HL-LHC Higgs physics

Workshop on the Circular Electron-Positron Collider
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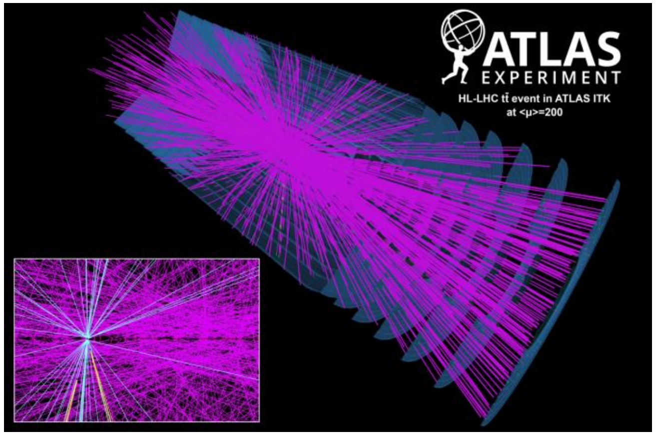
High Luminosity LHC

- Operation at up to **L=7.5·10^34^Hz/cm^2^** (LHC Run-2: $2\cdot10^{34}$) to collect up to L_{int} = **3000 fb^{-1}**

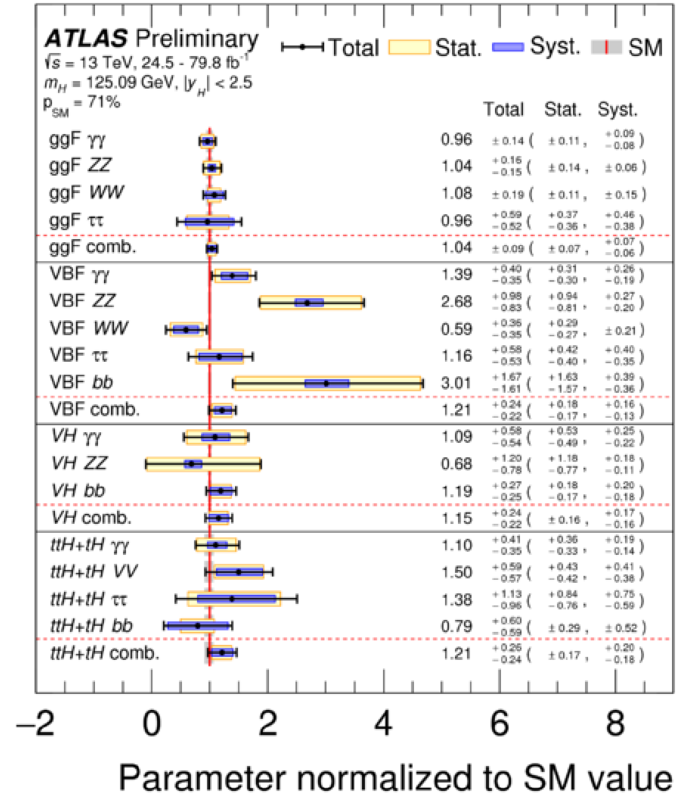
- Up to **200** (~ 37) **pp collisions** per bunch crossing at HL-LHC (LHC Run2)
  - Very challenging experimental conditions
  - Extensive detector upgrades to operate under HL-LHC conditions



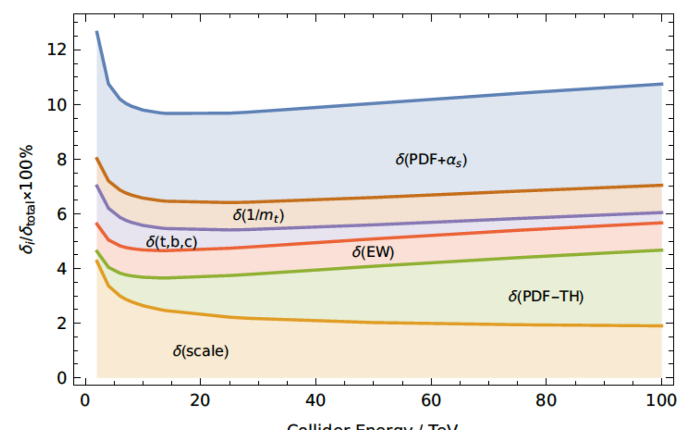
$t\bar{t}$ simulated event at average pile-up of 200 collisions per bunch crossing

Higgs Physics at (HL-)LHC

ATLAS-CONF-2019-005



- Wide range of Higgs boson couplings explored at **LHC**
  - Recent observation: *ttH* production
  - Still unobserved $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$ decays
  - Many measurements still **statistically limited**
- **Precise** characterization of the Higgs boson main **priority** of **HL-LHC**. With L=3 ab^{-1} :
  - Reduced **statistical** uncertainties
  - Reduced **experimental** systematic uncertainties
  - Reduced **background uncertainties** from high-statistics control regions
- Crucial to also reduce **theory** uncertainties
  - New precision **PDF sets** including HL-LHC data
    - Exploit improved experimental precision and enhanced forward acceptance of upgraded detectors
  - Increasing availability of **higher order** theory calculations
- Crucial to also improve **luminosity:** aim to 1% precision



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Higgs measurements@HL-LHC : methods

Recent new projections in the Yellow Report 1902.00134

1. **Extrapolations from Run 2 data to 3 ab^{-1}**
   - **Efficiencies, resolutions, fake rates** assumed **unchanged** from the Run 2 values
     - assumption is that upgraded detectors compensate pileup effects
2. **Analysis of simulated samples with HL-LHC conditions**
   - Number of pileup interactions **μ=200**
   - Upgraded detectors
   - Performed for new analysis or significantly improved analysis wrt Run2 ones

- Main scenario in YR for systematic uncertainties (S2):
  - Most **theoretical uncertainties** scaled down by **a factor ½**
  - **experimental uncertainties scaled** down by √L until they reach a defined lower limit
- Scenario for comparison: using Run 2 systematic uncertainties (S1)
  - In all cases uncertainties due to the finite number of simulated events are neglected

Example:
Jet systematics uncertainties expected at HL-LHC

Uncertainity component	Percentage Uncertainty (Baseline Estimate)	Percentage Uncertainty (Optimistic Estimate)
Absolute JES scale	1% - 2%	1% - 2%
Pileup	0 - 4%	0 - 2%
JET flavour composition	0 - 1%	0 - 0.5%
JET flavour response	0 - 1.5%	0 - 0.8%

Higgs couplings: single channels

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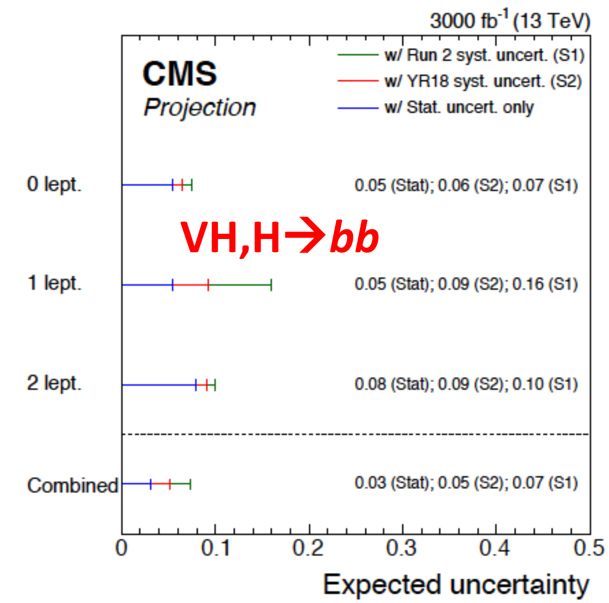
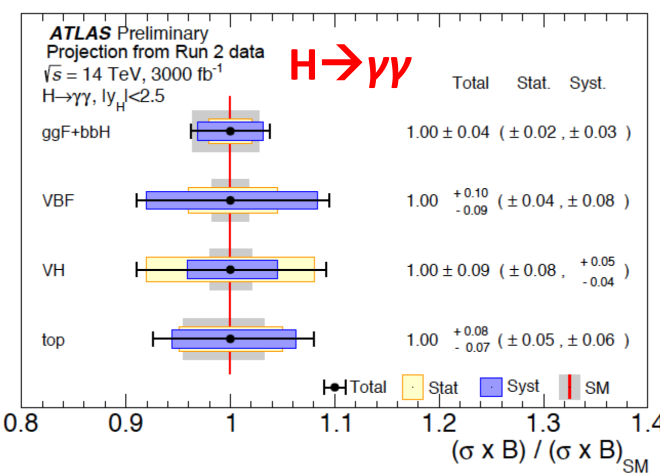
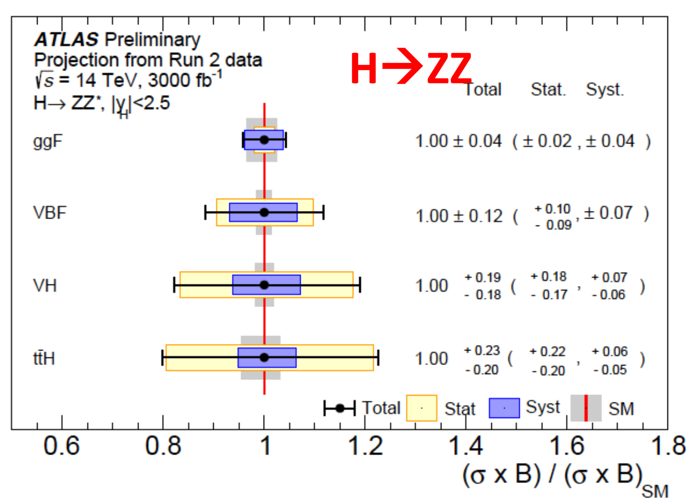
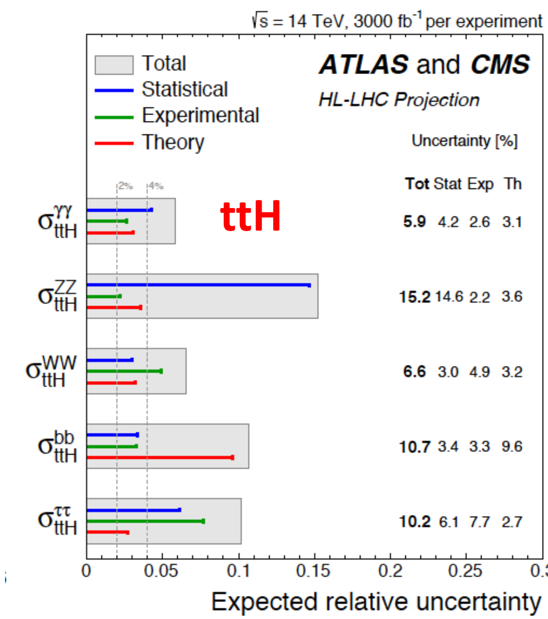
- Projection of combined measurements of Higgs boson couplings using data collected in Run2
  - main production: **ggF, VBF, VH, *ttH***
  - decay modes: ***γγ, ZZ, WW, bb, ττ, μμ, Zγ***
- Most channels dominated by **systematic uncertainties**:
  - exception: *ttH, H→γγ, ZZ* and *VH, H→ZZ, γγ*
- **Rare H→μμ** decay mode expected to be **observed**
  - and precisely measured!
- **Expected evidence** for rare **H→Zγ** decay

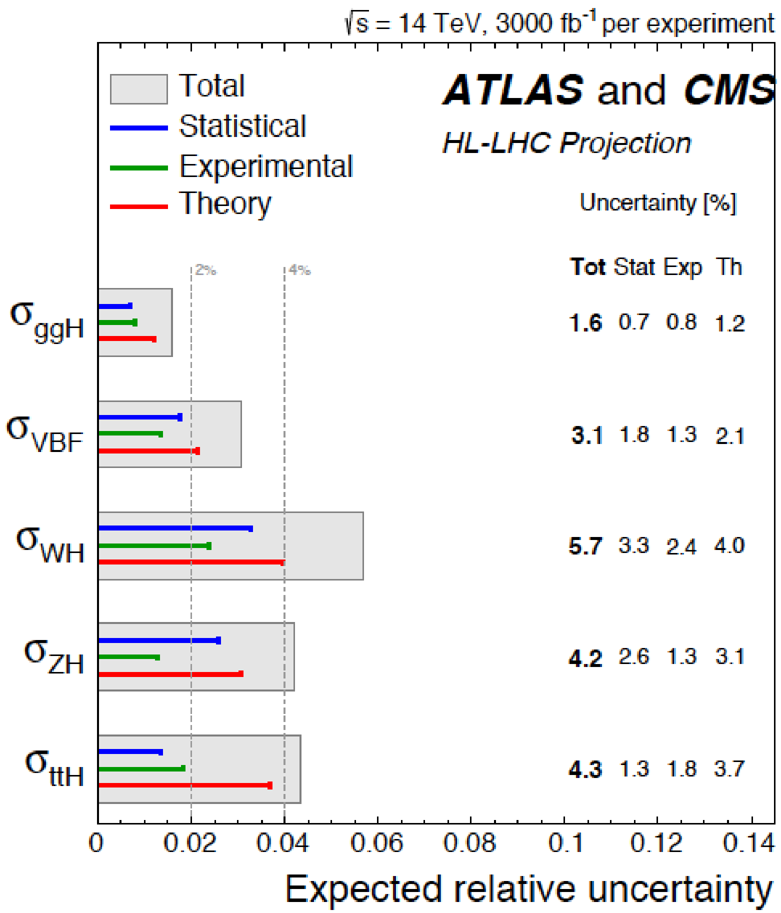


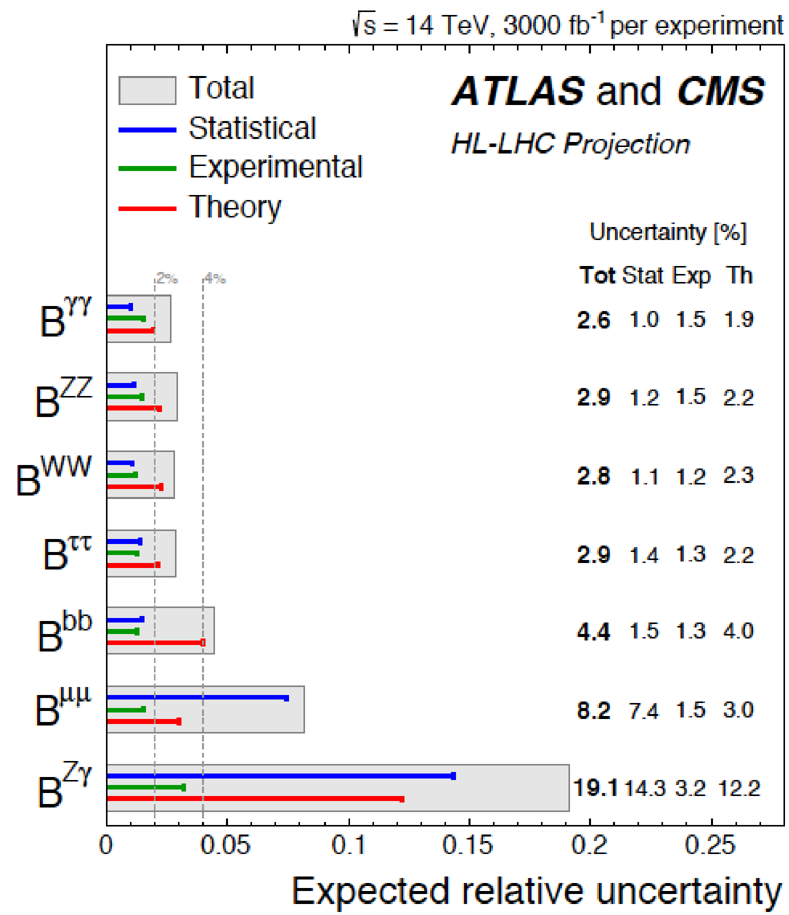






Combined Higgs cross section and BR measurements





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- **BR H→μμ** and **BR H→Zγ** statistically limited
- Other branching ratios and cross sections dominated by **theoretical** uncertainties

Combined Higgs coupling measurements

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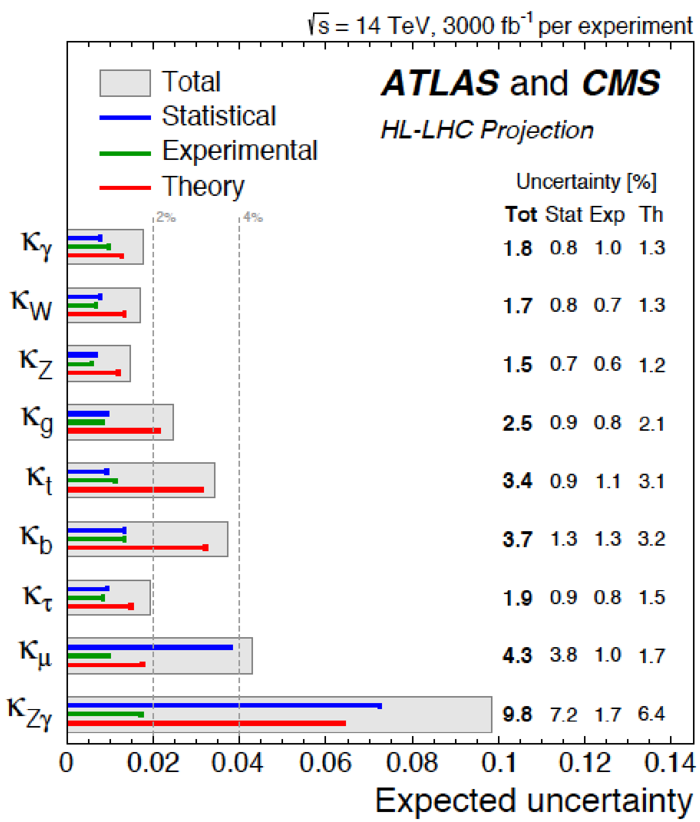
Coupling modifiers for production process or decay mode j

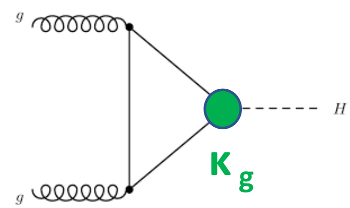
$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}.$$

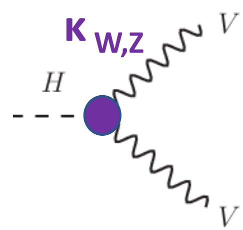
Ratio of coupling modifiers

$$\lambda_{ij} = \kappa_i/\kappa_j$$

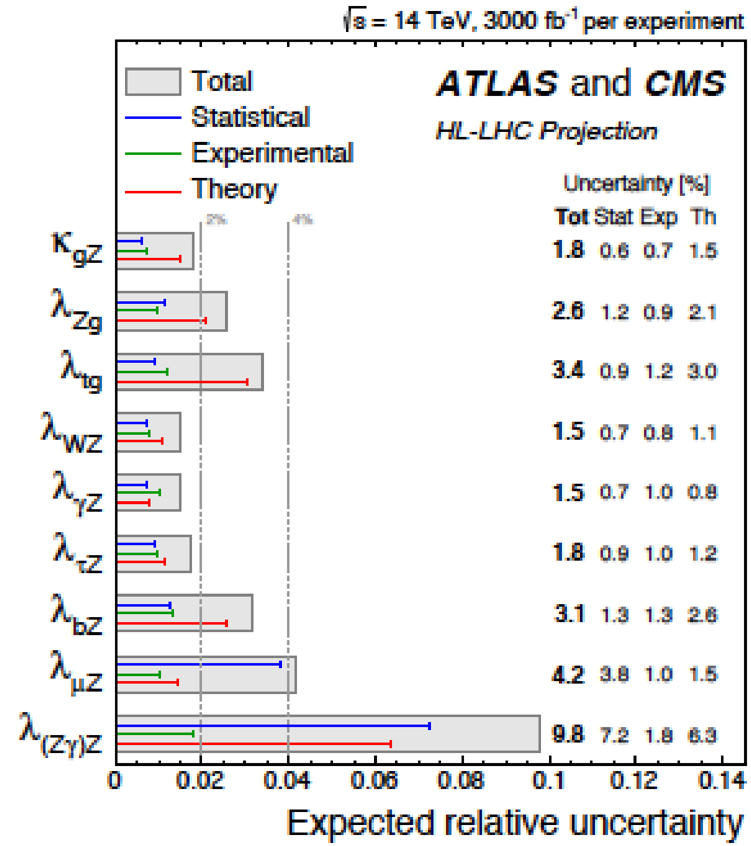


$\sigma_{ggF} = \kappa_g^2\, \sigma_{ggF}(SM)$





$\Gamma_{W,Z} = \kappa^2_{W,Z}\, \Gamma_{W,Z}(SM)$



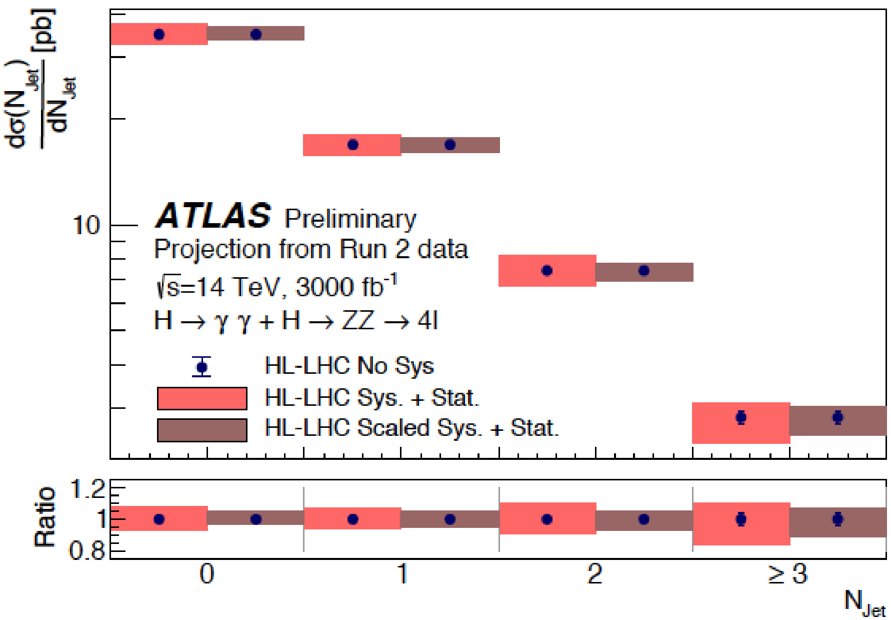
Uncertainties on the κ's **2-5%**, apart from Zγ.
Mostly limited by theoretical uncertainties

- Uncertainties on λ_{ij} **1.5-4%**, a part $\lambda_{Z\gamma Z}$
- $\lambda_{\gamma Z}$ best measured, allows to probe new particles in the H→γγ loop

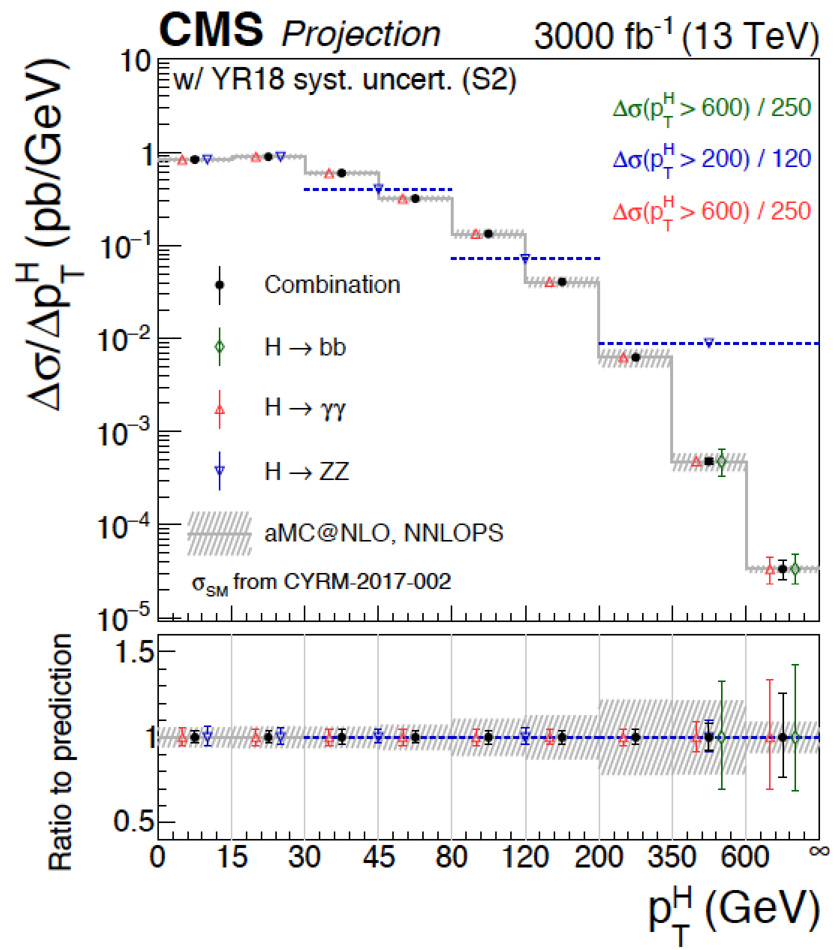
Differential cross sections

Projection of **H→γγ** and **H→ZZ→4l** differential cross sections

Measurement of p_T^H distribution
- probes perturbative QCD calculations
- gives information about (new) particles contributing to the gluon fusion loop
- high p_T^H region sensitive to new physics effects



Precision **5-15%** depending on N_{jet} bin



Precision **~10%** for $p_T^H > 350$ GeV, statistically limited

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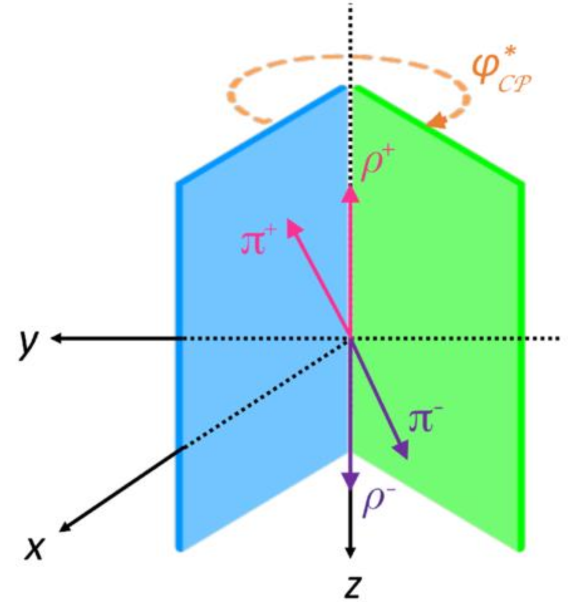
CP nature of the Higgs boson coupling to ττ leptons at HL-LHC

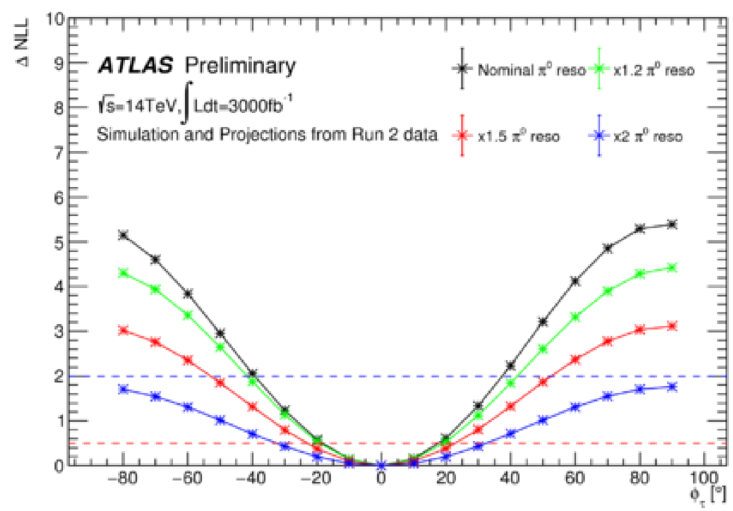
- *SM predictions: Higgs boson is scalar* JCP =0++
- CP state already probed with many diboson couplings
  - CP-odd contributions to the bosonic production/decay strongly suppressed in many BSM models
- **Fermonic** decays more sensitive:
  - CP-odd contributions at the same level as the CP-even ones



$$\mathcal{L} = g_{\tau\tau}(\cos(\phi_\tau)\overline{\tau}\tau + \sin(\phi_\tau)\overline{\tau}i\gamma_5\tau)h,$$

SM: $\phi_\tau = 0$
maximal CPV: ϕ_τ=90

- **Strategy**: **Use $\tau \rightarrow \rho\nu \rightarrow \pi^{\pm}\pi^{0}\nu$** decay
  - measurement of acoplanarity angle between charged and neutral π
  - Sensitive to ϕ_τ
  - Use substructure τ information
- **Results at HL-LHC**:
  - $\Delta\ \phi_\tau$ = ±18% (± 33%) with Run2 (twice worse Run2) π^0 energy resolution
  - Pseudoscalar hypothesis excluded even with 1.5 π^0 resolution



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Higgs Boson width

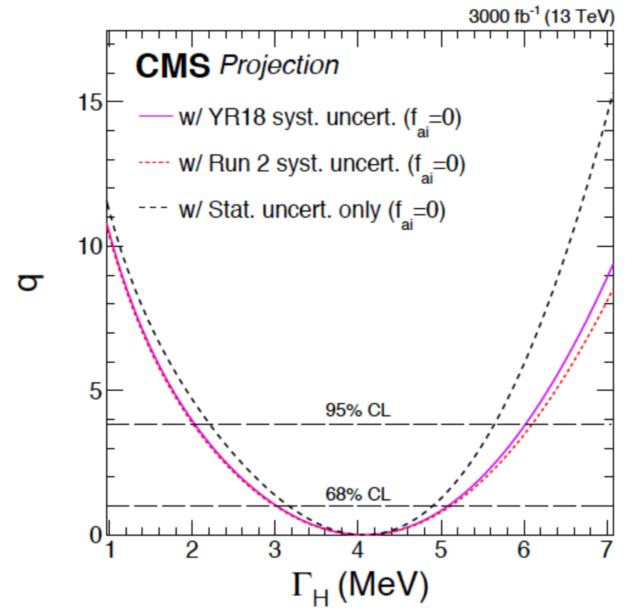
- SM expectation Γ_H = 4 MeV
- At hadron collides, direct measurement via invariant mass of products is **challenging**
  - Detector resolution limits precision to ~ 1 GeV

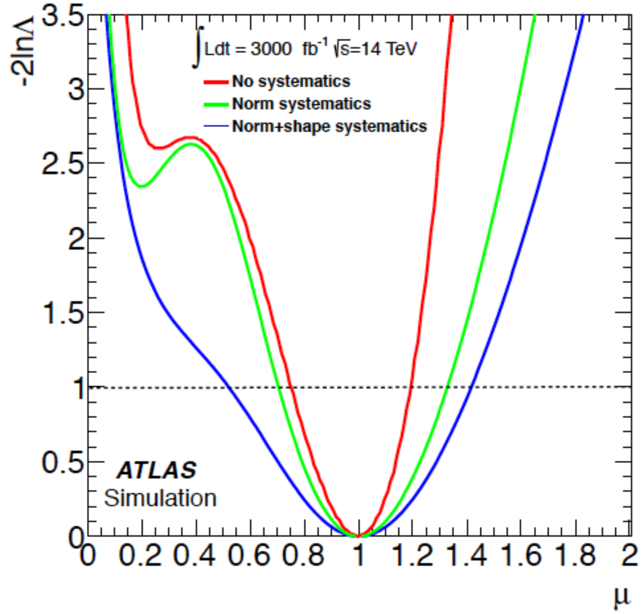
- **Strategy**: Comparison of **on- and off-shell rates** in H➔ZZ➔4l can constrain the Higgs boson width
  - Assumption: same on shell and off-shell couplings

- Current constraints using Run1+Run2 data:
  Γ < 14.4 MeV (ATLAS), Γ < 9.2 MeV (CMS)

- Projection to 3ab^{-1}:$\mathbf{4.1^{+1.0}_{-1.1}}$ ($^{+1.5}_{-2.1}$) MeV for CMS (ATLAS)
  - ATLAS projection of Run 1 analysis, larger theoretical uncertainties than in CMS projection

- Combined constraint $\mathbf{4.1^{+0.7}_{-0.8}}$ MeV assuming CMS sensitivity





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Higgs Boson mass

- Current ATLAS+CMS: m_H = 125.18 ± 0.16 GeV pdg 2018
  - Using H → ZZ* → 4l and H → $\gamma\gamma$
  - H→$\gamma\gamma$ limited by uncertainty on photon energy scale

- Detailed studies for the muons, electrons and photons calibration at HL-HC not yet done
- Precision of **10-20 MeV plausible**

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- ATLAS extrapolation from Run2 m_H = 124.79 ± 0.36 (stat.) ± 0.05 (syst.) GeV, assuming:
  - improvement in **μ momentum resolution** from the new inner tracker
  - Improvement in uncertainty in **μ momentum scale**

	Δ_{tot} (MeV)	Δ_{stat} (MeV)	Δ_{syst} (MeV)
Current Detector	52	39	35
μ momentum resolution improvement by 30% or similar	47	30	37
μ momentum resolution/scale improvement of 30% / 50%	38	30	24
μ momentum resolution/scale improvement 30% / 80%	33	30	14

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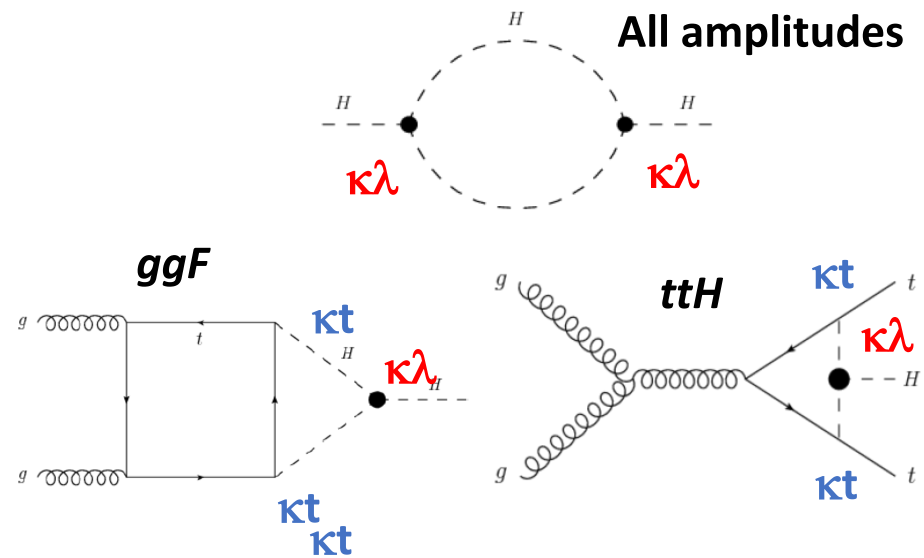
Differential cross sections: probing Higgs-self coupling

- Single-Higgs production depends on self coupling via one-loop corrections
- **Corrections** to the tree-level cross-sections depend on:
  - production mode → mainly **ttH**, tH, VH
  - kinematics properties of the event



- Study on **ttH(→γγ)** differential cross-section measurement:
  - At 95% CL: **$-4.1<\kappa_\lambda<14.1$** if only κ_λ varied

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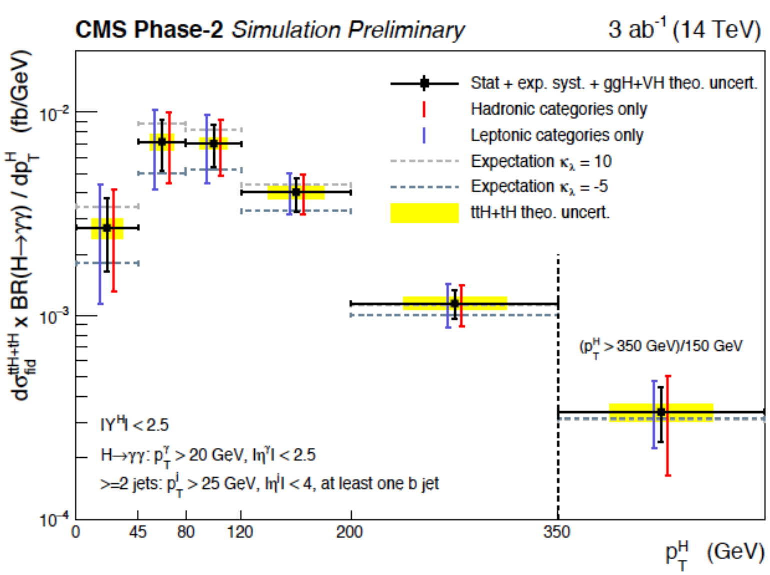
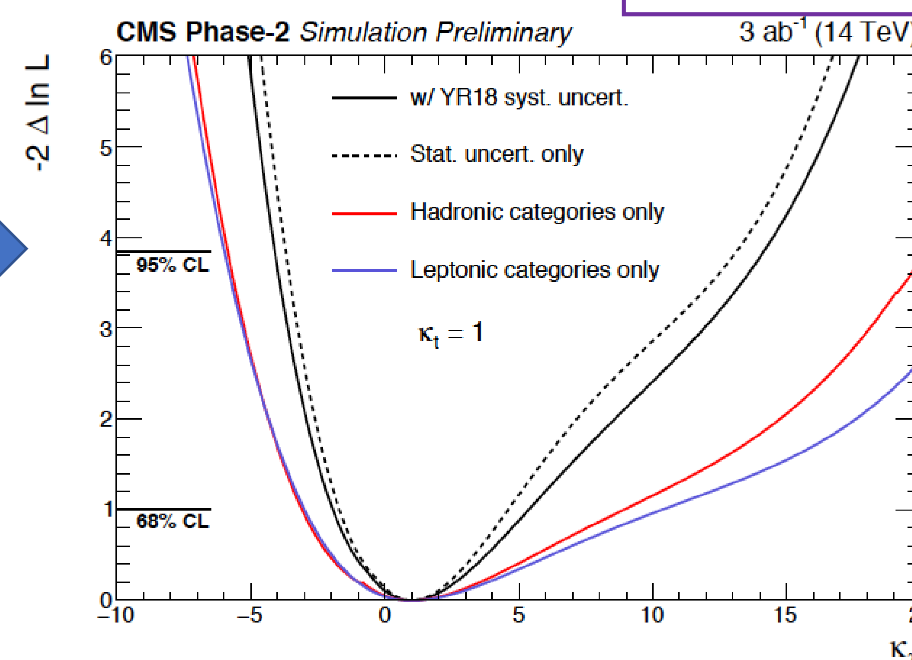
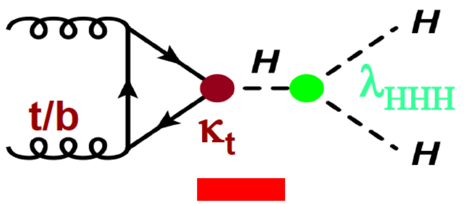


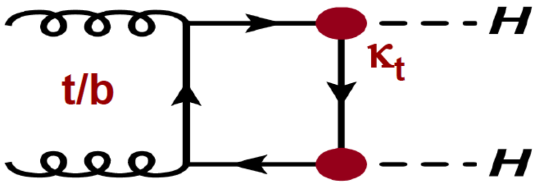


Higgs-self coupling

- Motivation for **Higgs-selfcoupling λ**
  - Shape of Higgs potential
  - Probe EW Symmetry Breaking mechanism
  - Probe new physics

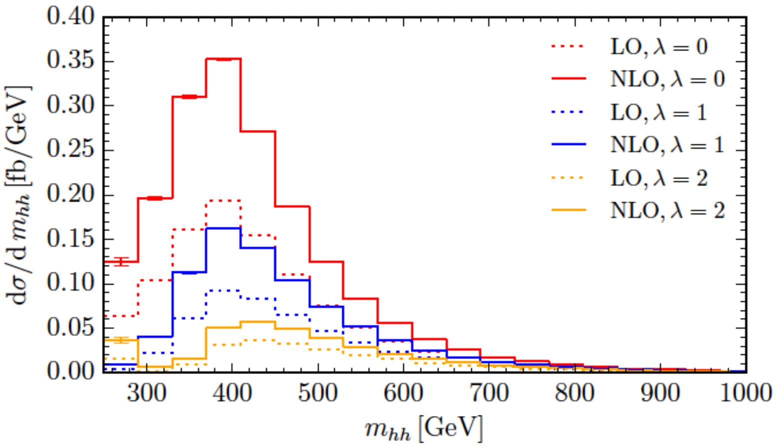
Triangle diagram





Box diagram

- **Non-resonant HH production** sensitive to λ:
  - **rare** process of the SM: σ(gg→HH) ≈ 0.1%*σ(gg→H)
    - destructive interference between box and triangle diagram
  - Strong dependence of inclusive cross section and m_{hh} shape on λ



- **SM prediction**:
  - ggF: NNLO calculation with finite m_t effects at NLO
  - -8% wrt YR4, used in previous projections

$\sqrt{s}$ [TeV]	$\mathrm{NNLO_{FTa}}$ [fb]	m_t unc.	PDF unc.	α_S unc.	PDF+α_S unc.
14	$36.69^{+2.1\%}_{-4.9\%}$	±2.7%	±2.1%	±2.1%	±3.0%

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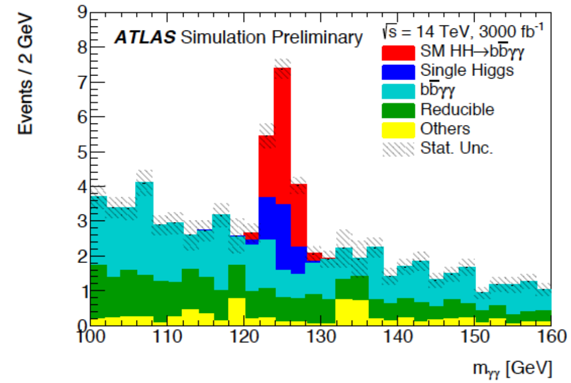
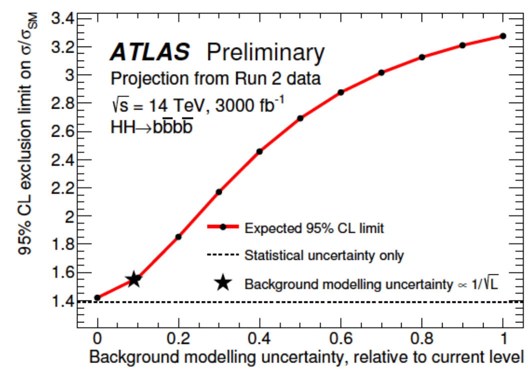
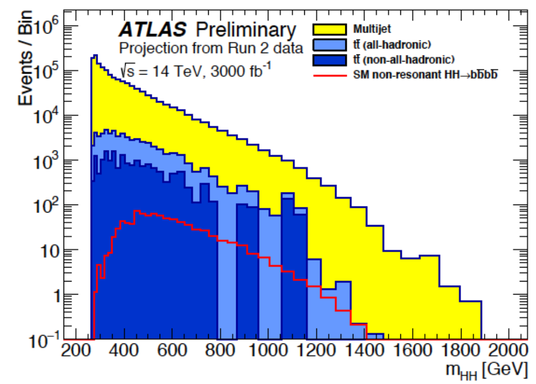
Higgs-self coupling: input channels

- **HH→bbγγ:**
  - Small BR: 291 events with 3ab $^{-1}$
  - Low bkg
  - Photon resolution critical

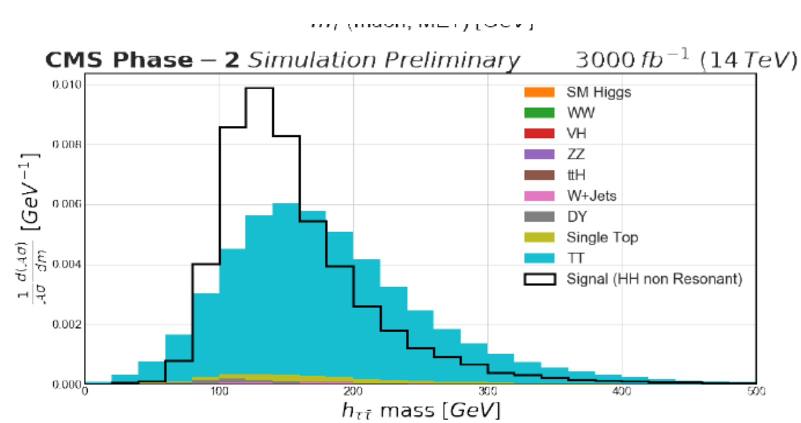


- **HH→4b:**
  - Large BR: ~37k events with 3ab^{-1}
  - Large QCD bkg
  - Large dependence on background modelling uncertainty





- **HH→bbττ:**
  - Sizeable BR: ~8k events with 3ab $^{-1}$
  - Relatively low background
  - Incomplete reconstruction of the event due to the presence of neutrinos
    → Challenging separation from tt and Drell-Yan bkg



- **HH→bbVV (llνν), HH→bbZZ(ll)** projections by CMS only

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HH production and Higgs-self coupling

- Expected **significance** of HH production with(without) systematics at HL-LHC
  - **4σ (4.5σ) expected with ATLAS+CMS !**

	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	

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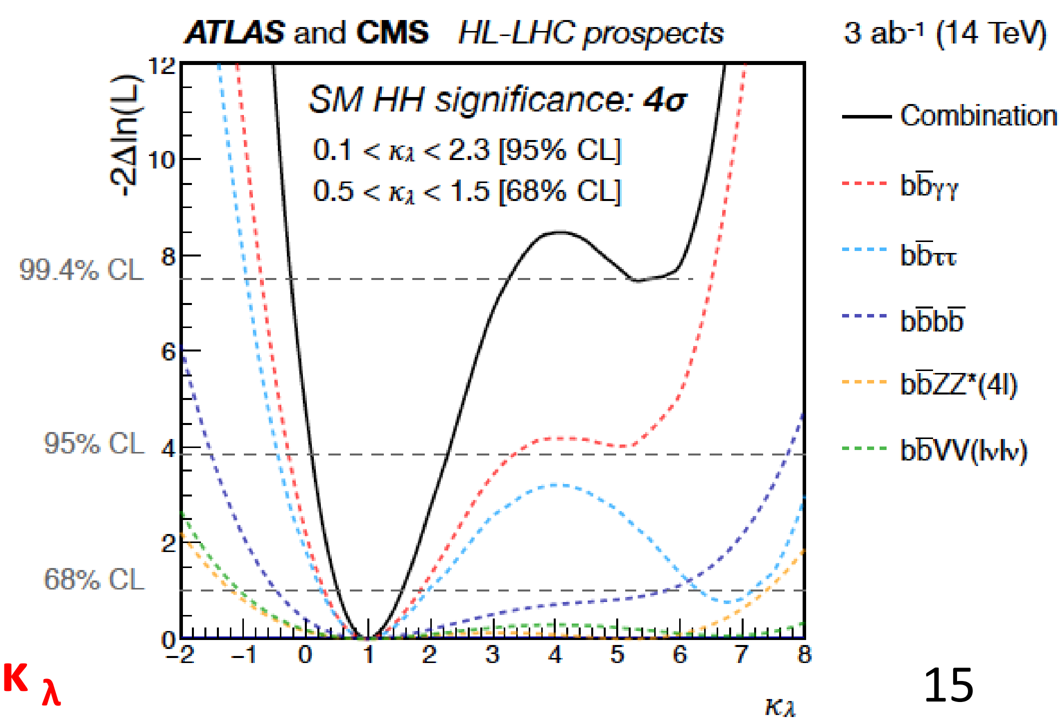
- Measurement of **μ** (SM signal injected):
  - ~**30%** (25%) with (without) systematics



- Measurement of **κ_λ:**
  - **$0.52(0.57) < \kappa_\lambda < 1.5$** without/with systematics
  - 2^{nd} minimum is excluded at 99% thanks to m_{HH} shape information
- Not all channels optimized to measure **κ_λ**

Higgs coupling to light quarks

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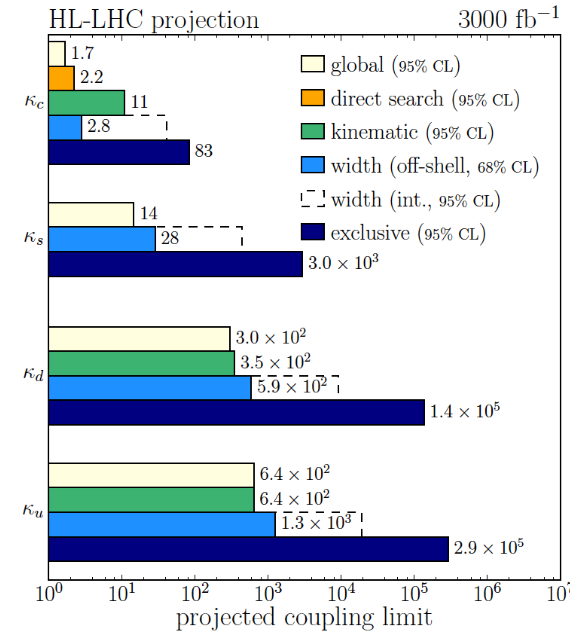
- Yukawa couplings of the Higgs boson to the **first and second generation quarks**
  - Run2: only upper limits
  - **Challenging**: Small BR, large hadronic bkg, c-jet tagging
- Indirect measurements:
  - direct global fits, diff. cross section, width



- **Inclusive searches**: VH, H→cc. SM BR H→cc = 2.9 %
  - HL-LHC projection: σ(pp → ZH) × B(H → cc) < 6.3 SM
  - **Exclusive searches**: H → J/ψγ
  - SM prediction: BR($H \to J/\psi\ \gamma$) ~3 × 10^{-6}
  - HL-LHC projection: σ(pp → H) × B(H → J/ψ γ) < 14 SM

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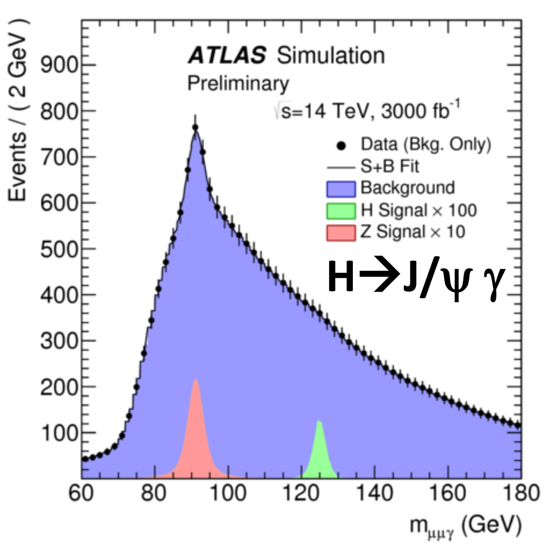
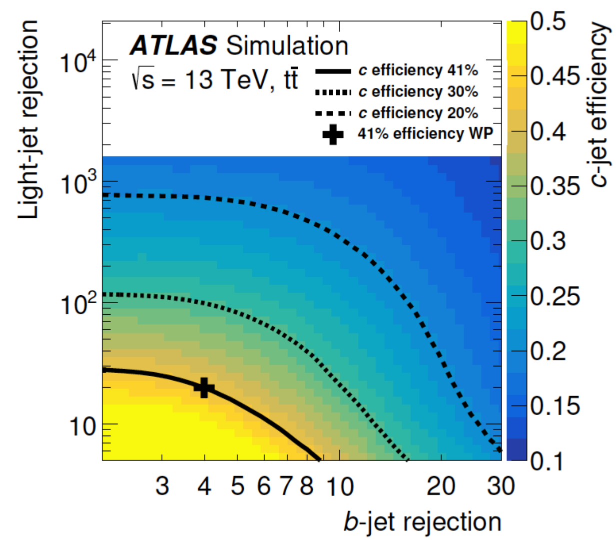


PhysRevLett.120.211802



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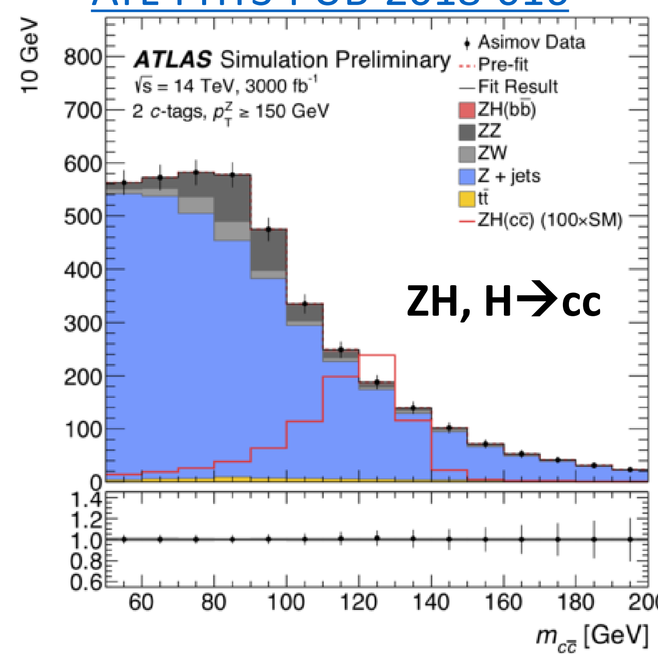
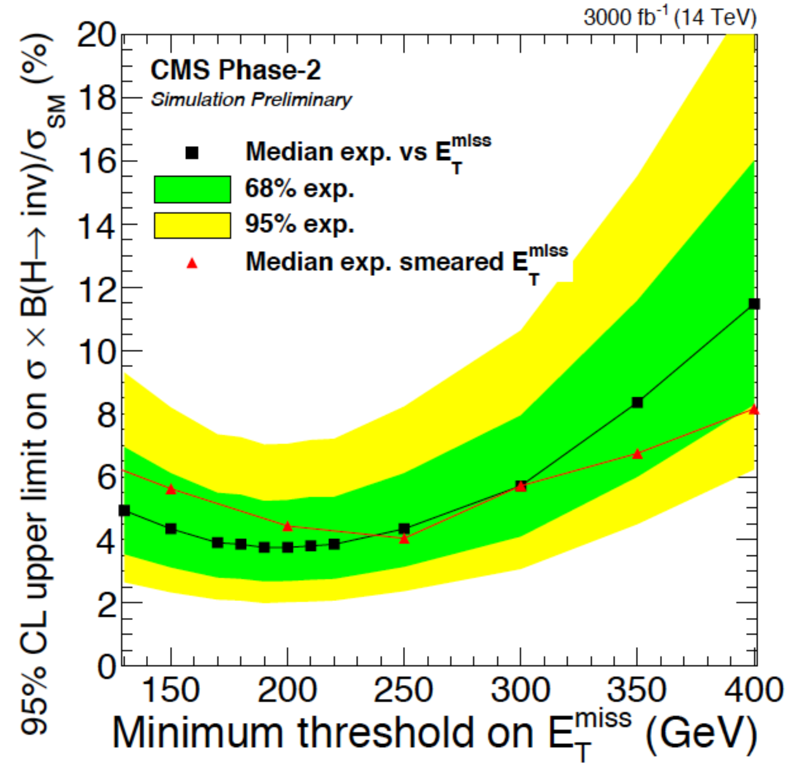
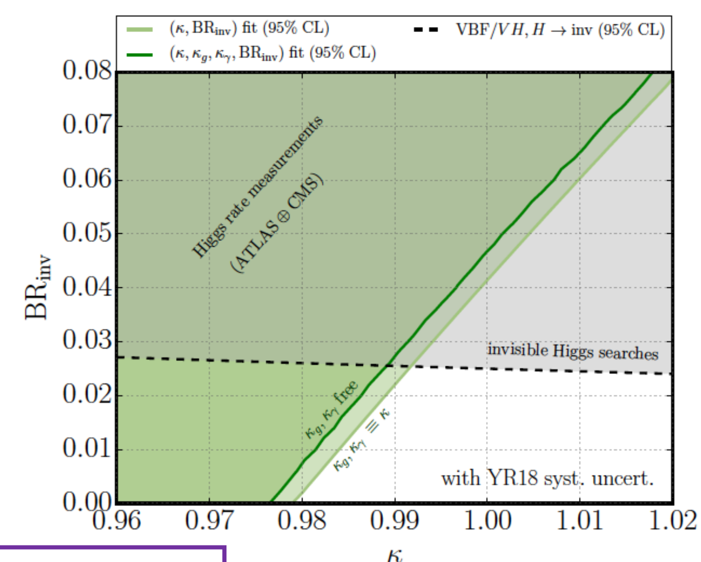


Higgs to invisible decays

- SM BR H→invisible = 0.1 %
- Run2: BR_{inv} < 26 (22%) obs., exp 17(17)% for ATLAS(CMS)
- Experimentally **challenging: pile-up** effects degradation in E_T^{miss}, tagging of VBF jets
- **VBF** channel most sensitive
- At HL-LHC (CMS) **B_{inv} < 3.8%** at 95% CL
  - Limited by syst. exp. uncertainties
  - Degradation of E_T^{miss} resolution does not impact the sensitivity significantly
- Assuming same sensitivity of experiments for VH and VBF, and using ATLAS projection with VH:
  - **B_{inv} < 2.5%** at 95% CL
- Using Higgs rate measurements, and assuming universal Higgs couplings modifiers:
  - **BR_{inv} (κ==1) < 4.2%**





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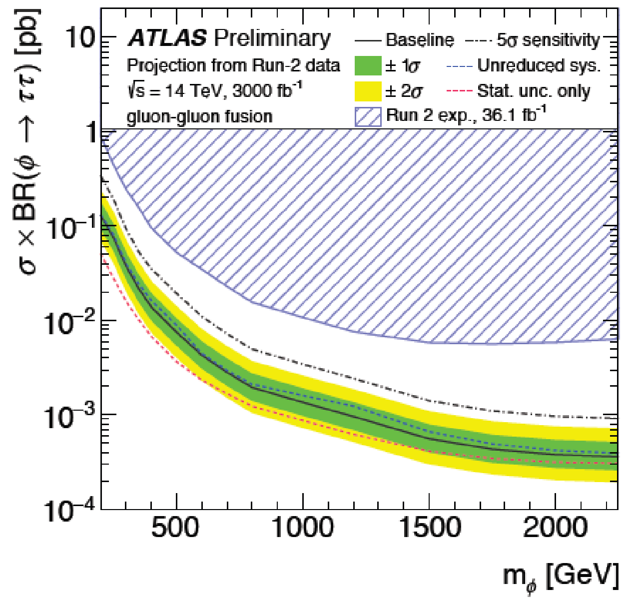
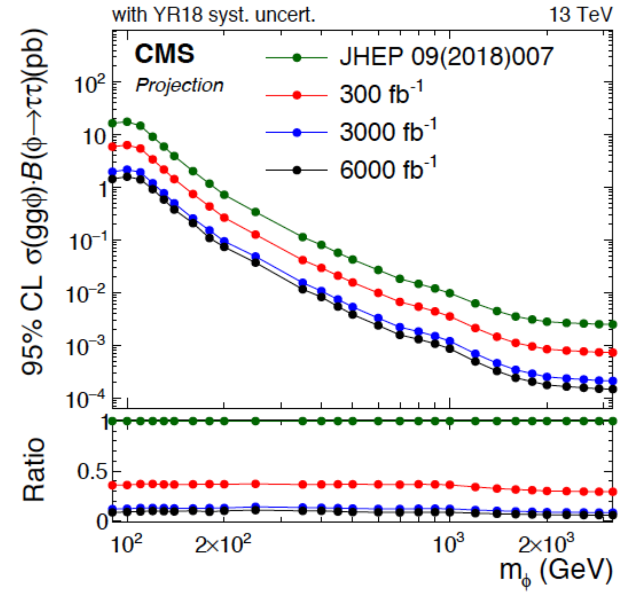
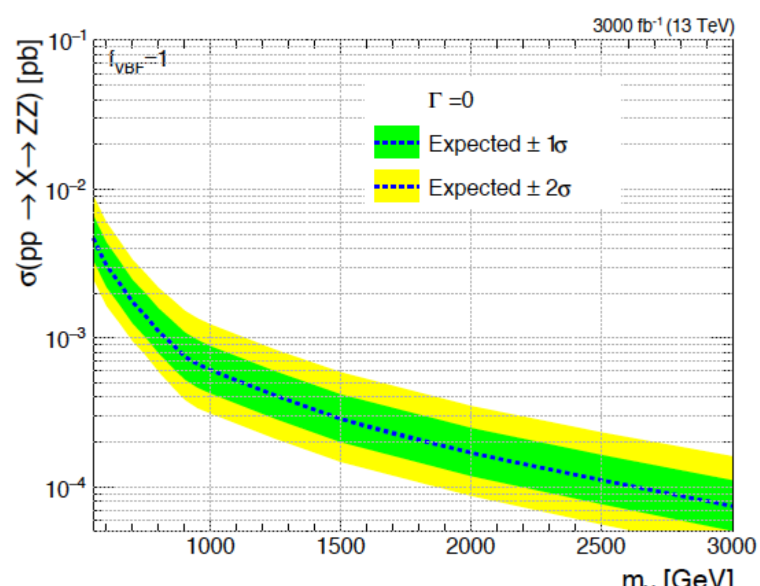
Searches for additional heavy Higgs states

- Search for **$\phi \rightarrow \tau\tau$ decay**
- MSSM benchmark mode
  - Coupling to down-type quark enhanced
- With 3 ab^{-1} **large limit improvement** wrt to Run2
  - Especially at high mass
- Significant impact of systemat
  - Dominated by fake τ and high p_T τ reco+ID





- Search for **$X \rightarrow ZZ$ decay**
- With 3 ab^{-1} **X 10 limit improvement** wrt Run2 for m_X > 1TeV
- At HL-LHC still statistically limited



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Anomalous HVV couplings

Amplitude describing the interaction of a **spin-0** particle and and **two spin-one gauge** bosons

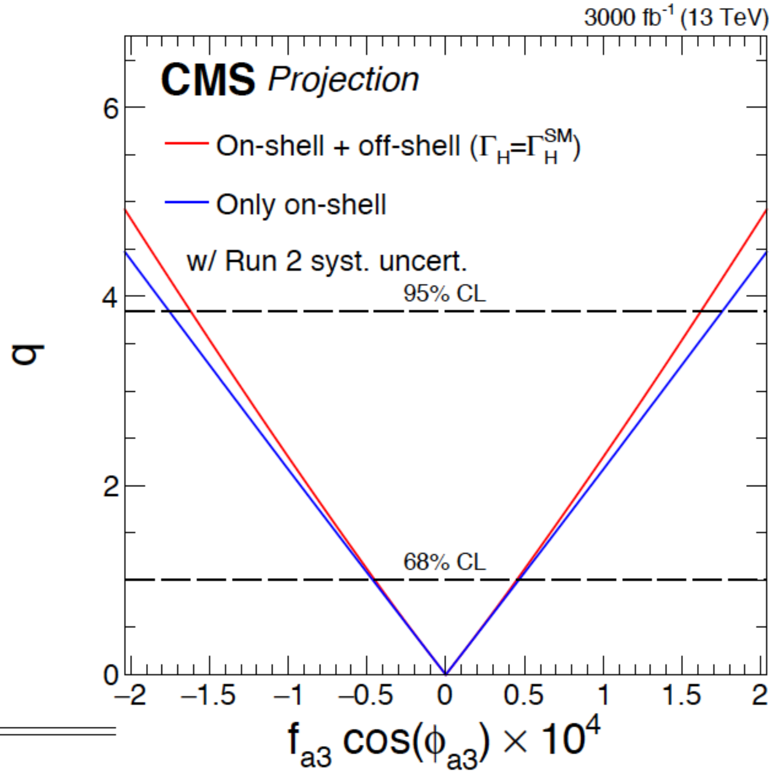
$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V}1}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V}2}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}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

- *Coupling* $a1$($a2$) describe the tree-level(loop-induced) interaction of a CP even scalar
- *Coupling* ***a3*** describes the interactions of **a CP odd scalar**, SM a3 = 0
- Λ is scale of NP

Fit fractional contribution to on-shell H → ZZ

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

Parameter	Scenario	Projected 95% CL interval
$f_{a3}\cos(\phi_{a3})$	Only on-shell	$[-1.8, 1.8] \times 10^{-4}$
$f_{a3}\cos(\phi_{a3})$	On-shell and off-shell	$[-1.6, 1.6] \times 10^{-4}$



Run1+Run2 1901.00174.pdf

Parameter	Scenario	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	on-shell	$-0.0001^{+0.0004}_{-0.0015}$ $[-0.163, 0.090]$	$0.0000^{+0.0019}_{-0.0019}$ $[-0.082, 0.082]$
	any Γ_{H}	$0.0000^{+0.0003}_{-0.0010}$ $[-0.0165, 0.0087]$	$0.0000^{+0.0015}_{-0.0015}$ $[-0.038, 0.038]$
	$\Gamma_{\mathrm{H}} = \Gamma_{\mathrm{H}}^{\mathrm{SM}}$	$0.0000^{+0.0003}_{-0.0009}$ $[-0.0067, 0.0050]$	$0.0000^{+0.0014}_{-0.0014}$ $[-0.0098, 0.0098]$

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Large improvements on limits at HL-LHC

Conclusions

The precise determination of Higgs boson properties, and their connection to electroweak symmetry breaking is a primary target of the HL-LHC physics program

What we expect:

- main Higgs boson **couplings** at the **percent level**
- **Rare** $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$ decays **visible**
- **HH** production: sensitivity of 4σ
- …

To reach this goal, need to

- reach the expected **reduction** of **experimental** and **theoretical** uncertainties
- face challenging experimental conditions with **unprecedented pileup** levels
- build **new detectors**

→ Hard and exciting work for the next ~15 years !

Backup

Spin and parity

Amplitude describing the interaction of a spin-0 particle and and two spin-one gauge bosons

$$A(X_{J=0} \to VV) = v^{-1}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3 f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

- *Coupling g*1(*g*2) describe the tree-level(loop-induced) interaction of a CP even scalar
- *Coupling g*4 describes the interactions of a CP odd scalar
- *Coupling g3* can be absorbed into *g2*
- SM prediction, CP-conserving tree-level interaction:*g1* >0 and $g_{2,3,4}$ =0.

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Parametrization:

$$f_{g_i} = \frac{|g_i|^2\sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}; \quad \phi_{g_i} =$$

f_{g4} < 0.037 and f_{g2} < 0.12
at 95% CL for 3000 fb^{-1}

Sensitive test of the tensor structure of
→*ZZ** couplings a the high luminosity LH