Projected sensitivity of Higgs boson pair production combining the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ decay channels at the HL-LHC with the ATLAS detector

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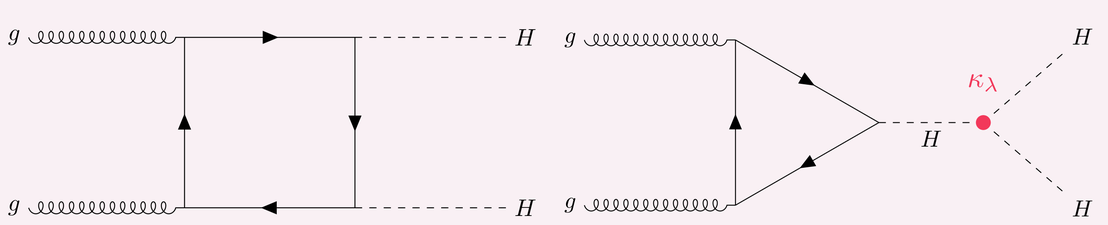
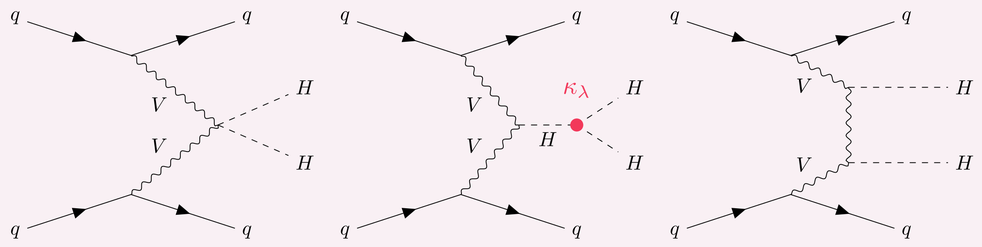
Introduction

The Higgs boson pair production

- The **Higgs self-couplings** are a major property of the Higgs boson that is still largely unconstrained. They determine the **shape of the Higgs potential** which has important physics implications such as the stability of the Universe.
- In particular, the trilinear Higgs self-coupling can be directly accessed through the **Higgs pair production** (HH) process. **Modification** of the **coupling strength** ($\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM} \neq 1$) may indicate **new physics**.



gluon–gluon fusion (ggF)
$\sigma_{HH}^{ggF} = 31.05$ (13 TeV), 36.69 (14 TeV)



vector boson fusion (VBF)
$\sigma_{HH}^{VBF} = 1.726$ (13 TeV), 2.055 (14 TeV)

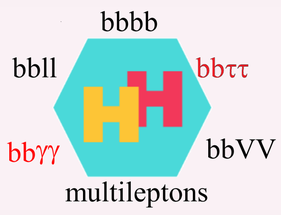
- The **Standard Model (SM) HH production** is an **extremely rare** process ($\sigma_{HH} \approx 32.8$ fb), with only ~4000 events in LHC Run 2.

The High Luminosity LHC

- The **High Luminosity LHC (HL-LHC)** project plans to increase the peak luminosity of pp collisions by a factor of five with respect to Run 2 of the LHC, and ultimately to **deliver 3000 fb^{-1} of integrated luminosity at $\sqrt{s}$ =14 TeV**.
- Finding **evidence for HH production is feasible at the HL-LHC**, which is expected to produce ~100,000 events .

Combination input analyses

- The $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ analyses have released new HL-LHC projection results assessed through **extrapolations of the full LHC Run 2 dataset**.
- Statistically independent decay channels are combined to maximize sensitivity of HH searches.
  (Ref Projection: ATL-PHYS-PUB-2022-005)



- $b\bar{b}\gamma\gamma$: Small branching ratio, but clean diphoton signature for triggering and signal extraction.
  (Ref Run2: ANA-HDBS-2018-34-PAPER)
  (Ref Projection: ATL-PHYS-PUB-2022-001)
- $b\bar{b}\tau^+\tau^-$: Higher production rate than $b\bar{b}\gamma\gamma$. However, hadronically decaying tau leptons are hard to disentangle from QCD jets.
  (Ref Run 2: ATLAS-CONF-2021-016)
  (Ref Projection: ATL-PHYS-PUB-2021-044)

Branching Ratio	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

Extrapolation Procedure

- To extrapolate results from Run 2 to HL-LHC, **scale factors** are applied to the **signal and background distributions** to account for
  1. **Luminosity scaling** from 139 fb^{-1} to 3000 fb^{-1} (~x20)
  2. **Increased cross-section** from 13 TeV to 14 TeV (~x1.2).
- In the combination, **uncertainties from common systematic sources are correlated** across channels.
- Systematic uncertainties are **rescaled** to reflect improvements expected at the HL-LHC. In particular, **detector performance is expected to remain similar** but uncertainties on **heavy jet tagging expected to decrease** while **theory systematics are expected to be halved**.
- **Four main uncertainty scenarios** are considered for the combination:
  - No systematic uncertainties
  - **Baseline** : Exp. uncerainties scaled, and theory uncerainties halved
  - Theory uncerainties halved - but with Run 2 exp. uncerainties
  - Run 2 systematic uncerainties

Results

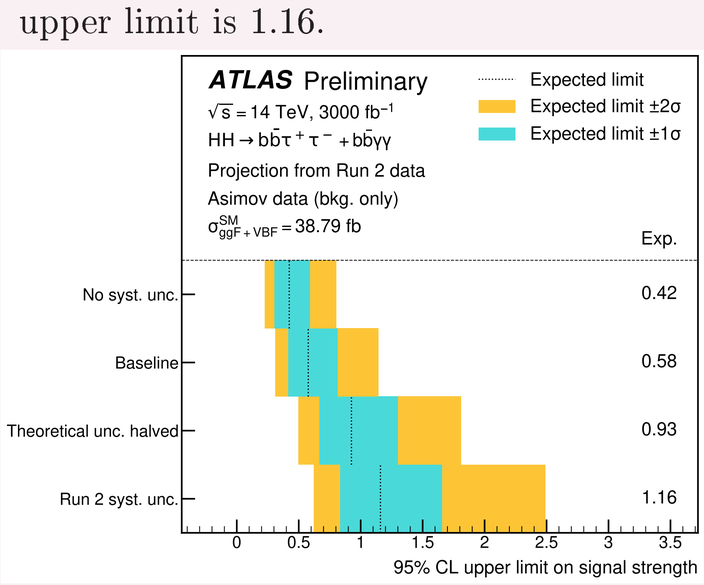
Significance and Signal Strength Measurement

- Expected **HH signal significance** and **precision** on the measured **signal strength** ($\sigma_{HH}/\sigma_{HH}^{SM}$).
- (Baseline scenario) Major sources of systematics include **theoretical uncertainties** on ggF, VBF and W-associated **single Higgs production** and on **HH cross-section**.
- * Previous combination (2018) includes also the $b\bar{b}b\bar{b}$ channel. The gain in $b\bar{b}\tau^+\tau^-$ is mainly from **improved object ID**.

Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Comb.	Measured combined signal strength
No systematic uncertainties	2.3	4.0	4.6	1 ± 0.23
Baseline	2.2	2.8	3.2	1 ± 0.32
Theory uncertainties halved	1.1	1.7	2.0	1 ± 0.50
Run 2 systematic uncertainties	1.1	1.5	1.7	1 ± 0.59
Previous combination (2018)	2.0	2.0	2.9*	1 ± 0.40*

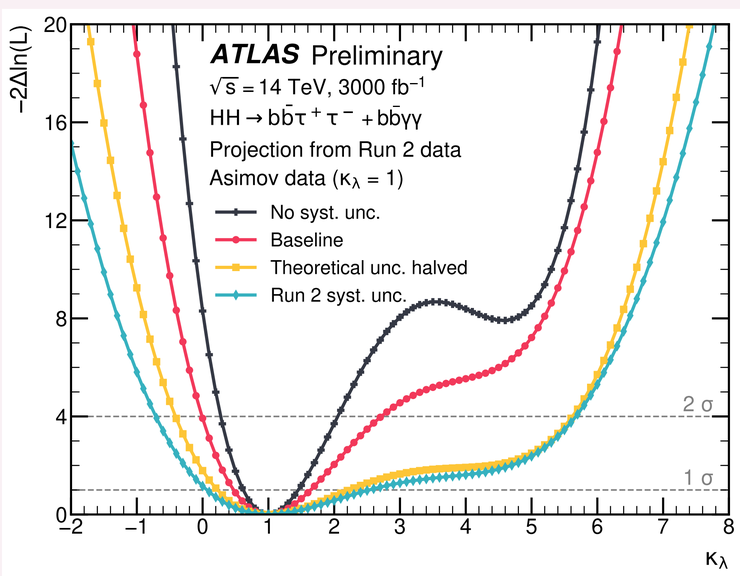
Upper Limit on SM Signal Strength

- 95% CL upper limit on the signal strength under the **background-only hypothesis**.
- SM HH production is expected to be excluded in all considered scenarios, except for the "Run 2 systematics" scenario where the upper limit is 1.16.



κ_λ Likelihood Scan

- Negative log-profile-likelihood ratio as a function of κ_λ under the SM hypothesis.
- (Baseline scenario) κ_λ is constrained to within [0.5, 1.5] ([0.0, 2.7]) at 1σ (2σ) confidence interval.



Significance as a function of κ_λ

- Expected **significance** as a function of the **self-coupling modifier** κ_λ.
- (Baseline scenario) Evidence for HH production (3σ) is expected if $\kappa_\lambda < 1.1$ or $\kappa_\lambda > 4.8$ (pink circles) , while observation (5σ) is expected if $\kappa_\lambda < 0.1$ or $\kappa_\lambda > 5.9$ (blue circles).