

# CMS HIGGS ANALYSES WISH-LIST AND PLANS

In view of preparation for the **HE/HL-LHC YR**

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on behalf of **CMS UPSG & HIG Future Studies groups**  
CERN, 20<sup>th</sup> March 2018



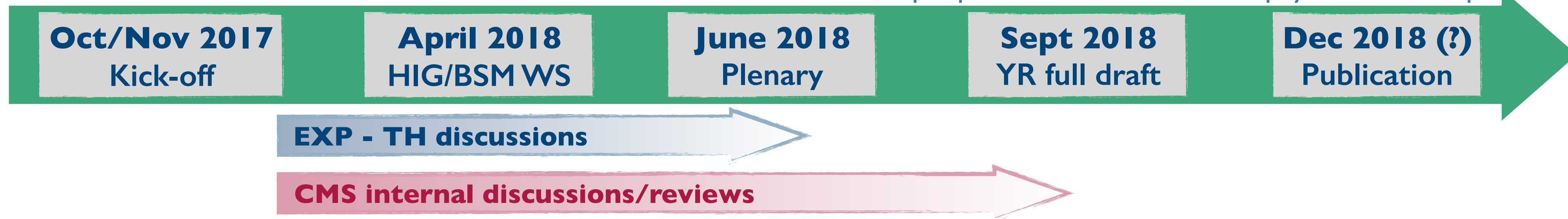


# Towards the HE/HL-LHC YR..

## Reminder: timeline, authorship, review, ...

- Effort/report timeline:

More info: <http://lpcc.web.cern.ch/hlhe-lhc-physics-workshop>



- Volume 1: will contain summary of public studies from experiments (authored by individuals)
- Approved CMS analyses will be made **public as CMS PAS-es towards/during summer** (fully included in Volume 2)

## Some common EXP/TH (HIG) organisational aspects:

- **Physics/results/presentation:**
  - Cover as wide spectrum of physics results as achievable (some overlap between WGs expected)
    - Define early enough the set of analyses and results for YR,
  - Agree on recommendation for extrapolation scenarios, ultimate experimental/theoretical systematics, etc.
- **Near-term future (HIG-related) discussions:**
  - ATLAS/CMS/LHCb pre-discussion today (on analyses, scope of results, extrapolation scenarios, combinations)
  - Discussion at HXSWG meeting next week (on plans and scope of results, theoretical systematics, etc.)
  - HIG/BSM workshop @FNAL in April 2018... and beyond...

# CMS HIG wishlist : a "brief" overview (I)

## H(125) couplings/properties measurements:

- Full-sim studies of prospects for several/individual channels
- Projections from combined Run-2 measurements @13 TeV
- Rare decays and anomalous couplings

scope / target	measurements / studies	type of study	YR chapter
<b>H(125) couplings/properties measurements</b>			
Prospects for several "important" channels/couplings	$H \rightarrow \gamma\gamma, H \rightarrow ZZ$	full-sim/Delphes	2, 4, 5
	$H \rightarrow \tau\tau, H \rightarrow \mu\mu$		2
	$ttH, tHq$	projections	2, 4
Projections from combination of measurements @13 TeV	combined HIG coupling "modifiers"	projections	2
	combined differential XS		
Rare decays & anomalous couplings	(HVV) anomalous couplings	projections	2
	$H \rightarrow cc, \text{boosted } ggH \rightarrow bb$	projections	7

- Many studies exist as public results: Snowmass, ECFA'16, CMS Phase-2 TP and TDRs, etc.
  - Update the results taking into account increased dataset and advanced exp. techniques
- **Projections:** BKG rates, efficiencies, exp. systematics extracted from expected performance for upgraded detector

# CMS HIG wishlist : a "brief" overview (2)

## HH measurements and self-coupling:

- Full-sim studies of prospects for main channels
- Combinations of HH measurements (cross-check with projections from 13TeV)

## BSM HIG searches:

- Full-sim/Delphes studies of several exotic signatures

scope / target	measurements / studies	type of study	YR chapter
<b>HH and self-coupling measurements</b>			
Prospects using main HH channels	$bb\tau\tau, bb\gamma\gamma, bbVV, bbbb, VBFHH$	full-sim/Delphes	3
	HH combinations		
Prospects from precision physics	$H \rightarrow \gamma\gamma$		
<b>BSM HIG searches</b>			
Exotic H(125) decays	$H \rightarrow \text{invisible}$	full-sim/Delphes	6
	$H \rightarrow \varphi_D \varphi_D \rightarrow 4\text{jets}, H \rightarrow \gamma_D \gamma_D \rightarrow 4\mu$		6
	LFV Higgs		7
Search for additional scalars	MSSM $H \rightarrow \tau\tau$	full-sim/Delphes	8
	Low-mass searches		8

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# Prospects for several production/decay modes

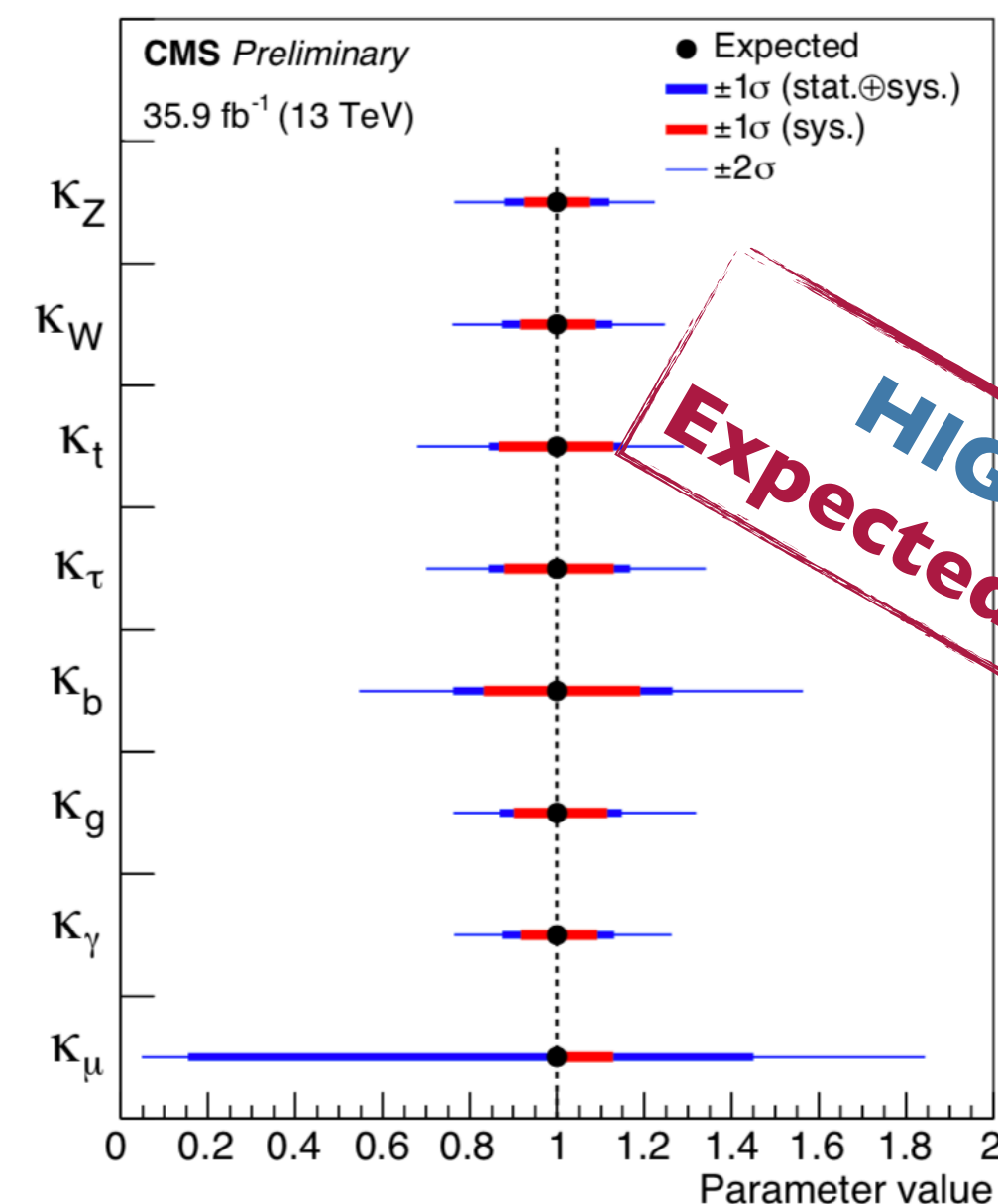
- **General:**
  - Dedicated full-sim/Delphes analyses for sensitivity to individual decay channels.
  - Studies used to **assess the systematics and inputs for projections** of 13TeV results.
- **Bosonic decay channels considered:**
  - **H** → **ZZ**: Provide sensitivity to individual **ggH/VBF/VH/ttH production modes** using  $H \rightarrow 4l$ .
  - **H** →  $\gamma\gamma$ : Obtain limits on **anomalous H(125) self-coupling** using single H production (see HH discussion)
- **Fermionic decay channels considered:**
  - **H** →  $\tau\tau$ , **H** →  $\mu\mu$ : Provide sensitivity to corresponding **fermionic couplings** (building on the existing CMS Phase-2 TDR studies).
  - **V(H → bb)**: Perform dedicated studies and provide sensitivity to **Hbb couplings** (and beyond...).
- **Yukawa  $Y_t$  coupling:**
  - **ttH and tHq**: Provide sensitivity to the **magnitude and sign of the H-top Yukawa** coupling. Projections from results @13TeV (systematic uncertainties to be understood in details).

# H(125) "couplings"

## Performance estimated using combined HIG coupling "modifiers" @13 TeV:

- Consider model(s) with the important physics message:  $K_t, K_b, K_\tau, K_\mu, K_W, K_Z, (+ K_g, K_\gamma)$

	ggF	VBF	VH	ttH
H → ZZ → 4l	•	•	•	•
H → $\gamma\gamma$	•	•	•	•
H → WW	•	•	•	•
H → bb	•		•	•
H → $\tau\tau$	•	•		•
H → $\mu\mu$	•	•		
H → inv	•	•	•	





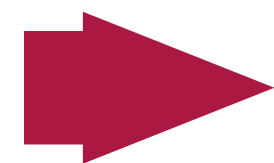
# H(125) "couplings"

## Performance estimated using combined HIG coupling "modifiers" @13 TeV:

- Consider model(s) with the important physics message:  $\kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_W, \kappa_Z, (+ \kappa_g, \kappa_\gamma)$

**Sanity-checks : comparisons to the "Snowmass" (and partially ECFA'16) results**  
(reported as % uncertainty, no change in systematics assumed) [arxiv:1307.7135](https://arxiv.org/abs/1307.7135)

L ( $\text{fb}^{-1}$ )	$\kappa_\gamma$	$\kappa_W$	$\kappa_Z$	$\kappa_g$	$\kappa_b$	$\kappa_t$	$\kappa_\tau$	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR <sub>SM</sub>
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]



**Update results on expected performance @3000fb<sup>-1</sup>**

**Expect to see a very good agreement overall.**

(Some differences:  $H \rightarrow Z\gamma$  will not be included, expect improvement in  $\kappa_t$  due to inclusion of  $ttH \rightarrow \text{multileptons}/\tau\tau$  analyses)

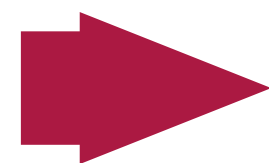
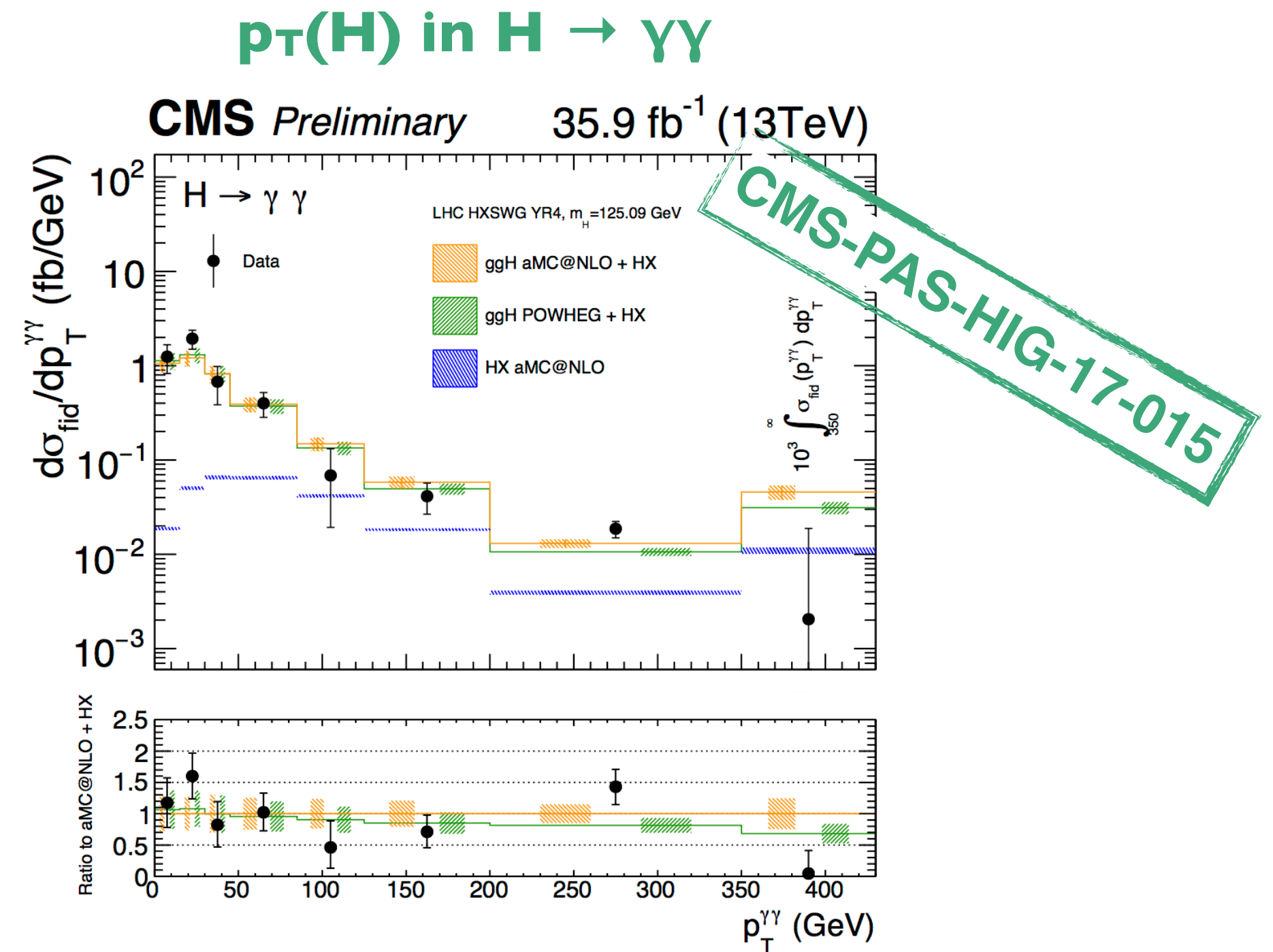
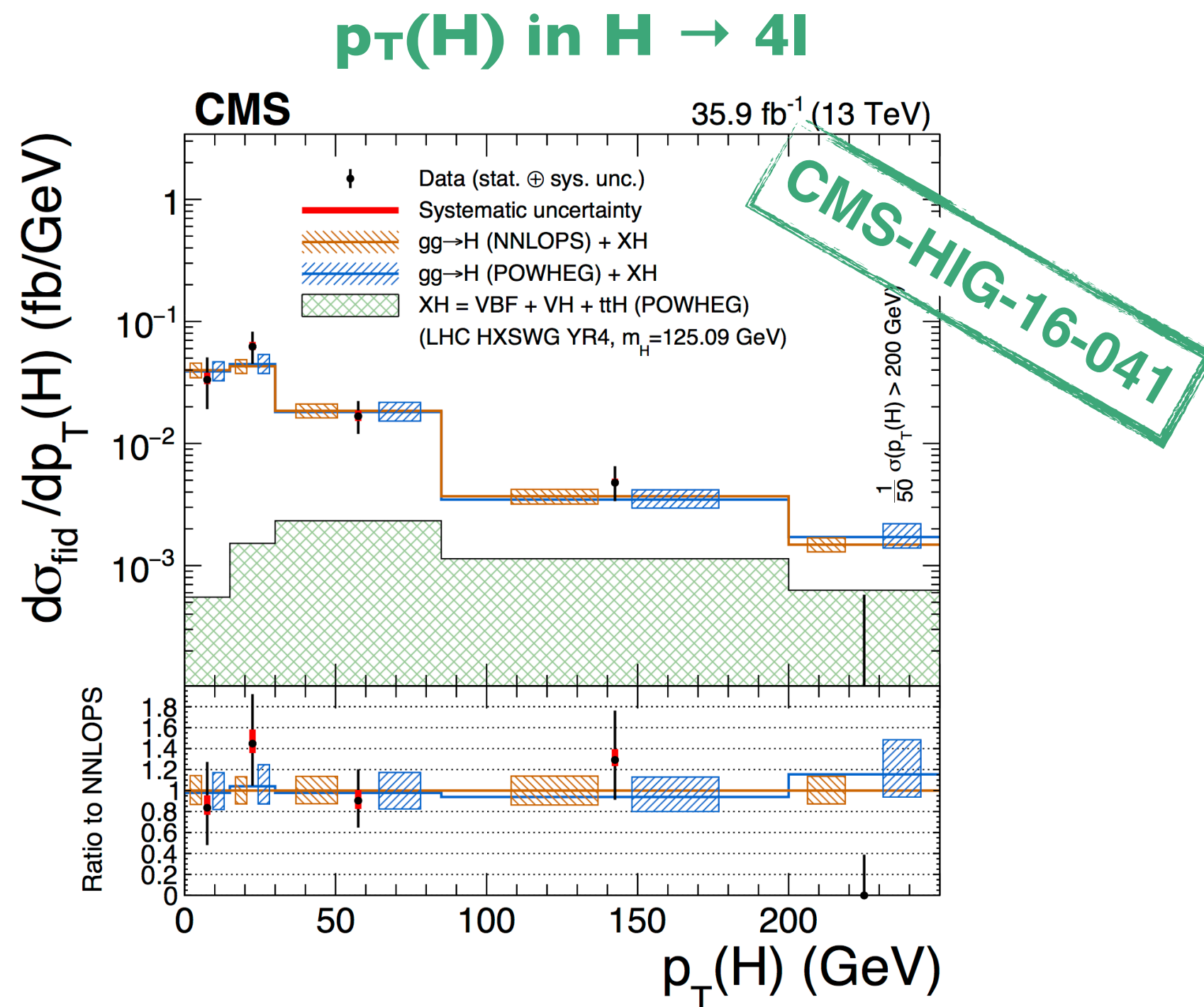
## Expected uncertainties and points to be understood/addressed:

- Experimental systematics generally dominates (partially will be reduced due to constraints from data).
  - Need to check if some can be reduced having in mind future improvements
- What measurements need to be performed to improve on limiting systematic uncertainties (fragmentation, hadronisation, underlying event, PDFs,...)?
- What are the limiting theory uncertainties and possible improvements (agree on scaling within HXSWG)?

# Differential cross sections

## Projections of the combination of fiducial differential XS @13 TeV (36.6 fb<sup>-1</sup>):

- Sensitivity to modelling of hard quark and gluon radiation, BSM effects in the loops, etc.
- Sensitivity from the shape important with higher lumi.



**Extrapolate differential measurements to @3000fb<sup>-1</sup>**

## Some points considered:

- Results will be based on binning defined/agreed between ATLAS and CMS for Run-2
- Extract limits on BSM models and/or EFT parameters? (competitiveness with direct probes of Higgs couplings)



# Anomalous HVV couplings

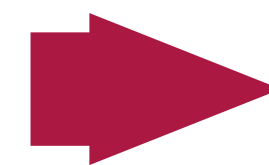
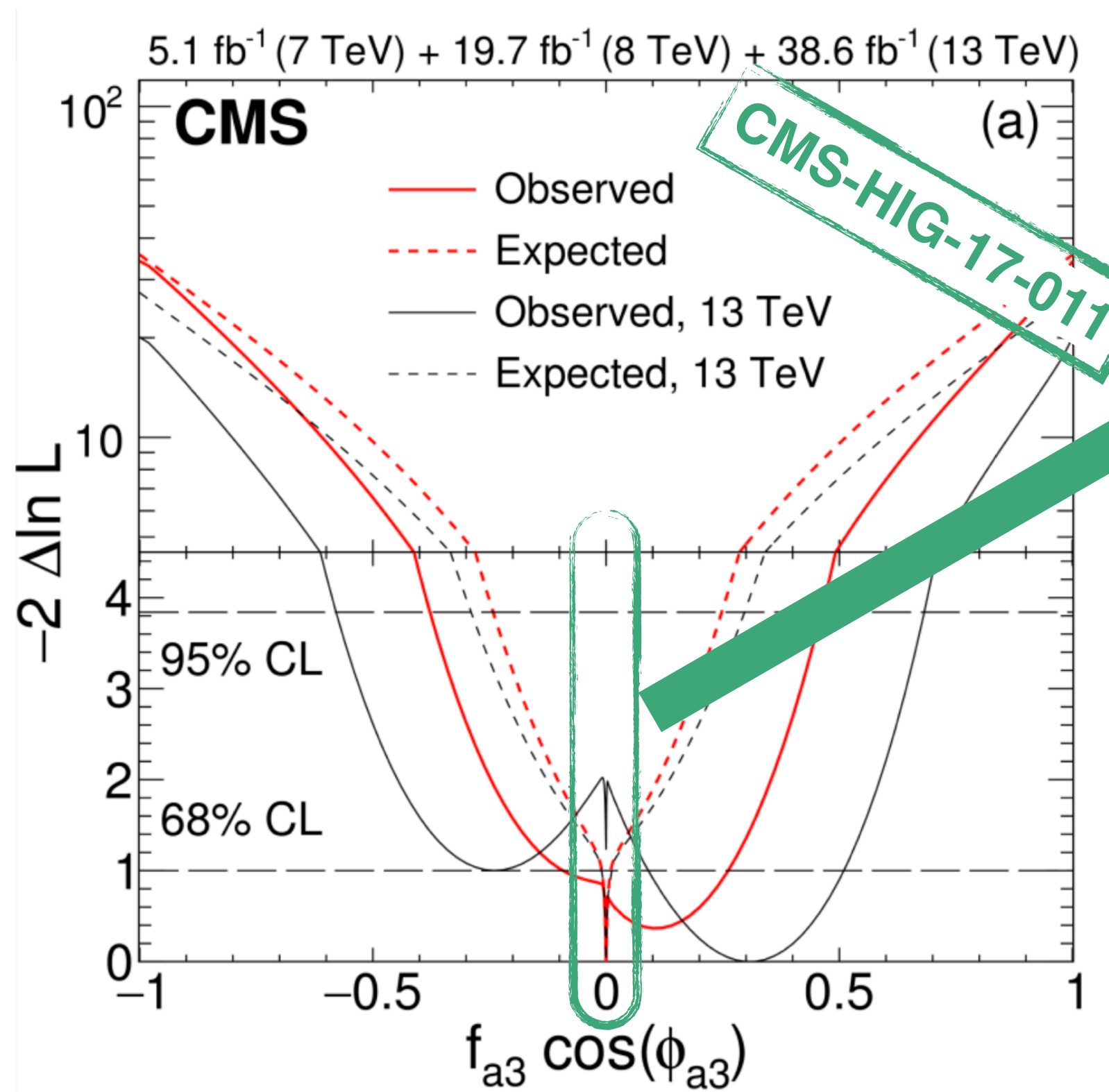
## Performance to be estimated using the $H \rightarrow 4\ell$ analysis @13 TeV.

- Parameterisation of decay amplitude:

$$A = \frac{1}{v} \left[ \underbrace{a_1^{VV}}_{\text{SM}} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\underbrace{(\Lambda_1^{VV})^2}_{\text{leading momentum expansion}}} + \frac{\kappa_3^{VV} (q_1 + q_2)^2}{\underbrace{(\Lambda_Q^{VV})^2}_{\text{higher order cp-even}}} \right] m_{V_1}^2 \epsilon_{V_1}^* \epsilon_{V_2}^* + \underbrace{a_2^{VV}}_{\text{cp-odd}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \underbrace{a_3^{VV}}_{\text{cp-odd}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

## YR extrapolation will be based on the new analysis/methodology:

- Sensitivity will be driven by production-level information @high-stat.



Extrapolate to @3000fb<sup>-1</sup>

Expect to have significant improvement (x50-100) in expected limits w.r.t ECFA'16 public results

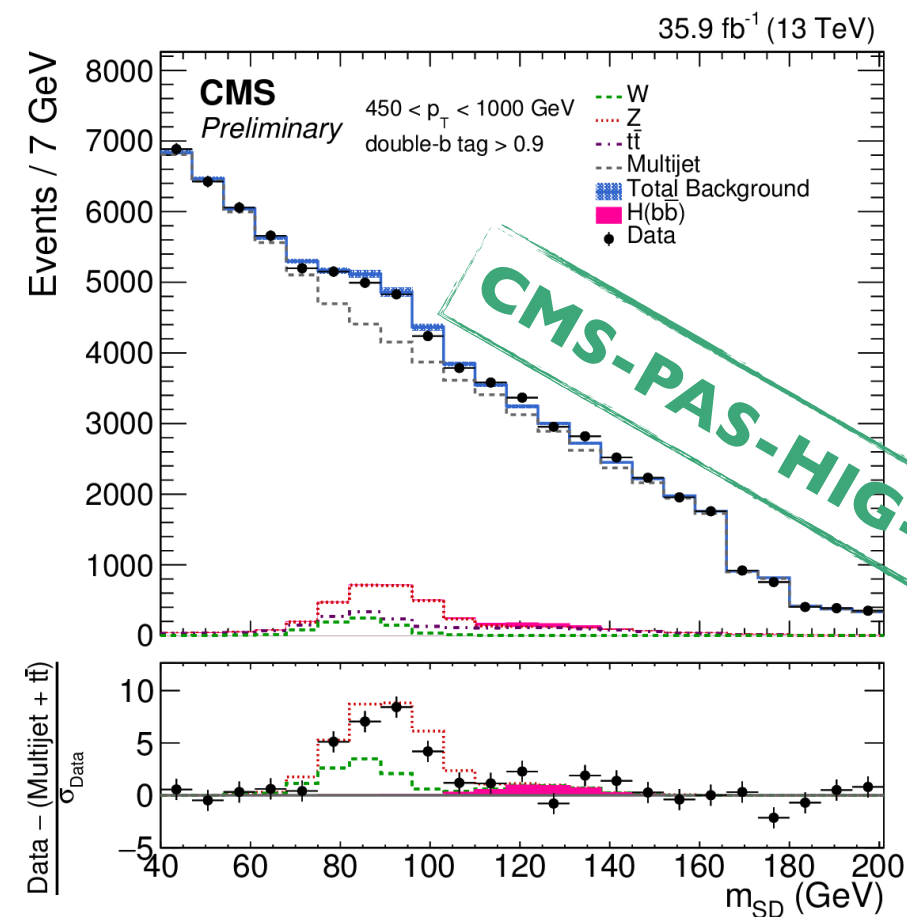
## Some points to be considered:

- Most sensitivity is from angles between jets - need to understand detector upgrade effects (jets acceptance)
- Should CMS/ATLAS express results in a common language (e.g. POs as discussed within HXSWG)?
- Possibility to separately perform analysis with fermionic decays to probe for anomalous HVV or Hff couplings. (e.g. as with  $H \rightarrow b\bar{b}$  in Run-1)

# (Anomalous) Hff couplings and rare decays

## Anomalous effects from boosted ggH → bb:

- Exploits boosted topologies - important to probe H(125) produced with high  $p_T(H)$ .



Extrapolate to @3000fb<sup>-1</sup>  
 in bins of p<sub>T</sub>(H)

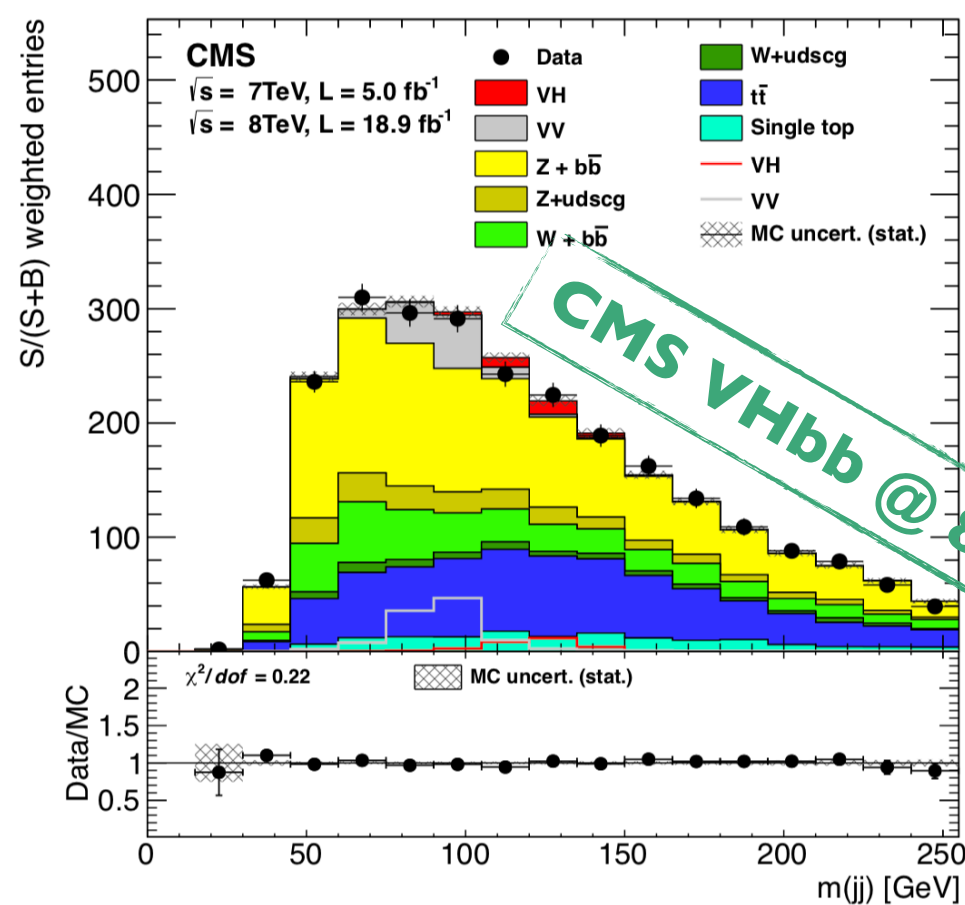


## Some points to consider:

- Possibility to extract limits on BSM and/or EFT parameters for effective  $K_t$ .
- Implies need for better theory description of high- $p_T(H)$  tails

## (Anomalous) H → cc couplings:

- Important long-term measurement for HL-LHC program that requires/benefits from large statistics

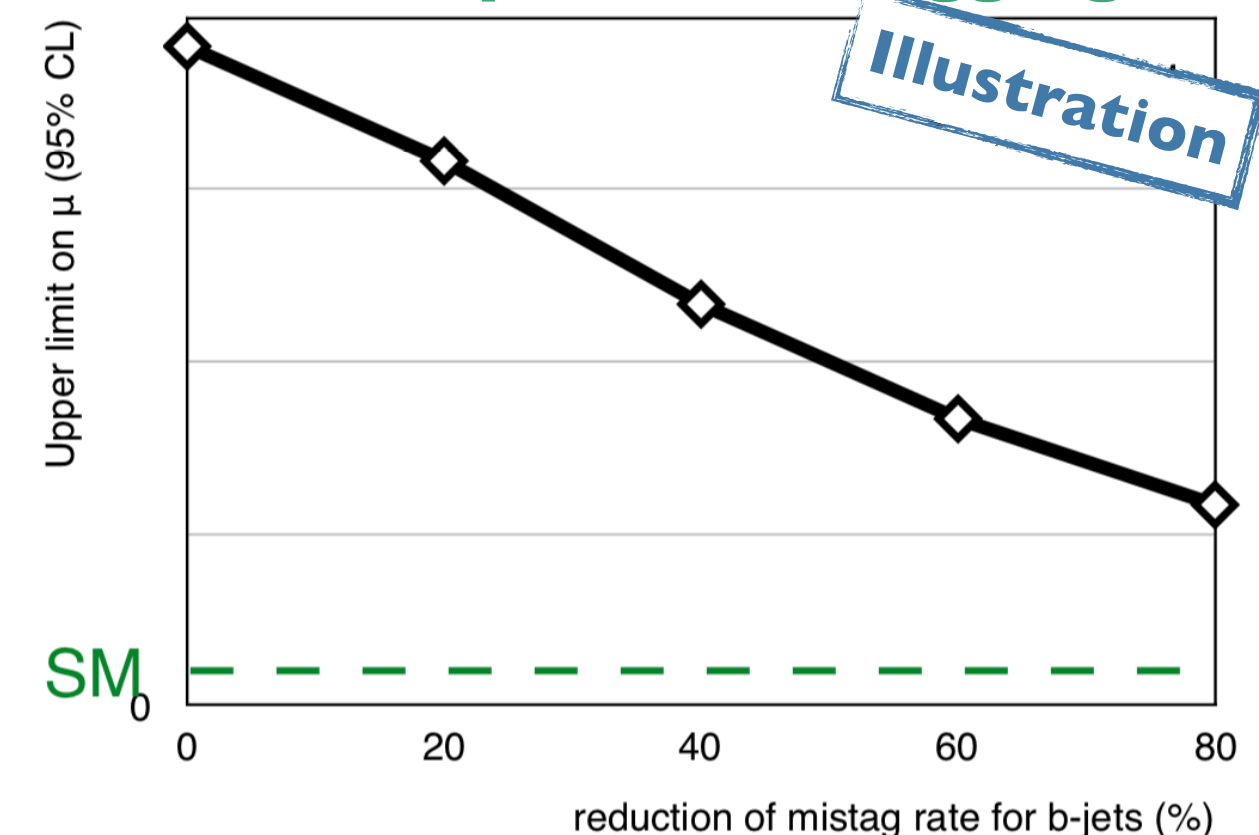


Projection as recast of  
 public CMS Hbb results



Limitation: Performance of the  
 flavour tagging (e.g. c-tagging)

## Upper limit on $\mu$ as function of an improved c-tagging

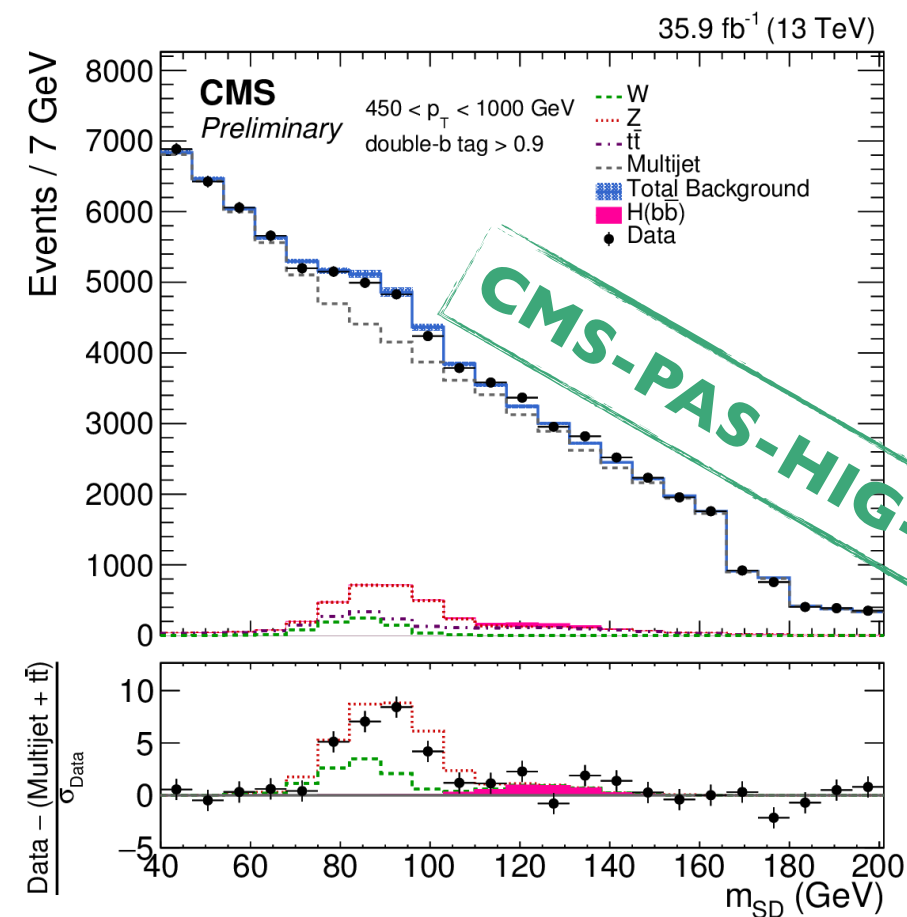




# (Anomalous) Hff couplings and rare decays

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- Exploits boosted topologies - important to probe H(125) produced with high  $p_T(H)$ .



CMS-PAS-HIG-17-010

Extrapolate to @3000fb<sup>-1</sup> in bins of p<sub>T</sub>(H)

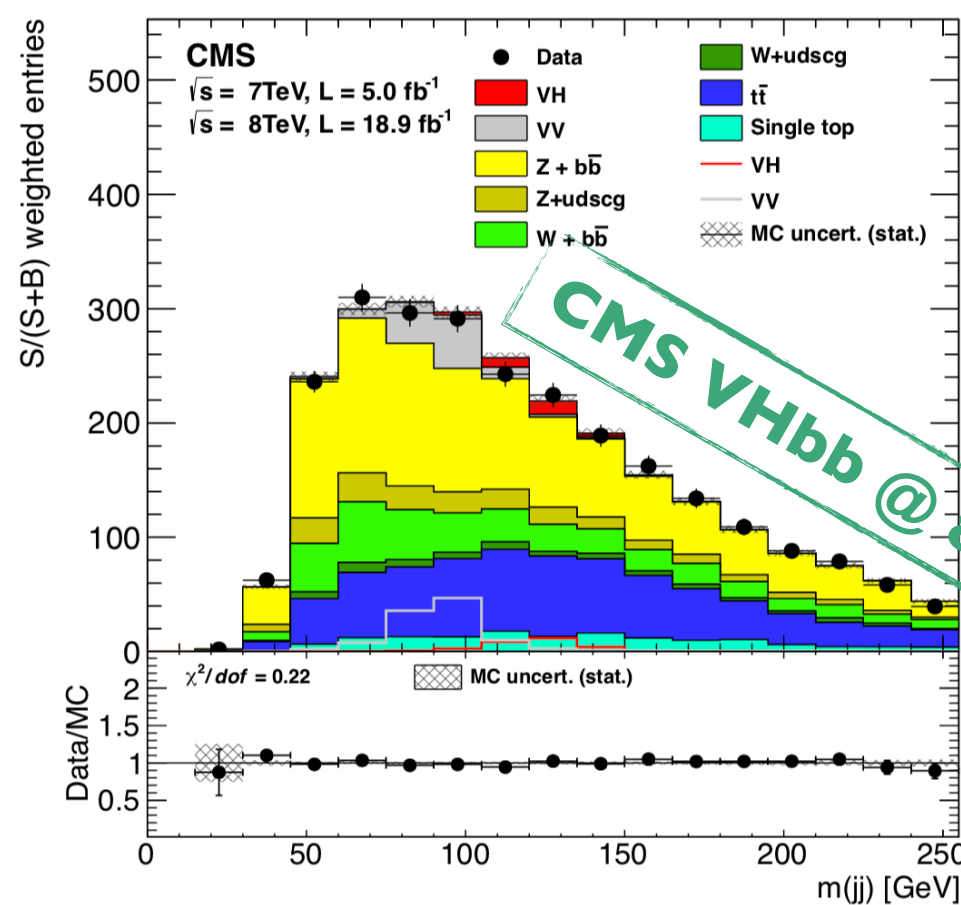


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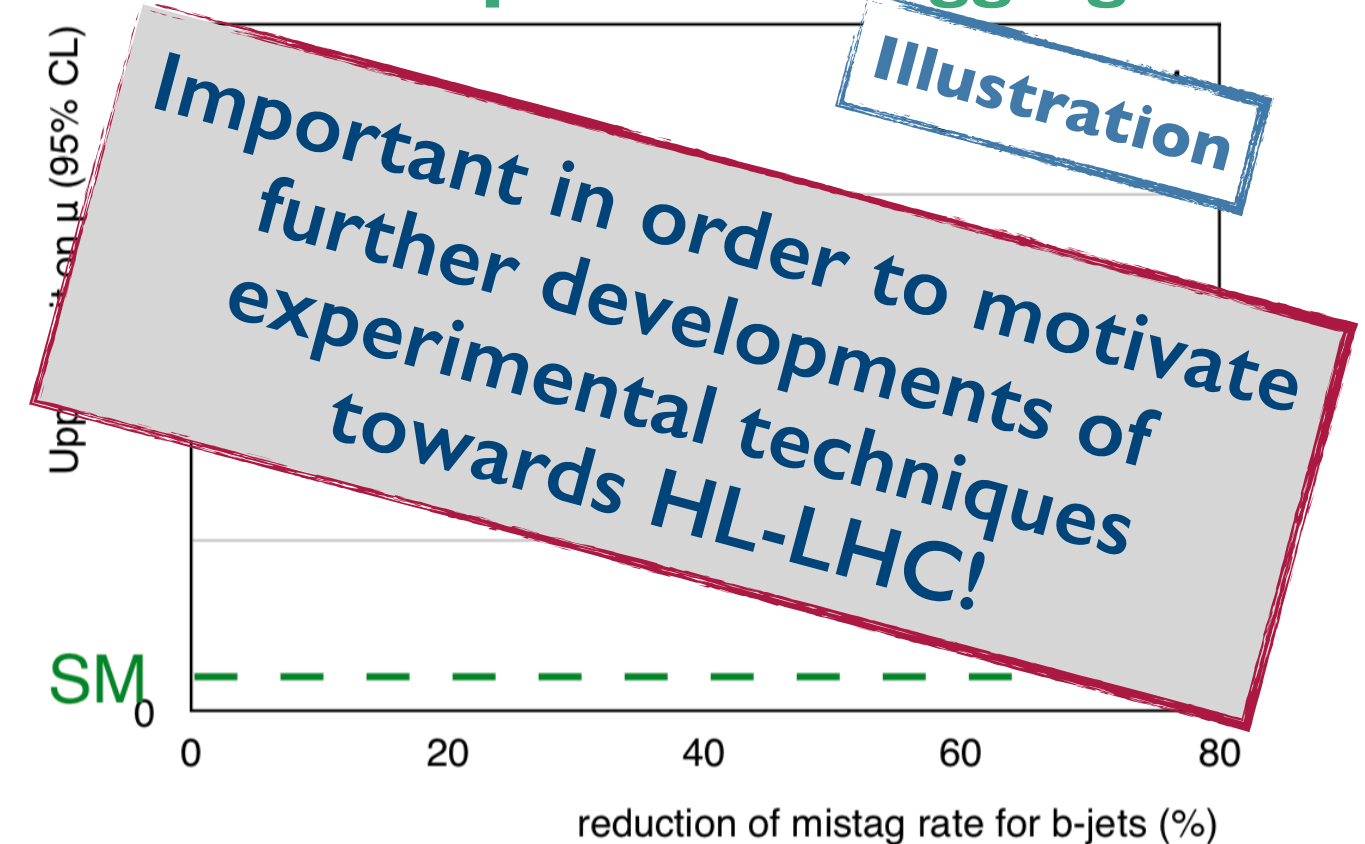
CMS VHbb @ 8 TeV

Projection as recast of public CMS Hbb results



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## Upper limit on μ as function of an improved c-tagging



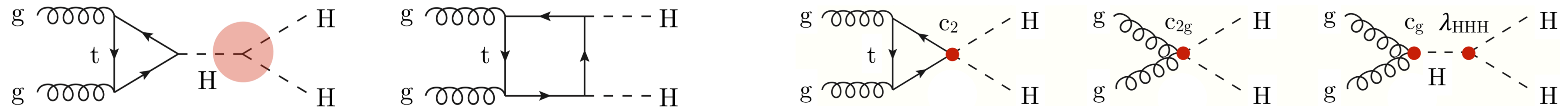
Important in order to motivate further developments of experimental techniques towards HL-LHC!

Illustration

# HH

## Probing HIG boson trilinear coupling $\lambda_{HHH}$ important @HL-LHC

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



## Plans for individual analyses and combination:

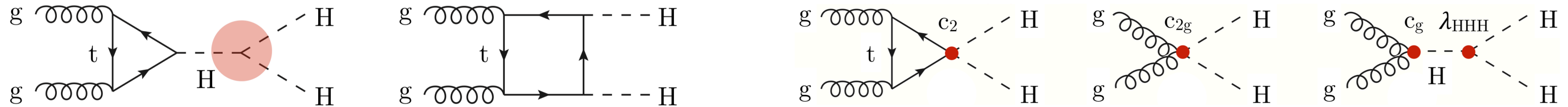
- Individual HH analyses based on full-sim/Delphes (**bbbb**, **bbVV**, **bb $\tau\tau$** , **bb $\gamma\gamma$** , also **VBF for VVHH studies**)
- Combination of all channels** (projection from CMS HH combination @13TeV as cross-check)
  - Possible combination with ATLAS projections (strong wish by HE/HL-LHC community)



# HH

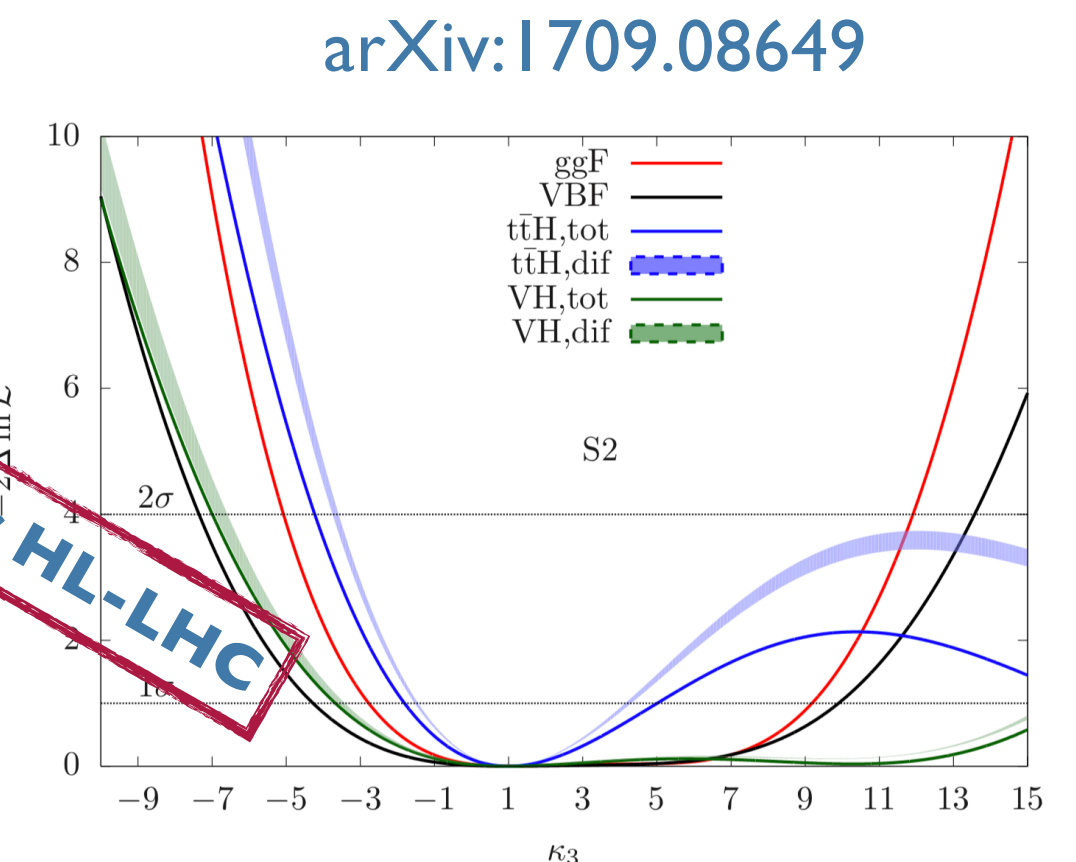
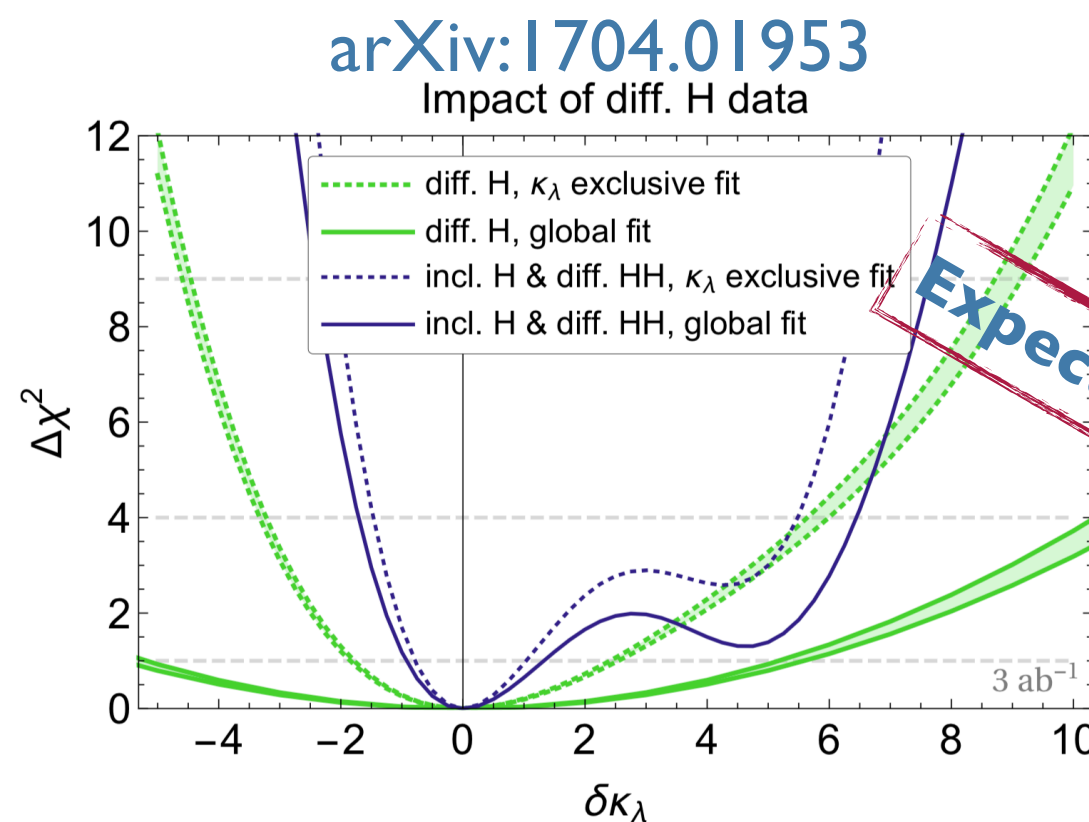
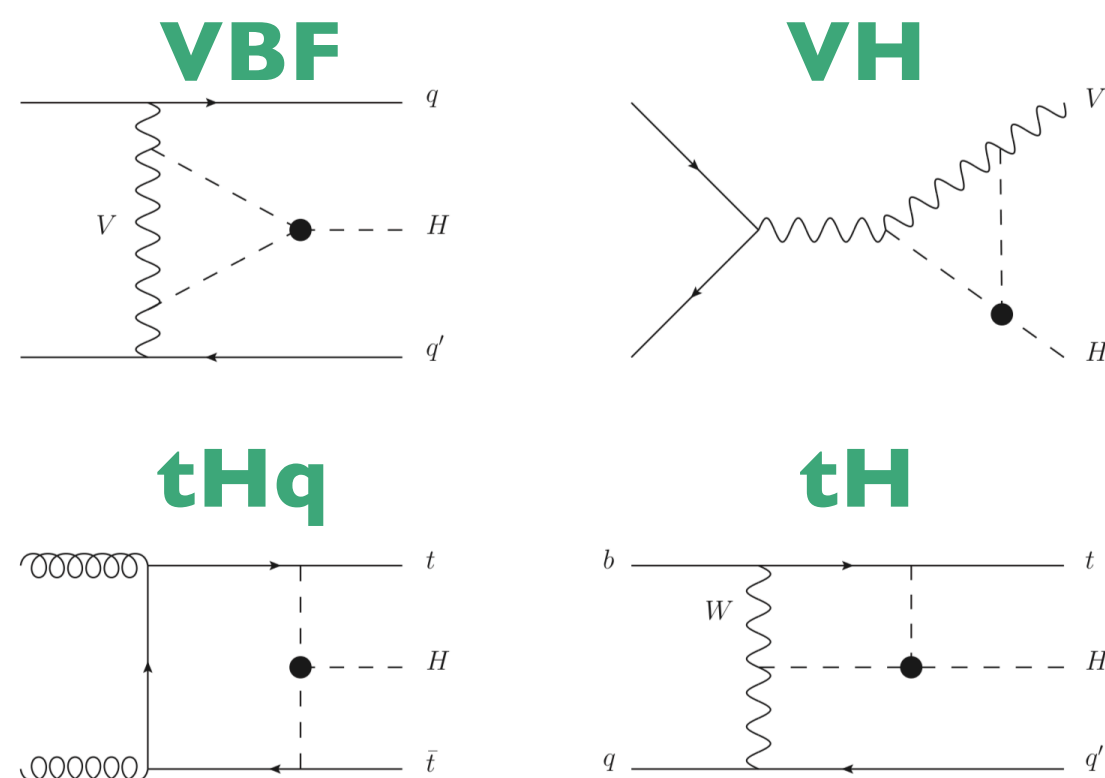
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## Plans for individual analyses and combination:

- Individual HH analyses based on full-sim/Delphes (**bbbb**, **bbVV**, **bb $\tau\tau$** , **bb $\gamma\gamma$** , also **VBF for VVHH studies**)
- Combination of all channels** (projection from CMS HH combination @13TeV as cross-check)
  - Possible combination with ATLAS projections (strong wish by HE/HL-LHC community)
- Possibility to **constrain  $\lambda_{HHH}$  from single Higgs precision measurements** (in  $H \rightarrow \gamma\gamma$  channel)
  - HH differential information further improves the measurement



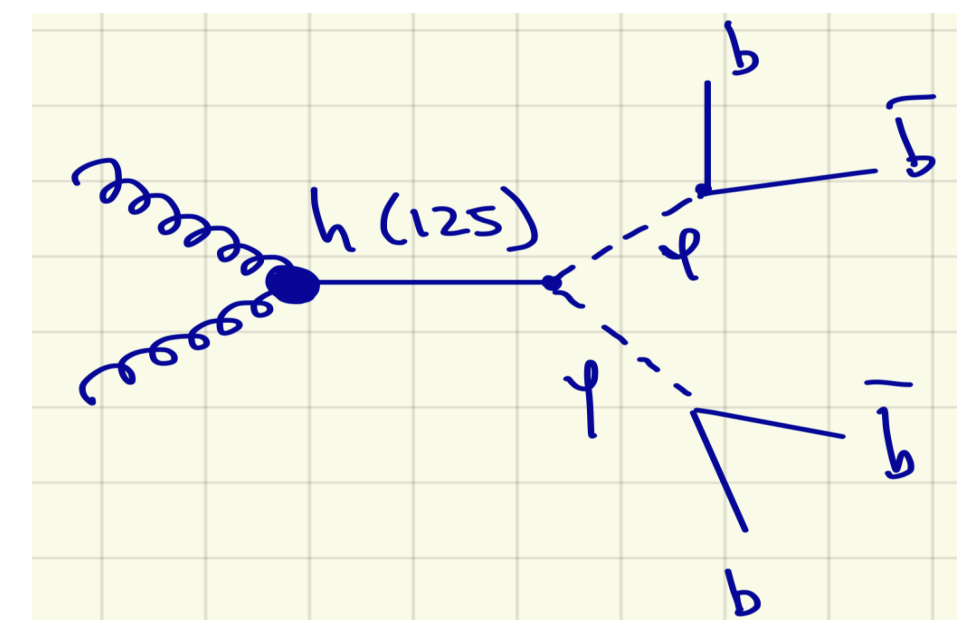
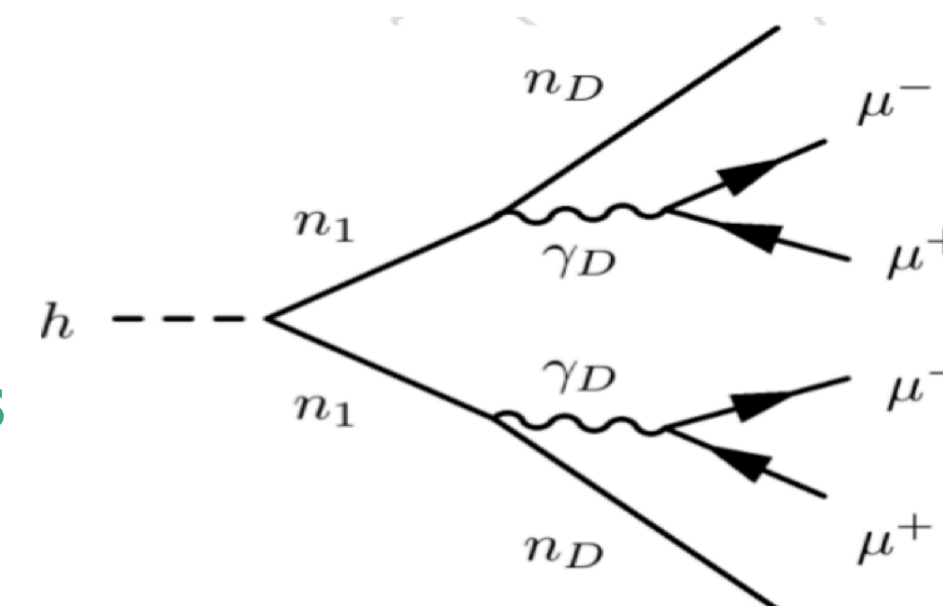
# Exotic H(125) decays

## H → invisible:

- Based on CMS Phase-2 TDR studies and Run-2 results with 36fb<sup>-1</sup>
- Primary effort in understanding MET performance @HL-LHC.

## H(125) as a portal to the "dark sector":

- **H → γ<sub>D</sub>γ<sub>D</sub> → 4μ** : Exploits signature with displaced muons.
  - Provide a (model-independent) **sensitivity for "dark" photons searches**
  - Exemplary case for **displaced muon reconstruction capabilities** of upgraded muon system @HL-LHC (impact of trigger thresholds, reconstruction efficiencies, etc.)
- **H → φ<sub>D</sub>φ<sub>D</sub> → 4jets** : Exploits signature displaced b-tagged jets.
  - Based both on ggH and VH production modes (first studies promising)
  - Exemplary case for **challenging LI triggers with "lifetime" tagging** @HL-LHC.



## LFV HIG decays:

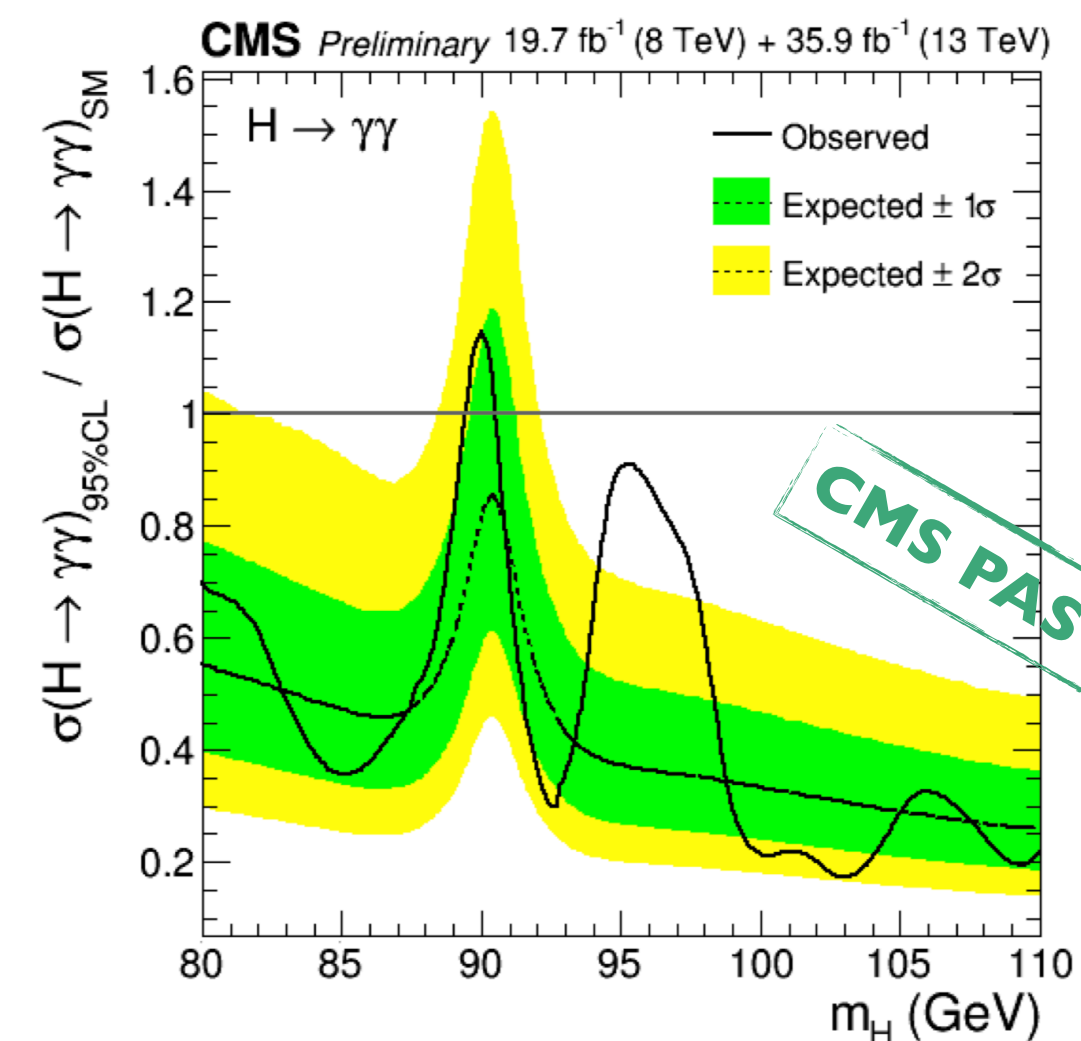
- Provide **sensitivity to searches for H → μτ and H → eτ LFV decays** (projections from Run-2: **HIG-17-001**)
- Roughly expect sensitivity @HL-LHC of 0.01%



# Additional BSM HIG searches

## Searches for additional low-mass Higgs bosons:

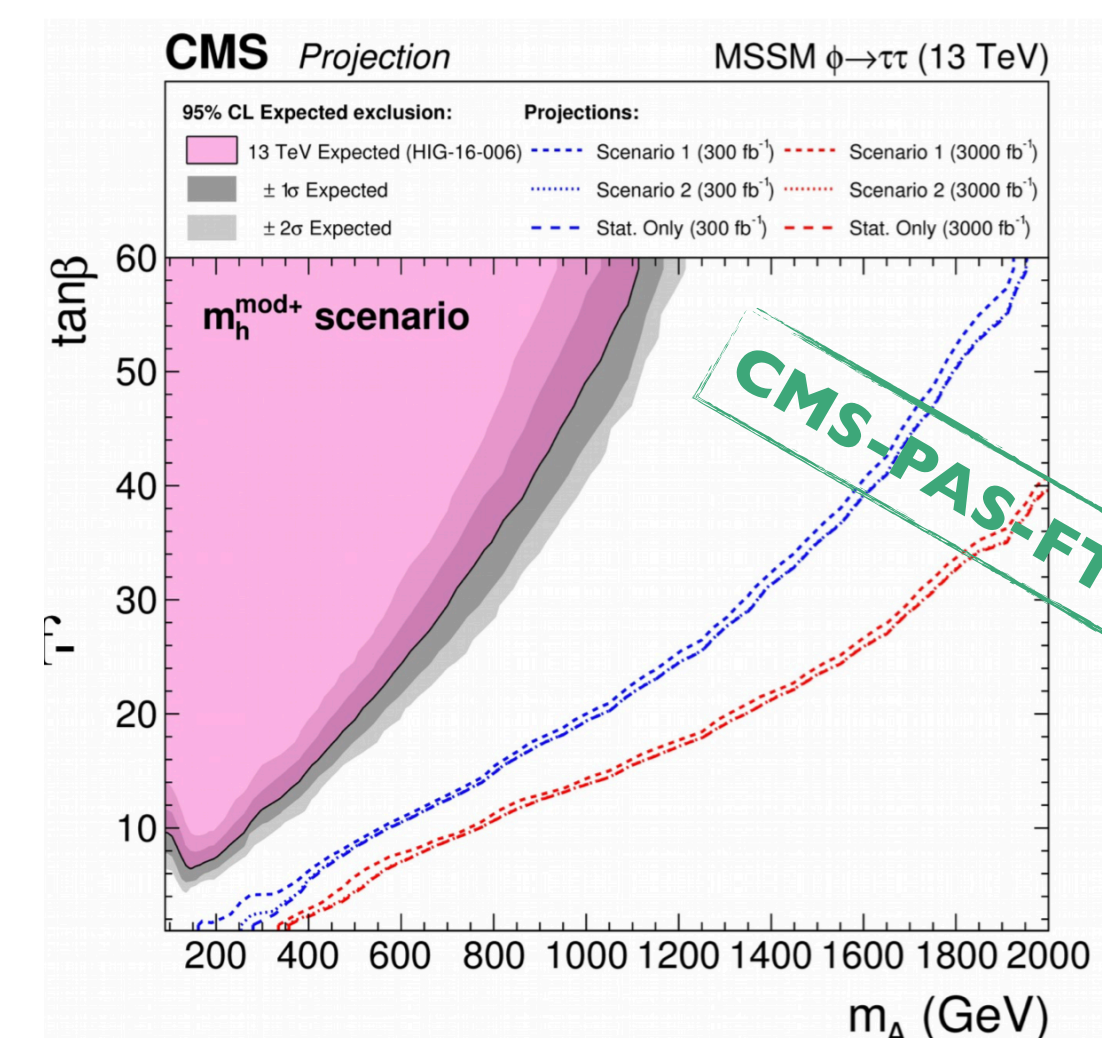
- High interest by the theory community in propagating Run2 low-mass searches to the HL-LHC.
- Build on the CMS Run-2 results for low-mass  $h$  searches in range  $70/80 < m_h < 110$  GeV
- Need dedicated study of fake photons and trigger issues.



## Search for MSSM $H \rightarrow \tau\tau$ decays:

- One of the key BSM Higgs searches: Most sensitive analysis over a large region of the MSSM parameter space.
- Extension of the ECFA'16 projections on the basis of the updated analysis with 36fb<sup>-1</sup> (plan to also perform study with Delphes)
- Exploring also possibility of adding  $H \rightarrow t\bar{t}$  prospects

## MSSM $H \rightarrow \tau\tau$ parameter scan:



# Preliminary HIG wish-list by CMS

scope / target	measurements / studies	type of study	YR chapter
<b>H(125) couplings/properties measurements</b>			
Prospects for several "important" channels/couplings	$H \rightarrow \gamma\gamma, H \rightarrow ZZ$	full-sim/Delphes	2, 4, 5
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Rare decays & anomalous couplings	(HVV) anomalous couplings	projections	2
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	LFV Higgs		7
Search for additional scalars	MSSM $H \rightarrow \tau\tau$	full-sim/Delphes	8
	Low-mass searches		8

## Next steps:

- Converge on list/scope of physics results for YR (although evolution of the results/analyses is still possible)
- Agree on extrapolation scenarios, ultimate experimental/theory systematics, combination, etc. (see next talks)