中国科学技术大学

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HH prospects at HL-LHC

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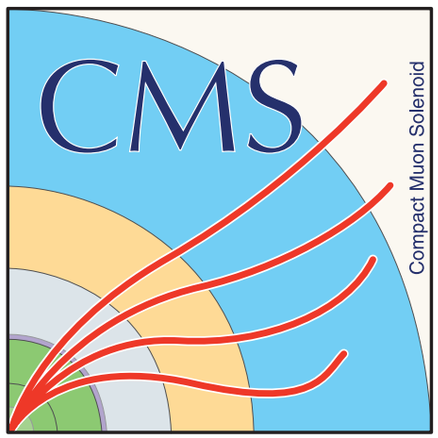
On behalf of ATLAS and CMS collaborations



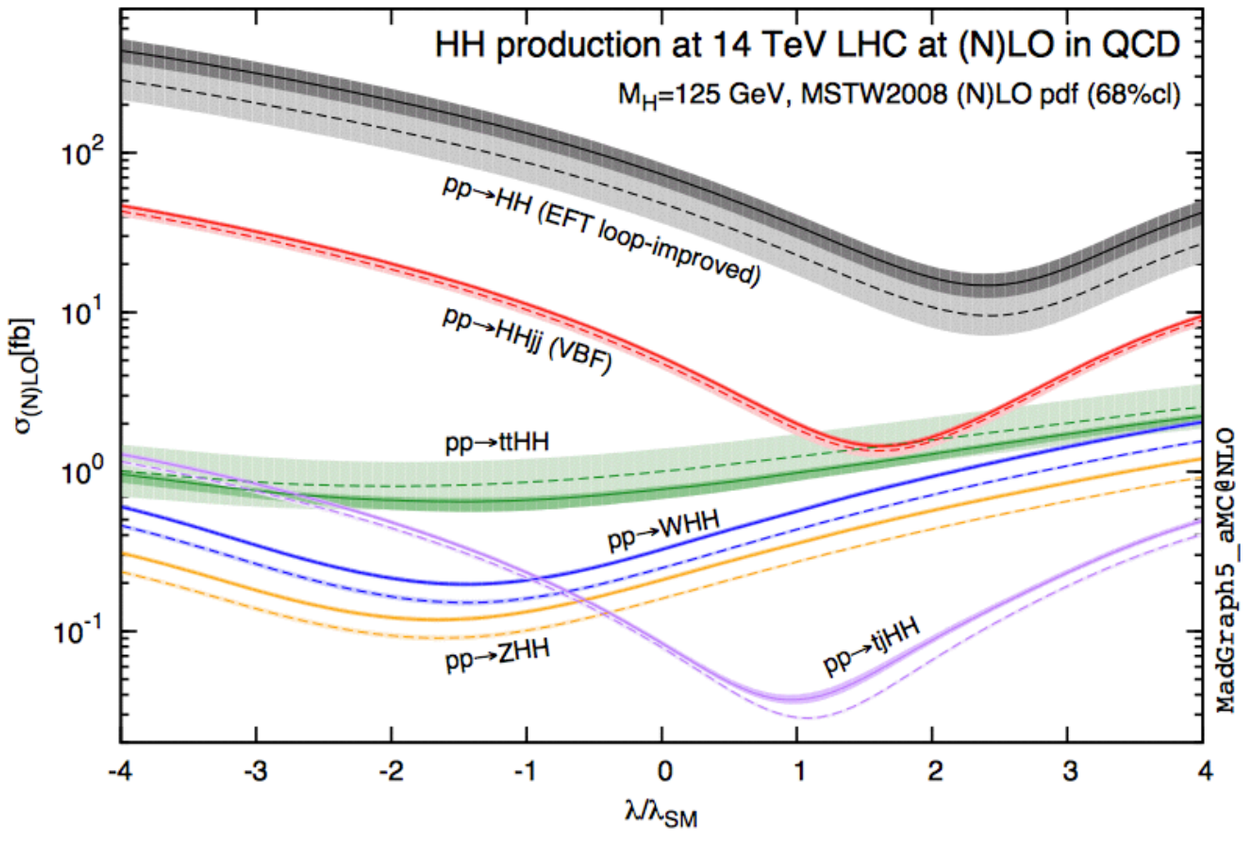
Higgs Pairs Workshop 2022
May 30 - June 03, 2022

Higgs self-coupling

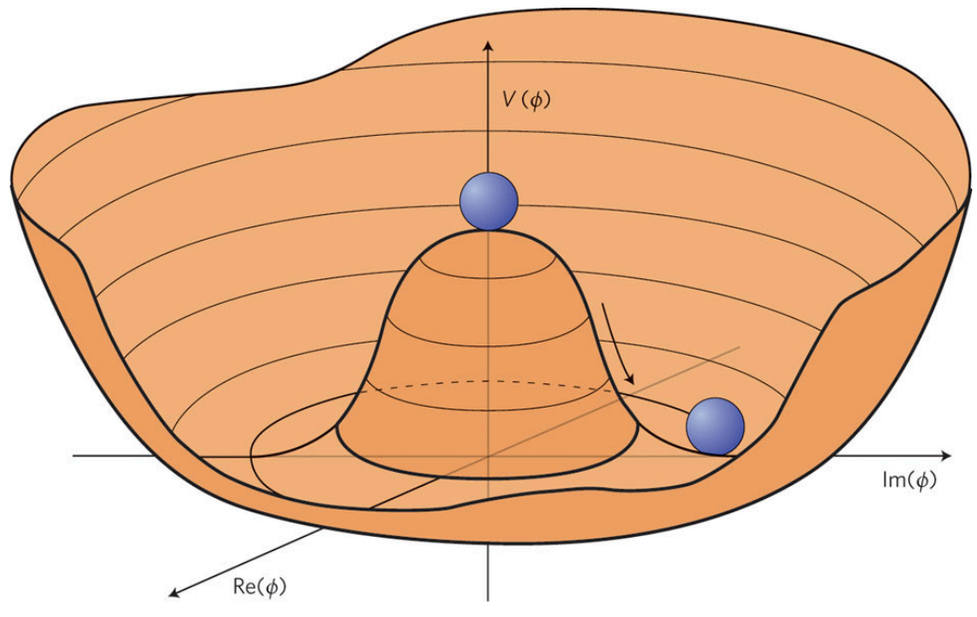
- Higgs self-coupling probes the nature of the Higgs potential:

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$

  - $\lambda_3 = \lambda_4$ in Standard Model
- λ_3 probed directly via HH production, extremely challenging to measure at LHC, accessible at HL-LHC
- Single Higgs measurements also sensitive to λ_3 through NLO EW correction



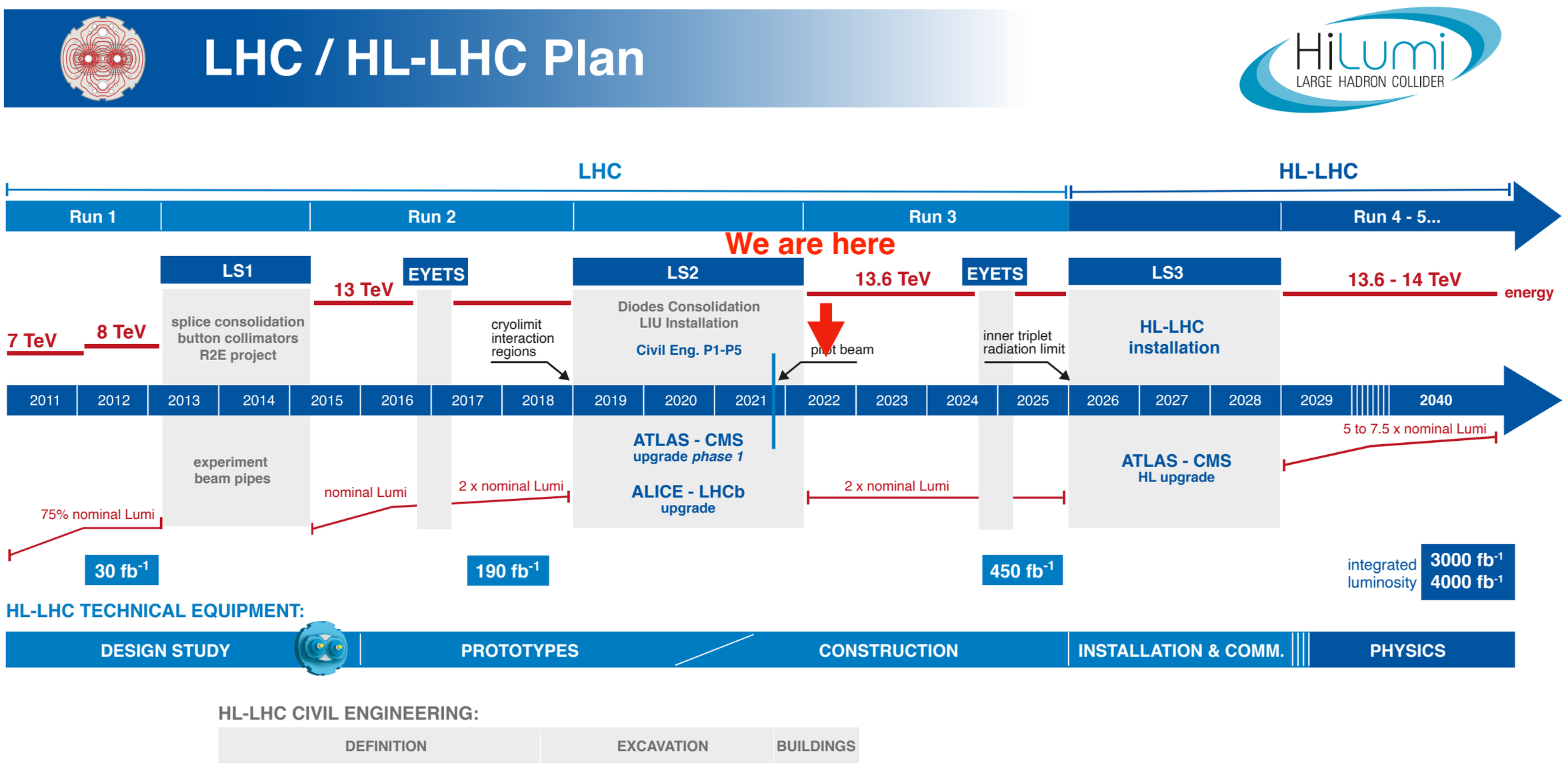
R.Frederix et al: Phys.Lett. B732 (2014) 142-149



Large Hadron Collider Timeline

Physics reach at HL-LHC serves as a preference point for the planning of next generation collider experiments

- about 5% of pp collision data delivered so far at LHC, HL-LHC 3000 fb^{-1} @14 TeV



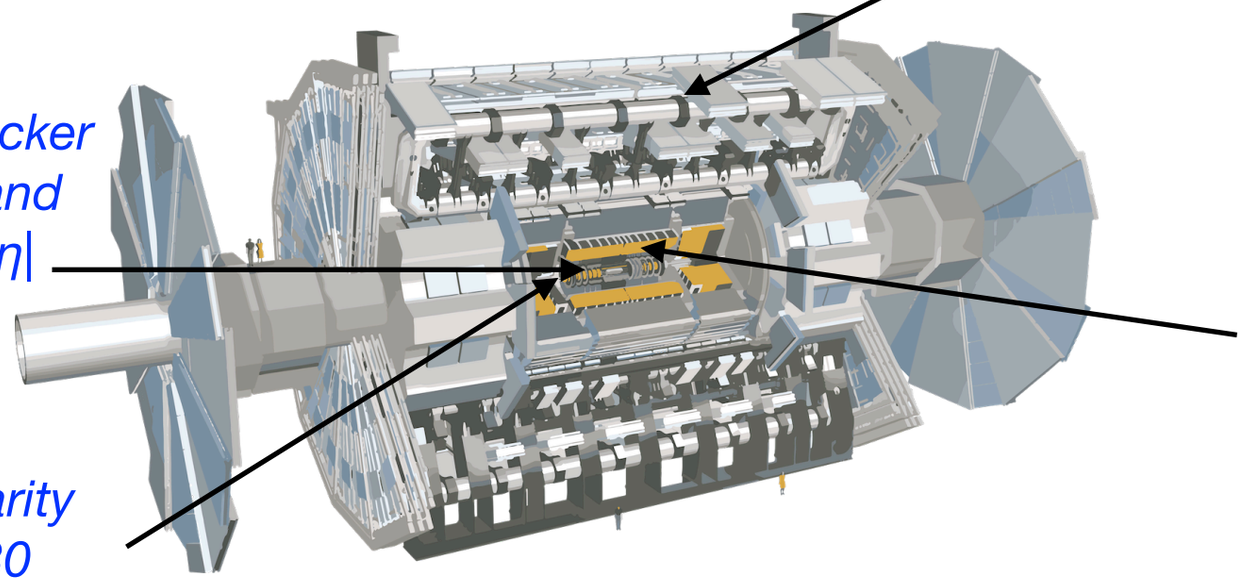
https://hilumilhc.web.cern.ch/content/hl-lhc-project
https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

Highlights of the ATLAS Phase-2 detector upgrade

Upgrade to trigger and DAQ:
L1 rate increased to 1 MHz
High Level trigger rate to 10 kHz

Tracker:
Completely new Inner Tracker (ITk), comprised of Pixel and Strip sub-detectors with $|\eta|$ coverage up to 4

Forward:
New endcap high-granularity timing detector (HGTD): 30 ps/track in $2.4 < |\eta| < 4.0$
upgrades for other detectors



Muon system:
new RPC and sMDT muon detector in the barrel inner region, new sTGC in the endcap inner region

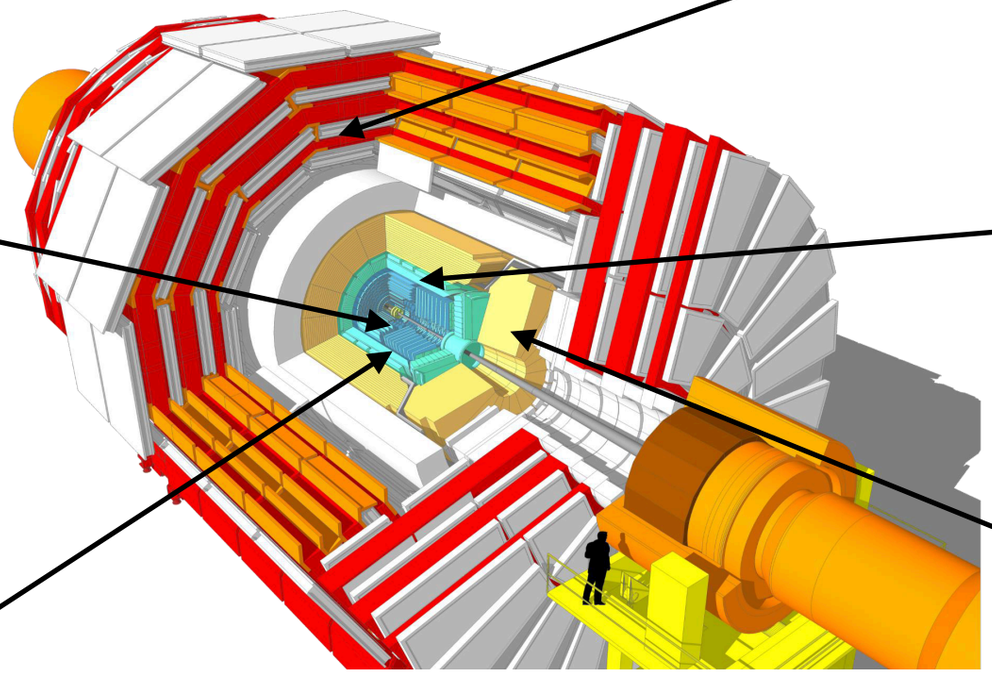
Calorimeter:
Front-end and back-end electronics replacement for 40MHz continuous readout

Highlights of the CMS Phase-2 detector upgrade

Upgrade to trigger and DAQ:
Tracks, particle flow like selection, and machine learning in L1/HLT/DAQ
HLT output 7.5 kHz

Tracker:
All silicon Pixel and strip detectors with increased granularity
extended coverage to η~4
P_T module design for tracking in Level1-Trigger

MIP Timing detector :
30-40 ps time resolution for charged particles up to η~ 3 between tracker and ECAL/CE



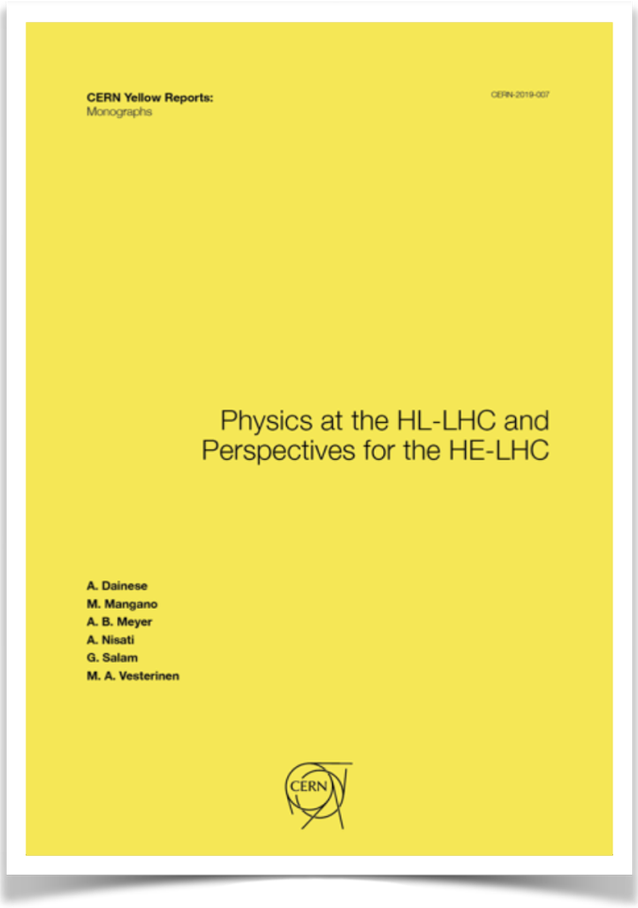
Muon system:
DT&CSC new FE/BE readout, new GEM/RPC
Extended coverage to η~ 2.8

Calorimeter Barrel:
ECAL precision timing for high energy photon/electron > 30 GeV
ECAL/HCAL new back-end boards.

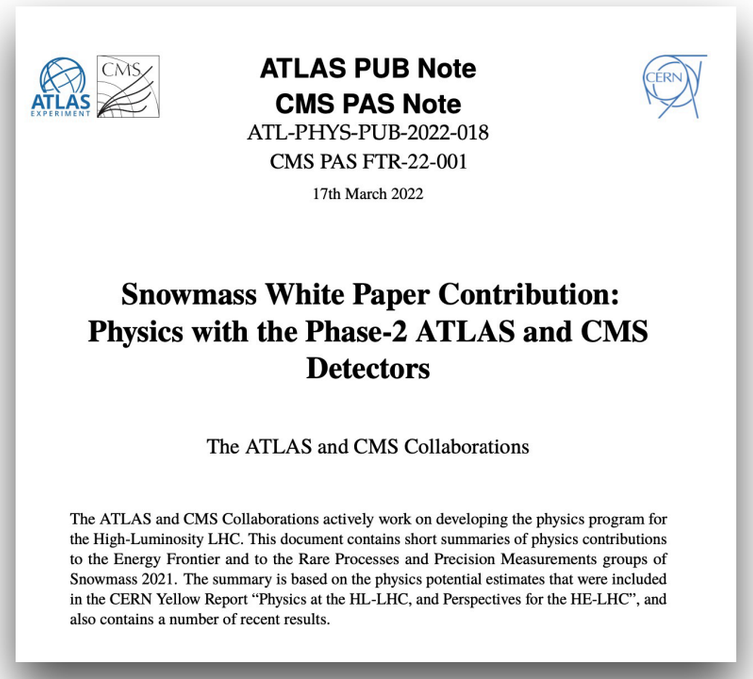
Calorimeter Endcap:
3D showering topology
Precision timing for high energy showers
Si, Scint+SiPM in Pb/W-SS

Overview of HL-LHC Higgs prospect studies

- **Yellow Report 18 "Higgs Physics at the HL-LHC and HE-LHC"** arXiv:1902.00134 (input to the European Strategy): https://e-publishing.cern.ch/index.php/CYRM/article/view/952



- **ATLAS and CMS Snowmass white paper:** Document summarizes HL-LHC physics prospect from YR18 + several new analyses: ATLAS-PHYS-PUB-2022-018/CMS-PAS-FTR-22-001 https://cds.cern.ch/record/2806962



Systematic uncertainty scenarios for HL-LHC prospect study

- S1: Run 2 systematic uncertainties (conservative scenario)
- **S2 (baseline for HL-LHC projection study): based on estimates of ultimate performance for experimental uncertainties, a factor of 1/2 reduction for theoretical uncertainties**

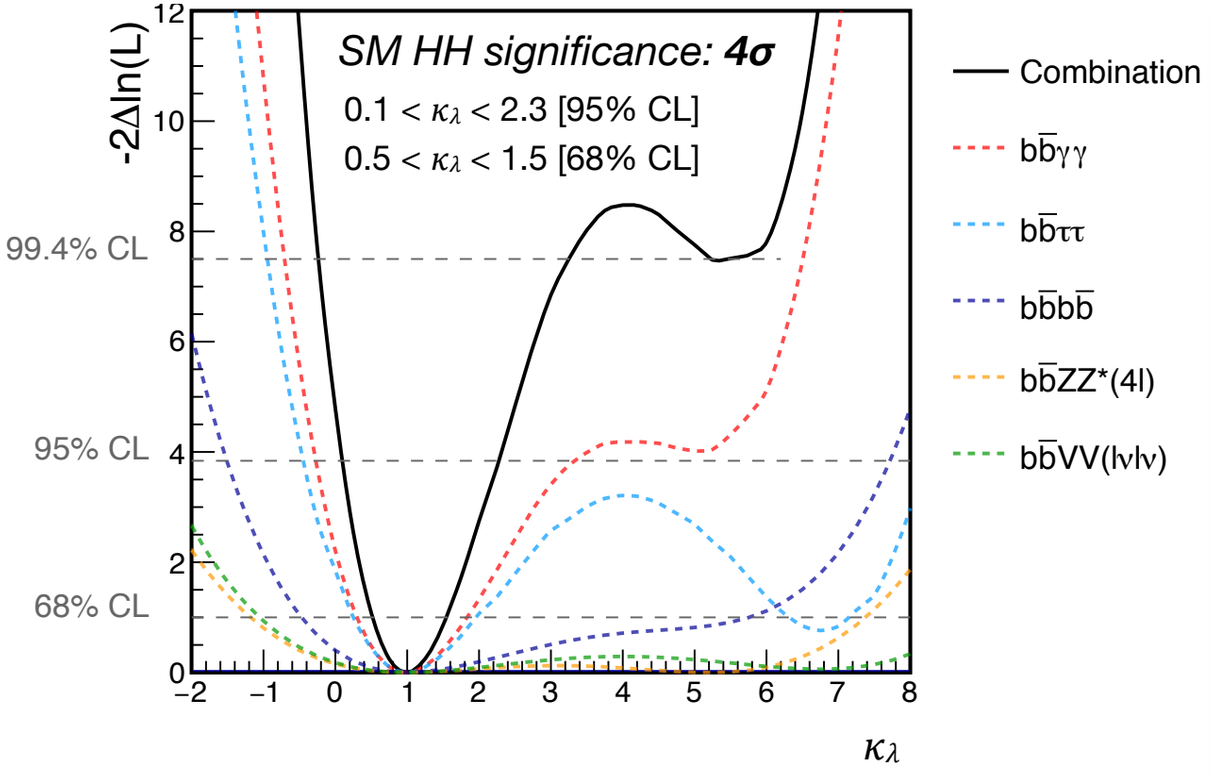
Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	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%

YR18 HL-LHC prospect of Higgs self-coupling

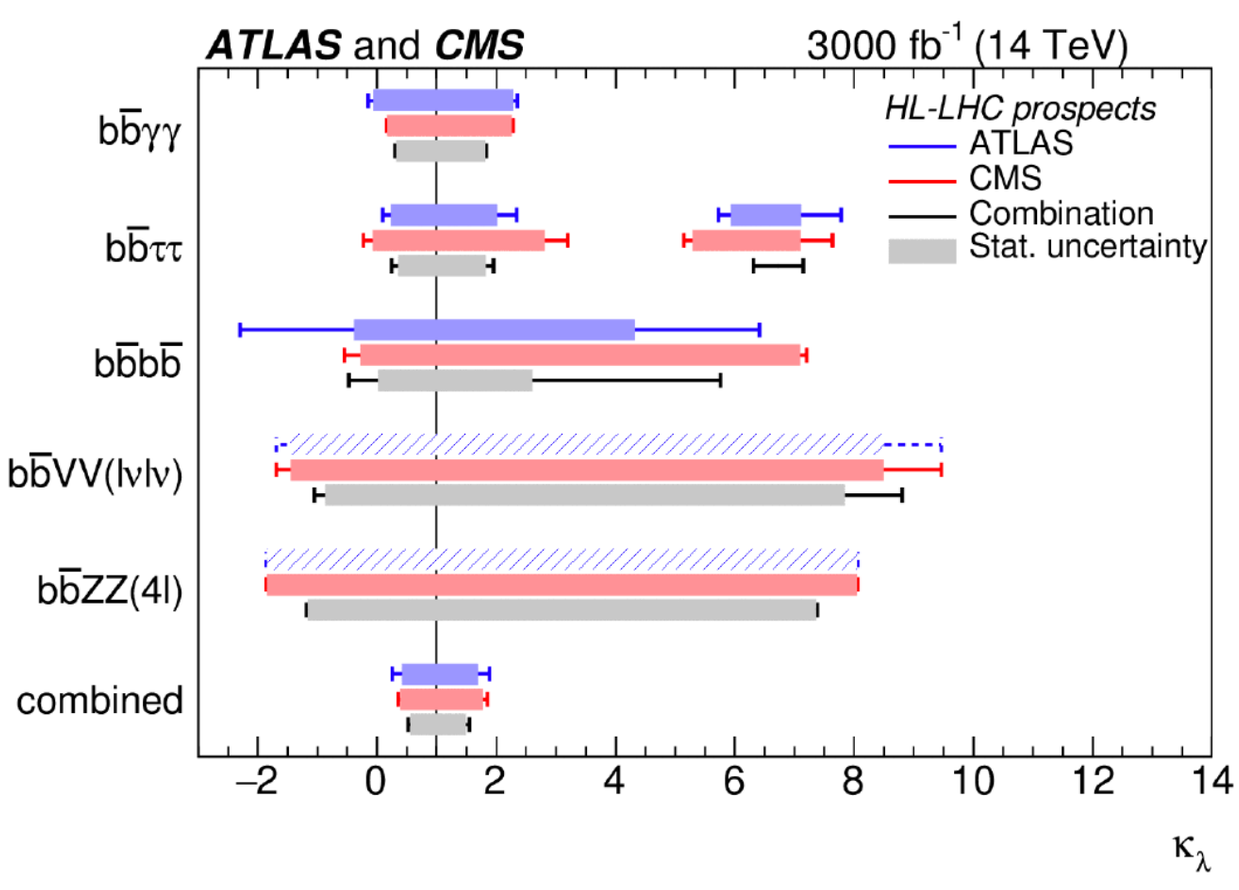
- HH production expected to reach **4.0σ Significance** CMS + ATLAS
- Accessible to Higgs self-coupling: 50% precision from ggHH mode

arXiv:1902.00134

	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		Combined	
	4.5		4.0	

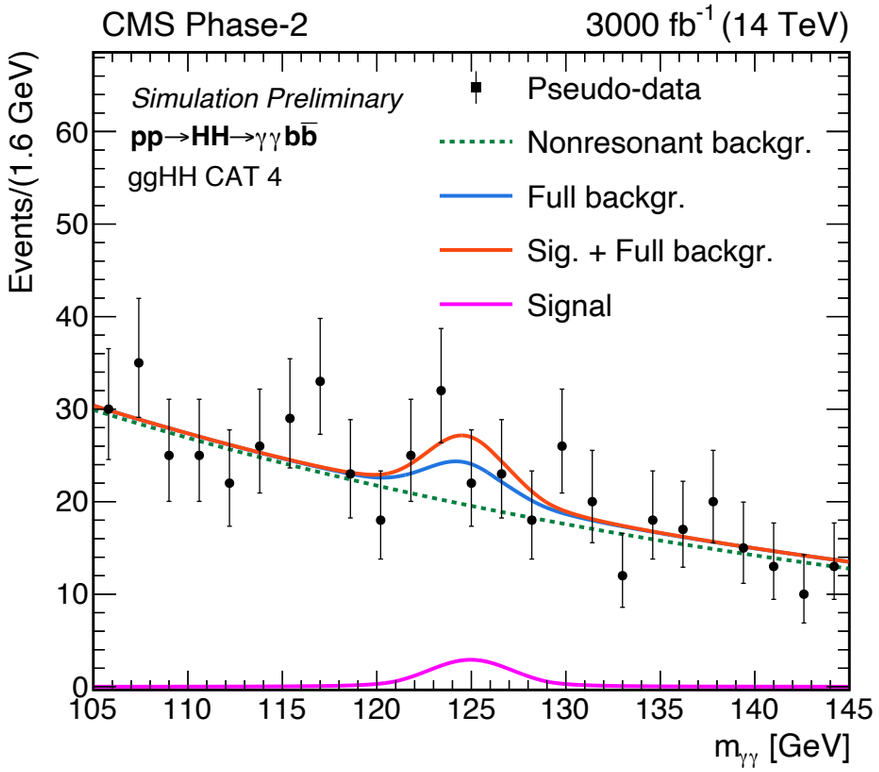


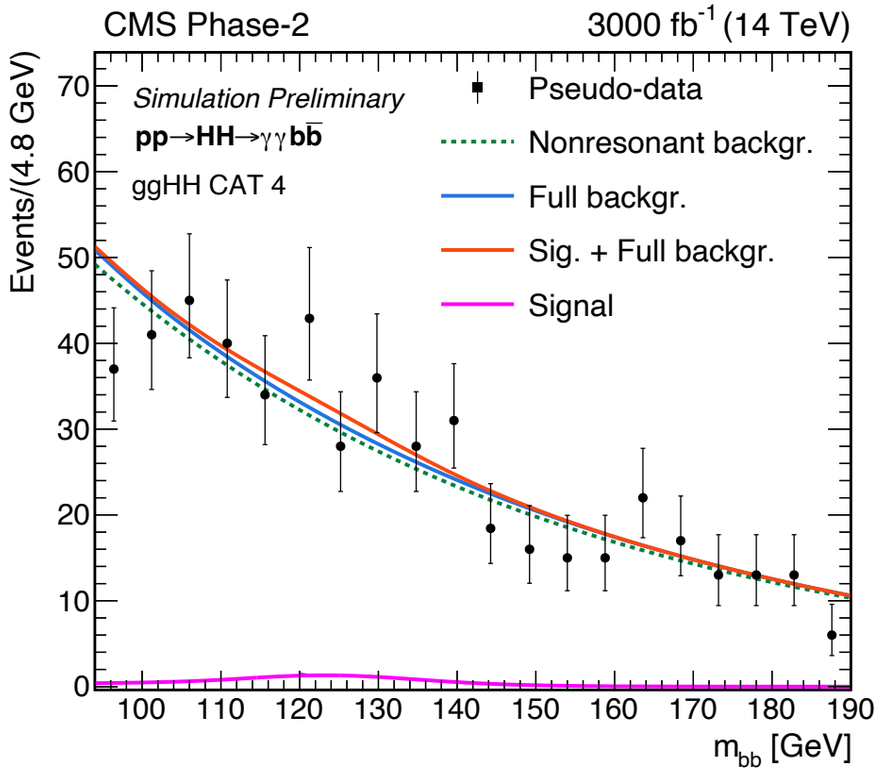
$$\kappa_\lambda = \lambda_3/\lambda_3^{SM}$$



Snowmass CMS HH→bbγγ updates

FTR-21-004

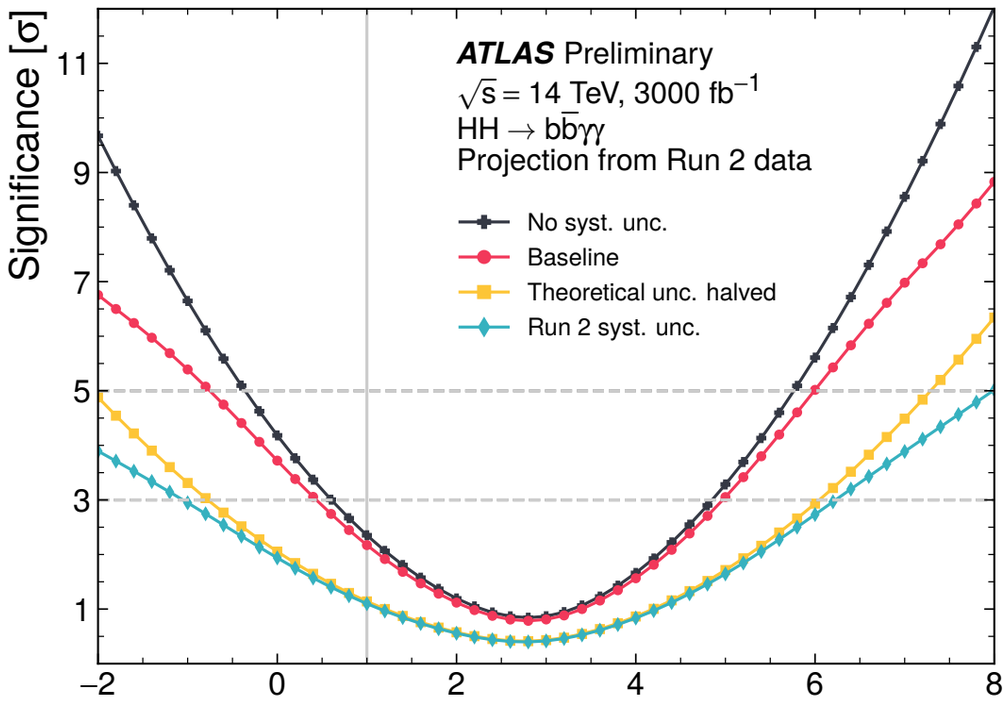


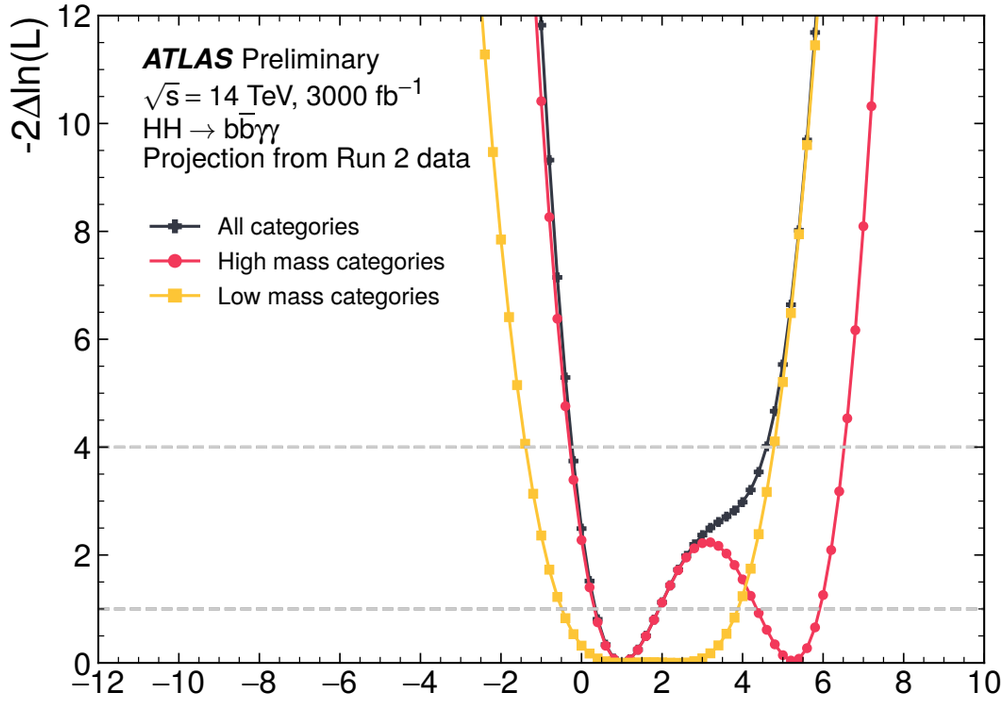


- Analysis using Delphes CMS HL-LHC simulation samples
- Analysis strategy based on Run 2 analysis
- HH→bbγγ signal extraction: 2D fit in m_{bb}-$m_{\gamma\gamma}$
- Improved ttH rejection, VBF-HH categories, improved photon and b-jet identification from MTD detector => expected significance of 2.16σ (wrt 1.86σ in YR18)

ATL-PHYS-PUB-2022-001

Snowmass ATLAS HH→bbγγ updates



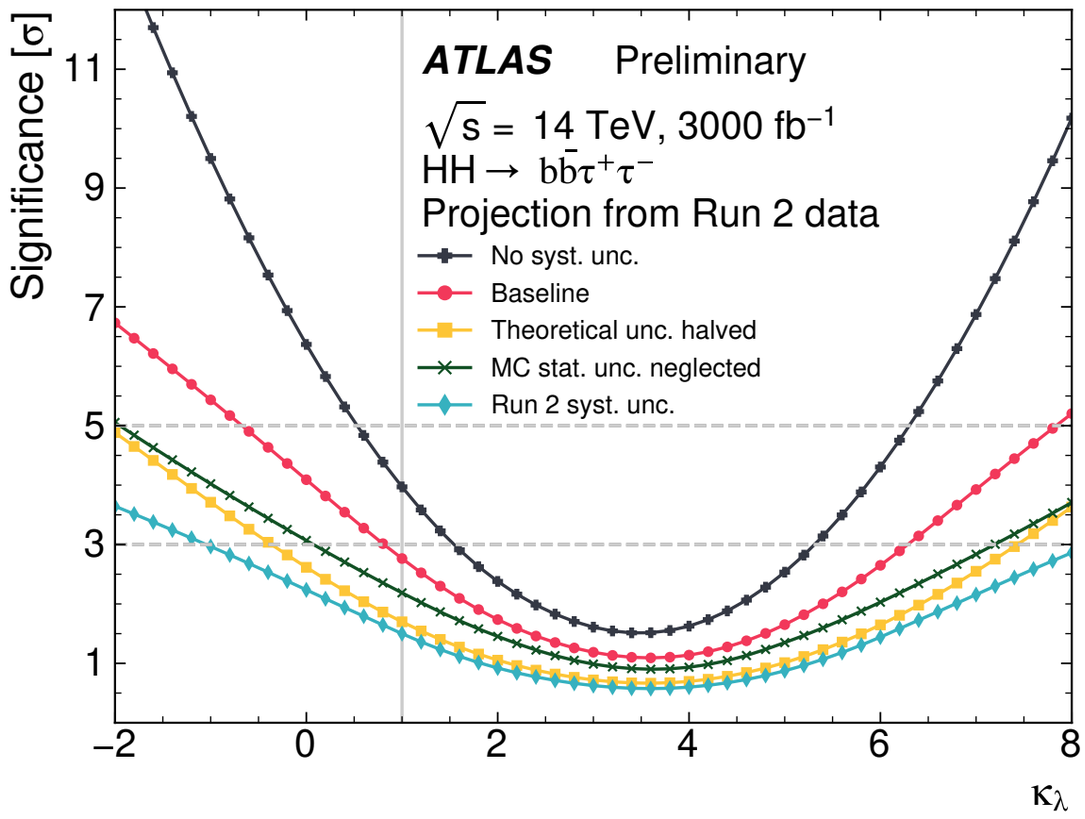


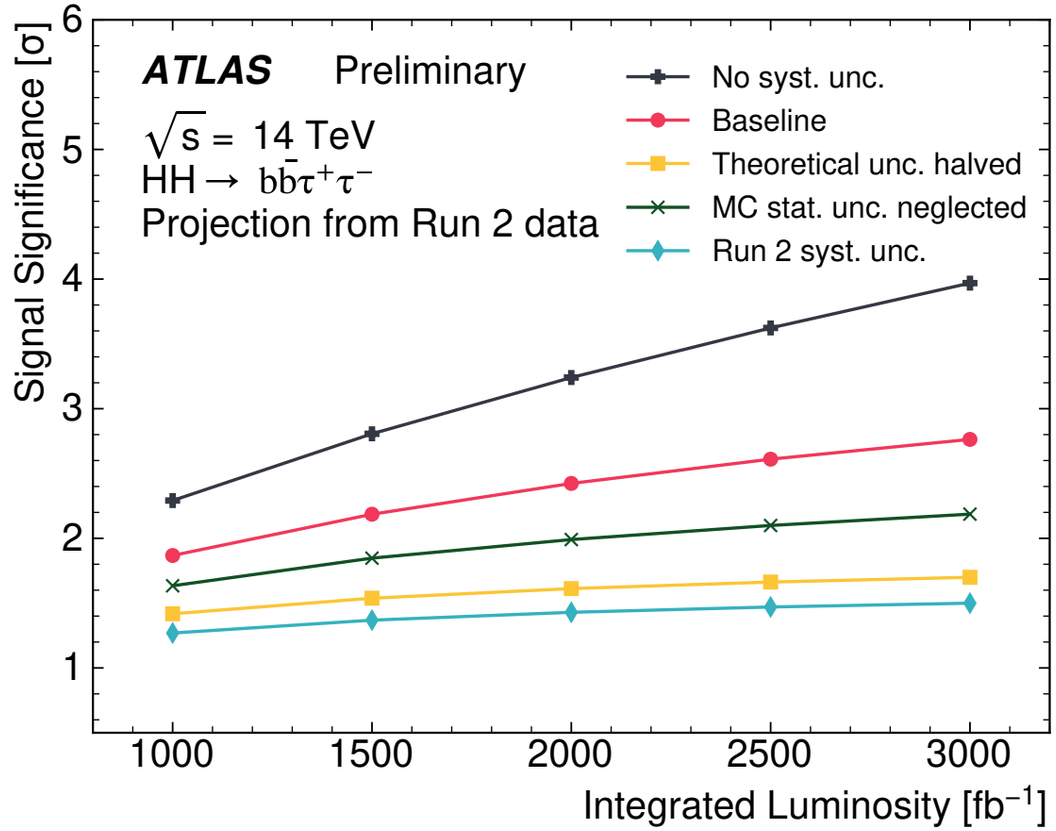
- Projection based on Run 2 analysis, 10% improvement wrt YR18 study
- precision on κ_λ improved via event classification based on modified four-body mass: $m^*_{\gamma\gamma bb}$ = $m_{\gamma\gamma bb}$ −(m_{bb} −125 GeV)−($m_{\gamma\gamma}$ −125 GeV)
- Projected significance of SM HH signal: 2.2σ (2.3σ) w/ (w/o) syst unc, constraint on κ_λ:

Uncertainty Scenario	Likelihood Scan 1σ CI	Likelihood Scan 2σ CI
No syst. unc.	[0.4, 1.8]	[−0.1, 4.6]
Baseline	[0.3, 1.9]	[−0.2, 4.6]
Theoretical unc. halved	[−0.1, 4.3]	[−0.8, 5.7]
Run 2 syst. unc.	[−0.1, 4.3]	[−1.0, 5.8]

ATL-PHYS-PUB-2021-044

Snowmass ATLAS HH→bbττ updates



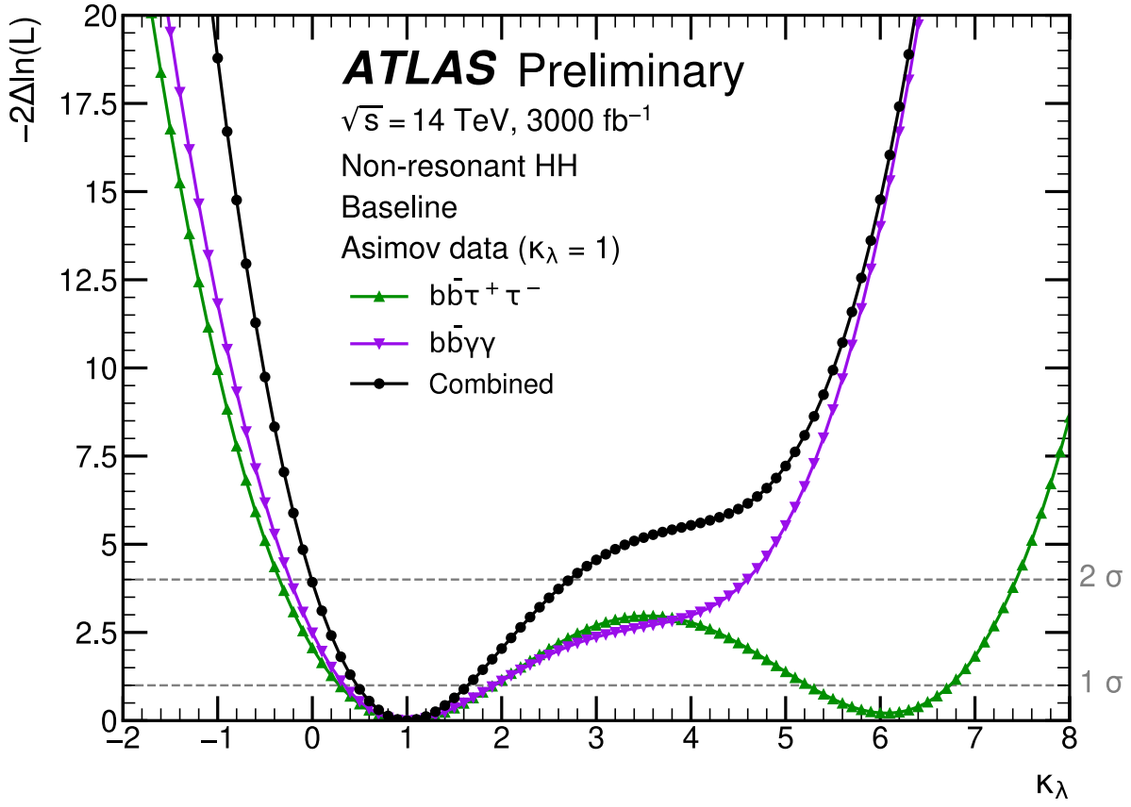


- Projection based on Run 2 analysis, 30% improvement wrt YR18 study
- Projected significance of SM HH signal: 2.8σ (4.0σ) w/ (w/o) syst unc, constraint on κ_λ:

Uncertainty Scenario	Likelihood Scan 1σ CI	Likelihood Scan 2σ CI
No syst. unc.	$[0.5, 1.6]$	$[0.1, 2.5] \cup [4.5, 6.5]$
Baseline	$[0.3, 1.9] \cup [5.2, 6.7]$	$[-0.3, 7.4]$
Run 2 syst. unc.	$[-0.2, 7.3]$	$[-1.2, 8.3]$
MC stat. unc. neglected	$[0.0, 2.2] \cup [4.9, 7.1]$	$[-0.8, 8.0]$
Theoretical unc. halved	$[0.0, 2.9] \cup [4.2, 7.1]$	$[-0.8, 7.9]$

Snowmass ATLAS HH→bbττ+bbγγ combination

ATL-PHYS-PUB-2022-005



- SM HH significance and measurement of signal strength

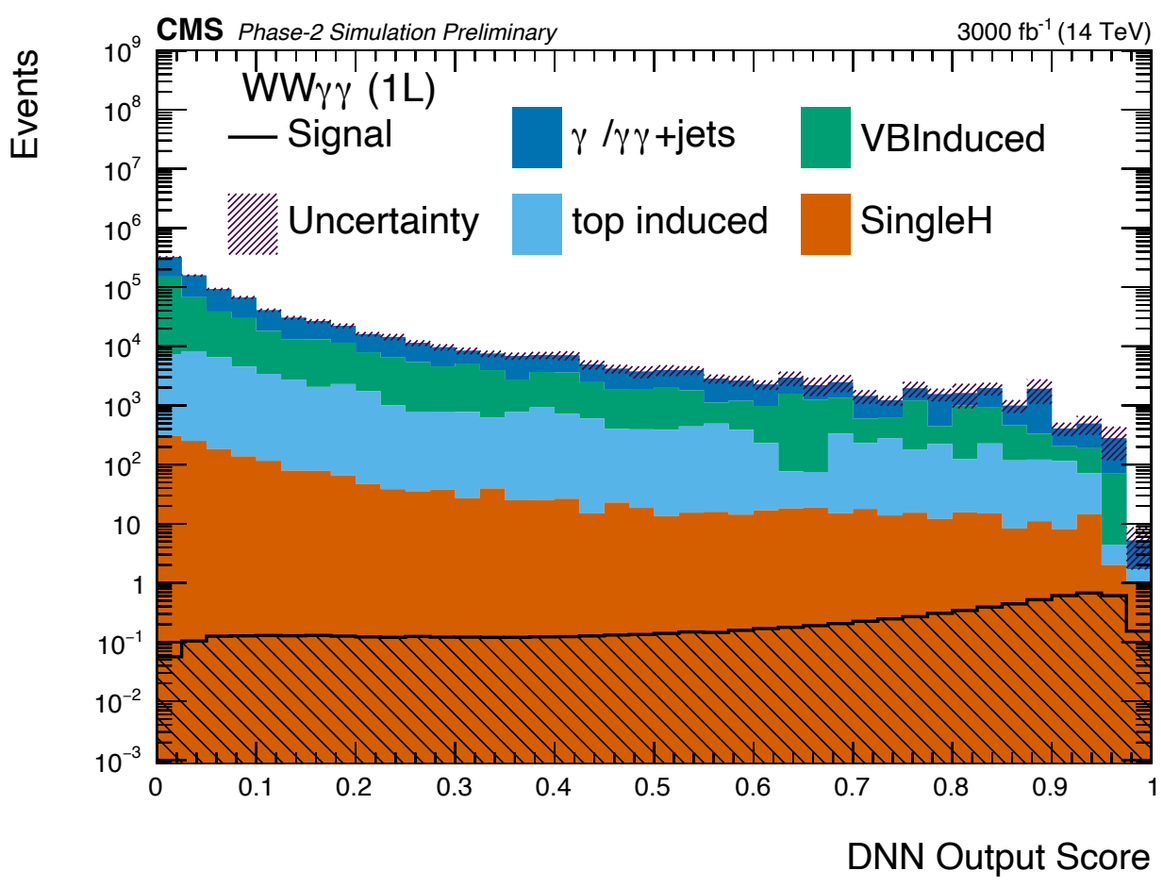
Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination	Combined signal strength precision [%]
No syst. unc.	2.3	4.0	4.6	$-23/+23$
Baseline	2.2	2.8	3.2	$-31/+34$
Theoretical unc. halved	1.1	1.7	2.0	$-49/+51$
Run 2 syst. unc.	1.1	1.5	1.7	$-57/+68$

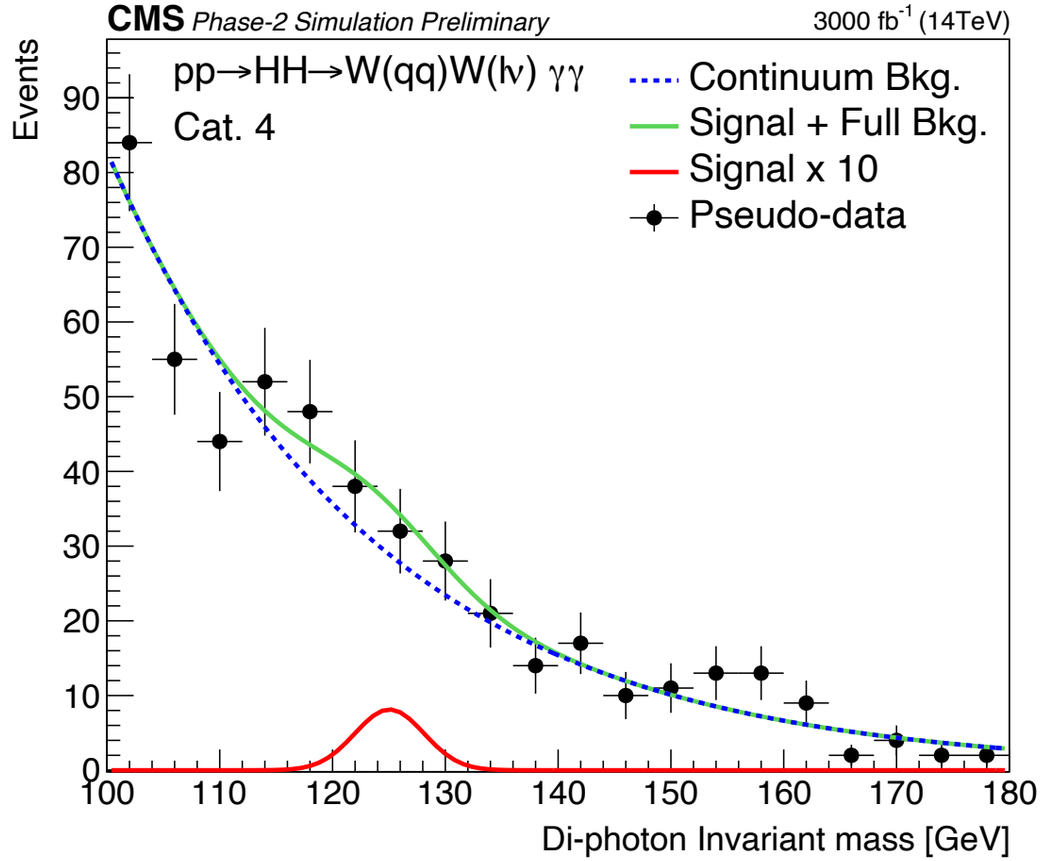
- constraint on κ_λ

Uncertainty scenario	Likelihood scan $1\,\sigma$ CI	Likelihood scan $2\,\sigma$ CI
No syst. unc.	$[0.6, 1.5]$	$[0.3, 2.1]$
Baseline	$[0.5, 1.6]$	$[0.0, 2.7]$
Theoretical unc. halved	$[0.2, 2.2]$	$[-0.4, 5.6]$
Run 2 syst. unc.	$[0.1, 2.5]$	$[-0.7, 5.7]$

Snowmass new decay mode HH→WWγγ,ττγγ

FTR-21-003





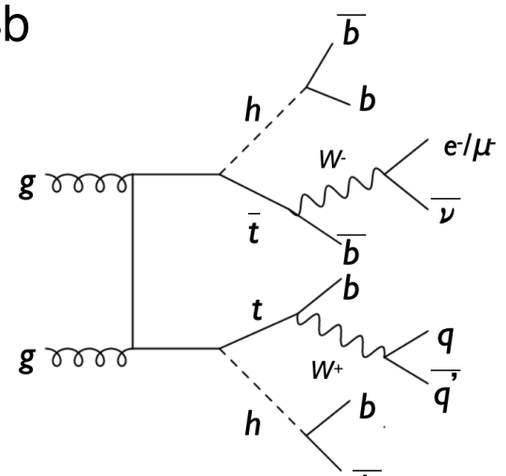
- Analysis using Delphes CMS HL-LHC simulation samples
- First study of HL-LHC projection of HH→WWγγ,ττγγ
- Signal extraction: 1D fit in $m_{\gamma\gamma}$
- Presence of leptons and photons, DNN helps reducing background

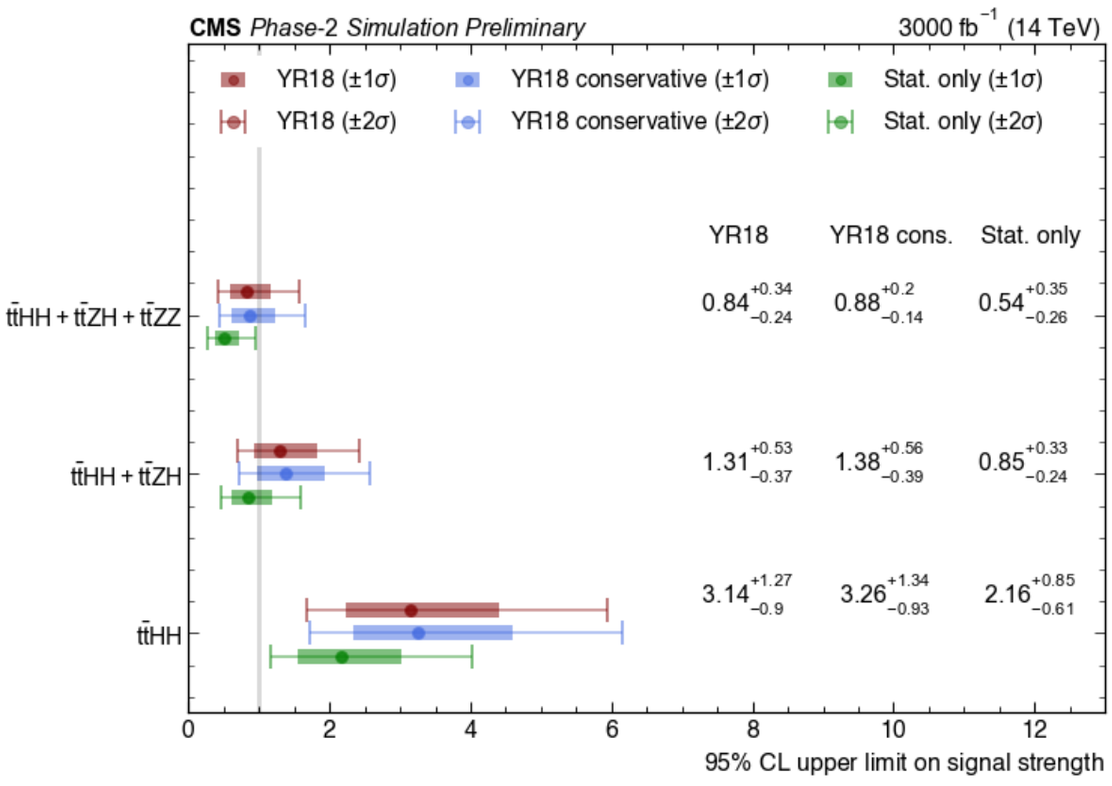
Snowmass new production mode ttHH

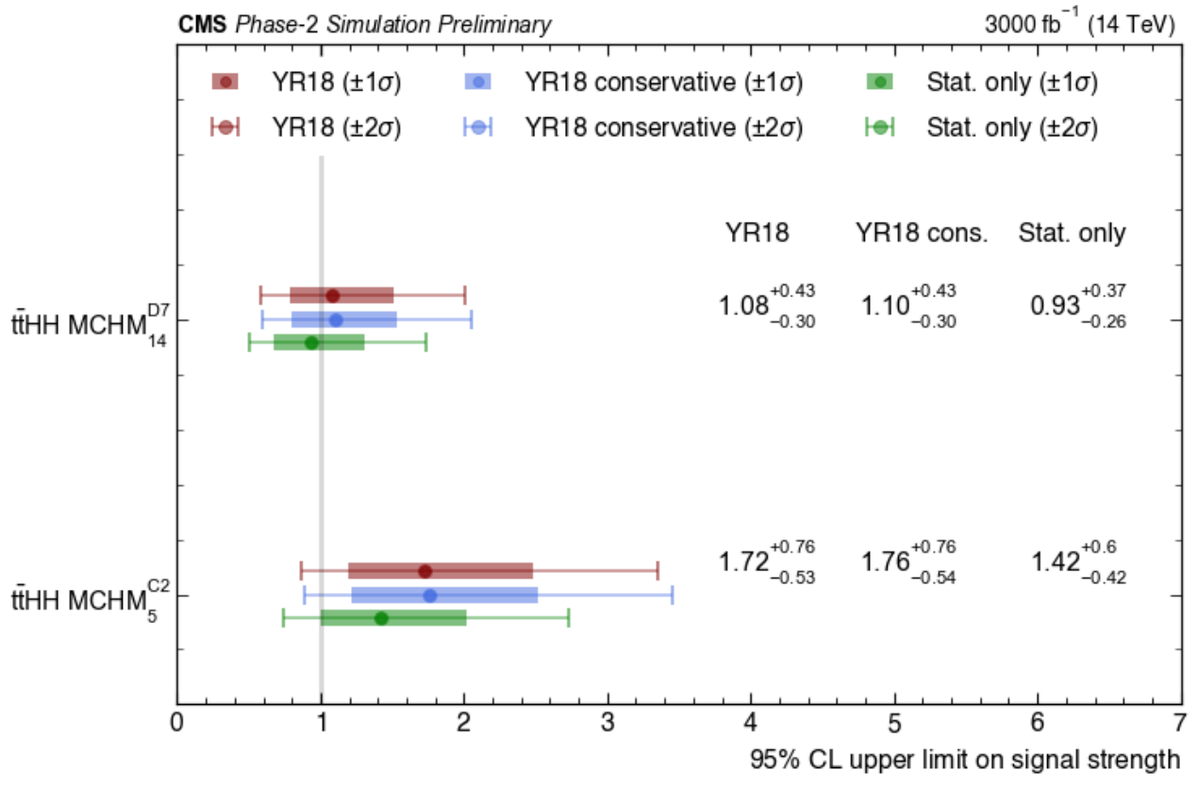
CMS-PAS-FTR-21-010

- ttHH can provide
  - complimentary constraint on κ_λ
  - sensitivity to BSM models such as Minimal Composite Higgs Model (MCHM)
- Expected upper limit σ(ttHH) < 3.14 x SM

- semileptonic decay of top-antitop pair
- HH→4b







HL-LHC HH prospect with Snowmass updates

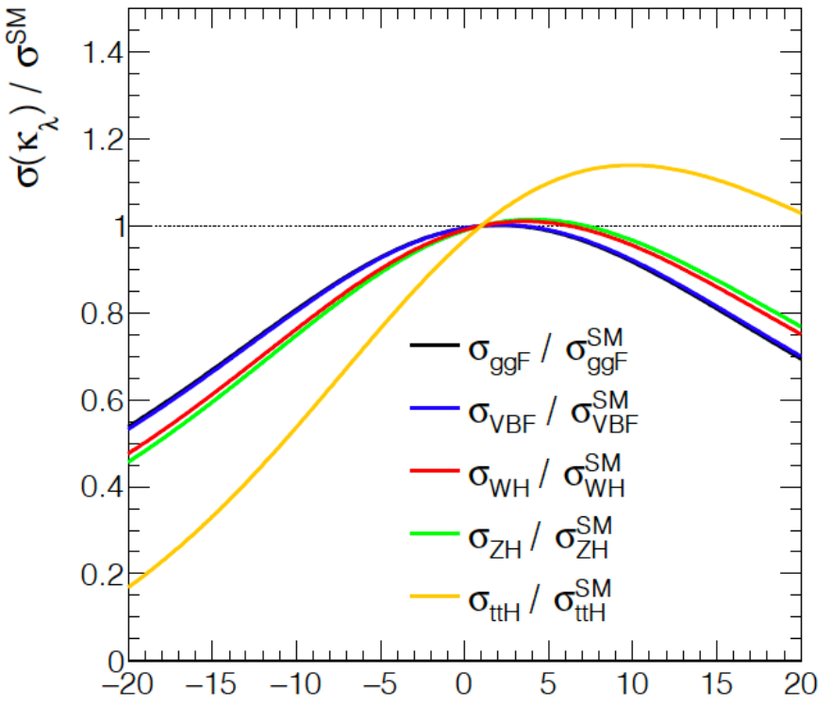
summary of **YR18 results** and **Snowmass updates**

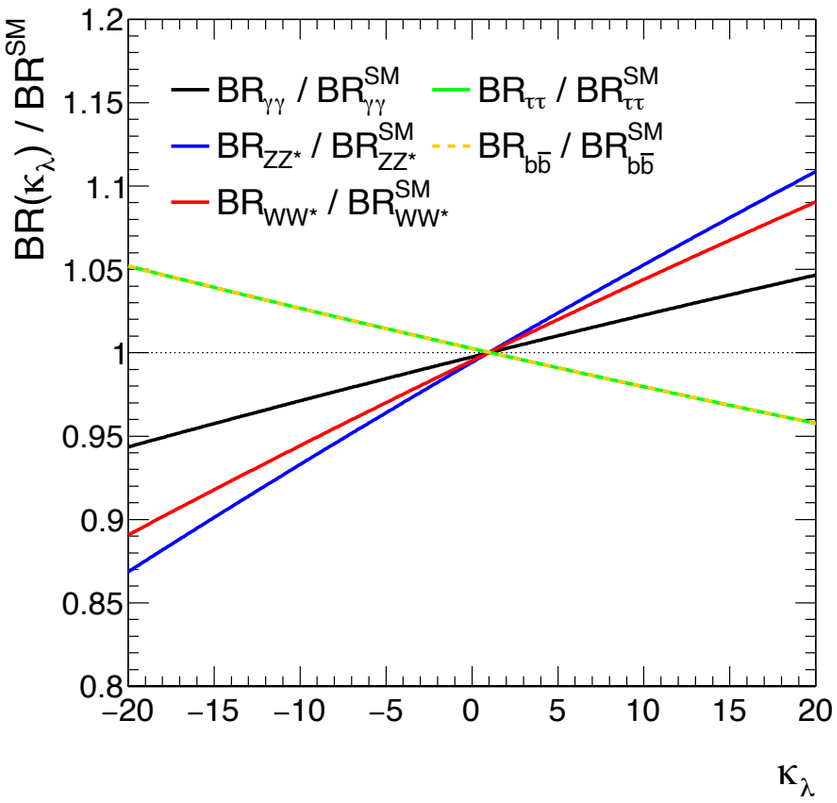
channels	ATLAS	CMS
bbbb	0.61σ	0.95σ
bbττ	2.8σ (2.1σ)	1.4σ
bbγγ	2.2σ (2.0σ)	2.16σ (1.8σ)
bbVV(llvv)	-	0.56σ
bbZZ(llll)	-	0.37σ
WWγγ + ττγγ	-	0.22σ

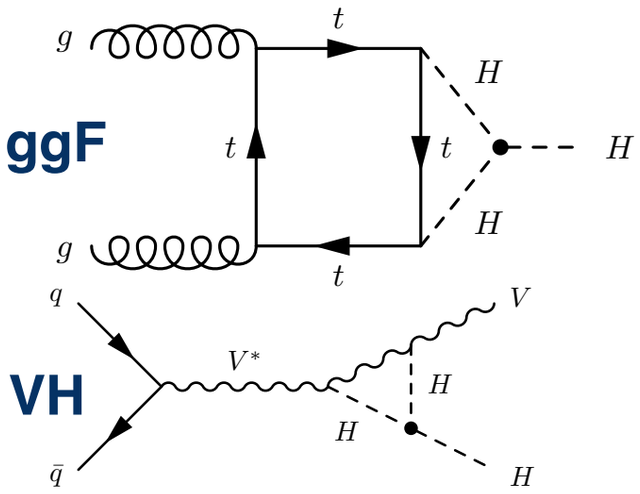
- **Expected upper limit σ(ttHH) < 3.14 xSM**
- Naively combining latest projections from ATLAS and CMS (sum in quadrature individual results): 4.6σ at HL-LHC wrt YR18 result 4.0σ
- New analysis techniques, inclusion of boosted Higgs signatures, trigger improvements are expected. Promising to reach 5.0σ discovery at HL-LHC.

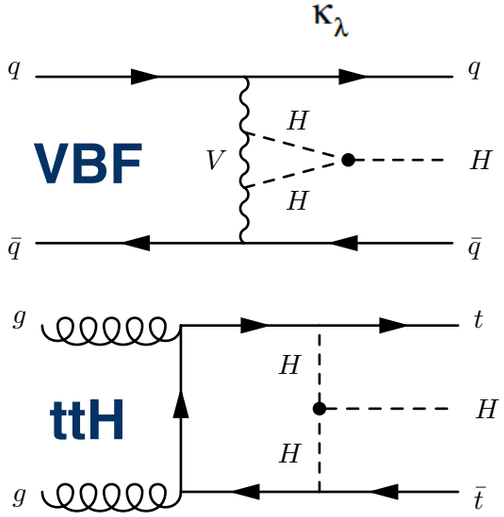
Constrain self-coupling using single Higgs

- Single Higgs boson production & decay rates, kinematics, are sensitive to the Higgs self-coupling λ_3 through EW corrections => can be used to indirectly constrain κ_λ, assuming no other BSM effects
- H measurements crucial for reducing the correlation between Higgs self-coupling and other Higgs coupling measurements

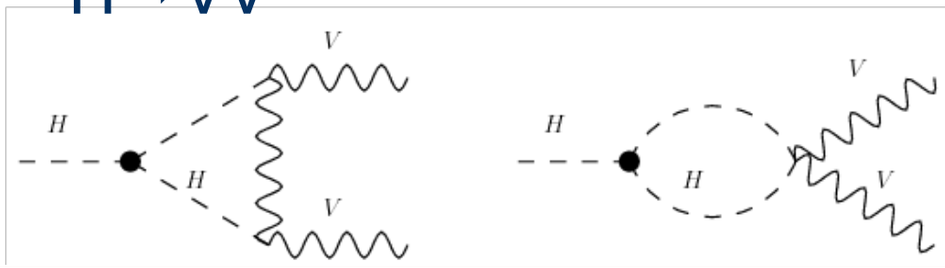








H→VV

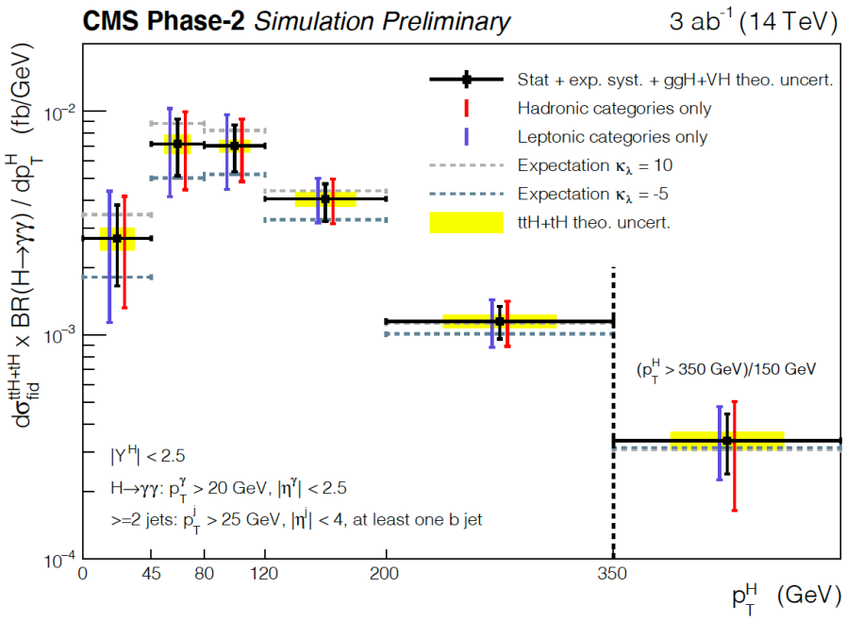


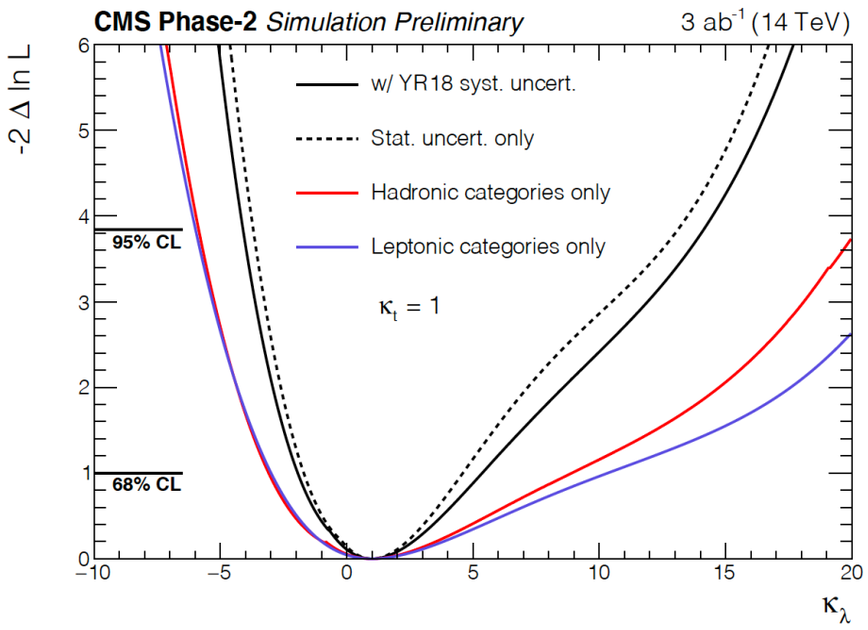
G. Degrassi et. al., JHEP 12 (2016) 080
F. Maltoni et. al., EPJC 77 (2017) 887

Constrain self-coupling using single Higgs

YR18 HL-LHC prospect study: CMS ttH(H→γγ) pT(H) differential measurements constrain κ_λ [-1.9, 5.3] at 68% CL

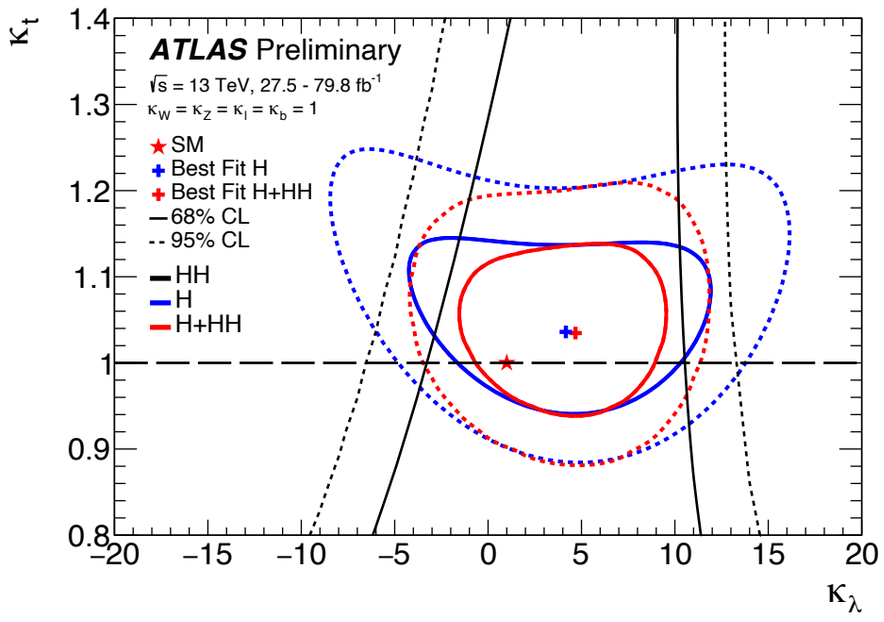
FTR-18-020

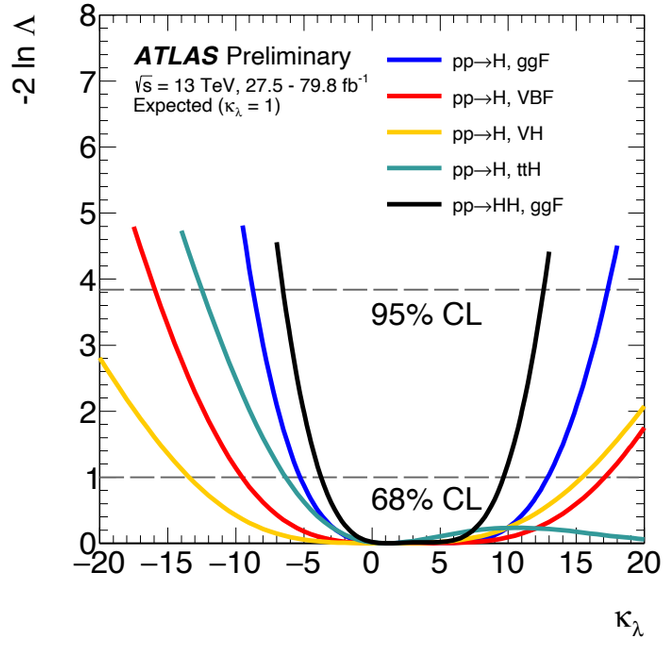




ATLAS partial Run 2 data H+HH combination ATLAS-CONF-2019-049

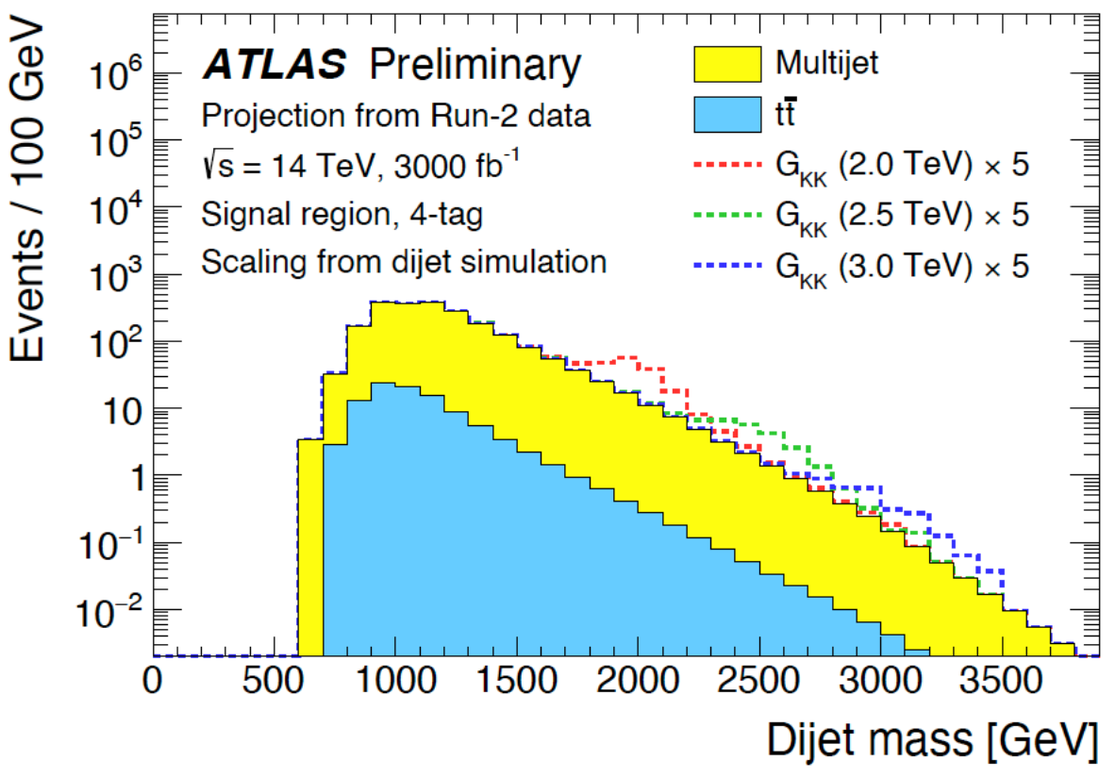
Expect improvements on κ_λ constraint in HL-LHC prospect as well from H+HH combination

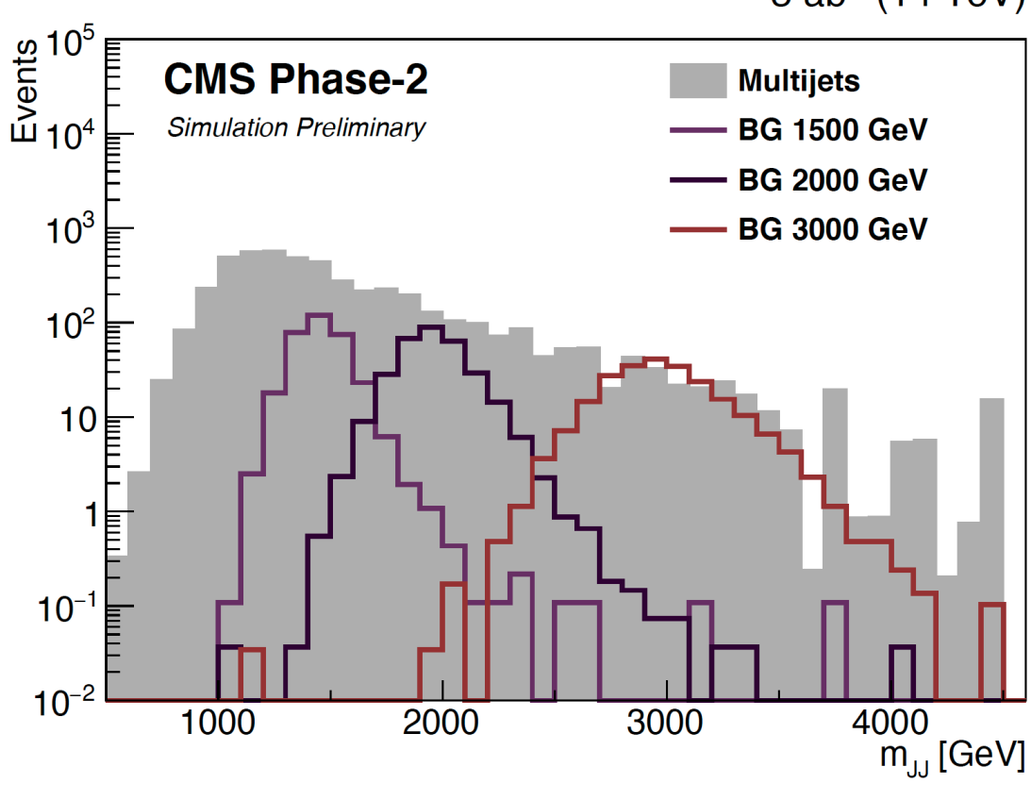




Search for heavy new resonance using HH

- Several BSM scenarios predict new resonances decaying to a pair of Higgs bosons
- YR18 study: boosted Higgs signature allows experimental reach of new resonances up to a few TeV mass scale at HL-LHC:
  - ATLAS study: increase mass reach by a factor of > 2 with 2016 Run 2 analysis, using ggF production mode
  - CMS study: discovery potential 2.6σ for bulk graviton of mass 2 TeV and cross section of 1 fb in the VBF mode





signal: spin-2 bulk gravitons

Summary

- Measurement of the Higgs self-coupling is one of the most important physics goals of the HL-LHC
- YR18 HL-LHC study: 50% precision on κ_λ, 4σ evidence of SM HH
- Snowmass studies have improved YR18 projections via new analysis techniques (e.g. 30% improvement for bbττ), studying new production modes (VBFHH, ttHH) and decay channels (WWγγ,ττγγ)

Looking forward to new breakthroughs in HH studies in the future!