CMS contribution to Snowmass EF01

Nan Lu

California Institute of Technology

On behalf of the CMS Collaboration

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Introduction to CMS contribution to Snowmass

CMS letter of interest (LoI) to Snowmass: https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF1_EF10-RF5_RF7_CMSCollaboration-109.pdf

- Topics are high-level, **built upon Yellow Report (YR) "Higgs Physics at the HL-LHC and HE-LHC"** arXiv:1902.00134 (input to the European Strategy) and add new and updated analyses

- **Two major approaches for HL-LHC prospect study for Snowmass:** projection based on Run 2 physics analysis, DELPHES fast simulation based study and their combination.

  - DELPHES fast simulation tuned to CMS Phase-2 full MC simulation, incorporating the latest Phase-2 physics object performance developments

CMS LoI: expected topics for Snowmass EF01

List of expected topics.

Public results are given with citations, new or modified analyses are indicated in italic font.

EF01: EW Physics: Higgs Boson properties and couplings

1. Non resonant gluon-gluon fusion HH production [10]
2. Sensitivity projections for Higgs boson properties measurements [11]
3. Search for invisible decays of a Higgs boson in VBF [12]
4. *Non resonant ttHH production and constraints on the Higgs boson self-coupling from ttH* [13]
5. *H mass and width measurements* [11]
6. *Non resonant VBF HH production*
7. *Rare decays of the Higgs boson*
8. *Measurement of differential VBF Higgs boson cross sections*
9. *HHH and quartic couplings*
10. *Higgs EFT studies*

link to CMS LoI: https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF1_EF10-RF5_RF7_CMSCollaboration-109.pdf

This talk focuses on potential new or improved analyses wrt Yellow Report

Systematic uncertainty scenarios for HL-LHC prospect study

Yellow Report uncertainty recommendation: 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%

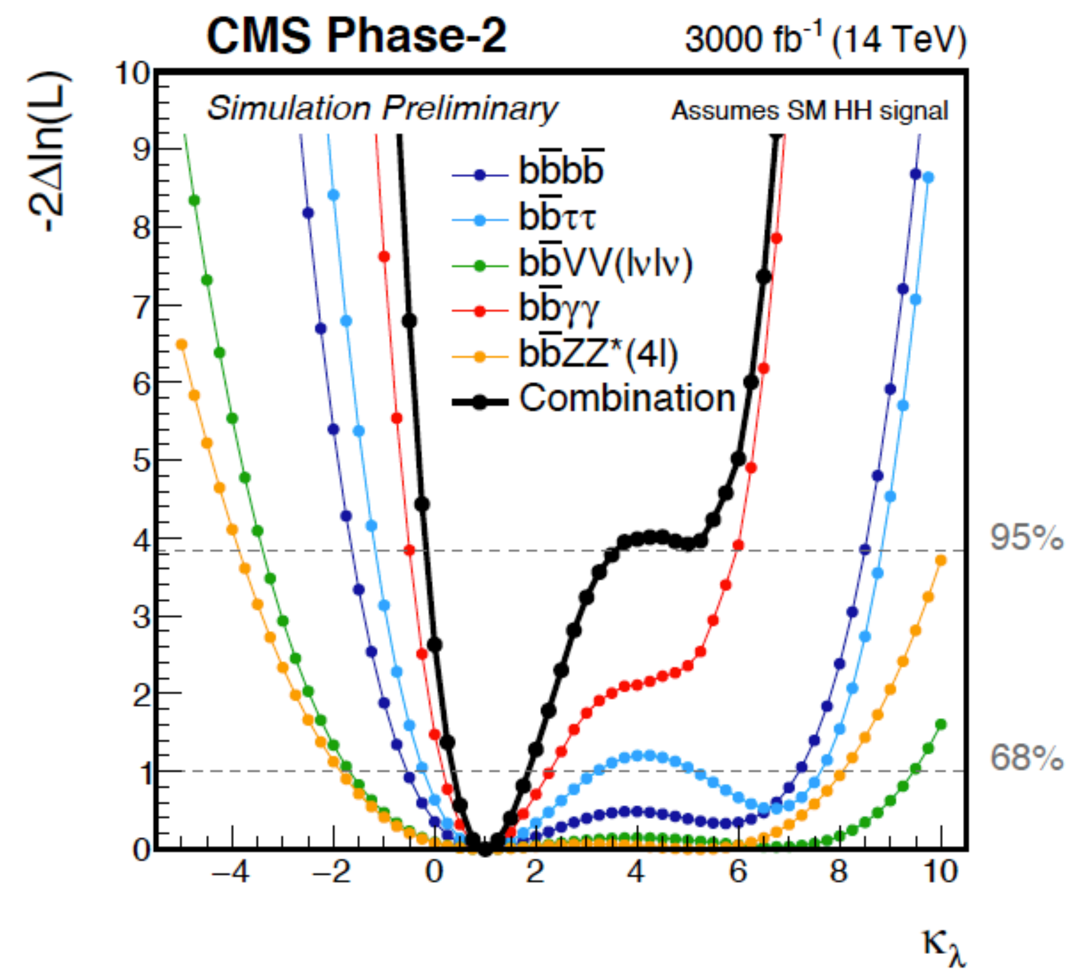
HL-LHC prospect of HH production and Higgs self-coupling

arXiv:1902.00134

- Yellow Report:
  - CMS + ATLAS: **4.0σ for HH production and** 50% precision for Higgs trilinear self-coupling
  - focused on gluon fusion production mode

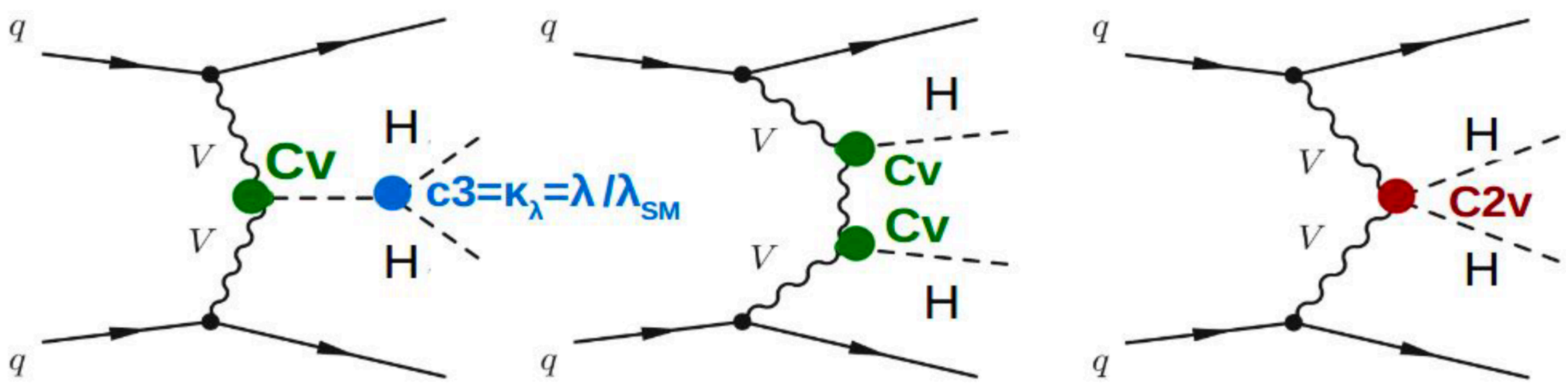
- Snowmass plan:
  - improve analyses strategy: bbγγ channel
  - new channel: WWγγ
  - new channel: ttHH, HH→bbbb

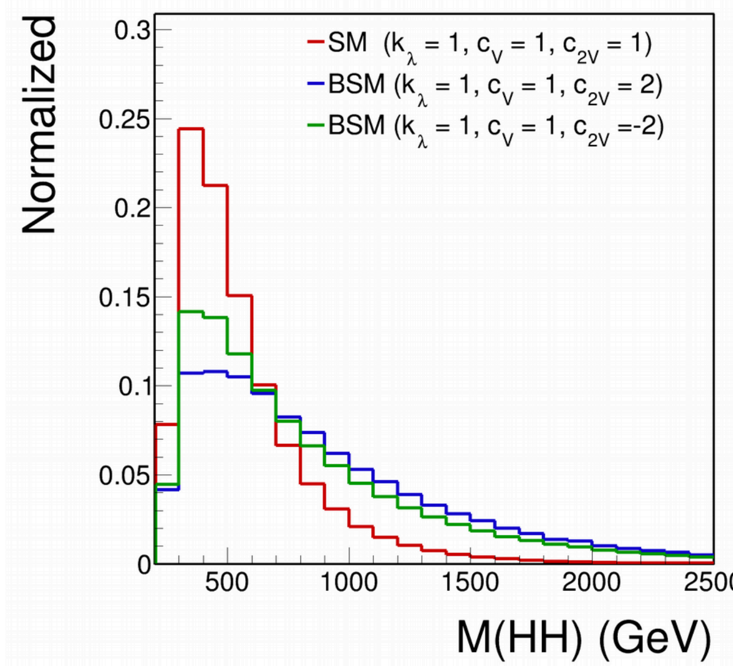
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6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



VBFHH production mode

- Sensitive to Higgs self-coupling and VVHH (C_{2V}) coupling:
  - small modifications of C_{2V} coupling could induce a striking change of the cross section as a function of the m(HH) distribution





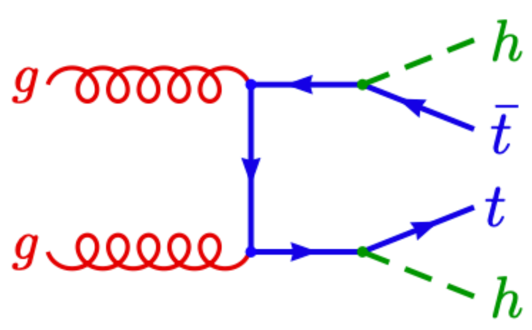
- Snowmass plan: prospect study for VBFHH production and C_{2V} coupling at HL-LHC, built upon Run 2 analysis expertise
  - bbγγ channel
  - WWγγ channel

ttHH production mode

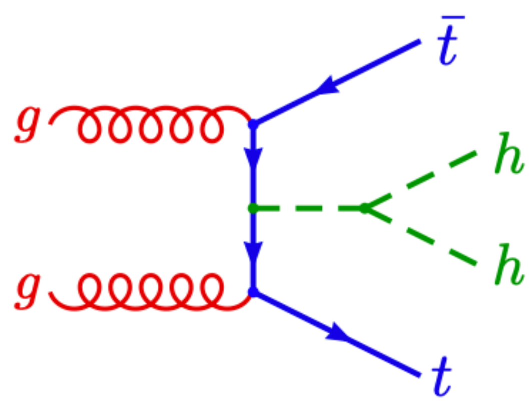
arxiv: 2008.13026

- ttHH provides a unique handle to probe BSM physics

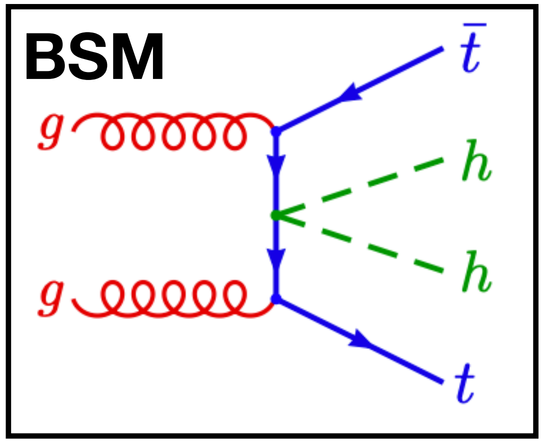
Yukawa vertex



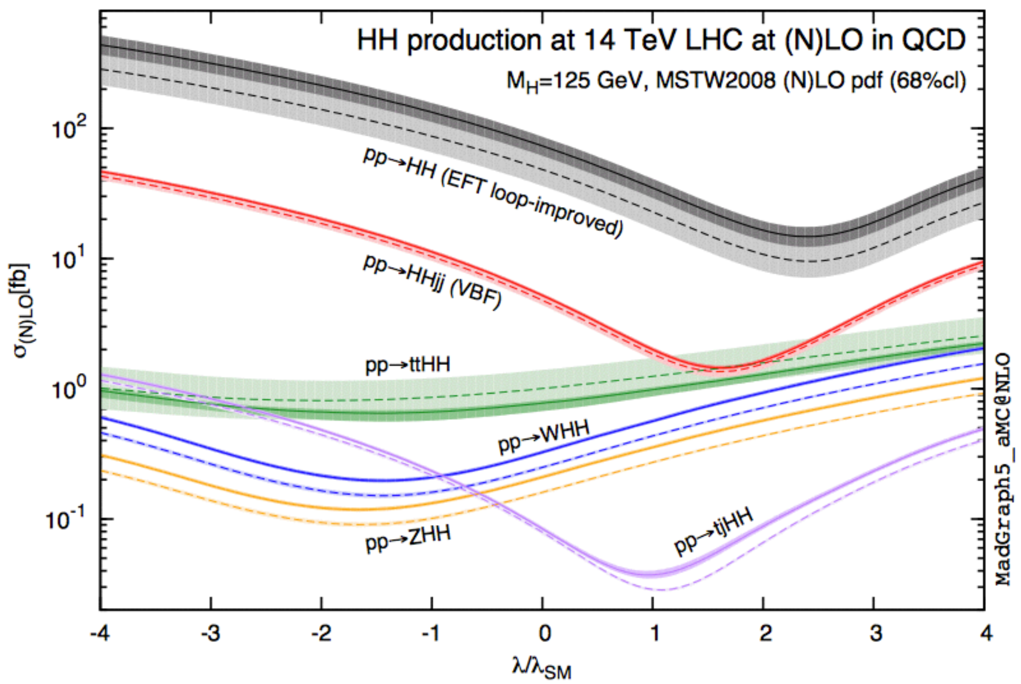
Higgs trilinear self-coupling
~ 20% of total ttHH cross in SM



"double Higgs" Yukawa vertex arising in composite Higgs scenarios, does not exist in the SM



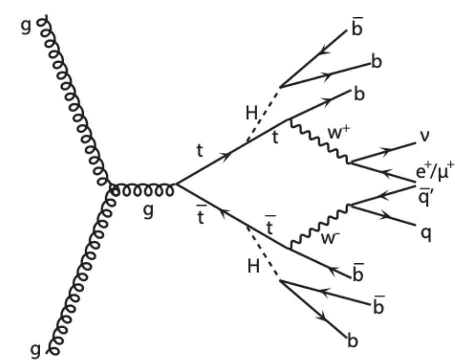
- Despite the small rate in SM, different shape of ttHH cross section dependency of Higgs trilinear self-coupling wrt ggHH and VBFHH mode provides a complementary input to Higgs trilinear self-coupling extraction.

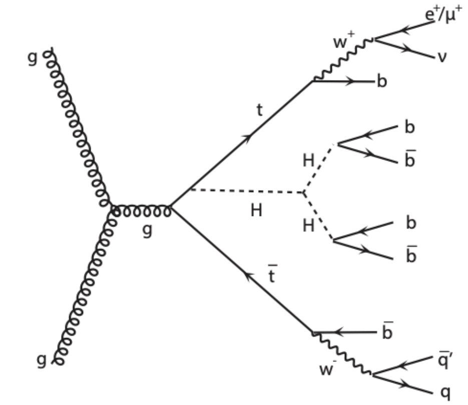


Phys.Lett. B732 (2014) 142-149

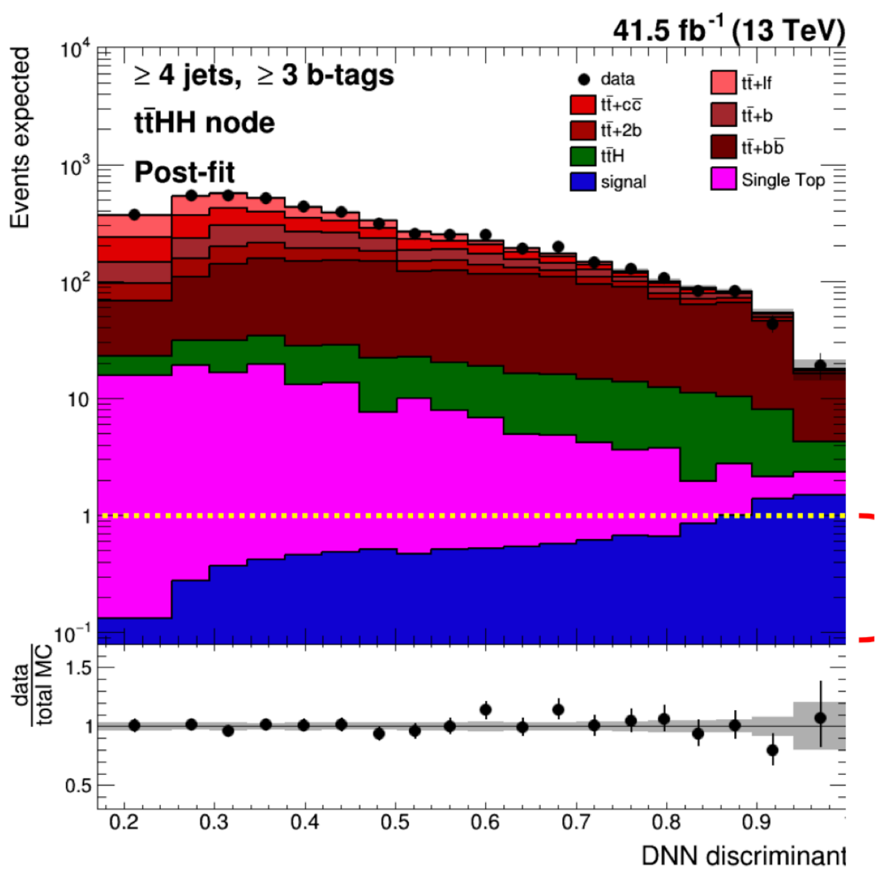
ttHH study in Run 2 and plans for Snowmass

- ttHH study using CMS Run 2 2017 data:
  - Leonidas Prado PhD thesis (https://inspirehep.net/files/60d77fcbdf577e9c0ceb4f0f828c2406) based on CMS 2017 data, $t\bar{t}$ semi-leptonic decay, HH→4b
  - 95% CL upper limit for ttHH cross section: observed (expected): 33 (29) × SM





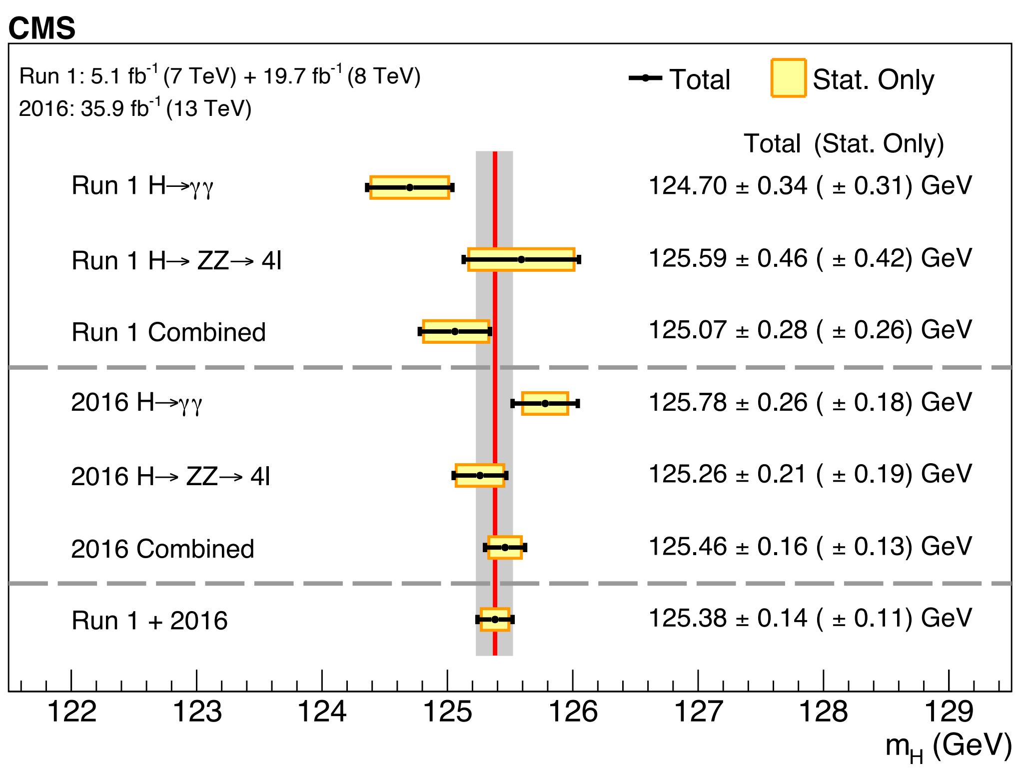
DNN to reject background (dominated by $t\bar{t}$)



- Snowmass plan:
  - HL-LHC prospect of search for ttHH production mode
  - improve analysis strategy

Higgs boson mass and width

- m_H is a free parameter in the SM. Once m_H is known, all Higgs boson couplings to Standard Model particles are fixed.
- Current precision on m_H has reached ~1%
- Yellow Report: plausible to reach $\sigma(m_H)$ ~10-20 MeV at HL-LHC
- Snowmass plan:
  - aiming for HL-LHC prospect of m_H measurement and direct measurement of Higgs boson width Γ_H, using γγ and 4l channels
  - potential to study constraint on Γ_H using interference in the $gg\to H\to\gamma\gamma$ channel on-shell rate and Higgs mass shift

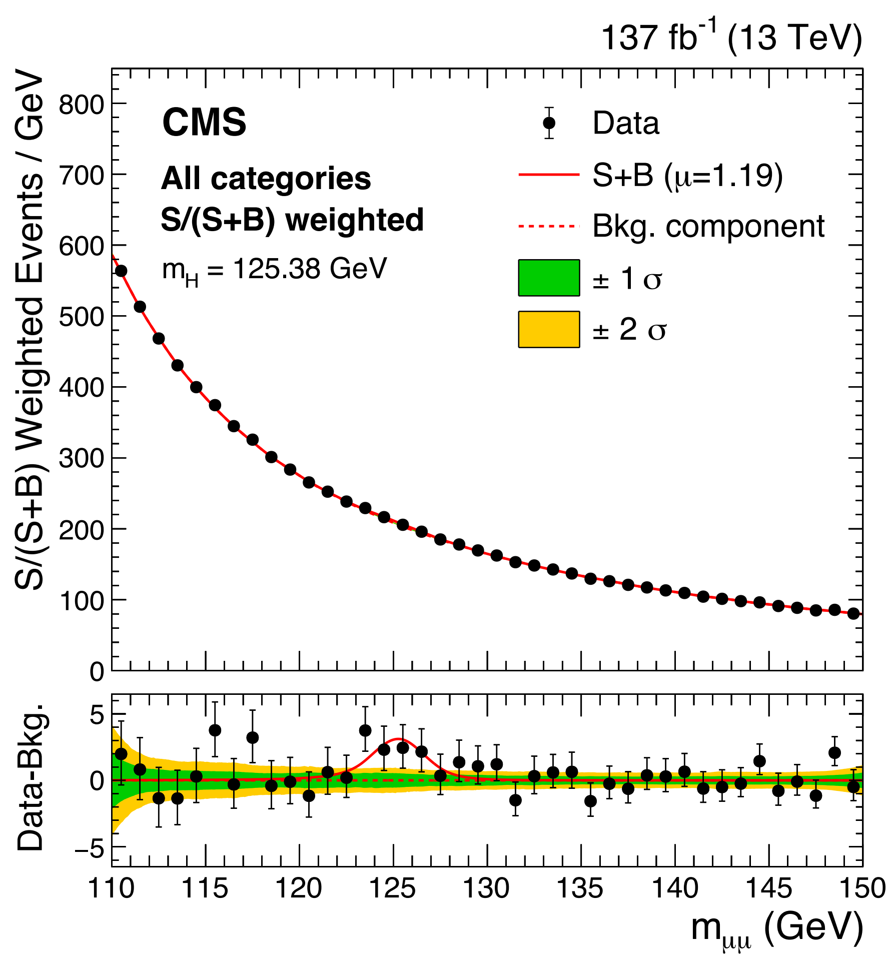


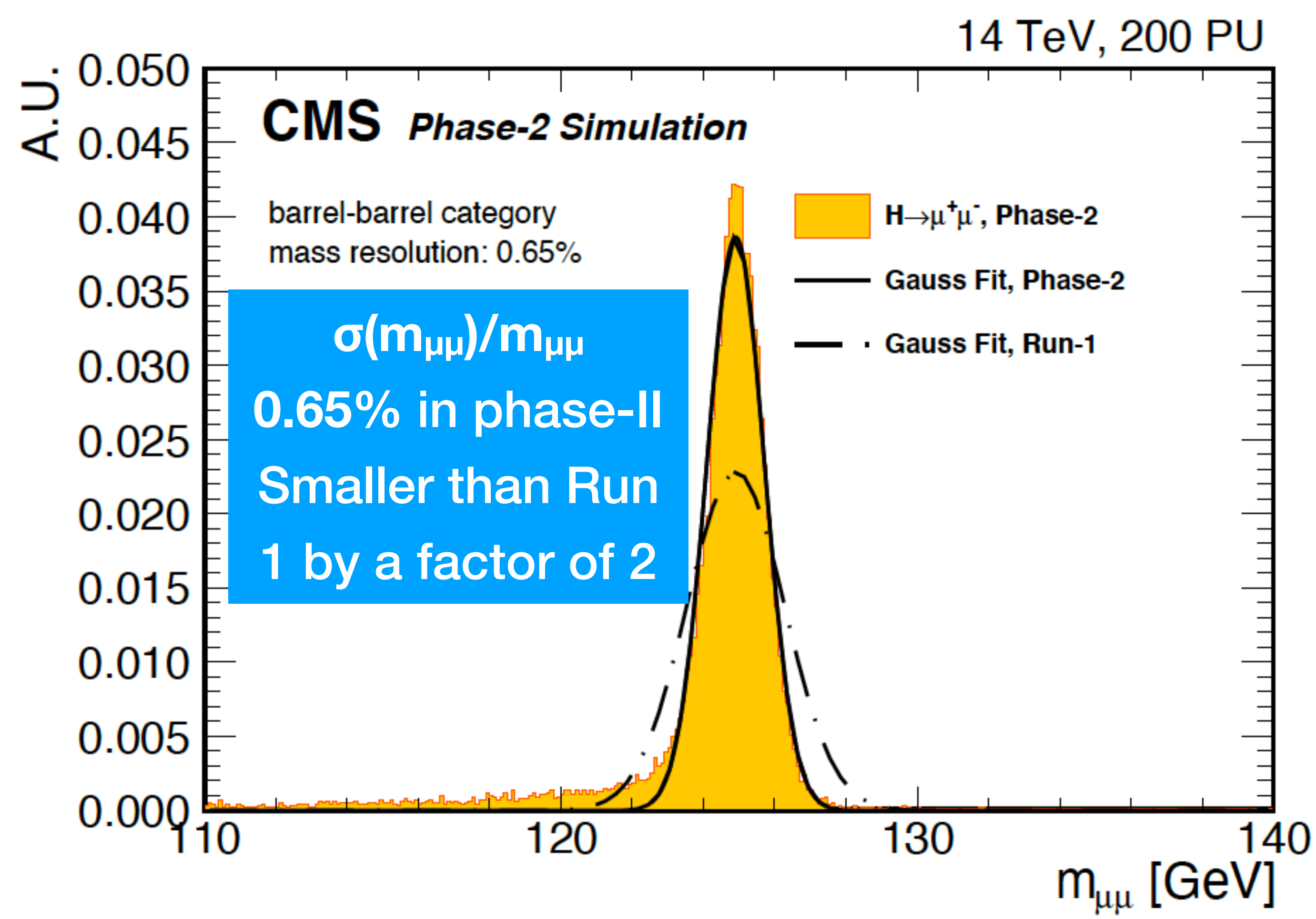
Rajdeep Chatterjee et. al., "The Ultimate Measurements of the Higgs Boson Mass and Width in Run 3, the HL-LHC, and Beyond" Snowmass EF01 WGM Aug 50, 2020

Higgs boson rare decay: H→μμ

- Yellow Report HL-LHC projection: Higgs boson coupling to muon precision reaches 5% from CMS and 4.3% from CMS+ATLAS, still stats. unc. dominated
  - CMS analysis mainly focused on ggH and VBF production modes
- Snowmass study: plan to update H→μμ projection at HL-LHC, built upon the full Run 2 analysis JHEP01(2021)148

Run 2: observed 3σ significance





Summary

- We are working on HL-LHC Higgs prospect topics specified in the CMS Snowmass LoI, according to our plans we will have them submitted to arXiv before March 2022

- Consultations with ATLAS are ongoing on how to present common topics and summarize those analyses that are already in Yellow Report

Thank you!

Backup Slides

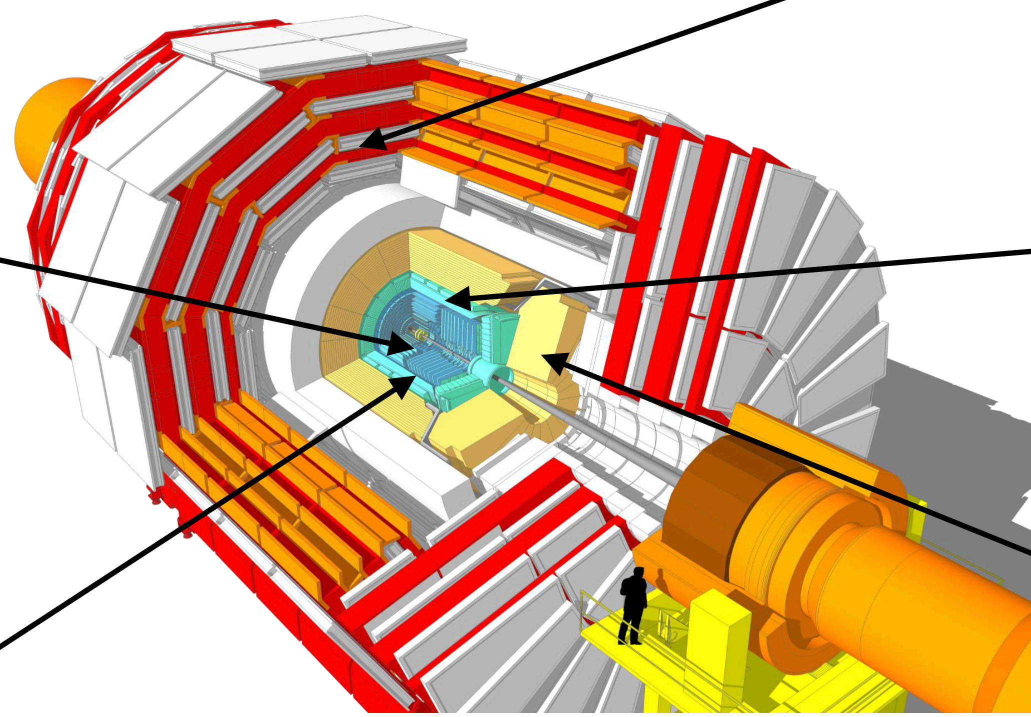
Highlights of the CMS Phase-2 detector upgrade

- All silicon tracker with η coverage extended to about 4
- New precision timing capability (~30 ps) in MIP timing detector and calorimetry
- New trigger capabilities e.g. at L1 trigger: tracks, complex particle-flow like object and machine learning technique, significantly lowered trigger threshold

L1-Trigger/HLT/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~3.8
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.

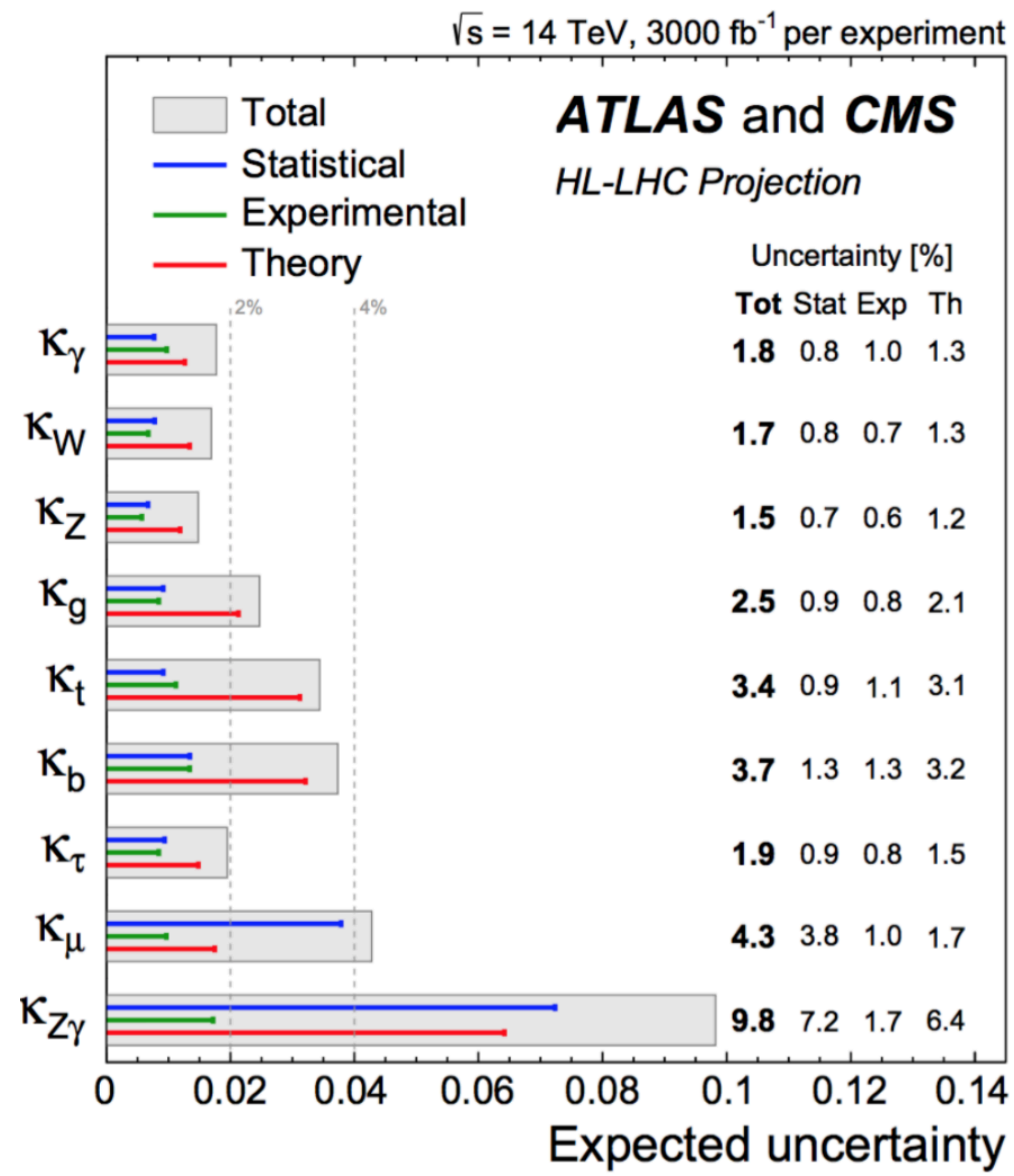
Calorimeter Endcap:
3D showering topology
Precision timing for high energy showers
Si, Scint+SiPM in Pb/W-SS

Higgs boson couplings

- Most of the measurements are expected **not to be limited by statistical uncertainty**, overall precision expected **at percent level**

arXiv:1902.00134

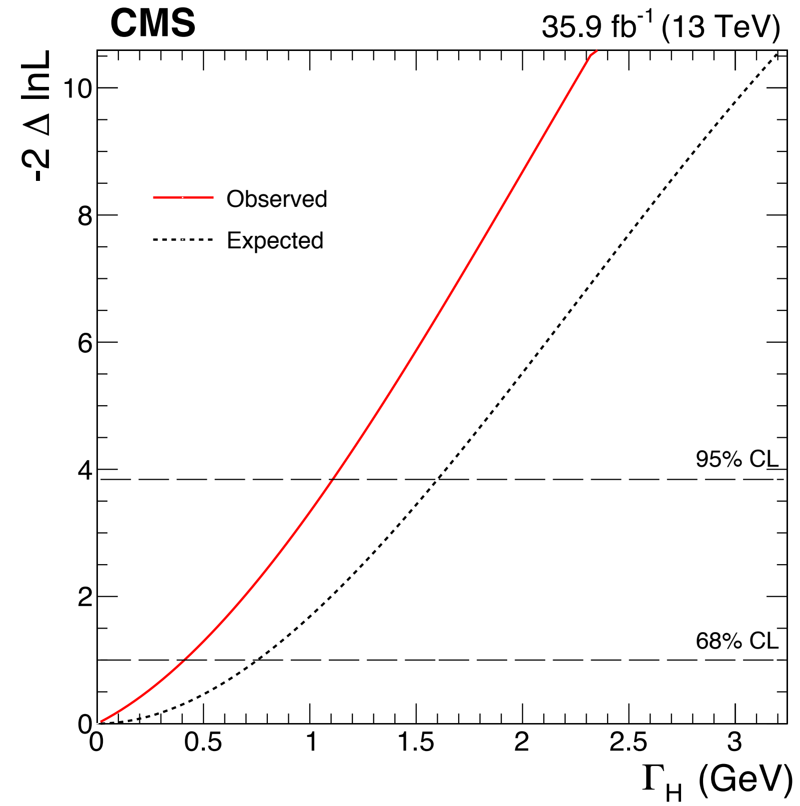
		CMS				
		3000 fb^{-1} uncertainty [%]				
		Total	Stat	SigTh	BkgTh	Exp
κ_γ	S1	2.9	1.1	1.8	1.0	1.7
	S2	2.0	1.1	0.9	0.8	1.2
κ_W	S1	2.6	1.0	1.7	1.1	1.1
	S2	1.8	1.0	0.9	0.8	0.8
κ_Z	S1	2.4	1.0	1.7	0.9	0.9
	S2	1.7	1.0	0.9	0.7	0.7
κ_g	S1	4.0	1.1	3.4	1.3	1.2
	S2	2.5	1.1	1.7	1.1	1.0
κ_t	S1	5.5	1.0	4.4	2.7	1.6
	S2	3.5	1.0	2.2	2.1	1.2
κ_b	S1	6.0	2.0	4.3	2.9	2.3
	S2	4.0	2.0	2.0	2.2	1.8
κ_τ	S1	2.8	1.2	1.8	1.1	1.4
	S2	2.0	1.2	1.0	0.9	1.0
κ_μ	S1	6.7	4.7	2.5	1.0	3.9
	S2	5.0	4.7	1.3	0.8	1.1



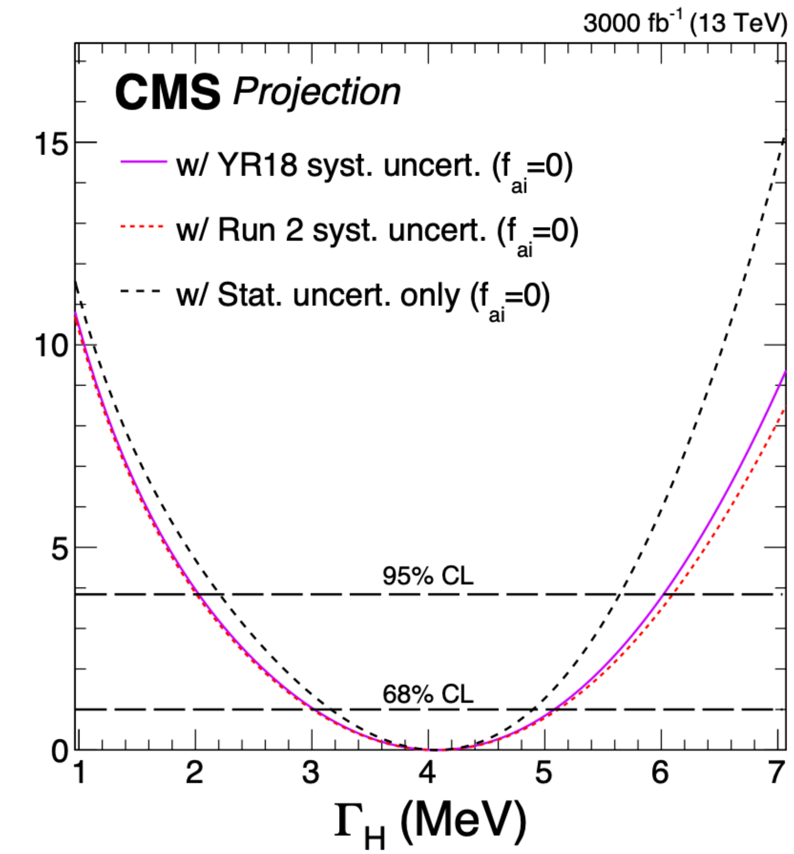
Higgs boson width

- Direct measurement of Higgs boson width limited by the detector resolution
  - observed (expected) limit $\Gamma_H < 1.1$ (1.6) GeV at 95% CL using 2016 data with $H \to ZZ \to 4l$ channel

arxiv:1706.09936



- Indirect constraint: combining on-shell and off-shell Higgs measurements, assuming on-shell and off-shell couplings are the same, expected precision from CMS for HL-LHC: $\Gamma_H = 4.1^{+1.0}_{-1.1}\ MeV$

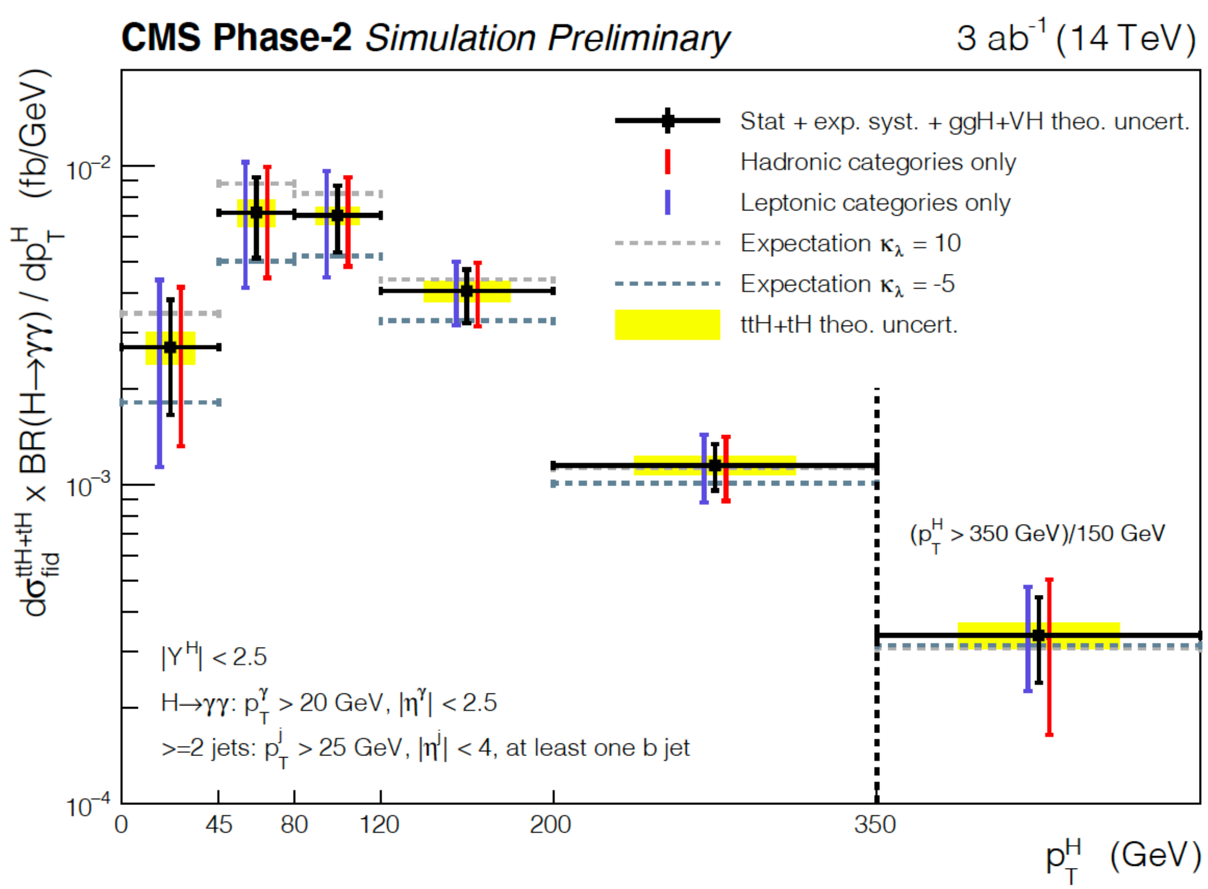


Higgs boson self-coupling: constraint from single Higgs

arXiv:1902.00134

HL-LHC prospect:

- Yellow report study CMS ttH(H→γγ) pT(H) differential measurements bound κ_λ [-1.9, 5.3] at 68% CL



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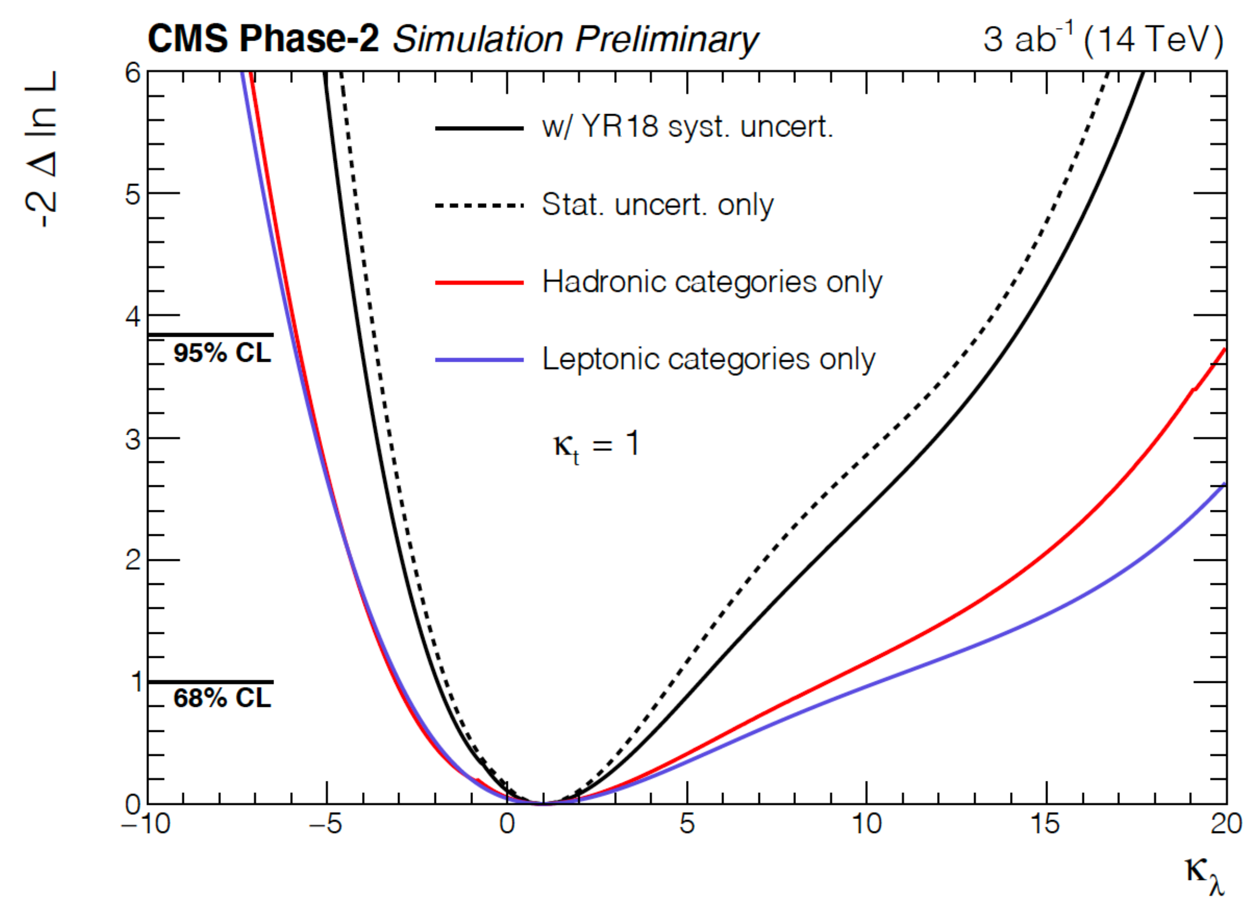
κ_λ [-1.9, 5.3] at 68% CL



Search for VBF,H→invisible

arXiv:1902.00134

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