ\gamma}$, …
  - Select events with $H \to$ “nothing”
  - 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 with CepC.
- 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%

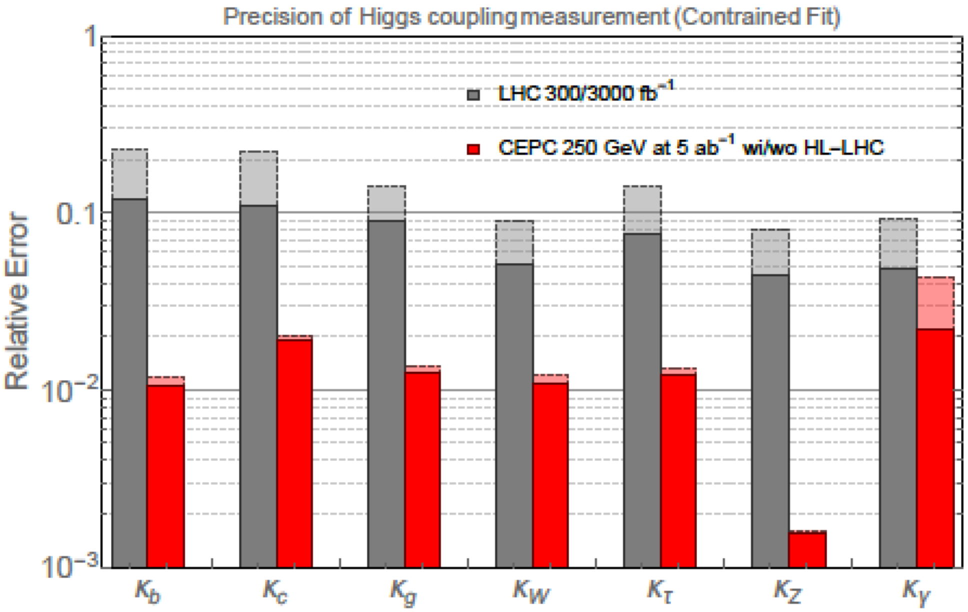
CepC CDR

Higgs coupling measurements

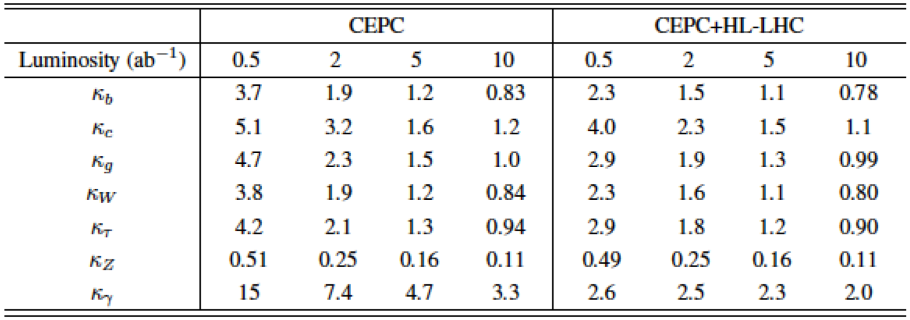
- 10 parameters $\kappa_b,\ \kappa_c,\ \kappa_\tau,\ \kappa_\mu,\ \kappa_Z,\ \kappa_W,\ \kappa_\gamma,\ \kappa_g,\ \mathrm{BR}_{\mathrm{inv}},\ \Gamma_h$
- assuming lepton universality → 9 paramete $\kappa_b,\ \kappa_c,\ \kappa_\tau = \kappa_\mu,\ \kappa_Z,\ \kappa_W,\ \kappa_\gamma,\ \kappa_g,\ \mathrm{BR}_{\mathrm{inv}},\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

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

CepC CDR



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

Summary about Higgs couplings

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

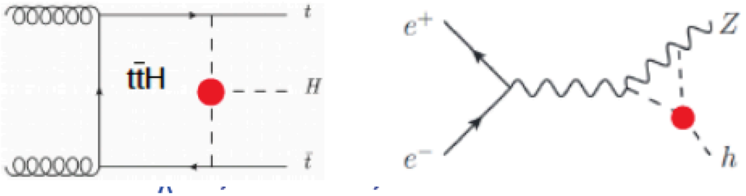
$$\kappa_b,\ \kappa_c,\ \kappa_\tau = \kappa_\mu,\ \kappa_Z,\ \kappa_W,\ \kappa_\gamma,\ \kappa_g$$

kappa-3 scenario	HL-LHC+								
	ILC$_{250}$	ILC$_{500}$	CLIC$_{380}$	CLIC$_{1500}$	CLIC$_{3000}$	CEPC	FCC-ee$_{240}$	FCC-ee$_{365}$	FCC-ee/eh/hh
κ_W (%)	1.1	0.29	0.75	0.4	0.38	0.95	0.95	0.41	0.2
κ_Z(%)	0.29	0.23	0.44	0.39	0.39	0.18	0.19	0.17	0.17
κ_g(%)	1.4	0.84	1.5	1.1	0.86	1.1	1.2	0.89	0.53
κ_γ (%)	1.3	1.2	1.5∗	1.3	1.1	1.2	1.3	1.2	0.36
$\kappa_{Z\gamma}$ (%)	11.∗	11.∗	11.∗	8.4	5.7	6.3	11.∗	10.	0.7
κ_c (%)	2.	1.2	4.1	1.9	1.4	2.	1.6	1.3	0.97
κ_t (%)	2.7	2.4	2.7	1.9	1.9	2.6	2.6	2.6	0.95
κ_b (%)	1.2	0.57	1.2	0.61	0.53	0.92	1.	0.64	0.48
κ_μ (%)	4.2	3.9	4.4∗	4.1	3.5	3.9	4.	3.9	0.44
κ_τ (%)	1.1	0.64	1.4	0.99	0.82	0.96	0.98	0.66	0.49
BR$_{\mathrm{inv}}$ (<%, 95% CL)	0.26	0.22	0.63	0.62	0.61	0.27	0.22	0.19	0.024
BR$_{\mathrm{unt}}$ (<%, 95% CL)	1.8	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.

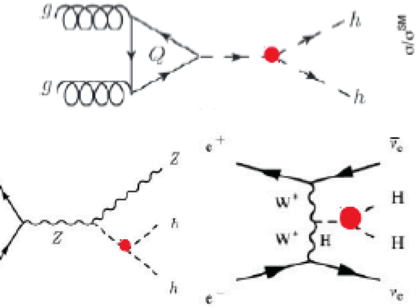
All ee colliders achieve major (and comparable) improvements in their first stage already in probing Higgs sector compared to HL-LHC: at least half of couplings get improved by factor 5 or more
W/Z effective couplings and BR(H→invisible) probed to ~$3\mathrm{x}10^{-3}$
Model-independent total cross section measurement → access to width, untagged BR
Clean environment to study H if/when anomalies are seen to understand underlying physics

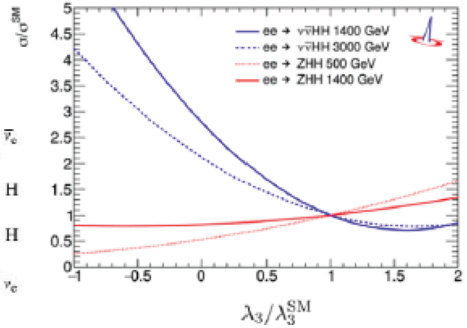
Higgs studies for FCC-hh/SppS: HH

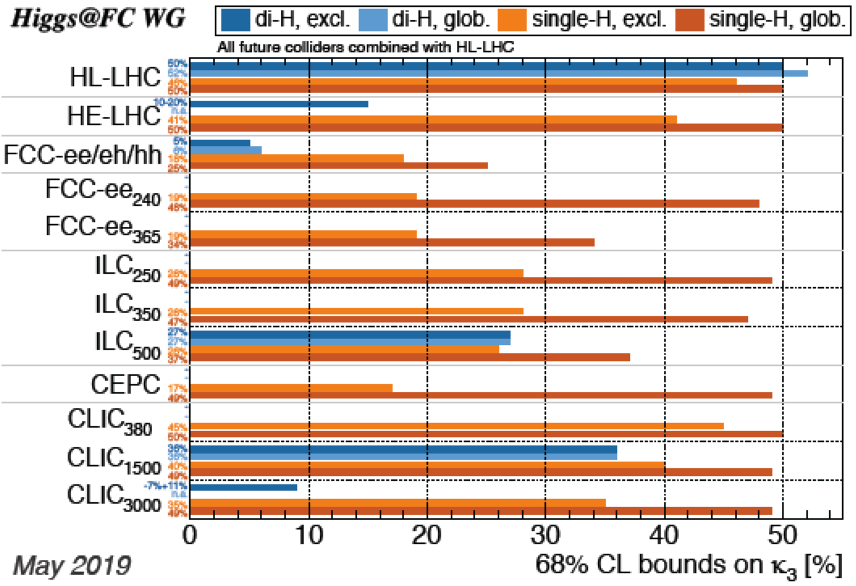
- **Single-H production**
  - Sensitivity via loop diagrams



- **HH production**
  - hh: σ(HH)0.01σ(H); must use differential measurements;
  - ee: Complementarity of ZHH and VBF production







Single-H: FCC-ee or ILC ~ 35% (global analysis)

HH production:

HL-LHC: ~50% (perhaps can do better)?
HE-LHC: ~15%
ILC500: ~27%; CLIC1500 ~36%
CLIC3000: ~9%; FCC-hh ~5%

The process towards a decision

- **Granada Symposium (May 13-16)** https://cafpe.ugr.es/eppsu2019/
  - Opportunity for community to get together and exchange ideas.
  - Role of the Symposium: collect input from the community and organize scientific arguments that will determine the future strategy of particle physics
- **Now: compiling Briefing Book.**
  - In parallel, ESG working groups on
    - Social and career aspects for the next generation
    - Organizational structure for European participation in global projects
    - Relations with external bodies and fields of physics
    - Knowledge and technology transfer
    - Outreach, education and communication
  - Briefing Book Draft to be handed from ESG to CERN Council: Sep 10
- **Strategy Update: Drafting Session Jan 20-24 (Bad Honhef, Germany)**
- **New Strategy to CERN Council: March 2020; Council approval: May 2020.**

Many issues

- CHF, €, $, ¥, Yuan, £, GDr, MiniBots
  - Explaining all this to Condensed Matter Physicists, Biologists, Lawyers, etc …
- Time scales; T0 .AND. Program duration (time to deliver full result)
- Sociological:
  - Number of experiments… Linear ~implies single-experiment setup (push-and-pull alternative… but…?!? Double line? Costs… half the lumi…)
  - Time scales: potential loss of expertise (accelerator/detectors), N generations
- Location and parallelism
  - What if Japan proceeds with the ILC? Does it make sense to have another ee collider? If yes, what type of ee collider? What if China builds the CEPC?
  - Does it make sense to go straight to an inexpensive FCC-hh? CSC @ 37.5 TeV? (new homework… along with what does FCC-hh look like without an FCC-ee beforehand?)
- Power consumption, long-term sustainability…
  - E efficiency can be significantly be improved in: District heating, energy storage, magnet design, RF power generation, cryogenics, SRF cavity technology, beam energy recovery
- Integrating potential (very long-term) technology breakthroughs?
  - Plasma Wakefield Acceleration? 150 TeV hh? Muon collider?
  - Ultimate limitations? Beam size/Luminosity for ee? Synchrotron radiation for pp?

Summary/Conclusions

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

- Per-cent level precision on most Higgs couplings
- $B_{inv} < 2.5\%$ @ 95% CL
- Width measurable to within 1 MeV

Many inclusive measurements limited by systematic uncertainties ➔ work needed from theoretical and experimental side

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 $\Gamma(H\rightarrow\text{invisible})$
- show evidence of BSM Higgs

FCC-hh/SppS:

Large potential on Higgs physics and more… if realized it will be the future of the field

An exciting journey ahead!

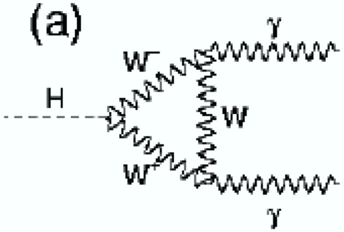
Backup

H→γγ

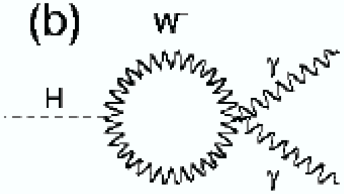
H→γγ

CMS-HIG-16-040 (arXiv:1804.02716)
CMS-PAS-HIG-17-015
ATLAS-2016-21 (arXiv:1802.04146)

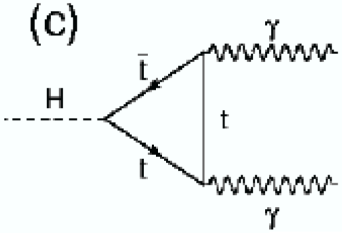
(a)



(b)



(c)



Indirect probe of coupling through production loops

- Sensitive to vector/fermion couplings (k_V, k_F)
- Can test NP in the loops

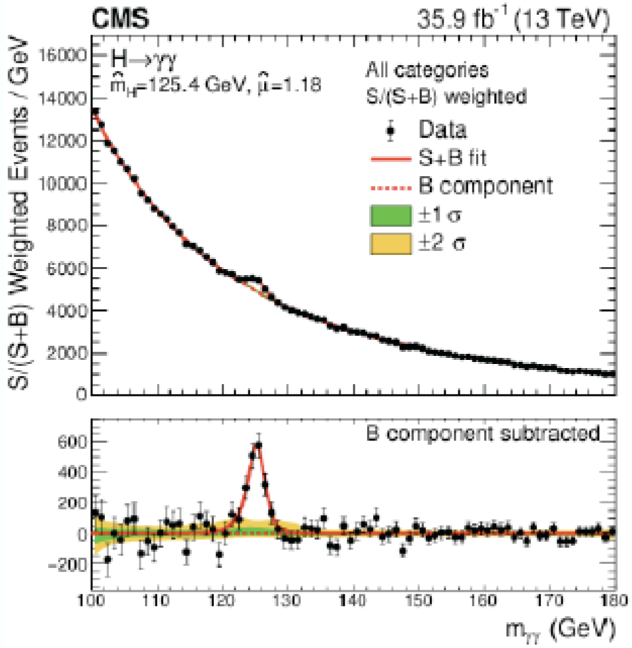
Search strategy: peak over (abundant) and regular background

Observed width dominated by detector resolution

Efficient selection (40%)

- Trigger, photon ID, E_T, isolation,…
- Abundant number of selected events allows for a large number of categories→sensitivity to different production/decay modes

Main uncertainties: photon ID/resolution, luminosity, statistical uncertainty still the largest factor

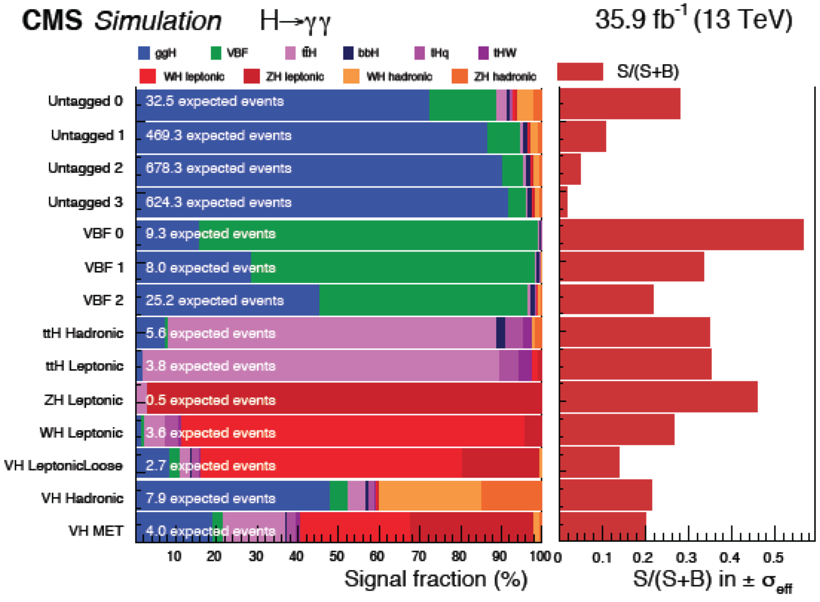


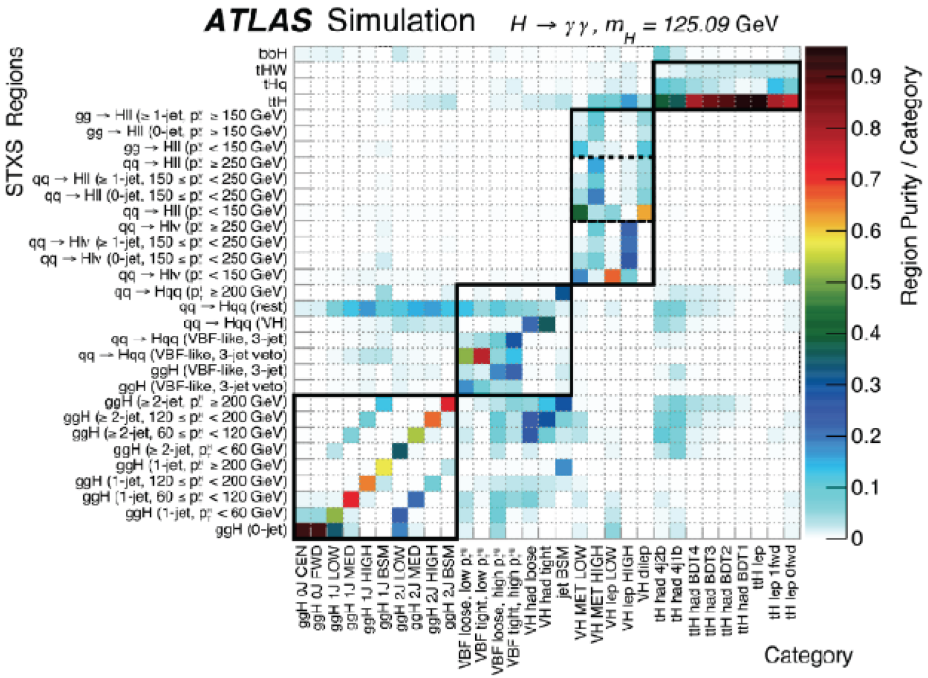
$H\rightarrow\gamma\gamma$: categorization

Vertex+photonID+kinematic BDT to select and classify the events

Large number of categories, with different S/B ratios and sensitive to different production modes

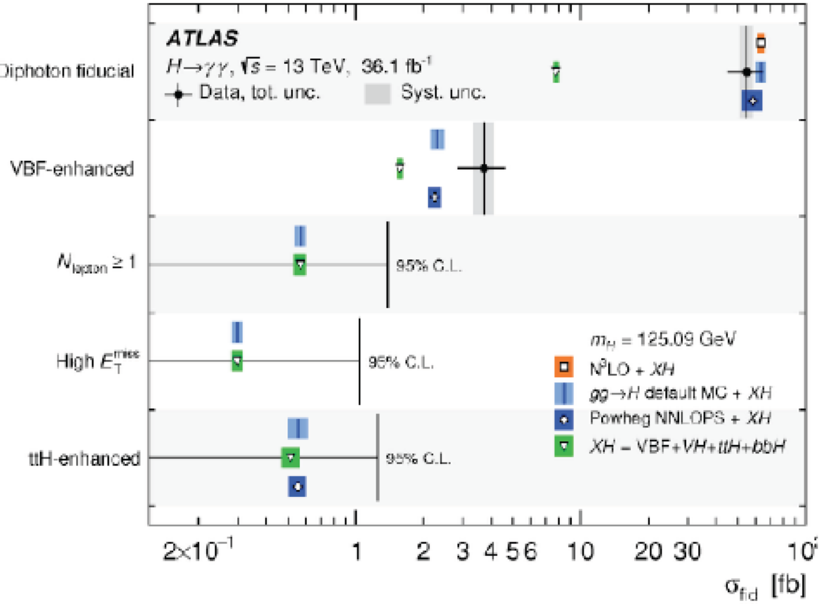
- Can be tuned to increase sensitivity to the STXS scheme (ATLAS)

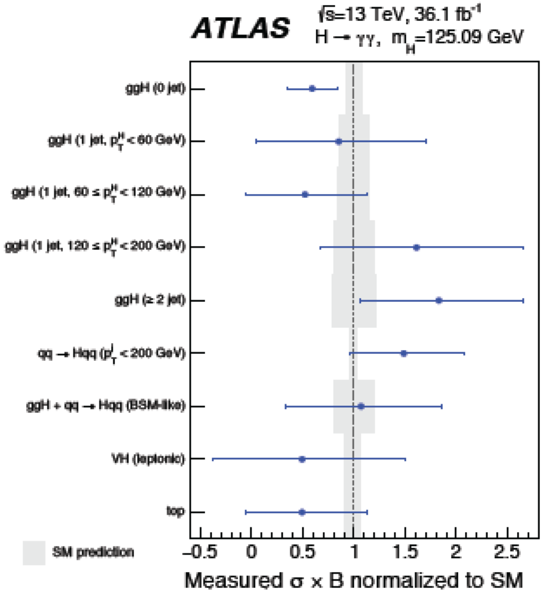


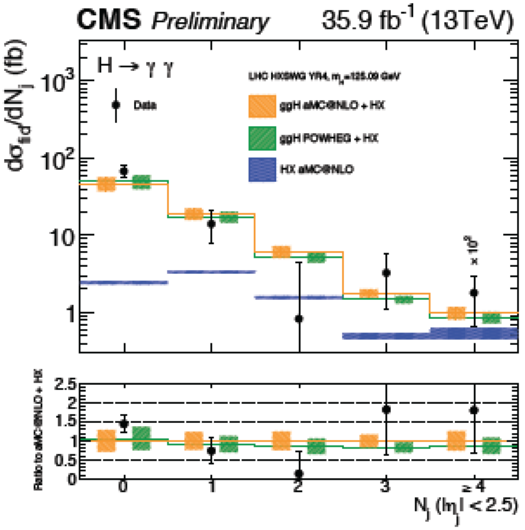


H→γγ: cross section

CMS-PAS-HIG-17-015
ATLAS-2016-21 (arXiv:1802.04146)







Both fiducial (inclusive) cross section, STXS, and differential distributions show good agreement with theoretical predictions

Experimental uncertainties are comparable to theoretical ones in the most populated bins (low p_T, low N_{jets})

Differential cross-section as a function of $p_T(H)$, N_{jet}, y_H, $\cos\vartheta^*$ (see backup)

ATLAS: EFT reinterpretation to probe anomalous couplings

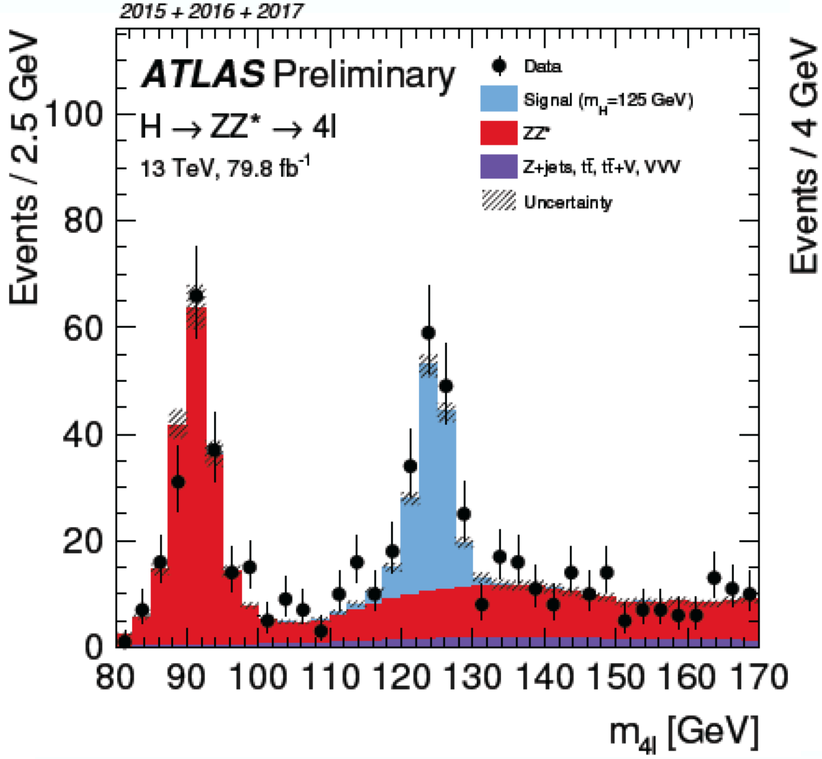
H→ZZ

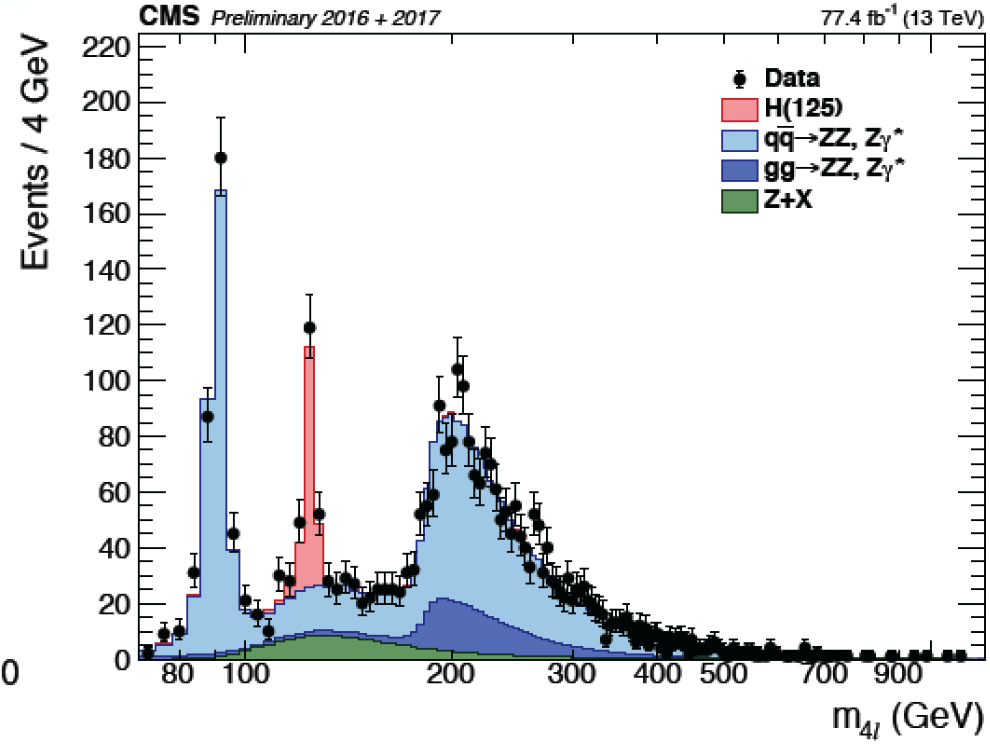
H→ZZ→4l

CMS-PAS-HIG-18-001 JHEP 03 (2018) 095
Phys. Lett. B 775 (2017) 1 ATLAS-CONF-2018-018

Low signal rate, but very clear signal topology over a small, flat background (mainly qqZZ, Z+jets)

- 4 isolated leptons in final state combined in 2 Z pairs
- Kinematical information (matrix element KD discriminants) or BDT techniques to separate signal and background and categorise events

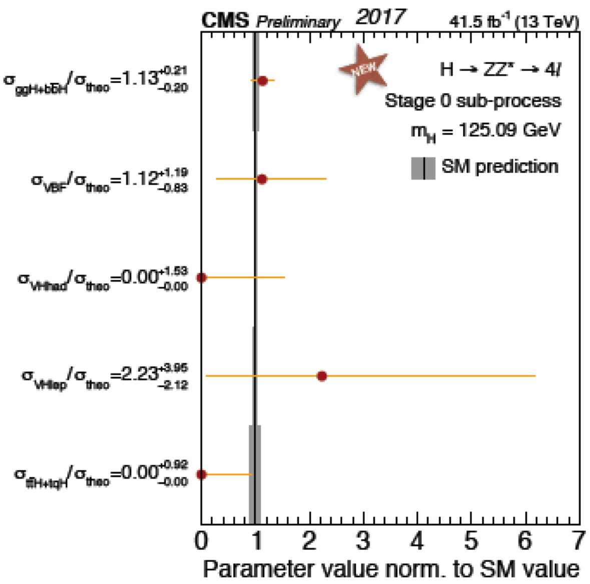


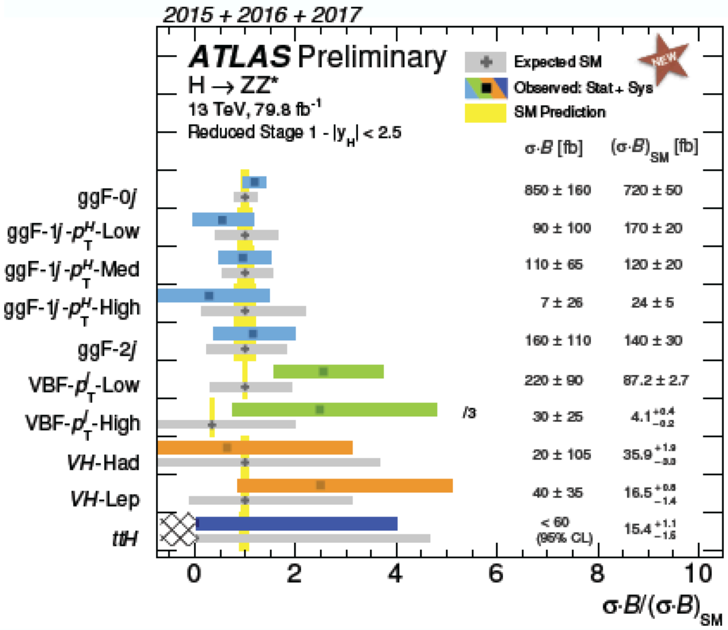


Analysis is still being improved:

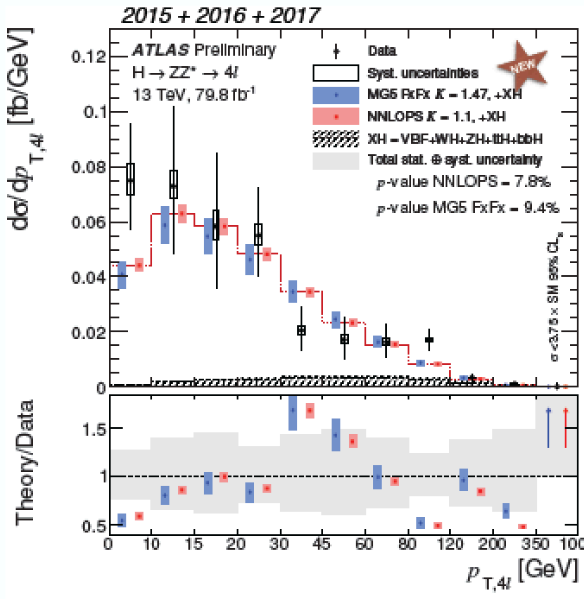
- Improved event categorisation to target VH and ttH productions
- CMS: dedicated discriminants to target different production modes (ggH, VBF, VH)

H→ZZ→4l: cross section





$\sigma \cdot B$ [fb]	$(\sigma \cdot B)_{SM}$ [fb]
850 ± 160	720 ± 50
90 ± 100	170 ± 20
110 ± 65	120 ± 20
7 ± 26	24 ± 5
160 ± 110	140 ± 30
220 ± 90	87.2 ± 2.7
30 ± 25	$4.1^{+0.4}_{-0.2}$
20 ± 105	$35.9^{+1.9}_{-3.0}$
40 ± 35	$16.5^{+0.8}_{-1.4}$
< 60 (95% CL)	$15.4^{+1.1}_{-1.5}$



ATLAS already attempting at (simplified) stage-1 STXS subprocesses.

CMS show a small excess (mostly driven by excess in 2e2μ)

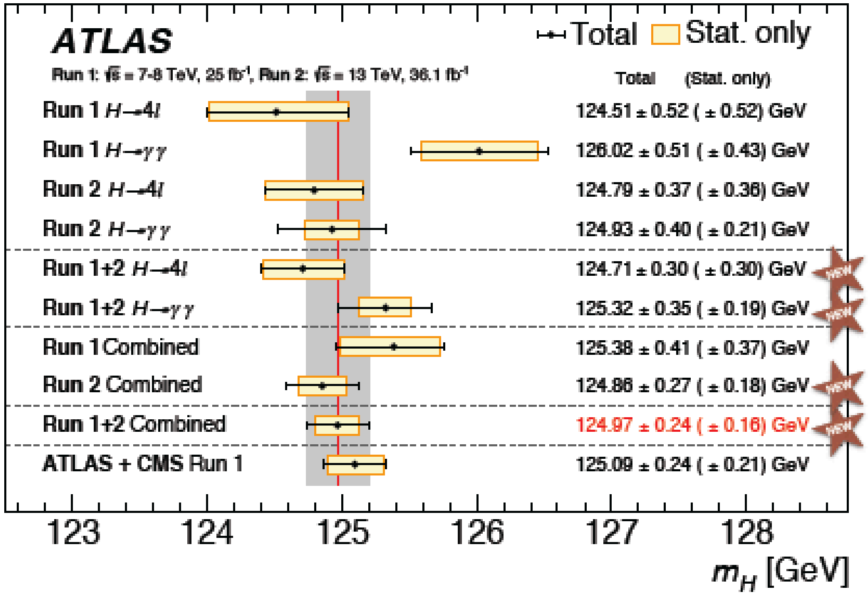
no ttH event observed yet in either of the experiments

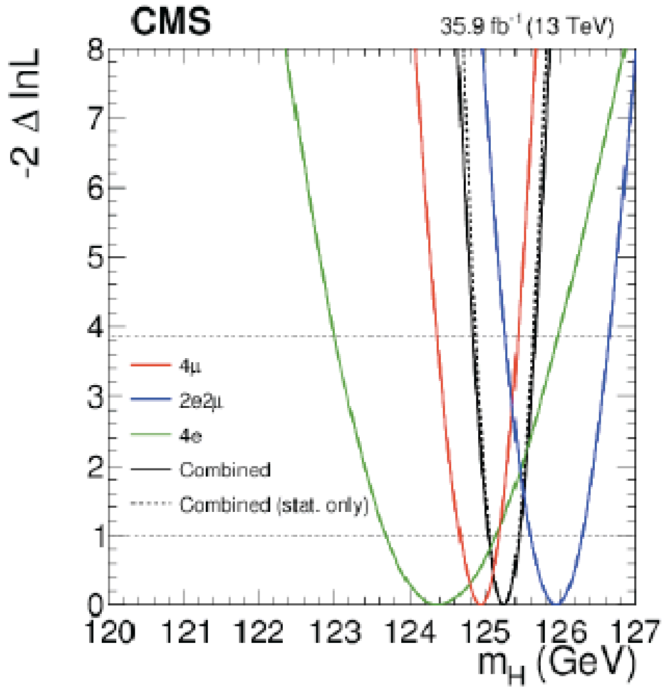
H→ZZ→4l + H→γγ: mass measurement

CMS-PAS-HIG-16-041
arXiv:1806.00242

H→ZZ→4l and H→γγ are the final states with the highest precision for the mass measurement

ATLAS performed the combined measurement of the Run1 and Run2 (2015+2016) H→ZZ→4l and H→γγ mass measurements, m_H = 124.97±0.24 GeV



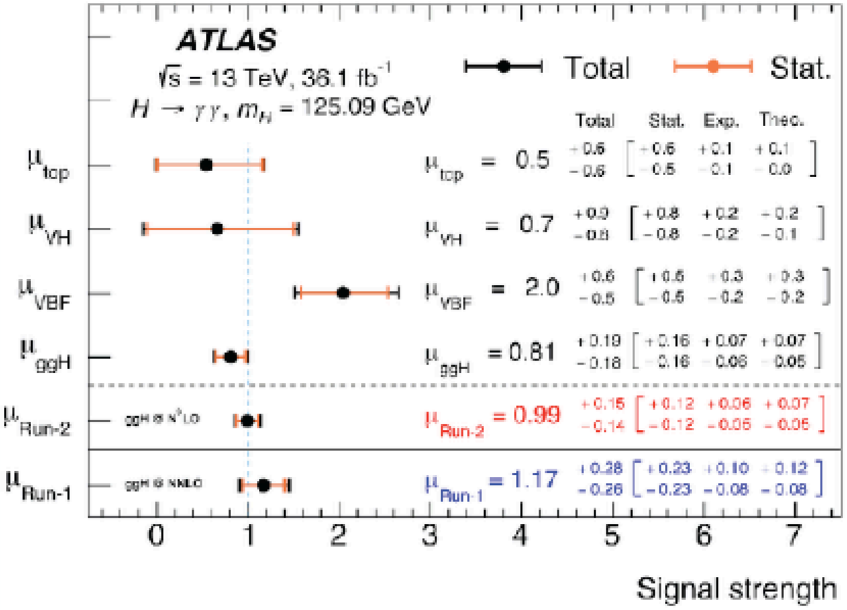


Most precise measurement at the moment comes from CMS H→ZZ→4l mass measurement with 2016 data m_H = 125.26±0.21 GeV

H→ZZ→4l + H→γγ: signal strength

H→γγ

$$\widehat{\mu}_{\mathrm{CMS}} = 1.18^{+0.17}_{-0.14} = 1.18\ ^{+0.12}_{-0.11}\,(\mathrm{stat})^{+0.09}_{-0.07}\,(\mathrm{syst})^{+0.07}_{-0.06}\,(\mathrm{theo})$$



Very good agreement between measurements and with expectations.
Run1: ATLAS excess, CMS deficit

25% improvement on Run1 combination

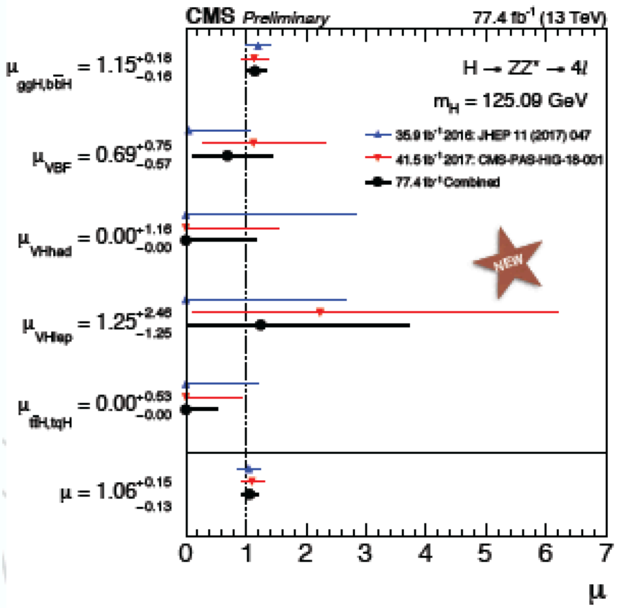
H→ZZ→4l

ATLAS 2015+2016+2017:

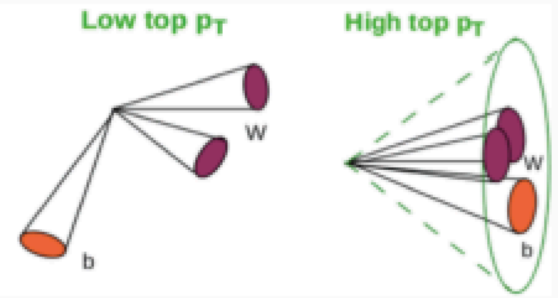
$$\mu = 1.20 \pm 0.12(\mathrm{stat.}) \pm 0.06(\mathrm{exp.})^{+0.08}_{-0.07}(\mathrm{th.})$$

$$= 1.20^{+0.16}_{-0.15}.$$

NEW



New resonances



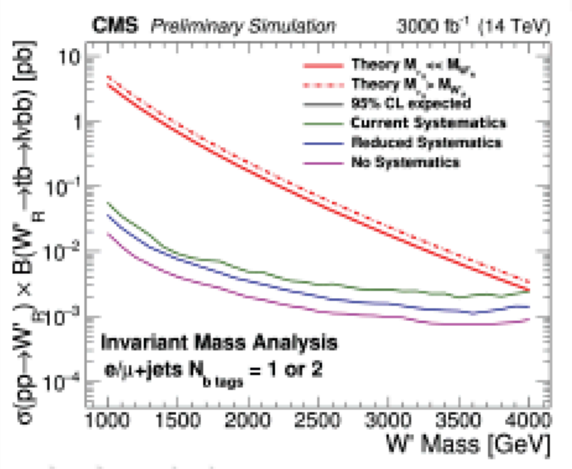
Performance estimated using Z' and W' searches @ 13 TeV (HVT or RS model)

- **W' → tb → bbℓν :** high-p_T lepton, significant E_{Tmiss}, two b-jets
- **Z' → tt → ℓνb qq'b / qq'b qq'b :** Exploit boosted topologies

Search for resonance decaying to HH (WED or KK model)

- Exploit boosted H->bb final states (narrow width approximation).

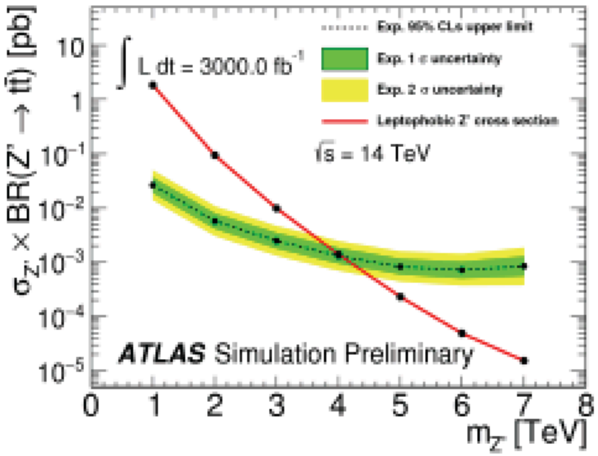
W' → tb → bbℓν



Exclusion: m(W') > 4 TeV

current limits about 2.7 TeV

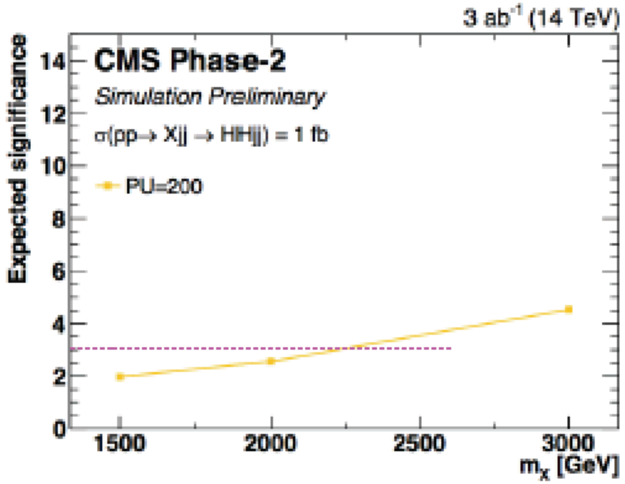
Z' → tt (hadronic)



Exclusion: m(Z') > 4 TeV

current limits about 2 TeV

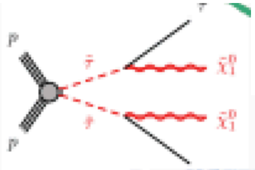
X → HH → bbbb (boosted)

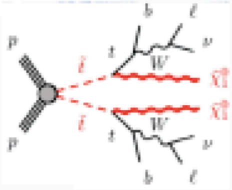


Evidence: m(X) < 2.2 TeV

for narrow width, 1fb cross section

SUSY searches

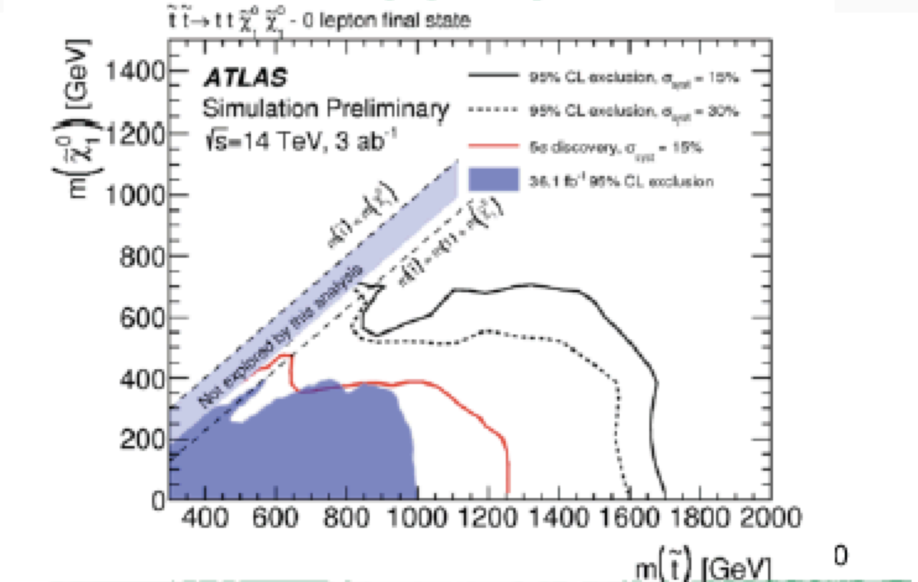




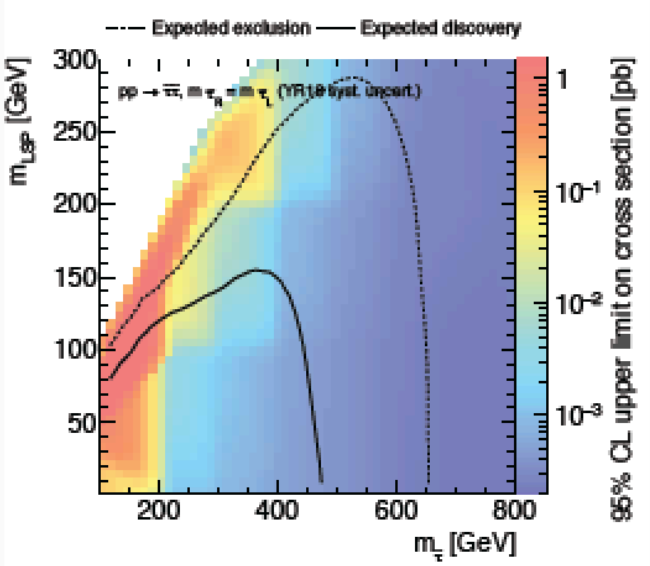
Performance estimated using the (simplified) analyses

- **Direct stau pair production:** Simplified models, assume 100% BR of τ → τ χ^0_1
  - Main background: W+jets, ttbar
- **Direct stop pair production:** Compressed mass spectra
  - Low stop - neutralino mass difference, channel needs high luminosity

Direct stop pair production:



Direct stau pair production:

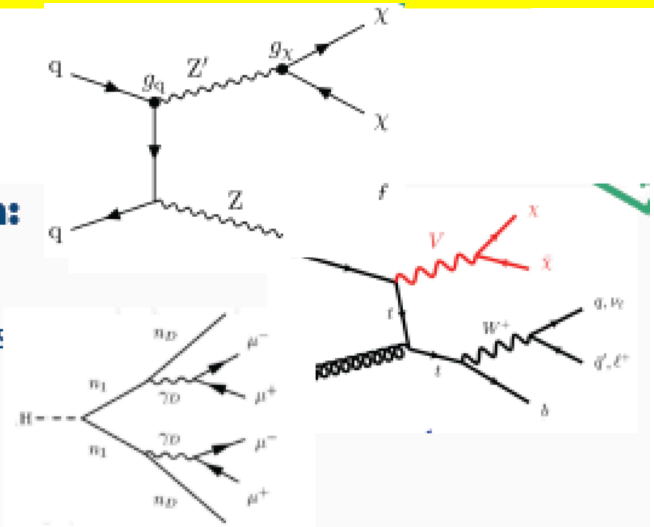


Discovery reach m(stop) < 1.25 TeV

Discovery reach m(stau) < 470 GeV

current exclusion limits about 110 GeV

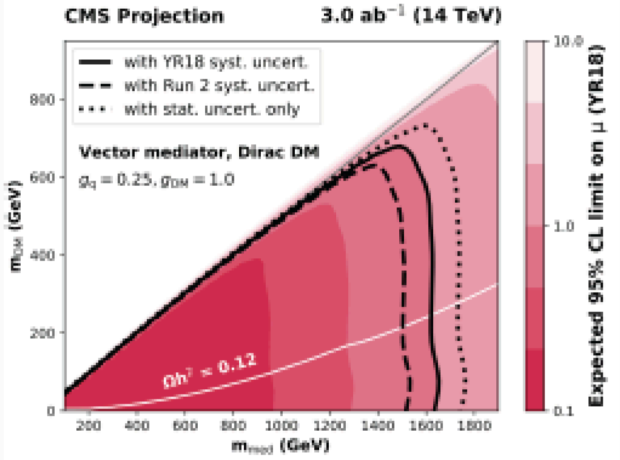
Dark sector



Simplified models for comparisons with direct detection:

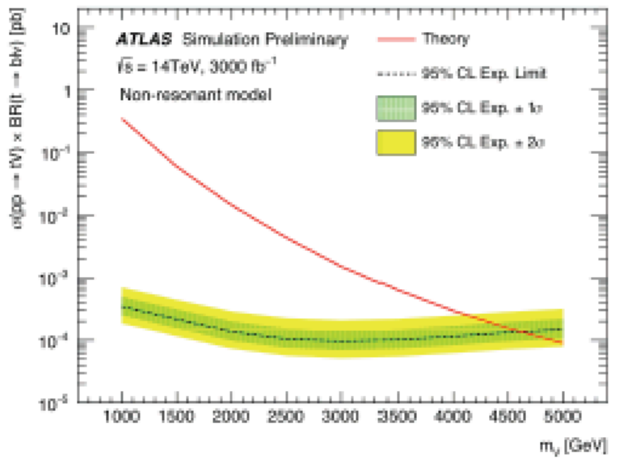
- **mono-Z :** Z accompanied by a mediator decaying to DM particles
- **mono-top :** Top accompanied by a mediator decaying to DM particles
- **dark photon :** It can couple to SM particles via kinetic mixing.
  (possible long-lived signatures for small kinetic mixing)

Mono Z search



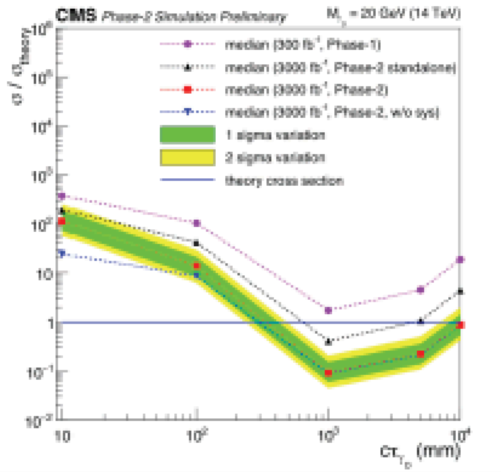
Exclusion: m(med) > 1.6 TeV

Mono top search



Exclusion: m(V') > 4.6 TeV

Dark photon search



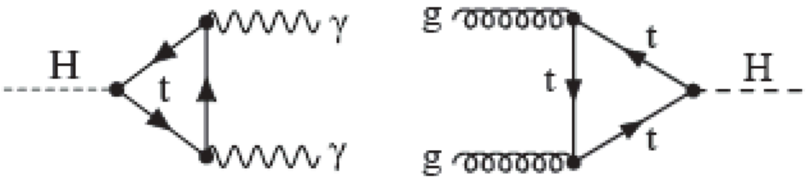
Excl.: 10 < m(γ_D) < 30 GeV
depending on kin. mixing.

ttH

ttH – topHiggs coupling

Motivation

- Provides a **direct probe** of the important top–Higgs coupling
  - Yukawa coupling $y_t \sim 1$
  - Indirect loop measurements can be influenced by BSM physics



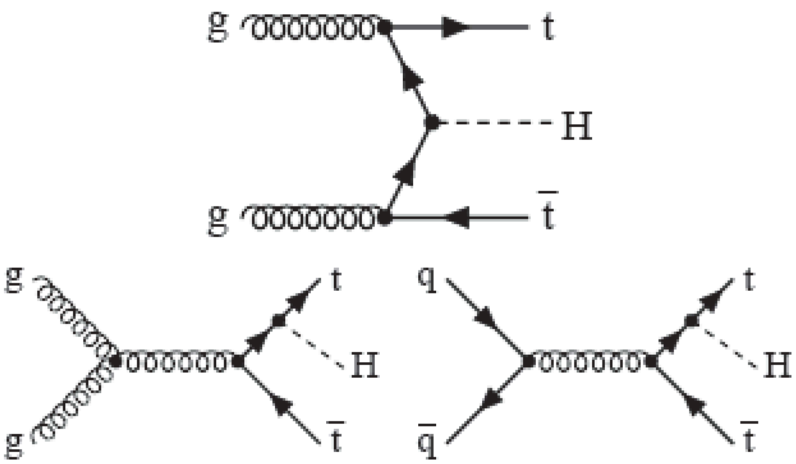
- First measurement of Higgs coupling to up-type fermion
- Non-SM ttH rate could indicate presence of new physics

Properties

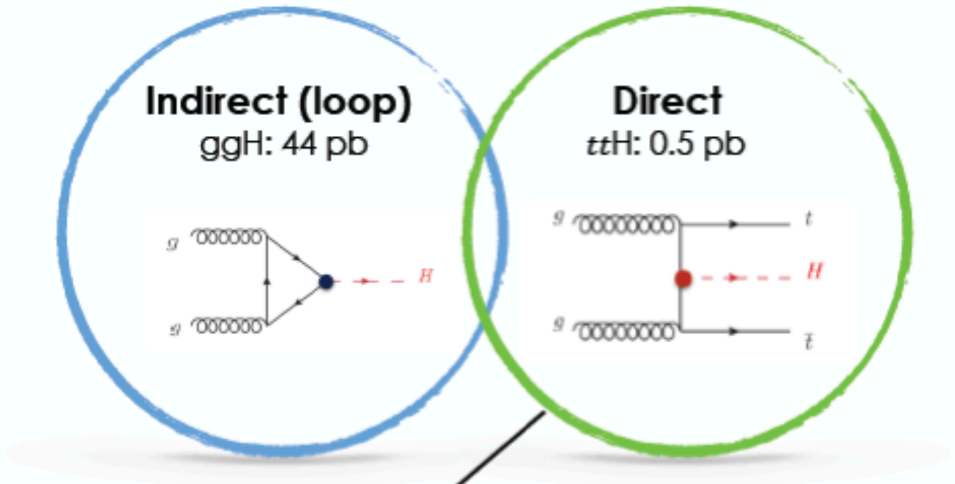
CERN-2017-002-M

LHC Higgs Cross Section WG Report 4

- Xsec: 0.5071 pb +6.8/−9.9%
  - NLO QCD and NLO EW accuracy
- **Expect ~18,000 SM ttH events** in 2016 data at CMS
  - ~ 36 fb^{-1}
- LO Feynman diagrams:



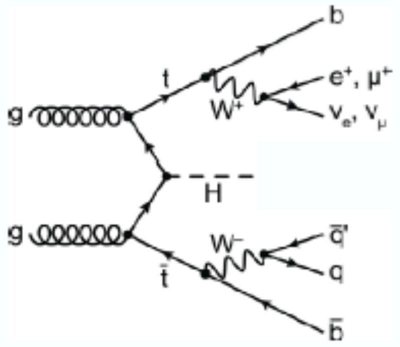
ttH experimental search

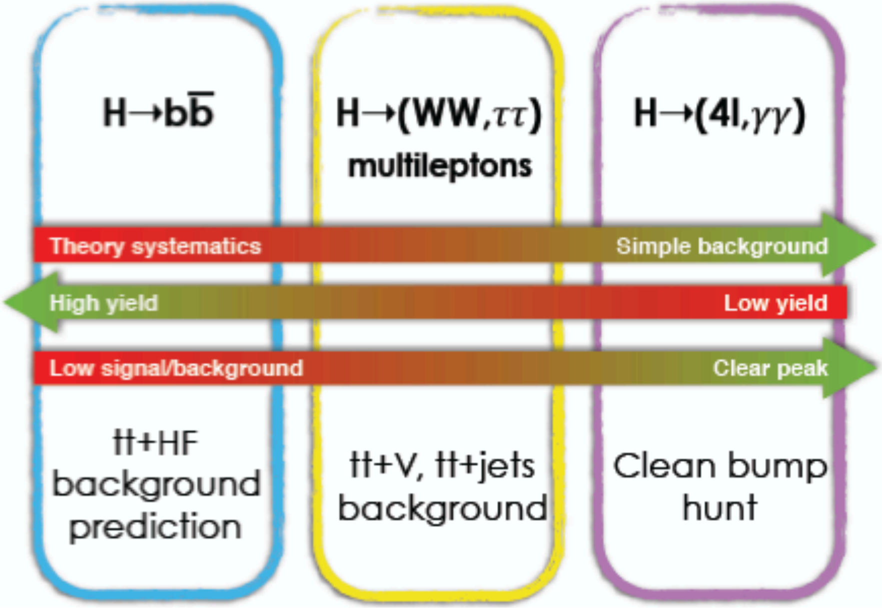


Indirect (loop)
ggH: 44 pb

Direct
$t\bar{t}$H: 0.5 pb

Final state with additional leptons, jets, b-jets





$H \to b\bar{b}$

$H \to (WW, \tau\tau)$
multileptons

$H \to (4l, \gamma\gamma)$

Theory systematics → **Simple background**

High yield ← **Low yield**

Low signal/background → **Clear peak**

tt+HF background prediction

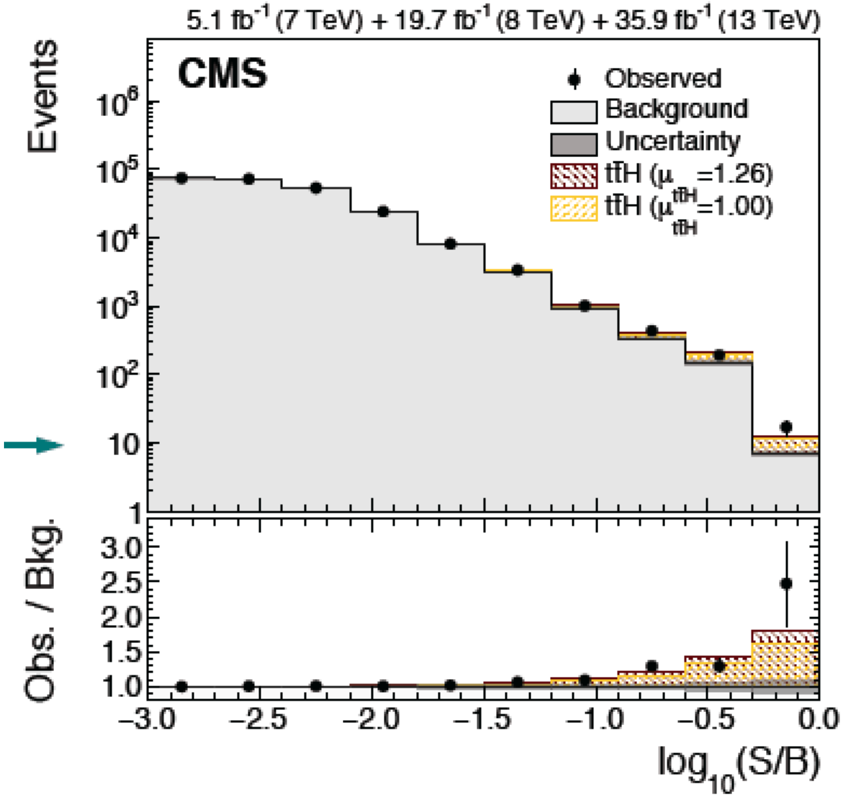
tt+V, tt+jets background

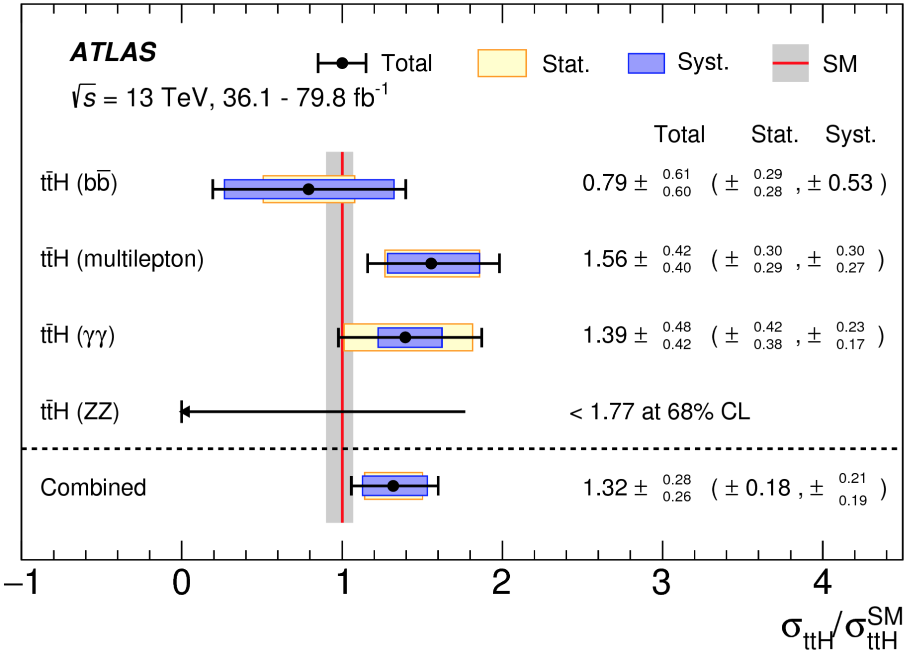
Clean bump hunt

ttH observation

CMS Phys. Rev. Lett. 120, 231801 (2018)
ATLAS arxiv:1806.00425

Decay channels analysed:
Fermions: H→bb H→ττ
Bosons: H→WW H→ZZ H→γγ





CMS Run 2 (2016)	**4.5σ obs.** (4.1σ exp.)
ATLAS Run 2 (2015-2016)	**4.2σ obs.** (3.8σ exp.)
ATLAS Run 2 (2015-2017)	**5.8σ obs.** (4.9σ exp.)
CMS Run 1 + Run 2 (2016)	**5.2σ obs.** (4.2σ exp.)
ATLAS Run 1 + Run 2 (2015-2017)	**6.3σ obs.** (5.1σ exp.)

- First observation of tree-level Higgs–top coupling
- Consistent with standard model Higgs within 1 sigma

Strategy for BSM physics @ HL-LHC

- HL-LHC is a great opportunity to address some of the questions mentioned
- Focus on relatively broad scenarios with rather generic expectations
- Make use of either consistent EFT approach when possible or simplified models
- Perform specific "signature based" analyses with minimum theoretical bias → model independent studies
- Think about new strategies optimized for HL-LHC and maybe not been overlooked because not optimal at LHC (different triggers)
- In case of a deviation from the SM prediction focus on more specific BSM assumptions to identify the origin of new physics
- In case of no deviation the constraint should be set in the most model independent way possible.

Higgs @ HL-LHC in a nutshell

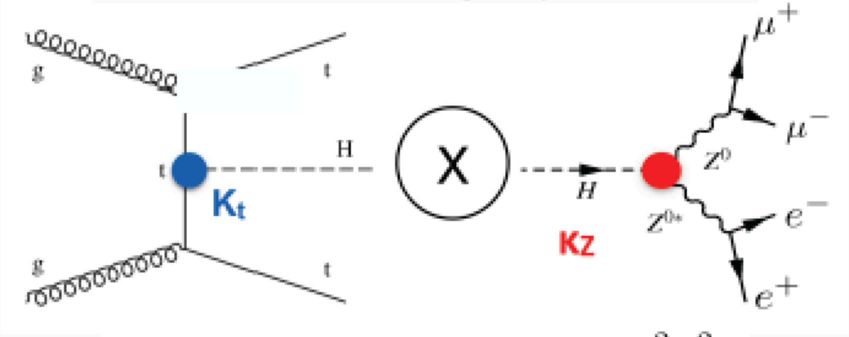
HL-LHC as a "Higgs Factory":

- Expected: ~170M Higgs bosons,
  ~120k of HH pairs
- Enables a rich Higgs physics program, including couplings precision measurements.

Higgs boson couplings @ HL-LHC:

- ATLAS and CMS measure a range of processes with different production and decay modes
- Projections based on LHC Run-2 results (36-80 fb^{-1})
- Consider model(s) with the most important physics message: κ_t, κ_b, κ_τ, κ_μ, κ_W, κ_Z, (+ κ_g, κ_γ)

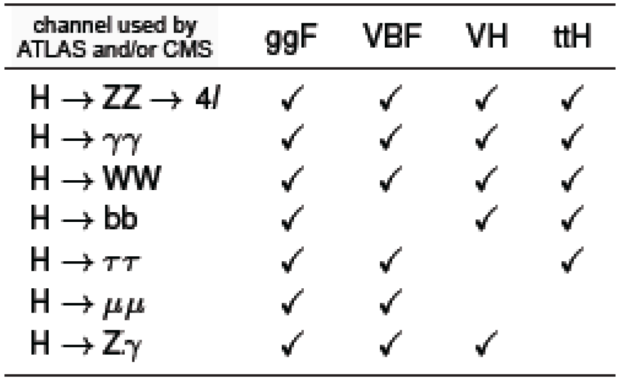
κ-framework : coupling modifiers



$$\sigma_{\rm SM}(ttH)\cdot B_{\rm SM}(H\to ZZ)\cdot\frac{\kappa_t^2\kappa_Z^2}{\kappa_H^2}$$

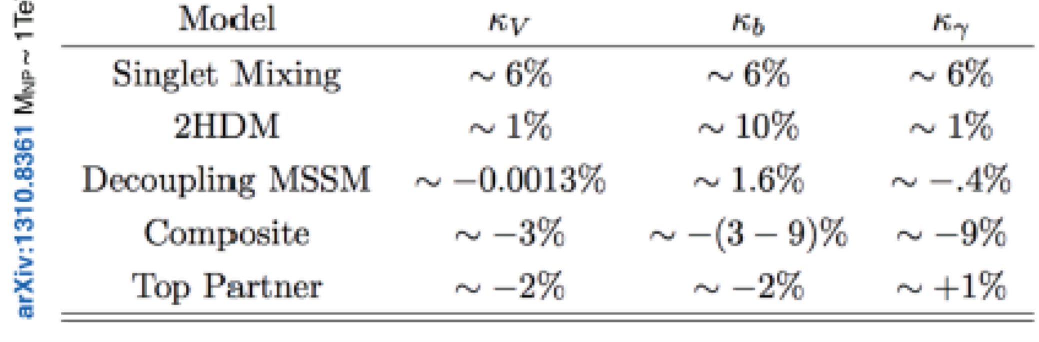
see Andrew's and Stefan's talks for details

Channels used by ATLAS and/or CMS



channel used by ATLAS and/or CMS	ggF	VBF	VH	ttH
$H\to ZZ\to 4l$	✓	✓	✓	✓
$H\to\gamma\gamma$	✓	✓	✓	✓
$H\to WW$	✓	✓	✓	✓
$H\to bb$	✓		✓	✓
$H\to\tau\tau$	✓	✓		✓
$H\to\mu\mu$	✓	✓		
$H\to Z\gamma$	✓	✓	✓	

BSM effects on Higgs coupling (1-10%)



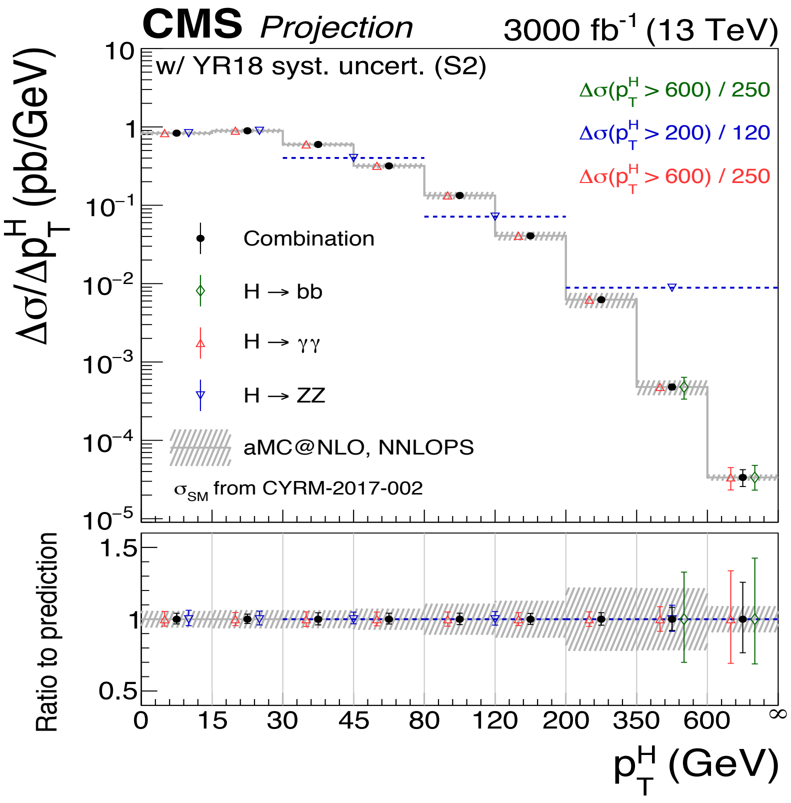
arXiv:1310.8361 $M_{NP}\sim$ 1TeV

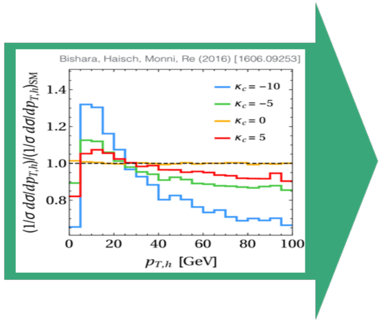
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

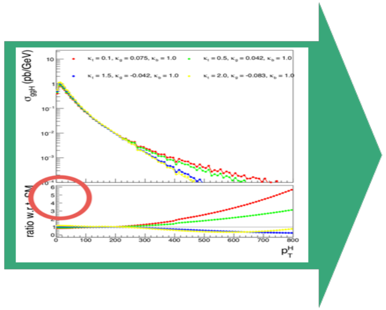
Higgs boson properties

Projections based on Run-2 combined differential XS (HIG-17-028):

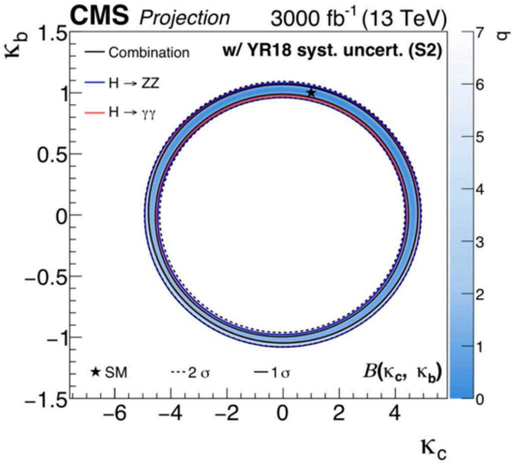
- Channels: H→γγ, H→ZZ→4l, boosted H→bb (in the high p_T^H tail)
- Constraints on effective kb, kc, kt, cg couplings (competitive with direct probes).



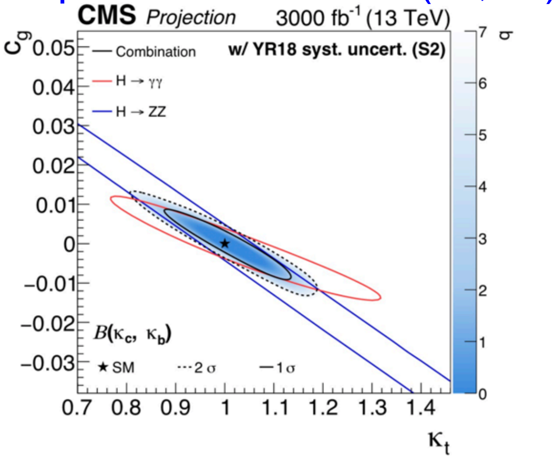




Expected 2D limits in (cg, kt)



Expected 2D limits in (kb, kc)



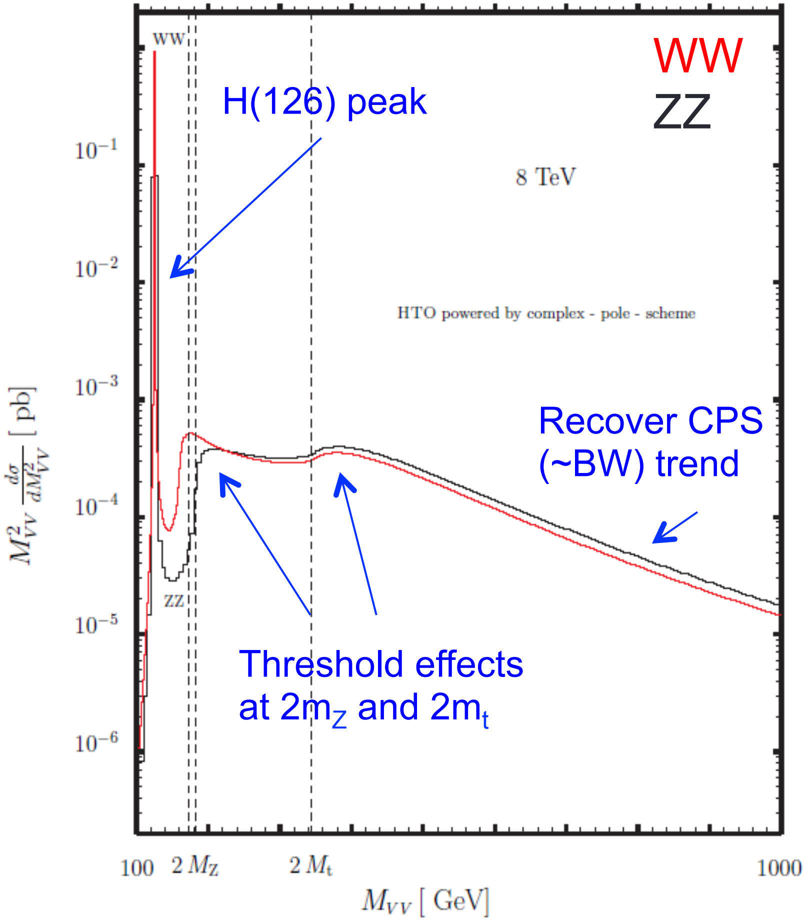
Reduction of uncertainties @3ab^{-1}:

- High-p_T^H region: x10
- Low-p_T^H region: x4

ttH, H→bb

Constraint on the Γ_H from H*(126)→ZZ

gluon-gluon fusion production



H(126) peak

Recover CPS (~BW) trend

Threshold effects at $2m_Z$ and $2m_t$

Off-shell H*(126)→VV (V=W,Z)

- In N. Kauer and G. Passarino, JHEP 08 (2012) 11 it has been shown that the off-shell production cross section is sizeable at high ZZ invariant mass
- that comes from a peculiar cancellation between BW trend and Γ(H→VV)
- Enhancement of **7.6%** of total cross section in the ZZ final state

	Tot[pb]	$M_{ZZ} > 2\,M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

Constraint on the Γ_H from $H^*(126)\rightarrow ZZ$

F. Caola, K. Melnikov (Phys. Rev. D88 (2013) 054024) and
J. Campbell et al. (arXiv:1311.3589)
showed how this feature can be turned into a **constraint on the total Higgs width**

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g_{ggH}g_{HZZ}\frac{F(m_{ZZ})}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H} \Rightarrow \sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH}g^2_{HZZ}}{\Gamma_H}, \quad \sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH}g^2_{HZZ}$$

--> so measuring the ratio of $\sigma^{\text{off-peak}}$ and $\sigma^{\text{on-peak}}$ → measurement of Γ_H

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa^2_g\kappa^2_Z}{r}(\sigma\cdot \text{BR})_{\text{SM}} \equiv \mu(\sigma\cdot\text{BR})_{\text{SM}}$$

$$\frac{d\sigma^{\text{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa^2_g\kappa^2_Z\cdot\frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu r\frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

$$\kappa_g = g_{ggH}/g^{\text{SM}}_{ggH}$$
$$\kappa_Z = g_{HZZ}/g^{\text{SM}}_{HZZ}$$
$$\boxed{r = \Gamma_H/\Gamma^{\text{SM}}_H}$$

Once μ is fixed a determination of r is obtained and so for Γ_H :

μ from CMS 4l paper arXiv:1312.5333 and provide result in **two** ways:

- "μ expected": use expected signal strength
- "μ observed": use observed signal strength

The interference with continuum gg → ZZ is taken into account at high mass → **gg2VV/MCFM**
VBF production is 10% at high mass → **PHANTOM**

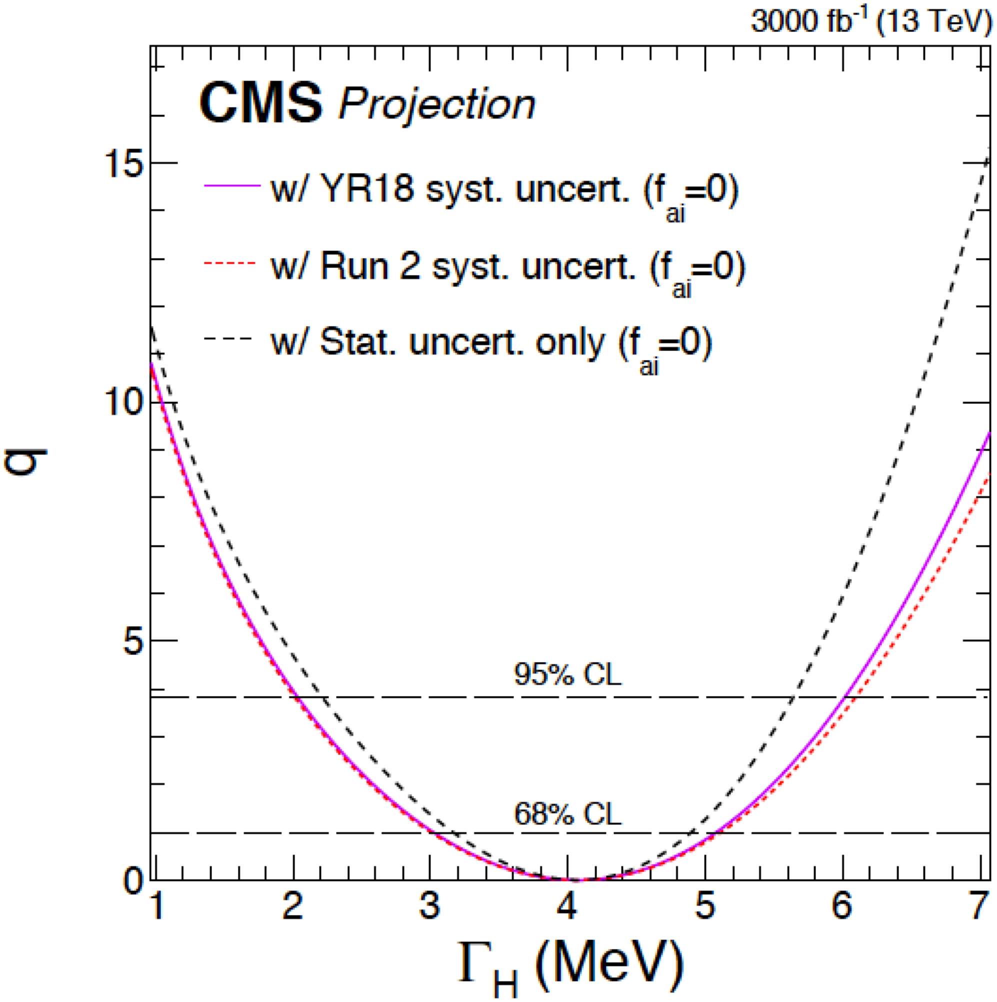
Limits on the Higgs width: off-shell anaysis

Systematic uncertainty:

- 10% additional uncertainty applied on the QCD NNLO K factor on the gg background process is kept the same in this approximated S2 in order to remain conservative on the understanding of these corrections on this background component.

Precision reachable combining CMS and ATLAS predictions with 3000 fb^{-1}

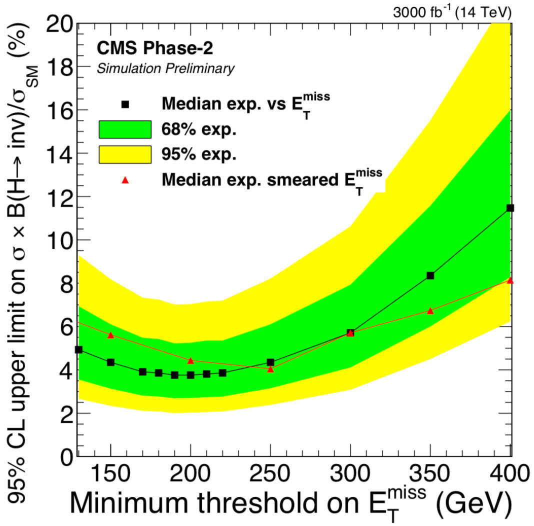
$$4.1^{+0.7}_{-0.8}\ \text{MeV}$$

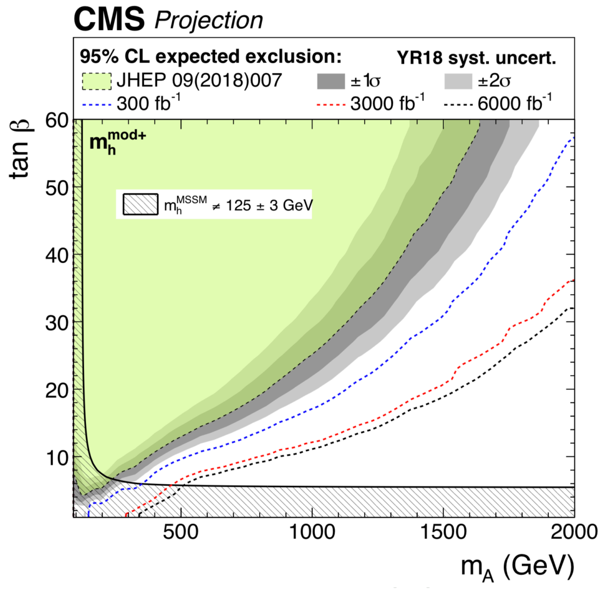


Sensitivity to BSM effects in Higgs physics

Several studies on probing the BSM effects in the Higgs physics :

- Probe for anomalous interactions & rare/exotic decays:
  - H→ invisible
    B_{INV} **< 4%** (compare to 20% @Run2) [FTR-18-016]
  - Exotic/rare/forbidden decays and signatures
    - B_{BSM} **< 6%** from couplings combination (compare to 34% @Run2) [FTR-18-011]
    - H→BSM or LFV decays [FTR-18-035, not in time for YR v2)
  - L1T TrackJet for BSM Higgs signatures
    - signatures with displaced jets [FTR-18-018]
  - Anomalous couplings and width:
    - significant improvement in limits on anom. coupl. Width: $\Gamma_H \subset$ **[2,6] MeV @ 95%CL** [FTR-18-011]
- Search for additional Higgs bosons and/or scalars :
  - MSSM H→ττ search [FTR-18-017]
  - High mass search X→ZZ->2l2q [FTR-18-040)

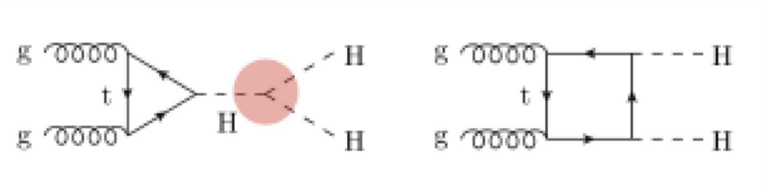




HH production and self couplings

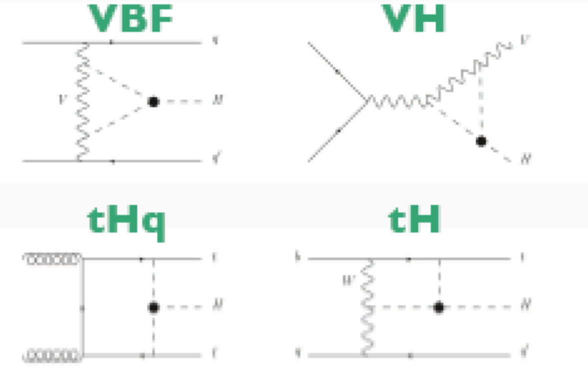
Probing HIG boson trilinear coupling λ_{HHH} important @HL-LHC

- Information on the shape of the scalar Higgs potential, and potential anomalous effects

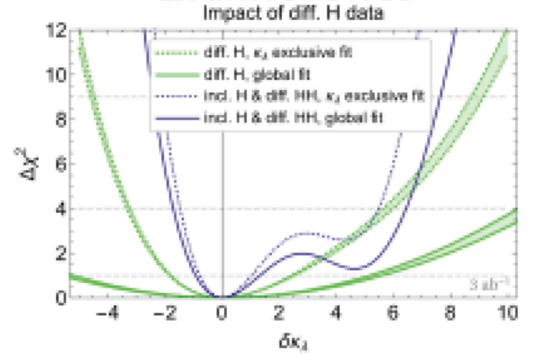


ATLAS and CMS performing extensive sensitivity studies in individual channels:

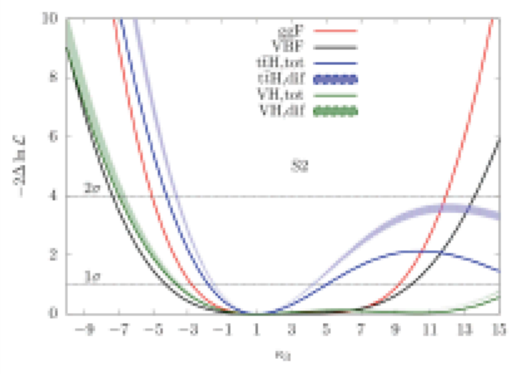
- Analyses in **bbbb, bbVV, $bb\tau\tau$, $bb\gamma\gamma$** (expertise from LHC Run-2 + further optimisation/developments)
- Performing combination of all channels, and also **ATLAS+CMS combination** (to be public soon)



arXiv:1704.01953



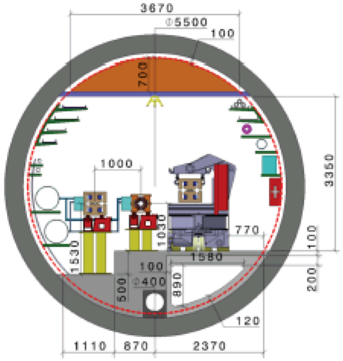
arXiv:1709.08649

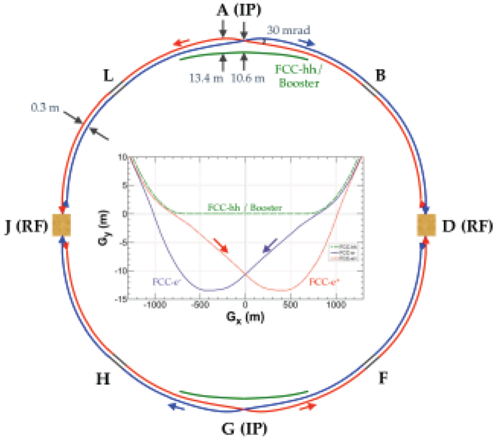


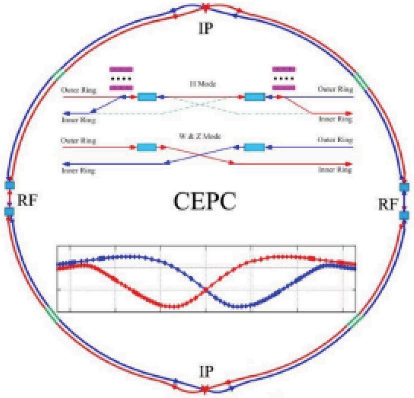
- Important possibility to **constrain λ_{HHH} from single Higgs precision measurements**
  - HH differential information further improves the measurement

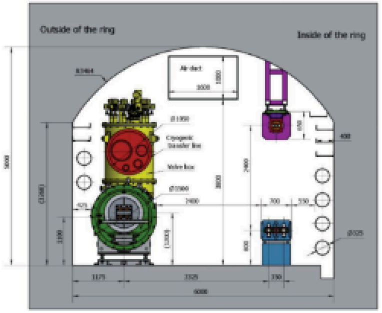
FCC-ee and CepC

- **Double–ring colliders with full-energy top-up booster ring**
  - CEPC started as 54 km, single-ring design; nowadays ~ FCC-ee 100 km, double-ring
  - 2 IPs, 2 RF straights, tapering of arc magnet strengths to match local energy
  - Common use of RF systems for both beams at highest energy working point
  - Synchrotron radiation: 50 MW (30 MW) at FCC-ee (CEPC)
  - Beam lifetime >12 min; top-up injection, e^+ rate ~10^{11}/s.
- **Asymmetric IRs: limit SR of incoming beams towards detectors**
  - → large crossing angle









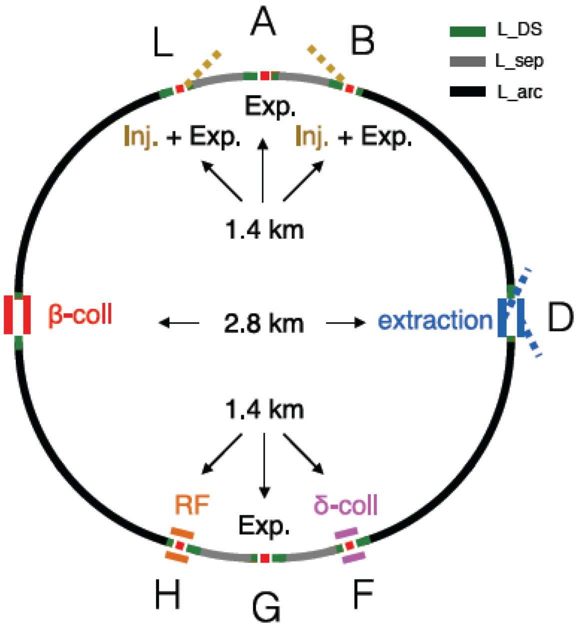
FCC-hh and SppC

- Circumference ~100 km, high luminosity 3(1) x 10^{35}cm^{-2}s^{-1} (SppC)
  - Two IRs at high lumi potentially two more experiments (possibly combined with injection section, collimation insertions, extraction/dump insertion, RF insertion,

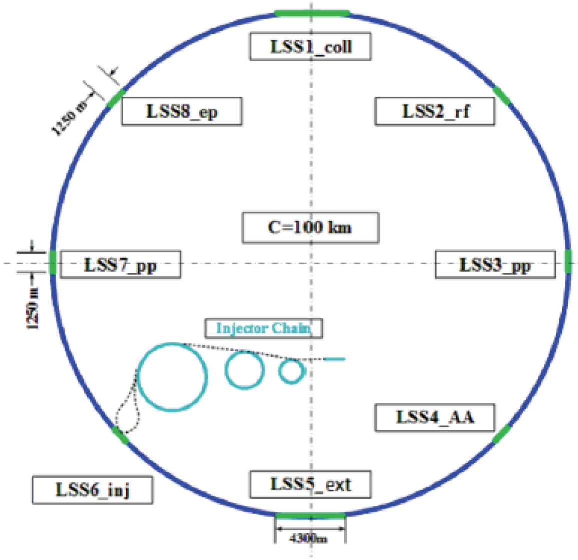
FCC-hh

based on existing CERN injector chain,

Luminosity goal ~20 ab^{-1} per main IP within 25 years



SppC



new injector chain,

simultaneous operation with e⁺e⁻ collider

Higgs physics at ee/pp colliders

- Biggest difference (in H physics reach) between ee and pp colliders:
  - Lepton colliders: measure Γ_H from total $\sigma(ZH)$
    - BR_{unt}, κ's and BR_{inv} constrained via joint fit to data.
  - Hadron colliders: not directly sensitive to Higgs width
    - Need additional theoretical assumption (eg $|\kappa_V| \leq 1$ or constraint from off-shell Higgs measurements) has to be imposed when untagged decays are allowed
    - Can probe H further, at high p_T. This is not included…
- Kappa framework vs SMEFT
  - καππα: simplest parametrization which can probe the deviation from the SM induced by some well-motivated BSM models (SUSY, composite Higgs, ..)
    - Fit for κ_W, κ_Z, κ_c, κ_b, κ_t , κ_τ , κ_μ and effective κ_g, κ_γ & $\kappa_{Z\gamma}$
  - But some limitations
    - H couplings keep SM helicity structure; SMEFT doesn't
    - Blind to power of polarization; SMEFT not

$$\Gamma_H = \frac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{unt})}$$

"Invisible" width: constrained directly at all future colliders (ZH, VBF H→invisible)

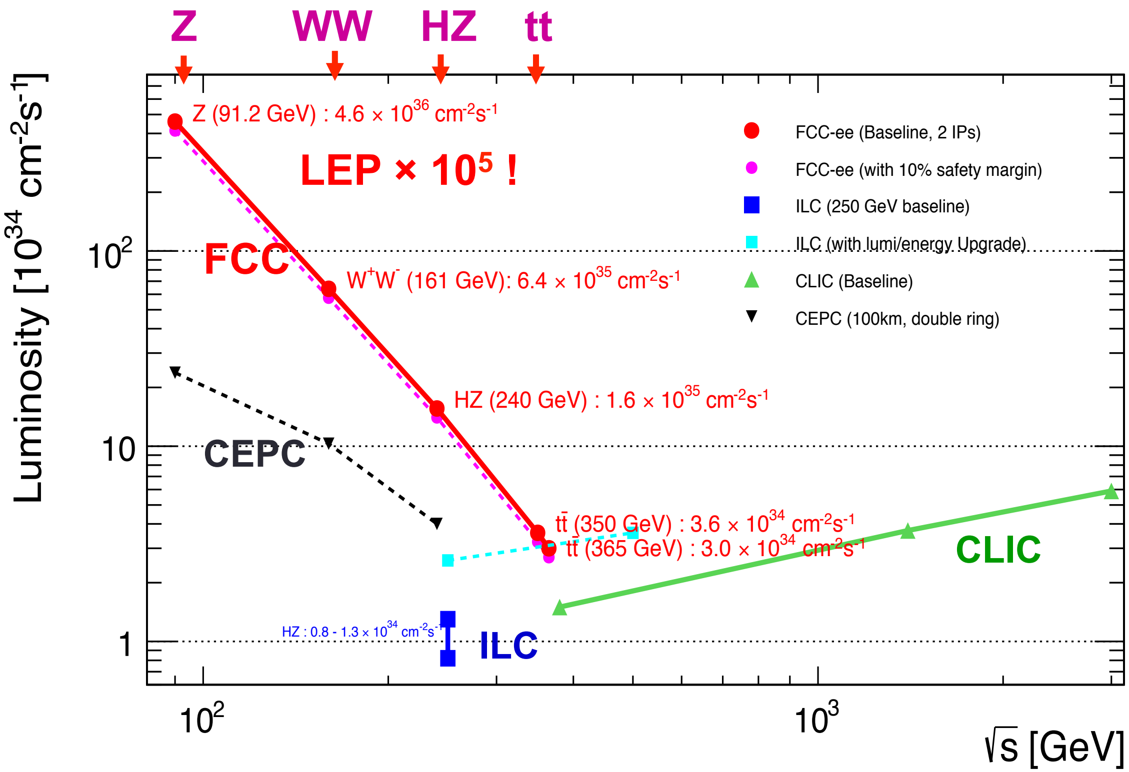
"Untagged" width:
h(125)→XX.
Includes BSM decays and rare SM decays

FCC-ee/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.

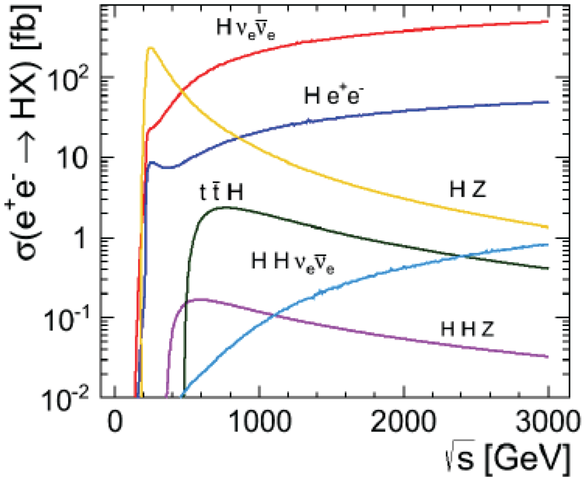


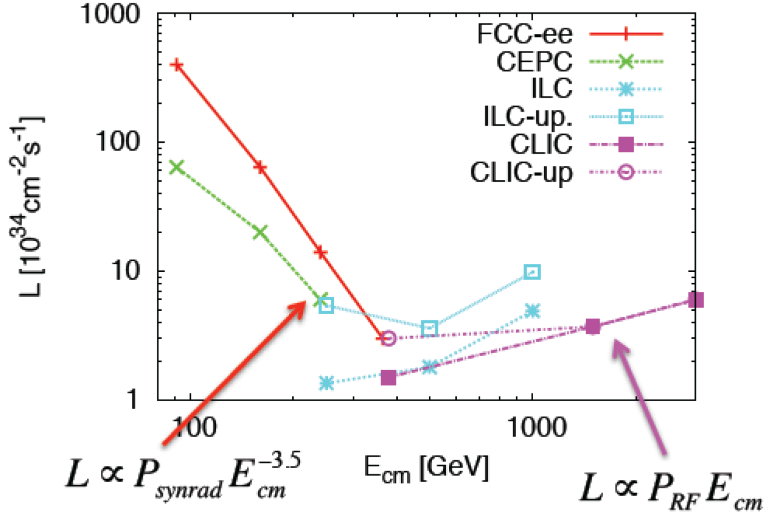
Compared with hadron collisions at LHC, e^+e^- collisions are not affected by underlying events and pile-up effects.

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

FCC-ee can reach the ttbar threshold

Higgs factories





$L \propto P_{synrad} E_{cm}^{-3.5}$

$L \propto P_{RF} E_{cm}$

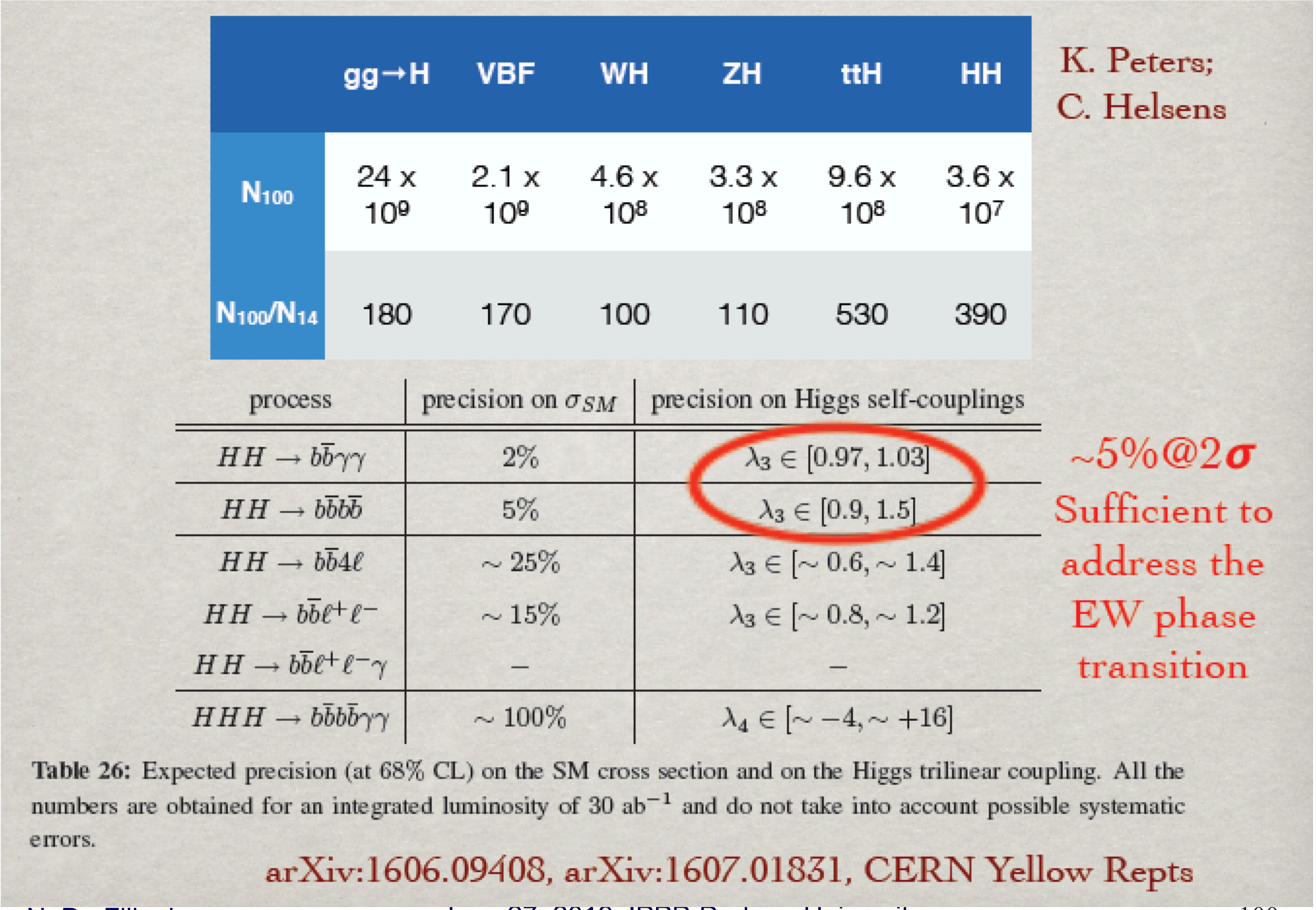
Schemes for increasing luminosity:

- FCC-ee: consider more IRs/running longer
- ILC: more bunches per pulse, doubling repetition rate?
    - Each: x 2 in lumi; higher power consumption and somewhat higher cost
- CLIC: doubling repetition rate at 380 GeV?
    - Factor 2 in lumi; power increases from 170 MW to 220 MW (+slight cost increase)

Low energies: circular colliders superior performance
Higher energies: CC lumi reduction due to synchrotron radiation; linear colliders better: luminosity per beam power roughly constant

Longit. polarisation: only at Linear Colliders
e^-: 80%; e^+: 30% @ ILC; 0 @ CLIC (not needed)
FCC-ee: transverse polarization for precise E_{beam}

FCC studies: HH



	gg→H	VBF	WH	ZH	ttH	HH
N_{100}	24 x 10^9	2.1 x 10^9	4.6 x 10^8	3.3 x 10^8	9.6 x 10^8	3.6 x 10^7
N_{100}/N_{14}	180	170	100	110	530	390

K. Peters;
C. Helsens

process	precision on σ_{SM}	precision on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	2%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$\sim 25\%$	$\lambda_3 \in [\sim 0.6, \sim 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$\sim 15\%$	$\lambda_3 \in [\sim 0.8, \sim 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$\sim 100\%$	$\lambda_4 \in [\sim -4, \sim +16]$

~5%@2σ

Sufficient to address the EW phase transition

Table 26: Expected precision (at 68% CL) on the SM cross section and on the Higgs trilinear coupling. All the numbers are obtained for an integrated luminosity of 30 ab^{-1} and do not take into account possible systematic errors.

arXiv:1606.09408, arXiv:1607.01831, CERN Yellow Repts